Séminaires de physique expérimentale, LAPP (Annecy), 14 October 2011

PAUL SCHERRER INSTITUT

Recent Results from the MEG Experiment

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Paul Scherrer Institut, Villigen (CH)
and
INFN Roma

Outline

- Theoretical Overview;
- The MEG Experiment - $\mu \rightarrow e \gamma$ at BR ~ 10^{-13}:
  - The detector;
  - Calibration procedures;
  - Data analysis;
- Future perspectives.

Lepton Flavour Violation (I)

- In the Standard Model (SM), if we neglect the neutrino mass, lepton flavour is exactly conserved:

QUARK SECTOR

$$\mathcal{L} \subset -\frac{g}{\sqrt{2}} W_\mu \overline{U'}_L \gamma^\mu D'_L - \frac{v}{\sqrt{2}} \overline{U'}_L Y'_U U'_R - \frac{v}{\sqrt{2}} \overline{D'}_L Y'_D D'_R$$

$$\longrightarrow -\frac{g}{\sqrt{2}} W_\mu \overline{U}_L \gamma^\mu V_U^\dagger V_D D_L - \frac{v}{\sqrt{2}} \overline{U}_L M_U U_R - \frac{v}{\sqrt{2}} \overline{D}_L M_D D_R$$

LEPTON SECTOR

$$\mathcal{L} \subset -\frac{g}{\sqrt{2}} W_\mu \overline{\nu'}_L \gamma^\mu \ell'_L - \frac{v}{\sqrt{2}} \overline{\ell'}_L Y'_\ell \ell'_R$$

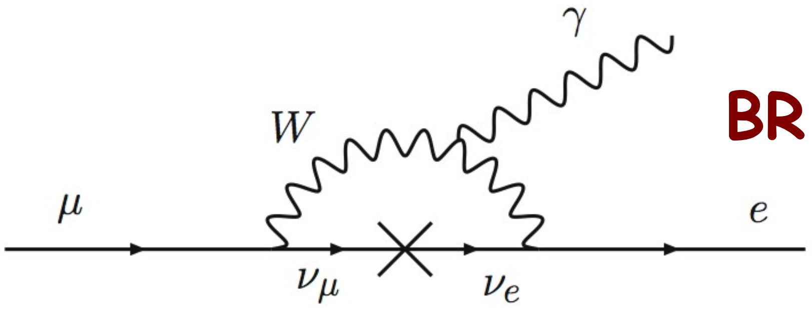
$$\longrightarrow -\frac{g}{\sqrt{2}} W_\mu \overline{\nu}_L \gamma^\mu \ell_L - \frac{v}{\sqrt{2}} \overline{\ell}_L M_U \ell_R$$

$$U = \begin{pmatrix} u \\ c \\ t \end{pmatrix}, \qquad D = \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\ell = \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}, \qquad \nu = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

Lepton Flavour Violation (II)

- Lepton flavour conservation is an *accidental symmetry* of the SM:
  - not a consequence of gauge symmetries;
  - simply follows from the particle content of the SM;
  - *NATURALLY VIOLATED IN MOST OF THE EXTENSIONS OF THE SM;*
- Lepton flavour violation (LFV) already observed in the neutrino sector (*neutrino oscillations*):
  - negligible contribution to LFV in charged lepton decays.



BR < 10^{-50}

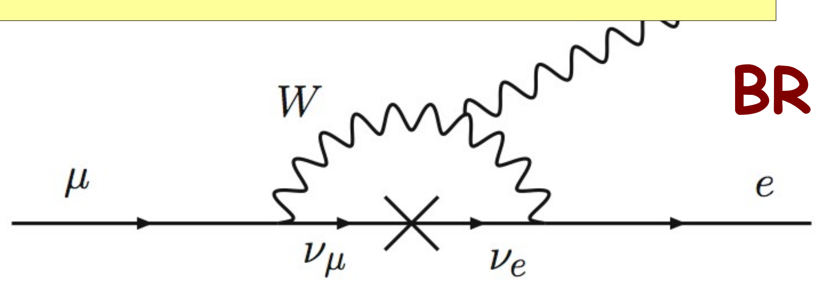
Lepton Flavour Violation (II)

- Lepton flavour conservation is an *accidental symmetry* of the SM:
  - no
  - si M;
  - *N*
    EX
- Lepto e
  neutr

1) *Lepton Flavour Violation is a very sensitive probe for physics beyond the SM*

2) *The observation of $\mu \to e\,\gamma$ at a level of 10^{-13} would be an unambiguous evidence of New Physics*

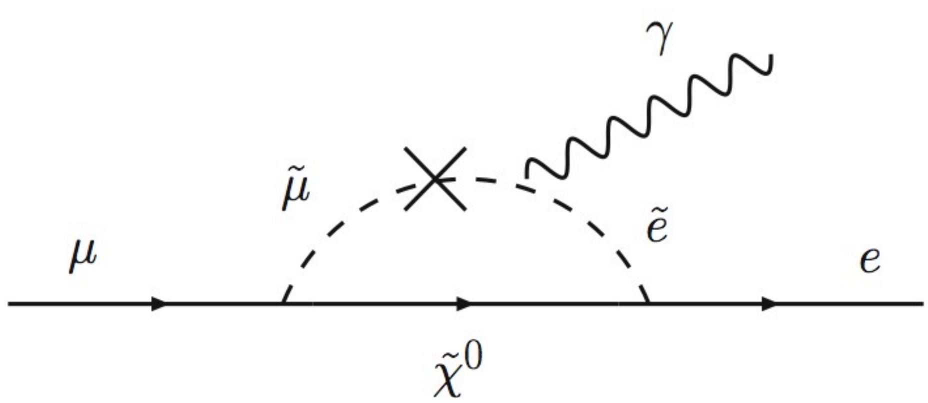
  - negligible contribution to LFV in charged lepton decays.



BR < 10^{-50}

LFV beyond the SM (I)

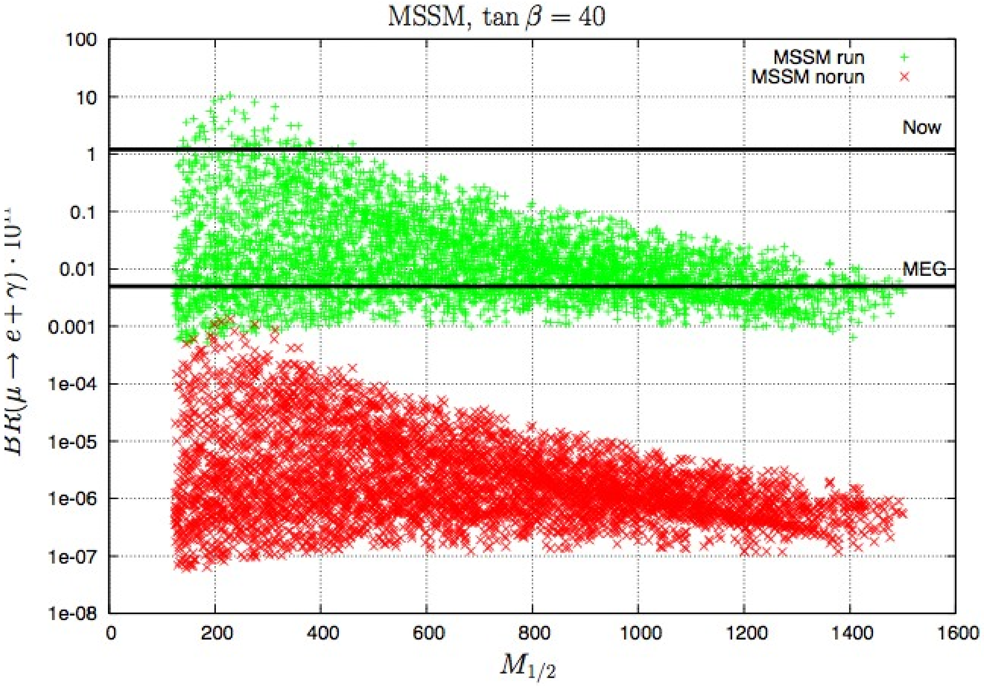
- Many SM extensions predict LFV decays at an observable level;
- SUSY:
  - Off-diagonal terms in the slepton mass matrix appear for free (from renorm. group eqns.) $\rightarrow$ slepton "oscillations";
  - leptons couple to sleptons $\rightarrow$ slepton oscillations mediate LFV:

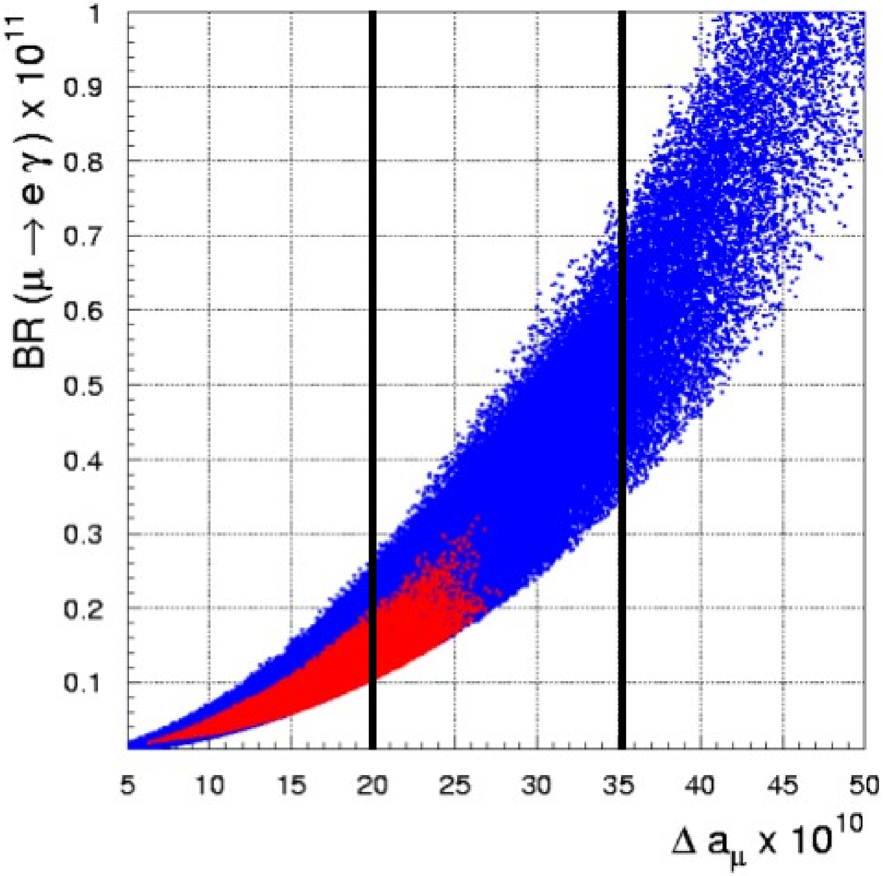


LFV beyond the SM (II)

- Some specific SUSY models

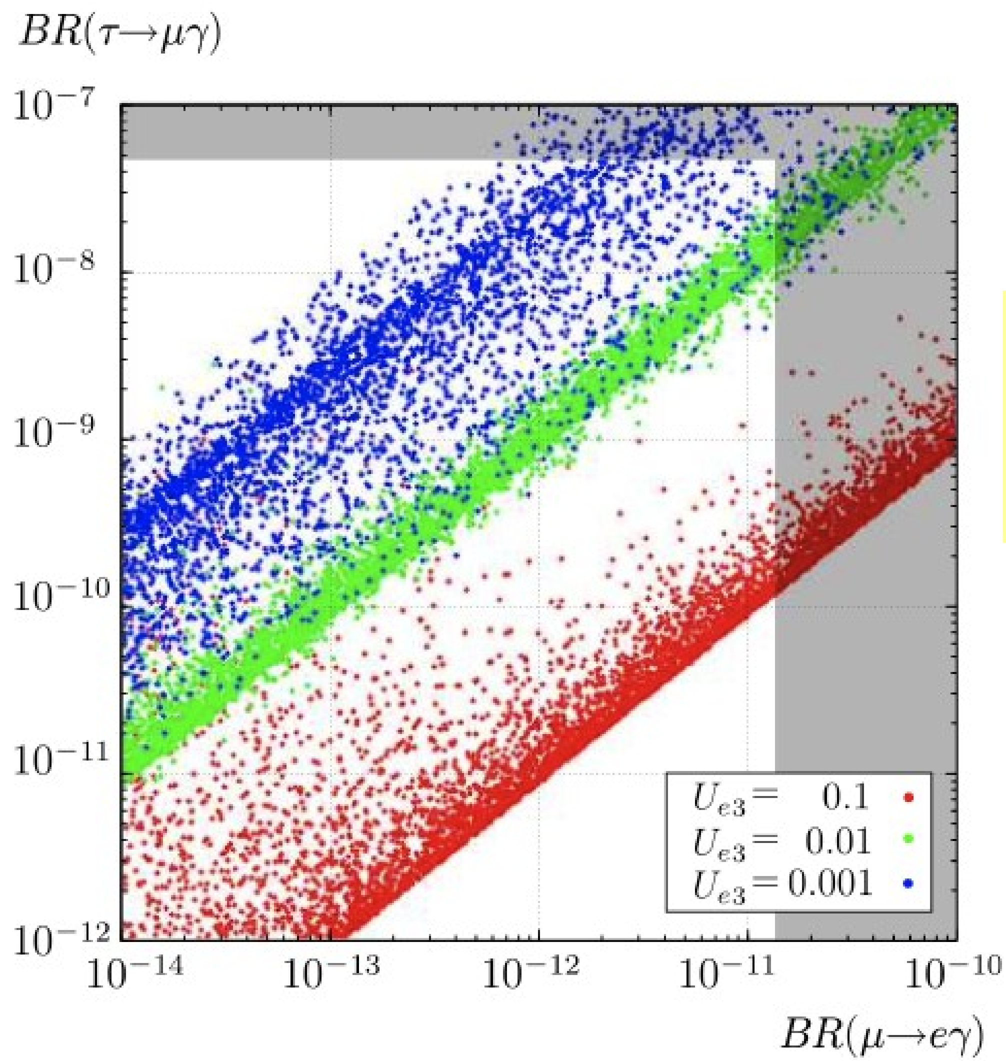
SO(10) SUSY GUT w/ see-saw
(Calibbi, Faccia, Masiero, Vempati '07)





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

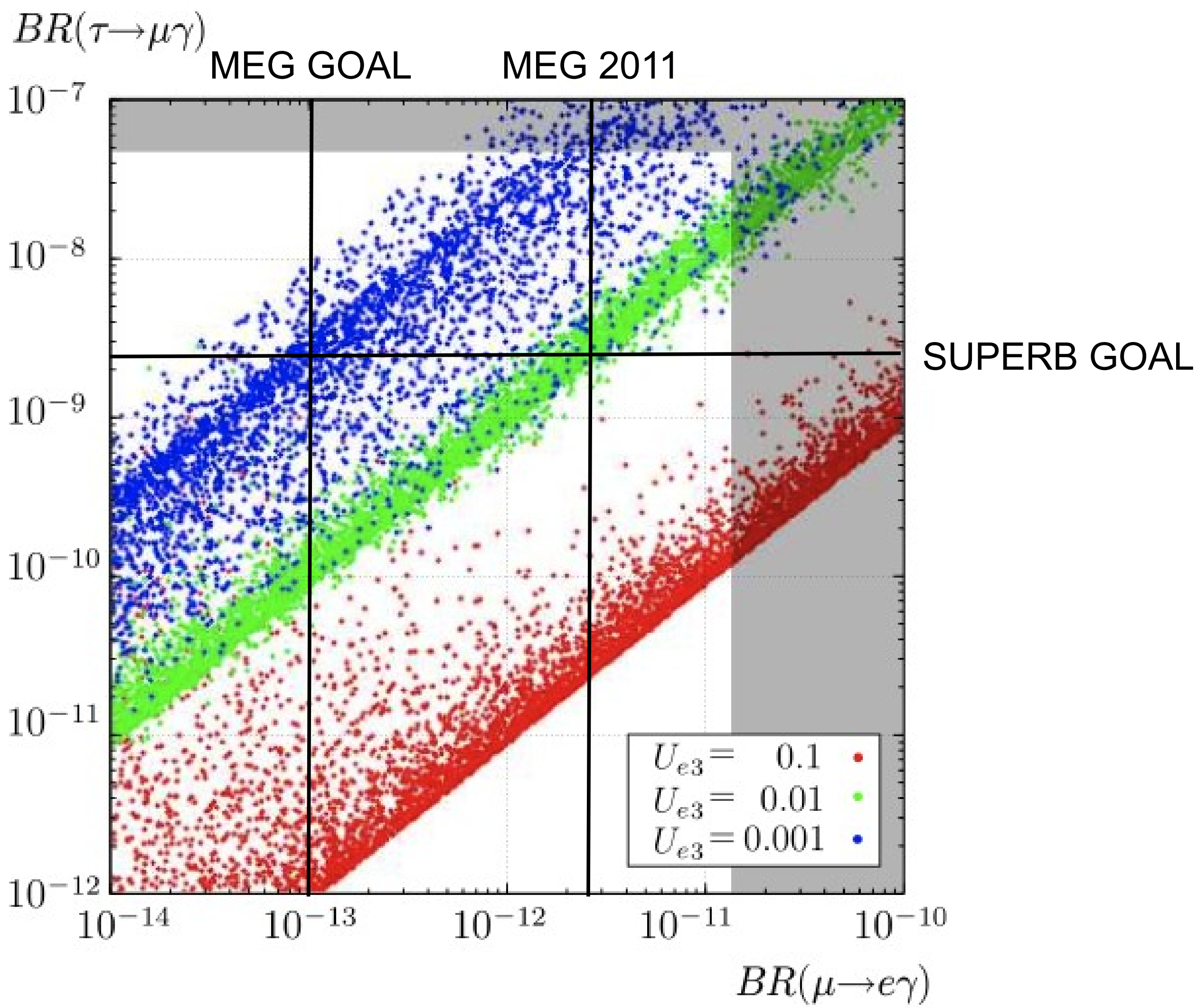
LFV in μ and τ sectors



ν mixing parameter
$U_{e3} < 0.03$
(CHOOZ)

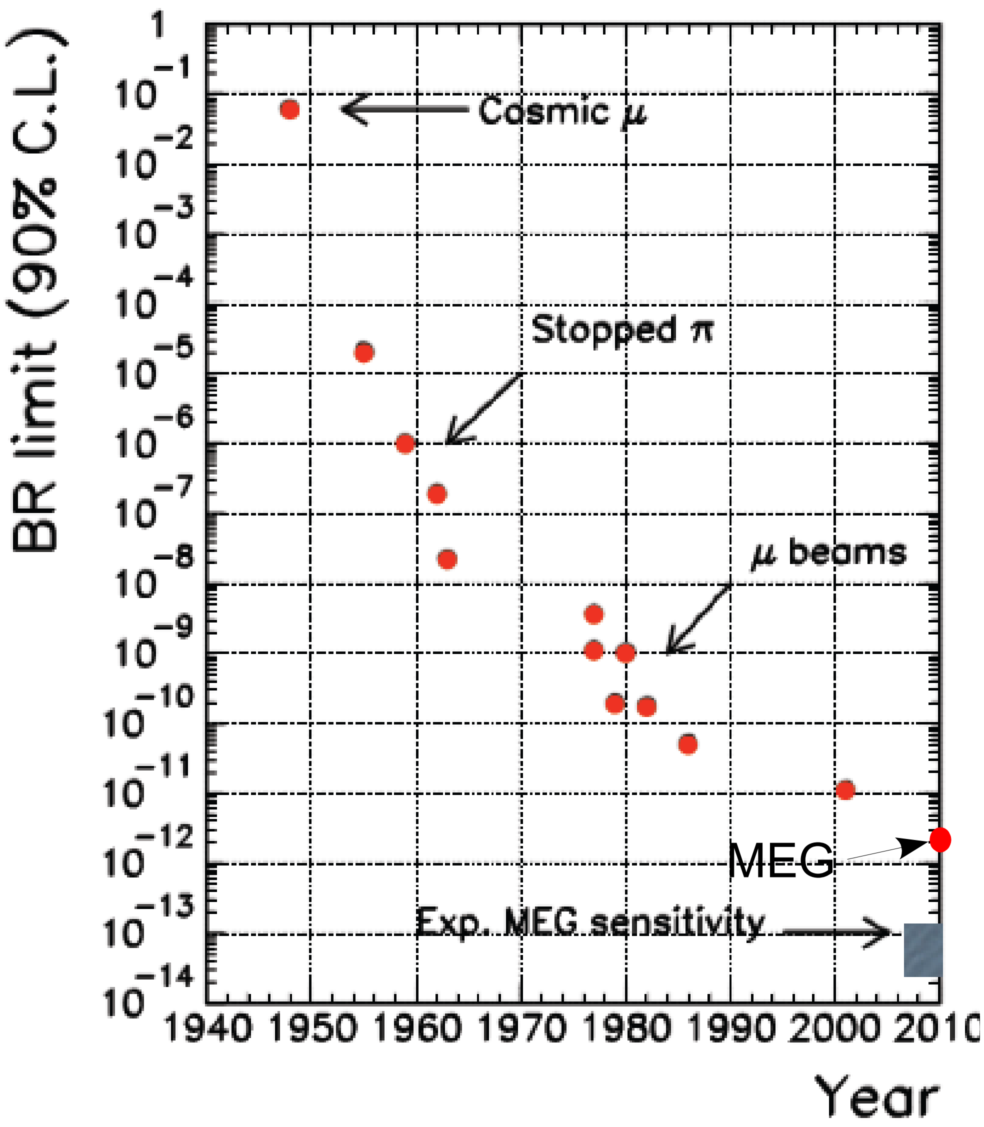
SUSY SU(5) with right-handed neutrino (Hisano, Nagai, Paradisi, Shimizu '09)

LFV in μ and τ sectors



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

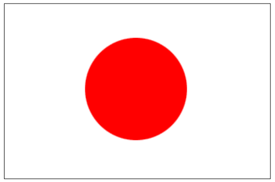
μ → e γ: Historical Review



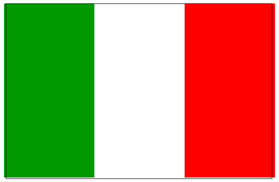
- 1947 – Hinks & Pontecorvo:
  - First limit;
- 1977 – Van der Schaaf *et al.* (PSI) Depommier *et al.* (TRIUMF):
  - First experiments with muon beams.
- 1999 – MEGA (LANL):
  - Best limit before MEG;
  - BR < 1.2 x 10^{-11} @ 90% C.L.

The MEG Experiment

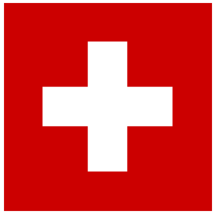
The MEG Collaboration



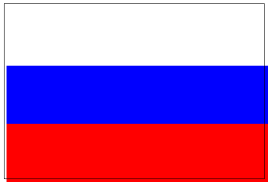
KEK
TOKYO UNIVERSITY
WASEDA UNIVERSITY



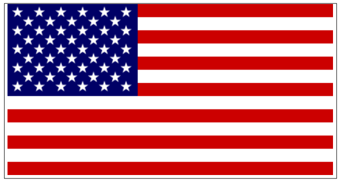
GENOVA
LECCE
PAVIA
PISA
ROMA



PSI

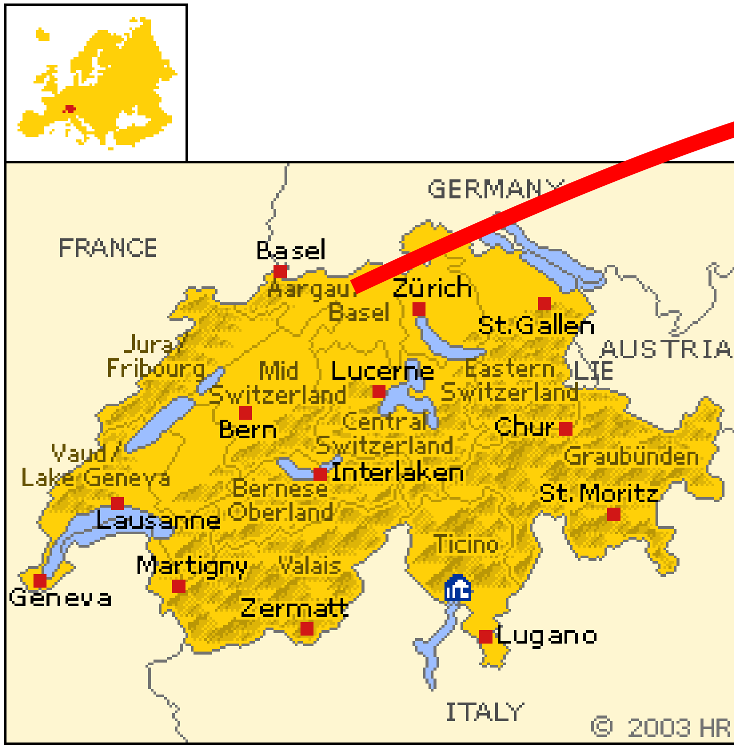


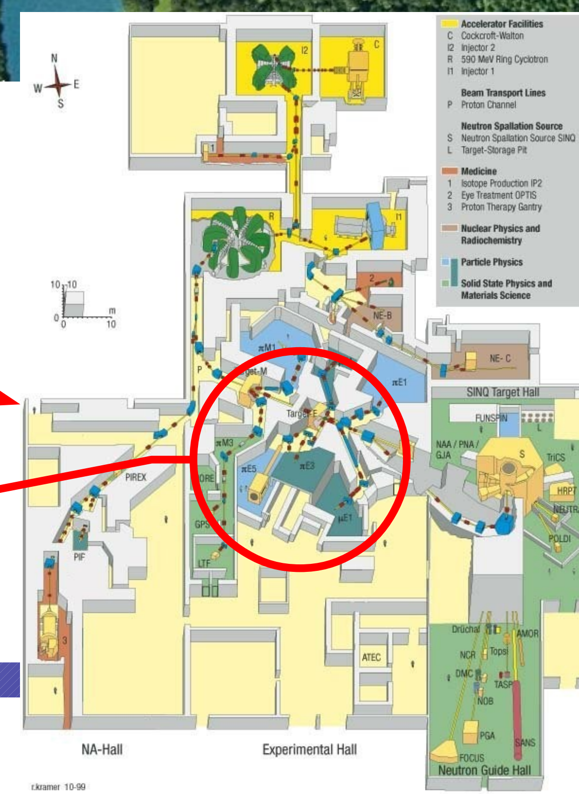
BINP - NOVOSIBIRSK
JINR - DUBNA



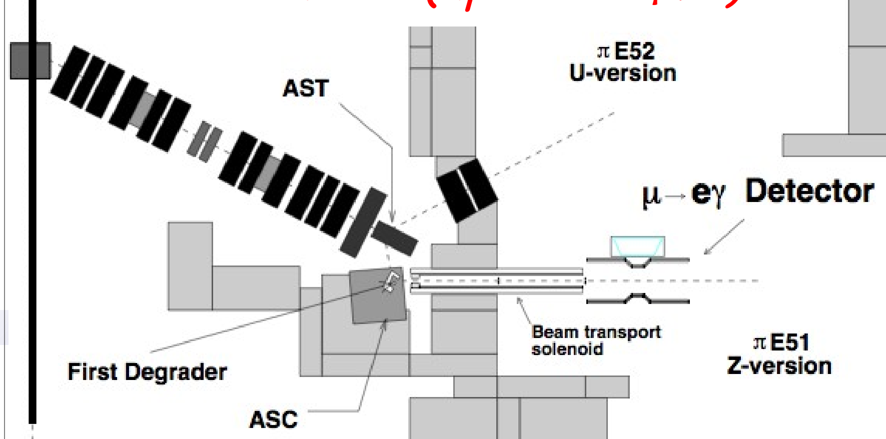
UC IRVINE

The MEG Experiment (I)





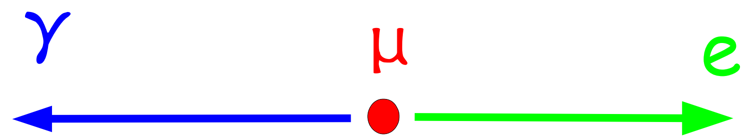
the most intense DC muon beam in the world (up to 10^8 μ/s)



Experimental Signature

- To get 10^{-13} sensitivity:
  - high statistics;
  - high resolutions (energy, time, angle) for low background;

SIGNAL $\propto$ μ rate

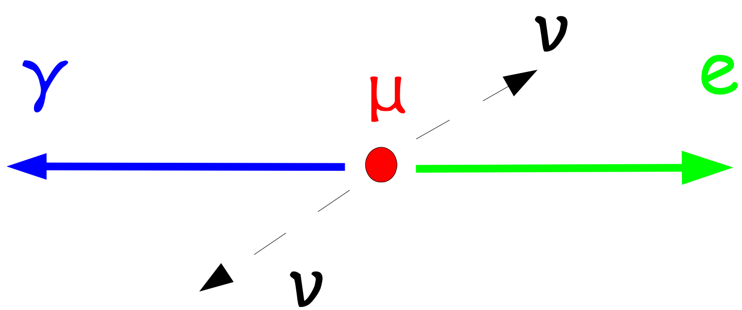


$E_\gamma = E_e = 52.8$ MeV,

$\Theta_{e\gamma} = 180°$, $T_e - T_\gamma = 0$

RADIATIVE

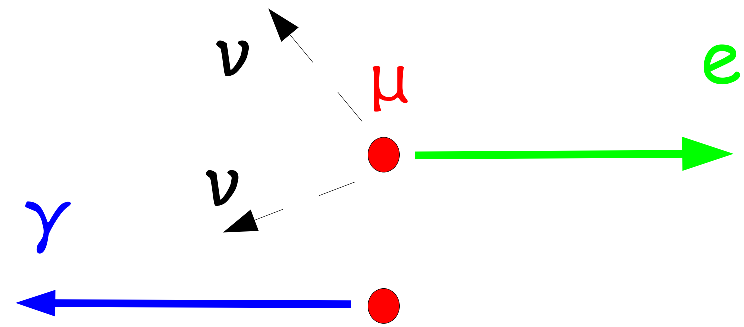
DECAY $\propto$ μ rate



DOMINANT

ACCIDENTAL

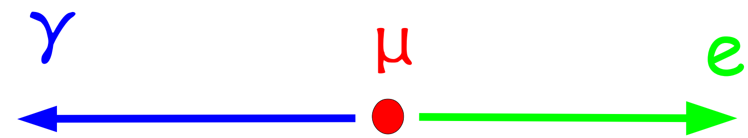
$\propto$ $(\mu \text{ rate})^2$



Experimental Signature

- To get 10^{-13} sensitivity:
  - high statistics;
  - high resolutions (energy, time
    a

SIGNAL ∝ μ rate

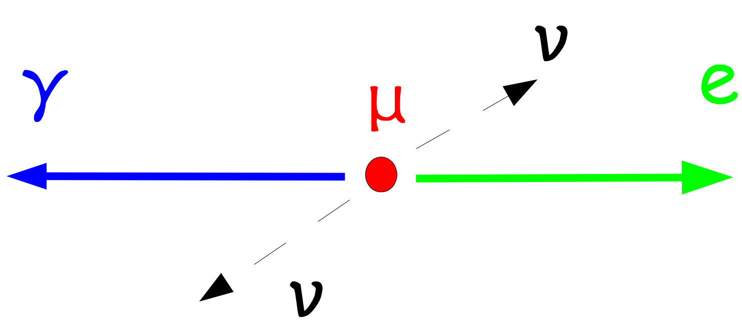


E = E = 52.8 MeV,

0

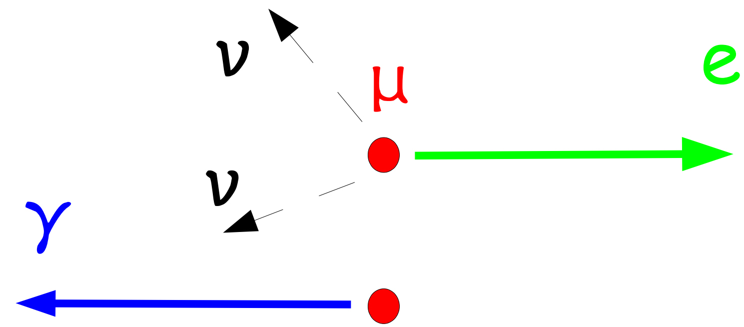
$$\Gamma_{acc} = \Gamma_{\mu} \cdot \delta E_e \cdot \delta T_{e\gamma} \cdot (\delta E_{\gamma})^2 \cdot (\delta \Theta_{e\gamma})^2$$

DECAY ∝ μ rate

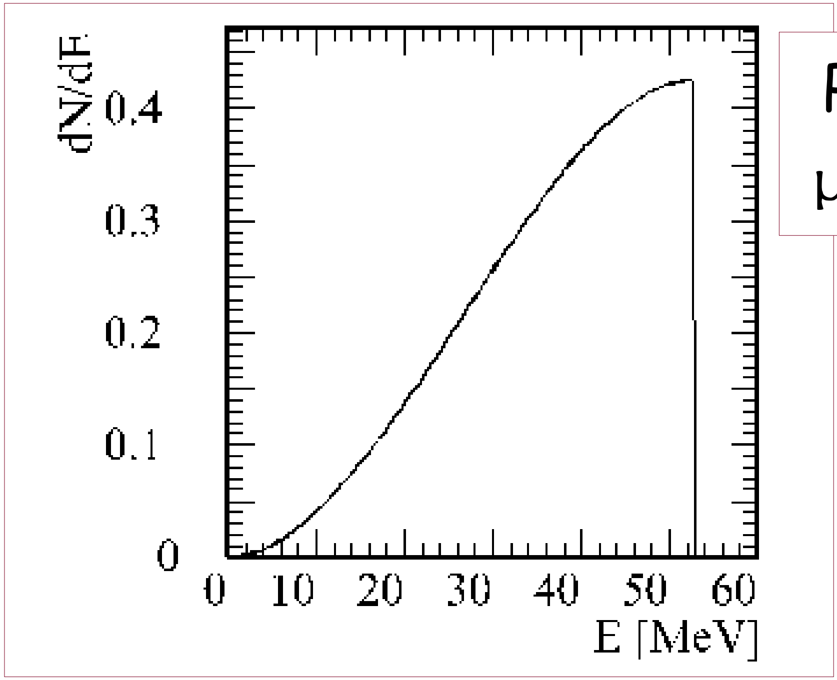


DO

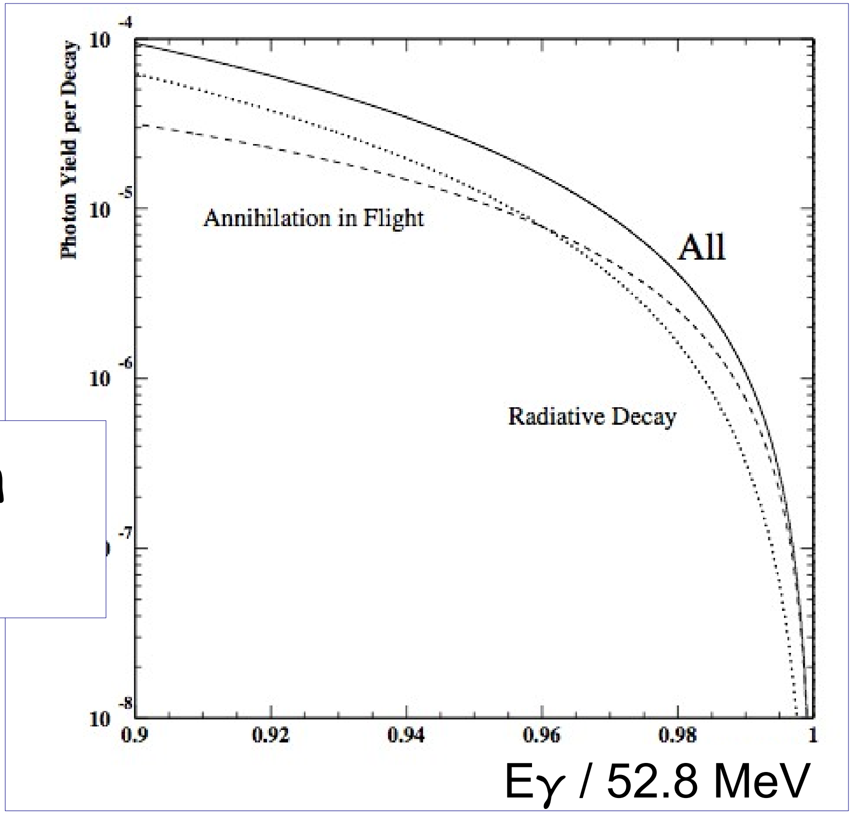
∝ $(\mu\ \text{rate})^2$



Background Spectra

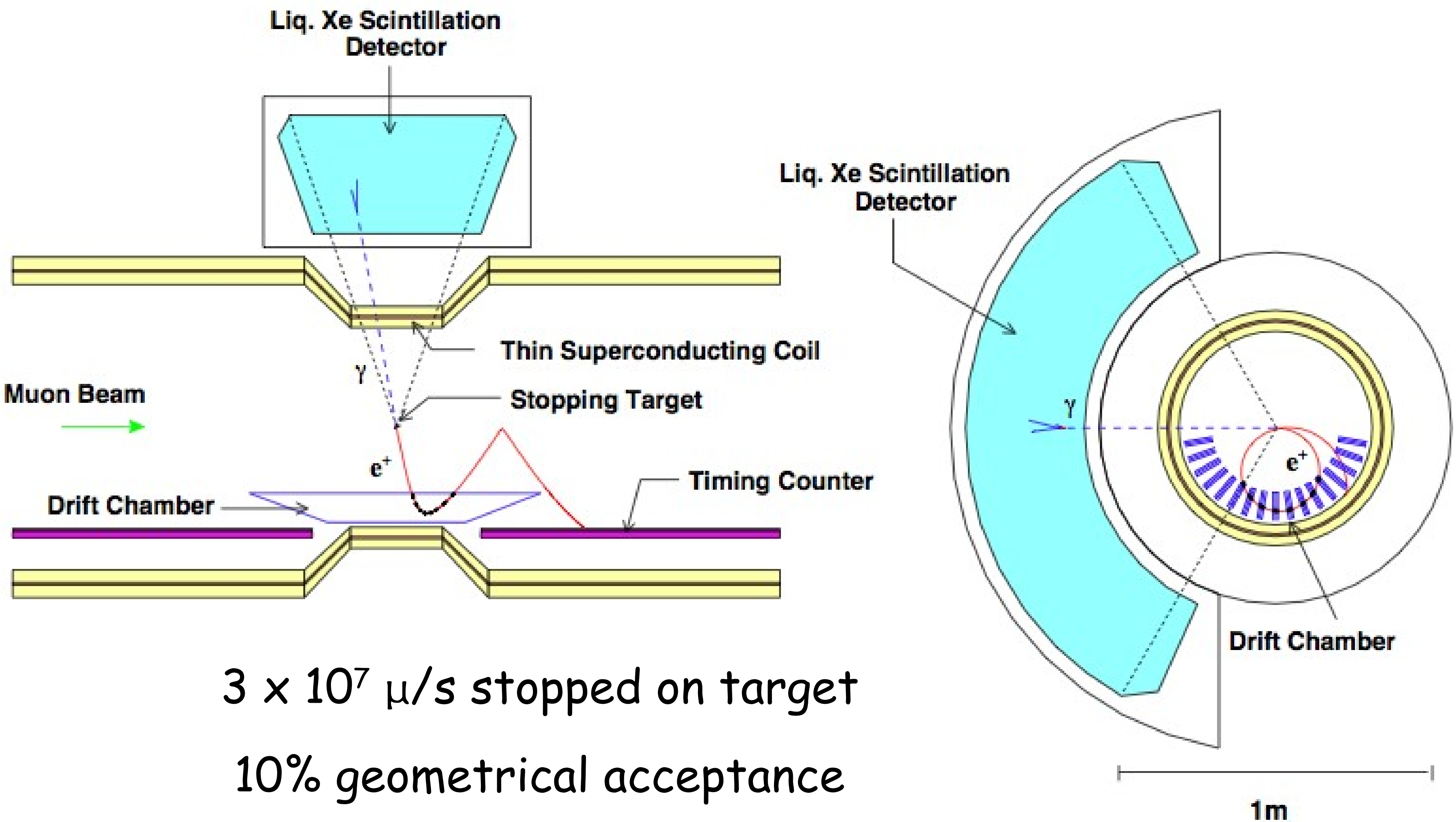


Positron spectrum from
$\mu \rightarrow e\,\nu\,\nu$ (Michel decay)



Integrated photon
spectrum

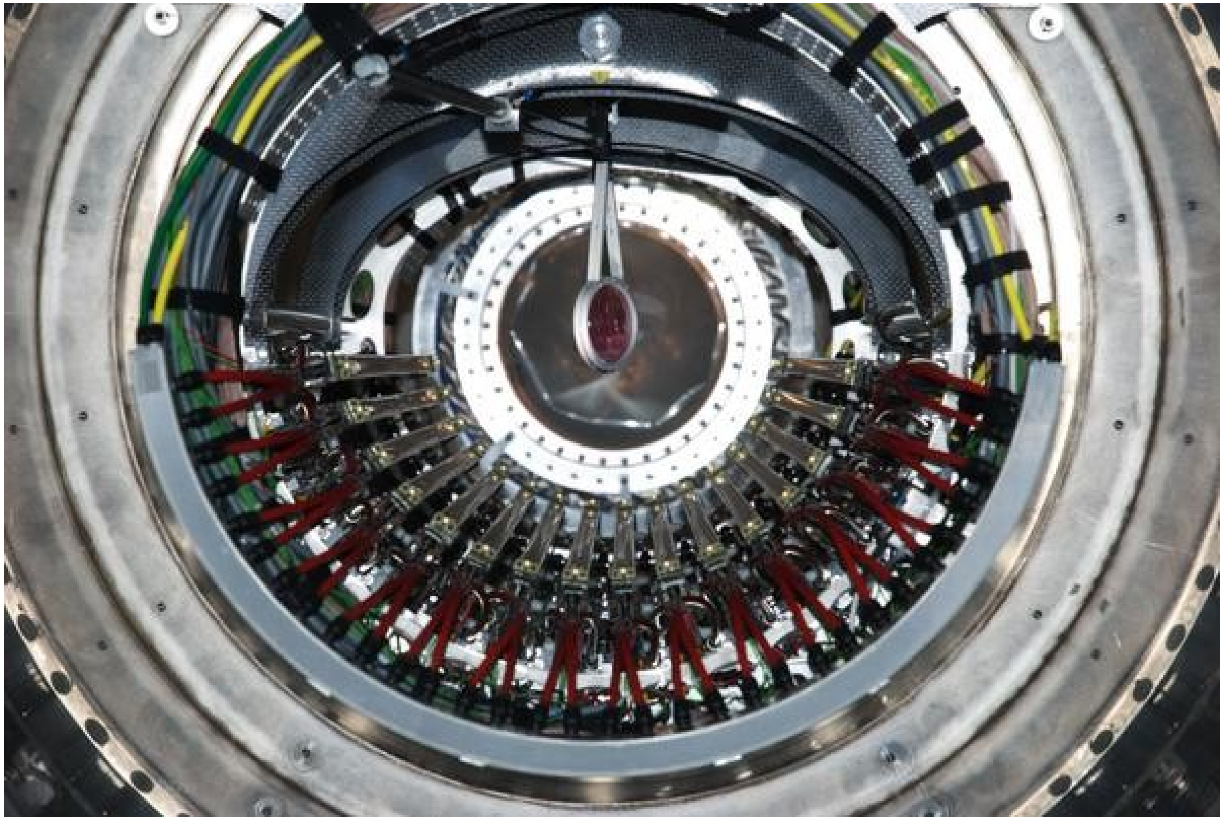
The MEG Experiment



3×10^7 μ/s stopped on target

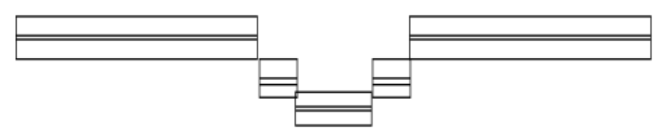
10% geometrical acceptance

Positron Spectrometer



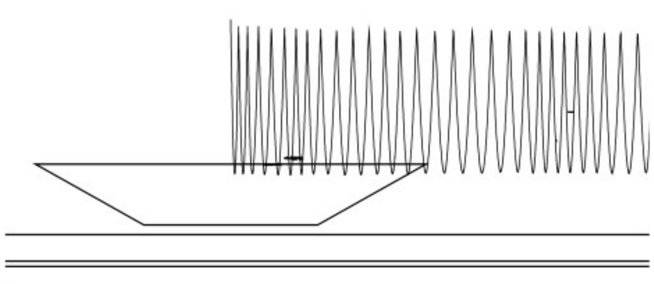
The Concept

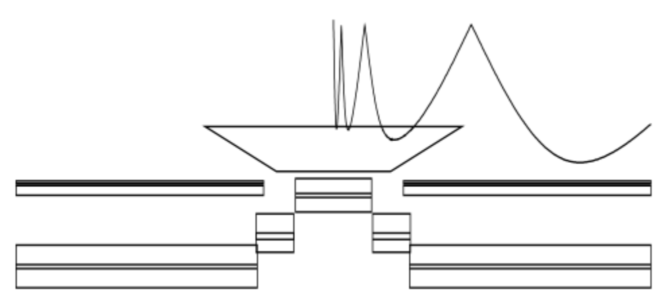
- MEG requirements:
  - good momentum resolution (few hundred keV @ 52.8 MeV);
  - low pile-up (for low background and better tracking);
- The solution:
  - Drift Chambers in a *Graded Magnetic Field*.



Uniform Field

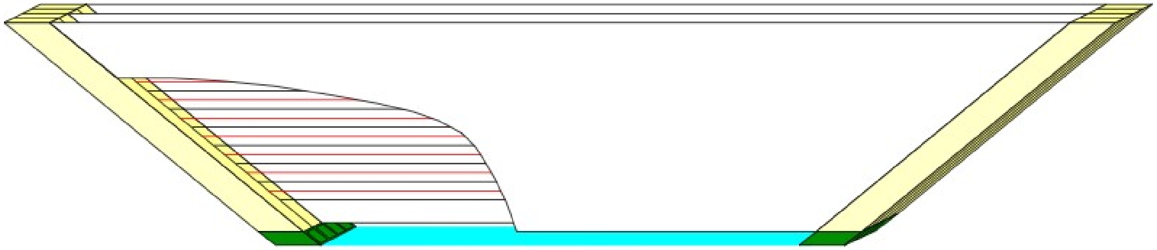
Graded Field



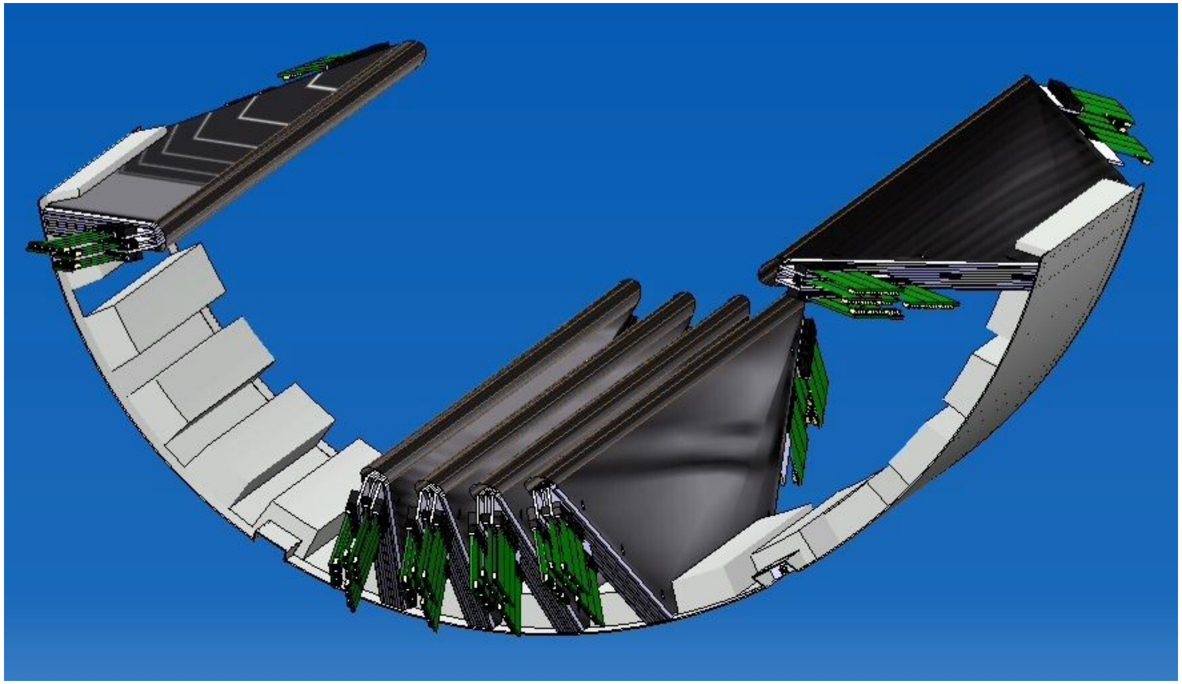


Drift Chambers (DC)

- 16 Drift Chambers;
- 2 planes per chamber;
- He-C_2H_6 (50%-50%).



0.3% X_0 through the full track length!



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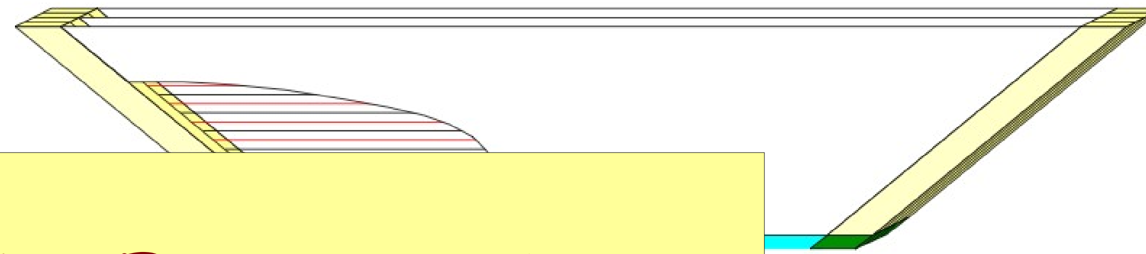
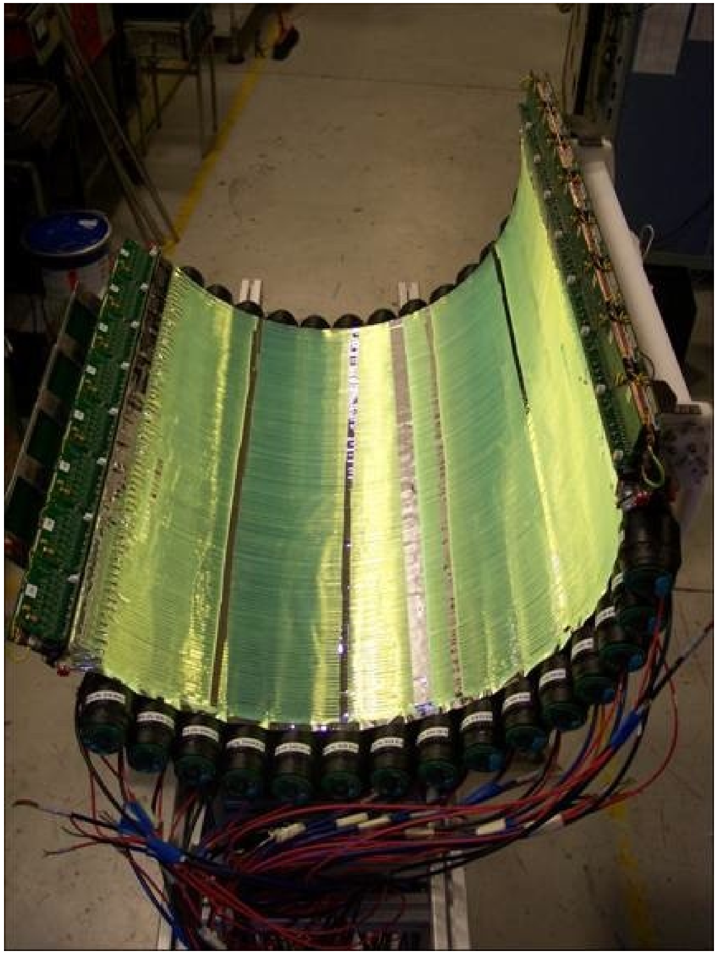


0.3% X_0 th
the full t
length.

ACHIEVED RESOLUTIONS

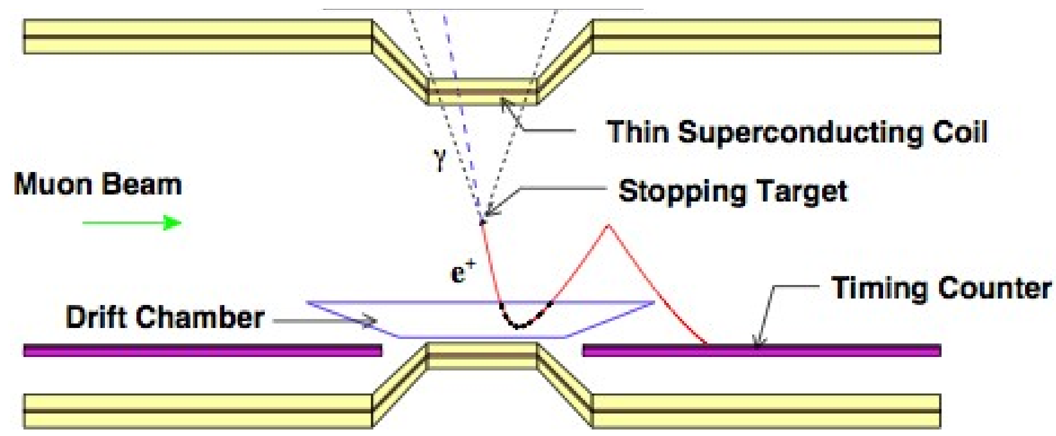
Momentum: 330 keV/c (core)
Direction: 9.4 – 6.7 mrad (θ,φ)
μ Decay Point: 1.1 – 2.5 mm (Y,Z)

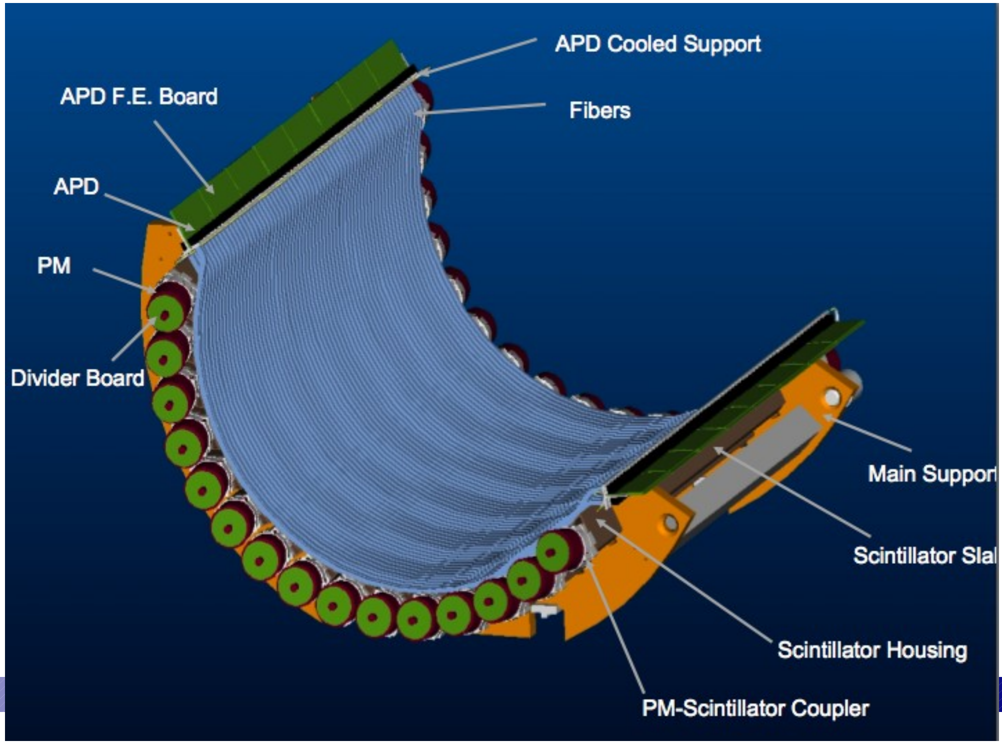
Timing Counter (TC)



The Concept

- 2 detectors (upstream & downstream) for precise positron timing and trigger;
- 15 plastic scintillating bars per detector read by PMTs:
  - timing
  - phi position
- 1 layer of scintillating fibers per detector, read by APDs:
  - z position
  - operational since 2011





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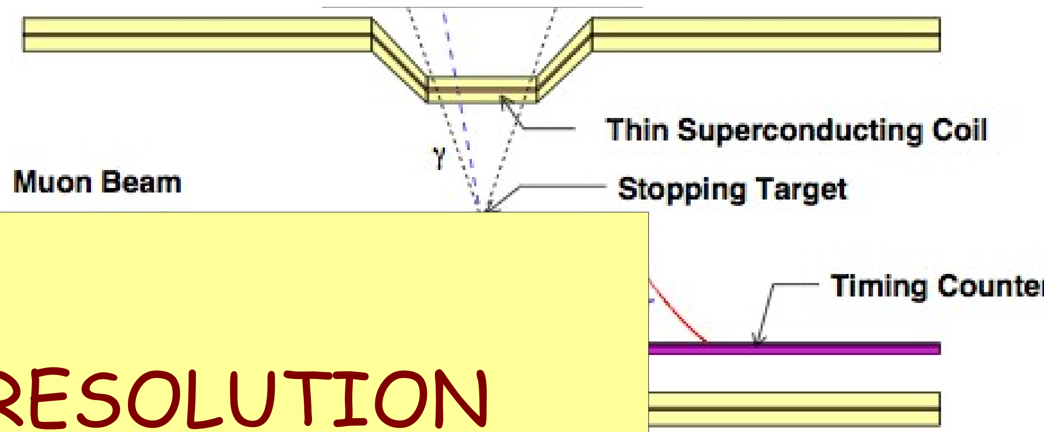
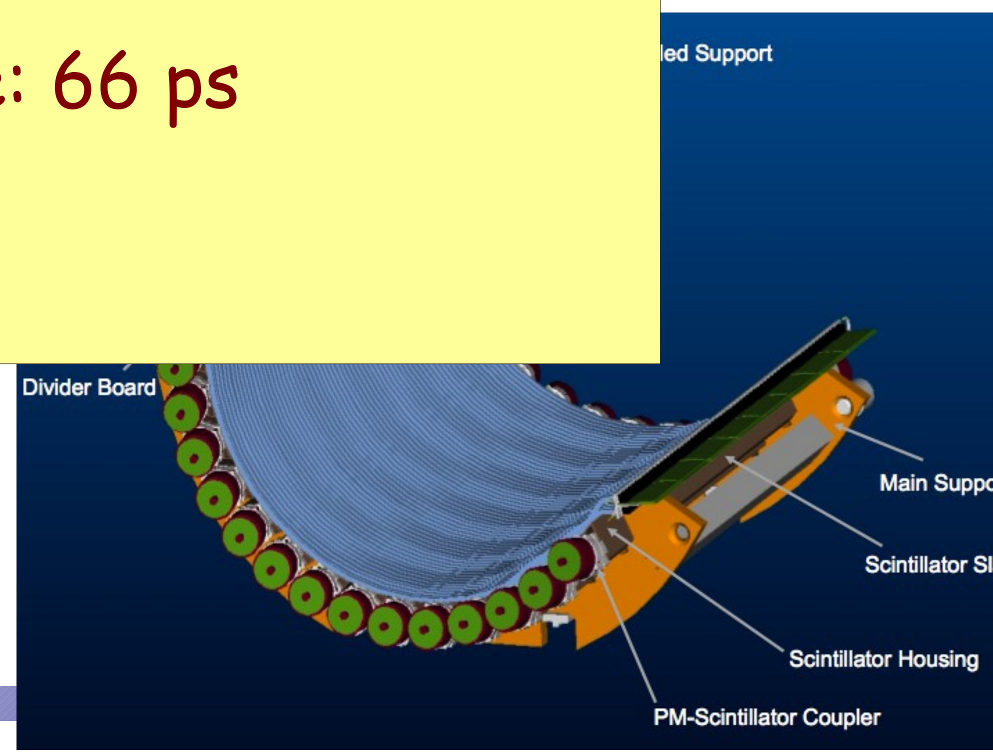
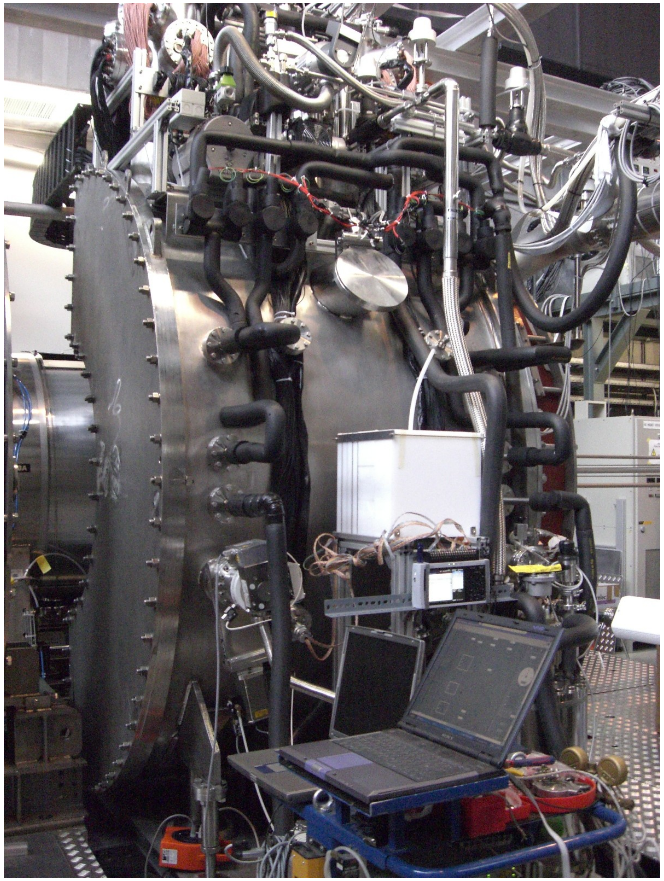


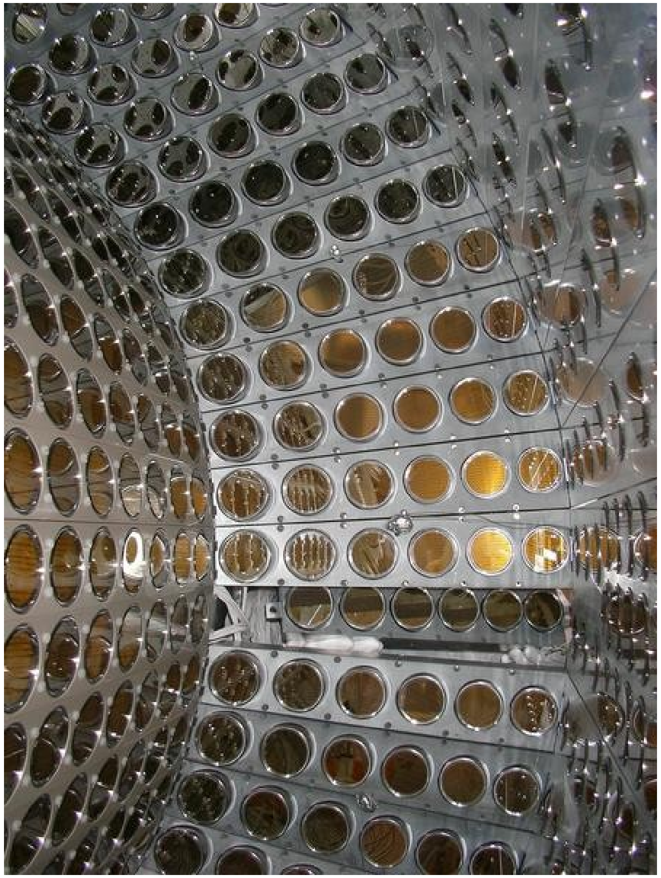
ACHIEVED RESOLUTION

Time: 66 ps



LXe Calorimeter (XeC)

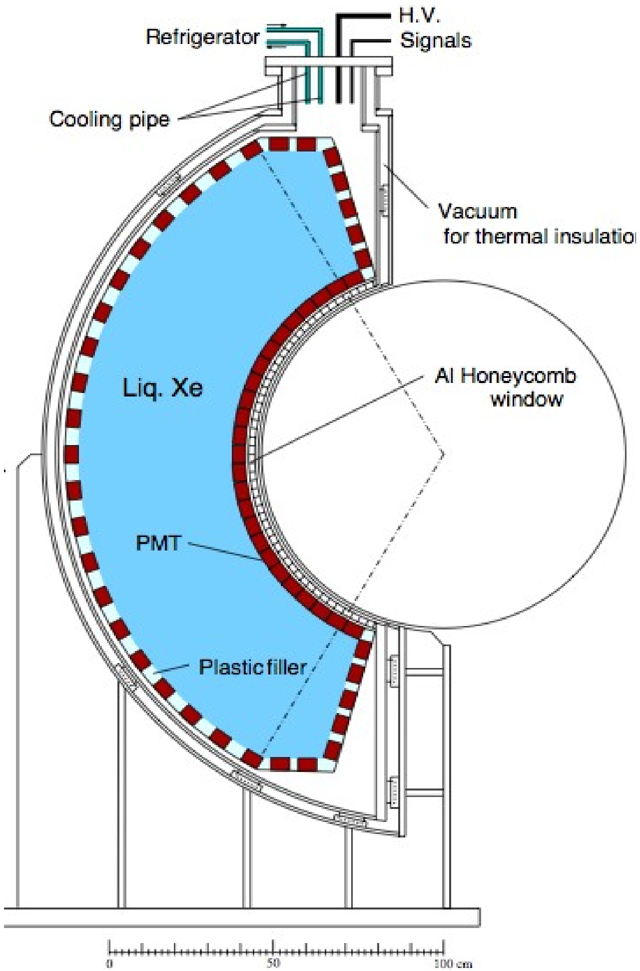




The Concept

- The largest LXe calorimeter in the world:
  - 800 liters;
- Fast response:
  - τ = 4ns / 22ns / 45ns;
- Good light yield:
  - ~ 75% of NaI(Tl);
- Light collected by 846 PMTs.

Hamamatsu R9288



The Concept

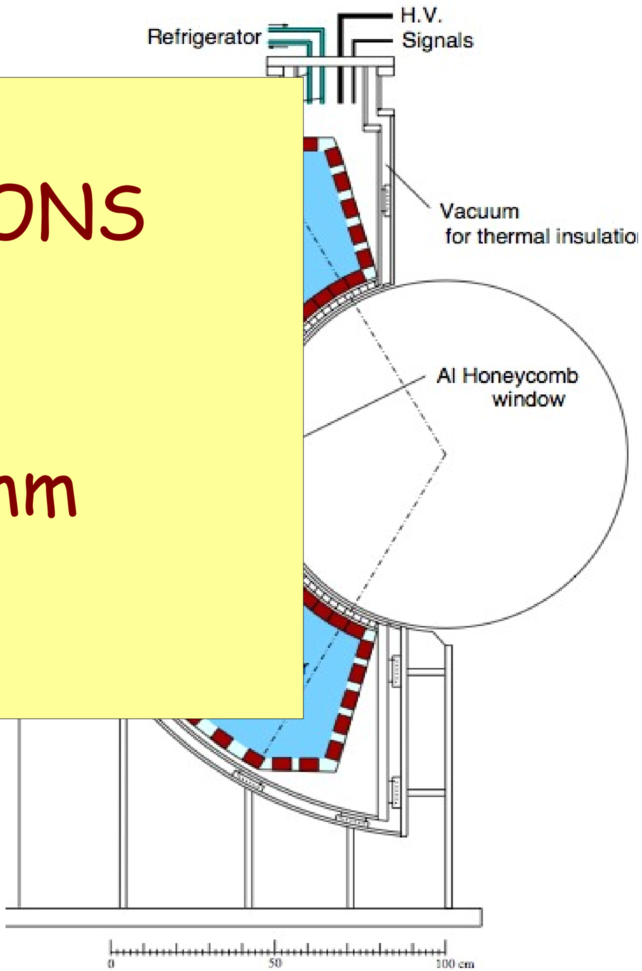
- The largest LXe calorimeter in the world:
  - 800 liters;
- Fast res
  - τ = 4
- Good lig
  - ~ 75
- Light co

ACHIVED RESOLUTIONS

Energy: 1 MeV

Conversion Point: 5 mm

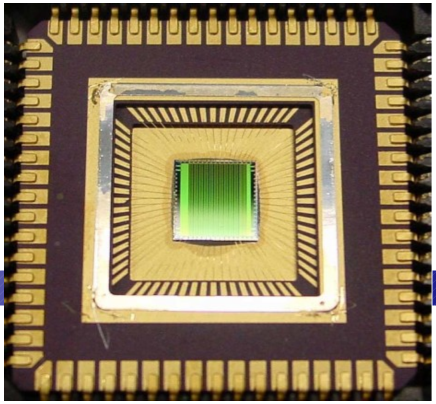
Time: 67 ps



Hamamatsu
R9288

DAQ & Trigger

- High accidental background rejection (~ 10^7) with ~100% signal efficiency required at the trigger level:
  - online determination of γ energy, e - γ timing and e - γ collinearity (fully digital implementation);
  - ~ 5 – 10 Hz trigger rate during normal data acquisition;
- Very fast waveform digitalization (0.5 - 4.5 GHz) for offline analysis:
  - custom chip (Domino Ring Sampling, DRS) designed @ PSI;
  - 10 channels x 1024 bins per chip;
  - All chips synchronized at 30ps level.



Calibration Procedures

Calibrations

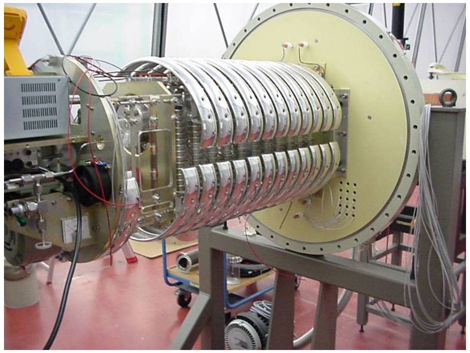
Charge Exchange (CEX)

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

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

high energy photons for XeC energy & relative time calibrations

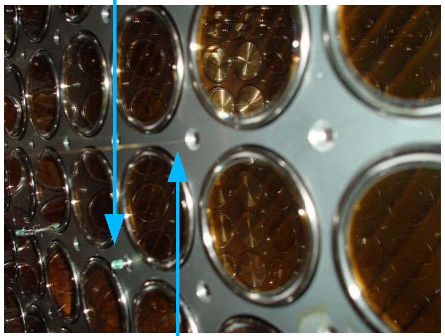
Cockcroft-Walton accelerator



Protons on a Lithium Tetra-borate target

low-energy photons for XeC energy & relative time calibration

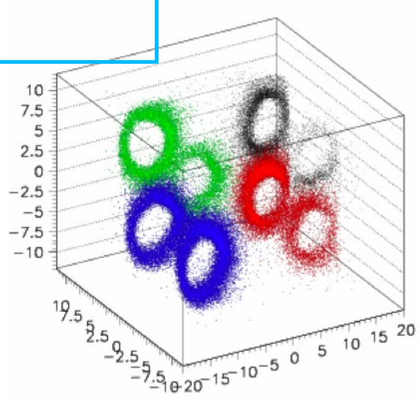
LED



Installed inside the XeC

PMT gain calibration

α sources



Installed in wires inside the XeC

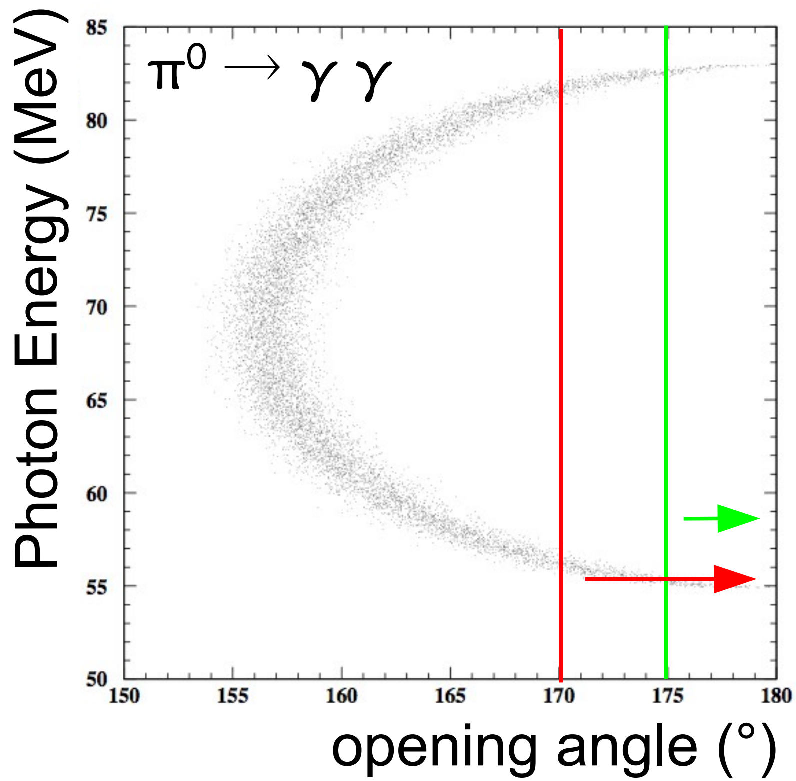
Calibration of Q.E., attenuation length, position

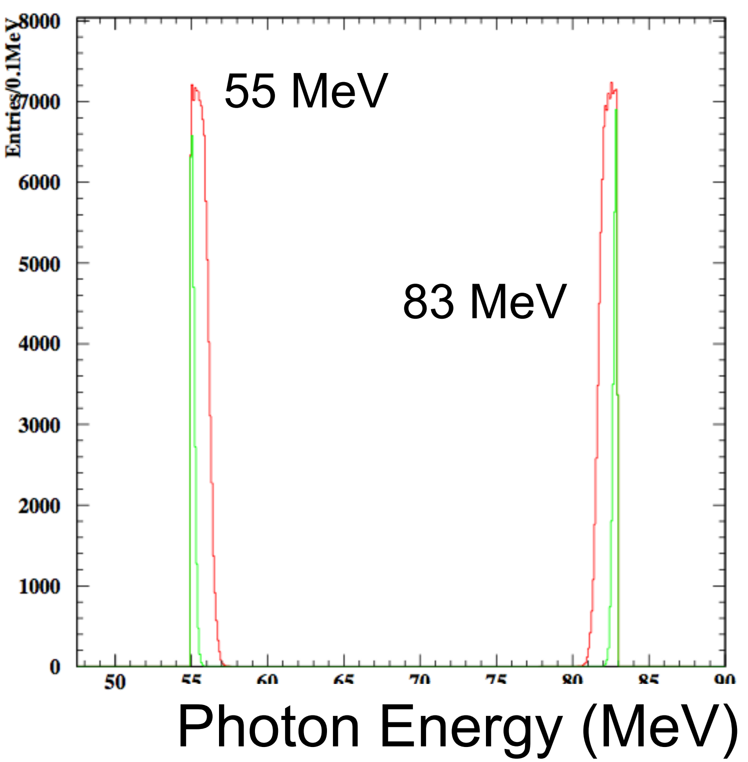
CEX

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.





Cockcroft Walton

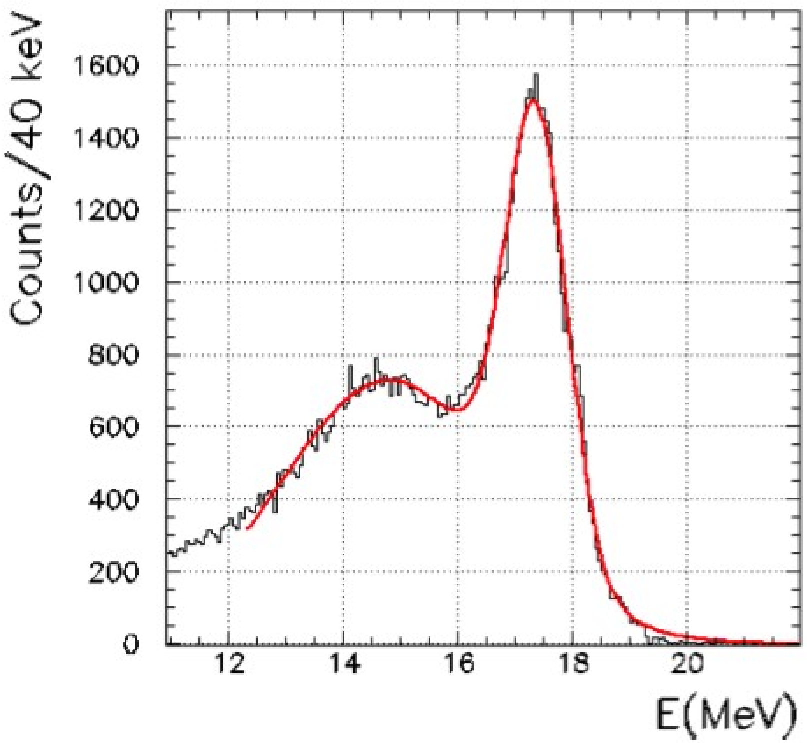
- Calibration with low energy photons from the reactions:

$p + {}_3^7Li \longrightarrow {}_4^8Be + \gamma$

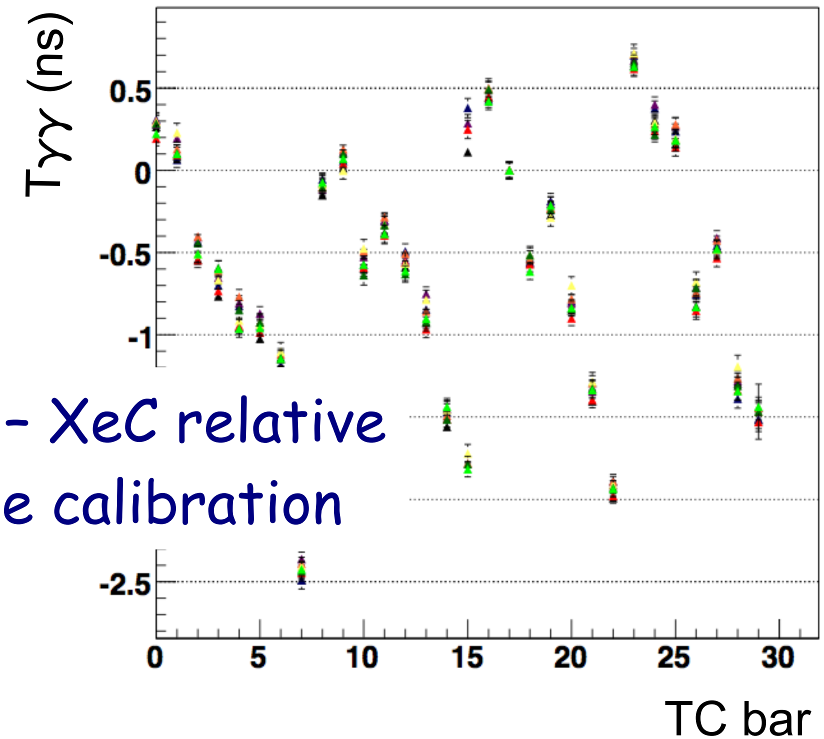
$p + {}_5^{11}B \longrightarrow {}_6^{12}C^{**} + \gamma$

${}^{12}C^{**} \longrightarrow {}^{12}C\ \gamma$

2 γ lines (14.6 MeV & 17.6 MeV)

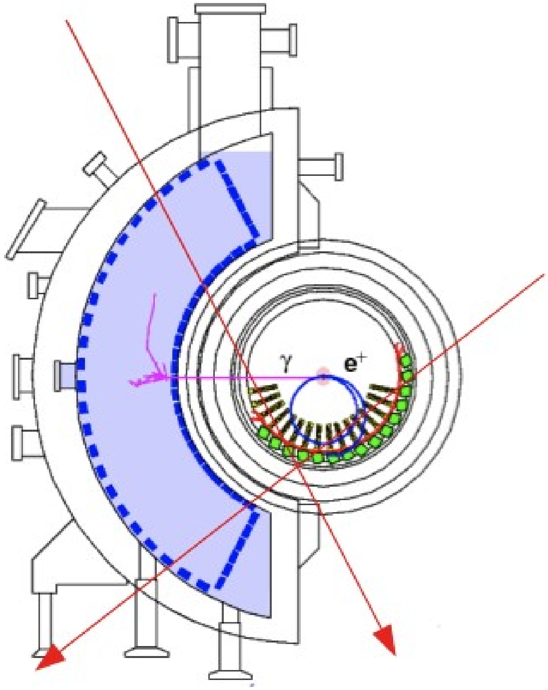


TC - XeC relative time calibration



Detector Alignment

- Very careful geometrical alignment is needed:
  - no physical process to check for biases in relative angle measurement;

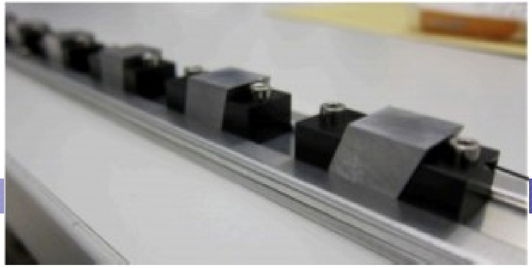


Optical survey to measure the DC & target position;

Collimators in known position to calibrate the reconstructed position in XeC;

Cosmic rays for internal DC alignment and cross-check of relative DC-XeC alignment.

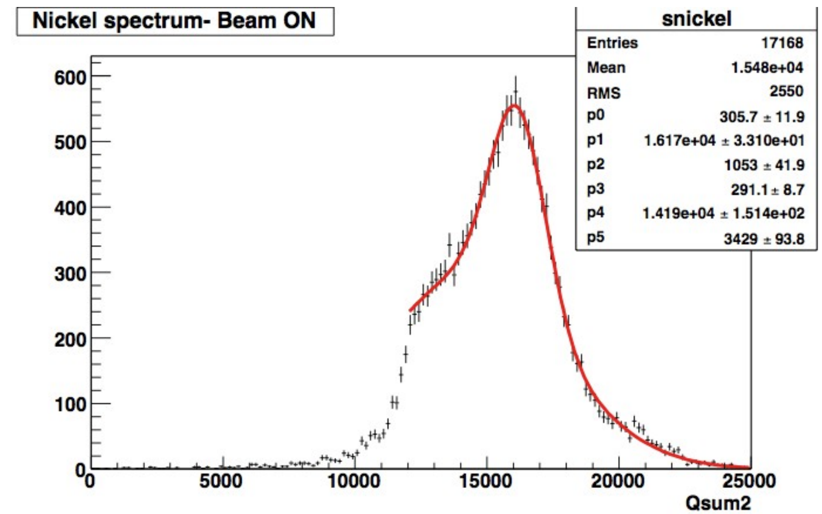
relative alignment precision: 2 mm

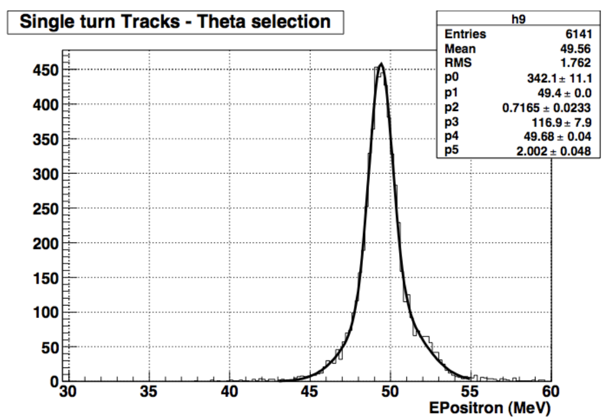


Recent developments

Pulsed neutron generator to produce
9 MeV γ line from n-capture in Ni :

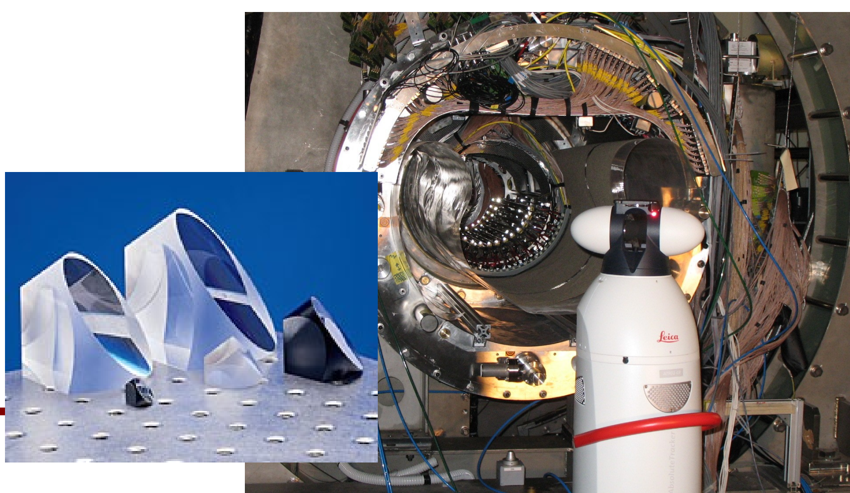
- ✔ LXe calibration in parallel with normal MEG data taking.





Dedicated runs with monochromatic
40 - 60 MeV positron beams :

- ✔ monochromatic peak from Mott scattering to check the spectrometer performances;



Improved DC *optical survey procedures*.

Summary of Performances

RESOLUTIONS

	GOAL	2009	2010
Gamma Energy	1.2 – 1.5 %	1.9 %	1.9 %
Gamma Timing	65 ps	96 ps	67 ps
Gamma Position	2 – 4 mm	5 – 6 mm	5 – 6 mm
e+ Momentum	200 keV	330 keV (core)	330 keV (core)
e+ Timing	45 ps	107 ps	107 ps
e+ Angle (θ,φ)	4.5 mrad	9.4 – 6.7 mrad	11 – 7.2 mrad
μ Decay Point	0.9 mm	1.5 – 1.1 mm	2.0 – 1.1 mm
Gamma – e+ Timing	80 ps	146 ps	122 ps

Summary of Performances

EFFICIENCIES

CONTRIBUTION	GOAL	2009	2010
Gamma	> 40%	58%	59%
Positron	65%	40%	34%
Trigger	100%	91%	92%

Data Analysis

Data Sample (I)

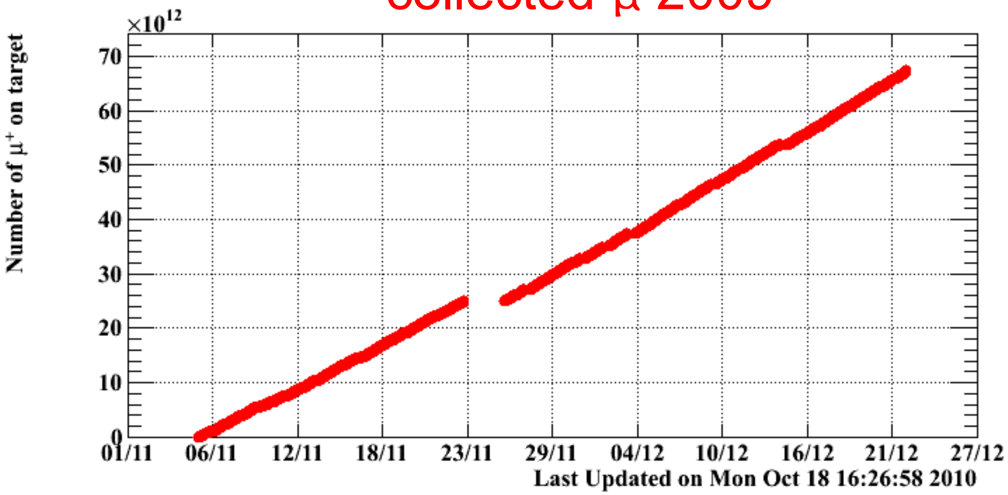
- 2008 run:
  - 48 days of data taking → ~ 9 x 10^{13} collected μ;
  - affected by severe detector instabilities (DC HV, LXe purity);
  - first MEG limit (Nucl. Phys. B834 (2010) 1-12)

$BR(\mu \rightarrow e\,\gamma) < 2.4 \times 10^{-11}$

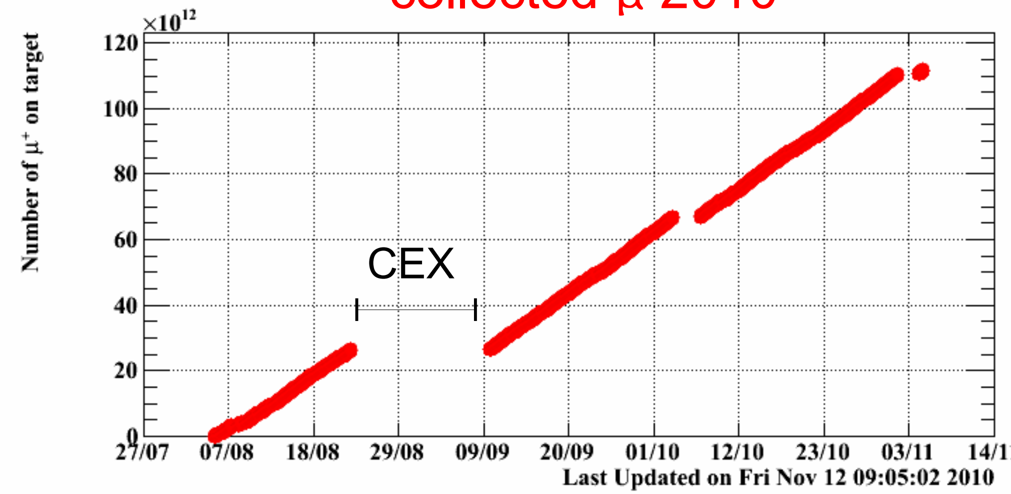
- 2009 - 2010 runs:
  - 91 days of data taking → ~ 17.5 x 10^{13} collected μ;
  - stable detector operations;
  - data analysis presented here.

Data Sample (II)

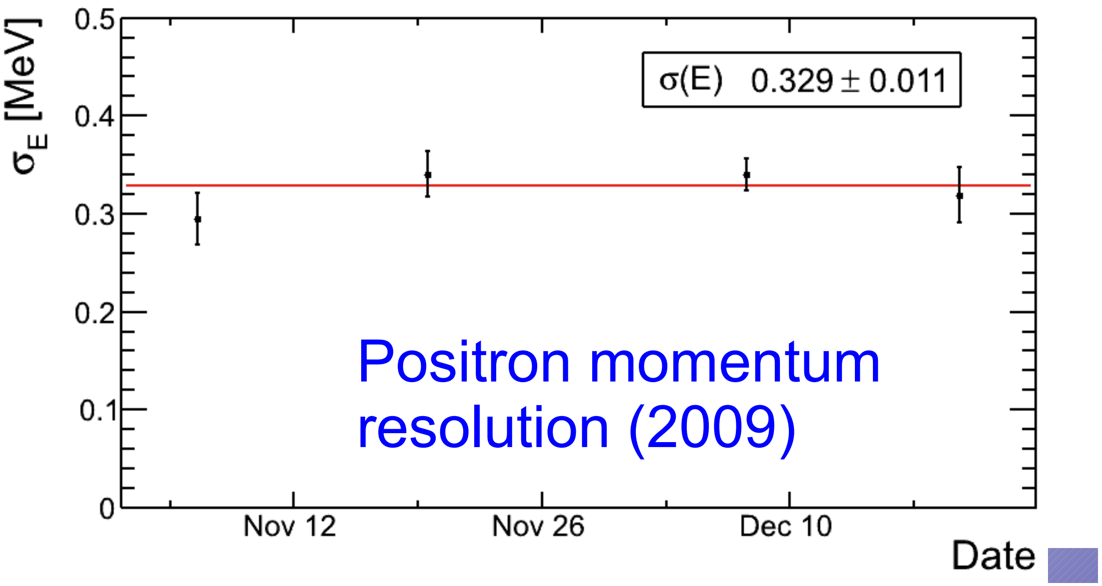
collected μ 2009

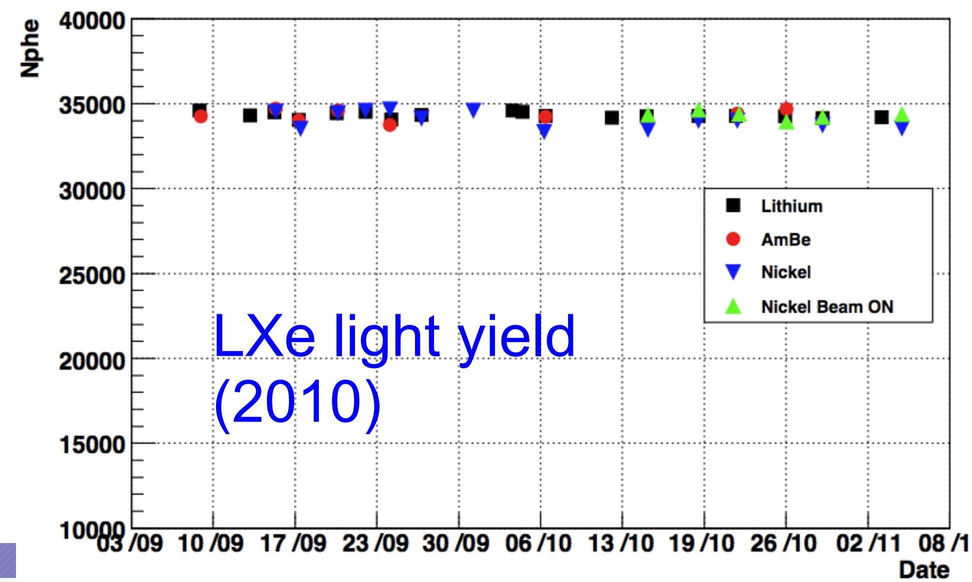


collected μ 2010



Good beam and detector stability





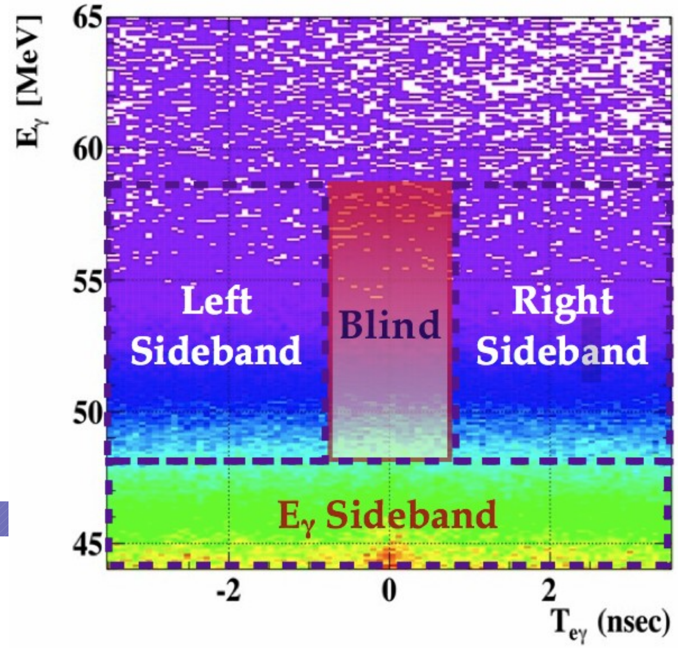
Analysis Strategy (I)

- Likelihood analysis of 5 discriminating variables

$x = (E_{e+}, E_\gamma, \theta_{e\gamma}, \phi_{e\gamma}, T_{e\gamma})$

$$\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}) = \frac{e^{-N}}{N_{\rm obs}!} \underbrace{e^{-\frac{1}{2}\frac{(N_{\rm BG}-\langle N_{\rm BG}\rangle)^2}{\sigma^2_{\rm BG}}} e^{-\frac{1}{2}\frac{(N_{\rm RMD}-\langle N_{\rm RMD}\rangle)^2}{\sigma^2_{\rm RMD}}}}_{\text{sideband constraint}} \times \prod_{i=1}^{N_{\rm obs}} (N_{\rm sig}S(\vec{x}_i) + N_{\rm RMD}R(\vec{x}_i) + N_{\rm BG}B(\vec{x}_i))$$

- Year- and event-dependent PDFs;
- Analysis developed w/o using data in the E_γ – $T_{e\gamma}$ signal region (blind analysis)



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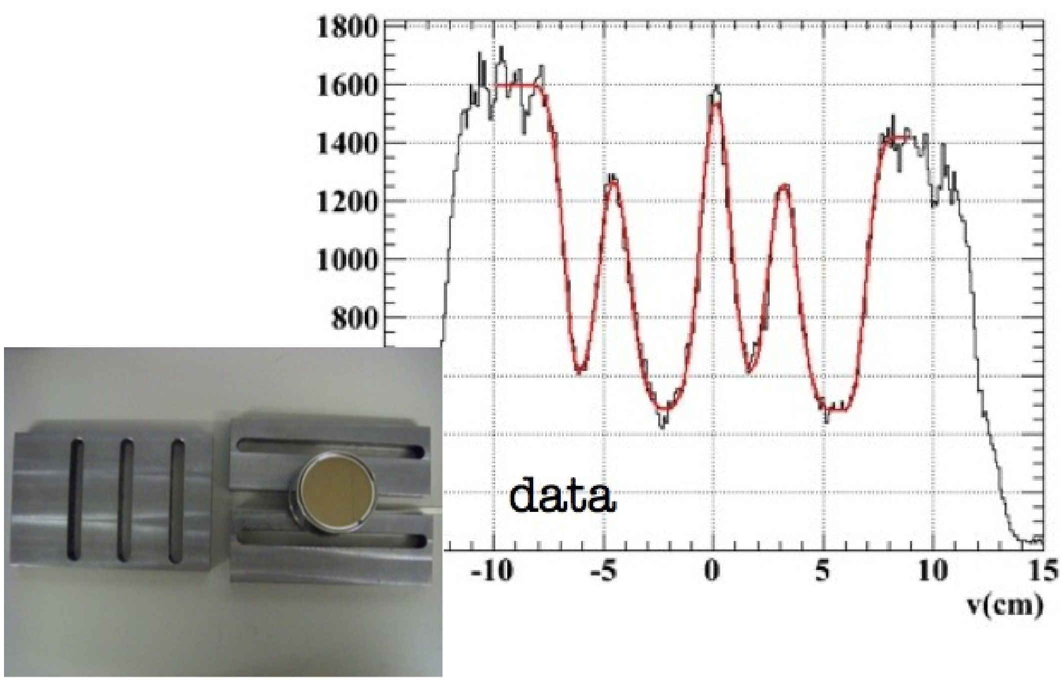
$$\mathcal{L}(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{BG}}) = \frac{e^{-N}}{N_{\text{obs}}!} \underbrace{e^{-\frac{1}{2}\frac{(N_{\text{BG}}-\langle N_{\text{BG}}\rangle)^2}{\sigma_{\text{BG}}^2}} e^{-\frac{1}{2}\frac{(N_{\text{RMD}}-\langle N_{\text{RMD}}\rangle)^2}{\sigma_{\text{RMD}}^2}}}_{\text{sideband constraint}} \times \prod_{i=1}^{N_{\text{obs}}} (N_{\text{sig}} S(\vec{x}_i) + N_{\text{RMD}} R(\vec{x}_i) + N_{\text{BG}} B(\vec{x}_i))$$

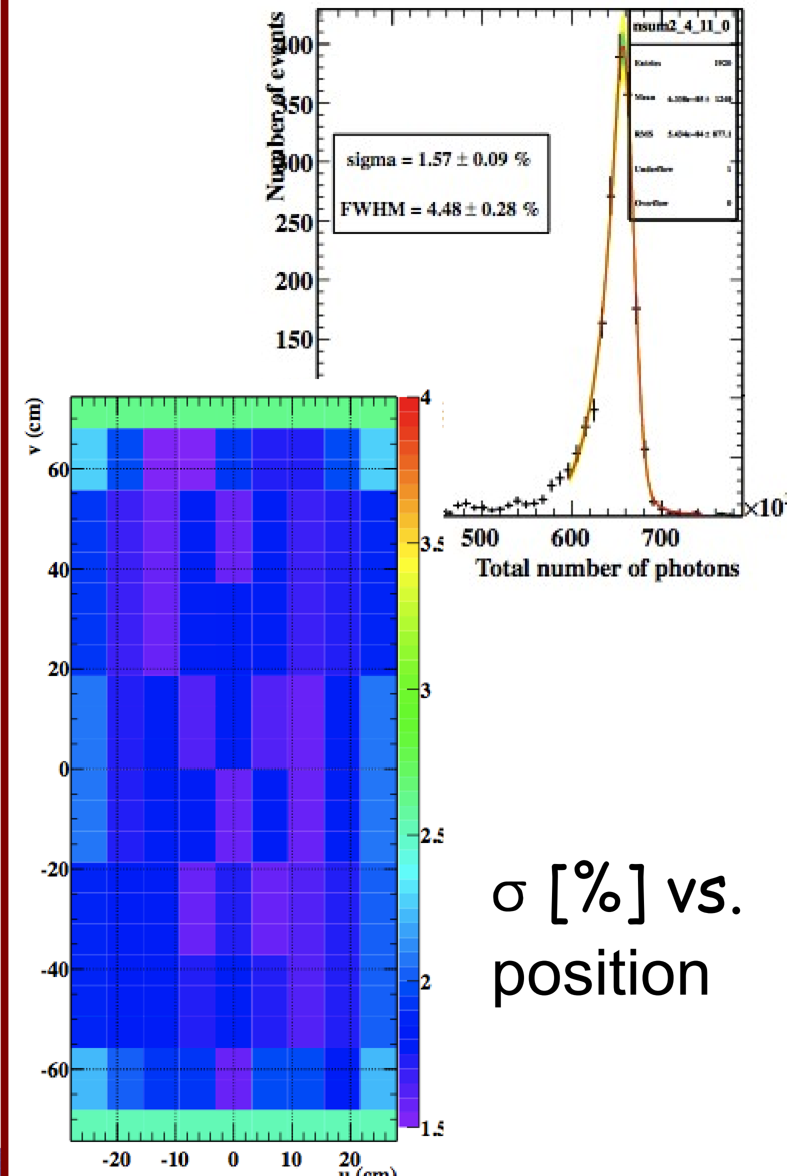
- Statistical approach:
  - Likelihood Ratio Profile (LR_p);
  - Frequentistic upper limit with LR_p ordering (à la Feldman-Cousins + systematics).

$$LR_p(N_{sig}) = \frac{\max_{N_{BG}, N_{RD}} \mathcal{L}}{\max_{N_{BG}, N_{RD}, N_{sig}} \mathcal{L}}$$

Signal PDFs - Photon

- Photon Energy PDF from CEX run:
  - position-dependent;
- Photon conversion point PDFs from CEX runs with Pb collimators:
  - position-dependent;

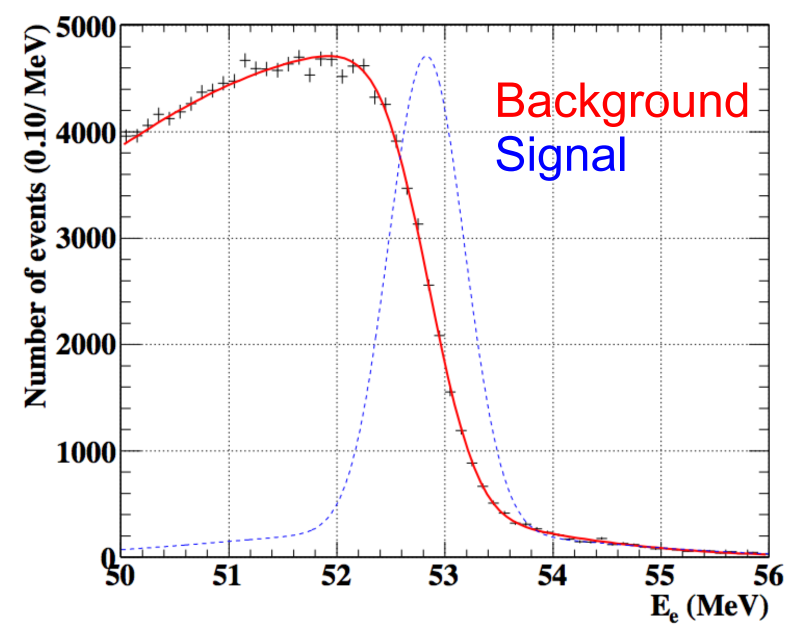


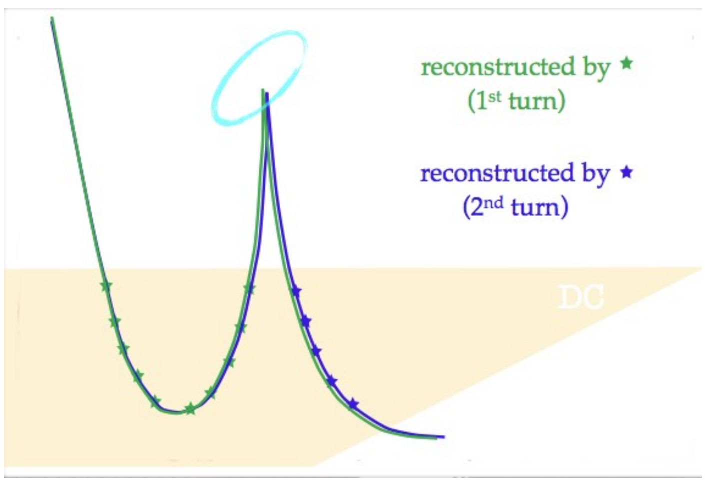


σ [%] vs. position

Signal PDFs - Positron

- Positron Energy PDF:
  - fit of the Michel spectrum;
- Positron angles & vertex PDFs:
  - comparison of different track segments (two turns).



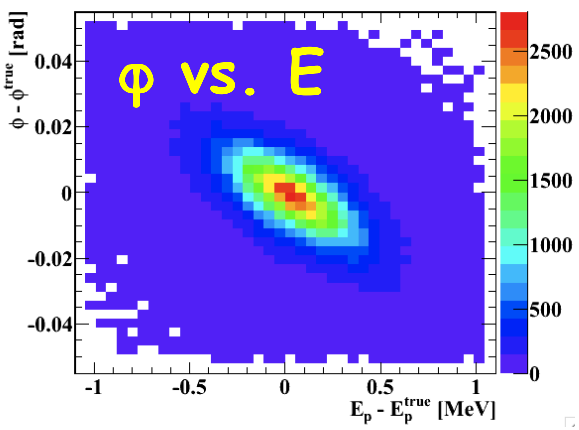


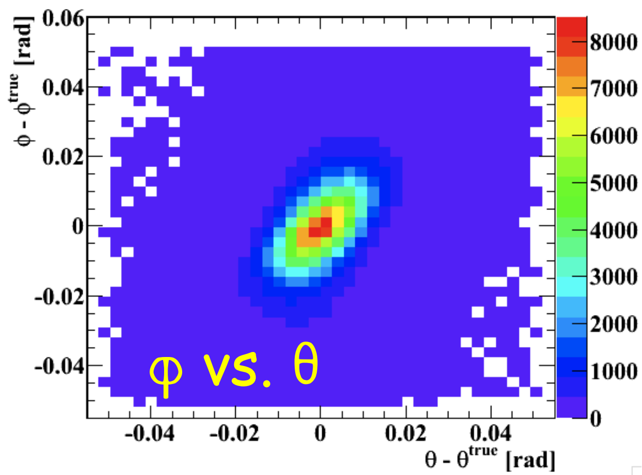
2 Track Quality categories

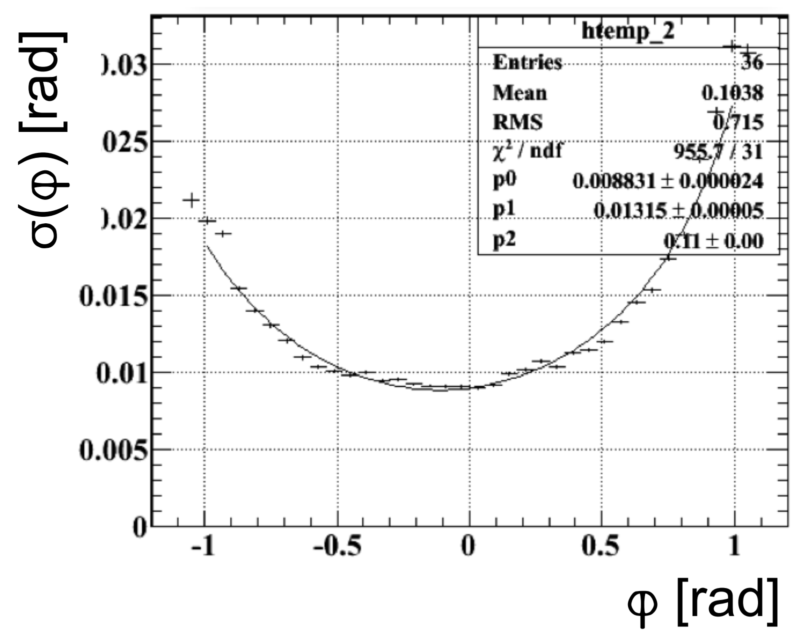
Signal PDFs - Positron

- Account for *correlations among variables* and *φ dependence of angular resolutions*, mostly <u>measured on data</u> (two turns);

just a few examples...



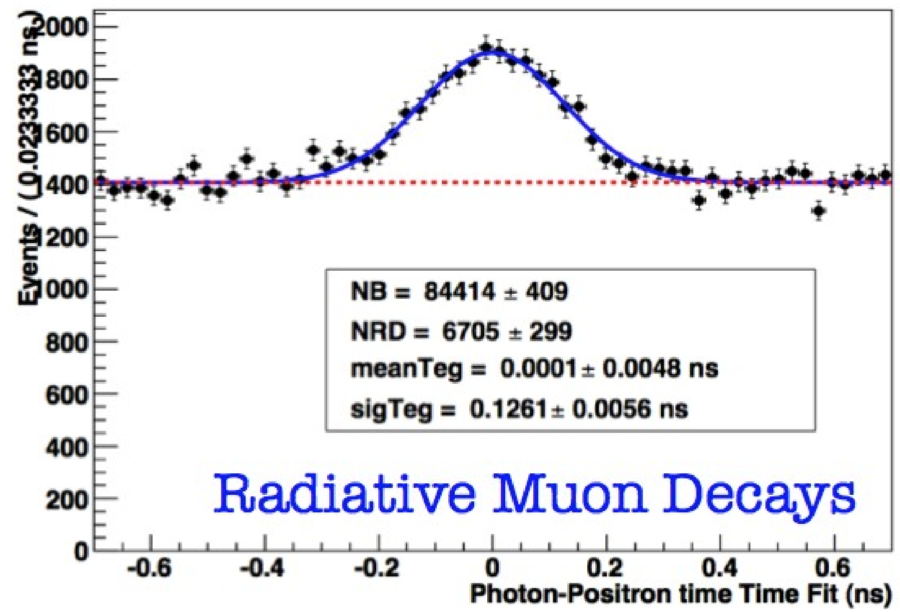




- All correlations are well understood:
  - geometrical effects from the definition of the vertex as the intersection of the track with the target plane.

Combined PDFs

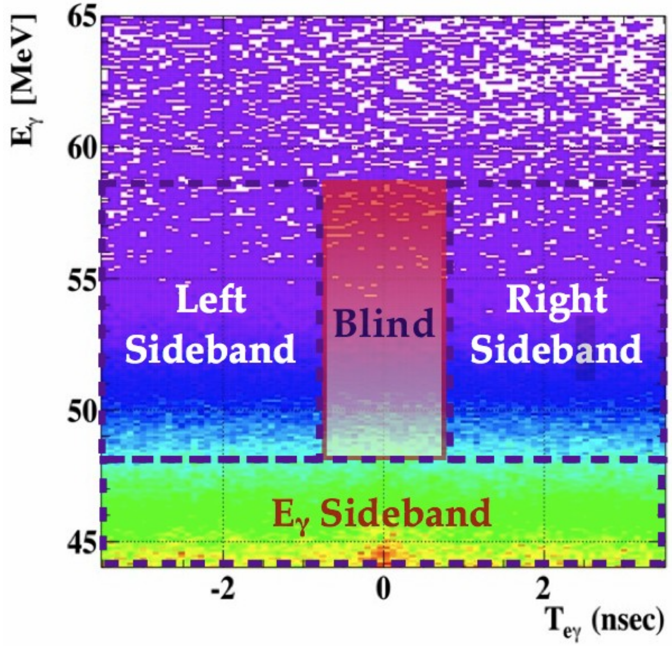
- Relative eγ time PDF from radiative muon decays;

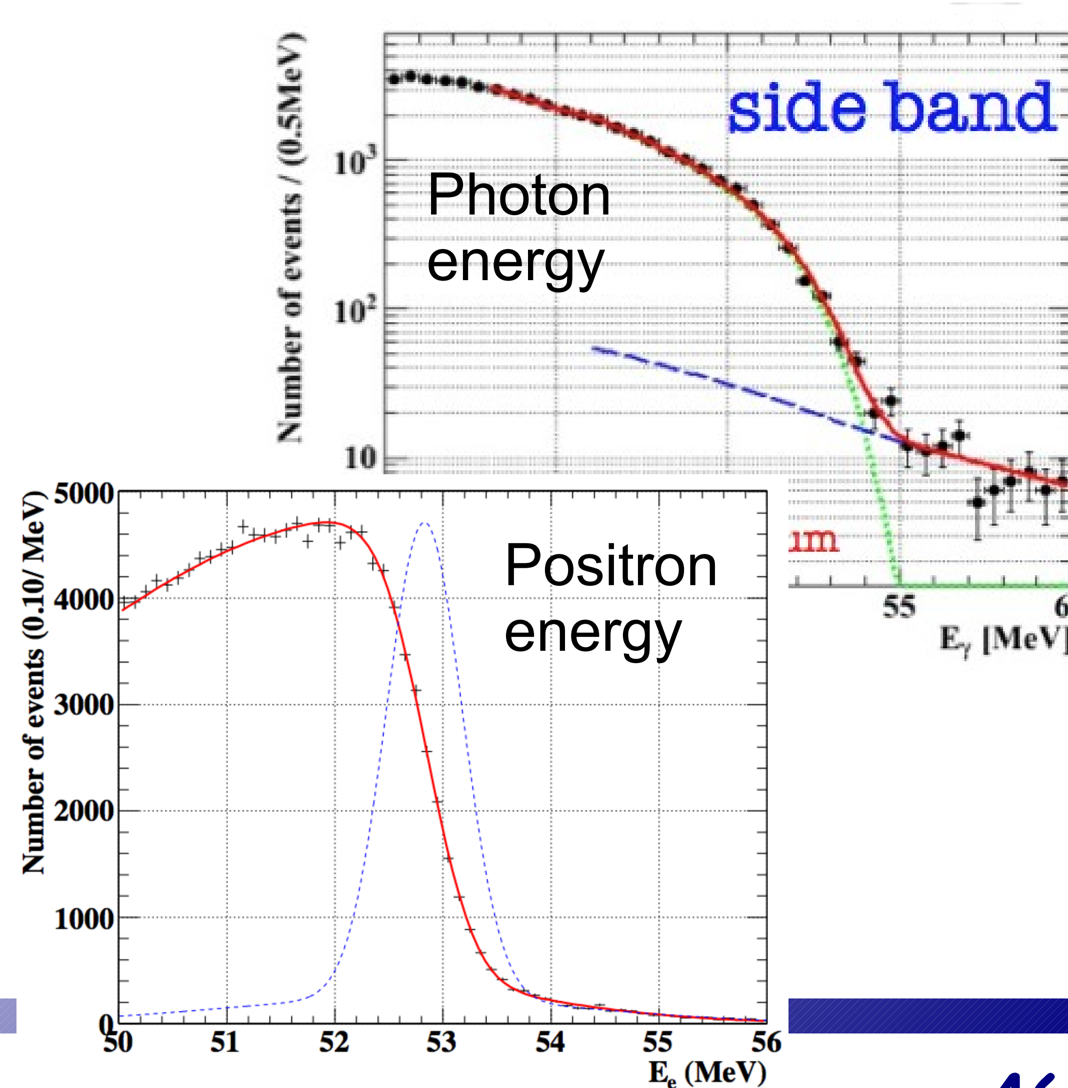


- Relative eγ angle PDFs by statistically combining:
  - photon conversion point PDFs;
  - positron angles & vertex PDFs;

Background PDFs

- Accidental background PDFs are *measured on data using sidebands.*





Normalization

- The BR is normalized to the number of observed $\mu \rightarrow e \nu \bar{\nu}$ decays:
  - positron-only trigger acquired in parallel to $e\gamma$ trigger;
  - correction factors to take into account, photon efficiency and acceptance, kinematical and trigger differences between $\mu \rightarrow e \gamma$ and Michel.

$$\frac{\mathcal{B}(\mu^+ \to e^+\gamma)}{\mathcal{B}(\mu^+ \to e^+\nu\bar{\nu})} = \frac{N_{\rm sig}}{N_{e\nu\bar{\nu}}} \times \frac{f^e_{e\nu\bar{\nu}}}{P \cdot \epsilon_{\rm pu}} \times \frac{\epsilon^{\rm trig}_{e\nu\bar{\nu}}}{\epsilon^{\rm trig}_{e\gamma}} \times \frac{\epsilon^{\rm DC}_{e\nu\bar{\nu}}}{\epsilon^{\rm DC}_{e\gamma}} \times \frac{1}{A^{\rm geo}_{e\gamma}} \times \frac{1}{\epsilon_{e\gamma}}$$

$\sim N_{sig} \times 3 \cdot 10^{-13}$
(7% error)

Normalization

- The BR is … $\rightarrow e\,\nu\,\bar{\nu}$ decays:
  - positr… trigger;
  - corre… efficie… ger differ…

Successfully cross checked with radiative decay's rate

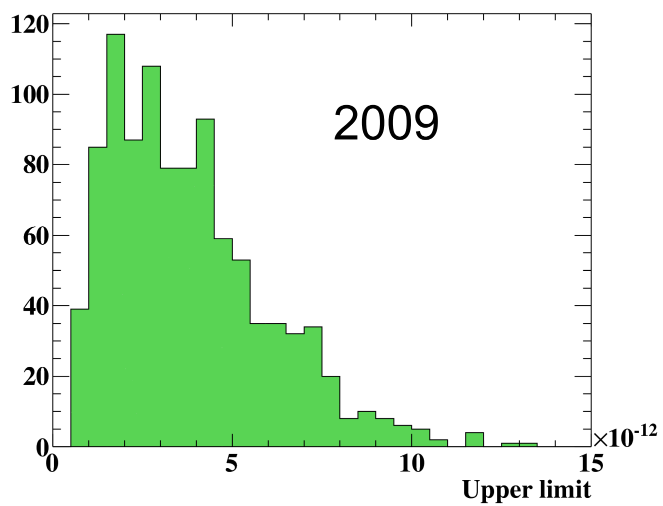
(also a proof that we correctly describe this process in the PDFs)

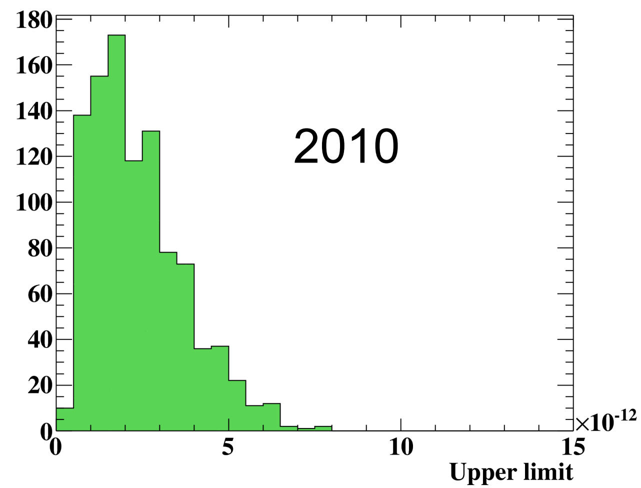
~ $N_{sig} \times 3 \cdot 10^{-13}$
(7% error)

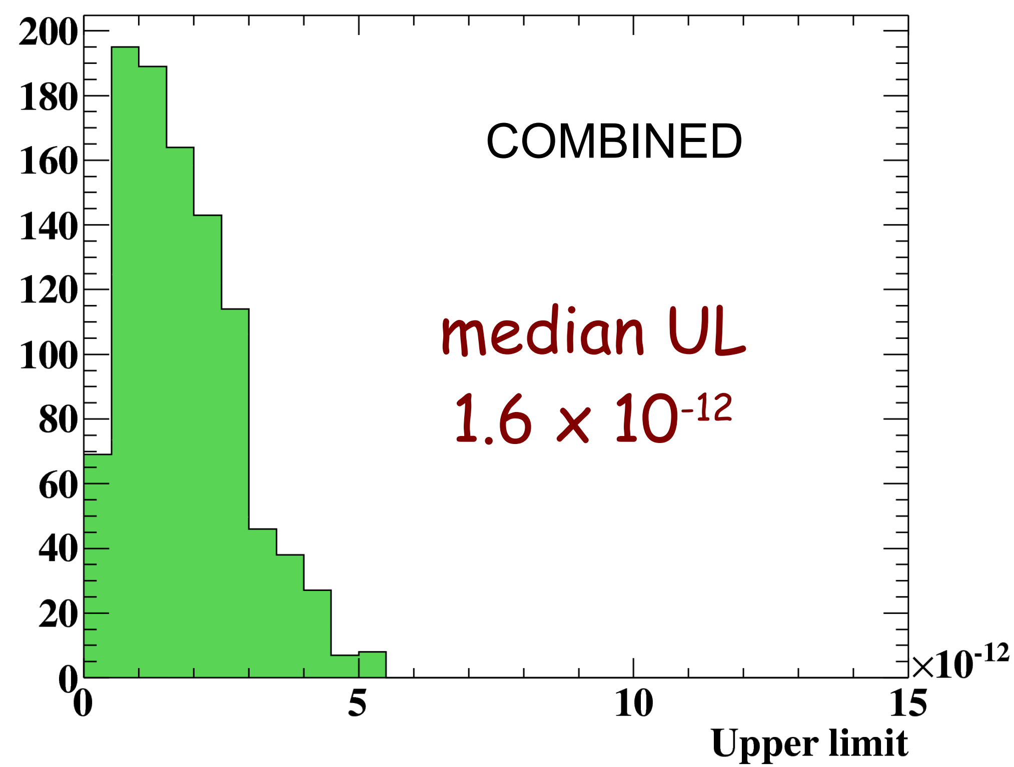
$$\frac{\mathcal{B}(\mu^+ \rightarrow e^+\gamma)}{\mathcal{B}(\mu^+ \rightarrow e^+\nu\bar{\nu})} = \frac{N_{\rm sig}}{N_{e\nu\bar{\nu}}} \times \boxed{\frac{f^e_{e\nu\bar{\nu}}}{P\cdot\epsilon_{\rm pu}} \times \frac{\epsilon^{\rm trig}_{e\nu\bar{\nu}}}{\epsilon^{\rm trig}_{e\gamma}} \times \frac{\epsilon^{\rm DC}_{e\nu\bar{\nu}}}{\epsilon^{\rm DC}_{e\gamma}}} \times \boxed{\frac{1}{A^{\rm geo}_{e\gamma}} \times \frac{1}{\epsilon_{e\gamma}}}$$

Sensitivity (Toy MC)

- BR sensitivity assessed with 1000 pseudo-experiments generated according to the PDFs.





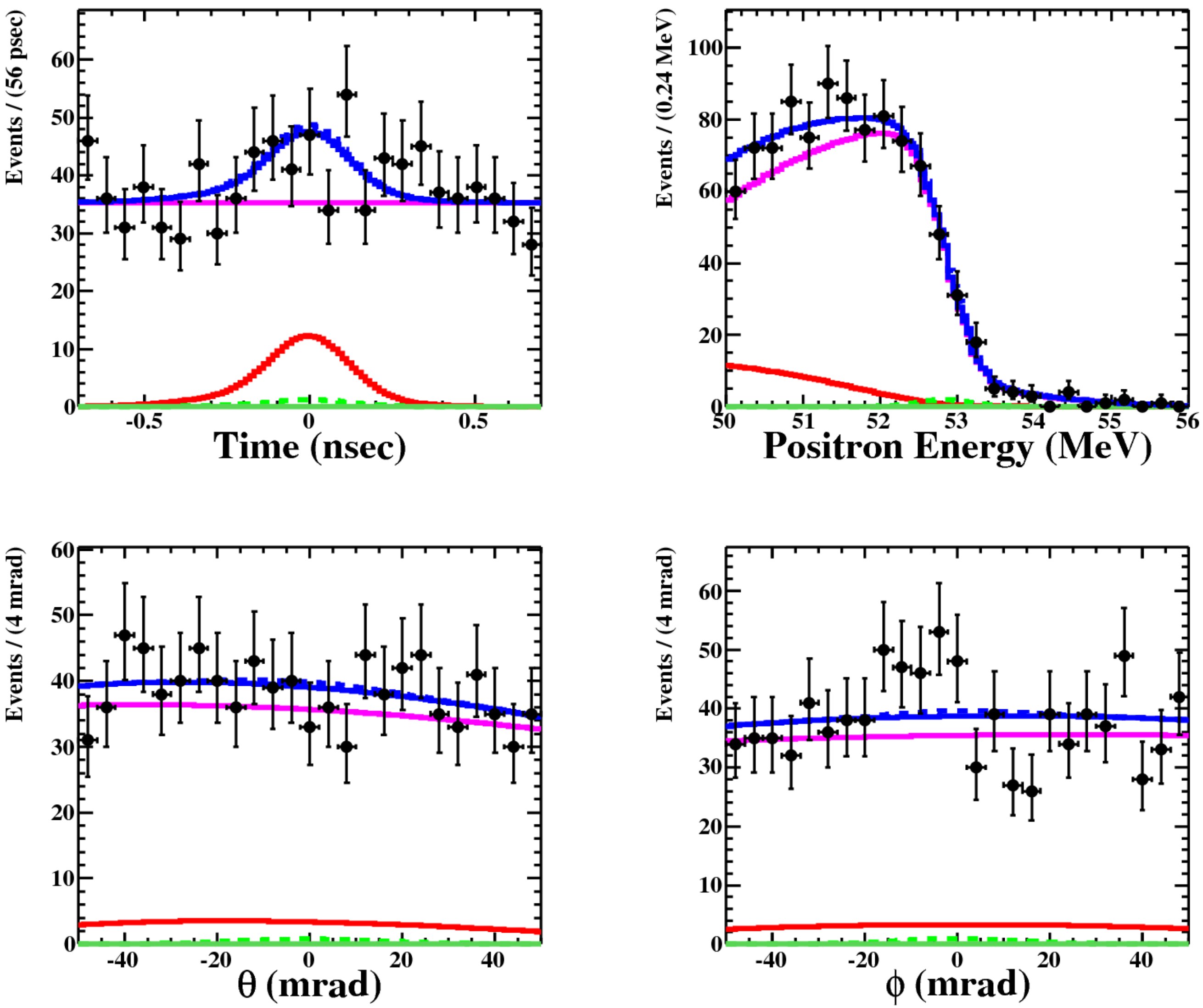


Control Samples

- Fit is tested on signal-free sidebands ($T_{e\gamma}$, $\theta_{e\gamma}$ and $\varphi_{e\gamma}$ sidebands):
  - no fake signal is found;
  - sensitivity consistent with expectations from toy MC.

Sideband	Nsig
$-2.7 < T_{e\gamma} < -1.3$ ns	0.8 (+8.2/-5.2)
$1.3 < T_{e\gamma} < 2.7$ ns	-7.0 (+5.7/-2.2)
$-150 < \theta_{e\gamma} < 50$ mrad	-2.6 (+5.5/-2.7)
...	...

Fit Results (2009 + 2010)



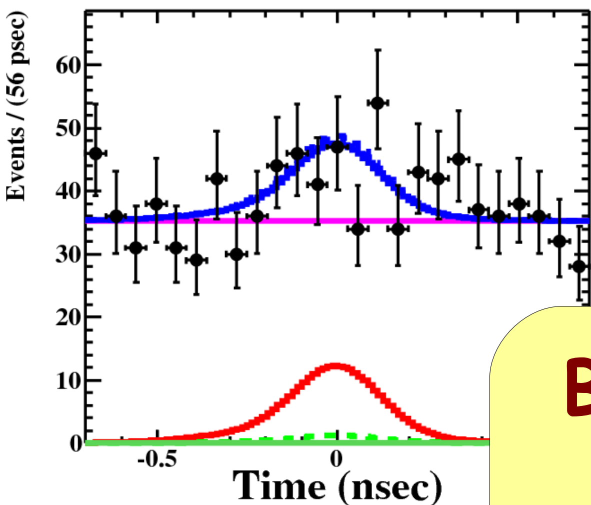
$N_{sig} = -0.5^{+7.9}_{-4.7}$

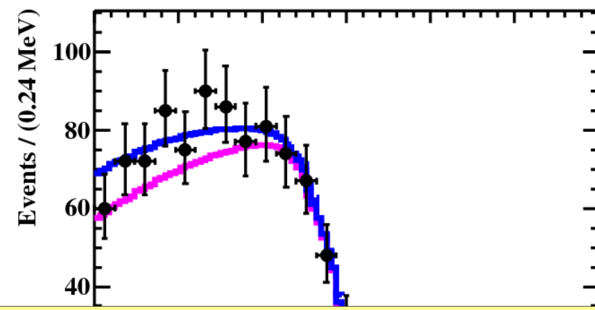
$N_{bkg} = 882 \pm 22$

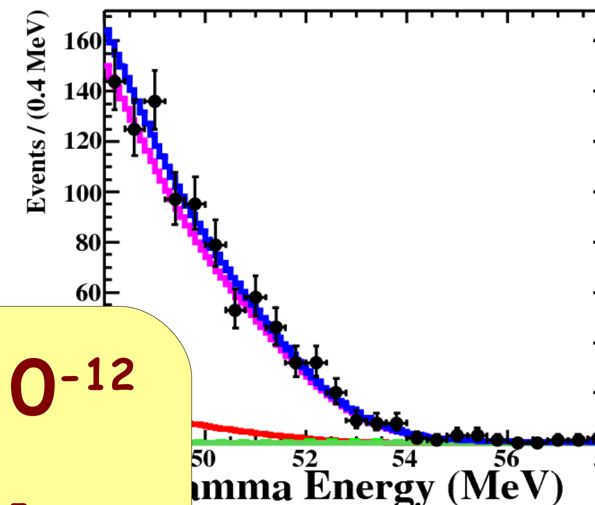
$N_{RD} = 76.5 \pm 12$

(MINOS errors)

Fit Results (2009 + 2010)



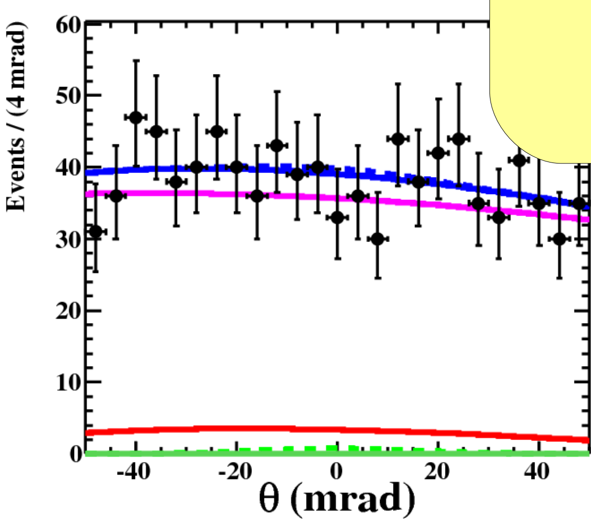


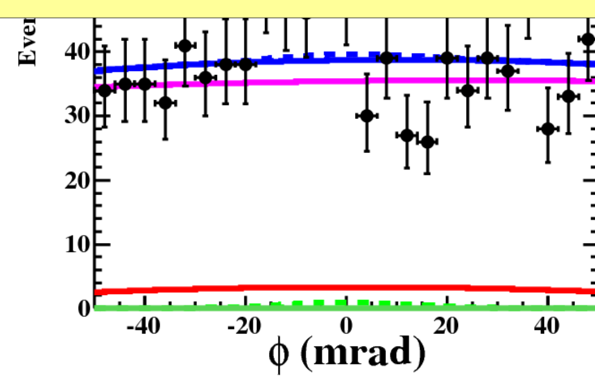


BR($\mu \rightarrow e\ \gamma$) < 2.4 x 10^{-12}

arXiv:1107.5547 [hep-ex]

accepted by Phys. Rev. Lett.





$_{ig} = -0.5^{+7.9}_{-4.7}$

$N_{bkg} = 882 \pm 22$

$N_{RD} = 76.5 \pm 12$

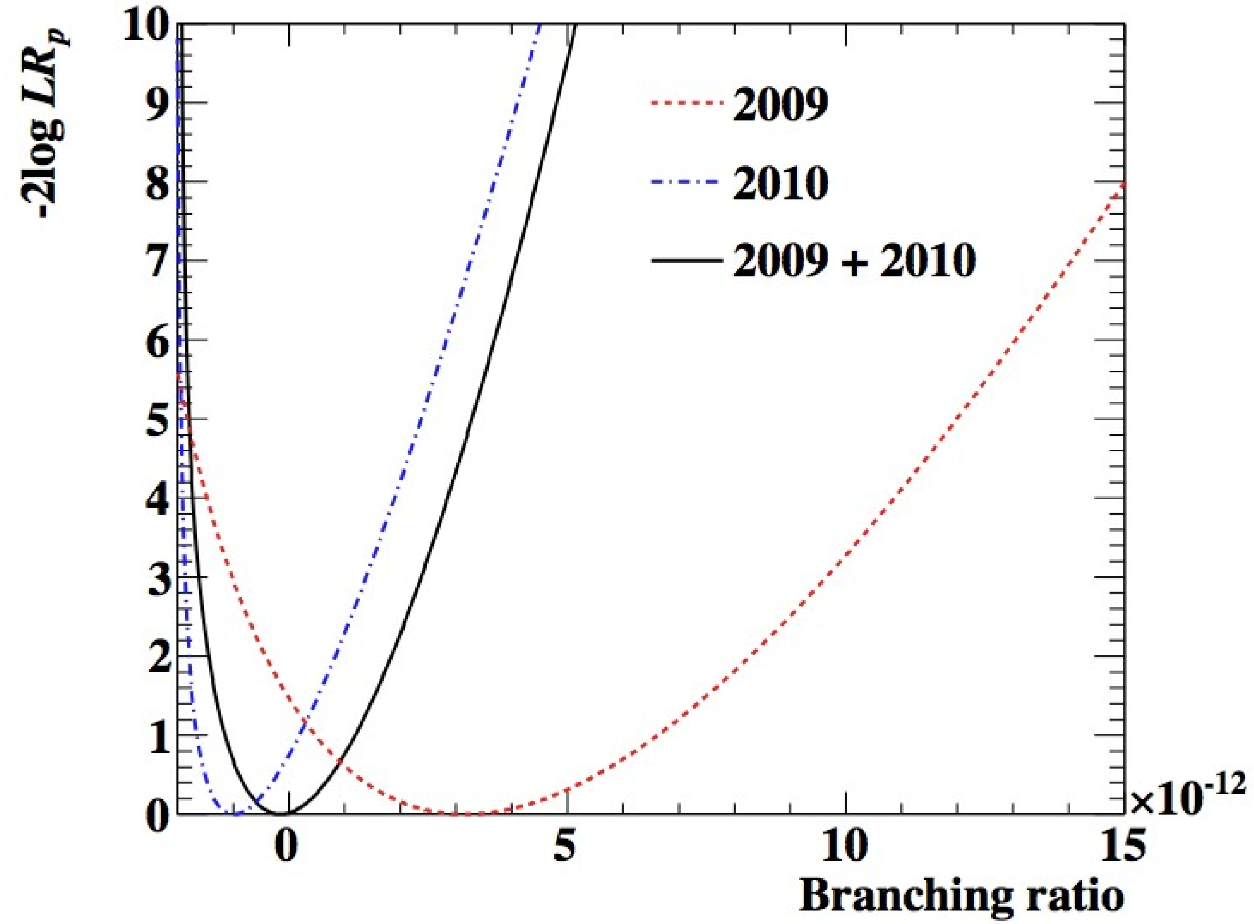
(MINOS errors)

Systematic Uncertainties

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

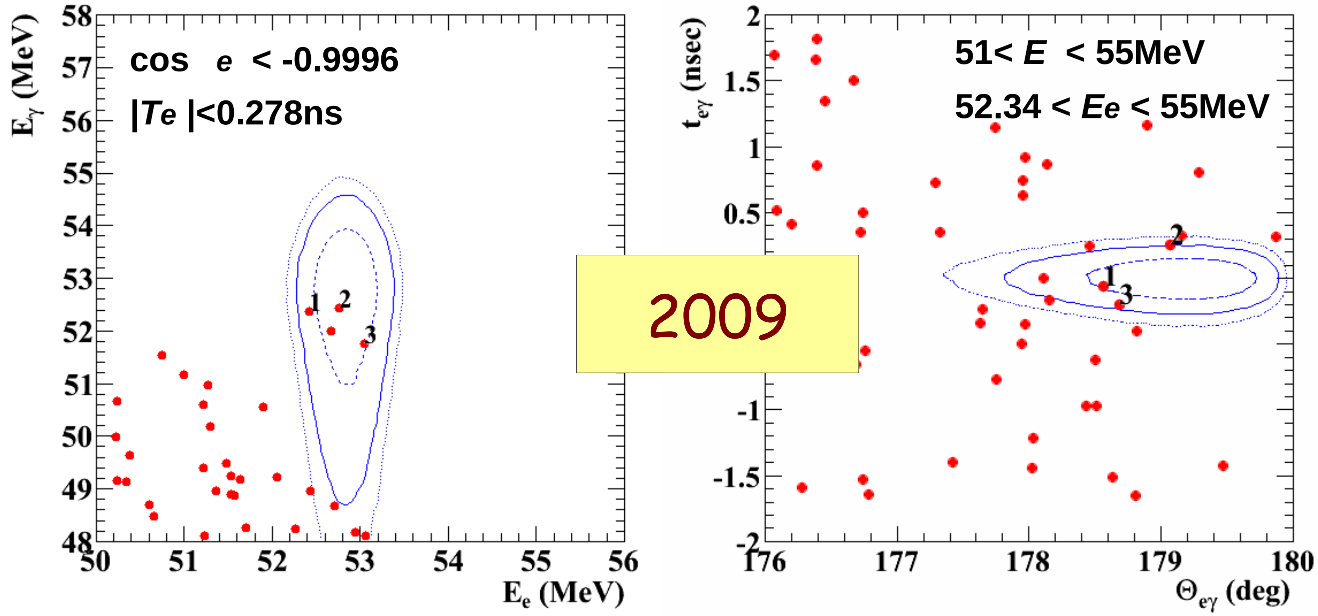
	$\Delta log(LR_p)$
Center of $\theta_{e\gamma}$ and $\phi_{e\gamma}$	0.18
Positron correlations	0.16
Normalization	0.13
E_γ scale	0.07
E_e bias, core and tail	0.06
$t_{e\gamma}$ center	0.06
E_γ BG shape	0.04
E_γ signal shape	0.03
Positron angle resolutions (θ_e, ϕ_e, z_e, y_e)	0.02
γ angle resolution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

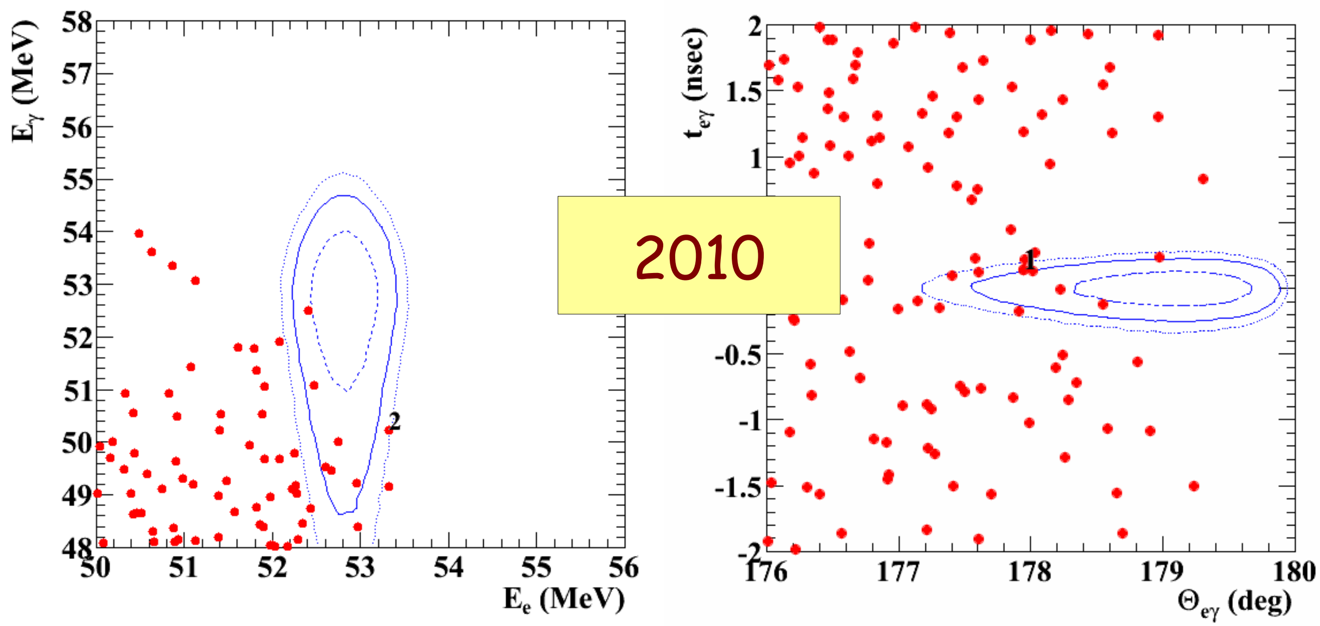
Profile Likelihood Ratio



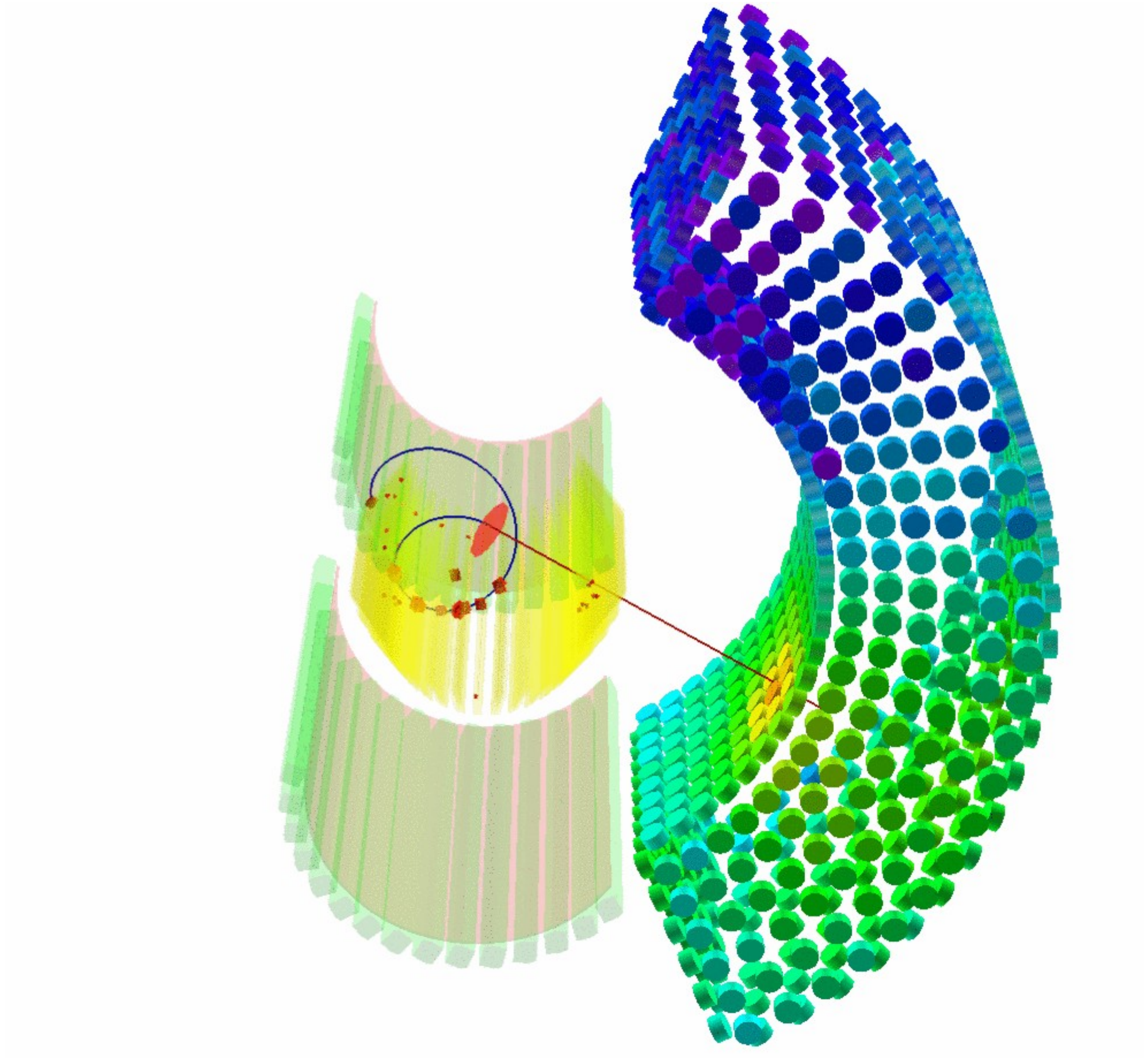
A look at the event distibutions

contours:
1σ, 1.64σ, 2σ



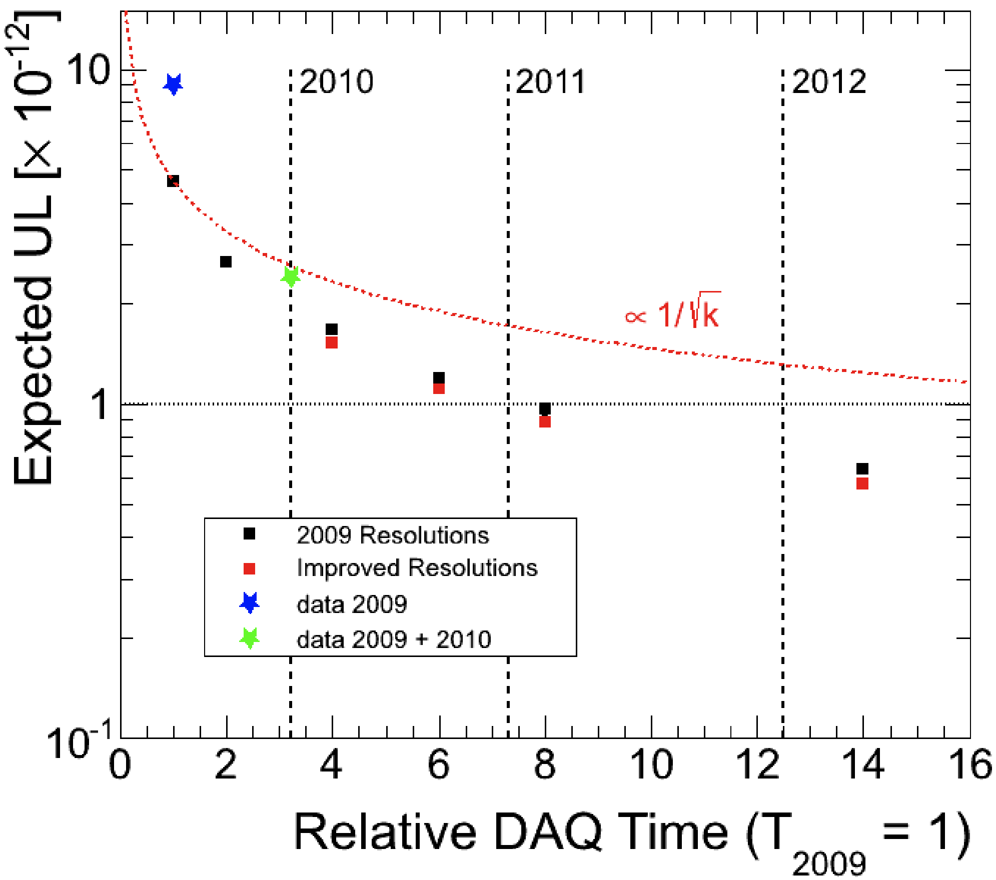


High-Signal-Likelihood Event



Status & Perspectives

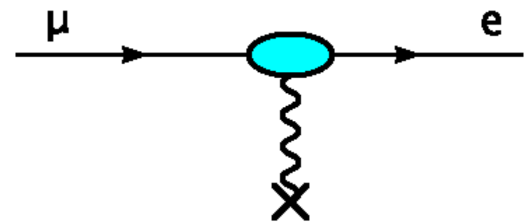
- The goal of MEG is to reach a sensitivity of a few 10^{-13} (UL) within 2012:
  - improved detector conditions (lower electronic noise, TC fibers now operative);
  - improved calibration tools;
  - improved analysis (tracking, calorimeter, etc.)



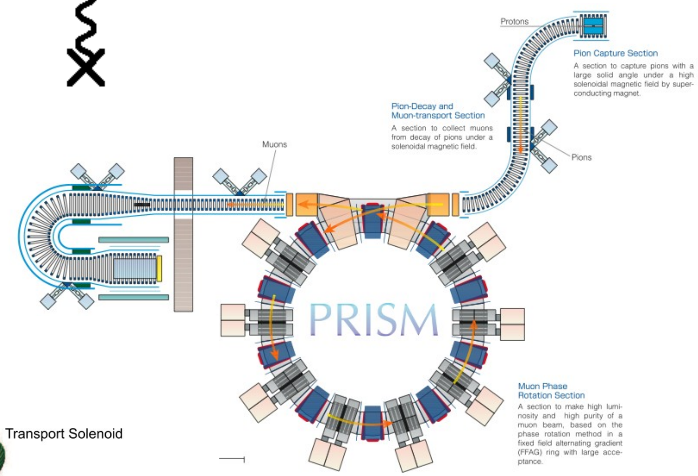
Incremental/major upgrade options are also under study

What else about LFV...

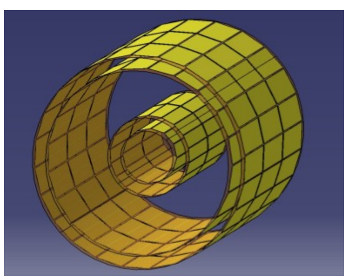
- New μ LFV experiments are expected in a few years:
  - $\mu \to e$ conversion in nuclei:

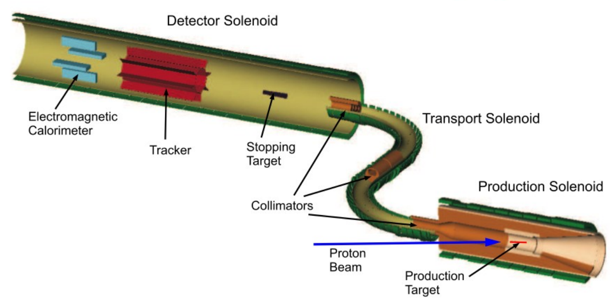


    - COMET (J-PARC, Japan)
    - mu2e (FERMILAB, USA);



  - $\mu \to e\, e\, e$ (proposal, PSI);





- τ LFV sensitivity will be improved by 1-2 orders of magnitude by the next generation of B-Factories (SuperB, Italy – Super-KEKB, Japan).

Conclusions

- LFV in the charged lepton sector is a standard probe for New Physics beyond the standard model:
  - most of the models are already strongly constrained by the present limits;
- MEG plays a leading role, searching for $\mu \to e \gamma$ at 10^{-13} level:
  - BR < 2.4×10^{-12} - the most stringent limit for μ LFV;
- We expect to improve significantly this limit in the next couple of years, waiting for the next generation of LFV experiments.