Search for Charged Lepton Flavor Violation in Muon and Tau Decays

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Flavor Physics and CP Violation 2009
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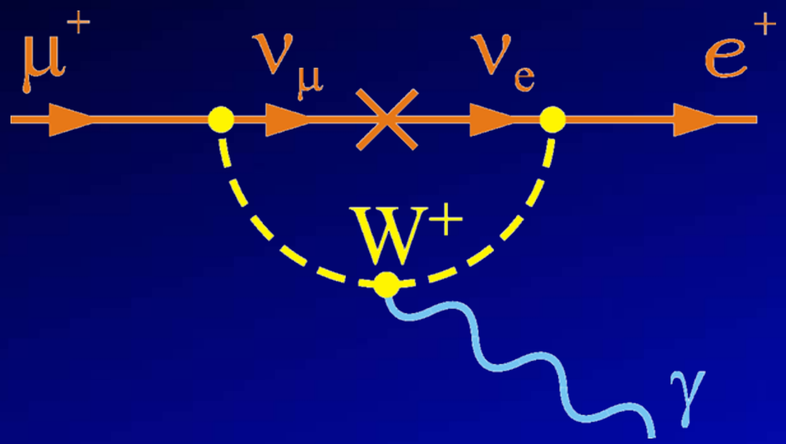
Why Search for Charged Lepton Flavor Violation?

- In Standard Model not there ⇨ discovery of neutrino mass implies it is present, but at an unobservable rate
- Hence, any signal unambiguous evidence of new physics
- Exquisite sensitivities can be obtained experimentally ⇨ sensitivities that allow favored beyond-the-standard-model theories to be tested



$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2$$

$$\approx 10^{-54}\left(\frac{\sin^2 2\theta_{13}}{0.15}\right)$$

Lepton flavor conservation accidental in the extended Standard Model

Where to Search for Lepton Flavor Violation

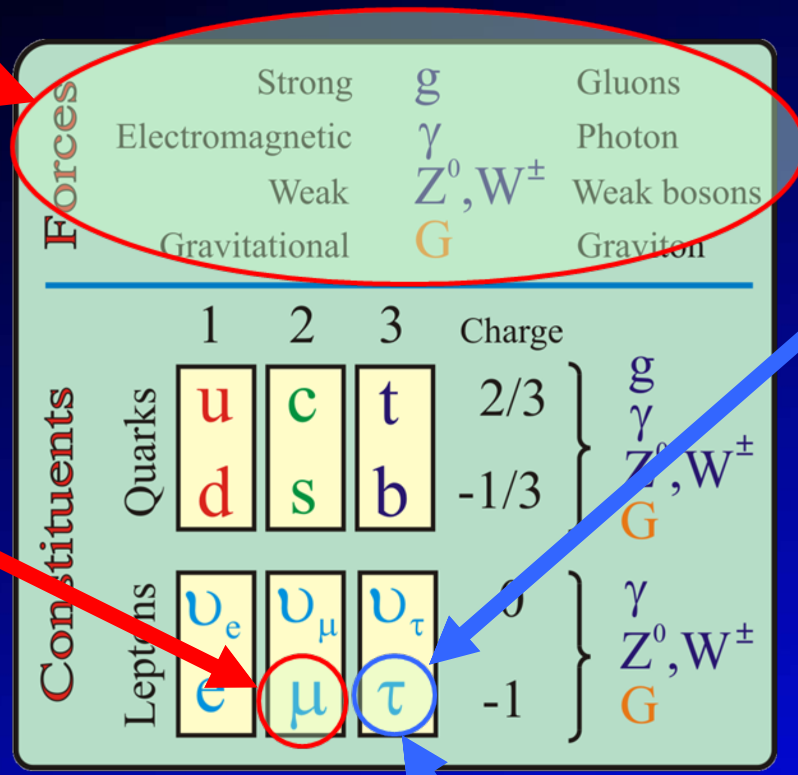
- Many different channels have been searched
- Muon and tau decays appear to be the most promising for future searches

Reaction	Present Limit	Experiment
$\mu^- Au \rightarrow e^- Au$	$< 7.0 \times 10^{-13}$	SINDRUM II
$\mu^- \rightarrow e^- \gamma$	$< 1.2 \times 10^{-11}$	MEGA
$\mu^- \rightarrow e^- e^+ e^-$	$< 1.0 \times 10^{-12}$	SINDRUM I
$\tau^- \rightarrow e^- \gamma$	$< 1.1 \times 10^{-7}$	BaBar
$\tau^- \rightarrow \mu^- \gamma$	$< 4.5 \times 10^{-8}$	Belle
$\tau^- \rightarrow \mu^- \mu^+ \mu^-$	$< 3.2 \times 10^{-8}$	Belle
$\tau^- \rightarrow e^- e^+ e^-$	$< 3.6 \times 10^{-8}$	Belle
$\tau^- \rightarrow e^- K_S$	$< 3.3 \times 10^{-8}$	BaBar
$Z \rightarrow e^\pm \mu^\mp$	$< 1.7 \times 10^{-6}$	OPAL
$Z \rightarrow e^\pm \tau^\mp$	$< 9.8 \times 10^{-6}$	OPAL
$Z \rightarrow \mu^\pm \tau^\mp$	$< 1.2 \times 10^{-5}$	DELPHI
$K^+ \rightarrow \pi^+ \mu^+ e^-$	$< 1.3 \times 10^{-11}$	BNL 865
$K_L \rightarrow e^\pm \mu^\mp$	$< 4.7 \times 10^{-12}$	BNL 871
$B^\circ_d \rightarrow e^\pm \mu^\mp$	$< 9.2 \times 10^{-8}$	BaBar
$B^+_u \rightarrow K^+ e^\pm \mu^\mp$	$< 9.1 \times 10^{-8}$	BaBar
$B^\circ_s \rightarrow e^\pm \mu^\mp$	$< 6.1 \times 10^{-6}$	CDF

I won't be talking about

- Total lepton number violation
  - Neutrinoless double-β decay: $(Z,A) \rightarrow (Z+2,A) + e^- + e^-$
- Hadronic flavor-changing CLFV
  - $K_L \rightarrow e\mu$
- Charged Lepton-antilepton conversion
  - $\mu^- + (Z,A) \rightarrow e^+ + (Z-2,A)$

New Flavor Factories Coming Soon!



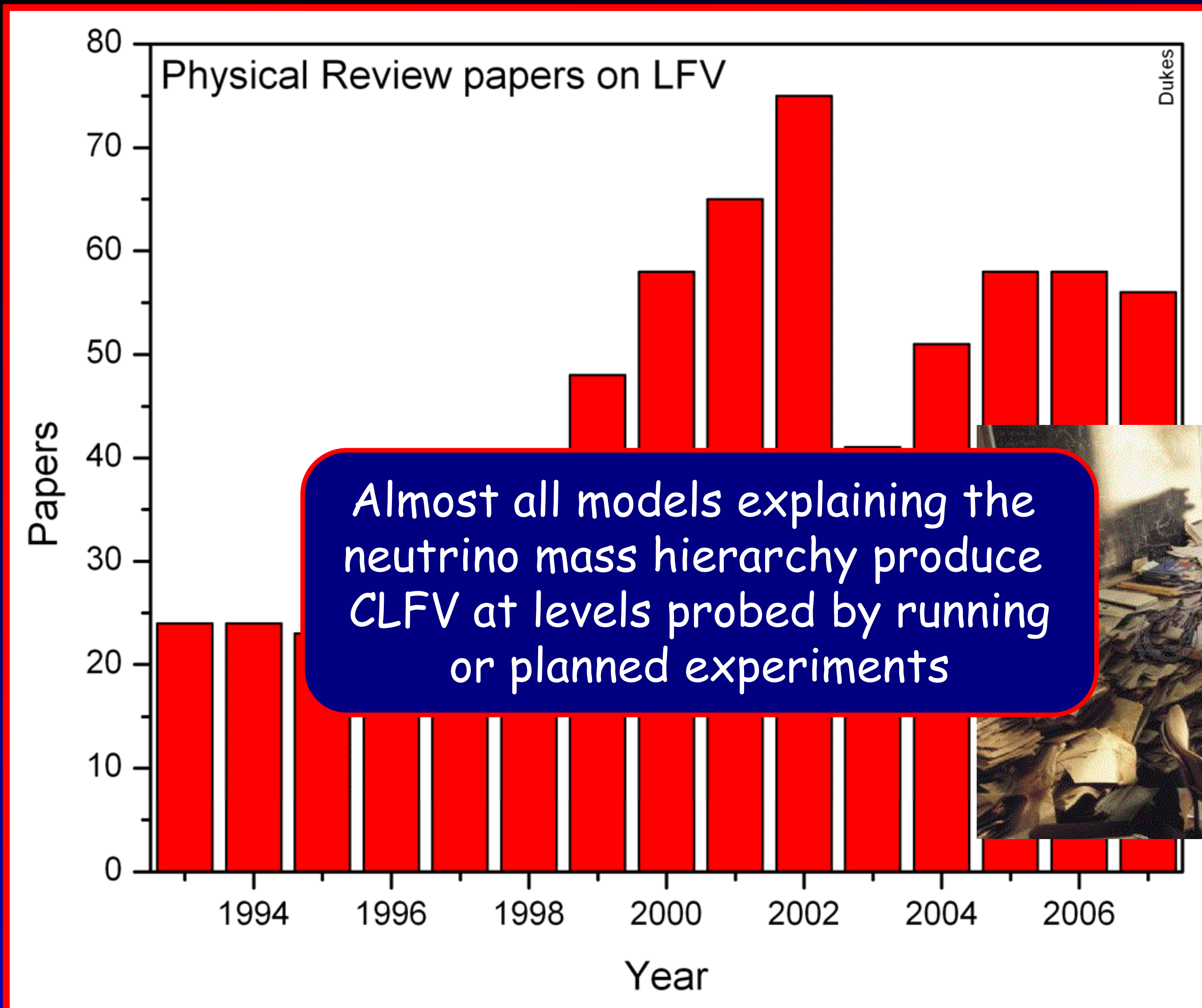
$100-1{,}000$ billion μ/s

10 billion $\tau\bar{\tau}$ / yr

30 million $\tau\bar{\tau}$ / yr

BEBC-II tau-charm Factory at Beijing, China

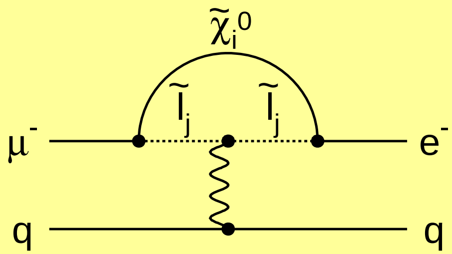
Theoretical Predictions



Almost all models explaining the neutrino mass hierarchy produce CLFV at levels probed by running or planned experiments

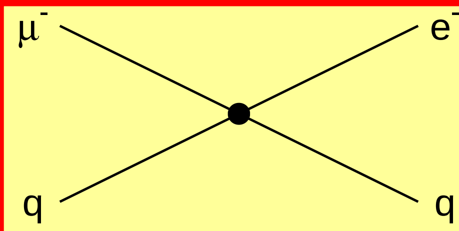
CLFV Sensitive to Many Sources of New Physics

Supersymmetry



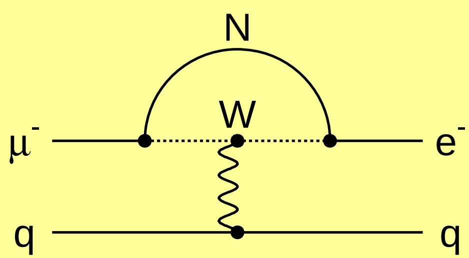
Predictions at 10^{-13}

Compositeness



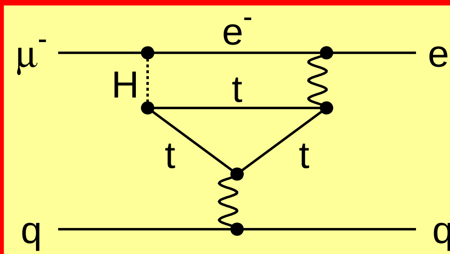
$$\Lambda_c \approx 3000\ \mathrm{TeV}$$

Heavy Neutrinos



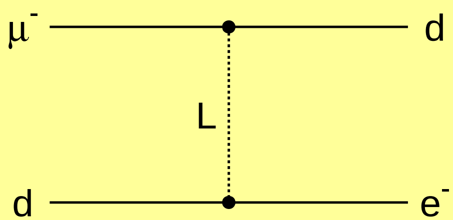
$$\left|U^*_{\mu N} U_{eN}\right|^2 \approx 8\times 10^{-13}$$

Second Higgs doublet



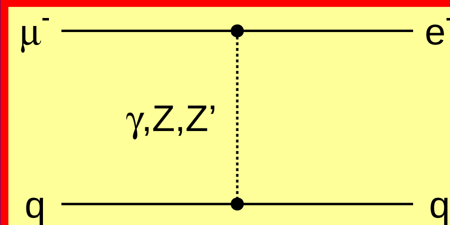
$$g_{H\mu e} = 10^{-4} \times g_{H\mu\mu}$$

Leptoquarks



$$M_L \approx 3000\sqrt{\lambda_{\mu d}\lambda_{ed}}\ \mathrm{TeV/c}^2$$

Heavy Z' Anomalous Z coupling

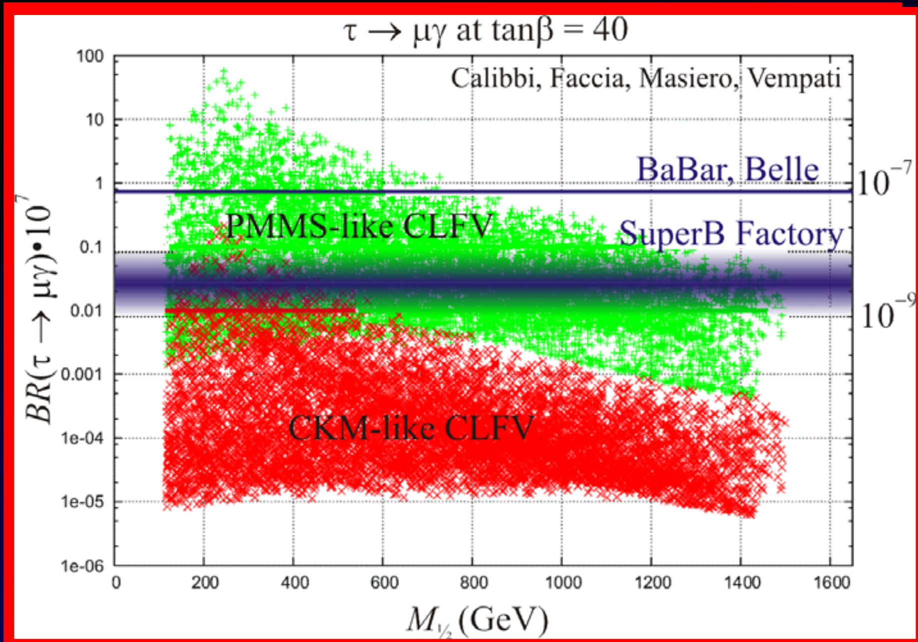


$$M_{Z'} \approx 3000\ \mathrm{TeV}/c^2$$
$$@B(Z\to\mu e) < 10^{-17}$$

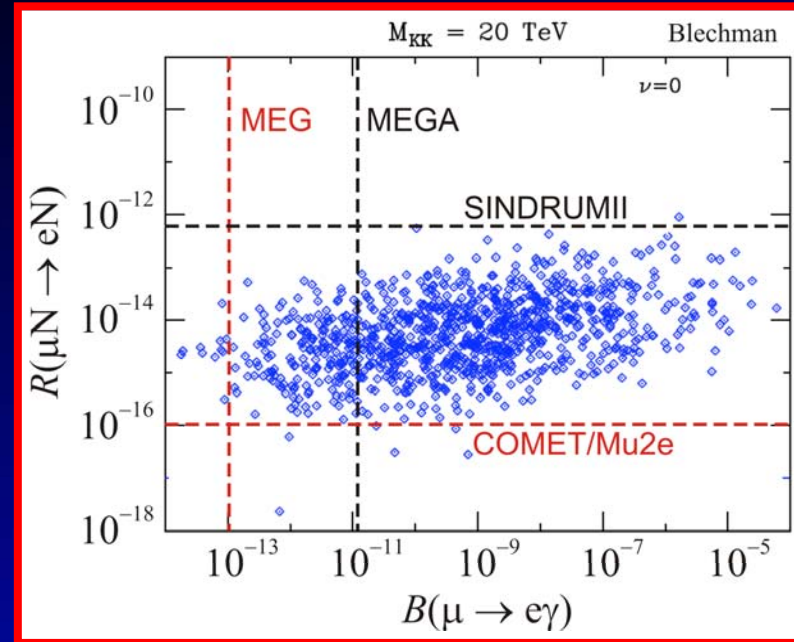
New physics probed by μN→eN (Marciano)

A Few Model Examples

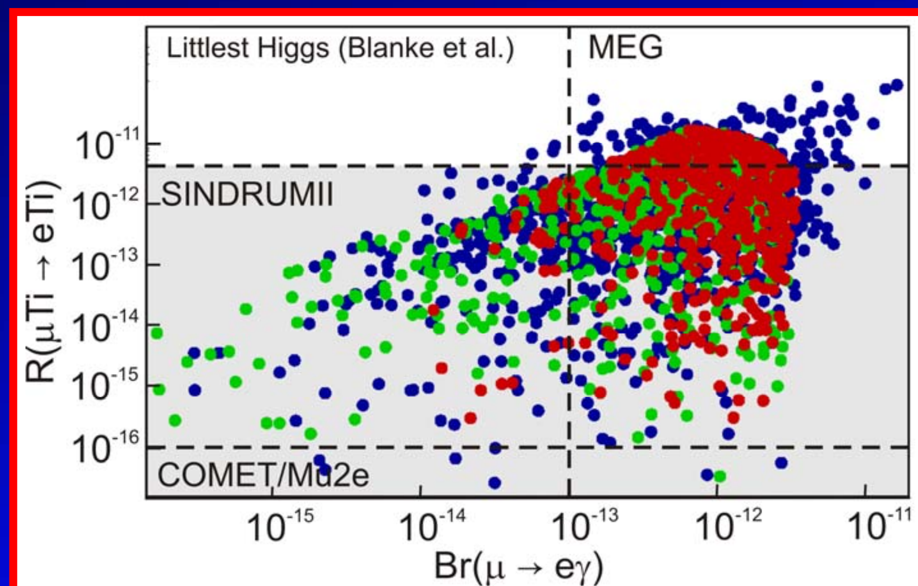
SUSY GUT w Seesaw



Randall-Sundrum



Littlest Higgs w T-parity



If CLFV Seen: Where is it Coming From?

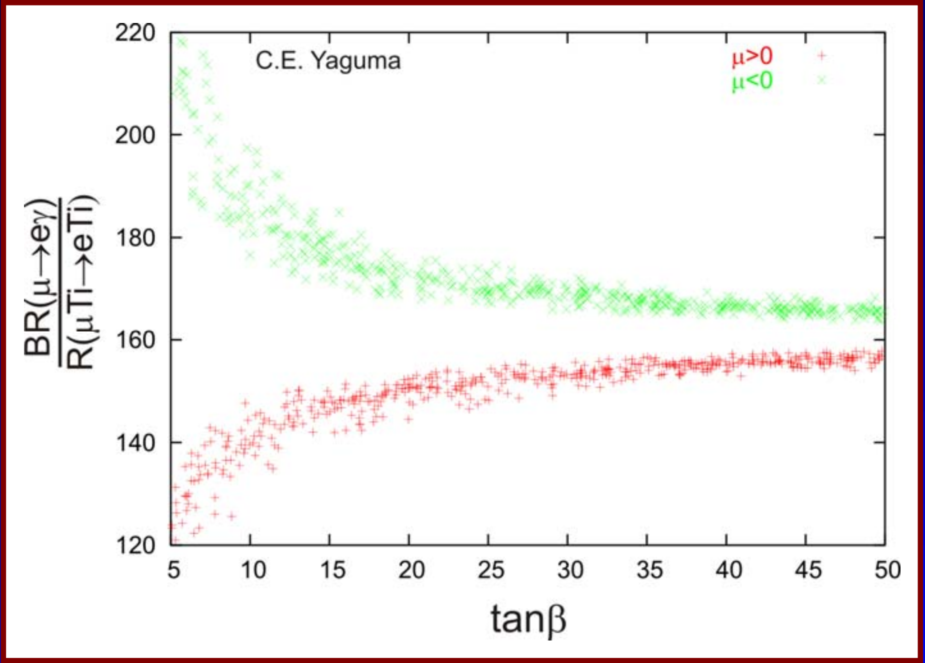
Huge number of models predict CLFV: which is it?

Need:

1. observation of CLFV in more than one channel, and/or
2. evidence from LHC, g-2, or elsewhere

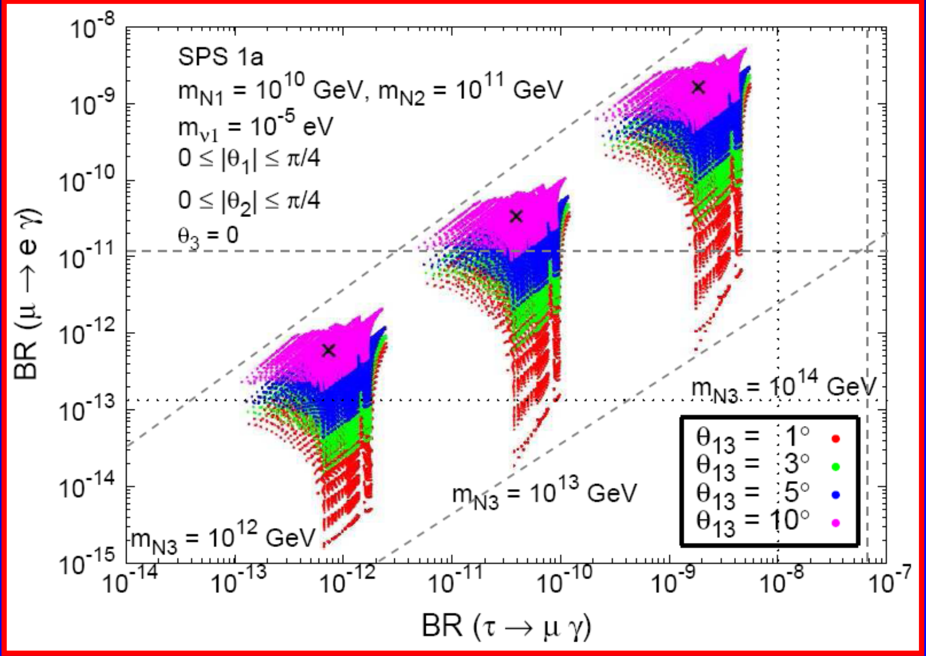
to allow discrimination between different models

MSSM w mSUGRA bc



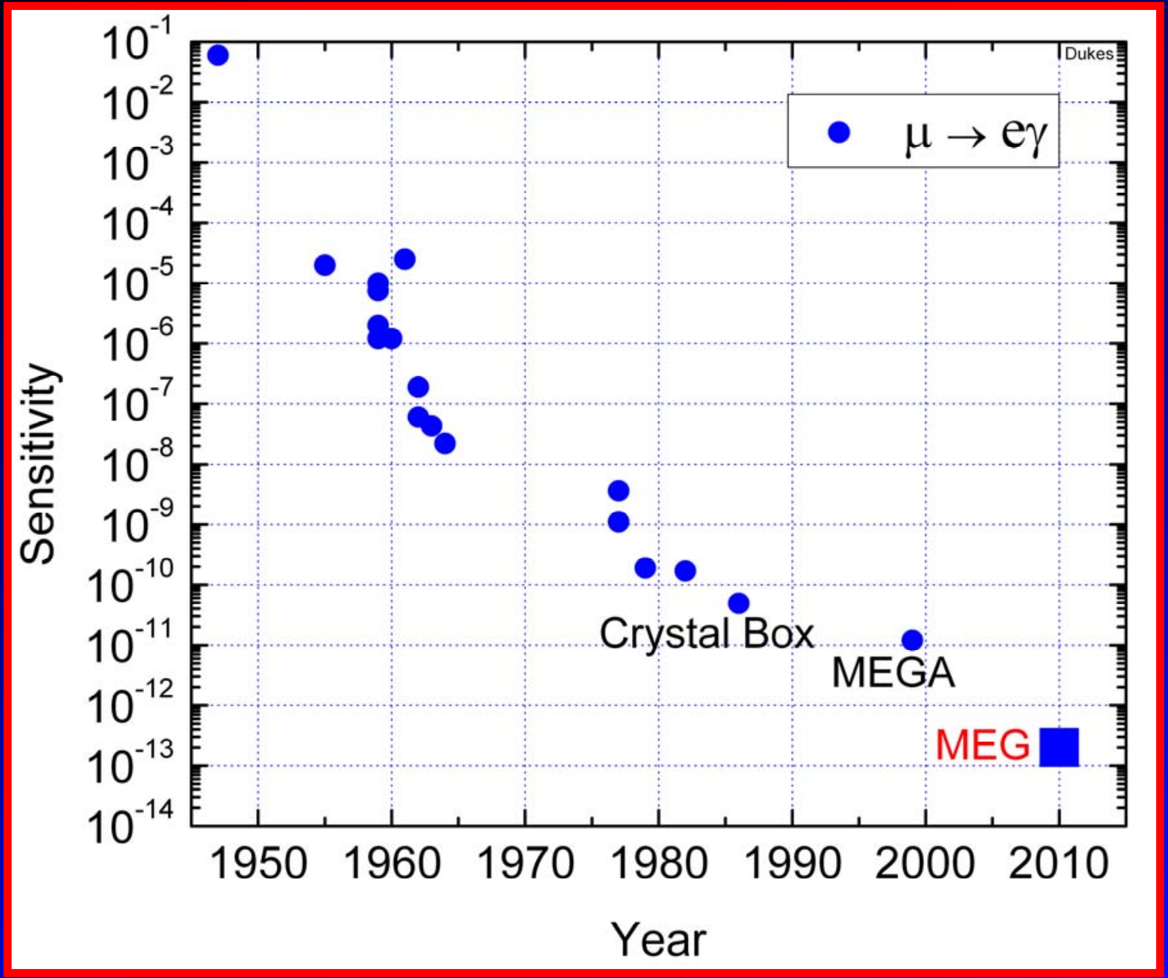
Yaguma, 2006

CMSSM-seesaw



Antusch, Arganda, Herrero, Teixeira, 2006

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

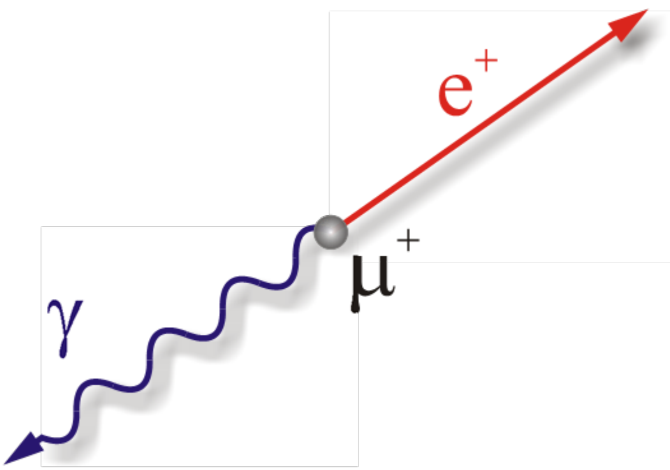


$\mu^+ \to e^+\gamma$

Signature

- Time coincident back-to-back electron and photon
- $E_e = E_\gamma = 52.8$ MeV

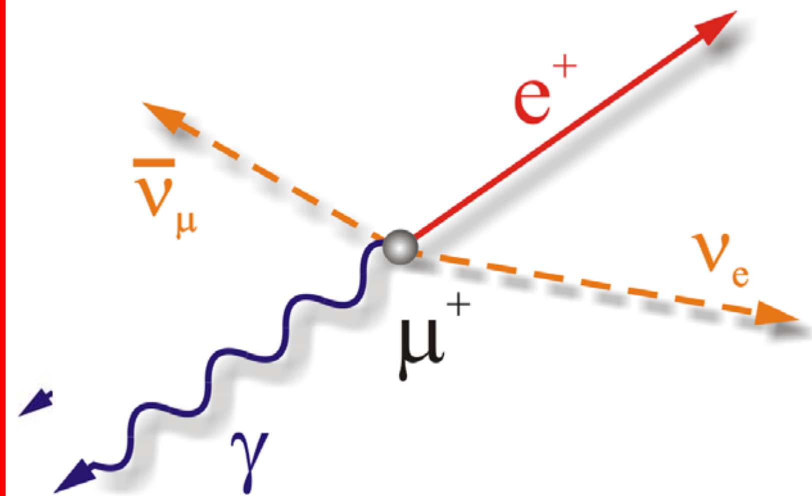
Dominant



Measure: E_e, E_γ, $\theta_{e\gamma}$, $t_{e\gamma}$

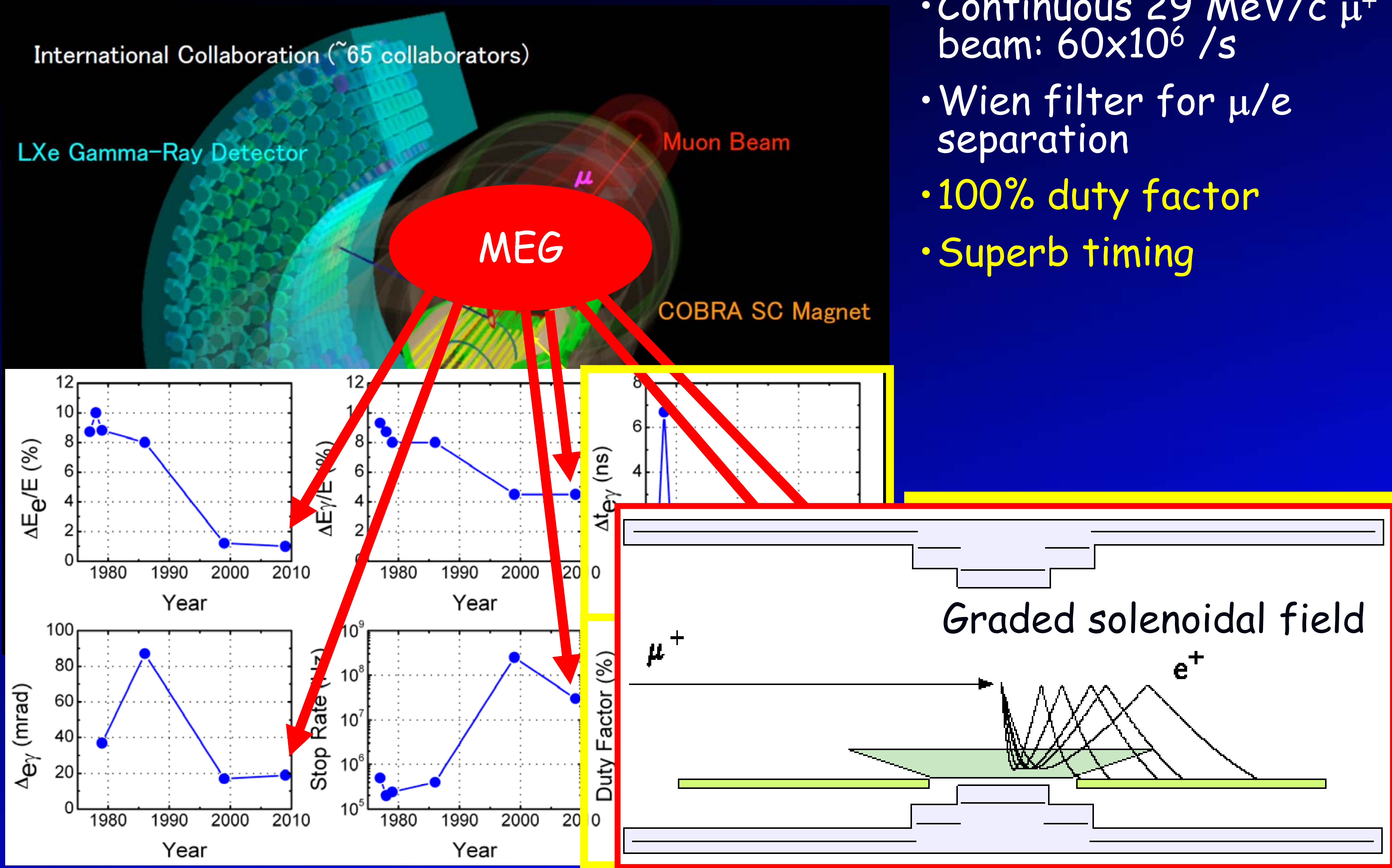
Backgrounds

- Prompt: $\mu^+ \to e^+ \nu_\mu \nu_e \gamma$
- Accidental: $\mu^+ \to e^+ \nu_\mu \nu_e$ + random γ ($e^+e^- \to \gamma\gamma$, $\mu^+ \to e^+ \nu_\mu \nu_e \gamma$, $eN \to eN\gamma$)



$$R_{acc} \propto R_\mu^2 \Delta E_e \Delta E_\gamma^2 \Delta\theta^2 \Delta t$$

MEG Experiment at PSI: $\mu^+ \rightarrow e^+\gamma$



- Continuous 29 MeV/c μ^+ beam: 60×10^6 /s
- Wien filter for μ/e separation
- 100% duty factor
- Superb timing

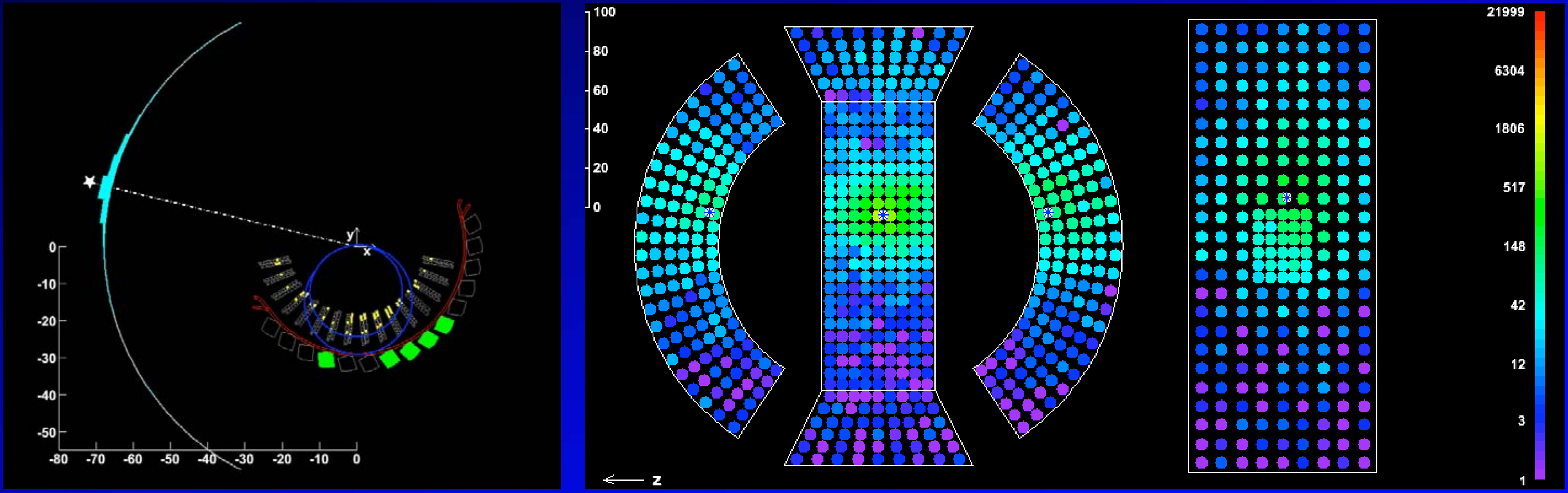
MEG Experiment at PSI: $\mu^+ \rightarrow e^+ \gamma$

- Status:
  - Engineering runs in 2007 and 2008
  - Improvements to detector were made
  - Spectrometer performance close to specifications
  - Rates are as expected
  - Presently running, with first results 2009-2010

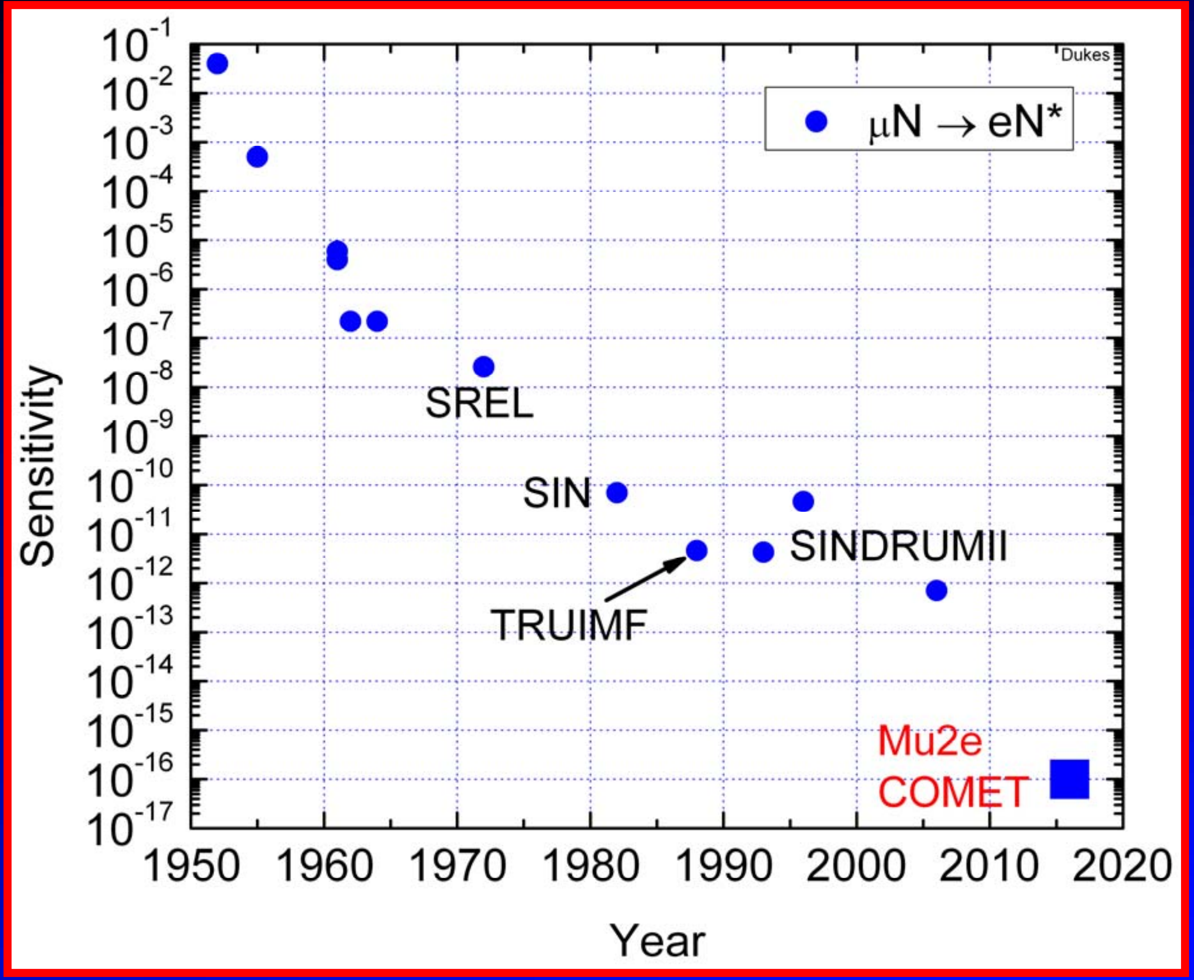
Sensitivity Goals	
2008 (12 wks)	$30\text{-}50 \times 10^{-13}$
2009	$3\text{-}5 \times 10^{-13}$
Goal	0.5×10^{-13}

MEGA: 1.2×10^{-11}

Candidate event from 2008 run



$\mu^- N \to e^- N$



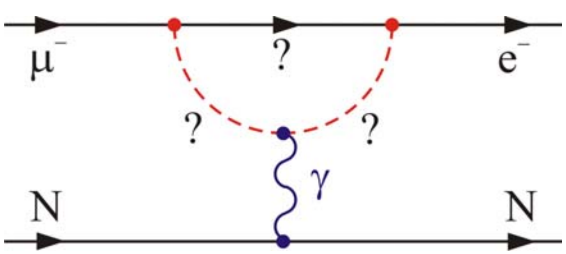
Dukes
$\mu N \to eN^*$
Sensitivity
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
SREL
SIN
TRUIMF
SINDRUMII
Mu2e
COMET
1950
1960
1970
1980
1990
2000
2010
2020
Year

CLFV in $\mu^+ \to e^+\gamma$ and $\mu^- N \to e^- N$

Model independent effective CLFV Lagrangian

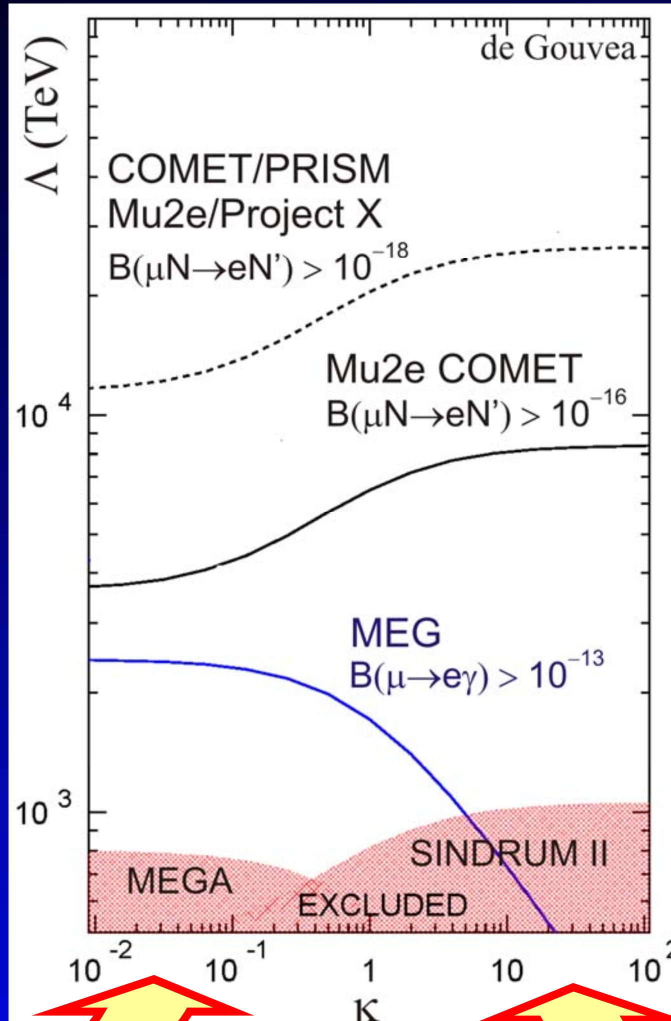
$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma$$

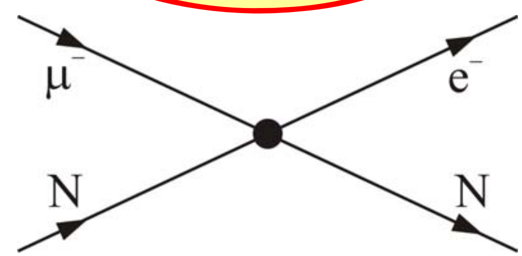
Mass scales probed ~10,000 times that probed directly by LHC



κ << 1
magnetic moment type operator

$\mu \to e\gamma$ rate ~300X $\mu N \to eN$ rate





κ >> 1
four-fermion interaction

$\mu N \to eN$ rate many orders of magnitude greater than $\mu \to e\gamma$ rate

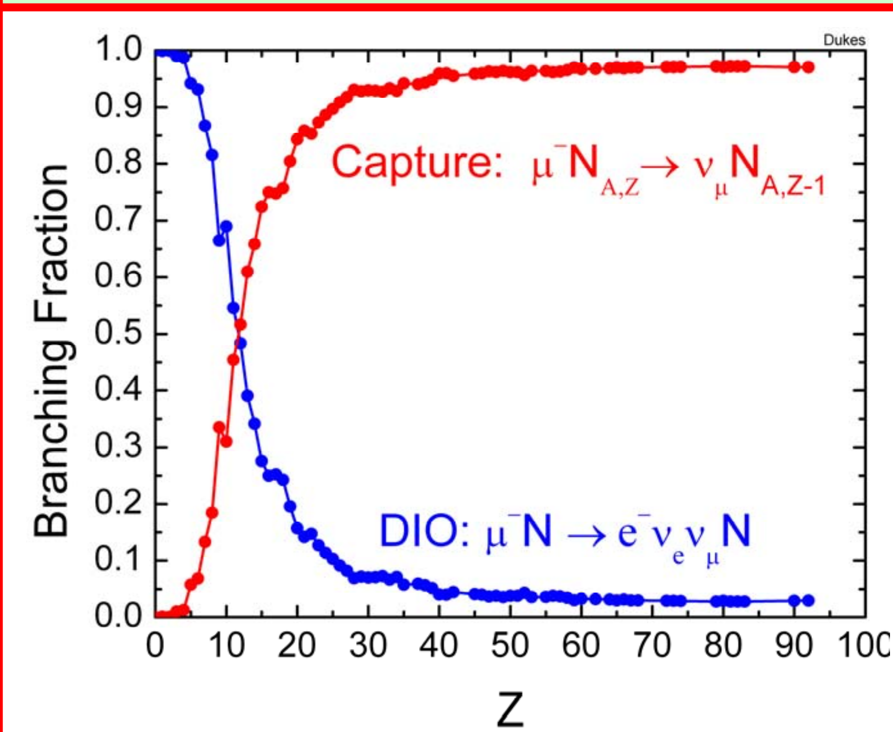
$\mu^- N \to e^- N$

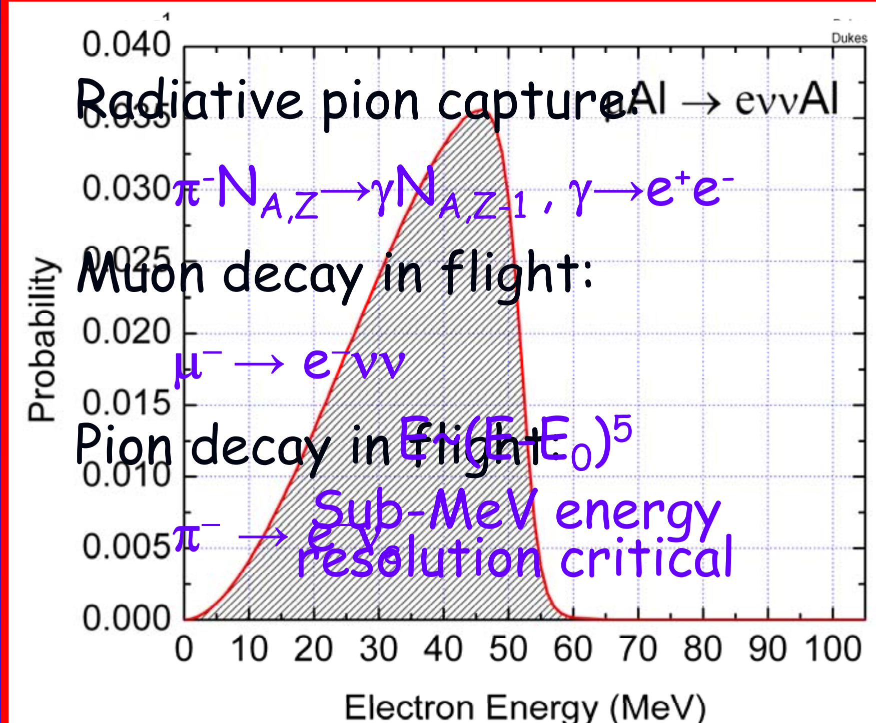
Signature

- Muon stops in atom, goes to 1S state
- coherently interacts with nucleus leaving it in ground state
- single isolated electron
- $E_e = m_\mu - E_{NR} - E_b \sim 104.97$ MeV (Al)

Backgrounds

- Intrinsic: muon decay in orbit, $\mu^- N_{A,Z} \to e^- \nu_\mu \nu_e N_{A,Z}$
- Beam related: radiative π capture, beam, pion- and muon-decay electrons
- Misc: cosmic rays, track errors





Radiative pion capture:

$\pi^- N_{A,Z} \to \gamma N_{A,Z-1}$, $\gamma \to e^+ e^-$

Muon decay in flight:

$\mu^- \to e^- \nu\nu$

Pion decay in flight:

$\pi^- \to e^- \nu$

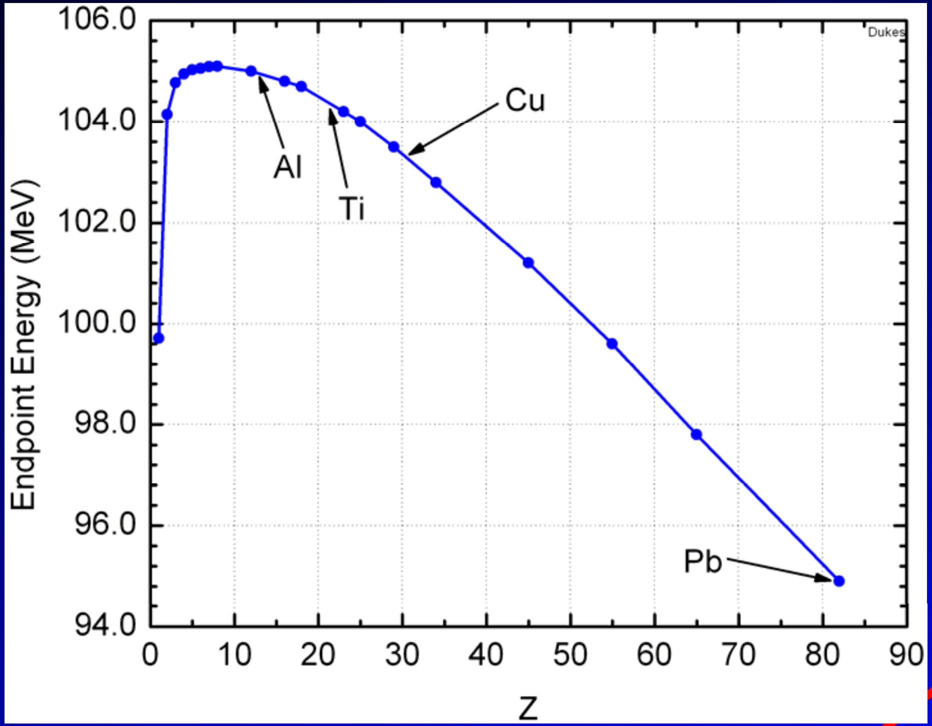
$E \sim (E - E_0)^5$

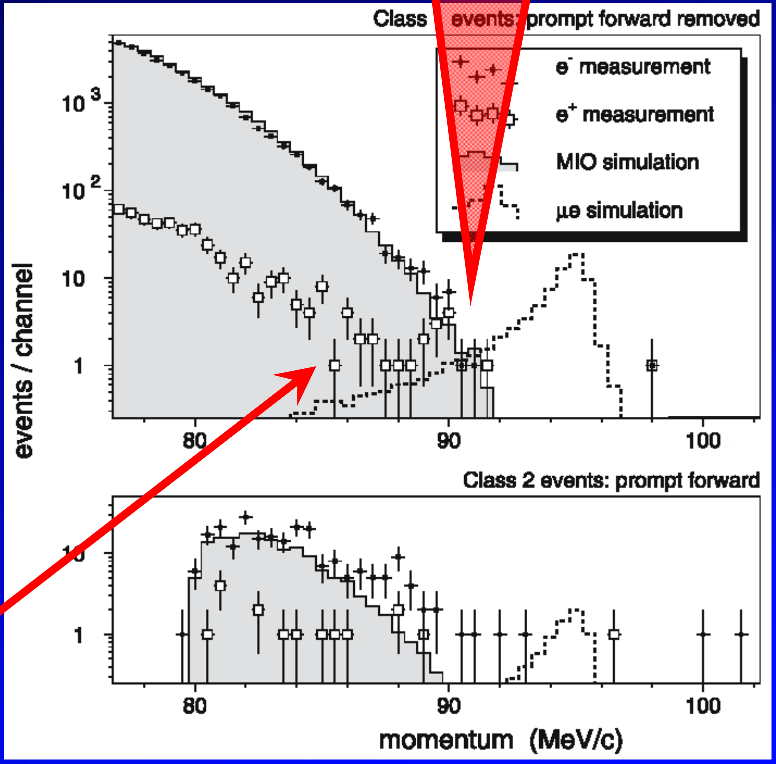
Sub-MeV energy resolution critical

SINDRUM II (PSI) Has Best $\mu^- N \to e^- N$ Limit

- Best limits on:
  - $\mu^+ \to e^+ e^- e^+$: 1.2×10^{-11} (SINDRUM I)
  - $\mu^- N \to e^- N$: 7.3×10^{-13} (SINDRUM II: Au)
- Continuous muon beam: 10^7-10^8 /s
- Muon degrader to remove π background

Note large shift in energy: B_μ=10.08 MeV



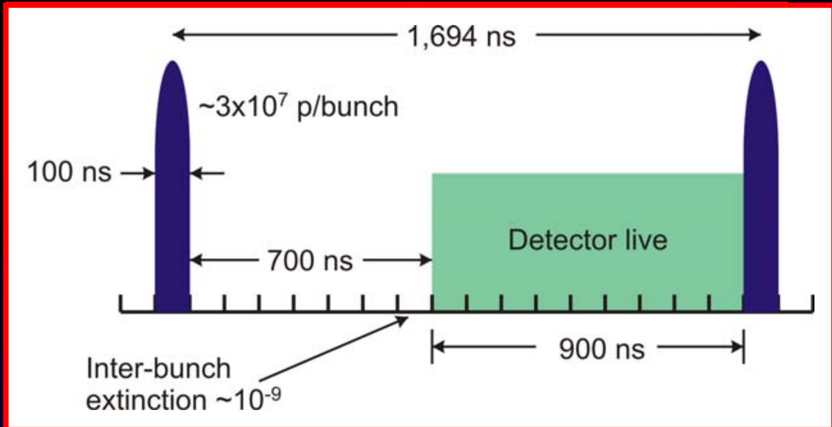


High energy tail of coherent Decay-in-orbit (DIO)

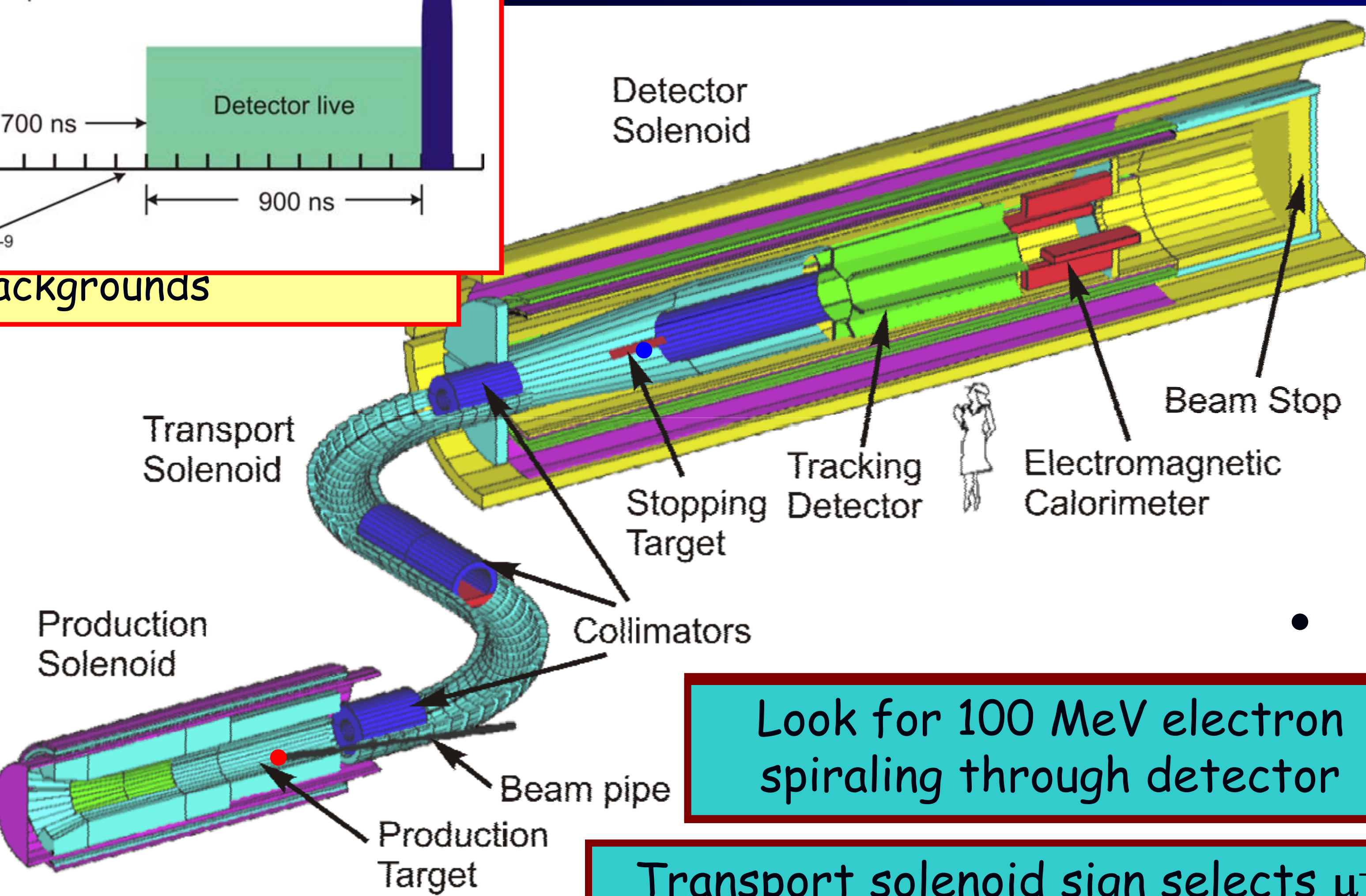
Two New $\mu^-N \rightarrow e^-N$ Experiments: Mu2e and COMET

- Fermilab: Mu2e ⇨ Mu2e/ProjectX — Approved!
- J-PARC: COMET ⇨ PRISM/PRIME — Proposal stage
- Both use bunched beam and solenoidal transport technique first proposed by MECL in 1992 and pushed forward by MECO in 1997-2005
- Both intend to improve SINDRUMII sensitivity by four orders of magnitude: $R(\mu^- + Al \rightarrow e^- Al) < 10^{-16}$

Mu2e



prompt backgrounds



Look for 100 MeV electron spiraling through detector

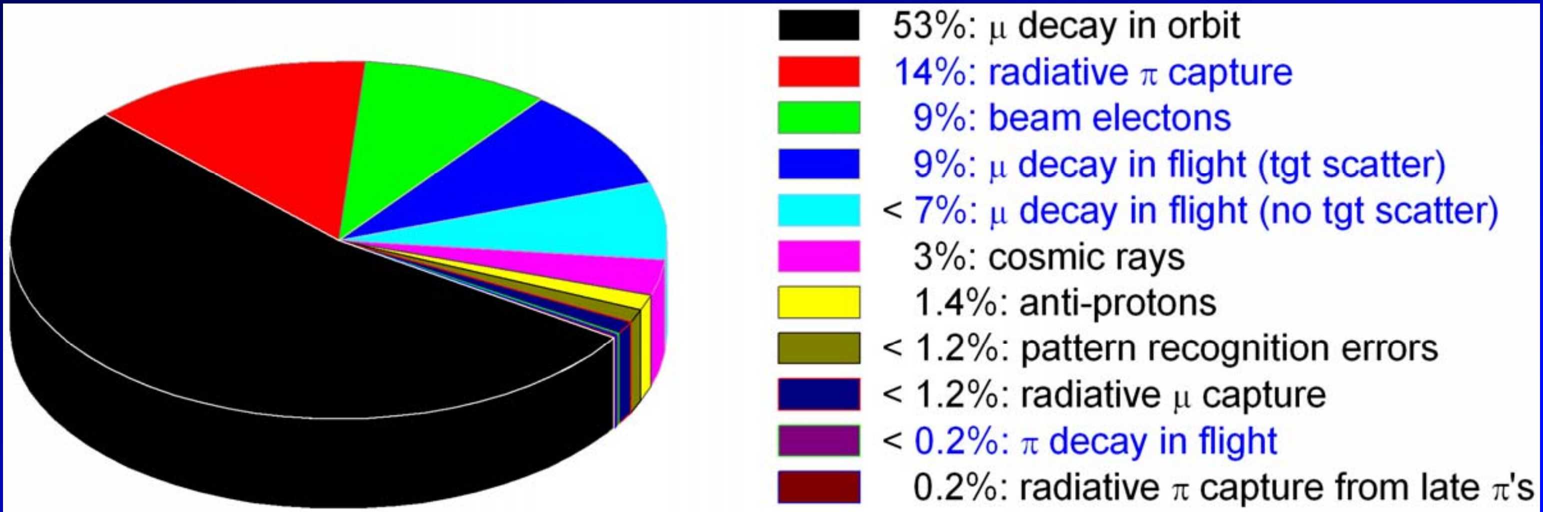
Transport solenoid sign selects μ^- and eliminates neutrals

Mu2e Sensitivity

$$R_{\mu e} = \frac{\Gamma(\mu N \to eN)}{\Gamma(\mu N \to \nu_\mu N^*)}$$

$$= \frac{N_{ve} / N_s \times 1/\varepsilon_{\mu e}}{\Lambda_{\mu v} / \Lambda_{tot} \, (=0.609)}$$

Proton flux	1.8×10^{13} p/s
Running time	2×10^{7} s
Total protons	3.6×10^{20} p
μ^- stops/incident proton	0.0025
μ^- capture probability	0.61
Time window fraction	0.49
Electron trigger eff.	0.80
Reconstruction and selection eff.	0.19
Sensitivity (90% CL)	6×10^{-17}
Detected events for $R_{\mu e} = 10^{-16}$	4
Estimated background events	0.4



COMET: (Coherent Muon to Electron Transition)

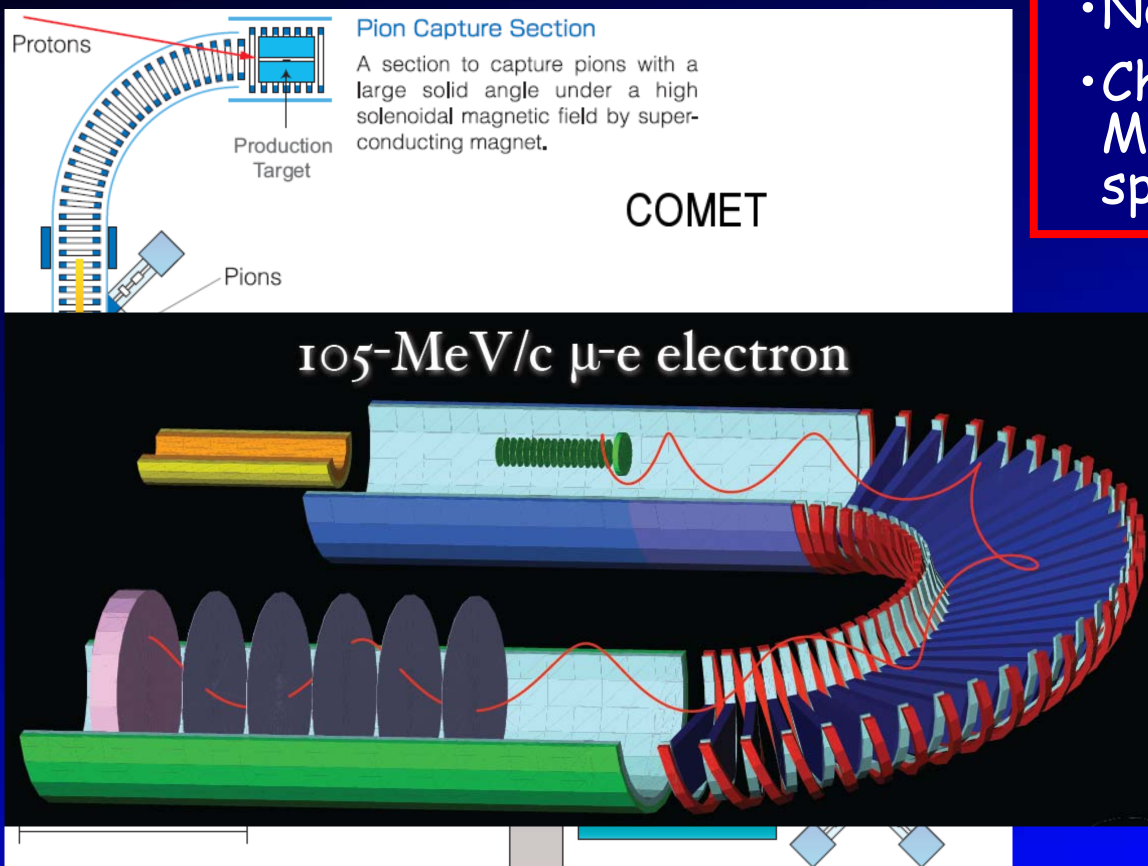
Similar to Mu2e:

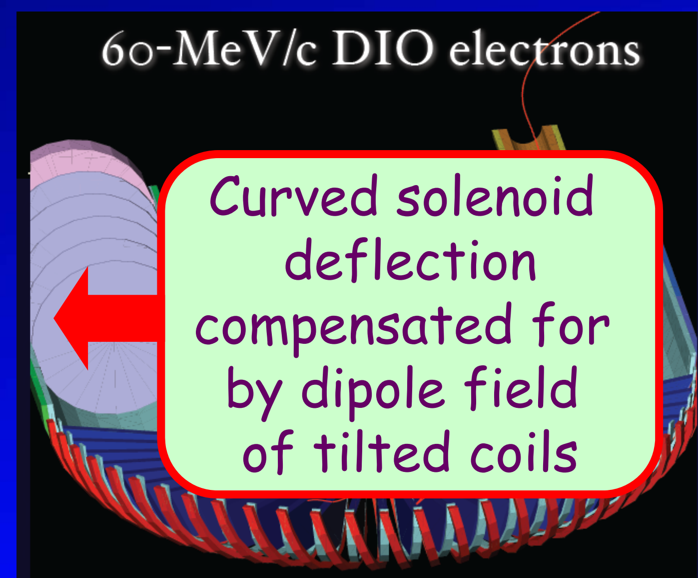
- $R(\mu^- + Al \rightarrow e^- Al) < 10^{-16}$
- Same μ production scheme
- U, not S-shaped transport solenoid

Proposed to J-PARC

Detector different than Mu2e:

- In U-shaped solenoid
- No line of sight for neutrals
- Charged particles with p < 80 MeV/c not transported to spectrometer ⇨ rate lower





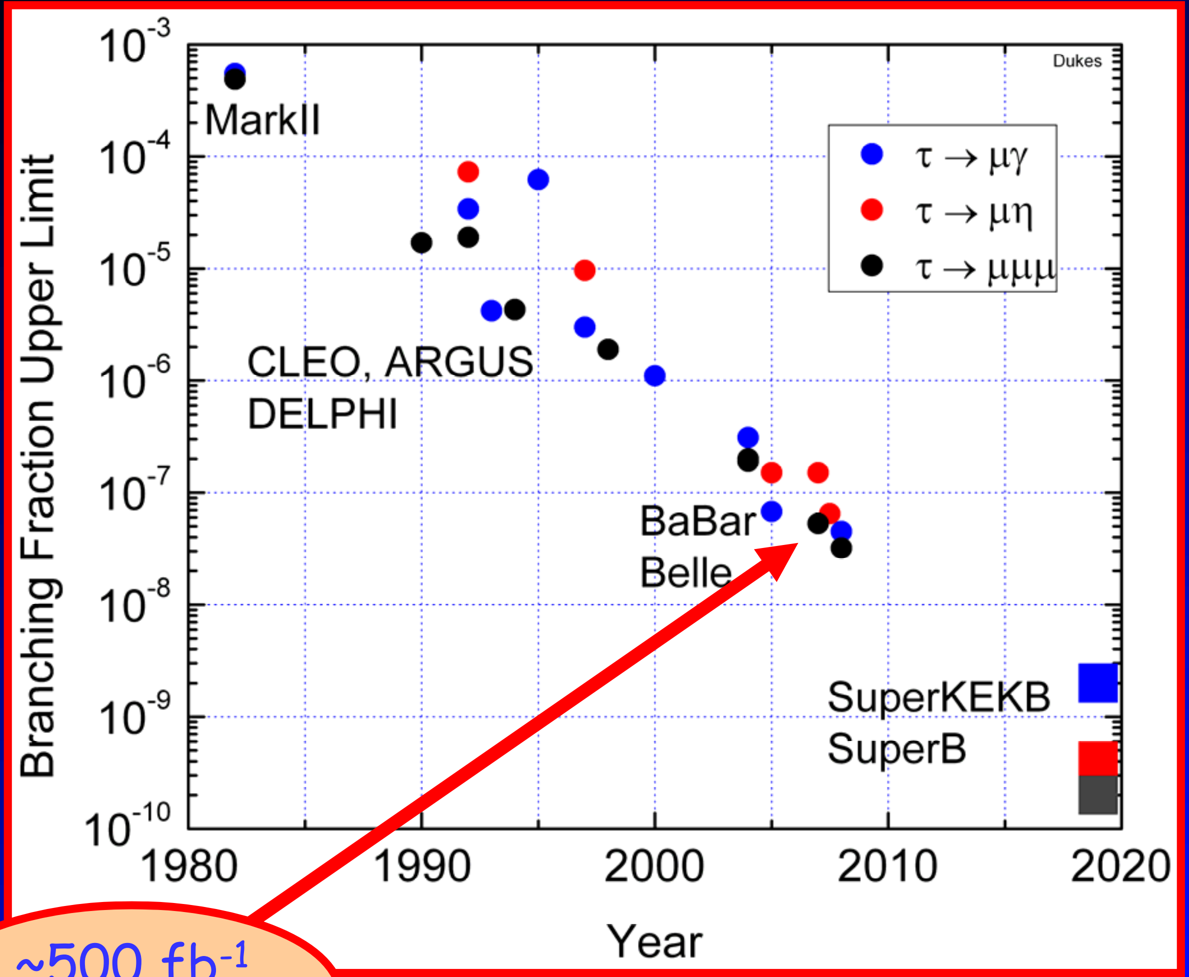
Future: Exploiting Muon Production Potential

High-power proton accelerators such as JHF and Project X will produce more muons than Mu2e and COMET can handle

Exploit muon collider and neutrino factory ideas on how to produce and cool muons

10^{12} – 10^{14} muons/s possible

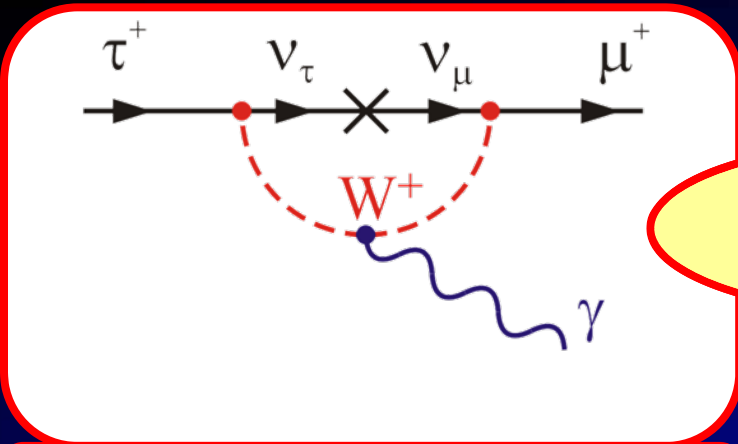
Lepton Flavor Violation in τ decays



~500 fb^{-1}
~0.5×10^9 $\tau^+\tau^-$

Lepton Flavor Violation in τ decays

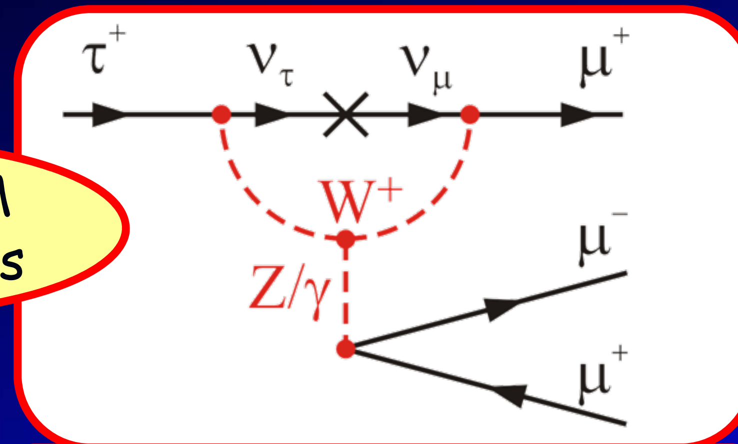
Highly suppressed in Standard Model



SM BR ~ 10^{-40}

Lee, Shrock, 1977

Milder GIM cancellations



SM BR ~ 10^{-14}

Pham, 1999

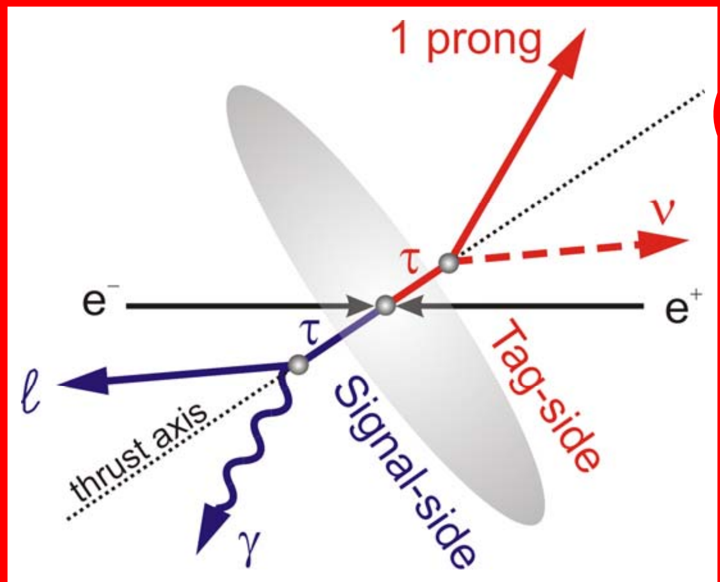
Good News:

In general beyond-standard model rates are several orders of magnitude larger than in associated muon modes

Bad News:

τ's hard to produce: ~10^9 τ/yr vs ~10^{11} μ/s in fixed-target experiments (Mu2e/COMET)

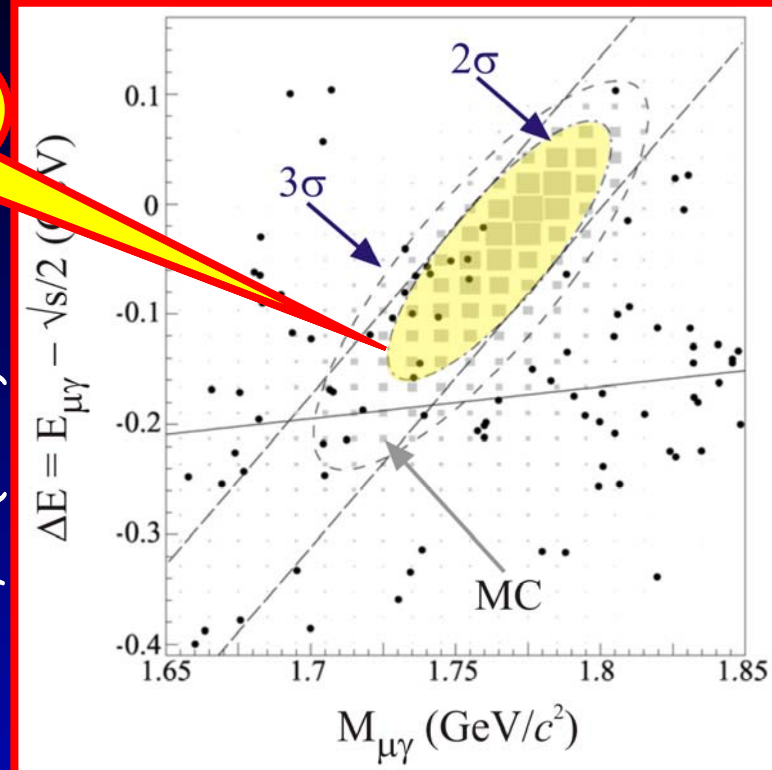
LFV in τ→μγ, eγ at Belle



Blind Analysis

- 2 oppositely charged tracks + ≥ 1γ
- thrust: 0.90 – 0.98
- p_{mis} > 0.4 GeV
- 0.4 < $\cos\theta_{\mu\gamma}$ < 0.8

PLB 666, 16 (2008)

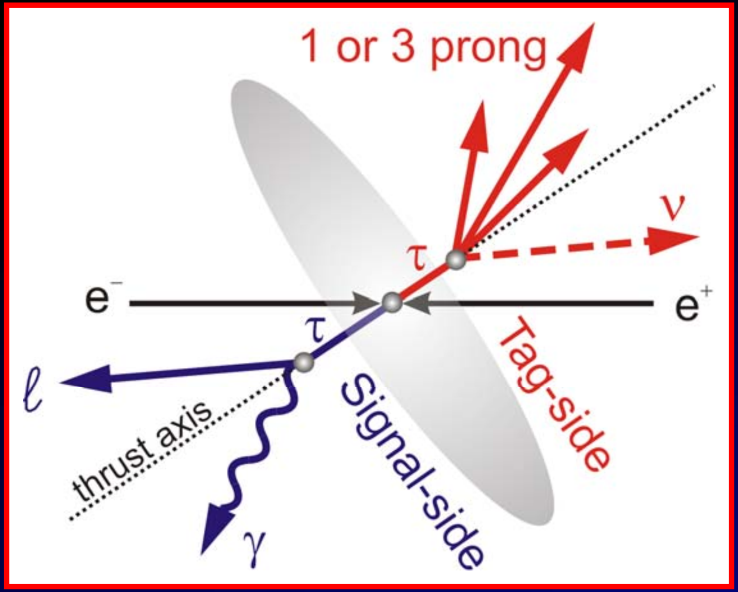


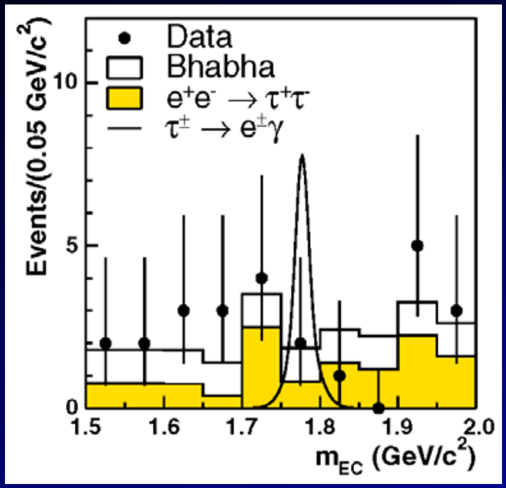
ττ→eμγ

Backgrounds	Source	τ→μγ	τ→eγ
	$\tau^+\tau^-\gamma$	59%	80%
	$\mu^+\mu^-\gamma$ ($e^+e^-\gamma$)	13%	20%
	$e^+e^-\mu^+\mu^-$	5%	0%

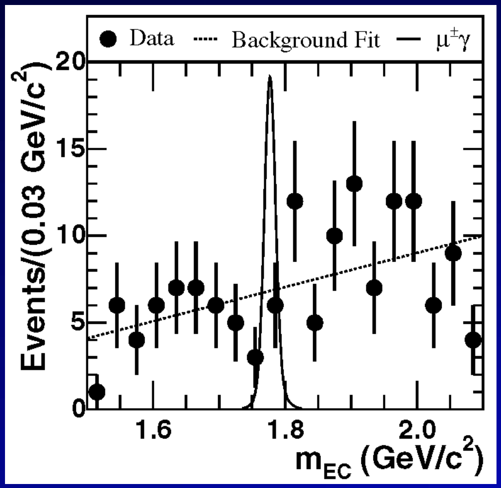
$$B(\tau^- \to \mu^- \gamma) < 4.5\times10^{-8} \quad 14\ \text{Bkg}$$
$$B(\tau^- \to e^- \gamma) < 12.0\times10^{-8} \quad 5\ \text{Bkg}$$

LFV in $\tau\to\mu\gamma$, $e\gamma$ at BaBar



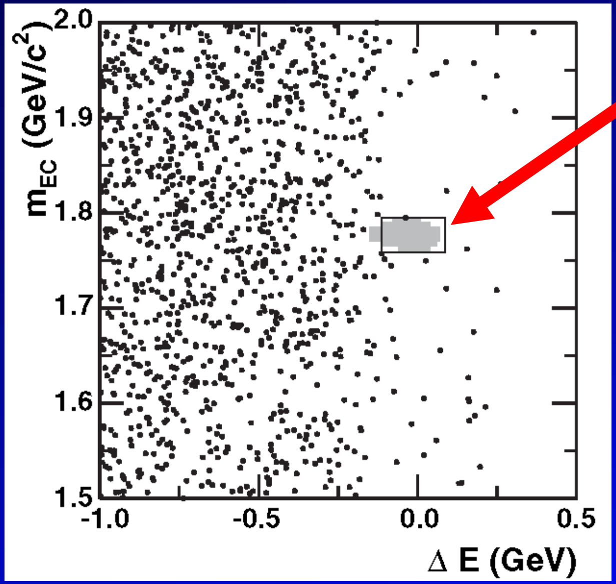


PRL96, 041801 (2006)



PRL95, 041802 (2005)

$\tau \to e\gamma$

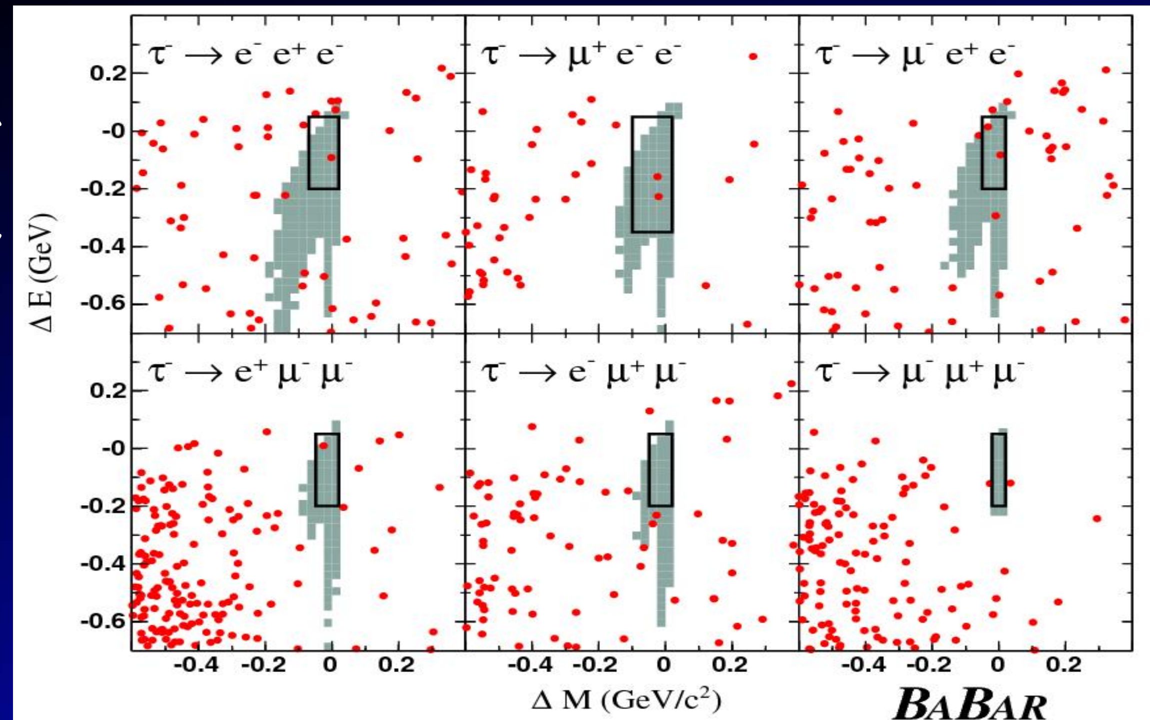


2σ signal region

$$B(\tau^- \to \mu^- \gamma) < 6.8\times10^{-8} \quad 4\,\text{Bkg}$$
$$B(\tau^- \to e^- \gamma) < 11.0\times10^{-8} \quad 1\,\text{Bkg}$$

LFV in τ→*lll* at BaBar

PRL99, 251803 (2007)



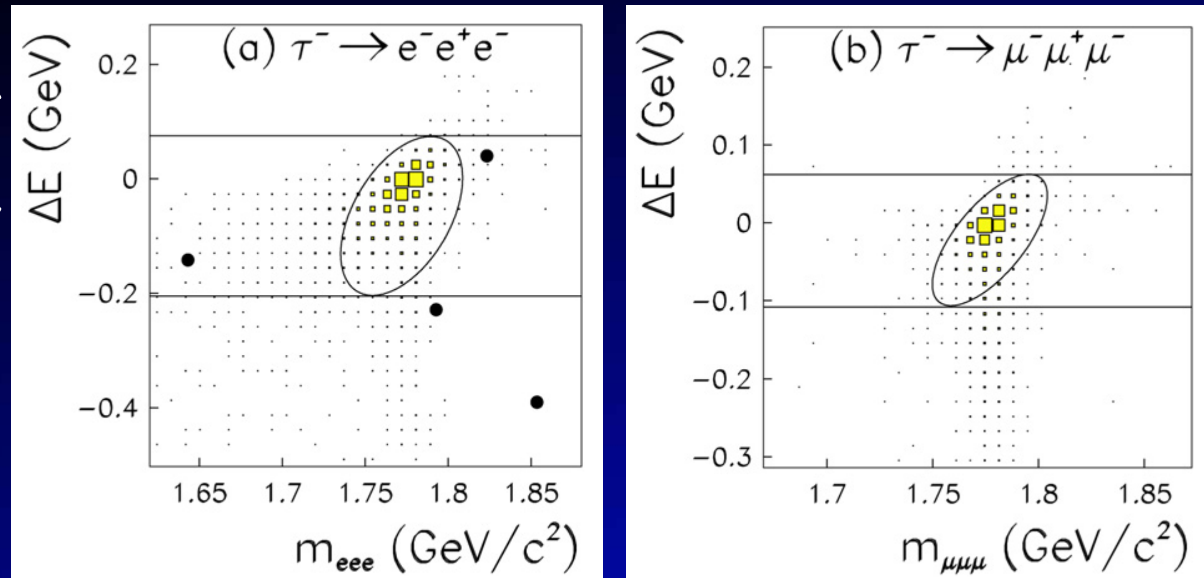
Negligible Background

Mode	Eff. [%]	N_{bgd}	$\mathrm{UL}_{90}^{\mathrm{exp}}$	N_{obs}	$\mathrm{UL}_{90}^{\mathrm{obs}}$
$e^- e^+ e^-$	8.9 ± 0.2	1.33 ± 0.25	4.9	1	4.3
$\mu^- e^+ e^-$	8.3 ± 0.6	0.89 ± 0.27	5.0	2	8.0
$\mu^+ e^- e^-$	12.4 ± 0.8	0.30 ± 0.55	2.7	2	5.8
$e^+ \mu^- \mu^-$	8.8 ± 0.8	0.54 ± 0.21	4.6	1	5.6
$e^- \mu^+ \mu^-$	6.2 ± 0.5	0.81 ± 0.31	6.6	0	3.7
$\mu^- \mu^+ \mu^-$	5.5 ± 0.7	0.33 ± 0.19	6.7	0	5.3

$\times 10^{-8}$

LFV in $\tau \rightarrow lll$ at Belle

PRB660, 154 (2008)



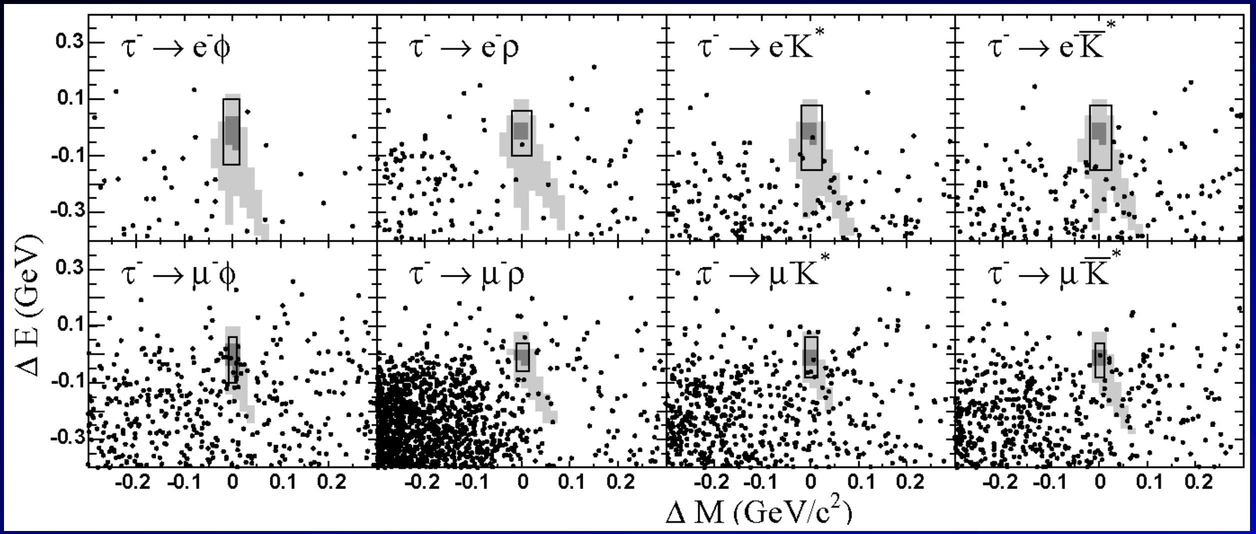
No Background

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	s_{90}	$\mathcal{B}(\times 10^{-8})$
$\tau^- \rightarrow e^- e^+ e^-$	6.00	0.40 ± 0.30	9.8	0	2.10	3.6
$\tau^- \rightarrow \mu^- \mu^+ \mu^-$	7.64	0.07 ± 0.05	7.4	0	2.41	3.2
$\tau^- \rightarrow e^- \mu^+ \mu^-$	6.08	0.05 ± 0.03	9.5	0	2.44	4.1
$\tau^- \rightarrow \mu^- e^+ e^-$	9.29	0.04 ± 0.04	7.8	0	2.43	2.7
$\tau^- \rightarrow e^+ \mu^- \mu^-$	10.8	0.02 ± 0.02	7.6	0	2.44	2.3
$\tau^- \rightarrow \mu^+ e^- e^-$	12.5	0.01 ± 0.01	7.7	0	2.46	2.0

$\times 10^{-8}$

Similar Limits in Semi-leptonic Modes

arXiv:0904.0339v2



Non-zero Background

Mode	$\varepsilon[\%]$	$N_{\rm bgd}$	$N_{\rm obs}$	$N_{\rm UL}^{90}$	$\mathcal{B}_{\rm exp}^{90}$	$\mathcal{B}_{\rm UL}^{90}$
$e\phi$	6.43 ± 0.16	0.68 ± 0.12	0	1.8	5.0	3.1
$\mu\phi$	5.18 ± 0.27	2.76 ± 0.16	6	8.7	8.2	19
$e\rho$	7.31 ± 0.18	1.32 ± 0.17	1	3.1	4.9	4.6
$\mu\rho$	4.52 ± 0.41	2.04 ± 0.19	0	1.1	8.9	2.6
eK^*	8.00 ± 0.19	1.65 ± 0.23	2	4.3	4.8	5.9
μK^*	4.57 ± 0.36	1.79 ± 0.21	4	7.1	8.5	17
$e\overline{K}^*$	7.76 ± 0.18	2.76 ± 0.28	2	3.2	5.4	4.6
$\mu\overline{K}^*$	4.11 ± 0.32	1.72 ± 0.17	1	2.7	9.3	7.3

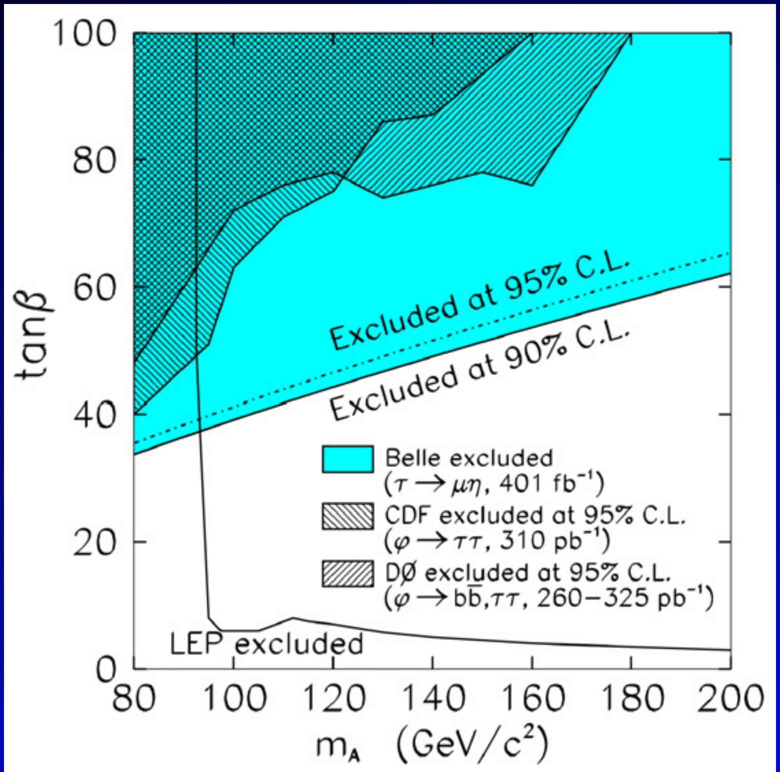
$\times 10^{-8}$

Belle Search for τ→μη, τ→eη

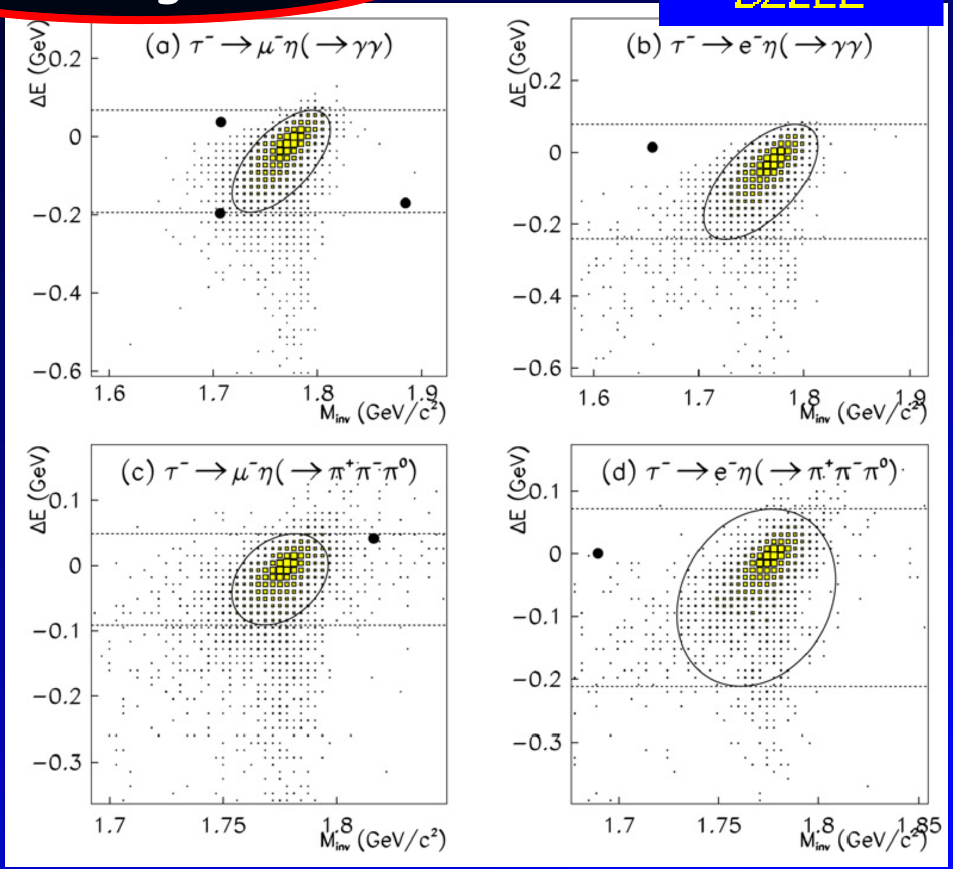
τ→μη 8x τ→μμμ
SUSY model
Sher, PRD66, 057301 (2002)

No Background

$$BR(\tau\to\mu\eta)=(0.84\times10^{-6})\left(\frac{\tan\beta}{60}\right)^6\left(\frac{100\,\mathrm{GeV}}{m_A}\right)^4$$



PLB 648, 341 (2007)



$$B(\tau^-\to\mu^-\eta)<6.5\times10^{-8}\quad 0\,\mathrm{Bkg}$$
$$B(\tau^-\to e^-\eta)<9.2\times10^{-8}\quad 0\,\mathrm{Bkg}$$

Future Prospects for B Factories

- Tor Vergata
- 2015-2016
- Rebuilt BaBar detector

SuperB

Super KEKB
Quest for BSM

- Tsukuba
- 2012-2015
- Rebuilt Belle detector

B Factory	
$\sigma_{\tau\tau}$	= 0.9 nb
$\sqrt{s}$	= 10.6 GeV
$\mathcal{L}$	~ 200×10^{34} $cm^{-2}s^{-1}$ (SuperB)
	~ 100 ab^{-1} /5yr
$\mathcal{L}$	~ 80×10^{34} $cm^{-2}s^{-1}$ (Super KEKB)
	~ 40 ab^{-1} /5yr
$N(\tau)$	~ 18 x 10^9 /yr (SuperB)
	~ 7 x 10^9 /yr (Super KEKB)

50-100X present B factories		
$\mathcal{L}$(PEP-II)	= 1.2×10^{34} $cm^{-2}s^{-1}$	~0.4 ab^{-1}
$\mathcal{L}$(KEKB)	= 2.0×10^{34} $cm^{-2}s^{-1}$	~0.7 ab^{-1}

$\propto 1/\sqrt{\mathcal{L}}$

$\tau\rightarrow\mu\gamma$, $e\gamma$

~10X improvement

modes: $\propto 1/\mathcal{L}$

$\tau\rightarrow lll$, $\tau\rightarrow\mu\eta$

~100X improvement

τ-charm Factory
$\sigma_{\tau\tau}$ = 3.5 nb
$\sqrt{s}$ = 4.25 GeV
$\mathcal{L}$ = 1.0×10^{35} $cm^{-2}s^{-1}$
$N(\tau)$ = 3.5×10^9 /yr

BEBCII
1×10^{33} $cm^{-2}s^{-1}$

Prospects at the LHC: τ-decays

Good News

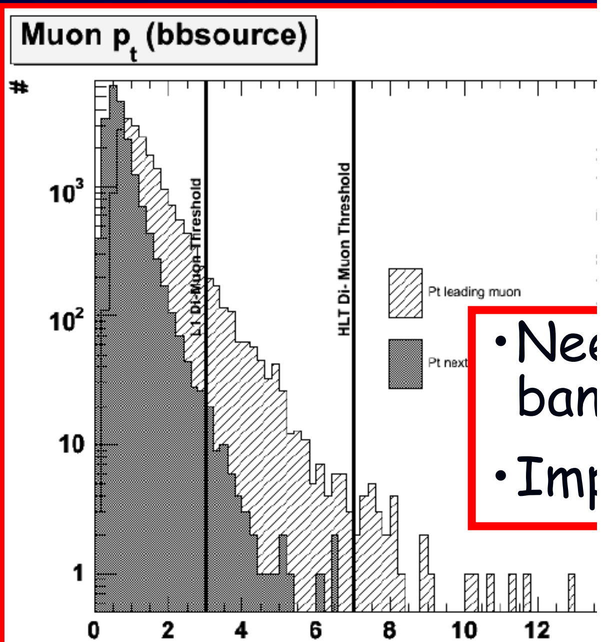
Huge number of

- ~10^{12} τ/yr (@ 10^3
- Most from B and

Nτ/yr (10 fb^{-1})
1.5×10^8
2.9×10^7
3.1×10^{11}
3.4×10^{11}
9.4×10^{10}
6.0×10^{11}

luminosity running!

al. PRD 77, 07310 (2008)



- Nee ban
- Imp

CERN/LHCC 2006-021
CMS TDR 8.2
26 June 2006

CMS Physics

Technical Design Report

Volume II:

Physics Performance

No mention of LFV

CMS Software and Physics, Reconstruction and Selection (PRS) Projects

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ents recorded
d
s
seable
and Z decays

Prospects at the LHC: τ-decays

Possible Decay Modes

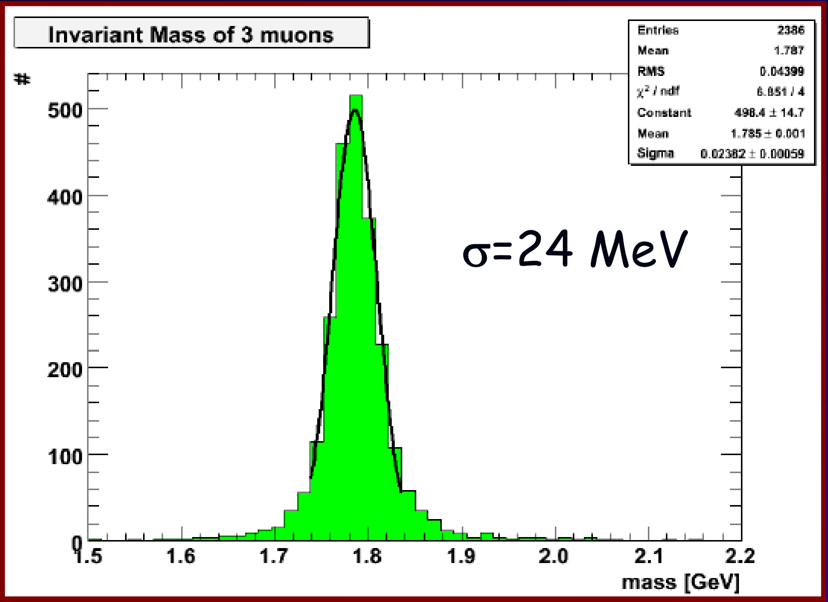
- $\tau \to \mu\gamma$, $\tau \to e\gamma$ impossible
- $\tau \to \mu\mu\mu$ promising

Main Backgrounds

- charm and bottom decays

$D_s \to \mu\phi + X$, $\phi \to \mu\mu(\gamma)$

$D_s \to \mu\eta + X$, $\phi \to \mu\mu(\gamma)$



Giffels et al. PRD 77, 07310 (2008)

Corresponds to current B-factory limits

$\tau \to \mu\mu\mu$ expected limits (30fb^{-1})

- W source: 3.8×10^{-8}
- Z source: 3.4×10^{-7}

Conclusions

- Almost all BSM theories predict charged LFV at levels that are being probed or will be probed experimentally
- Current experimental limits are already quite constraining
- Don't rely on theoretical guidance ⇨ CLFV should be attacked from all possible fronts, including those not discussed here
- LHC will not competitive with super-B factories for τ decays until selective high-rate triggers are implemented
- B factories
  - BaBar, Belle have limits that are interesting in several modes
  - For modes where the sensitivity continues to scale with $1/\mathcal{L}$, a factor of up to 100 improvement will be seen with the next generation accelerators
- Muon experiments
  - Planned muon conversion experiments at Fermilab and J-PARC will probe deepest into the BSM phase space
  - We all eagerly await first MEG results

Outlook for next Decade Very Exciting!