Searching for μ → eγ with MEG

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Les Rencontres de Physique de la Vallée d'Aoste

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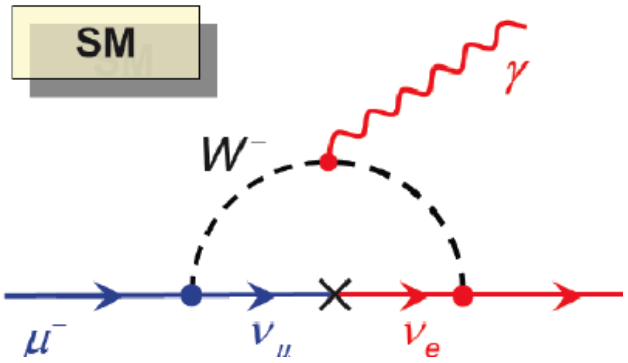
Outline

- Why MEG and its detectors
- Data analysis 2009-2010
- Results
- Perspectives

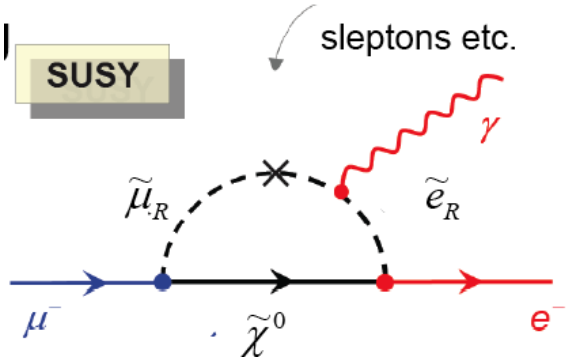
Zero probability in SM!



$$\Gamma(\mu \to e\gamma) \approx \underbrace{\frac{G_F^2 m_\mu^5}{192\pi^3}}_{\mu-\text{decay}} \underbrace{\left(\frac{\alpha}{2\pi}\right)}_{\gamma-\text{vertex}} \underbrace{\sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)}_{\nu-\text{oscillation}}$$

$$\approx \frac{G_F^2 m_\mu^5}{192\pi^3}\left(\frac{\alpha}{2\pi}\right)\sin^2 2\theta_\odot \left(\frac{\Delta m^2}{M_W^2}\right)^2,$$

Relative probability ~ 10^{-55}

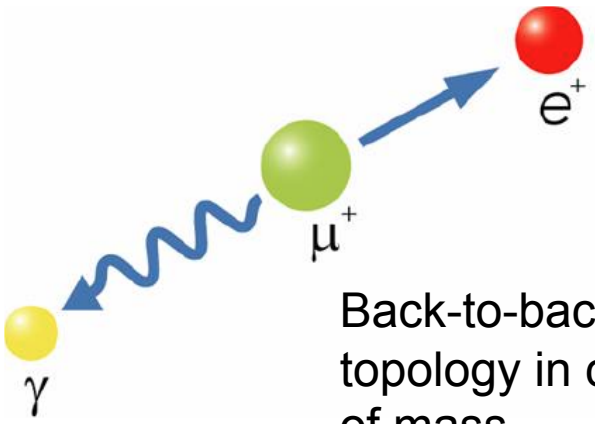


New Physics models have a mechanisms to enhance the rate!

Observation is a clear indication of New Physics

The signature

$$E_e \cong E_\gamma = \quad 52.8\ MeV$$

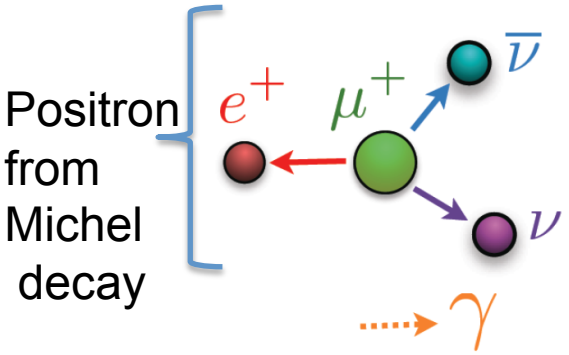


Back-to-back topology in center of mass

$$\theta_{e\gamma} = 180^o$$

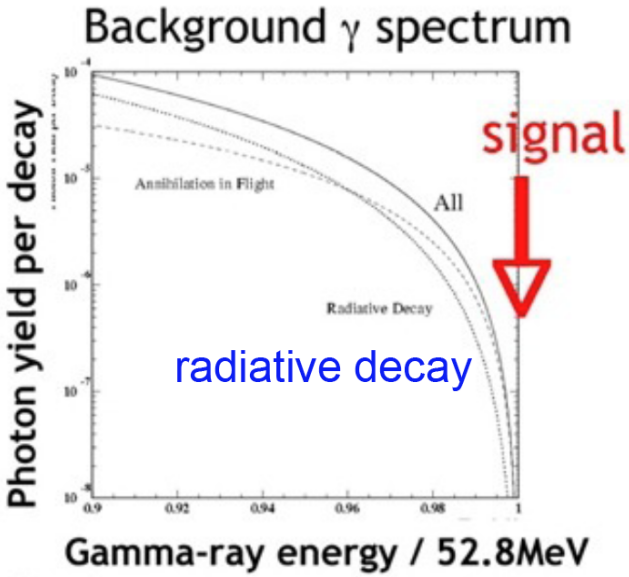
- ***Two-body process***
  - Well-defined photon and positron energy
- ***Resolutions and efficiency should be optimized***
  - Background rejection at the lowest cost…
- ***Enormous amount of muon decays***
  - High beam rate to be effective

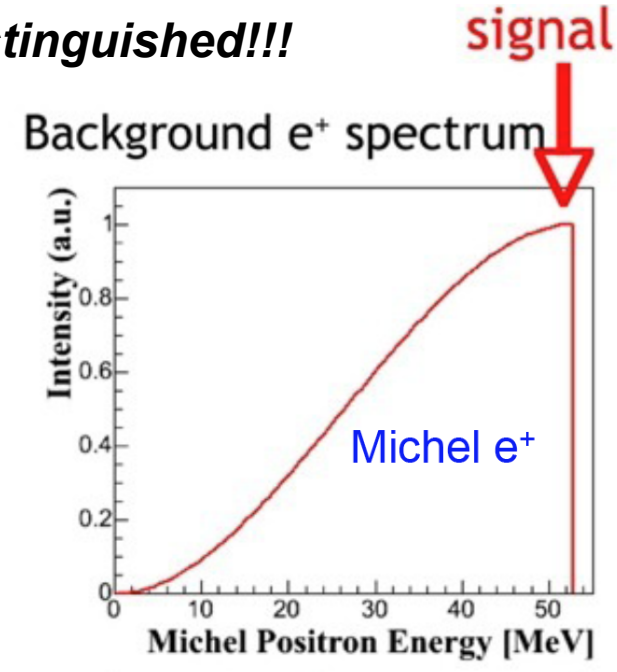
The Accidental Background



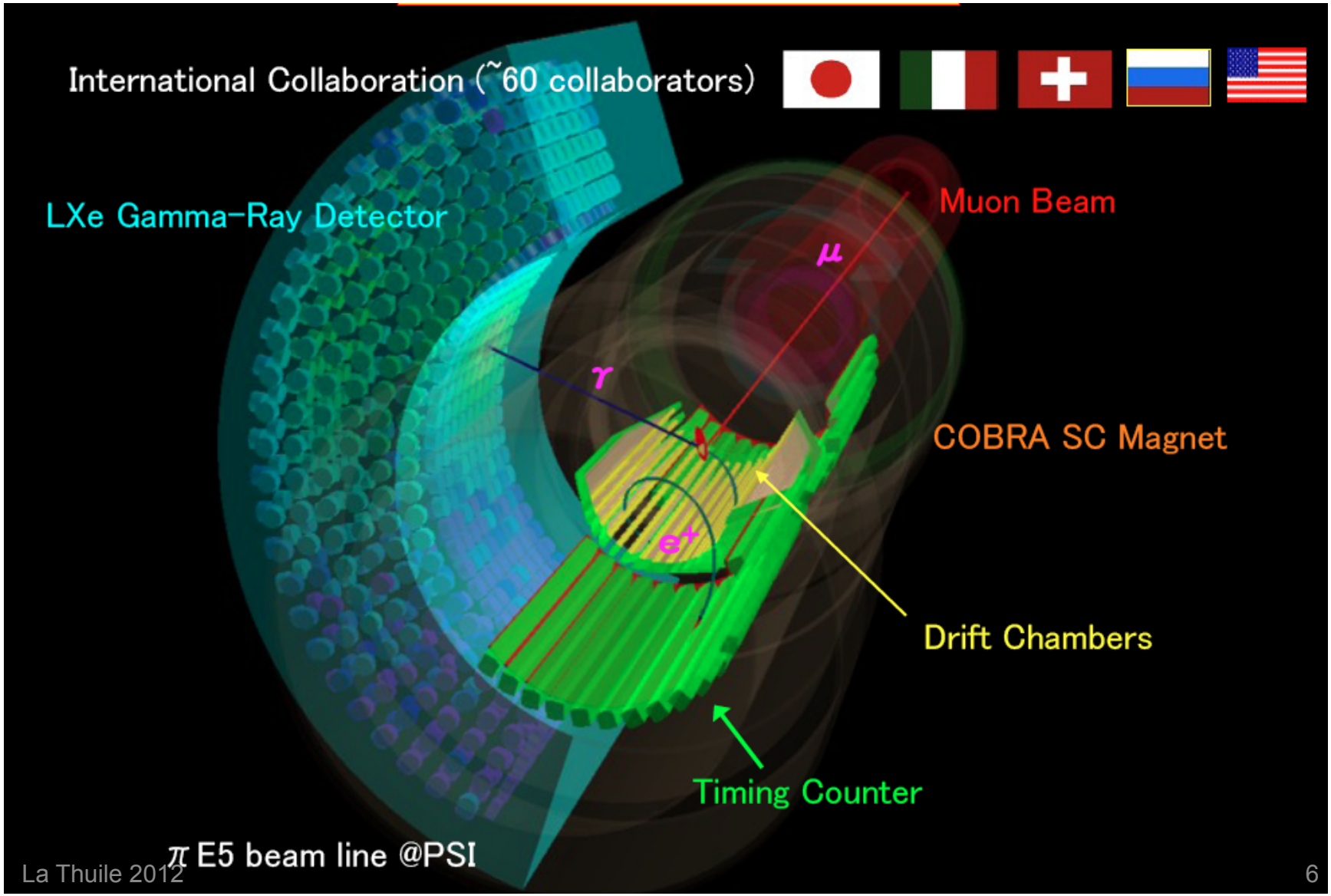
– Photon from
  » Radiative Michel $\mu \rightarrow e\nu\bar{\nu}\gamma$
  » Annihilation in flight $e^+e^- \rightarrow \gamma\gamma$
  » Bremsstrahlung $e^+N \rightarrow e^+N\gamma$

So close in time they cannot be distinguished!!!

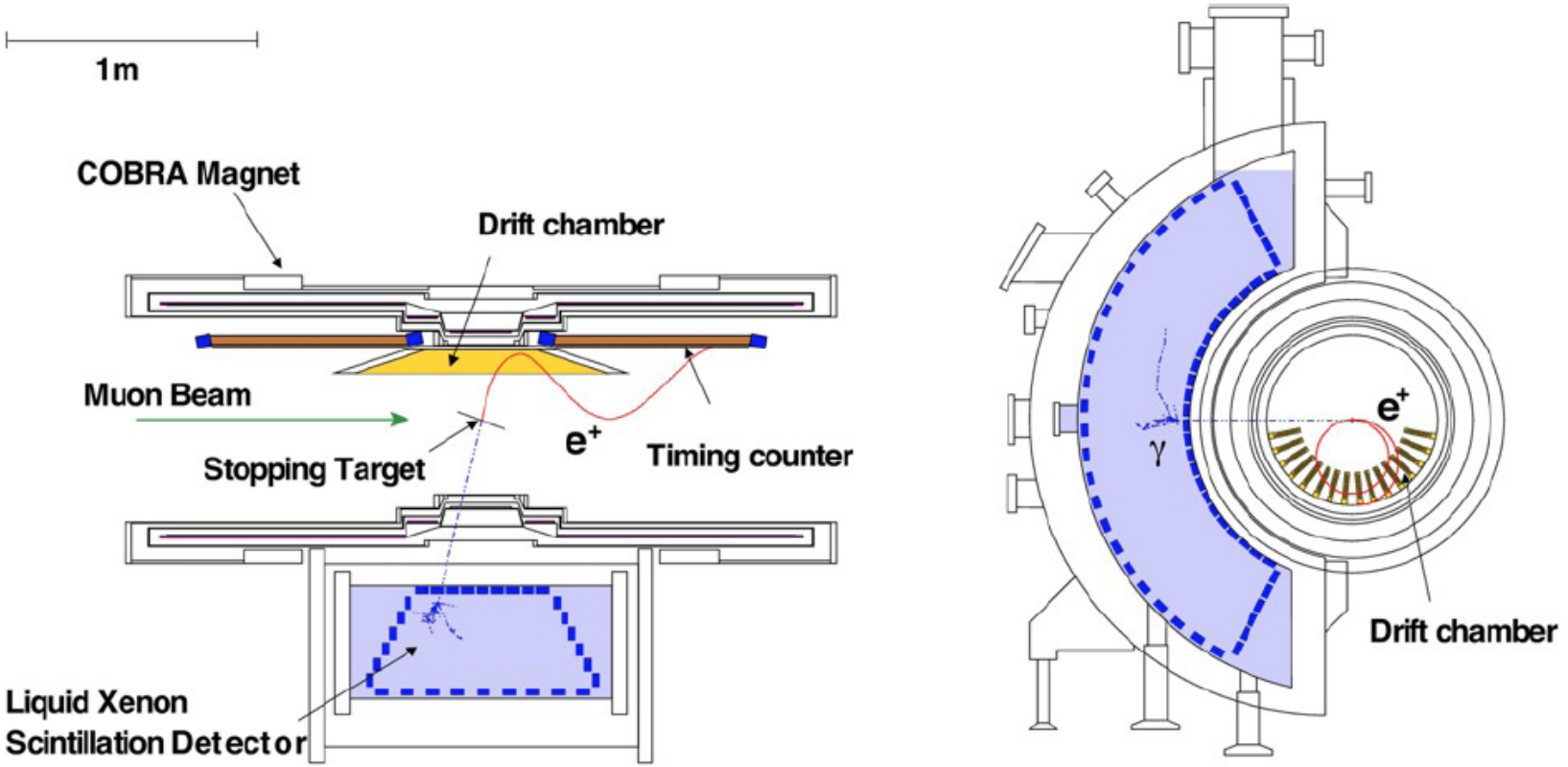




The MEG experiment

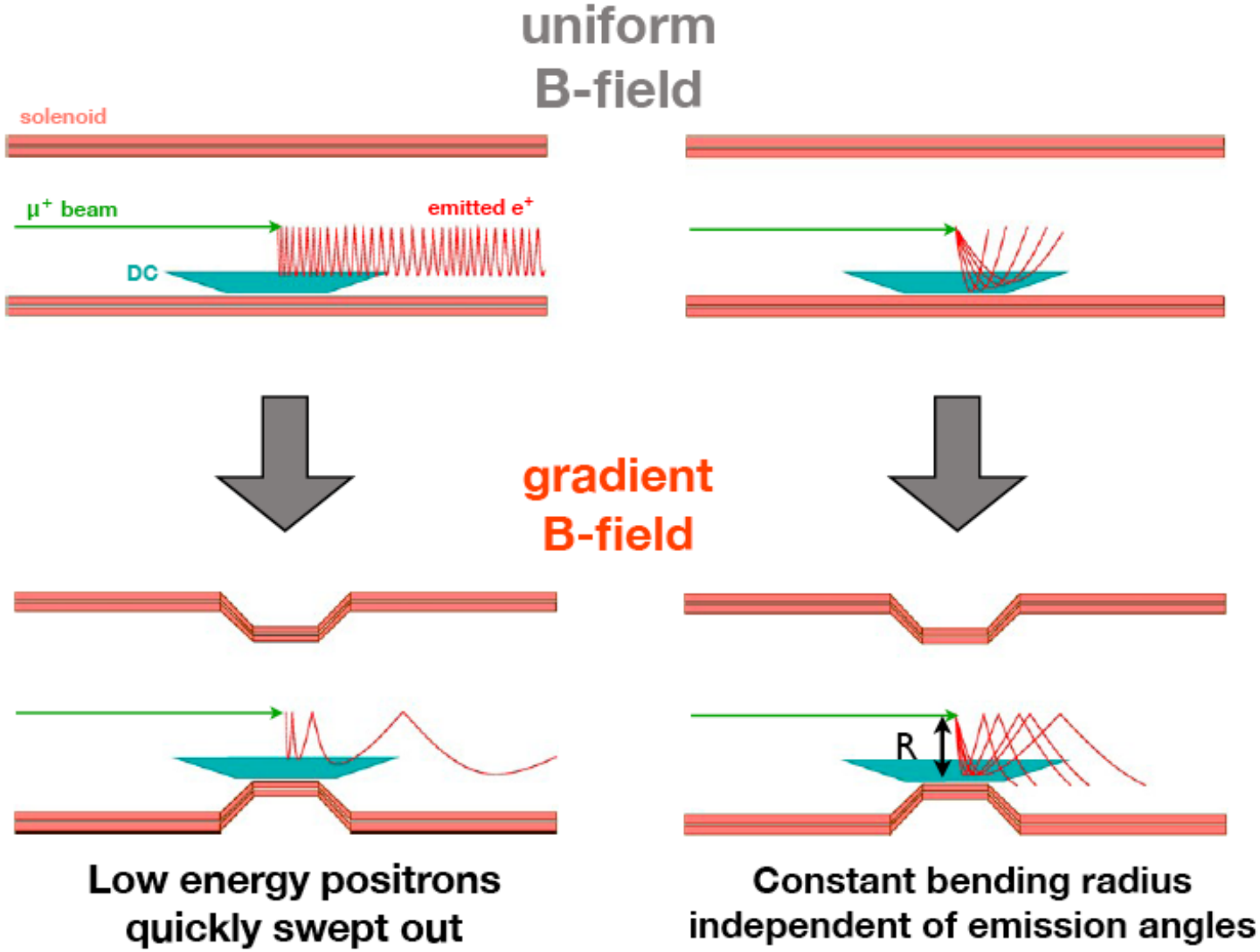


The detector layout

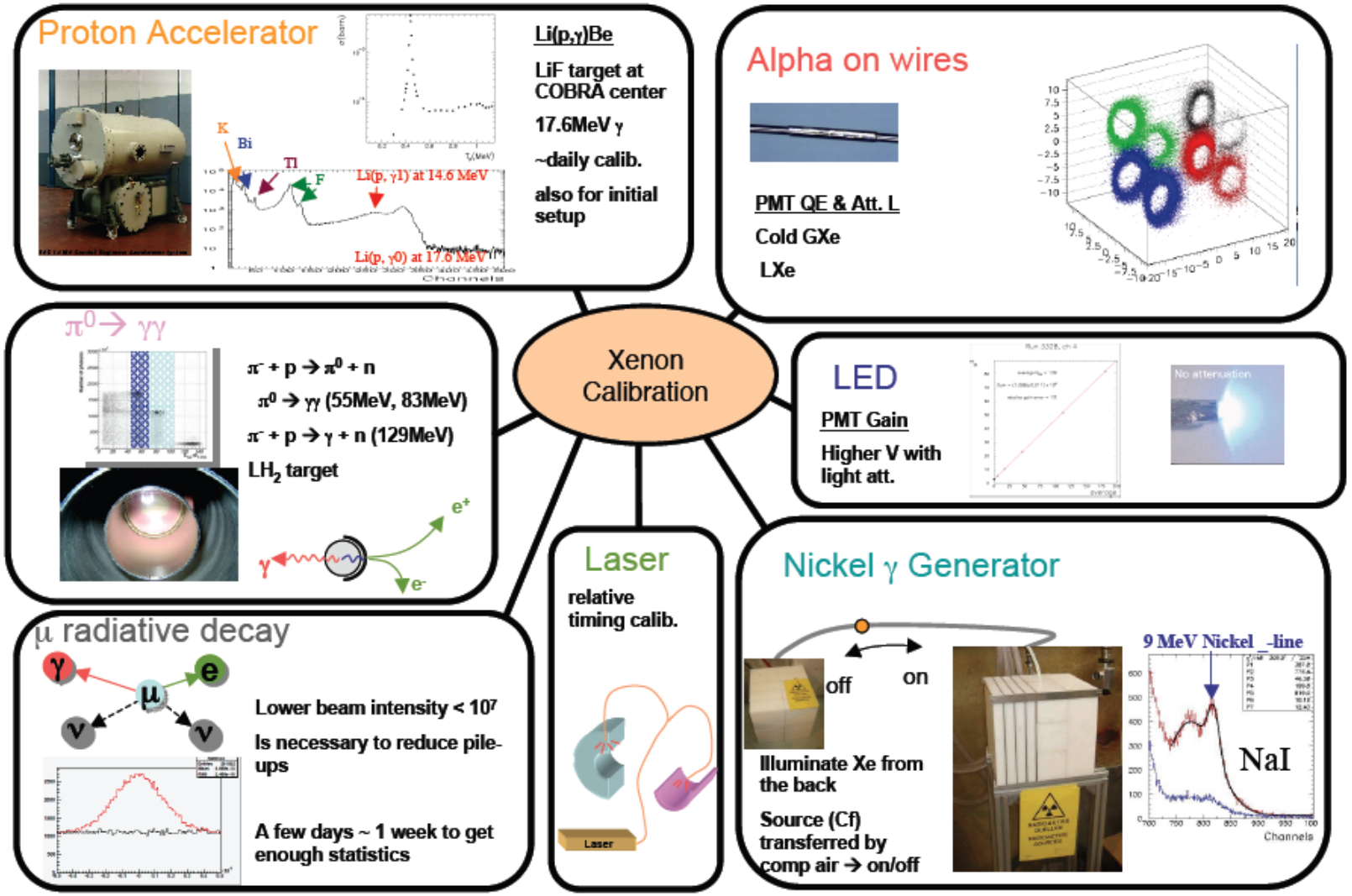


- Asymmetric coverage: no material in front of calorimeter: high photon detection efficiency!!!

The advantage of a COBRA

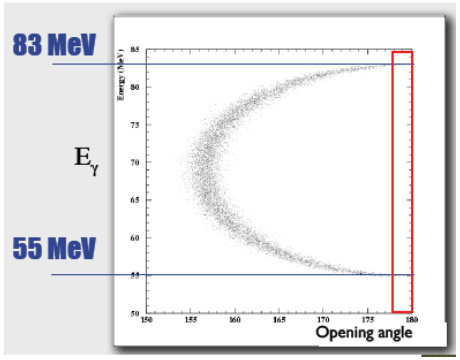


Calibration overview

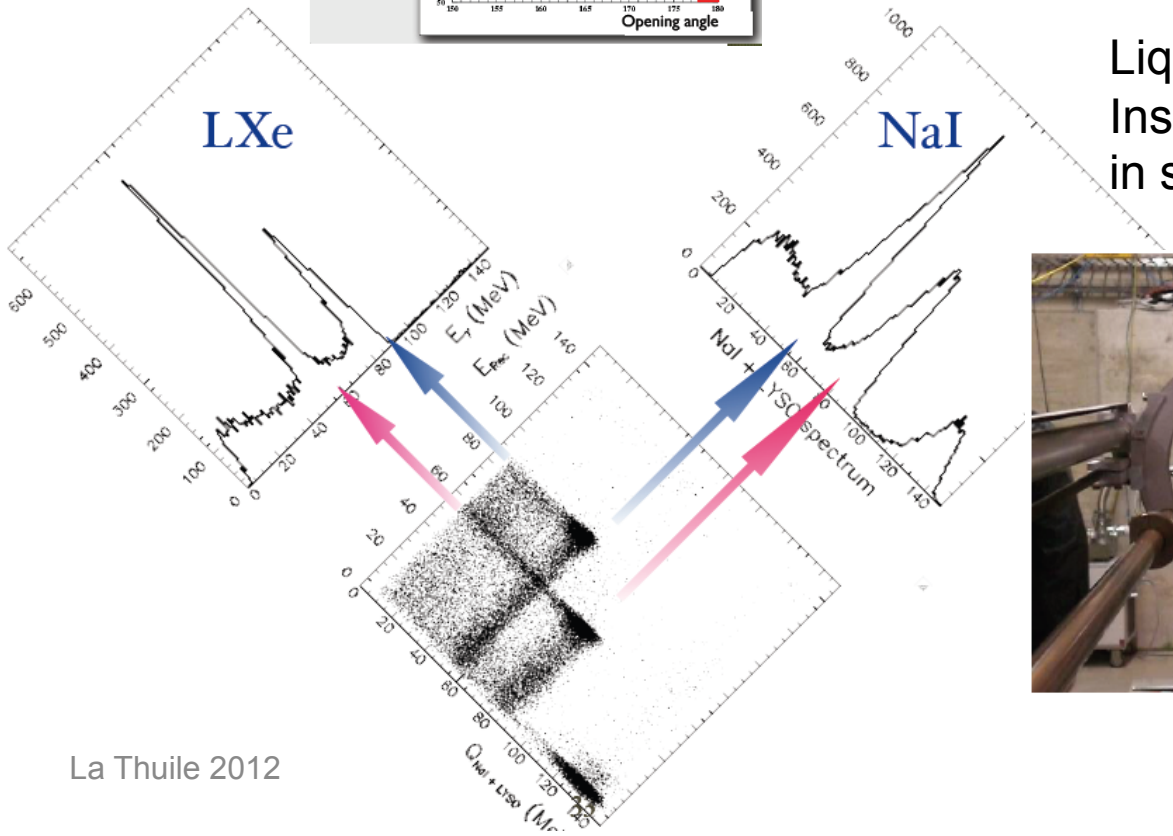


CEX measurement

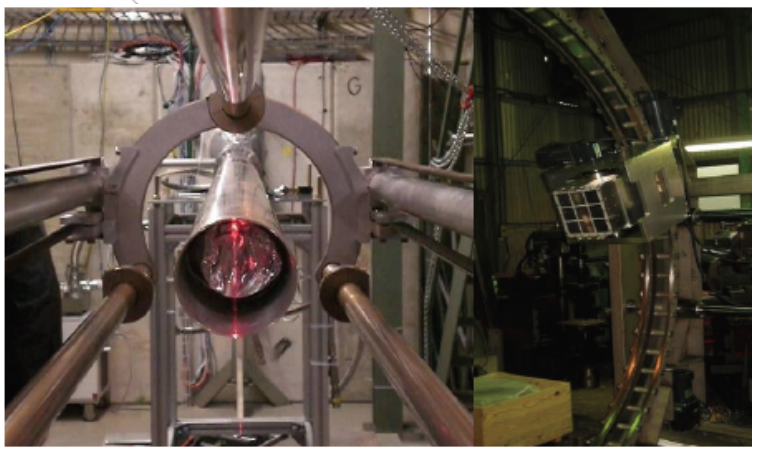
$$\pi^- p \rightarrow \pi^0 n \rightarrow \gamma\gamma n$$



"opposite" side crystal NaI calorimeter to measure the other photons



Liquid hydrogen target
Inserted in COBRA volume
in special data-taking periods



MEG analysis in a nutshell

- Extended maximum likelihood analysis
  - Determine number of signal S in signal region
  - Constraints on background rate (Accidental [A] and radiative [R]) from sidebands
- Observables :$E_\gamma, E_e, T_{e\gamma}, \theta_{e\gamma}, \varphi_{e\gamma}$
- Probability Density Function (PDF) from data
  - Measured resolutions in sideband or dedicated samples
- Different PDF implementations (as cross-check)
  - Event by event information or averaged, different functional forms…

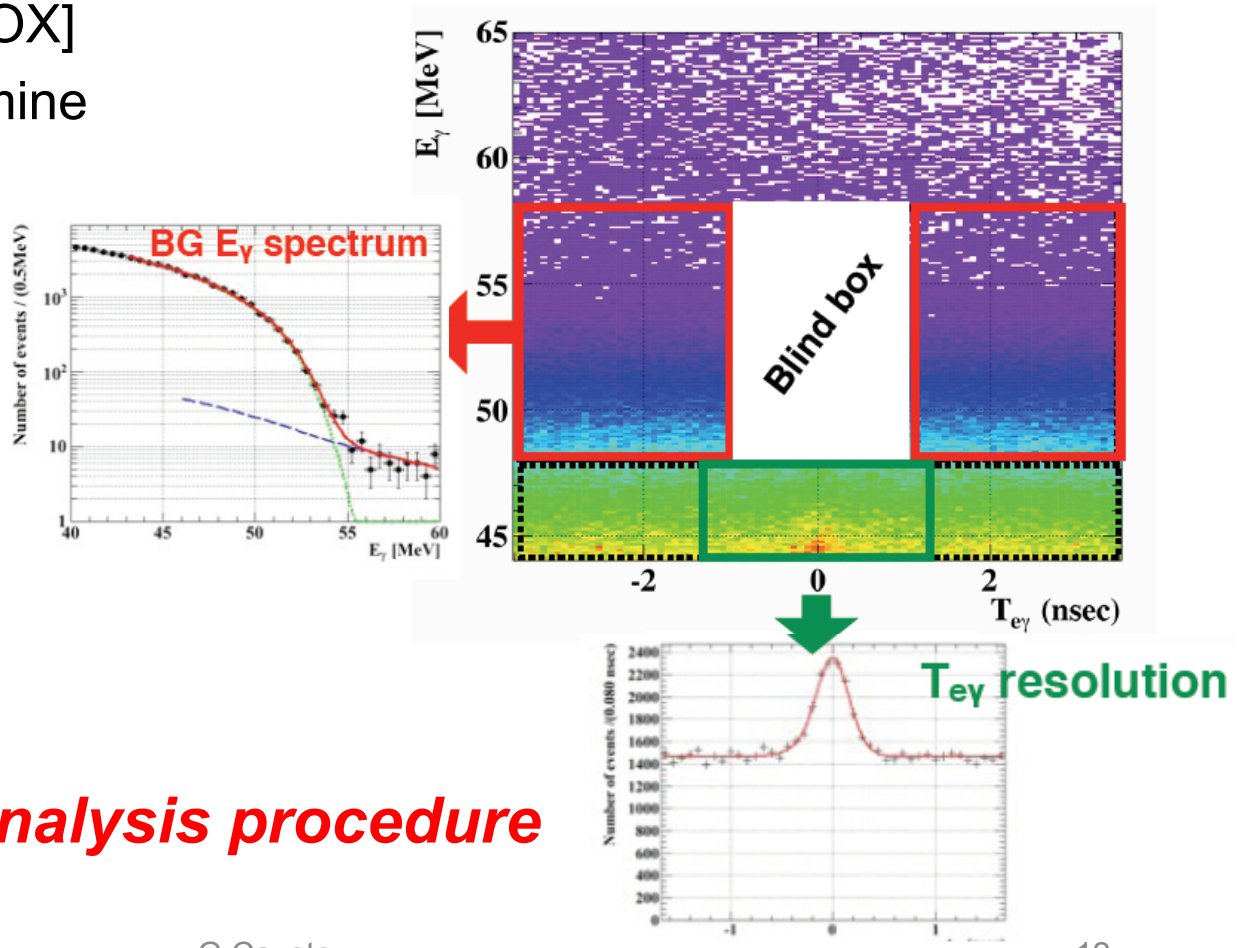
$$\mathcal{L}(\vec{x}_1,\ldots,\vec{x}_N,R_\diamond,A_\diamond|\hat{S},\hat{R},\hat{A}) = \frac{e^{-\hat{N}}}{N!} e^{-\frac{1}{2}\frac{(A_\diamond-\hat{A})^2}{\sigma_A^2}} e^{-\frac{1}{2}\frac{(R_\diamond-\hat{R})^2}{\sigma_R^2}} \prod_{i=1}^{N}\left(\hat{S}s(\vec{x}_i)+\hat{R}r(\vec{x}_i)+\hat{A}a(\vec{x}_i)\right)$$

PDFs

Background rate constraints

The general method

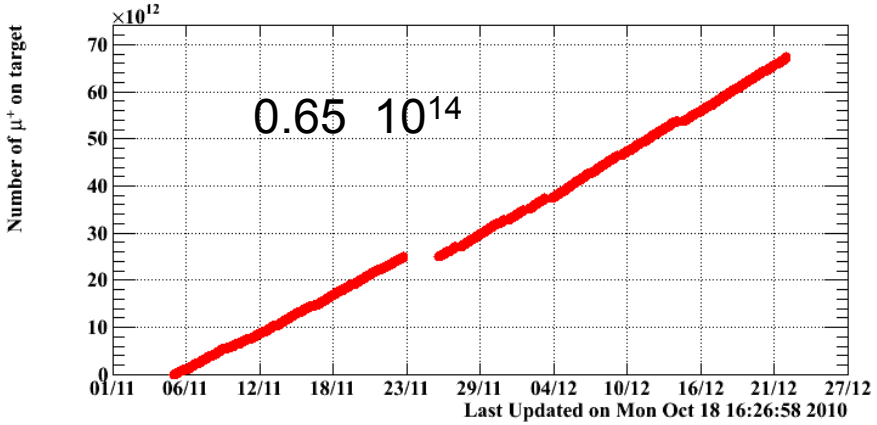
- A portion of analysis fit region is kept ***hidden*** [BLIND BOX]
- Use ***sidebands*** to determine ***background*** shape
- Use ***ONLY*** sideband or alternative samples to determine resolutions
- ***Reprocess*** data ***whenever*** a better reconstruction algorithm or calibration is available



This is a blind analysis procedure

MEG dataset

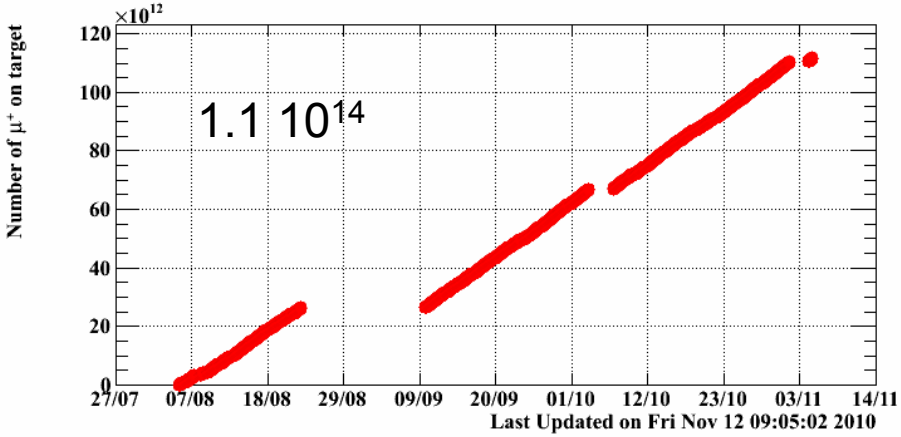
2009 muons on target



DAQ time : 35 days

Fully efficient detector
Stable conditions (DCH, LXe light)

2010 muons on target

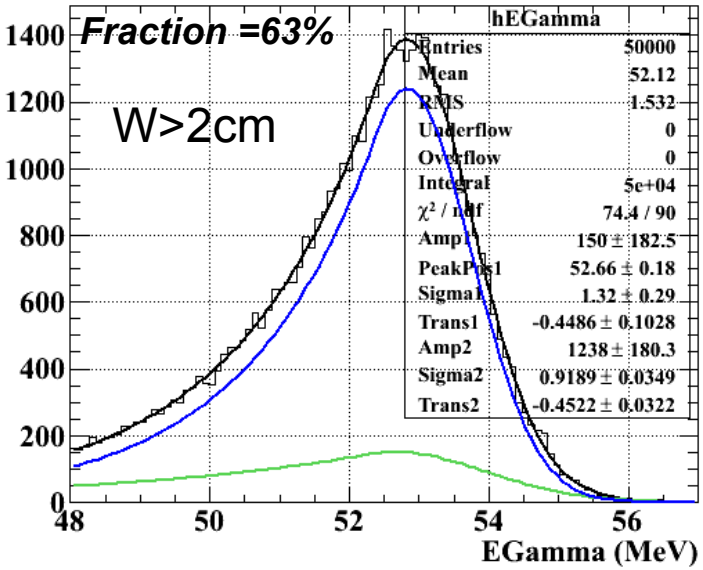


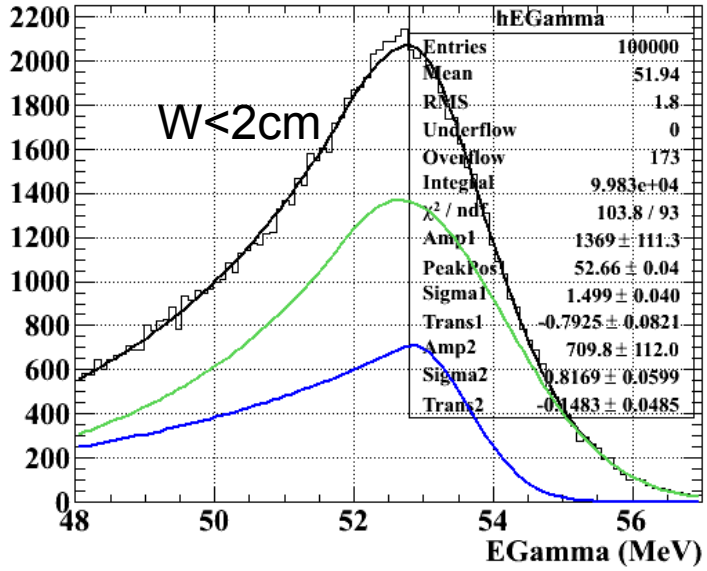
DAQ time : 56 days

Optimized beam (degrader)
Improved electronics timing
Slightly worse DCH conditions

Signal photon energy PDF

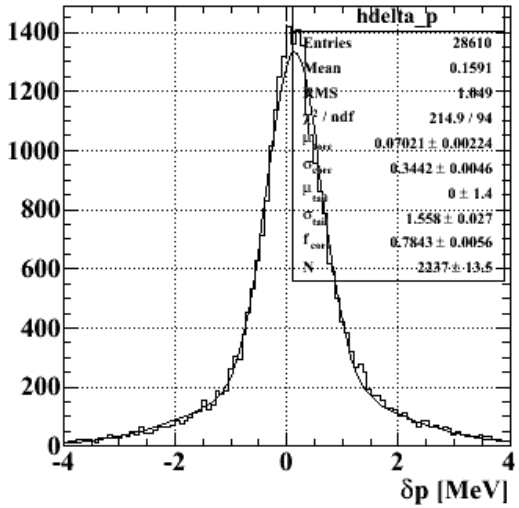
- Detailed calibration based on CEX runs
- Energy scale stability cross-checked with several frequent calibration
- Use event-by-event correction, here average PDF

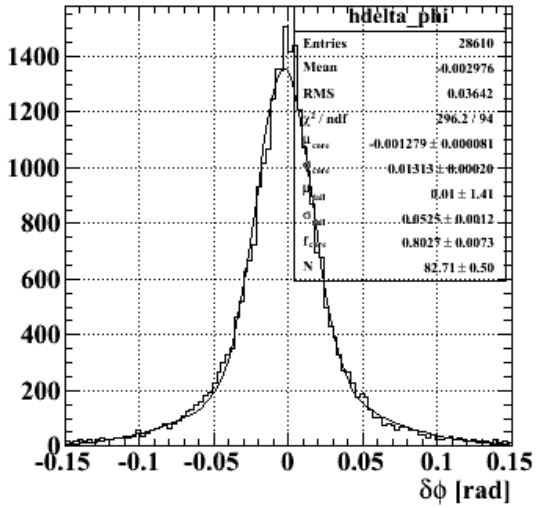


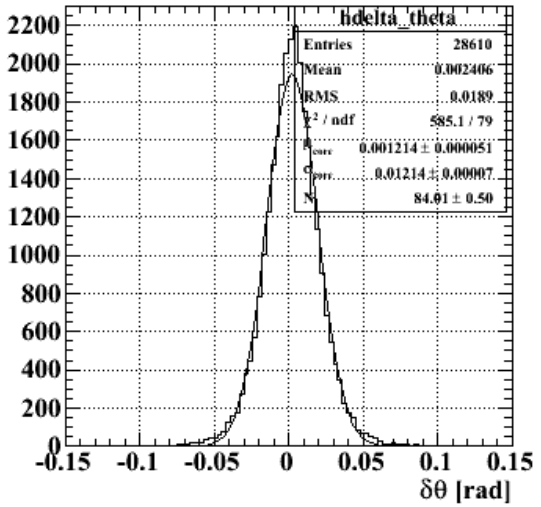


Signal positron resolutions

– From double turn track studies







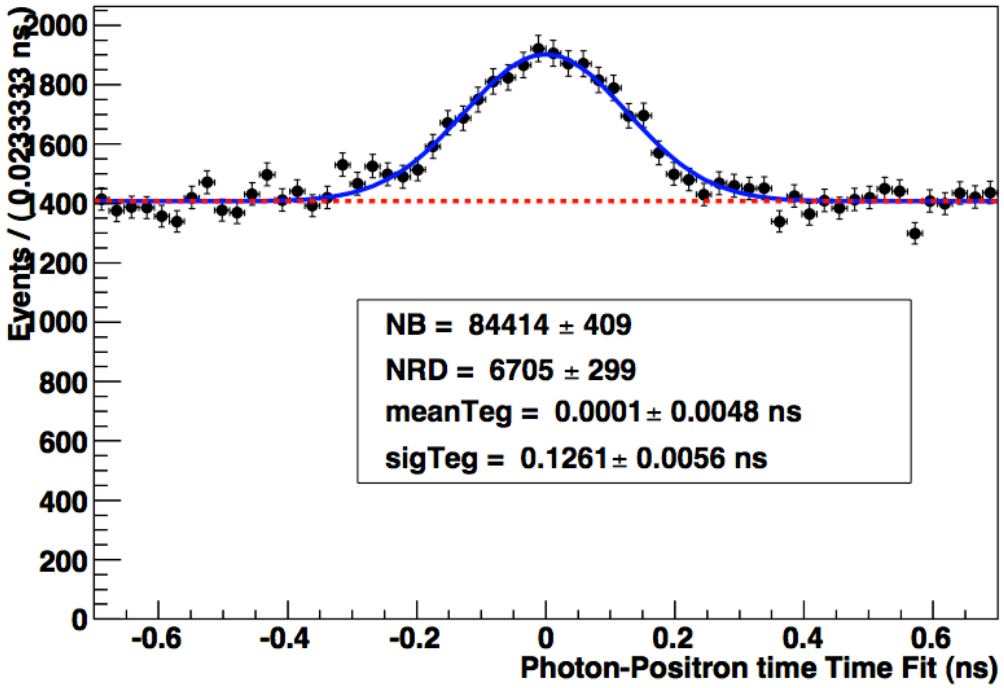
Nominal Positron momentum PDF from fit to Michel edge

After DCH alignment and B field optimization
residual bias accounted for in systematics

High quality and low quality tracks treated in different categories

Signal relative timing

– Fit to radiative events $T_{e\gamma}$ in E_γ sidebands
  - Clear signal, used to find center of signal region and signal resolution (scaled by E_γ)

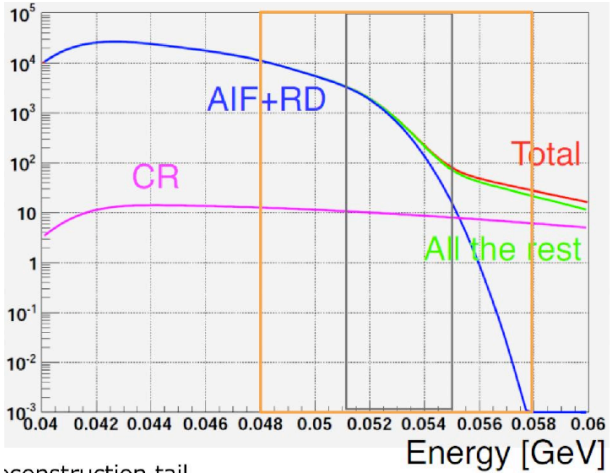


Resolution does not depend significantly on TC bar

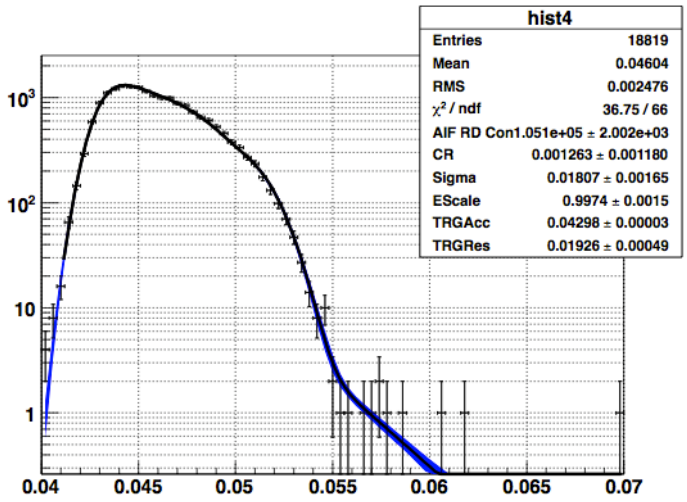
Significant *improvement* compared to 2009

Background ACC PDF

- MEASURED directly on data sideband
  - Use same selection as for final signal region, detailed dependence (on gamma position)
    - » Positron E : Michel spectrum
    - » Relative angles: effective distributions
    - » Gamma E : Combination of RD +AIF + pileup+ cosmics
      - Consistent with signal resolution



ACC Gamma energy

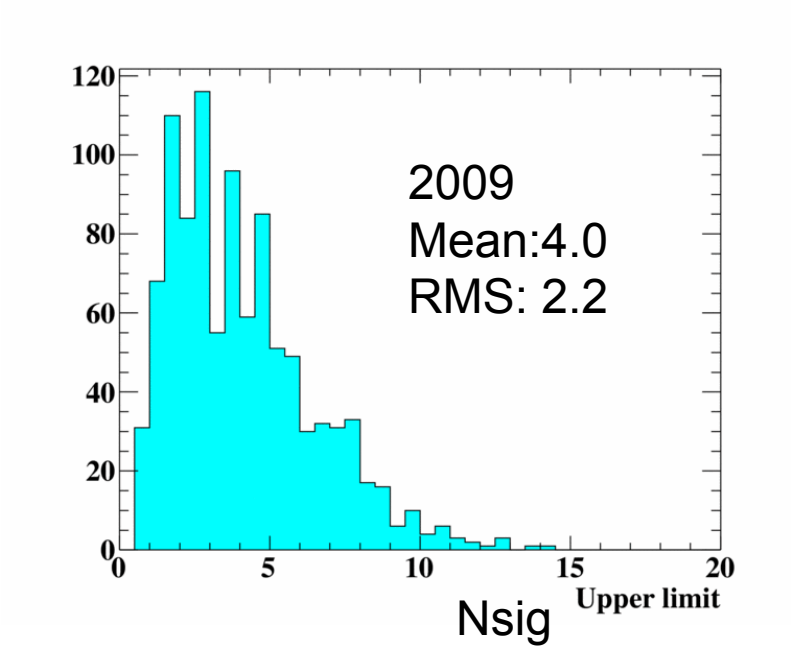


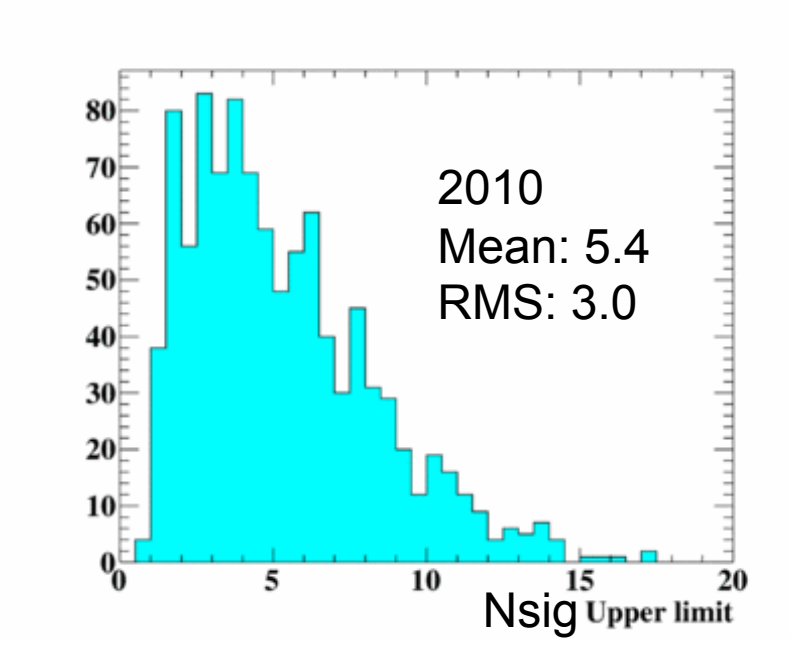
Summary of MEG performance

	2009	2010
Gamma E [σ_R, w>2cm – 63%]	1.9%	1.9%
Relative timing $T_{e\gamma}$ (RMD)	150ps	130ps
Positron E [Michel edge]	330 keV(82% core)	330 keV (79% core)
Positron θ	9.4 mrad	11.0 mrad
Positron φ [at zero]	6.7 mrad	7.2 mrad
Positron Z/Y	1.5/1.1(core) mm	2.0/1.1(core)mm
Gamma position	5(u,v)6(w) mm	5(u,v)6(w) mm
Trigger efficiency	91%	92%
Gamma efficiency	58%	59%
Positron efficiency	40%	34%
Muon stopping rate	$2.9\ 10^{7}$ s-1	$2.9\ 10^{7}$ s-1
DAQtime/real time	35/43 days	56/67 days
SES [analysis region]	$0.92\ 10^{-12}$	$0.44\ 10^{-12}$

Sensitivity on 2009-2010

Including systematics





Use median to define expected UL on BF at 90%C.L. (“sensitivity”)

2009: 3.3 10^{-12} ***2010: 2.2 10^{-12}***

Combined: 1.6 10^{-12}

Fit to $T_{e\gamma}$ sidebands (2010)

- Acc background counted in large region ($1<|T_{e\gamma}|<3.7$ns) and scaled

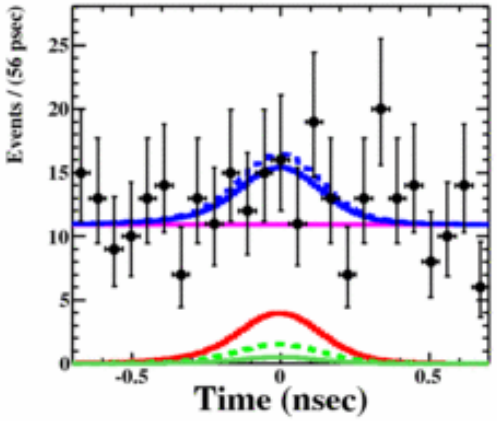
	[1.3,2.7] ns	**[-2.7,-1.3] ns**
NSIG	-4 +6 -2	2+8 -5
NBG	595+24 -24	620 +25 -25
NRMD	14 +24 -21	-8 + 19 -21
Upper limit on Nsig	2.7	5.2

Error from MINOS [1.645 σ]

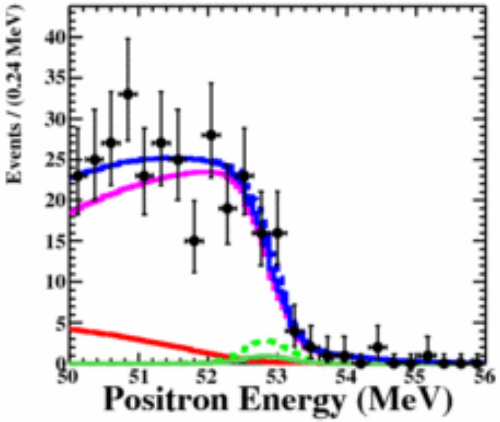
Upper limits well within the expectation

Fit to 2009 data

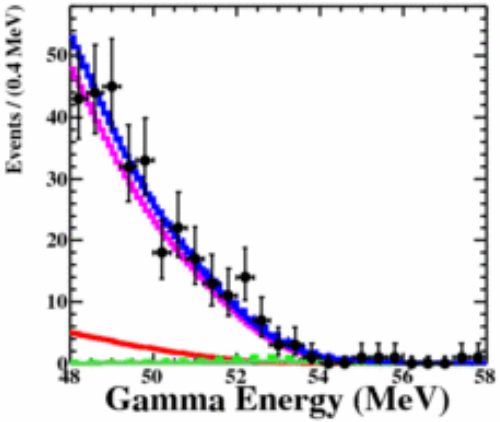
Total
Accidental
Radiative
signal



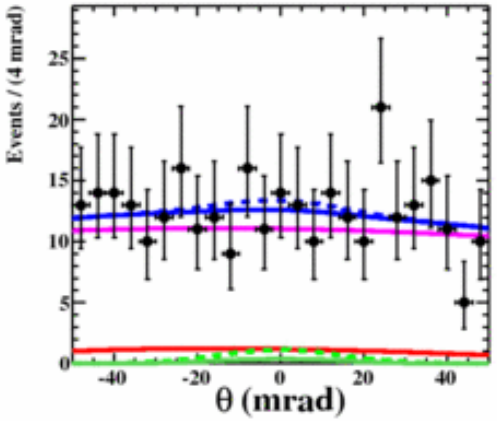
$T_{e\gamma}$



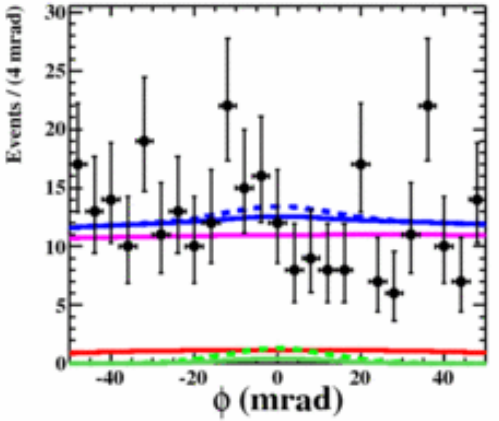
E_e



E_γ



$\theta_{e\gamma}$



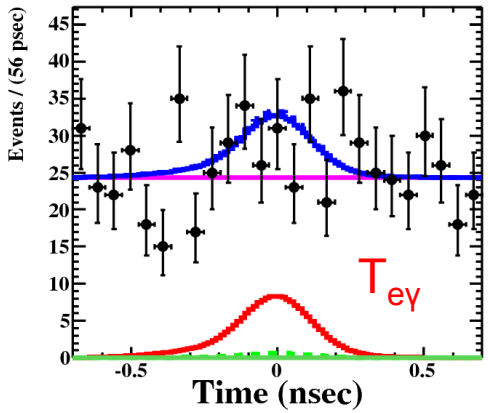
$\varphi_{e\gamma}$

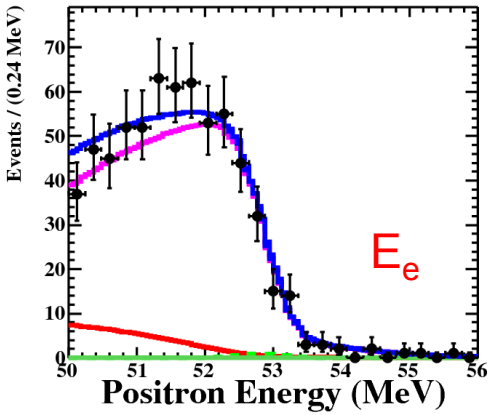
Param	Best fit	MINOS [1.645 σ]
NSIG	3.4	+6.6 - 4.3
NBG	273	+12 -12
NRMD	26.9	+4.5 - 4.5

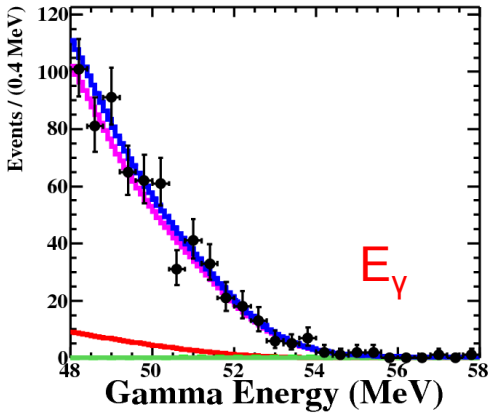
UL at 90% C.L on NSIG : 10.4

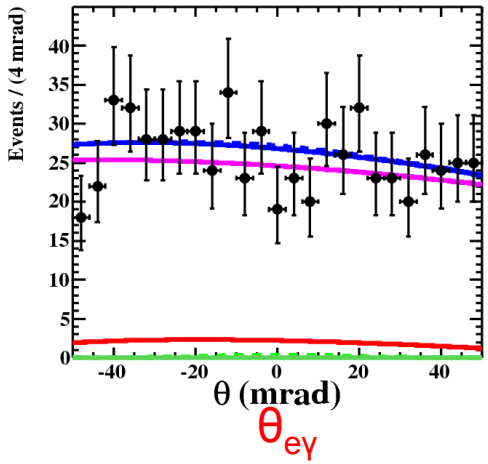
Fit to signal region 2010

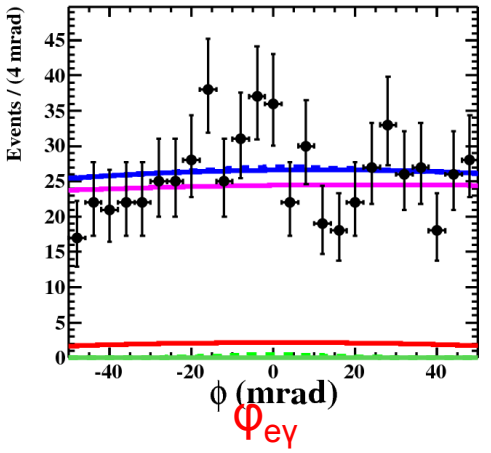
Total
Accidental
Radiative
Signal







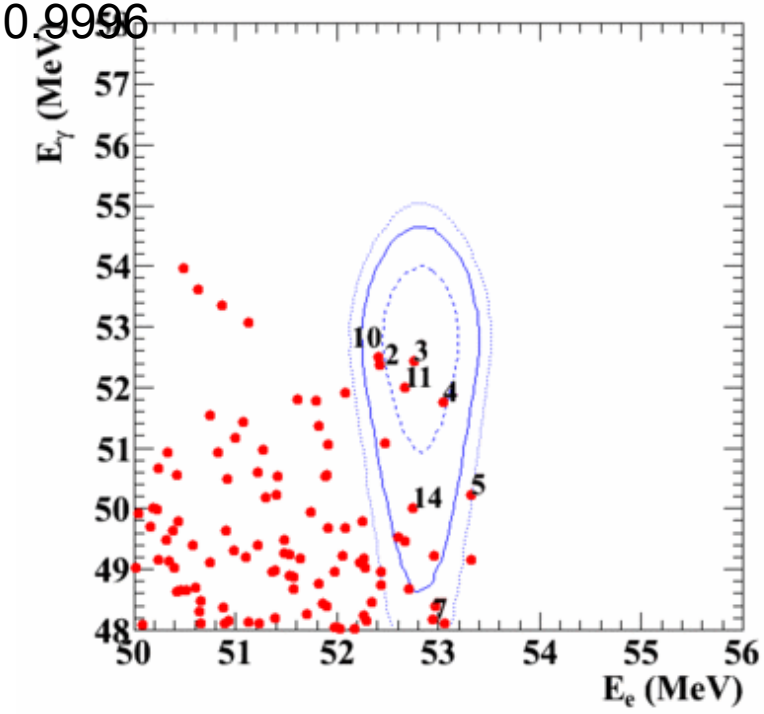




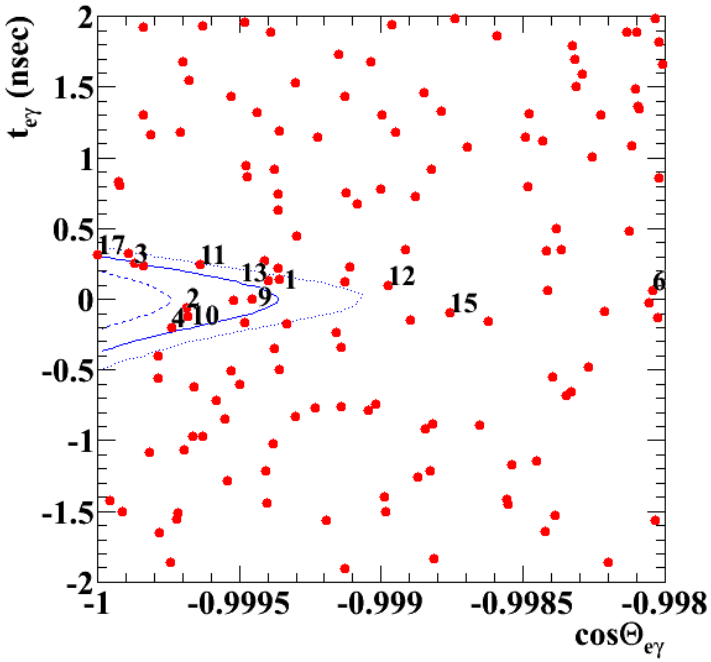
Param	Best fit	MINOS [1.645σ]
NSIG	-2.2	+5.0 -1.9
NBG	609	+19 -19
NRMD	50.2	+9.2 - 9.2

2009+2010 event distribution

Selection: $|T_{e\gamma}|<0.278$ns; $\cos\Theta_{e\gamma}<0.9996$



$51<E_\gamma<55$ MeV; $52.34<E_e<55$ MeV



Cosine Relative angle (3D)

Rank of variables
In each sample

$$R_{sig} = Log_{10}\left(\frac{L_{sig}}{0.1L_{RMD} + 0.9L_{BG}}\right)$$

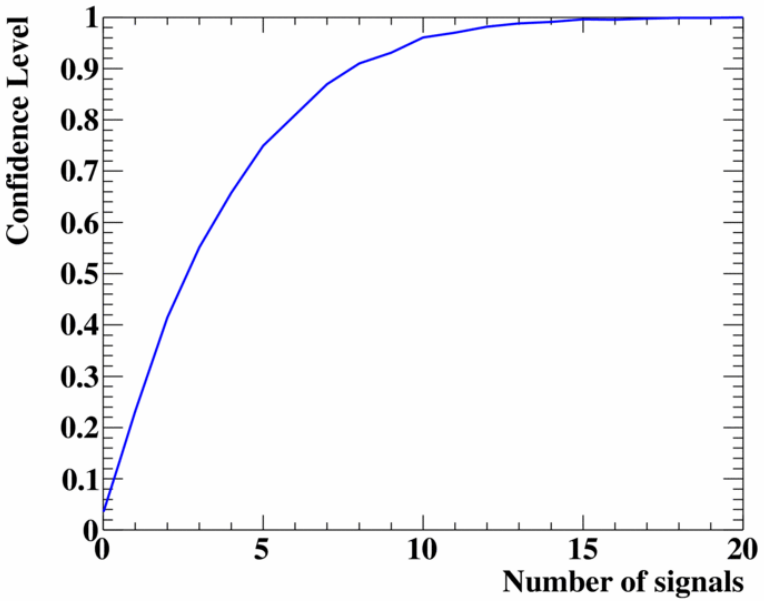
1, 1.64, 2 σ contours

MEG result on BF(μ→eγ)

Combination of 2009 and 2010 data gives a 2.4 10^{-12} UL at 90%C.L on BF

Combination account for different resolution in sub-dataset.

Constraints from sidebands used for accidental and radiative decay backgrounds.

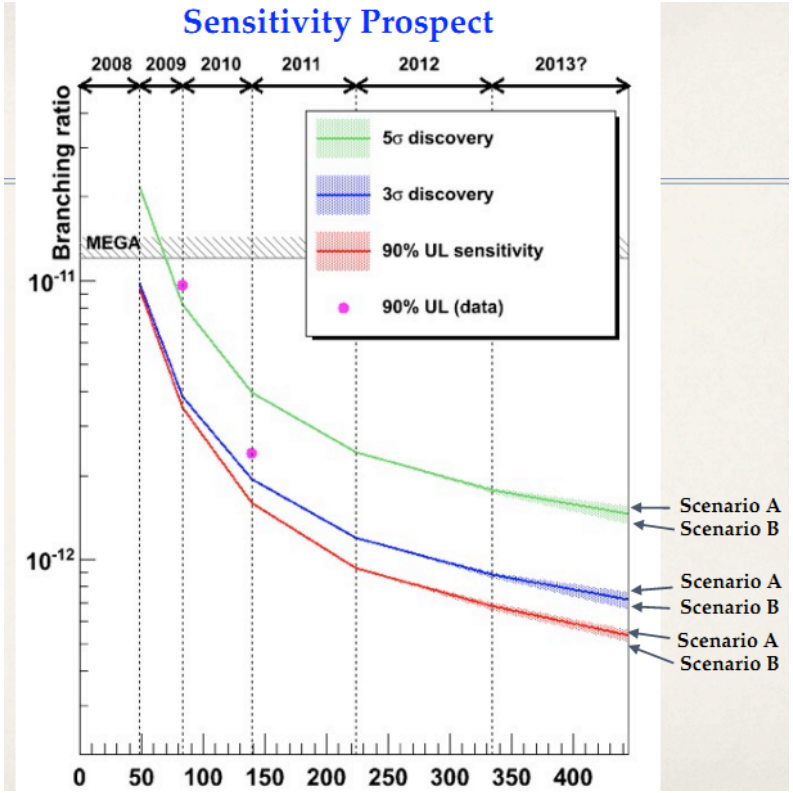


J.Adam et al Phys. Rev. Lett. **107**. *171801 (2011)*

Perspectives

Adding more data from 2011 and 2012 will reduced this limit

- Estimate with toyMC exp. and likelihood analysis



Small improvements on detector resolution foreseen

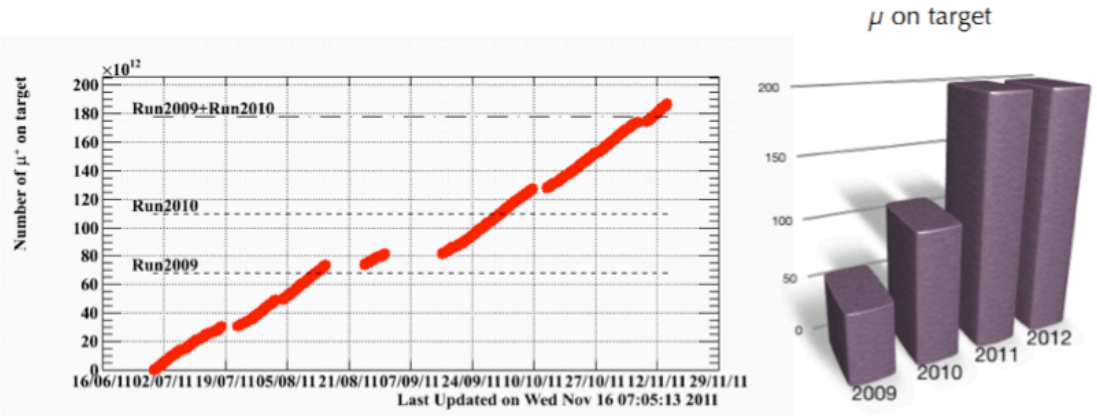
Conclusions

No evidence of signal in MEG dataset

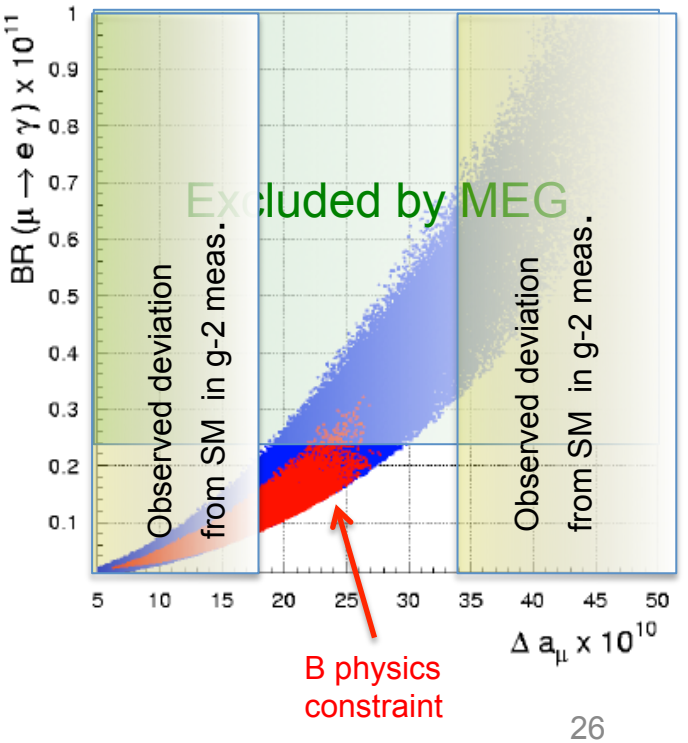
Combination of 2009 and 2010 improves by a factor 5 the best MEGA limit

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

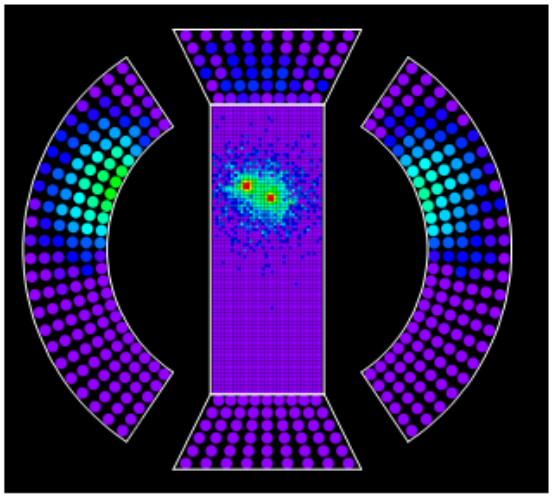
MEG is already finalizing 2011 data analysis



Restarting data-taking in May2012

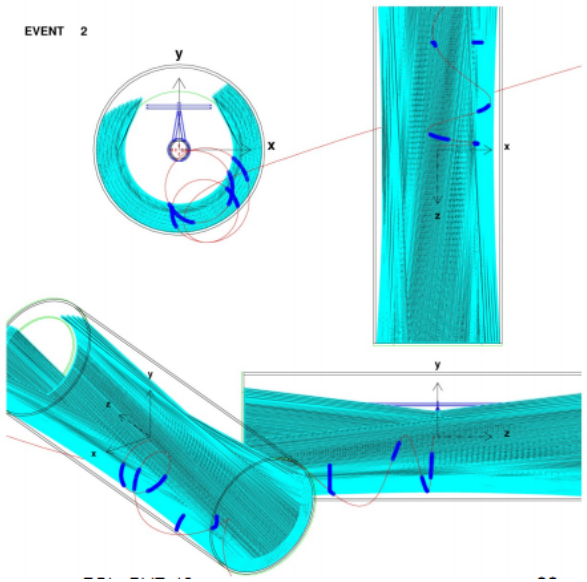


Towards an upgraded MEG



New LXe SiPM readout
(higher efficiency and resolution
for shallow events)
Ionization readout investigated

Studying a cylindrical
all-stereo layers DCH



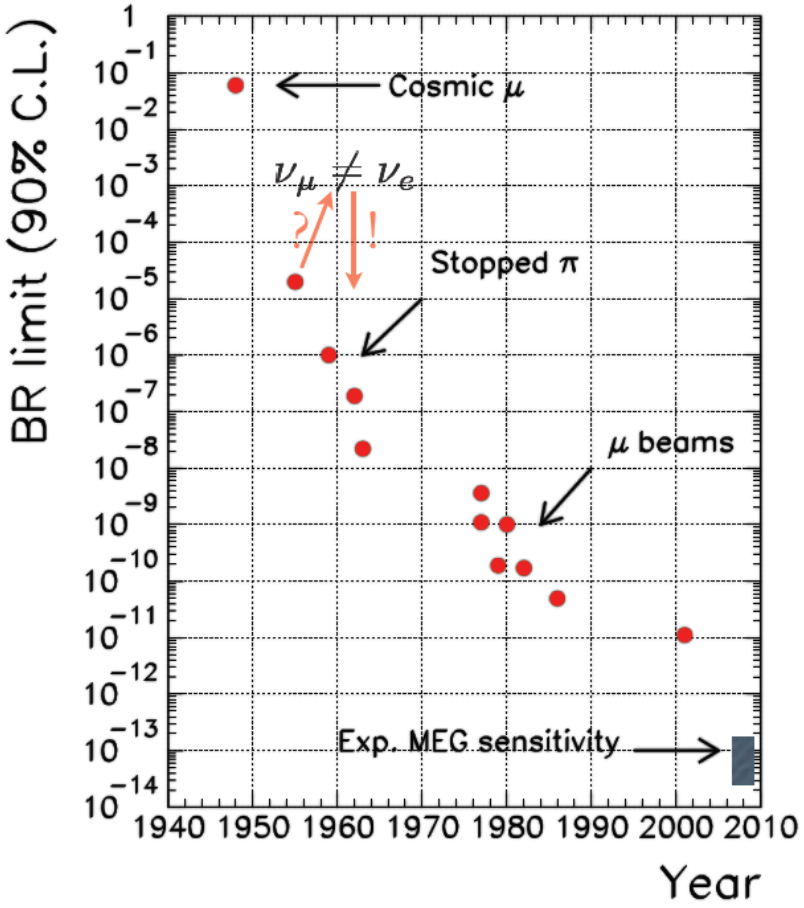
Active target

Aiming to

5 10^{-14} sensitivity!

Back-up slides

A long quest…



- Step forward in sensitivity linked to technology upgrades!
- Best upper limit on BF before MEG

$<1.2\cdot10^{-11}$ @90%C.L. MEGA

MEG plans to improve two order of magnitudes this limit

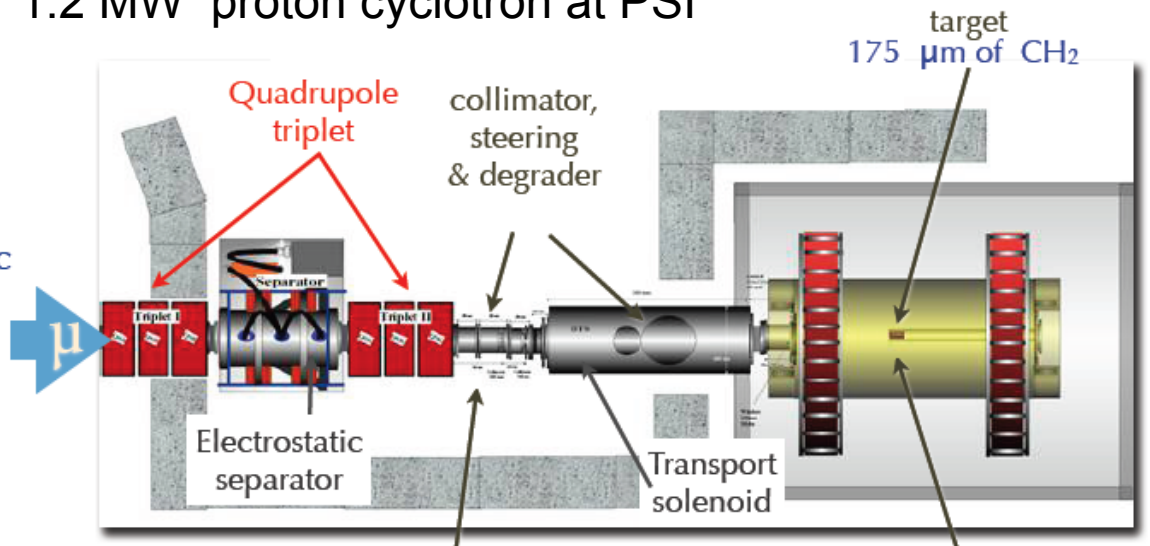
Beam line details

1.2 MW proton cyclotron at PSI

πE5 beam line at PSI

Optimization of the beam elements:

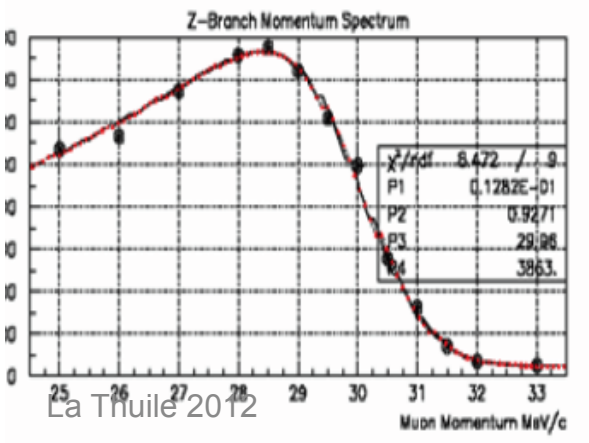
- Muon momentum ~ 29 MeV/c
- Wien filter for μ/e separation
- Solenoid to couple beam and spectrometer (BTS)
- Degrader to reduce the momentum for a 175 μm target

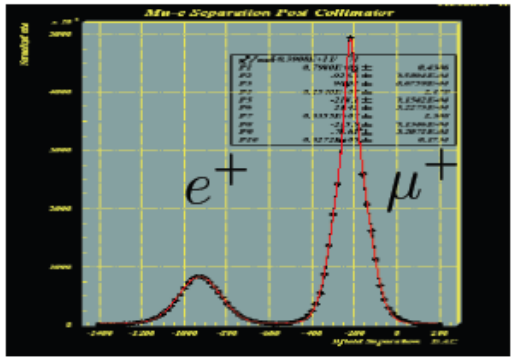


μ/e separation 11.8 cm (7.2 σ)

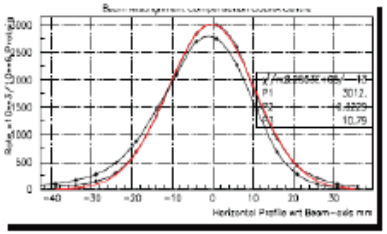
R_μ (exp. on target) >6 10^7 μ^+/s

μ spot (exp. on target) $\sigma_V \approx \sigma_H \approx$ 11 mm





σ_x = 11 mm



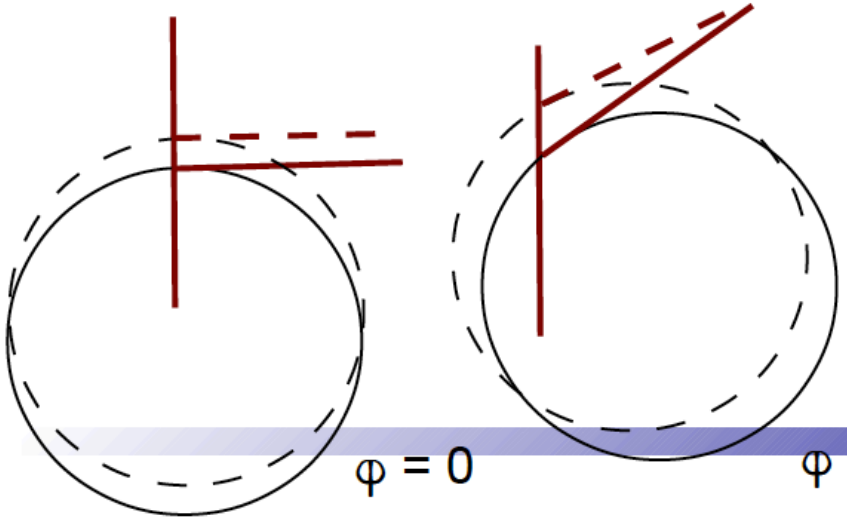
σ_y = 11 mm

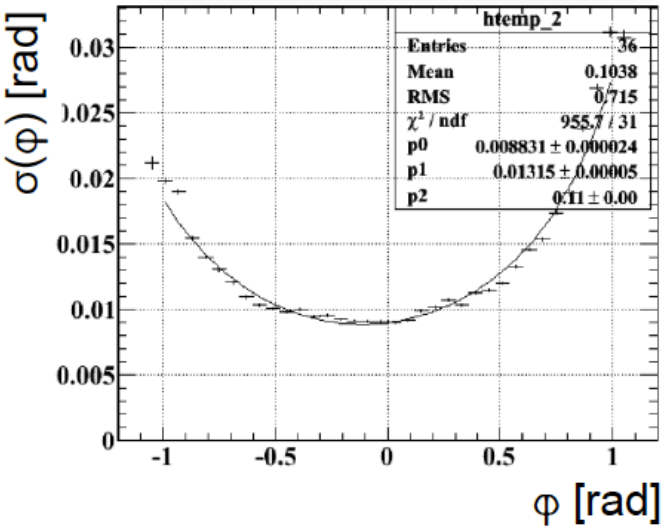
A note on phi resolution

- Geometrical effects worsen the effective φ resolution at φ ≠ 0:

$$\sigma_\phi = \sqrt{\sigma_0^2 + (k \tan \phi)^2}$$

parameterization from a simple geometrical model





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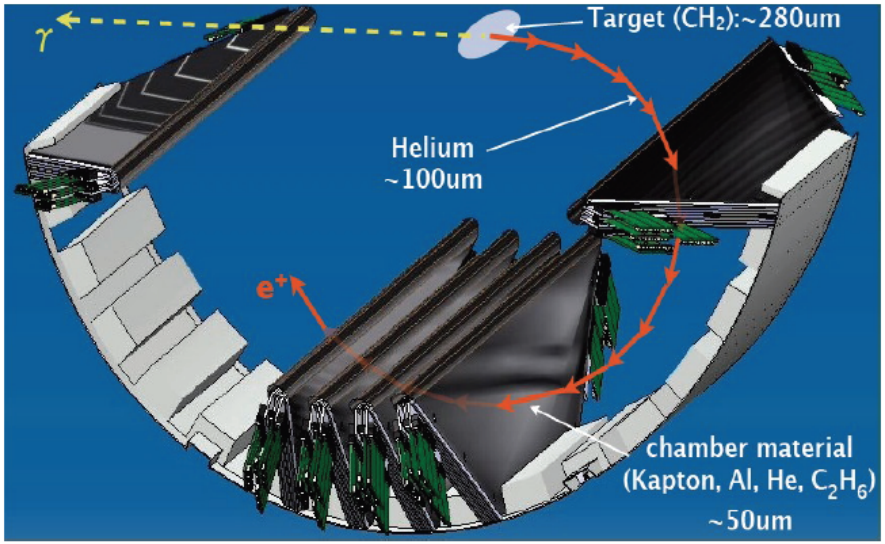
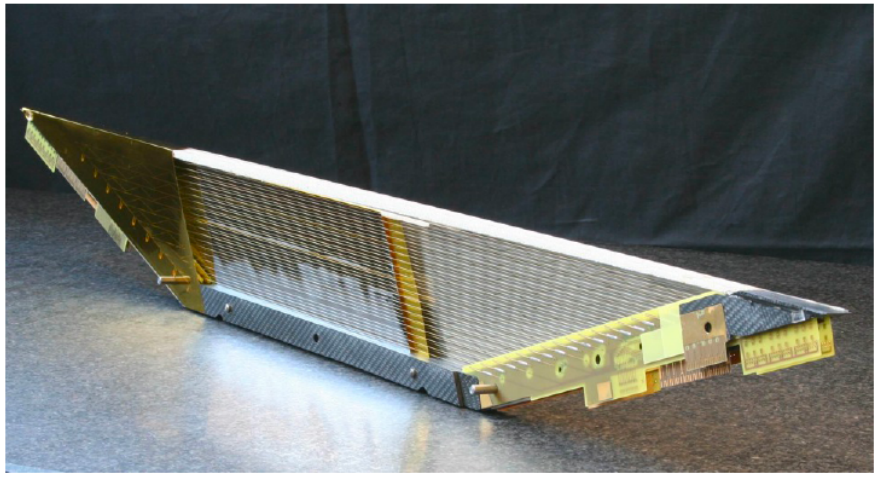
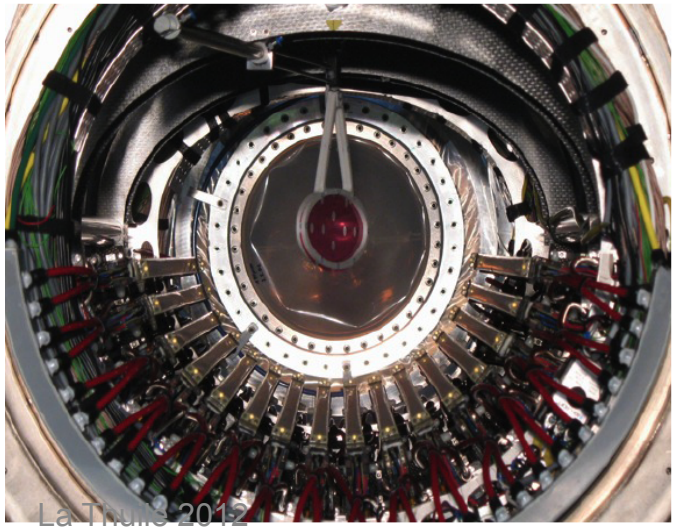
Low mass Drift chambers



A DC Module

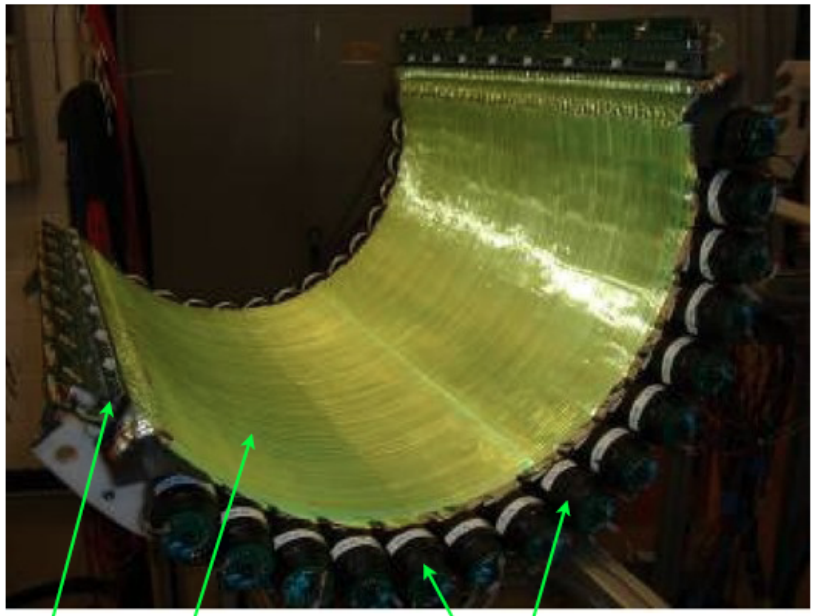




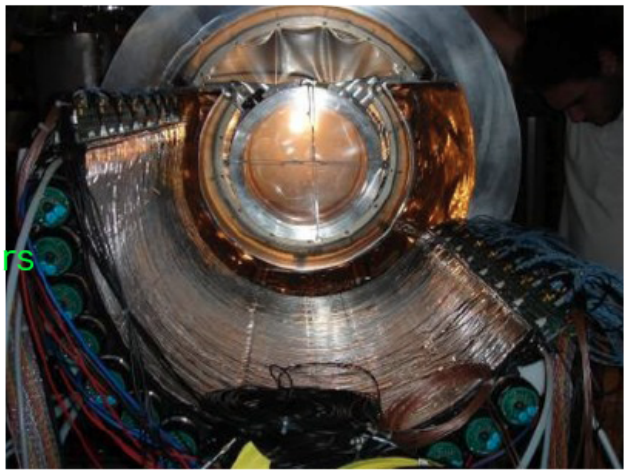
- Only 2 10^{-3} X_0 along track
- Operated with 50:50 He:ethane mixture
- Installed in a He-filled bag inside COBRA

σ(z)~700μm(core)
σ(r)~250μm(core)

Positron Timing Counters



- Scintillator arrays placed at each end of the spectrometer
- Measures the impact point of the positron to obtain precise timing

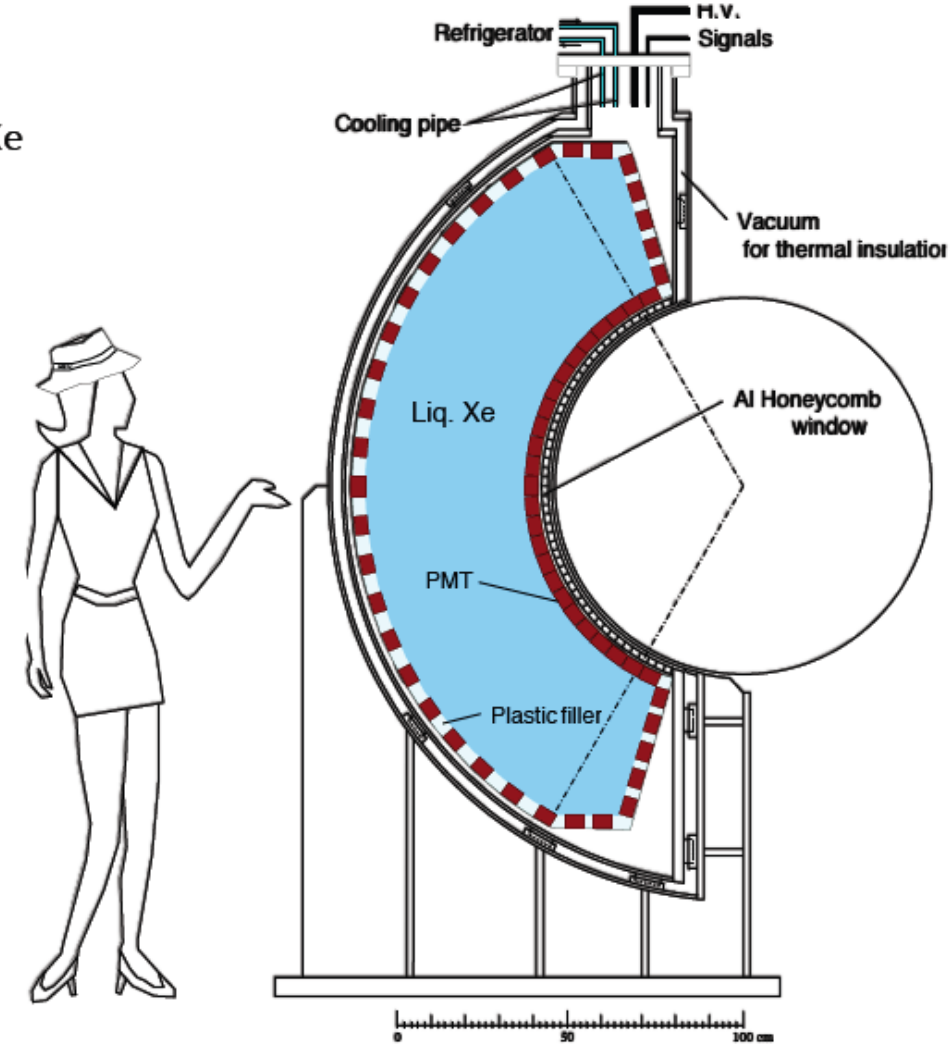


installing inside COBRA

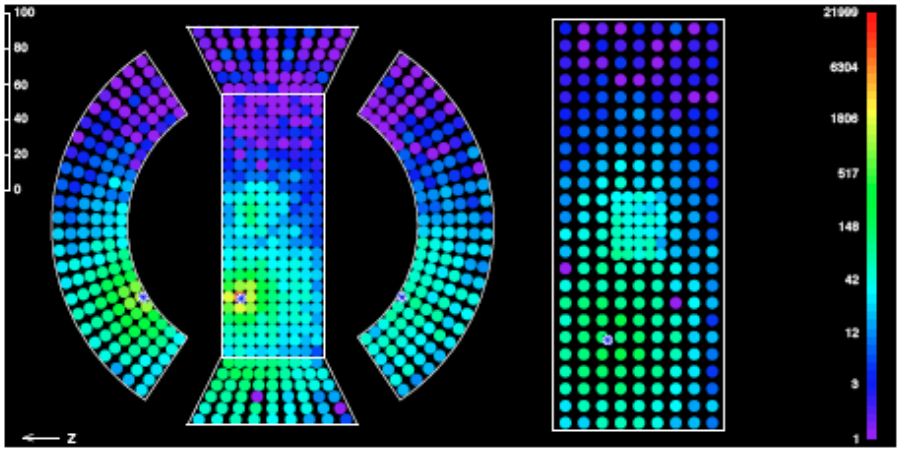
- Critical for triggering (time coincidence with calorimeter and rough positron direction)

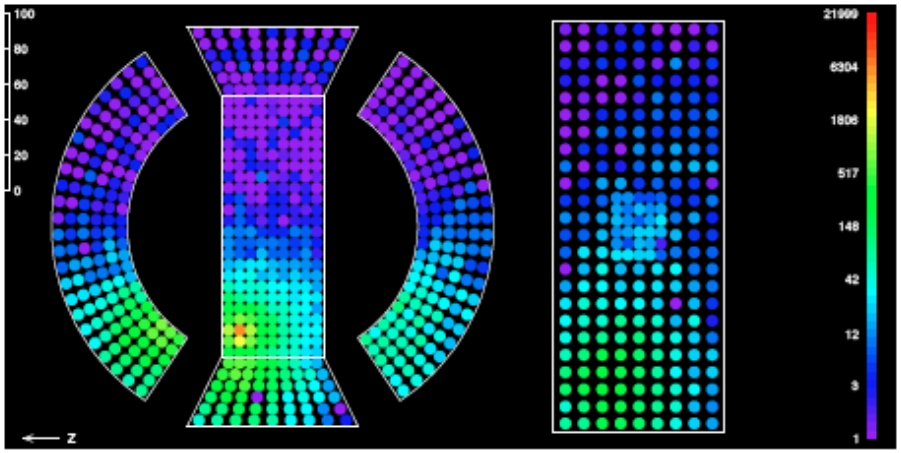
A liquid Xenon Photon Detector

- γ Energy, position, timing
- Homogeneous 0.8 m^3 volume of liquid Xe
  - 10 % solid angle
  - $65 < r < 112$ cm
  - $|\cos\theta| < 0.35 \quad |\phi| < 60^o$
- Only scintillation light
- Read by 848 PMT
  - 2'' photo-multiplier tubes
  - Maximum coverage FF (6.2 cm cell)
  - Immersed in liquid Xe
  - Low temperature (165 K)
  - Quartz window (178 nm)
- Thin entrance wall
- Singularly applied HV
- Waveform digitizing @2 GHz
  - Pileup rejection

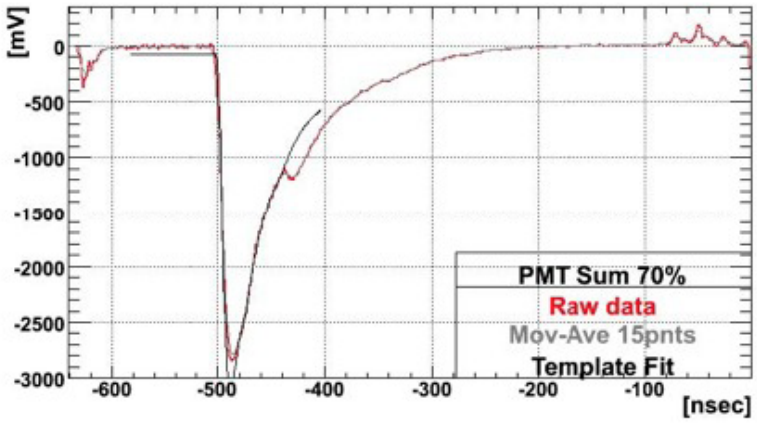


Pile-up rejection





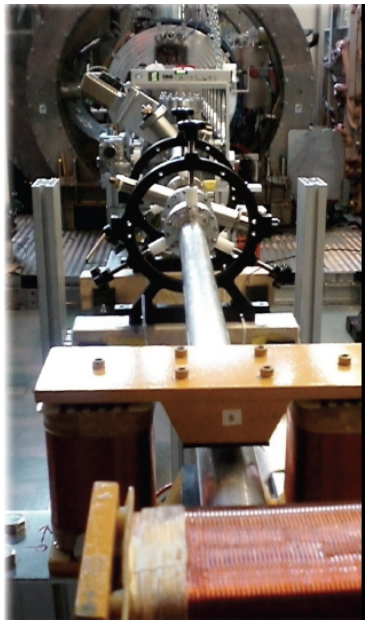
- Multiple photons in the same event recorded by the LXe
- Waveform analysis, timing and position resolution helps in rejecting this



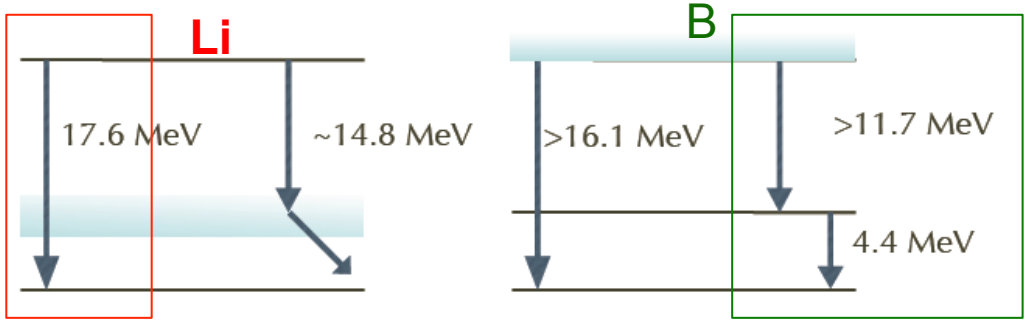
Expected $T_{e\gamma}$ resolution

Contribution	resolution(ps) 2009/2010	Notes
T_γ	~96/67	
XEC intrinsic	~38/36	- measured
DRS	~69/24	- measured - diff. boards improved vs 2009
other contributions (depth rec. uncert.)	~50 for both runs	
T_e	~107	
T_{TC} +DRS	~65	- measured
L_e/c	~75	- scaled from MC (factor 1.5)
TC calib	~40	- measured
$T_{e\gamma}$	~144/126	sum of the above contributions

A special accelerator



Reaction	Peak energy	σ peak	γ-lines
Li(p,γ)Be	440 keV	5 mb	(17.6, 14.6) MeV
B(p,γ)C	163 keV	2 10^{-1} mb	(4.4, 11.7, 16.1) MeV

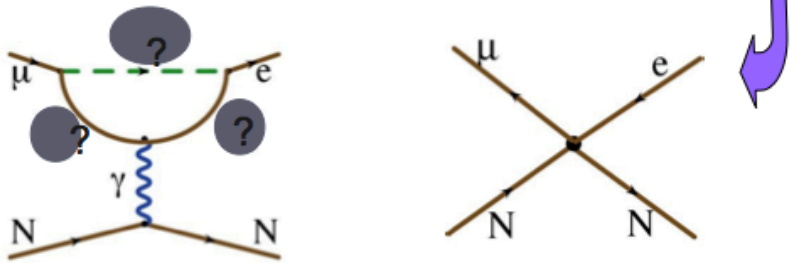


- A Cockroft-Walton accelerator accelerates protons up to ~1 MeV hitting a special target ($Li_2B_4O_7$) to produce monochromatic photons
- Reaction with one or two (coincident) photons to calibrate and monitor LXe energy measure and LXe-TC relative timing

Model independent picture

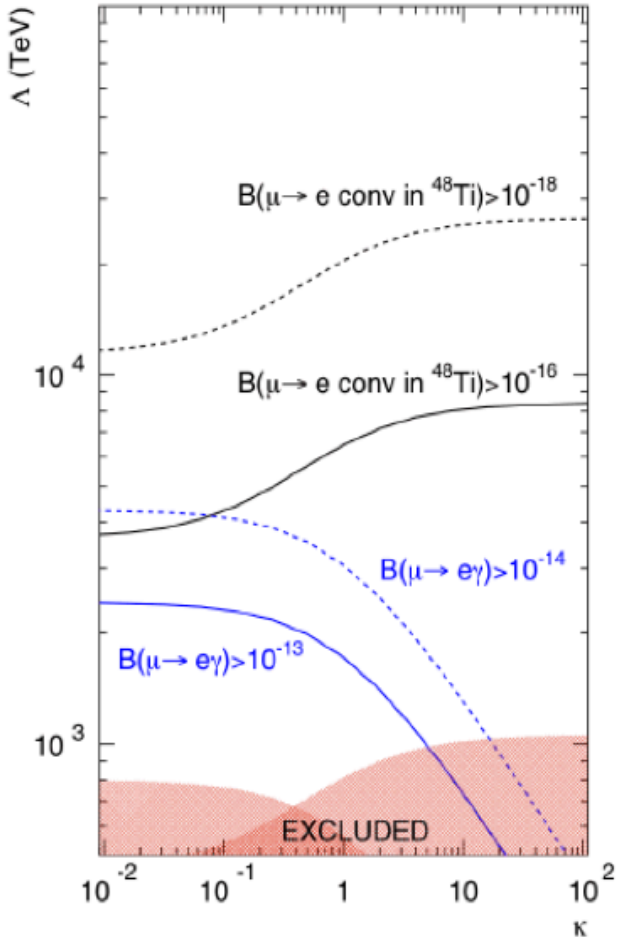
Mass reach 10^4 TeV

$$\frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right).$$



Loops

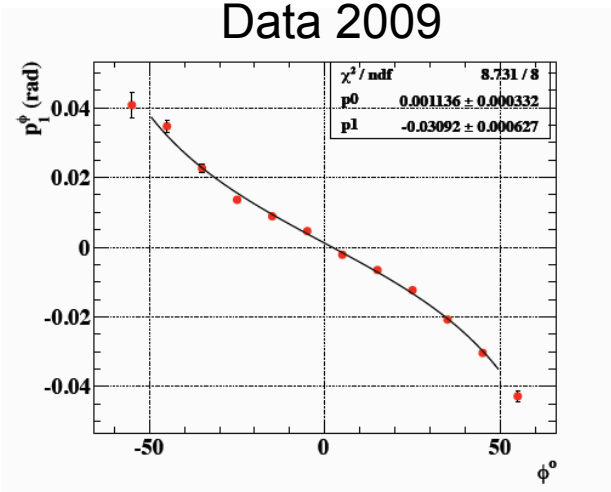
Contact terms



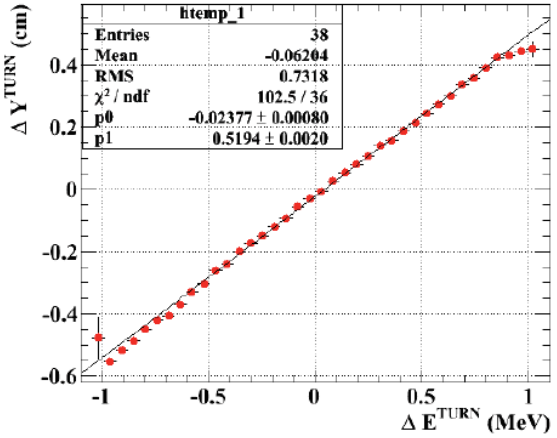
Positron variables correlation

- Positron PDF takes into account correlations among angles and momentum
  - Geometrical effect due to target constraint
  - Very good agreement data with model prediction

Data 2009



$$\delta\phi_e = -2\tan\phi_e\frac{\delta R}{R} = -2\tan\phi_e\frac{\delta E}{E}$$



$$\delta Y = 2\delta R\cos\phi_e + R\sin\phi_e\delta\phi_e = \frac{2R}{\cos\phi_e}\frac{\delta E}{E}$$

Time sideband fits and Sensitivity

Time sidebands	[1.3,2.7] ns	[-2.7,-1.3] ns
NSIG	-7 +5 -3	-2+5 -2
NBG	278+17 -17	266 +17 -16
NRMD	-5 +17 -14	10 + 18 -15
Upper limit on Nsig	3.8	3.0

Error from MINOS [1.645 σ]

Analysis region

$48<E_\gamma<58$ MeV

$50<E_e<56$ MeV

$|T_{e\gamma}|<0.7$ns

$|\theta_{e\gamma}|,|\varphi_{e\gamma}|<50$ mrad

Average UL on Nsig: 4.0

Results from sideband fits are consistent with expectation from toy exp's

Normalization evaluation

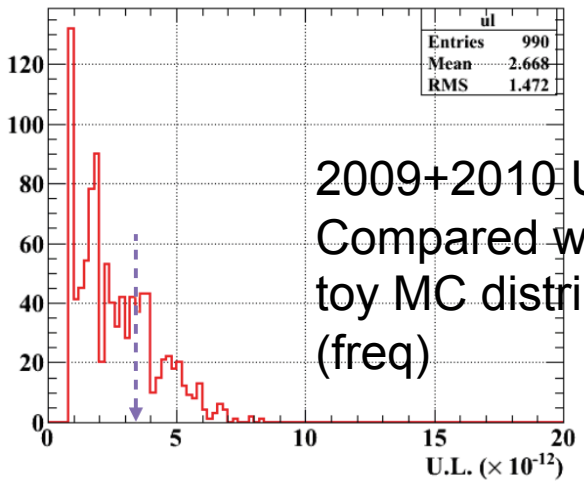
$$
\begin{aligned}
N_{sig} &= N_\mu \times Br_{e\gamma} \times \tau_{e\gamma} \times \epsilon^{trig}_{e\gamma} \times G^{DC}_{e\gamma} \times A^{TC}_{e\gamma} \times \epsilon^{DC}_{e\gamma} \times A^{LXe}_{e\gamma} \times \epsilon^{LXe}_{e\gamma} \\
N_{e\nu\bar{\nu}} &= N_\mu \times Br_{e\nu\bar{\nu}} \times \tau_{e\nu\bar{\nu}} \times \epsilon^{trig}_{e\nu\bar{\nu}} \times G^{DC}_{e\nu\bar{\nu}} \times A^{TC}_{e\nu\bar{\nu}} \times \epsilon^{DC}_{e\nu\bar{\nu}} \times f^{E}_{e\nu\bar{\nu}} \times P
\end{aligned}
$$

- Normalization factor from Michel
  - $k^{2009}_{Michel} = (1.03 \pm 0.09) \times 10^{12}$ (9%)
  - $k^{2010}_{Michel} = (2.22 \pm 0.20) \times 10^{12}$ (9%)

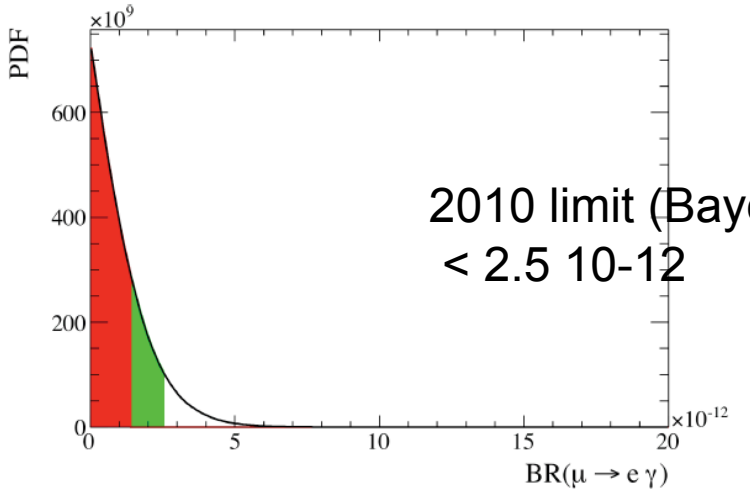
- Normalization factor from RD
  - $k^{2009}_{RD} = \left(1.15 \pm 0.082(stat) \pm 0.065(sys)\right) \times 10^{12}$ (9.1%)
  - $k^{2010}_{RD} = \left(2.29 \pm 0.14(stat) \pm 0.23(sys)\right) \times 10^{12}$ (11.8%)

Alternative analysis

– UL extraction on 2010 data was done with alternative analysis: averaged PDF (no event-by-event information) different functional forms for PDFs
  » Done by Italian groups independently from our Jap colleagues
  » Both Bayesian and frequentist approach
  » Very useful to understand problems or develop studies



2009+2010 UL
Compared with
toy MC distribution
(freq)

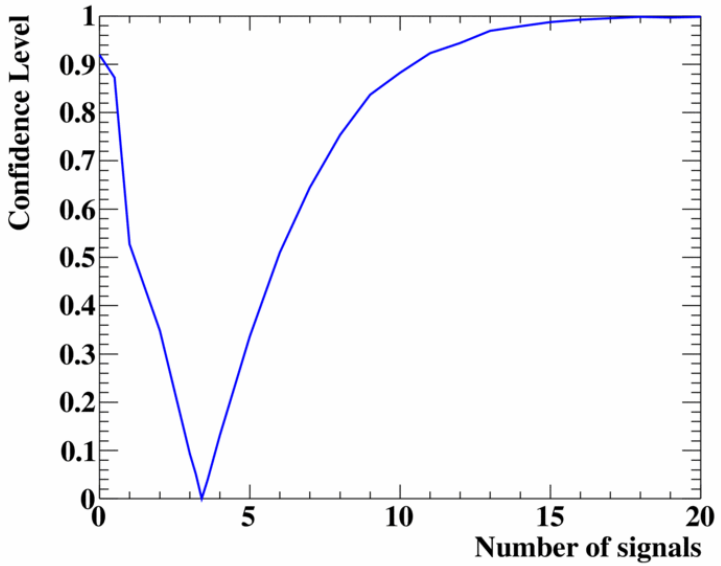


2010 limit (Bayes)
< 2.5 10-12

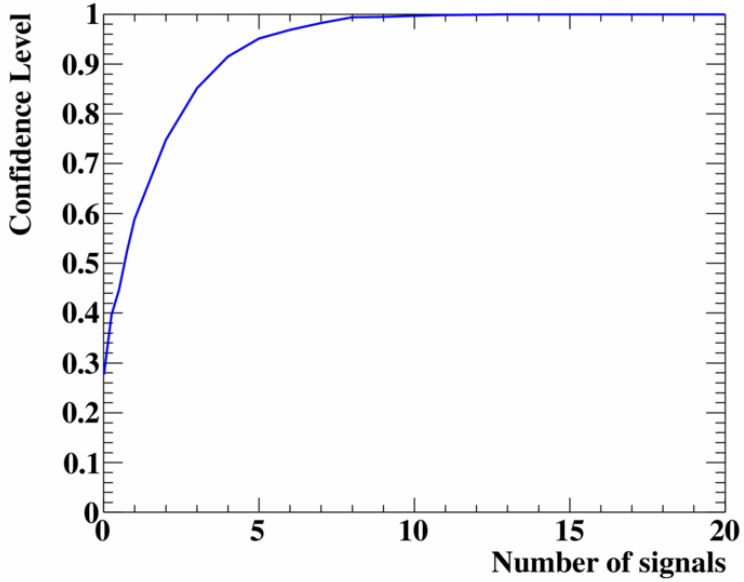
Confidence intervals

Including systematics

2009



2010



Limit on Branching fraction (90%C.L.)

Lower Limit: $0.2\ 10^{-12}$
Upper Limit: $9.6\ 10^{-12}$
CL at 0 : 0.92

Upper Limit : $1.7\ 10^{-12}$

Systematics effects estimate

2010 data were fitted 100 times, with changing PDF using its uncertainty.
RMS of the unconstrained (negative) best fit and the UL is calculated

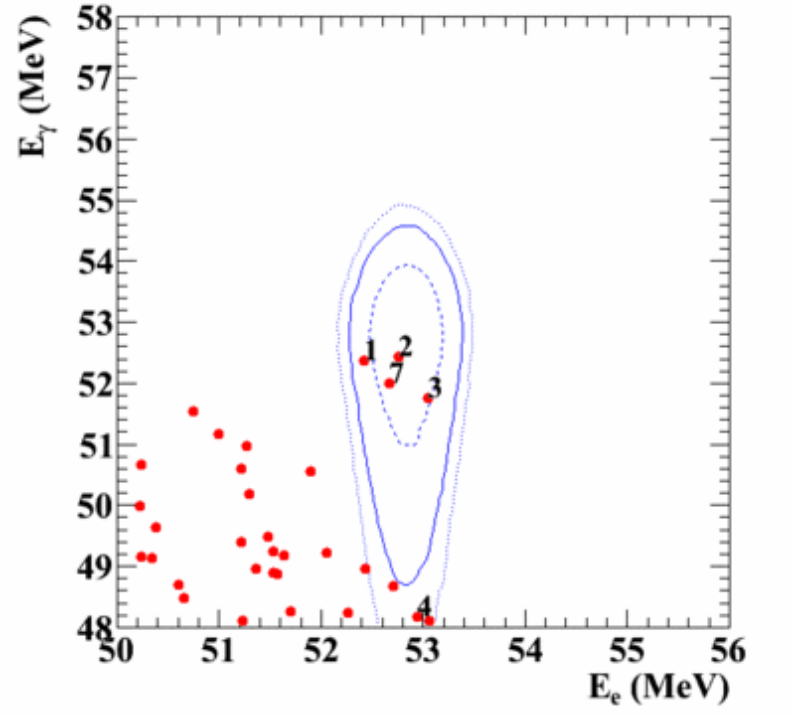
	Uncertainty	Nsig RMS	UL RMS
θeγ center	3.4 ⊕ 2 mrad	1.8	0.7
θ vs ϕ	25%	0.6	0.3
Ee bias for correlation	O(100 keV)	0.2	0.3
ϕeγ center	3.4 ⊕ 2 mrad	0.4	0.3
δϕeγ vs δEe correlation anomaly	Betta	0.2	0.2
δze vs δθe corr	Beta/Francesco note	0.5	0.2
γ position resolution	0.3(UV), 0.7(W) mm	0.4	0.2
Time center	15 psec	0.5	0.2
Eγ BG shape	Fitting error	0.4	0.1
ϕe and vertex resolution	Beta/Francesco note	0.1	0.1
Time signal shape	Fitting error	0.1	0.1
θe and vertex resolution	Beta/Francesco note	0.2	0.1
Ee tail bias	250 keV	0	0.1
Eγ signal shape	Fitting error	0.1	0.1
δϕeγ vs δEe corr	Beta/Francesco note	0.1	0.1
σϕe vs ϕe	Beta/Francesco note	0.1	0.1
Eγ scale	0.31%	0.6	0
Ee Michel shape	Fitting error	0.1	0
Ee bias	25 keV	0	0
Ee signal shape	Fitting error	0	0
BG angle shape	Fitting error	0	0
All		**2.2**	**0.9**

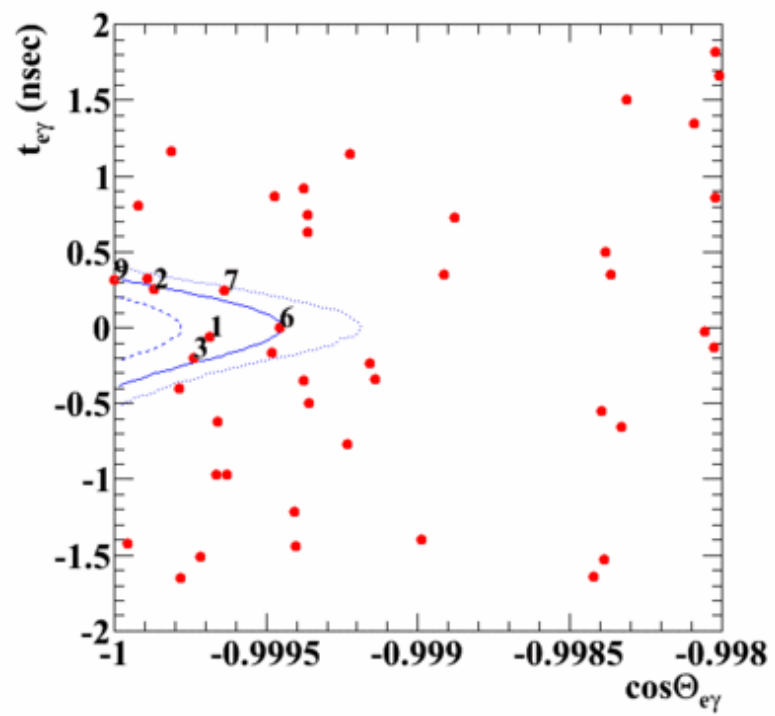
Target geometry

B-field and alignment

2009 data events distribution

Selection: $|T_{e\gamma}|<0.278$ns; $\cos\Theta_{e\gamma}<0.9996$ $51<E_\gamma<55$ MeV; $52.34<E_e<55$ MeV





Rank of variables
In each sample

1, 1.64, 2 σ contours

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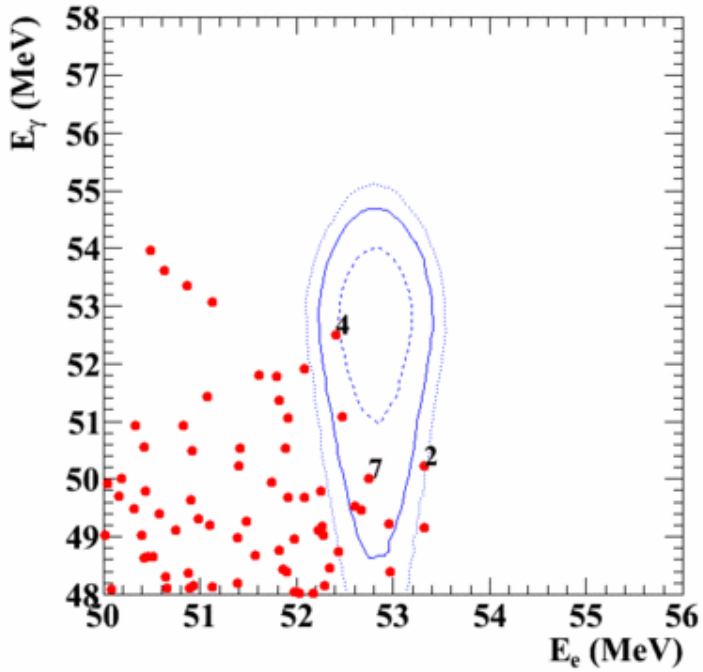

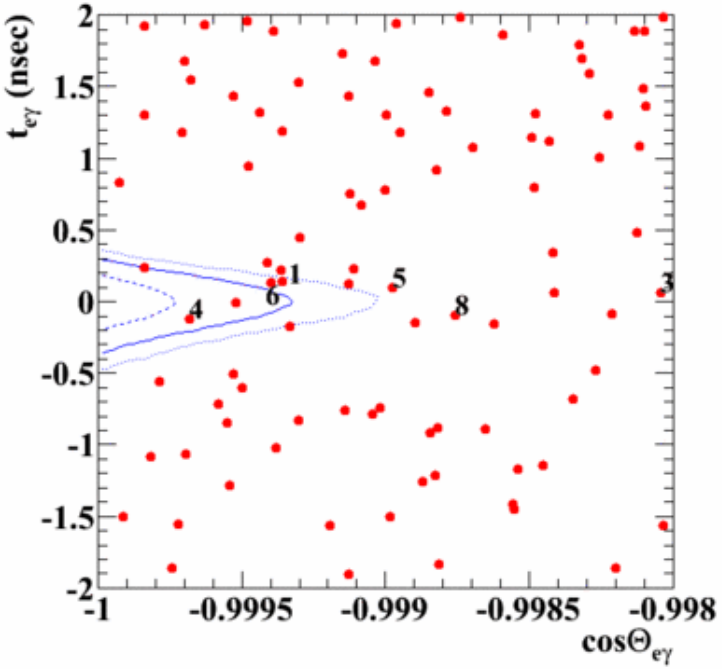

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