The MEG Experiment: a search for the LFV decay $\mu \rightarrow e \gamma$ down to BR ~ 10^{-13}

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SAPIENZA - Università di Roma
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SuperB Physics Workshop - Frascati, November 30th, 2009

Outline

- Theoretical Introduction;
- Experimental Challenges;
- The MEG Experiment:
  - Beam & Target;
  - Positron Momentum: the Positron Spectrometer;
  - Positron Time: the Timing Counter;
  - Photon Energy & Time: the LXe calorimeter;
  - Trigger;
  - Calibrations;
- Status (the 2008 run) and perspectives.

Lepton Flavour Violation

- Lepton Flavour conservation is an *accidental symmetry* in the Standard Model:
  - Not related to gauge structure of the theory;
  - Naturally violated in SM extensions;
- Lepton Flavour Violation already observed in the neutrino sector (*neutrino oscillations*) :
  - Can be explained with a heavy right-handed neutrino;
  - Very small SM contribution to the $\mu \to e \gamma$ BR ($\sim 10^{-54}$)

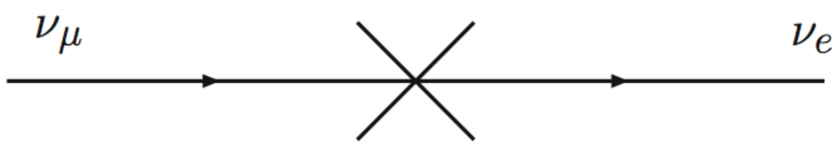
Present Limit:
$BR(\mu \to e \gamma) < 1.2 \times 10^{-11}$
@ 90% C.L.
(MEGA Collab.)

$\mu \to e \gamma$ at the 10^{-13} level
would be an unambiguous evidence of
New Physics beyond the SM

Neutrino Mass & Oscillations

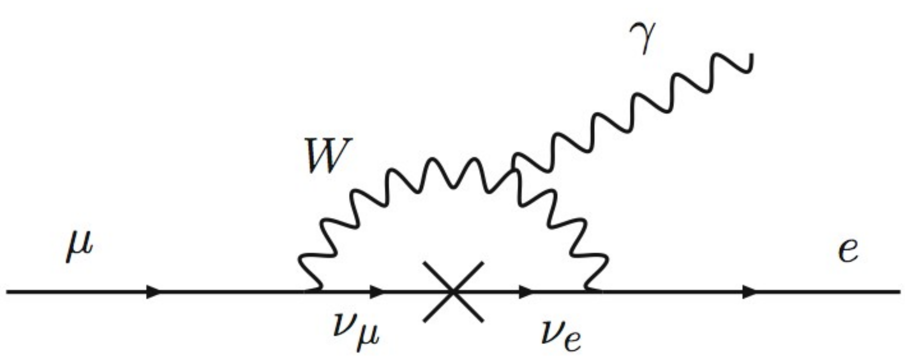
- Neutrino mass & oscillations can be accounted for by introducing a right-handed neutrino:

$$\mathcal{L} \supset \overline{\nu} M_\nu \nu$$



$$M_\nu = \begin{pmatrix} M_{ee} & M_{e\mu} & M_{e\tau} \\ M_{\mu e} & M_{\mu\mu} & M_{\mu\tau} \\ M_{\tau e} & M_{\tau\mu} & M_{\tau\tau} \end{pmatrix}$$

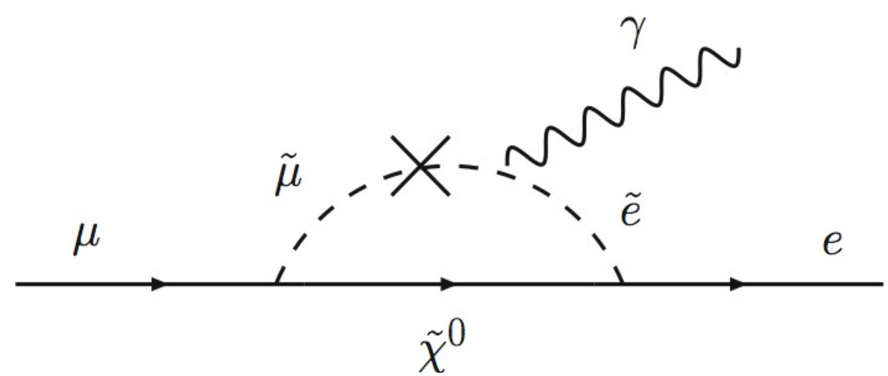
- Neutrino oscillations can mediate a $\mu \rightarrow e \gamma$ decay, but...



BR ~ m_ν^4/m_W^4 ~ 10^{-54}

LFV beyond the SM

- Many SM extensions predict a $\mu \rightarrow e\gamma$ BR at a measurable level;
- SUSY:
  - Off-diagonal terms in the slepton mass matrix appears for free (e.g. through RG evolution) and induce LFV.

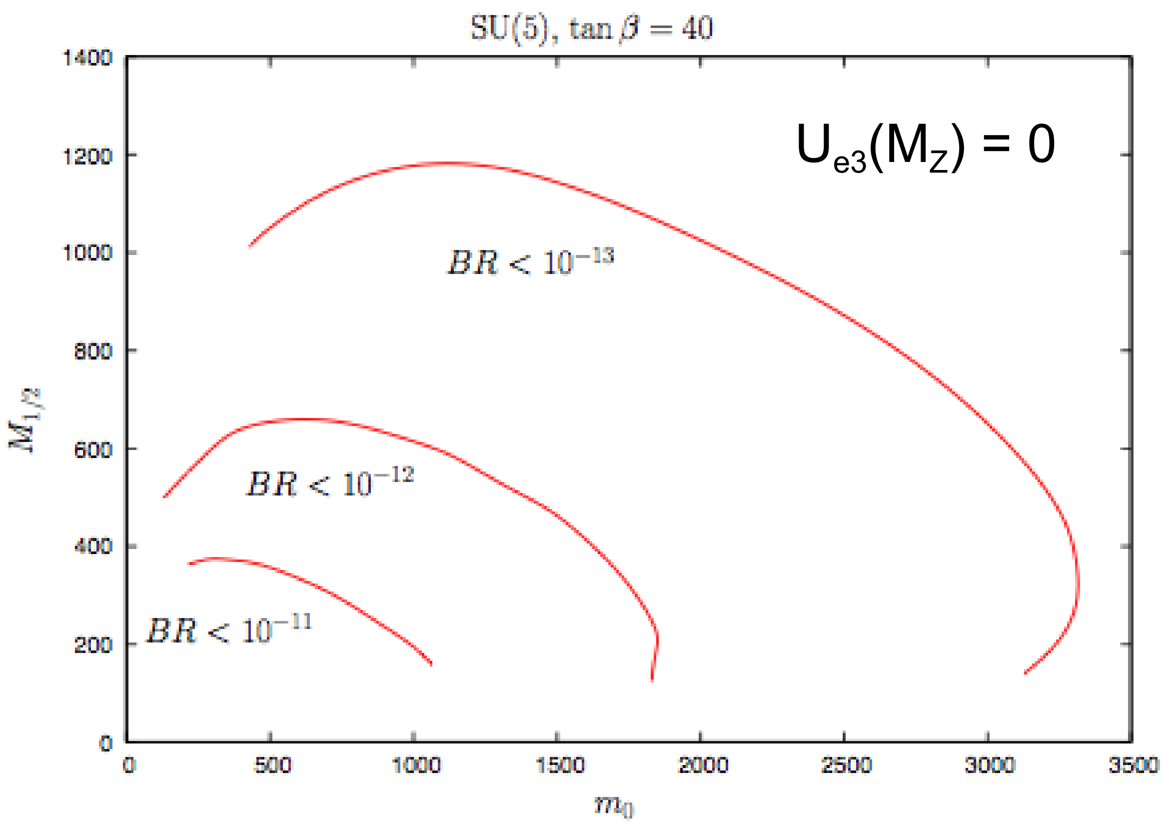


$$BR(\ell_i \rightarrow \ell_j \gamma) \propto \delta_{ij}^2 \tan^2\beta$$

$$(\tilde{l}_L^\dagger \tilde{l}_R^\dagger) \begin{pmatrix} m_L^2(1+\delta_{LL}) & (A-\mu\tan\beta)m_l + m_L m_R \delta_{LR} \\ (A-\mu\tan\beta)m_l + m_L m_R \delta_{LR}{}^\dagger & m_R^2(1+\delta_{RR}) \end{pmatrix} \begin{pmatrix} \tilde{l}_L \\ \tilde{l}_R \end{pmatrix}$$

LFV in SO(10) SUSY-GUT

- In SUSY-GUT scenarios, LFV parameters can be related to the CKM matrix (*minimal mixing*) or the PMNS matrix (*maximal mixing*);
- In the PMNS case, $\mu \to e\,\gamma$ strongly related to U_{e3}.



Masiero *et al.*
Nucl.Phys.B649:189,2003

Calibbi *et al.*
JHEP,0707:012,2007

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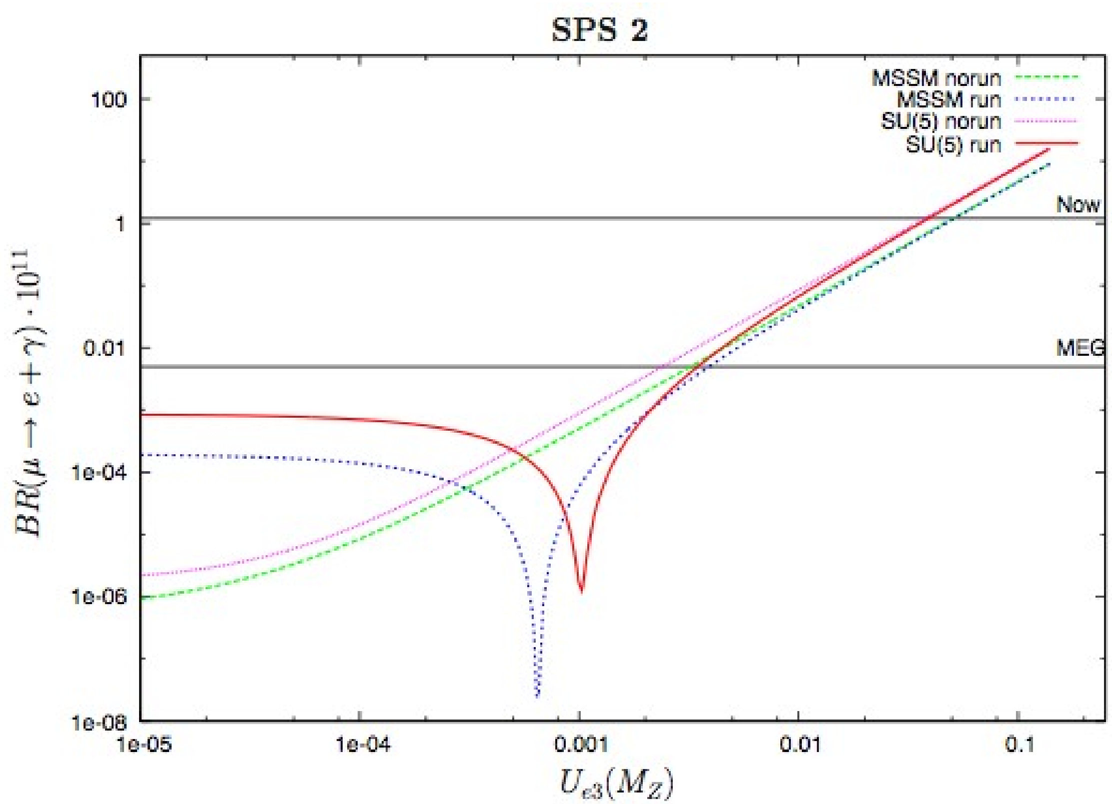

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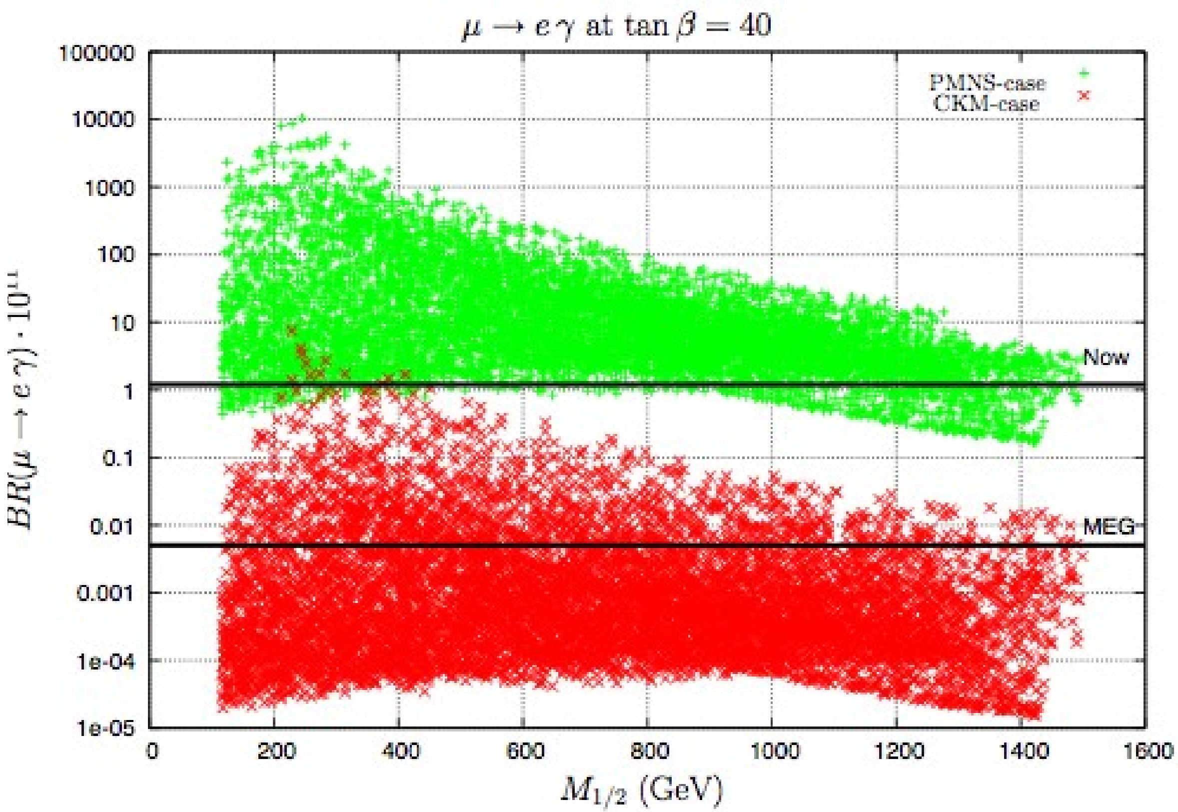

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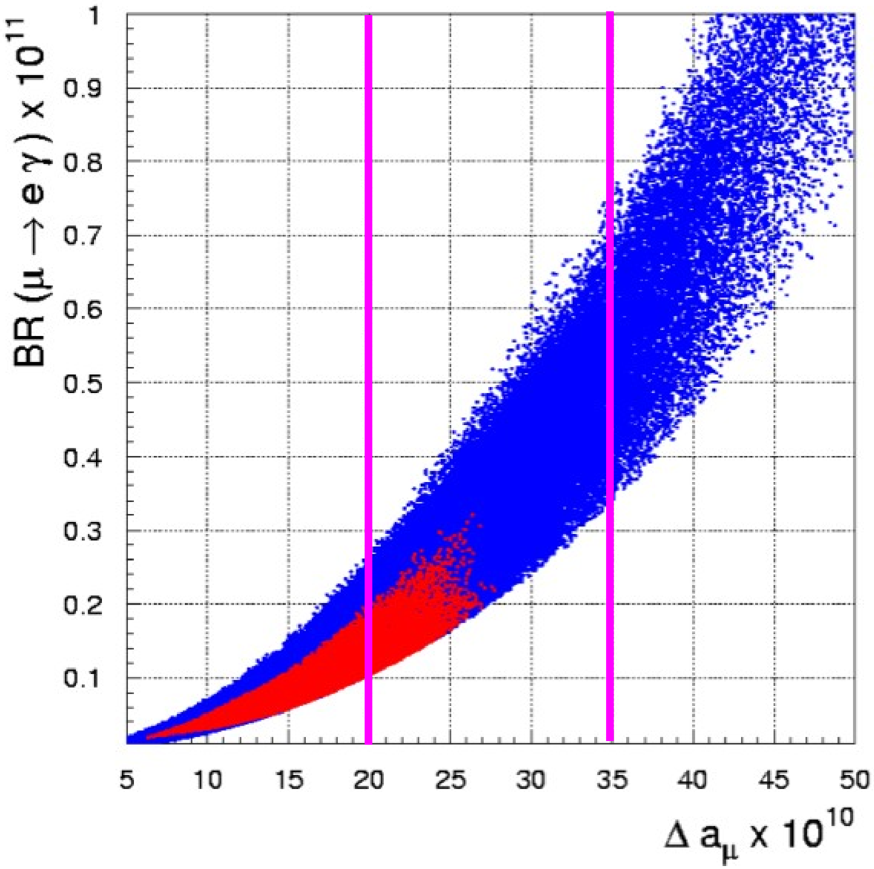
Connection to g_μ - 2

- The SUSY solution of the (possible) g_μ - 2 anomaly provides a connection between g_μ - 2 and $\mu \rightarrow e \gamma$;

- $\mu \rightarrow e \gamma$ could be just round the corner.



Isidori et al. Phys.Rev.D75:115019,2007

(MLFV, large tanβ)

$\mu \to e\,\gamma$ vs. $\tau \to l\,\gamma$

- The importance of $\mu \to e\,\gamma$ vs. $\tau \to l\,\gamma$ depends on the specific structure of the slepton mass matrix;
- Example I - SO(10) SUSY-GUT:
  - $\mu \to e\,\gamma$ tends to be the most sensitive channel;
  - $\tau \to e\,\gamma$ dominates in the PMNS scenario if U_{e3} is small;
- Example II – MLFV at large tanβ:
  - $\mu \to e\,\gamma$ could be within the MEG reach;
  - $\tau \to l\,\gamma$ unlikely to exceed 10^{-9} ;

$\mu \to e\gamma$ vs. $\tau \to l\gamma$

TABLE XIV: Reach in $(m_0, m_{\tilde{g}})$ of the past, present and upcoming experiments from their LFV sensitivity. LHC means that all the LHC testable parameter space will be probed; all means that soft masses up to $(m_0, m_{\tilde{g}}) \lesssim 5$ TeV will be probed.

Experiment	PMNS		CKM	
	$t_\beta = 40$	$t_\beta = 10$	$t_\beta = 40$	$t_\beta = 10$
μe sector				
MEGA	LHC 1.1 TeV[a]	2 TeV no[a]	no	no
MEG	all LHC[a]	all 1.1 TeV[a]	1.3 TeV	no
PRISM/PRIME[b]	all	all LHC[a]	all	2.8 TeV
$\tau\mu$ sector				
BaBar, Belle	1.2 TeV	no	no	no
SuperKEKB	2 TeV	0.9 TeV	no	no
Super Flavour[b]	2.8 TeV	1.5 TeV	0.9 TeV	no

[a] $U_{e3} = 0$
[b] Post–LHC era, planned/discussed experiment

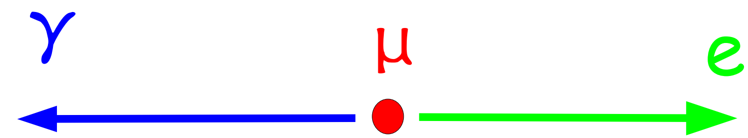
SO(10) SUSY-GUT

Calibbi *et al.* Phys.Rev.D74: 116002,2006

Experimental Signature

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

SIGNAL ∝ μ rate

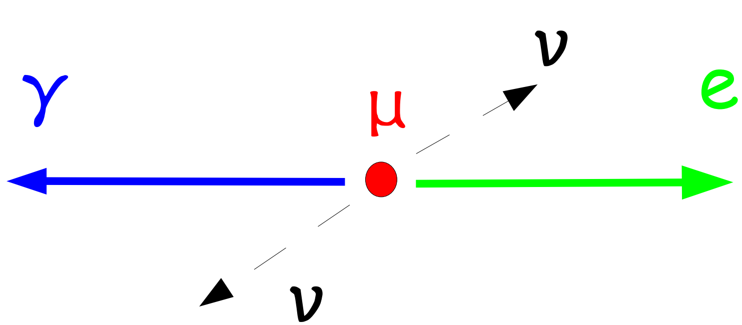


$E_\gamma = E_e = 52.8$ MeV,

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

RADIATIVE

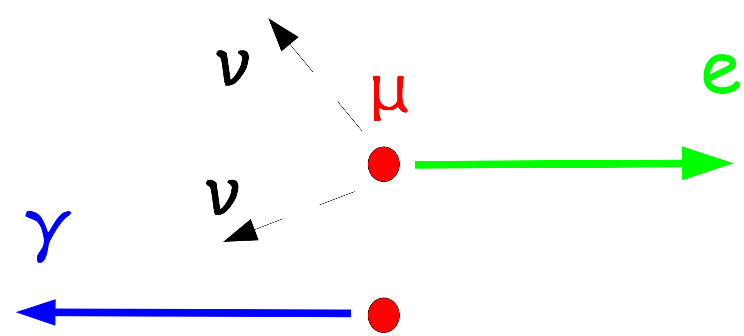
DECAY ∝ μ rate



DOMINANT

ACCIDENTAL

∝ $(\mu \text{ rate})^2$



Experimental Signature

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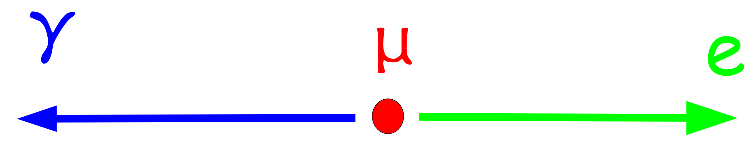
  - high statistics;
  - high resolutions (energy, time
    a

SIGNAL ∝ μ rate

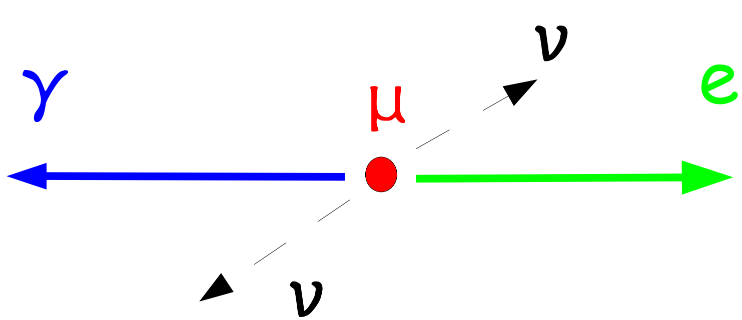


E = E = 52.8 MeV,

0

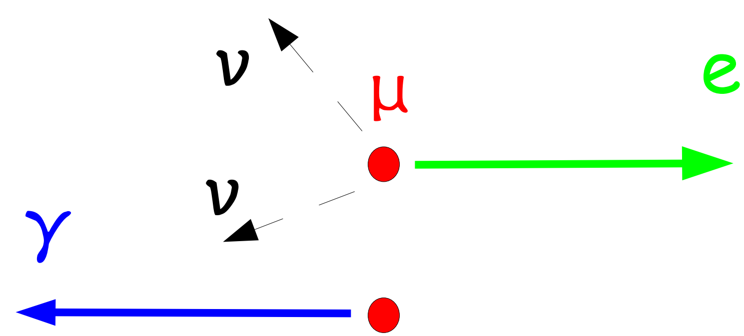
$$\Gamma_{acc} \propto \Gamma_\mu^2 \cdot \delta E_e \cdot \delta T_{e\gamma} \cdot (\delta E_\gamma)^2 \cdot (\delta\theta_{e\gamma})^2$$

DECAY ∝ μ rate

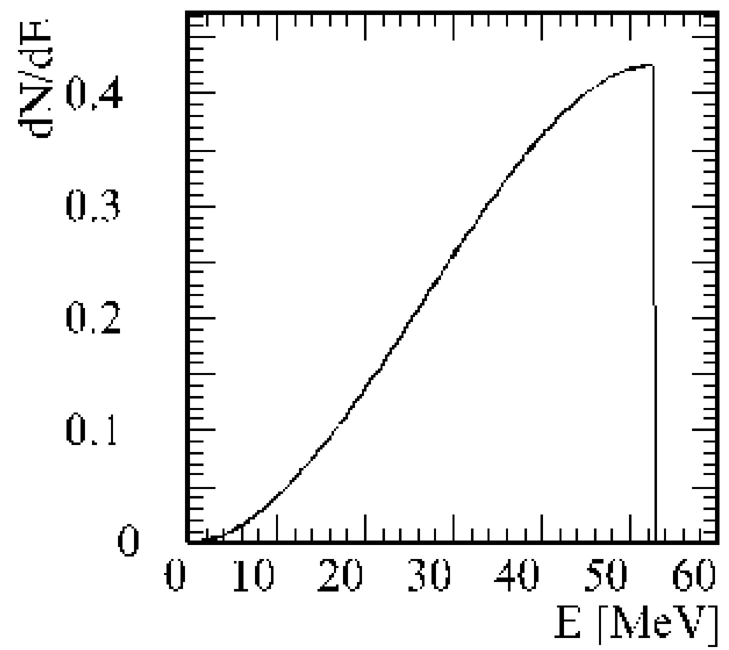


DO

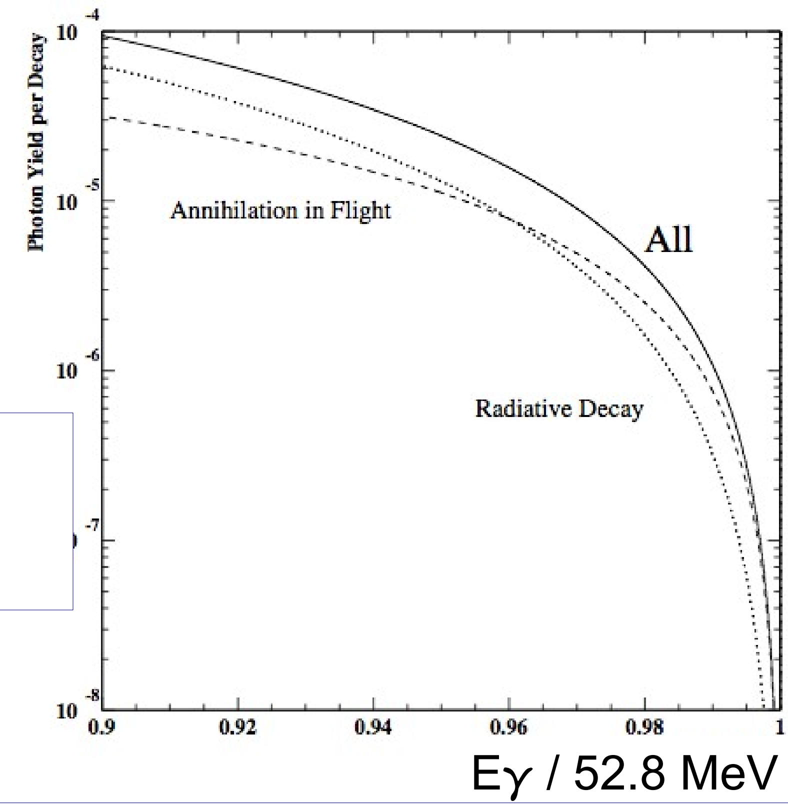
∝ (μ rate)^2



Background Spectra

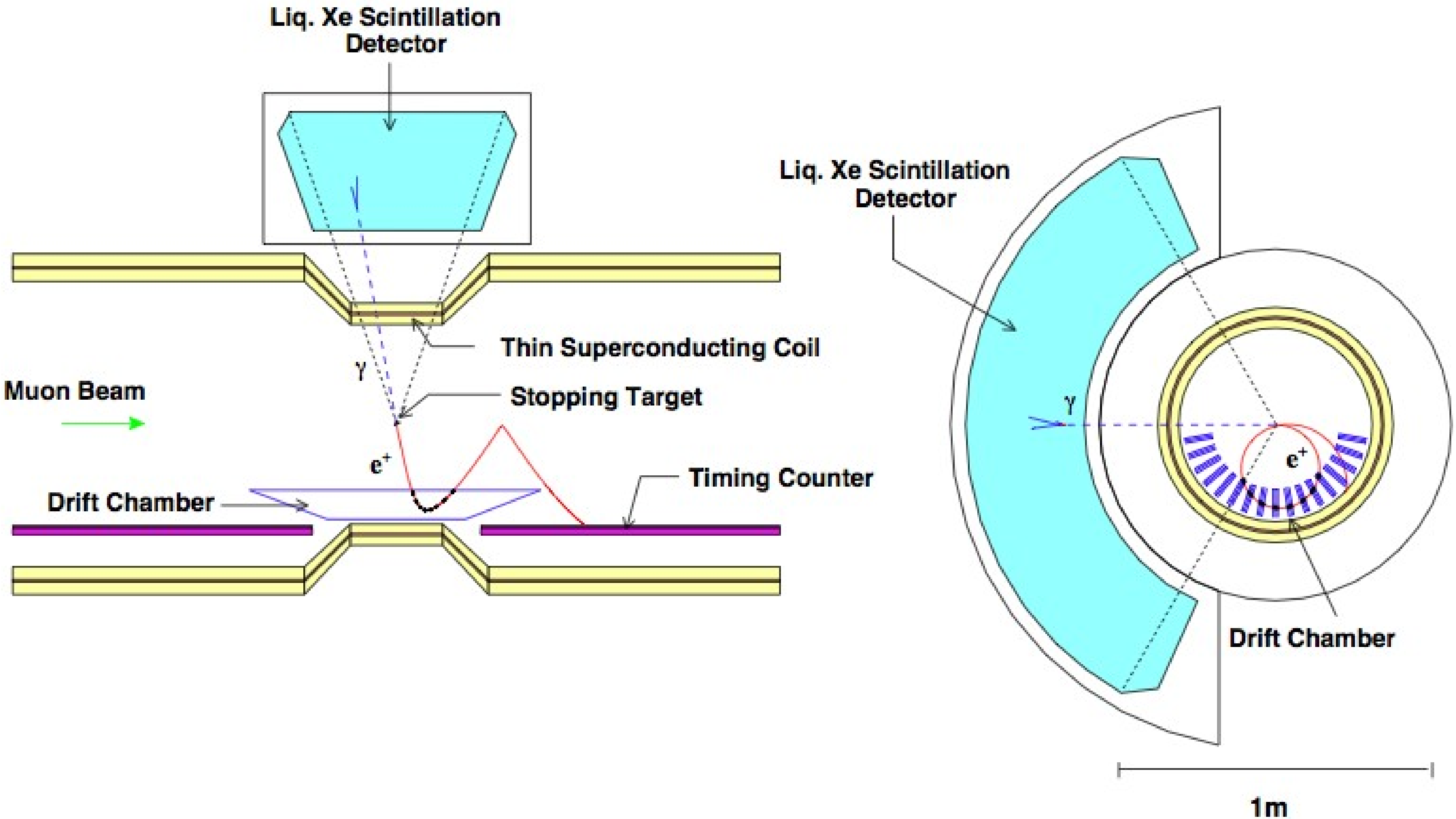


Positron spectrum from
μ → e ν ν (Michel decay)

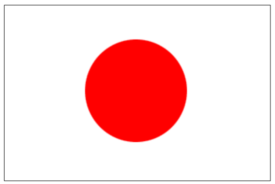


Integrated photon spectrum

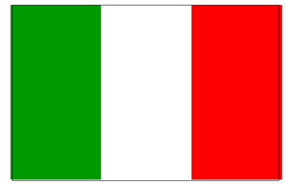
The MEG Experiment



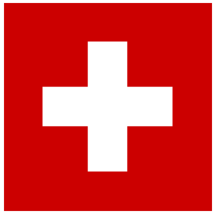
The MEG Collaboration



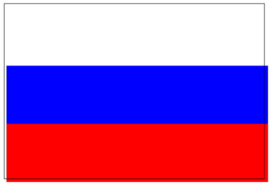
KEK
TOKYO UNIVERSITY
WASEDA UNIVERSITY



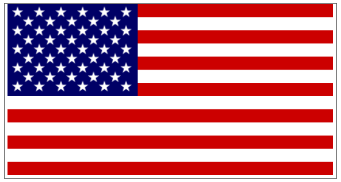
GENOVA
LECCE
PAVIA
PISA
ROMA



PSI



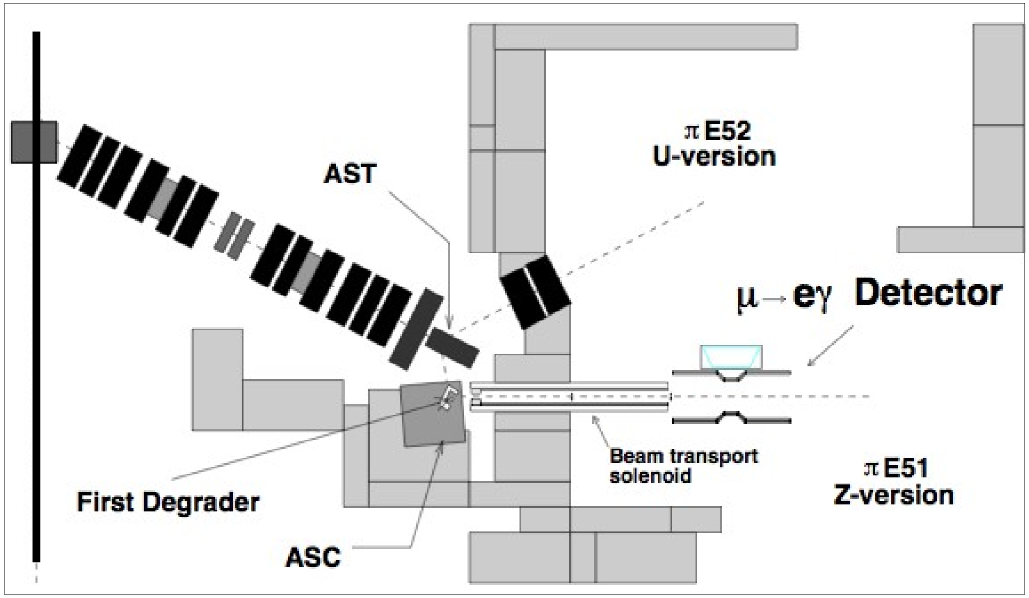
BINP - NOVOSIBIRSK
JINR - DUBNA



UC IRVINE

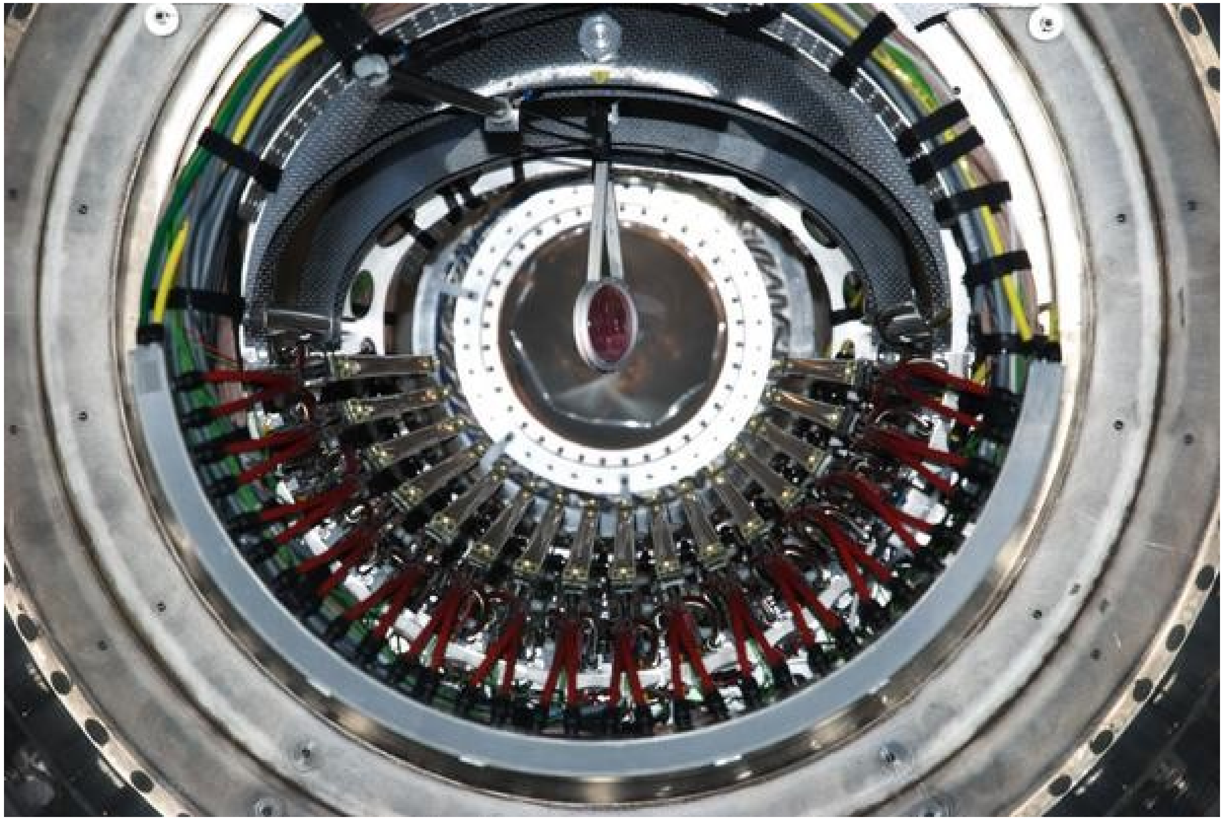
The πE5 Beam @ PSI

- The 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 (reduced accidental rate);



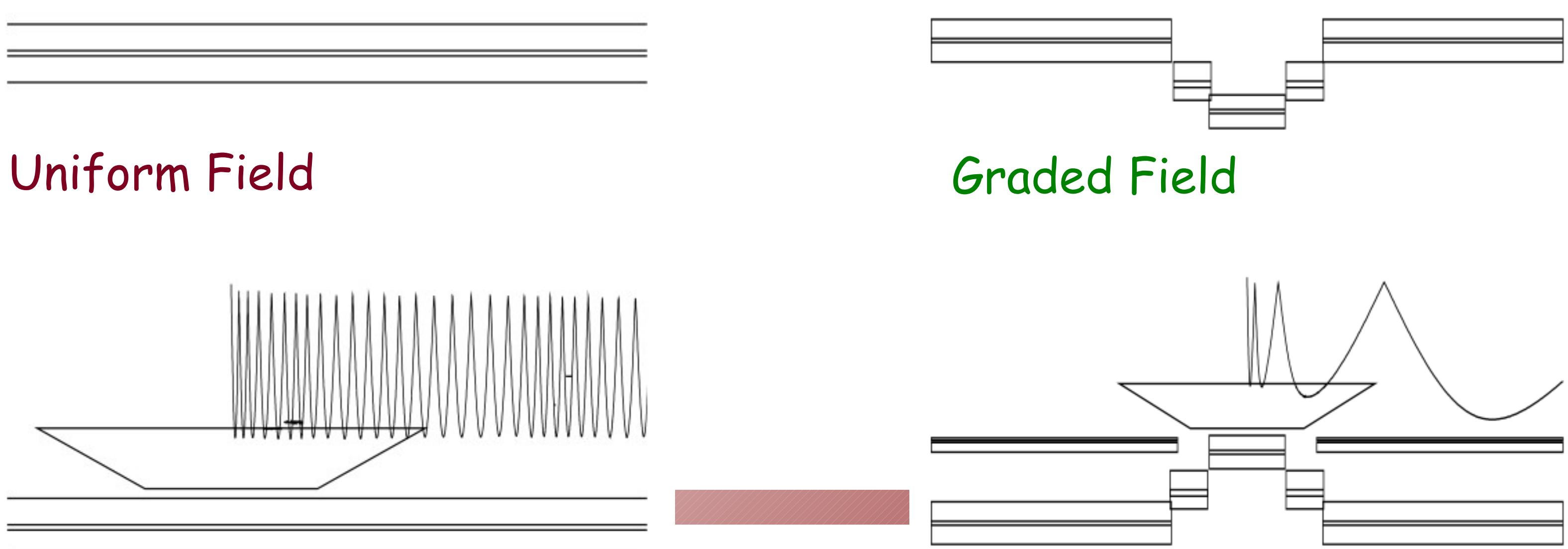
Proton beam current	:	~ 2 mA
Muon production	:	from π decaying in the target surface (surface muons)
Muon Momentum	:	28 MeV/c ± 3%

Positron Spectrometer



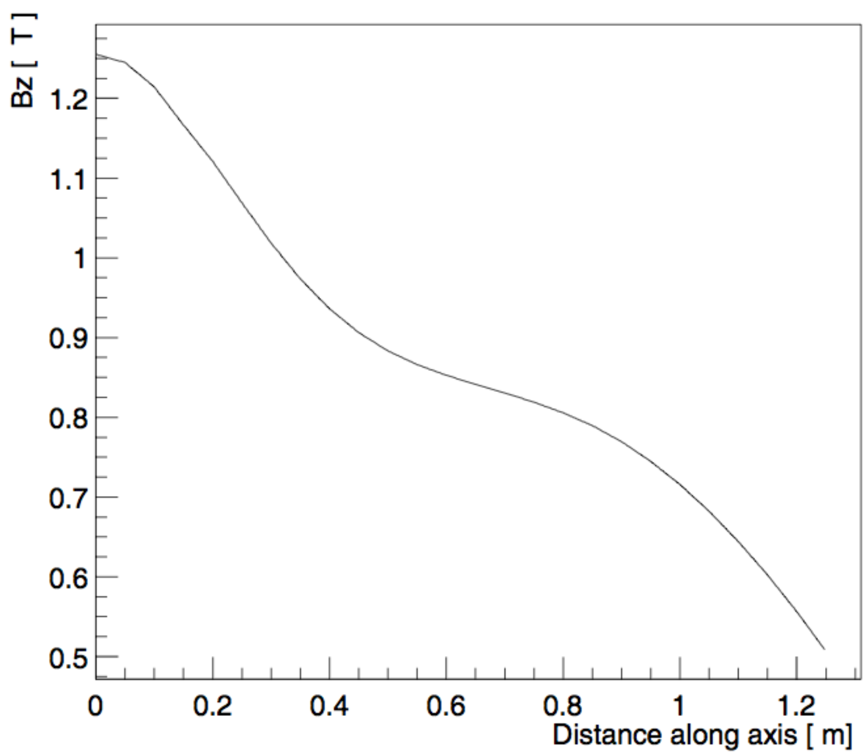
The Concept

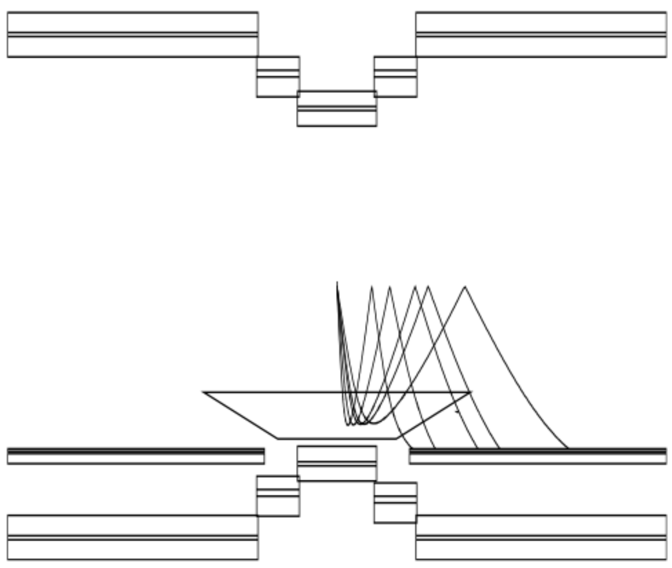
- MEG requirements:
  - good momentum resolution (~ 200 keV @ 52.8 MeV);
  - low pile-up (for low background and better tracking);
- The solution:
  - Drift Chambers in a *Graded Magnetic Field*.



COBRA Magnet

- COBRA (COnstant Bending RAdius):
  - Superconducting Magnet providing a graded field.

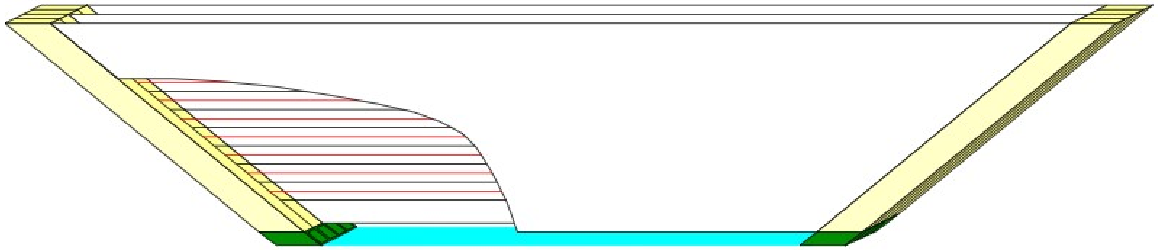


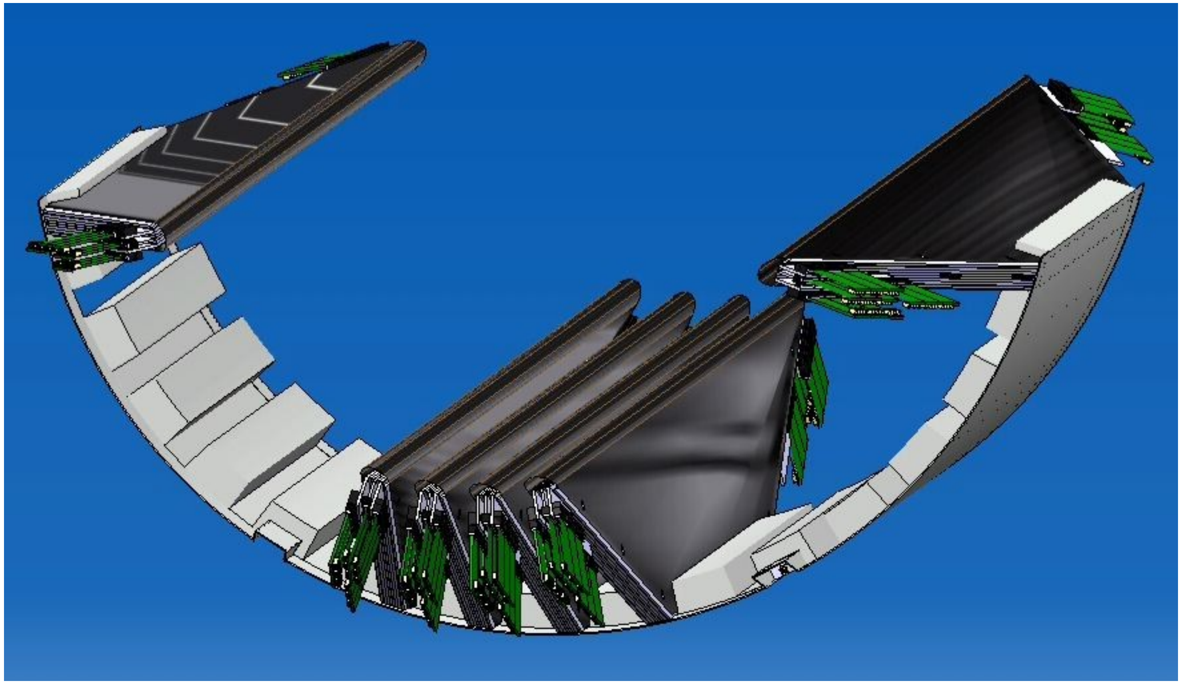


Bending Radius is independent of the positron angle

Drift Chambers (DCH)

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





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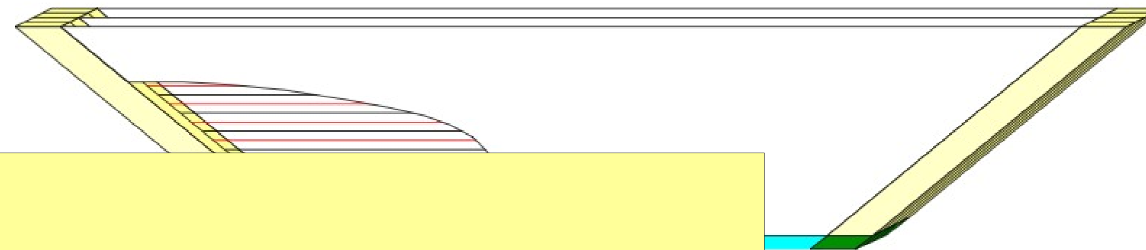
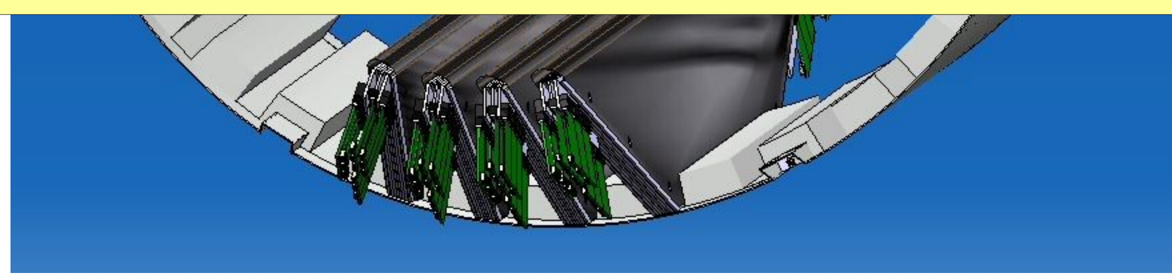
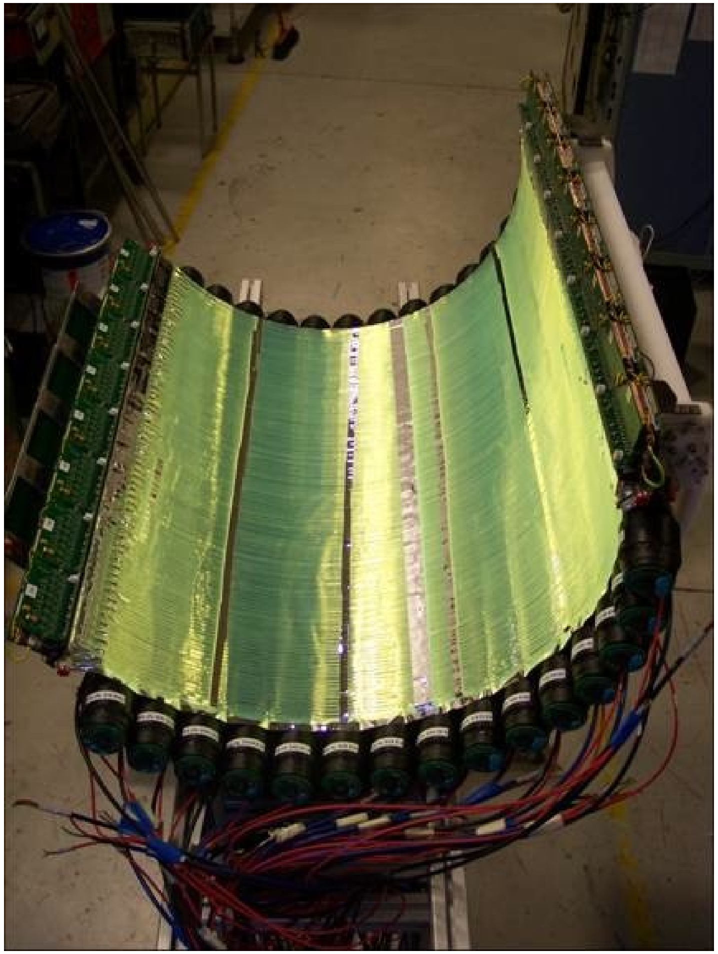


GOAL RESOLUTIONS

Momentum: 200 keV/c
Direction: 4.5 mrad
μ Decay Point: 4.5 mm

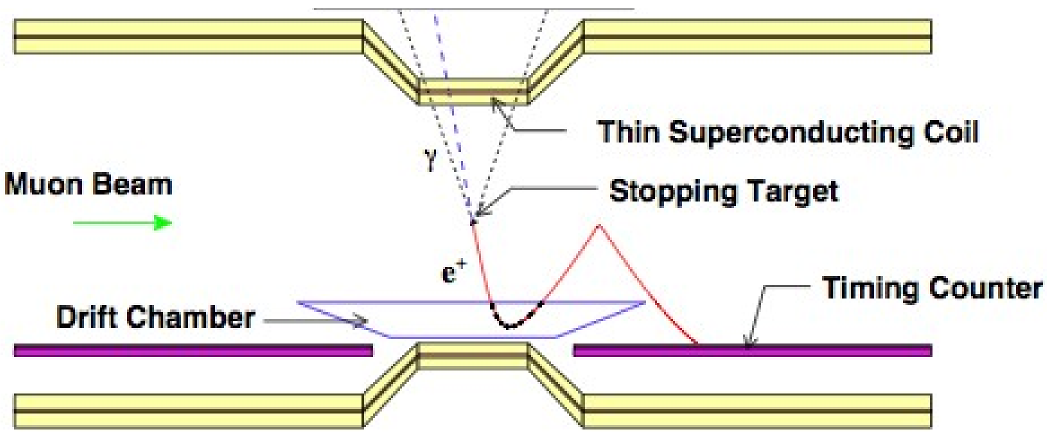


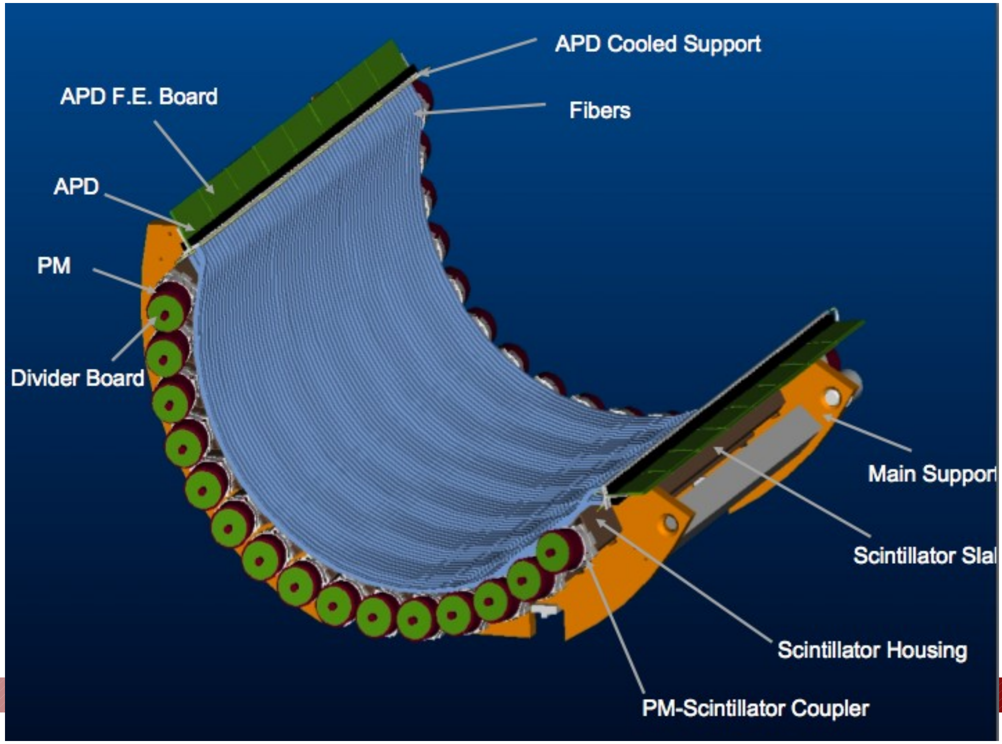
Timing Counter (TC)



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
  - not yet fully operational





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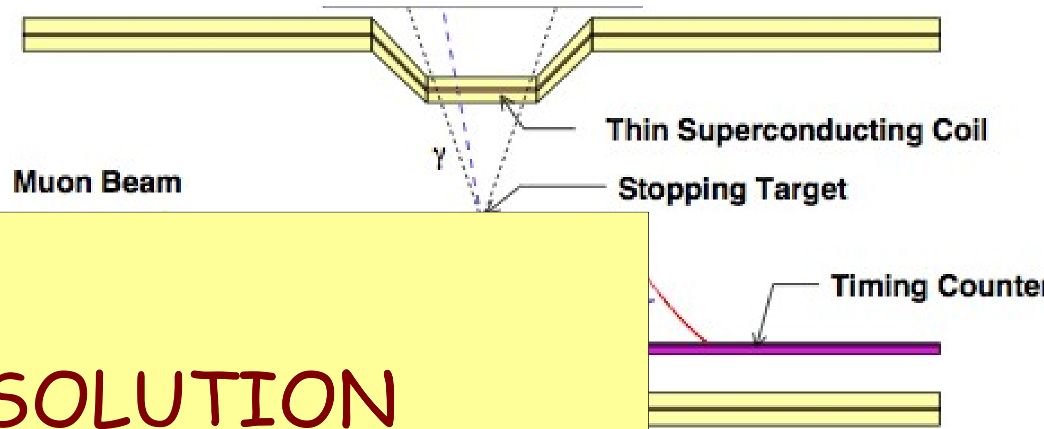
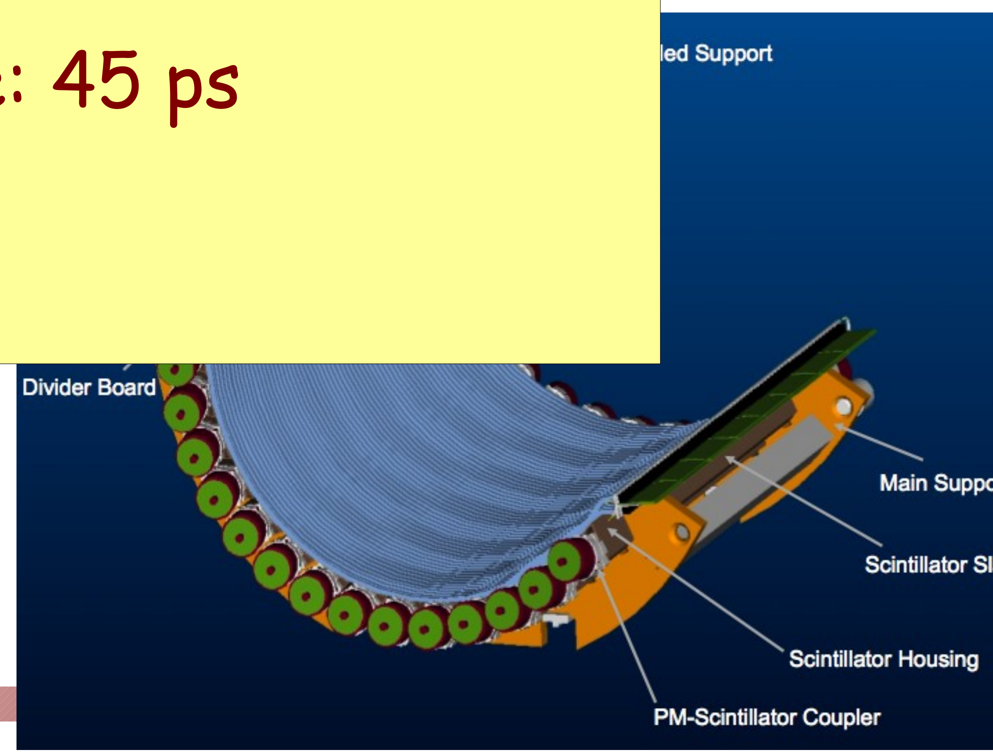
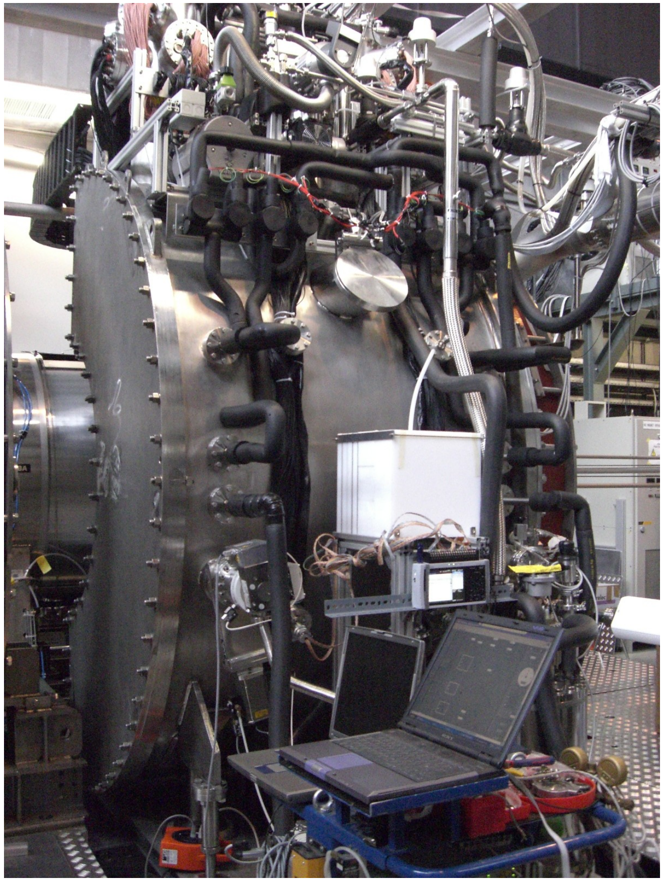


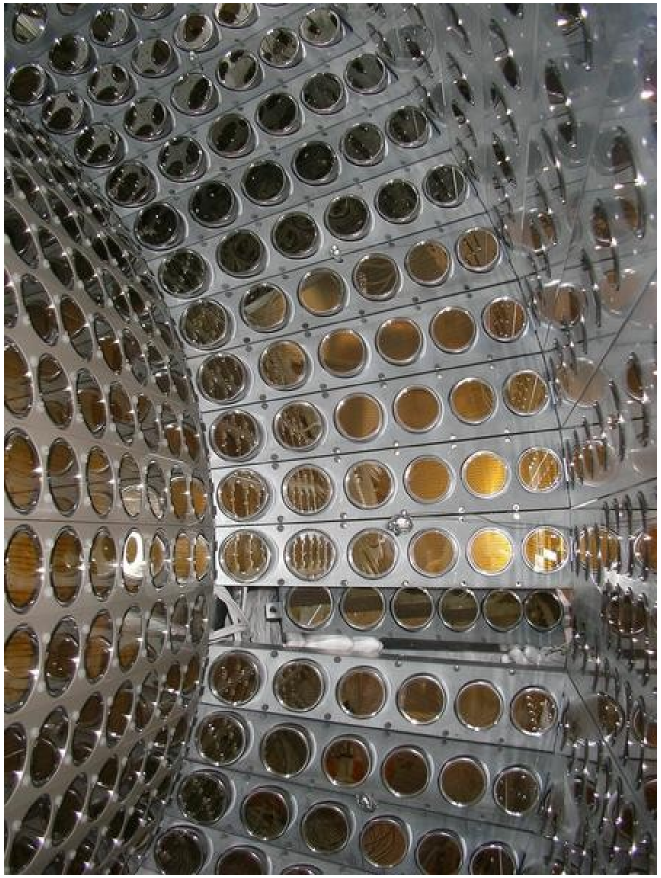
GOAL RESOLUTION

Time: 45 ps



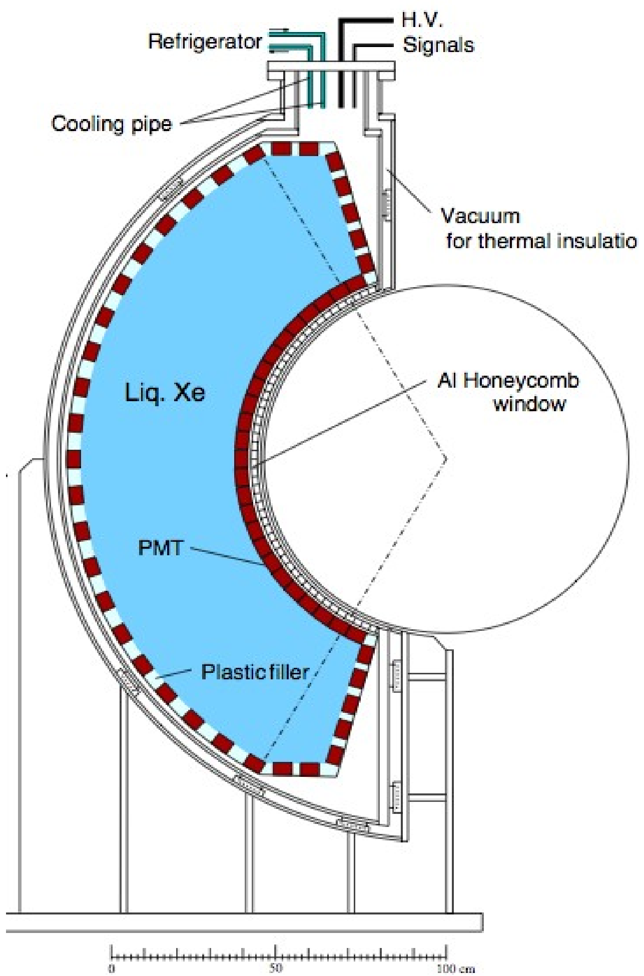
LXe Calorimeter (XeC)





The Concept

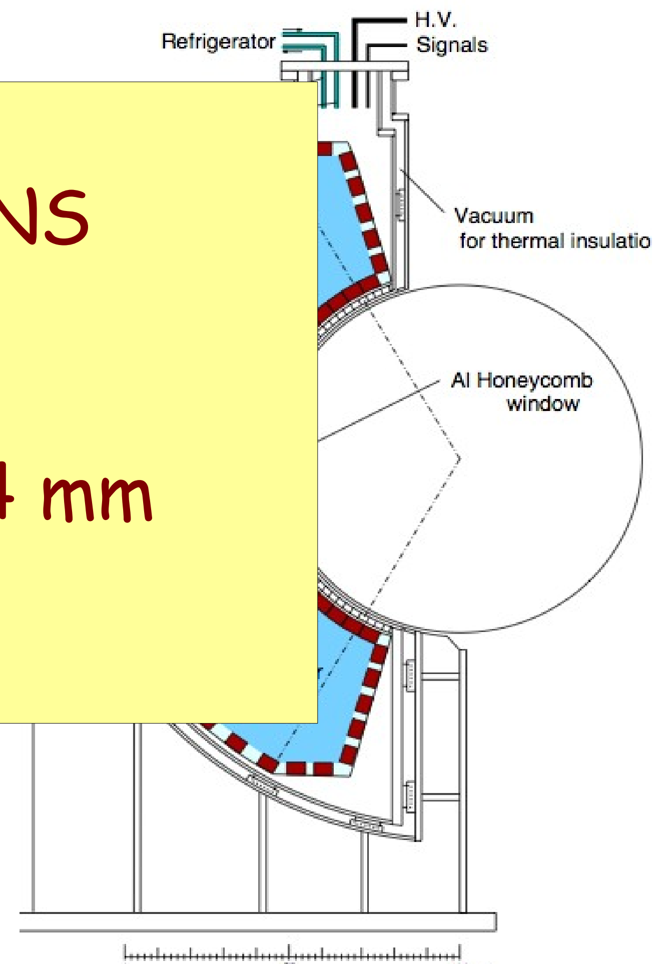
- The largest LXe calorimeter in the world:
  - 800 liters;
- Fast response:
  - τ = 4ns / 22ns / 45ns;
- Good light yield:
  - ~ 75% of NaI(Tl);
- Light collected by 846 PMTs.



Hamamatsu
R9288

The Concept

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



GOAL RESOLUTIONS

Energy: 800 keV

Conversion Point: 2 - 4 mm

Time: 65 ps

Hamamatsu
R9288

Calibrations

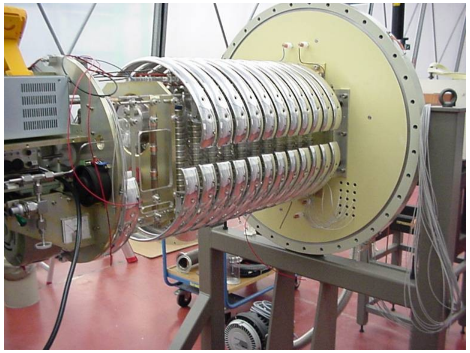
Charge Exchange (CEX)

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

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

high energy photons for XeC energy & relative time calibrations

Cockcroft-Walton accelerator

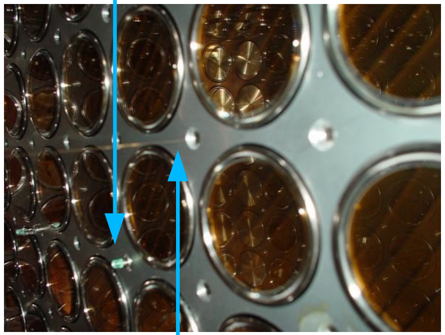


Protons on a Lithium Tetra-borate target

low-energy photons for XeC energy & relative time calibration

LED

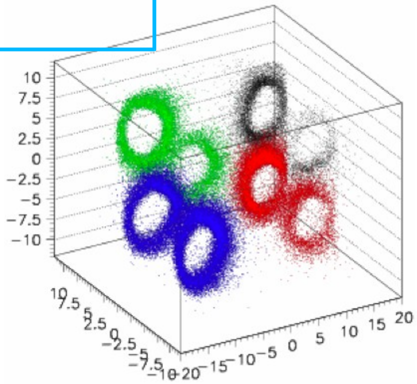
Installed inside the XeC



PMT gain calibration

α sources

Installed in wires inside the XeC

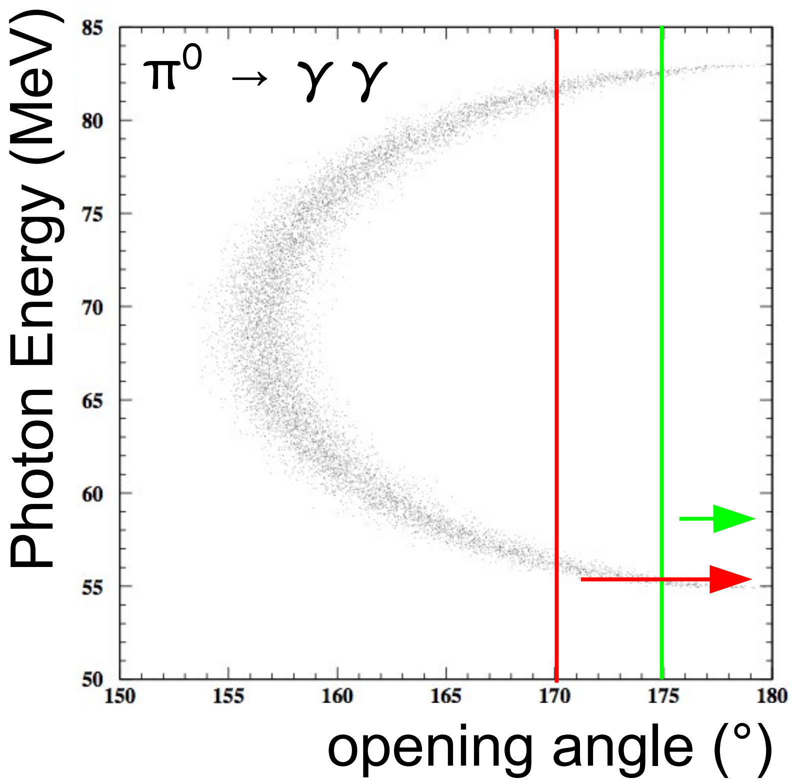


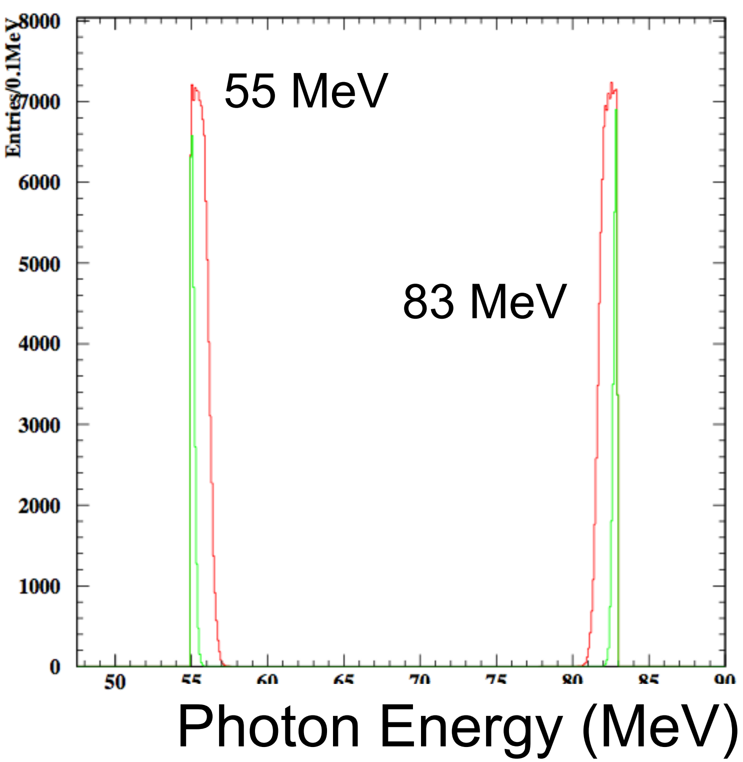
Calibration of Q.E., attenuation length, position

CEX

ENERGY CALIBRATION

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





Cockcroft Walton

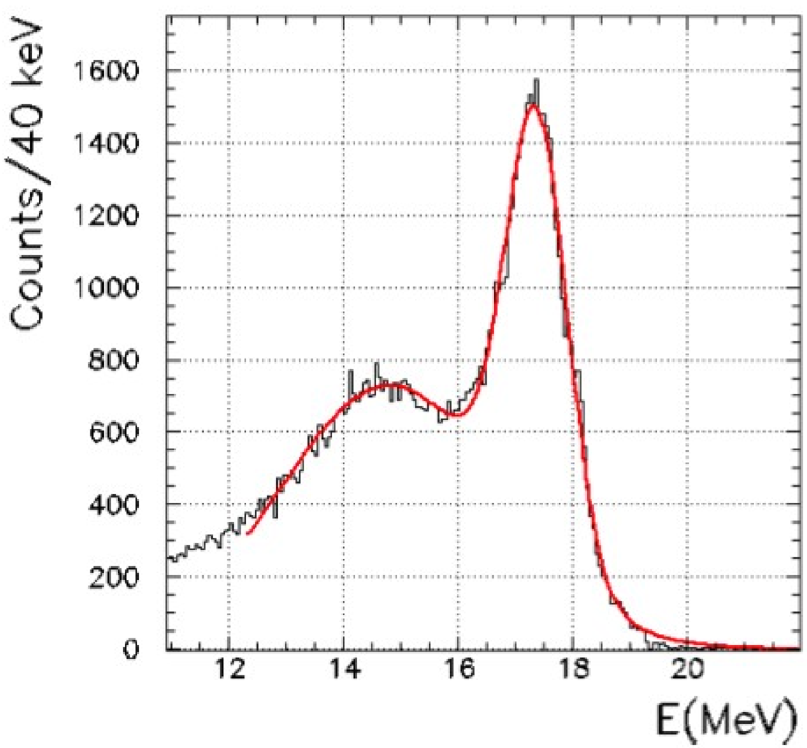
- Calibration with low energy photons from the reactions:

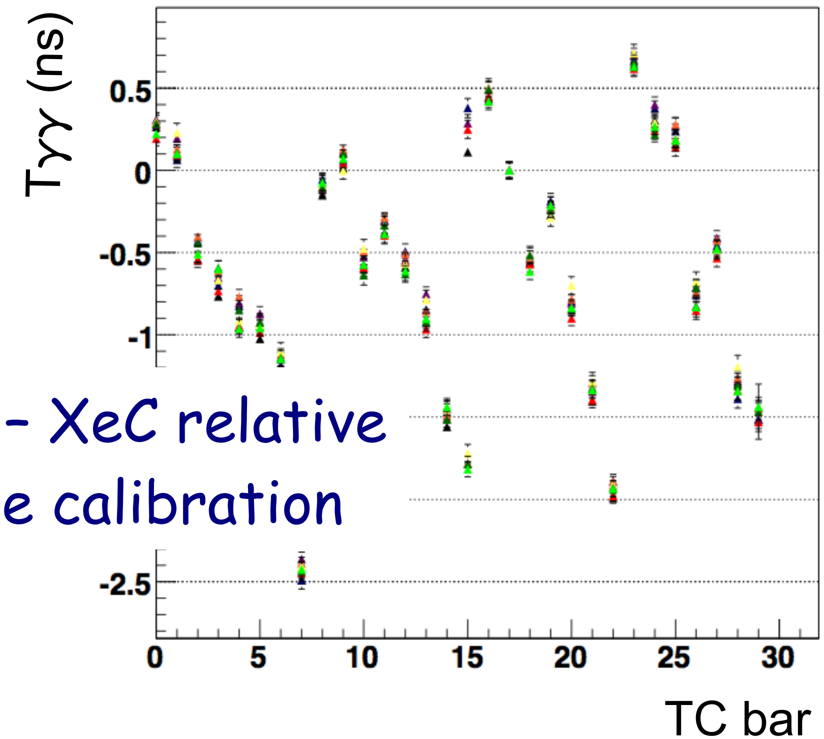
$p + {}_{3}^{7}Li \rightarrow {}_{4}^{8}Be + \gamma$

$p + {}_{5}^{11}B \rightarrow {}_{6}^{12}C^{**} + \gamma$

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

2 γ lines (14.6 MeV & 17.6 MeV)

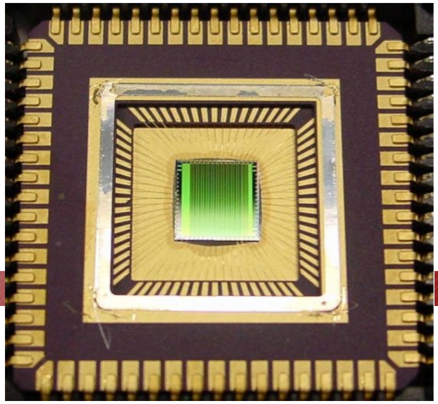




TC – XeC relative time calibration

DAQ & Trigger

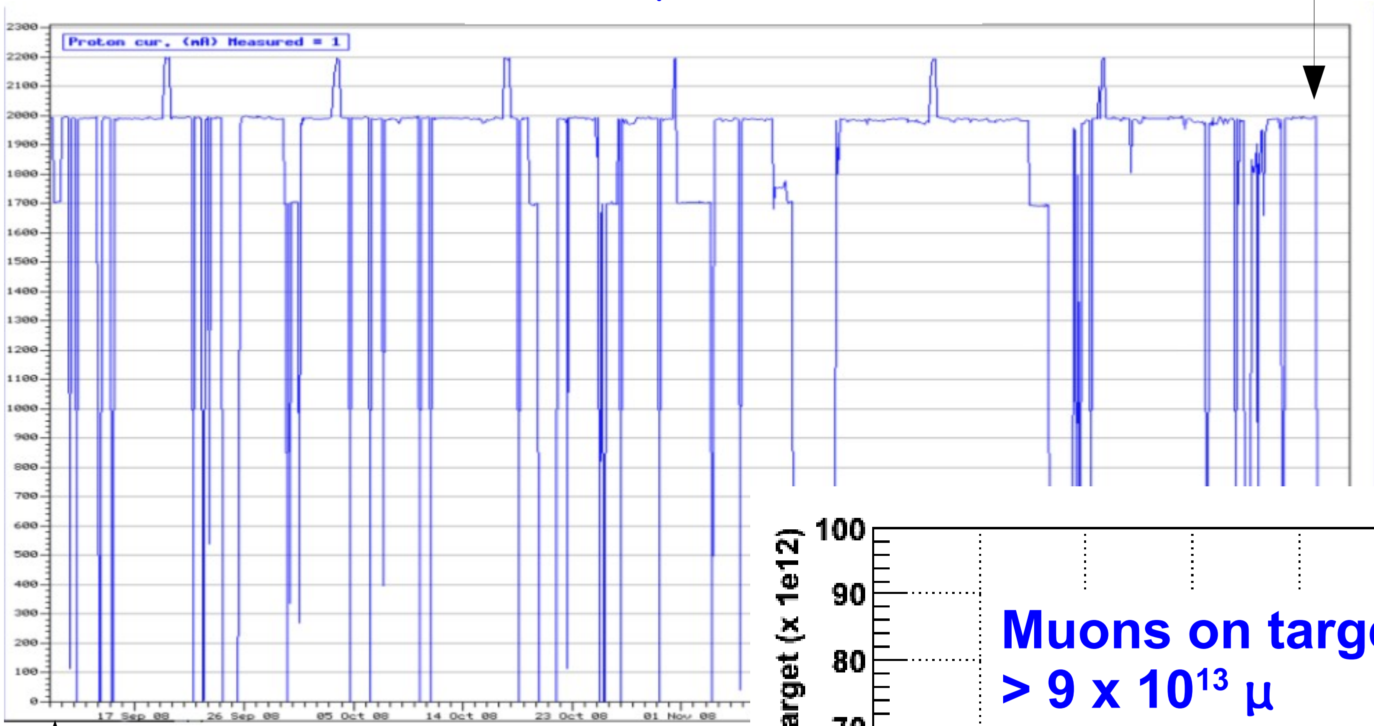
- High accidental background rejection (~ 10^7) with ~100% signal efficiency required at the trigger level:
  - online determination of γ energy, e - γ timing and e - γ collinearity (fully digital implementation);
  - ~ 5 - 10 Hz trigger rate during normal data acquisition;
- Very fast waveform digitalization (0.5 - 4.5 GHz) for offline analysis:
  - custom chip (Domino Ring Sampling, DRS) designed @ PSI;
  - 10 channels x 1024 bins per chip;
  - 40 ps time accuracy at 2.5 GHz;



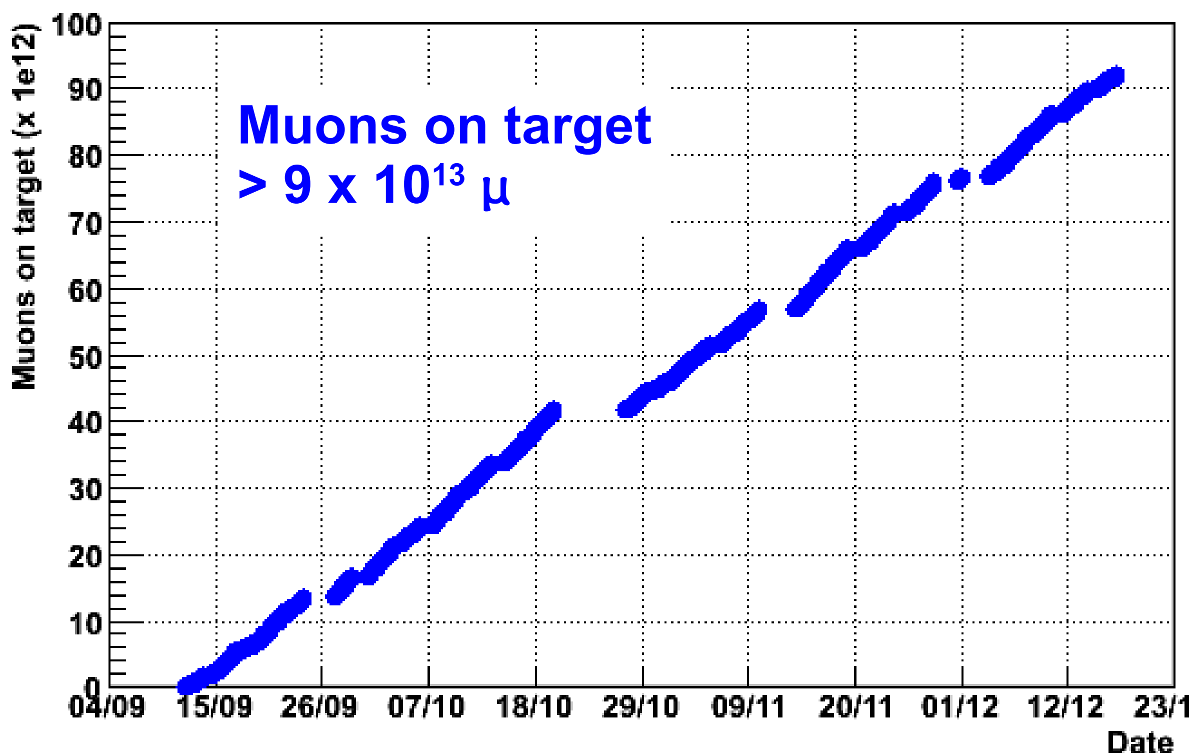
2008: The First Physics Run

Beam Current

December 23



September 10



Drift Chamber Instability

- Several DCH trips affected the 2008 data taking:
  - some chambers down for most of the run time.
- ~ 30% tracking efficiency for signal-like positrons:
  - expected ~ 90% from MC with all chambers on;
- Total positron efficiency (tracking + TC + trigger) ~ 12%;

⬇

Important limiting factor for current sensitivity

- Hardware problem has been understood and solved:
  - DCHs repaired and safely operated for > 6 months.

Performances (I)

EFFICIENCIES

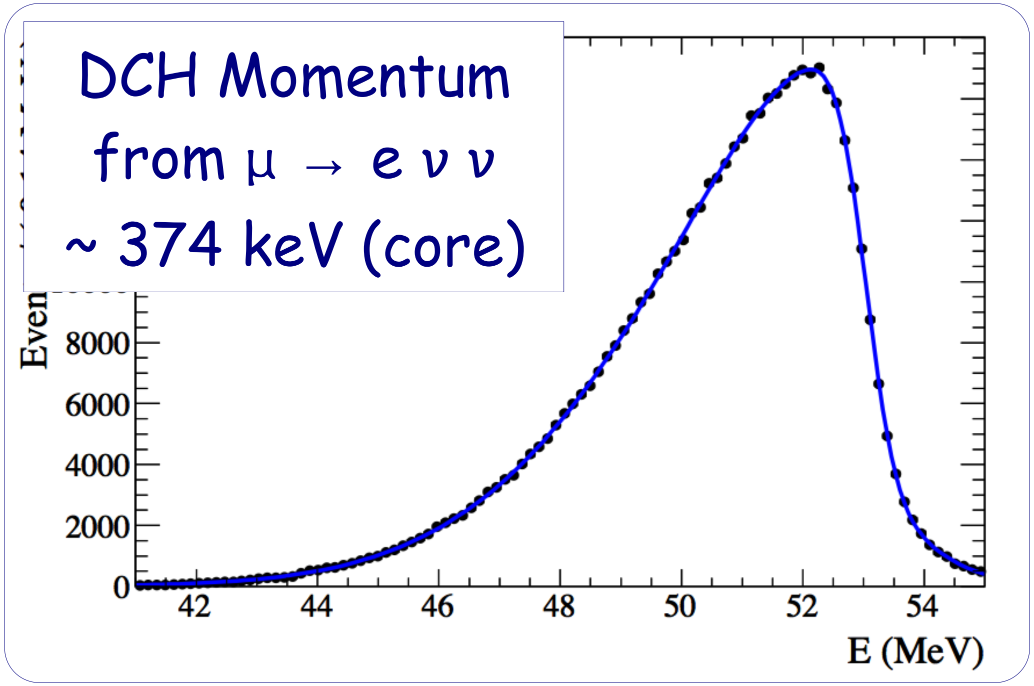
CONTRIBUTION	GOAL	2008
Gamma	> 40%	55%
Positron	65%	12%
Trigger	100%	65%
Selection	66%	32%
DAQ	> 90%	74%
Calibrations	> 95%	70%

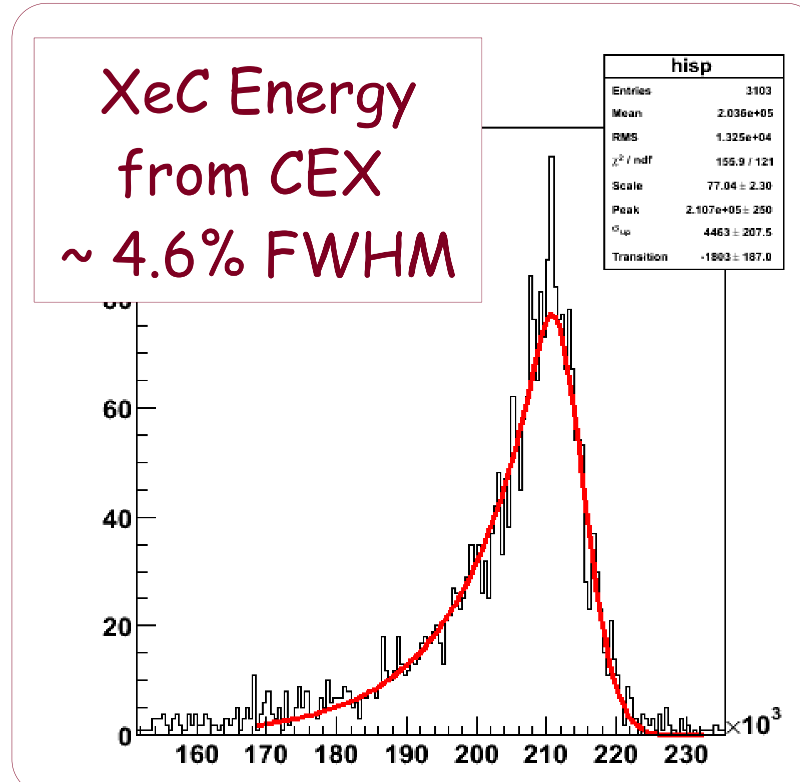
Performances (II)

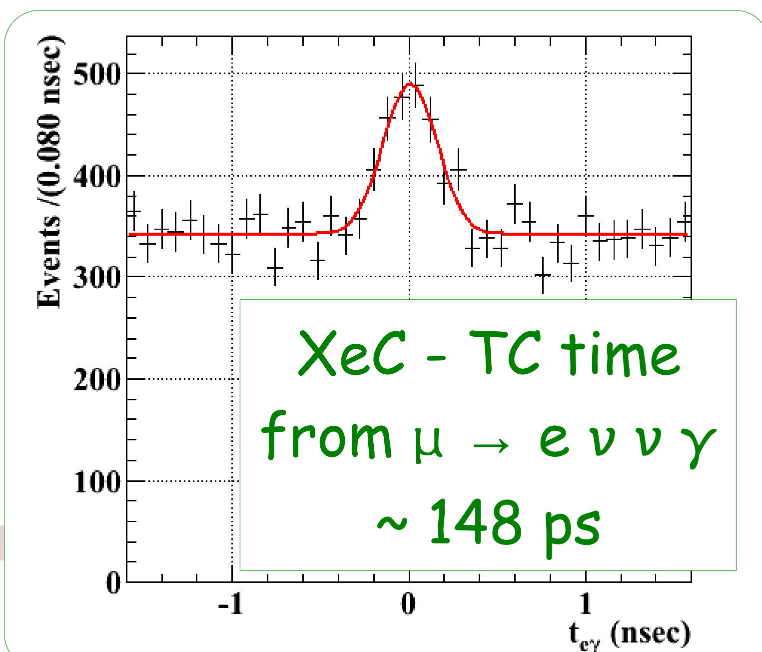
RESOLUTIONS

	GOAL	2008
Gamma Energy	1.2 – 1.5 %	2.6% (2% core)
Gamma Timing	65 ps	80 ps
Gamma Position	2 – 4 mm	4 – 5 mm
e+ Momentum	0.35 %	1.34% (0.7% core)
e+ Timing	45 ps	65 ps
e+ Angle	4.5 mrad	10 / 18 mrad
μ Decay Point	0.9 mm	3.2 / 4.5 mm
Gamma – e+ Timing	80 ps	148 ps

Performances (III)





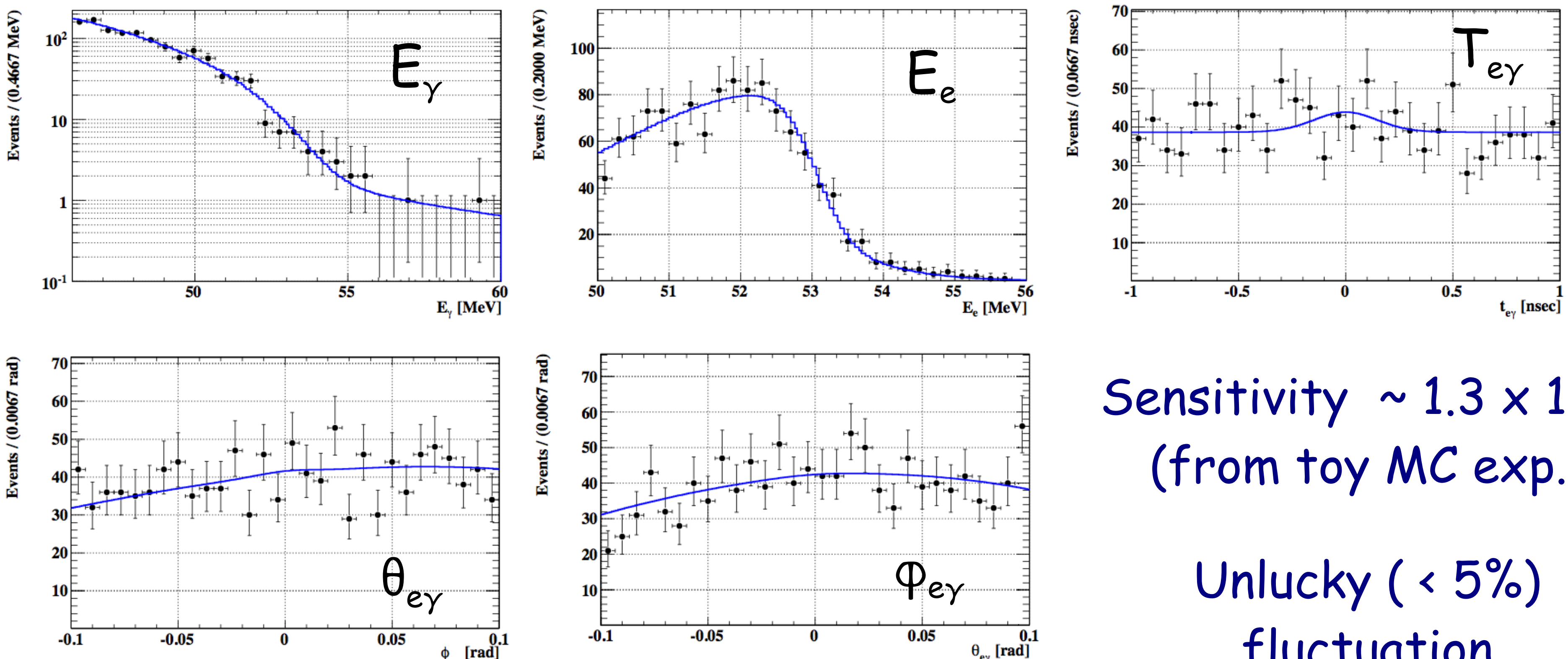


Some Resolutions
(2008 run)

Likelihood Analysis

arXiv: 0000.0000

- Extended ML fit including SIGNAL, ACCIDENTAL and RADIATIVE DECAY.



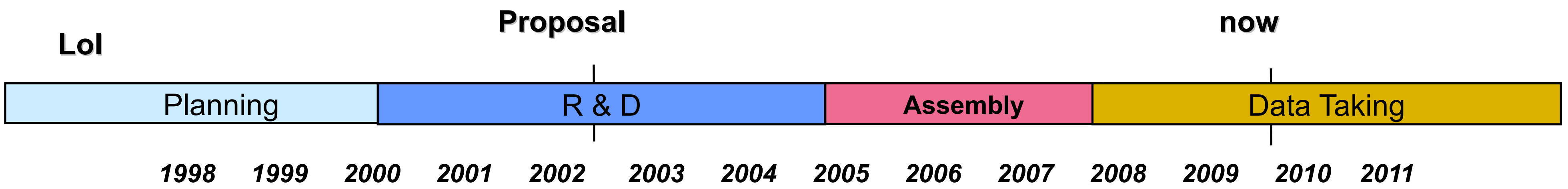
Sensitivity ~ 1.3×10^{-11}
(from toy MC exp.)

Unlucky (< 5%) fluctuation

**$BR(\mu^+ \to e^+ \gamma) < 3 \times 10^{-11}$ @ 90% C.L.
(Feldman-Cousins)**

Perspectives

- 2009 Run from October to December;
- Electronics improved DRS2 → DRS4;
- Factor 3 – 5 efficiency improvement (DCH, trigger, etc.);
- Significant resolution improvements;
- Corresponding 2009 sensitivity: $2 - 4 \times 10^{-12}$;
- Continue running in 2010 + 2011 for the final (10^{-13}) goal.



Conclusions

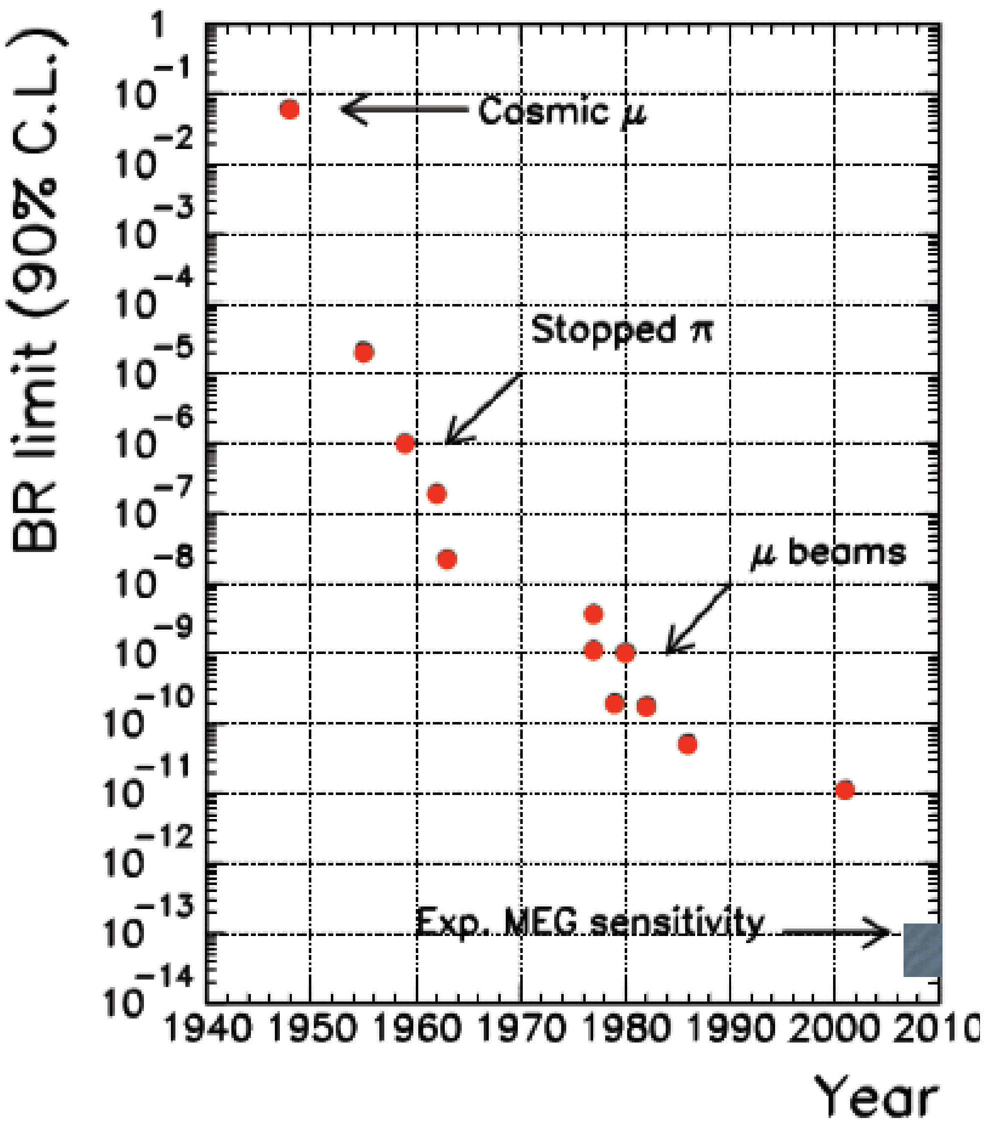
- The search for LFV is one of the main challenges of particle physics;
- MEG is designed to search for $\mu \rightarrow e\,\gamma$ down to BR ~ 10^{-13}:
  - complementarity with $\tau \rightarrow \mu\,\gamma$ searches and LHC program;
- MEG started taking data and already provided a very preliminary result:

$BR(\mu^+ \rightarrow e^+ \gamma) < 3 \times 10^{-11}$ @ 90% C.L.

- Performances are improving continuously and the experiment is planned to run until 2011.

Backup

Historical Review



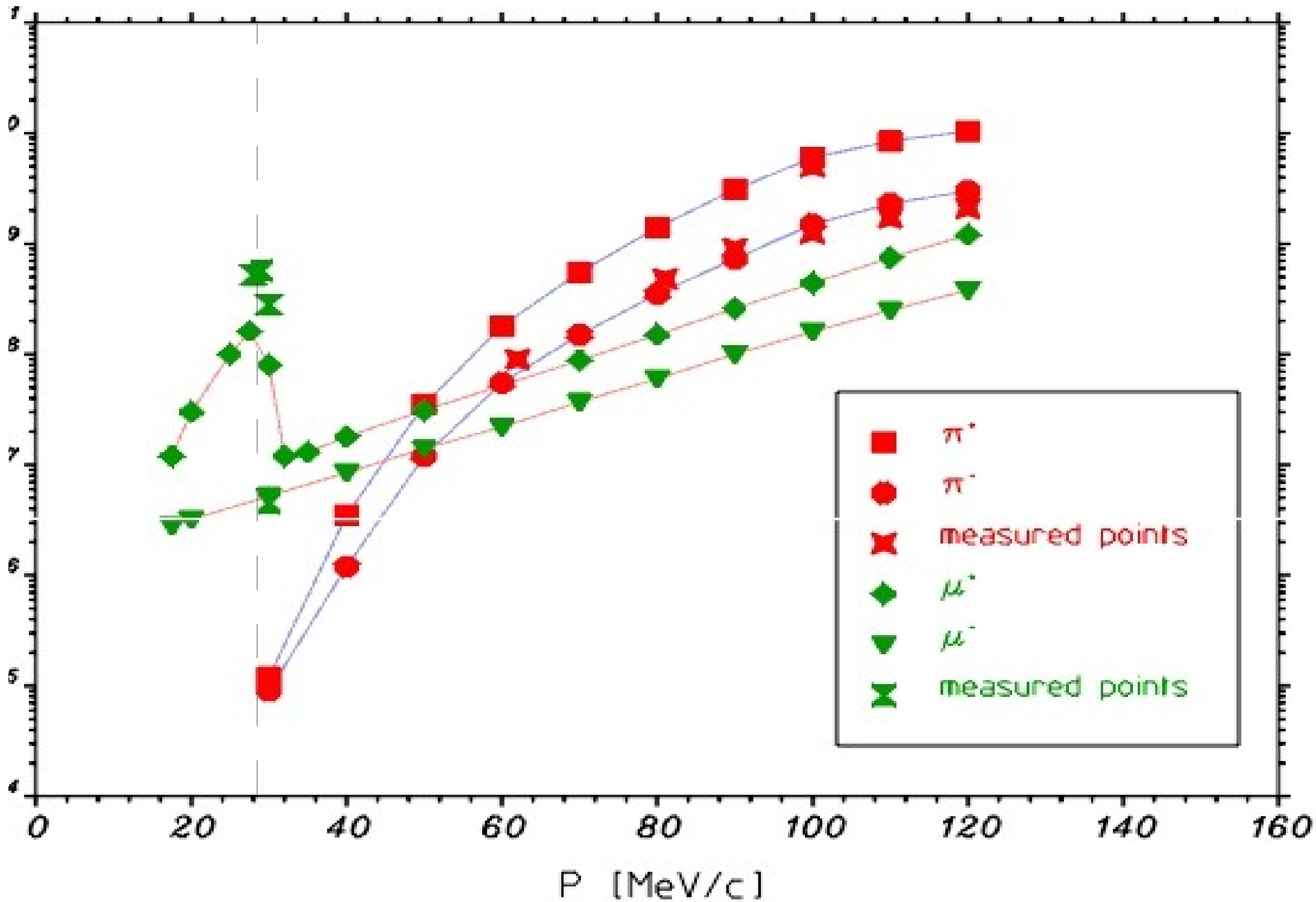
- 1947 – Hinks & Pontecorvo:
  - First limit;
- 1977 -
  Van der Schaaf *et al.* (PSI)
  Depommier *et al.* (TRIUMF):
  - First experiments with muon beams.
- 1999 – MEGA (LANL):
  - Present best limit
  - BR < 1.2×10^{-11} @ 90% C.L.

The πE5 Beam (I)

solid angle acceptance	150 msr
momentum range	20–120 MeV/c
length	10.4 m
momentum band (FWHM)	10%
momentum resolution (FWHM)	2%
horizontal emittance	15.3 cm·rad
vertical emittance	3.6 cm·rad
spot size	4×4 cm^2

- Muons in πE5:
  - mainly come from pions decays;
  - 29 MeV from pions decaying at rest in the proton target surface (*surface muons*);
  - Polarized when produced, but lose polarization in degraders.

The πE5 Beam (II)

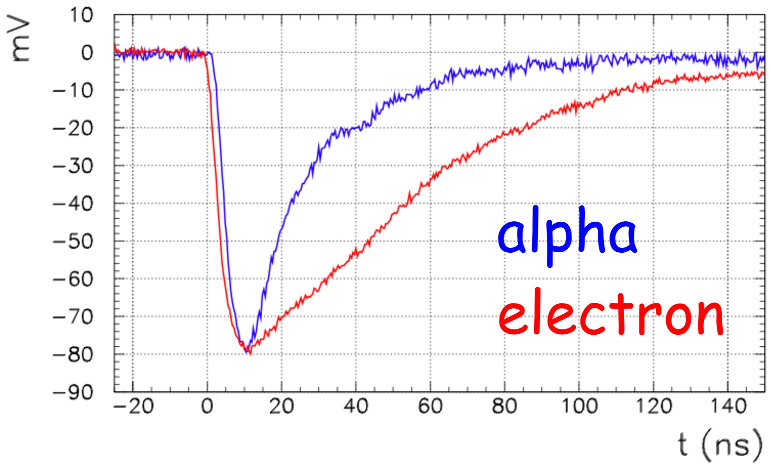


- 29 MeV muons (surface muons) used for maximum μ/π ratio.

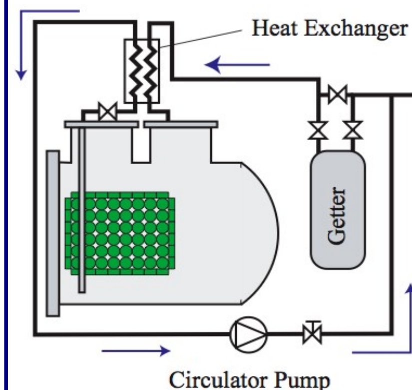
LXe Properties

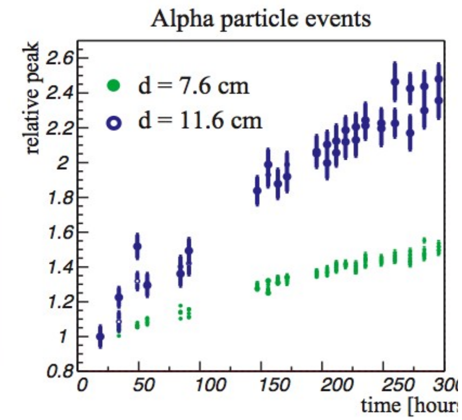
- LXe:
  - Scint. light: λ = 175 nm;
  - Boiling point: 165 K;
  - Absorption length: > 3 m.
  - 40000 photons/MeV;
  - R_M = 4.1 cm.

Good separation between α and photons/electrons



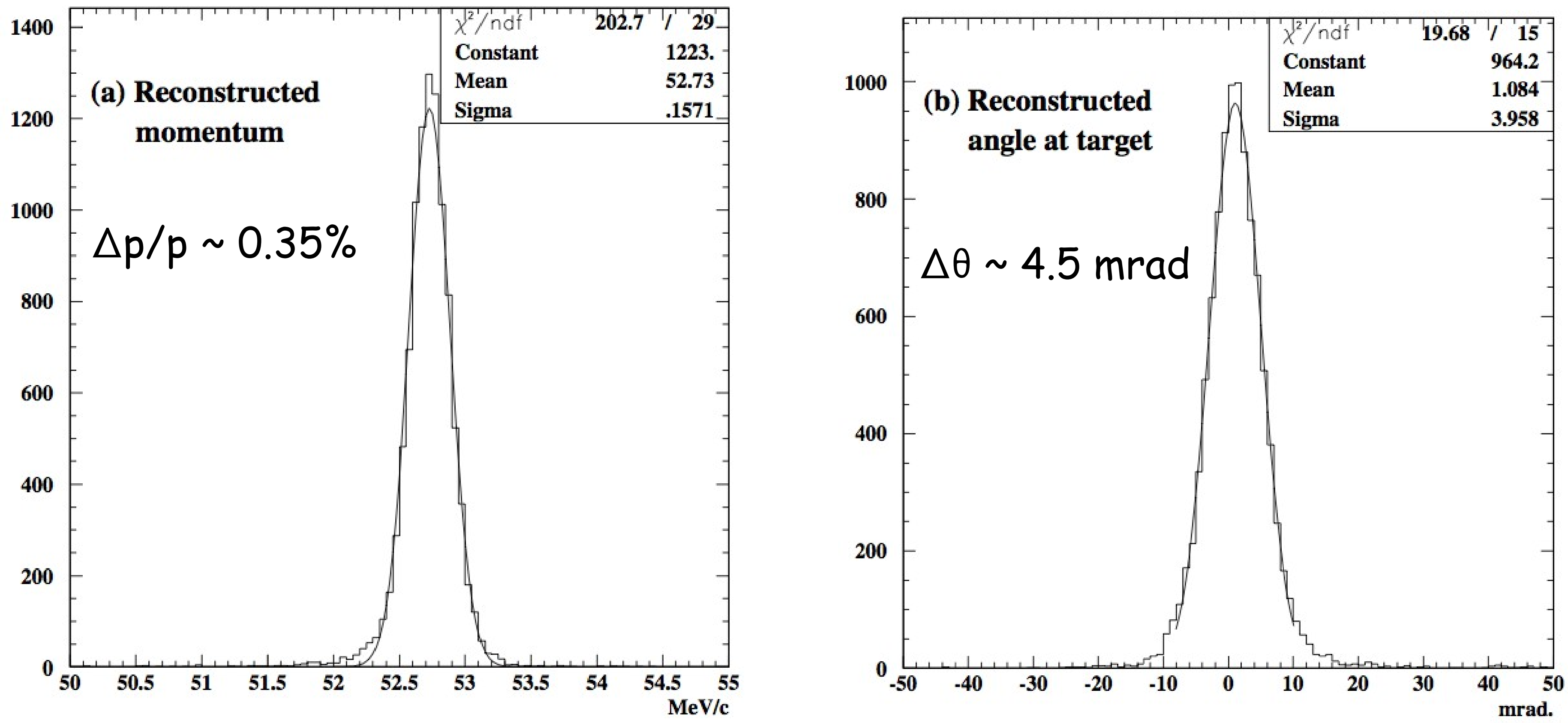
Online purification system





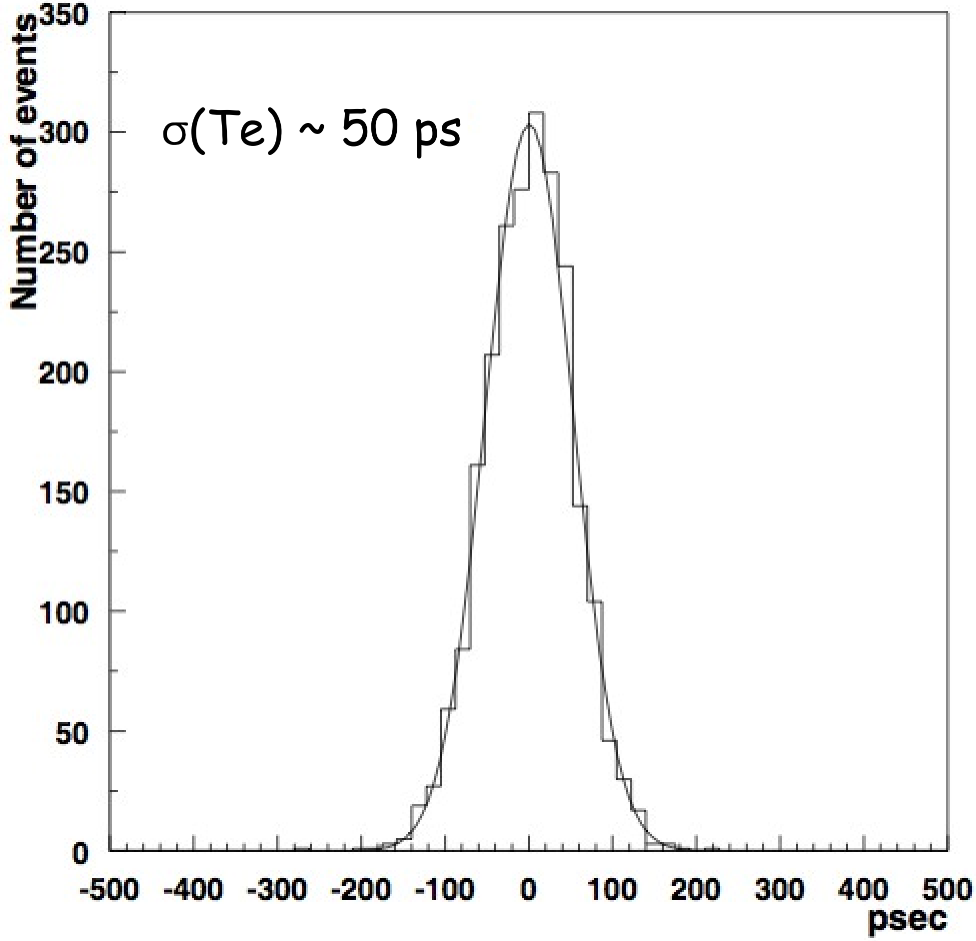
Design Performances (DCH)

FROM SIMULATIONS



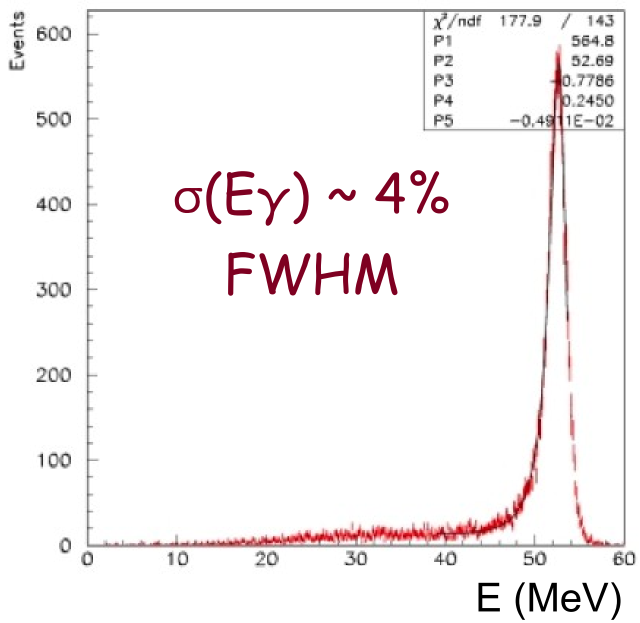
Design Performances (TC)

FROM SIMULATIONS

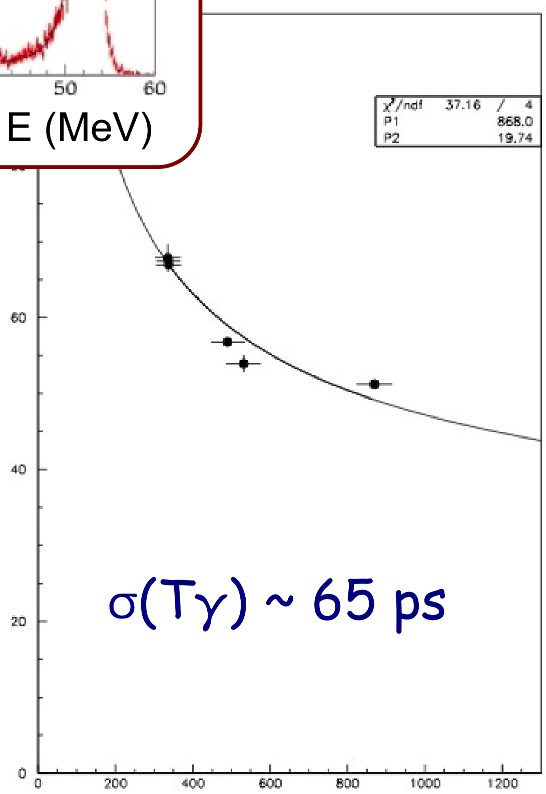


Design Performances (XEC)

FROM SIMULATIONS

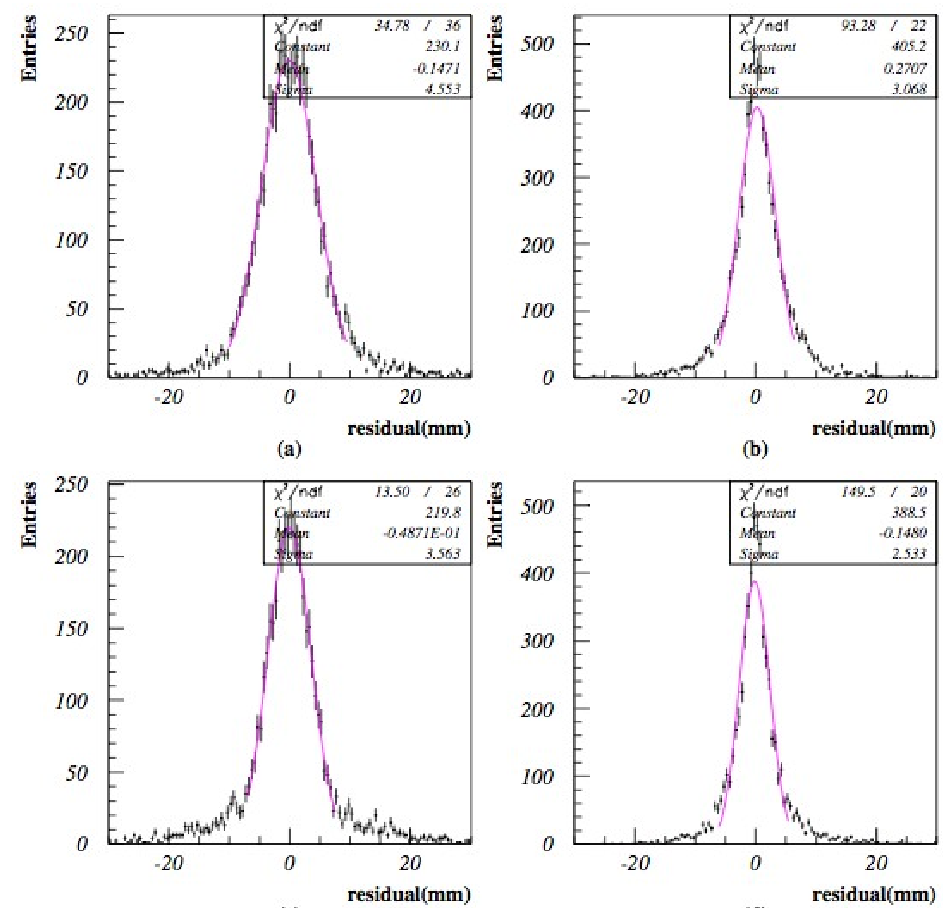


$\sigma(E\gamma) \sim 4\%$ FWHM



$\sigma(T\gamma) \sim 65$ ps

$\sigma(x), \sigma(y) \sim 2 - 4$ mm



Required Performances

BR ($\mu \rightarrow e\gamma$) ≈ 10^{-13} reachable

BRacc.b. ≈ 2 10^{-14} and BRphys.b. ≈ 0.1 BRacc.b. with the following resolutions

FWHM (applies to $\Delta E_e/E_e$, $\Delta E_\gamma/E_\gamma$, $\Delta t_{e\gamma}$, $\Delta\theta_{e\gamma}$)

Exp./Lab	Year	$\Delta E_e/E_e$ (%)	$\Delta E_\gamma/E_\gamma$ (%)	$\Delta t_{e\gamma}$ (ns)	$\Delta\theta_{e\gamma}$ (mrad)	Stop rate (s^{-1})	Duty cyc.(%)	BR (90% CL)
SIN	1977	8.7	9.3	1.4	-	5×10^5	100	3.6×10^{-9}
TRIUMF	1977	10	8.7	6.7	-	2×10^5	100	1×10^{-9}
LANL	1979	8.8	8	1.9	37	2.4×10^5	6.4	1.7×10^{-10}
Crystal Box	1986	8	8	1.3	87	4×10^5	(6..9)	4.9×10^{-11}
MEGA	1999	1.2	4.5	1.6	17	2.5×10^8	(6..7)	1.2×10^{-11}
MEG	2011	0.8	4	0.15	19	2.5×10^7	100	1×10^{-13}

Need of a DC muon beam