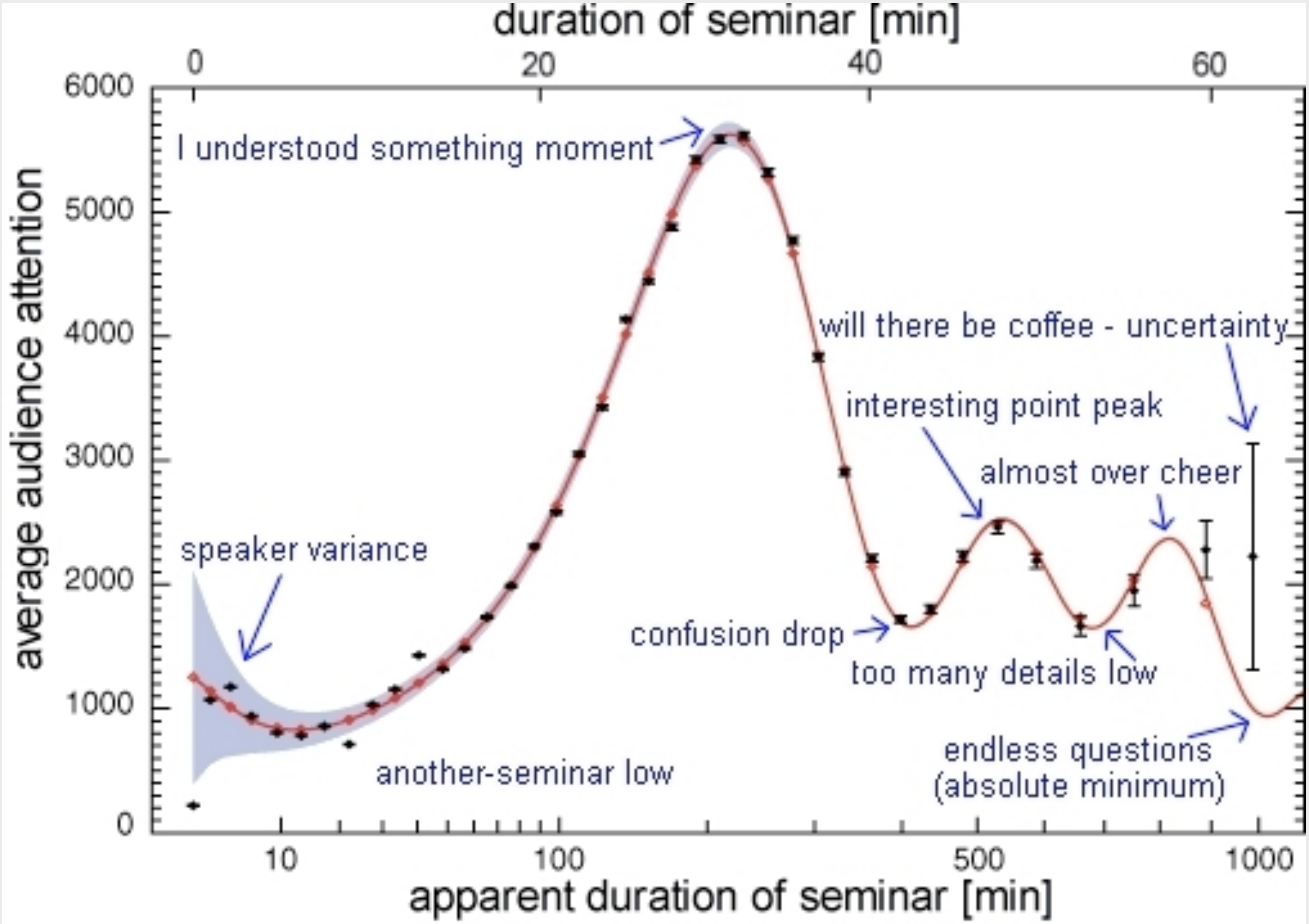
Outline



http://th.physik.uni-frankfurt.de/~hossi/Bilder/BR/powerspectrum.jpg

$\mu \longrightarrow e\gamma$

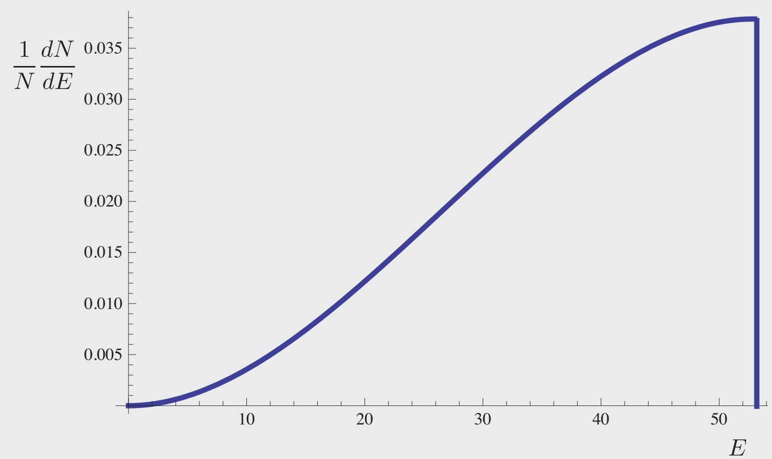
- We have seen (Peter's lecture) that the field has gone back and forth on converting the photon
  - don't convert: get rate, lose resolution on the photon
  - convert: lose rate, get resolution
- Track Record:
  - Crystal Box did not convert, did well
  - MEGA: pattern recognition led to problems
  - MEG: did not convert, doing great

Central Issue

- A significant part of the history of $\mu \longrightarrow e\gamma$ searches is the negotiation of the tradeoffs between rate, duty factor, running time, and sensitivity.

What Drives Background?

- If you don't convert the photon, you are fighting free muon Michel spectrum: electron from one event combined with a photon from another



- And then radiative muon decay, (neutrino momenta small) $\mu^+ \to e^+\gamma\nu_e\bar{\nu}_\mu$

store for $\mu \to 3e$

- other bkgs, but the first dominates so far

Encapsulated in this Equation

- Background is driven by these resolutions:
  - This is proportional to "1/number of muons to see one background event"
  - So $\mathcal{B} \propto (\frac{R_\mu}{D})(\Delta t_{e\gamma})\frac{\Delta E_e}{m_\mu/2}\left(\frac{\Delta E_\gamma}{15m_\mu/2}\right)^2\left(\frac{\Delta\theta_{e\gamma}}{2}\right)^2$
    - Rate/Duty Factor (less time for same rate increases accidental coincidences)
    - time, electron energy linear
    - angle, photon energy quadratic

Key Ideas

$$\mathcal{B} \quad \propto \quad (\frac{R_\mu}{D})(\Delta t_{e\gamma})\frac{\Delta E_e}{m_\mu/2}\left(\frac{\Delta E_\gamma}{15 m_\mu/2}\right)^2\left(\frac{\Delta\theta_{e\gamma}}{2}\right)^2$$

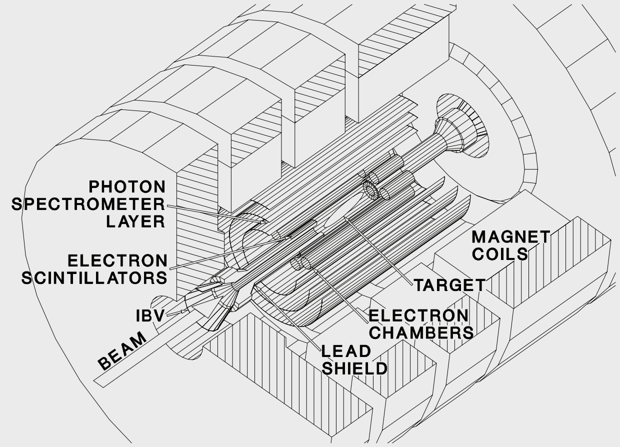
1. The time difference between any two stops is essentially random, hence the $\Delta t_{e\gamma}$ term and the R_μ/D dependences.
2. The Michel spectrum is $\Gamma(\epsilon)\,d\epsilon \propto (3-2\epsilon)\epsilon^2\,d\epsilon$, where $\epsilon = 2E_e/m_\mu$. Near $\epsilon = 1$ at the maximum the derivative is zero. Hence the $\Delta E_e/(m_\mu/2)$ dependence.
3. the radiative decay $\mu \to e\nu\nu\gamma$ near the zero-energy neutrino edge is a bremsstrahlung term that behaves as $(1-y)\,dy$ where $y = 2E_\gamma/m_\mu$. Hence the background under the $\mu \to e\gamma$ peak is proportional to the integral over the resolution window of width Δ: $\int_{(1-\Delta)}^{1}(1-y)\,dy$ which is just proportional to Δ^2.
4. The angular term is simple as well. Since the direction of the photon in a $\mu \to e\gamma$ decay is opposite to the direction of the electron, the area of the angular phase space is a small patch of area $\Delta\theta_{e\gamma}\Delta\phi_{e\gamma}$, yielding a quadratic dependence in angular resolution. The precise form will depend on whether the photon is converted and details of the apparatus.

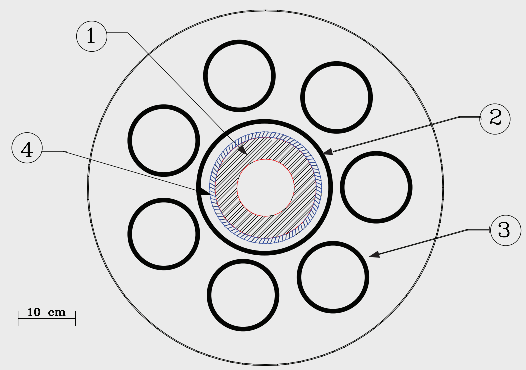
Crystal Box

- Did not convert photon
- at LAMPF (pub. 1984)
    - 300 μA, 800-MeV proton beam at 120 pulses per second, with duration 530 μsec. The average duty factor for the experiment was 6.4%. This small duty factor ultimately limited the experiment by causing pile-up in the tracking chambers, frequently making track reconstruction unsuccessful and reducing the acceptance.

MEGA

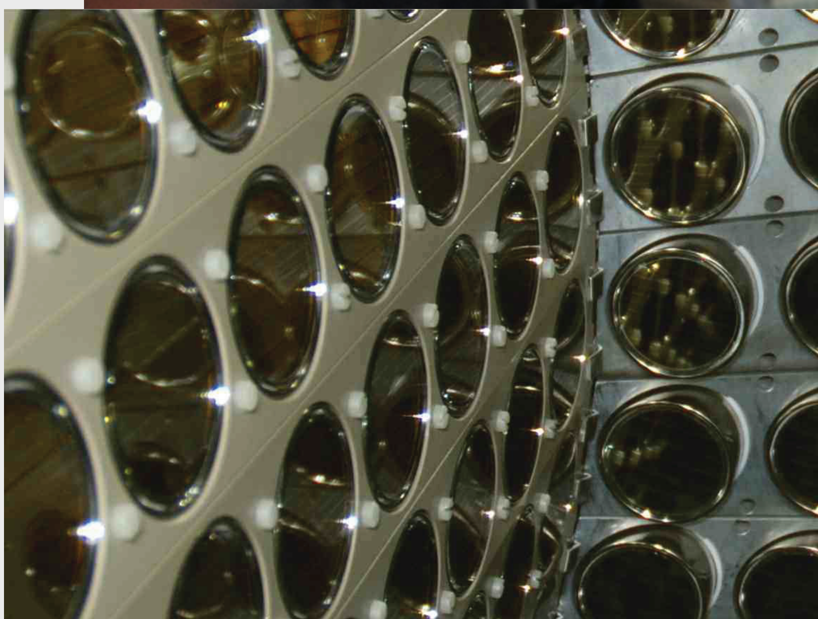
- Converted photon in concentric layers of converter
  - this idea is being repeated in PX suggestions
- Peter covered this in detail; will not repeat



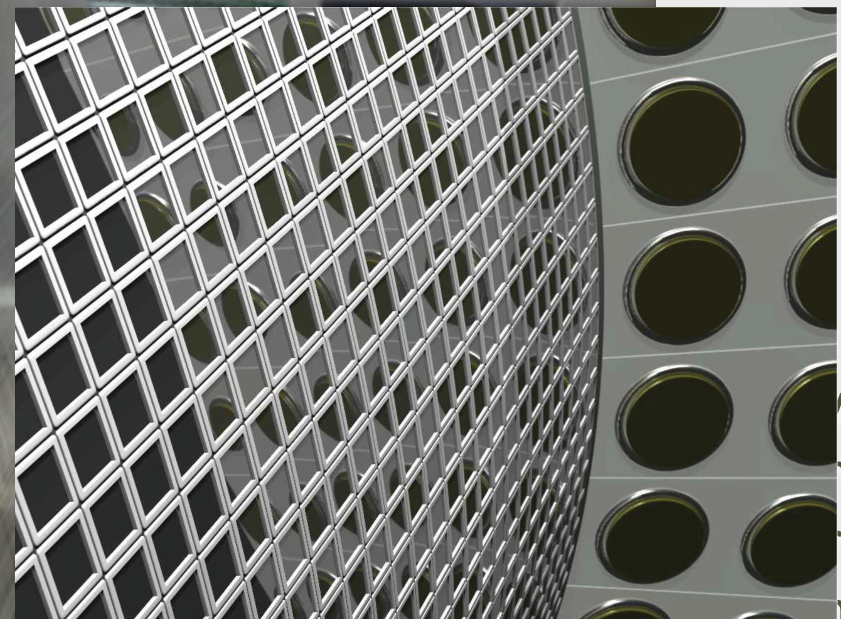


MEG

better PMT coverage, particularly on sides



(a) Present detector

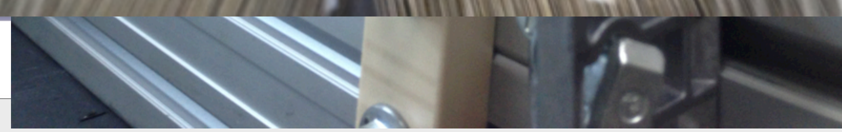


(b) Upgraded detector (CG)

vative
mass
ift
mber
from Lecce

Possible replacement of 216 PMTs in the entrance face with smaller photo-sensors (about 4000 MPPCs with 12 x 12 mm^2 area each).

5.



MEG Magnetic Field

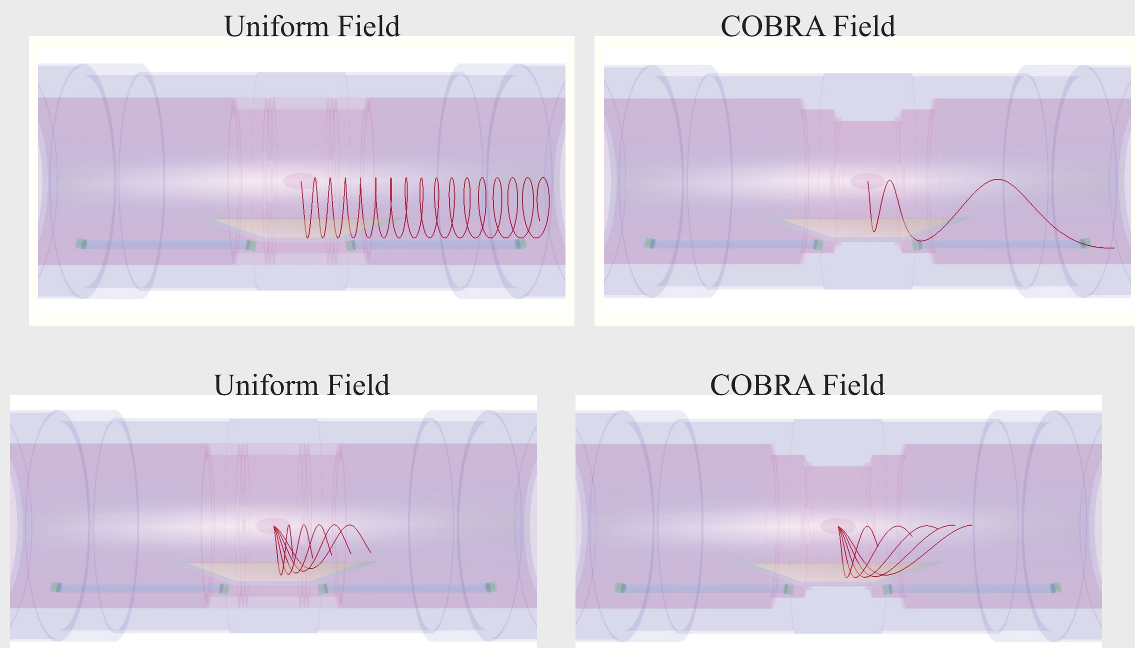
- Solenoidal fields have the advantage of confining low momentum tracks, which is useful for keeping Michel positrons out of the detector.
- But a simple solenoidal field has two disadvantages:
  - positrons emitted close to 90^{o} to the field curl many times, yielding large numbers of hits and potential problems in pattern recognition and momentum resolution
  - the bending radius depends on the angle, which makes it difficult to select the desired high-momentum tracks at the Michel peak.

COBRA Spectrometer

- Therefore MEG adopted a gradient field near that slowly decreased as |z| increased. This gradient quickly sweeps out the positrons near 90^o

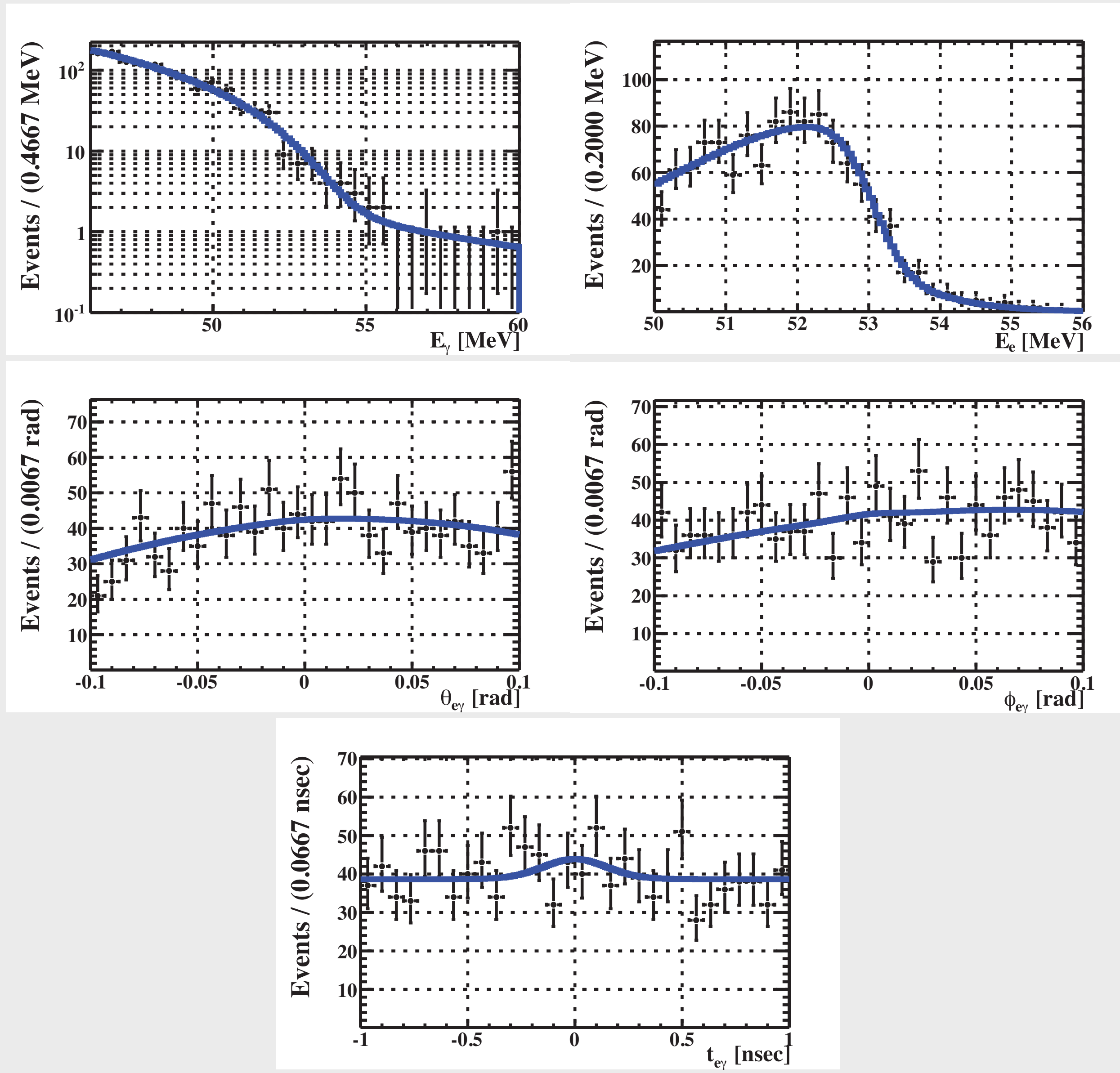
- The precise gradient is set so that monochromatic positrons follow a (CO)nstant projected (B)ending (RA)dius independent of emission angle. The bending radius is thus set by the absolute momentum, not the transverse component --- hence the name COBRA.

z from 1.25 to 0.49 T



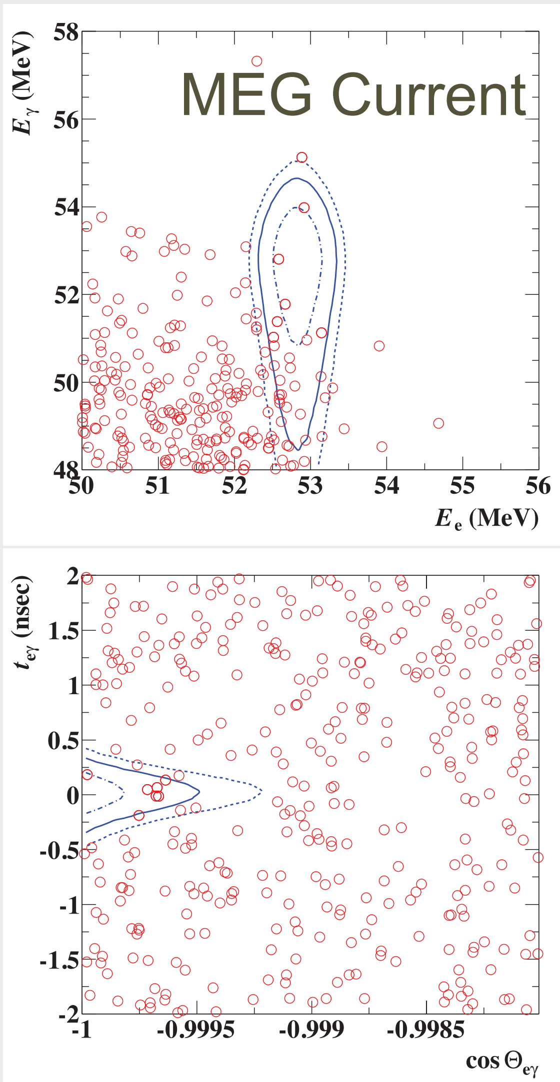
MEG Resolutions

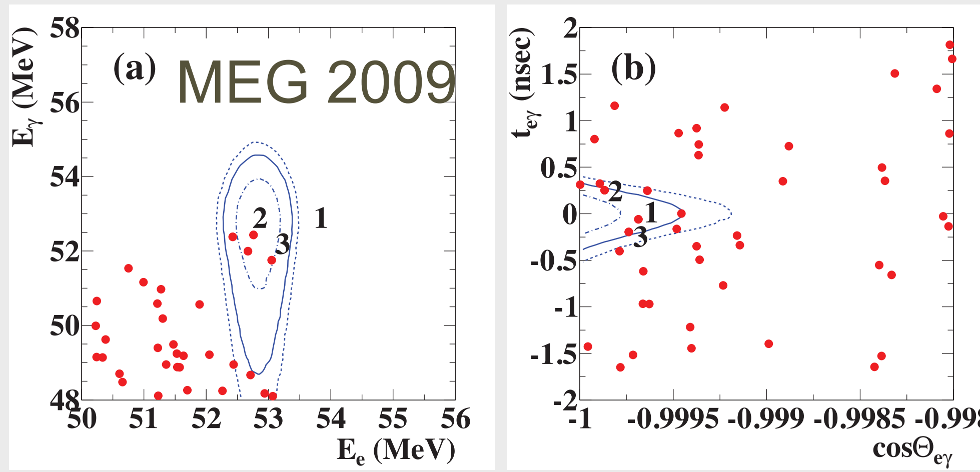
- Kinematic and time distributions from Adam et al. [2011] demonstrating the background dependences.
- The "bump" in $\Delta t_{e\gamma}$ near t = 0 is from radiative muon decay.
- Shift in the $\Delta\theta_{e\gamma}$ and $\Delta\varphi_{e\gamma}$ distributions. These exist because there is a slight correlation between angle and energy in the apparatus; since the experiment is performed at the kinematic edge one tends to have an average underestimate of the momentum (seen in the E_e distribution), which then causes the correlation.

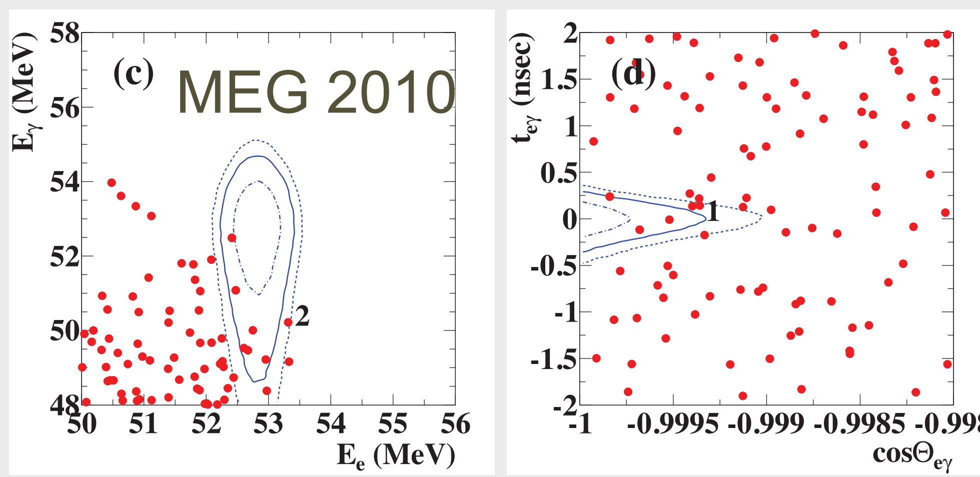


Looking at Results

- Recall enhancement at $\Delta t_{e\gamma}=0$







Resolutions

from MEG upgrade proposal

Variable	Foreseen	Obtained
ΔE_γ (%)	1.2	1.9
Δt_γ (psec)	43	67
γ position (mm)	4 (u,v), 6(w)	5(u,v),6(w)
γ efficiency	> 40	60
Δp_e (keV/c)	200	380
e^+ angle (mrad)	$5(\phi_e), 5(\theta_e)$	$11(\phi_e), 9(\theta_e)$
Δt_{e^+} (psec)	50	107
e^+ efficiency (%)	90	40
$\Delta t_{e\gamma}$ (psec)	65	120

what they proposed vs. what was obtained

$$\mathcal{B} \quad \propto \quad (\frac{R_\mu}{D})(\Delta t_{e\gamma})\frac{\Delta E_e}{m_\mu/2}\left(\frac{\Delta E_\gamma}{15m_\mu/2}\right)^2\left(\frac{\Delta\theta_{e\gamma}}{2}\right)^2$$

MEG Upgrade

$$\mathcal{B} \quad \propto \quad (\frac{R_\mu}{D})(\Delta t_{e\gamma})\frac{\Delta E_e}{m_\mu/2}\left(\frac{\Delta E_\gamma}{15m_\mu/2}\right)^2\left(\frac{\Delta\theta_{e\gamma}}{2}\right)^2$$

Variable	Present	Upgrade
e^+ energy (keV)	306(core)	130
$e^+\theta$ (mrad)	9.4	5.3
$e^+\phi$(mrad)	8.7	3.7
e^+vertex (mm) Z/Y(core)	2.4/1.2	1.1/1.0
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
$\gamma - e^+$ timing (ps)	122	84

Efficiency(%)	Present	Upgrade
trigger	≈ 99	≈ 99
γ	63	69
e^+	40	88

see upgrade proposal for details, but overall improvement clear

Going Beyond MEG

- Why did MEG at PSI not convert?
  - can only get about as much beam as they are getting
  - therefore can't afford big loss to conversion; if 10% of a radiation length, order-of-magnitude worse limit
  - clearly right choice for them and for their upgrades
  - and MEGA experience was scary

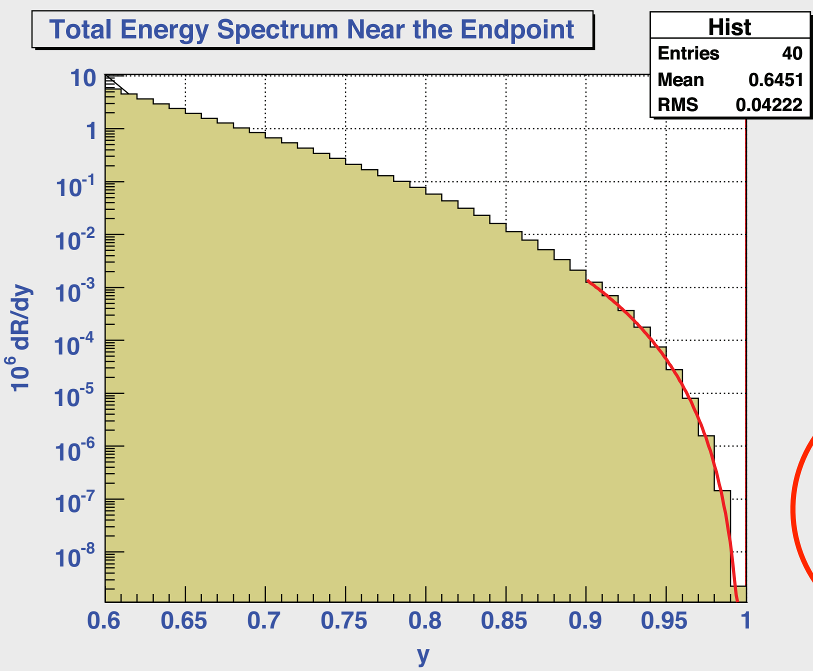
$\mu \longrightarrow 3e$

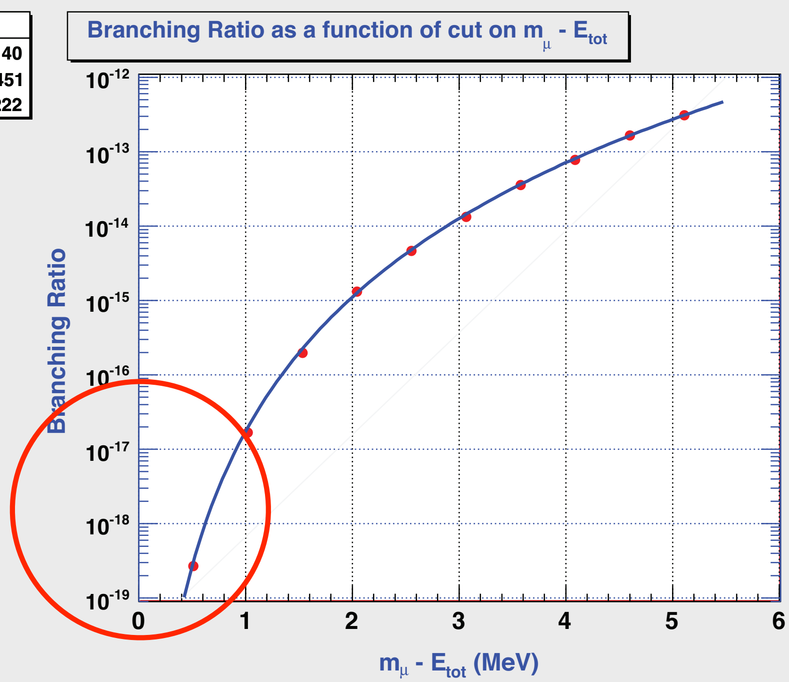
- Often a sister experiment to $\mu \rightarrow e\gamma$
- New Proposal at PSI for just this mode
- Multi-stage:
  - First Stage SES Ultimate SES of ~10^{-15}
    - 10^8 muons/sec
  - Ultimate SES of ~10^{-16}
    - 2 x 10^9 muons/sec
    - requires upgrade at PSI using spallation neutron source; in planning stages

$\mu \to 3e$

- Background of Radiative Muon Decay:

$$R = 2.99 \times 10^{-19} \left(\frac{m_\mu - E_{\text{charged leptons}}}{m_e} \right)^6 \qquad \mu \to 3e\nu\nu$$

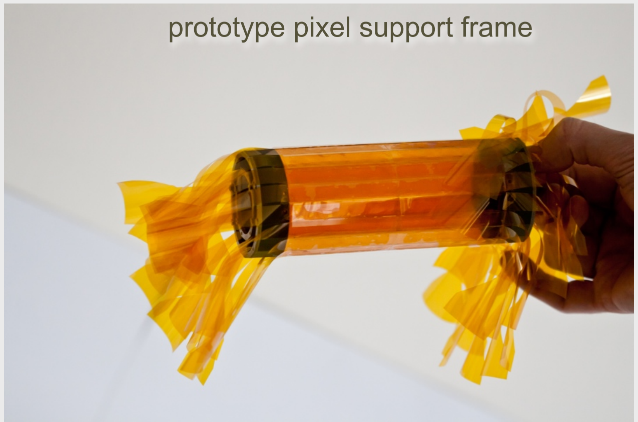




90%CL depends on resolution: how far out does one integrate?

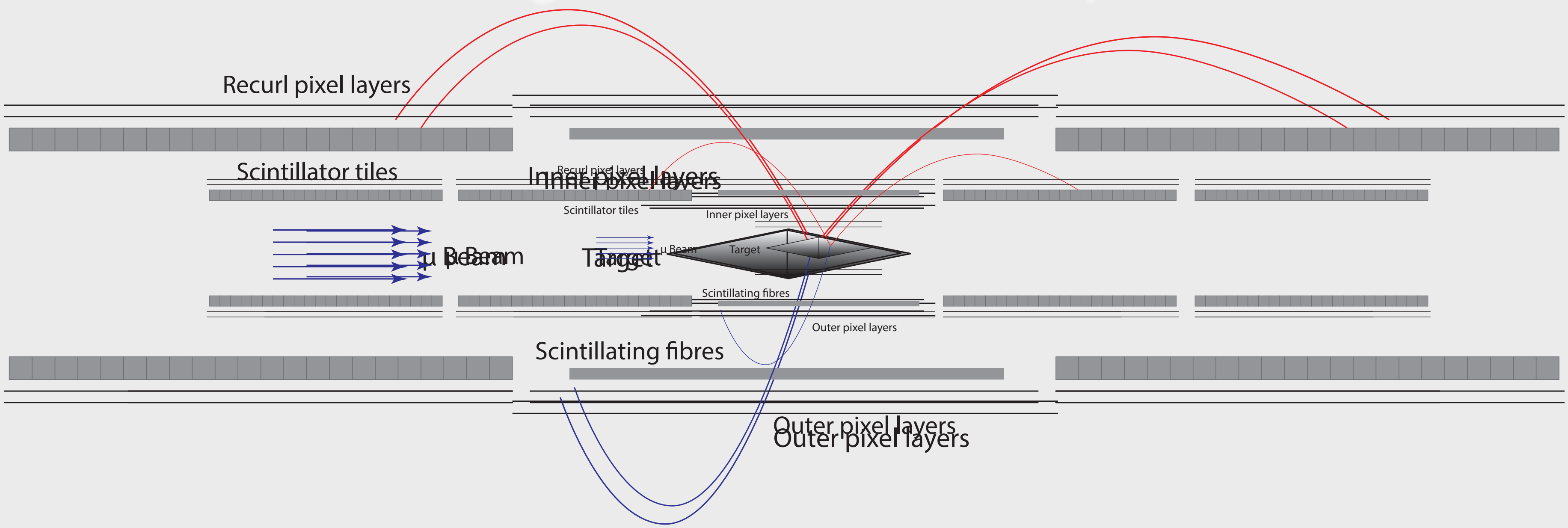
$\mu \rightarrow 3e$ at PSI

- So it's all about resolution and non-gaussian tails
- Approved at PSI: 10^4 beyond previous experiment
  - Stopped μ^+ beam with Pixels and Scintillating Fiber



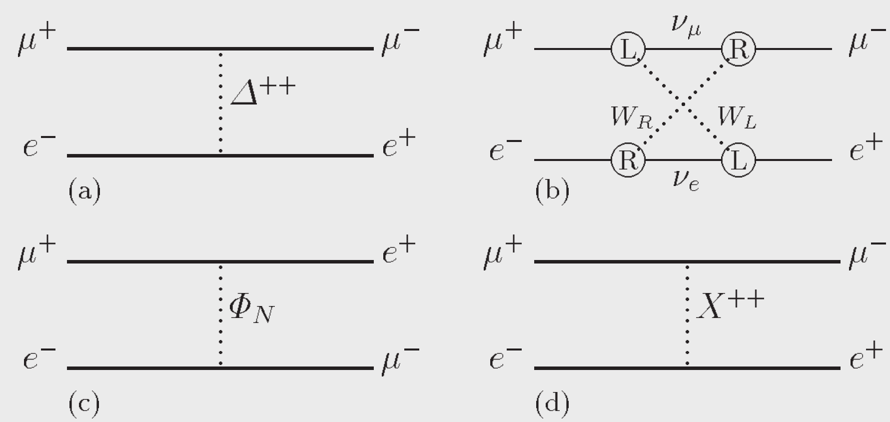
Design

- Not too different in geometry from previous experiments: stopping target surrounded by apparatus
- New part is resolution of detector with pixels and scintillating fiber TOF hodoscope

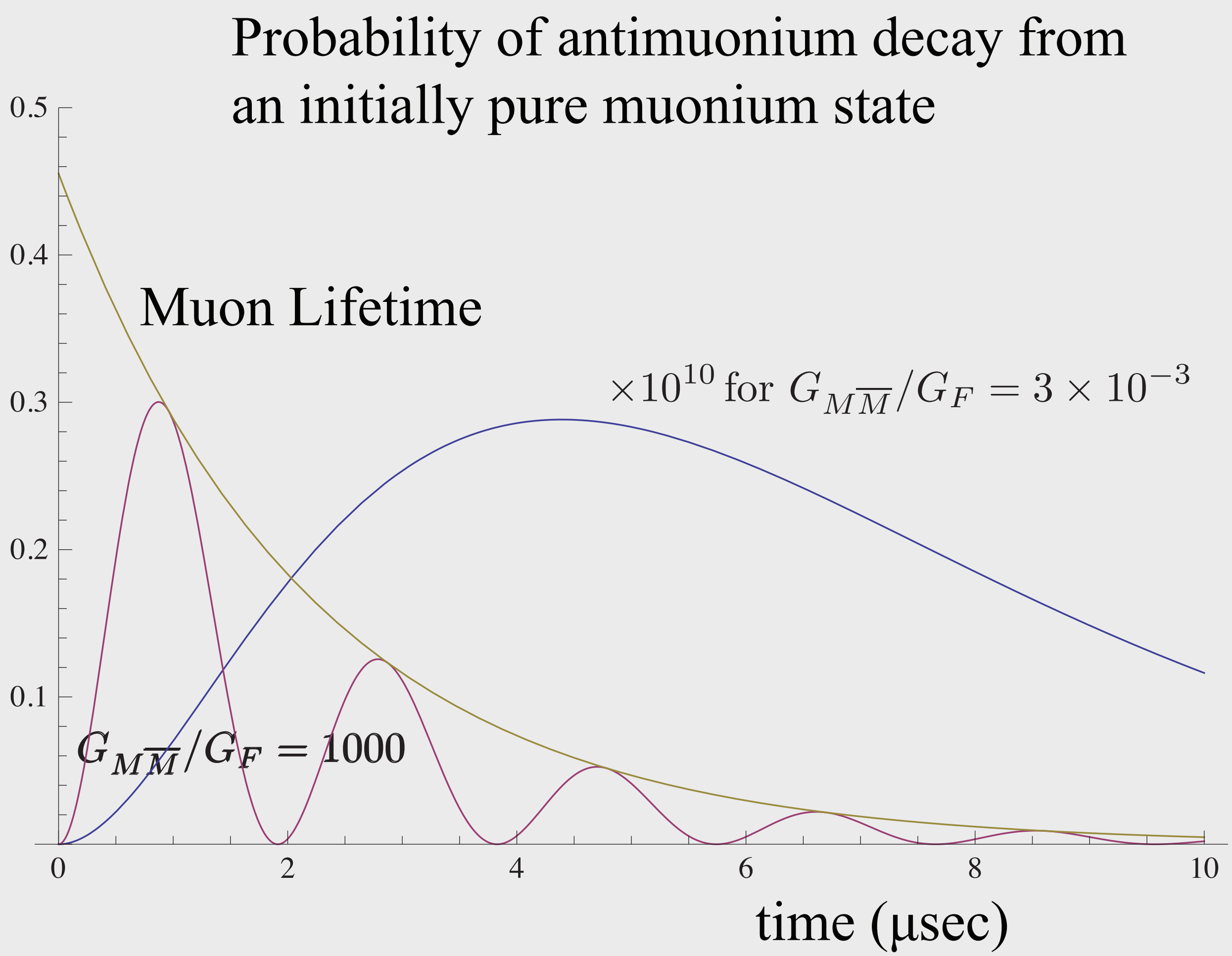


Muonium-Antimuonium

- $\mu^+e^- \leftrightarrow \mu^-e^+$
  - Leptoquarks, doubly charged Higgs, Heavy Majorana neutrinos,...
  - New interactions break degeneracy
  - Not unlike $K^0\ \overline{K}^0$ system
  - Usually parameterize as G/G_F



Math



best paper on muonium-antimuonium theory:

G. Feinberg and S. Weinberg, Phys.Rev. 123, 1439 (1961).

Relevant Equations

$$\frac{\delta}{2} = \frac{8\,G_F}{\sqrt{2}n^2\pi a_o^3}\left(\frac{G_{\mathrm{Mu}\overline{\mathrm{Mu}}}}{G_F}\right)$$

where n is the principal quantum number and a_o is the Bohr radius of the muonium atom. For $n = 1$,

$$\delta = 2.16 \times 10^{-12}\,\frac{G_{\mathrm{Mu}\overline{\mathrm{Mu}}}}{G_F}\ \mathrm{eV}$$

Assuming an initially pure μ^+e^- state, the probability of transition is given by:

$$\mathcal{P}(t) = \sin^2\left(\frac{\delta t}{2\hbar}\right)\ \lambda_\mu e^{-\lambda_\mu t}$$

where λ_μ is the muon lifetime. Modulating the oscillation probability against the muon lifetime tells us the maximum probability of decay as anti-muonium occurs at $t_{\mathrm{max}} = 2\tau_\mu$. The overall probability of transition is

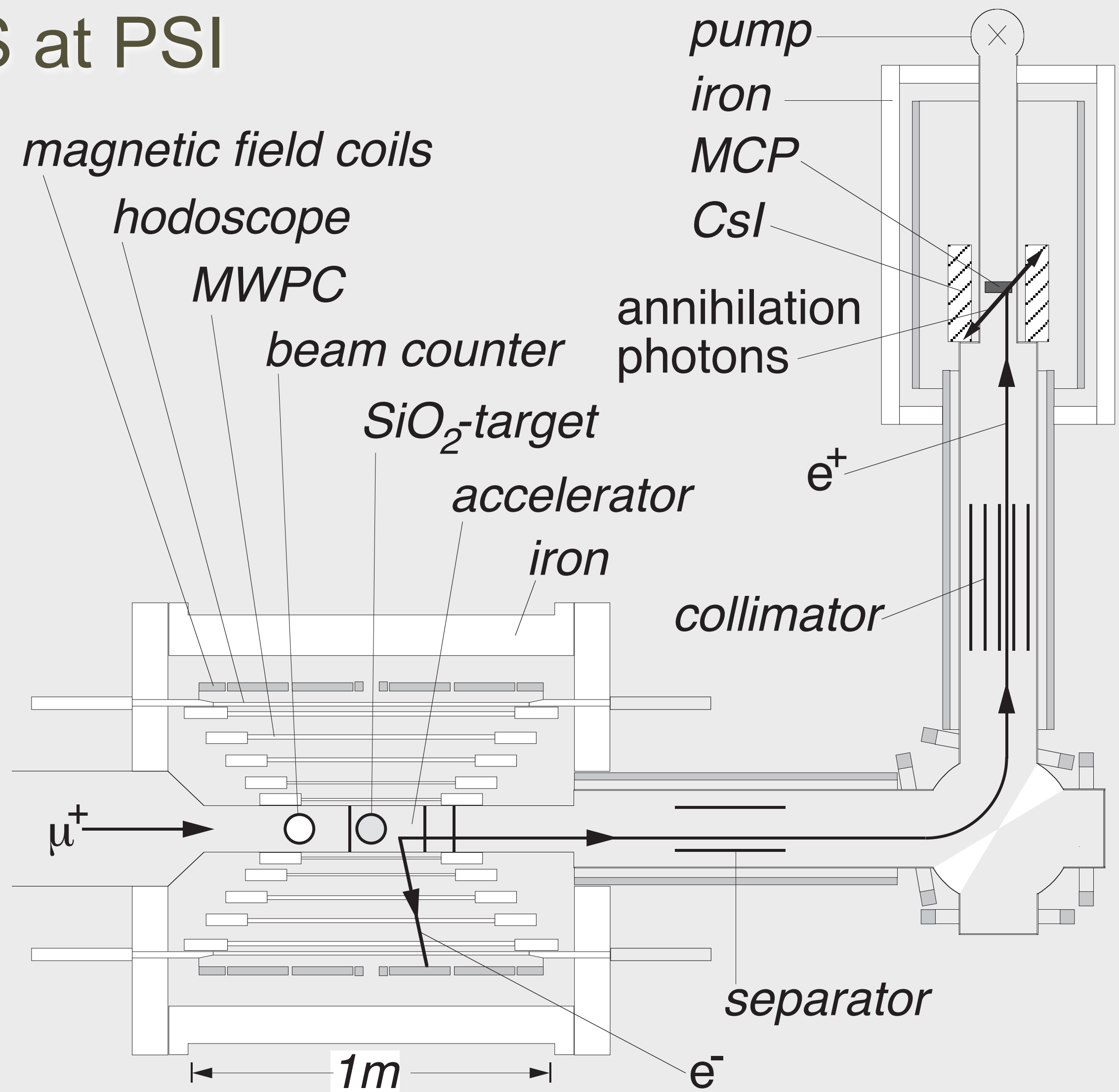
$$P_{\mathrm{total}} = 2.5 \times 10^{-3}\left(\frac{G_{\mathrm{Mu}\overline{\mathrm{Mu}}}}{G_F}\right)$$

Beautiful Experimental Methods

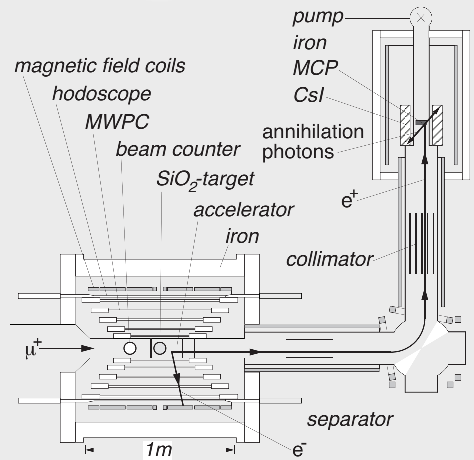
- How do you make muonium?
  - make a sub-surface beam
    - sub-surface beams stop inside, not on surface, and have a lower momentum distribution than surface beams
    - this yields a smaller straggling by $\Delta R \sim p^{3.5}$ and a tighter spatial stopping distribution (MEG is considering this)
  - let the positive muons stop in SiO_2 powder, a technique invented at TRIUMF
  - The powder structure stops the positive muon and the voids permit the muonium to escape
  - Other new ideas, but no time... see article and J-PARC work

Experiment

- MACS at PSI



Signal and Background

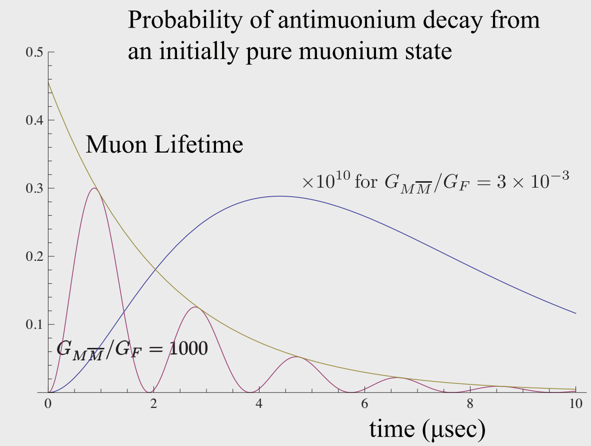


- Signal:
  - μ^- decay (e^- near Michel peak) in coincidence with e^+
- Backgrounds:
  - 1. The rare decay mode $\mu^+ \to e^+ e^+ e^- \nu_e \bar{\nu}_\mu$ with a branching ratio of 3.4×10^{-5}. If one of the positrons has low kinetic energy and the electron is detected, this channel can fake a signal.

    2. The system starts as muonium, hence $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ yields a positron. If the e^+ undergoes Bhabha scattering, an energetic electron can be produced. Background results from the coincidence of that scattering with a scattered e^+. The positron's time-of-flight is is used to reject background.

$e^+ e^- \to e^+ e^-$, annihilation or scattering

How to do better?

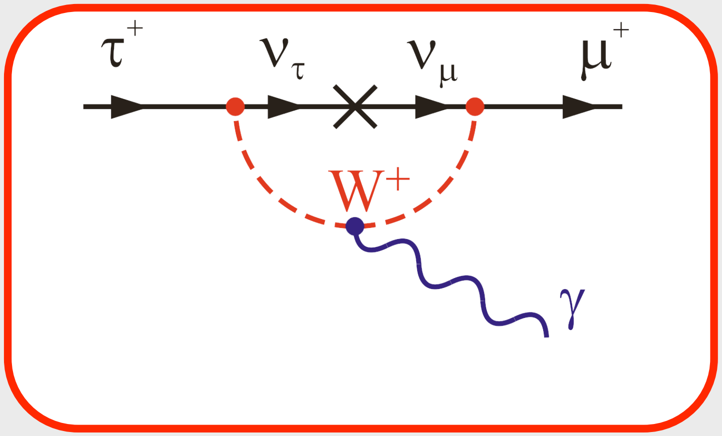


- Both backgrounds can be suppressed with a pulsed beam and by waiting for the muon lifetime to suppress the muon decay
  - can make up the muon flux at a hotter beam, which did not exist at the time of MACS
- Modern detectors have much better resolution
- discussions with experts: x100 should be achievable

CLFV and Tau Decays

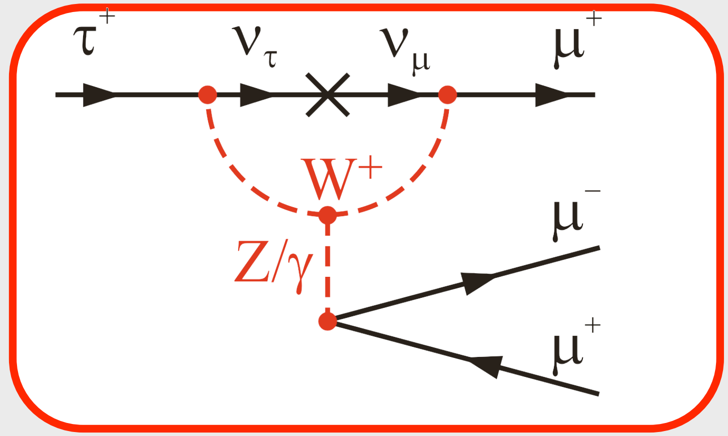
Highly suppressed in Standard Model

Lee, Shrock
Phys.Rev.D16:1444,1977



SM ~ 10^{-40}

Milder
GIM
Cancellations



SM ~ 10^{-14}

Pham, hep-ph/9810484

read this paper!

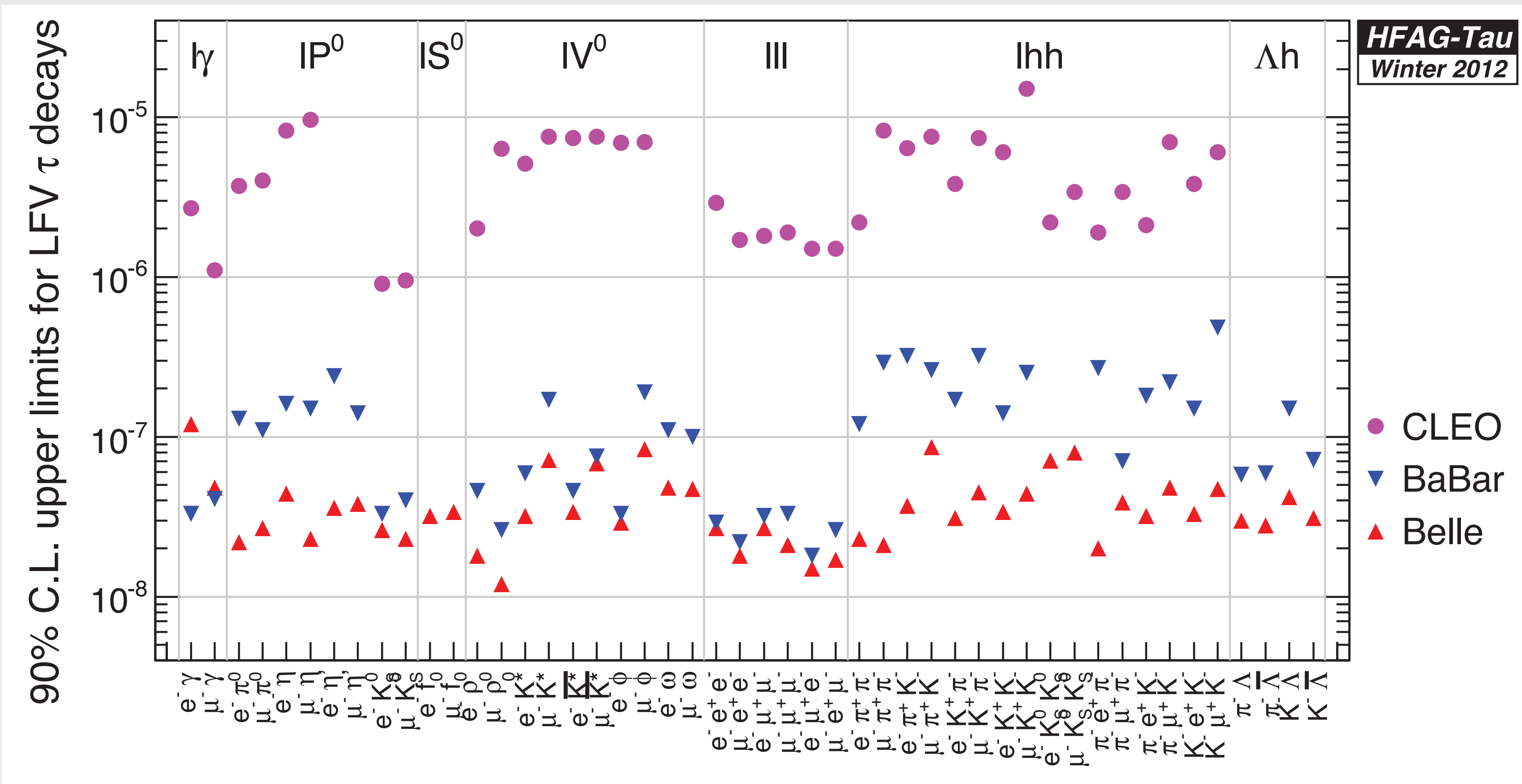
Good News:
BSM rates are several orders of magnitude larger than in associated muon decays

Bad News:
τ's hard to produce:
~10^9 τ/yr vs ~10^{11} μ/s

note right hand diagram is like $\mu\rightarrow 3e$

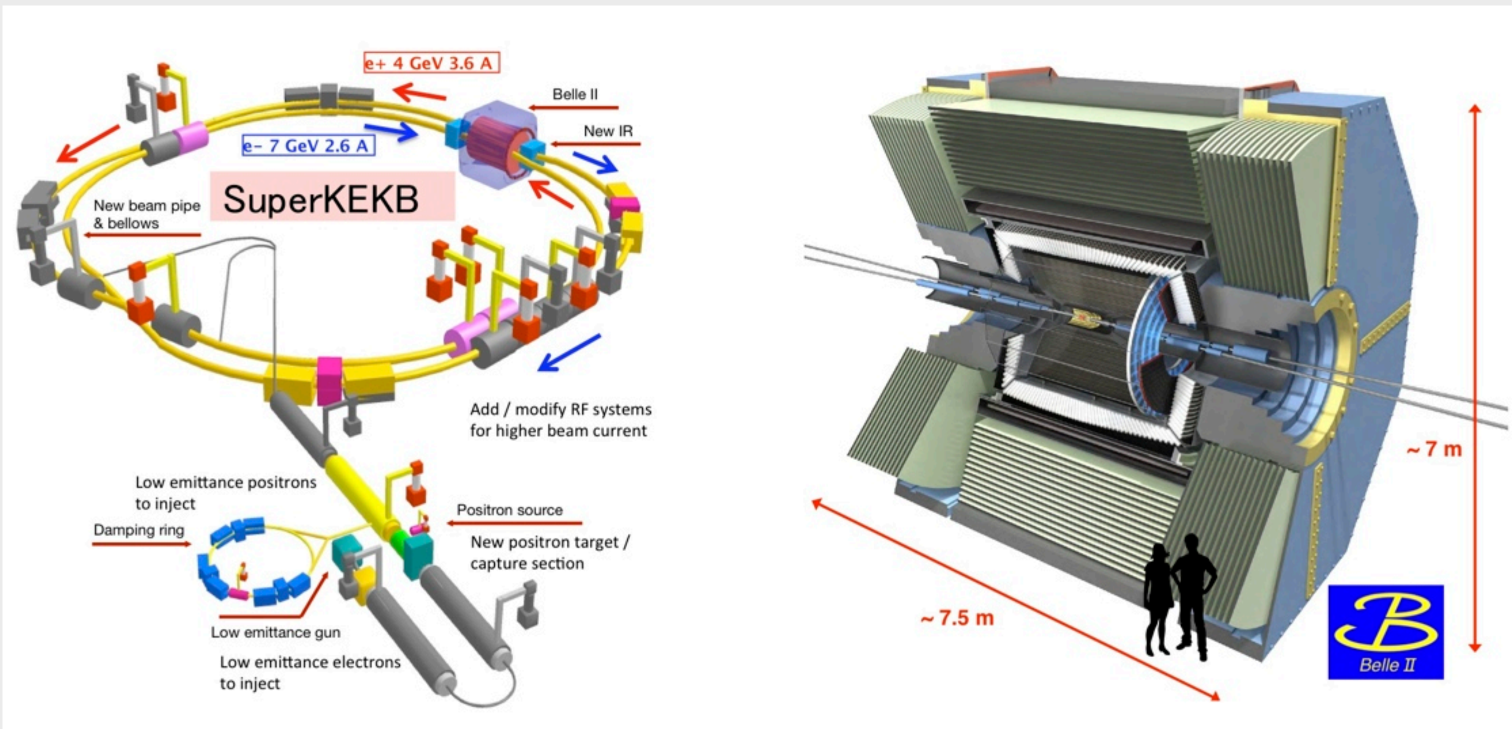
Extensive Program at e^+e^-

- 48 τ modes, typically at few x 10^{-8}
- Expect x10 – x100 in many modes at BELLE-II



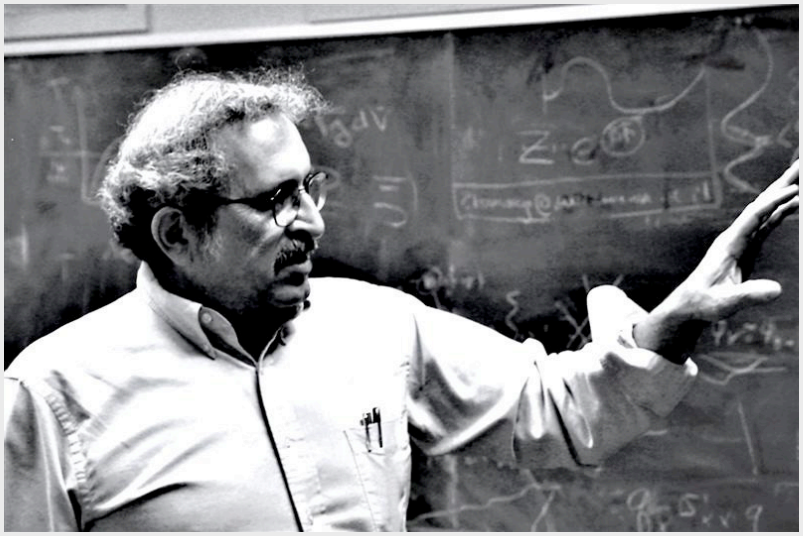
B Physics: Future Facilities

- SuperKEKB and BELLE-II: **50 x 10^9** $\overline{B}B$ pairs
  - Peak L ~ 8 x 10^{35} cm^{-2} s^{-1}, x 40 KEKB, 50 ab^{-1} by 2023

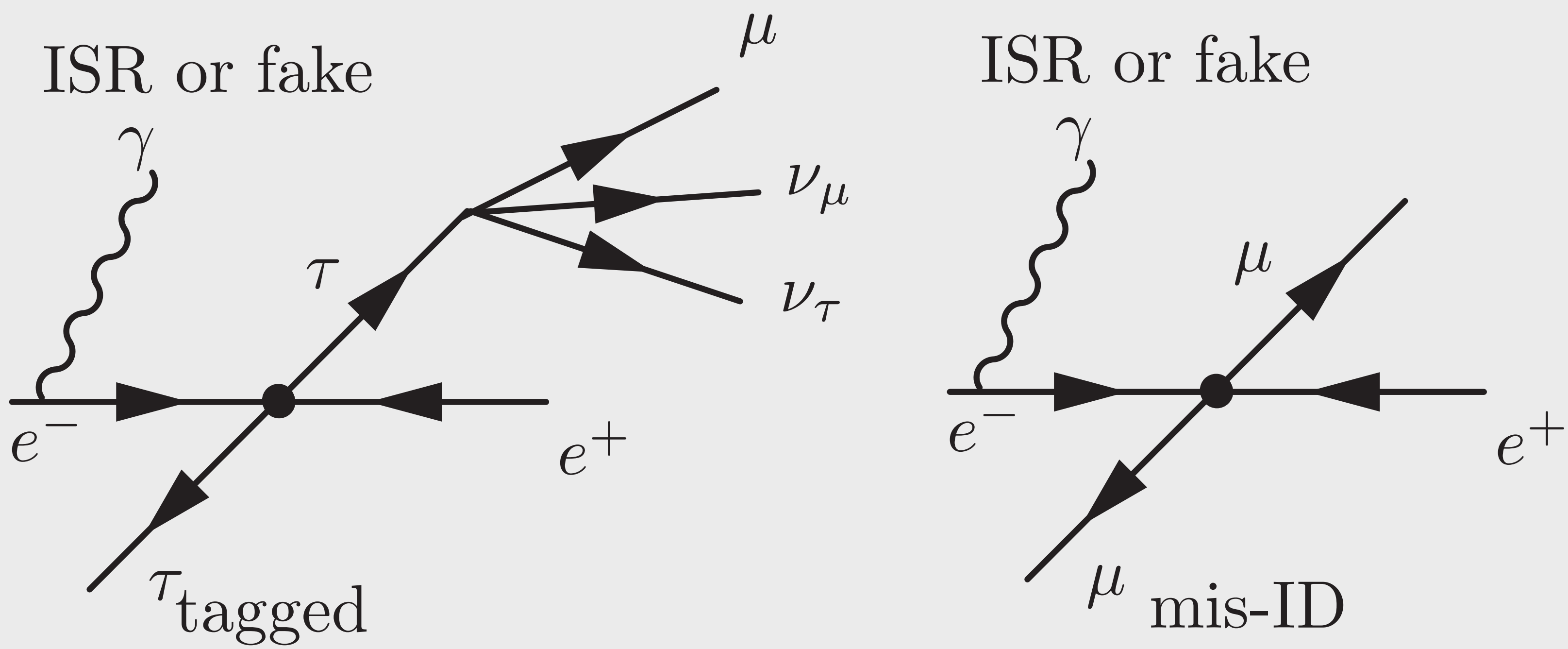


CLFV at $e^+ e^-$ Machines

- Many points of agreement:
  - $e^+ e^-$ colliders are extremely clean
  - can get incisive measurements
  - can look at Higgs CLFV modes directly
- Let's concentrate on existing measurements



Tau-Based Modes



- Tag one tau
- Look for muon in opposite hemisphere
- Backgrounds are various combinations of Initial State Radiation or mis-ID

Searches at LHCb

- Trade between statistics and cleanliness common in hadron/lepton collider comparisons
- LHCb not as good in neutral modes
  - I am sure LHCb will contest this
- LHCb has far more statistics
  - I am sure LHCb will not contest this
  - x100 BaBar and BELLE/yr

ATLAS/CMS

- If you see SUSY, lots to do...look for CLFV decays!
- If not,then $Z \rightarrow e\mu$ is promising but

  H $\rightarrow e\mu,\ e\tau$ are there too; see Roni's talk
- First results out; see clfv.infn.it or paper, but keep checking the arXiv!

First LHCb Results

- Both lepton number and baryon number violating modes; results changing quickly and limits changing all the time

Mode	Limit
$\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-)$	6.3×10^{-8} (90% CL)
$\mathcal{B}(\tau^- \to p\mu^-\mu^-)$	4.6×10^{-7}(90% CL)
$\mathcal{B}(\tau^- \to \bar{p}\mu^+\mu^-)$	3.4×10^{-7}(90% CL)
$\mathcal{B}(B^+ \to \pi^-\mu^+\mu^+)$	5.8×10^{-7}(95% CL)
$\mathcal{B}(B^+ \to K^-\mu^+\mu^+)$	5.4×10^{-8}(95% CL)

A Few Words about B Searches

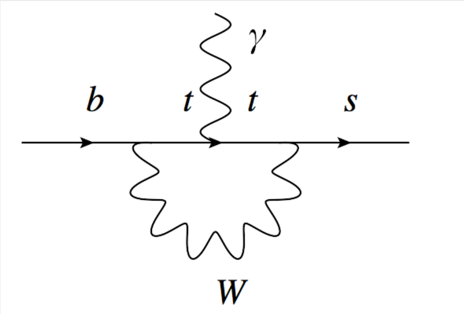
- 2nd-3rd generation fermions (escape bounds from kaon physics)
    - e.g. in SUSY GUTs the near-maximal θ_{23} may imply large mixing between s_R and b_R and $\tilde{s}_R$ and $\tilde{b}_R$
- $B \to X_s \gamma$ especially interesting (3% at SuperKEKB)
    - SUSY in loops, ~ analogous to $\mu \to e\gamma$ or $\mu N \to eN$ diagrams

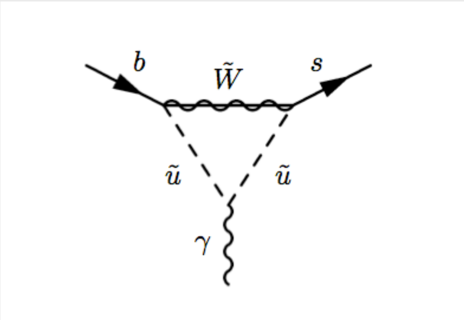
finding deviations from SM

$B \to X_s \gamma$

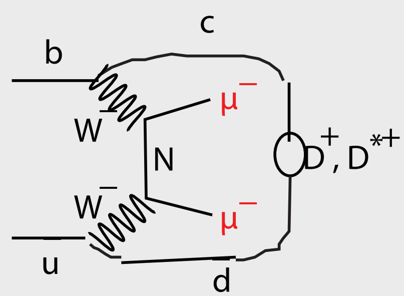
is complementary to

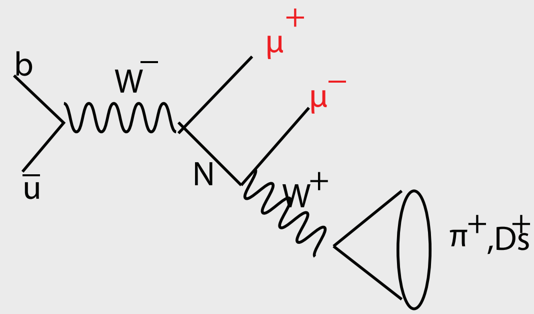
$\mu \to e\gamma$ discovery





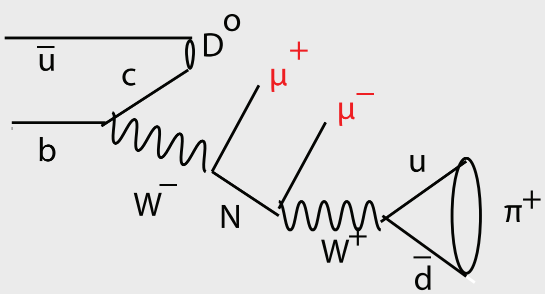
B mesons, Kaons, $0\nu2\beta$: Frontier Invariant



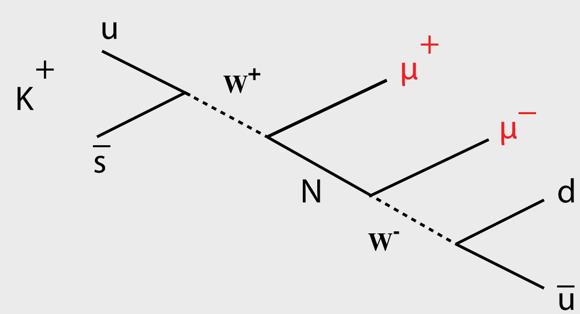


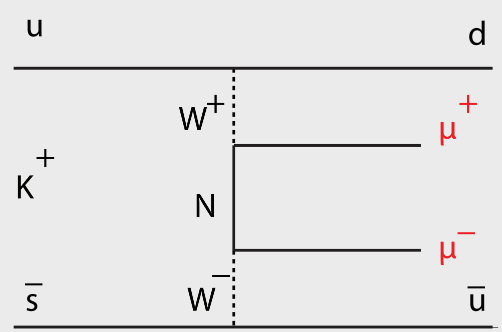
B mesons

heavy neutrinos: Majorana or Dirac?



N: particle to antiparticle





Kaons

Conclusions

- CLFV is a rich subject with a long history
- It has an exciting future with a broad variety of terrific experiments
- And I hope the 3rd edition of Chris' book will need a chapter on it