Lepton flavor violation in $\mu^+ \rightarrow e^+ \gamma$ decay: results from the MEG experiment

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on behalf of the MEG collaboration

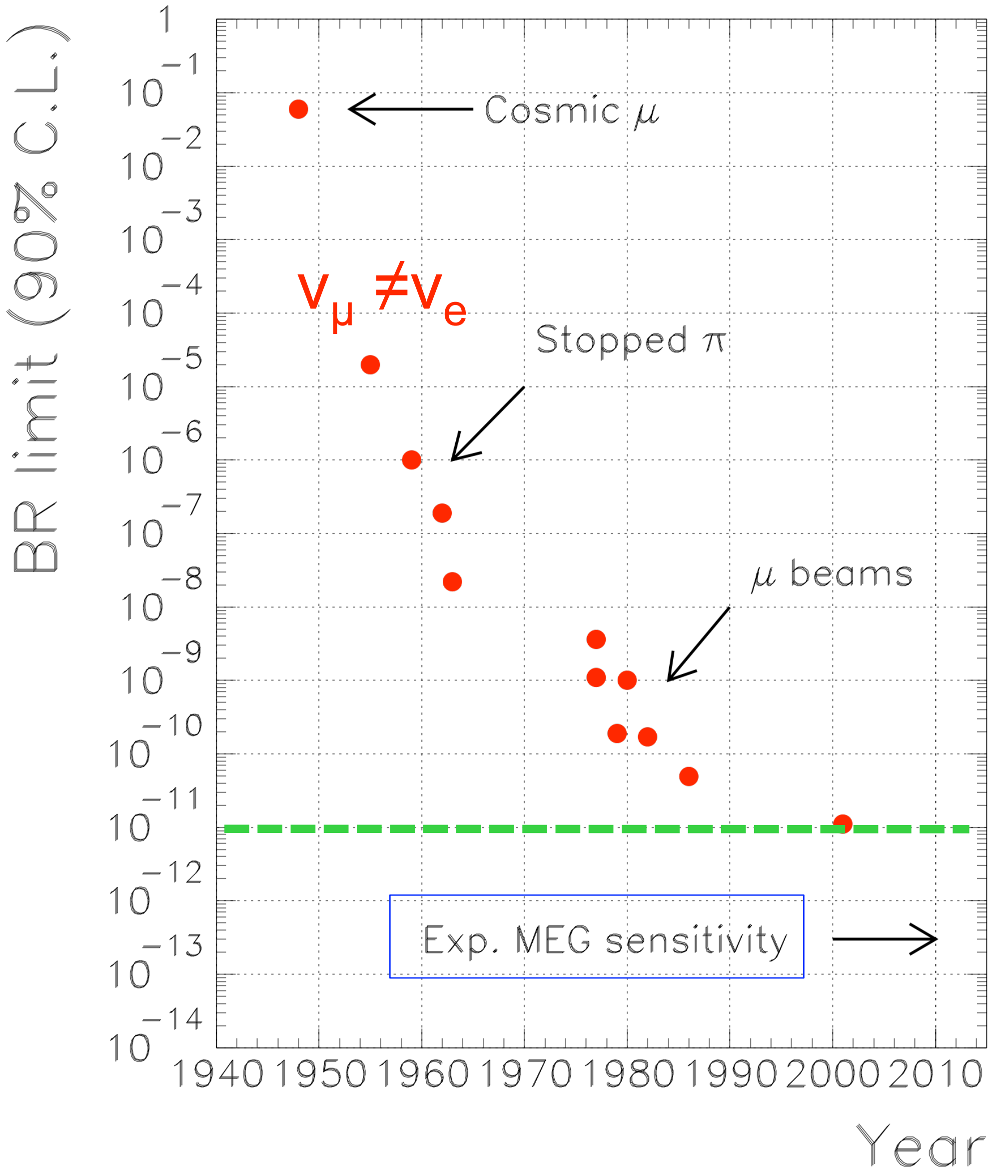
FPCP 2010

Torino 25-29 May 2010

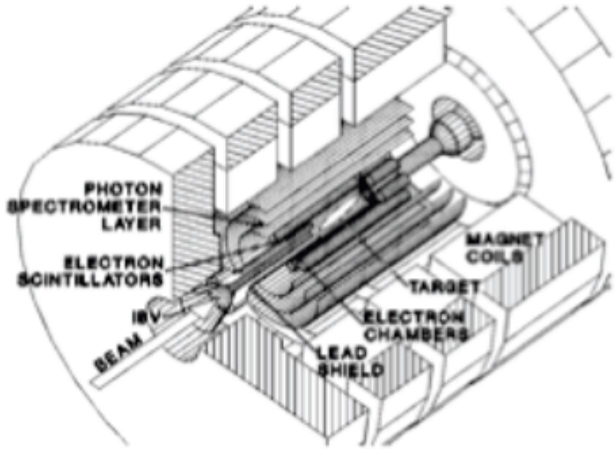
Outline

- History of $\mu^+ \rightarrow e^+\gamma$ searches
- Physics motivation
- Experimental technique
- The MEG detector and performances
- Analysis of 2008 data
- Prospects for 2009 and beyond

μ−>eγ: a long search



MEGA experiment (2001)
present limit
$1.2*10^{-11}$@90%C.L.

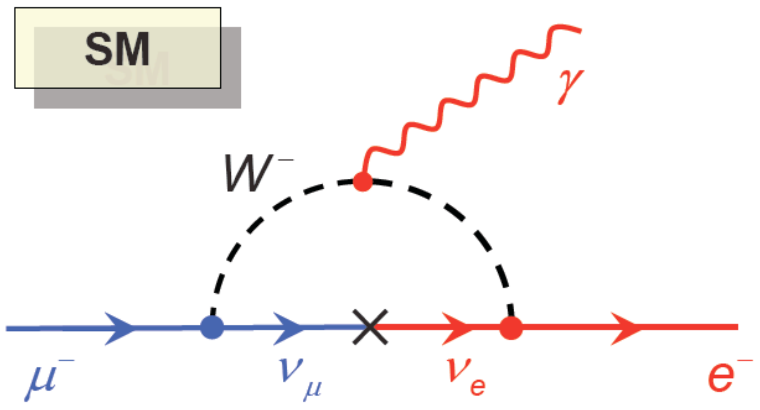


MEG goal:
improve sensitivity by two orders of magnitude
=> 10^{-13} (2011)

Improvements linked with better beams and detector resolutions

μ−>eγ and New Physics searches

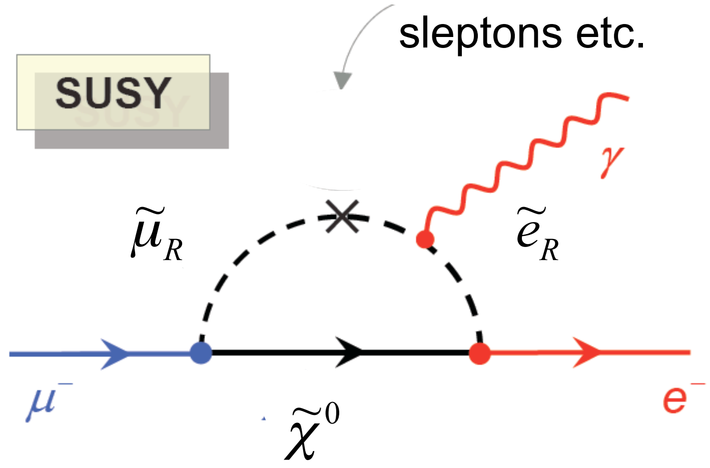
- Standard Model (SM) with ν mass and oscillation:



Charged LVF very small

$$BR(\mu \to e\gamma)\big|_{SM} \propto \frac{m_\nu^4}{m_W^4} \approx 10^{-54}$$

- Beyond Standard Model e.g

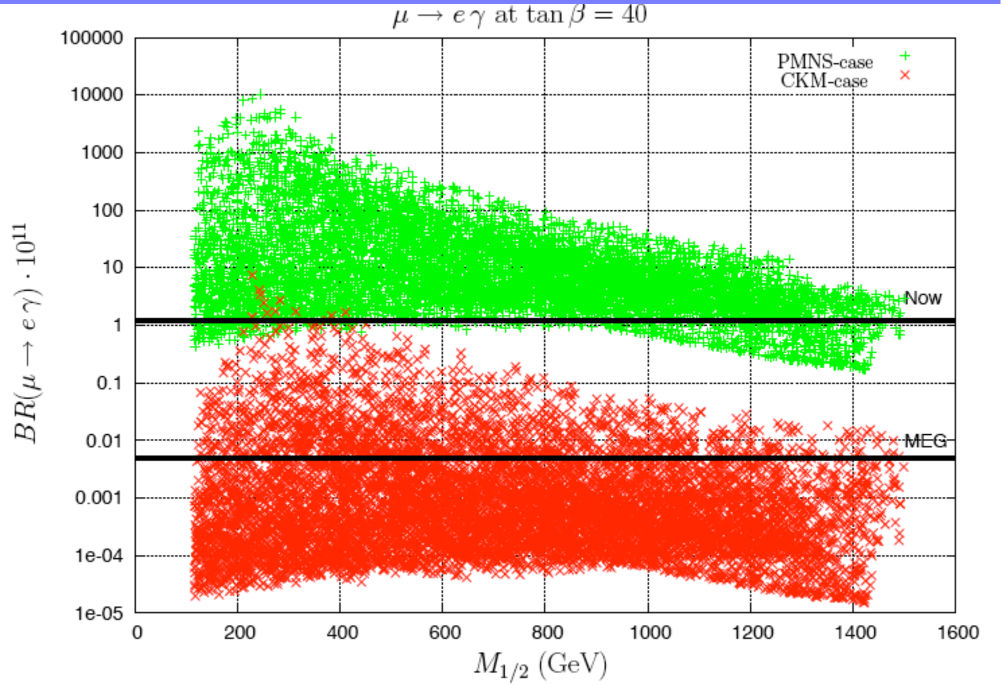


Charged LVF can be largely enhanced, in some models just below the experimental limit (<$1.2 \cdot 10^{-11}$ @90%C.L. MEGA)

Observation of μ→eγ is Physics beyond SM (no SM background)

Some Examples

- SUSY GUT SO(10) with see-saw



CKM–like

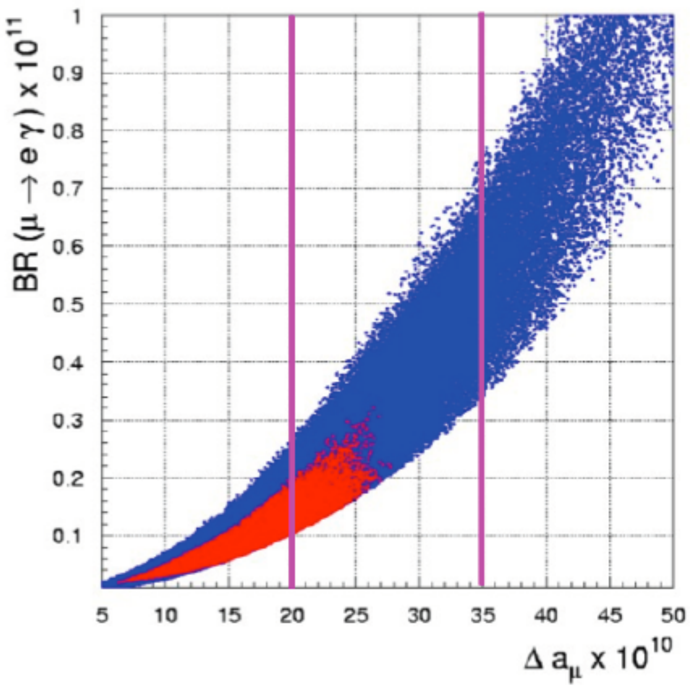
Neutrino-matrix like (PMNS)

Calibbi *et al.*, Phys.Rev.D74 (2006) 116002

- Muon g-2

Connection with g_μ-2, predicts signal in MEG accessible region

Isidori *et al.*, Phys.Rev.D75 (2007) 115019



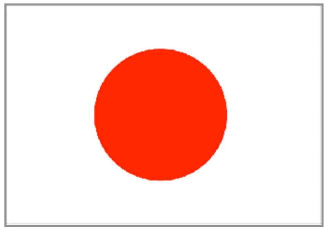
The MEG experiment @PSI

The Paul Scherrer Institute

The MEG collaboration:

69 physicists from

Tokyo U.
Waseda U.
KEK



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INFN&U.Roma

UC Irvine

PSI

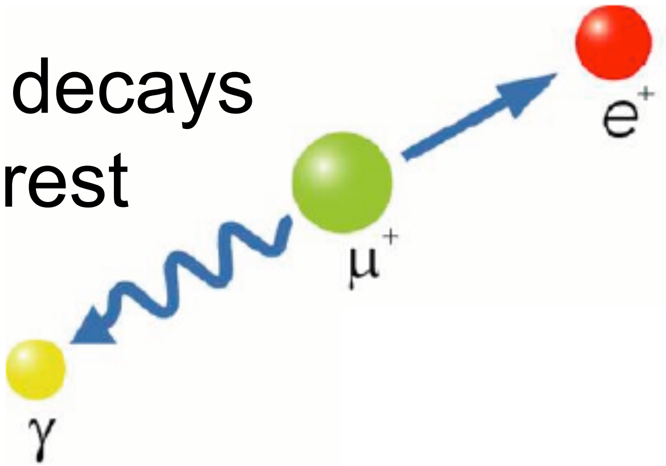
JINR Dubna
BINP Novosibirsk

The signal..

- High intensity muon source@ PSI:

$I_\mu \approx 3 \cdot 10^7$ μ/sec stopped in a polyethylene target

μ^+ decays at rest



$$N_{sig} \propto I_\mu \cdot BR(\mu \to e\gamma)$$

- $E_\gamma \approx E_{e+} = 52.8$ MeV

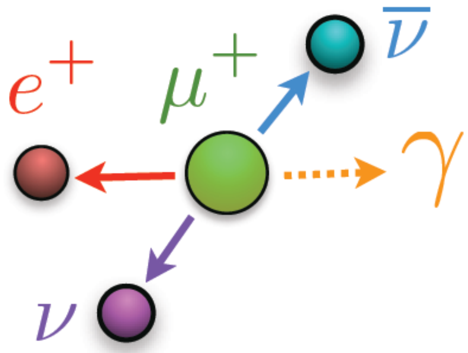
- Back-to-back: $\theta_{e\gamma} = 180^o$

- Simultaneous production: $T_{e\gamma} = 0$

… and the backgrounds

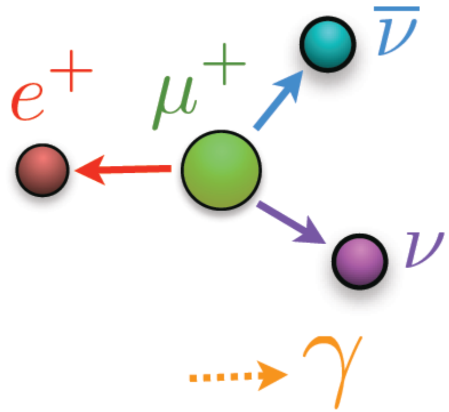
μ radiative decay

$$N_{rad} \propto I_\mu \cdot BR(\mu \to e\nu\bar{\nu}\gamma)$$



Accidentals

$$N_{acc} \propto I_\mu^2 \cdot \Delta\vartheta^2 \Delta E_\gamma^2 \Delta T_{e\gamma} \Delta E_e$$

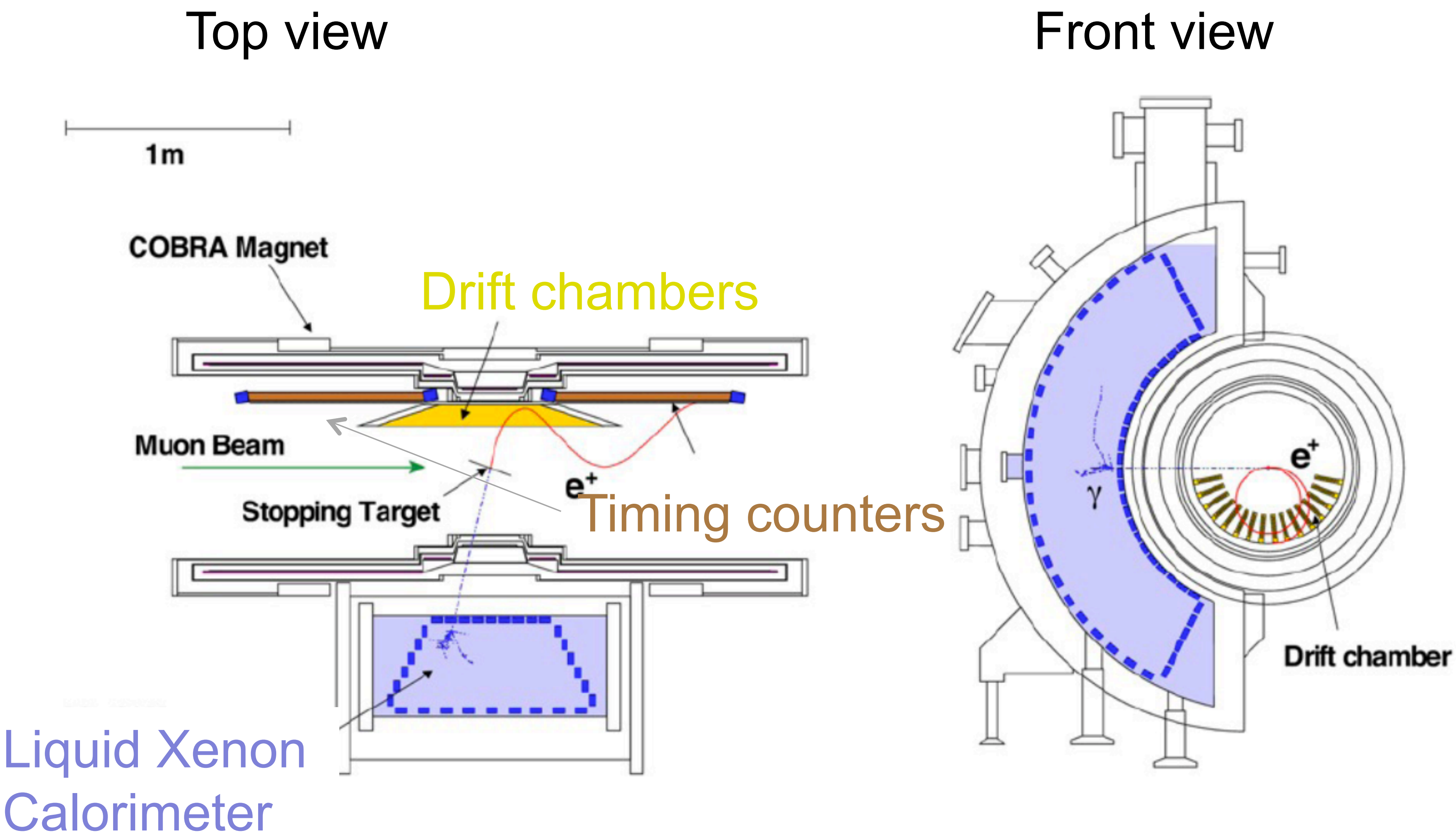


The accidental background is dominant:

e^+ from Michel μ decay and a γ (from radiative decay or bremsstrahlung or annihilation in flight) so close in time that they cannot be distinguished

Detector resolutions are critical

The MEG detector



Dedicated detector with non-symmetric coverage

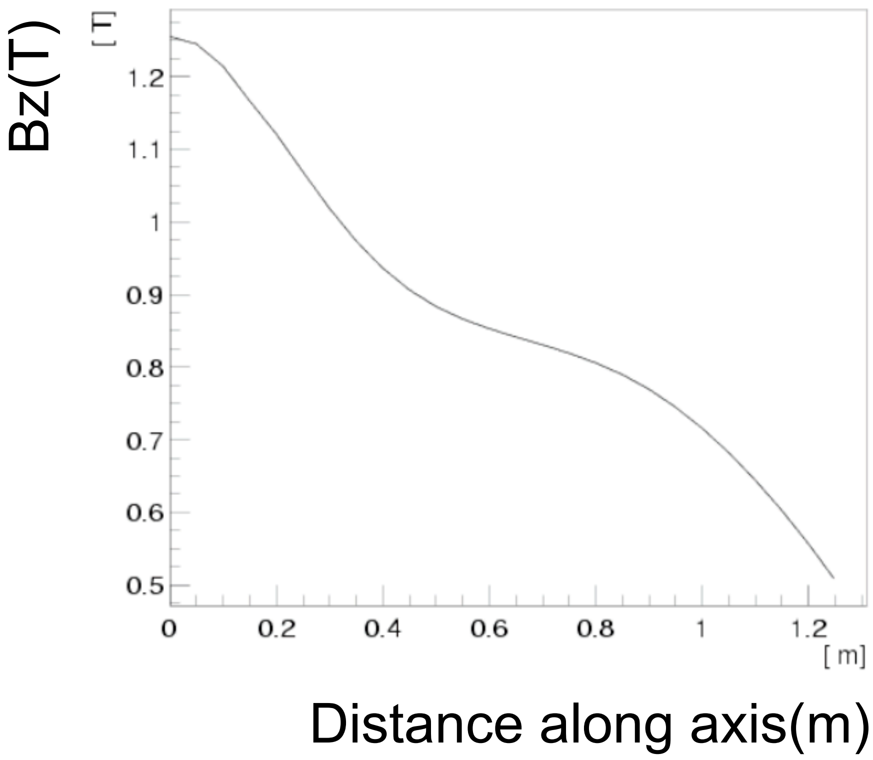
COBRA (COnstant Bending RAdius) magnet

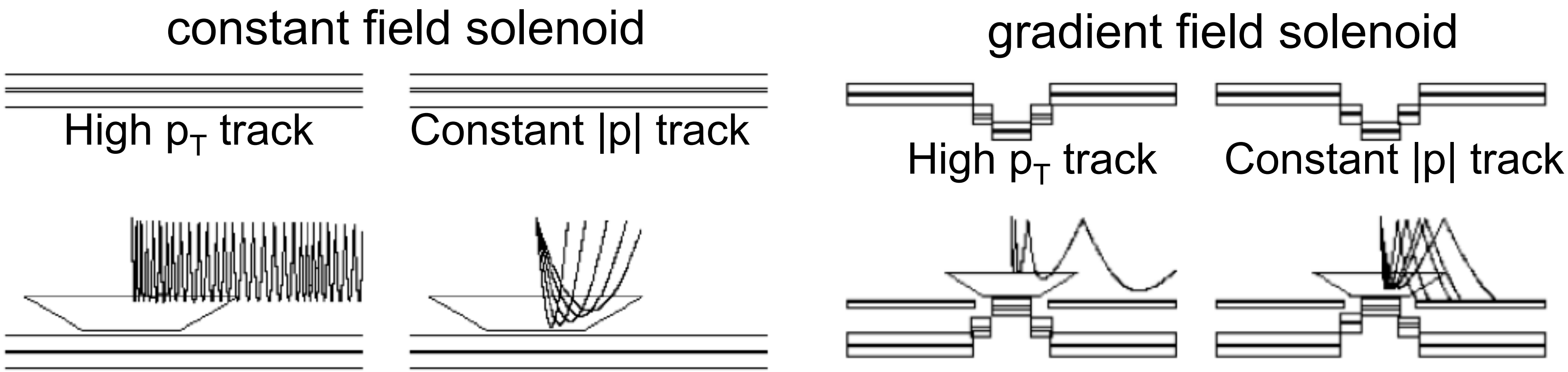
Gradient field solenoid:

- High p_T track swept away
  => Can work at high rate

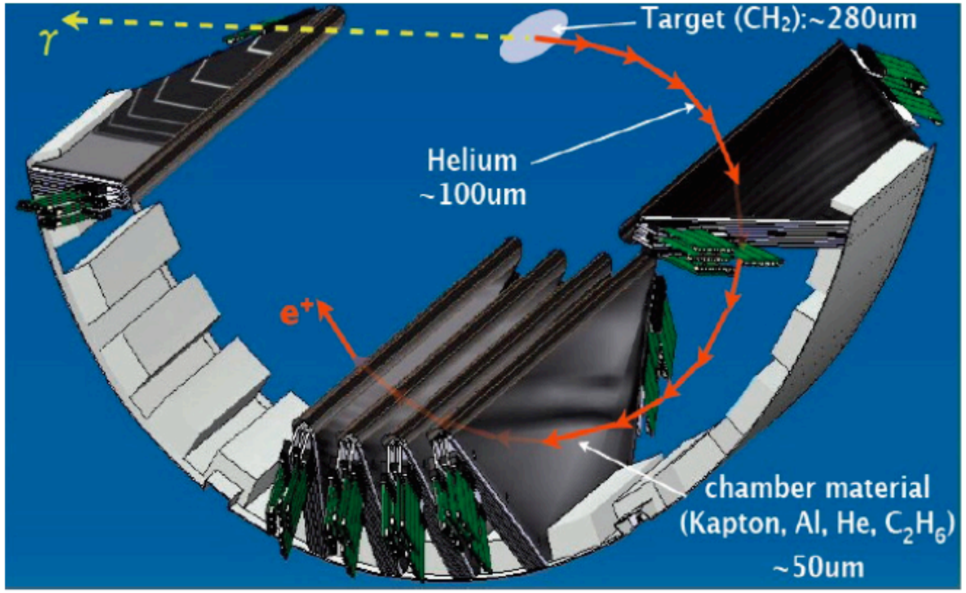
- Bending radius independent of emission angle

- $0.2X_0$ in front of calorimeter



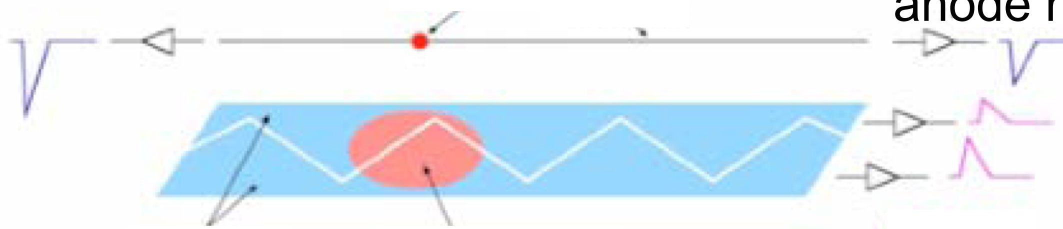


The Drift Chambers



- 16 chambers radially aligned in He:Ethane (50:50)
- 2 staggered arrays of drift cells
- Low mass: $2 \times 10^{-3} X_0$ along positron trajectory

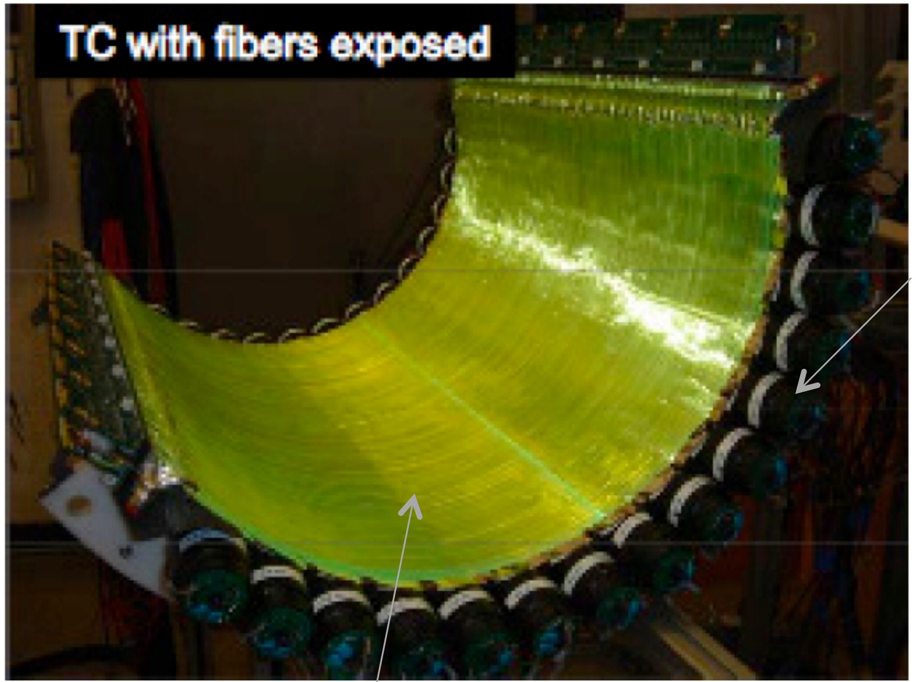
1 signal wire (radius from drift time) and 2x2 Vernier cathode strips (z position)



Goal performances:

$$\sigma_R = 100\,\mu m$$
$$\sigma_Z = 400\,\mu m$$

The Timing Counters



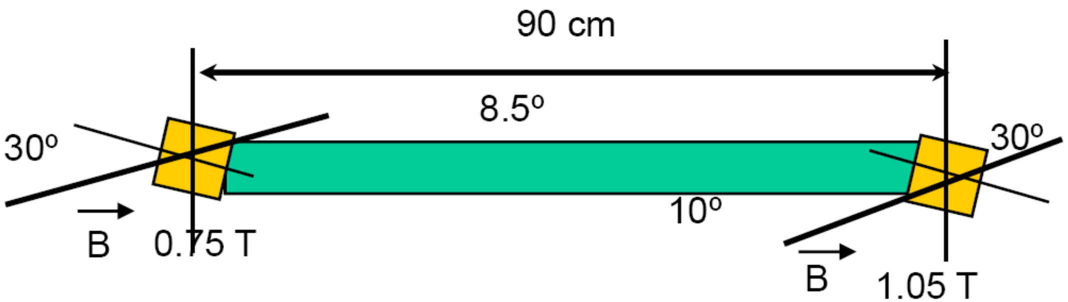
- Two sectors: upstream and downstream

15x2 scintillating bars read by PMTs

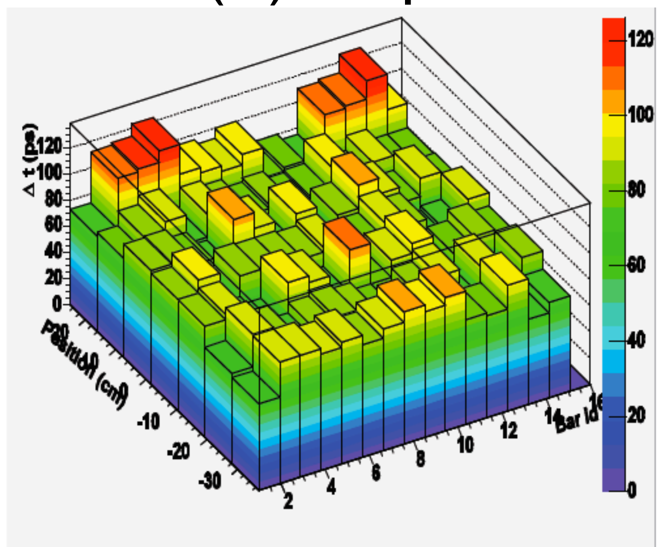
- Measure e+ time of impact
- Used in trigger (time coincidence with γ and positron direction)

256x2 scintillating fibers read by APD

- measure z coordinate
- eventually in the trigger



σ(T)~60ps



The Photon calorimeter

- Largest liquid Xenon calorimeter in the world: (900 l)

- Fast response
  - τ_{scint} = 4.2 ns, 22ns, 45ns
- High light yield (~100%NaI)

- Scintillation light read by 846 PMTs digitized@ 1.6GHz with custom DRS chip (allowing pile-up identification)

- Crucial to maintain Xenon purity (purification)

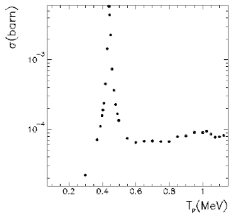
Goal performances @signal energy:

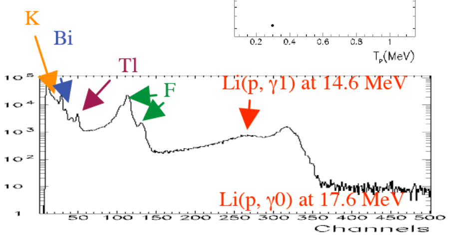
$$\sigma(E_\gamma) = 630 keV$$
$$\sigma(T_\gamma) = 45 ps$$

Calibrations

- Redundant calibration procedures and constant monitoring of the detector, in particular for photon detector

Proton Accelerator





Li(p,γ)Be

LiF target at COBRA center

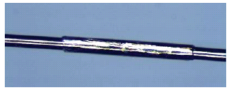
17.6MeV γ

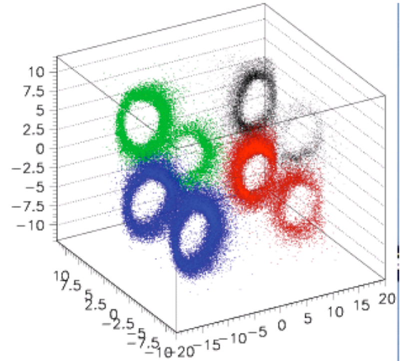
~daily calib.

also for initial setup

B target for TC timing

Alpha on wires



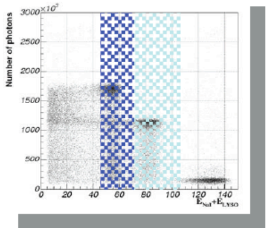


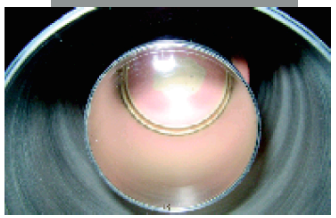
PMT QE & Att. L

Cold GXe

LXe

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



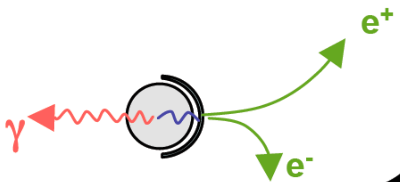


$\pi^- + p \rightarrow \pi^0 + n$

$\pi^0 \rightarrow \gamma\gamma$ (55MeV, 83MeV)

$\pi^- + p \rightarrow \gamma + n$ (129MeV)

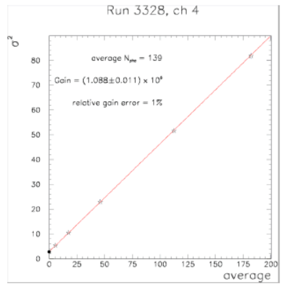
LH_2 target

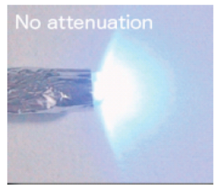


LED

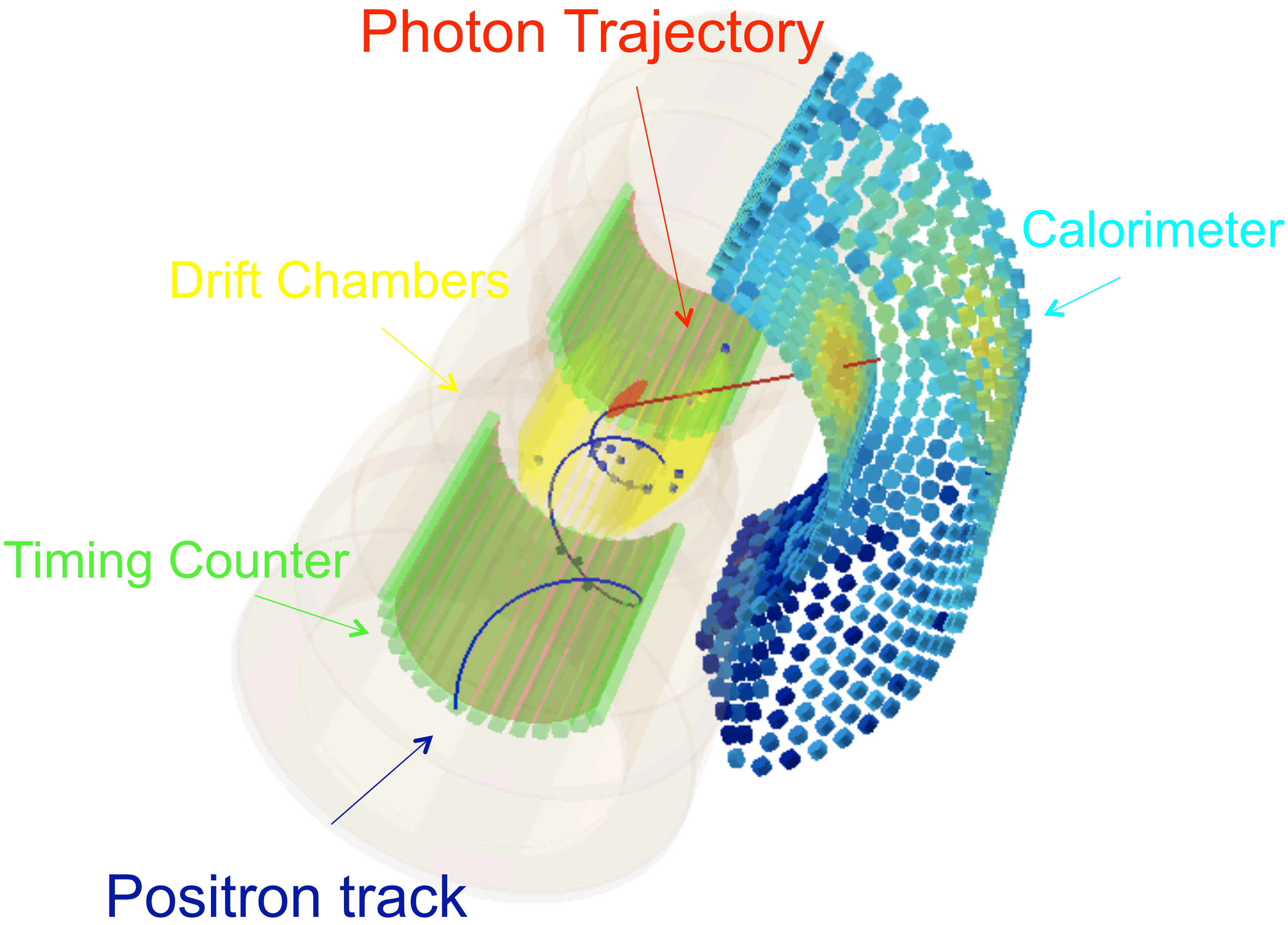
PMT Gain

Higher V with light att.





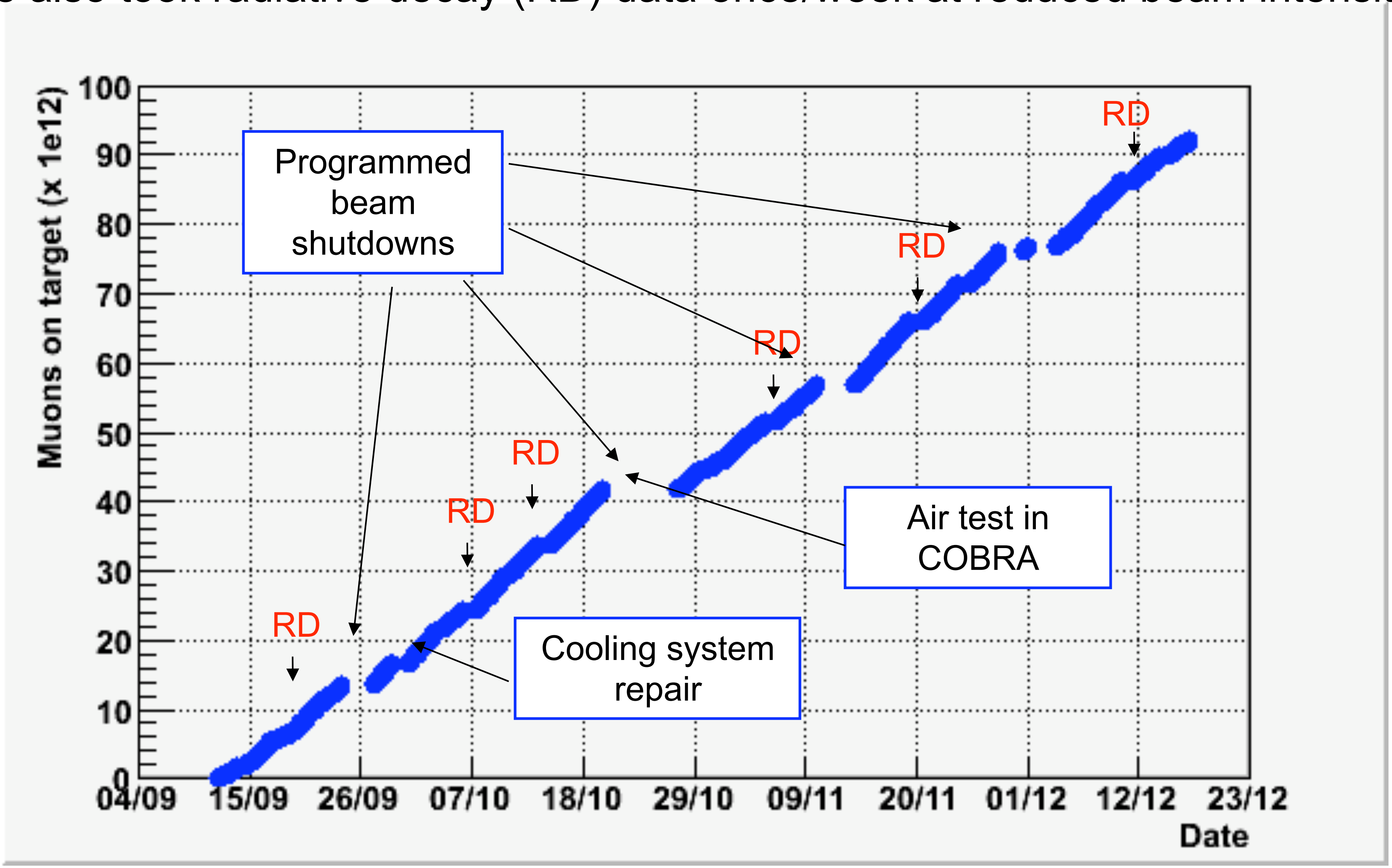
A $\mu^+ \rightarrow e^+\gamma$ like event



2008 Data-taking

12/Sep-16/Dec 2008: MEG Physics Run (11.5 weeks beamtime)

We also took radiative decay (RD) data once/week at reduced beam intensity



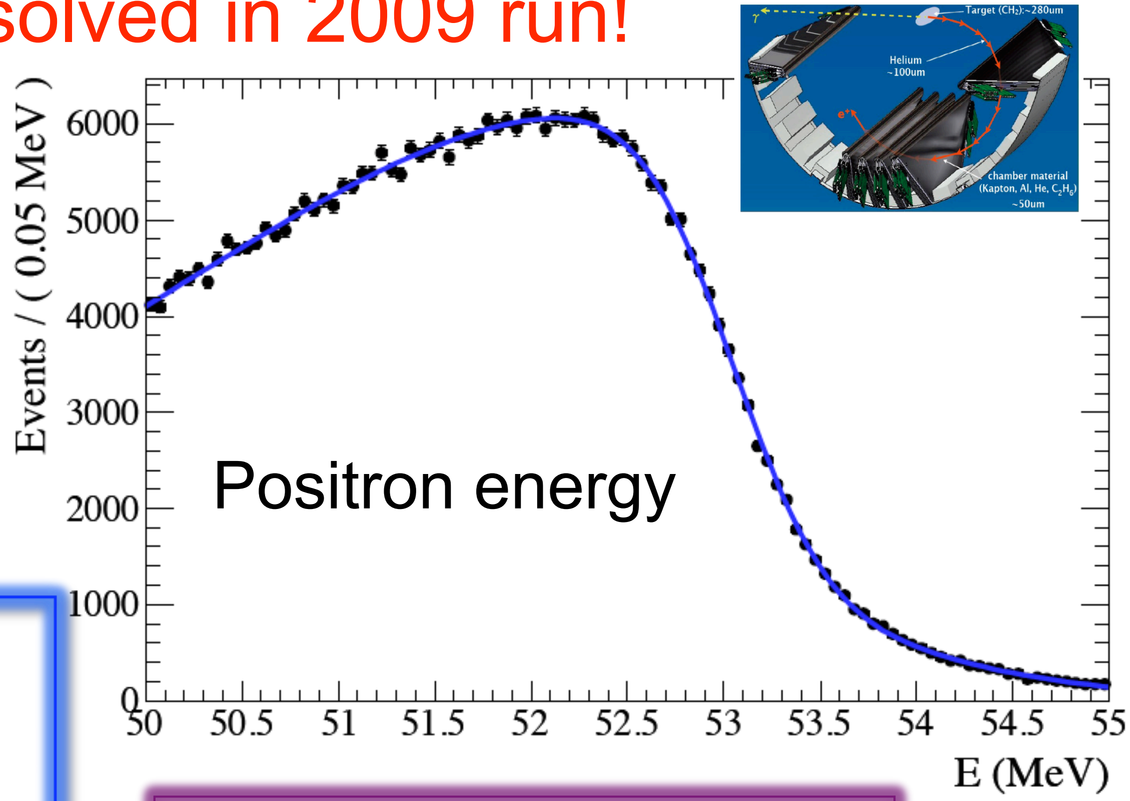
2008 performances: tracking

DC HV instabilities affected tracking efficiency and resolution.The problem was due to He penetration in HV distribution board: solved in 2009 run!

Positron energy resolution

obtained by fitting kinematic edge of Michel spectrum

σ(core)=374 KeV (60%)
σ(tail) =1.06 MeV (33%)
2.00 MeV (7%)



Angular resolutions:
σ(φ) = 10mrad σ(θ)=18mrad

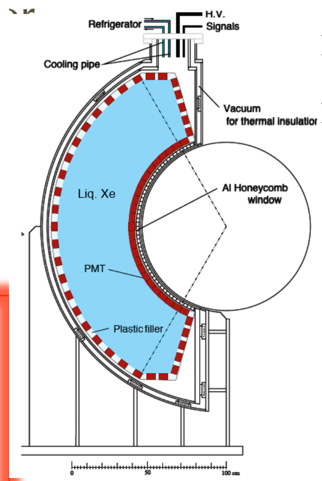
Vertex resolutions:
3.2mm/4.5mm in vertical/ horizontal directions on the target plane

2008 performances: γ energy and efficiency

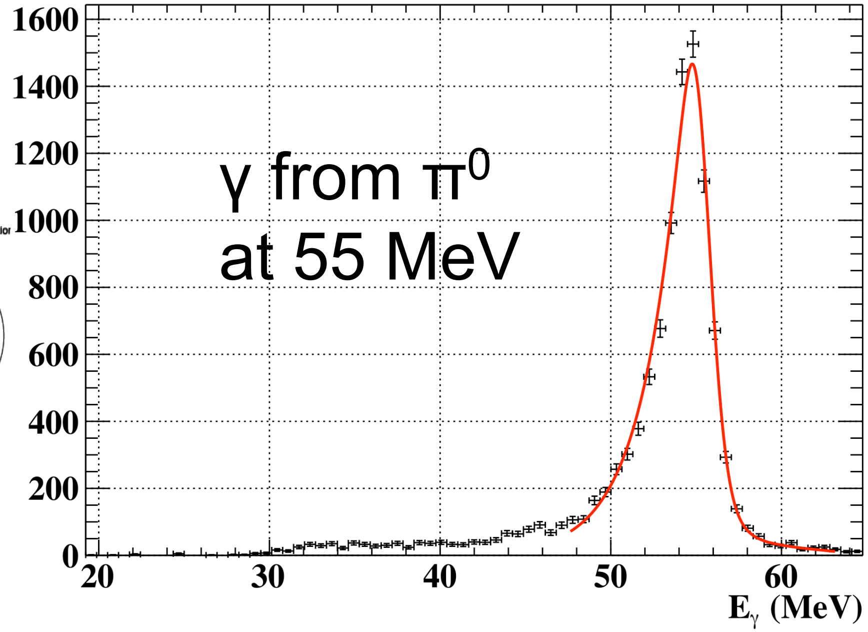
Photon energy resolution

measured in special
charge-exchange run

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



σ_{right} = 2.00±0.15%
for deep conversion(>2cm)



Detection efficiency

(normalized to fiducial volume)
from MC confirmed in π^0
data and radiative decay data

ε_γ=0.63±0.04

Conversion point

from MC and data taken with
a lead collimator

~5/6 mm along orthogonal
front face sides/depth direction

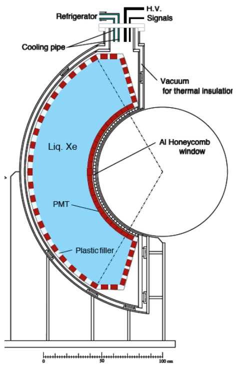
Eγ(a.u.)

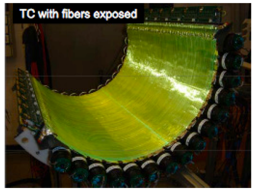
2008 performances: timing

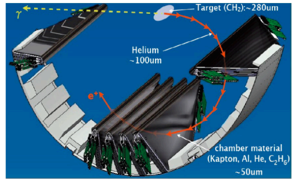
Relative γ-e^+ timing

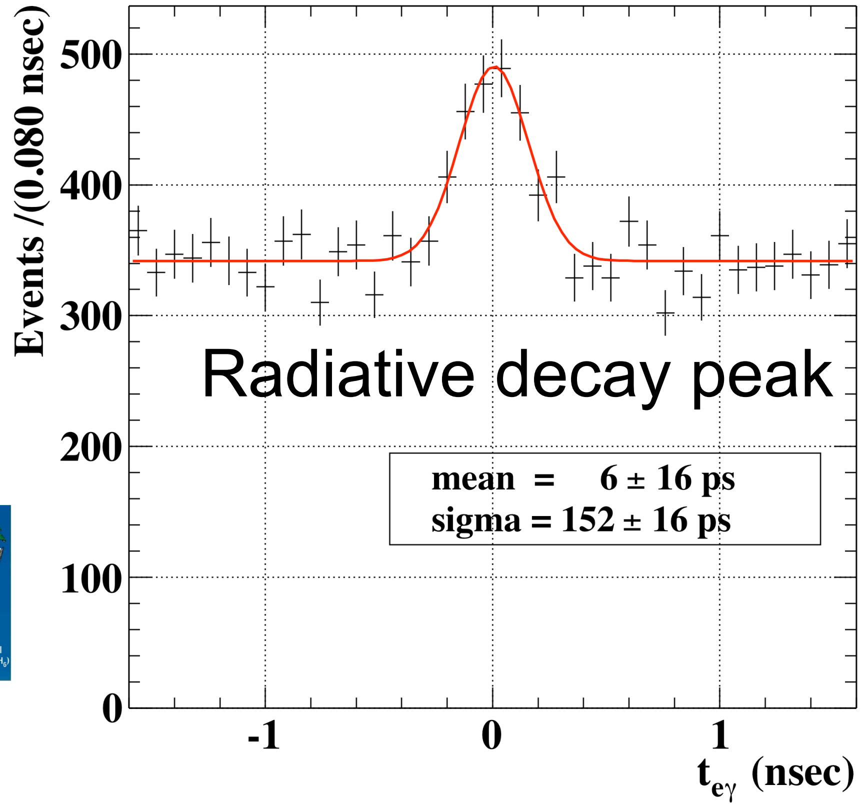
from radiative decays taken at normal beam intensity

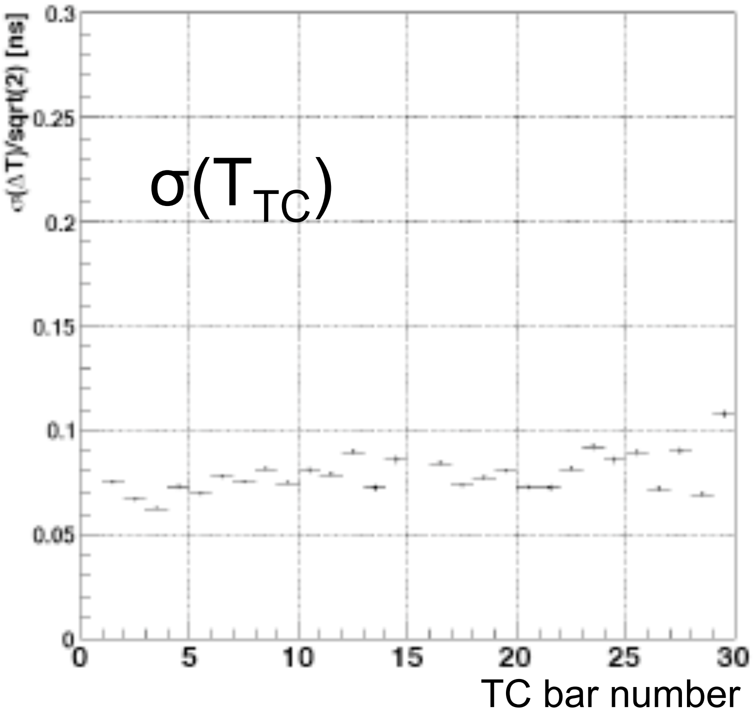
σ = 148 ± 17 ps
@signal energy











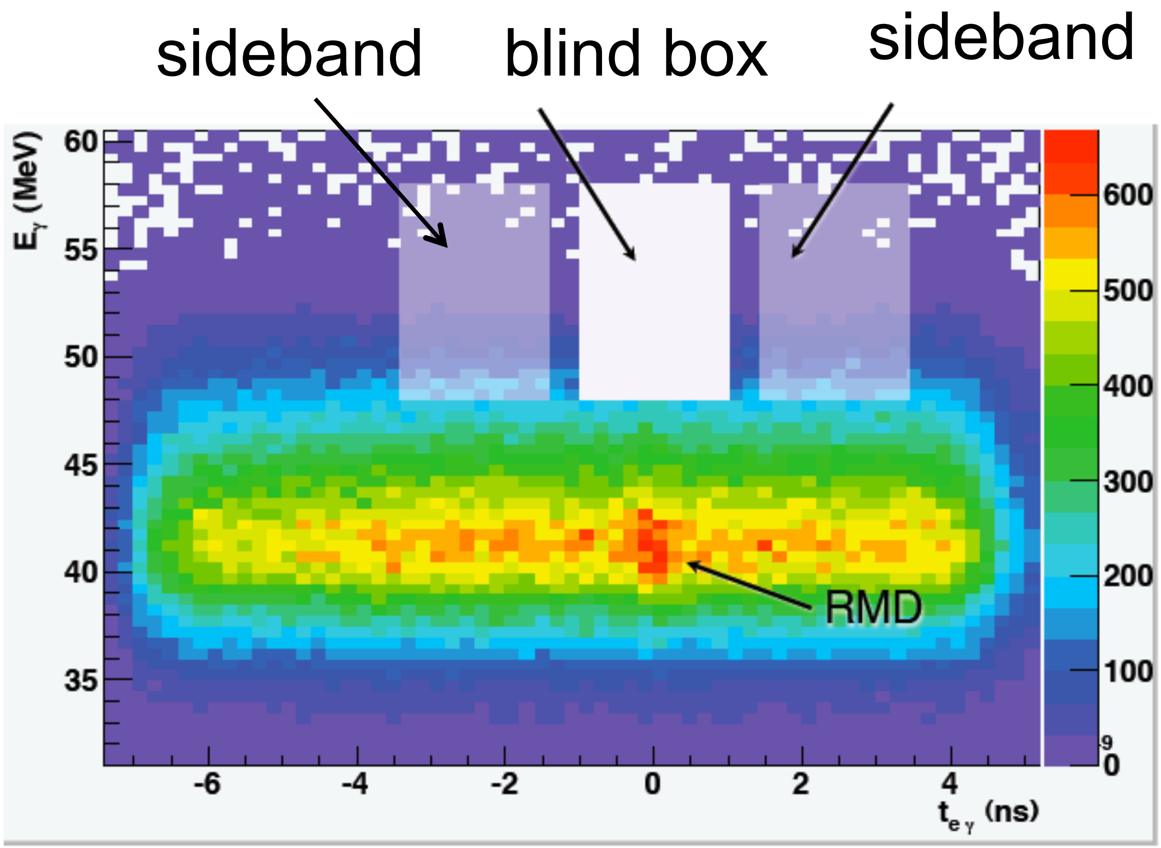
Timing counter intrinsic resolution

from e^+ hitting two consecutive bars

< 60-90ps

Analysis strategy

- Blind-box likelihood analysis strategy
- Blinding variables: E_γ and $T_{e\gamma}$
- Observables: $E_{e+}, E_\gamma, \theta_{e\gamma}, T_{e\gamma}$



Likelihood analysis

- The likelihood function is built in terms of signal, radiative decay and accidental backgrounds and their probability density functions:

$$\mathcal{L}(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{BG}}) = \frac{N^{N_{\text{obs}}} \exp^{-N}}{N_{\text{obs}}!} \prod_{i=1}^{N_{\text{obs}}} \left[\frac{N_{\text{sig}}}{N} S + \frac{N_{\text{RMD}}}{N} R + \frac{N_{\text{BG}}}{N} B \right]$$

- Probability density functions
  - Signal: from detector resolutions
  - Radiative decay: from theoretical model and data
  - Accidental background: from sidebands on data

- Normalization

Number of muons from the detected Michel decays, $N_{e\nu\nu}$ independent of istantaneous beam rate and of acceptance and efficiency

$$\text{BR}(\mu^+ \to \text{e}^+\gamma) = \frac{N_{\text{sig}}}{N_{e\nu\bar{\nu}}} \times \frac{f^E_{e\nu\bar{\nu}}}{P} \times \frac{\epsilon^{trig}_{e\nu\bar{\nu}}}{\epsilon^{trig}_{e\gamma}} \times \frac{A^{TC}_{e\nu\bar{\nu}}}{A^{TC}_{e\gamma}} \times \frac{\epsilon^{DC}_{e\nu\bar{\nu}}}{\epsilon^{DC}_{e\gamma}} \times \frac{1}{A^{LXe}_{e\gamma}} \times \frac{1}{\epsilon^{LXe}_{e\gamma}}$$

2008 Result

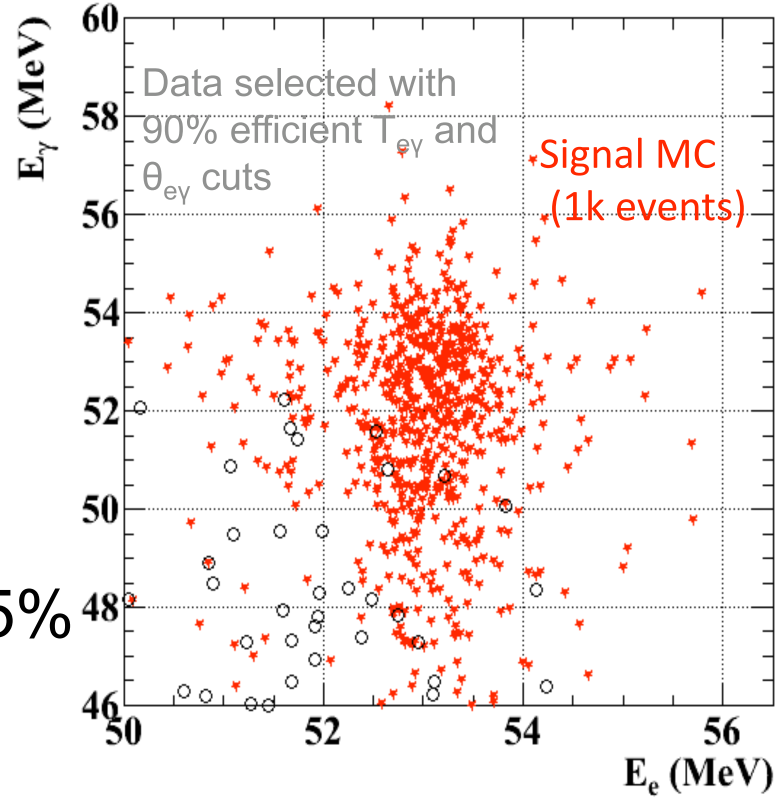
Nucl.Phys.B 834 (2010)

- "Feldman-Cousins" prescription adopted to quote the results (cross-checked with "Bayesian" approach and independent analyses)

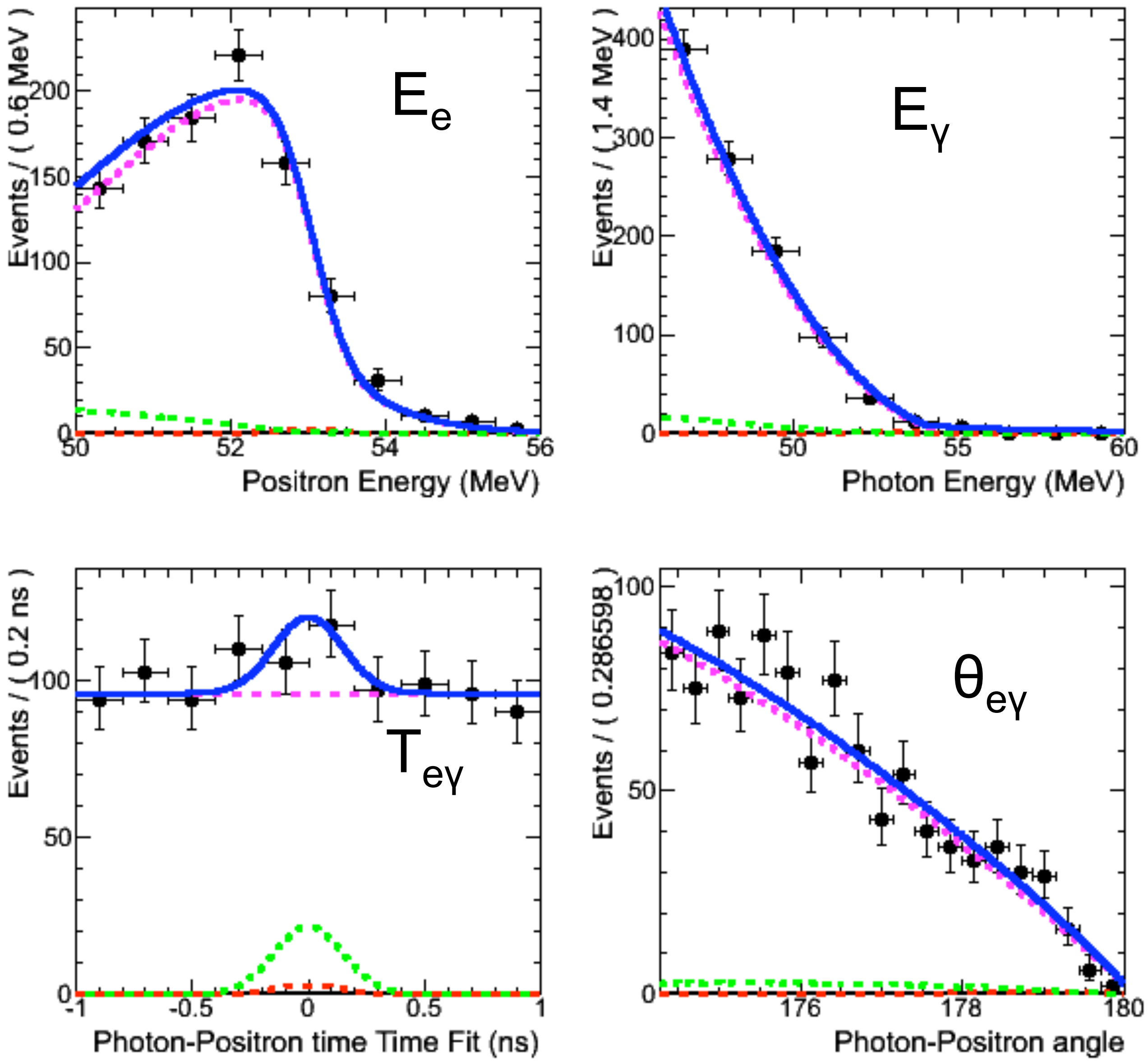
N_{sig}<14.7@90%C.L.

$$BR(\mu^+ \rightarrow e^+\gamma) < 2.8 \cdot 10^{-11} @ 90\% C.L.$$

- Expected 90% C.L. UL on BR (from toy MC): ~1.3x10^{-11}
- 90% CL from data sidebands: (0.9-2.1)x10^{-11}
- Probability of getting this or worse result for a statistical fluctuation: ~3-5%
- Systematic error included



Signal region fit



Accidental background

Radiative decay background

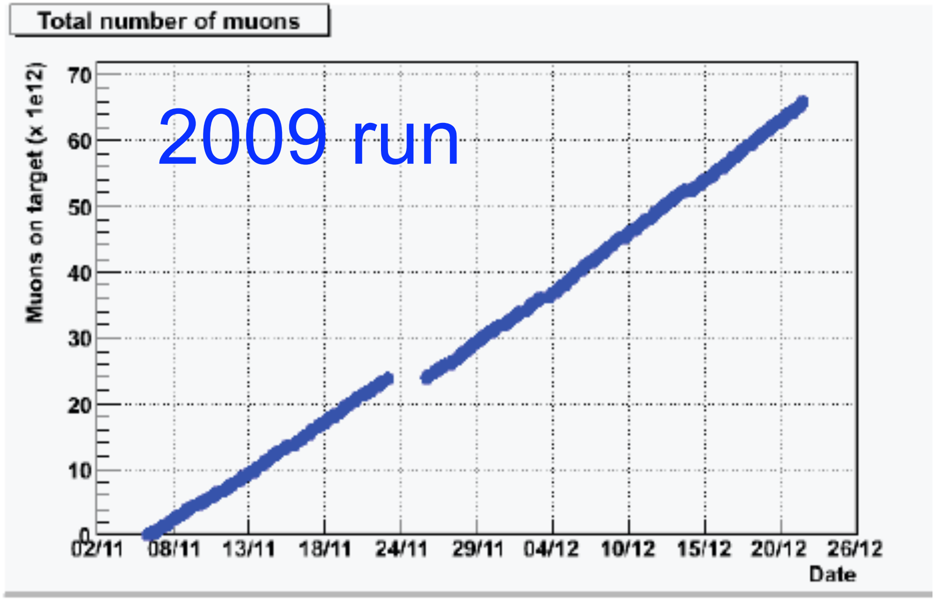
Signal

Total

Summary and perspectives

- First Physics MEG run gave comparable result with previous limit despite Drift Chambers HV instabilities

- Second run in 2009:
  - DC HV problem solved => DC fully efficient
  - Improved electronics
  - Other improvements in efficiencies and resolutions



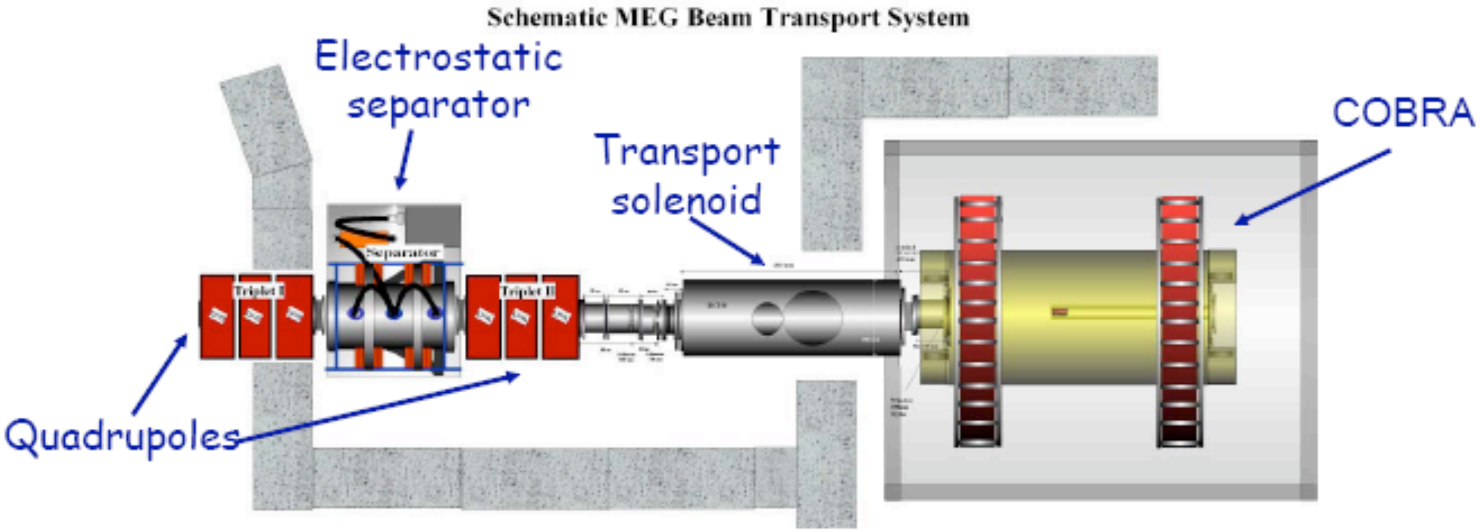
- Sensitivity expected at ~$5x10^{-12}$ for 2009 run, (target: summer conferences)

- Target sensitivity @end of 2011 run: $O(10^{-13})$

Backup

Beam-line

μ beam



Intensity' (μ-stop/s)

- Low 2.5×10^6
- Normal 3.2×10^7
- High 8.6×10^7

characteristics

- P = 27.7 MeV/c
- ΔP = 0.3 MeV/c
- σ_X = 9.5 mm
- σ_Y = 10. mm

Past, present and future performances

	2008	2009 (preliminary)	"Goal"
Gamma Energy (%)	2.0(w>2cm)	←	1.2
Gamma Timing (psec)	80	>67	43
Gamma Position (mm)	5(u,v)/6(w)	←	3.8(u,v)/5.9(w)
Gamma Efficiency (%)	63	←	60
e^+ Timing (psec)	<125	←	50
e^+ Momentum (%)	1.6	0.85	0.3-0.38(100%)
e^+ Angle (mrad)	10(ϕ)/18(θ)	8(ϕ)/11(θ)	3.8-5.1
e^+ Efficiency (%)	14	40	90
e^+-gamma timing (psec)	148	<180	64
Muon Decay Point (mm)	3.2(R)/4.5(Z)	2.2(R)/3.1(Z)	0.9-1.1
Trigger efficiency (%)	66	88	100
Stopping Muon Rate (sec^{-1})	3×10^7 (300μm)	2.9×10^7 (300μm)	3×10^7
DAQ time/Real time (days)	48/78	35/43	300/-

Table of resolutions

Exp./Lab	Year	ΔEe/Ee (%)	ΔEγ /Eγ (%)	Δteγ (ns)	Δθeγ (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	2008 - x	1	4.5	0.15	19	3×10^7	100	2×10^{-13}

$$B_{\text{prompt}} \approx 0.1 \times B_{\text{acc}}$$

at $3x10^7$ μ–stop/s

$$B_{\text{acc}} \approx R_\mu \Delta E_e \Delta E_\gamma^2 \Delta\theta^2 \Delta t$$

Trigger and DAQ

Trigger: 100 MHz waveform digitizer on VME boards that uses:

- γ energy
- $e^+\gamma$ time coincidence
- $e^+\gamma$ collinearity

Readout electronics:

- 2GHZ Waveform digitization for all channels:
- DRS chip (domino ring sampling ring)
- Custom chip designed at PSI
- Upgraded version 4 used 2009 run)

MEG 2008 Run

Running conditions
MEG run period

- Live time ~50% of total time
- Total time ~ 7×10^6 s
- μ stop rate: 3×10^7 μ/s
- Trigger rate 6.5 ev/s ; 9 MB/s

The missing 50% is composed of:

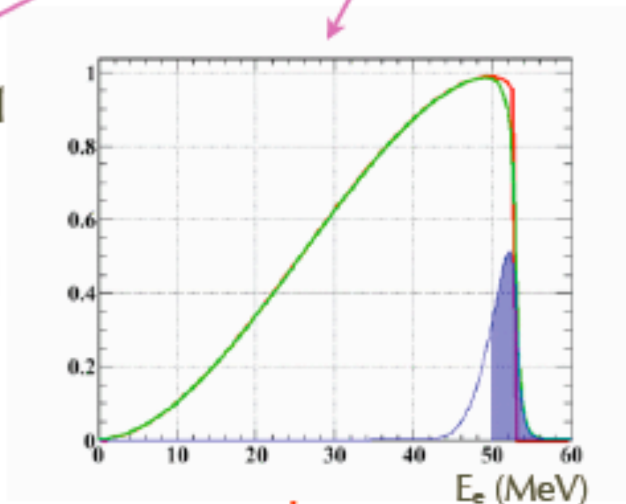
- 17% DAQ dead time
- 14% programmed beam shutdowns
- 7% low intensity Radiative muon decay runs (RMD)
- 11% calibrations
- 2% unforeseen beam stops

Normalization

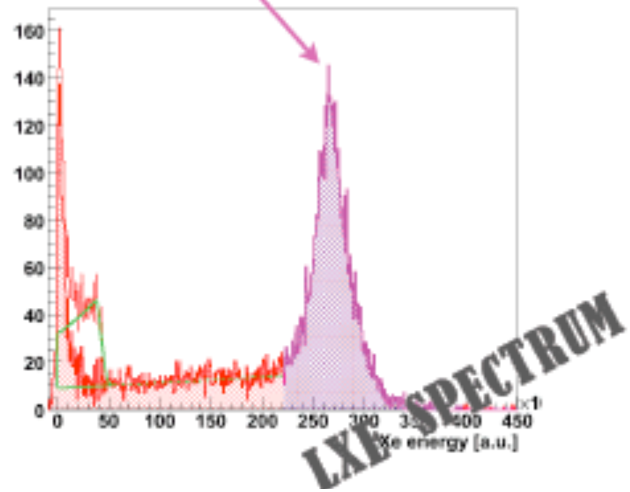
$$\mathrm{BR}(\mu^+ \to e^+\gamma) = \frac{N_{\mathrm{sig}}}{N_{e\nu\bar{\nu}}} \times \frac{f^E_{e\nu\bar{\nu}}}{P} \times \frac{\epsilon^{trig}_{e\nu\bar{\nu}}}{\epsilon^{trig}_{e\gamma}} \times \frac{A^{TC}_{e\nu\bar{\nu}}}{A^{TC}_{e\gamma}} \times \frac{\epsilon^{DC}_{e\nu\bar{\nu}}}{\epsilon^{DC}_{e\gamma}} \times \frac{1}{A^{LXe}_{e\gamma}} \times \frac{1}{\epsilon^{LXe}_{e\gamma}}$$

= ~1

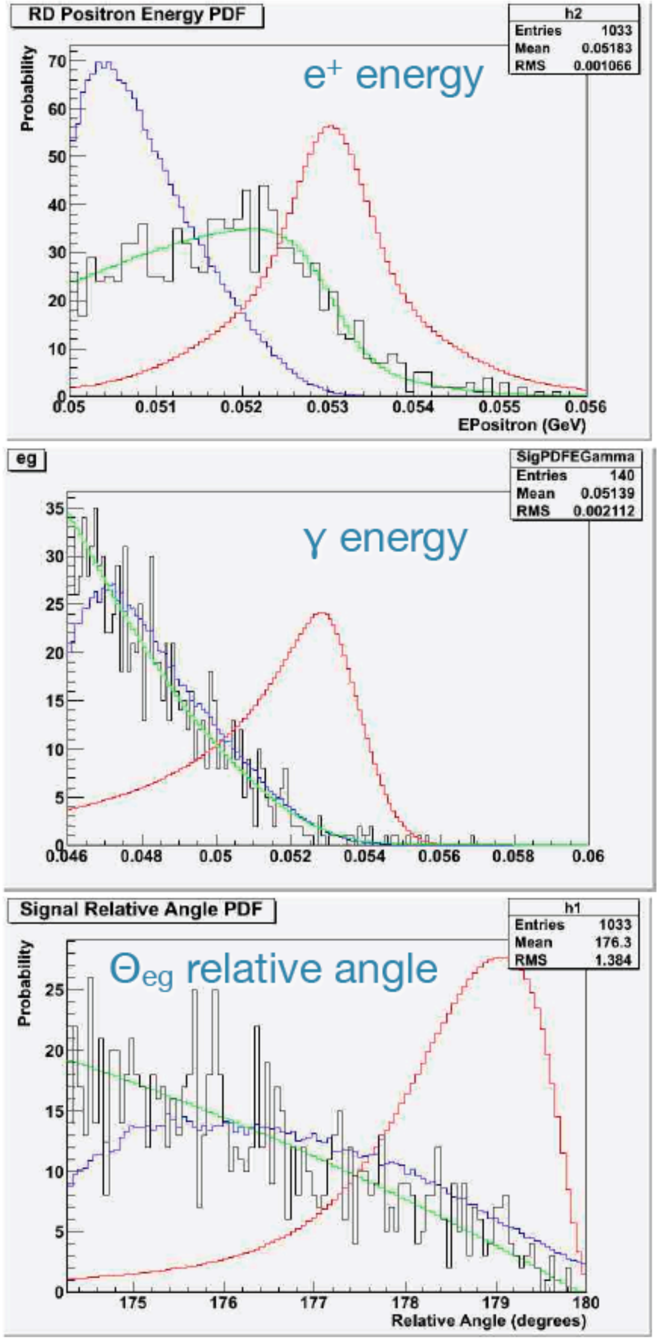
count # of Michel decays in the analysis window with a pre-scaled trigger



theory
resolution
acceptance



PDFs



Legend (*):

Black: data

Red: Signal PDF

Blue: RMD PDF

Green: BG PDF

Other LFV processes

Process	Present bound	Future sensitivity	
$\mu \to e\gamma$	1.2×10^{-11}	$O(10^{-13}-10^{-14})$	MEG
$\mu \to eee$	1.0×10^{-12}	-	
$\mu \to e$ in Ti	4.3×10^{-12}	$O(10^{-18})$*	PRISM/PRIME
$\mu \to e$ in Au	7×10^{-13}	-	
$\mu \to e$ in Al	-	$O(10^{-16})$*	COMET/Mu2e
$\tau \to \mu\gamma$	4.4×10^{-8}	$O(10^{-8},10^{-9})$*	SuperKEKB, SuperB
$\tau \to e\gamma$	3.3×10^{-8}	$O(10^{-8}-10^{-9})$*	
$\tau \to \mu\mu\mu$	3.2×10^{-8}	$O(10^{-8},10^{-9})$*	
$\tau \to eee$	3.6×10^{-8}	$O(10^{-8},10^{-9})$*	

* = proposed future experiment

Complementarity between different searches in constraining New Physics models