MEG Experiment

Ryu Sawada
The University of Tokyo
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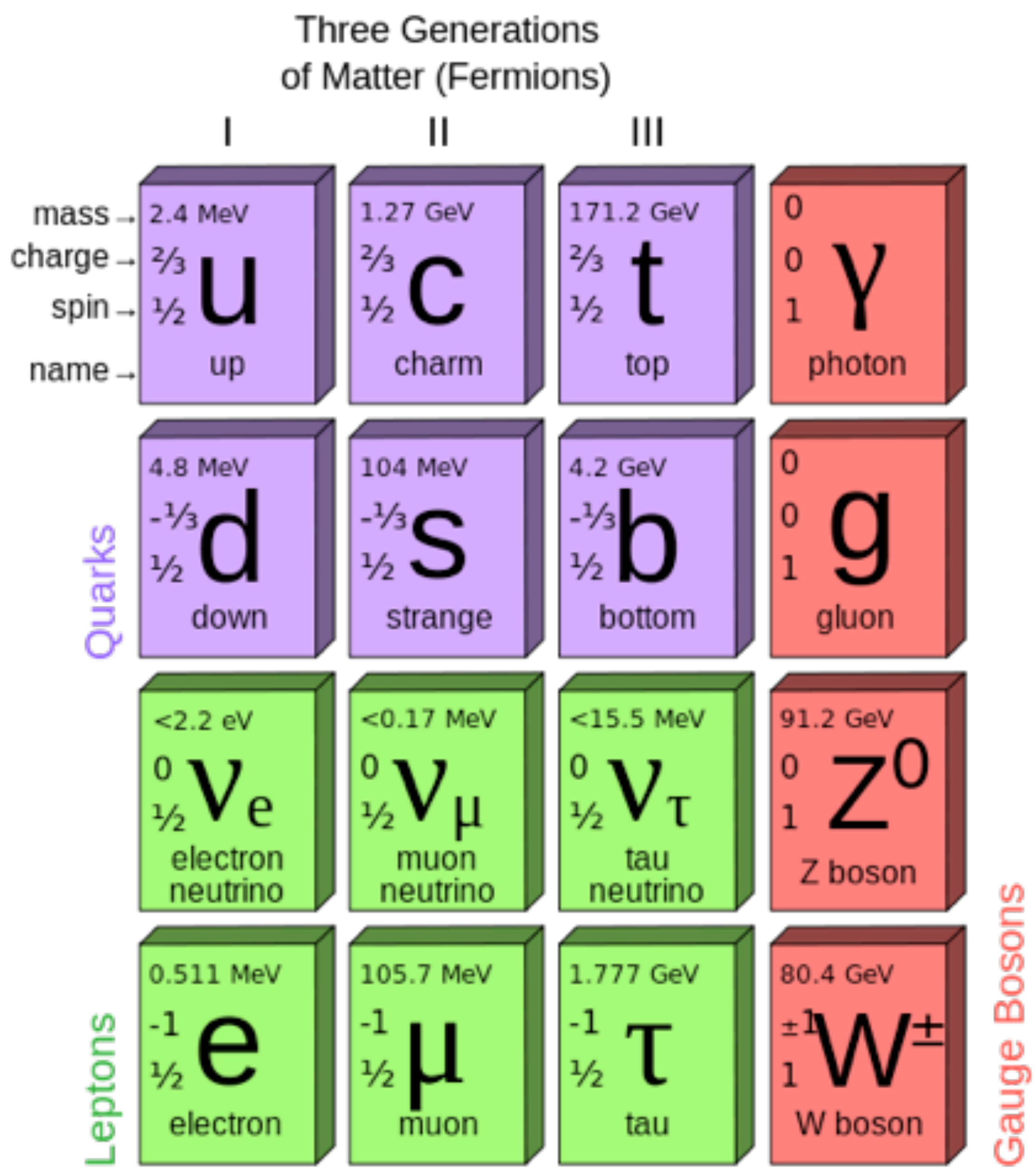
Outline

- Introduction
- Apparatus
- Analysis
- Run2009+Run2010 result
- Status and future prospect

The standard model



Wikipedia

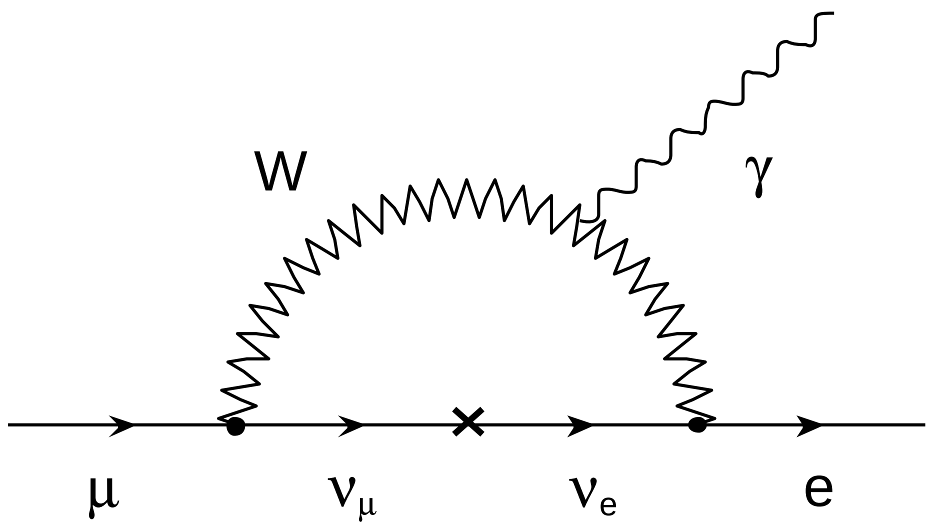
Quarks : CKM mixing

Neutrinos : Oscillation

Charged : ??

$\mu \rightarrow e\gamma$ diagram

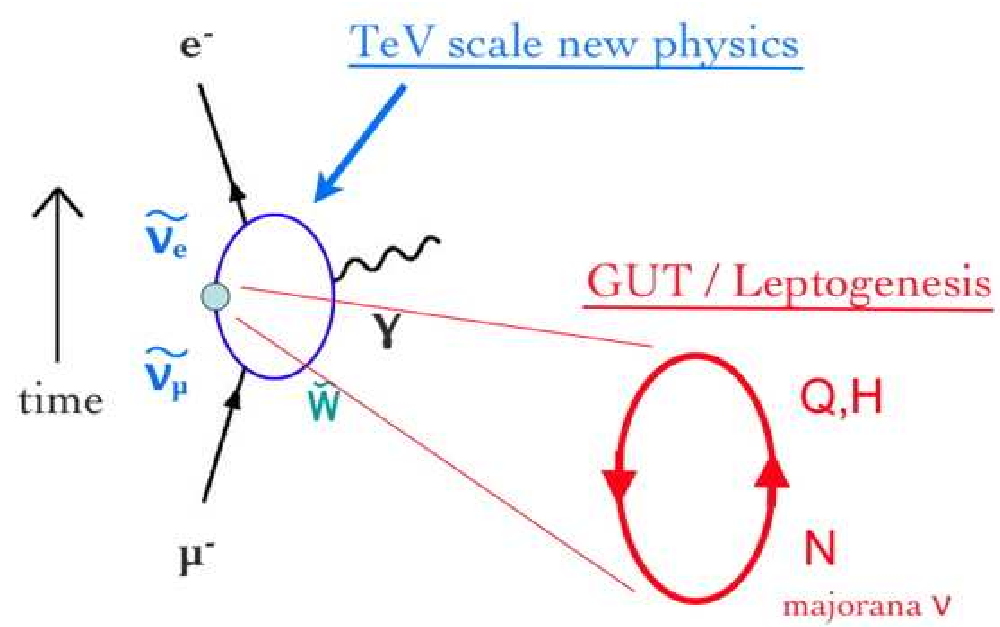
Standard model



Br ~ 10^{-50}

New physics

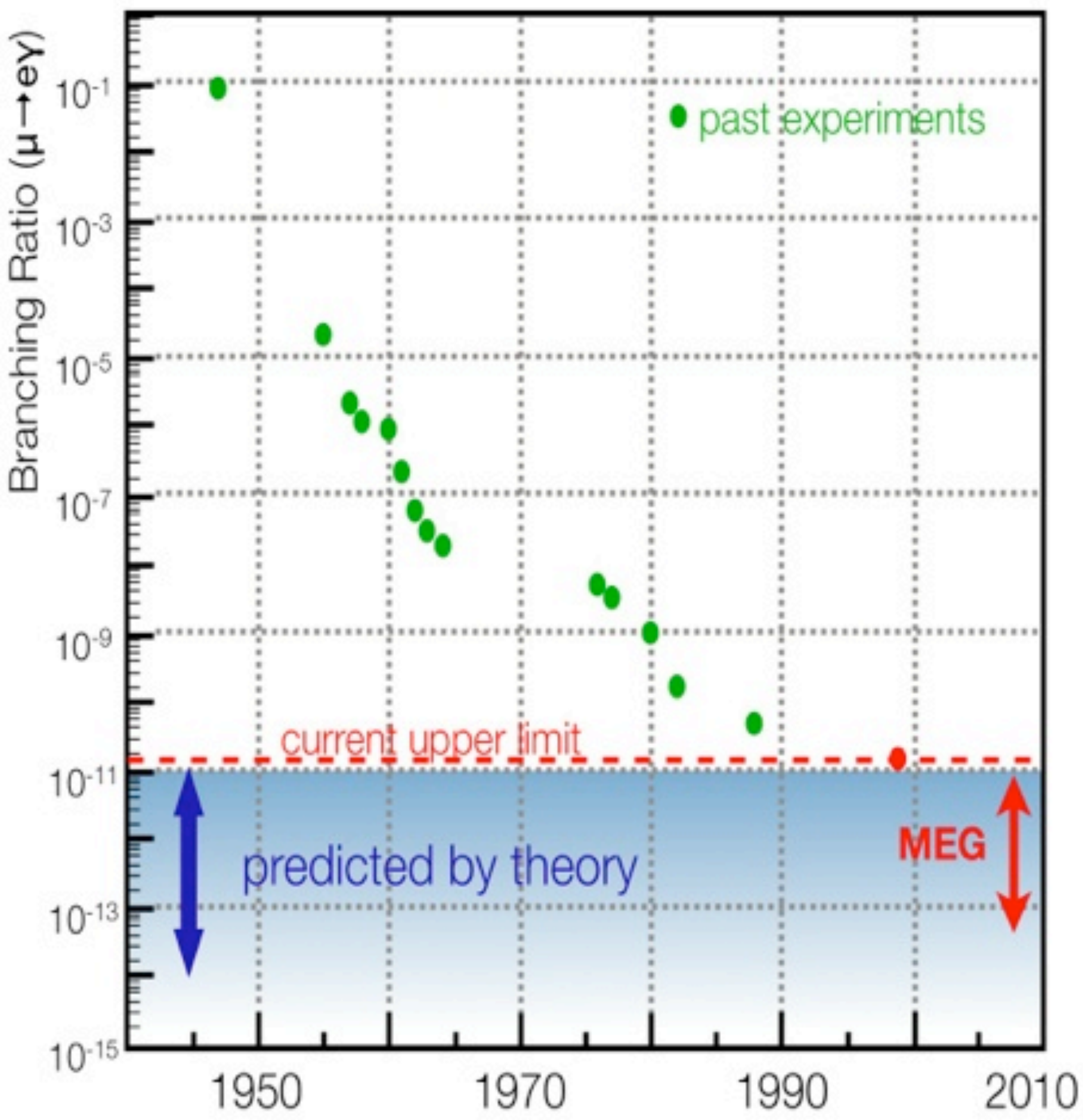
Br ~ 10^{-14}-10^{-11}



T.Mori hep-ex/0605116

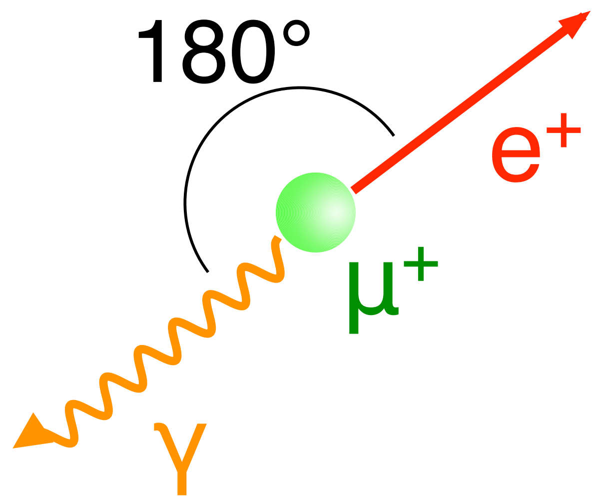
Lepton Flavor Violation

- $\mu \to e\gamma$ decay
  - Lepton flavor violating decay
  - In the SM with neutrino oscillation, the branching ratio is tiny($\sim 10^{-50}$)
  - Previous experimental upper limit (before MEG experiment)
    - 1.2×10^{-11} (1999, MEGA)
  - Well motivated new physics (SUSY-GUT, SUSY seesaw,...) predict the branching ratio around 10^{-11} -10^{-13} region
- MEG experiment
  - Explore down to 10^{-13} level

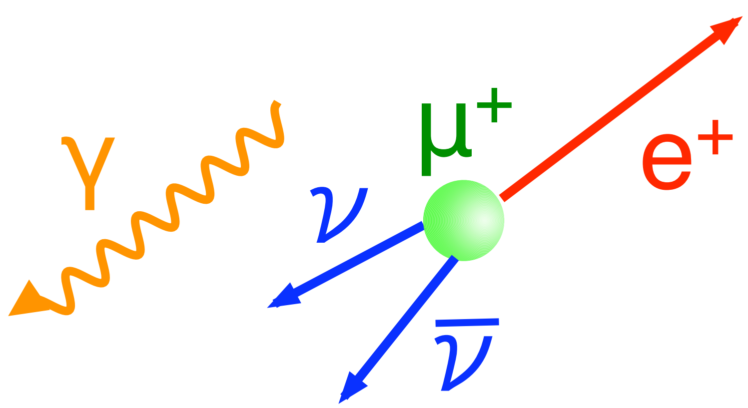


Signal & background

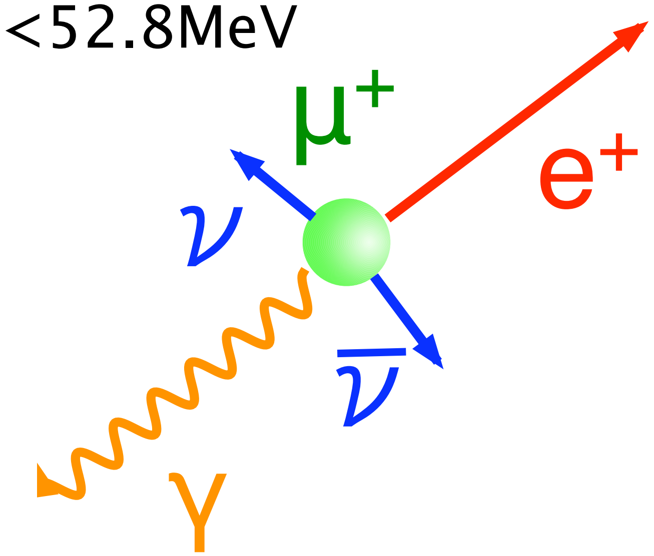
- Signal
  - μ^+ decay at rest
  - 52.8MeV (half of M_μ) (E_γ,E_e)
  - Back-to-back ($\theta_{e\gamma}$,$\varphi_{e\gamma}$)
  - Timing coincidence ($T_{e\gamma}$)



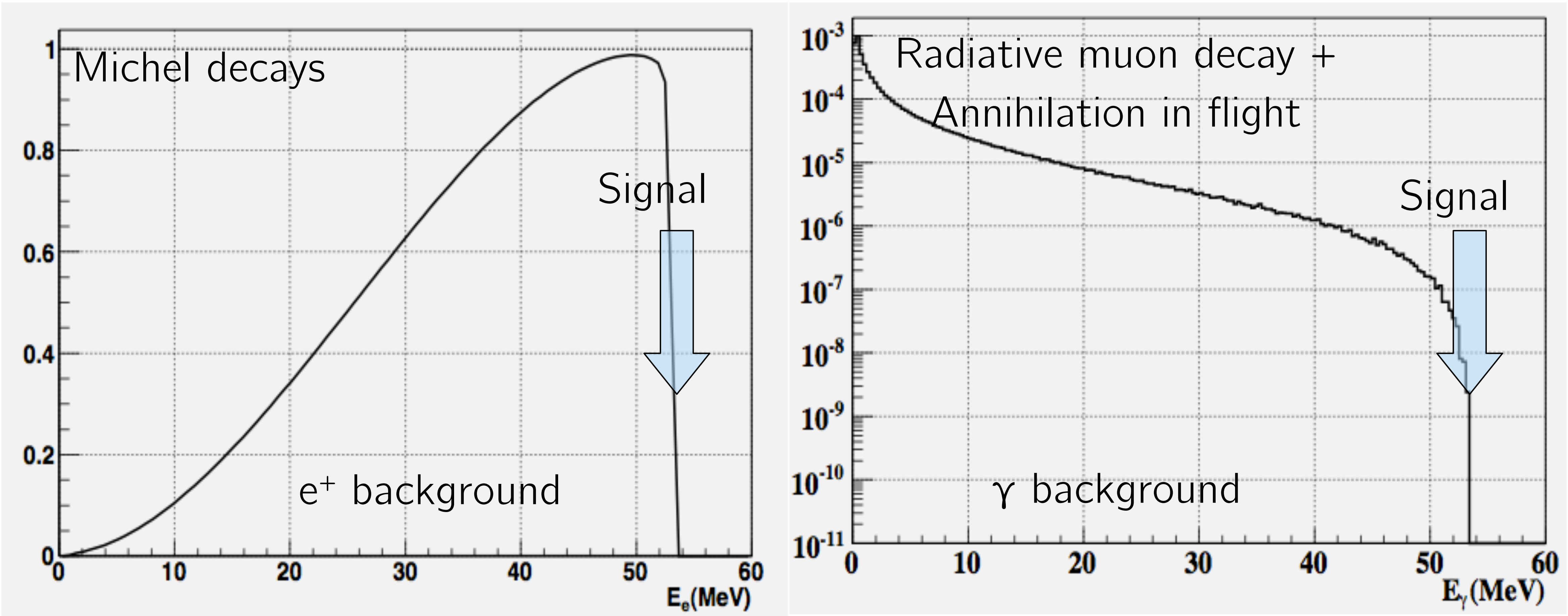
- Accidental background
  - Michel decay e^+ + random γ
  - Dominant background for us
  - Random timing, angle, <52.8MeV



- Radiative muon decay
  - μ -> $e\nu\nu\gamma$
  - Timing coincident, not back-to back, <52.8MeV



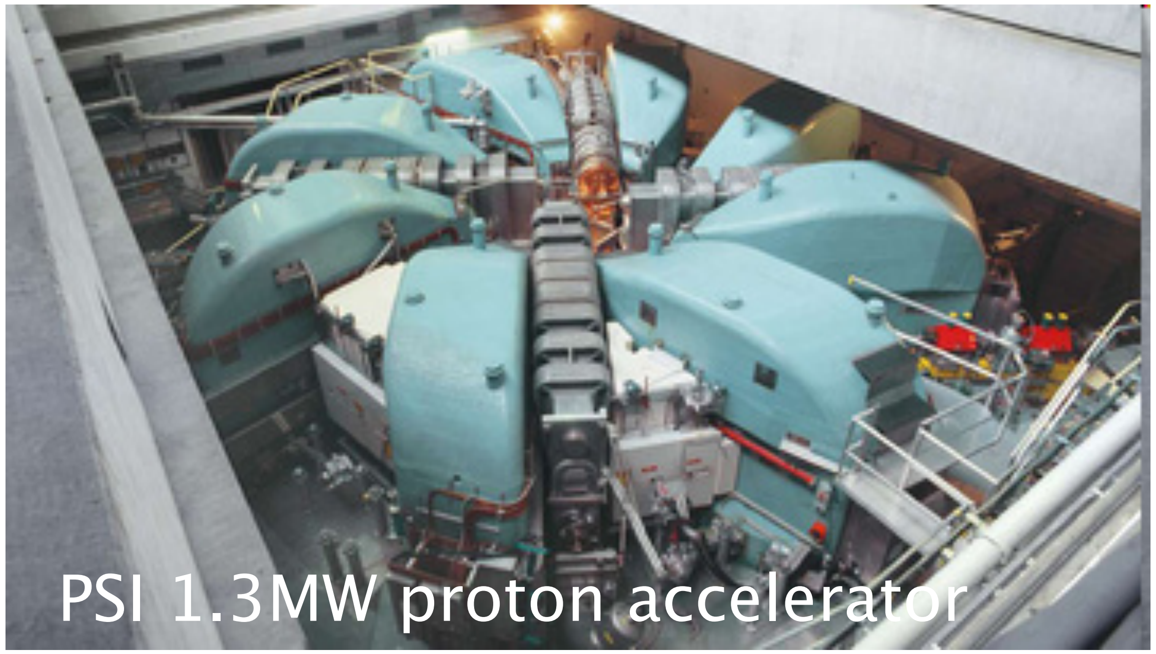
Background spectra



$$N_{\mathrm{acc}} \propto R^2 \cdot \delta E_{\mathrm{e}} \cdot \delta E_{\gamma}^2 \cdot \delta\theta_{\mathrm{e}\gamma}^2 \cdot \delta t_{\mathrm{e}\gamma}$$

Good resolution to reduce background
High rate positron measurement

MEG experiment



Most intense DC muon beam ($>1\text{x}10^8 \mu^+/s$) possible

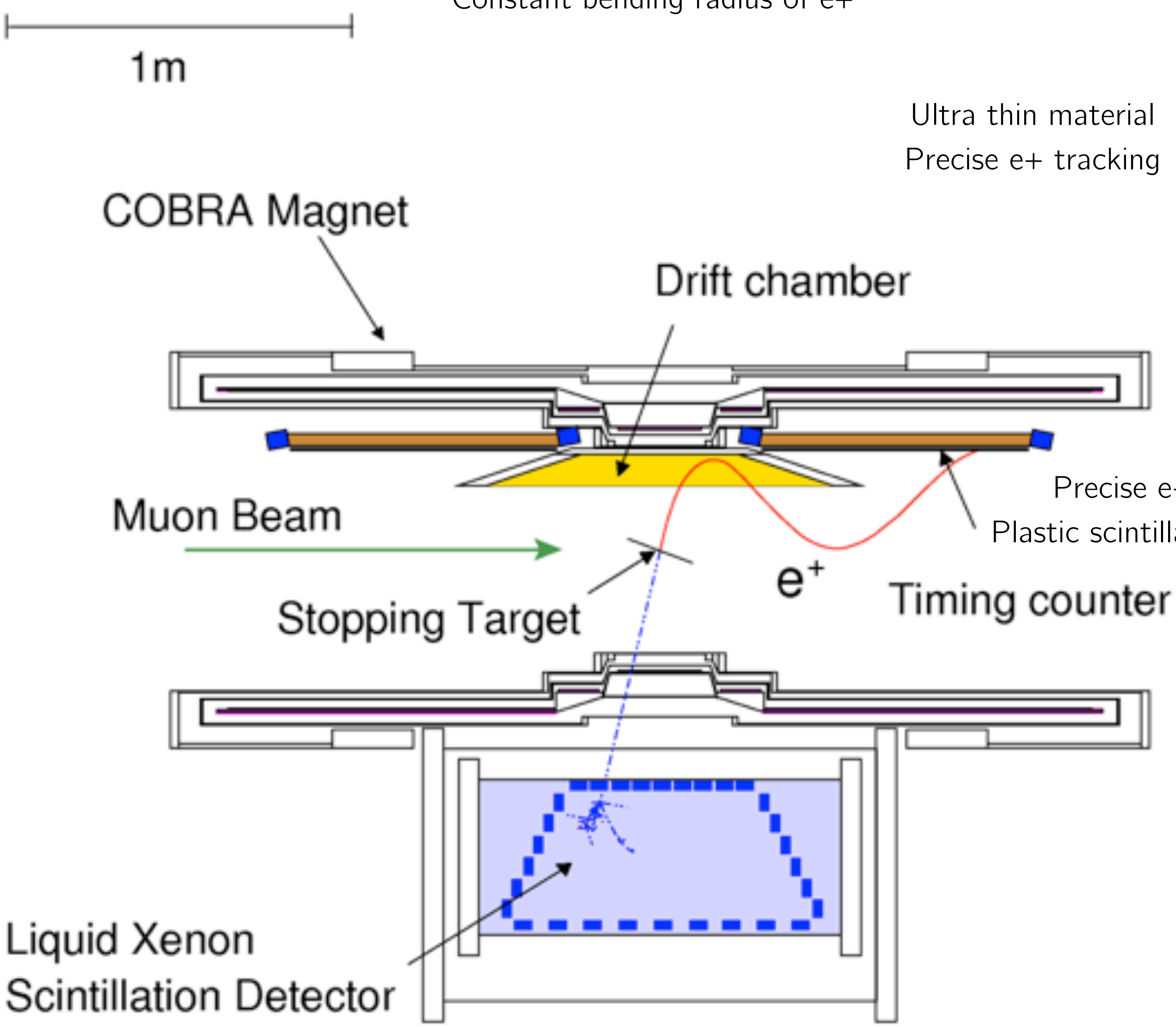
- Requirement:
  - Need many muon decays
  - Detectors(e^+) should be working in high rate environment
  - Good energy, timing, and position resolutions

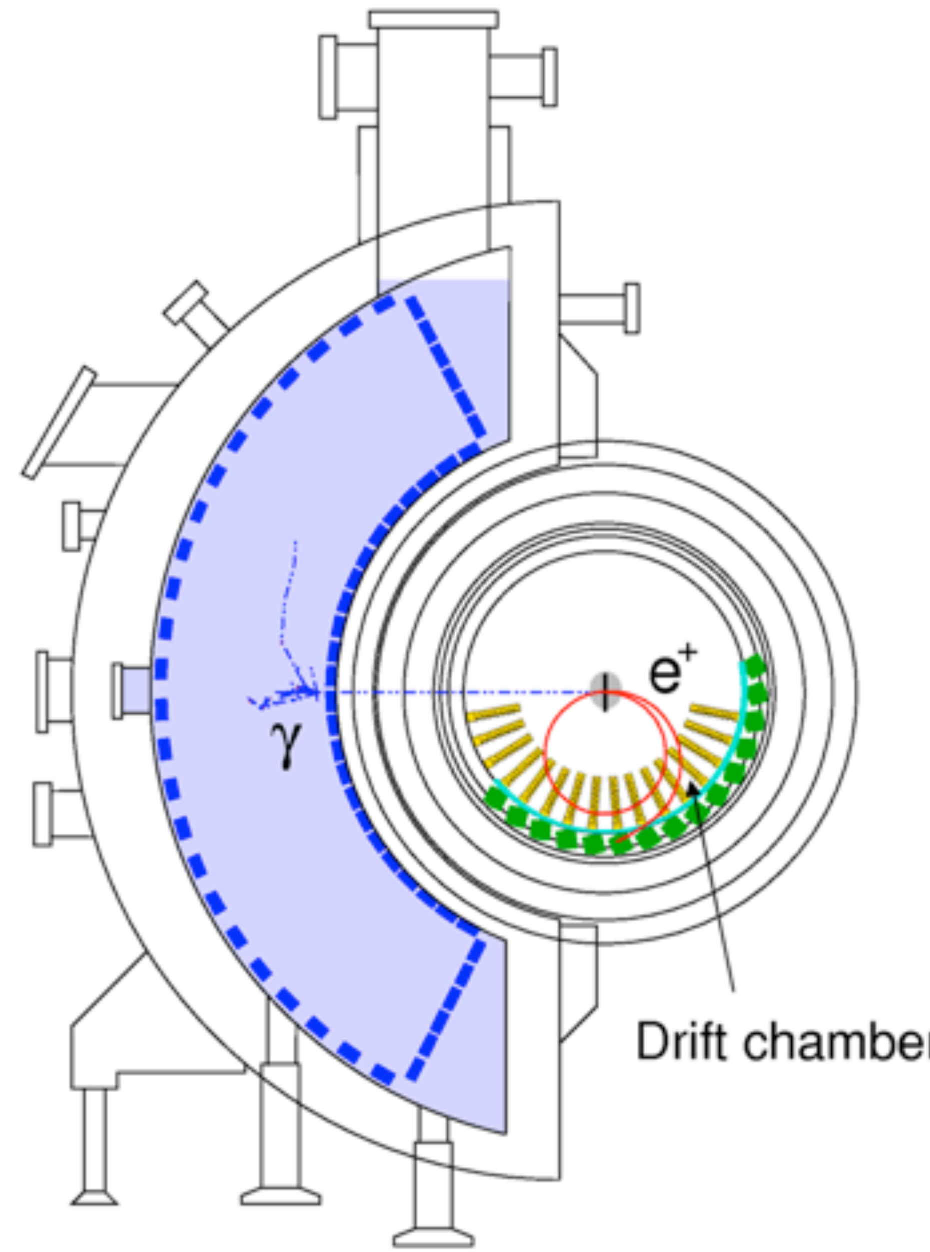
MEG detector

Special gradient magnetic field
Sweeps out high rate e+ quickly
Constant bending radius of e+

Ultra thin material
Precise e+ tracking

Precise e+ timing
Plastic scintillator + PMTs

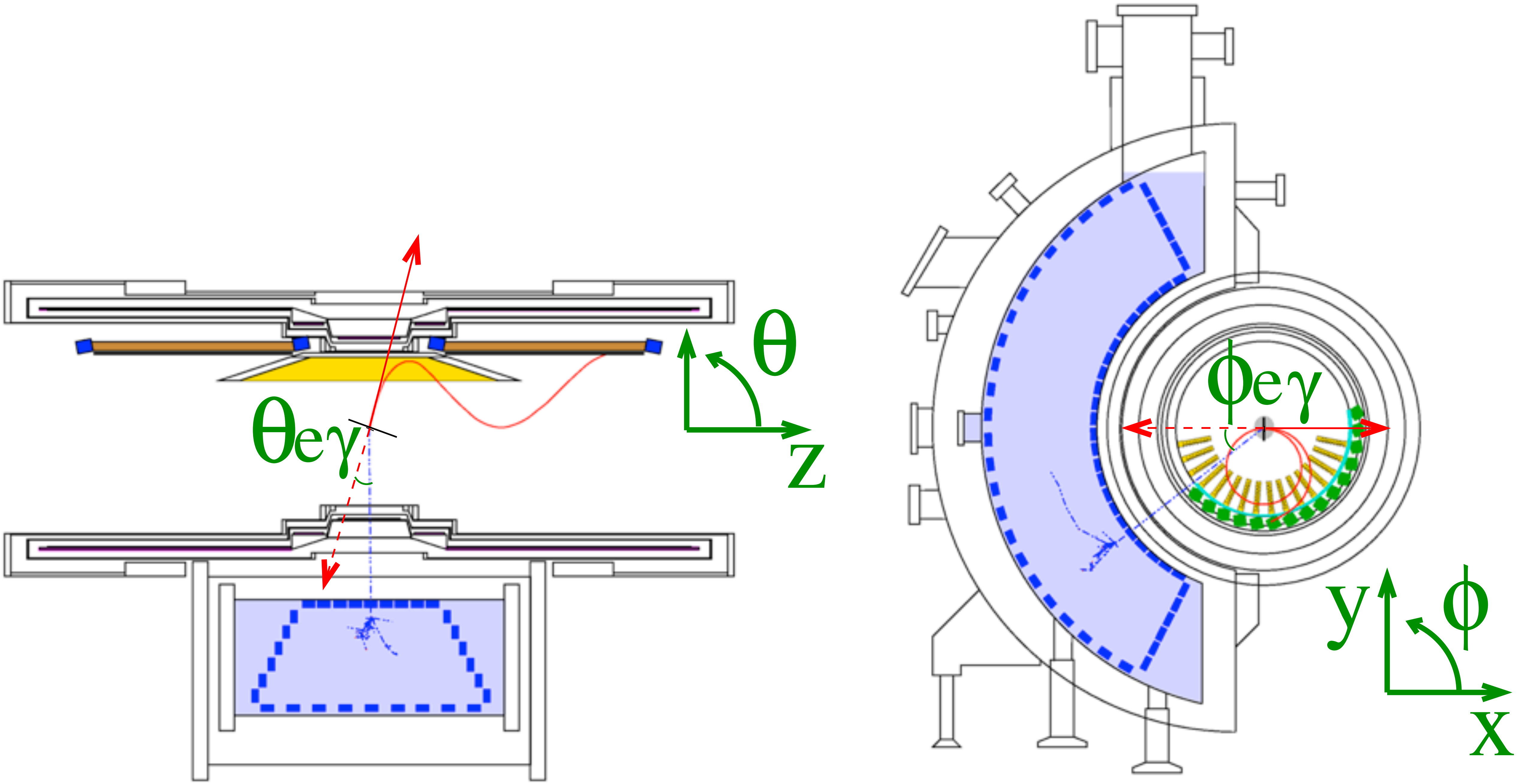


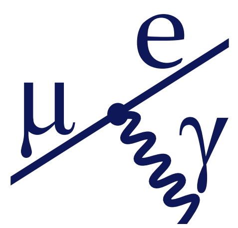


2.7 ton of liquid xenon
Homogeneous detector
Good time, position, energy resolution

Waveform digitizer for all detectors (pileup ID)

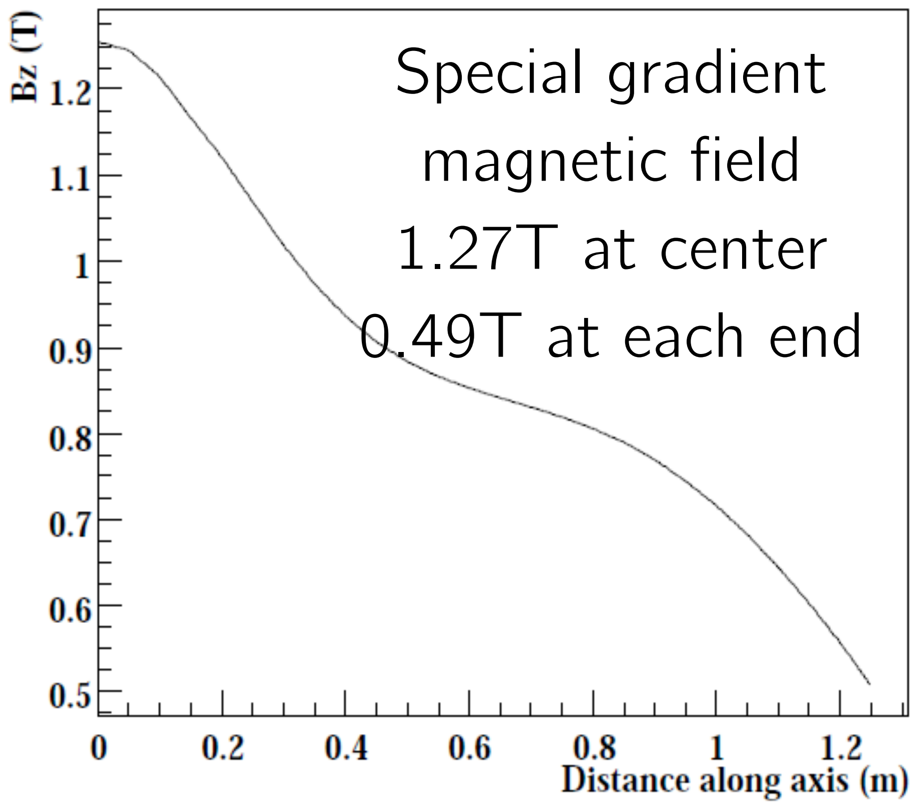
Coordinate system

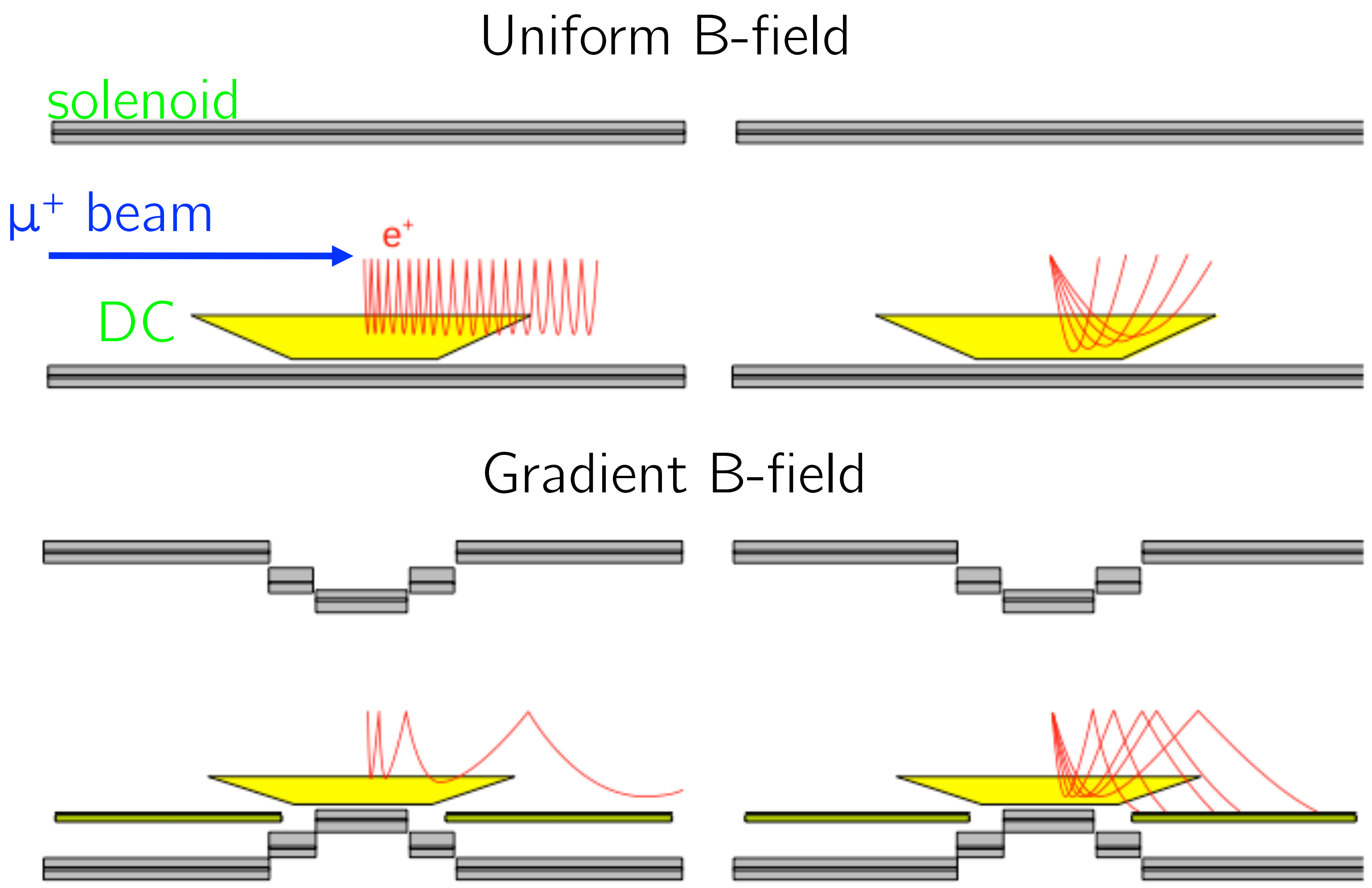




Positron spectrometer

Positron spectrometer

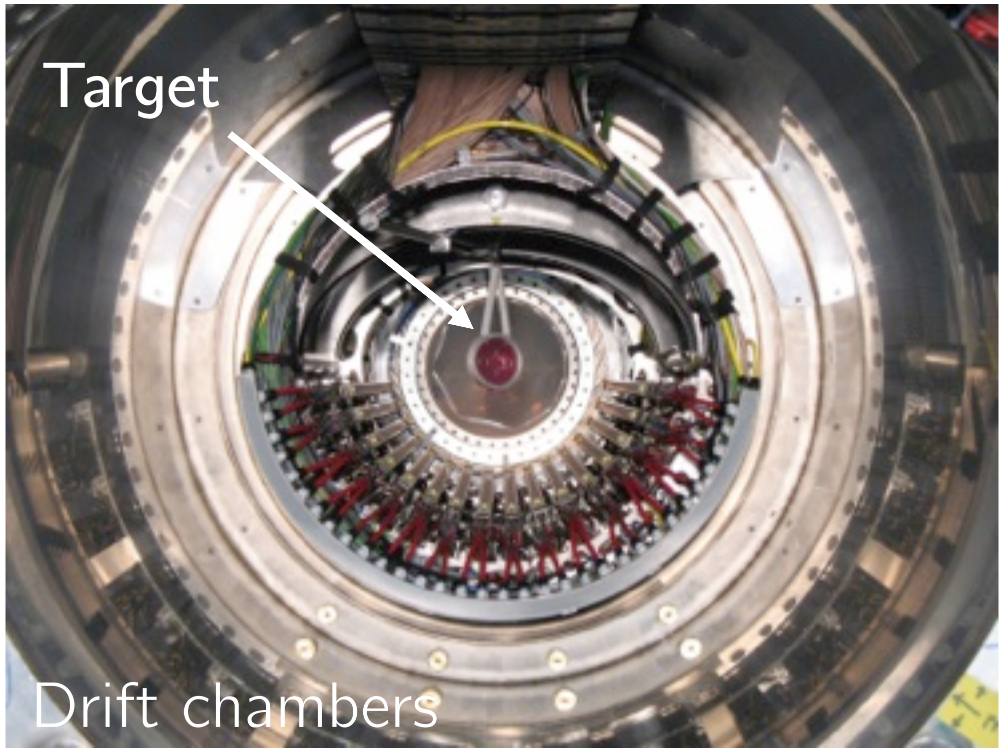


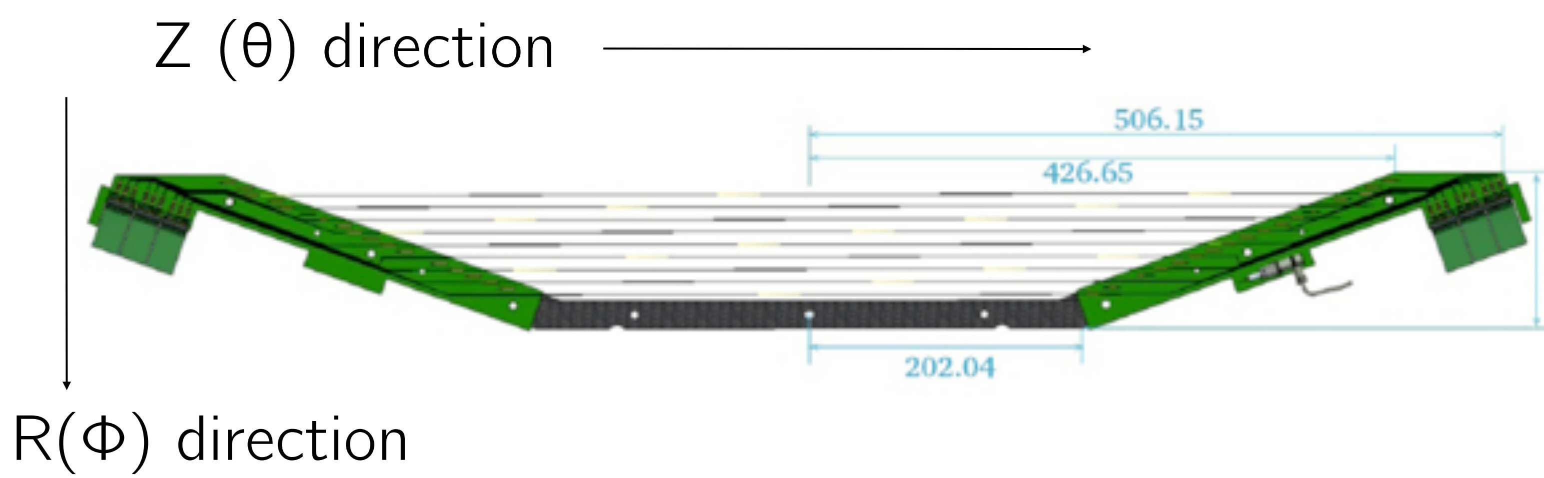


Low energy positron quickly swept away

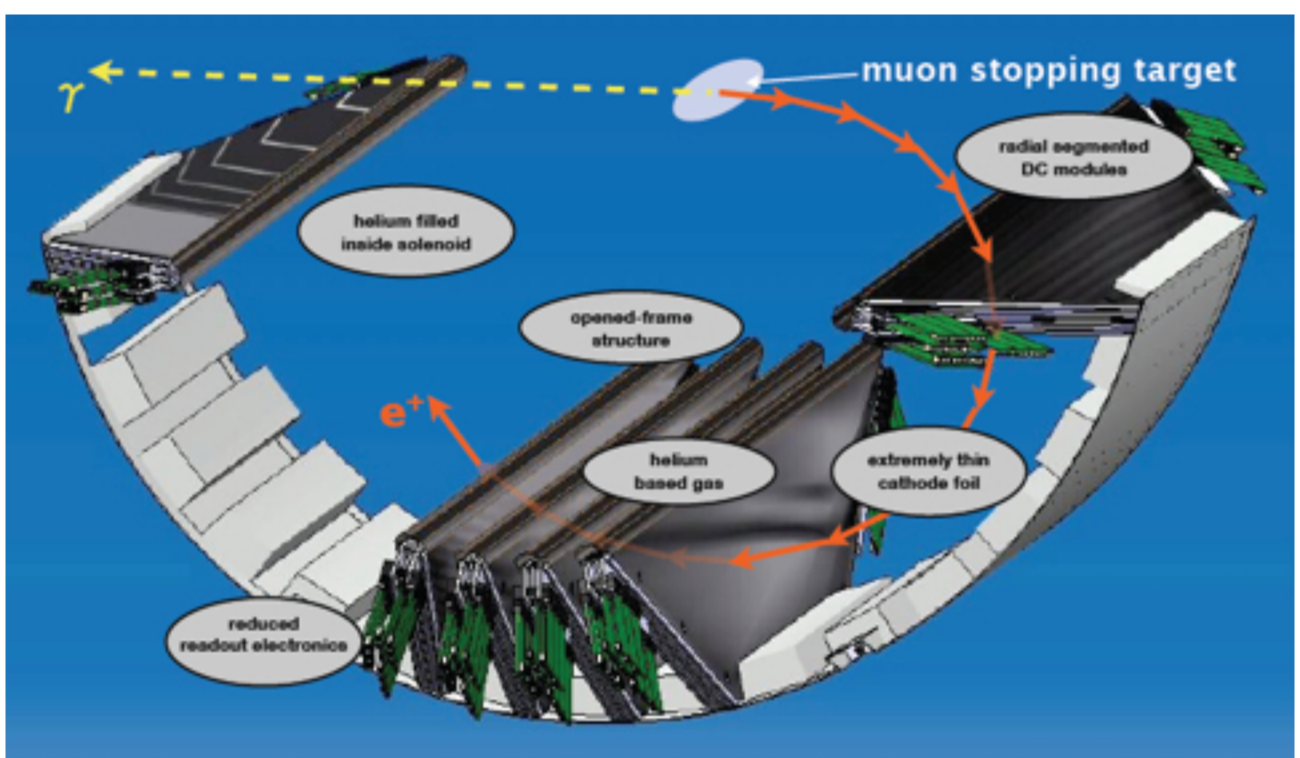
COnstant **B**ending **RA**dius independent of emission angles

Drift chambers



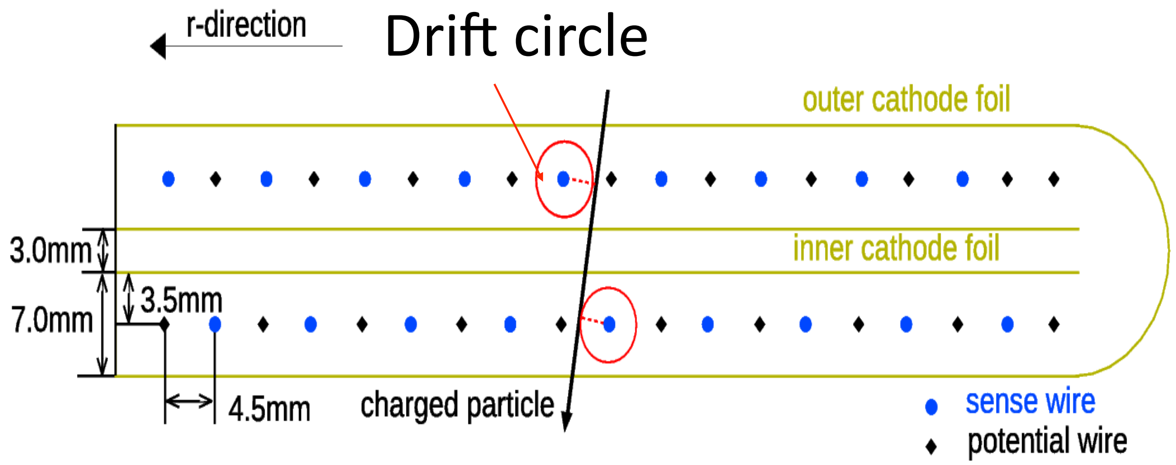


- Positron tracking
  - Momentum, emission angle (θ,φ)
- 16 radial drift chambers
  - Only high momentum e^+ (>40MeV, 19.3cm<r<27.9cm)
- Chamber gas He:C_2H_6 = 50:50
- Low material budget
  - Open frame at the target side
  - Low MS, low γ background

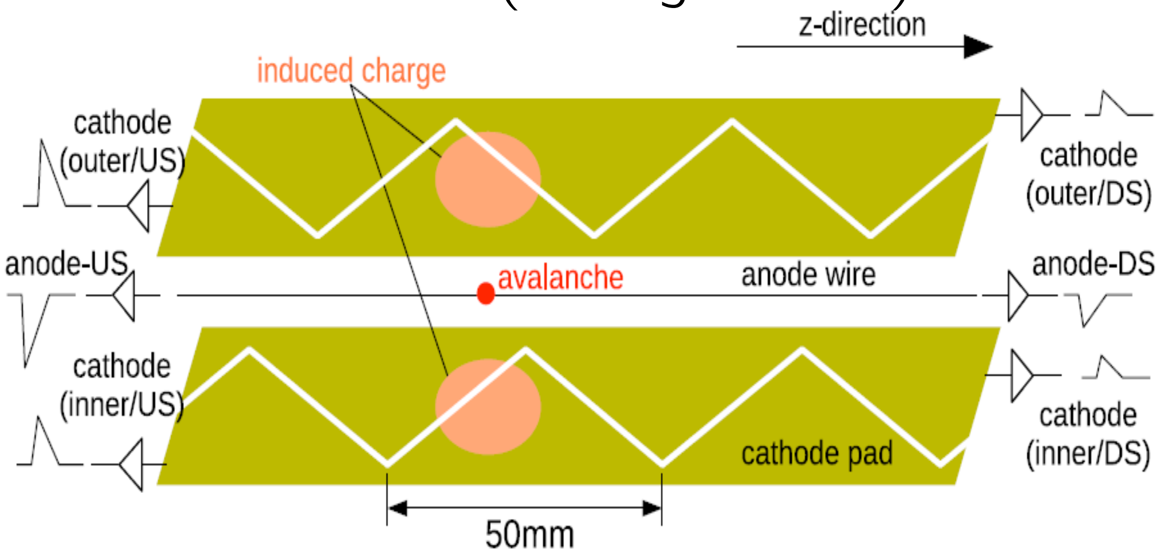


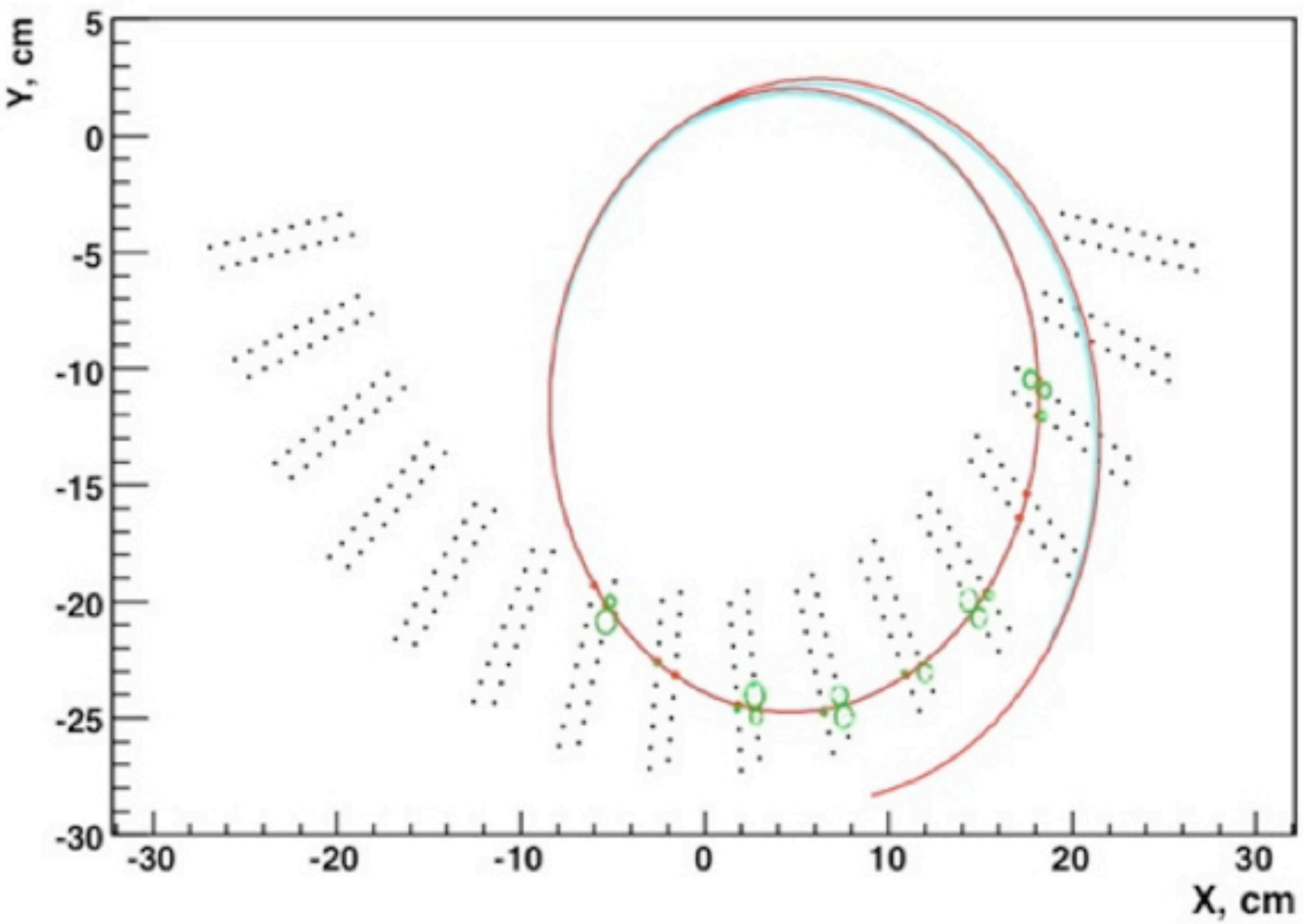
Track reconstruction

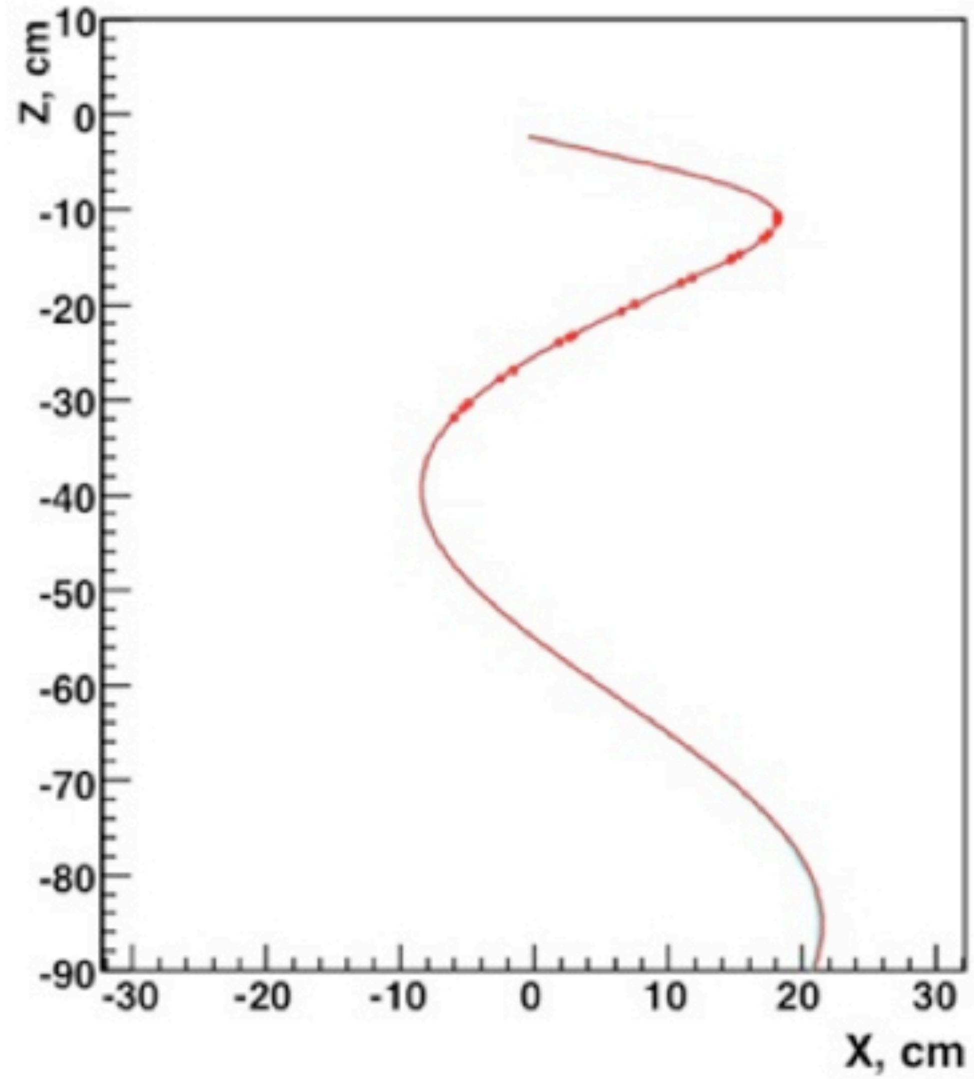
R direction (drift time)



Z direction (charge ratio)

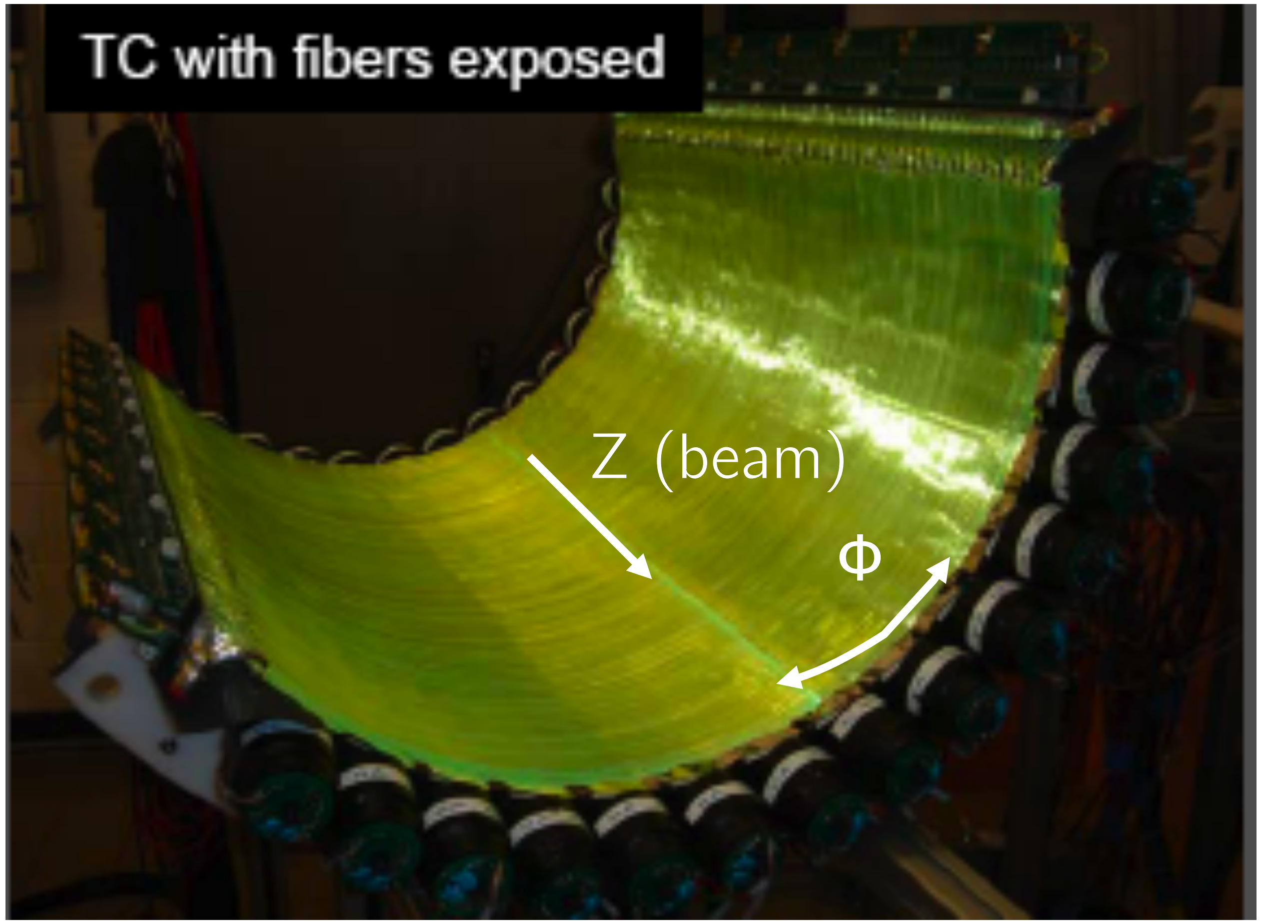


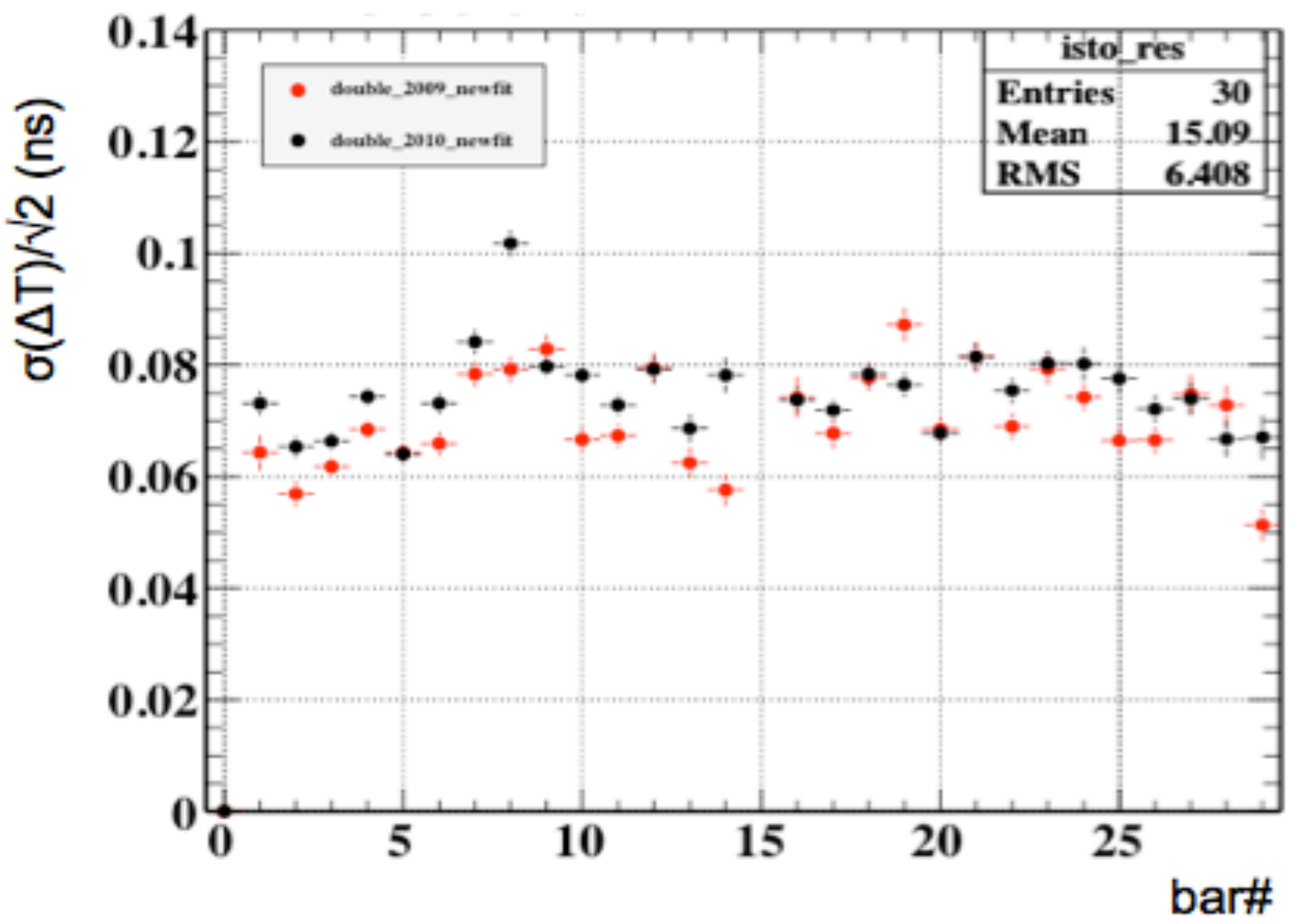




Timing counter

- 15x2(Upstream/Downstream) plastic scintillator bars ($4x4x80cm^3$)
  - Fine mesh PMTs at both ends, positron timing measurement (σ~65ps)
  - Positron φ, z position reconstruction(~5cm)
- Scintillating fibers ($6x6mm^2$) + APD
  - Precise z position measurement, fast θ emission angle information





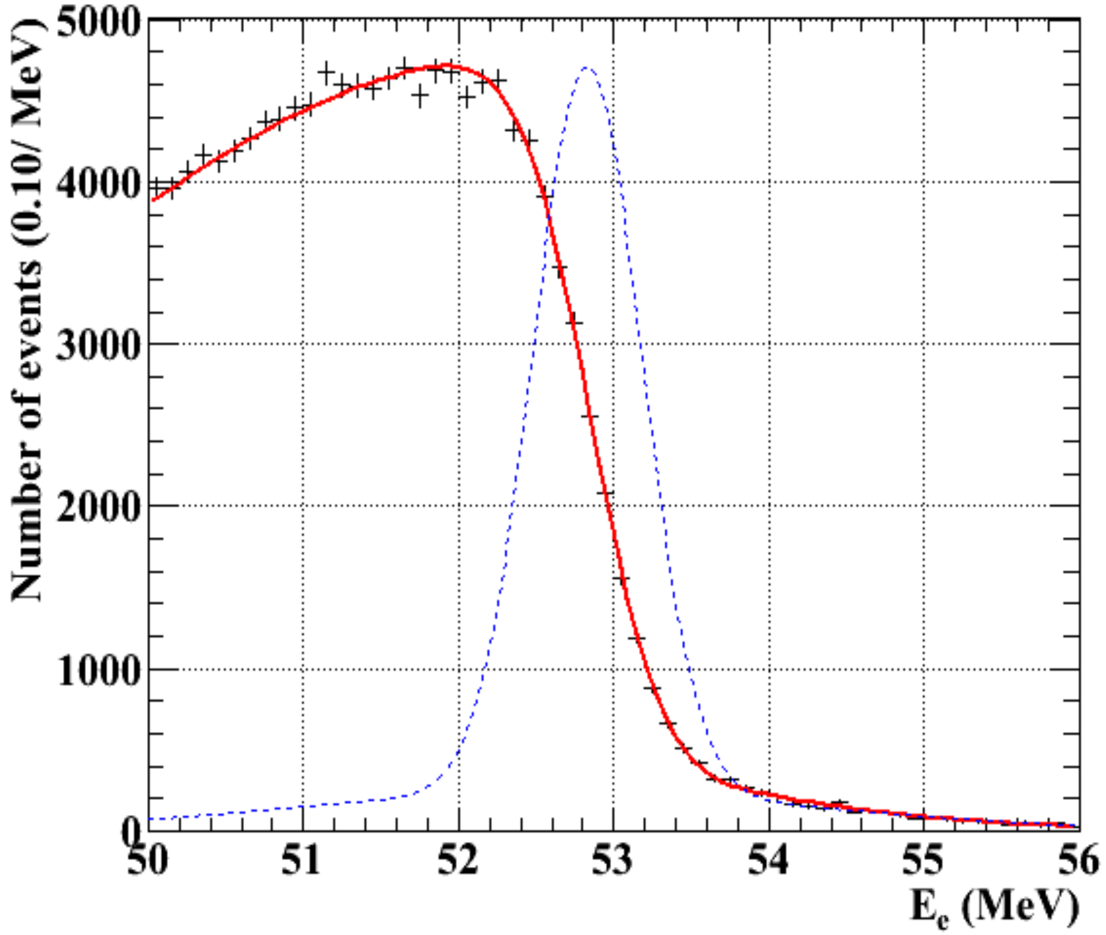
Positron spectrometer performance

2009 : almost all drift chamber working correctly after fixing 2008 HV discharge problem

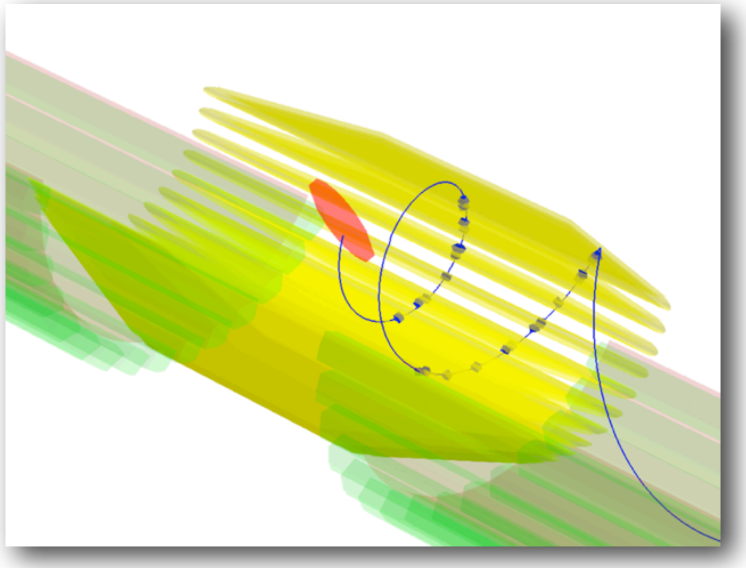
2010 : 5 DC chambers are replaced before 2010 run

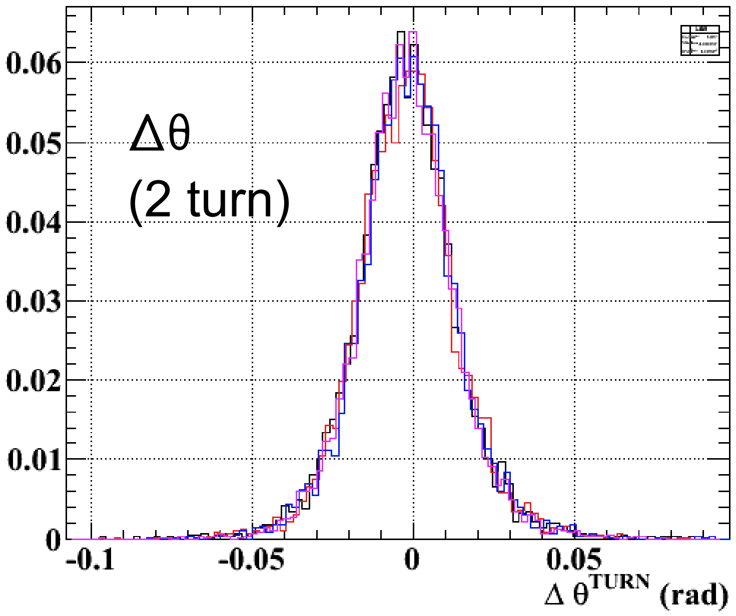
more bad planes and slightly worse noise situation

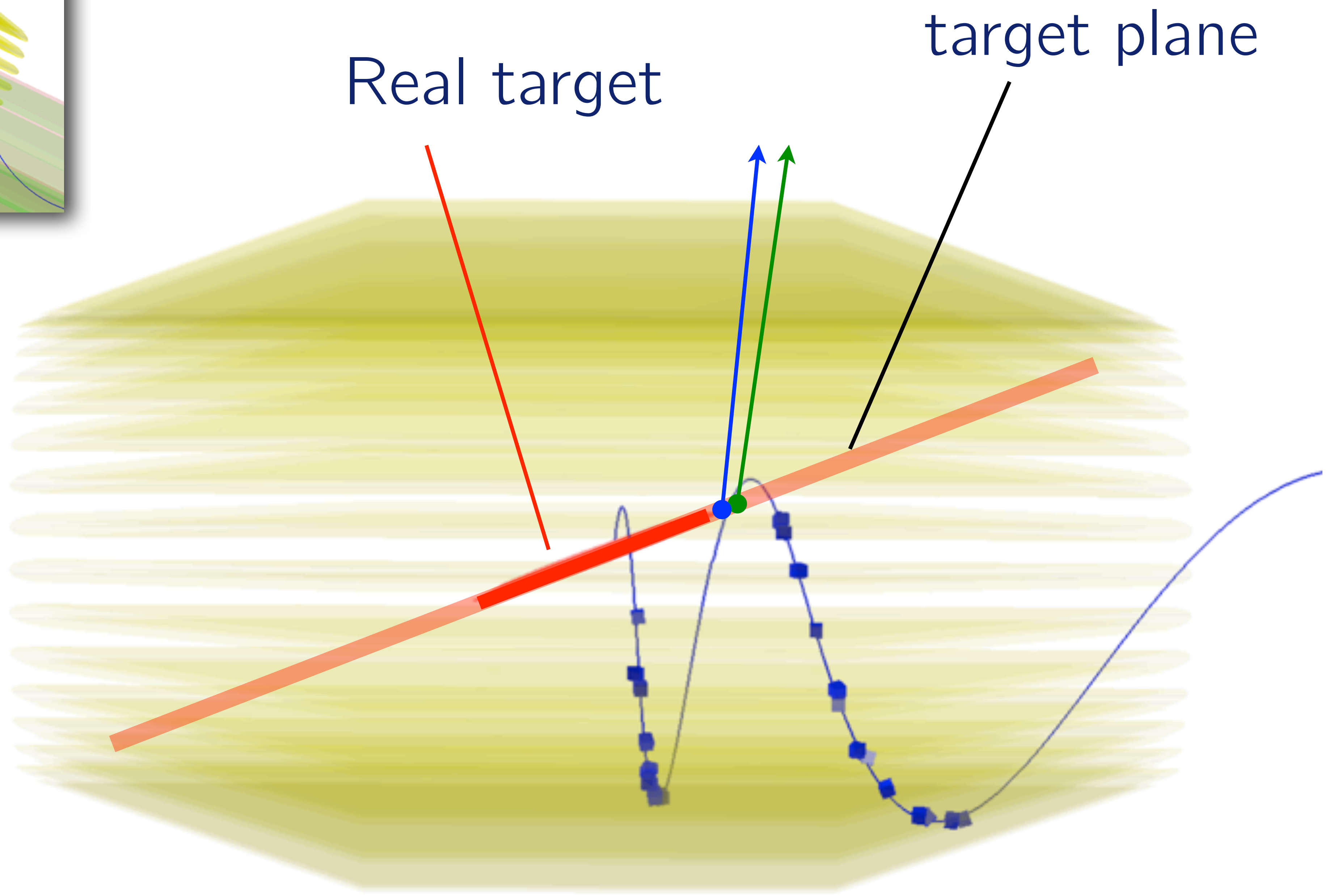
- Momentum resolution is extracted from a fit to Michel edge spectrum
- Detector response
  - triple gaussian + acceptance
  - 2009
    - σ_p = 310keV (80%) + 1.0MeV(13%) + 2.0MeV(7%)
  - 2010
    - σ_p = 330keV (79%) + 1.0MeV(14%) + 2.0MeV(7%)



two turn method







Positron spectrometer performance, cont.

Muon decay point, angular resolution : from tracks with two turns inside the drift chambers

2009

Vertex z/y

= 1.5/1.1mm

σ_θ = 9.4mrad

σ_φ = 6.7mrad (φ=0)

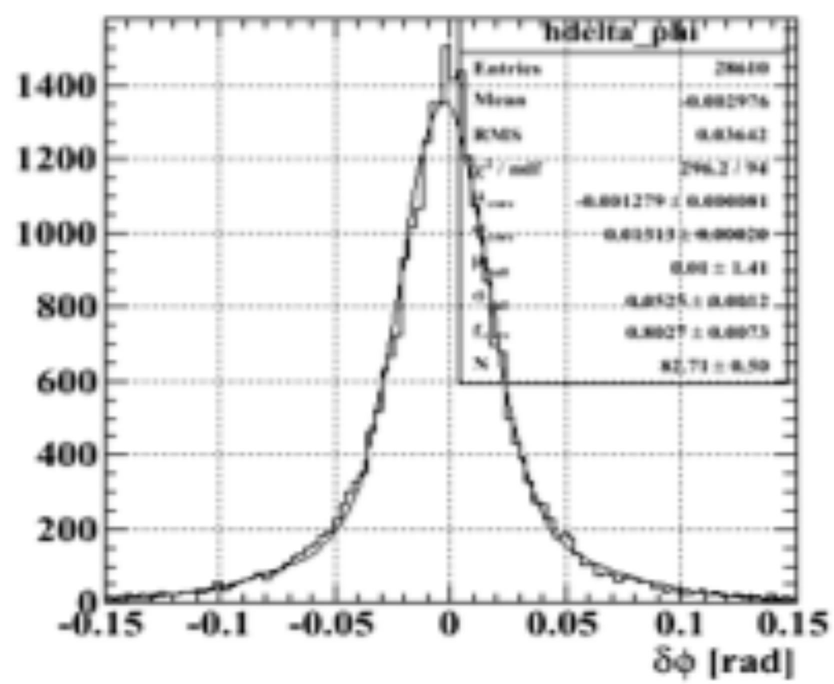
2010

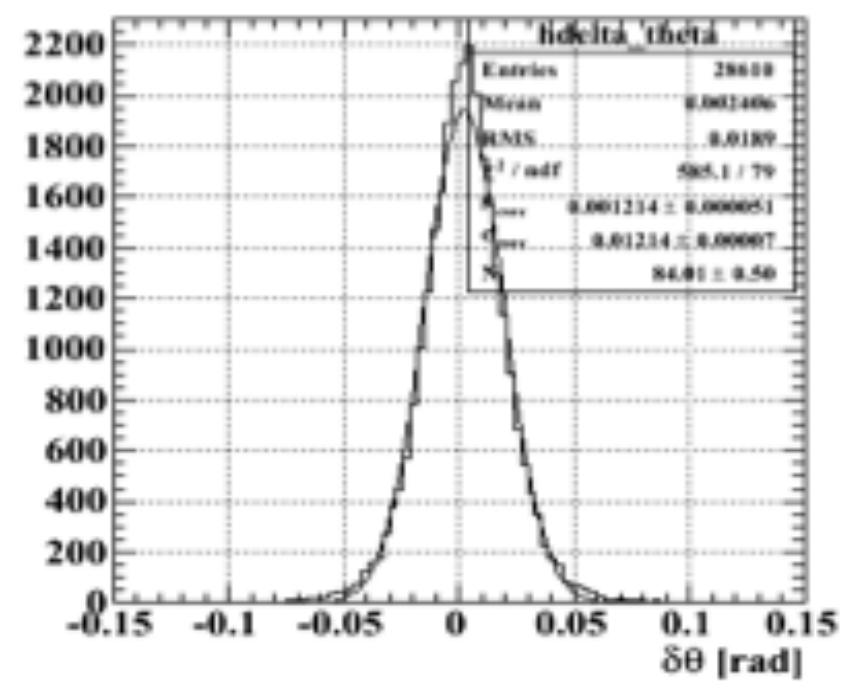
Vertex z/y

= 2.0/1.1mm

σ_θ = 11.0mrad

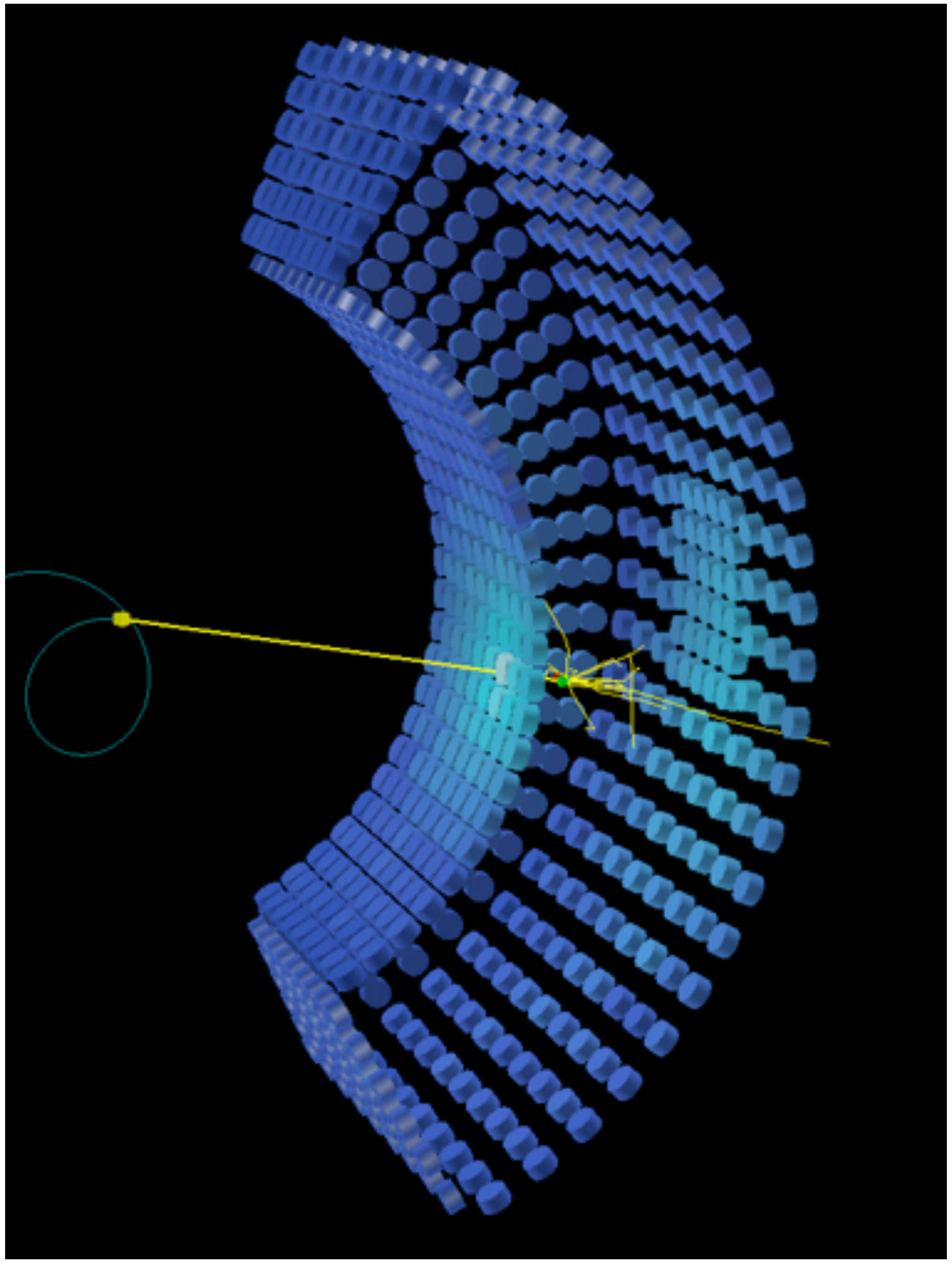
σ_φ = 7.2mrad (φ=0)





LXe calorimeter

2.7t Liquid xenon gamma-ray detector



- 900L liquid xenon
- 846 2" PMTs (Hamamatsu)
  - Submerged in Liquid
- γ energy, position, and timing reconstruction
- Merits
  - High light output(80% of NaI)
  - Fast timing response(45ns)
  - Heavy(3g/cm^3)
- Challenges
  - Low temperature(160K)
    - 200W pulse tube cryocooler
  - Short scintillation wavelength (178nm)
  - Gas/liquid purification

Reconstruction & Goal of gamma ray detector

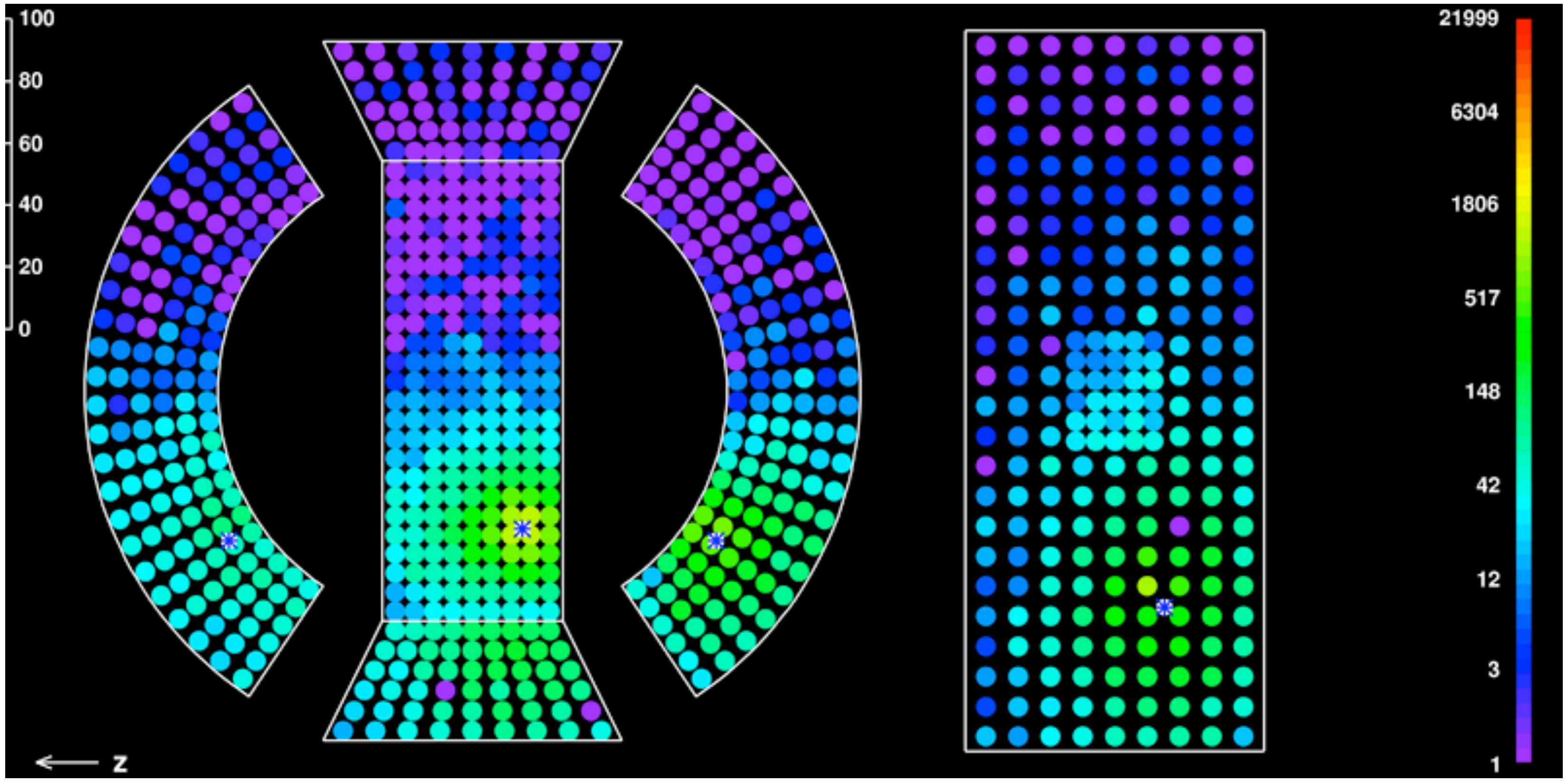
- Reconstruction
  - Energy: weighted sum of all PMTs
  - Position: peak fitting of light distribution
  - Time: fitting time of PMTs
- Pileup detection
  - Light distribution
  - Time distribution of PMTs

Goal

Energy resolution: 1.2-1.5%

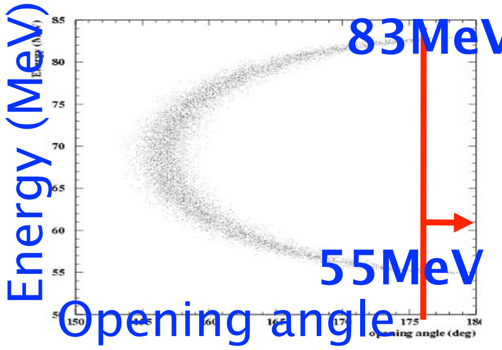
Interaction point (Opening angle): 2-4mm

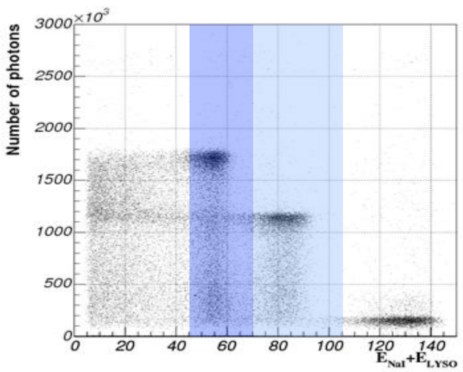
Time resolution: 65ps

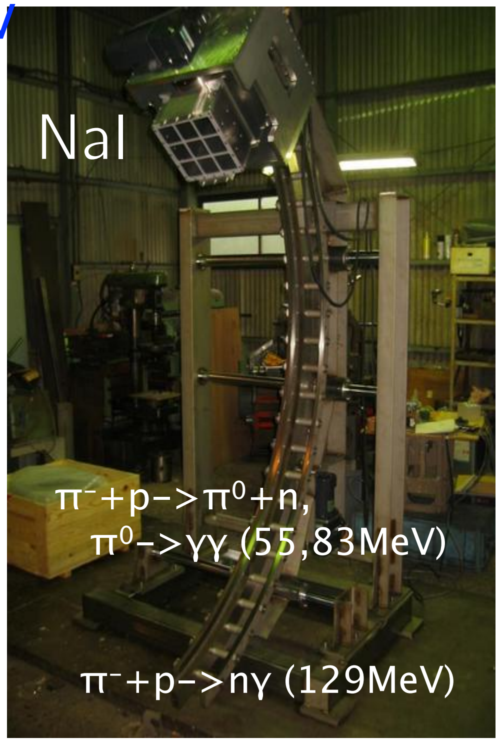


Calibration methods

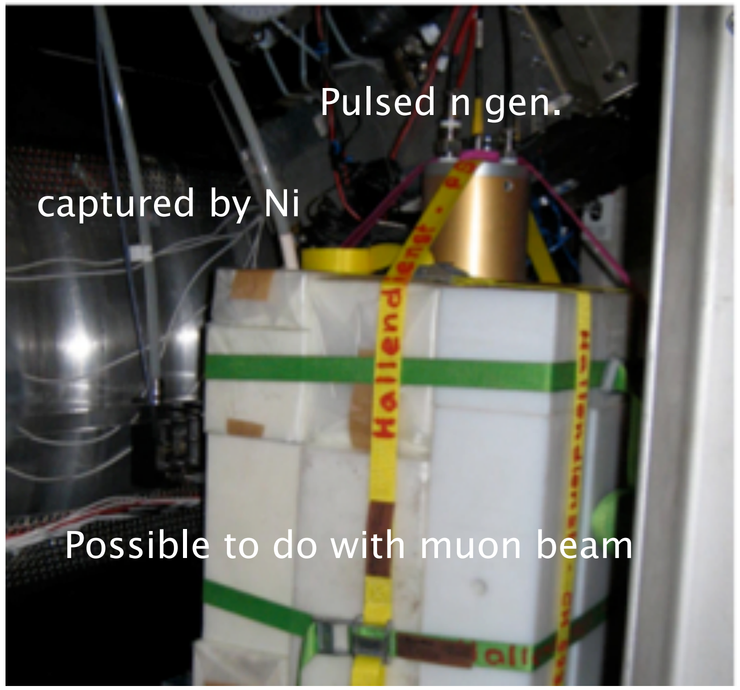
55MeV γ (CEX)



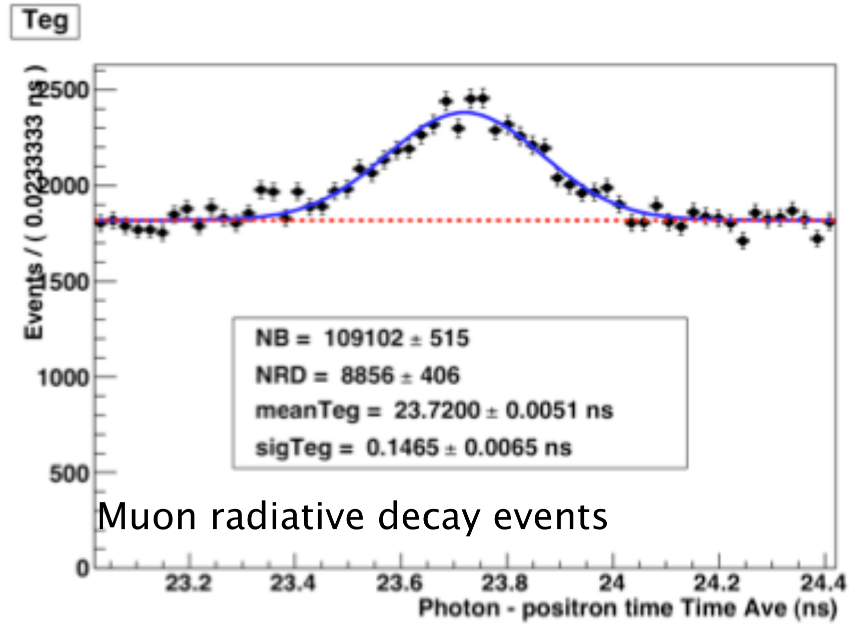




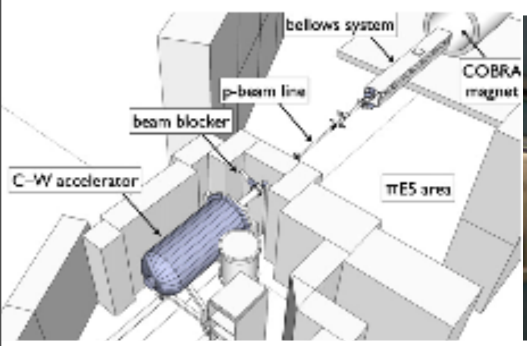
9MeV γ

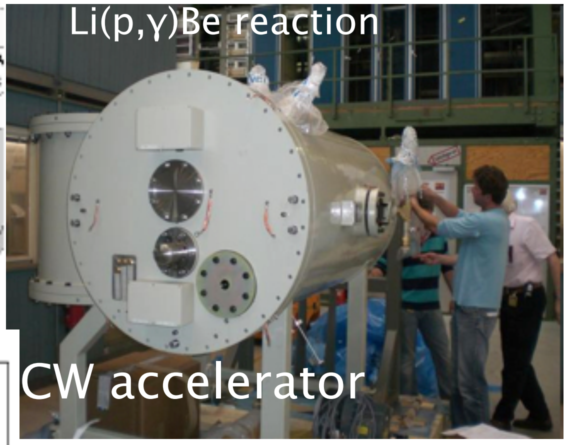


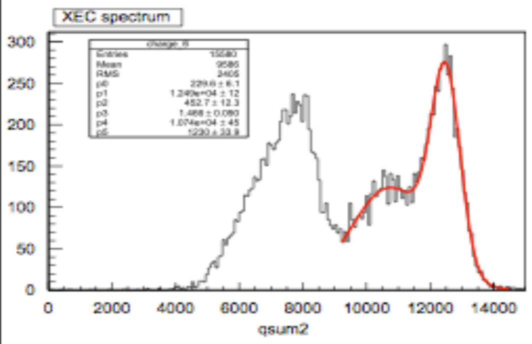
Timing resolution



17.6MeV γ







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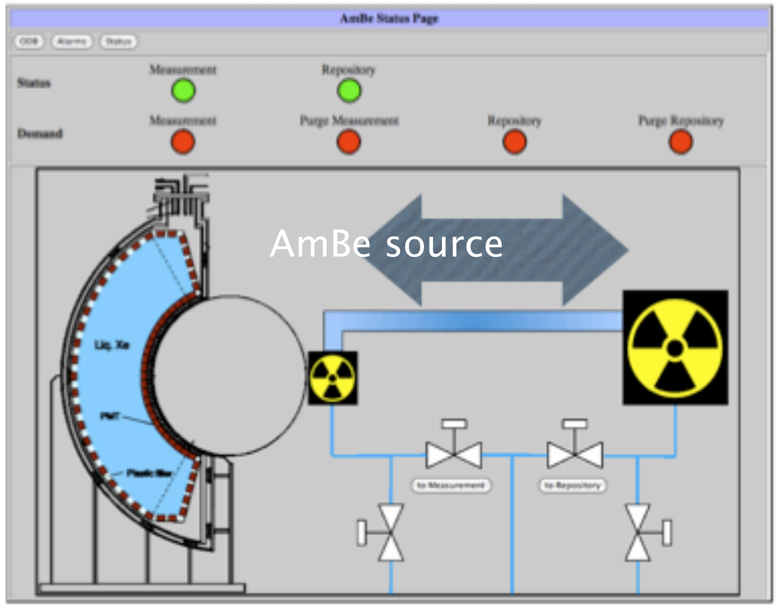
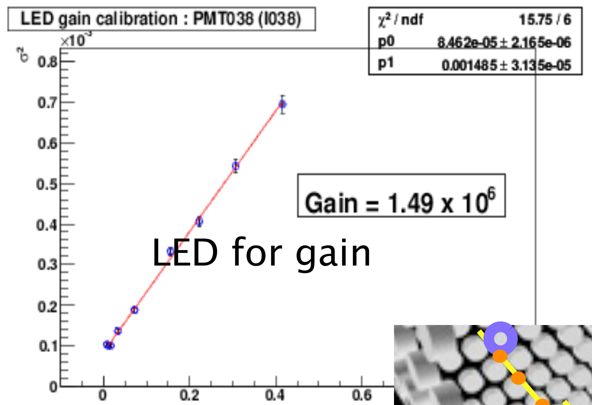
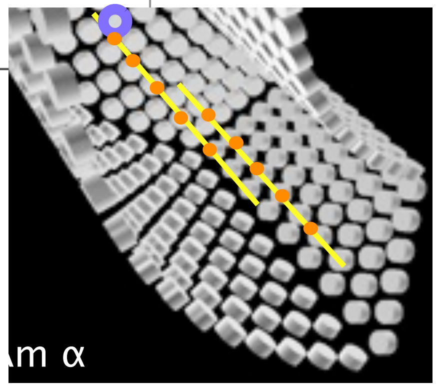
NIMA641(2011)19-32

4.4MeV γ



PMT calibration

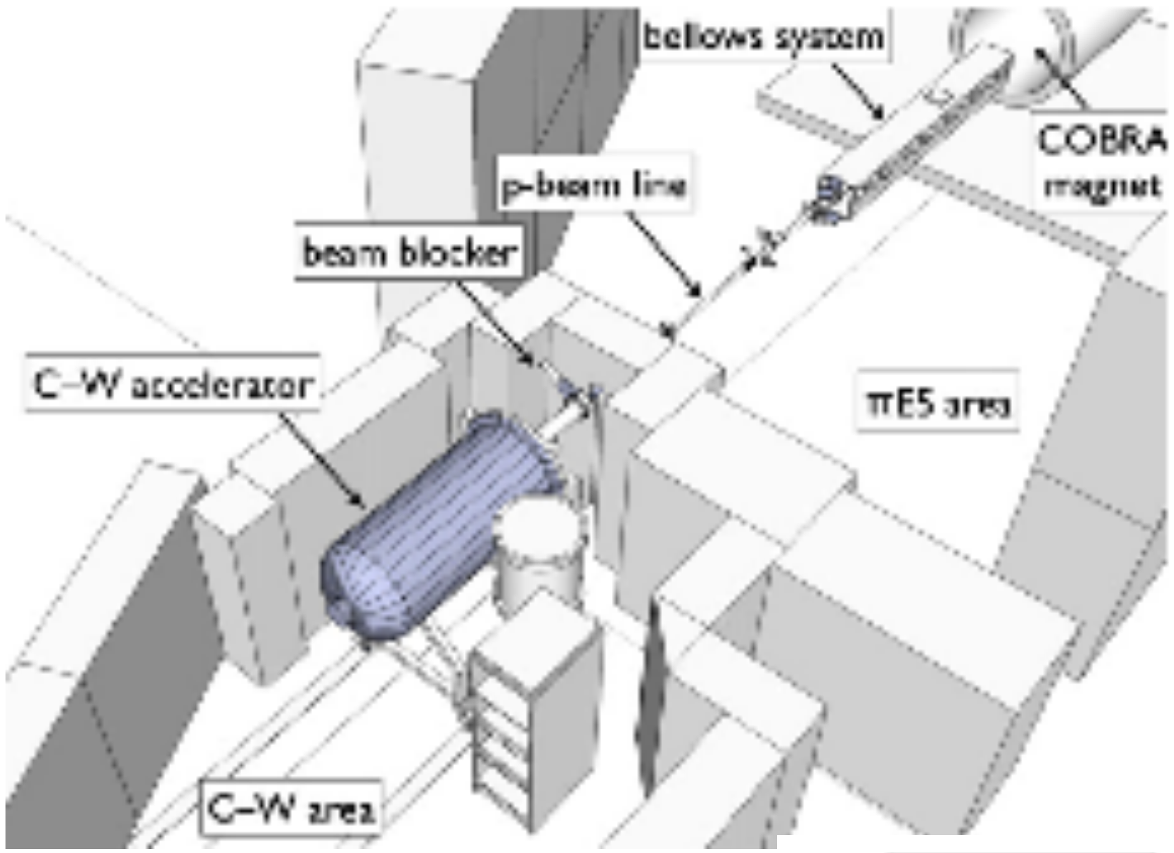




Calibration methods

- 17.6MeV γ

Li(p,γ)Be reaction



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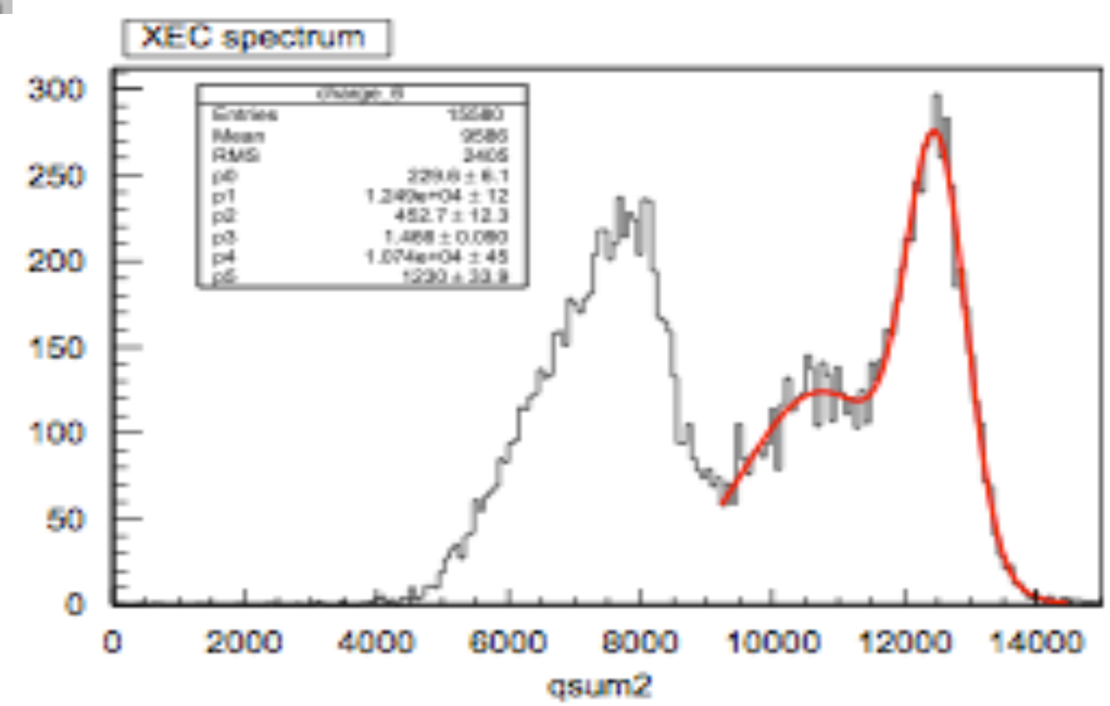
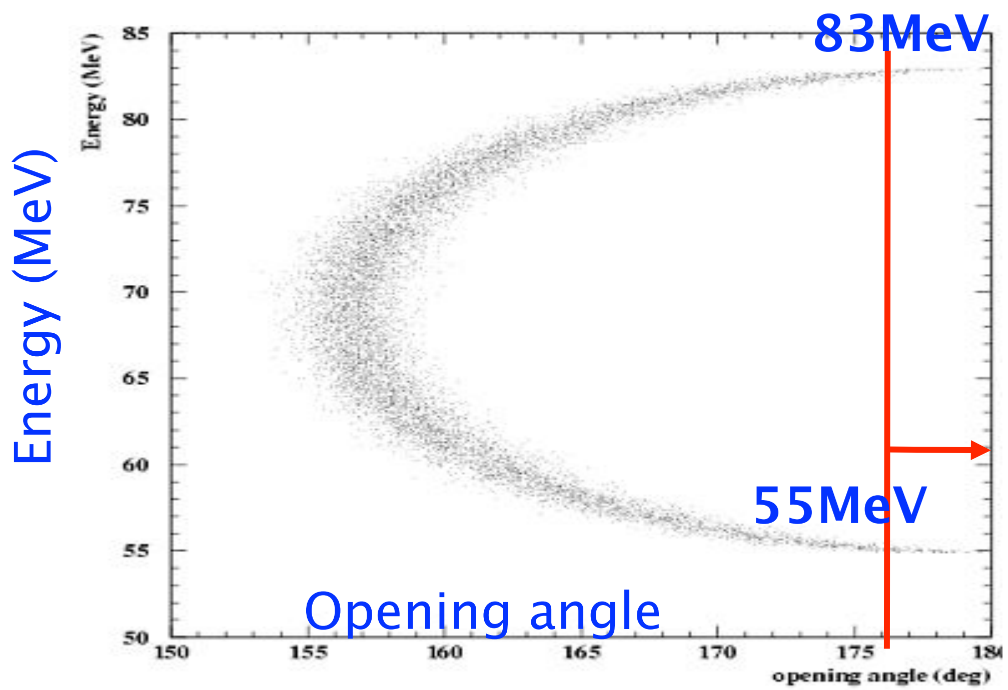
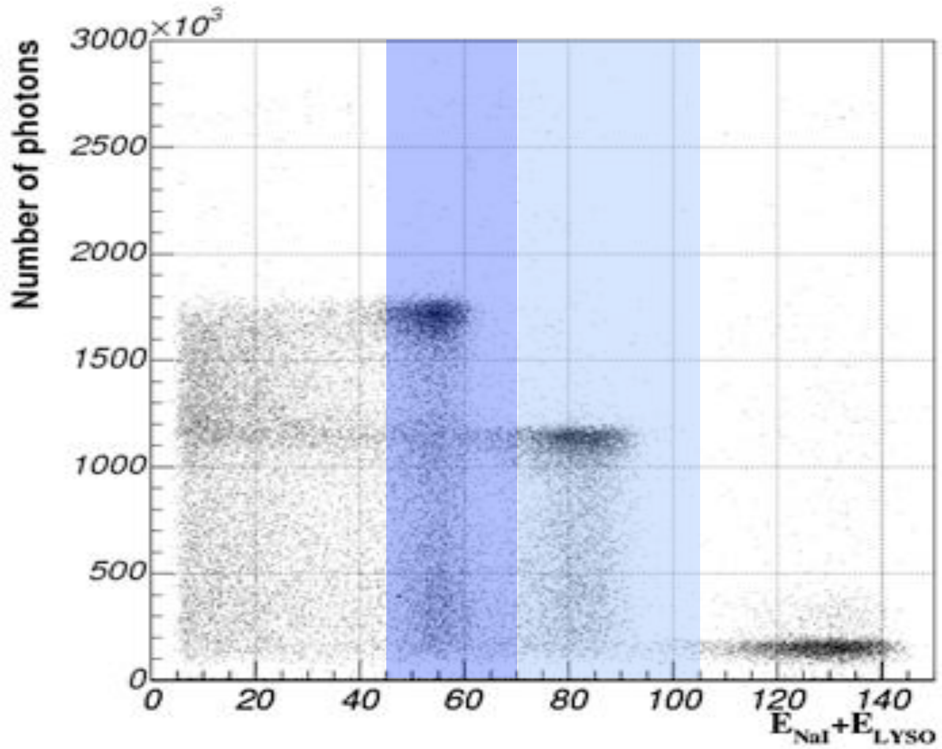


Calibration methods

- 55MeV γ (CEX)

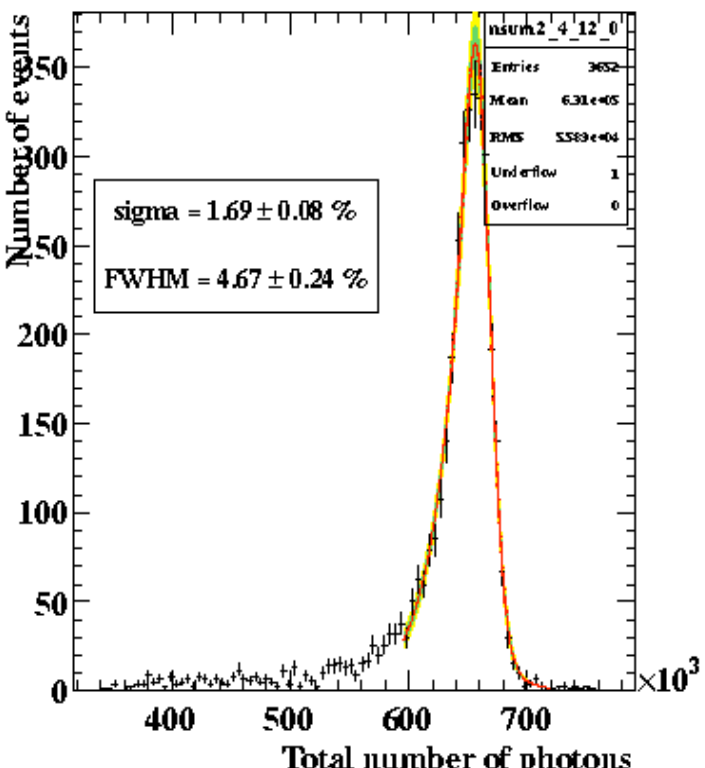
$\pi^- + p \rightarrow \pi^0 + n$,
$\pi^0 \rightarrow \gamma\gamma$ (55,83MeV)

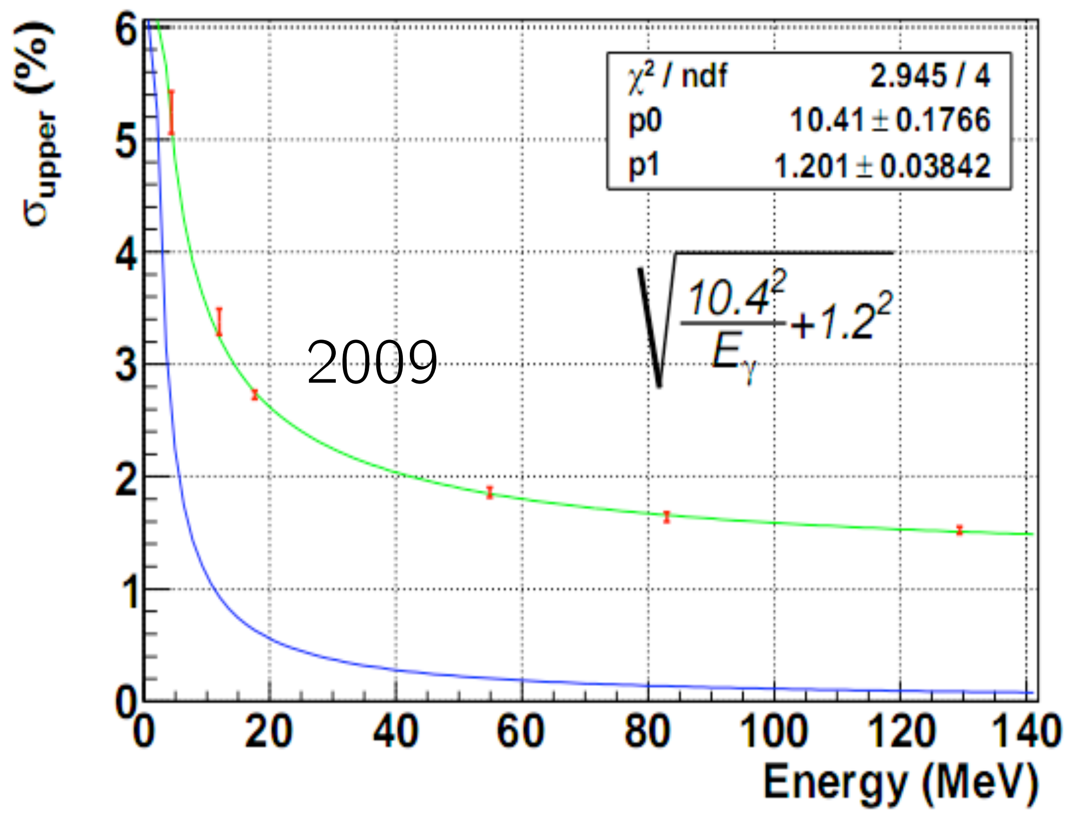


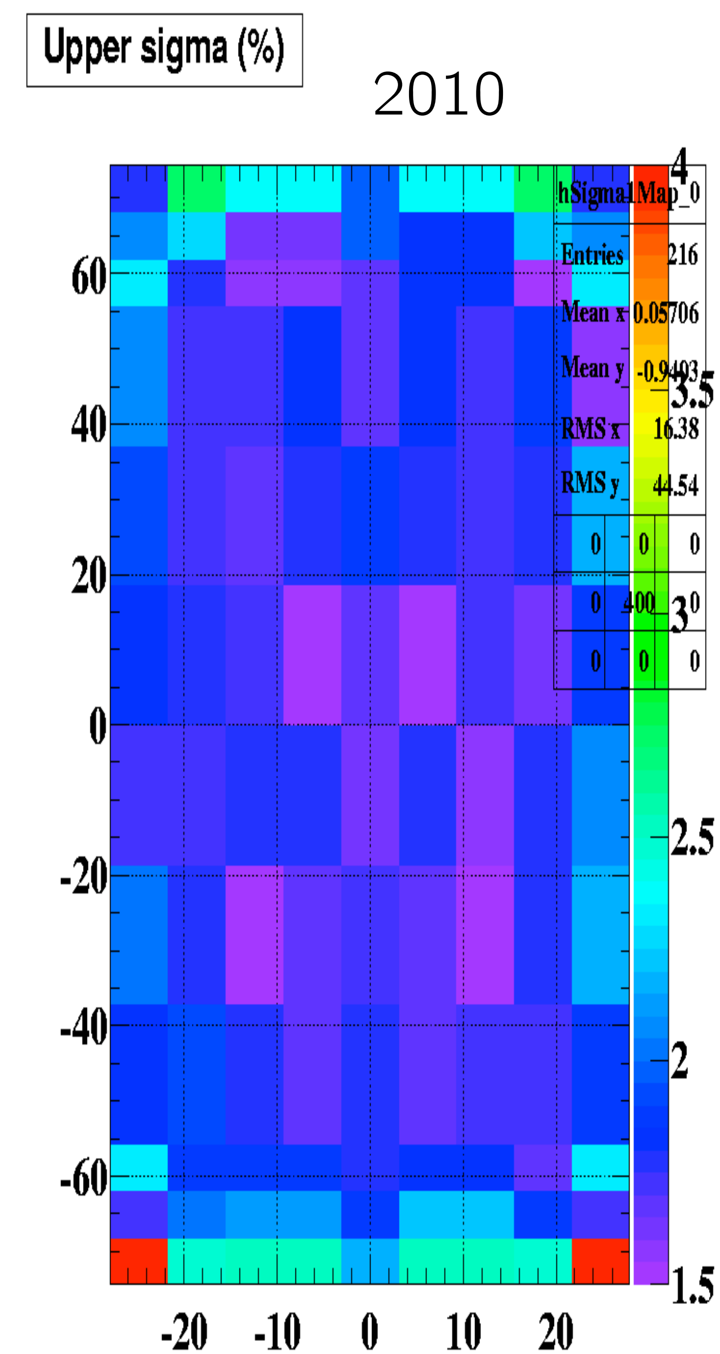


Energy resolution

- Energy resolution is evaluated with 55MeV γ in CEX data
  - $\pi^- + p \to \pi^0 + n,\ \pi^0 \to \gamma\gamma$
- Resolution map on incident position is measured by moving NaI detector

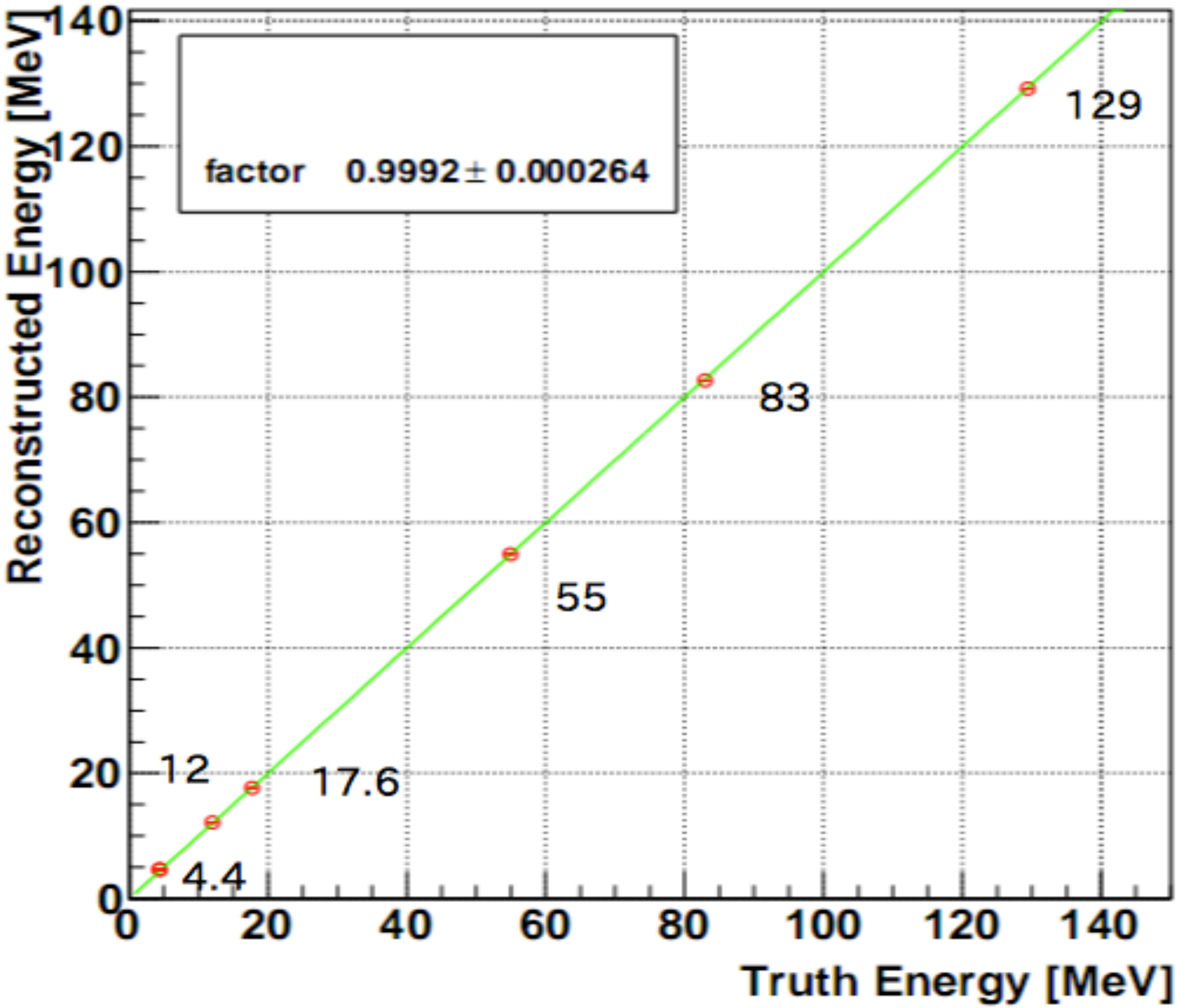






- Result of resolution in 2010
  - 1.9% (depth>2cm), 2.4% (depth<2cm)

Linearity



factor 0.9992 ± 0.000264
129
83
55
17.6
12
4.4
Reconstructed Energy [MeV]
Truth Energy [MeV]
0
20
40
60
80
100
120
140

Energy response

Non-uniformity due to

Geometry

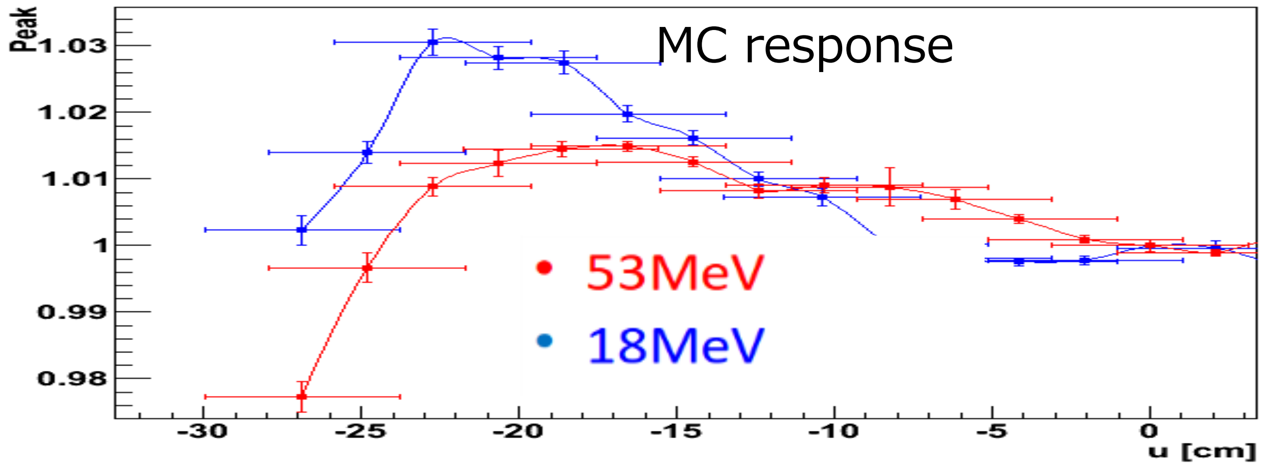
Reconstruction algorithm

Correction using

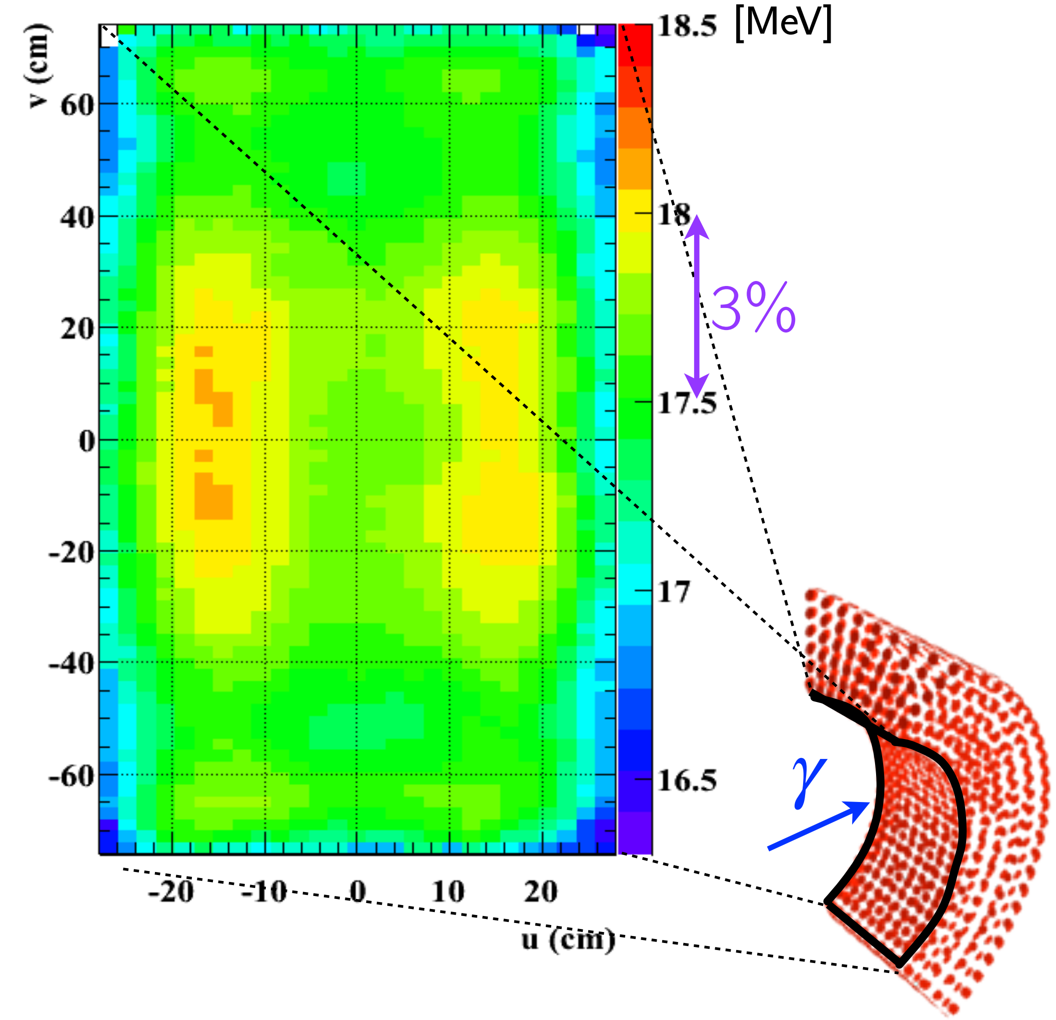
- 18 MeV calibration gamma (High stat)
- Additionally, 55 MeV calibration gamma

Energy dependence correction

After correction : **~0.2 % uniform**



18 MeV data, uniformity before correction



Energy stability

Energy absolute scale calibration

CEX 55, 83 MeV γ

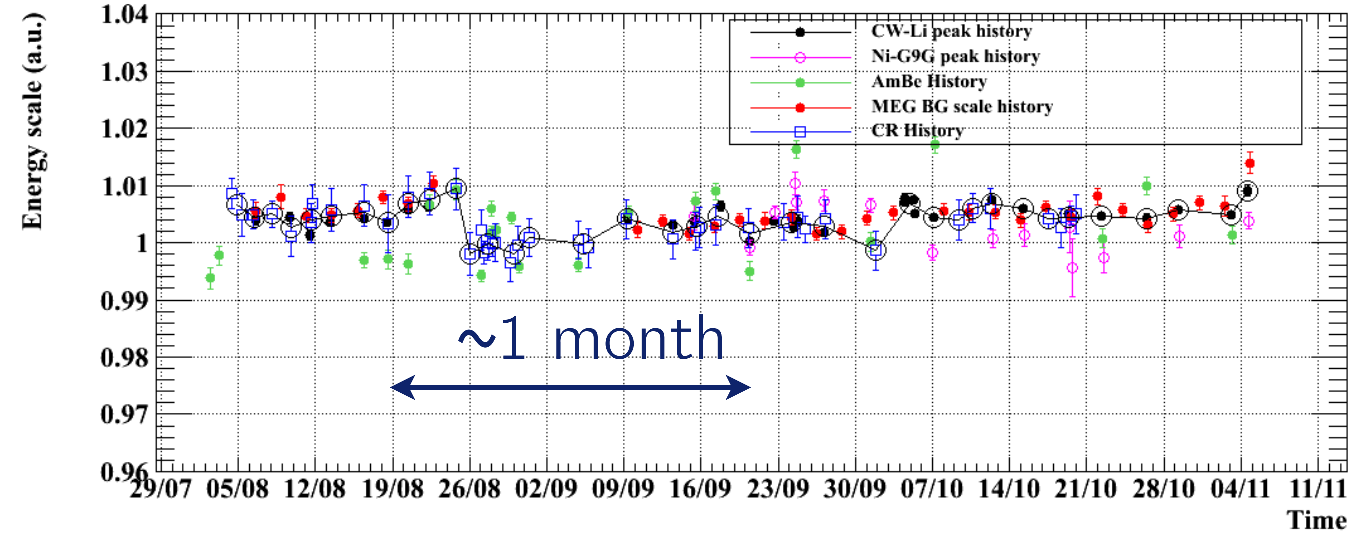
Energy scale time-variation calibration

CW 18 MeV γ

Ni-n 9 MeV γ

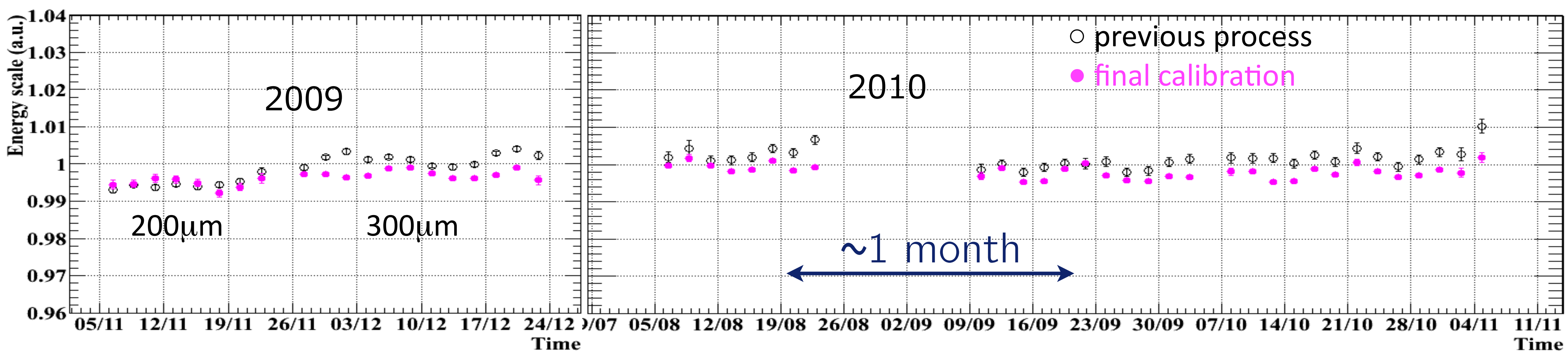
AmBe 4.4 MeV γ

CR peak



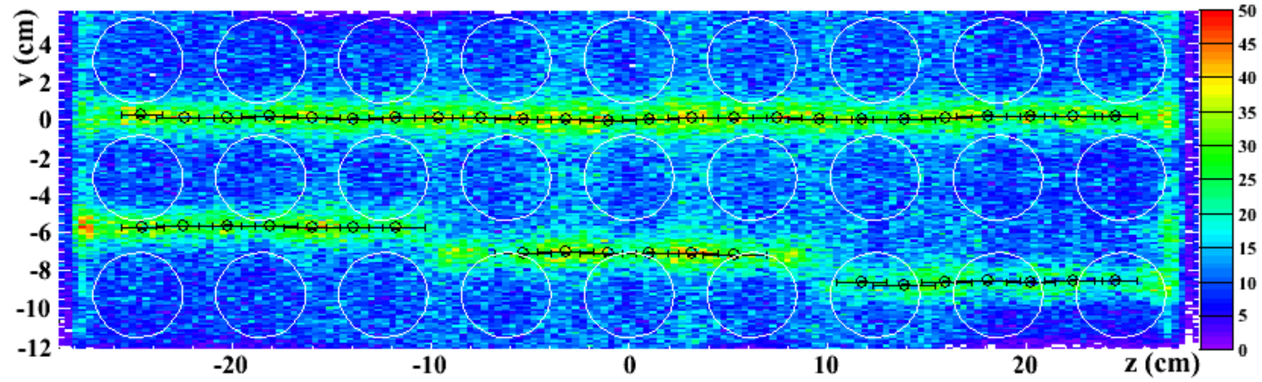
Check

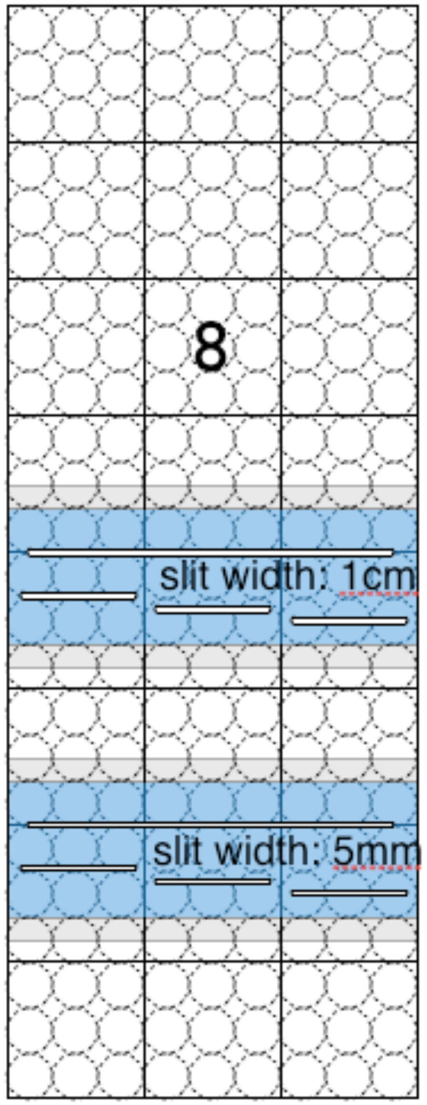
Fitting RMD γ

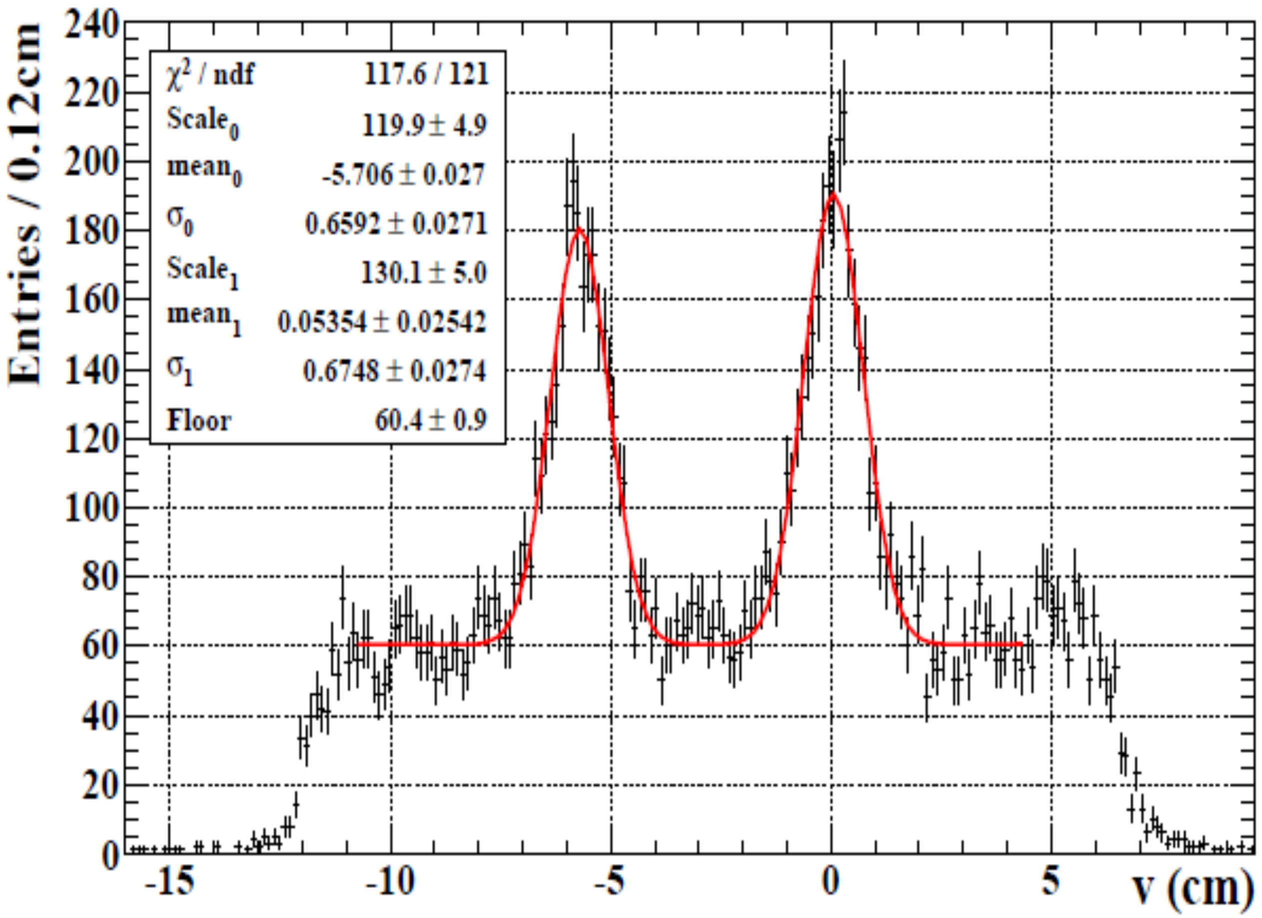


Position resolution

- Position resolution is evaluated CEX data with lead collimator



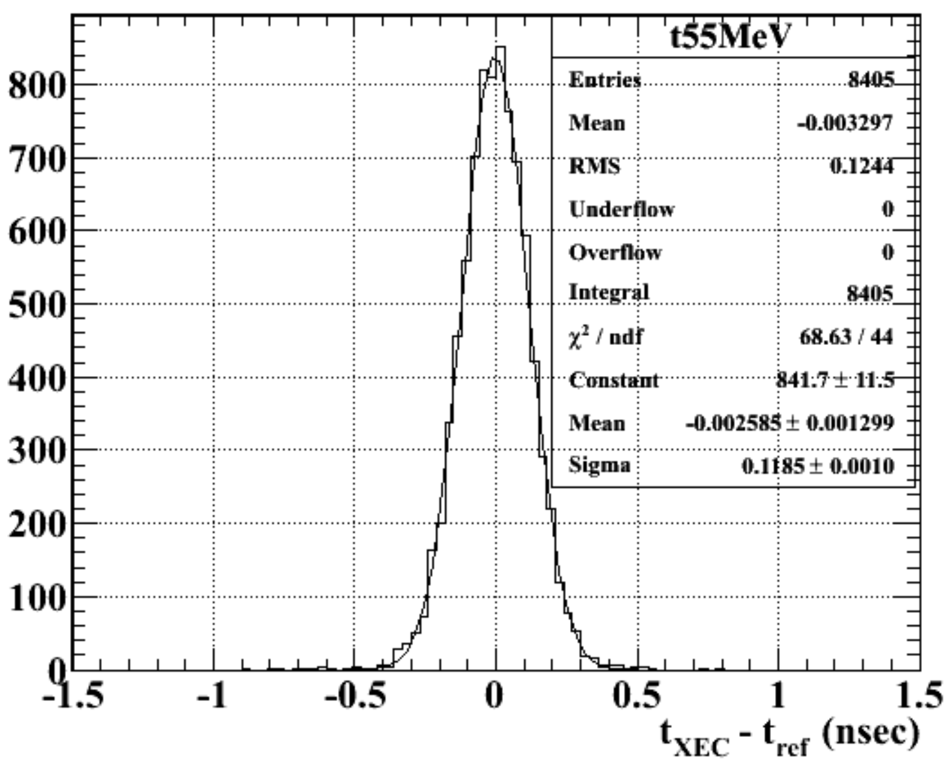


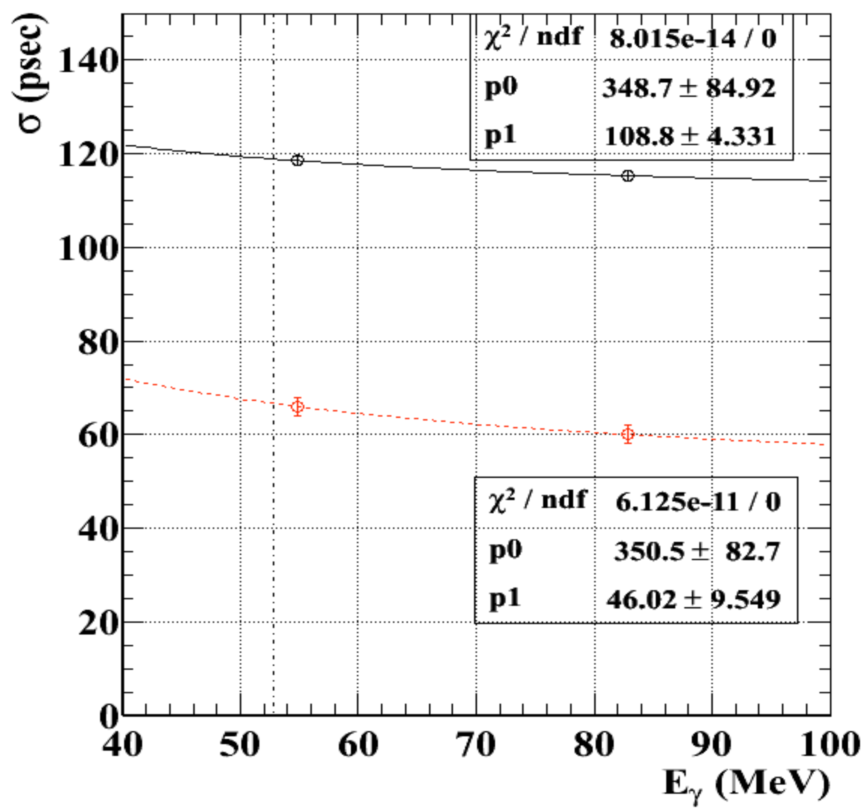


- Resolution in 2009
  - XY direction: 5mm
  - Depth: 6mm
  - MC expectation: 4.5mm (due to insufficient Q.E. Estimation?)

Timing resolution

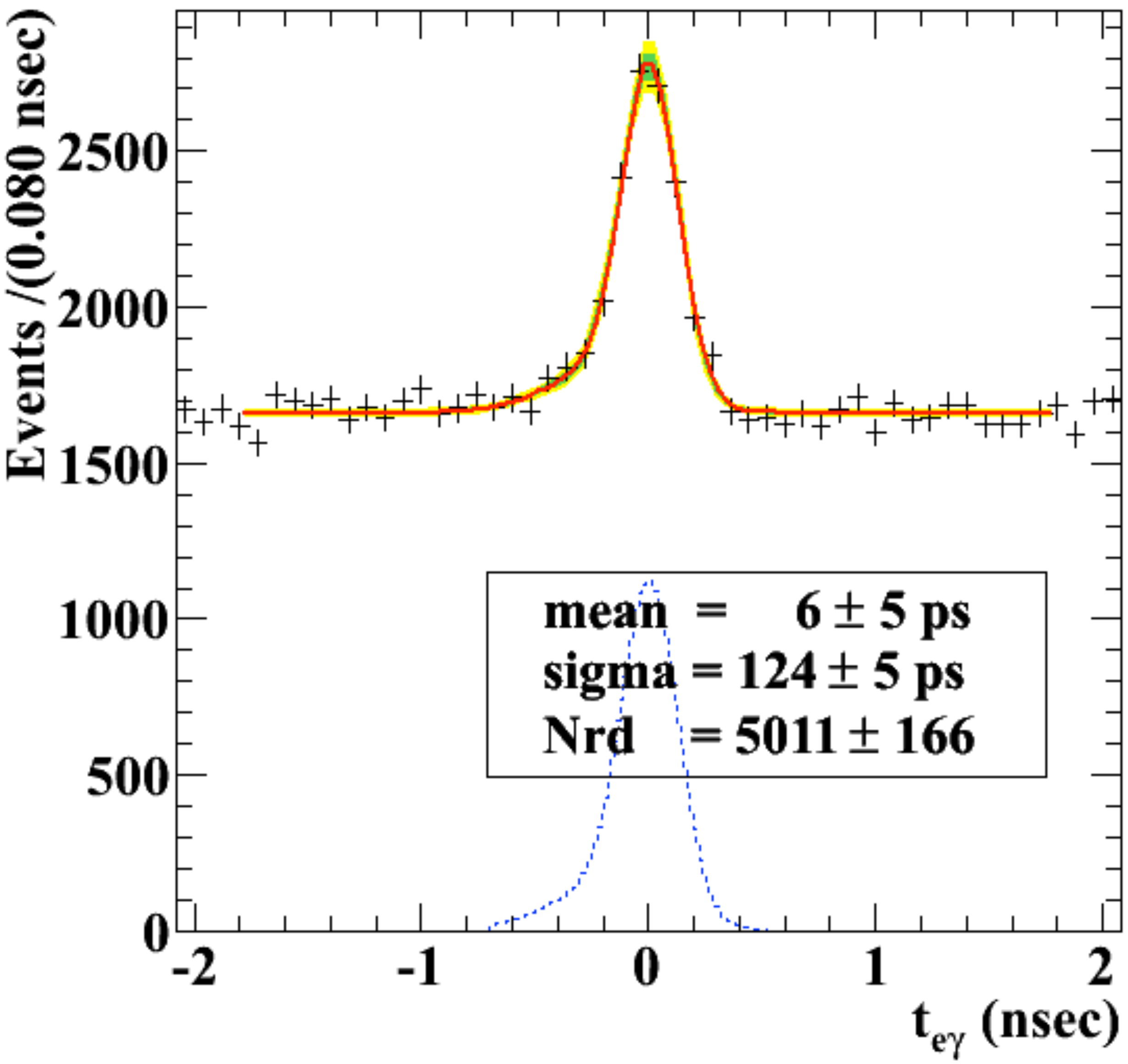
- Time difference between XEC and reference





- Result
  - 119ps at 55MeV (171ps in 2009, thanks to electronics improvement)
  - XEC resolution : ~67ps
    - 119ps – beam spread(58ps) – resolution of reference counter(81ps)
    - Breakdown
      - XEC intrinsic(36ps), ToF(20ps), DRS(24ps), and 46ps
    - Further improvement only possible by new detectors
      - higher Q.E. PMT etc.

Positron – photon timing



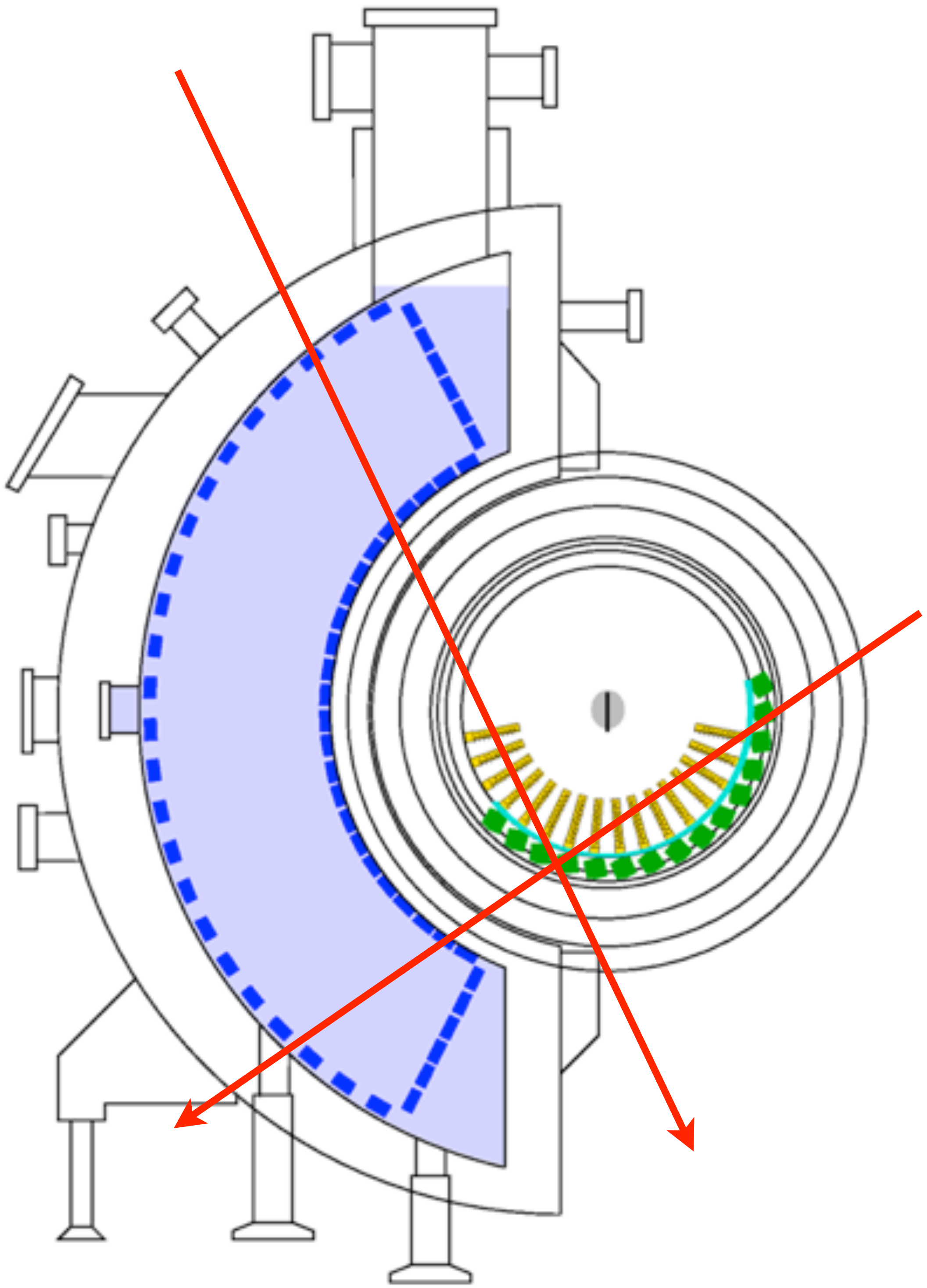
- Radiative muon decay peak
  - In a normal physics run
  - Corrected by small energy dependence
- Timing resolution of $T_{e\gamma}$
  - 122ps in 2010
  - Breakdown
    - Photon T_{γ} : 67 ps
    - T_{e} : 107 ps
      - T_{TC} : 65 ps (measured by double TC Michel events)
      - Le/c : 75 ps (MC scaled, x1.5)
      - TC calib: 40 ps

Alignment between detectors

- Positron spectrometer
  - Optical survey
- Photon detector
  - PMT position scan using AmBe source
  - Calibration 18 MeV gamma, with lead collimators

Cosmic rays passing both systems

~1mm agreement



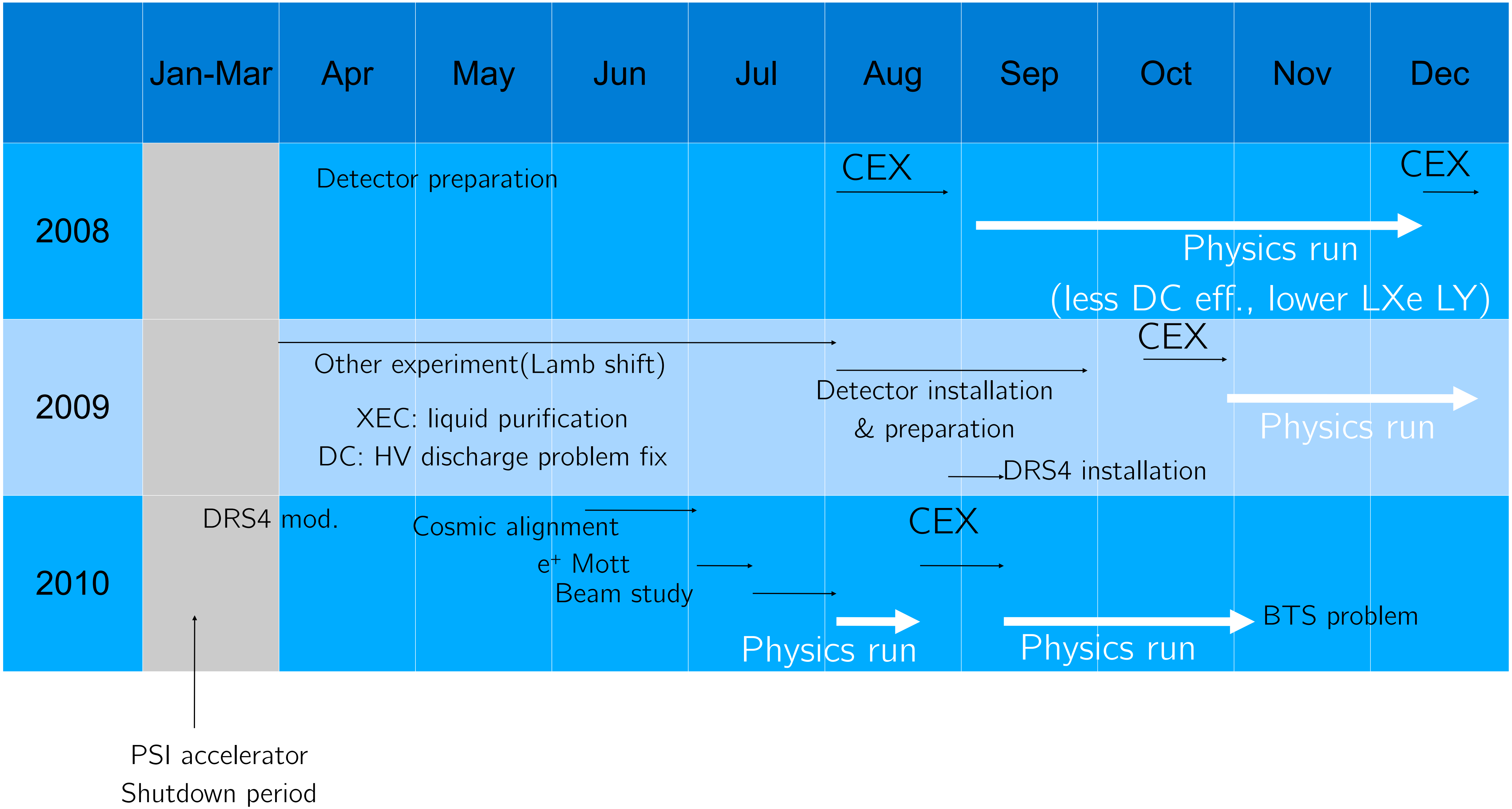
Performance summary

	2009	2010
Gamma energy (w>2cm)	1.9 %	1.9 %
Gamma timing	96 ps	67 ps
Gamma position	5(xy)/6(depth) mm	5(xy)/6(depth) mm
Gamma efficiency	58 %	59 %
e^+ momentum	310keV (80% core)	330keV (79% core)
e^+ φ (φ=0)	6.7 mrad	7.2 mrad
e^+ θ	9.4 mrad	11.0 mrad
e^+ vertex Z/Y	1.5/1.1 mm (core)	2.0/1.1 mm (core)
e^+ timing	107 ps	107 ps
e^+ efficiency	40 %	34 %
$T_{e\gamma}$	146 ps	122 ps
Trigger efficiency	91	92
Stopping Muon Rate	2.9×10^7 / sec	2.9×10^7 / sec
DAQ time/real time	35/43 days	56/67 days
Expected 90% C.L. Upper Limit	3.3×10^{-12}	2.2×10^{-12}

2009+2010 Combined

Expected 90% C.L. Upper Limit : 1.6×10^{-12}

MEG experiment 2008–2010



Analysis

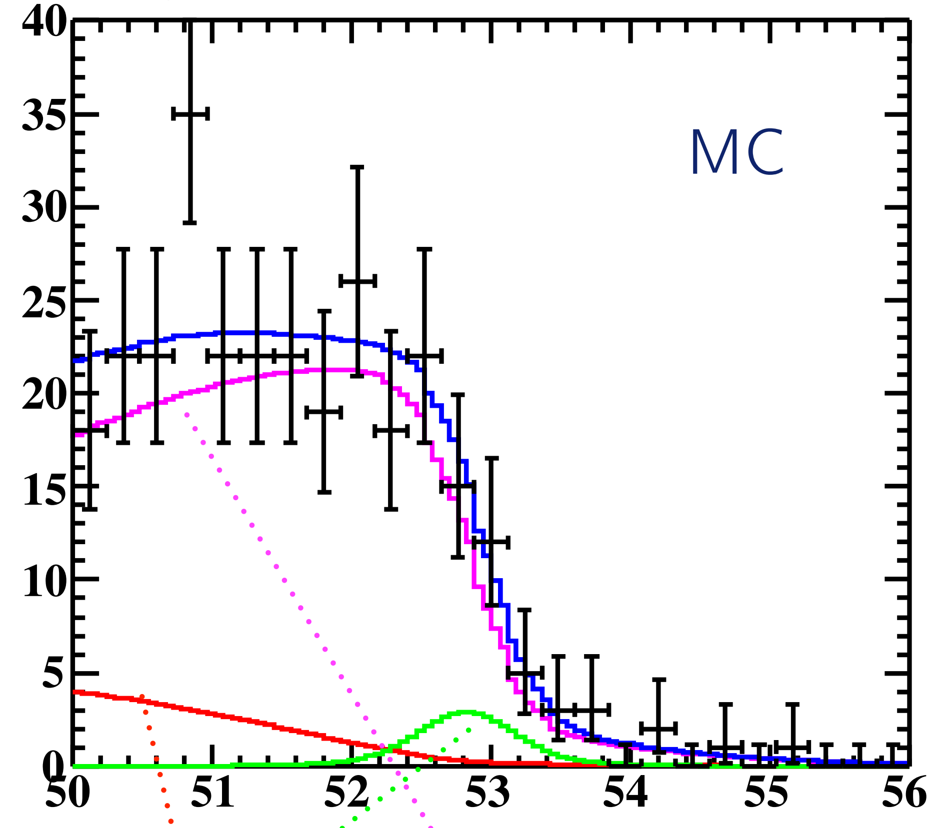
Run2009 + Run2010

Analysis method

Likelihood fitting with 5 observables

$$\vec{x} = \begin{cases} E_\gamma & : \text{Gamma energy} \\ E_e & : \text{Positron energy} \\ t_{e\gamma} & : \text{Time difference} \\ \vartheta_{e\gamma} & : \vartheta \text{ angle difference} \\ \varphi_{e\gamma} & : \varphi \text{ angle difference} \end{cases}$$

Projection to E_e



Unbinned likelihood fitting

I will explain later...

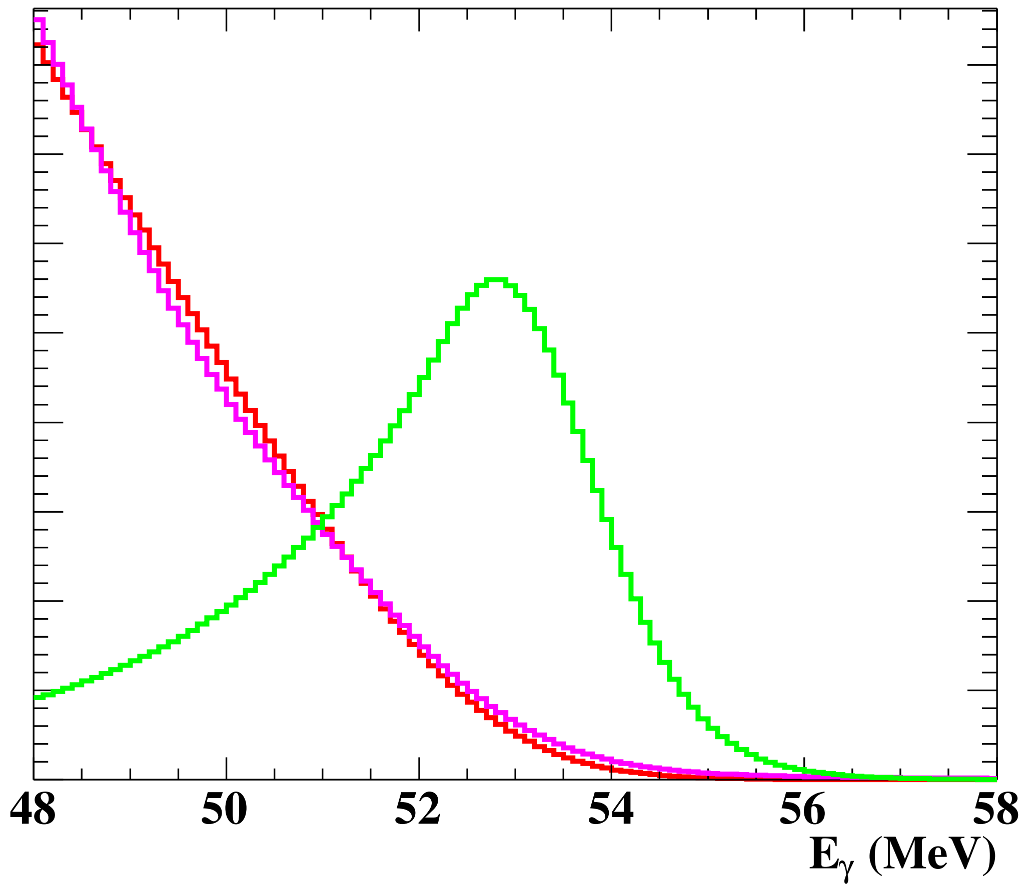
$$\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}) = f(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}) \times \prod_{i=1}^{N_{\rm obs}} \left(N_{\rm sig} S(\vec{x}_i) + N_{\rm RMD} R(\vec{x}_i) + N_{\rm BG} B(\vec{x}_i)\right)$$

BG : Accidental
RMD : Radiative muon decay

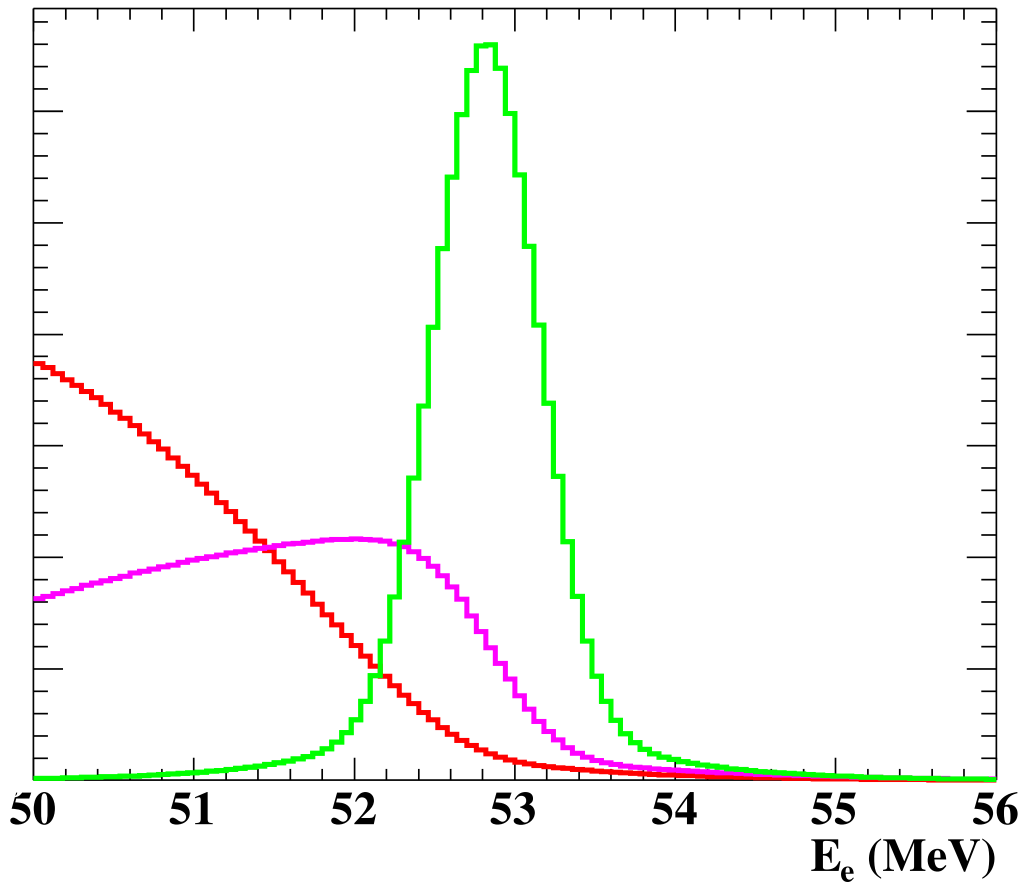
Probability density functions (PDF)

Signal RMD BG

E_γ



E_e



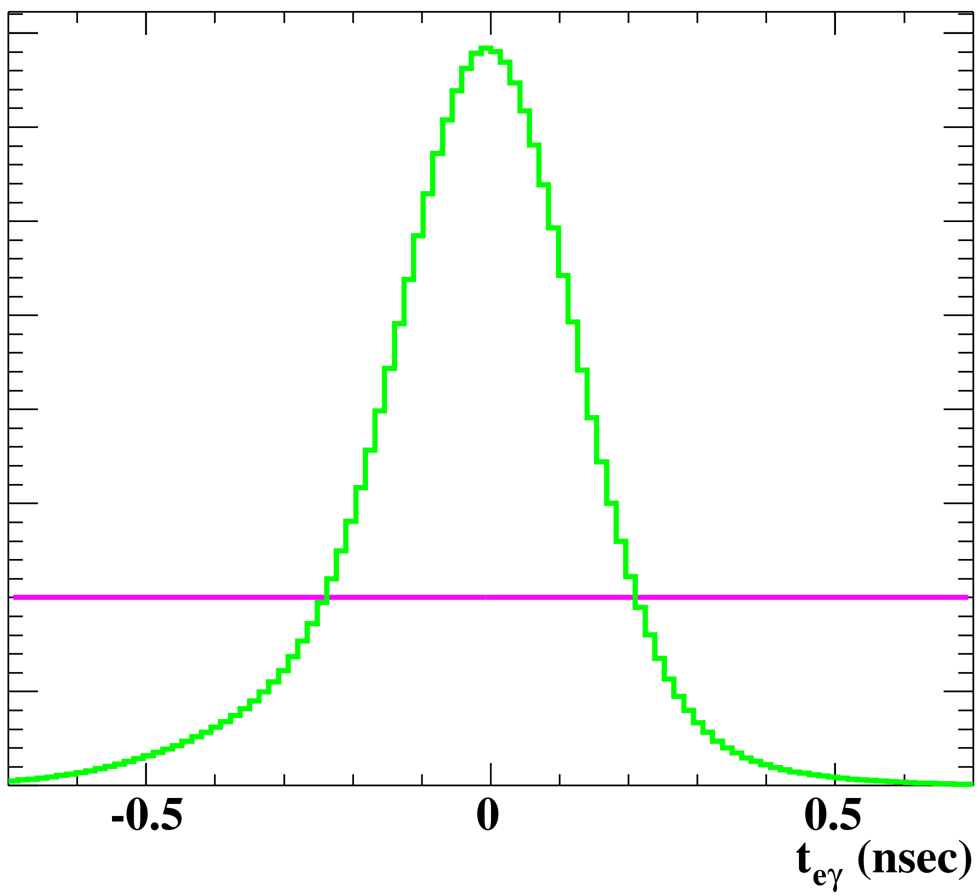
Signal : CEX data
BG : Sideband data
RMD : SM + detector response

Signal : Michel e^+ edge fitting
BG : Sideband data
RMD : SM + detector response

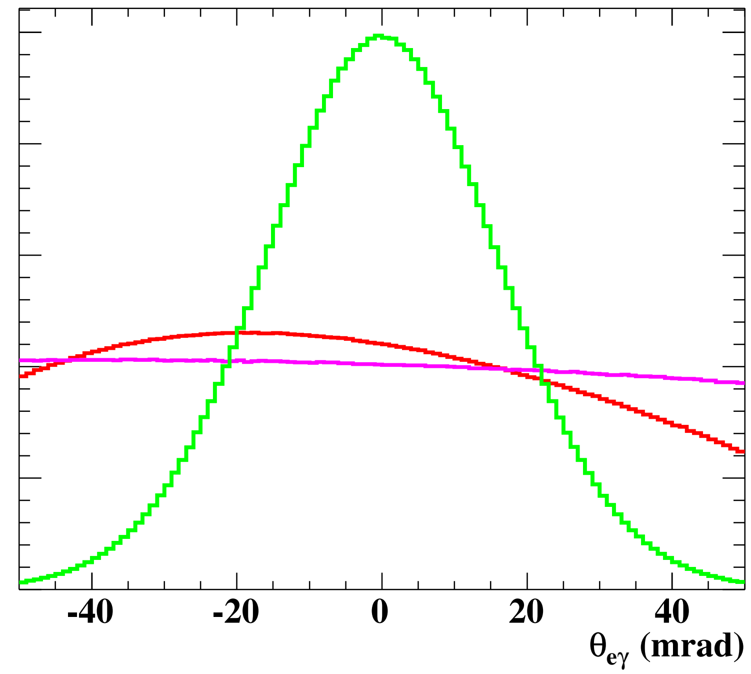
Probability density functions (PDF)

Signal RMD BG

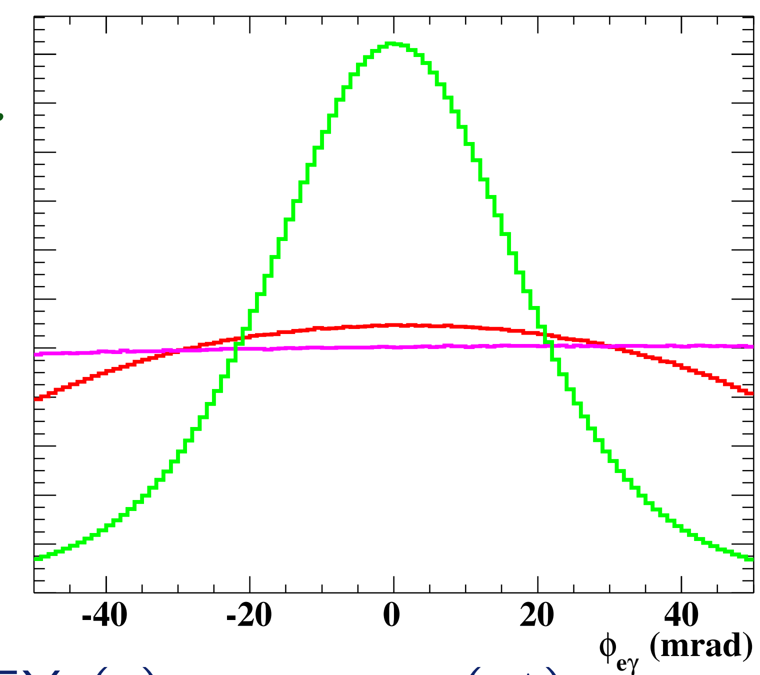
$t_{e\gamma}$



$\vartheta_{e\gamma}$



$\varphi_{e\gamma}$



Signal : RMD data
BG : Flat
RMD : SM + detector response

Signal : MC+CEX (γ), two turn (e^+)
BG : Sideband data
RMD : SM + detector response

Likelihood and test-statistic

$$\mathcal{L}\left(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}\right) = \frac{e^{-N}}{N_{\rm obs}!} e^{-\frac{\left(N_{\rm RMD}-\langle N_{\rm RMD}\rangle\right)^2}{2\sigma_{\rm RMD}^2}} e^{-\frac{\left(N_{\rm BG}-\langle N_{\rm BG}\rangle\right)^2}{2\sigma_{\rm BG}^2}} \times \prod_{i=1}^{N_{\rm obs}} \left(N_{\rm sig} S\left(\overrightarrow{x_i}\right) + N_{\rm RMD} R\left(\overrightarrow{x_i}\right) + N_{\rm BG} B\left(\overrightarrow{x_i}\right)\right)$$

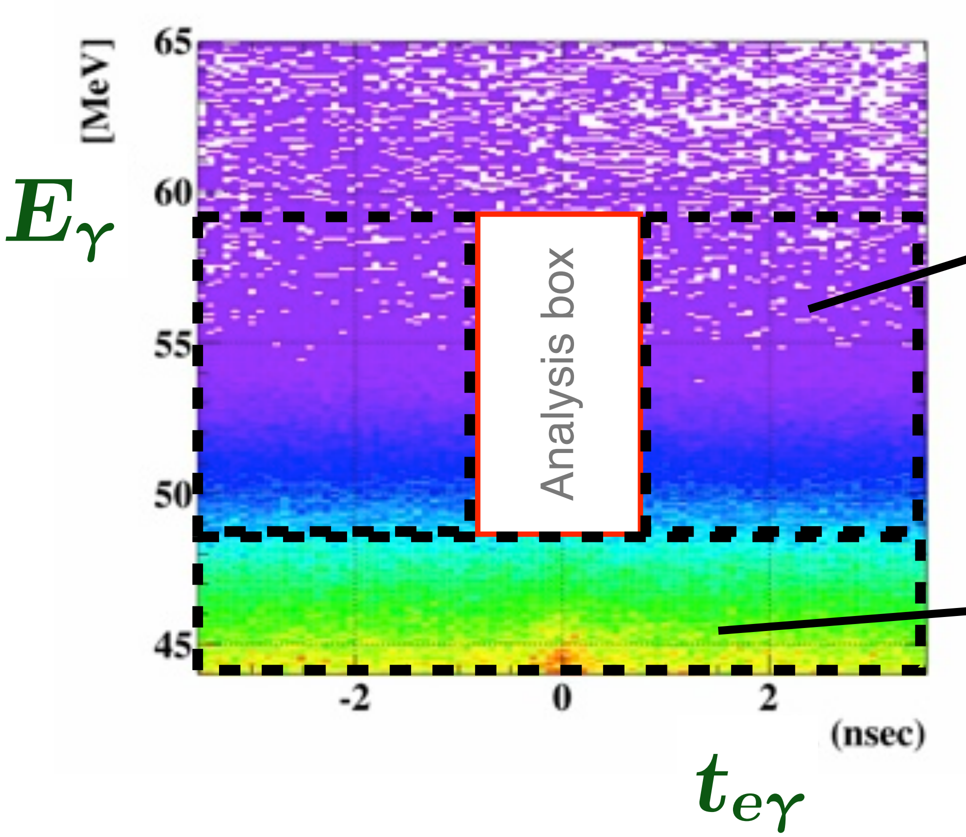
Two Gaussian constrain $N_{\rm RMD}$ and $N_{\rm BG}$

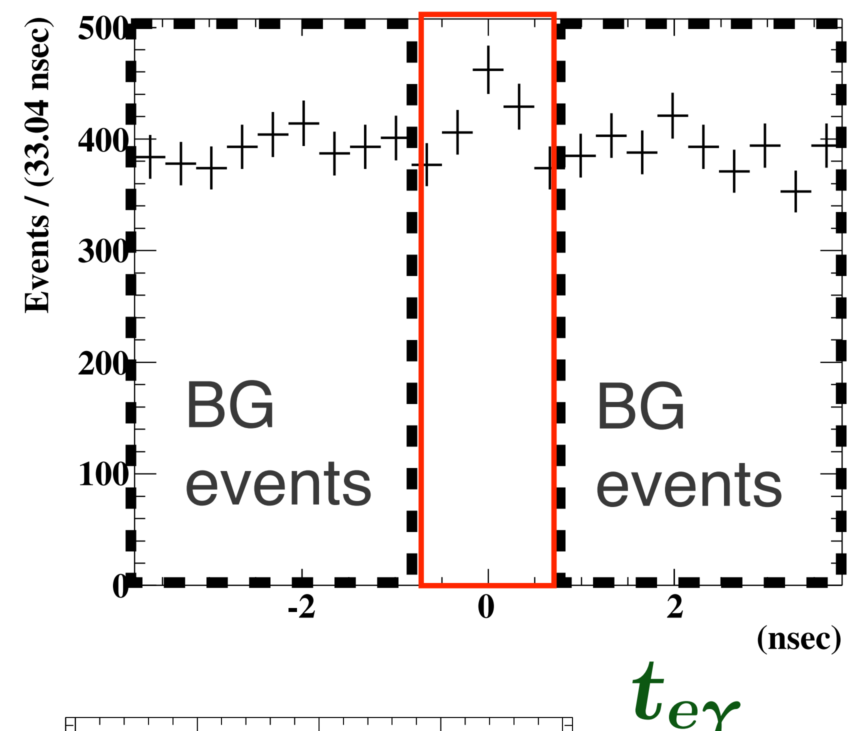
Likelihood and test-statistic

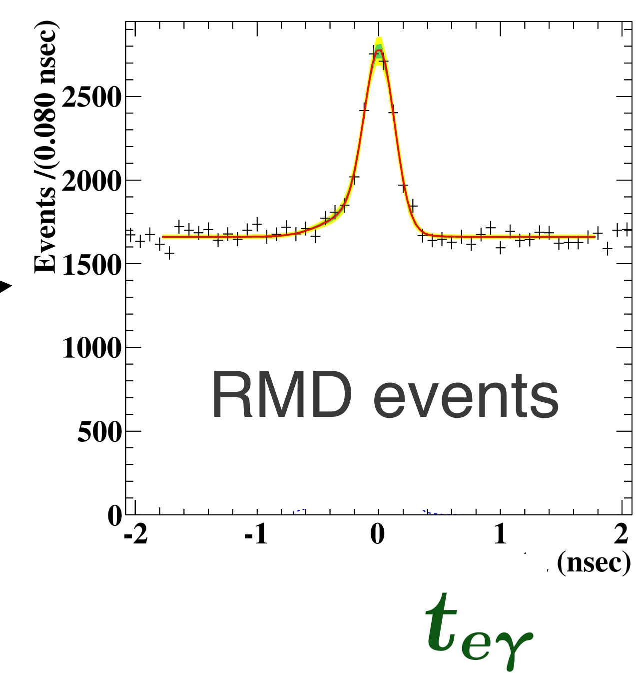
Two Gaussian constrain N_{RMD} and N_{BG}

Eγ vs T distribution without any selection.

$$\mathcal{L}\left(N_{\mathrm{sig}}, N_{\mathrm{RMD}}, N_{\mathrm{BG}}\right) = \frac{e^{-N}}{N_{\mathrm{obs}}!} e^{-\frac{\left(N_{\mathrm{RMD}} - \langle N_{\mathrm{RMD}}\rangle\right)^2}{2\sigma^2_{\mathrm{RMD}}}} e^{-\frac{\left(N_{\mathrm{BG}} - \langle N_{\mathrm{BG}}\rangle\right)^2}{2\sigma^2_{\mathrm{BG}}}} \times \prod_{i=1}^{N_{\mathrm{obs}}} \left(N_{\mathrm{sig}} S\left(\vec{x_i}\right) + N_{\mathrm{RMD}} R\left(\vec{x_i}\right) + N_{\mathrm{BG}} B\left(\vec{x_i}\right)\right)$$





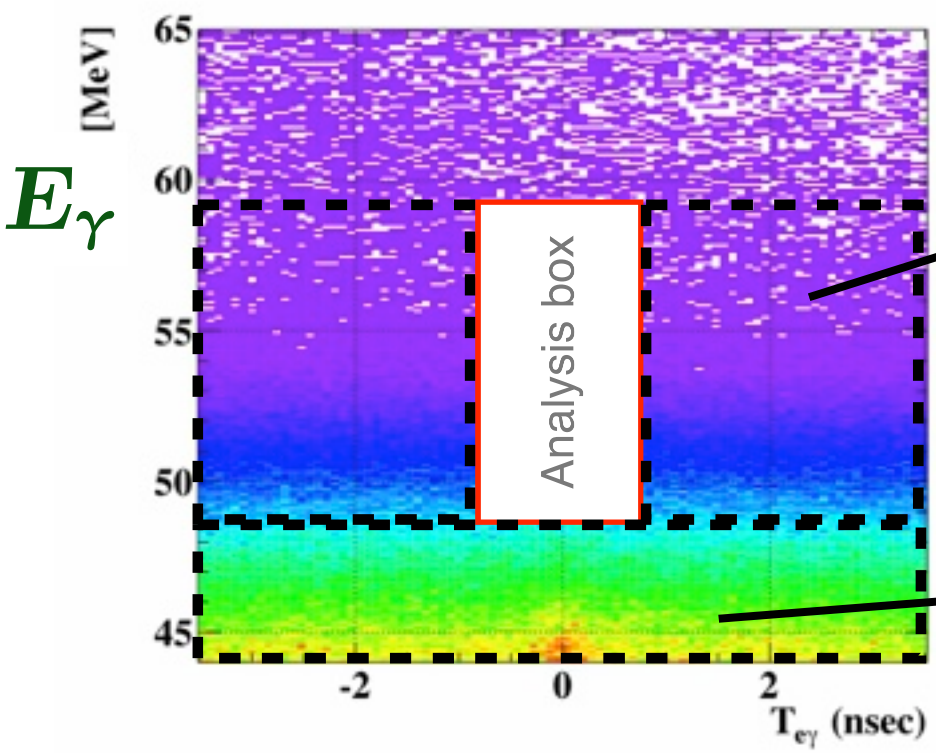


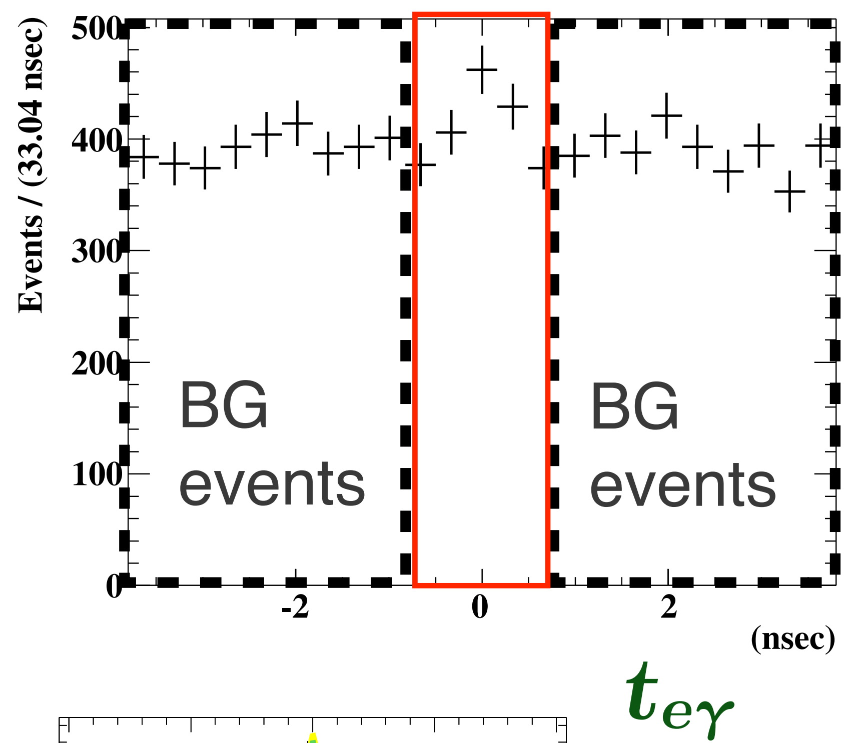
Likelihood and test-statistic

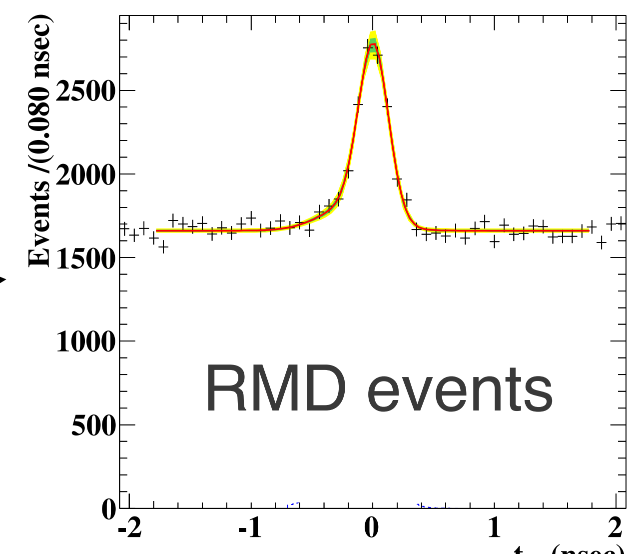
E_γ vs T distribution without any selection.

$$\mathcal{L}\left(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}\right) = \frac{e^{-N}}{N_{\rm obs}!} e^{-\frac{(N_{\rm RMD}-\langle N_{\rm RMD}\rangle)^2}{2\sigma^2_{\rm RMD}}} e^{-\frac{(N_{\rm BG}-\langle N_{\rm BG}\rangle)^2}{2\sigma^2_{\rm BG}}} \times \prod_{i=1}^{N_{\rm obs}} \left(N_{\rm sig} S\left(\vec{x_i}\right) + N_{\rm RMD} R\left(\vec{x_i}\right) + N_{\rm BG} B\left(\vec{x_i}\right)\right)$$

Two Gaussian constrain $N_{\rm RMD}$ and $N_{\rm BG}$



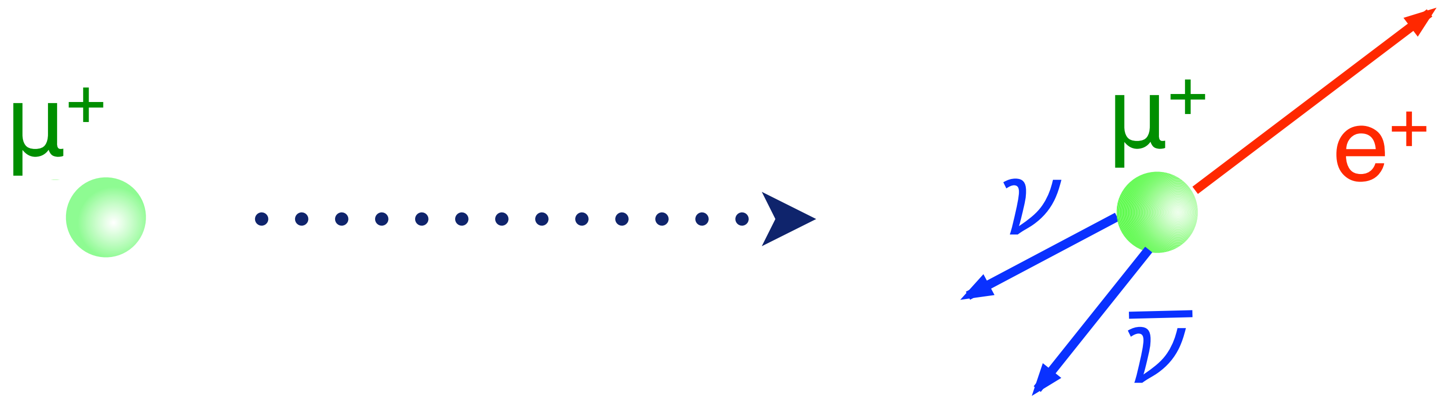




$$\lambda_{\rm p}(N_{\rm sig}) = \frac{\mathcal{L}(N_{\rm sig}, \hat{\hat{N}}_{\rm RMD}(N_{\rm sig}), \hat{\hat{N}}_{\rm BG}(N_{\rm sig}))}{\mathcal{L}(\hat{N}_{\rm sig}, \hat{N}_{\rm RMD}, \hat{N}_{\rm BG})}$$

Profile likelihood ordering
Feldman-Cousins approach

Normalization



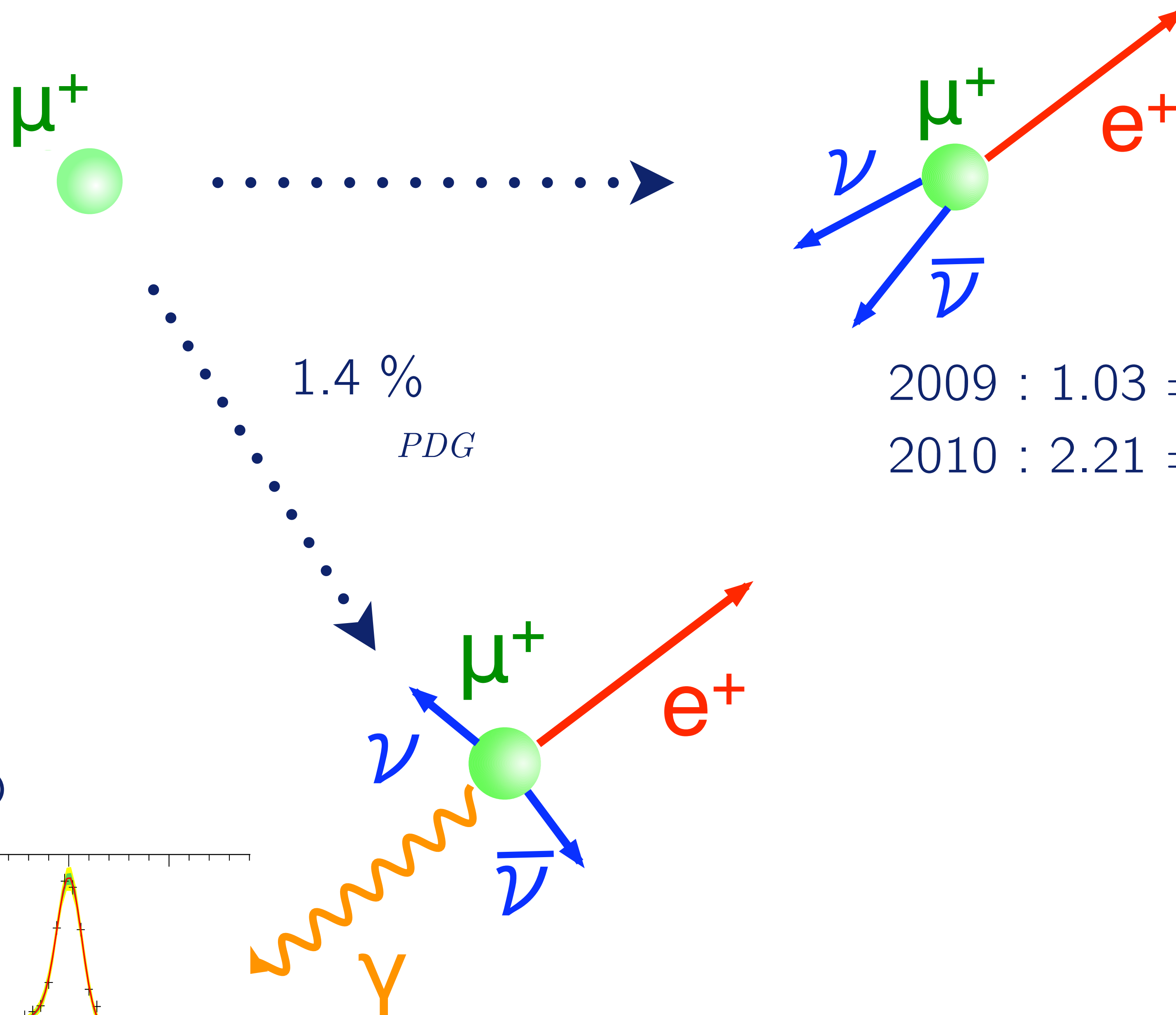
Michel decay

2009 : 1.03 ± 0.09

2010 : 2.21 ± 0.2

~ 10% Uncertainty

Normalization



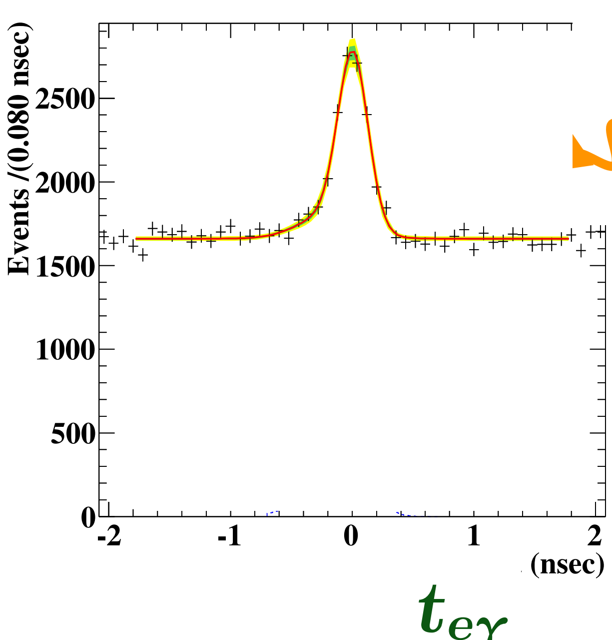
Michel decay

2009 : 1.03 ± 0.09

2010 : 2.21 ± 0.2

~ 10% Uncertainty

RMD

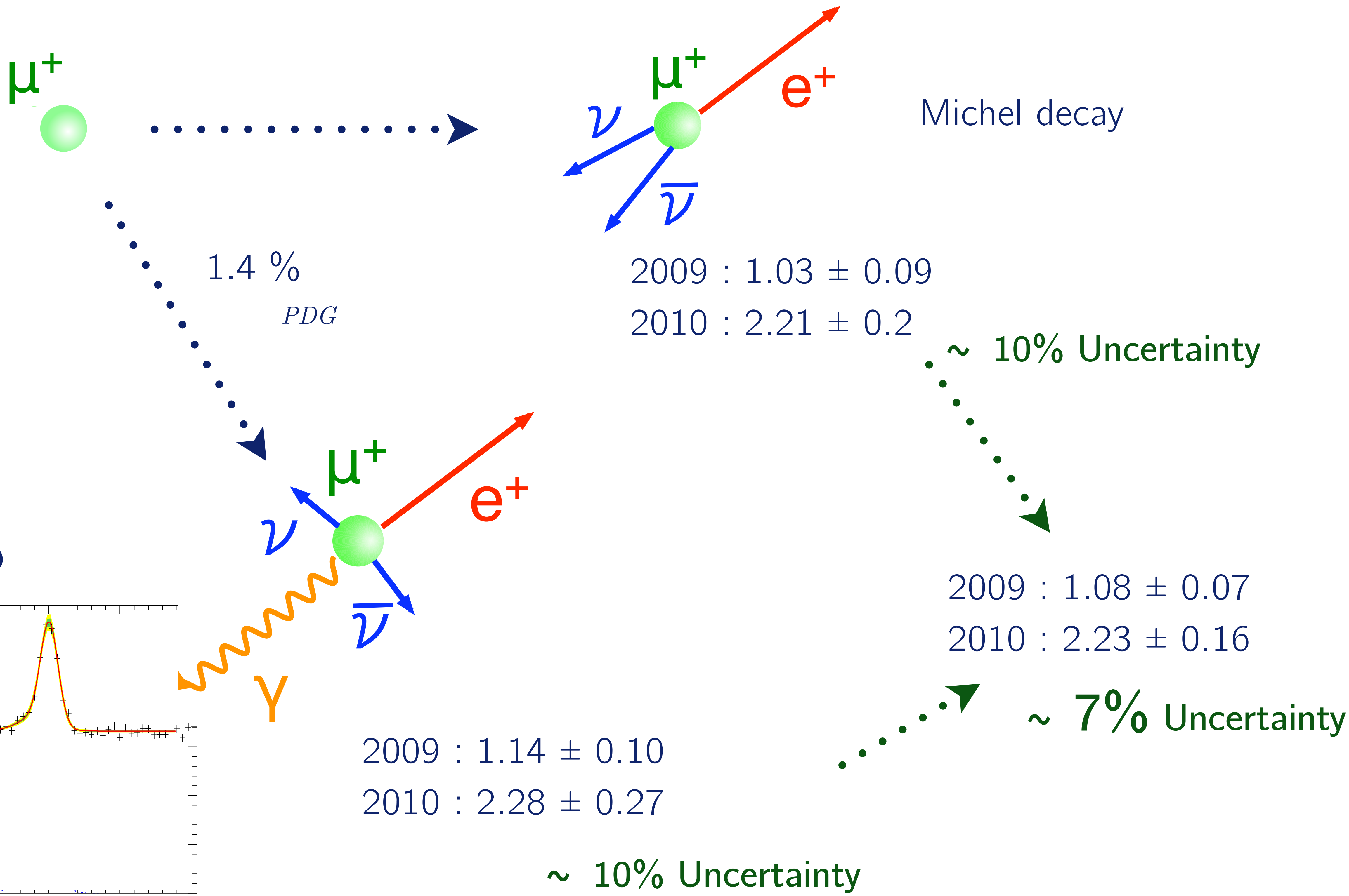


2009 : 1.14 ± 0.10

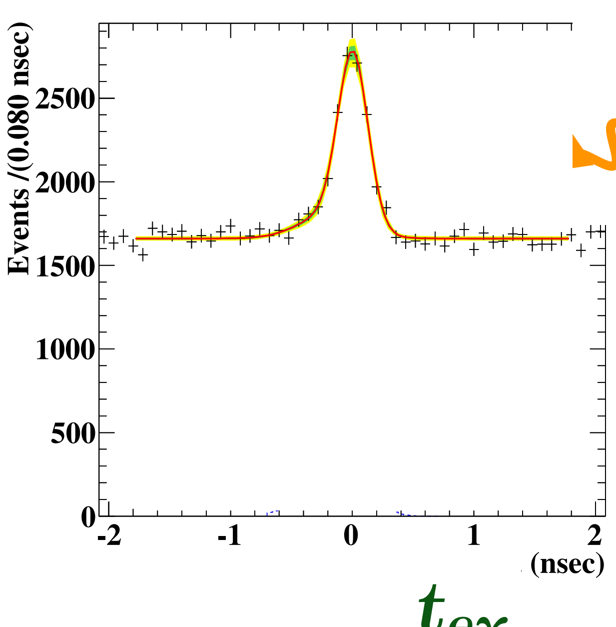
2010 : 2.28 ± 0.27

~ 10% Uncertainty

Normalization



RMD

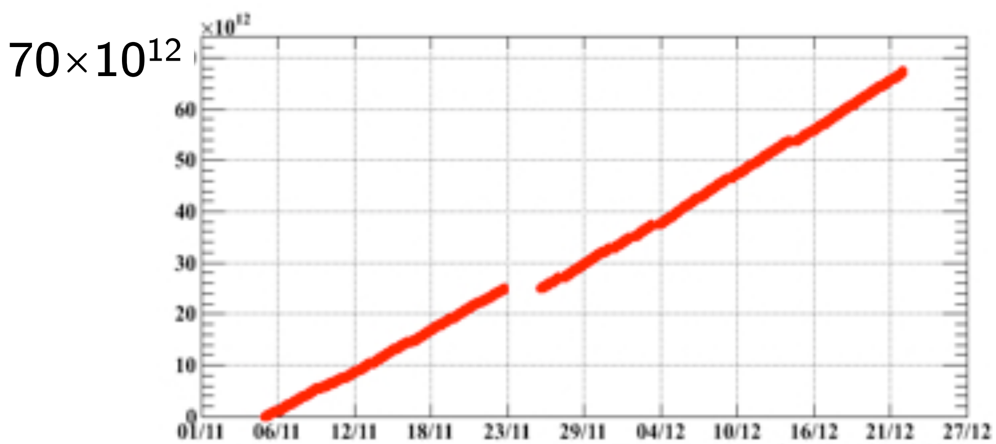


Result

Data statistics

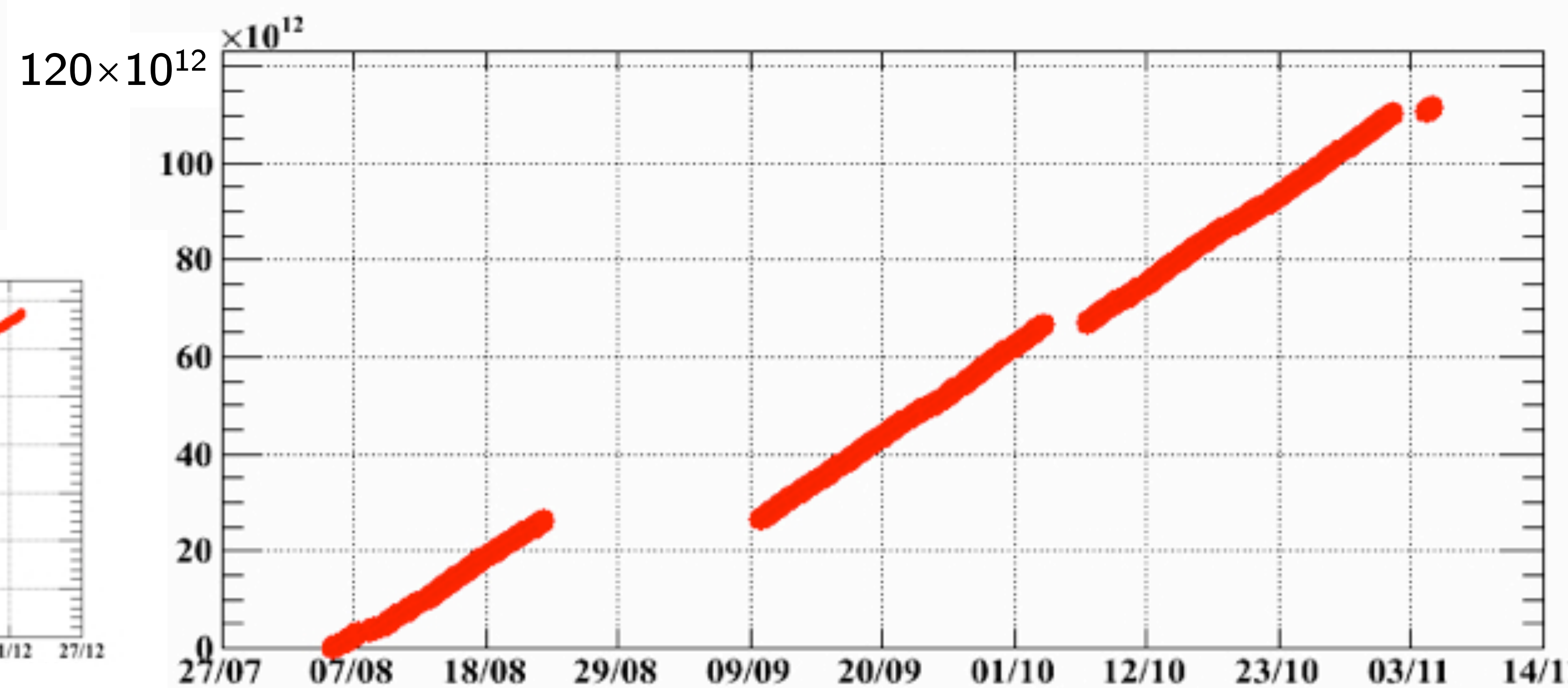
of muons stopped on the target

2009



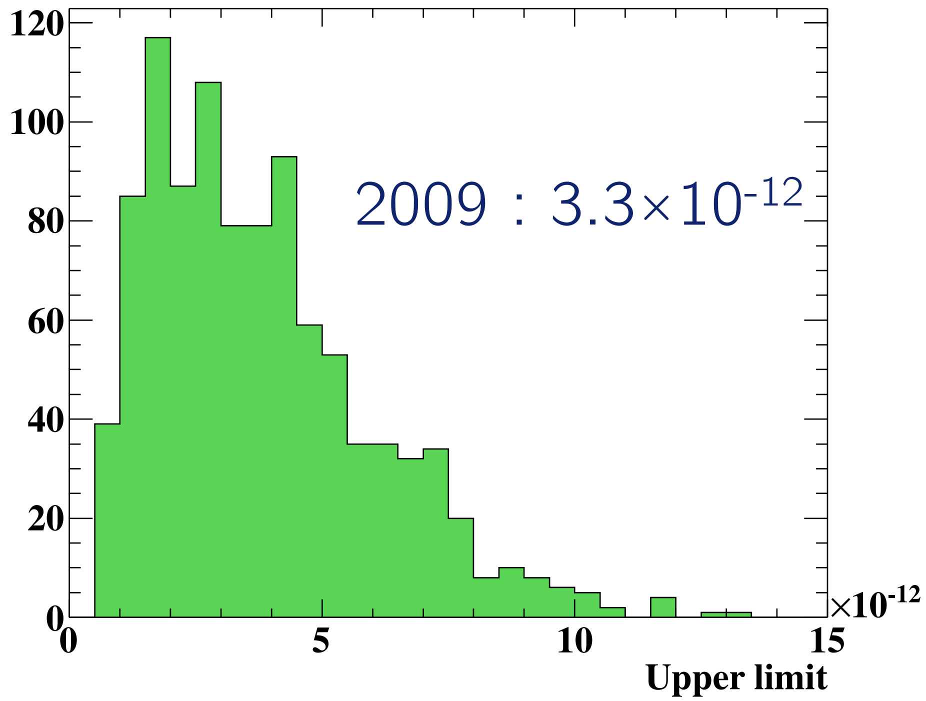
~1.5 months

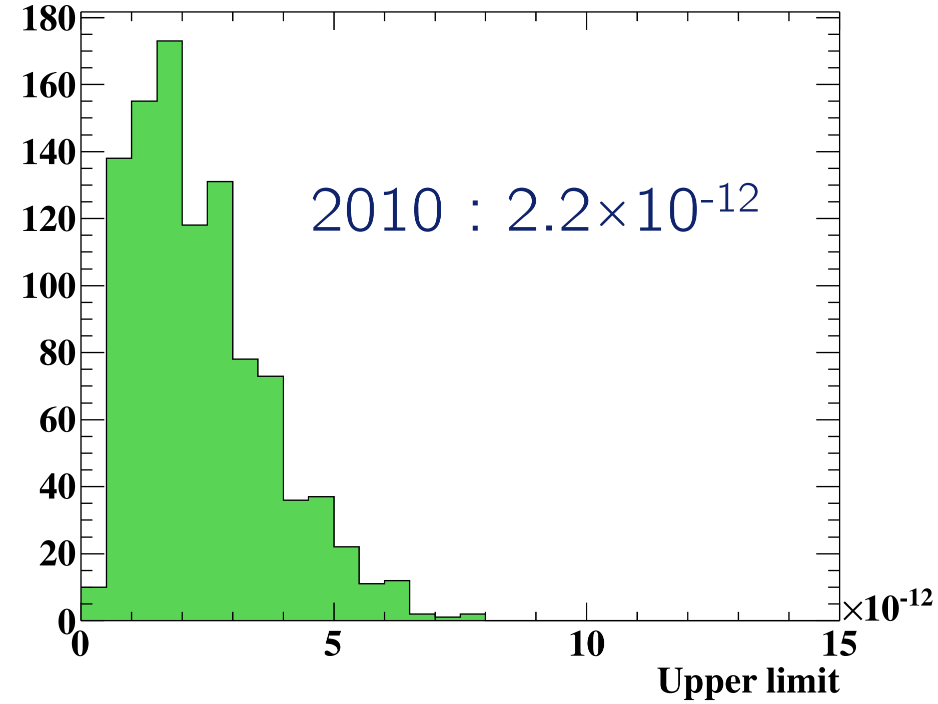
2010



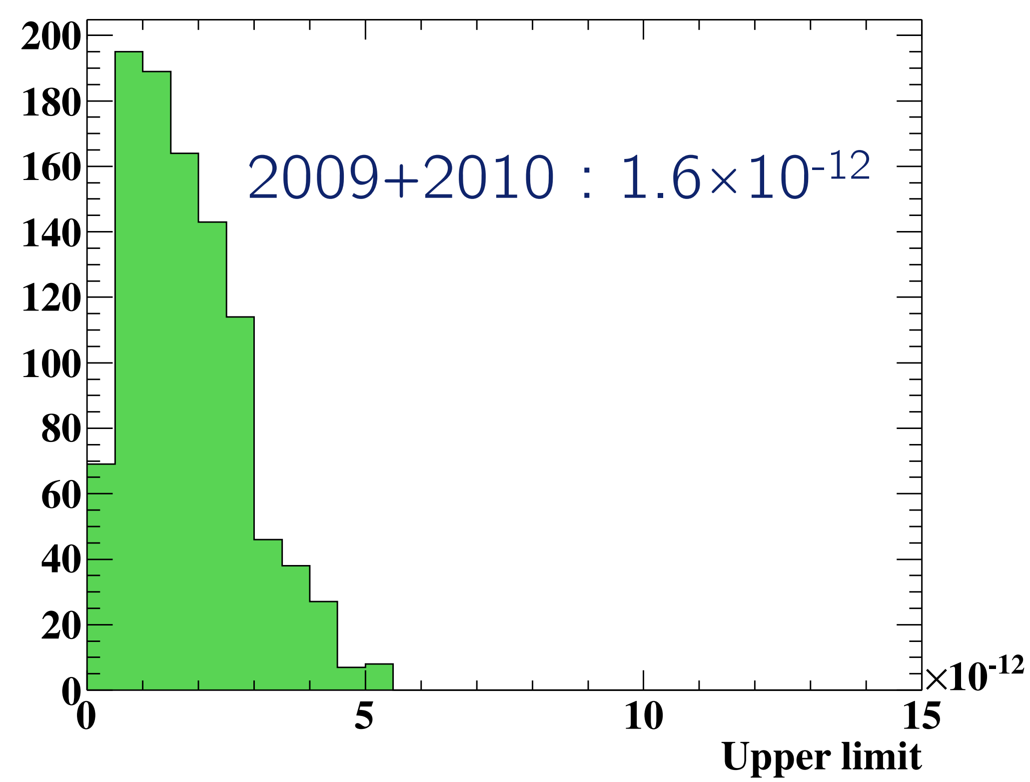
~3 month

Sensitivity

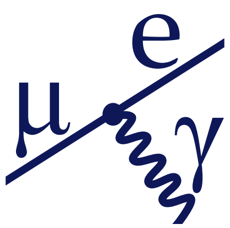


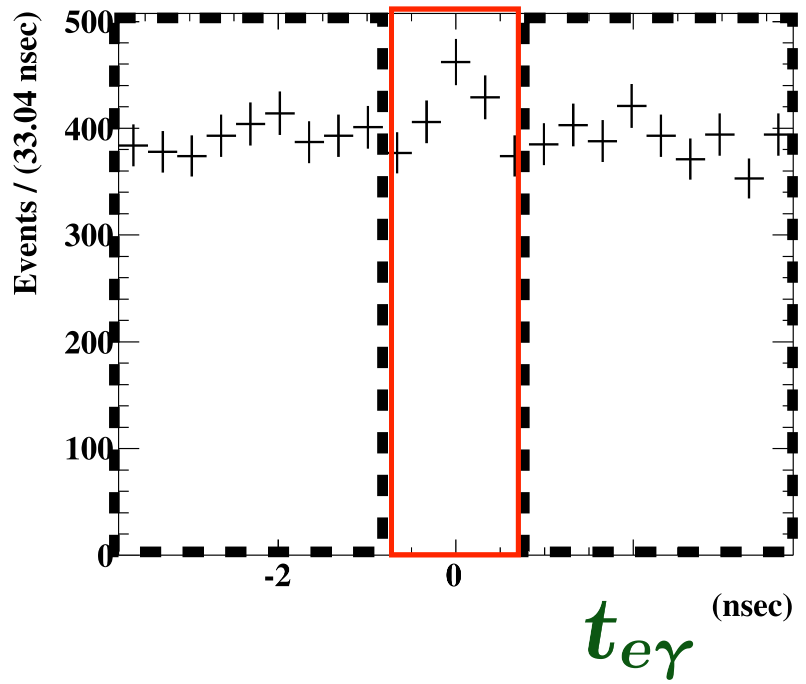


Sensitivity : Median UL of MC with
background-only hypothesis



Time side-bands

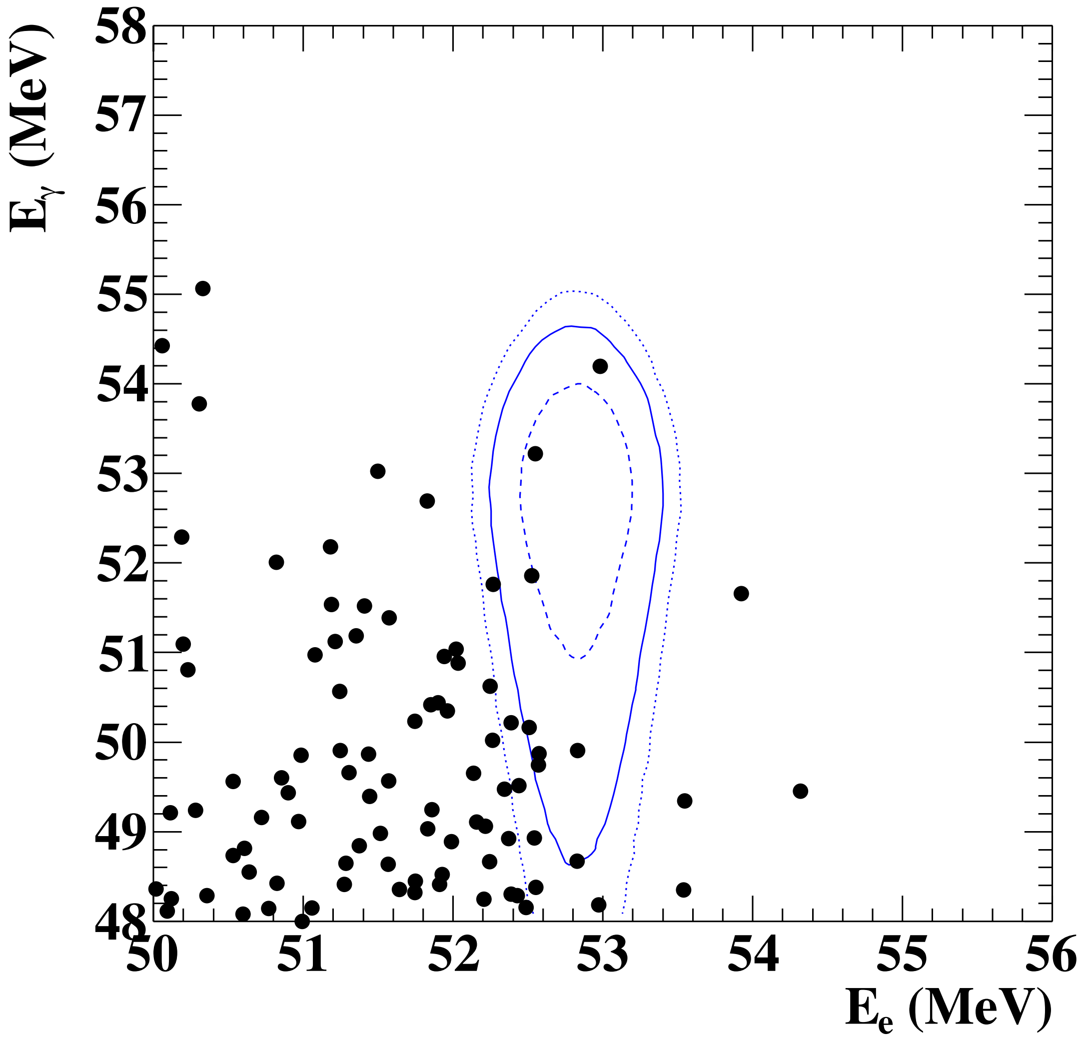


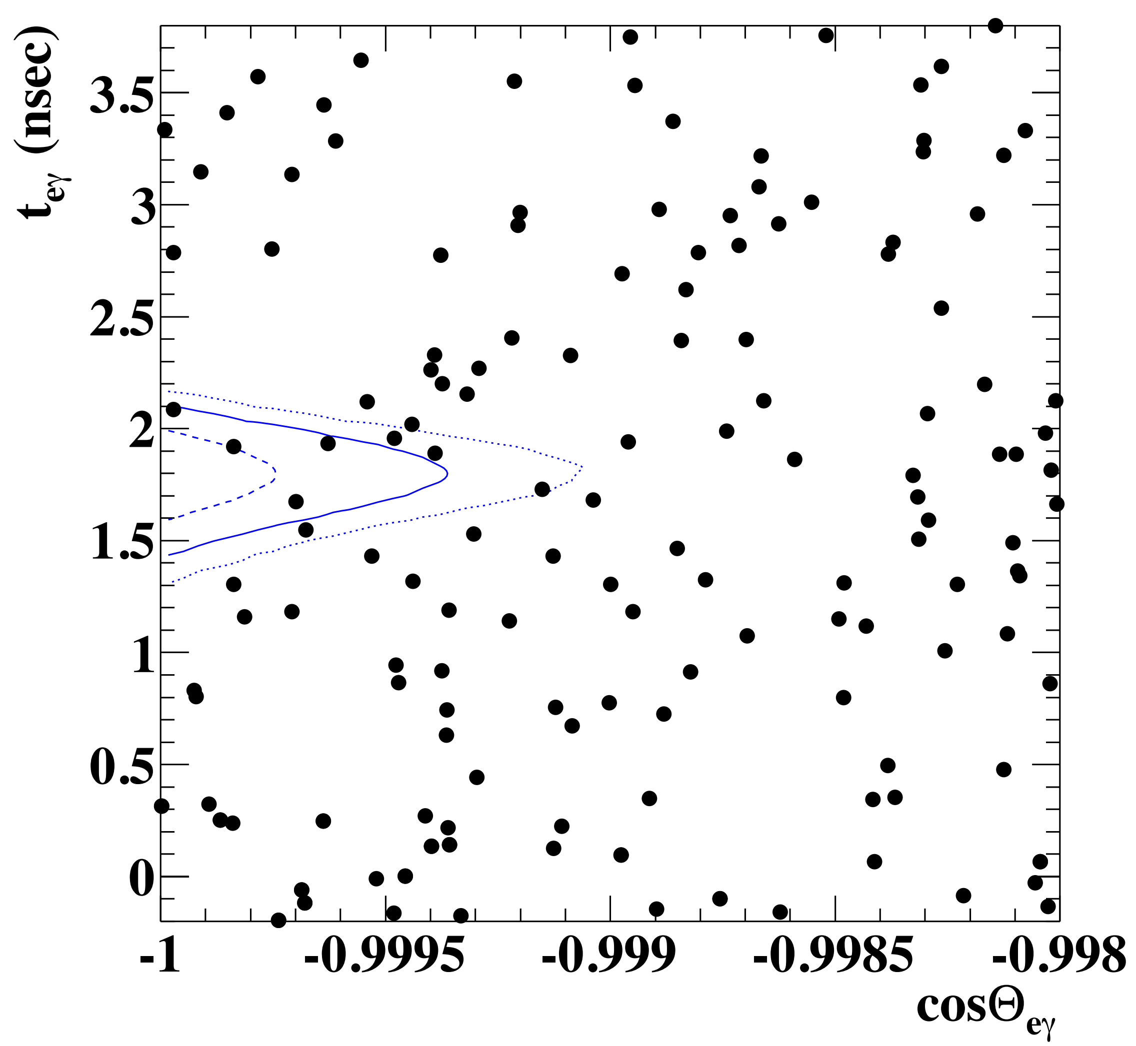


sideband

$\mathcal{B}(\mu \rightarrow e\gamma) < \mathbf{1\text{-}3} \times 10^{-12}$

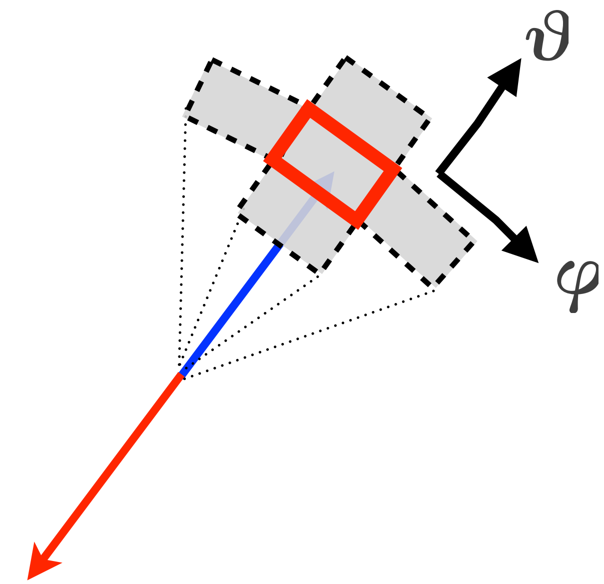
consistent with U.L. of MC experiments w/o signal

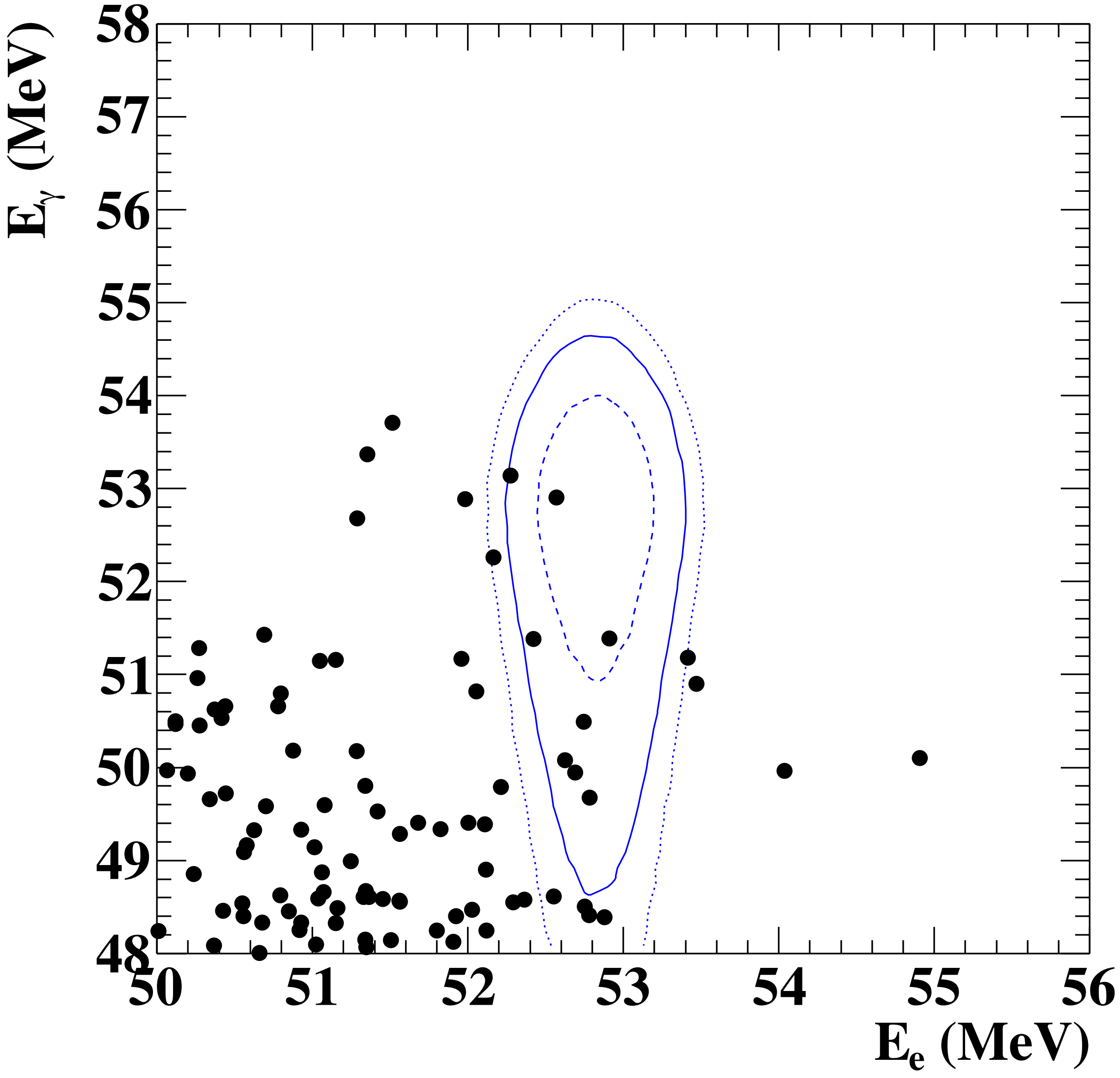


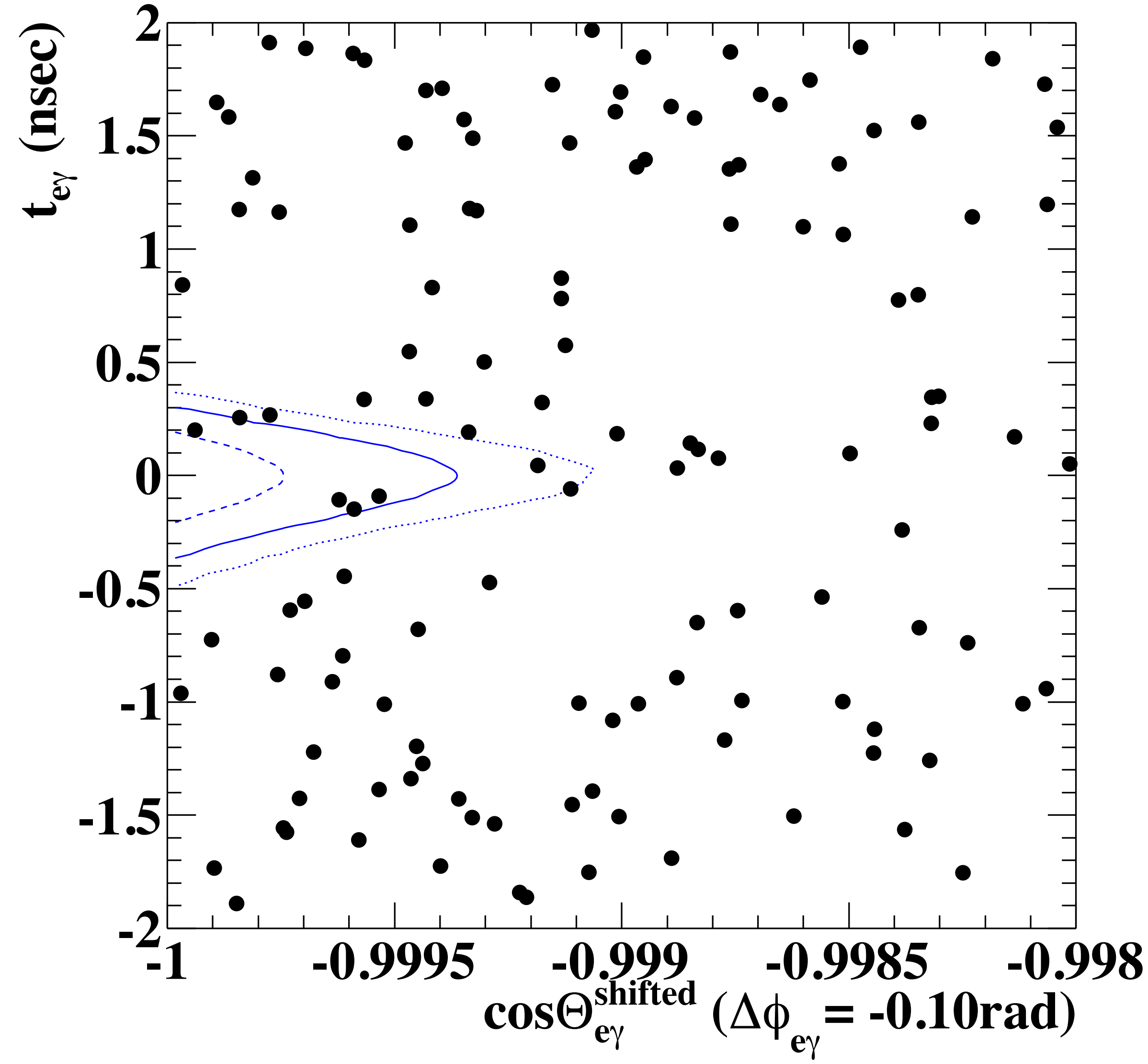


contour : signal PDF (39.3, 74.2, 86.5 %)

Angle side-bands



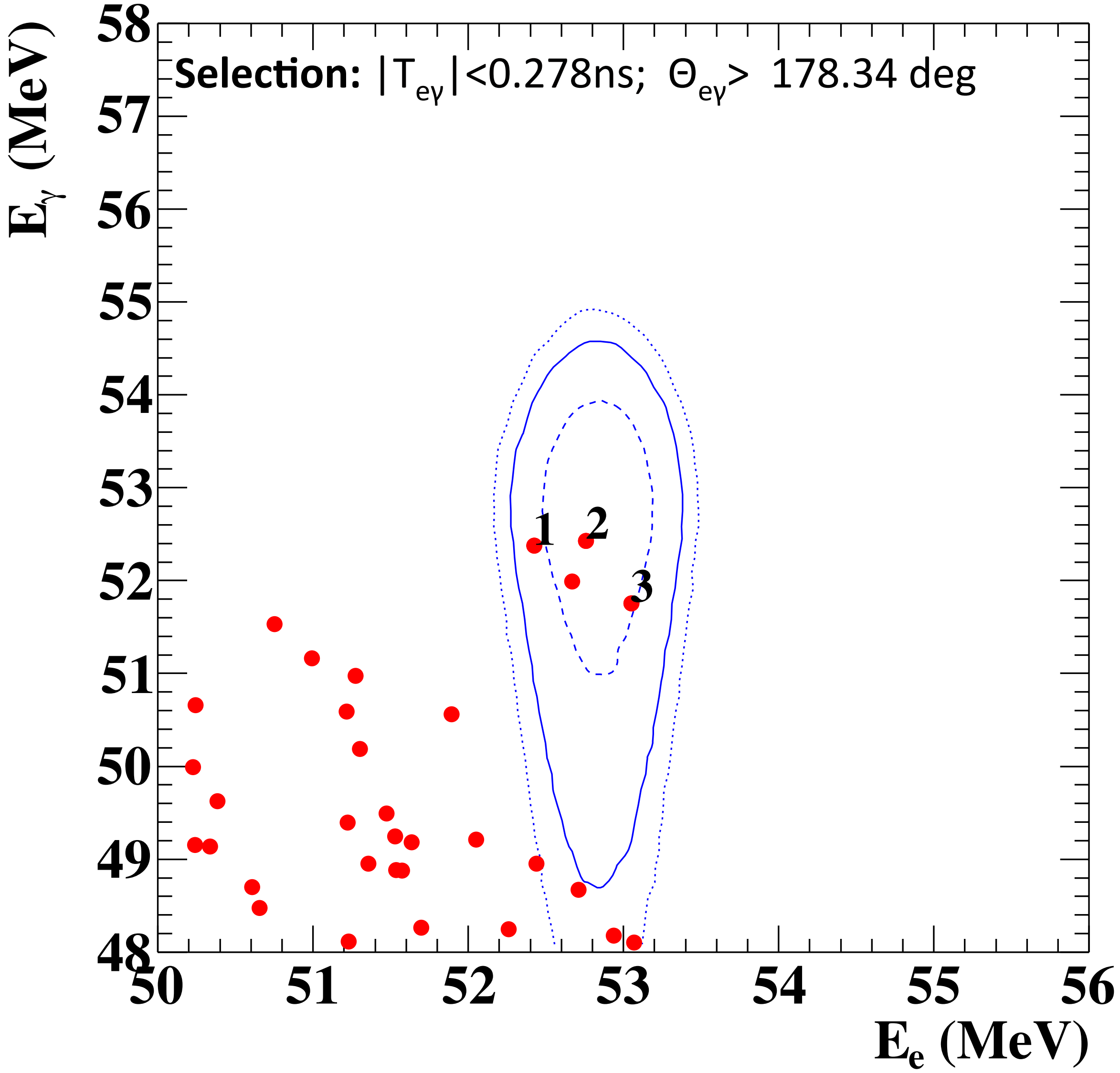


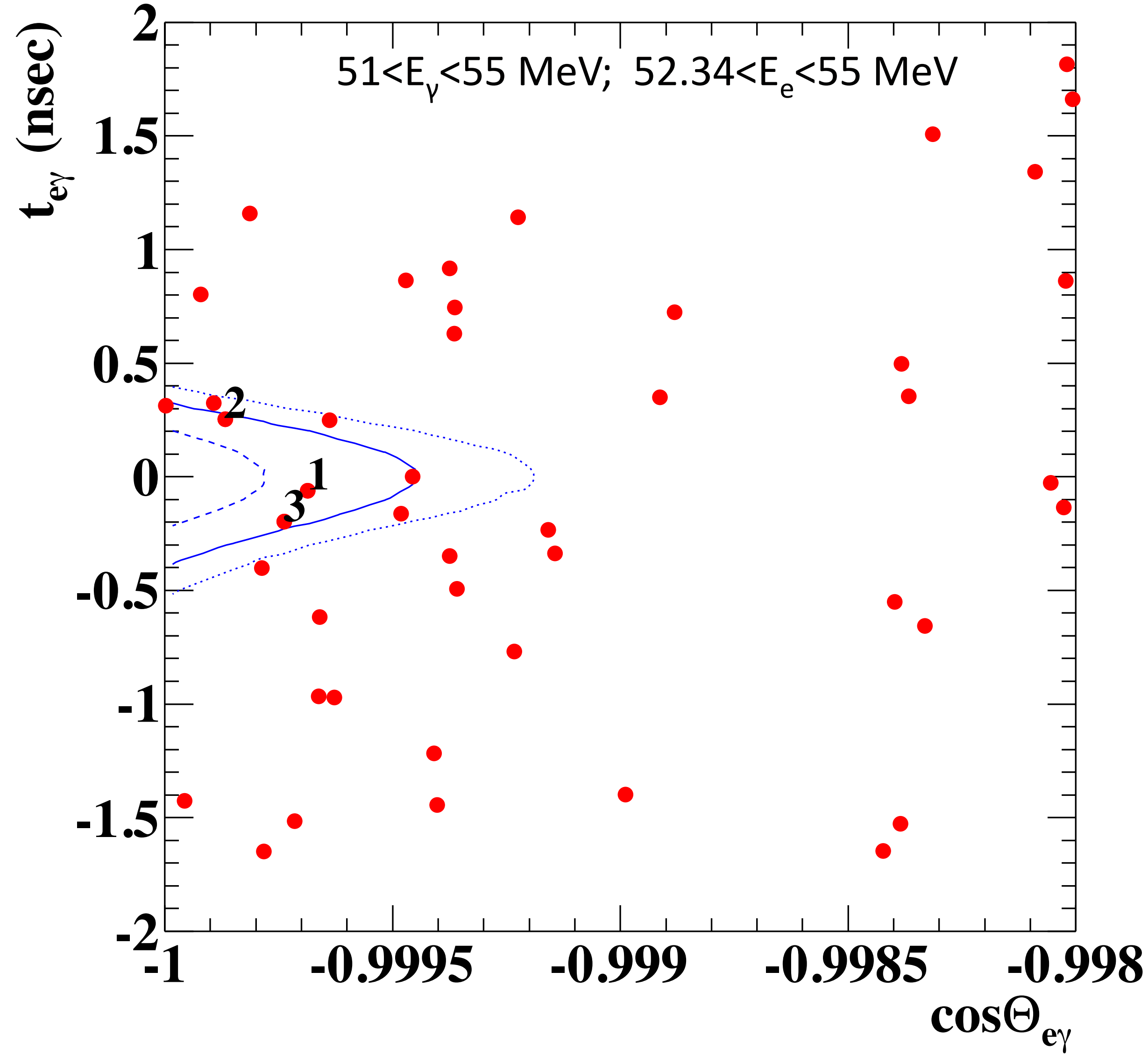


no unexpected time correlated background

contour : signal PDF (39.3, 74.2, 86.5 %)

2009

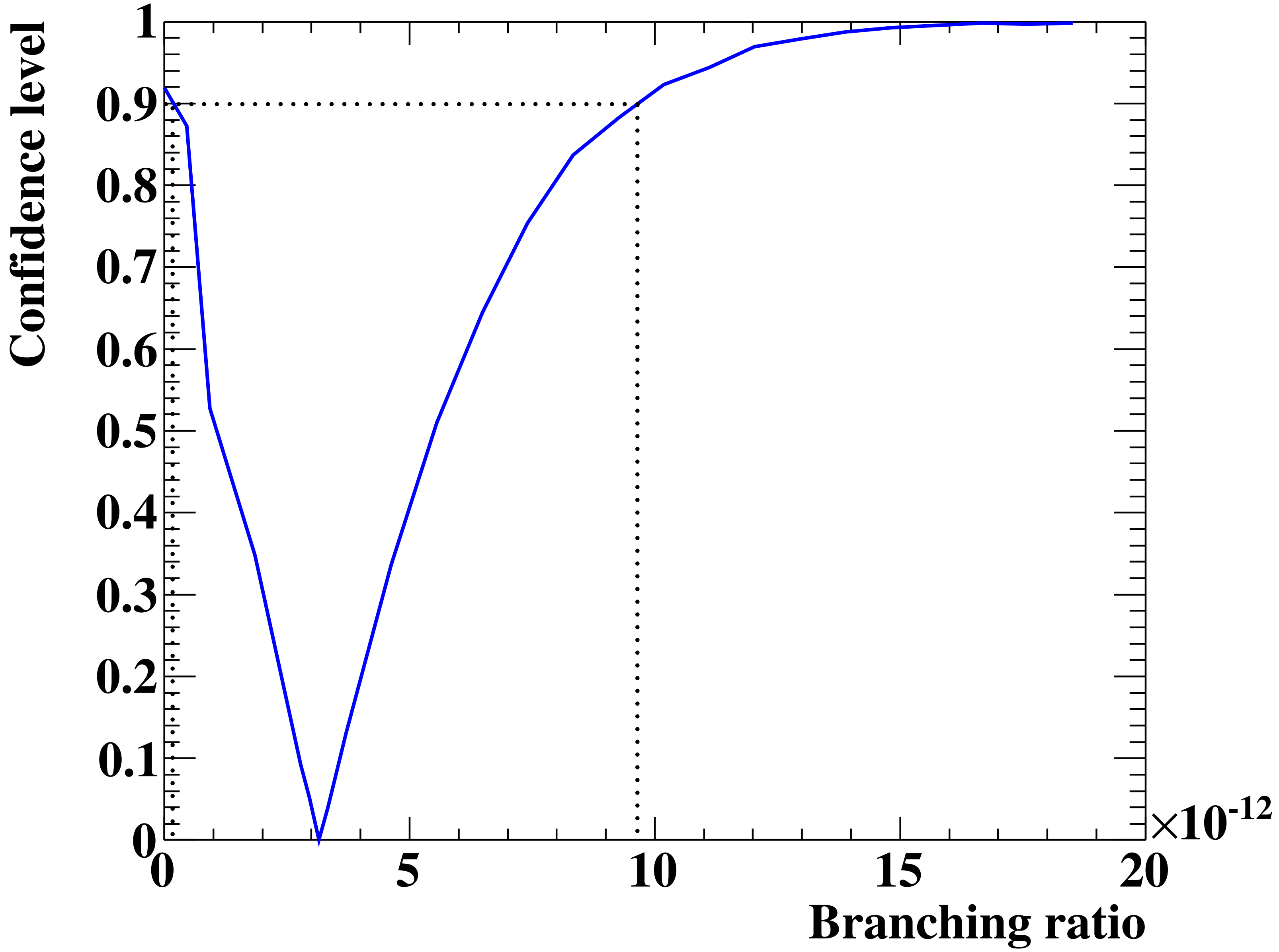




contour : signal PDF (39.3, 74.2, 86.5 %)

2009, Result

Nsignal Best fit : 3.0(preliminary) → 3.4(updated result) **2009 result stable**

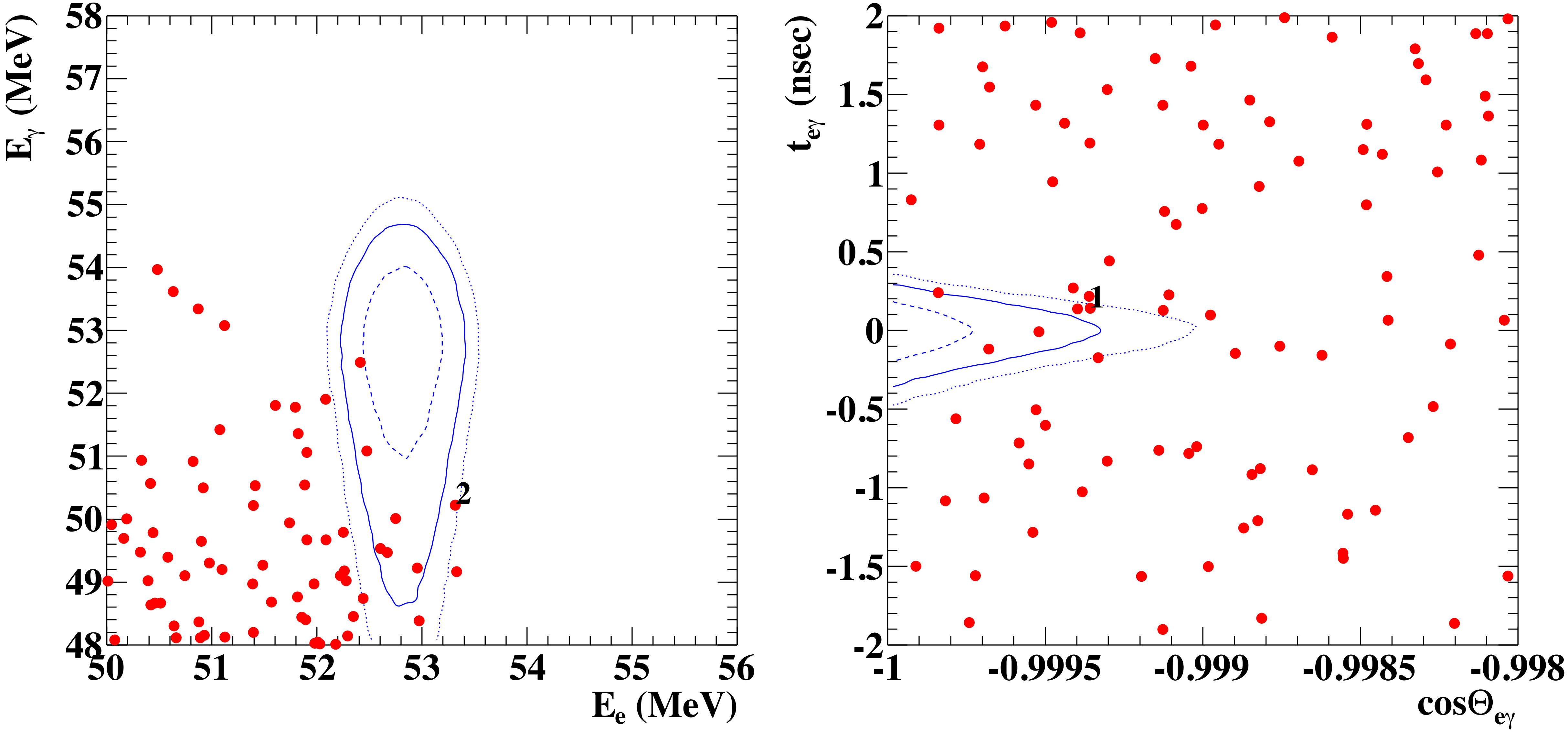


$$\mathbf{1.7} \times 10^{-13} < \mathcal{B}(\mu \to e\gamma) < \mathbf{9.6} \times 10^{-12}$$ @ 90% C.L.

Best fit : $\mathbf{3.2} \times 10^{-12}$

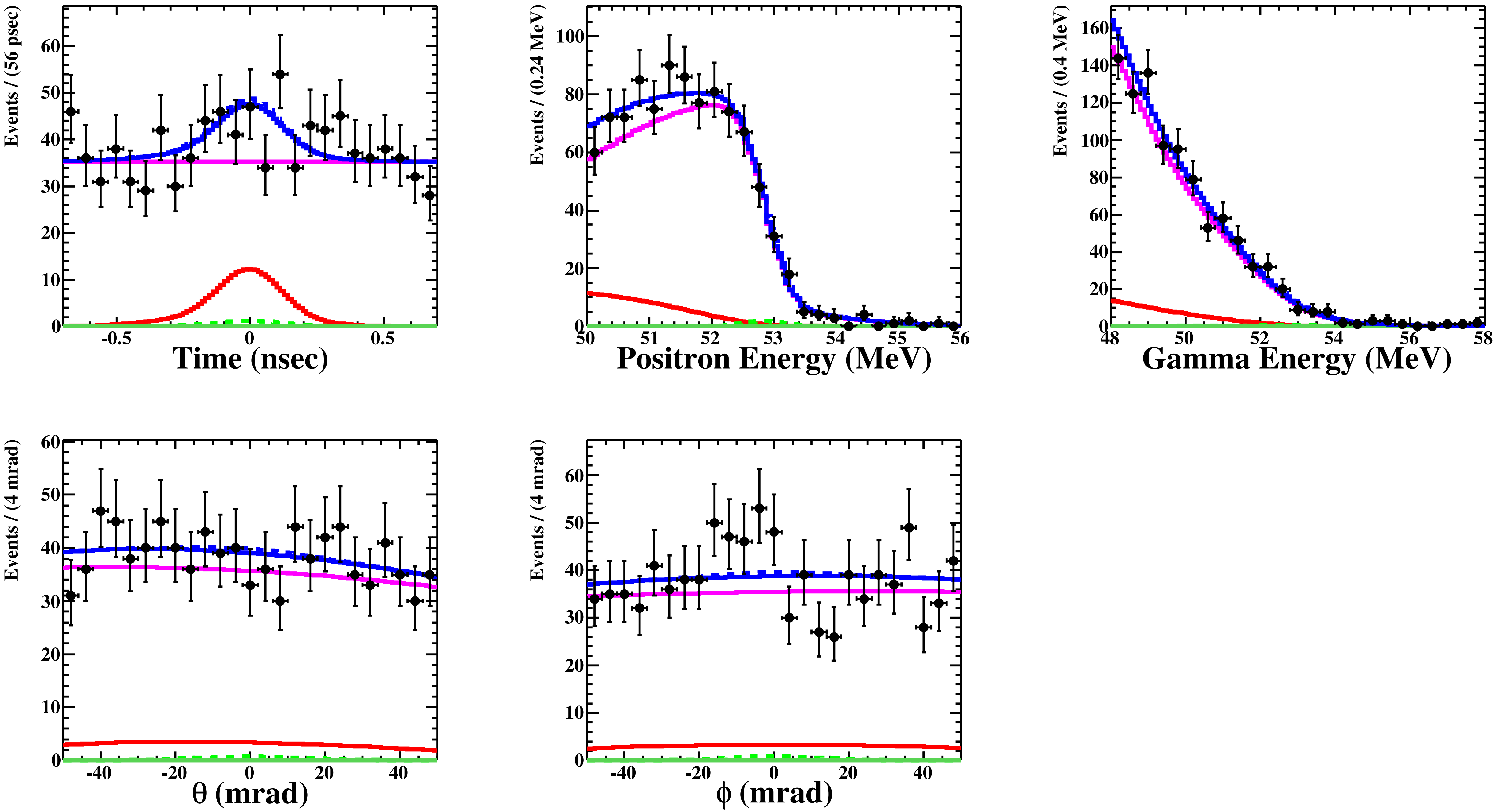
p-Value of background-only hypothesis: ***8%***

2010



contour : signal PDF (39.3, 74.2, 86.5 %)

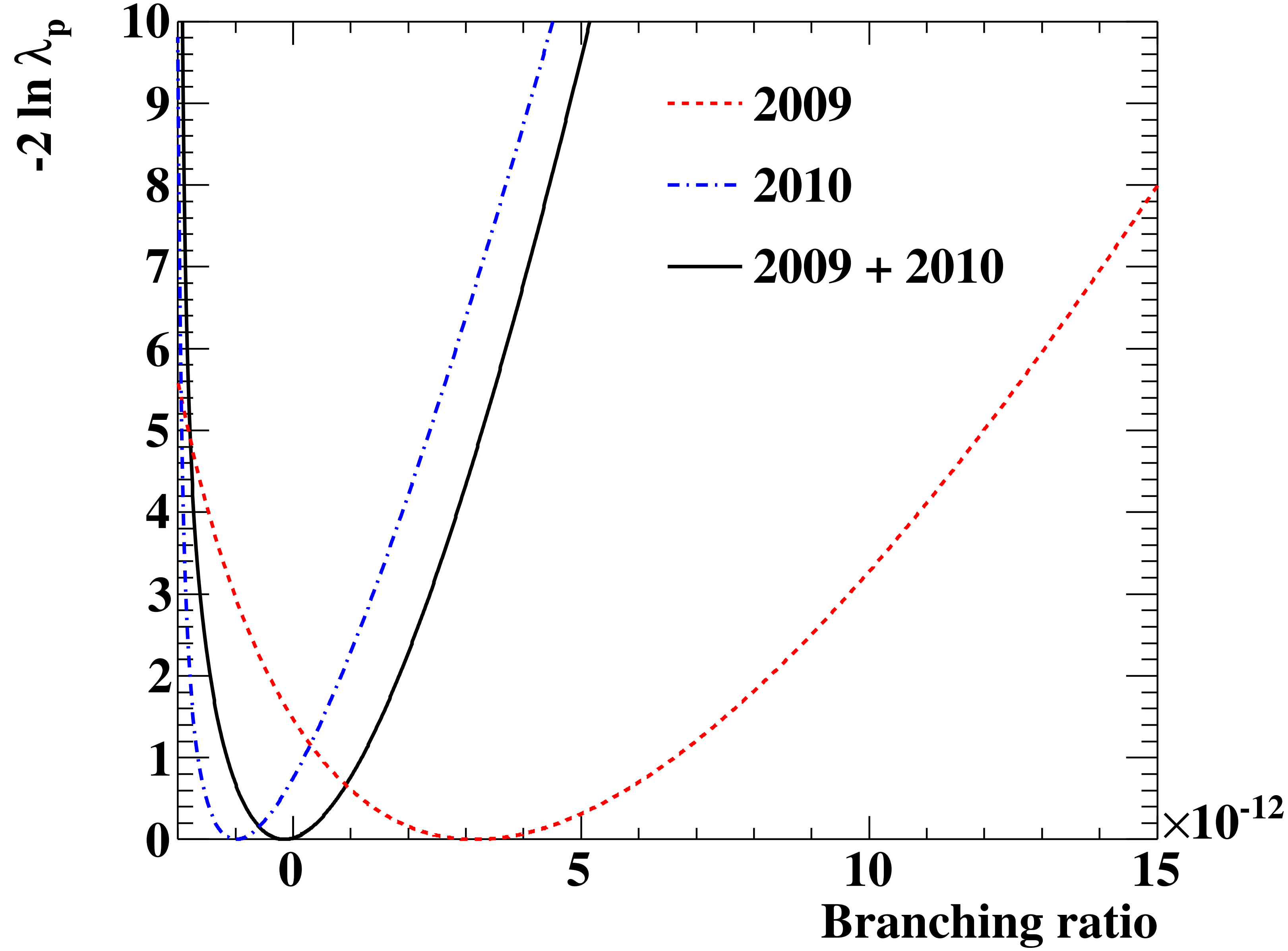
2009+2010



Events / (56 psec)
Time (nsec)
Events / (0.24 MeV)
Positron Energy (MeV)
Events / (0.4 MeV)
Gamma Energy (MeV)
Events / (4 mrad)
θ (mrad)
Events / (4 mrad)
ϕ (mrad)

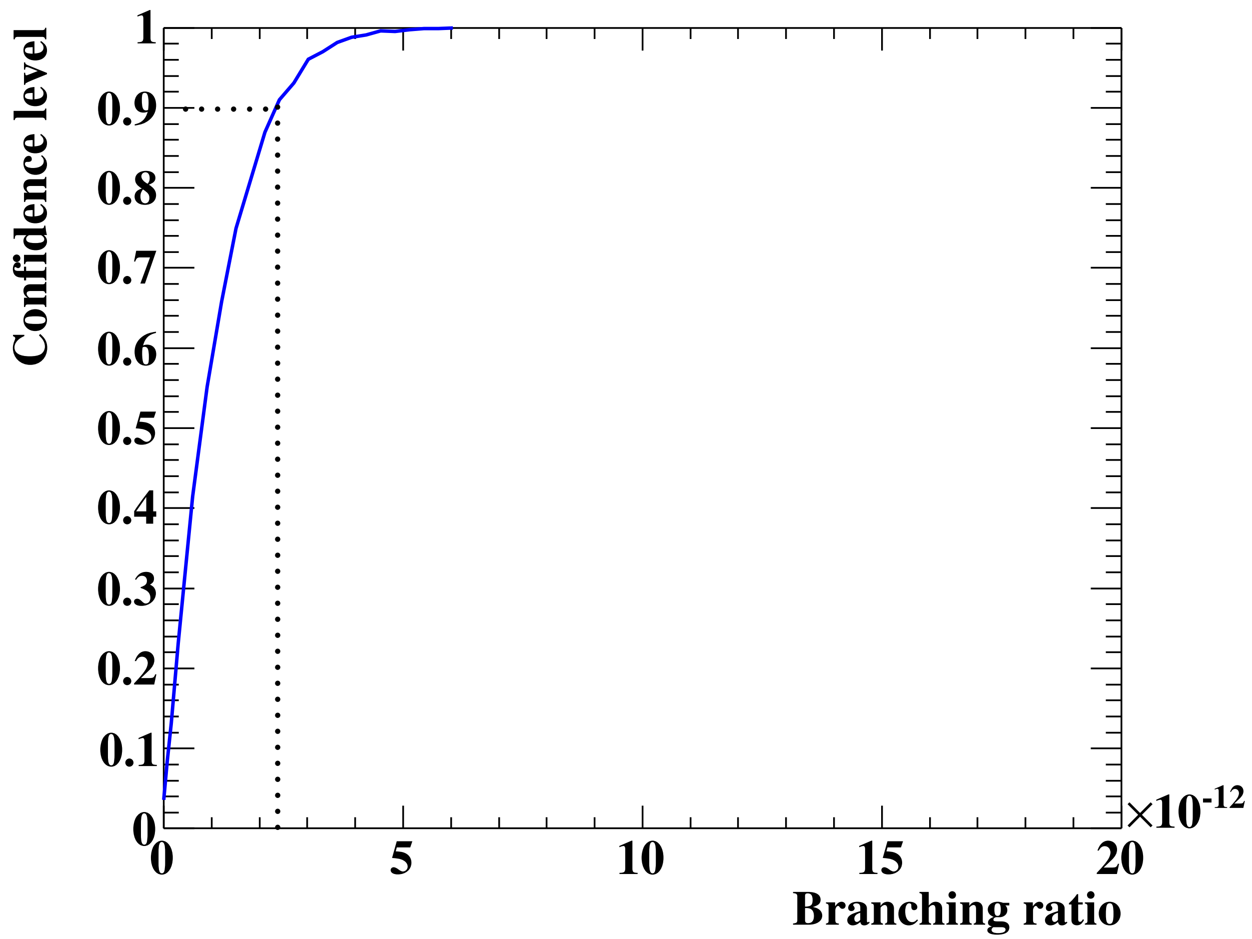
2009+2010 likelihood

$$\lambda_p(N_{sig}) = \frac{\mathcal{L}(N_{sig}, \hat{\hat{N}}_{RMD}(N_{sig}), \hat{\hat{N}}_{BG}(N_{sig}))}{\mathcal{L}(\hat{N}_{sig}, \hat{N}_{RMD}, \hat{N}_{BG})}$$



Note these curves are not directly used to derive the U.L., which are obtained in a frequentist approach

2009+2010 result



arXiv:1107.5547 [hep-ex]
PRL accepted

$$\mathcal{B}(\mu \to e\gamma) < 2.4 \times 10^{-12}$$ @ 90% C.L.

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}

Systematic uncertainties (in total 2% in UL)

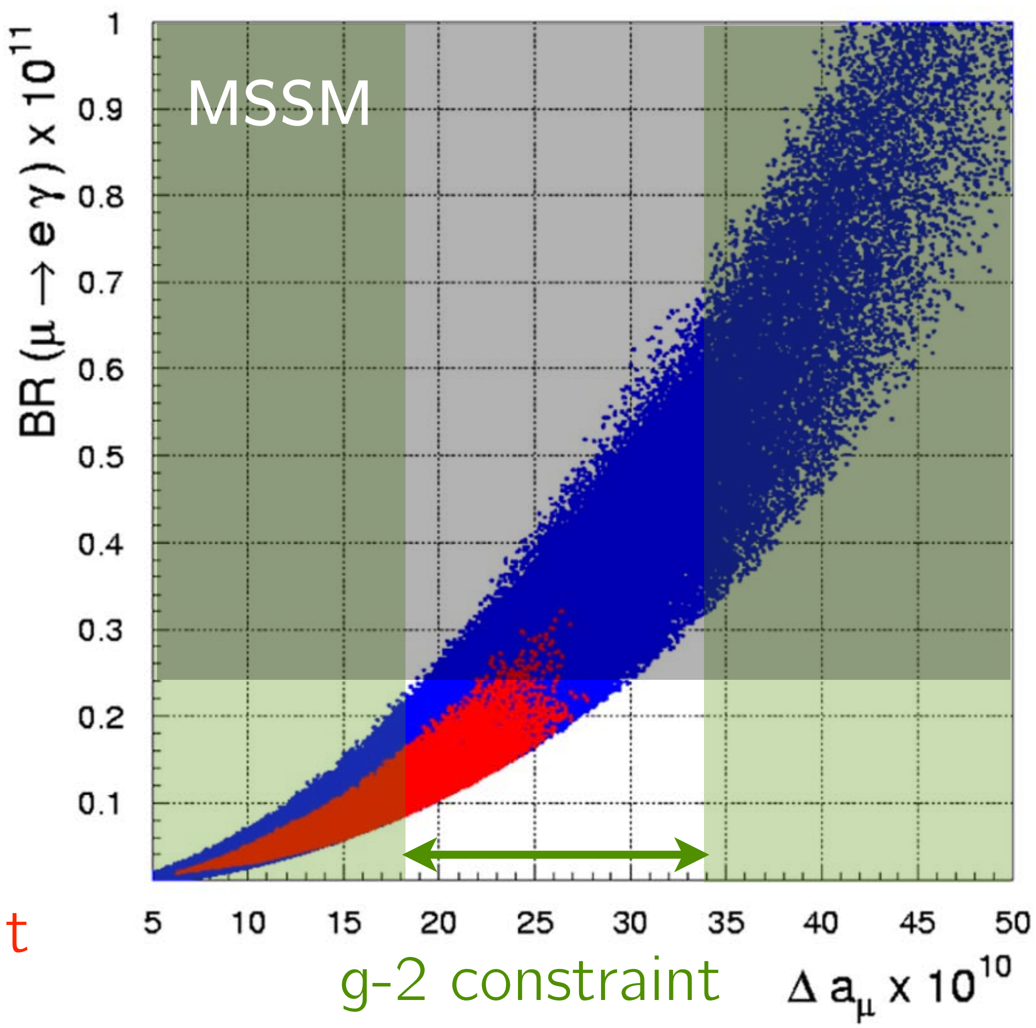
- relative angle offsets
- correlations in e^+ observables
- normalization

- 2009+2010 data
  - Zero-signal is consistent
  - 5 times tighter new limit

$$\mathcal{B}(\mu \to e\gamma) < 2.4 \times 10^{-12}$$

@ 90% C.L.

G. Isidori *et al* 2007 *PRD* **75** 115019



← 2009 UL

MEG constraint

← 2009+2010 UL

← 2009+2010 Sensitivity

B-physics constraint

g-2 constraint

$[\mathcal{B}(B_s \to \mu^+\mu^-) < 8 \times 10^{-8},\ 1.01 < R_{Bs\gamma} < 1.24,\ 0.8 < R_{B\tau\nu} < 0.9,\ \Delta M_{B_s} = 17.35 \pm 0.25\ \mathrm{ps}^{-1}]$

K. Hagiwara *et al* 2011 *J. Phys. G: Nucl. Part. Phys.* **38** 085003

2011 run

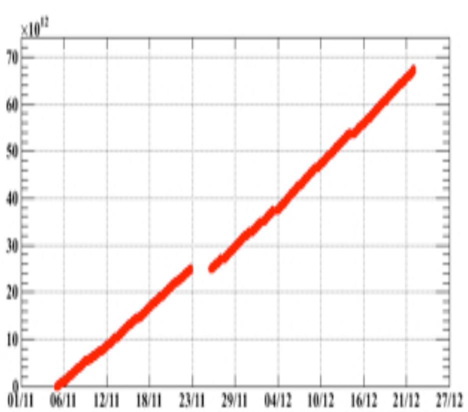
	Jan-Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2008		Detector preparation				CEX	Physics run (less DC eff., lower LXe LY)			CEX
2009		Other experiment(Lamb shift) XEC: liquid purification DC: HV discharge problem fix				Detector installation & preparation	DRS4 installation	CEX	Physics run	
2010	DRS4 mod.		Cosmic alignment	e+ Mott Beam study		Physics run	CEX Physics run		BTS problem	
2011	BTS repair work 7 DC repair work				Physics run		CEX Physics run			

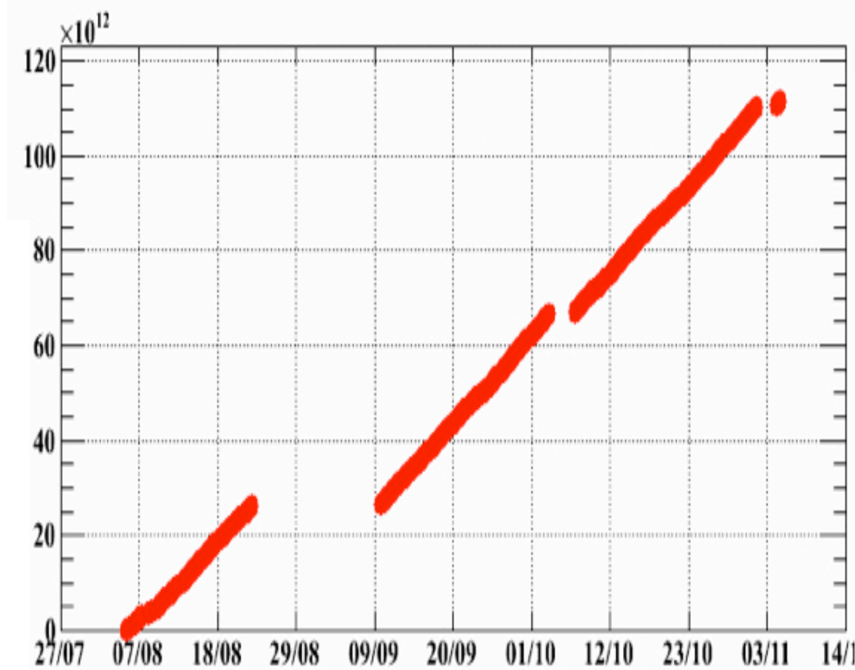
PSI accelerator
Shutdown period

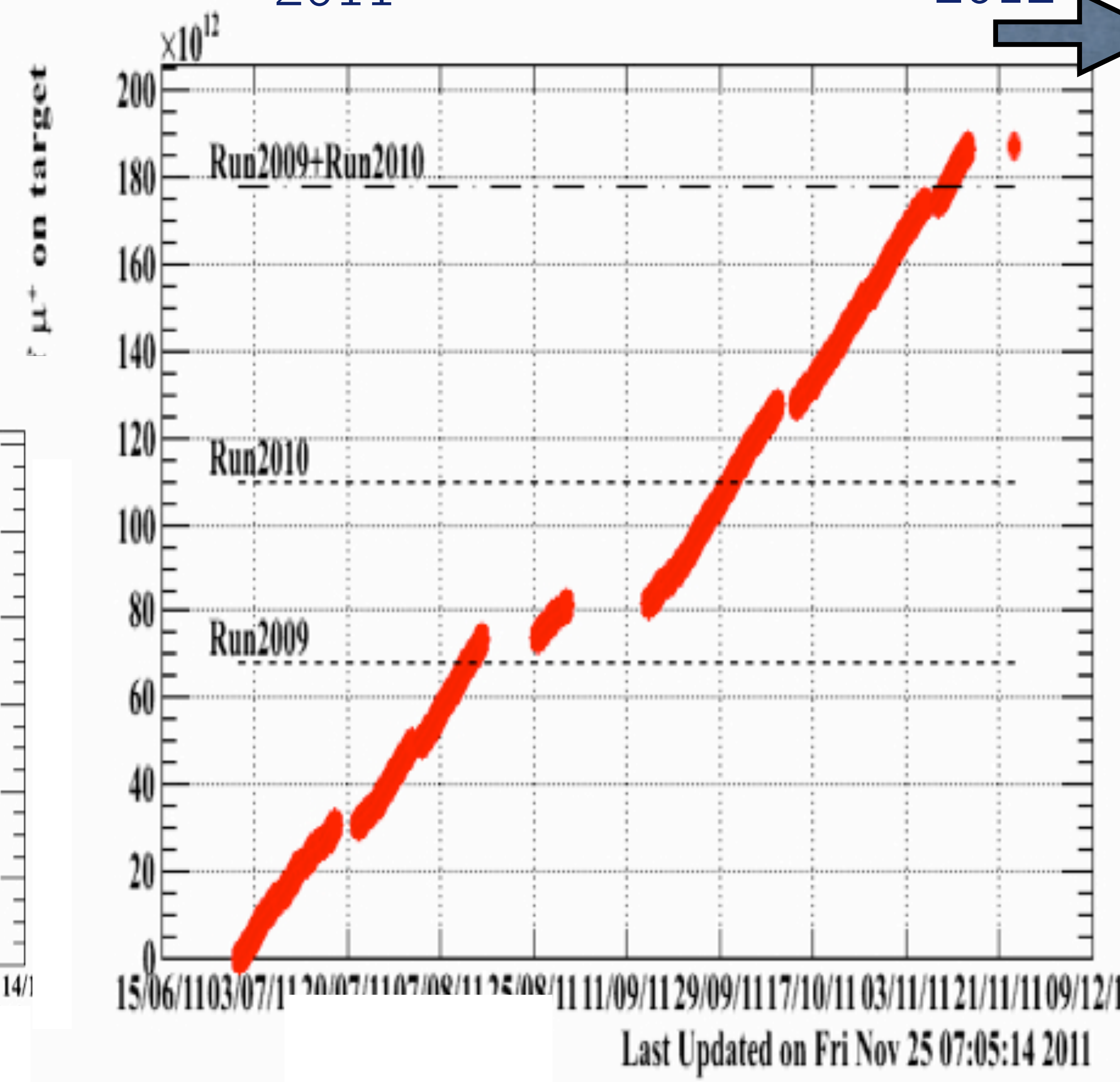
Data statistics : present and future

2009 2010 2011 2012

# of muons stopped on the target







~1.5 months

~3 month

~6 month

Summary

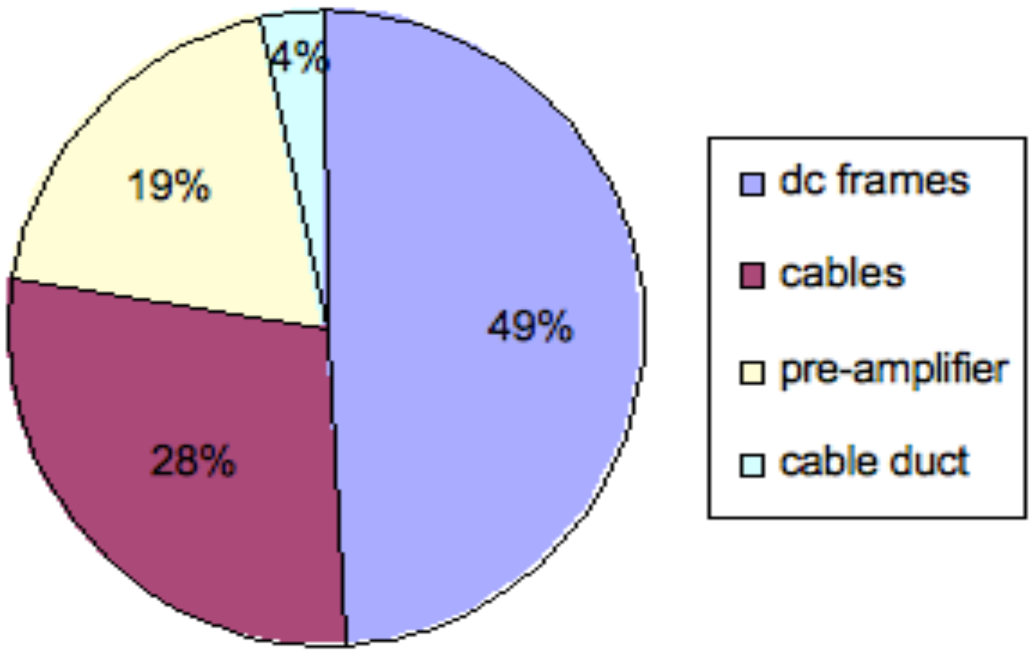
- MEG experiment has started physics run in 2008, and MEG detector has been working since then, and the performance is still being improved.
- 2009+2010 data : 5 times stringent new limit on Br than the MEGA result (1.2×10^{-11})
  - Sensitivity : 1.6×10^{-12}
  - Consistent with 0 signal
  - Upper limit : 2.4×10^{-12} @ 90%CL
- MEG physics run has restarted since the end of June 2011, and MEG is accumulating more data 2011-2012 to reach $O(10^{-13})$ sensitivity.
- Possible major upgrades of experiment (sensitivity$<\sim 10^{-13}$?) are being discussed.

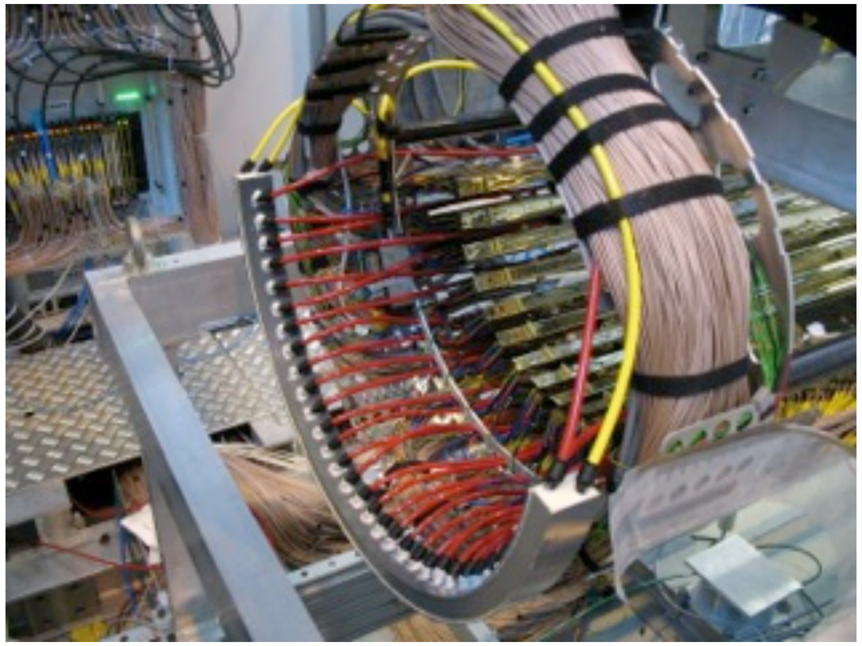
Back up

What can improve our result?

- Statistics : still the most important thing
  - 2011 data > 2009 data + 2010 data
  - 2012 data ≥ 2011 data
- Multi-buffer scheme for DAQ
  - Livetime improved, wider direction match table can be used
- Better e^+ resolution & detection efficiency
  - One of noise sources (HV distributor) is removed in 2011.
  - Thinner DC cables, preamplifiers, rearrangement of cable layout etc.
- Better gamma resolution & calibration
  - Stable & better quality data with new detector (BGO) for CEX
  - New reconstruction algorithm, improve Q.E. estimation etc.

Positron detection efficiency





- Positron efficiency ~ 40%
- New design of DC frames
  - Design of a new DC system – is a long term activity
- Feasible starting point for improvements
  - Thinner signal cables (1728ch)
  - Thinner Preamplifier PCB (576 pcb)
  - Expected: (50 +x) %

Purification system

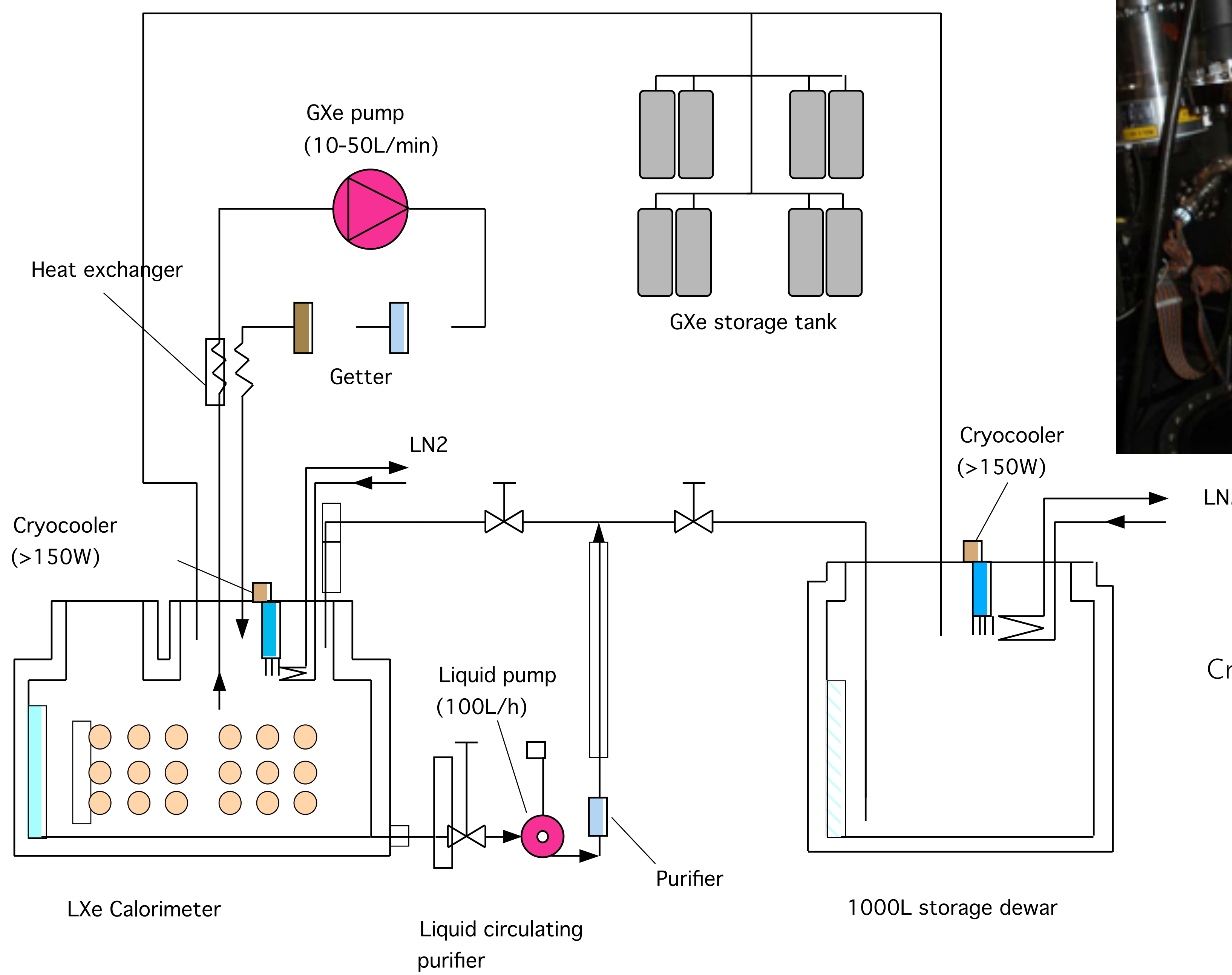
Gaseous purification

Metal heated getter

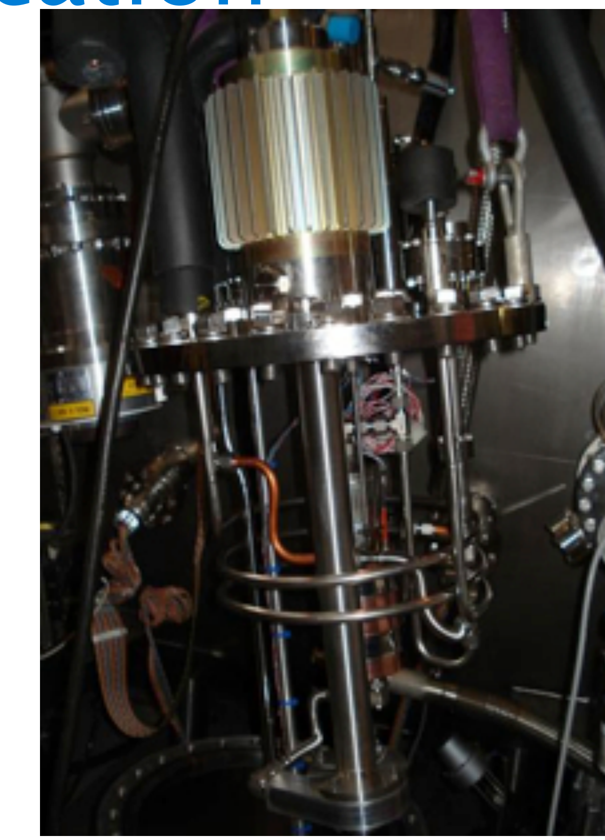
H_2O, O_2, N_2,...

Diaphragm pump

~1L/h



Liquid purification



Molecular sieves

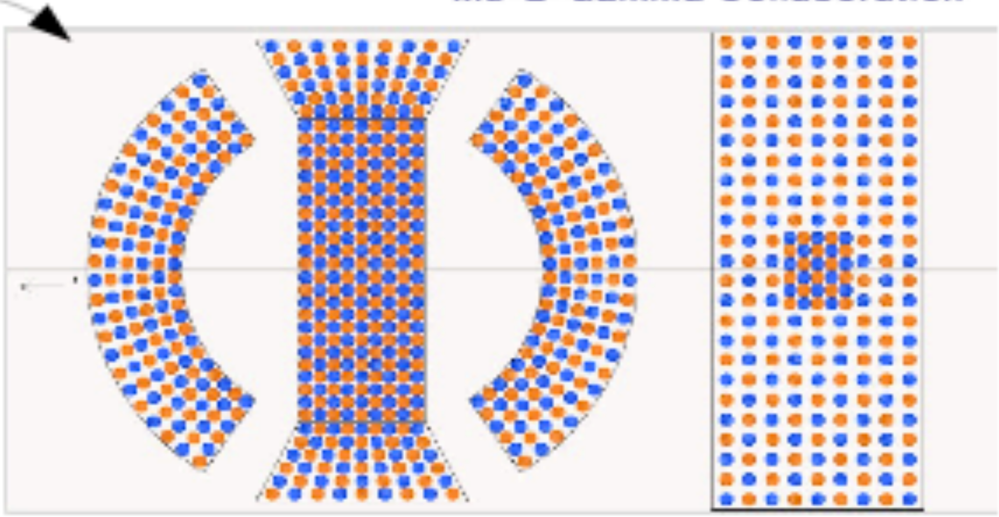
Mainly H_2O rejection

Cryogenic centrifugal pump

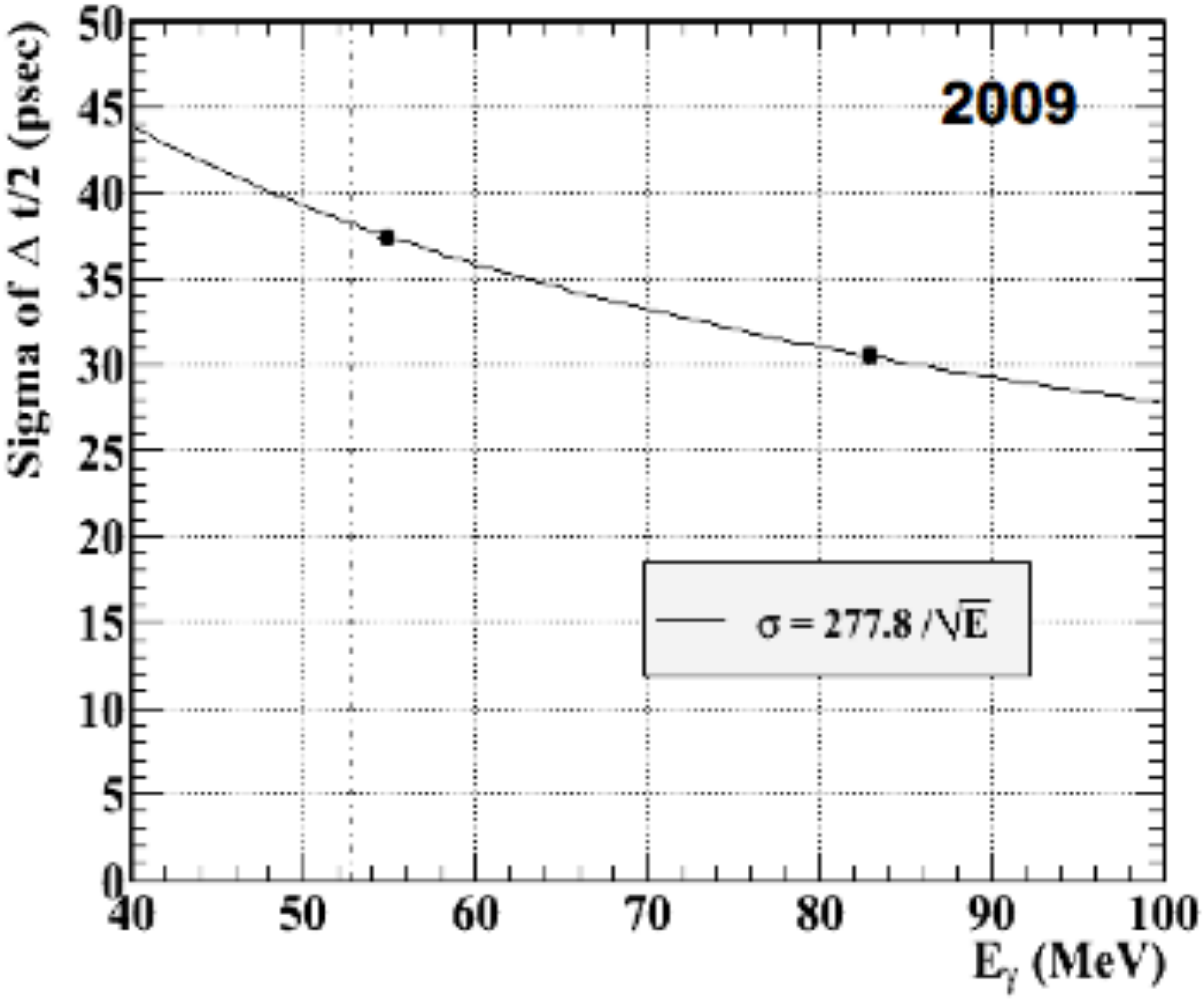
~100L/h

Intrinsic resolution

- PMTs are divided into 2 groups (odd, even)
- See difference of rec. time by the two
  - Electronics contribution canceled out
  - $\sigma((T_{odd} - T_{even})/2)$



	55 MeV	83 MeV
2008	44.7	36.0
2009	37.5	30.5
2010	36.4	28.4



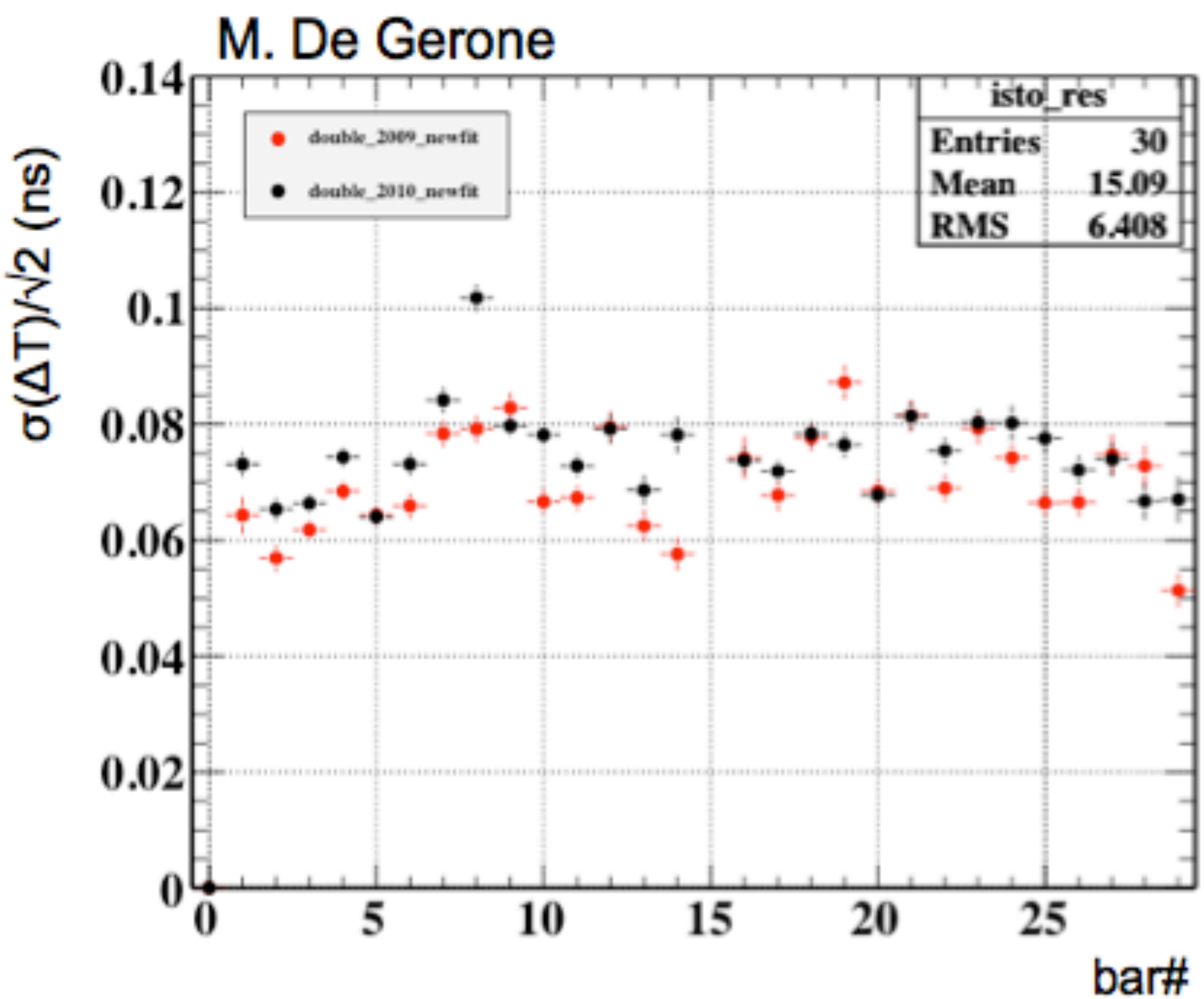
Intrinsic time resolution is dominated by p.e. statistics

16/Feb/2011 Yusuke UCHIYAMA

TC resolution: intrinsic+DRS

- $\sigma(\Delta T)/\sqrt{2}$ in double bar Michel events ⇒upper limit on TC intrinsic resolution +DRS

$$\Delta T = T_A - T_B$$

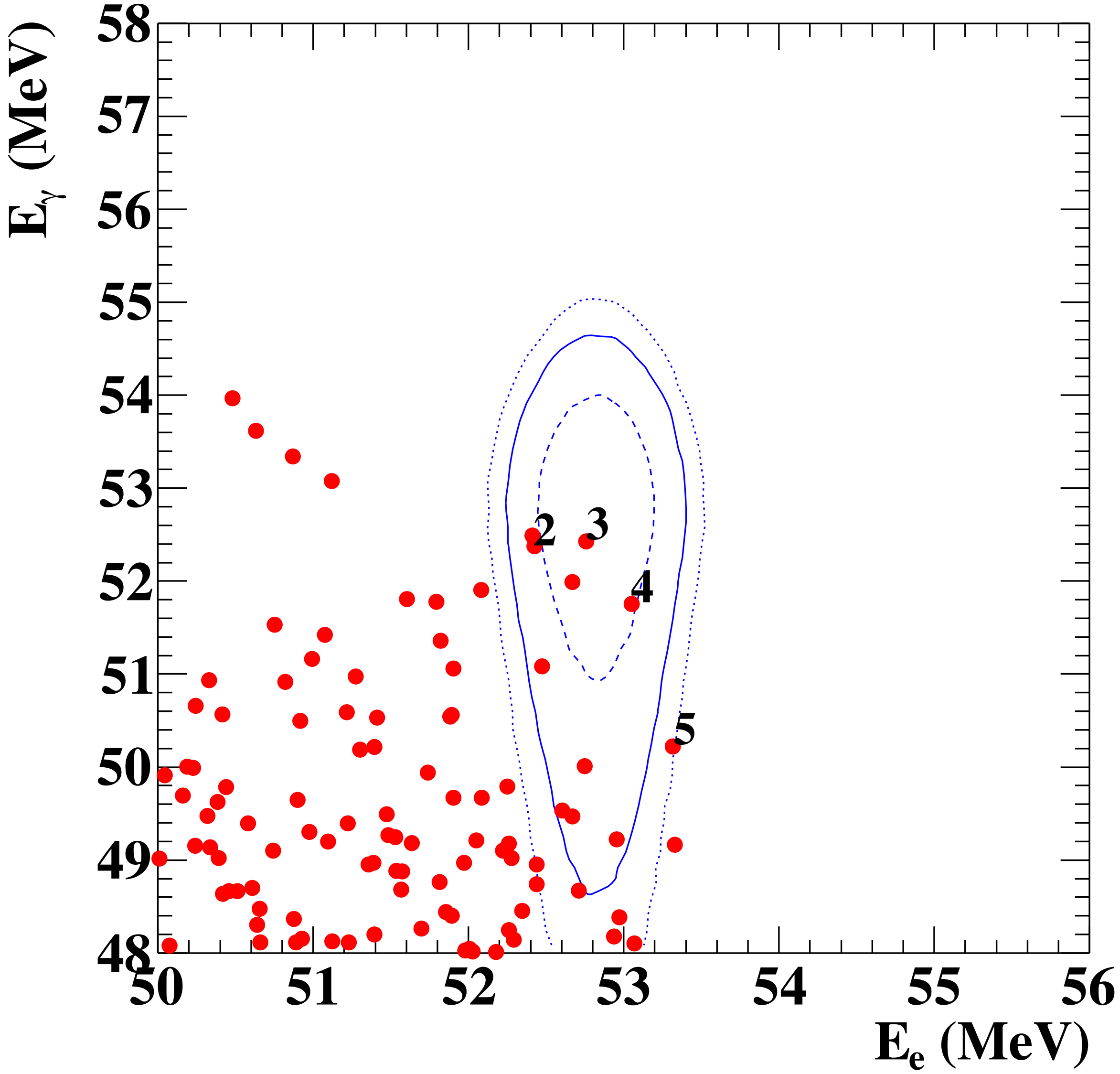


Estimate of resolution on positron impact point at TC: $\sigma(T_{TC})$~65 ps

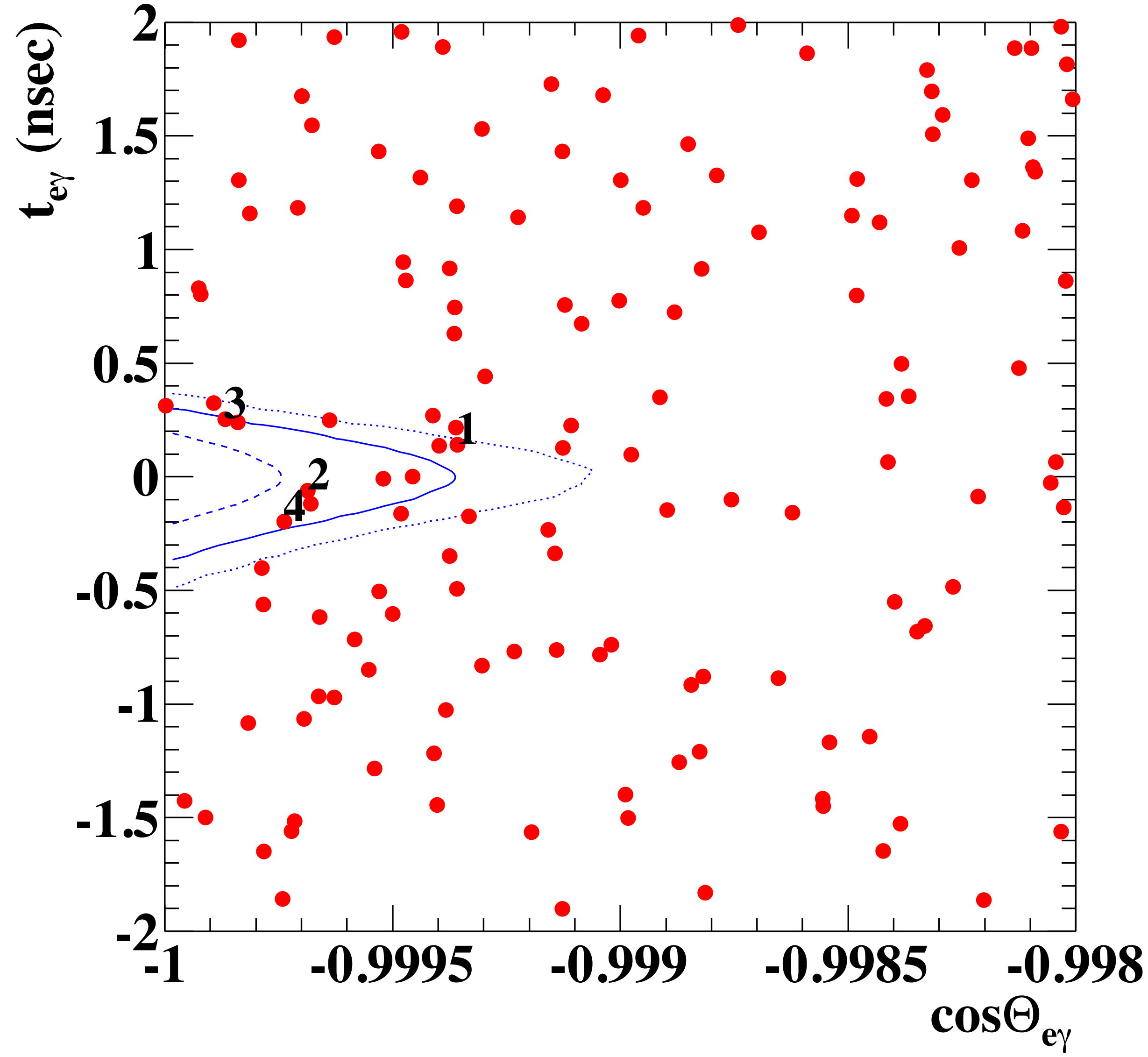
Resolution on average ~5 ps worse in 2010 with respect to 2009

4

2009+2010



E_γ (MeV)
E_e (MeV)
58
57
56
55
54
53
52
51
50
49
48
50
51
52
53
54
55
56
2
3
4
5



$t_{e\gamma}$ (nsec)
$\cos\Theta_{e\gamma}$
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-1
-0.9995
-0.999
-0.9985
-0.998
1
2
3
4

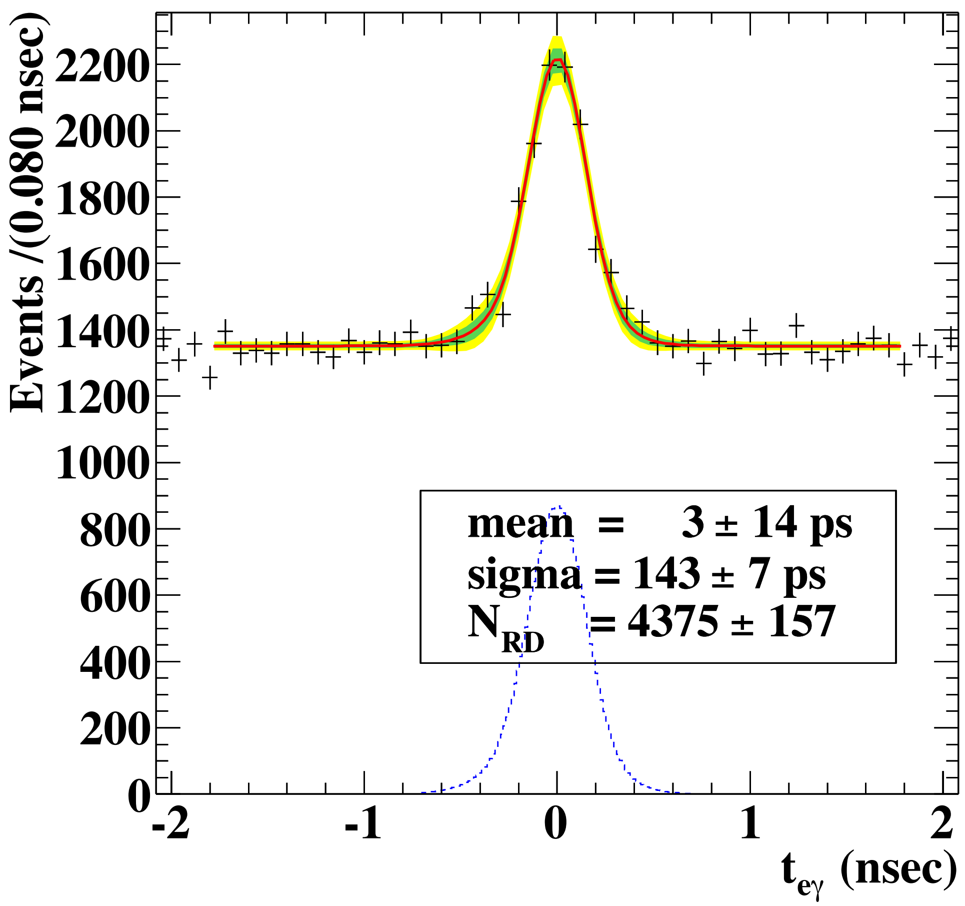
Timing

DRS, Electronics timing accuracy :

130→48 psec

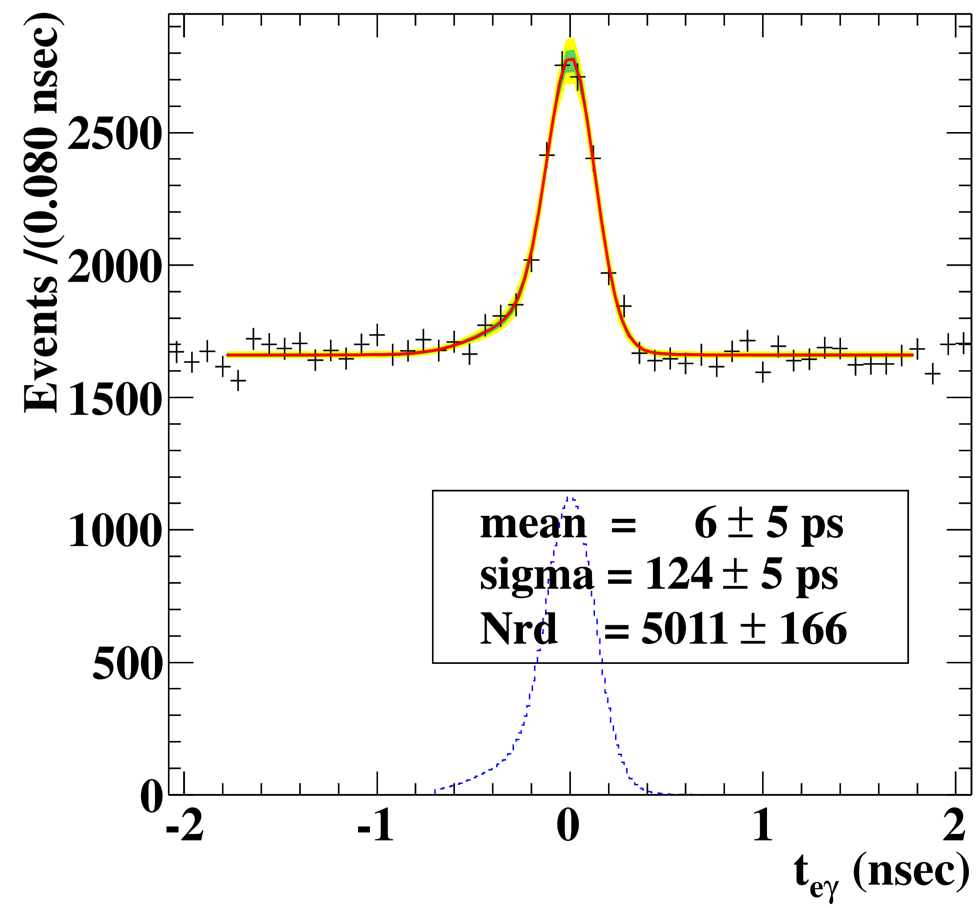
2009

143 ps



2010

124 ps

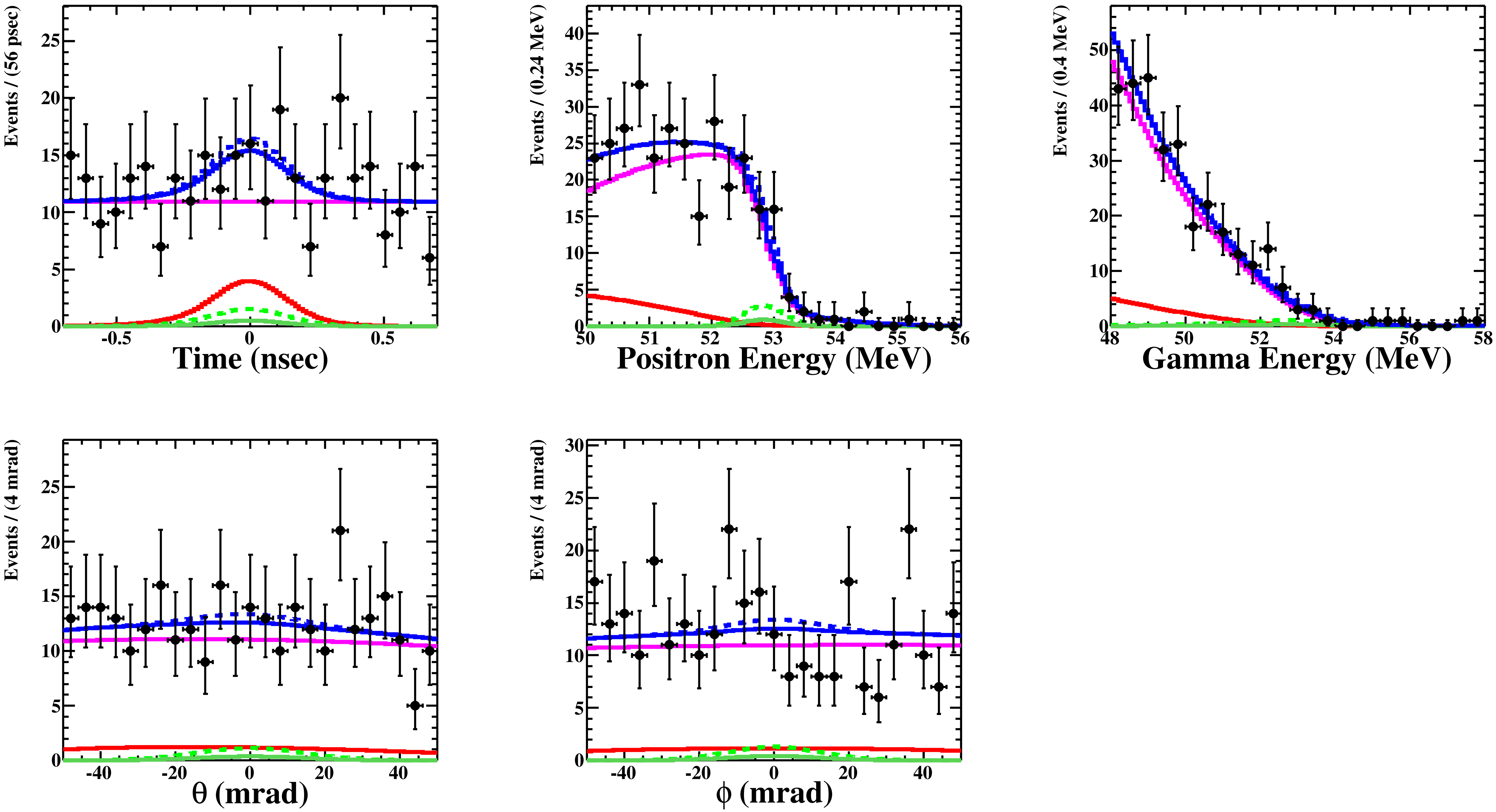


95% limit

$\mathcal{B} \times 10^{12}$

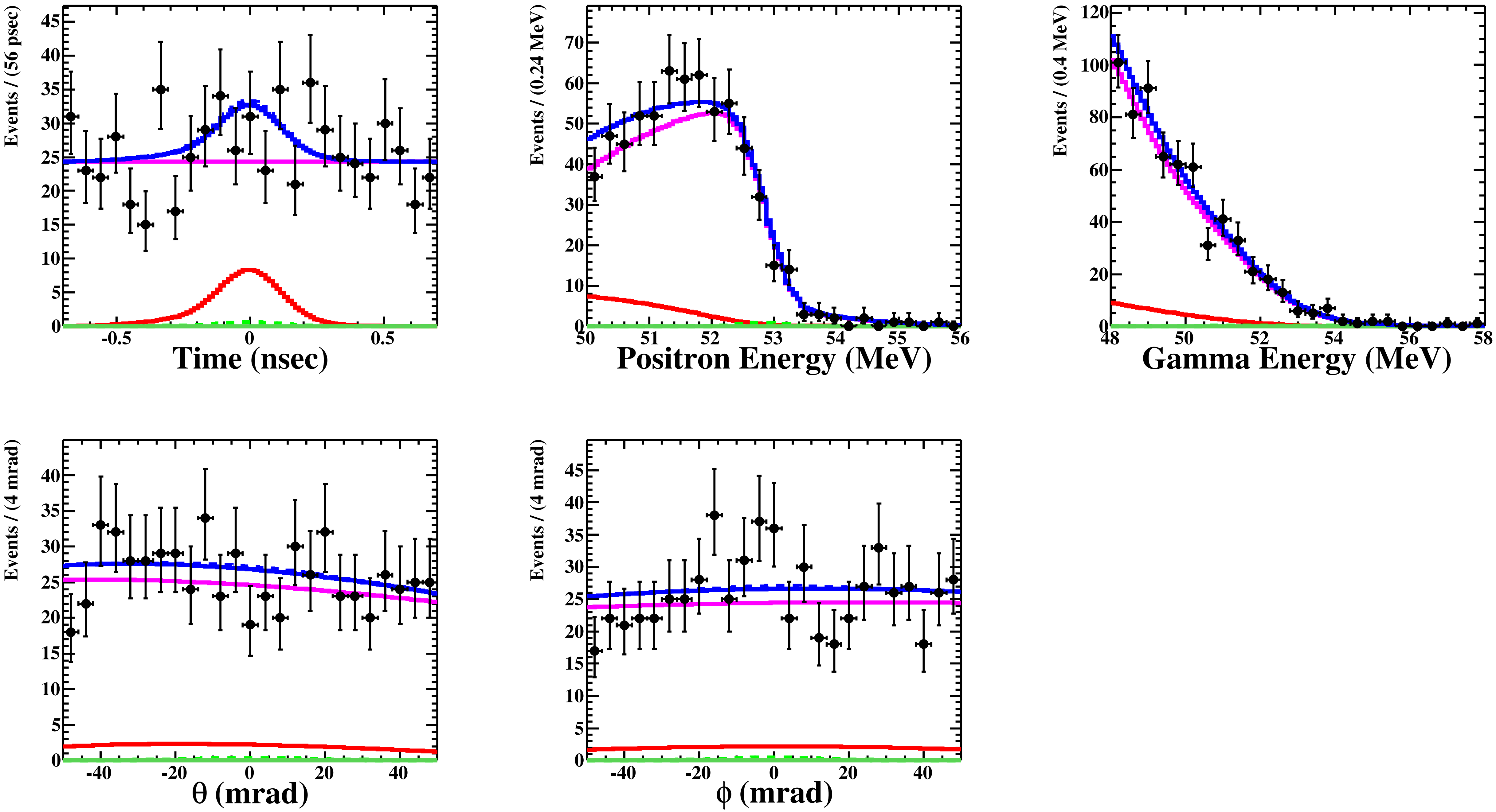
Data set	Best fit	LL (90% C.L.)	UL (90% C.L.)	UL (95% C.L.)
2009	3.2	0.17(0.17)	9.6 (9.4)	11 (11)
2010	-0.99	–	1.7 (1.7)	2.3 (2.2)
Combined	-0.15	–	2.4 (2.3)	2.9 (2.8)

2009



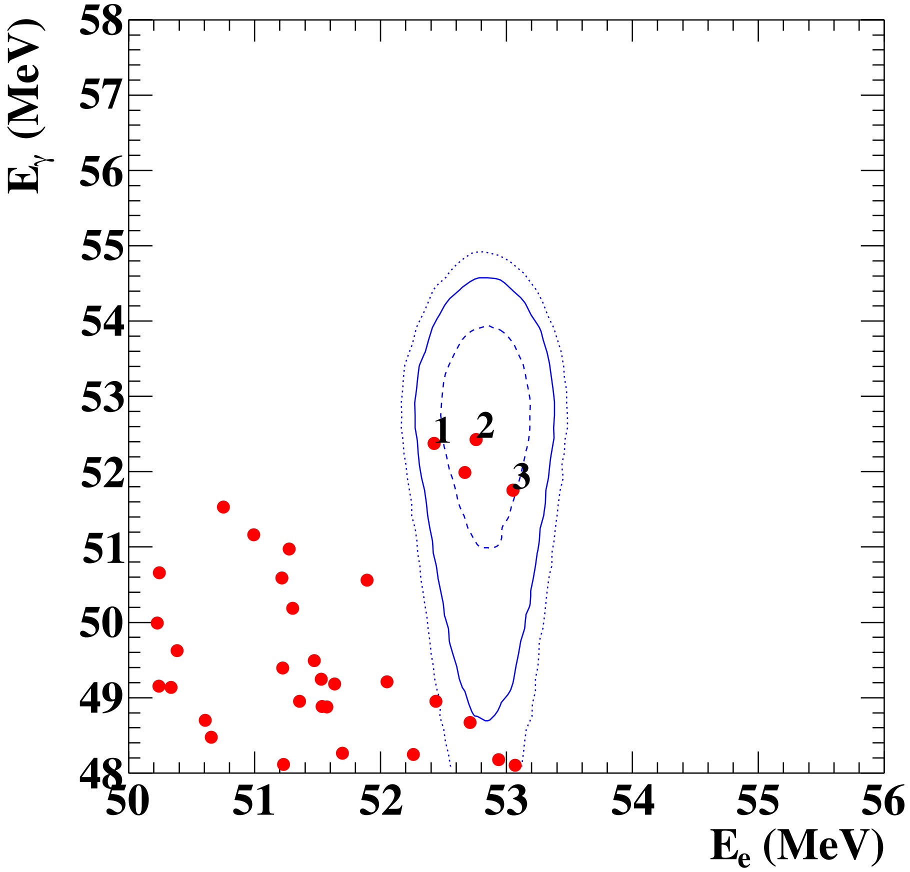
Events / (56 psec)
Time (nsec)
Events / (0.24 MeV)
Positron Energy (MeV)
Events / (0.4 MeV)
Gamma Energy (MeV)
Events / (4 mrad)
θ (mrad)
Events / (4 mrad)
ϕ (mrad)

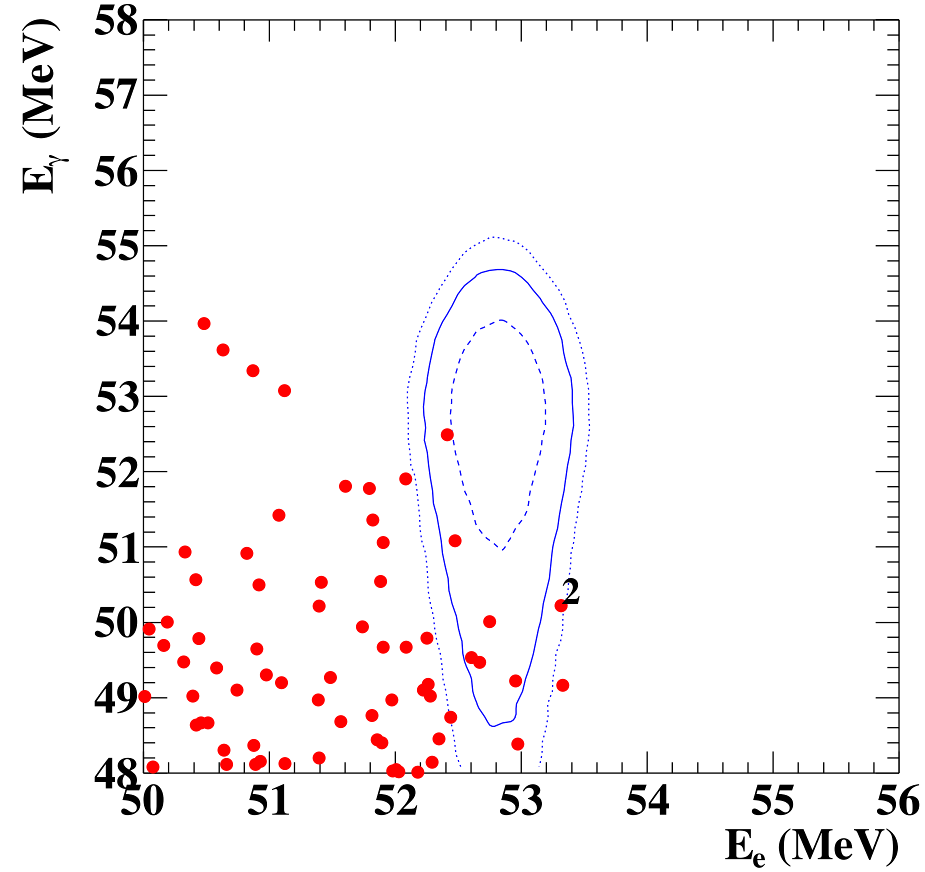
2010

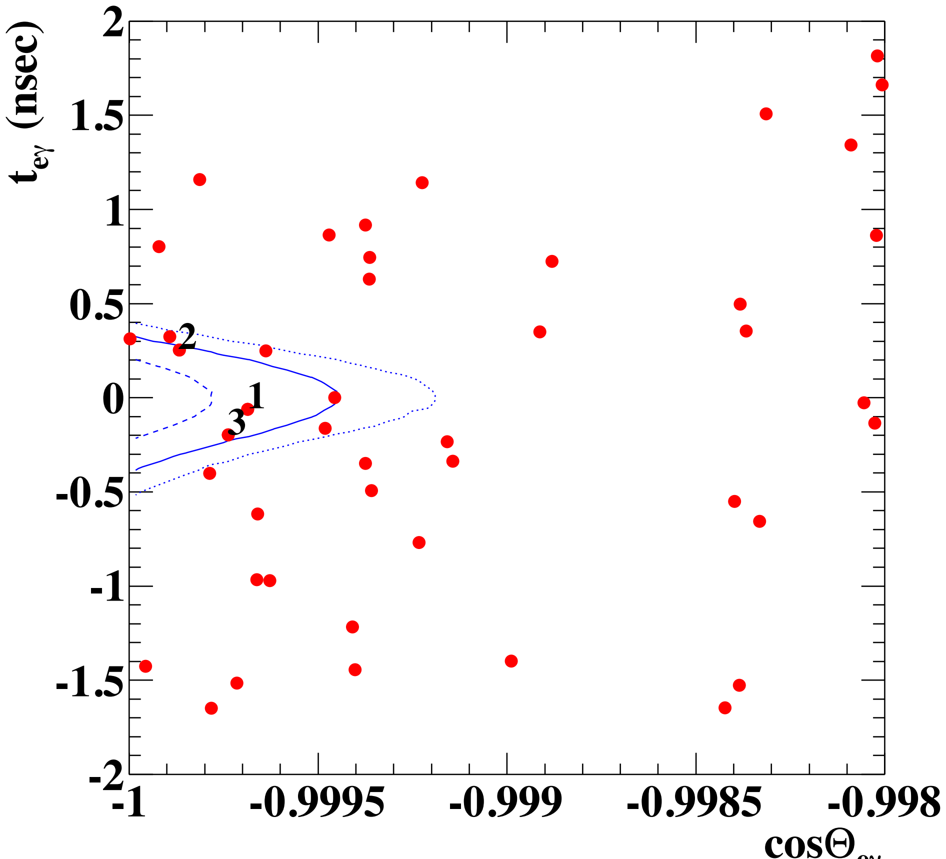

Events / (56 psec)
Time (nsec)
-0.5
0
0.5
Events / (0.24 MeV)
Positron Energy (MeV)
50
51
52
53
54
55
56
Events / (0.4 MeV)
Gamma Energy (MeV)
48
50
52
54
56
58
Events / (4 mrad)
θ (mrad)
Events / (4 mrad)
ϕ (mrad)
-40
-20
0
20
40

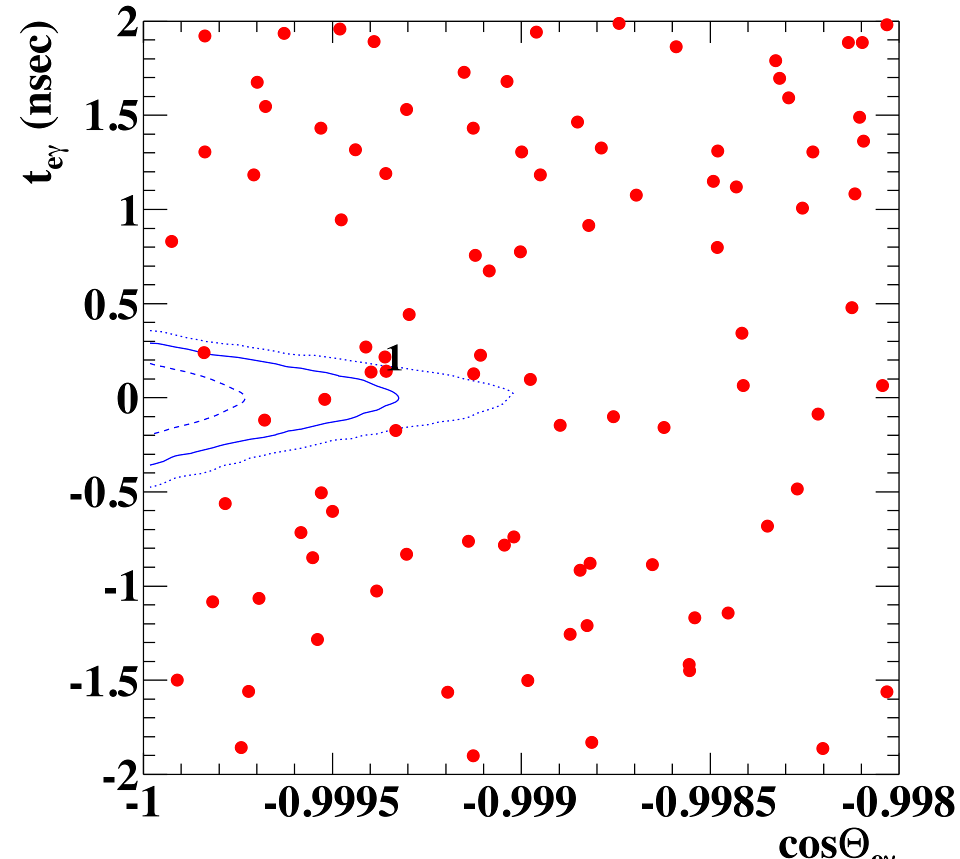
2009

2010


E_γ (MeV)
E_e (MeV)
58 57 56 55 54 53 52 51 50 49 48
50 51 52 53 54 55 56
1 2 3

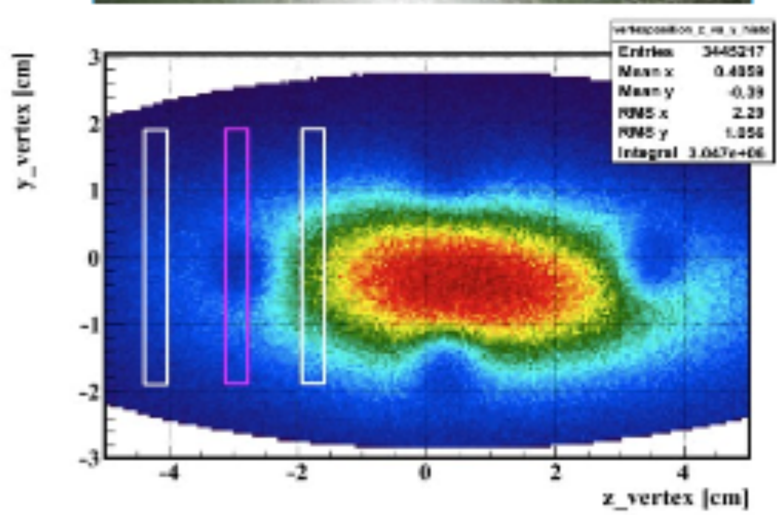

E_γ (MeV)
E_e (MeV)
58 57 56 55 54 53 52 51 50 49 48
50 51 52 53 54 55 56
2

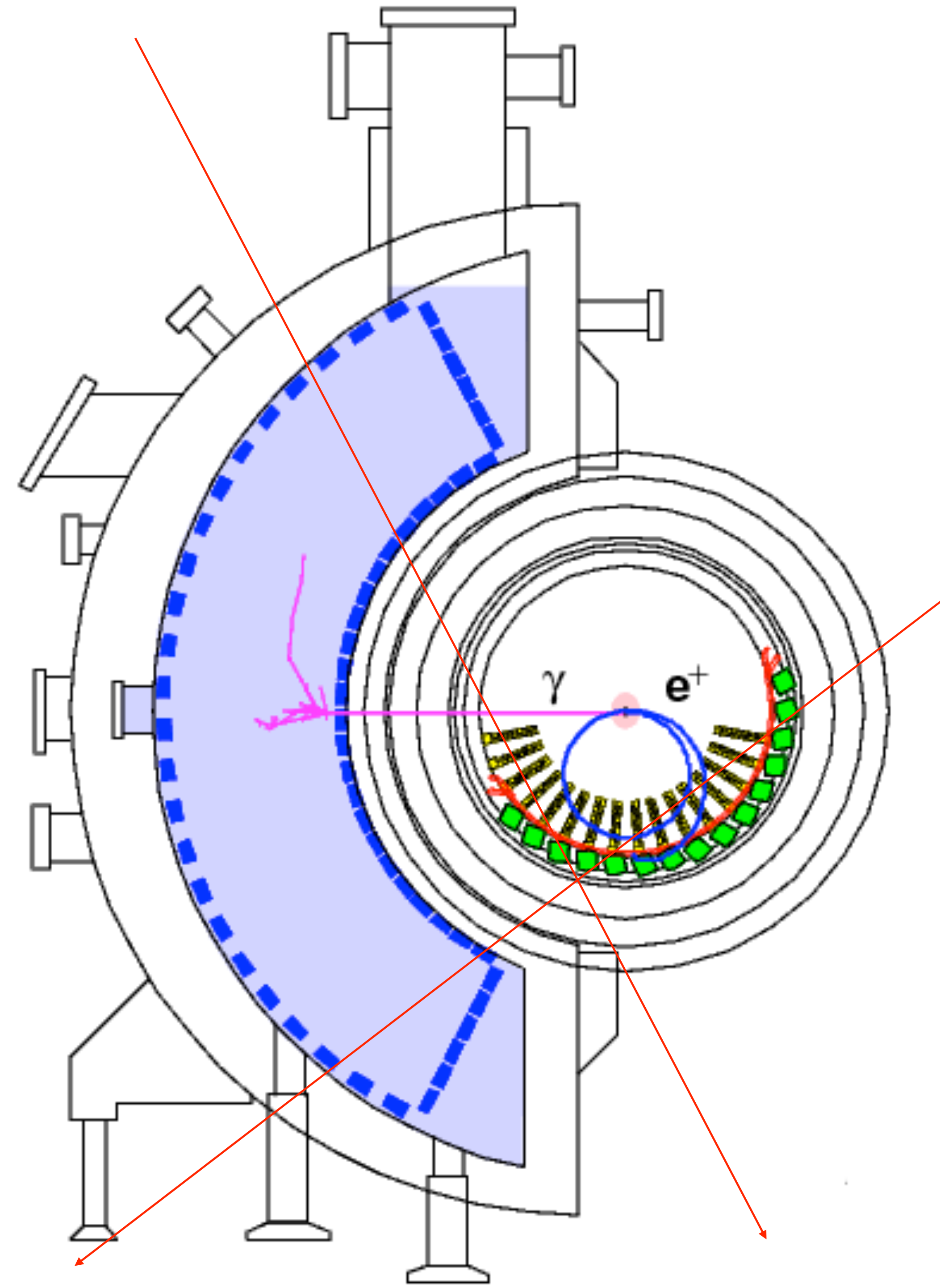

$t_{e\gamma}$ (nsec)
$\cos\Theta_{e\gamma}$
2 1.5 1 0.5 0 -0.5 -1 -1.5 -2
-1 -0.9995 -0.999 -0.9985 -0.998
1 2 3


$t_{e\gamma}$ (nsec)
$\cos\Theta_{e\gamma}$
2 1.5 1 0.5 0 -0.5 -1 -1.5 -2
-1 -0.9995 -0.999 -0.9985 -0.998
1

Alignment inside/among detectors

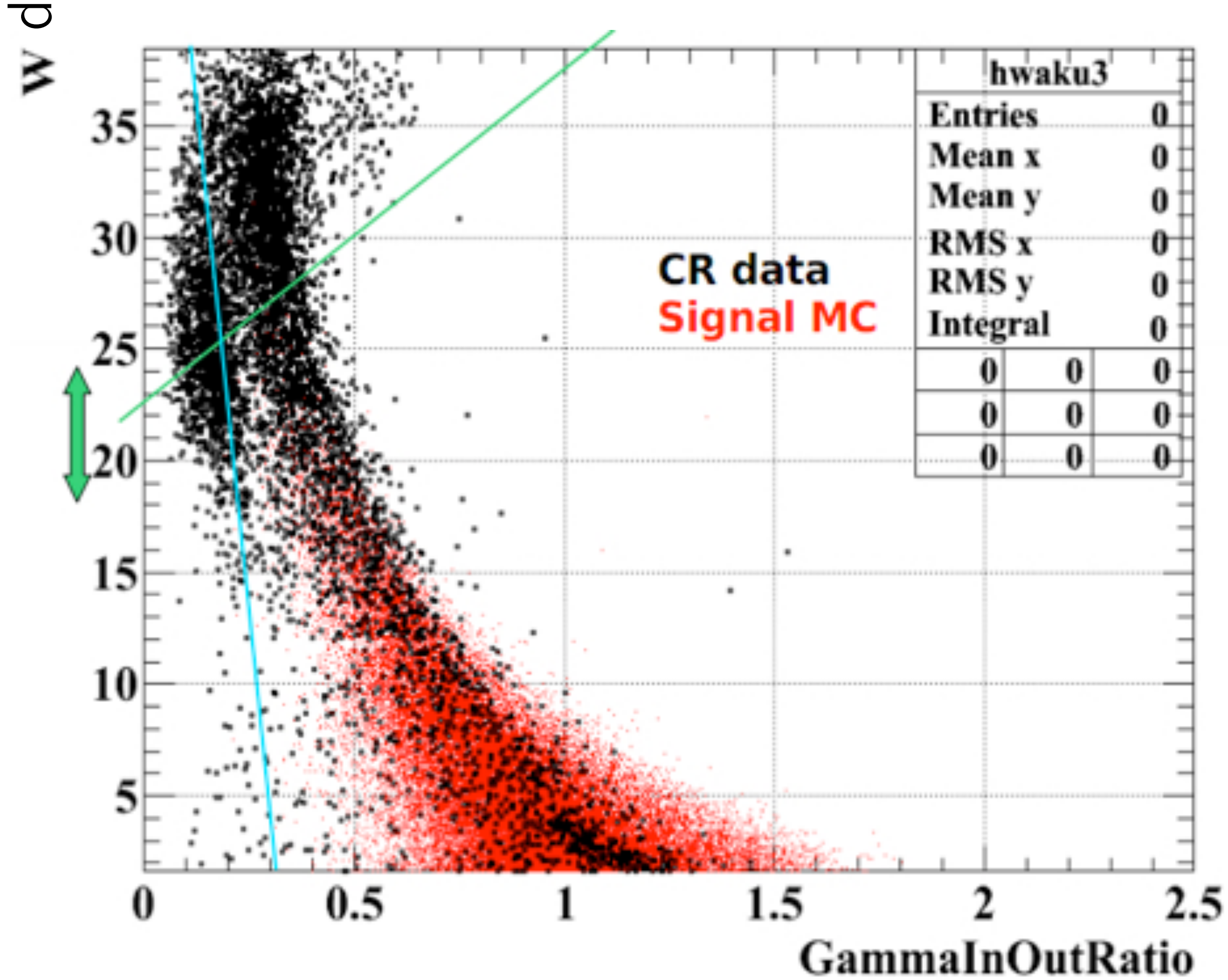
- Optical surveys
  - DC – target
  - double-checked by target holes
- Alignment by CR
  - DC – XEC
  - DC
- LXe
  - Pb collimators
  - AmBe





Background rejection

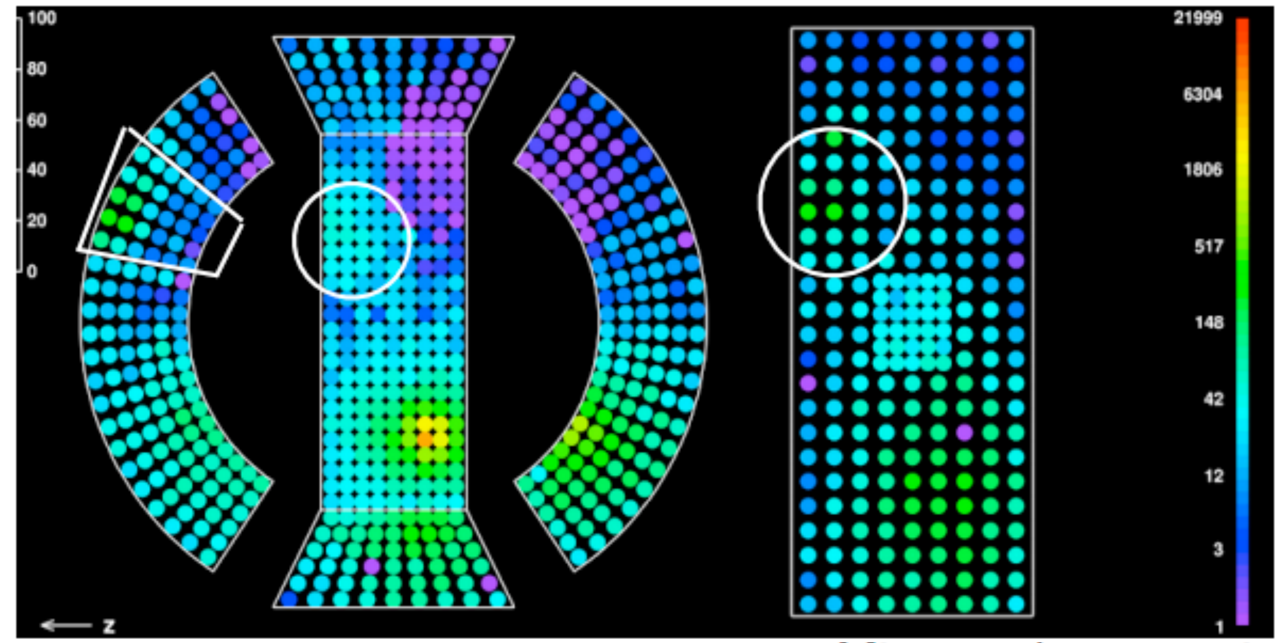
Cosmic ray rejection



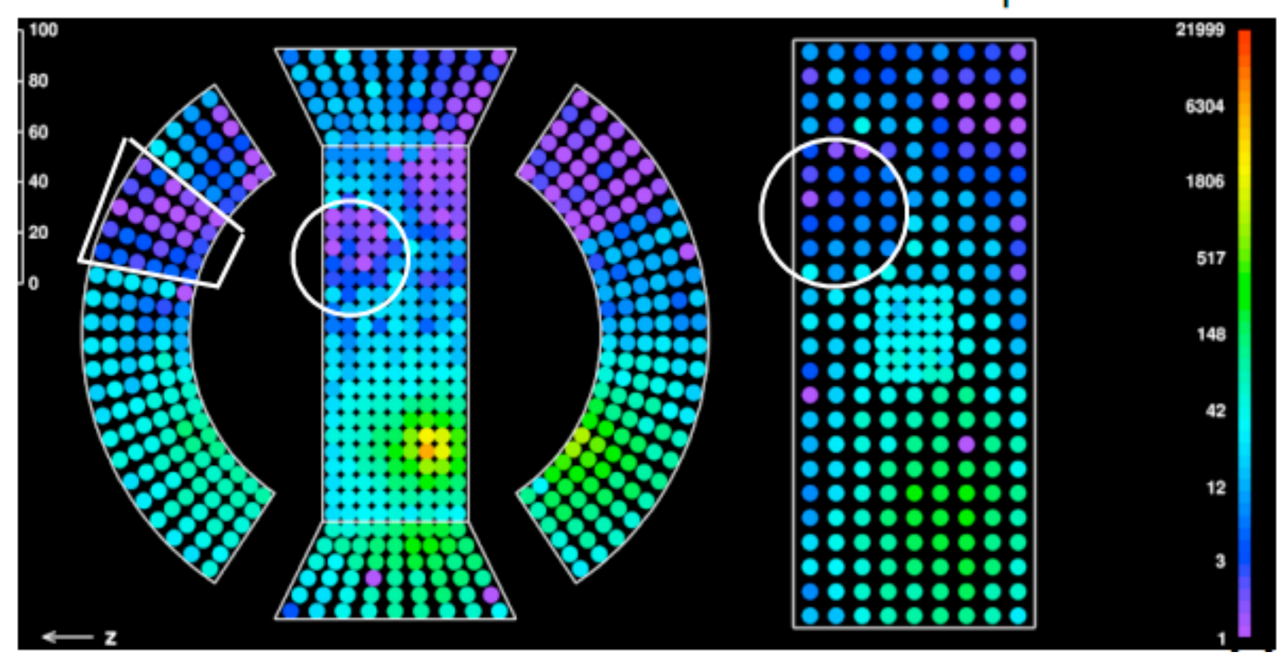
Inner/Outer charge Ratio

Pileup elimination

Original

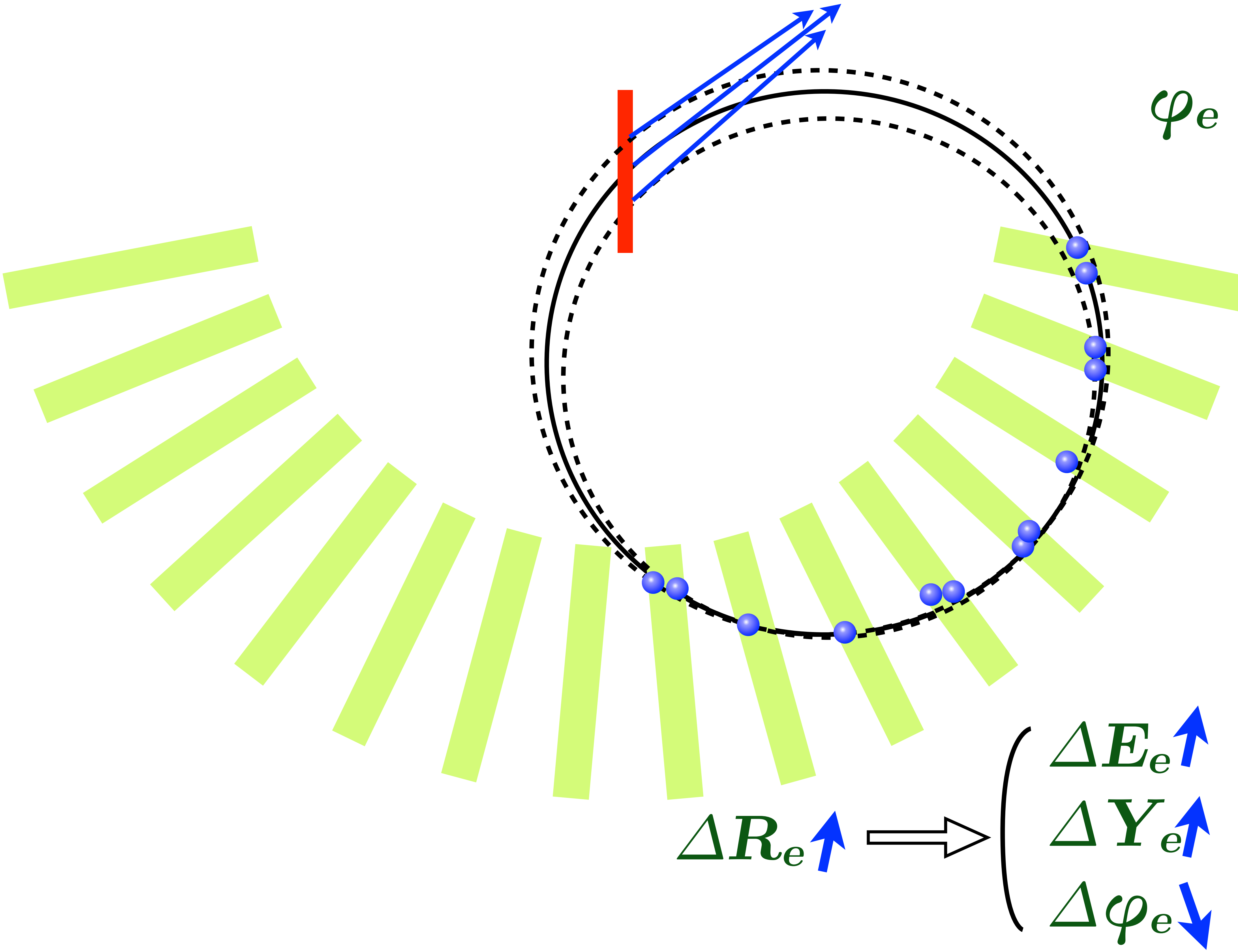


After replacement

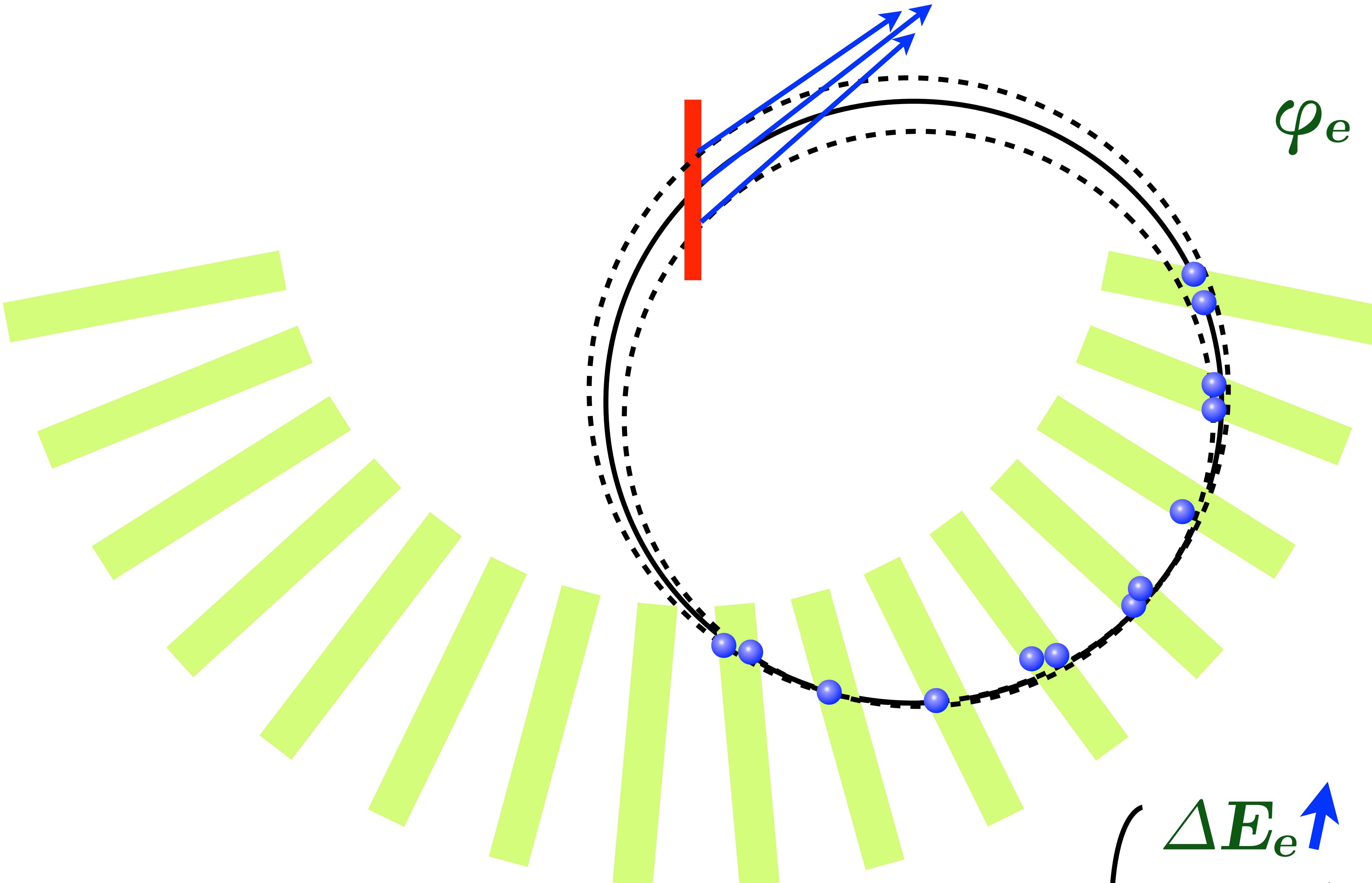


1. Find pileup
2. Reconstruct energy w/o pileup region, calculate expected charge
3. Replace these charge

Correlations in positron variables



Correlations in positron variables

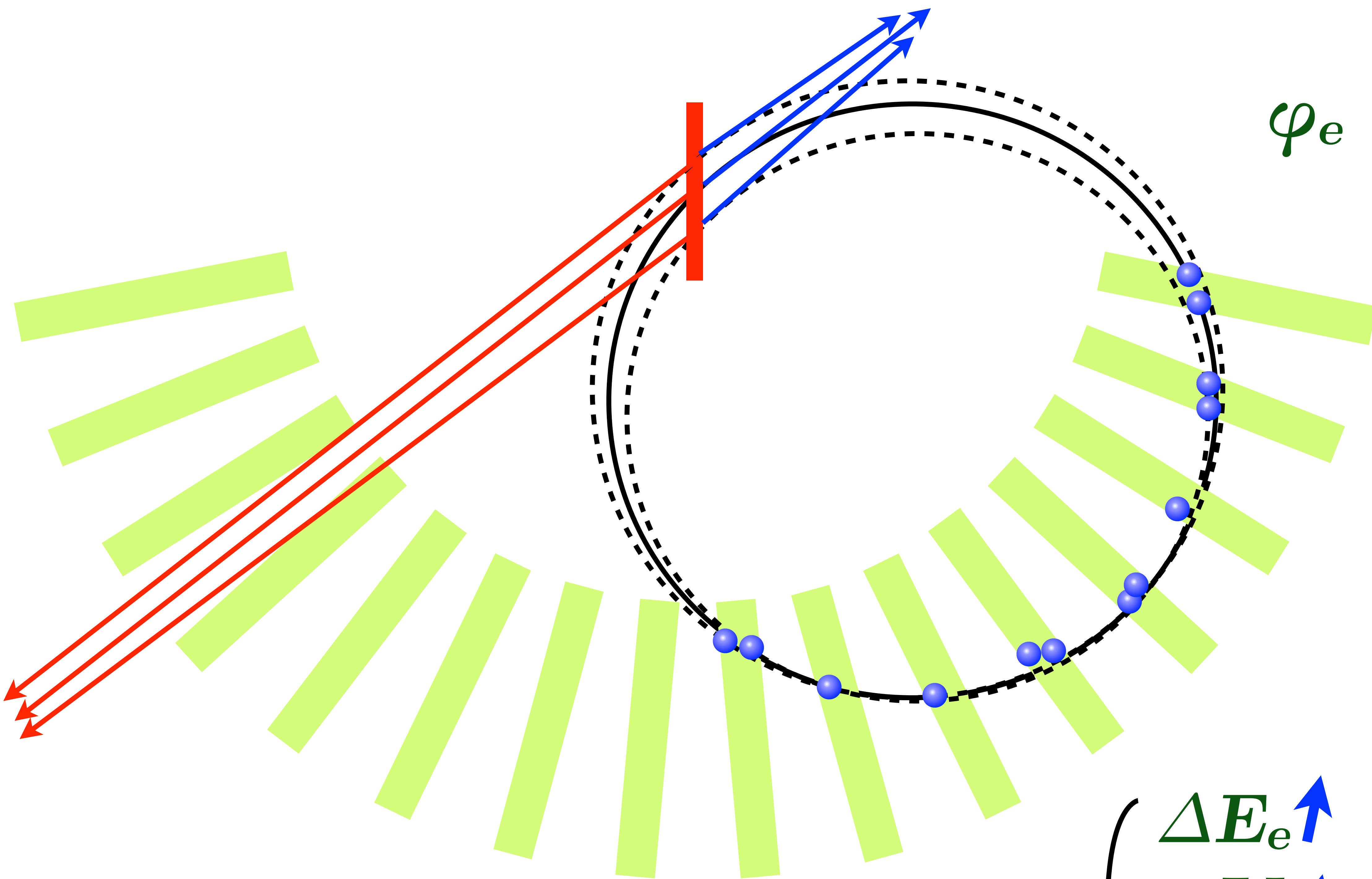


$\varphi_e > 0$

$\Delta R_e \uparrow \Rightarrow \begin{cases} \Delta E_e \uparrow \\ \Delta Y_e \uparrow \\ \Delta \varphi_e \downarrow \end{cases}$

$\Delta R_e \uparrow \Rightarrow \Delta t_e \downarrow$

Correlations in positron variables

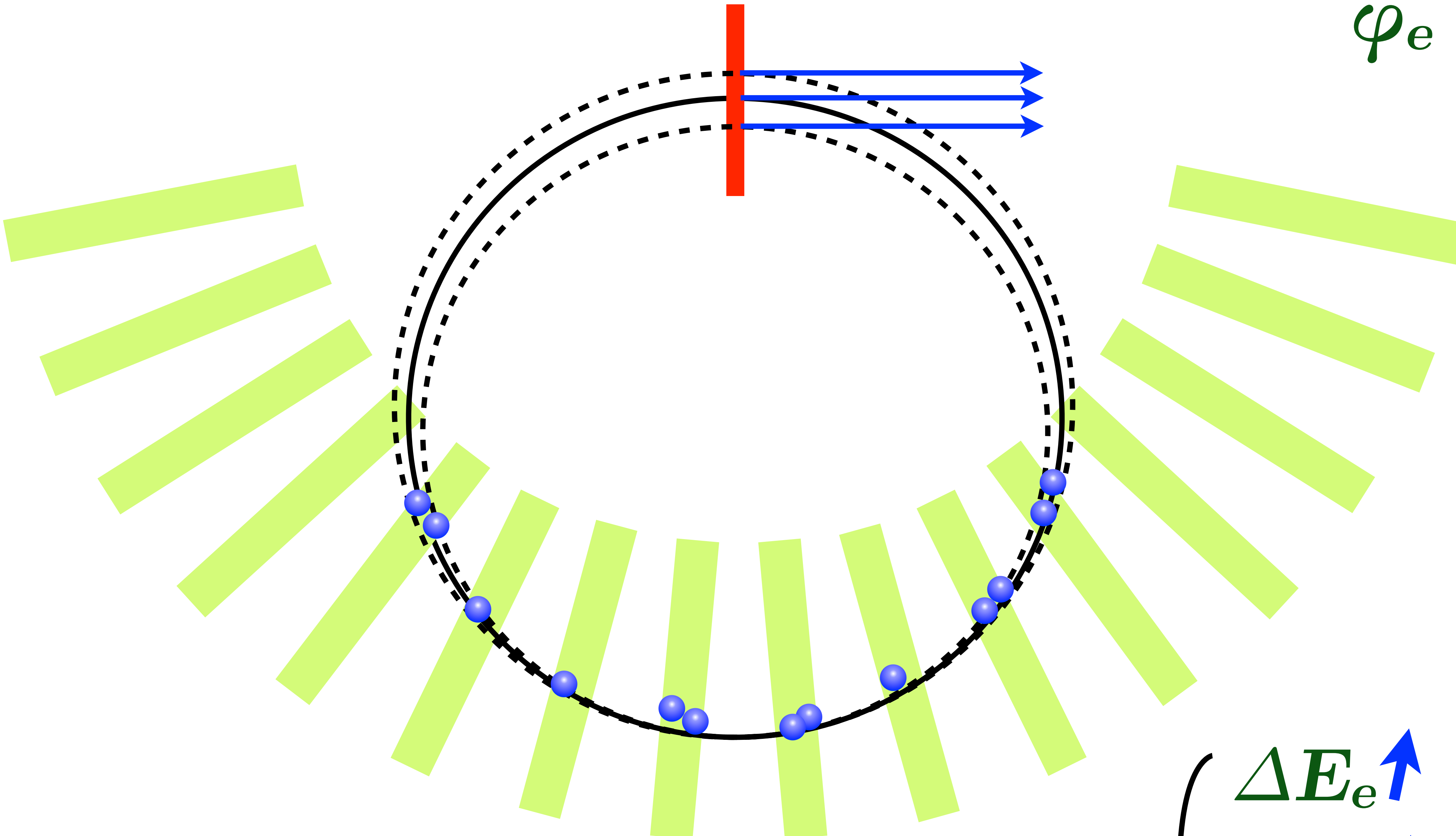


$$\Delta R_e \uparrow \Rightarrow \left(\begin{array}{l} \Delta E_e \uparrow \\ \Delta Y_e \uparrow \Rightarrow \Delta\varphi_\gamma \uparrow \\ \Delta\varphi_e \downarrow \end{array} \right.$$

$$\Delta R_e \uparrow \Rightarrow \Delta t_e \downarrow$$

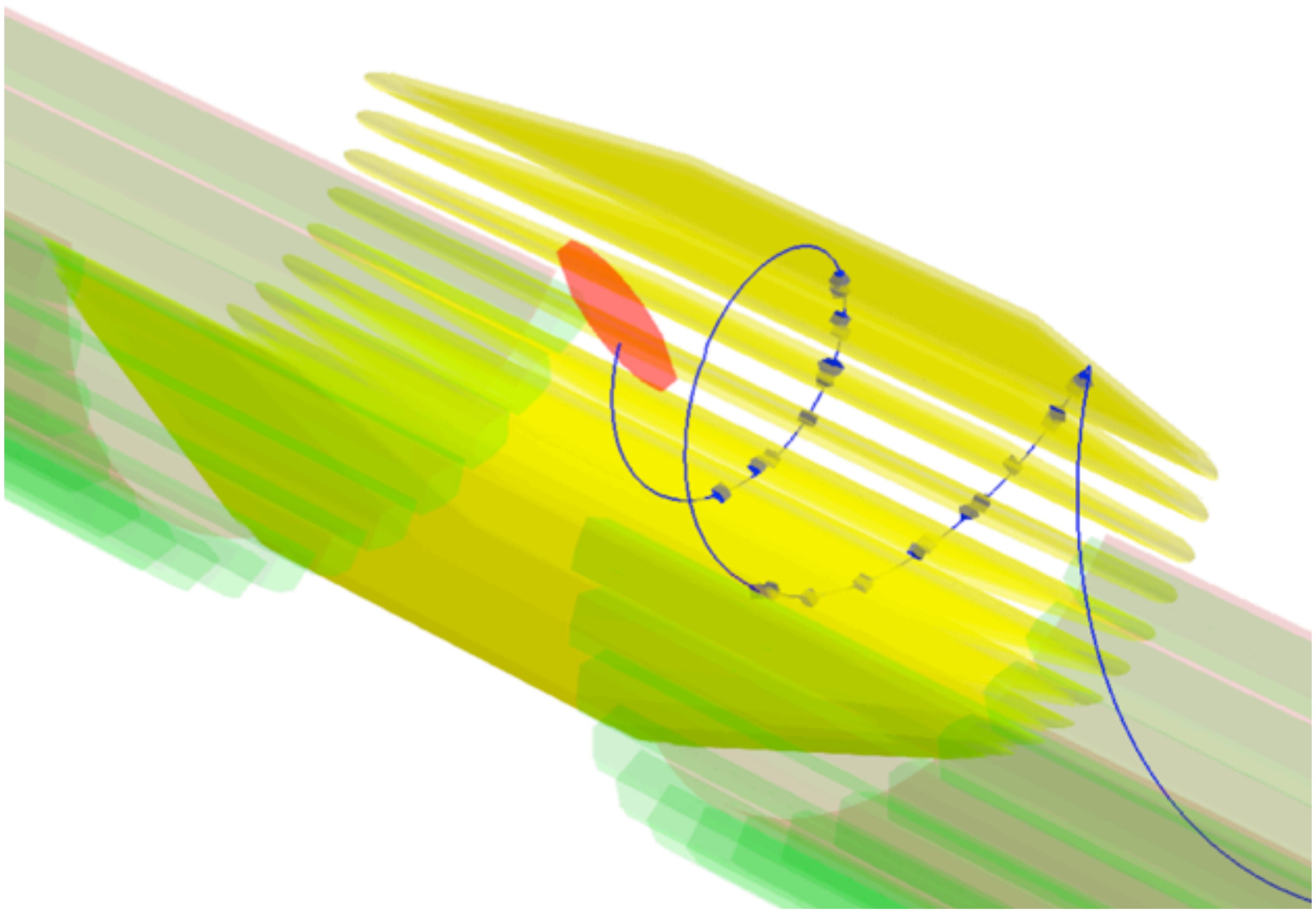
Correlations in positron variables

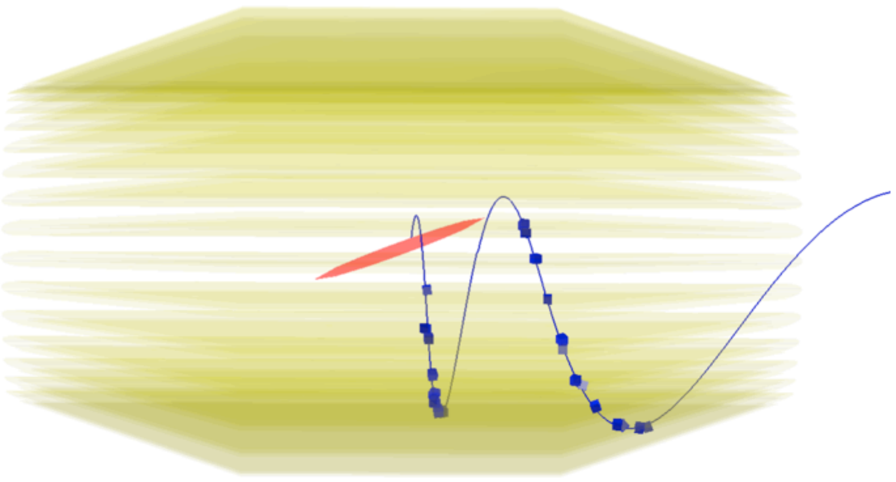
$\varphi_e = 0$

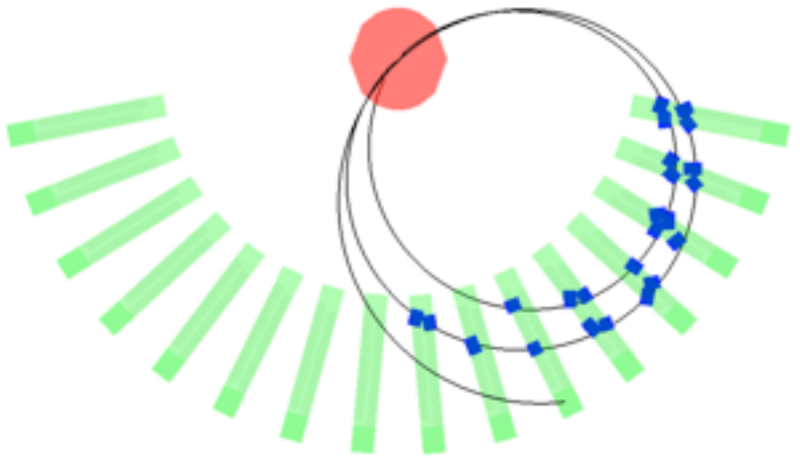


$\Delta R_e \uparrow \Longrightarrow \begin{cases} \Delta E_e \uparrow \\ \Delta Y_e \uparrow \\ \Delta \varphi_e = 0 \end{cases}$

two turn method



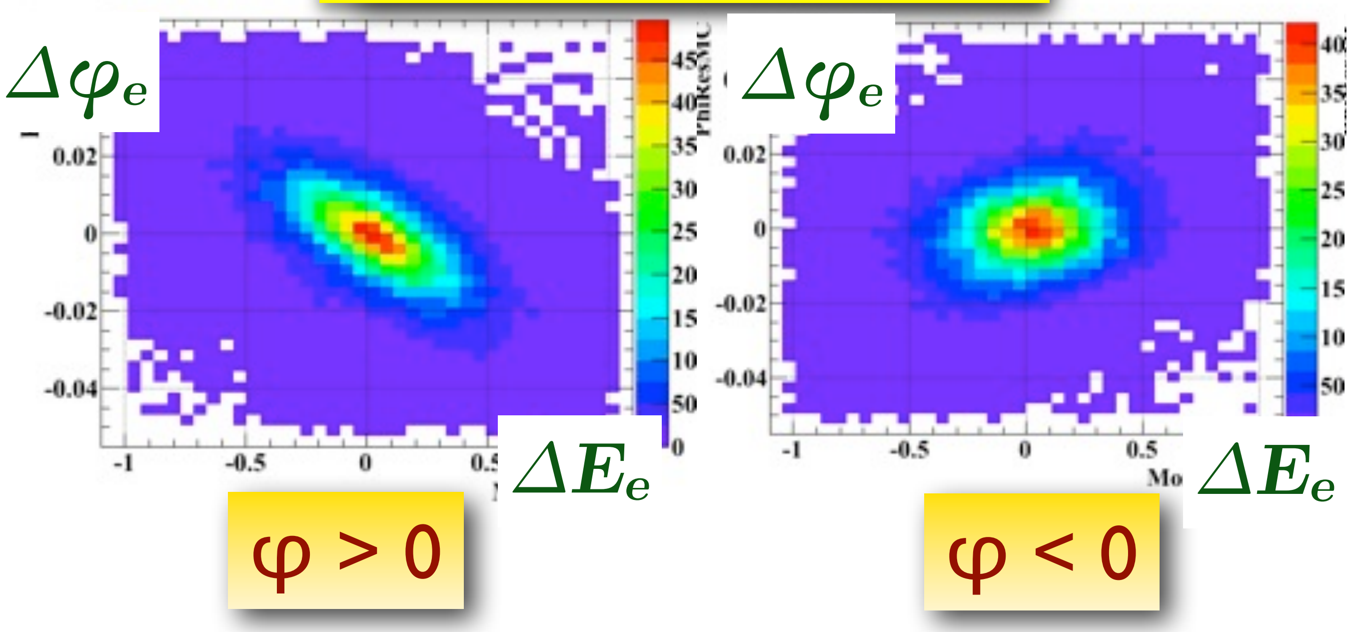




Correlations

e.g. Δφ vs ΔE

MC : Observed - True

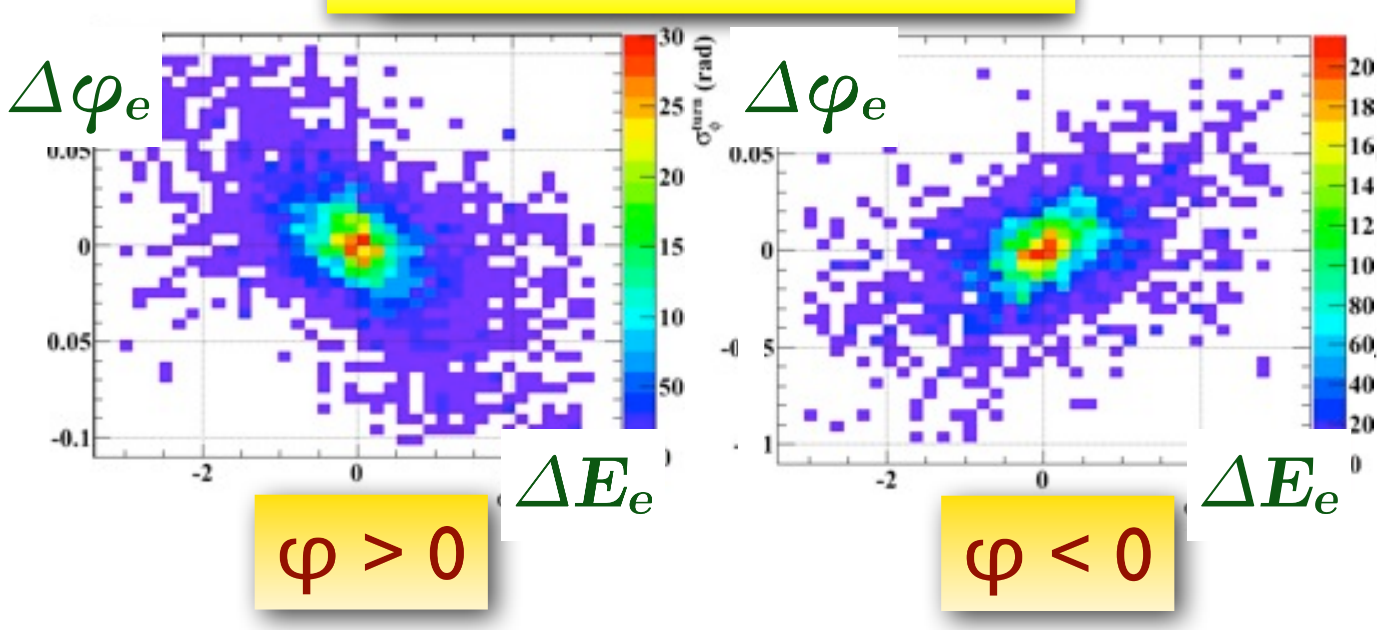


Many of correlations can be measured using data

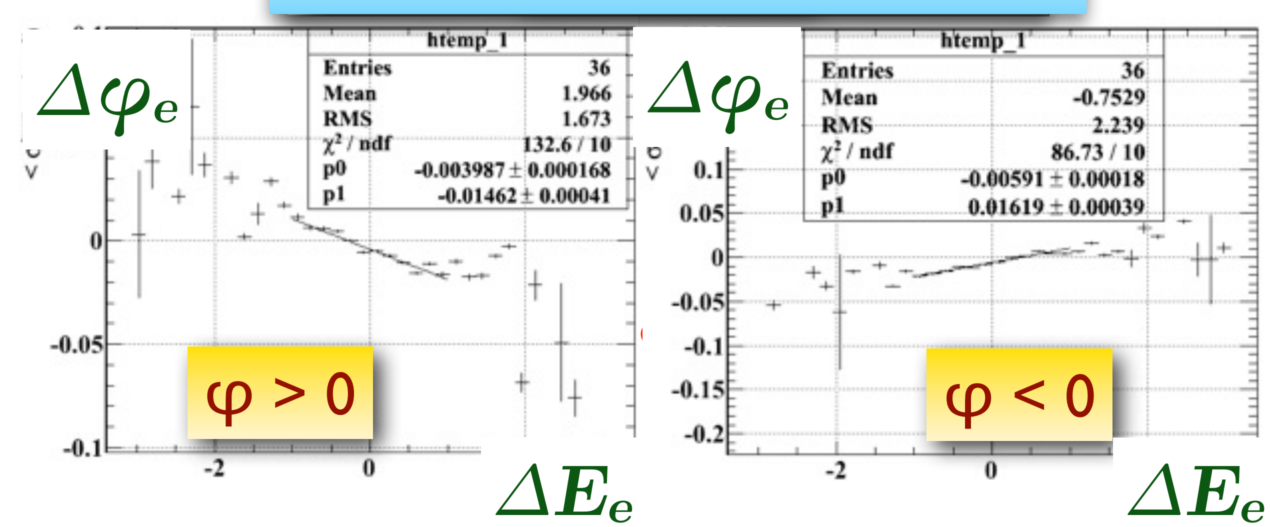
Agreement with MC <10%

Large uncertainty 25% is assigned to un-measurable correlations

MC : two turn method



Data : two turn method



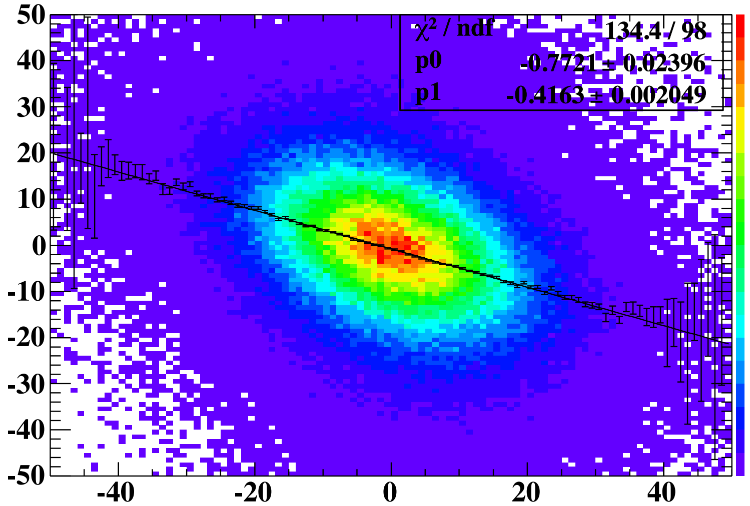
Correlations and physics analysis

All the known correlations are implemented in signal PDF including event-by-event feature

Both the **fitting** and the **toy-MC generation**

Full MC $\varphi_{e\gamma}$ vs $\vartheta_{e\gamma}$

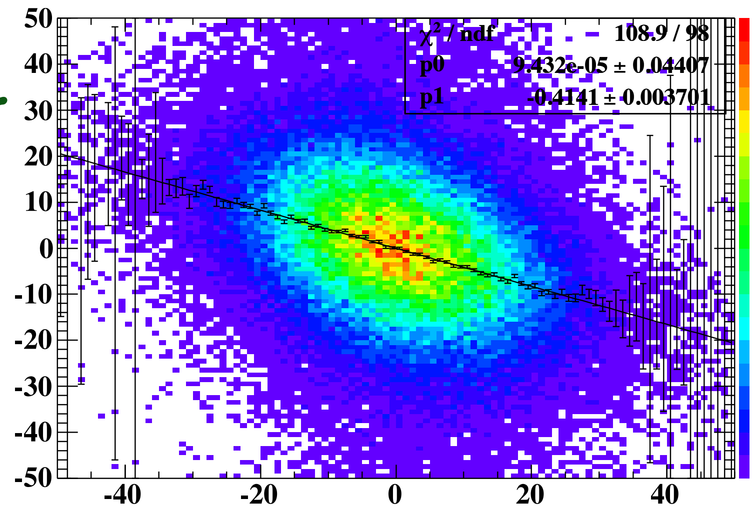
$\varphi_{e\gamma}$



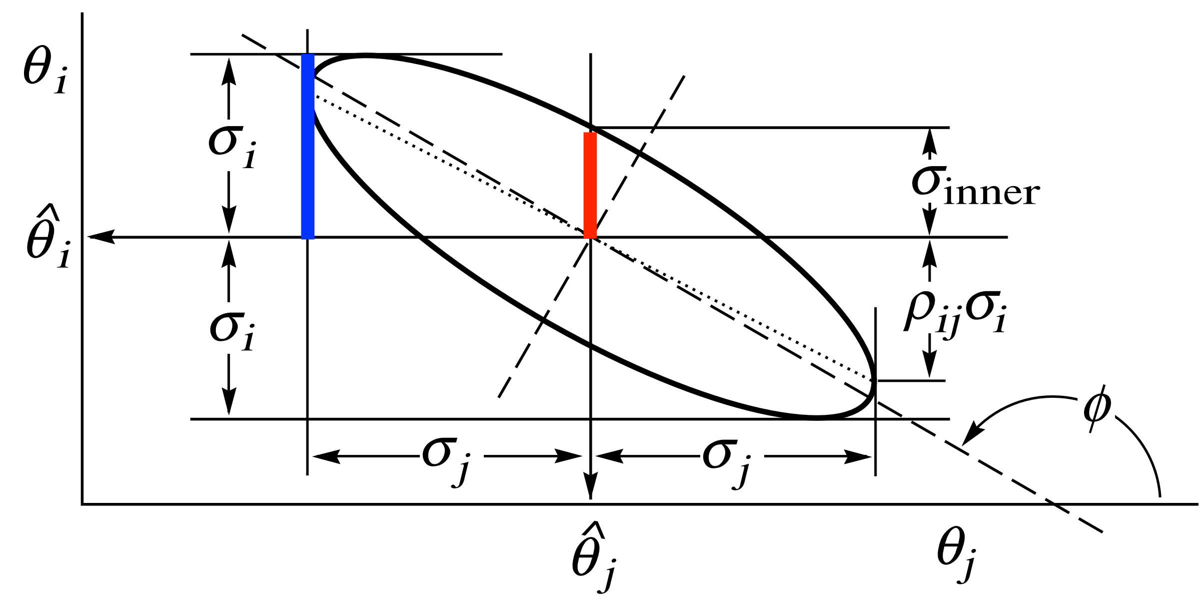
$\vartheta_{e\gamma}$

Toy MC $\varphi_{e\gamma}$ vs $\vartheta_{e\gamma}$

$\varphi_{e\gamma}$



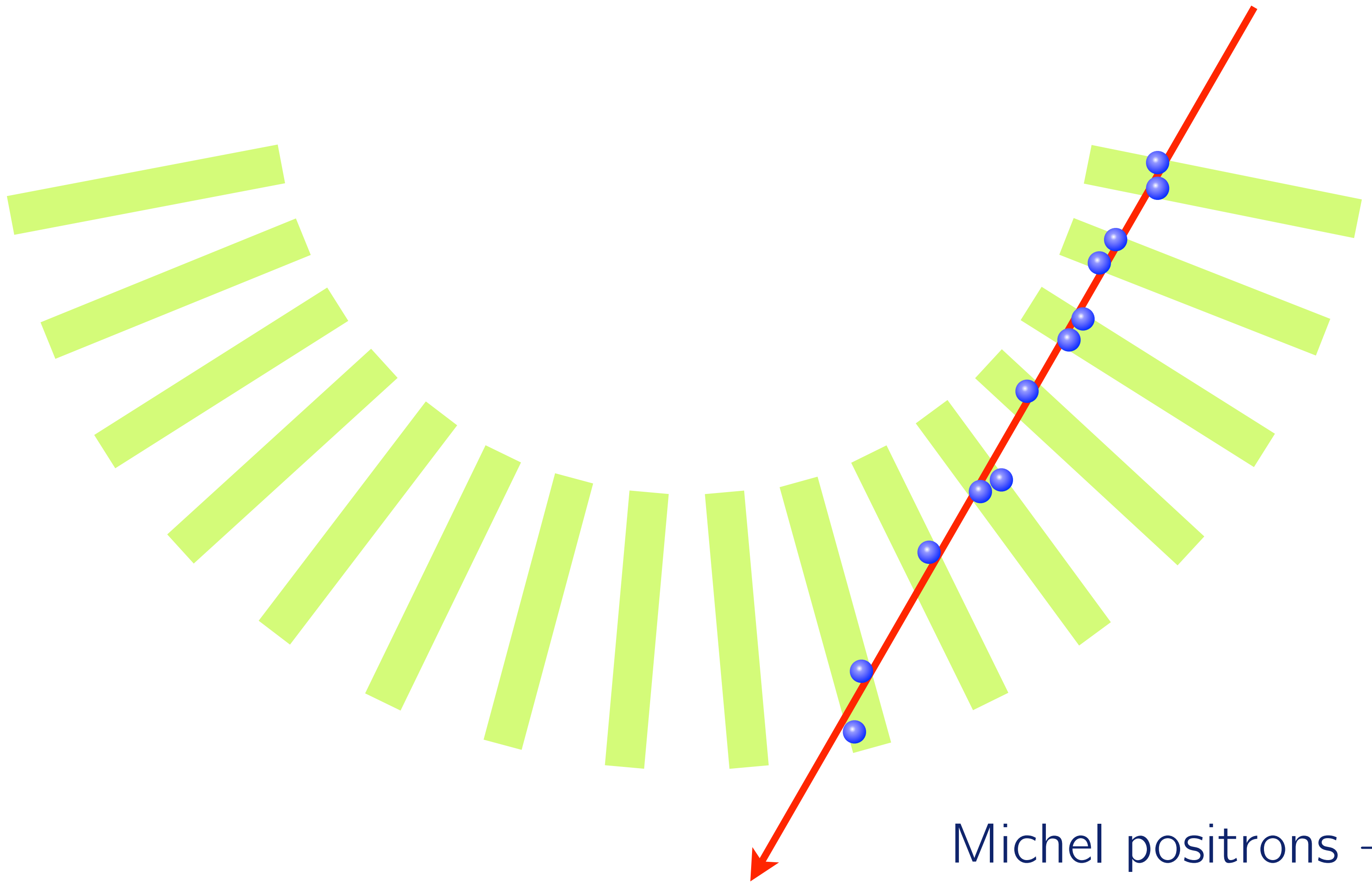
$\vartheta_{e\gamma}$



When correlation is included,

σ_{inner} is used, instead of σ_i

Alignment of drift chambers



Initial values : optical survey

Michel positrons → Cosmic rays

Iterative process → Fitting all chambers

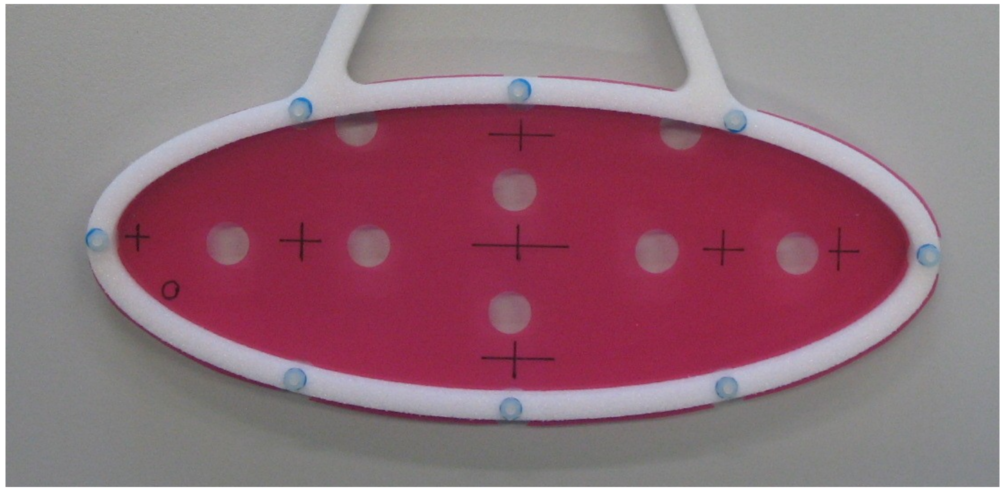
Millipede method,
CMS-NOTE-2006-011

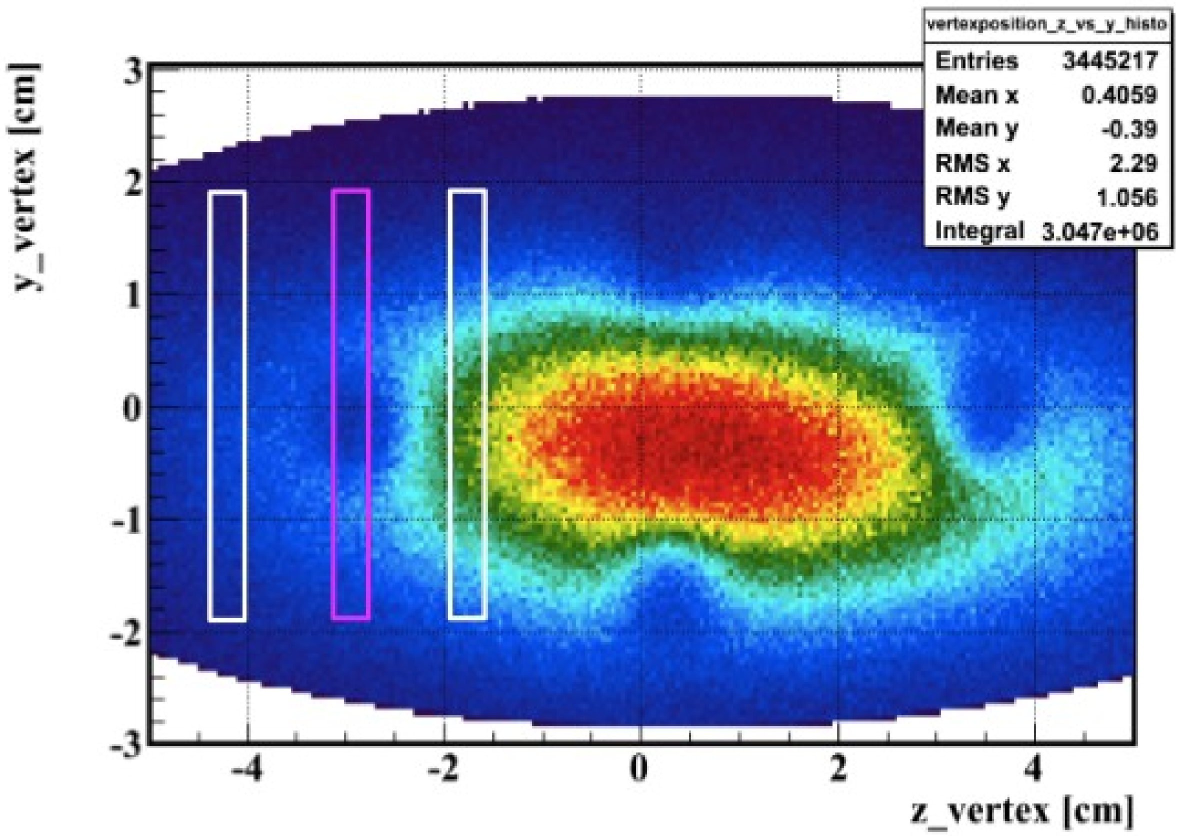
Independent of initial values

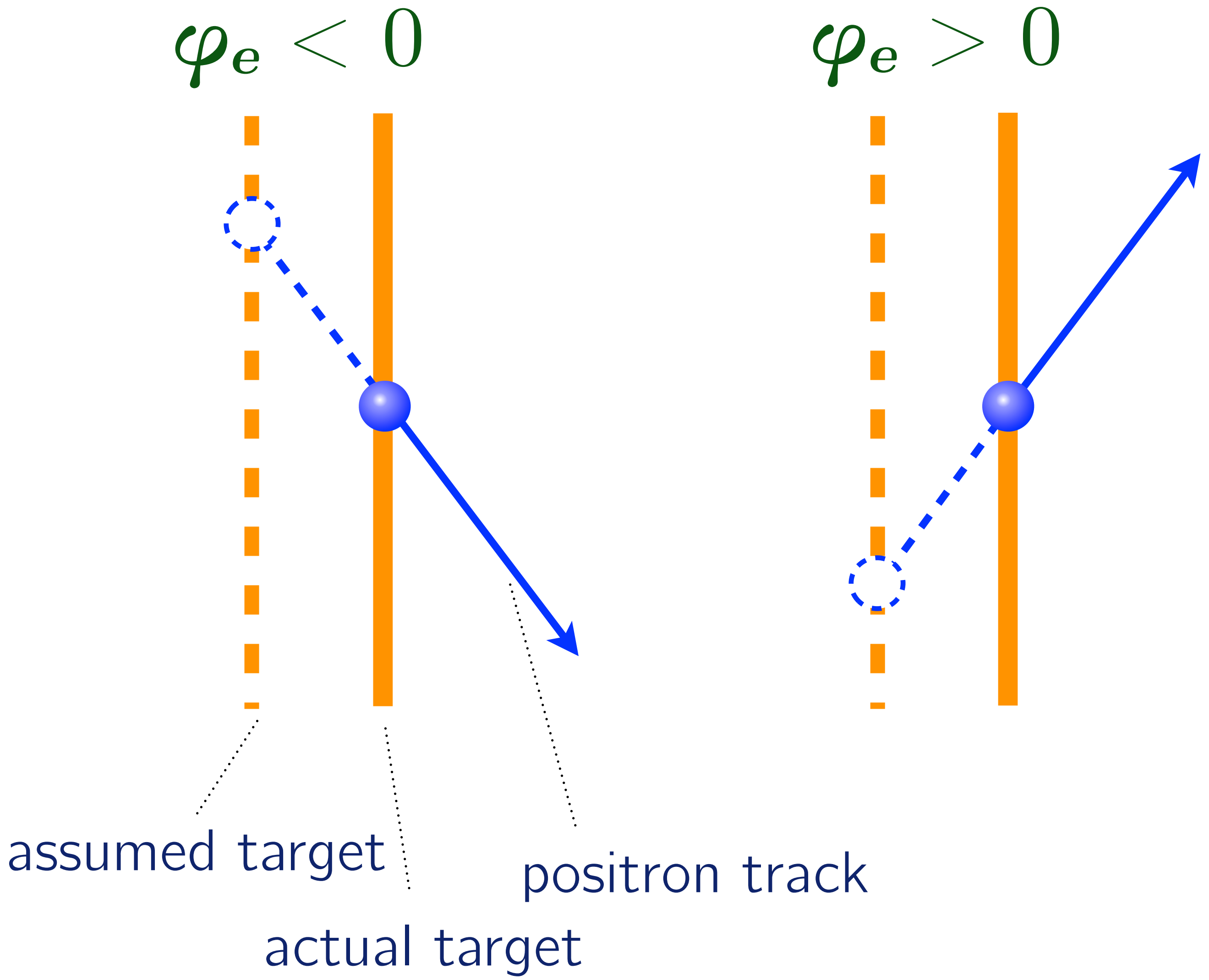
1.5 um and **10^{-2} mrad** level reproducibility, from different initial alignment.

Fitting error : **130 um** and **0.2 mrad**.

Alignment of the target





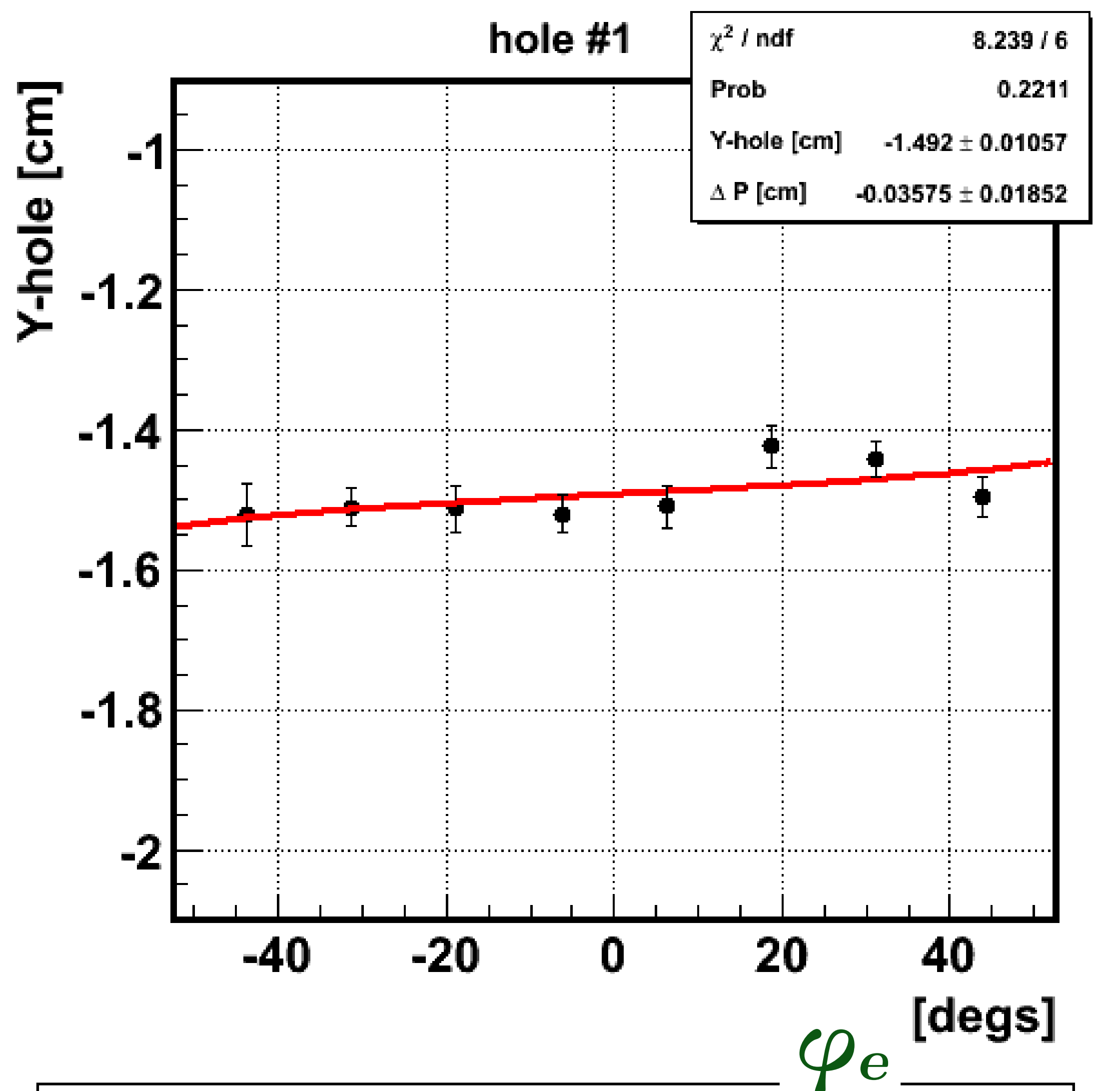


When mis-alignment exists...

hole position depends on angle

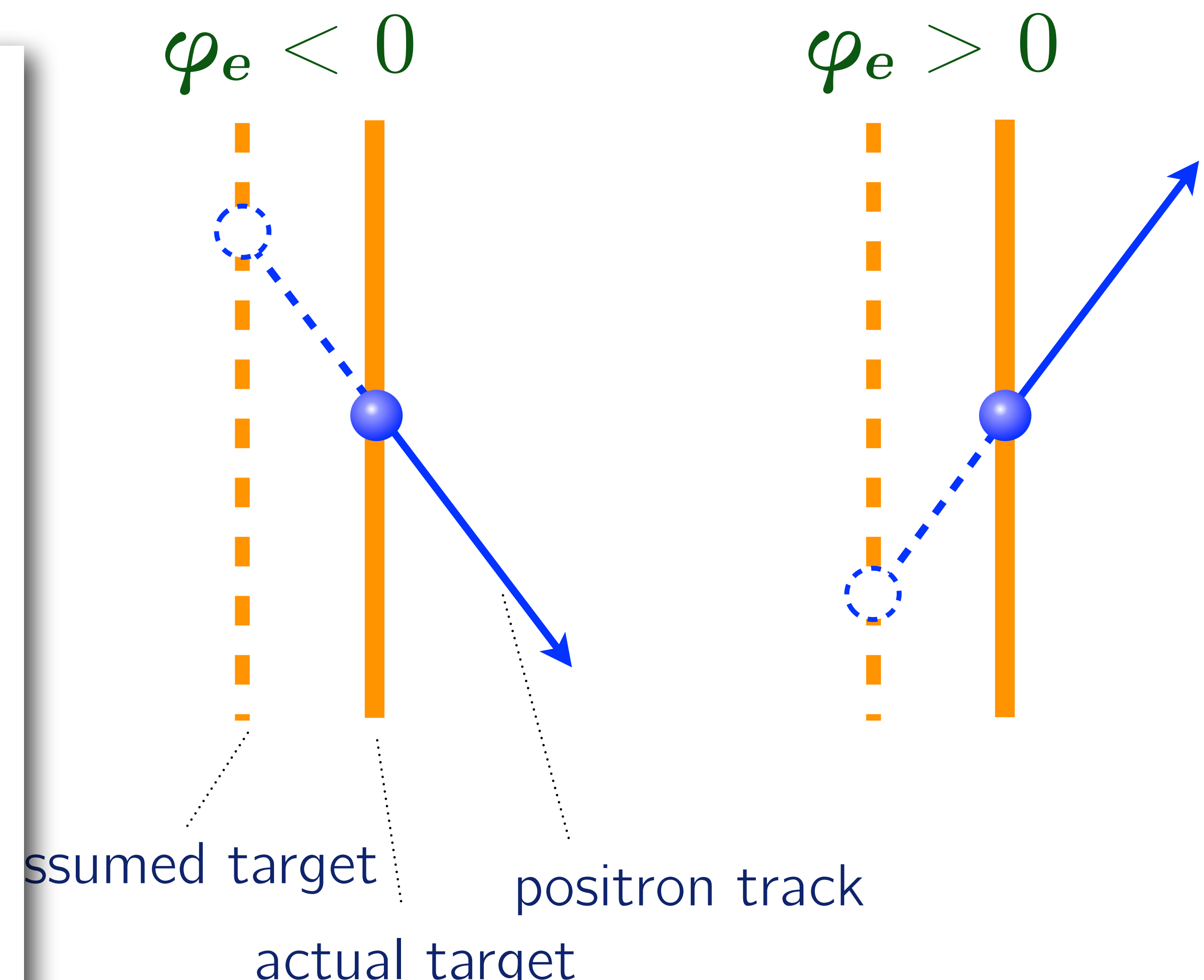
Alignment of the target

Result



Confirmed that

Optical survey position is correct



When mis-alignment exists...

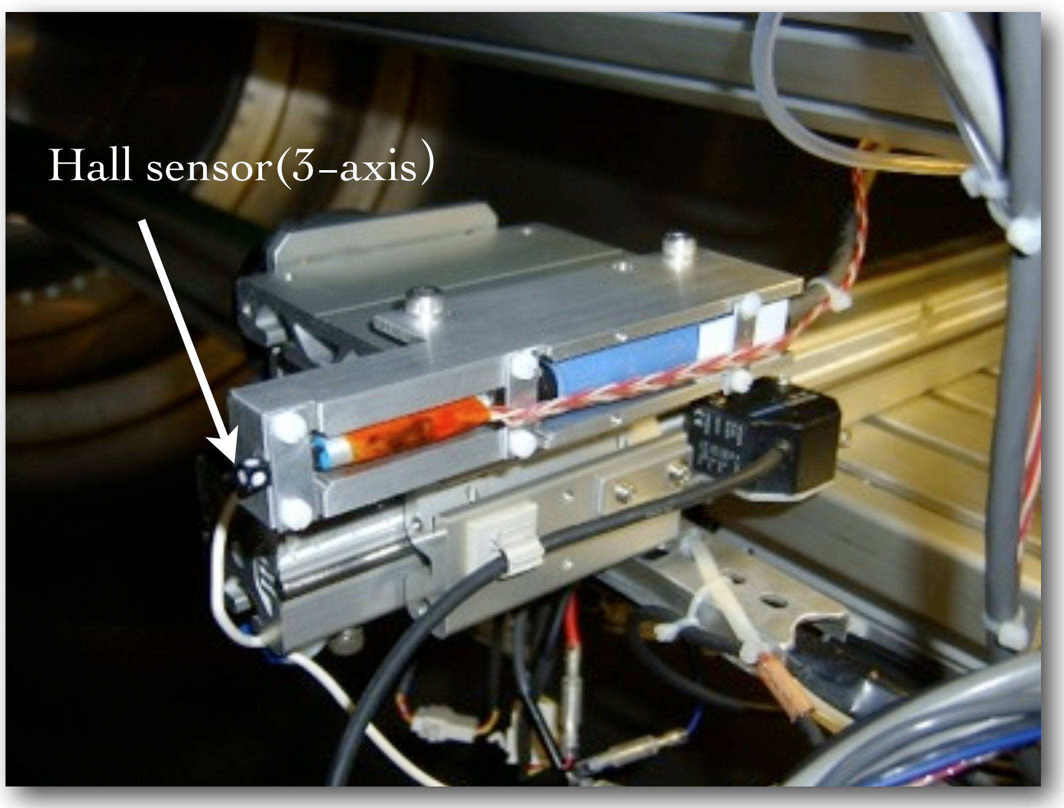
hole position depends on angle

Magnetic field

1. Calculated field : Accurate, but possible systematic differences
2. Measured field : Realistic, but possible measurement errors

Possible misalignment of hall sensors

⟹ causes false B_ϕ and B_r from B_z — Secondary effect



1.27T @center, 0.49T @ends

$$\begin{pmatrix} B_z^{\rm meas} \\ B_r^{\rm meas} \\ B_\phi^{\rm meas} \end{pmatrix} = \begin{pmatrix} 1 & \theta_{zr} & \theta_{z\phi} \\ \theta_{rz} & 1 & \theta_{r\phi} \\ \theta_{\phi z} & \theta_{\phi r} & 1 \end{pmatrix} \begin{pmatrix} B_z \\ B_r \\ B_\phi \end{pmatrix}$$

Non-negligible

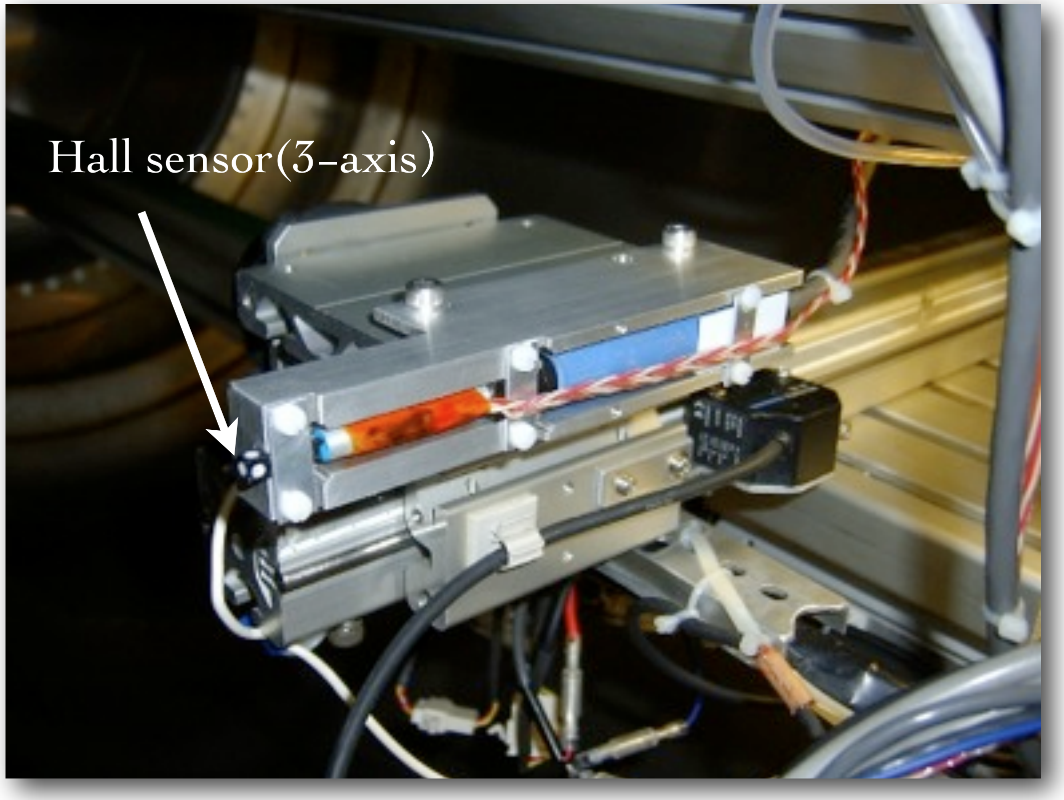
Ideally zero

Magnetic field

1. Calculated field : Accurate, but possible systematic differences
2. Measured field : Realistic, but possible measurement errors
3. **Reconstructed field : Realistic, and measurement errors are reduced**

Possible misalignment of hall sensors

⟹ causes false B_ϕ and B_r from B_z Secondary effect



1.27T @center, 0.49T @ends

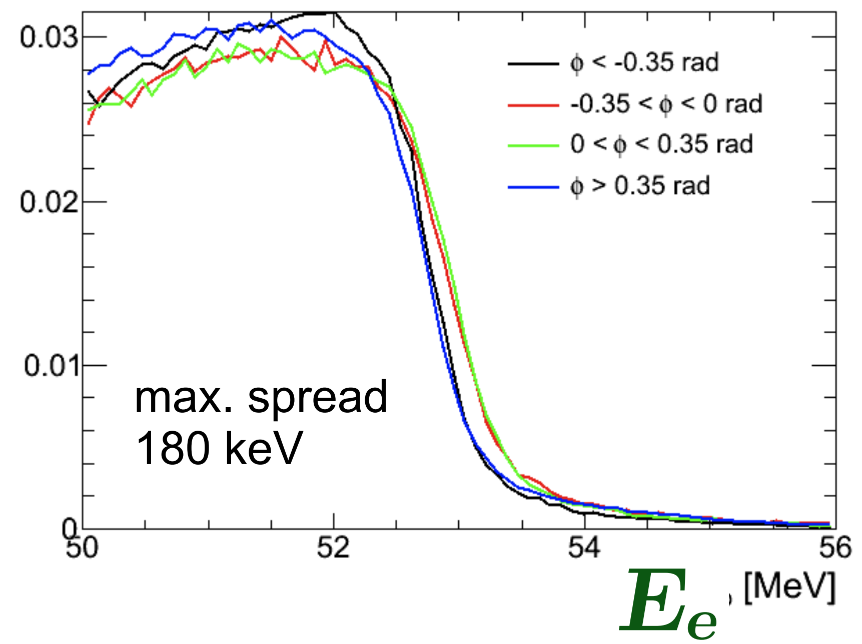
$$\begin{pmatrix} B_z^{meas} \\ B_r^{meas} \\ B_\phi^{meas} \end{pmatrix} = \begin{pmatrix} 1 & \theta_{zr} & \theta_{z\phi} \\ \theta_{rz} & 1 & \theta_{r\phi} \\ \theta_{\phi z} & \theta_{\phi r} & 1 \end{pmatrix} \begin{pmatrix} B_z \\ B_r \\ B_\phi \end{pmatrix}$$

Small (<0.2×Bz)

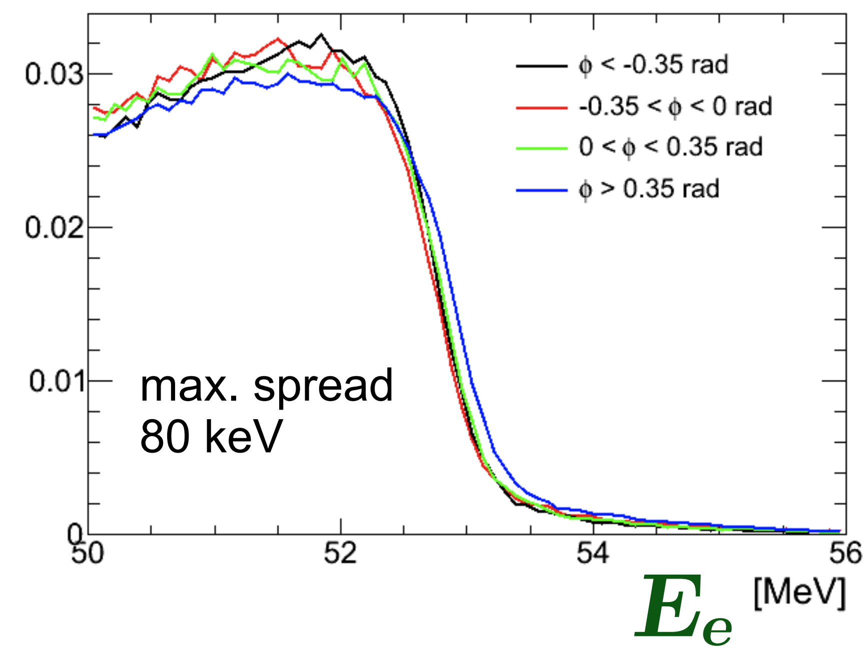
Ideally zero

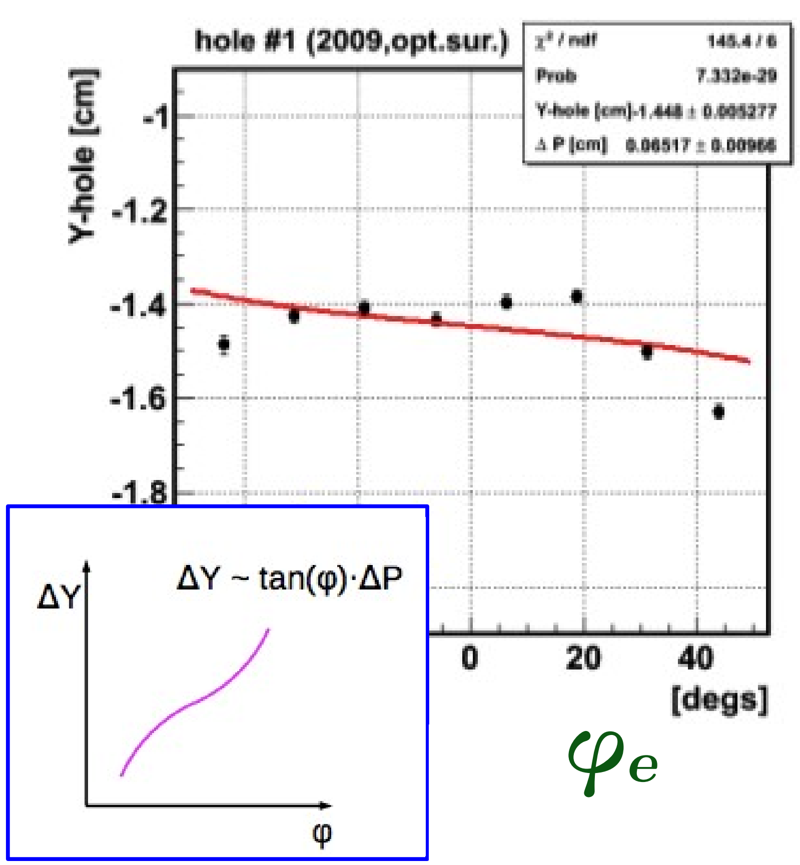
⟹ Can be found and corrected using Maxwell equations

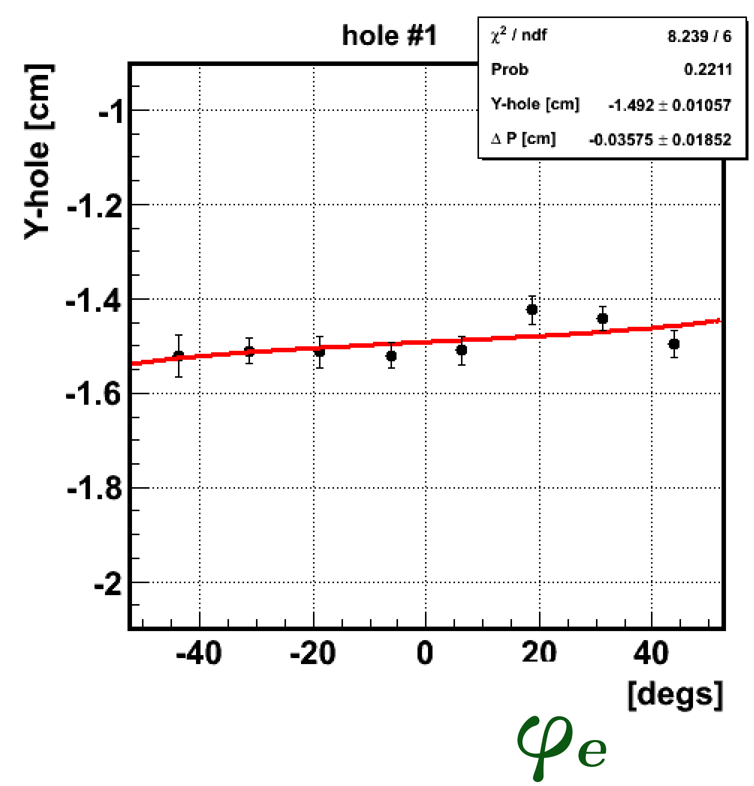
2009 data
DCH alignment using Michel tracks
Calculated B field



2009 data
Millipede alignment
Reconstructed B field







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

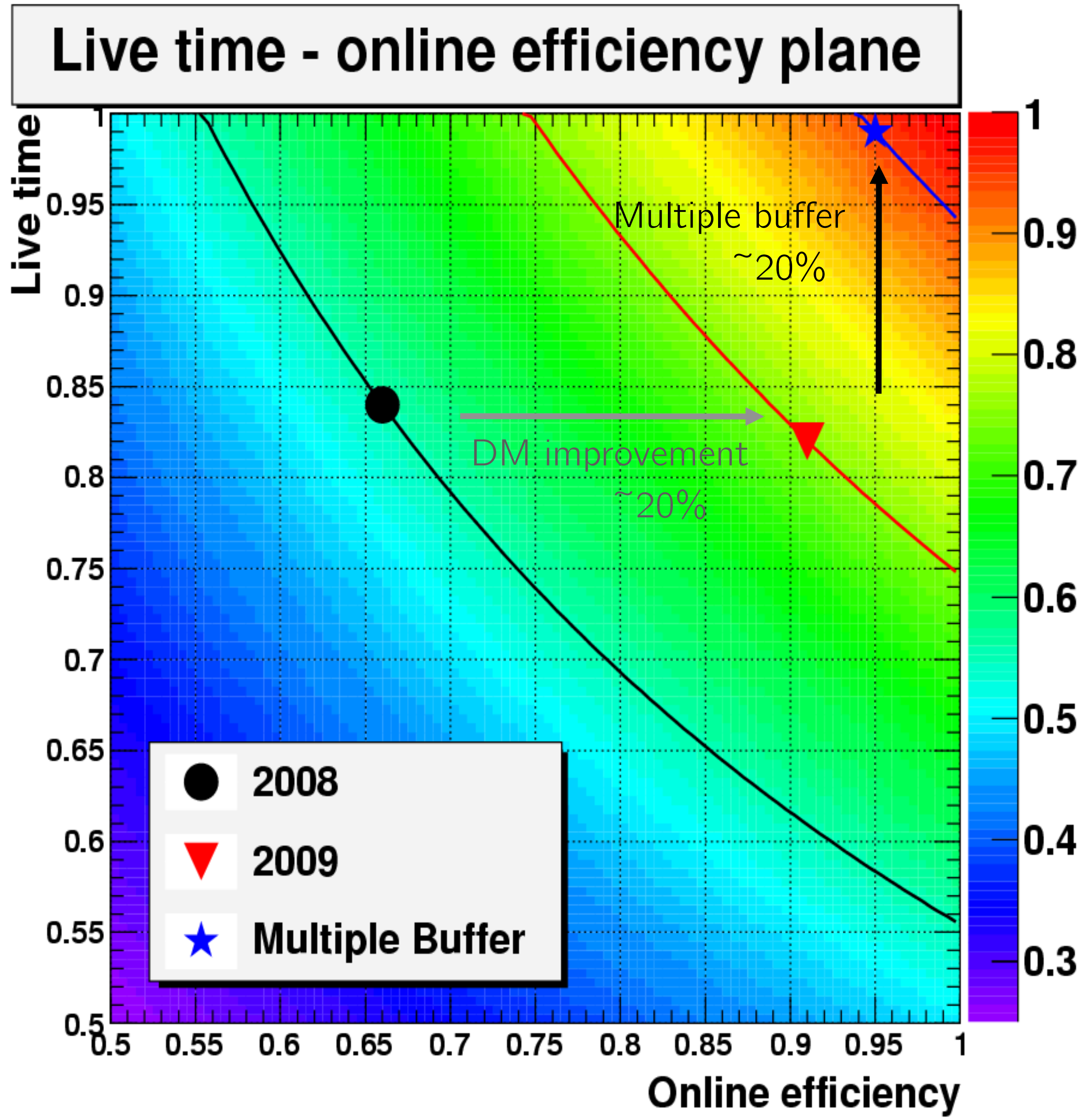
Contribution of each item was studied with toy-experiment by comparing the result with nominal PDF and that with fluctuated one.

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

Multi buffer DAQ

- Dead time in 2009-2010
  - 25ms/event ~ 83% livetime @ 6Hz
- Multi buffer DAQ
  - Installed at the end of 2010
  - >99% livetime @ 10Hz
  - Direction match table between positron and photon can be widen (92% -> 96%).



Current Status of MEG

- Physics data taking started in 2008
  - 2008 data
    - Br(μ->eγ)<2.8x10^{-11} at 90%C.L., published in Nucl.Phys.B834:1-12,2010
    - Sensitivity: 1.3x10^{-11}
  - 2009 data
    - Br(μ->eγ)<1.5x10^{-11} at 90%C.L. (preliminary)
    - Sensitivity: 6.1x10^{-12} (preliminary)
  - 2010 data
    - 1.9x statistics of 2009
    - 2009+2010 combined analysis result was presented this year
    - Br(μ->eγ)<2.4x10^{-12} at 90%C.L.
    - Sensitivity: 1.6x10^{-12}

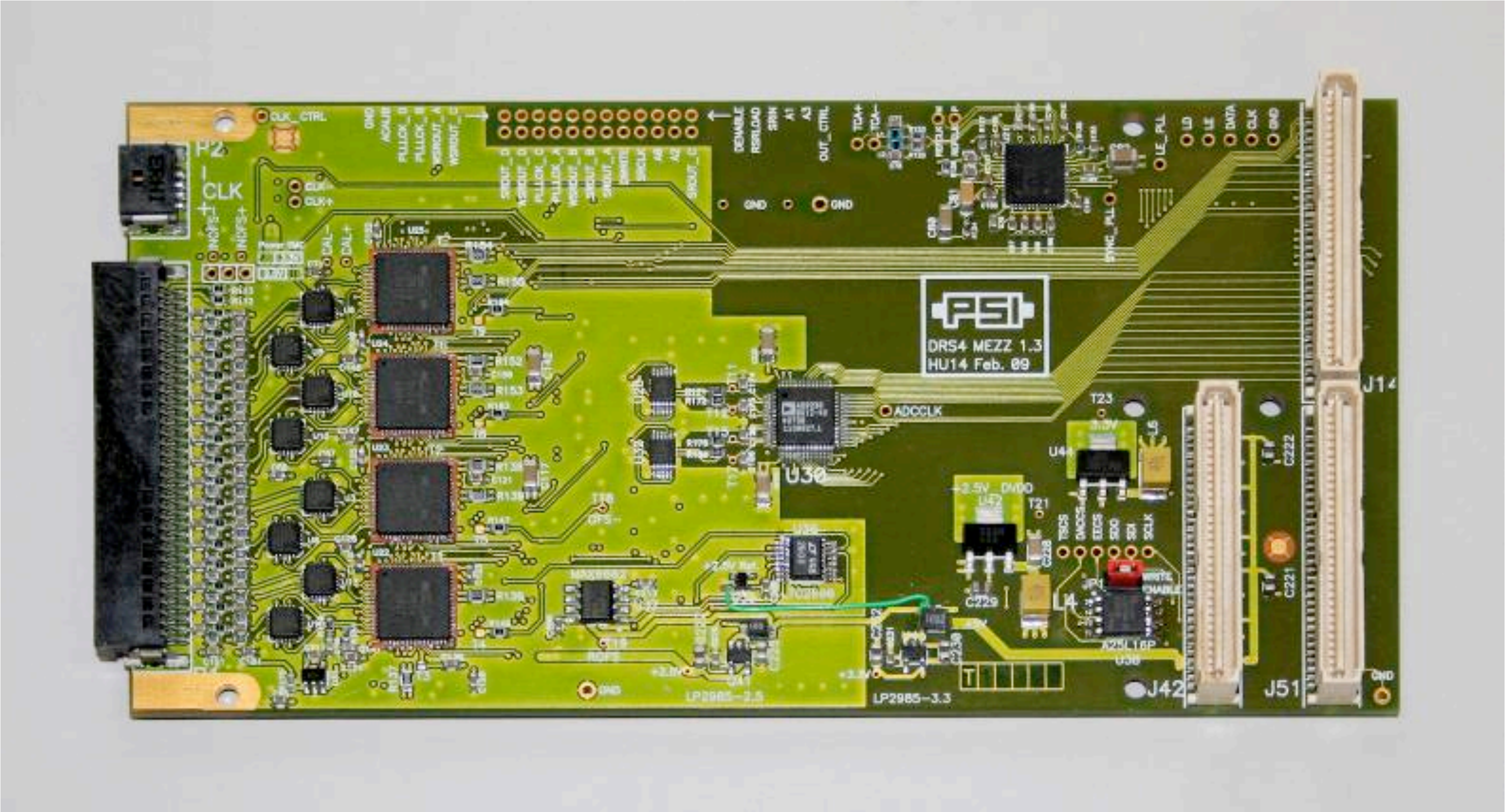
- MEG Collaboration
  - ~55 Collaborators from Japan, Italy, Switzerland, Russia, and USA

What's new in 2010

- 2010 data = 2 x 2009 data
  - There was a problem of beam transport solenoid, and 2010 beam time finished prematurely.
- Timing improvement by waveform digitizer
- Positron tracking performance and efficiency slightly worse
  - due to noise problem and more unstable DC layers
- Better calibrations of data
  - Alignments inside/among detectors

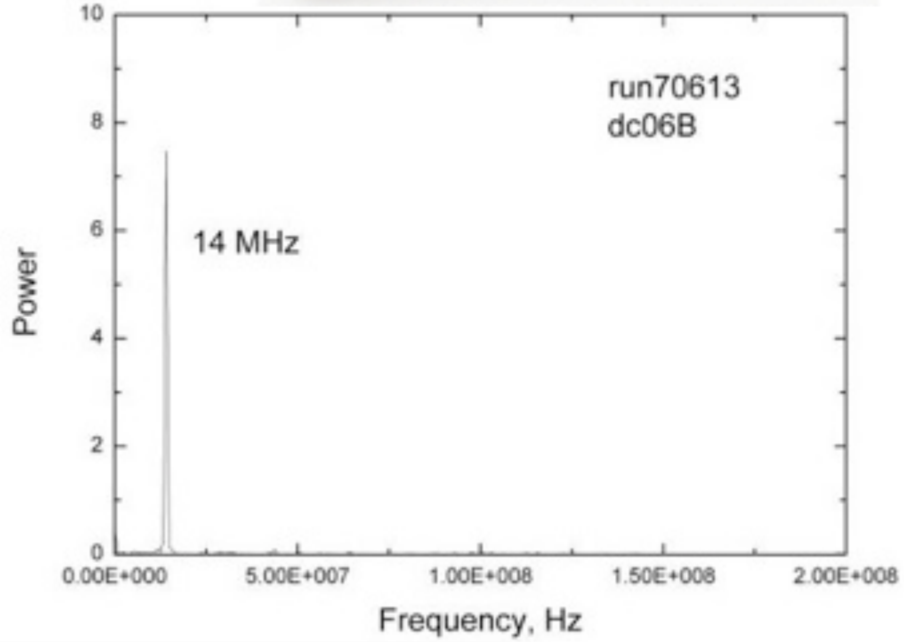
Waveform digitizer upgrade

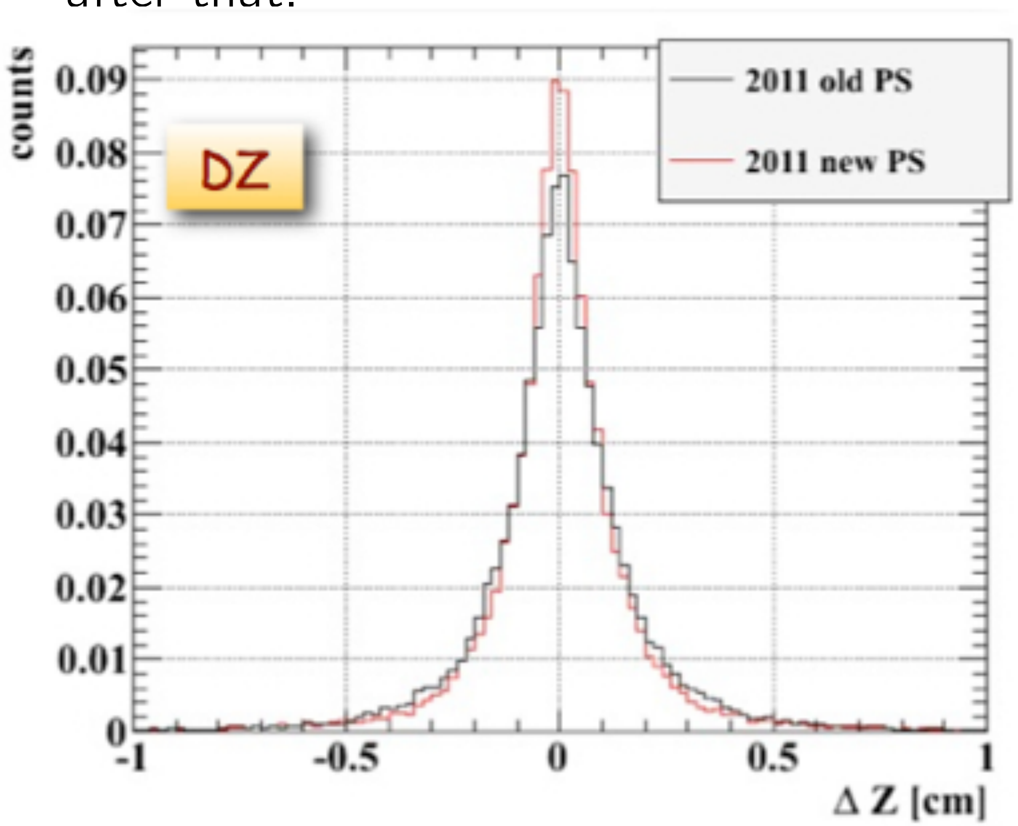
- DRS chip developed at PSI
- Fine tuning of DRS4 digitization board (introduced in 2009)
  - Noise reduction on digital board & time jitter minimization
  - Contribution of timing resolution from electronics
    - 130ps in 2009 -> 50ps in 2010

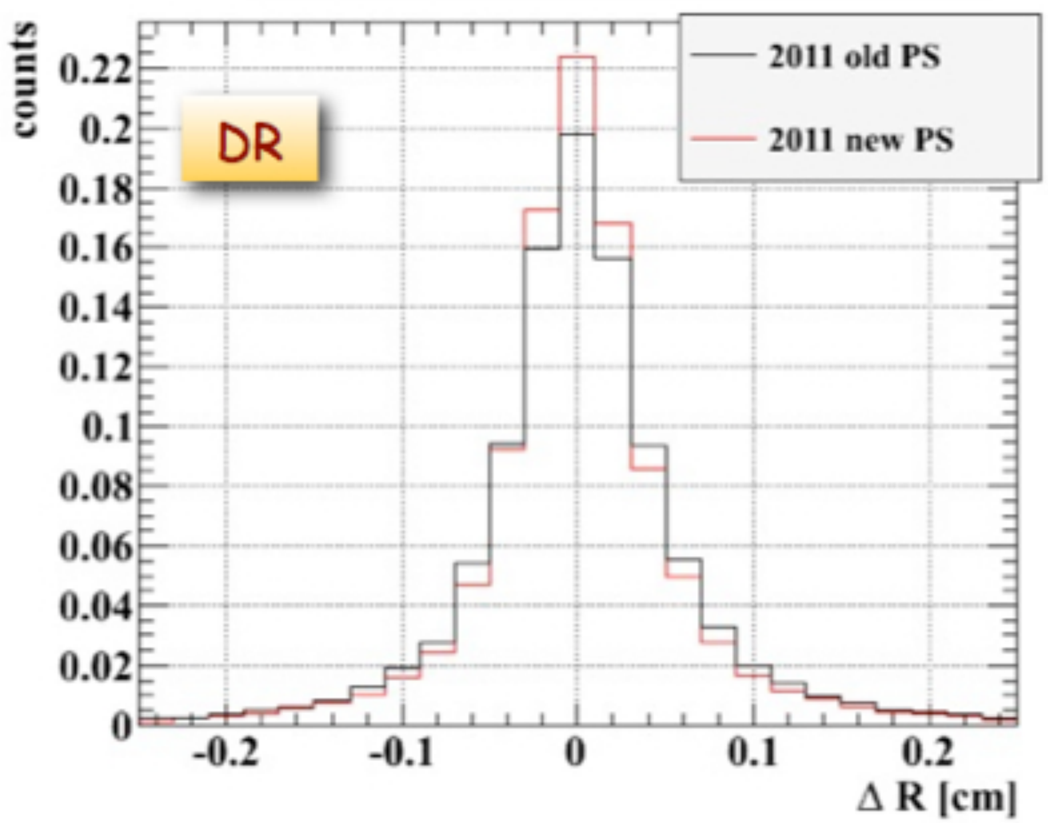


DC performance in 2011

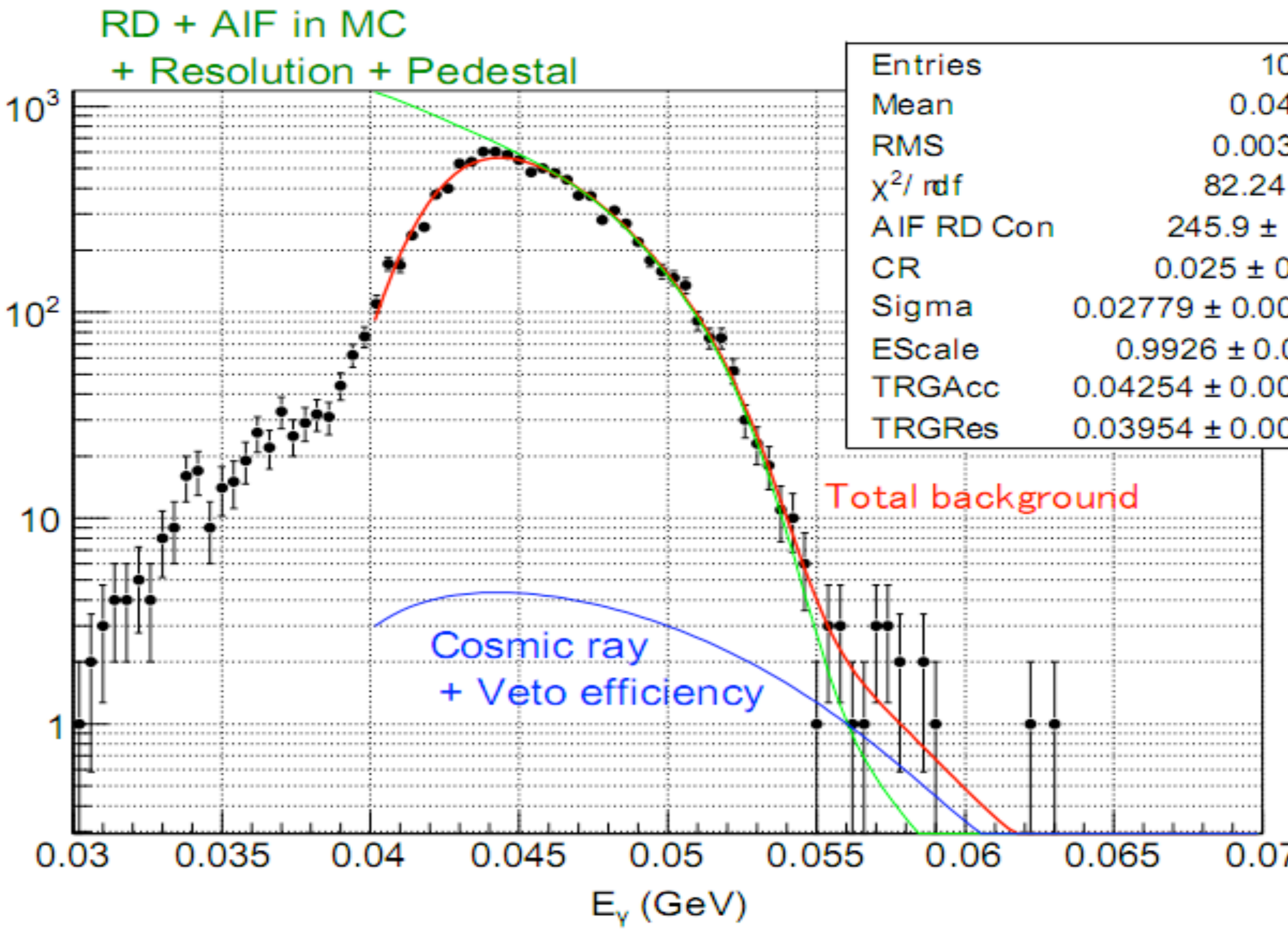
- Found that one of noises (14MHz) coming from DC HV distribution system
  - 1 primary HV power supply(ISEG EHQ 103M) and 16 HV distribution modules with 2 ch. each (PSI)
- 2011 physics run (in a month after starting)
  - 32 different primary HV power supplies(ISEG EHS)
  - dz, dr improved before/after exchange in 2011
  - DC calibration is on-going. θ, φ resolution will be checked after that.







Background spectrum



Contribution of background events in signal region (51-55MeV)

RD+AIF (single gamma)	93%
Cosmic ray	1%
Remaining (pileup, tail etc.)	6%

Position dependent γ background spectra --> PDF for likelihood analysis

These can be extracted directly by time sideband data

Detector response (energy resolution, energy scale) can be double checked by this,

And the result is consistent with CEX data