Latest News from the MEG Experiment

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Outline

- Lepton Flavour Violation (LFV):
  - a historical perspective;
- The MEG Experiment;
  - experimental setup;
  - recent improvements;
  - latest results;
- The MEG upgrade;
- Future perspectives of LFV searches.

The muon decay

In 1948...

- The nature of the muon decay products is still debated;
- Hincks and Pontecorvo
  [Phys. Rev. 73 (1948) 257]
  - BR($\mu \rightarrow e\,\gamma$) < 10%;
  - muon is not an "excited electron";
  - arguments in favor of the $\mu \rightarrow e\,\nu\,\nu$ hypothesis.

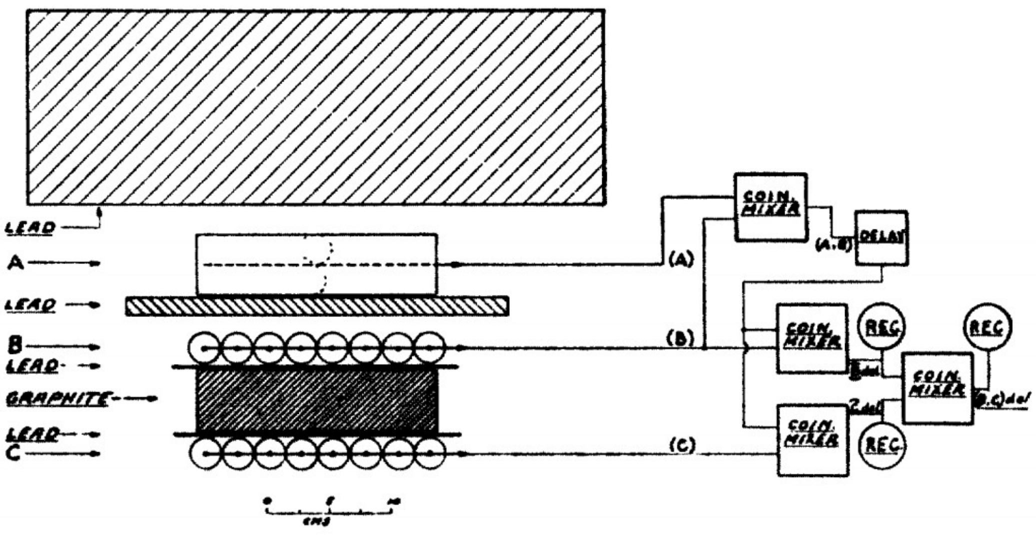


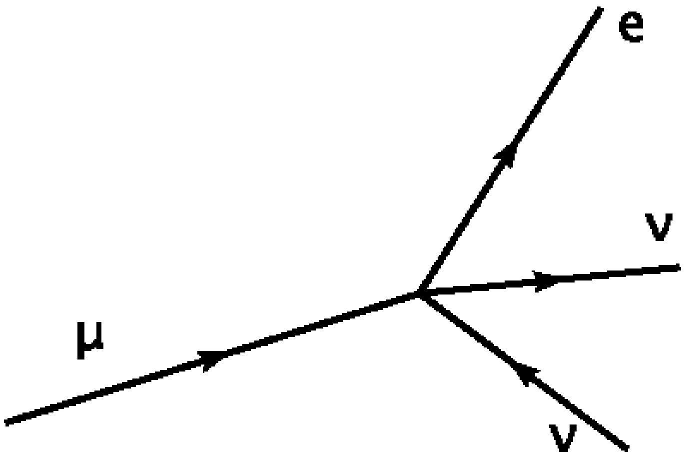
FIGURE 1 - ARRANGEMENT OF APPARATUS

Lepton Flavor Violation searches concurred to the development of particle physics well before the very concepts of Lepton and Flavour were developed

One or two neutrinos?

In 1955…

- It is not yet clear if the two neutrinos produced in the muon decay are of the same nature;



One or two neutrinos?

In 1955…

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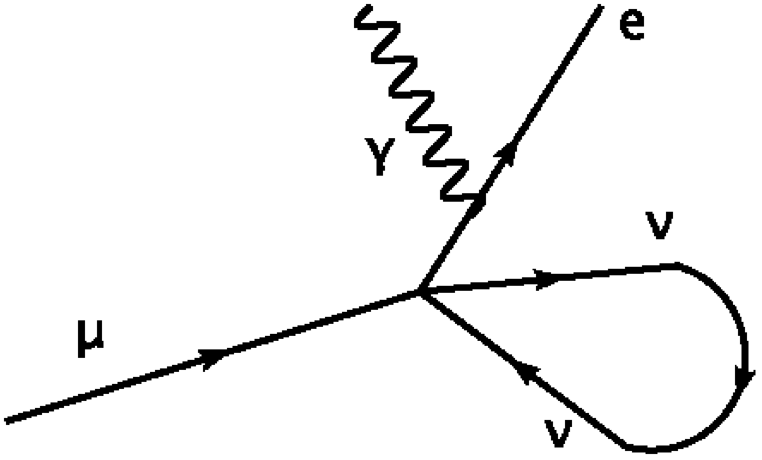
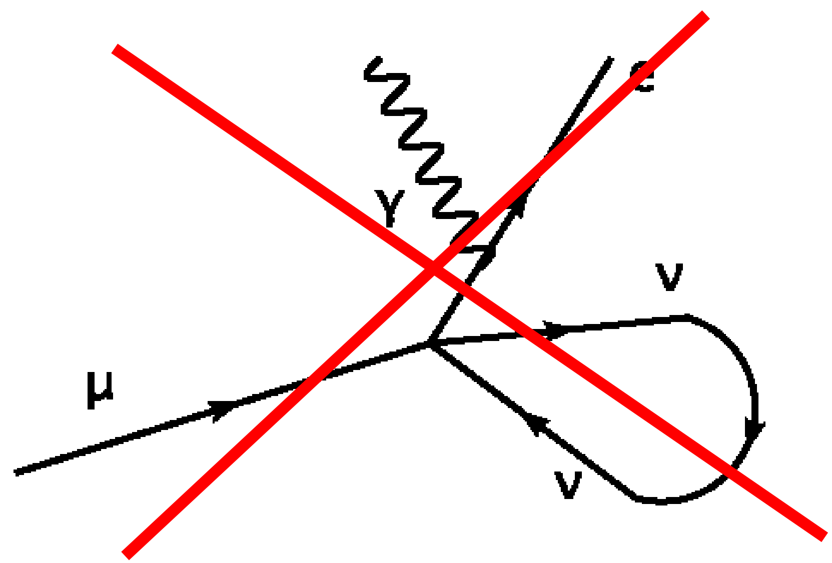


One or two neutrinos?

In 1955…

- It is not yet clear if the two neutrinos produced in the muon decay are of the same nature;

- Lokanathan and Steinberger
  [Phys. Rev. A 98 (1955) 240]
  - BR($\mu \rightarrow e\,\gamma$) < 2 x 10^{-5};
  - strong argument in favor of the $\nu_e + \nu_\mu$ hypothesis.

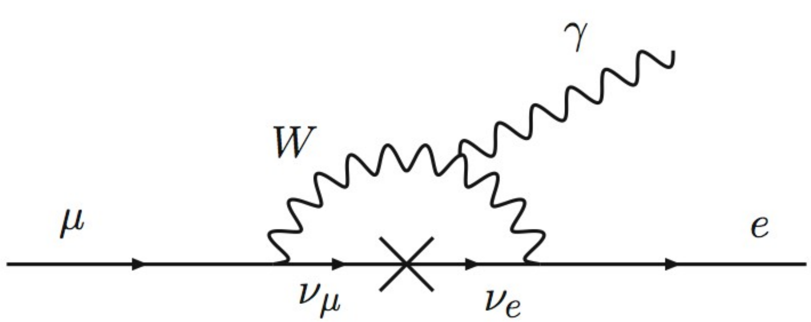


The lepton flavor "saga" begins

LFV Today

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

SM (BR < 10^{-40})

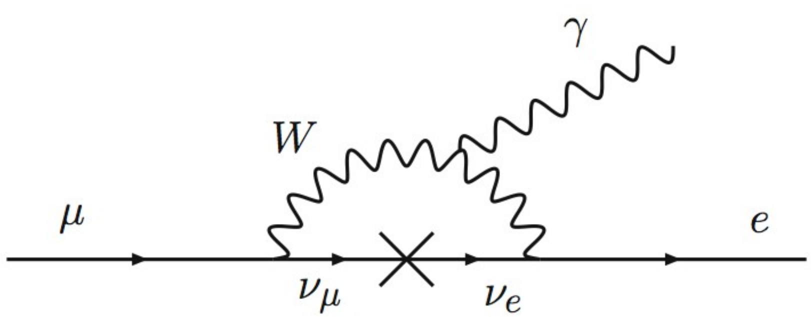


Observing LFV would be an ***unambiguous evidence of NP***

LFV Today

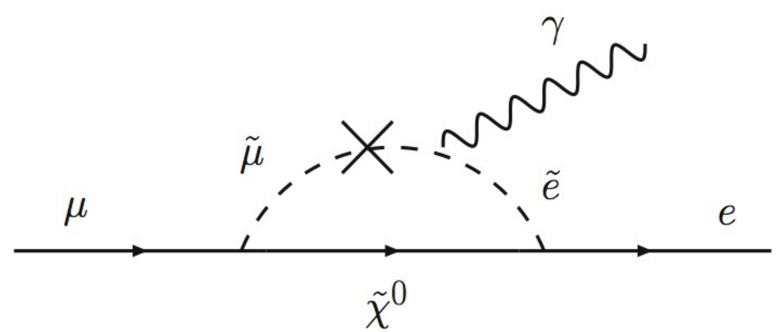
- LFV is a standard probe for New Physics (NP) beyond the Standard Model (SM):
  - unobservable rates in the SM;
  - naturally enhanced by NP (SUSY, Extra dimensions, unparticles, etc.);

SM (BR < 10^{-40})



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

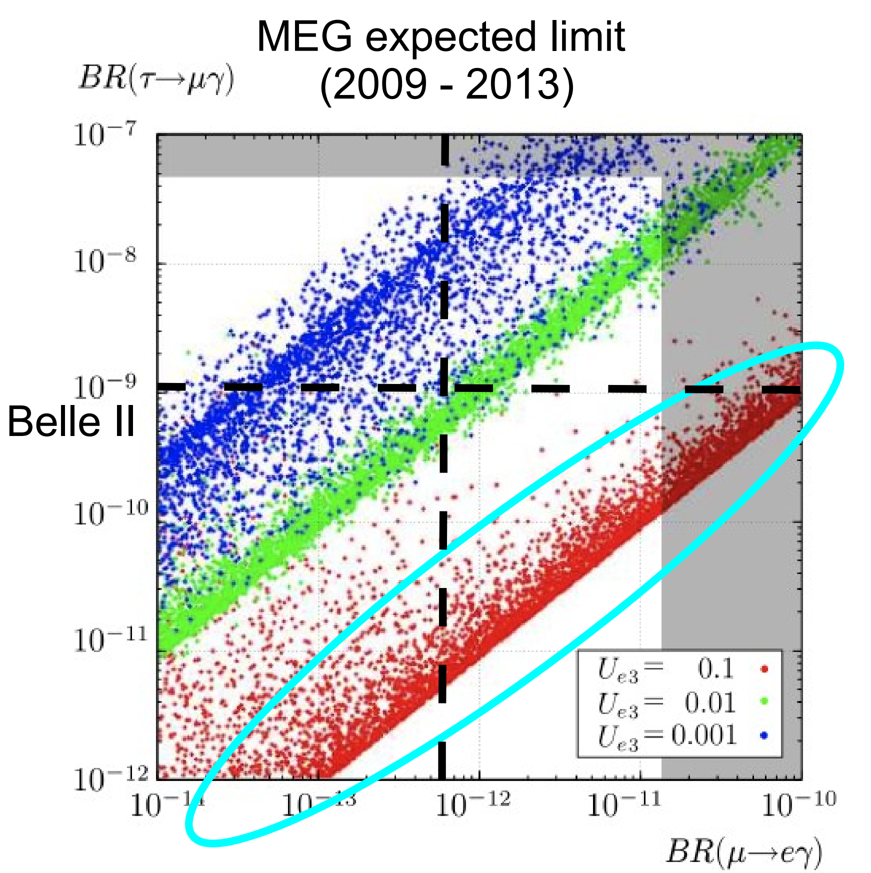
SUSY (BR ~ 10^{-11} - 10^{-15})



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

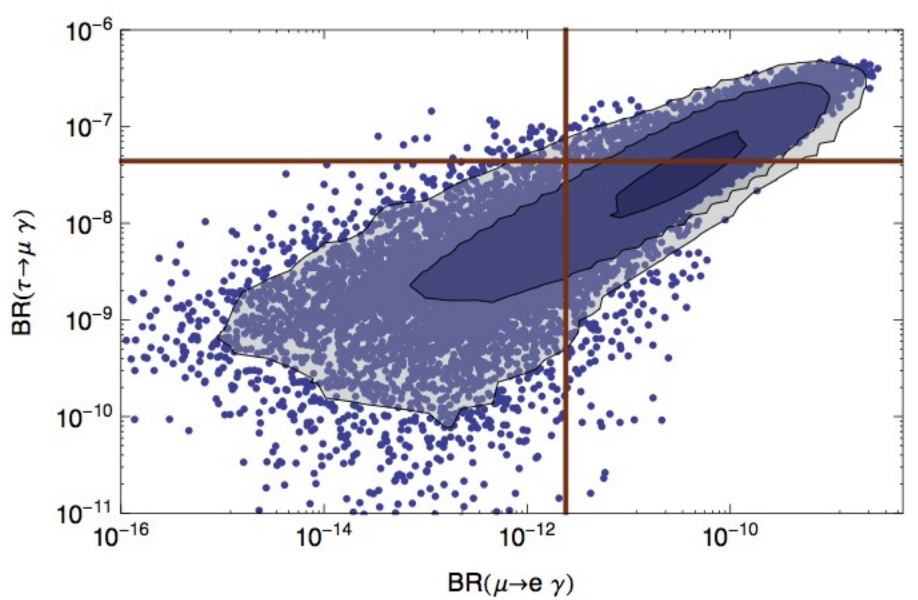
LFV in muon and τ decays

- In SUSY GUTs, the relatively large measured value of θ_{13} tends to favor LFV in μ decays.



Hisano, Nagai, Paradisi, Shimizu '09

- The are scenarios where τ LFV searches are still competitive

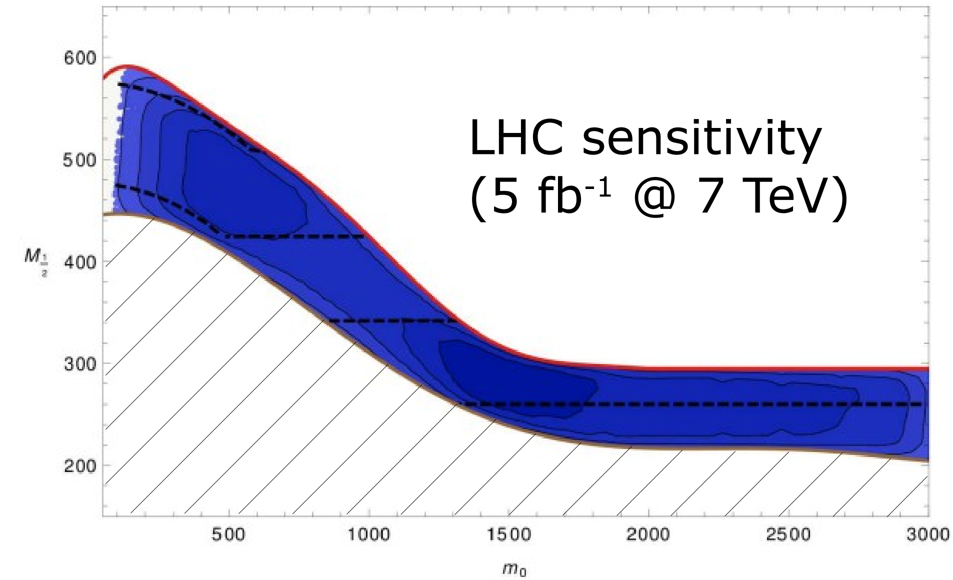


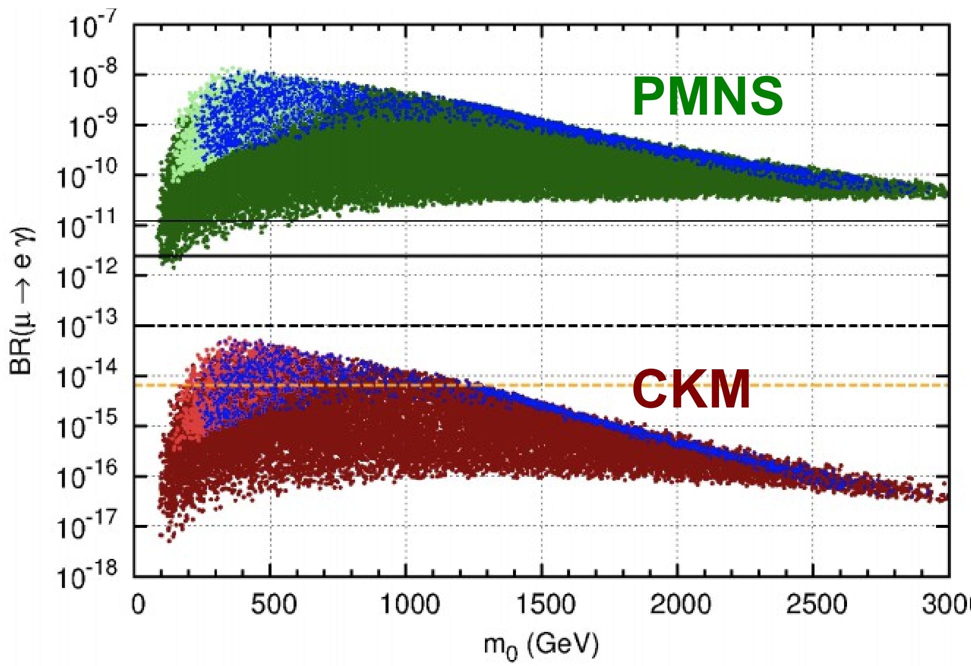
Blankenburg, Isidori, Jones-Pérez '12

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.

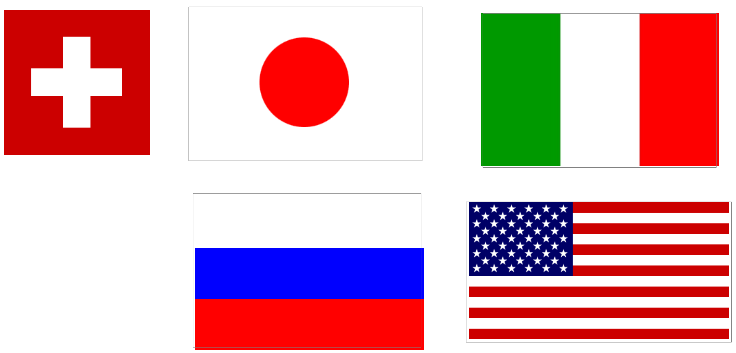
Calibbi, Hodgkinson, Jones Perez, Masiero, Vives '11

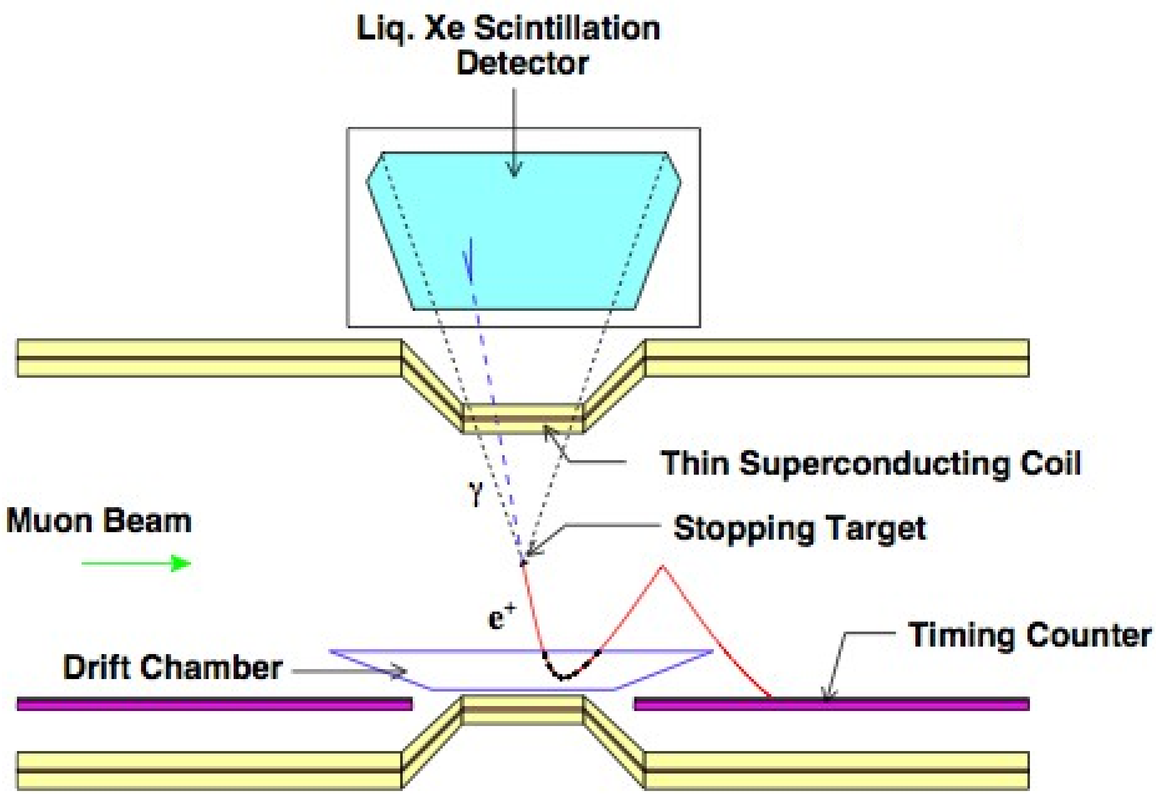




The MEG experiment (arXiv:1303.2348)

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

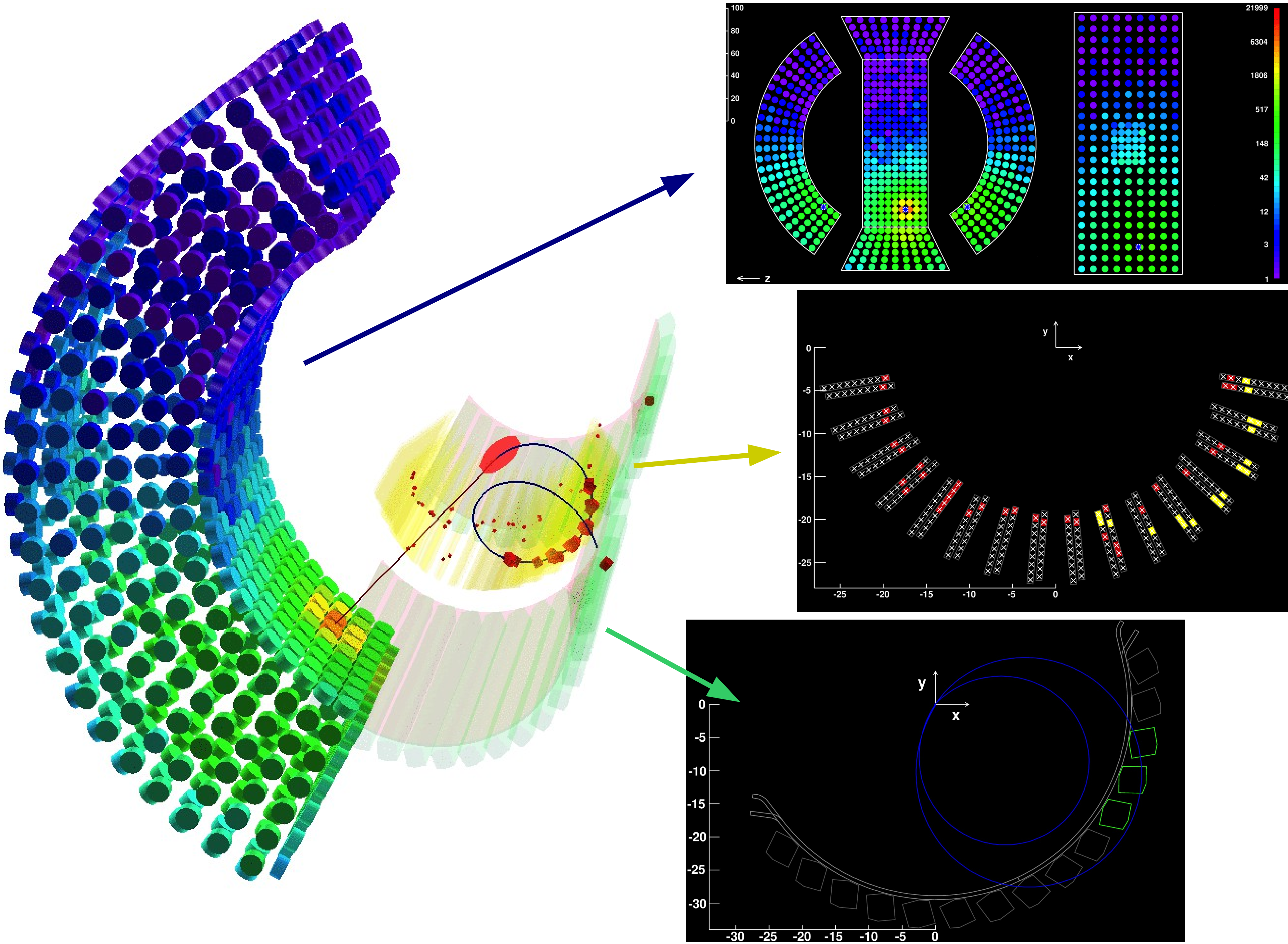




LXe calorimeter for photon detection

16 drift chambers for positron tracking

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


100
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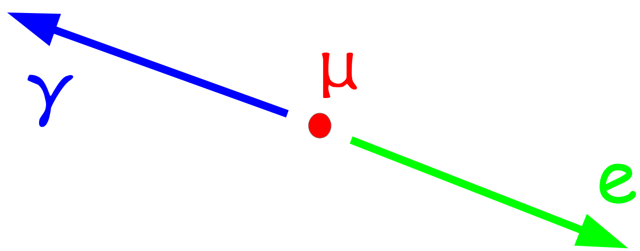
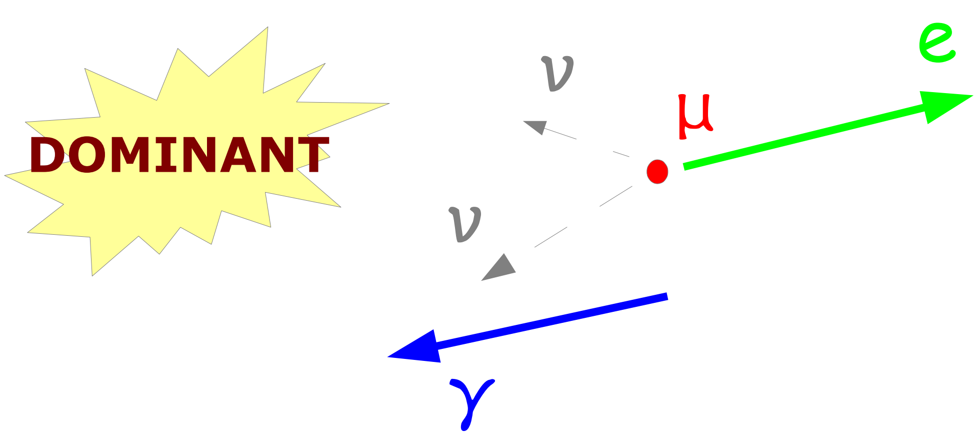
Signal & Background

SIGNAL

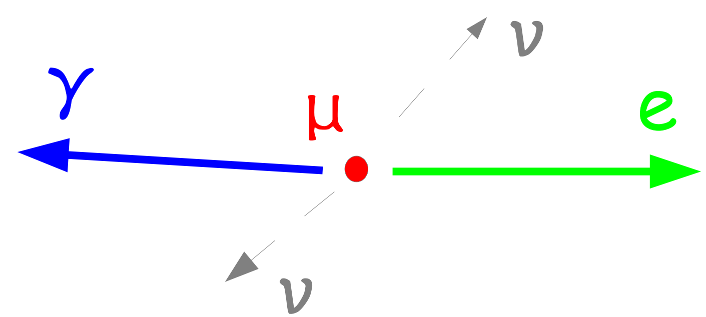


Monochromatic (52.8 MeV), back-to-back $e^+ \gamma$ produced at the same time;

ACCIDENTAL BACKGROUND

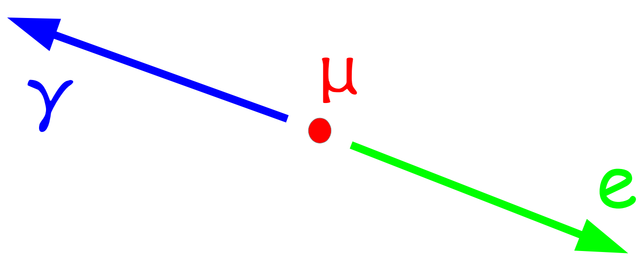


RADIATIVE MUON DECAY (RMD)



Signal & Background

SIGNAL

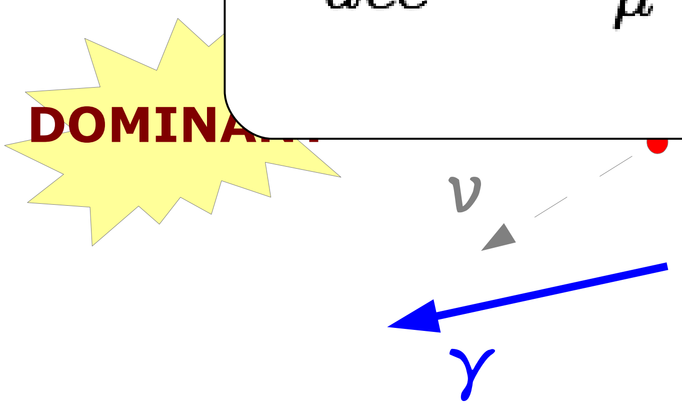


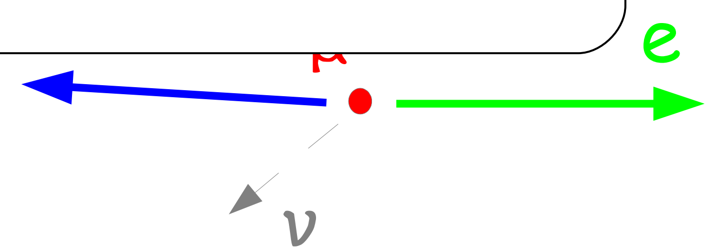
Monochromatic (52.8 MeV), back-to-back $e^+ \gamma$ produced at the same time;

ACC

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

(RMD)

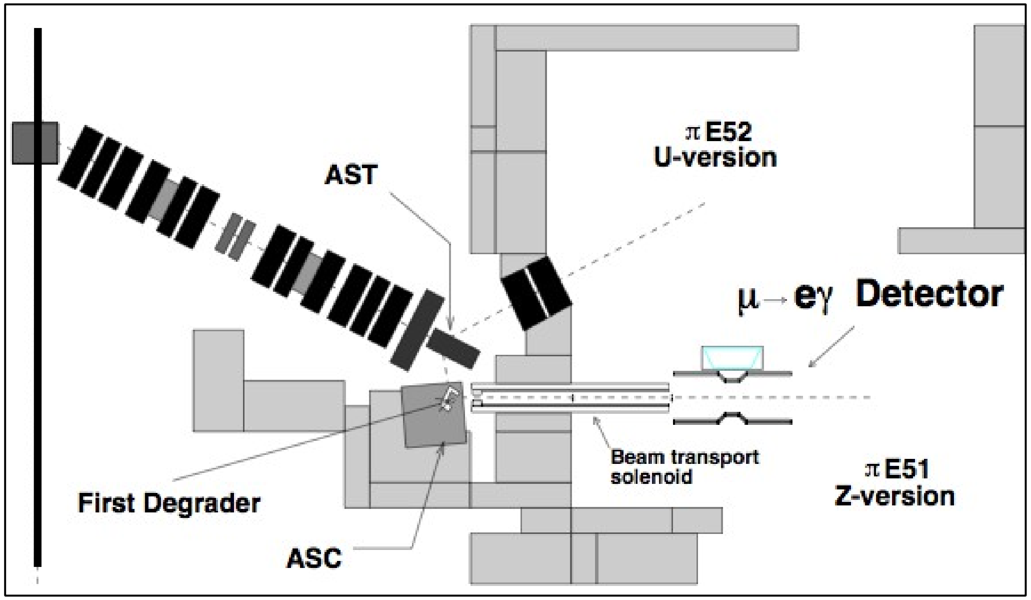




Signal/Background discrimination from ***photon and positron energies, relative angles and relative time***

The πE5 beam line at PSI

- Most intense DC muon beam in the world:
  - up to 10^8 μ/s;
  - only 3×10^7 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

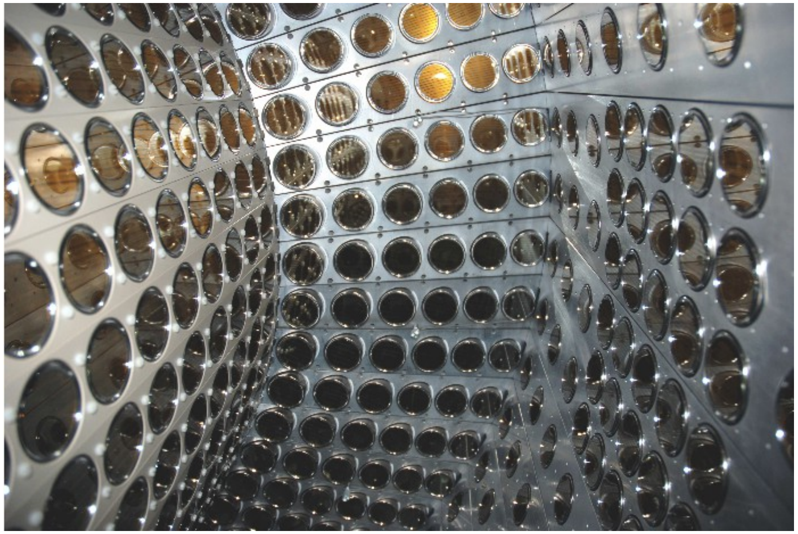
800 liter LXe detector read by 846 PMTs

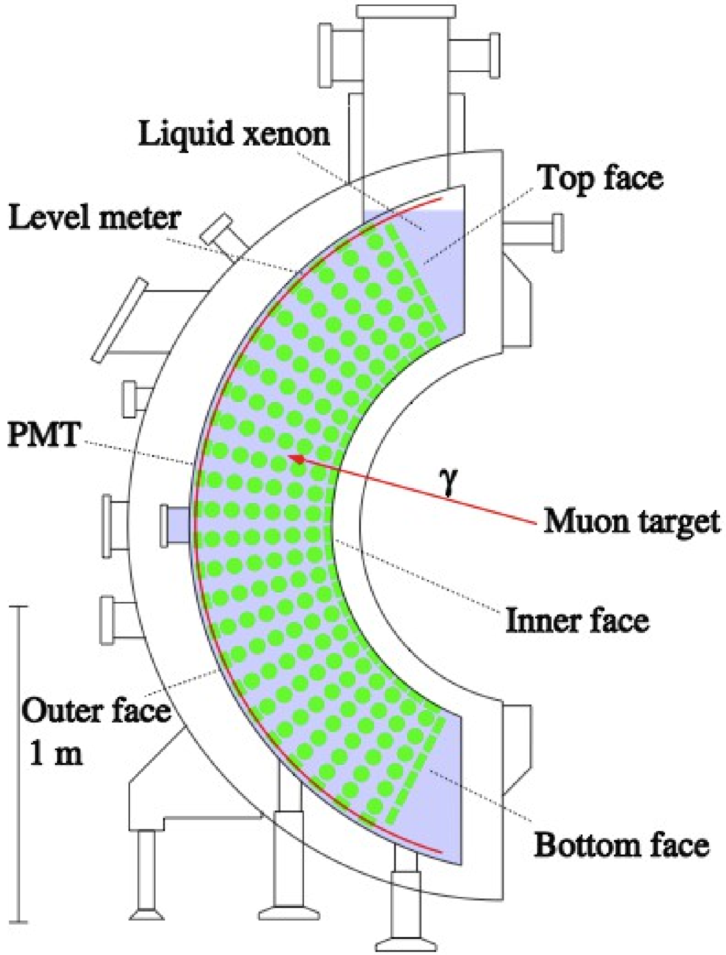
Not just a calorimeter!

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

$\sigma_{xy} \sim 5 – 6$ mm

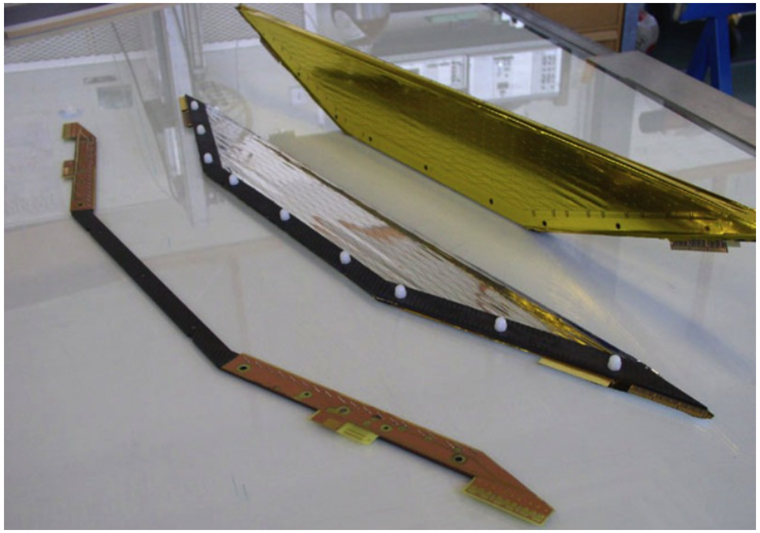
$\sigma_T \sim 60$ ps

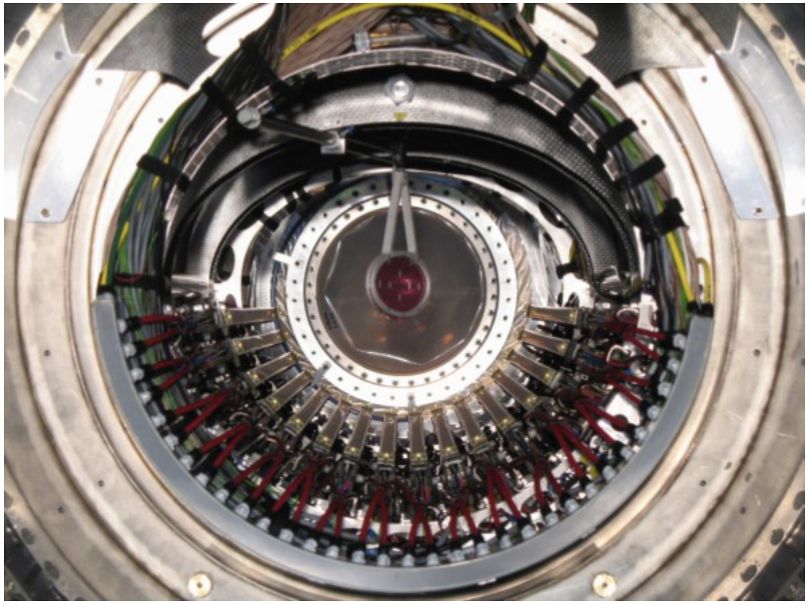




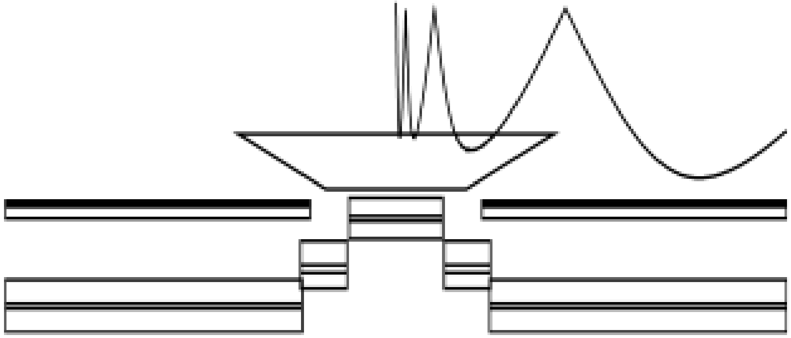
Drift Chamber Spectrometer

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





Gradient magnetic field



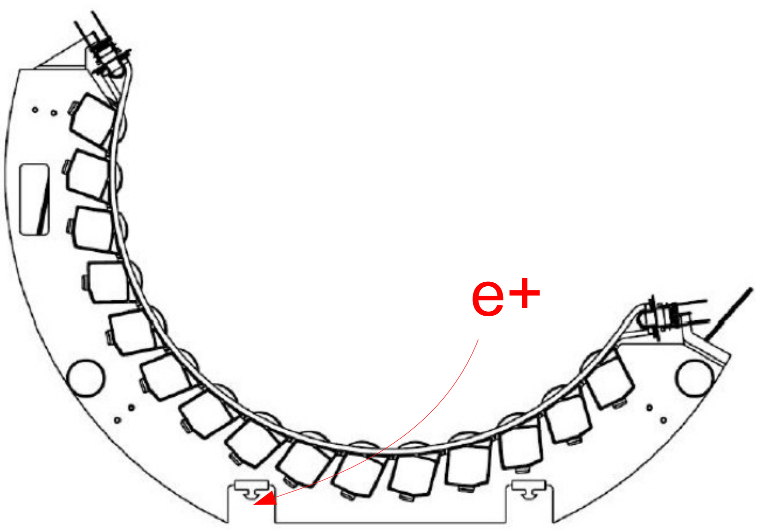
Tracking performances

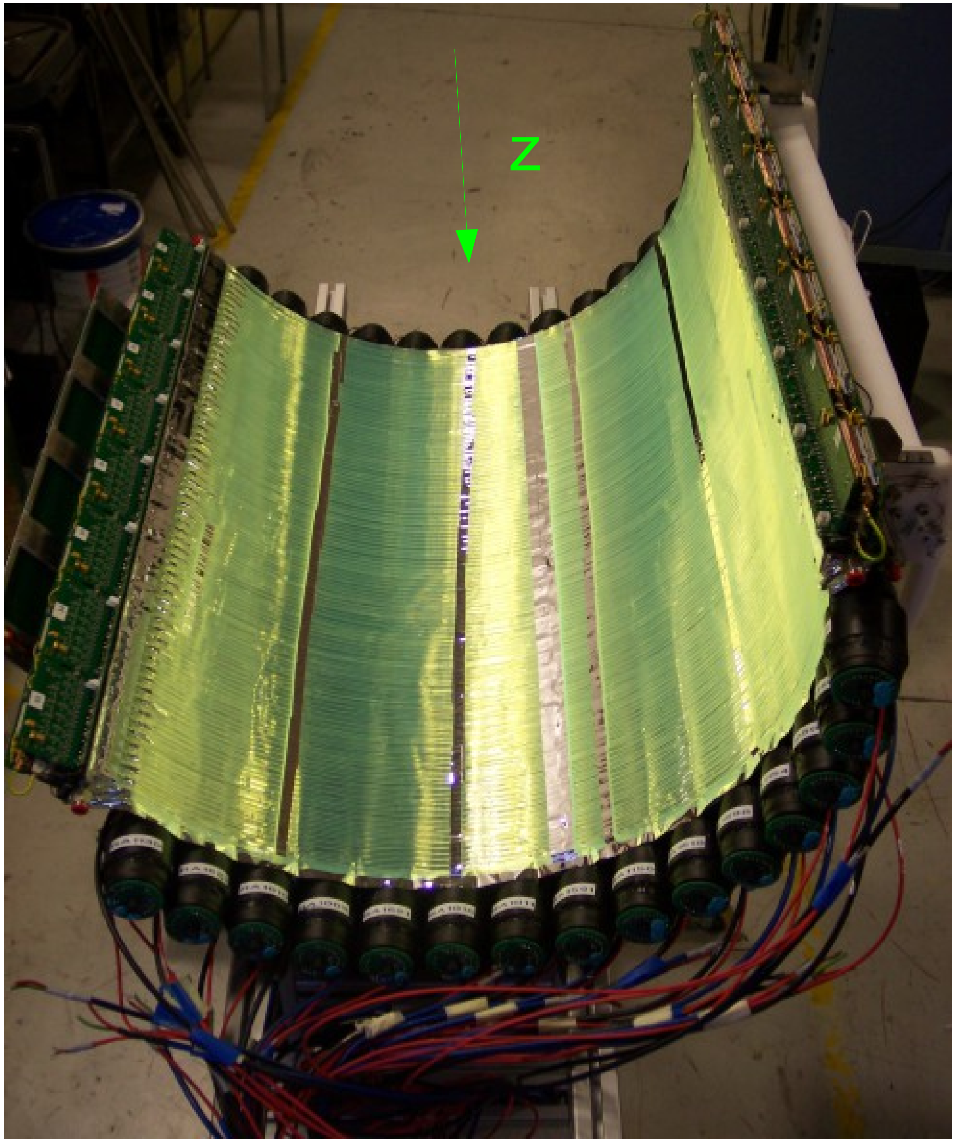
$\sigma_P \sim 300$ keV
$\sigma_{vtx} \sim 1.2$ (x), 2.4 (y)
$\sigma_{\theta,\varphi} \sim 9$ mrad

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



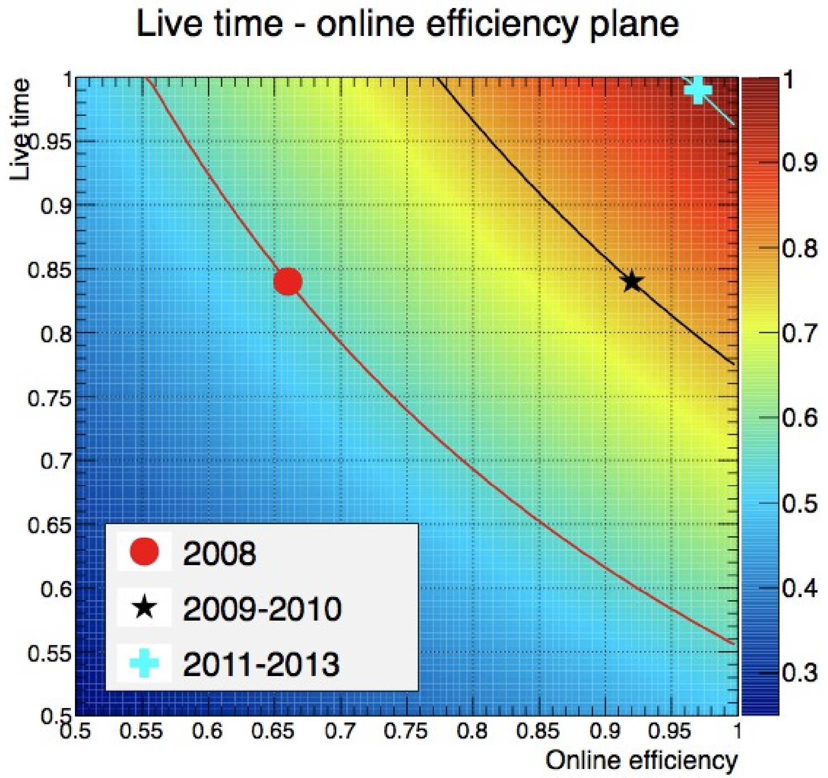


Trigger and DAQ

- FPGA based trigger system;

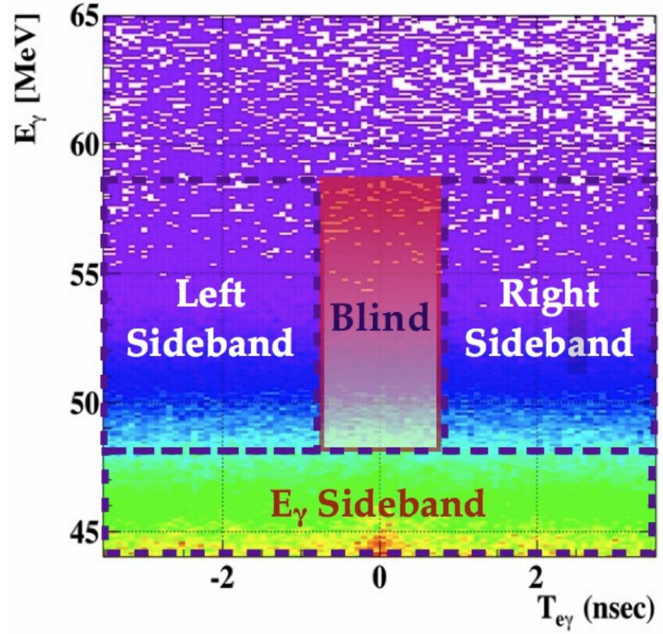
```
Beam Intensity x acceptance.........10⁶ Hz
 + XEC Energy E > 45 MeV............10³ Hz
 + e – γ Timing Teg < 10ns..........10² Hz
 + e – γ Angle......................10 Hz
```

- 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

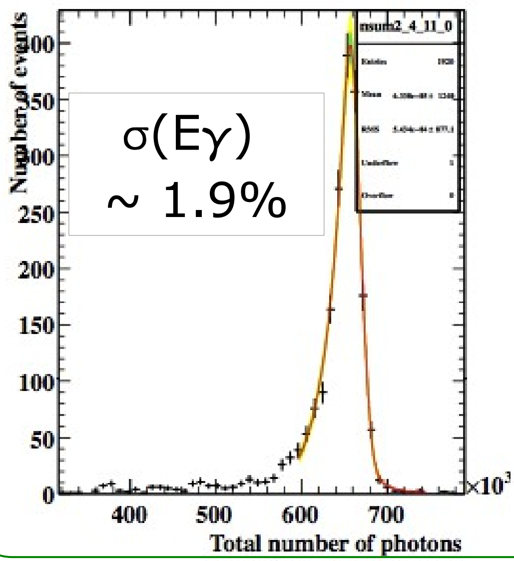
- Likelihood analysis of 5 discriminating variables (E_e,E_γ,$\theta_{e\gamma}$,$\varphi_{e\gamma}$,$T_{e\gamma}$):
  - year-by-year and event-by-event PDFs;
  - careful treatment of **correlations** (from well understood geometrical effects)



- 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)



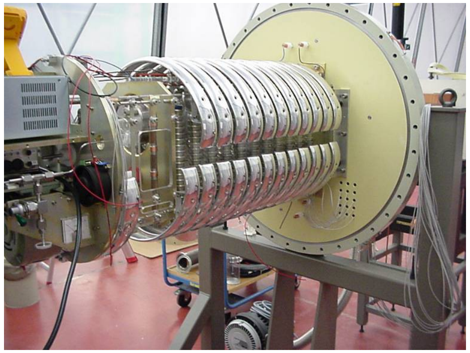
~ monochromatic γ @ 55 MeV from...

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

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

...by selecting back-to-back γ's

Cockcroft-Walton accelerator

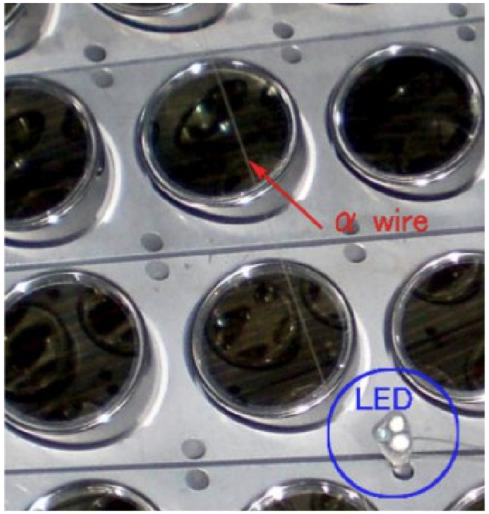


Protons on a Lithium Tetra-borate target

bi-weekly monitoring of calorimeter's energy scale

LEDs

Installed inside the XeC



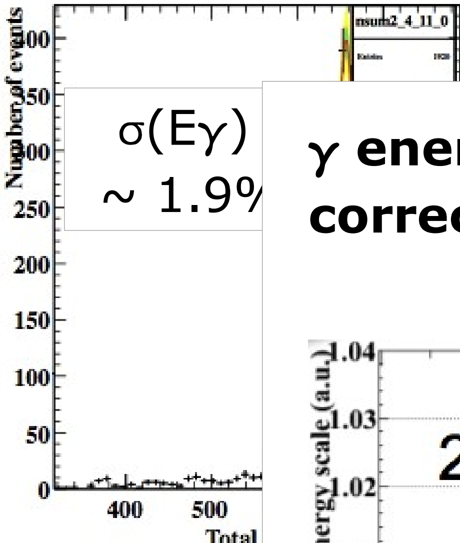
α sources

Installed in wires inside the XeC

bi-weekly calibration of PMT quantum efficiencies and gains

Calibrations & Monitoring (I)

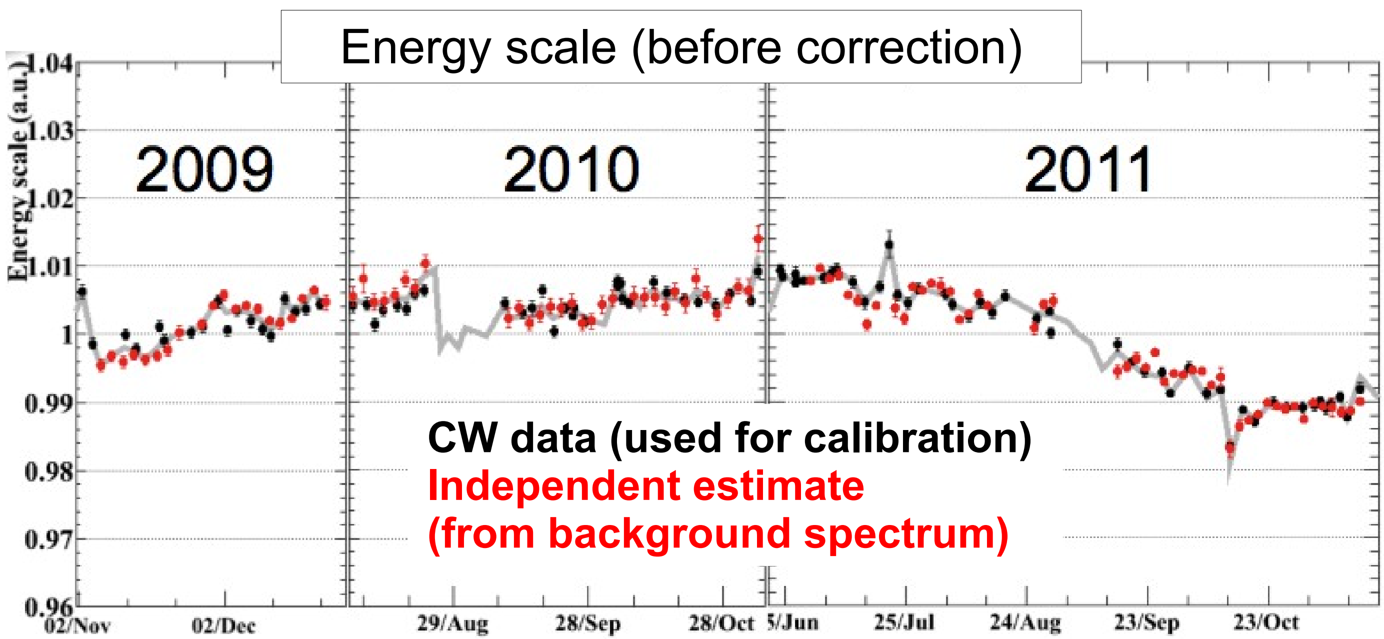
Charge Exchange (CEX)



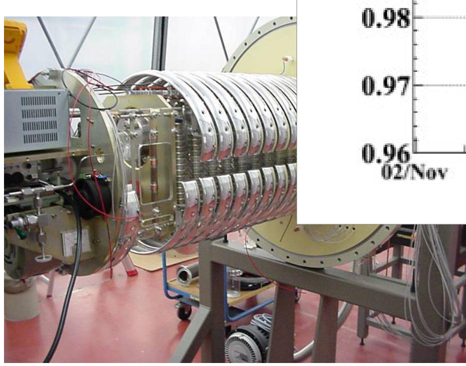
σ(Eγ) ~ 1.9%

~ monochromatic γ

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



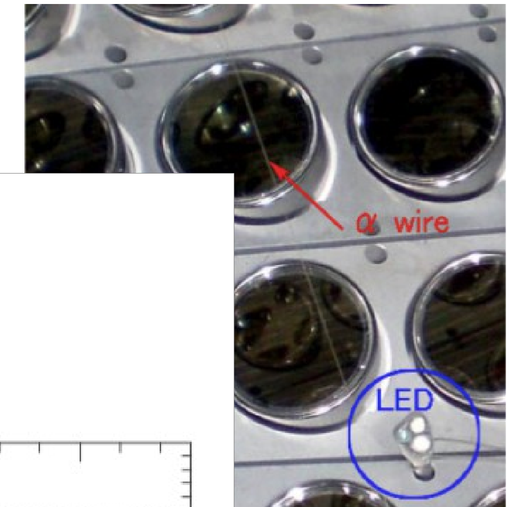
Cockcroft-

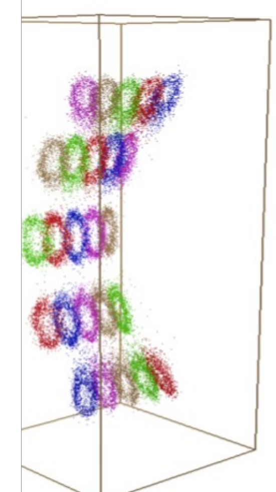


calorimeter's energy scale

LEDs

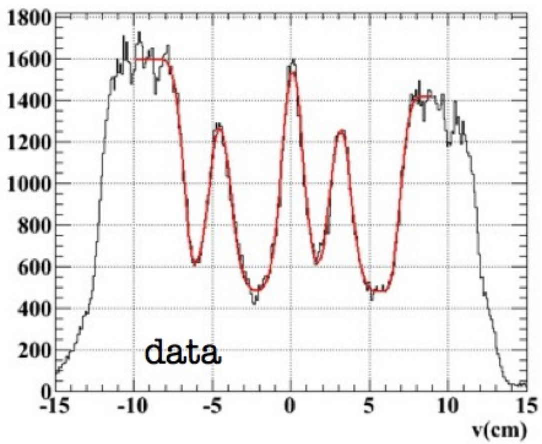
Installed inside





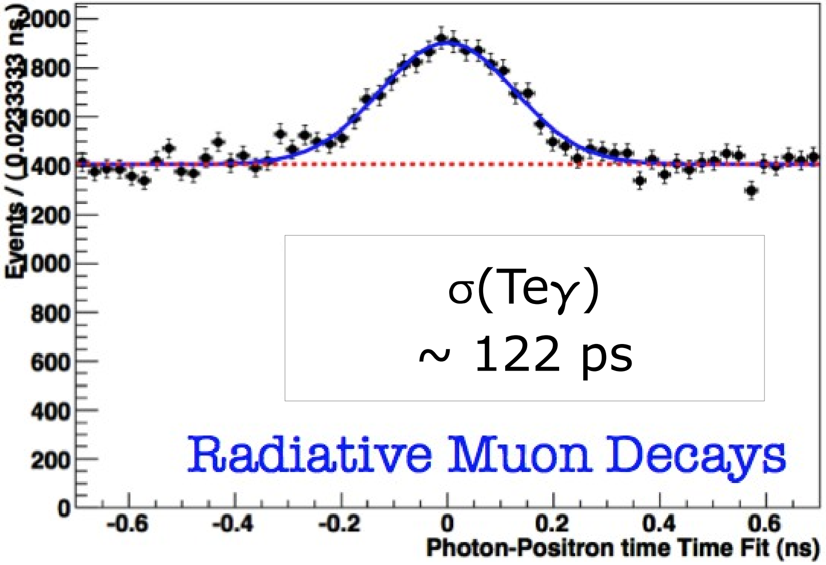
bi-weekly calibration of PMT quantum efficiencies and gains

Calibrations & Monitoring (II)



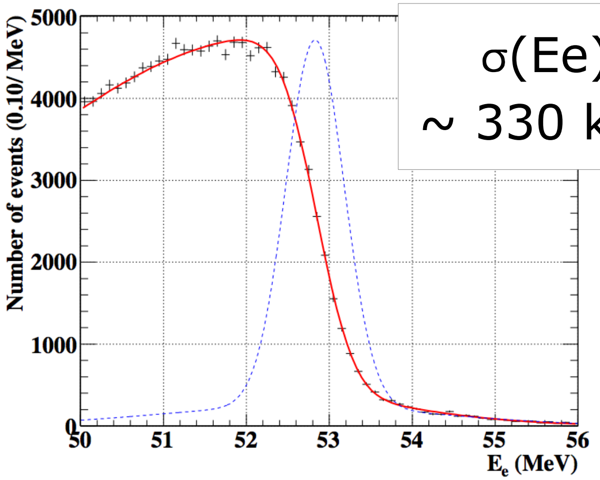
σ(uvw)
~ 5-6 mm

γ position resolution from special data taking w/ collimators



σ(Teγ)
~ 122 ps

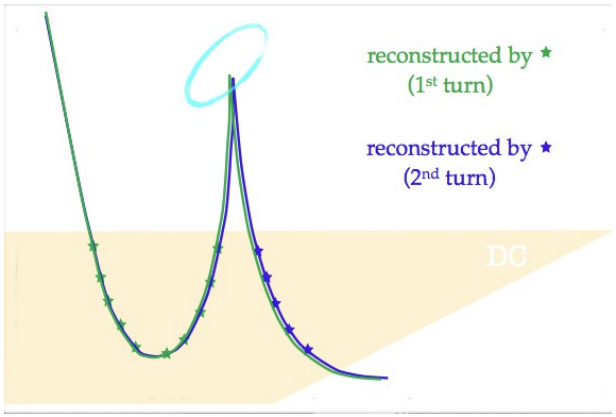
Tracks from μ → e ν ν and cosmics to calibrate the positron spectrometer



σ(Ee)
~ 330 keV

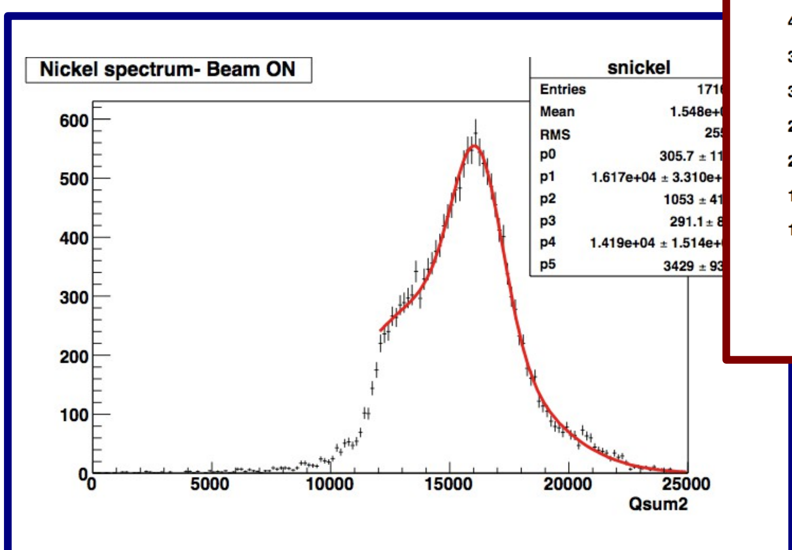
momentum resolution and scale from the μ → e ν ν kin. edge

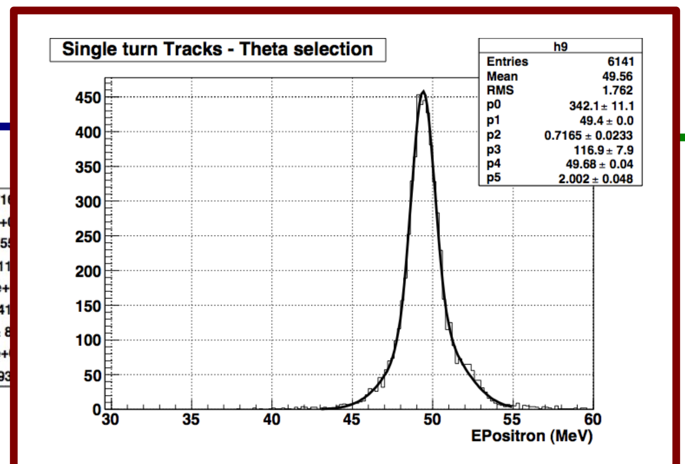
angle & vertex resolution from multi-turn tracks

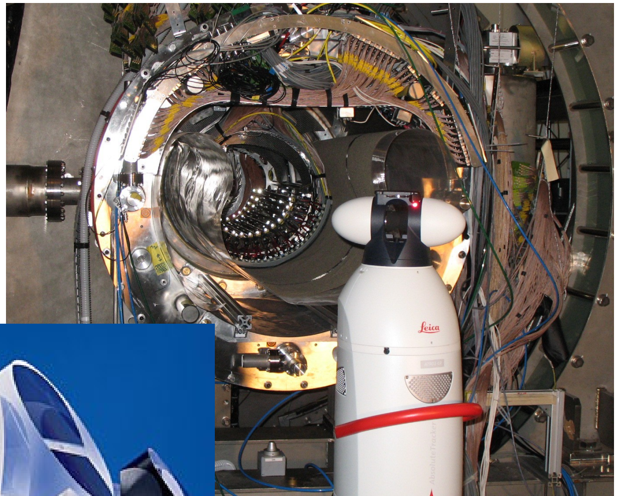


New calibration tools

- 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*

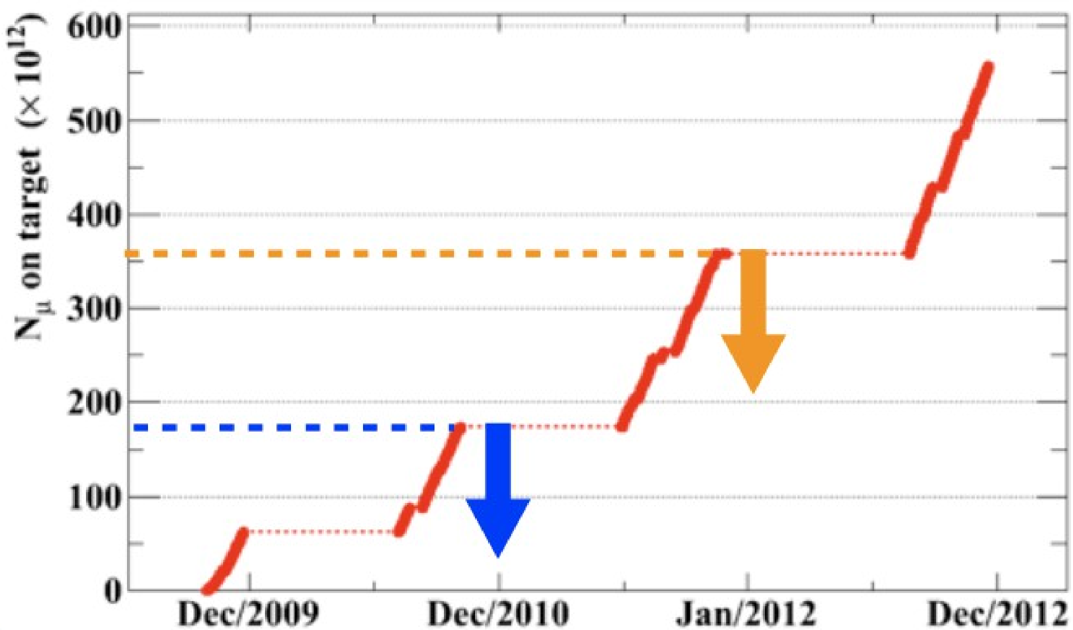






Data Sets

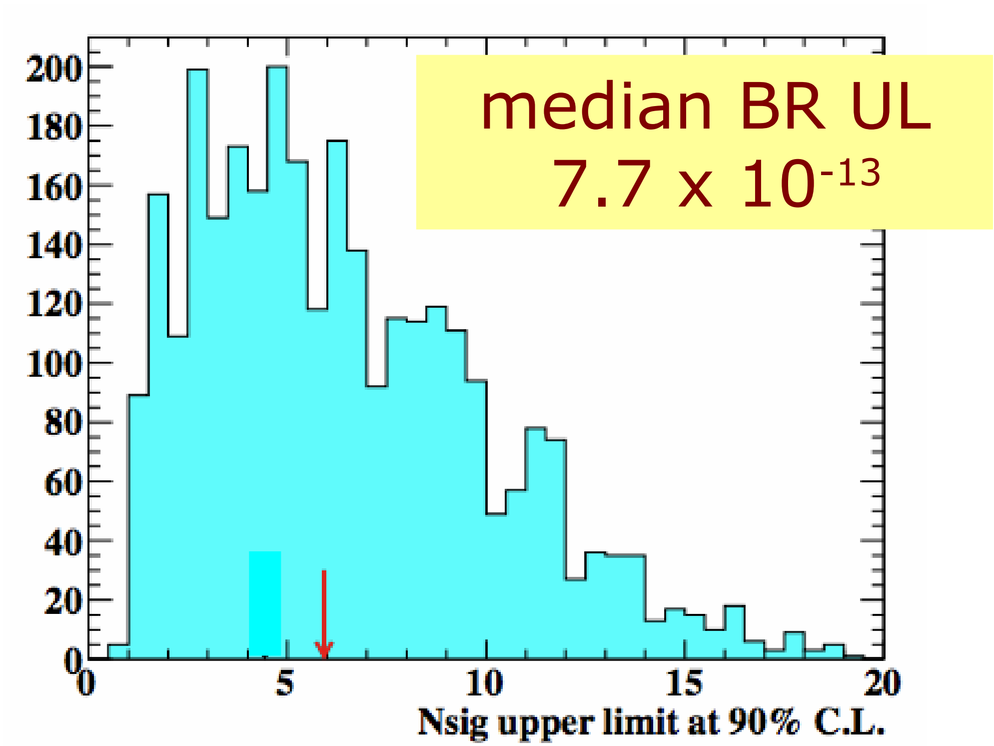
- First run in 2008 with poor detector stability:
  - First result, BR < 2.8 x 10^{-11} **Nucl. Phys. B834 1-12 (2010)**
- Stable run in 2009 – 2012:
  - First analysis of 2009-2010, BR < 2.4 x 10^{-12} **PRL 107 171801**
  - Improved analysis of 2009-2010 data and analysis of 2011 data (presented in 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 $N_{SIG} \sim 6$
- Normalization factor: **(7.8 ± 0.3) x 10^{12}**, from the observed yields of $\mu \to e\,\nu\,\nu$ and RMD.

Analysis Improvements (I)

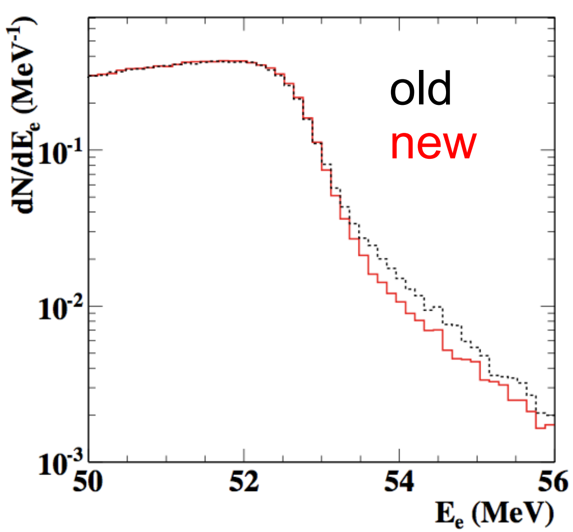
TRACK FIT

- 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).

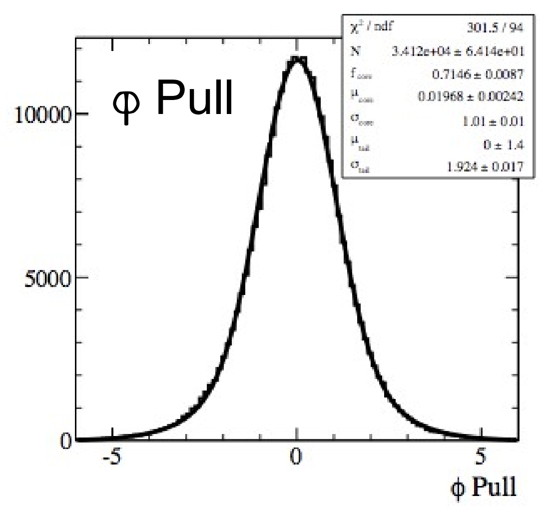
Analysis Improvements (II)

- 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)

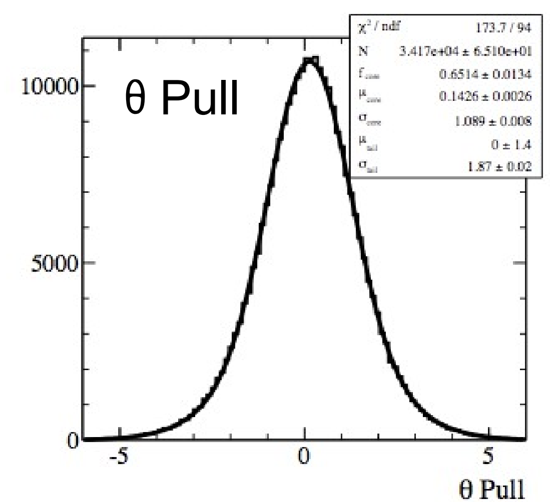
reduced tails



(almost) normal pulls



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

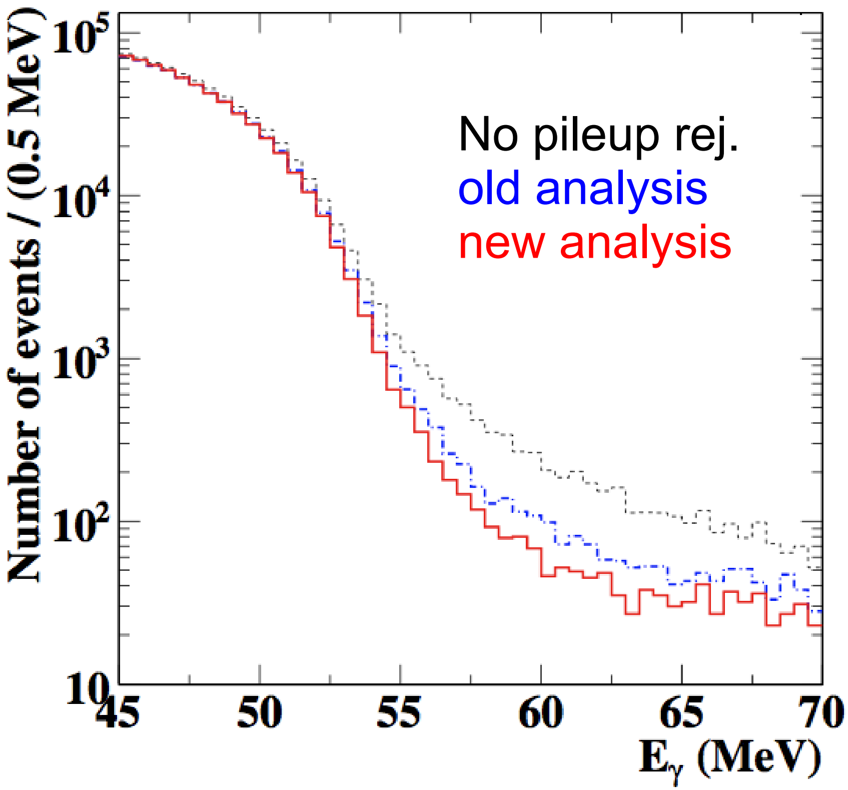


$\sigma_{core} = 1.089 \pm 0.008$

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.

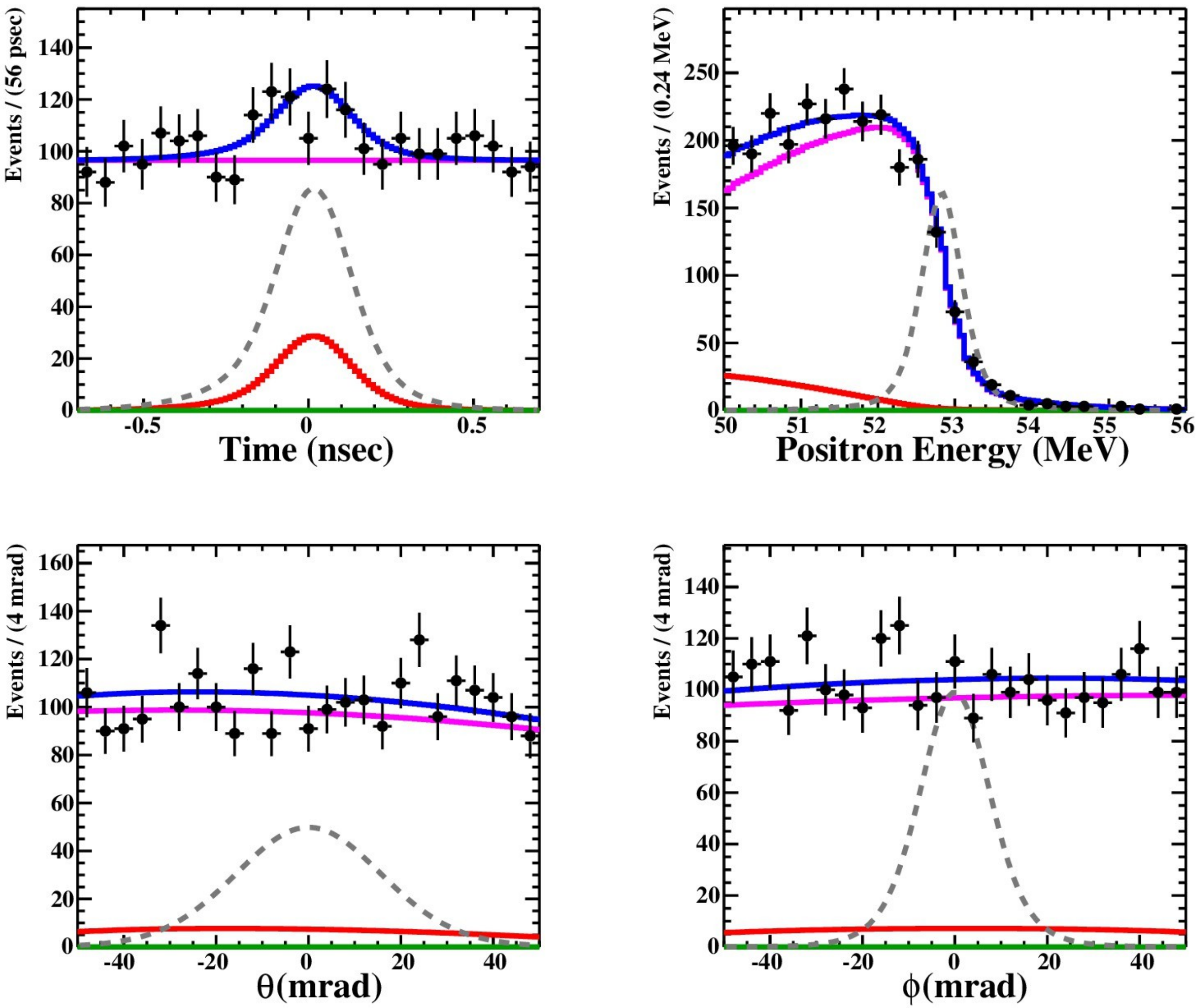


Analysis Improvements (IV)

IMPACT ON SENSITIVITY

- The recent improvements in the analysis improved the $\mu \rightarrow e \gamma$ 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.

Combined analysis 2009-2011 (I)



- - - - - SIGNAL WITH BR ~ 3×10^{-11}

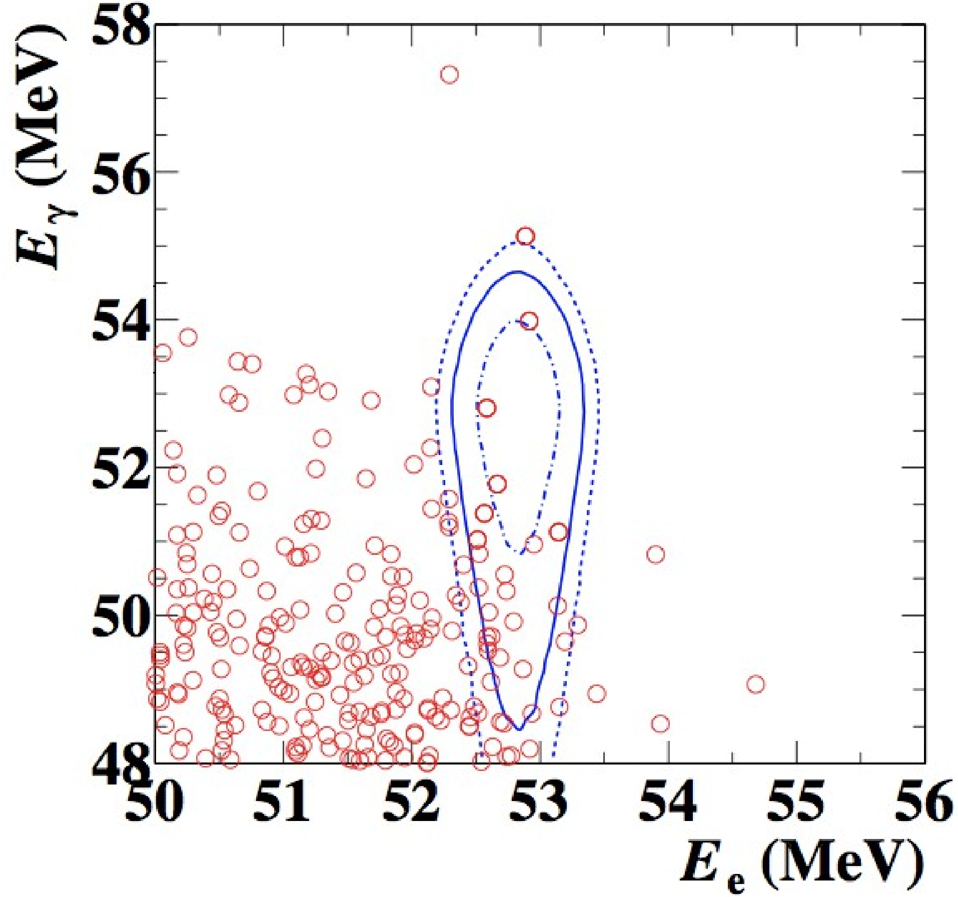
Based on
~ 36×10^{13} μ
stopped at the target

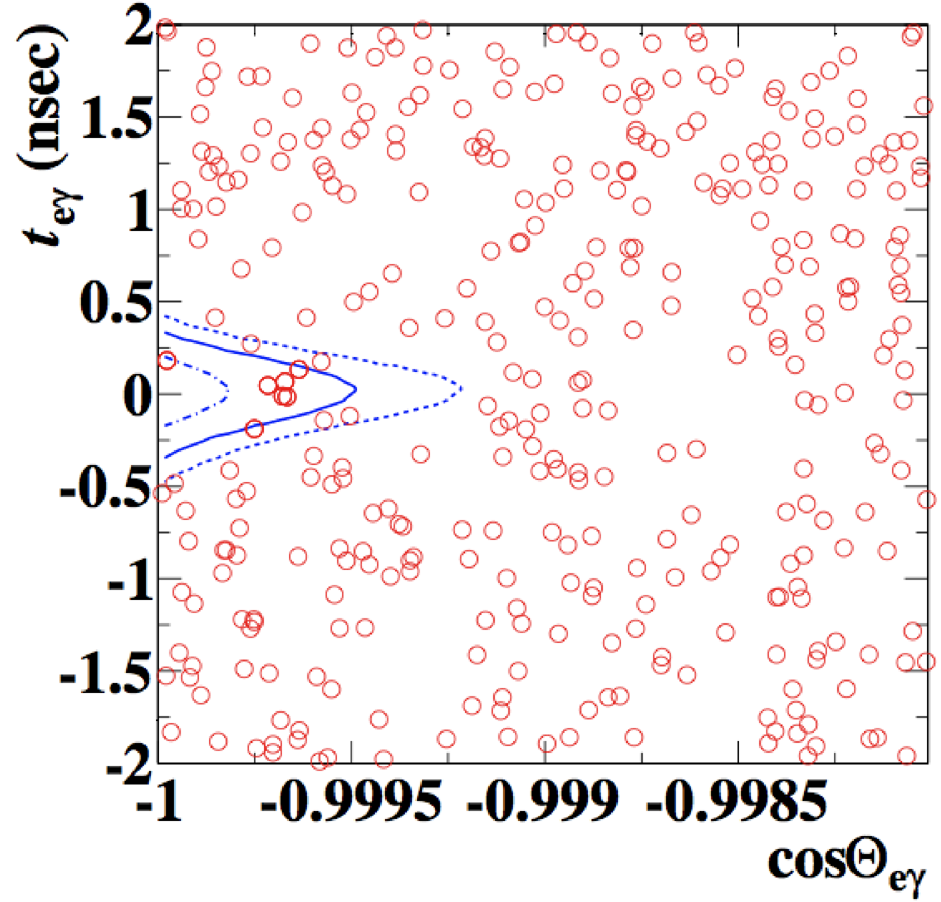
$N_{sig} = -0.4^{+4.8}_{-1.9}$

$N_{bkg} = 2413 \pm 37$

$N_{RD} = 167 \pm 24$

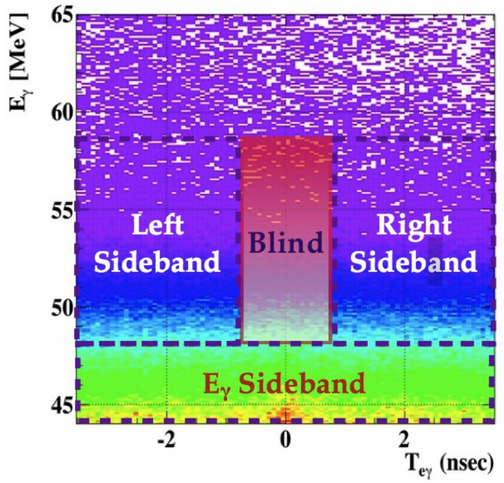
Combined analysis 2009-2011 (II)

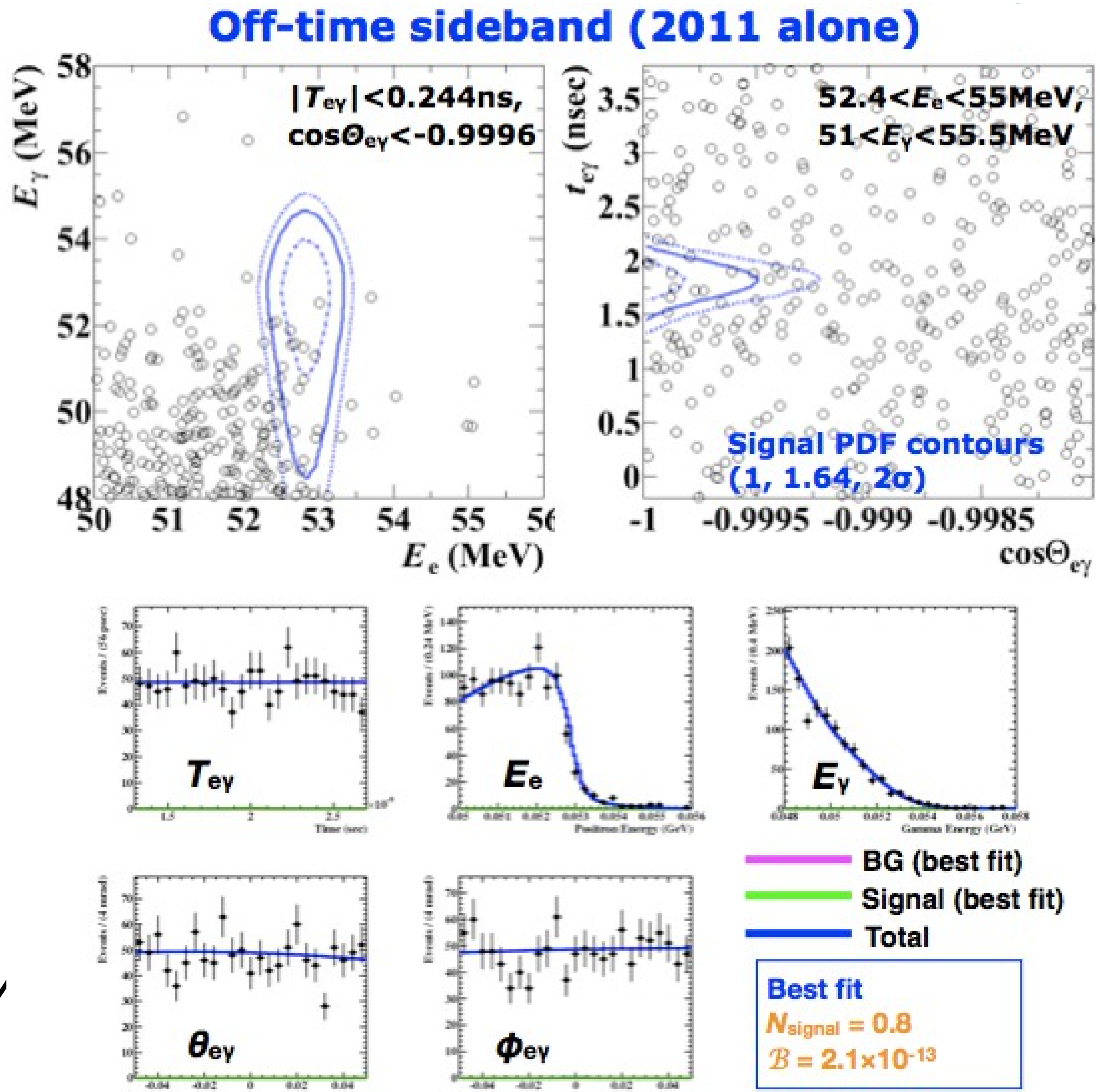




contours (Signal PDF): 1σ, 1.64σ, 2σ

Control samples





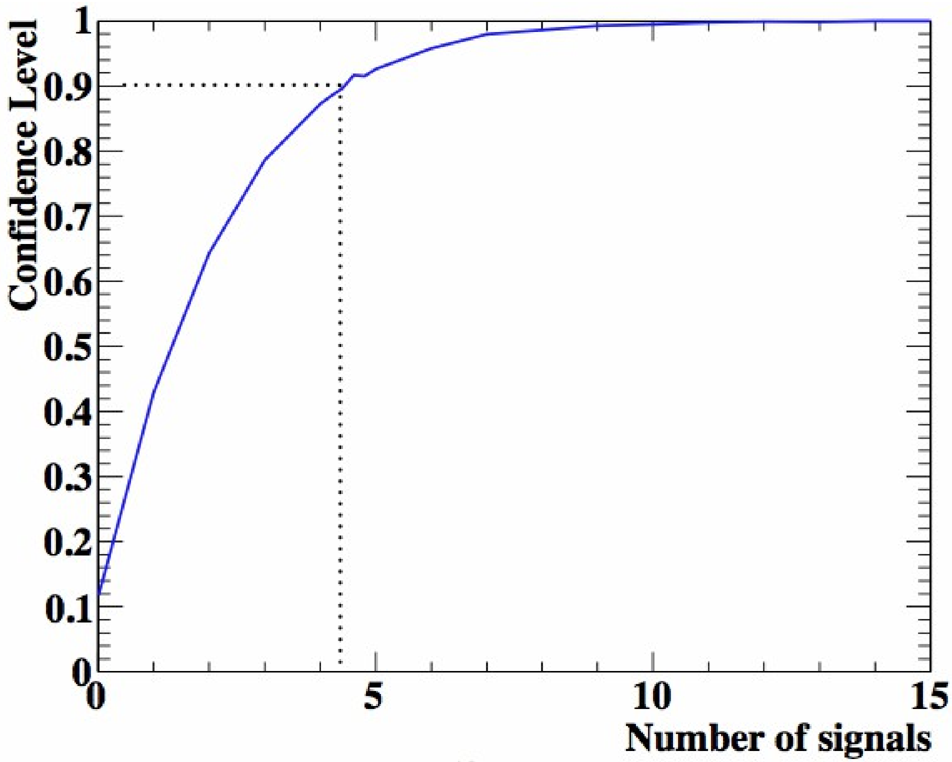
Fictitious analysis regions in the **sidebands** of E_γ, $T_{e\gamma}$ and relative angles used as control samples

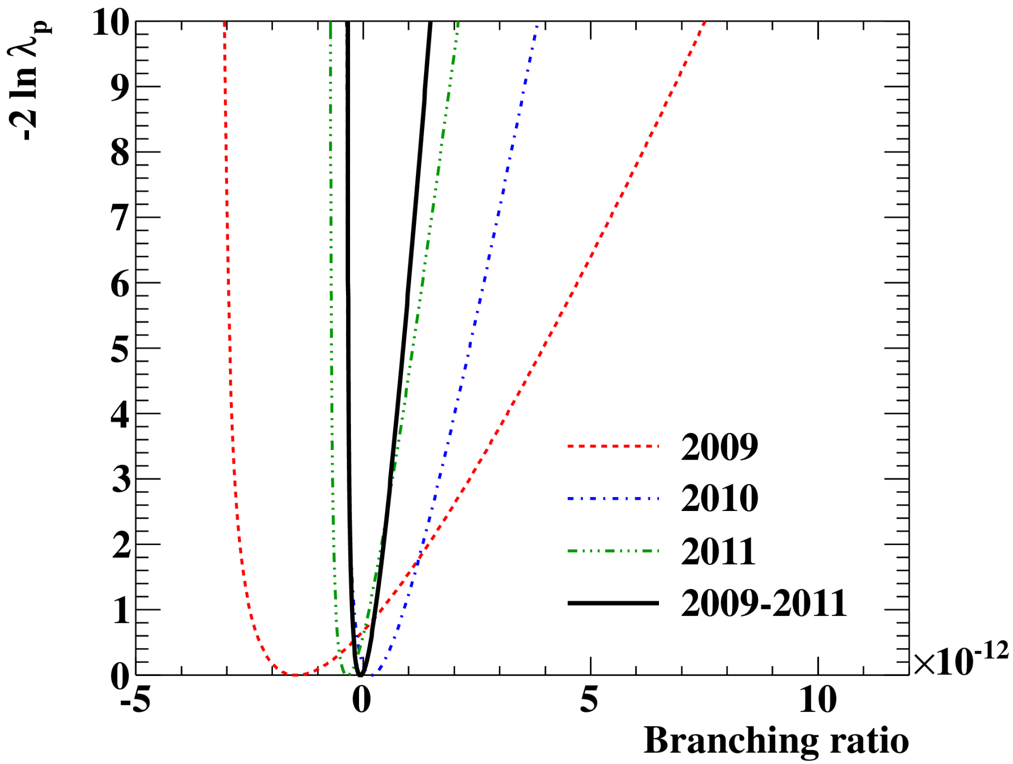
Limits consistent with toy MC studies

Confidence Intervals

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

incl. systematics





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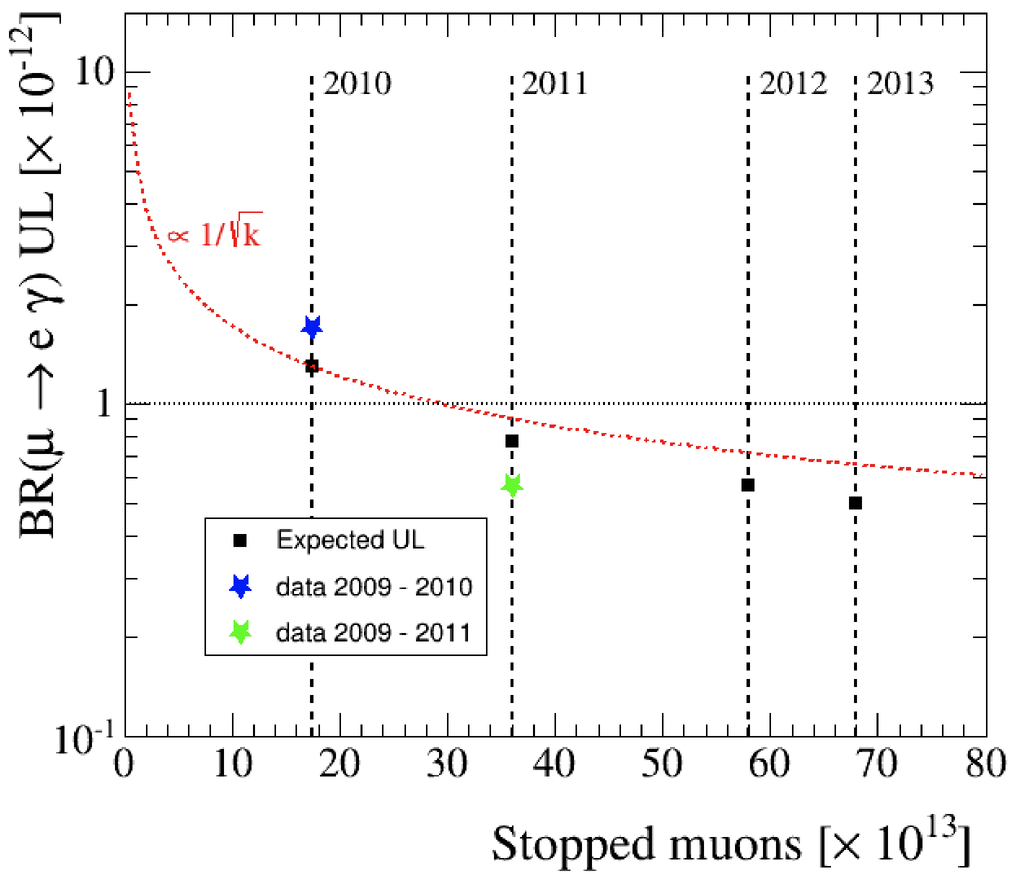
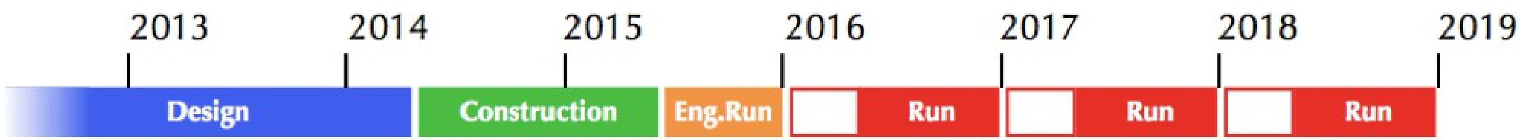
2012 and 2013 Runs

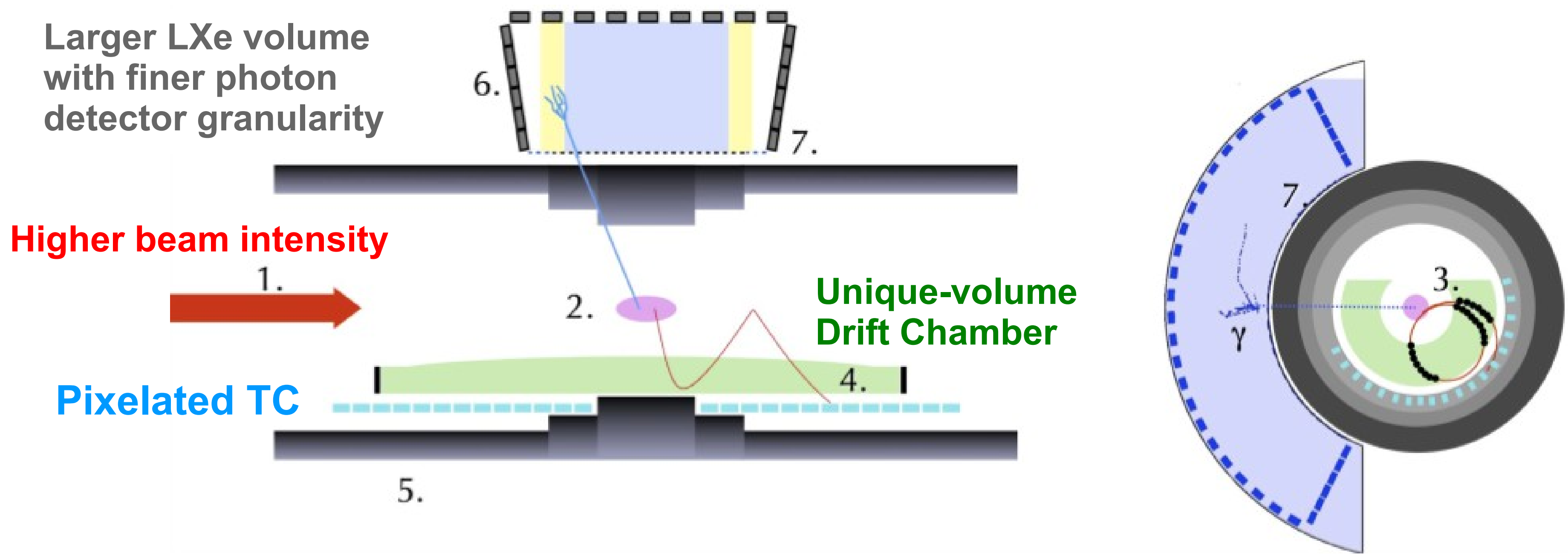
- ~ 22 x 10^{13} stopped μ during 2012 (~ 60% of the 2009 + 2010 + 2011 statistics);
- Analysis on going:
  - exp. sens. ~ 5.7 x 10^{-13}
- A 3-month run is planned from May 2013:
  - final sens. ~ 5 x 10^{-13}



The MEG Upgrade (arXiv:1301.7225)

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





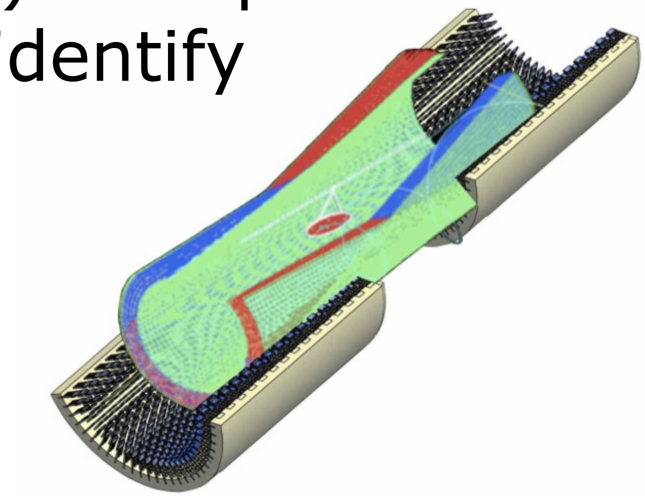
Drift Chamber Design

- 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;

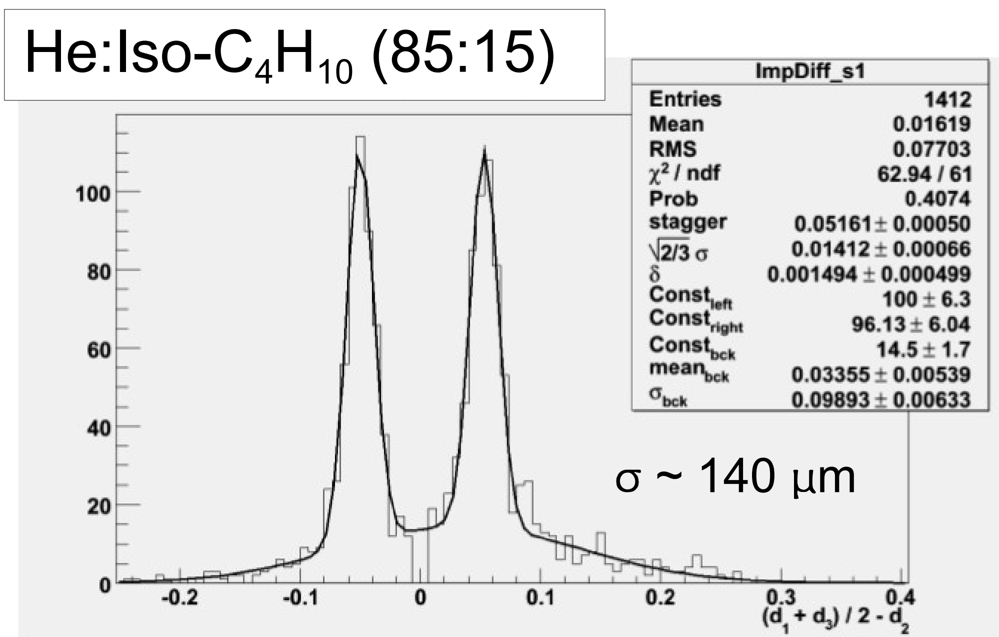
$\sigma(XY) \sim 120\ \mu m$
$\sigma(Z) \sim 900\ \mu m$
$\Rightarrow$
$\sigma(p) \sim 130$ keV
$\sigma(\theta,\varphi) \sim 5$ mrad



Drift Chamber R&D (I)

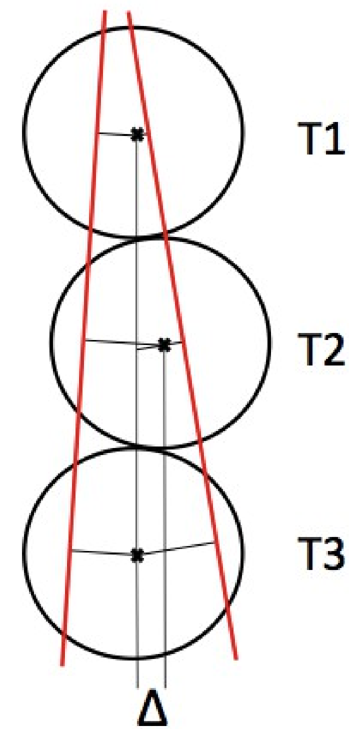
PRELIMINARY TESTS

- 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.



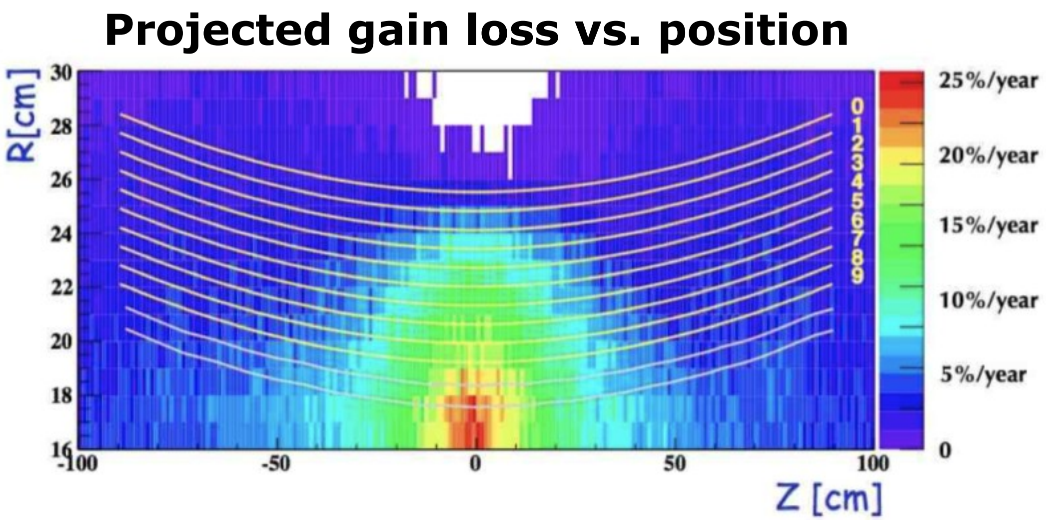
$$\frac{d_1 + d_3}{2} - d_2 = \pm\Delta$$

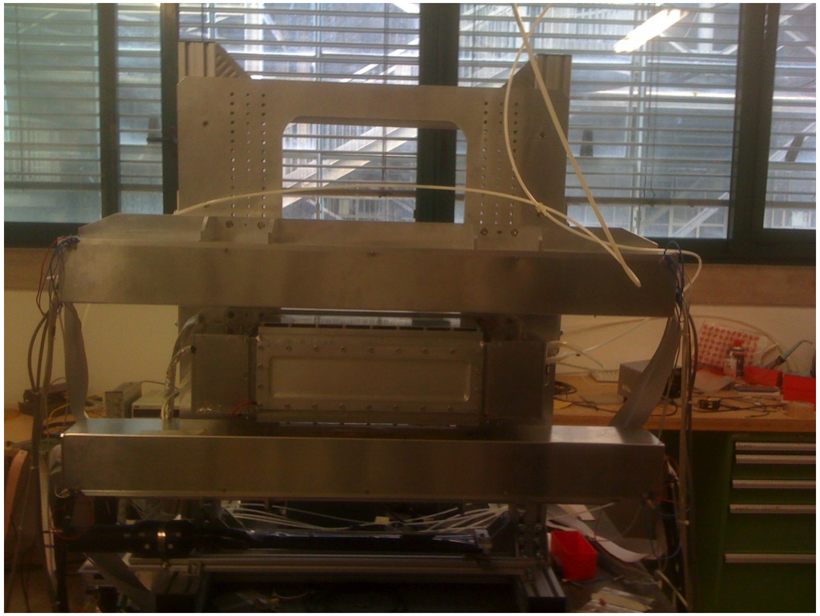
$$\sigma_\Delta \cong \sqrt{\frac{3}{2}}\,\sigma_d$$



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;

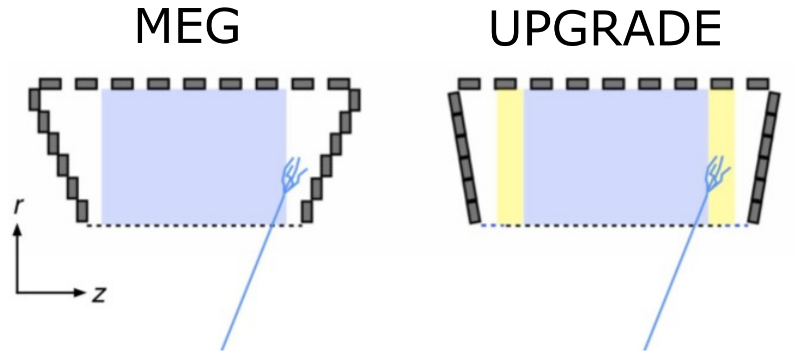




- Next steps:
  - optimization of geometry and materials;
  - construction of more complex prototypes to validate the performances and the construction procedures.

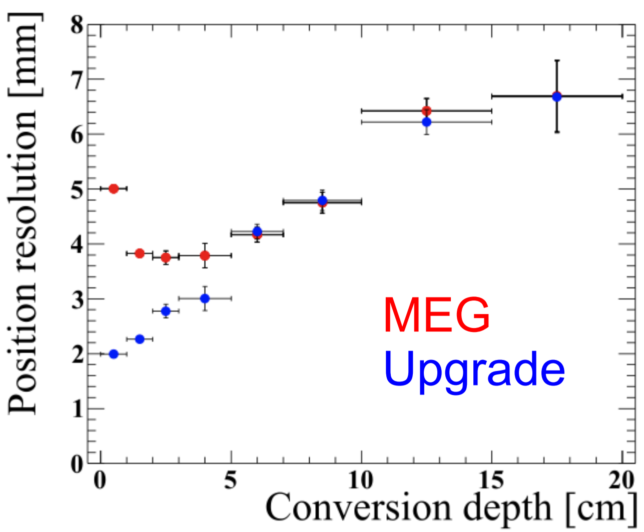
LXe Detector Design

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



MAIN IMPROVEMENTS

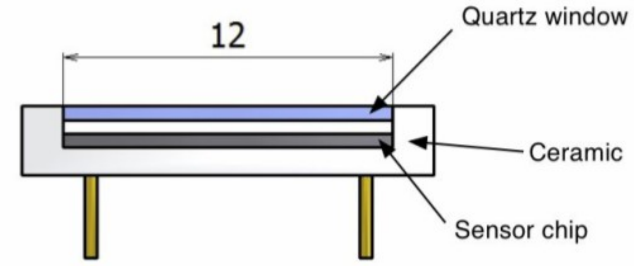
- Larger fiducial volume;
- Finer granularity in the inner face:
  - better resolutions for shallow γ;
- Better control of reflexions in the lateral faces.

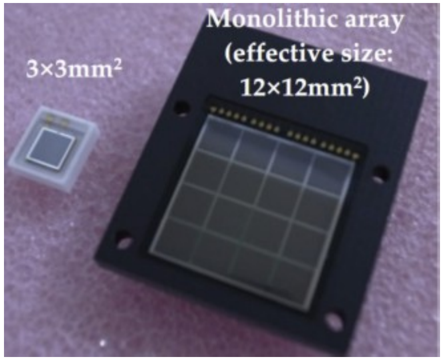


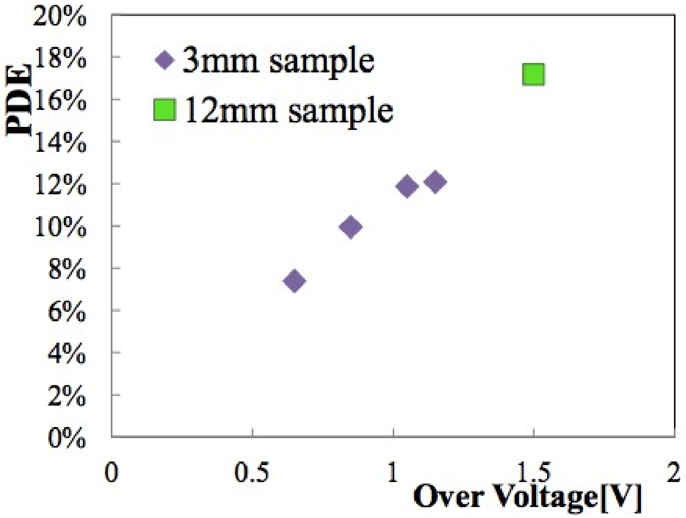
σ(E) ~ 1%   σ(position) ~ 2 (5) mm in x,y (z)

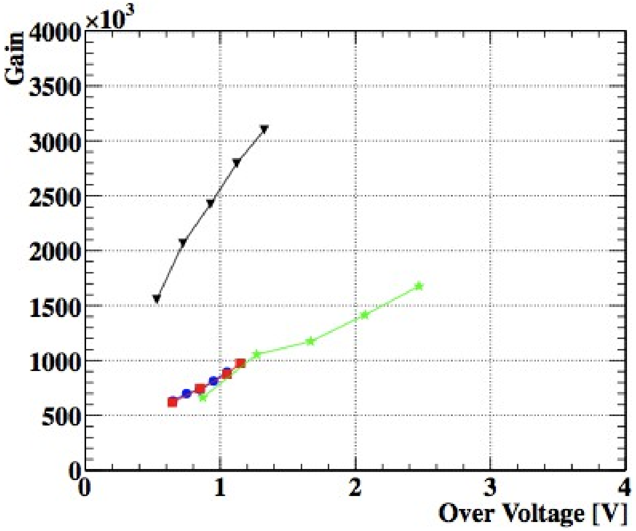
LXe Detector R&D

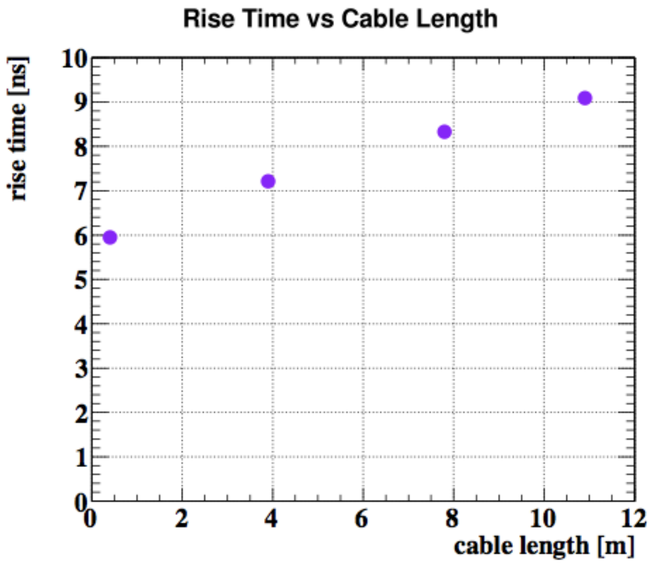
- Development of dedicated UV-sensitive large-area SiPM in collaboration with Hamamatsu;
- Several measurements performed (photon detection efficiency, gain, signal deterioration by feedthrough and cables);
- Next step: test with LXe prototype;









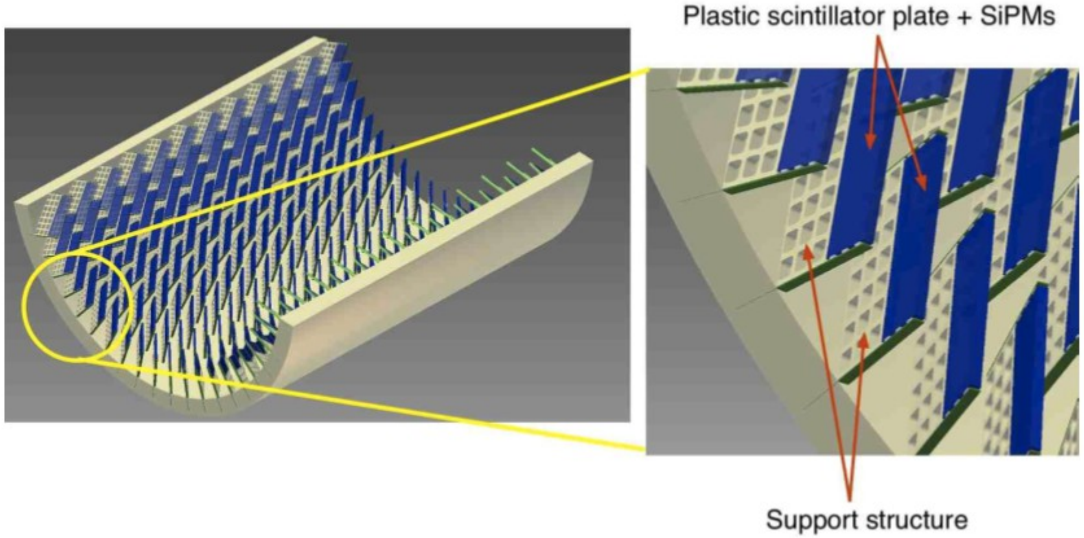


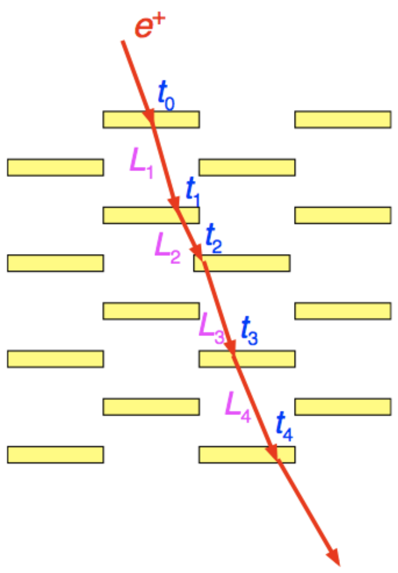
Timing Counter Design

- *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.

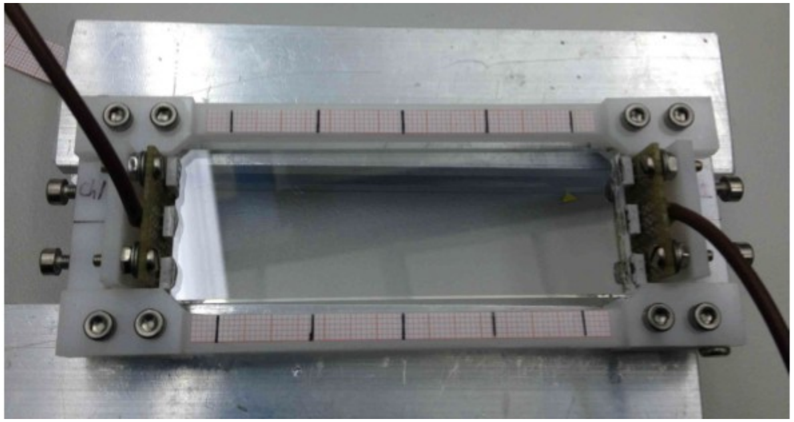


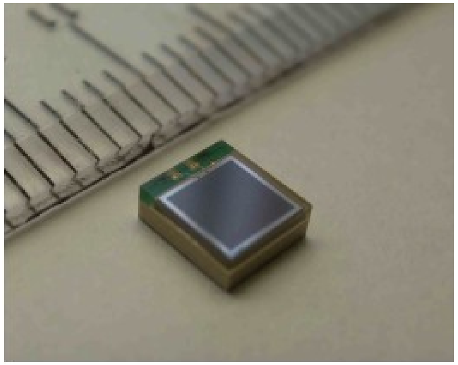


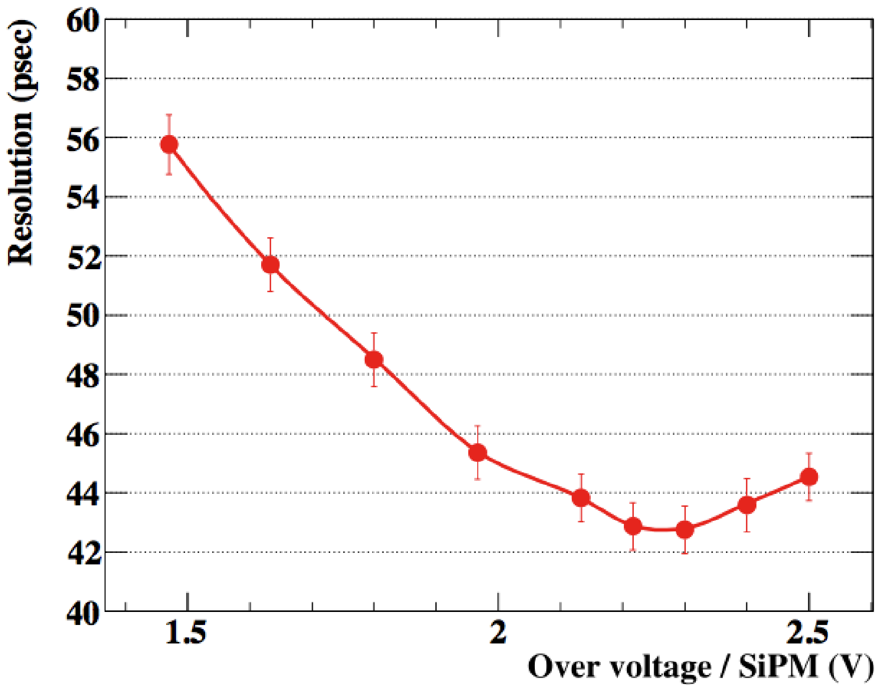
$$\sigma^2_{\text{overall}} = \frac{\sigma^2_{\text{single}}}{N_{\text{hit}}} + \frac{\sigma^2_{\text{inter-pixel}}}{N_{\text{hit}}} + \sigma^2_{\text{MS}}(N_{\text{hit}})$$

Timing Counter R&D

- Test of a single counter showed the desired resolutions;







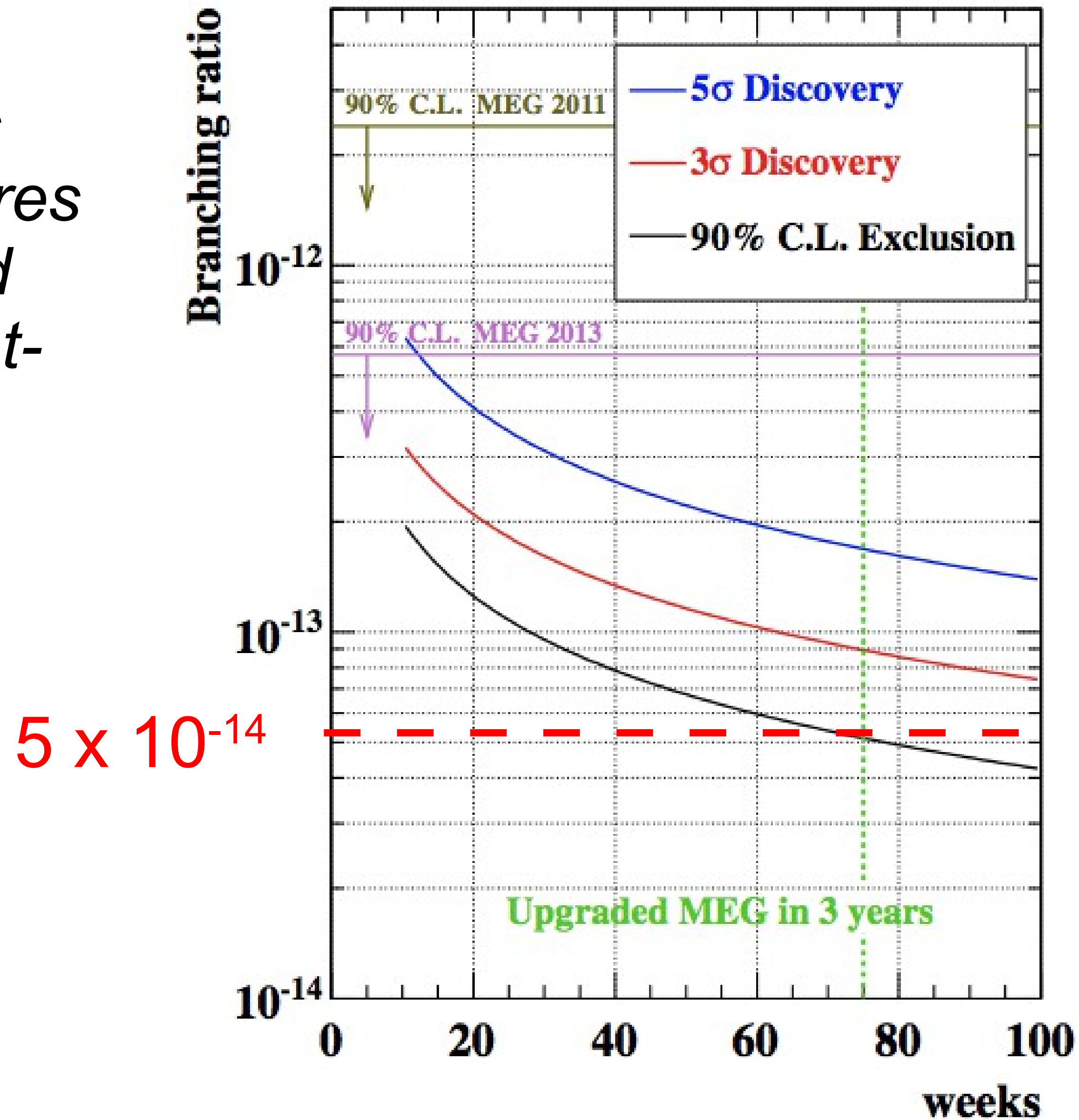
- Next step: study of multi-hit resolution with beam tests on a small prototype.

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

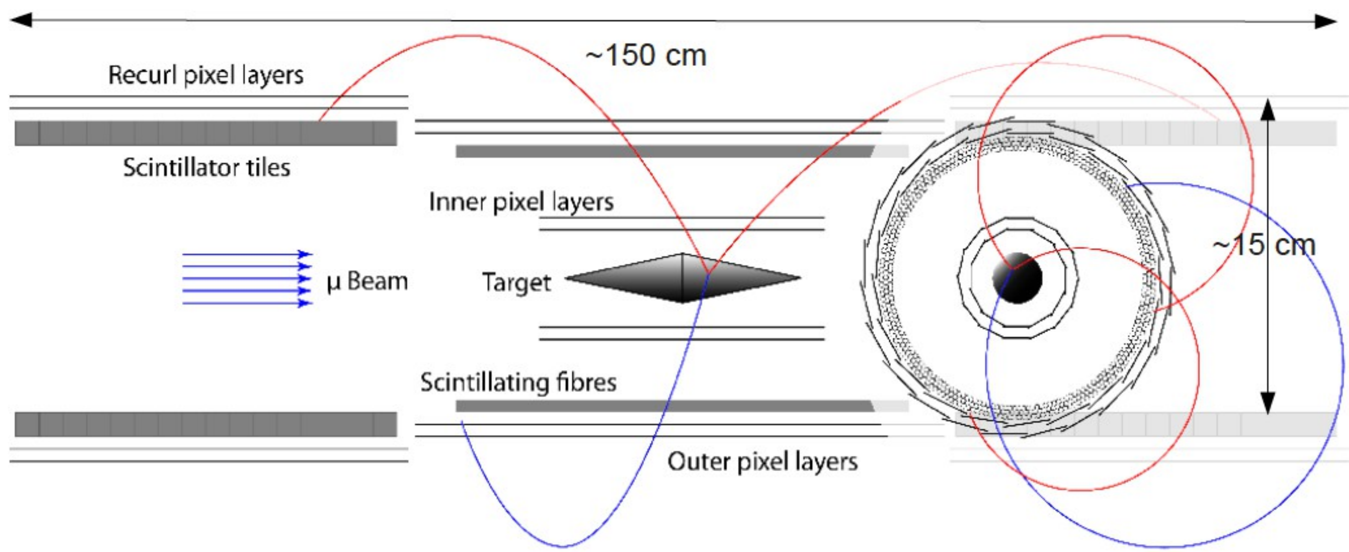
From Toy MC experiments including all relevant features observed in MEG data and upgrade simulations (event-dependent resolutions, correlations, etc.).



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}

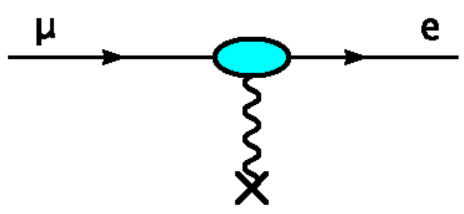


- Two-phase project (low and high beam intensity):
  - first phase potentially superimposed to the MEG upgrade (PSI could consider the possibility of some beam time sharing, if Mu3e is also approved).

Other μ LFV searches (II)

SEARCHES FOR μ → e CONVERSION IN NUCLEI

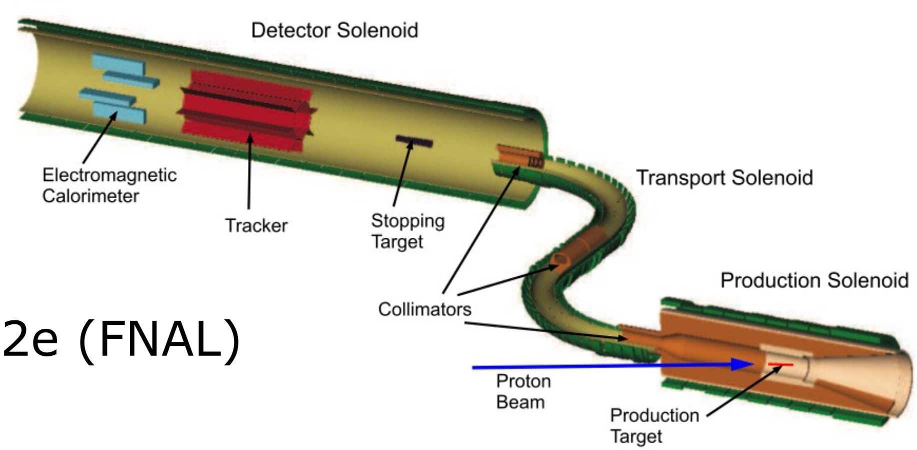
- Two R&D to search for μ → e conversion in the interaction with nuclei at a level of < 10^{-16}.



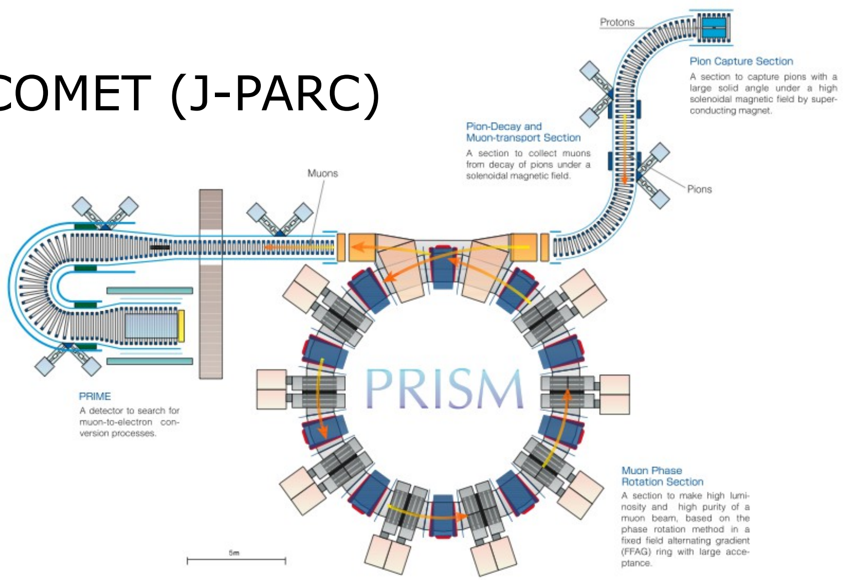
In many models:

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

COMET (J-PARC)

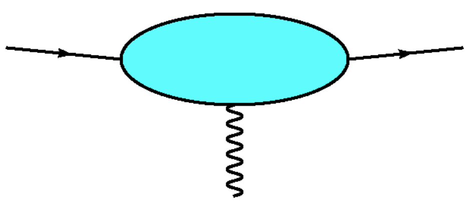


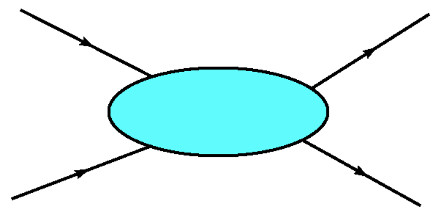
Mu2e (FNAL)



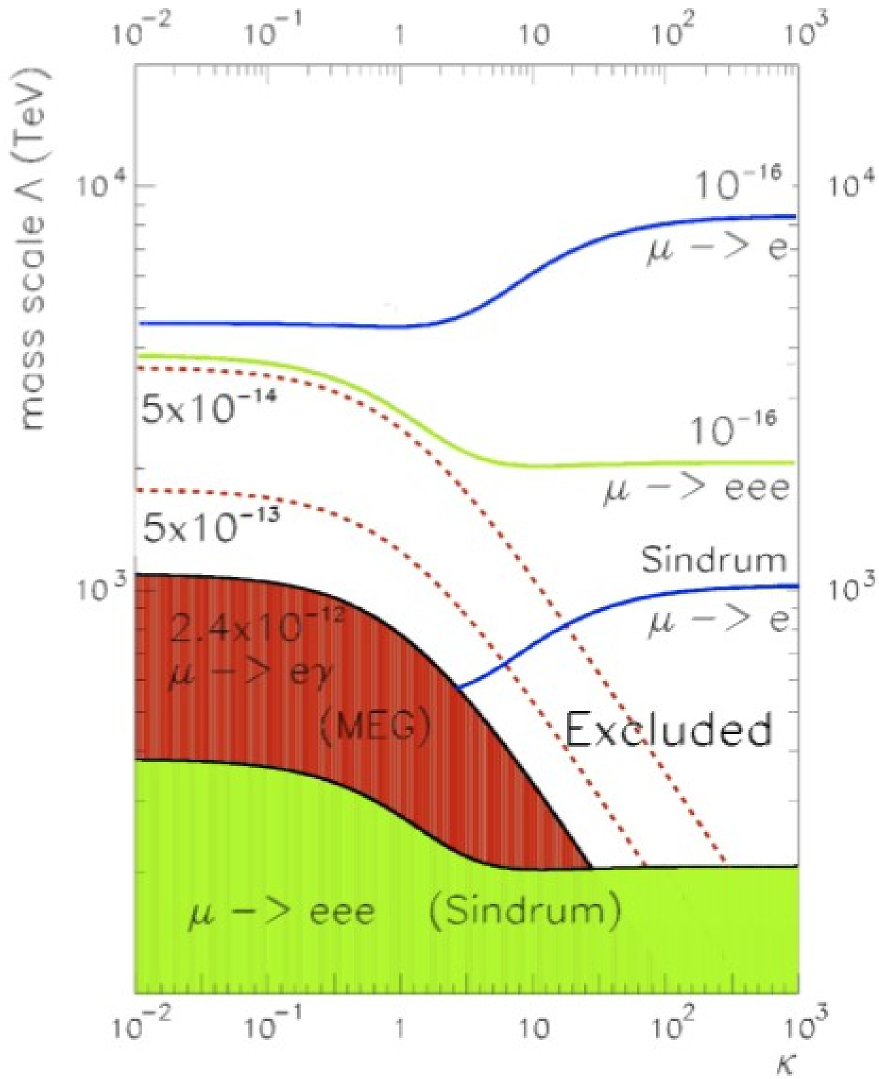
Comparison of Sensitivities

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

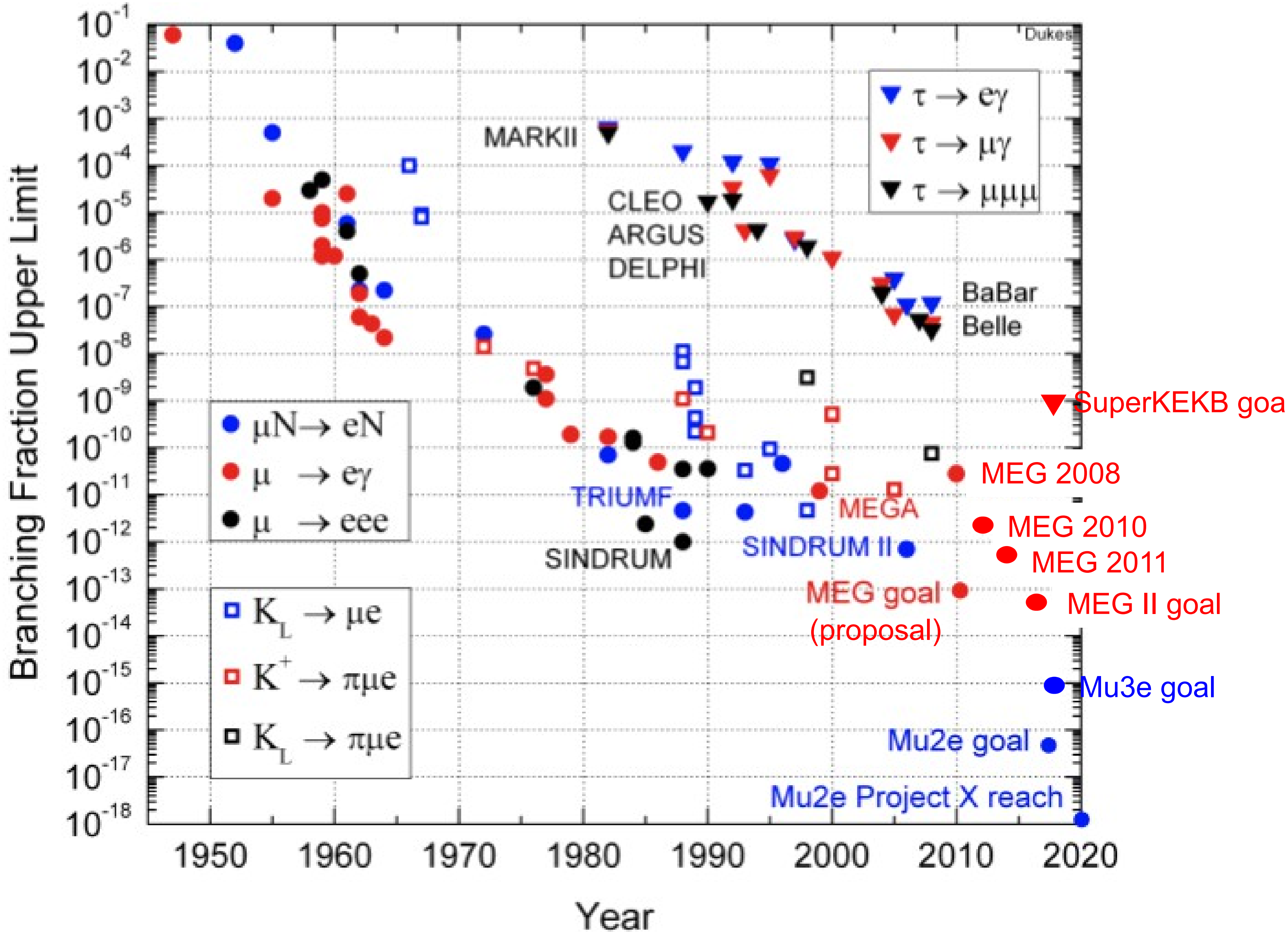




If LFV is predominantly produced by dipole-like interactions (as in SUSY-GUTs), the MEG upgrade will be competitive with Mu3e and the first phase of the $\mu \to e$ conversion experiments.

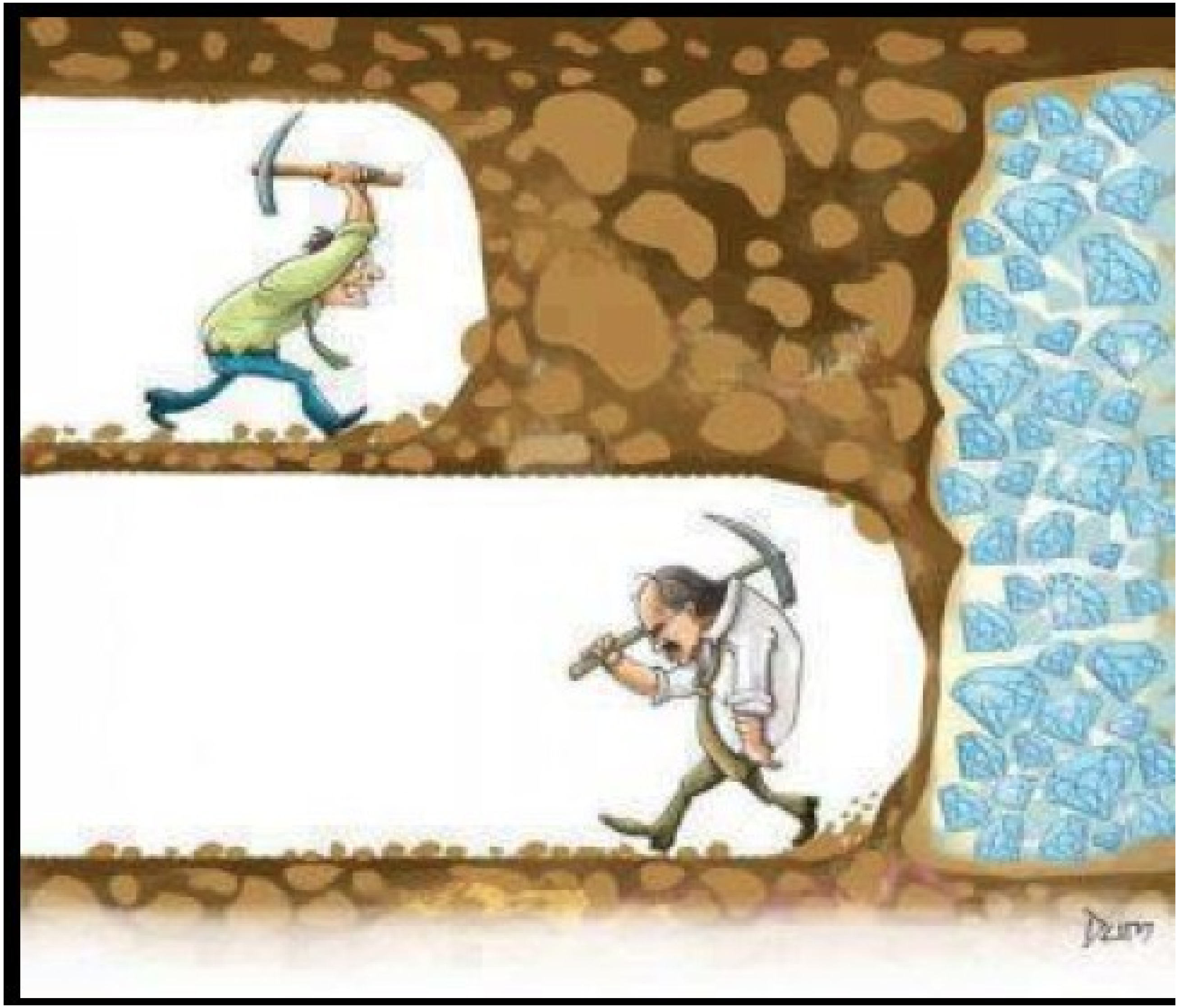


History of Searches for LFV



E. C. Dukes, TAU2010

Do not stop searching!



Backup

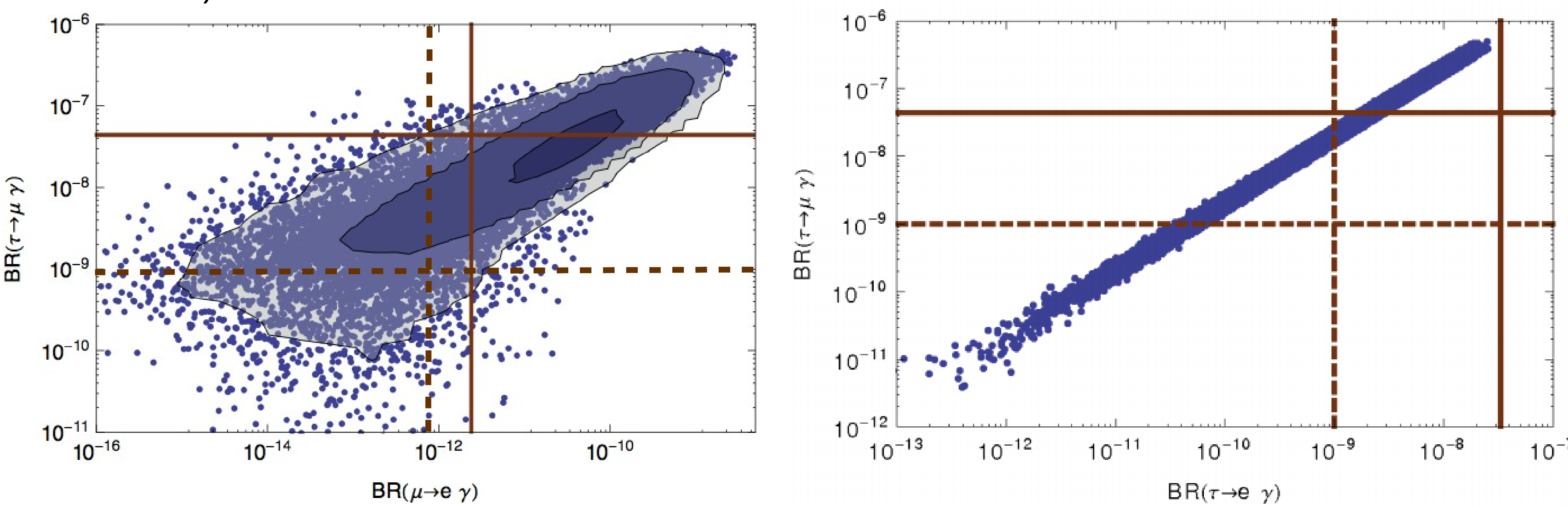
LFV and θ_{13}

- 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

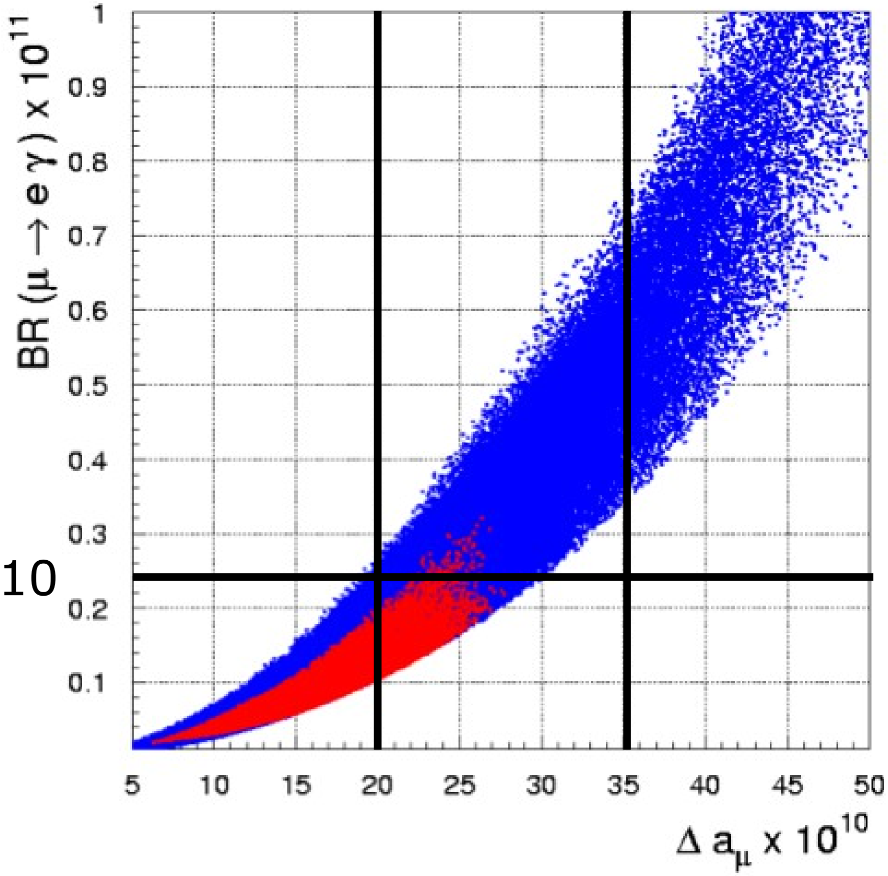
- Strict relation of LFV and leptonic dipole moments in many NP models.

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

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

E821 experiment

MEG 2010



MSSM with large tanβ

(Isidori, Mescia, Paradisi '07)

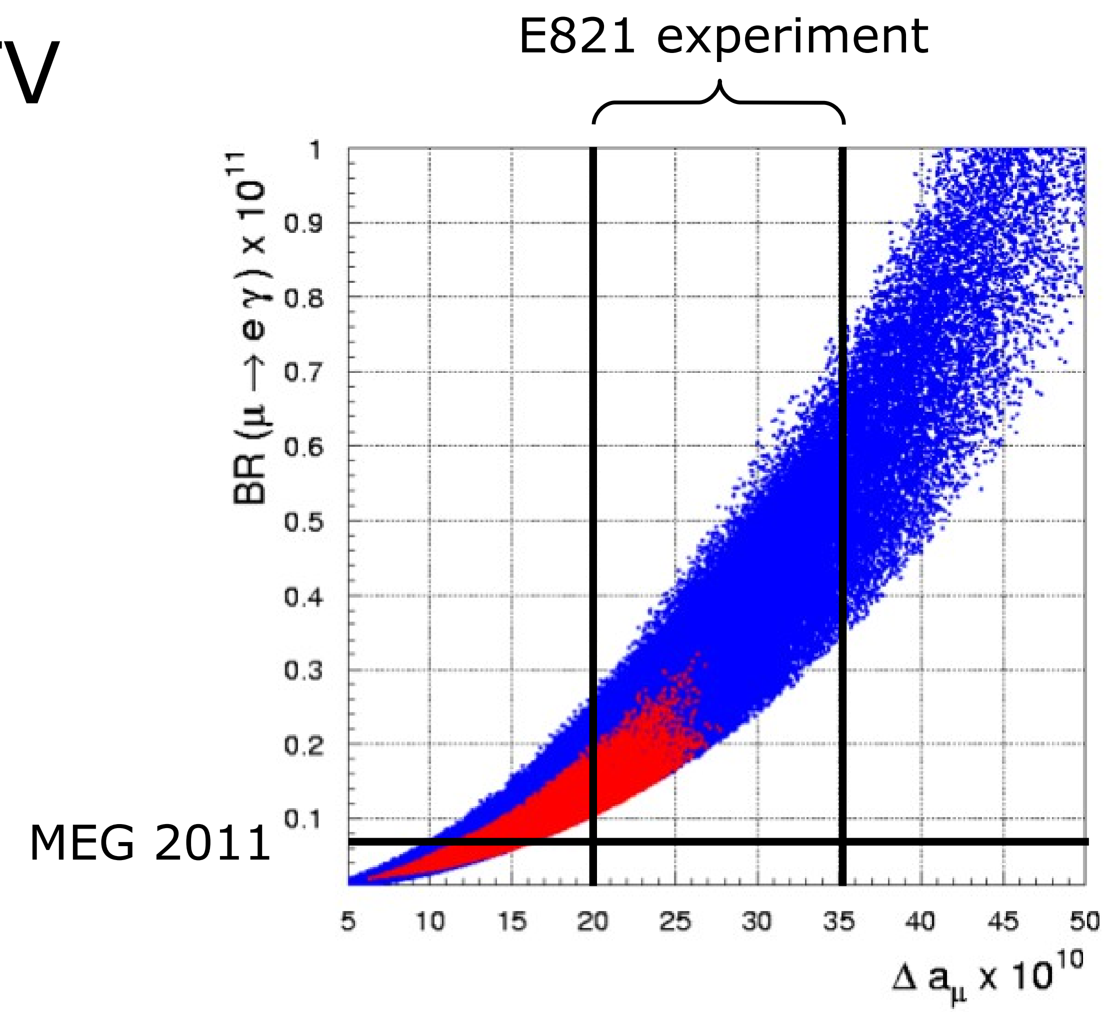
the red area includes B physics constraints ($B_s \to \mu\mu$ evidence at LHCb not included)

LFV and dipole moments

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

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

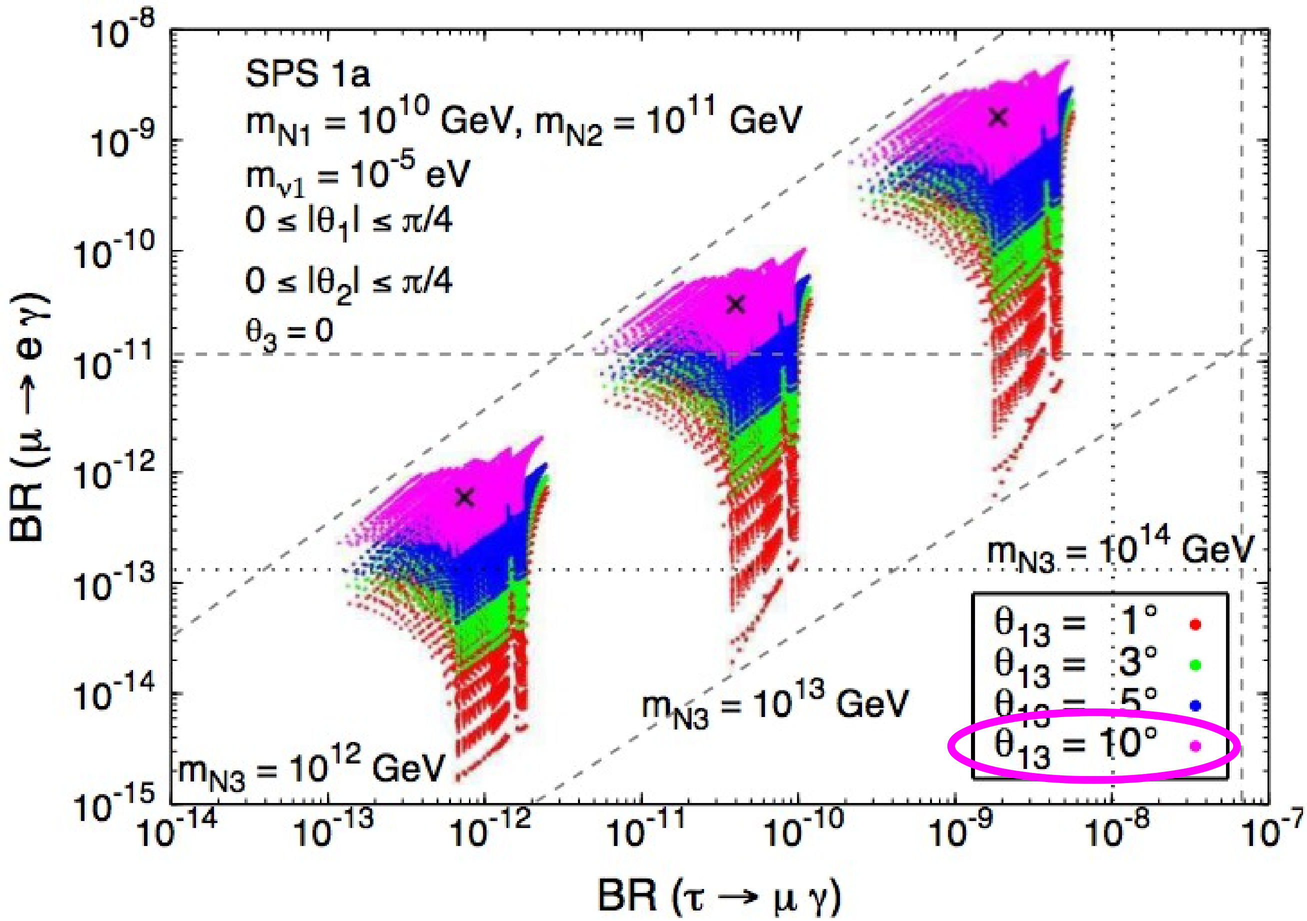
$$\Delta a_\mu = a_\mu - a_\mu^{SM}$$



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

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)

LXe properties

NaI(Tl)

2.59 cm

4.13 cm

230 ns

410 nm

30 cm

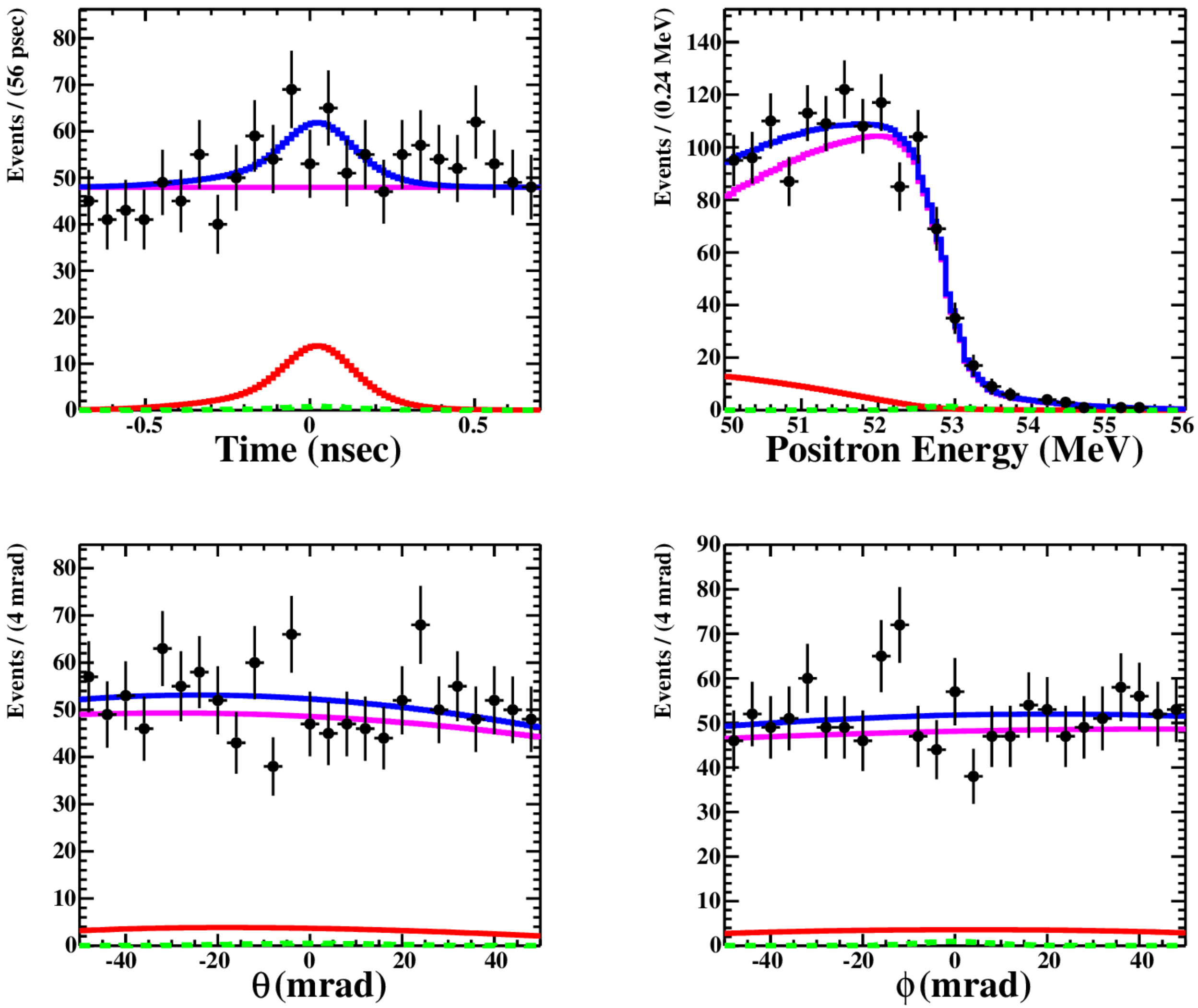
Material Properties	Value & Unit	Conditions
Atomic Number	54	
Atomic Weight A	131.29 g/mole	
Boiling point T_b	165.1 K	1 atm
Melting point T_m	161.4 K	1 atm
Density ρ_{liq}	2.98 g/cm^3	161.35 K
Volume ratio $\rho_{\mathrm{gas}}/\rho_{\mathrm{liq}}$	550	15 °C, 1 bar
Critical point T_c, P_c	289.7 K, 58.4 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	
$-(\mathrm{d}E/\mathrm{d}x)_{\mathrm{mip}}$	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)	~ 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

New Analysis of 2009/2010 data



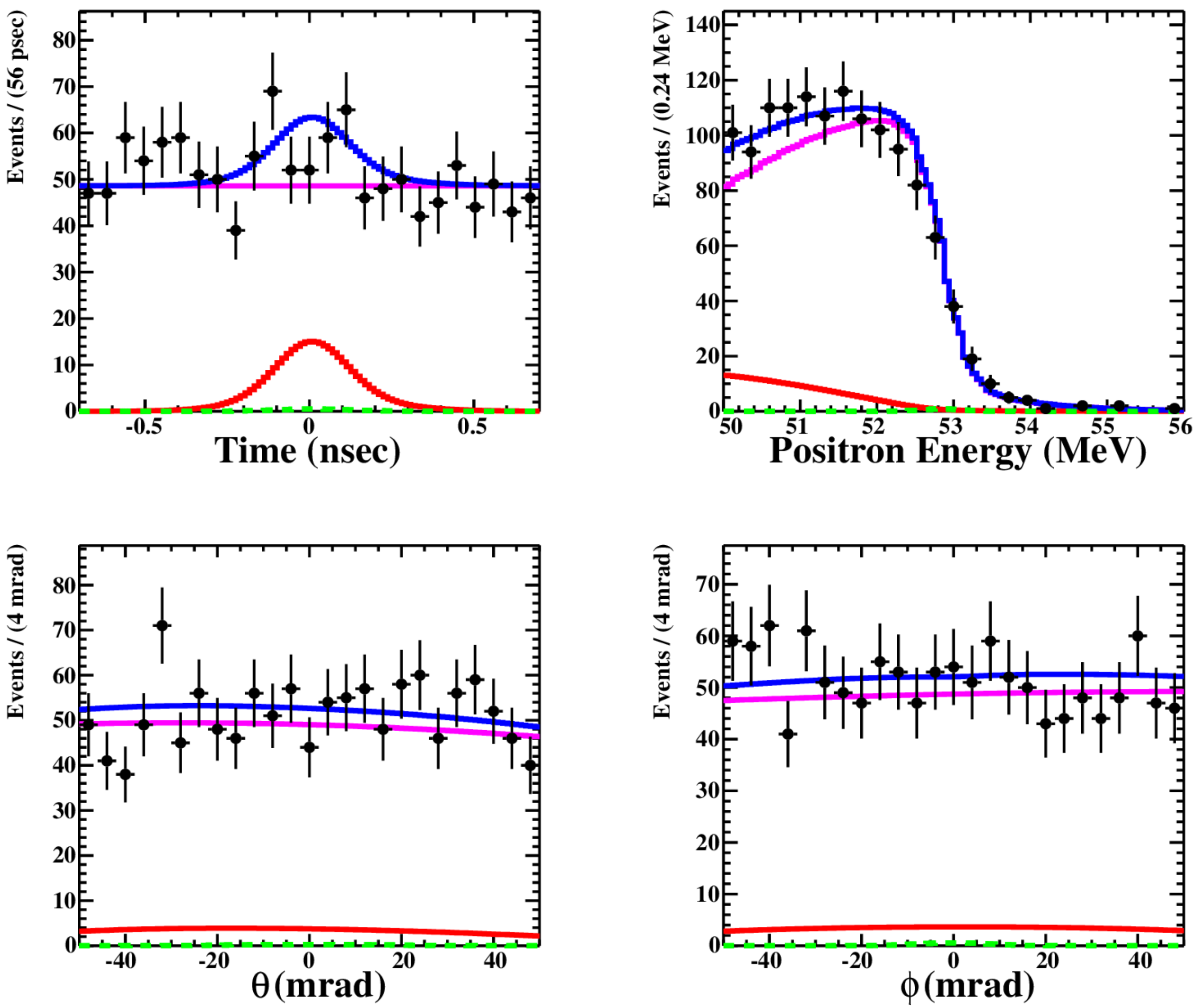
Based on
~ 17.5 x 10^{13} μ
stopped at the target

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

$N_{bkg} = 1198 \pm 26$

$N_{RD} = 83 \pm 13$

Analysis of 2011 data



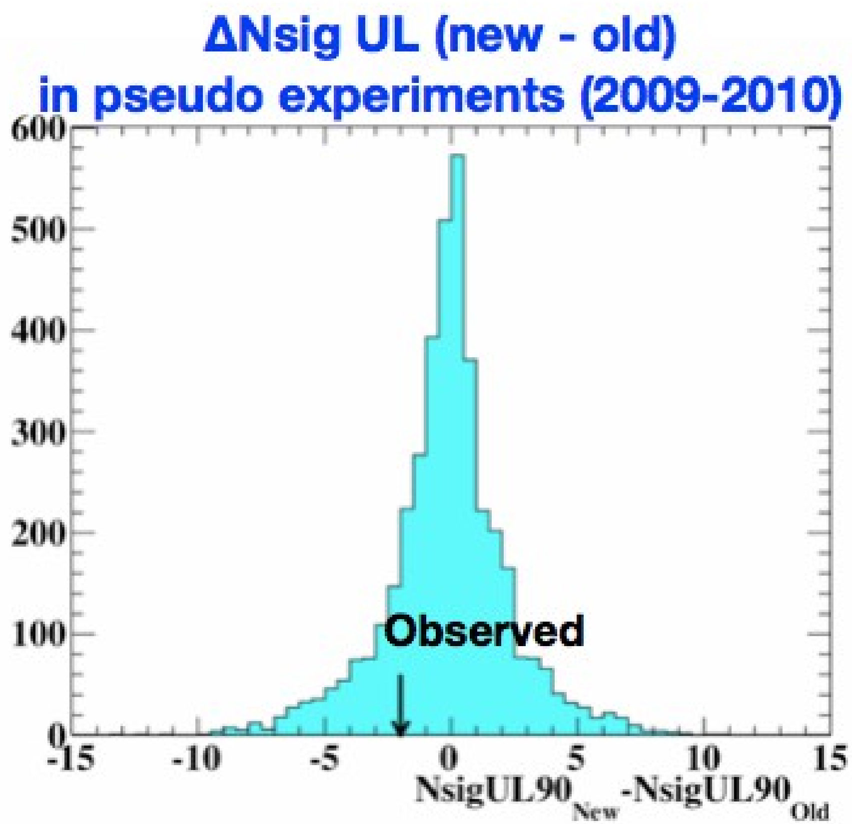
Based on
~ 18.5 x 10^{13} μ
stopped at the target

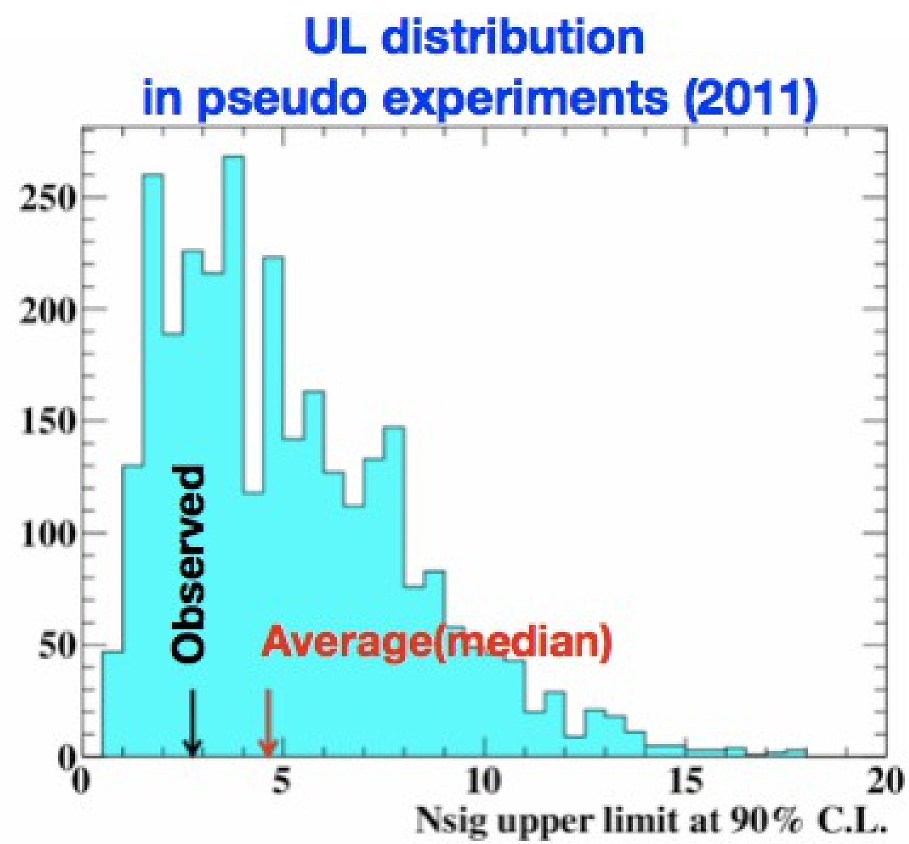
$N_{sig} = -1.4^{+3.8}_{-1.9}$

$N_{bkg} = 1215 \pm 26$

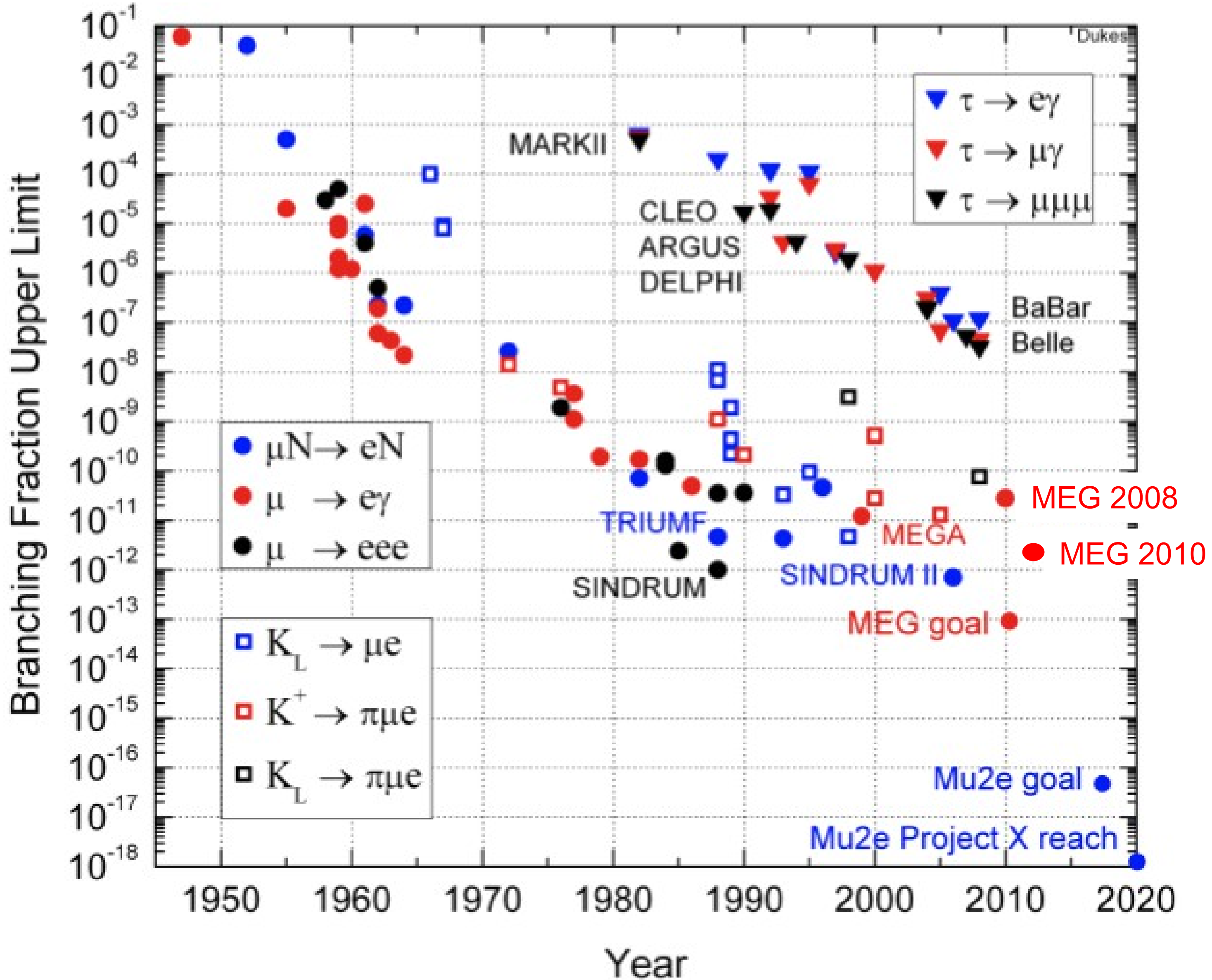
$N_{RD} = 85 \pm 13$

Consistency Check





History of Searches for LFV



E. C. Dukes, TAU2010