Imperial College London

CLFV2016: A Summary

Yoshi Uchida

Imperial College London

2nd International Conference on Charged Lepton Flavour Violation
20–22 June 2016, Charlottesville, Virginia

- Muon Experiments
  - $\mu \to e + \gamma$
    - From the beginnings of CLFV
    - MEG at PSI
    - Suppression of Muonic CLFV
  - Muon-to-Electron Conversion
    - Z-Dependence
    - Next Generation of Experiments
    - Decay of Muons Bound to Nuclei
    - Cautionary Tales
  - $\mu \to 3e$
  - Physics Reach of Experiments
- Other Experiments
  - NA48/2 and NA62
  - Current Anomalies in Data
  - Collider Experiments
- The Connection with Neutrinos
- Closing Remarks
  - Statistics in CLFV Physics and PhyStat-ν (next at Fermilab in September)
  - The First Signs of BSM Physics

1947

Nuclear Capture of Mesons and the Meson Decay

B. PONTECORVO
National Research Council, Chalk River Laboratory, Chalk River, Ontario, Canada
June 21, 1947

...Returning to the actual decay of the meson, an experiment suggests itself which might answer the following question: Is the electron emitted by the meson with a mean life of about 2.2 microseconds accompanied by a photon of about 50 Mev? This experiment is being attempted at the present time, since it is felt that the available analysis[10] of the soft component in equilibrium with its primary meson component is probably insufficient to decide definitely whether the meson decays into either an electron plus neutral particle(s) or electron plus photon.

1947

10 years after discovery of the muon

having been distinguished from Yukawa's meson (Conversi *et al*)

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- Weak interaction universality from atomic e and μ-capture
  - discussion of whether muon decay involves "β-decay"s: $\mu \to e + \nu$ (with a single type of neutrino)

1947

Search for Gamma-Radiation in the 2.2-Microsecond Meson Decay Process

E. P. Hincks and B. Pontecorvo
National Research Council, Chalk River Laboratory, Chalk River, Ontario, Canada

December 9, 1947

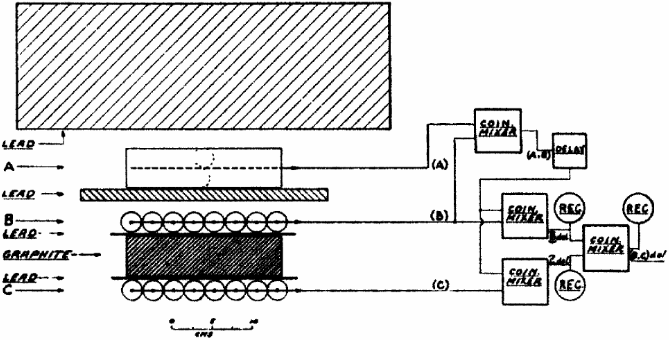
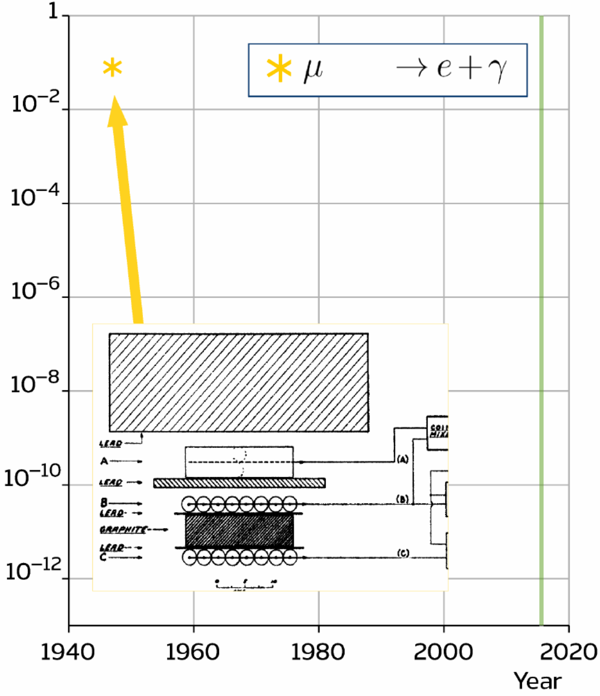


FIGURE 1 - ARRANGEMENT OF APPARATUS

Charged Lepton Flavour Violation



90% C.L.
upper limit on
branching ratios

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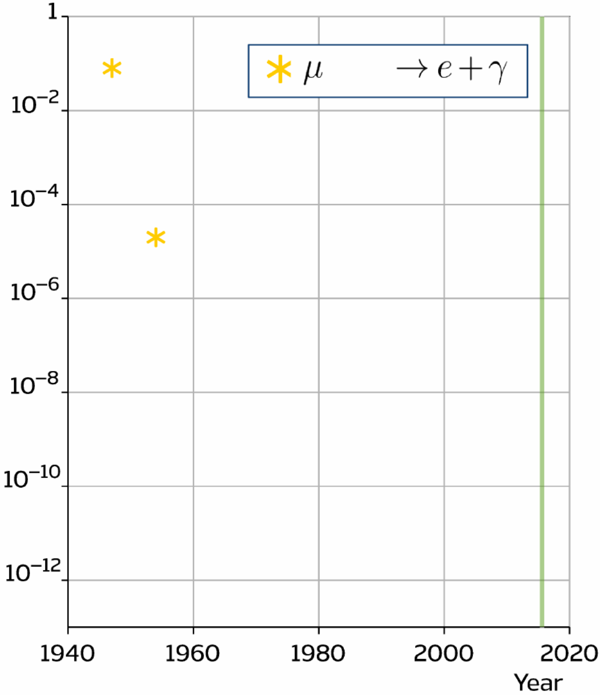
Charged Lepton Flavour Violation



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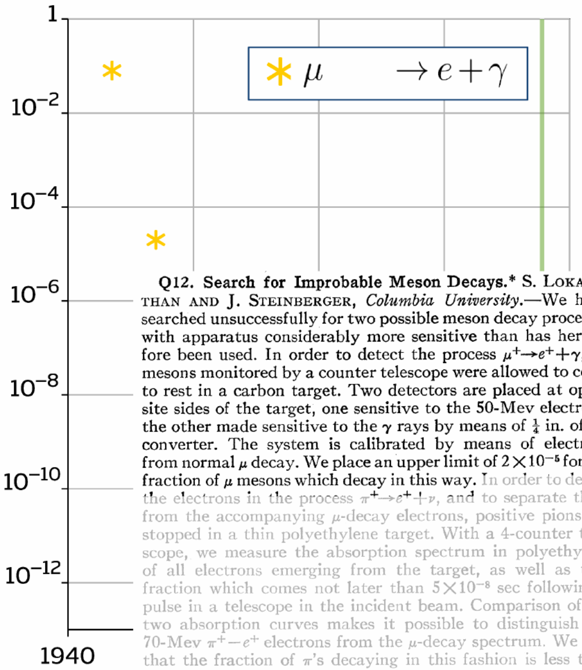
Charged Lepton Flavour Violation

Minutes of the 1954 APS Thanksgiving Meeting

90% C.L. upper limit on branching ratios



Q12. Search for Improbable Meson Decays.* S. Lokanathan and J. Steinberger, *Columbia University.*—We have searched unsuccessfully for two possible meson decay processes with apparatus considerably more sensitive than has heretofore been used. In order to detect the process $\mu^+ \to e^+ + \gamma$, π^+ mesons monitored by a counter telescope were allowed to come to rest in a carbon target. Two detectors are placed at opposite sides of the target, one sensitive to the 50-Mev electrons, the other made sensitive to the γ rays by means of $\frac{1}{4}$ in. of Pb converter. The system is calibrated by means of electrons from normal μ decay. We place an upper limit of 2×10^{-5} for the fraction of μ mesons which decay in this way. In order to detect the electrons in the process $\pi^+ \to e^+ + \nu$, and to separate them from the accompanying μ-decay electrons, positive pions are stopped in a thin polyethylene target. With a 4-counter telescope, we measure the absorption spectrum in polyethylene of all electrons emerging from the target, as well as that fraction which comes not later than 5×10^{-8} sec following a pulse in a telescope in the incident beam. Comparison of the two absorption curves makes it possible to distinguish the 70-Mev $\pi^+ - e^+$ electrons from the μ-decay spectrum. We find that the fraction of π's decaying in this fashion is less than 5×10^{-5}.

* This work was performed under the joint program of the Office of

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1959

ELECTROMAGNETIC TRANSITIONS BETWEEN μ MESON AND ELECTRON*

S. Weinberg†
Columbia University, New York, New York

G. Feinberg‡
Brookhaven National Laboratory, Upton, New York

(Received June 15, 1959)

The existence of the ordinary μ decay, $\mu \to e + \nu + \bar{\nu}$, seems to prove that the muon and electron do not differ in any quantum numbers.[1] It follows that weak electromagnetic transitions between muons and electrons could occur, if there is a mechanism to produce them. For example, one such mechanism would exist if the μ decay was not caused by a direct $\bar{\mu}e\bar{\nu}\nu$ Fermi interaction but instead involved a virtual charged boson. This particular possibility seems ruled out, since the predicted[2] rate for $\mu \to e + \gamma$ would be considerably greater than the upper limit set by recent experiments.[3,4] The purpose of this note is to discuss phenomenologically (without attachment to any specific mechanism) other kinds of electromagnetic transitions between muon and electron that may be possible even if $\mu \to e + \gamma$ is somehow suppressed.

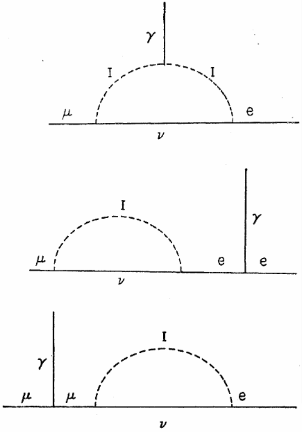

FIG. 1. Feynman diagrams for $\mu \to e + \gamma$ through an intermediate boson. I labels the intermediate boson field.

Feinberg, 1958

Lepton Flavour Conservation to $O(10^{-6})$

- Severe constraint on models of the weak interaction
- New conservation laws
- Forced lepton flavour conservation to be written into SM

1955

Considering electric **charge conservation as a model** for (heavy) **particle number conservation**

Phys. Rev. 98, 5 (1955)

Conservation of Heavy Particles and Generalized Gauge Transformations

T. D. Lee, *Columbia University, New York, New York*

and

C. N. Yang, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 2, 1955)

The possibility of a heavy-particle gauge transformation is discussed.

If we take the conservation of heavy particles to mean invariance under the transformation

$$\psi_N \rightarrow e^{i\alpha}\psi_N, \quad \psi_P \rightarrow e^{i\alpha}\psi_P, \tag{1}$$

Such a gauge transformation is formally completely identical with the electromagnetic gauge transformation. Invariance under such a transformation therefore necessitates the existence of a neutral vector massless field coupled to all heavy particles. A nucleon would have a "heavy-particle charge" of $+\eta$ in such a field and an antinucleon would have a "heavy-particle charge" of $-\eta$. The force between two massive bodies therefore would contain a contribution from the Coulomb-like repulsion between such "heavy-particle charges." The total force including the gravitational attraction is:

$$\text{Force} = -G(M_1M_2/R^2) + \eta^2(A_1A_2/R^2). \tag{2}$$

Here M_1, M_2, A_1, and A_2 are the inertia masses and mass numbers of the two bodies.

1955

Conservation of electric charge is a consequence of gauge invariance and a massless gauge boson

Similar arguments for particle number conservation lead to a repulsion between the conserved particles

Gauge invariance cannot explain "heavy particle" number (baryon number, lepton number etc) conservation

Phys. Rev. 98, 5 (1955)

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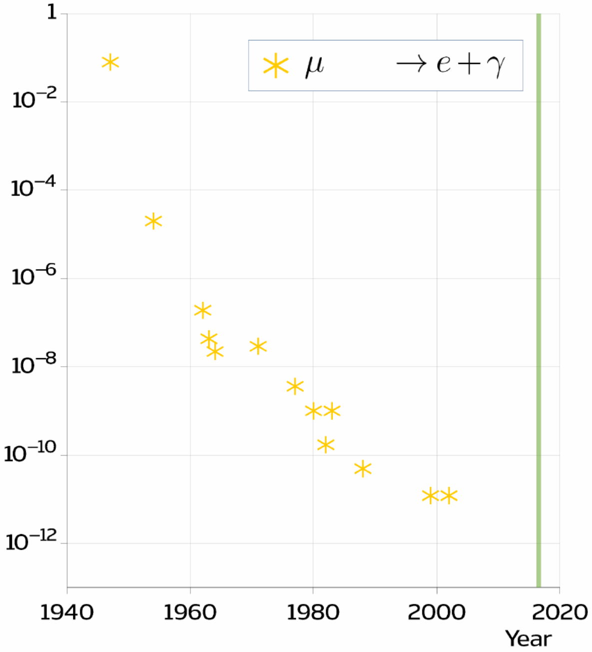
Lepton Flavour Conservation in the Standard Model

- In the Standard Model:
  - Lepton flavour is conserved absolutely
    - not through a fundamental principle, but **through the *choice* of fields**
    - an *accidental* symmetry

- Deviations from the SM can introduce Lepton Flavour Violation

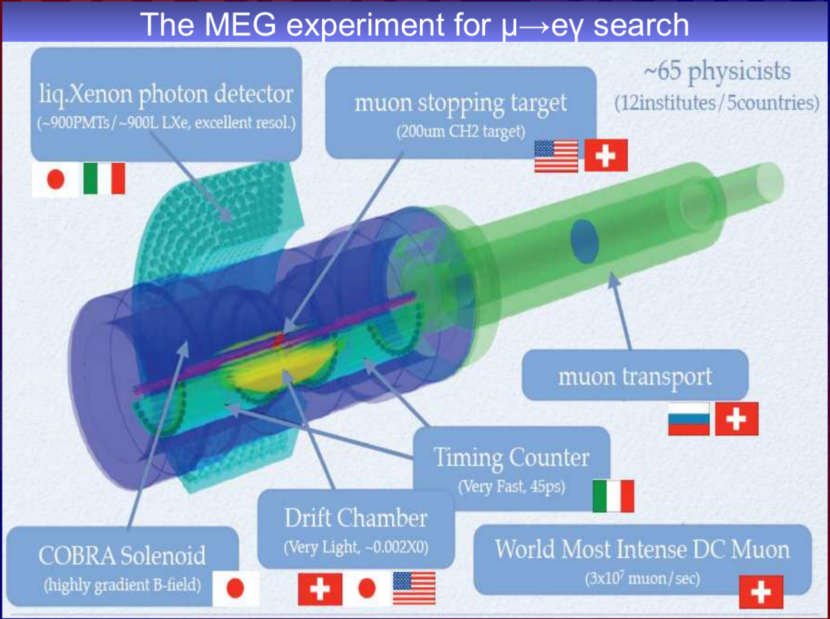
Muonic CLFV

Before MEG (ca. 2002)



90% C.L.
upper limit on
branching ratios

MEG at PSI



Cecilia Voena

MEG at PSI

From CLFV203, Lecce

- In 2013, data-taking was about to come to an end
- Final results released this year
- MEG-II Upgrade to start taking data soon

Conclusions

- First $\mu \to e\gamma$ search with $O(10^{-13})$ sensitivity
  - Sensitivity : 7.7×10^{-13}
  - No excess was found
  - 4 times stringent new limit : $\mathcal{B} < 5.7\times10^{-13}$ @ 90% C.L.
- Data taking will be done until summer 2013
  - Double the statistics
  - Expected sensitivity : $\sim5\times10^{-13}$
- Upgrade proposal was accepted, and R&D ongoing
  - More intense beam, double the efficiency and half the resolutions.
  - Expected sensitivity : $\sim5\times10^{-14}$ in 3 years starting from 2016

Related posters

"Measurement of inner Bremsstrahlung in polarized muon decay with MEG"	by Y. Uchiyama
R&D on the drift chamber for MEG upgrade	by L. Galli et al
Active target for MEG upgrade	by A. Papa et al

MEG at PSI

Cecilia Voena

- In 2013, data-taking was about to come to an end
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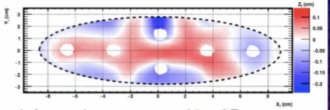
Improvements in the analysis vs last publication

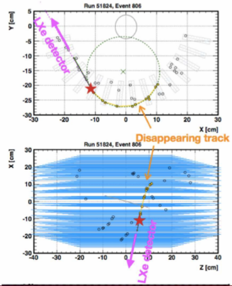
- Non planar, non negligible target deformation observed
  - taken into account in the likelihhod analysis
  - 13% worse sensitivity

Comparison 2009-2011 vs last publication ok



deformation measured by 3D scanner

- Photons from e+ annihilations inside DC were identified & removed
  - background rejection~2%
  - signal inefficiency~1%
- Revised the algorithm to recover missing first turn of positron in the DC
  - Signal efficiency improved by 4%



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Some difficulties; much to learn from their experience

MEG at PSI

Cecilia Voena

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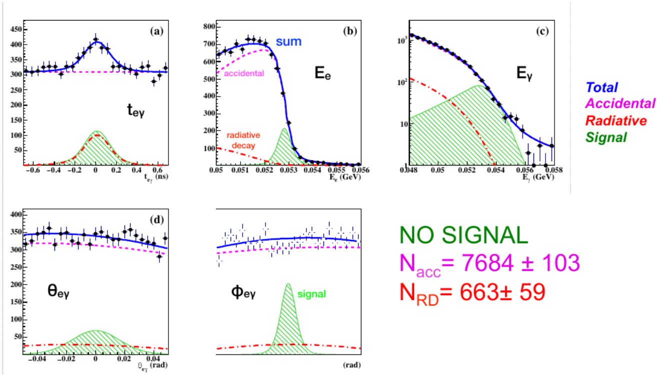
Unblinding the full data set: likelihood fit

The best fitted likelihood function (projection) is shown
"Signal" is magnified for illustrative purposes



NO SIGNAL
N_{acc} = 7684 ± 103
N_{RD} = 663± 59

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MEG at PSI

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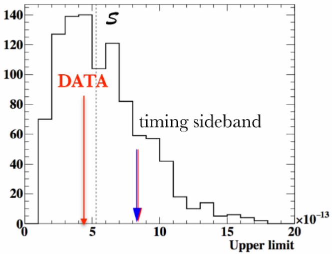
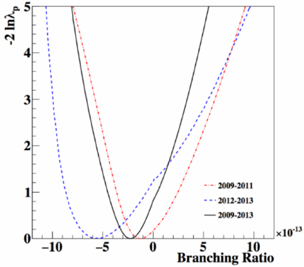
BR(μ→eγ) limit result

BR (μ→eγ) < 4.3x 10^{-13} at 90% C.L.

submitted to EPJC





Note: Upper limit from frequentistic procedure a la Feldman-Cousins

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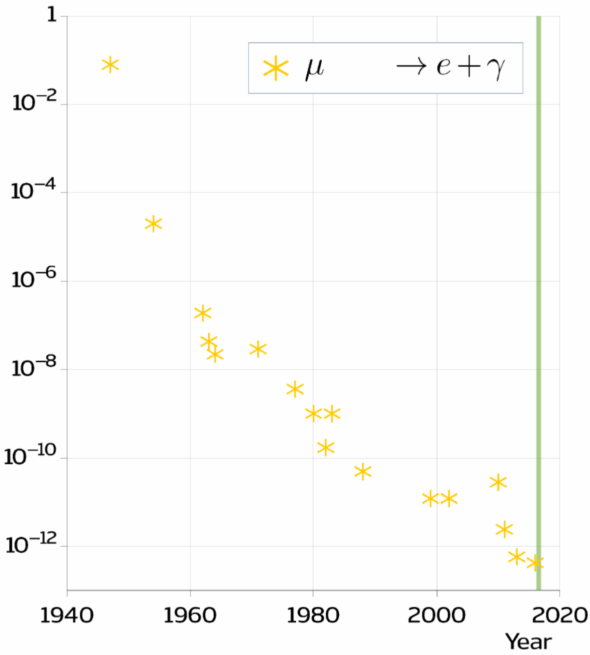
Muonic CLFV

After MEG (2016)



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MEG at PSI

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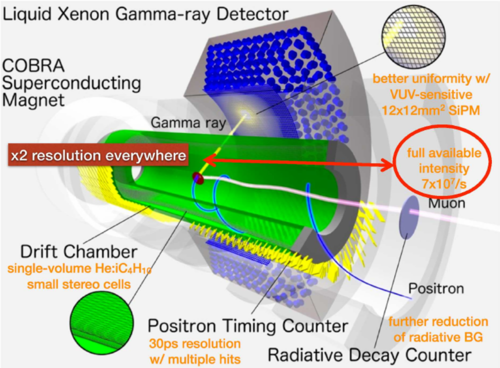
Next: MEG upgrade: MEG-II

- Extending the search of $\mu \to e\gamma$ is complementary to New Physics searches at the high energy frontier



optimized to enhance sensitivity (accidental background prop. to I^2_μ)

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MEG at PSI

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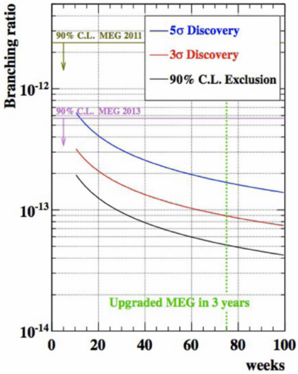
MEG-II goals

- **Beam rate ~7×10^{7} μ/s**
- **Final sensitivity: 4×10^{-14}**

PDF parameters	Present MEG	Upgrade scenario
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad)	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency (%)		
trigger	≈ 99	≈ 99
γ	63	69
e^+	40	88



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MEG at PSI

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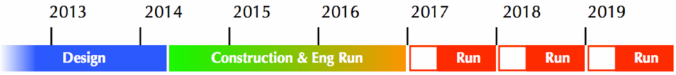
MEG-II schedule

- Successfull pre-engineering run in late 2015
- Engineering run foreseen at end of 2016 with several parts of the MEG-II detector
- Expect full detector ready and run in 2017



Note: this schedule assume exclusive use of PiE5 beam line by MEG-II

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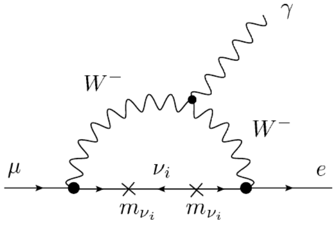
Suppression of Muon CLFV Originating from Massive Neutrinos

Suppression of CLFV originating from $m_\nu \neq 0$:

- from small neutrino masses?
- or GIM mechanism?

In the standard model with tiny neutrino masses



$$\mathrm{BR}(\mu \to e\gamma) \sim \frac{m_\nu^4}{m_W^4} < 10^{-50}$$

Charged lepton flavor violation, $\mu \to e\gamma$, is induced, but very tiny

Kazuhiro Tobe

Suppression of Muon CLFV Originating from Massive Neutrinos

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- from small neutrino masses?
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Flavor changing effects in SM

Couplings of Brout–Englert–Higgs boson h to fermions:

$$-\mathcal{L} = \sum_{f=e,\mu,\tau,d,s,b,u,c,t} h\left(\frac{m_f}{v}\right)\overline{f}f\,.$$

Flavor violation in SM only for quarks via CKM matrix (charged currents), lepton flavor is conserved.

Even non-zero neutrino masses typically only induce *tiny* LFV. E.g. light Dirac neutrinos:

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu_\alpha \overline{\nu}_\beta)} \simeq \frac{3\alpha_{\text{EM}}}{32\pi}\left|\sum_{j=2,3} U_{\alpha j}\frac{\Delta m^2_{j1}}{M_W^2}U^\dagger_{j\beta}\right|^2 < 5\times 10^{-53}\,.$$

LFV = new physics!

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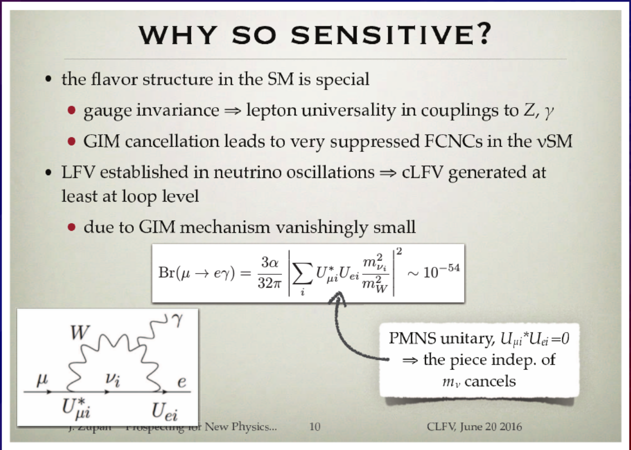

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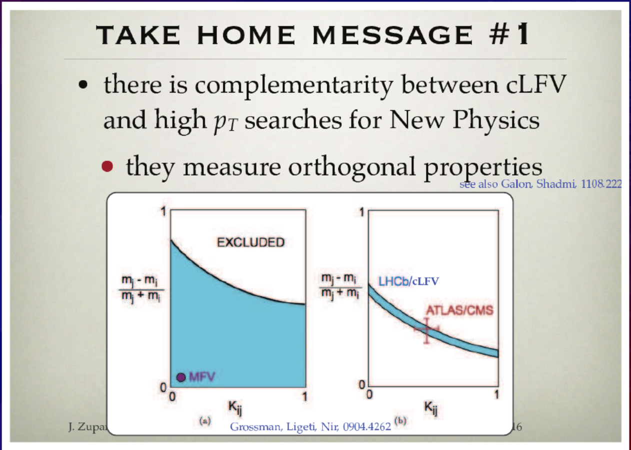
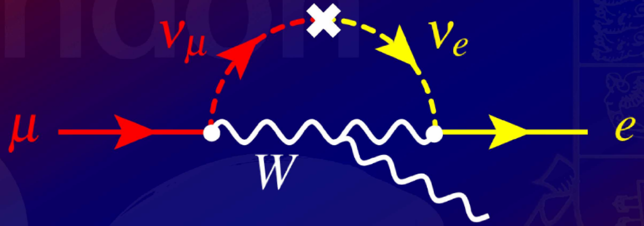


Suppression of Muon CLFV

- **Beyond-the-Standard Model Physics** can cause CLFV
  - e.g. **introduction of non-zero neutrino mass**

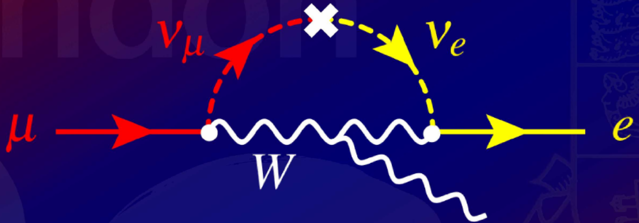


- but this is ***GIM-suppressed:***

$$\mathrm{Br}(\mu \to e\gamma) \sim 10^{-54} \times \frac{\sin^2 2\theta_{13}}{0.15}$$

Suppression of Muon CLFV

- **Beyond-the-Standard Model Physics** can cause CLFV
  - e.g. **introduction of non-zero neutrino mass**



  - but this is ***GIM-suppressed:***

$$\mathrm{Br}(\mu \to e\gamma) \sim 10^{-54} \quad \left(\sim \frac{m_\mu}{30 m_\oplus}\right)$$

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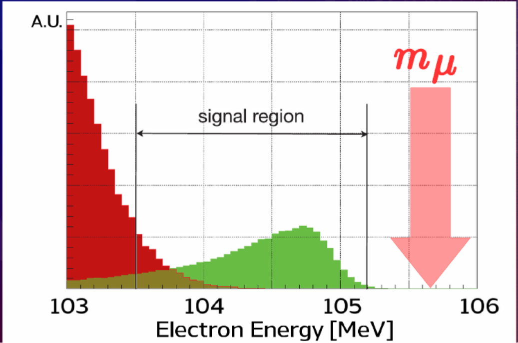
Muon-to-Electron Conversion

- Search for the process

$$\mu^- + N(A,Z) \quad \rightarrow \quad e^- + N(A,Z)$$

muonic atom — mono-energetic electron ($E_e \leq$105 MeV)

- Time available after formation of muonic atom: up to about **1 microsecond (Z-dependent)**
- $E_e = m_\mu - E_{\text{bind}} - E_{\text{recoil}}$
- **observed signal is smeared because** of detector effects



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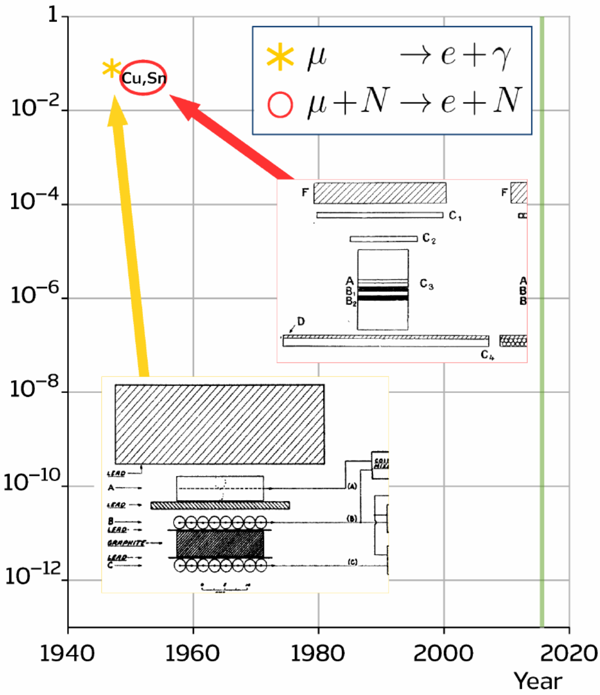
Charged Lepton Flavour Violation



90% C.L. upper limit on branching ratios

Yoshi.Uchida@imperial.ac.uk

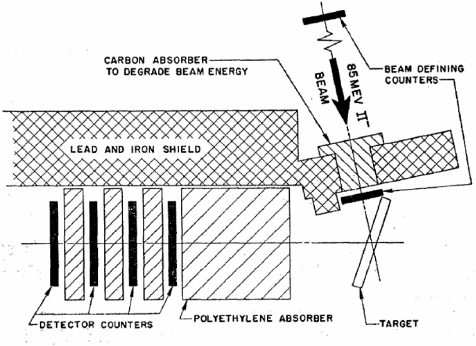
1955

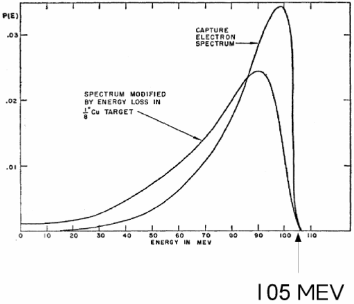
Electrons from Muon Capture*

J. Steinberger and Harry B. Wolfe
Columbia University, New York, New York

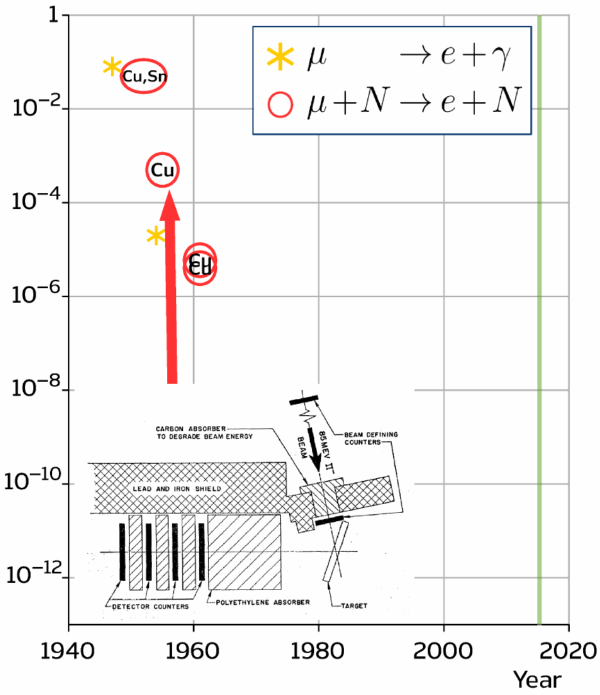
(Received August 31, 1955)

We have searched for the process $\mu^- + p \rightarrow p + e^-$ or $\mu^- + n \rightarrow n + e^-$ for μ mesons stopped in a Cu target. Scintillation counters were employed to detect the electrons from the process. No counts attributable to the electrons were obtained and we place an upper limit of $\sim 5 \times 10^{-4}$ for the relative rate of this process to that for the usual nuclear capture reaction.





Charged Lepton Flavour Violation



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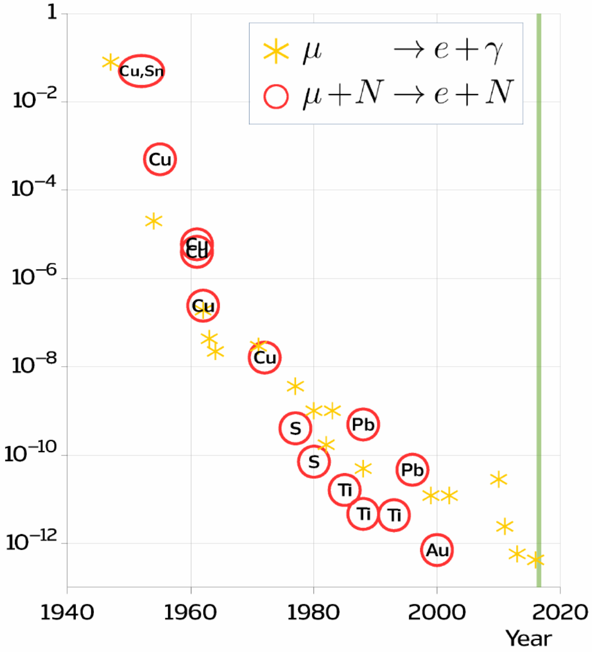
Muonic CLFV

Today



90% C.L.
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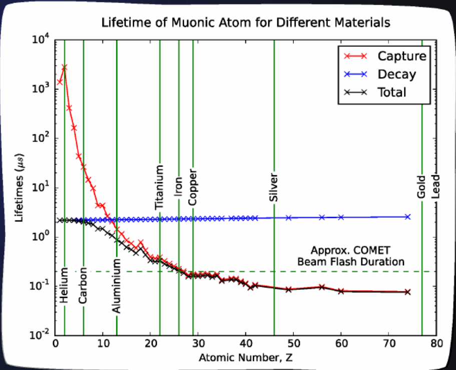
Z-Dependence of Bound Muon Lifetime

Z-dependence of the bound muon lifetime

- Competing effects on bound muon lifetime
- Becomes very short above, say, Titanium or Iron

Muon Lifetime

- Decay partial lifetime
  - Increases with Z
  - Bound muon momentum increases $\Rightarrow$ Time dilation
- Capture partial lifetime
  - Incoherent $\Rightarrow$ Grows linearly with Z
  - Eventually muon completely contained in nucleus $\Rightarrow$ levels out



Based on parametrisation in Geant4 v10.2

The COMET Experiment, 2 June 2016 14 Ben Krikler: bek07@imperial.ac.uk

Ben Krikler

Z-Dependence of Bound Muon Lifetime

Z-dependence of the bound muon lifetime

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Muon Lifetime

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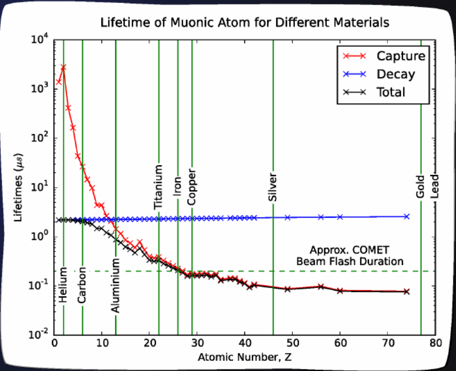
  - Bound muon momentum increases ⇒ Time dilation
- Capture partial lifetime
  - Incoherent ⇒ Grows linearly with Z
  - Eventually muon completely contained in nucleus ⇒ levels out



Based on parametrisation in Geant4 v10.2

The COMET Experiment, 2 June 2016 14 Ben Krikler: bek07@imperial.ac.uk

Ben Krikler

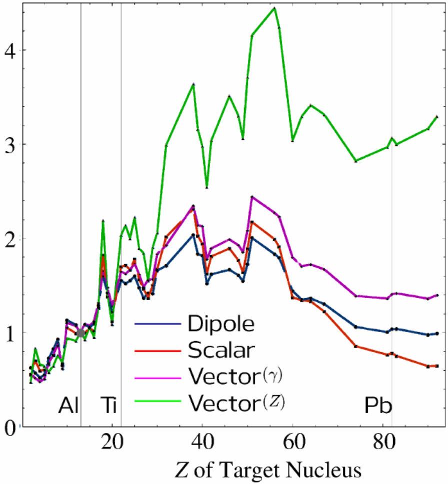
Z-Dependence of Muon-to-Electron Conversion

Z-Dependence of Muon-to-Electron Conversion

- differs according to type of New Physics interaction

Relative dependences of the muon-to-electron conversion branching ratio on the target nucleus

For different nuclei, different
size of nucleus,
radius of orbit,
u- and d-quark composition



V. Cirigliano et al., Phys. Rev. D 80, 013002 (2009)

DeeMe at J-PARC

Muon-to-Electron Conversion Experiment

- Aiming for data-taking next year
-

Yohei Nakatsugawa

DeeMe at J-PARC

Muon-to-Electron Conversion Experiment

- Aiming for data-taking next year
-

DeeMe Collaboration

M.Aoki [1], D.Bryman [2], Y.Furuya [3], M.Ikegami [4], Y.Irie [3,4], N.Kawamura [5,11], M.Kinsho [6], H.Kobayashi [4], S.Makimura [5,11], H.Matsumoto [4], S.Meigo [6], T.Mibe [7], S.Mihara [7], Y.Miyake [5,11], D.Nagao [1], Y.Nakatsugawa [5], H.Natori [7], H.Nishiguchi [7], T.Numao [8], C.Ohomori [4], S.Ritt [10], P.K.Saha [6], N.Saito [7,11], Y.Seiya [3], K.Shimomura [5,11], P.Strasser [5,11], N.Teshima [3], N.D.Thong [1], N.M.Truong [1], K.Yamamoto [6], K.Yamamoto [3], M.Yoshii [4], K.Yoshimura [9]

(1) Osaka University
(2) UBC
(3) Osaka City University
(4) KEK Accelerator
(5) KEK IMSS
(6) JAEA
(7) KEK IPNS
(8) TRIUMF
(9) Okayama University
(10) PSI
(11) J-PARC Center

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Yohei Nakatsugawa

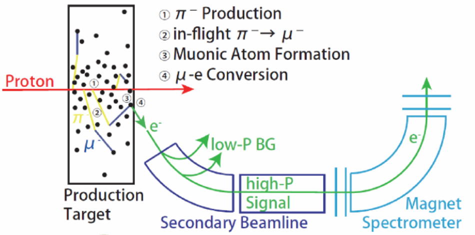
DeeMe at J-PARC

Muon-to-Electron Conversion Experiment

- Aiming for data-taking next year

Principle of Experiment

Concept of DeeMe



= μ^- stopping target → NO π^- decay volume, NO additional stopping target

utilize muonic atoms formed in the production target ↔ conventional μ–e search

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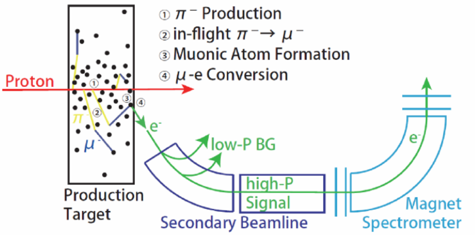
Muon-to-Electron Conversion Experiment

- Aiming for data-taking next year

Principle of Experiment

Concept of DeeMe



- Fully utilizing existing facility (high quality beam from RCS, muon target, etc)

... Early realization of the experiment

new physics result in timely manner

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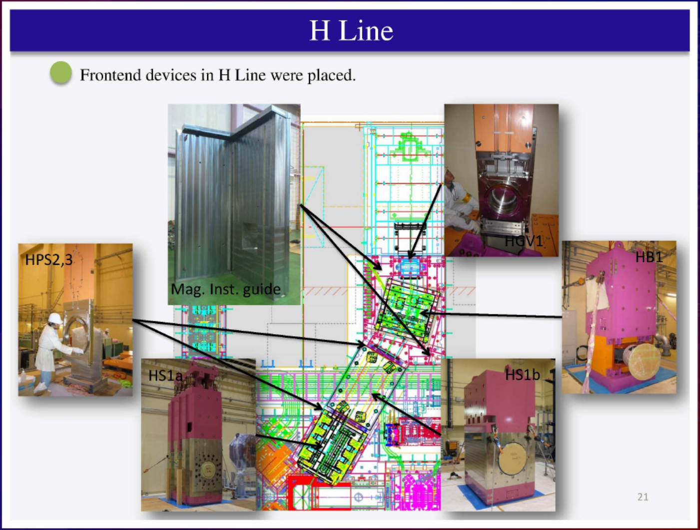
Muon-to-Electron Conversion Experiment

- Aiming for data-taking next year



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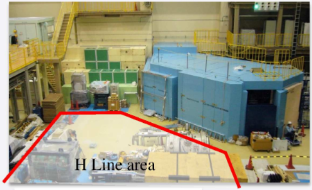
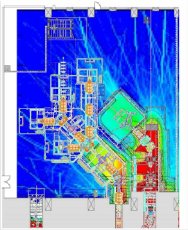
Muon-to-Electron Conversion Experiment

- Aiming for data-taking next year

H Line

- H Line under construction





- Beamline shield is designed based on Full M.C. simulation of dose using PHITS by N. Kawamura(KEK IMSS).
- Construction of beamline shield will start soon.

current status of the Exp. Hall

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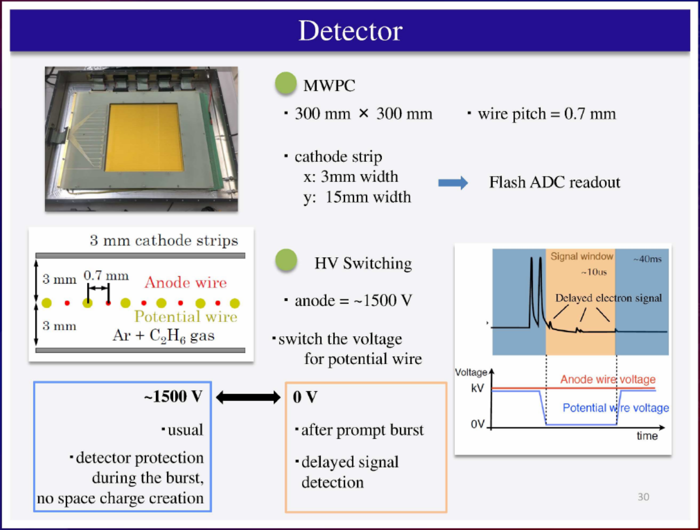
Yohei Nakatsugawa

DeeMe at J-PARC

Muon-to-Electron Conversion Experiment

- Aiming for data-taking next year



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DeeMe at J-PARC

Muon-to-Electron Conversion Experiment

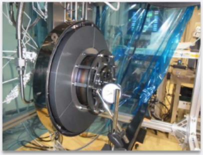
- Aiming for data-taking next year

Silicon Carbide Muon Production Target

- SiC target ~ **6 times higher physics sensitivity** than current carbide target

Material	$\Sigma f_c \times f_{MC}$
Graphite (C)	0.08
Silicon Carbide (SiC)	0.46

- Rotating SiC target



prototype of
SiC rotating target

compared with graphite ...

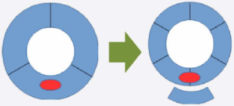
10 times strength → ← 80 times thermal stress

8 times larger risk under beam irradiation

▪SiC target is under development.

> increase disk partition and reduce disk radius
→ lower thermal stress and thermal difference.

current design



beam

> additional SiC
→ stop more π, μ

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Yohei Nakatsugawa

DeeMe at J-PARC

Muon-to-Electron Conversion Experiment

- Aiming for data-taking next year

Summary & Prospects

- DeeMe , μ – e conversion search at J-PARC MLF
  - Sensitivity : **1.2 ×** $\mathbf{10^{-13}}$ for **C** target , **2.1 ×** $\mathbf{10^{-14}}$ for **SiC** target
- A new beamline (H Line) is under construction.
- The spectrometer magnet is ready.
  - test operation, field magnet, Opera-3d
- HV-Switchin MWPC was developed.
  - All MWPC's will be ready soon.
- After-Proton measured
- SiC muon production target under development
- DeeMe will start data taking soon after H Line completed (Japan FY 2016).

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Yohei Nakatsugawa

DeeMe at J-PARC

Muon-to-Electron Conversion Experiment

- Aiming for data-taking next year
- The "Dark Horse" experi-ment!

Summary & Prospects

- DeeMe , μ – e conversion search at J-PARC MLF
  - Sensitivity : **1.2 ×10^{-13}** for **C** target , **2.1 ×10^{-14}** for **SiC** target
- A new beamline (H Line) is under construction.
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Yohei Nakatsugawa

Mu2E at Fermilab and COMET at J-PARC

Muon-to-Electron Conversion Experiments

- Collaborations
  - *m*uch larger than previous generation

COMET Collaboration

- International collaboration composed of 175+ researchers of 33 institutes from 15 countries

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COMET: Yuki Fujii

Mu2e collaboration

Over 200 scientists from 34 institutions

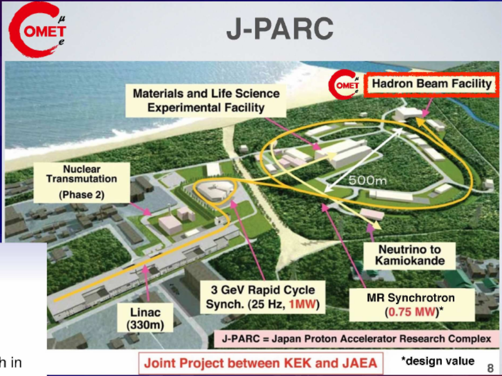
Argonne National Laboratory, Boston University, Brookhaven National Laboratory University of California, Berkeley, University of California, Irvine, California Institute of Technology, City University of New York, Joint Institute for Nuclear Research, Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionali di Frascati, Helmholtz-Zentrum Dresden-Rossendorf, University of Houston, INFN Genova, Kansas State University, Lawrence Berkeley National Laboratory, INFN Lecce and Università del Salento, Lewis University, University of Louisville, Laboratori Nazionali di Frascati and Università Marconi Roma, University of Minnesota, Muons Inc., Northern Illinois University, Northwestern University, Novosibirsk State University/Budker Institute of Nuclear Physics, Institute for Nuclear Research, Moscow, INFN Pisa, Purdue University, Rice University, University of South Alabama, Sun Yat Sen University, University of Virginia, University of Washington, Yale University

Mu2E: Andrei Gaponenko

Mu2E at Fermilab and COMET at J-PARC

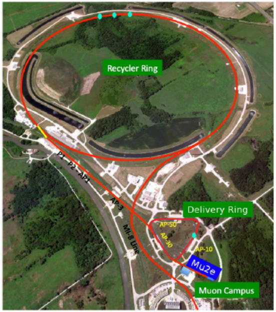
Muon-to-Electron Conversion Experiments

- COMET: Dedicated beam time needed
  - 56 kW proton beam
- Mu2E: Can run alongside other experiments (neutrino etc.)
  - 8 kW beam



COMET: Yuki Fujii

Mu2e beam delivery



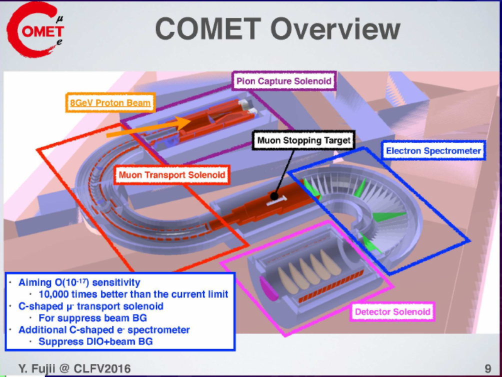
- A single beam bunch in the delivery ring at a time
- Revolution period is 1695 ns
- Resonant extractions "peels" a fraction of the bunch each turn
- Extracted beam: $\epsilon \approx 2 \times 10^{-5}$

Mu2E: Andrei Gaponenko

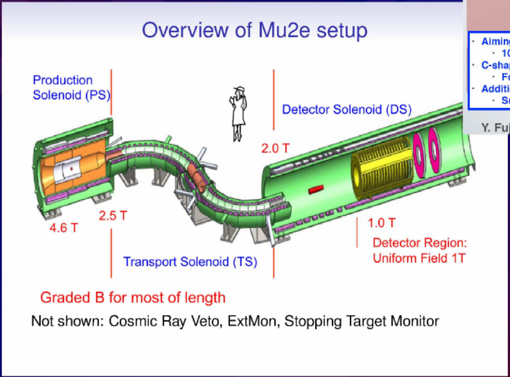
Mu2E at Fermilab and COMET at J-PARC

Muon-to-Electron Conversion Experiments

Share fundamental principles (descended from MELC proposal ca. 1990)



COMET: Yuki Fujii



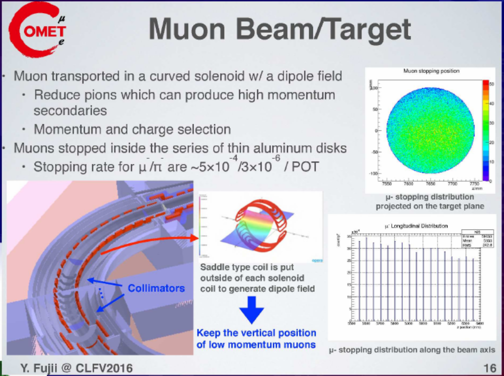
Mu2E: Andrei Gaponenko

- COMET: Two "C-shaped" solenoids
- Mu2E: One "S-shaped" solenoid

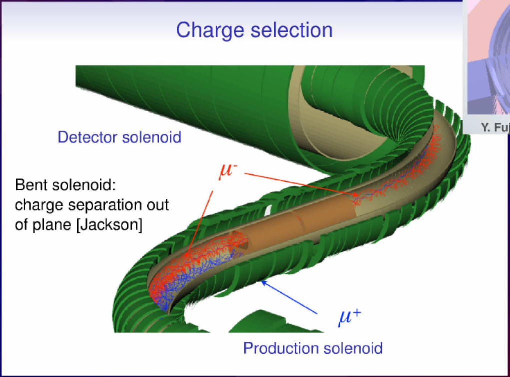
Mu2E at Fermilab and COMET at J-PARC

Muon-to-Electron Conversion Experiments

- Mu2E: Pure curved solenoids
- COMET: Curved solenoids with superimposed vertical B-field



COMET: Yuki Fujii

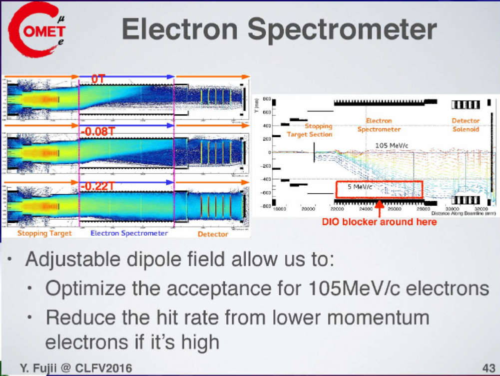


Mu2E: Andrei Gaponenko

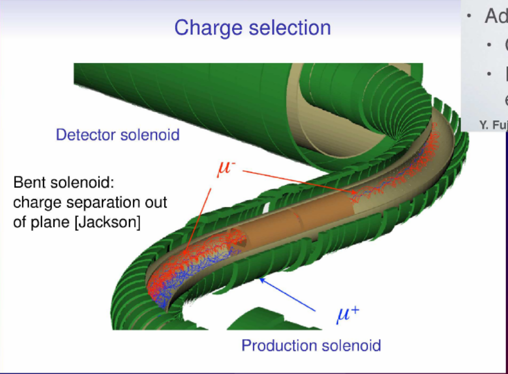
Mu2E at Fermilab and COMET at J-PARC

Muon-to-Electron Conversion Experiments

- Mu2E: Pure curved solenoids
- COMET: Curved solenoids with superimposed vertical B-field
  - allows momentum of central trajectory to be tuned



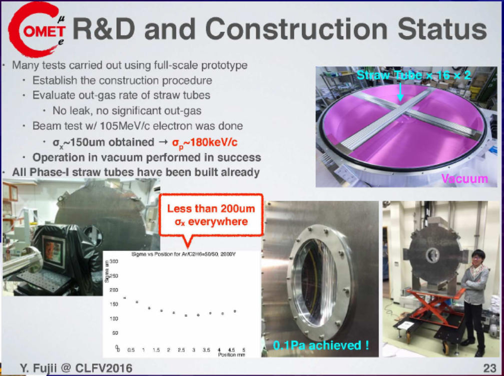
COMET: Yuki Fujii



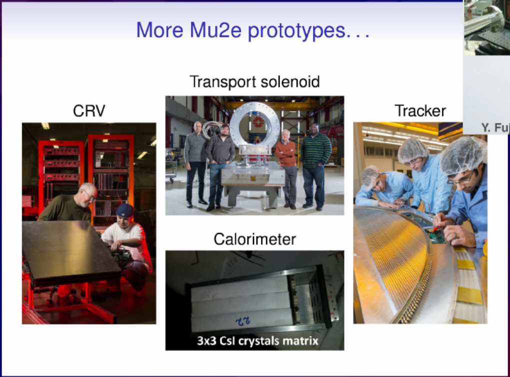
Mu2E: Andrei Gaponenko

Mu2E at Fermilab and COMET at J-PARC

Muon-to-Electron Conversion Experiments



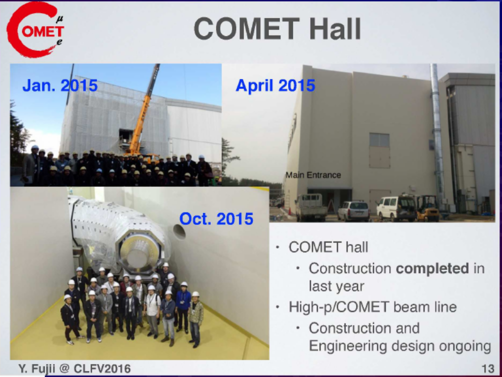
COMET: Yuki Fujii



Mu2E: Andrei Gaponenko

Mu2E at Fermilab and COMET at J-PARC

Muon-to-Electron Conversion Experiments



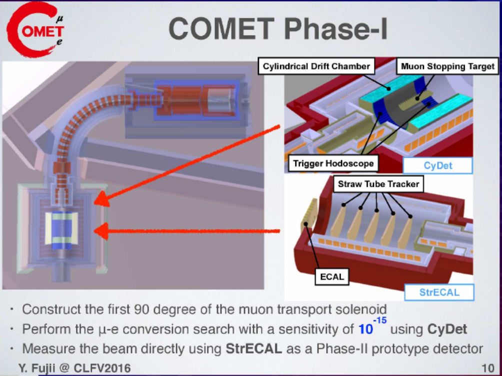
COMET: Yuki Fujii

Mu2E: Andrei Gaponenko

Mu2E at Fermilab and COMET at J-PARC

Muon-to-Electron Conversion Experiments

- Unique to COMET: two-phase construction
- In Phase-I:
  - study "first half" of novel curved solenoid beam line
  - also perform CLFV physics with "CyDet"



COMET: Yuki Fujii

COMET: Yuki Fujii

- Phase-I facility/detector /solenoid/electronics/software construction advanced
- "StrECAL" observes beam directly, and acts as Phase-II detector prototype

Mu2E at Fermilab and COMET at J-PARC

Muon-to-Electron Conversion Experiments

Similar ultimate sensitivities

- COMET Phase-II: Aim to reach full sensitivity before Mu2E

Summary

- COMET searches for μ-e conversion with S.E.S of 3×10^{-15} (2.6×10^{-17}) in Phase-I (Phase-II) @J-PARC
  - Phase-II S.E.S. with 1 year DAQ is comparable to that of Mu2e
- A lot of studies are intensively ongoing
- Recent Highlights
  - Completion of CDC construction
  - StrawECAL combined test
  - Daisy chain for EROS/ROESTI
  - Beam test for Diamond detector
  - Large scale MC production
  - Revisited Phase-II study with updated magnetic fields / geometry / software
- Data taking will start in 2018/2019 for Phase-I
- Phase-II can be a few years after Phase-I depending on the budget
  - Almost all R&Ds for Phase-II will be completed in Phase-I

Y. Fujii @ CLFV2016 48

COMET: Yuki Fujii

Conclusion

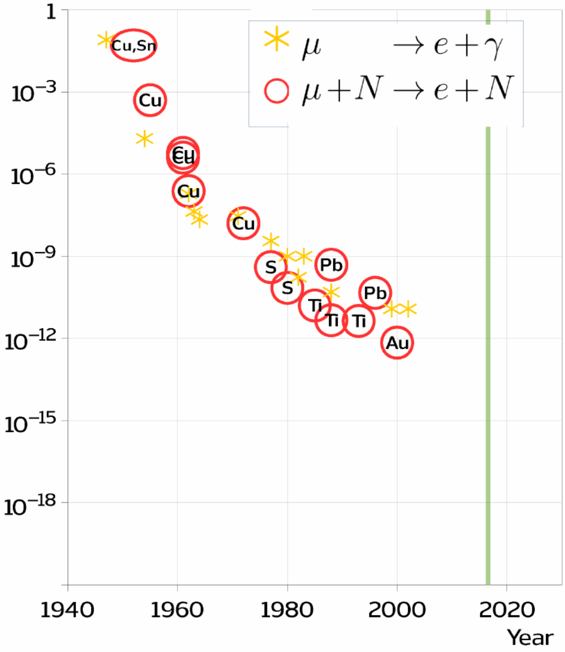
- Mu2e will test the physics of flavor and generations.
- Excellent physics potential
  - Aim for 4 orders of magnitude improvement: $R_{\mu e} \approx 2.5\times10^{-17}$ single event sensitivity at ≈ 0.5 events background
  - Mass scale reach far beyond direct production at colliders
    - $\times$ 10 improvement over current $\mu N \to eN$ measurement
- Building construction is almost finished
- Detectors are in advanced prototyping stage
- Solenoids are on schedule for data taking in 2021
- Mu2e had a successful CD-3 review last week. CD-3 gives the Project authority to construct the entire detector. The Project is fully funded.
- More information: http://mu2e.fnal.gov

Mu2E: Andrei Gaponenko

- Mu2E: Aim to reach full sensitivity before COMET Phase-II

Muonic CLFV

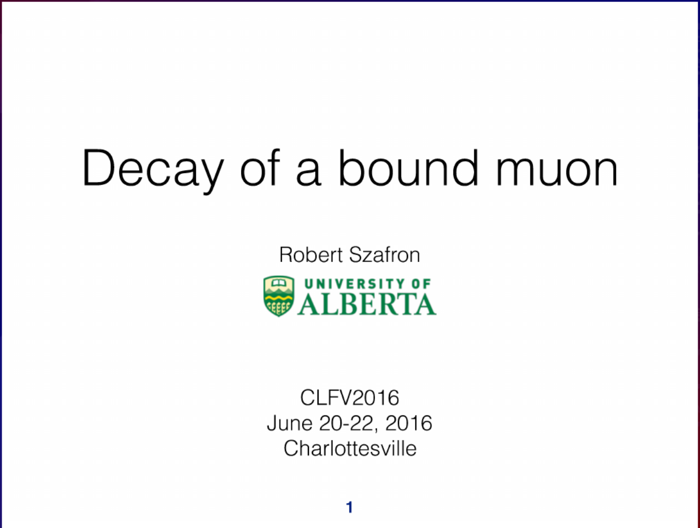
Today



90% C.L.
upper limit on
branching ratios

Decay of Muons Bound to Nuclei

Important background to muon-to-electron conversion



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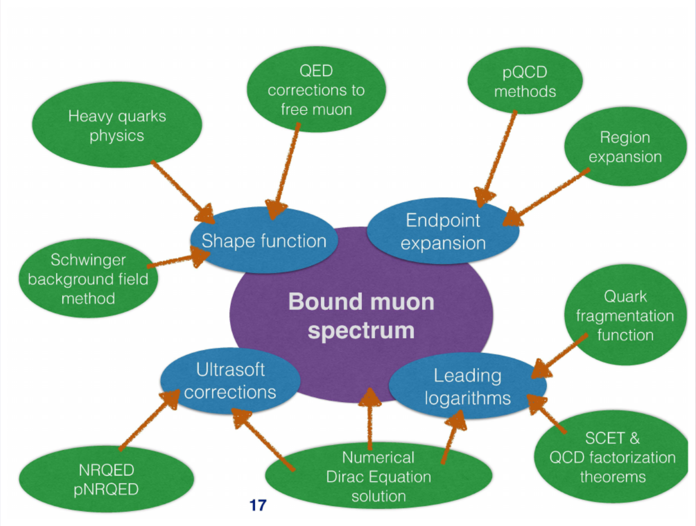
Decay of Muons Bound to Nuclei

Important background to muon-to-electron conversion



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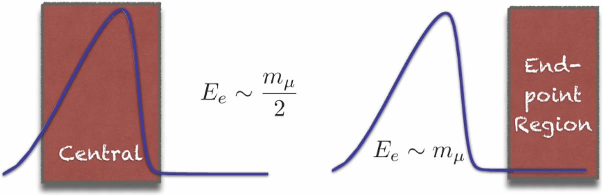
Decay of Muons Bound to Nuclei

Important background to muon-to-electron conversion

DIO spectrum regions



- Measured by the TWIST experiment in 2009
- Muon motion dominates

- Background for the conversion experiments
- Will be measured in conversion experiments

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Decay of Muons Bound to Nuclei

Important background to muon-to-electron conversion

Vacuum polarization

$$V(r) = -\frac{Z\alpha}{r} + Z\alpha\frac{\alpha}{\pi}V_U(r, m_e)$$

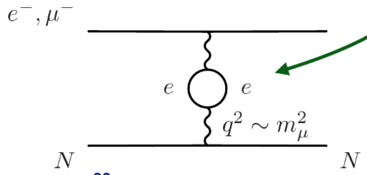
Electron loop generates long distance potential and this leads to large logarithmic corrections

$$r \sim \frac{1}{m_e} \gg \frac{1}{m_\mu Z\alpha}$$

Correction range — Atom size

$$\ln\frac{Z\alpha m_\mu}{m_e}$$

$$\ln\frac{m_\mu}{m_e}$$



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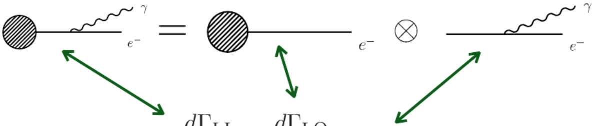
Decay of Muons Bound to Nuclei

Important background to muon-to-electron conversion

Soft-Collinear Factorization



$$\frac{d\Gamma_{\mathrm{LL}}}{dE_e} = \frac{d\Gamma_{\mathrm{LO}}}{dE_e} \otimes D_e$$

with the perturbative fragmentation function

$$D_e(x) = \delta(1-x) + \frac{\alpha}{2\pi} \ln\left(\frac{m_\mu^2}{m_e^2}\right) P_{ee}^{(0)}(x) + \ldots$$

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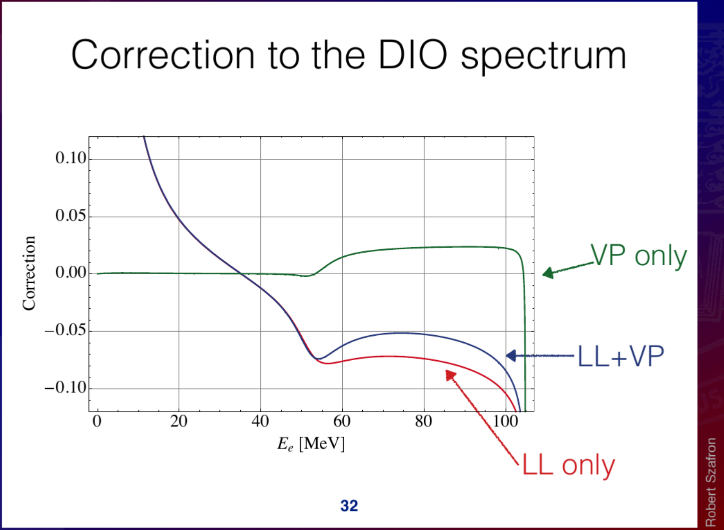
Decay of Muons Bound to Nuclei

Important background to muon-to-electron conversion

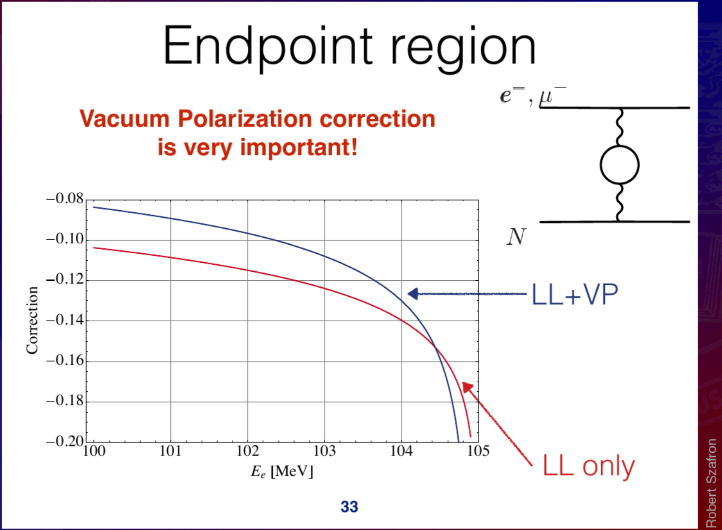
- VP: vacuum polarisation correction
- LL: leading logarithmic correction



Decay of Muons Bound to Nuclei

Important background to muon-to-electron conversion

- VP: vacuum polarisation correction
- LL: leading logarithmic correction



Decay of Muons Bound to Nuclei

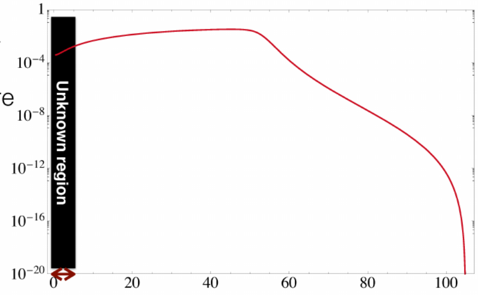
Important background to muon-to-electron conversion

- Can we help, experi-mentally?

Summary

If you want to discover New Physics, first you have to understand the Standard Model

DIO spectrum — a quantity that is changing by more than 16 orders is calculated including the leading corrections



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Cautionary Tales in Muon CLFV Experiments

From CLFV2013 Summary Talk

Cautionary Tales

LFV Experiments	Limit Reached	Goal; (Result/Goal)	“Comments”
Badertscher et al. 1982 μ->e	7×10^{-11}		
TRIUMF TPC Ahmad et al. 1987 μ->e	4.6×10^{-12}	2×10^{-12} (2)	Data collection took 5x as long as originally guessed (1 month!)
SINDRUM II Bertl et al. 2006 μ->e	7×10^{-13} Au	“10^{-14}” (1987)-> 3×10^{-14} (1993) “engineering” Ti (>60)	Flux lower by 10; pion suppression device didn’t work; unanticipated high electron bkg.; shorter running.
MEGA Ahmed et al. 2002 μ->eγ	1.2×10^{-11}	0.9->4×10^{-13} “engineering” (133-35)	Death by a thousand blows to acceptance

D. Bryman CLFV, Lecce, Italy 19

Cautionary Tales in Muon CLFV Experiments

From CLFV2013 Summary Talk

Case Study I: MEGA at LAMPF

$$\mathcal{B} = \left(\frac{R_\mu}{d}\Delta t\right)\left(\frac{\Delta E_e}{m_\mu/2}\right)\left(\frac{\Delta E_\gamma}{15 m_\mu/2}\right)^2\left(\frac{\Delta\theta}{2}\right)^2 f(\theta_\gamma)\eta_{\mathrm{IBV}}.$$

TABLE VII. The contributions to the signal sensitivity of the MEGA experiment at the design stage and after a complete analysis of the data.

Quantity	Designed	Achieved	Degradation factor
$N_{e\gamma}$ (90% C.L.)	$\leqslant 2.3$	$\leqslant 5.1$	2.2
$\Omega/4\pi$	0.42	0.31	1.4
ϵ_e	0.95	0.53	1.8
ϵ_γ	0.051	0.024	2.1
N_s	3.6×10^{14}	1.2×10^{14}	3.0
Total factor			34.9

TABLE VIII. The contributions to the background sensitivity of the MEGA experiment at the design stage and after a complete analysis of the data.

Quantity	Designed	Achieved	Degradation factor
R_μ (MHz)	30.0	15.0	0.5
$t_{e\gamma}$ (ns)	0.8	1.6	2.0
E_e (MeV)	0.25	0.54	1.5
E_γ (MeV)	1.7	1.7,3.0	1.6
$\theta_{e\gamma}$ (deg)	1.0	1.9	3.6
θ_γ (deg)	10.0	10.0	1.0
η_{IBV}	0.2	1.0	5.0
Total factor			43.3

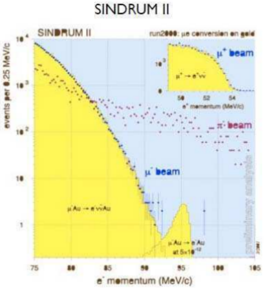
Phys.Rev. D65 (2002) 112002

D. Bryman CLFV, Lecce, Italy 20

Cautionary Tales in Muon CLFV Experiments

From CLFV2013 Summary Talk

Case study II: SINDRUM II PSI



- Proposed 10^8 stops; (muE1) beam was only 10^7
- Designed "PMC" to kill pions; simulated; swamped unexpectedly by electrons; solenoid took years longer to obtain.
- Eventually went to very low momentum (50 MeV/c) killing pions by range; pion background persisted.
- Final result obtained in a couple of months; group had dispersed…." could have done better"….

D. Bryman   CLFV, Lecce, Italy   21

Cautionary Tales in Muon CLFV Experiments

From CLFV2013 Summary Talk

Remarks: How to lose a factor 10 (100…) in a LFV experiment?

Tension between needing high rates and high sensitivities.

- Optimistic resolutions – excessive rates or beam contamination?
- Optimistic acceptances – extra losses due to cuts?
- Missing background sources e.g. due to high energy production or multiple low probability events …
- Cosmic rays and other effects?
- Fill in your own….

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Cautionary Tales in Muon CLFV Experiments

From CLFV2013 Summary Talk

Useful Advanced Measurements for μ-e Conversion Experiments

- Extinction rate
- Particle fluxes (e,μ,π,K,$\bar{p}$...)at detector (Comet phase I)
- p and n rates from μ Capture (in the works at PSI)
- Cosmic rays – could be done in a test setup?
- Radiative pion capture –> 100MeV electrons ?
- Pbar background rate –> 100MeV electrons ?
- …

General questions for high sensitivity μ-e Conversion Experiments

- What are the uncertainties and risk factors in the background, acceptance estimates ?
- How are the backgrounds to be measured during the experiment ?
- How is a blind analysis to be done ?
- What would make a believable signal ?

D. Bryman CLFV, Lecce, Italy 38

Mu2E Posters

No.	Name	Topic
1	Boi, Steven	Impact from Beam Induced Radiation Backgrounds on the Cosmic Ray Veto Detector at the Mu2e Experiment
5	Ehrlich, Ralf	Cosmic Ray Background in the Mu2e Cosmic Ray Veto
7	Frank, Martin	Mu2e Cosmic Ray Veto Test Beam Results
9	Jenkins, Merrill	The Mu2e Cosmic Ray Veto
12	Oksuzian, Yuri	Wavelength-Shifting Fiber Performance for the Mu2e Cosmic Ray Veto
18	Uzunyan, Sergey	Radiation Damage Tests of Silicon Photo-Multipliers (SiPMs) for the Cosmic Ray Veto System of the Mu2e Experiment
2	Bono, Jason	The Mu2e Tracker
4	Edmonds, Andrew	An 8-Straw Prototype Tracker for Mu2e
10	Kargiantoulakis, Manolis	Front-End Electronics for the Mu2e Tracker
13	Palladino, Anthony	Normalization System for the Mu2e Experiment; The Stopping-Target Monitor
15	Sarra, Ivano	New Tests with the New Large Area SiPMs for the Mu2e Calorimeter

Other Posters

No.	Name	Topic
3	Chiarello, Gianluigi	The Full Stereo Drift Chamber for the MEG II Upgrade
6	Fael, Matteo	NLO Corrections to $\mu \to e\nu\nu\gamma$ and $\mu \to eee\nu\nu$ Decays in the SM
8	Glaser, Charles	PEN: A Precision Analysis in the $\pi \to e + \nu$ Branching Ratio
11	Le, Trinh	CLFV from the Perspective of a Neutrino Mass Model
14	Quirk, John	Results and Outlook of the Aluminum Capture Experiment
16	Shrestha, Shruti	Electronics for the Cosmic Ray Veto
17	Teshima, Natsuko	Development of High-rate Tolerant HV-Switching Multi-Wire Proportional Chamber and its Readout Electronics for DeeMe Experiment

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More on this later…

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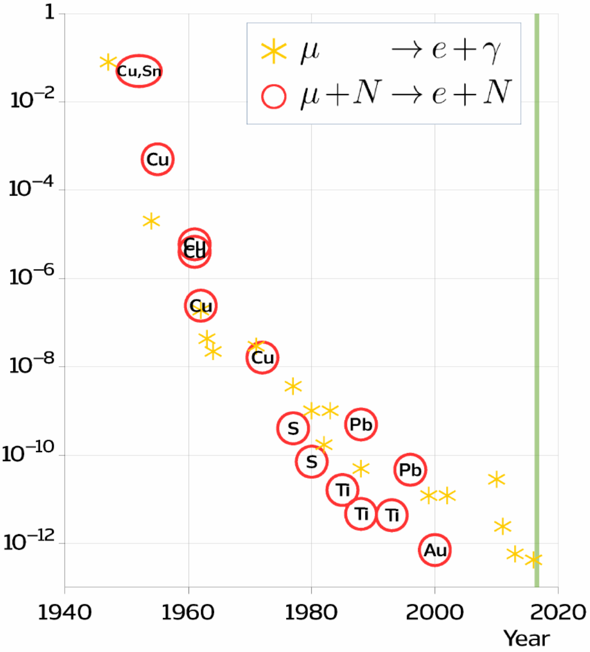
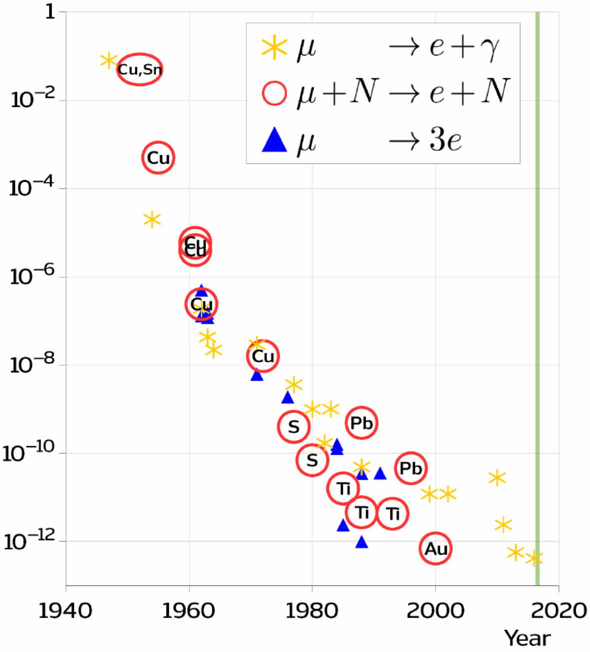
Charged Lepton Flavour Violation in Muons



90% C.L.
upper limit on
branching ratios

Charged Lepton Flavour Violation in Muons

- Previous $\mu \to 3e$ results were in 1998



90% C.L. upper limit on branching ratios

Mu3E at PSI

The Mu3e Experiment

Dorothea vom Bruch

for the Mu3e Collaboration

2nd International Conference on Charged Lepton Flavor Violation

Charlottesville, VA

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

Dorothea vom Bruch

Mu3E at PSI

Institutions

- University of Geneva
- Heidelberg University
- Karlsruhe Institute of Technology
- Mainz University
- Paul Scherrer Institut
- ETH Zurich
- University of Zurich

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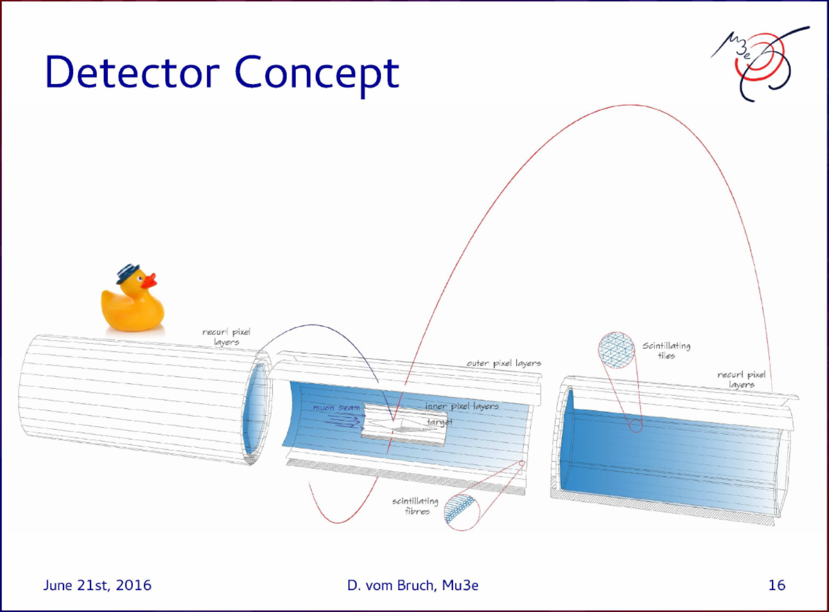
Mu3E at PSI



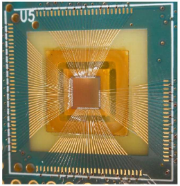
Dorothea vom Bruch

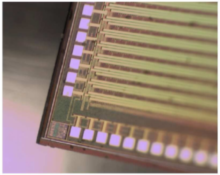
Mu3E at PSI

- Continued R&D of 50 micron-thick digital-readout silicon pixel sensors

Mupix Protoype

- Mupix7: latest prototype
- Thinned to 50 µm
- 32 x 40 pixel matrix
- Pixel size: 103 µm x 80 µm
- 3.2 x 3.2 mm²



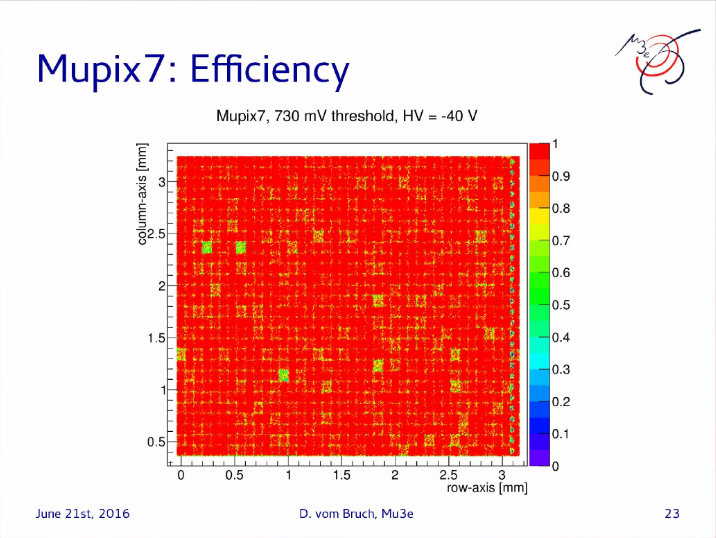


- Readout electronics on chip
- Fast LVDS link: 1.25 Gbit/s

June 21st, 2016 D. vom Bruch, Mu3e 21

Mu3E at PSI

- Continued R&D of 50 micron-thick digital-readout silicon pixel sensors



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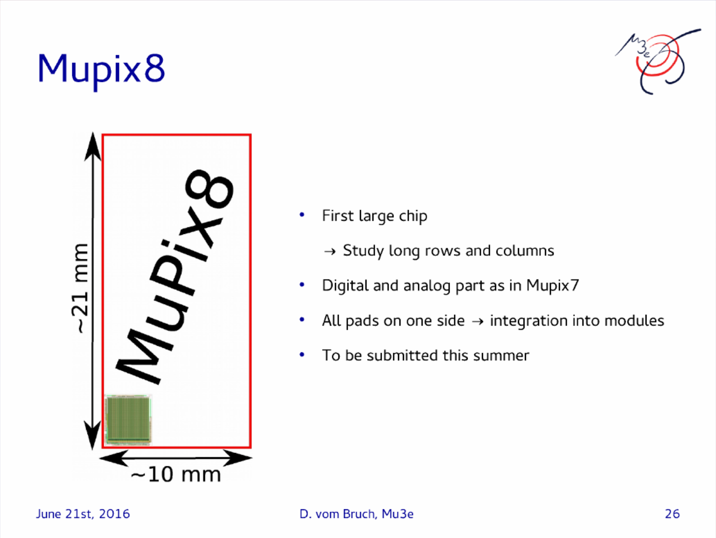
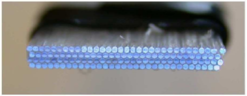


Mu3E at PSI

- Continued R&D of 50 micron-thick digital-readout silicon pixel sensors
- Fast scintillating fibres

Scintillating Fibers

- 2 or 3 layers of scintillating fibers
- Two types of prototypes, 250 μm diameter:
  - Round
  - Square
- Read out by Silicon Photomultipliers (SiPMs) at both ends
- Thickness < 0.1 % radiation length per layer



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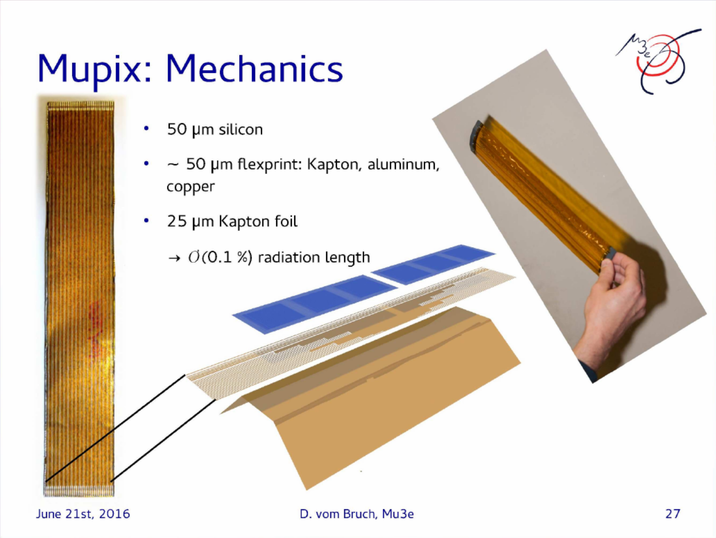
Mu3E at PSI

- Continued R&D of 50 micron-thick digital-readout silicon pixel sensors
- Fast scintillating fibres
- Further advanced R&D

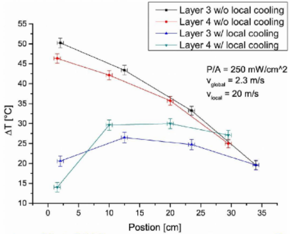


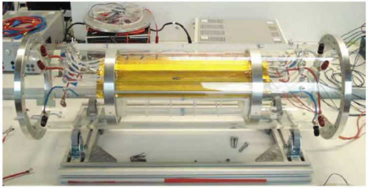
Mu3E at PSI

- Continued R&D of 50 micron-thick digital-readout silicon pixel sensors
- Fast scintillating fibres
- Further advanced R&D

Cooling with Gaseous Helium

- Heatable module prototypes
- Temperature sensors
- Flow container
- Local and global helium flow





June 21st, 2016 D. vom Bruch, Mu3e 35

Mu3E at PSI

- Continued R&D of 50 micron-thick digital-readout silicon pixel sensors
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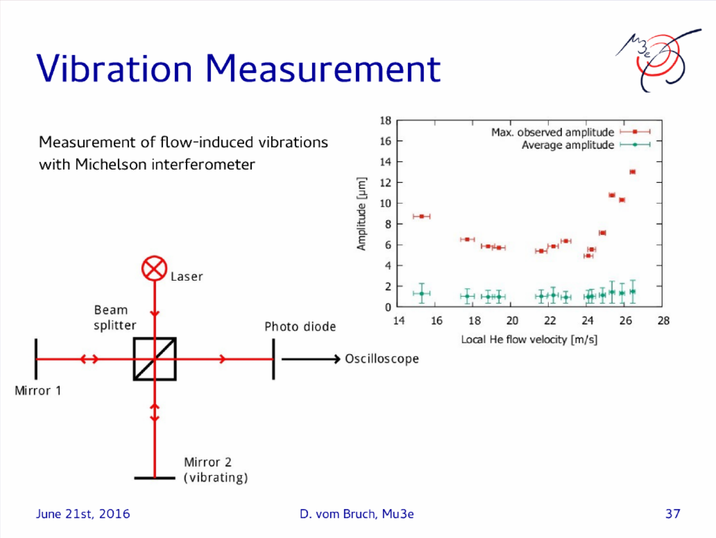
- Further advanced R&D



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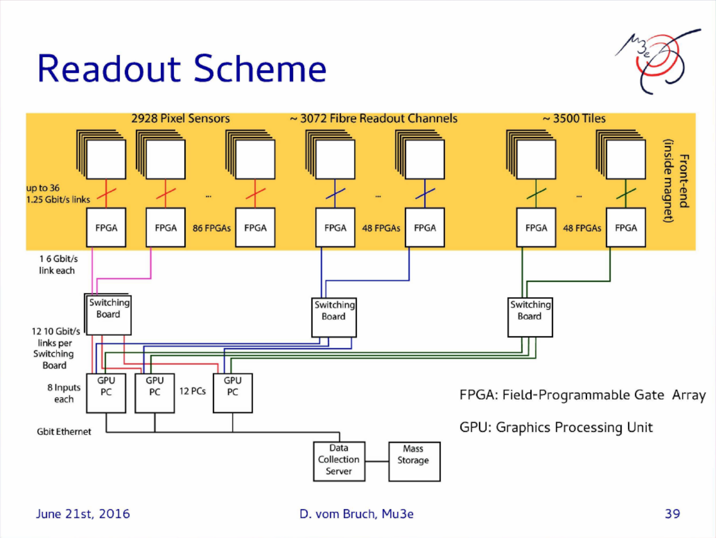


Mu3E at PSI

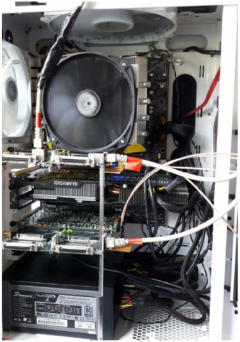
- Continued R&D of 50 micron-thick digital-readout silicon pixel sensors
- Fast scintillating fibres
- Further advanced R&D

Online Filter Farm

- Triggerless readout →

  50 Gbit/s data rate @ 10^9 muons/s
- Online data reduction
- DAQ PCs with GPUs and FPGAs
- Online track and vertex reconstruction
- 10^{10} track fits/s achieved
- Data reduction by factor ~1000

  → Store < 100 MB/s



June 21st, 2016 D. vom Bruch, Mu3e 40

Mu3E at PSI

- Continued R&D of 50 micron-thick digital-readout silicon pixel sensors
- Fast scintillating fibres
- Further advanced R&D
- Turning on in near future

Summary

- Search for $\mu^+ \rightarrow e^+e^-e^+$ with a sensitivity in branching ratio of 10^{-16}
- High rates up to 10^9 muons/s
- Minimum material budget
- Pixel, fiber and tile prototypes meet the requirements
- Magnet will be delivered in 2017
- Commissioning in 2017

June 21st, 2016 D. vom Bruch, Mu3e 45

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Physics Reach of Experiments

Graphical representations of physics reach of experiments (even if somewhat over-simplified) can be useful....

- Proton decay
- EDMs
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  - Perhaps an area which can be improved

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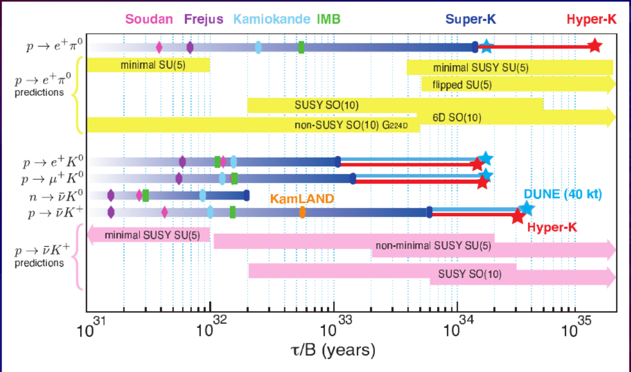

DUNE CDR

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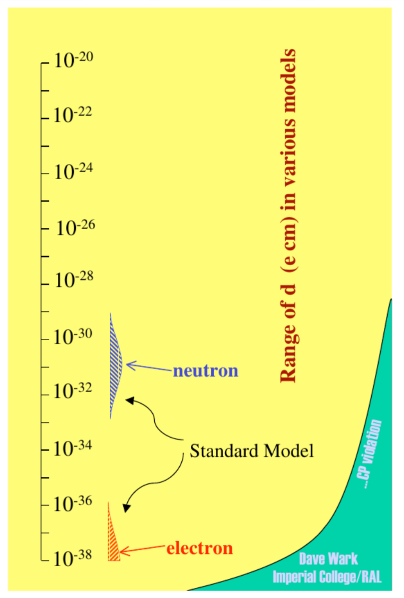

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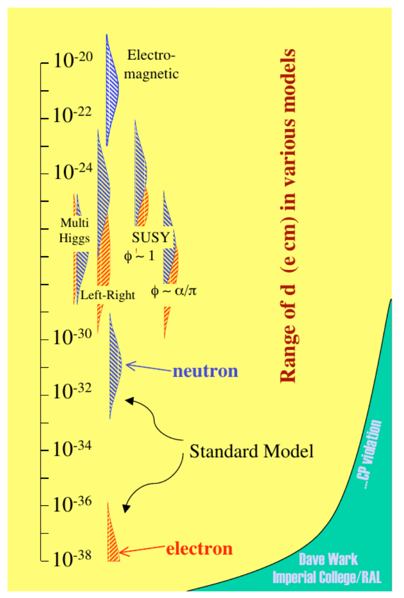

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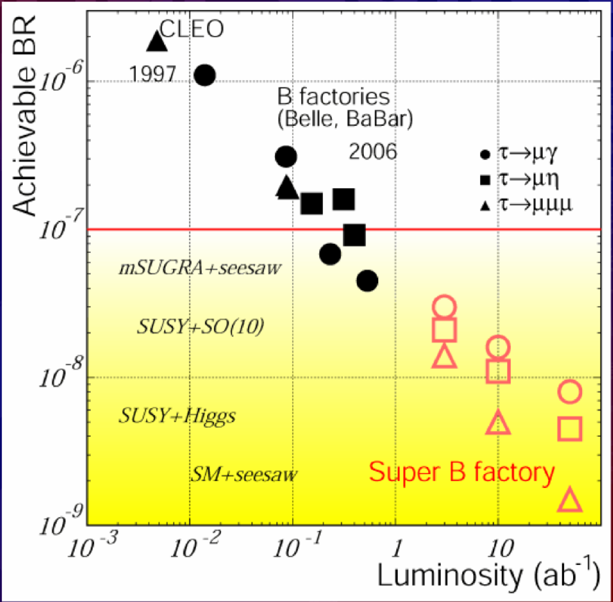

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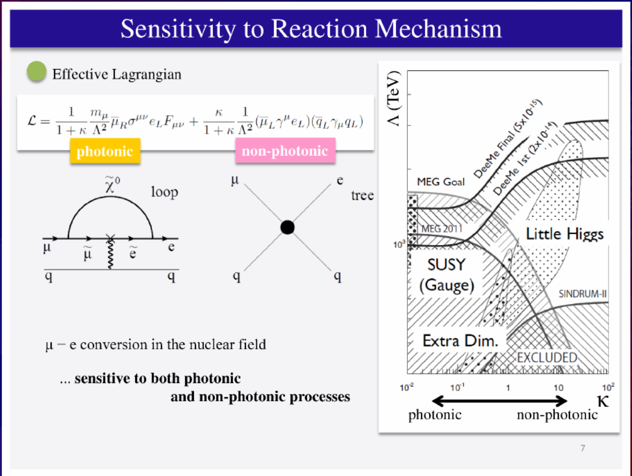

Yohei Nakatsugawa

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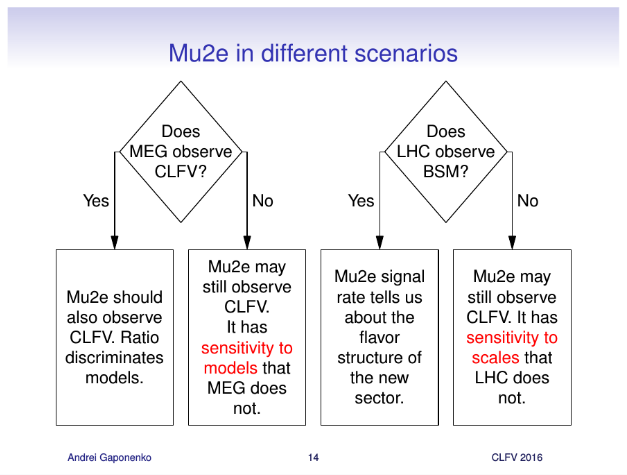

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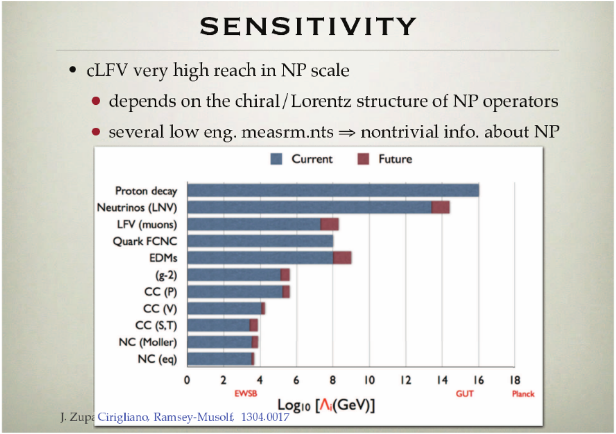

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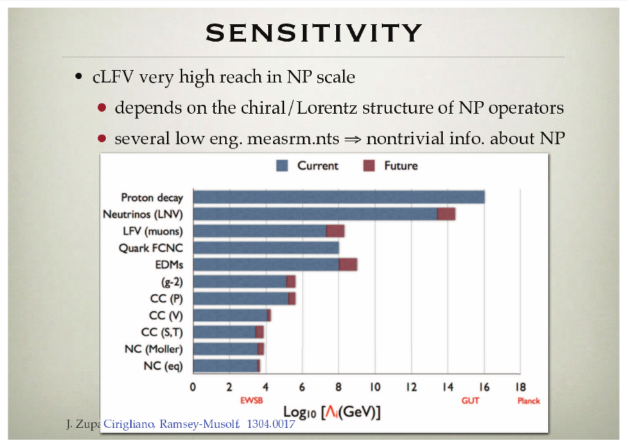

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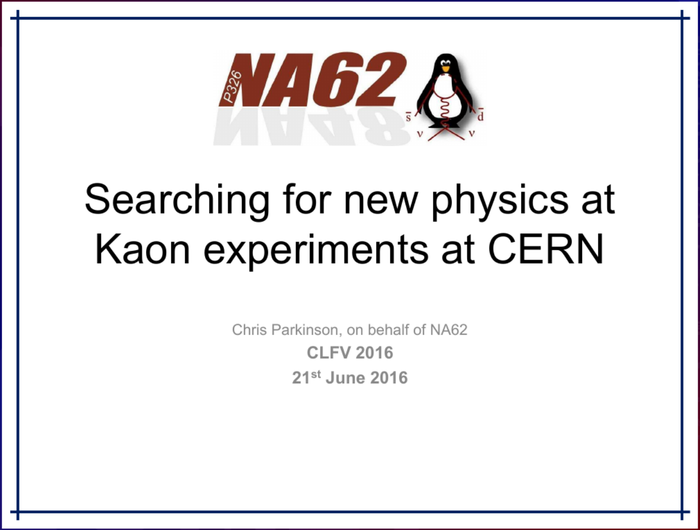

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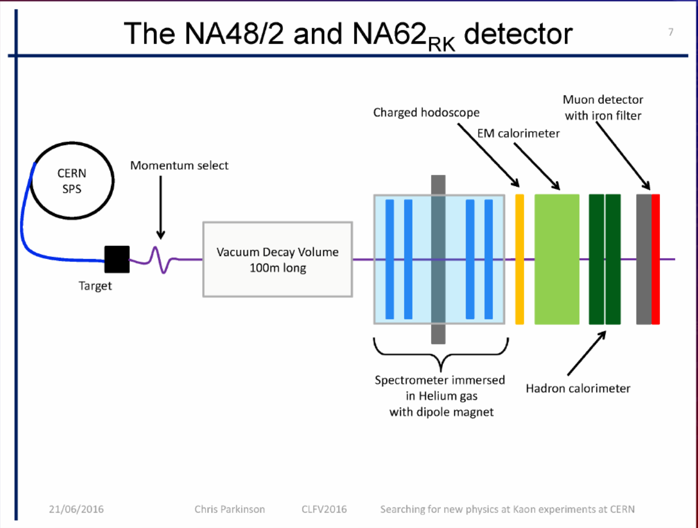

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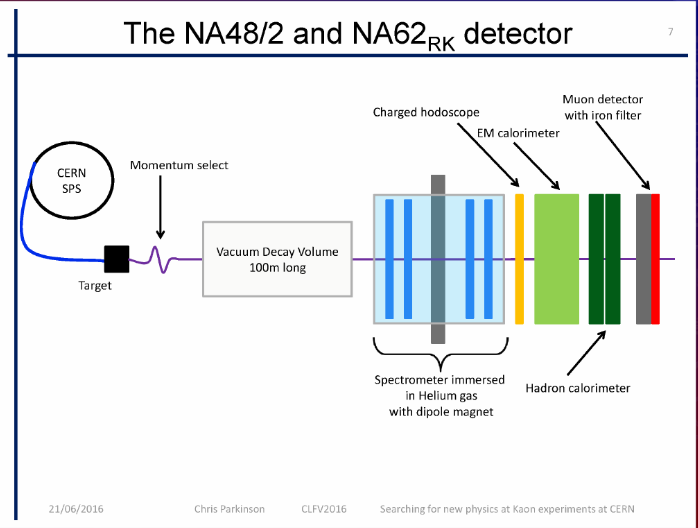

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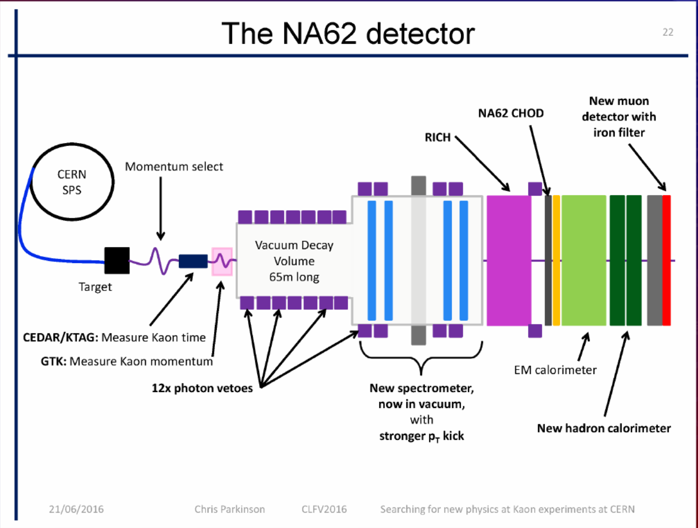

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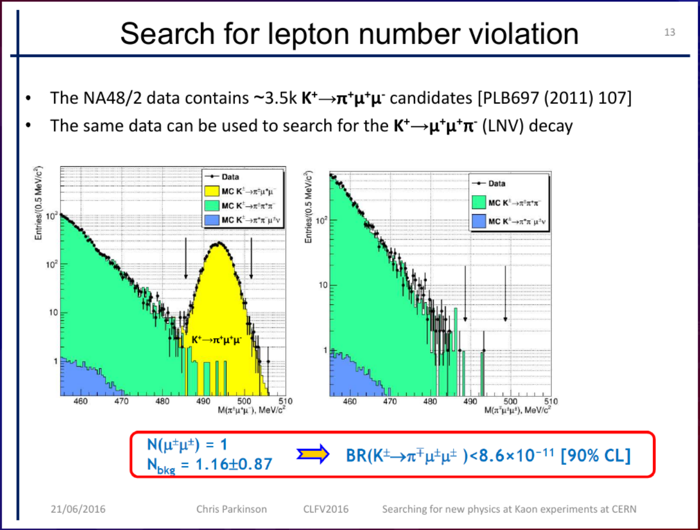

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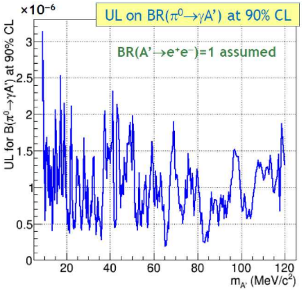
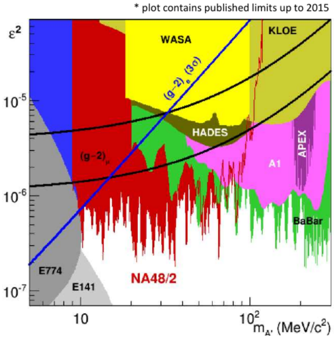
Search for dark photons

18

- No local significance greater than 3σ → no hint of the dark photon





- NA48/2 constraints exclude dark photon explanation of the $(g-2)_\mu$ discrepancy
  [PLB 746 (2015) 178-185]

21/06/2016 Chris Parkinson CLFV2016 Searching for new physics at Kaon experiments at CERN

Chris Parkinson

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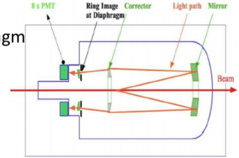
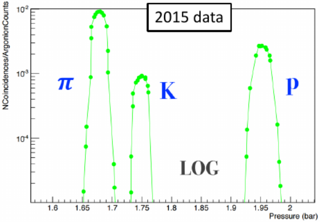
K^+ tagging – CEDAR/KTAG

- Kaons are tagged with the **CEDAR/KTAG** system
- **CEDAR** – collects Cherenkov light with fixed diaphragm
- **KTAG** – 8-fold PMT array with **σ_t ≈80 ps**
- Nominal Kaon rate ≈ **45 MHz**





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STRAW spectrometer

- Position and momentum of π^+ measured by the **STRAW** spectrometer
- Straw tubes operated in vacuum – very low material budget

	NA48/2	NA62-RK	NA62
Spectrometer thickness, X_0	2.8%	2.8%	1.8%
Spectrometer P_T kick, MeV	120	265	270
$M(K\rightarrow\pi^+\pi^+\pi^-)$ resolution, MeV	1.7	1.2	0.8

- $\sigma_p/p \approx 0.32\% \oplus 0.008\%\ p$ [GeV/c]
  - **Comparable momentum resolution to muons in LHCb** [LHCb muons 2015]

(Straw production facilities now used for COMET)

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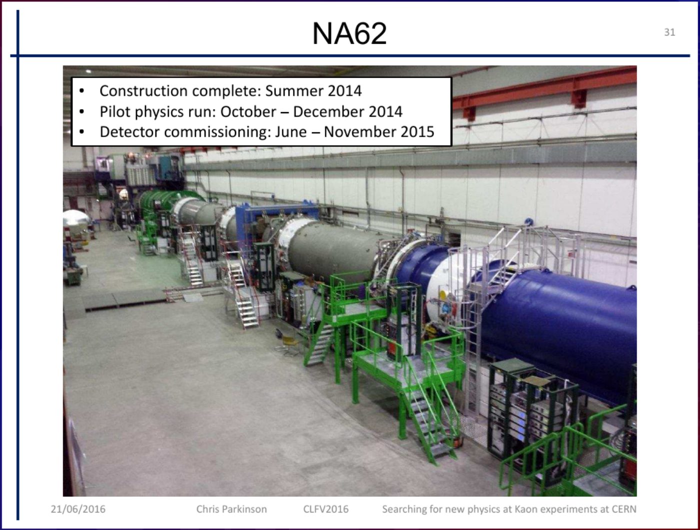

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The NA62 L0 Trigger in 2016

35

- The lowest-level of the NA62 trigger system (L0) is implemented in hardware, based on FPGA technology

- **A multiple track trigger** (MT) can be built requiring signals in 10 RICH PMTs and two (NA62)CHOD quadrants
- **Dielectron trigger: multiple track +** more than 10GeV of energy in the LKr
- **Dimuon trigger: multiple track +** signals in two MUV3 tiles
- **LFV (muon-electron) trigger: multiple track +** more than 10GeV of energy in the LKr and signal in one MUV3 tile (selects **$K^+ \rightarrow \pi\mu e$** decays)

- In simulations the total rate from the above L0 triggers ~ few 100 kHz, which is sufficiently low to run in parallel to the $K^+ \rightarrow \pi^+\nu\nu$ trigger
- Validation of the trigger rates with data is **currently underway**

21/06/2016 Chris Parkinson CLFV2016 Searching for new physics at Kaon experiments at CERN

Chris Parkinson

NA48/2 and NA62

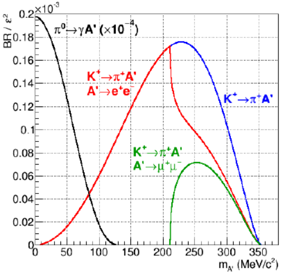
- Kaon decays very sensitive to deviations from SM
- Beam configurations differ between NA48 and NA62R_K
- NA48/2 data continues to be analysed
- NA62 undergoing commissioning
- Dedicated CLFV trigger established
- Data forthcoming

Physics prospects

- Searches for **$K^+ \to \pi\mu e$** have potential to probe to 10^{-12}

Mode	UL at 90% CL	Experiment	Reference
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11}	E777/E865	PRD 72 (2005) 012005
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	E865	PRL 85 (2000) 2877
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}		

- Sensitivity to dark photons with LFV couplings, masses from 100 to 350 MeV



Chris Parkinson

- Muon Experiments
  - $\mu \to e + \gamma$
    - From the beginnings of CLFV
    - MEG at PSI
    - Suppression of Muonic CLFV
  - Muon-to-Electron Conversion
    - Z-Dependence
    - Next Generation of Experiments
    - Decay of Muons Bound to Nuclei
    - Cautionary Tales
  - $\mu \to 3e$
  - Physics Reach of Experiments
- Other Experiments
  - NA48/2 and NA62
  - Current Anomalies in Data
  - Collider Experiments
- The Connection with Neutrinos
- Closing Remarks
  - Statistics in CLFV Physics and PhyStat-ν (next at Fermilab in September)
  - The First Signs of BSM Physics

Current Anomalies

Direct searches for CLFV are providing strong constraints on BSM Physics—other observables may be giving us hints of New Physics

- Muon $g-2$
- B-systems
- Higgs decays
- Dark Matter
- Naturalness
- Proton radius....

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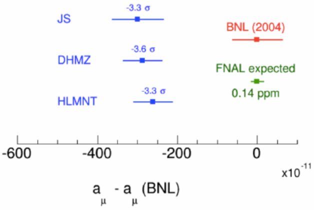
Current experimental limits on a_μ

- Most precise measurement performed at BNL (1999-2001)
- Accuracy of ~0.5 ppm

$$a_\mu^{exp} = 116\,592\,089\,(0.54)_{st}(0.33)_{sy}(0.63)_{tot} \times 10^{-11}$$

- Uncertainty is dominated by statistics



- Measurement differs from theory by ~3.5 σ

$$\Delta a_\mu^{(\text{today})} = (287 \pm 80) \times 10^{-11}$$

21/06/2016

Joe Price

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If this anomaly is due to new physics, ...

The size of anomaly

$$\delta a_\mu = (26.1 \pm 8.0) \times 10^{-10}$$

is comparable to the electroweak contribution

$$a_\mu^{\mathrm{EW}} = (15.4 \pm 0.1) \times 10^{-10}$$

we expect new particles with EW scale mass

⟶ strong constraints from EW precision data
⟶ good target at near future experiments

We may be able to discover the new physics
before new experiment or/and new (improved) calculation for muon g-2.
So, we should study it NOW!

Kazuhiro Tobe

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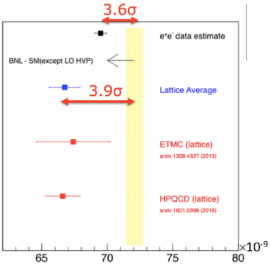
Anticipated improvements to SM

- HVP can be tied to experimental data from e^+e^- collisions
  - New data expected from SND, CMD-3. BES-III, Belle-II...
  - Continuously updating SM prediction
- Alternative lattice calculation agrees with this prediction



- Hadronic light by light must be calculated by theory - lattice
- Factor of 2 improvement in SM calculation expected by end of data taking

21/06/2016

Joe Price

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Summary

- a_μ sensitive to new physics
- Discrepancy shows no signs of going away with improved theory
- Main experimental improvement from increased stats
  - Expecting 21 times more data ~ 1.5×10^{11} muons
  - Available due to improved facilities at FNAL
- Additional improvements in experimental uncertainties
  - Improved uniformity in B field, calibration procedures, ...
  - New calorimeters, trackers, kickers, ...
- Data taking starts in summer 2017

18/06/2016

Joe Price

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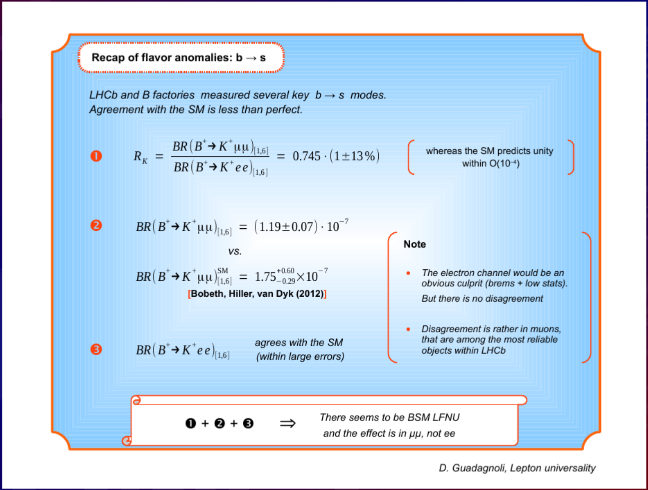

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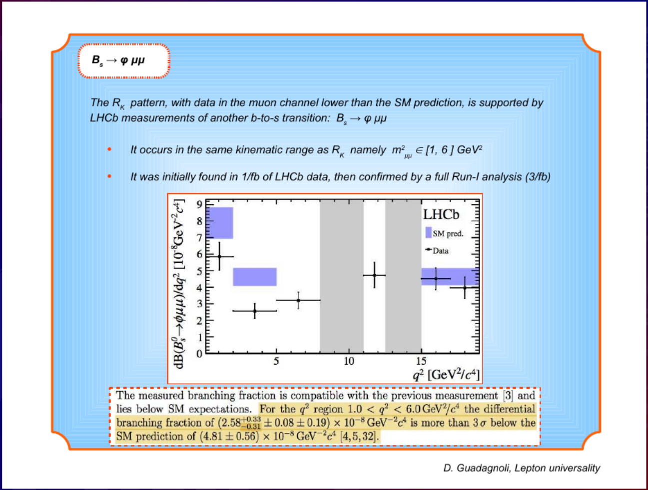

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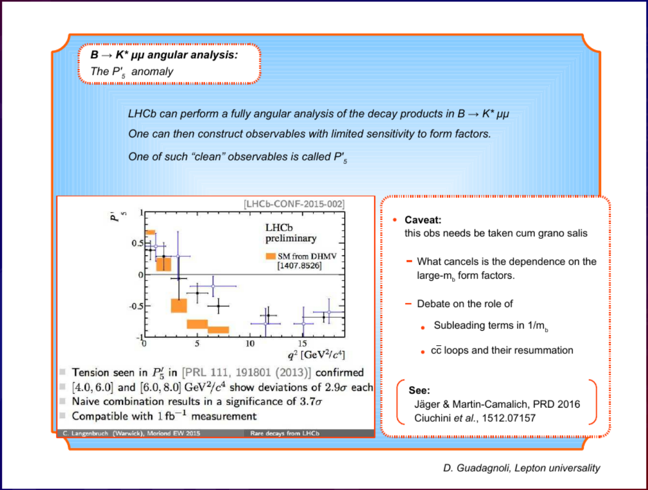

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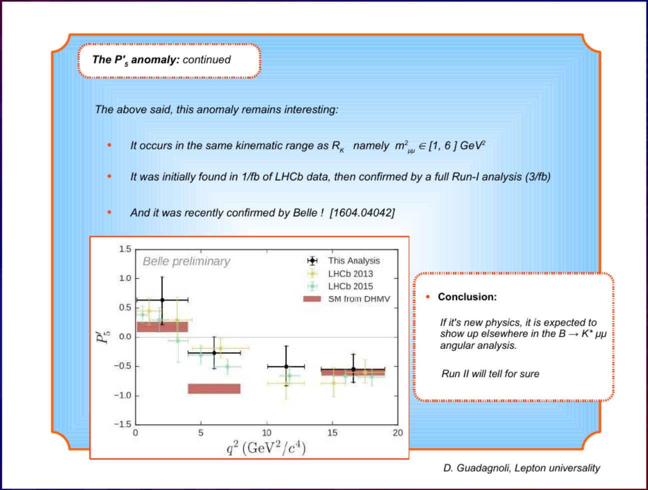

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$B_s \to \mu\mu$

$$\frac{BR(B_s \to \mu\mu)_{exp}}{BR(B_s \to \mu\mu)_{SM}} = 0.77 \pm 0.20$$

$$BR(B_s \to \mu\mu)_{exp} = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

[LHCb&CMS full-Run I combination]

$$BR(B_s \to \mu\mu)_{SM} = (3.65 \pm 0.23) \times 10^{-9}$$

[C. Bobeth et al., PRL 14]

- Theory prediction now very solid. All (known) theory systematics included.
  - "large-$\Delta\Gamma_s$" effect [K. De Bruyn et al., PRL 12]
  - soft-photon corr's [Buras, Girrbach, DG, Isidori, EPJC 12]
  - NLO EW & NNLO QCD corr's [Bobeth, Gorbahn, Stamou, PRD 14; Hermann, Misiak, Steinhauser, JHEP 13]
  - current error (~6%) dominated by CKM and f_{Bs}

- Exp error will go to: ~ 10% by end of Run II
  ~ 5% w/ LHCb upgrade

D. Guadagnoli, Lepton universality

Current Anomalies

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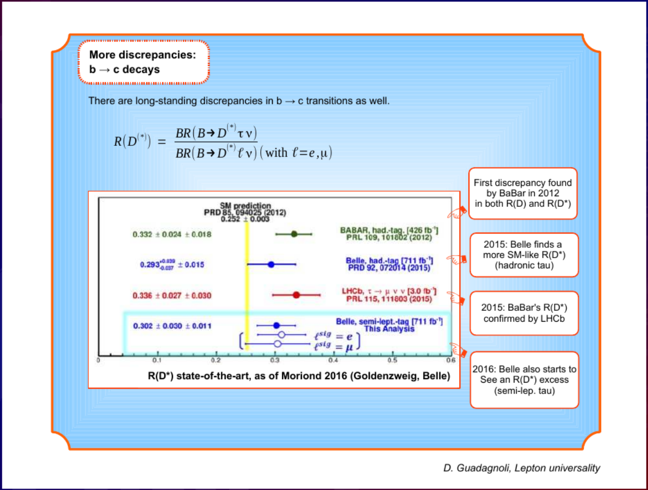

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Conclusions

- *In flavor physics there are by now several persistent discrepancies with respect to the SM. Their most convincing aspects are the following:*
  - ***Experiments:** Results are consistent between LHCb and B factories.*
  - ***Data:** Deviations concern two independent sets of data: $b \to s$ and $b \to c$ decays.*
  - ***Data vs. theory:** Discrepancies go in a consistent direction. A BSM explanation is already possible within an EFT approach.*
- *Early to draw conclusions. But Run II will provide a definite answer*
- *Timely to propose further tests. One promising direction is that of LFV. Plenty of channels, many of which largely untested.*

D. Guadagnoli, Lepton universality

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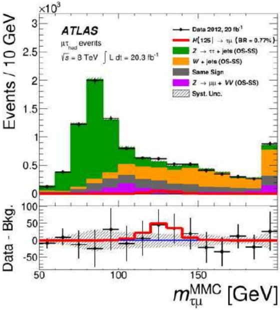

ATLAS: arXiv: 1508.03372

ATLAS

$$\mathrm{BR}(h \to \mu\tau) = (0.77 \pm 0.62)\%$$

ATLAS: arXiv: 1508.03372

In Moriond EW 2016
ATLAS:
BR = 0.53 ± 0.51% < 1.43% (95% CL)

consistent with CMS

CMS best fit:

$$\mathrm{BR}(h \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$$

2.4 σ excess

Hint for new physics!

Kazuhiro Tobe

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CLFV, muon g-2 and EDM in a general two Higgs doublet model

(both Higgs doublets couple to all fermions)

Refs: JHEP 1505, 028 (2015), arXiv: 1511.08880
Omura, Senaha, Tobe
+ work in progress

Kazuhiro Tobe

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Summary

★ Experimental and theoretical studies for flavor are important to understand a mystery of flavor in the SM.

★ Searches for CLFV (EDM) will be sensitive to (well-motivated) new physics models around TeV scale.

★ In the LHC era, the interplay between LHC physics and flavor physics will be important since it provides interesting ideas for new physics sometimes.

★ General 2HDM with μ-τ flavor violation can explain both CMS excess in $h\to\mu\tau$ and muon g-2 anomaly. The rate of $\tau\to\mu\gamma$ can be within the reach of the future B factory. The precision measurement of τ decay will also provide a crucial test of this scenario. Furthermore, unknown flavor structure in this model will provide a rich flavor phenomenology.

Kazuhiro Tobe

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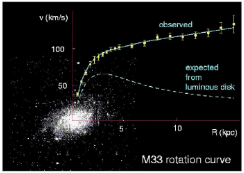
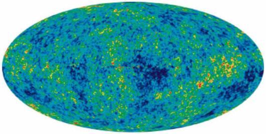
Dark Matter Evidence





Identity of dark matter?
What is its mass?
Possible interactions?

Mu-Chun Chen

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Flavored Dark Matter

- Dark matter come in multiple copies
- Non-trivial flavor structure in couplings to quarks and leptons
  - distinct signatures
- FCNC constraints
  - universal couplings
  - minimal flavor violation — Batell, Pradler, Spannowsky (2011)
  - beyond MFV: "dark minimal flavor violation" — Agrawal, Blanke, Gemmler (2014)
    - dark matter coupling: only new source of flavor violation
    - implemented in quark sector
    - lepton sector unexplored ⇒ this work

Mu-Chun Chen

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Beyond Minimal Flavor Violation

Quark Flavored DM: $G_{QF} \times SU(3)_\chi$ — Agrawal, Blanke, Gemmler (2014)

DM: Dirac fermion $\chi \sim 3$ of $SU(3)_\chi$

mediator: scalar $\phi \sim 1$ of $SU(3)_\chi$

coupling: $\lambda \bar{d}_R \chi \phi$, $\lambda \sim (3, \bar{3})$ of $SU(3)_d \times SU(3)_\chi$

constraints: meson-antimeson mixing, K, B decays, ...

Lepton Flavored DM: $G_{LF} \times SU(3)_\chi$ — MCC, Huang, Takhistov (2015)

DM: Dirac fermion $\chi \sim 3$ of $SU(3)_\chi$

mediator: scalar $\phi \sim 1$ of $SU(3)_\chi$

coupling: $\lambda \bar{e}_R \chi \phi$, $\lambda \sim (3, \bar{3})$ of $SU(3)_E \times SU(3)_\chi$

constraints: cLFV processes ($\mu \to e\gamma$, ...)

Mu-Chun Chen

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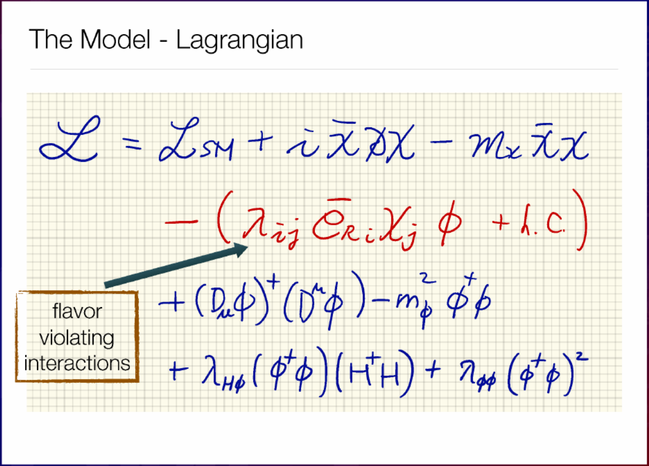

Mu-Chun Chen

Current Anomalies

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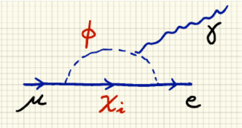
- Muon $g-2$
- B-systems
- Higgs decays
- Dark Matter

  Must obey constraints from CLFV, Muon $g-2$, Relic abundance, DM direct detection, AMS, Fermi-LAT
- Naturalness
- Proton radius....

Constraints: cLFV



Current exp limit:

$Br(\mu \to e\gamma) < 5.7 \times 10^{-13}$

(MEG @ PSI, 90% CL)

$$Br(\mu \to e\gamma) \propto \frac{1}{G_F^2 m_\phi^4} \left[\sum_{i=1}^{3} (\lambda_{1i}^* \lambda_{2i}) \; F\left(\frac{m_{\chi_i}^2}{m_\phi^2}\right) \right]^2$$

$\chi = (\chi_1, \chi_2, \chi_3)$

$F(x) \sim (1-6x+\cdots)(1-x)^{-4}$

Mu-Chun Chen

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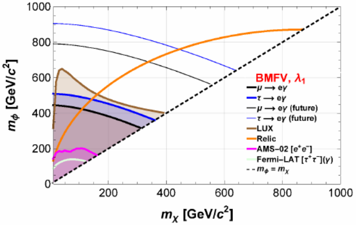
Summary

- Lepton Flavored DM: beyond MFV with SU(3)χ
- Contrast to quark flavored DM case: no automatic stabilizing symmetry
- Most stringent constraints from cLFV processes
- Interesting collider signatures
- UV Theory of (B)MFV?



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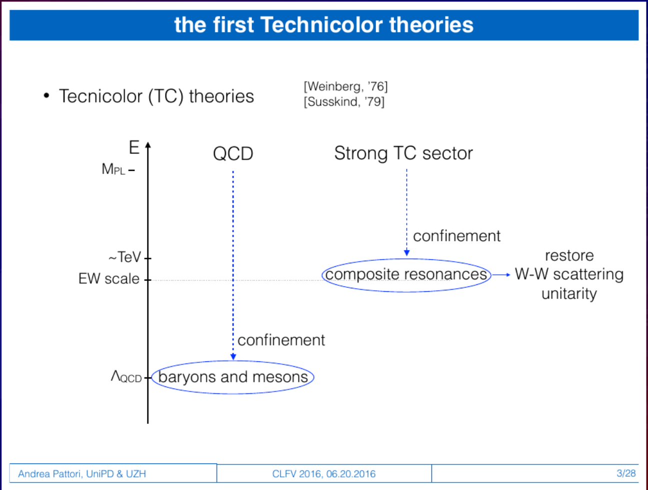

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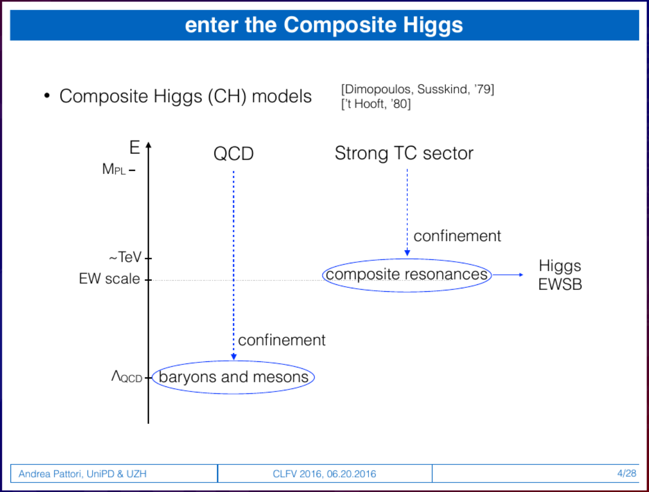

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conclusions

- Composite Higgs models are appealing proposals
  - natural solution to the hierarchy problem
  - Partial Compositeness address the flavor puzzle(s)
- At present days RS-GIM mechanism is challenged by CLFV
  - Anarchic scenarios gets serious bounds
  - Flavor symmetries are a not-so-easy way out
- The simplified approach gives a different perspective
  - Interesting insights in the flavor structure of these scenarios
  - Viable models have specific LFV patterns

Andrea Pattori, UniPD & UZH | CLFV 2016, 06.20.2016 | 28/28

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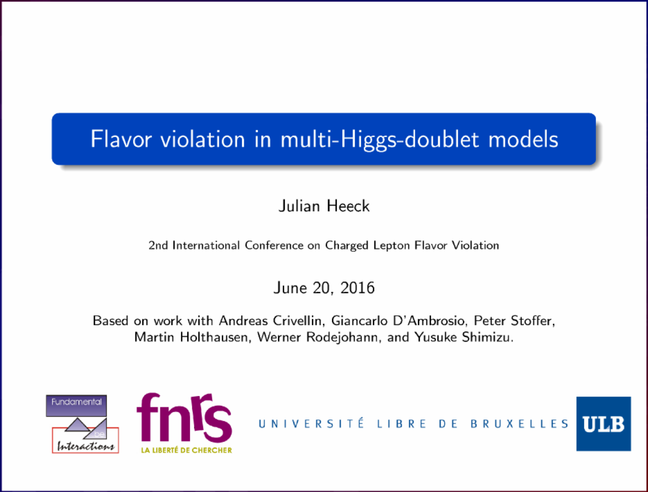

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Two-Higgs-Doublet Model (2HDM)

Simple extension of SM: add one more scalar doublet.[2]

- Arises often in BSM, e.g. SUSY, axion models.
- New physical scalars: H, A, H^+.
- $\rho = M_W^2/M_Z^2 \cos^2\theta_W = 1$ at tree level; $\langle\Phi_1\rangle/\langle\Phi_2\rangle = \tan\beta$.
- Brings additional CP violation (useful for baryogenesis).
- Generally induces flavor-changing processes (both quarks and leptons), e.g.

$$\ell_\alpha \to \ell_\beta \gamma\,, \qquad h \to \ell_\alpha \bar{\ell}_\beta\,,^{3} \qquad Z \to \ell_\alpha \bar{\ell}_\beta\,.$$

- Limits up to $m_{A,H} > 10^3$–$10^5\,\text{TeV}$ for $\mathcal{O}(1)$ $e\mu$ or ds couplings.

Why flavor-changing?

[2] Lee, 1973; extensive review of 2HDM in Branco et al, arXiv:1106.0034.
[3] Davidson, Grenier, 2010; Blankenburg, Ellis, Isidori; Harnik, Kopp, Zupan, 2012.

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Gauged $U(1)_{L_\mu - L_\tau}$ flavor symmetry

$L_\mu - L_\tau$ well known symmetry:

- Current $j'_\alpha = \bar{\mu}\gamma_\alpha\mu - \bar{\tau}\gamma_\alpha\tau + \bar{\nu}_\mu\gamma_\alpha P_L \nu_\mu - \bar{\nu}_\tau\gamma_\alpha P_L \nu_\tau$.
- Anomaly free in SM.[20]
- Light Z' could resolve $(g-2)_\mu$ anomaly.[21]
- Good zeroth order approximation to neutrino mixing with quasi-degenerate masses ($m_{1,2,3} \simeq 1\,\mathrm{eV}$ and $\beta = \pi/2$):

$$\mathcal{M}_\nu = U_{\mathrm{PMNS}}\,\mathrm{diag}(m_1, m_2, m_3) U^T_{\mathrm{PMNS}}$$
$$\simeq \begin{pmatrix} 0.96 & -0.20 & -0.22 \\ \cdot & 0.11 & -0.97 \\ \cdot & \cdot & -0.07 \end{pmatrix} \mathrm{eV} \sim \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix} \leftarrow L_\mu - L_\tau$$

- $L_\mu - L_\tau$ gives $\theta_{23} = \pi/4$ and $\theta_{13} = 0$.[22]

[20] He, Joshi, Lew, Volkas, PRD 1991; Foot, MPLA 1991.
[21] Baek et al, PRD 2001; Altmannshofer et al, PRL 2014; Baek, 1510.02168.
[22] Binetruy, Lavignac, Petcov, Ramond, NPB 1997; Bell, Volkas, PRD 2001; Choubey, Rodejohann, EPJC 2005.

Julian Heeck (ULB) Flavor violation in multi-Higgs-doublet models 16 / 38

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$L_\mu - L_\tau$ in a 2HDM

- 2HDM: $\Phi_1 \sim -2$, $\Phi_2 \sim 0$ under $U(1)_{L_\mu - L_\tau}$.[23]
- Plus scalar singlet $S \sim 1$ and three $\nu_R \sim (0, 1, -1)$ for seesaw.
- $S \to \langle S \rangle$ generates $\Delta\mathcal{M}_R$ for valid PMNS, $M_{Z'}/g' = \langle S \rangle$, and $S^2 \Phi_2^\dagger \Phi_1 \to m_{12}^2 \Phi_2^\dagger \Phi_1$.
  $\Rightarrow$ small VEV $\langle \Phi_1 \rangle$ induced! ($\leftarrow$ large $\tan\beta$ region.)
- Lepton Yukawa couplings:[24]

$$Y_{\ell_2} = \mathrm{diag}(y_e, y_\mu, y_\tau)\,, \qquad Y_{\ell_1} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \xi_{\tau\mu} & 0 \end{pmatrix}.$$

$\Rightarrow$ Gauge symmetry sets all other LFV couplings zero!

Coupling $h\mu\tau$ now generated by scalar mixing and lepton mixing.

[23] J.H., Rodejohann, PRD 2011, see Dutta, Joshipura, Vijaykumar, PRD 1994, for $L_e - L_{\mu,\tau}$.
[24] J.H., Holthausen, Rodejohann, Shimizu, NPB (2015), 1412.3671.

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Summary

General nHDM perfect environment for flavor:

- Flavor non-universality & violation.
- Potentially large $h \to \ell_i \bar{\ell}_j$ & $\ell_i \to \ell_j \gamma$.
- Light A/H could solve $(g-2)_\mu$.
- H^+ could solve $R(D^{(*)})$.

Controlled flavor violation via $U(1)'$:

- Z' could solve $b \to s$ anomalies.
- Light Z' could induce $\ell_i \to \ell_j Z'$.

Wait for new ~~data~~ physics.

Julian Heeck (ULB) Flavor violation in multi-Higgs-doublet models 38 / 38

Current Anomalies

Direct searches for CLFV are providing strong constraints on BSM Physics—other observables may be giving us hints of New Physics

- Muon $g-2$
- B-systems
- Higgs decays
- Dark Matter
- Naturalness
- Proton radius....

Proton Structure from the Measurement of 2S-2P Transition Frequencies of Muonic Hydrogen

Aldo Antognini,[1,2*] François Nez,[3] Karsten Schuhmann,[2,4] Fernando D. Amaro,[5] François Biraben,[3] João M. R. Cardoso,[5] Daniel S. Covita,[5,6] Andreas Dax,[7] Satish Dhawan,[7] Marc Diepold,[1] Luis M. P. Fernandes,[5] Adolf Giesen,[4,8] Andrea L. Gouvea,[5] Thomas Graf,[8] Theodor W. Hänsch,[1,9] Paul Indelicato,[3] Lucile Julien,[3] Cheng-Yang Kao,[10] Paul Knowles,[11] Franz Kottmann,[2] Eric-Olivier Le Bigot,[3] Yi-Wei Liu,[10] José A. M. Lopes,[5] Livia Ludhova,[11] Cristina M. B. Monteiro,[5] Françoise Mulhauser,[11] Tobias Nebel,[1] Paul Rabinowitz,[12] Joaquim M. F. dos Santos,[5] Lukas A. Schaller,[11] Catherine Schwob,[3] David Taqqu,[13] João F. C. A. Veloso,[6] Jan Vogelsang,[1] Randolf Pohl[1]

Accurate knowledge of the charge and Zemach radii of the proton is essential, not only for understanding its structure but also as input for tests of bound-state quantum electrodynamics and its predictions for the energy levels of hydrogen. These radii may be extracted from the laser spectroscopy of muonic hydrogen (μp, that is, a proton orbited by a muon). We measured the $2S_{1/2}^{F=0}$-$2P_{3/2}^{F=1}$ transition frequency in μp to be 54611.16(1.05) gigahertz (numbers in parentheses indicate one standard deviation of uncertainty) and reevaluated the $2S_{1/2}^{F=1}$-$2P_{3/2}^{F=2}$ transition frequency, yielding 49881.35(65) gigahertz. From the measurements, we determined the Zemach radius, r_Z = 1.082(37) femtometers, and the magnetic radius, r_M = 0.87(6) femtometer, of the proton. We also extracted the charge radius, r_E = 0.84087(39) femtometer, with an order of magnitude more precision than the 2010-CODATA value and at 7σ variance with respect to it, thus reinforcing the proton radius puzzle.

Science 25 January 2013: Vol. 339 no. 6118 pp. 417-420 DOI: 10.1126/science.1230016

7σ deviation—only mentioned in passing!

- Muon Experiments
  - $\mu \to e + \gamma$
    - From the beginnings of CLFV
    - MEG at PSI
    - Suppression of Muonic CLFV
  - Muon-to-Electron Conversion
    - Z-Dependence
    - Next Generation of Experiments
    - Decay of Muons Bound to Nuclei
    - Cautionary Tales
  - $\mu \to 3e$
  - Physics Reach of Experiments
- Other Experiments
  - NA48/2 and NA62
  - Current Anomalies in Data
  - Collider Experiments
- The Connection with Neutrinos
- Closing Remarks
  - Statistics in CLFV Physics and PhyStat-ν (next at Fermilab in September)
  - The First Signs of BSM Physics

Latest Updates from Collider Experiments

Selected results

- **ATLAS**
- CMS
- LHCb
- Belle & Belle II
- BES III

Higgs $\rightarrow \mu\tau$

JHEP 11 (2015) 211
arXiv: 1508.03372 and
Submitted to EPJC
arXiv: 1604.07730

Events with μ and τ decaying hadronically or leptonically.

Use τ kinematics and missing E_T vector to correct for undetected ν using Missing Mass Calculator (MMC).

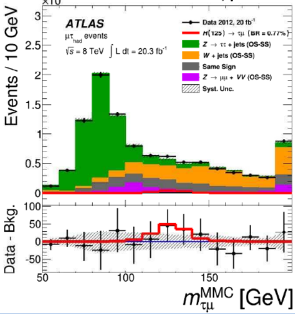
Two signal regions: one dominated by $Z/\gamma^* \rightarrow \tau\tau$ at lower $\mu\tau$ mass and one dominated by W + jets at higher mass.

Require moderate missing E_T to suppress $Z/\gamma^* \rightarrow \mu\mu$.

BR ($H \rightarrow \mu\tau$) < 1.43% (95% CL)

Theory: BR < ~10% from
$\tau \rightarrow \mu\gamma$ and $(g-2)_{e,\mu}$

Combined, post fit



Craig Blocker (Brandeis University) CLFV2016 7

Latest Updates from Collider Experiments

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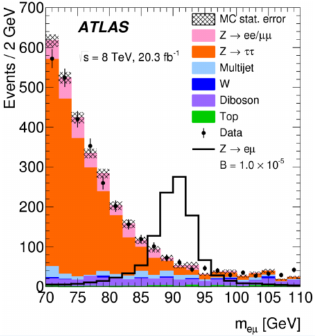
$Z \to e\mu$

PRD 90, 072010 (2014)
arXiv: 1408.5774

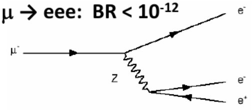


Fit to background + signal.

BR ($Z \to e\mu$) < 7.5×10^{-7} (95% CL)

LEP: BR < 1.7×10^{-6} (95% CL)

Limit inferred from
$\mu \to eee$: BR < 10^{-12}



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Latest Updates from Collider Experiments

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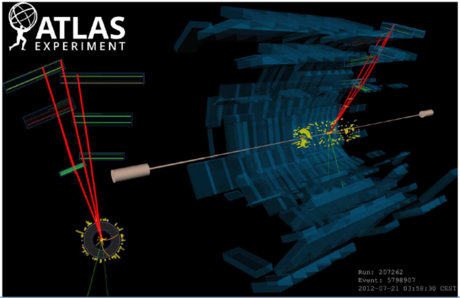
$\tau \to \mu\mu\mu$

EPJC (2016) 76
arXiv: 1601.03567

$pp \to W \to \tau\,\nu \to (\mu\mu\mu)\,\nu$

Use Boosted Decision Tree based on E_T^{miss}, muon momenta, track and vertex quality, W kinematics, etc.



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Latest Updates from Collider Experiments

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- **ATLAS**
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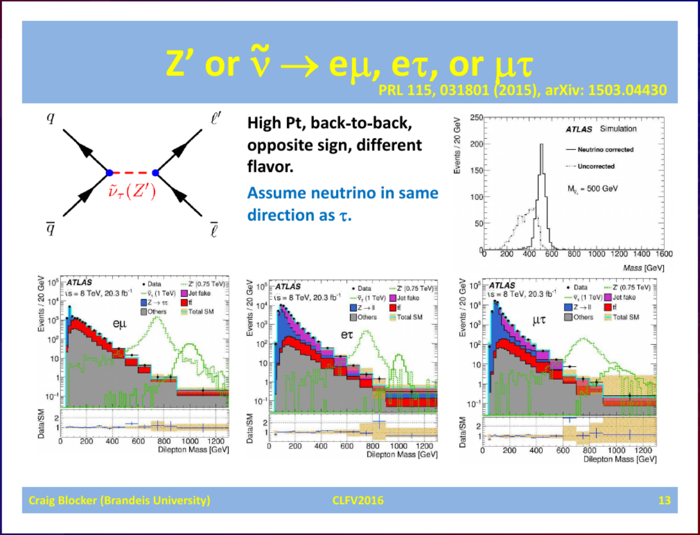

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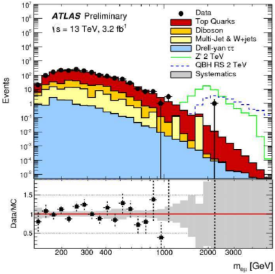
Z' or QBH → eμ

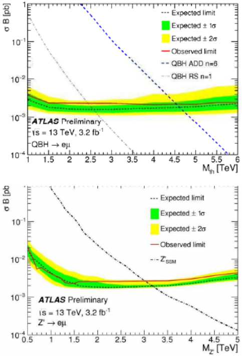
ATLAS-CONF-2015-072
cds.cern.ch/record/214844

13-TeV analysis. **Similar to 8-TeV eμ search.**

Look for high p_T e and μ of opposite sign.

Quantum Black Holes (QBH) might be produced in theories with large extra dimensions and are expected to not conserve lepton flavor.





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Latest Updates from Collider Experiments

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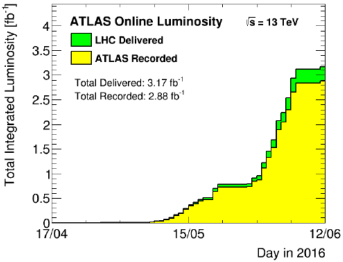
Summary

- ATLAS has searched for lepton flavor violation in the 8-TeV and 13-TeV data via
  - decays of Standard-Model particles (Z, H)
  - decays of possible new particles ($\tilde{\nu}$, Z’, $\tilde{\chi}$)
  - decays of Quantum Black Holes.
- No excess over the Standard Model expectations is seen.
- Limits are placed on various production and decay mechanisms.
- LHC is running at 13 TeV, and we look forward to studying the increased data sets.



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Latest Updates from Collider Experiments

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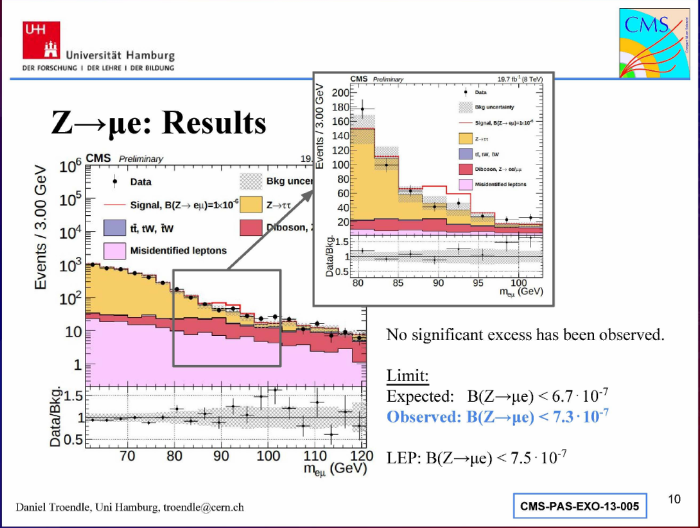

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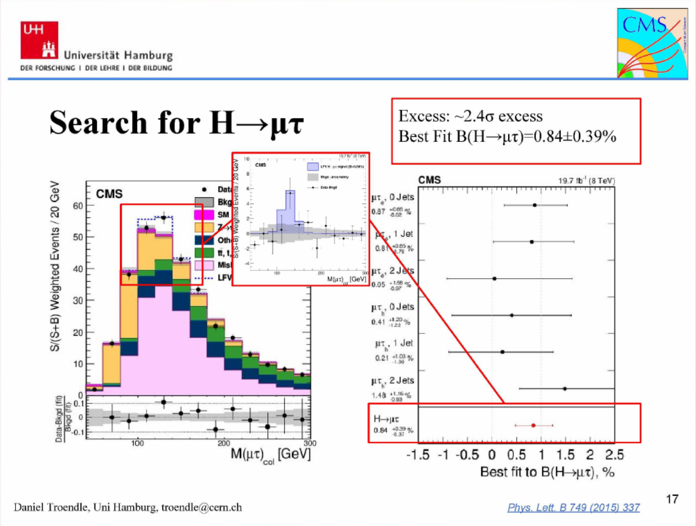

Latest Updates from Collider Experiments

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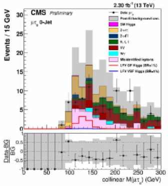
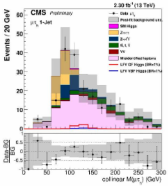
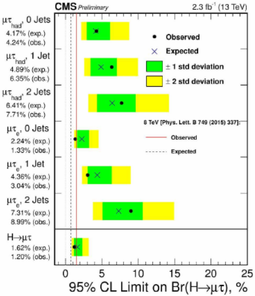
Search for H→μτ @ 13TeV!

- Repetition of 8TeV H→μτ analysis: no change of strategy and kinematic cuts
- **Slight excess of 8TeV analysis could not be confirmed so far, but also not excluded!**
- Updated B(H→μτ) Limit: B(H→μτ)<1.2% observed (1.62% expected)







Daniel Troendle, Uni Hamburg, troendle@cern.ch

CMS-PAS-HIG-16-005

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"Statistically-limited; can still hope!"

Latest Updates from Collider Experiments

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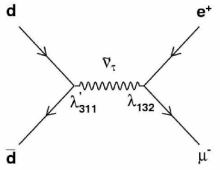
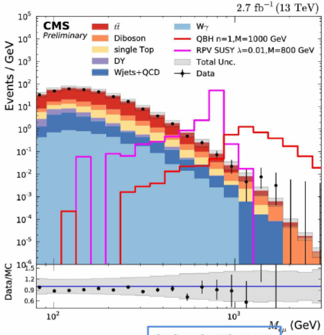
CMS

Search for high mass resonances in the eμ final states at 13 TeV

Resonant sneutrino decays (RPV-SUSY) or non-resonant Quantum-Black-Holes (QBH) could decay into eμ pairs (+others models).





CMS-PAS-EXO-16-001

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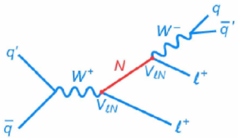
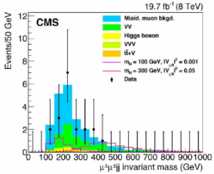
CMS

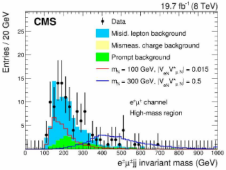
Search for Heavy Majorana Neutrinos

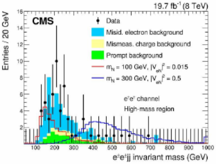


Search Strategy:

- Two tight leptons with same sign($e^{\pm}e^{\pm}$,$\mu^{\pm}\mu^{\pm}$,$e^{\pm}\mu^{\pm}$)
- Mass dependent cust:
  - Low mass m_N < 90 GeV: MET<30 GeV , m (lljj)<200 GeV, m(jj)<120 GeV
  - High mass m_N> 90 GeV: MET<35 GeV, m (jj)=$m_W \pm 30$ GeV







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JHEP 04 (2016) 169
Phys. Lett. B 748 (2015) 144

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"Do you see a signal?"

Latest Updates from Collider Experiments

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- ATLAS
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CMS

Conclusion

- Strong portfolio of CLFV searches in CMS
- New Physics models on CLFV tested up to multi-TeV scale already
- LHC Run-II: expect more interesting updates by the end of the year!

http://cms-results.web.cern.ch/cms-results/public-results/publications/

Daniel Troendle, Uni Hamburg, troendle@cern.ch

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Latest Updates from Collider Experiments

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faculty of mathematics and natural sciences

van swinderen institute for particle physics and gravity

Nikhef

cLFV @ LHCb

Status & Prospects

cLFV 2016

Gerco Onderwater

on behalf of the LHCb collaboration

LHCb

cLFV2016, Charlottesville VA, USA, 20-22 June 2016

Latest Updates from Collider Experiments

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LHCb

Result

$$\frac{\mathbb{P}(\theta_{up}(X) < \theta|\theta)}{\mathbb{P}(\theta_{up}(X) < \theta|0)} \leq \alpha' \text{ for all } \theta.$$

- Robust analysis method
- Statistics limited
- No significant evidence for excess of events

$B(\tau^- \to \mu^-\mu^+\mu^-) < 4.6 \times 10^{-8}$

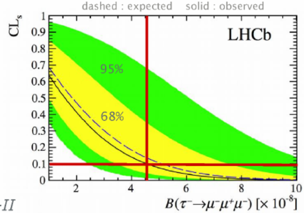
@ 90% C.L.

Belle 2.1×10^{-8} @ 90% C.L.

BaBar 3.3×10^{-8} @ 90% C.L.

@Run2: LHCb may overtake Belle

... which will then be overtaken by Belle-II



Gerco Onderwater, cLFV2016

JHEP 02 (2015) 121

Latest Updates from Collider Experiments

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LHCb

Result

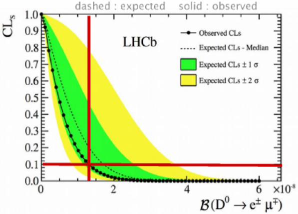
$$\frac{\mathbb{P}(\theta_{up}(X) < \theta|\theta)}{\mathbb{P}(\theta_{up}(X) < \theta|0)} \leq \alpha' \text{ for all } \theta.$$

- Robust analysis method
- Statistics limited
- No significant evidence for excess of events

$B(D^0 \to e\mu) < 1.3 \times 10^{-8}$

@ 90% C.L.

20x improvement over previous result
Effectively deal with backgrounds
Bremsstrahlung complicates analysis
Difficult to do at e^+e^- colliders



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PLB 754 (2016) 167

Latest Updates from Collider Experiments

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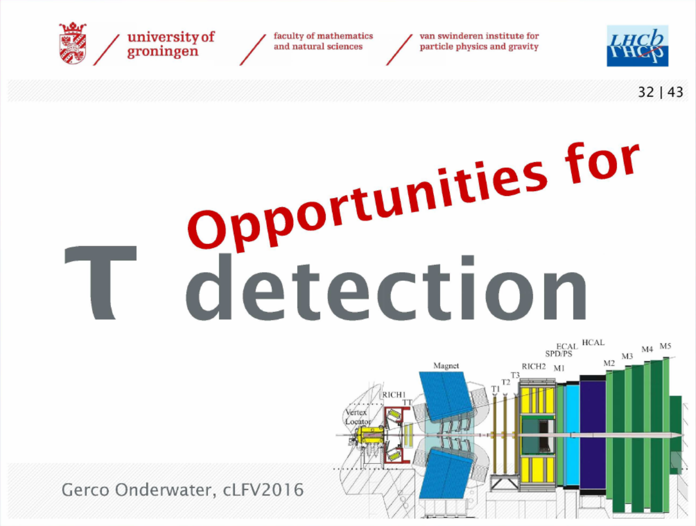

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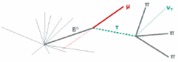
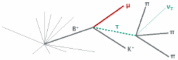
Possibly interesting channels

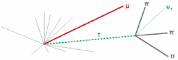
$B_{(s)} \rightarrow e/\mu\tau$



$B^+ \rightarrow K^+ e/\mu\tau$



$\Upsilon(nS) \rightarrow e/\mu\tau$



Benefit from $\overline{B}^0 \rightarrow D^{*+}\tau\overline{\nu}_\tau$

Phys. Rev. Lett. 115, 111803 (2015)

Latest Updates from Collider Experiments

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LHCb

Take away message

LHCb : diverse program studying flavor physics with <u>all</u> three quark & lepton generations

With LHC **Run-I** data **LHCb** sharpened limits for many LFV, LNV, and BNV channels

No significant deviations from **SM** seen

Demonstrated sensitive **BSM** searches @ hadron collider

Many more options around, lots of additional data expected in **Run-II** (just restarted) & **Run-III**

Gerco Onderwater, cLFV2016

Latest Updates from Collider Experiments

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BELLE Belle II

Indian Institute of Technology Guwahati

Charged Lepton Flavor Violation at Belle & Belle II

Bipul Bhuyan

(On behalf of the Belle and Belle II Collaborations)

2nd International Conference on CLFV 2016
University of Virginia, Charlottesville
June 22, 2016

Latest Updates from Collider Experiments

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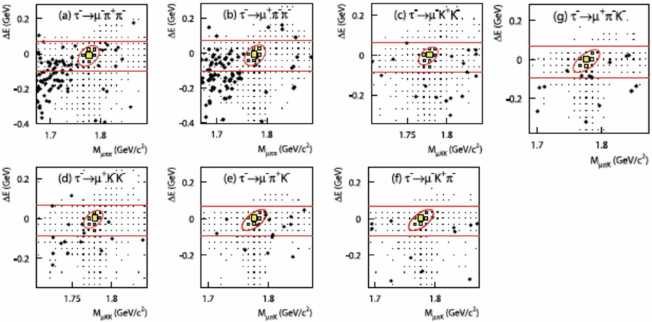
$\tau \to \mu\, h\, h'$ Results



- In the signal region: 1 event in $\mu^+ \pi^- \pi^-$ and $\mu^- \pi^+ K^-$ (consistent with expected background). 0 events in other modes.

Bipul Bhuyan I 2nd International Conference on CLFV 2016 21/06/16 12

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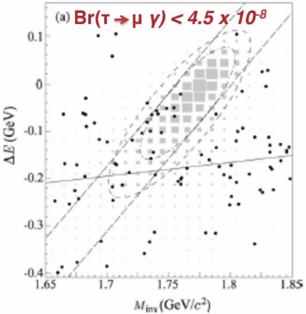
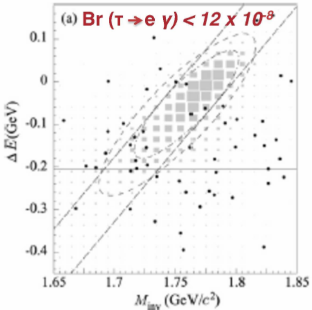
$\tau \to l\,\gamma$



Observed 94 (23) events in the 5 σ (3σ) regions.
Expected: 88.4 ± 7.4 (15 ± 3.1)



Observed 55 (13) events in the 5 σ (3σ) regions.
Expected: 42.8 ± 3.7 (8.1 ± 1.6)

Bipul Bhuyan I 2nd International Conference on CLFV 2016 21/06/16 17

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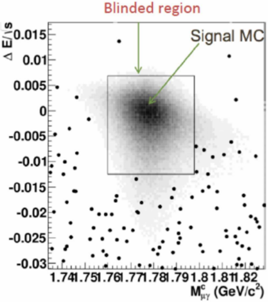
τ → μ γ : *Updated Analysis*

- Full data sample from Belle: 980 fb^{-1} .
- ~6.5% signal selection efficiency
- Expected background: 115 ± 11
- About a factor of 1.5 increase in sensitivity.



Preliminary results

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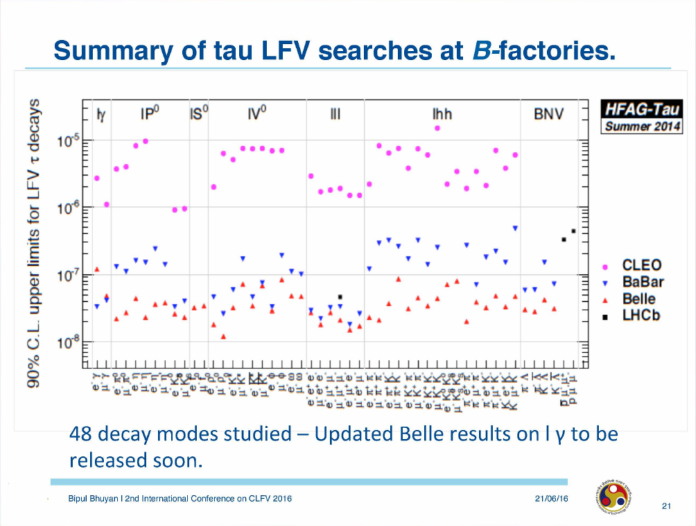

Look forward to $\tau \to \mu + \gamma$ results

Latest Updates from Collider Experiments

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- BES III

cLFV and New Physics Searches at BESIII

Dayong Wang

dayong.wang@pku.edu.cn

(for BESIII Collaboration)

北京大学

PEKING UNIVERSITY

CLFV2016@UVA, Jun 22 2016

Latest Updates from Collider Experiments

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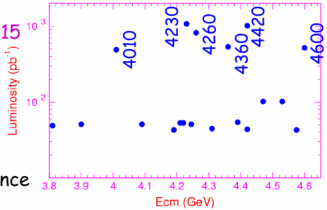
BESIII data samples

~ 0.5 B	$\psi(3686)$ events	~ 24×CLEO-c
~ 1.3 B	J/ψ events	~ 21×BESII
~ 2.9/fb	$\psi(3770)$	~ 3.5×CLEO-c
~5/fb	**XYZ** states above 4 GeV	Unique

- 20 points for R &QCD Scan: 500/pb finished in May 1st, 2015
- Y(2175) resonance: 100 /pb : finished in June 15, 2015

2016: just finish 3/fb Ds data at 4170 MeV ~ 5×CLEO-c

~ other data sets: tau, Λ_c, resonance scan and continuum, etc.



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Motivation for $J/\psi \to e\mu$

- With finite neutrino masses included, Lepton Flavor Violation (LFV) is allowed, but the smallness of the mass leads to the predicted branching fraction well beyond current experimental sensitivity.
- However, there are various theoretical models such as SUSY may enhance LFV effects up to a detectable level.
- Any detection of a LFV decay indicates the existence of new physics.
- The LFV decay have been searched in lepton decay, pseudoscalar meson decay and vector meson decay. It is equally important to search it in heavy quarkonium decays.

2016/6/22 cFLV2016 Dayong Wang 9

Latest Updates from Collider Experiments

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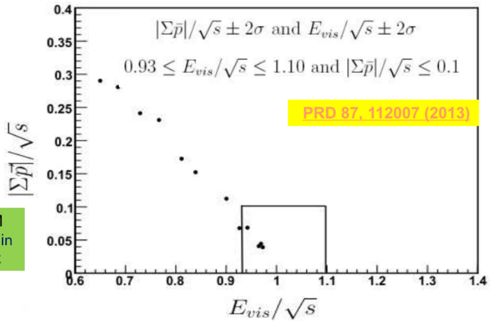
- Belle & Belle II
- BES III

BESIII — J/ψ → eμ: Unblinded Data and Results



Among 225M J/ψ, 4 events in the signal box

$$\mathcal{B}(J/\psi \to e\mu) < 1.6 \times 10^{-7} \text{ (90\% C.L.)}$$

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Latest Updates from Collider Experiments

Selected results

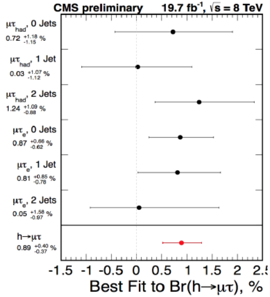
- ATLAS
- CMS
- LHCb
- Belle & Belle II
- BES III

BESIII $\Psi(1S,2S) \rightarrow e\,\tau / \mu\tau / \gamma e\tau / \gamma\mu\tau$

Could non-trivial Yukawa Coupling be a new interaction?
=>Flavor Changing rates be enhanced

$$BR(h \to \tau^{\pm}\mu^{\mp}) < 1.57\% \text{ (95\% C.L.)}$$
$$|y_{\tau\mu}| \leq 3.6 \times 10^{-3}$$

$$BR(h \to \tau^{\pm}\mu^{\mp}) = 0.89 \begin{matrix} +0.40 \\ -0.37 \end{matrix} \%(2.46\sigma)$$
$$|y_{\tau\mu}| \simeq 2.7 \times 10^{-3}$$
$$\sim \sqrt{y_\tau y_\mu} = 2.48 \times 10^{-3}$$



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Latest Updates from Collider Experiments

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- BES III

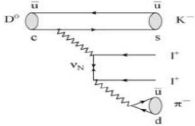
BESIII — Rare Decays to probe NP

- **Rare Charmonia Decays**
  - Semileptonic weak decays
  - Two-body weak hadronic decays
  - C/P violation decays
  - Invisible decays
  - LFV, INV, BNV decays

$$Br(J/\psi \to D_s^- e^+ \nu_e + c.c.) < 1.3\times10^{-6}$$
$$Br(J/\psi \to D_s^{*-} e^+ \nu_e + c.c.) < 1.8\times10^{-6}$$
$$Br(J/\psi \to D_s^- \rho^+) < 1.3\times10^{-5}$$
$$Br(J/\psi \to \bar{D}^0 \bar{K}^{*0}) < 2.5\times10^{-6}$$
$$Br(J/\psi \to \gamma\gamma) < 2.7\times10^{-7}$$
$$Br(J/\psi \to \gamma\phi) < 1.4\times10^{-6}$$

- **Rare Charm decays**
  - LNV : $c \to u\mu^+\mu^+$ forbidden in SM
    - ✓ Majorana neutrino: ~ $10^{-30\sim-23}$ level, PRD64 (2001) 114009
    - ✓ May be greatly enhanced: ~$10^{-5\sim-6}$ with EPJC71 (2011) 1715)

H.R. Dong, F. Feng and H.B. Li, Chin, Phys. C **39** 013101 (2015)



(a) $D^0 \to K^- \ell^+ \ell^+ \pi^-$ (CF)

- FCNC : $c \to u\mu^+\mu^-$ highly suppressed in SM by GIM mechanism BF_{th}~10^{-9} [PRD64 (2001) 114009] while can be enhanced by physics BSM [PRD 76 (2007) 074010]
- Rare FCNC: $D^0 \to \gamma\gamma$

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Latest Updates from Collider Experiments

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- ATLAS
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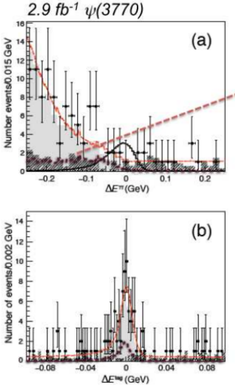
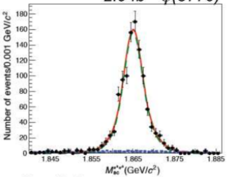
BESIII $D^0 \to \gamma\gamma$ Results



Major background $D^0 \to \pi^0\pi^0$ is determined in data with similar double-tag method.



$B(D^0 \to \pi^0\pi^0) = (8.24 \pm 0.21 \pm 0.30) \times 10^{-4}$

2-D fit to ΔE in both tag side and γγ sides to determine $D^0 \to \gamma\gamma$ yield.

$$B(D^0 \to \gamma\gamma) < 3.8 \times 10^{-6}$$

consistent with BaBar result, will update with a 4X larger sample.

PRD91, 112015 (2015)

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Latest Updates from Collider Experiments

Selected results

- ATLAS
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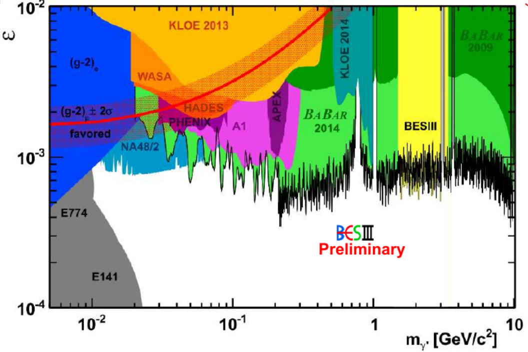
BESIII ISR search results



Some searches with meson decays are also going on with BESIII data, but less competitive

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PEN/PIENU

- PIENU at TRIUMF
- PEN at PSI

PEN/PIENU: is $g_e = g_\mu$?

a new round of $B_{\pi \to e\nu}$ measurements

Andries van der Schaaf

Physik-Institut Zurich University

2nd International Conference on Charged Lepton Flavor Violation
University of Virginia, Charlottesville, USA
20-22 June 2016

PEN/PIENU

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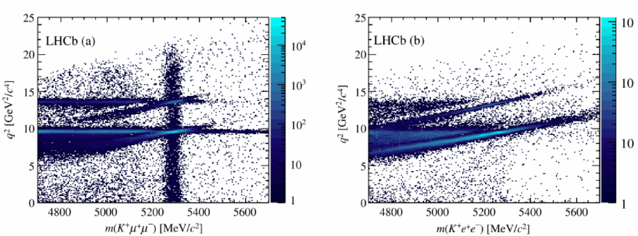
- PEN at PSI

Lots of excitement and creativity by model builders after this LHCb result[3]:



Dilepton invariant mass squared versus $K^+l^+l^-$ invariant mass

$$\Gamma(B^+ \to K^+\mu\overline{\mu})/\Gamma(B^+ \to K^+e\overline{e}) = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

a 2.6σ deviation!

[3]R. Aaij *et al.*, LHCb Collaboration, Phys.Rev.Lett. **113**, 151601 (2014).

PEN/PIENU

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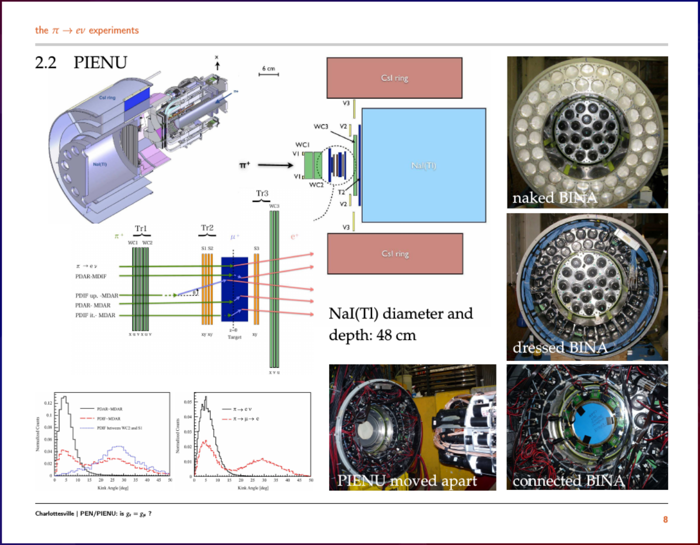
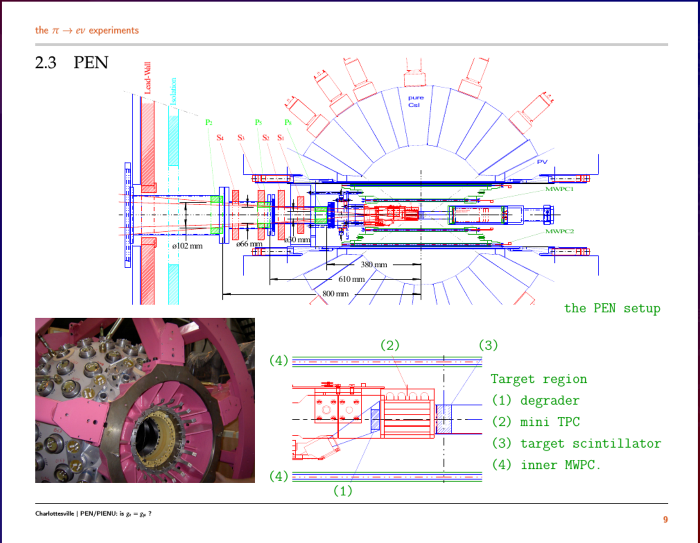
- PEN at PSI



PEN/PIENU

- PIENU at TRIUMF
- PEN at PSI

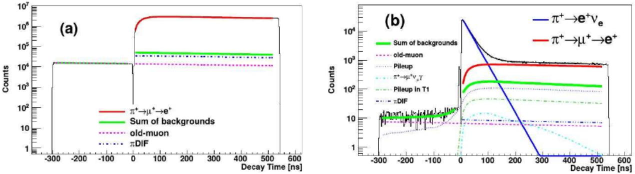


PEN/PIENU

- PIENU at TRIUMF
- PEN at PSI

8 a first result from PIENU

Based on ≈ 10% of all recorded data.
0.5×10^6 $\pi \to e\nu$ events enter the time analysis.



Decay-time analysis of events with e^+ energy below **(a)** or above **(b)** 52 MeV.
At this cut the tail-fraction amounts to $3.16 \pm 0.12\%$.

1992 TRIUMF result:	$B = (1.2265 \pm 0.0034(\text{stat}) \pm 0.0044(\text{syst})) \times 10^{-4}$
1993 PSI result:	$B = (1.2350 \pm 0.0035(\text{stat}) \pm 0.0036(\text{syst})) \times 10^{-4}$
combined:	$B = (1.2312 \pm 0.0035) \times 10^{-4}$
2015 TRIUMF result[10]:	$B = (1.2344 \pm 0.0023(\text{stat}) \pm 0.0019(\text{syst})) \times 10^{-4}$
new average:	$B = (1.2329 \pm 0.0019) \times 10^{-4}$

[10] A. Aguilar-Arevalo *et al.*, [PIENU Collaboration], Phys. Rev. Lett. **115** (2015) 071801.

PEN/PIENU

- PIENU at TRIUMF
- PEN at PSI

9 Outlook

PEN finished data-taking five years ago and has been studying these data in great detail ever since. Energy, time and geometry calibrations are done and most features observed are understood and reproduced by simulation.

The question remains when one might expect to "open the box" and finish the project by publishing the branching ratio. Unfortunately, that question can't be answered for sure but it should happen within the next year.

It is likely that PIENU will be finished by then as well so a significant reduction in the experimantal error of the world avarage can be anticipated.

Connection with Neutrinos

Charged leptons and neutrinos are closely related—and plenty of BSM behaviour in neutrinos

- Sterile neutrinos
- Seesaw mechanism

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cLFV and New Physics

- **Flavour violation in charged lepton sector:** Physics beyond SM_{m_ν} !

  Are neutral and charged LFV related?

  Does cLFV arise from ν-mass mechanism? Or entirely different nature?

- **Two approaches to address these questions:** Effective (model-independent)

  (well-motivated) New Physics models

- **LFV in models of New Physics**

  Flavour violating extensions of the SM: Little Higgs, extra dimensions, general SUSY, ...

  Models of neutrino mass generation: Low-scale seesaws, SUSY seesaw, ...

  Hints of an organising principle - LFV and symmetries: LR models, GUTs, ...

- **cLFV arising in SM "minimally" extended via sterile fermions !**

- Hints on the mechanism of ν-mass generation...?

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Beyond the 3-neutrino paradigm

- **Sterile fermions:** singlets under $SU(3)_c \times SU(2)_L \times U(1)_Y$

  Interactions with SM fields: through **mixings** with **active neutrinos** (via Higgs)

  No bound on the **number** of sterile states, **no limit** on their **mass scale(s)**

  Present in several theoretical models accounting for **ν masses and mixings**

- **Interest & phenomenological implications** - strongly dependent on their **mass!**

  eV scale ↔ extra neutrinos suggested by short baseline ν oscillation anomalies
  (oscillation results not explained within 3 flavour oscillation)

  keV scale ↔ warm dark matter candidates; explain pulsar velocities (kicks)
  (extensive bounds to be complied with...)

  MeV - TeV scale ↔ experimental testability! (and BAU, DM, m_ν generation...)
  (direct and indirect effects, both at the high-intensity and high-energy frontiers)

  Beyond 10^9 GeV ↔ theoretical appeal: standard seesaw, BAU, GUTs

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Theoretical frameworks of ν_s

- **Numerous SM extensions aiming at accounting for ν masses and mixings**

  ⇝ Right-handed neutrinos (low scale seesaws: type I, νMSM, ...)

  $$\mathcal{L}_{\text{type I}} = -Y^{\ell}\,\bar{L}_L\,H\,e_R - Y^{\nu}\,\overline{\nu_R}\,\tilde{H}\,\nu_L - \tfrac{1}{2}\,\overline{\nu_R}\,M_N\,\nu_R^c \qquad \Rightarrow m_\nu \sim \frac{v^2\,Y_\nu^2}{M_N}$$

  ⇝ Other neutral fermions (ν_R + extra sterile states in Inverse Seesaw, ...)

  $$\mathcal{L}_{\text{ISS}} = -Y^{\nu}\,\overline{\nu_R}\,\tilde{H}\,L - M_R\,\overline{\nu_R}\,X - \tfrac{1}{2}\mu_X\,\bar{X}^c\,X + \tfrac{1}{2}\mu_R\,\overline{\nu_R}\,\nu_R^c \qquad \Rightarrow m_\nu \sim \frac{v^2\,Y_\nu^2}{M_R}\,\frac{\mu_X}{M_R}$$

  ⇒ Neutrino oscillation data; leptogenesis; DM (?); very rich phenomenology

- **Simplified "toy models" for phenomenological analyses: SM + ν_s**

  "ad-hoc" construction (no specific assumption on mechanism of mass generation)

  encodes the effects of N additional sterile states in a **single one**

  ... Not to be confused with oscillation anomaly solution!...

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"Toy model" for phenomenological analyses: S▒ ▒ ν_s

▶ **Assumptions:** 3 active neutrinos + 1 sterile state $n_L = (\nu_{Le}, \nu_{L\mu}, \nu_{L\tau}, \nu_s^c)^T$

interaction basis ⇝ physical basis $n_L = U_{4\times4}\,\nu_i$

$U^T_{4\times4}\,M\,U_{4\times4} = \text{diag}(m_{\nu_1}, ..., m_{\nu_4})$ "**Majorana** mass": $\mathcal{L}_{\text{toy}} \sim n_L^T C M n_L$

▶ **Active-sterile mixing $\mathbf{U}_{\alpha i}$:**

rectangular matrix ← $\mathbf{U} = U|_{3\times4}$

▶ **Left-handed lepton mixing $\tilde{U}_{\text{PMNS}}$:**

3×3 sub-block, non-unitary!

$$U_{4\times4} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

▶ **Physical parameters: 4 masses** [3 light (mostly active) + 1 heavier (mostly sterile) states]

6 mixing angles [θ_{12}, θ_{23}, θ_{13}, & θ_{i4}] and **6 phases** [(3 Dirac and 3 Majorana)]

▶ **Modified charged ($W^\pm$) and neutral (Z^0) current interactions:**

$$\mathcal{L}_{W^\pm} \sim -\frac{g_w}{\sqrt{2}}\,W^-_\mu \sum_{\alpha=e,\mu,\tau}\sum_{i=1}^{3+n_S} \mathbf{U}_{\alpha i}\,\bar{\ell}_\alpha\,\gamma^\mu\,P_L\,\nu_i$$

$$\mathcal{L}_{Z^0} \sim -\frac{g_w}{2\cos\theta_w}\,Z_\mu \sum_{i,j=1}^{3+n_S} \bar{\nu}_i\,\gamma^\mu \left[P_L\,(\mathbf{U}^\dagger\mathbf{U})_{ij} - P_R\,(\mathbf{U}^\dagger\mathbf{U})^*_{ij}\right] \nu_j$$

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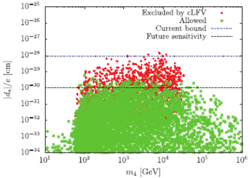
Impact for lepton properties

- **Leptonic CP violation: electric dipole moments**

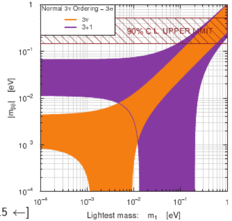


- Majorana (and Dirac) phases ⇒ **lepton EDMs**
- **Non-vanishing** contributions: at least **two sterile** ν
- $|d_e|/e \geq 10^{-30}$ cm for $m_{\nu_{4,5}} \sim$ [100 GeV, 100 TeV]

[Abada and Toma, '15]

- **Lepton number violation: $0\nu2\beta$ decays**
  - ν_s can strongly impact **predictions for $|m_{ee}|$**
    ⇒ **augmented ranges** for effective mass *(IO and NO)*
  - **Observation of $0\nu2\beta$ signal** in future experiments
    does not imply Inverted Ordering for light νs

[Abada, De Romeri and AMT, '14; ...; Giunti et al, '15 ←]



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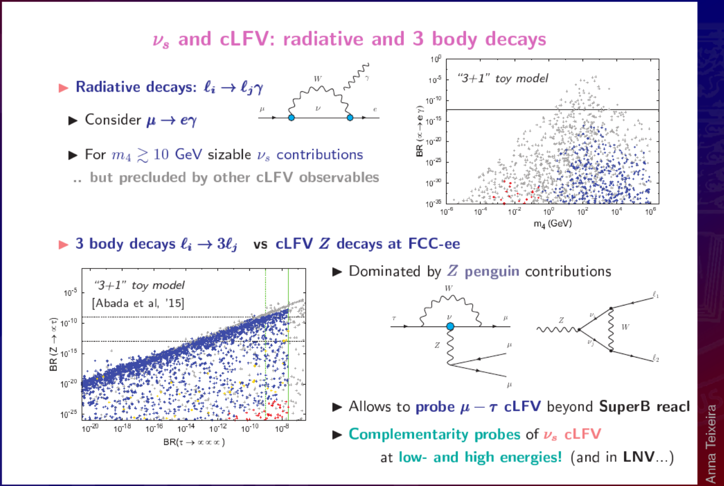

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cLFV in "muonic" atoms: Coulomb enhanced decays

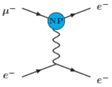
- **Muonic atom decay:** $\mu^- e^- \to e^- e^-$ [Koike et al, '10]

  Initial μ^- **and** e^-: **1s** state bound in Coulomb field of the **muonic atom's nucleus**

- **Coulomb interaction** increases overlap between

  Ψ_{μ^-} and Ψ_{e^-} wave functions

  $$\Gamma(\mu^- e^- \to e^- e^-,\ \mathrm{N}) \propto \sigma_{\mu e \to ee} v_{\mathrm{rel}} \left[(Z-1)\,\alpha\, m_e\right]^3 / \pi$$



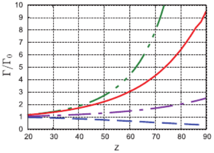
- **Clean experimental signature:** back-to-back electrons, $E_{e^-} \approx m_\mu/2$

  larger phase space than $\mu \to 3e$

- **Rate strongly enhanced** in **large Z atoms**

  $\Gamma/\Gamma_0 \gtrsim (Z-1)^3$ [Uesaka et al, '15-'16]

  Consider experimental setups for **Pb, U !?**



- **Experimental status:** **New observable!**

  Hopefully included in Physics programmes of **COMET** & **Mu2e** (?)

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Connection with Neutrinos

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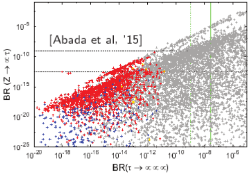
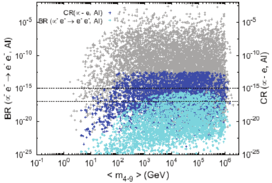
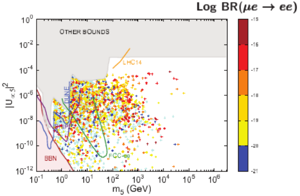
cLFV: (3,3) ISS realisation

- **At high energies (FCC-ee):** BR($Z \to \tau\mu$) allows to **probe $\mu - \tau$ cLFV** beyond **SuperB reach**
- **Rich low-energy phenomenology (cLFV, LFU, ...)**
  For $M_R \gtrsim \Lambda_{EW}$: **cLFV observables** within **exp reach**
  NA62, Mu2e, COMET, FCC...



(3,3) ISS realisation [Abada, De Romeri and AMT, '15]





- **Sizeable values for the different observables!**
  Within reach of **high-intensity facilities and colliders** ⇒ **complementary probes!**

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Connection with Neutrinos

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cLFV and sterile neutrinos: outlook

- **Lepton flavour violation and New Physics**

  cLFV observables can provide (indirect) **information on the underlying NP model**

  Numerous observables **currently being searched for!**

  $\Rightarrow$ very intensive worldwide experimental programme

- **Extending the SM with sterile fermions**

  Theoretically and phenomenologically motivated; impact on many **observables!**

  Sterile states: actively searched for at **high energy, high intensity and in cosmology**

- **Sterile neutrinos and cLFV**

  Sizable contributions to many observables (some leading to **stringent constraints**)

  including BR($\ell_i \to \ell_j \gamma$), BR($\ell_i \to 3\ell_j$), CR($\mu - e$, N) and BR($\mu^- e^- \to e^- e^-$)

  $\Rightarrow$ potentially within experimental reach

  Analysis carried for simple "3+1 toy model" and **mechanisms of ν mass generation**

  low-scale type I, Inverse Seesaw, νMSM

  Interplay at high-intensity & high-energy: probe the underlying source of LFV

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Connection with Neutrinos

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Seesaw Models, CLFV and Leptogenesis

Emiliano Molinaro

CP3 Origins
Cosmology & Particle Physics

University of Southern Denmark

CLFV 2016, 20-22 June

Connection with Neutrinos

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Origin of neutrino mass and mixing

Why do neutrinos have a non-zero tiny mass ?

Symmetry principles give us an answer, even if the dynamics involved is not understood

Electroweak Theory + Quantum Chromodynamics:

- Lorentz invariance
- Gauge invariance: SU(3)xSU(2)xU(1)
- Renormalizability

The Standard Model is not sufficiently “complicated” to violate baryon and lepton number conservation (except for tiny quantum effects unobservable at the temperature of the present universe)

We can relax the renormalizability requirement and introduce all the possible interaction operators which are allowed by gauge and Lorentz symmetries (*effective field theories*). In this case we introduce *new scales* in the theory, suppressing the new interactions.

When we do experiments to detect neutrino oscillations or proton decay, what we are measuring are the *non-renormalizable effective interactions* added to the renormalizable part of the Standard Model

Connection with Neutrinos

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Low energy effects of RH neutrinos

$$m_\nu \simeq -m_D M^{-1} m_D^T \qquad m_D \simeq \lambda v$$

naively for $M = 1$ TeV $\curvearrowright m_D \approx 10^{-4}$ GeV $\Rightarrow \lambda \approx 10^{-6}$

low energy effects very suppressed:

- tiny EDMs
- tiny lepton radiative decays
- tiny deviations from EW precision observables
- production cross-section at colliders is suppressed (except when RH neutrino has additional interactions, e.g. $U(1)_{B-L}$)

conversely, testing the seesaw mechanism at colliders and / or from low energy observables requires large Yukawa couplings. Again naively,

$$\lambda = 0.1, \qquad M = 1\ \text{TeV} \quad \Rightarrow \quad m_\nu \approx 0.1\ \text{GeV}$$

is it possible to have seesaw models at low scale consistent with light neutrino masses and sizeable Yukawa couplings ?

Mohapatra, '86
Mohapatra, Valle, '86
Pilaftsis, '92;'95
Pilaftsis, Underwood, 2005
de Gouvea, 2007
Kersten, Smirnov, 2007
...

Connection with Neutrinos

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RH neutrinos and large Yukawa couplings

Sizable couplings of RH neutrinos to Standard Model leptons

Lagrangian mass terms:

$$\mathcal{L}_\nu \;=\; -\,\overline{\nu_{\ell L}}\,(m_D)^*_{\ell a}\,\nu_{aR} - \frac{1}{2}\,\overline{\nu^C_{aL}}\,(M)^*_{ab}\,\nu_{bR} \;+\; \text{h.c.}$$

$$M = V^*\hat{M}V^\dagger,\; \hat{M} \equiv \text{diag}(M_1, M_2),\; R^* \simeq m_D M^{-1}$$

Heavy Majorana Neutrino Interactions

$$\mathcal{L}^N_{CC} \;=\; -\,\frac{g}{2\sqrt{2}}\,\bar{\ell}\,\gamma_\alpha\,(RV)_{\ell k}(1-\gamma_5)\,N_k\,W^\alpha \;+\; \text{h.c.}$$

$$\mathcal{L}^N_{NC} \;=\; -\,\frac{g}{4c_w}\,\overline{\nu_{\ell L}}\,\gamma_\alpha\,(RV)_{\ell k}\,(1-\gamma_5)\,N_k\,Z^\alpha \;+\; \text{h.c.}$$

$$\mathcal{L}^N_{H} \;=\; -\,\frac{g M_k}{4\,M_W}\,\overline{\nu_{\ell L}}\,(RV)_{\ell k}\,(1+\gamma_5)\,N_k\,h \;+\; \text{h.c.}$$

Low energy effects are parametrized by (RV)

Emiliano Molinaro (CP³-Origins) | Seesaw Models, CLFV and Leptogenesis | CLFV2016, June 21 | 15

Connection with Neutrinos

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RH neutrinos and large Yukawa couplings

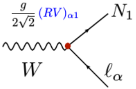
the flavour structure of the neutrino Yukawa couplings is fixed by neutrino oscillation data and *RV* can be calculated in terms of few parameters:

- maximum Yukawa coupling: y
- RH neutrino masses: M_1 and M_2
- a phase: ω

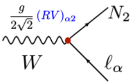
$U \equiv U_{\rm PMNS}$

NH:

$$(RV)_{\alpha 1} = -e^{i\omega} y\, v \sqrt{\frac{M_2}{M_2+M_1}} \sqrt{\frac{m_3}{m_2+m_3}} \left(U_{\alpha 3} + i\sqrt{m_2/m_3}\, U_{\alpha 2}\right)$$



$$(RV)_{\alpha 2} = \mp i\, e^{i\omega} y\, v \sqrt{\frac{M_1}{M_2+M_1}} \sqrt{\frac{m_3}{m_2+m_3}} \left(U_{\alpha 3} + i\sqrt{m_2/m_3}\, U_{\alpha 2}\right)$$



pseudo-Dirac heavy neutrino state $M_1 \sim M_2$

$$(RV)_{\alpha 2} = \pm i\,(RV)_{\alpha 1} \sqrt{\frac{M_1}{M_2}}$$

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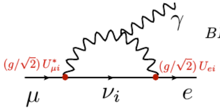
Connection with Neutrinos

Charged leptons and neutrinos are closely related—and plenty of BSM behaviour in neutrinos

- Sterile neutrinos
- Seesaw mechanism

Charged lepton flavour violation

Standard contribution

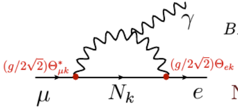


Petcov, '77
Marciano, Sanda, '77

$$BR(\mu \to e+\gamma) = \frac{3\alpha_{\rm em}}{32\pi}\left|\frac{\Delta m^2_{\rm sol}}{M_W^2}U_{e2}U^*_{\mu 2} + \frac{\Delta m^2_{\rm atm}}{M_W^2}U_{e3}U^*_{\mu 3}\right|^2 < 10^{-54}$$

Sizeable couplings, but strong GIM suppression, $\Delta m^2/M_W^2$

New contribution



$$BR(\mu \to e+\gamma) = \frac{3\alpha_{\rm em}}{8\pi}\left|\Theta^*_{\mu 1}\Theta_{e1}\right|^2 \left|G(M_1^2/M_W^2) - G(0)\right|^2$$

No GIM suppression, observable effects!

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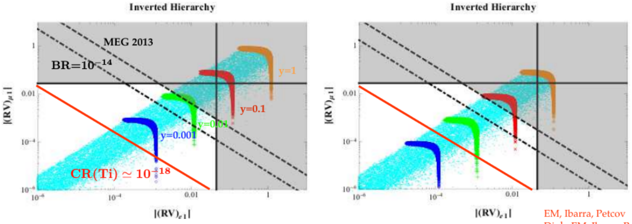
$\mathbf{M_1} = \mathbf{100}$ GeV | $\mathbf{M_1} = \mathbf{1000}$ GeV



EM, Ibarra, Petcov
Dinh, EM, Ibarra, Petcov

$$(RV)_{\ell k}(1-\gamma_5)\, N_k\, W^{\alpha} \;+\; \text{h.c.},$$

$$\mathcal{L}_{NC}^{N} \;=\; -\frac{g}{4c_w}\, \nu_{\ell L}\, \gamma_\alpha\, (RV)_{\ell k}\, (1-\gamma_5)\, N_k\, Z^{\alpha} \;+\; \text{h.c.}$$

$$(RV)_{\ell k} \propto y\, v / M_k$$

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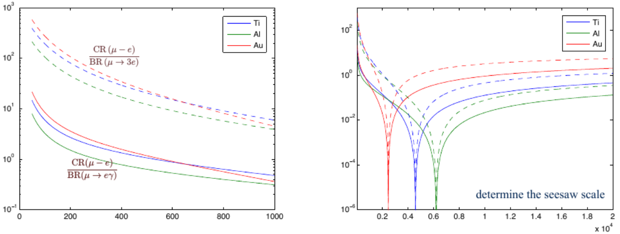
Muon conversion to electron in nuclei



$$\frac{\mathrm{CR}(\mu\,\mathrm{Ti} - e\,\mathrm{Ti})}{\mathrm{BR}(\mu \to e\gamma)} \gtrsim 6\ (0.5) \quad \text{for } M_1 = 100\ (1000)\ \mathrm{GeV}$$

Dinh, Ibarra, EM, Petcov, 2012
see also Alonso, Dhen, Gavela, Hambye, 2012

$$\frac{\mathrm{BR}(\mu \to 3e)}{\mathrm{BR}(\mu \to e\gamma)} \gtrsim 0.03 \quad \text{for } M_1 \geq 100\ \mathrm{GeV}$$

conversion ratio highly affected by M_1!

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Summary and outlook

A minimal extension of the Standard Model, which provides a mechanism for the generation of neutrino masses and mixing, consists of adding singlet RH neutrinos

The RH neutrino mass introduces a new scale in the theory, which can be of the same order as or smaller than the EW symmetry breaking scale

❖ It is possible to probe the mechanism of neutrino mass generation with experiments at the energy and intensity frontiers

❖ Baryon asymmetry can originate *only* from New Physics in the lepton sector: leptogenesis mechanism

❖ Baryogenesis can be achieved from CP violating oscillations of (sterile) RH neutrinos with **masses in the GeV range**. *Theory possibly testable in laboratory experiments:*

Any experiment that improves the present bounds has the potential to discover GeV RH neutrinos responsible for baryogenesis and neutrino masses

❖ Low scale seesaw scenarios can also predict production of keV sterile neutrino dark matter in the early Universe (*a smoking signature is monochromatic X-ray line*)

- Muon Experiments
  - $\mu \to e + \gamma$
    - From the beginnings of CLFV
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  - Statistics in CLFV Physics and PhyStat-ν (next at Fermilab in September)
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Cautionary Tales in Muon CLFV Experiments

From CLFV2013 Summary Talk

Useful Advanced Measurements for μ-e Conversion Experiments

- Extinction rate
- Particle fluxes (e,μ,π,K,$\bar{p}$...)at detector (Comet phase I)
- p and n rates from μ Capture (in the works at PSI)
- Cosmic rays – could be done in a test setup?
- Radiative pion capture –> 100MeV electrons ?
- Pbar background rate –> 100MeV electrons ?
- …

General questions for high sensitivity μ-e Conversion Experiments

- What are the uncertainties and risk factors in the background, acceptance estimates ?
- How are the backgrounds to be measured during the experiment ?
- How is a blind analysis to be done ?
- What would make a believable signal ?

D. Bryman CLFV, Lecce, Italy 38

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Back to this...

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Statistics in CLFV Experiments

Use of statistical concepts important:

- Single event sensitivities
- Average 90% C.L. limit from null-hypothesis
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- Combining experimental results
- Parameter fitting/hypothesis testing
- Machine learning methods
- Indications / Observations / Discovery
- (advert to follow)

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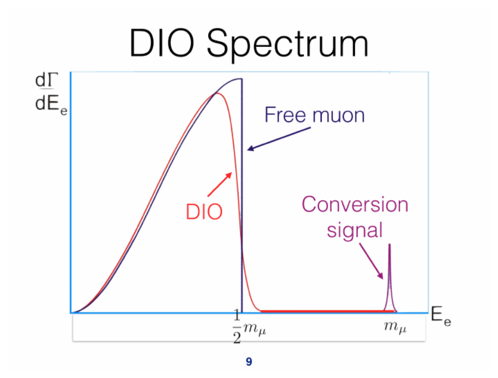

Robert Szafron

Not a problem if your data is like this....

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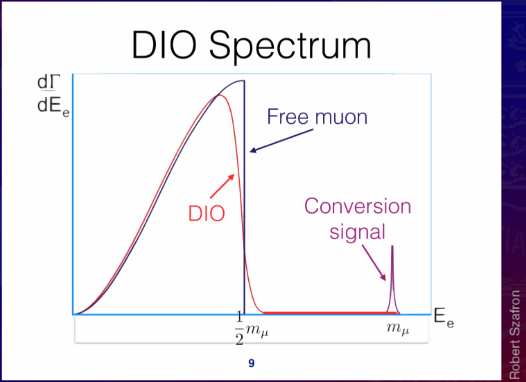

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- Currently writing up a summary document
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PhyStat-ν will address statistical issues in the broad range of modern neutrino physics, including making measurements of model parameters, setting limits, discovery criteria, discrete choice of models, Bayesian vs. frequentist inference, and combining experiments.

Two workshops are planned for 2016: this workshop at the Kavli Institute for the Physics and Mathematics of the Universe in Kashiwa, Japan in May, and a second workshop at Fermilab in the autumn.

These workshops will consist of invited and contributed talks, and poster and discussion sessions, and will bring together experts in the analysis of neutrino data with experts in statistics to explore the statistical issues in neutrino physics.

PhyStat-ν IPMU Workshop Introduction 30 May 2016 2 Yoshi.Uchida@imperial.ac.uk

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Recognising the First Signs of BSM Physics

From the 2nd Neutrino conference in 1974, in Pennsylvania:

- The Solar Neutrino talk:

The ^{37}Ar production rates for the standard model and the low Z model are 5.6 ± 1.8 SNU and 1.4 ± 0.35 SNU, respectively. Taking Davis's result[1] without run 27 to be 0.2 ± 0.8 SNU I find that the discrepancy between the experiment and the standard model to be 2.7σ and while the discrepancy with the low Z model is 1.4σ.

(R.K. Ulrik)

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(R.P. Feynman)

Conclusion

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  - Theory: multi-Higgs-doublet, composite Higgs, sterile neutrinos, dark matter, lepton (non-)universality, seesaw, leptogenesis
    - The emphasis can change significantly—
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    - “SUSY” or “Supersymmetry” appeared 94 separate times on the slides at CLFV2013 (and twice in the programme)
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And now, time for a Symmetry Break† ....

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† those not present at the Provost's Welcome Talk may not recognise this expression