MANCHESTER 1824

Lepton Flavour Violation (Experiment)

George Lafferty

University of Manchester

Flavour and the Fourth Family

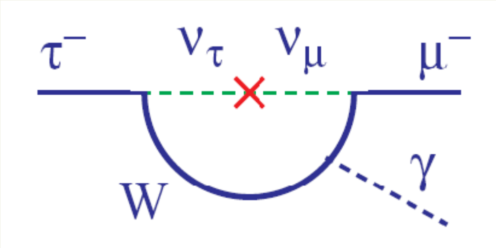
14th-16th September 2011

IP3

Outline: A review of recent experimental results in Lepton Flavour Violation, and a look to the future

- Introduction to LFV and (brief) theory
- Some history
- Recent results and current status
- Prospects and proposals for future experiments

- Lepton flavour violation (LFV) is forbidden in the Standard Model (SM), but …
- Allowed (indeed observed) in SM extended to include neutrino oscillations, but …
  - Charged lepton flavour violation is suppressed by of order $(\Delta m_\nu^2/M_W^2)^2$
  - Charged LFV from SM unobservable in any current or foreseeable experiment



- Charged LFV is expected in many New Physics (NP) extensions to the SM, with parameter spaces allowing rates up to current limits
- Any observation of charged LFV would be a clear sign of NP
- Any observation of NP at LHC must be compatible with limits on, or observations of, LFV

Some of the most interesting LFV reactions have

- clean experimental signatures
- good prospects for experimental sensitivity
- relatively clean theoretical predictions

$\mu^- \rightarrow e^- \gamma$

$\mu^- \rightarrow e^+ e^- e^-$

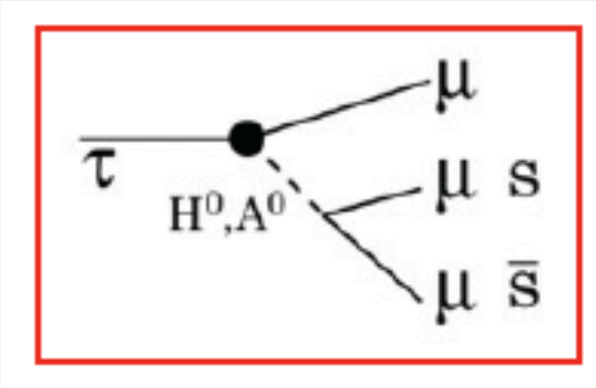
$\mu^- N \rightarrow e^- N$

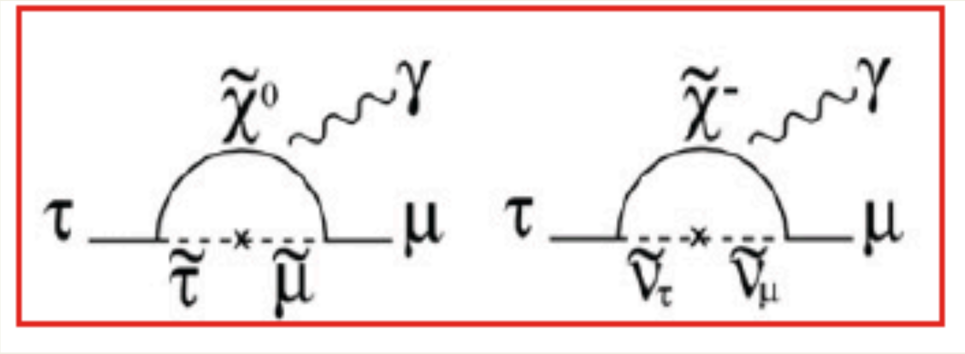
$\tau^- \rightarrow \mu^- \gamma$

$\tau^- \rightarrow \mu^+ \mu^- \mu^-$

Some (of many) New Physics predictions for LFV in tau decays

Model	References	Limits $\tau \to \mu\gamma$	$\tau \to lll$
SM + ν mixing	Lee, Shrock, PRD 16,1444(1977) Cheng, Li, PRD 45,1908(1980)	10^{-40}	10^{-14}
SUSY Higgs	Dedes, Ellis, Raidal, PLB 549,159(2002) Brignole, Rossi, PLB 566,517(2003)	10^{-10}	10^{-7}
SM + heavy Majorana ν	Cvetic, Dib, Kim, Kim, PRD 66,034008(2002)	10^{-9}	10^{-10}
Non-universal Z'	Yue, Zhang,Liu, PLB 547,252(2002)	10^{-9}	10^{-8}
SUSY SO(10)	Masiero, Vempati, Vives, NPB 649,189(2003) Fukuyama, Kikuchi, Okada, PRD 68,033012(2003)	10^{-8}	10^{-10}
MSUGRA + Seesaw	Ellis et al., EPJ C14, 319(2002) Ellis, Hisano, Raidal, Shimizu, PRD 66,115013(2002)	10^{-7}	10^{-9}



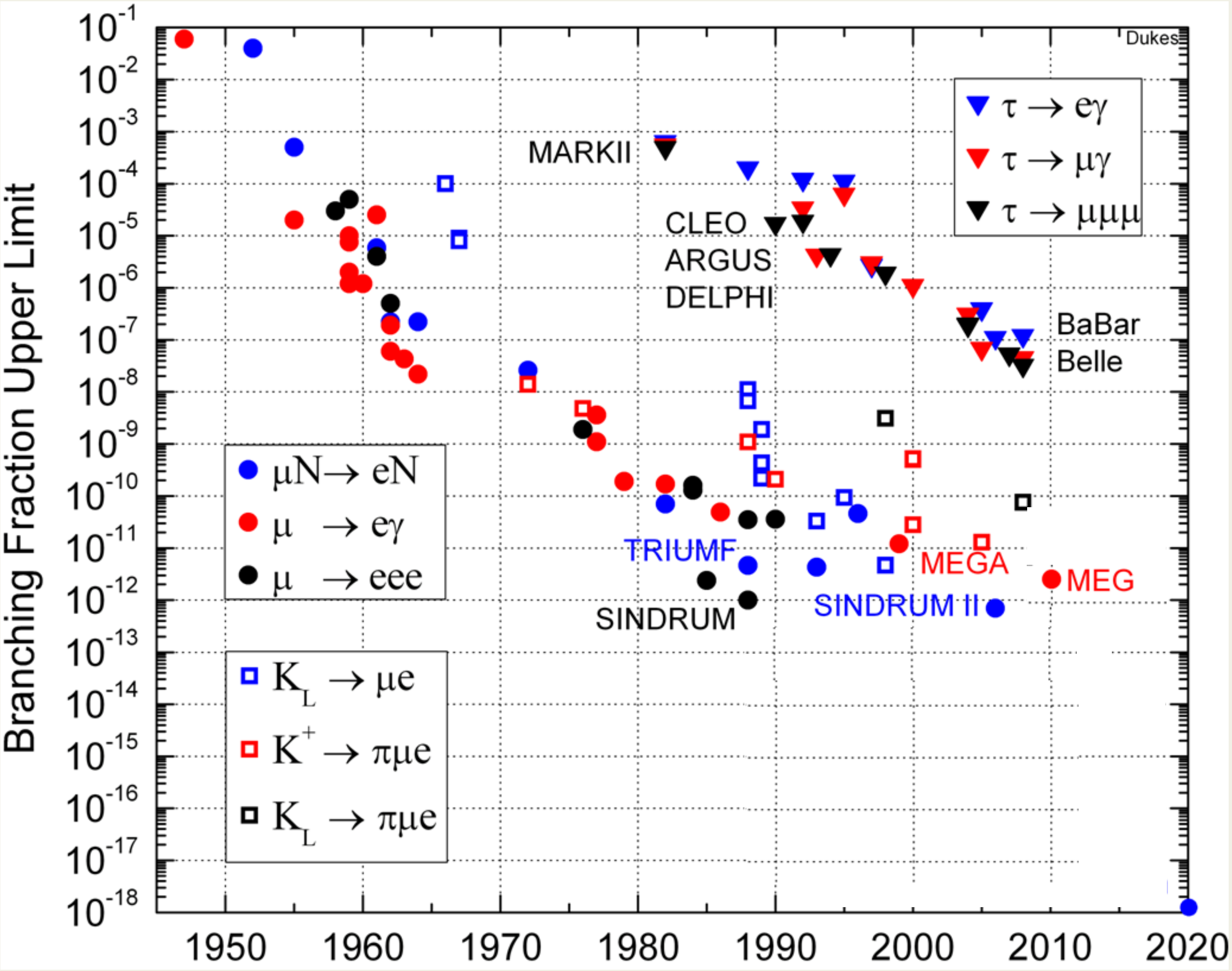


A **sample** of various charged lepton flavour violating reactions

Reaction	Current bound	Expected	Possible
$\mathcal{B}(\mu^+ \to e^+\gamma)$	$<1.2 \times 10^{-11}$	2×10^{-13}	2×10^{-14}
$\mathcal{B}(\mu^\pm \to e^\pm e^+ e^-)$	$<1.0 \times 10^{-12}$	–	10^{-14}
$\mathcal{B}(\mu^\pm \to e^\pm \gamma\gamma)$	$<7.2 \times 10^{-11}$	–	–
$R(\mu^- \mathrm{Au} \to e^- \mathrm{Au})$	$<7 \times 10^{-13}$	–	–
$R(\mu^- \mathrm{Al} \to e^- \mathrm{Al})$	–	10^{-16}	10^{-18}
$\mathcal{B}(\tau^\pm \to \mu^\pm \gamma)$	$<5.9 \times 10^{-8}$		$\mathcal{O}(10^{-9})$
$\mathcal{B}(\tau^\pm \to e^\pm \gamma)$	$<8.5 \times 10^{-8}$		$\mathcal{O}(10^{-9})$
$\mathcal{B}(\tau^\pm \to \mu^\pm \mu^+ \mu^-)$	$<2.0 \times 10^{-8}$		$\mathcal{O}(10^{-10})$
$\mathcal{B}(\tau^\pm \to e^\pm e^+ e^-)$	$<2.6 \times 10^{-8}$		$\mathcal{O}(10^{-10})$
$Z^0 \to e^\pm \mu^\mp$	$<1.7 \times 10^{-6}$		
$Z^0 \to e^\pm \tau^\mp$	$<9.8 \times 10^{-6}$		
$Z^0 \to \mu^\pm \tau^\mp$	$<1.2 \times 10^{-5}$		
$K_L^0 \to e^\pm \mu^\mp$	$<4.7 \times 10^{-12}$		10^{-13}
$D^0 \to e^\pm \mu^\mp$	$<8.1 \times 10^{-7}$		10^{-8}
$B^0 \to e^\pm \mu^\mp$	$<9.2 \times 10^{-8}$		10^{-9}

From Marciano, Mori and Roney, Ann. Rev. Nucl. Part. Sci. 2008. 58:315-41

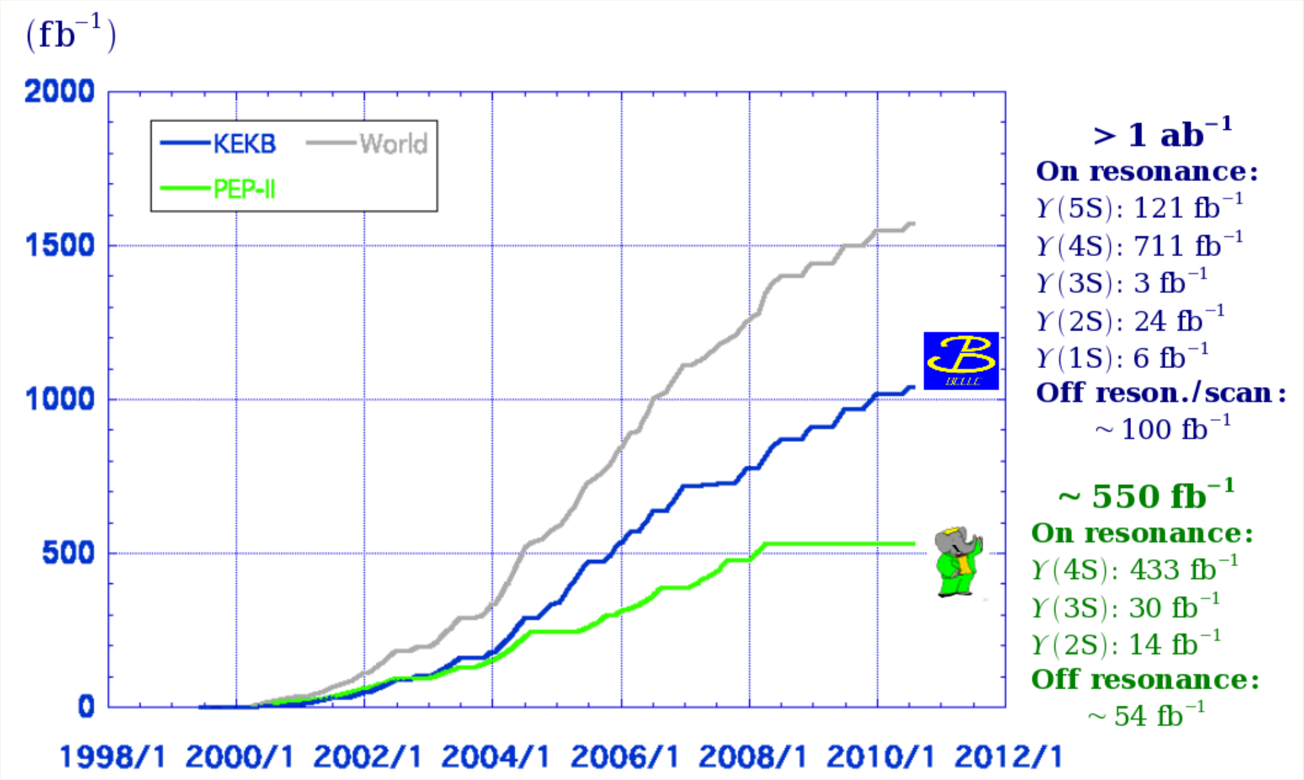
Trends in improvements in experimental sensitivity to LFV



Based on slide presented by Craig Dukes at Tau 2010

Many recent new LFV results come from **BaBar** and **Belle** using all (or almost all) available integrated luminosity (500 fb^{-1} (BaBar) and 1000 fb^{-1} (Belle)) ...

B Factories integrated luminosity



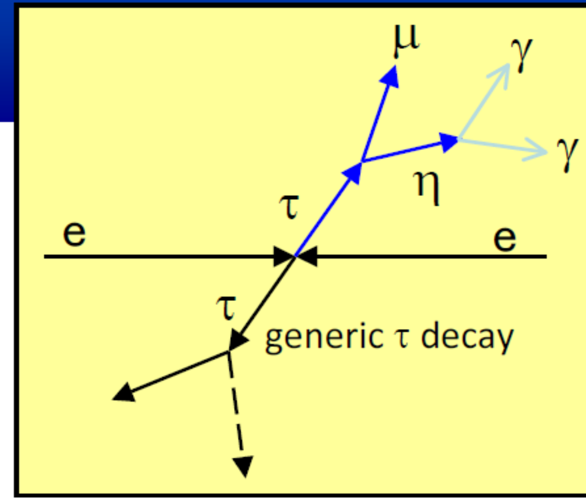
- BaBar stopped data-taking April 2008
- Belle stopped June 2010
- Final analyses ongoing and preparations for Belle II and SuperB underway

- $\sigma(e^+e^- \rightarrow \tau^+\tau^-)$ = 0.9 nb at B Factory energies
- → ~10^9 (BaBar) + ~2 x 10^9 (Belle) produced taus
- With ~ 5 - 10% efficiencies and very low backgrounds, search limits down to ~10^{-8}

General analysis procedures to search for LFV tau decays at B Factories

Analysis procedure

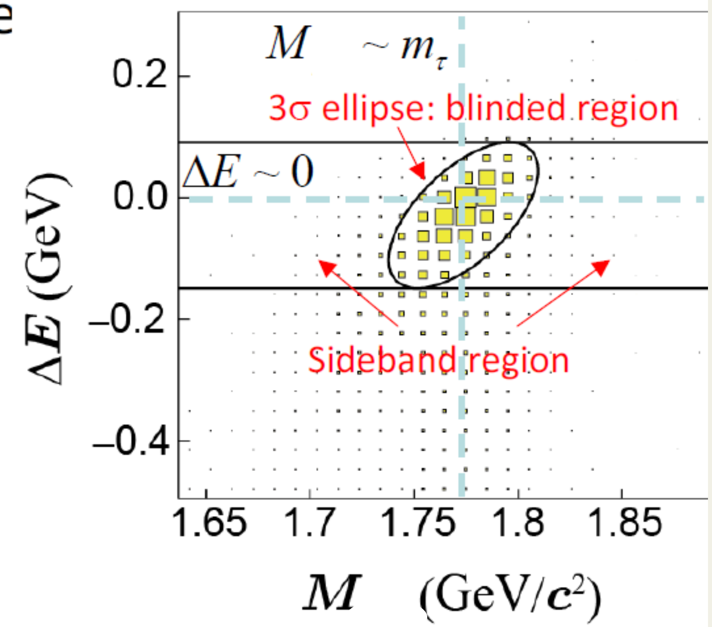
- $e^+e^- \rightarrow \tau^+\tau^-$ Br~85%
  - τ^- → 1 prong + missing (tag side)
  - τ^+ → $\mu+\eta$ (signal side), Fully reconstructed, η → $\gamma+\gamma$



Signal extraction: $M_{\mu\eta}-\Delta E$ plane

$$M_{\mu\eta} = \sqrt{(E_{\mu\eta}^2 - p_{\mu\eta}^2)}$$

$$\Delta E = E_{\mu\eta}^{CM} - E_{beam}^{CM}$$

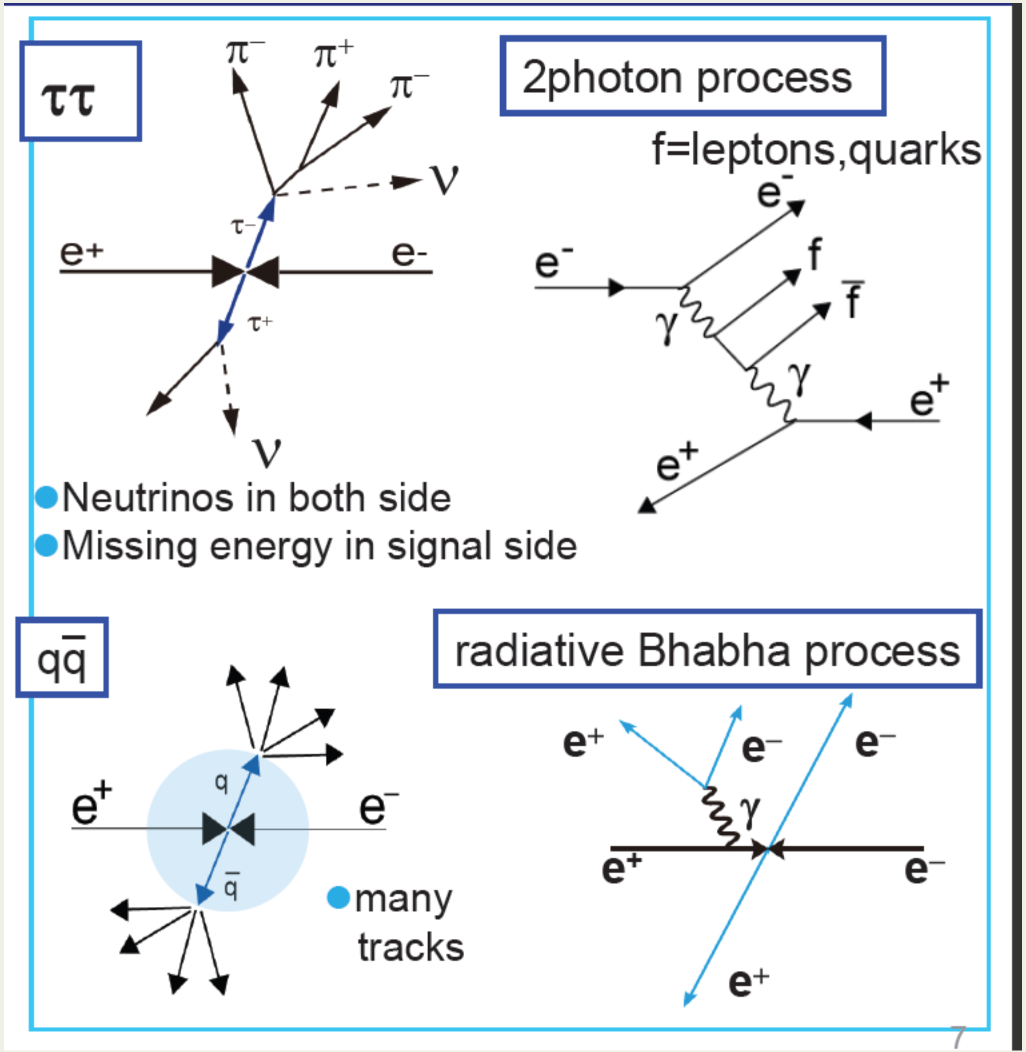


Blind analysis ⇒Blind signal region

Estimate number of BG in the signal region using sideband data and MC

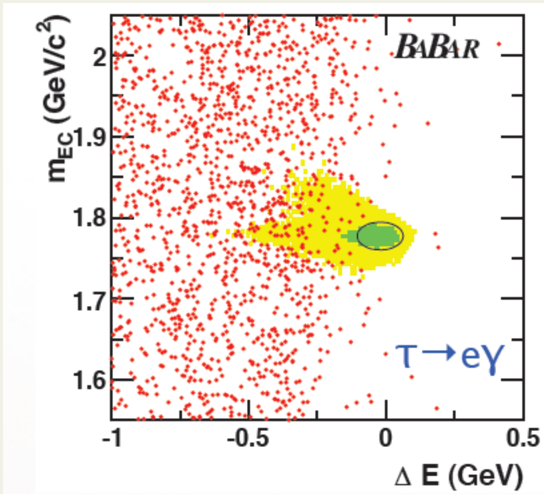
Presented by Kenji Inami at Tau 2010

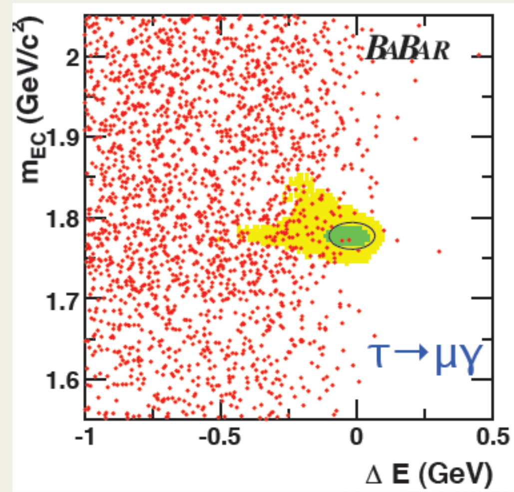
Illustrating general **backgrounds** in searches for LFV tau decays at B Factories



Presented by Kenji Inami at Tau 2010

BaBar limits on $\tau^- \rightarrow \mu^-\gamma$ and $\tau^- \rightarrow e^-\gamma$ using 515 fb^{-1}





τ→eγ

Efficiency (2σ) = 3.9 ± 0.3 %

Expected Bkg = 1.6 ± 0.5 events

Expected Upper Limit: 9.8 x 10^{-8}

Observed Number of events: 0

τ→μγ

Efficiency (2σ) = 6.1 ± 0.5 %

Expected Bkg = 3.6 ± 0.6 events

Expected Upper Limit: 8.1 x 10^{-8}

Observed Number of events: 2

$$\mathcal{B}\ (\tau^{\pm} \rightarrow e^{\pm}\gamma) < 3.3 \times 10^{-8}$$

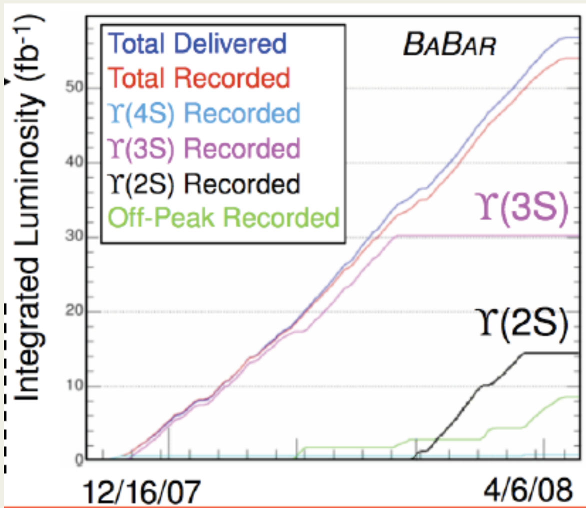
$$\mathcal{B}\ (\tau^{\pm} \rightarrow \mu^{\pm}\gamma) < 4.4 \times 10^{-8}$$

PRL 104, 021802 (2010)

Presented by Alberto Cervelli at Tau 2010

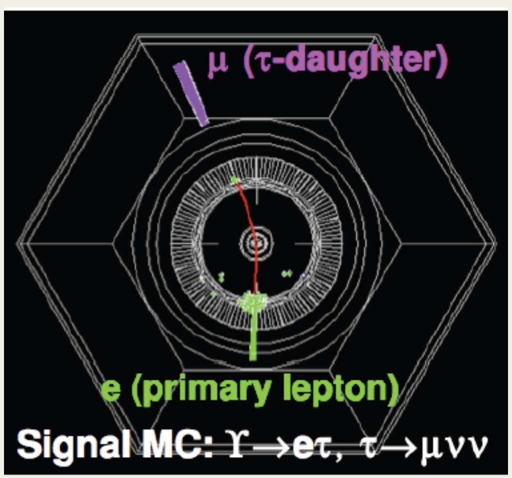
BaBar search for LFV in Υ decays

BaBar recorded 122M $\Upsilon(3S)$ and 99M $\Upsilon(2S)$ decays



Search channels

Process	τ decay	Channel
$\Upsilon(3,2S)\to e\tau$	$\tau\to\mu\nu\nu$	leptonic $e\tau$
$\Upsilon(3,2S)\to e\tau$	$\tau\to\pi^{\pm}\pi^{0}\nu/\pi^{\pm}\pi^{0}\pi^{0}\nu$	hadronic $e\tau$
$\Upsilon(3,2S)\to \mu\tau$	$\tau\to e\nu\nu$	leptonic $\mu\tau$
$\Upsilon(3,2S)\to \mu\tau$	$\tau\to\pi^{\pm}\pi^{0}\nu/\pi^{\pm}\pi^{0}\pi^{0}\nu$	hadronic $\mu\tau$



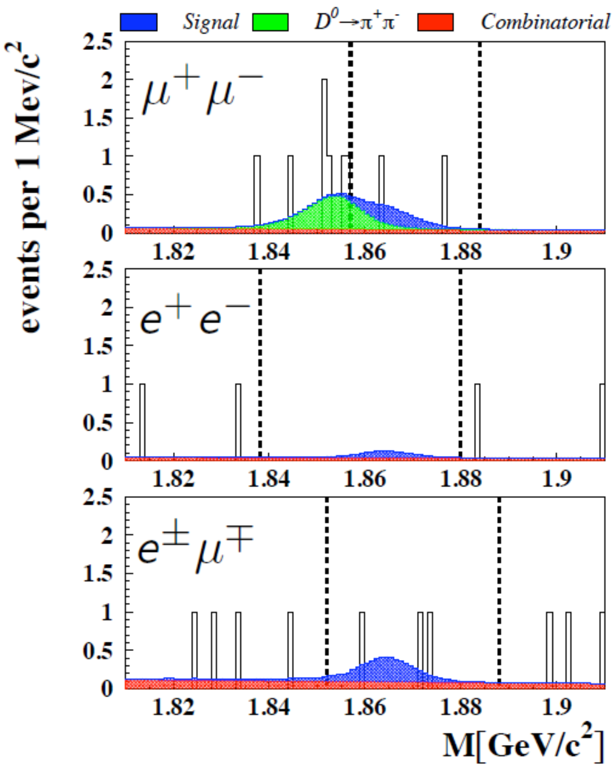
Limits

PRL 104, 151802 (2010)

	$\mathcal{B}\ (10^{-6})$	90% UL (10^{-6})
$\mathcal{B}(\Upsilon(2S)\to e^{\pm}\tau^{\mp})$	$0.6^{+1.5+0.5}_{-1.4-0.6}$	< 3.2
$\mathcal{B}(\Upsilon(2S)\to \mu^{\pm}\tau^{\mp})$	$0.2^{+1.5+1.0}_{-1.3-1.2}$	< 3.3
$\mathcal{B}(\Upsilon(3S)\to e^{\pm}\tau^{\mp})$	$1.8^{+1.7+0.8}_{-1.4-0.7}$	< 4.2
$\mathcal{B}(\Upsilon(3S)\to \mu^{\pm}\tau^{\mp})$	$-0.8^{+1.5+1.4}_{-1.5-1.3}$	< 3.1

Presented by Elisa Guido at DISCRETE2010

Search for $D^0 \to \ell^+\ell^-$ - Results



Channel	events	estimated bkg.
$\mu^+\mu^-$	2	3.1±0.1
e^+e^-	0	1.7±0.2
$e^\pm\mu^\mp$	3	2.6±0.2

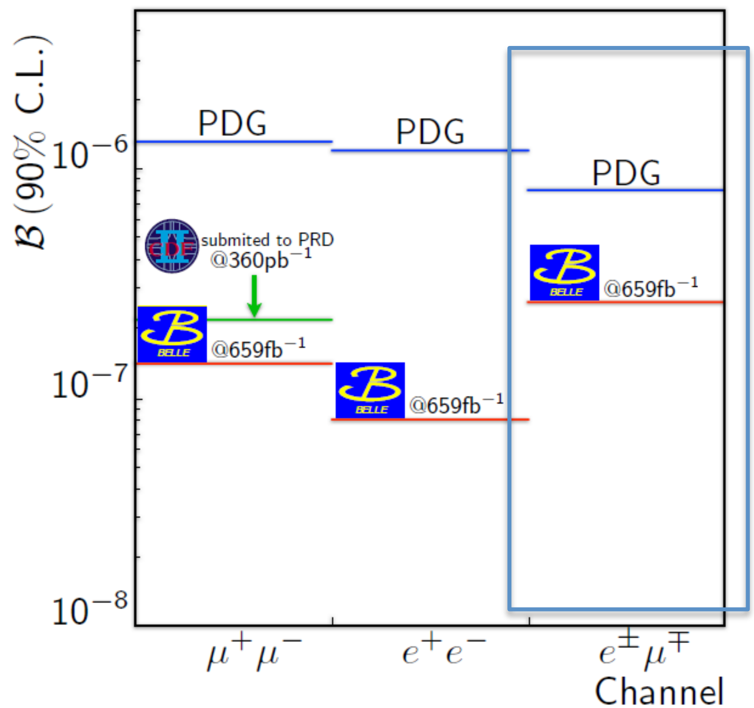
90% C.L. upper limits with pole.f

$$\mathcal{B}\left(D^0 \to \mu^+\mu^-\right) < 1.4 \times 10^{-7}$$

$$\mathcal{B}\left(D^0 \to e^+e^-\right) < 7.9 \times 10^{-8}$$

$$\mathcal{B}\left(D^0 \to e^\pm\mu^\mp\right) < 2.6 \times 10^{-7}$$

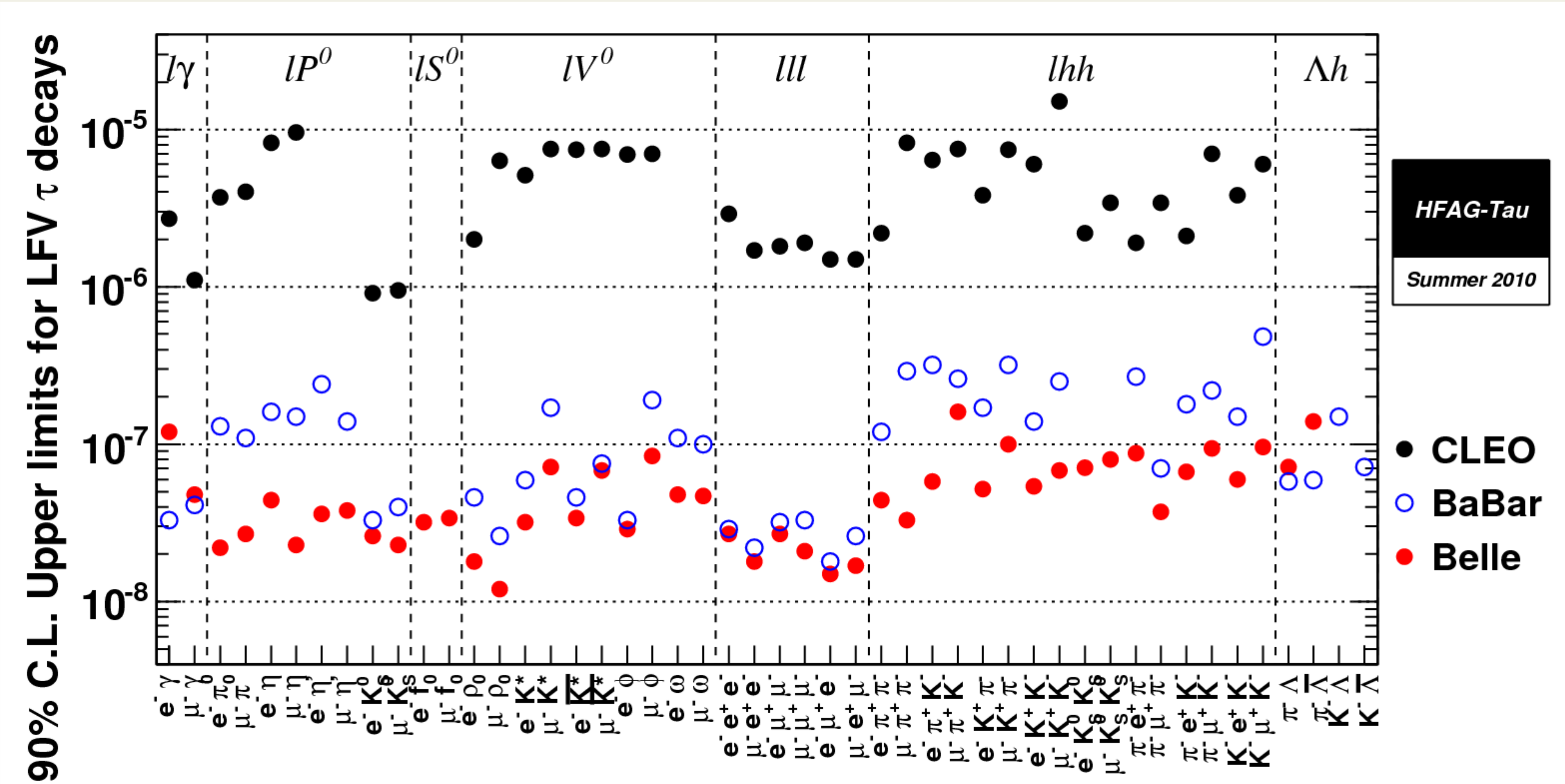
Lowest upper limit up to now



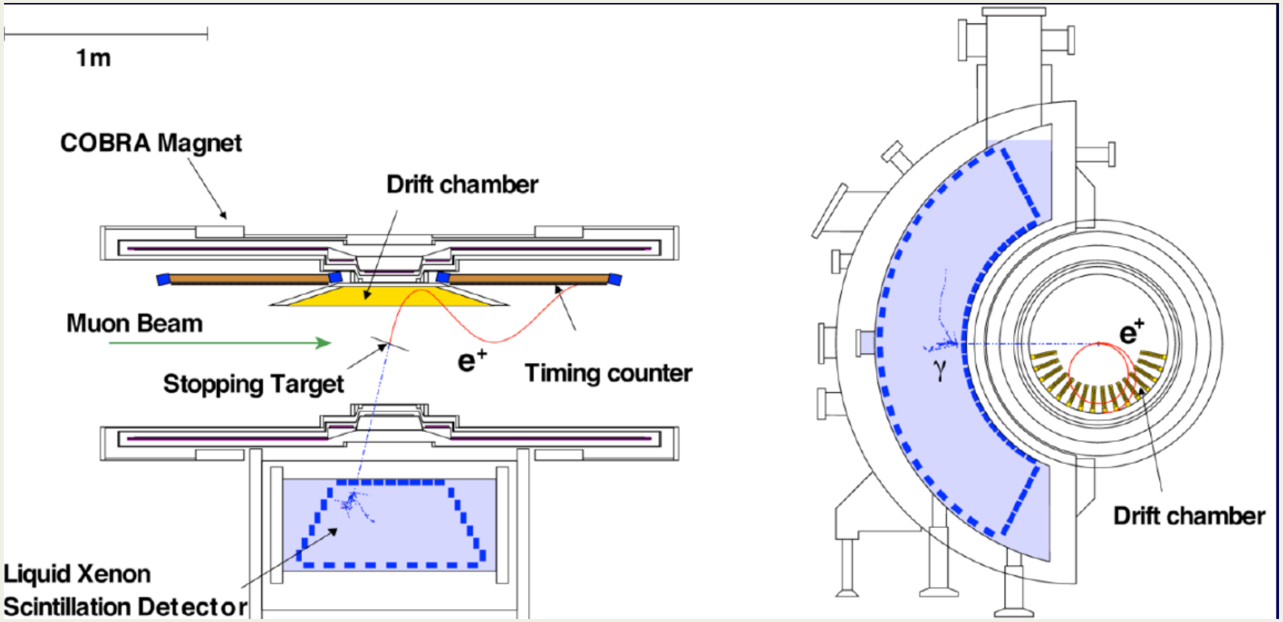
PRD 81, 091102(R) (2010)

Presented by M. Petric at Tau2010

Compilation by **Heavy Flavor Averaging Group** of LFV limits for tau decays

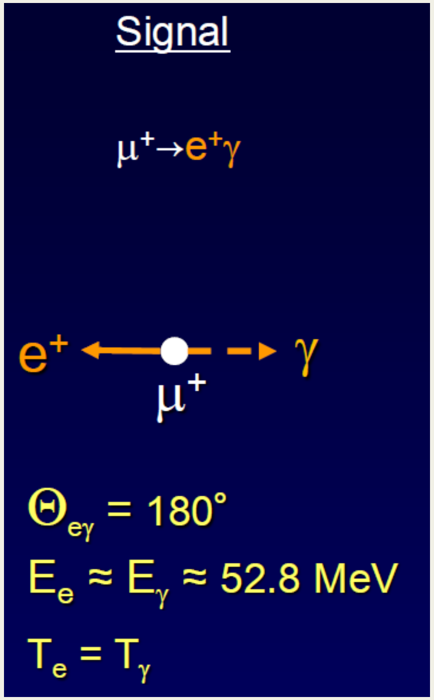


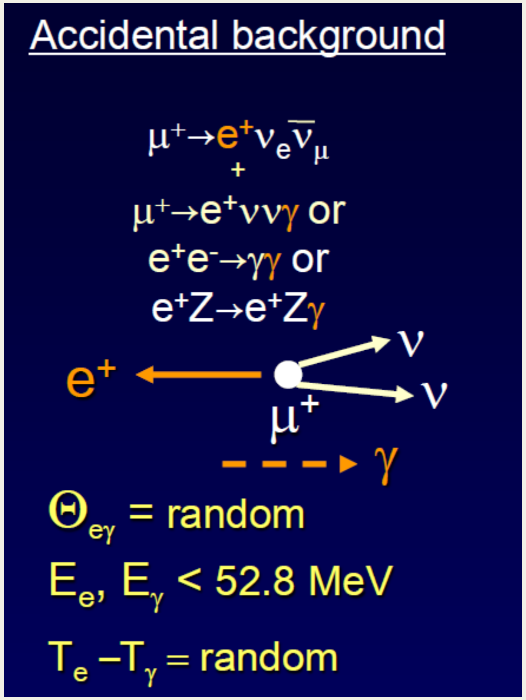
The **MEG** experiment at PSI: search for $\mu^+ \rightarrow e^+ \gamma$

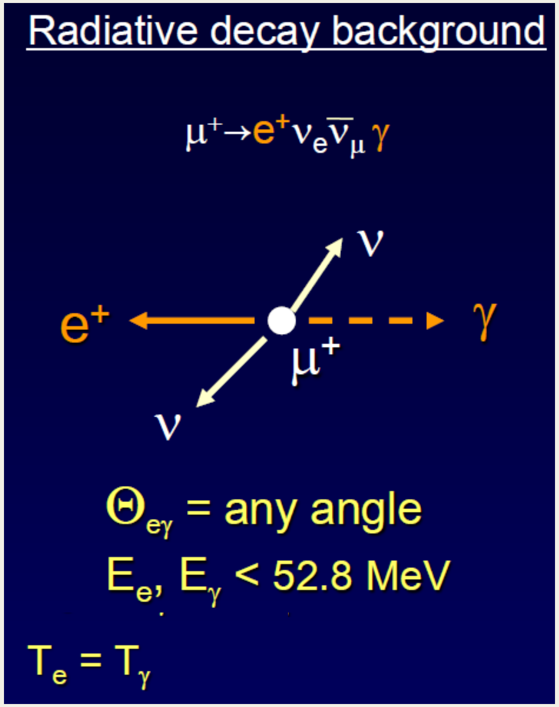


- ~3 x 10^7 μ^+ per second on a thin stopping target
- Decay $\mu^+ \rightarrow e^+ \gamma$ in would produce back-to-back, mononergetic e^+ and γ
- Positron detection by B-field, drift-chambers and scintillation counters
- Photon energy, posision and time measured by liquid Xe calorimeter

- Propose to reach sensitivity of **~10^{-13}** with data taking during 2008 – 2012
- Results so far available from 2009 and 2010 runs

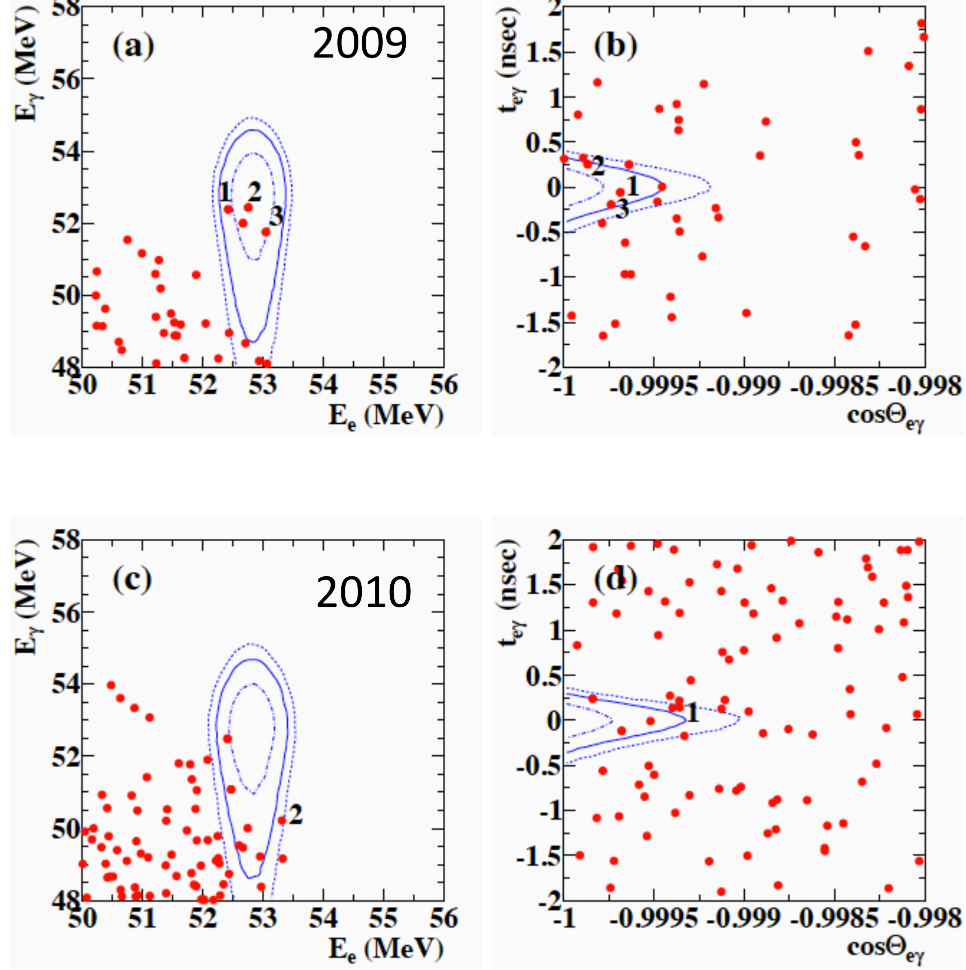






Accidentals make up the dominant background at rates high enough to reach sensitivity of 10^{-13}

Presented by Ben Golden at Tau2010



MEG analysis of 2009+2010 data

Total of 1.8 x 10^{14} μ^+ decays

Extended maximum likelihood fit

N_{sig} = number of signal events
N_{RD} = number of radiative decays
N_{acc} = number of accidental events
Observables in pdfs: E_e, E_γ, $T_{e\gamma}$, $\phi_{e\gamma}$, $\theta_{e\gamma}$

$$\mathcal{L}\left(N_{\mathrm{sig}}, N_{\mathrm{RMD}}, N_{\mathrm{BG}}\right) = \frac{e^{-N}}{N_{\mathrm{obs}}!} e^{-\frac{(N_{\mathrm{RMD}}-\langle N_{\mathrm{RMD}}\rangle)^2}{2\sigma^2_{\mathrm{RMD}}}} e^{-\frac{(N_{\mathrm{BG}}-\langle N_{\mathrm{BG}}\rangle)^2}{2\sigma^2_{\mathrm{BG}}}} \times$$

$$\prod_{i=1}^{N_{\mathrm{obs}}} \left(N_{\mathrm{sig}} S(\vec{x}_i) + N_{\mathrm{RMD}} R(\vec{x}_i) + N_{\mathrm{BG}} B(\vec{x}_i)\right)$$

Sensitivity for combined 2010+2011: 1.6 x 10^{-12}

Observed limit: **< 2.4 x 10^{-12} at 90% CL**

Prospects for MEG

Analysis of 2009+2010 data now published
Improvement of an order of magnitude on limit from 2009 data alone

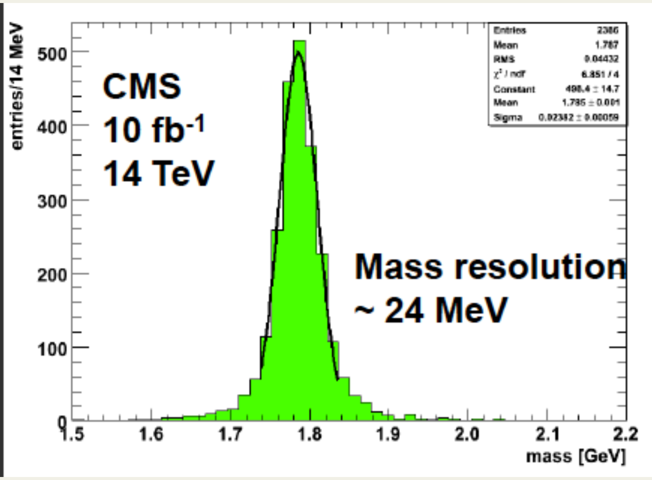
Resolution(σ) or Efficiency	2009	2010 (estimate)
Gamma Energy (%)	2.1(w>2cm)	1.5(w>2cm)
Gamma Timing (psec)	>67	68
Gamma Position (mm)	5(u,v) / 6(w)	←
Gamma Efficiency (%)	58	←
e^+ Momentum (%)	0.74(core)	0.7
e^+ Angle (mrad)	7.4(φ, core)/11.2(θ)	8(φ)/8(θ)
e^+ Efficiency (%)	40	←
e^+-gamma timing (psec)	142(core)	120
Muon Decay Point (mm)	2.3(R)/2.8(Z)	1.4(R)/2.5(Z)
Trigger efficiency (%)	84	94
Stopping Muon Rate (sec^{-1})	2.9×10^7(300μm)	3×10^7 (300μm)
DAQ time/Real time (days)	35/43	95/117
Sensitivity	6.1×10^{-12}	2.0×10^{-12}
BR upper limit (obtained)	1.5×10^{-11}	2.4×10^{-12}

Data-taking is continuing

A few x 10^{-13} in the next few years

Presented by Ben Golden at Tau2010

LFV at LHC: $\tau^- \rightarrow \mu^+\mu^-\mu^-$ at CMS

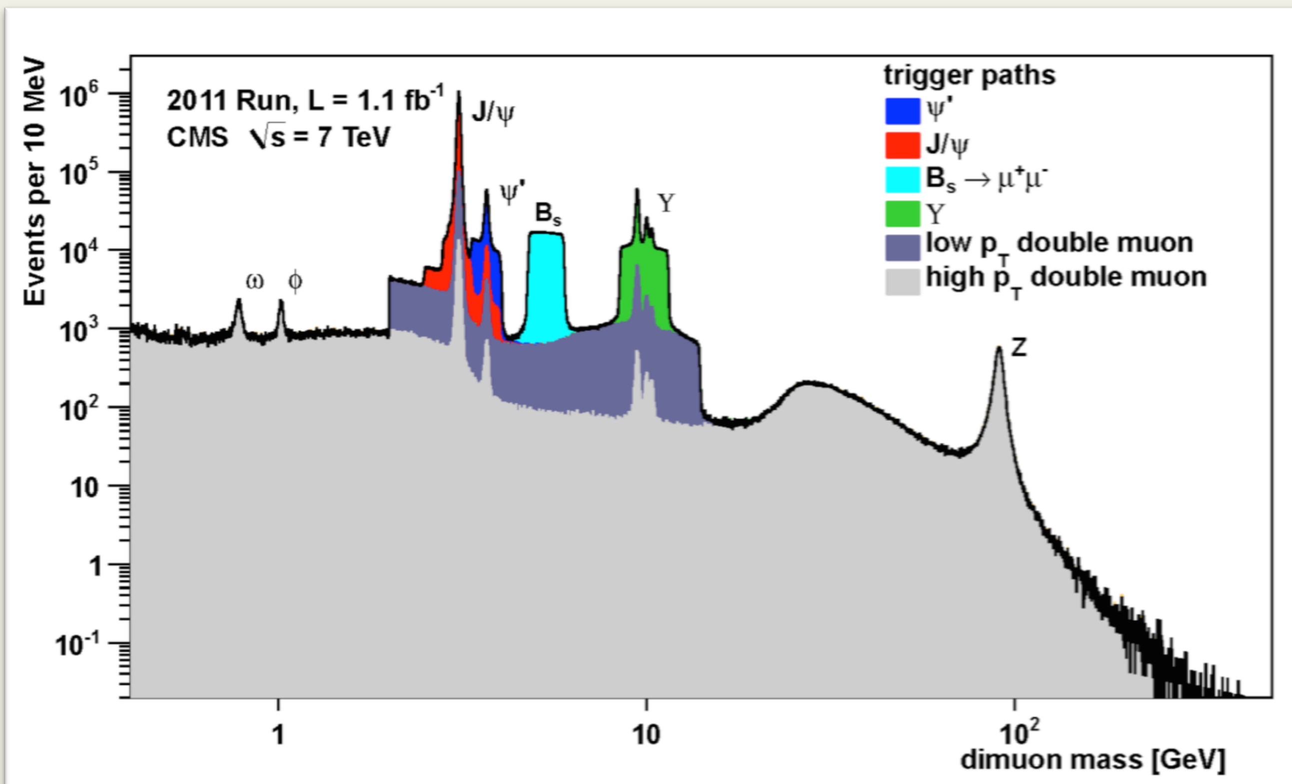


reconstructed invariant mass of $\tau \rightarrow >3\mu$
➔good capability to reduce background events, like Bd → $\mu\mu$.

Expected upper limit in CMS

W source:	**7.0×10^{-8}**	**for 10 fb^{-1}**
	3.8×10^{-8}	**for 30 fb^{-1}**
Z source	**3.4×10^{-7}**	**for 30 fb^{-1}**
B mesons	**2.1×10^{-7}**	**for 30 fb^{-1}**

From Kajari Mazumdar
NuGoa, April 2009



"Given that in recent times we have been able to do things that we did not think would be possible in the design and construction phases of CMS, I cannot say any longer that we cannot build a trigger for tau to 3 mu, for the 2012 run. However, detailed studies still have to be done."

Gigi Rolandi

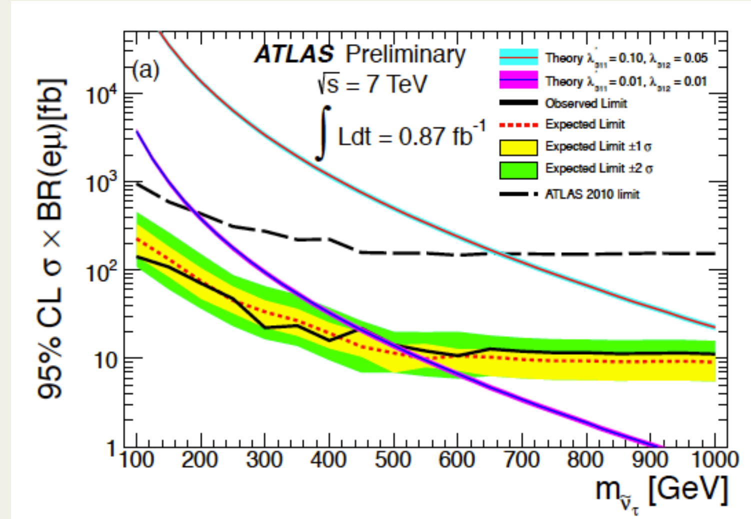
LFV at LHC: ATLAS

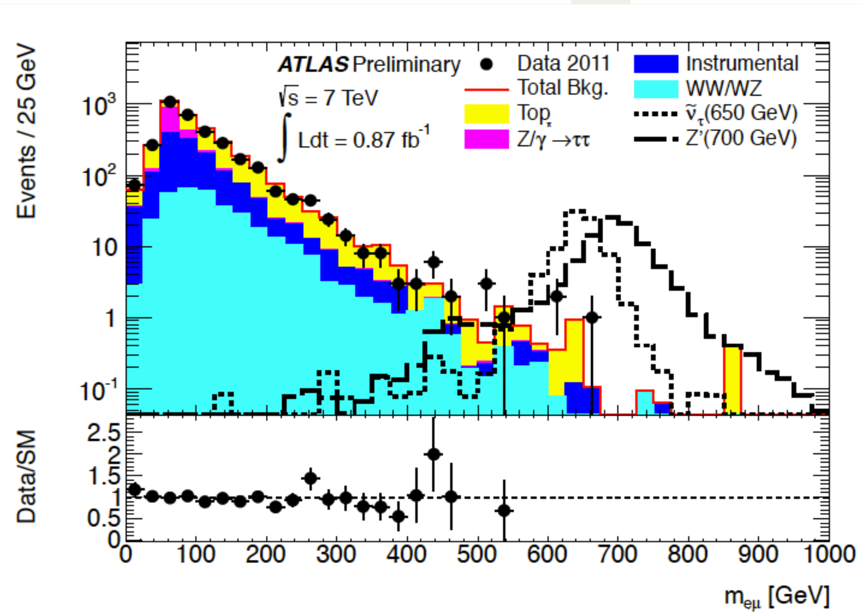
Search for a heavy neutral particle decaying into an electron and a muon pair using $L = 0.87\ fb^{-1}$ of ATLAS data

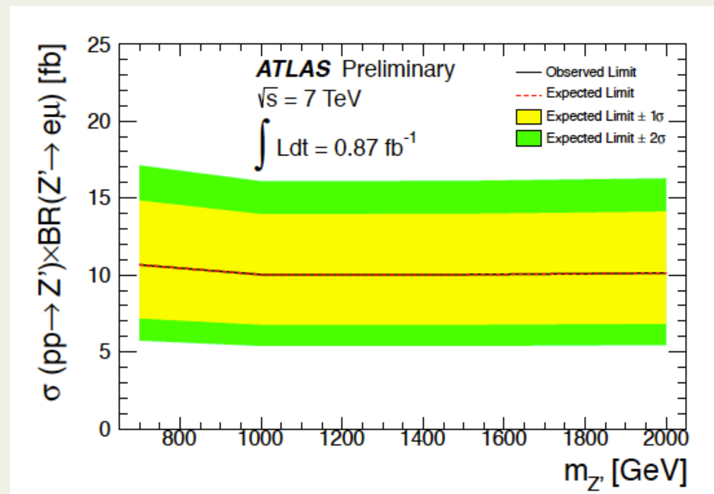
ATLAS-CONF-2011-109

Process	Number of events
$Z/\gamma^* \to \tau\tau$	614 ± 53
$t\bar{t}$	1281 ± 168
WW	318 ± 24
Single top	125 ± 17
WZ	18.2 ± 1.9
$W/Z + \gamma$	67 ± 11
Jet instrumental background	984 ± 105
Total background	3408 ± 230
Data	3338

$m_{e\mu}$	Data	SM prediction
> 200 GeV	224	236 ± 21
> 250 GeV	119	111 ± 11
> 300 GeV	51	55 ± 6
> 350 GeV	29	30 ± 4
> 400 GeV	18	14.2 ± 2.2
> 450 GeV	9	8.2 ± 1.5
> 500 GeV	7	5.3 ± 1.1
> 550 GeV	3	3.4 ± 0.8
> 600 GeV	3	2.2 ± 0.7
> 650 GeV	1	0.9 ± 0.4
> 700 GeV	0	0.8 ± 0.4







ATLAS plans for other LFV analyses are "quite murky" at the moment

LFV at LHC: $\tau^- \rightarrow \mu^+\mu^-\mu^-$ and $\tau \rightarrow p\,\mu\,\mu$ at LHCb

Tau production at the LHC is almost exclusively from D_s and B decays

Decay chain	Probability (%)
$D_s \to \tau$	78.3
$D_s \to \tau$	68.9
$B_x \to D_s \to \tau$	9.4
$D^+ \to \tau$	4.9
$D^+ \to \tau$	4.7
$B_x \to D^+ \to \tau$	0.2
$B_x \to \tau$	16.8

Sources of tau leptons at LHCb (from Jon Harrison)

LHCb, with forward geometry, low-pT triggers, vertex locator and good mass resolution is well suited for these tau produciton channels

Prospects for $\tau^- \rightarrow \mu^+ \mu^- \mu^-$ at LHCb look good:

- Preliminary analysis of 2010 data sample indicates a possibility to get close to the current world limit (~10^{-8}) with the 2011 data sample (~ 1 fb^{-1})

- But dependent on how backgrounds behave

LHCb can put limits on $\tau \rightarrow p\mu\mu$ at ~O(10^{-7}) level with 2011 data

- No limit currently exists on this mode, which violates both lepton and baryon number

Super Flavour Factories

Summary of Super*B* LFV reach

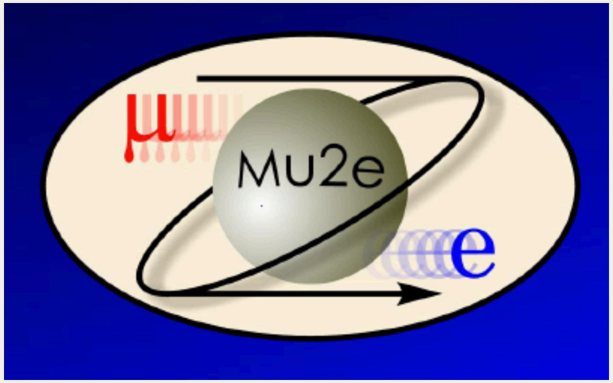
Process	Expected 90% CL upper limit	3σ evidence reach
$BF(\tau \to \mu\gamma)$	$2.4 \cdot 10^{-9}$	$5.4 \cdot 10^{-9}$
$BF(\tau \to e\gamma)$	$3.0 \cdot 10^{-9}$	$6.8 \cdot 10^{-9}$
$BF(\tau \to \ell\ell\ell)$	$2.3–8.2 \cdot 10^{-10}$	$1.2–4.0 \cdot 10^{-9}$

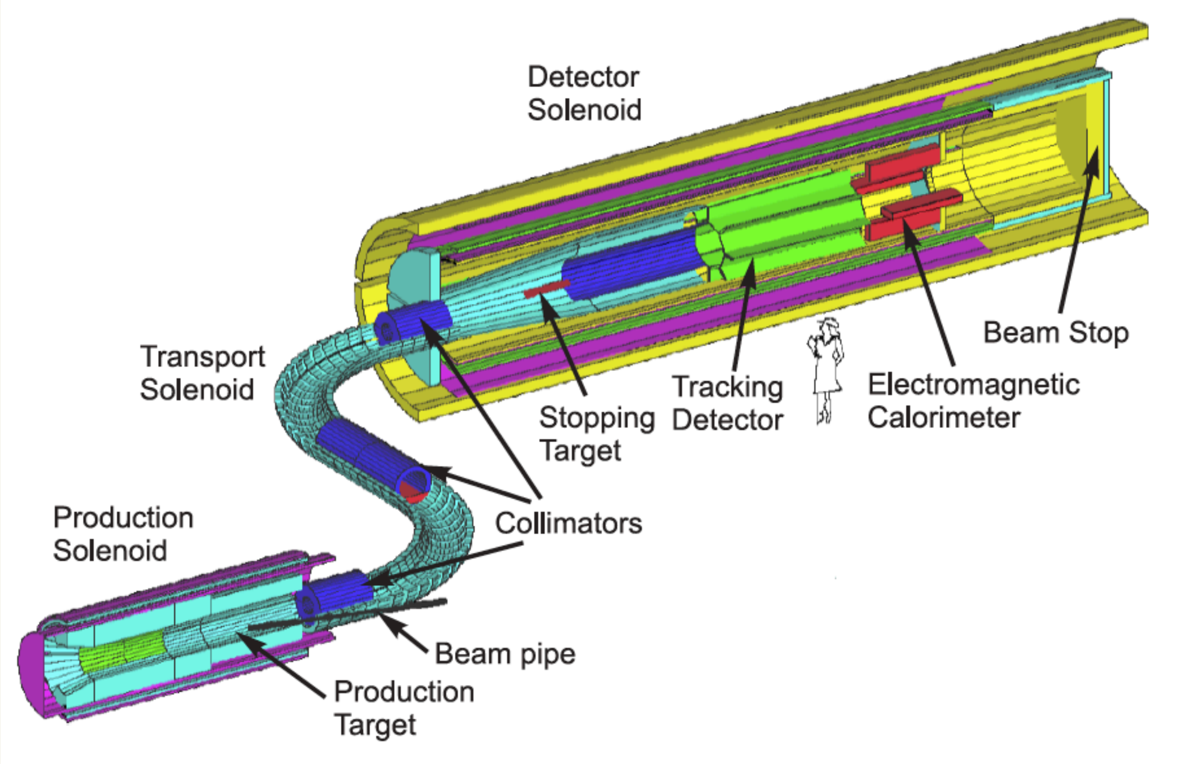
Similar sensitivity expected from Belle II

Results expected 2018 – 2020

Presented by Alberto Lusiani at Tau2010

Mu2e: Mu to E conversion in presence of a nucleus





- Stop muon in atom
- Muon rapidly (10^{-16}s) cascades to 1S state
- Circles the nucleus for up to ~2 μs
- Two things most likely happen:
  1. muon is captured by the nucleus: $\mu^- N_{A,Z} \rightarrow \nu_\mu N_{A,Z-1}$
  2. muon decays in orbit: $\mu^- N_{A,Z} \rightarrow e^- \nu_\mu \nu_e N_{A,Z}$
- In $\mu^- N \rightarrow e^- N$ the muon coherently interacts with nucleus leaving it in ground state
  - signature single isolated electron
  - $E_e = m_\mu - E_{NR} - E_b \sim 104.97$ MeV (Al)

- Graded solenoidal field for pion capture
- Muon transport in curved solenoid to eliminate neutral and positive particles
- Pulsed beam to eliminate prompt backgrounds

Presented by Craig Dukes at Tau2010

$$R_{\mu e} = \frac{\Gamma(\mu^- Al \to e^- Al)}{\Gamma(\mu^- Al \to \nu_\mu Mg)}$$

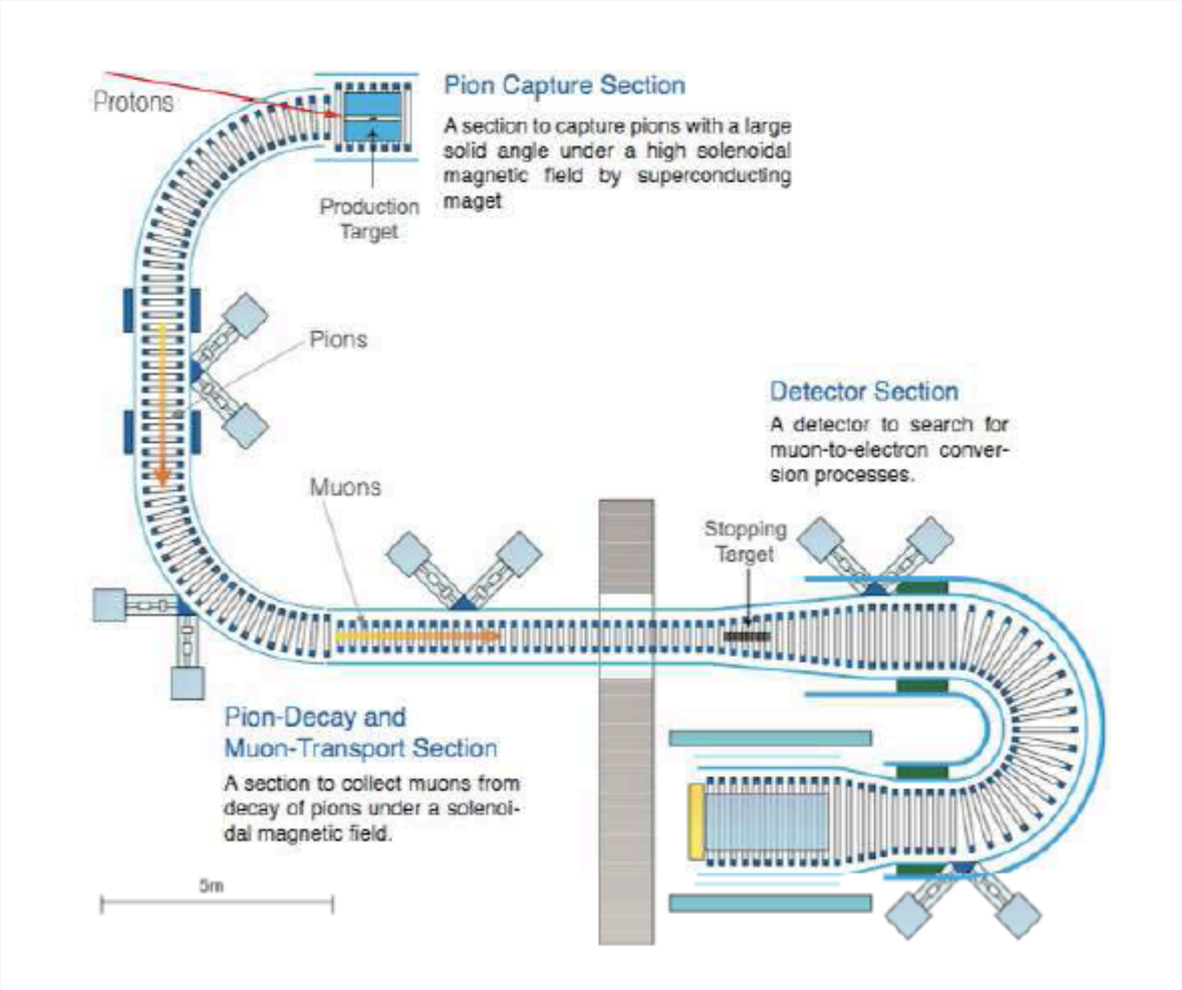
Measure ratio of conversion rate to capture rate

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

- Total project cost estimate $180M
- Proposal received FNAL stage-1 approval in autumn 2008
- CD-0 status granted Nov 2009
- R&D funding granted
  ($4M in FY2010, $10M 2011, $20M 2012)
- Hope to start construction (CD-3) late 2012
- Could later combine with Project X

Presented by Craig Dukes at Tau2010

COMET: Mu to E conversion in presence of a nucleus



Sensitive to $\mu^- N \rightarrow e^- N$ at rate of **~10^{-16}**

Similar sensitivity as Mu2e

Has Stage-1 approval at J-PARC

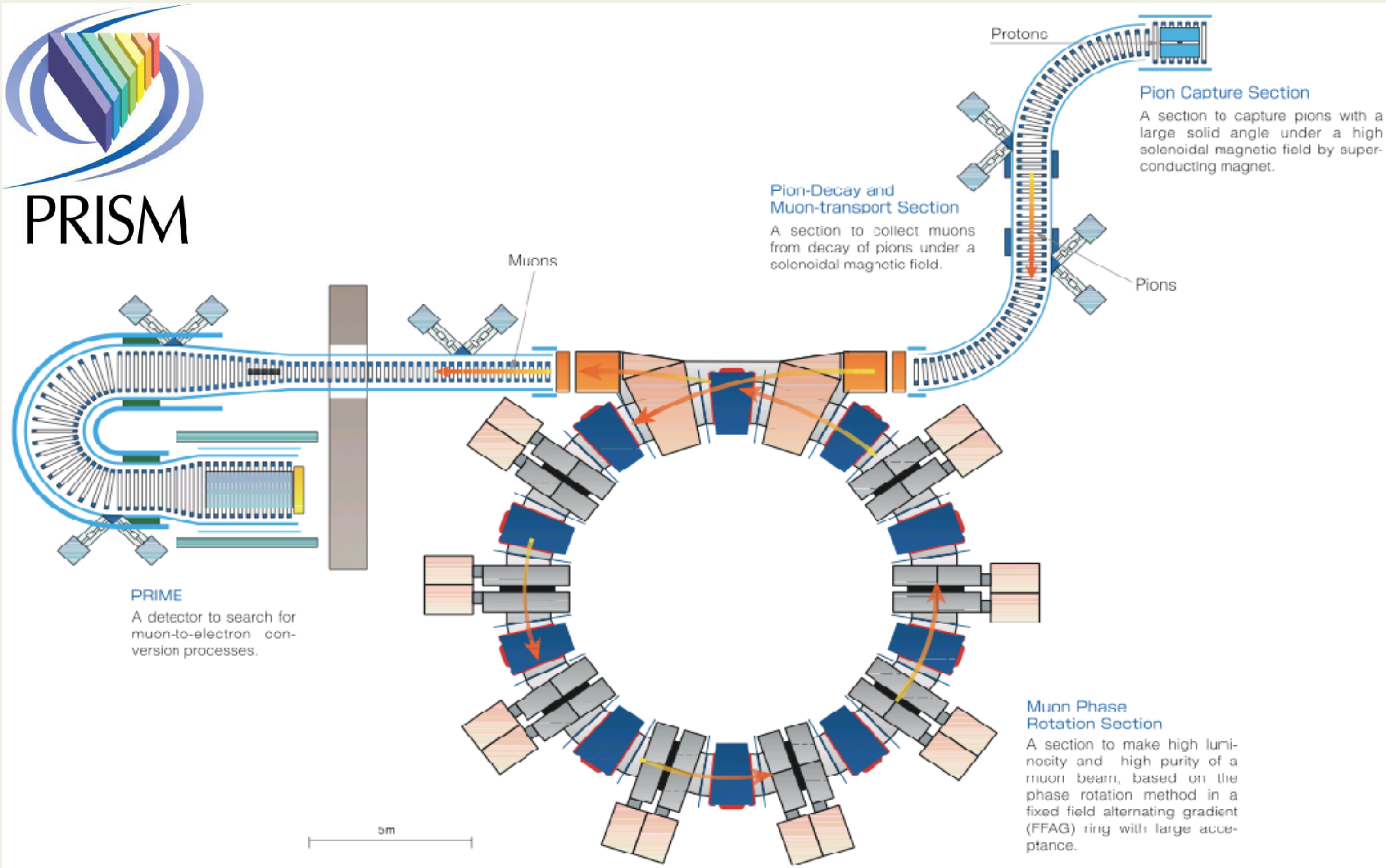
Preparation of TDR in progress

Later proposal to combine with PRISM, high intensity muon accelerator, to make PRIME

PRISM/PRIME: The next generation for Mu to E conversion

PRISM: Phase Rotated IntenSe Muon source
PRIME: PRIsm Mu E conversion

Proposal for 2 orders of magnitude more sensitivity than COMET
Sensitive to $\mu^- N \rightarrow e^- N$ at rate of **~10^{-18}**



A sample of various charged lepton flavour violating reactions

Reaction	Current bound	Expected	Possible
$\mathcal{B}(\mu^+ \to e^+\gamma)$	$<1.2 \times 10^{-11}$	2×10^{-13}	2×10^{-14}
$\mathcal{B}(\mu^\pm \to e^\pm e^+ e^-)$	$<1.0 \times 10^{-12}$	–	10^{-14}
$\mathcal{B}(\mu^\pm \to e^\pm\gamma\gamma)$	$<7.2 \times 10^{-11}$	–	–
$R(\mu^- \mathrm{Au} \to e^- \mathrm{Au})$	$<7 \times 10^{-13}$	–	–
$R(\mu^- \mathrm{Al} \to e^- \mathrm{Al})$	–	10^{-16}	10^{-18}
$\mathcal{B}(\tau^\pm \to \mu^\pm\gamma)$	$<5.9 \times 10^{-8}$		$\mathcal{O}(10^{-9})$
$\mathcal{B}(\tau^\pm \to e^\pm\gamma)$	$<8.5 \times 10^{-8}$		$\mathcal{O}(10^{-9})$
$\mathcal{B}(\tau^\pm \to \mu^\pm\mu^+\mu^-)$	$<2.0 \times 10^{-8}$	LHCb	$\mathcal{O}(10^{-10})$
$\mathcal{B}(\tau^\pm \to e^\pm e^+ e^-)$	$<2.6 \times 10^{-8}$		$\mathcal{O}(10^{-10})$
$Z^0 \to e^\pm\mu^\mp$	$<1.7 \times 10^{-6}$		
$Z^0 \to e^\pm\tau^\mp$	$<9.8 \times 10^{-6}$		
$Z^0 \to \mu^\pm\tau^\mp$	$<1.2 \times 10^{-5}$		
$K^0_L \to e^\pm\mu^\mp$	$<4.7 \times 10^{-12}$		10^{-13}
$D^0 \to e^\pm\mu^\mp$	$<8.1 \times 10^{-7}$		10^{-8}
$B^0 \to e^\pm\mu^\mp$	$<9.2 \times 10^{-8}$		10^{-9}

MEG

COMET, Mu2e -> PRISM/PRIME, Project X

Belle II, SuperB

ATLAS, CMS ?

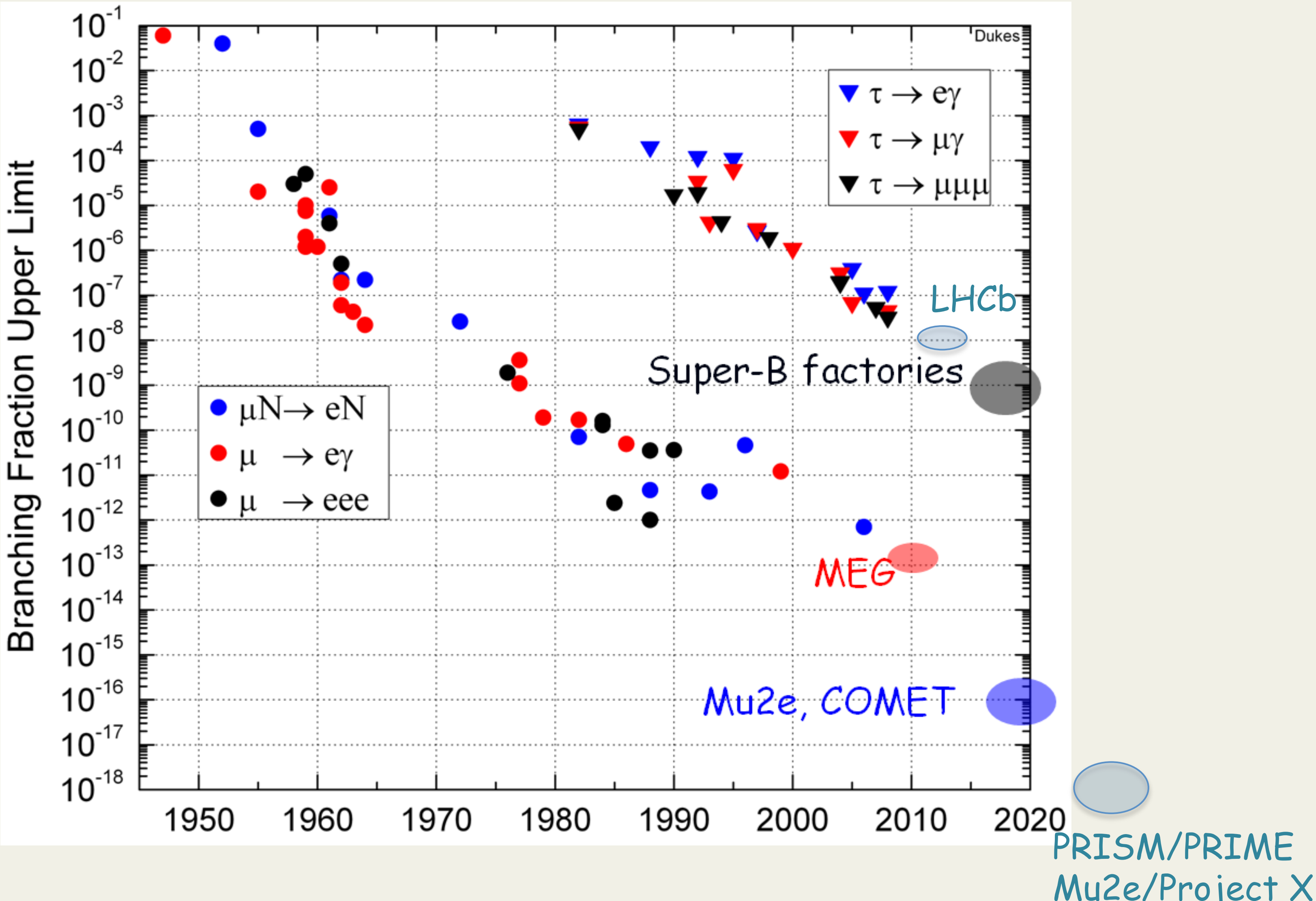
Data from current experimental bounds, expected improvements from existing or funded experiments, and possible long-term advances.

From Marciano, Mori and Roney, Ann. Rev. Nucl. Part. Sci. 2008. 58:315-41

Summary of principal future **prospects** for LFV ...

- MEG 2011-2012 runs
- LHC (e.g. $\tau^- \rightarrow \mu^+ \mu^- \mu^-$ at LHCb)
- Belle II and SuperB
- A Super tau-charm factory (?)
- Mu2e
- COMET
- Mu2e/Project X
- PRISM/PRIME

Conclusions: Where are we and where are we going with charged LFV?



From slide presented by
Craig Dukes at Tau2010