Imperial College London

Charged Lepton Flavour Violation and Future Facilities

—An Experimental Overview—

12 August 2015

Yoshi Uchida

NuFact 2015, Rio de Janeiro

CLFV Talks This Week

• MEG	Dmitry Grigoriev
• MEG Upgrade	Angela Papa
• Mu2e	Kevin Lynch
• COMET	Ben Krikler
• DeeMee	Masaharu Aoki
• Mu3e	Roman Gredig
• CLFV at ATLAS	Alexander NEHRKORN
• CLFV at BELLE	Claudia Cecchi
• CLFV at CMS	Craig Blocker
• Connections between g-2, EDMs, CLFV and LHC (Theory Overview)	Paride Paradisi
• PRISM	Jaroslaw Pasternak
• Mu2E (beam line)	Vladimir Nagaslaev
• Muon beam line for COMET	Ye Yang

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

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*)

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.

- Weak interaction universality from atomic e and μ-capture
- discussion of whether muon decay involves "β-decay"s:

$$\mu \rightarrow e + \nu \quad \text{(with a single type of neutrino)}$$

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

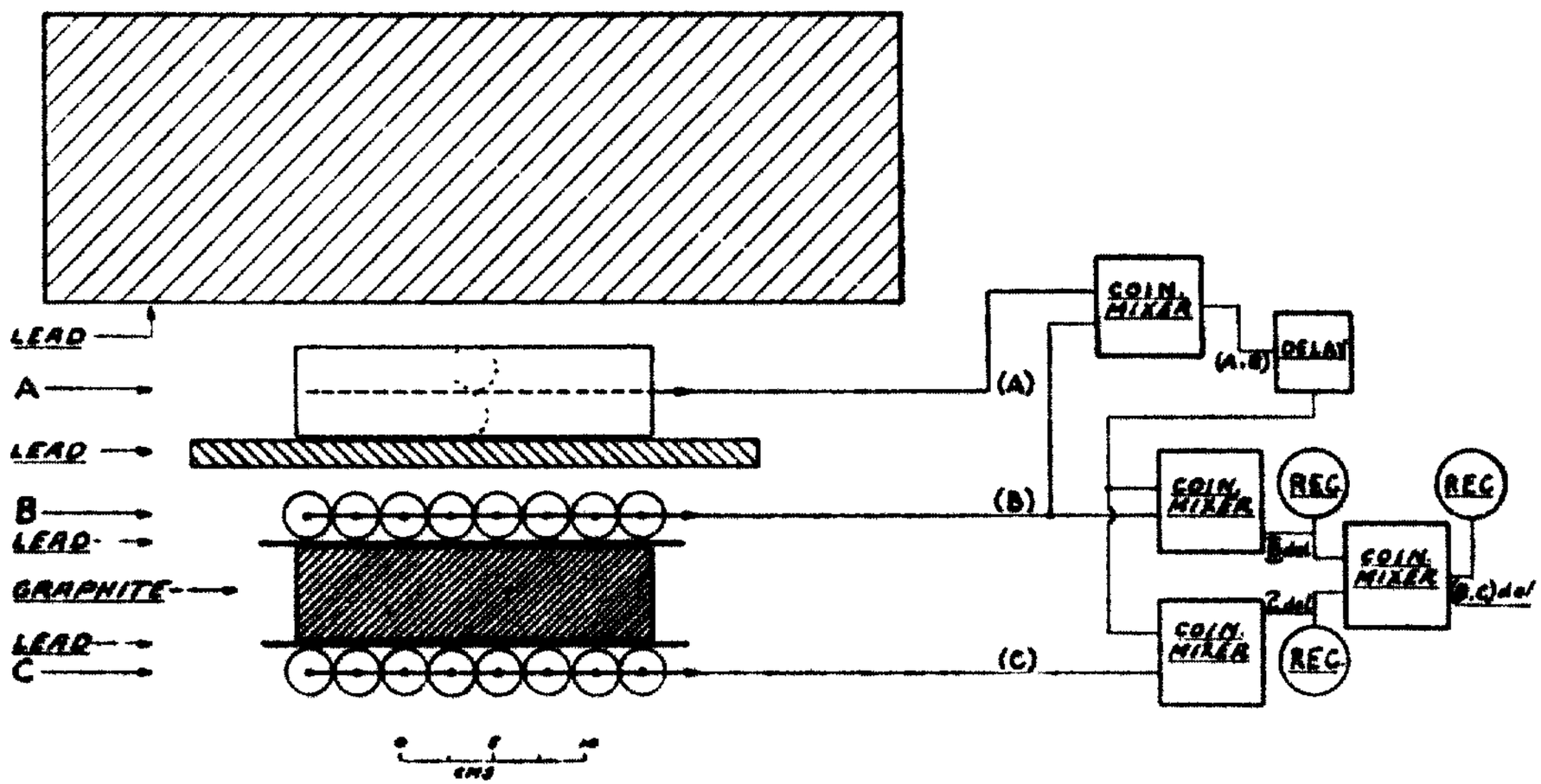


FIGURE 1 - ARRANGEMENT OF APPARATUS

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

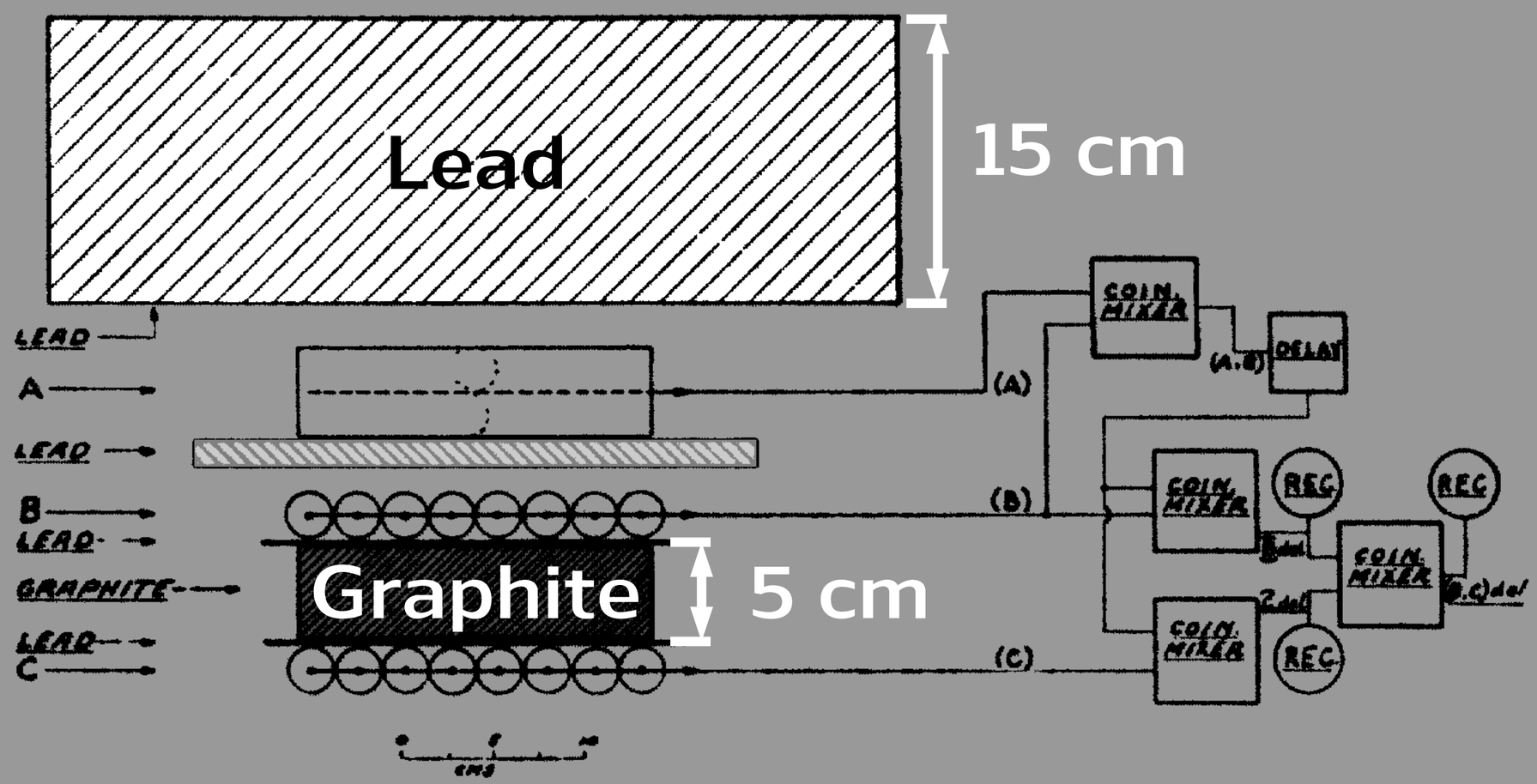


FIGURE 1 - ARRANGEMENT OF APPARATUS

also similar investigations by Sard and Althaus [1948]

1947

Studies of fundamental properties of muon decay

using $O(1000)$ cosmic events

decay into how many particles, and which ones

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

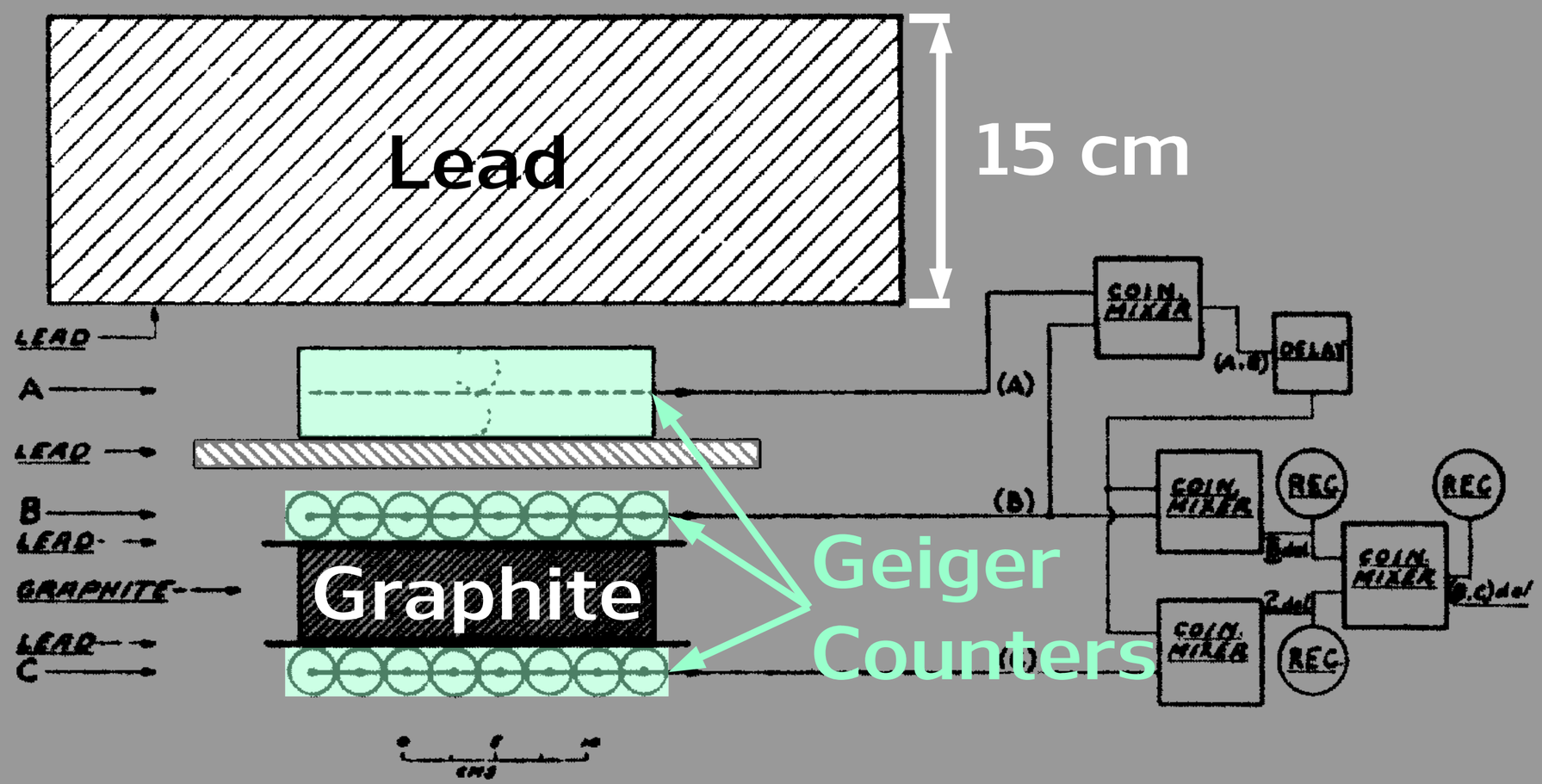
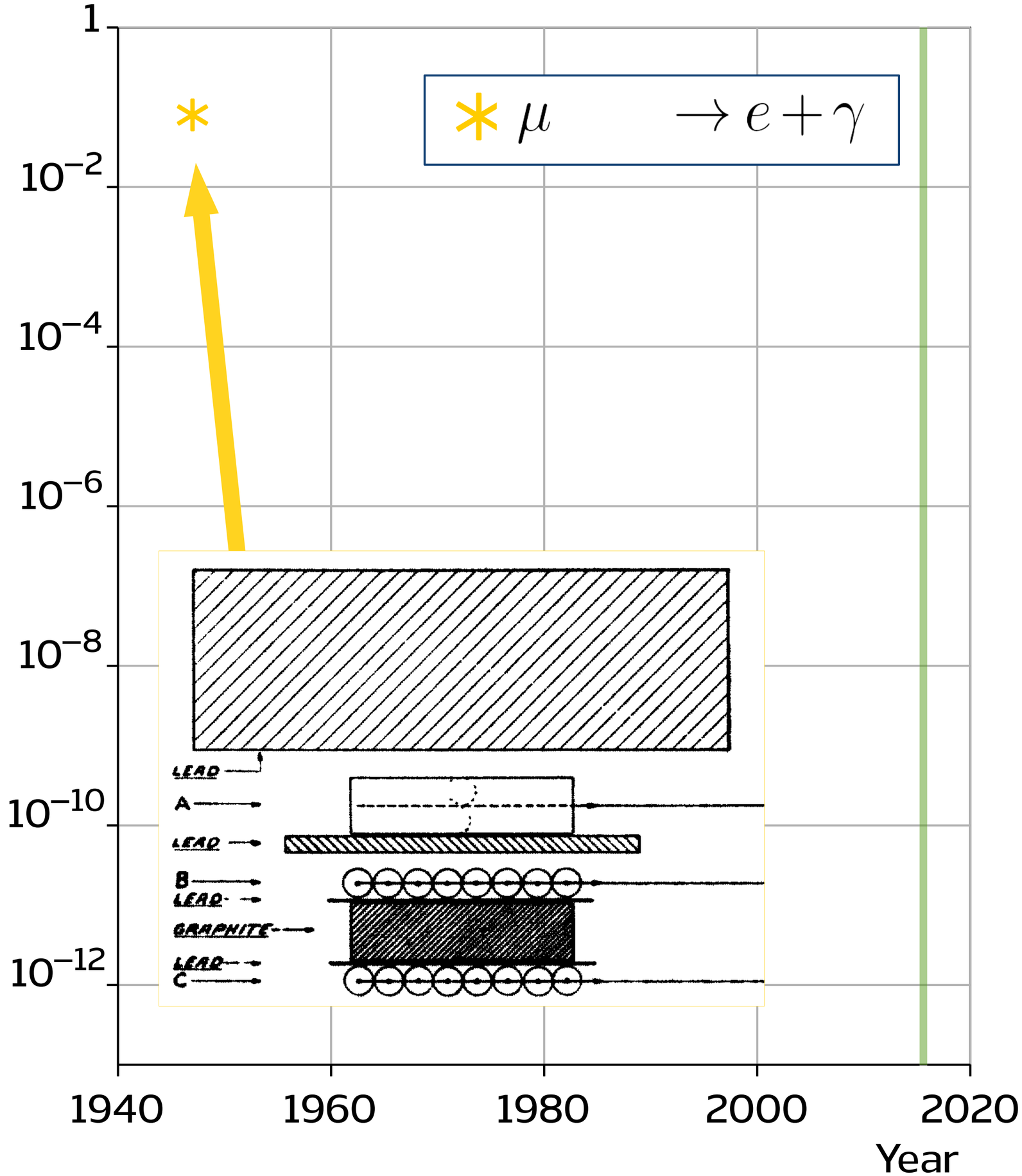


FIGURE 1 - ARRANGEMENT OF APPARATUS

Demonstrated $\mu \to e + \gamma$ is not a major component of μ-decay

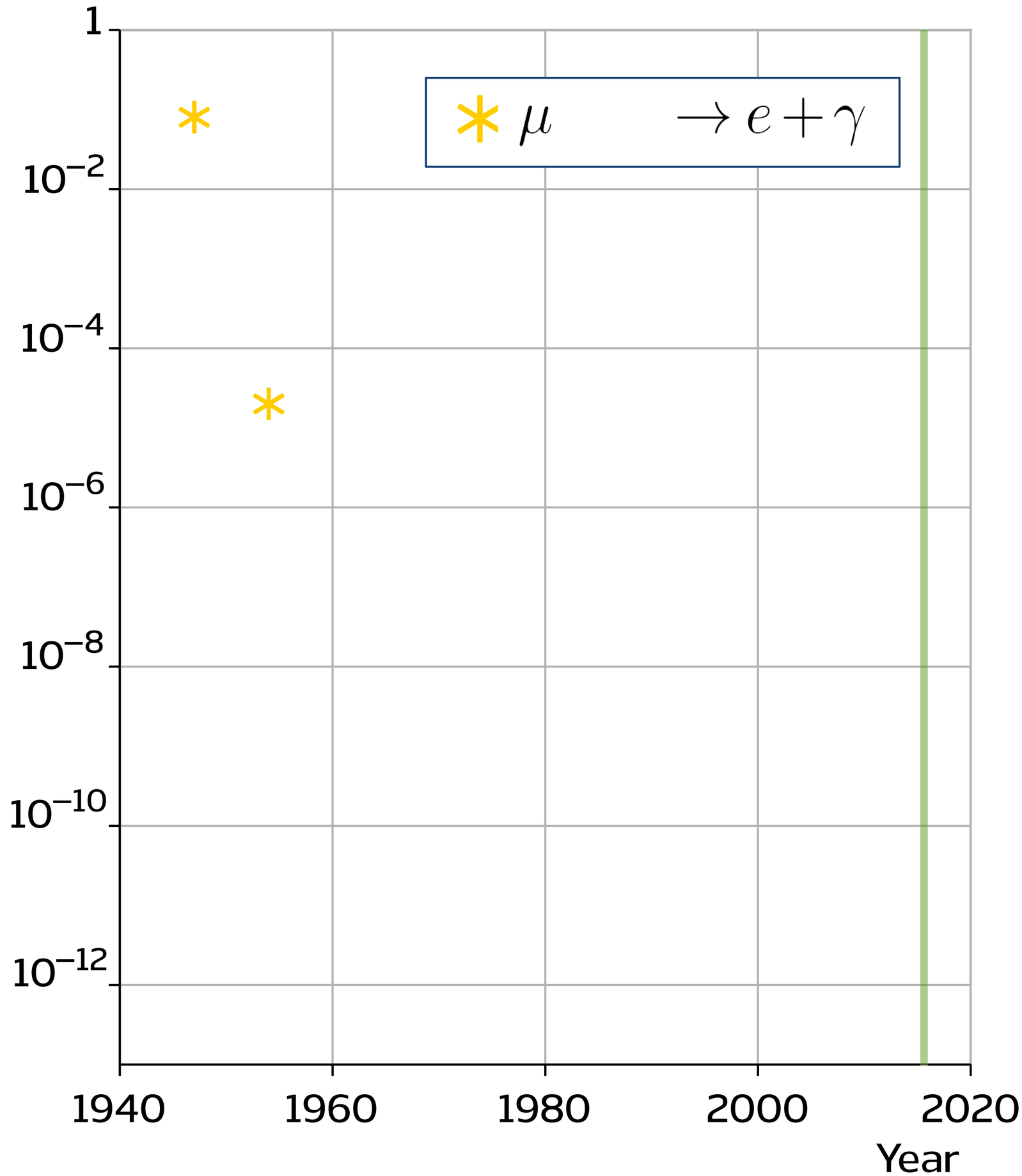
Charged Lepton Flavour Violation



90% C.L.
upper limit on
branching ratios

Yoshi.Uchida@imperial.ac.uk

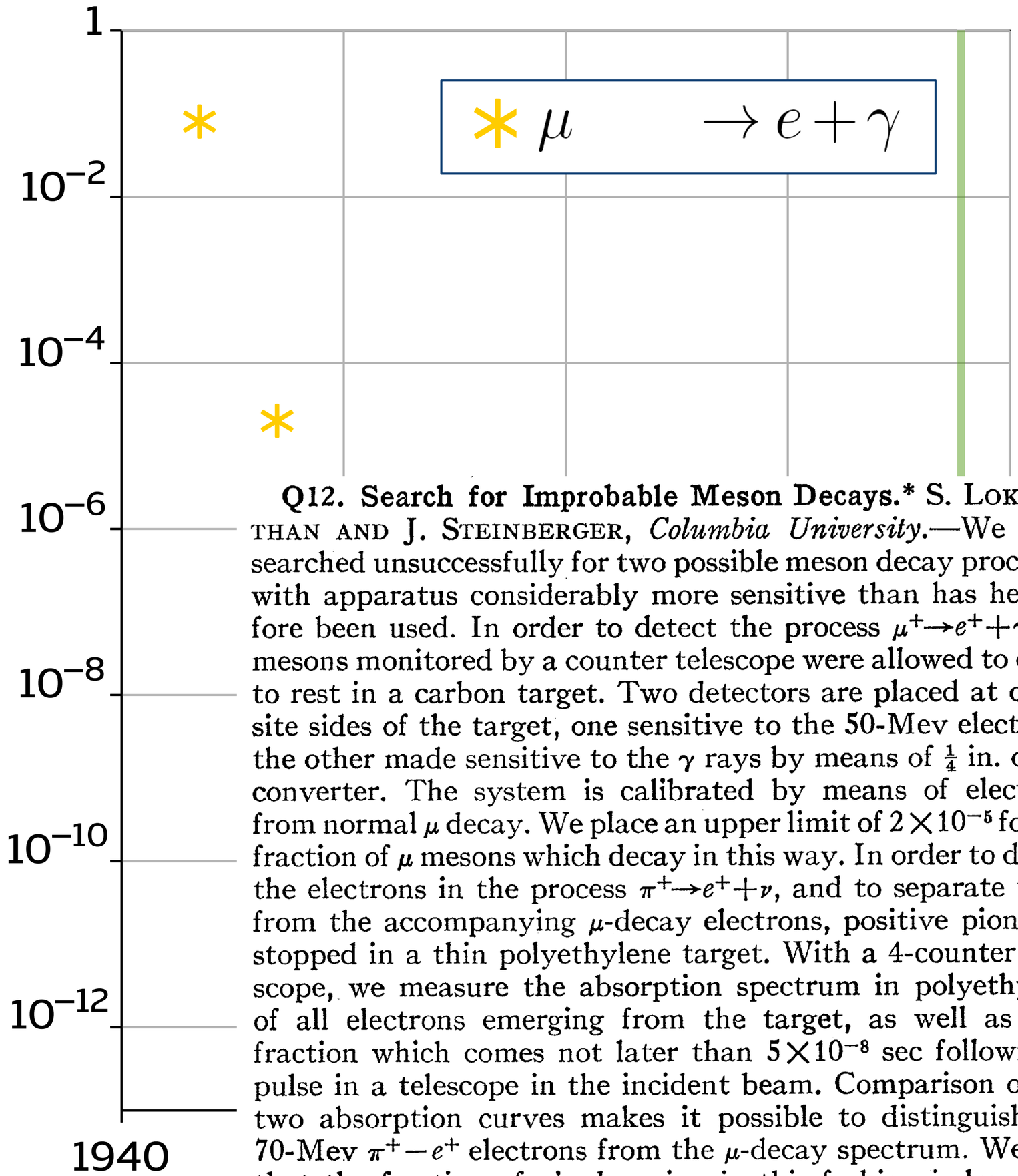
Charged Lepton Flavour Violation



90% C.L.
upper limit on
branching ratios

Yoshi.Uchida@imperial.ac.uk

Charged Lepton Flavour Violation



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 $\mu^+ \rightarrow e^+ + \gamma$, 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 $\pi^+ \rightarrow e^+ + \nu$, 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}.

Minutes of the 1954 APS Thanksgiving Meeting

90% C.L. upper limit on branching ratios

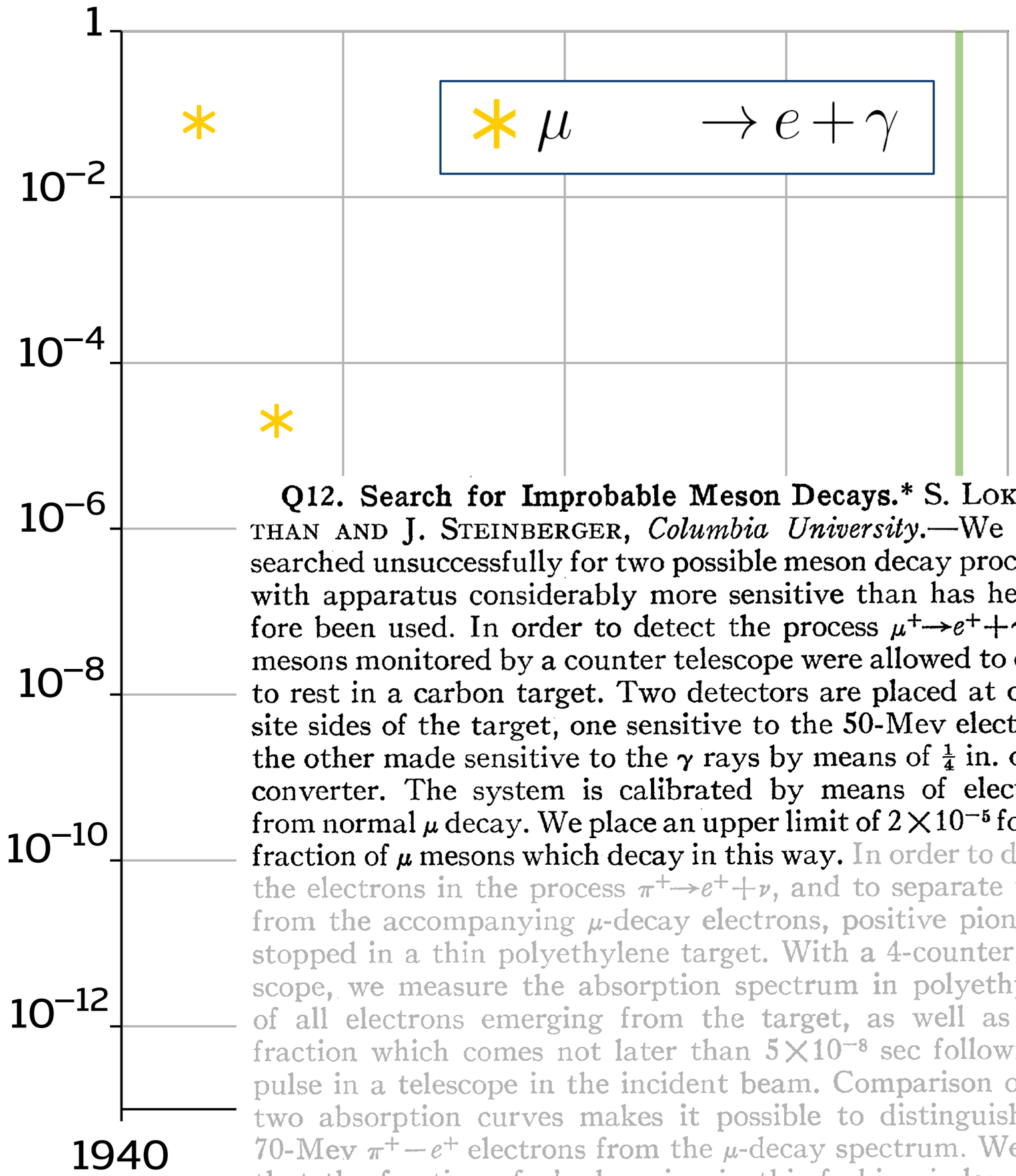
Yoshi.Uchida@imperial.ac.uk

Charged Lepton Flavour Violation

Minutes of the 1954 APS Thanksgiving Meeting

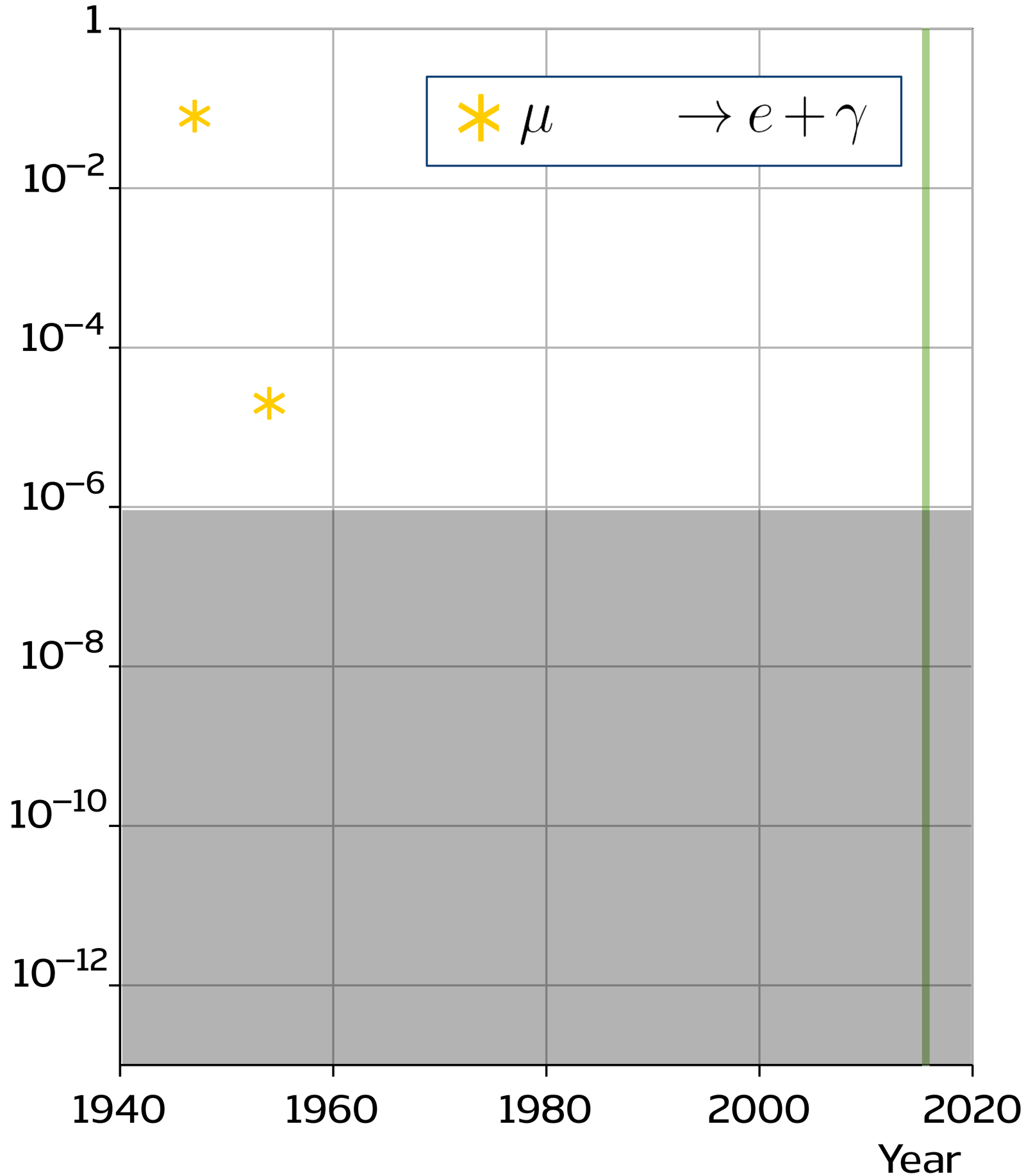
90% C.L. upper limit on branching ratios

Yoshi.Uchida@imperial.ac.uk



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}.

Charged Lepton Flavour Violation



90% C.L.
upper limit on
branching ratios

Yoshi.Uchida@imperial.ac.uk

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, $\mu \rightarrow e + \nu + \bar{\nu}$, 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 $\mu \rightarrow e + \gamma$ 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 $\mu \rightarrow e + \gamma$ is somehow suppressed.

1959

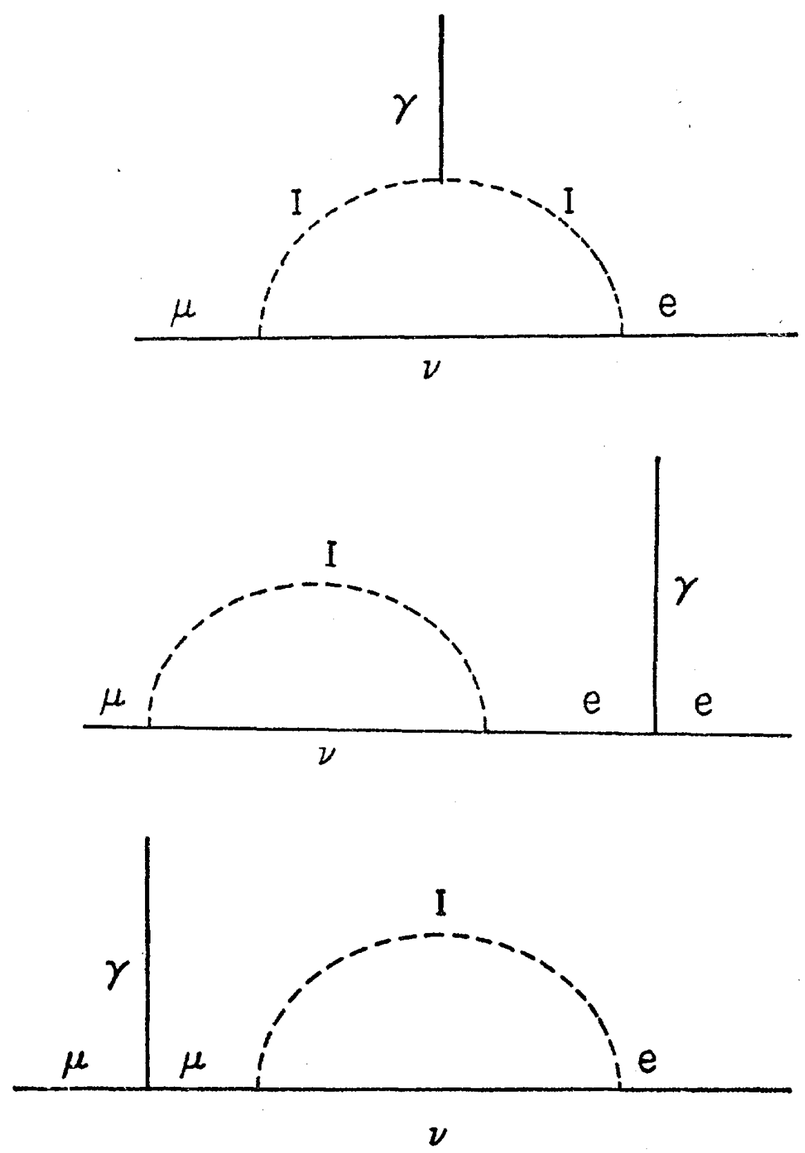


FIG. 1. Feynman diagrams for $\mu \to e + \gamma$ through an intermediate boson. I labels the intermediate boson field.

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.

Feinberg, 1958

1961

LAW OF CONSERVATION OF MUONS*

G. Feinberg†
Department of Physics, Columbia University, New York, New York

S. Weinberg
Department of Physics, University of California, Berkeley, California

(Received February 8, 1961)

The apparent absence of muon-electron transitions without neutrinos, such as $\mu \rightarrow e + \gamma$, $\mu \rightarrow 3e$, and $\mu^- + p \rightarrow e^- + p$, leads one to suspect that there is a new conservation law forbidding them. Calculations[1] of the rate of such processes, assuming no such law exists, have indicated that it is hard to understand their absence in an intermediate boson theory of weak interactions....

If we assume that μ^--e^- transitions are forbidden by a selection rule, the nature of the selection rule remains an open question. It has been suggested[3] that an additive quantum number exists which is always conserved, and which[4] is +1 for μ^- and zero for e^-. In order to make this consistent with known weak interactions, it is necessary to assume that there are two neutrinos, which are distinguished by their value of this quantum number. The conservation law forbids all reactions in which any nonzero number of muons change into electrons, without neutrinos.

also Salam, Nishijima, Schwinger and others

Yoshi.Uchida@imperial.ac.uk

1961

LAW OF CONSERVATION OF MUONS*

G. Feinberg†
Department of Physics, Columbia University, New York, New York
S. Weinberg
Department of Physics, University of California, Berkeley, California
(Received February 8, 1961)

The apparent absence of muon-electron transitions without neutrinos, such as $\mu \to e + \gamma$, $\mu \to 3e$, and $\mu^- + p \to e^- + p$, leads one to suspect that there is a new conservation law forbidding them. Calculations[1] of the rate of such processes, assuming no such law exists, have indicated that it is hard to understand their absence in an intermediate boson theory of weak interactions....

If we assume that μ^--e^- transitions are forbidden by a selection rule, the nature of the selection rule remains an open question. It has been suggested[3] that an additive quantum number exists which is always conserved, and which[4] is +1 for μ^- and zero for e^-. In order to make this consistent with known weak interactions, it is necessary to assume that there are two neutrinos, which are distinguished by their value of this quantum number. The conservation law forbids all reactions in which any nonzero number of muons change into electrons, without neutrinos.

also Salam, Nishijima, Schwinger and others

Yoshi.Uchida@imperial.ac.uk

1962: The Second Neutrino Flavour

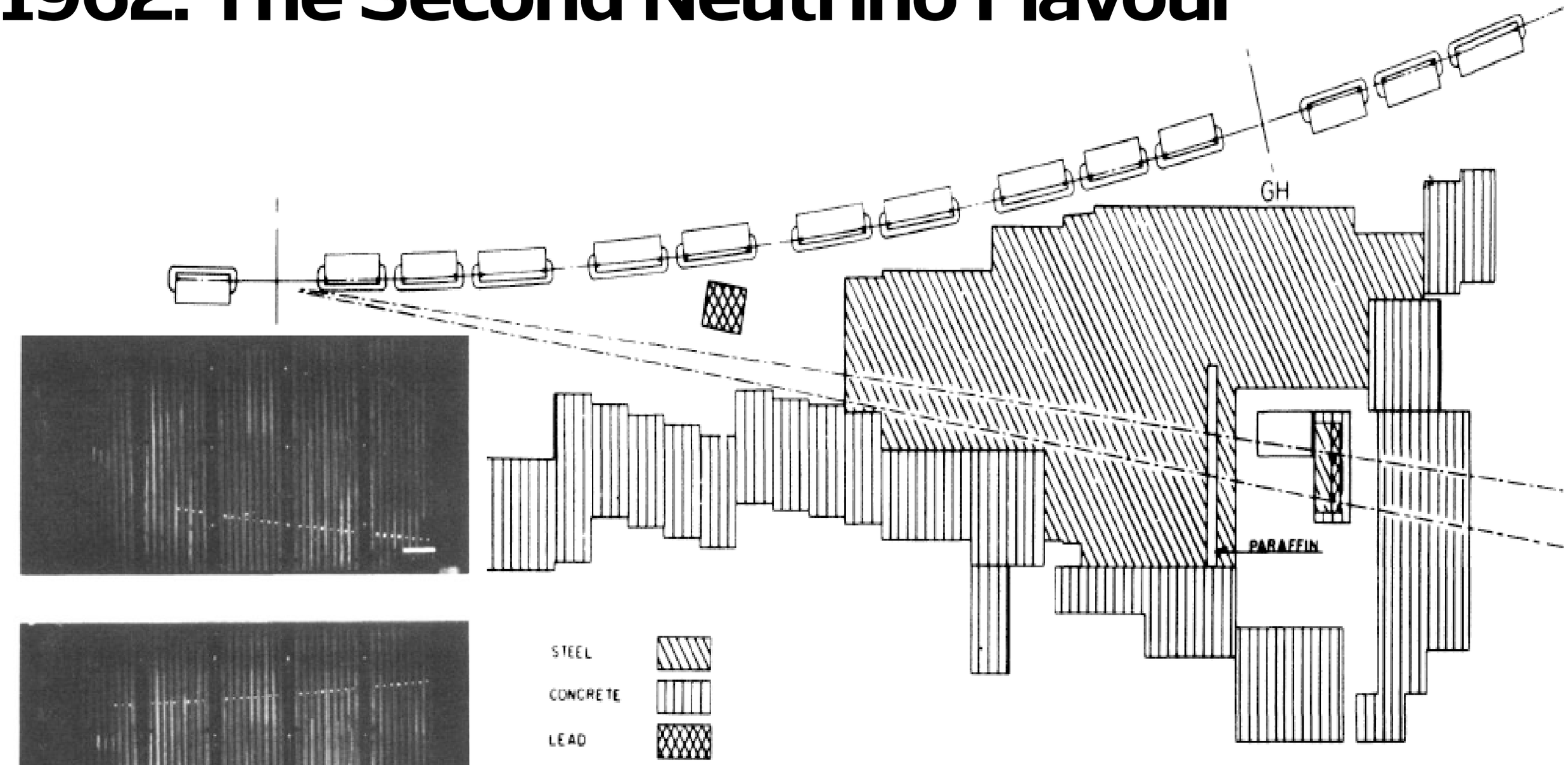
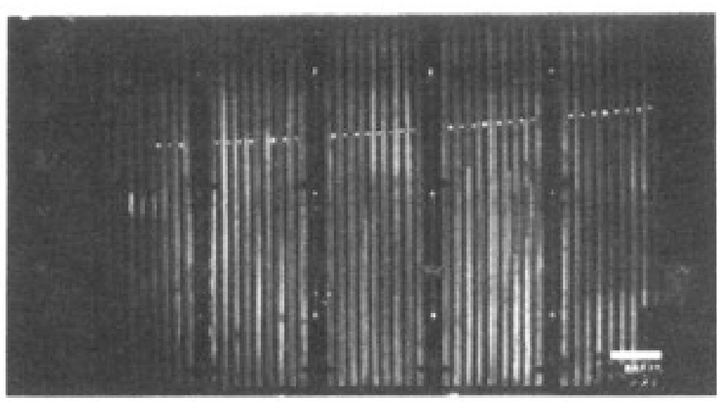
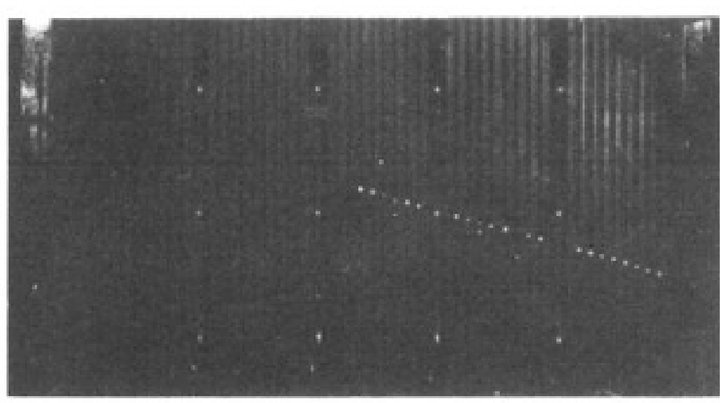


FIG. 1. Plan view of AGS neutrino experiment.





Discovery of muon neutrinos at Brookhaven
(Lederman, Schwartz, Steinberger)

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**

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.

Phys. Rev. 98, 5 (1955)

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)

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.

Lepton Flavour Conservation in the Standard Model

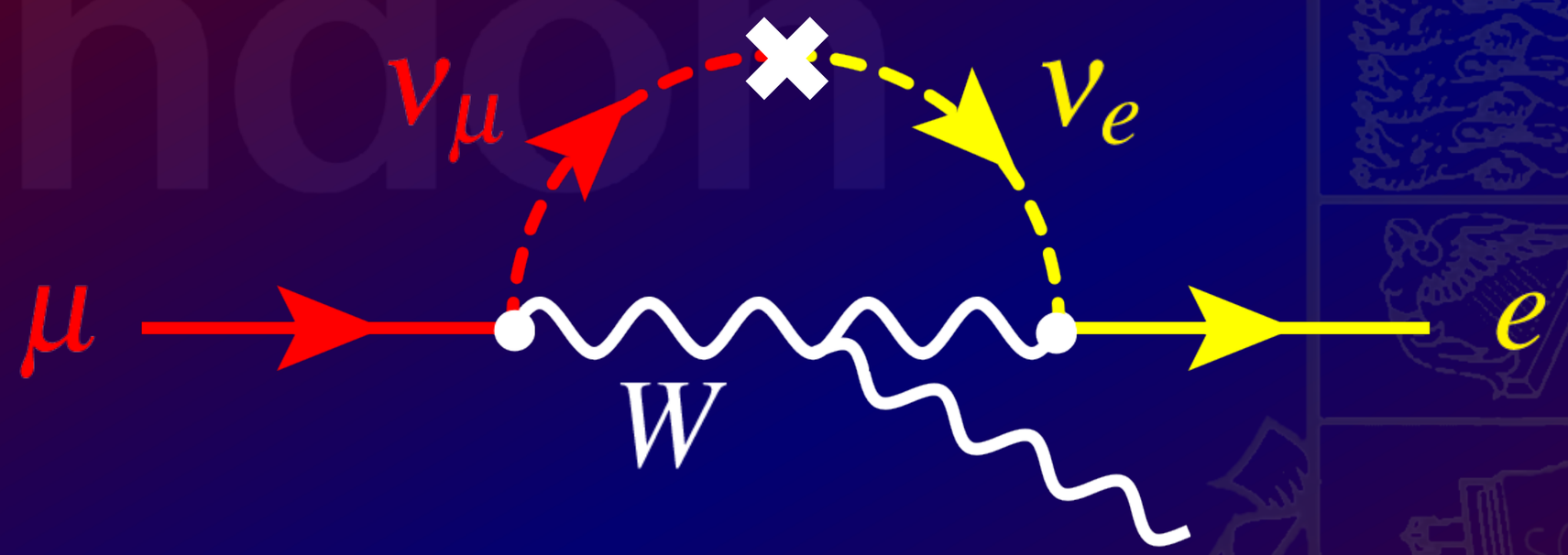
- In the Standard Model:
  - Lepton flavour is conserved absolutely
    - not through a fundamental principle, but **through the *choice* of fields**
    - an *accidental* symmetry
- Deviations from the SM can introduce Lepton Flavour Violation

Charged Lepton Flavour Violation

- **Beyond-the-Standard Model Physics** can cause CLFV

Charged Lepton Flavour Violation

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

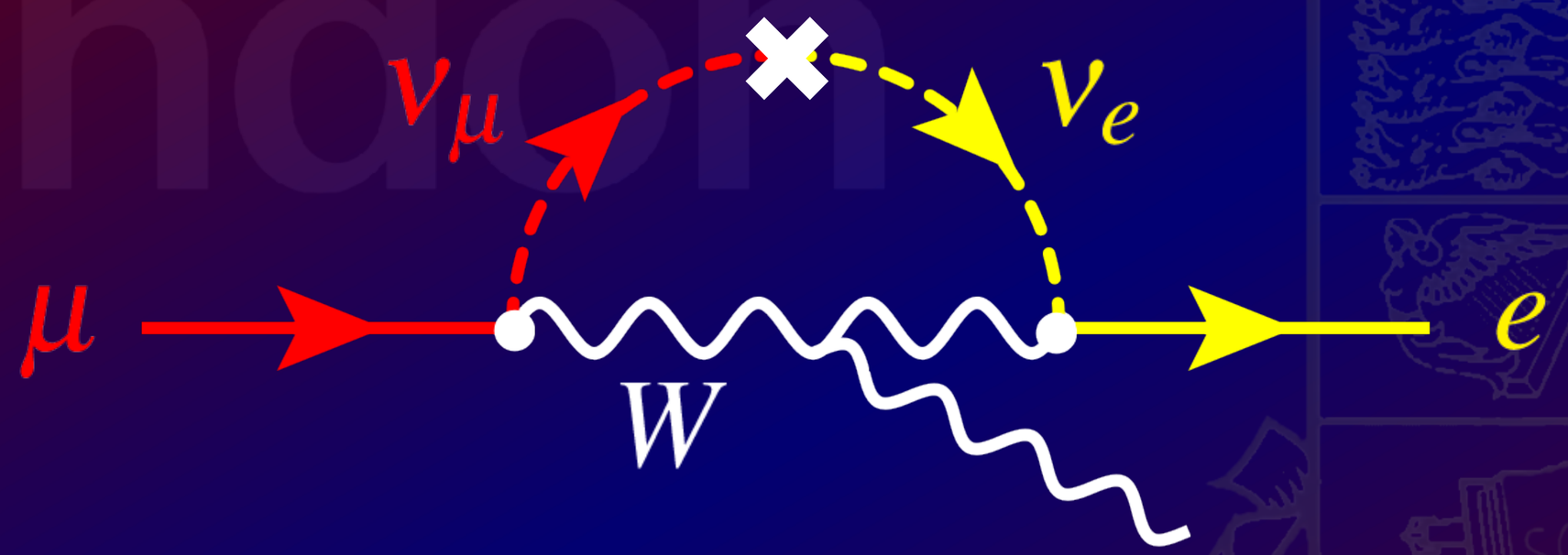


- but this is ***GIM-suppressed:***

$$B(\mu \to e + \gamma) = \frac{3\alpha}{32\pi} \left| \sum_\ell V^*_{\mu\ell} V_{e\ell} \frac{\Delta m^2_{\nu_\ell}}{m^2_W} \right|^2$$

Charged Lepton Flavour Violation

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

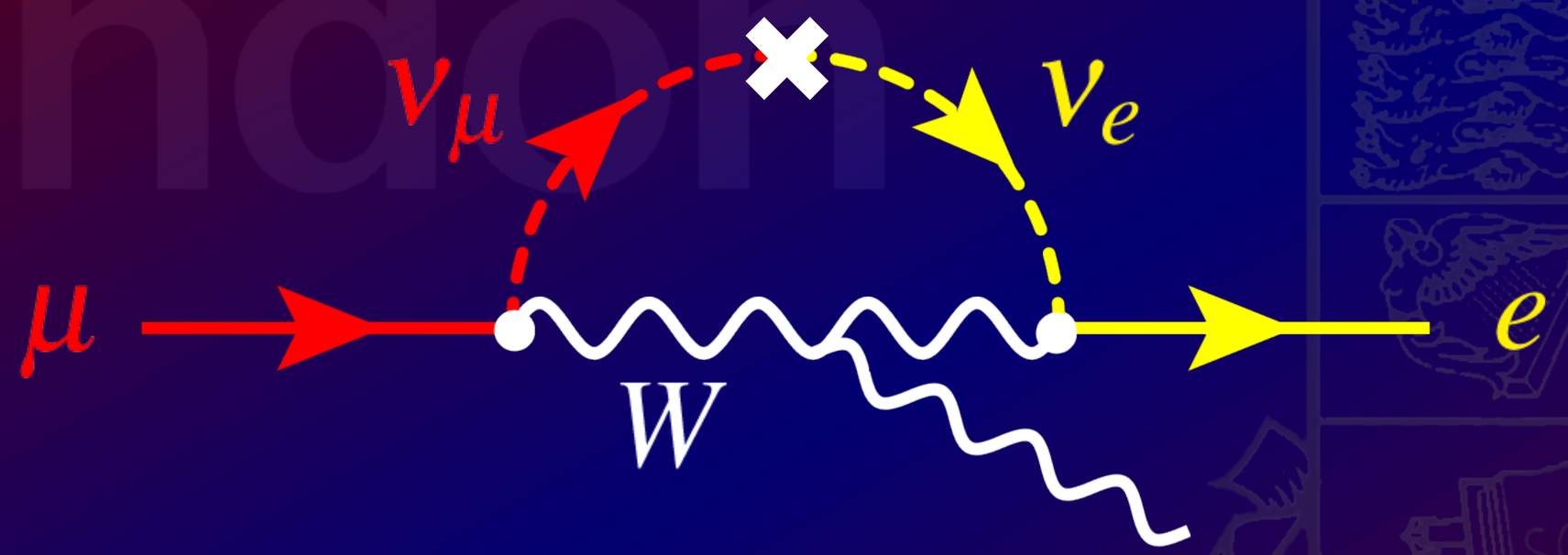


- but this is ***GIM-suppressed:***

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

Charged Lepton Flavour Violation

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

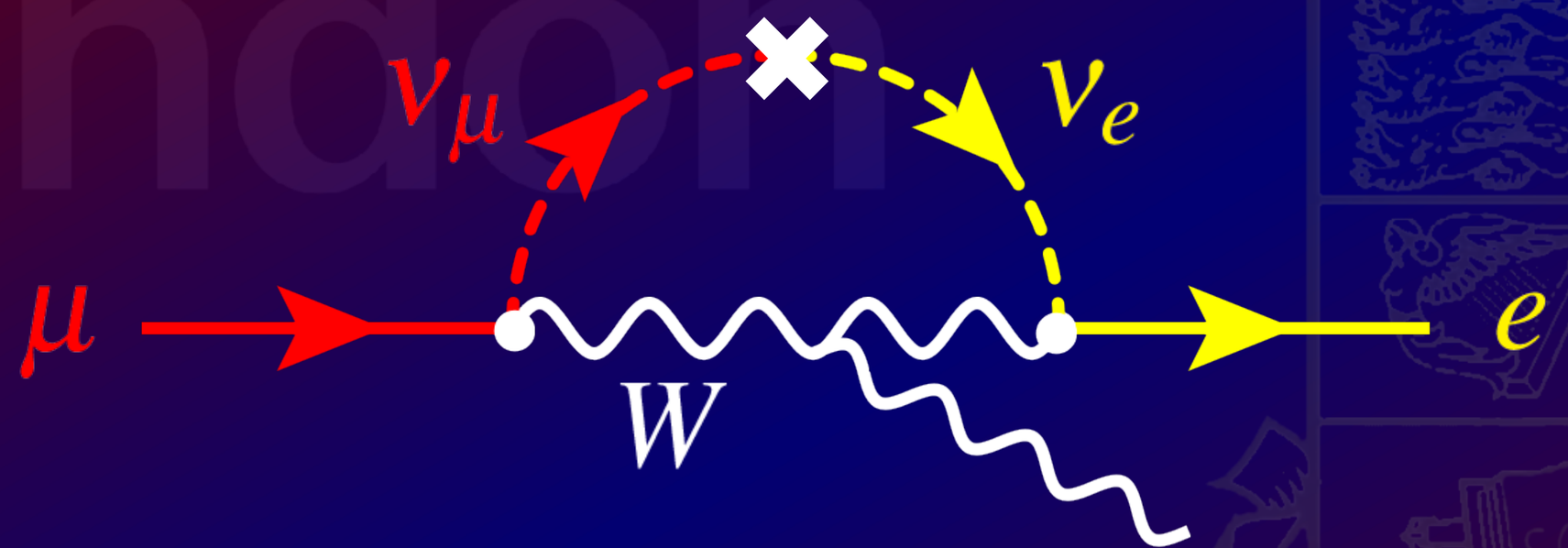


- but this is ***GIM-suppressed:***

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

Charged Lepton Flavour Violation

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



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

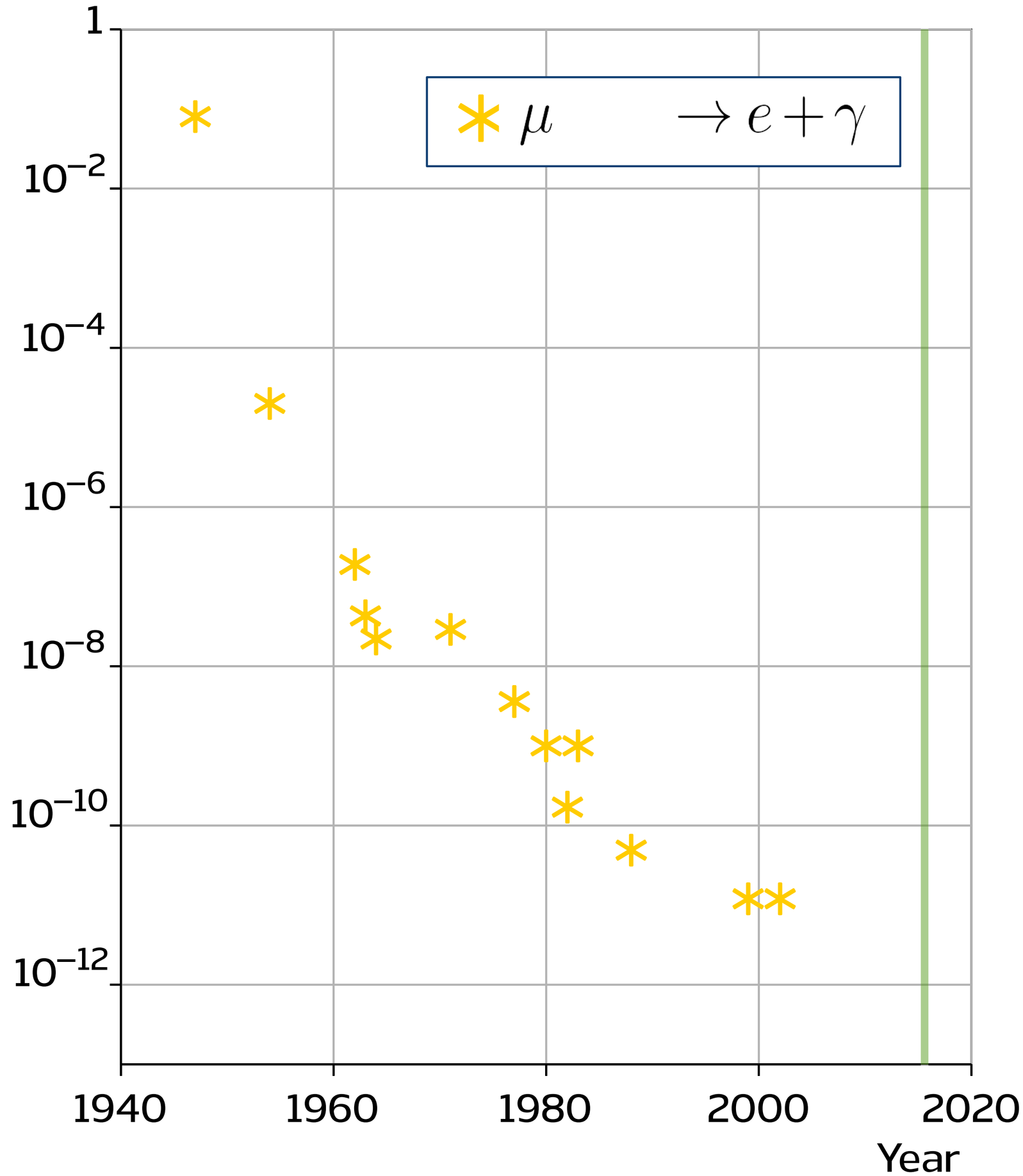
$$B(\mu \to e + \gamma) \sim 10^{-54} \quad \left(\sim \frac{m_\mu}{30 m_\oplus}\right)$$

- **if CLFV seen, *unambiguous signal* for new physics (beyond Dirac $m_\nu > 0$)**
- without such cancellations, CLFV signal can be much larger

Charged Lepton Flavour Violation

- Forbidden entirely in SM
- BSM Physics can give rise to CLFV
  - e.g. massive neutrinos
    - but CLFV suppressed to less than $O(10^{-50})$
    - background-free for further new physics
      - Majorana or Dirac? Lepton Number Violation?
      - Seesaw mechanism?
- more generally, CLFV rates can be much larger
- highly-sensitive probes to BSM physics

Charged Lepton Flavour Violation



90% C.L.
upper limit on
branching ratios

Yoshi.Uchida@imperial.ac.uk

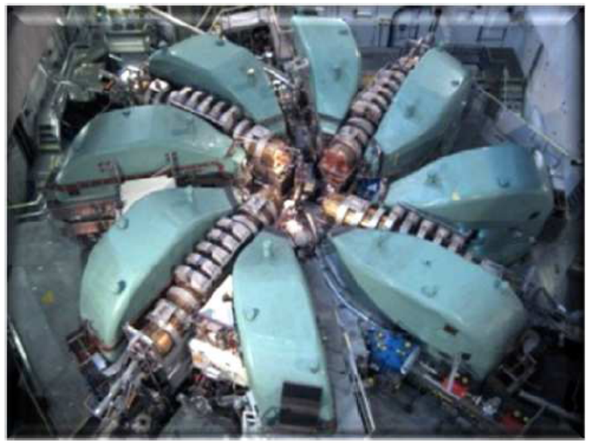
MEG and MEG-II at PSI

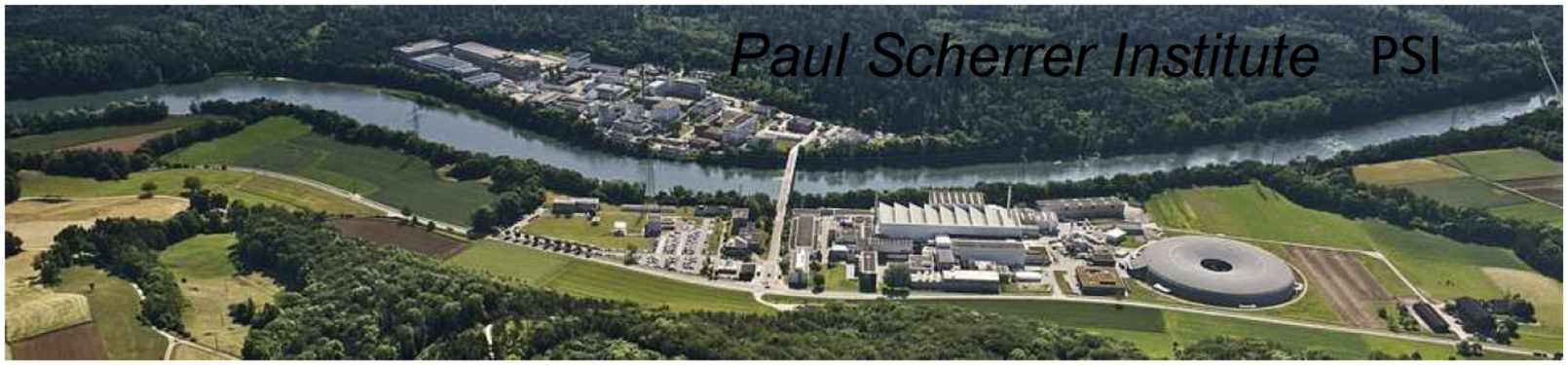
a search for the process

$$\mu^+ \to e^+ + \gamma$$

Yoshi.Uchida@imperial.ac.uk

MEG HOME





Switzerland

PSI, ETH-Z

Russia

BINP, Novosibirsk, JiNR, Dubna

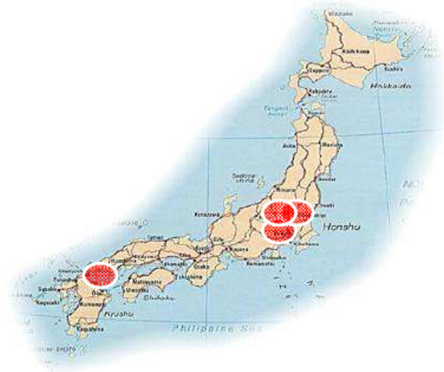
MEG Collaboration

some 65 Physicists

5 Countries, 14 Institutes

Japan

Univ.Tokyo, KEK Waseda Univ., Kyushu Univ.

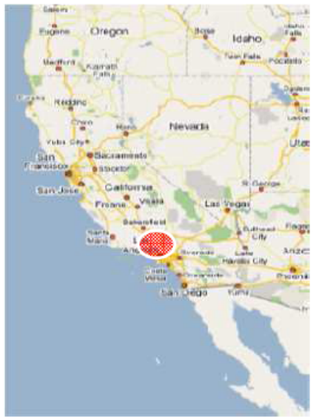


Italy

INFN + Univ. : Pisa, Genova, Pavia, Roma I & Lecce

USA

University of California Irvine UCI



Signal and backgrounds

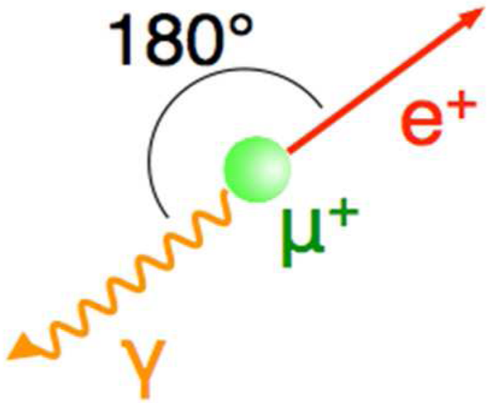
Dmitry Grigoriev

Signal μ+ decay at rest

52.8 MeV (half of M_μ) (E_γ,E_e)

Back-to-back ($\theta_{e\gamma}$,$\varphi_{e\gamma}$)

Timing coincidence ($T_{e\gamma}$)



Accidental background (dominant)

Michel decay e^+ + random γ

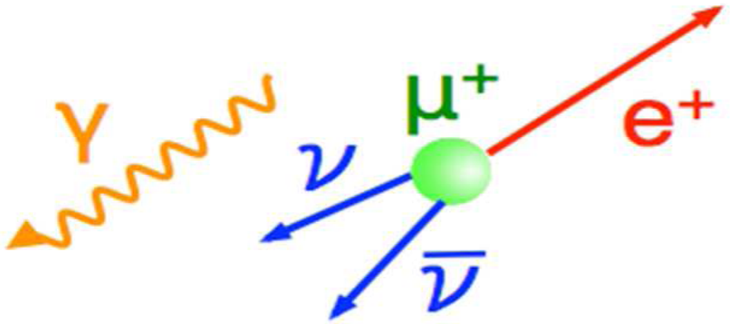
Random timing, angle, E < 52.8MeV

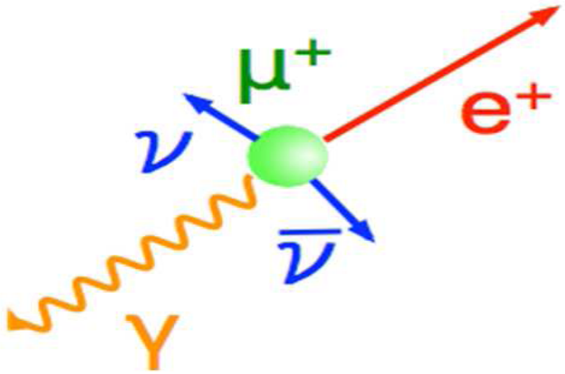
Radiative muon decay

$\mu^+ \rightarrow e^+\nu\nu\gamma$

Timing coincident, not back-to back,

E <52.8MeV





Experimental set-up

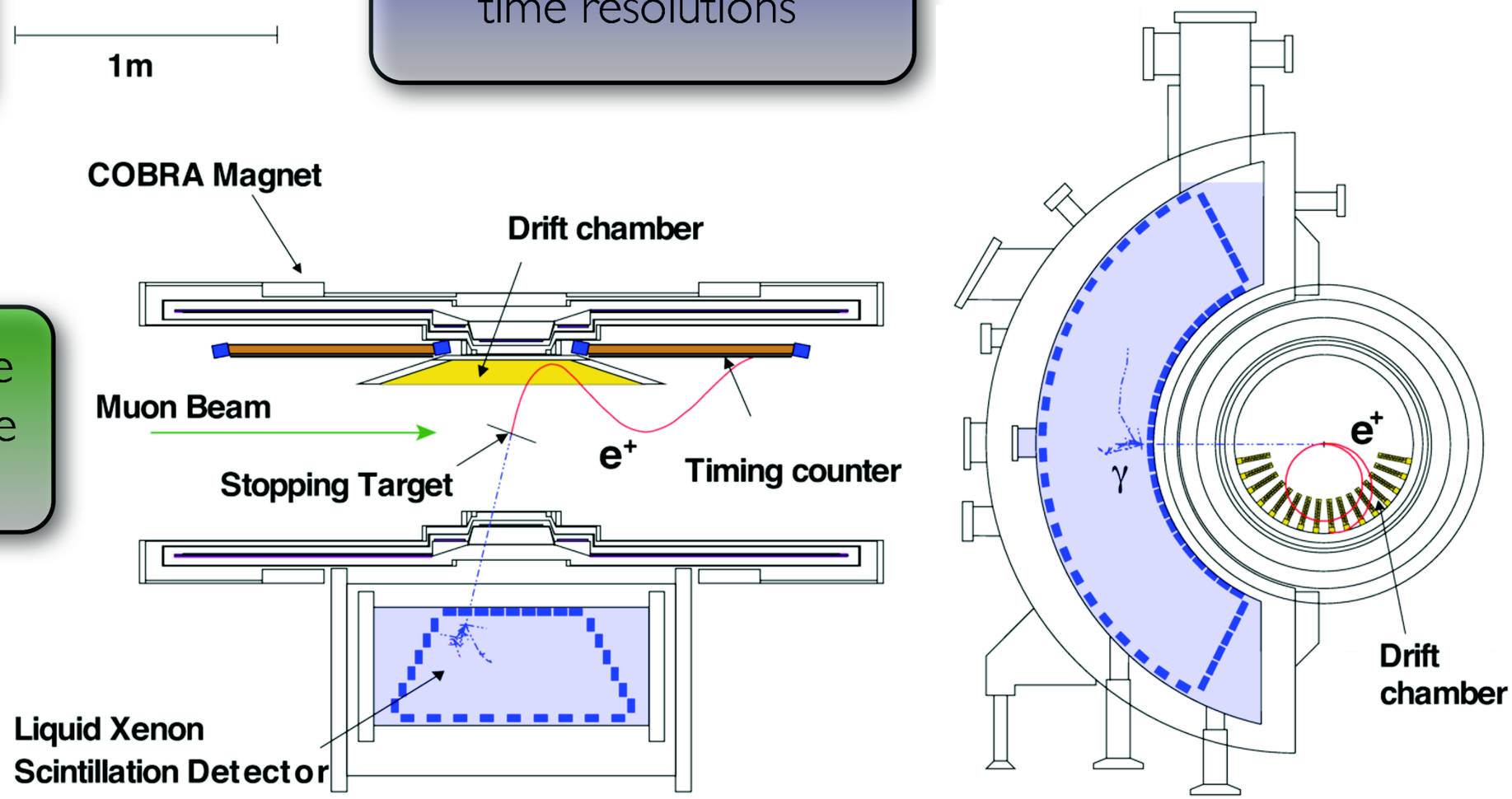
Angela Papa

Eur. Phys. J. C (2013) 73:2365

The most intense DC muon beam

Gamma High energy and time resolutions

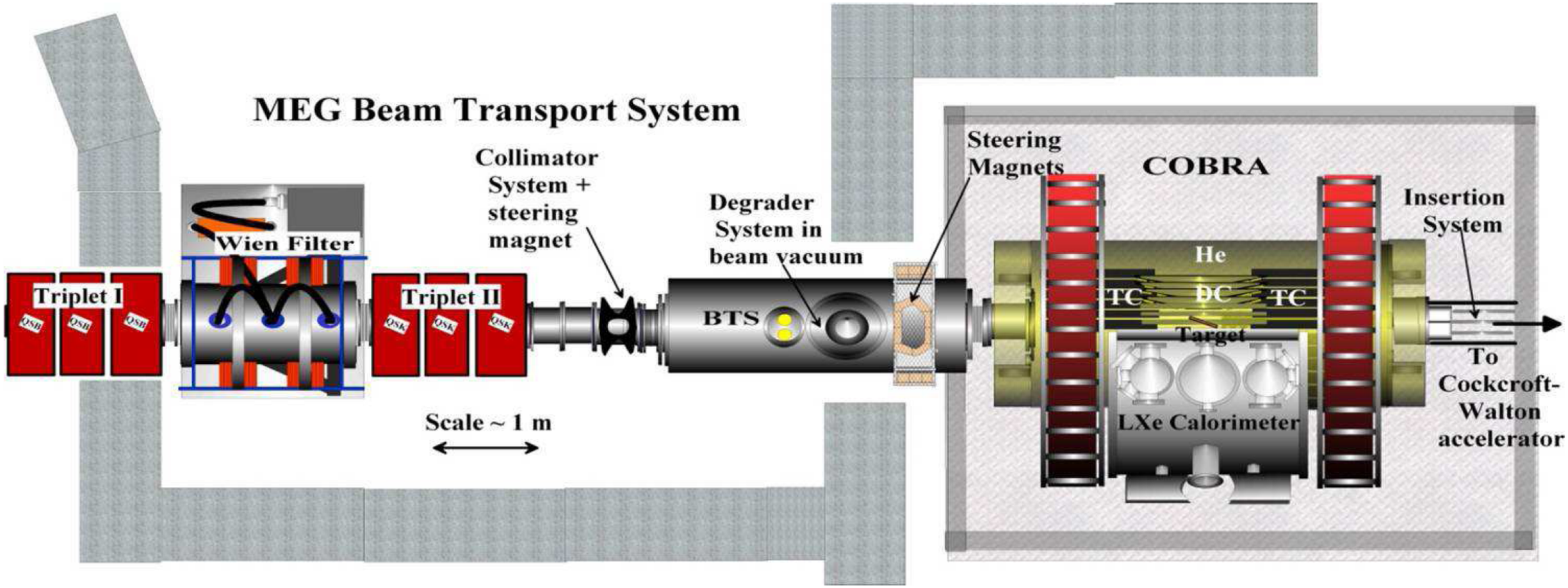
Positron Very precise momentum and time resolutions



High efficiency event selection and frequency signal digitization

Complementary calibration and monitoring methods

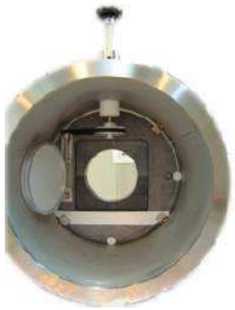
Layout of the experiment



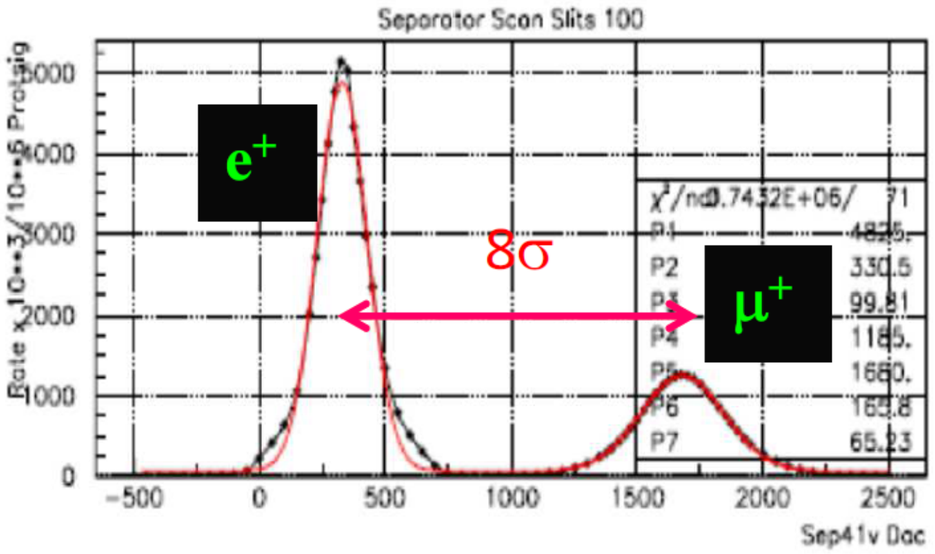
MEG:
Dmitry Grigoriev

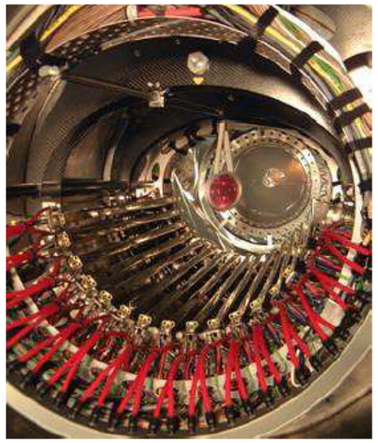
Beam line

- High-intensity DC surface muon beam - πE5+MEG
  ⇨ capable of>10^8 μ^+/s at 28 MeV/c(optimal rate 3×10^7/s)
- "pure" muon beam - Wien filter(ExB)+Collimator system
- ⇨ μ-e separation at collimator >7.5σ (12 cm)
- Small beam-spot + high transmission -BTS
  ⇨ focus enhancement, beam σ~10 mm at target
  ⇨ second focus at centre BTS – degrader 300 μm
- Thin stopping target + minimal scattering – end-caps
  ⇨18mg/cm^2 CH_2 target at 70°+He COBRA environment
  + remote Target & End-cap insertion system

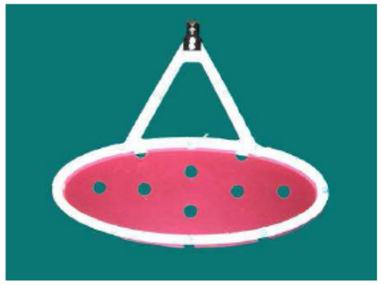


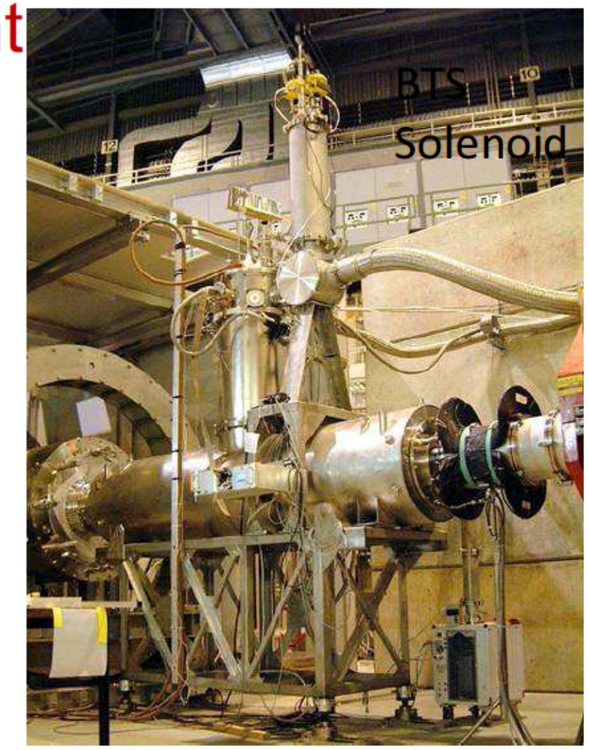
collimator





Target





MEG: Dmitry Grigoriev

Results

Phy. Rev. Lett. 110, 201801 (2013)

Data taking finished at 31.08.2013
Statistics is doubled compare to published

year	Nstop μ, $x10^{13}$	Sensitivity, $x10^{-13}$	Br, Upper limit (CL 90%), $x10^{-13}$
2009+2010	17.5	13	13
2011	18.5	11	6,7
2009+2010+2011	36.0	7.7	**5.7** (20 times better than MEGA)
All data (expected)	~80	~5	

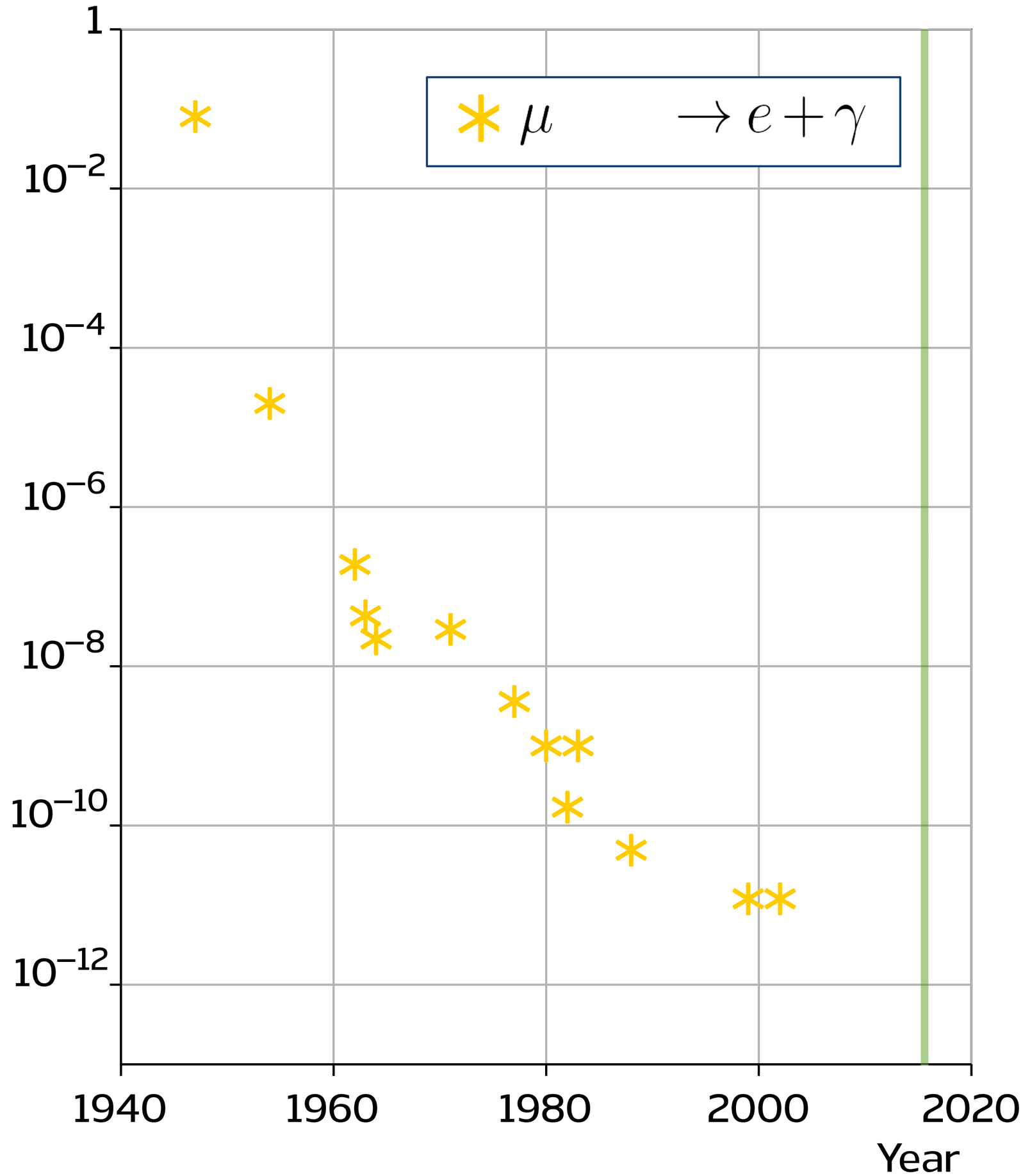
Final result of analysis is expected by the end of 2015 with the improved analysis. The data are reprocessed now.

Improvement of the analysis

- Event reconstruction algorithm.
- Calibration procedures.
- Background rejection techniques.
  - recover positron tracks which cross the target twice (missing turn analysis)
  - Identify background γ-rays generated when a positron annihilates with an electron on some detector material (annihilation-in-flight (AIF) analysis)
  - refine the alignment procedure of the target and drift chamber system.

About half the total dataset being analysed now; the collaboration is making sure they do it right

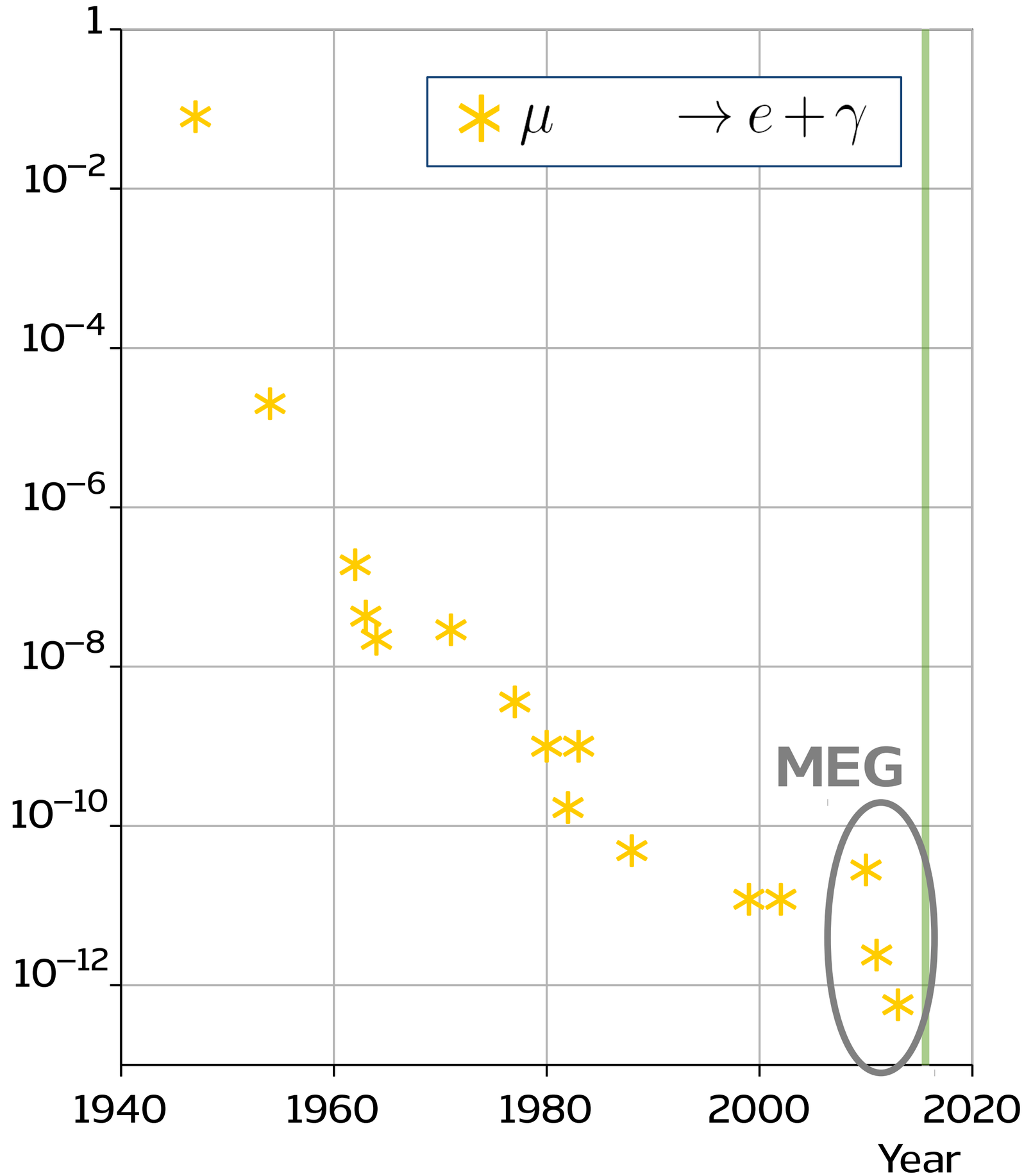
Charged Lepton Flavour Violation



90% C.L.
upper limit on
branching ratios

Yoshi.Uchida@imperial.ac.uk

Charged Lepton Flavour Violation



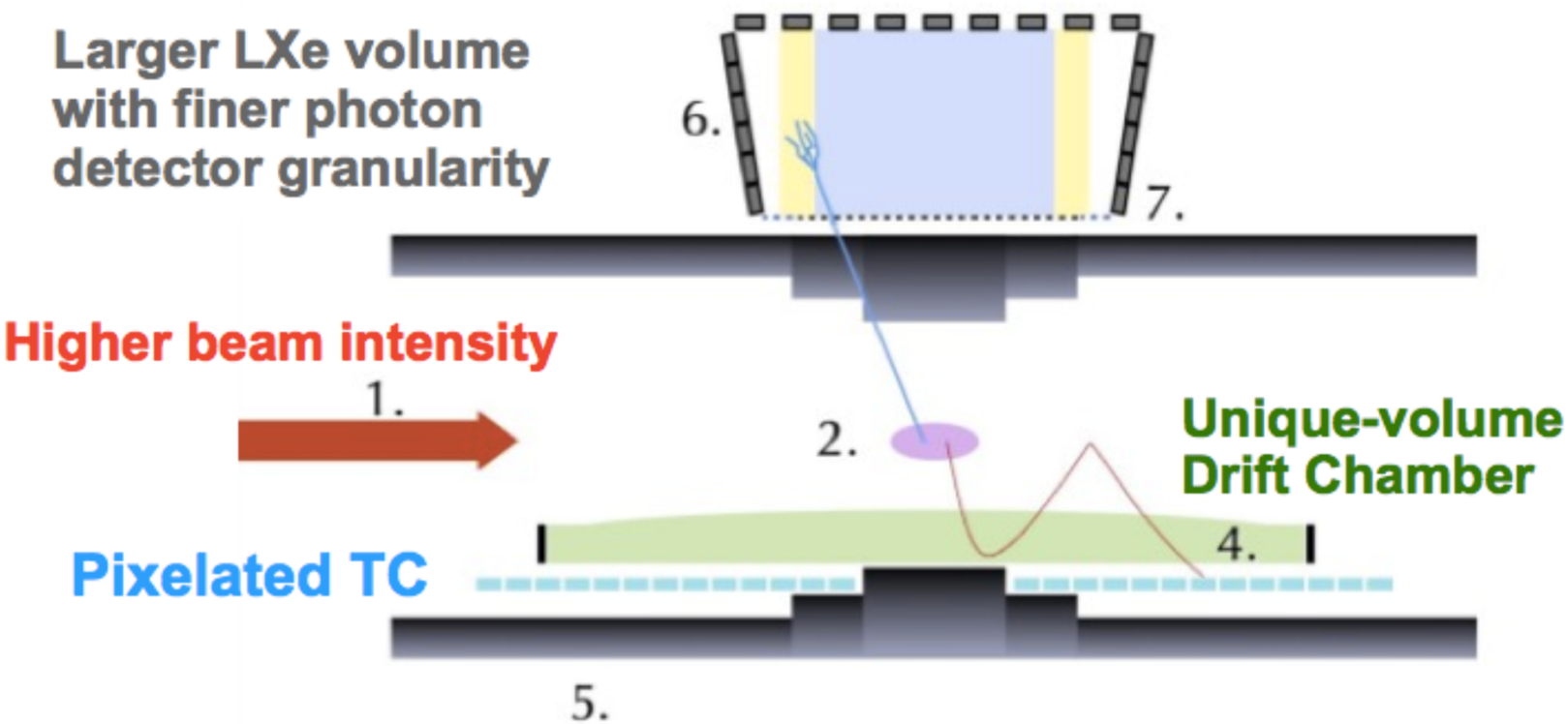
90% C.L.
upper limit on
branching ratios

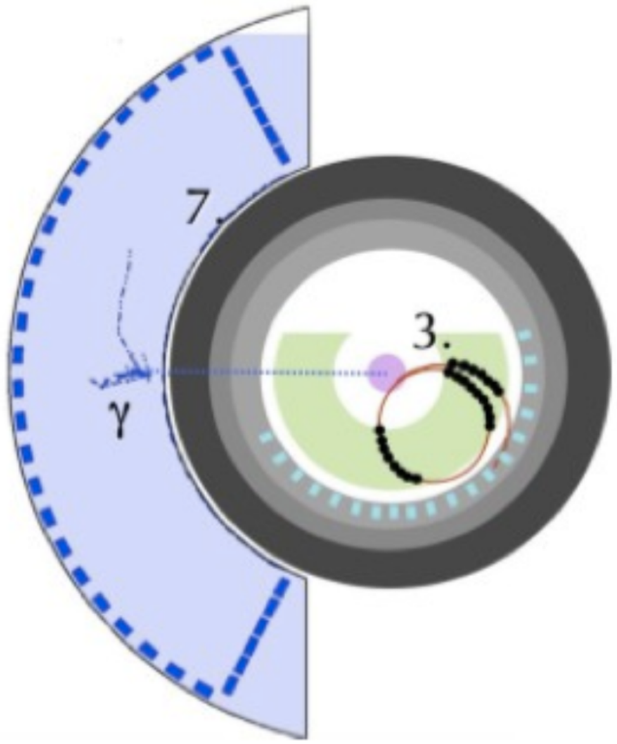
Yoshi.Uchida@imperial.ac.uk

Angela Papa

The MEGII experiment

- An upgrade of MEG, aiming at a sensitivity improvement of one order of magnitude (**down to 5 x 10^{-14}**) approved by PSI and funding agencies is ongoing





How the sensitivy can be pushed down?

MEGII: Angela Papa

- More sensitive to the signal...

high statistics

$$SES = \frac{1}{R \times T \times A_g \times \varepsilon(e^+) \times \varepsilon\,(gamma) \times \varepsilon(TRG) \times \varepsilon(sel)}$$

beam rate

acquisition time

geometrical acceptance

detector efficiency

selection efficiency

- More effective on rejecting the background...

high resolutions

$$B_{acc} \sim R \times \Delta E_e \times (\Delta E_{gamma})^2 \times \Delta T_{egamma} \times (\Delta \Theta_{egamma})^2$$

momentum resolution

Energy resolution

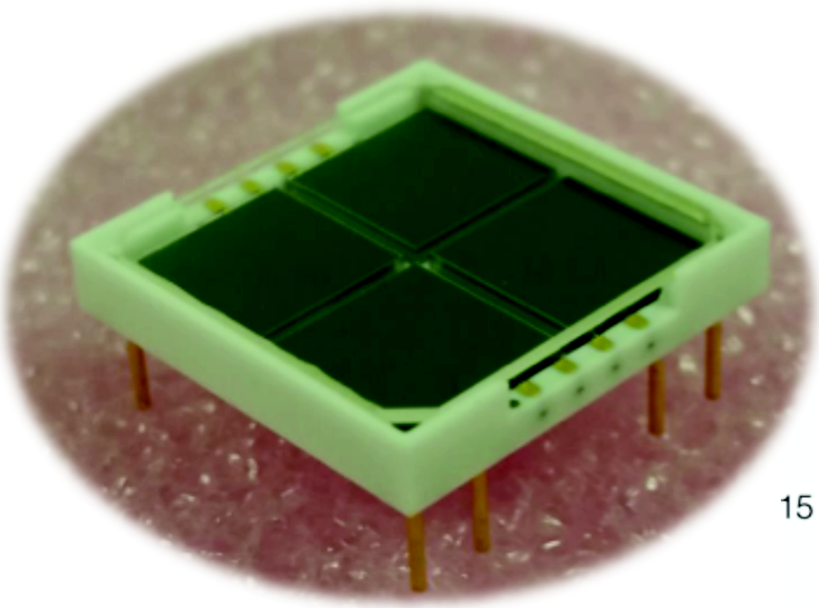
Relative timing resolution

Relative angular resolution

R&D in collaboration with Hamamatsu: VUV-sensitive SiPM (MPPC using Hamamatsu convention)

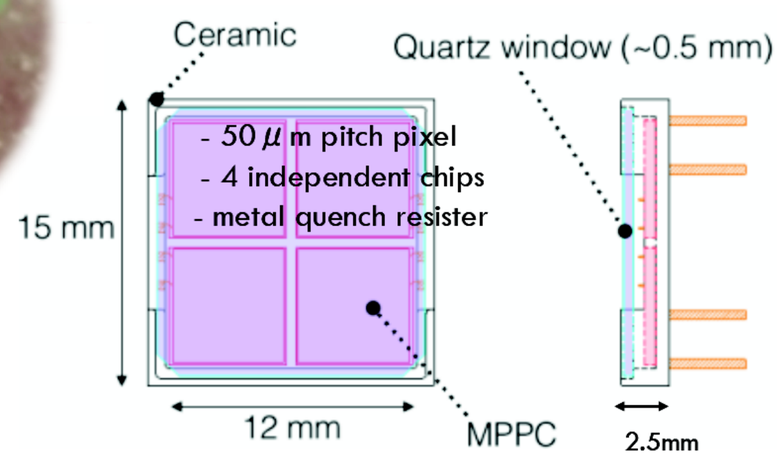
MEGII: Angela Papa

For the LXe photon calorimeter
To replace 2-inch PMTs used by MEG

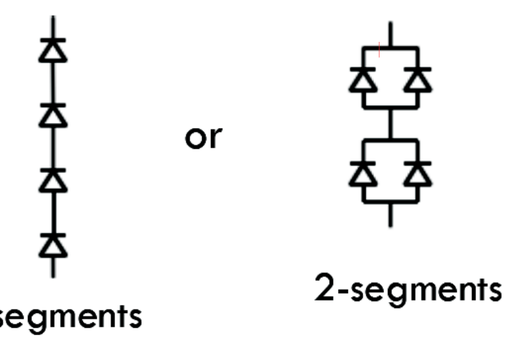


We have successfully developed **VUV-MPPC** in collaboration with Hamamatsu Photonics. K.K.

- **Sensitive to VUV-light**
  → Protection coating is removed, VUV-transparent quartz window is used for protection.
- **Large area (12x12 mm^2)**
  → signal tail become long due to large capacitance.
  →Reduce capacitance by connecting 4 chips in series.

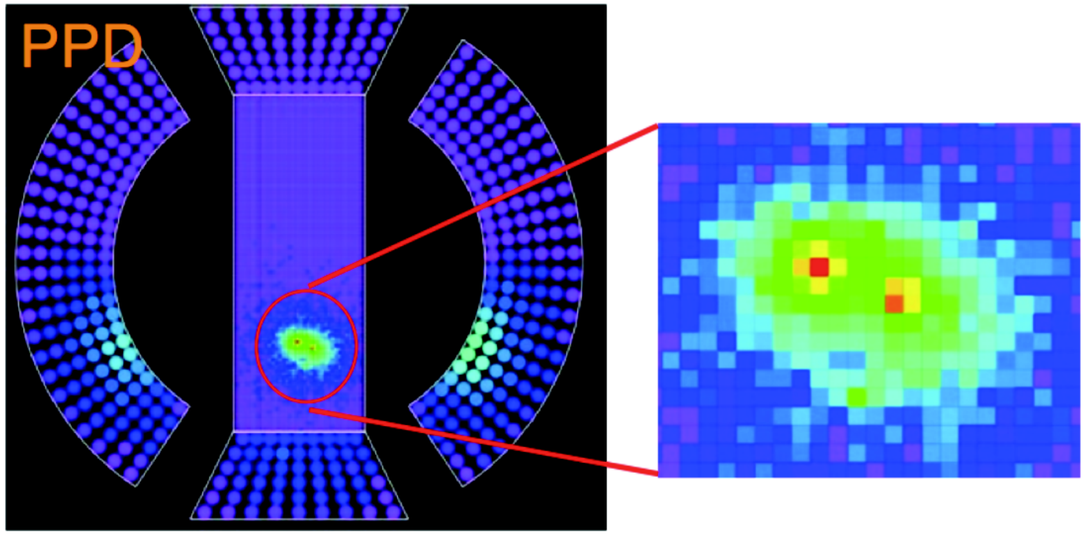


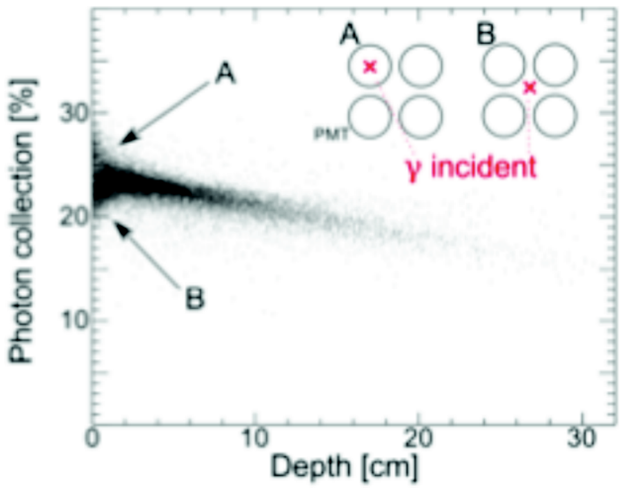
Hamamatsu S10943-3186(X)

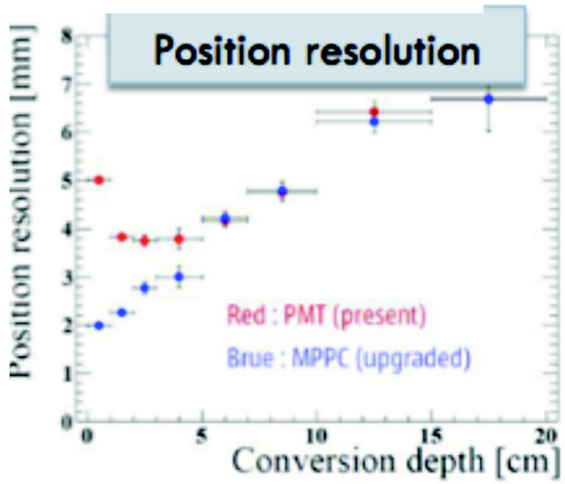


The upgraded Liquid Xenon calorimeter (in numbers)

Resolution	MEGI	MEGII
u (mm)	5	2.4
v (mm)	5	2.2
w (mm)	6	3.1
E_γ (w<2cm)	2.4%	1.1%
E_γ (w>2cm)	1.7%	1.0%
t_γ (ps)	67	60



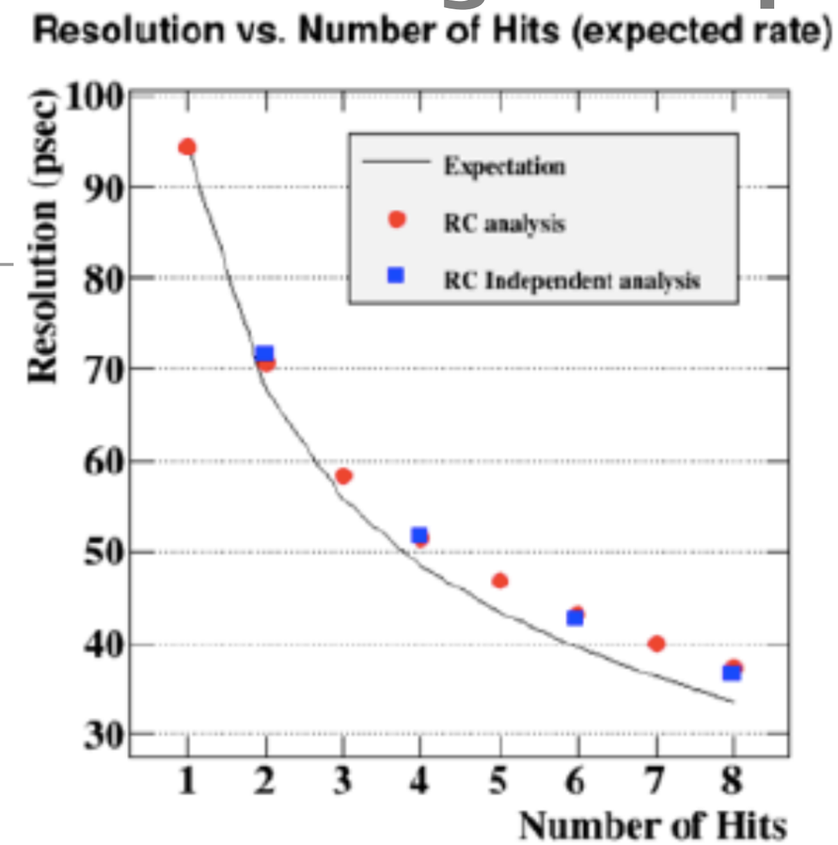


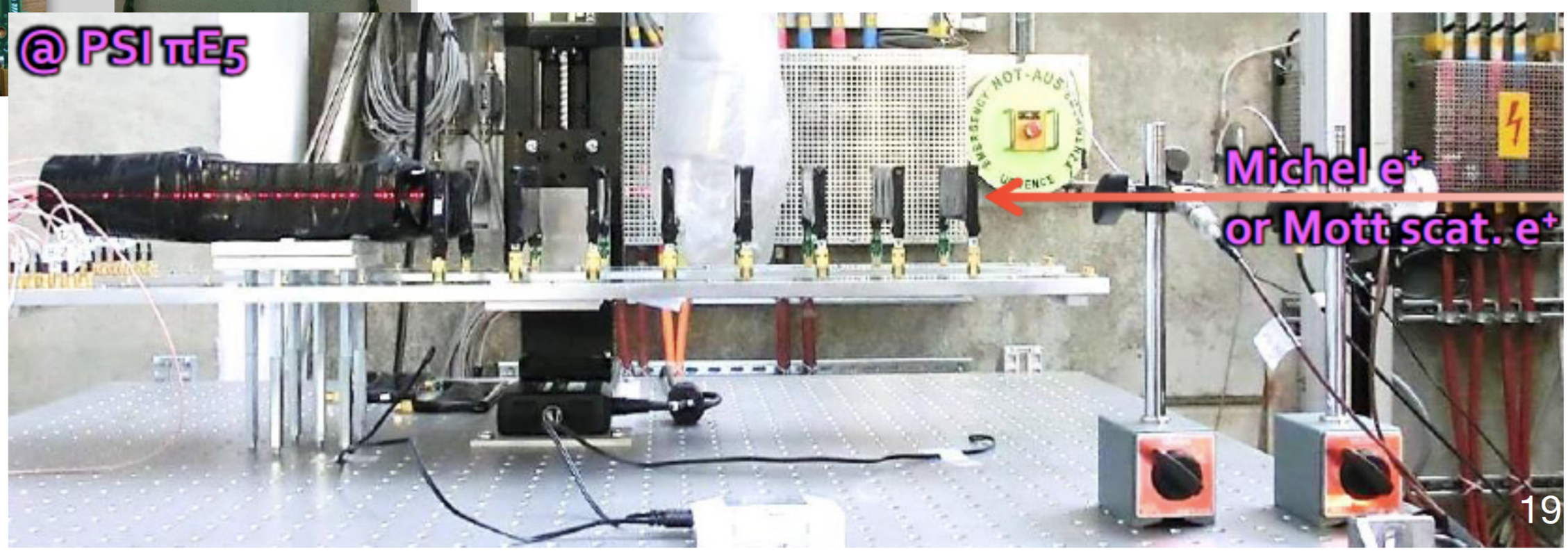


MEGII: Angela Papa

A new re-designed spectrometer: the pixelized Timing Counter (in numbers)

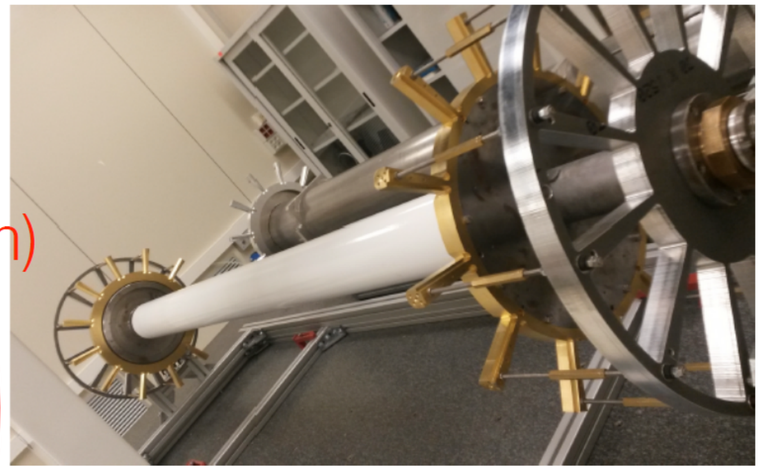
Timing resolution:
35 ps at the MEGII rate conditions



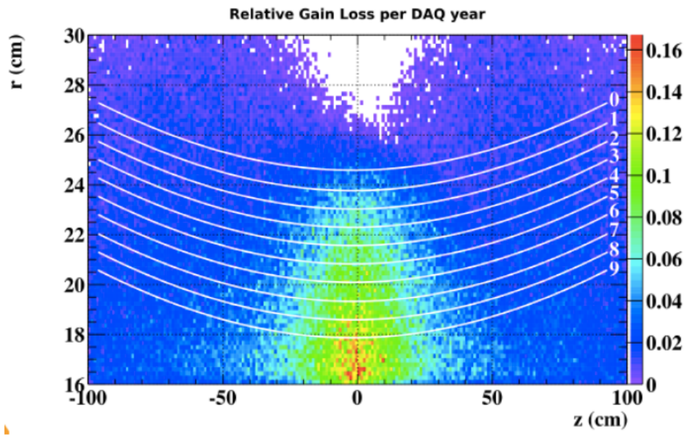


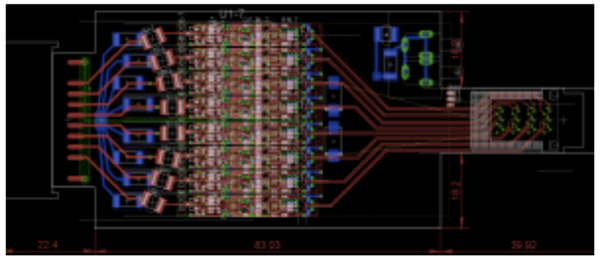
The new re-designed spectrometer: the single volume chamber (in numbers)

- Positron momentum and direction measurement
- Unique volume gas chamber
  - Single hit resolution 50 ÷ 100 μm in r (250 μm)
  - Momentum resolution ~130 KeV (310 KeV)
  - Angular resolution ~5 mrad (8-11 mrad)
  - Trasparency towards TC ~80 % (40%)
- Target (default solution)
  - Thinner passive target 140 um (205 um)



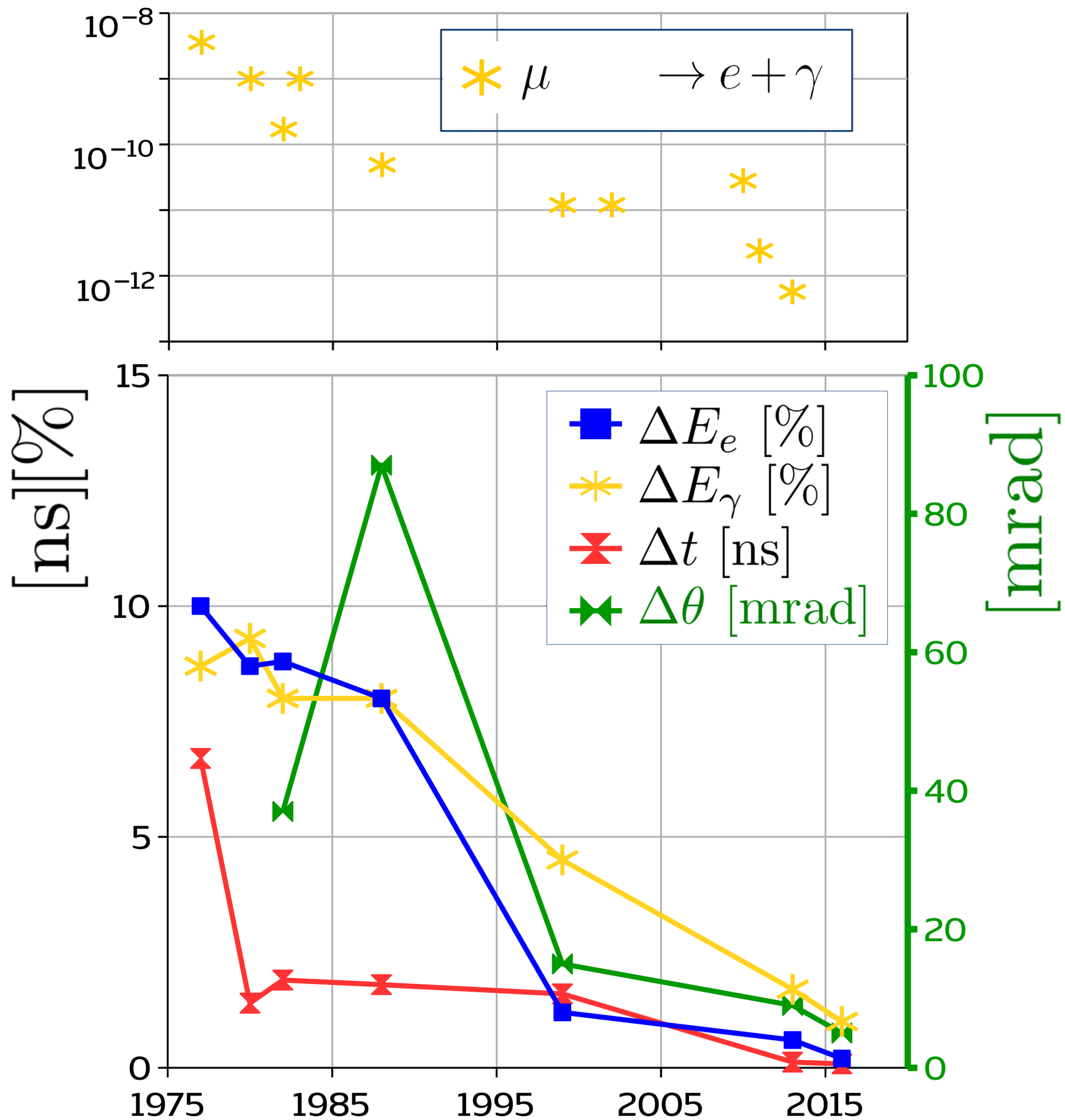
Ageing tests:





Front End Electronics:
3dB bandwidth
around 1GHz

$\mu \to e + \gamma$: Detector Performance



Yoshi.Uchida@imperial.ac.uk

Summary

MEGII: Angela Papa

- MEG completed successfully
  - data sample 2009-2011: best upper limit of any particle decay **$B(\mu^+ \rightarrow e^+ \gamma) < 5.7 \times 10^{-13}$**
  - data sample 2009-2013: final result just around the corner
- MEGII preparation in good shape
  - improved sensitivity by a factor of 10 reaching **5×10^{-14}**

- Unique DC muon beam at PSI
  - high intensity **$O(10^8)$ muon$^+$/s**
  - feasibility studies ongoing to increase it, aiming at **$O(10^{10})$ muon$^+$/s**

Muon-to-Electron Conversion

Mu2e (Fermilab)

COMET (J-PARC)

DeeMee (J-PARC)

Yoshi.Uchida@imperial.ac.uk

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)**
- $E_e = m_\mu - E_{\text{bind}} - E_{\text{recoil}}$

Muon-to-Electron Conversion

- Search for the process

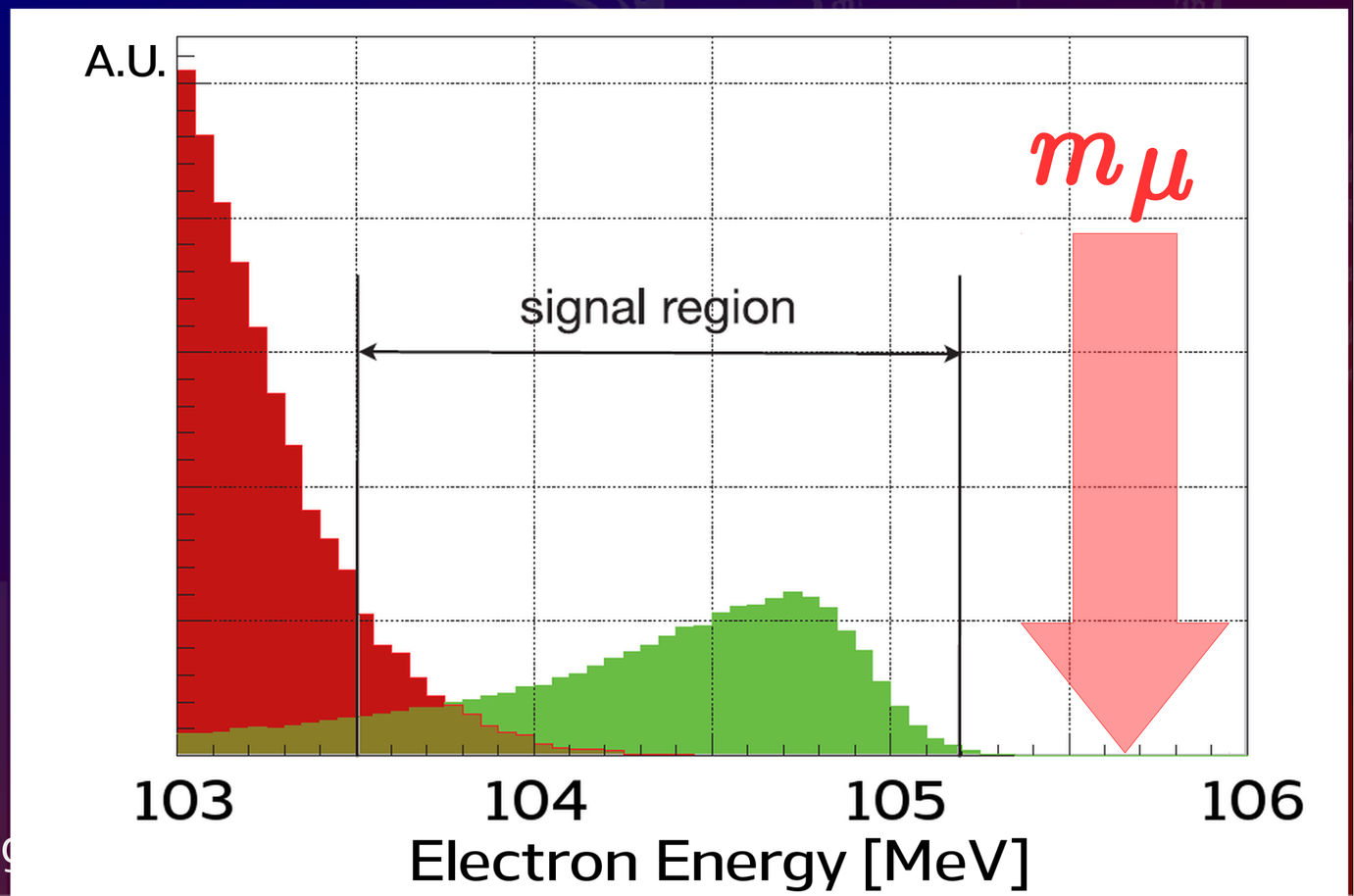
$$\mu^- + N(A,Z) \quad \rightarrow \quad e^- + N(A,Z)$$

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

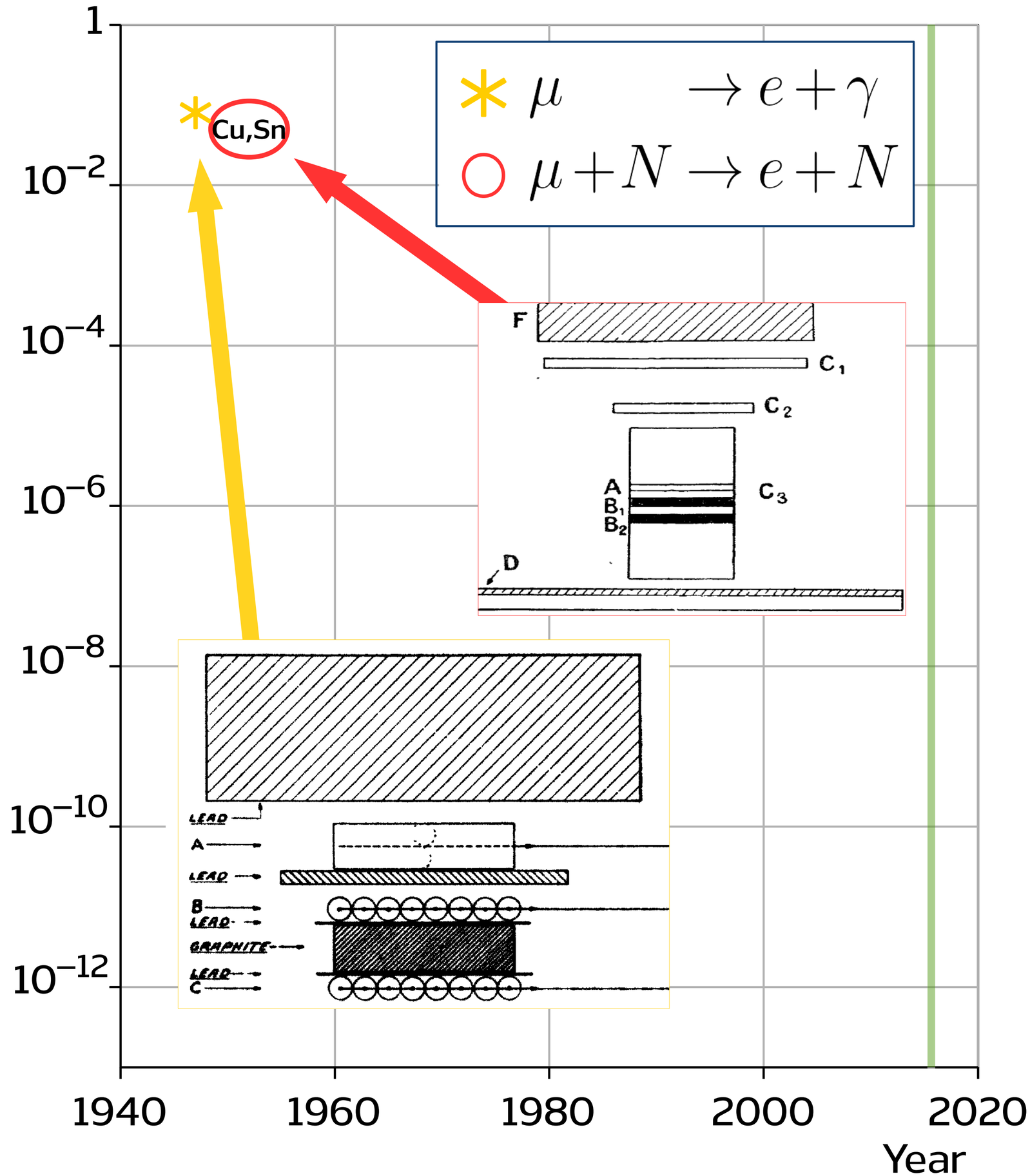
- Time available after formation of muonic atom: up to about **1 microsecond (Z-dependent)**

- $E_e = m_\mu - E_{\text{bind}} - E_{\text{recoil}}$

- **observed signal is smeared because** of detector effects



Charged Lepton Flavour Violation



90% C.L.
upper limit on
branching ratios

Yoshi.Uchida@imperial.ac.uk

Soient N^+ et N^- les nombres de mésons μ de chaque signe arrêtés et n^+ et n^- les nombres de mésons émettant un électron visible.

La proportion N_e/N du nombre de mésons négatifs émettant un électron est égale à

$$\frac{N_e}{N} = \frac{n^-}{N^-}\,\frac{N^+}{n^-},$$

9 000 photo

D'où

Soit λ_ν la pr a probabilité de capture s :

$\lambda_e + \lambda_\nu$

τ^+ est la vie moyenne du méson μ positif et τ^- est la vie moyenne apparente du méson μ négatif à l'arrêt dans l'élément considéré. τ^- a été mesuré par Harrisson et al. (²) dans le cuivre et l'antimoine :

$$\tau^-_{Cu} = 1,22.10^{-7} \pm 0,14\ \text{s}, \qquad \tau^-_{Sb} = 0,5.10^{-7} \pm 0,06\ \text{s}.$$

Assimilant l'antimoine ($Z = 51$) à l'étain ($Z = 50$) nous trouvons :

$$\text{Cuivre :}\quad \frac{\lambda_e}{\lambda_e + \lambda_\nu} = 4\,\% \pm 5\,\%; \qquad \text{Étain :}\quad \frac{\lambda_e}{\lambda_e + \lambda_\nu} = 4,3\,\% \pm 4\,\%.$$

Ces résultats montrent que les réactions (II) sont interdites ou très improbables devant les réactions (I).

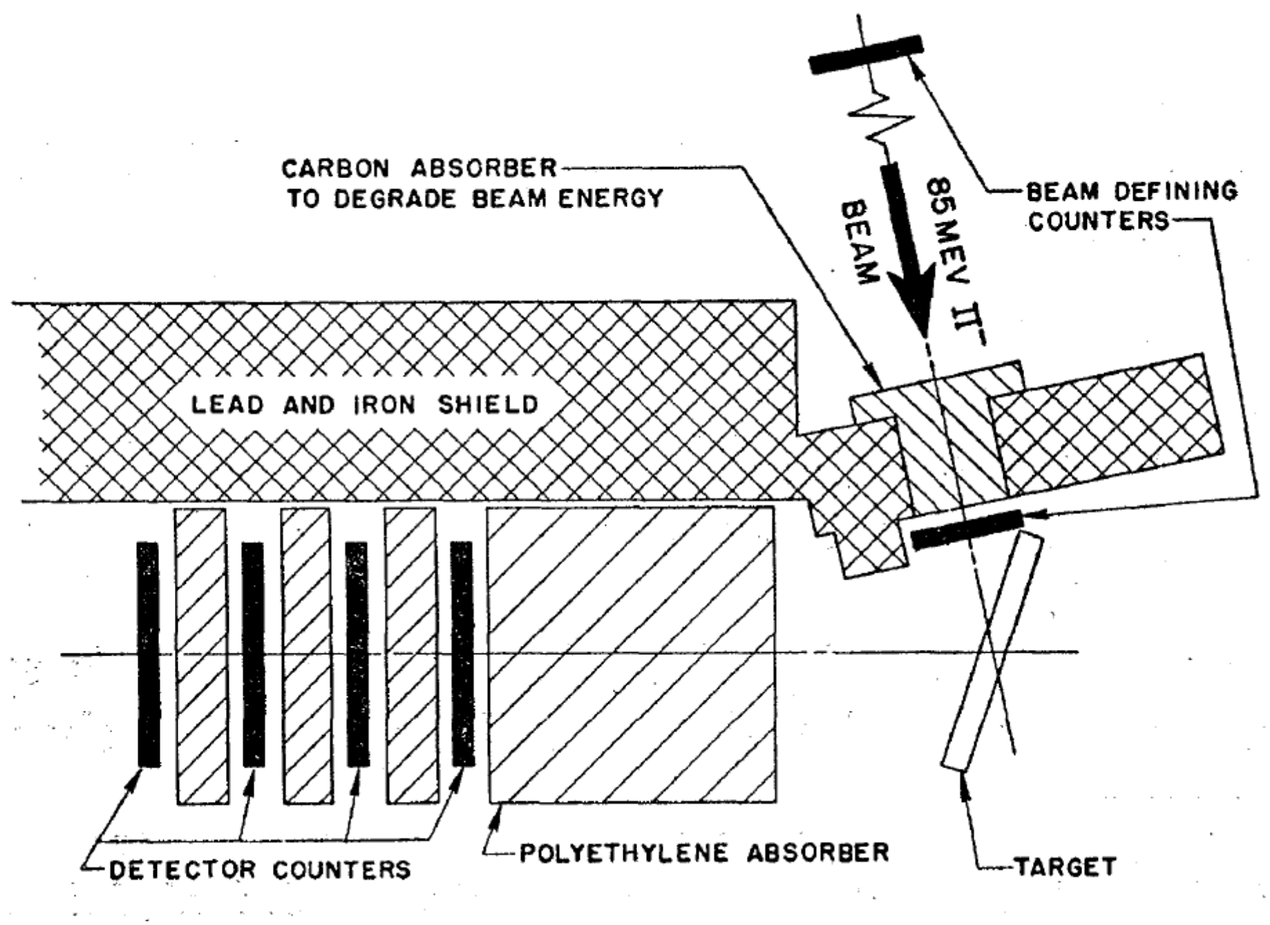
1955

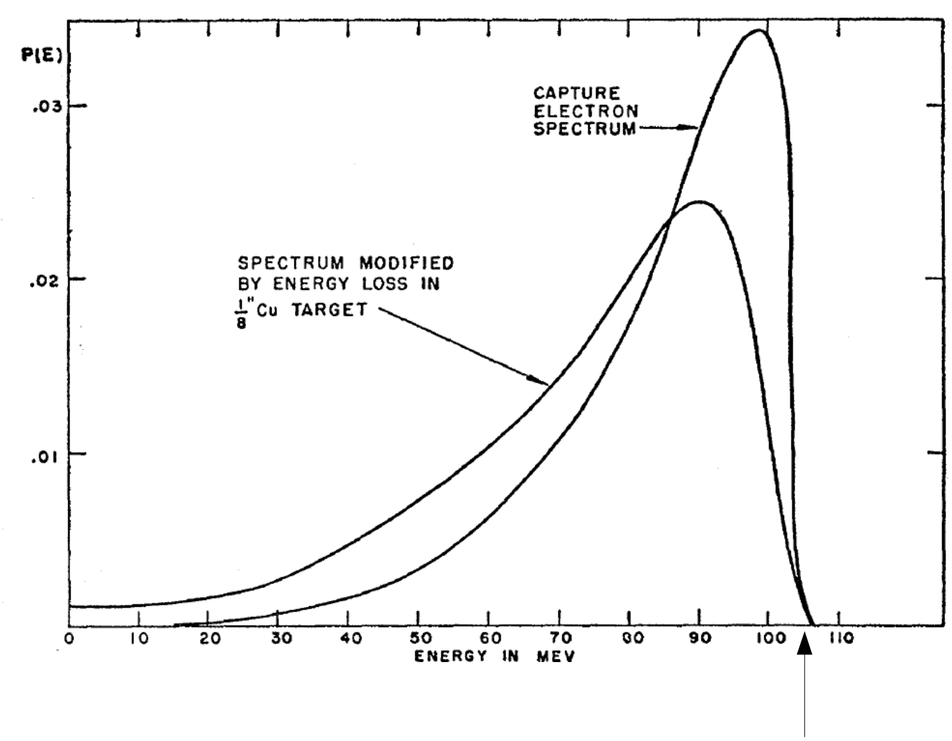
Electrons from Muon Capture*

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

(Received August 31, 1955)

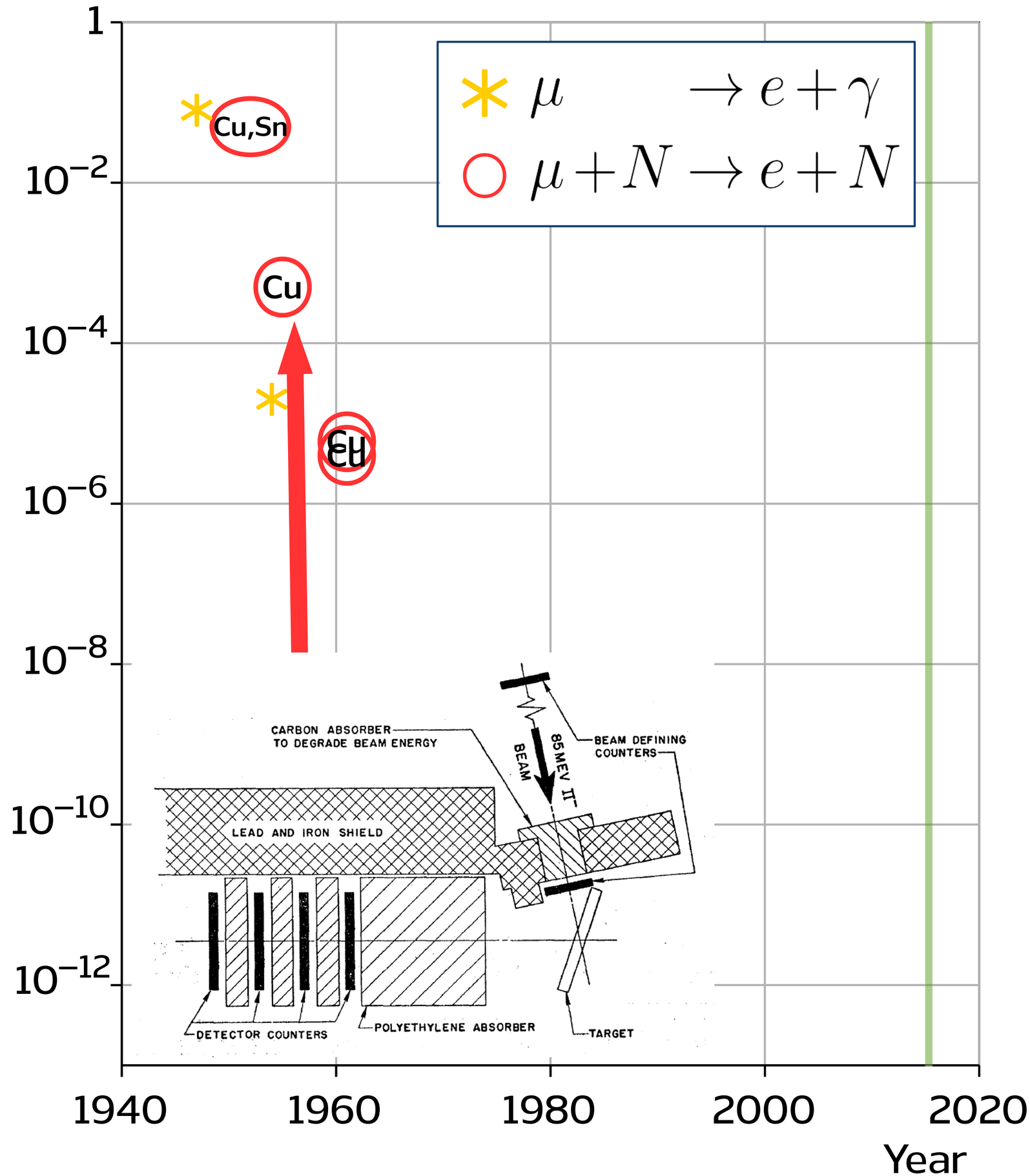
We have searched for the process $\mu^- + p \rightarrow p + e^-$ or $\mu^- + n \rightarrow n + e^-$ for μ mesons stopped in a Cu target. Scintillation counters were employed to detect the electrons from the process. No counts attributable to the electrons were obtained and we place an upper limit of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





105 MEV

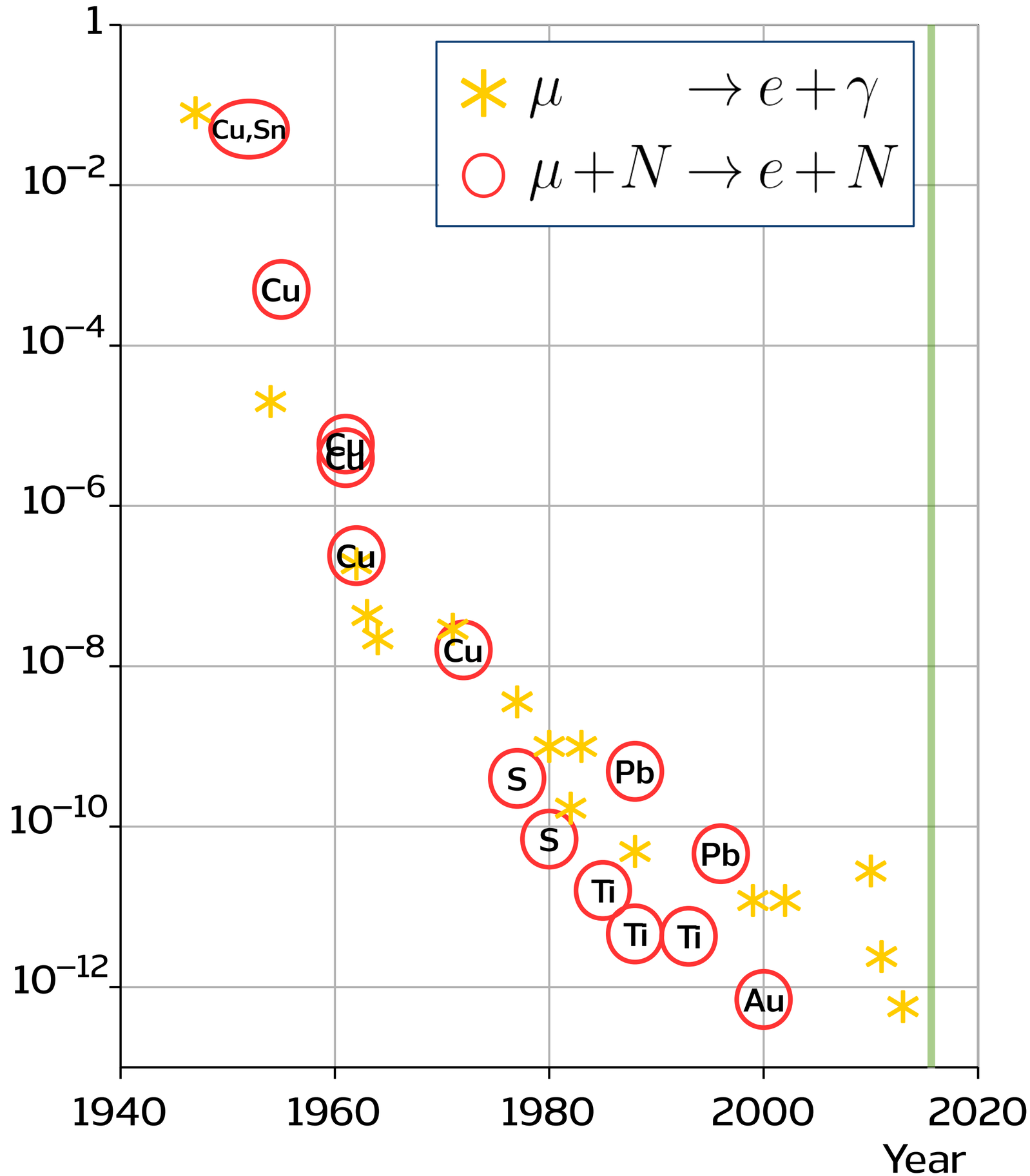
Charged Lepton Flavour Violation



90% C.L. upper limit on branching ratios

Yoshi.Uchida@imperial.ac.uk

Charged Lepton Flavour Violation



90% C.L.
upper limit on
branching ratios

Yoshi.Uchida@imperial.ac.uk

Search for Lepton-Flavor-Violating Rare Muon Processes

"MELC" proposal from 1980s

R. M. Djilkibaev* and V. M. Lobashev**

Institute for Nuclear Research, Russian Academy of Sciences, pr. Shestidesyatiletiya Oktyabrya 7a, Moscow, 117312 Russia

Received March 26, 2010; in final form, July 12, 2010

Abstract—A new approach to seeking three lepton-flavor-violating rare muon processes ($\mu \to e$ conversion, $\mu \to e + \gamma$, and $\mu \to 3e$) on the basis of a single experimental facility is proposed. This approach makes it possible to improve the sensitivity level of relevant experiments by factors of 10^5, 600, and 300 for, respectively, the first, the second, and the third of the above processes in relation to the existing experimental level. The approach is based on employing a pulsed proton beam and on combining a muon source and the detector part of the facility into a unified magnetic system featuring a nonuniform field. A new detector design involving separate units and making it possible to study all three muonic processes at a single facility that admits a simple rearrangement of the detectors used is discussed.

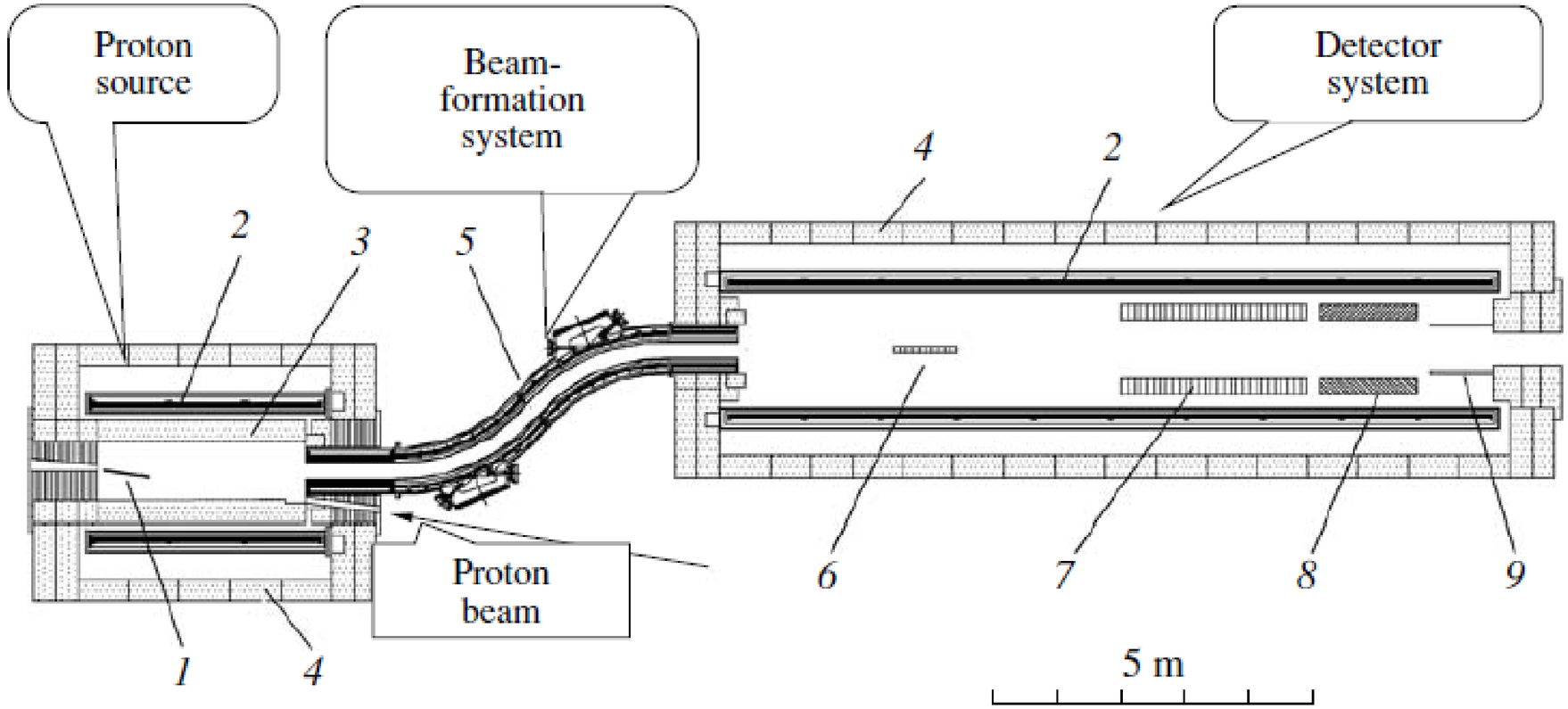
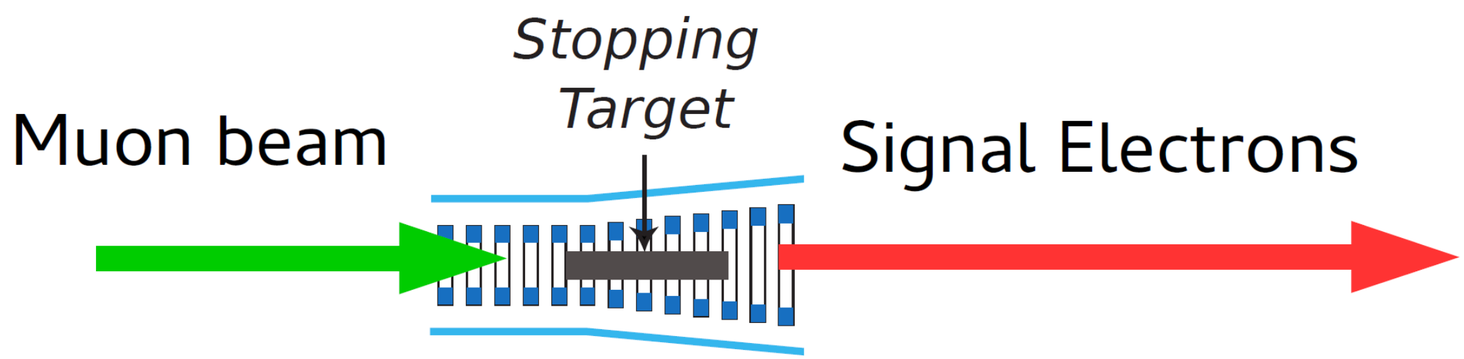
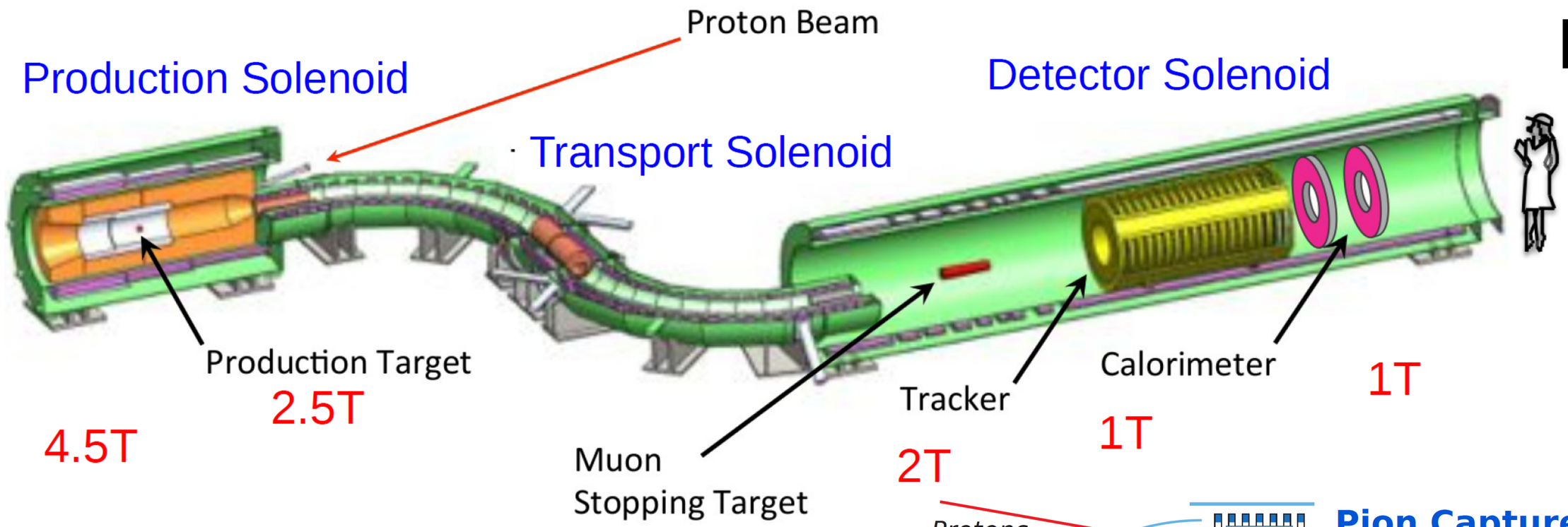


Fig. 1. Central horizontal cut of the MELC facility: (*1*) proton target, (*2*) superconductor solenoid, (*3*) shield of the solenoid, (*4*) steel yoke, (*5*) transport solenoid and collimator, (*6*) detector target, (*7*) coordinate detector, (*8*) calorimeter, and (*9*) detector shield and beam trap.

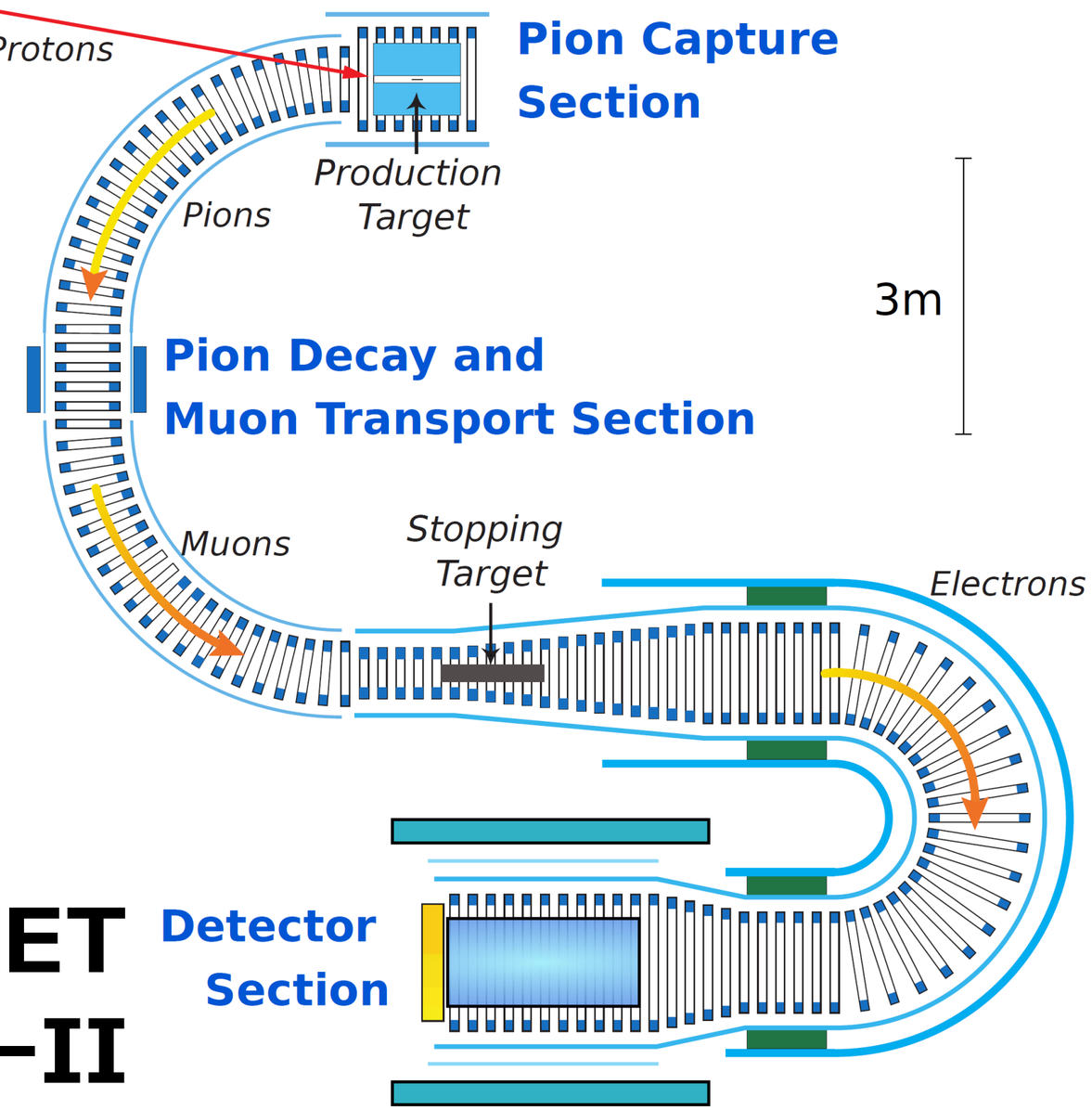

Stopping
Target
Muon beam
Signal Electrons

Mu2E



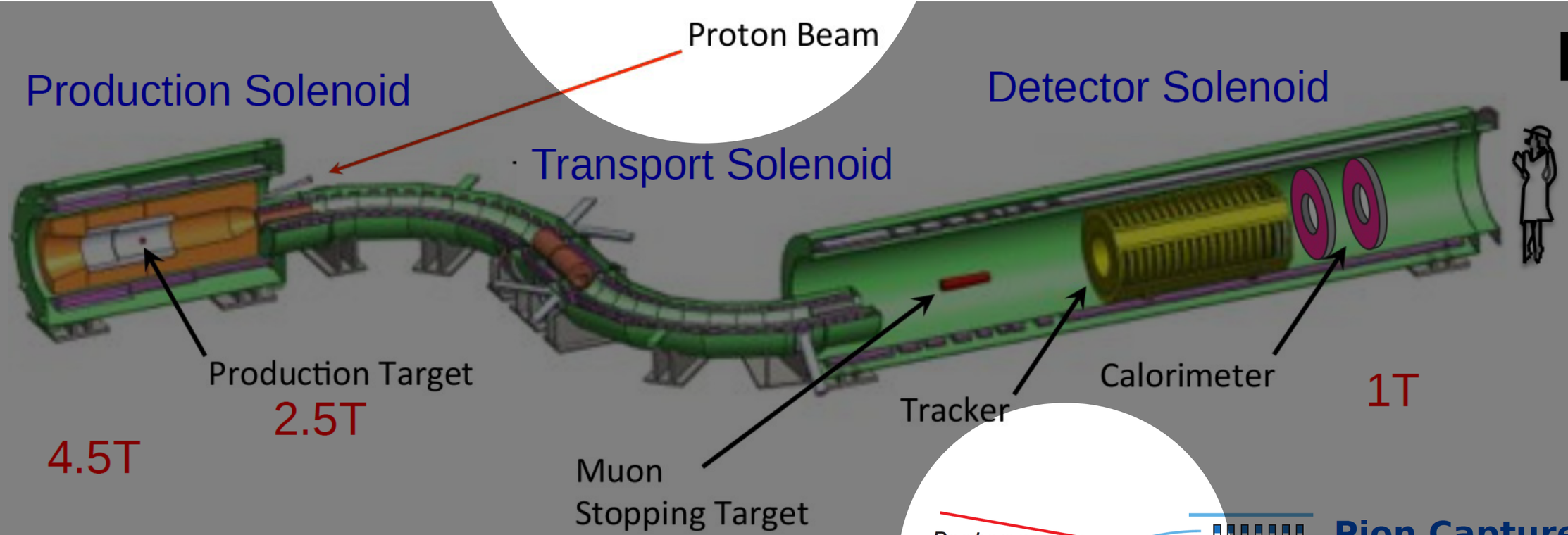
Experimental Layouts

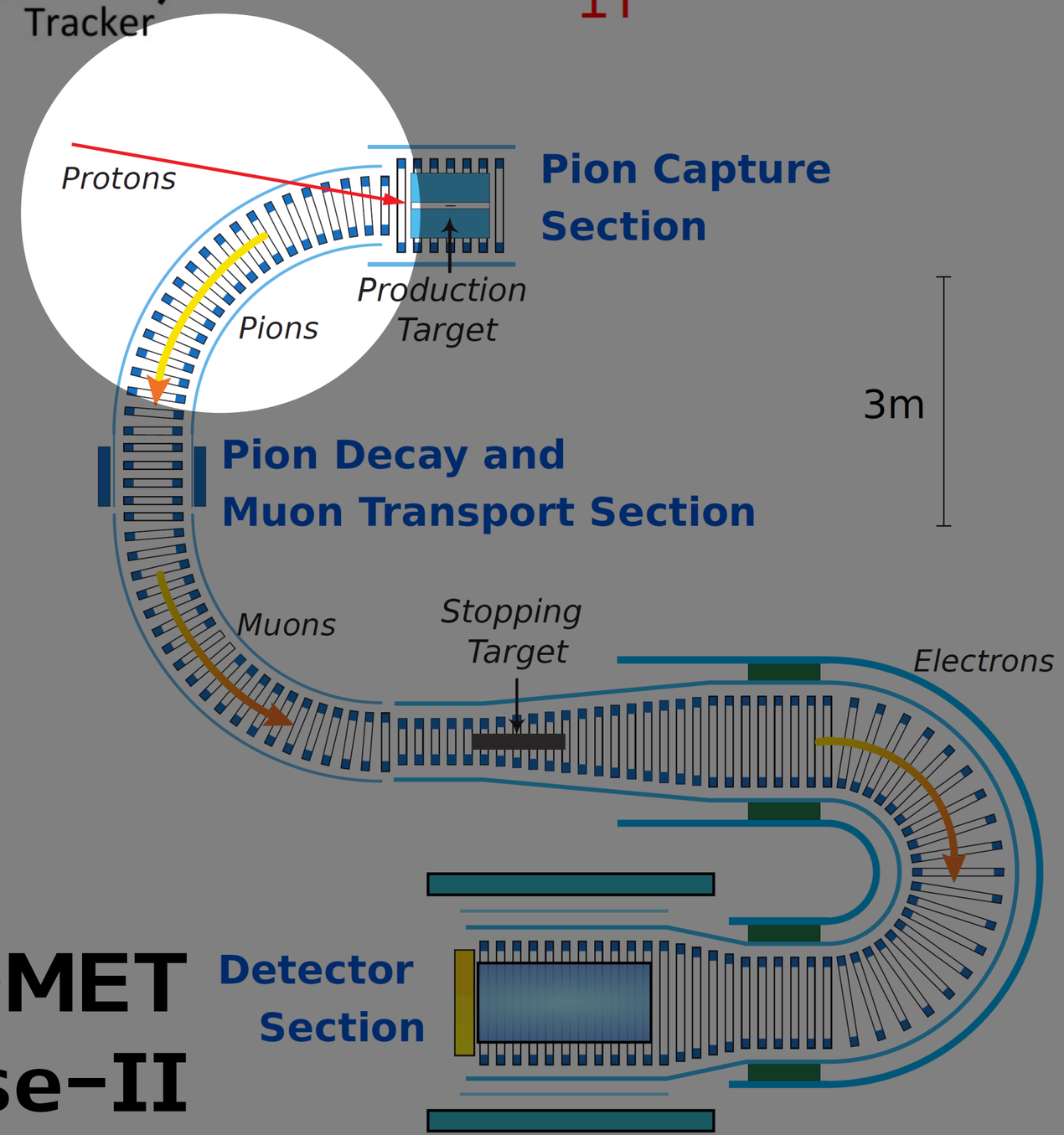
Mu2e is truer to the original MELC design



COMET Phase-II

Experimental Layouts



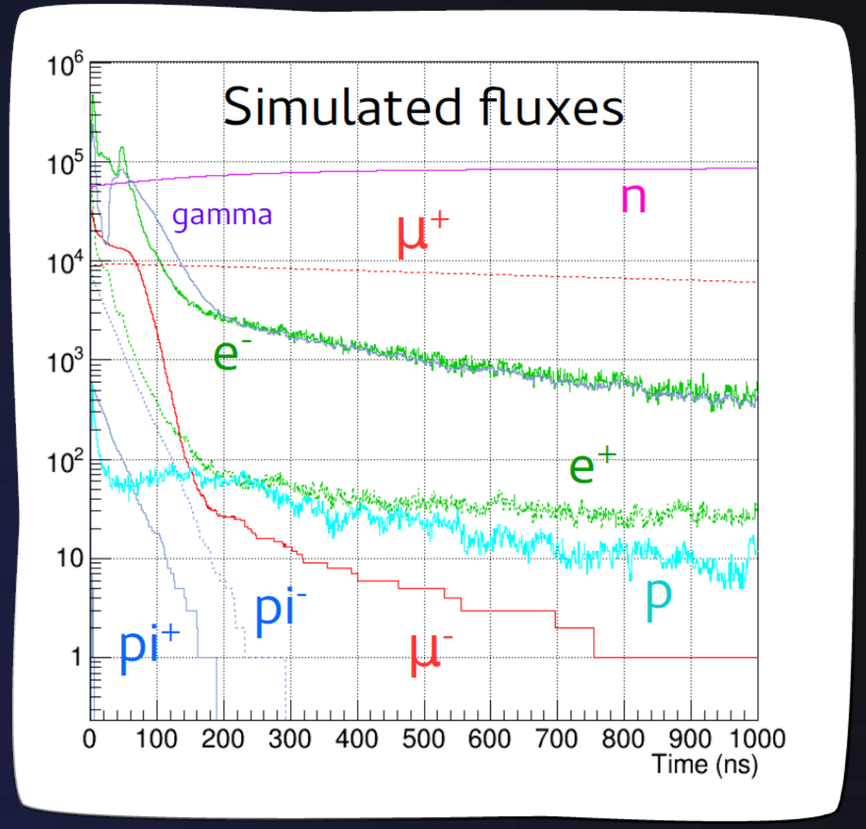


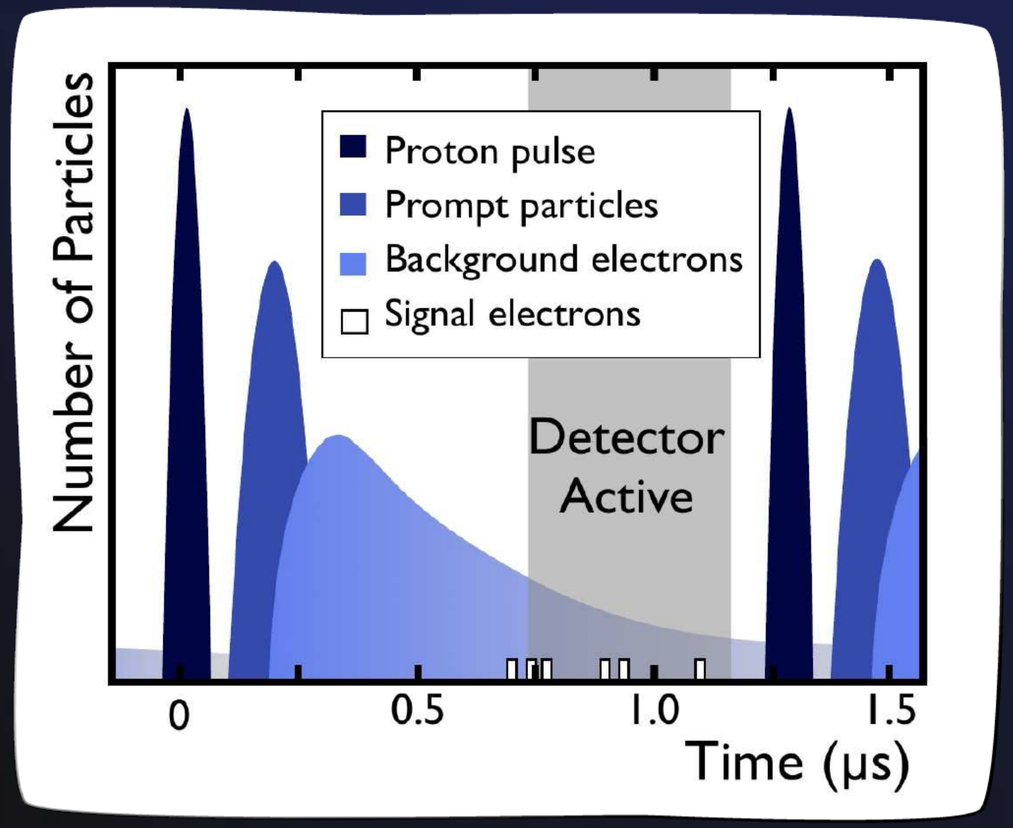
COMET Phase-II

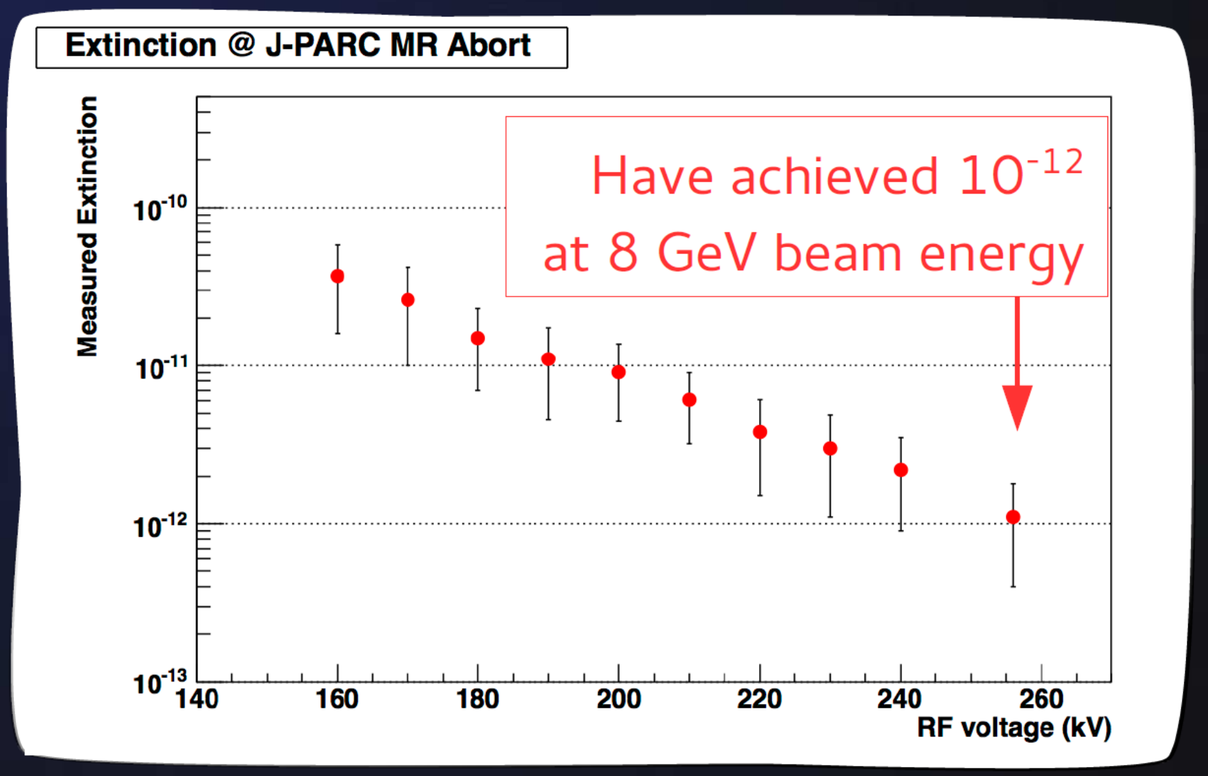
Proton Beam: Timing

- Pulsed beam removes beam-related backgrounds
- Need pulse timing > muon lifetime in aluminium
  - Muon lifetime on Aluminium: 864 ns
- As few protons between pulses as possible:
  - Extinction factor:

$$\text{Extinction} = \frac{\text{N(Protons between pulse)}}{\text{N(Protons in bunch)}}$$



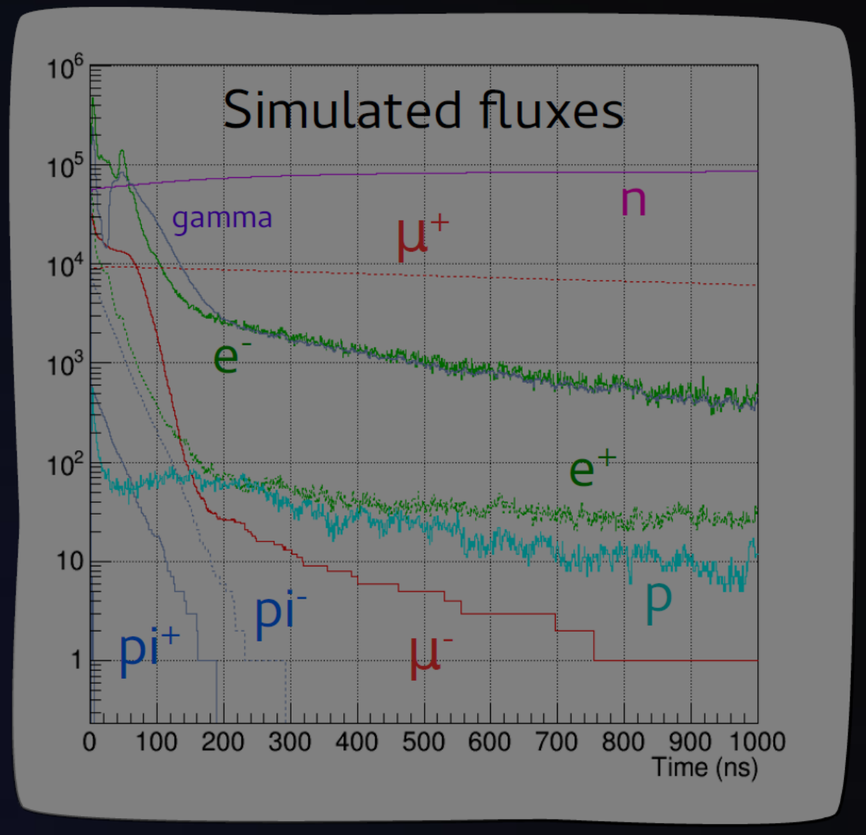


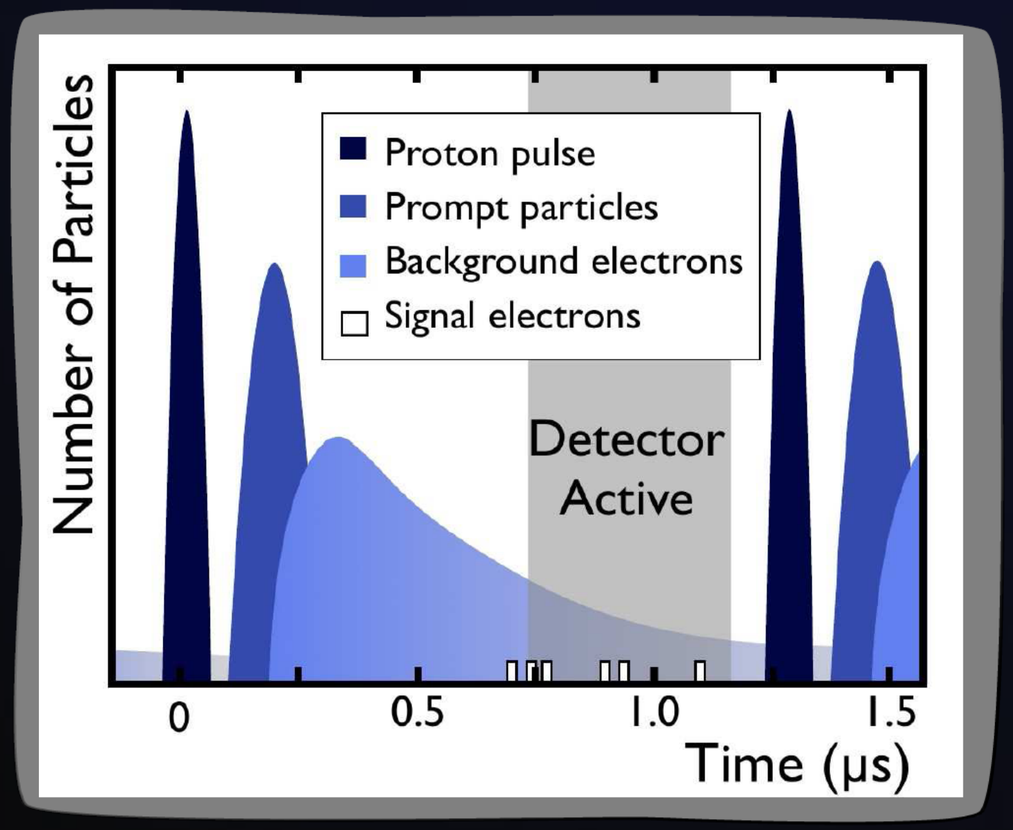


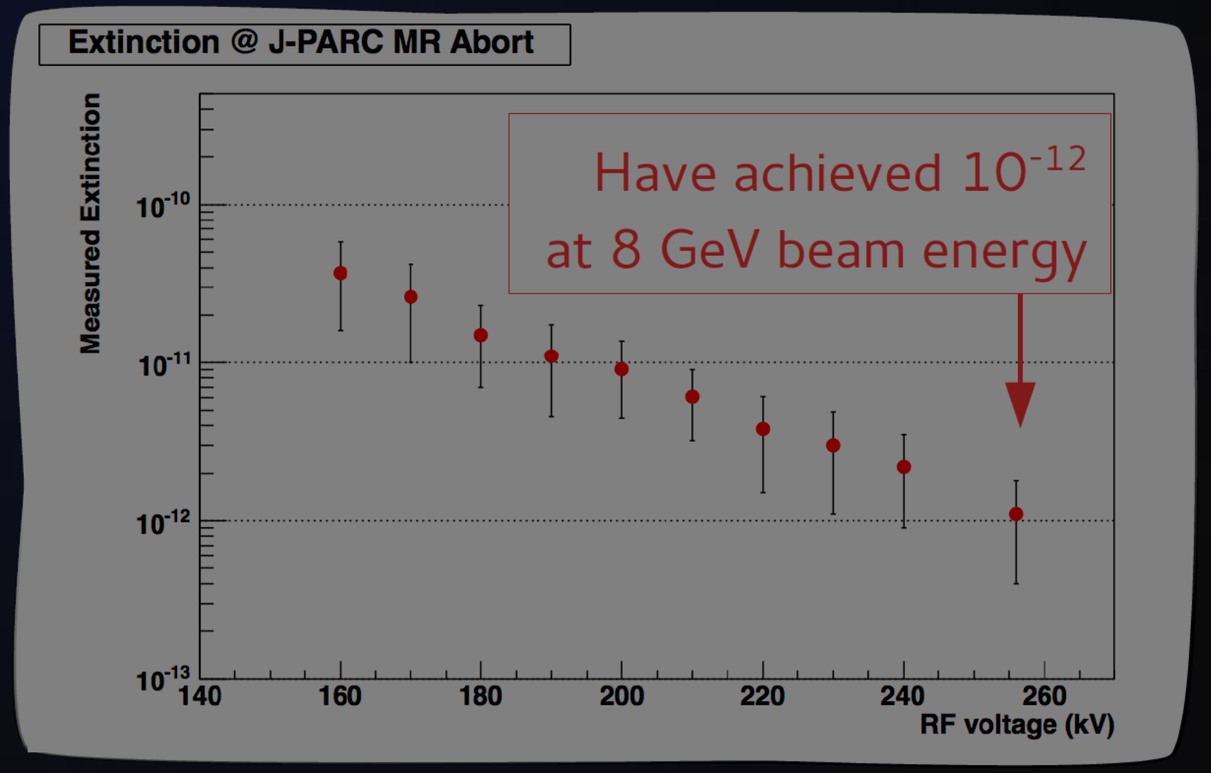
Proton Beam: Timing

- Pulsed beam removes beam-related backgrounds
- Need pulse timing > muon lifetime in aluminium
  - Muon lifetime on Aluminium: 864 ns
- As few protons between pulses as possible:
  - Extinction factor:

$$\text{Extinction} = \frac{\text{N(Protons between pulse)}}{\text{N(Protons in bunch)}}$$

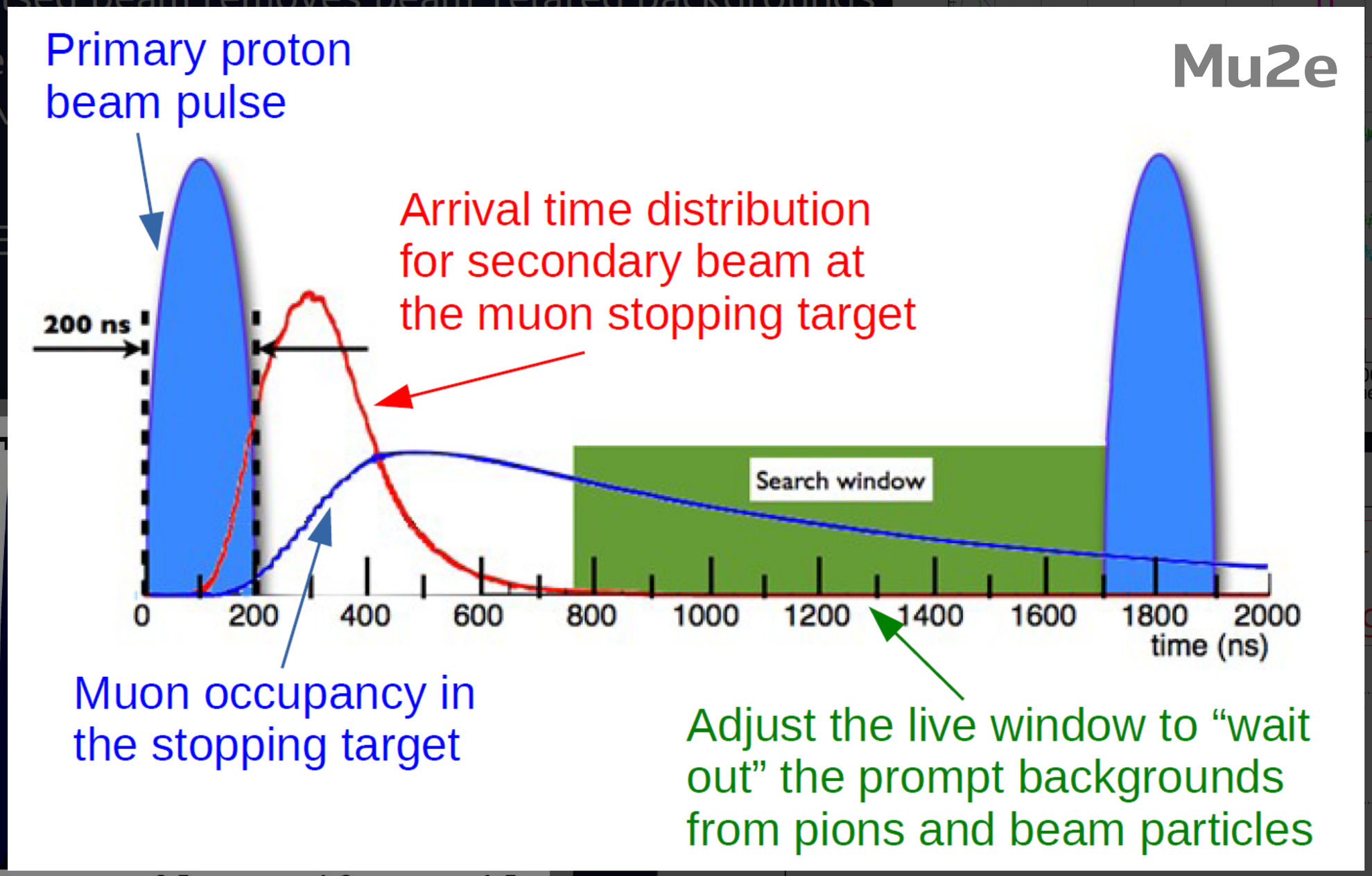






Proton Beam: Timing

- Pulsed beam removes beam-related backgrounds
- Ne
  - N
- As
  - E

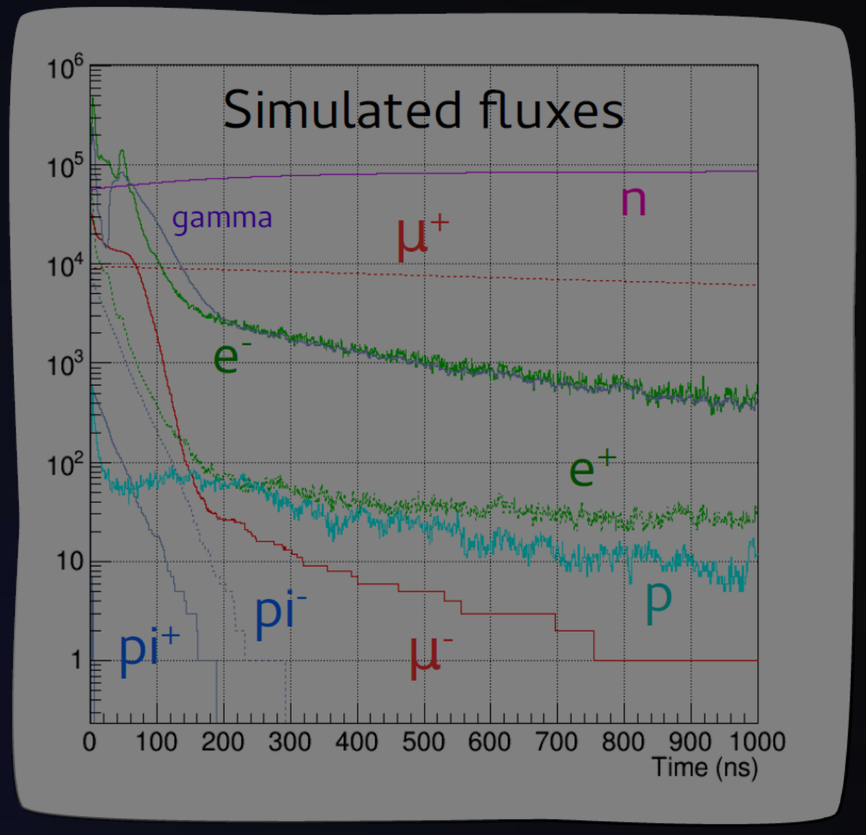


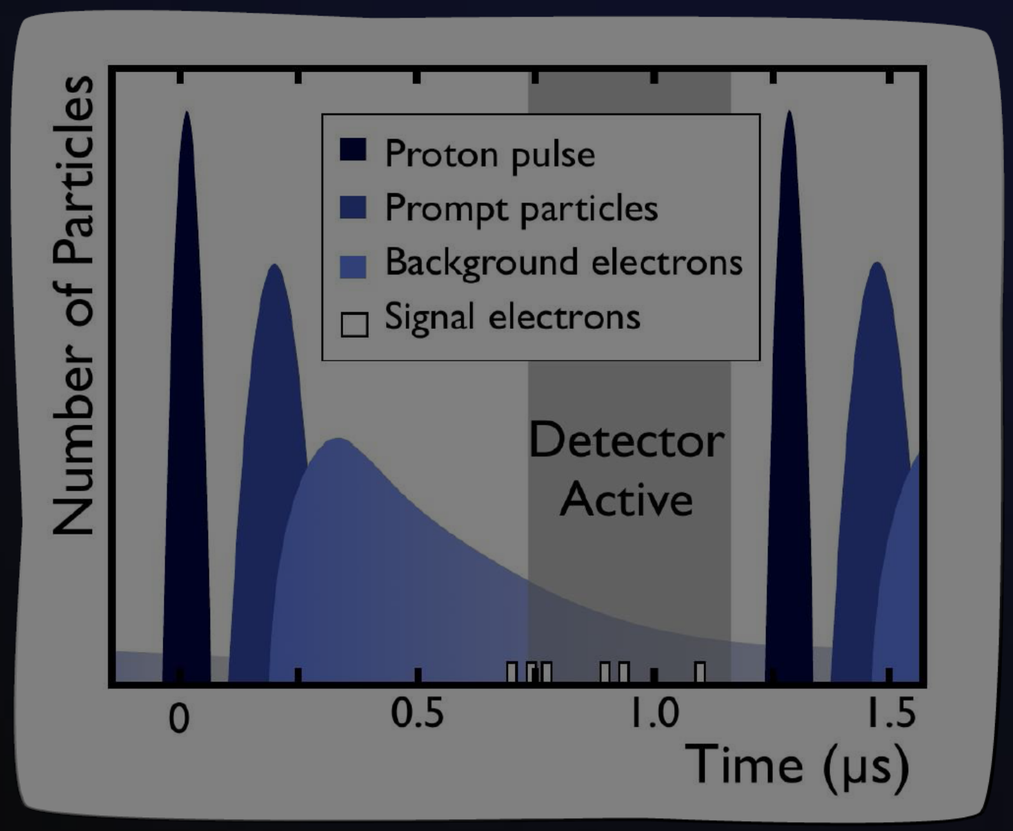
Vladimir Nagaslaev (Thursday) for Mu2e accelerator details

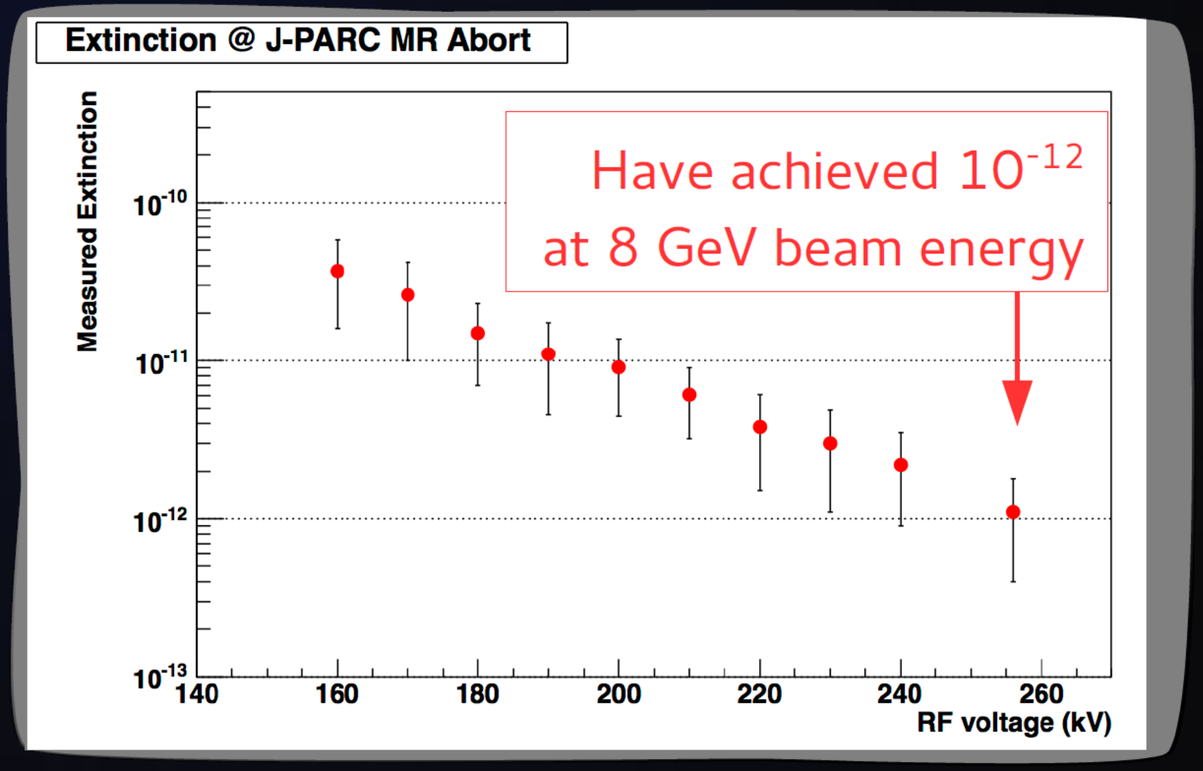
Proton Beam: Timing

- Pulsed beam removes beam-related backgrounds
- Need pulse timing > muon lifetime in aluminium
  - Muon lifetime on Aluminium: 864 ns
- As few protons between pulses as possible:
  - Extinction factor:

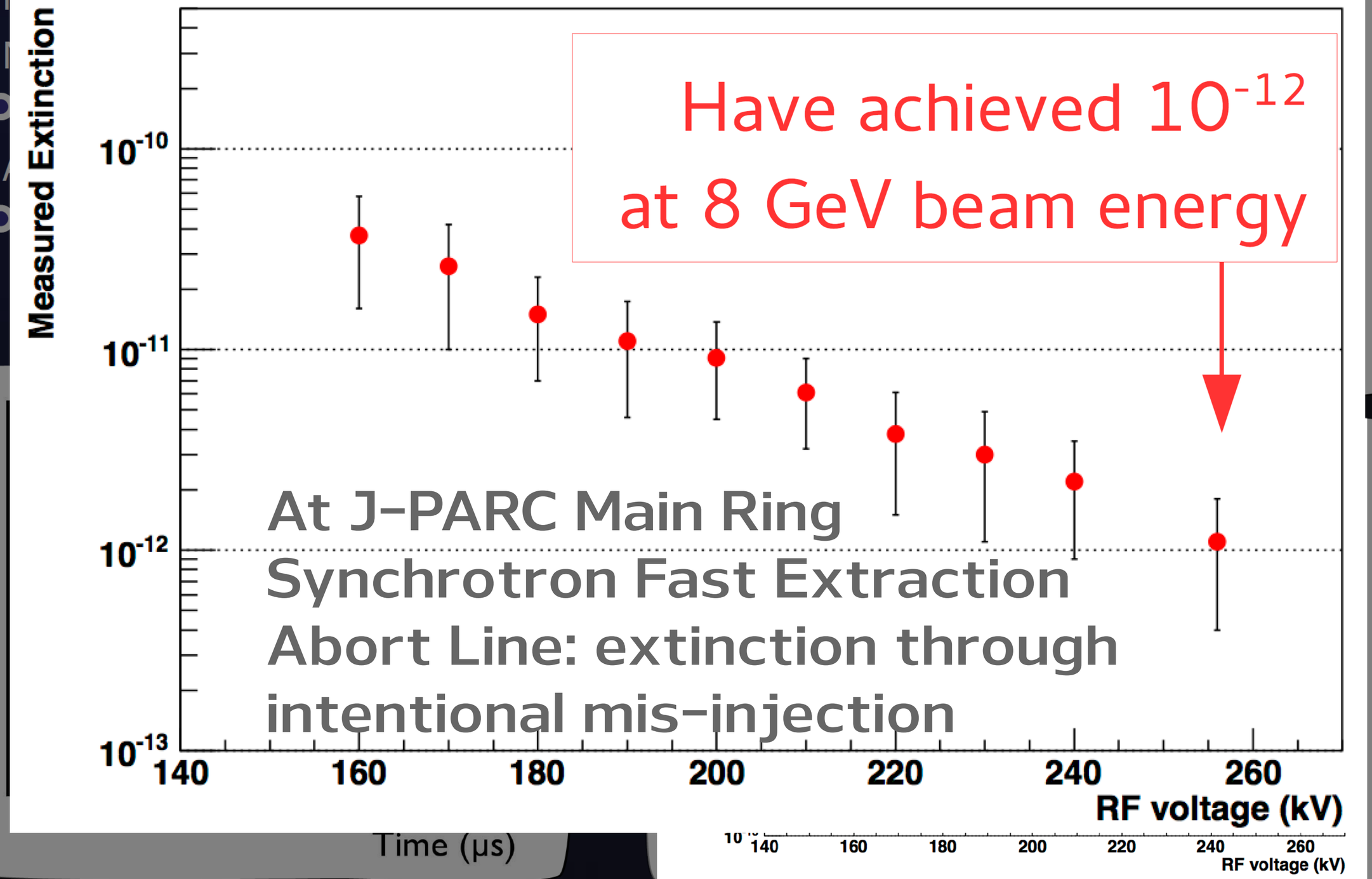
$$\text{Extinction} = \frac{\text{N(Protons between pulse)}}{\text{N(Protons in bunch)}}$$





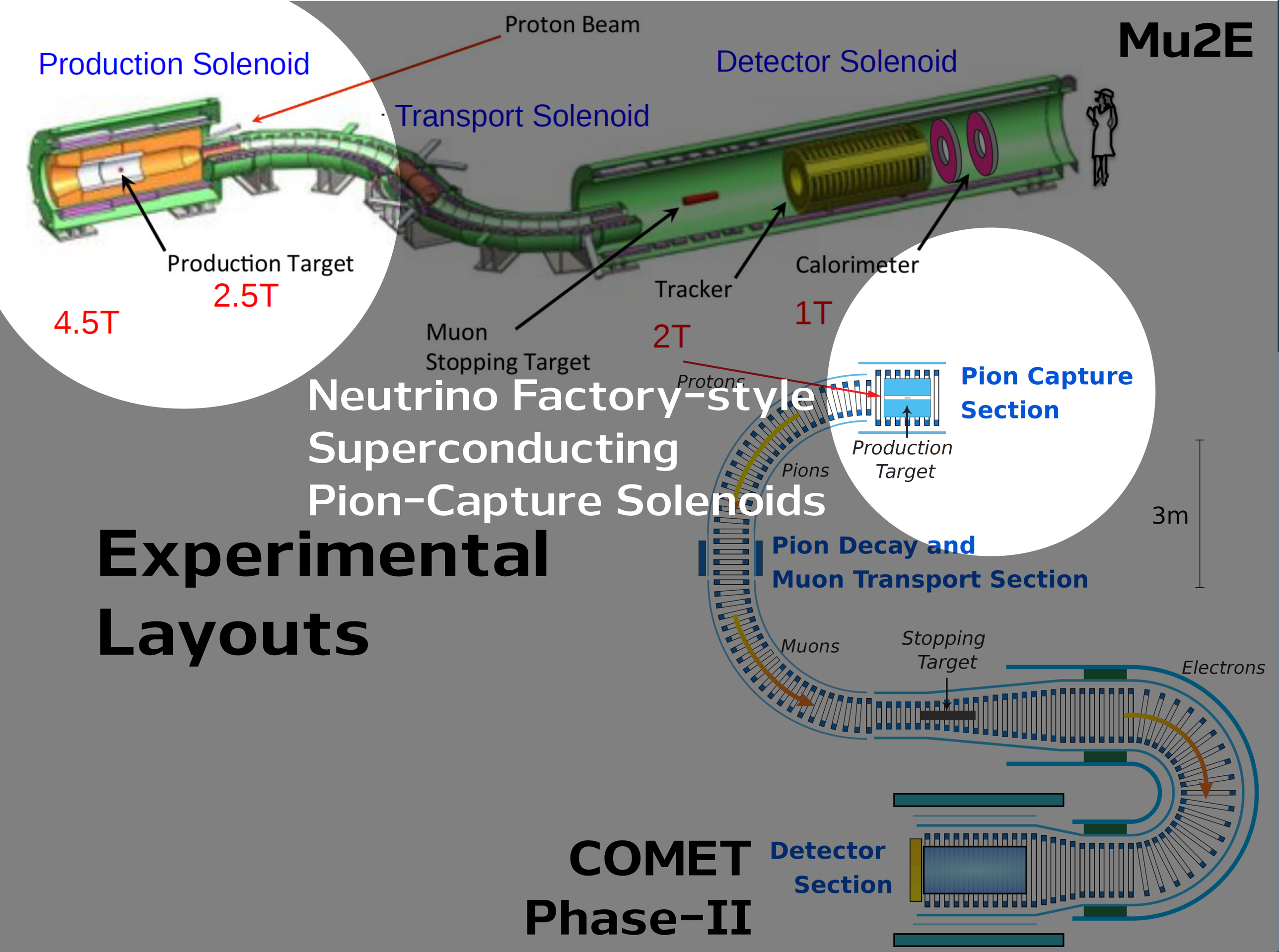


Proton Beam: Timing



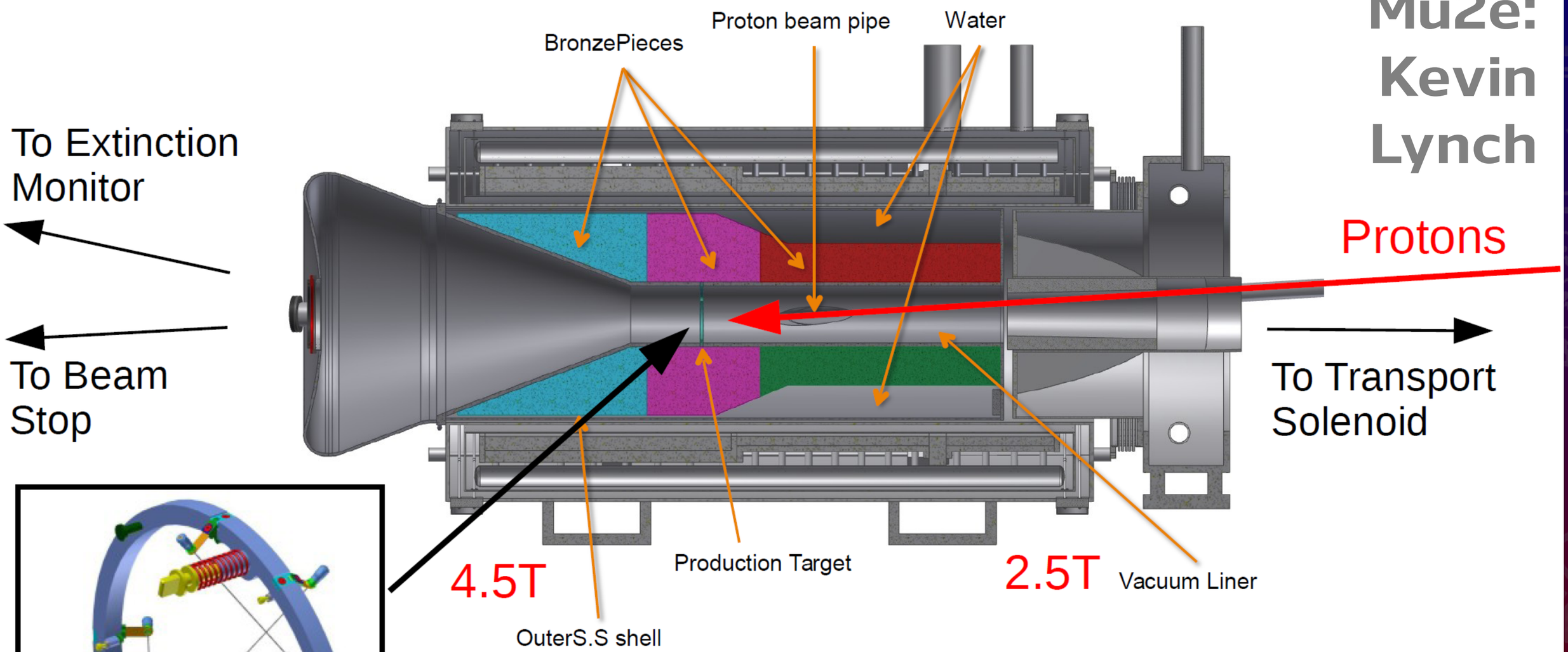
At J-PARC Main Ring Synchrotron Fast Extraction Abort Line: extinction through intentional mis-injection

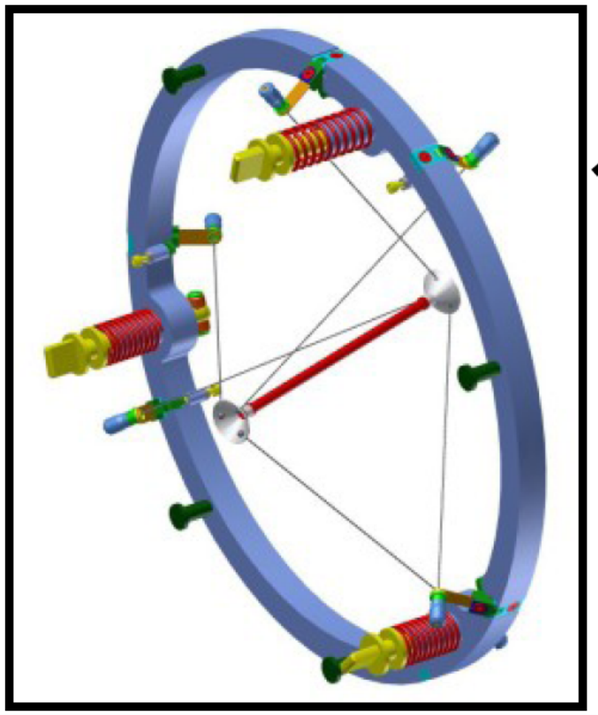
Experimental Layouts



The production solenoid produces a backward beam to reduce backgrounds

Mu2e: Kevin Lynch



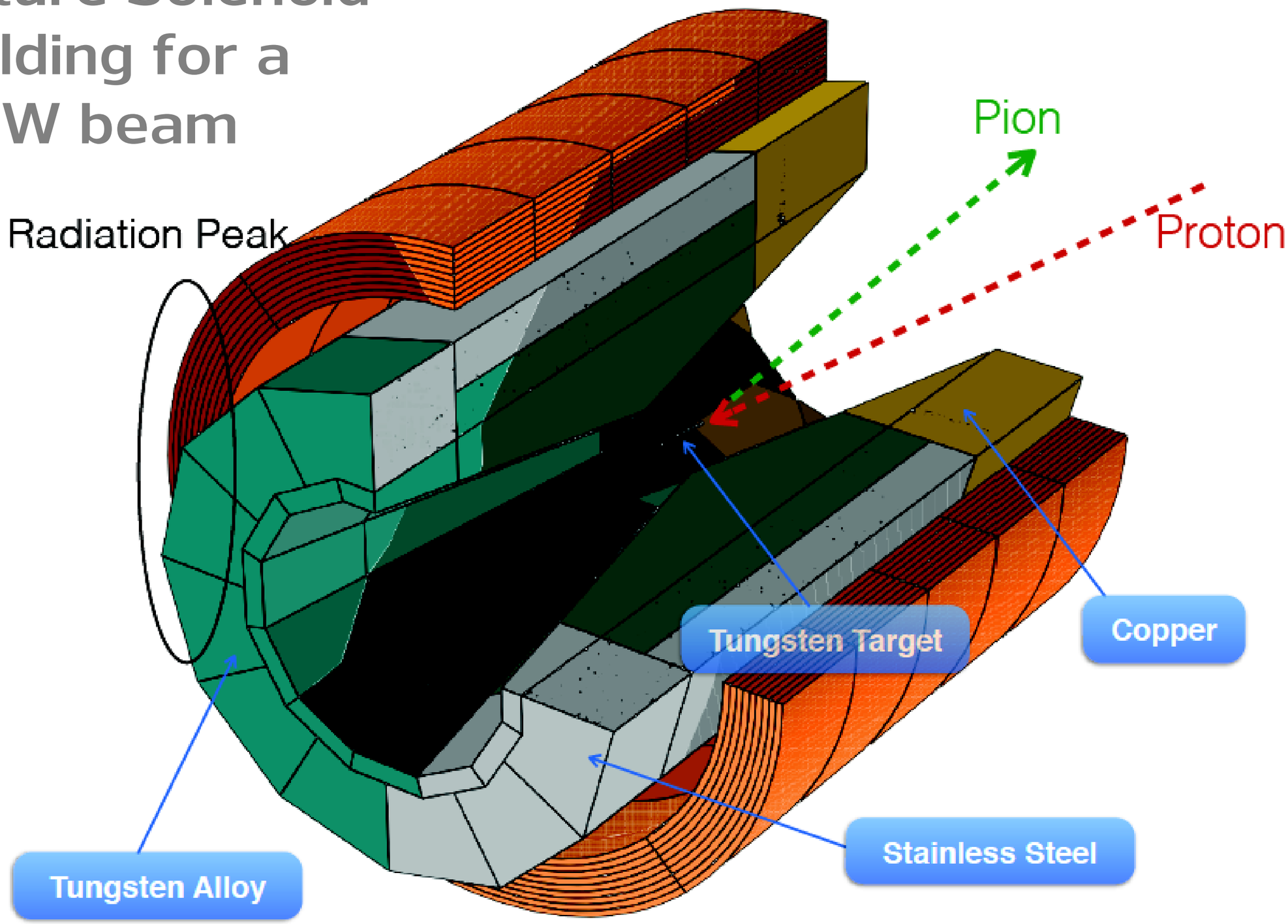


The tungsten production target is about the size of a pencil

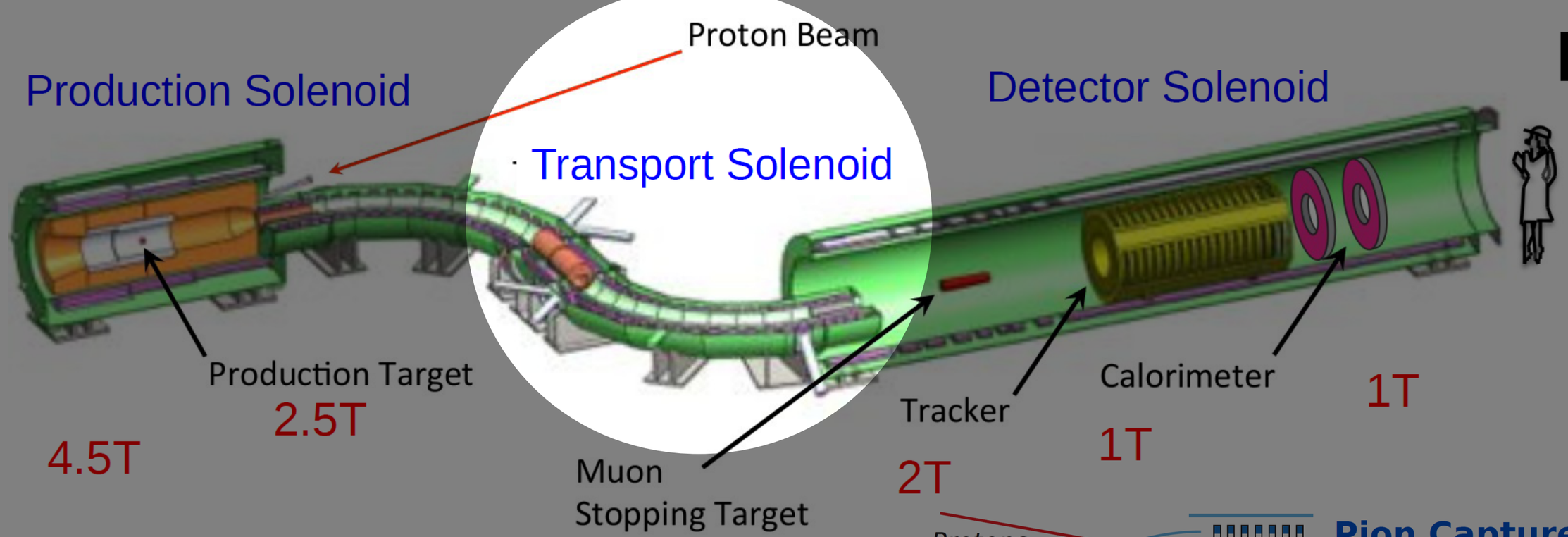
The graded field acts as a “mirror” for charged particles, increasing the flux of muons into the TS

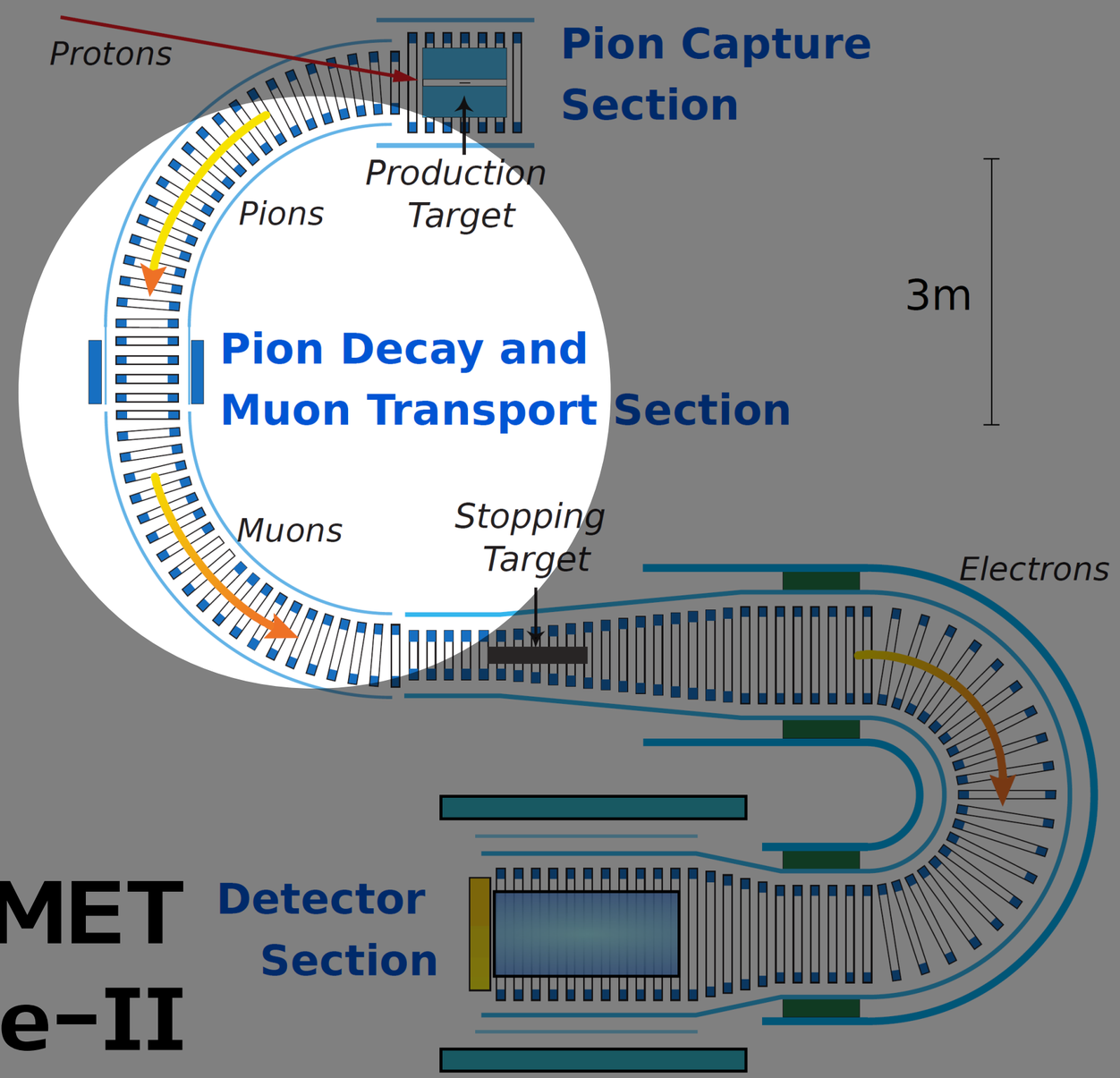
COMET Beam Line: Ye Yang (Thursday)

Capture Solenoid Shielding for a 56 kW beam



Experimental Layouts

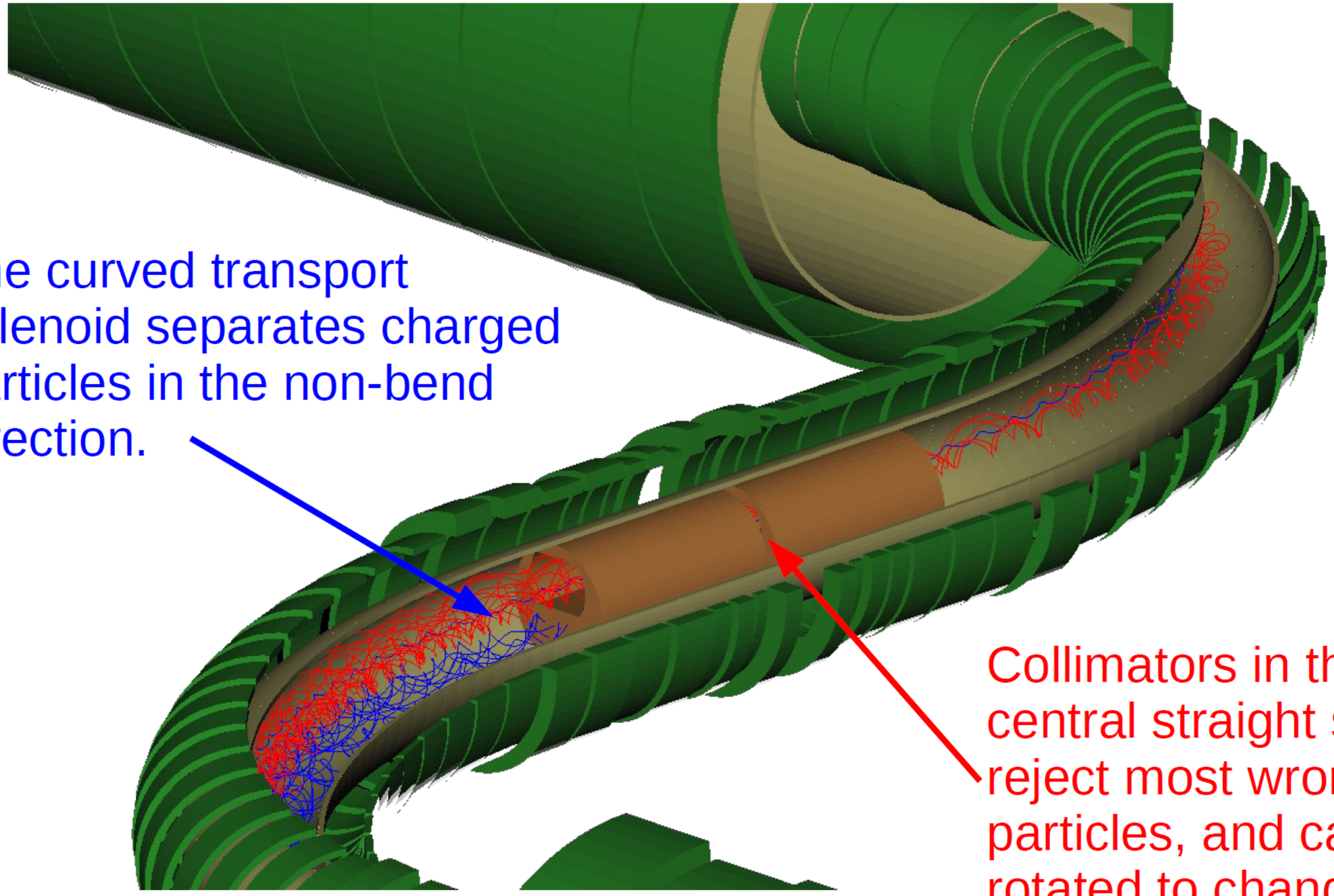




COMET Phase-II

The transport solenoid sign selects charged particles

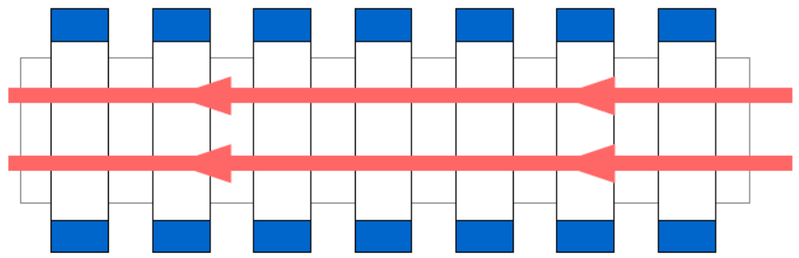
Mu2e: Kevin Lynch



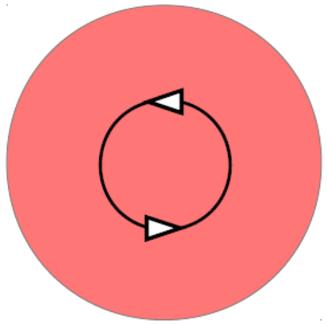
The curved transport solenoid separates charged particles in the non-bend direction.

Collimators in the central straight section reject most wrong sign particles, and can be rotated to change sign for calibration runs.

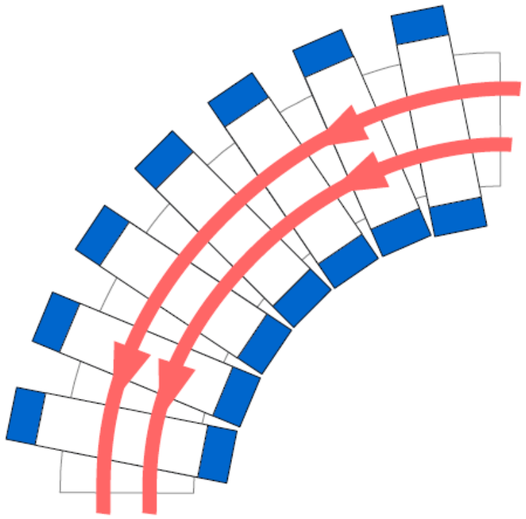
Muon Beam: Bent Solenoid Drifts



- Uniform B field
- Linear field lines



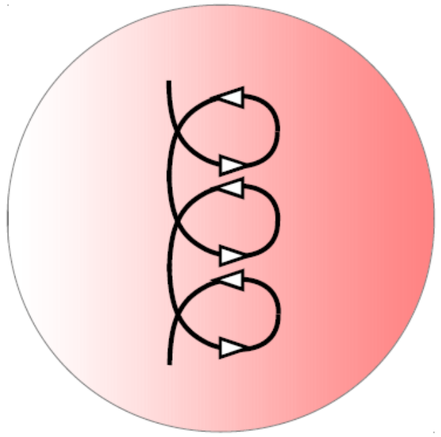
Circular motion about field lines



- Radial gradient in magnetic field
- Cylindrical field lines

$$D \propto \frac{1}{qB}\left(\frac{p_l^2 + \frac{1}{2}p_t^2}{p_l}\right)$$

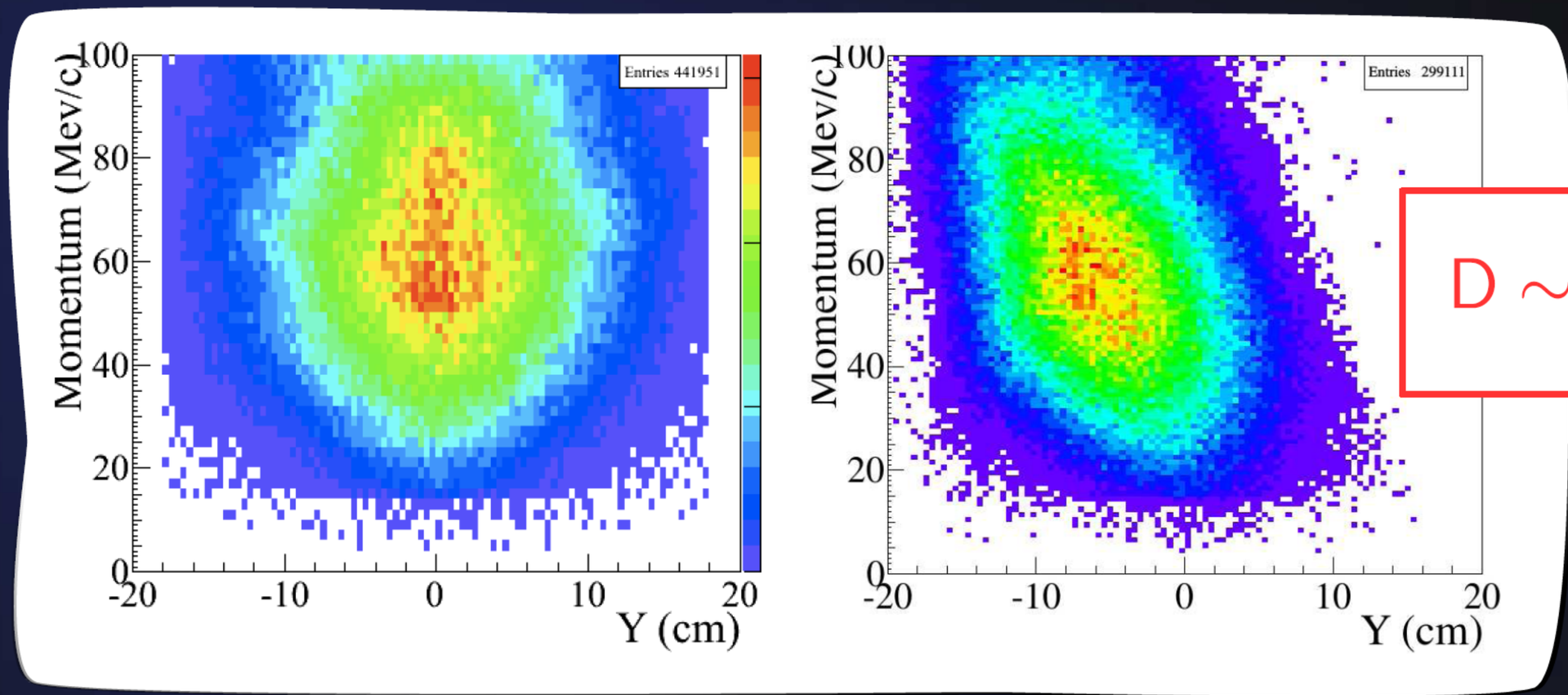
$$\propto \frac{1}{qB}\frac{p}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$



Circular motion about a drifting centre.

MUSIC Facility at Osaka

Muon Beam: Bent Solenoid Drifts



$$D \sim \frac{p}{q}$$

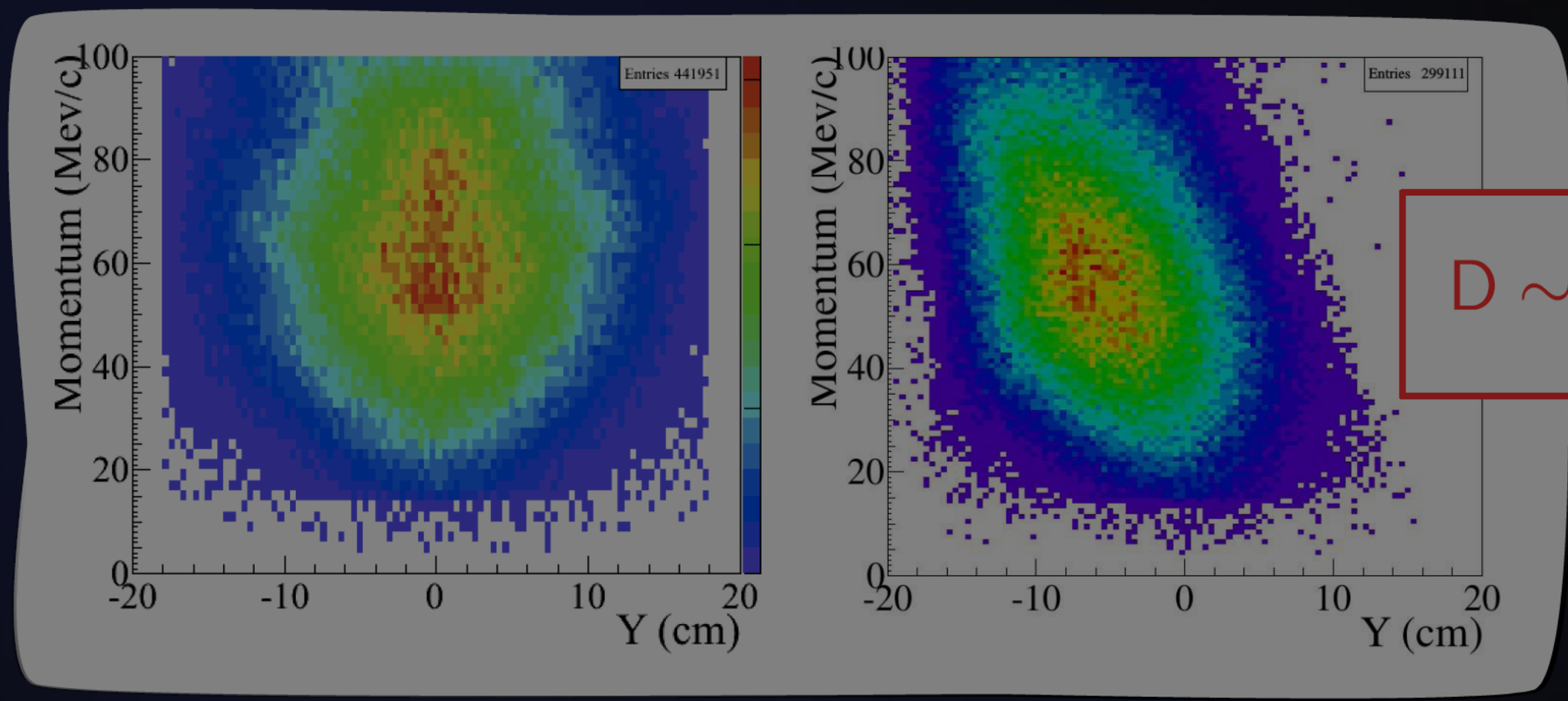
At entrance to bent solenoid

After 90° of bent solenoid

- Drift due to bent solenoid: position and momentum correlated
- Vertical dipole field applied
  - Tuned to maintain nominal momentum on axis
- Collimators select for charge and momentum

See talk by Yang Ye on Thursday

Muon Beam: Bent Solenoid Drifts



$$D \sim \frac{p}{q}$$

At entrance to bent solenoid

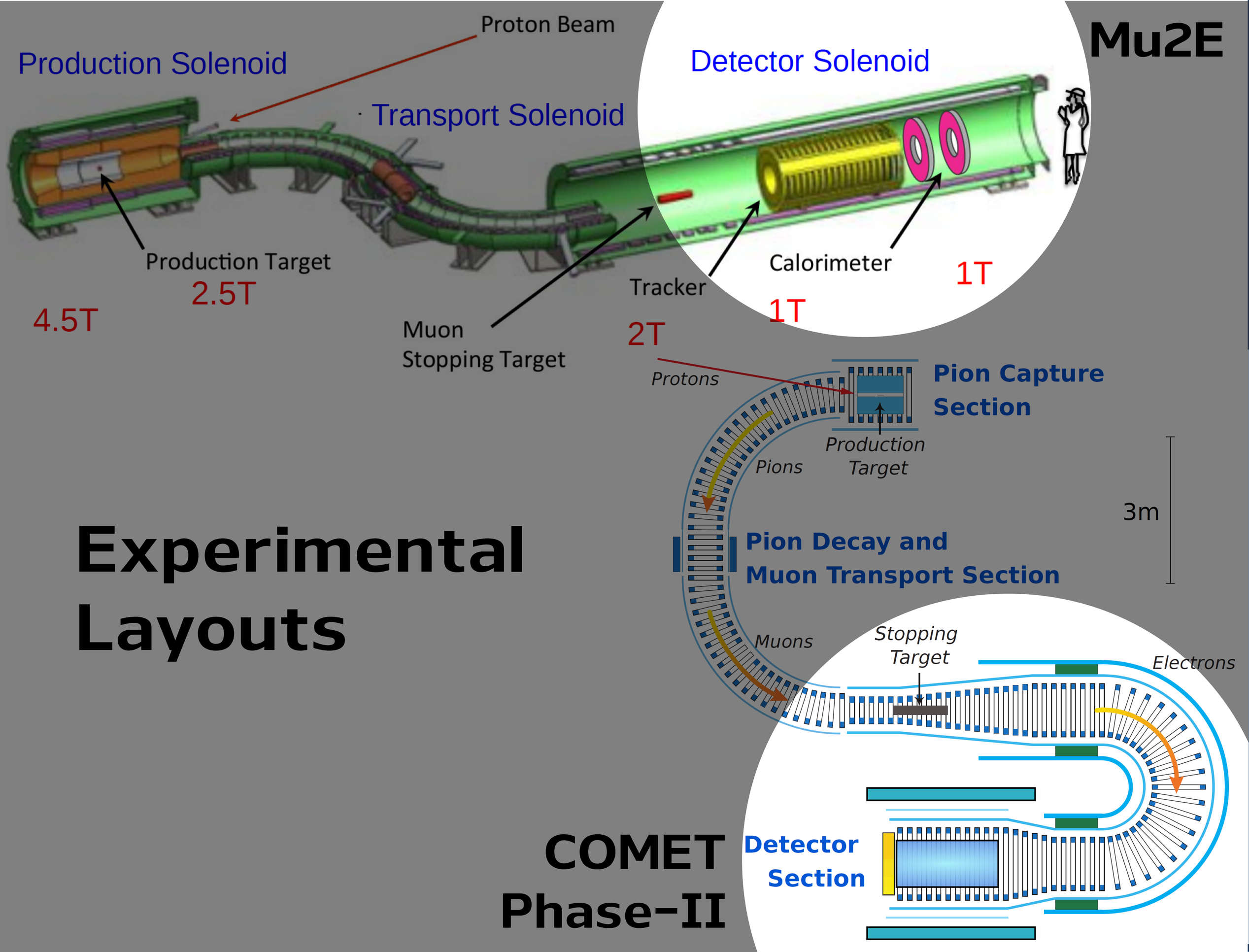
After 90° of bent solenoid

- Drift due to bent solenoid: position and momentum correlated
- Vertical dipole field applied
  - Tuned to maintain nominal momentum on axis
- Collimators select for charge and momentum

Different design choice to Mu2e

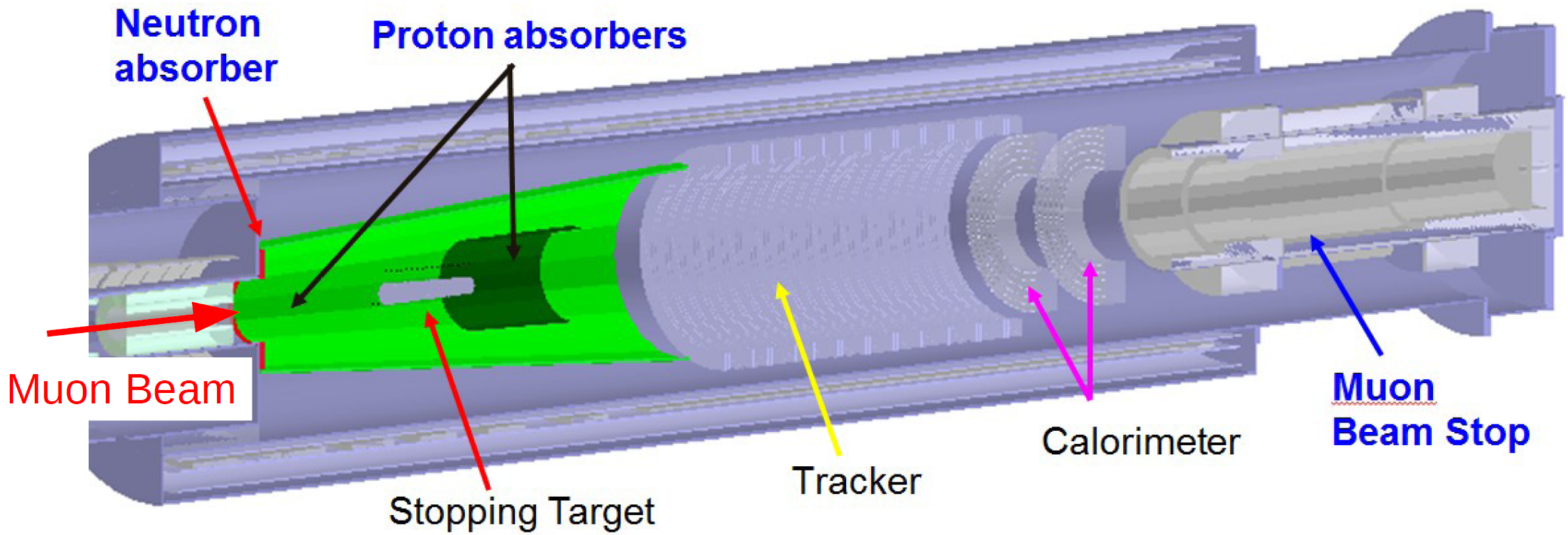
See talk by Yang Ye on Thursday

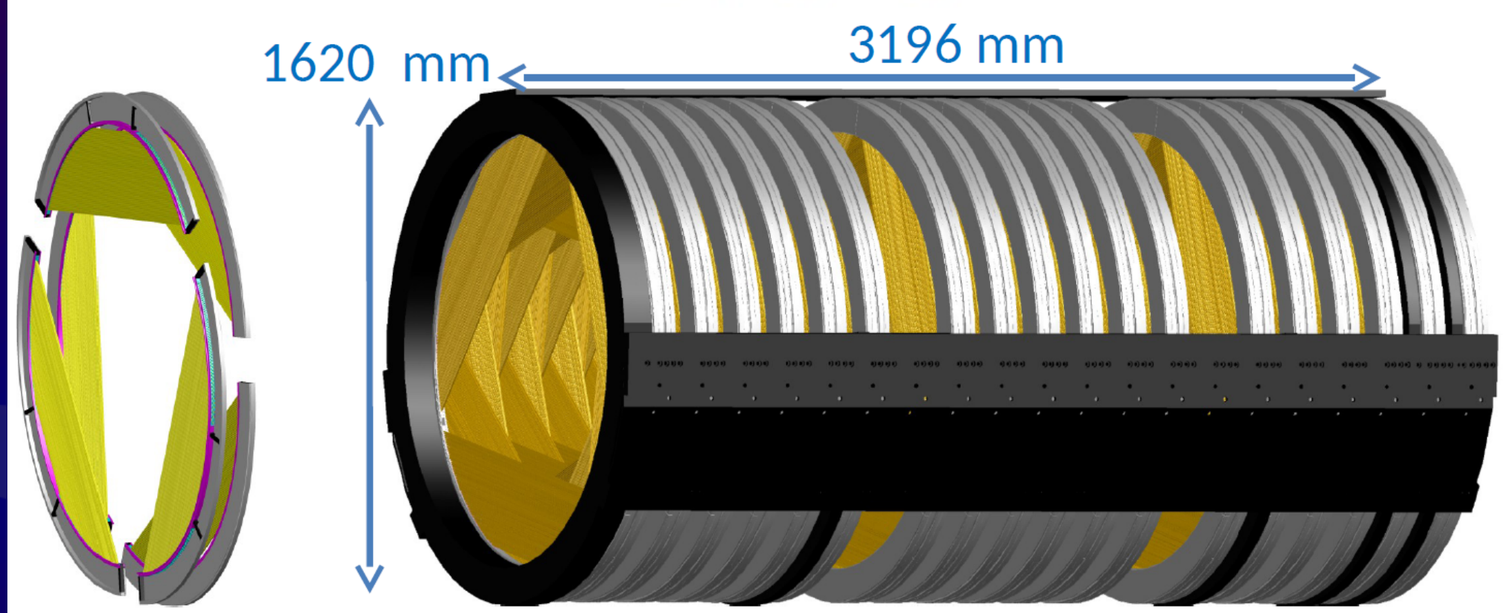
Experimental Layouts



COMET Phase-II

The detector solenoid forms the heart of the experiment

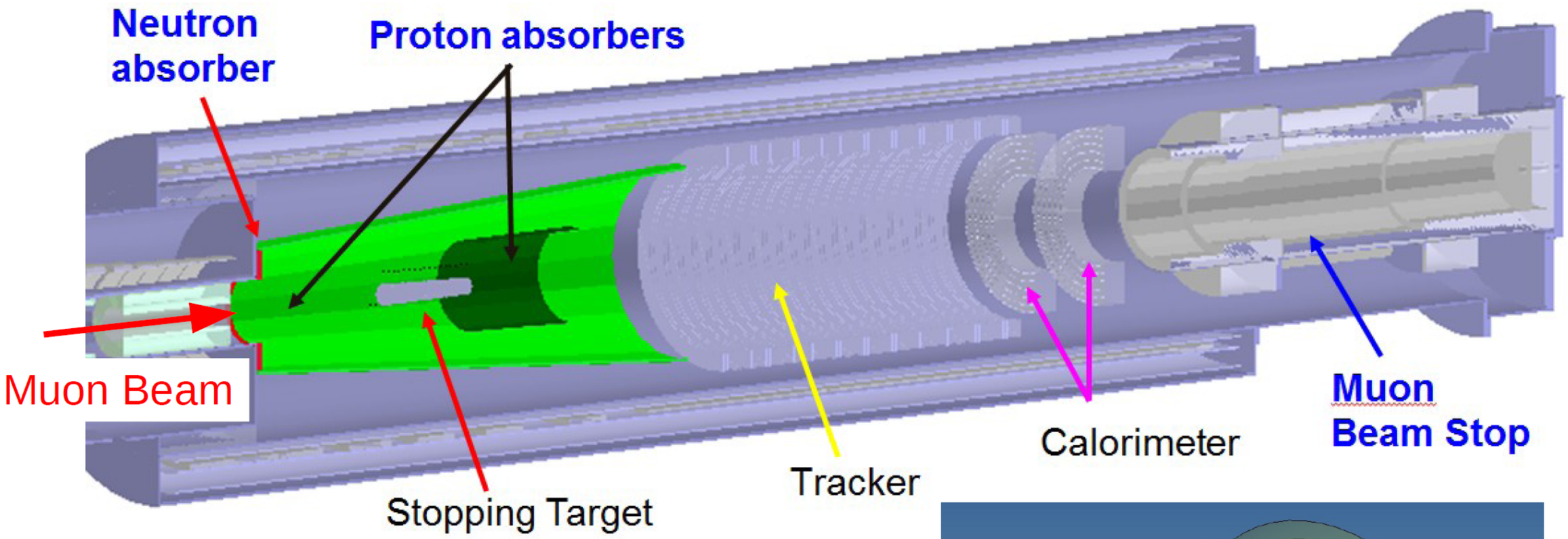




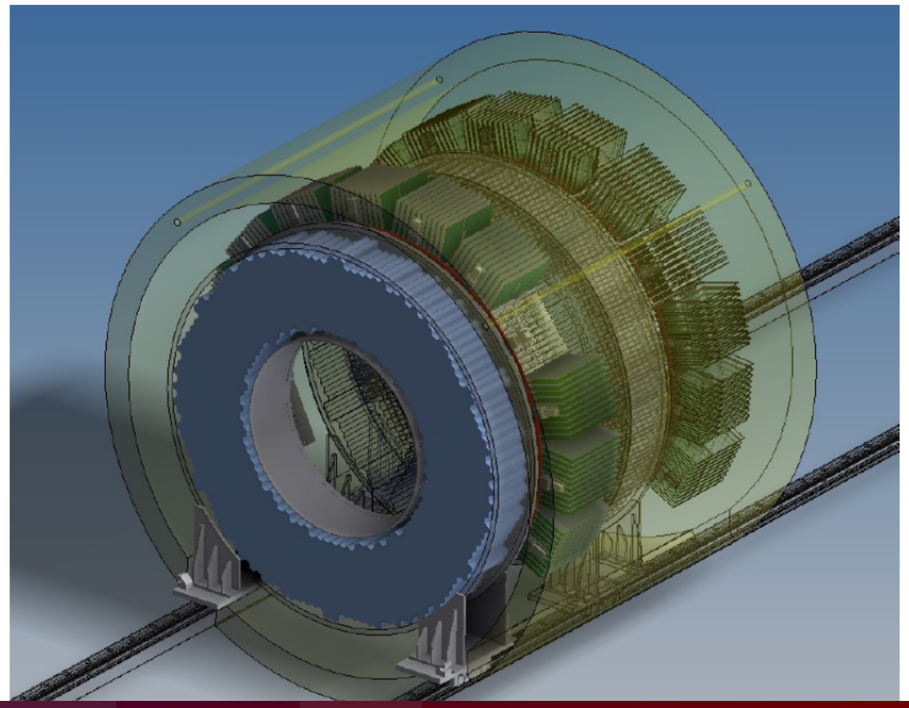
The electron tracker is a low mass straw tube design with 18 planes of tubes transverse to the secondary beam

Mu2e: Kevin Lynch

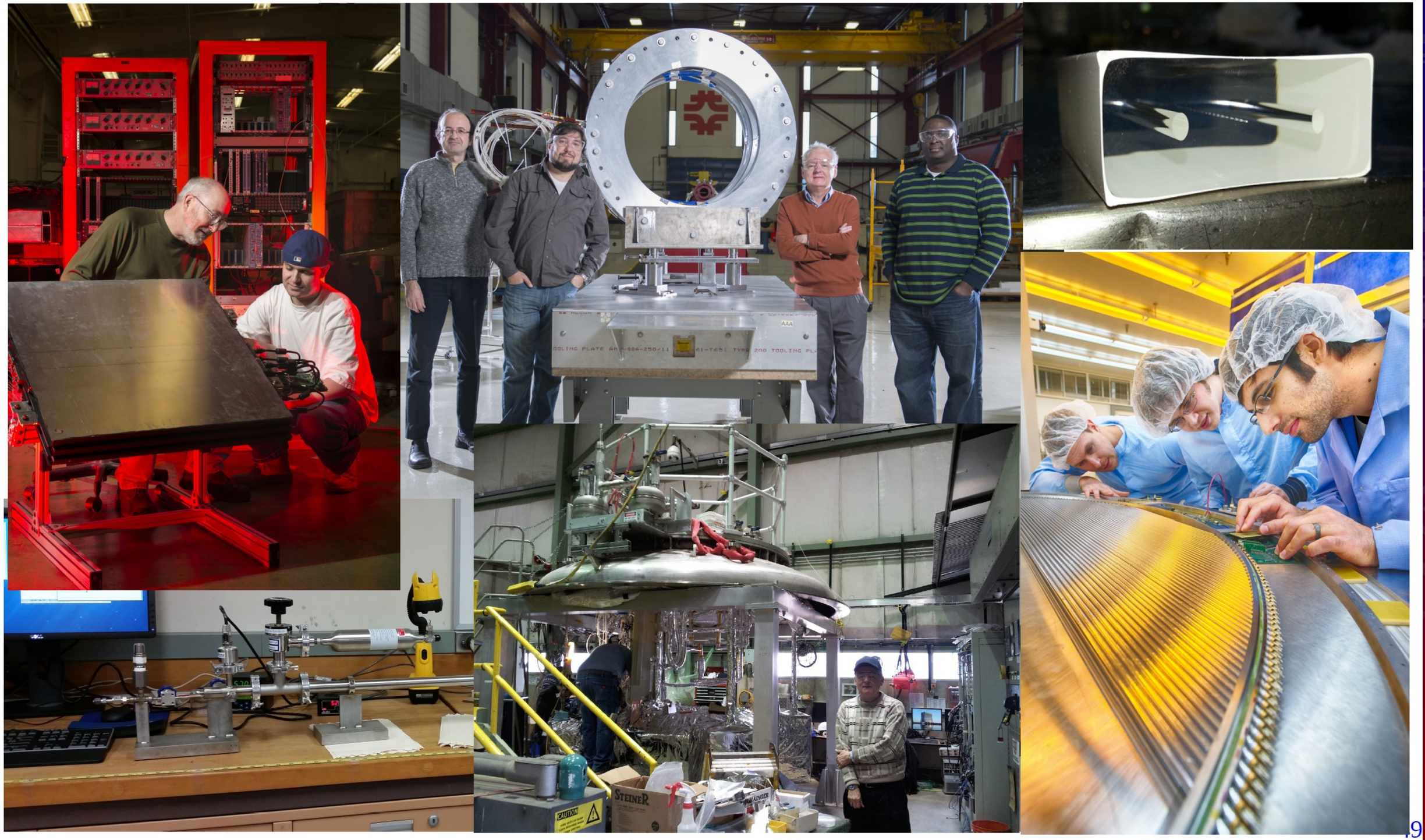
The detector solenoid forms the heart of the experiment



The calorimeter is a two layer, annular crystal calorimeter



We are making significant progress on R&D and prototypes in preparation for CD3c review in 2016

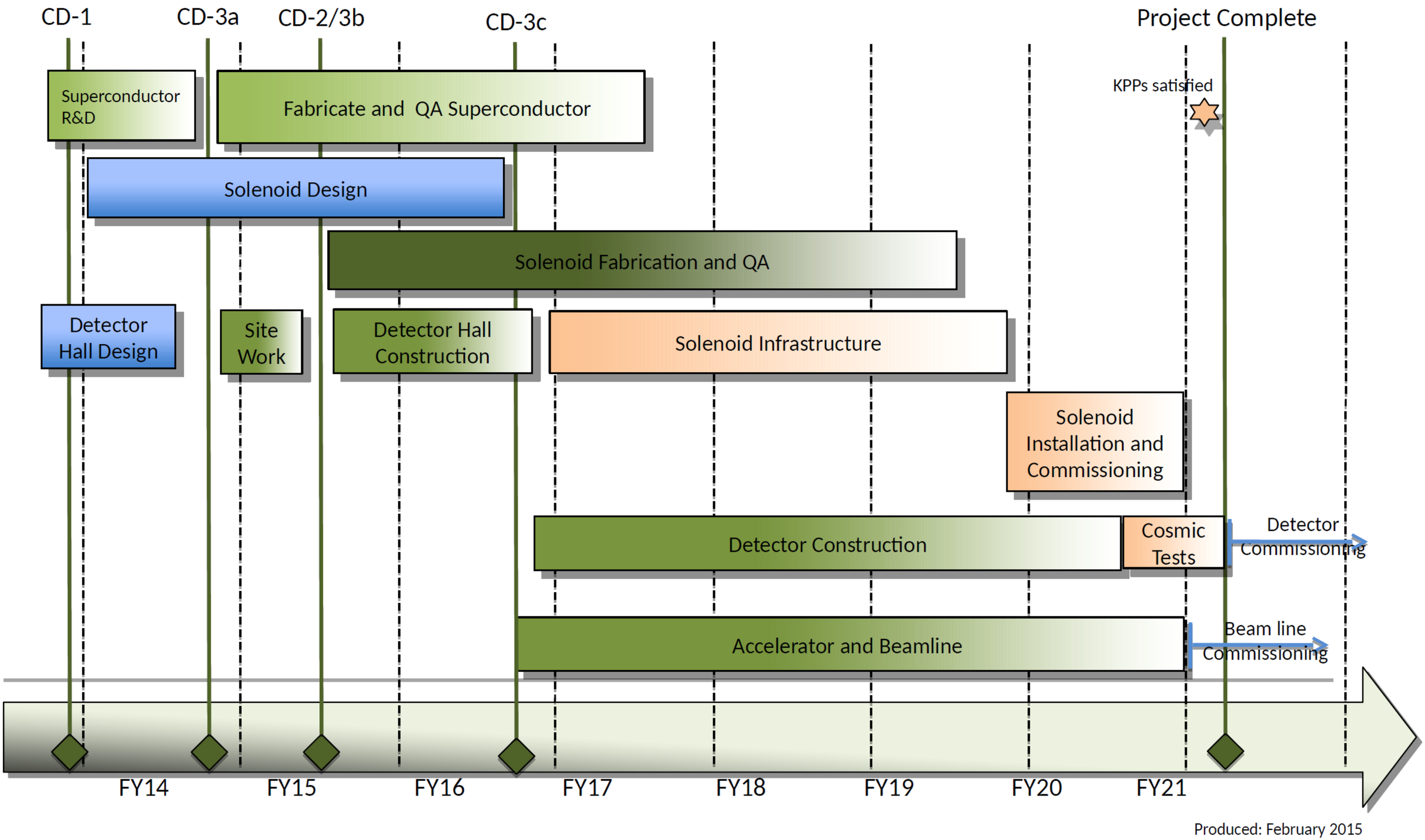


Mu2e

Groundbreaking
April 18, 2015,

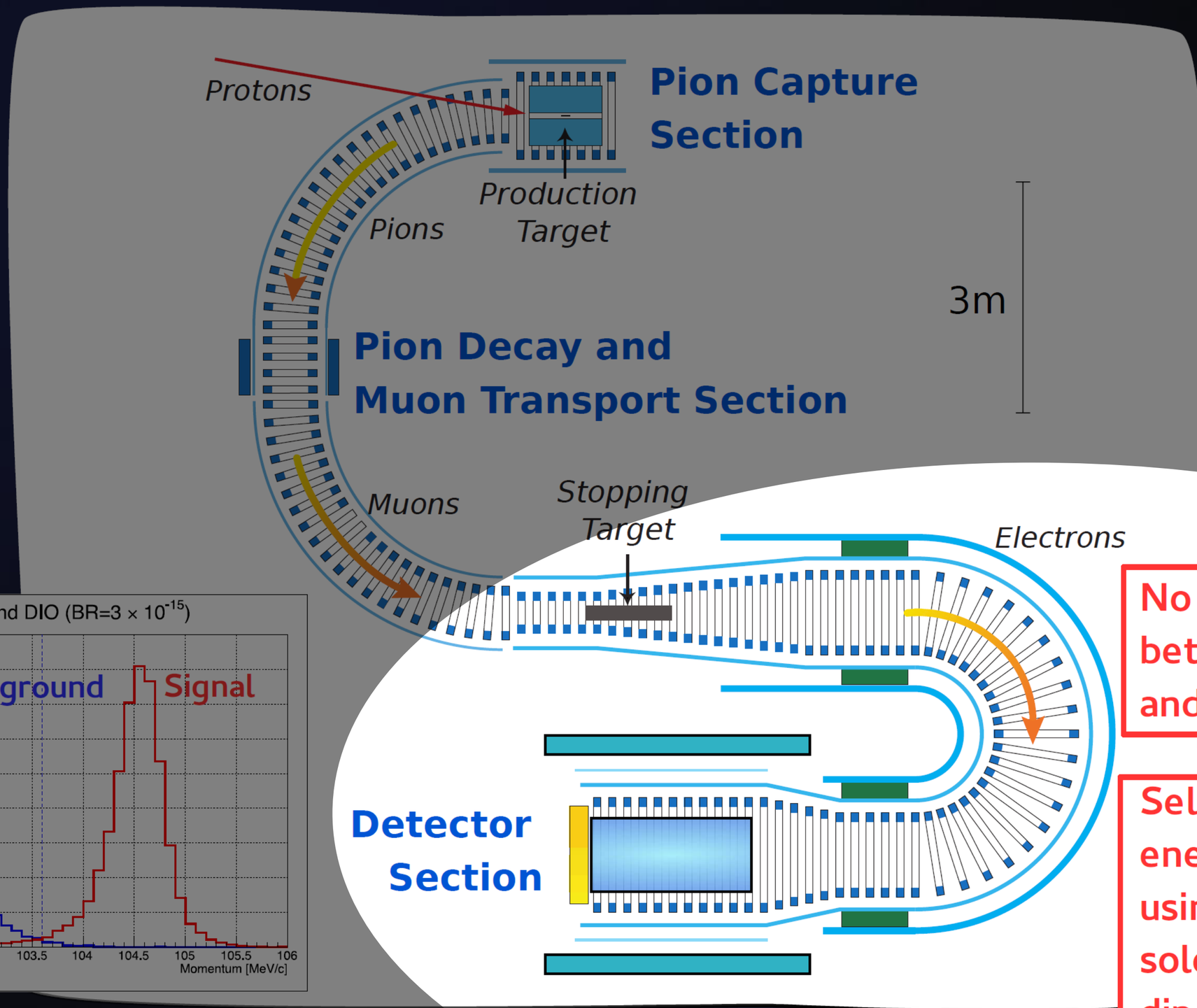
Final floor pour
on July 28, 2015

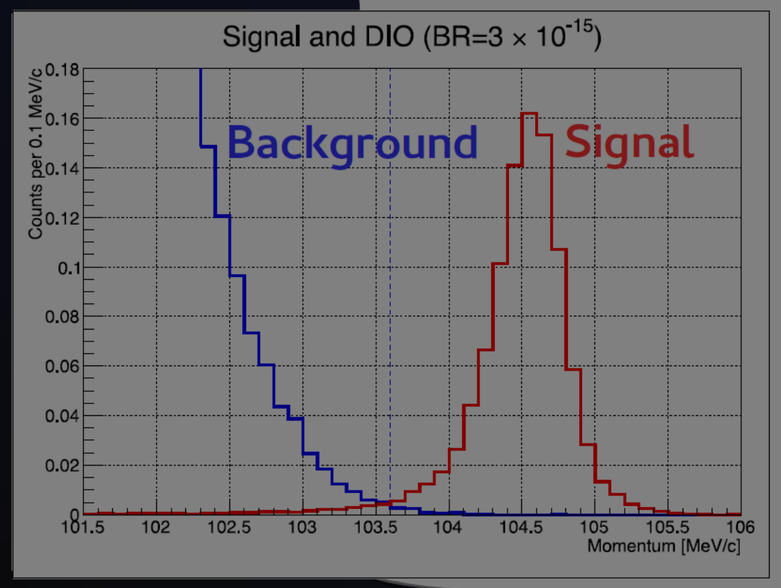
Mu2e has a technically limited schedule that will lead to data very early in the 2020s



COMET: Phase-II

COMET: Ben Krikler

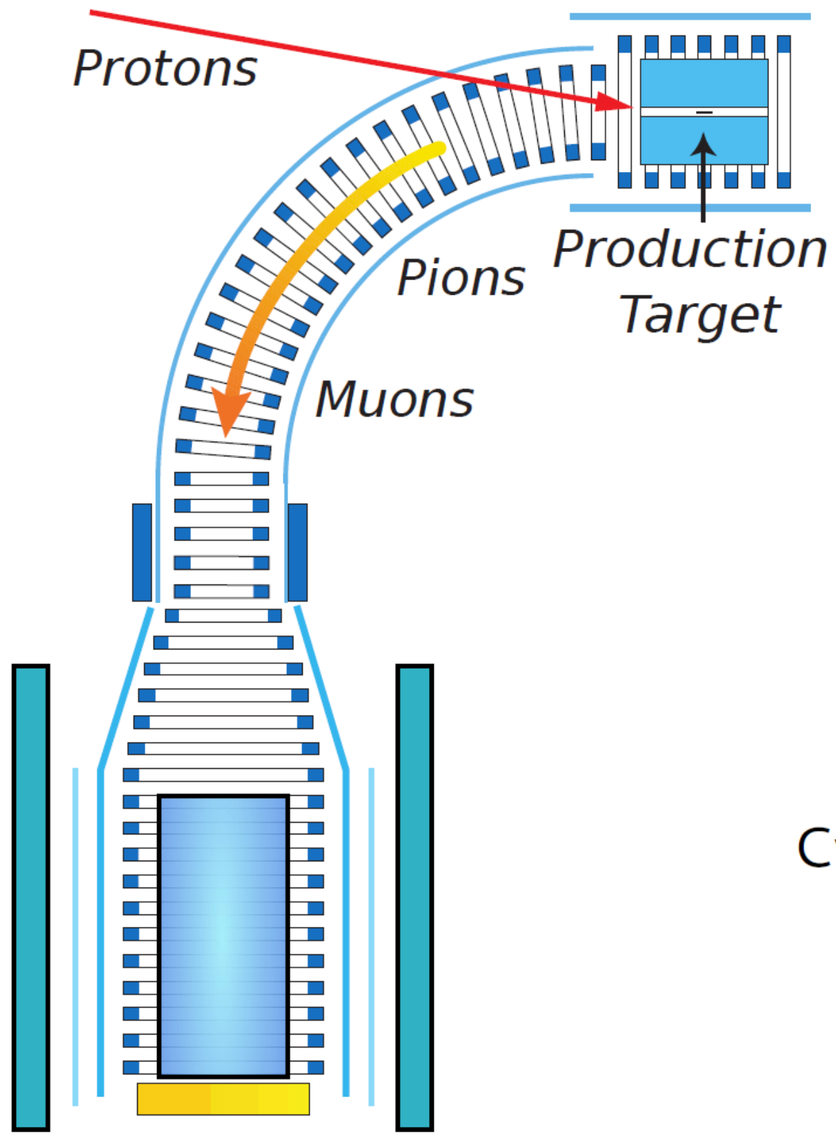




No line of sight between target and detector

Select for high energy electrons using bent solenoid and dipole field

COMET: Phase–I



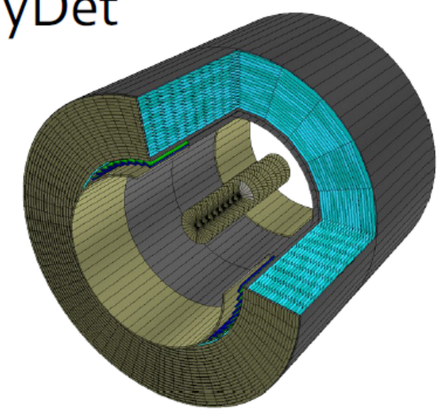
Pion Capture Section

Detector Section

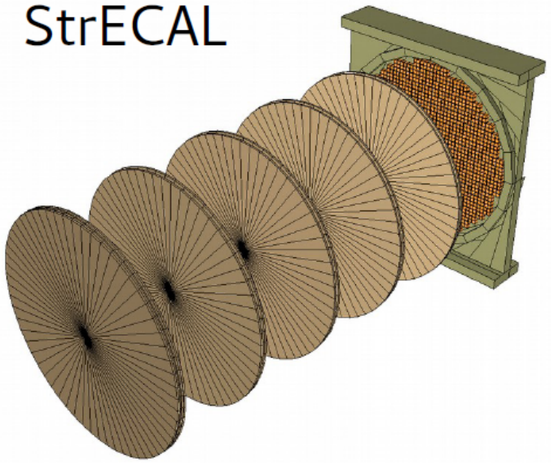
Goals of Phase–I

- Understand production system
- Understand bent solenoid dynamics
- Prototype the detector
- μ-e conversion search at: 3×10^{-15}

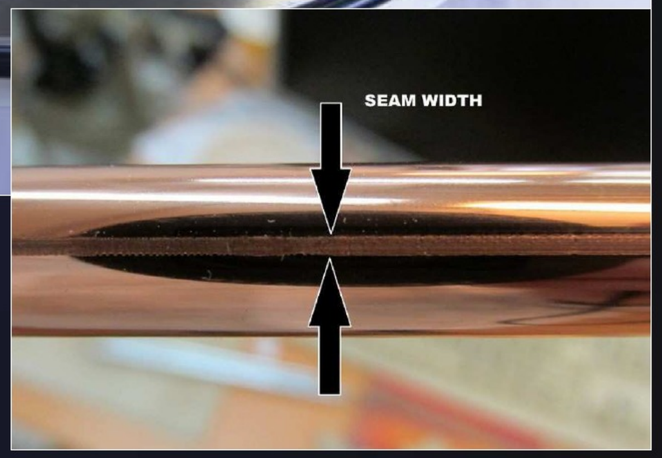
CyDet



StrECAL

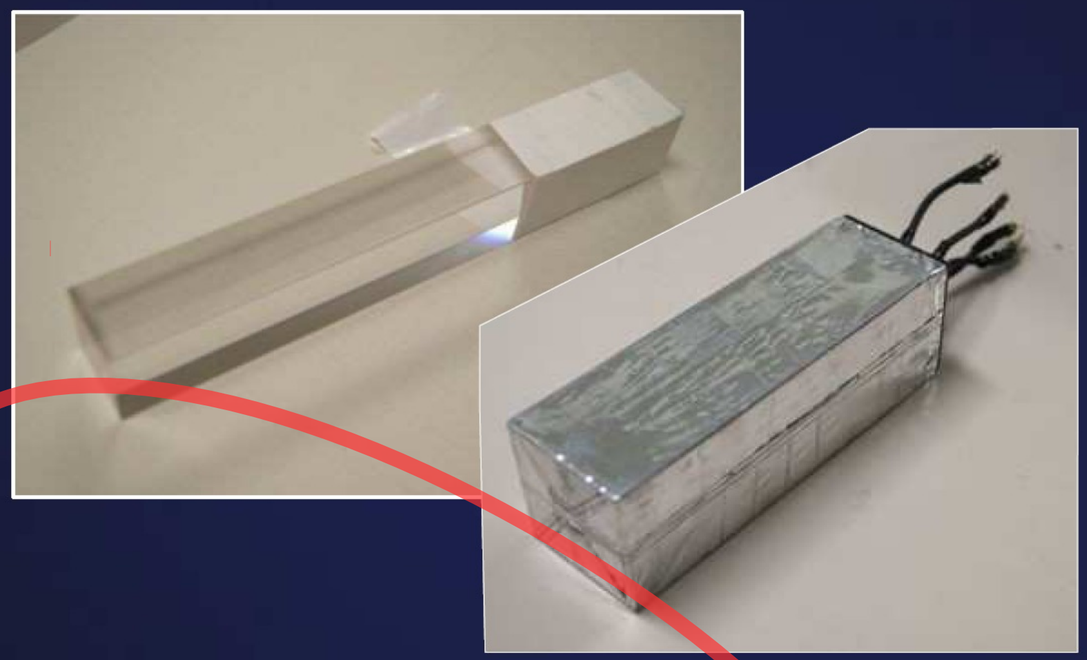


Straw Tracker

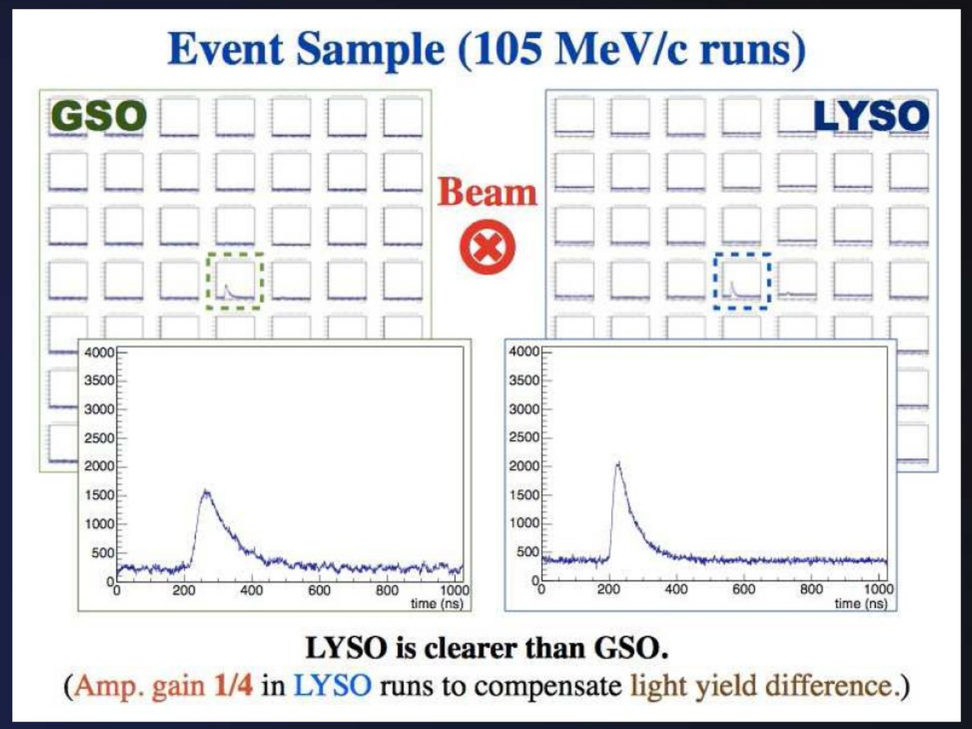


- Phase-I Straw Design
  - Based on NA62 Straws with single seam weld
  - 20 micron aluminised mylar
  - 9.8 mm diameter tubes
- Phase-II possibilities:
  - 5 mm diameter
  - 12 micron Al-mylar
- Status
  - Phase-I production finished (2500 straws)
  - Aging tests, resolution studies underway

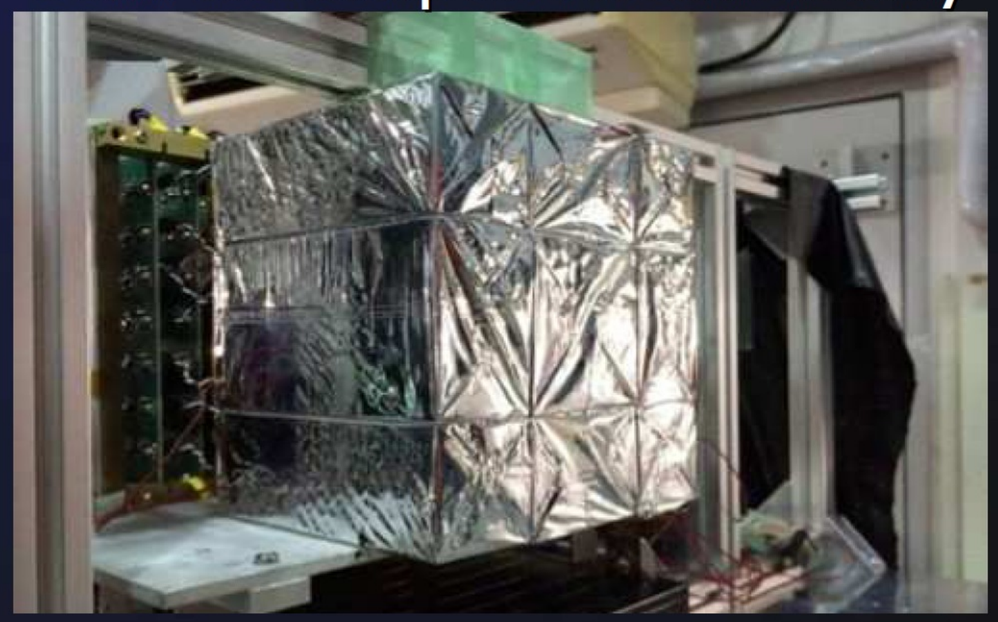
ECAL *StrECAL Trigger and Energy Measurement for PID*



- 2272 LYSO Crystals
  - Dimensions: 2x2x12 cm
- Status:
  - Crystal purchasing on-going
  - Test bench being built
  - Beam tests for resolution studies, PID and DAQ underway
  - Calibration system being designed

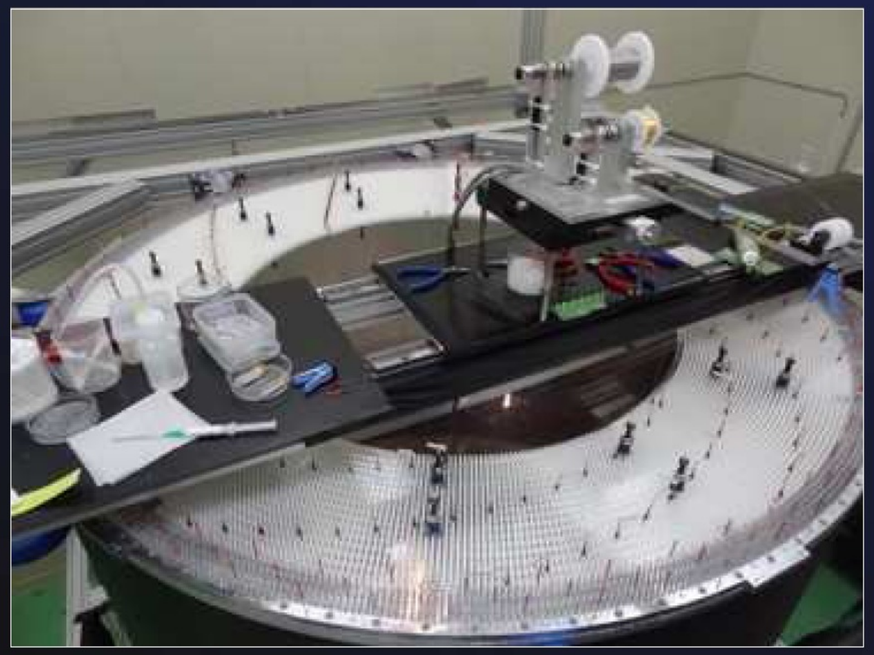


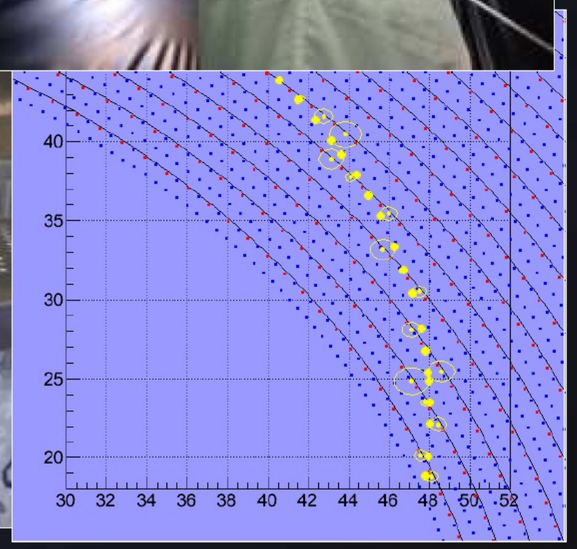
Beam test setup for resolution study



Cylindrical Drift Chamber (CDC)

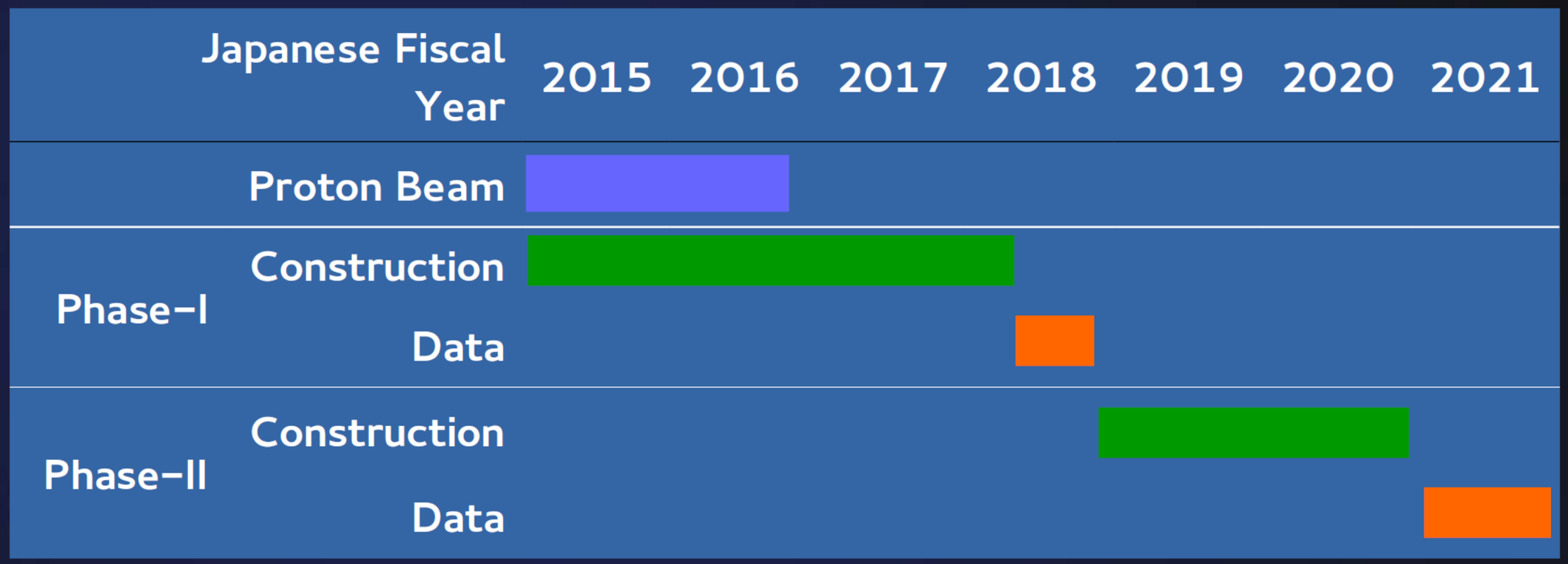
- 20 layers with alternating stereo angles of ±4°
  - Sense wires: Gold plated tungsten, 25 μm
  - Field wires: Pure Aluminium, 120 μm
  - Between 800 and 1200 wires per layer
- Status:
  - Wire stringing:
    - 150 days total
    - 40% complete



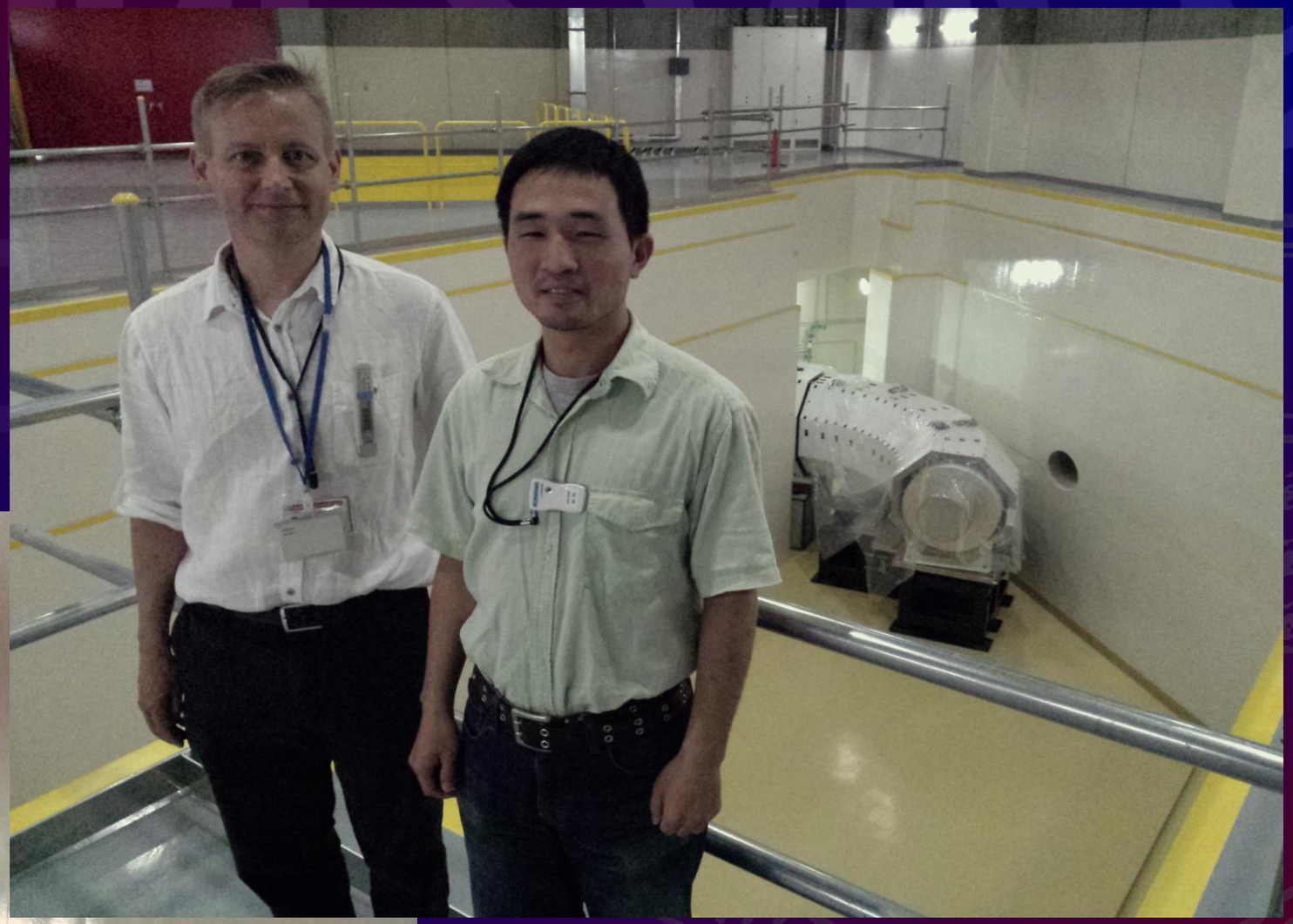


Schedule

COMET: Ben Krikler



The COMET Experimental Hall



In summary

Within the next 10 years, Mu2e will either unambiguously discover cLFV or push the limit on muon conversion by four orders of magnitude.

For more information
- Mu2e Homepage: http://mu2e.fnal.gov
- Technical Design Report: http://arxiv.org/abs/1501.05241

Contact:
Doug Glenzinski, *douglasg@fnal.gov*,
or
Jim Miller, *miller@bu.edu*.

Summary

Muon-to-electron conversion is a strong probe of new physics

COMET's staged approach and unique design makes it highly sensitive to this process

Development and construction are well under way

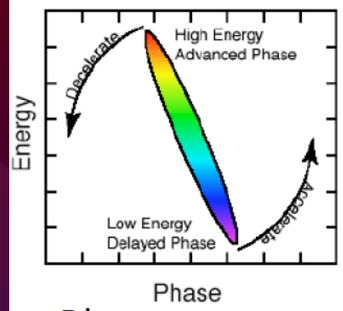
COMET Phase-I
2018
Sensitivity < 3×10^{-15}
110 days
3.2 kW proton beam

COMET Phase-II
2021
Sensitivity < 3×10^{-17}
1 Year
56 kW proton beam

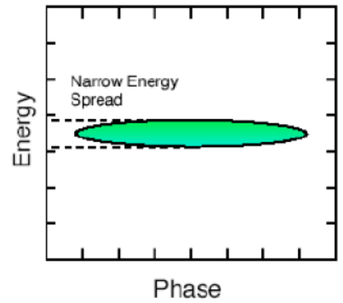
The future:
PRISM / PRIME
Sensitivity $\ll 10^{-18}$
See talk by J. Pasternak

PRISM FFAG

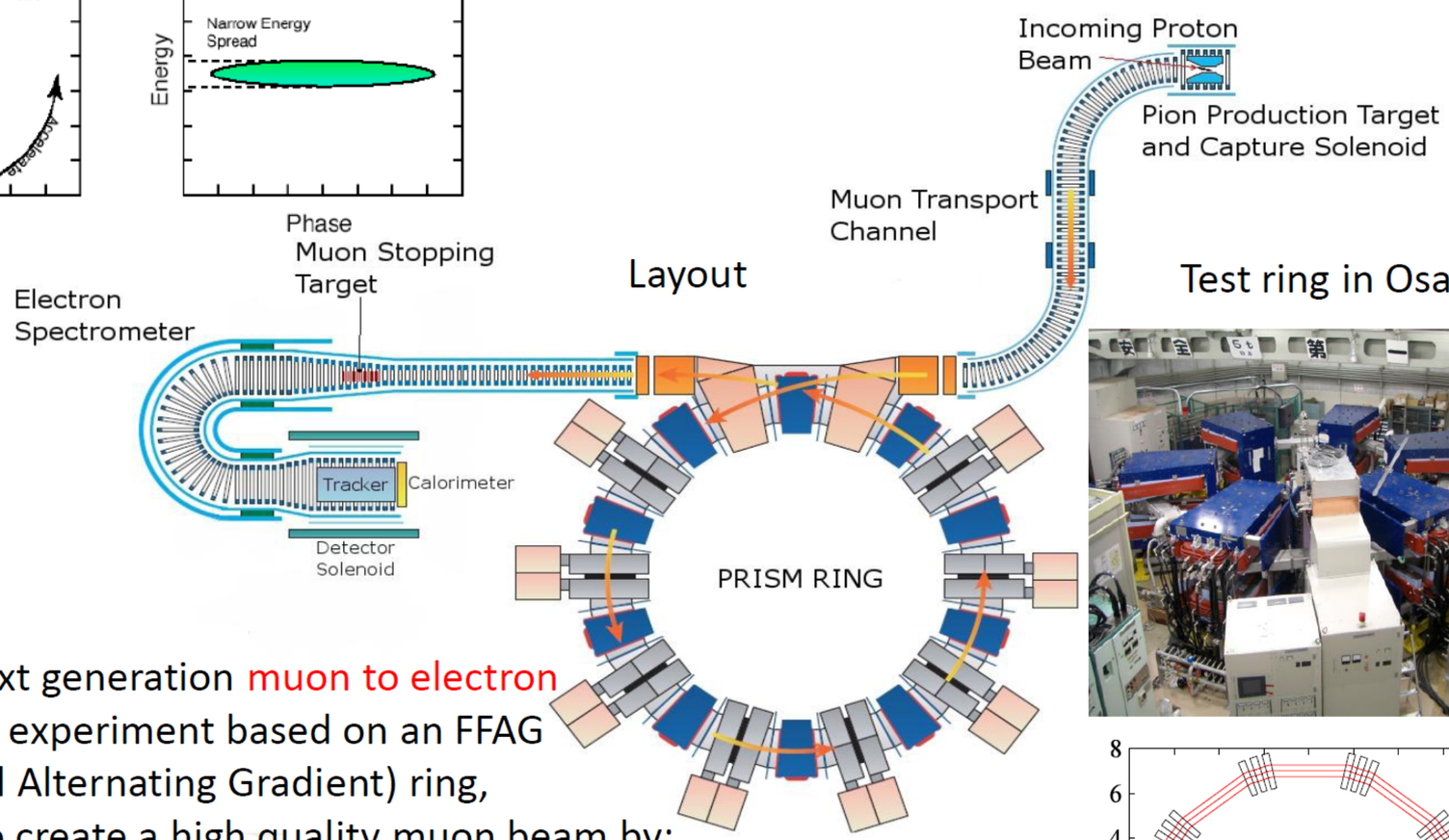
PRISM - Phase Rotated Intense Slow Muon beam



Phase Rotation



Layout

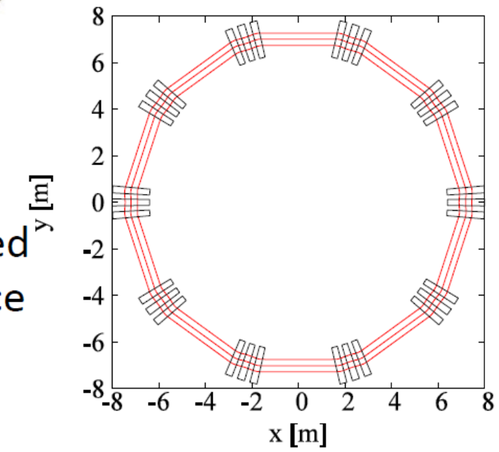


Test ring in Osaka

PRISM:

- It is the next generation muon to electron conversion experiment based on an FFAG (Fixed Field Alternating Gradient) ring,
- It allows to create a high quality muon beam by:
  - reducing the muon beam energy spread by RF phase rotation,
  - purifying the muon beam in the storage ring.
- It will have single event sensitivity – 3×10^{-19}
- Design details are being addressed by the Task Force led by Jaroslaw Pasternak (contact him for more details).

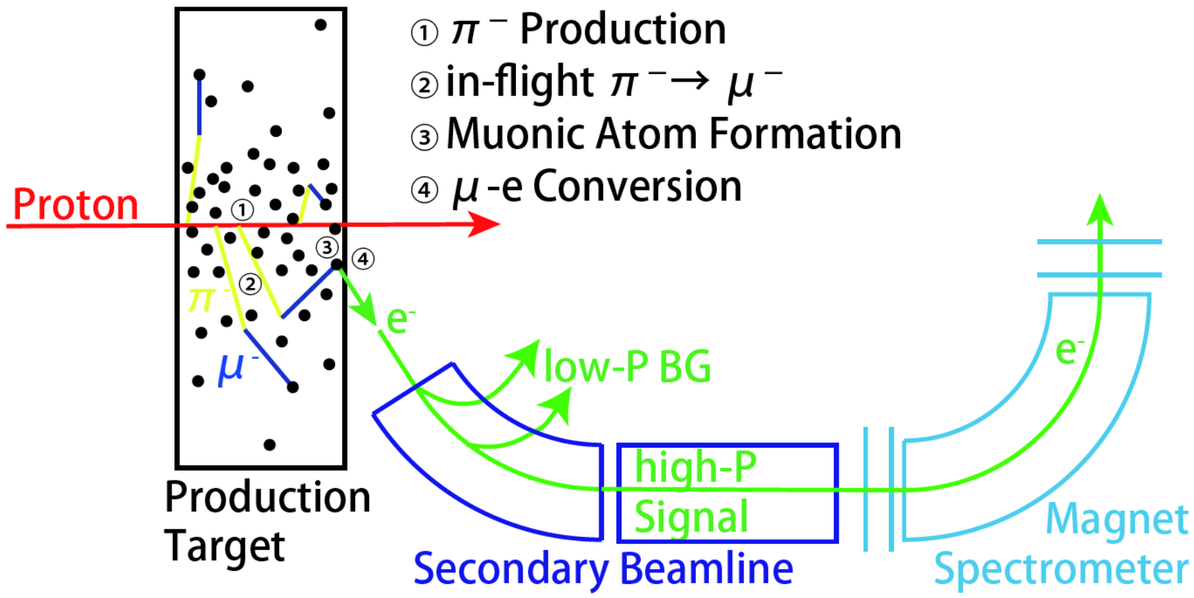
Alternative ring designed by Task Force



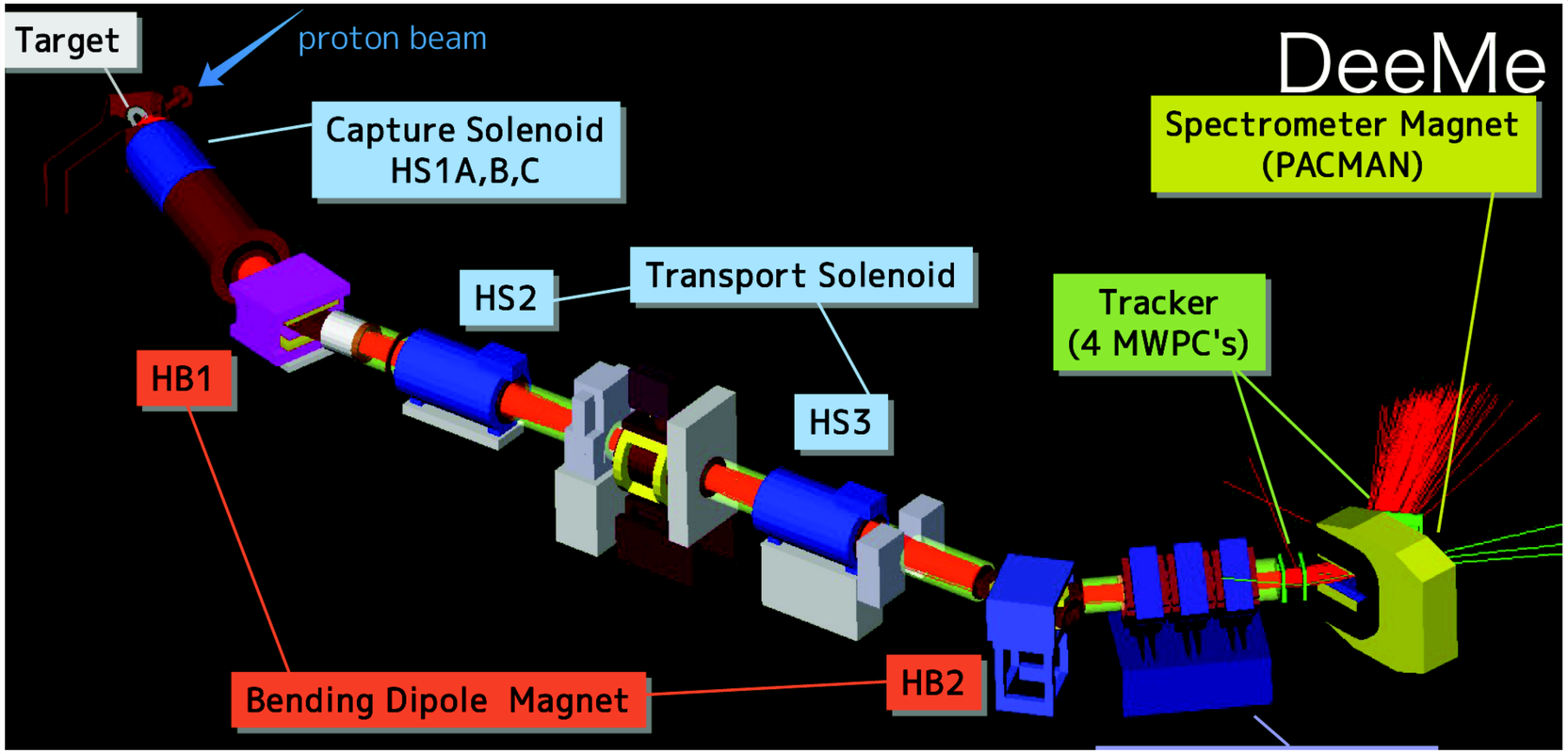
Jaroslaw Pasternak (Thursday)

Masaharu Aoki

DeeMe: Search for μ-e Conversion



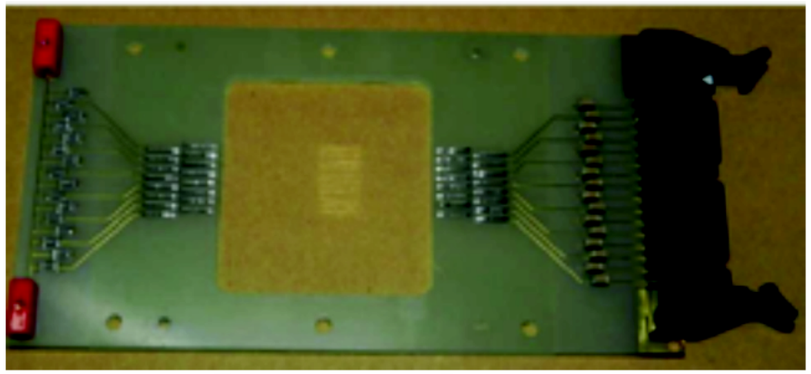
- **IMSS/Muon PAC: Stage-2 Approved**
- **J-PARC/RCS**: High-Power High-Purity Pulsed Proton Beam.
- **Production Target as μ-stopping target**.
- **H-Line/MLF**: Large-Acceptance Beam line.
- **State-of-the-Art MWPC** Technology
- **S.E.S. — BR~5 x 10^{-15}**
  (8 x 10^7 sec of data taking with SiC target)
- Start the physics run with graphite target
  - S.E.S. — 1 x 10^{-13} (2 x 10^7 sec)
- Aiming to start the engineering run in **2016**.



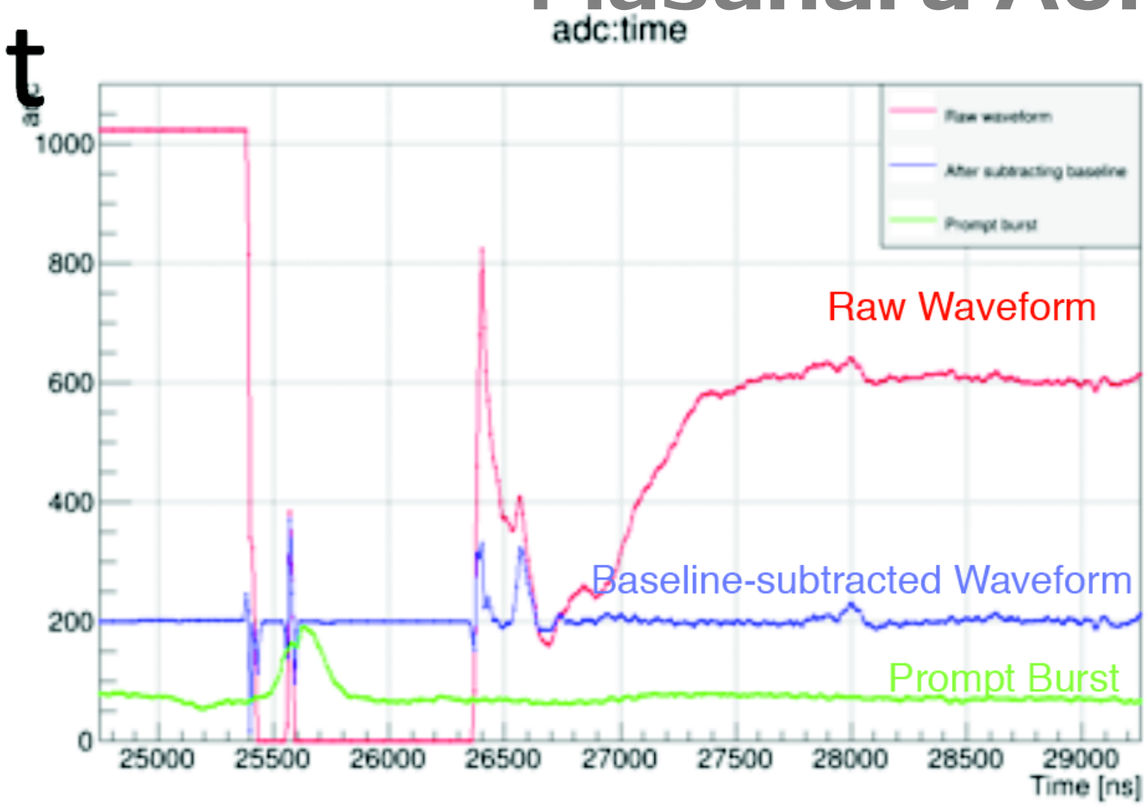
Magnet leased from TRIUMF

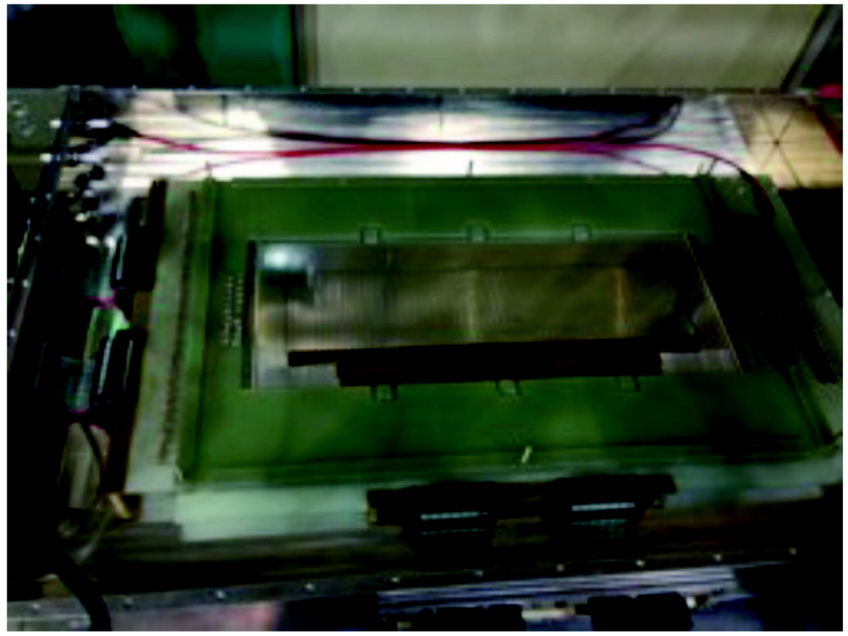
Masaharu Aoki

MWPC Development

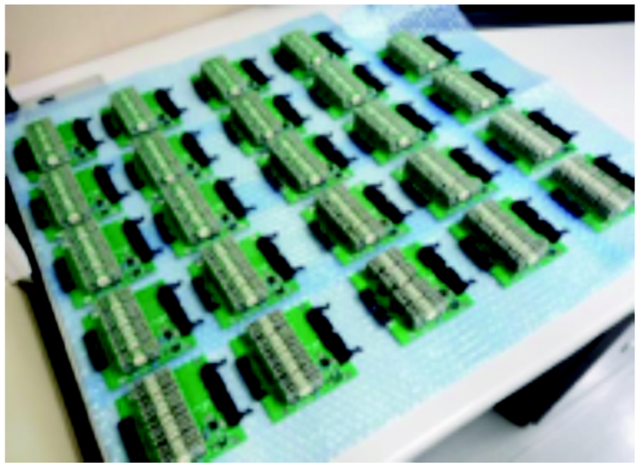


Prototype 1 @2012





Prototype 2 @2014

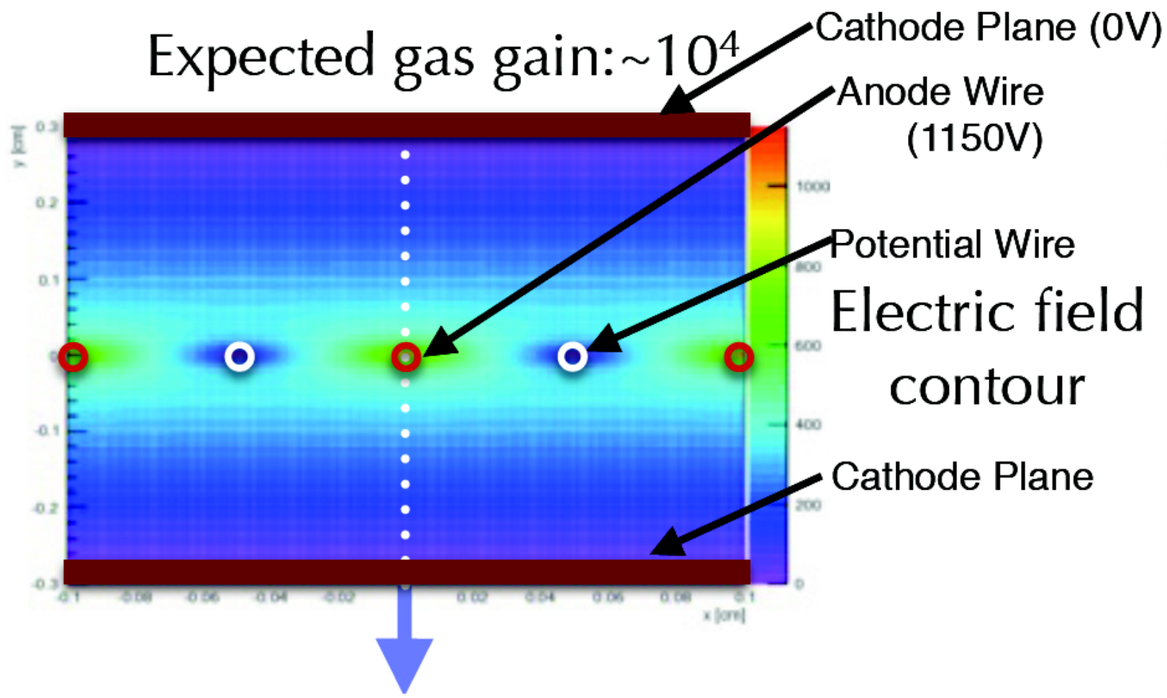


Preamps @ 2015

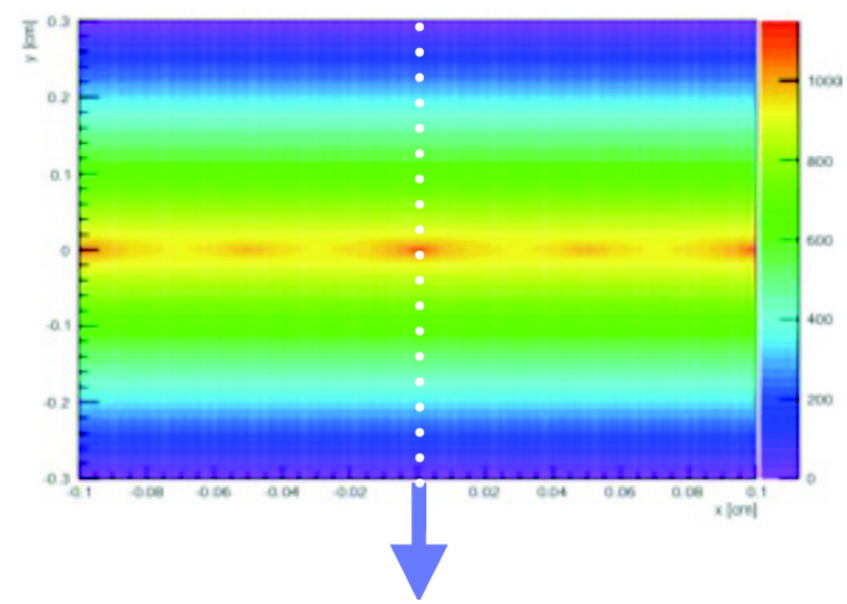
Production @ 2015

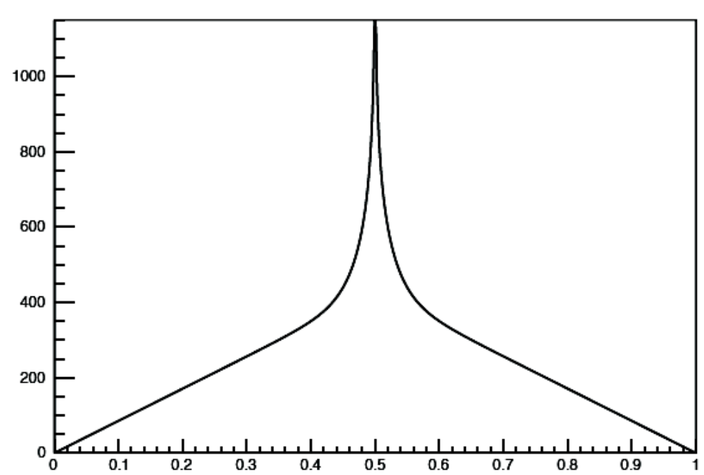
Potential-Wire Voltage Switching MWPC

Anode wire: 1150V
Potential wire: 0V
Expected gas gain:~10^4

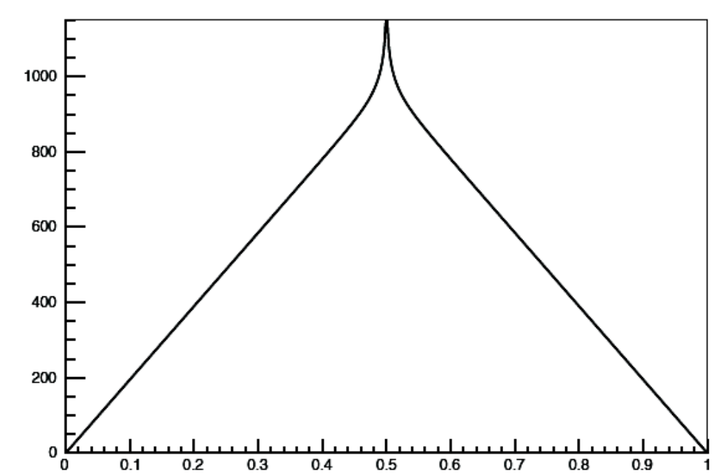


Anode wire: 1150V
Potential wire: 1000V
Expected gas gain:~7





Electric field
Profile



Mu3e at PSI

a search for the process

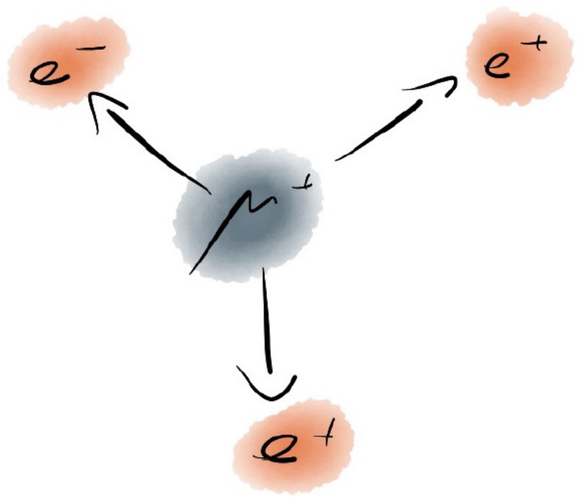
$$\mu^+ \to e^+ + e^- + e^+$$

Yoshi.Uchida@imperial.ac.uk

The Mu3e Experiment

- Mu3e is a dedicated experiment searching for $\mu^+ \to e^+e^-e^+$
- aimed sensitivity $\mathcal{B}(\mu \to eee) < 10^{-16}$
- stopped muons per second: 10^9
- main background: $\mu \to eee\nu_e\nu_\mu$, with $\mathcal{B} = 3.4 \cdot 10^{-5}$ and accidentals

Signal:

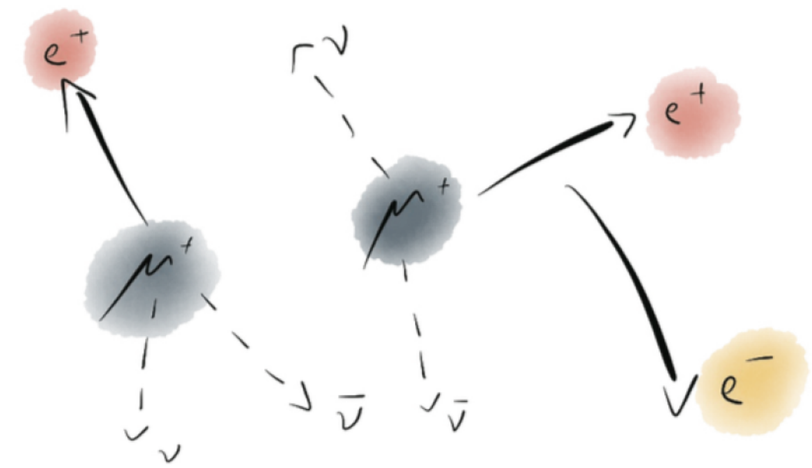


- $\Sigma\vec{p}_i = 0$
- common vertex
- $p < 53\,\mathrm{MeV}$

BG: Internal Conversion

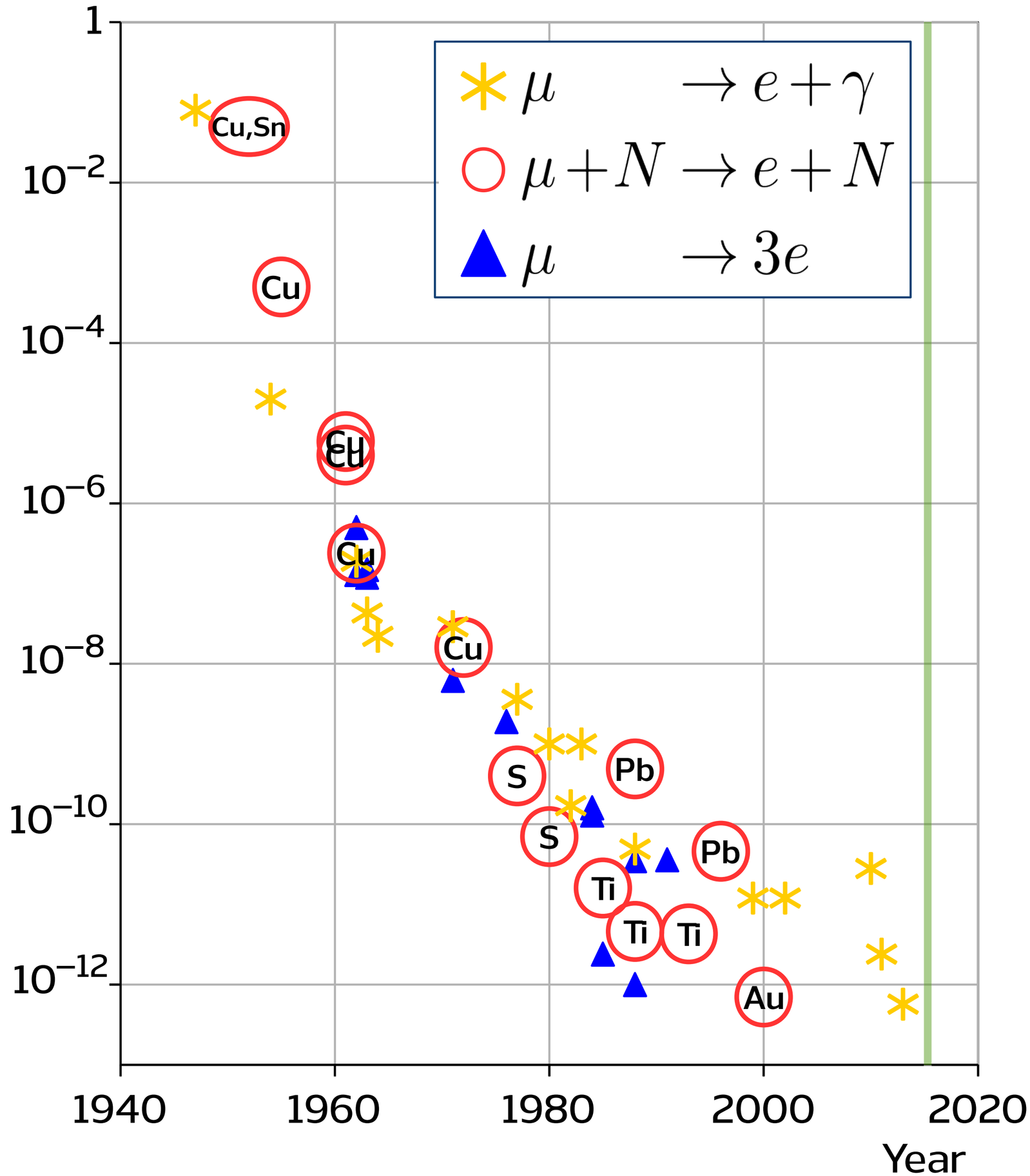
- $\Sigma\vec{p}_i \neq 0$
- common vertex

BG: Accidental



- non common vertex
- not in coincidence

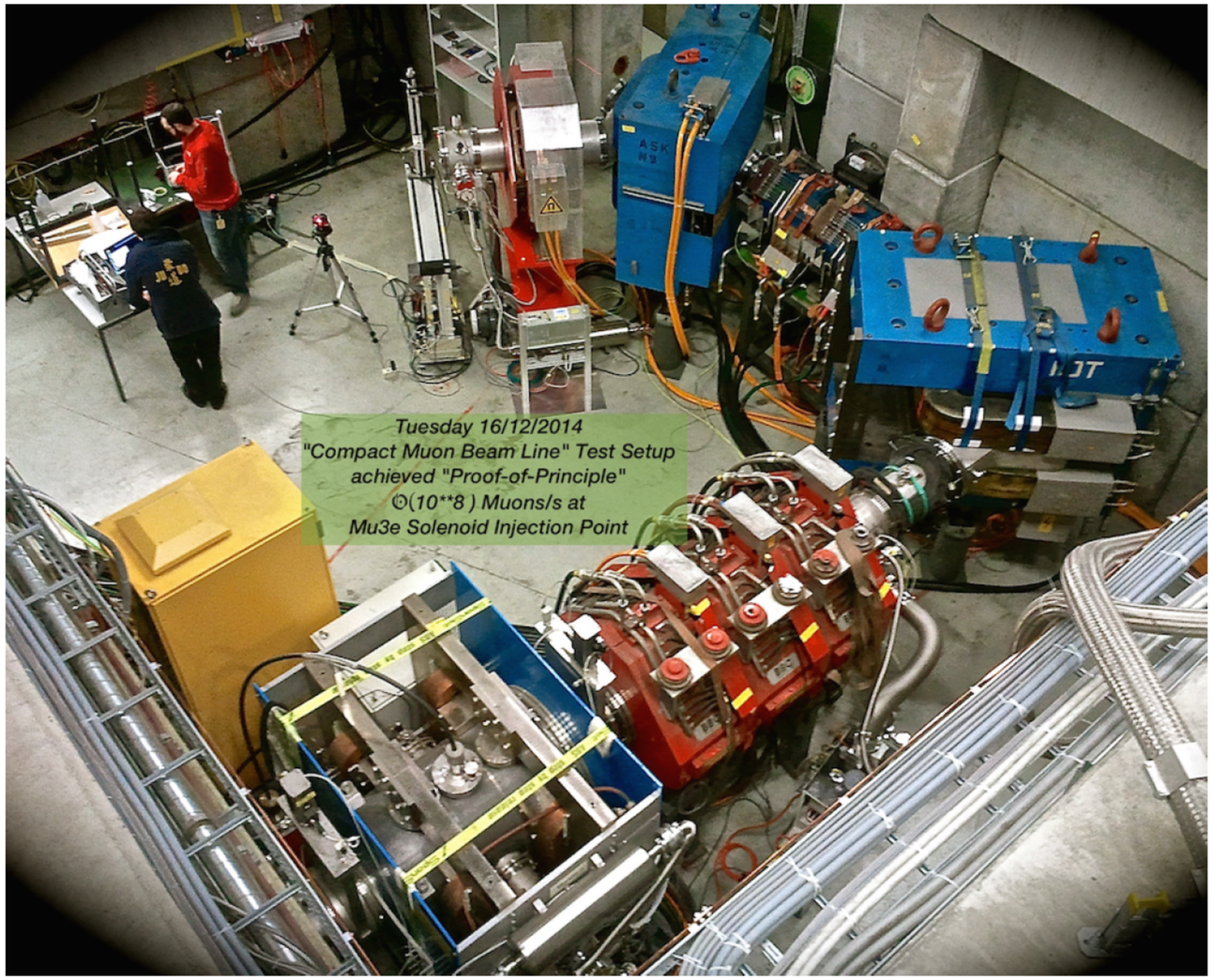
Charged Lepton Flavour Violation



90% C.L.
upper limit on
branching ratios

Yoshi.Uchida@imperial.ac.uk

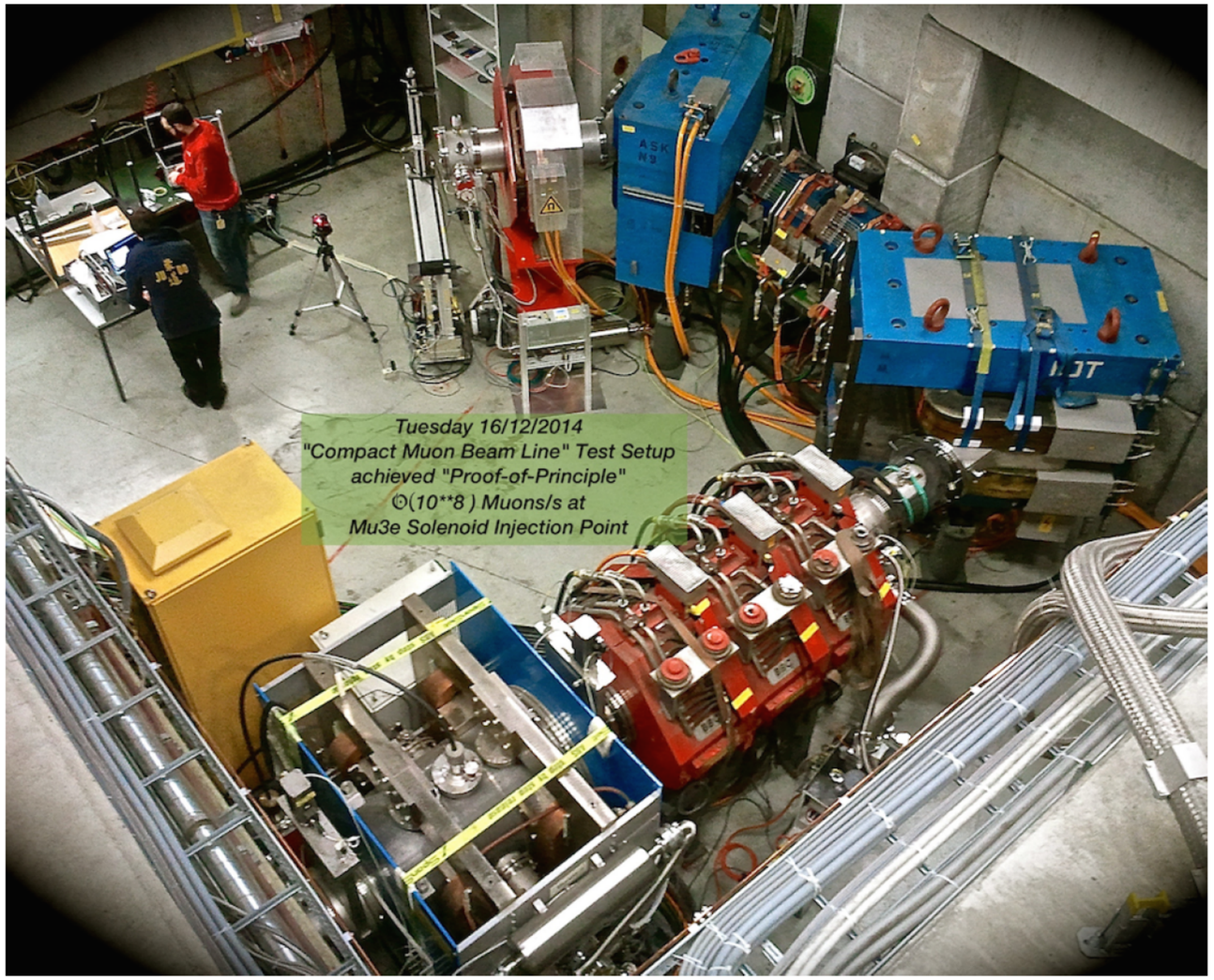
Muon Beam at PSI



- muon beamline at PSI
- low energy DC beams
- πE5 beamline: $\sim 10^8$ 28 MeV/c surface muons
  - shared with MEG
  - works for Phase I $\rightarrow$ approved
- HiMB:
  High intensity muon beam
  study ongoing
  needed for Phase II
  Mu3e: $\sim 10^9$ μ^+/s
  PSI Goal: $\sim 10^{10}$ μ^+/s

Aug. 11, 2015 R. Gredig, NuFact15 Rio

Muon Beam at PSI



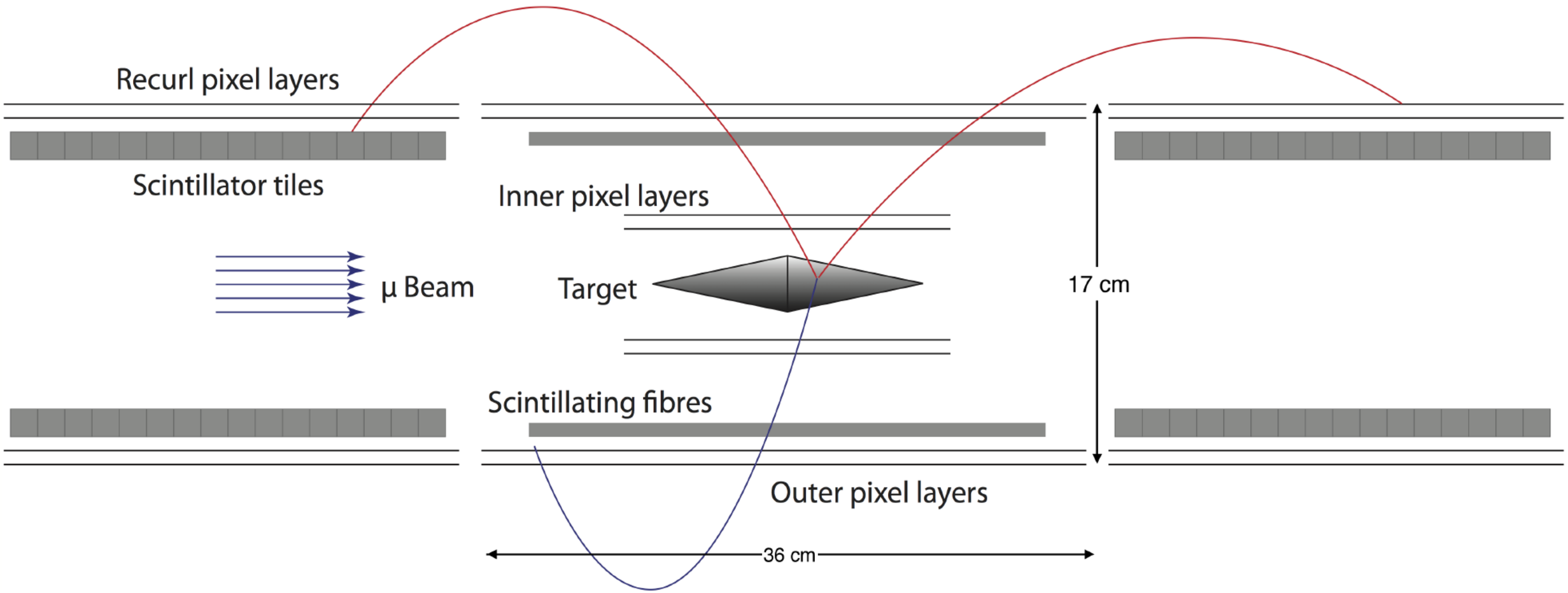
- **MEG is here**
  - muon beamline at PSI
  - low energy DC beams
  - πE5 beamline: $\sim 10^8$ 28 MeV/c surface muons
    - shared with MEG
    - works for Phase I $\rightarrow$ approved
  - HiMB:
    High intensity muon beam
    study ongoing
    needed for Phase II
    Mu3e: $\sim 10^9$ μ^+/s
    PSI Goal: $\sim 10^{10}$ μ^+/s

Muon Beam at PSI

- **MEG is here**
  - muon beamline at PSI
  - low energy DC beams
  - πE5 beamline: $\sim 10^8$ 28 MeV/c surface muons
    - shared with MEG
    - works for Phase I $\rightarrow$ approved
  - HiMB:
    High intensity muon beam
    study ongoing
    needed for Phase II
    Mu3e: $\sim 10^9$ μ^+/s
    PSI Goal: $\sim 10^{10}$ μ^+/s

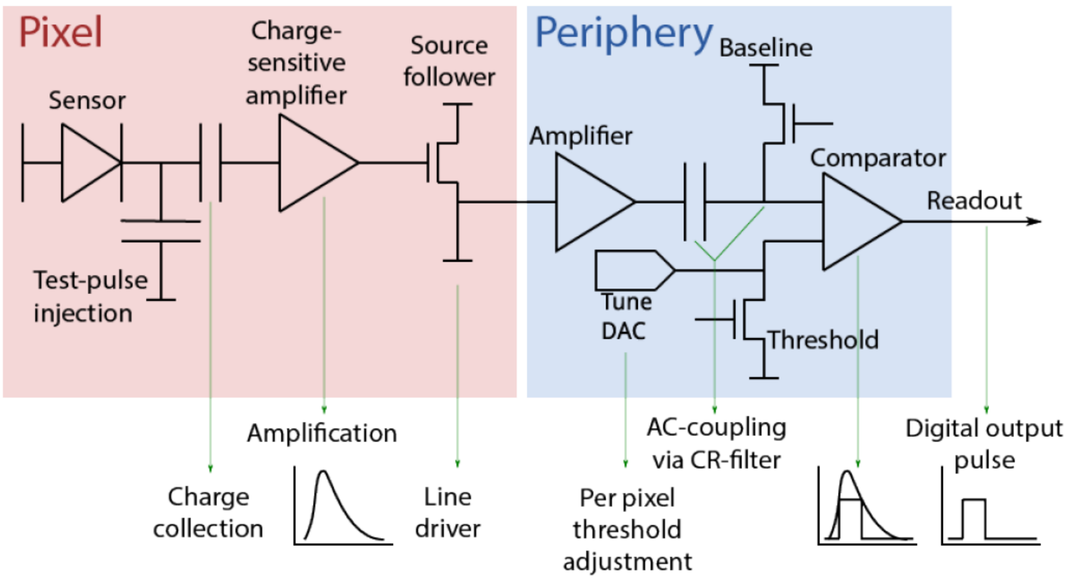
Detector Concept

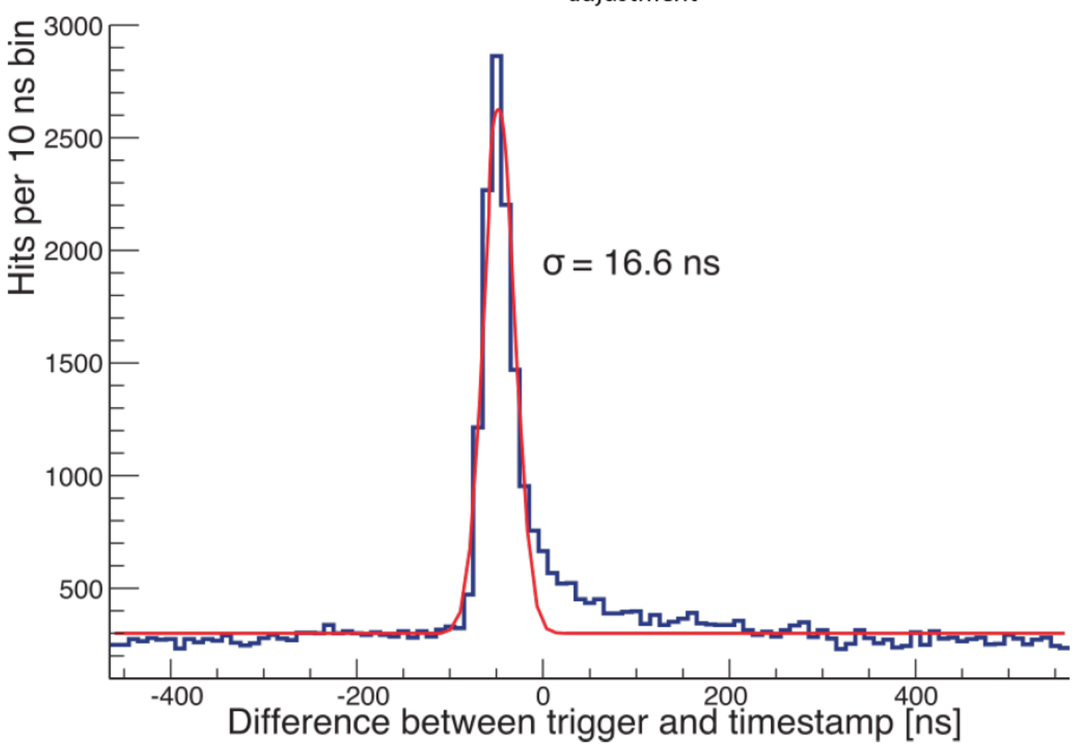
- Phase Ib: muon stopping $\sim 10^8\ \mu^+/s$ (2017)
- central module upgraded with 250 µm diameter scintillation fibres (three layers)
- two additional recurl modules including pixel and scintillation tiles $\Rightarrow$ better timing



Monolithic Active Pixel Sensors

Mu3e:
Roman Gredig





MuPix currently in its 7th generation:

- MuPix 2
  - $30 \times 39\,\mu m^2$ pixel size
  - $1.8 \times 1.2\,mm^2$ active area
  - proof of concept
- MuPix 3 and 4
  - $80 \times 92\,\mu m^2$ pixel size
  - $2.9 \times 3.2\,mm^2$ active area
- MuPix 6
  - same geometry
  - second amplifier added

MuPix 7

- still small scale prototype
- full digital readout + fast serial link

Next version may be final

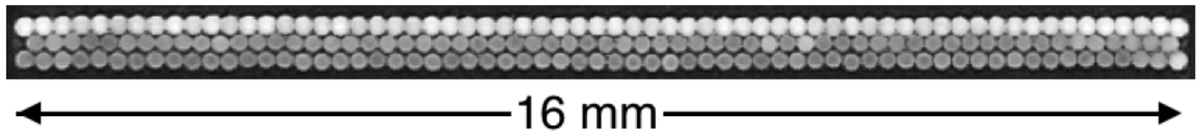
Less than 50 microns thick,
$2 \times 2\,cm^2$ area with 80 micron pixels

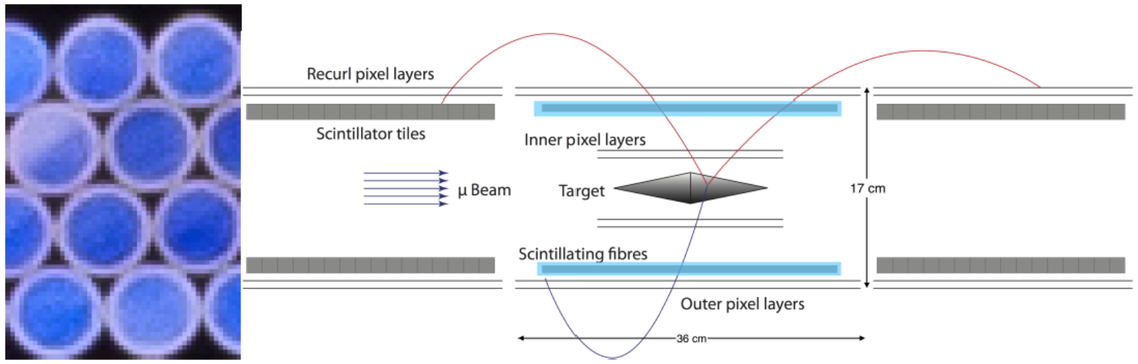
Aug. 11, 2015 R. Gredig, NuFact15 Rio

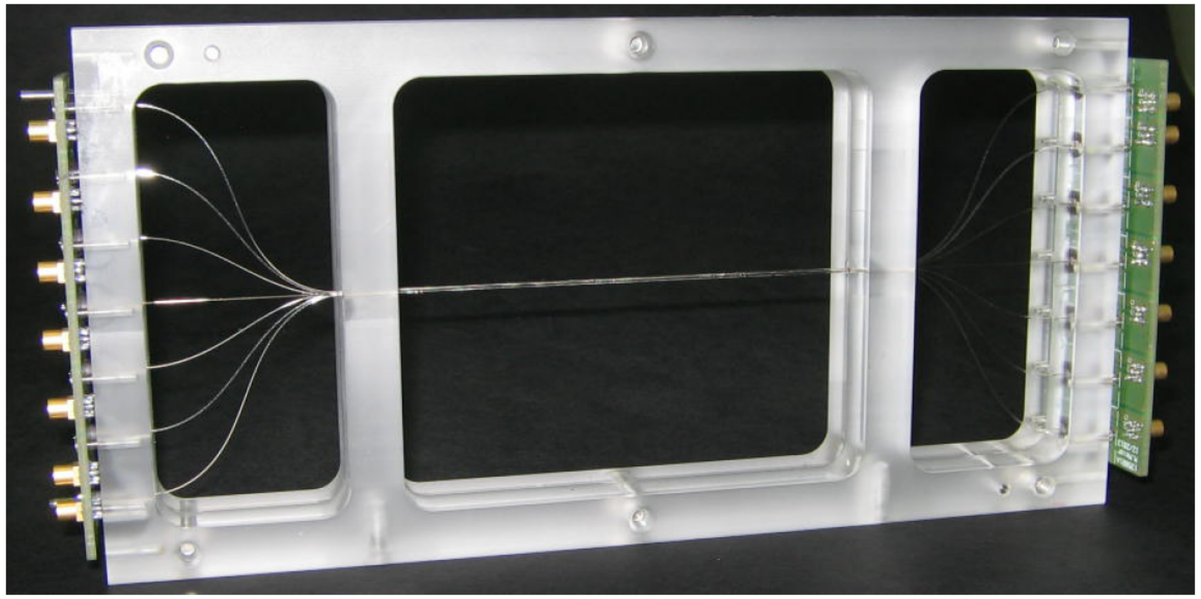
Scintillating Fibres

Mu3e:
Roman Gredig

- three layers of $\sim$ 1500 fibres with a diameter of 250 µm
- produced as 16 mm wide modules with a length of 30 cm
- read out on both ends with silicon photomultiplier arrays and custom ASIC (STiC chip)
  (either columns wise or individual with fanout)
- time resolution goal: $<$1 ns
- two fibre types under investigation:
  - round double cladding fibres
  - squared double cladding fibres







Summary and Outlook

Mu3e:
Roman Gredig

- new experiment for the search of $\mu \to eee$ with sensitivitiy $< 10^{-16}$
- staged approach and modular principle
  - Phase Ia: Sensitivity $\mathcal{B}(\mu \to eee) < 10^{-14}$ (2016)
  - Phase Ib: Sensitivity $\mathcal{B}(\mu \to eee) < 10^{-15}$ (2017)
  - Phase II : Sensitivity $\mathcal{B}(\mu \to eee) < 10^{-16}$ (2019)
- thin active pixel sensors: HV-MAPS
- precise timing: $\mathcal{O}(100\,\text{ps})$
- high momentum resolution: $\sim 0.5\,\text{MeV}/c$
- triggerless readout

CLFV at Colliders

BELLE/BELLE-II

CMS

ATLAS

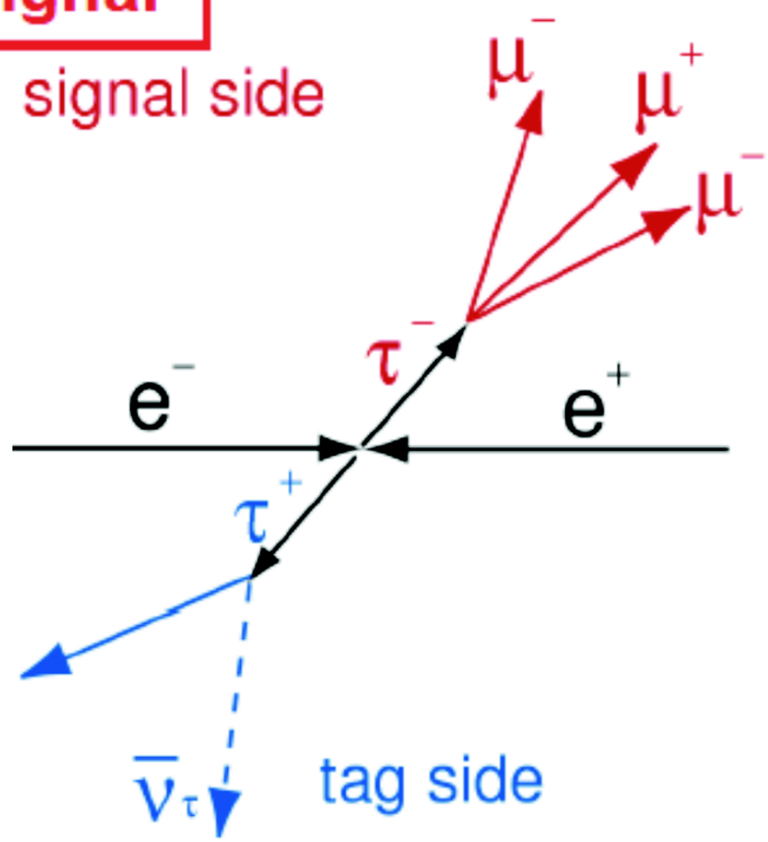
Yoshi.Uchida@imperial.ac.uk

CLFV tau decays

BELLE: Claudia Cecchi

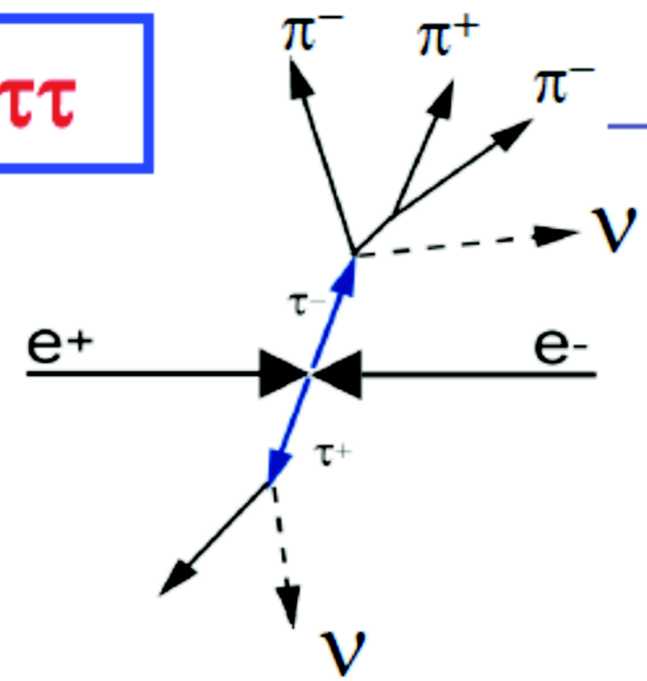
signal

signal side



- Neutrino(s) in tag side
- Particle ID

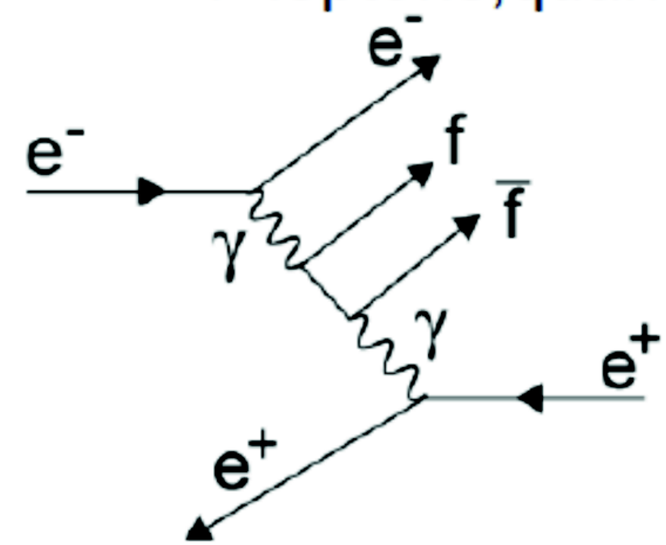
ττ



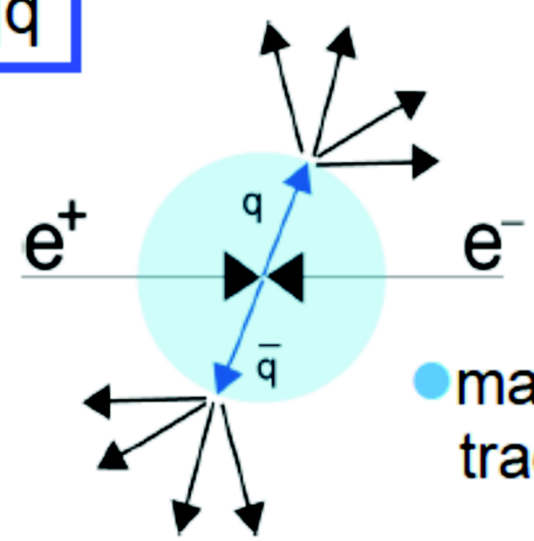
- Neutrinos in both sides
- Missing energy in signal side

2photon process

f=leptons,quarks

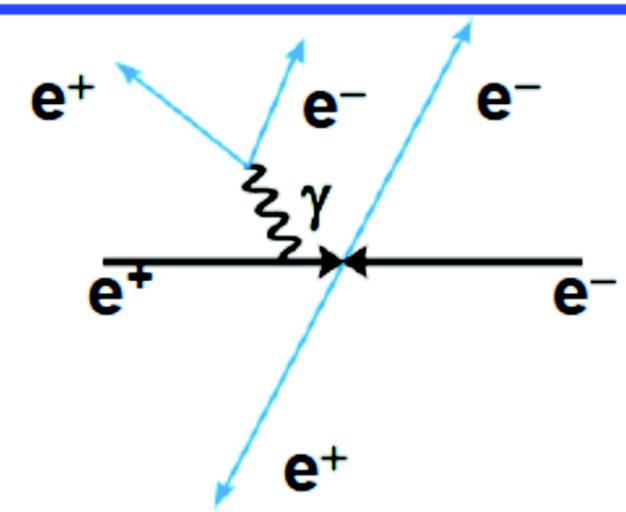


$q\bar{q}$



- many tracks

radiative Bhabha process



Conclusions

Tau lepton is a good probe for NP searches like LFV
B factories produced a huge data sample $O(10^9)$ tau pairs

BELLE:

- 48 LFV decay modes have been investigated 100x sensitive results w.r.t. CLEO
- 90% C.L. Upper Limits have been set in $O(10^{-8})$
- $\tau \rightarrow \mu\gamma/e\gamma$ will be updated with the full data set

BELLEII:

- machine upgrade is finished and detector upgrade is ongoing smoothly
  - detector improvement will play a key role in background elimination and reduction of systematic effects
- start of full physics 2018, reach 50 ab^{-1} by 2023-2024
- LFV will be probed up to $O(10^{-9} - 10^{-10})$

LHCb can investigate some modes; sensitivity comparable to B factories

Healthy competition with LHCb is very important to go forward

CMS: Alexander Nehrkorn

arXiv:1502:07400

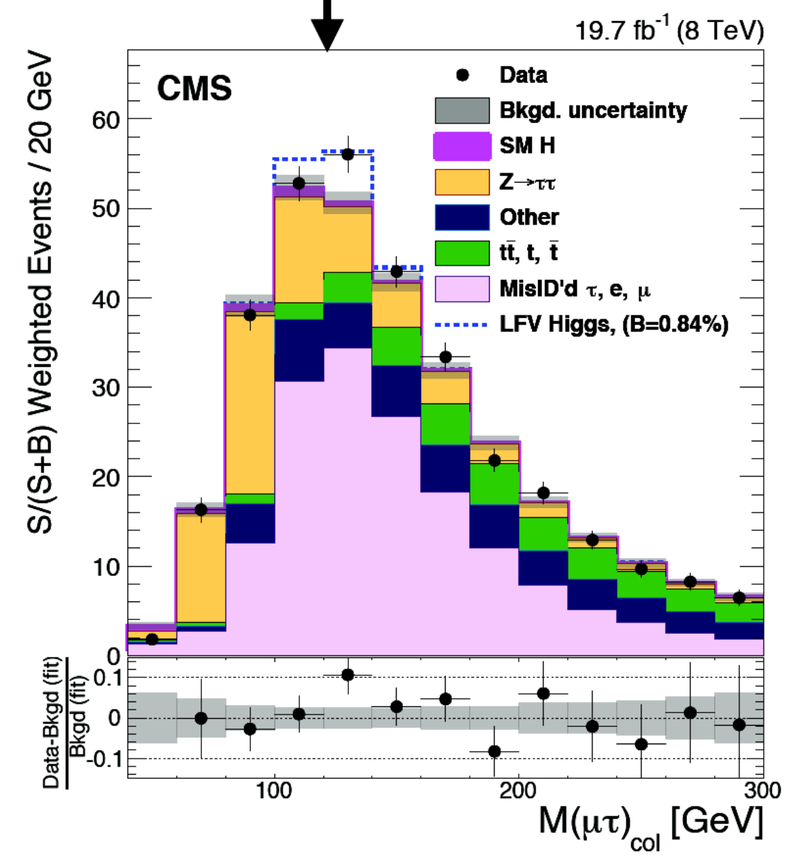
Search Strategy for H→μτ_e and H→μτ_h

Select different production mechanisms

Use collinear approximation

Use kinematic variables

Lepton selection → Categorize: n_{jet}= 0, 1 or 2 → Calculate $m_{\mu\tau}$ → Background suppression



Determine $\mathcal{B}$(H→μτ)

$$\mathcal{B}(H \to \mu\tau)_{\text{best fit}} = (0.84^{+0.39}_{-0.37})\%$$

Determine limit on $\mathcal{B}$(H→μτ)

Summary

CMS: Alexander Nehrkorn

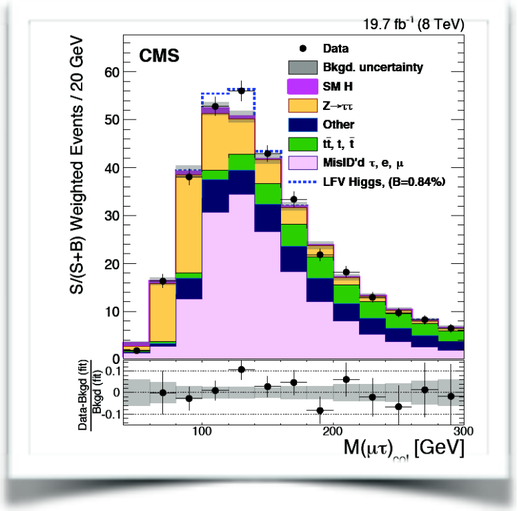
- H→μτ:
  - 2.4σ deviation from SM observed
  - Limits on branching fraction & LFV Yukawa couplings set:

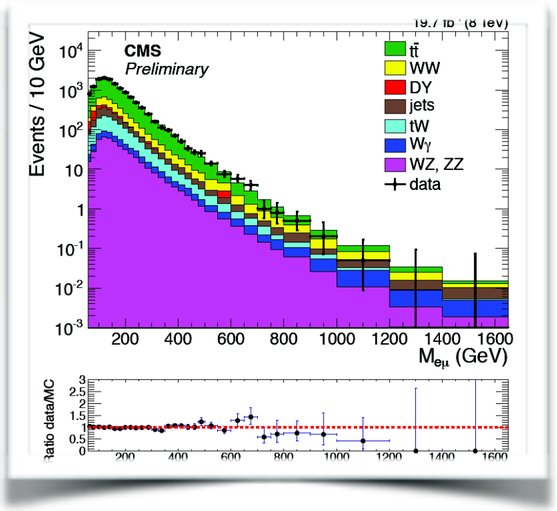
$$\mathcal{B}(H \to \mu\tau) < 1.51\%$$

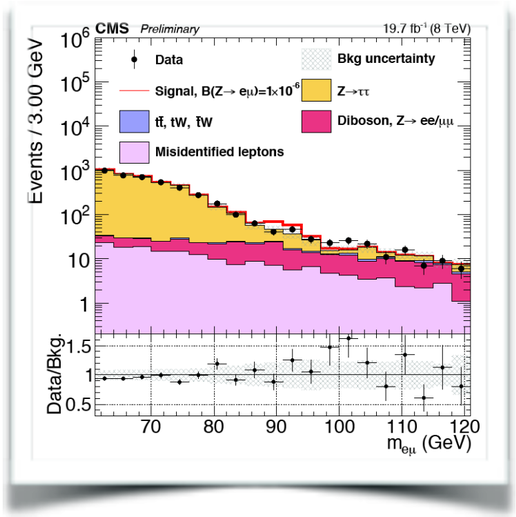
$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.6 \cdot 10^{-3}$$

- Heavy states:
  - Model-independent analysis
    - τ sneutrino: m < 1.28 (2.11) TeV for $\lambda_{132} = \lambda_{311} = 0.01$ ($\lambda_{132} = 0.05$, $\lambda_{311} = 0.1$)
    - QBHs: m < 1.99 - 3.63 TeV for $n_{\text{extra dim.}} = 0 - 6$
    - Z'/a': no sensitivity, yet

- Z→eμ:
  - Obtained most stringent direct limit on branching fraction: $\mathcal{B}(Z \to e\mu) < 7.3 \cdot 10^{-7}$







Higgs → μτ

Events with μ and hadronically decaying τ.

Use τ kinematics and missing Et to correct for undetected ν.

NEW!

Two signal regions

SR1: $m_T(\mu, E_T^{miss}) > 40$ GeV and $m_T(\tau_{had}, E_T^{miss}) < 40$ GeV

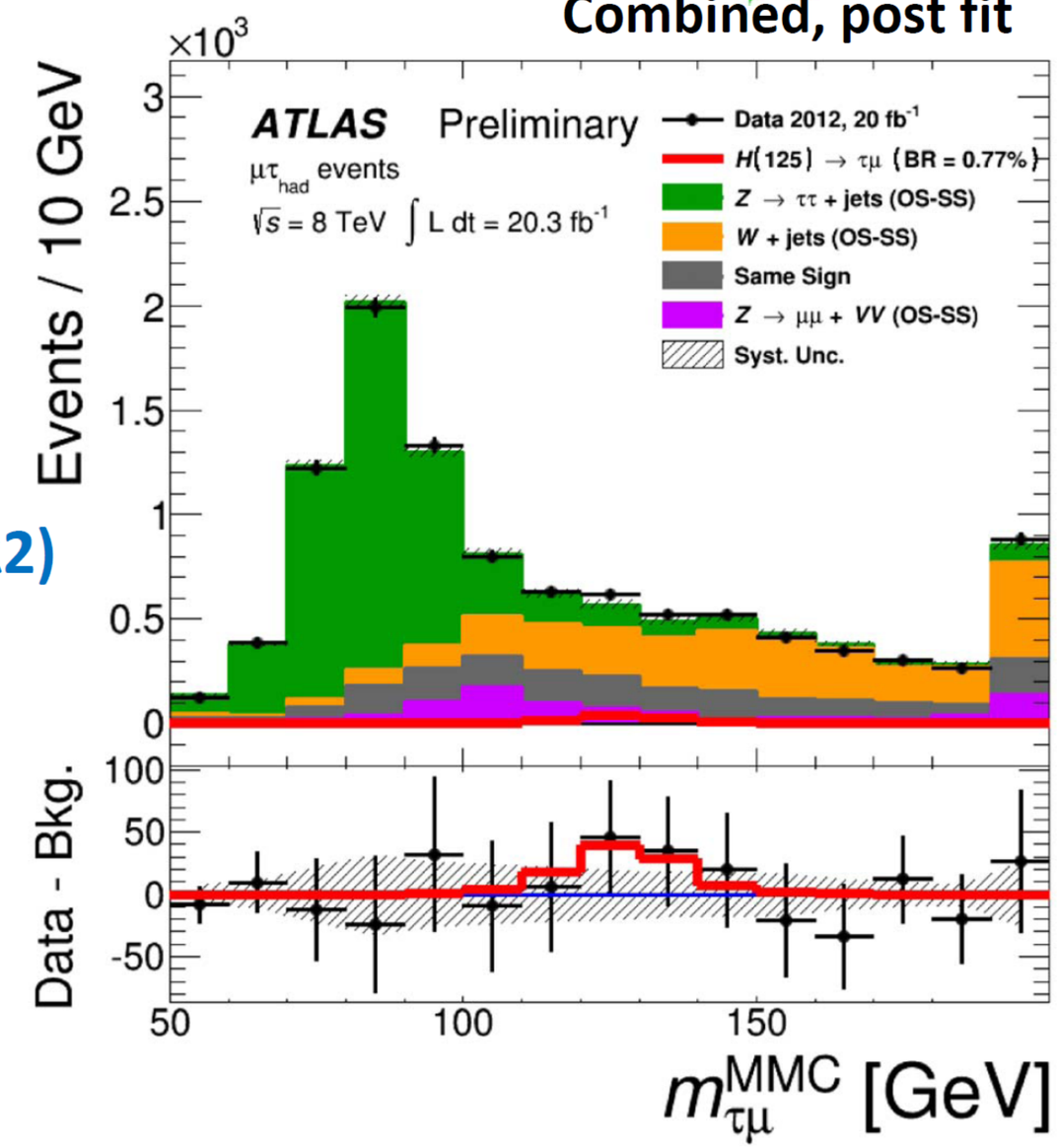
SR2: $m_T(\mu, E_T^{miss}) < 30$ GeV and $m_T(\tau_{had}, E_T^{miss}) < 60$ GeV

Dominant backgrounds are $Z/\gamma^* \rightarrow \tau\tau$ (SR2) and W + jets (SR1)

BR < 1.85% (95% CL)

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

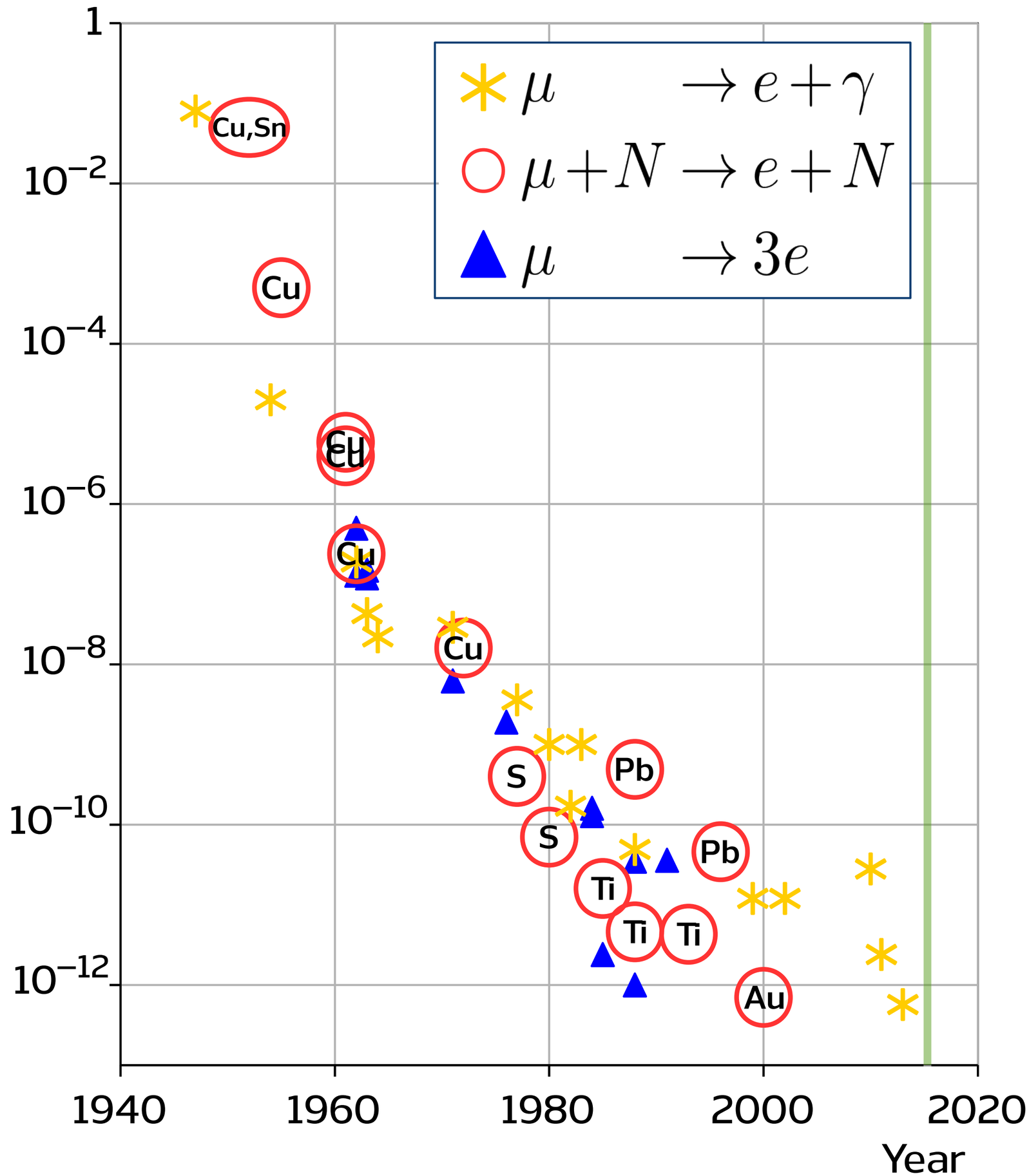
Combined, post fit



Summary

- ATLAS has searched for lepton flavor violation in the 8-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.
- We look forward to analyzing the 13-TeV data currently being taken.

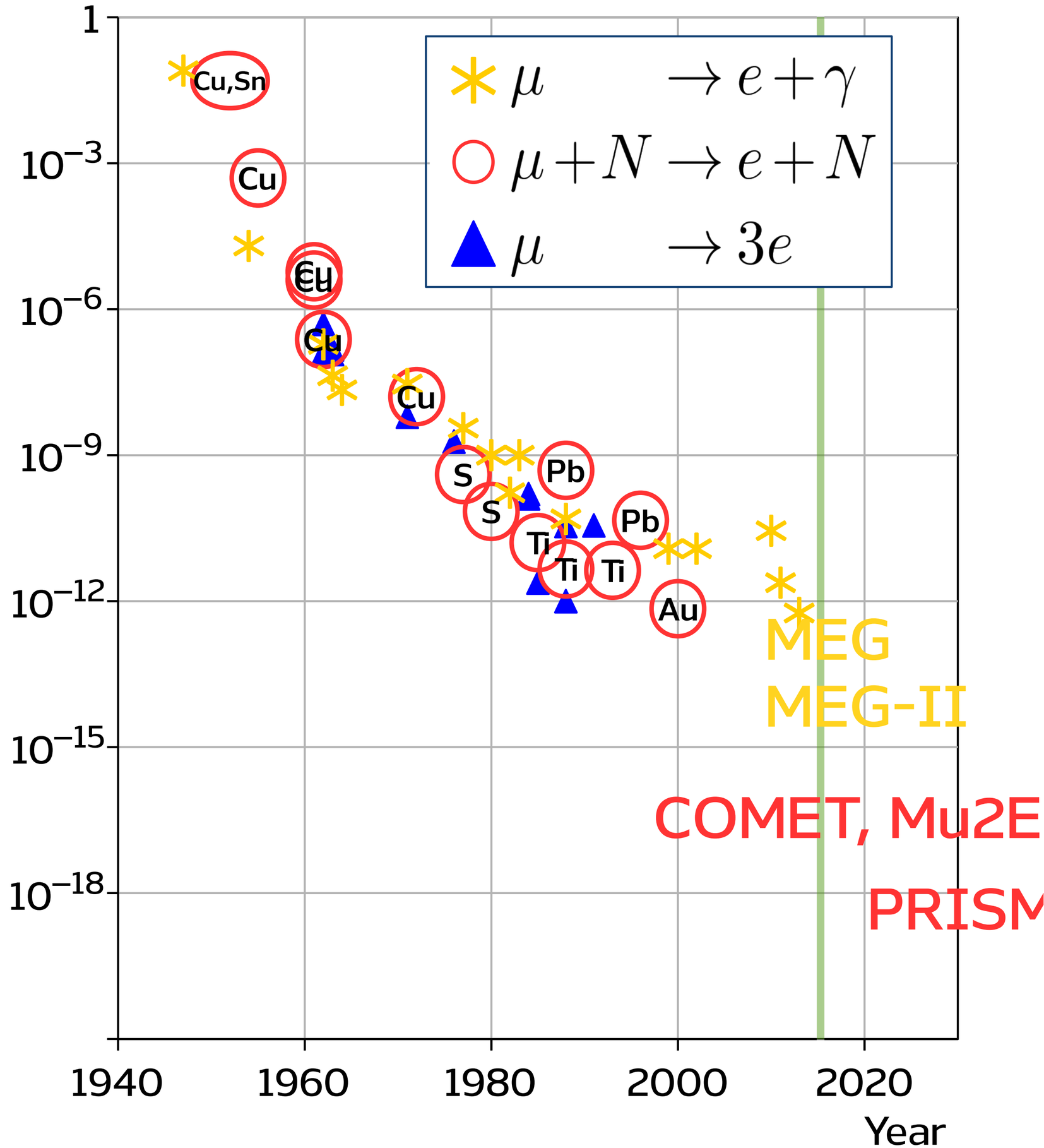
The Current State of Muon Flavour Violation Searches



90% C.L.
upper limit on
branching ratios

Yoshi.Uchida@imperial.ac.uk

Future Muon Flavour Violation Searches



90% C.L.
upper limit on
branching ratios

Yoshi.Uchida@imperial.ac.uk

Experimental Limits on Lepton Flavour Violation

Reaction	Present limit
$\mu^+ \to e^+\gamma$	$< 5.7 \times 10^{-13}$
$\mu^+ \to e^+e^+e^-$	$< 1.0 \times 10^{-12}$
$\mu^- Ti \to e^- Ti$	$< 6.1 \times 10^{-13}$
$\mu^- Au \to e^- Au$	$< 7 \times 10^{-13}$
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$
$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$
$\tau \to eee$	$< 2.7 \times 10^{-8}$
$\pi^0 \to \mu e$	$< 3.8 \times 10^{-10}$
$K_L^0 \to \mu e$	$< 4.7 \times 10^{-12}$
$K^+ \to \pi^+\mu^+e^-$	$< 1.3 \times 10^{-11}$
$K_L^0 \to \pi^0\mu^+e^-$	$< 7.6 \times 10^{-11}$
$Z^0 \to \mu e$	$< 1.7 \times 10^{-6}$
$Z^0 \to \tau e$	$< 9.8 \times 10^{-6}$
$Z^0 \to \tau\mu$	$< 1.2 \times 10^{-5}$

90% C.L. upper limits on branching ratios

Complementarity of CLFV Channels

- The various CLFV channels *complement* each other
  - CLFV muons and tau decays
    - different muon-to-electron conversion nuclei
  - CLFV decays of heavier particles
    - mesons, vector bosons, Higgses....
- The relative rates can tell us the nature of the BSM physics

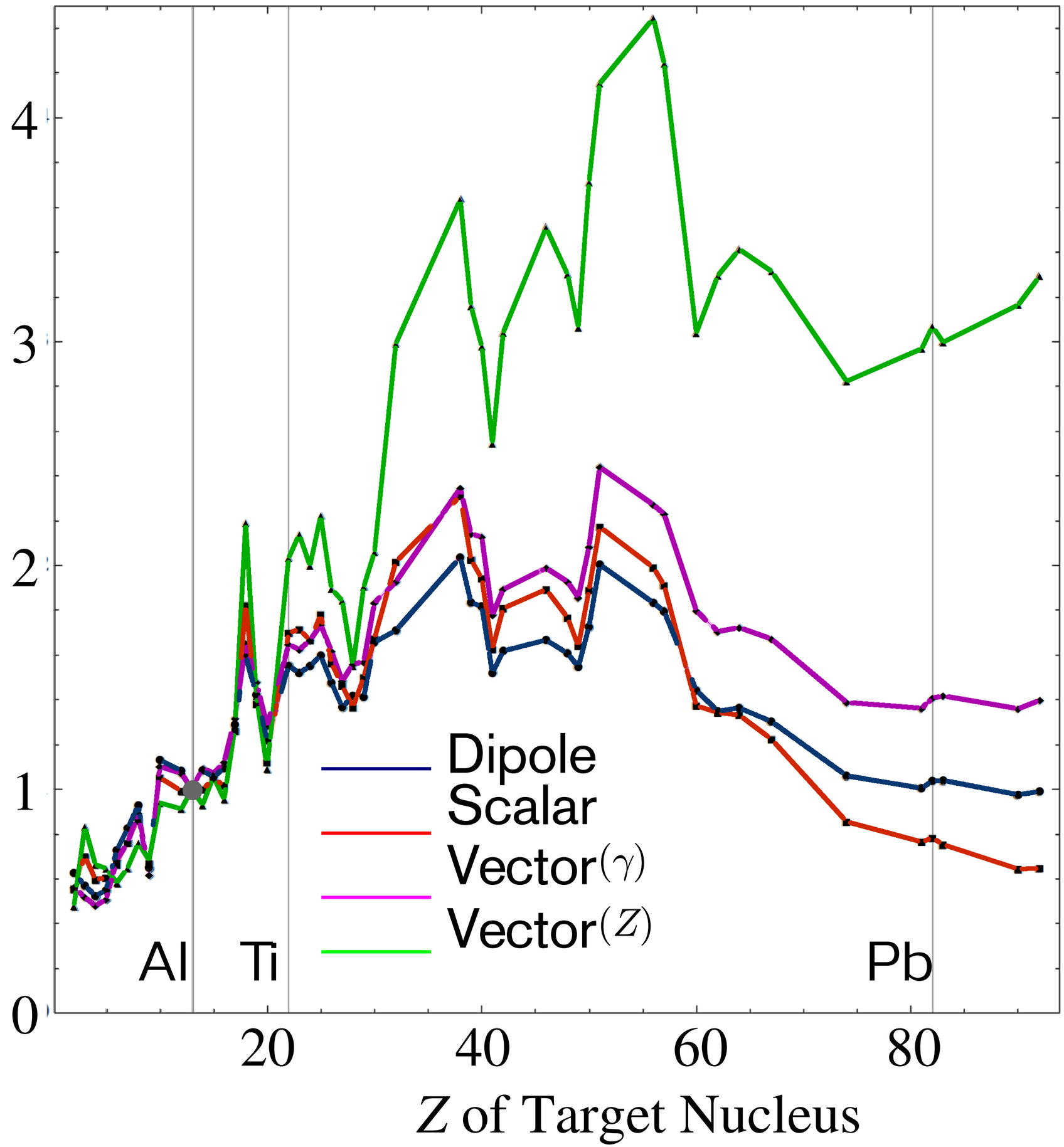
Complementarity of CLFV Channels

- The various CLFV channels *complement* each other
  - CLFV muons and tau decays
    - different muon-to-electron conversion nuclei
  - CLFV decays of heavier particles
    - mesons, vector bosons, Higgses....
- The relative rates can tell us the nature of the BSM physics

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



Summary

- Charged lepton flavour violation is a powerful probe for physics beyond the Standard Model
- Numerous experiments to come online in next few years
  - challenging experiments resulting in much innovation, from beam lines to detectors
  - significant improvements and discovery potential
  - many technical connections to neutrino experiments
    - pion production and capture, manipulation of intense muon fluxes, intense proton and muon beam diagnostics, novel detector systems, **daq, software and computing**
- The big discovery which transforms CLFV may be just round the corner, just like with neutrinos in the 1990s....

Forthcoming CLFV Talks This Week

- Thursday Plenary, 10am:
  - "Connections between g-2, EDMs, CLFV and LHC (Theory Overview)" Paride Paradisi
- Thursday WGs 3&4
  - 2.30pm: "PRISM" Jaroslaw Pasternak
  - 2.53pm: "Mu2E (beam line)" Vladimir Nagaslaev
  - 3.38pm: "Muon beam line for COMET" Ye Yang

- **Also many closely-related topics in today's WG4 session immediately following this plenary session**

Comet
California
CPFC