Recent result from the MEG experiment

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弘前大学

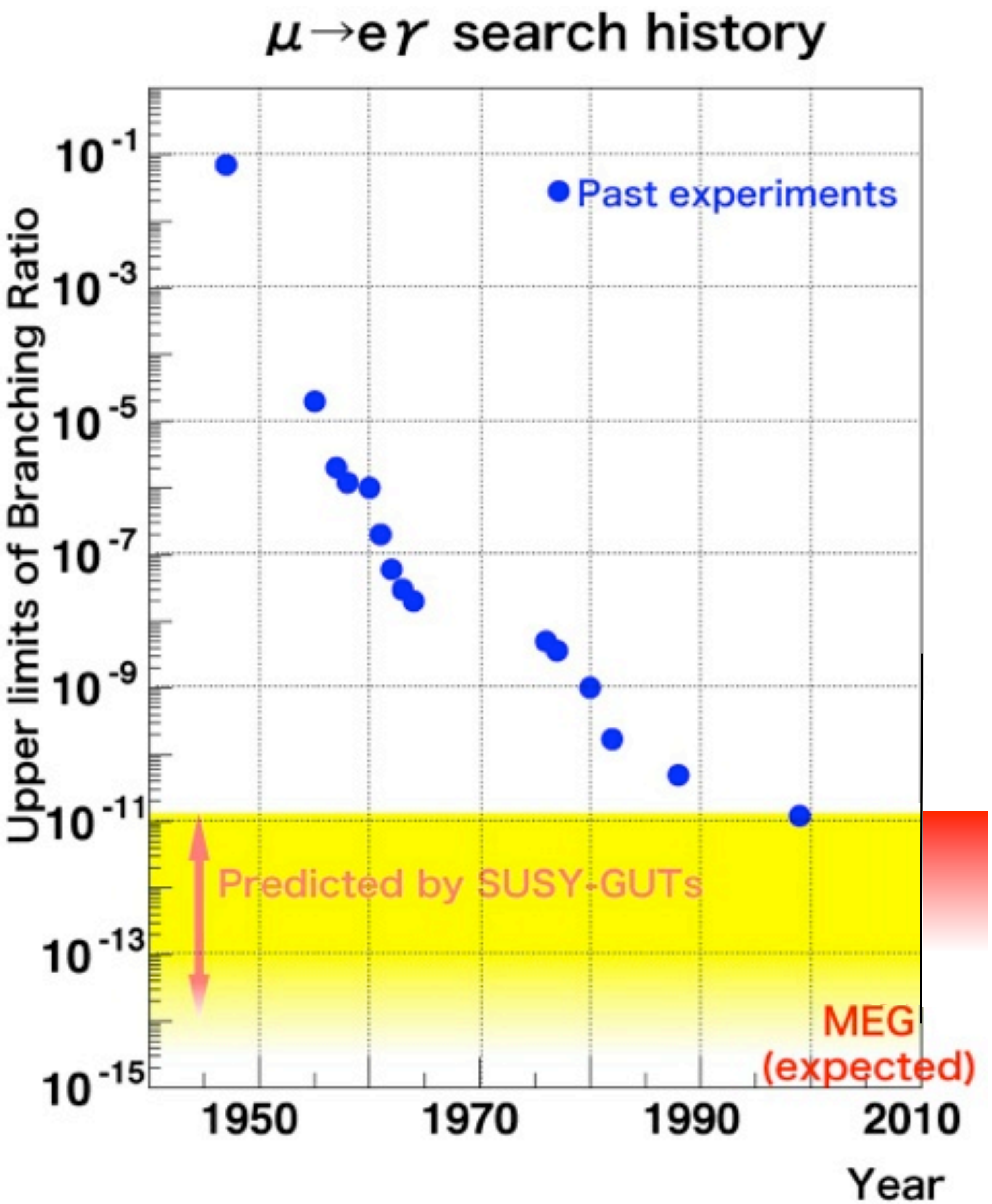
Outline

- Introduction
- Analysis
- Result
- Future prospect and summary

Introduction of the MEG experiment

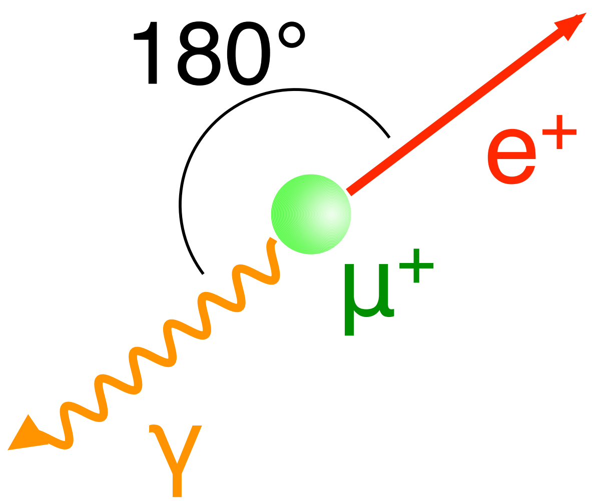
Physics Motivation

- Forbidden in the standard model
- Discovery → evidence of new physics.
- Previous upper limit (**1.2×10^{-11}**) is close to prediction.
- New physics predict B.R. from 10^{-15} to 10^{-11}.
- MEG goal : ~10^{-13}

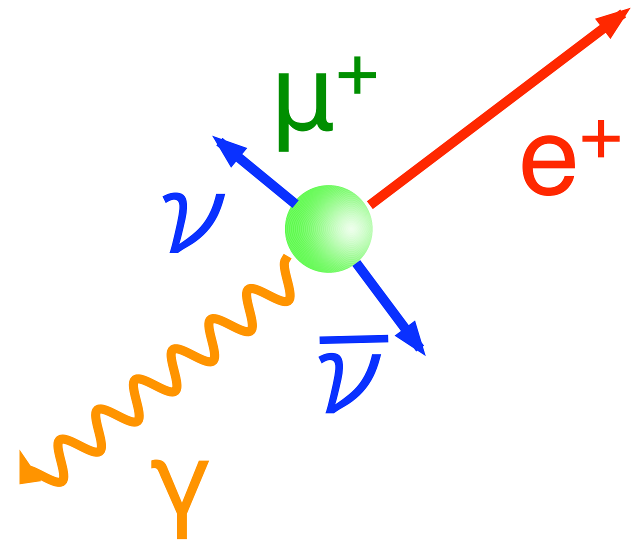


Signal and Background

Signal

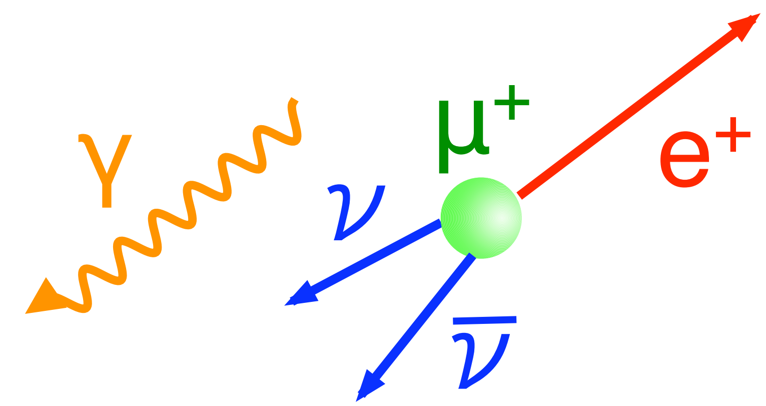


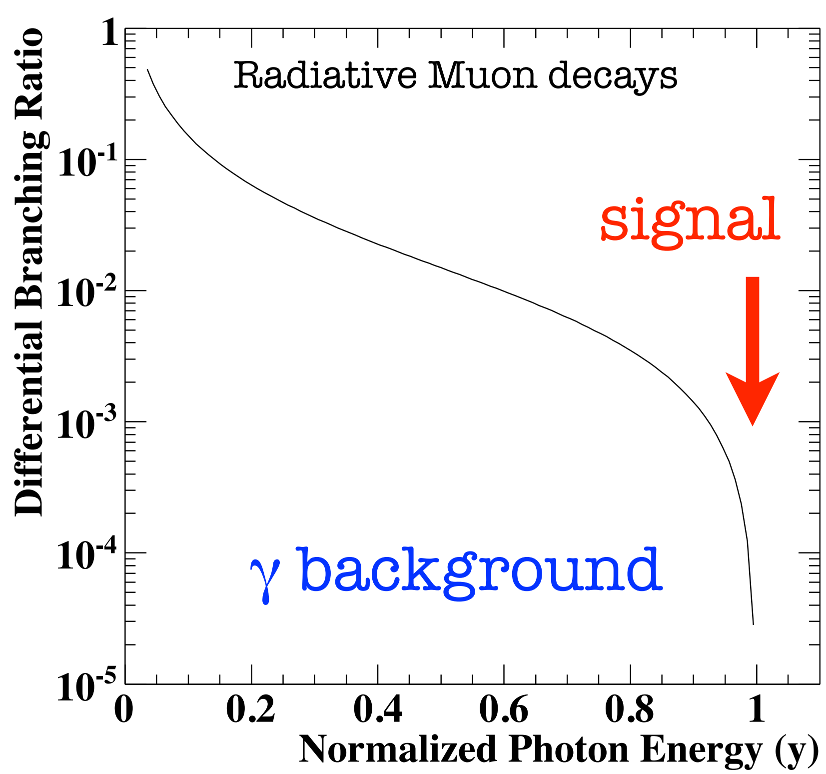
Prompt Background

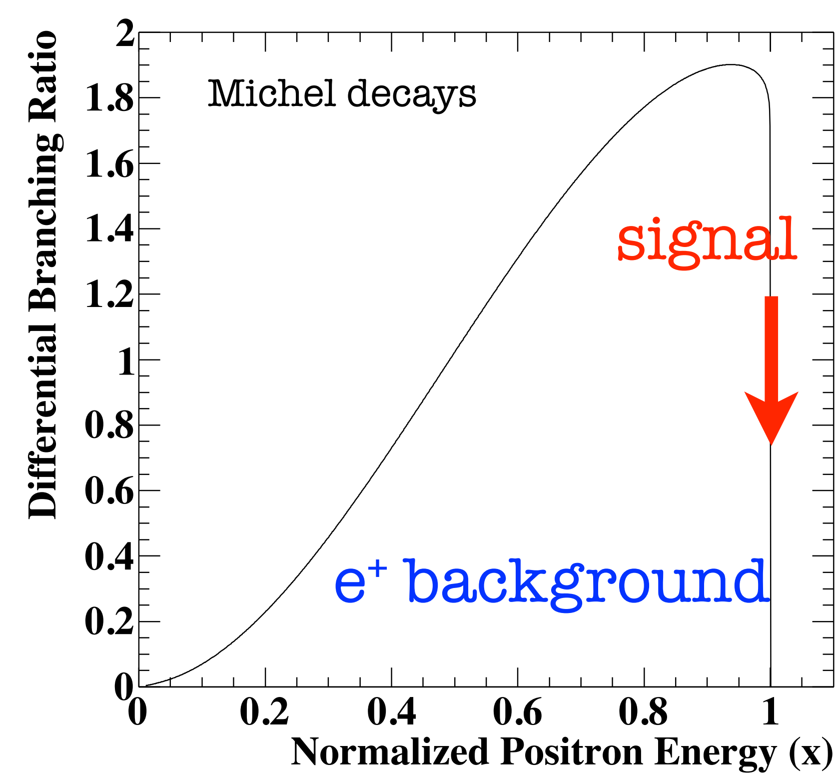


Accidental Background

Dominant

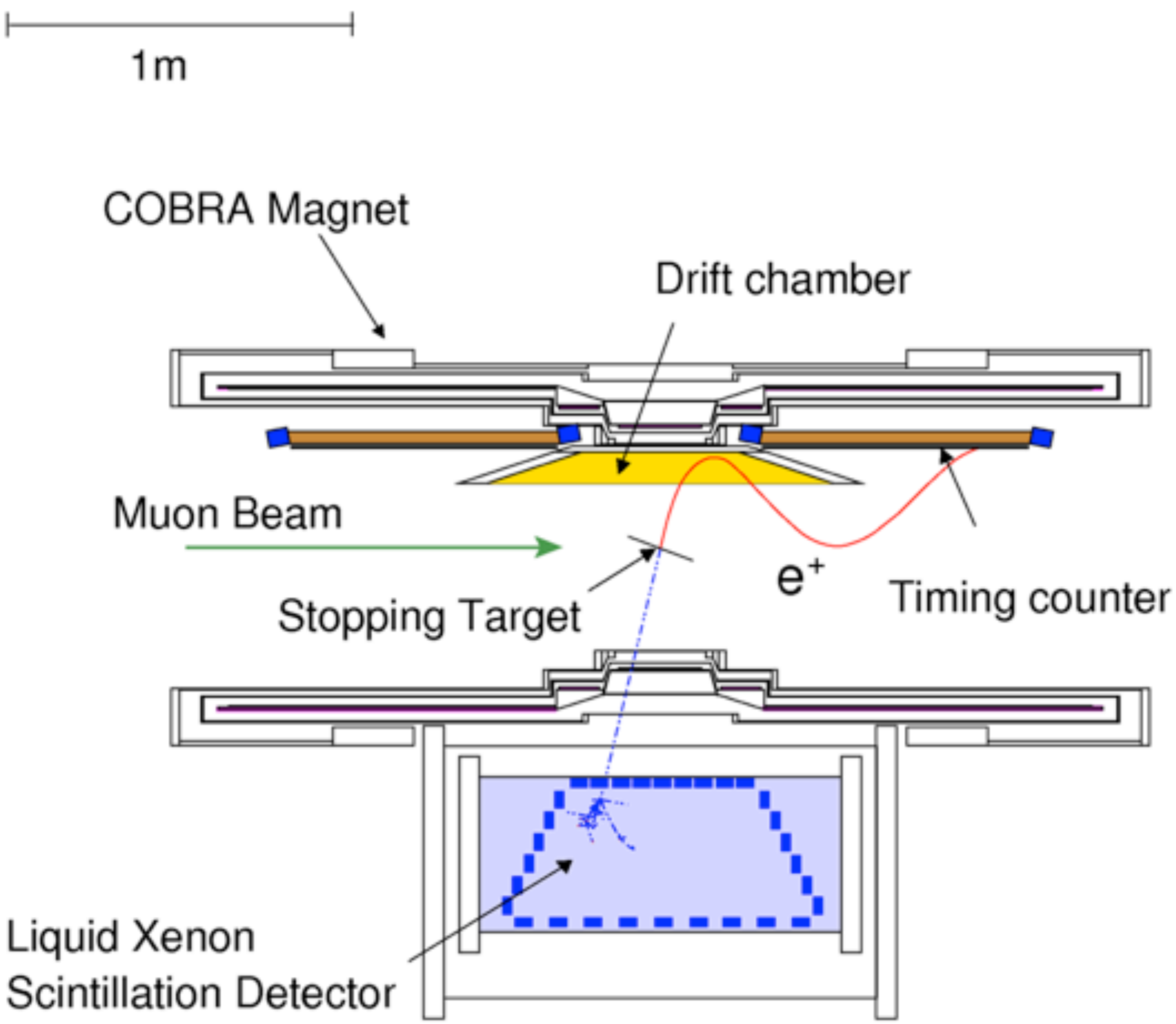


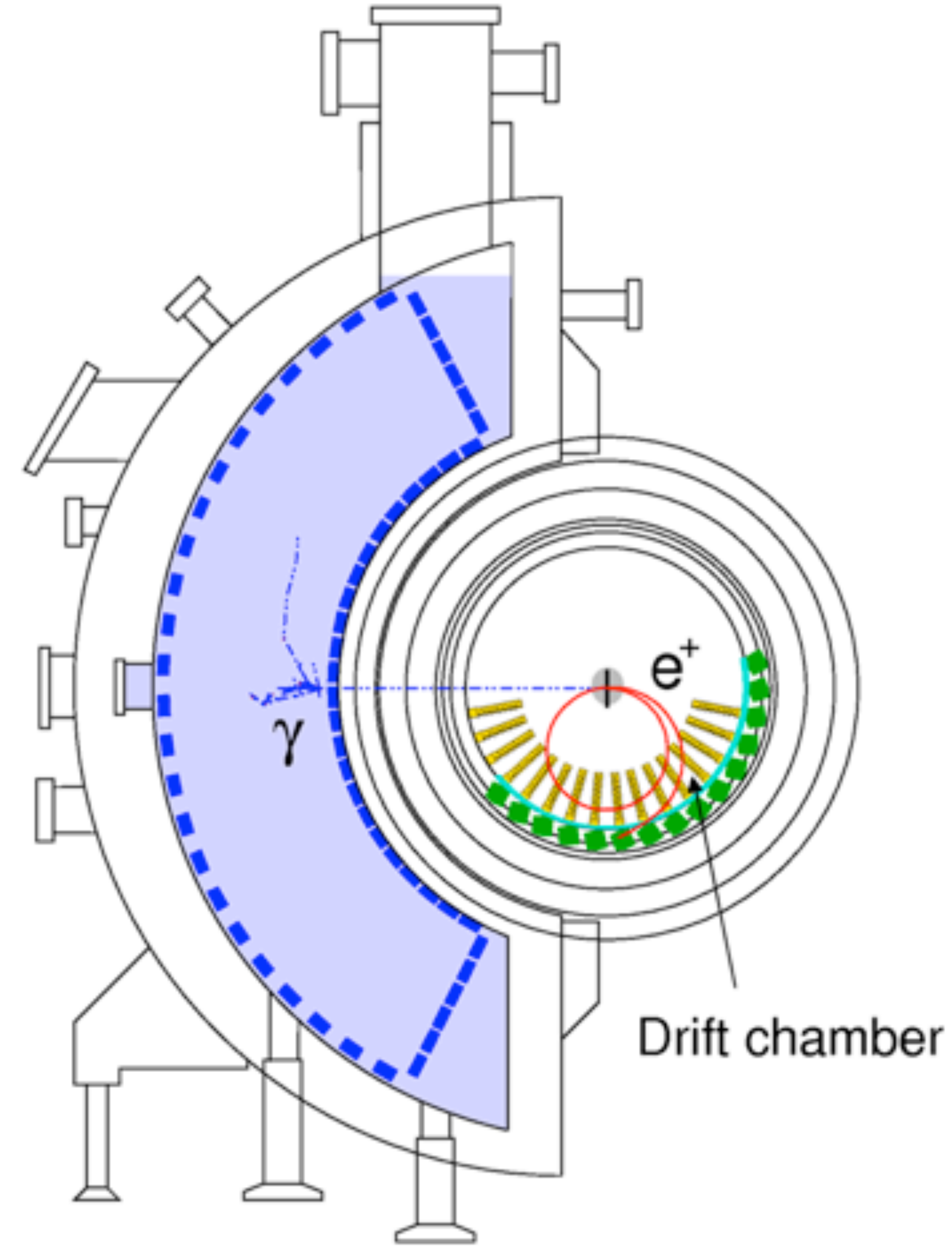




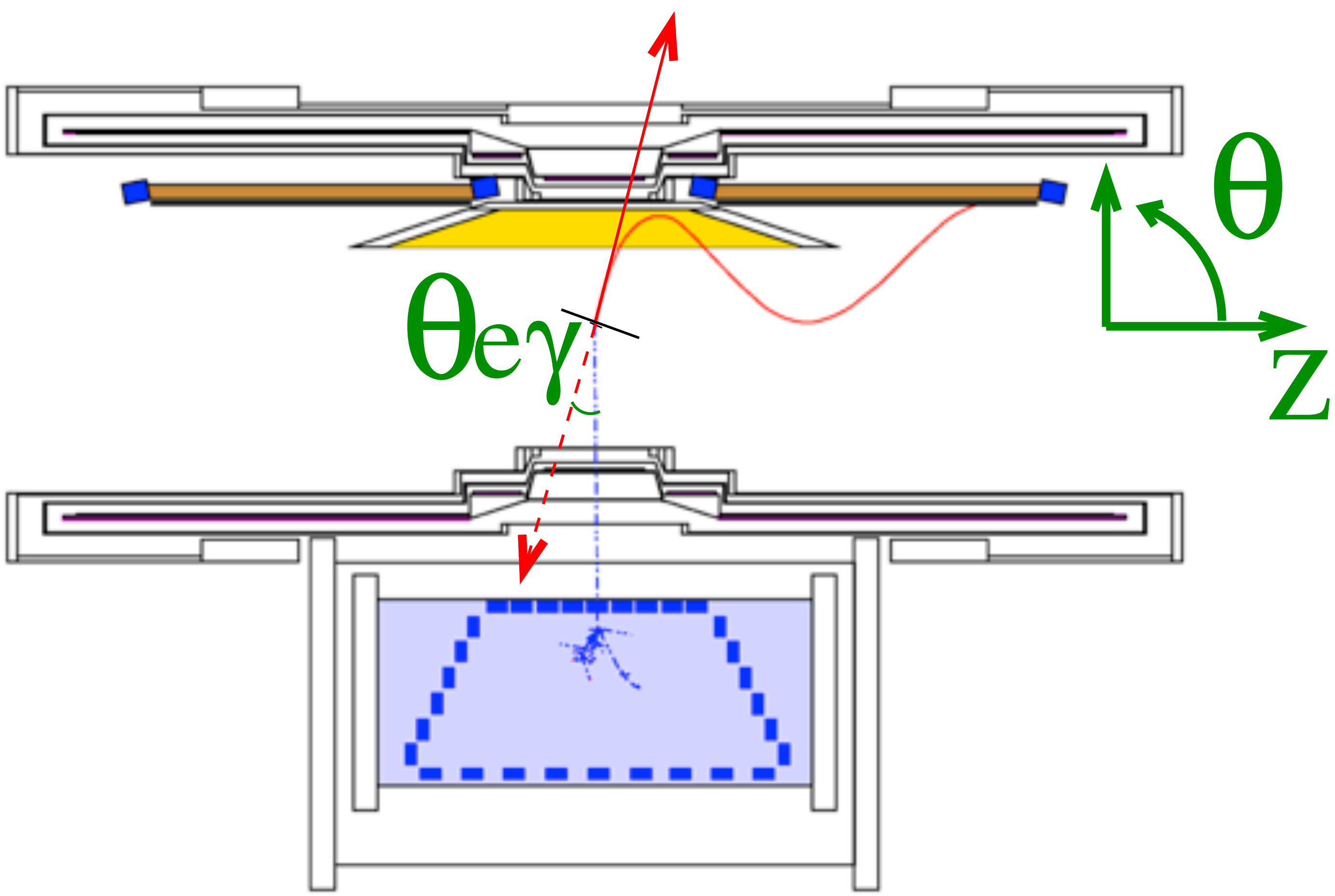
The detector

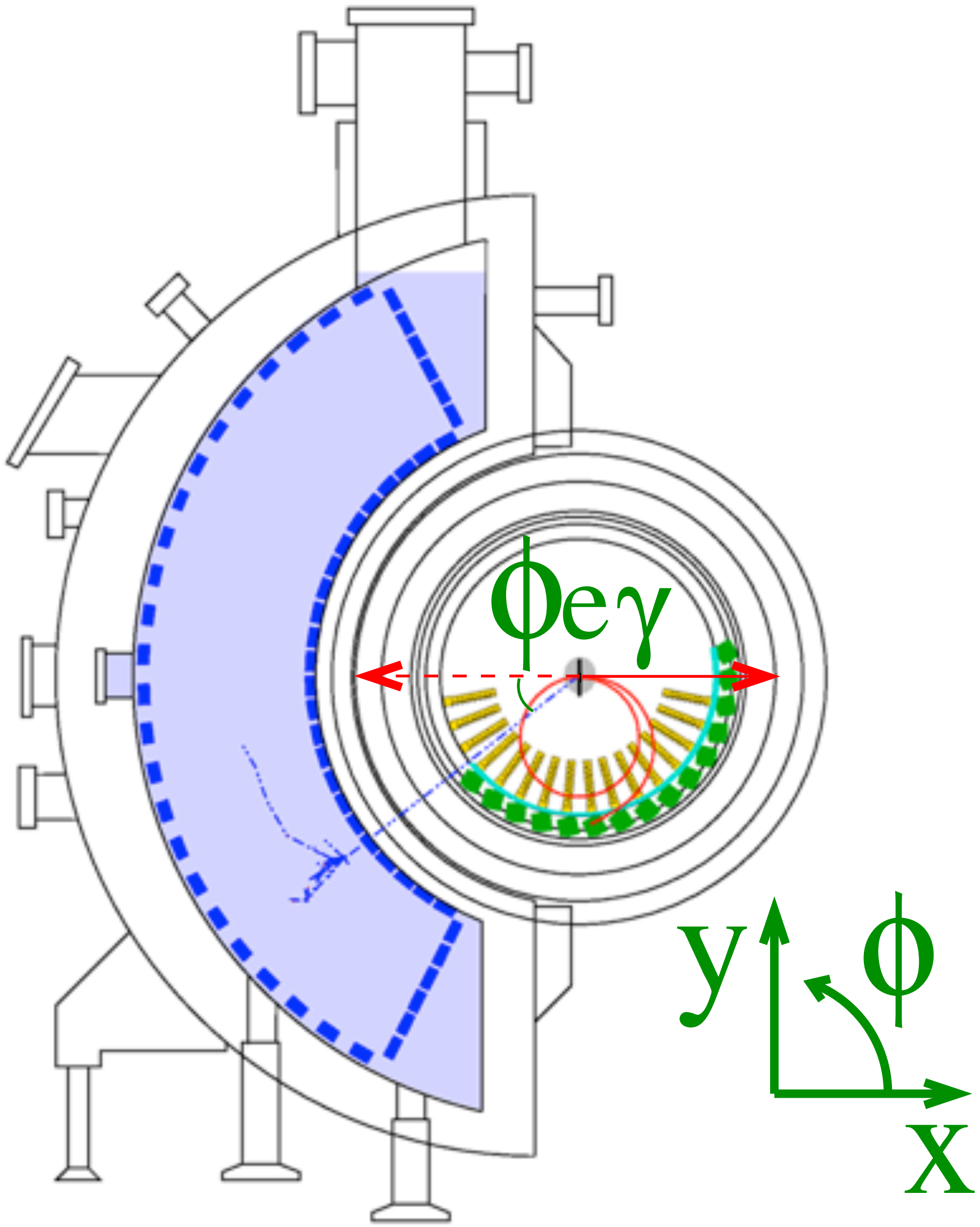
PSI : most intense DC muon





Coordinate system



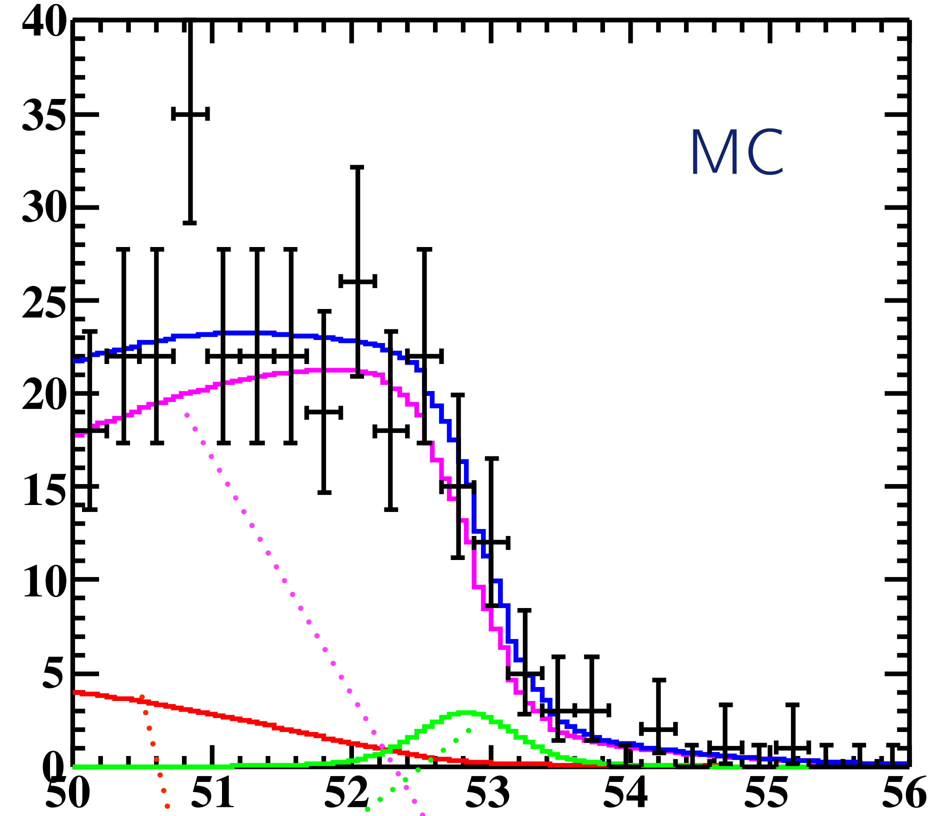


Analysis method

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...

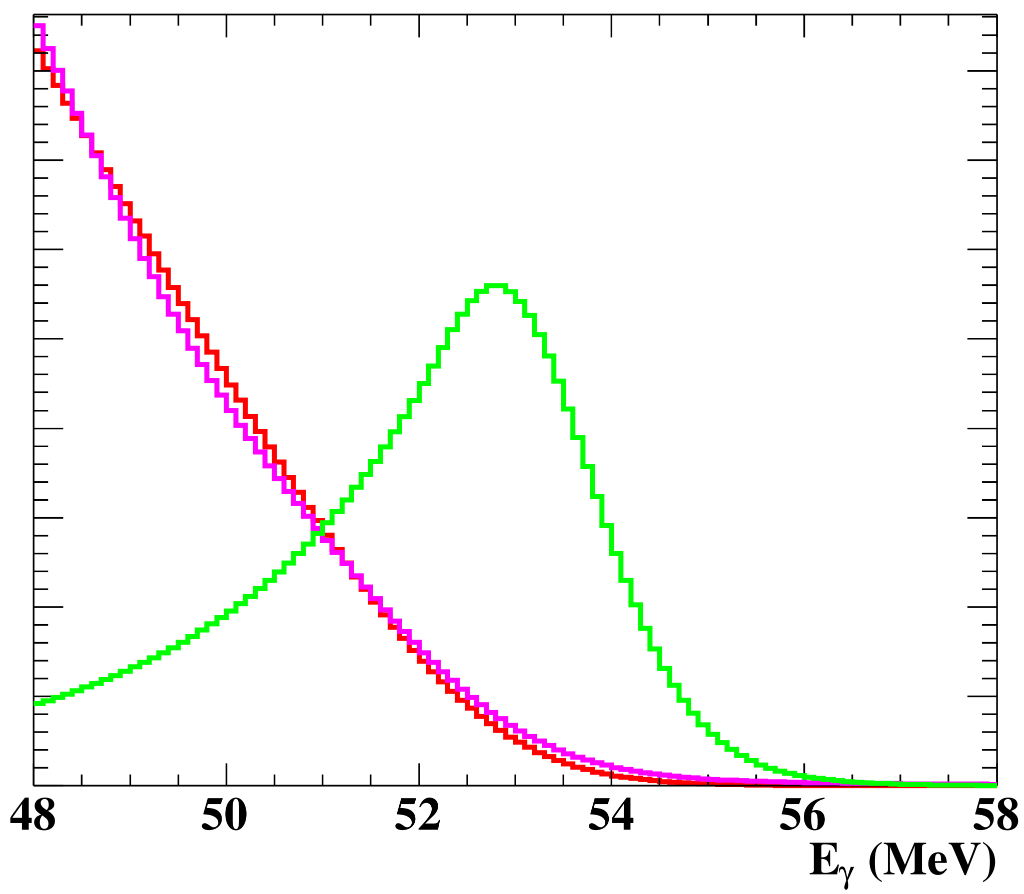
$$\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}) = f(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}) \times \prod_{i=1}^{N_{\rm obs}} (N_{\rm sig} S(\vec{x}_i) + N_{\rm RMD} R(\vec{x}_i) + N_{\rm BG} B(\vec{x}_i))$$

BG : Accidental
RMD : Radiative muon decay

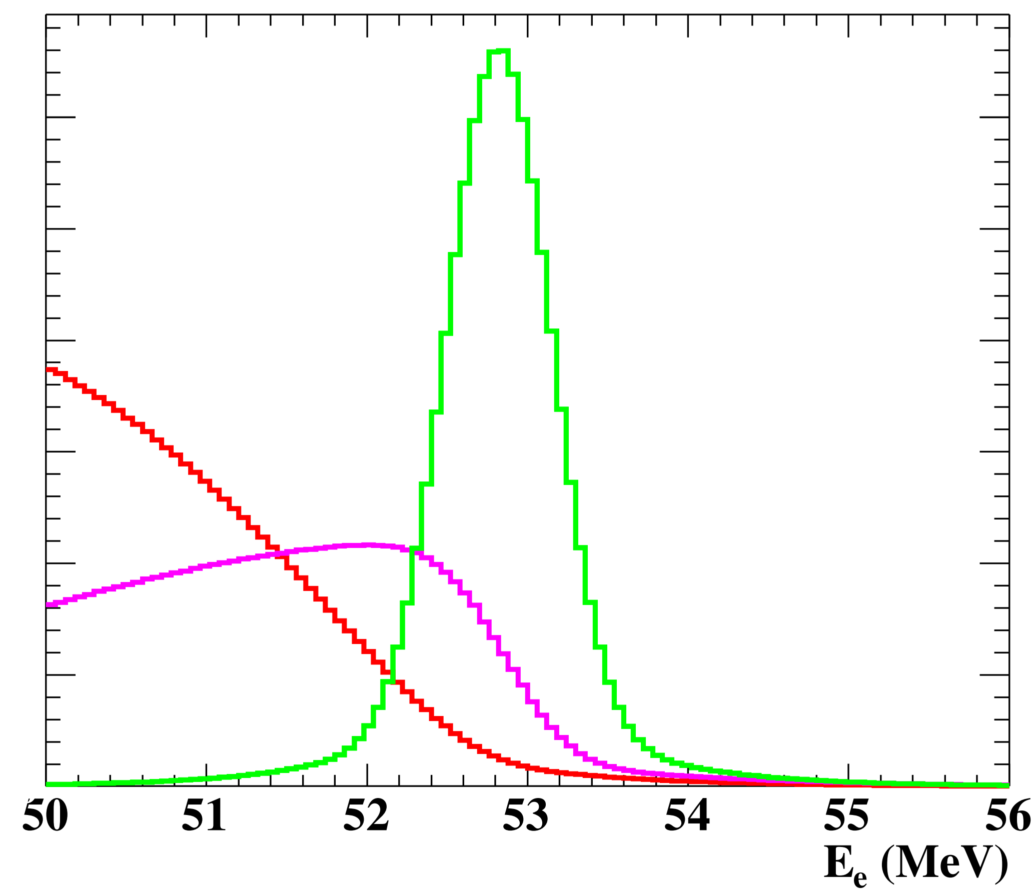
Probability density functions (PDF)

Signal RMD BG

E_γ



E_e



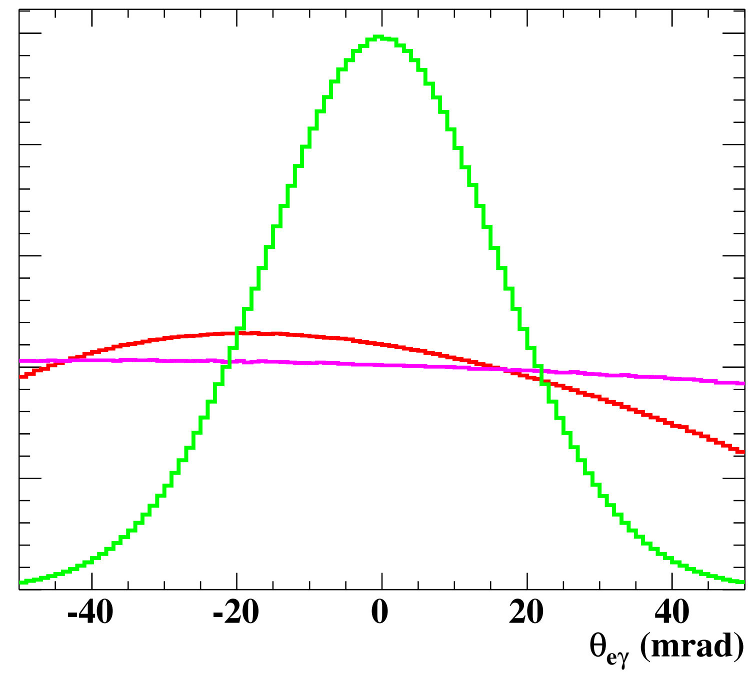
Signal : CEX data
BG : Sideband data
RMD : SM + detector response

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

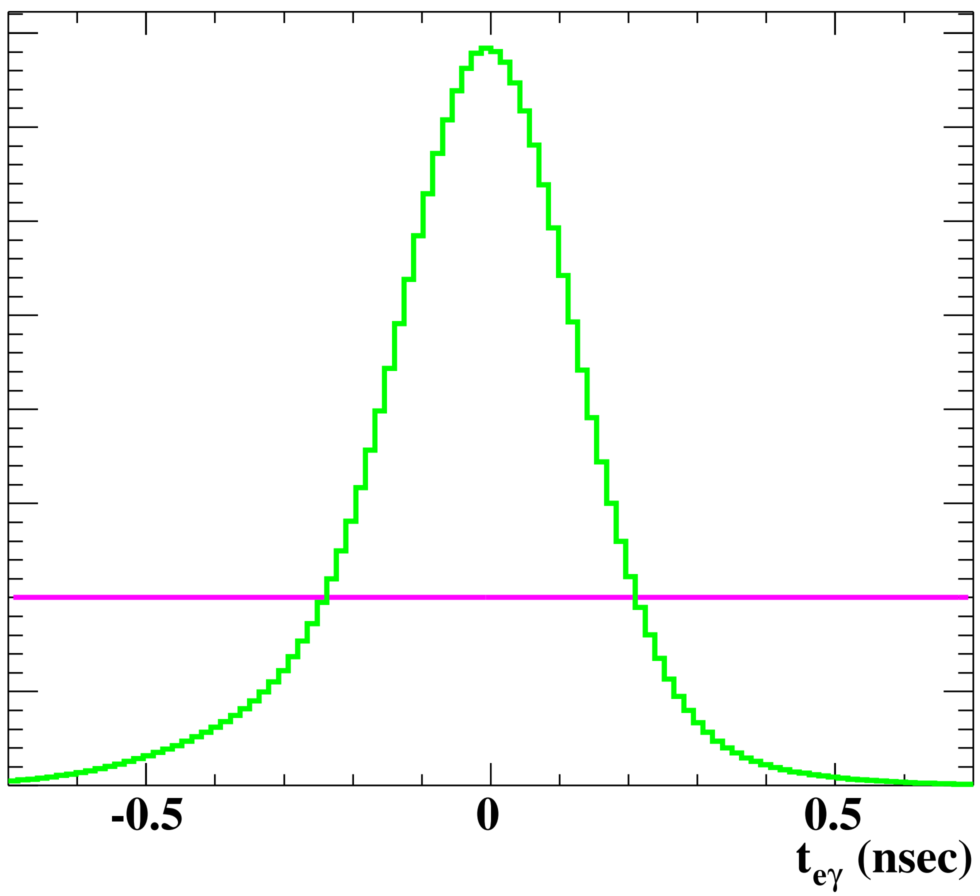
Probability density functions (PDF)

Signal RMD BG

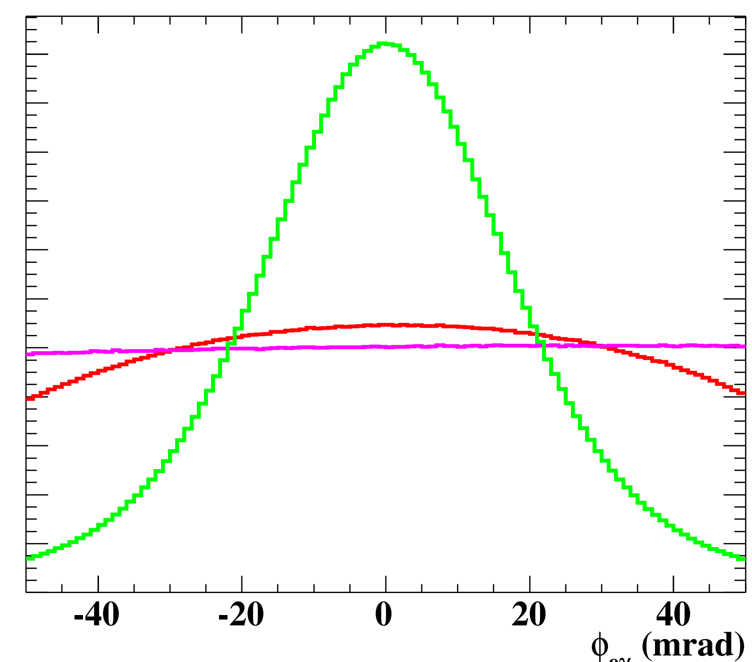
$\vartheta_{e\gamma}$



$t_{e\gamma}$



$\varphi_{e\gamma}$



Signal : RMD data

BG : Flat

RMD : SM + detector response

Signal : MC+CEX (γ), two turn (e^+)

BG : Sideband data

RMD : SM + detector response

Analysis

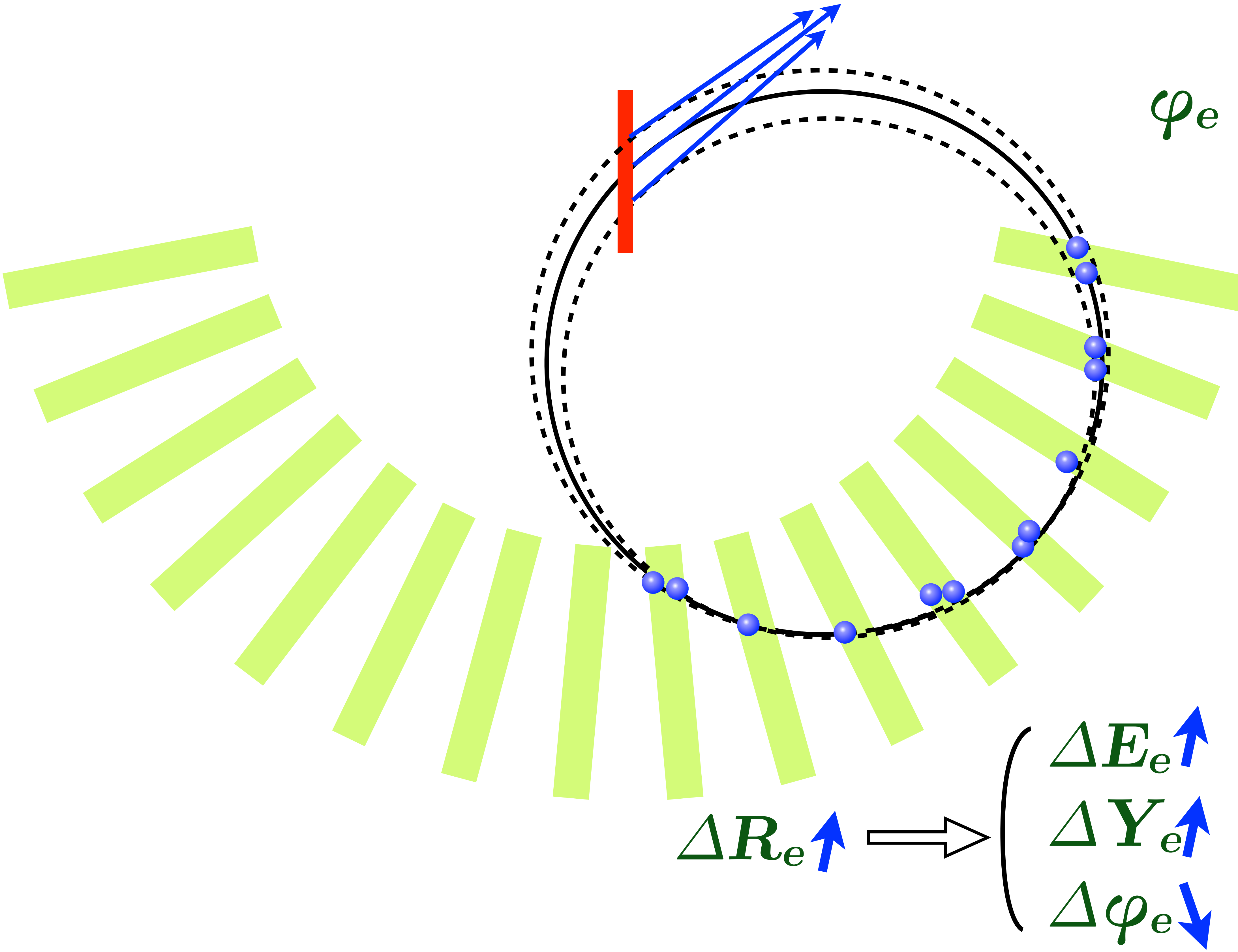
Positron analysis

Gamma analysis

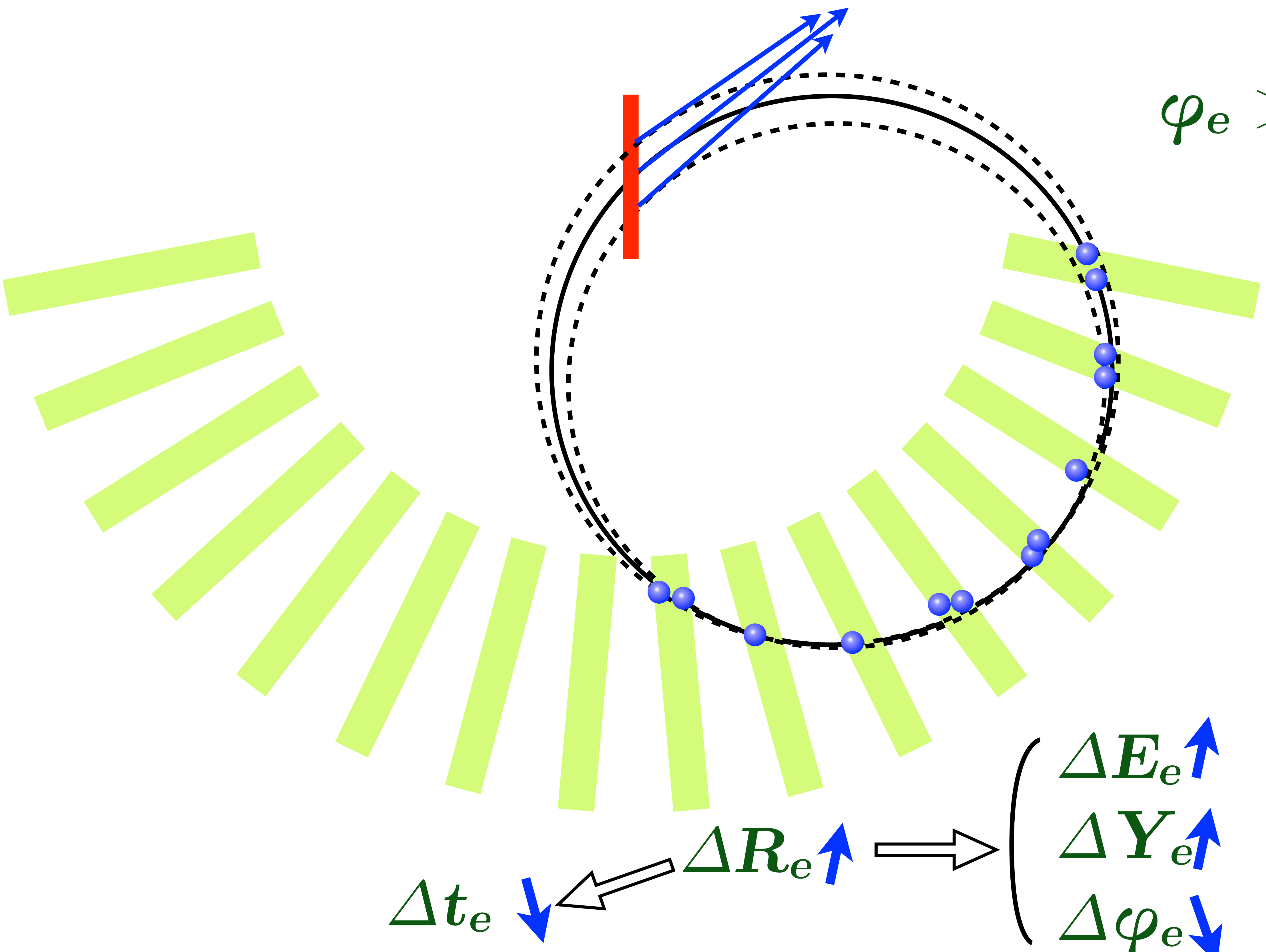
Relative alignment

Physics analysis

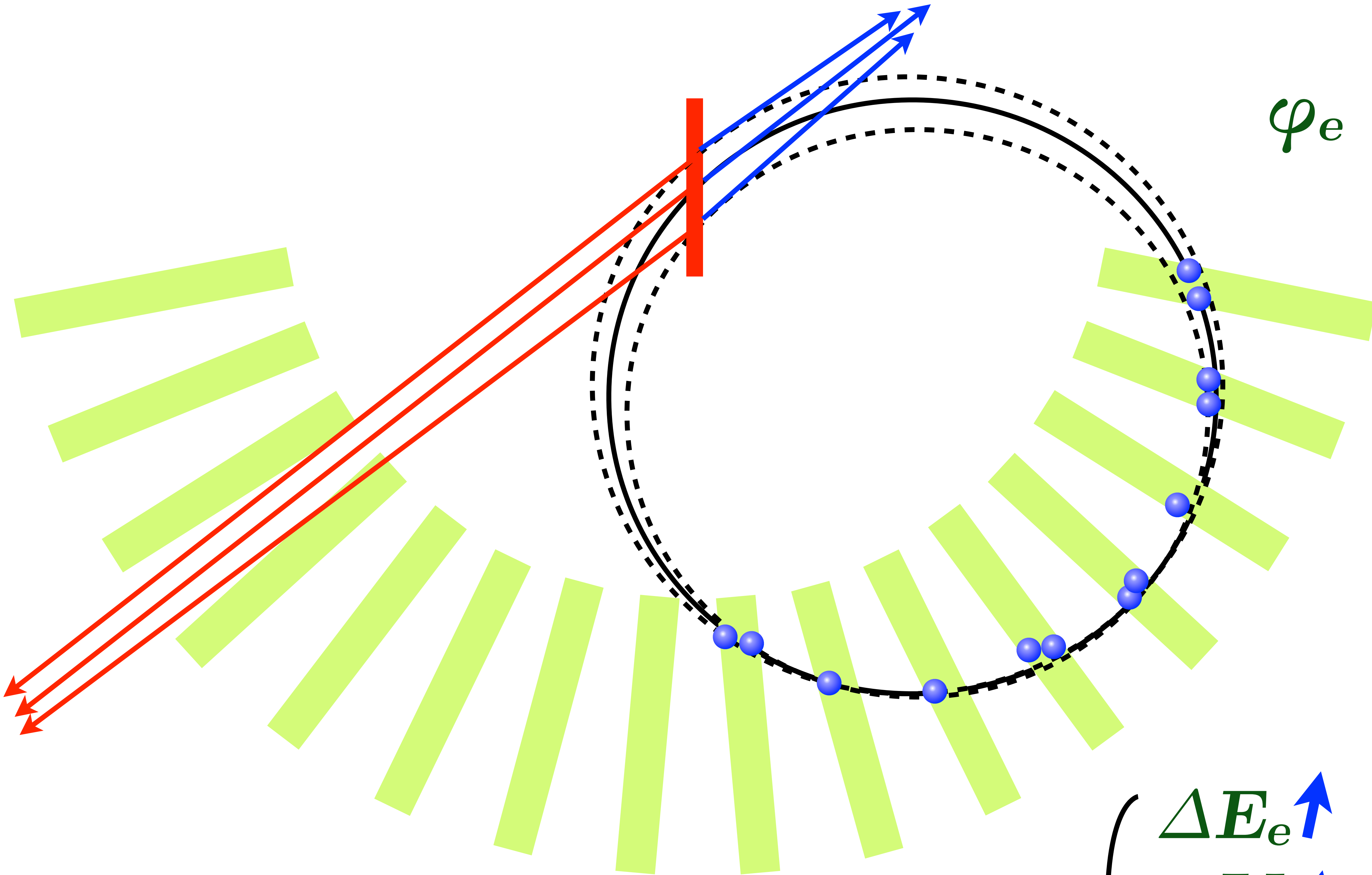
Correlations in positron variables



Correlations in positron variables



Correlations in positron variables

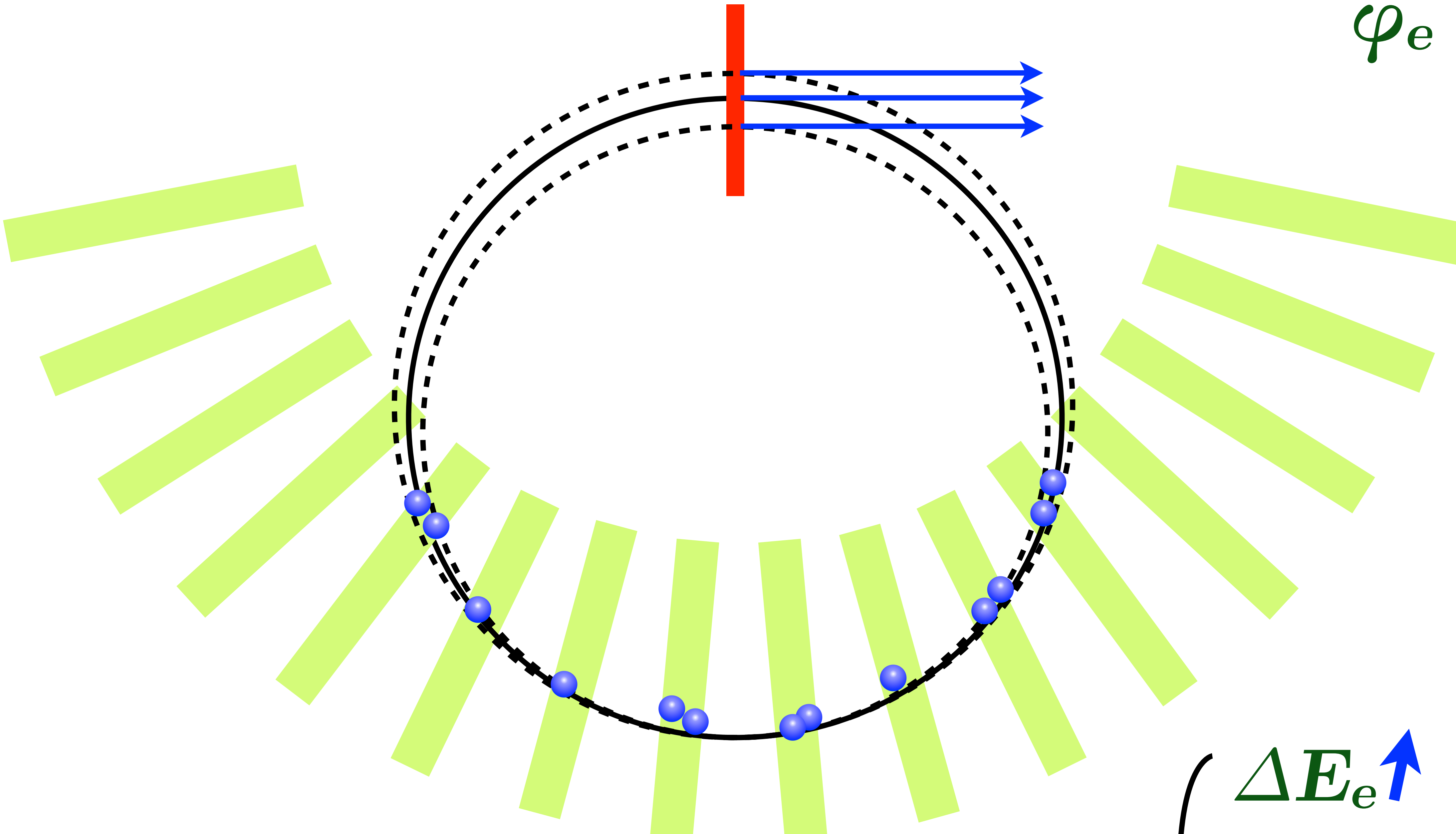


$\varphi_e > 0$

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

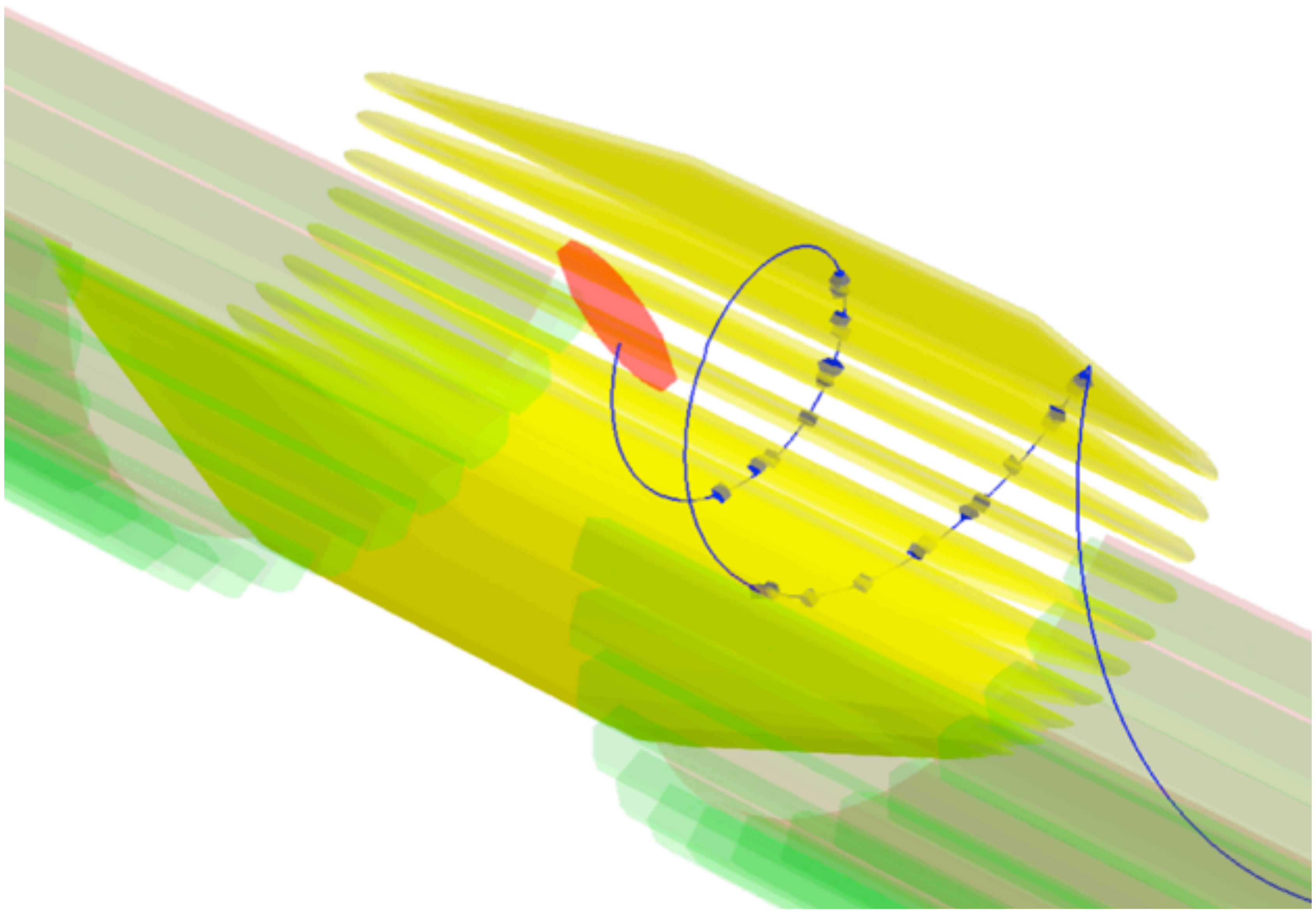
Correlations in positron variables

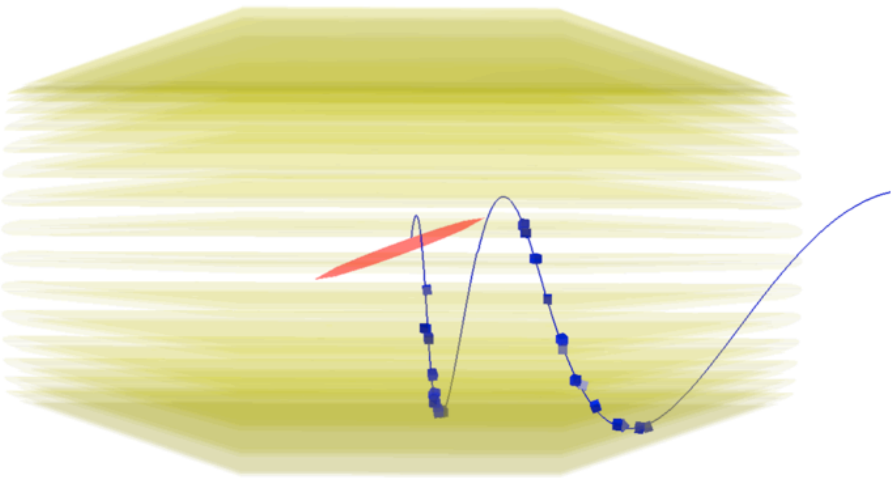
$$\varphi_e = 0$$

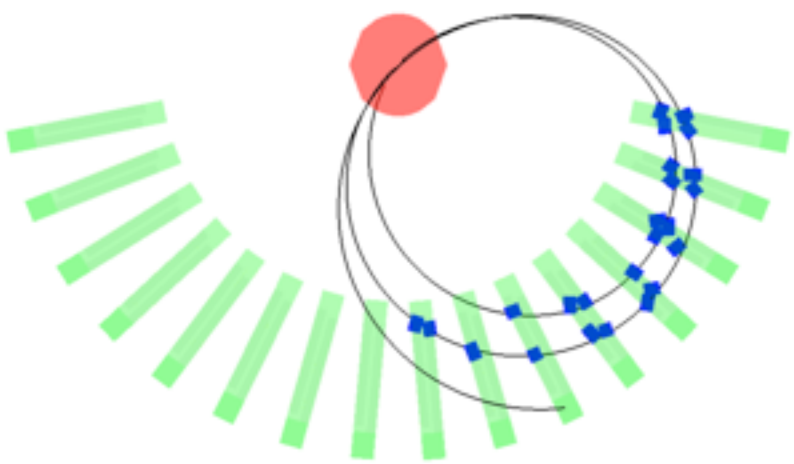


$$\Delta R_e \uparrow \Longrightarrow \left(\begin{array}{l} \Delta E_e \uparrow \\ \Delta Y_e \uparrow \\ \Delta \varphi_e = 0 \end{array} \right.$$

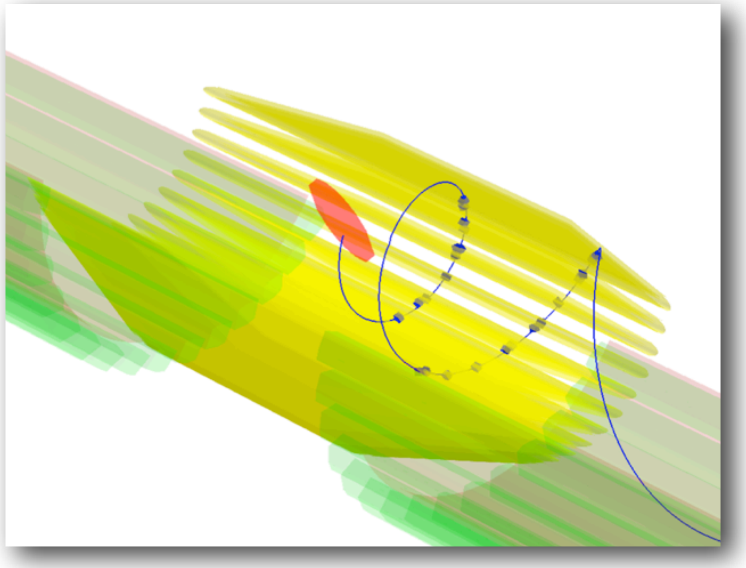
two turn method

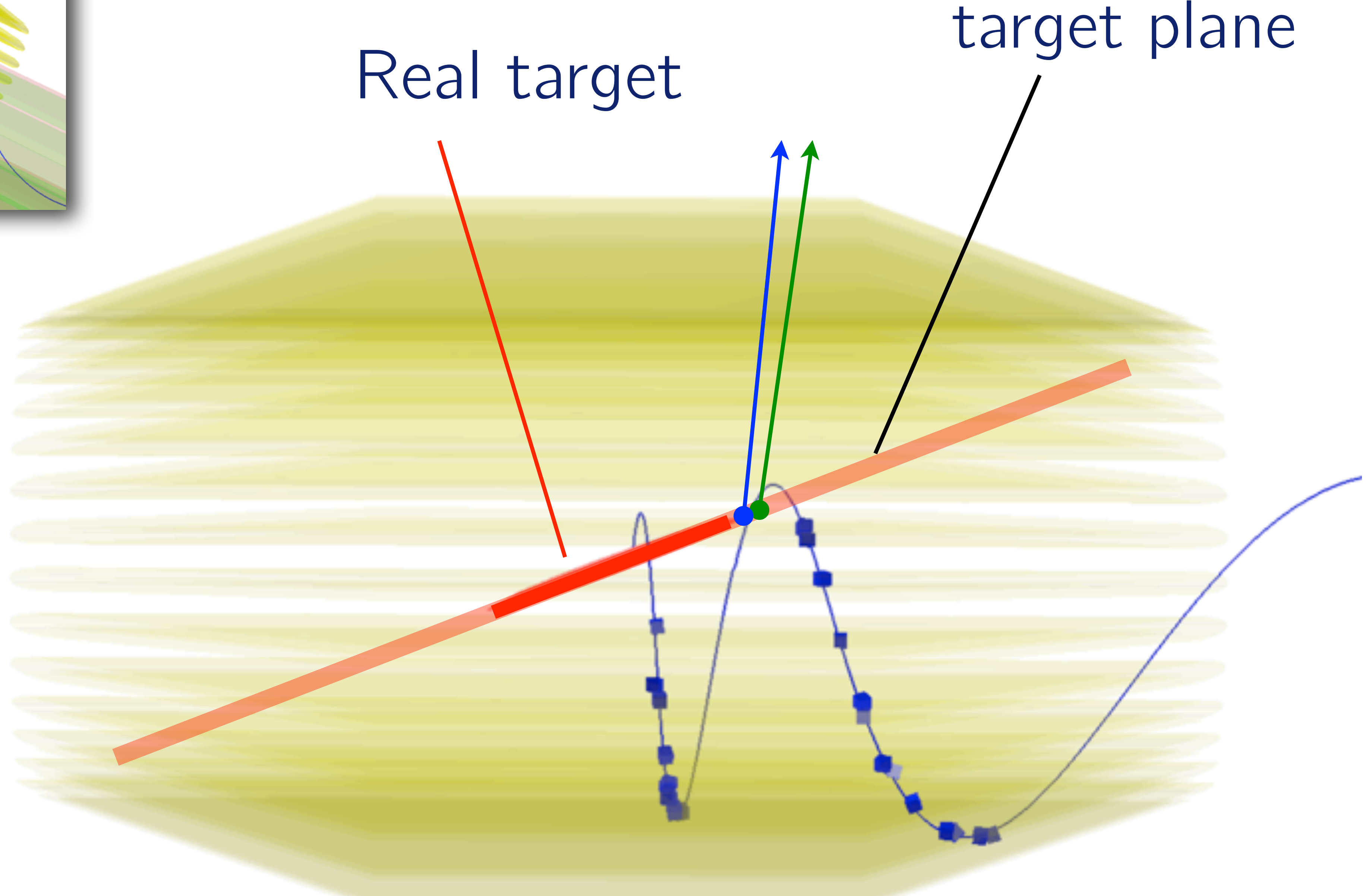


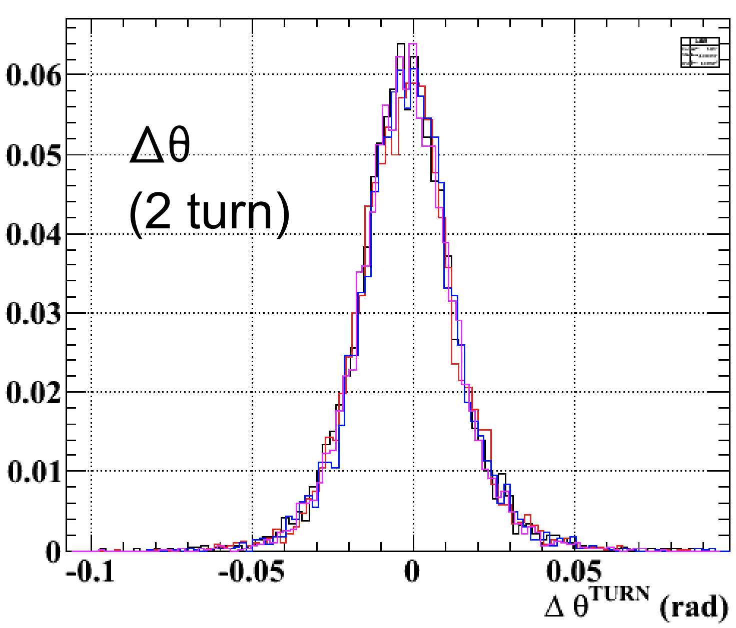




two turn method



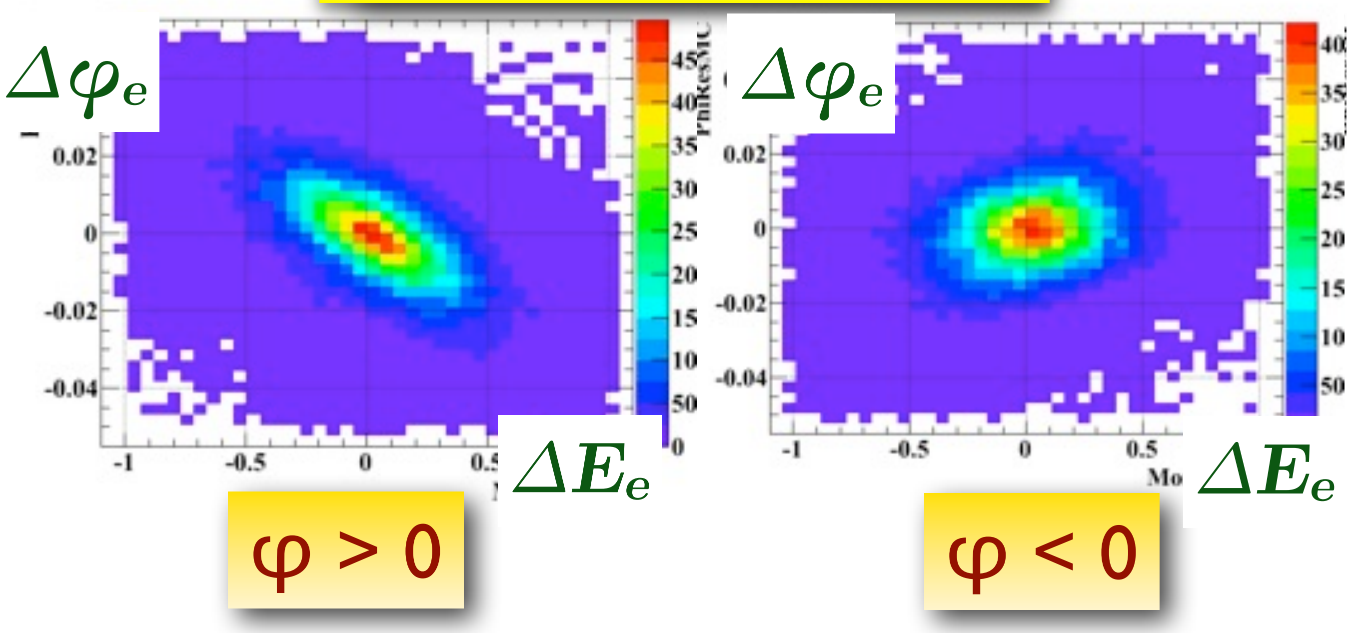




Correlations

e.g. Δφ vs ΔE

MC : Observed - True

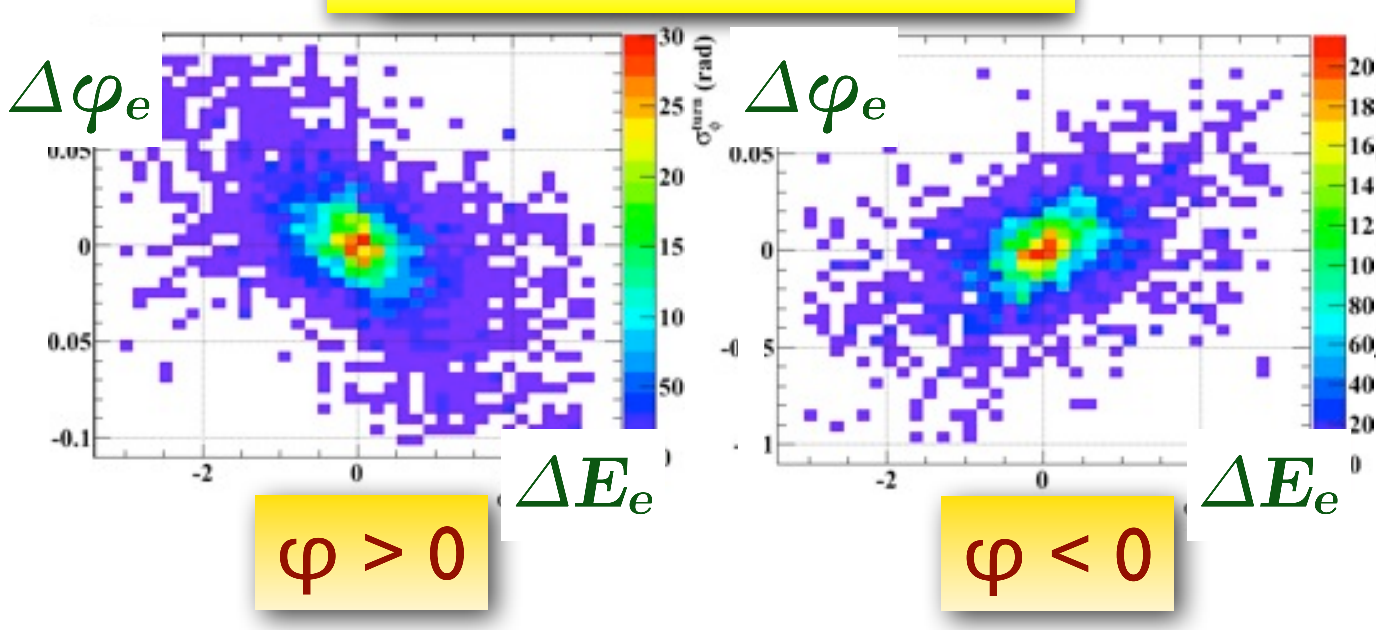


Many of correlations can be measured using data

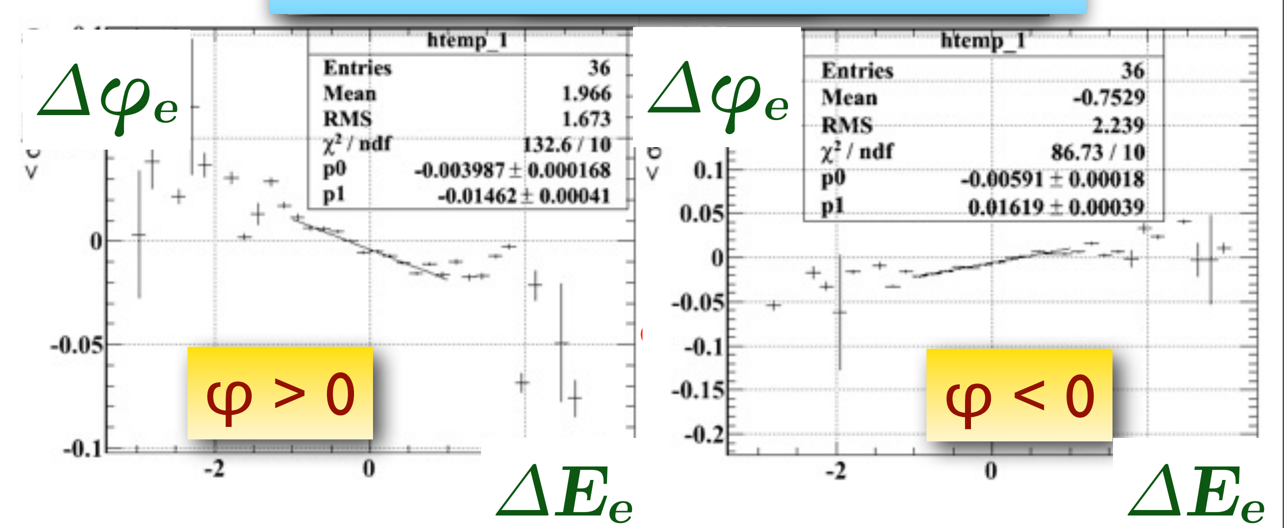
Agreement with MC <10%

Large uncertainty 25% is assigned to un-measurable correlations

MC : two turn method



Data : two turn method



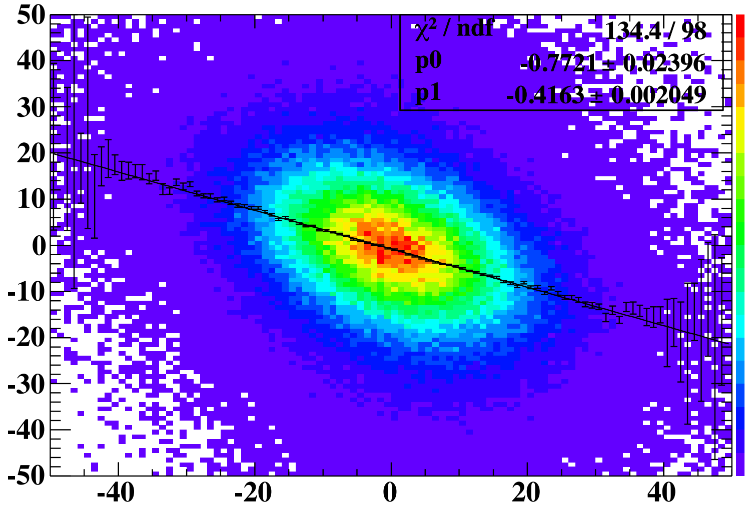
Correlations and physics analysis

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 $\vartheta_{e\gamma}$

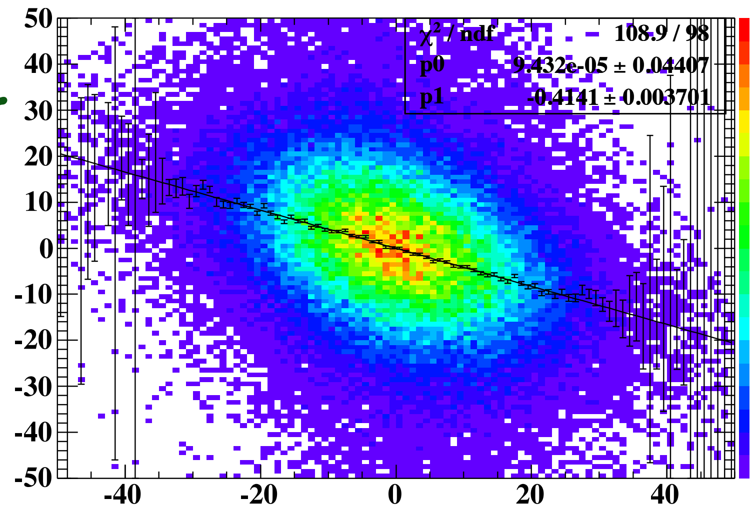
$\varphi_{e\gamma}$



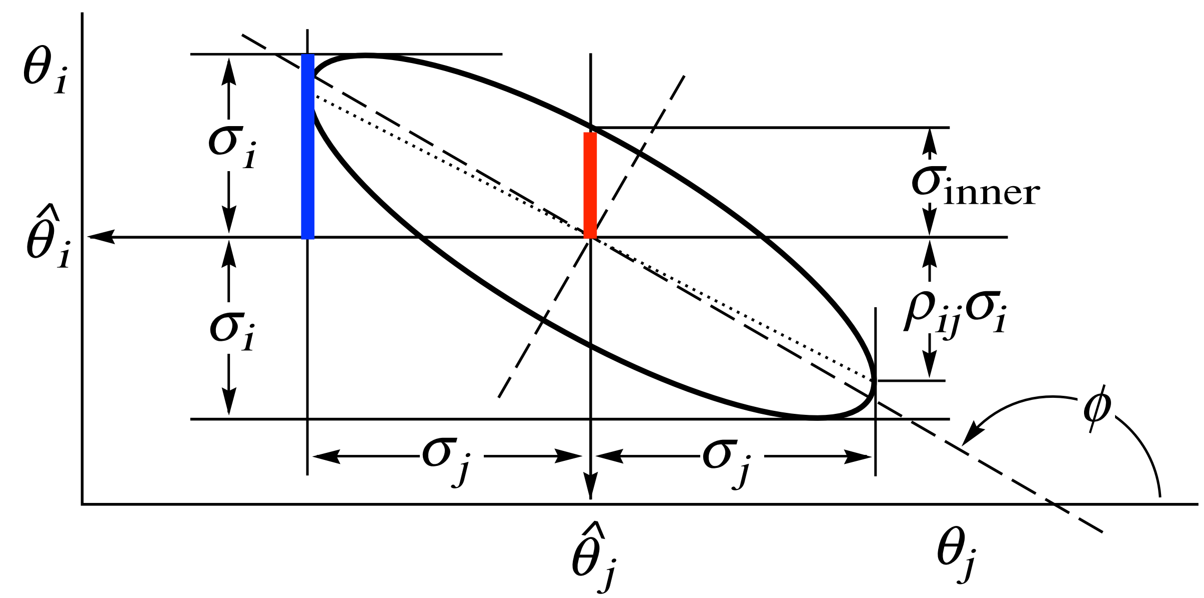
$\vartheta_{e\gamma}$

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

$\varphi_{e\gamma}$



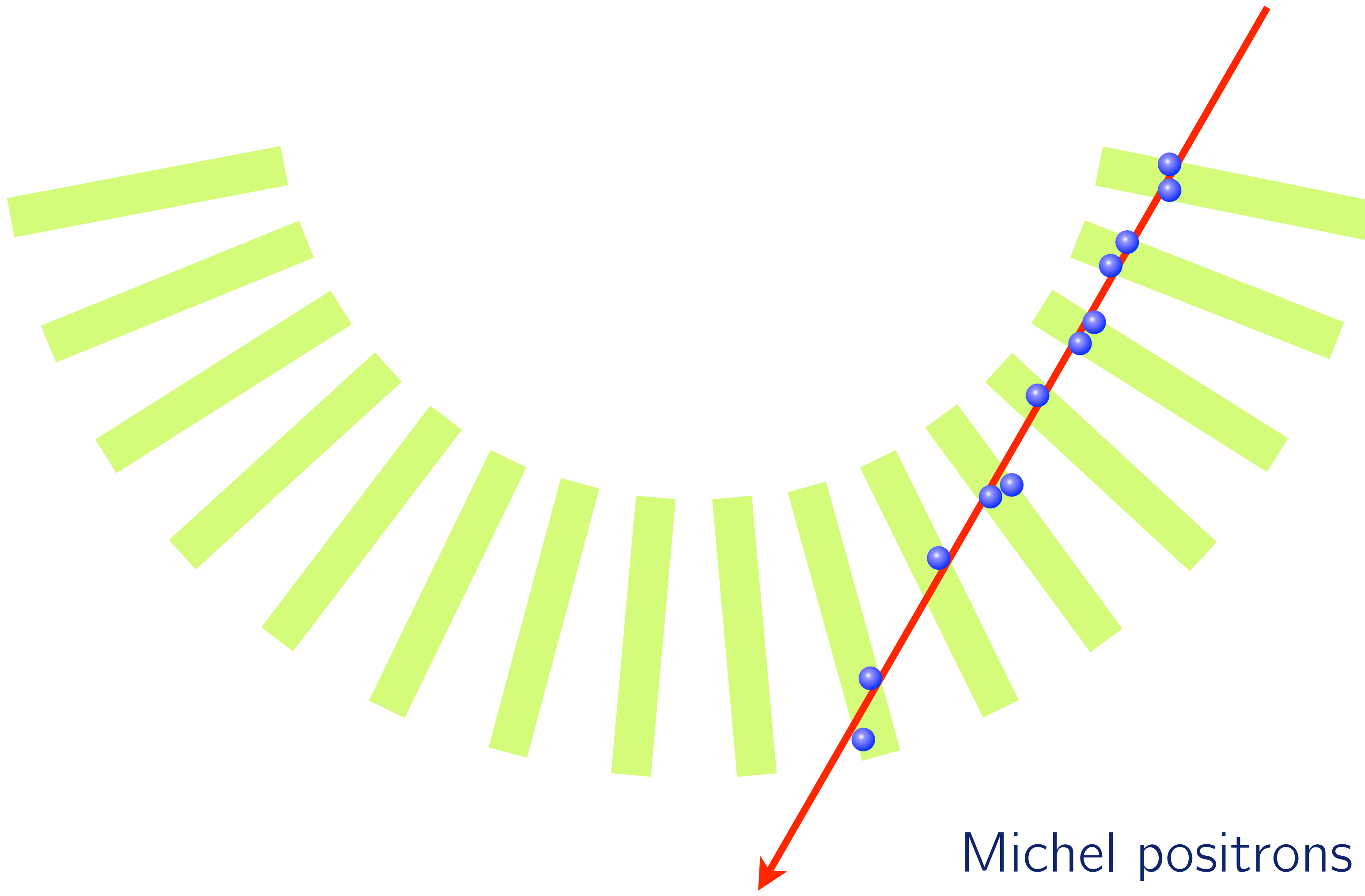
$\vartheta_{e\gamma}$



When correlation is included,

σ_{inner} is used, instead of σi

Alignment of drift chambers



Initial values : optical survey

Michel positrons → Cosmic rays

Iterative process → Fitting all chambers

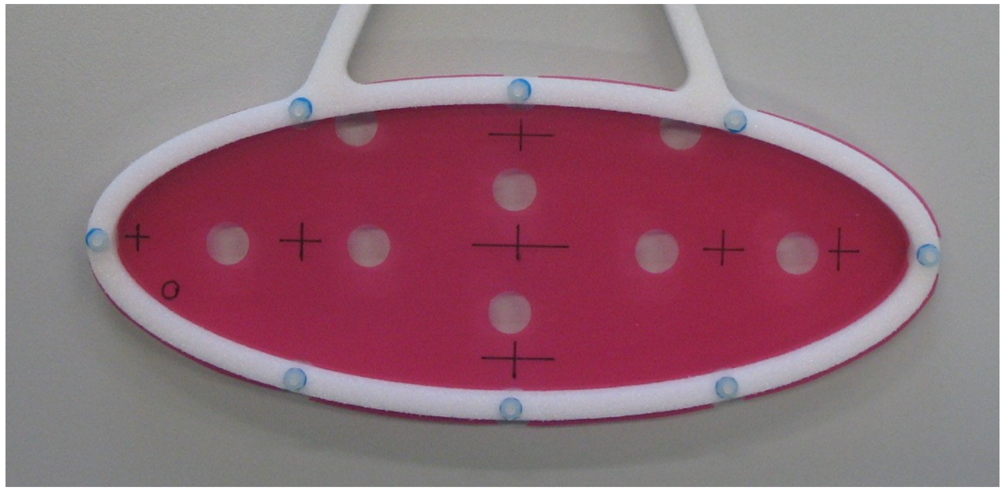
Millipede method,
CMS-NOTE-2006-011

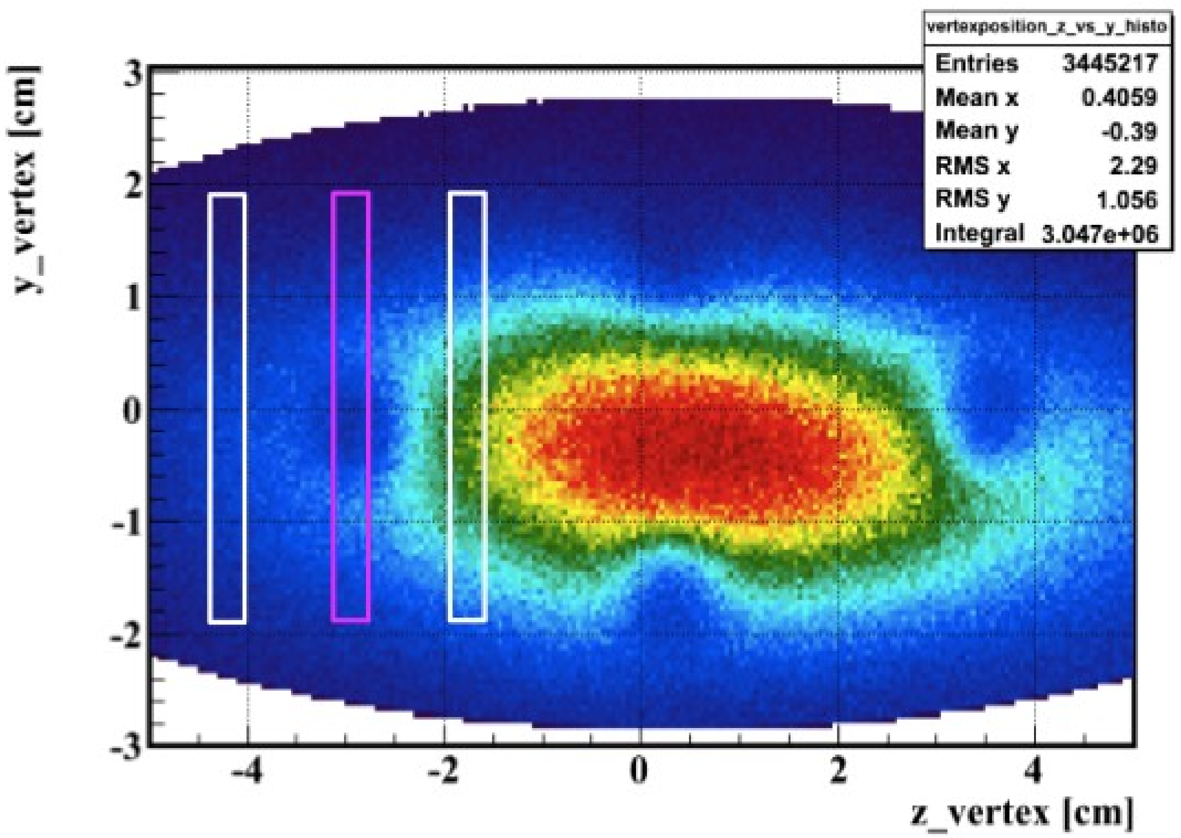
Independent of initial values

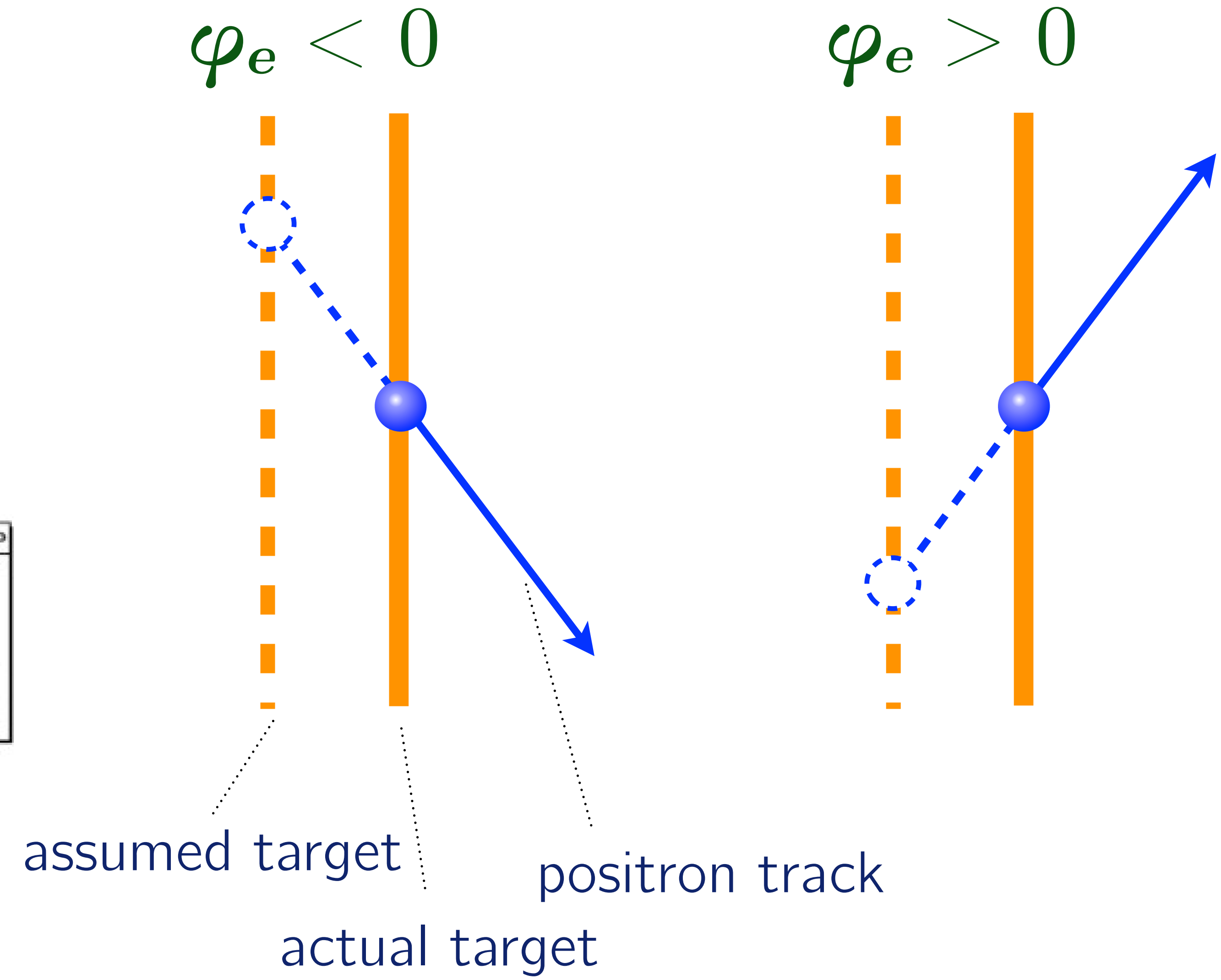
1.5 um and **10^{-2} mrad** level reproducibility, from different initial alignment.

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

Alignment of the target





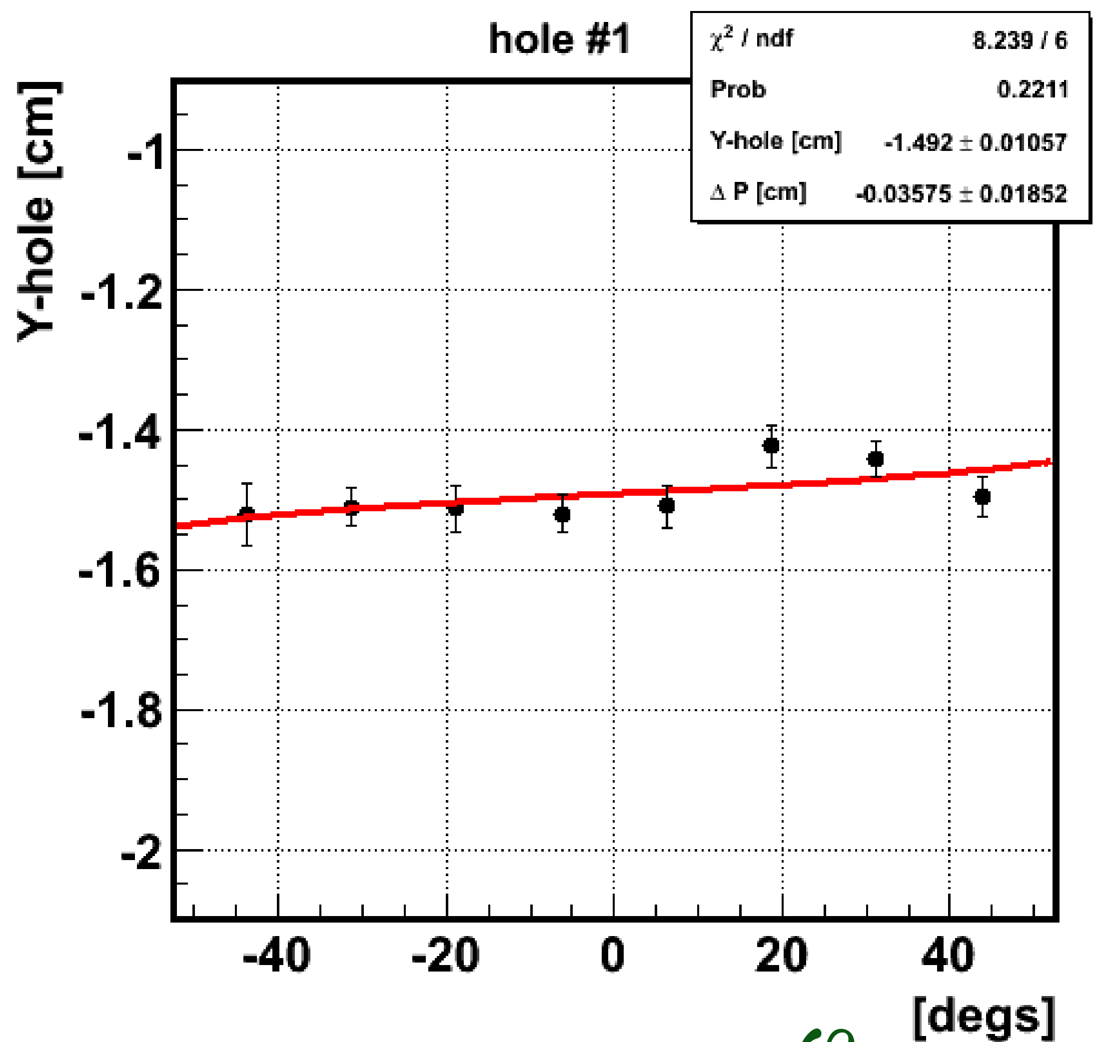


When mis-alignment exists...

hole position depends on angle

Alignment of the target

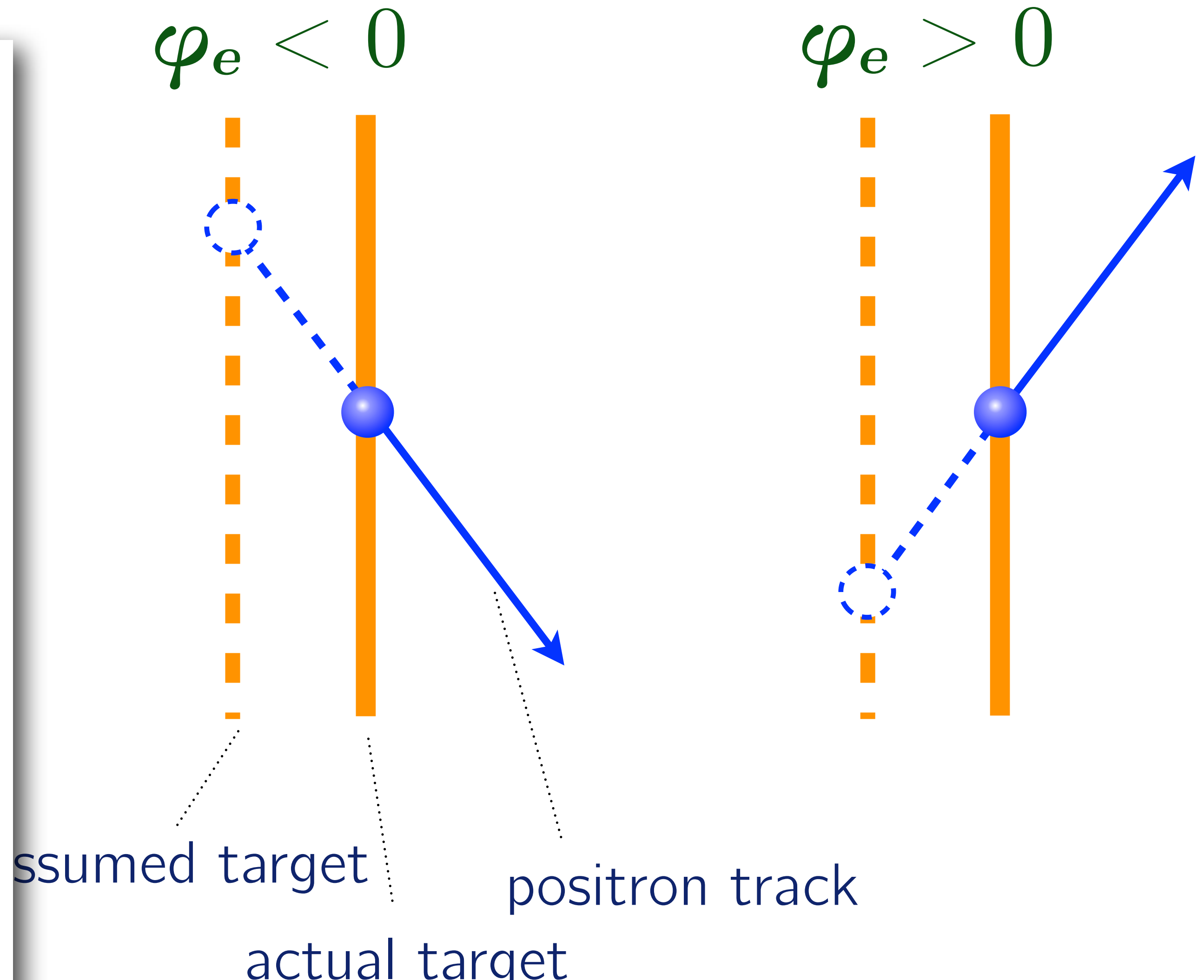
Result



φ_e

Confirmed that

Optical survey position is correct



When mis-alignment exists...

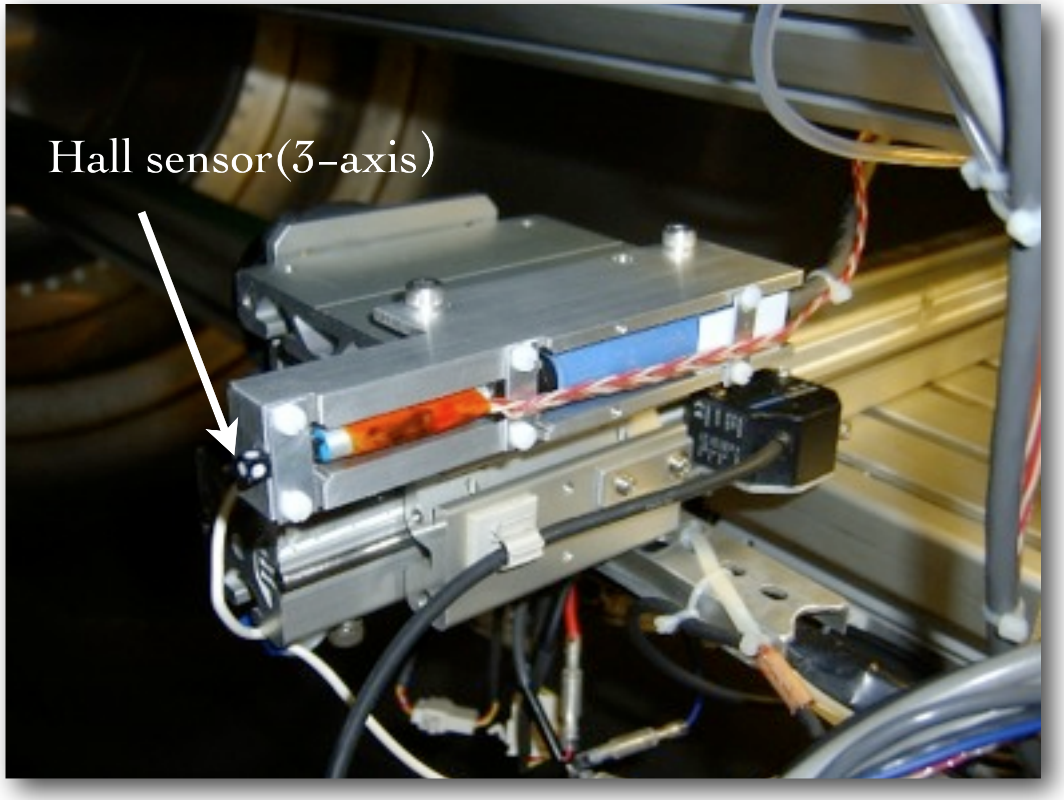
hole position depends on angle

Magnetic field

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

Possible misalignment of hall sensors

$\Longrightarrow$ causes false B_ϕ and B_r from B_z Secondary effect



1.27T @center, 0.49T @ends

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

Non-negligible

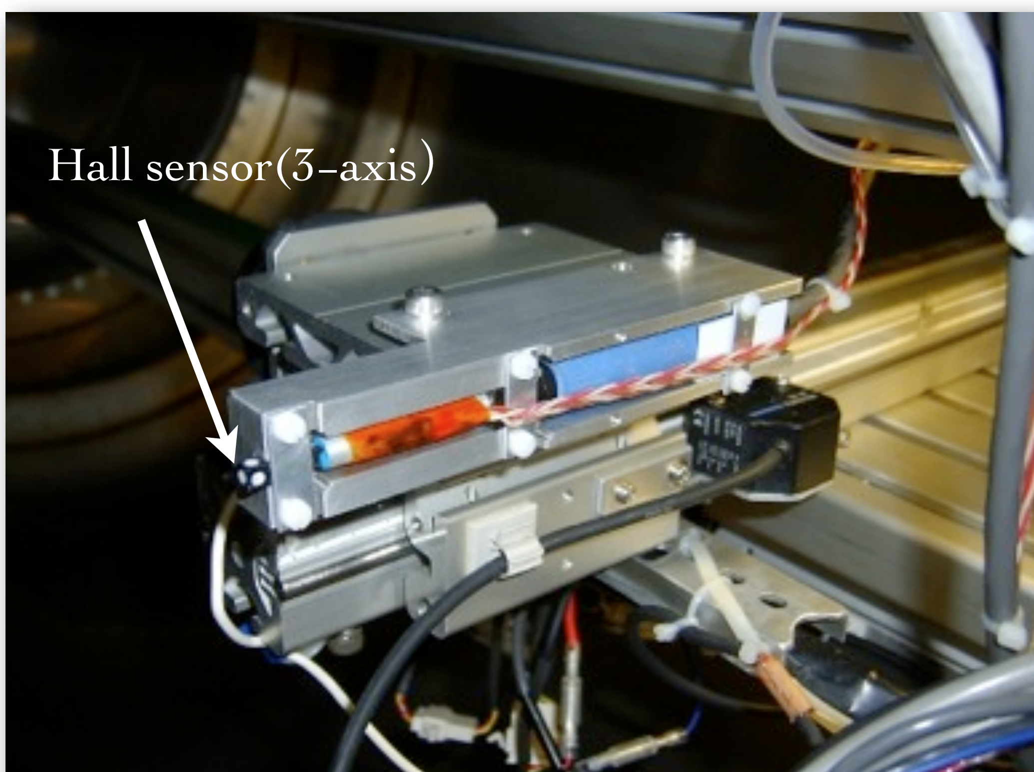
Ideally zero

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

$\Longrightarrow$ causes false B_ϕ and B_r from B_z Secondary effect



1.27T @center, 0.49T @ends

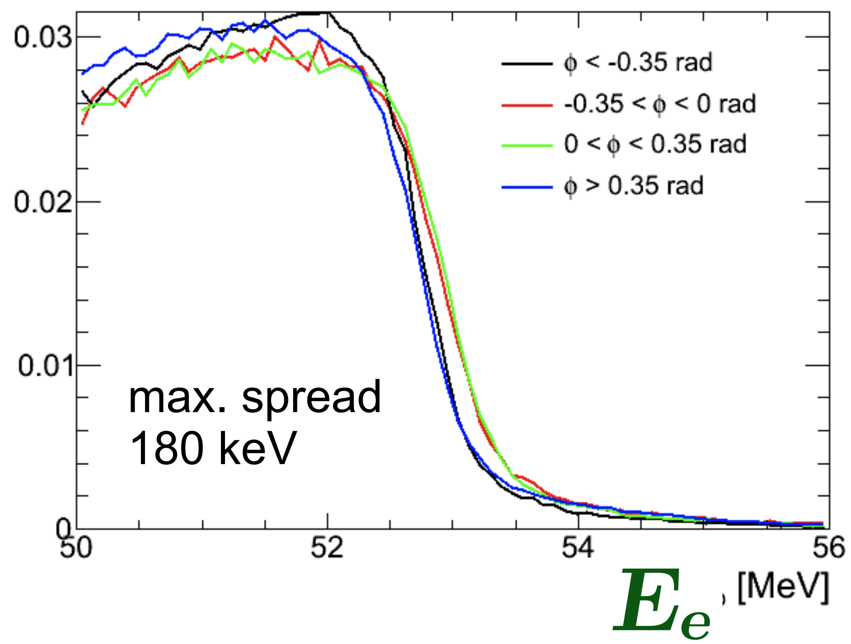
$$\begin{pmatrix} B_z^{\mathrm{meas}} \\ B_r^{\mathrm{meas}} \\ B_\phi^{\mathrm{meas}} \end{pmatrix} = \begin{pmatrix} 1 & \theta_{zr} & \theta_{z\phi} \\ \theta_{rz} & 1 & \theta_{r\phi} \\ \theta_{\phi z} & \theta_{\phi r} & 1 \end{pmatrix} \begin{pmatrix} B_z \\ B_r \\ B_\phi \end{pmatrix}$$

Small (<0.2×Bz)

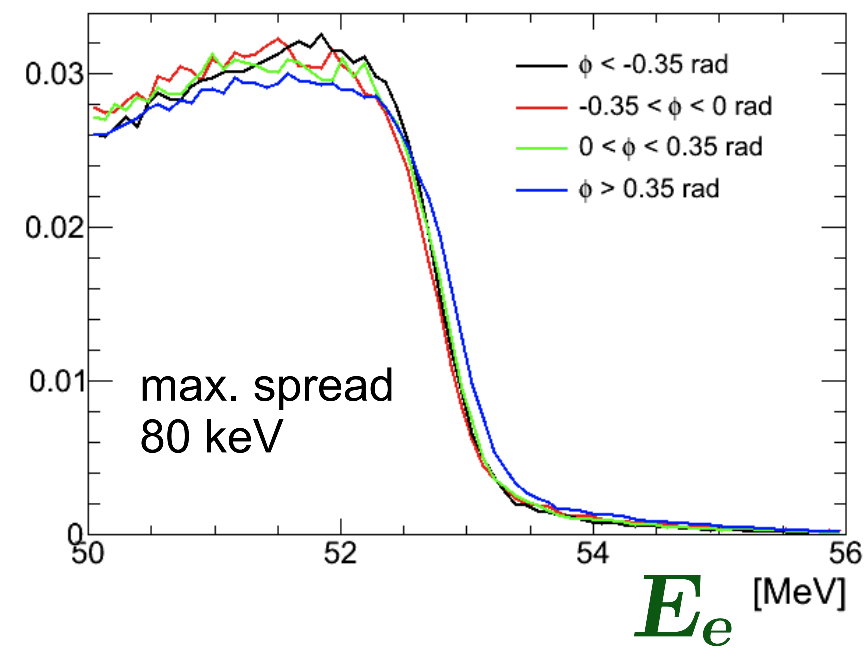
Ideally zero

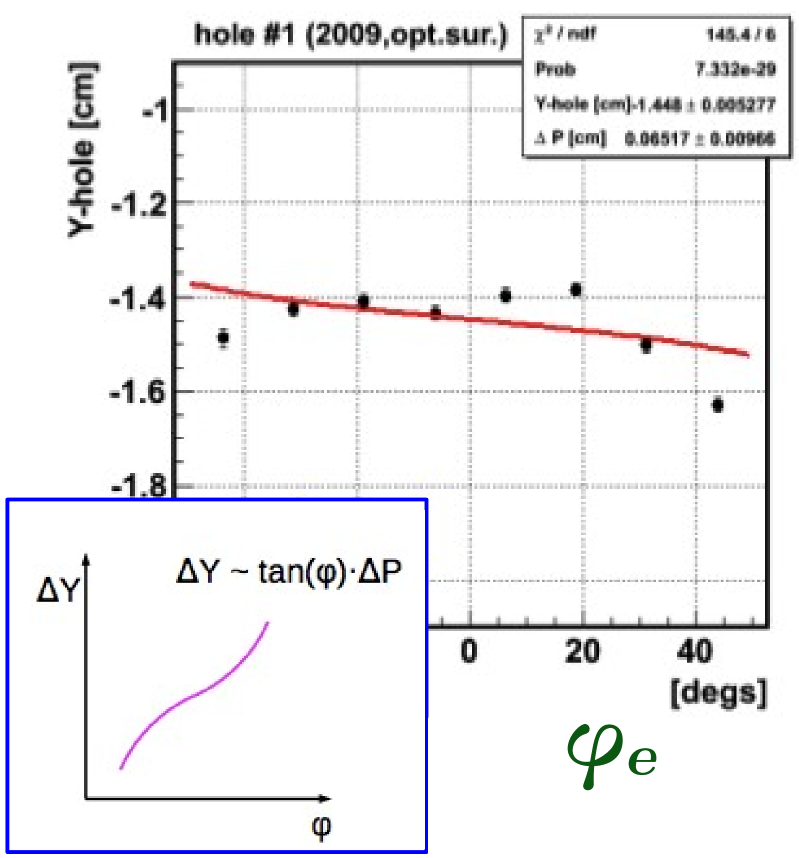
$\Longrightarrow$ Can be found and corrected using Maxwell equations

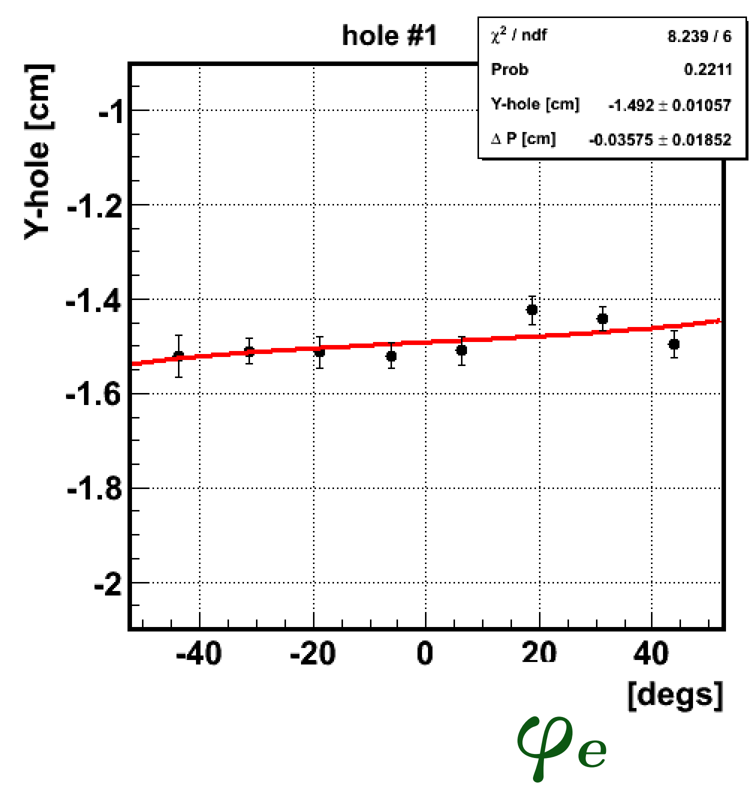
2009 data
DCH alignment using Michel tracks
Calculated B field



2009 data
Millipede alignment
Reconstructed B field







Analysis

Positron analysis

Gamma analysis

Relative alignment

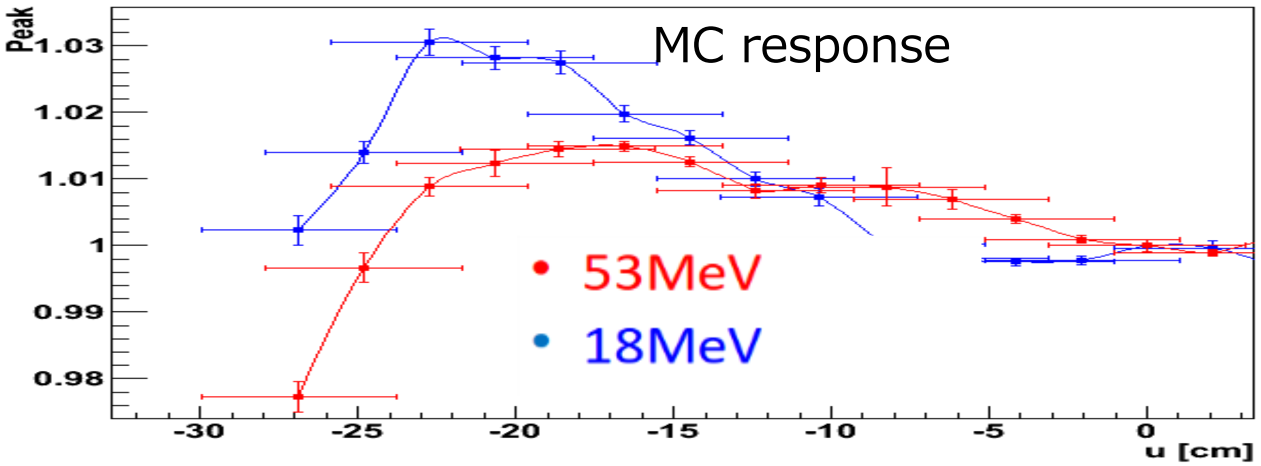
Physics analysis

Energy response

Non-uniformity due to

Geometry

Reconstruction algorithm

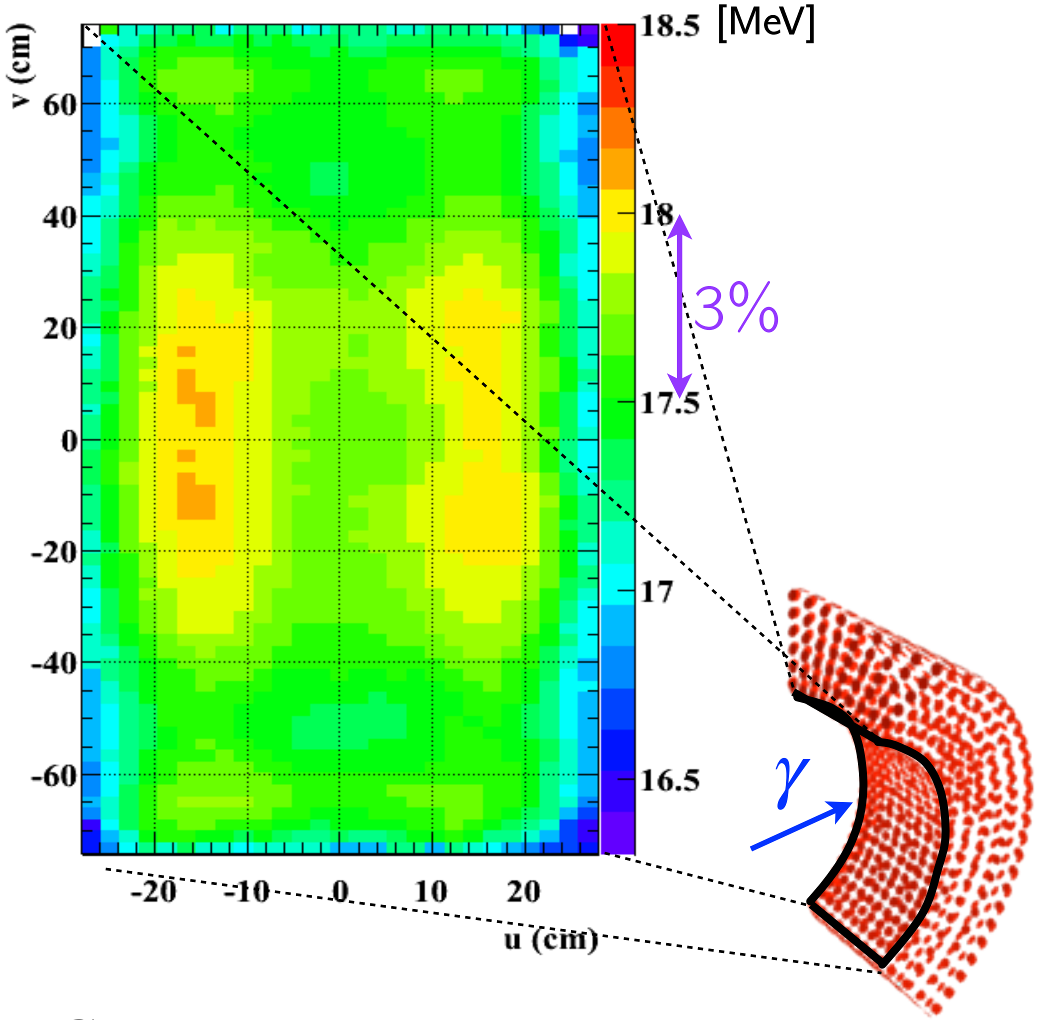


Correction using

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

Energy dependence correction

18 MeV data, uniformity before correction



After correction : **~0.2 % uniform**

Energy stability

Energy absolute scale calibration

CEX 55, 83 MeV γ

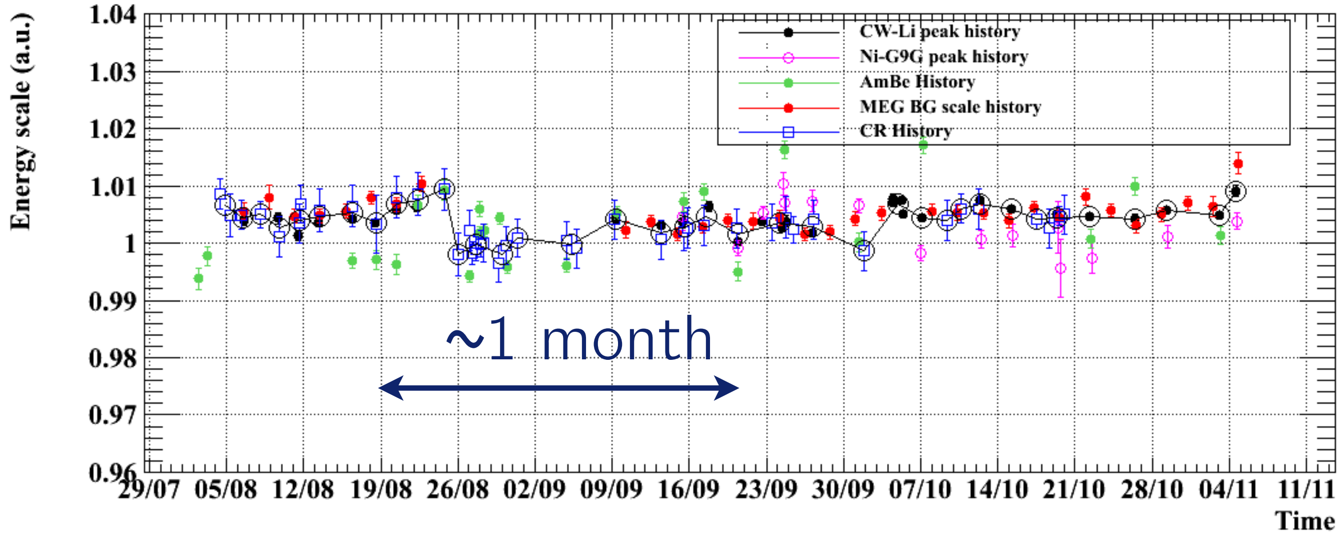
Energy scale time-variation calibration

CW 18 MeV γ

Ni-n 9 MeV γ

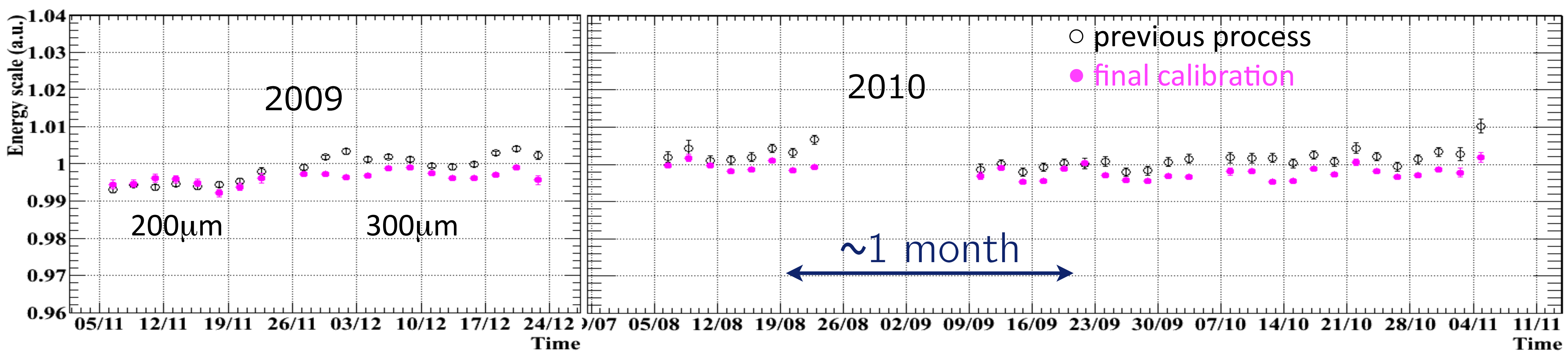
AmBe 4.4 MeV γ

CR peak



Check

Fitting RMD γ



Analysis

Positron analysis

Gamma analysis

Relative alignment

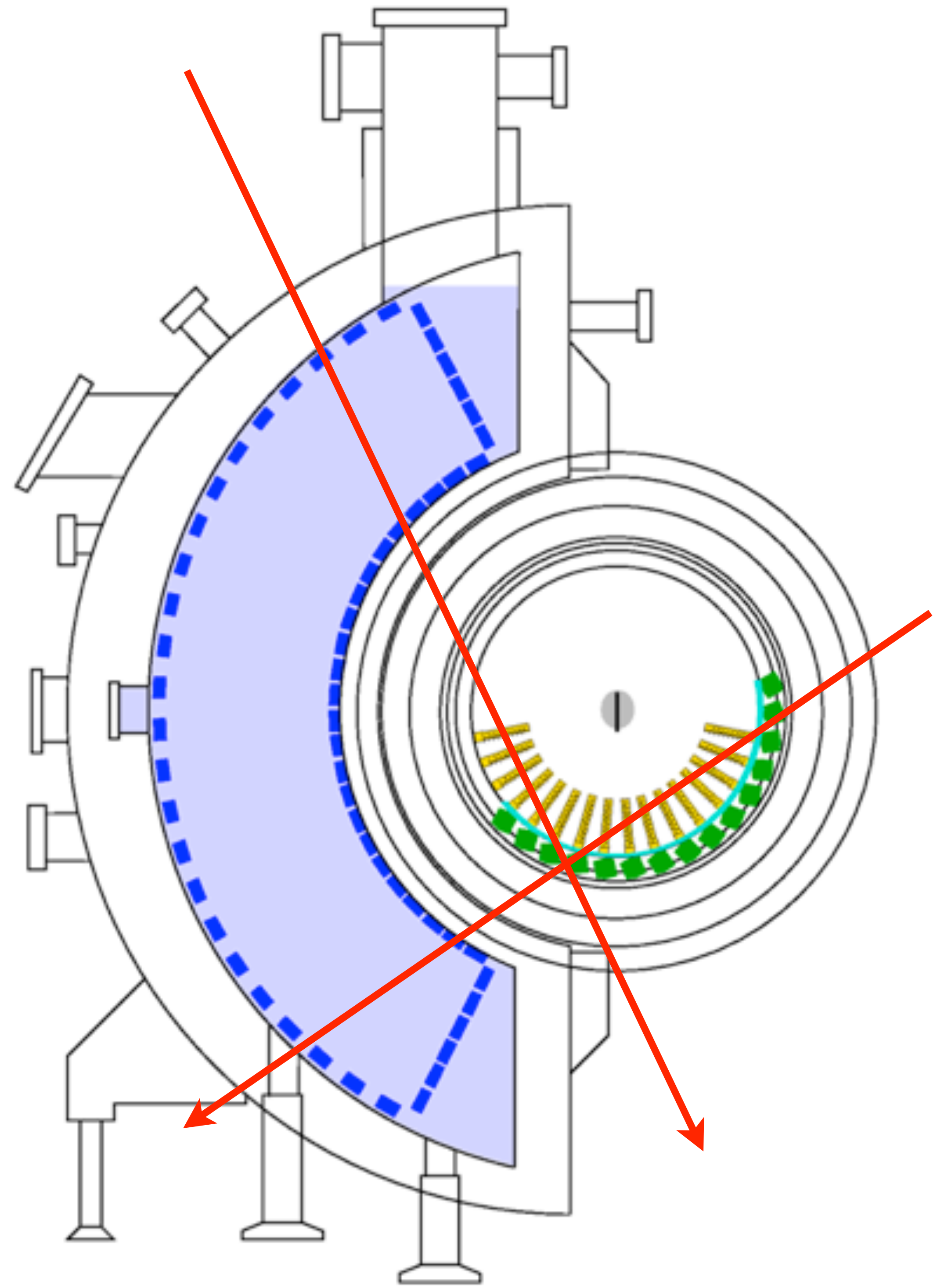
Physics analysis

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



Analysis

Positron analysis

Gamma analysis

Relative alignment

Physics analysis

Likelihood function

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

Likelihood and test-statistic

$$\mathcal{L}\left(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}\right) =$$

$$\frac{e^{-N}}{N_{\rm obs}!} \boxed{e^{-\frac{\left(N_{\rm RMD}-\langle N_{\rm RMD}\rangle\right)^2}{2\sigma_{\rm RMD}^2}} e^{-\frac{\left(N_{\rm BG}-\langle N_{\rm BG}\rangle\right)^2}{2\sigma_{\rm BG}^2}}} \times$$

$$\prod_{i=1}^{N_{\rm obs}} \left(N_{\rm sig} S\left(\overrightarrow{x_i}\right) + N_{\rm RMD} R\left(\overrightarrow{x_i}\right) + N_{\rm BG} B\left(\overrightarrow{x_i}\right)\right)$$

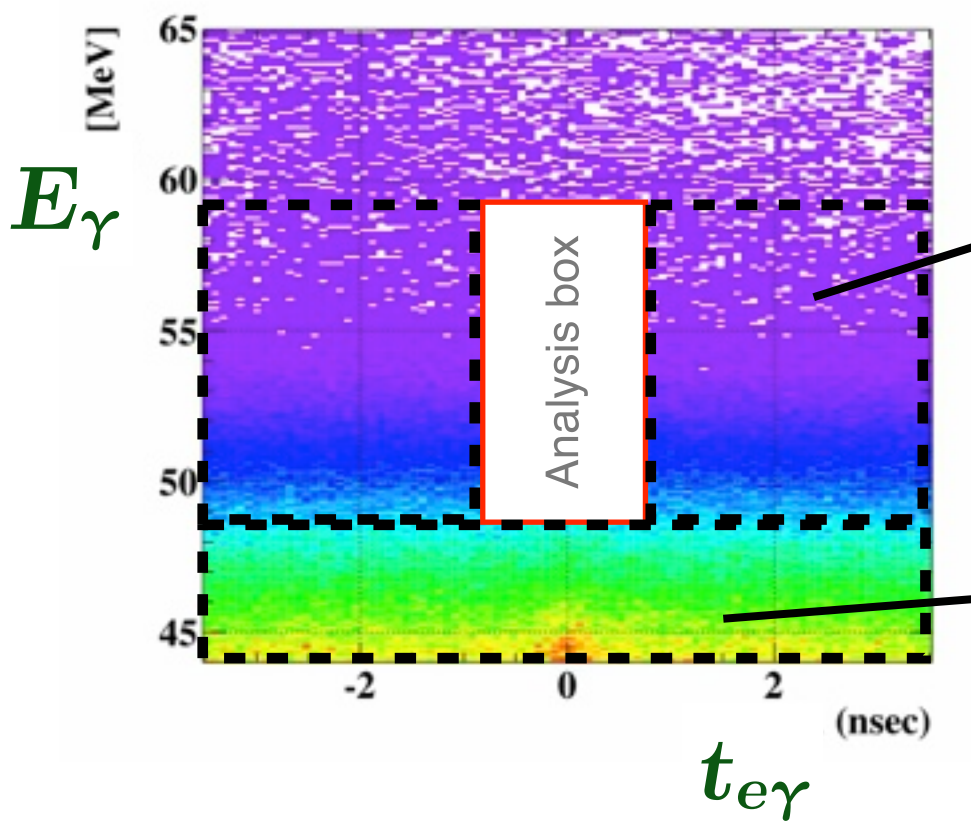
Two Gaussian constrain $N_{\rm RMD}$ and $N_{\rm BG}$

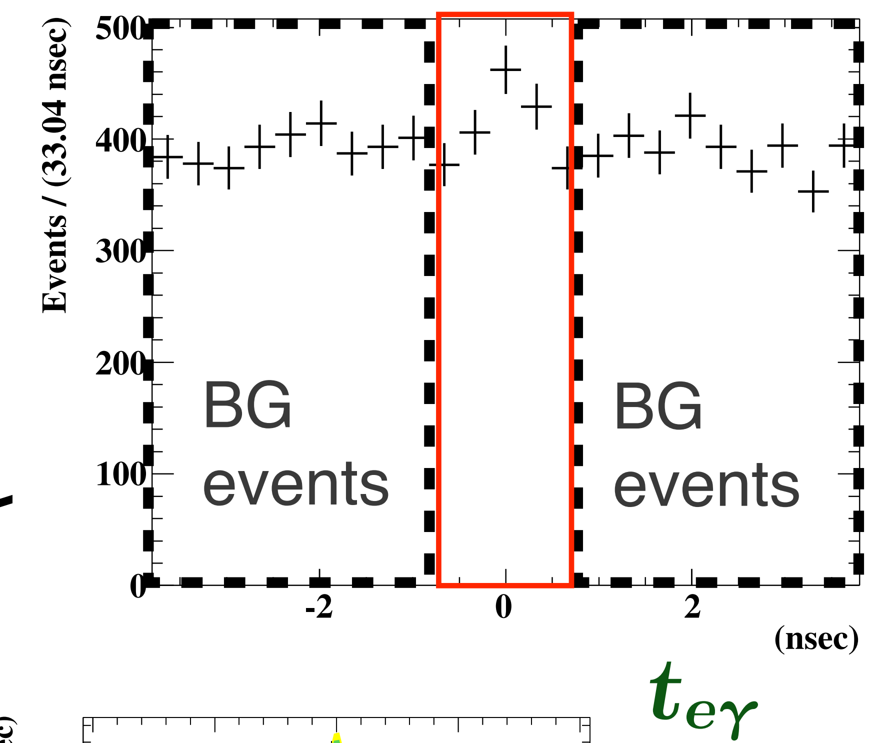
Likelihood and test-statistic

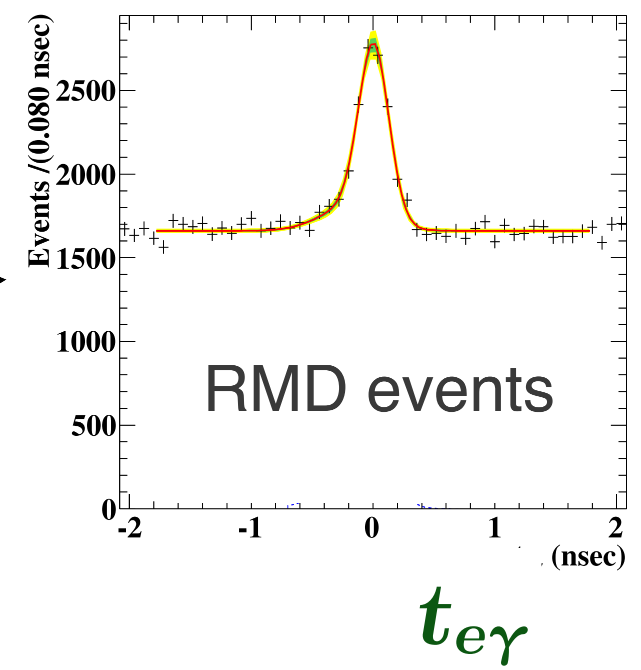
E_γ vs T distribution without any selection.

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

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







Likelihood and test-statistic

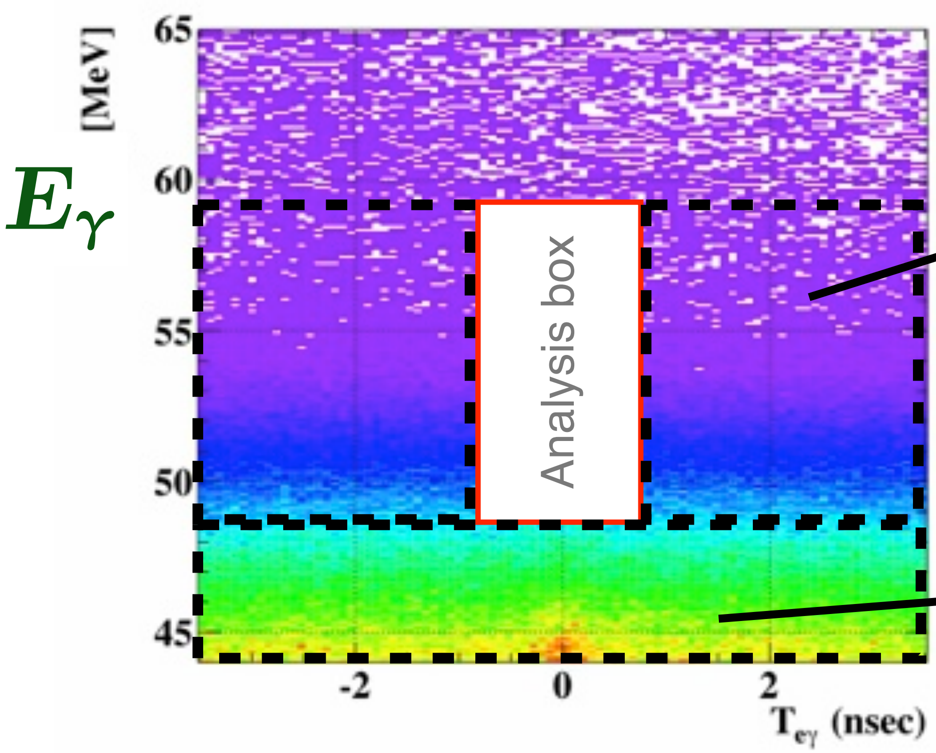
E_γ vs T distribution without any selection.

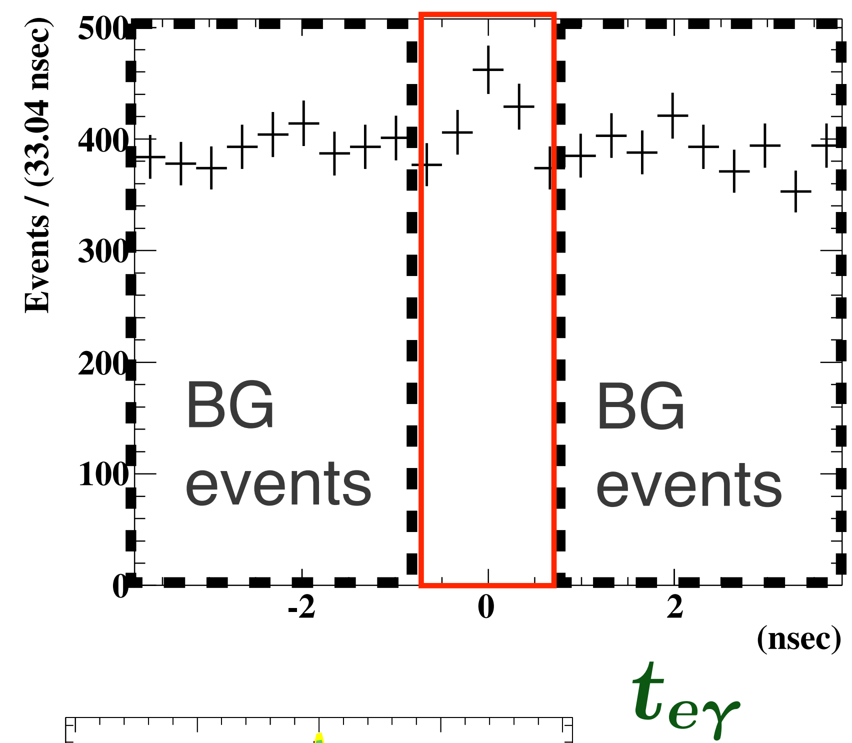
$$\mathcal{L}\left(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}\right) =$$

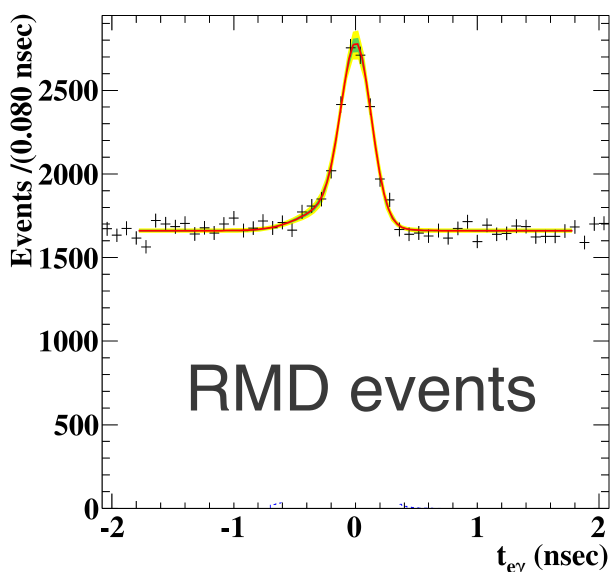
$$\frac{e^{-N}}{N_{\rm obs}!} \boxed{e^{-\frac{(N_{\rm RMD}-\langle N_{\rm RMD}\rangle)^2}{2\sigma^2_{\rm RMD}}}\; e^{-\frac{(N_{\rm BG}-\langle N_{\rm BG}\rangle)^2}{2\sigma^2_{\rm BG}}}} \times$$

$$\prod_{i=1}^{N_{\rm obs}} \left(N_{\rm sig} S\left(\vec{x_i}\right) + N_{\rm RMD} R\left(\vec{x_i}\right) + N_{\rm BG} B\left(\vec{x_i}\right)\right)$$

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



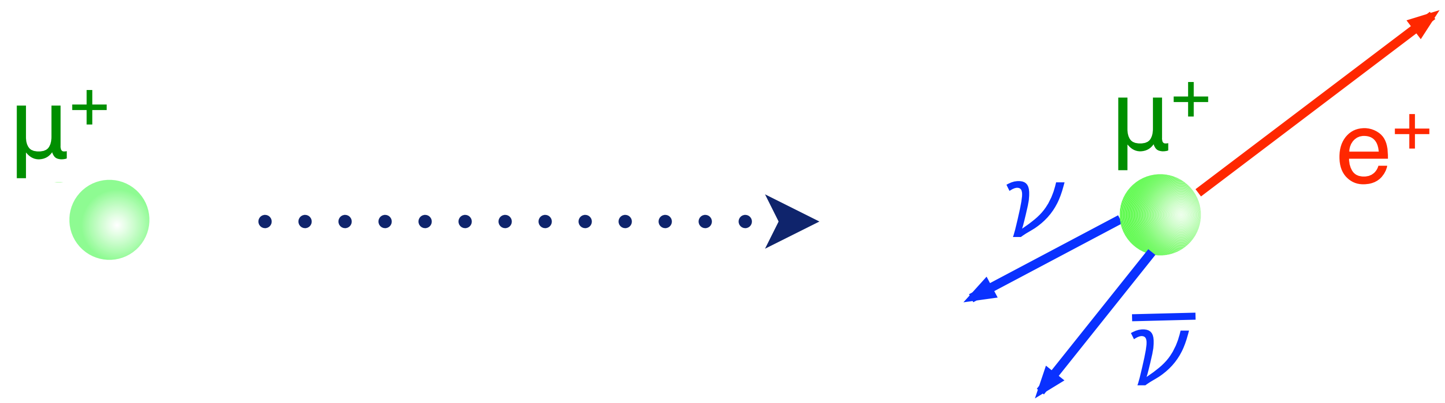




$$\lambda_{\rm p}(N_{\rm sig}) = \frac{\mathcal{L}(N_{\rm sig}, \hat{\hat{N}}_{\rm RMD}(N_{\rm sig}), \hat{\hat{N}}_{\rm BG}(N_{\rm sig}))}{\mathcal{L}(\hat{N}_{\rm sig}, \hat{N}_{\rm RMD}, \hat{N}_{\rm BG})}$$

Profile likelihood ordering
Feldman-Cousins approach

Normalization



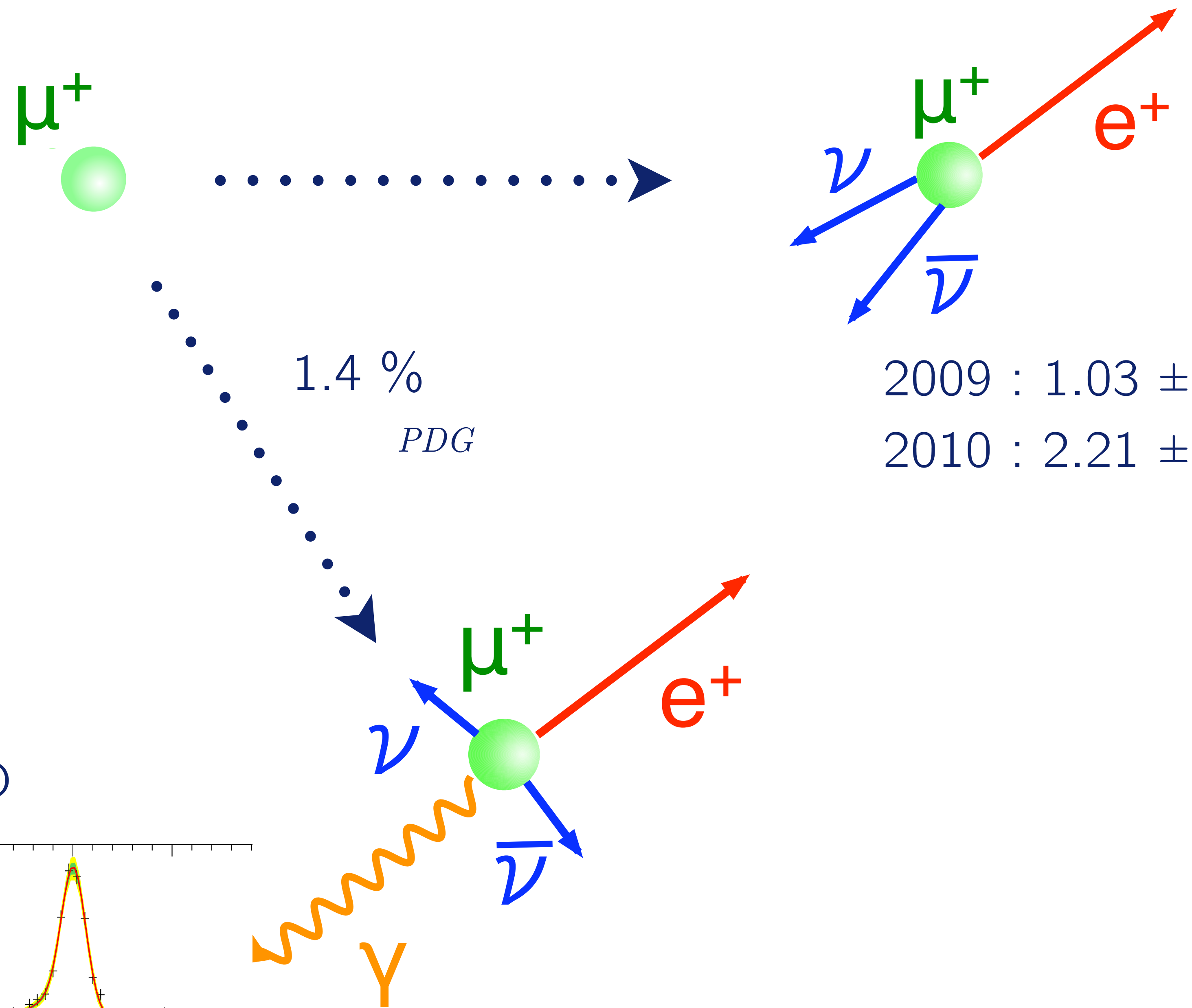
Michel decay

2009 : 1.03 ± 0.09

2010 : 2.21 ± 0.2

~ 10% Uncertainty

Normalization



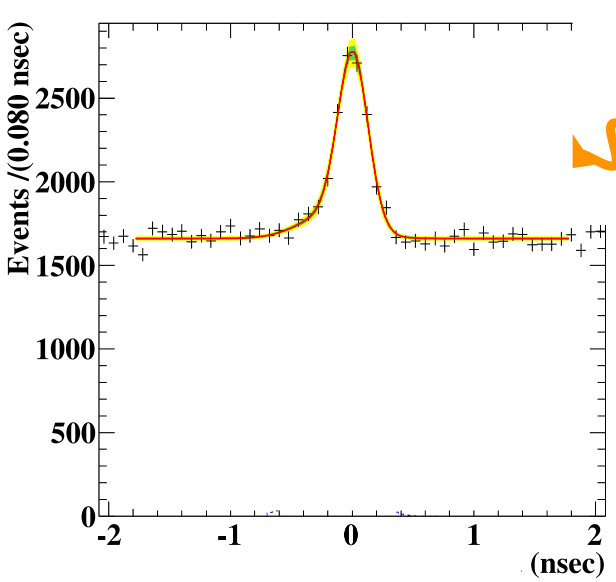
Michel decay

2009 : 1.03 ± 0.09

2010 : 2.21 ± 0.2

~ 10% Uncertainty

RMD



$t_{e\gamma}$

2009 : 1.14 ± 0.10

2010 : 2.28 ± 0.27

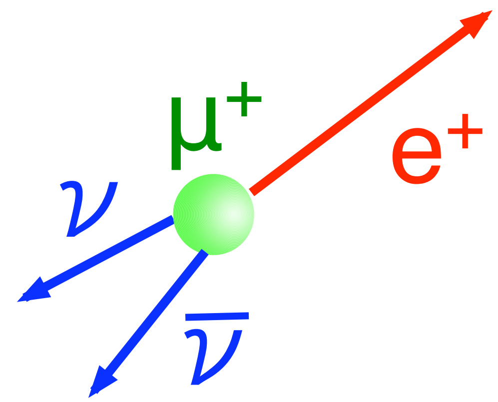
~ 10% Uncertainty

Normalization

μ^+

1.4 %

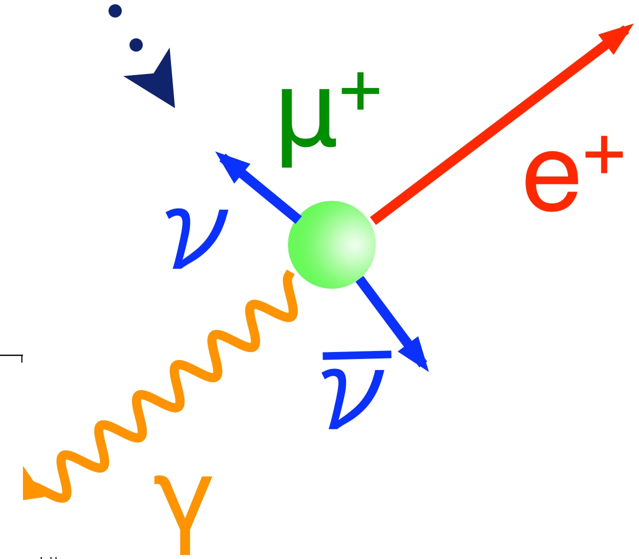
PDG



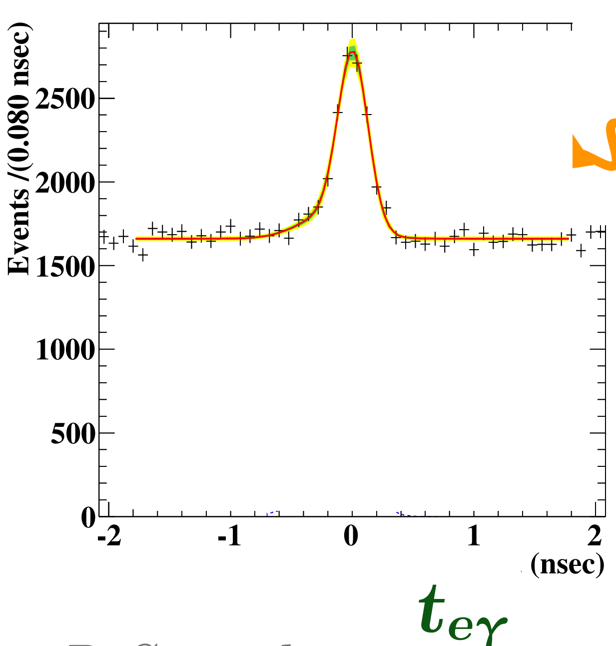
Michel decay

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

2009 : 1.08 ± 0.07
2010 : 2.23 ± 0.16

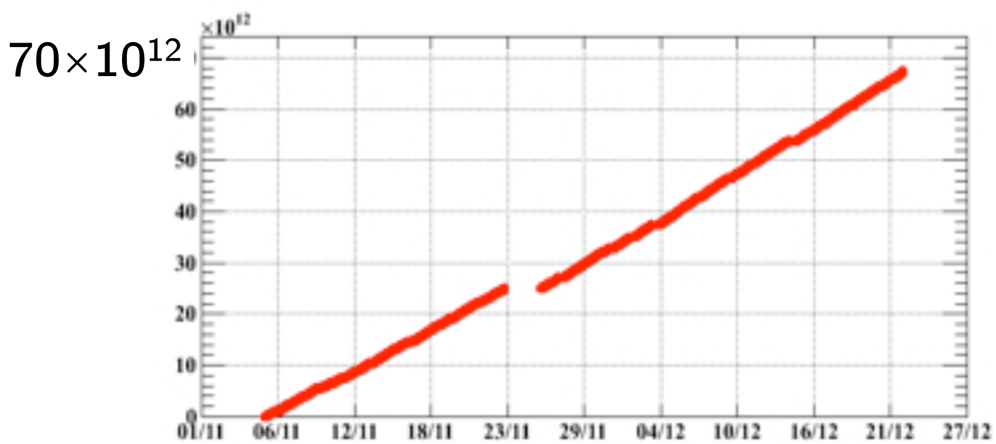
~ **7%** Uncertainty

Result

Data statistics

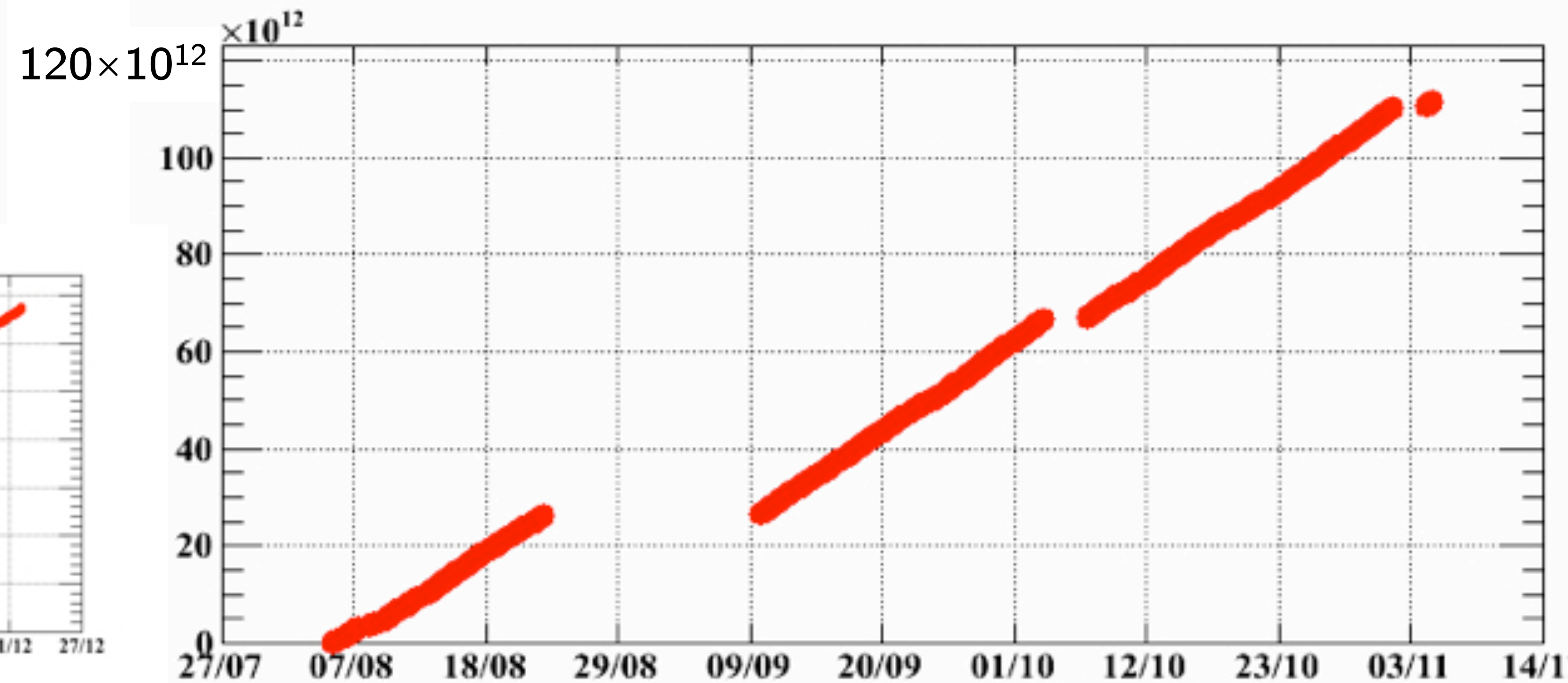
of muons stopped on the target

2009



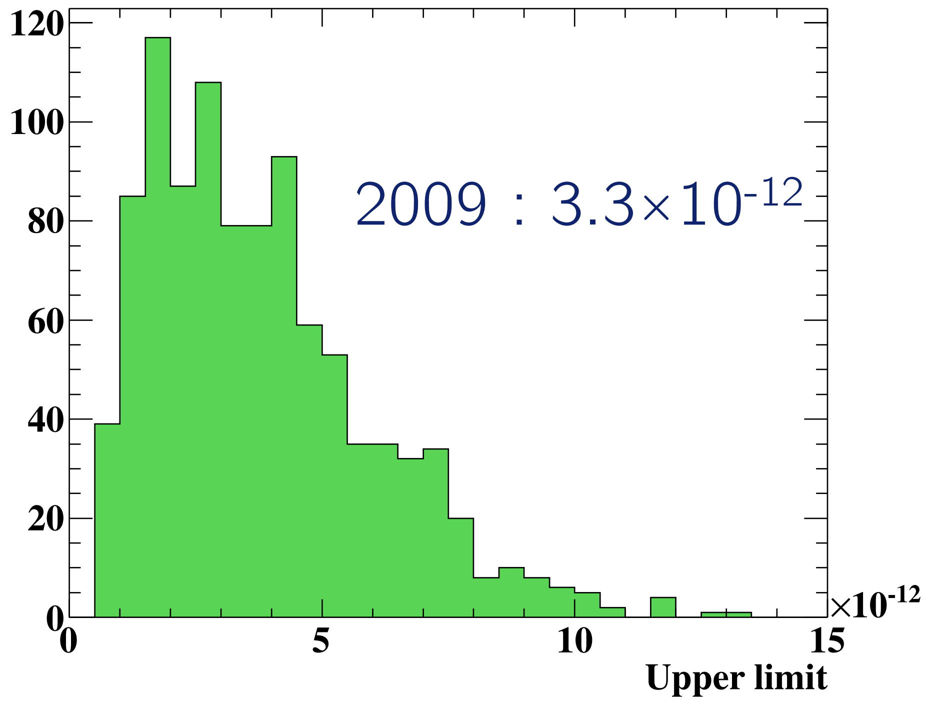
~1.5 months

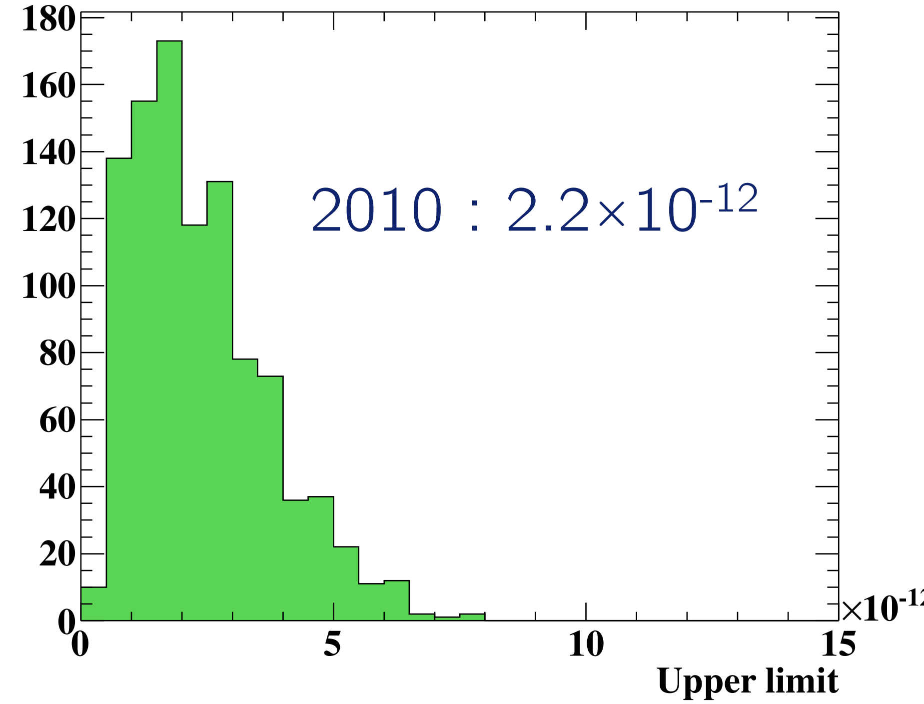
2010



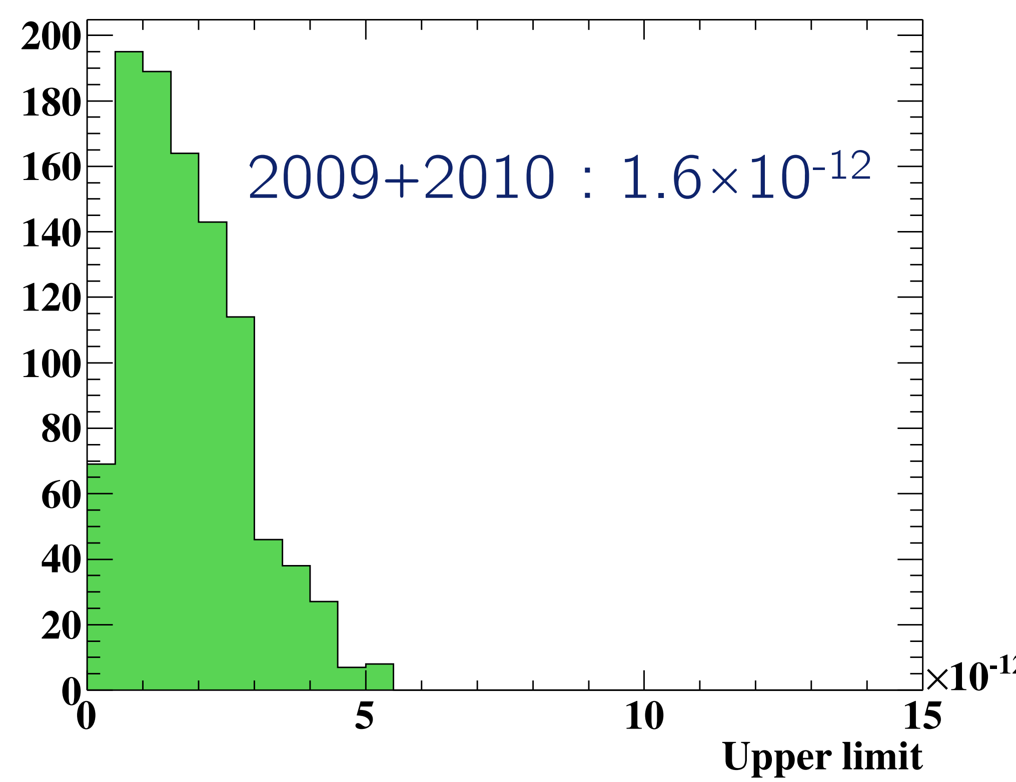
~3 month

Sensitivity

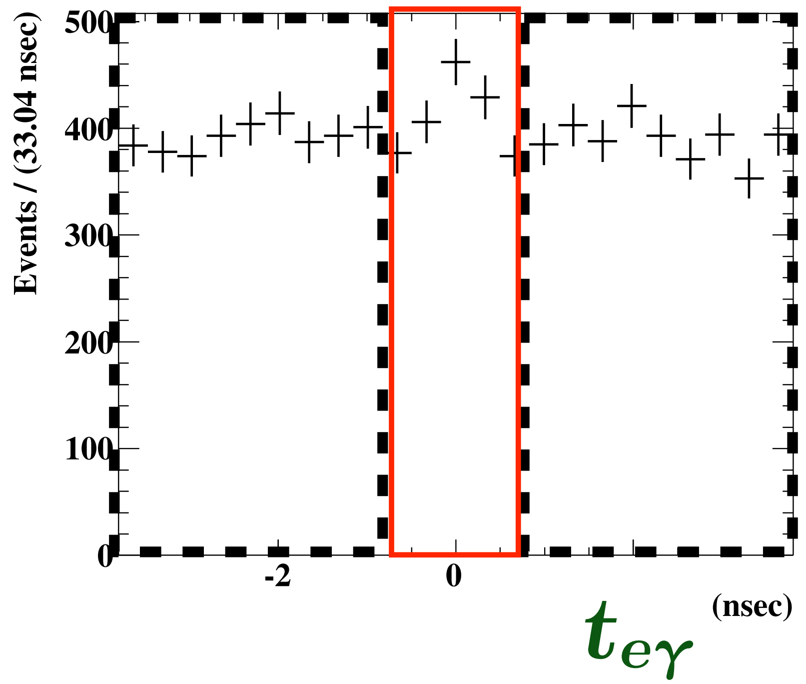




Sensitivity : Median UL of MC with background-only hypothesis



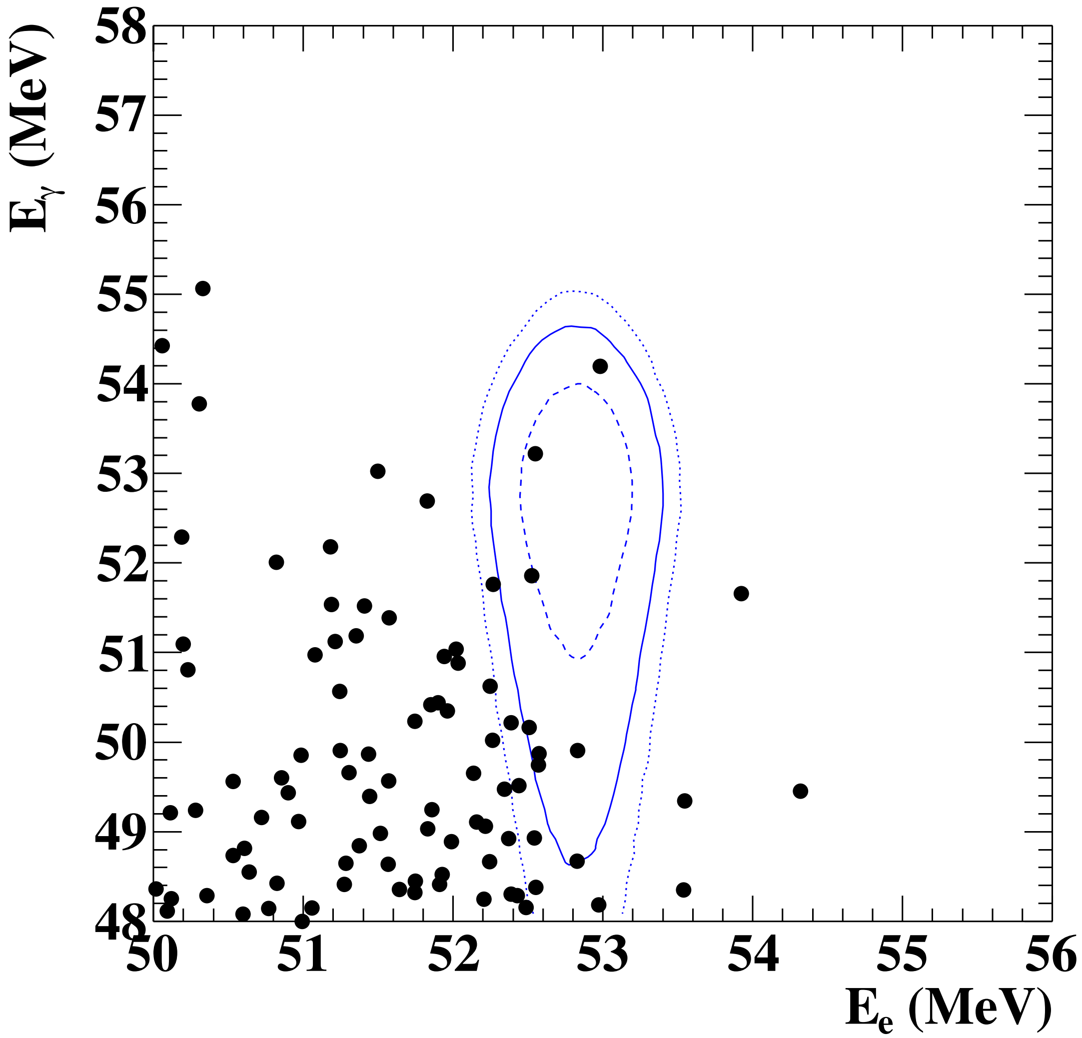
Time side-bands

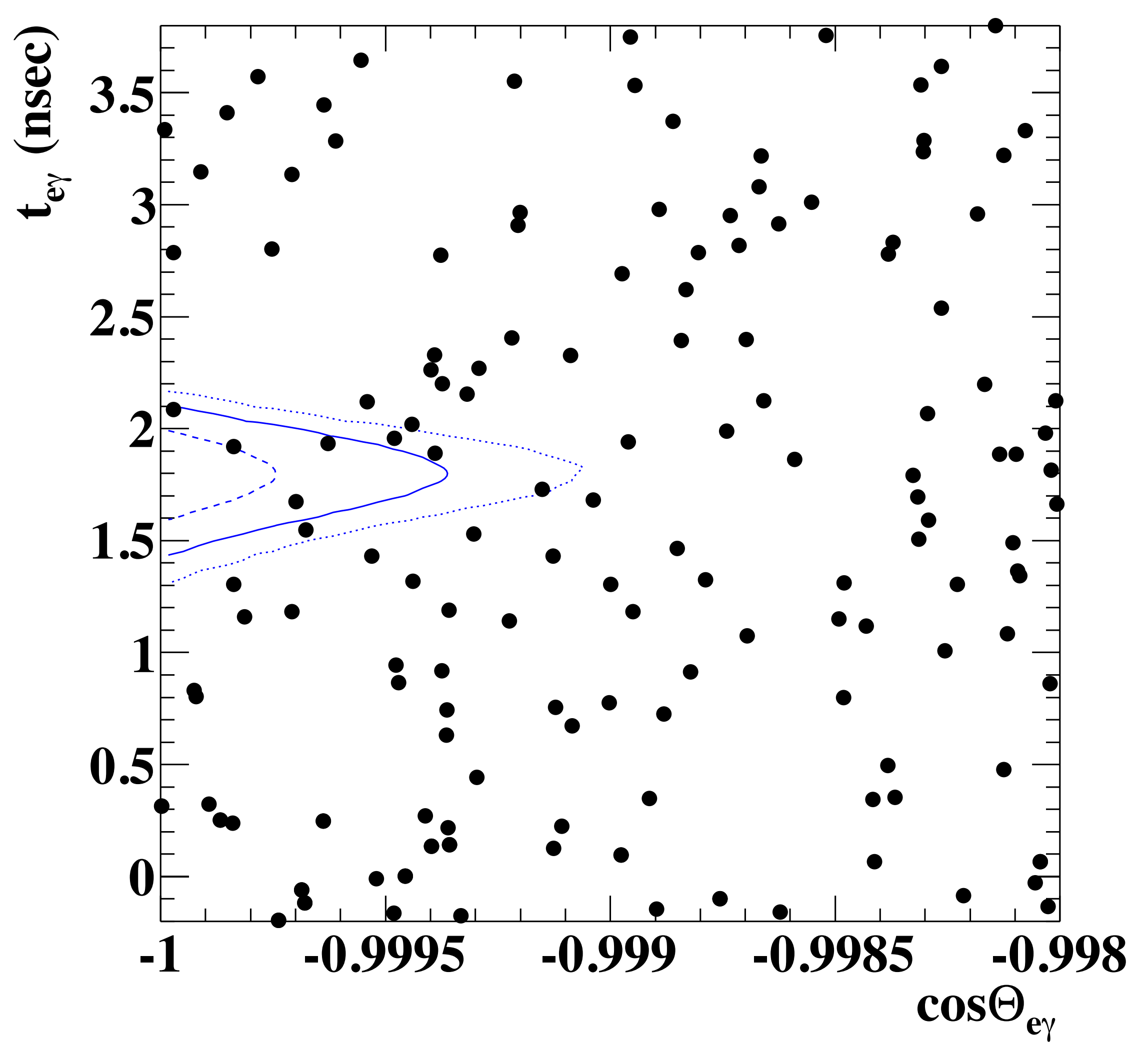


sideband

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

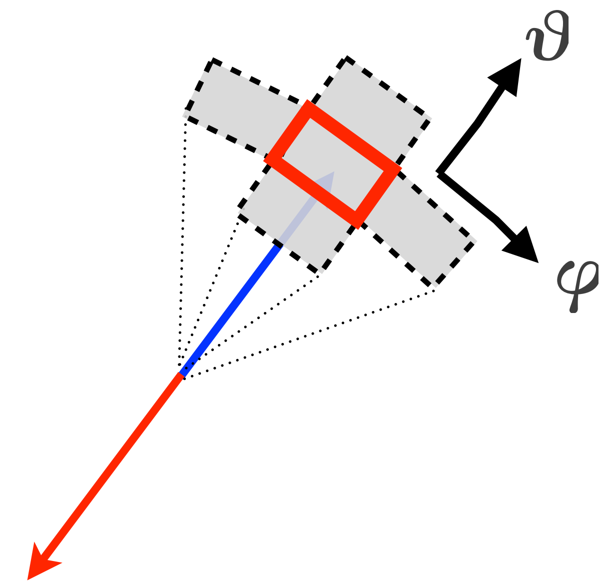
consistent with U.L. of MC experiments w/o signal

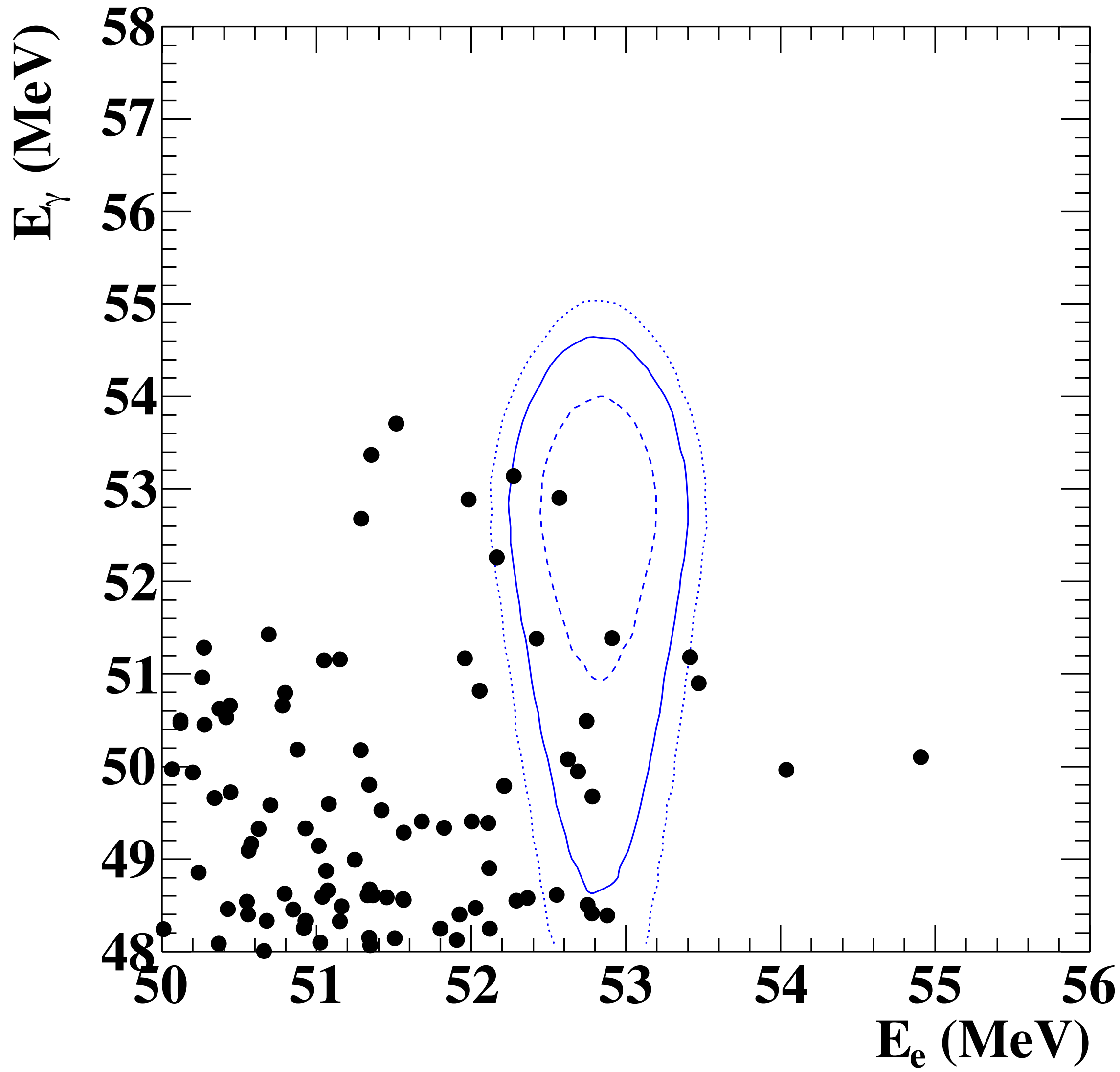


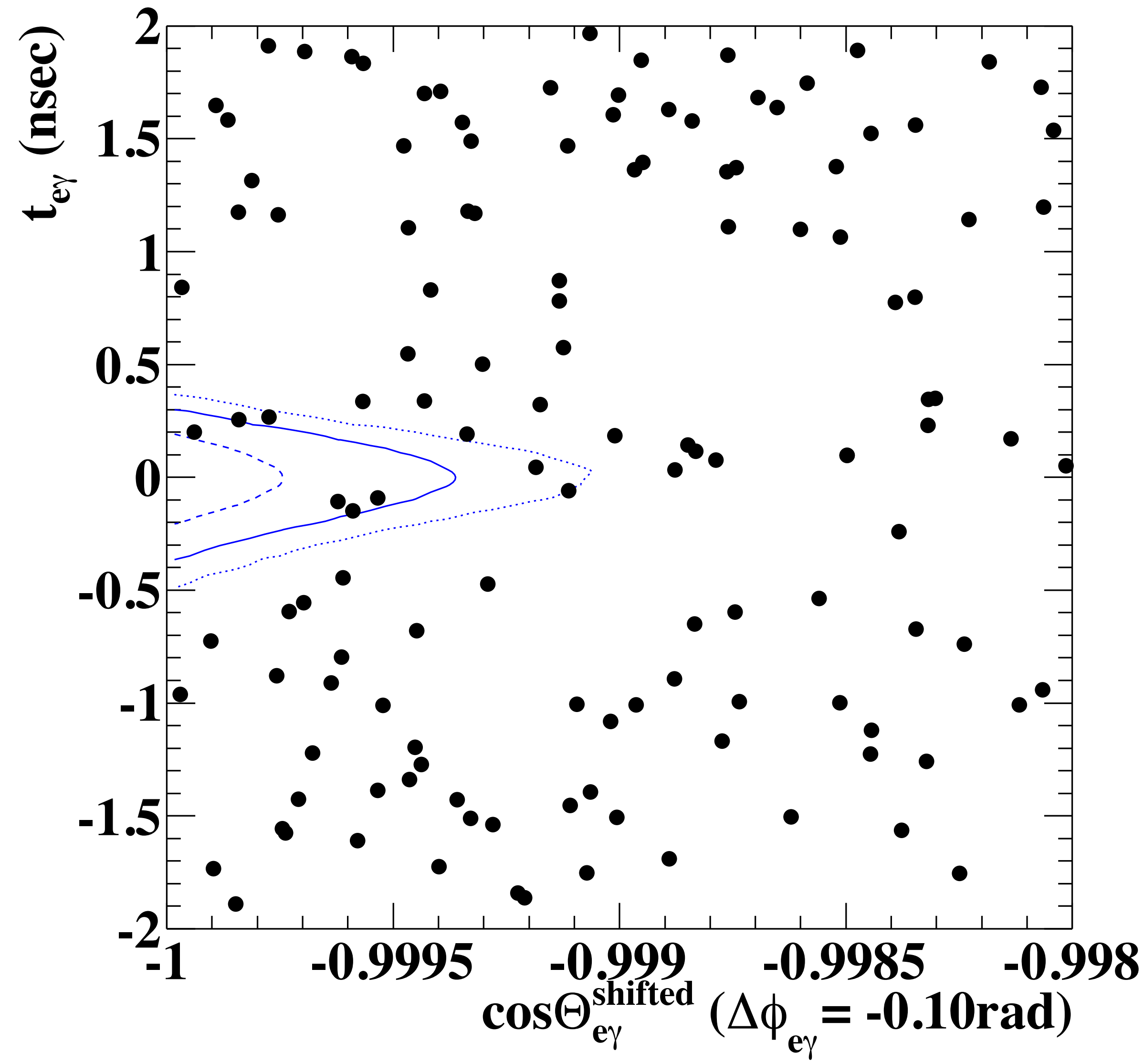


contour : signal PDF (39.3, 74.2, 86.5 %)

Angle side-bands



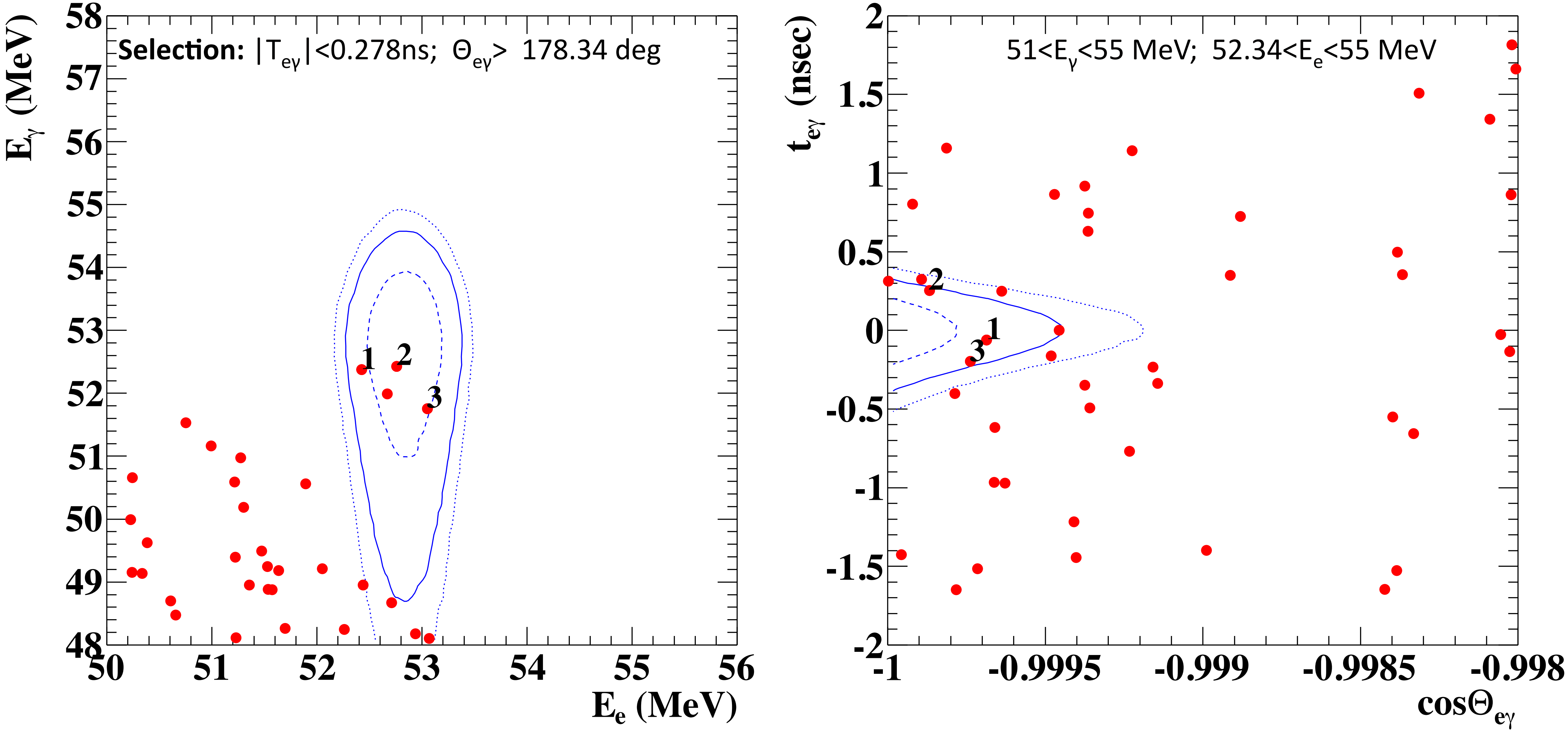




no unexpected time correlated background

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

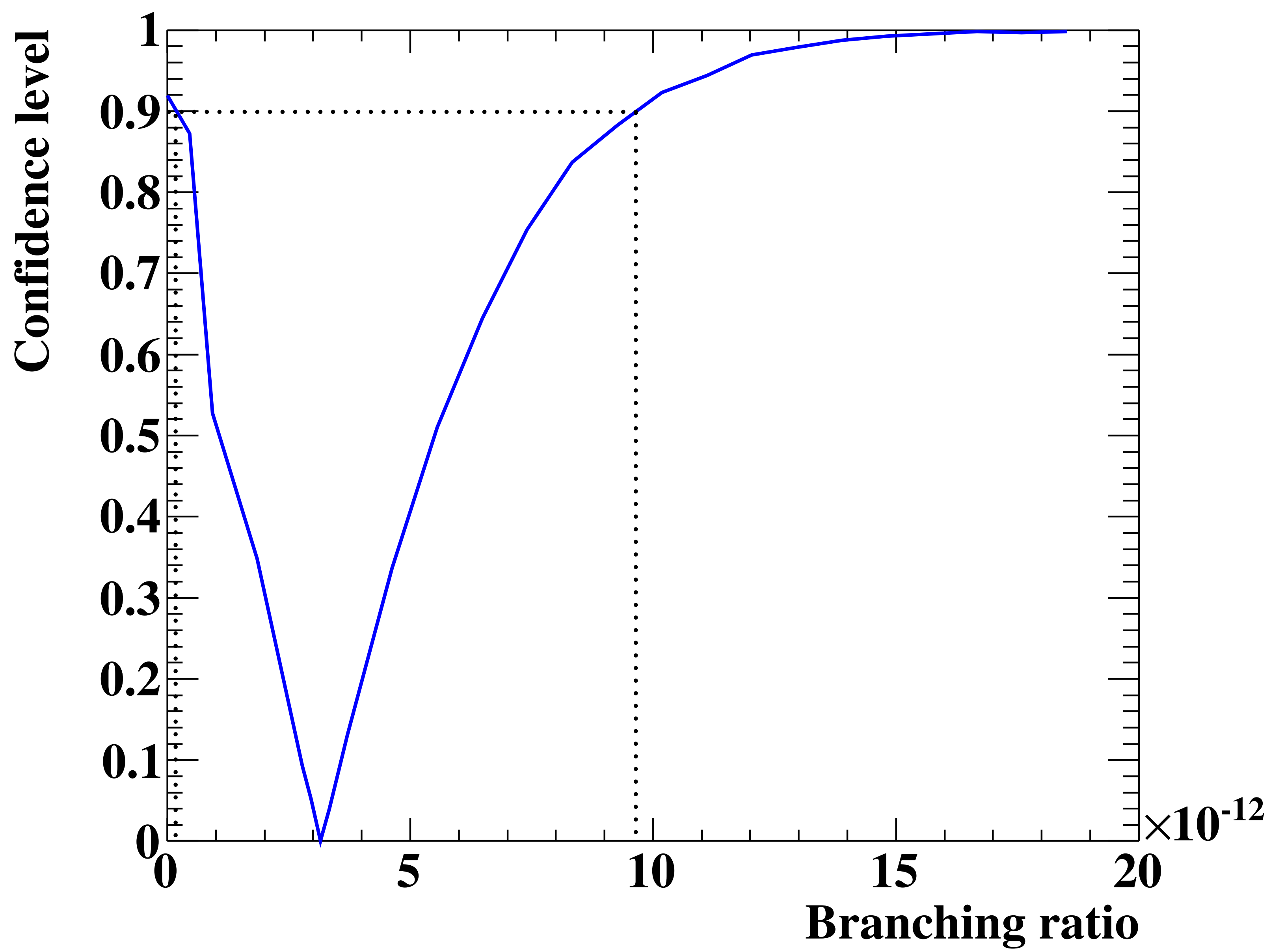
2009



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

2009, Result

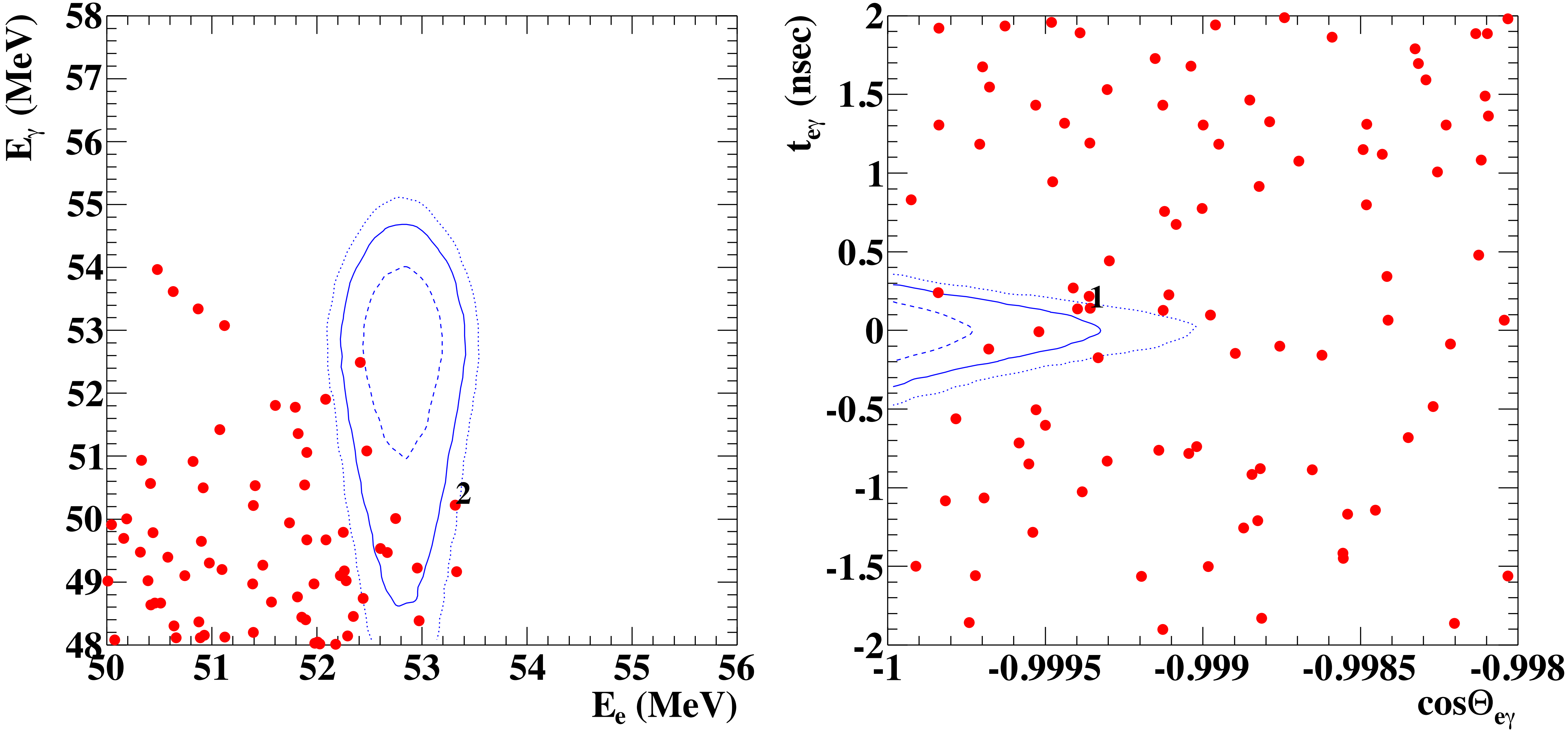
Nsignal Best fit : 3.0(preliminary) $\rightarrow$ 3.4(updated result)   2009 result stable



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

Best fit : $\mathbf{3.2} \times 10^{-12}$ p-Value of background-only hypothesis: ***8%***

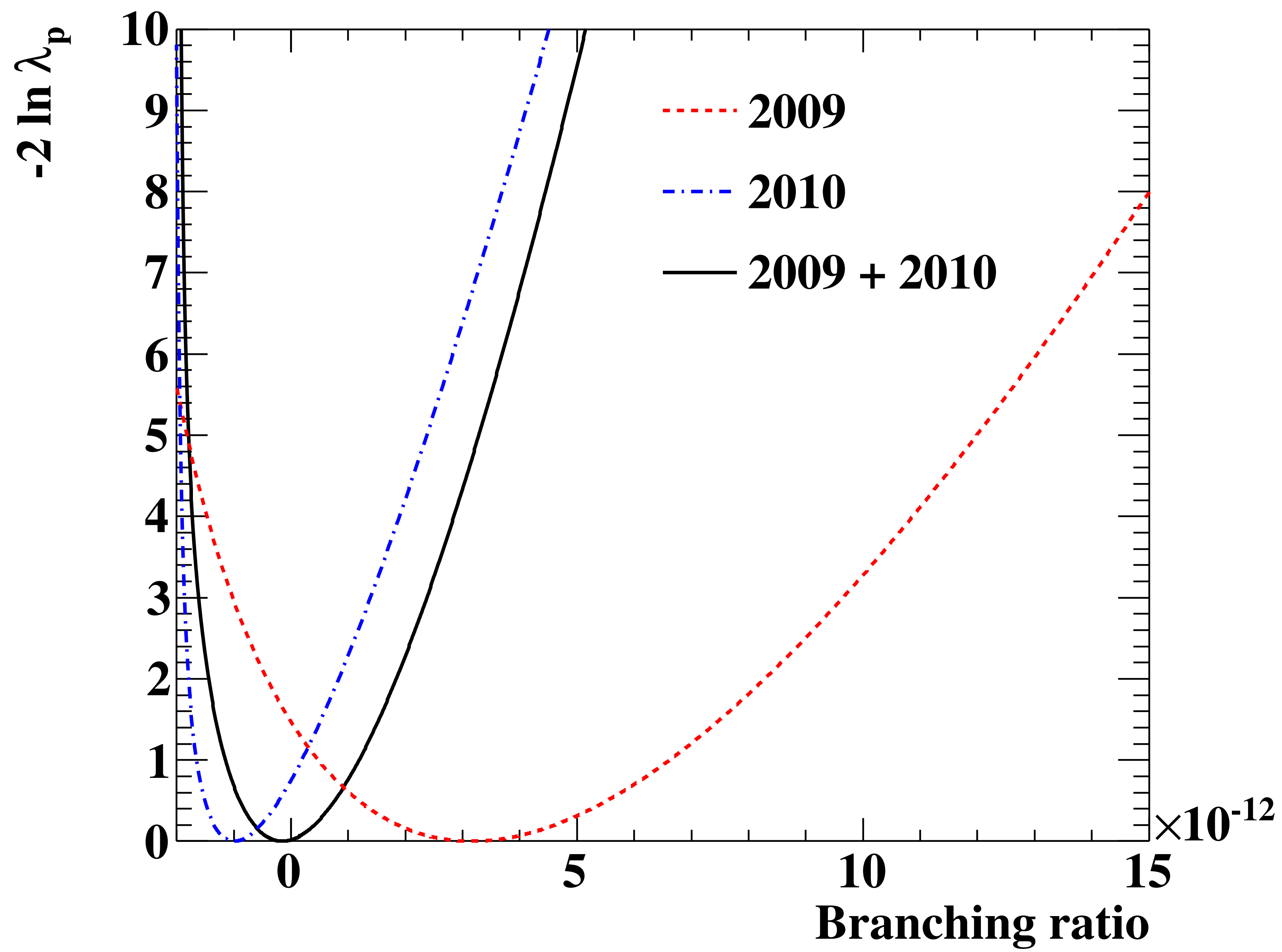
2010



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

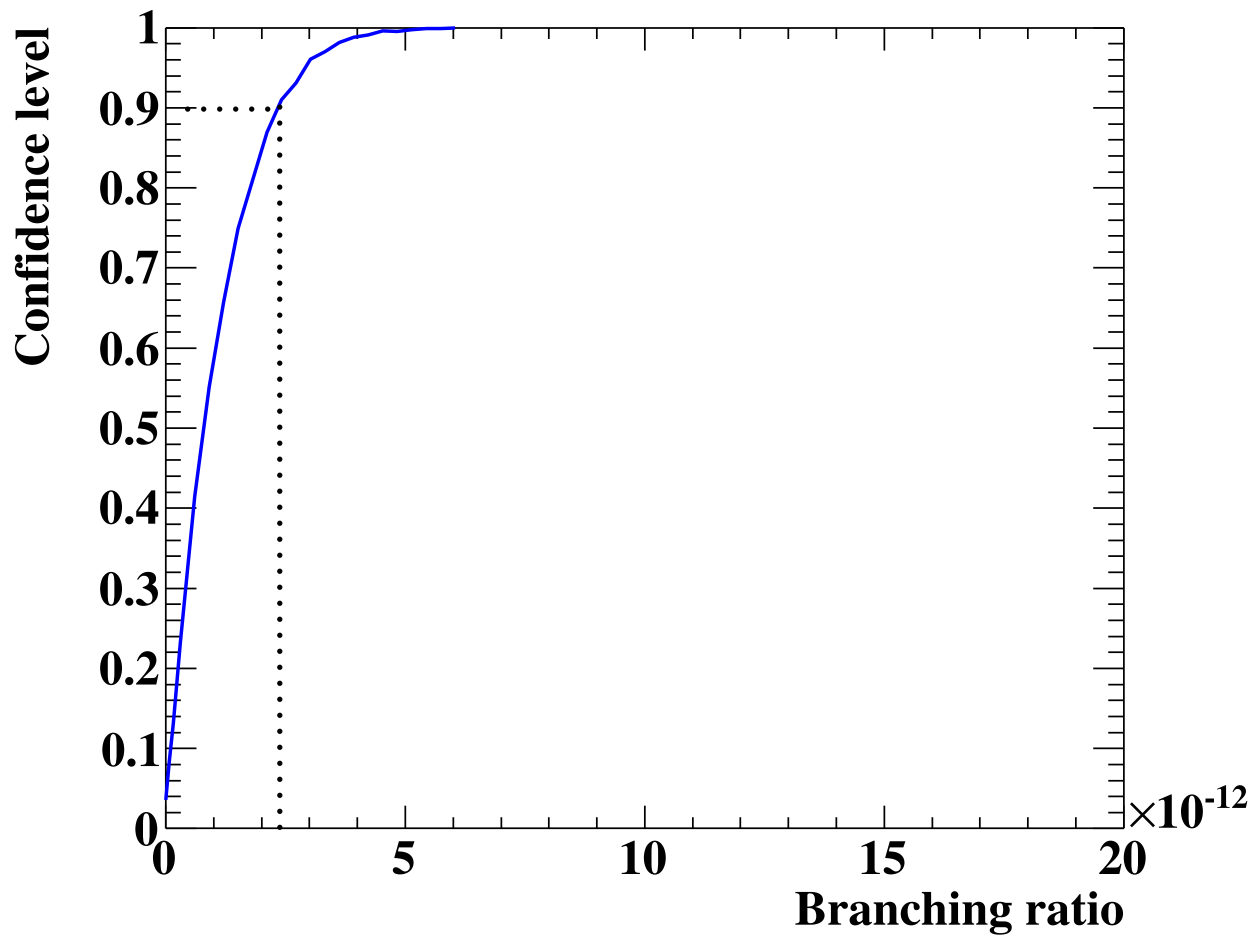
2009+2010 likelihood

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



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

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

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

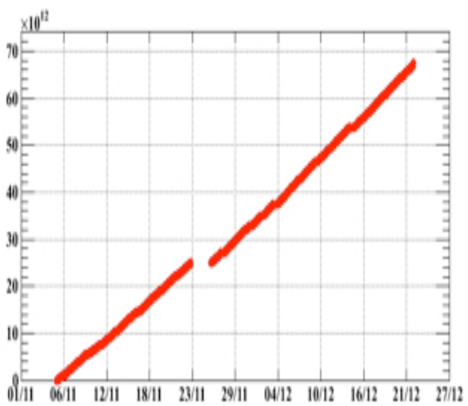
Systematic uncertainties (in total 2% in UL)

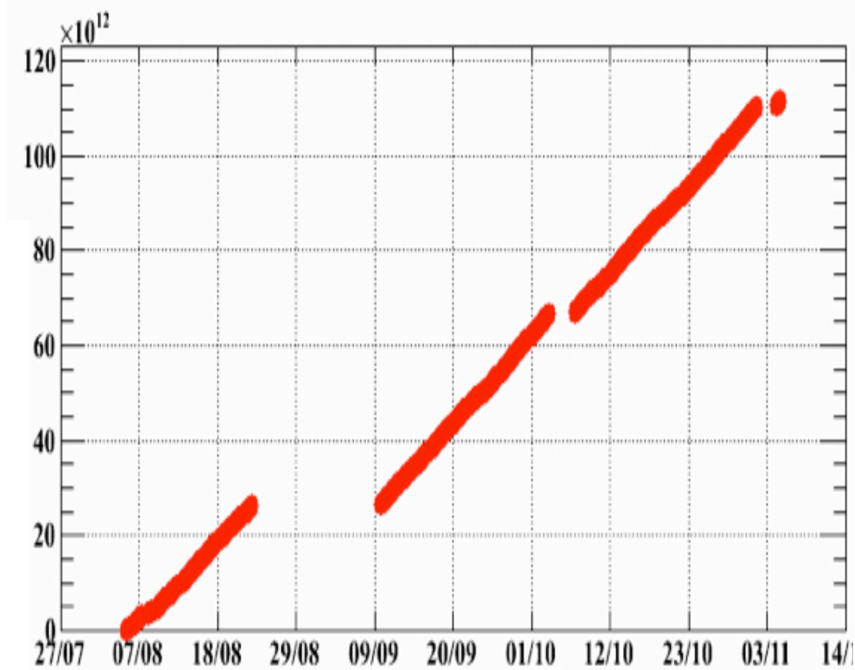
- relative angle offsets
- correlations in e^+ observables
- normalization

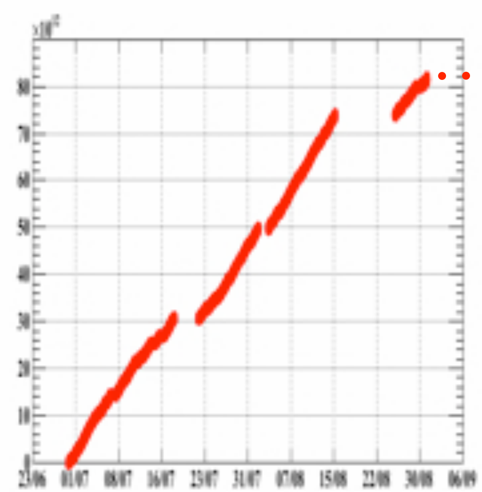
Data statistics : future

2009 2010 2011 2012

\# of muons stopped on the target







~1.5 months

~3 month

~6 month

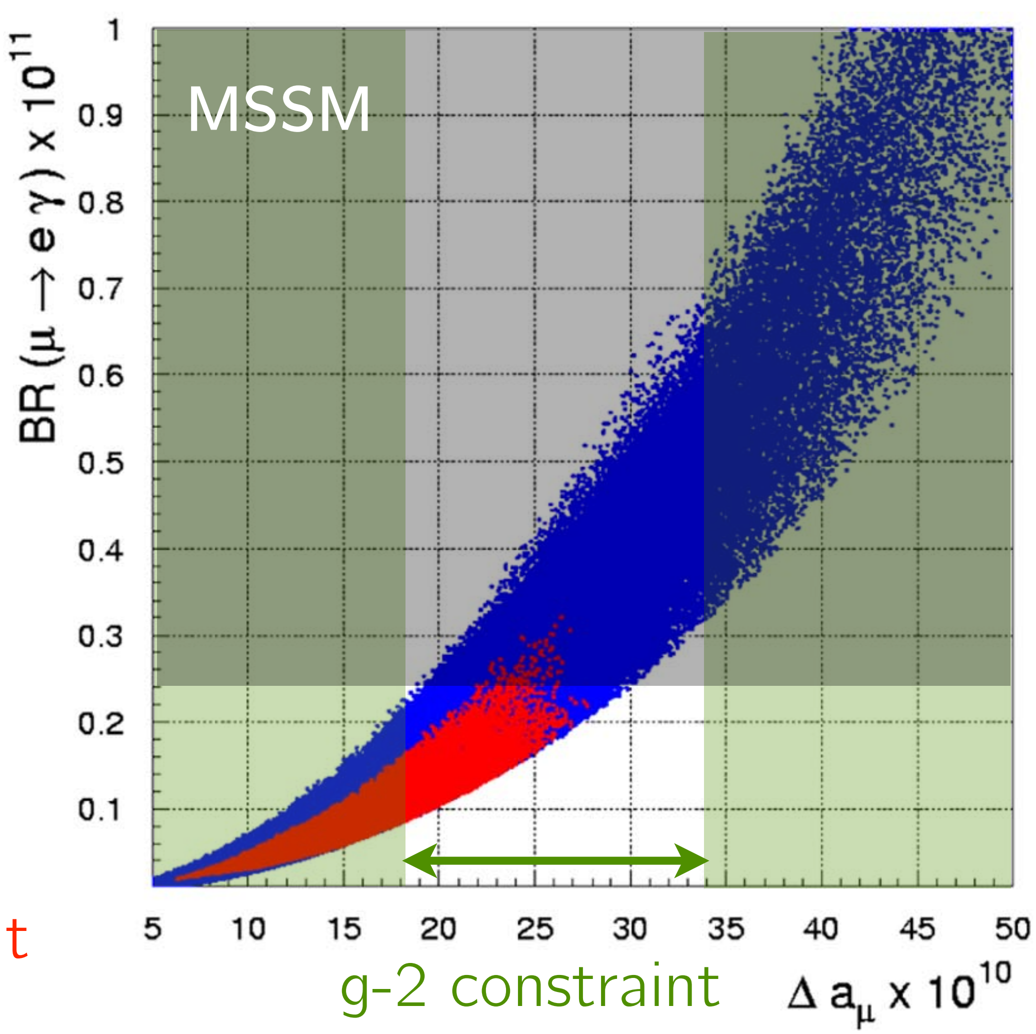
Summary

- 2009+2010 data
  - Zero-signal is consistent
  - 5 times tighter new limit
- 2x2010 data in 2011 and 2012

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

@ 90% C.L.

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



2009 UL

MEG constraint

2009+2010 UL

2009+2010 Sensitivity

B-physics constraint

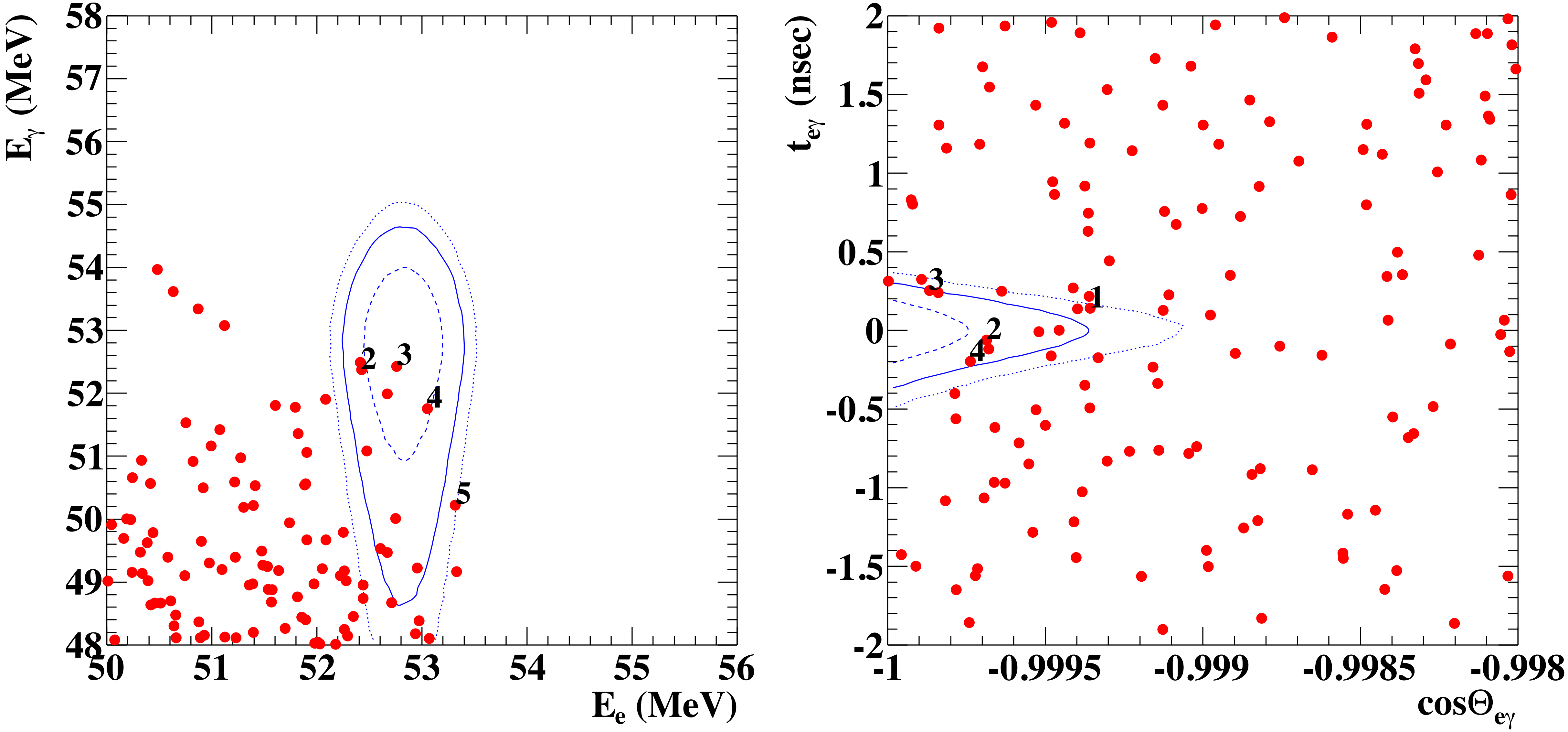
g-2 constraint

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

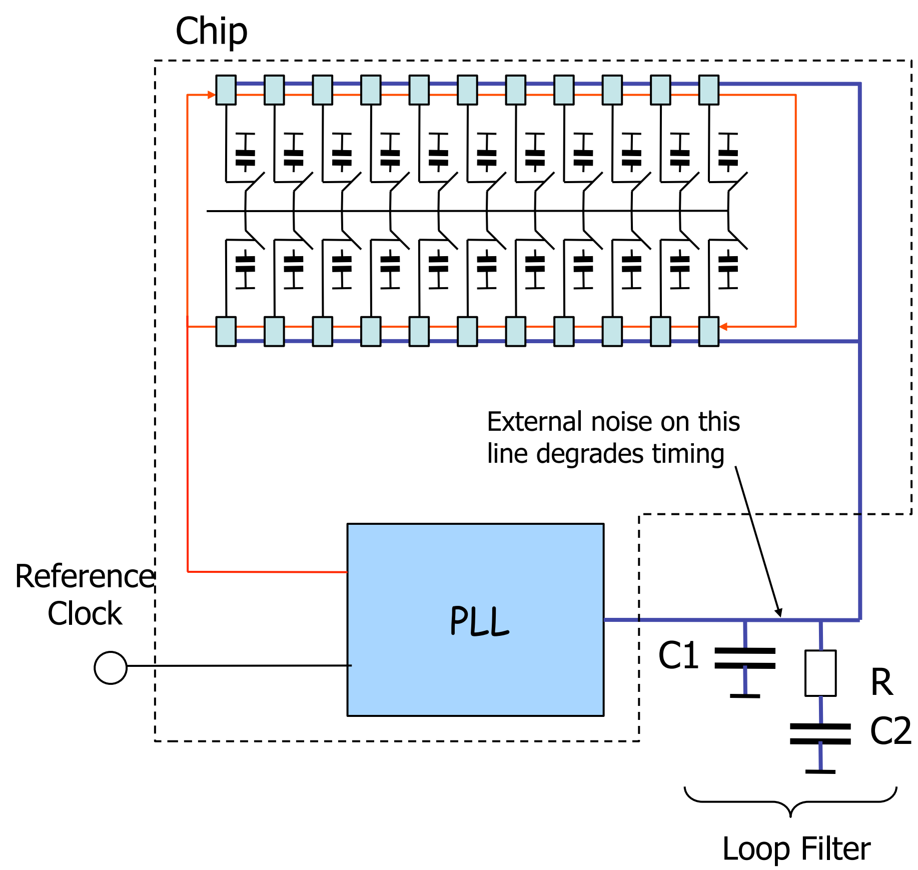
K. Hagiwara *et al* 2011 *J. Phys. G: Nucl. Part. Phys.* **38** 085003

Back up

2009+2010

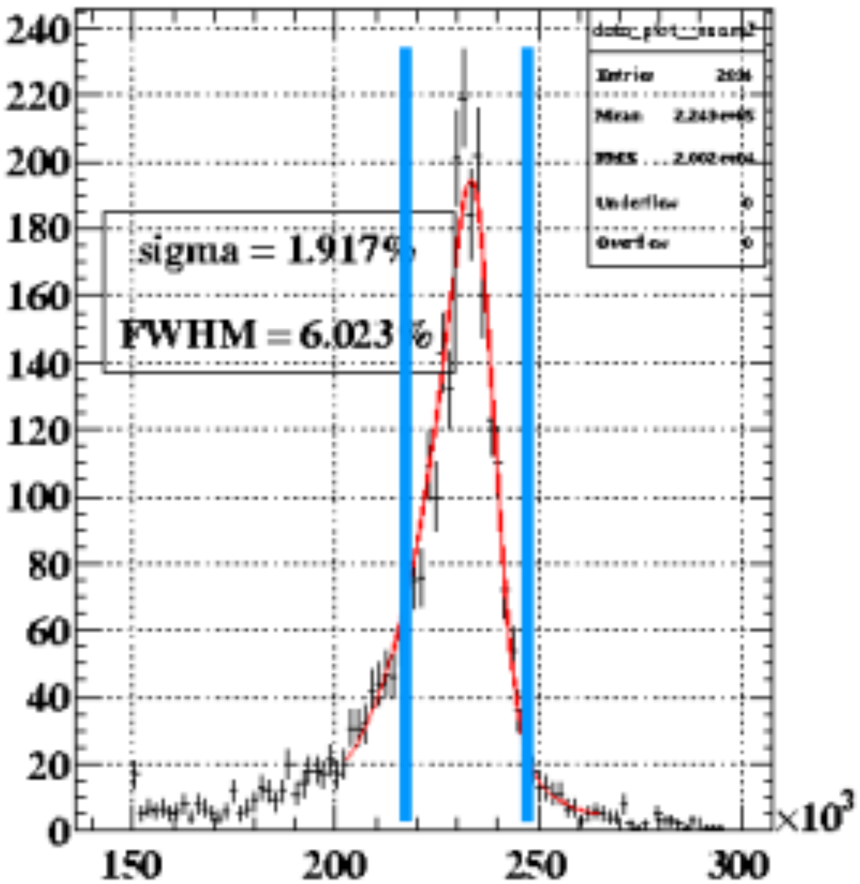


E_γ (MeV)
58
57
56
55
54
53
52
51
50
49
48
50
51
52
53
54
55
56
E_e (MeV)
2
3
4
5
$t_{e\gamma}$ (nsec)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-1
-0.9995
-0.999
-0.9985
-0.998
$\cos\Theta_{e\gamma}$
1
2
3
4


Chip
External noise on this
line degrades timing
Reference
Clock
PLL
C1
R
C2
Loop Filter

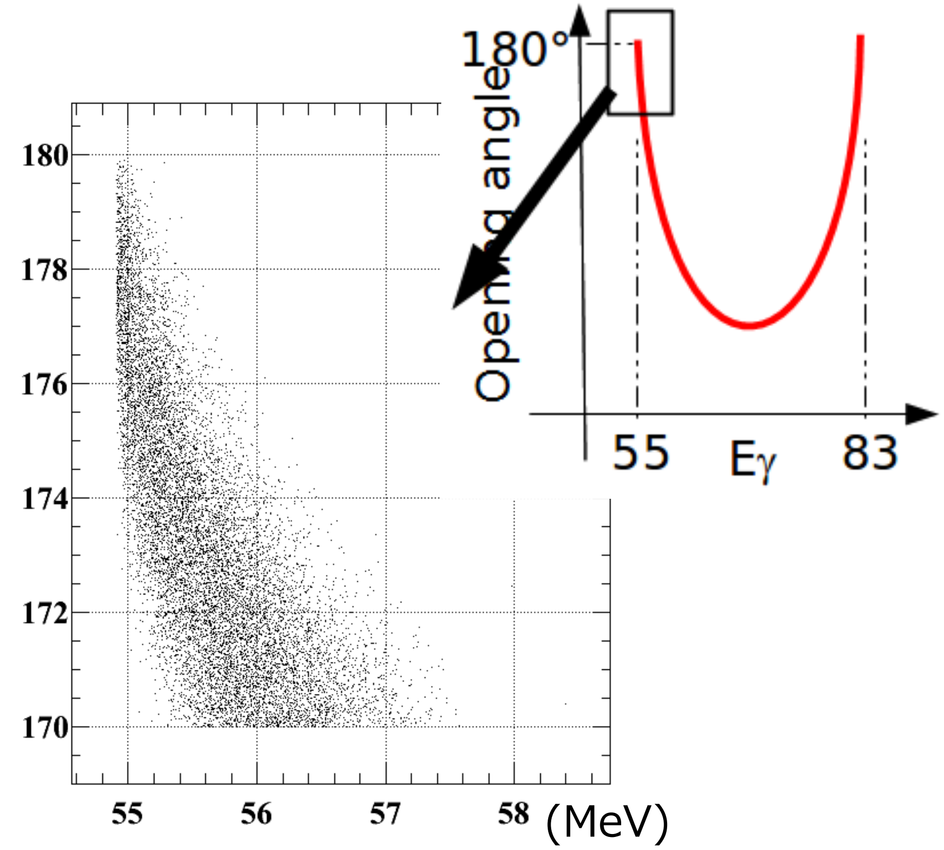
Energy reconstruction

Optimize weights by
minimizing pi0 peak width

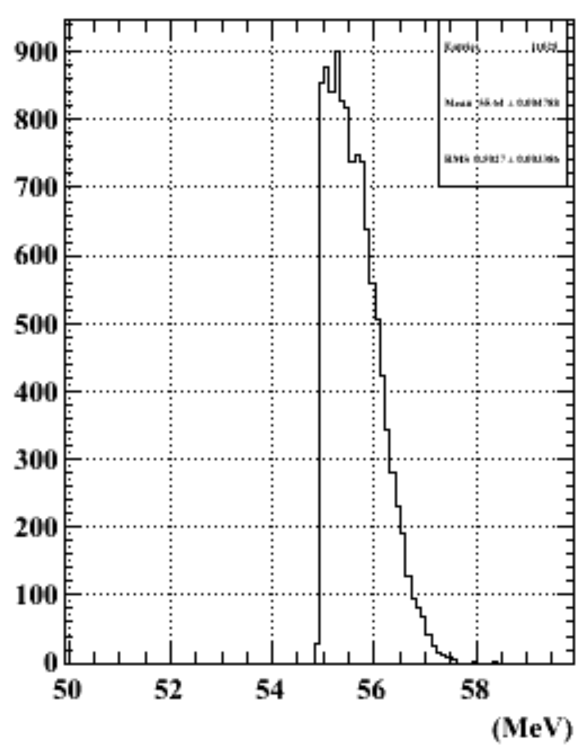


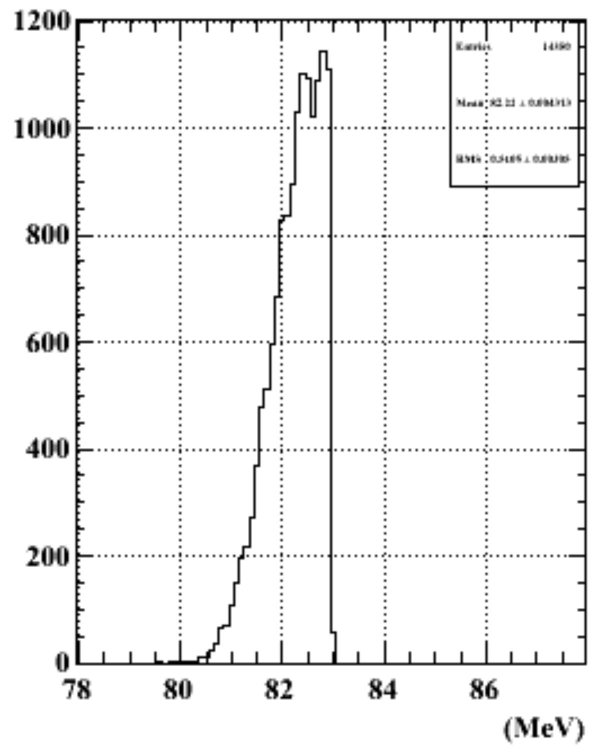
Energy resolution

Correction for original gamma width



True Eγ distribution after cut by reconstructed opening angle > 170°



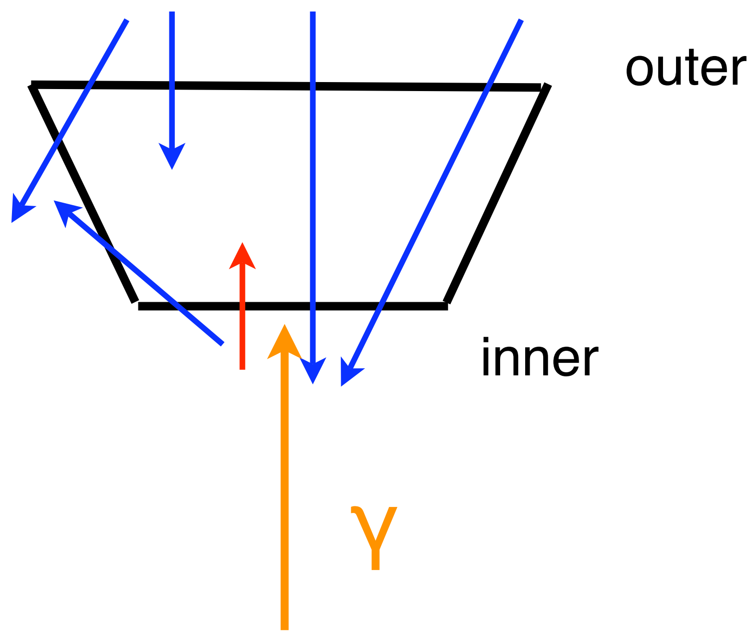


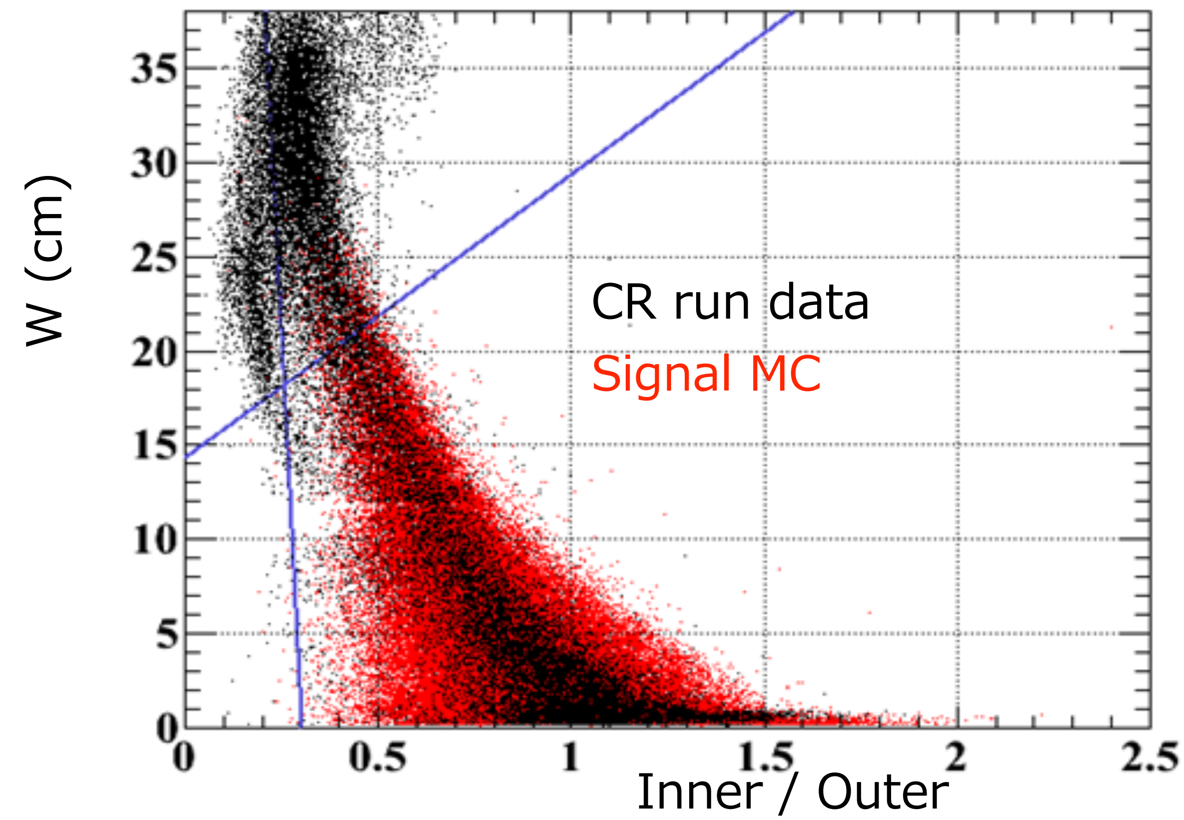
Actual resolution is better than the measured by ~0.15%

Better linearity of 55 and 83 MeV

Cosmic ray rejection

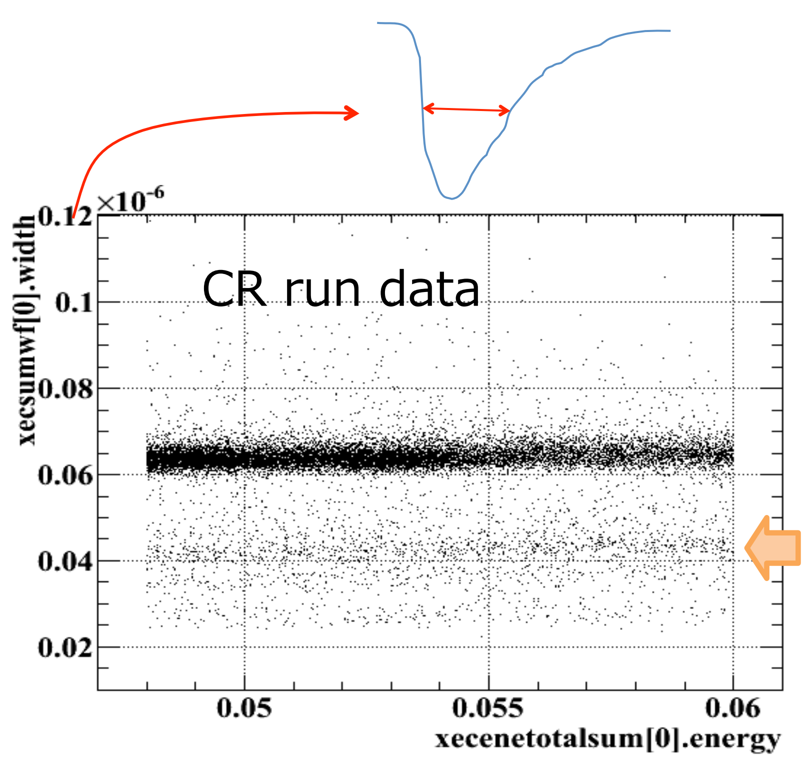
Two variables cut
- Ratio of Inner and Outer charge
- Depth

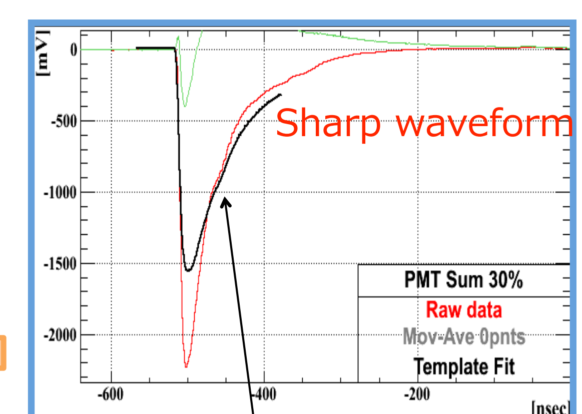




Additional cut using waveform

Waveforms of a small fraction of CR are narrow.





Average shape of a γ interaction

Performance summary

	2009	2010
Gamma Energy (%)	1.9	1.9
Gamma Timing (psec)	96	67
Gamma Position (mm)	5 (u,v), 6 (w)	5 (u,v), 6 (w)
Gamma Efficiency (%)	58	59
e^+ Timing (psec)	107	107
e^+ Momentum (keV)	310 (80% core)	330 (79% core)
e^+ θ (mrad)	9.4	11.0
e^+ ϕ (mrad)	6.7	7.2
e^+ vertex Z/Y (mm)	1.5 / 1.1 (core)	2.0 /1.1 (core)
e^+ Efficiency (%)	40	34
e^+-gamma timing (psec)	146	122
Trigger efficiency (%)	91	92
Stopping Muon Rate (sec^{-1})	2.9×10^{7}	2.9×10^{7}
DAQ time/ Real time (days)	35/43	56/67
Expected 90% C.L. Upper Limit	3.3×10^{-12}	2.2×10^{-12}

Timing improvement by waveform digitizer upgrade in 2011;
The e+ tracking slightly worse due to DC noise problem in 2011

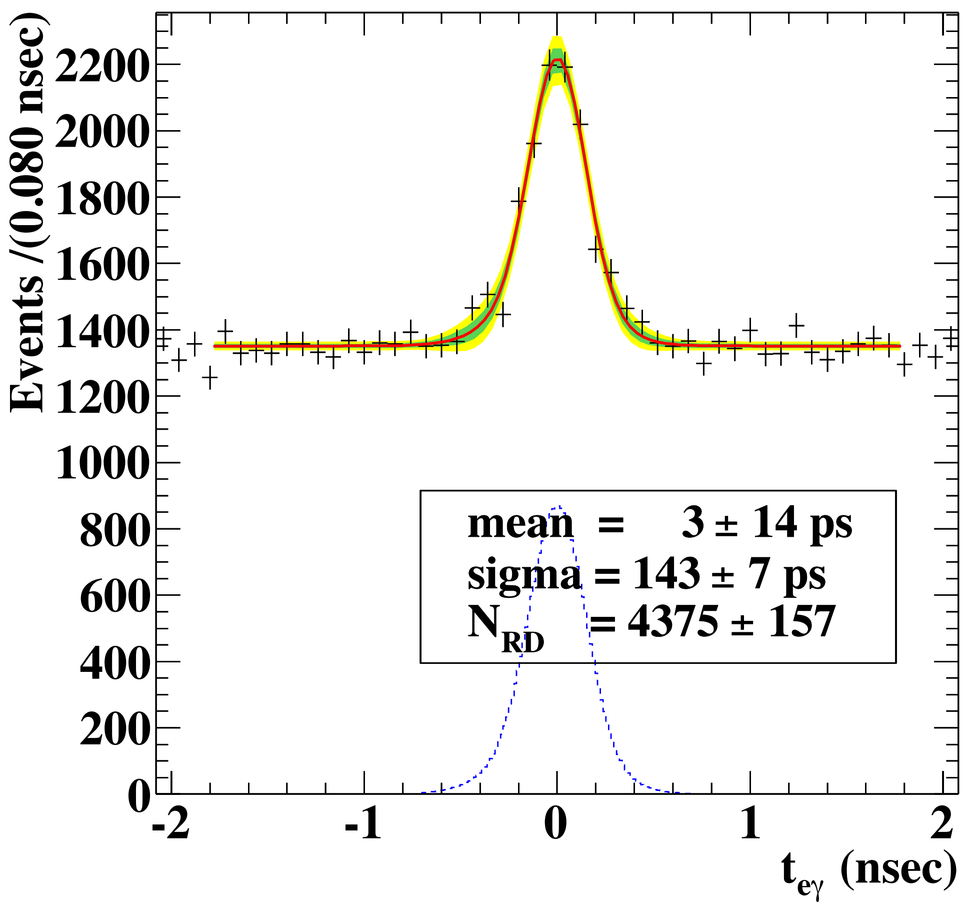
Timing

DRS, Electronics timing accuracy :

130→48 psec

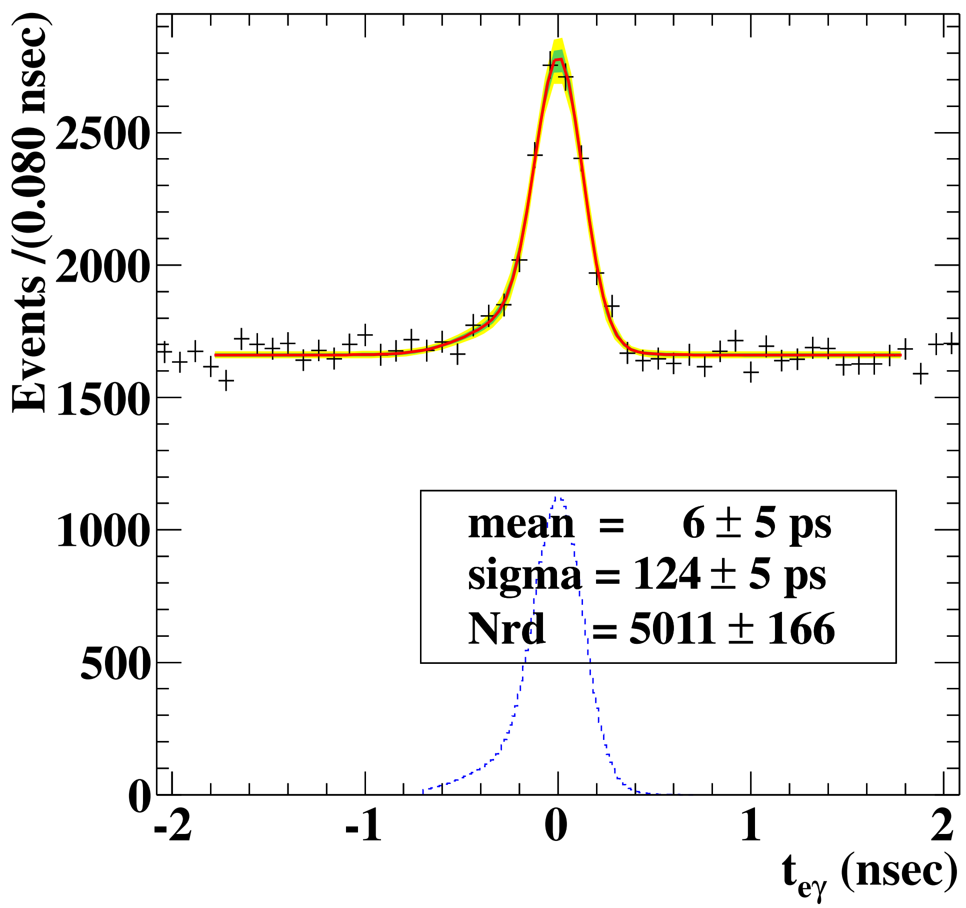
2009

143 ps



2010

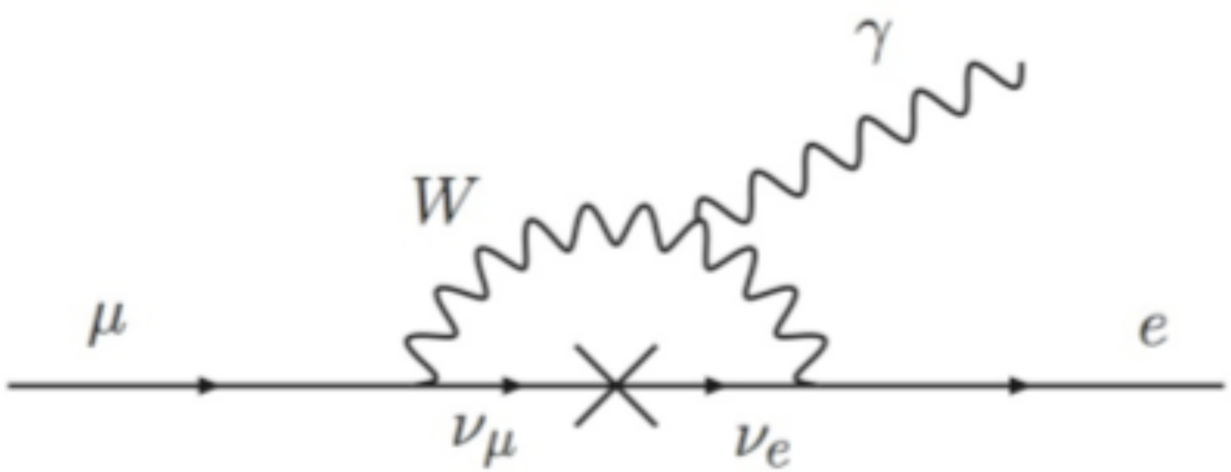
124 ps

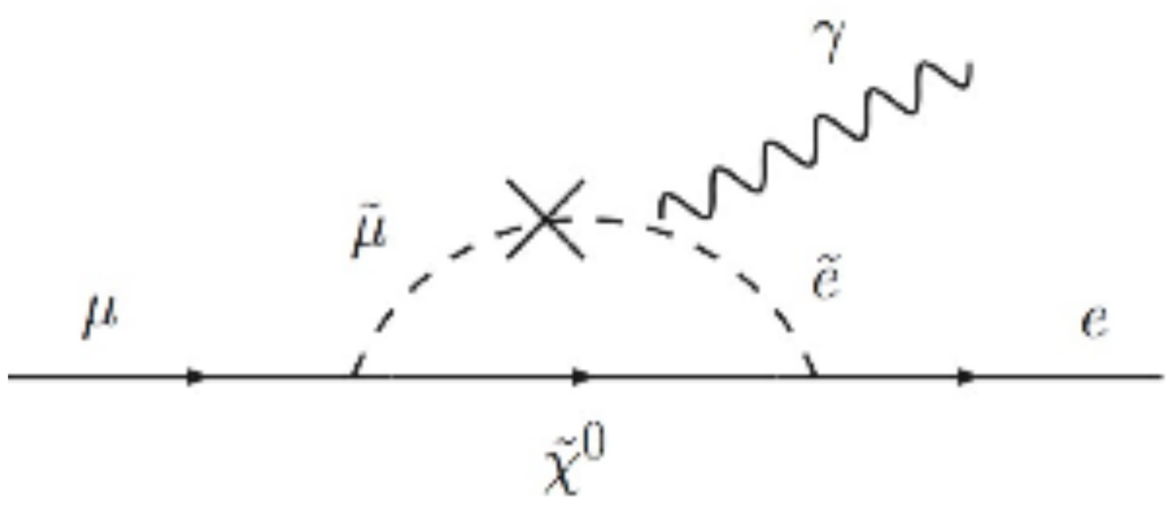


95% limit

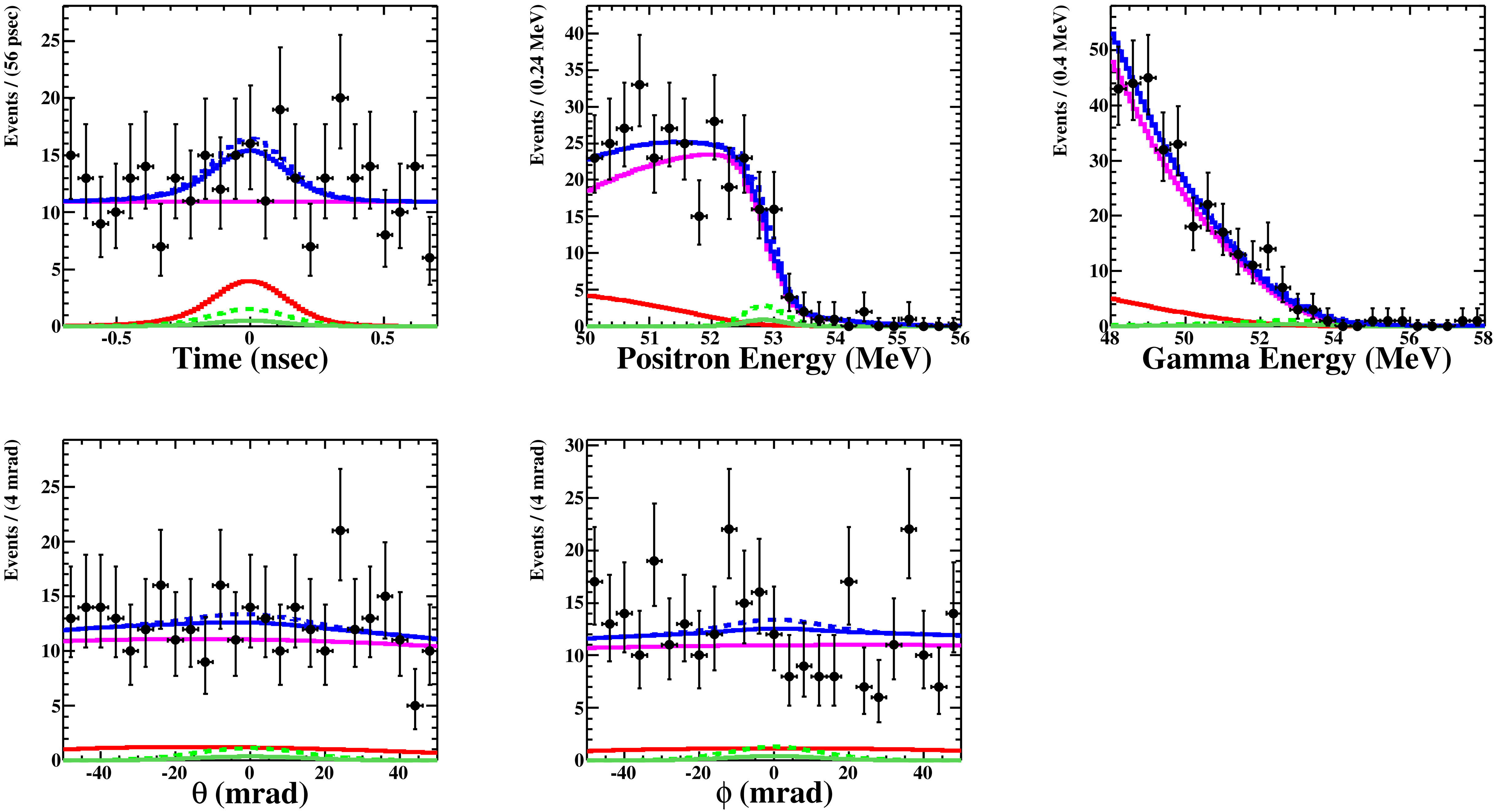
$\mathcal{B} \times 10^{12}$

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)


γ
W
μ
e
ν_μ
ν_e

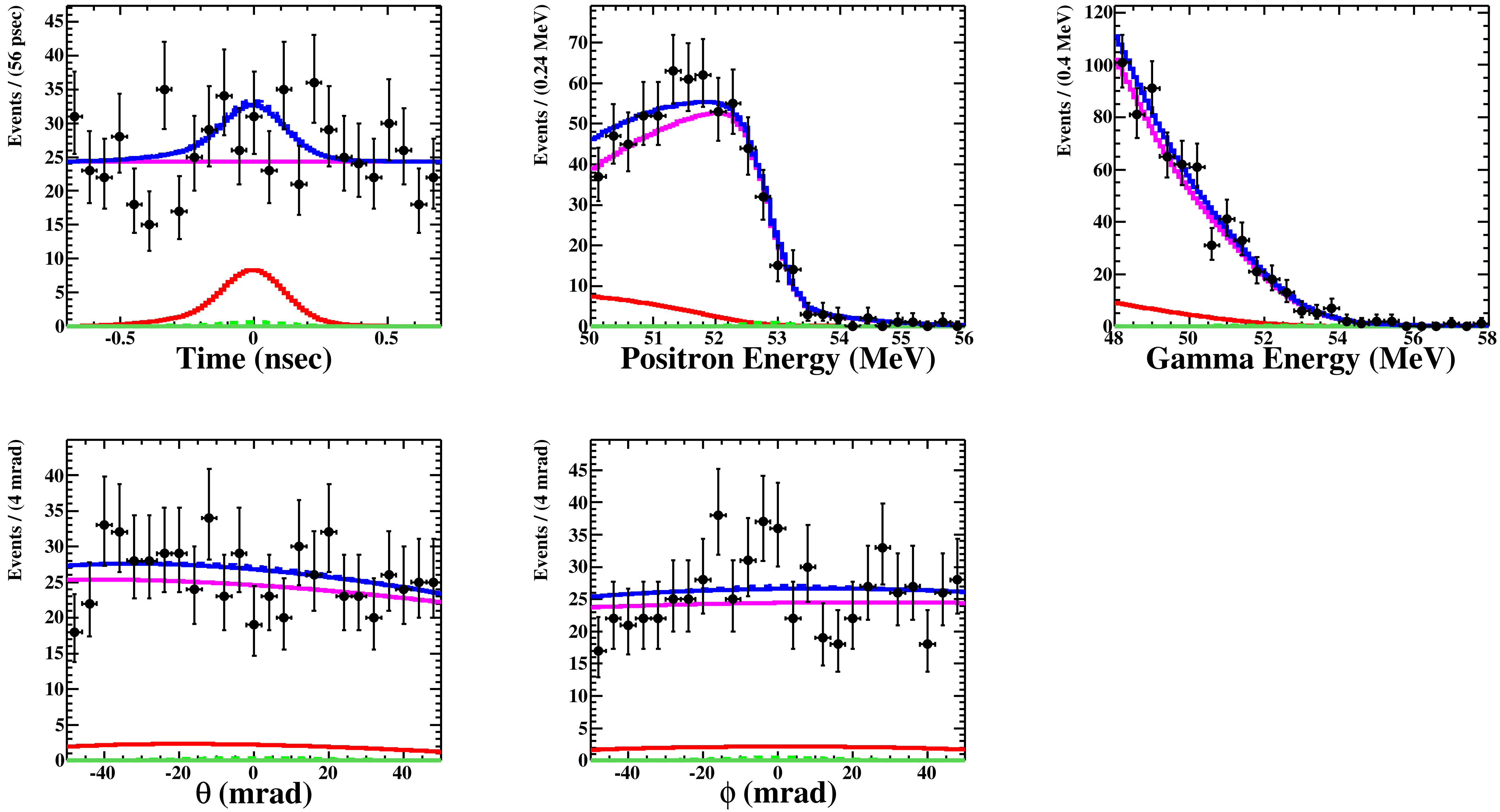

γ
$\tilde{\mu}$
$\tilde{e}$
μ
e
$\tilde{\chi}^0$

2009

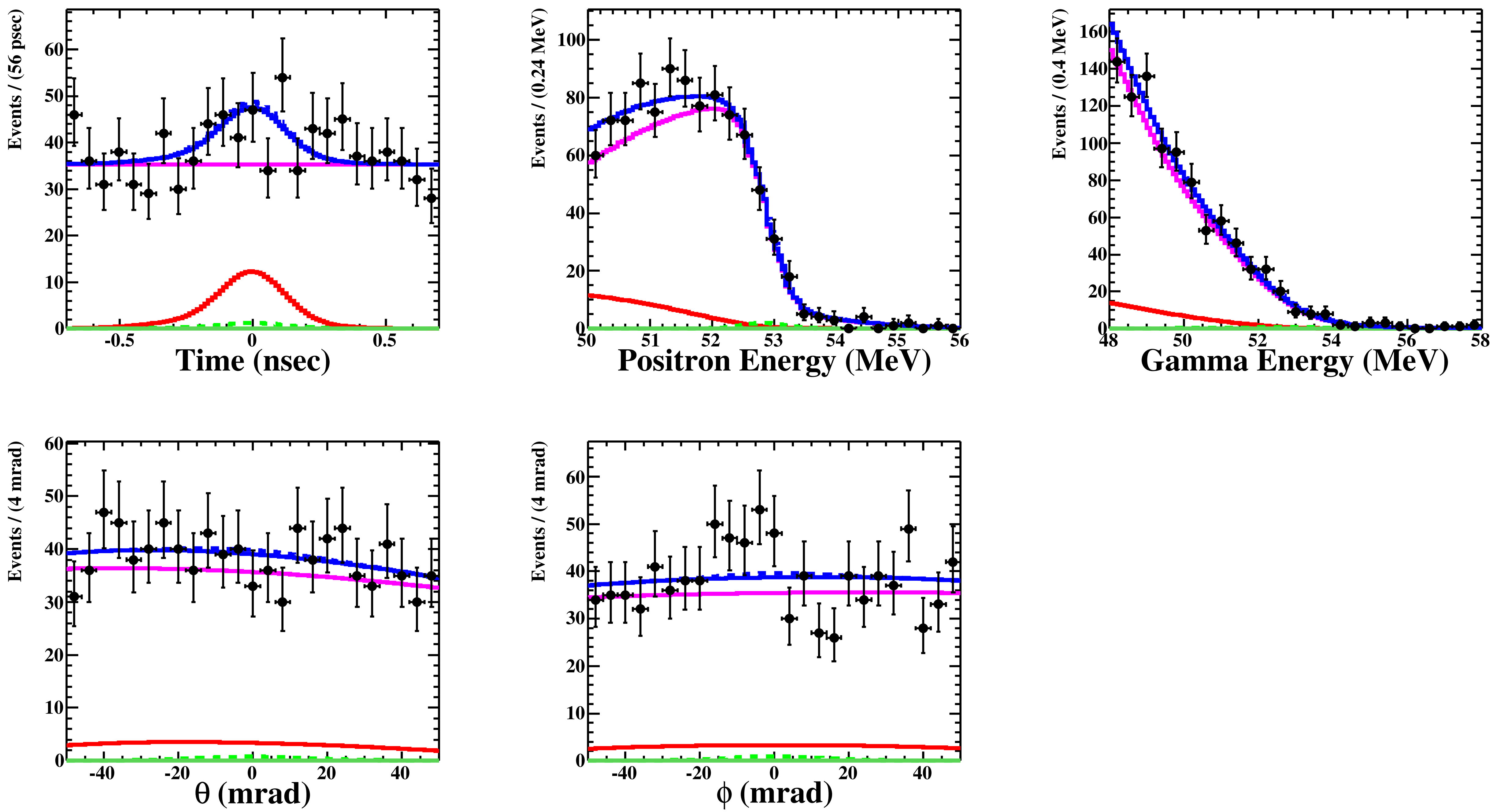


Events / (56 psec)
Time (nsec)
-0.5
0
0.5
Events / (0.24 MeV)
Positron Energy (MeV)
50
51
52
53
54
55
56
Events / (0.4 MeV)
Gamma Energy (MeV)
48
50
52
54
56
58
Events / (4 mrad)
θ (mrad)
Events / (4 mrad)
ϕ (mrad)
-40
-20
0
20
40

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)

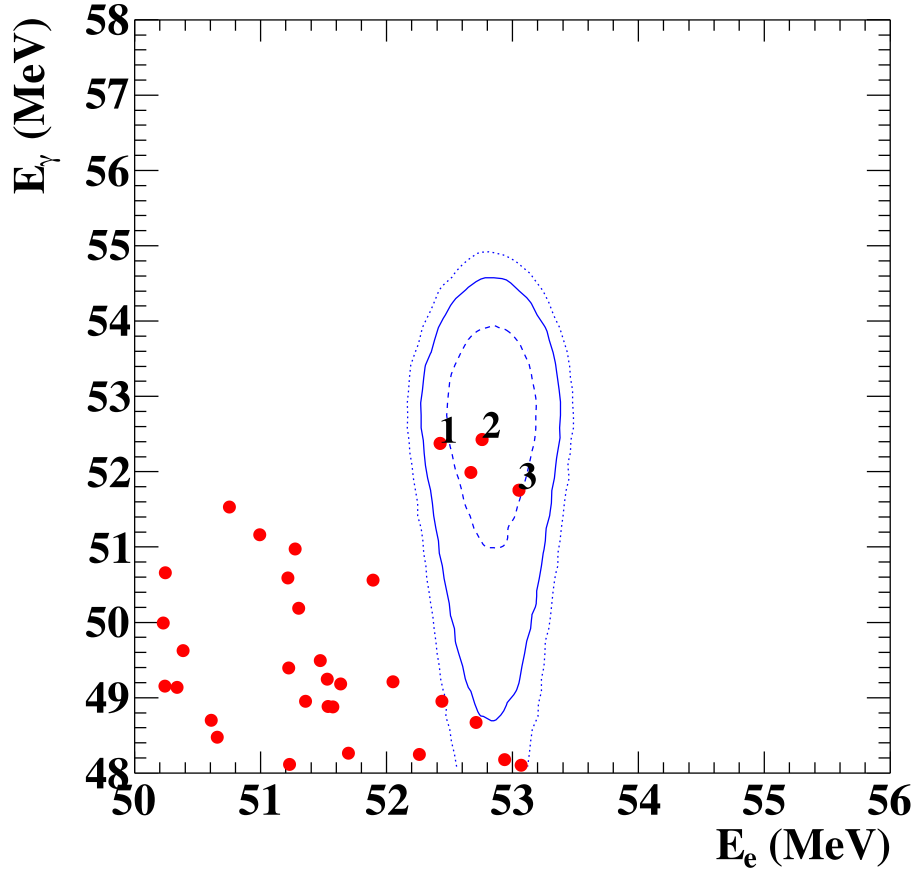
2009+2010



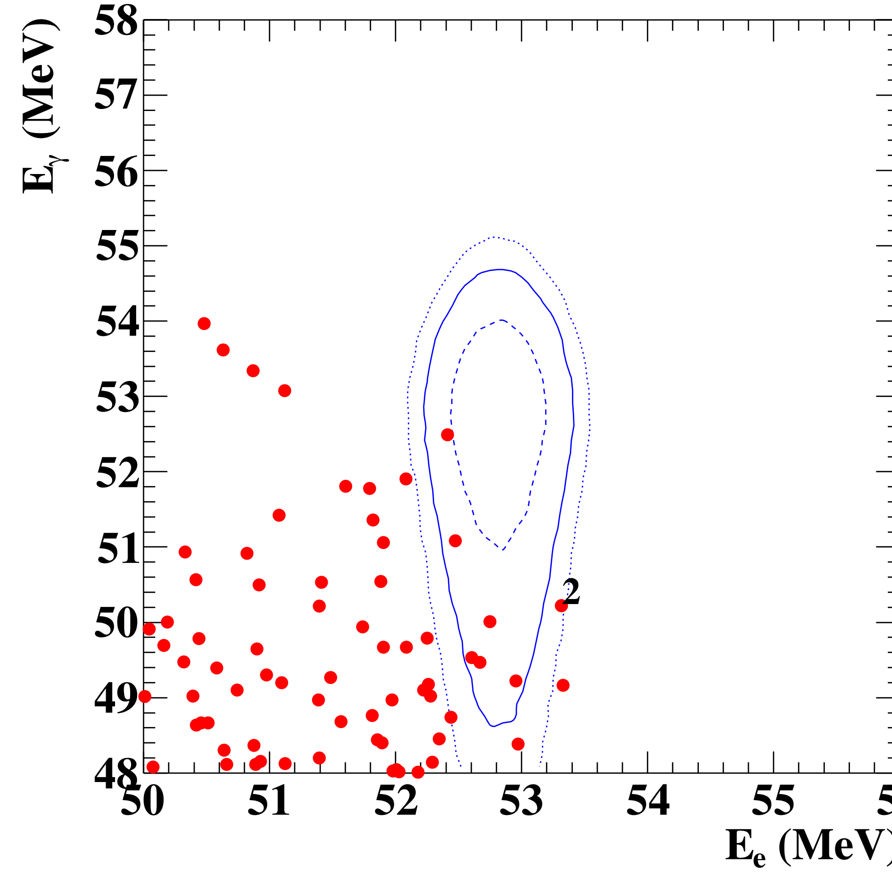
Events / (56 psec)
Time (nsec)
Events / (0.24 MeV)
Positron Energy (MeV)
Events / (0.4 MeV)
Gamma Energy (MeV)
Events / (4 mrad)
θ (mrad)
Events / (4 mrad)
φ (mrad)

2009

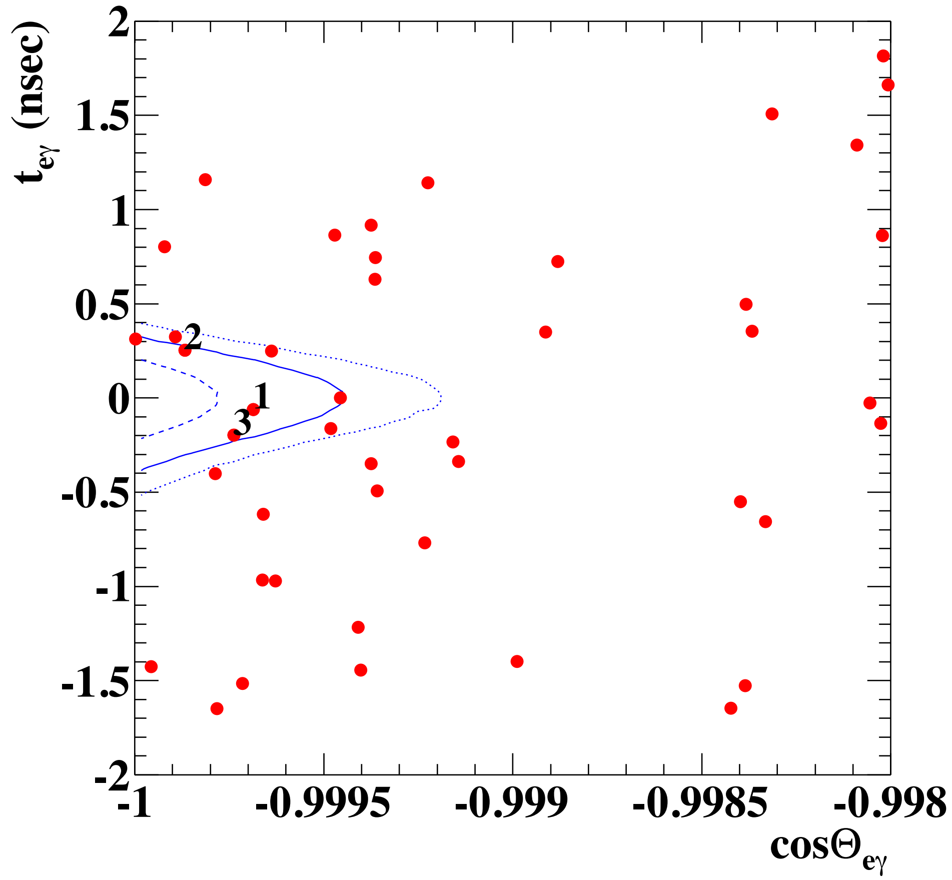
2010



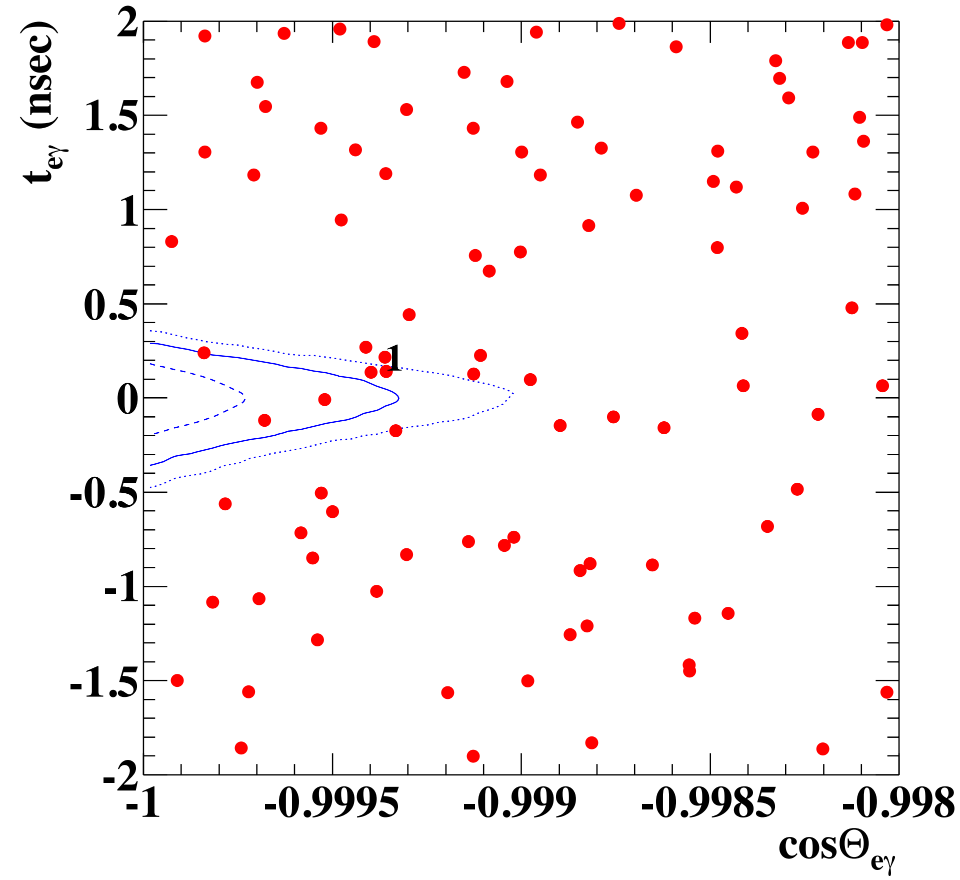
E_γ (MeV)
E_e (MeV)
48
49
50
51
52
53
54
55
56
57
58
1
2
3



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



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