Latest News from the MEG Experiment

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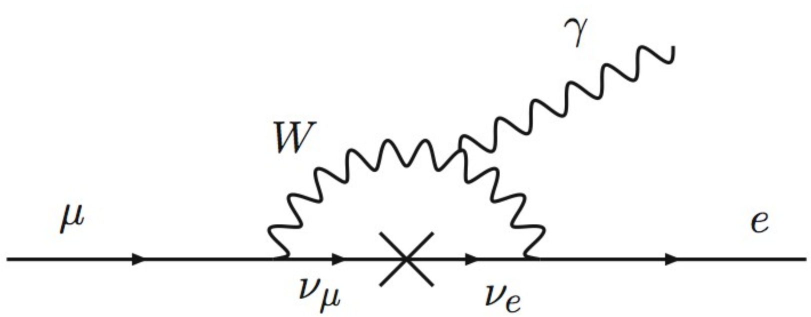
Outline

- Theoretical introduction on Lepton Flavour Violation (LFV);
- The MEG Experiment;
  - experimental setup;
  - recent improvements;
  - latest results;
- The MEG upgrade;
- Future perspectives of LFV searches.

Lepton Flavour Violation

- LFV is a standard probe for New Physics (NP) beyond the Standard Model (SM):
  - unobservable rates in the SM;

SM (BR < 10^{-40})

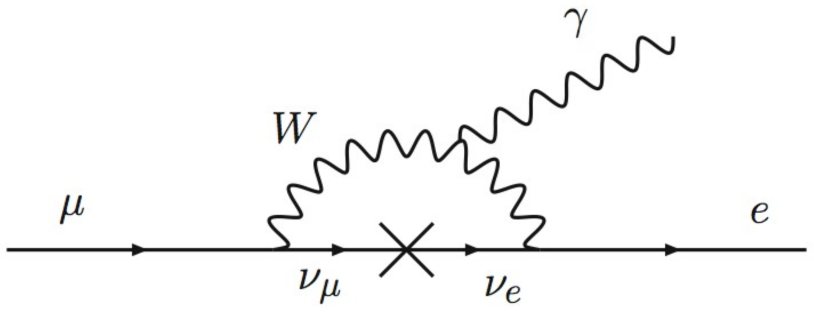


*Observing LFV would be an **unambiguous evidence of NP***

Lepton Flavour Violation

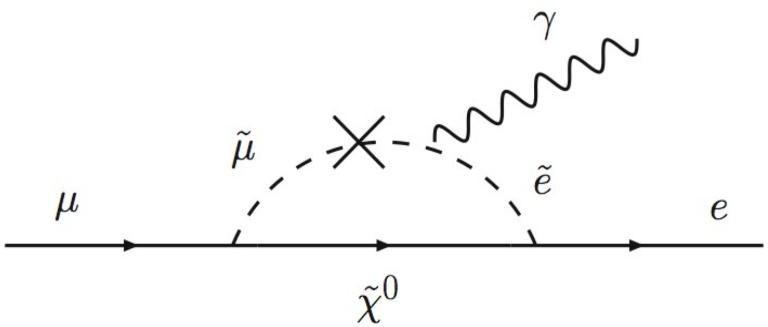
- LFV is a standard probe for New Physics (NP) beyond the Standard Model (SM):
  - unobservable rates in the SM;
  - naturally enhanced by NP (SUSY, Extra dimensions, unparticles, etc.);

SM (BR < 10^{-40})



*Observing LFV would be an **unambiguous evidence of NP***

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

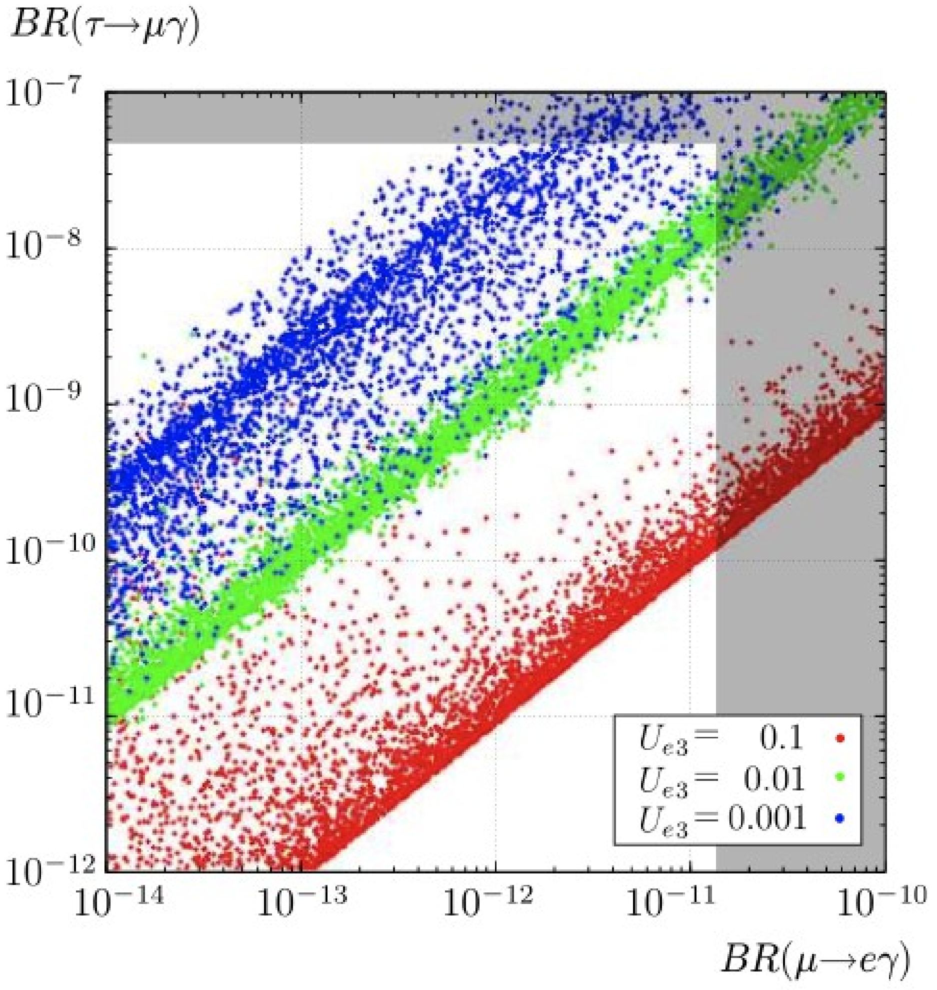


LFV through renormalization group running even if the theory is LF conserving at the high energy scale

LFV and θ_{13}

- In SUSY GUTs, LFV in μ decays is strongly related to the neutrino mixing angle θ_{13}.

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



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

LFV and θ_{13}

- In SUSY GUTs, LFV in μ decays is strongly related to the neutrino mixing angle θ_{13}.

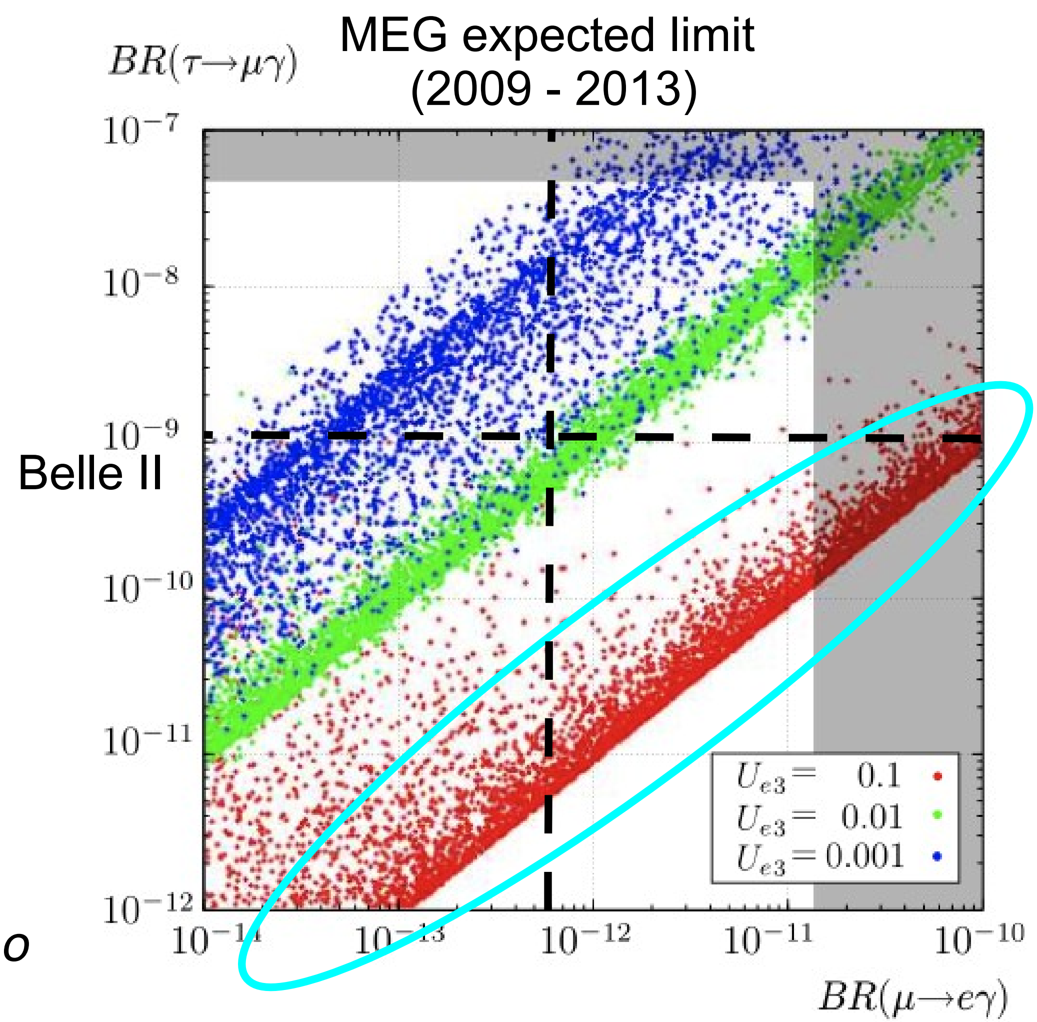
ν mixing parameter

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

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

(Daya Bay)

μ LFV is favored!



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

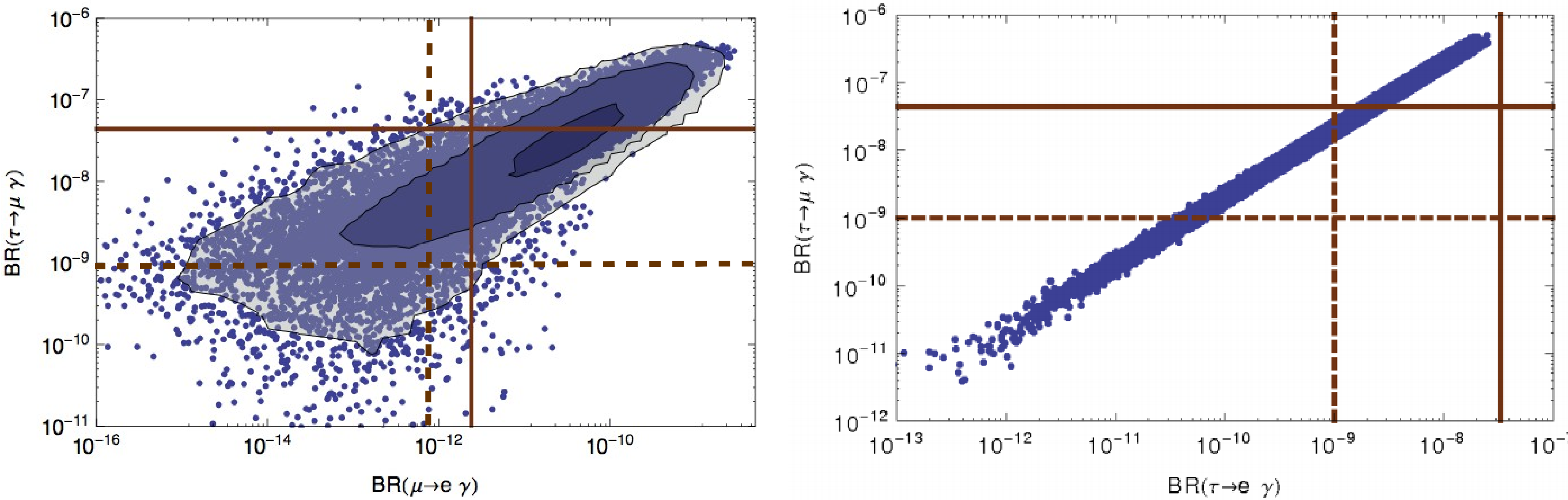
LFV and θ_{13}

- In other scenarios τ LFV searches still competitive:
  - high complementarity!

MEG 2010/BaBar/Belle

Expected limits (MEG 2013/SuperKEKB)

courtesy of the authors



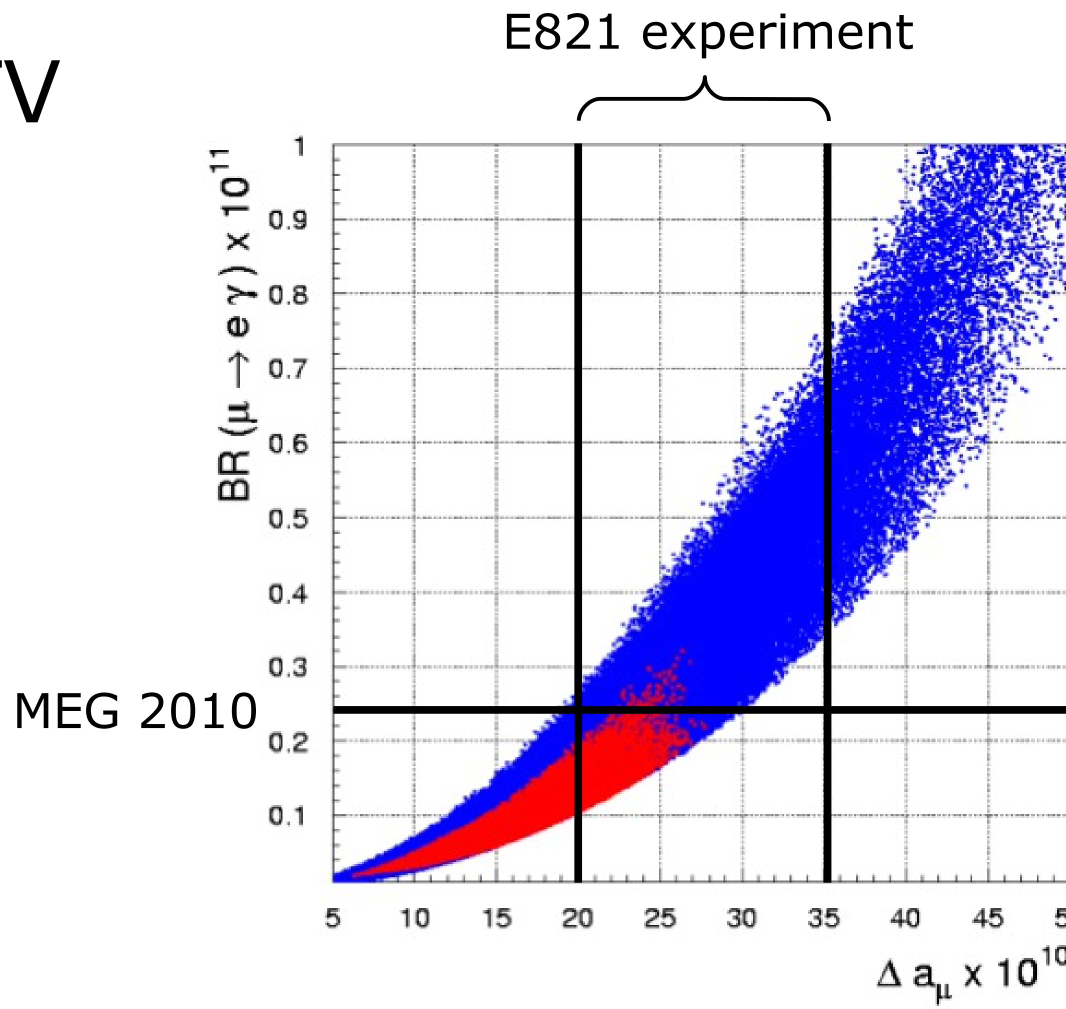
SUSY with minimally broken flavor symmetries and $\sin(\theta_{13}) \sim 0.15$
(Blankenburg, Isidori, Jones-Pérez '12)

LFV and dipole moments

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

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

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

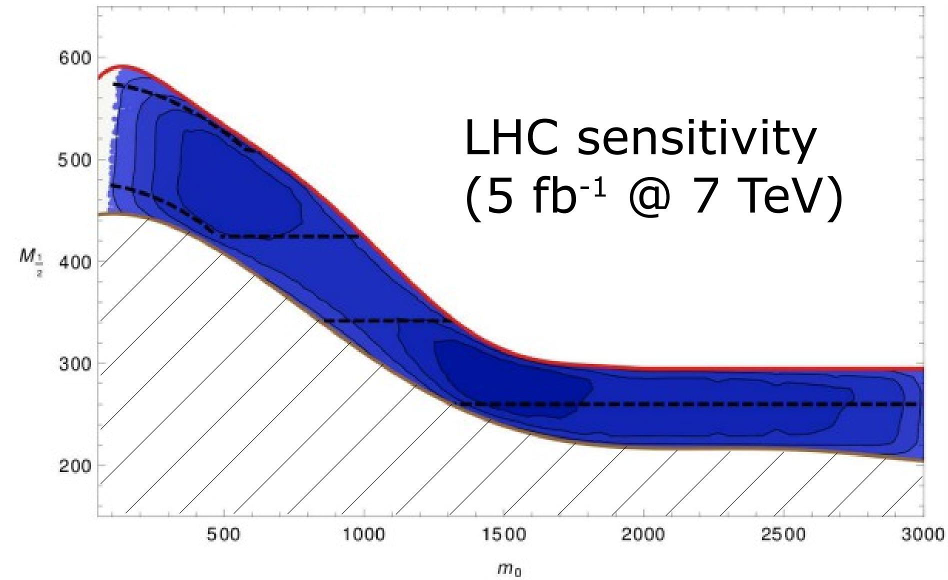


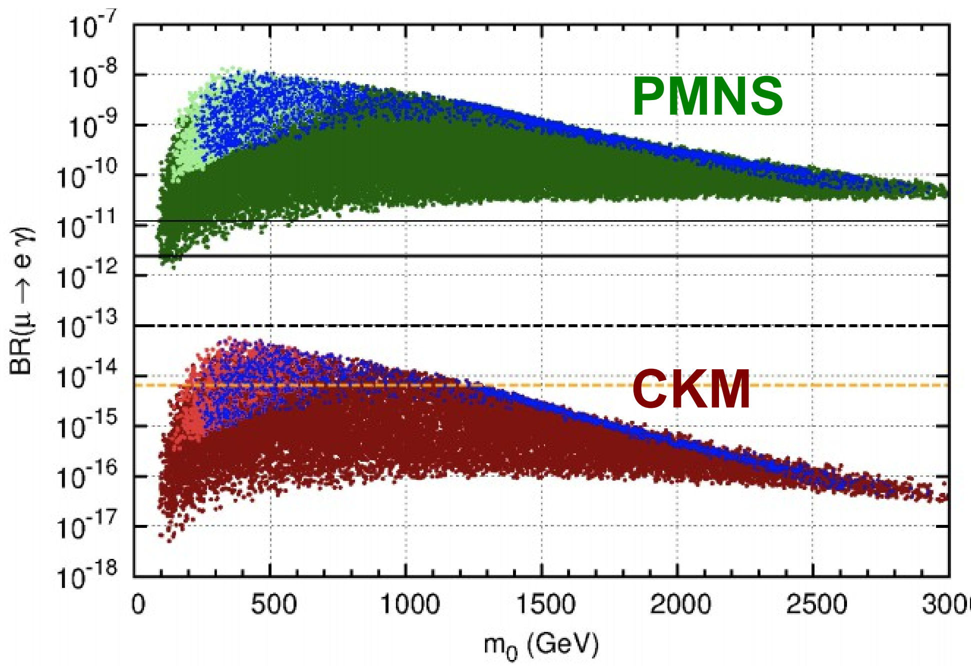
MSSM with large tanβ
(Isidori, Mescia, Paradisi '07)

the red area includes B physics constraints
($B_s \to \mu\mu$ evidence at LHCb not included)

LFV searches and the LHC

- LFV rates strongly depend on the details of the flavour structure of new physics:
  - even within the same model, LFV constraints can be much stronger or much weaker that LHC constraints;
  - i.e. LHC constraints still leave a lot of space for LFV searches.

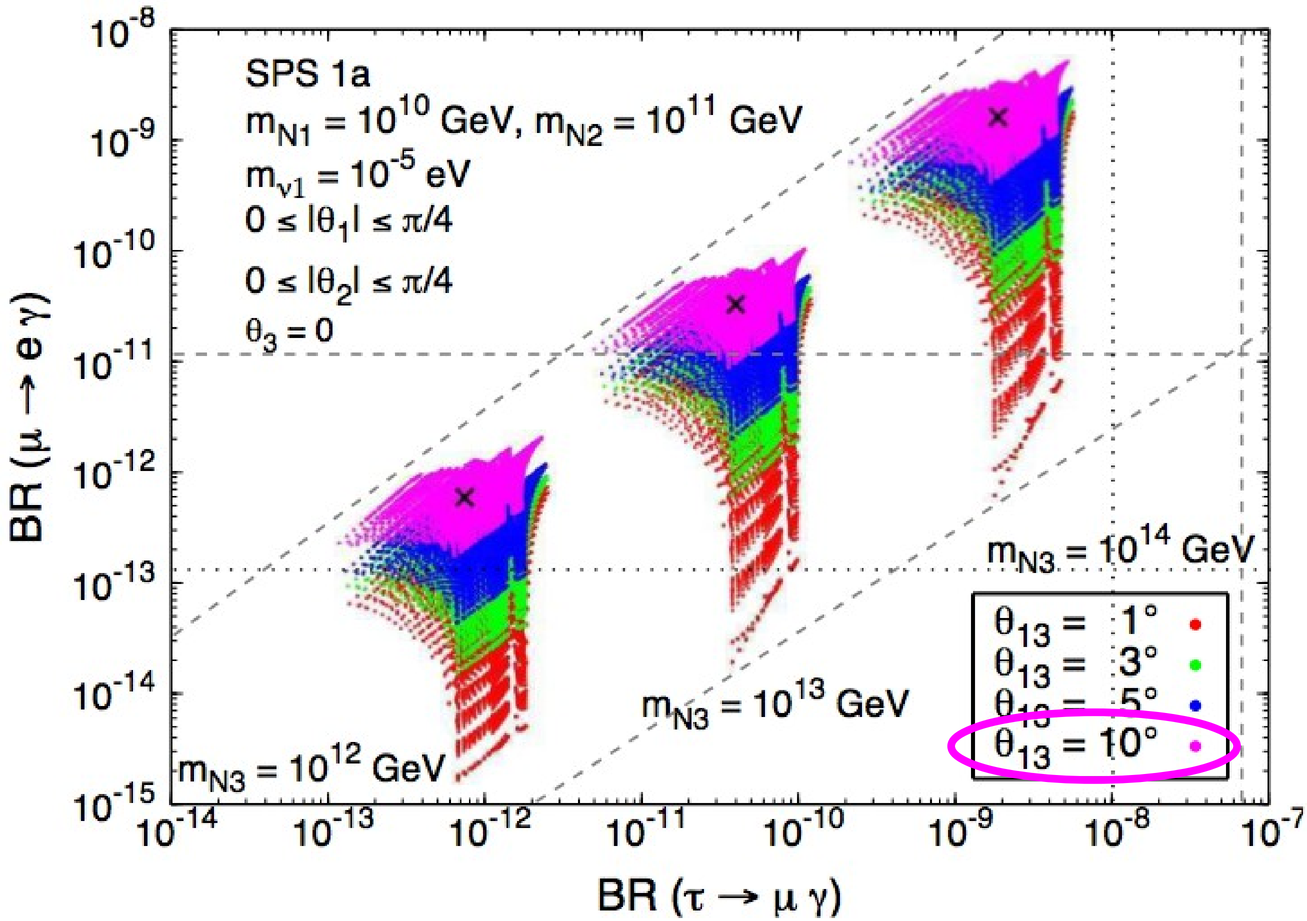




CMSSM (Calibbi, Hodgkinson, Jones Perez, Masiero, Vives '11)

LFV searches and the LHC

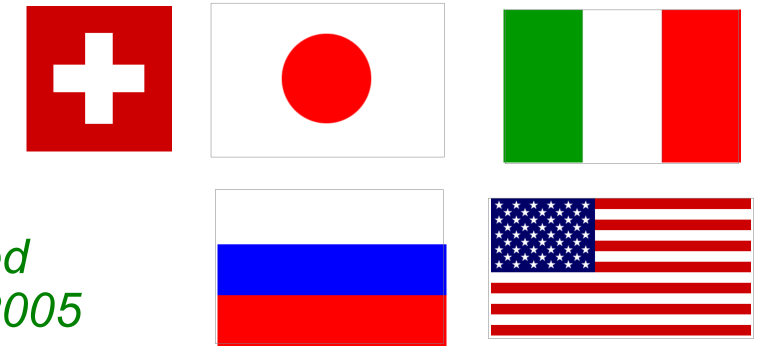
- Even a well defined SUSY mass spectrum can give a large range of predictions for LFV, depending on other parameters.

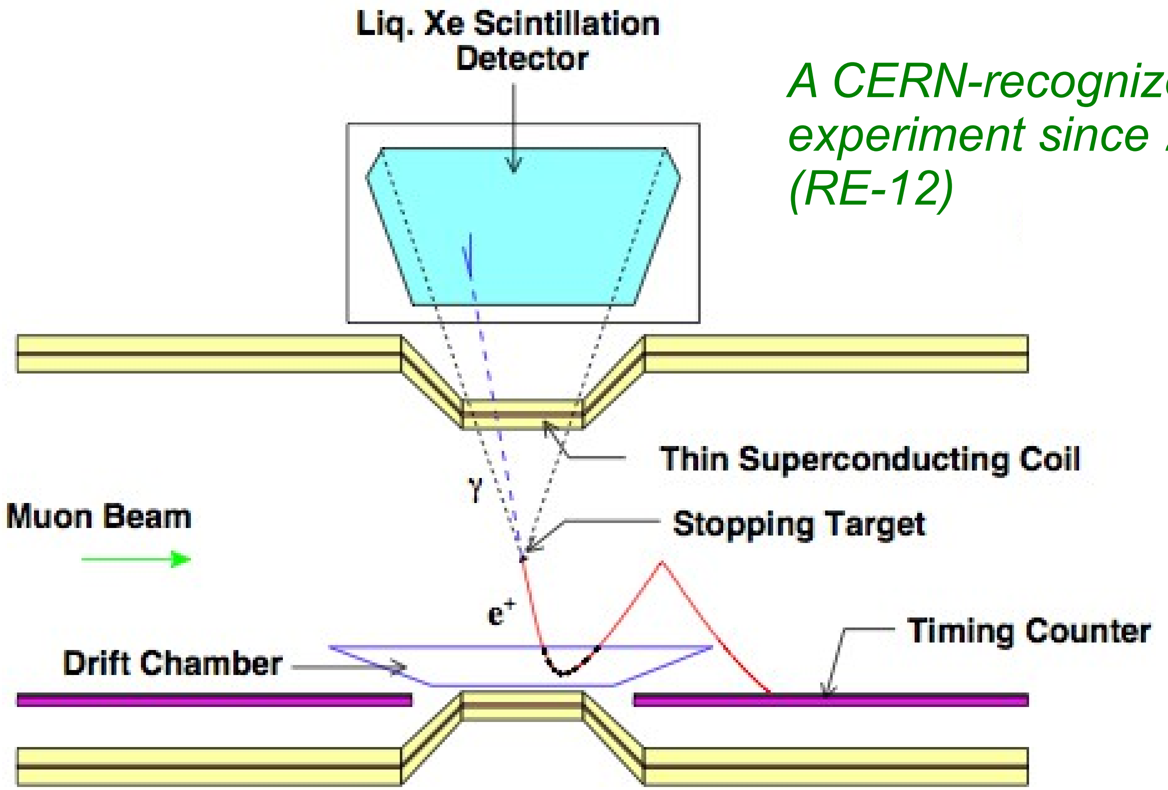


CMSSM + Seesaw (Antusch, Arganda, Herrero, Teixeira '06)

The MEG experiment (arXiv:1303.2348)

- 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.





A CERN-recognized experiment since 2005 (RE-12)

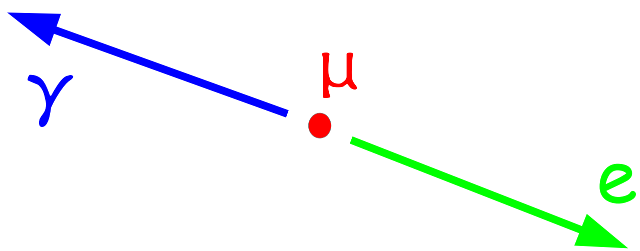
LXe calorimeter for photon detection

16 drift chambers for positron tracking

30 scintillating bars for positron timing and trigger (Timing Counter, TC)

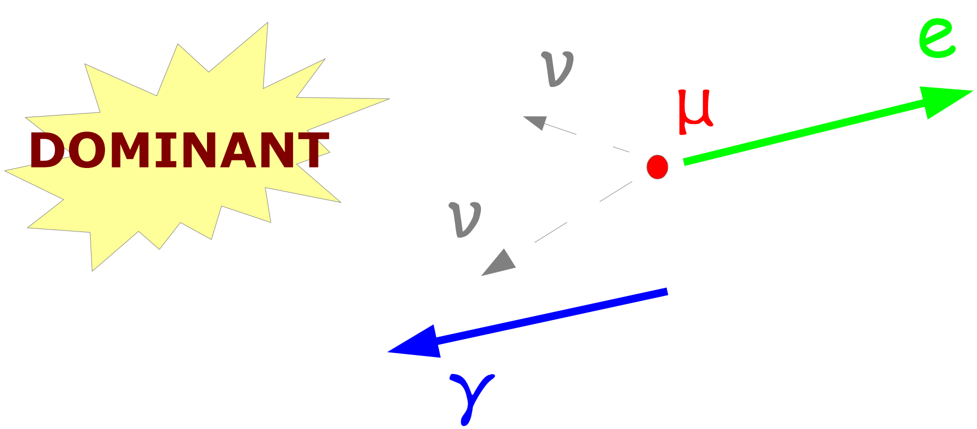
Signal & Background

SIGNAL

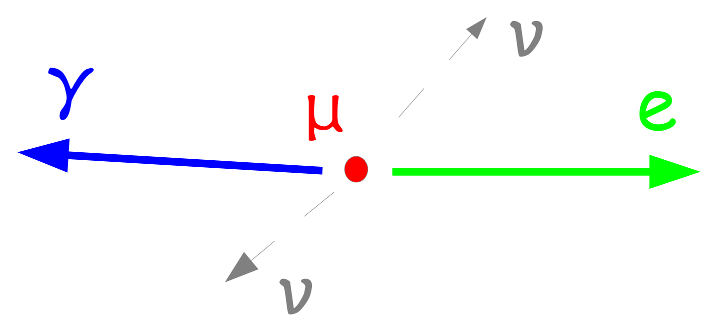


Monochromatic (52.8 MeV), back-to-back $e^{+}\ \gamma$ produced at the same time;

ACCIDENTAL BACKGROUND

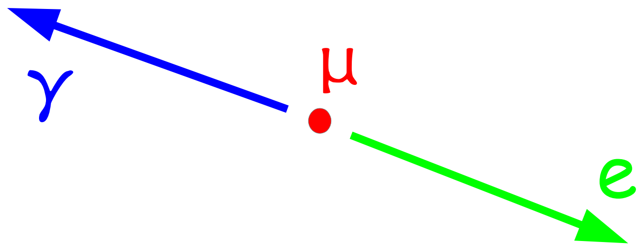


RADIATIVE MUON DECAY (RMD)



Signal & Background

SIGNAL

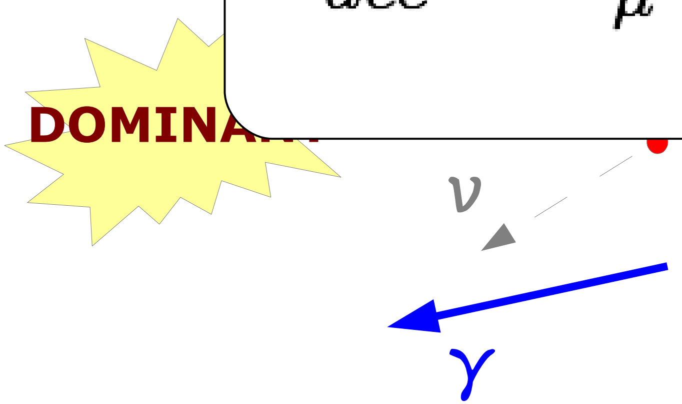


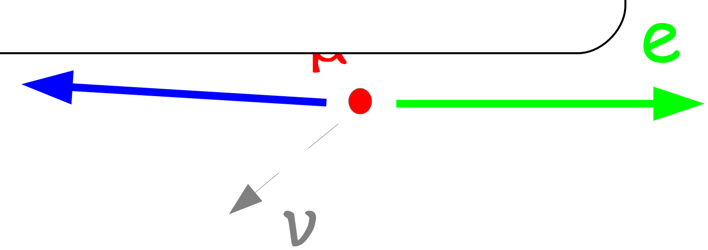
Monochromatic (52.8 MeV), back-to-back $e^+ \gamma$ produced at the same time;

ACC

(RMD)

$$\Gamma_{acc} \propto \Gamma_\mu^2 \cdot \delta E \cdot \delta T_{e\gamma} \cdot (\delta E_\gamma)^2 \cdot (\delta \Theta_{e\gamma})^2$$

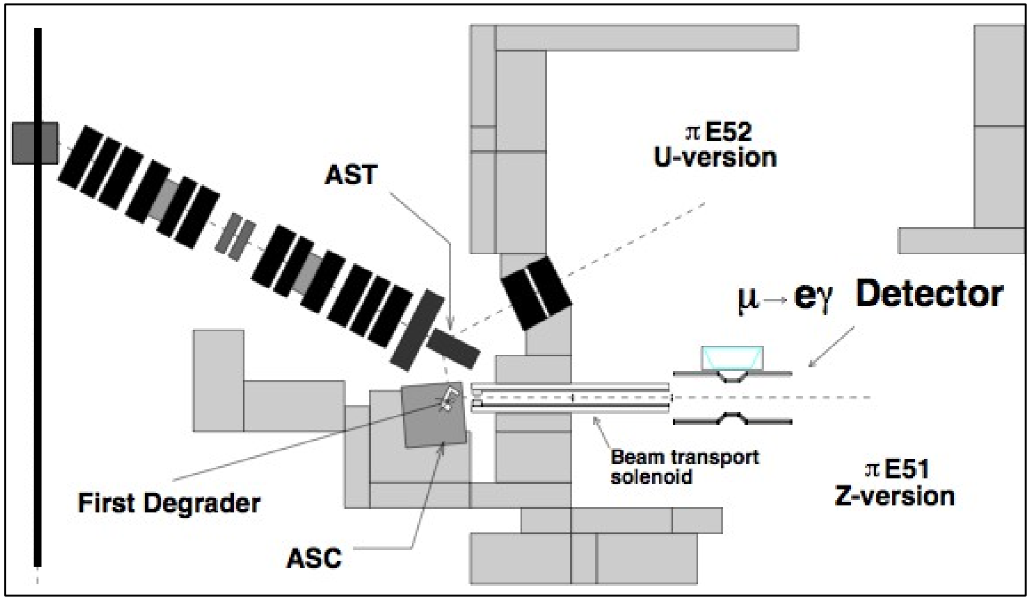




Signal/Background discrimination from ***photon and positron energies, relative angles and relative time***

The πE5 beam line at PSI

- Most intense DC muon beam in the world:
  - up to 10^8 μ/s;
  - only 3 x 10^7 μ/s for the MEG running (optimized statistics vs. background)



Proton beam current : ~ 2.2 mA

Muon production : from π decaying in the proton target surface

Muon Momentum : 28 MeV/c ± 3%

LXe Calorimeter

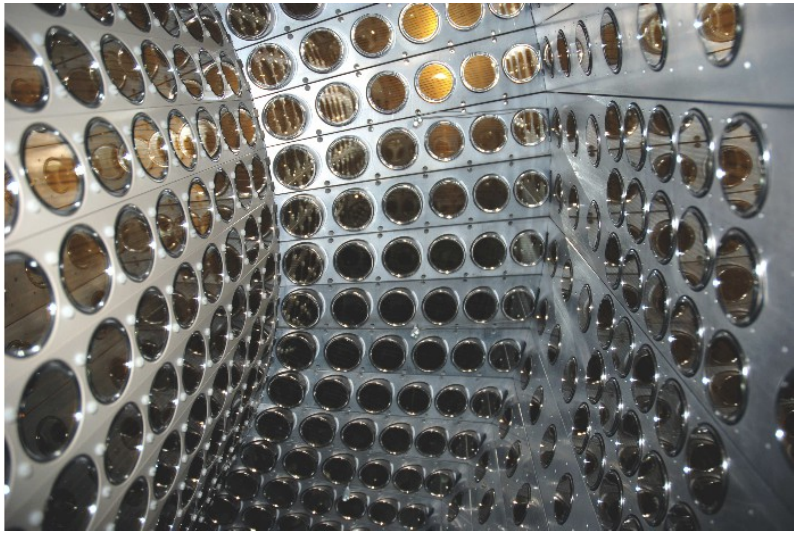
800 liter LXe detector read by 846 PMTs

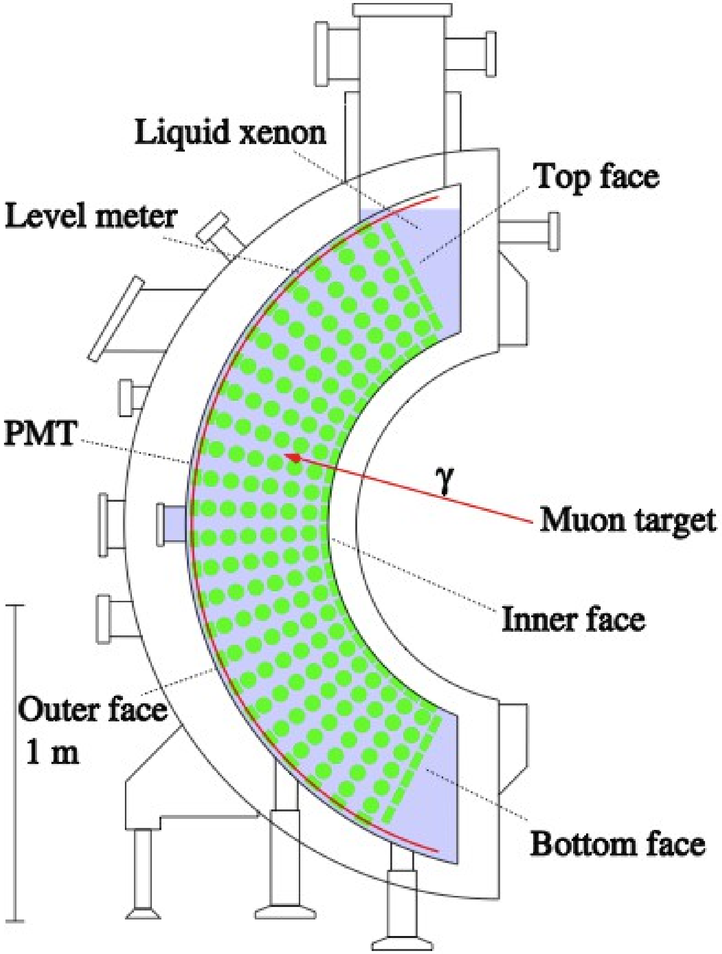
Not just a calorimeter!

$\sigma_E \sim 1.9\%$ @ 52.8 MeV

$\sigma_{xy} \sim 5 – 6$ mm

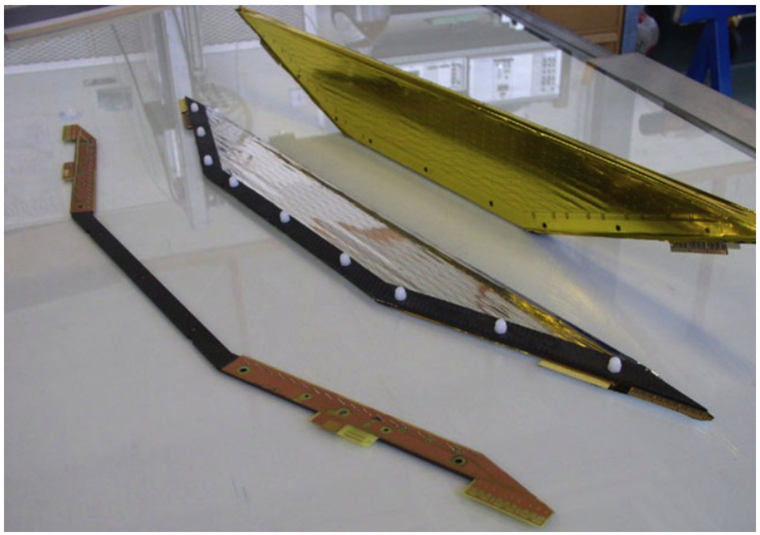
$\sigma_T \sim 60$ ps

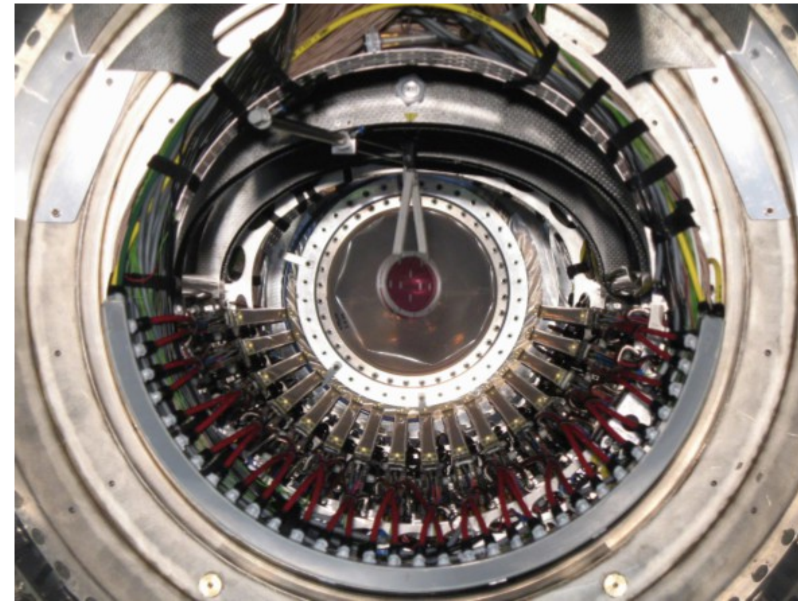




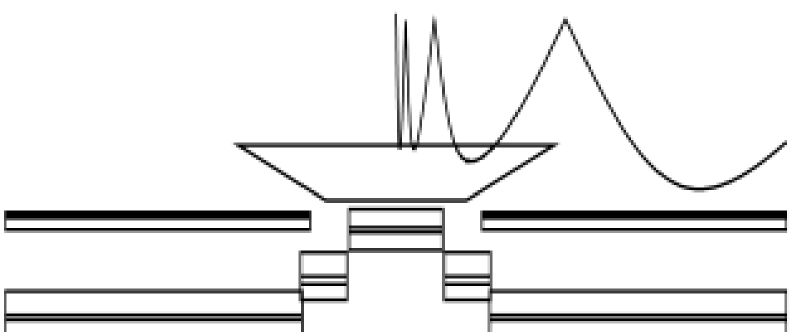
Drift Chamber Spectrometer

16 drift chambers
$\sigma_R \sim 300\ \mu m$, $\sigma_Z \sim 1$ mm





Gradient magnetic field



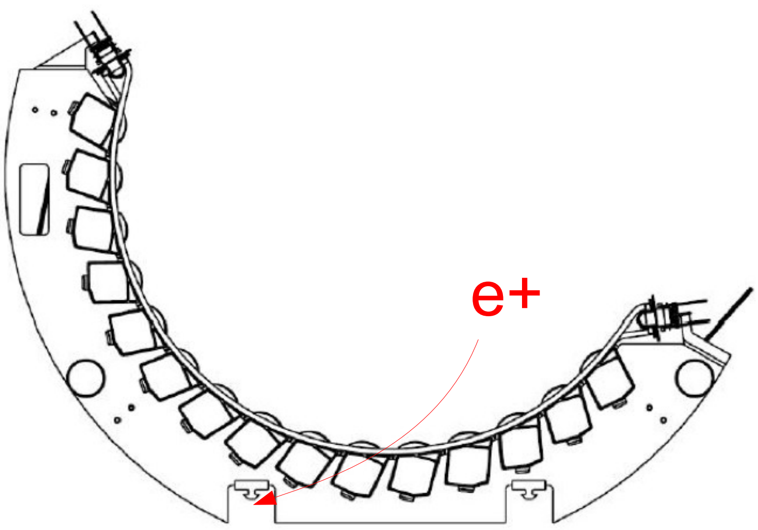
Tracking performances

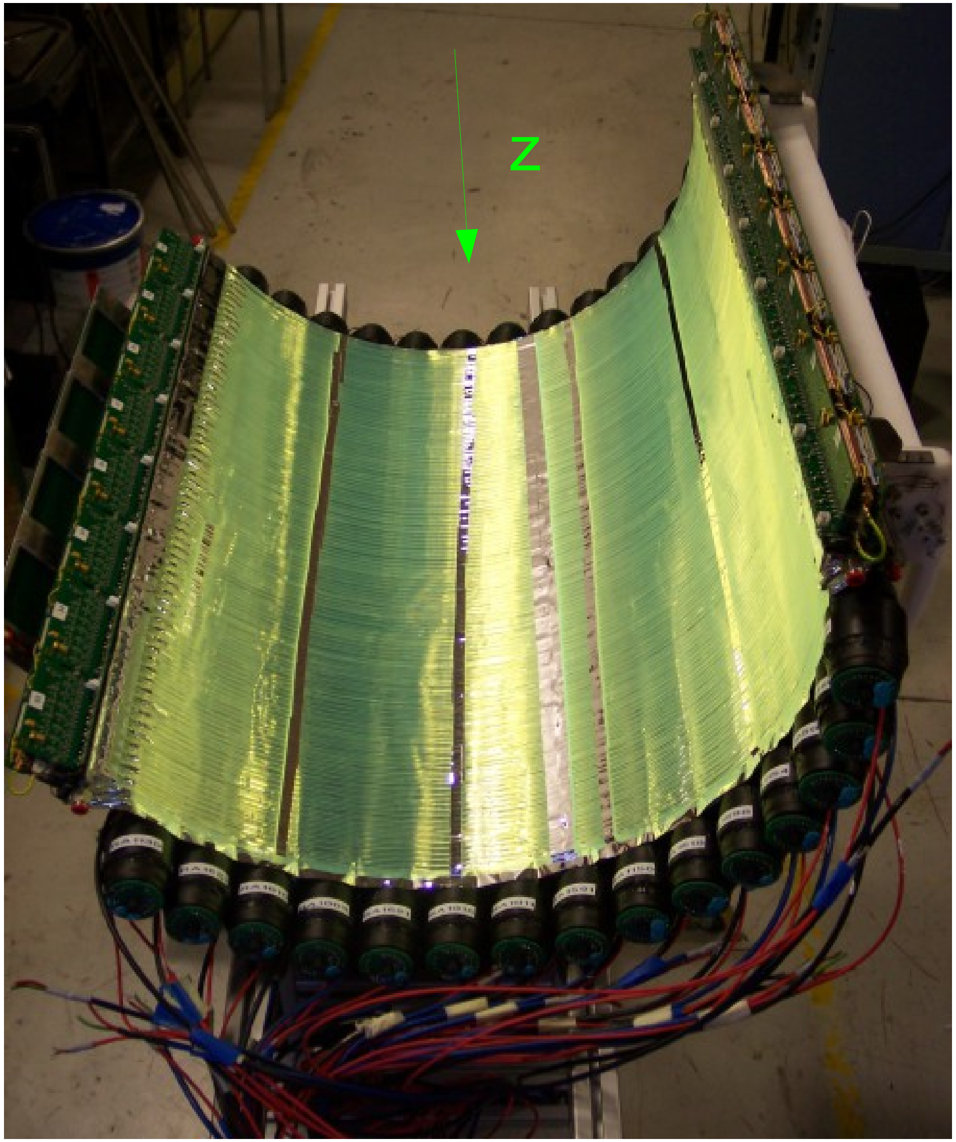
$\sigma_P \sim 300$ keV
$\sigma_{vtx} \sim 1.2$ (x), 2.4 (y)
$\sigma_{\theta,\varphi} \sim 9$ mrad

Timing Counter

2 x 15 scintillating bars for trigger and positron timing ($\sigma_T \sim 60$ ps)

2 x 256 fibers to measure the z coordinate





Trigger and DAQ

- FPGA based trigger system;

```
Beam Intensity x acceptance.........10⁶ Hz
 + XEC Energy E > 45 MeV............10³ Hz
 + e – γ Timing Teg < 10ns..........10² Hz
 + e – γ Angle......................10 Hz
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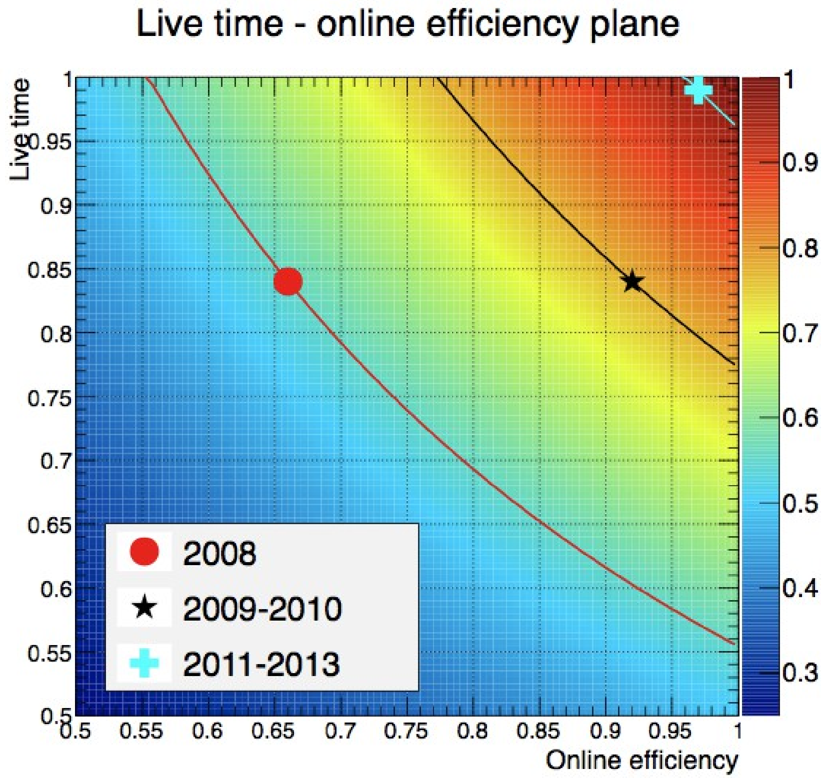
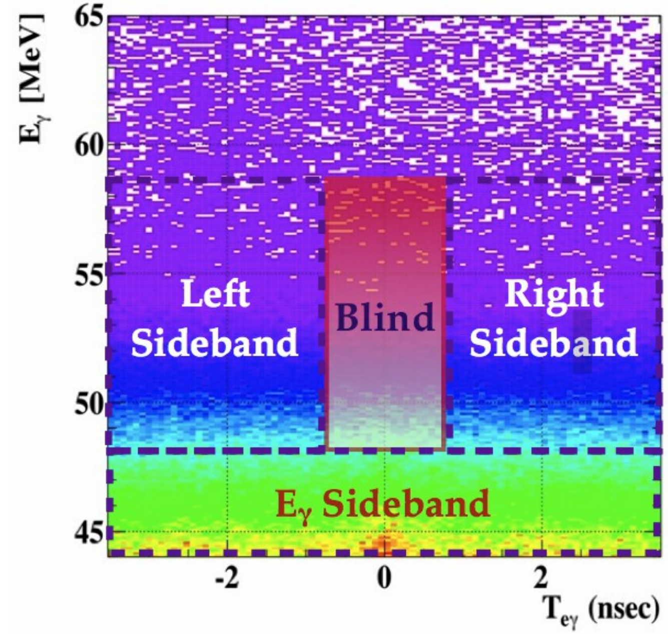
- Buffering for dead time suppression since 2011;
  - normalization factor +20%;
- Full digitization of all readout channels for offline analysis:
  - custom digitization chip (DRS).



Analysis Strategy

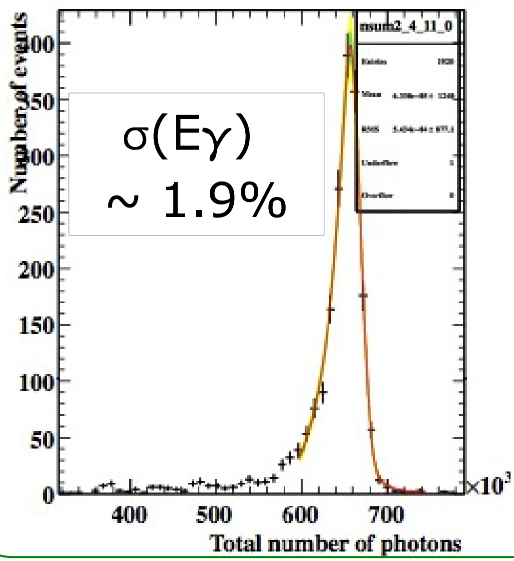
- Likelihood analysis of 5 discriminating variables ($E_e, E_\gamma, \theta_{e\gamma}, \varphi_{e\gamma}, T_{e\gamma}$):
  - year-by-year and event-by-event PDFs;
  - careful treatment of **correlations** (from well understood geometrical effects)



- Accidental **background PDFs** are fully defined **from data** sidebands:
  - very solid determination of the (largely) dominant background;
- Signal and radiative decay PDFs by combining the results of the **calibration procedures**;

Calibrations & Monitoring (I)

Charge Exchange (CEX)



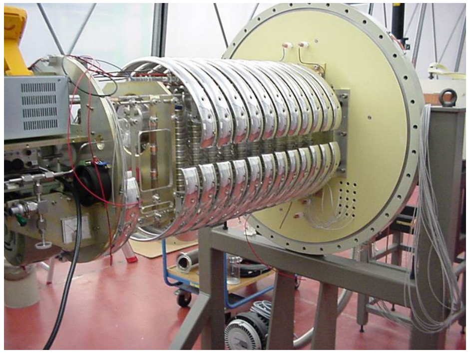
~ monochromatic γ @ 55 MeV from...

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

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

...by selecting back-to-back γ's

Cockcroft-Walton accelerator

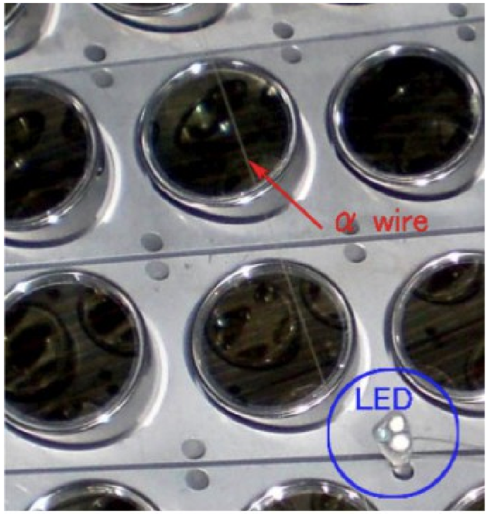


Protons on a Lithium Tetra-borate target

bi-weekly monitoring of calorimeter's energy scale

LEDs

Installed inside the XeC



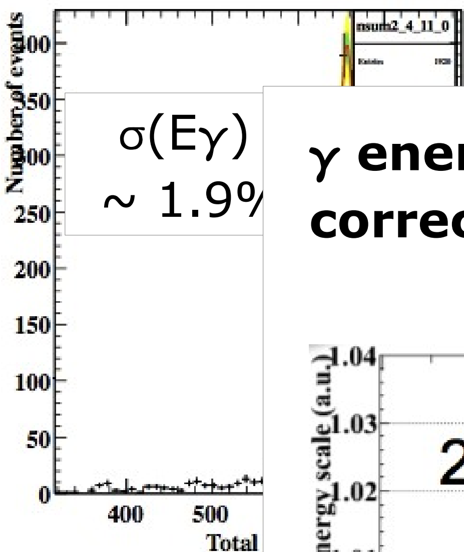
α sources

Installed in wires inside the XeC

bi-weekly calibration of PMT quantum efficiencies and gains

Calibrations & Monitoring (I)

Charge Exchange (CEX)

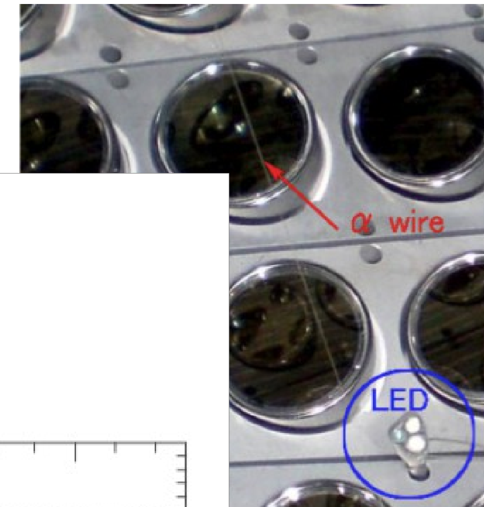


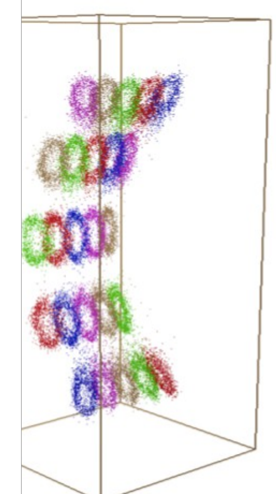
$\sigma(E\gamma)$
$\sim$ 1.9%

$\sim$ monochromatic γ

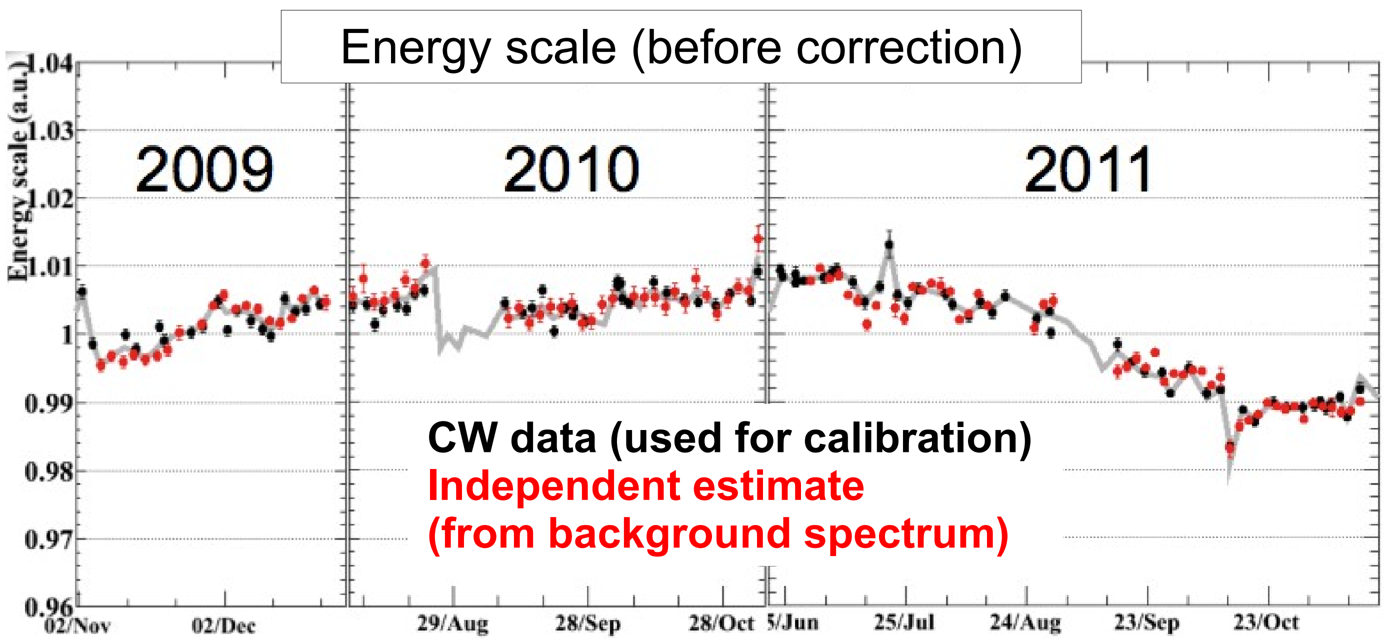
LEDs

Installed inside

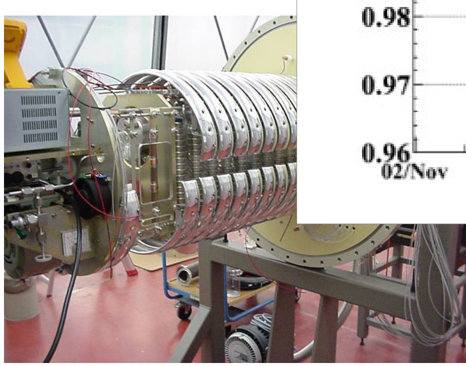




γ energy scale variations can be caught and corrected with a 0.2% precision



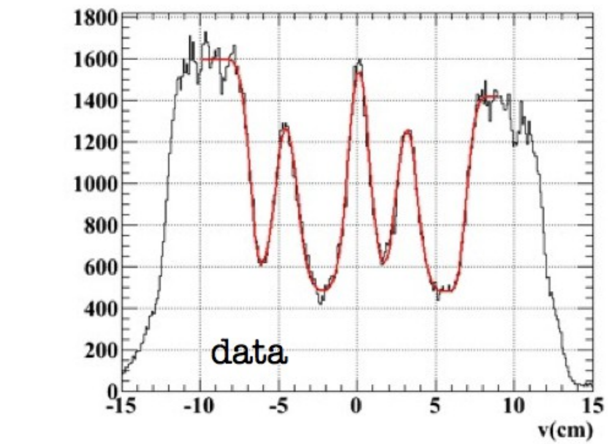
Cockcroft-



calorimeter's energy scale

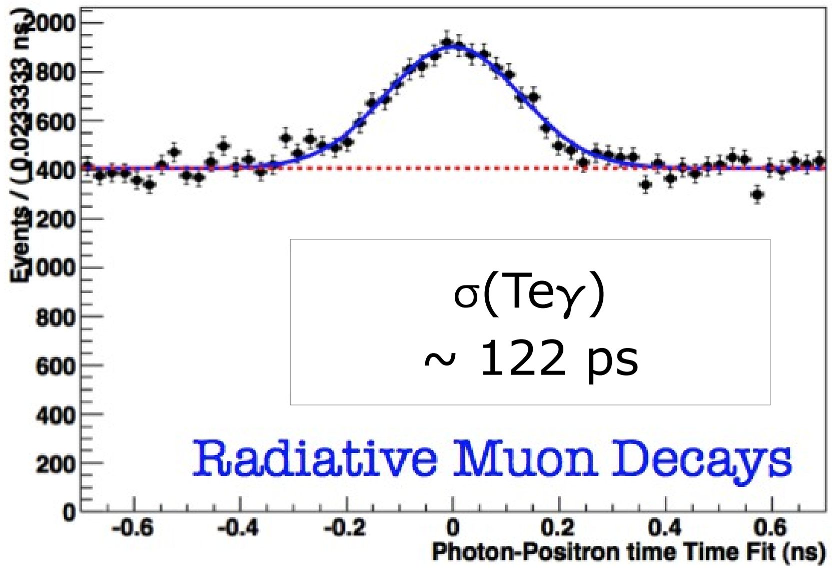
bi-weekly calibration of PMT quantum efficiencies and gains

Calibrations & Monitoring (II)



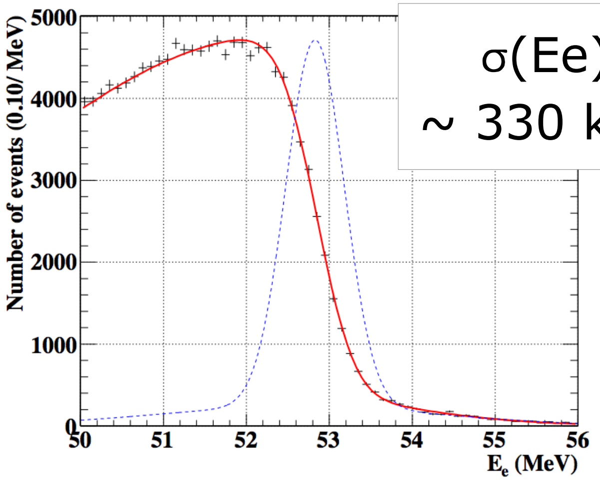
σ(uvw)
~ 5-6 mm

γ position resolution from special data taking w/ collimators



σ(Teγ)
~ 122 ps

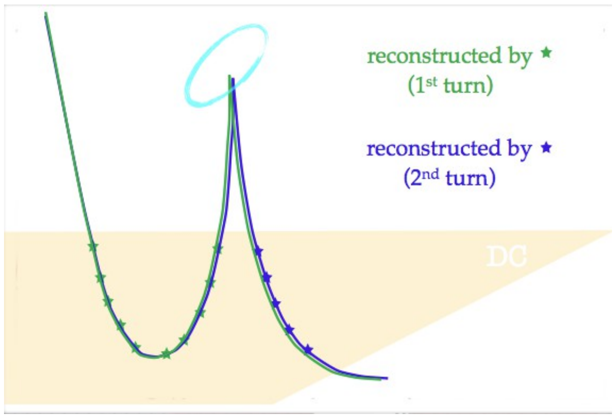
Tracks from $\mu \to e \nu \nu$ and cosmics to calibrate the positron spectrometer



σ(Ee)
~ 330 keV

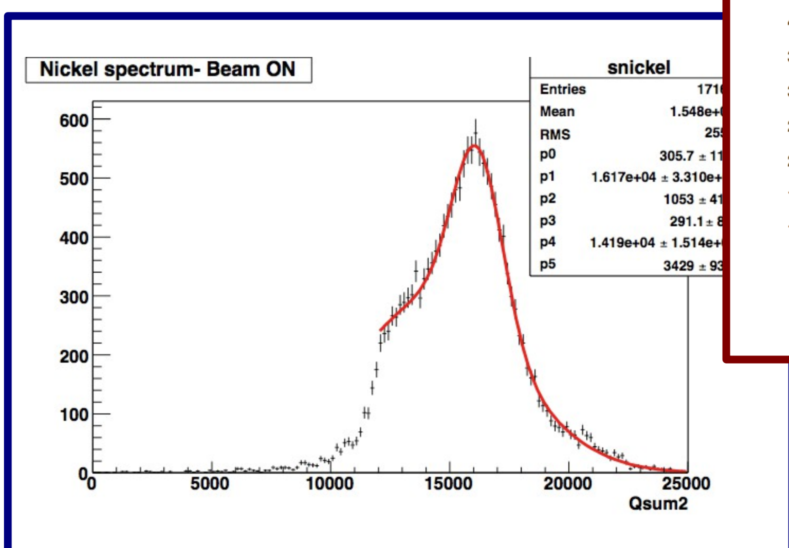
momentum resolution and scale from the $\mu \to e \nu \nu$ kin. edge

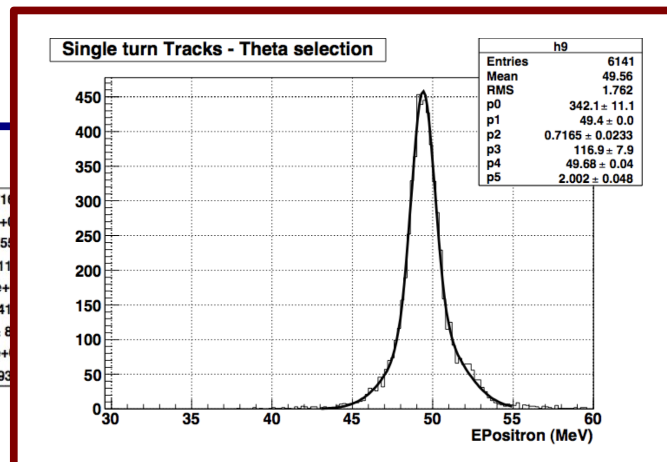
angle & vertex resolution from multi-turn tracks

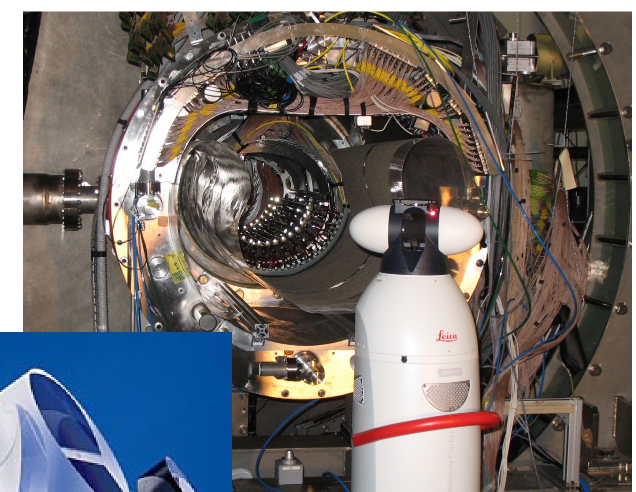


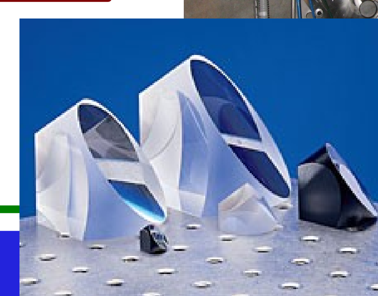
New calibration tools

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



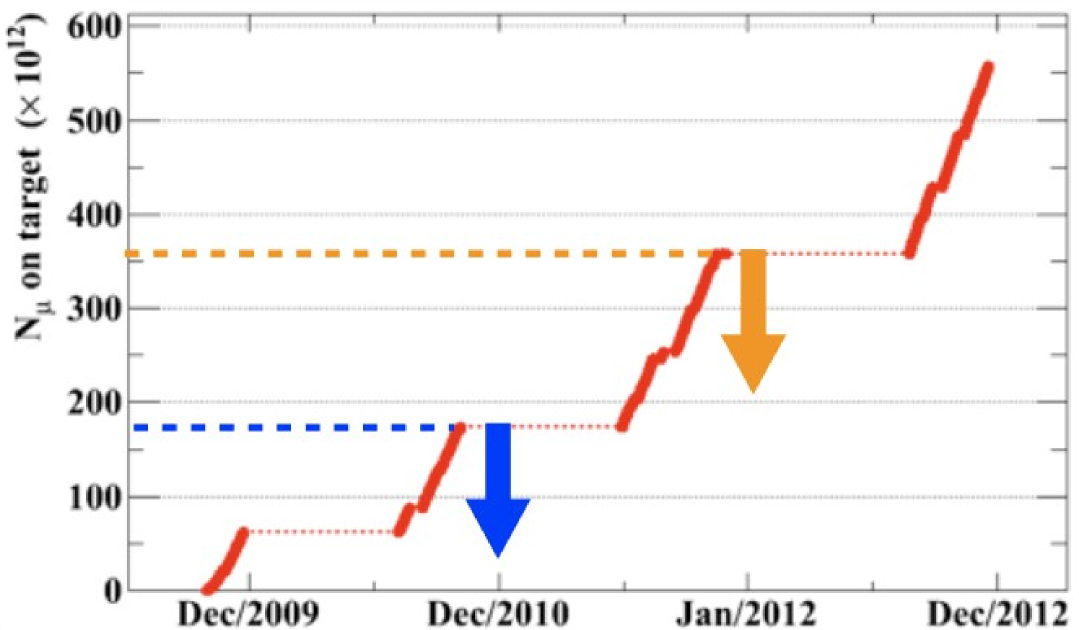






Data Sets

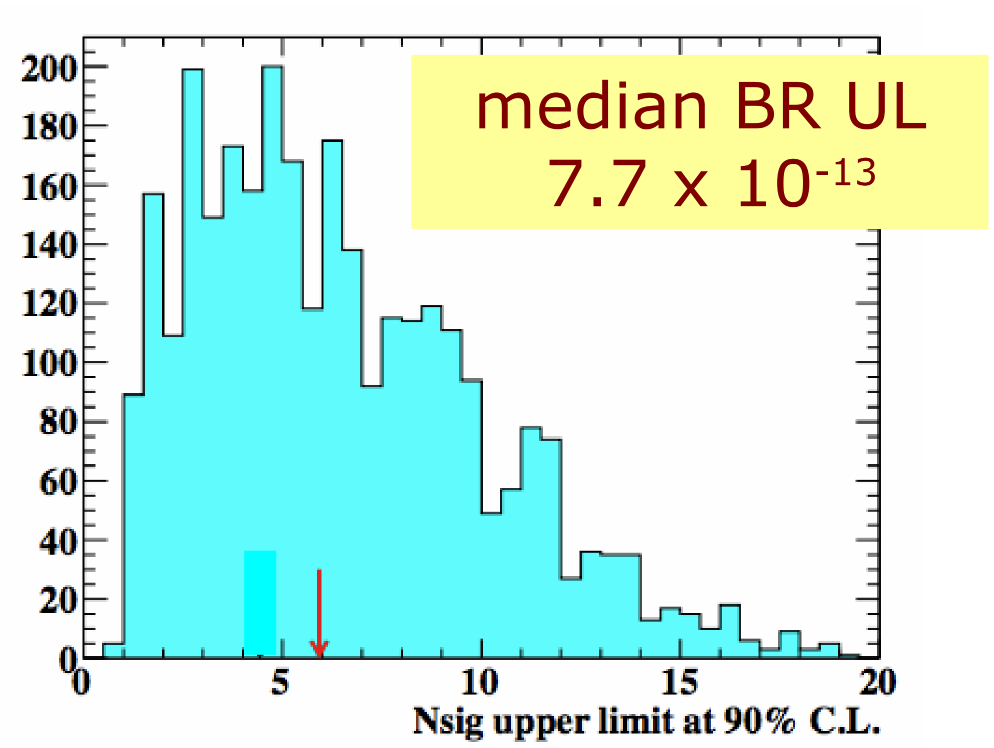
- First run in 2008 with poor detector stability:
  - First result, BR < 2.8 x 10^{-11} **Nucl. Phys. B834 1-12 (2010)**
- Stable run in 2009 – 2012:
  - First analysis of 2009-2010, BR < 2.4 x 10^{-12} **PRL 107 171801**
  - Improved analysis of 2009-2010 data and analysis of 2011 data (presented in this seminar) **arXiv:1303.0754**



Statistical Approach & Sensitivity

- Confidence intervals from a frequentistic procedure based on the **profile likelihood ratio**

$$\lambda_p(N_{SIG}) = \frac{\max_{N_{RMD},N_{ACC}} \mathcal{L}(N_{SIG}, N_{RMD}, N_{ACC})}{\max_{N_{SIG},N_{RMD},N_{ACC}} \mathcal{L}(N_{SIG}, N_{RMD}, N_{ACC})}$$



2009 – 2011 SENSITIVITY FROM TOY MC

- Median UL on N_{SIG} ~ 6
- Normalization factor: **$(7.8 \pm 0.3) \times 10^{12}$**, from the observed yields of $\mu \rightarrow e\, \nu\, \nu$ and RMD.

Analysis Improvements (I)

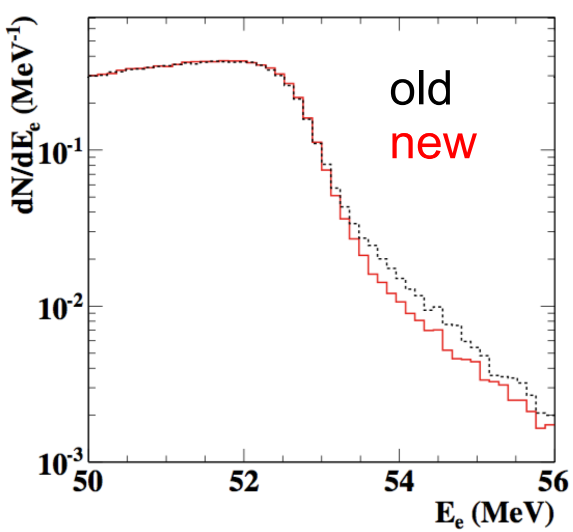
TRACK FIT

- A new Kalman Filter track fit has been developed to overcome the weakness of the previous fitter:
  - better description of detector materials and geometry (GEANT-based);
  - several improvements in the handling of the DC measurements (left/right ambiguities, time-to-distance relations, outlier removal);
  - improved versatility (to allow detailed detector studies).

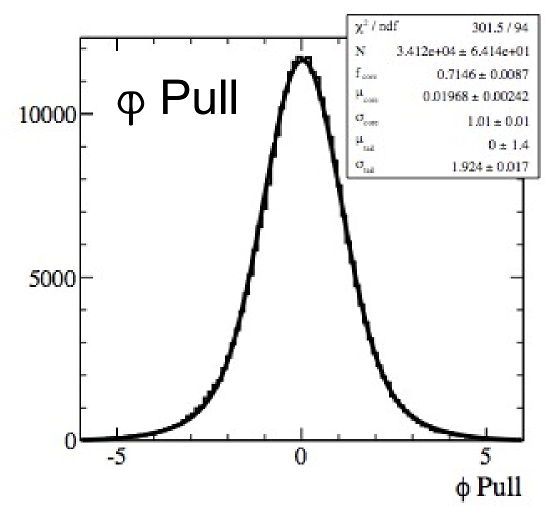
Analysis Improvements (II)

- The new Kalman filter produces:
  - 7% increase in tracking efficiency;
  - smaller resolution tails;
  - reliable per-event estimate of track parameter uncertainties (to be used in the likelihood analysis)

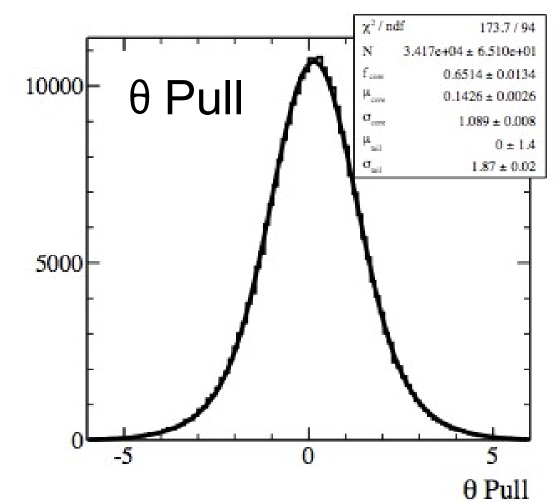
reduced tails



(almost) normal pulls



$\sigma_{core} \sim 1.01 \pm 0.01$

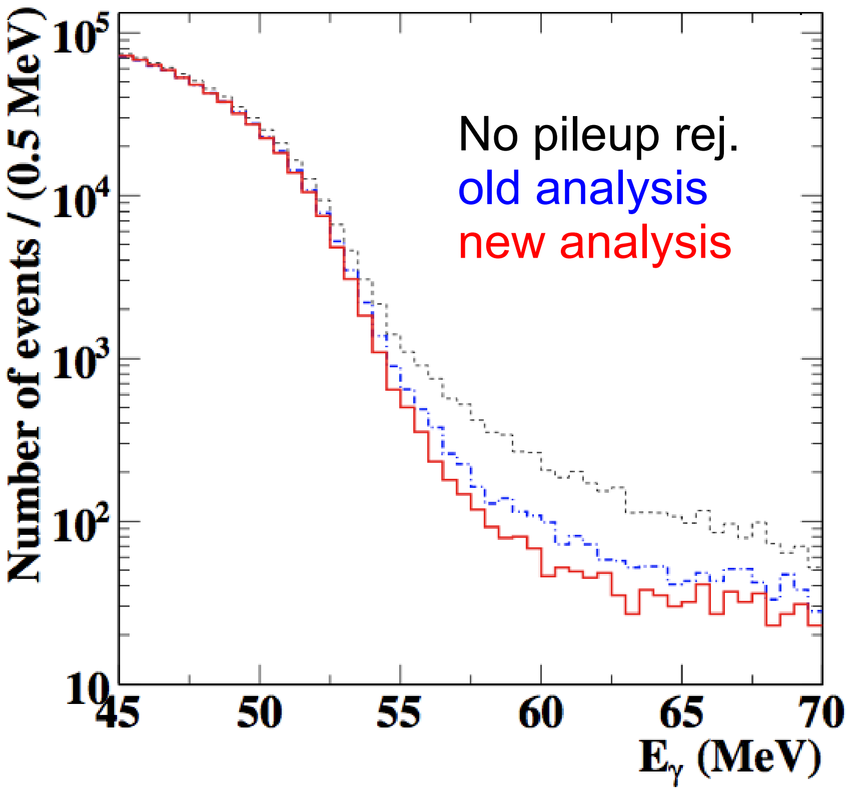


$\sigma_{core} = 1.089 \pm 0.008$

Analysis Improvements (III)

PHOTON PILEUP REJECTION

- An new analysis of the signal waveforms has been developed to reject the photon pileup in the LXe detector:
  - 7% increase in photon detection efficiency;
  - suppressed rate of unrecognized pileup events.

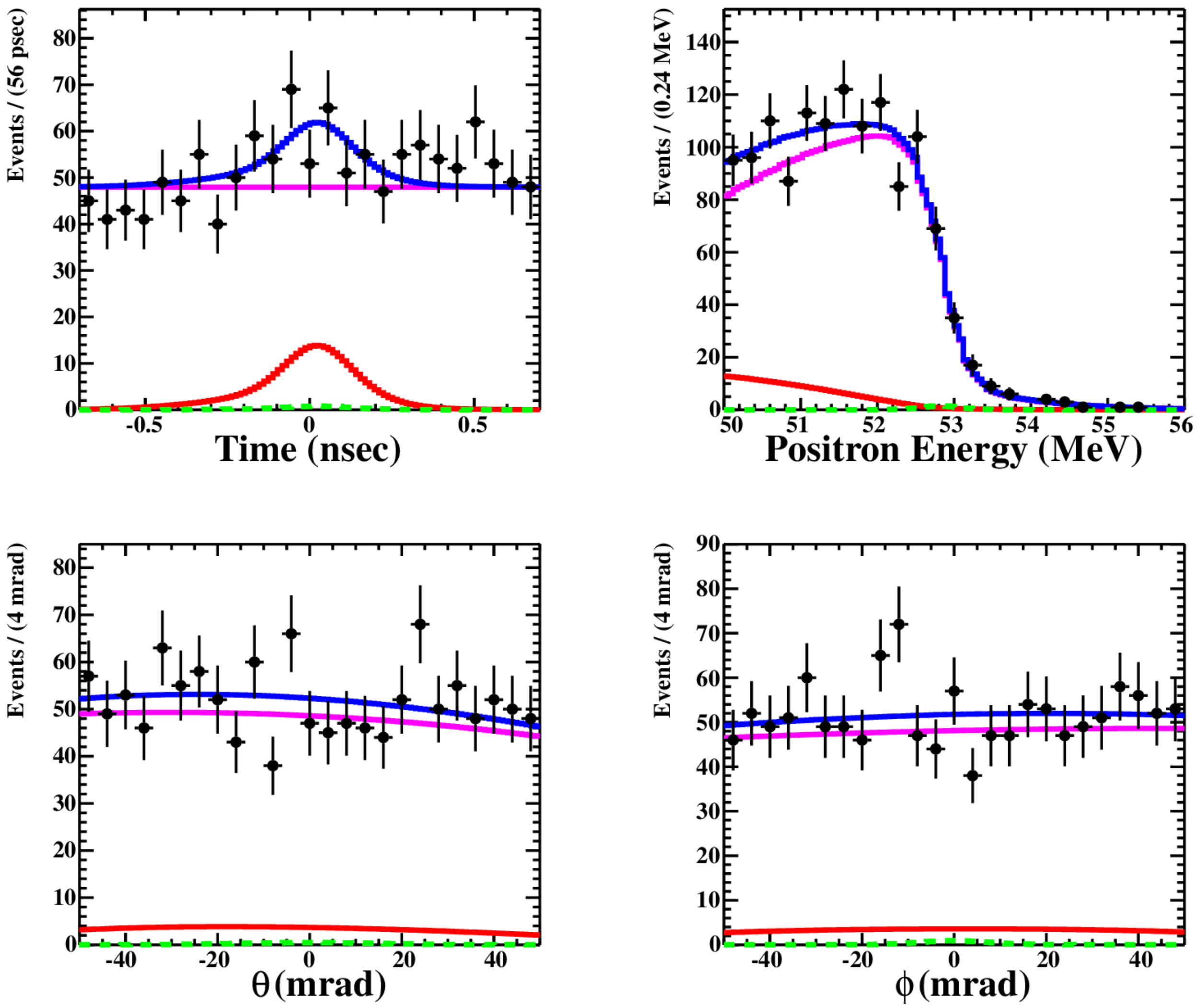


Analysis Improvements (IV)

IMPACT ON SENSITIVITY

- The recent improvements in the analysis improved the $\mu \to e \gamma$ sensitivity by:
  - 6% thanks to the improved positron efficiency;
  - 6% thanks to the improved photon efficiency;
  - 10% thanks to the use of positron per-event errors in the likelihood analysis;
- Further improvements obtained from a new noise filtering procedure in the drift chamber analysis.

New Analysis of 2009/2010 data



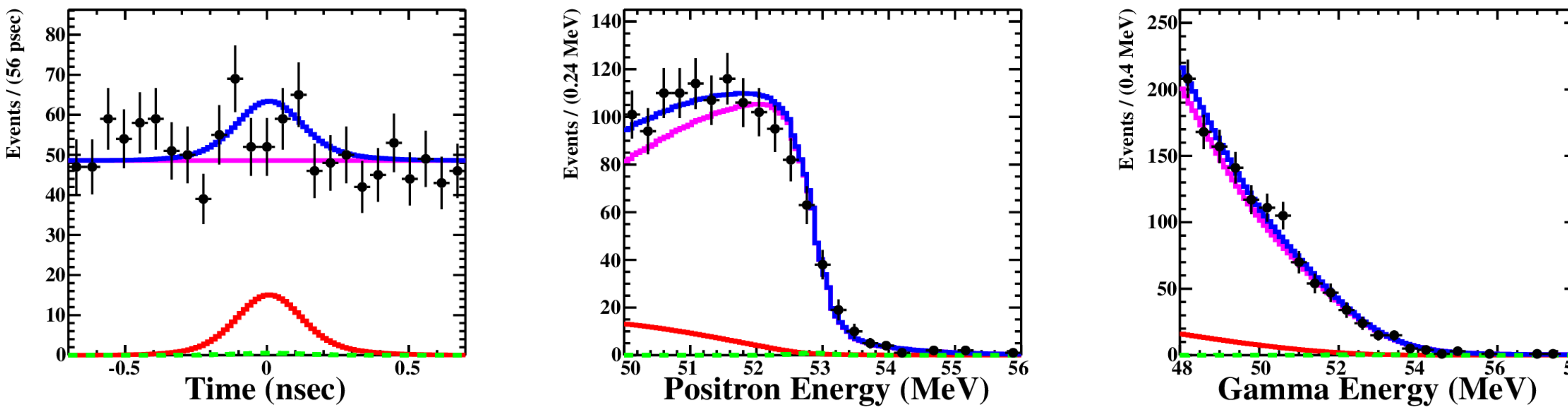
Based on
~ 17.5 x 10^{13} μ
stopped at the target

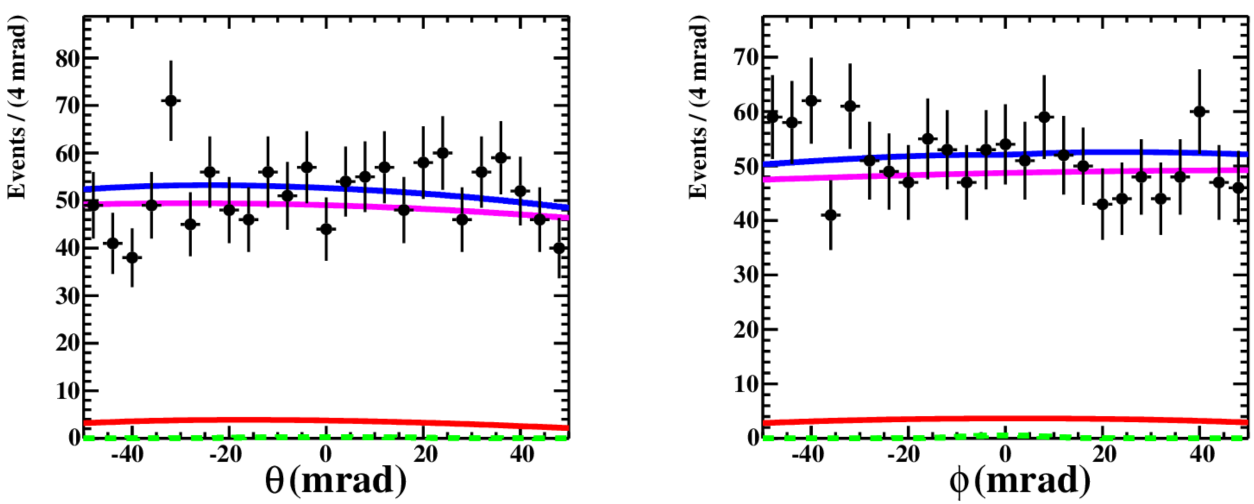
$N_{sig} = 0.3^{+4.1}_{-1.5}$

$N_{bkg} = 1198 \pm 26$

$N_{RD} = 83 \pm 13$

Analysis of 2011 data





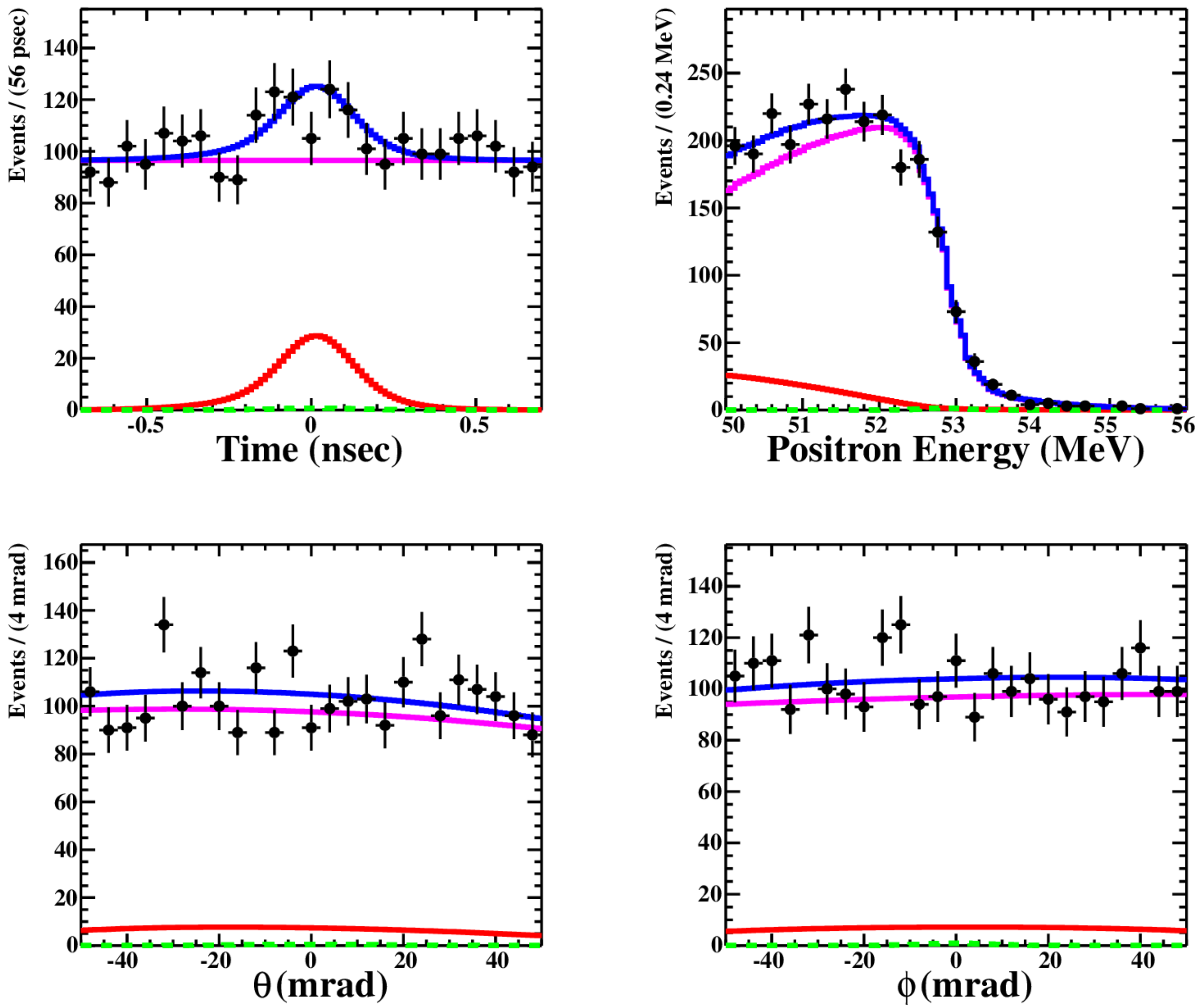
Based on
~ 18.5 x 10^{13} μ
stopped at the target

$N_{sig} = -1.4^{+3.8}_{-1.9}$

$N_{bkg} = 1215 \pm 26$

$N_{RD} = 85 \pm 13$

Combined analysis 2009-2011 (I)



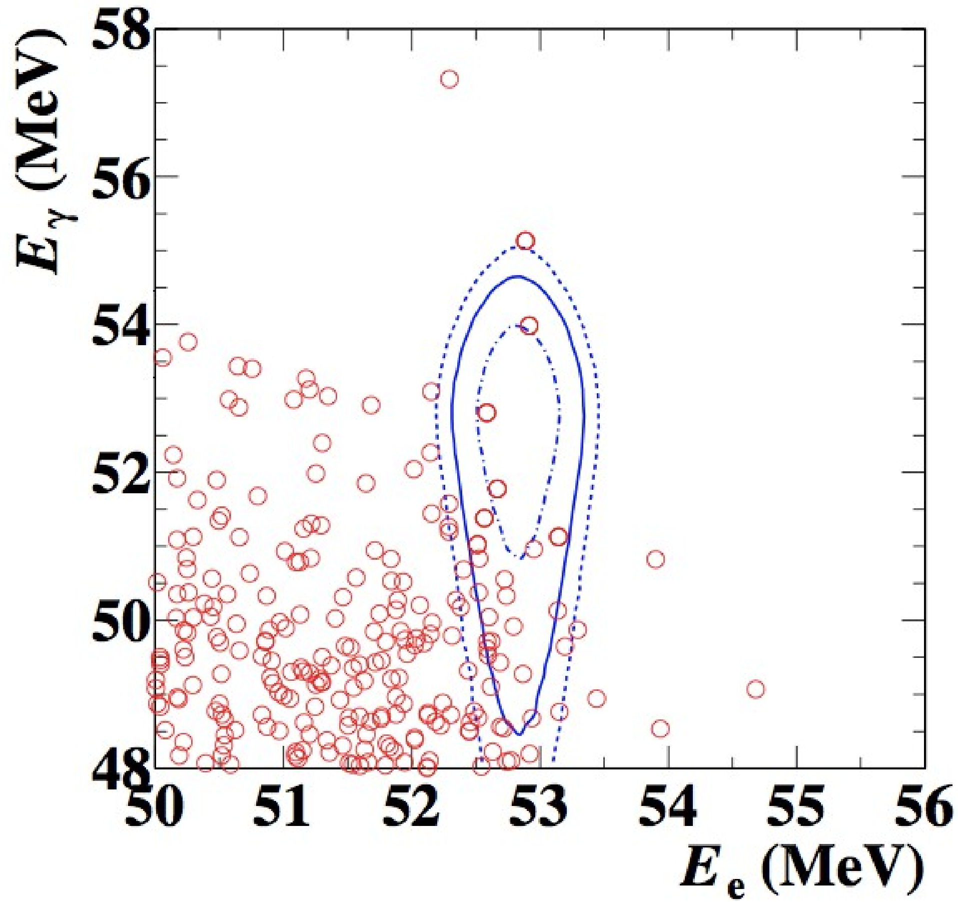
Based on
~ 36 x 10^{13} μ
stopped at the target

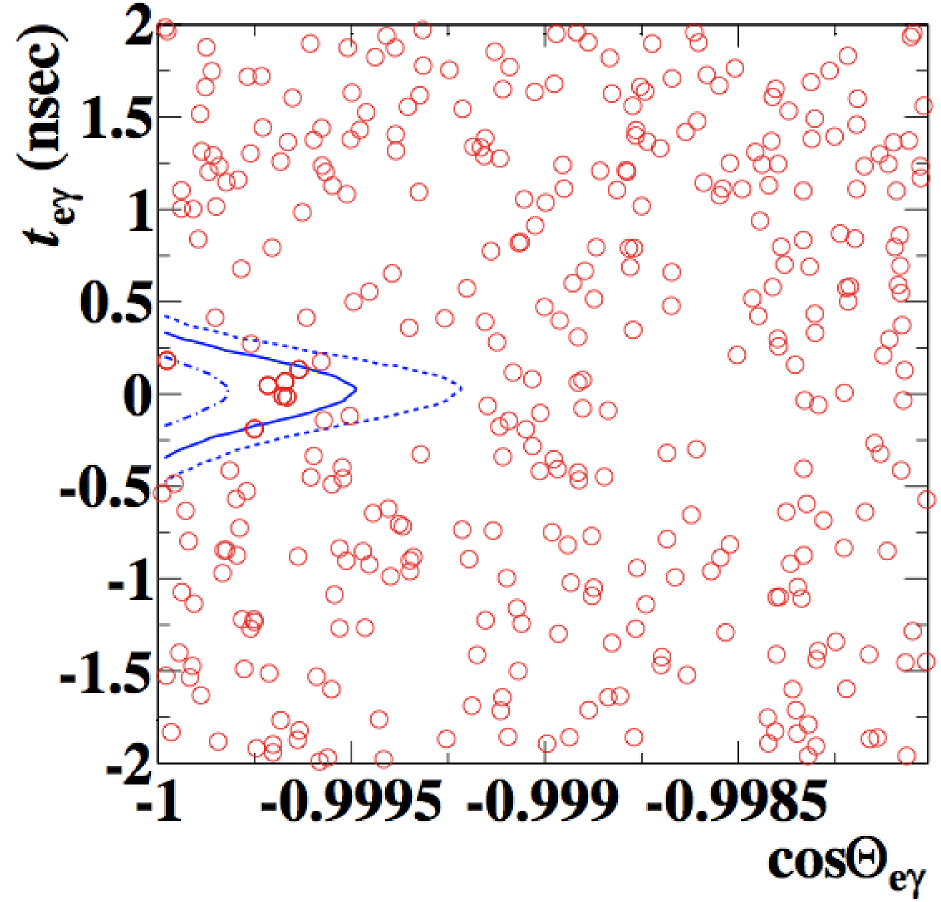
$N_{sig} = -0.4^{+4.8}_{-1.9}$

$N_{bkg} = 2413 \pm 37$

$N_{RD} = 167 \pm 24$

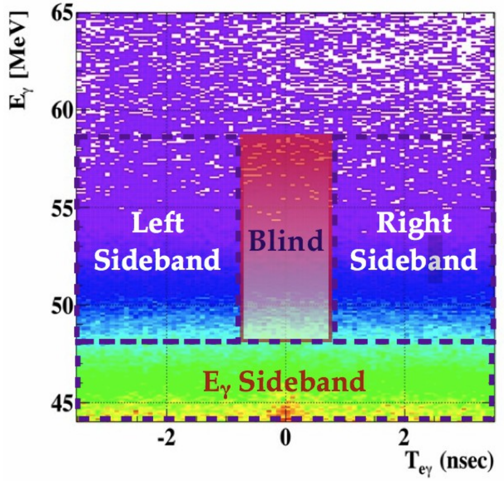
Combined analysis 2009-2011 (II)

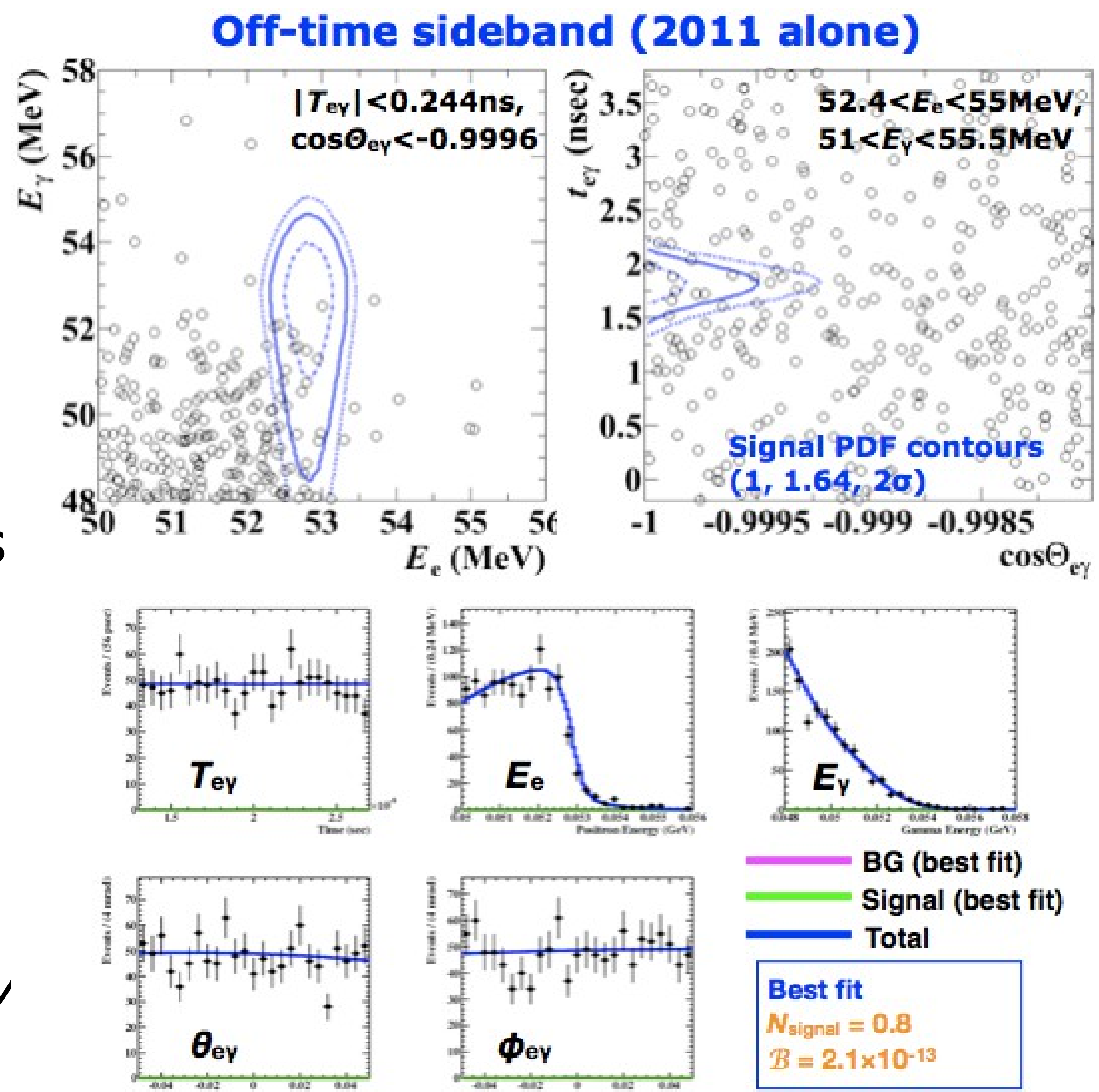




contours (Signal PDF): 1σ, 1.64σ, 2σ

Control samples





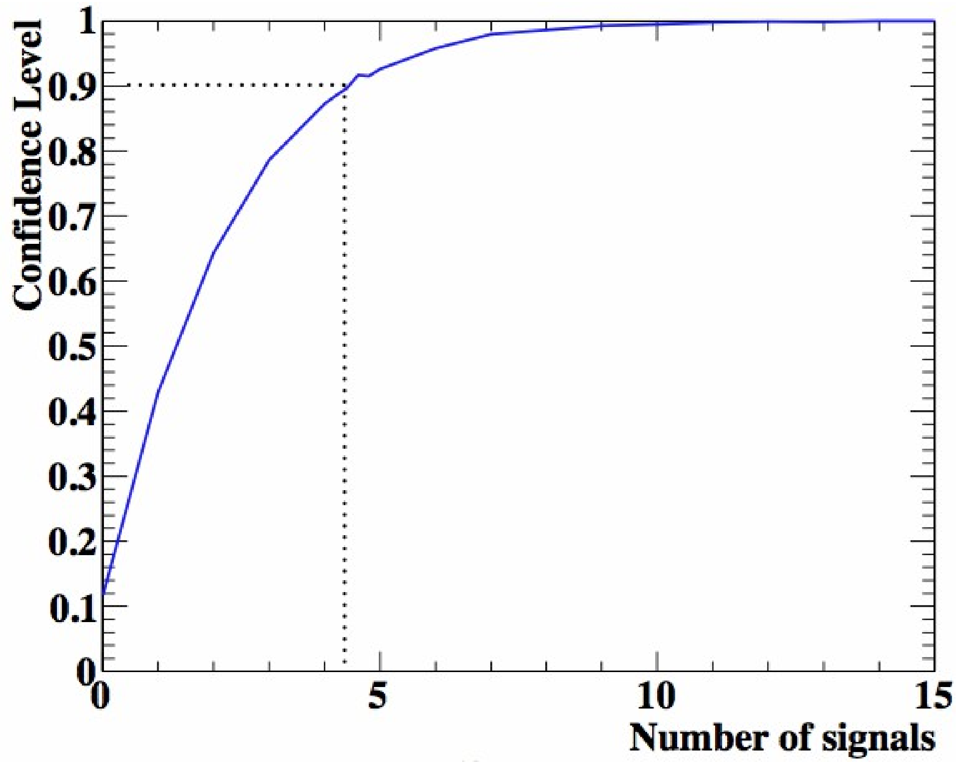
Fictitious analysis regions in the **sidebands** of E_γ, $T_{e\gamma}$ and relative angles used as control samples

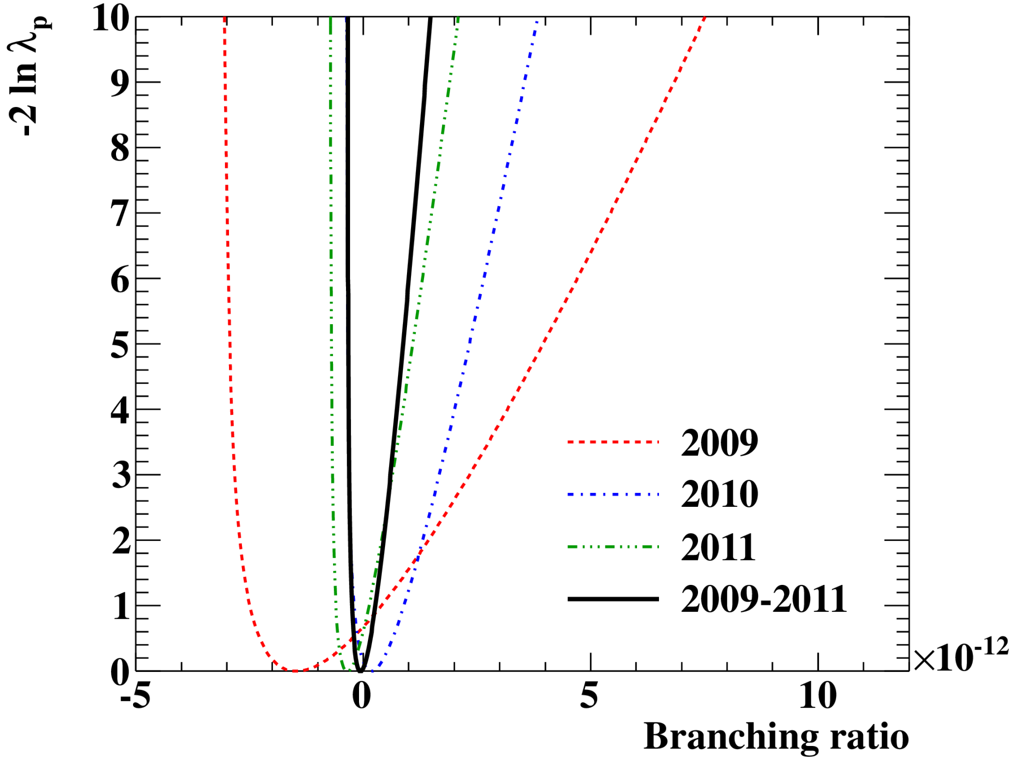
Limits consistent with toy MC studies

Confidence Intervals

$BR(\mu \rightarrow e\,\gamma) < 5.7 \times 10^{-13}$

incl. systematics





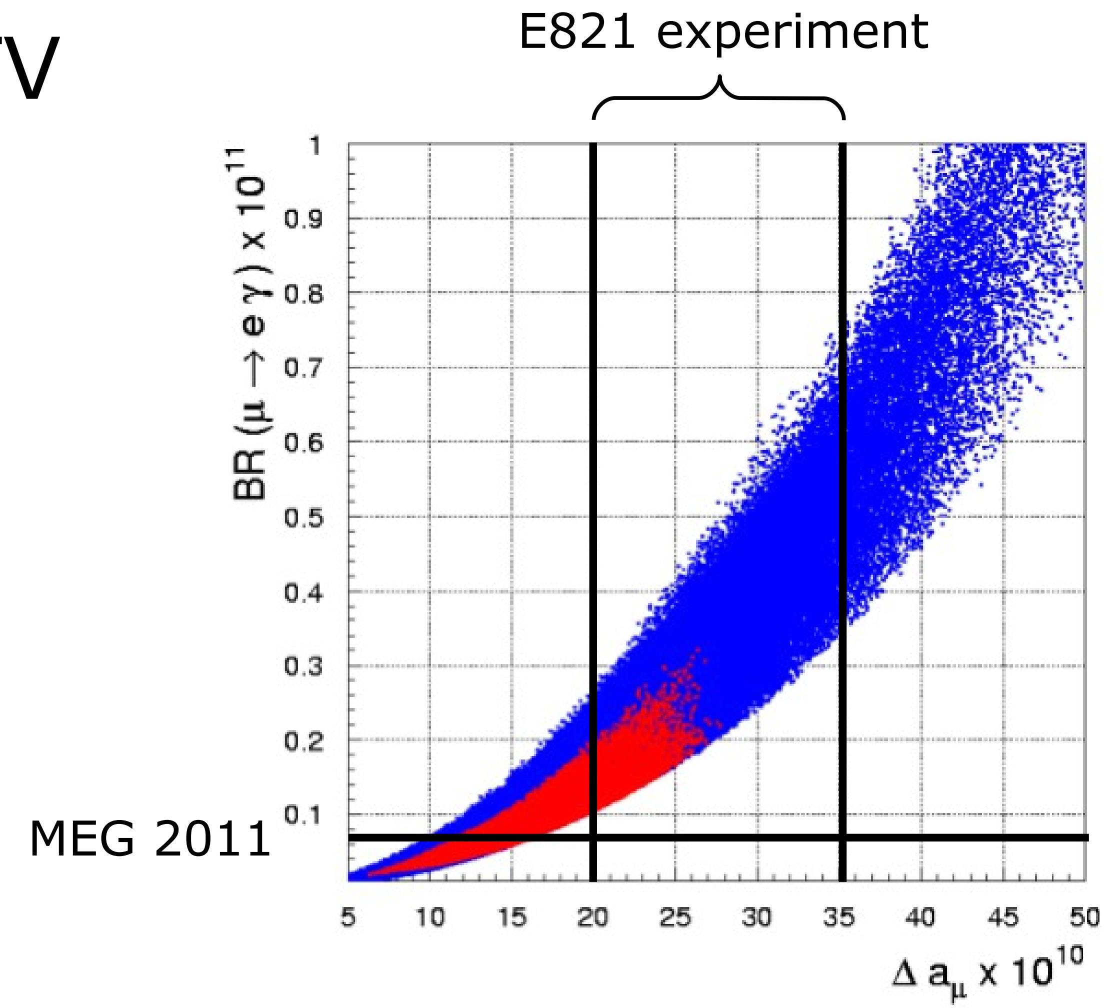
arXiv:1303.0754, Accepted by Phys. Rev. Lett.

LFV and dipole moments

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

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

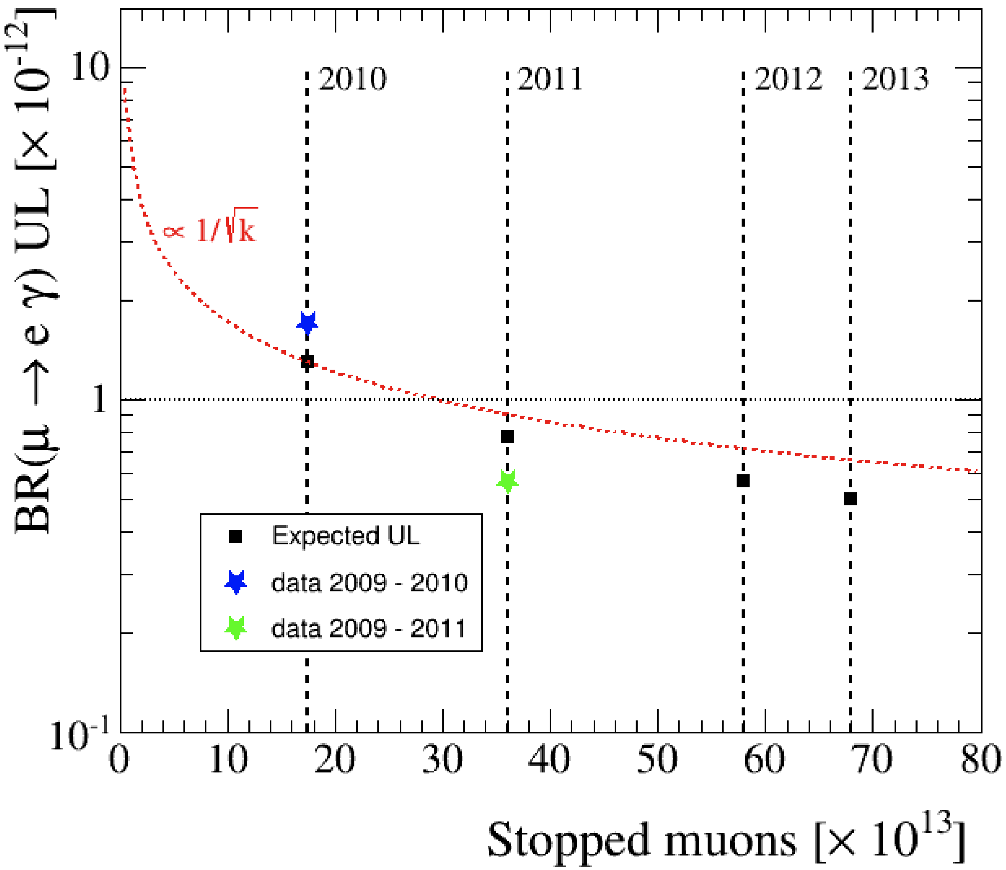
$$\Delta a_\mu = a_\mu - a_\mu^{SM}$$



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

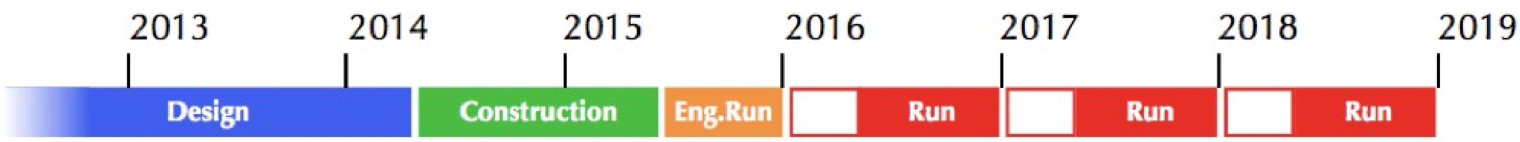
2012 and 2013 Runs

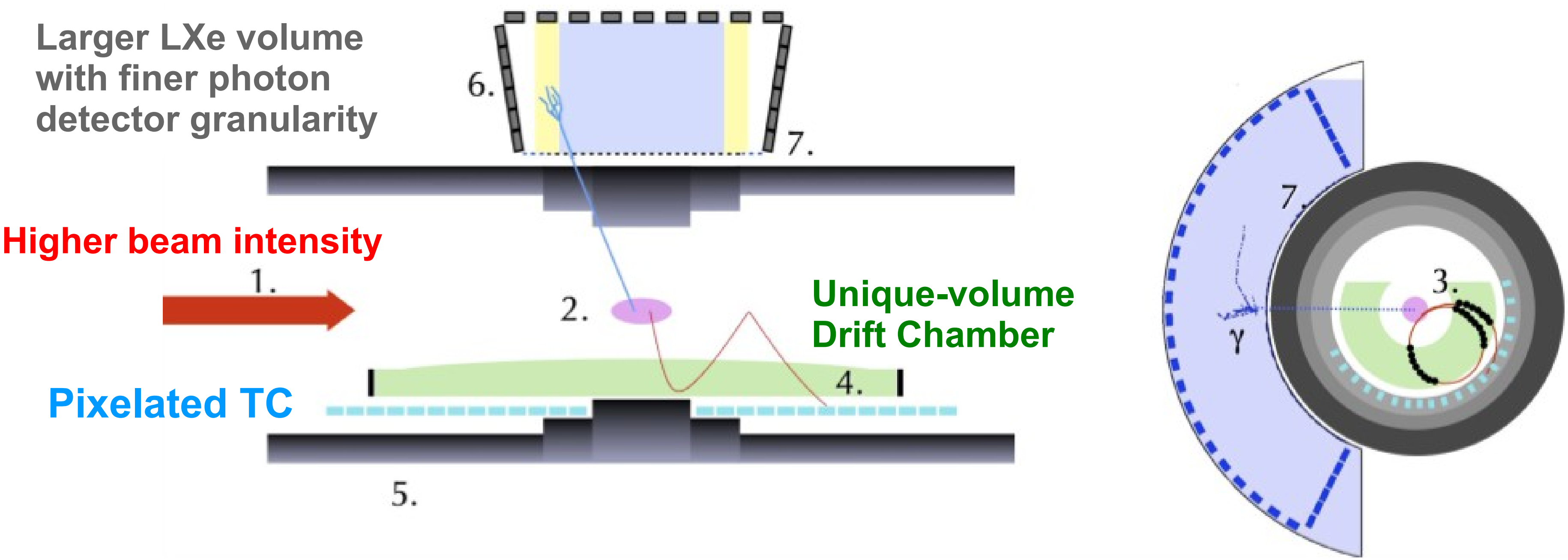
- ~ 22 x 10^{13} stopped μ during 2012 (~ 60% of the 2009 + 2010 + 2011 statistics);
- Analysis on going:
  - exp. sens. ~ 5.7 x 10^{-13}
- A 3-month run is planned from May 2013:
  - final sens. ~ 5 x 10^{-13}



The MEG Upgrade (arXiv:1301.7225)

- An upgrade of MEG, aiming at a sensitivity improvement of **one order of magnitude** (down to 5×10^{-14}) is under design;
- Strong endorsement by the PSI Scientific Committee, and funding agencies in Japan and Italy.





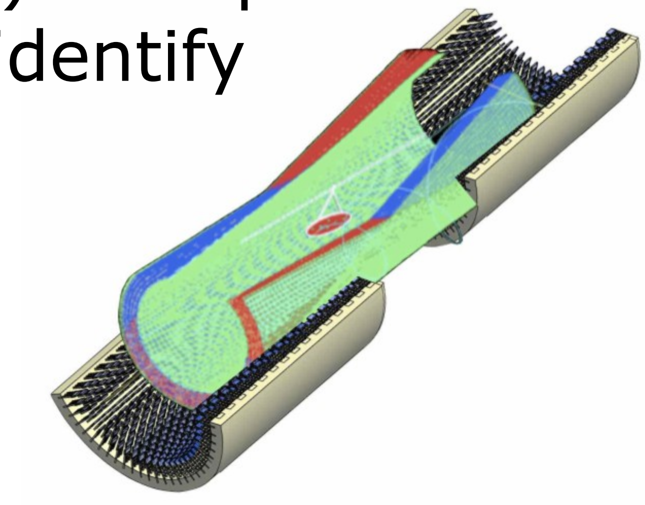
Drift Chamber Design

- Unique-volume drift chamber with **stereo wires** and helium-isobutane gas admixture, to replace the current system of 16 independent chambers;

MAIN IMPROVEMENTS

- Longer tracking region with finer granularity;
- Lower material budget (30% less X_0);
- Faster readout electronics (~ GHz BW) to improve the drift time resolution and possibly identify single ionization cluster;

$\sigma(XY) \sim 120\ \mu m$
$\sigma(Z) \sim 900\ \mu m$
$\Rightarrow$
$\sigma(p) \sim 130\ keV$
$\sigma(\theta,\varphi) \sim 5\ mrad$

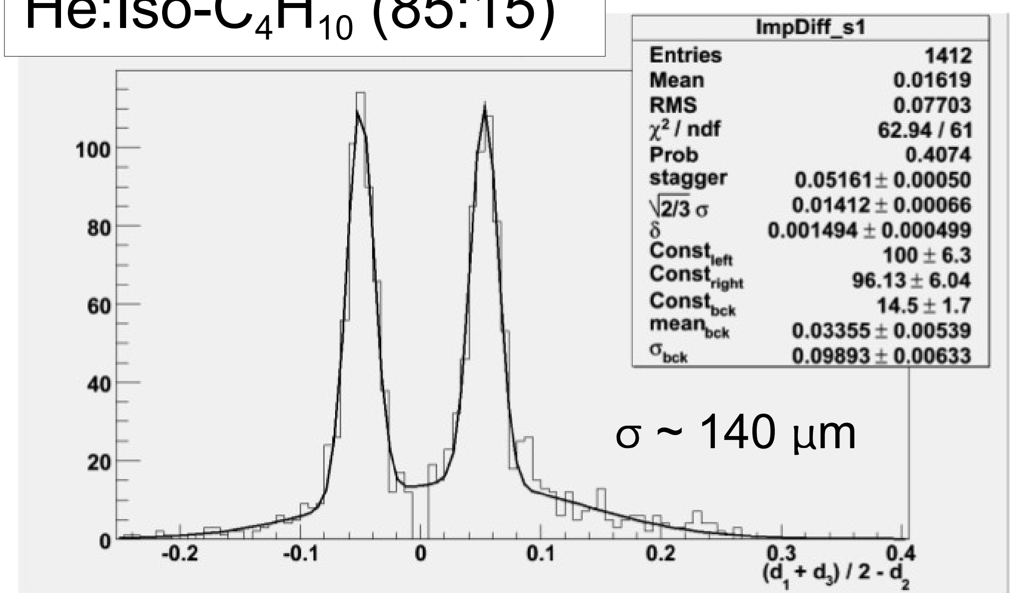


Drift Chamber R&D (I)

PRELIMINARY TESTS

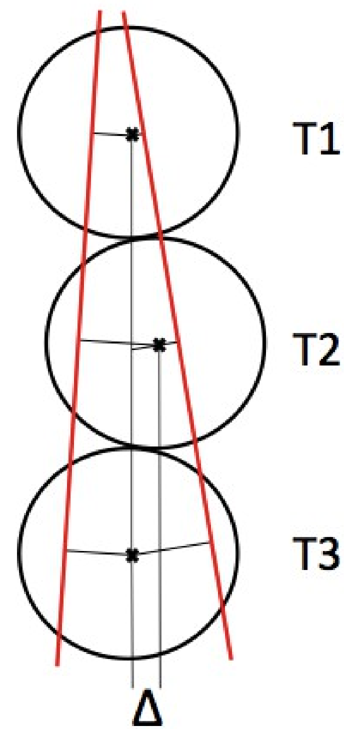
- A system of 3 drift tubes, with a small stagger Δ, has been used to prove the possibility of reaching resolutions < 150 μm with a light gas mixture.

He:Iso-C_4H_{10} (85:15)



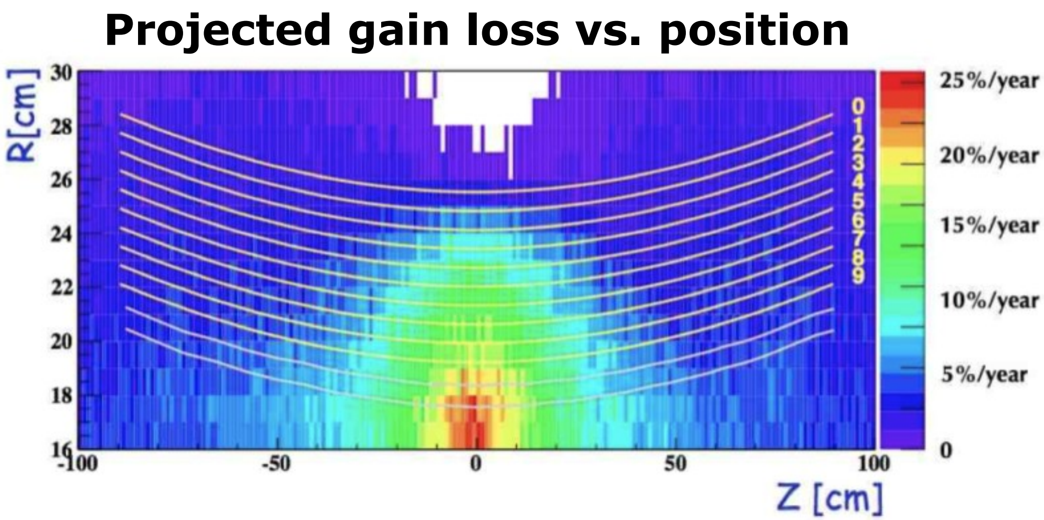
$$\frac{d_1 + d_3}{2} - d_2 = \pm\Delta$$

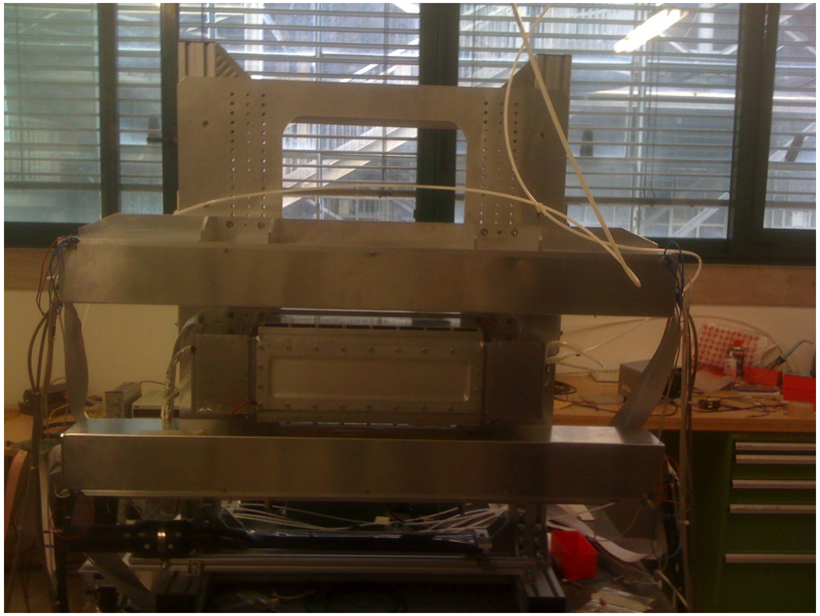
$$\sigma_\Delta \cong \sqrt{\frac{3}{2}}\,\sigma_d$$



Drift Chamber R&D (II)

- Successful aging tests have been performed;
- Measurement of resolution with a small prototype on a silicon detector cosmic ray telescope is on going;

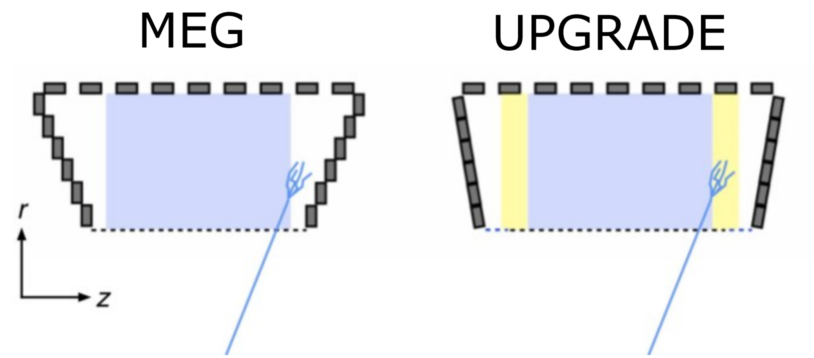




- Next steps:
  - optimization of geometry and materials;
  - construction of more complex prototypes to validate the performances and the construction procedures.

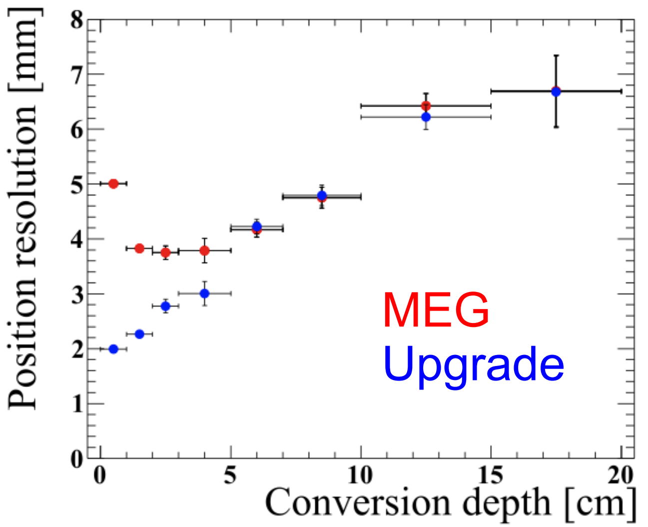
LXe Detector Design

- Silicon Photomultipliers (SiPM) to replace the PMTs in the inner face;
- New geometry of lateral faces.



MAIN IMPROVEMENTS

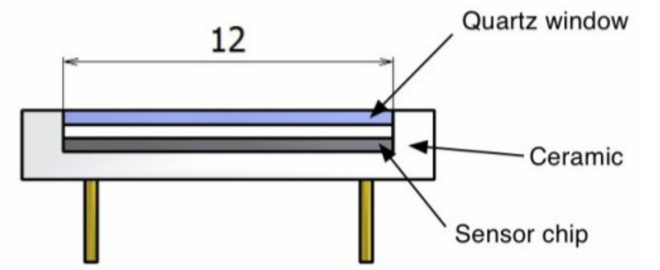
- Larger fiducial volume;
- Finer granularity in the inner face:
  - better resolutions for shallow γ;
- Better control of reflexions in the lateral faces.

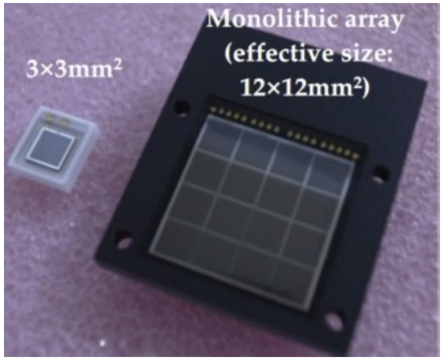


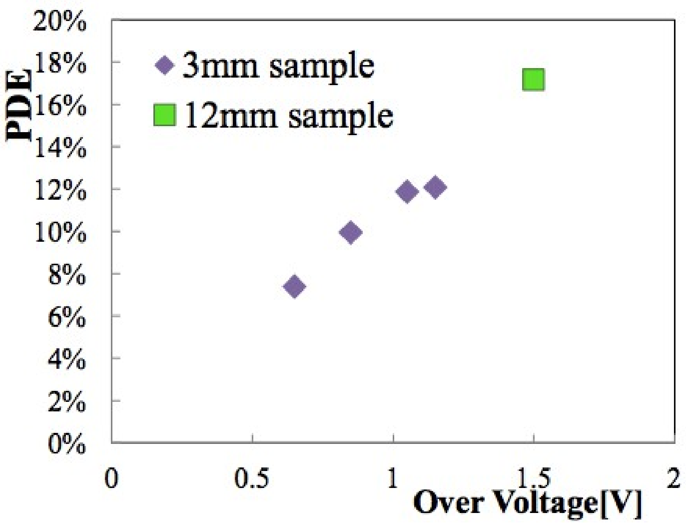
σ(E) ~ 1%   σ(position) ~ 2 (5) mm in x,y (z)

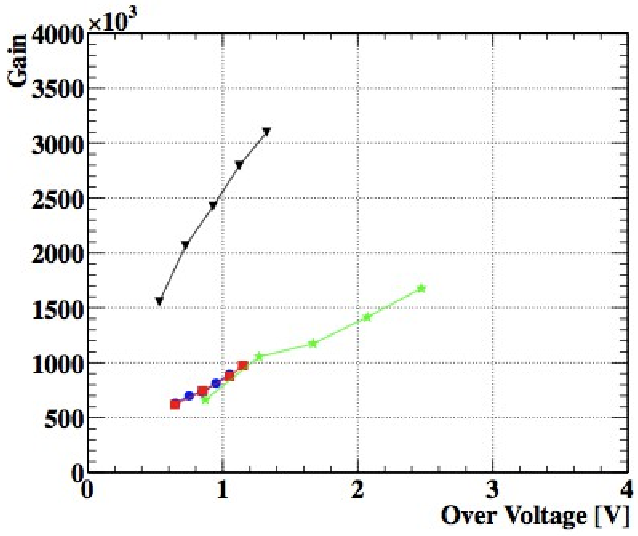
LXe Detector R&D

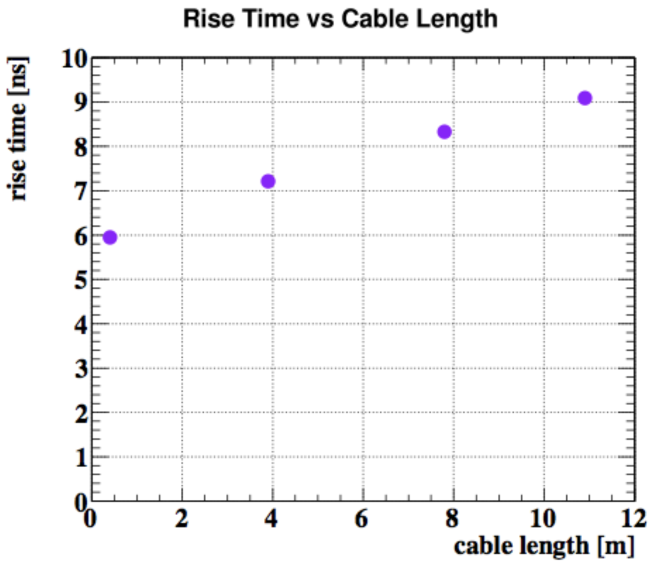
- Development of dedicated UV-sensitive large-area SiPM in collaboration with Hamamatsu;
- Several measurements performed (photon detection efficiency, gain, signal deterioration by feedthrough and cables);
- Next step: test with LXe prototype;









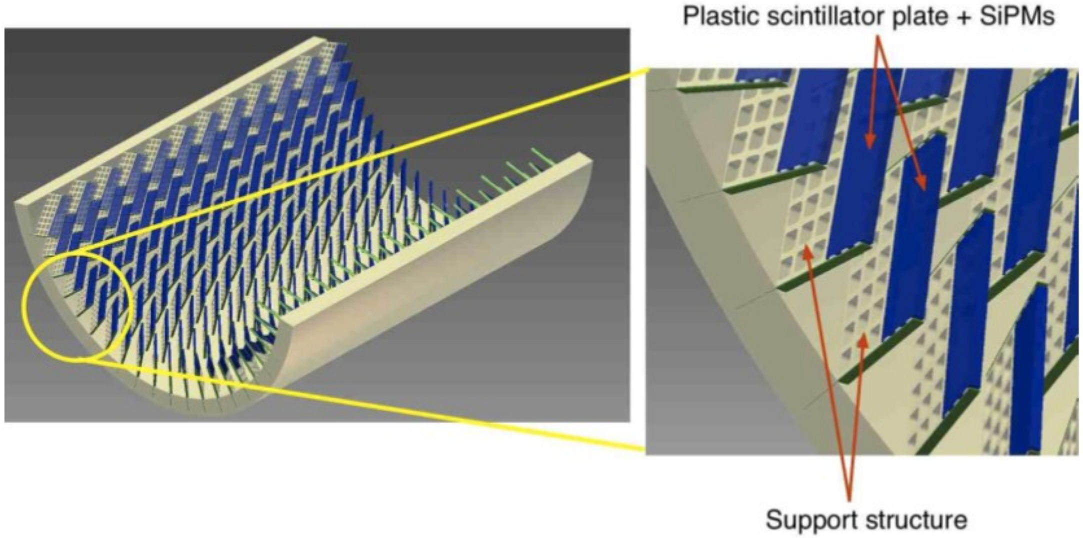


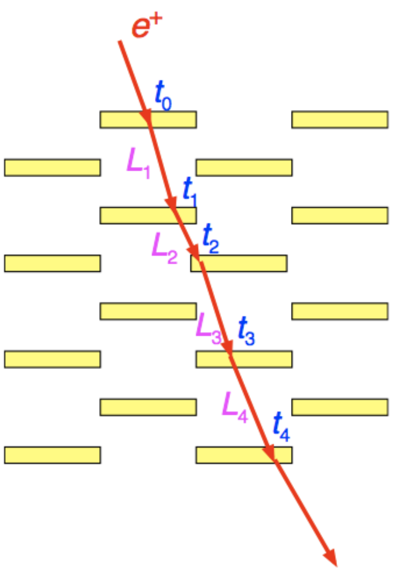
Timing Counter Design

- *Pixelated TC*: ~ 500 – 800 scintillating tiles, read out by SiPM, to replace the 30 bars of the present TC;

MAIN IMPROVEMENTS

- Better time resolution and multiple time measurements for the same positron;
- Higher rate tolerance.

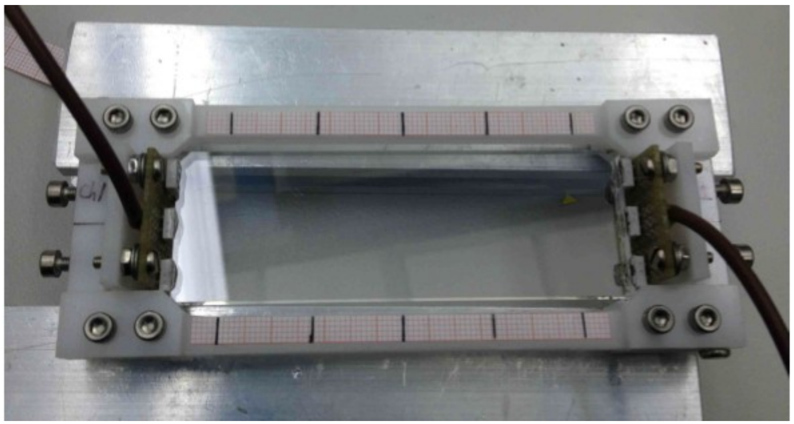


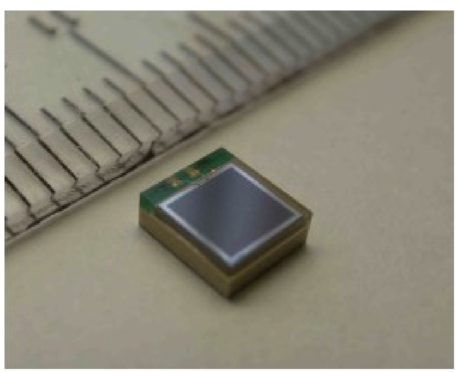


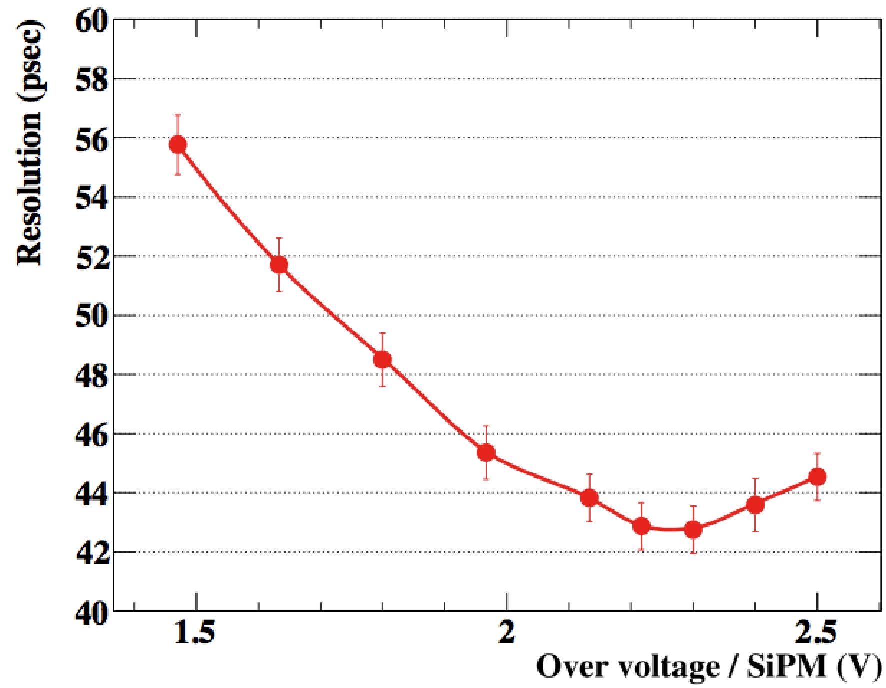
$$\sigma^2_{\text{overall}} = \frac{\sigma^2_{\text{single}}}{N_{\text{hit}}} + \frac{\sigma^2_{\text{inter-pixel}}}{N_{\text{hit}}} + \sigma^2_{\text{MS}}(N_{\text{hit}})$$

Timing Counter R&D

- Test of a single counter showed the desired resolutions;







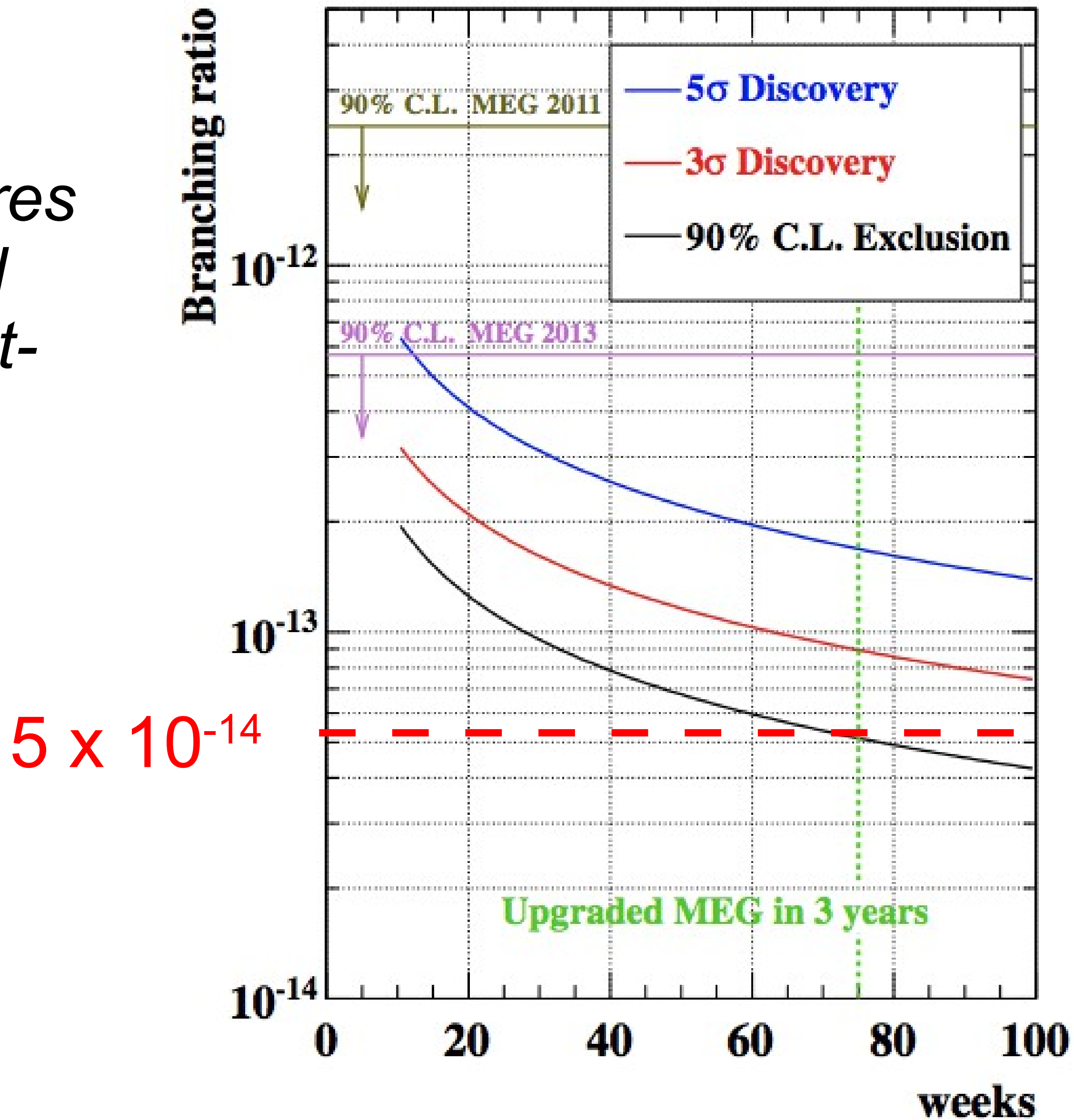
- Next step: study of multi-hit resolution with beam tests on a small prototype.

DAQ & Trigger

- In MEG, full waveforms are acquired for all channels of the detector (with a custom digitizing chip, the *DRS*).
- A similar scheme is planned for the upgrade, but adopting a new DAQ board design (*WaveDREAM*):
  - large bandwidth for DC applications;
  - compact design;
  - Trigger, DAQ and SiPM HV in the same board;
  - possibility of higher-level trigger.

Projected Sensitivity

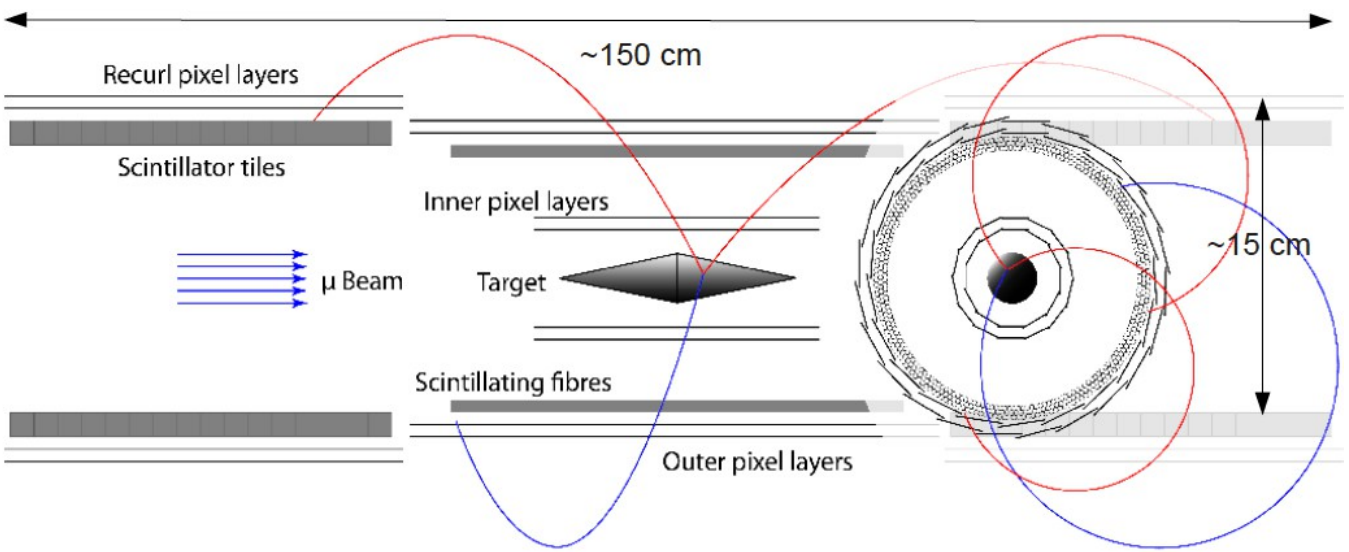
From Toy MC experiments including all relevant features observed in MEG data and upgrade simulations (event-dependent resolutions, correlations, etc.).



Other μ LFV searches (I)

PROPOSED SEARCH FOR $\mu^+ \rightarrow e^+ e^+ e^-$ @ PSI (Mu3e)

A search for $\mu^+ \rightarrow e^+ e^+ e^-$ down to BR ~ 10^{-16}

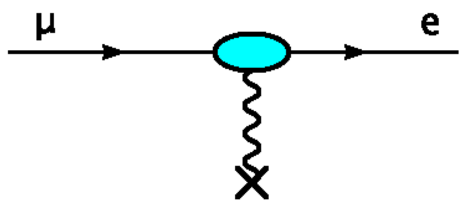


- Two-phase project (low and high beam intensity):
  - first phase potentially superimposed to the MEG upgrade (PSI could consider the possibility of some beam time sharing, if Mu3e is also approved).

Other μ LFV searches (II)

SEARCHES FOR $\mu \to e$ CONVERSION IN NUCLEI

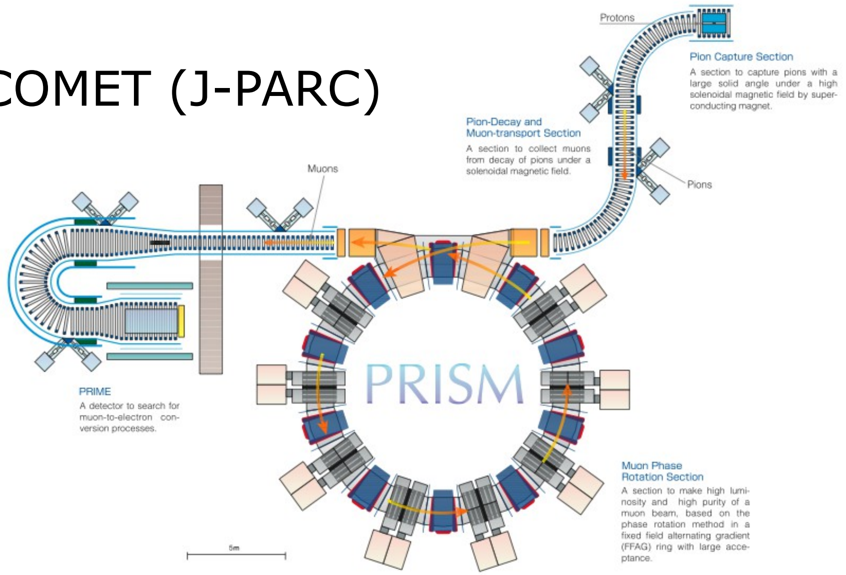
- Two R&D to search for $\mu \to e$ conversion in the interaction with nuclei at a level of $< 10^{-16}$.

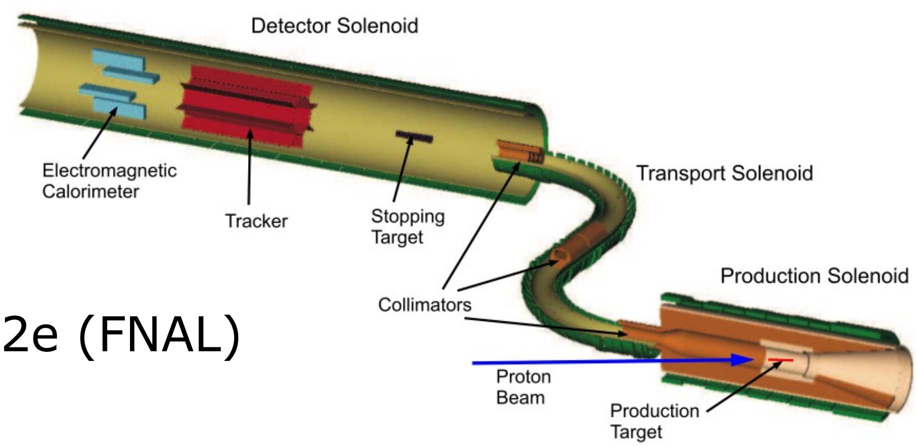


In many models:

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

COMET (J-PARC)

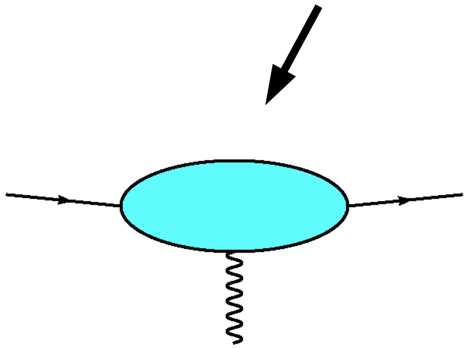


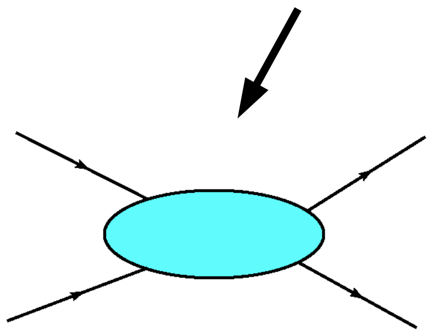


Mu2e (FNAL)

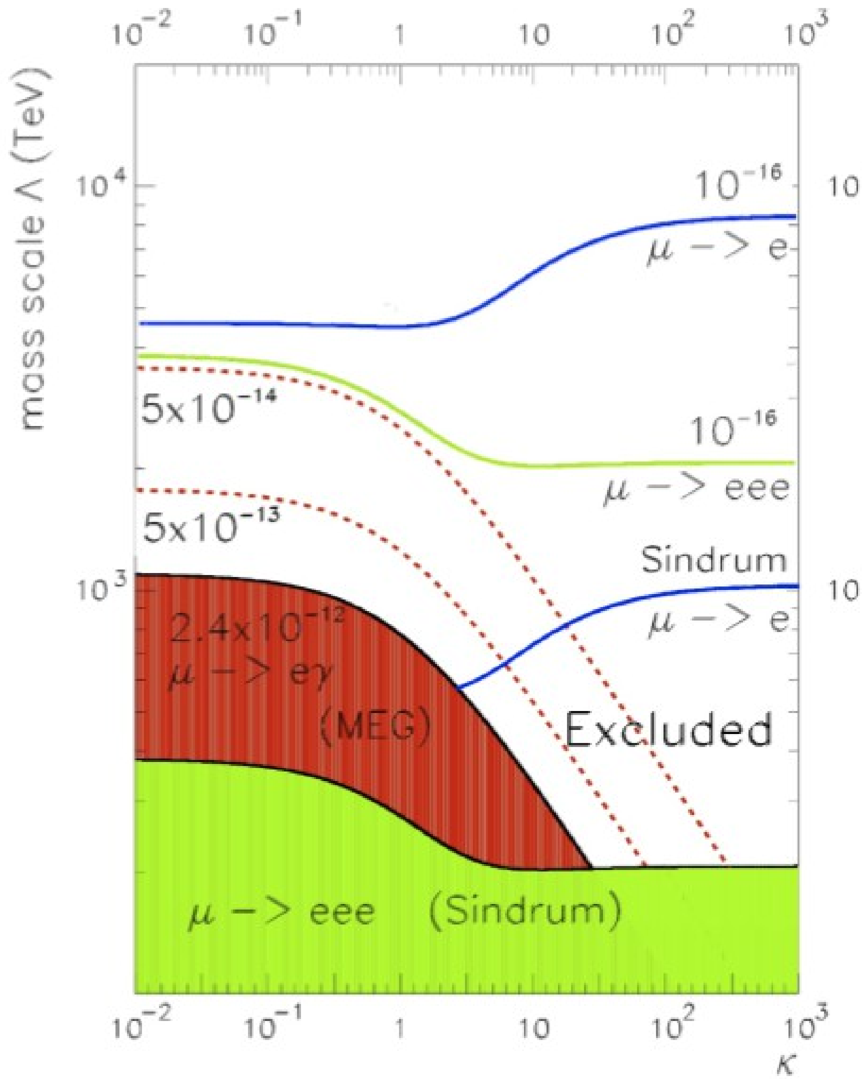
Comparison of Sensitivities

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

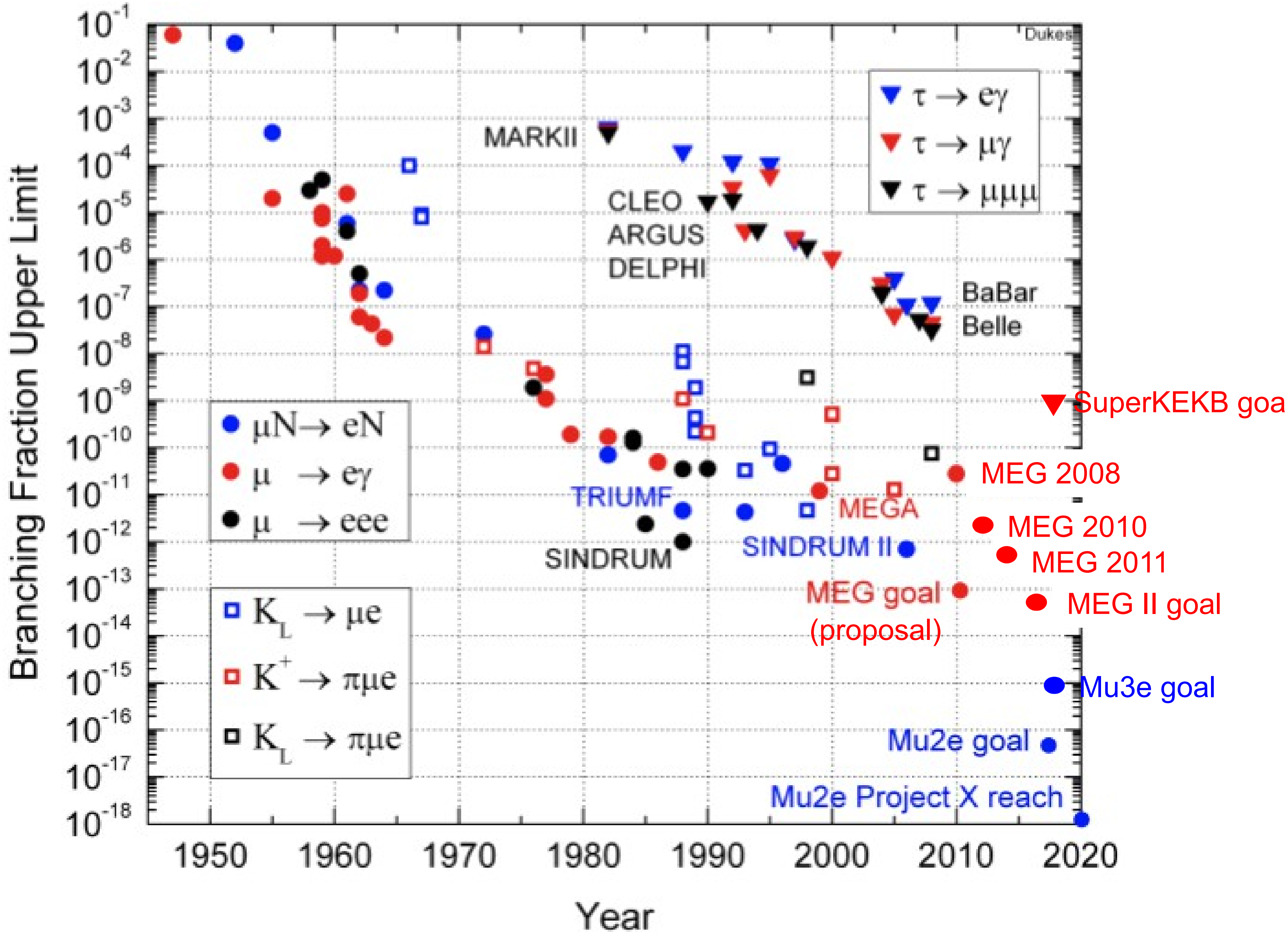




If LFV is predominantly produced by dipole-like interactions (as in SUSY-GUTs), the MEG upgrade will be competitive with Mu3e and the first phase of the $\mu \to e$ conversion experiments.

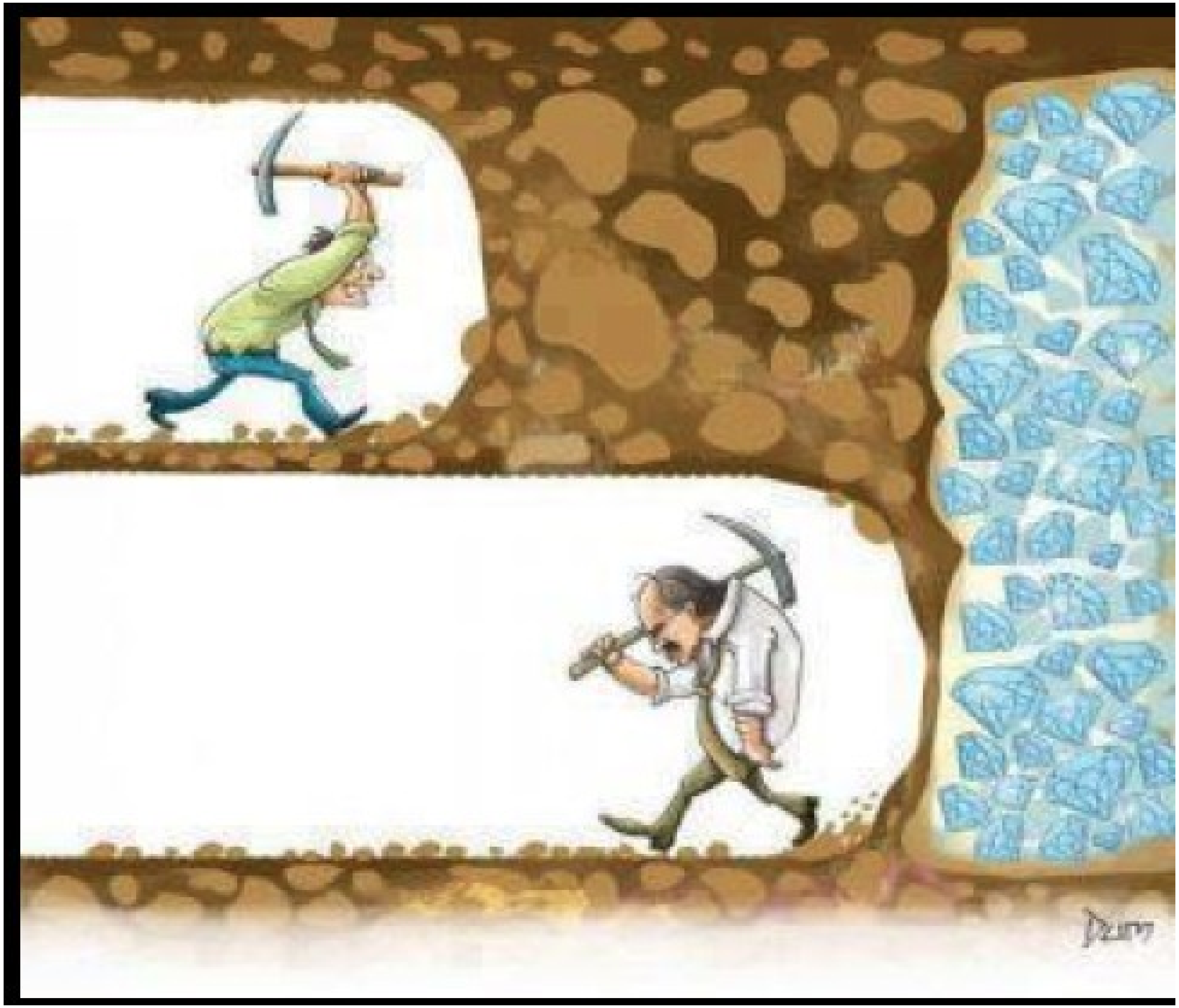


History of Searches for LFV



E. C. Dukes, TAU2010

Do not stop searching!



Backup

LXe properties

NaI(Tl)

- 2.59 cm (Radiation length X_0)
- 4.13 cm (Molière radius R_M)
- 230 ns (Lifetime triplet τ_t)
- 410 nm (Peak emission wavelength λ_{scint})
- 30 cm (Scint. Absorption length λ_{abs})

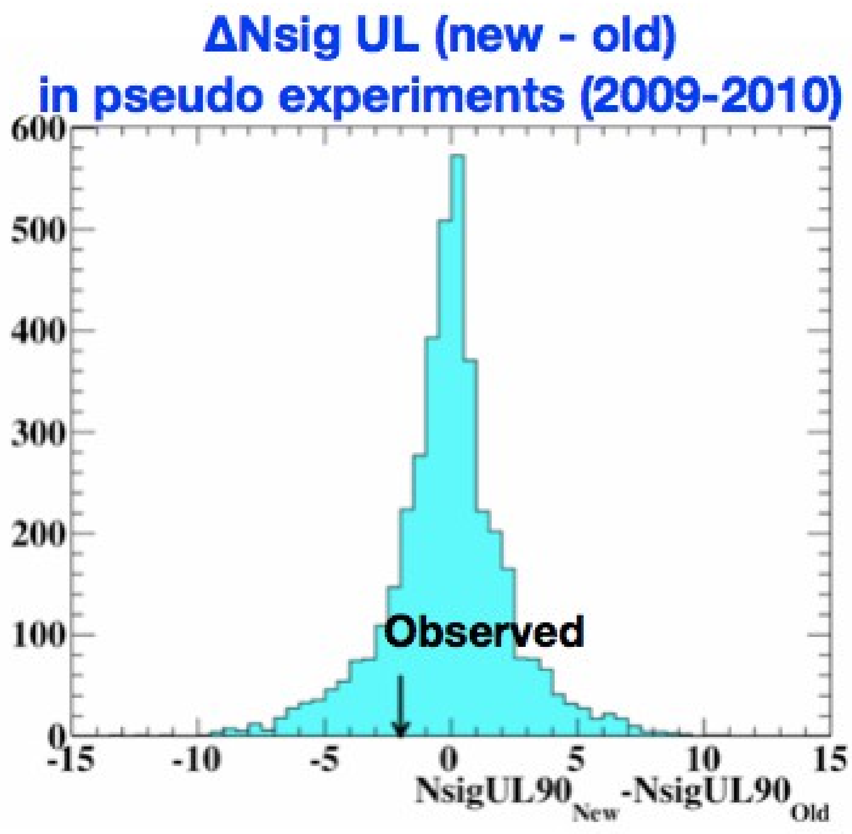
Material Properties	Value & Unit	Conditions
Atomic Number	54	
Atomic Weight A	131.29 g/mole	
Boiling point T_b	165.1 K	1 atm
Melting point T_m	161.4 K	1 atm
Density ρ_{liq}	2.98 g/cm^3	161.35 K
Volume ratio ρ_{gas}/ρ_{liq}	550	15 °C, 1 bar
Critical point T_c, P_c	289.7 K, 58.4 bar	
Triple point T_3, P_3	161.3 K, 0.816 bar	
Radiation length X_0	2.77 cm	in liquid
	8.48 g/cm^2	
Molière radius R_M	5.6 cm	
Critical Energy	10.4 MeV	
$-(dE/dx)_{mip}$	1.255 MeV cm^2/g	
Refractive index	$1.6 \div 1.72$	in liquid at 178 nm
Fano Factor	0.041	theoretical
	unknown	experimental
Energy/scint. photon W_{ph}	(23.7 ± 2.4) eV	electrons
	(19.6 ± 2.0) eV	α-particles
Lifetime singlet τ_s	22 ns	
Lifetime triplet τ_t	4.2 ns	
Recombination time τ_r	45 ns	dominant for e, γ
Peak emission wavelength λ_{scint}	178 nm	
Spectral width (FWHM)	$\sim$ 14 nm	
Scint. Absorption length λ_{abs}	$>$ 100 cm	
Rayleigh scattering length λ_R	(29 ± 2) cm	
Thermal neutron σ_{tot}	(23.9 ± 1.2) barn	Natural composition

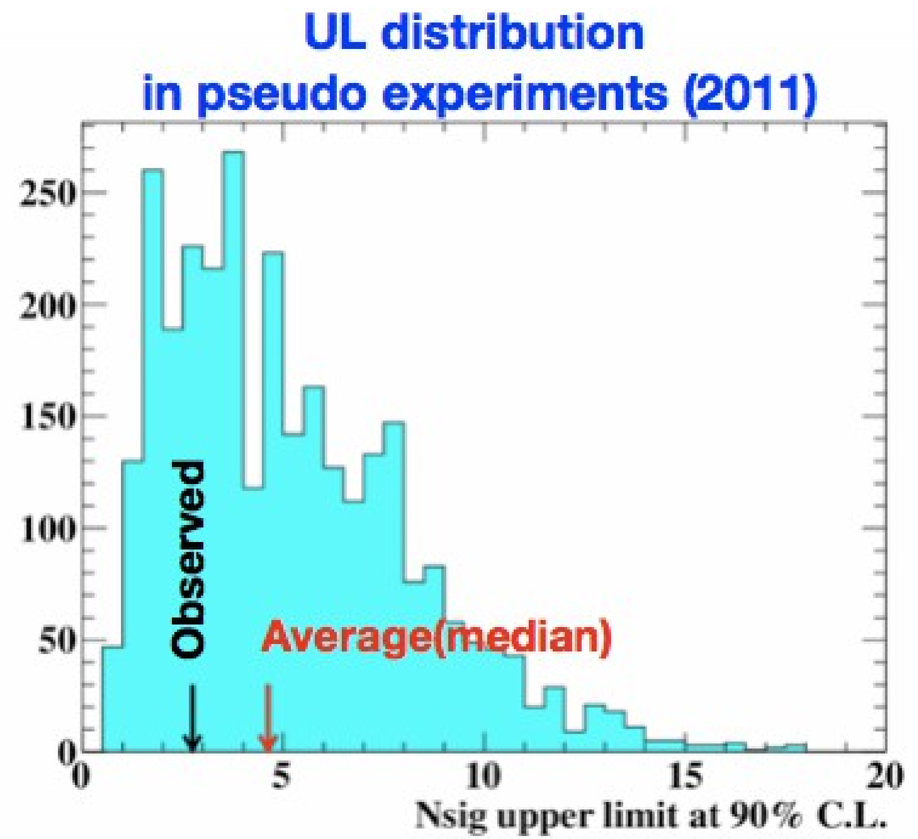
Systematics

Table 16: Relative contributions of uncertainties to upper limit of $\mathcal{B}$.

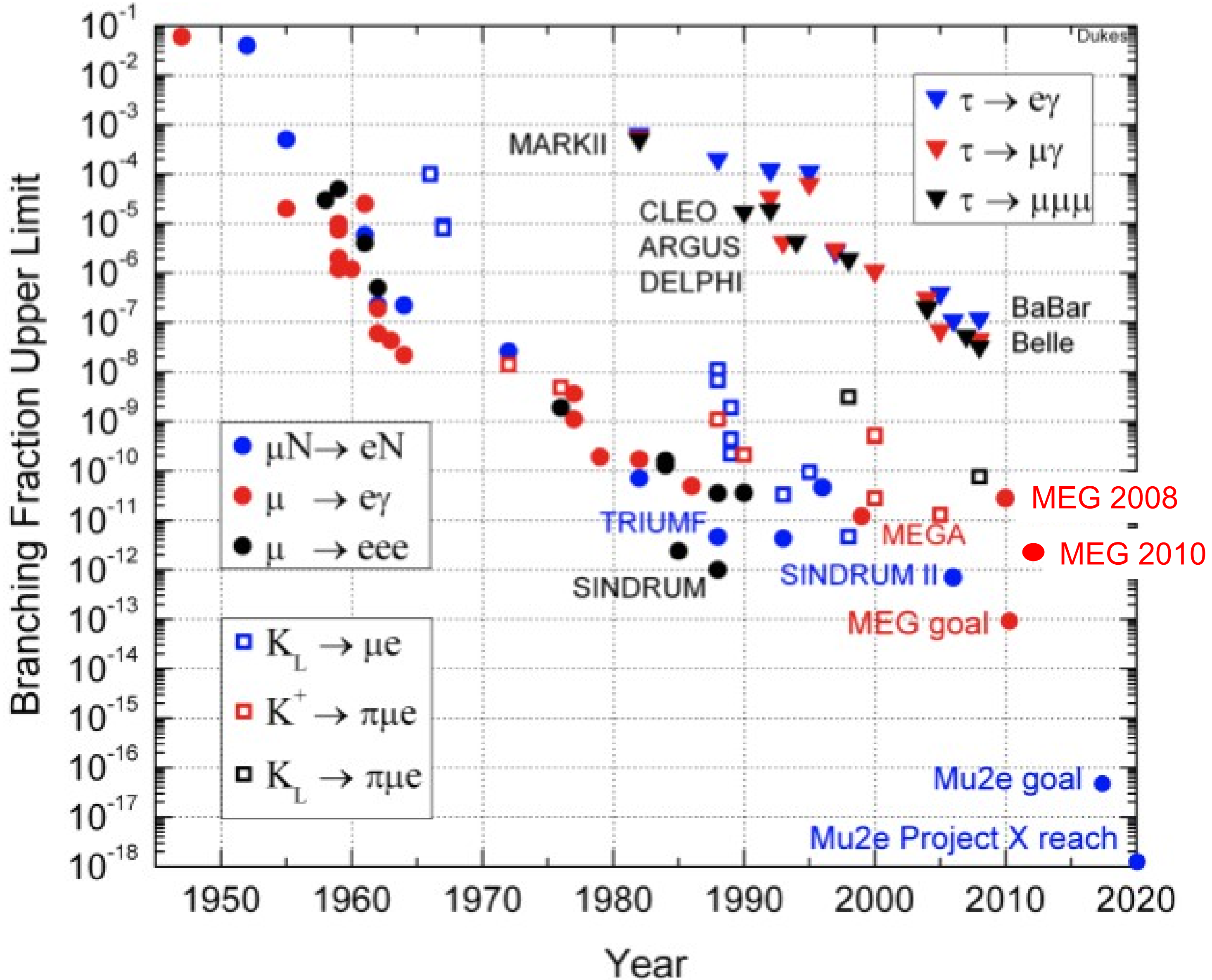
Center of $\theta_{e\gamma}$ and $\phi_{e\gamma}$	0.18
Positron correlations	0.11
E_γ scale	0.07
E_e bias	0.06
$t_{e\gamma}$ signal shape	0.06
$t_{e\gamma}$ center	0.05
Normalization	0.04
E_γ signal shape	0.03
E_γ BG shape	0.03
Positron angle resolutions (θ_e, ϕ_e, z_e, y_e)	0.03
γ angle resolution (u_γ, v_γ, w_γ)	0.03
E_e BG shape	0.01
E_e signal shape	0.01
Angle BG shape	0.00
Total	0.25

Consistency Check





History of Searches for LFV



E. C. Dukes, TAU2010