Eduardo Rodrigues

Particle Physics Seminar
University of Bristol, 8 February 2012

Searching for Lepton Flavour Violation

- Motivating LFV
- Mini-review of searches on LFV μ decays
- Mini-review of searches on LFV τ decays
- Intro to LFV phenomenology
- Activities at the LHC
- Outlook

Motivating LFV

Clear signature of New Physics !

Lepton number(s) and conservation law(s)

- 1953: introduction of the lepton number L by Konopinski and Mahmoud

- Lepton number conservation verified empirically

- Pontecorvo later introduced (1959) a separate lepton number for muons
  $\Rightarrow L_e$ and L_μ

- Separate conservation of L_e and L_μ observed experimentally
  to high precision:
  - e.g. no observation of

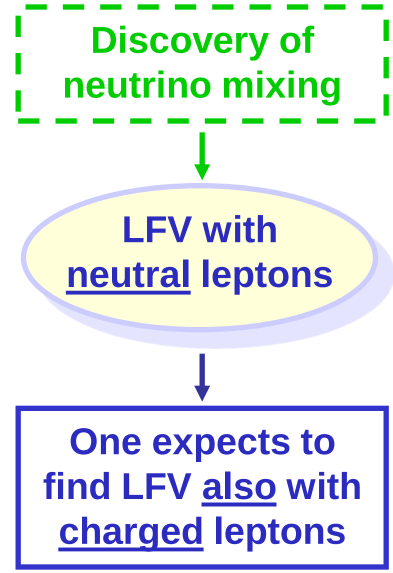
$$\mu \to e\,\gamma \quad , \quad 3e$$
$$\tau \to 3\mu \quad , \quad e\,\gamma$$

But …

Why so much enthusiasm for LFV?

Experimental motivation:

- LFV: a reality in neutral leptons sector – neutrinos oscillate !



Theoretical motivations:

- Lepton number conservation verified experimentally to very high precision but is not a consequence of a known gauge symmetry
- LFV in the charged sector will mean New Physics (NP) !
- Almost any model beyond the SM (BSM) predicts LFV. Some models allow branching fractions for certain τ decays at the ~10^{-7} level, already reachable(ed) experimentally
- Baryogenesis via Leptogenesis

✓ **What is the missing link among all this? Neutrinos !**

$\Longrightarrow$ **Increasing interest in LFV stimulated by great progress in neutrino physics in the last decade**

BSM « frameworks »

Non-exhaustive list of models :

- MSSM
- CMSSM (constrained MSSM) see-saw models
- νMSM (SM + 3 singlet neutrinos)
- SUSY models
- R-parity violating Supersymmetry (SUSY)
- mSUGRA + see-saw
- 2HDM (two-Higgs doublet models)
- Left-right symmetric models
- Models with heavy Dirac or Majorana neutrinos
- Topcolour models
- …

LFV is always "around the corner" in these models …

… particularly "large effects" in SUSY GUTs

Disclaimer: LFV relates to many topics! (Not all for this talk ;-))

SM

CKM

FCNC

ν oscillations

BSM

NP

CPV

PMNS

ν masses

SUSY

MSSM

LFV

See-saw

MFV

GUT

Baryogenesis

Dirac ν

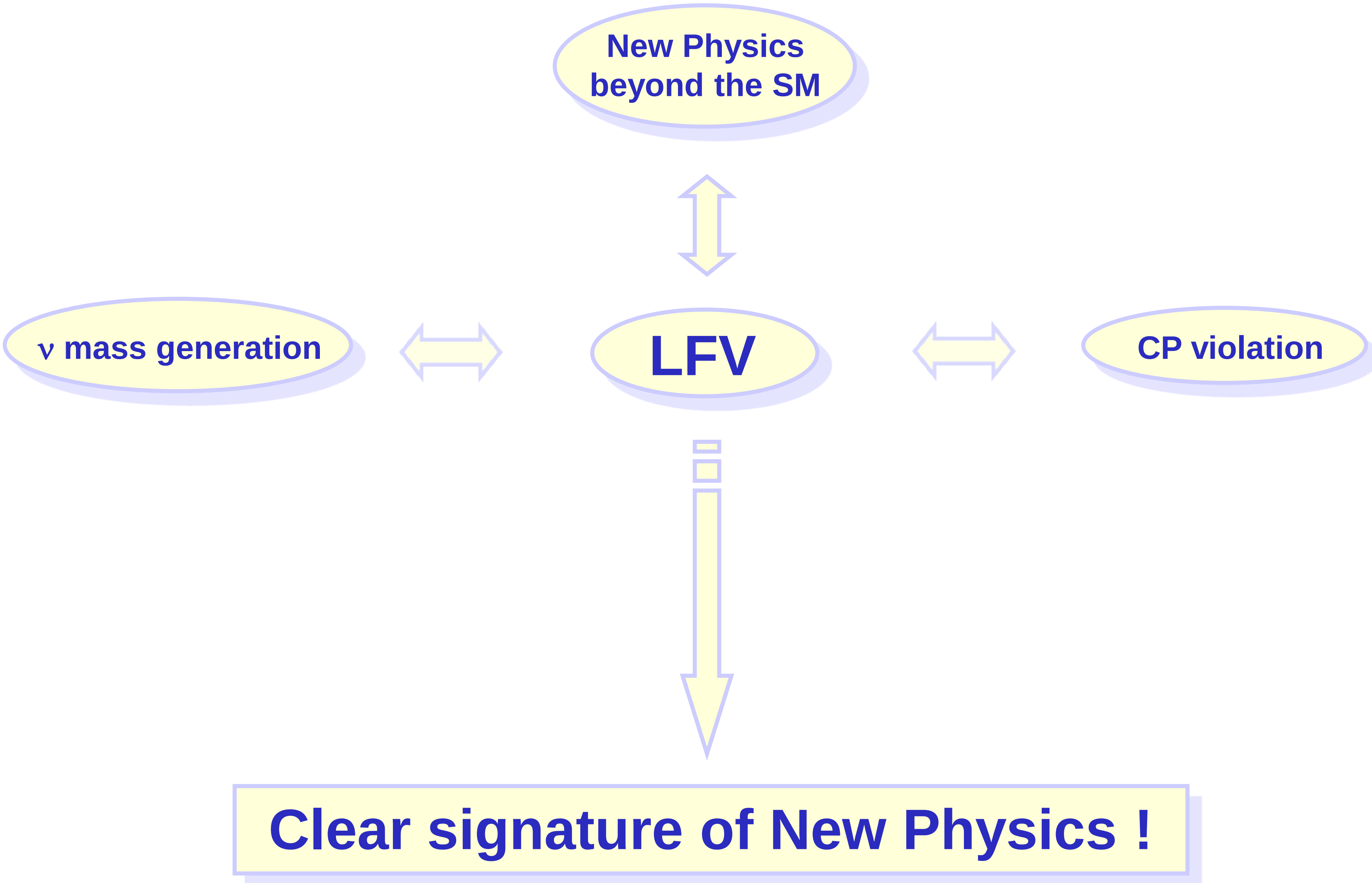
EWPT

BAU

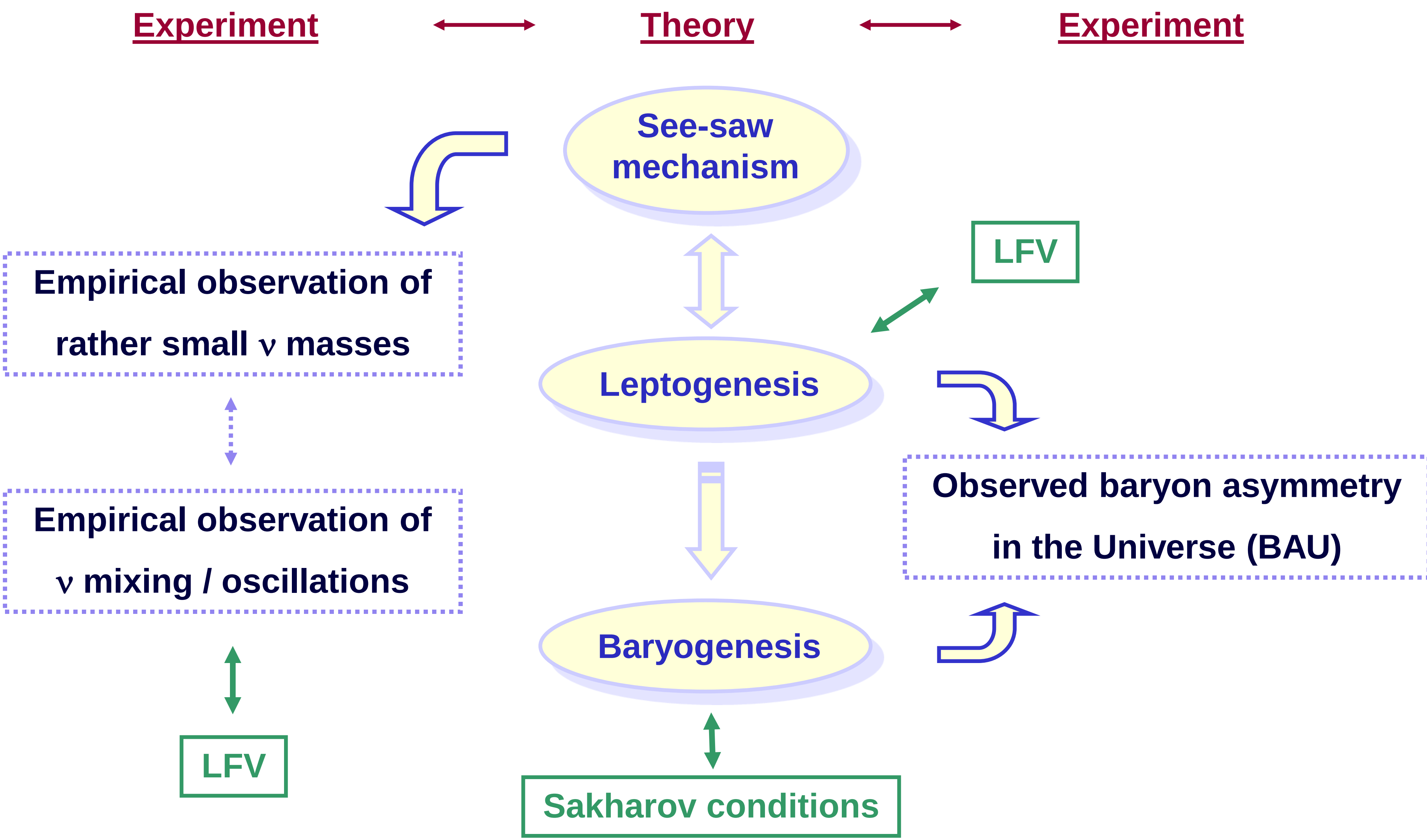
Leptogenesis

Majorana ν

Sphalerons


New Physics
beyond the SM
ν mass generation
LFV
CP violation
Clear signature of New Physics !

The big picture beyond HEP – my schematic summary !



At this stage you should be more than convinced about the justified interest in LFV

How to measure LFV or constrain/test predictions?

- Most if not all BSM models predict LFV effects
- They should be visible in decays of muons and tau leptons
  - which decays are dominant? (i.e. enhanced)
- Important to probe "at the various fronts"
- Certain observables may help
  choosing or ruling out models
- LFV has been searched for in decays of:
  - muons, taus
  - π^0's, kaons, J/Ψ's, Υ's, D's, B's,
  - Z bosons
  - etc.

Disclaimer: LFV & LNV topics not covered

LFV & LNV with kaons :

- **Searches performed by NA62 @ CERN**
  - See e.g. arXiv:1105.5957 [hep-ex]

LFV @ HERA:

- **Searches for leptoquarks in ep collisions: e p $\rightarrow$ μ X, τ X**
  - See e.g. arXiv:1108.1134 [hep-ex] for a review

LFV searches with quarkonia :

- **See back-up slides for example results from BES II & CLEO**

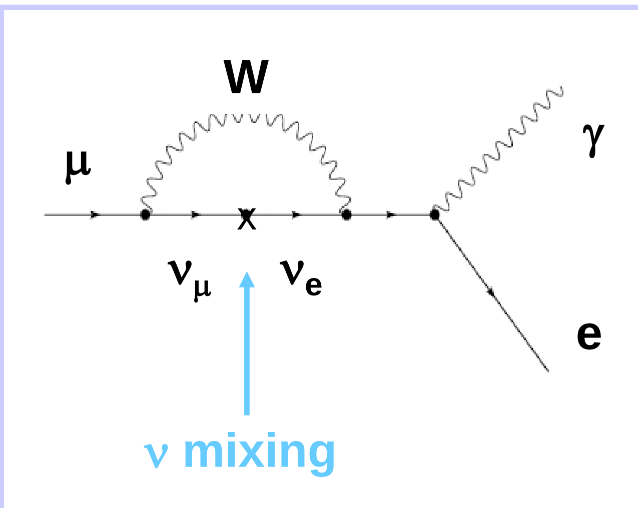
LNV :

- **Searches by Belle, e.g. $B^+ \rightarrow D^- l^+ l'^+$ (arXiv:1107.0642 [hep-ex])**
  - Sensitivities at the level of 10^{-6}

LFV μ decays

A mini-review

LFV μ processes

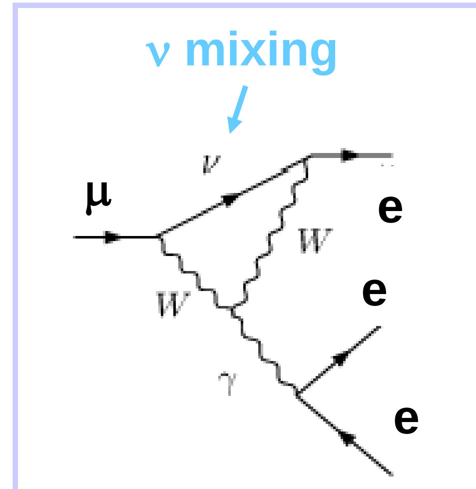


$\mu \rightarrow e\ \gamma$

$\mu \rightarrow e\ \gamma\ \gamma$

$\mu \rightarrow e\ e\ e$

$\mu \rightarrow e$ *conversion in nuclei*



- Other measurements looking for NP with muons involve: muonium $\mu^+e^- \rightarrow$ anti-muonium μ^-e^+ conversion and the g-2 anomalous moment of the μ

$\mu \to e\,\gamma$: theoretical aspects (1/2)

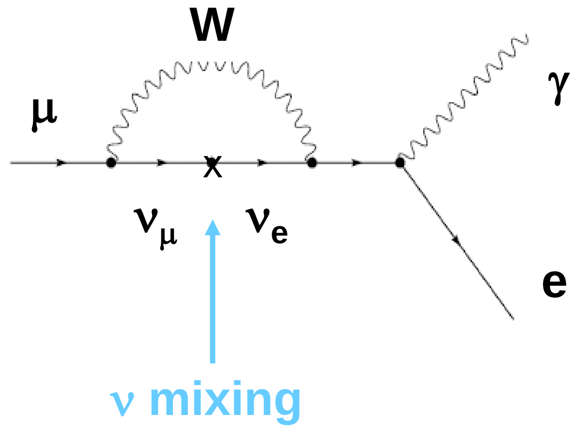
Interlude: what is the "SM" prediction?

- Let's extend the SM simply allowing for non-zero neutrino masses, and neutrino mixing
- LFV is then allowed via loop diagrams

Decay probability:

$$\Gamma(\mu \to e\gamma) \approx \frac{G_F^2 m_\mu^5}{192\pi^3}\left(\frac{\alpha}{2\pi}\right)\sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)$$

$\Gamma(\mu\to e\nu\nu)$; γ-vertex ; ν oscillation term



In practice, the probability of such a decay is infinitesimal, 10^{-54} – 10^{-40} !

$\mu \to e\,\gamma$: theoretical aspects (2/2)

- Expected to have high sensitivity to SUSY GUTs compared to other LFV processes such as $\mu \to 3e$, $\mu \to e$ conversion in nuclei, $\tau \to e\,\gamma$ decays
- Predicted to be the highest BF LFV μ decay by many SUSY models
- Large BF e.g. in SUSY SU(5), SO(10) models or models with right-handed neutrinos

- The angular distribution of the electron w.r.t the muon spin direction is of the form

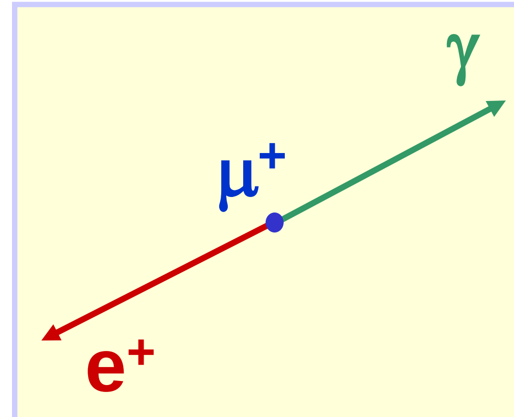
$$1 + A_{\mu \to e\gamma} P_{\mu} \cos\theta$$

$\Rightarrow$ value of A may distinguish among models

$\mu \rightarrow e\,\gamma$: experimental aspects

Experimental signature :

✓ μ beam $\Rightarrow$ μ's stopped
$\Rightarrow$ a 52.8 MeV γ and a 52.8 MeV e, aligned back-to-back,
in time coincidence, with common origin



Main background :

✓ Random coincidences between e from $\mu \rightarrow e\,\nu\,\nu$
and high-energy photon from $\mu \rightarrow e\,\nu\,\nu\,\gamma$

✓ Radiative muon decay $\mu \rightarrow e\,\nu\,\nu\,\gamma$ (bkg. source ~ 1/10 the previous)

Old experiments :

- ❑ SIN ("ex-PSI"), TRIUMF, Crystal Box @ Los Alamos National Lab.
- ❑ MEGA experiment @ Los Alamos Meson Physics Facility (data in 1985-95)

Ongoing experiment :

- ❑ MEG experiment @ PSI (data taking: 12/09/2008 -)

Future experiments :

- ❑ Maybe a future proposal @ J-PARC ?

New Limit for the Lepton-Family-Number Nonconserving Decay $\mu^+ \to e^+\gamma$

(MEGA Collaboration)

An experiment has been performed to search for the muon- and electron-number nonconserving decay $\mu^+ \to e^+\gamma$. The upper limit for the branching ratio is found to be $\Gamma(\mu^+ \to e^+\gamma)/\Gamma(\mu^+ \to e^+\nu\overline{\nu}) < 1.2 \times 10^{-11}$ with 90% confidence.

$$\frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\overline{\nu})} \le \frac{5.1}{N_\mu} = 1.2 \times 10^{-11} \text{ (90\% C.L.)}$$

The data for this experiment have been taken in three calendar years, 1993–1995. The full data set is based on 1.2×10^{14} muon stops collected over 8×10^6 s of live time and results in 4.5×10^8 events on magnetic tape.

The acceptance of the apparatus—which includes geometrical, trigger, and pattern recognition constraints—is obtained by simulating 1.2×10^7 unpolarized $\mu^+ \to e^+\gamma$ decays and finding that 5.2×10^4 events survive processing by the same codes used for the data analysis. Thus the probability that a $\mu^+ \to e^+\gamma$ decay would be detected is 4.3×10^{-3}. This value is reduced by 9% for the inefficiency of manual scanning. The acceptance is further reduced by 20% to account for inadequacies in the MC simulation that overestimate the acceptance.

MEGA Collaboration,
M. L. Brooks *et al.*, Phys. Rev. Lett. 83, 1521 (1999)
arXiv:hep-ex/9905013v1

$\mu^+ \to e^+ \gamma$: the MEG experiment @ PSI

Goal :

- Achieve a single-event sensitivity 2 orders of magnitude lower than that obtained by the MEGA experiment
  $\Rightarrow$ BF sensitivity down to 10^{-13} ! (in 3 years of data)

http://meg.web.psi.ch

Status :

LoI	Proposal		Status
Planning	R & D	Assembly	Data Taking …

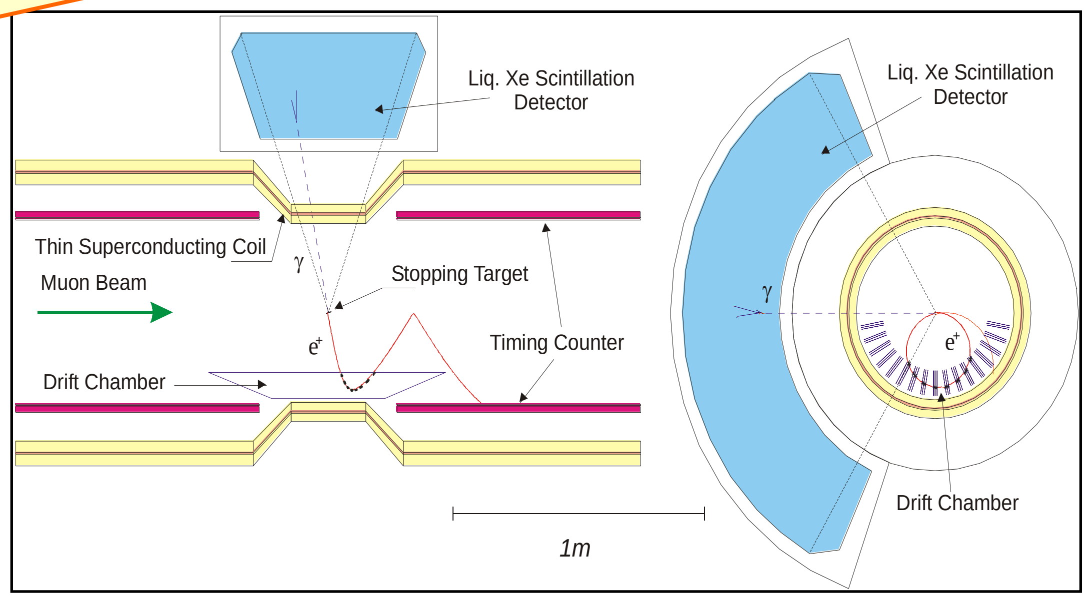
1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010

Taking data since

12 Sep. 2008 !

Source of μ's :

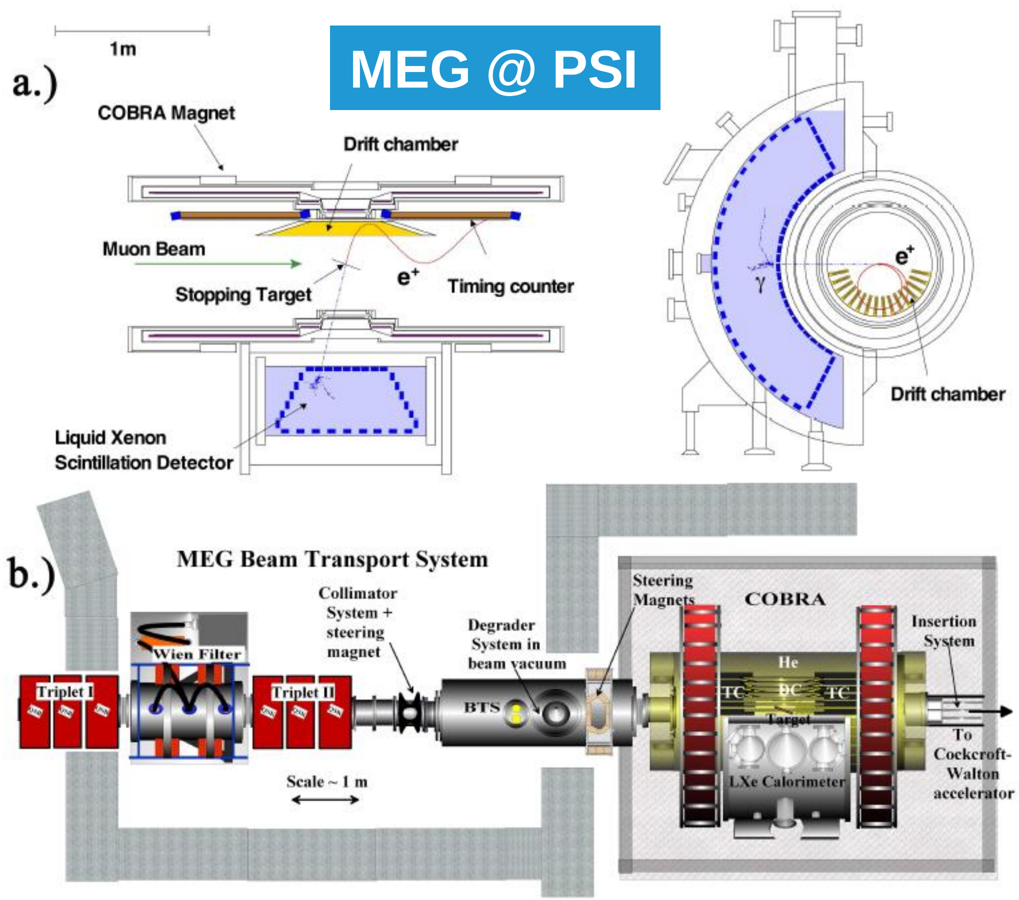
- Stopped beam of $3x10^7$ μ's/sec in a thin polyethylene target



A limit for the $\mu \to e\gamma$ decay from the MEG experiment

(MEG Collaboration)

A search for the decay $\mu^+ \to e^+\gamma$, performed at PSI and based on data from the initial three months of operation of the MEG experiment, yields an upper limit on the branching ratio of $\mathrm{BR}(\mu^+ \to e^+\gamma) \leqslant 2.8 \times 10^{-11}$ (90% C.L.). This corresponds to the measurement of positrons and photons from $\sim 10^{14}$ stopped μ^+-decays by means of a superconducting positron spectrometer and a 900 litre liquid xenon photon detector.



Taking data since 12 Sep. 2008 !

http://meg.web.psi.ch

Result from the 1st 3 months of data taking in 2008

$$\mathrm{BR}(\mu^+ \to e^+\gamma) \leqslant 2.8 \times 10^{-11} \quad (90\%\ \mathrm{C.L.})$$

Goal:
BF sensitivity down to 10^{-13} ! (in 3 years of data)

MEG Collaboration, Nucl. Phys. B834, 1-12 (2010)

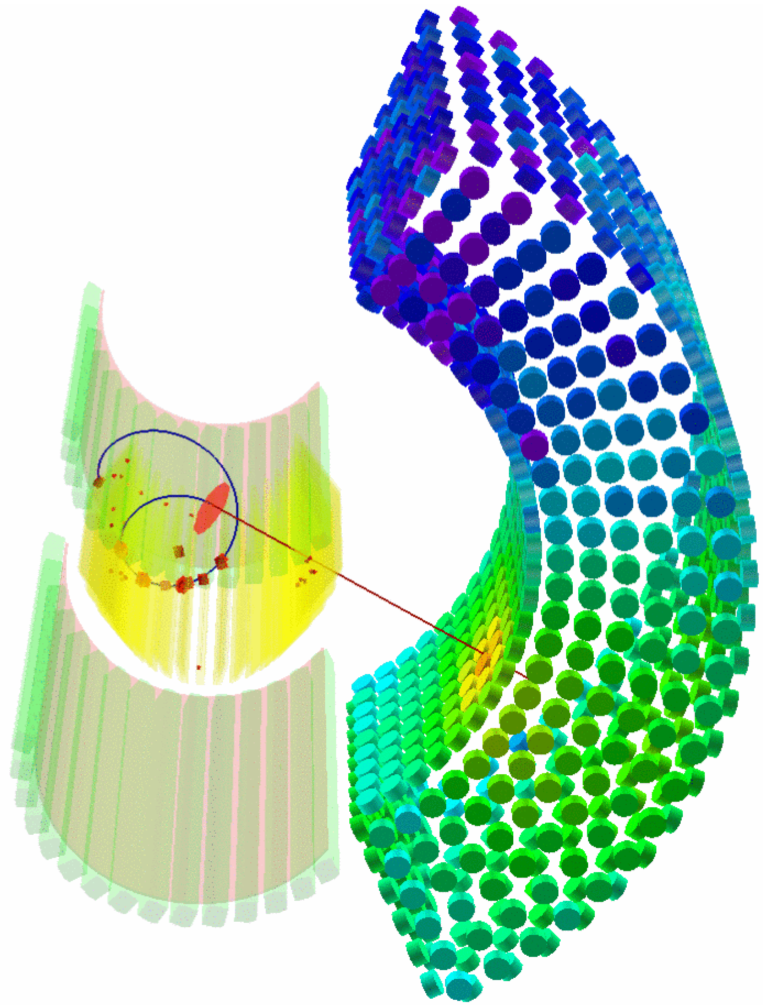
New Limit on the Lepton-Flavor-Violating Decay $\mu^+ \to e^+\gamma$

(MEG Collaboration)

- Reconstructed candidate event
  - run 77431, event 1715

- The 900 litre C-shaped liquid Xenon detector with its 846 photo-multipliers (PMTs), used to detect the light from the interacting photon, is shown on the right. The colour of each PMT reflects the amount of light it has detected (blue=low, orange=high), while the total amount of summed light reflects the energy of the incident photon.

- The curved track on the left comes from a positron curling-up in the magnetic spectrometer which measures its energy and time using a set of central tracking chambers (yellow) and scintillation counter bars (green) respectively.



http://meg.web.psi.ch/news/index.html

New Limit on the Lepton-Flavor-Violating Decay $\mu^+ \to e^+\gamma$

(MEG Collaboration)

- **Sample = 1.8×10^{14} μ decays !**

Likelihood (blinded) analysis

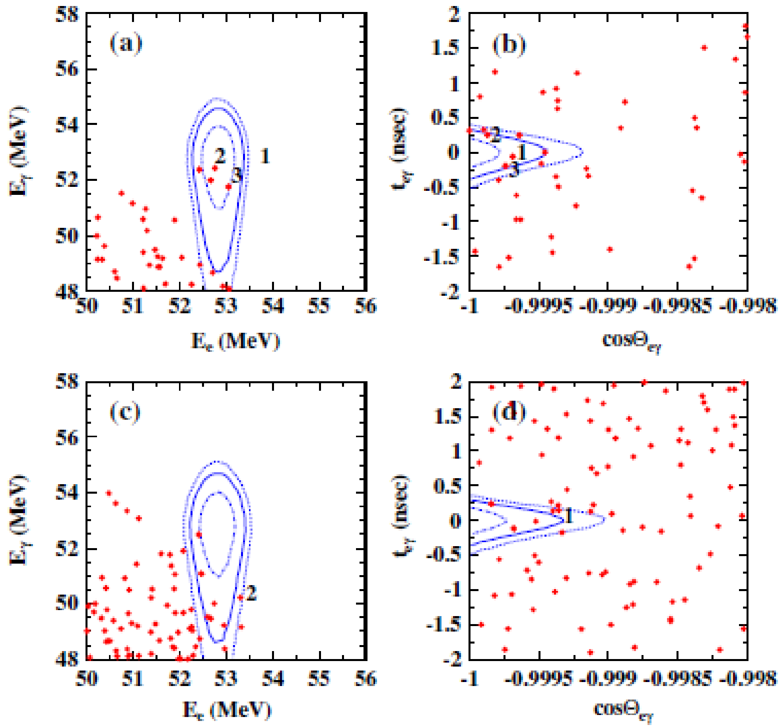


FIG. 1 (color online). Event distributions in the analysis region of (a) E_γ vs E_e and (b) $t_{e\gamma}$ vs $\cos\Theta_{e\gamma}$ for 2009 data and of (c) E_γ vs E_e and (d) $t_{e\gamma}$ vs $\cos\Theta_{e\gamma}$ for 2010 data. The contours of the PDFs (1σ, 1.64σ, and 2σ) are shown, and a few events with the highest signal likelihood are numbered for each year. [The two highest signal likelihood events in 2010 data appear only in (c) or (d).]

TABLE I. Best fit ($\mathcal{B}_{\rm fit}$), lower limits (LL), and upper limits (UL) at the 90% C.L. of the branching ratio for the 2009, 2010, and combined 2009 and 2010 data sets.

Data set	$\mathcal{B}_{\rm fit}$	LL	UL
2009	3.2×10^{-12}	1.7×10^{-13}	9.6×10^{-12}
2010	-9.9×10^{-13}	...	1.7×10^{-12}
2009 and 2010	-1.5×10^{-13}	...	2.4×10^{-12}

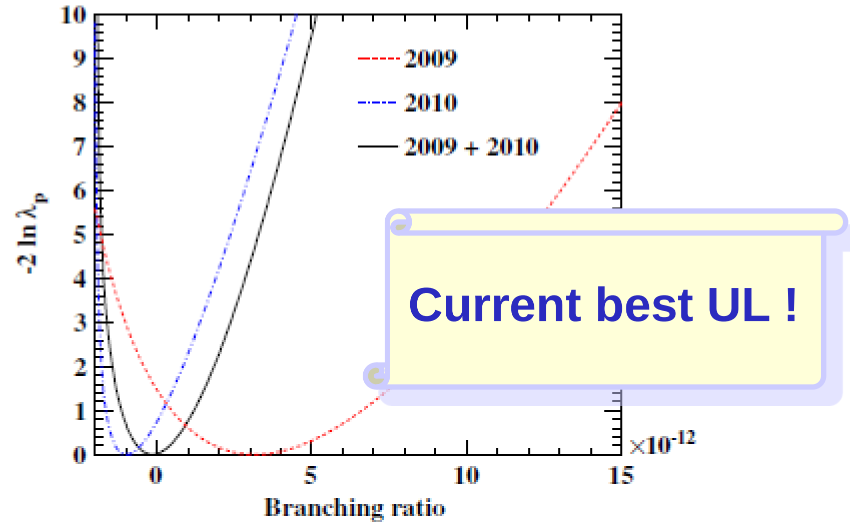


FIG. 2 (color online). Profile likelihood ratios as a function of the $\mu^+ \to e^+\gamma$ branching ratio for 2009, 2010, and the combined 2009 and 2010 data sample.

MEG Collaboration,
Phys. Rev. Lett. 107, 171801 (2011)

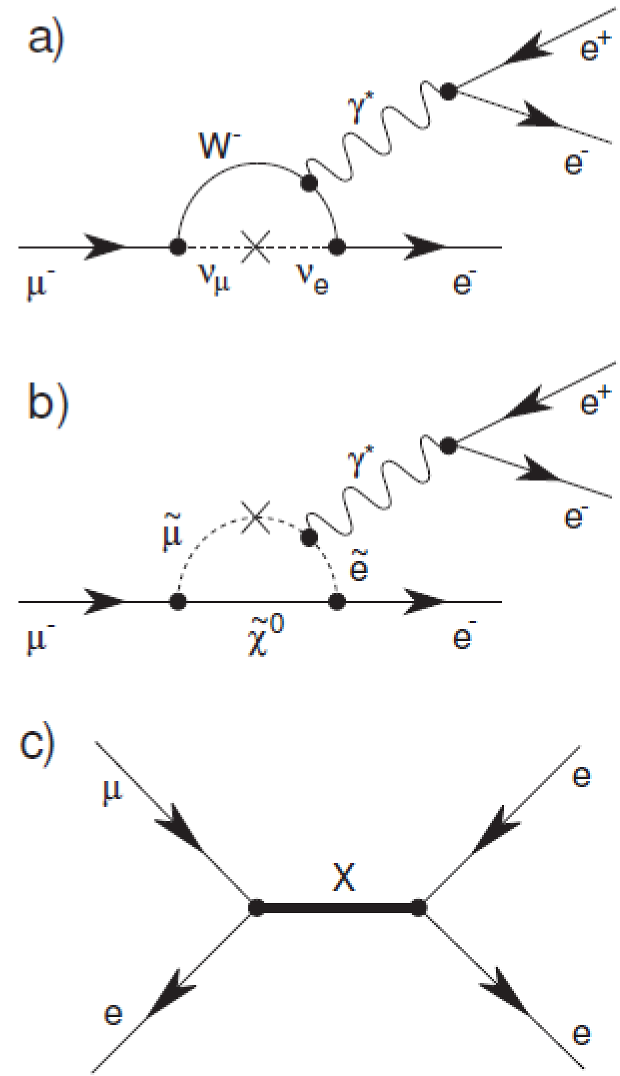
$\mu \to 3e$: theoretical aspects

Types of contributing diagrams :

a) Via neutrino oscillation

b) In processes involving a SUSY particle

c) Tree-level exchange of a (new) heavy particle



(taken from: N. Berger, arXiv:1110.1504 [hep-ex])

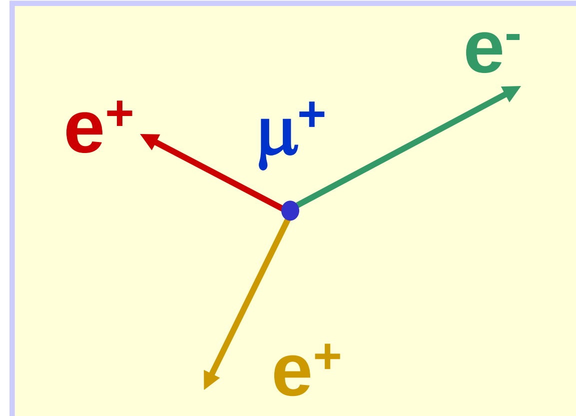
$\mu \to 3e$ vs $\mu \to e\,\gamma$:

- ❑ Under reasonable (NP) assumptions, $BF(\mu \to 3e) / BF(\mu \to e\,\gamma) \approx 10^{-2}$
  $\Rightarrow$ competitive LFV limits from $BF(\mu \to 3e)$ need be 2 orders of magnitude smaller than best limit from $\mu \to e\,\gamma$!

$\mu \to 3e$: experimental aspects

Main background :

- ✓ Accidental backgrounds
- ✓ Decay $\mu \to e\, e\, e\, \nu\, \nu$ (internal conversion)



- ❑ **Best current upper limit:**

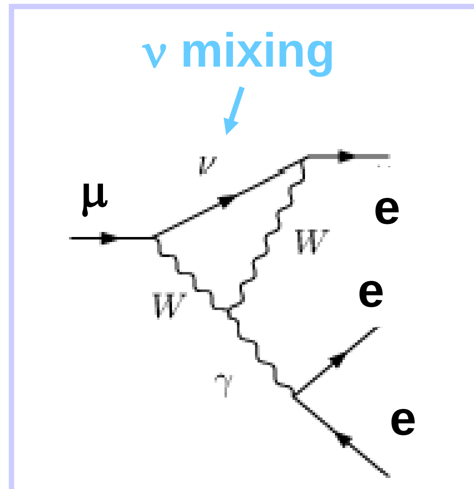
BF ($\mu \to 3e$) < 1.0×10^{-12} @ 90% C.L.

Old experiments :

- ❑ Crystal Box @ Los Alamos Meson Physics Facility
- ❑ SINDRUM @ SIN (became PSI afterwards)
  - data taking: 1983 - 86

Future experiments :

- ❑ New proposal @ PSI (see in a few slides)
- ❑ Maybe a future proposal @ J-PARC ?



SEARCH FOR THE DECAY $\mu^+ \to e^+e^+e^-$

SINDRUM Collaboration

The search for the decay $\mu^+ \to e^+e^+e^-$ with the SINDRUM spectrometer has been continued. The result is a new upper limit for the branching ratio $B_{\mu\to 3e} = \Gamma(\mu \to 3e)/\Gamma(\mu \to e2\nu) < 1.0 \times 10^{-12}$ (90% CL).

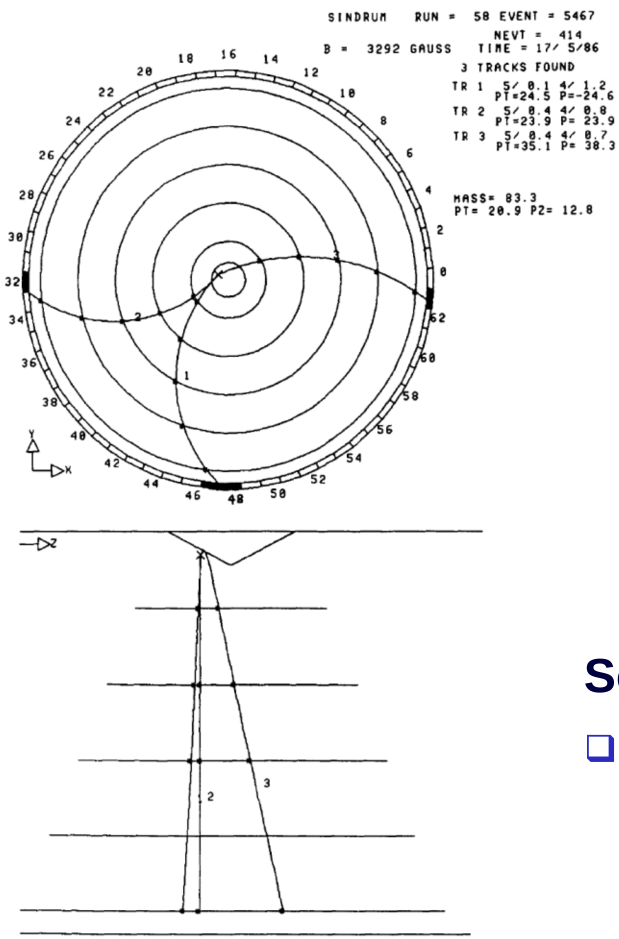


Fig. 1. A reconstructed event shown in the r-φ and r-z projections.

Result from full data sample: 1983 - 86

$$B_{\mu\to 3e} < 1.0 \times 10^{-12}\ (90\%\ \mathrm{CL})$$

No prompt events are seen in a region containing 95% of the simulated $\mu \to 3e$ events. The upper limit for the branching ratio of the decay was calculated using

$$B_{\mu\to 3e} < \frac{2.3}{N_{\mu\to 3e2\nu}} \cdot \frac{\varepsilon_{\mu\to 3e2\nu}}{\varepsilon_{\mu\to 3e}} \cdot B_{\mu\to 3e2\nu}\ (90\%\ \mathrm{CL}).$$

Source of μ^+'s :

- μ^+ beam of 28 MeV stopped at rate of ~5×10^6 μ^+/sec (1986 run)

SINDRUM Collaboration,
U. Bellgardt *et al.*, Nucl. Phys. B299, 1-6 (1988)

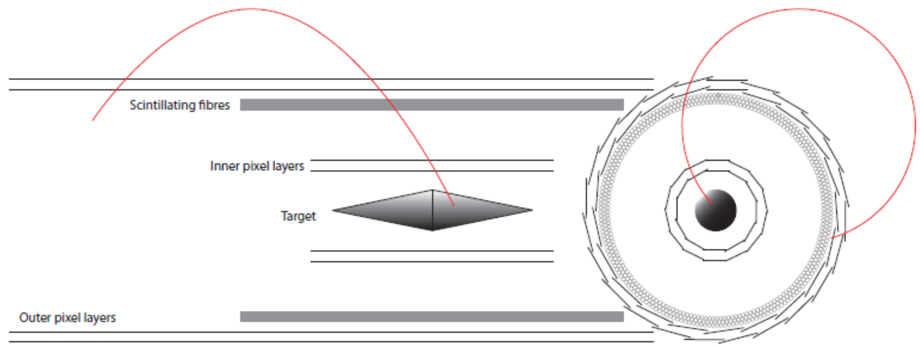
$\mu \rightarrow 3e$: proposal for a new experiment @ PSI

Goal :

- Reach a sensitivity 4 orders of magnitude lower than previous experiments !
  $\Rightarrow$ B.F. sensitivity down to 10^{-16} !

Source of μ's :

- Stopped beam of ~10^9 μ's/sec on target
  $\Rightarrow$ need upgraded beam-line



Backgrounds and technologies:

- Accidental backgrounds : excellent vertex and timing resolutions
  $\mu \rightarrow e\ e\ e\ \nu\ \nu$: missing momentum $\Rightarrow$ precise track reconstructiuon
- Precise tracking at high rates $\leftrightarrow$ thin HV monolithic active pixel sensors
  High-resolution time measurements $\leftrightarrow$ scintillating fibers
- More details at A. Schöning's talk at the 2011 CHIPP Annual Plenary Meeting:
  https://indico.cern.ch/contributionDisplay.py?contribId=26&confId=136534

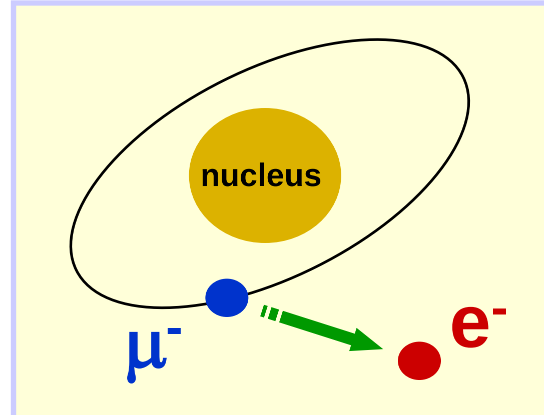
Contribution to NuFact11
N. Berger, arXiv:1110.1504 [hep-ex]

$\mu \to$ e conversion in nuclei

Process :

μ-e conversion in the Coulomb field of the nucleus

$$\mu^- + (A,Z) \to e^- + (A,Z)$$



Signature :

Single isolated electron

Results:

- Best upper limit on conversion probability uses Ti:
  $P(\mu \to e, Ti) < 4.2 \times 10^{-12}$
- Several target nuclei used: mainly Au, Ti, Pb

Old experiments :

- SINDRUM II experiment @ PSI (data in 1987-2000)

Future experiments :

- Mu2e experiment @ Fermilab
- COMET & PRIME experiments @ J-PARC
  $\Rightarrow$ to probe conversion rate down to 10^{-18} !

- The Z-dependence of the μ-e conversion processes may allow different LFV scenarios to be distinguished

Search for $\mu^- \rightarrow e^-$ Conversion with SINDRUM II

The SINDRUM II collaboration

ABSTRACT: A status report is given on an experiment started in 1987 at PSI to search for the lepton flavour violating muon to electron conversion process. The motivation for this experiment, the design and performance of the detector (SINDRUM II), and results of a first run are presented.
No candidate of the process μ^-Ti $\rightarrow$ e$^-$Ti was found, and, using two independent determinations of the muon stop rate, an upper limit for the branching ratio relative to muon capture $B_{\mu e} < 4.4 \cdot 10^{-12}$ (90% C.L.) was obtained. This result confirms the current best value for the upper limit found at TRIUMF ($4.6 \cdot 10^{-12}$).

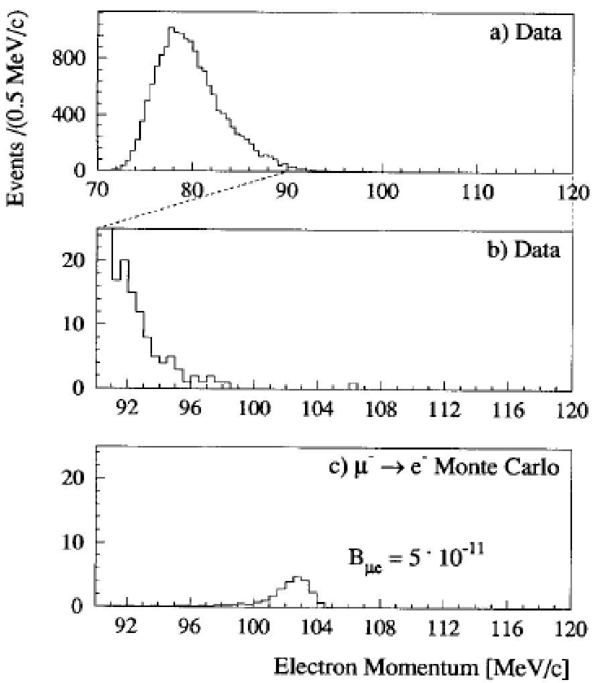


Figure 4: a) Electron momentum spectrum of muon induced events, b) Expanded view of the momentum spectrum in the range 90 MeV/c to 120 MeV/c, c) Spectrum of a Monte Carlo simulation for $\mu^- \rightarrow e^-$ conversion, assuming a branching ratio of $B_{\mu e} = 5 \times 10^{-11}$.

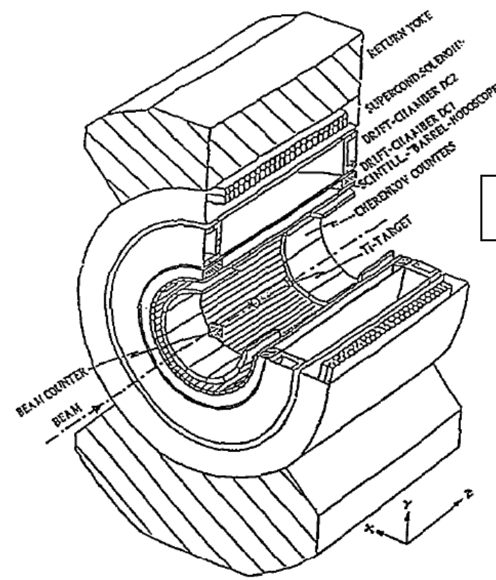


Figure 1: Cut-away view of the superconducting magnet containing the detector (not to scale). The forward and backward mirror plates are not shown.

http://sindrum2.web.psi.ch/

SINDRUM II Collaboration,
A. Badertscher *et al.*, Nucl. Part. Phys. 17, S47 (1991)

$\mu \rightarrow e$: the Mu2e experiment @ Fermilab

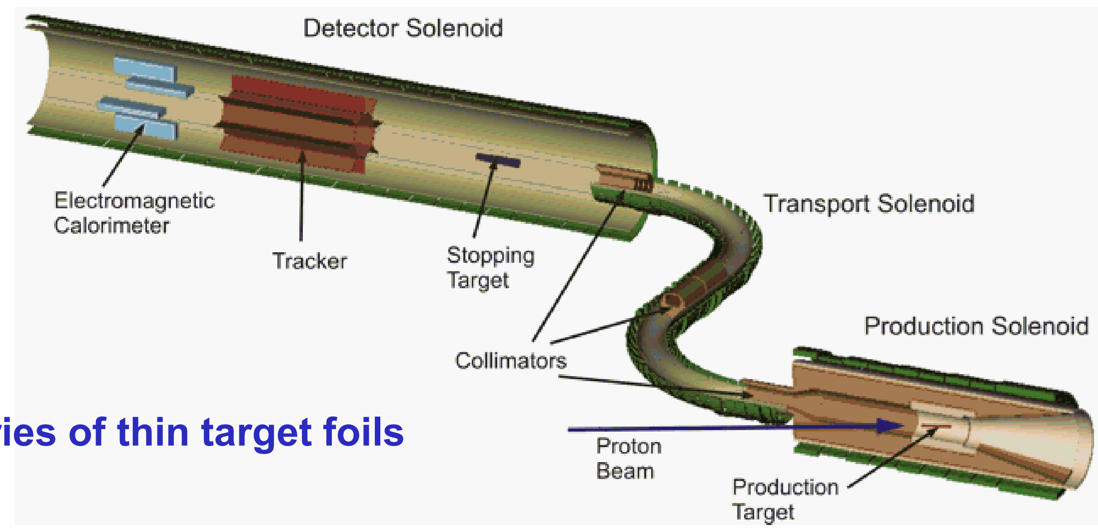
Goal :

- Achieve a sensitivity down to a few 10^{-17} !

http://mu2e.fnal.gov/

Planning :

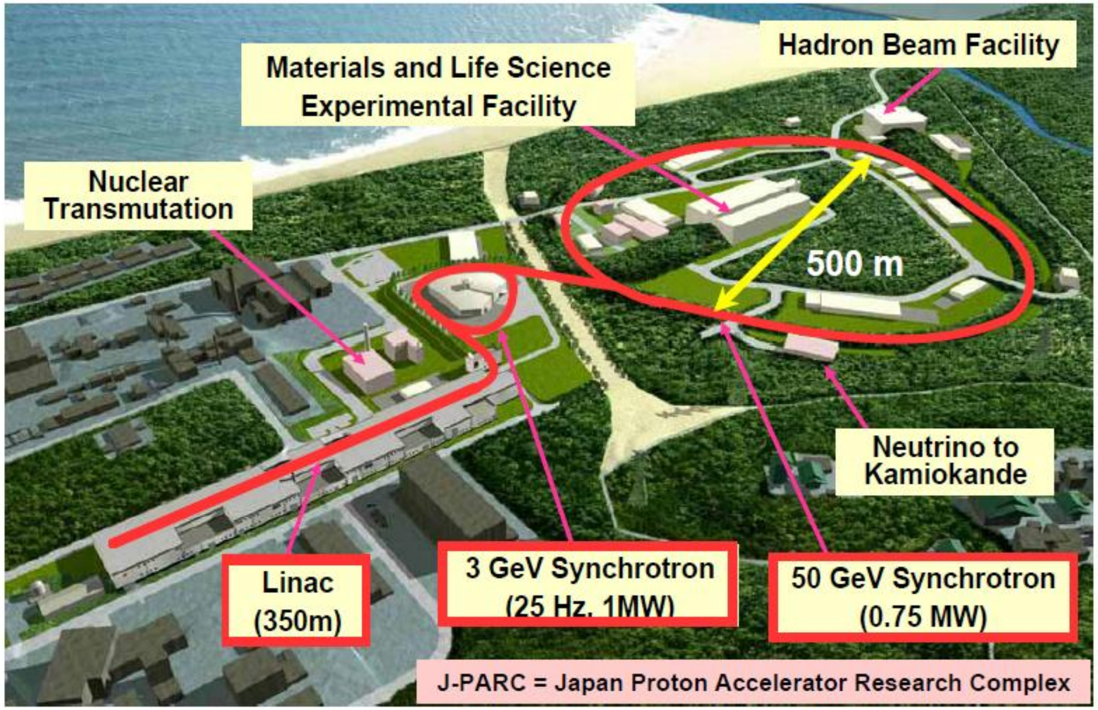
- Construction to start ~ 2013
- Data taking to start ~ 2017



Exp. set up :

- Beam of slow μ's stopped in a series of thin target foils
- μ's captured into atomic orbits
- Standard μ decays in orbit ⇒ electron continuous energy spectrum
- μ conversion to electron ⇒ mono-energetic electron with energy=end-point energy of continuous spectrum

Intermezzo – J-PARC



Facilities :

- ❑ Both nuclear physics and HEP, etc.
- ❑ MW proton source foreseen
- ❑ Intense μ source

- ❑ In construction …

28 Jan. 2008

HEP program - examples :

- ❑ μ – e conversion experiment
- ❑ Long baseline ν oscillations experiment
- ❑ Extremely rare K decays
- ❑ Etc.

$\mu \rightarrow e$: the COMET/PRIME experiment @ J-PARC

Goal :

- **Achieve a sensitivity down to 10^{-16} (COMET) and then 10^{-18} with an upgrade (PRISM/PRIME) !**

Planning :

- **Engineering run in 2016 (for 1 year)**
- **Data taking in 2017**

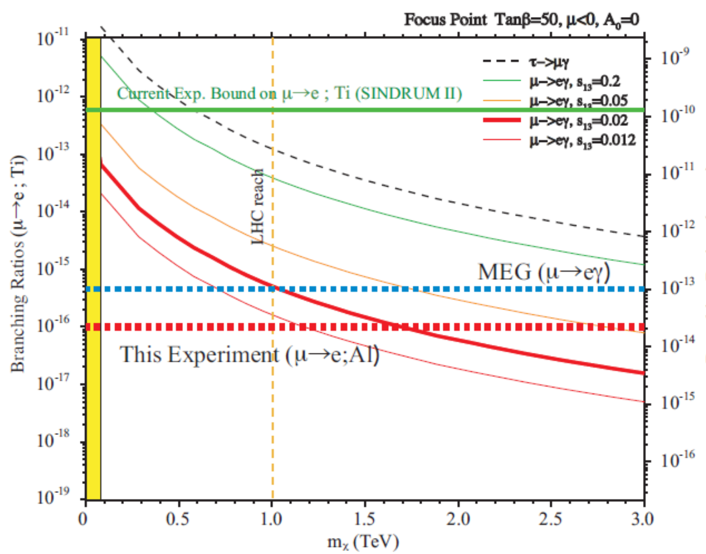


Figure 1.7: Prediction of the branching ratio of $\mu^- - e^-$ conversion in Ti in the SUSY-Seesaw models as a function of SUSY mass scale (neutralino). The sensitivity of the proposed experiment is also shown.

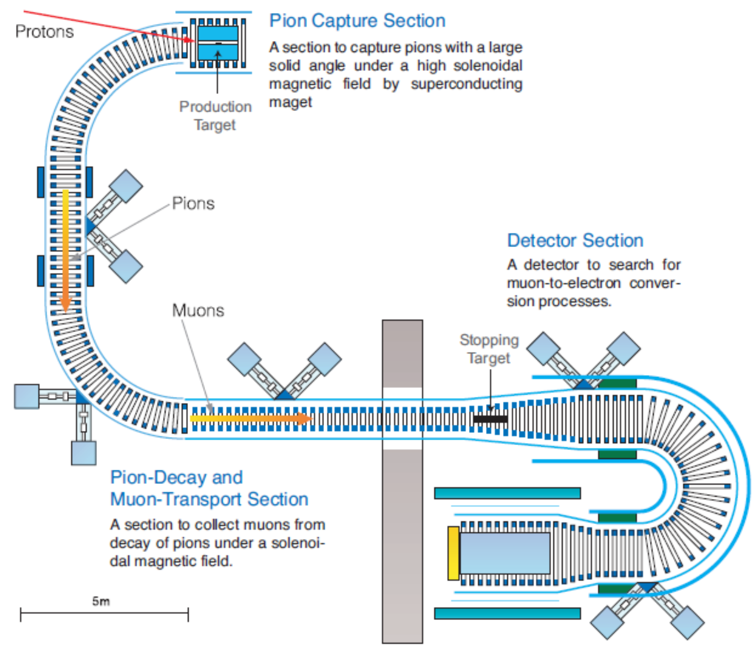
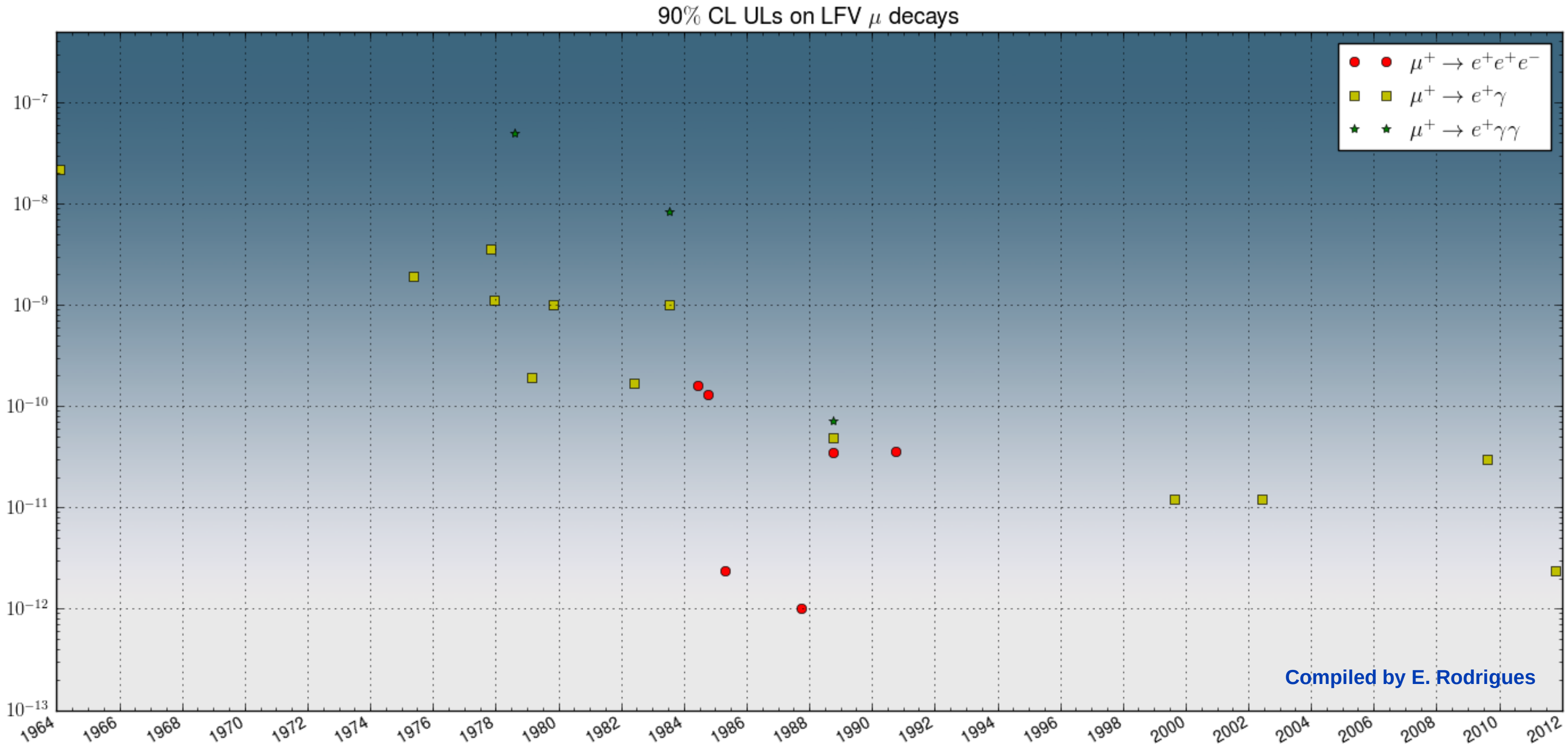


Figure 3.1: Schematic layout of the muon beamline and detector for the proposed search for $\mu^- - e^-$ conversion, the COMET experiment.

Note: COMET/PRISM results will effectively probe BF($\mu \rightarrow e\gamma$) in SUSY models given that CR($\mu \rightarrow e$ in N) ~ α_{em} x BF($\mu \rightarrow e\gamma$)

LFV μ decays: history



LFV τ decays

A mini-review

Classification of decays - examples

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

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

$\tau^- \rightarrow e^- \pi^0 (\rightarrow \gamma\gamma)$
$\tau^- \rightarrow e^- K^0_S (\rightarrow \pi^+ \pi^-)$
$\tau^- \rightarrow e^- \eta (\rightarrow \gamma\gamma)$
$\tau^- \rightarrow e^- \eta' (\rightarrow \eta \pi^+ \pi^-)$

DECAY TYPES

- $\tau \rightarrow l\,\gamma$
- $\tau \rightarrow l\,l\,l$
- $\tau \rightarrow l\,P^0$
- $\tau \rightarrow l\,h\,h$
- $\tau \rightarrow l\,V^0$
- $\tau \rightarrow l\,S^0$
- $\tau \rightarrow \Lambda\,h$

$\tau^- \rightarrow e^- \pi^+ \pi^-$
$\tau^- \rightarrow e^- \pi^+ K^-$
$\tau^- \rightarrow e^- K^+ \pi^-$
$\tau^- \rightarrow e^- K^+ K^-$
$\tau^- \rightarrow \mu^- \pi^+ \pi^-$
$\tau^- \rightarrow e^+ \pi^- \pi^-$
$\tau^- \rightarrow e^+ \pi^- K^-$
$\tau^- \rightarrow e^+ K^- K^-$
$\tau^- \rightarrow \mu^+ \pi^- \pi^-$

$\tau^- \rightarrow e^- \phi (\rightarrow K^+ K^-)$
$\tau^- \rightarrow \mu^- \phi (\rightarrow K^+ K^-)$
$\tau^- \rightarrow e^- K^*(892)^0 (\rightarrow K^+ \pi^-)$
$\tau^- \rightarrow e^- \bar{K}^*(892)^0 (\rightarrow \pi^+ K^-)$
$\tau^- \rightarrow e^- \rho^0 (\rightarrow \pi^+ \pi^-)$
$\tau^- \rightarrow e^- \omega (\rightarrow \pi^+ \pi^- \pi^0)$

« Main players »: accelerators and experiments

CESR @ Cornell :

- CLEO experiment probed LFV in τ decays down to BF ~10^{-6} with ~ 10M τ pairs

B factories PEP-II and KEKB :

- $\sigma_{\tau\tau}$ ~ 0.9 nb to compare with σ_{bb} ~ 1.1 nb
  $\Rightarrow$ the B factories are also τ factories ! (and charm factories)
  $\Rightarrow$ large τ-pair samples:
  a few 100M τ pairs available to search for LFV decays

- BaBar @ SLAC
- Belle @ KEK

  probed at the ~10^{-8} level

- Probing BF < 10^{-8} will require a super-B factory …

SEARCH FOR LEPTON-NUMBER AND LEPTON-FLAVOUR VIOLATION IN TAU DECAYS

ARGUS Collaboration

We have searched for neutrinoless tau decays into three charged particles as evidence for lepton-flavour or lepton-number violation. The data were collected using the ARGUS detector at the DORIS II storage ring. Tau pairs were produced by e^+e^- annihilation at centre-of-mass energies near 10 GeV. No evidence for lepton-number or lepton-flavour violation was observed, but the upper limits obtained are an order of magnitude lower than those previously published.

Upper limits on three-prong neutrinoless tau decays at the 90% CL. (The ℓ^- can be e^- or μ^-.)

Decay mode	ARGUS	MARK II [4]
$\tau^- \to e^-e^+e^-$	3.8×10^{-5}	4.0×10^{-4}
$e^-\mu^+\mu^-$	3.3×10^{-5}	3.3×10^{-4}
$\mu^-e^+e^-$	3.3×10^{-5}	4.4×10^{-4}
$\mu^-\mu^+\mu^-$	2.9×10^{-5}	4.9×10^{-4}
$\ell^\mp\ell^\pm\ell^-$	3.8×10^{-5}	
$e^-\pi^+\pi^-$	4.2×10^{-5}	
$\mu^-\pi^+\pi^-$	4.0×10^{-5}	
$e^-\rho^0$	3.9×10^{-5}	3.7×10^{-4}
$\mu^-\rho^0$	3.8×10^{-5}	4.4×10^{-4}
$\ell^\mp\pi^\pm\pi^-$	6.3×10^{-5}	
$e^-\pi^+K^-$	4.2×10^{-5}	
$\mu^-\pi^+K^-$	1.2×10^{-4}	
e^-K^{*0}	5.4×10^{-5}	(e^-K^0) 1.3×10^{-3}
μ^-K^{*0}	5.9×10^{-5}	(μ^-K^0) 1.0×10^{-3}
$\ell^\mp\pi^\pm K^-$	1.2×10^{-4}	

Our analysis was based on an integrated luminosity of 177 pb^{-1} corresponding to about 180 000 tau pairs. The data were collected using the ARGUS detector at the electron–positron storage ring DORIS II at DESY.

	LF violating	LN violating
$\tau^- \to$	$e^-e^+e^-$	
	$e^-\mu^+\mu^-$	$e^+\mu^-\mu^-$
	$\mu^-e^+e^-$	$\mu^+e^-e^-$
	$\mu^-\mu^+\mu^-$	
	$e^-\pi^+\pi^-$ and $e^-\rho^0$	$e^+\pi^-\pi^-$
	$\mu^-\pi^+\pi^-$ and $\mu^-\rho^0$	$\mu^+\pi^-\pi^-$
	$e^-\pi^+K^-$ and e^-K^{*0}	$e^+\pi^-K^-$
	$\mu^-\pi^+K^-$ and μ^-K^{*0}	$\mu^+\pi^-K^-$.

ARGUS Collaboration,
H. Albrecht *et al*., PL B185, 228 (1987)

New limits for neutrinoless tau decays

(CLEO Collaboration)

TABLE I. Detection efficiencies, event statistics, expected backgrounds, and upper limits for branching fractions at 90% confidence level.

Decay channel	Detection efficiency, %	Events observed	Expected bg events	Upper limits, 10^{-6}
$\tau^- \to e^- e^+ e^-$	17.0	1	0.21	2.9
$\tau^- \to \mu^- e^+ e^-$	16.8	0	0.18	1.7
$\tau^- \to \mu^+ e^- e^-$	19.5	0	0.12	1.5
$\tau^- \to e^- \mu^+ \mu^-$	16.5	0	0.32	1.8
$\tau^- \to e^+ \mu^- \mu^-$	19.9	0	0.12	1.5
$\tau^- \to \mu^- \mu^+ \mu^-$	15.0	0	0.11	1.9
$\tau^- \to e^- \pi^+ \pi^-$	13.2	0	0.43	2.2
$\tau^- \to e^- \pi^- K^+$	13.0	1	0.29	3.8
$\tau^- \to e^- \pi^+ K^-$	13.1	3	0.42	6.4
$\tau^- \to e^- K^+ K^-$	11.2	2	0.29	6.0
$\tau^- \to e^+ \pi^- \pi^-$	15.3	0	0.22	1.9
$\tau^- \to e^+ \pi^- K^-$	14.0	0	0.18	2.1
$\tau^- \to e^+ K^- K^-$	13.0	1	0.11	3.8
$\tau^- \to \mu^- \pi^+ \pi^-$	8.2	2	0.57	8.2
$\tau^- \to \mu^- \pi^- K^+$	6.7	1	0.48	7.4
$\tau^- \to \mu^- \pi^+ K^-$	6.5	1	0.49	7.5
$\tau^- \to \mu^- K^+ K^-$	4.5	2	0.50	15
$\tau^- \to \mu^+ \pi^- \pi^-$	8.6	0	0.36	3.4
$\tau^- \to \mu^+ \pi^- K^-$	7.0	1	0.33	7.0
$\tau^- \to \mu^+ K^- K^-$	4.8	0	0.35	6.0
$\tau^- \to e^- \rho^0$	14.4	0	0.45	2.0
$\tau^- \to e^- K^{*0}$	9.5	1	0.32	5.1
$\tau^- \to e^- \overline{K}^{*0}$	9.0	2	0.32	7.4
$\tau^- \to e^- \phi$	7.2	1	0.15	6.9
$\tau^- \to \mu^- \rho^0$	10.6	2	0.43	6.3
$\tau^- \to \mu^- K^{*0}$	6.5	1	0.46	7.5
$\tau^- \to \mu^- \overline{K}^{*0}$	6.5	1	0.37	7.5
$\tau^- \to \mu^- \phi$	4.1	0	0.11	7.0

Neutrinoless 3-prong tau lepton decays into a charged lepton and either two charged particles or one neutral meson have been searched for using 4.79 fb^{-1} of data collected with the CLEO II detector at Cornell Electron Storage Ring. This analysis represents an update of a previous study and the addition of six decay channels. In all channels the numbers of events found are compatible with background estimates and branching fraction upper limits are set for 28 different decay modes. These limits are either more stringent than those set previously or represent the first attempt to find these decays. [S0556-2821(98)04009-0]

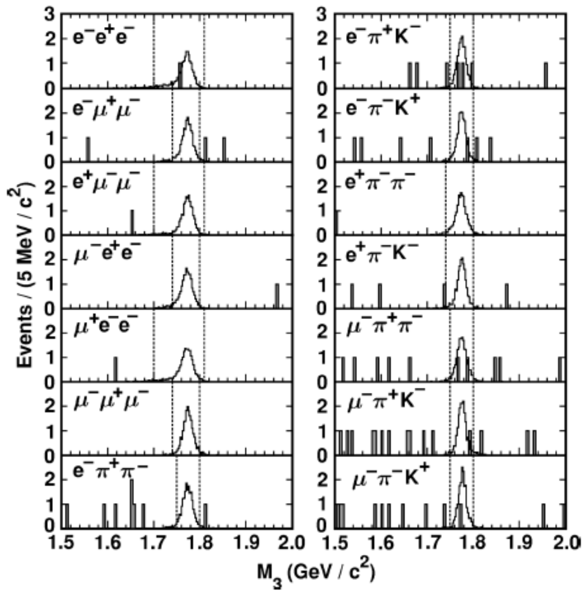


FIG. 1. Distributions of the invariant mass of the 3-prong side particles, M_3, for the data (shaded histogram) and signal Monte Carlo events (solid line). The expected signal shapes are shown with arbitrary normalization. The dotted lines indicate the boundaries of the signal regions used. See also Fig. 2.

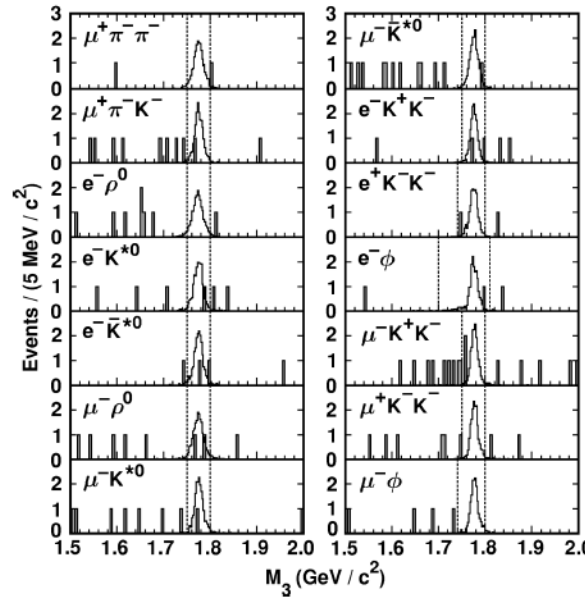
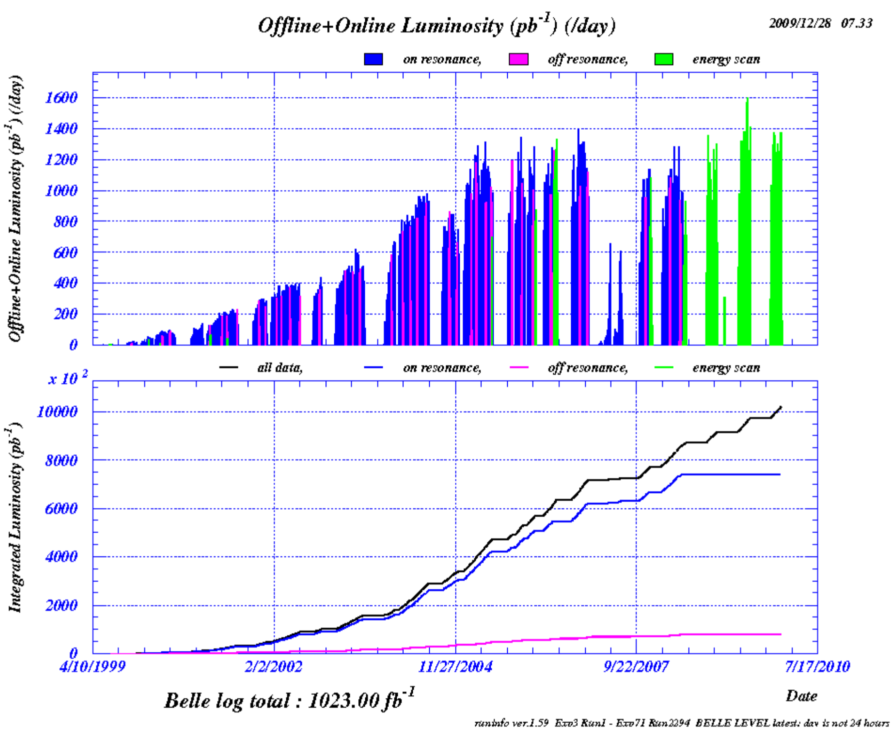


FIG. 2. Distributions of the invariant mass of the 3-prong side particles, M_3, for the data (shaded histogram) and signal Monte Carlo events (solid line). The expected signal shapes are shown with arbitrary normalization. The dotted lines indicate the boundaries of the signal regions used. See also Fig. 1.

CLEO Collaboration,
D. W. Bliss *et al.*, PR D57, 5903 (1998)
arXiv:hep-ex/9712010v1

B factories PEP-II & KEKB – integrated luminosity



PEP-II Records

Last update: April 8, 2008

Peak Luminosity

12.069×10^{33} cm^{-2}sec^{-1} — August 16, 2006

1722 bunches 2900 mA LER 1875 mA HER

Integration records of delivered luminosity

Best shift (8 hrs, 0:00, 08:00, 16:00)	339.0 pb^{-1}	Aug 16, 2006
Best 3 shifts in a row	910.7 pb^{-1}	Jul 2-3, 2006
Best day	858.4 pb^{-1}	Aug 19, 2007
Best 7 days (0:00 to 24:00)	5.411 fb^{-1}	Aug 14-Aug 20, 2007
Best week (Sun 0:00 to Sat 24:00)	5.137 fb^{-1}	Aug 12-Aug 18, 2007
Peak HER current	2069 mA	Feb 29, 2008
Peak LER current	3213 mA	Apr 7, 2008
Best 30 days	19.776 fb^{-1}	Aug 5 – Sep 3, 2007
Best month	19.732 fb^{-1}	August 2007

Total delivered 557 fb^{-1}

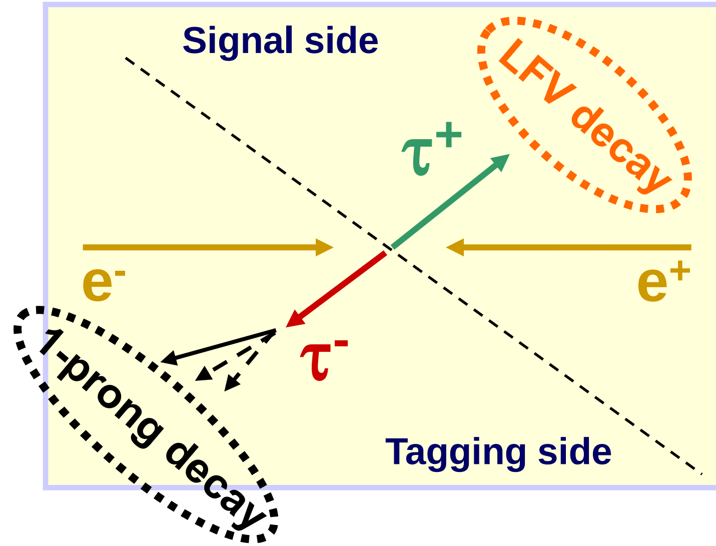
PEP-II turned off April 7, 2008

$\text{Belle logged} : \approx 1.023\ \text{ab}^{-1}$

$\text{PEP-II delivered} : 0.557\ \text{ab}^{-1}$

Analysis strategy @ B factories

In the centre-of-mass system



1. look for decays in *exclusive mode* (*low multiplicity*)
2. Separation into 2 hemispheres
   - signal-side: 1- or 3- prong decay
   - tag-side: 1-prong (BF ~ 80%)
3. Background (higher-order radiative Bhabha and $\mu\mu$, qq, $\tau\tau$ with wrong PID)
4. Sample selection
5. Signal should have $M_{inv}=M_\tau$ and $\Delta E=0$ ($E_\tau^{CM}-E_{beam}^{CM}$)
6. Blind analysis over signal region
7. Expected background evaluation in signal region
8. Blinded signal region opened and candidates observed
9. Calculation of an upper limit by Bayesian/ Feldman-Cousins or maximum likelihood method

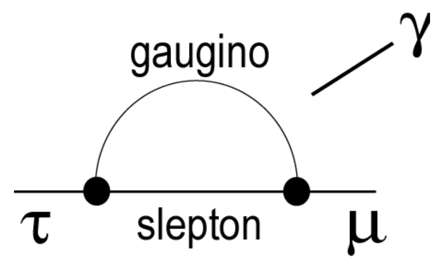
$\tau \to \mu\gamma$ and $\tau \to e\gamma$

✓ **BSM models often predict an enhanced BF up to ~10^{-8}**

$\Rightarrow$ experimental goal: reach sensitivity down to 10^{-9} - 10^{-8}

E.g. see-saw MSSM :

$$BF(\tau \to \mu\gamma) \cong (6\times10^{-7}) \left(\frac{\tan\beta}{60}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{SUSY}}\right)^4$$



Photonic diagram

Search for Lepton Flavor Violation in the Decay $\tau^\pm \to e^\pm\gamma$

(The *BABAR* Collaboration)

A search for the non-conservation of lepton flavor in the decay $\tau^\pm \to e^\pm\gamma$ has been performed with 2.07×10^8 $e^+e^- \to \tau^+\tau^-$ events collected by the *BABAR* detector at the PEP-II storage ring at a center-of-mass energy near 10.58 GeV. We find no evidence for a signal and set an upper limit on the branching ratio of $\mathcal{B}(\tau^\pm \to e^\pm\gamma) < 1.1 \times 10^{-7}$ at 90% confidence level.

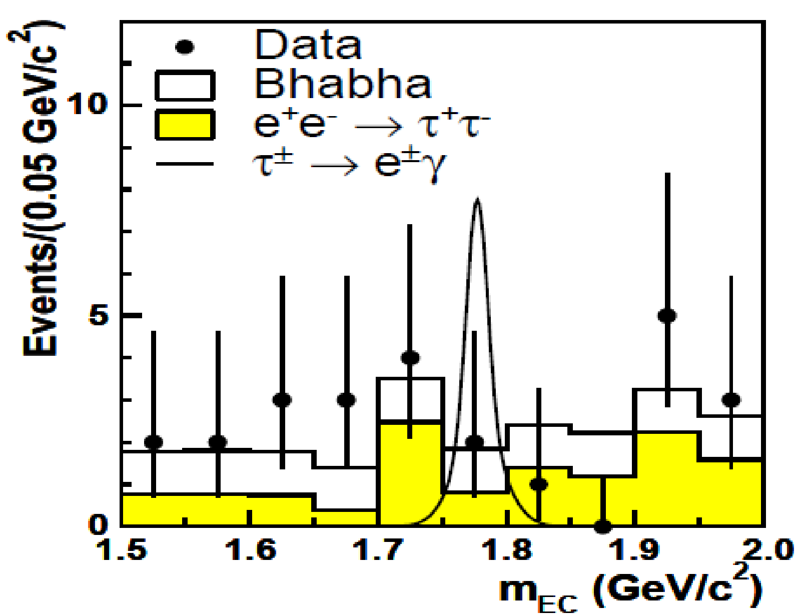


FIG. 2: $m_{\rm EC}$ distribution of data (dots), the expected backgrounds (histograms) and MC signal (curve with arbitrary normalization) for $|\Delta E - \langle \Delta E \rangle| < 2\sigma(\Delta E)$.

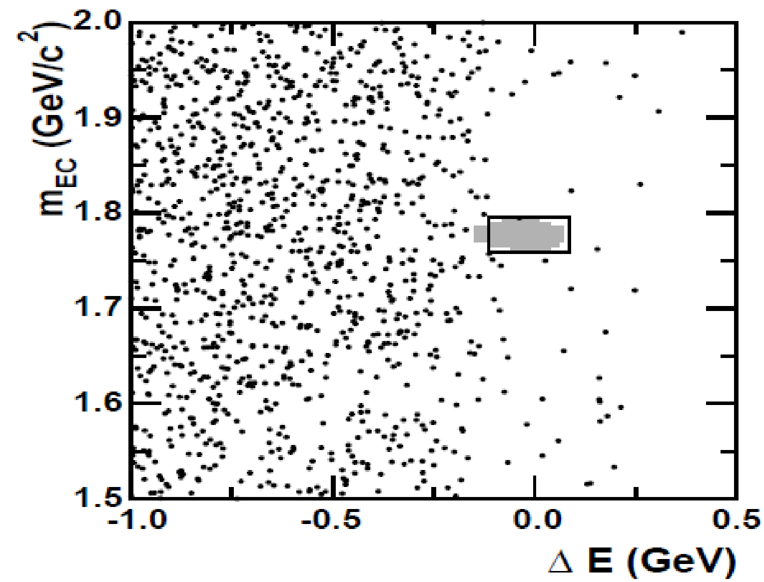


FIG. 1: $m_{\rm EC}$ vs. ΔE distribution of data (dots) and shaded region containing 50% of the selected signal MC events inside the Grand Signal Box, as defined in the text. The boundary of the $\pm 2\sigma$ signal box is also shown.

BaBar Collaboration,
B. Aubert *et al.*, PRL 96, 041801 (2006)
arXiv:hep-ex/0508012v2

$\tau \to l\,\gamma$: present status

Upper limits from BaBar / Belle at 90% C.L.

Decay Mode	Experiment	Reference	Result (90% UL)	Luminosity
			(10^{-8})	(fb^{-1})
$\tau^- \to \mu^- \gamma$	Belle	Phys.Lett.B666:16,2008	4.5	535
	BaBar	arXiv:0908.2381 [hep-ex]	4.4	470 @ Υ(4S), 31 @ Υ(3S), 15 @ Υ(2S)
$\tau^- \to e^- \gamma$	Belle	Phys.Lett.B666:16,2008	12	535
	BaBar	arXiv:0908.2381 [hep-ex]	3.3	470 @ Υ(4S), 31 @ Υ(3S), 15 @ Υ(2S)

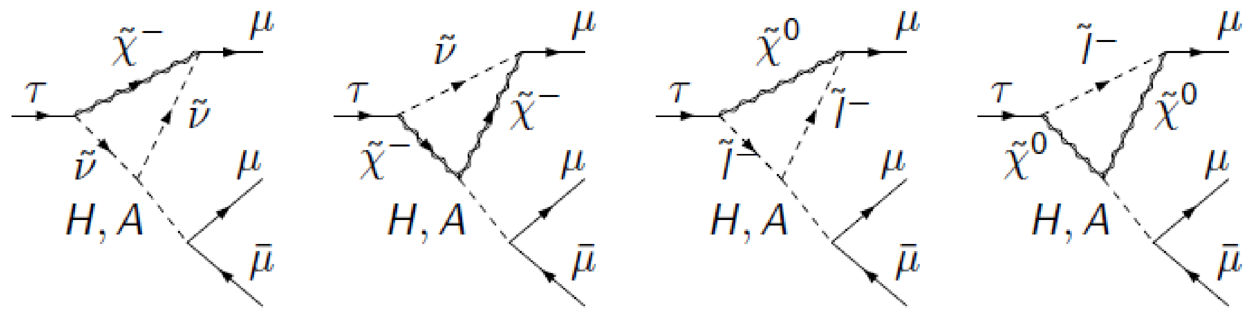
Summaries from HFAG
http://www.slac.stanford.edu/xorg/hfag/

$\tau \to 3\mu$: theoretically a hot topic

✓ **BSM models often predict an enhanced B.R. up to ~10^{-8}**

⇒ experimental goal: reach sensitivity down to 10^{-9} - 10^{-8}

See-saw MSSM:

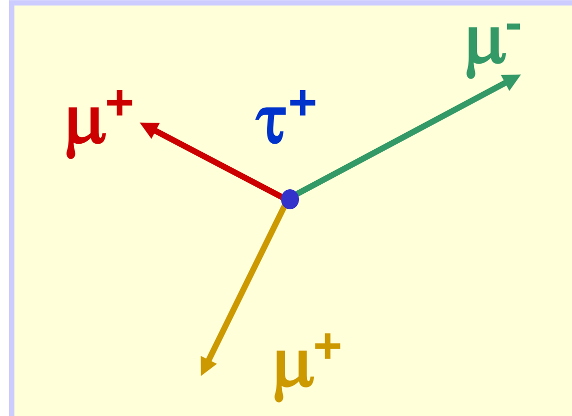


Promising approach: model-independent analysis

$$\begin{aligned}
\mathcal{L} = G\Big(& g^S_{LL}(\bar\mu P_R \mu)(\bar\mu P_L \tau) + g^S_{LR}(\bar\mu P_R \mu)(\bar\mu P_R \tau) + g^S_{RL}(\bar\mu P_L \mu)(\bar\mu P_L \tau) + g^S_{RR}(\bar\mu P_L \mu)(\bar\mu P_R \tau) \\
& + g^V_{LL}(\bar\mu \gamma_\nu P_R \mu)(\bar\mu \gamma^\nu P_L \tau) + g^V_{LR}(\bar\mu \gamma_\nu P_R \mu)(\bar\mu \gamma^\nu P_R \tau) + g^V_{RL}(\bar\mu \gamma_\nu P_L \mu)(\bar\mu \gamma^\nu P_L \tau) + g^V_{RR}(\bar\mu \gamma_\nu P_L \mu)(\bar\mu \gamma^\nu P_R \tau) \\
& + g^T_{LR}\Big(\bar\mu \frac{\sigma_{\rho\nu}}{\sqrt2} P_R \mu\Big)\Big(\bar\mu \frac{\sigma^{\rho\nu}}{\sqrt2} P_R \tau\Big) + g^T_{RL}\Big(\bar\mu \frac{\sigma_{\rho\nu}}{\sqrt2} P_L \mu\Big)\Big(\bar\mu \frac{\sigma^{\rho\nu}}{\sqrt2} P_L \tau\Big)\Big) \\
\equiv G & \sum_{a,b,c} g^c_{ab} (\bar\mu \Gamma^c \gamma^0 P_a \gamma^0 \mu)(\bar\mu \Gamma^c P_b \tau), \qquad (1)
\end{aligned}$$

See e.g.: M. Giffels et al., PR D77, 073010 (2008)

$\tau \to 3\mu$: experimental status



- **Best current upper limit:**

BF ($\tau \to 3\mu$) < 2.1 x 10^{-8} @ 90% C.L.

… from Belle, with ~80% of the available data sample

Old experiments :

- **MARK and ARGUS experiments (in the 80's)**
- **CLEO @ CESR (Cornell Uni.)**
- **BaBar @ SLAC, Belle @ KEKB**

Present experiments :

- **CMS, ATLAS (?)**
- **Is the ball in LHCb's hands ?**

Future experiments :

- **At super-B factories**

Leptonic τ decays: present status

Summaries from HFAG
http://www.slac.stanford.edu/xorg/hfag/

Decay Mode	Experiment	Reference	Upper Limit @ 90% C.L. (10^{-8})	Luminosity (fb^{-1} @ Υ(4S))
$\tau^- \to e^- e^+ e^-$	Belle	EPS2009	2.7	782
	BaBar	CIPANP09	2.9	468
$\tau^- \to \mu^- e^+ e^-$	Belle	EPS2009	1.8	782
	BaBar	CIPANP09	2.2	468
$\tau^- \to e^- \mu^+ \mu^-$	Belle	EPS2009	2.7	782
	BaBar	CIPANP09	3.2	468
$\tau^- \to \mu^- \mu^+ \mu^-$	Belle	EPS2009	2.1	782
	BaBar	CIPANP09	3.3	468
$\tau^- \to e^- \mu^+ e^-$	Belle	EPS2009	1.5	782
	BaBar	CIPANP09	1.8	468
$\tau^- \to \mu^- e^+ \mu^-$	Belle	EPS2009	1.7	782
	BaBar	CIPANP09	2.6	468

Possible @ LHCb !

On LFV semileptonic τ decays

- ✓ $\tau \to l\,\gamma$ and $\tau \to 3\mu$ raise most interest …
  … but other decay modes such as semileptonic may well be as relevant:

- ❑ **arXiv:0810.0163v1[hep-ph]**, "LFV in semileptonic τ decays and μ-e conversion in nuclei in SUSY-seesaw"

  - looks at $\tau \to \mu P$, μPP, μV^0 decays

  > In conclusion, we have shown that semileptonic tau decays nicely complement the searches for LFV in the $\tau - \mu$ sector, in addition to $\tau \to \mu\gamma$. The future prospects for $\mu - e$ conversion in Ti are the most promising for LFV searches. Both processes, semileptonic tau decays and $\mu - e$ conversion in nuclei are indeed more sensitive to the Higgs sector than $\tau \to 3\mu$.

- ❑ **arXiv:0812.0727v1[hep-ph]**, "Lepton Flavor Violating $\tau^- \to \mu^- V^0$ Decays in the Two Higgs Doublet Model III"

$\tau \to l\, V^0$ decays: present status

Summaries from HFAG
http://www.slac.stanford.edu/xorg/hfag/

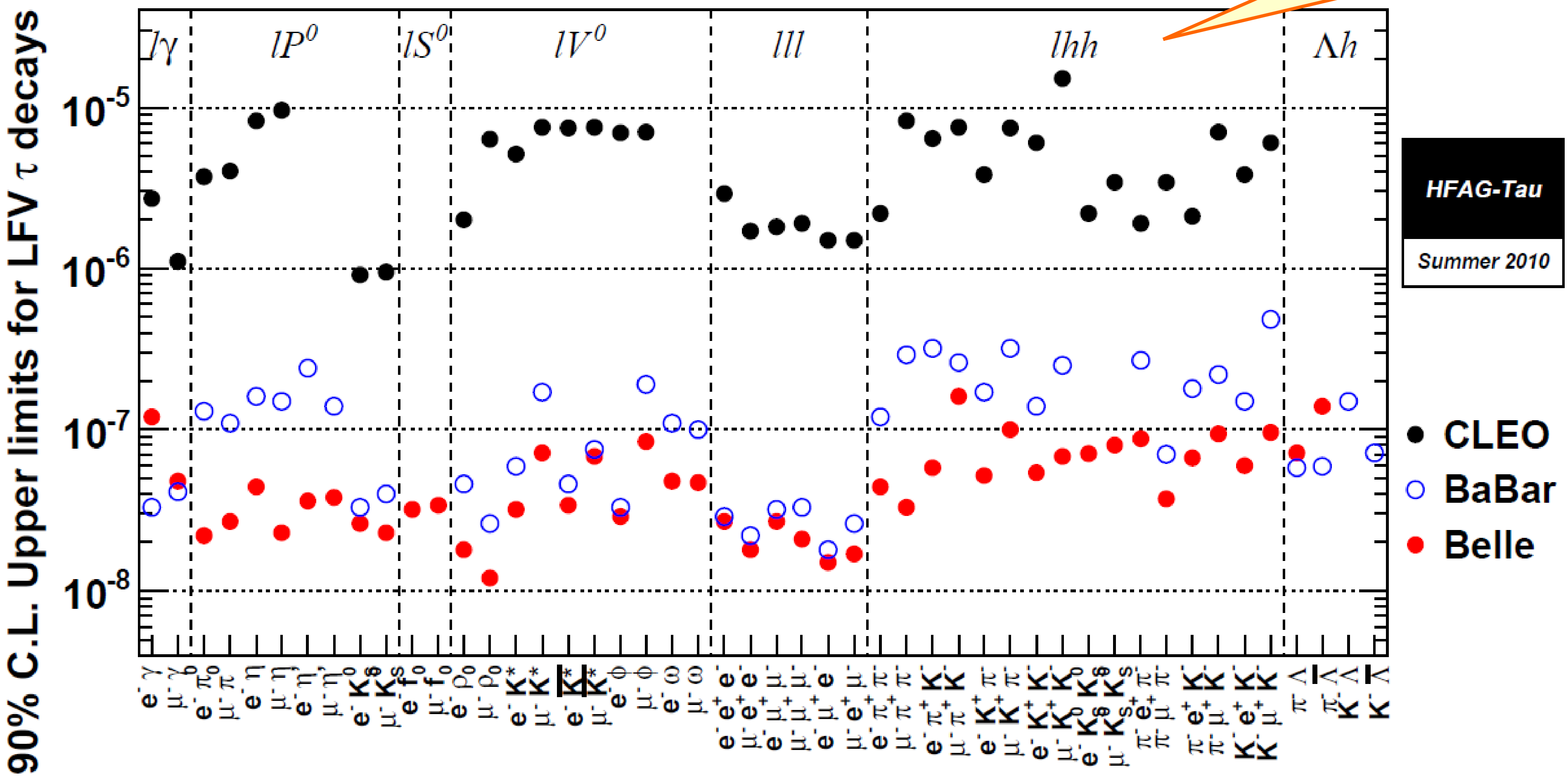
Decay Mode	Experiment	Reference	Upper Limit @ 90% C.L. (10^{-8})	Luminosity $(fb^{-1}$ @ $\Upsilon(4S))$
$\tau^- \to e^- \rho^0$	Belle	Phys.Lett.B664:35,2008	6.3	543
	BaBar	Phys.Rev.Lett.103:021801,2009	4.6	451
$\tau^- \to \mu^- \rho^0$	Belle	Phys.Lett.B664:35,2008	6.8	543
	BaBar	Phys.Rev.Lett.103:021801,2009	2.6	451
$\tau^- \to e^- K^*$	Belle	Phys.Lett.B664:35,2008	7.8	543
	BaBar	Phys.Rev.Lett.103:021801,2009	5.9	451
$\tau^- \to \mu^- K^*$	Belle	Phys.Lett.B664:35,2008	5.9	543
	BaBar	Phys.Rev.Lett.103:021801,2009	17	451
$\tau^- \to e^- \overline{K}^*$	Belle	Phys.Lett.B664:35,2008	7.7	543
	BaBar	Phys.Rev.Lett.103:021801,2009	4.6	451
$\tau^- \to \mu^- \overline{K}^*$	Belle	Phys.Lett.B664:35,2008	10	543
	BaBar	Phys.Rev.Lett.103:021801,2009	7.3	451
$\tau^- \to e^- \phi$	Belle	Phys.Lett.B664:35,2008	7.3	543
	BaBar	Phys.Rev.Lett.103:021801,2009	3.1	451
$\tau^- \to \mu^- \phi$	Belle	Phys.Lett.B664:35,2008	13	543
	BaBar	Phys.Rev.Lett.103:021801,2009	19	451
$\tau^- \to e^- \omega$	Belle	Phys.Lett.B664:35,2008	18	543
	BaBar	Phys.Rev.Lett.100:071802,2008	11	384
$\tau^- \to \mu^- \omega$	Belle	Phys.Lett.B664:35,2008	8.9	543
	BaBar	Phys.Rev.Lett.100:071802,2008	10	384

Possible @ LHCb ?

Just over ~ ½ of full dataset used

Summary: present status

Important activity at the B factories



⇒ most decay modes probed down to a few parts in 10^{-8} !

Super flavour factories – what, and what for?

SuperKEKB :

- Upgrade of current KEKB to luminosity ~ $10^{35\text{-}36}$ $cm^{-2}s^{-1}$
  $\Rightarrow$ also an upgraded Belle-II detector …

SuperB :

- New e^+e^- asymmetric collider with luminosity > 10^{36} $cm^{-2}s^{-1}$
- On Tor Vergata campus of University of Rome
- SuperB expected to integrate 75 ab^{-1} in 5 years !

SuperB – expected sensitivity on LFV τ decays

- Physics program at Super Flavour Factories (SFF) rather rich:
  - precision SM measurements
  - rare B decays
  - CP violation in charm
  - etc.

- Examples of expected reach for LFV τ decays:

Present best U.L. @ 90% C.L.

4.4×10^{-8} →

3.3×10^{-8} →

3.2×10^{-8} →

Process	Sensitivity
$\mathcal{B}(\tau \to \mu\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to e\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to \mu\mu\mu)$	2×10^{-10}
$\mathcal{B}(\tau \to eee)$	2×10^{-10}
$\mathcal{B}(\tau \to \mu\eta)$	4×10^{-10}
$\mathcal{B}(\tau \to e\eta)$	6×10^{-10}
$\mathcal{B}(\tau \to \ell K_s^0)$	2×10^{-10}

Intro to LFV phenomenology

Why are the decays $l_i \rightarrow l_j\, \gamma$ so popular?

$l_i \rightarrow l_j\, \gamma$:

- Decay induced by 1-loop diagrams with exchange of superpartners (in SUSY)
- Decay described by the dipole operator

$$\mathcal{L}_{\rm eff} = e\frac{m_i}{2}\bar{l}_i \sigma_{\mu\nu} F^{\mu\nu} (A_L^{l_i l_j} P_L + A_R^{l_i l_j} P_R) l_j + h.c.$$

$l_i \rightarrow l_j\, l_k\, l_k$ and $\mu - e$ conversion in nuclei :

- SUSY models predict unambiguously

$$\begin{aligned} \mathrm{BR}(\ell_i \to \ell_j \ell_k \ell_k) &\sim \alpha_{\rm em} \times \mathrm{BR}(\ell_i \to \ell_j \gamma) \\ \mathrm{CR}(\mu \to e \text{ in N}) &\sim \alpha_{\rm em} \times \mathrm{BR}(\mu \to e\gamma) \end{aligned}$$

as these processes are dominated by dipole transitions $l_i \rightarrow l_j\, \gamma^*$

(sizeable deviations from these predictions would indicate large Higgs-mediated LFV effects)

MSSM + see-saw mechanism with 3 heavy ν_R

Some general predictions :

- "Large" values for BF($\mu \to e \gamma$) are possible
- But parameter phase space for large values of BF($\tau \to \mu \gamma$) very constrained by present experimental bounds on BF($\mu \to e \gamma$)
- BF($\tau \to e \gamma$) is always very suppressed because of bound on BF($\mu \to e \gamma$)

Note :

- Neutrino mixing parameters impose useful constraints on the possible SUSY phasespace and relative BFs of decays above
  (from solar + atmospheric neutrino data)

How to identify the specific source(s) of LFV?

A couple of examples …

- Correlating different measurements such as BF($\mu \to e \gamma$), BF($\tau \to \mu \gamma$), the anomalous muon (g-2), leptonic electric dipole moments (EDMs)

- Studying e.g. the P-odd asymmetry in polarised $\mu \to e \gamma$:

$$A(\mu^+ \to e^+\gamma) = \frac{|A_L|^2 - |A_R|^2}{|A_L|^2 + |A_R|^2}$$

Ex.: Non-GUT SUSY + see-saw predicts

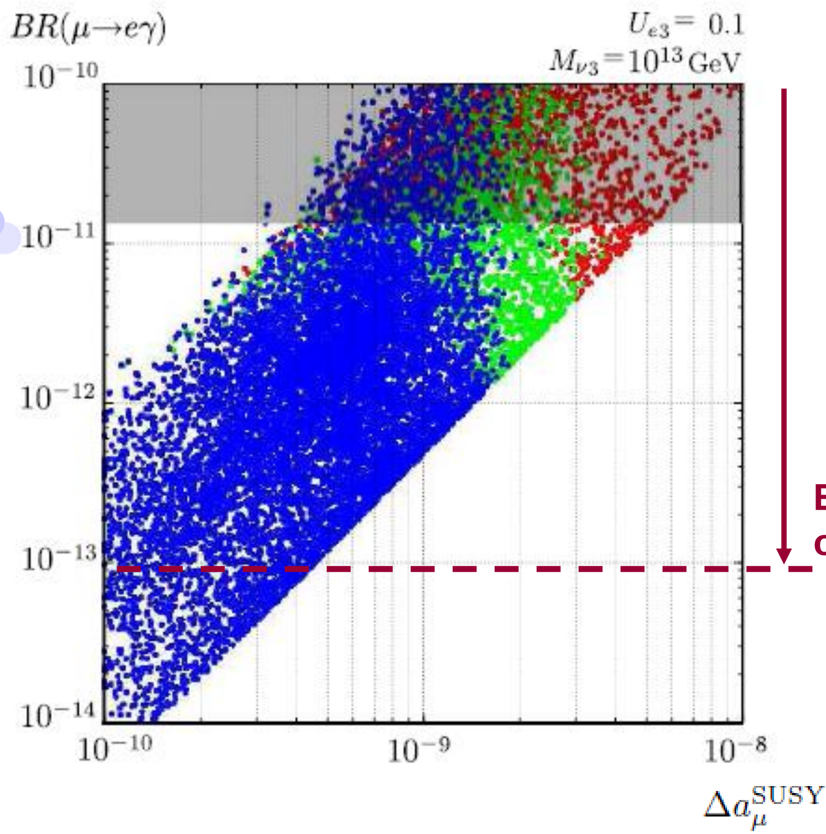
$$A(\mu^+ \to e^+\gamma) = +1$$

to a very good accuracy

$\Rightarrow$ large departure from +1 would support the idea of SUSY see-saw embedded in a GUT scenario

"The power of correlations" – examples (1/3)

SUSY effects to the μ (g-2) are well correlated with BF(μ→eγ)



(= SUSY contribution Δa_μ)

Expected final sensitivity of the running MEG experiment

For info, at present:

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} \approx (3 \pm 1) \times 10^{-9}$$

$$a_\mu = (g-2)/2$$

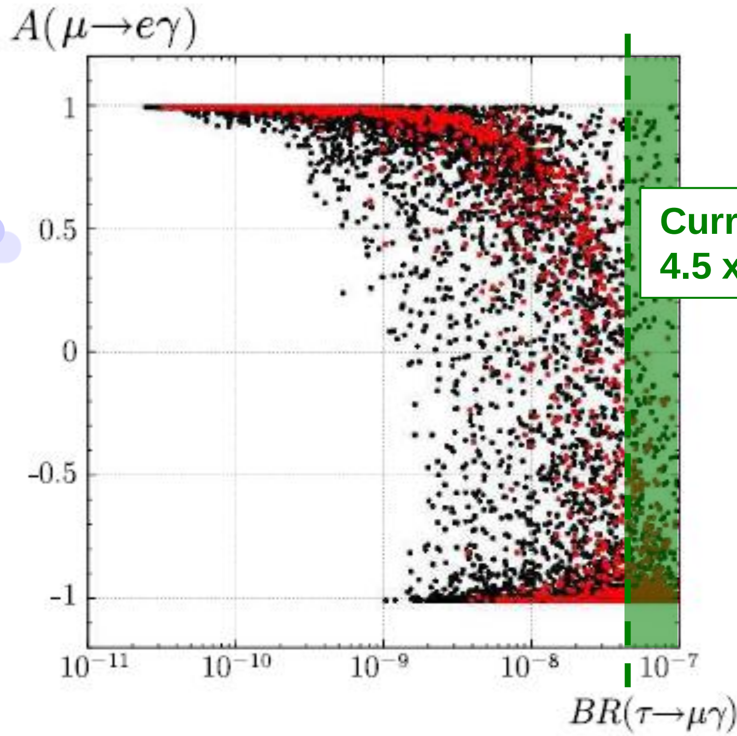
FIG. 3: BR($\mu \to e\gamma$) vs $\Delta a_\mu^{\rm SUSY}$ in the $SU(5)_{RN}$ model assuming a hierarchical spectrum for both light and heavy neutrinos, $m_{\nu_3} = 0.05$eV, $M_3 = 10^{13}$ GeV and $U_{e3} = 0.1$. The plot has been obtained varying the SUSY parameters in the following ranges: 100 GeV $< m_0, M_{1/2} <$ 1 TeV, $|A_0| < 3m_0$, $3 < \tan\beta < 50$ and $\mu > 0$. Green (blue) points satisfy the constraints from BR($B \to X_s\gamma$) at the 99% C.L. (90% C.L.) limit. The grey region is excluded by the current experimental upper bound on BR($\mu \to e\gamma$).

SUSY SU(5) model within a GUT scenario with 3 heavy ν_R

J. Hisano *et al.*,, arXiv:0904.2080v1 [hep-ph]

"The power of correlations" – examples (2/3)

For once, a lower limit could be set – for $\tau \to \mu\gamma$ - if $A(\mu \to e\gamma) < +1$!



Current best 90% C. L. BF upper limit: 4.5×10^{-8}

This is assuming evidence for $\mu \to e\gamma$ at the level $BF(\mu \to e\gamma) = 3 \times 10^{-12}$

FIG. 6: ~~Upper plot:~~ P-odd asymmetry in $\mu^+ \to e^+\gamma$, $A(\mu^+ \to e^+\gamma)$, vs U_{e3} in the $SU(5)_{RN}$ model for three different values of BR$(\mu \to e\gamma) = (3, 1, 0.3) \times 10^{-12}$. Lower plot: $A(\mu^+ \to e^+\gamma)$ vs BR$(\tau \to \mu\gamma)$ assuming BR$(\mu \to e\gamma) = 3 \times 10^{-12}$. Both plots have been obtained by means of a scan of the input parameters $m_0, M_{1/2} < 1$ TeV, $|A_0| < 3m_0$, $3 < \tan\beta < 50$ and $\mu > 0$. For the neutrino sectors, we have assumed a hierarchical spectrum for both light and heavy neutrinos and we take $m_{\nu_3} = 0.05$eV, $10^{10} < M_3 < 10^{15}$ GeV and $10^{-5} \leq U_{e3} \leq 0.1$. All the points of both plots satisfy the constraints from $b \to s\gamma$ at the 99% C.L. limit and $m_{h^0} > 111.4$ GeV. Red points in the lower plot also satisfy $\Delta a_\mu^{SUSY} \geq 1 \times 10^{-9}$.

J. Hisano *et al.*,, arXiv:0904.2080v1 [hep-ph]

"The power of correlations" – examples (3/3)

- If U_{e3} = 0.1 :
  BF($\tau \to \mu\gamma$)<~10-9
  $\Rightarrow$ out of reach
  even for super-B factories!
- If U_{e3} is very small :
  $\tau \to \mu\gamma$ still accessible at
  super-B even if MEG
  finds nothing
- In the U_{e3} intermediate region
  both have a word to say

U = PMNS neutrino mixing matrix

U_{e3}=0.1 : close to current exp. U. L.

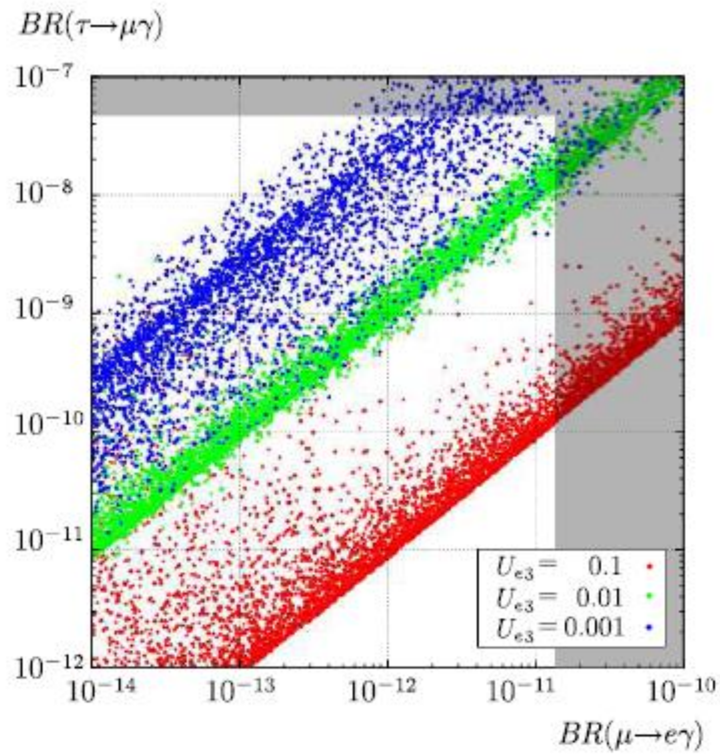


FIG. 7: BR($\mu \to e\gamma$) vs BR($\tau \to \mu\gamma$) in the $SU(5)_{RN}$ model. The plot has been obtained by means of a scan over the same input parameters of Fig. 4. The grey regions are excluded by the current experimental upper bounds on BR($\mu \to e\gamma$) and BR($\tau \to \mu\gamma$).

$\Rightarrow$ $\mu \to e\gamma$ and $\tau \to \mu\gamma$ are very complementary probes of LFV effects in SUSY !

J. Hisano *et al.*,,
arXiv:0904.2080v1 [hep-ph]

LFV searches @ LHC

Does the LHC have a word to say?

Sources of τ leptons at the LHC

Main production mode :

- D_s decays

Other production modes :

- B^0 and $B^\pm$ decays
- B_s decays

Both production modes exploitable by LHCb

Negligible production modes :

- Z decays
- W decays

Only viable solution for ATLAS/CMS (high-p_T triggers, background)

Sensitivity @ LHCb: back-of-the-envelope calculation (1/2)

- **Upper limit on Branching Fraction:**

$$BR_{UL} = \frac{\sqrt{B}}{\varepsilon_{sel}} \frac{1}{N_\tau}$$

based on $\sqrt{B}/S = 1$

- **Number of τ's produced in 1 year:**

$$N_\tau^{1\,\text{year}} = 2 \times \sigma_{c\bar{c}} \times \int \mathcal{L}\,dt \times \varepsilon_{\text{acc}}^{c\bar{c}} \times f(c \to D_s) \times BR(D_s \to \tau\nu_\tau)$$

With

$\sigma_{c\bar{c}} = 3.5\ \text{mb}$

$\int \mathcal{L}\,dt = 2\ \text{fb}^{-1}$

$\varepsilon_{\text{acc}}^{c\bar{c}} = 40\%$

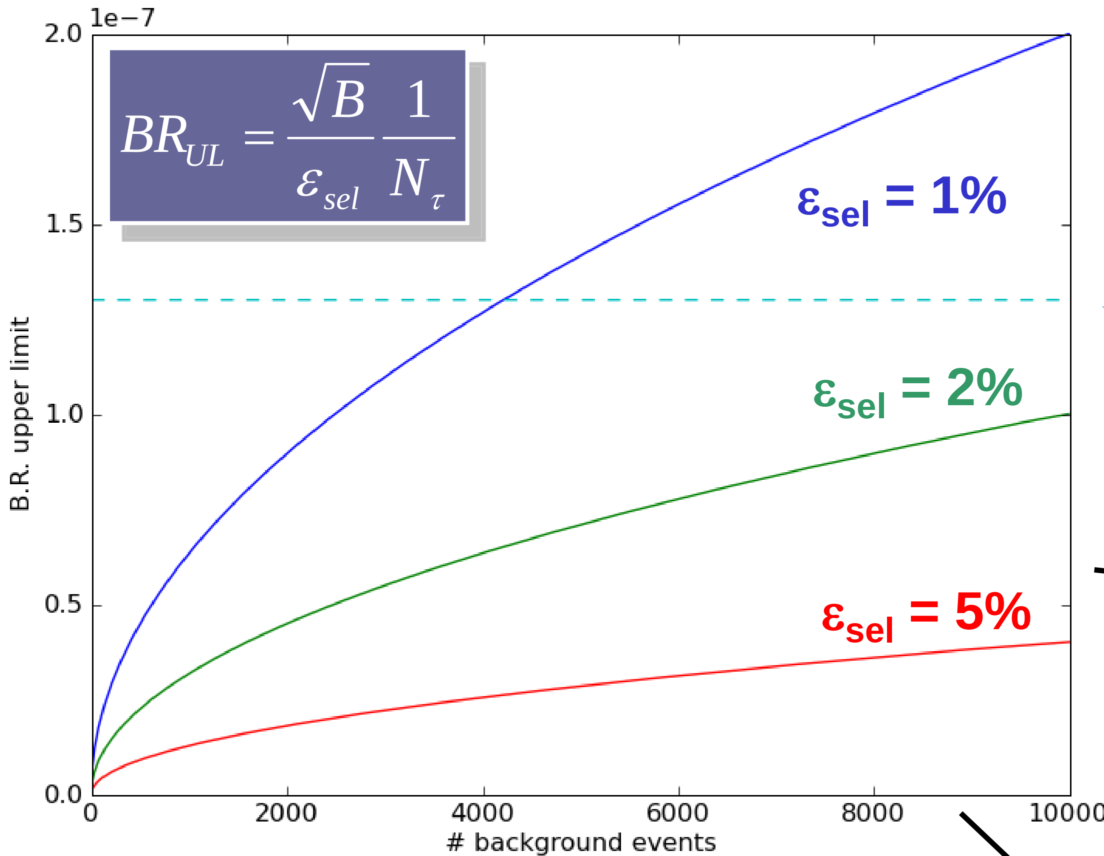
$f(c \to D_s) = 14\%$

$BR(D_s \to \tau\nu_\tau) = 6.6\%$

one gets $N_\tau^{1\text{year}} \approx 5 \times 10^{10}$

⇒ ~ 50 τ decays per year even if BF ~ 10^{-9} !

Sensitivity @ LHCb: back-of-the-envelope calculation (2/2)



We may be competitive with world best limits within $1 \rightarrow 2$-ish years !

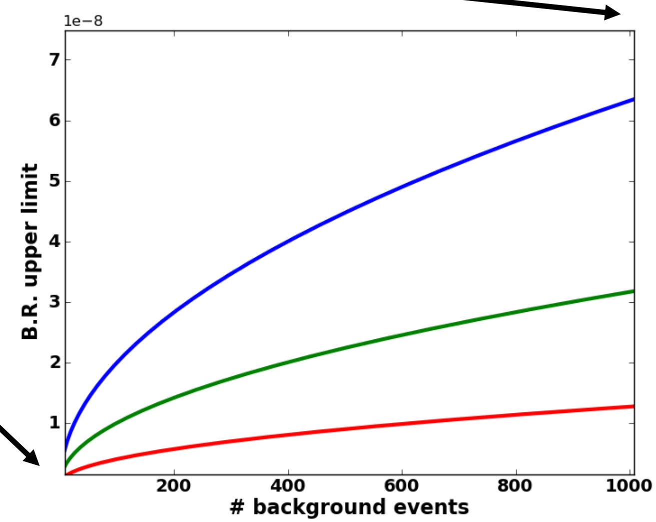
Example of the present $\tau \rightarrow \mu\,\phi$ 90% C.L. BF upper limit

LHCb $\tau \rightarrow \mu\mu\mu$ study:

selection+trigger efficiency ~1%

 # background events per year ~100 @ 95% C.L.

$\Rightarrow$ BF < 3.3x10-8 @ 90% C.L. obtained from analysis



LFV topics studied @ the LHC

- $\tau \to \mu\,\mu\,\mu$ (ATLAS, CMS, LHCb)
- $\tau \to \mu\,\phi$ (LHCb)
- $B_{d,s} \to e\,\mu$ (LHCb)
- $B_s \to \tau\,\mu$ (ATLAS)
- …?

$\tau \rightarrow 3\mu$ @ LHCb

M. Meissner, J. Blouw, U. Uwer
Rare Decays WG Meeting, 22 July 2009
+ private communication/update

- "Only" decay mode considered so far in LHCb

- Most recent study indicates a 90% C.L. upper limit
  $BF(\tau \rightarrow \mu\,\mu\,\mu) < 3.3 \times 10^{-8}$ in 1 nominal year of data (2 fb^{-1})
  (assuming no signal found)
  … to compare with the world best U. L. of 2.1 x 10^{-8}

- More detailed background studies are needed …

$\sigma(M_{3\mu}) \sim$ 8-10 MeV

Analysis ongoing … !

$\tau \to 3\mu$ @ ATLAS and CMS

- **Most likely only τ-decay mode exploitable in ATLAS/CMS environment**

- **ATLAS has an ongoing study … (admitedly no news on this)**
- **CMS has performed a detailed study (CMS Note 2002-037)**

CMS study :

- **~ 10^{12} τ leptons expected within the CMS tracker acceptance for 10 fb^{-1}**

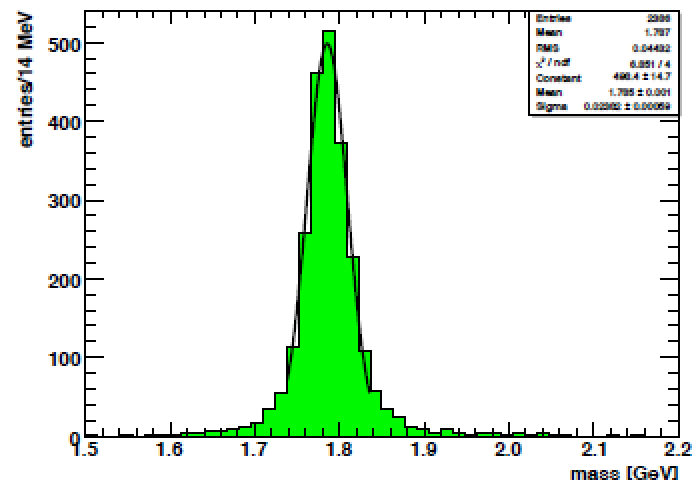
Sources of τ leptons at LHC

production channel	$N_\tau/10\ fb^{-1}$
$W \to \tau\nu_\tau$	$1.5 \cdot 10^8$
$Z \to \tau\tau$	$2.9 \cdot 10^7$
$B^0 \to \tau X$	$3.1 \cdot 10^{11}$
$B^\pm \to \tau X$	$3.6 \cdot 10^{11}$
$B_s \to \tau X$	$9.7 \cdot 10^{10}$
$D_s \to \tau X$	$6.3 \cdot 10^{11}$

- **"W-mode" is most promising:**
  - high p_T of μ's
  - predicted τ mass resolution ~ 24 MeV

  - 95% C.L. upper limit

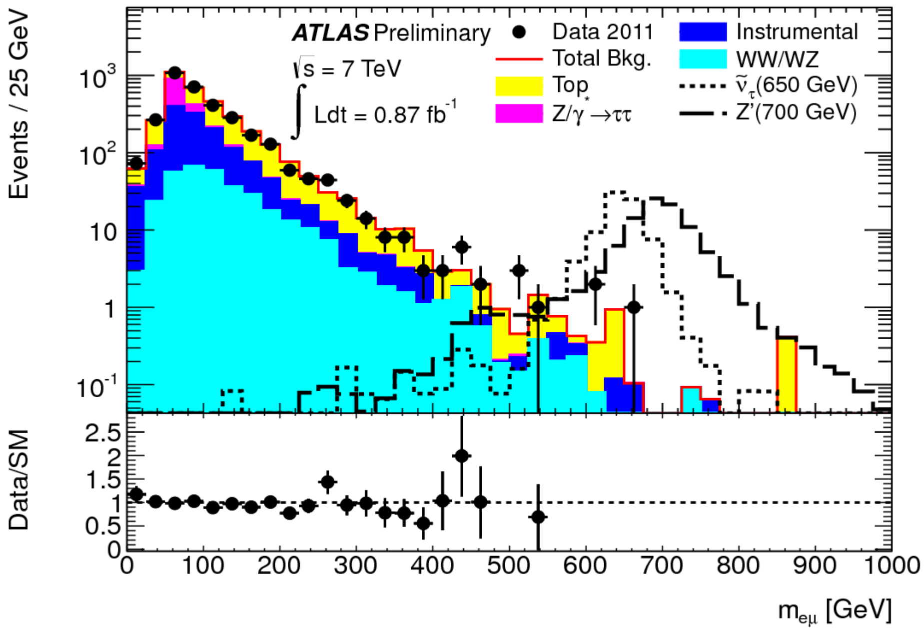
  $BF(\tau \to \mu\mu\mu) < 3.8(7.0)\ x10^{-8}$ with 30 fb^{-1}(10 fb^{-1})



Search for heavy $X^0 \rightarrow e\,\mu$ @ ATLAS

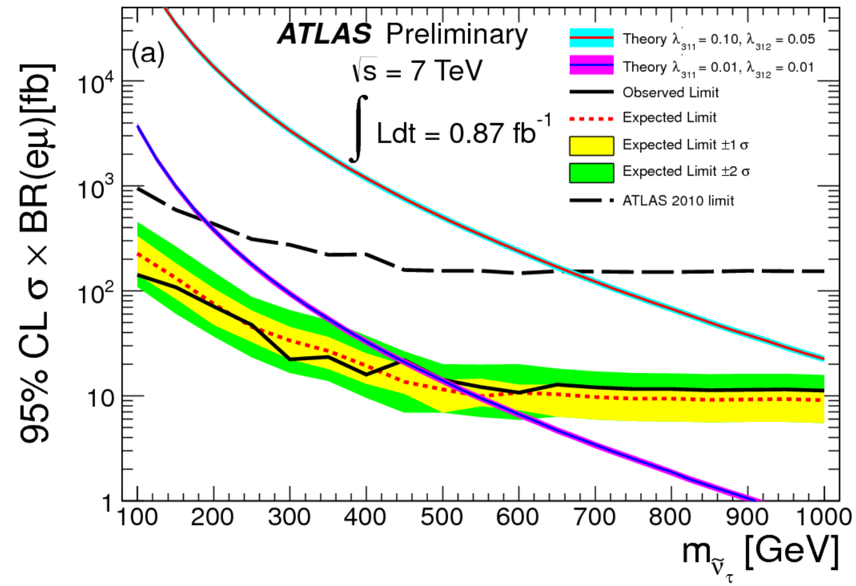
Luminosity: 0.87 fb^{-1}

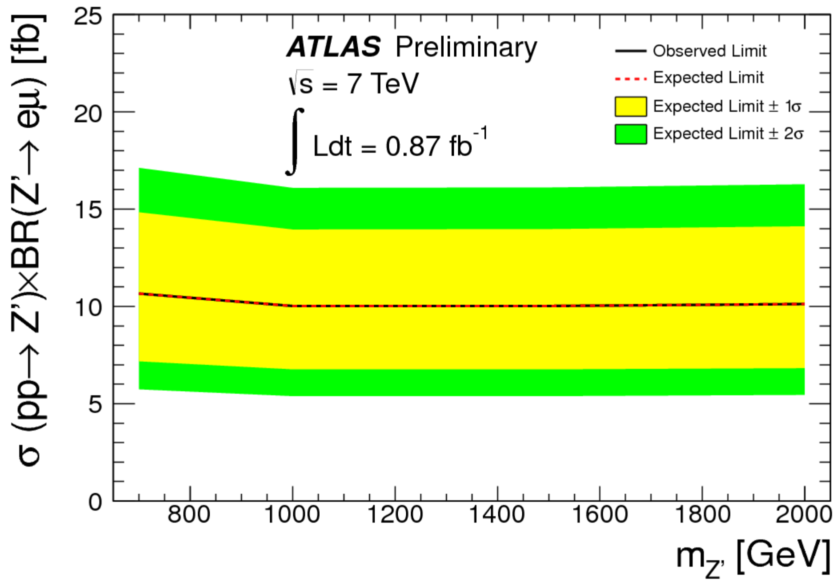
- Tau sneutrino in R-parity violating SUSY
- Z'-like boson in model with LFV



Process	Number of events
$Z/\gamma^* \rightarrow \tau\tau$	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

Sources identified and understood





ATLAS-CONF-2011-109

Search for $X^0 \rightarrow e\,\mu$ @ ATLAS – highest $m_{e\mu}$ candidate

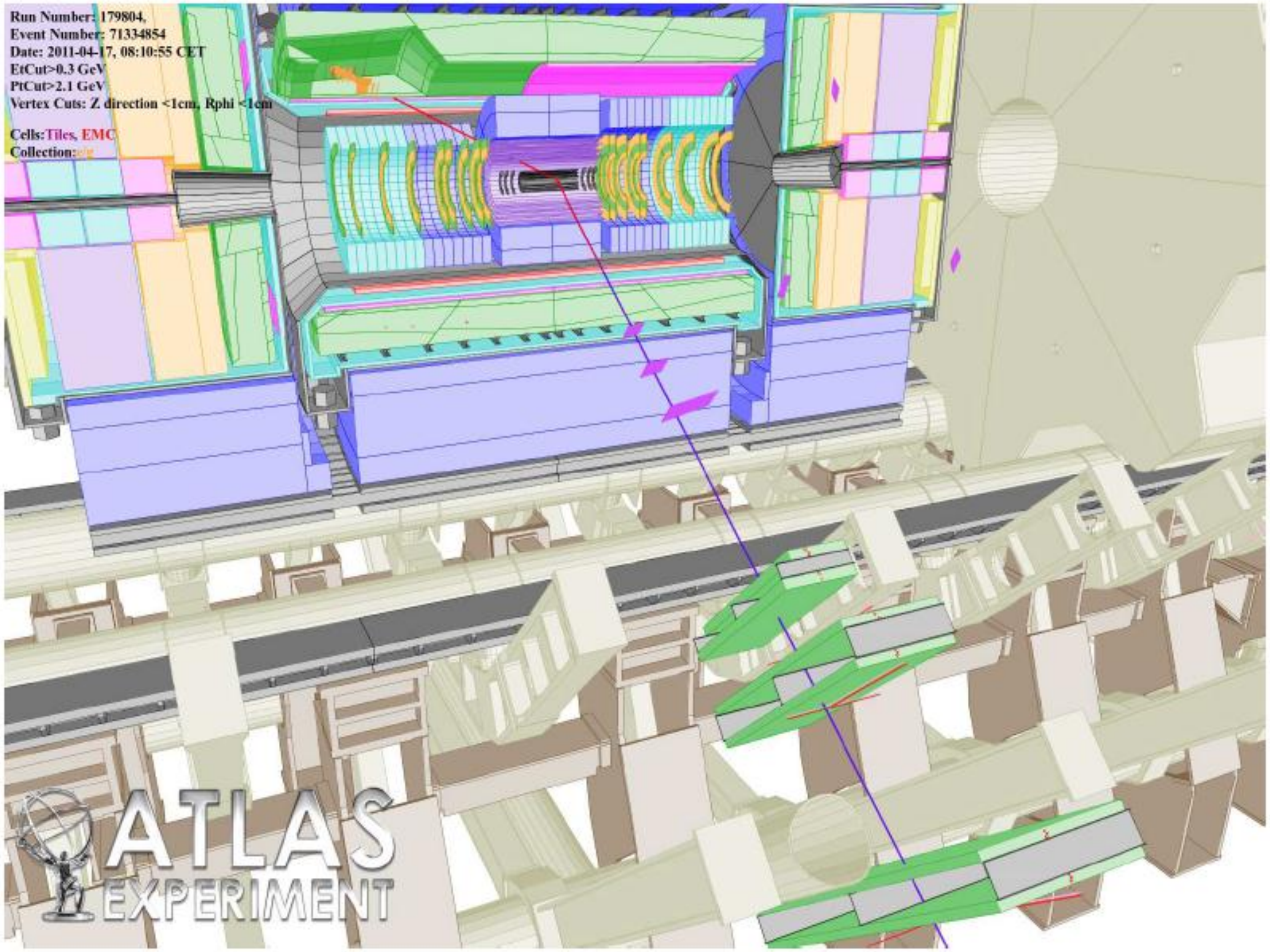


Figure 9: Event display for run 179804 event 71334854, the $e\mu$ pair in this event gives the highest $m_{e\mu}$. In this event, electron p_T = 341 GeV, $\eta = -1.17$, $\phi = 0.91$; muon p_T = 216 GeV, $\eta = 0.14$, $\phi = -2.36$; $m_{e\mu}$ = 662 GeV, $\Delta\phi_{e\mu} = 3.02$ and E_T^{miss} = 132 GeV. There is no jet with $p_T > 30$ GeV in this event.

ATLAS-CONF-2011-109

Outlook

An invitation to further investigation ...

Future prospects for LFV

- $\mu \rightarrow e \gamma$ with MEG @ PSI
- New $\mu \rightarrow 3e$ experiment @ PSI (if approved)

- Various LFV & LNV earches with ATLAS / CMS / LHCb @LHC

- Super B factories

- $\mu \rightarrow e$ conversion with Mu2e @ Fermilab
- $\mu \rightarrow e$ conversion with COMET @ J-PARC

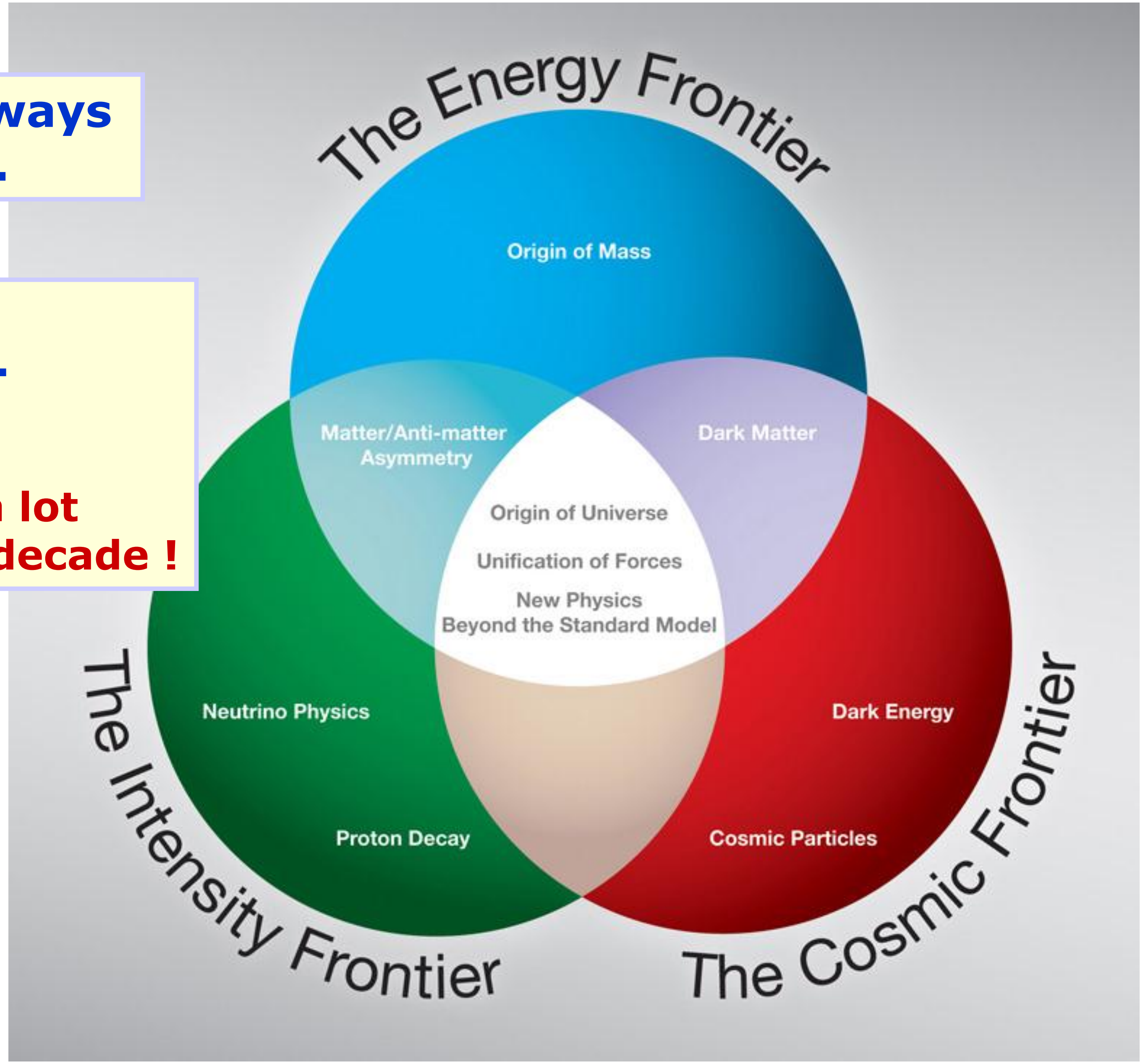
- $\mu \rightarrow 3e$ conversion with Mu23 / Project X @ Fermilab
- $\mu \rightarrow e$ conversion with PRIME / PRISM @ J-PARC

To reflect … as a conclusion …

3 complementary ways of exploring HEP …

… and LFV is often around the corner …

You WILL be hearing a lot about LFV in the next decade !



Back-up slides

Further reading

- arXiv:1112.4418 – LFV in MFV extensions of the seesaw
- arXiv:0904.2080 – "Waiting for $\mu \to e \gamma$ from the MEG experiment"
- JHEP 10, 039 (2007) – model-independent analysis of $\tau \to lll$
- μ - e conversion – COMET Proposal and CDR
- arXiv:0905.1613 – LFV and B_s Leptonic Final States at the LHC
- On $\tau \to \mu\mu\mu$:
  - CMS CR-2009/013
  - Phys. Rev. D77, 073010 (2008)
- arXiv:1112.3631 – μ g-2 and LFV in a 2HDM
- arXiv:1112.4403 – SuSeFLAV, program for calculating SUSY spectra and LFV

Searches for LFV with $J/\psi \to l\, l'$ decays

BES II @ BEPC:

- Searches by the BES (Beijing Spectrometer Experiment) at BEPC (Beijing Electron Positron Collider)
  - Beam energy in range 1-2.5 GeV
  - Peak luminosity ~ $5 \times 10^{30}\ cm^{-2}\ s^{-1}$

$$BF(J/\psi \to e\mu) < 1.1\times10^{-6}\ @\ 90\%\ C.L.$$

BES Collaboration,
Z. J. Bai *et al.*, Phys. Lett. B561, 49 (2003)

$$BF(J/\psi \to e\tau) < 8.3\times10^{-6}\ @\ 90\%\ C.L.$$

$$BF(J/\psi \to \mu\tau) < 2.0\times10^{-6}\ @\ 90\%\ C.L.$$

BES Collaboration,
M. Ablikim *et al.*, Phys. Lett. B598, 172 (2004)

Note:
- All results (both publications) using a sample of 5.8×10^7 J/ψ events from the 1999-2001 data sample
- $J/\psi \to e\,\tau$, $\tau \to \mu\,\nu\nu$
- $J/\psi \to \mu\,\tau$, $\tau \to e\,\nu\nu$

Searches for LFV with $\Upsilon \to l\, l'$ decays

BSM effective field theory with Wilson OPE:

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \frac{4\pi\alpha_N}{\Lambda^2}(\bar{\mu}\Gamma_\mu \tau)(\bar{b}\gamma^\mu b)$$

where Γ_μ is a vector (γ_μ) or axial-vector ($\gamma_\mu\gamma_5$) current or their combination, Λ is the scale of BSM physics, and α_N is the effective LFV coupling of the new gauge symmetry associated with BSM.

(parameterisation of BSM physics avoiding explicit invocation of unknown dynamics)

Effective field theory allows one to relate the dilepton and LFV branching fractions of Υ mesons to the scale Λ of LFV BSM physics [4,5] using

$$\frac{\Gamma(\Upsilon(nS) \to}{\Gamma(\Upsilon(nS) \to \mu\mu)} = \frac{}{2e_b^2}\left(\frac{\alpha_N}{\alpha}\right)^2\left(\frac{M[\Upsilon(nS)]}{\Lambda}\right)^4, \quad (3)$$

TABLE I. Information necessary to interpret our results in terms of BSM physics scale Λ and coupling α_N. We assume lepton universality and use our results for dielectron partial widths of Υ mesons [17]. Full widths are according to the PDG summary [14].

	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Mass (GeV/c^2)	9.46	10.02	10.36
N decays (millions)	20.8	9.3	5.9
$\Gamma(\Upsilon \to \mu\mu)$ (keV)	1.252	0.581	0.413
$\Gamma(\Upsilon)$ (keV)	53.0	43.0	26.3
$\mathcal{B}(\mu\mu)$ ($\times 10^{-3}$)	23.6	13.5	15.7
$\mathcal{B}(\mu\tau)$ (95% CL UL, $\times 10^{-6}$)	6.0	14.4	20.3
$\mathcal{B}(\mu\tau)/\mathcal{B}(\mu\mu)$ (95% CL UL, $\times 10^{-3}$)	0.25	1.1	1.3
Λ (95% CL LL, TeV, $\alpha_N = 1.0$)	1.30	0.98	0.98

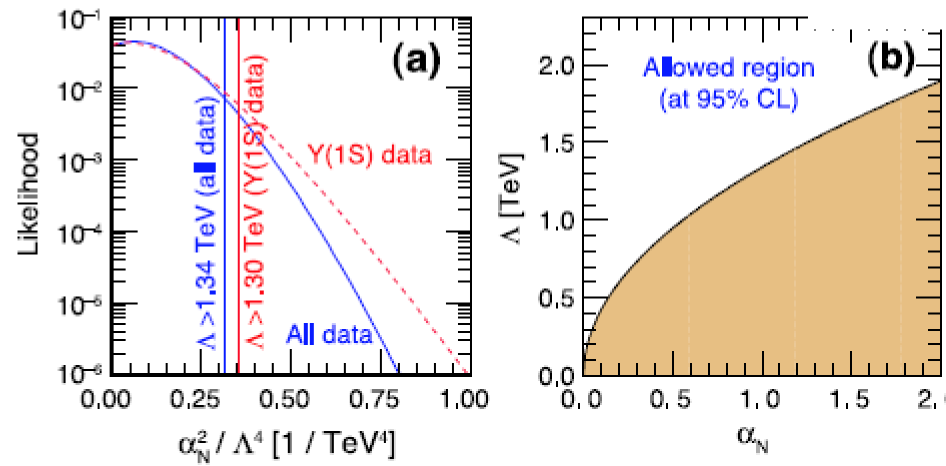
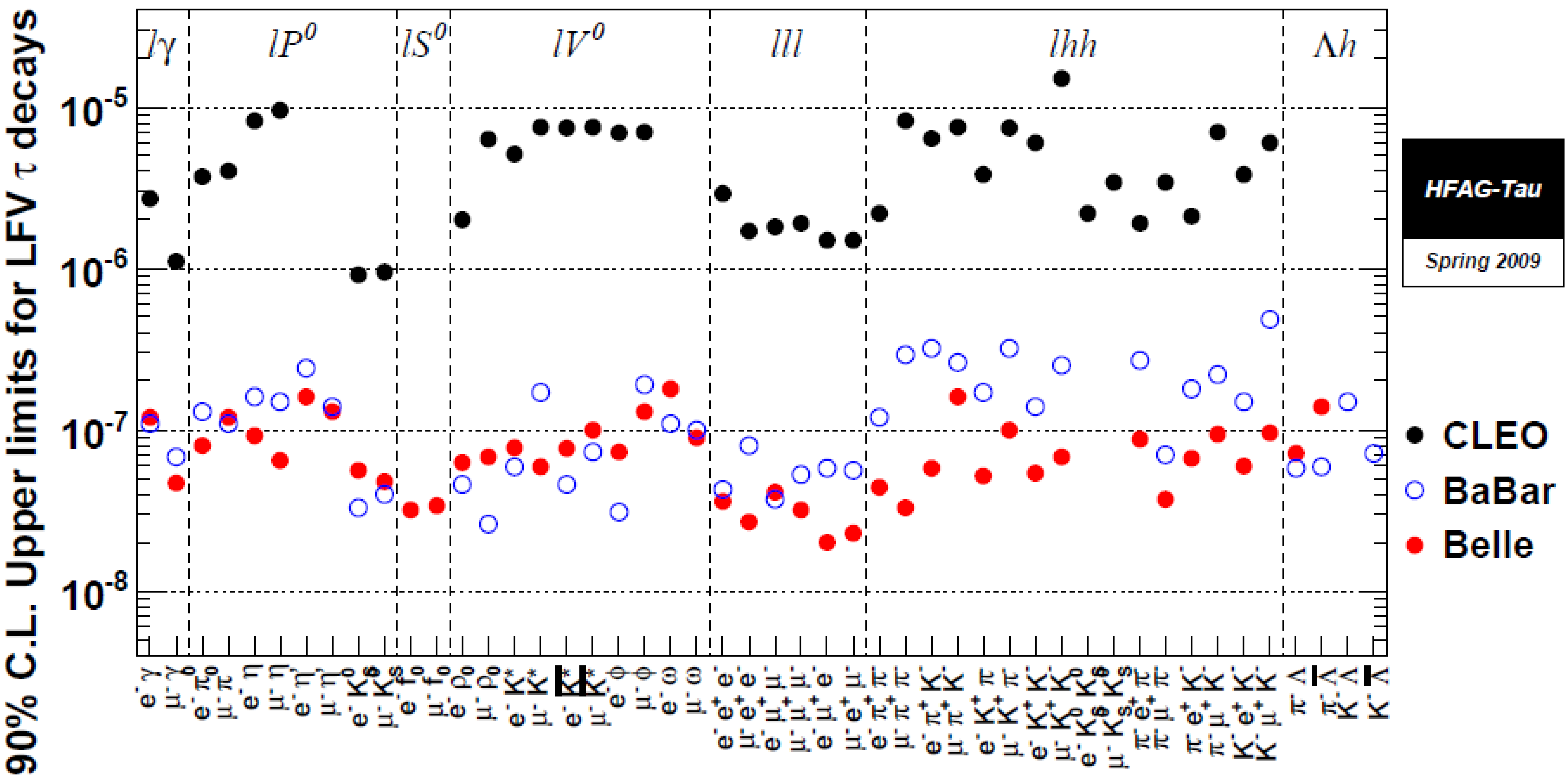


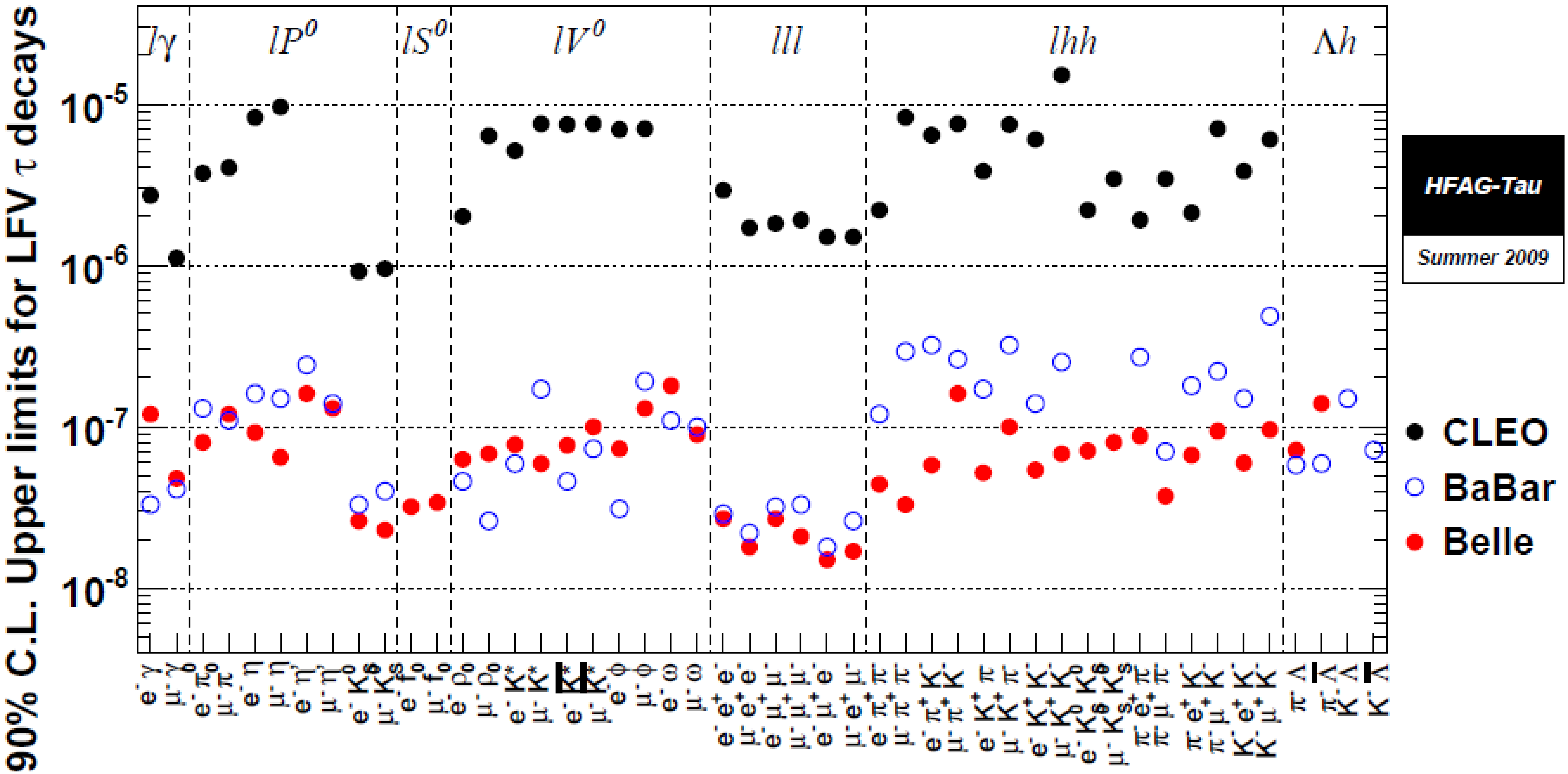
FIG. 3 (color online). (a) The distributions of the likelihood functions versus α_N^2/Λ^4 (95% CL ULs are shown assuming $\alpha_N = 1$) and (b) the exclusion plot for Λ versus α_N.

CLEO Collaboration,
W. Love *et al.*, Phys. Rev. Lett. 101, 201601 (2008)
arXiv:0807.2695v1 [hep-ex]

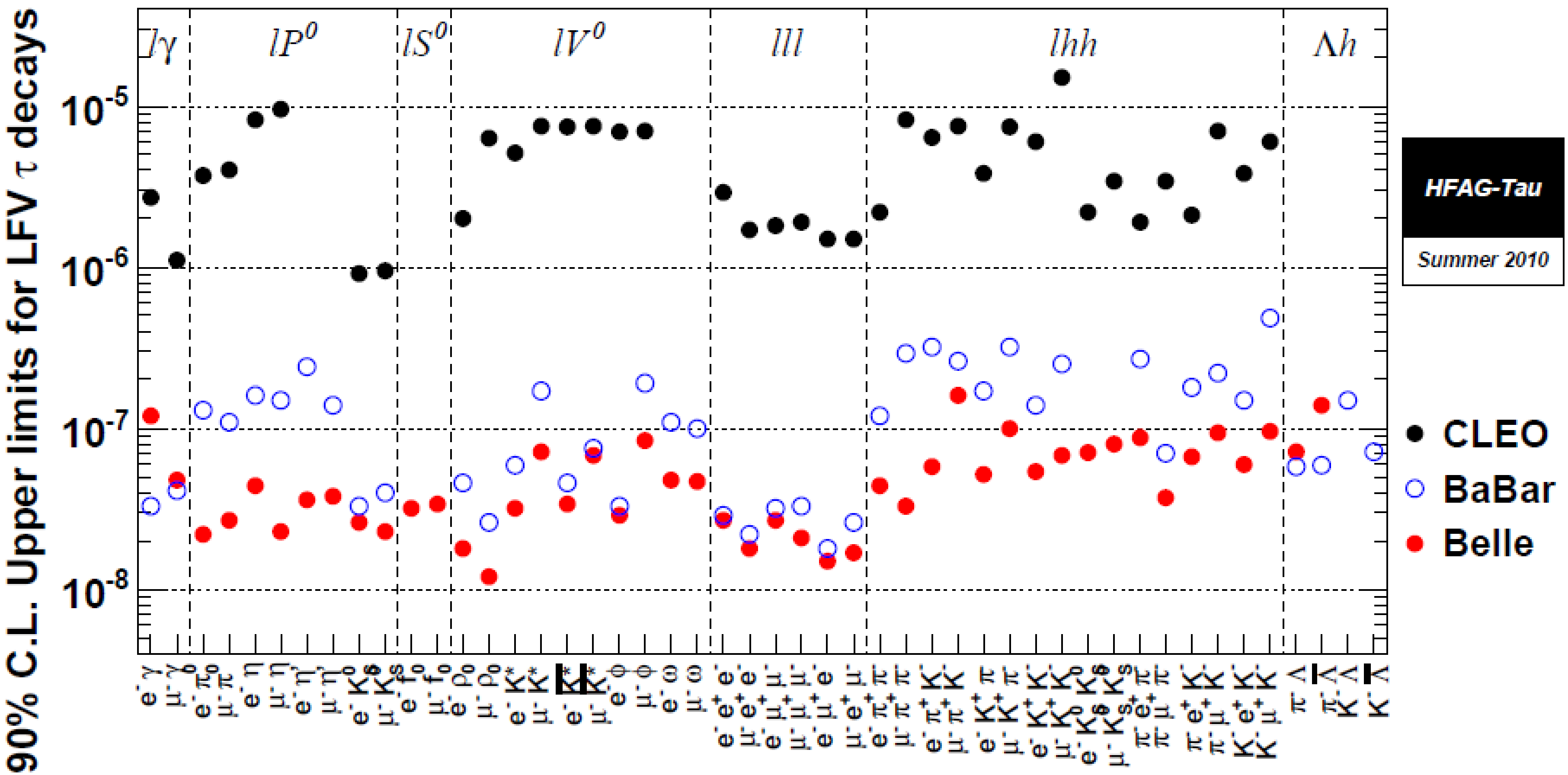
LFV τ decays – HFAG summary



LFV τ decays – HFAG summary



LFV τ decays – HFAG summary

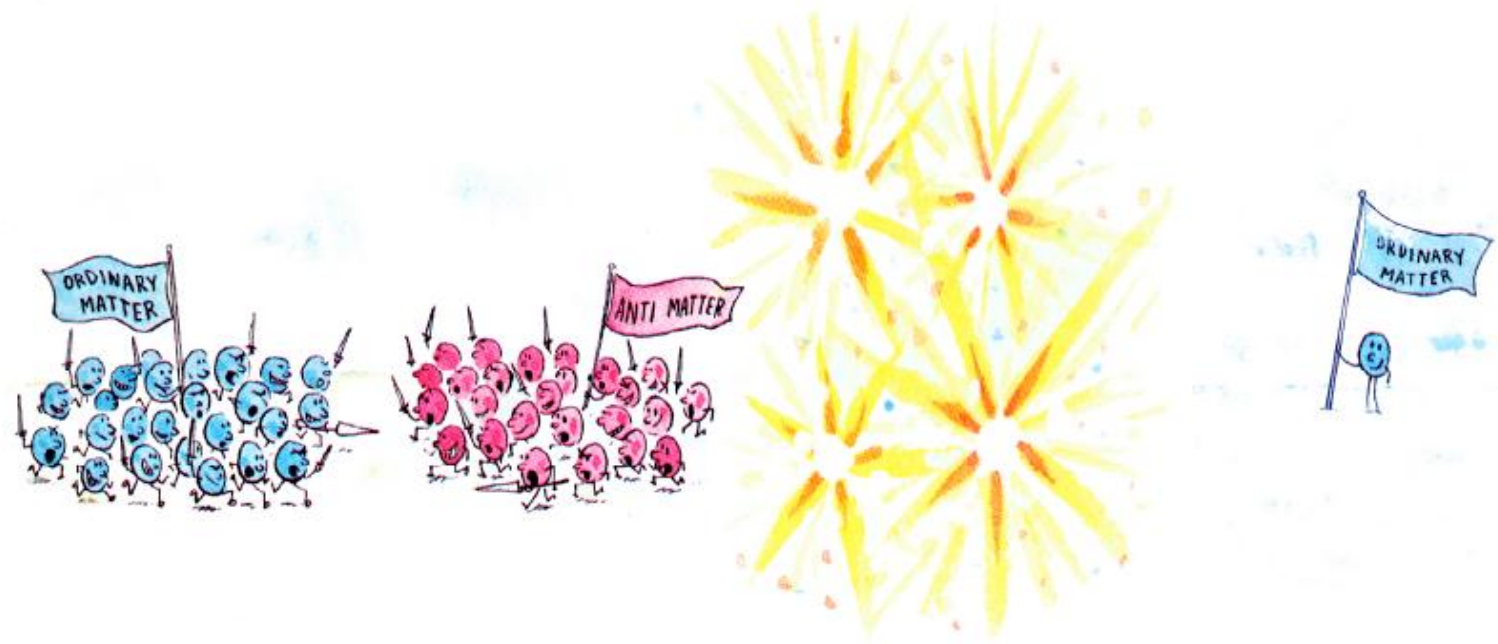


What links LFV with baryogenesis and leptogenesis?

Bare with me for a bit …

BAU – Baryon Asymmetry in the Universe

- **Common belief:**



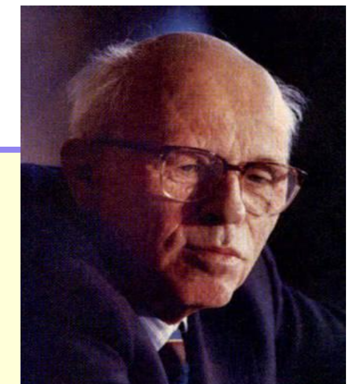
For every billion ordinary particles annihilating with antimatter in the early Universe, one extra was left "standing"

Experimentally:

$$\frac{n_B - n_{\overline{B}}}{n_\gamma} = (6.15 \pm 0.25) \times 10^{-10}$$

Baryogenesis « on a postcard »

Observed baryon asymmetry in the Universe ⟺ **Physical laws / properties**



- **In 1967 A. Sakharov formulated a set of general conditions that any mechanism of B-asymmetry generation has to meet :**
  1) Need a process that violates the baryon number B:
     (Baryon number of matter=1, of antimatter = -1)
  2) Both C and CP symmetries should be violated
  3) Conditions 1) and 2) should occur during a phase in which there is *no* thermal equilibrium (i.e. out of equilibrium)

Baryogenesis in the SM

Does the SM fulfill Sakharov's conditions in a satisfactory way? NO!

Baryon number violation :

B is violated in the SM in a non-trivial way, via "sphaleron interactions", i.e. quantum anomalies of the electroweak theory that violate B … and L.
Sphaleron interactions = quantum tunnelling (barrier potential of electroweak height) between vaccua of different B,L content. Strongly suppressed at T << 100 GeV.

C and CP violation :

The amount of CP violation provided by the CKM phase is far too small, as suppressed by small quark masses.

Out-of-equilibrium phase transition :

The electroweak phase transition (EWPT), seen as a possible out-of-equilibrium stage, occurs at T ~ 100 GeV and its (phase transition) order depends on the Higgs mass.
Out-of-equilibrium requires a small Higgs mass m_H <~ 70 GeV, ruled out by the present lower limit m_H >~ 115 GeV.

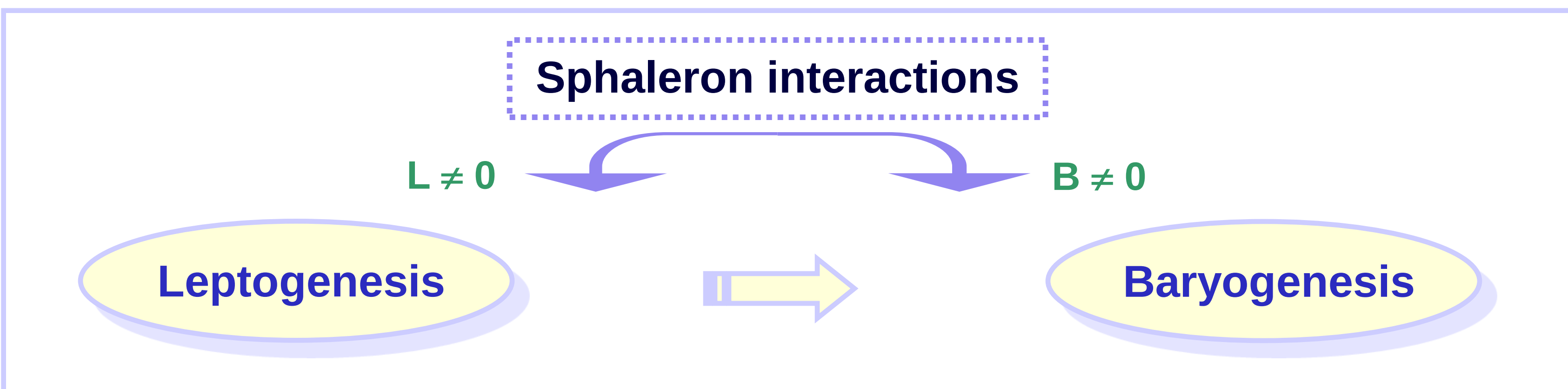
Baryogenesis via Leptogenesis

Baryogenesis :

Process by which an asymmetry between baryons and anti-baryons was produced in the very early universe, eventually resulting in the observed universe of today "dramatically" dominated by matter

Leptogenesis :

Process by which an asymmetry between leptons and anti-leptons was produced in the very early universe, resulting in the dominance of leptons over anti-leptons.



The see-saw mechanism « on a postcard »

Empirical observation of rather small ν masses ⟺ Underlying theory

- Minimal extensions of the SM incorporate heavy Majorana neutrinos ν_M (masses typically ~GUT scale)
- Presence of these heavy ν_M may explain the smallness of the SM ν masses by means of the see-saw mechanism:
  $m_\nu \sim 1/m_{\nu N}$ after spontaneous symmetry breaking
- It turns out that Majorana masses are expected on general symmetry grounds BSM, which makes this see-saw mechanism rather likely

Leptogenesis « on a postcard »

Basic leptogenesis :

- Existence of heavy right-handed neutrinos N with masses M
- Phase transition at T ~ M, with CP violating decays of the N ν_M's decay out of equilibrium $\Rightarrow$ excess of lepton number L
- BAU given sphaleron interactions: B $\Rightarrow$ L
- The 3 Sakharov conditions can then be satisfied !

- And a bonus: leptogenesis may relate the BAU to low-energy neutrino data and explain the small neutrino masses via the see-saw mechanism!

- There are many different leptogenesis scenarios (in the detail)

The big picture beyond HEP – my schematic summary !