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The University of Tokyo
on behalf of the MEG Collaboration

MEG Experiment: status and prospects

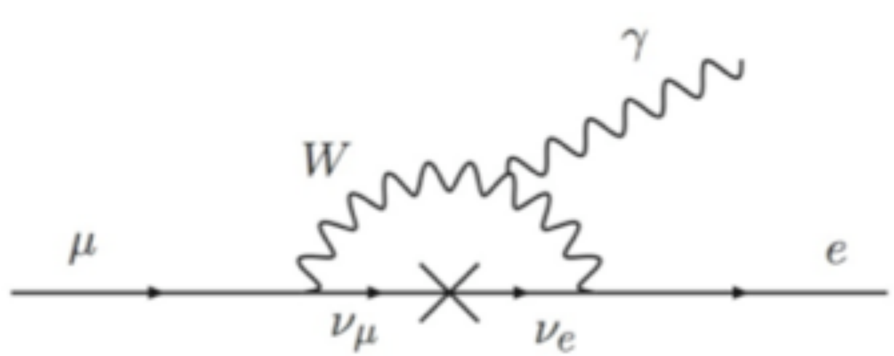
Tuesday, 24th June 2012
NuFact 2012
William & Mary University, Williamsburg, Virginia

Lepton Flavour Violation

- Lepton Flavour Conservation is an accidental symmetry of SM:
  - Not related to the gauge structure of the theory
  - Naturally violated in SM extensions

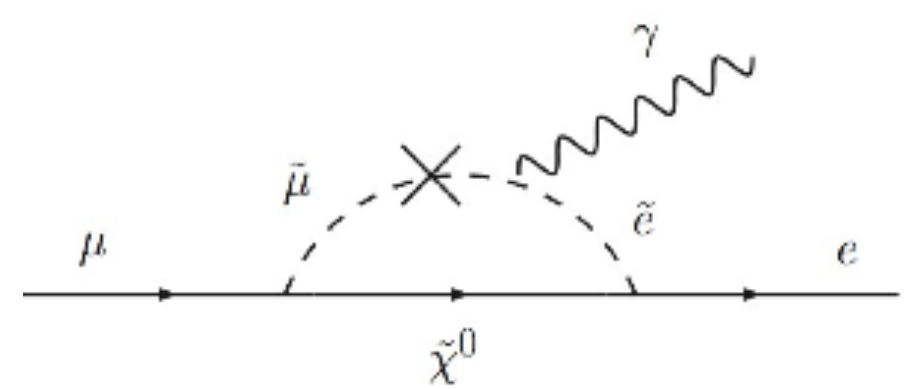
Observation of μ → e γ would be an unambiguous evidence of NP beyond SM

- LFV already observed in the neutral sector: neutrino oscillations
- LFV in charged sector could be mediated by
  - neutrino oscillation in SM extensions with massive neutrinos
  - off-diagonal terms in the slepton mass matrix (through RG evolution) in SUSY



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

BR (μ → e γ) ~ 10^{-54}



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

BR (μ → e γ) ~ 10^{-13} - 10^{-14}

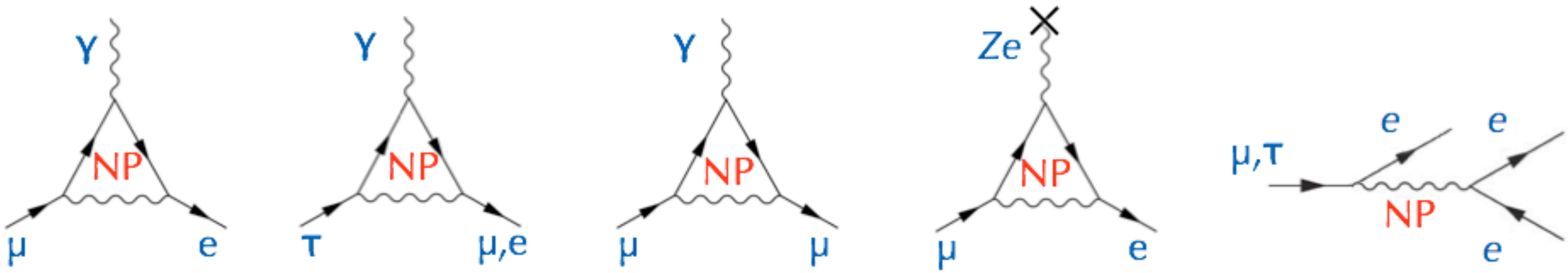
Charged LFV processes

Model independent effective cLFV Lagrangian

$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

new coupling (SUSY, heavy ν)

contact term (leptoquark, Z'...)



$\mu \to e\gamma$ | $\tau \to \mu\gamma$, $\tau \to e\gamma$ | $(g-2)_\mu$ | $\mu^- N \to e^- N$ | $\mu \to eee$

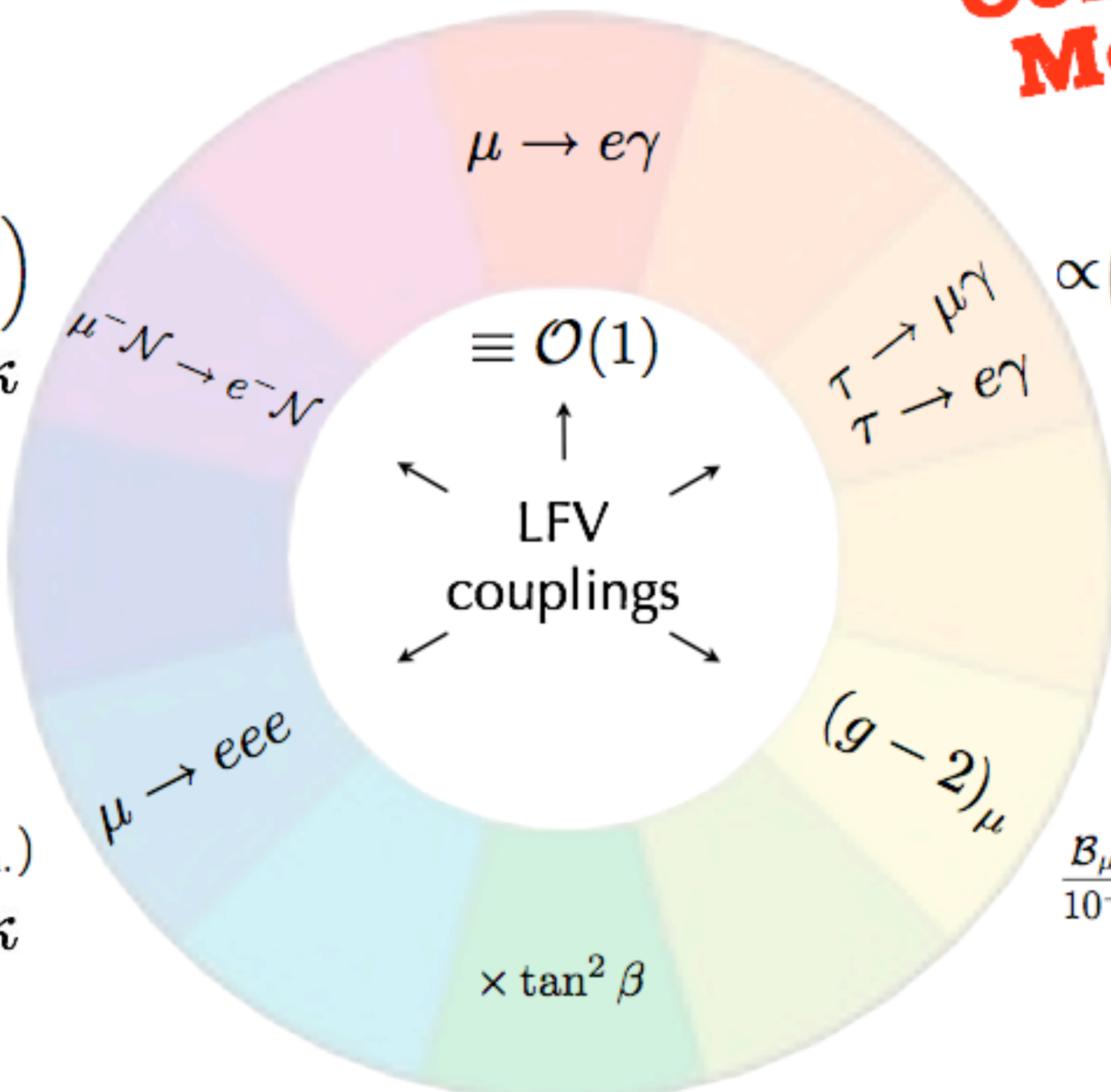
- cLFV processes are a wide field of research
  - LFV decays
  - Muon to electron conversion in matter
  - Anomalous magnetic moment

The cLFV wheel

Common Models

$\propto \left(\frac{Z\alpha}{\pi}\right)$

$+ \propto \kappa$



$\propto \left(\frac{m_\tau}{m_\mu}\right)^{2\div 4}$

$\frac{\mathcal{B}_{\mu e\gamma}}{10^{-12}} \propto \left(\frac{\Delta a_\mu}{10^{-9}}\right)^2$

$\propto (\alpha_{\mathrm{e.m.}})$

$+ \propto \kappa$

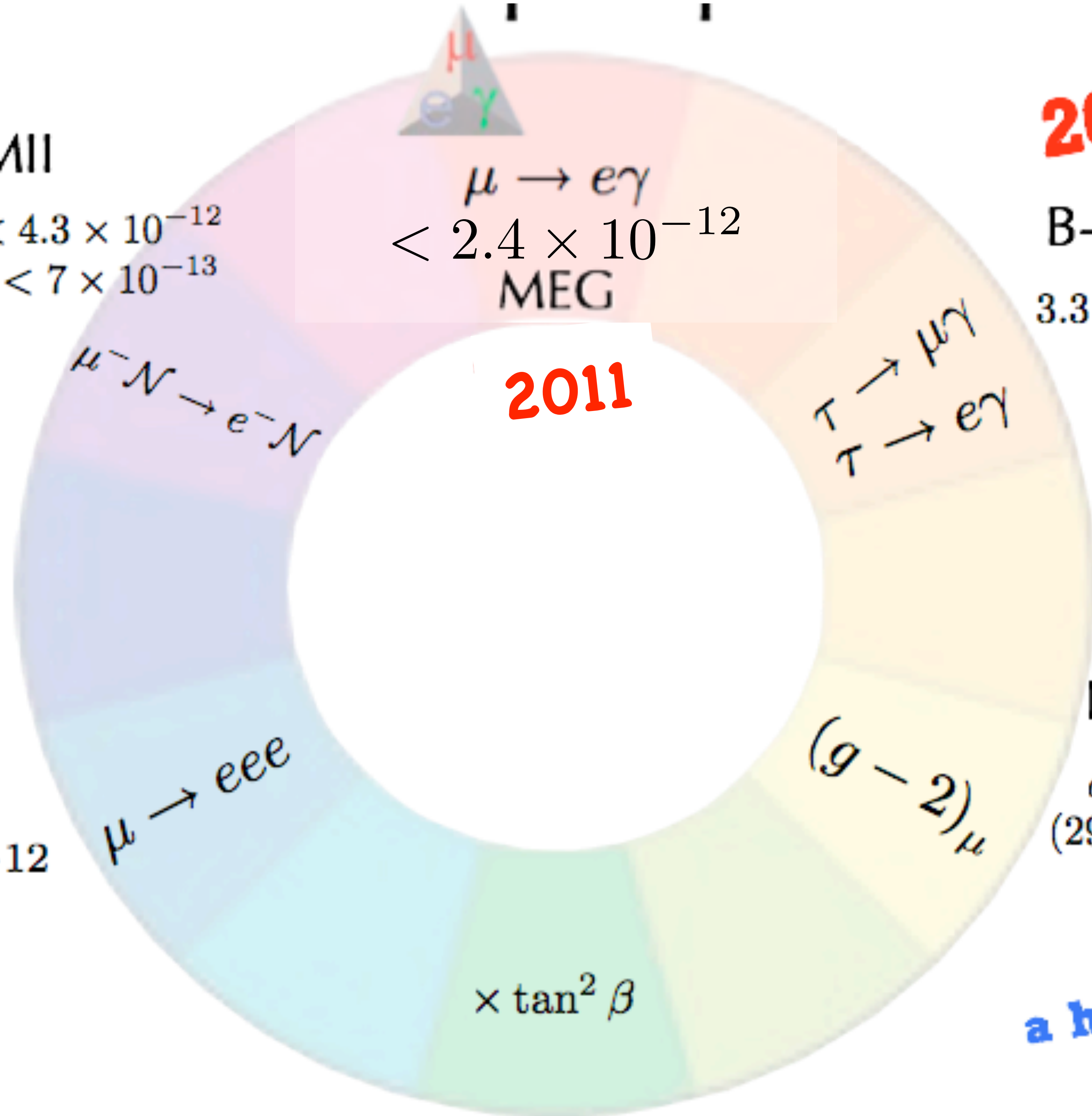
Present Limits

SINDRUMII

$\mathcal{B}(\mu \mathrm{Ti} \to e\mathrm{Ti}) < 4.3 \times 10^{-12}$

$\mathcal{B}(\mu \mathrm{Au} \to e\mathrm{Au}) < 7 \times 10^{-13}$

2006



2010

B-factories

$3.3 \div 4.5 \times 10^{-8}$

BNL E821

$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (296 \pm 81) \times 10^{-11}$

2004

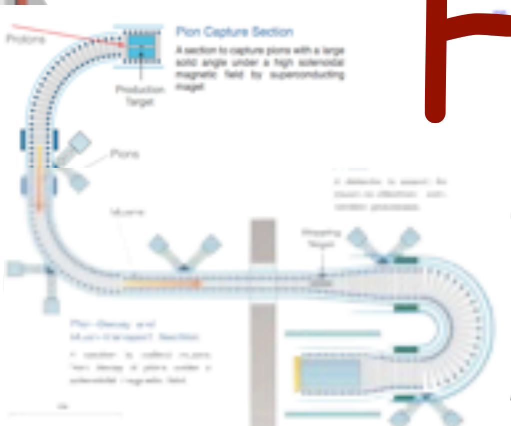
a hint for NP?

SINDRUM

1×10^{-12}

1988

Future Prospects



mu2e COMET

$10^{-15} - 10^{-17}$

2017→ 2019

DeeMe

$\mu^- N \rightarrow e^- N$

$\mu \rightarrow e\gamma$

MEG

~ 10^{-13}

running →2013

MEG II ? 5×10^{-14}

2015?

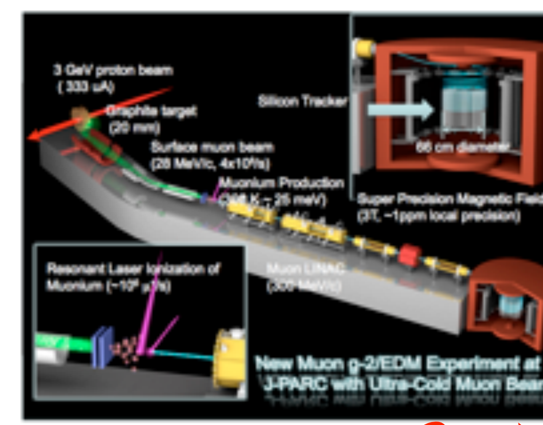
$\tau \rightarrow \mu\gamma$

$\tau \rightarrow e\gamma$

SuperB

$1 \div 2 \times 10^{-9}$

2015→

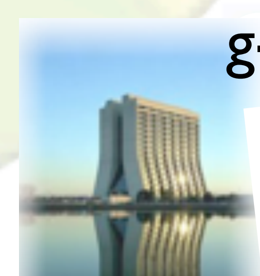


g-2 JPARC 2017?→

$(g-2)_\mu$

$\Delta a_\mu = (XXX \pm 34) \times 10^{-11}$

$3.6\sigma \rightarrow 8\sigma$ 0.1 ppm



g-2 FNAL

2017?→

$\mu \rightarrow eee$

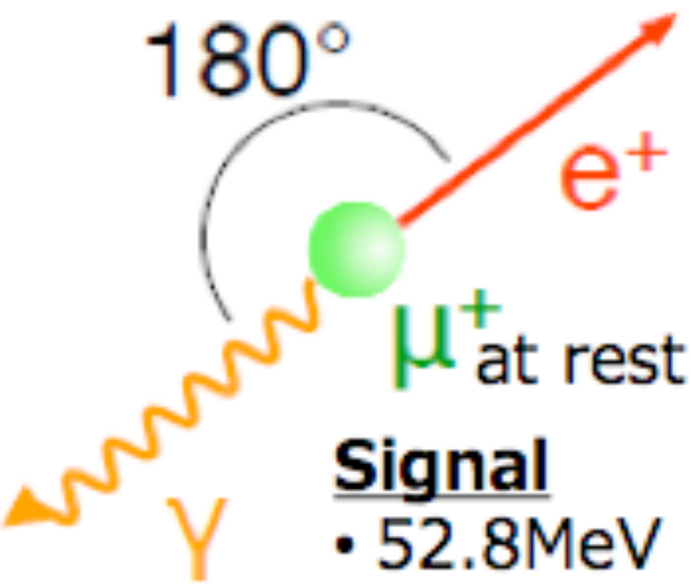
Heidelberg

$\sim 10^{-15 \div 16}$

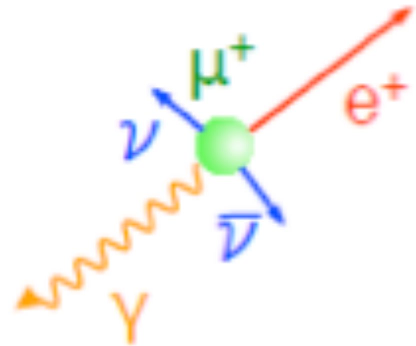
2015→ 2017

$\times \tan^2 \beta$

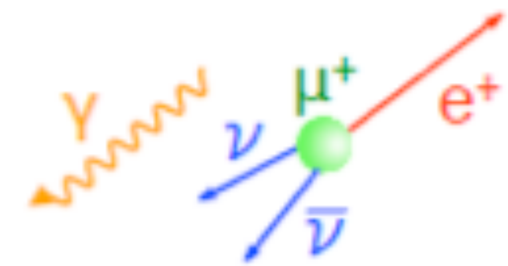
$\mu \to e\gamma$:experimental signature



Signal
- 52.8MeV
- Back-to-back
- Time coincidence

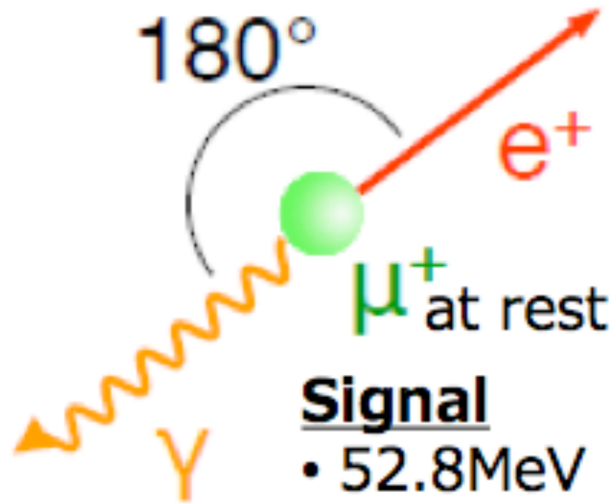


Physics BG
(radiative muon decay)
- <52.8MeV
- Any angle
- Time coincidence

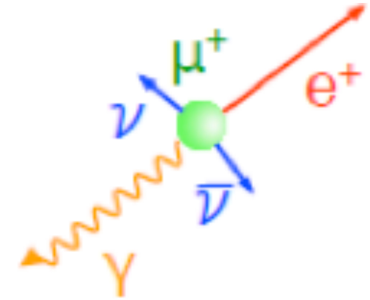


Accidental BG
- <52.8MeV
- Any angle
- Random

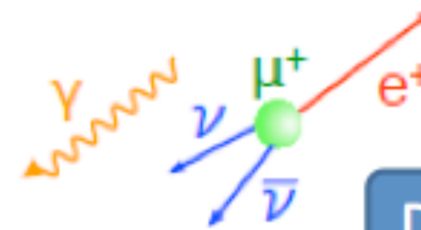
μ→eγ :experimental challenge!!



Signal
- 52.8MeV
- Back-to-back
- Time coincidence



Physics BG RMD
(radiative muon decay)
- <52.8MeV
- Any angle
- Time coincidence

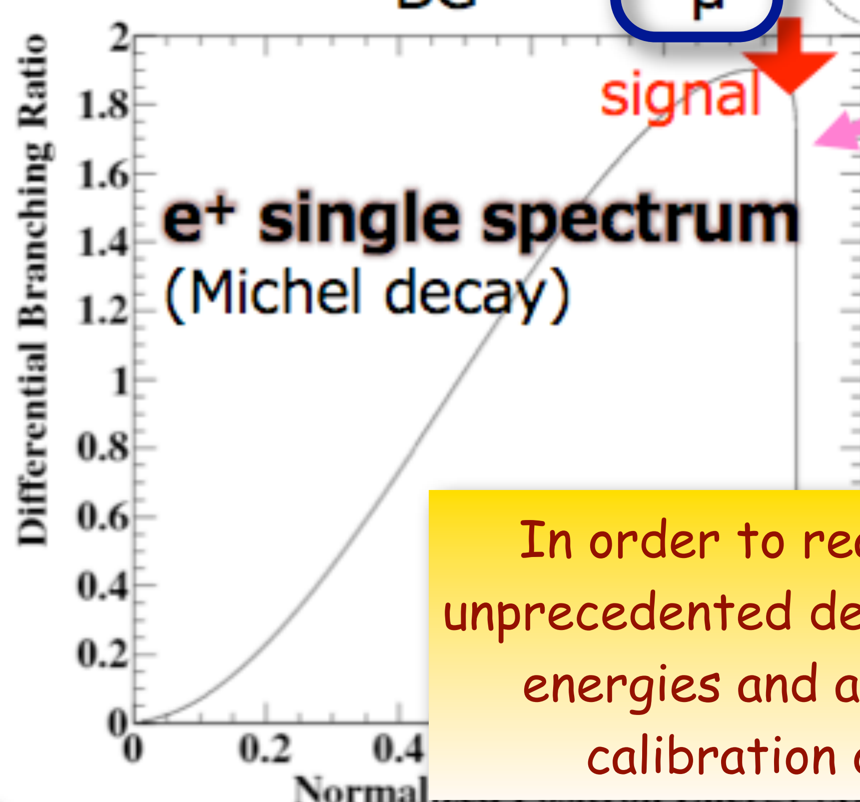


Accidental BG
- <52.8MeV
- Any angle
- Random

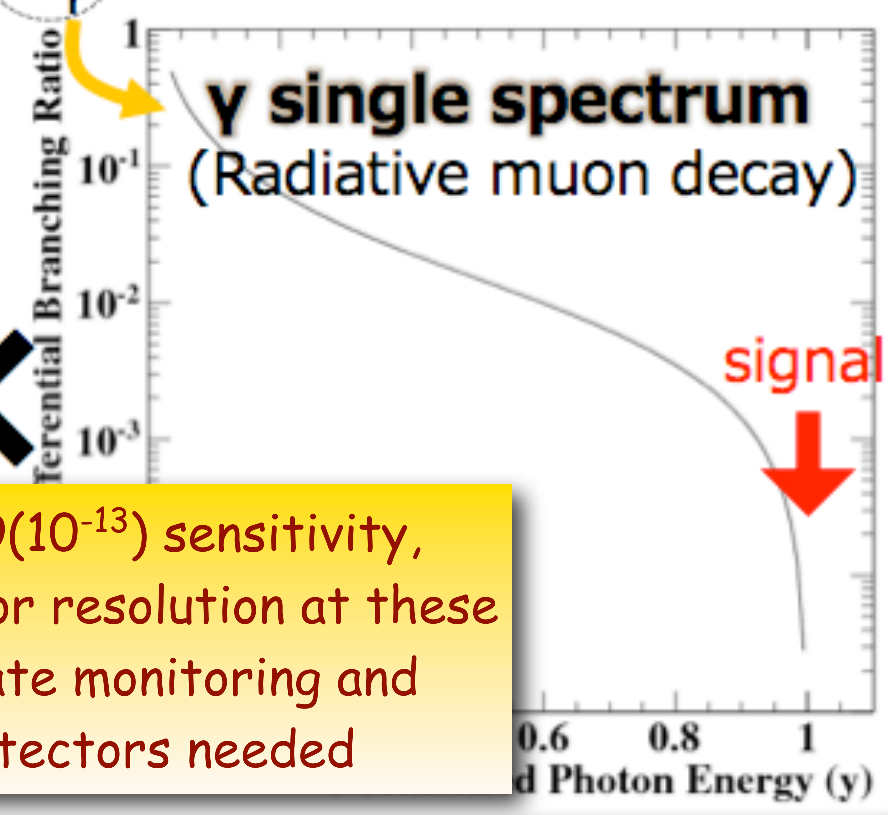
Dominant

Accidental background is determined by the experimental resolutions

$$R_{BG} \propto R_\mu^2 \cdot f_e \cdot f_\gamma \cdot \delta\omega/4\pi \cdot \delta t$$

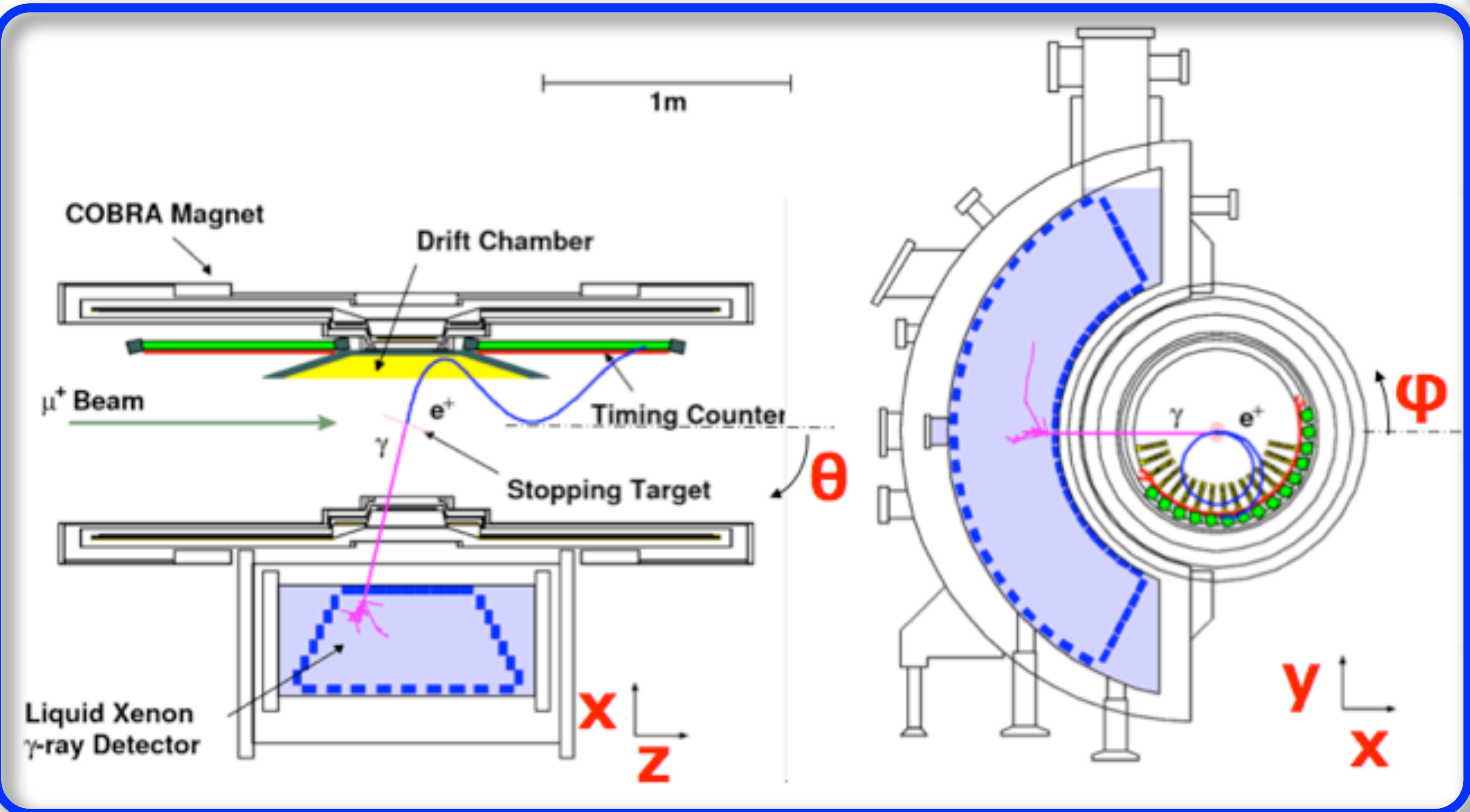


×

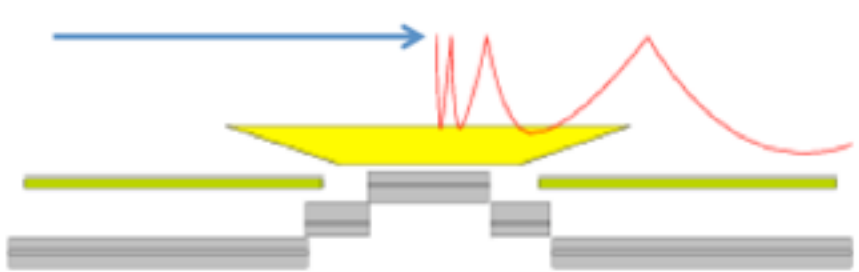


In order to reach $O(10^{-13})$ sensitivity, unprecedented detector resolution at these energies and accurate monitoring and calibration of detectors needed

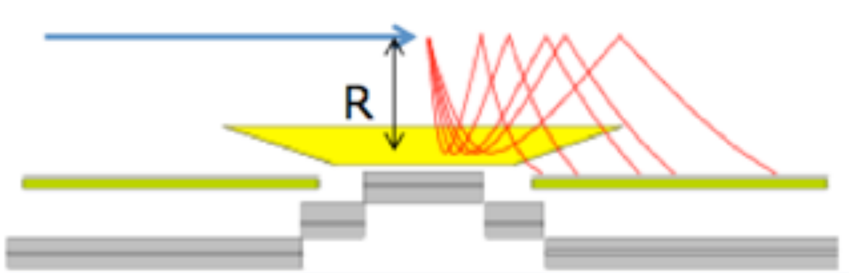
MEG in a nutshell



- Most intense DC muon beam of 3×10^7 muon/s at PSI
- Quasi-solenoidal spectrometer & low mass drift chamber for e^+ kinematic measurement
- Scintillator bars and fibers for e^+ timing read by PMT/APD
- Liquid Xenon calorimeter for photon detection read by PMT
- $\sim 10^7$ fully efficient trigger bkg suppression



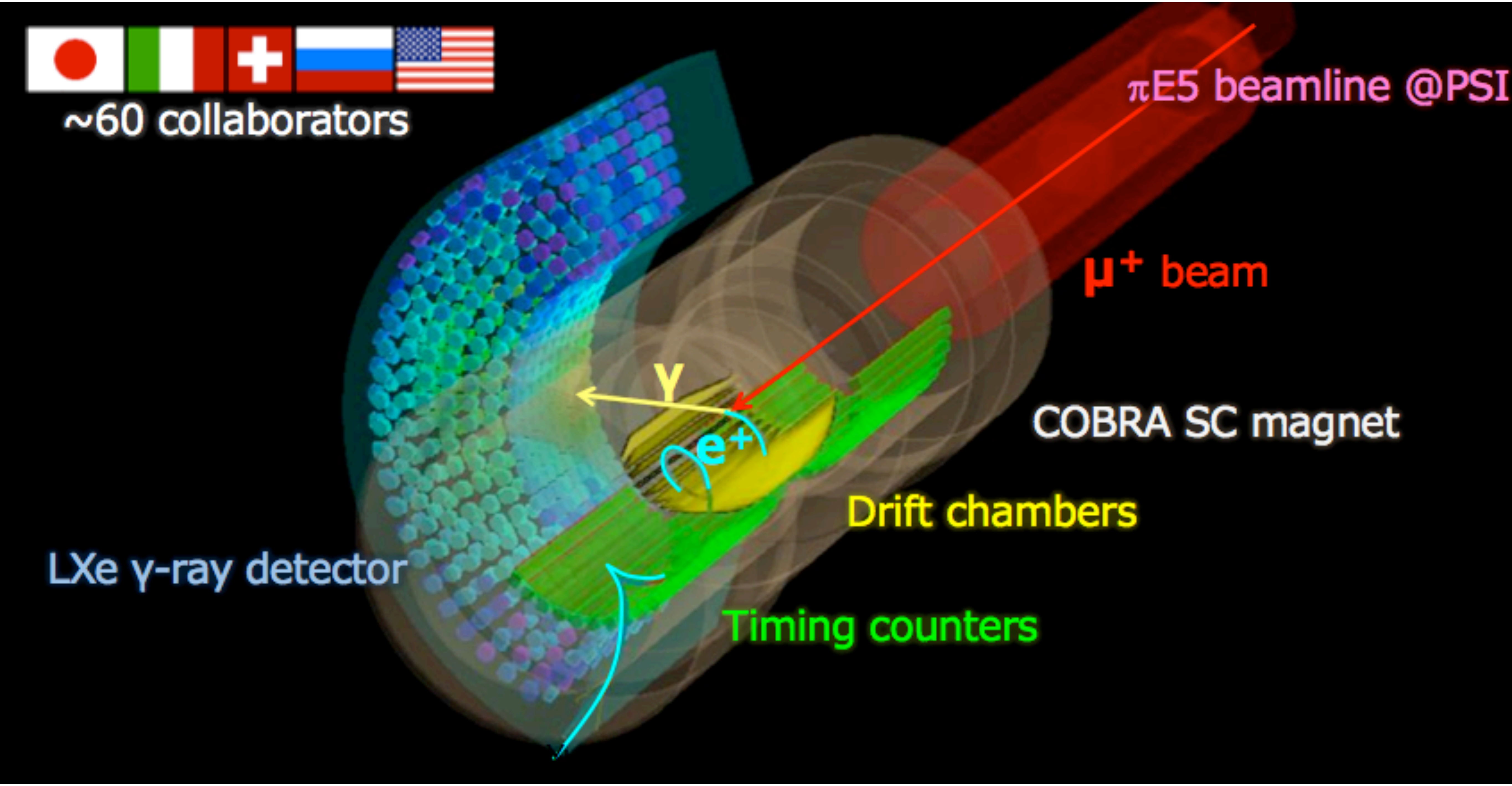
e^+ quickly swept out



Constant bending radius independent of emission angles

Gradient B field instead of uniform B field for good momentum resolution and high pile up rejection

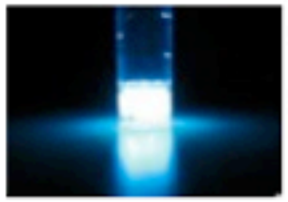
MEG picture

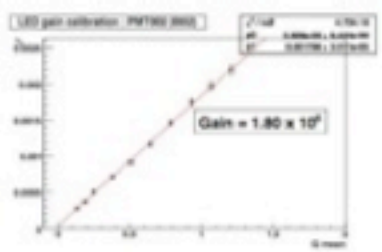

~60 collaborators
πE5 beamline @PSI
μ+ beam
γ
e+
COBRA SC magnet
Drift chambers
LXe γ-ray detector
Timing counters

Calibrations

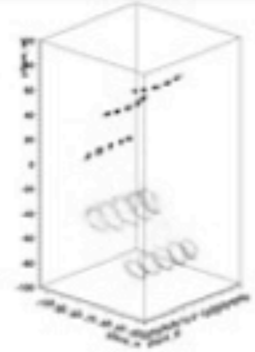
XENON CALIBRATION

LED
PMT gain

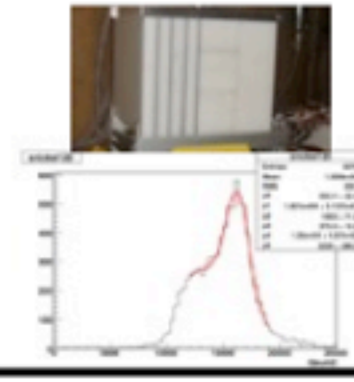




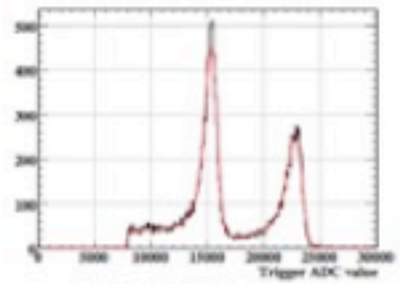
α source
PMT QE
Absorption length

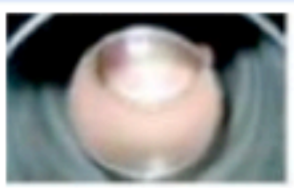


Ni γ generator
9 MeV γ-line
beam on/off calib.

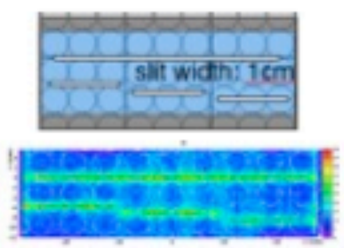


CEX
γ-resolutions:
- energy
- time
- impact point

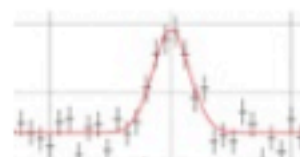




LH_2 target

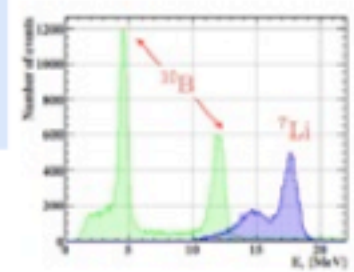


$\mu \rightarrow e\nu\bar{\nu}\gamma$

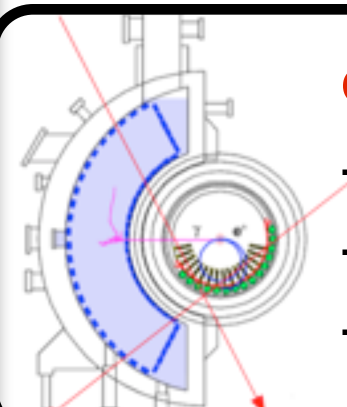


$t_{e\gamma}$

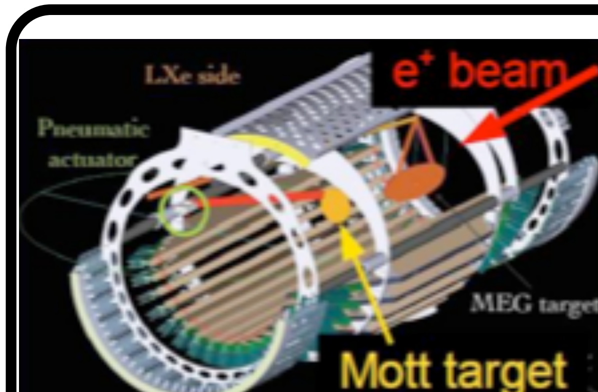
CW p-accel
Light Yield
LXe-TC t-calib



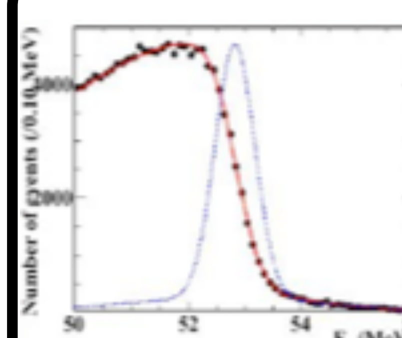
TRACKER CALIBRATION



Cosmic Ray
- DC alignment
-TC uniformity
-LXe monitoring



e⁺ Mott-scatter
- Monochromatic, tunable momentum bean

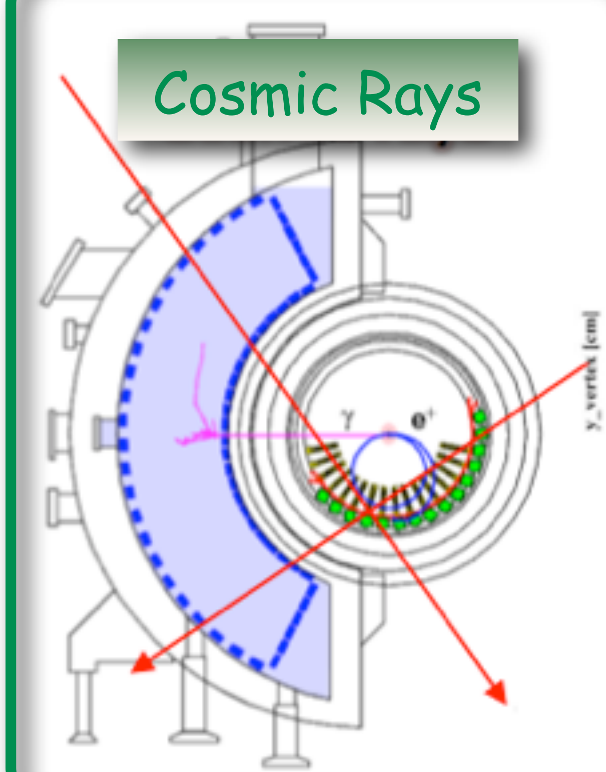


Michel decays
- μ→ e νν for momentum energy scale

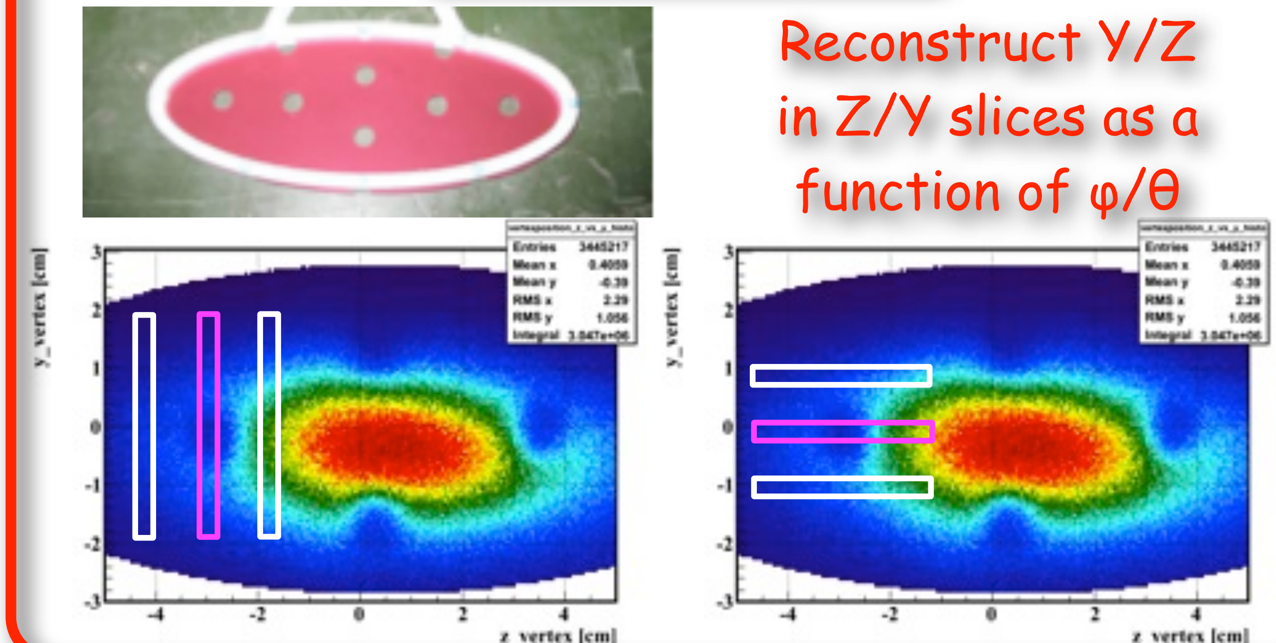
Alignment

- Good alignment is crucial to reduce systematics on relative photon-positron angle
  - No back to back source for calibration
  - Nonetheless, we improved alignment inside and among detectors
    - DC - B field - target - LXe
- Tools:
  - Optical surveys
  - DC: Millipede (a la CMS) with cosmic rays + Michel e^+
  - Target holes
  - LXe: Pb collimators
  - B field: resolutions and correlations

Cosmic Rays

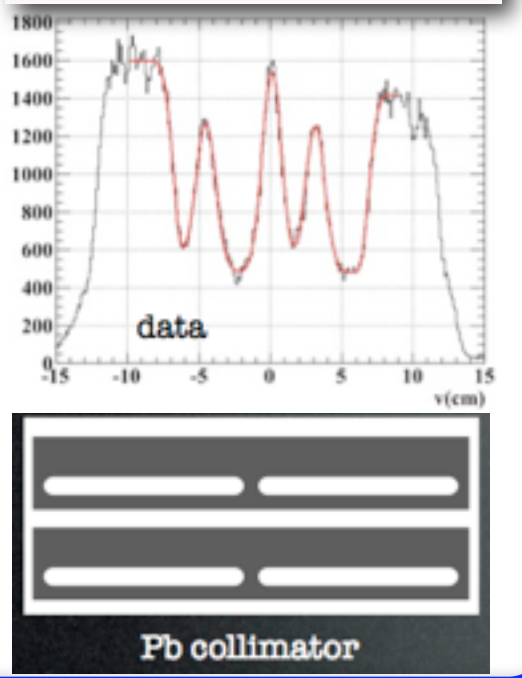


Target holes

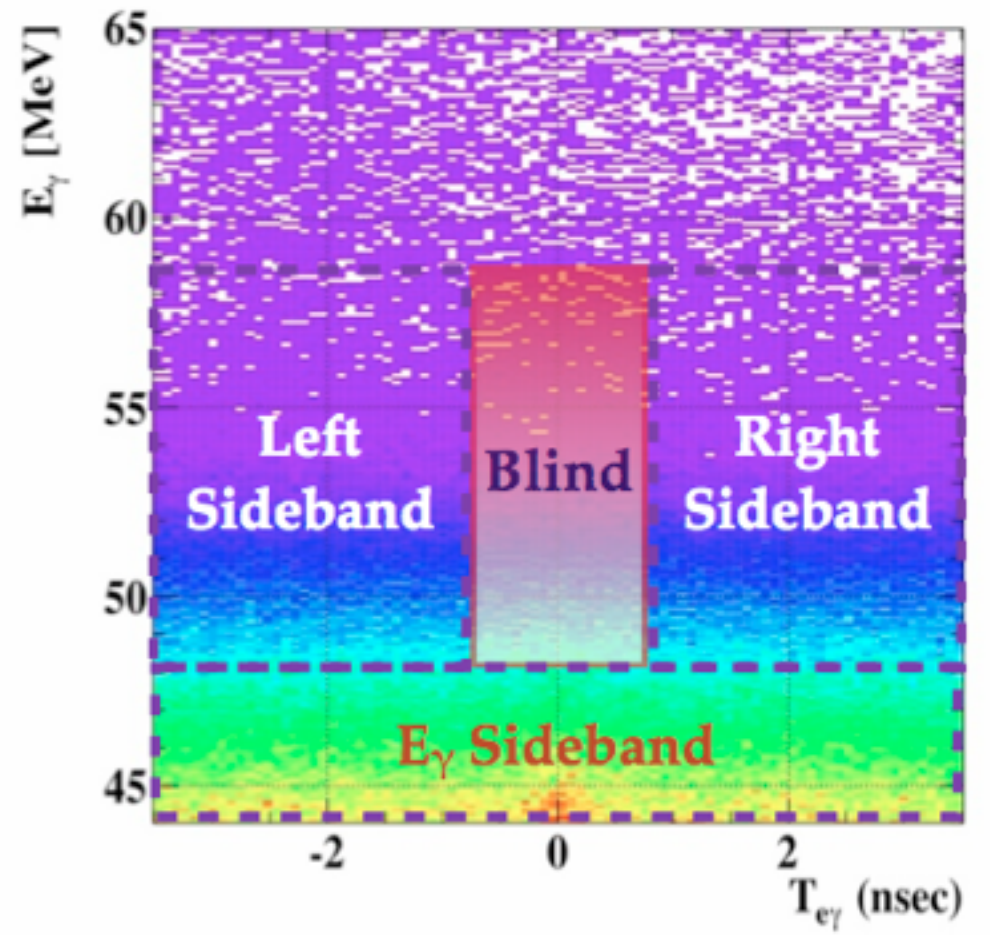


Reconstruct Y/Z in Z/Y slices as a function of φ/θ

Pb collimators in CEX run



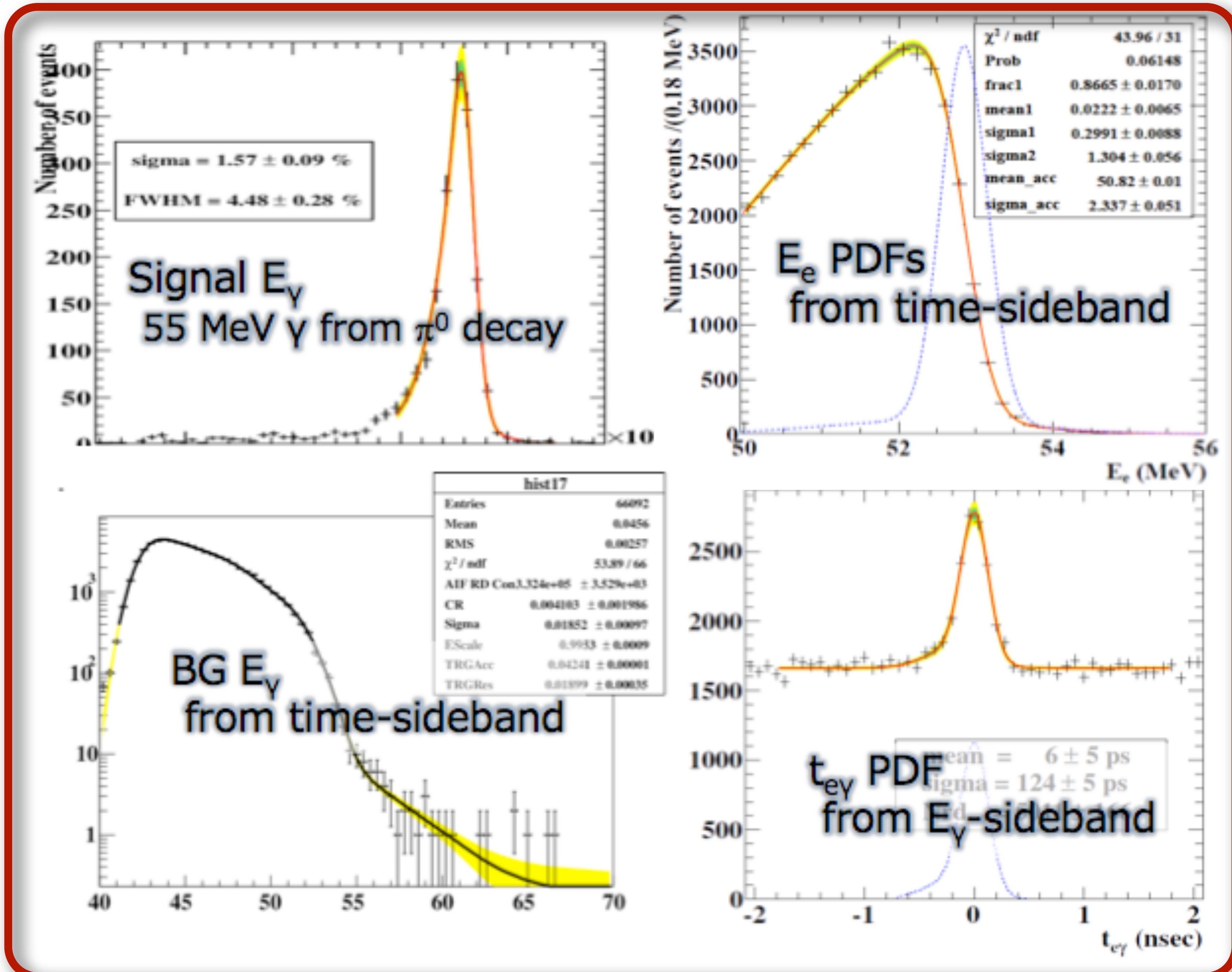
Analysis Technique



- Blind analysis technique adopted:
  - Events inside a signal region of E_γ and $t_{e\gamma}$ not used for analysis development
  - Background characterization from sidebands:
    - accidental bkg from off-time sidebands,
    - RMD from low energy E_γ sideband
- Extended unbinned ML fit of N_{sig}, N_{RMD} and N_{bkg}
  - Observables E_γ, E_e, $t_{e\gamma}$, $\theta_{e\gamma}$, $\varphi_{e\gamma}$,
- Number of muons stopped on target: 1.7×10^{14} (6.5×10^{13} (2009) + 1.1×10^{14} (2010))
  - Count unbiased Michel sample in physics data simultaneously with the signal
    - Count RMD sample in E_γ sideband (independent sample) for consistency check
  - Independent of instantaneous beam rate and insensitive to acceptance and efficiency

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

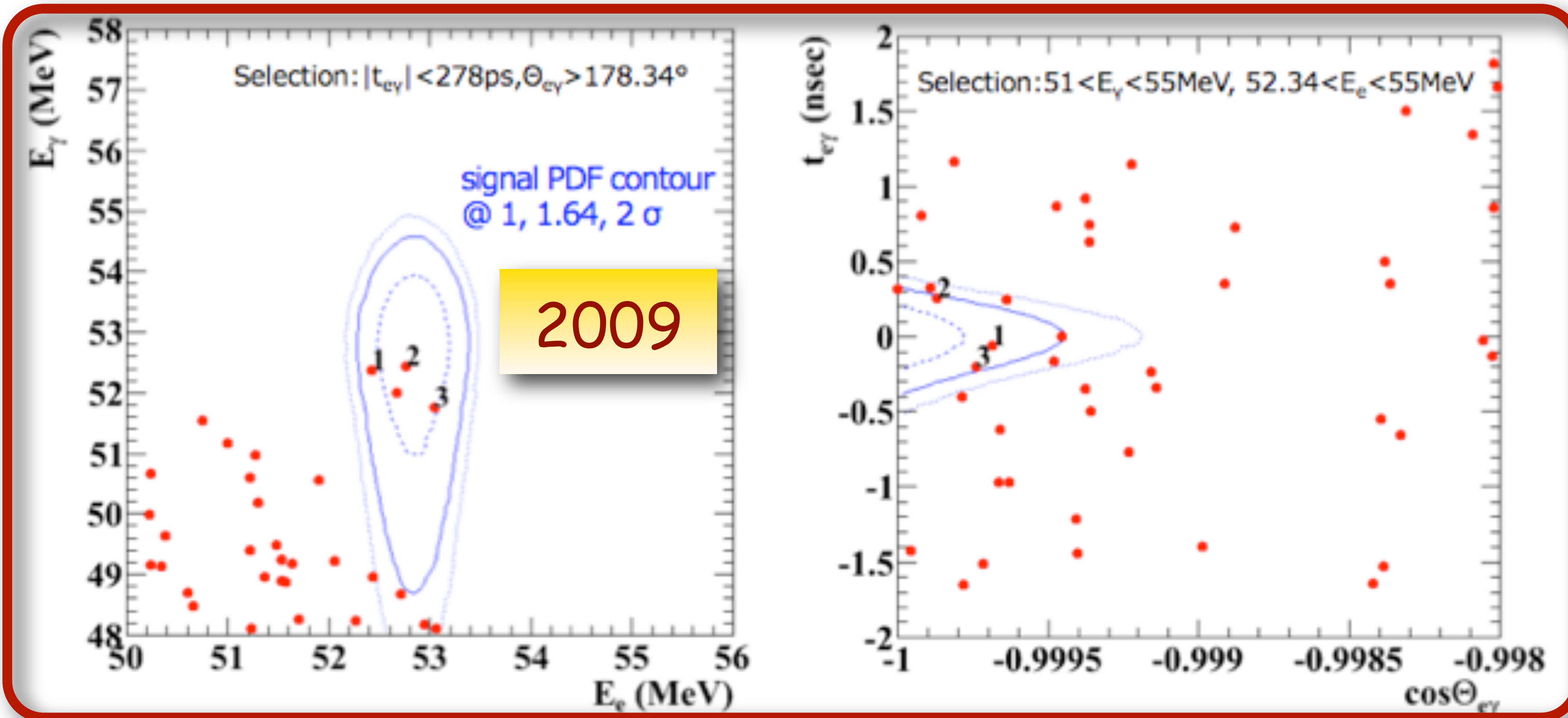
PDFs



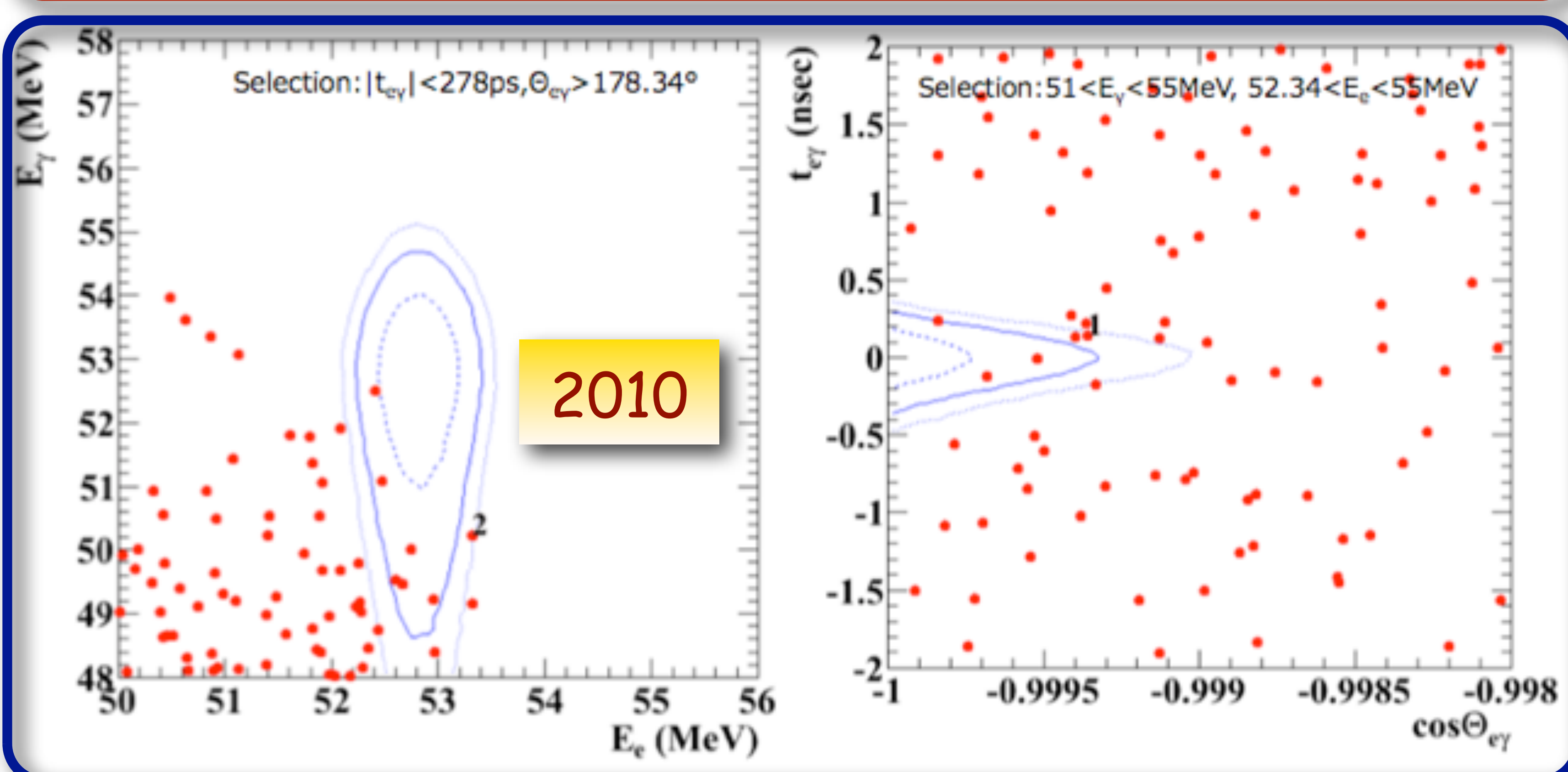
- Signal E_e PDF from fit to Michel edge data
- Signal angle PDFs measured on data from tracks which make two turns inside the spectrometer
- Background angle PDFs measured on time sideband
- RMD PDFs from theoretical distributions convoluted with measured resolutions

Fit variables: E_γ, E_e, $t_{e\gamma}$, $\theta_{e\gamma}$, $\varphi_{e\gamma}$

2009 and 2010 results

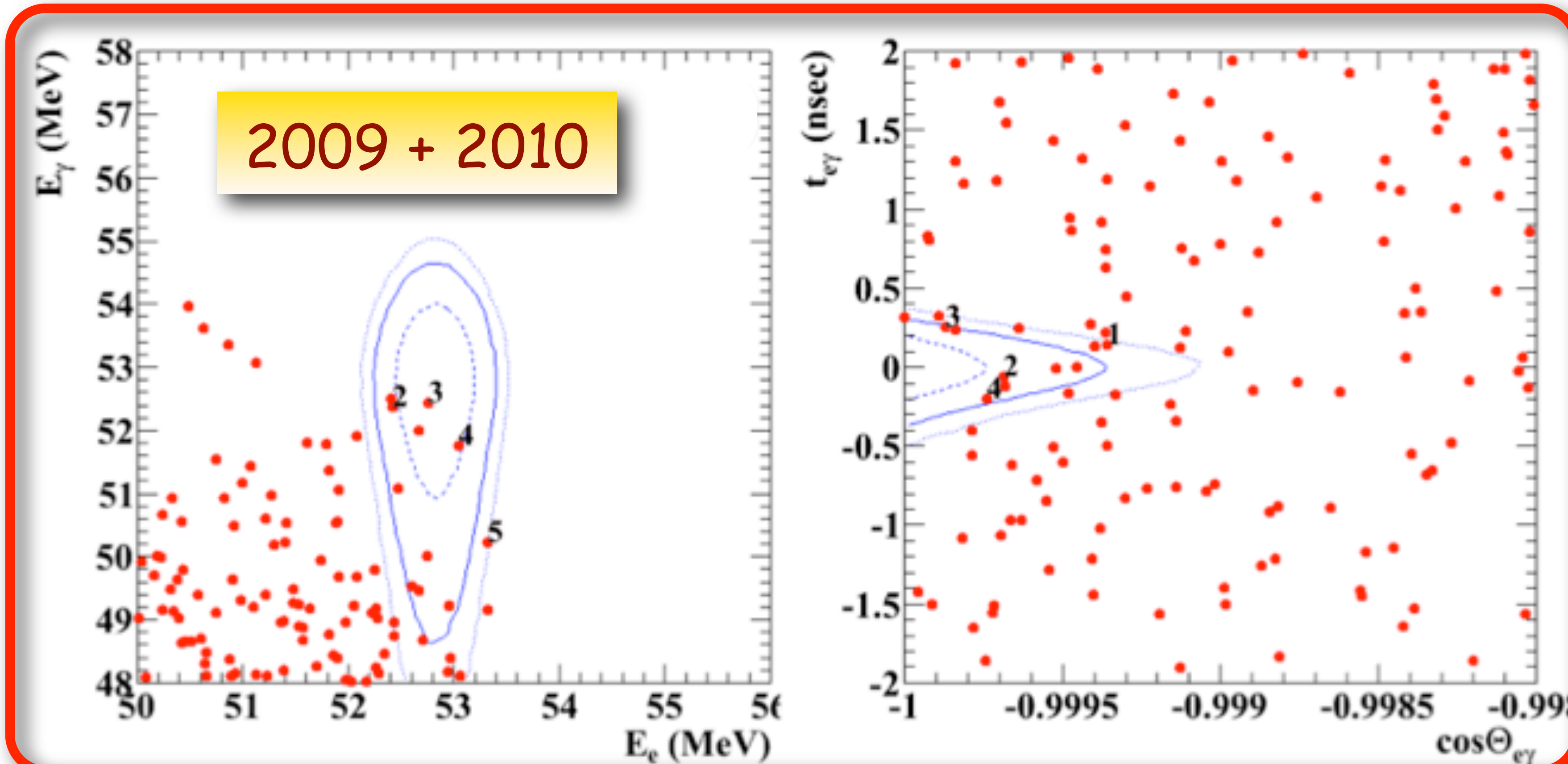


- 2009 data re-analyzed with improvements : best N_{sig} fit 3.4 (ICHEP '10 best N_{sig} fit 3.0) ---> **STABLE RESULT**
- $1.7\times 10^{-13} < BR < 9.6\times 10^{-12}$ @ 90% CL
- p-Value for null signal 8%



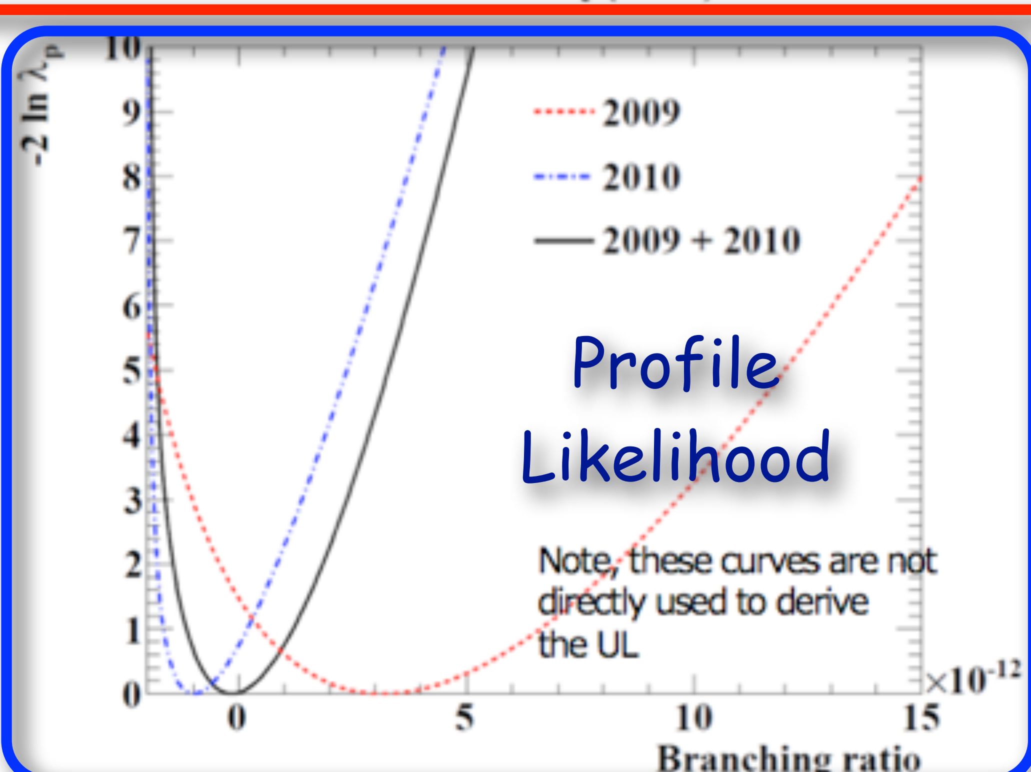
- 2010 data best N_{sig} fit -2.2
- $BR < 1.7\times 10^{-12}$ @ 90% CL
- Sensitivity 2.2×10^{-12}

Combined Result



Phys. Rev. Lett. 107, 171801 (2011)

	expected	best fit
N_{sig}		-0.5
N_{RMD}	79.4 ± 7.9	76 ± 12
N_{bkg}	881.7 ± 15.1	882 ± 22



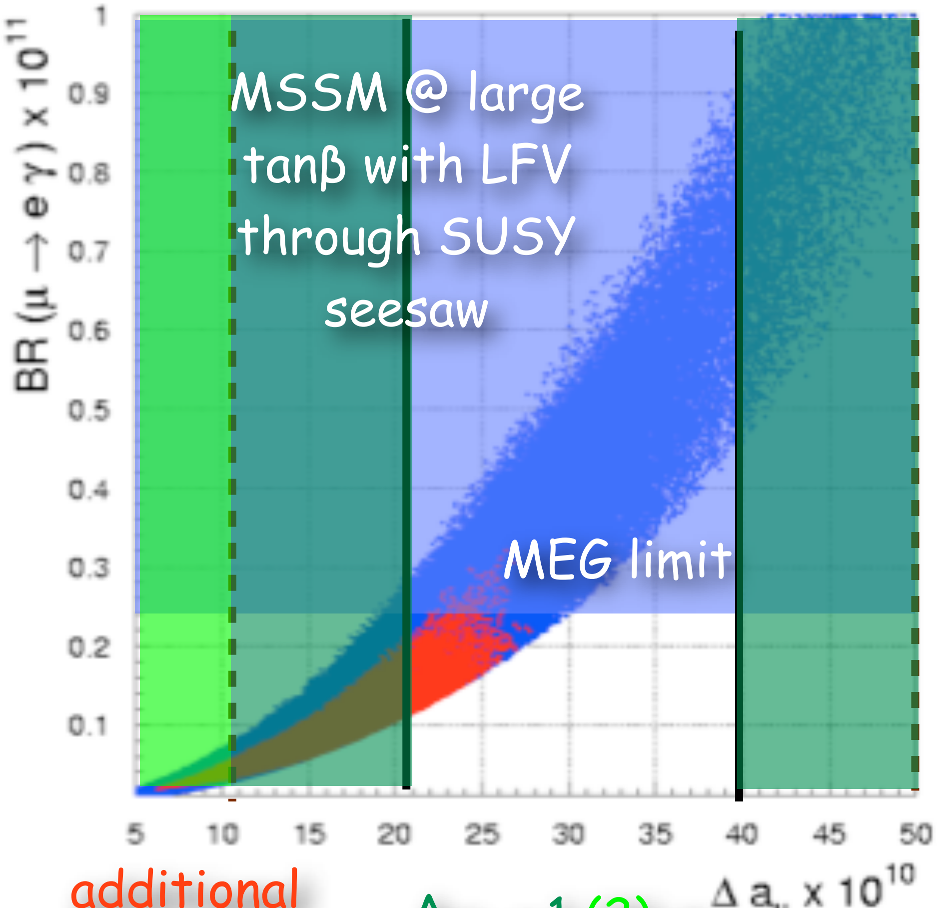
UL @ 90% CL BR < 2.4×10^{-12}

Present world most stringent UL

Data set	$\mathcal{B}_{fit}$	LL	UL
2009	3.2×10^{-12}	1.7×10^{-13}	9.6×10^{-12}
2010	-9.9×10^{-13}	–	1.7×10^{-12}
2009 + 2010	-1.5×10^{-13}	–	2.4×10^{-12}

Implications

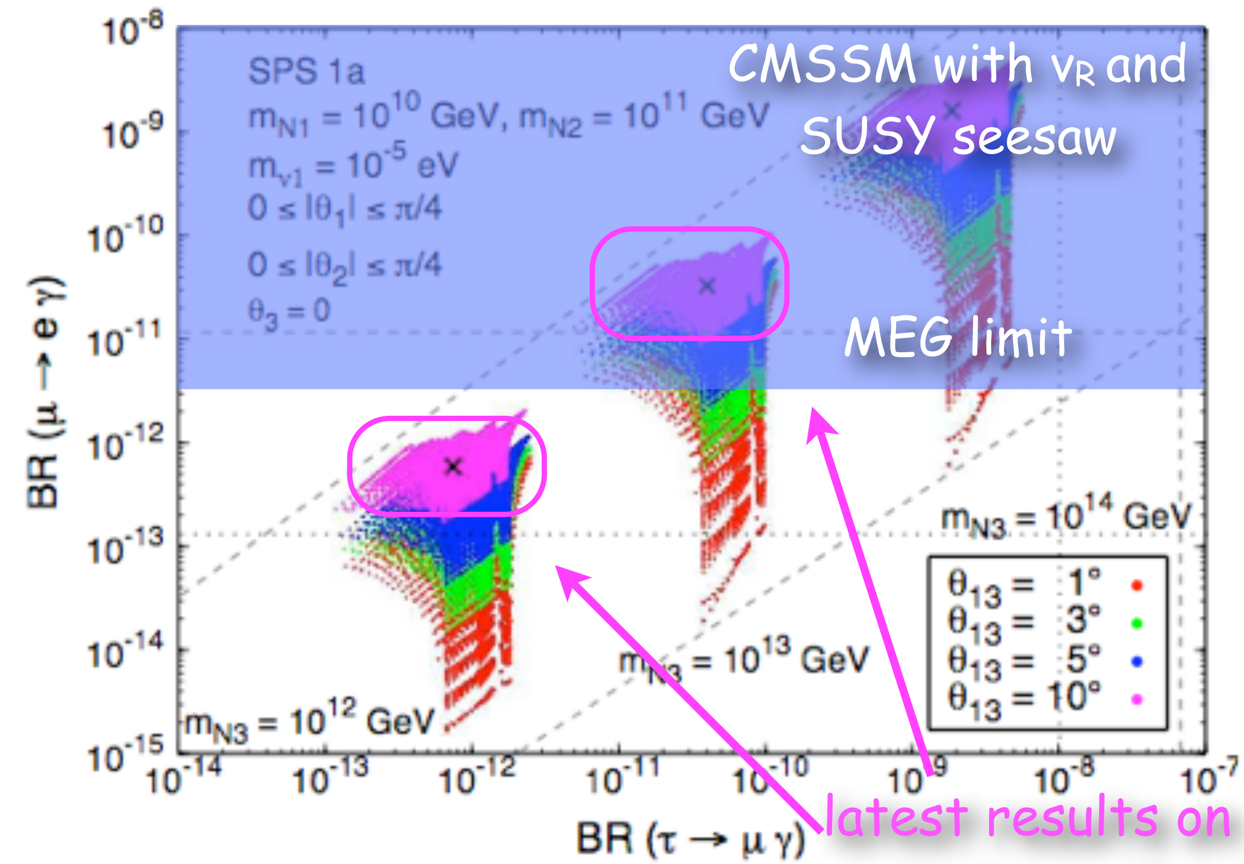
G. Isidori et al. Phys.Rev. D 75:115019, 2007



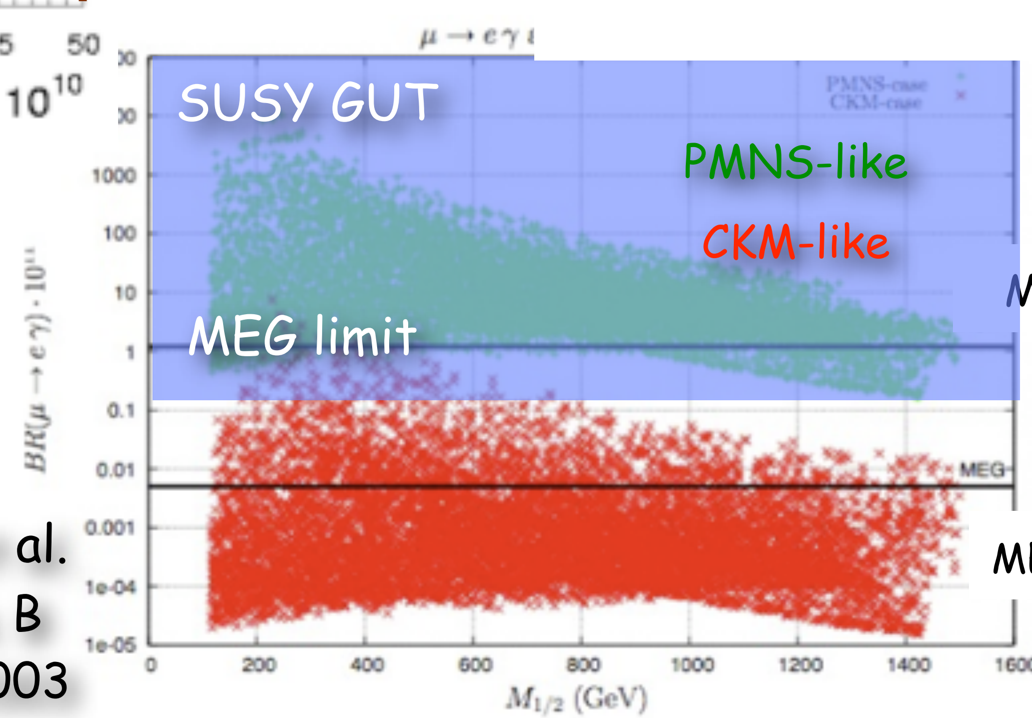
additional constraints from B physics

$\Delta a_\mu \pm 1$ (2) σ constraint

S. Antusch et al, JHEP 0611:090 (2006)



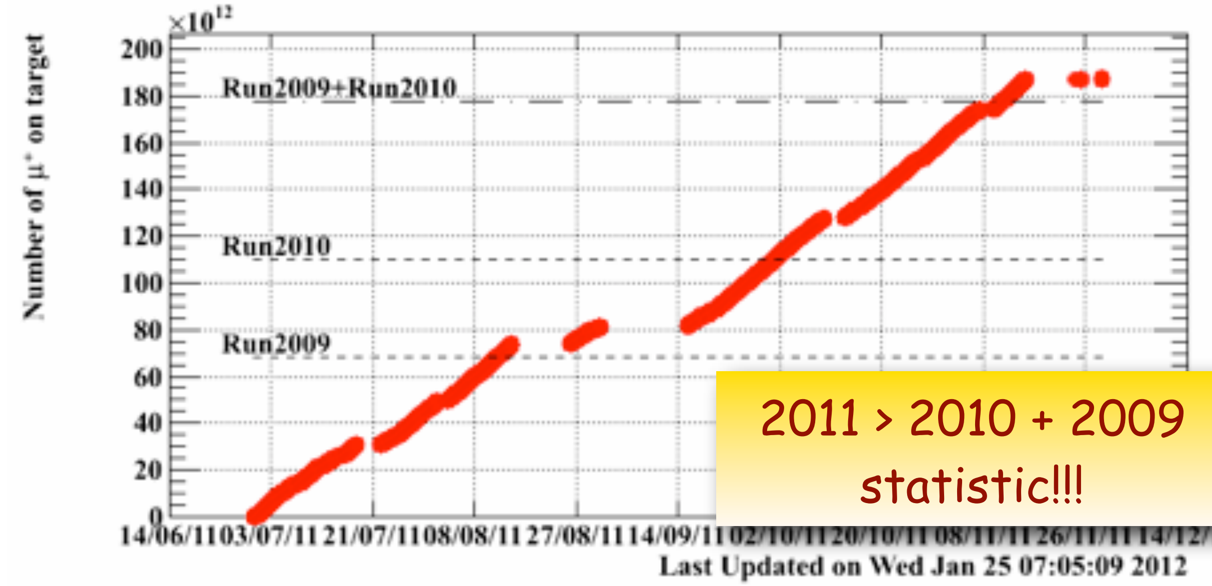
latest results on theta13 ~ 9°



Masiero et al. Nucl.Phys. B 649:189, 2003

2011 Run

- 2011 dataset > 2009 + 2010 datasets
  - Improved DAQ & trigger efficiency up to >99% live time with >95% efficiency
  - Improved noise conditions in DC thanks to new HV power supplies
  - New DC alignment
  - More efficient XEC calibrations
  - TC fibers APDs operational



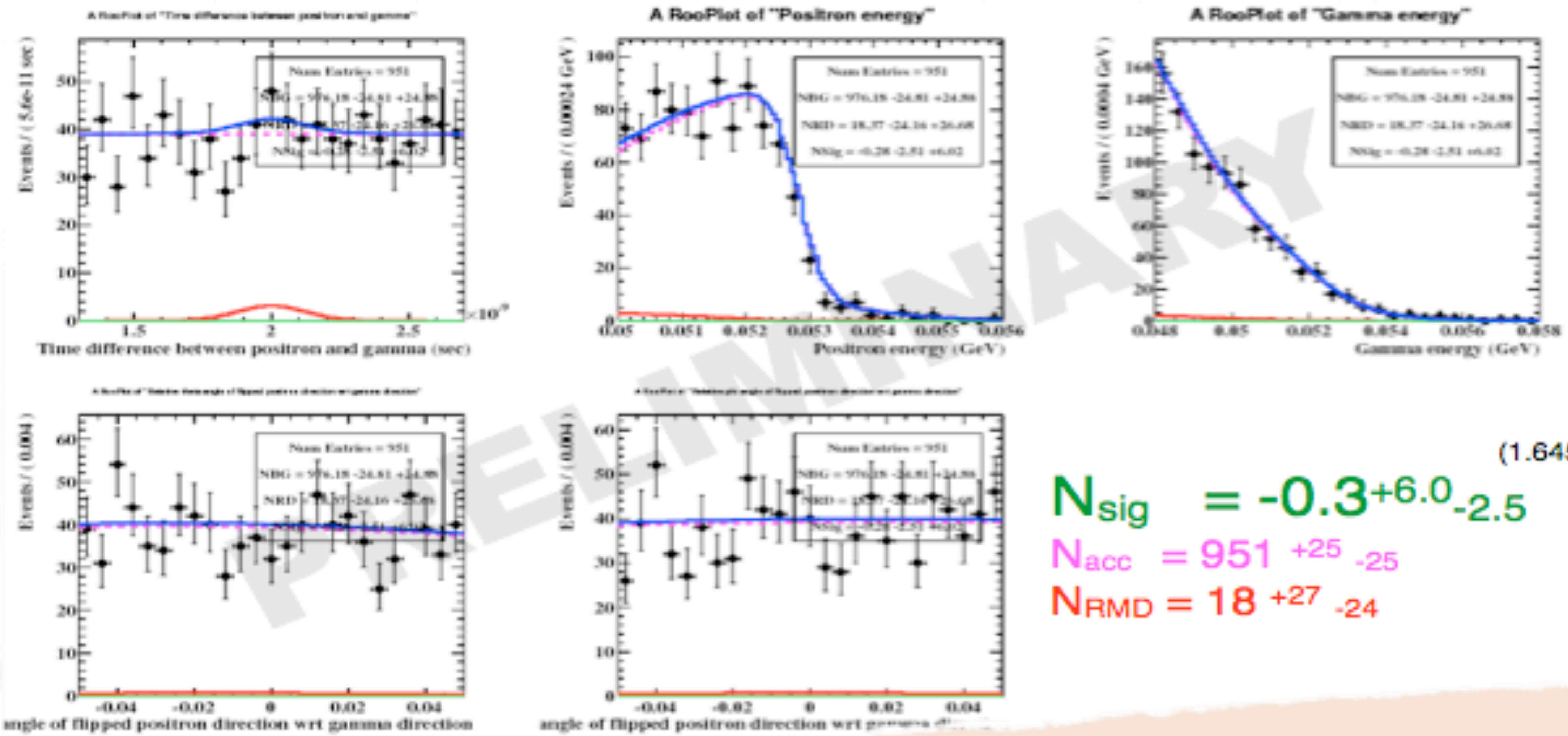
- Analysis improvements
  - New photon pile up rejection
  - Offline noise reduction in DC
  - New tracking code
  - Event by event PDF for e+

	2010	2011
γ Energy σE_γ (%)	1.9 (depth>2cm)	1.7 (depth>2cm)
γ Position σx_γ (mm)	5/6	←
γ Efficiency ε_γ (%)	59	63
e+ Mom. σp_e (%)	0.61(core 79%)	0.61(core 86%)
e+ Angle $\sigma \theta_e$ (mrad)	7.2(φ)/11(θ)	6.5(φ)/10.8(θ)
e+ Efficiency ε_e (%)	41	←
γ-e+ Timing σ_T (ps)	126(core)	133
μ+ decay vertex (mm)	2.0/1.1	1.9/1.0
Trigger Efficiency (%)	92	95
# of stopped μ	1.1×10^{14}	1.9×10^{14}
Sensitivity	2.2×10^{-12}	next slide !

PRELIMINARY

Expected 2011 sensitivity

Likelihood Fitting on Sideband Samples



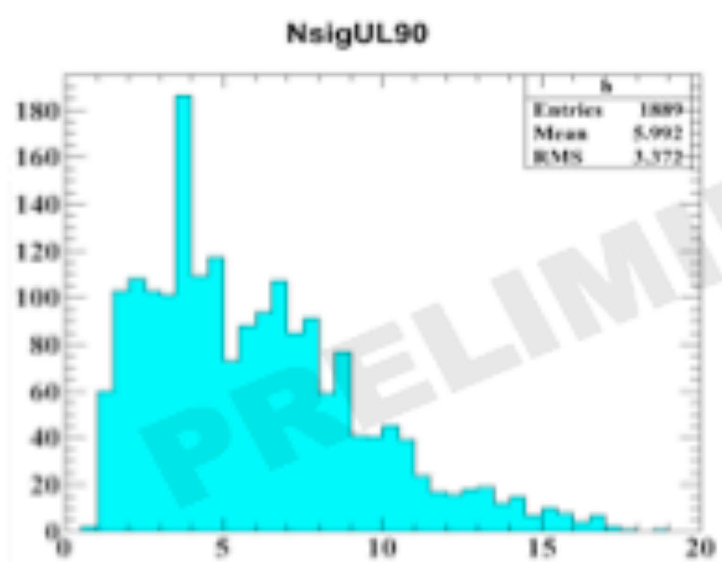
(1.645σ)

$N_{sig} = -0.3^{+6.0}_{-2.5}$

$N_{acc} = 951^{+25}_{-25}$

$N_{RMD} = 18^{+27}_{-24}$

N_{sig} UL (90% CL.)



median Nsig UL = 5.4

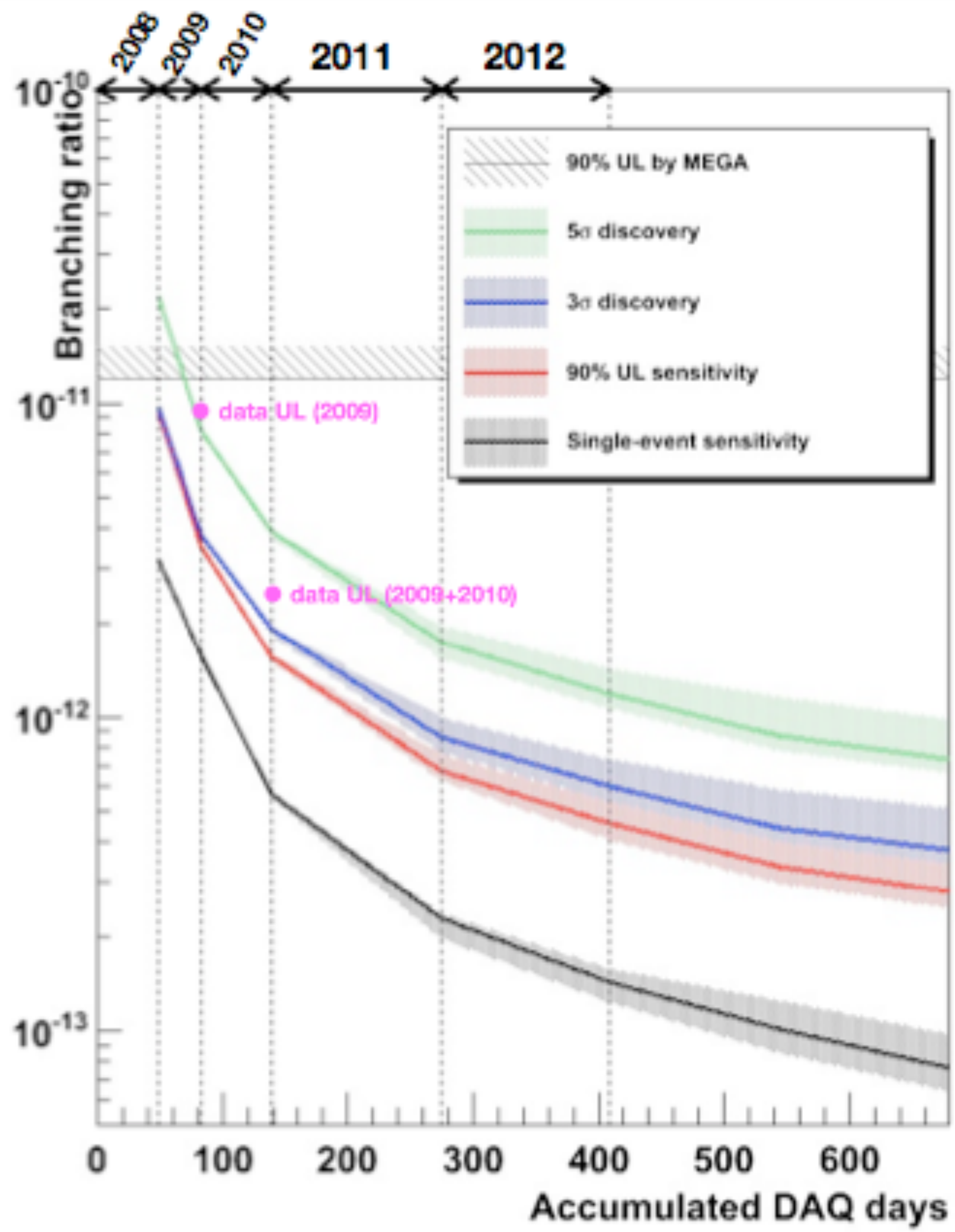
Sensitivity : 1.5×10^{-12}

Expected Sensitivity

$\sim 1 \times 10^{-12}$

(2011 data only)

Sensitivity prospects



- With 2011 data MEG entering O(10^{-13}) region
- With 2012 data, 3σ discovery potential if BR >~ 10^{-12}
- After 2012 we will be on the plateau of the sensitivity

Time to consider an upgrade of the experiment

MEG Upgrade

Sensitivity goal O(10^{-14})

Budget: 30% of original MEG construction budget

Variable	Foreseen	Obtained
ΔE_γ (%)	1.2	1.9
Δt_γ (psec)	43	67
γ position (mm)	4(u,v),6(w)	5(u,v),6(w)
γ efficiency (%)	> 40	60
ΔP_e (KeV)	200	380
e^+ angle (mrad)	5(ϕ_e),5(θ_e)	7(ϕ_e),9(θ_e)
Δt_{e^+} (psec)	50	107
e^+ efficiency (%)	90	40
$\Delta\Theta_{e\gamma}$ (mrad)	7.2	10.3
$\Delta t_{e\gamma}$ (psec)	65	120

not uniform light collection

very small signals on DC cathodes

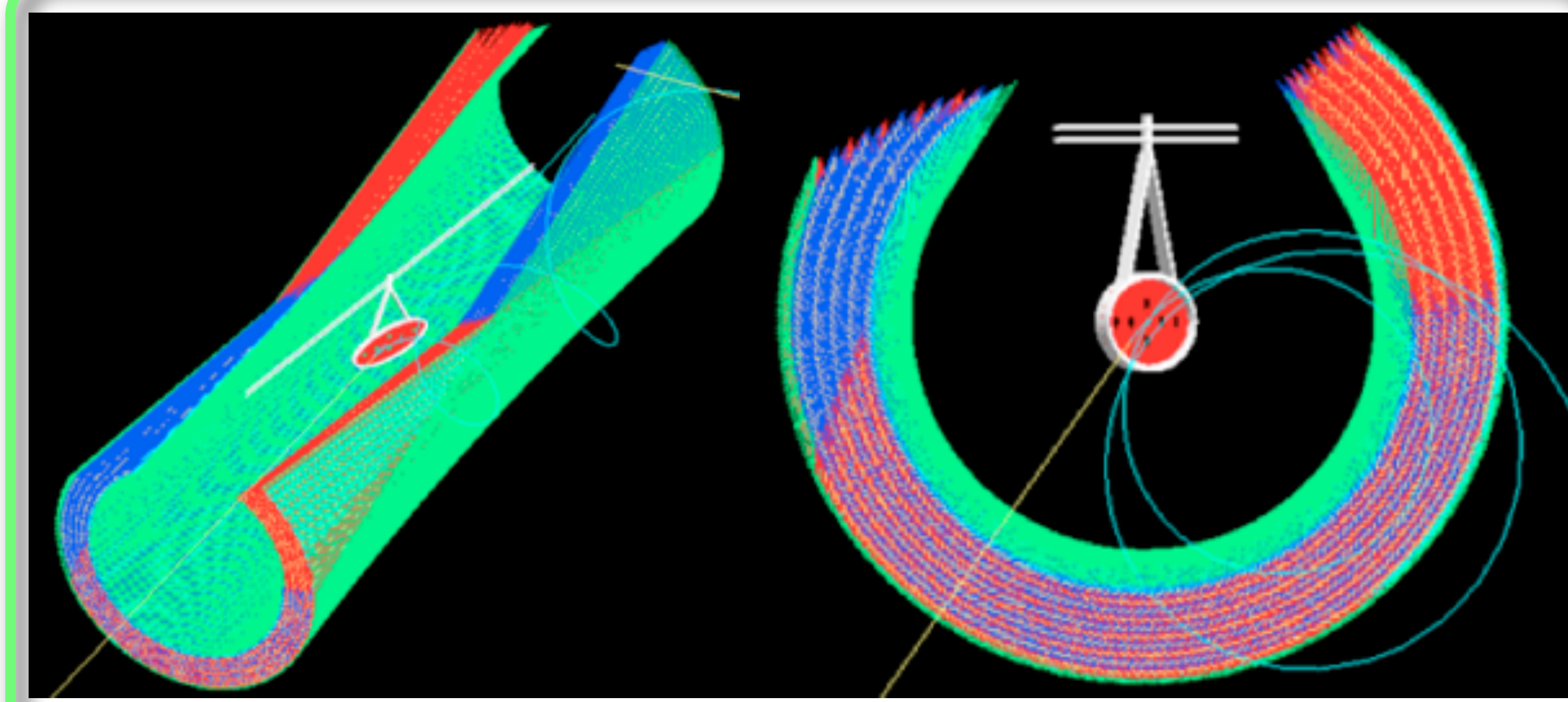
material between DC and TIC

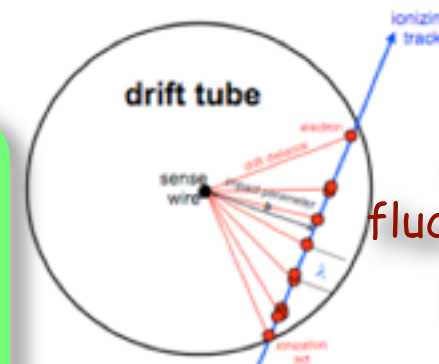
affected by tracking performances

- The aim is a substantial improvement w.r.t. MEG sensitivity with a reasonably short R&D and running time (~ 3 + 3 years)
- Major upgrades plus several alternative options:
  - Replace the positron tracker with full volume drift chamber for improved tracking performance and efficiency
  - Upgrade XEC photon detectors for an improved photon position and energy resolution
  - Replace TIC bars with smaller ultra fast scintillating plates read by SiPM
  - Run at ~ 10^8 μ/s and possibility to use sub-surface muons/thinner target
  - Alternative options: active target, vertex detector, TPC as an alternative tracker

DC Upgrade: DRAGO

- Detector concept:single volume low mass gas detector, with small cell ~ 7x7mm and all stereo
- Use of fast electronic to perform cluster timing for improved hit position resolution
- Less material along e+ path and tracking until TIC hit





cluster timing:reduce time fluctuation of first cluster adding information from other cls

- R&D status
  - Preliminary frontend developed and successfully tested
  - Small prototype for resolution study nearly ready
  - Additional prototype for aging study under construction

Expected performance from MC simulation:

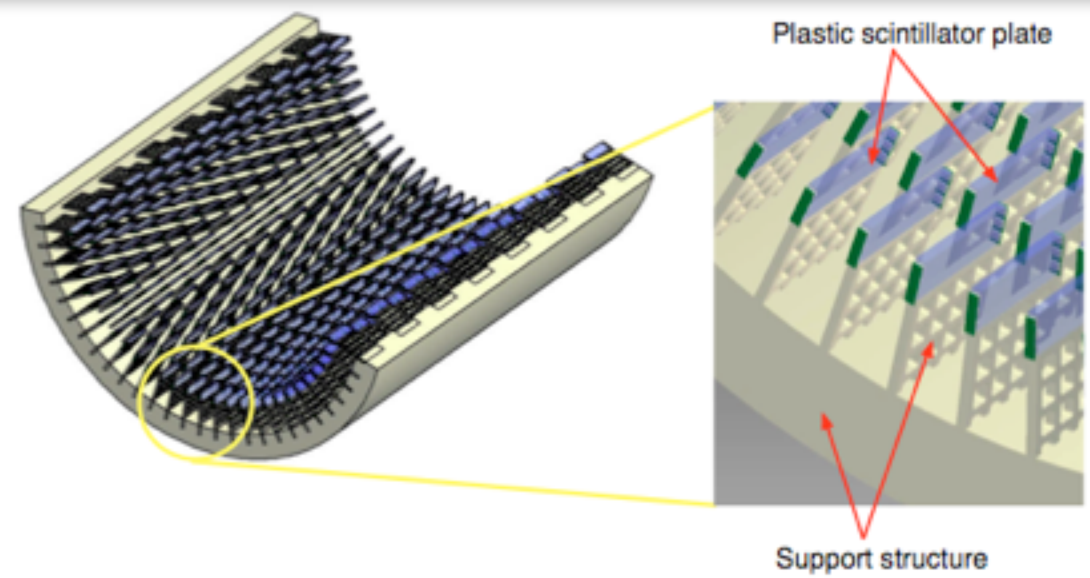
ε_{e+} = 90%

σ_P = 110 KeV

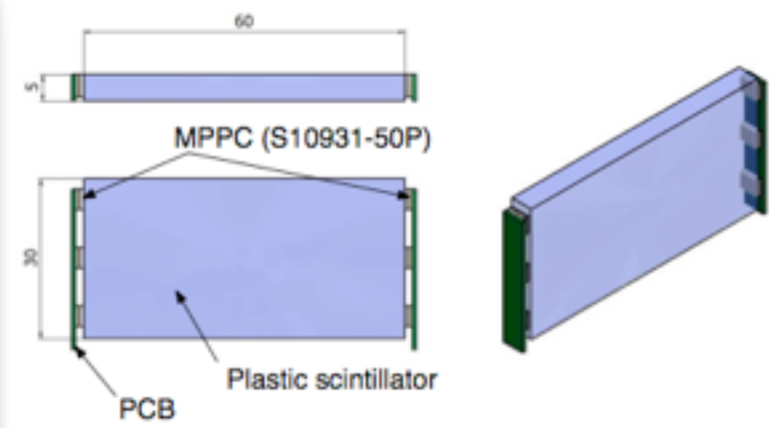
$\sigma_{\varphi/\theta}$ = 6-5 mrad

TIC Upgrade

- Detector concept: small scintillating pixel (~ 30x60x5 mm^3), read by MPPC from both ends
- Reduced path length ambiguity inside scintillator, reduce hit rate and pile up, provide multiple hit information and can be operated in the He atmosphere



- R&D status
  - Work already started in lab for:
    - characterization of longer pixels
    - test of combination of pixels output
    - test of cables and readout electronics effects

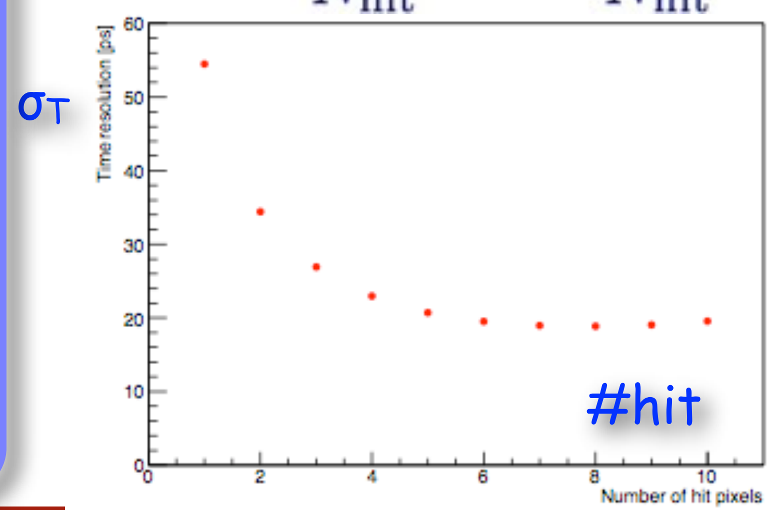


possible single pixel design

$$\sigma_{\text{single}} = \frac{19\text{ps}}{\sqrt{kE[\text{MeV}]}}$$

from data w/ a pixel w/ similar configuration tested at PSI

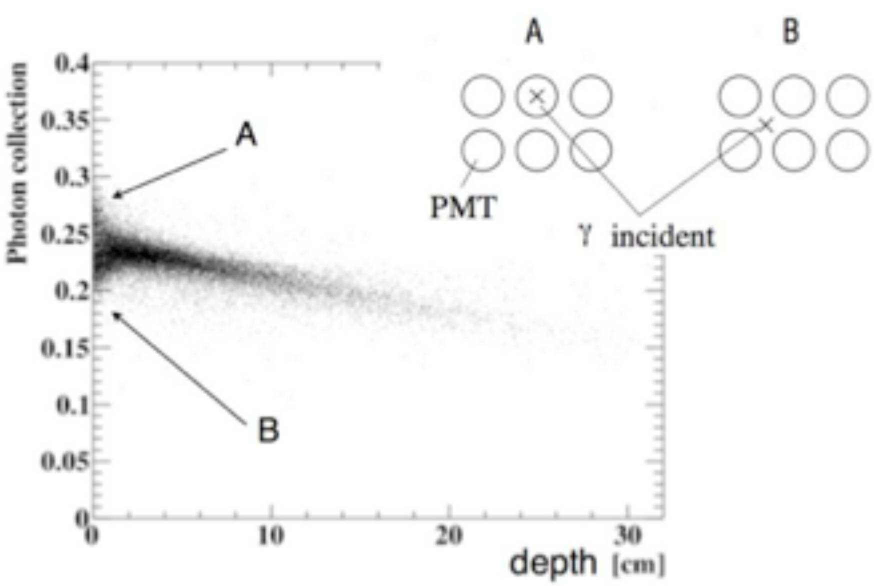
$$\sigma^2_{\text{overall}} = \frac{\sigma^2_{\text{single}}}{N_{\text{hit}}} + \frac{\sigma^2_{\text{inter-pixel}}}{N_{\text{hit}}} + \sigma_{\text{MS}}(N_{\text{hit}})$$

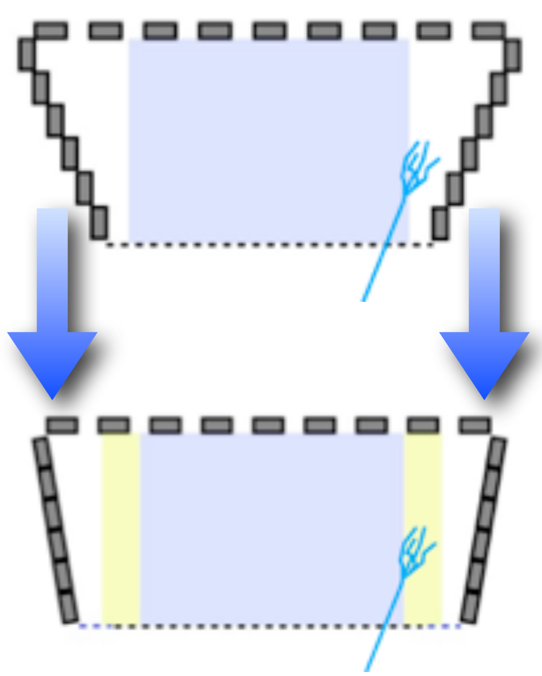


From data + MC simulation expected σ_T = 29 ps

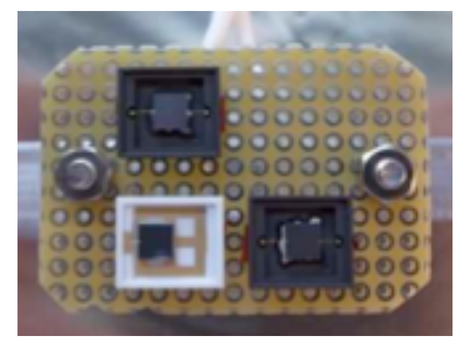
XEC Upgrade

- The idea: replace inner face PMT with smaller photosensors to reduce the non-uniform response due to non-uniform PMT coverage
  - MPPC
  - 1-inch square-shape PMT
  - 2-inch flat panel multi-anode PMT
- Further improvement possible from modification of lateral PMTs layout





- R&D status
  - MPPC PDE for VUV light and max dimensions to be addressed: develop MPPC in collaboration with Hamamatsu
  - test facility with 2l LXe at PSI for MPPC tests



  - preliminary tests show ~ 10% PDE

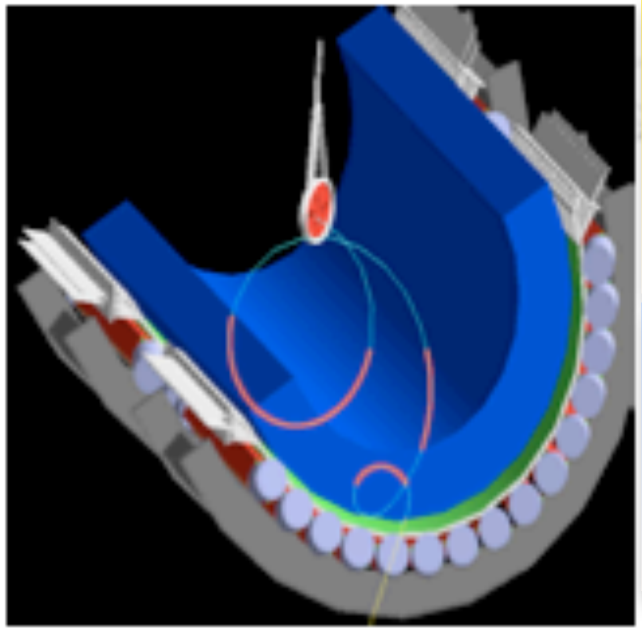
Expected performance from MC simulation:

$\sigma_E = 0.7 \sim 0.9$ %

$\sigma_X = 2 \sim 4$ mm

Alternative Upgrade R&D

Radial TPC base e⁺ tracker



Expected performance

ε_{e+} = 90%

σ_P = 140 KeV

$\sigma_{\varphi/\theta}$ = 9~4 mrad

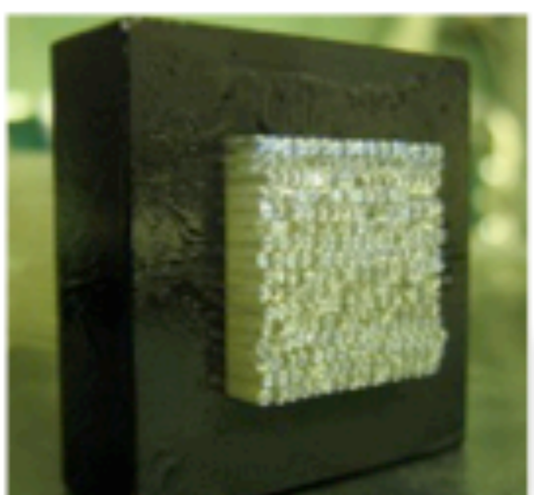
BUT: need for a E field uniformity < 0.2% , ultra-thin cylindrical electrode foils...several building issues

SVD option

Improves angular resolutions at the price of small loss in efficiency

BUT: need for a sensor < 100 μm thick

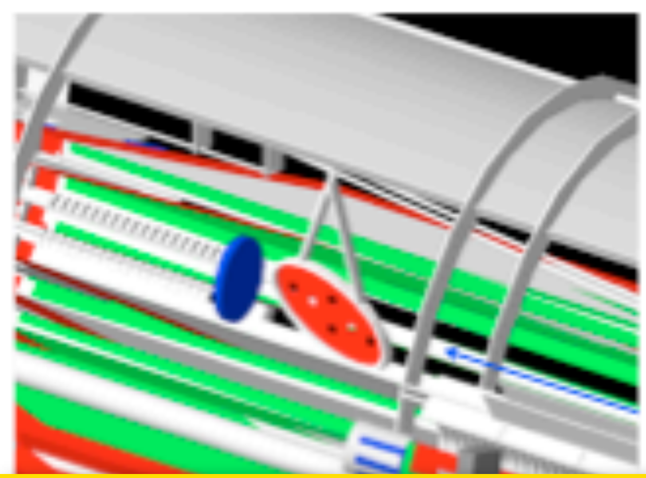
Active Target idea

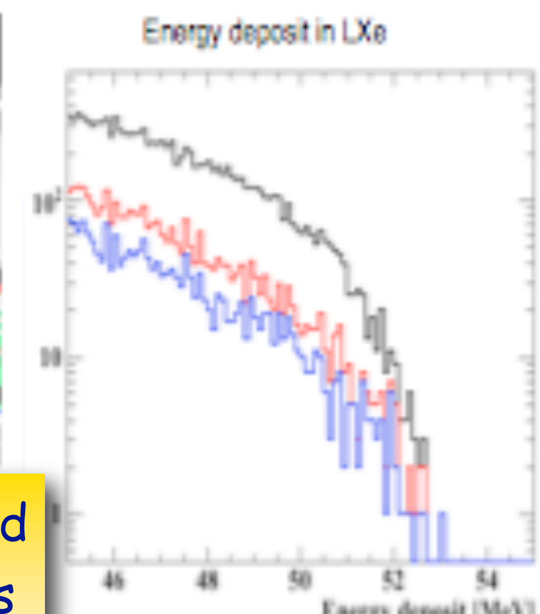


Improves phi and momentum resolutions at the price of higher material budget

Final performances depending on tracker and beam choice

Radiative decay Veto





Highly reduce γ background at the price of a small loss in efficiency

Conclusions & Prospects

- 2009 + 2010 MEG data analysis consistent with null signal
- Most stringent UL on LFV improved by a factor 5

$BR(\mu^+ \to e^+ \gamma) < 2.4 \times 10^{-12}$ @ 90% CL

- MEG 2011 dataset > 2010 +2009 statistic with improved trigger, DAQ and DC noise conditions

Expected sensitivity with 2011 data: 1×10^{-12}
Stay tuned!! :)

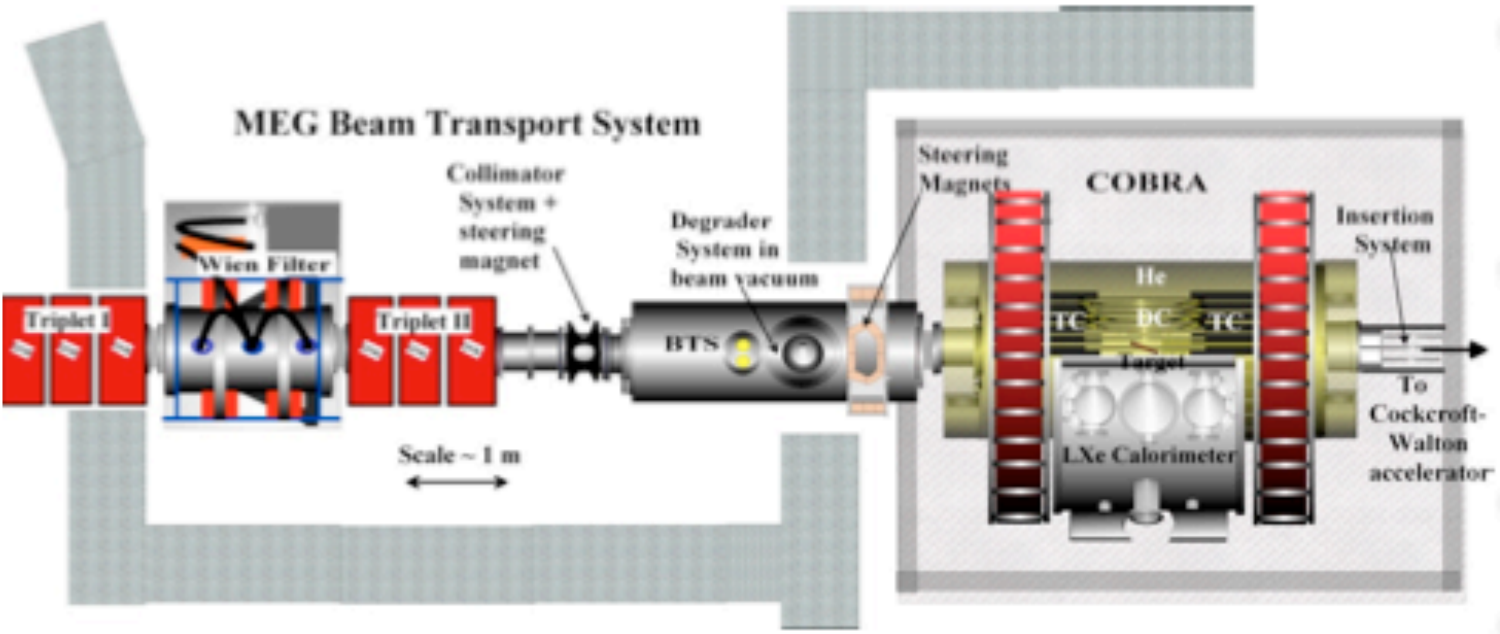
- 2012 data taking starting this week
- Upgrade proposal getting finalized and soon to be presented to INFN (this week) and PSI (end of the year)

Upgrade proposal sensitivity $O(10^{-14})$


INFN Genova
INFN Lecce
INFN Pavia
INFN Pisa
INFN Roma
Tokyo University
KEK
Waseda University
UC Irvine
PSI
JINP Dubna
BINP Novosibirsk
~ 60 collaborators
MEG
experiment
Thank you !!
The MEG Collaboration

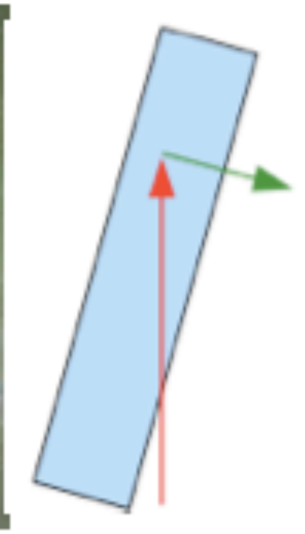
Backup slides

The PSI πE5 beam & target



- Most intense proton DC beam in the world : 2 mA @ 1.3 MW
- 28 MeV/c "surface muons" from decay of π at rest
- Wien filter for e/μ separation
- Solenoid to couple beam with the COBRA magnetic field

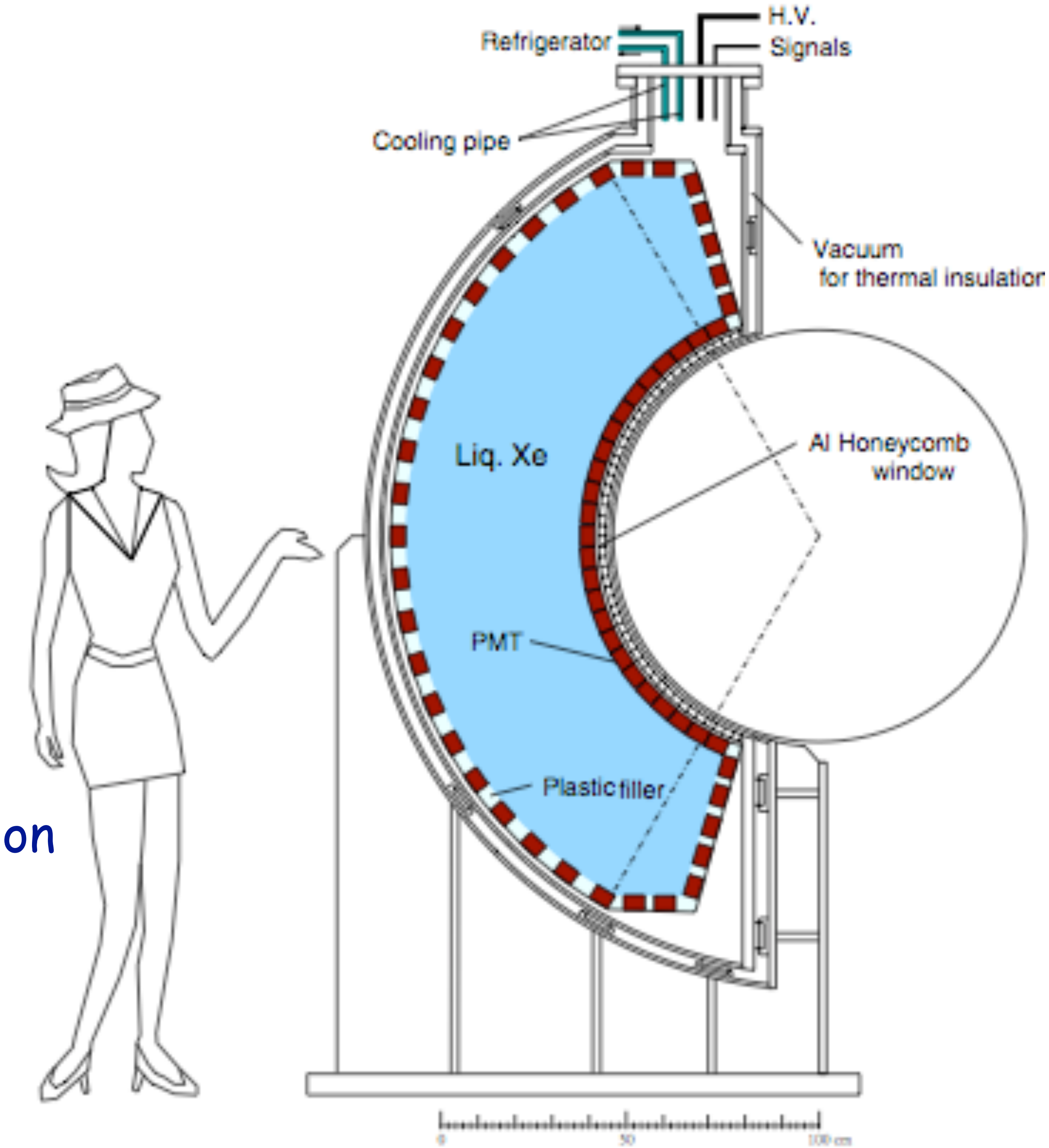
- Need enough material for stopping muons but low bremsstrahlung for signal positron:
  - degrader 200/300 μm + target 205 μm
  - 20.5° angle between beam and target
  - material with high radiation length X_0 (CH_2)



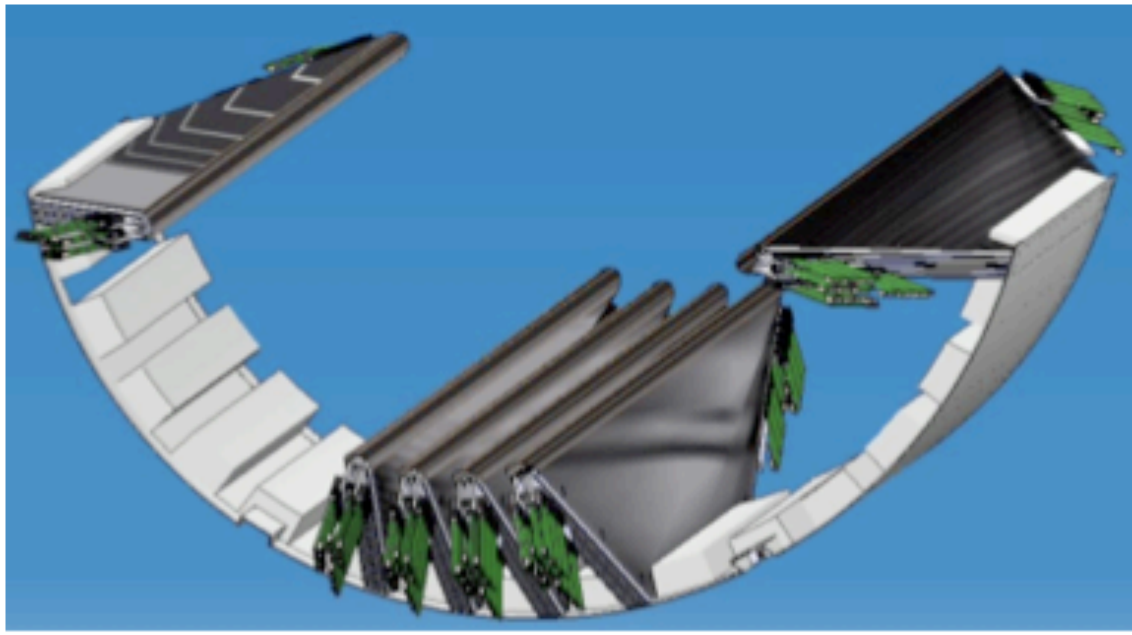
Liquid Xenon γ detector

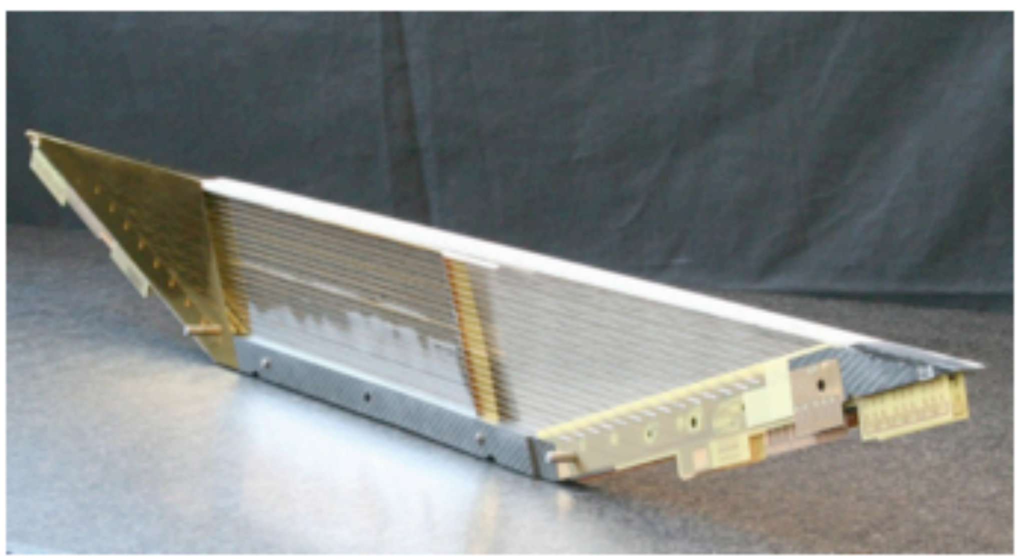
- First ton-scale (~ 900 L) LXe calorimeter in use in the world
- Pros
  - High light yield (~ 75% NaI)
  - Fast response (τ_{decay} = 45 ns)
  - High stopping power (X_0 = 2.8 cm)
  - No self absorption
  - Uniform, no segmentation, no aging
- Challenges
  - Vacuum ultra violet (178 nm)
  - Low temperature (165 K)
  - Need high purity
- Measure photon energy and time and position of conversion inside the LXe

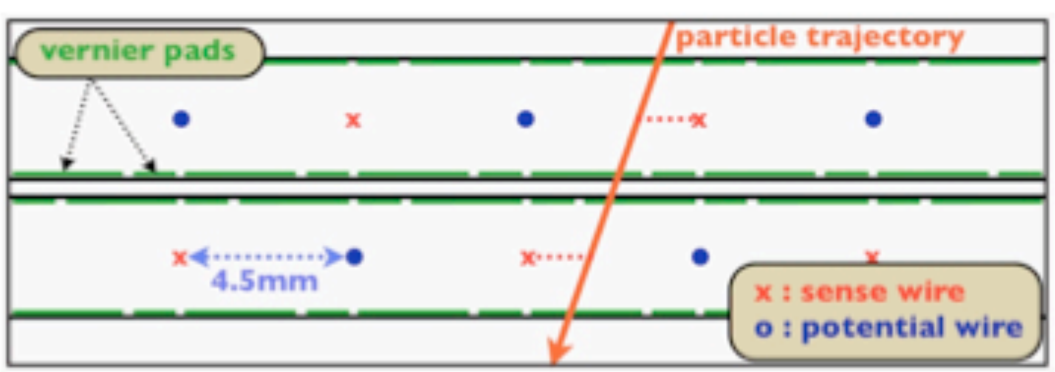
	proposal
σ_E/E < 2 % @ 52.8 MeV	1.2 %
σ_t = 67 ps	43 ps
σ_x = 5-6 mm	3.8-5.1 mm



Drift Chambers





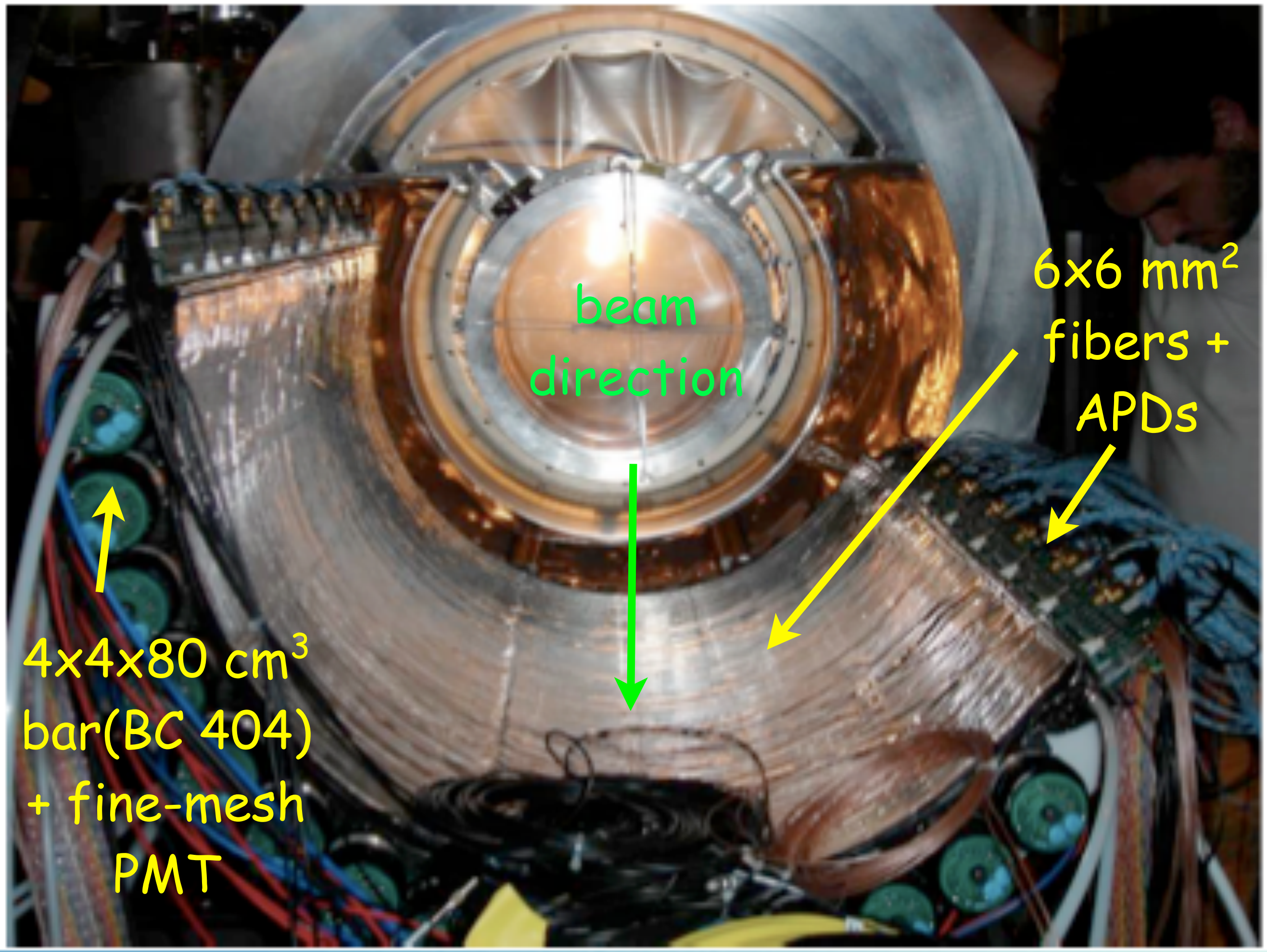


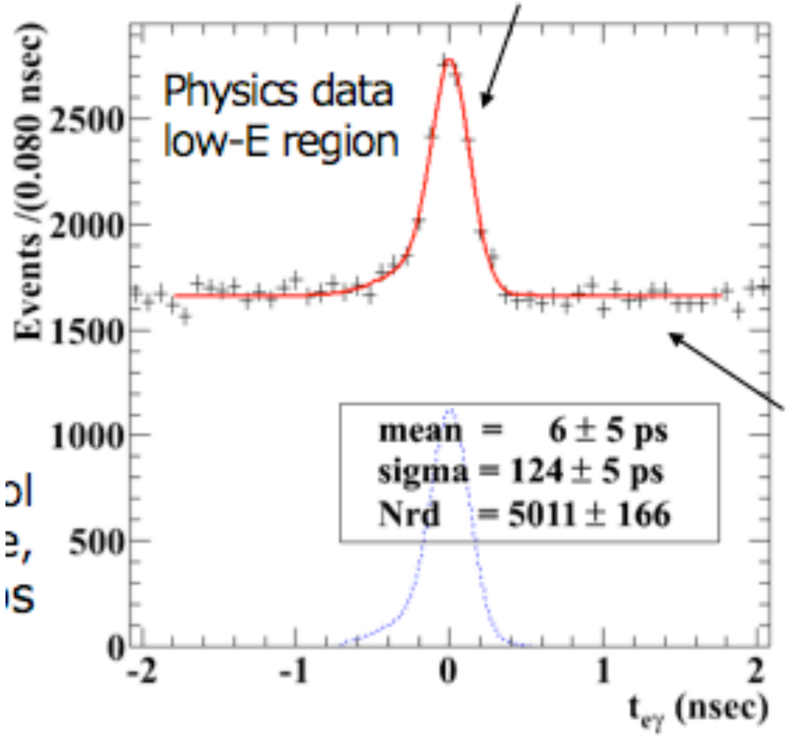
- 16 chamber sectors, 2 planes each
- Staggered array of drift cells
- Helium:Ethane 50/50 mixture
- Ultra low mass chamber to suppress MS that limits momentum and angular resolutions
  - 12.5 μm cathode foils with Vernier patter for Z hit position
  - ~ 0.2 % X_0 along e^+ trajectory
- Reconstruct e^+ momentum vector at target with Kalman filter technique

	proposal
σ_E/E ~ 0.6 %	0.3 %
σ_θ ~ 10 mrad	5 mrad
σ_φ ~ 7 mrad	5 mrad

Time Measurement

- Positron time measured by timing counter: 2 sections (upstream & downstream) of 15 bars each read by fine mesh PMTs
- Further z impact position measurement with scintillating fibers read by APDs
- Crucial for positron time measurement: intrinsic time resolution: current ~ 70 ps/ goal ~ 50 ps

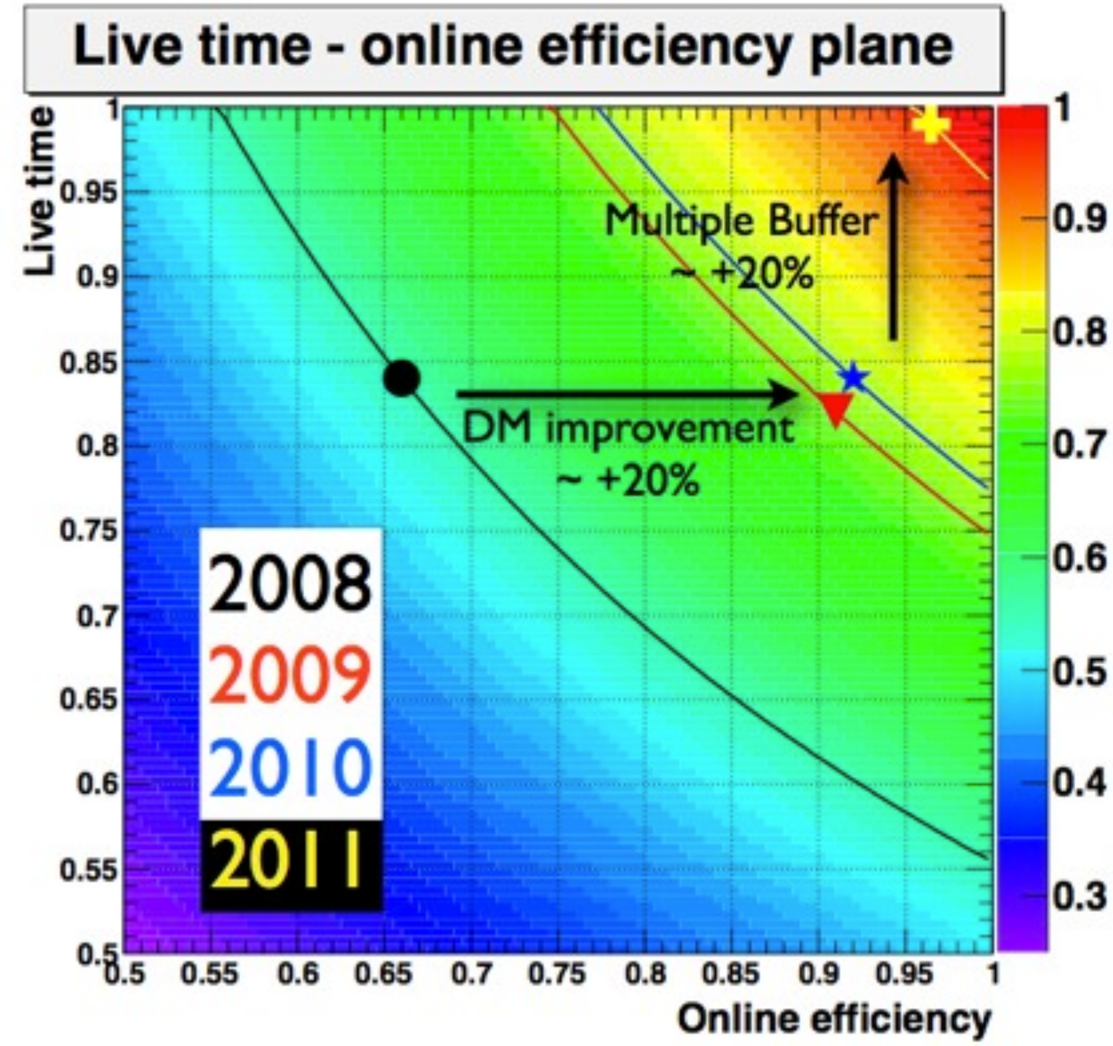




- Muon decay time:
  - TC hit time + e^+ flight length from DC
  - LXe hit time + γ flight lenght
  - $t_{e\gamma} = t_{e+} - t_\gamma$
- $\sigma_{te\gamma}$ = 122 ps from RMD

Trigger & DAQ

- DAQ
  - Custom WF digitizer DRS chip design at PSI
  - Sampling speed [800 MHz, 5 GHz]
  - Bandwidth 1 GHz
  - inter-chip synchronization < 30 ps
- Trigger experimental requirements
  - O (10^7) background suppression
  - > 95 % efficiency on signal
  - Maximum latency ~ 450 ns
  - Flexibility for physics analysis as well as calibrations
- MEG choices
  - 100 MHz digital conversion of input signals
  - Selection algorithms on FPGAs
  - Use of fast detector, LXe and TC:
    - E_γ > 45 MeV ---> rate 2 x 10^3 Hz
    - Δt between LXe and TC --> rate 100 Hz
    - Collinearity based on LUT tables --> 10 Hz



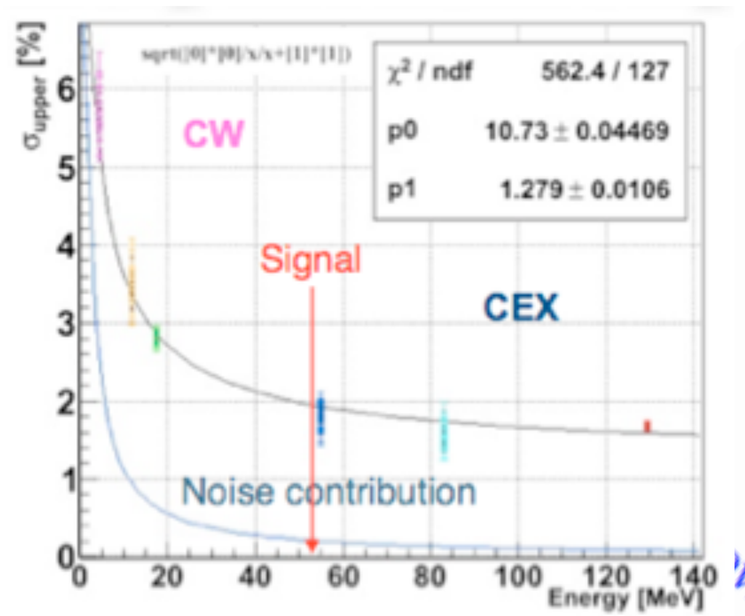
Trigger improvements through time thanks to improved online resolutions (DM improvement) and multiple buffer readout implementation (MB)

CW and CEX calibrations

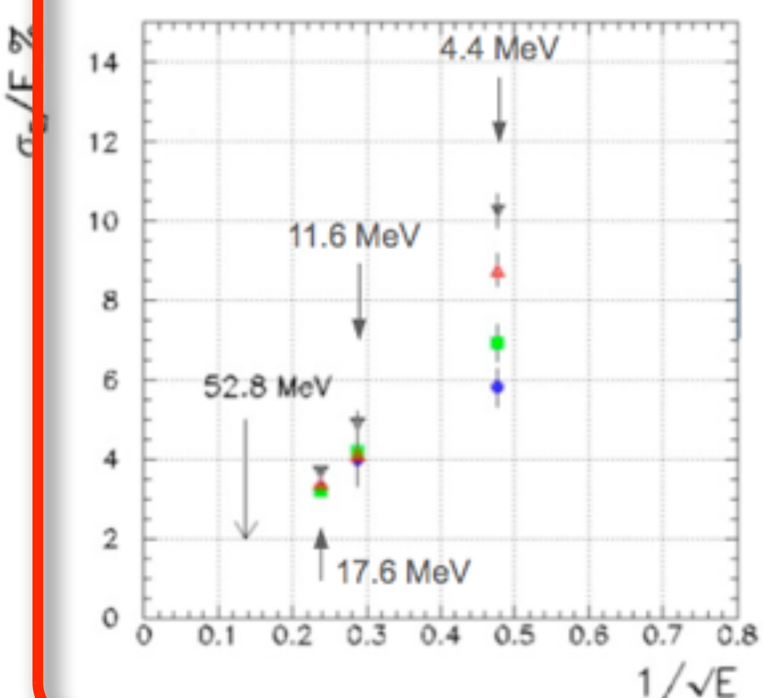
p + $_5^{11}$B → $_6^{12}$C** + γ
4.4, 11.7, ^{12}C** → ^{12}C γ
16.1 MeV ↓
at the same time ^{12}C γ γ

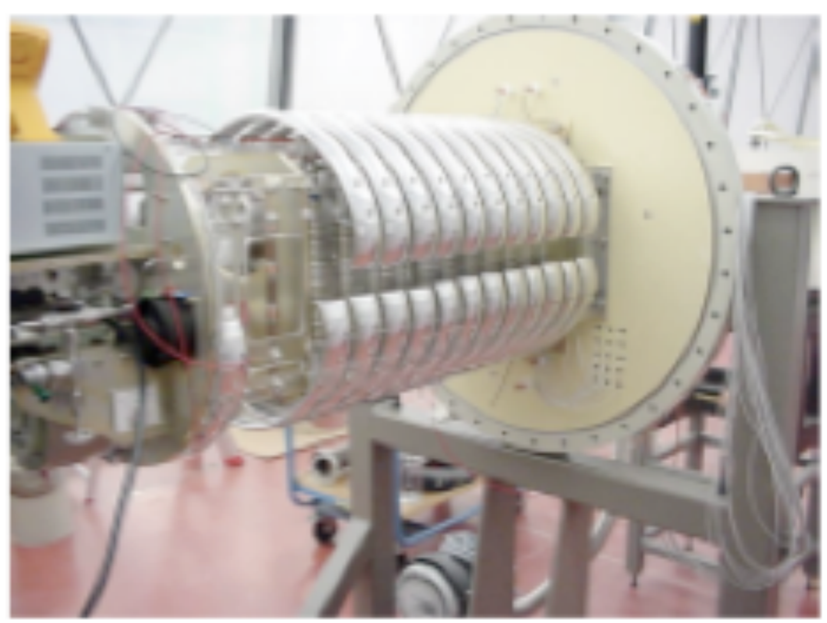
p + $_3^{7}$Li → $_4^{8}$Be + γ
17.6, 14.6 MeV

Target of $Li_2B_4O_7$ allows both calibrations at same time

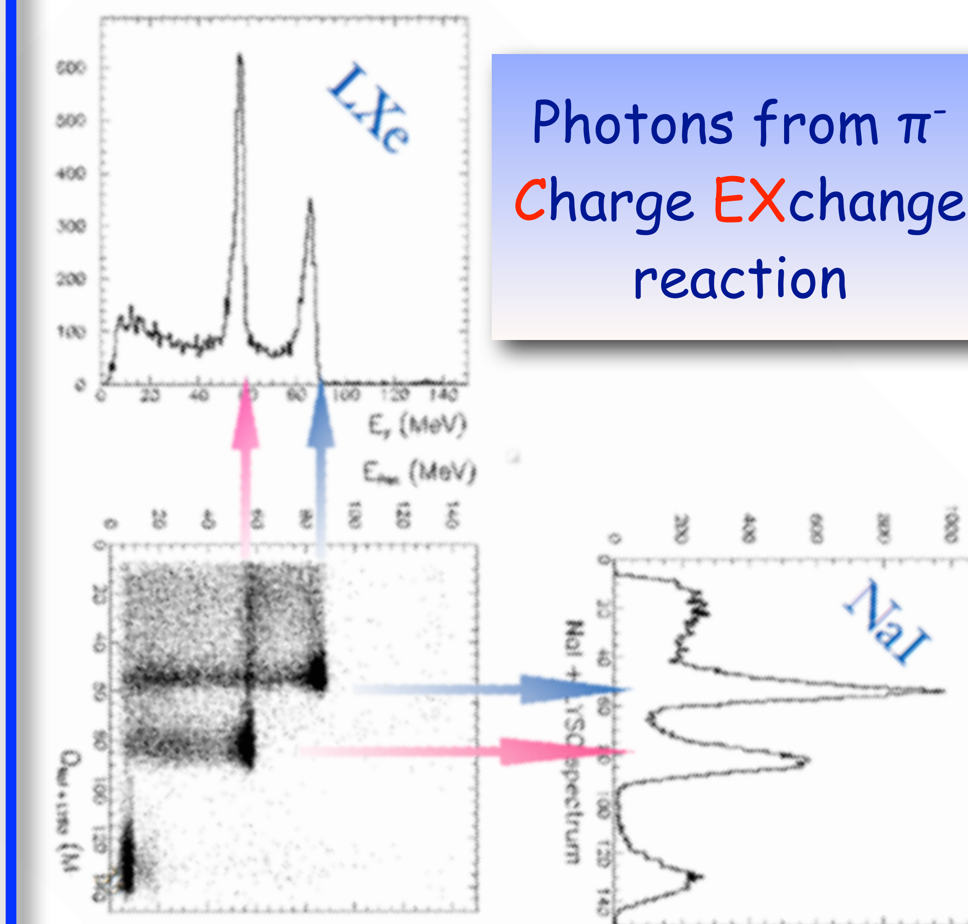


Cockcroft-Walton accelerator

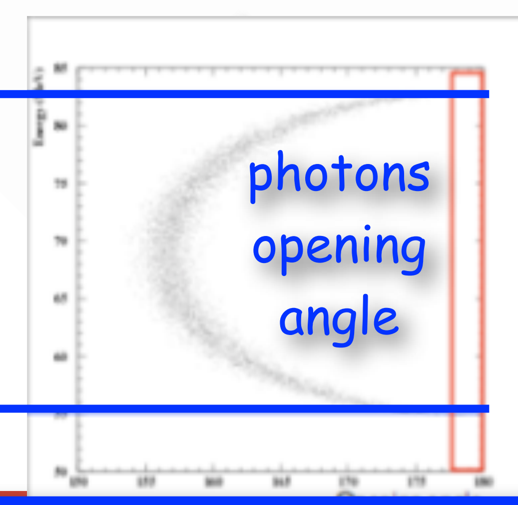




$\pi^- p \rightarrow \pi^0 n$
$\pi^0 \rightarrow \gamma\gamma$



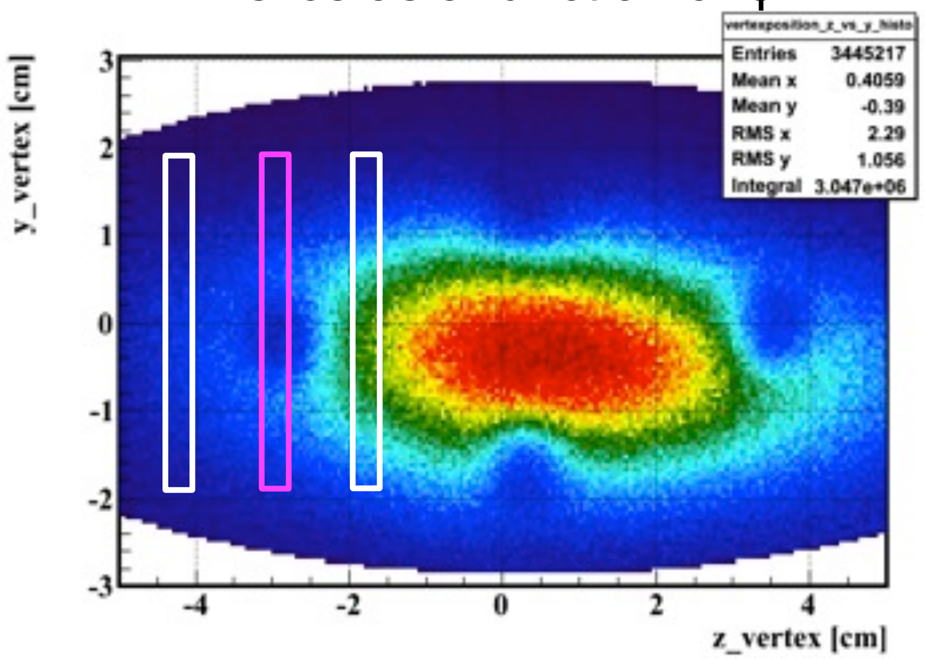
Photons from π⁻ Charge EXchange reaction

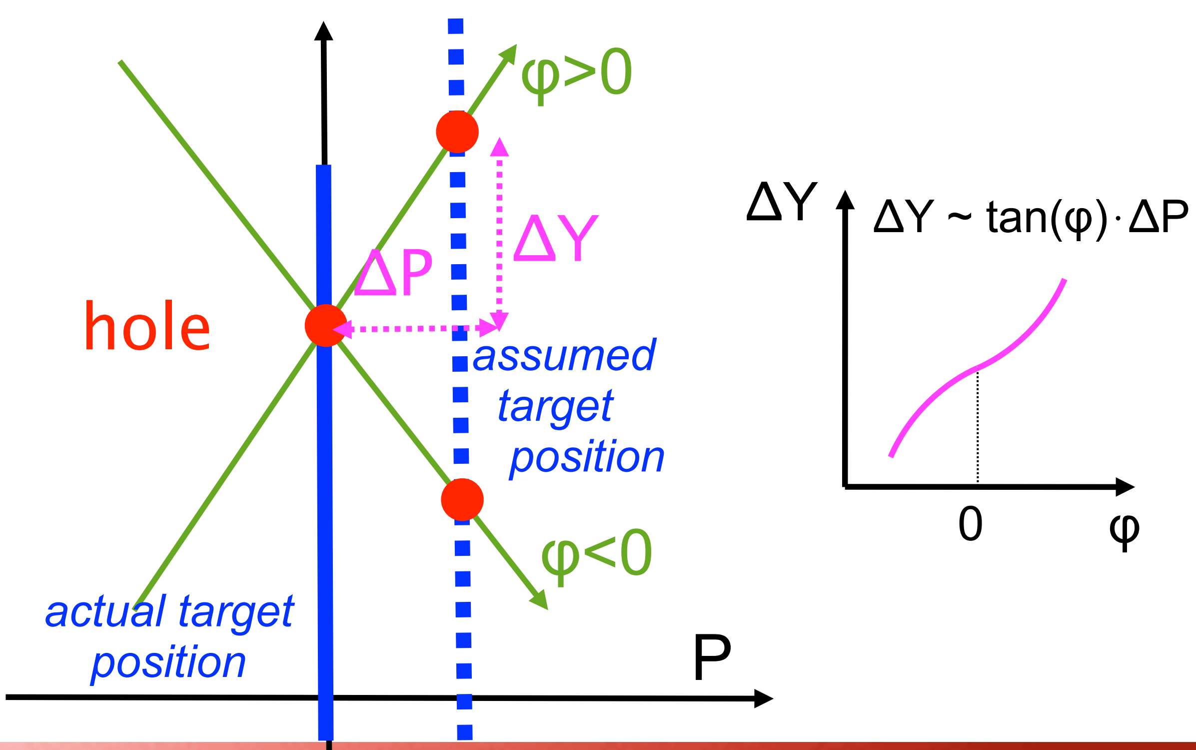


Target Holes

Method 1:

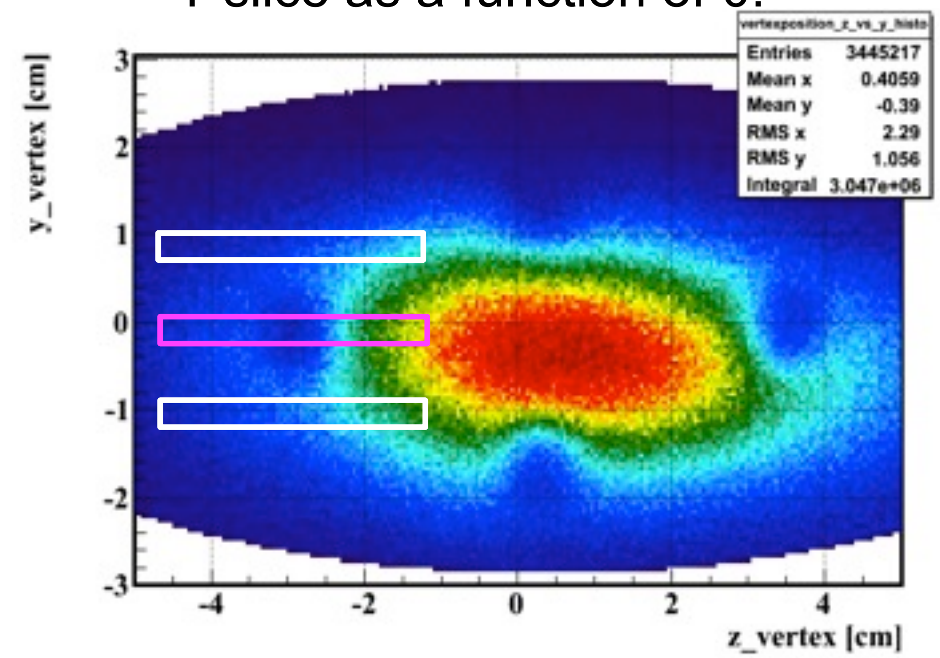
Reconstruct Y-coordinate in Z-slice as a function of φ:

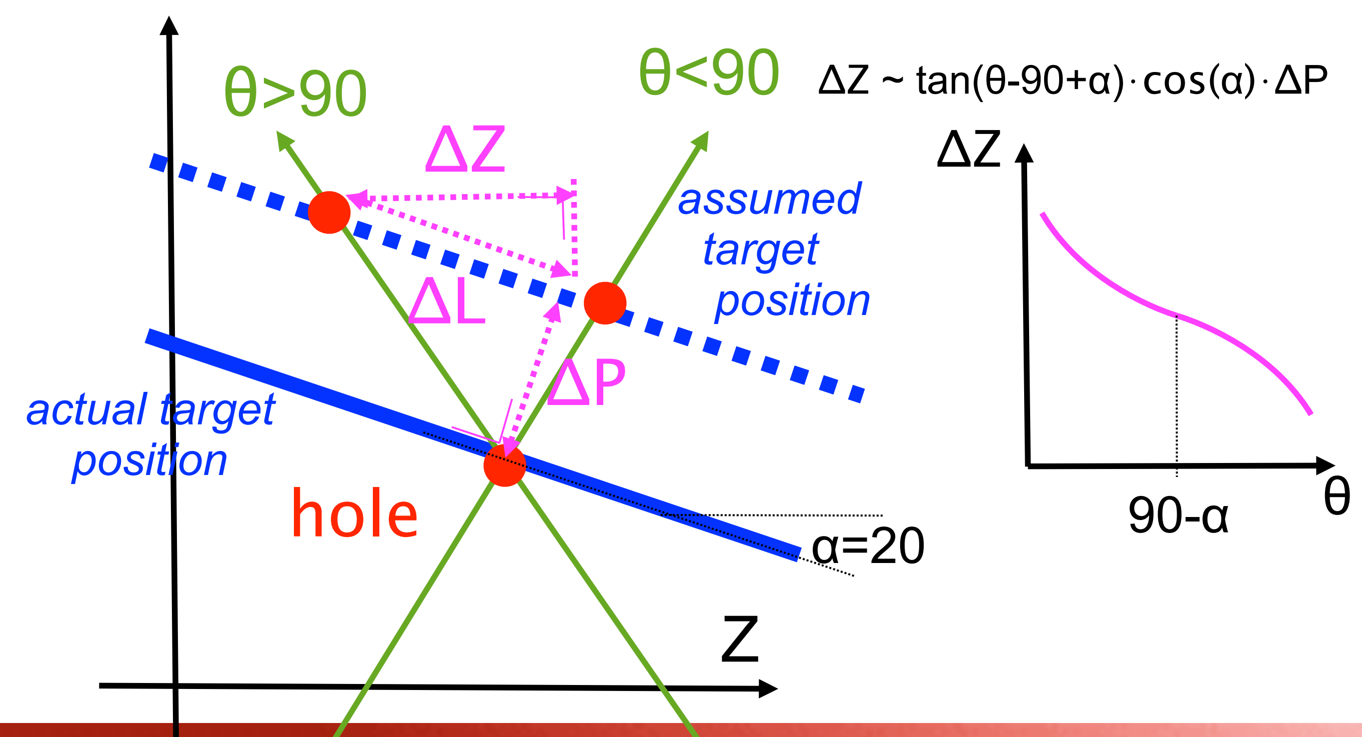




Method 2:

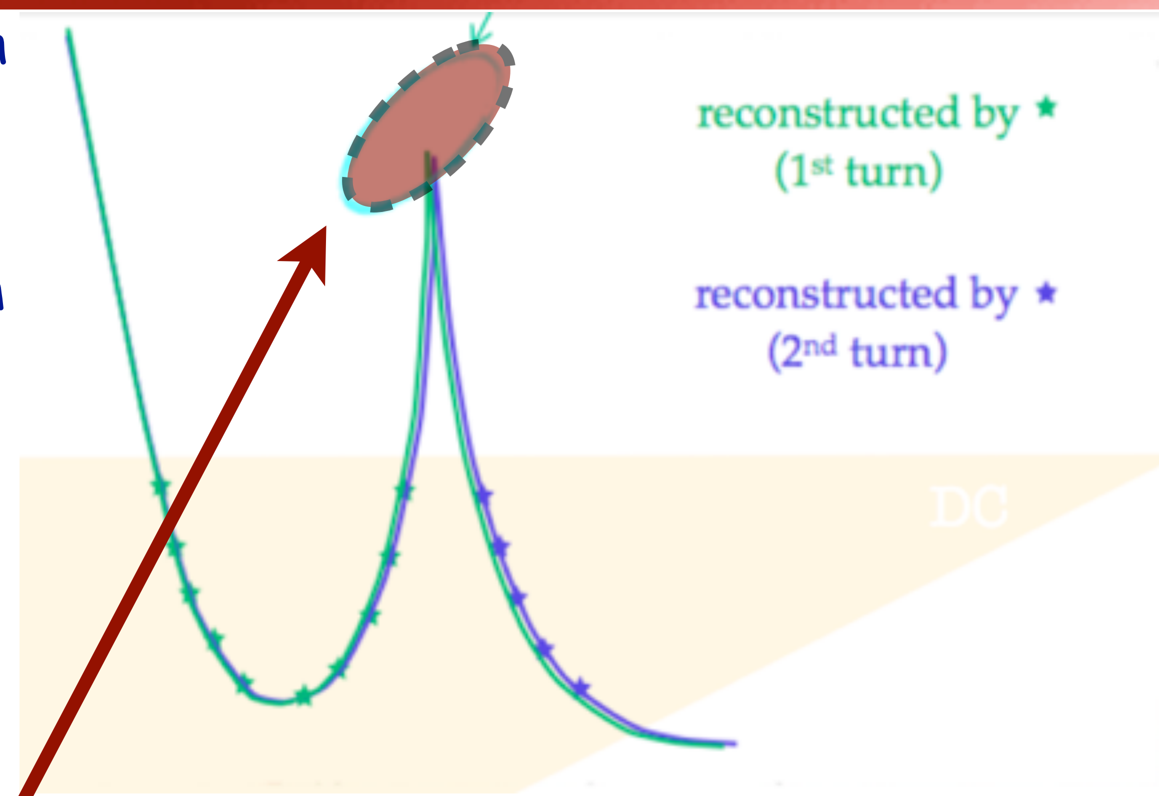
Reconstruct Z-coordinate in Y-slice as a function of θ:





Signal Positron PDFs & Correlations

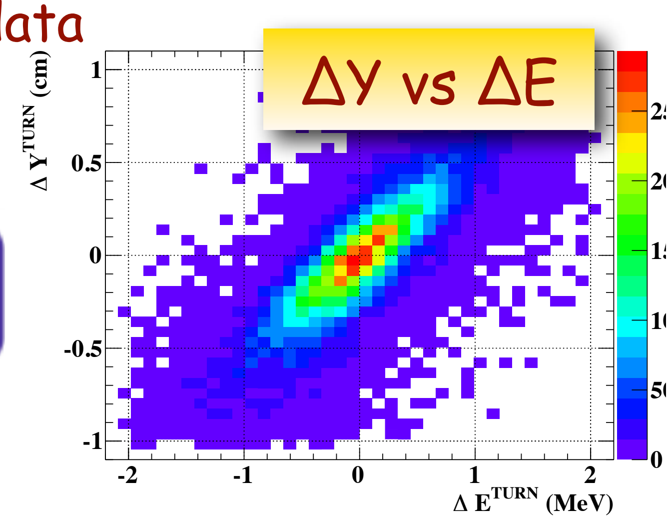
- Signal positron PDFs are evaluated from tracks which make 2 turns inside the spectrometer, treating each turn as an independent pseudo track
- Since all positrons must come from the target (~200 μm thick, fairly considered bidimensional in our analysis), this constraint removes one degree of freedom from the problem, introducing correlations among all positrons track parameters and resolutions
- This geometrical effect worsen resolutions, which can nevertheless be partially recovered taking correlations into account in the likelihood analysis
- Evaluating resolution at the 2-turn track turning point on a fictitious plane with same inclination as the target allows to extract correlations from data

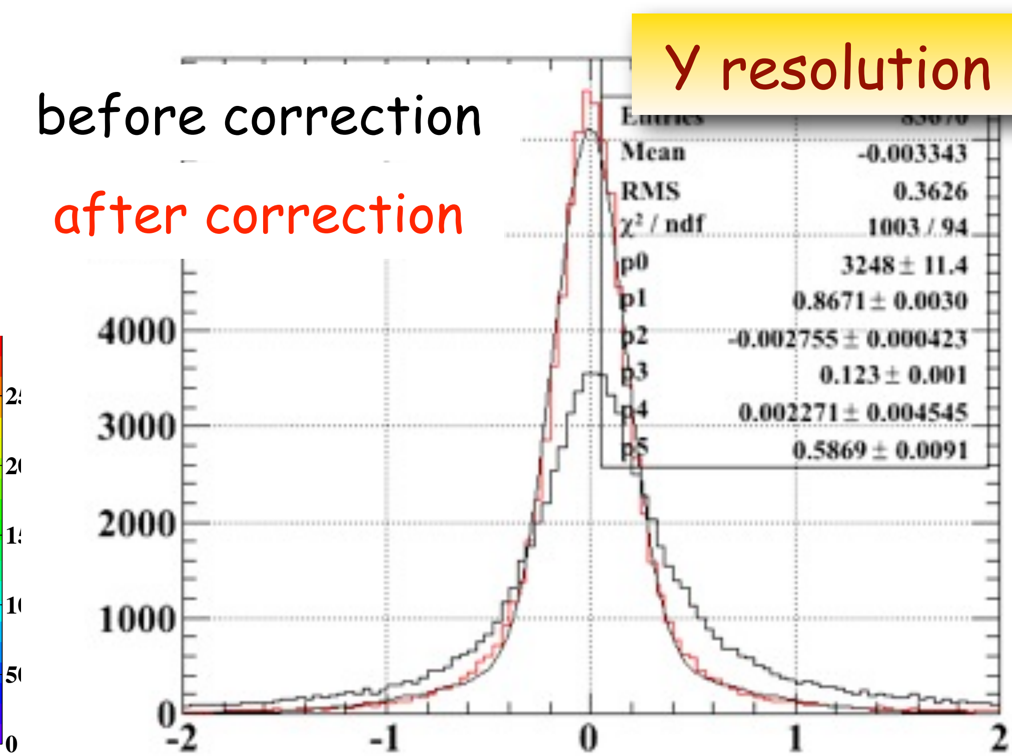


$$\delta\phi_e = -2\tan\phi_e\frac{\delta R}{R} = -2\tan\phi_e\frac{\delta E}{E}$$

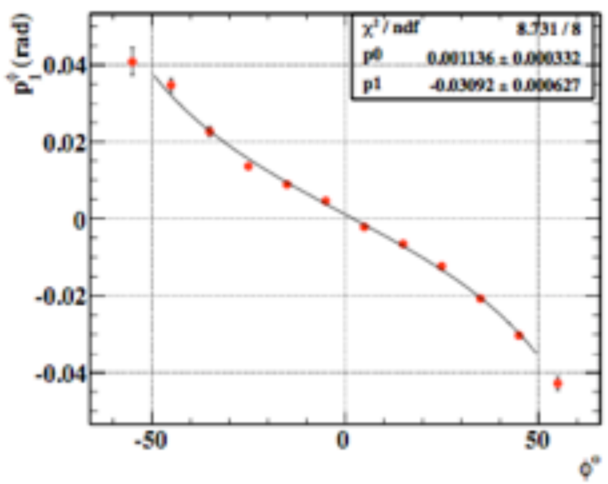
$$\delta Y = 2\delta R\cos\phi_e + R\sin\phi_e\delta\phi_e = \frac{2R}{\cos\phi_e}\frac{\delta E}{E}$$

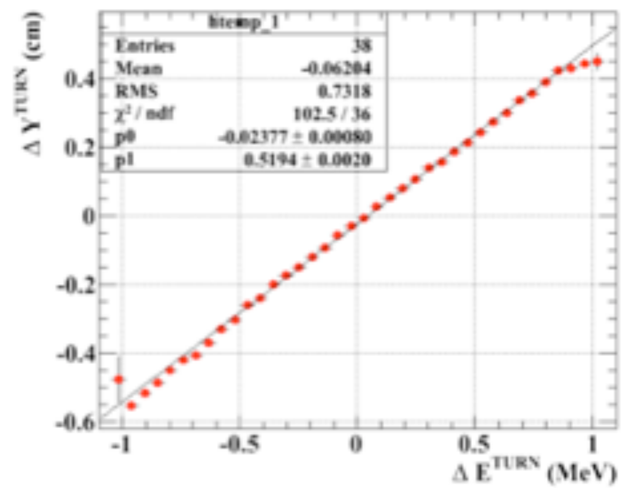
$$\delta Z = \frac{2R}{\sin^2\theta_e}\delta\theta_e - 2R\cot\theta_e\frac{\delta E}{E}$$

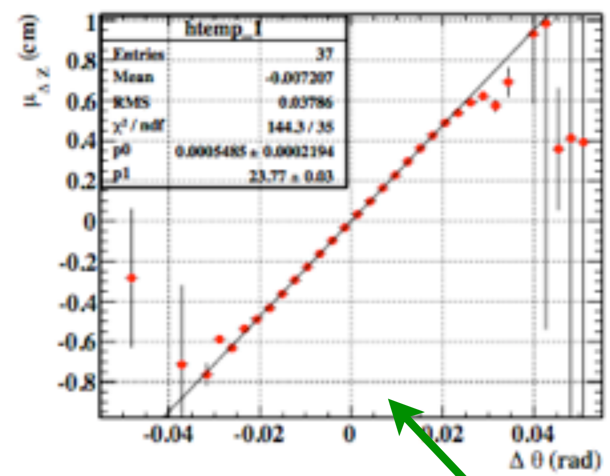


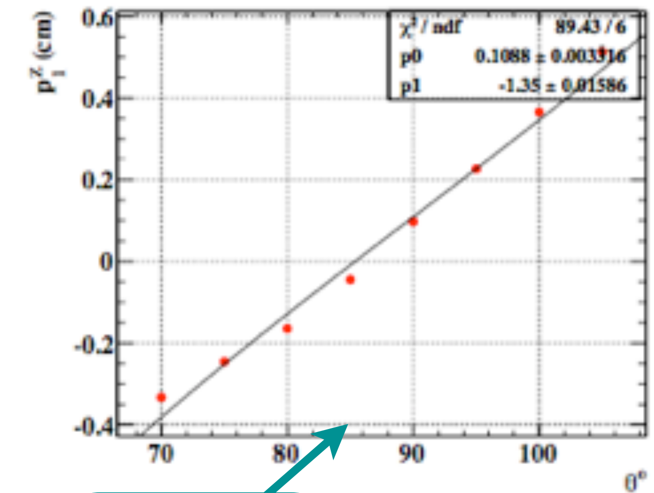


Correlations and Resolutions







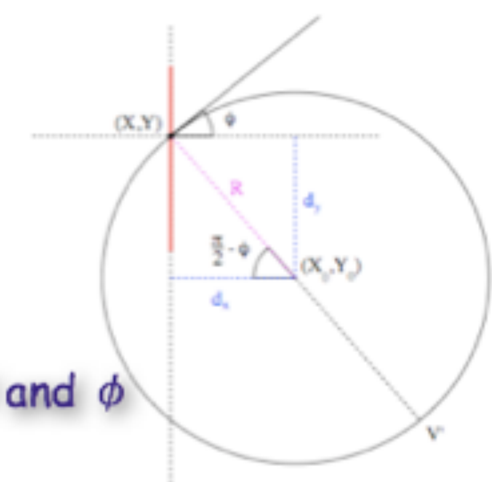


$$\delta\phi_e = -2\tan\phi_e \frac{\delta R}{R} = -2\tan\phi_e \frac{\delta E}{E}$$

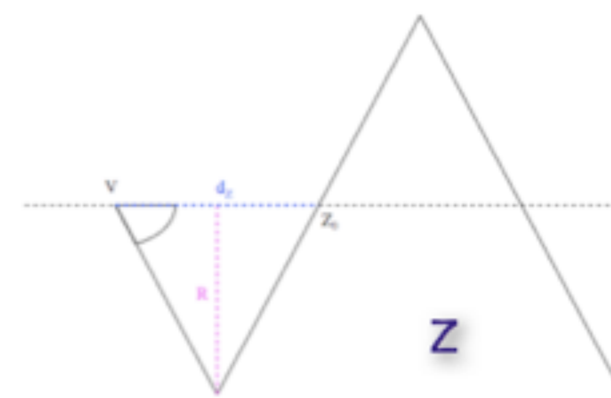
$$\delta Y = 2\delta R\cos\phi_e + R\sin\phi_e\delta\phi_e = \frac{2R}{\cos\phi_e}\frac{\delta E}{E}$$

$$\delta Z = \frac{2R}{\sin^2\theta_e}\delta\theta_e - 2R\cot\theta_e\frac{\delta E}{E}$$

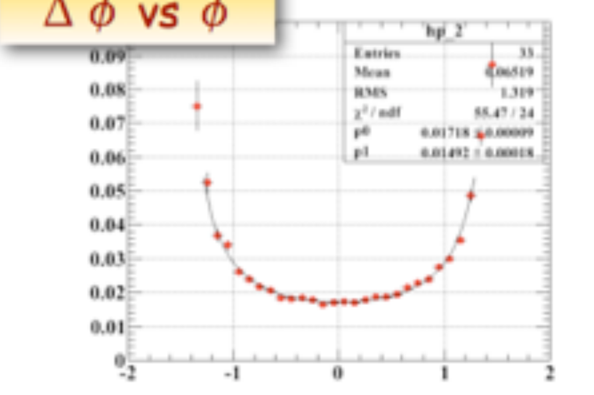
Y and ϕ

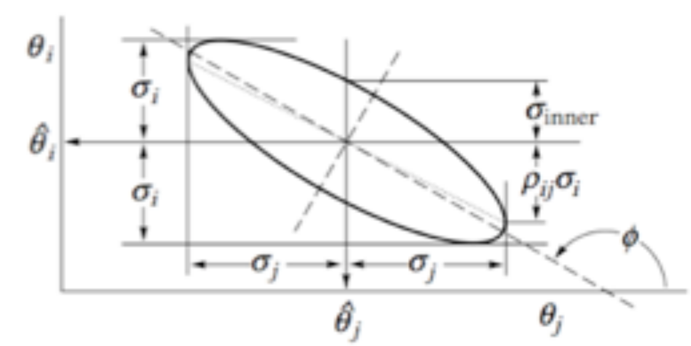


Z



$\Delta\phi$ vs ϕ





$$d\hat{\theta}_i/d\theta_j = \rho_{ij} \times \frac{\sigma_i}{\sigma_j}.$$

Phys. Rev. Lett. 107, 171801 (2011)

This result

- 2009 + 2010 dataset combined analysis (2010 data ~ 2 x 2009 data)
- Improved understanding of the experiment w.r.t. ICHEP 2010:
  - Improved alignment inside and among detectors through newly developed techniques
  - Improved magnetic field map
  - Implementation of correlations at the target in likelihood analysis, strongly reducing the systematics and the effective resolutions
- Improvements in the likelihood analysis technique w.r.t. ICHEP 2010
  - N_{bkg} constrained from sideband data
  - Profile-likelihood interval with Feldman-Cousins method

compare best UL 12×10^{-12}

Sensitivity confirmed on time AND angular sideband data

Sensitivity of combined data 1.6×10^{-12} @ 90% CL

3.3×10^{-12} in 2009 + 2.2×10^{-12} in 2010

Performances

	2009	2010
γ energy	1.9%(w> 2cm), 2.4%(w< 2cm)	1.9%(w> 2cm), 2.4%(w< 2cm)
γ timing	96 ps	67 ps
γ position	5 mm (u,v), 6 mm(w)	5 mm (u,v), 6 mm(w)
γ efficiency	58%	59%
e^+ timing	107 ps	107 ps
e^+ energy	0.31 MeV (80% core)	0.32 MeV (79% core)
e^+ angle (θ)	9.4 mrad	11.0 mrad
e^+ angle (φ)	6.7 mrad	7.2 mrad
e^+ vertex (Z/Y)	1.5 mm/1.1 mm(core)	2.0 mm/1.1 mm(core)
e^+ efficiency	40%	34%
e^+ - γ timing	146 ps	122 ps
Trigger efficiency	91%	92%
e^+ - γ angle (θ)	14.5 mrad	17.1 mrad
e^+ - γ angle (φ)	13.1 mrad	14.0 mrad
Stopping μ rate	2.9×10^7 s^{-1}	2.9×10^7 s^{-1}
DAQ time/ Real time	35 days/43 days	56 days/67 days
Total stopped μ	6.5×10^{13}	1.1×10^{14}

Slightly worse e^+ tracking in 2010 due to noise problem

Photon timing improvement thanks to WF digitizer upgrade in 2010

Some more numbers :)

- Fit region

  $48 \le E_\gamma \le 58$MeV, $50 \le E_e \le 56$MeV, $|t_{e\gamma}| \le 0.7$ns, $|\theta_{e\gamma}| \le 50$mrad, $|\phi_{e\gamma}| \le 50$mrad

Sensitivity

	2009	2010	Combined
N_{sig} (median)	3.6	4.8	5.2
BR (median)	3.3×10^{-12}	2.2×10^{-12}	1.6×10^{-12}

2009 + 2010 combined

	Best fit	LL (90% CL)	UL (90% CL)	UL (95% CL)	CL@0
N_{sig}	−0.5	–	7.8(7.7)	9.8(N/A)	–
BR	-1.5×10^{-13}	–	2.4×10^{-12}(2.3×10^{-12})	2.9×10^{-12}(N/A)	–

2009

	Best fit	Error (MINOS 1.645σ)
N_{sig}	+3.4	+6.6−4.4
N_{RMD}	+26.9	+4.5−4.5
N_{BG}	+273.1	+12.3−12.3

	Best fit	LL (90%CL)	UL (90%CL)	UL (95%CL)	CL@0
N_{sig}	3.4	0.2(0.2)	10.4(10.1)	11.9(N/A)	0.92(0.92)
BR	3.2×10^{-12}	1.7×10^{-13}(1.7×10^{-13})	9.6×10^{-12}(9.4×10^{-12})	1.1×10^{-11}(N/A)	0.92(0.92)

2010

	Best fit	Error (MINOS 1.645σ)
N_{sig}	−2.2	+5.0−1.9
N_{RMD}	+50.2	+9.2−9.2
N_{BG}	+608.5	+18.7−18.6

	Best fit	LL (90%CL)	UL (90%CL)	UL (95%CL)	CL@0
N_{sig}	−2.2	–	3.8(3.7)	5.0(N/A)	–
BR	-9.9×10^{-13}	–	1.7×10^{-12}(1.7×10^{-12})	2.3×10^{-12}(N/A)	–

Systematics

- Systematics effect taken into account in the calculation of confidence interval by profiling on (N_{RD}, N_{BKG}) and by fluctuating PDFs according to the uncertainty values
- All the results shown have systematic effects taken into account
- Size of systematic uncertainty in in total 2% on the UL: 2.3×10^{-12} --> 2.4×10^{-12}
- Contribution of each item in the list was studied with toy MC experiments by comparing the results with the nominal PDFs and the one with the fluctuated ones

Relative contributions on UL

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