Searches for Lepton Flavour Violation and Lepton Number Violation in Charged Lepton Decays

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on behalf of the MEG Collaboration

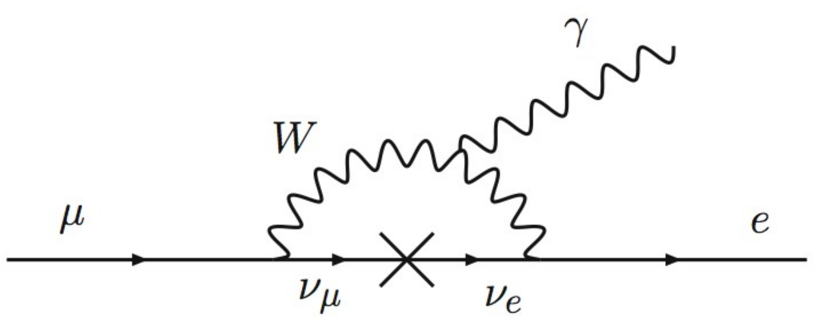
Outline

- Theoretical aspects of Lepton Flavor Violation (LFV) and Lepton Number Violation (LNV) in μ and τ decays;
- Searches for LFV and LNV in τ decays;
- $\mu \longrightarrow e \gamma$ search with the MEG experiment;
- Future perspectives.

LFV/LNV and New Physics

- LFV/LNV are a standard probe for New Physics (NP) beyond the Standard Model (SM):
  - unobservable rates in the SM;
  - naturally enhanced by NP;

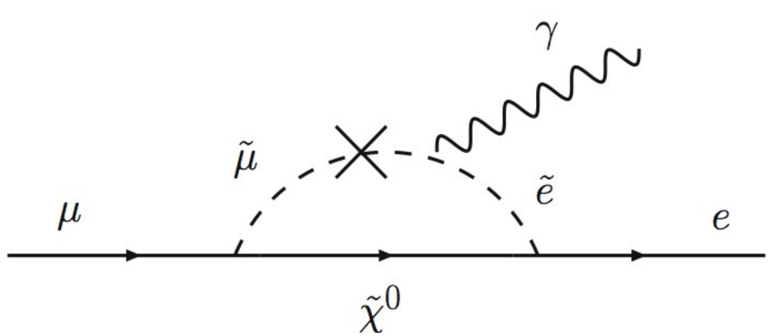
Observing LFV/LNV would be an unambiguous evidence of NP



SM (BR < 10^{-40})

LFV/LNV and New Physics

- LFV is naturally enhanced in many New Physics models;
- SUSY:
  - LFV arise through renormalization group running even if the theory is LF conserving at the high energy scale



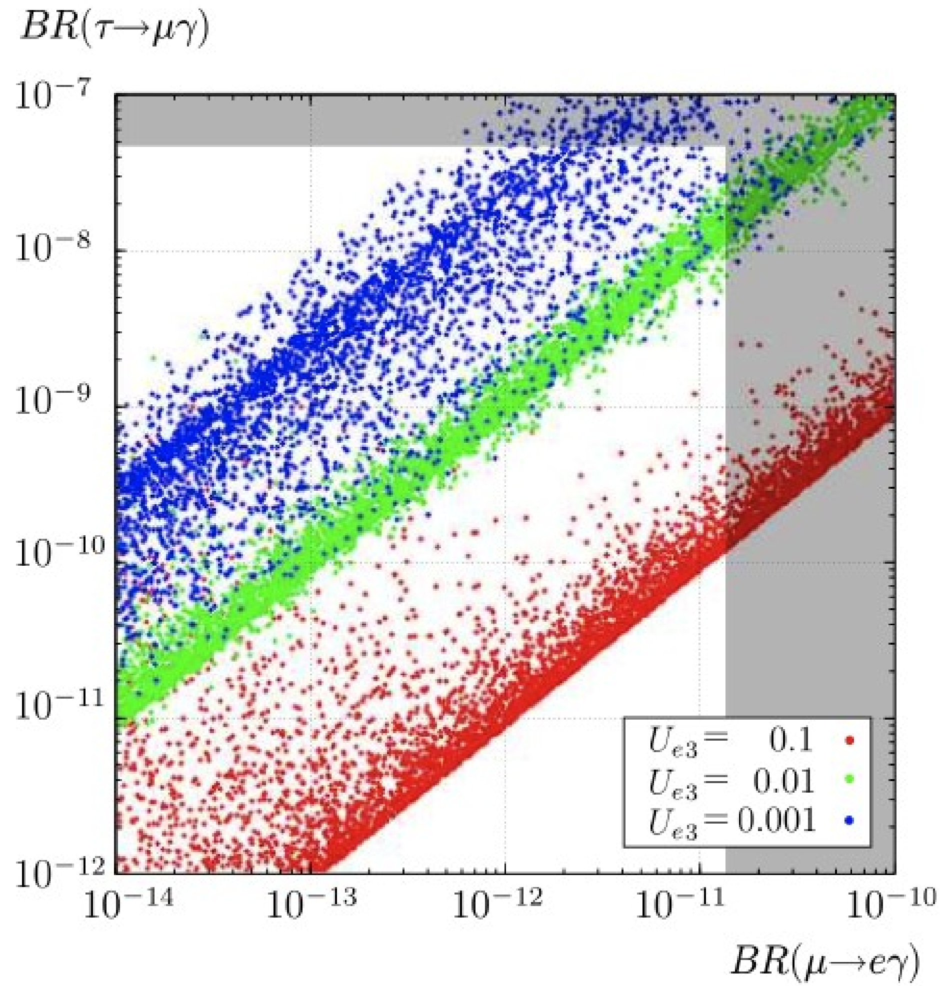
SUSY (BR ~ 10^{-11} - 10^{-15})

- Extra dimensions
- Unparticle Physics (Aliev, Cornell, Gaur '07)
- LNV in models with Majorana ν's
- ...

The μ and τ sectors

- Relative rate of LFV in μ and τ decays strongly depends on the flavor stucture of NP:
  - *high complementarity*

ν mixing parameter
$U_{e3} \sim \sin(\theta_{13})$



SUSY SU(5) with right-handed neutrino (Hisano, Nagai, Paradisi, Shimizu '09)

The μ and τ sectors

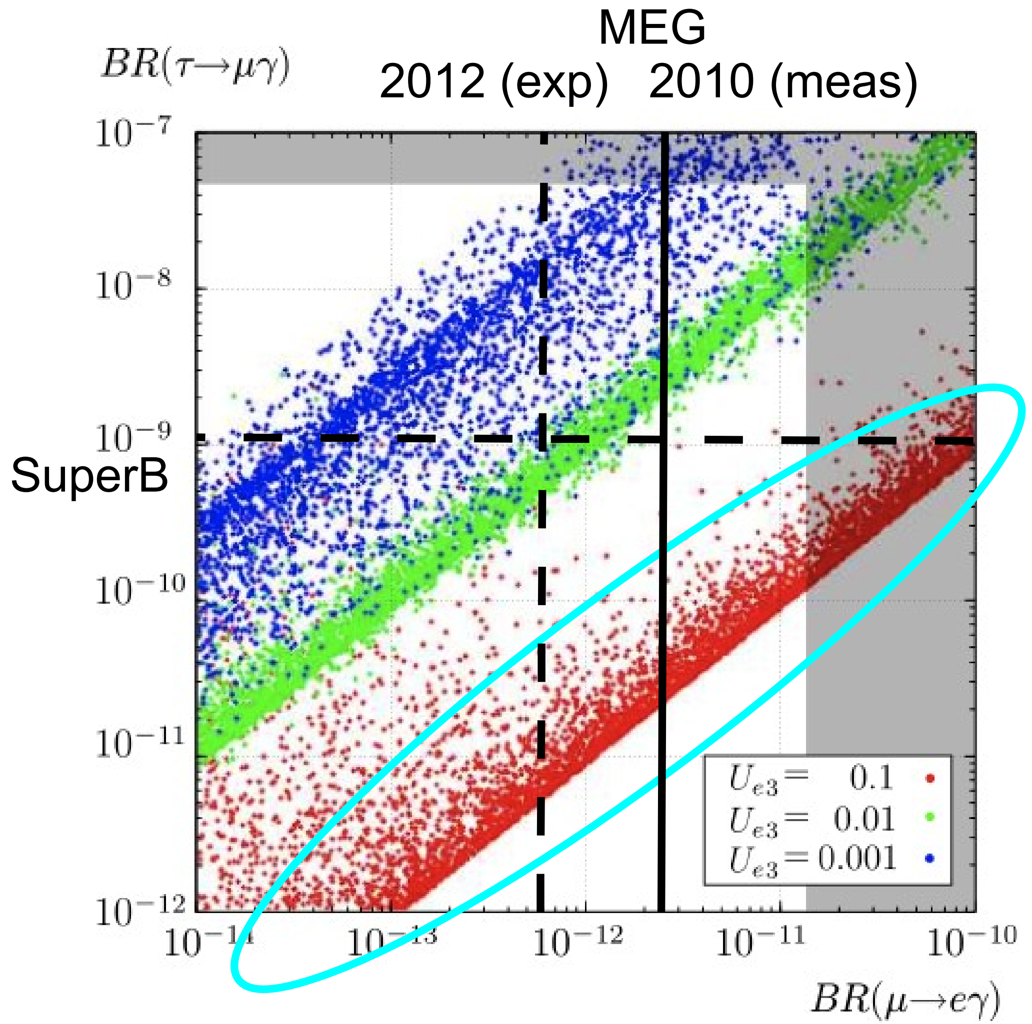
- Relative rate of LFV in μ and τ decays strongly depends on the flavor stucture of NP:
  - *high complementarity*

ν mixing parameter

$U_{e3} \sim \sin(\theta_{13}) \sim 0.15$

$\sin^2(2\theta_{13}) = 0.092 \pm 0.016 \pm 0.005$

(Daya Bay)

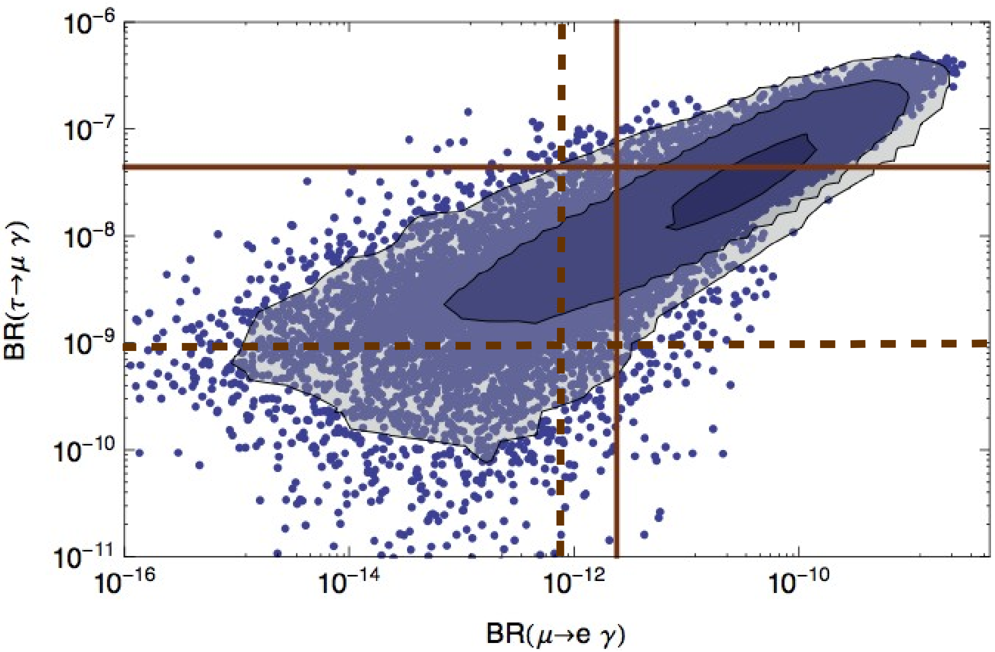


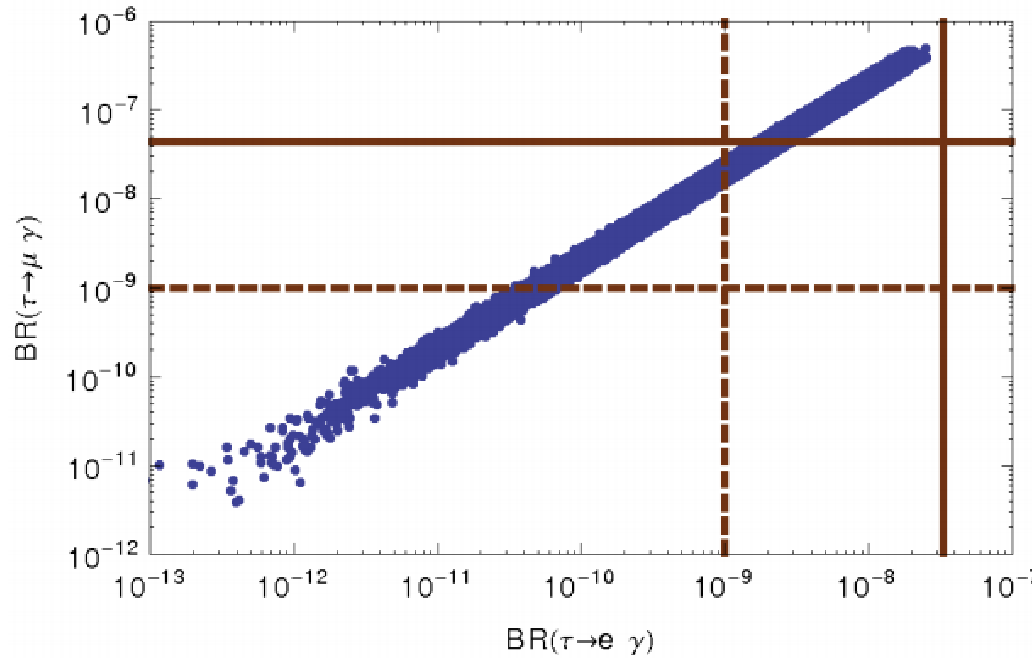
SUSY SU(5) with right-handed neutrino (Hisano, Nagai, Paradisi, Shimizu '09)

The μ and τ sectors

- Another scenario (with $\sin(\theta_{13}) \sim 0.15$)

courtesy of the authors





Current limits

Expected limits (MEG 2012/SuperB)

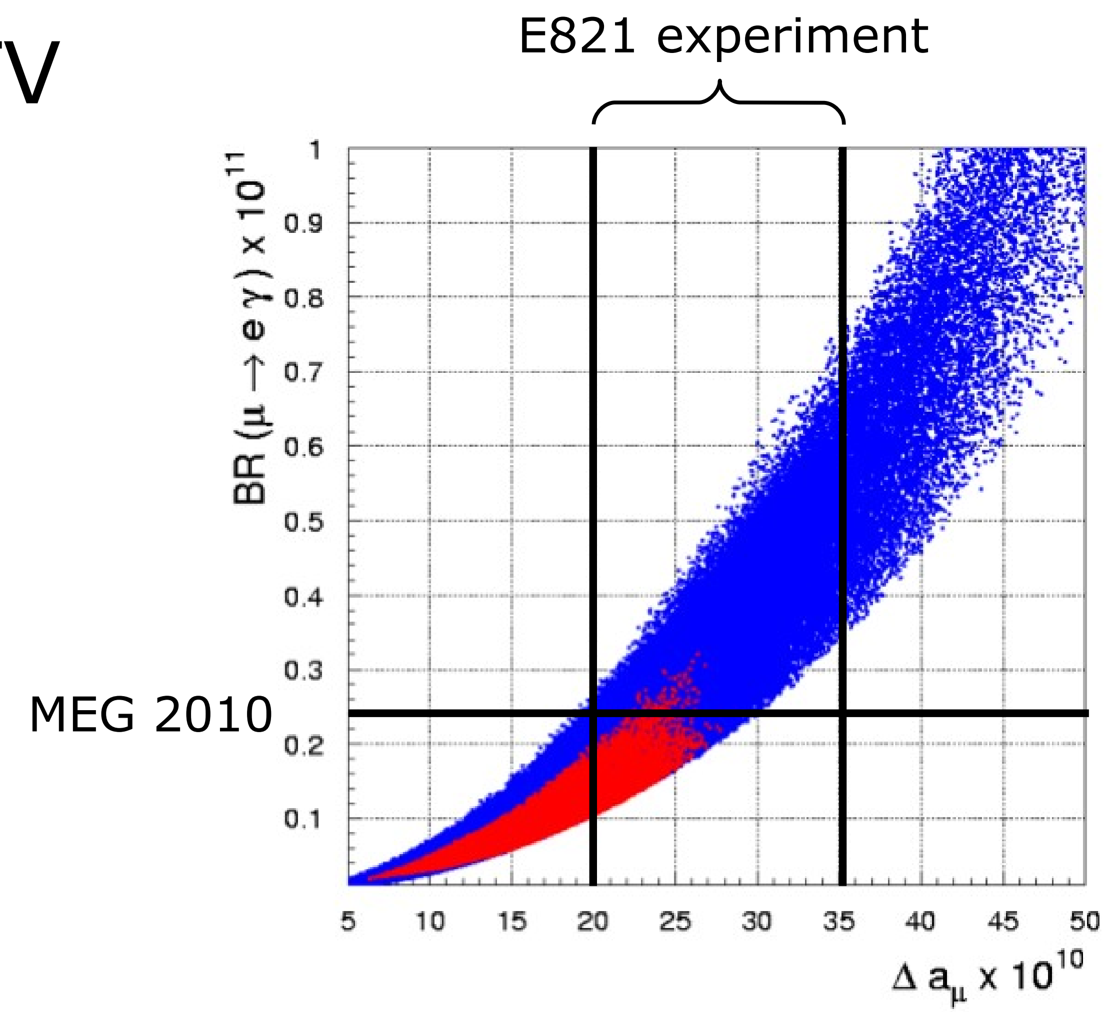
SUSY with minimally broken flavor symmetries (Blankenburg, Isidori, Jones-Pérez '12)

LFV and dipole moments

- Strict relation of LFV and leptonic dipole moments in many NP models.

$$a_\mu = \frac{g_\mu - 2}{2}$$

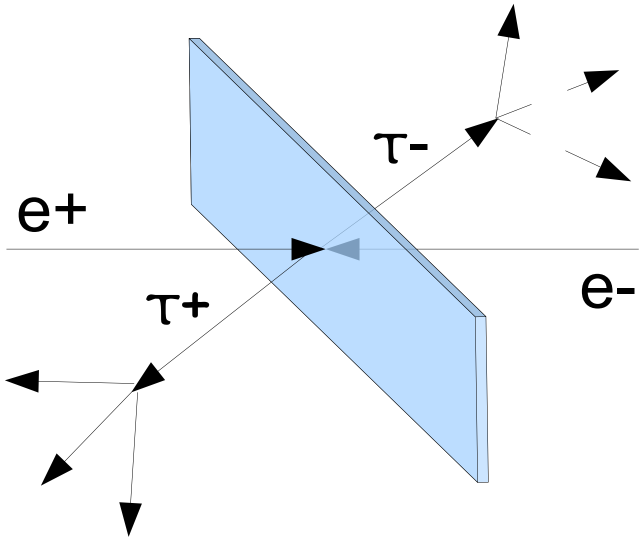
$$\Delta a_\mu = a_\mu - a_\mu^{SM}$$



MSSM with large tanβ (Isidori, Mescia, Paradisi '07)

τ LFV at the B-Factories

- $e^+e^- \rightarrow \tau^+\tau^-$:
  - B-Factories are also τ factories, $\sigma(\tau^+\tau^-) \sim \sigma(b\bar{b}) \sim 1\text{nb}$;
- Well established analysis techniques;
- 1 – 1 topology and 1 – 3 topology:
  - only one track is reconstructed from one τ (*tag* τ);
  - Signal τ is fully reconstructed (1 or 3 tracks + photons);
- Main backgrounds from $\tau\tau/\mu\mu$ (+ ISR), $e^+e^- \rightarrow \gamma^* \gamma^* e^+ e^-$, $e^+e^- \rightarrow q\bar{q}$:
  - rejection through reconstructed τ mass M_τ and missing energy $\Delta E = E_\tau^{CM} - E_{beam}^{CM}$



τ LFV – well known results

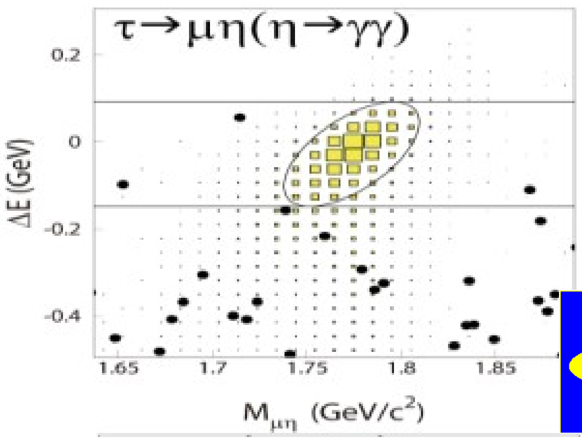
Channel	Best 90% C.L. Limit [x 10^{-8}]	Other 90% C.L. Limits [x 10^{-8}]
$\tau^+ \to e^+ \gamma$	**3.3 (BaBar)** PRL 104, 021802 (2010)	12 (Belle) PLB 666, 16 (2008)
$\tau^+ \to \mu^+ \gamma$	**4.4 (BaBar)** PRL 104, 021802 (2010)	4.5 (Belle) PLB 666, 16 (2008)
$\tau^+ \to e^+ e^+ e^-$	**2.7 (Belle)** PLB 687, 139 (2010)	3.4 (BaBar) PRD 81, 111101 (2010)
$\tau^+ \to e^+ \mu^+ \mu^-$	**2.7 (Belle)** ibidem	4.6 (BaBar) ibidem
$\tau^+ \to e^- \mu^+ \mu^+$	**1.7 (Belle)** ibidem	2.8 (BaBar) ibidem
$\tau^+ \to \mu^+ e^+ e^-$	**1.8 (Belle)** ibidem	3.7 (BaBar) ibidem
$\tau^+ \to \mu^- e^+ e^+$	**1.5 (Belle)** ibidem	2.2 (BaBar) ibidem
$\tau^+ \to \mu^+ \mu^+ \mu^-$	**2.1 (Belle)** ibidem	4.0 (BaBar) ibidem

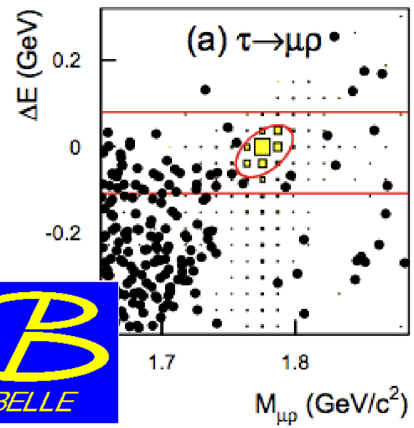
$\tau \to l\, h\ (h = P^0, V^0)$

- $\tau \to l\, P^0$, $P^0 \to \gamma\, \gamma$, $\pi^+ \pi^-$ $(+\ \gamma$'s)
  - $P^0 = \pi^0, \eta, \eta', K_S^0$
  - 1 – 1 or 1 – 3 topology
- $\tau \to l\, V^0$, $V^0 \to \pi^+ \pi^-$, $K^+ K^-$ $(+\ \gamma$'s)
  - $V^0 = \rho^0, \varphi, \omega, K^{*0}$
  - 1 – 3 topology
- Relevant backgrounds from specific physics processes (e.g. $\tau \to \pi\, \omega\, \nu$ with $\pi \to$ lepton mis-ID in the $\tau \to l\, \omega$ channel).

$\eta \to \gamma\, \gamma$	$\rho^0 \to \pi\, \pi$
$\eta \to \pi\, \pi\, \pi^0$	$\varphi \to K\, K$
$\eta' \to \pi\, \pi\, \eta$	$\omega \to \pi\, \pi\, \pi^0$
$\eta' \to \rho^0\, \gamma$	$K^{*0} \to K\, \pi$
$K_S^0 \to \pi\, \pi$	

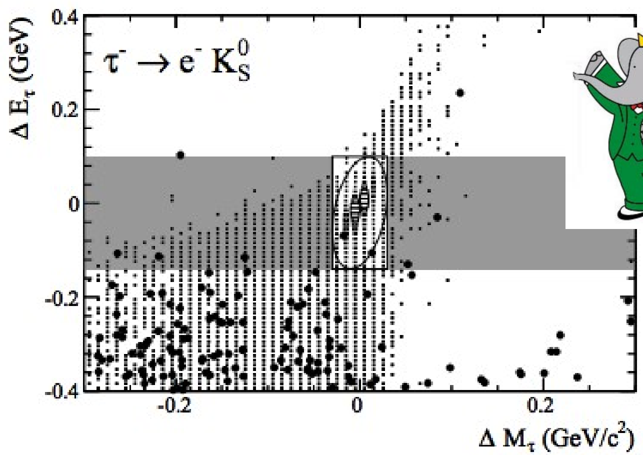
$\tau \to l\,h$ ($h = P^0, V^0$)





854 fb^{-1}, PLB 699 (2011) 251

Mode	ε (%)	$N_{\rm BG}$	$\sigma_{\rm syst}$ (%)	$N_{\rm obs}$	s_{90}	$\mathcal{B}_{\rm obs}$ ($\times 10^{-8}$)
$\tau^- \to \mu^- \rho^0$	7.09	1.48 ± 0.35	5.3	0	1.34	1.2
$\tau^- \to e^- \rho^0$	7.58	0.29 ± 0.15	5.4	0	2.17	1.8
$\tau^- \to \mu^- \phi$	3.21	0.06 ± 0.06	5.8	1	4.24	8.4
$\tau^- \to e^- \phi$	4.18	0.47 ± 0.19	5.9	0	2.02	3.1
$\tau^- \to \mu^- \omega$	2.38	0.72 ± 0.18	6.1	0	1.76	4.7
$\tau^- \to e^- \omega$	2.92	0.30 ± 0.14	6.2	0	2.19	4.8
$\tau^- \to \mu^- K^{*0}$	3.39	0.53 ± 0.20	5.5	1	3.81	7.2
$\tau^- \to e^- K^{*0}$	4.37	0.29 ± 0.14	5.6	0	2.17	3.2
$\tau^- \to \mu^- \bar{K}^{*0}$	3.60	0.45 ± 0.17	5.5	1	3.90	7.0
$\tau^- \to e^- \bar{K}^{*0}$	4.41	0.08 ± 0.08	5.6	0	2.34	3.4



$$\mathcal{B}(\tau^- \to e^- K^0_S) < 3.3 \times 10^{-8}$$

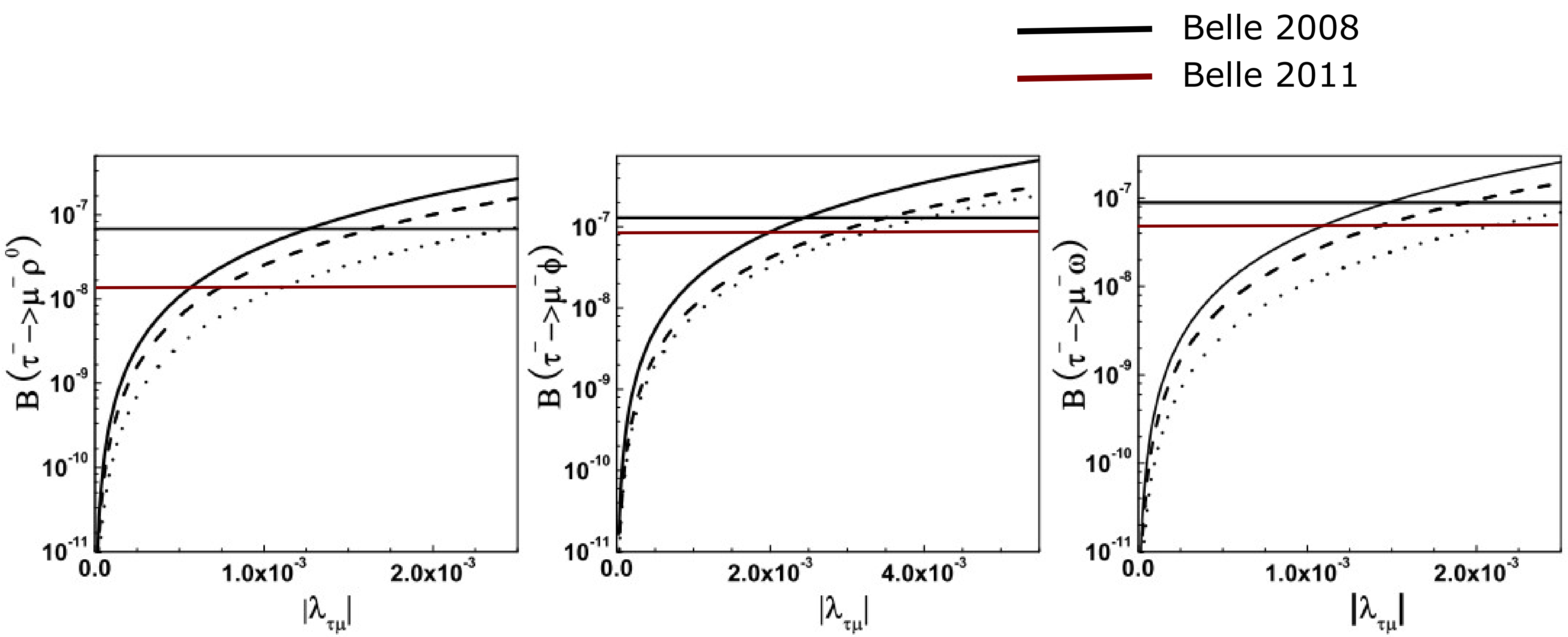
$$\mathcal{B}(\tau^- \to \mu^- K^0_S) < 4.0 \times 10^{-8}$$

469 fb^{-1}, PRD 79 (2009) 012004

τ→	Eff.	N_{BG}^{exp}	UL (x10^{-8})	τ→	Eff.	N_{BG}^{exp}	UL (x10^{-8})
$\mu\eta(\to\gamma\gamma)$	8.2%	0.63±0.37	3.6	$\mu\eta'(\to\pi\pi\eta)$	8.1%	0.00+0.16−0.00	10.0
$\mu\eta(\to\pi\pi\pi^0)$	6.9%	0.23±0.23	8.6	$\mu\eta'(\to\rho^0\gamma)$	6.2%	0.59±0.41	6.6
$\mu\eta$(comb.)			2.3	$\mu\eta'$(comb.)			3.8
$e\eta(\to\gamma\gamma)$	7.0%	0.66±0.38	8.2	$e\eta'(\to\pi\pi\eta)$	7.3%	0.63±0.45	9.4
$e\eta(\to\pi\pi\pi^0)$	6.3%	0.69±0.40	8.1	$e\eta'(\to\rho^0\gamma)$	7.5%	0.29±0.29	6.8
$e\eta$(comb.)			4.4	$e\eta'$(comb.)			3.6
$\mu\pi^0(\to\gamma\gamma)$	4.2%	0.64±0.32	2.7	$e\pi^0(\to\gamma\gamma)$	4.7%	0.89±0.40	2.2

901 fb^{-1}, K.Hayasaka (ICHEP 2010)

$\tau \to l\ h\ (h = P^0, V^0)$



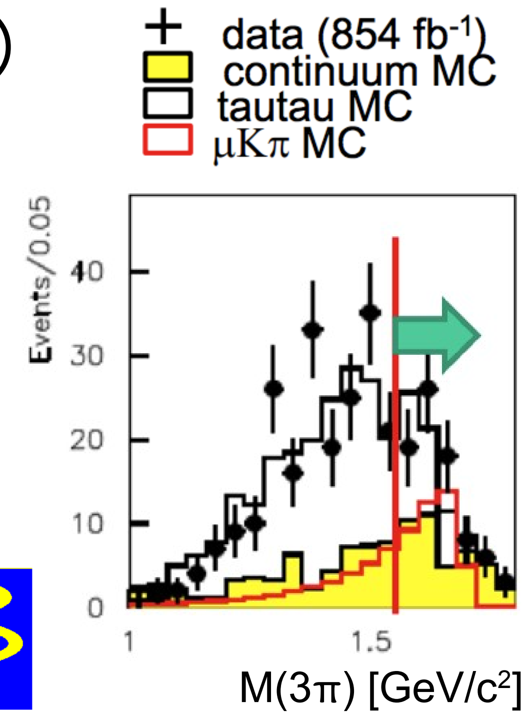
Two-Higgs-Doublet Model Type III
(Li, Ma, Liu, Guo '08)

$$\boxed{\xi_{ij}^{U,D}} = \lambda_{ij} \frac{\sqrt{m_i m_j}}{v}$$

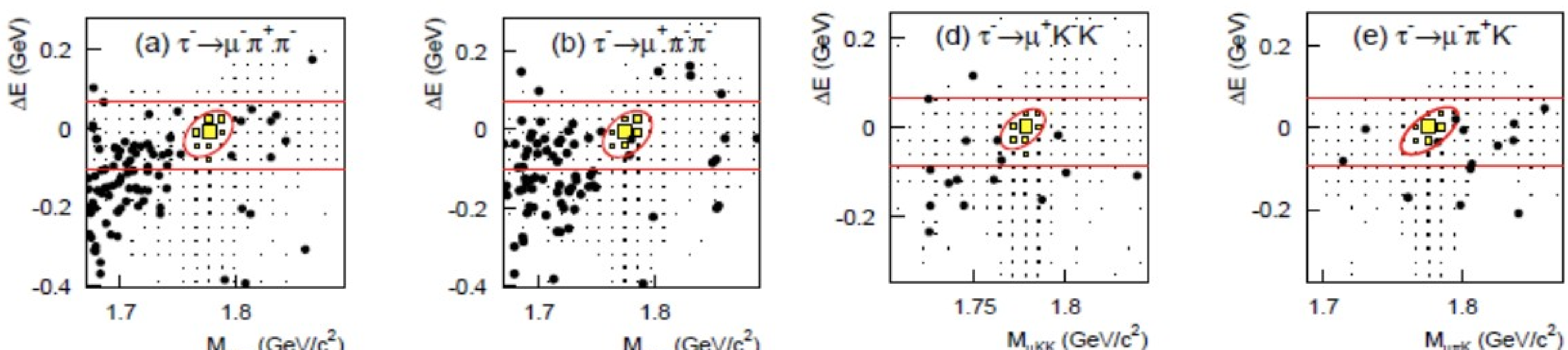
Yukawa couplings

$\tau \to l\, h\, h'$ ($h, h' = \pi^\pm, K^\pm$)

- 14 modes (8 LFV $\tau^- \to l^- h^+ h'^-$, 6 LNV $\tau^- \to l^+ h^- h'^-$)
- Similar analysis techniques as in $\tau \to l\, h$;
- Relevant background in $\tau \to \mu K \pi$ from $\tau \to \pi\pi\pi\nu$ with π mis-ID:
  - require $M(3\pi) > 1.52$ GeV/c^2 when all tracks are assigned a π mass;



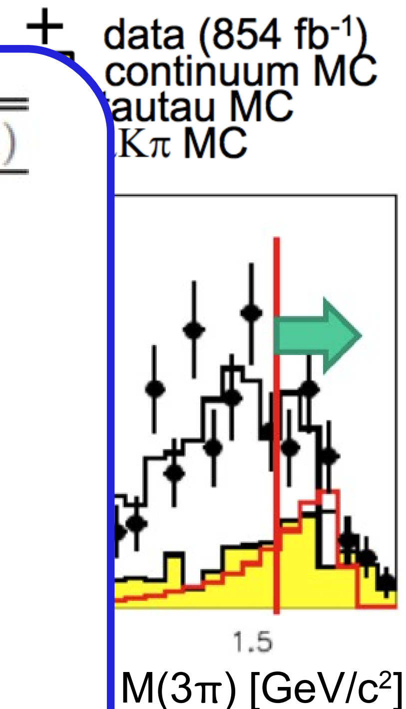
854 fb^{-1}, Y. Miyazaki, FPCP2011

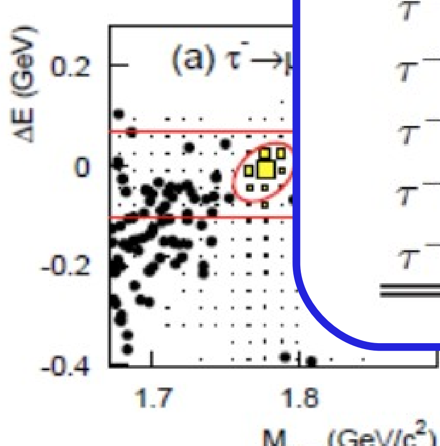


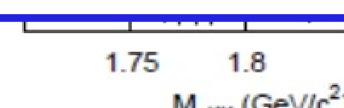
$\tau \to l\, h\, h'$ $(h, h' = \pi^\pm, K^\pm)$

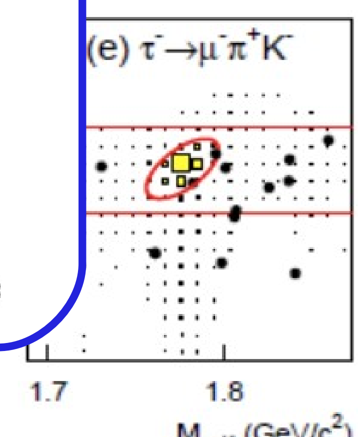
- 14 modes (8 LFV $\tau^- \to l^-h^+h'^-$, 6 LNV $\tau^- \to l^+h^-h'^-$)
- Similar
- Relevan
  $\tau \to \pi\pi$
  - requi
    track

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	s_{90}	$\mathcal{B}$ (10^{-8})
$\tau^- \to \mu^-\pi^+\pi^-$	5.83	0.63 ± 0.23	5.3	0	1.87	2.1
$\tau^- \to \mu^+\pi^-\pi^-$	6.55	0.33 ± 0.16	5.3	1	4.02	3.9
$\tau^- \to e^-\pi^+\pi^-$	5.45	0.55 ± 0.23	5.4	0	1.94	2.3
$\tau^- \to e^+\pi^-\pi^-$	6.56	0.37 ± 0.18	5.4	0	2.10	2.0
$\tau^- \to \mu^-K^+K^-$	2.85	0.51 ± 0.18	5.9	0	1.97	4.4
$\tau^- \to \mu^+K^-K^-$	2.98	0.25 ± 0.13	5.9	0	2.21	4.7
$\tau^- \to e^-K^+K^-$	4.29	0.17 ± 0.10	6.0	0	2.28	3.4
$\tau^- \to e^+K^-K^-$	4.64	0.06 ± 0.06	6.0	0	2.38	3.3
$\tau^- \to \mu^-\pi^+K^-$	2.72	0.72 ± 0.27	5.6	1	3.65	8.6
$\tau^- \to e^-\pi^+K^-$	3.97	0.18 ± 0.13	5.7	0	2.27	3.7
$\tau^- \to \mu^-K^+\pi^-$	2.62	0.64 ± 0.23	5.6	0	1.86	4.5
$\tau^- \to e^-K^+\pi^-$	4.07	0.55 ± 0.31	5.7	0	1.97	3.1
$\tau^- \to \mu^+K^-\pi^-$	2.55	0.56 ± 0.21	5.6	0	1.93	4.8
$\tau^- \to e^+K^-\pi^-$	4.00	0.46 ± 0.21	5.7	0	2.02	3.2





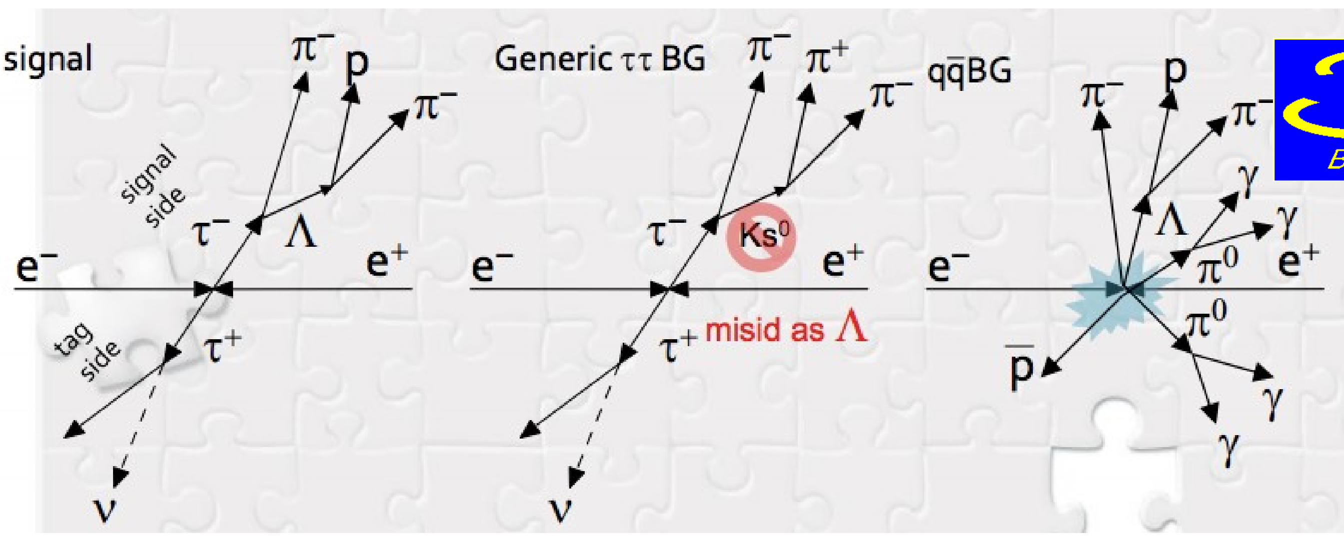


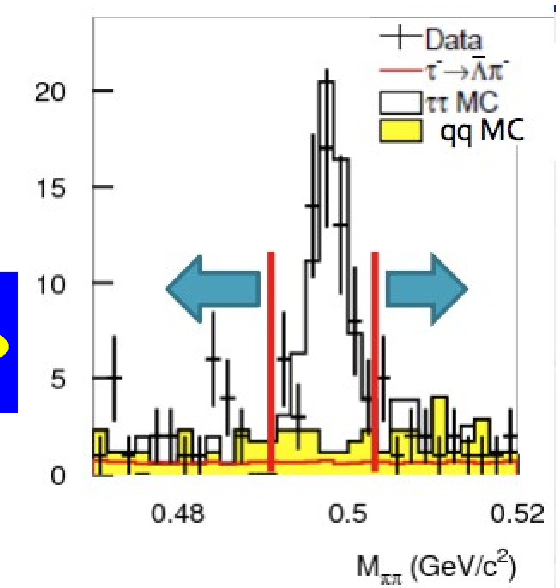


$\tau \to \Lambda\, h\ (h = \pi^{\pm}, K^{\pm})$

- Theoretical interest *(BNV with higher generations – Hou, Nagashima, Soddu '05)*
- 4 modes (B–L cons. $\tau^- \to \bar{\Lambda}\, h^-$, B-L viol. $\tau^- \to \Lambda\, h^-$)
- Relevant backgrounds from $q\bar{q}$ and $K_S^0 \to \Lambda$ mis-ID

Require no protons on the tag side

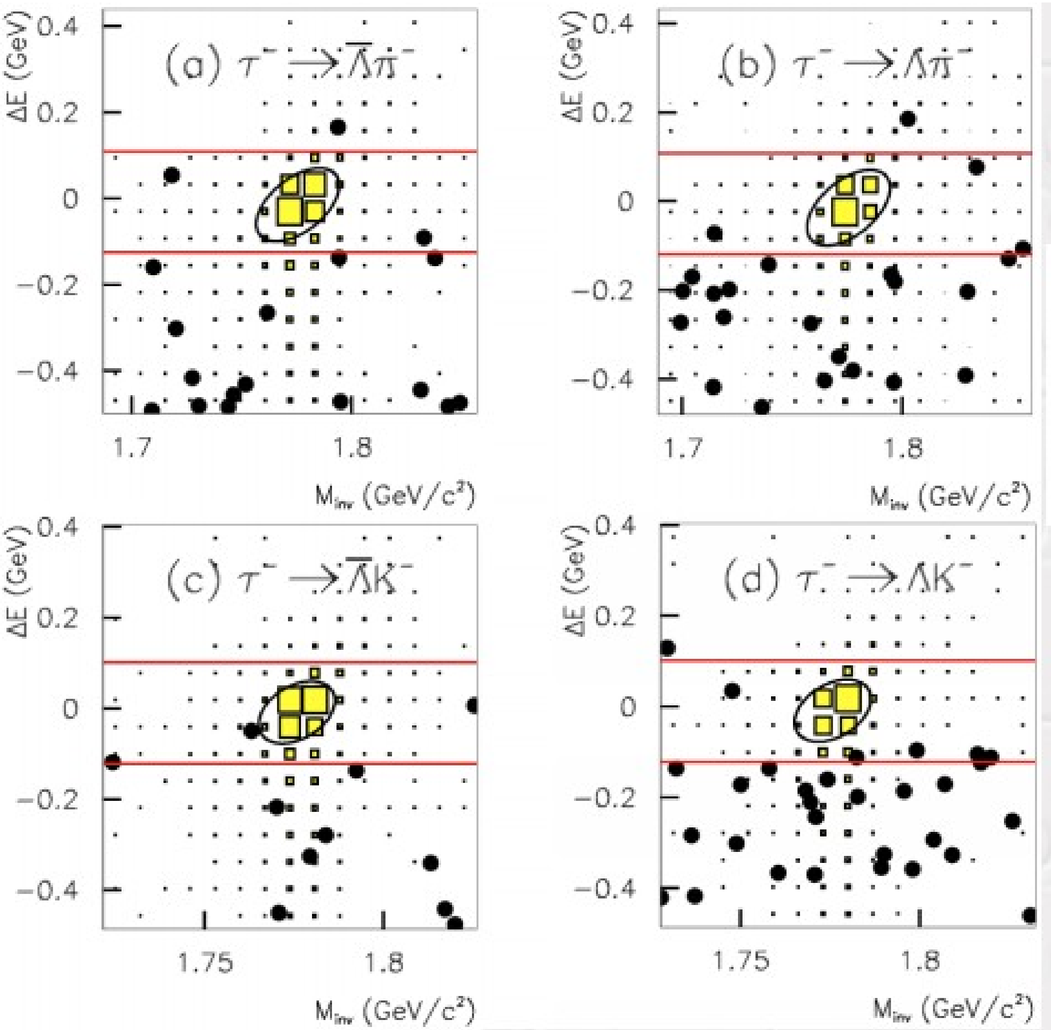




Reject $M(\pi\pi) \sim M(K_S)$ when all tracks are assigned a π mass

854 fb^{-1}, K.Hayasaka (EPS 2011)

$\tau \rightarrow \Lambda\ h\ (h = \pi^{\pm}, K^{\pm})$



854 fb^{-1}, K.Hayasaka (EPS 2011)

B – L cons.

$BR(\tau^- \rightarrow \bar{\Lambda}\ \pi^-) < 2.8 \times 10^{-8}$

$BR(\tau^- \rightarrow \bar{\Lambda}\ K^-) < 3.1 \times 10^{-8}$

B – L viol.

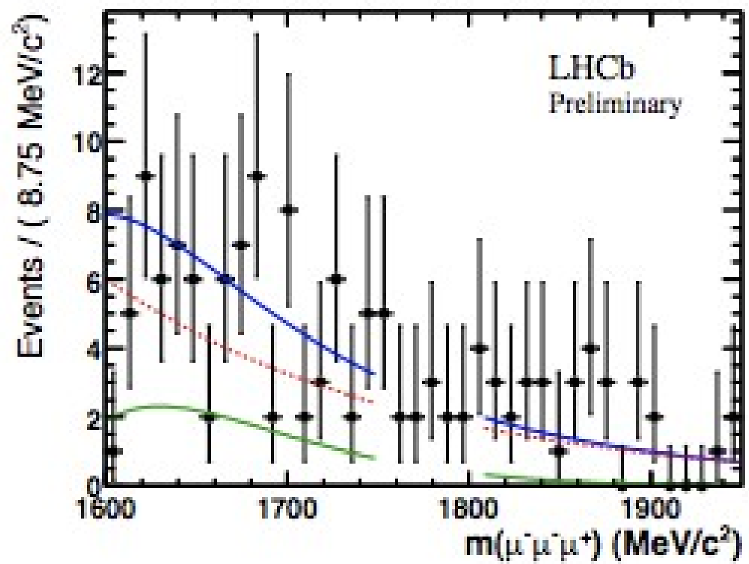
$BR(\tau^- \rightarrow \Lambda\ \pi^-) < 3.0 \times 10^{-8}$

$BR(\tau^- \rightarrow \Lambda\ K^-) < 4.2 \times 10^{-8}$

remaining background dominated by $\tau \rightarrow a_1(1260)\ \nu$ and $q\bar{q}$

τ decays at LHC

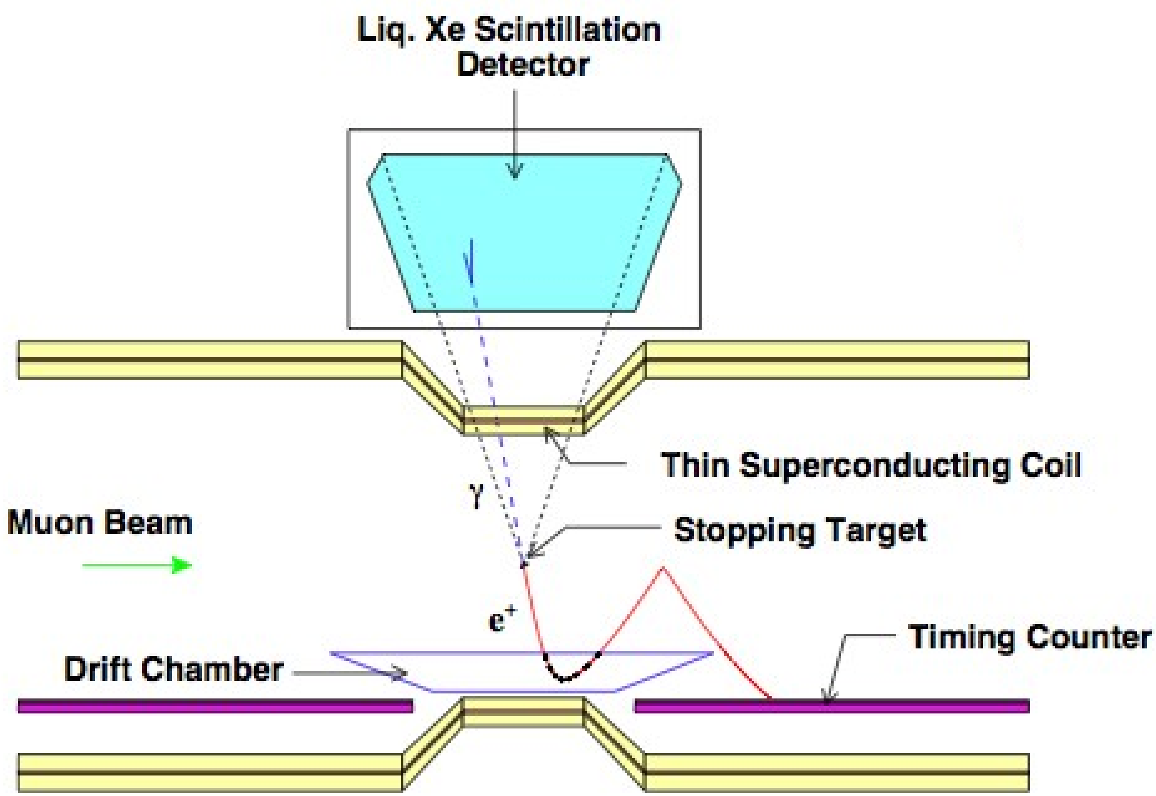
- LHC is also entering the game:
  - @ LHCb, τ's from $B_{(s)}$ and D_s decays, incl. $\sigma \sim 80\mu b$
- First result on $\tau \to \mu\,\mu\,\mu$ just presented here by P. Seyfert:
  - $BR(\tau \to \mu\,\mu\,\mu) < 6.3 \times 10^{-8}$ @ 90% C.L.
  - *Competitive with B-Factories*

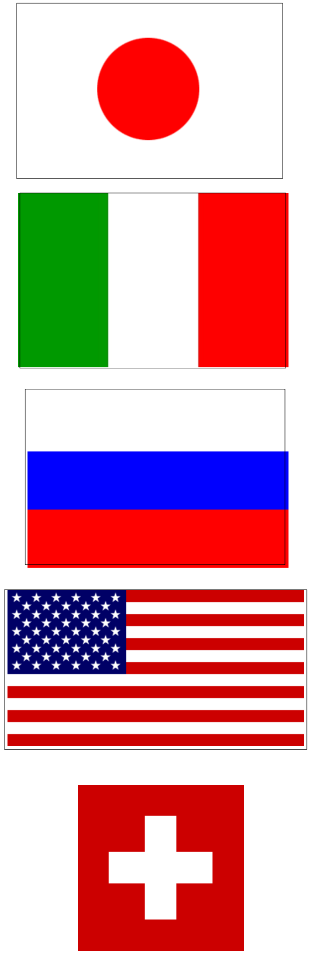


- Searches for $\tau \to \mu\varphi$, $\tau \to \mu hh'$ are also feasible with similar sensitivities.

The MEG experiment

- A search for $\mu \rightarrow e\,\gamma$ with the most intense DC muon beam of the world (3×10^7 μ/s @ PSI, Switzerland);
- Running since 2008.





U. Tokyo
KEK
Waseda U.

Genova Lecce
Pavia Pisa
Roma

Novosibirsk
Dubna

UC Irvine

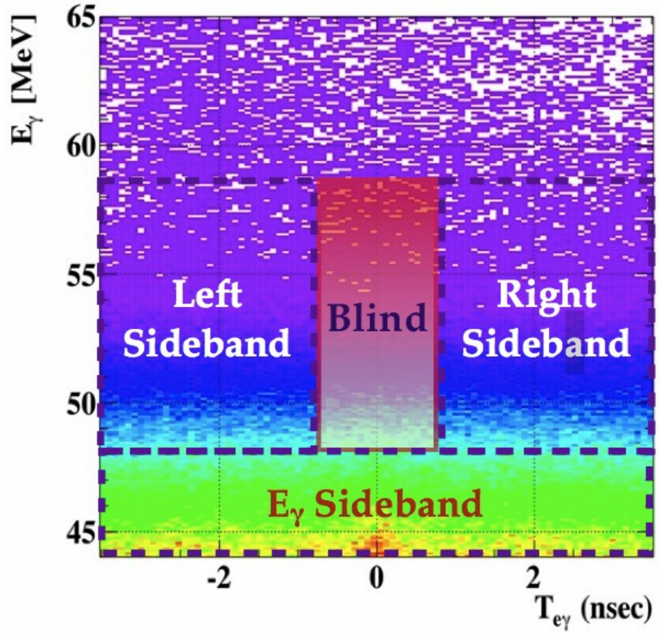
PSI

Signal & Background

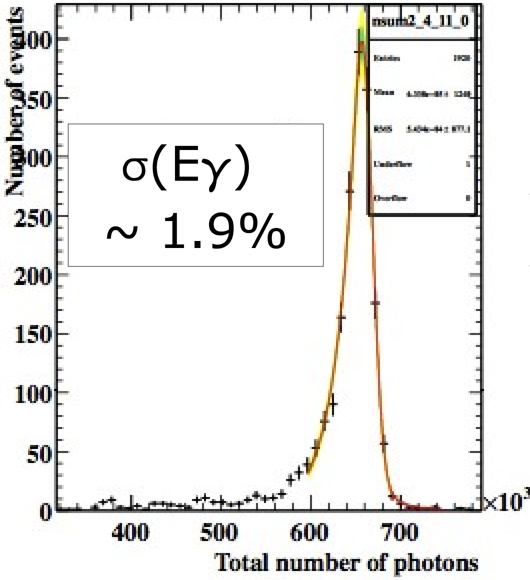
- Signal:
  - monochromatic (52.8 MeV), back-to-back $e^+ \gamma$ produced at the same time;
- Backgrounds:

DOMINANT

  - accidental time coincidence of e^+ & γ from different μ decays
  - radiative muon decays
- Likelihood analysis of 5 discriminating variables ($E_e, E_\gamma, \theta_{e\gamma}, \varphi_{e\gamma}, T_{e\gamma}$):
  - year-by-year and event-by-event PDFs.



Detector performances



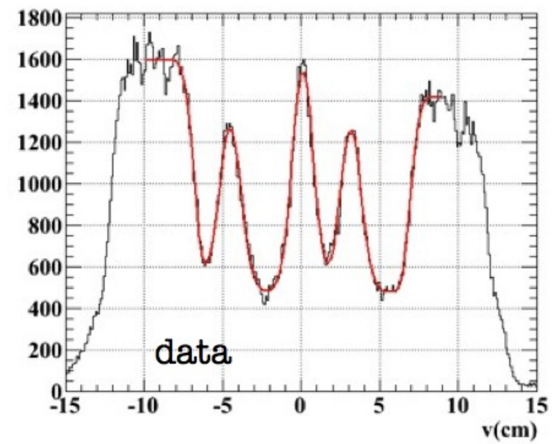
σ(Eγ) ~ 1.9%

~ monochromatic γ @ 55 MeV from...

$\pi^- + p \rightarrow \pi^0 + n$

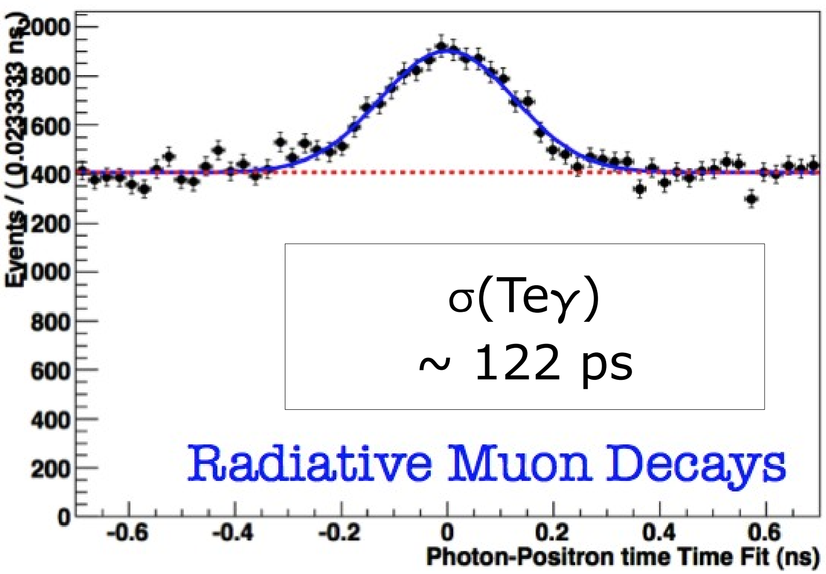
$\pi^0 \rightarrow \gamma\,\gamma$

...by selecting back-to-back γ's

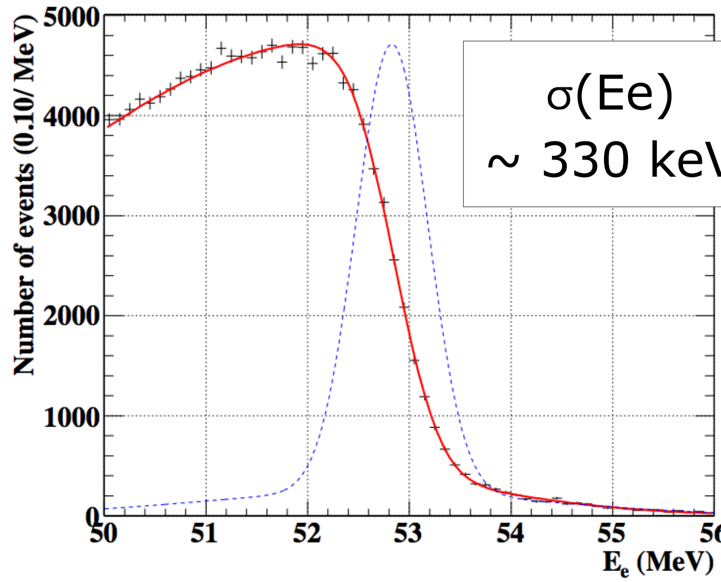


σ(uvw) ~ 5-6 mm

γ position resolution from special data taking w/ collimators



σ(Teγ) ~ 122 ps

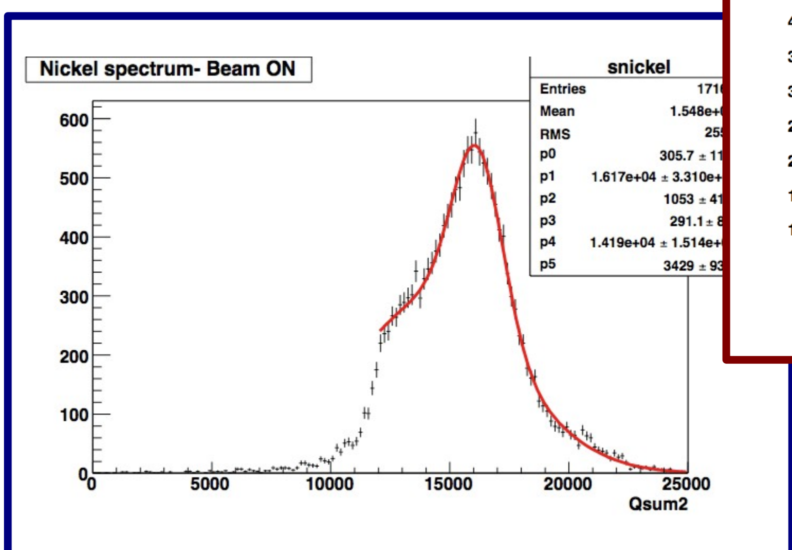


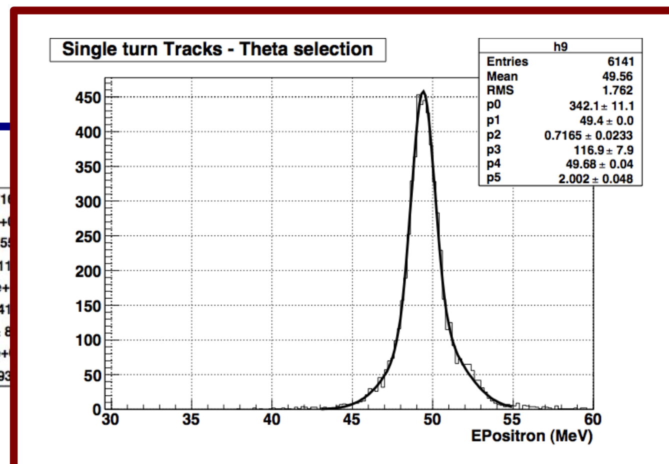
σ(Ee) ~ 330 keV

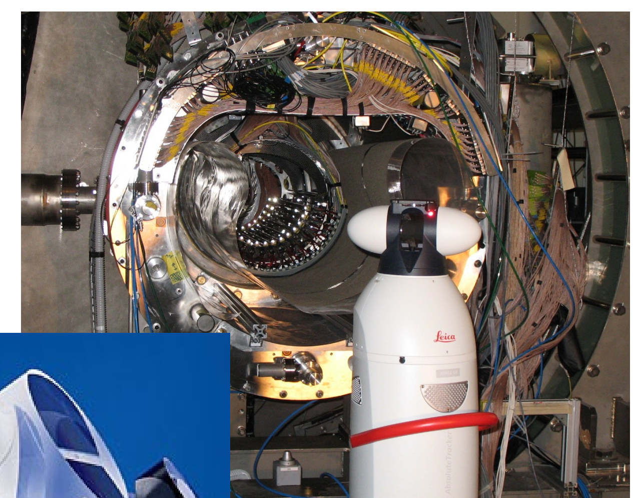
positron momentum edge from $\mu \rightarrow e\,\nu\,\nu$

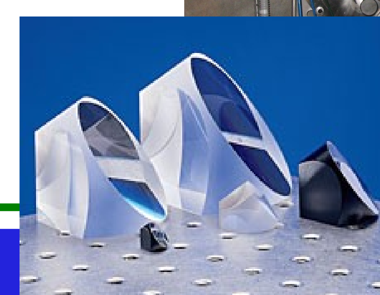
New calibration tools

- We recently enlarged our calibration toolbox:
  - Pulsed neutron generator to produce *9 MeV γ calibration line from neutron capture in Ni*
  - *Dedicated runs with monochromatic positron beams*
  - *Improved alignment procedures for the spectrometer*



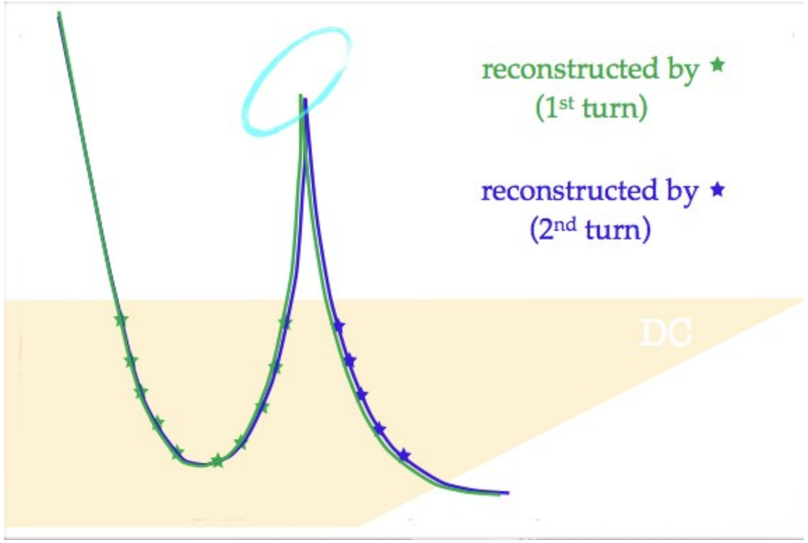






Definition of PDFs (I)

- Accidental background PDFs are fully defined from data sidebands:
  - very solid determination of the (largely) dominant background;
- Signal and radiative decay PDFs by combining results of calibrations:
  - positron angle & vertex PDFs from the comparison of different segments of the same track (two turns).

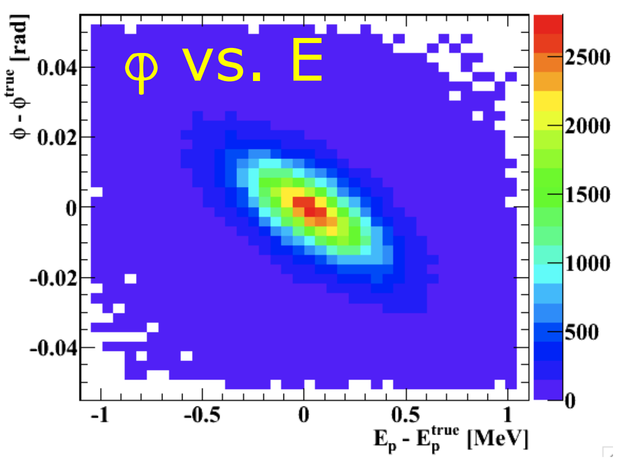


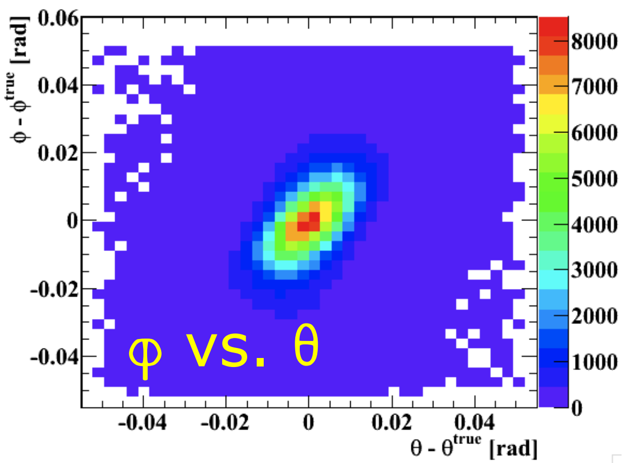
Definition of PDFs (II)

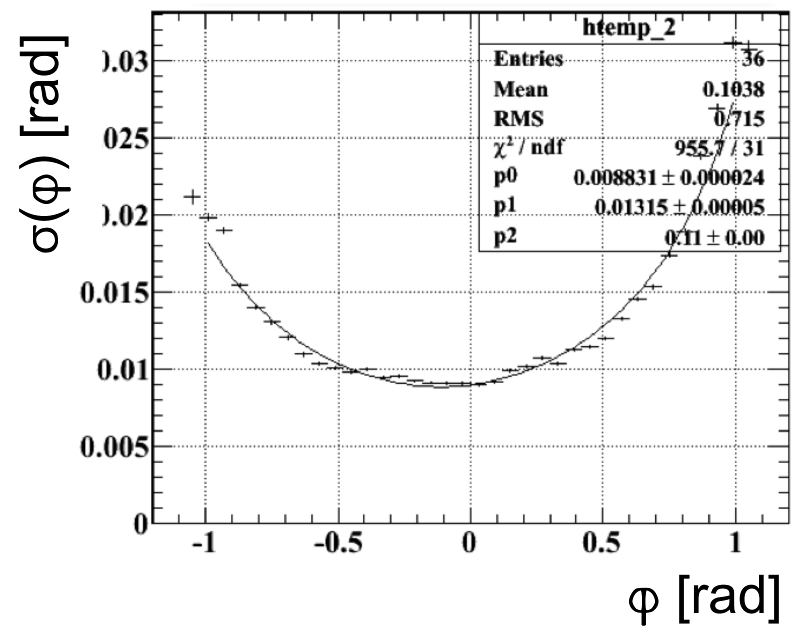
CORRELATIONS

- We account for *correlations* among positron variables and *direction-dependent positron resolutions*:
  - expected and well understood geometrical effects;
  - mostly <u>measured on data</u> from two turn tracks.

just a few examples...

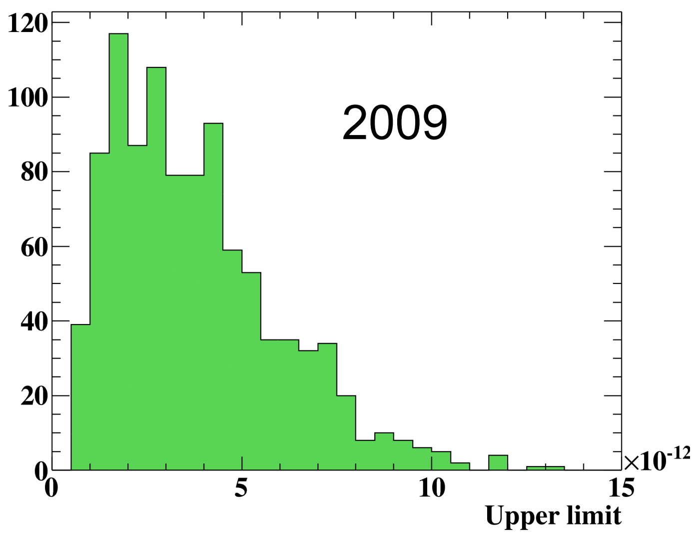


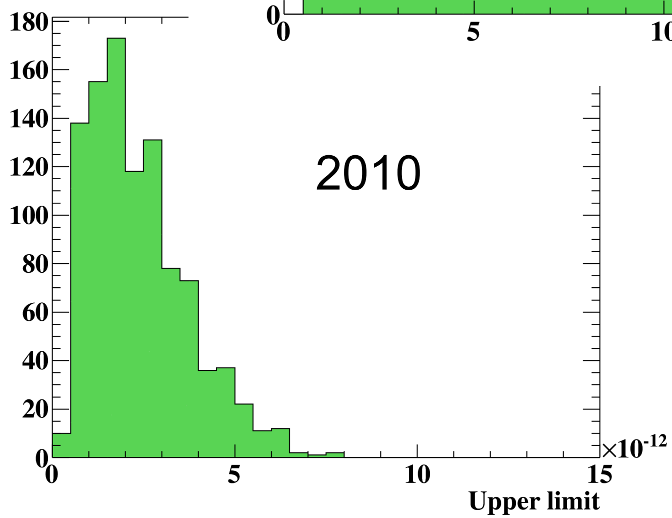


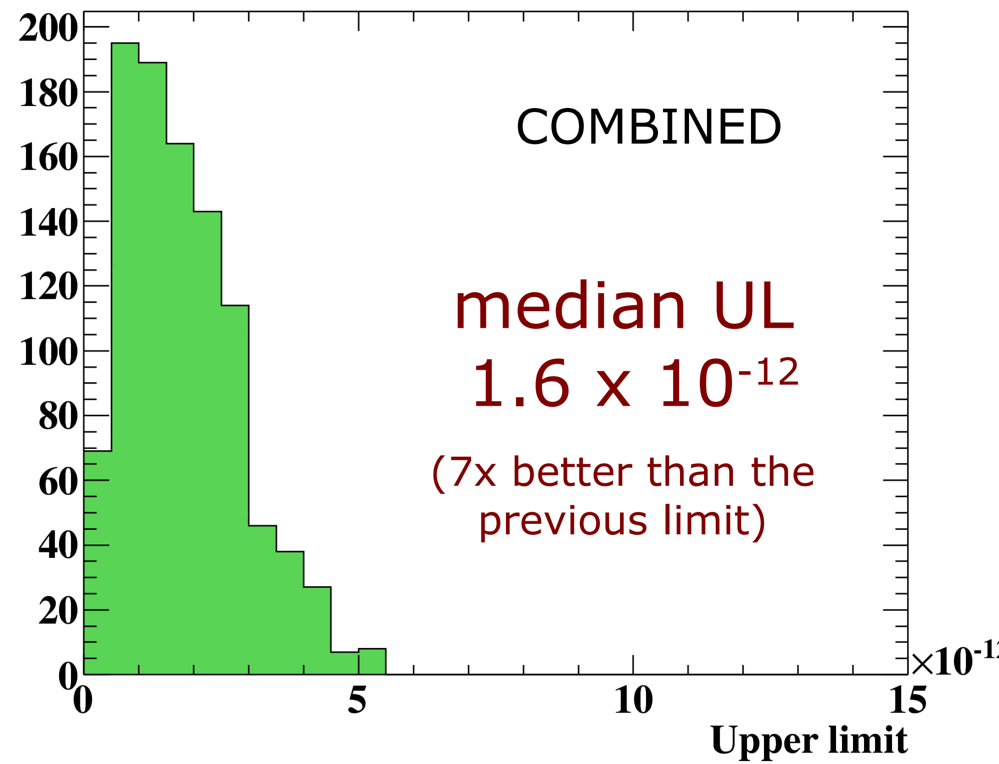


Sensitivity

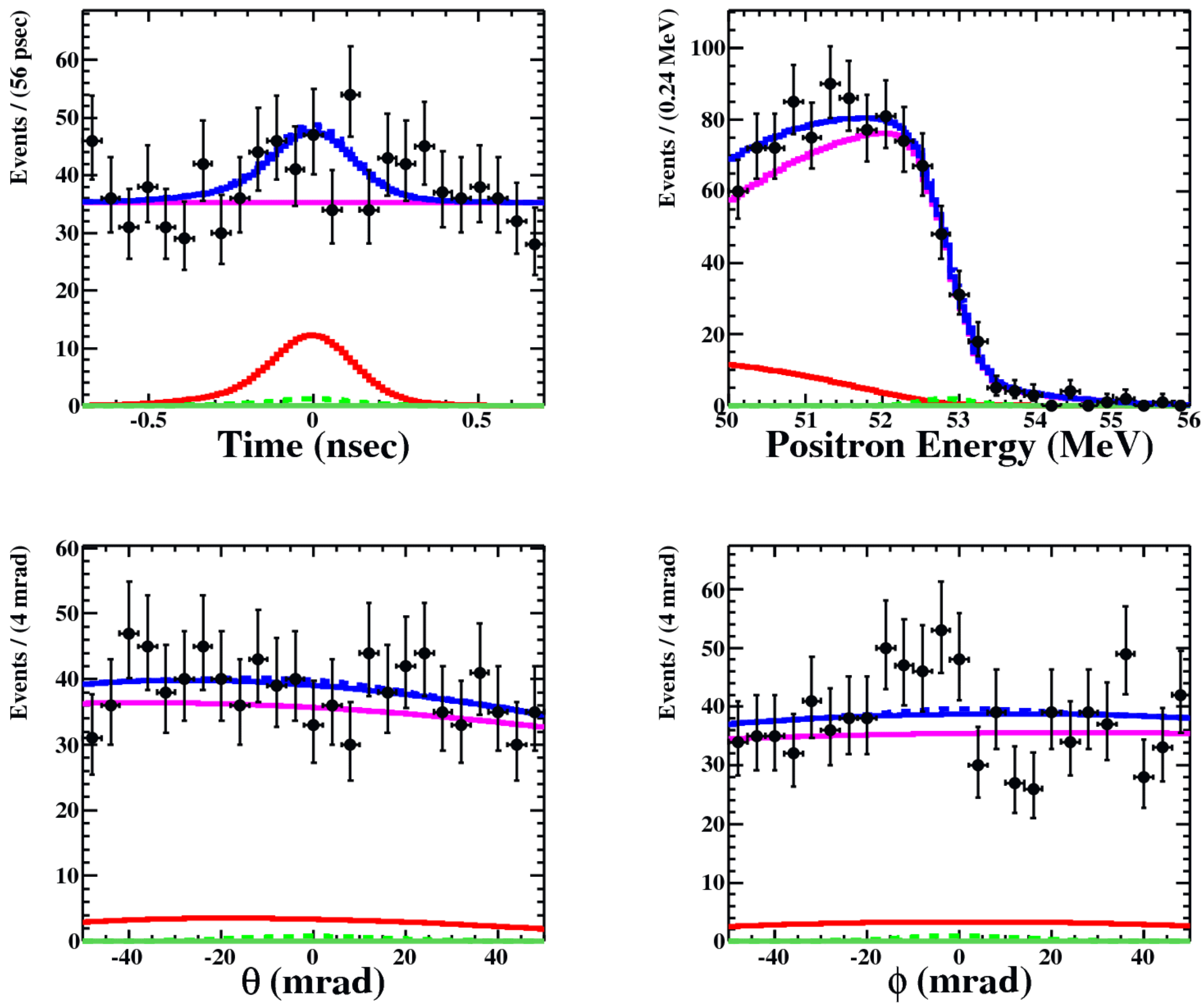
- From pseudo-experiments generated according to the PDFs (Toy MC) and including systematics.







Results (2009 - 2010)



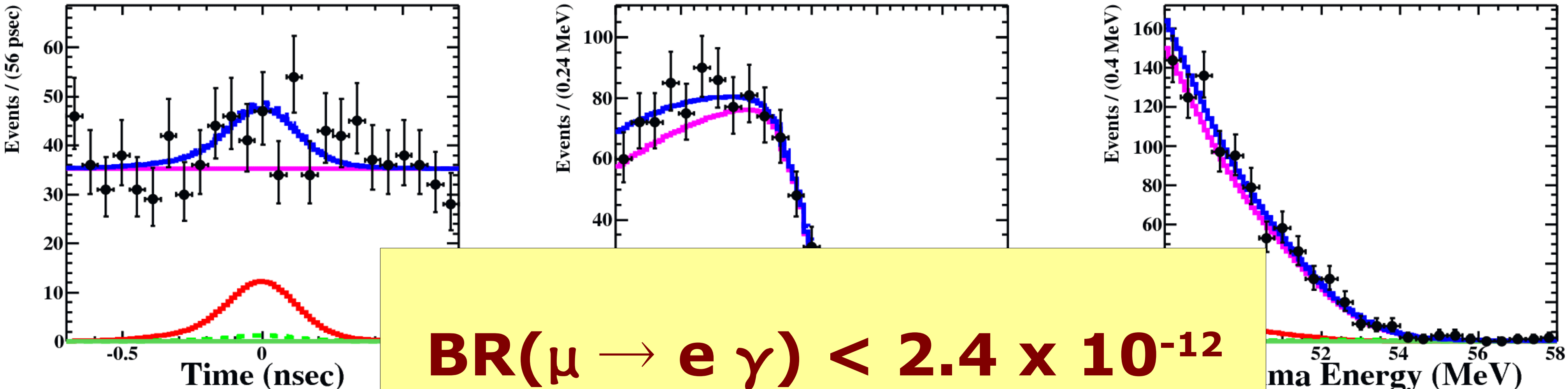
Based on
~ 17.5 x 10^{13} μ
stopped at the target

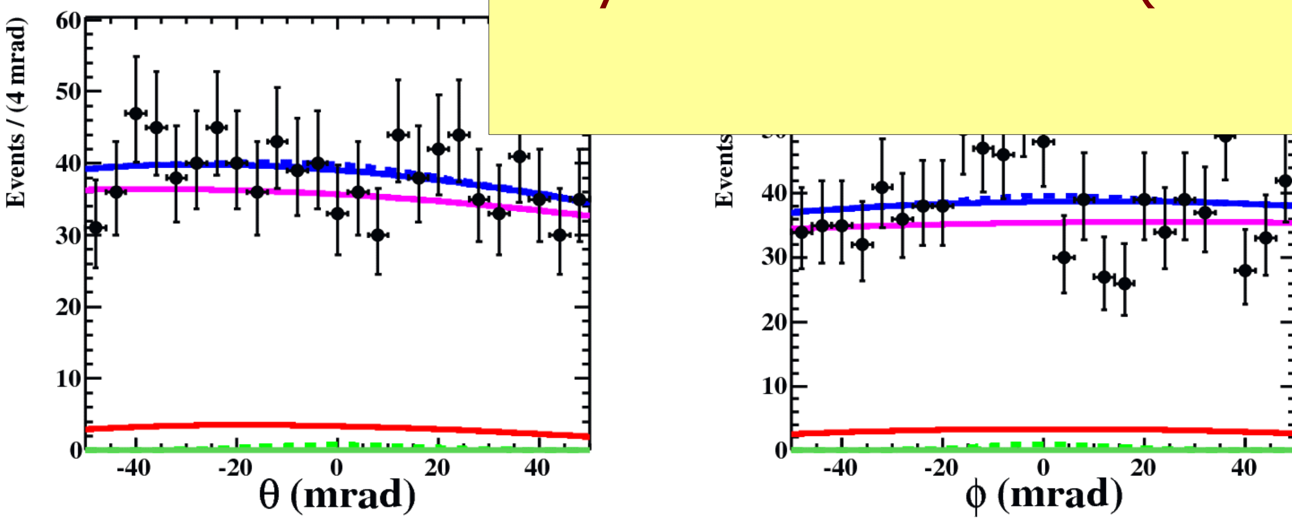
$N_{sig} = -0.5^{+7.9}_{-4.7}$

$N_{bkg} = 882 \pm 22$

$N_{RD} = 76.5 \pm 12$

Results (2009 - 2010)





BR($\mu \rightarrow e\,\gamma$) < 2.4 x 10^{-12}

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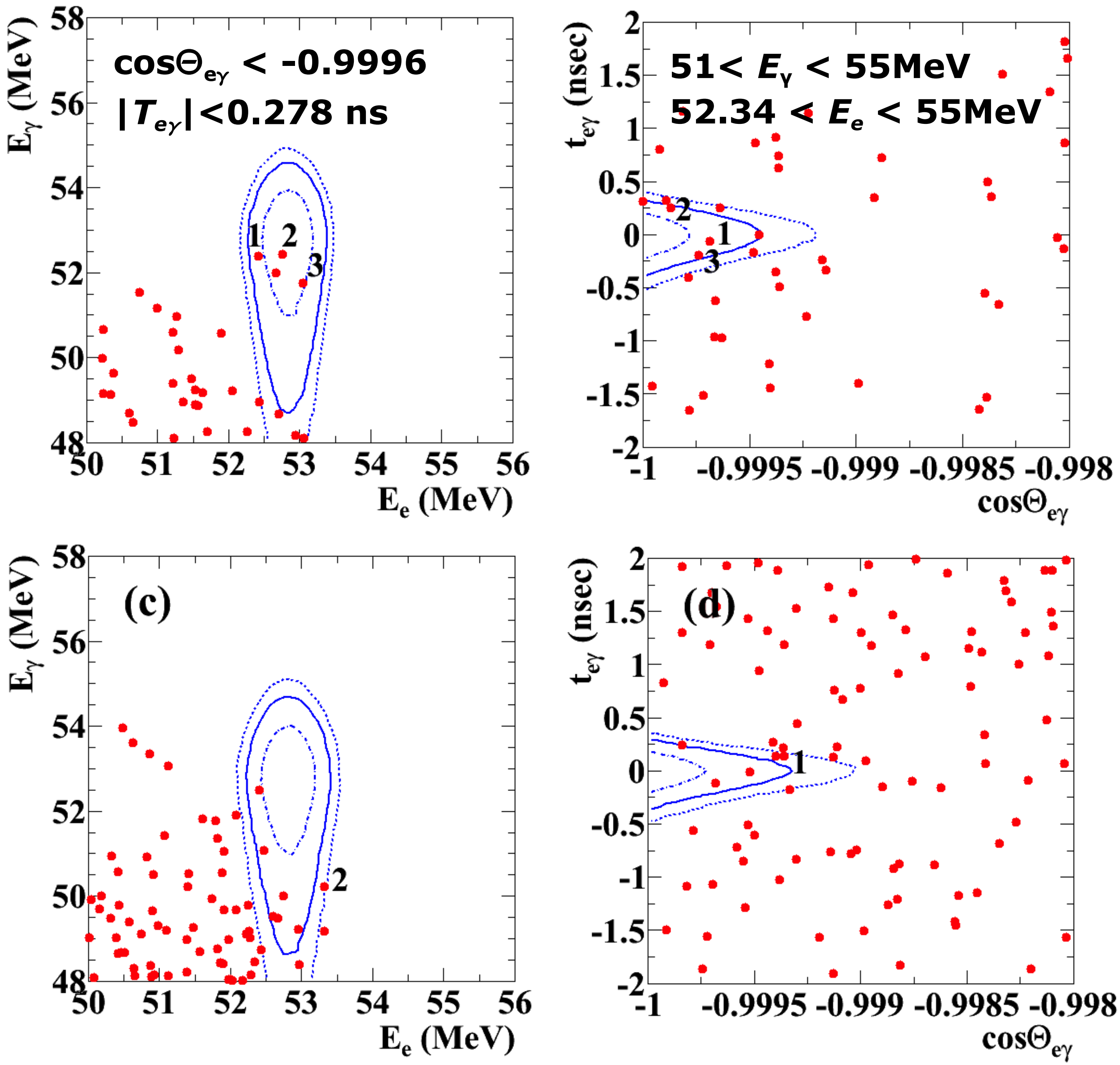
...ased on
...7.5 x 10^{13} μ
stopped at the target

N_{sig} = $-0.5^{+7.9}_{-4.7}$

N_{bkg} = 882 ± 22

N_{RD} = 76.5 ± 12

Results (2009 - 2010)



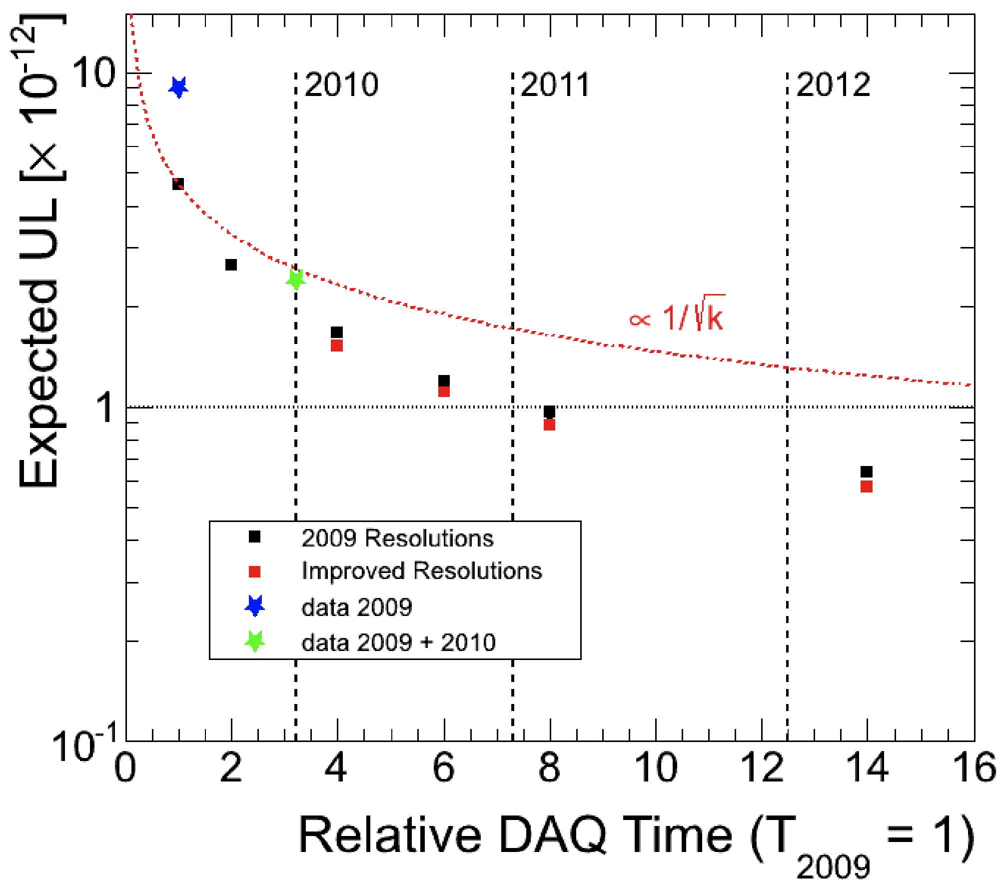
2009

2010

contours:
1σ, 1.64σ, 2σ

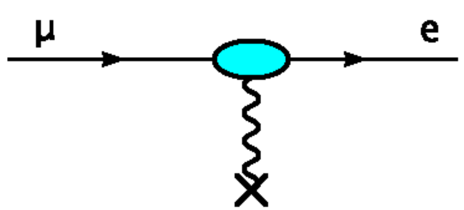
2011 run and perspectives

- ~ 19 x 10^{12} stopped μ during 2011 (~ 1.1x the 2009 + 2010 statistics);
- Analysis on going:
  - exp. limit ~ 10^{-12}
- 2012 run planned to start in a few weeks;
- A major upgrade (new tracker, improved photon detectors for the LXe calorimeter, etc.) is under study.



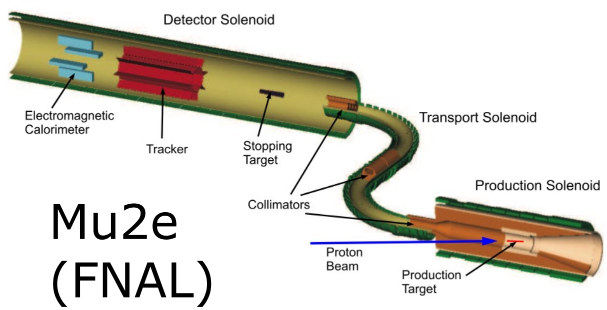
Future perspectives

- Super Flavour Factory projects aim to set limits ~ 10^{-9} on τ LFV;
- Two R&D to search for $\mu \rightarrow$ e conversion in the interaction with nuclei at a level of < 10^{-16}:



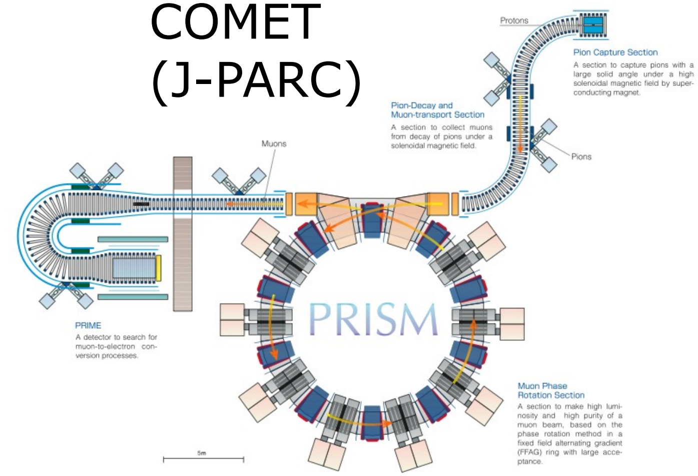
In many models:

$$\frac{BR(\mu N \rightarrow eN)}{BR(\mu \rightarrow e\gamma)} \sim O(100)$$



Mu2e (FNAL)

COMET (J-PARC)

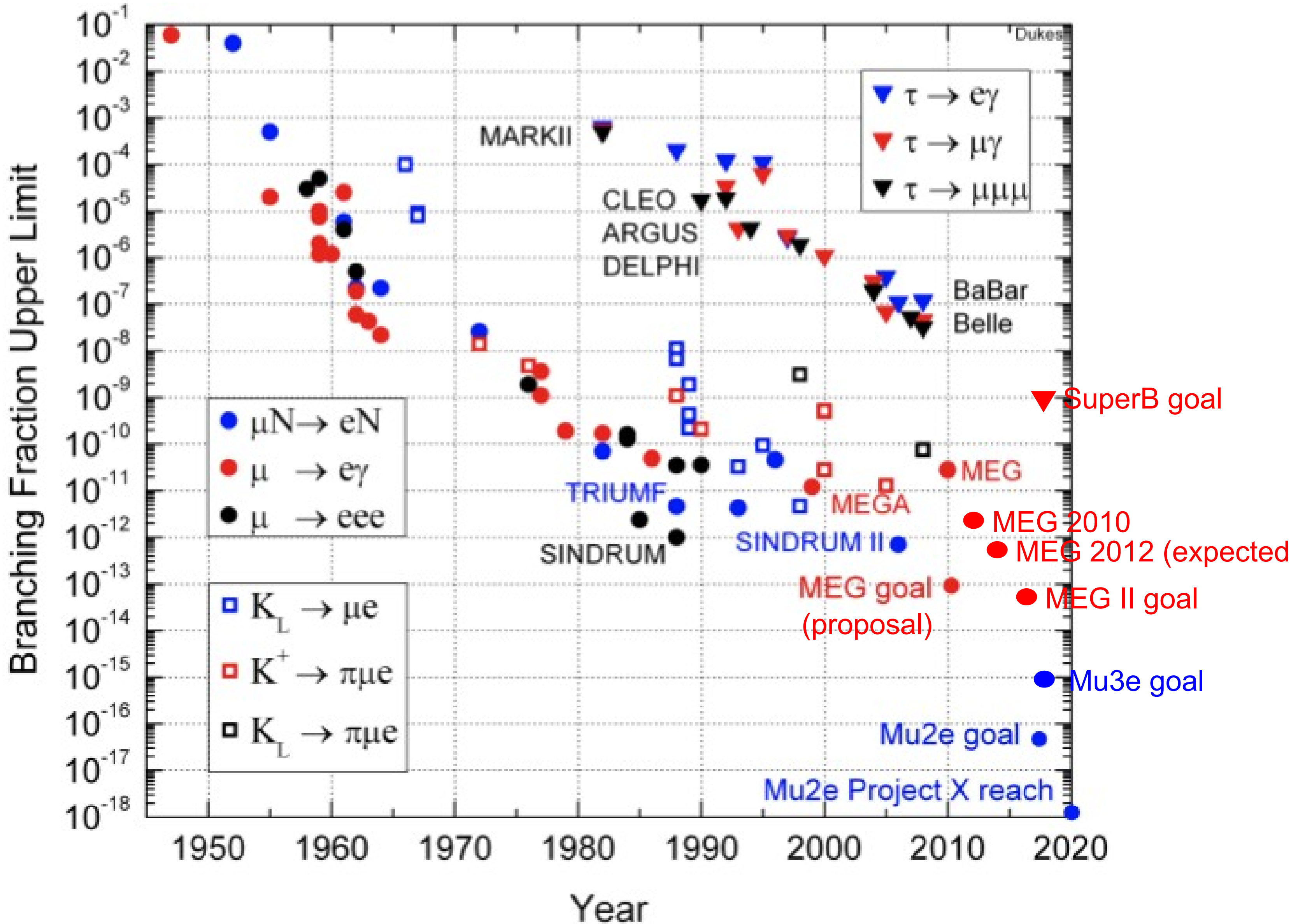


- An R&D is on going for $\mu \rightarrow$ e e e at PSI;
- A major upgrade of the MEG experiment could allow to set a limit of ~ 5 x 10^{-14} on $\mu \rightarrow e\,\gamma$:
  - competitive with initial phase of $\mu \rightarrow$ e conversion experiments, in a shorter time scale.

Summary

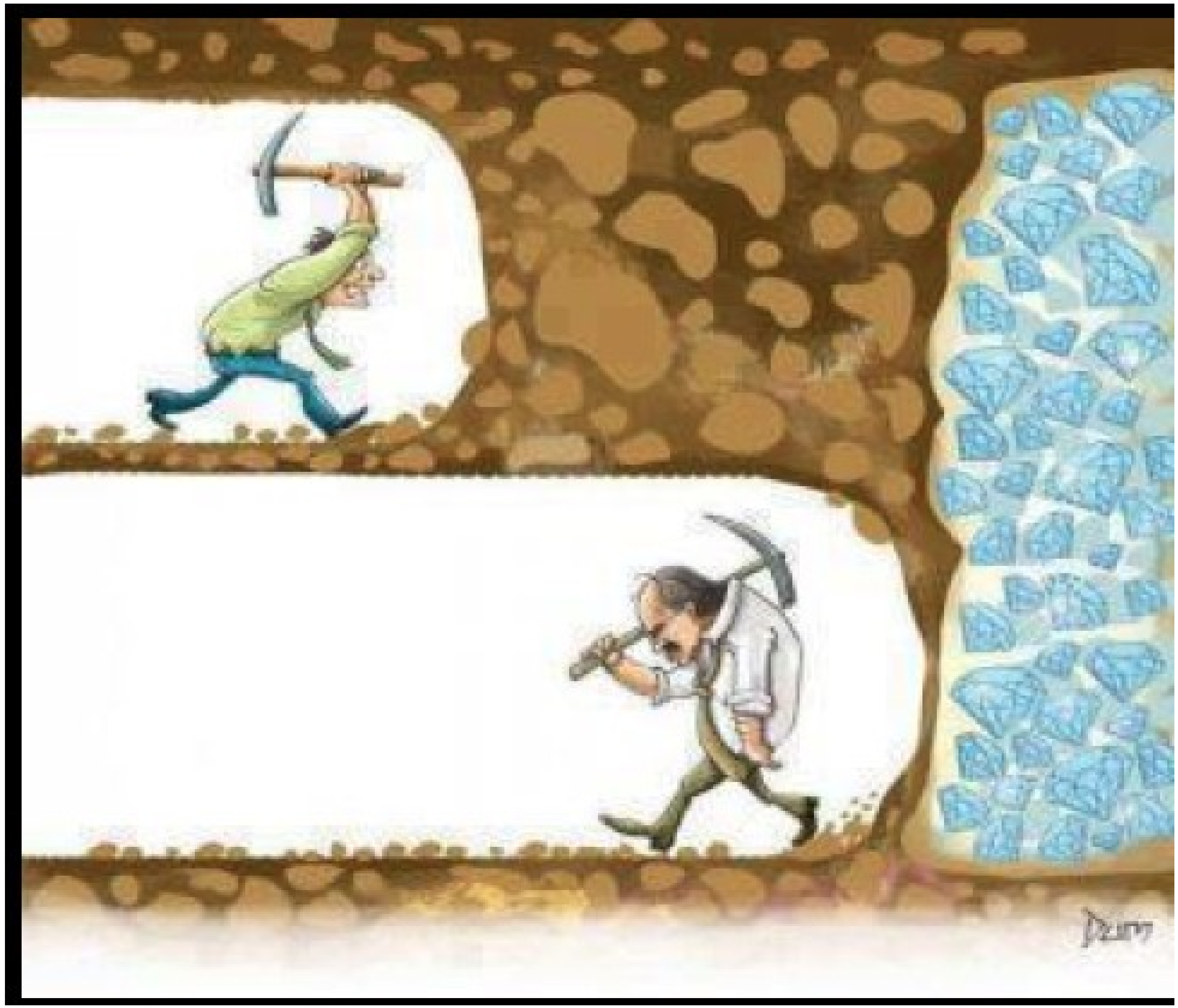
- Limits on τ LFV/LNV reached ~ few 10^{-8} at the B-Factories:
  - LHCb just starts to be competitive;
- $\mu \rightarrow e \gamma$ search at MEG set a limit of 2.4×10^{-12}:
  - expect ~ 6×10^{-13} at the end of the experiment lifetime;
- Present limits already severely constrain NP;
- A number of future experiments have been proposed to significantly improve these sensitivities.

LFV Timeline



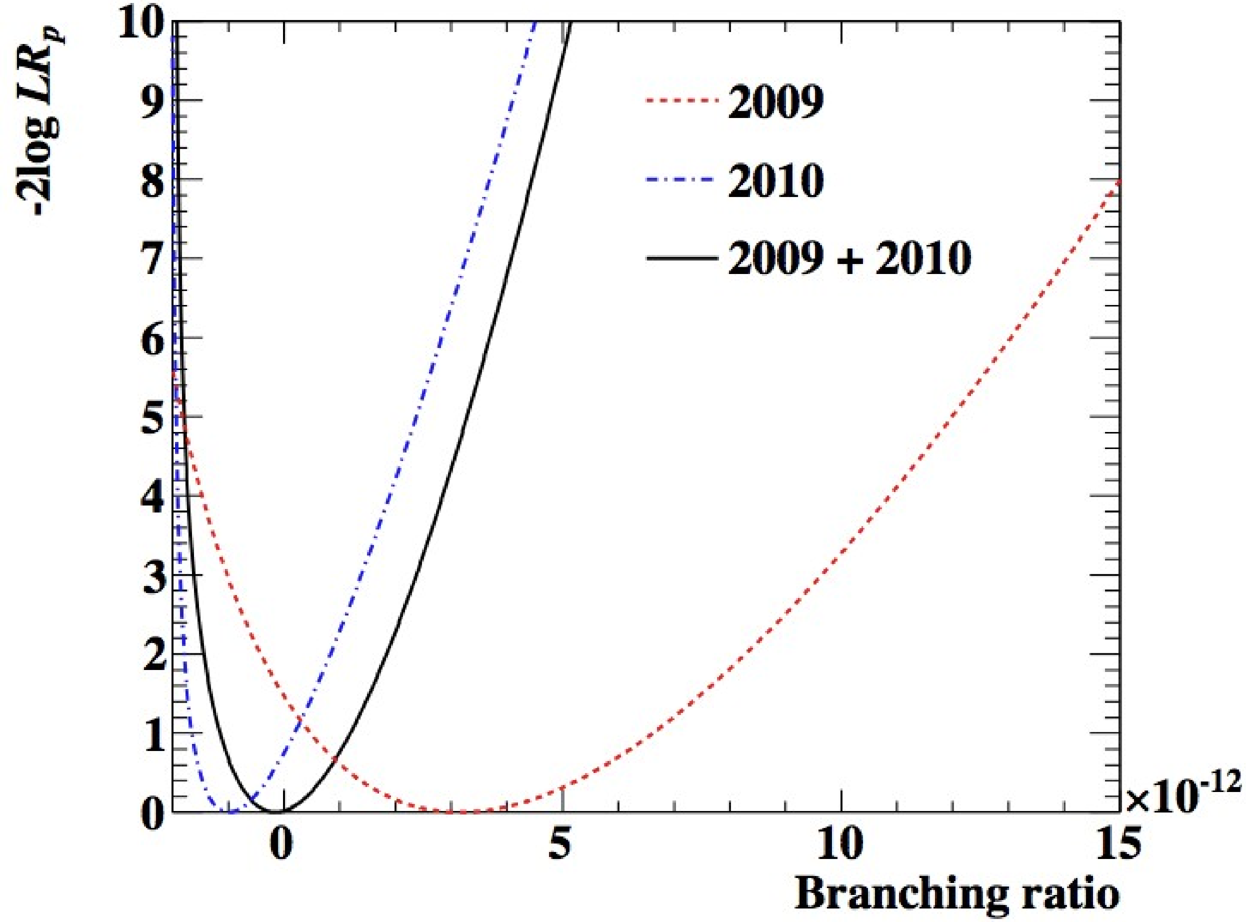
E. C. Dukes, TAU2010

Do not stop searching!



Backup

Profile Likelihood Ratio (MEG)



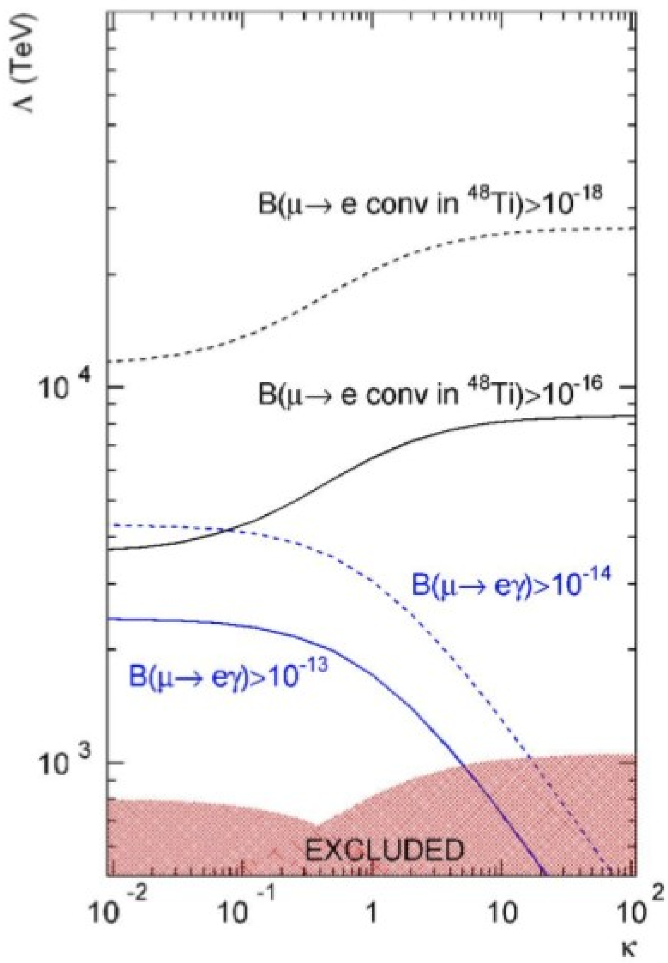
Systematics

- Systematic uncertainties are included in the calculation of the upper limit (2% effect on the UL);
- An idea from $\Delta\log(LR_p)$ at $N = N_{gen}$ in toy MC:

	$\Delta log(LR_p)$
Center of $\theta_{e\gamma}$ and $\phi_{e\gamma}$	0.18
Positron correlations	0.16
Normalization	0.13
E_γ scale	0.07
E_e bias, core and tail	0.06
$t_{e\gamma}$ center	0.06
E_γ BG shape	0.04
E_γ signal shape	0.03
Positron angle resolutions (θ_e, ϕ_e, z_e, y_e)	0.02
γ angle resolution (u_γ, v_γ, w_γ)	0.02
E_e BG shape	0.02
E_e signal shape	0.01

Effective cLFV lagrangian

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



Charge Exchange Calibration

ENERGY CALIBRATION

$\pi^- + p \rightarrow \pi^0 + n,\ \pi^0 \rightarrow \gamma\,\gamma$

- Monochromatic photons can be obtained by selecting a fixed opening angle between the two photons.