Search for $\mu \to e\gamma$ decay

MEG latest result

4/September/2011

Crimean conference @ Alushta

NEW TRENDS IN HIGH-ENERGY PHYSICS

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(for MEG collaboration)

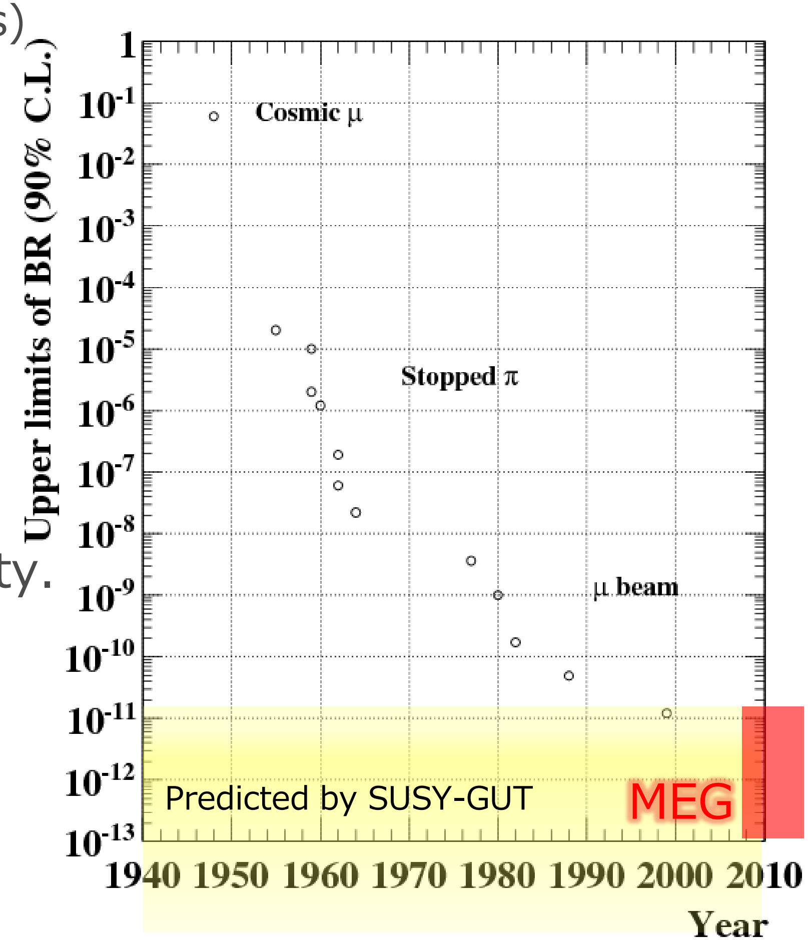
$\mu \rightarrow e\gamma$ search

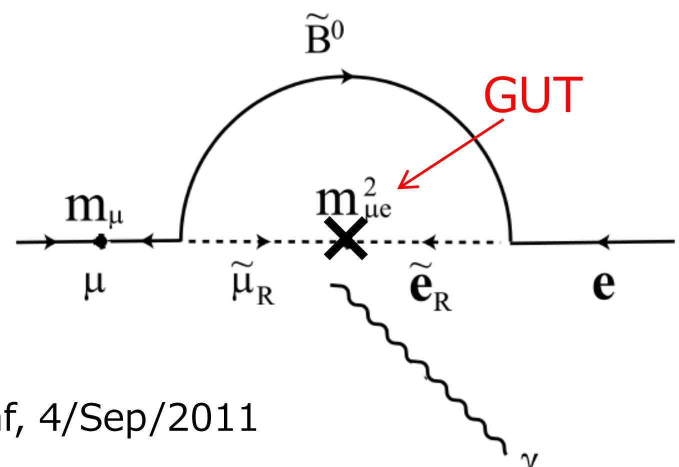
MEG
Mu-E-Gamma Collaboration

- Lepton-flavor violation (LFV) in charged lepton sector has not been observed.
  - Forbidden in SM ($<O(10^{-50})$ with finite ν mass)
  - But new physics predict observable rate
    - Ex) SUSY-seesaw, SUSY-GUT, etc.

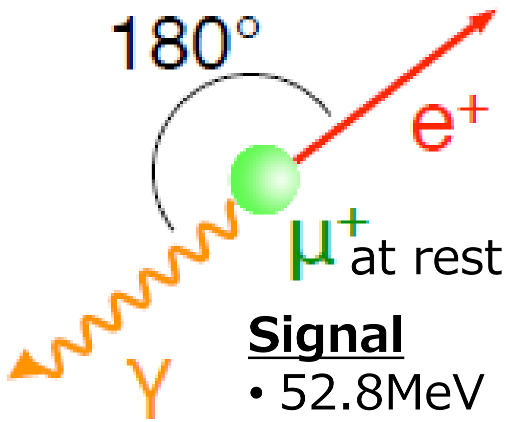
      $\mathcal{B}(\mu \rightarrow e\gamma) \sim \mathbf{10^{-15}\text{-}10^{-11}}$
- Existing experimental upper limit
  - $\mathcal{B}(\mu \rightarrow e\gamma) < \mathbf{1.2 \times 10^{-11}}$ (1999, MEGA@LAMPF)
- A $\mu \rightarrow e\gamma$ signal is a clear evidence for new physics
  - No SM background, no hadronic uncertainty.
- MEG aims at searching down to $O(\mathbf{10^{-13}})$

History of $\mu \rightarrow e\gamma$ search

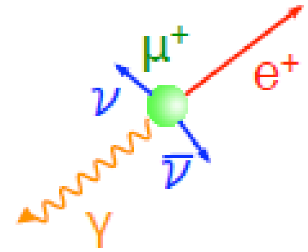




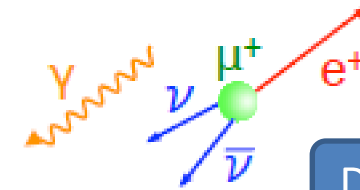
Signal & Background



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



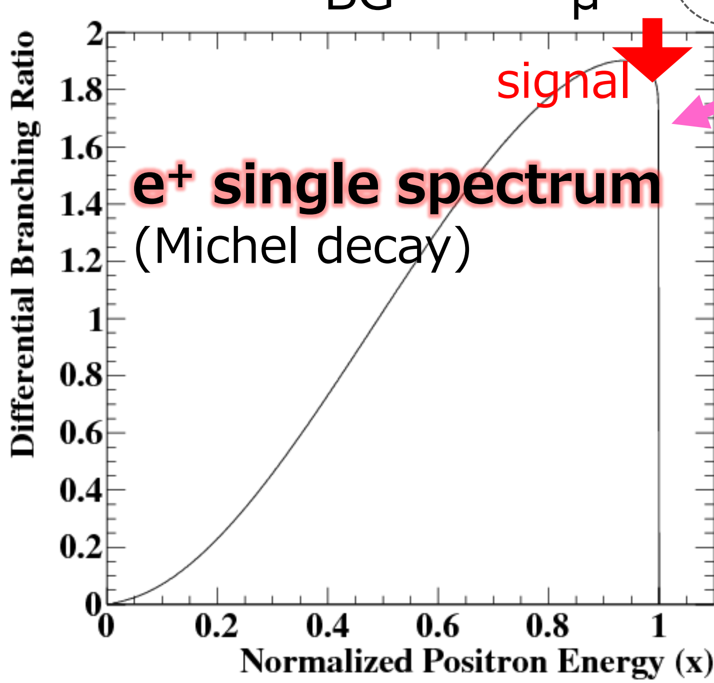
Physics BG
(radiative muon decay)
- <52.8MeV
- Any angle
- Time coincidence



Dominant

Accidental BG
- <52.8MeV
- Any angle
- Random

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



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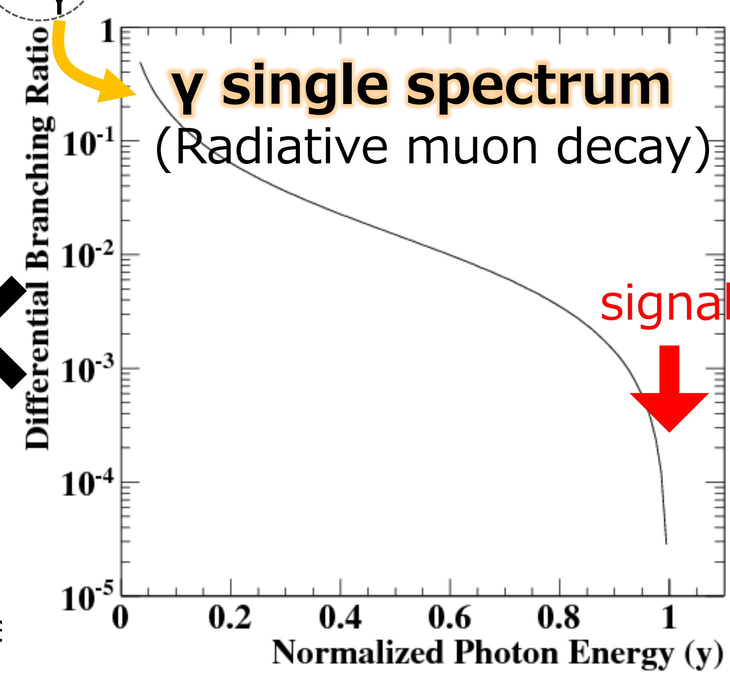
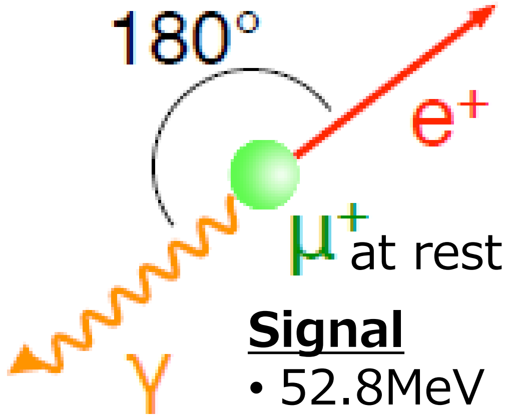


Signal & Background



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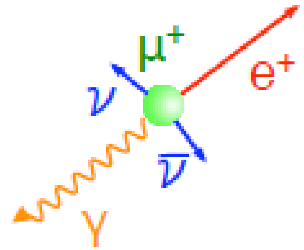

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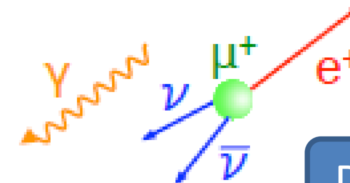

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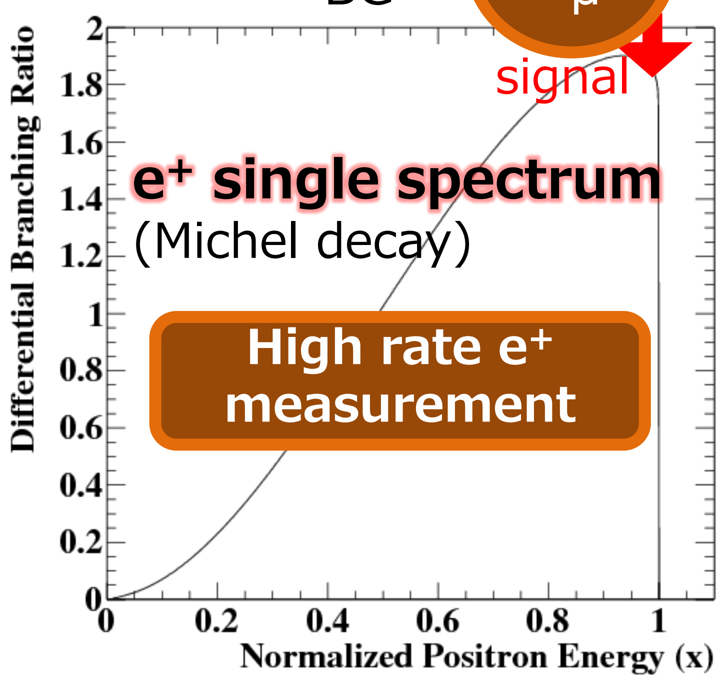

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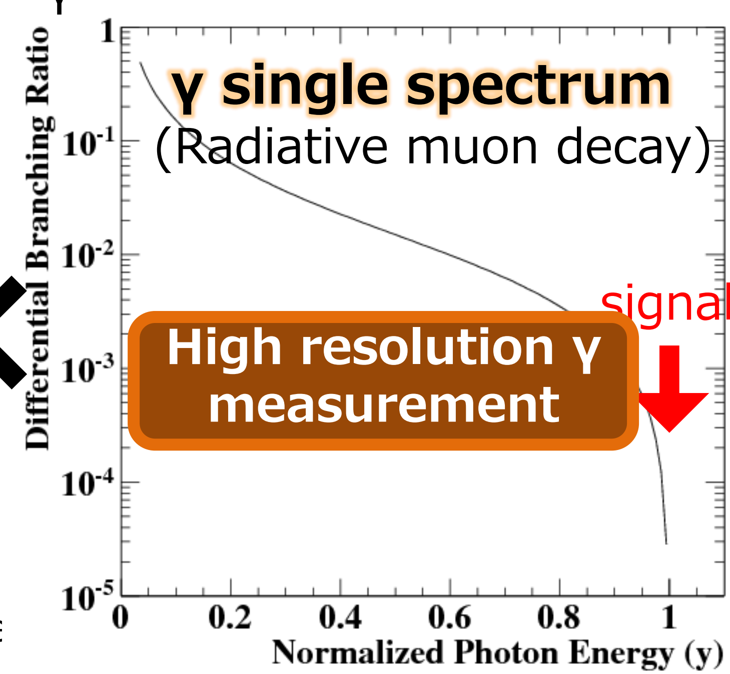
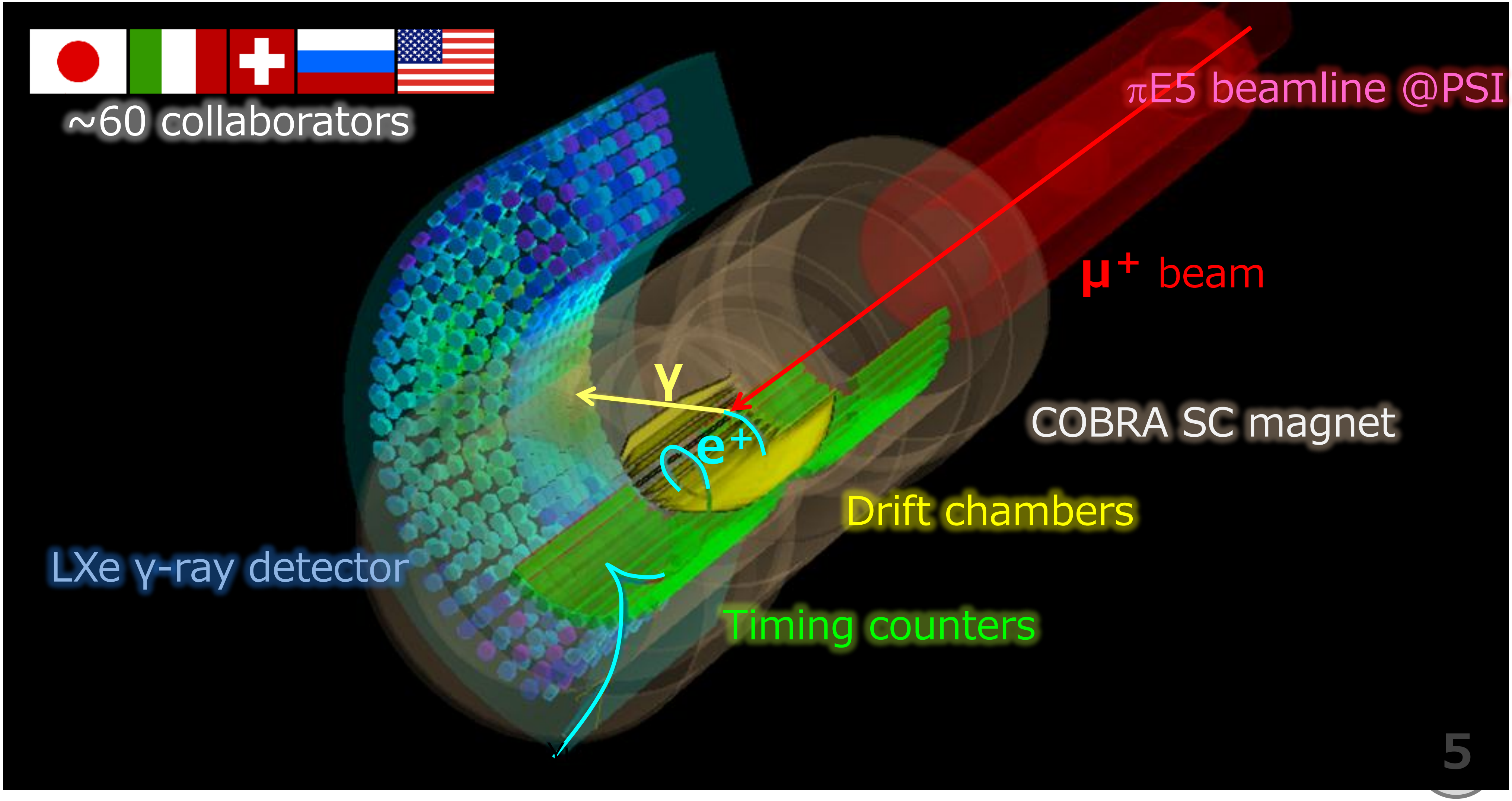


The MEG Experiment

- World's most intense **DC muon beam** @ PSI
- High-rate tolerable e^+ spectrometer with **gradient B-field**
- High performance γ-ray detector with **Liquid Xenon**



MEG History

MEG
Mu-E-Gamma Collaboration

1999		Proposal
…		… R&D …
2007		Engineering run
2008	Sep – Dec	1st physics data acquisition
2009		Analysis of 2008 data
		Hardware upgrade
	Nov – Dec	2nd physics data acquisition
2010		Analysis of 2009 data
	Aug – Oct	3rd physics data acquisition
2011		Analysis of 2009&2010 data
now	July – Nov	4th physics data acquisition
…		…

First result (2008 data)
(Nucl.Phys.B834 1)
Sensitivity : $\mathbf{1.3\times10^{-11}}$
90% UL : $\mathbf{2.8\times10^{-11}}$

Preliminary result of 2009
(presented in conferences)
Sensitivity : $\mathbf{6.1\times10^{-12}}$
90% UL : $\mathbf{1.5\times10^{-11}}$

Final result of 2009 & 2010
(arXiv:11075547, accepted PRL)
This talk

What's new

- New data
  - 2010 data = 2 × 2009 data
  - Combine 2009 & 2010
- Better understand of detector
  - Alignments inside/among detectors
  - Implement correlations among variables
  - → Reduction of systematic uncertainties
- Analysis methods
  - N_{BG} constrained from sideband data
  - Profile-likelihood interval with Feldman-Cousins method

PSI 1.2MW proton ring- cyclotron

590 MeV
2.2mA

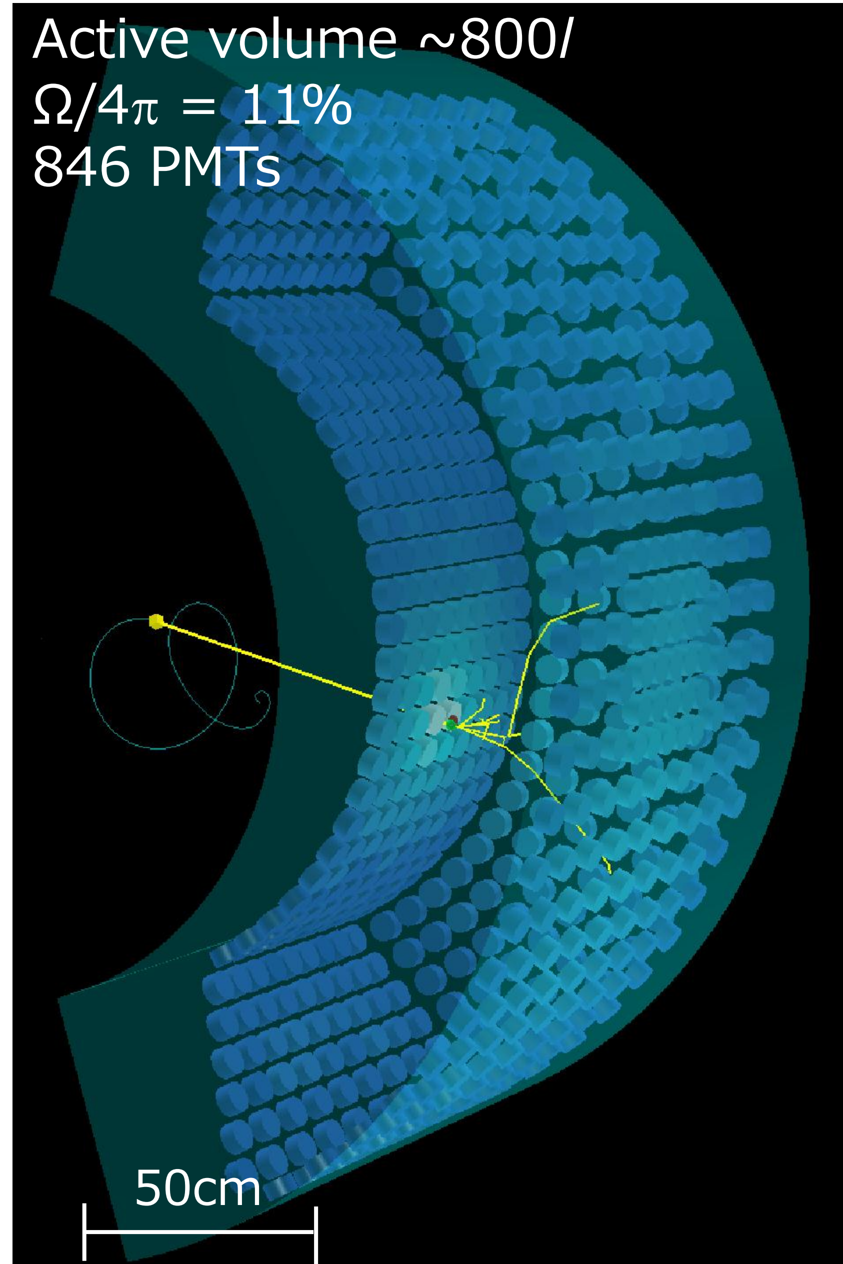
cf.
MEGA used pulsed beam
 6% duty cycle
 Instant intensity 2.6×10^8
 average 1.3×10^7

MEG
 Duty cycle 100%
 instant=ave **$3 \times 10^7 \mu^+/s$**

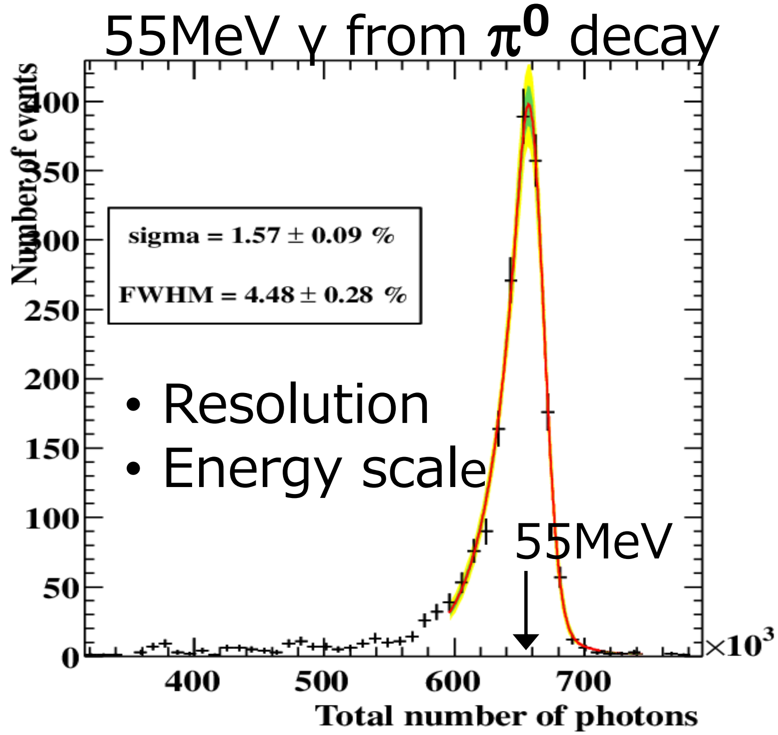
Provides world's most intense DC muon beam
(surface muon)

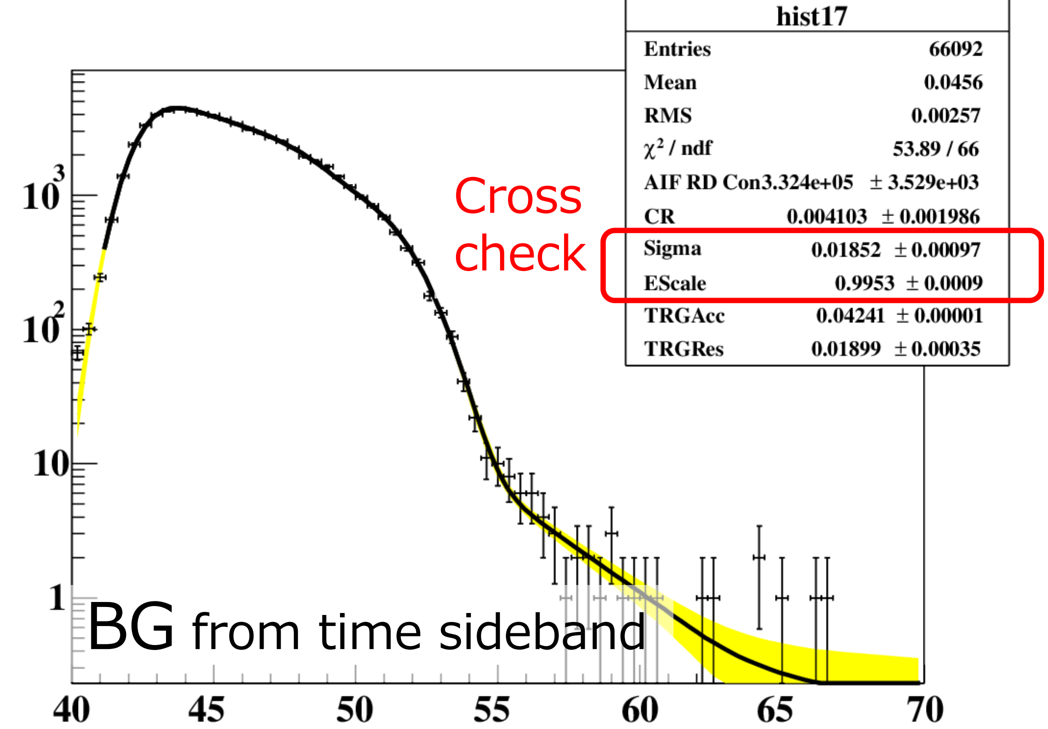
Liquid xenon γ-ray detector

- 900 liter liquid xenon
  - Scintillation medium
    - High light yield (75% of NaI(Tl))
    - Fast response (τ_{decay}=45ns)
    - High stopping power (X_0=2.8cm)
    - No self-absorption
    - Uniform, no-aging
  - Challenges
    - Vacuum ultra-violet (178nm)
    - Low temperature (165K)
    - Need high purity
  - No segmentation
- Measure energy, position, time at once
  - $\sigma_E/E < 2\%$ (@52.8MeV)
  - σ_t = 67 psec
  - σ_x = 5-6 mm

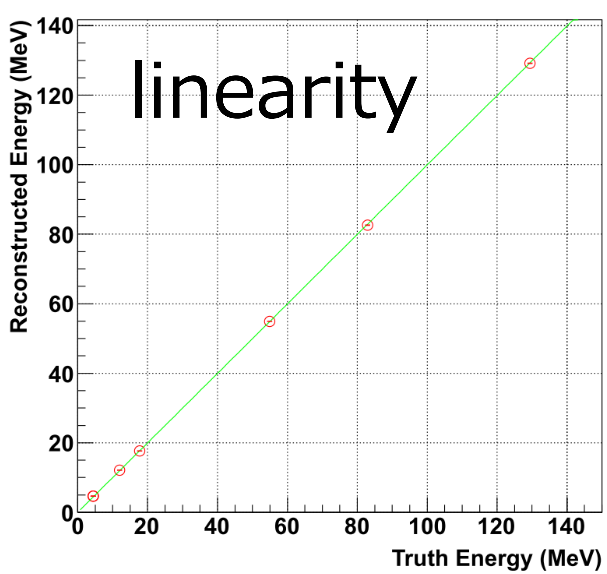


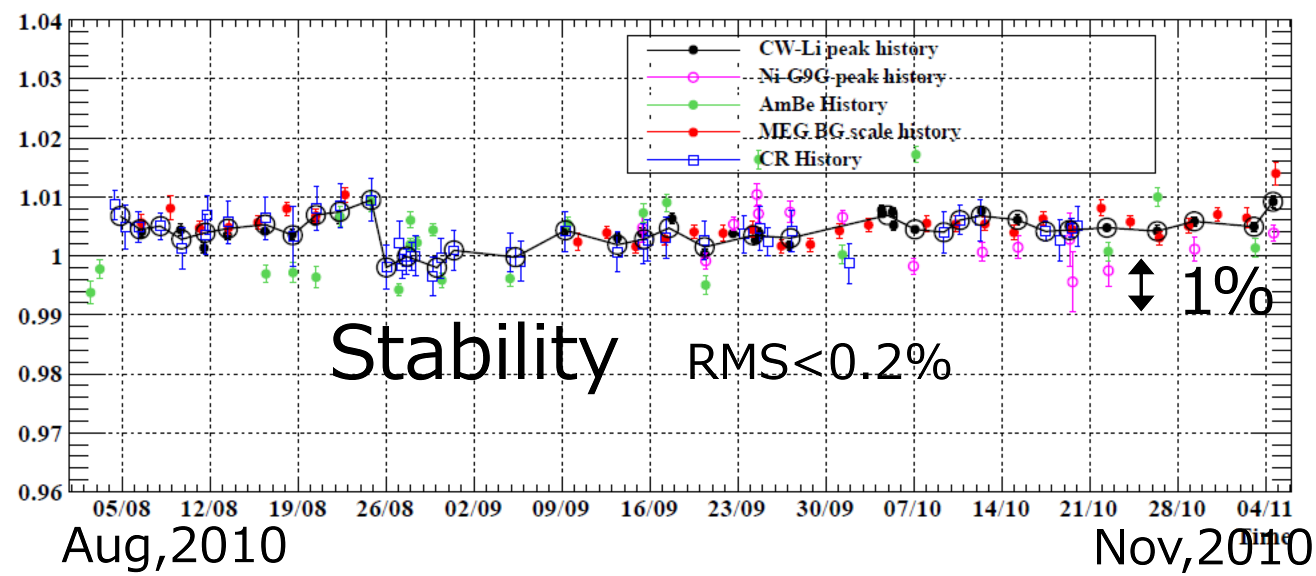
The first ton-scale LXe detector in use





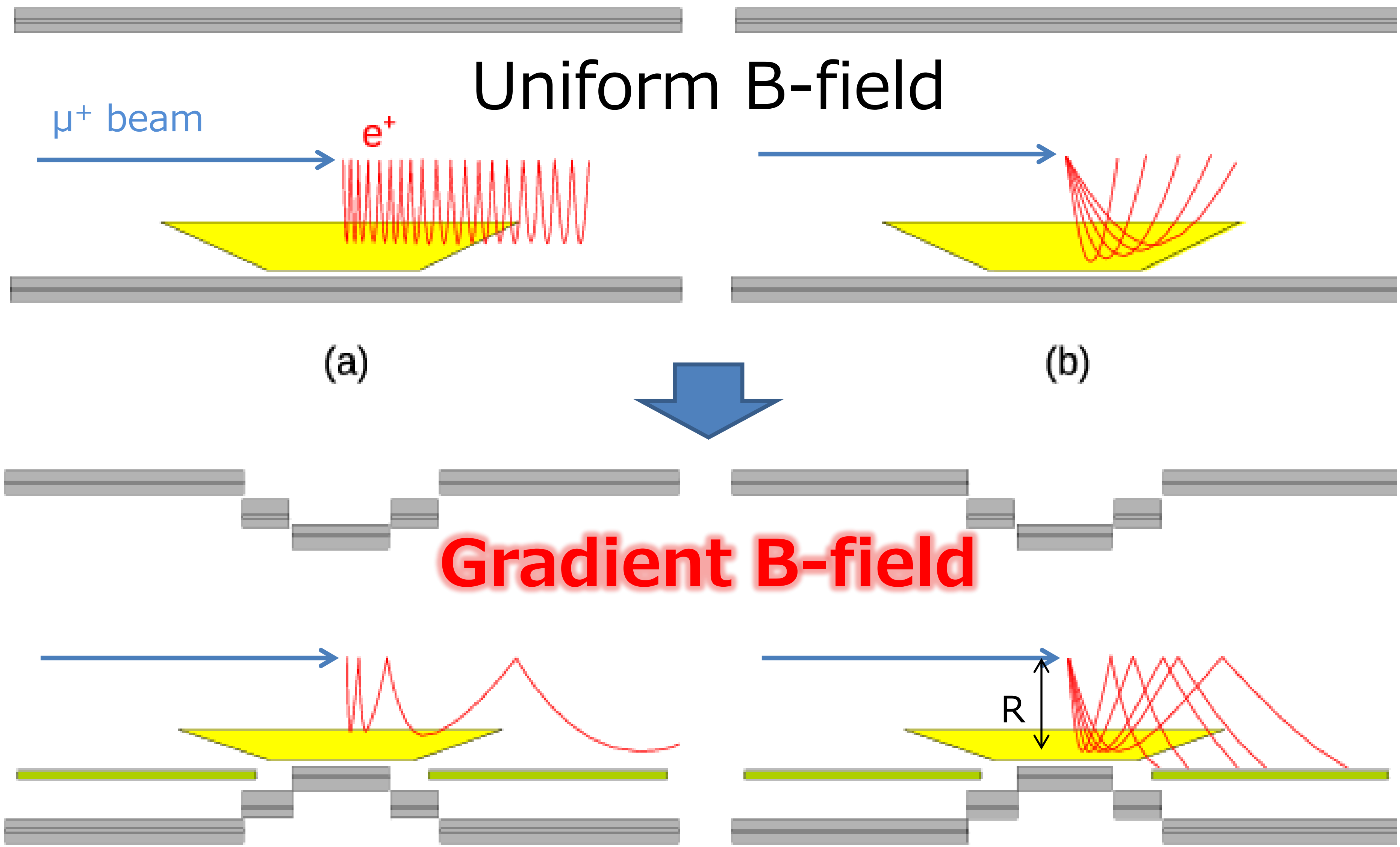
Various kinds of calibration verify the performance





Energy scale uncertainty ~ 0.3%

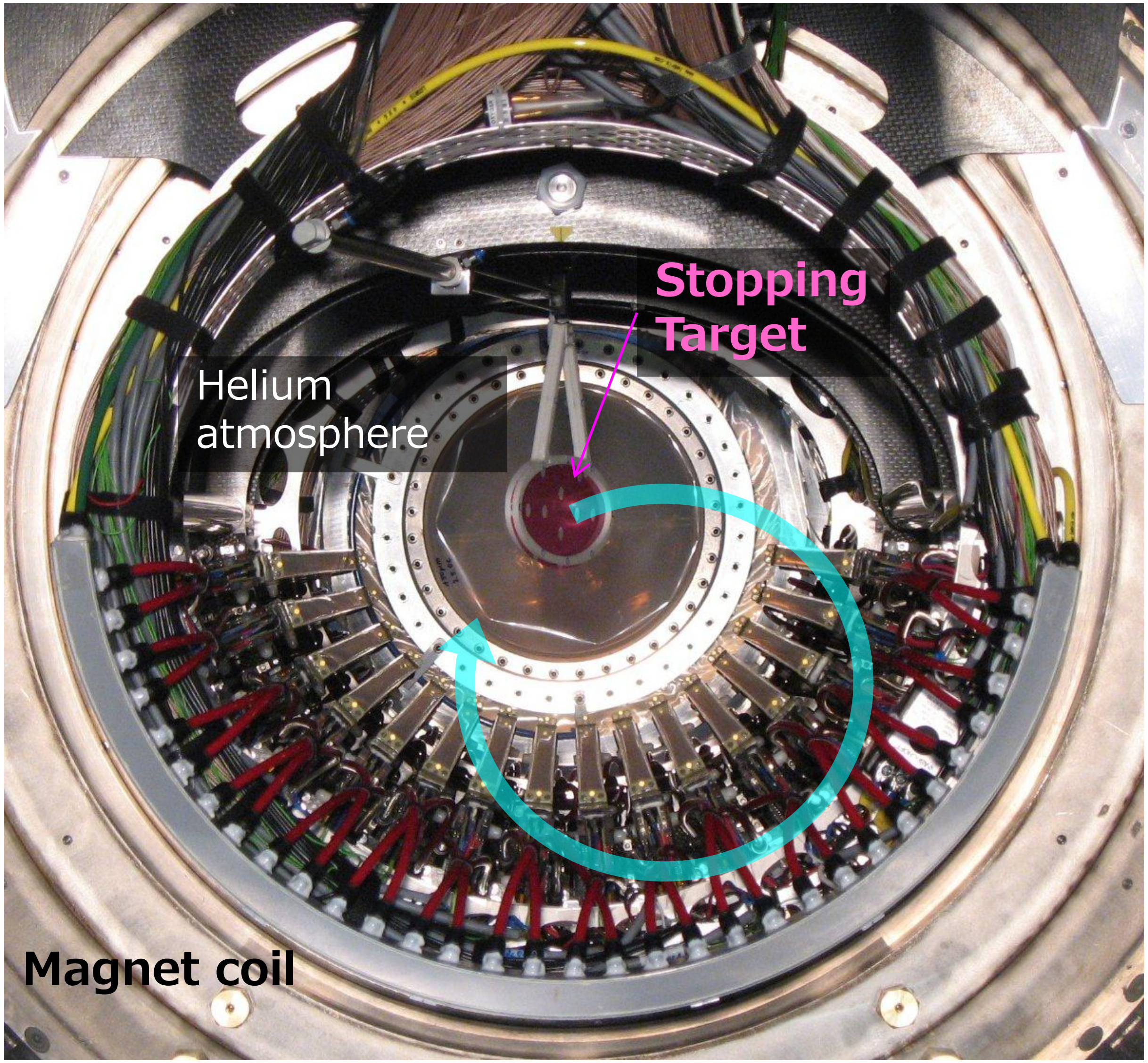
e^+ spectrometer



e^+ quickly swept out

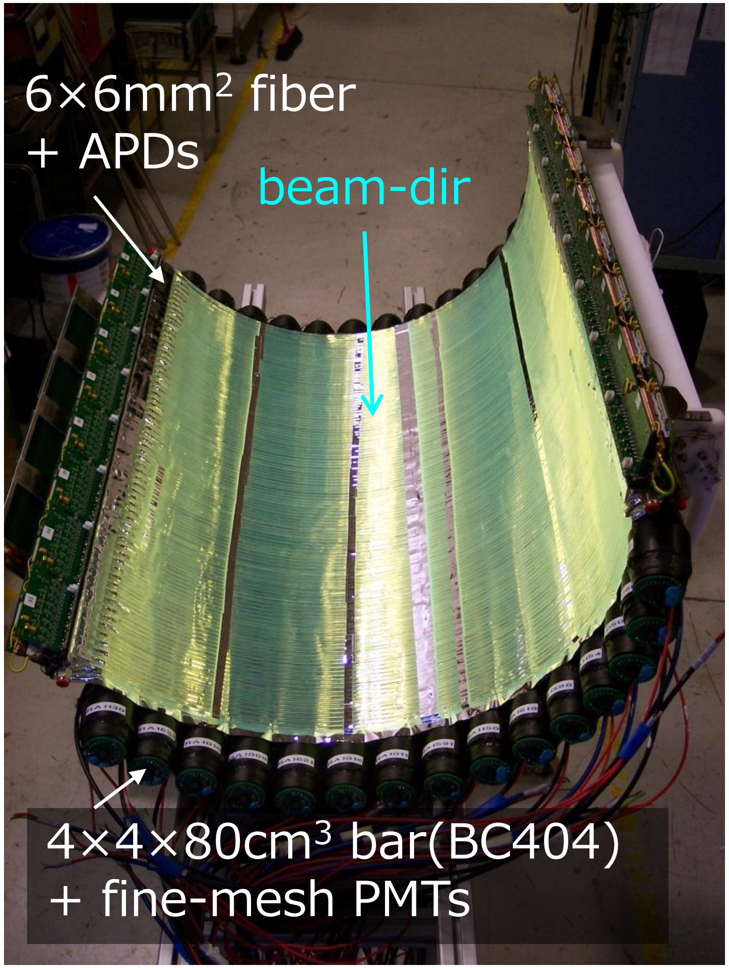
Constant bending radius independent of emission angles

Drift chamber



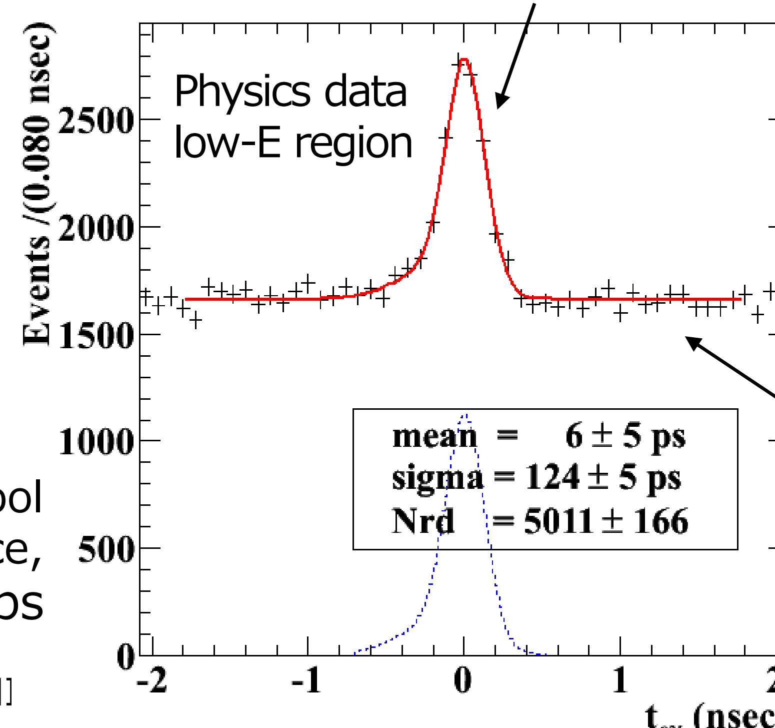
- 16 modules
  - Aligned concentrically (10.5°)
  - 2 layers per 1 module
- 12.5 μm thick cathode foil with vernier pattern
- He:ethane = 50:50
- Ultra low mass chamber
  - Multiple scatter limits the performance
  - To suppress γ BG source
  - In total, along e^+ trajectory $\sim 2.0\times 10^{-3}\,X_0$
- Tracking with Kalman filter
  - Reconstruct e^+ momentum vector on target
    - $\sigma_E/E = 0.6\ \%$
    - $\sigma_\theta \sim 10$ mrad
    - $\sigma_\varphi \sim 7$ mrad

Time measurement



- e^+ time measured by a set of timing counter
  - Two layers of plastic scintillator
- Reconstruct muon decay time
  - TC hit time + e^+ flight length from DC
  - LXe hit time + γ flight length (line)
  - $t_{e\gamma} = t_{e+} - t_\gamma$
- Total resolution : $\sigma_{te\gamma} = 122$ psec

Peak of radiative muon decay



Accidental background

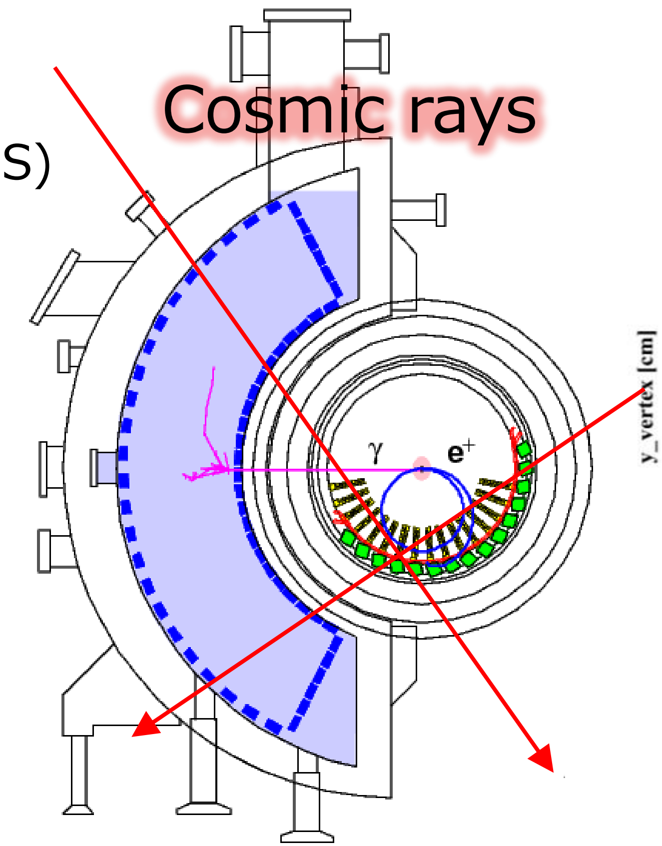
RMD peak is a powerful time calibration tool
measure all detector contribution at once,
in situ monitoring, stable <20ps

To be confident in angle measurement

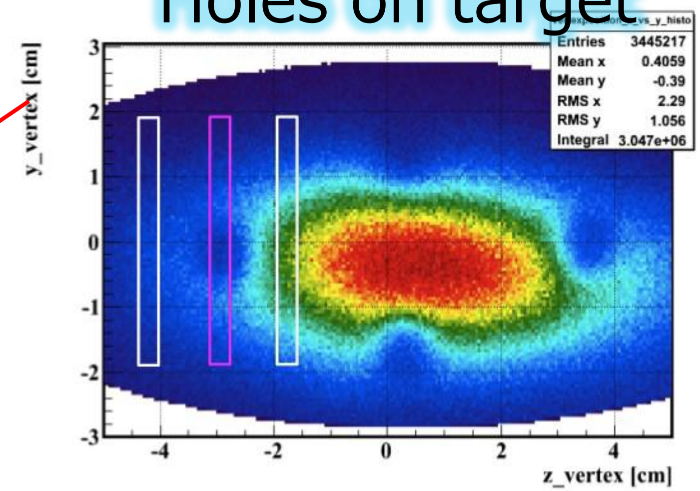
- Calibration of angle measurement is the most difficult.
  - No back-to-back source
- Improved alignment inside/among detectors
  - DC – B-field – target – LXe
- Understand the detail of correlations in e^+ measurement

- Optical surveys
- DC: MILLIPEDE (a la CMS)
- Target holes
- LXe: Pb collimators

Successfully reduced systematic uncertainty

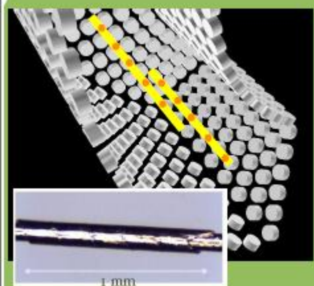


Holes on target



MEG Calibrations

Established



LED

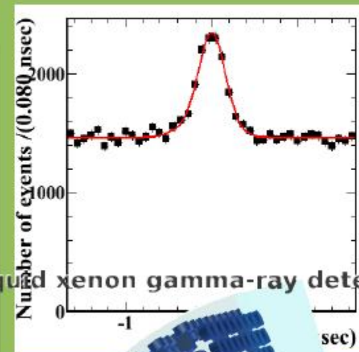
PMT Gain

Alpha

PMT QE

Absorption

Am source on wire

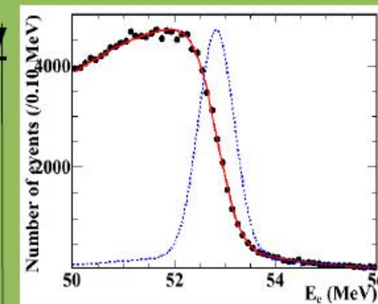


Radiative Decay

$\mu \to e\nu\nu\gamma$

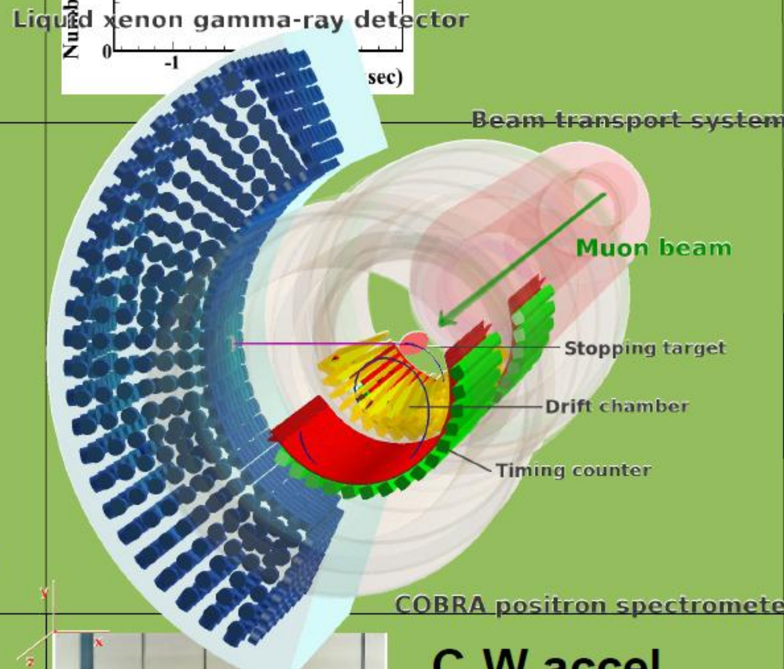
Relative timing

Similar topology

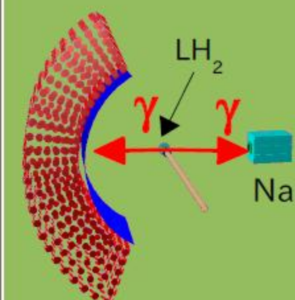


Michel Decay

$\mu \to e\nu\nu$



$\pi^- p \to \pi^0 n$



$\pi^0 \to \gamma\gamma$

55,83,129MeV

monochoro

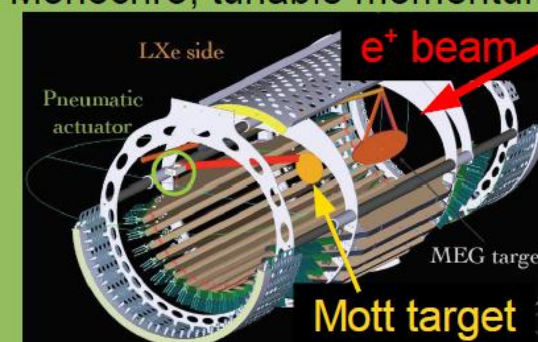
$\pi^0 \to \gamma e^+ e^-$

Relative timing

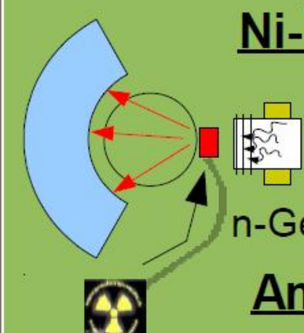
Similar topology

e^+ Mott-scatter

Monochro, tunable momentum



Ni-n



9MeV γ source

n-Generator

AmBe

AmBe source 4.4MeV γ source

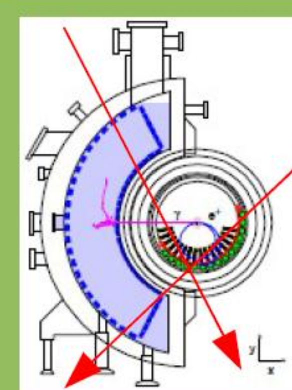
C-W accel.

Li(p,γ)Be

– 18MeV γ

B(p,γ)C

– 4,11MeV 2γ



CosmicRay

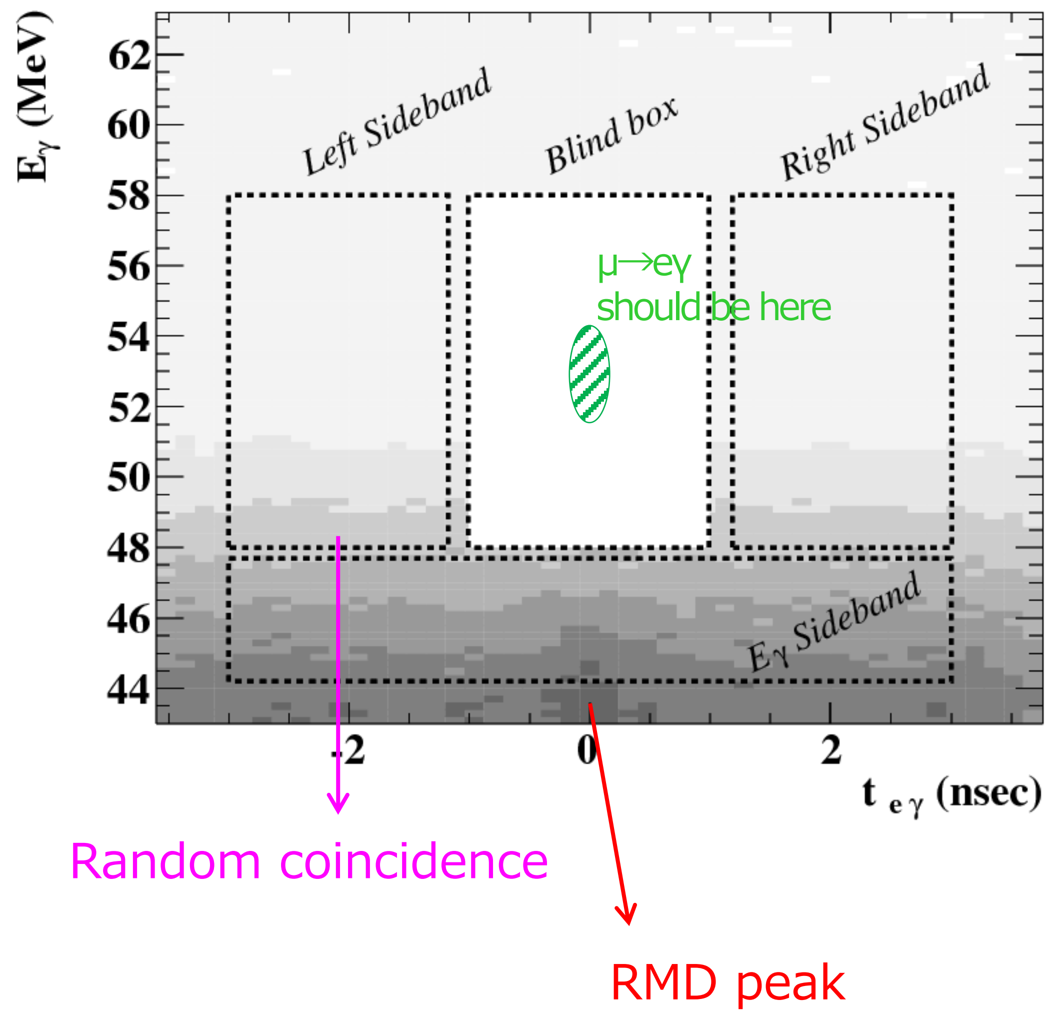
DC alignment

TC uniformity

LXe monitor

Analysis

- Blind analysis
  - Hidden parameters: ($\mathbf{E_\gamma}$, $\mathbf{t_{e\gamma}}$)
  - Any study (calibration, BG estimation, performance evaluation) can be done with events outside the box
- Sideband
  - Accidental BG can be studied with off-time sideband
  - Radiative muon decay(RMD) can be studied with low-energy E_γ sideband
- Normalization
  - Count unbiased Michel sample mixed in physics data
  - Count RMD sample in E_γ sideband
- Wide analysis region for likelihood fitting
  - Estimate Sig & BG simultaneously.
  - PDFs mostly from data



Likelihood fit

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Estimation from sideband

$$\mathcal{L}\left(N_{\mathrm{sig}}, N_{\mathrm{RMD}}, N_{\mathrm{BG}}\right) = \frac{e^{-N}}{N_{\mathrm{obs}}!} e^{-\frac{\left(N_{\mathrm{RMD}}-\langle N_{\mathrm{RMD}}\rangle\right)^2}{2\sigma^2_{\mathrm{RMD}}}} e^{-\frac{\left(N_{\mathrm{BG}}-\langle N_{\mathrm{BG}}\rangle\right)^2}{2\sigma^2_{\mathrm{BG}}}} \times$$

μ→eγ signal

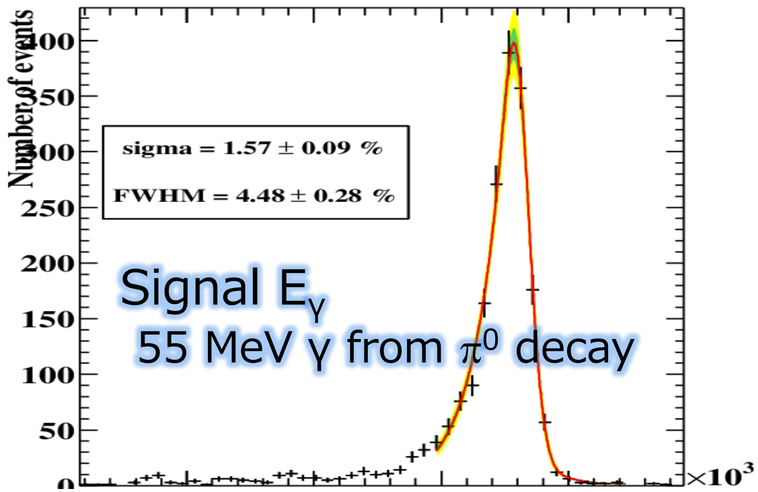
Radiative muon decay

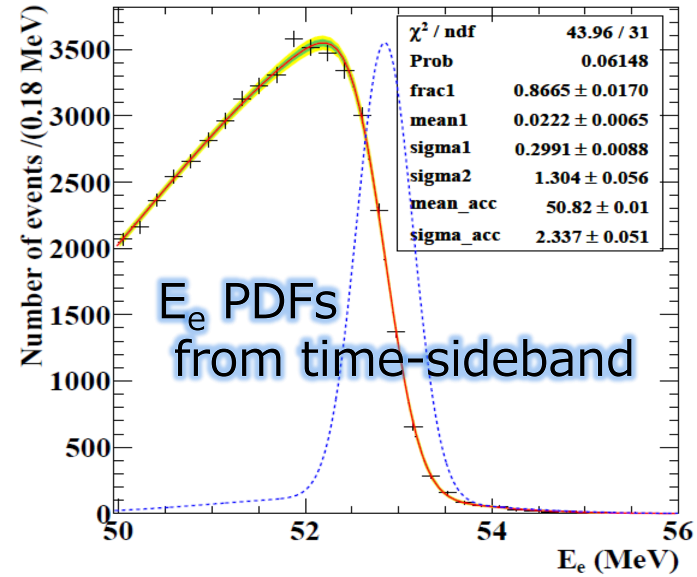
$$\prod_{i=1}^{N_{\mathrm{obs}}} \left(N_{\mathrm{sig}} S(\vec{x}_i) + N_{\mathrm{RMD}} R(\vec{x}_i) + N_{\mathrm{BG}} B(\vec{x}_i)\right),$$

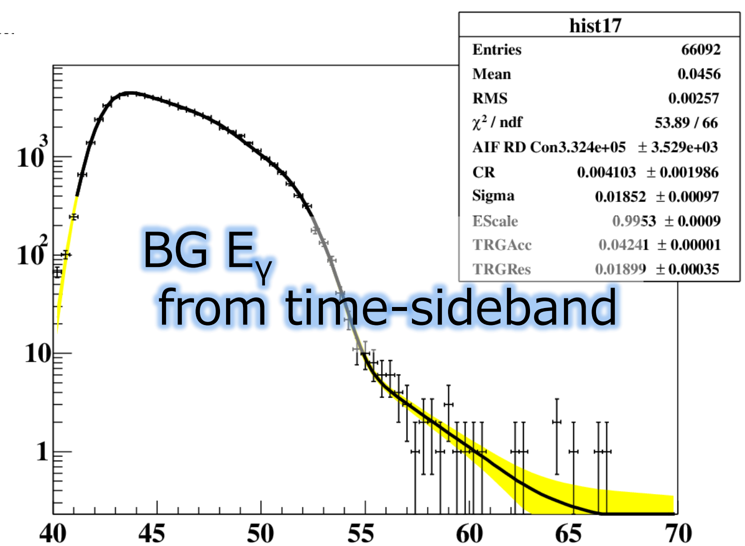
Accidental BG

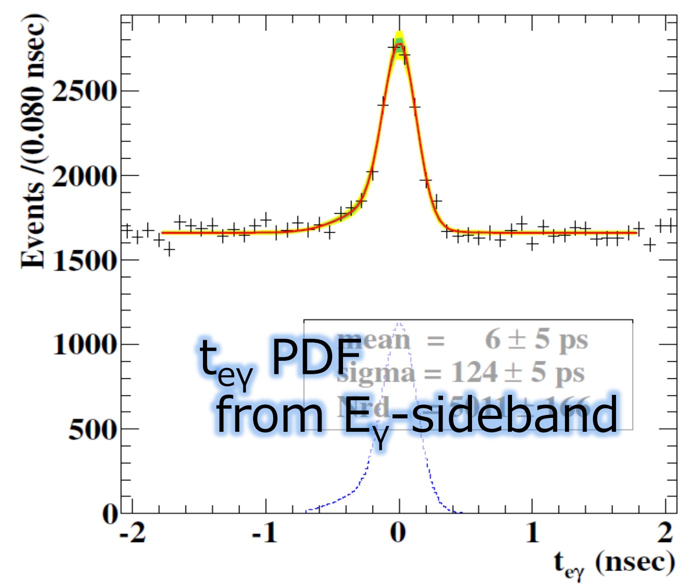
- **Extended unbinned maximum likelihood fit** on number of events
  - 3 fit parameters : **(N_{sig}, N_{RMD}, N_{BG})**, $N=N_{sig}+N_{RMD}+N_{BG}$
  - 5 observables : $\vec{x}$ = **(E_γ, E_e, $t_{e\gamma}$, $\underbrace{\theta_{e\gamma}, \varphi_{e\gamma}}$)**
    relative angle (inverse e^+ direction – γ direction)
  - Probability density functions (PDFs) for each event type (***S, R, B***)
    - Extract PDF from data
    - Use maximum information
      - position dependent for gamma, tracking-quality dependent for positron
  - Constrain (N_{RMD}, N_{BG}) by the independent measurements in sidebands
  - Fit in wide region (10σ) to extract signal & background simultaneously
  - Different (independent) analysis tools → to check, understand, and find bugs
    - Different PDF implementations
    - Different statistical approaches (ex. Frequentist or Bayesian)

PDFs





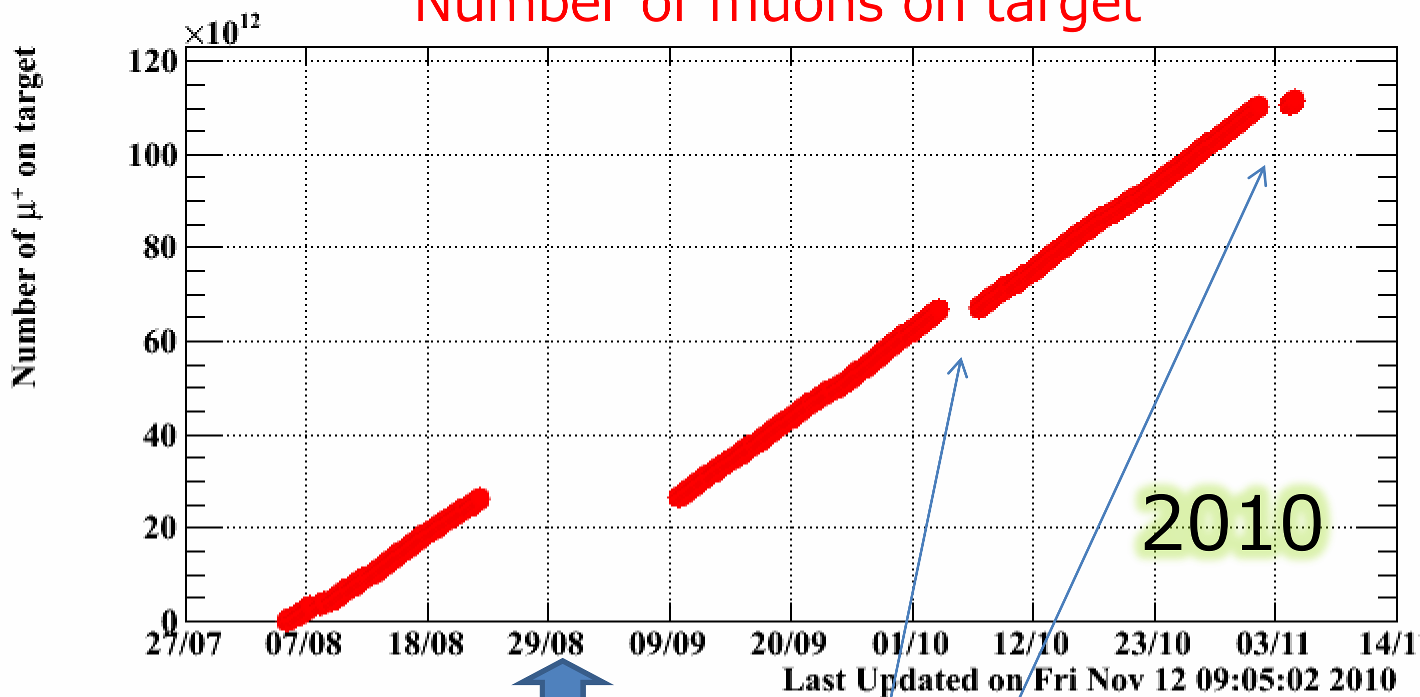


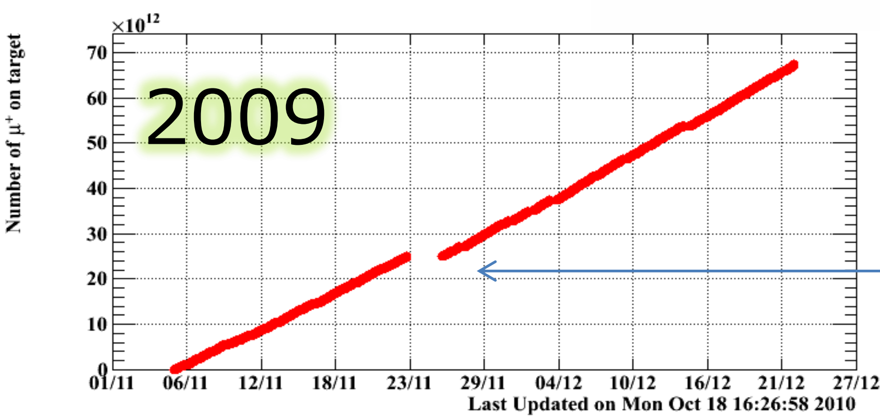


- Angle PDFs : signal from measured resolutions, BG from time sideband
- RMD PDF : theoretical distribution ⊗ measured resolutions

Number of muons

Number of muons on target





calibration period with π^- beam

Accelerator maintenance

What is the actual measured number of muons ?

Number of muons

- Normalize signal events with number of muon decays counted in control samples
  - Normalization channel 1: Count Michel e^+
    - Unbiased Michel trigger data mixed in physics run

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

  - Normalization channel 2: Count RMD events
    - In E_γ-sideband
  - Insensitive to beam-rate or detector-condition variations
  - Those two methods are complementary
    - Most of the systematics are independent.
    - Consistency check → very good agreement

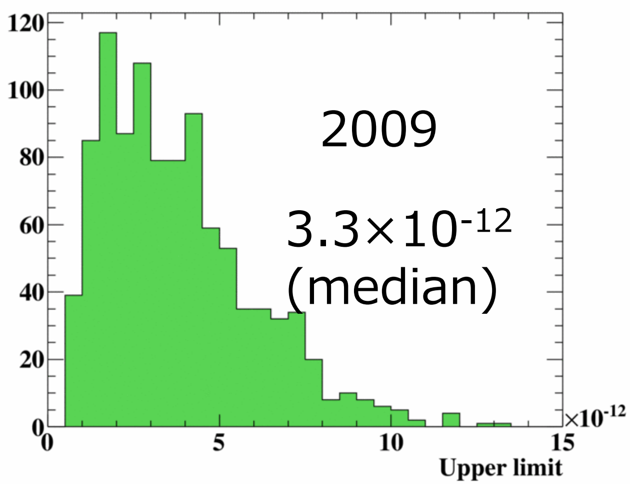
Normalization factor

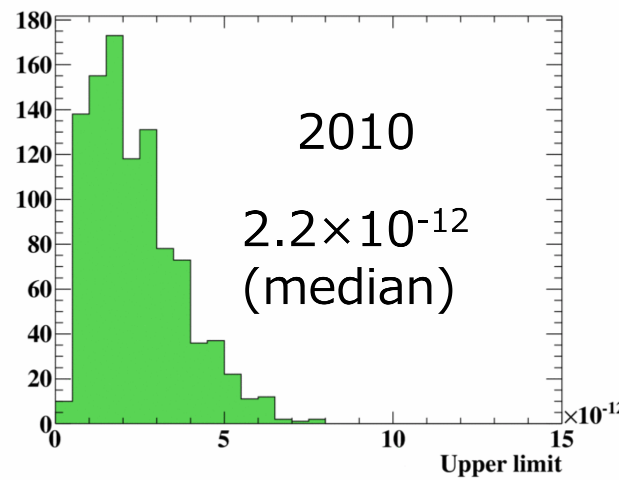
$$\mathcal{B}(\mu^+ \to e^+\gamma) = N_{sig} / (3.3 \pm 0.2)\times 10^{12}$$

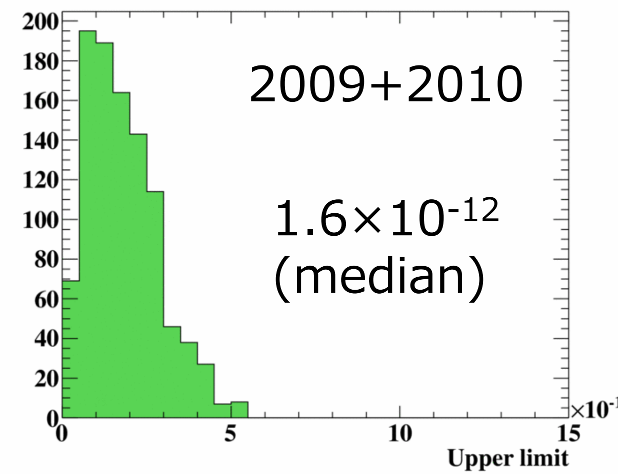
$(1.1\times10^{12}(2009) + 2.2\times10^{12}(2010))$

Sensitivity

- Expected upper limit (90%CL) on ensemble of toy-experiments
  - Null signal assumption
  - Toy-experiment: generate events with obtained PDFs
  - Repeat toy-experiments and calculate UL in the same way as real data







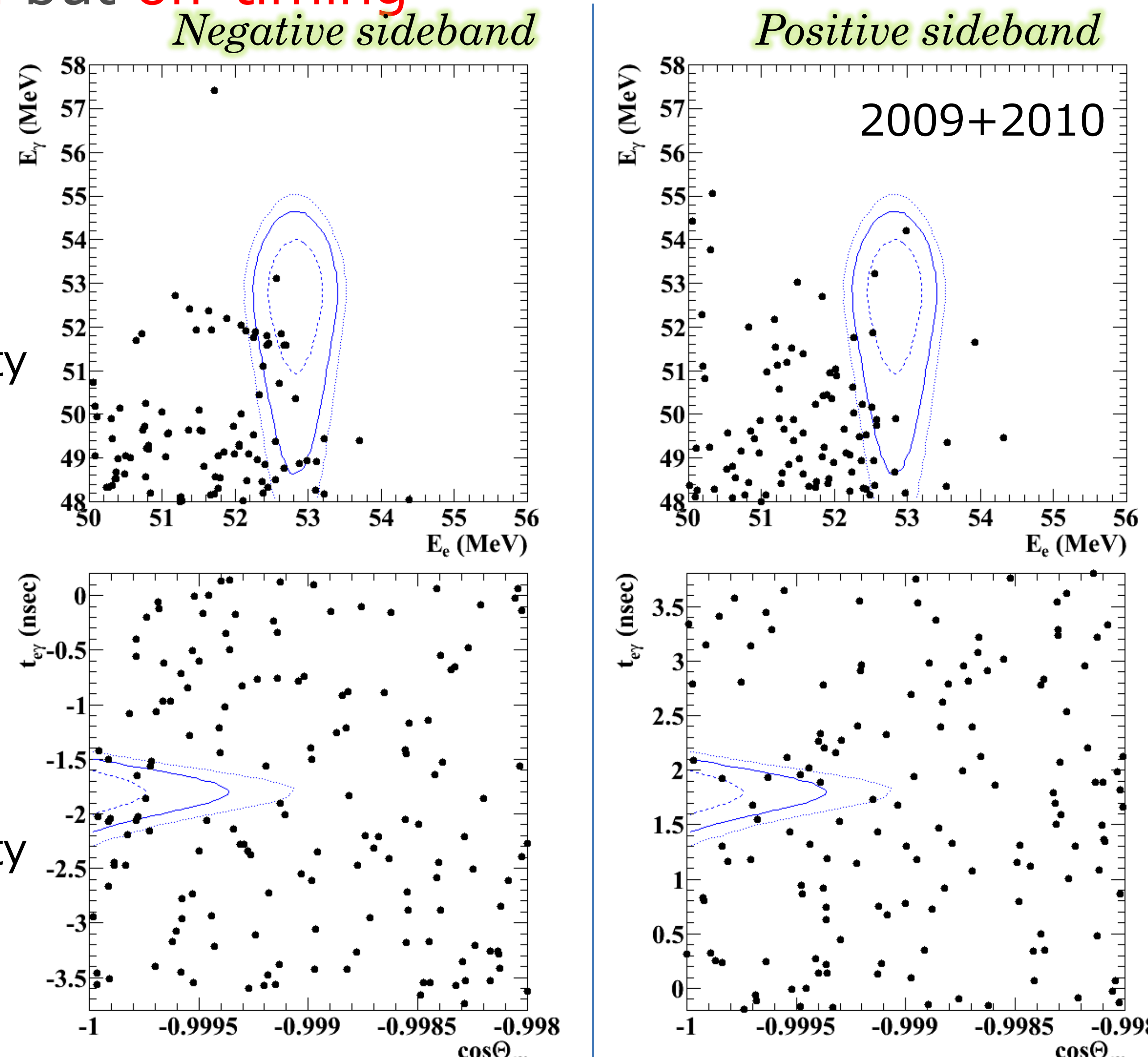
Sensitivity of combined data : 1.6×10^{-12}

c.f. Existing best upper limit: 12×10^{-12}

We can search for $\mu\to e\gamma$ for unexplored region by factor >7 !

Sideband analysis

- Analyzed real data but off-timing



- No signal in sidebands
- Our dominant BG is accidental one

→ Good test of our sensitivity

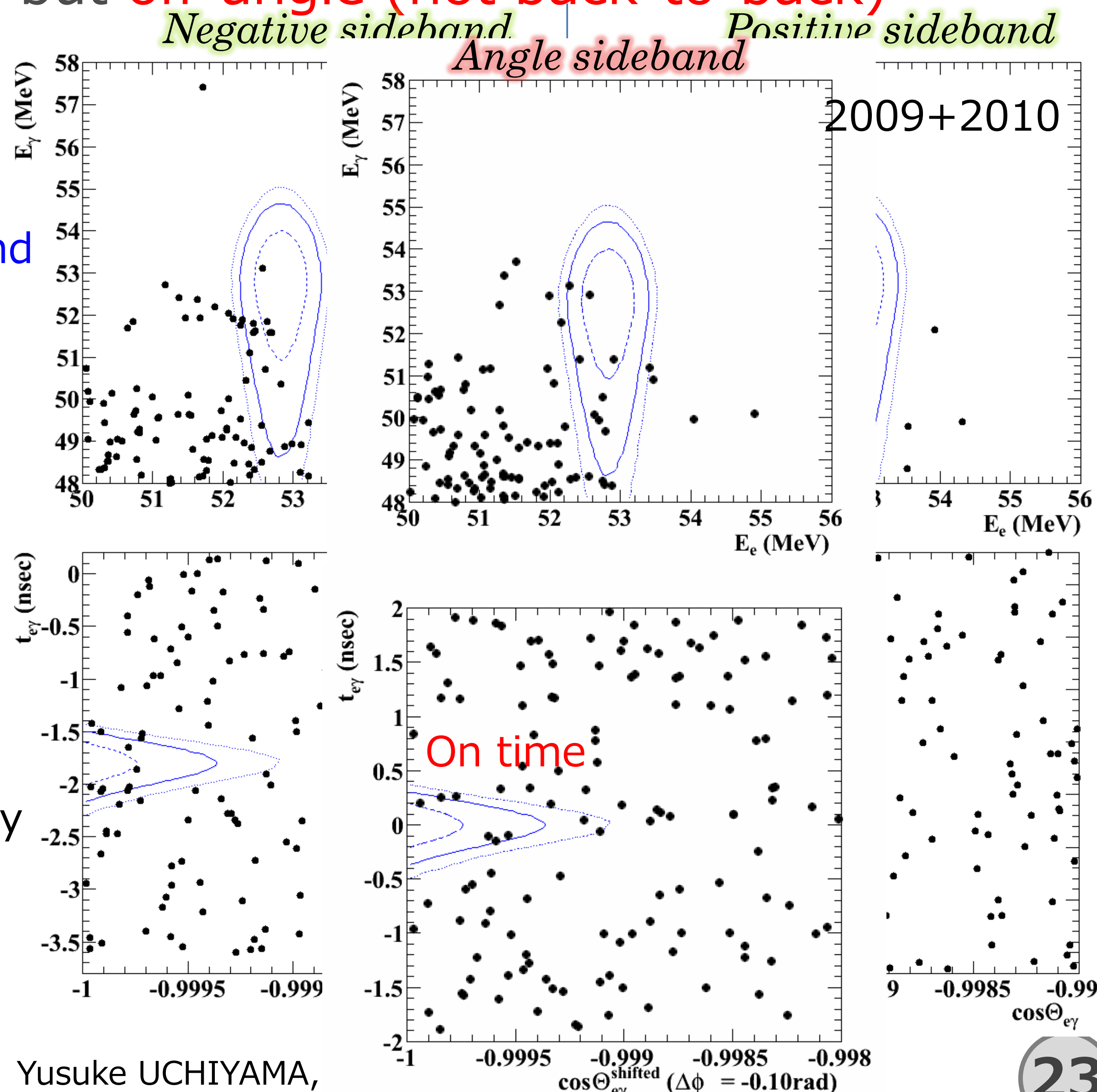
Results of likelihood analysis

$\mathcal{B}(\mu\to e\gamma) <$ 1–3 $\times 10^{-12}$
depending on region

consistent with the sensitivity

Sideband analysis

- Analyzed real data but off-angle (not back-to-back)



- No signal in sidebands
- Can check (unknown) time correlated background

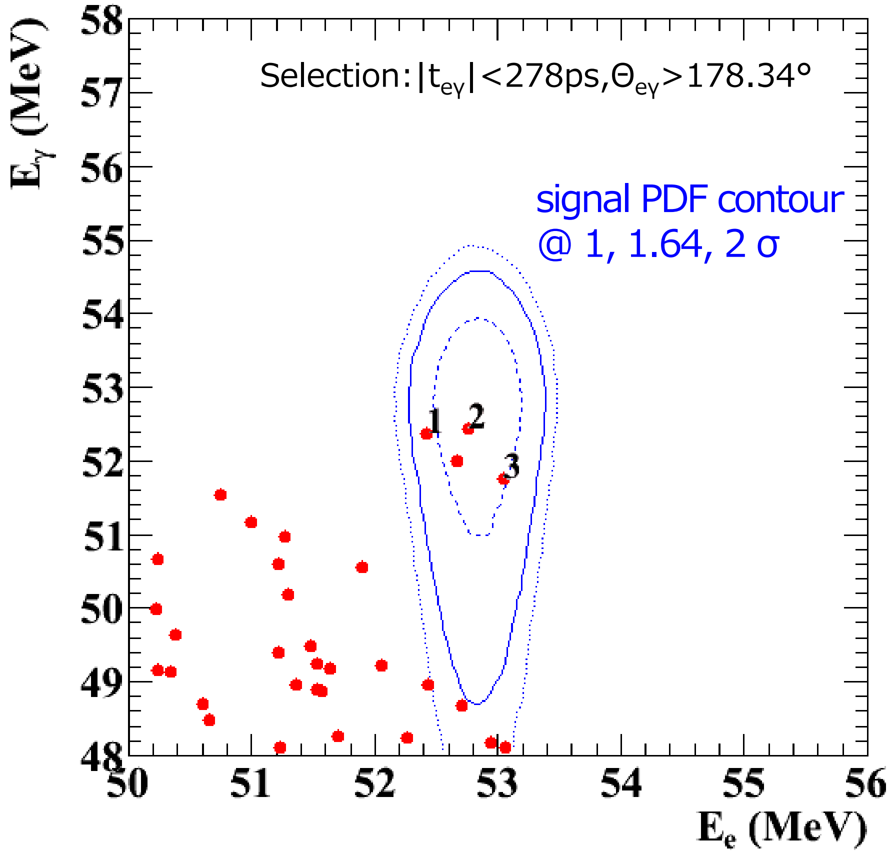
Results of likelihood analysis

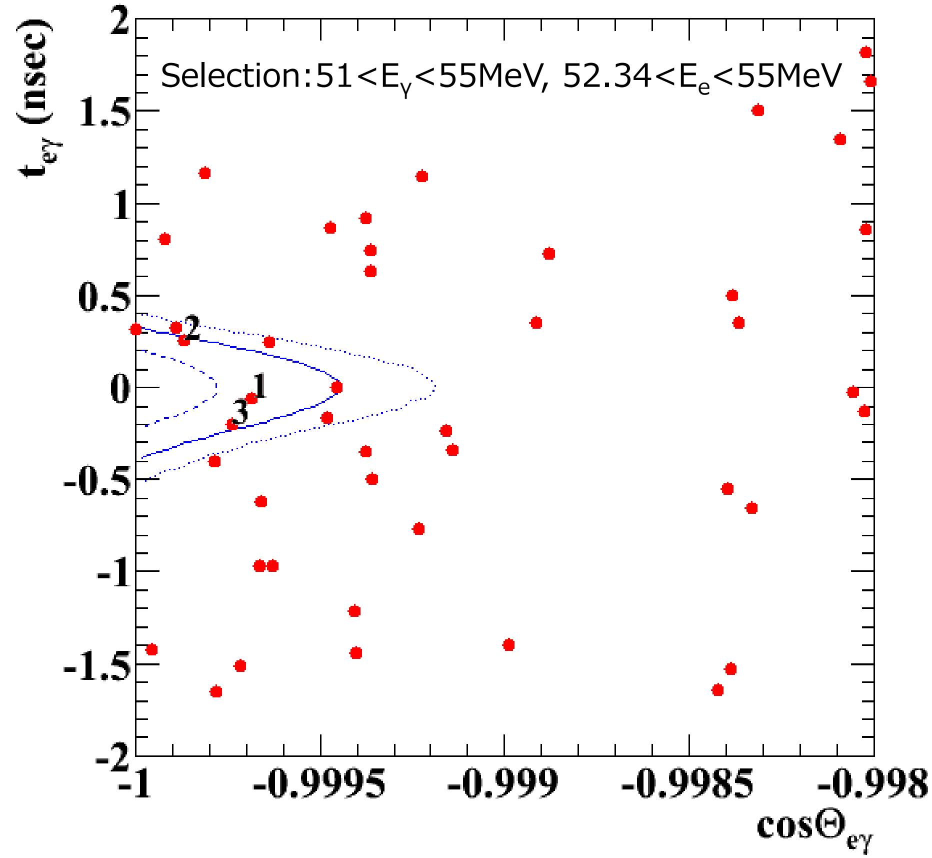
$\mathcal{B}(\mu\rightarrow e\gamma) <$ 1–3 $\times 10^{-12}$
depending on region

consistent with the sensitivity

2009 data update result

2009 data update





Numbers show rank of relative signal likelihood.
Same number, same event. (S/(0.1R + 0.9B))

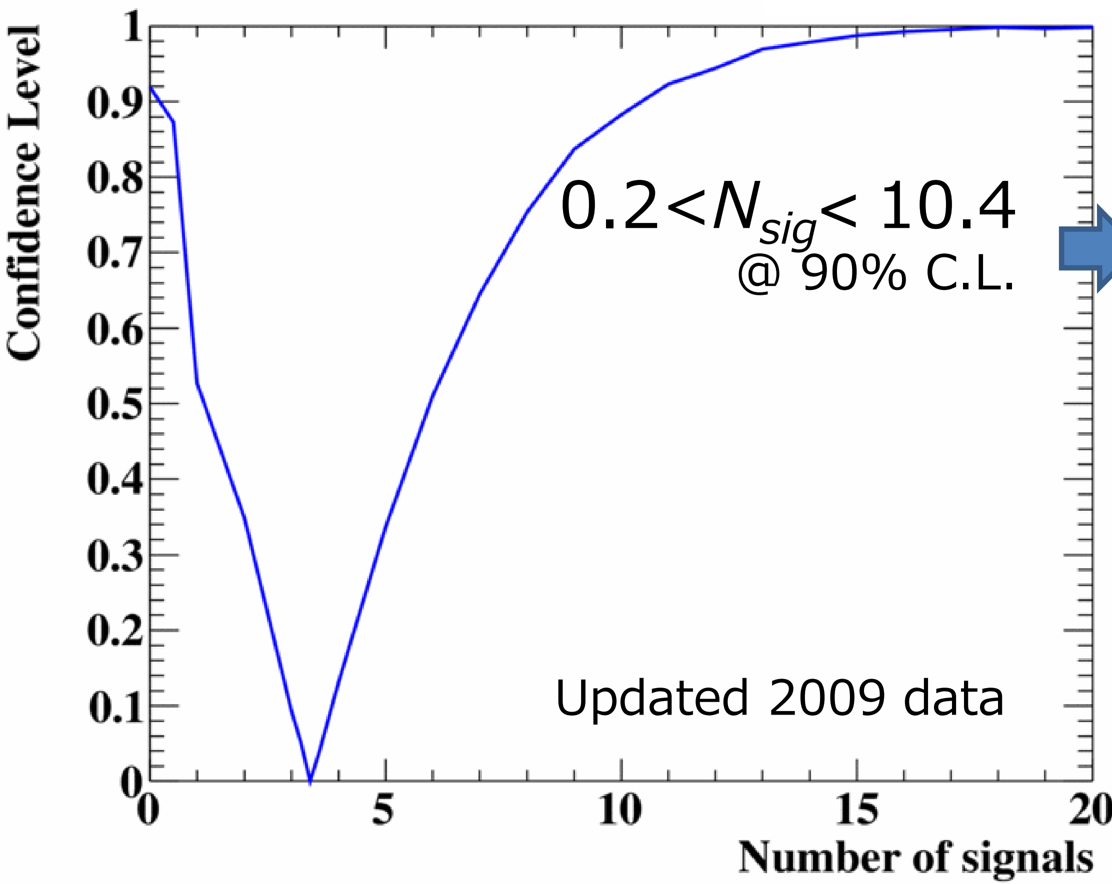
N_{sig} best-fit value : 3.0 (preliminary result) → 3.4

No significant change, result is stable.

Confidence interval

- Set confidence interval with Frequentist approach
  - Feldman-Cousins unified method with profile likelihood ratio ordering.

$$\lambda_{\rm p}(N_{\rm sig}) = \frac{\mathcal{L}(N_{\rm sig}, \widehat{\widehat{N}}_{\rm RMD}(N_{\rm sig}), \widehat{\widehat{N}}_{\rm BG}(N_{\rm sig}))}{\mathcal{L}(\widehat{N}_{\rm sig}, \widehat{N}_{\rm RMD}, \widehat{N}_{\rm BG})},$$



$1.7\times10^{-13} < \mathcal{B} < 9.6\times10^{-12}$

@ 90% C.L.

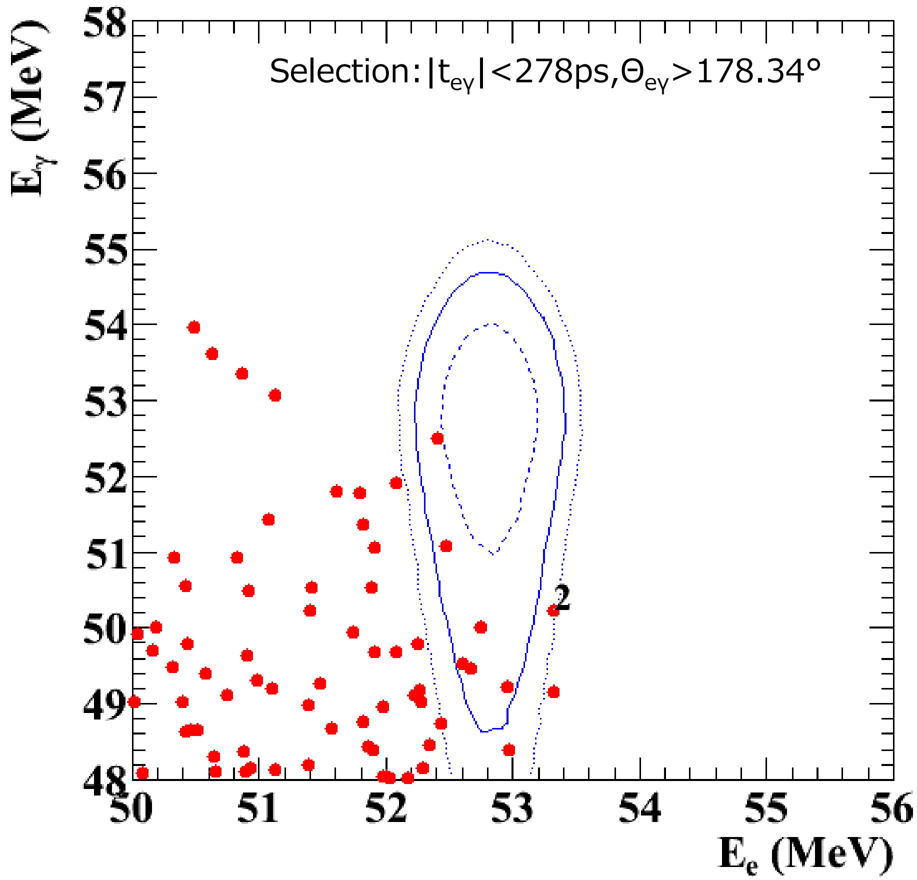
- We exceed previous experiment (11×10^{-12})
- We obtained lower limit (90% CL)

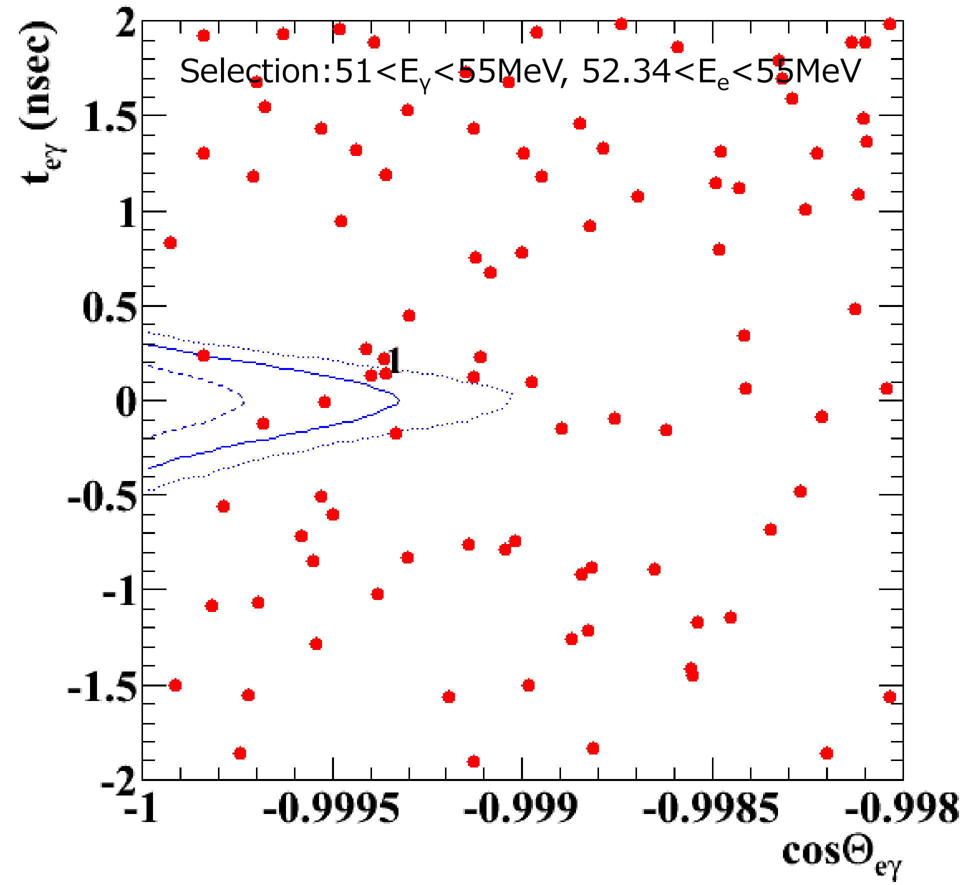
p-Value for null signal: 8 %

2010 data

We opened the blind box on Jul. 5...

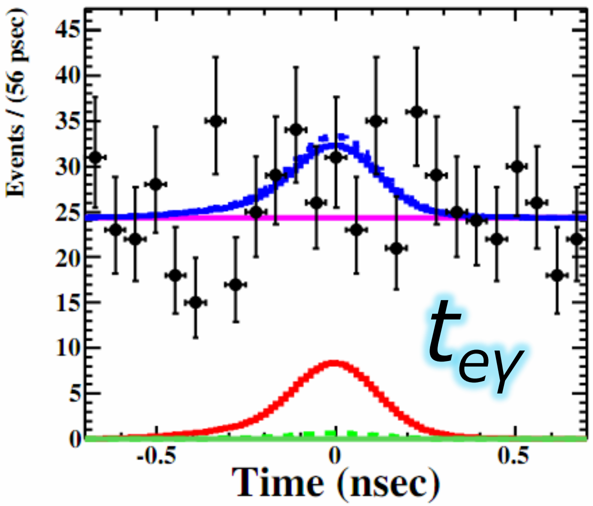
2010 data unblinded on Jul.5

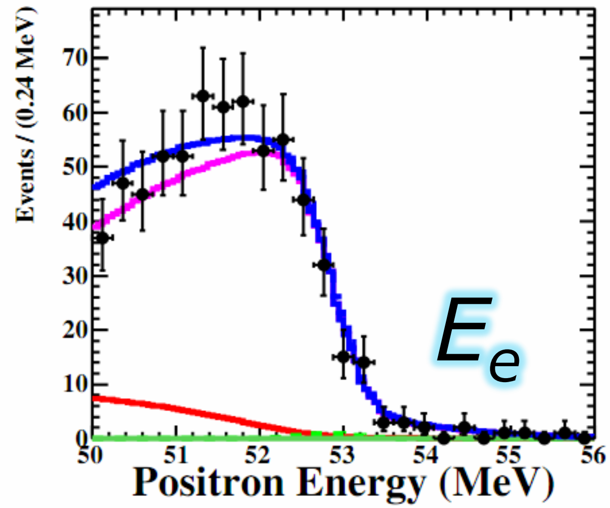


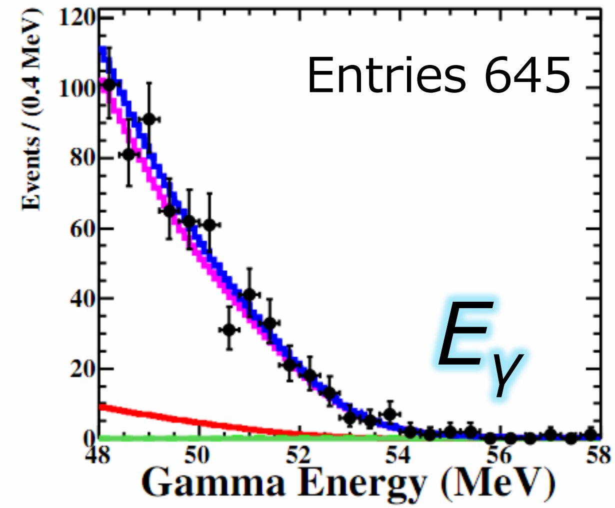


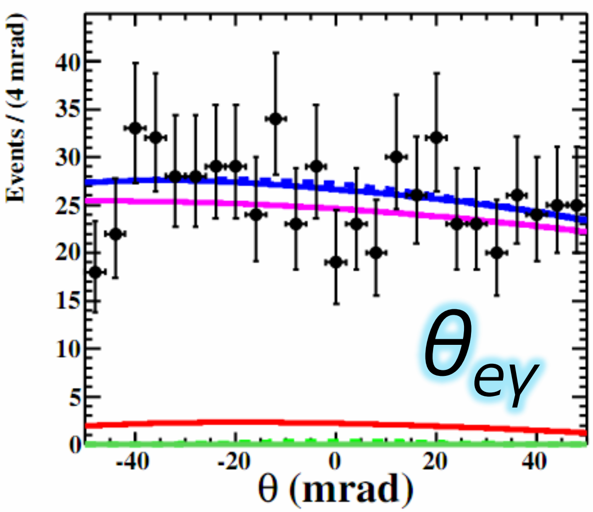
No events in common.

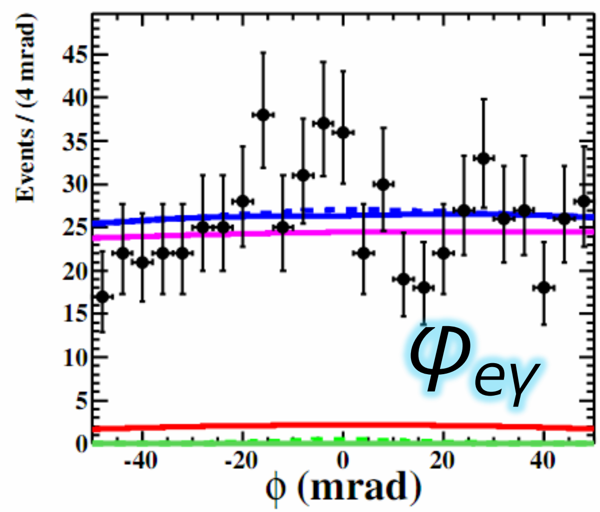
Likelihood fit to 2010 data











Total
Accidental
Radiative
Signal

Expectation (1σ error)

$\langle N_{RMD} \rangle = 52.2 \pm 6.0$

$\langle N_{BG} \rangle = 610.8 \pm 12.6$

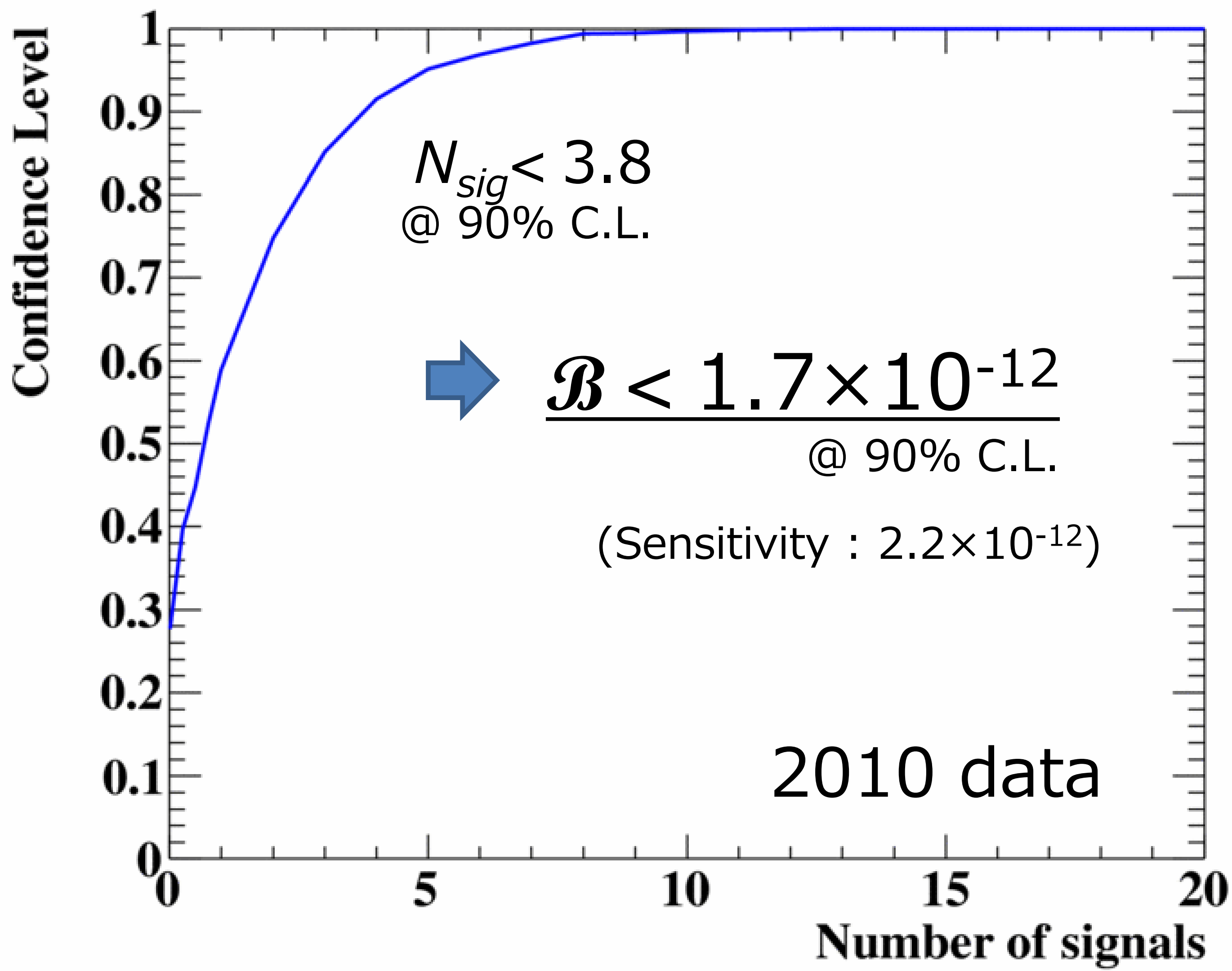
Best-fit value $(N_{sig}, N_{RMD}, N_{BG})$

$$= (-2.2^{+5.0}_{-1.9}, 50.2^{+9.2}_{-9.2}, 608.1^{+18.7}_{18.6})$$

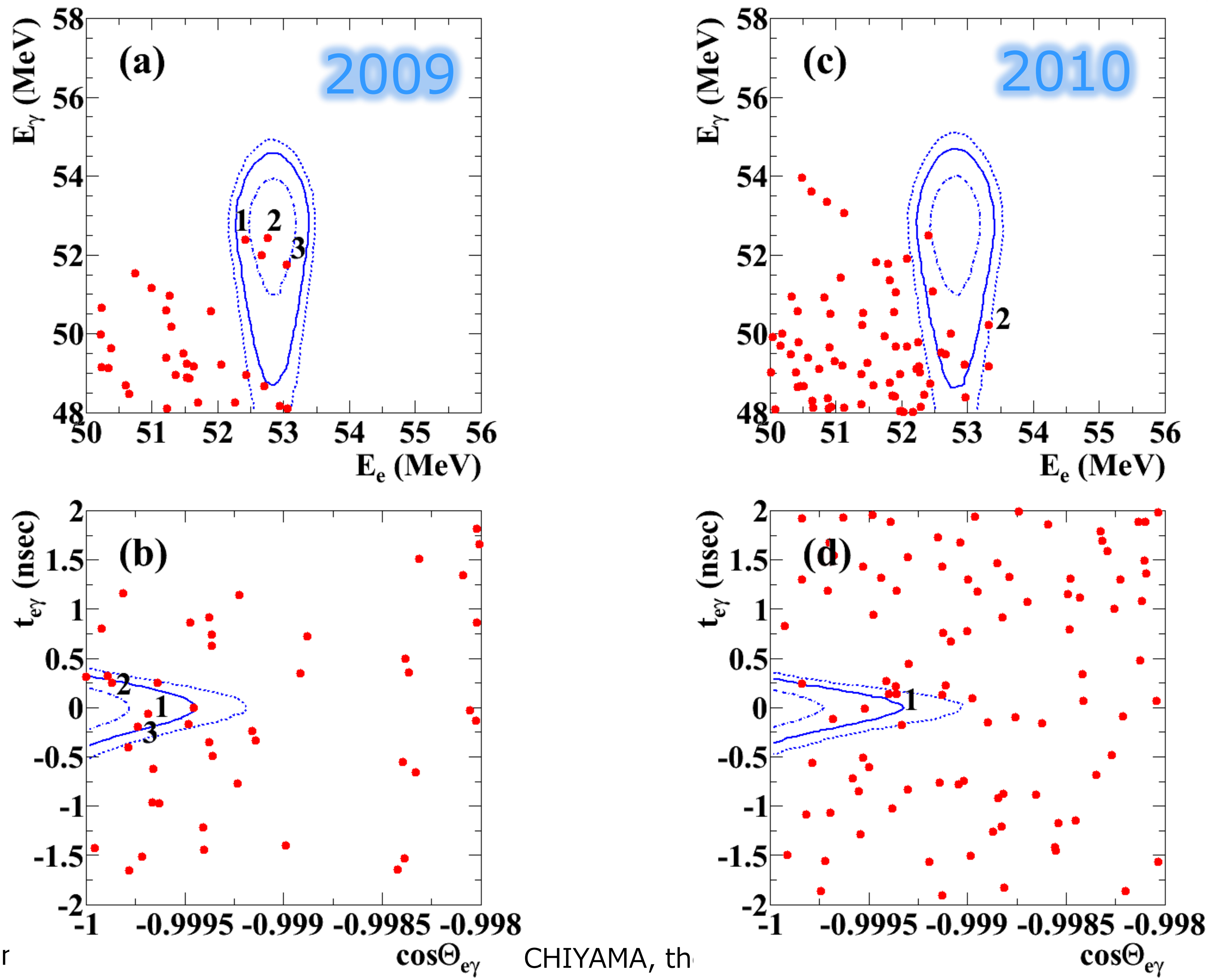
MINOS 1.6σ error

Upper limit

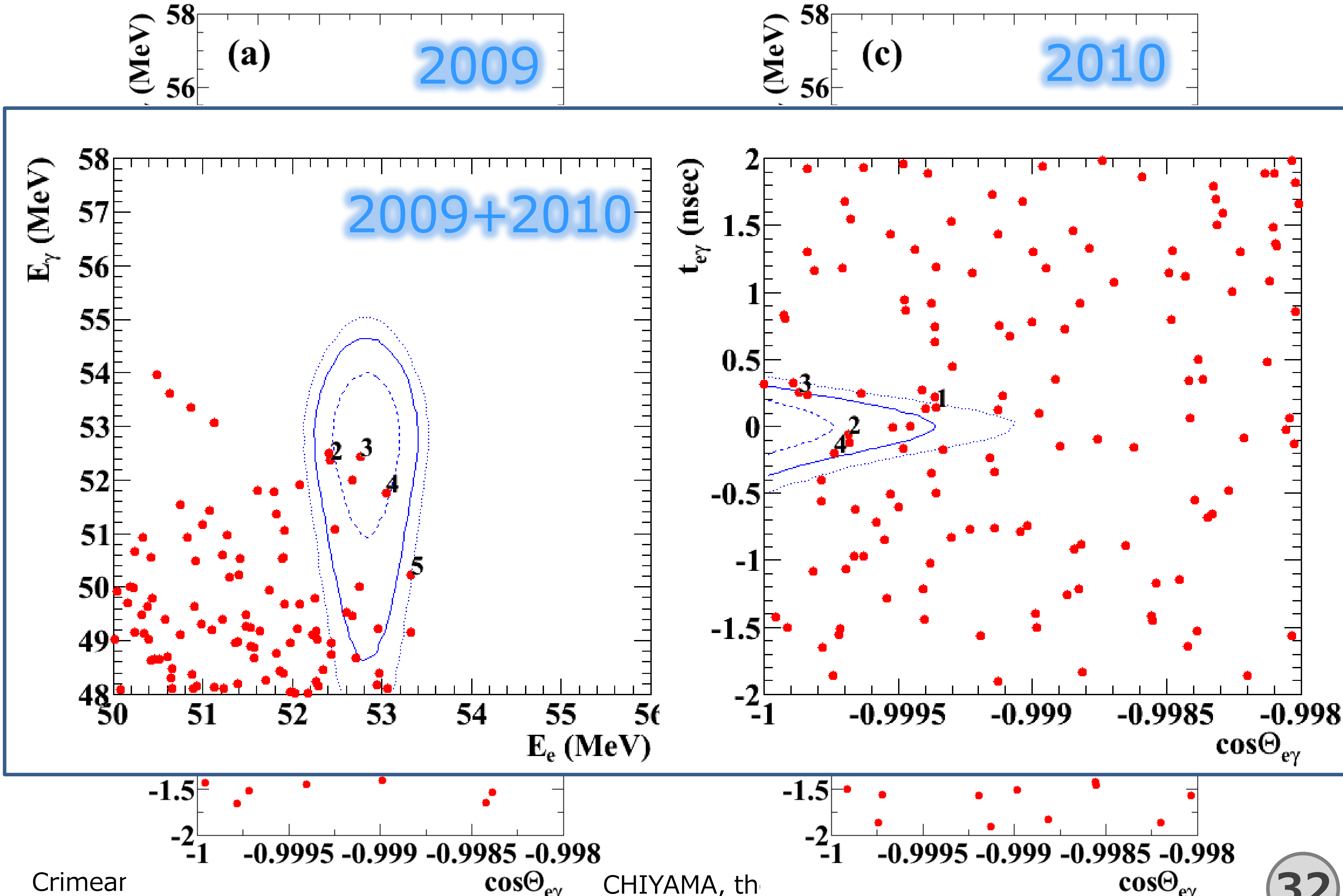
- Frequentist analysis set,



2009 and 2010

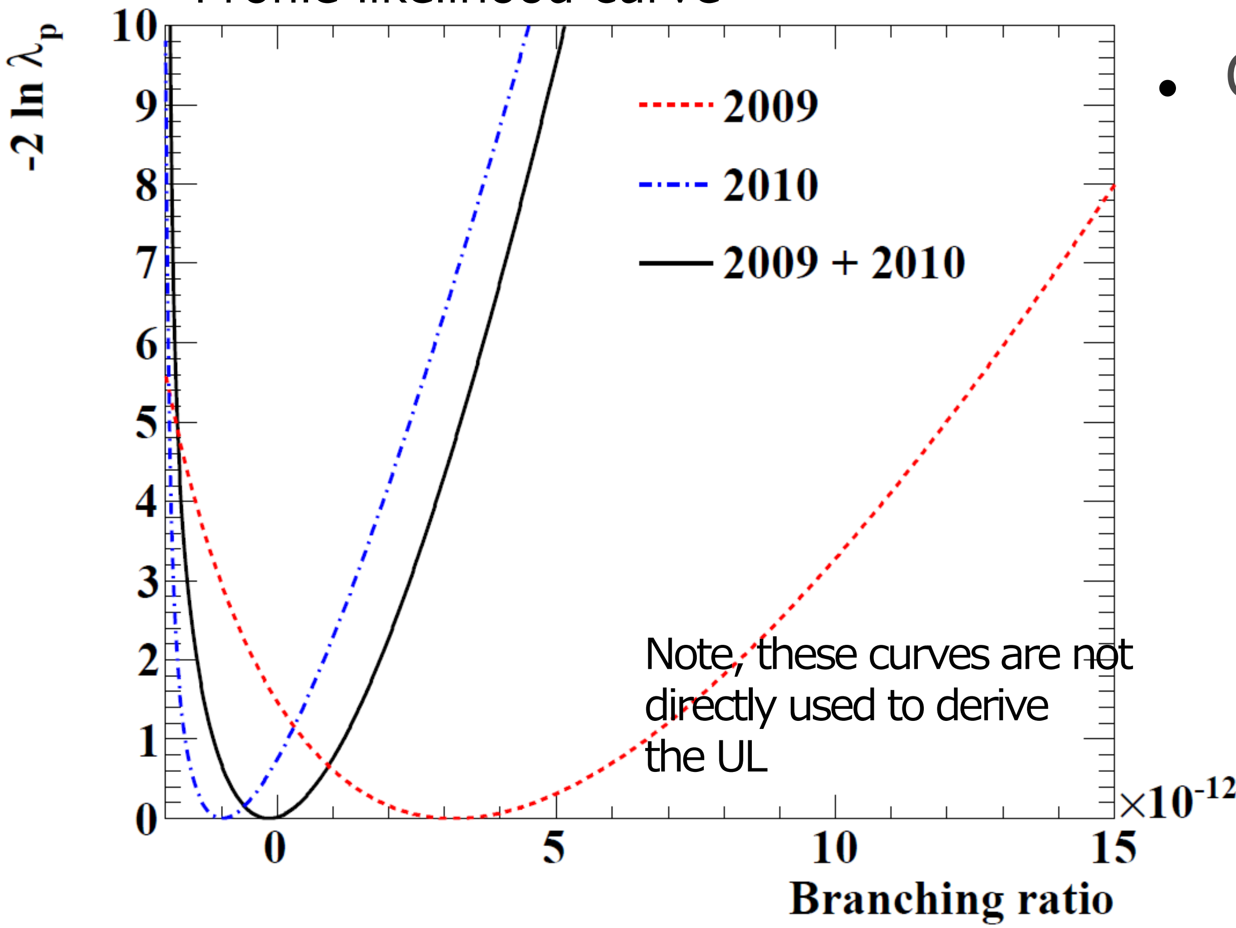


2009 and 2010



Combined analysis

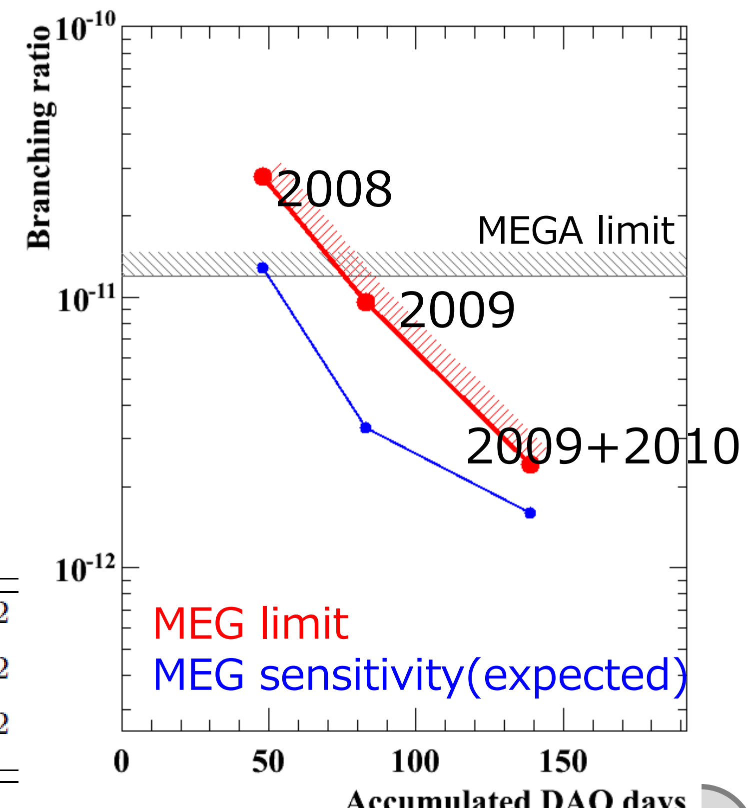
Profile likelihood curve



Data set	$\mathcal{B}_{\rm fit}$	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}

- Combined fit gives
  - Best-fit : N_{sig}= -0.5
  - Upper limit :

$\mathcal{B} < 2.4\times10^{-12}$



Systematics

- Systematic effects are taken into account in the calculation of confidence interval by profiling on (N_{RD},N_{BG}) and by fluctuating PDFs according to the uncertainty values
  - all the results shown so far already contain systematic effect.
- Size of effect of systematic uncertainty is in total 2% on the UL.
  - $2.3\times10^{-12} \rightarrow 2.4\times10^{-12}$ for combined result

Contribution of each item was studied with toy-experiment by comparing the result with nominal PDF and that with fluctuated one.

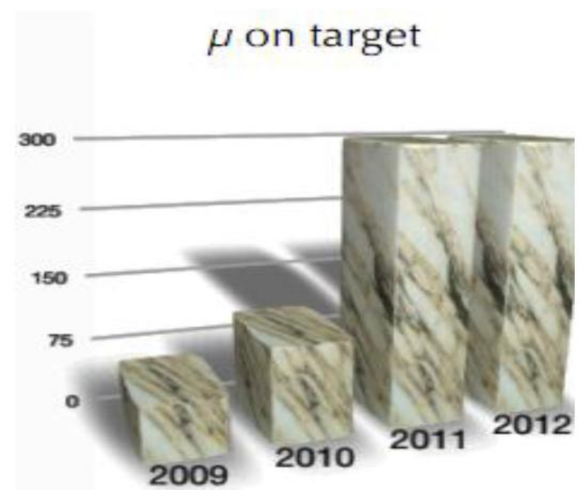
Relative contributions on UL

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

Prospects

- MEG is running
  - We resumed data-taking since July
  - Will acquire ×2 statistics in this year
    - Improved DAQ & trigger eff.

- We will run at least until 2012
  - To reach our goal of sensitivity at a few×10^{-13}



Conclusion

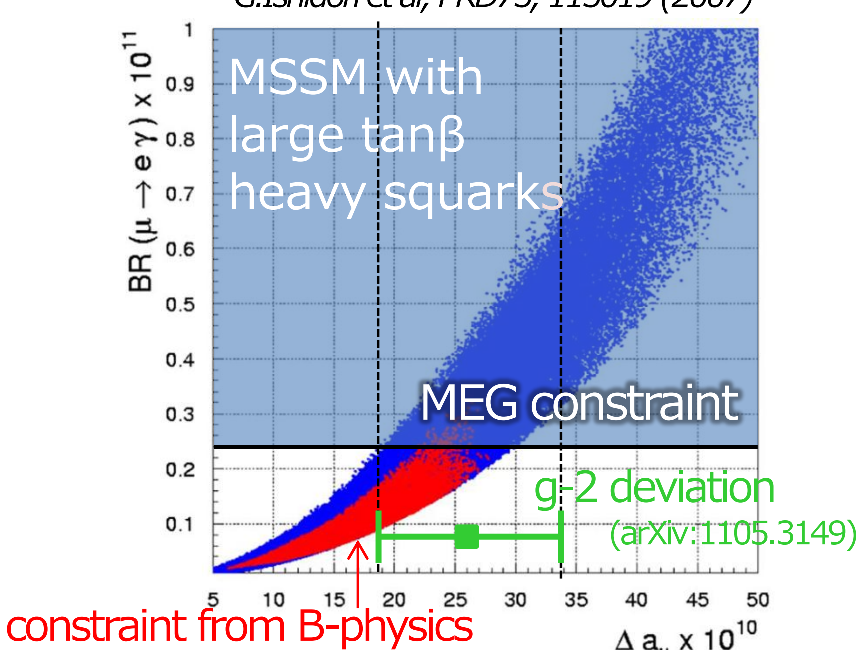
- Searched for unexplored region of lepton-flavor violating decay $\mu^+ \to e^+\gamma$ with sensitivity 1.6×10^{-12}
- 2009+2010 data is consistent with null signal
- New physics is now constrained by **5×** tighter upper limit:

$$\mathcal{B}(\mu^+\to e^+\gamma) < 2.4\times10^{-12} \quad @\ 90\%\ C.L.$$

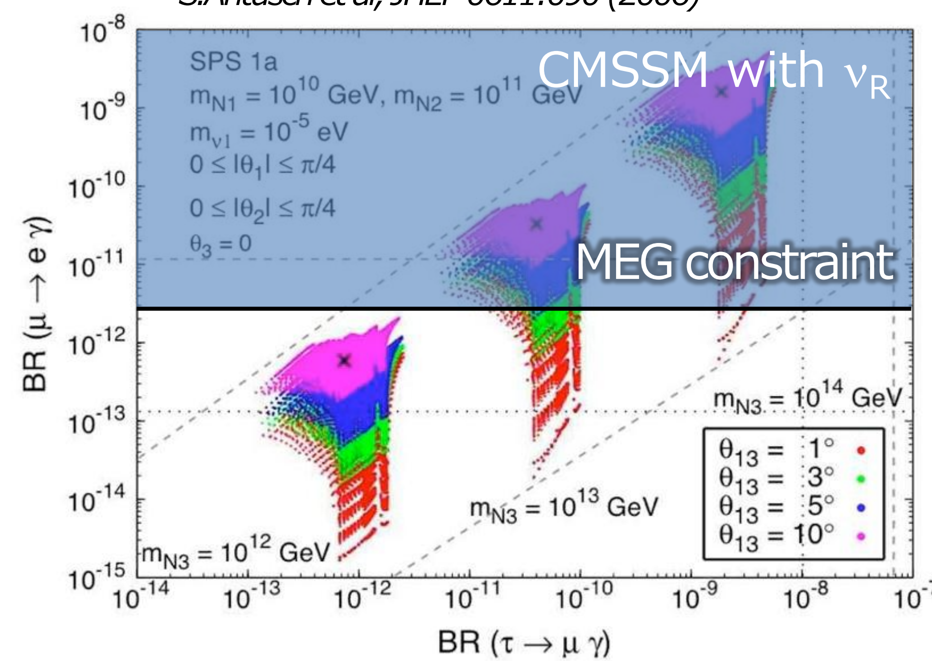
(http://arxiv.org/abs/1107.5547)

- MEG is accumulating more data this and next year to reach $O(10^{-13})$ sensitivity.

G.Ishidori et al, PRD75, 115019 (2007)



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



MEG
Mu-E-Gamma Collaboration

New limit on the lepton-flavour violating decay $\mu^+ \to e^+\gamma$

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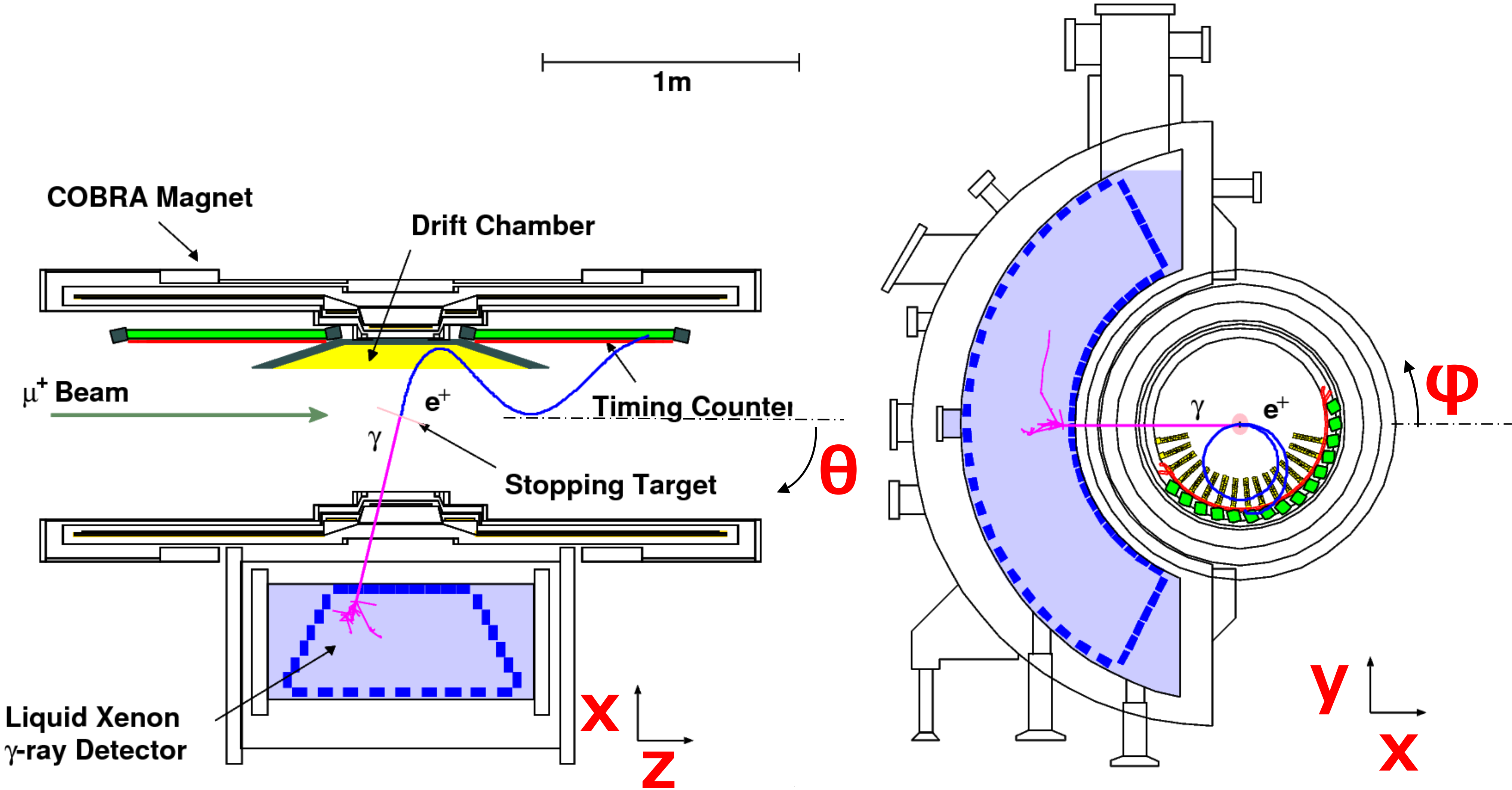
(Dated: August 27, 2011)

We present a new result based on an analysis of the data collected by the MEG detector at the Paul Scherrer Institut in 2009 and 2010, in search of the lepton flavour violating decay $\mu^+ \to e^+\gamma$. The likelihood analysis of the combined data sample, which corresponds to a total of 1.8×10^{14} muon decays, gives a 90% C.L. upper limit of 2.4×10^{-12} on the branching ratio of the $\mu^+ \to e^+\gamma$ decay, constituting the most stringent limit on the existence of this decay to date.

PACS numbers: 13.35.Bv; 11.30.Hv; 11.30.Pb; 12.10.Dm

Thank you

MEG Detector



Summary of performance

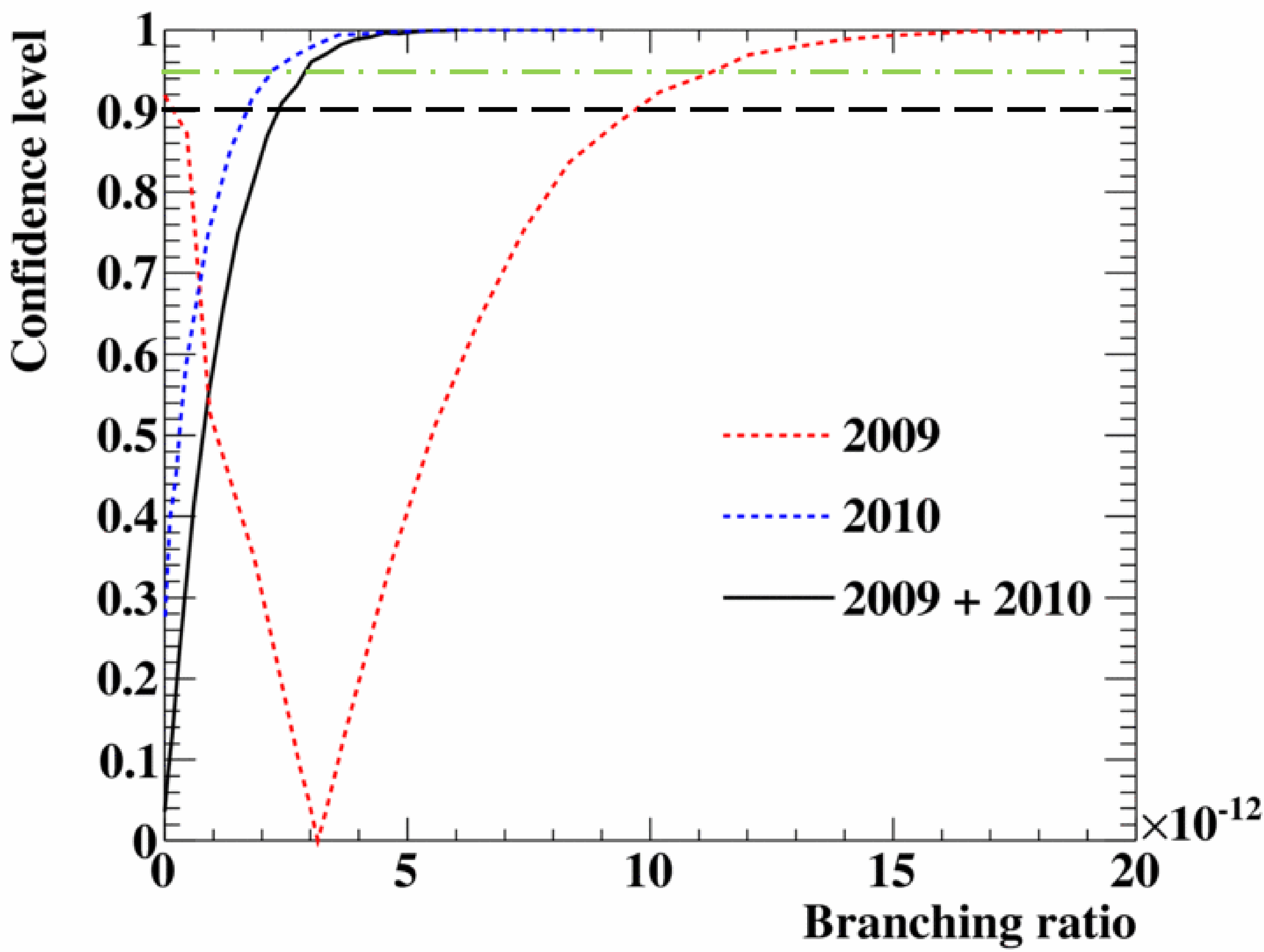
	2009	2010
γ energy	1.9%(w>2cm) 2.4%((w<2cm)	1.9%(w>2cm) 2.4%((w<2cm)
γ timing	96ps	67ps
γ position	5mm(u,v), 6mm(w)	5mm(u,v), 6mm(w)
γ efficiency †	58%	59%
e^+ timing	107ps	107ps
e^+ energy	0.31MeV (core 80%)	0.32MeV (core 79%)
e^+ angle (θ)	9.4mrad	11.0mrad
e^+ angle (ϕ)	6.7mrad	7.2mrad
e^+ vertex (Z/Y)	1.5mm/1.1mm(core)	2.0mm/1.1mm(core)
e^+ efficiency	40%	34%
$e^+-\gamma$ timing	146ps	122ps
Trigger efficiency	91%	92%
$e^+-\gamma$ angle (θ)	14.5mrad	17.1mrad
$e^+-\gamma$ angle (ϕ)	13.1mrad	14.0mrad
Stopping μ rate	$2.9\times10^7 s^{-1}$	$2.9\times10^7 s^{-1}$
DAQ time/ Real time	35days/43days	56days/67days
Total μ stops on target	6.5×10^{13}	1.1×10^{14}

† $\varepsilon_{detection} \times \varepsilon_{analysis}$ for E_γ >48MeV

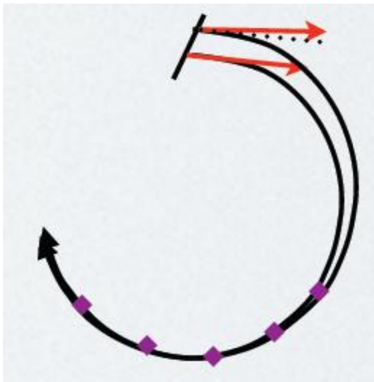
e^+ tracking slightly worse in 2010 due to noise problem

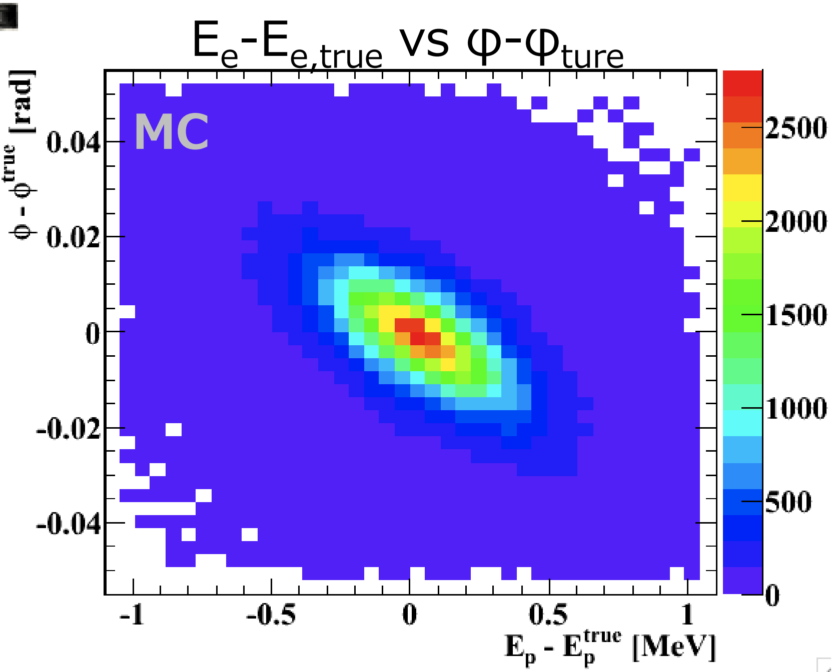
improvement by waveform digitizer upgrade in 2010

Confidence intervals



Correlation

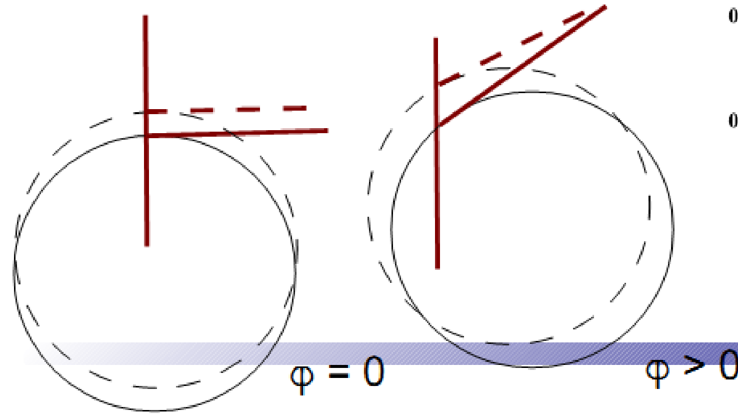


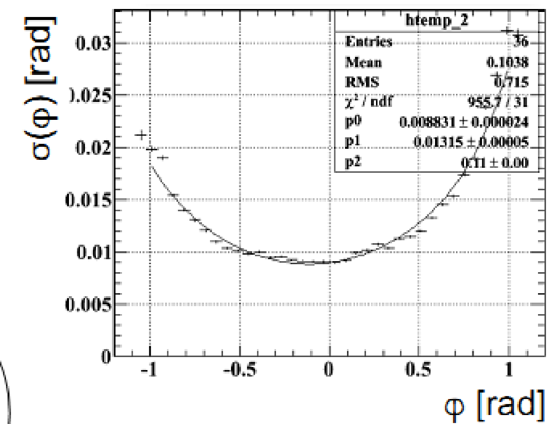


- Geometrical effects worsen the effective φ resolution at φ ≠ 0:

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

parameterization from a simple geometrical model (see note)



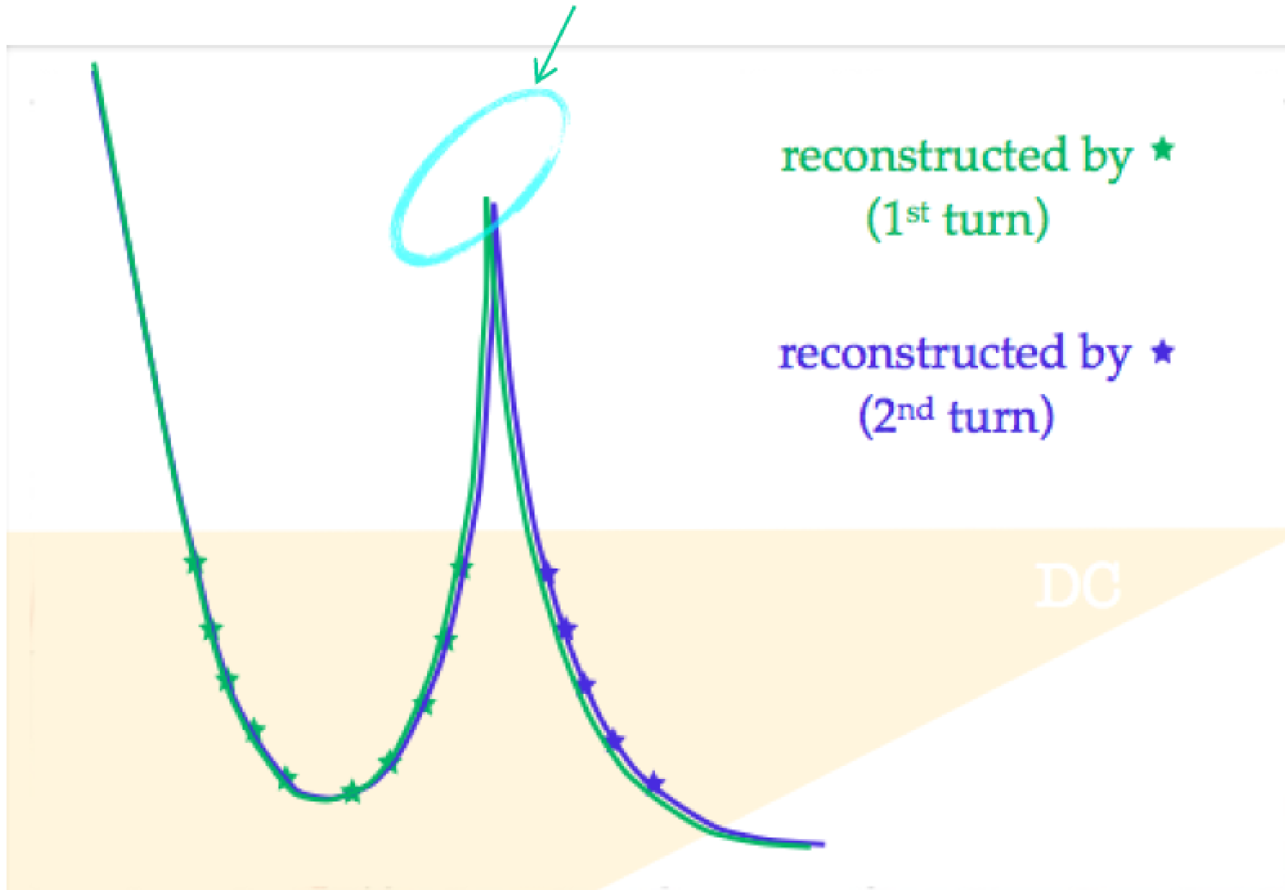


10

We know the e$^+$ momentum exactly for signal

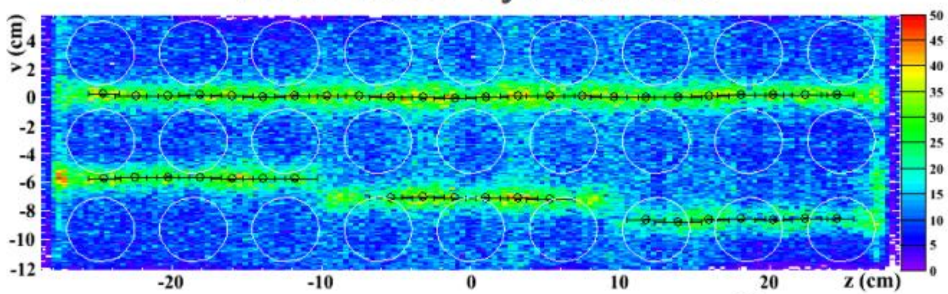
Tracker performance

- direction ➔ fit of double-turn positrons
  - track segments reconstructed as due to different particles
  - angular resolution obtained from the difference of the two reconstructions at the turning point

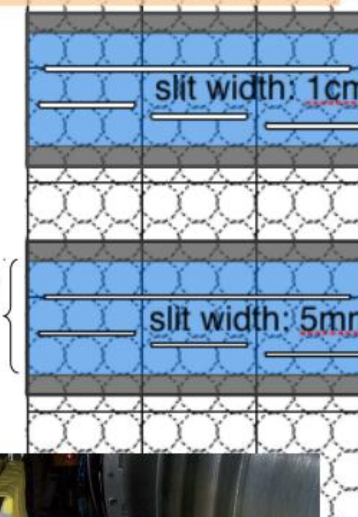


Position resolution

- Evaluate position resolution with Pb collimator
  - 2009 CEX run, modified Pb collimator
    - To reduce sys uncert



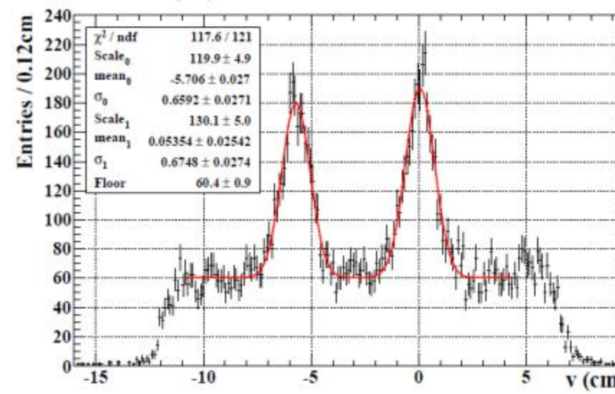
- Longer to cover all z-direction
- Wider to reduce trigger bias and improve efficiency
- Two slit width
- Slits at different position w.r.t PMT
- Fit to inner face curvature



Trigger region

- 2008 results are confirmed

σ_{xy}	~ 5mm
σ_{depth}	~ 6mm

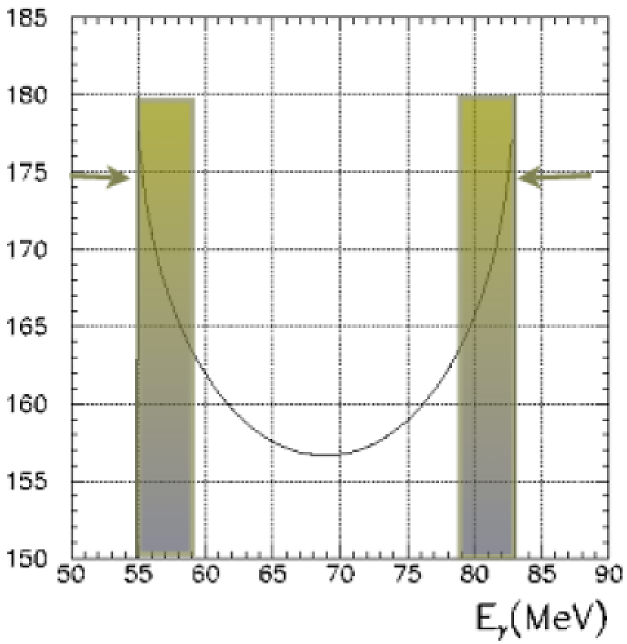


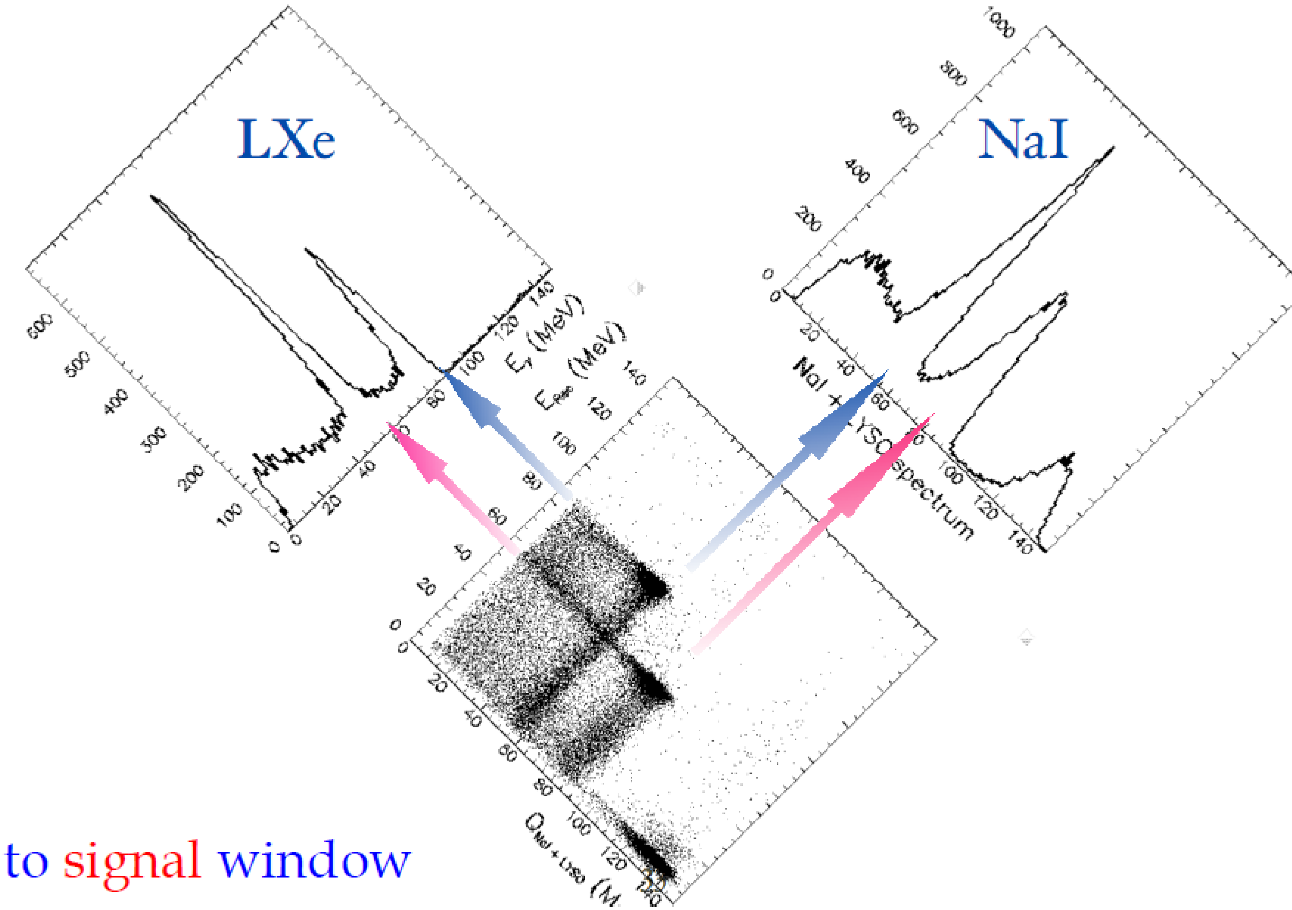
These results are slightly worse than MC.
Considered to be due to wrong QE
→ possibly down to 4.5 mm

- We skipped this measurement in 2010 CEX

γ from π⁻ charge exchange reaction

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



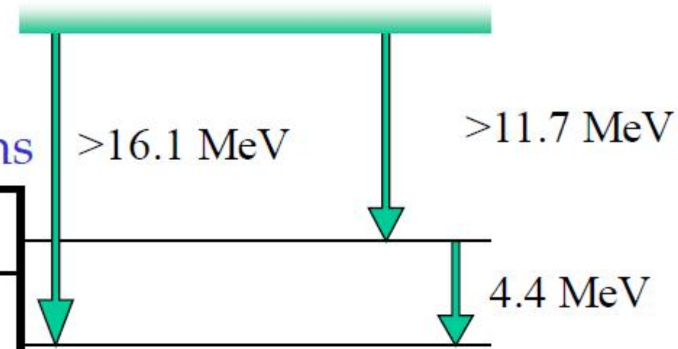


- E_γ = 55 (83) MeV ➔ close to signal window
- liquid H-target
- beam polarity and settings to be changed as well

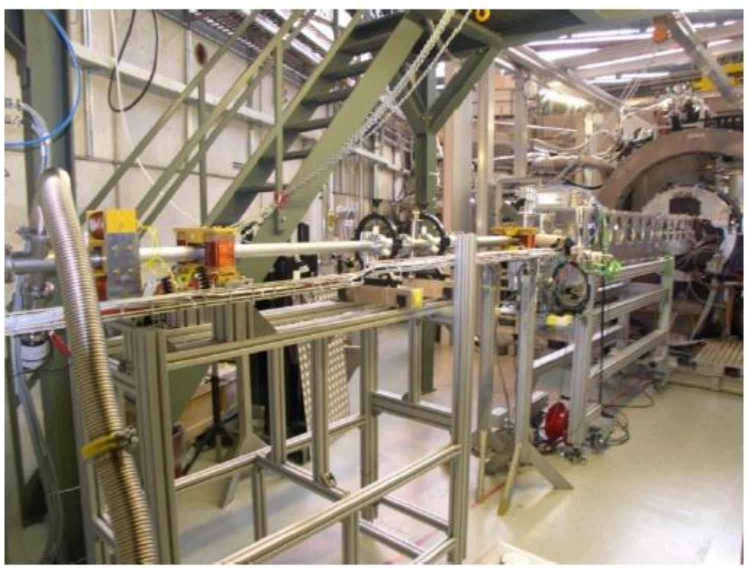
  → to be used quite seldom (~ 1/year)

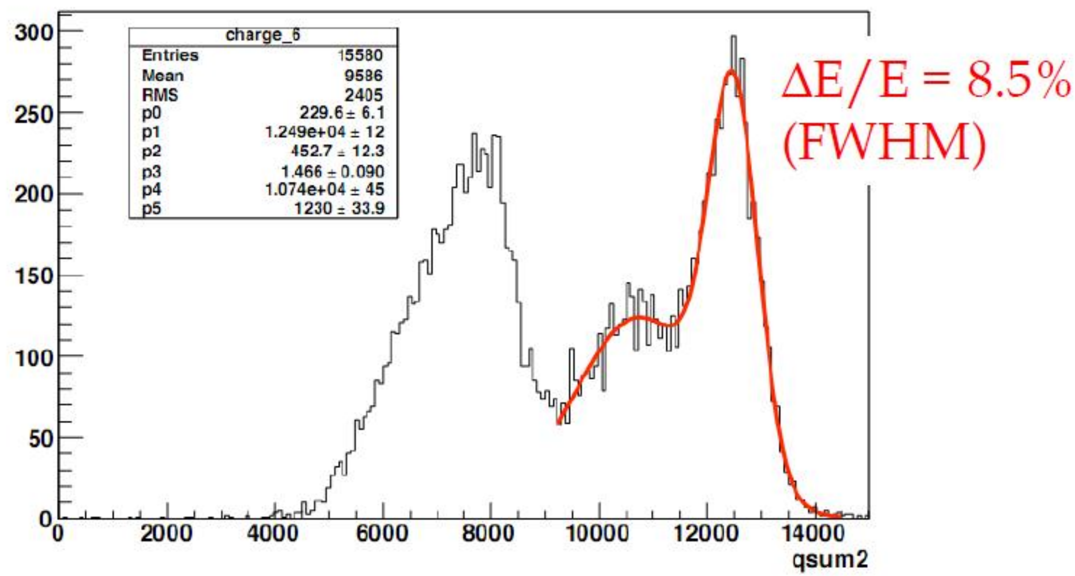
(p,γ) reaction

- Makes us of a Cockcroft-Walton accelerator to deliver tunable-energy protons to a $Li_2B_4O_7$ target
  - Li: high rate, higher energy photon
  - B: two (lower energy) time-coincident photons



Reaction	E_{res}	σ_{res}	*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





Pileup unfolding

•reconstruction of the main cluster
•replacement of Npe for pile-up cluster with expected values