MEG : Status and Upgrades

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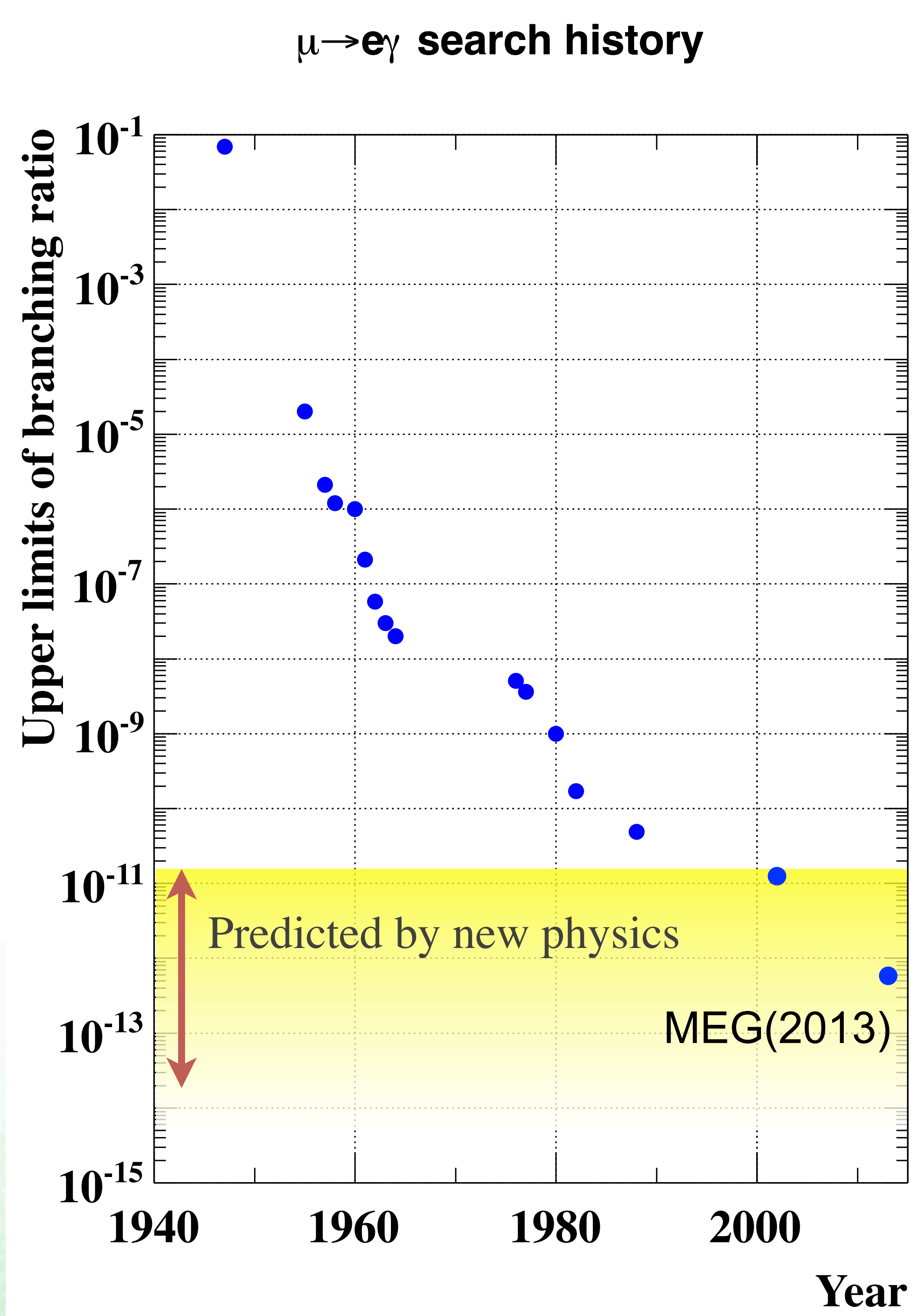
on behalf of MEG collaboration

7/May/2013
CLFV 2013

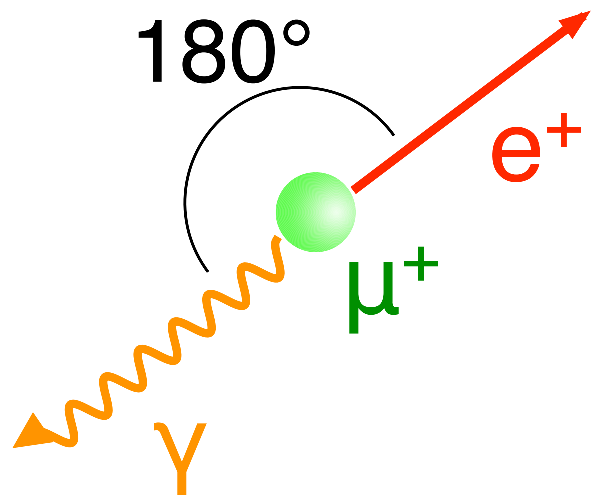
Physics Motivation

- Forbidden in the standard model
- Discovery → evidence of new physics.
- MEG is exploring the new physics region

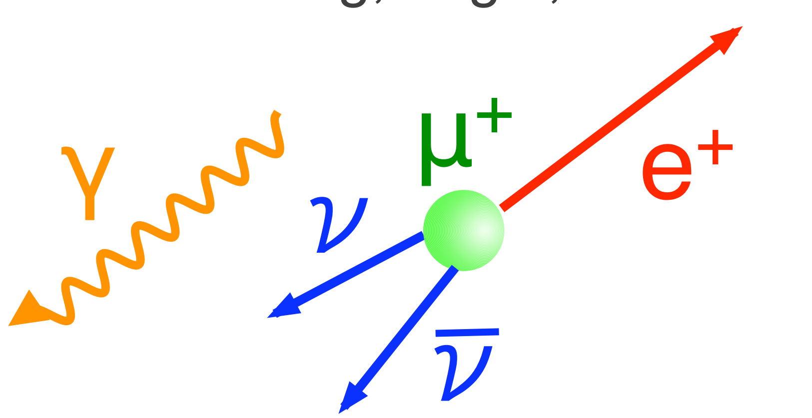


Signal & background

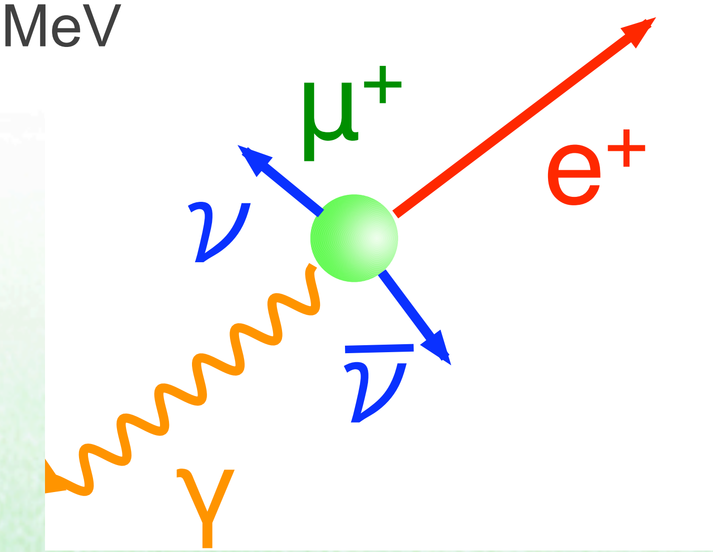
- Signal
  - μ^+ decay at rest
  - 52.8MeV (half of M_μ) (E_γ,E_e)
  - Back-to-back ($\theta_{e\gamma}$,$\varphi_{e\gamma}$)
  - Timing coincidence ($T_{e\gamma}$)



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

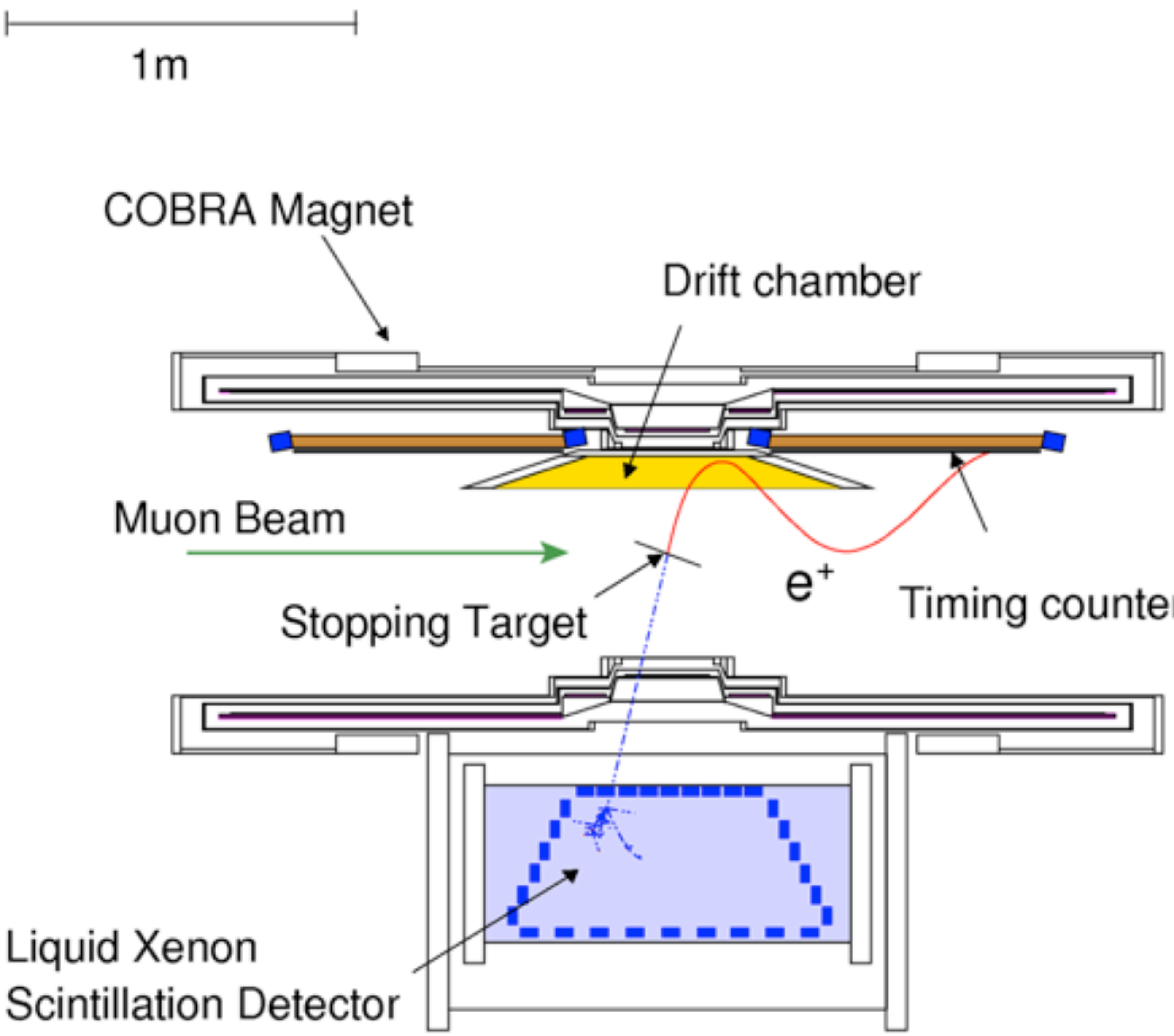


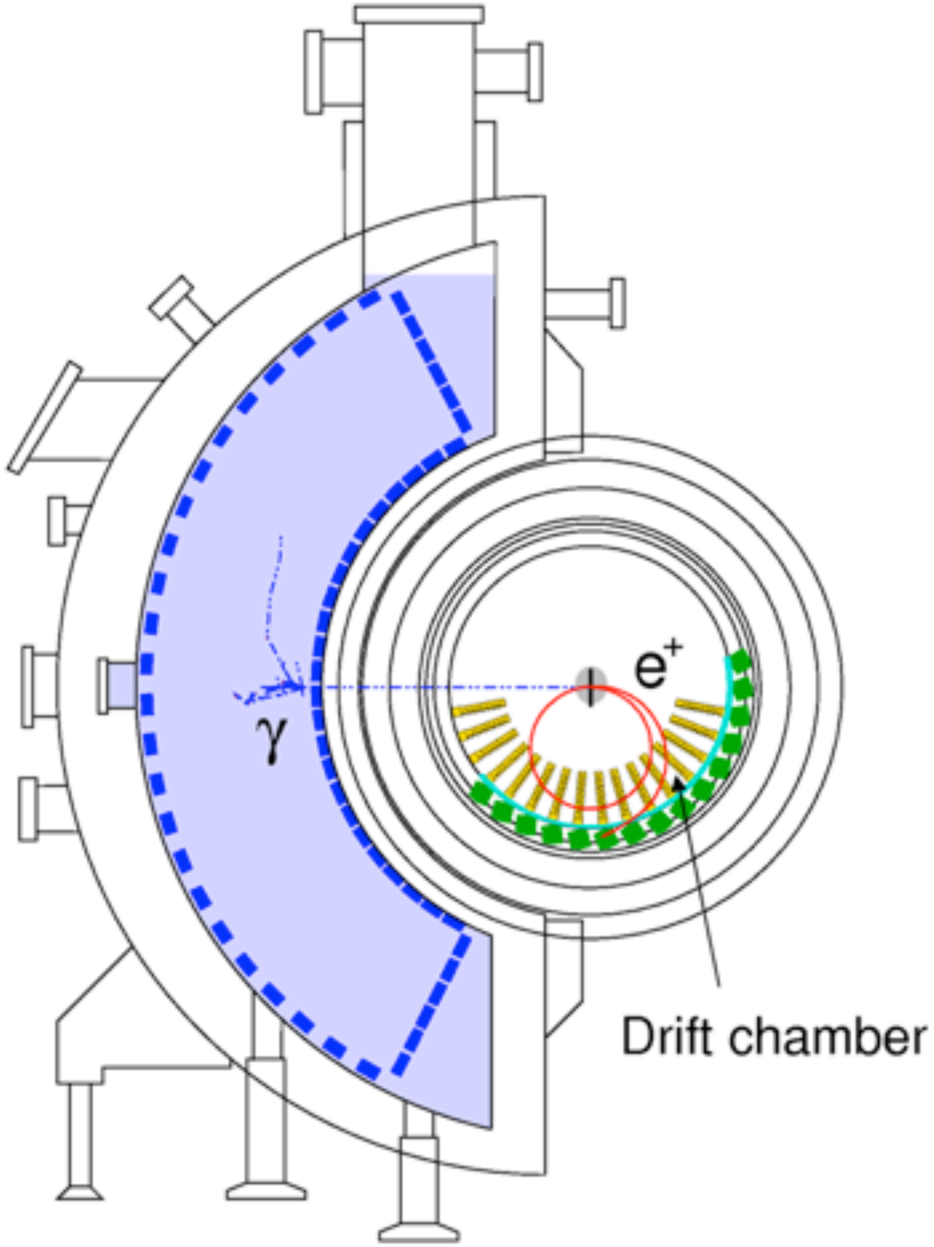
- Radiative muon decay
  - $\mu \rightarrow e\nu\nu\gamma$
  - Timing coincident, not back-to back, E < 52.8MeV



MEG detector

PSI in Switzerland





Eur. Phys. J. C, 73 (2013) 2365

Key items for $\mu \rightarrow e\gamma$ experiments

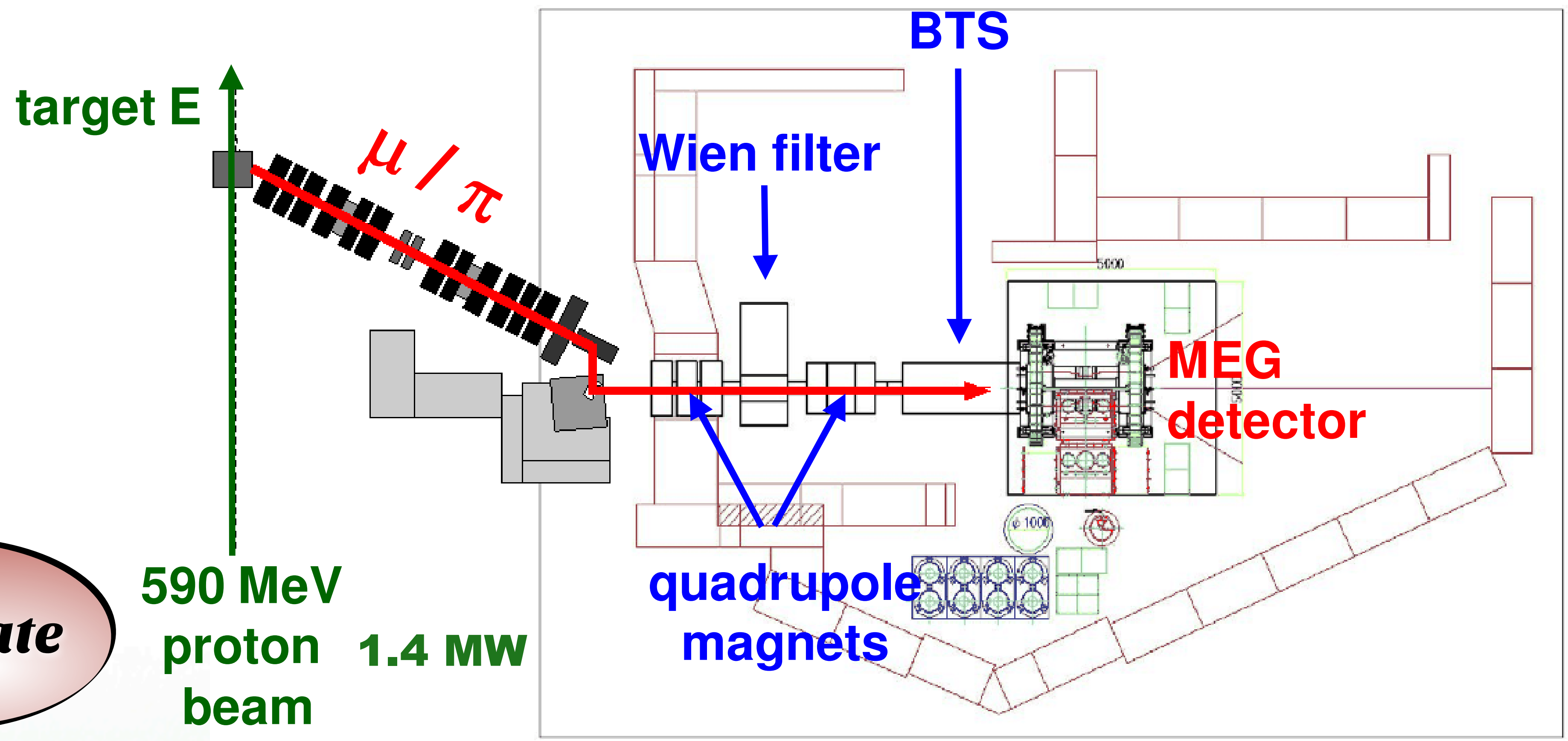
High rate Very high rate μ beam

Resolution Efficiency Good resolution for relatively low (52.8 MeV) energy particles

Background Reducing accidental backgrounds

Beam and target

PSI
πE5



High rate

Slit opening	Collimator position			COBRA center		
	R_μ (Hz) at 2mA	σ_x (mm)	σ_y (mm)	R_μ (Hz) at 2mA	σ_x (mm)	σ_y (mm)
250/280	$9 \cdot 10^7$	21.8	18.6	$7 \cdot 10^7$	9.6	10.1
115/115	$3.5 \cdot 10^7$	21.4	15.5	$2.9 \cdot 10^7$	8.9	8.8
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Beam and target

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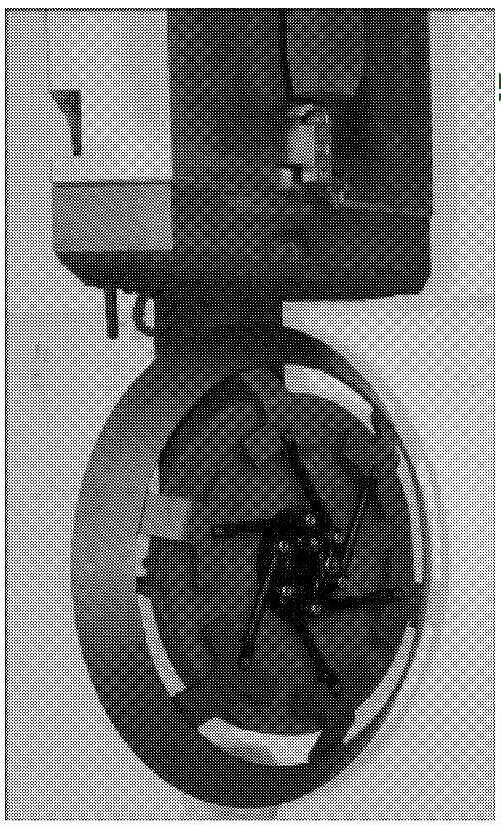

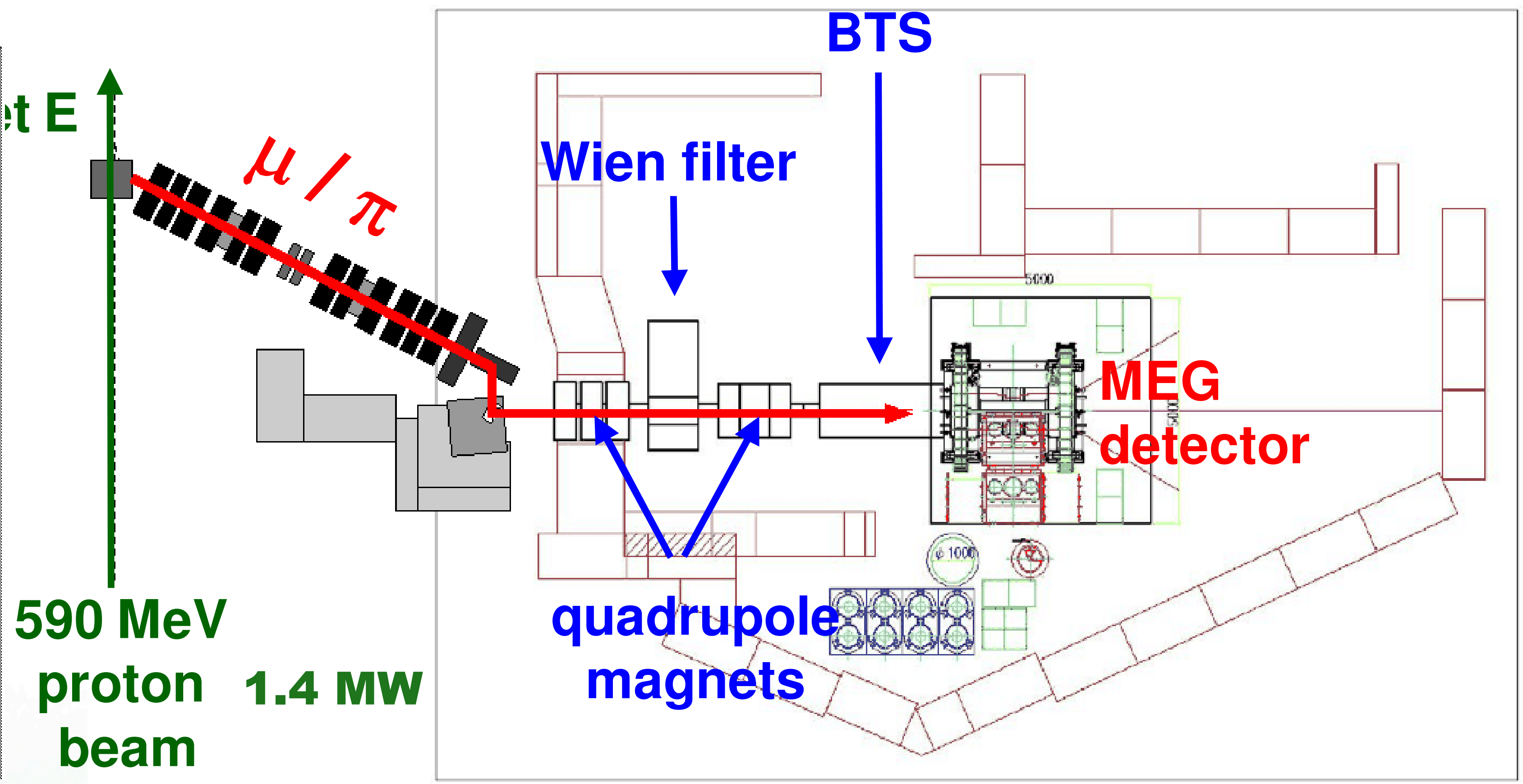

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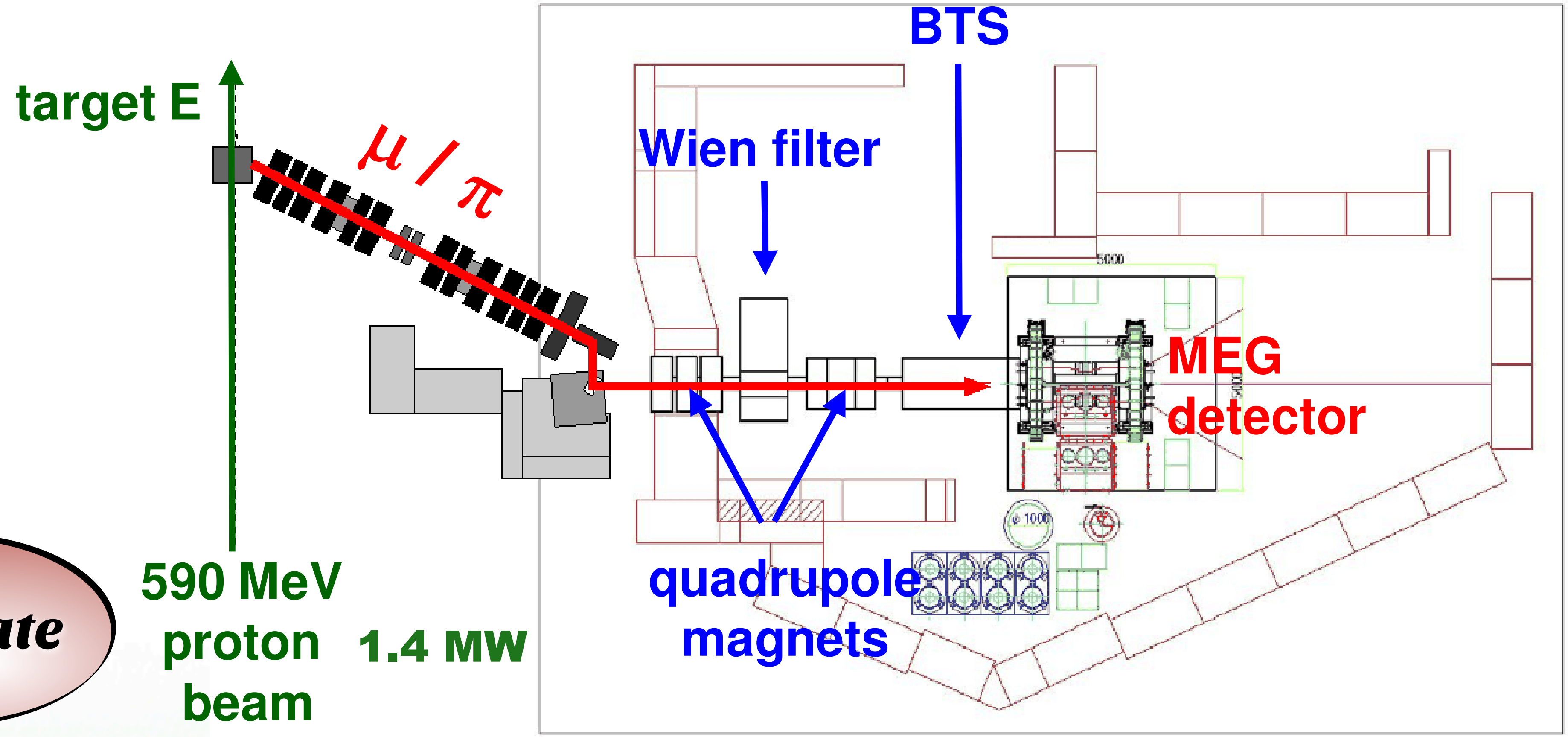

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Beam and target

Background

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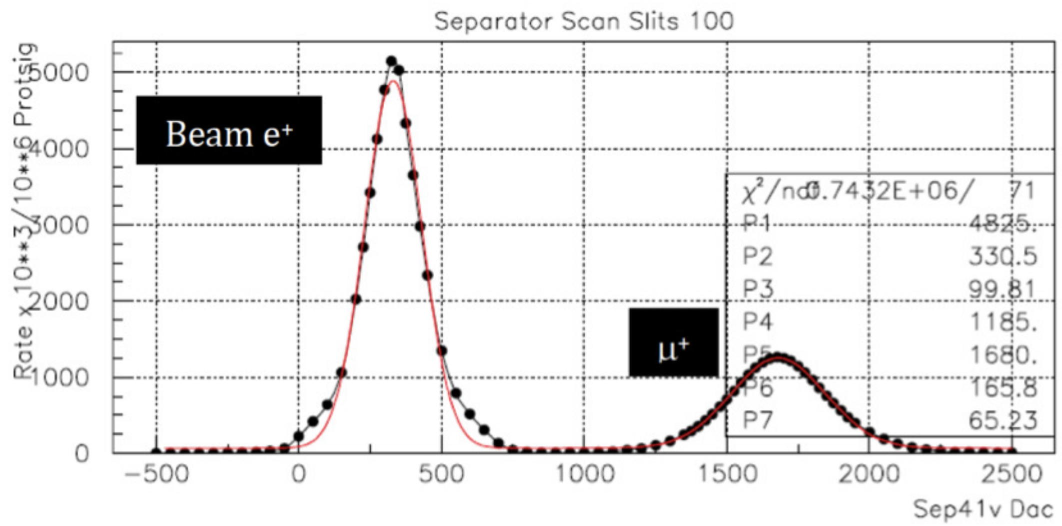
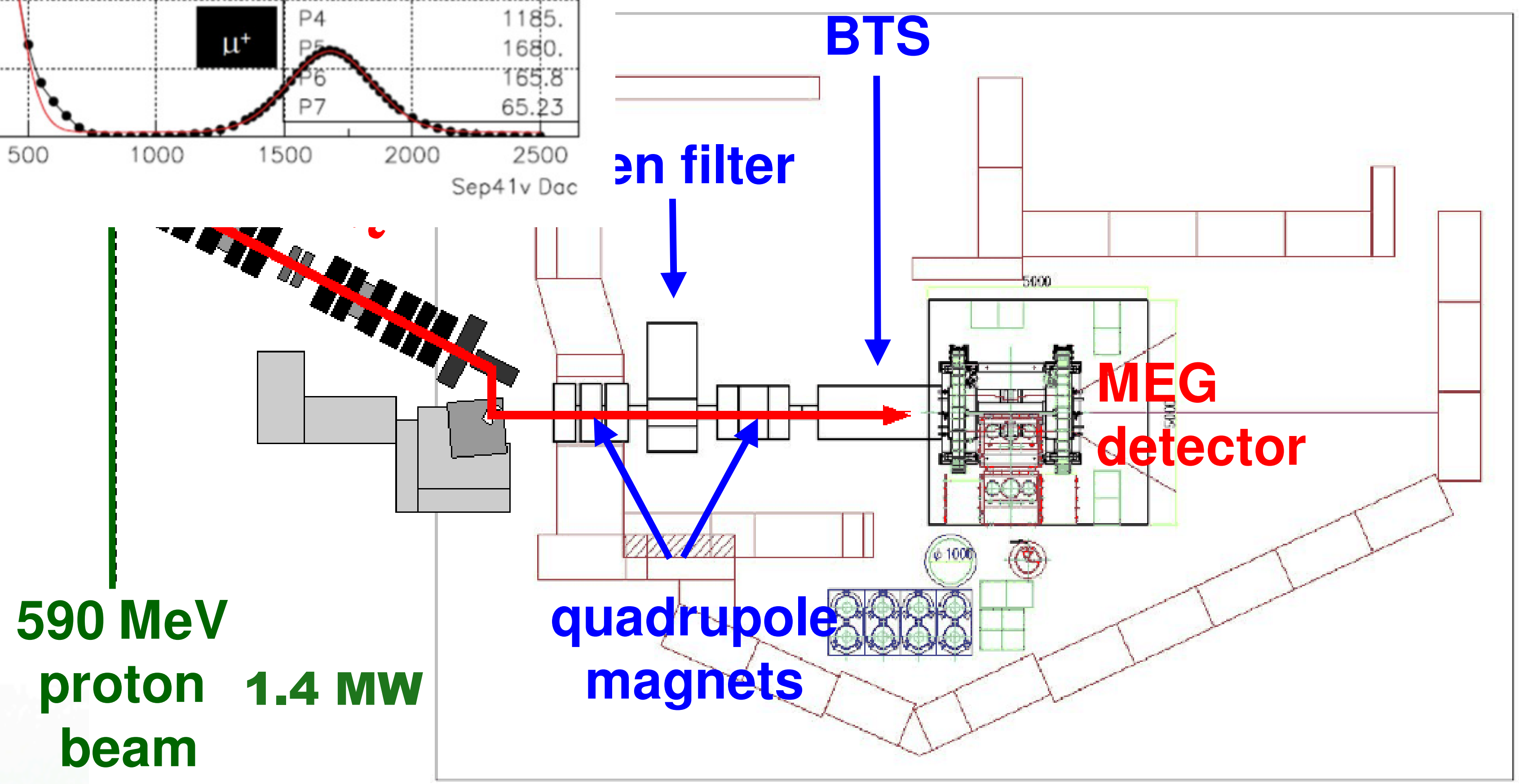
πE5





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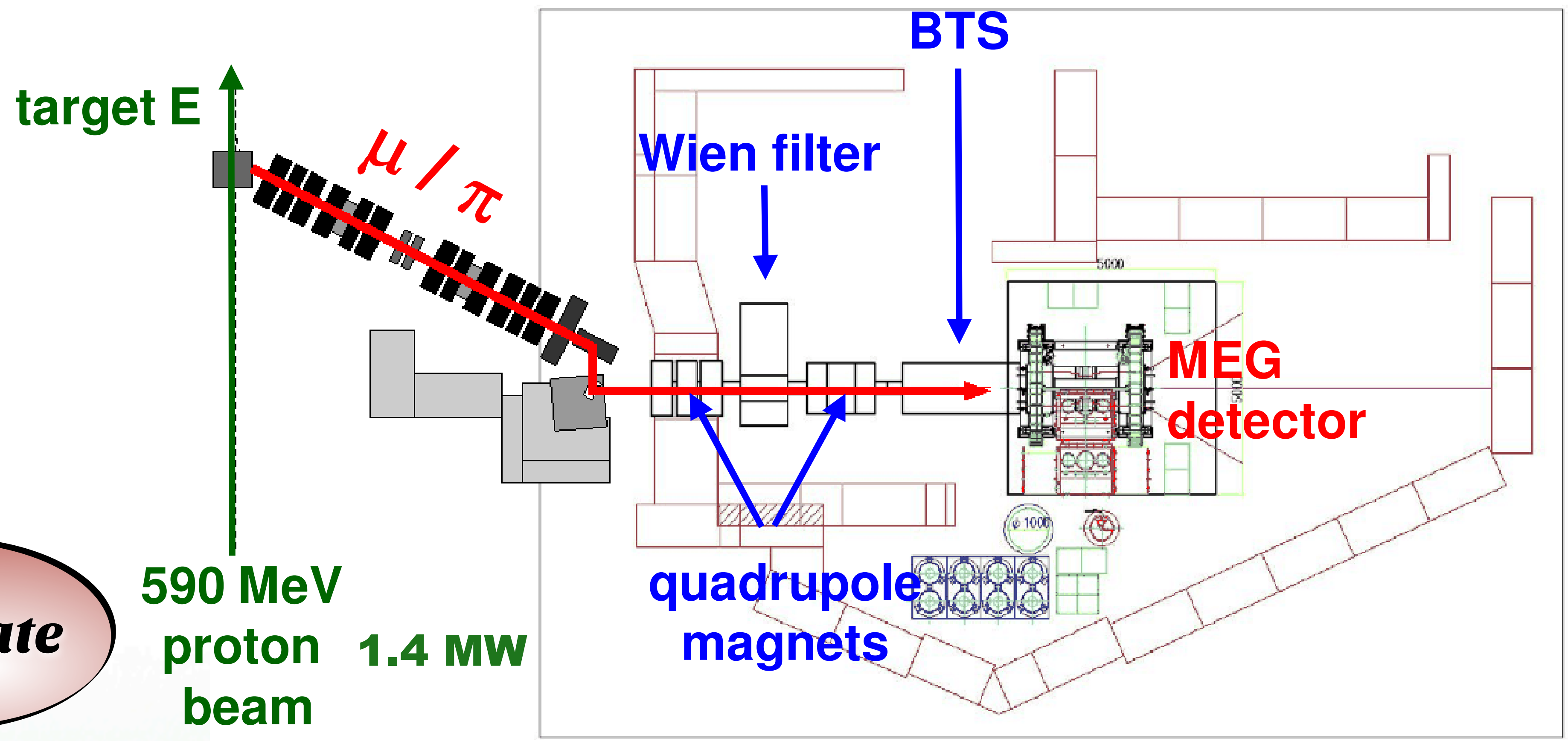

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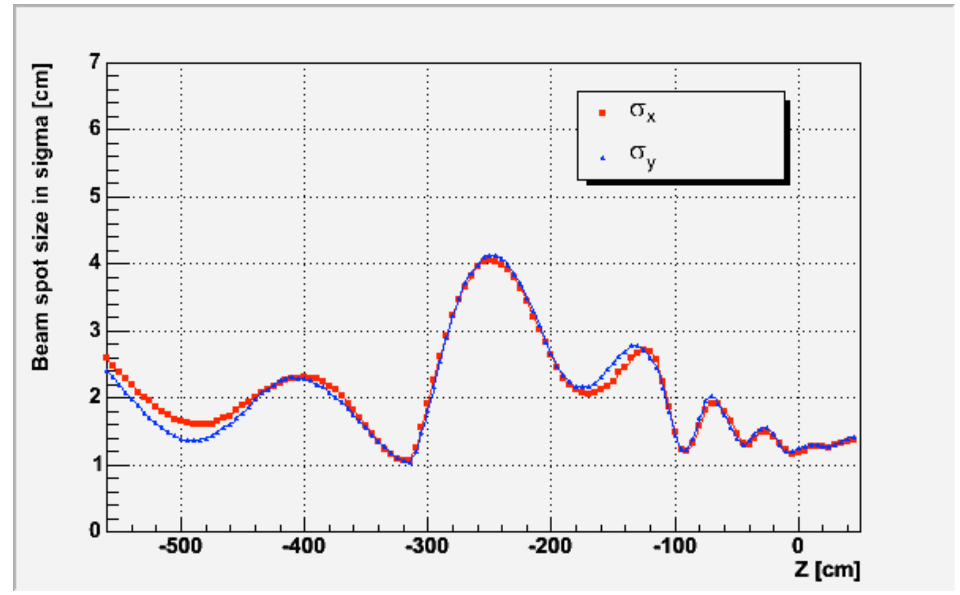

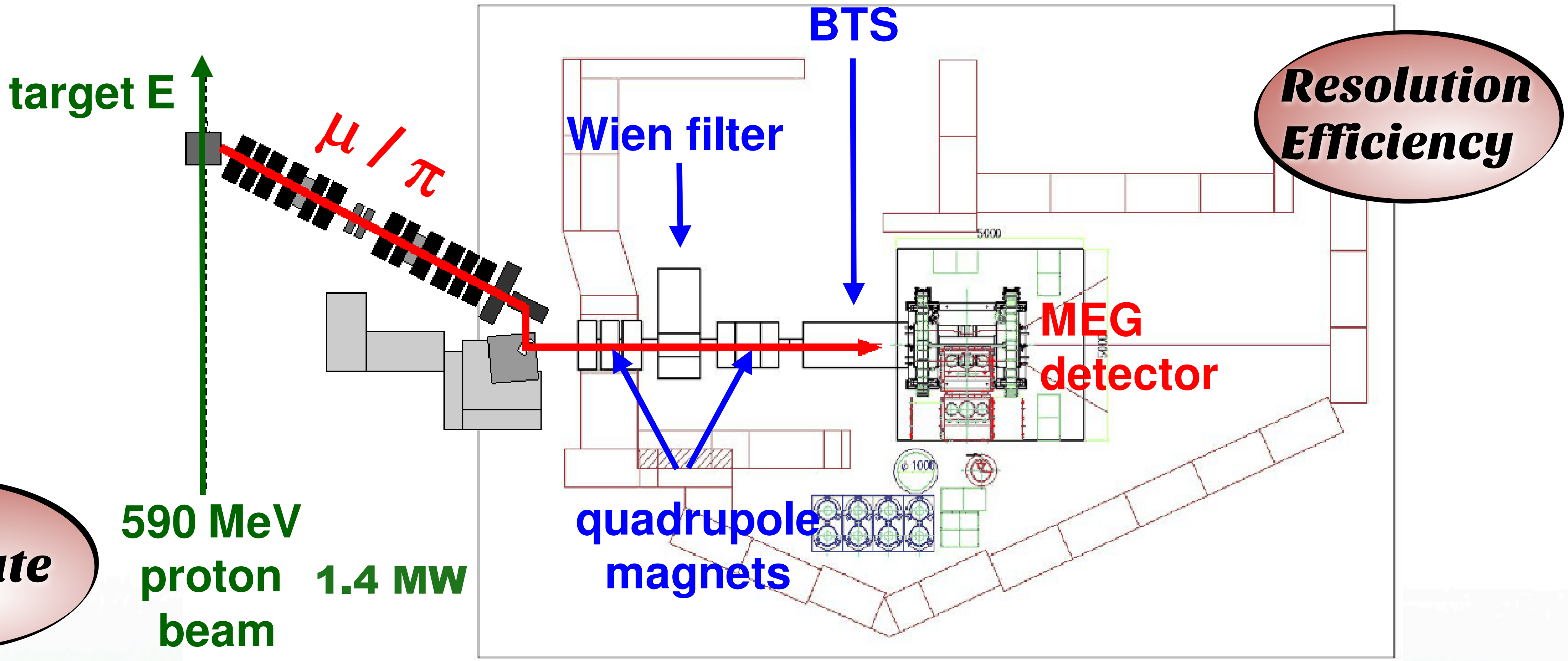

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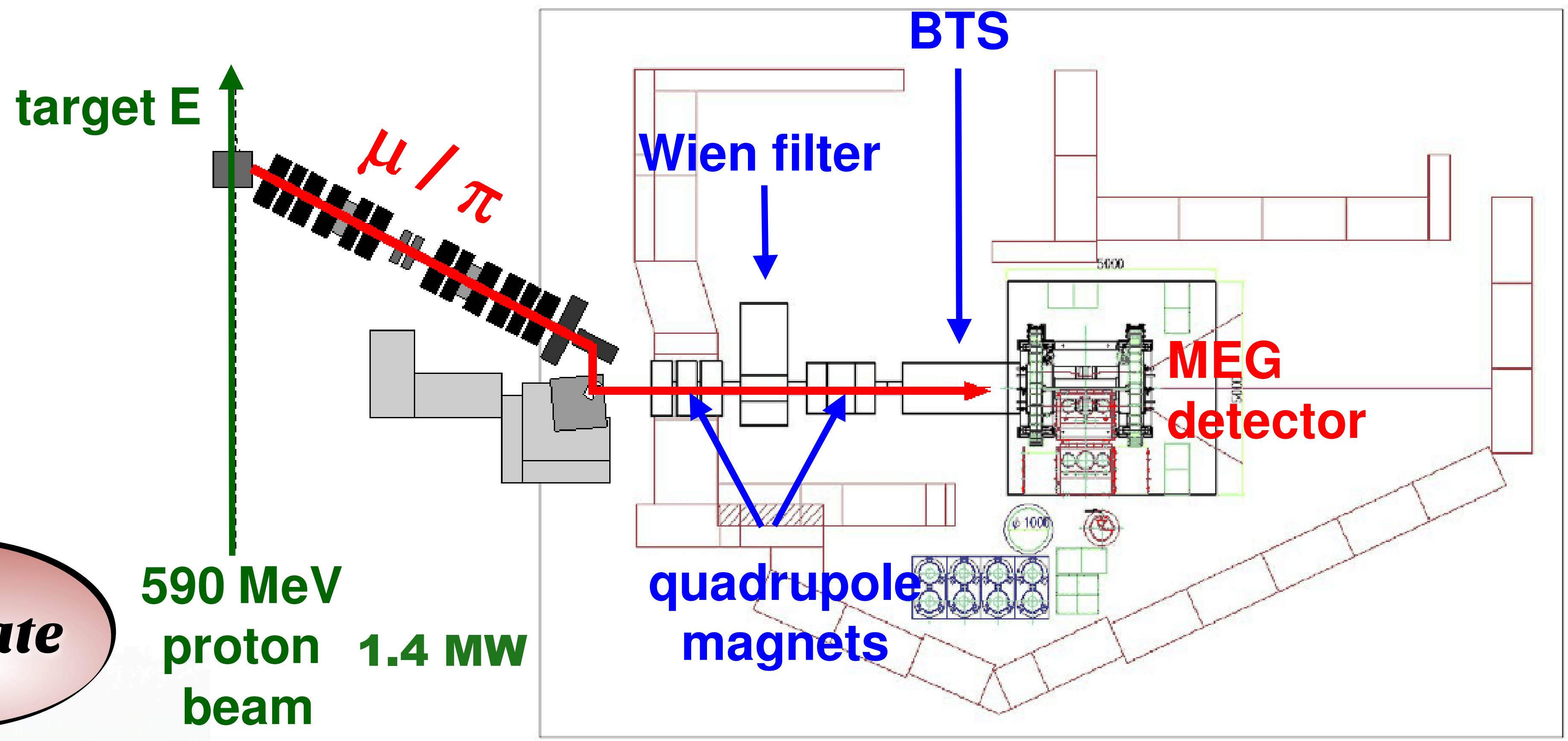

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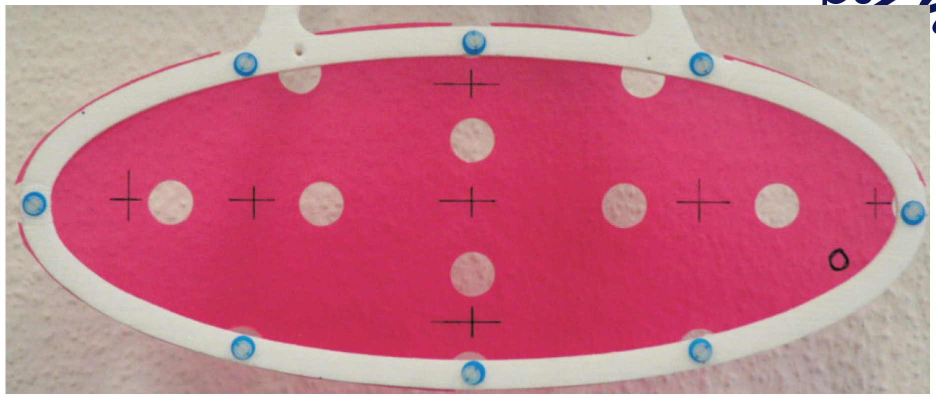

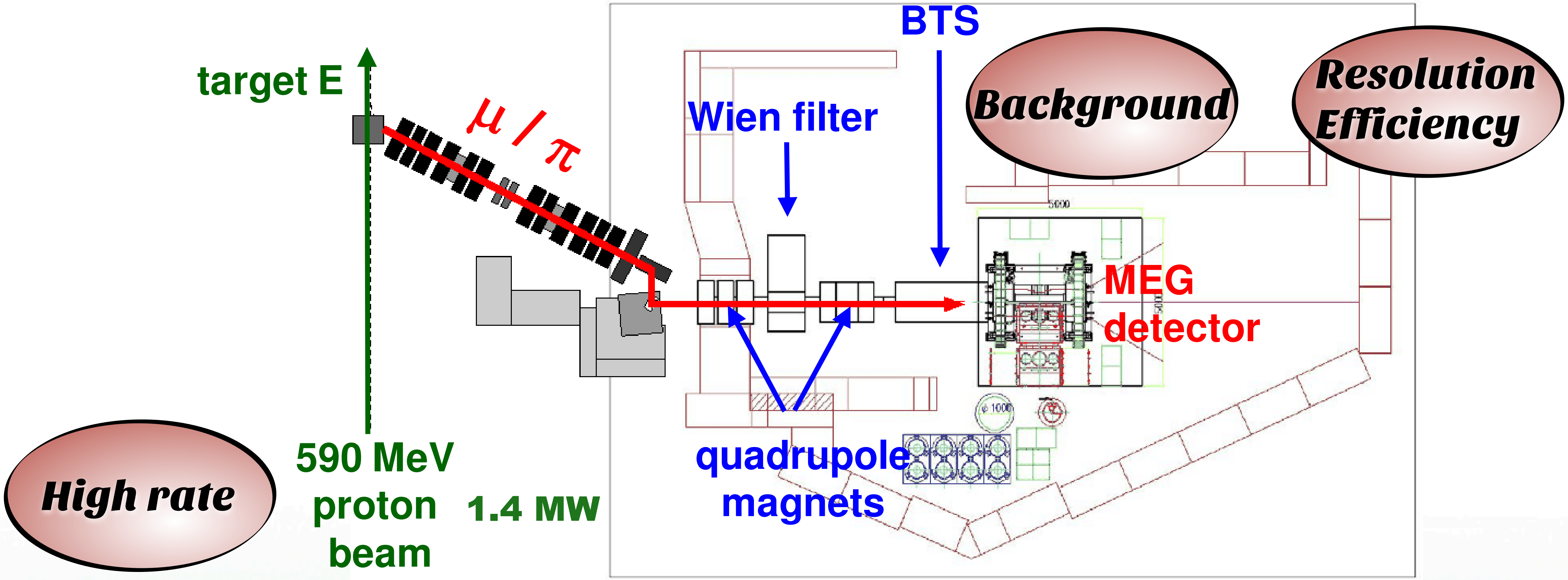

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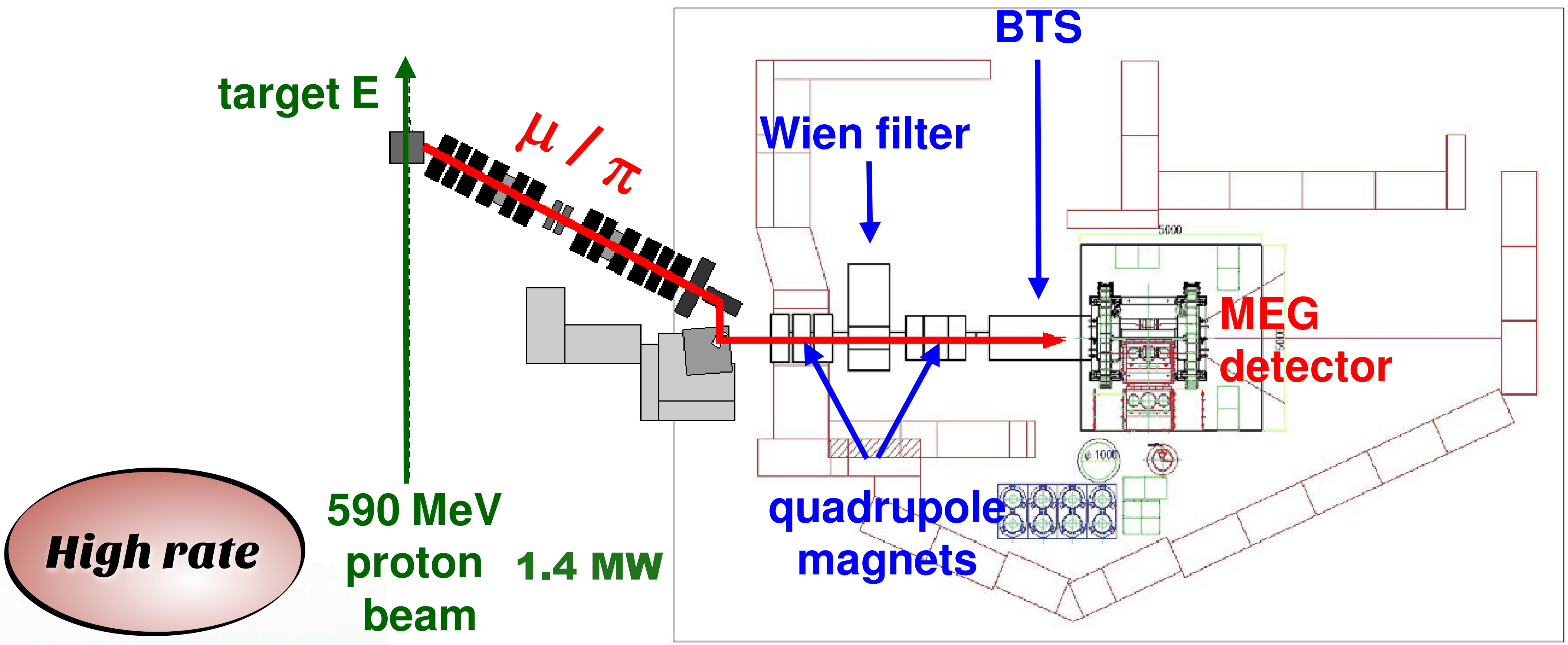
205 μm thick polyethylene plate
Slanted angle of 20.5°
79.8×200.5 mm
Stopping efficiency : 82%

Beam and target

PSI
πE5



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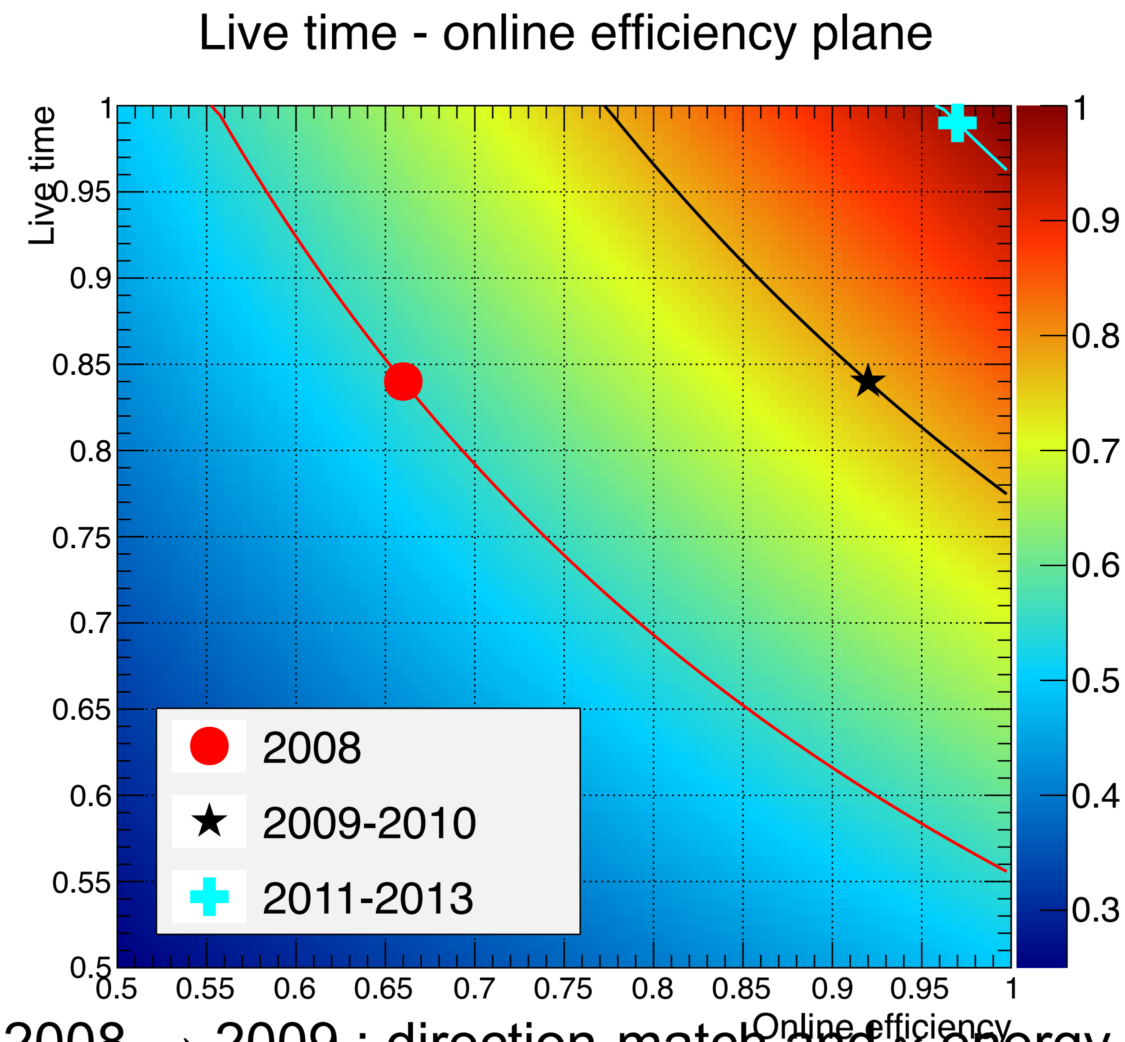
Trigger and Electronics

- Trigger
  - FPGA based trigger system
  - Physics-event trigger
    - γ energy → 2×10^3 Hz
    - Time coincidence between γ and e^+ → 100 Hz
    - Direction match → 10 Hz
  - >95% efficiency for signal

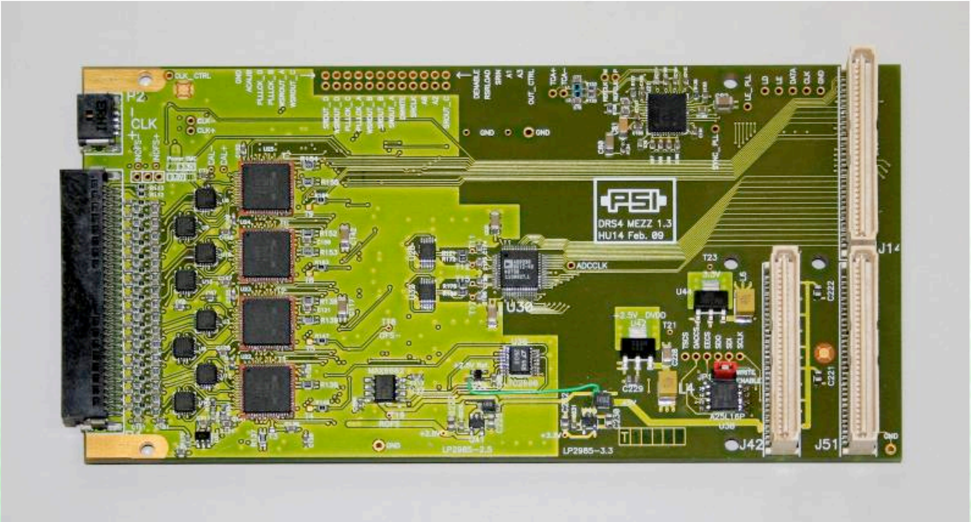


2008 → 2009 : direction-match and γ energy resolution improvement
2010 → 2011 : multiple-buffer readout

- Readout
  - DRS digitizer chip developed at PSI
    - Sampling up to 5GHz (0.8 or 1.6 GHz used in MEG)
    - 12 bit voltage digitization
    - 16 ch per VME board

http://midas.psi.ch/drs

DRS mezzanine board

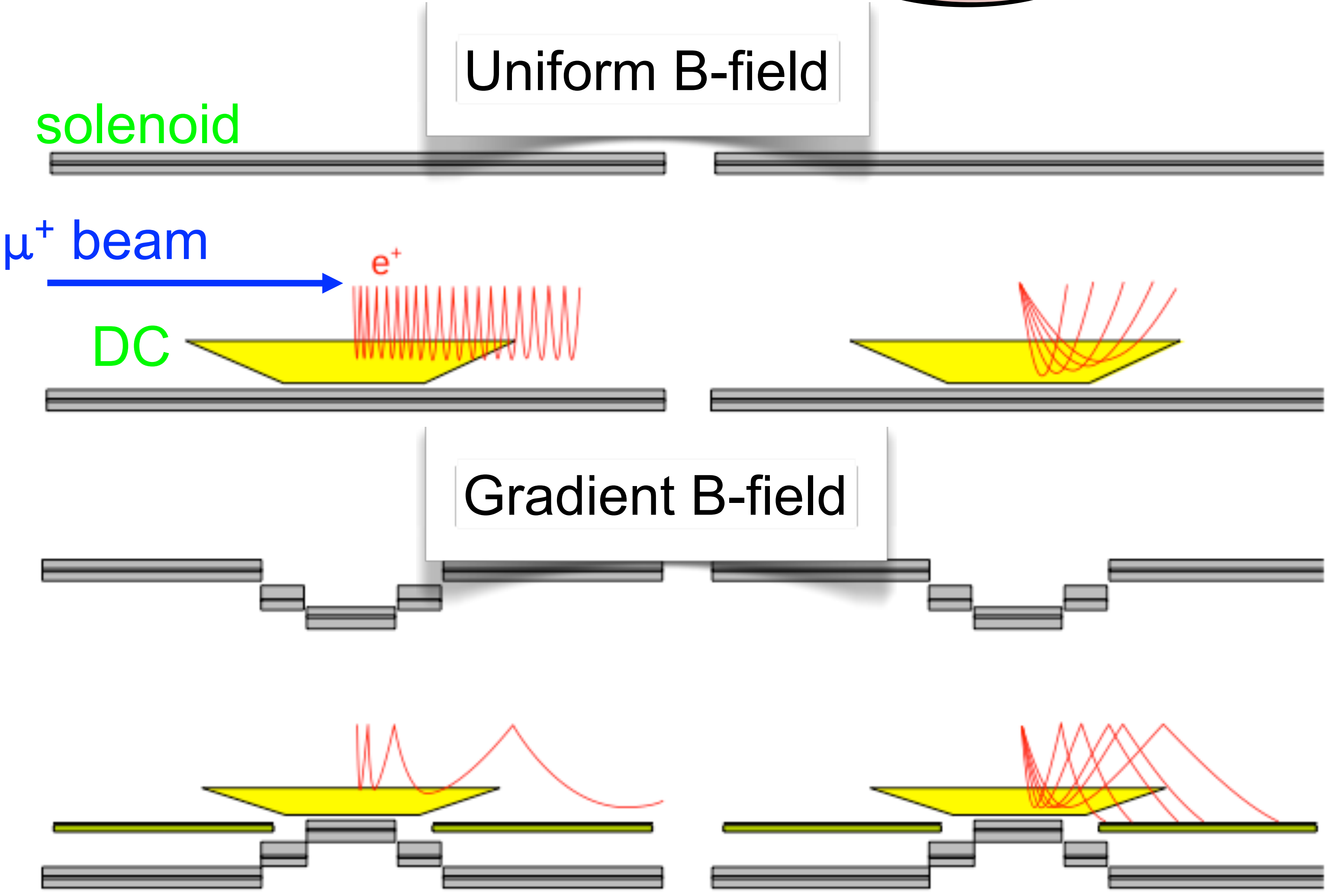


- Slow-control and DAQ
  - 9 frontend computers and an event builder
  - MIDAS DAQ framework
  - MSCB slow-control bus

http://midas.psi.ch

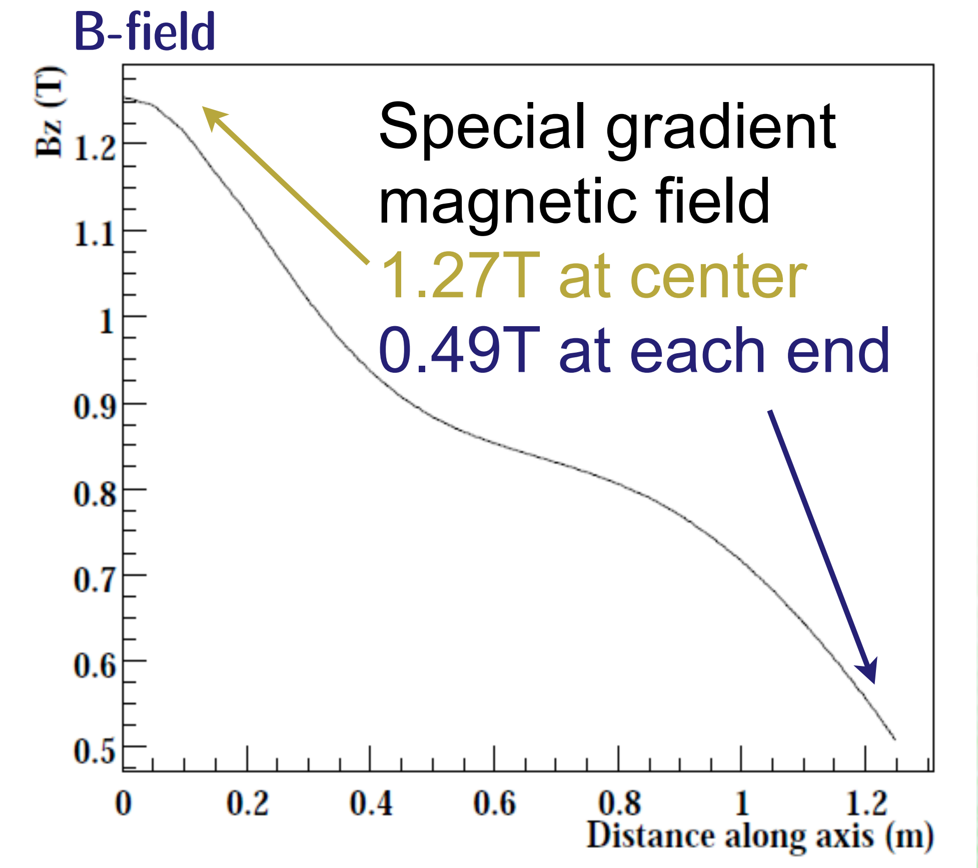
Positron spectrometer magnet

High rate



Low energy positron quickly swept away

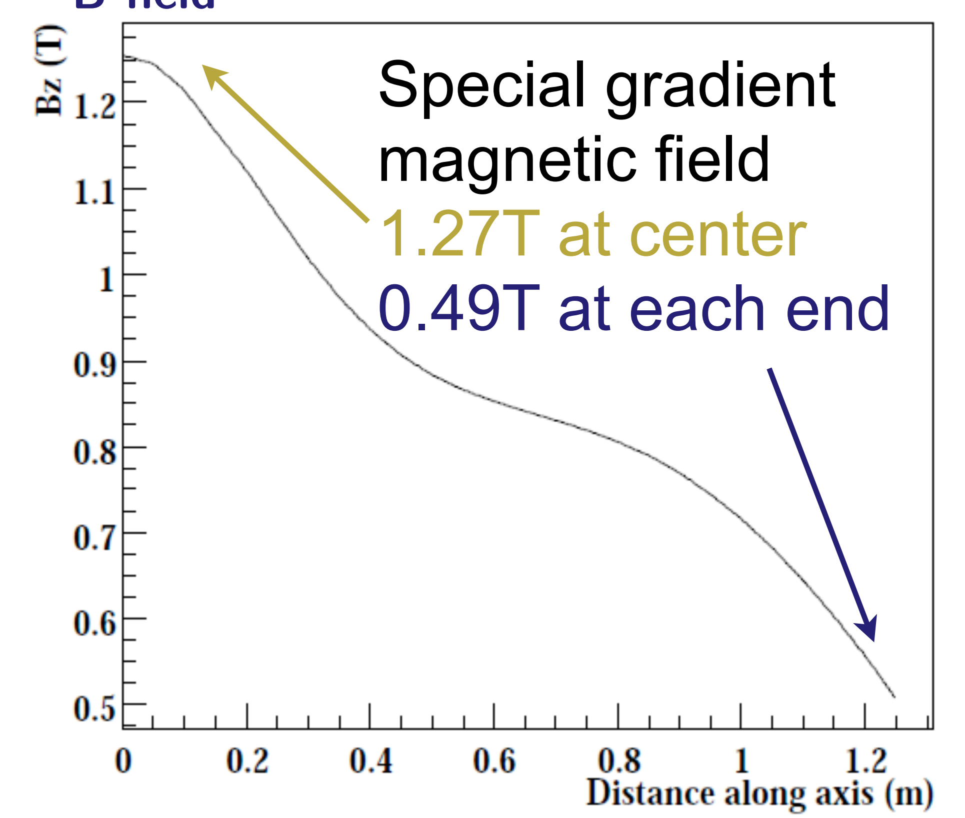
COnstant **B**ending **RA**dius independent of emission angles

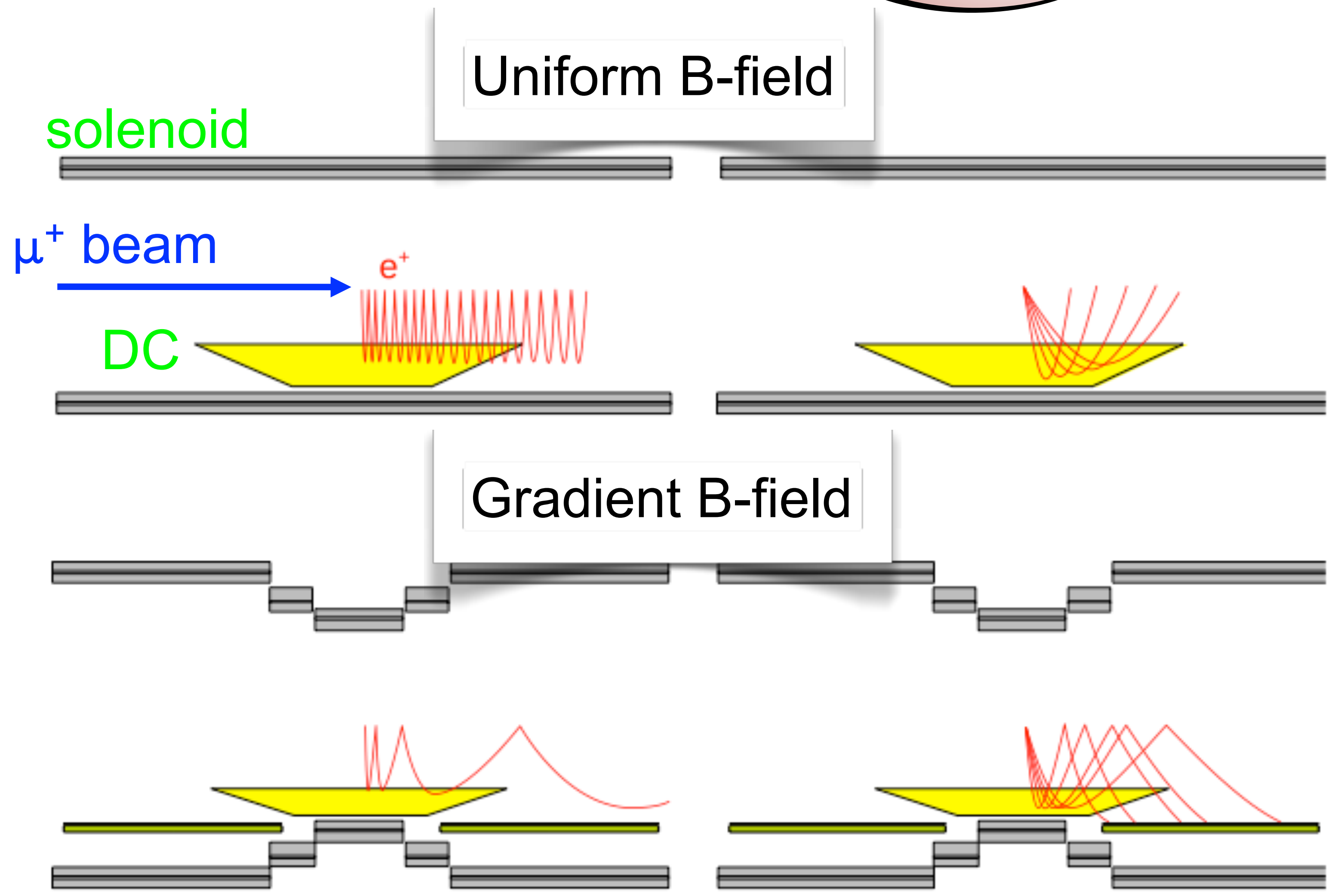


Positron spectrometer magnet

High rate

B-field





Low energy positron quickly swept away

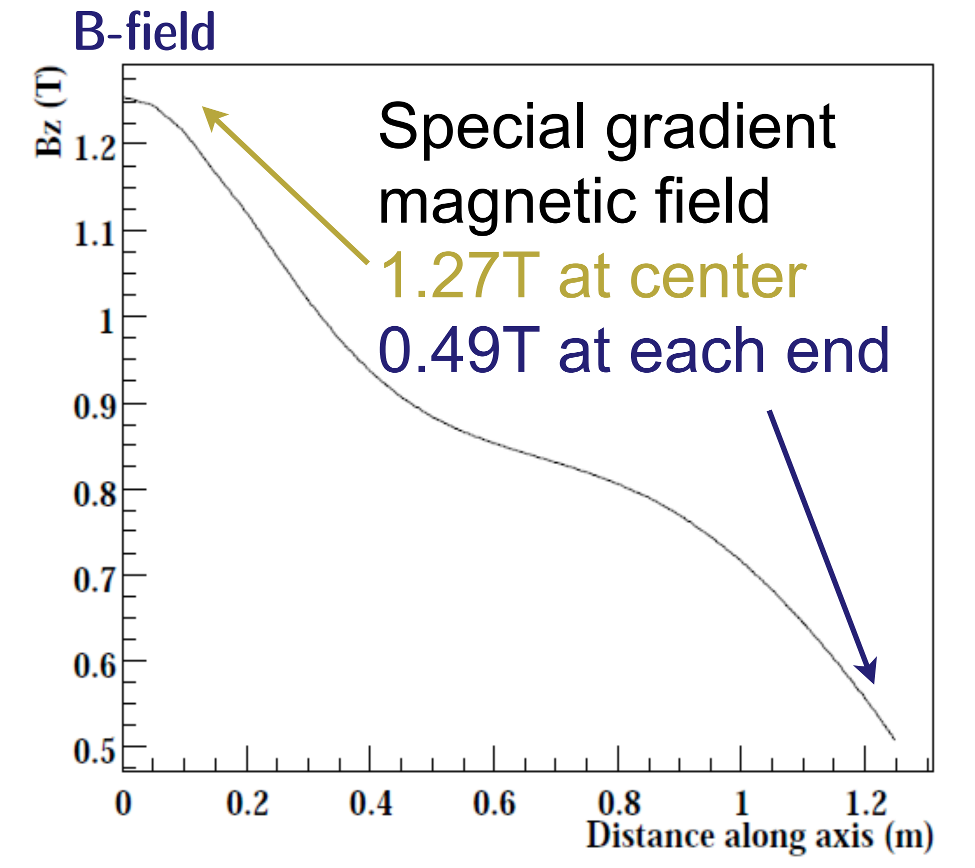
COnstant **B**ending **RA**dius independent of emission angles

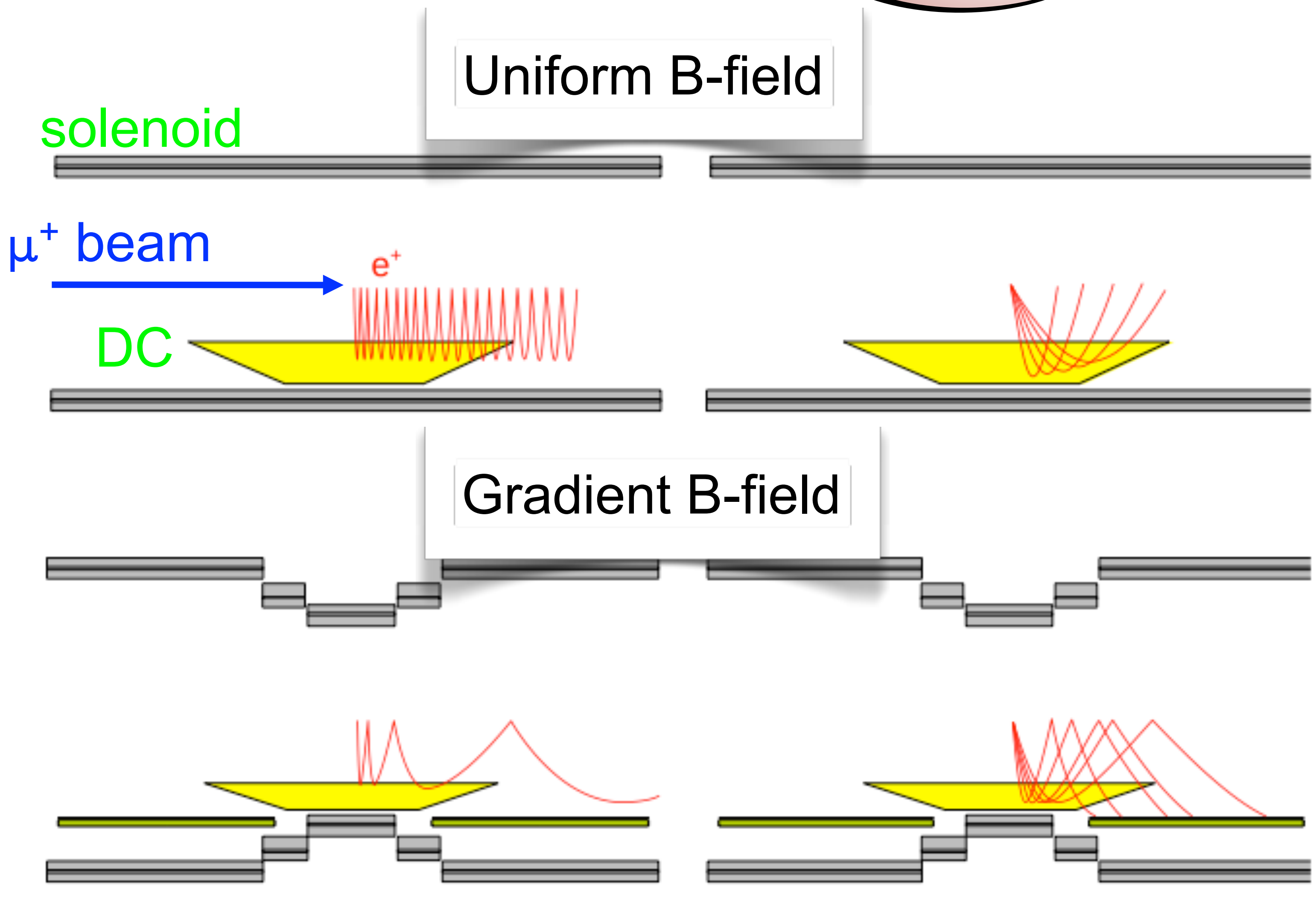
- Made of thin materials ($0.2X_0$)
- Precise 3D field mapping

Resolution Efficiency

Positron spectrometer magnet

High rate





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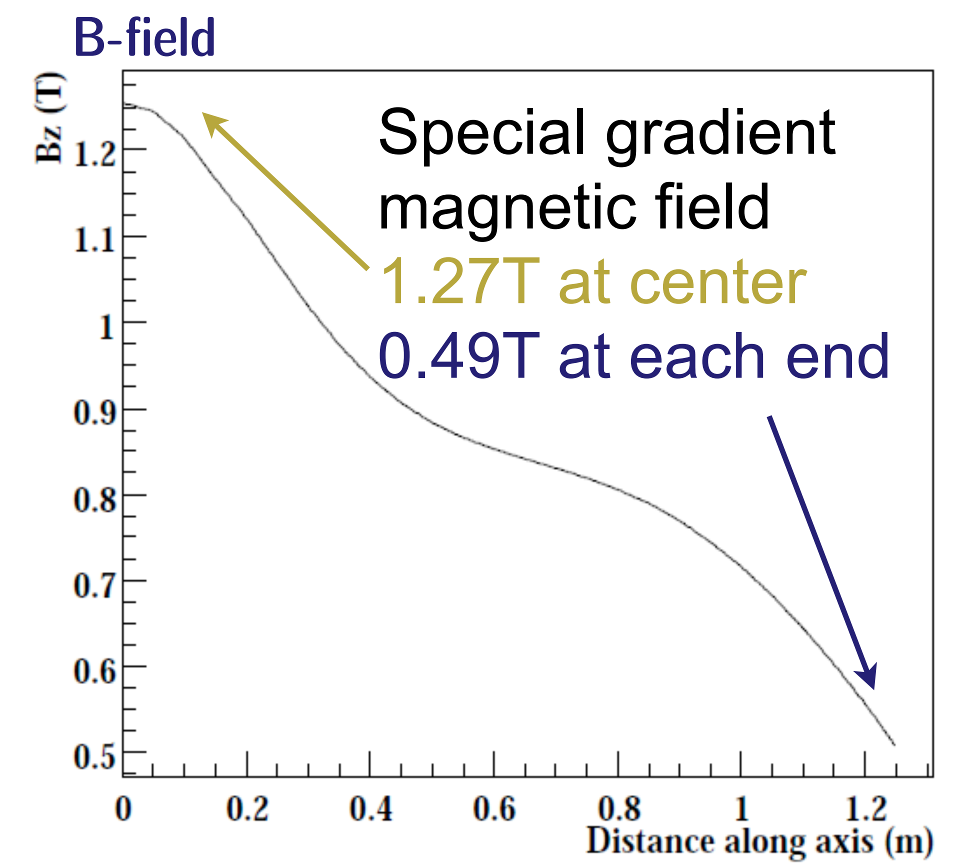
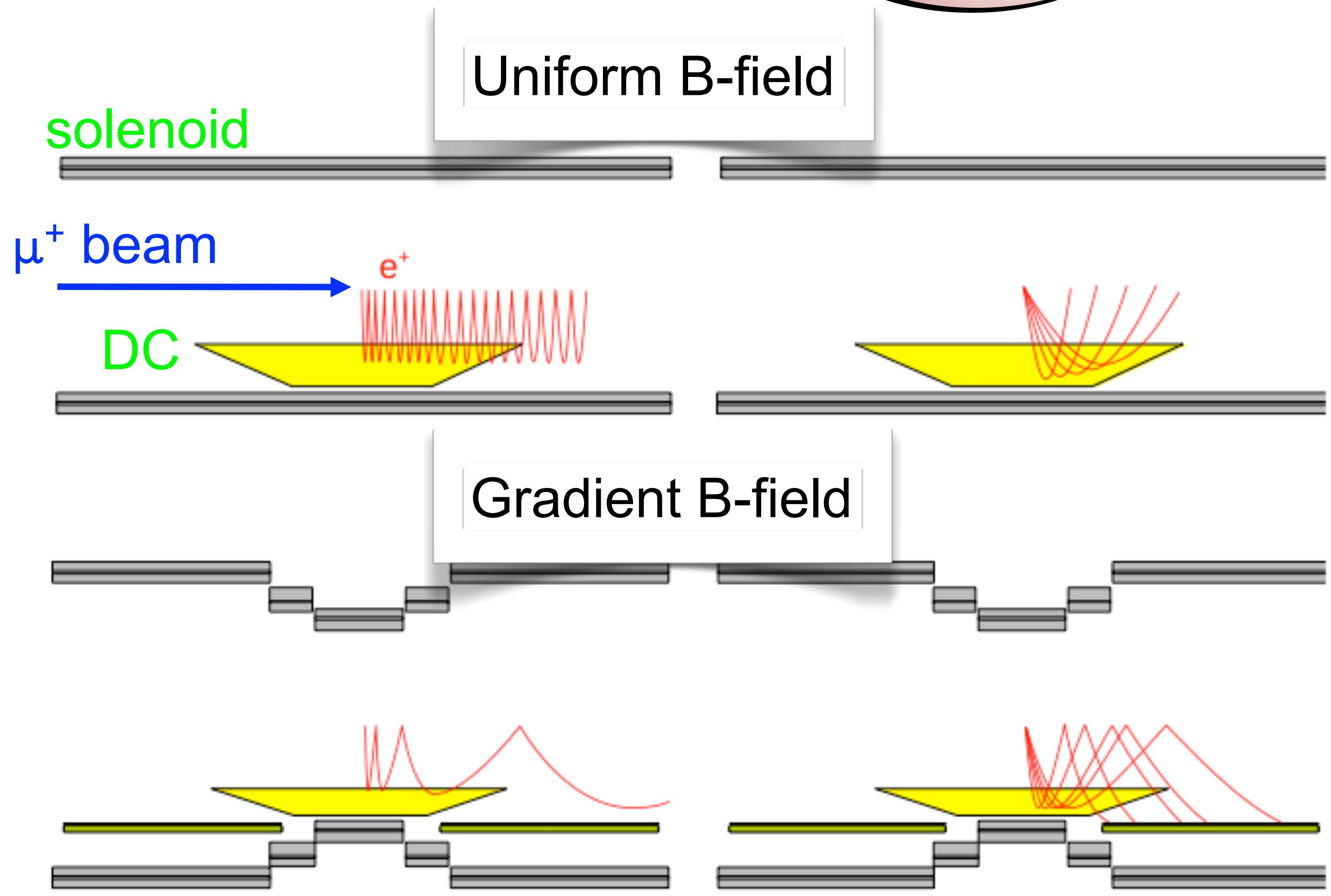
Positron spectrometer magnet

High rate





Low energy positron quickly swept away

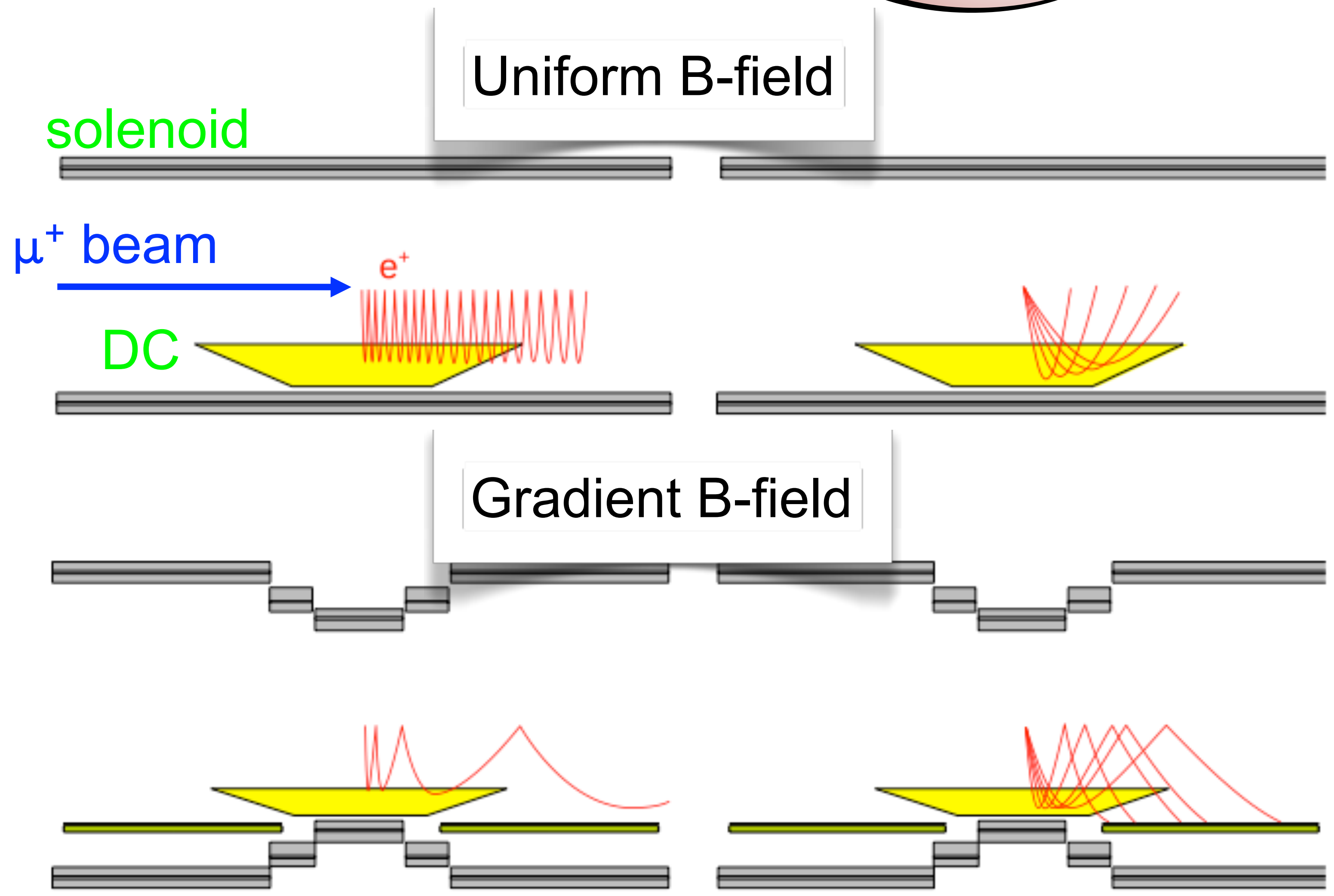
COnstant **B**ending **RA**dius independent of emission angles

- Positrons do not hit magnet walls

Background

Positron spectrometer magnet

High rate



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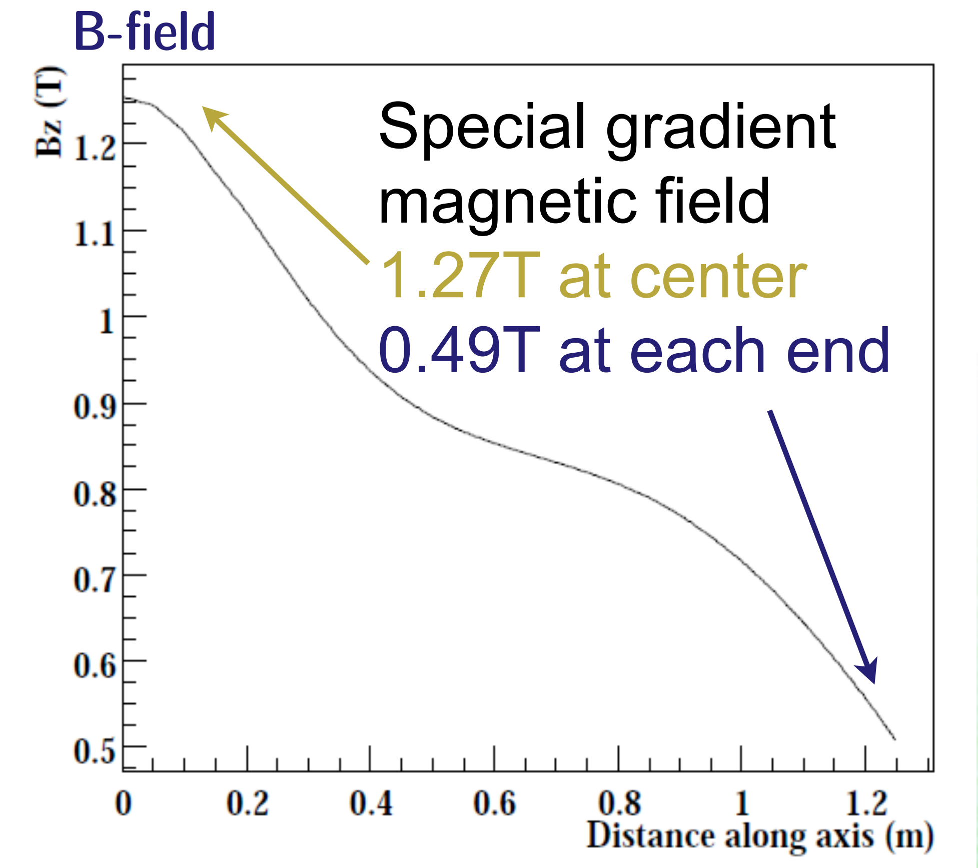
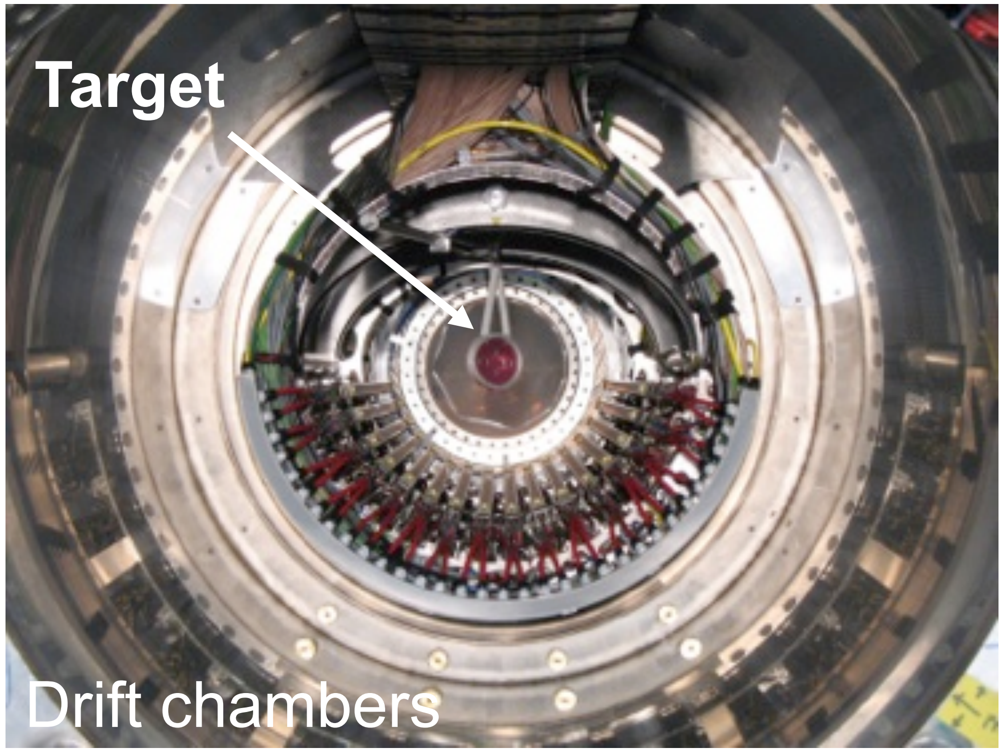
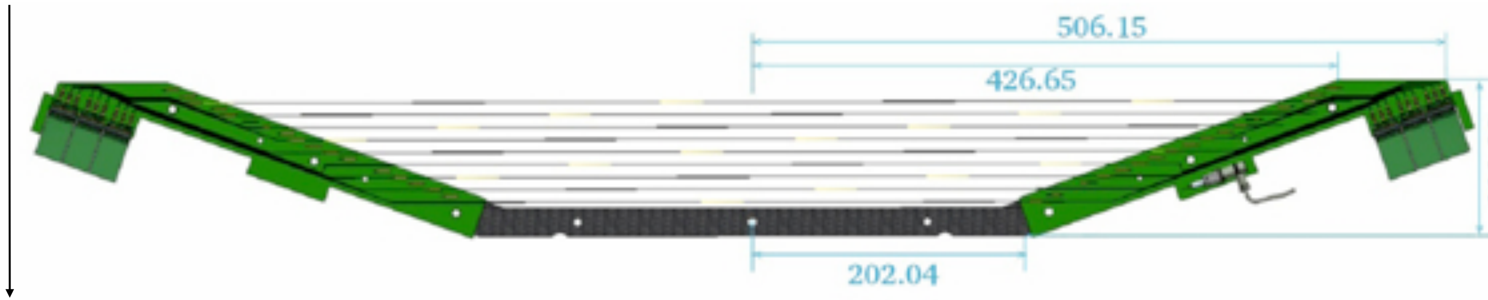


Drift chambers



Z (θ) direction



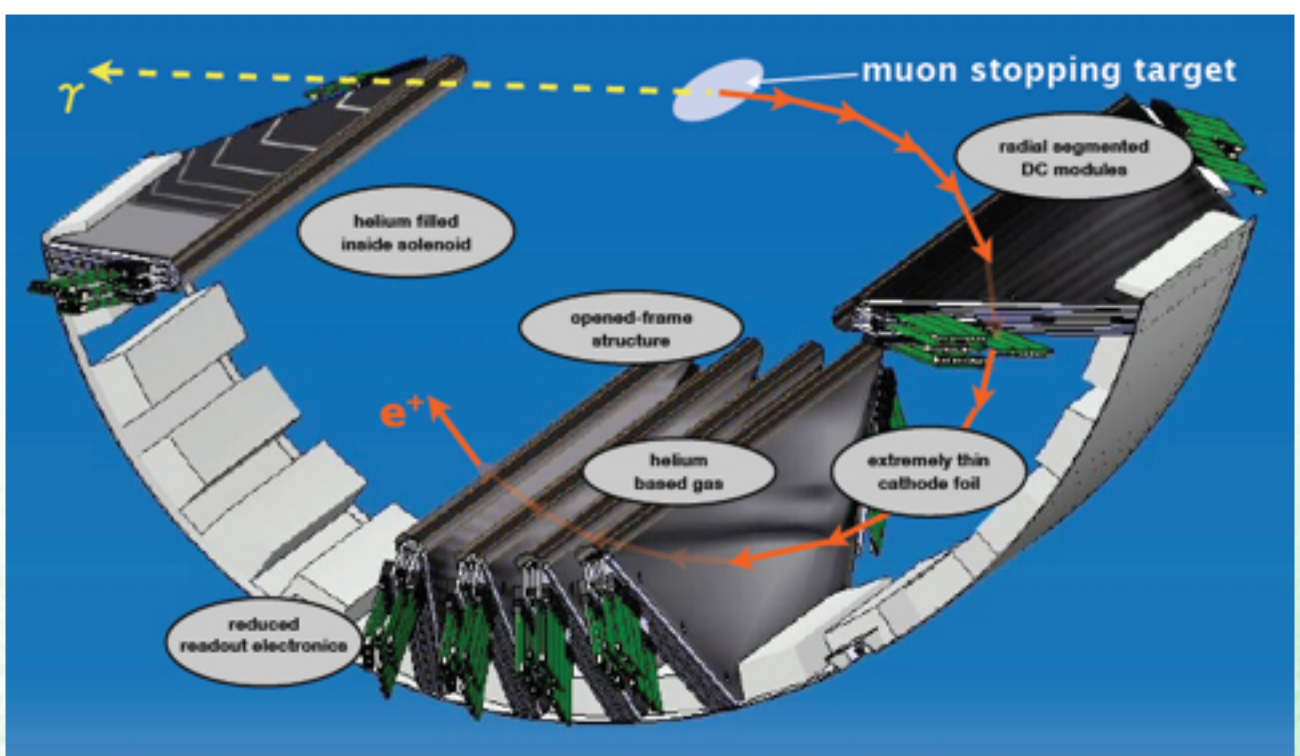
R(Φ) direction

- 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 (~$2\times10^{-3}X_0$ for one turn of e^+ trajectory)
  - Open frame at the target side
  - Low MS, low γ background

High rate

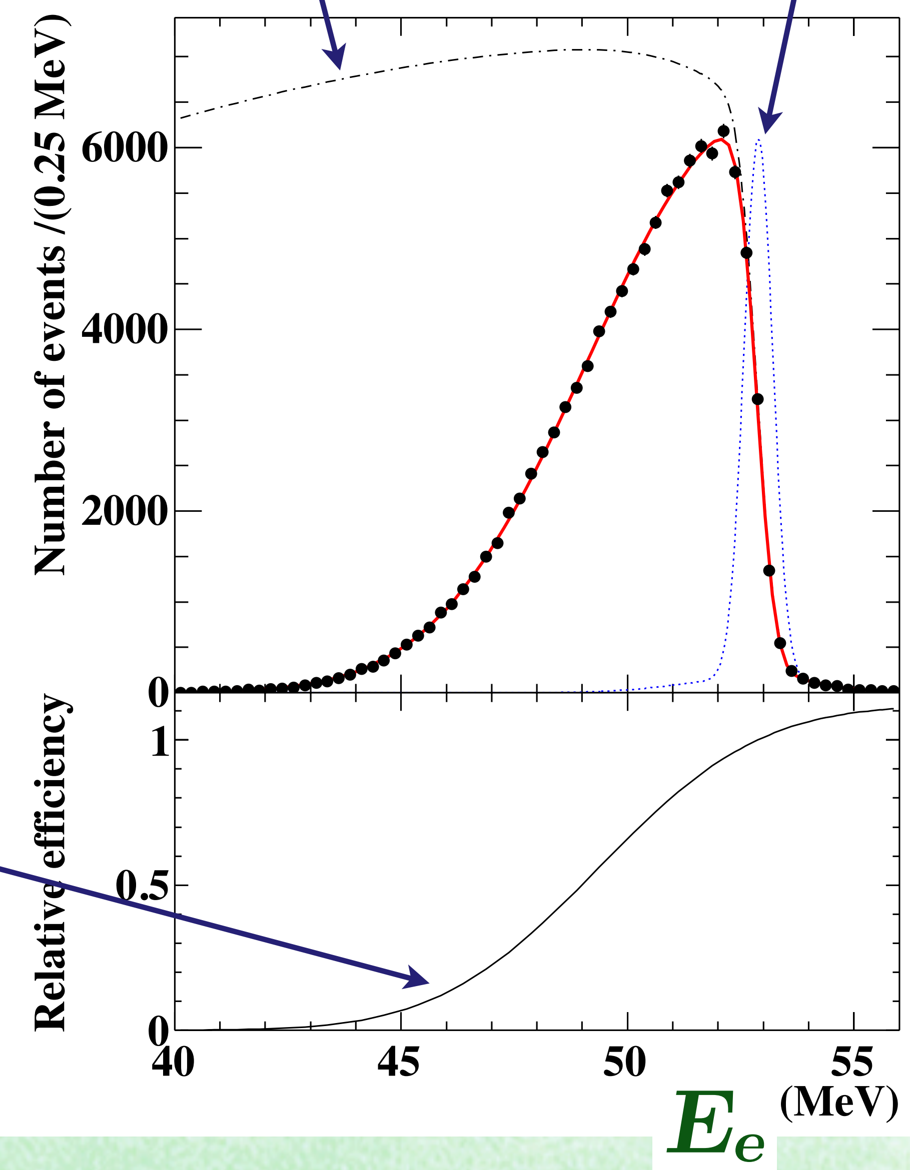
Resolution Efficiency

Background

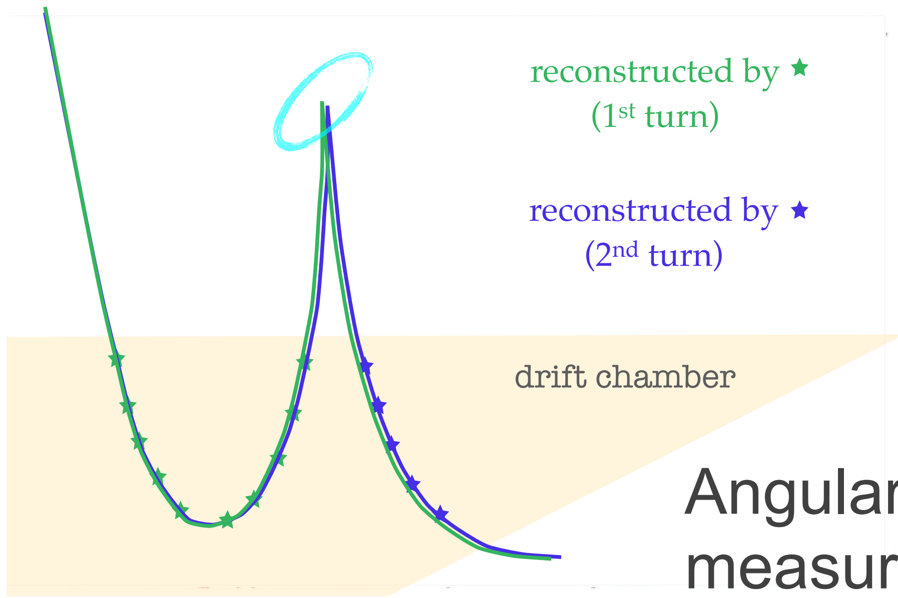


Positron spectrometer performance

- Momentum resolution is extracted from a fit to Michel edge spectrum
- Detector response
  - double gaussian + acceptance
  - σ_p = **330keV** (79%) + 1.56MeV(21%)

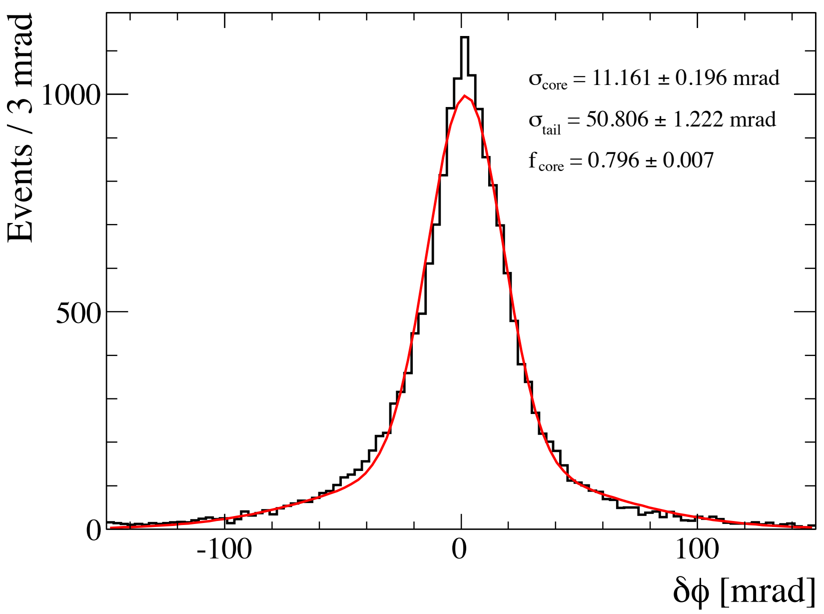


Positron spectrometer performance, cont.

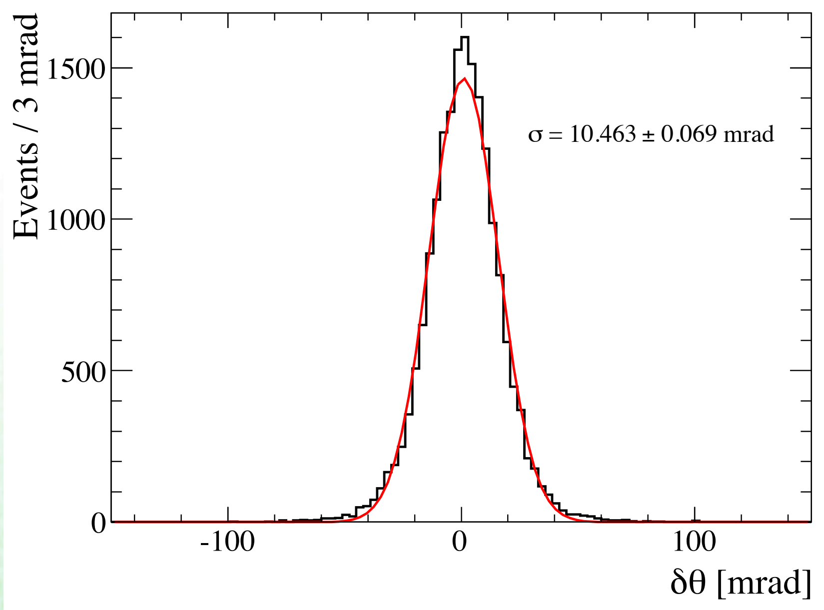


Angular resolutions measured comparing two-segments of 2-turn tracks

φ_e



ϑ_e



Resolutions for signal (after MC corrections)

Vertex position

σ_z **2.5mm**

σ_y **1.1mm(86%)**, 5.3mm(14%)

Emission angle

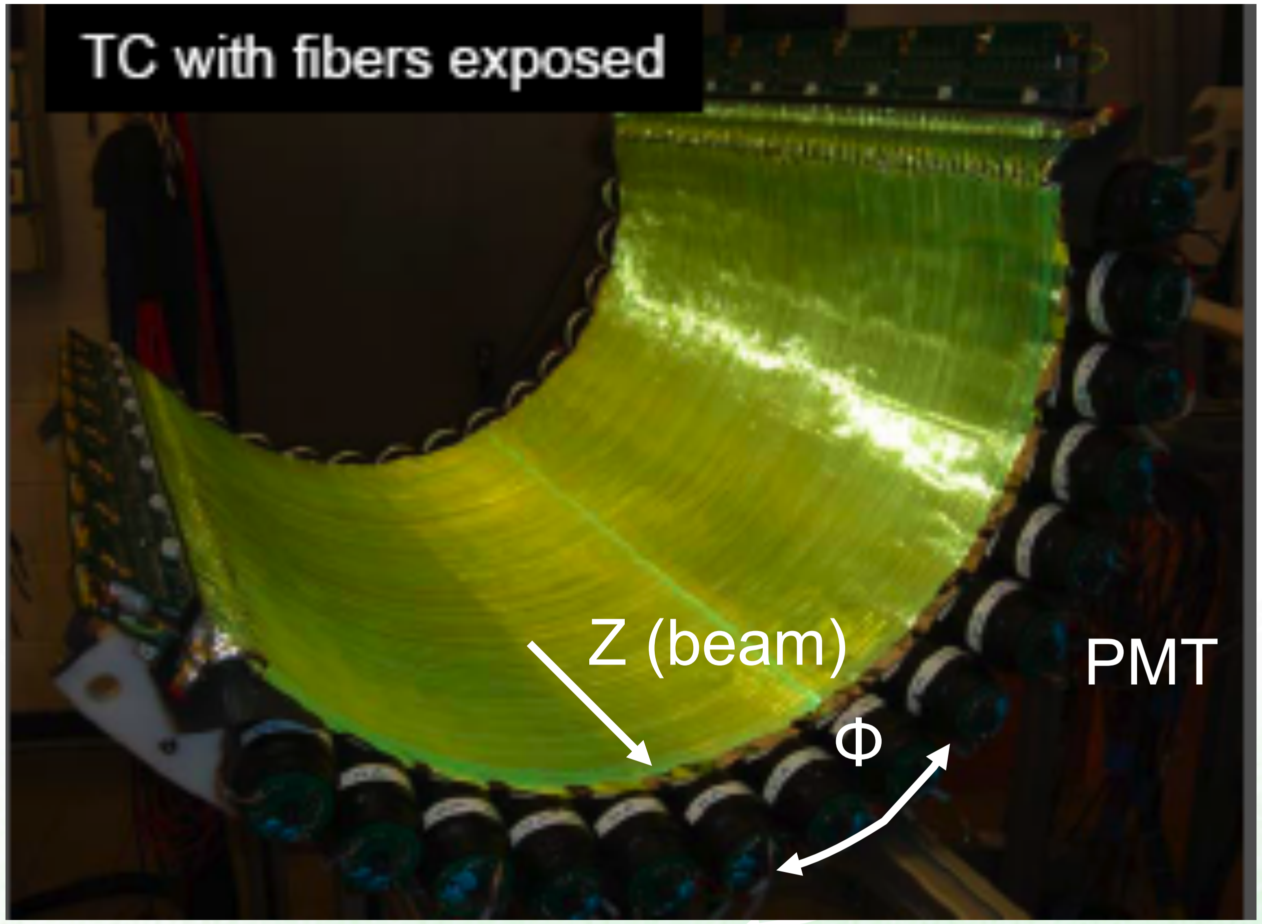
σ_θ **9.4mrad**

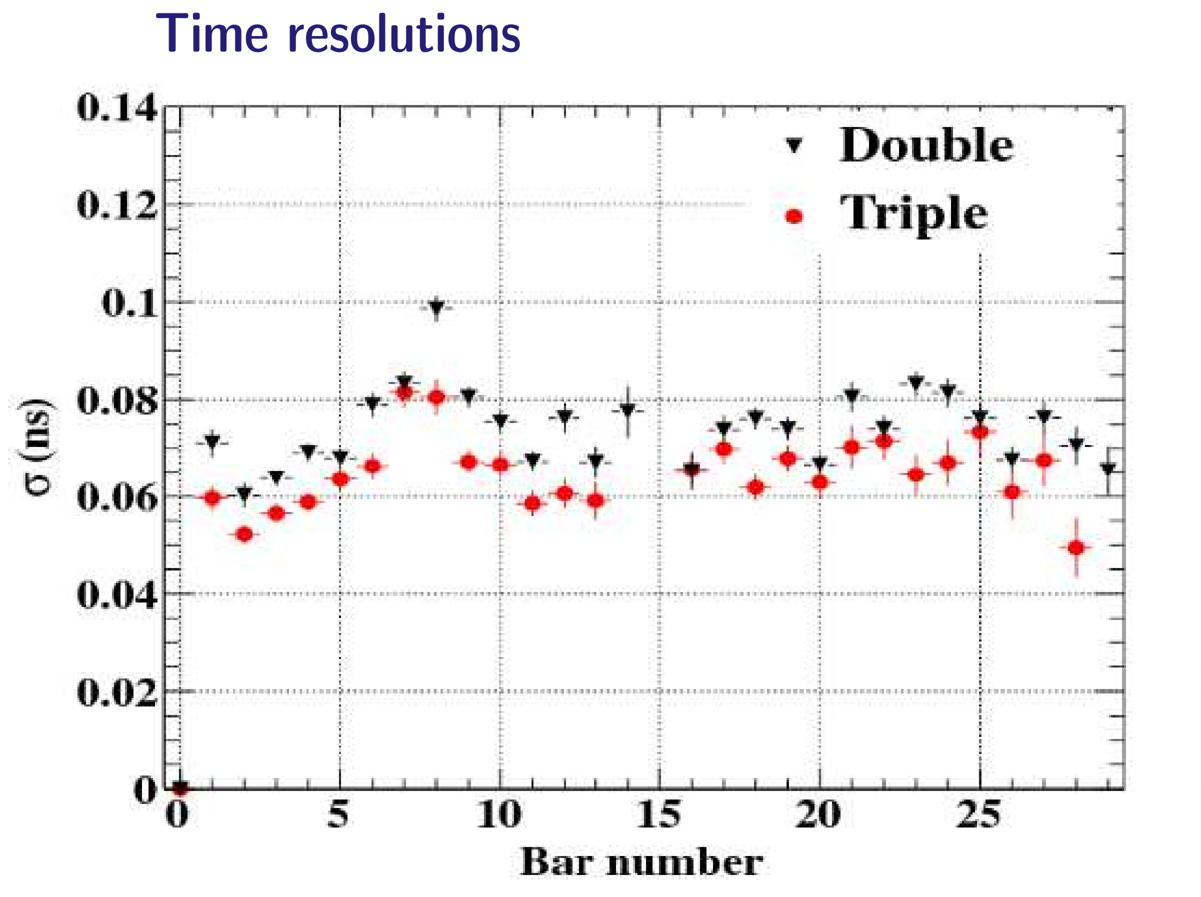
σ_φ **8.4mrad**(80%), 38mrad(20%) for φ=0

Timing counter

- 15×2(Upstream/Downstream) plastic scintillator bars ($4\times4\times80cm^3$)
  - Fine mesh PMTs at both ends, positron timing measurement
  - Positron φ, z position reconstruction using charge-ratio (online) or time-difference (offline).

Resolution
Efficiency





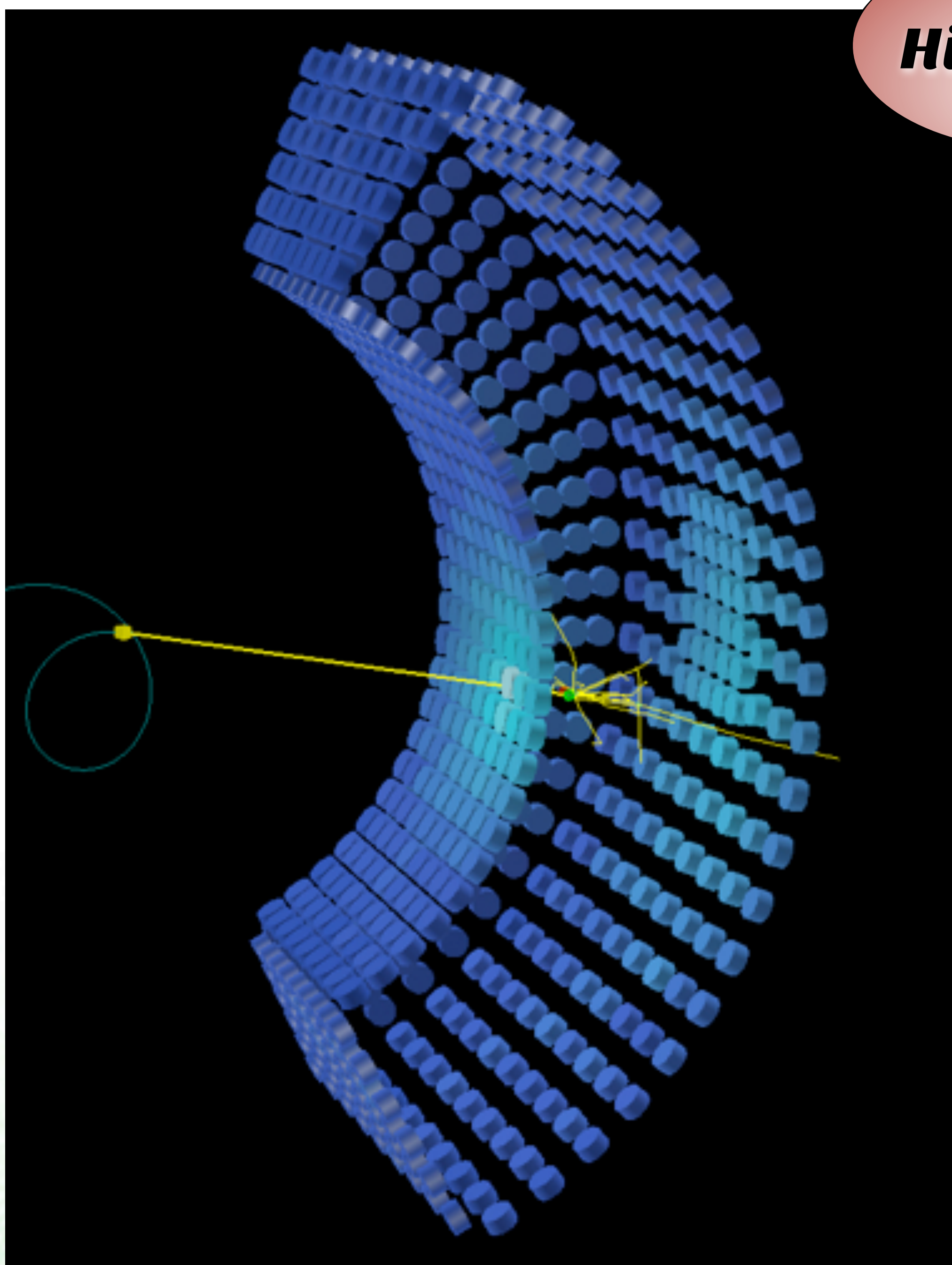
Timing resolution of TC : 65 psec

2.7t Liquid xenon gamma-ray detector

- γ measurement with high resolutions and efficiency in a large acceptance
- Pileup elimination in offline analysis

Resolution
Efficiency

High rate



- 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 (175nm)
  - Gas/liquid purification

Calibration and monitoring

PMT

LED
Alpha source (5.5 MeV)

Energy

AmBe (4.4MeV)
Neutron capture (9MeV)
Li(p,γ)Be (17.6 MeV)
π0→γγ (55, 83 MeV)
Cosmic ray (160 MeV)

Time

B(p,γ) (4.4+11.7 MeV)
π0→e⁺eγ (55-83 MeV)
Muon radiative decay

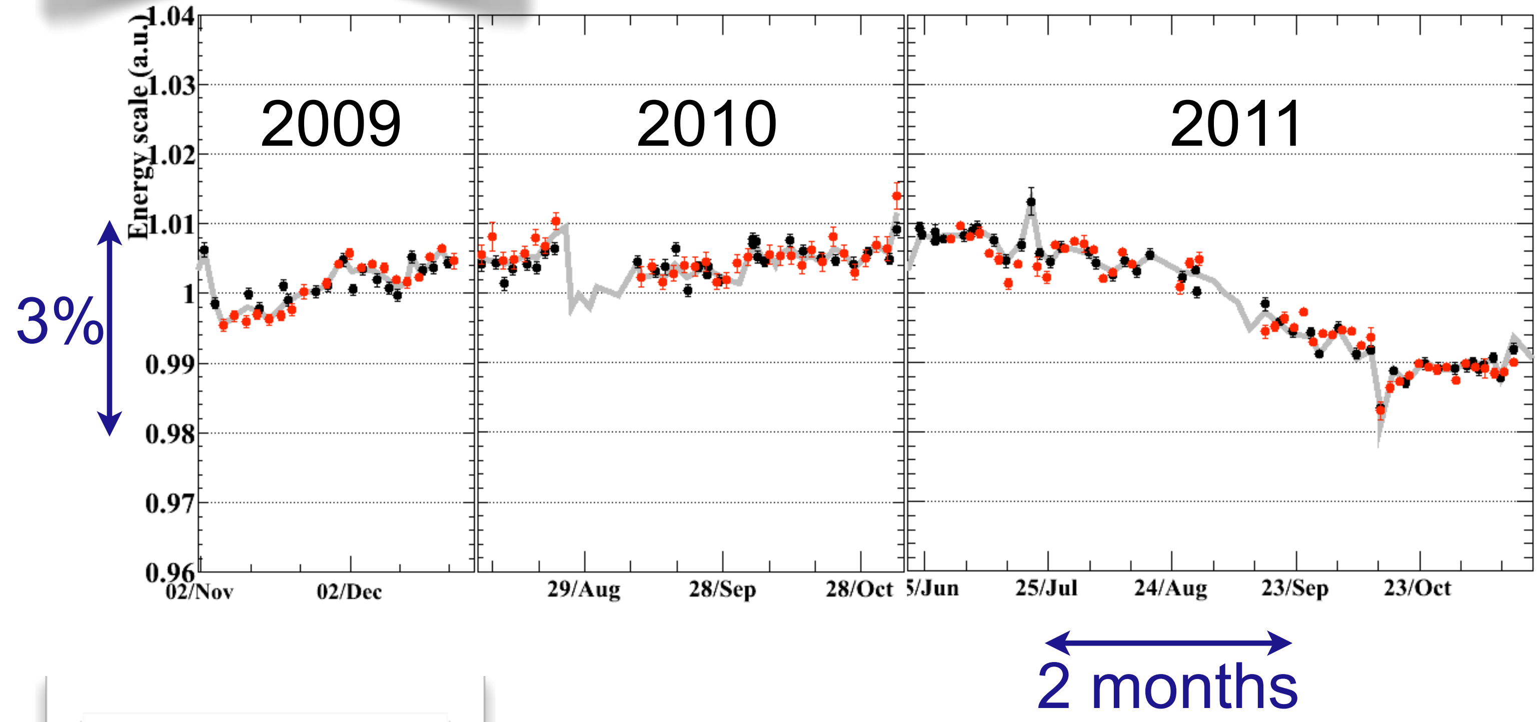
Process		Energy (MeV)	Frequency
Charge exchange	$\pi^- p \to \pi^0 n$	54.9, 82.9	yearly
	$\pi^0 \to \gamma\gamma$		
Charge exchange	$\pi^- p \to n\gamma$	129.0	yearly
Radiative μ^+ decay	$\mu^+ \to e^+\gamma\nu\nu$	52.83 endpoint	weekly
Proton accelerator	${}^7\mathrm{Li}(p, \gamma_{17.6(14.8)})^8\mathrm{Be}$	14.8, 17.6	weekly
	${}^{11}\mathrm{B}(p, \gamma_{4.4}\gamma_{11.6})^{12}\mathrm{C}$	4.4, 11.6	weekly
Nuclear reaction	${}^{58}\mathrm{Ni}(n, \gamma_{9.0})^{59}\mathrm{Ni}$	9.0	daily
AmBe source	${}^9\mathrm{Be}(\alpha_{^{241}\mathrm{Am}}, n)^{12}\mathrm{C}_*$	4.4	daily
	${}^{12}\mathrm{C}_* \to {}^{12}\mathrm{C}\gamma_{4.4}$		

Energy Scale Stability

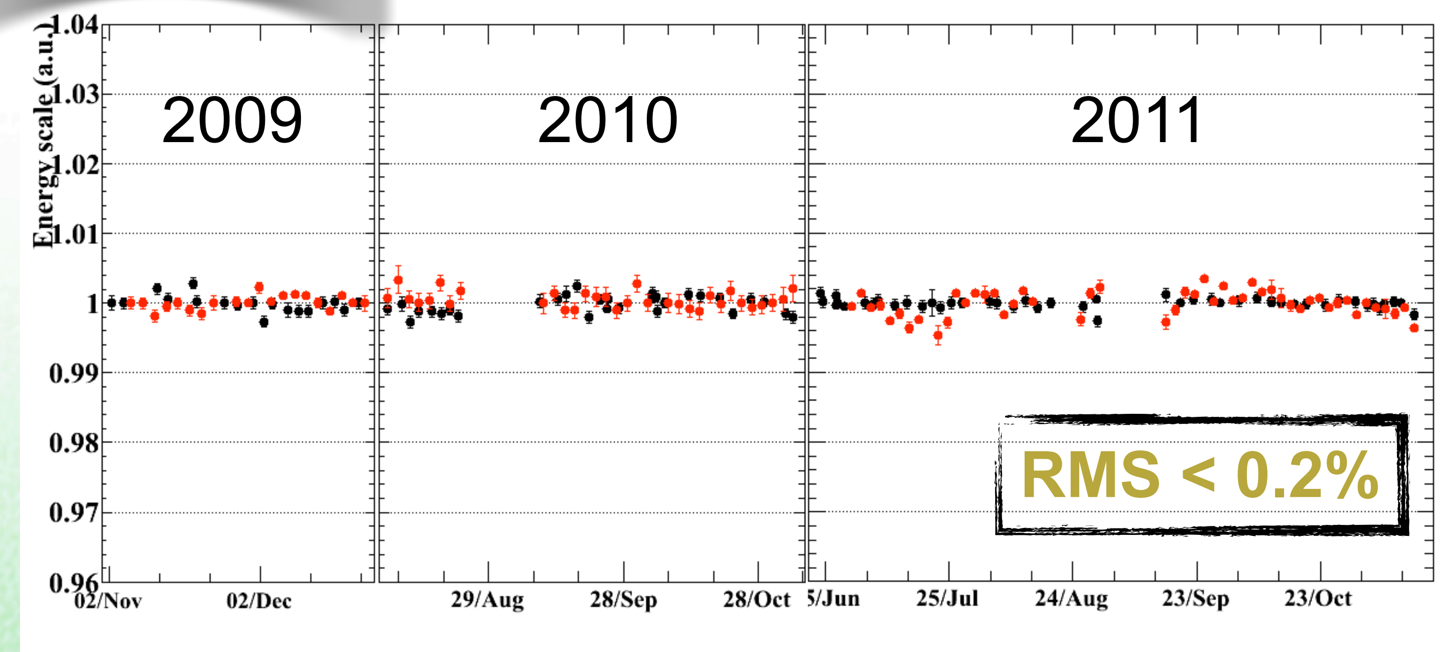
- Absolute scale calibration
  - 55 MeV CEX gamma
- Time variation corrected using
  - 17.6 MeV CW gamma
  - 9 MeV Ni-n gamma
  - 4.4 MeV AmBe gamma
  - Cosmic ray peak
- Checked using background gamma spectrum during physics run

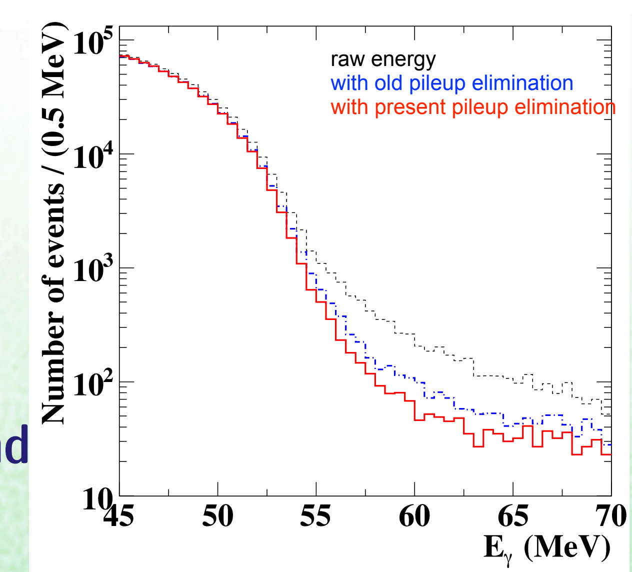
- ● CW data (used for correction)
- ● BG data (not used for correction)

Before correction



After correction



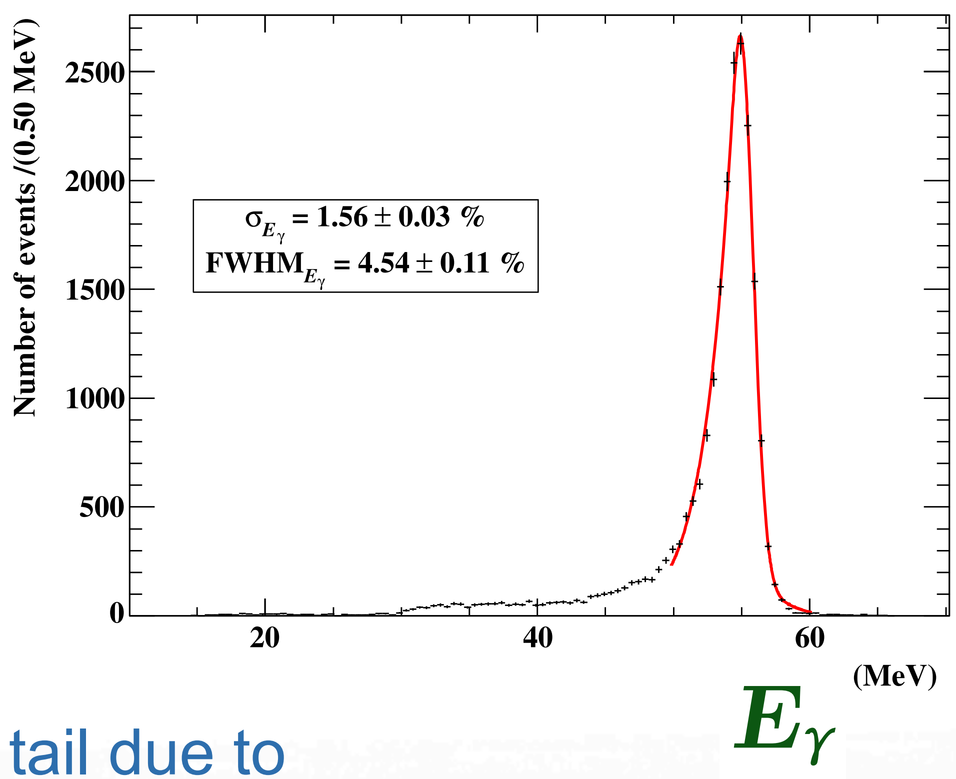


Background spectrum

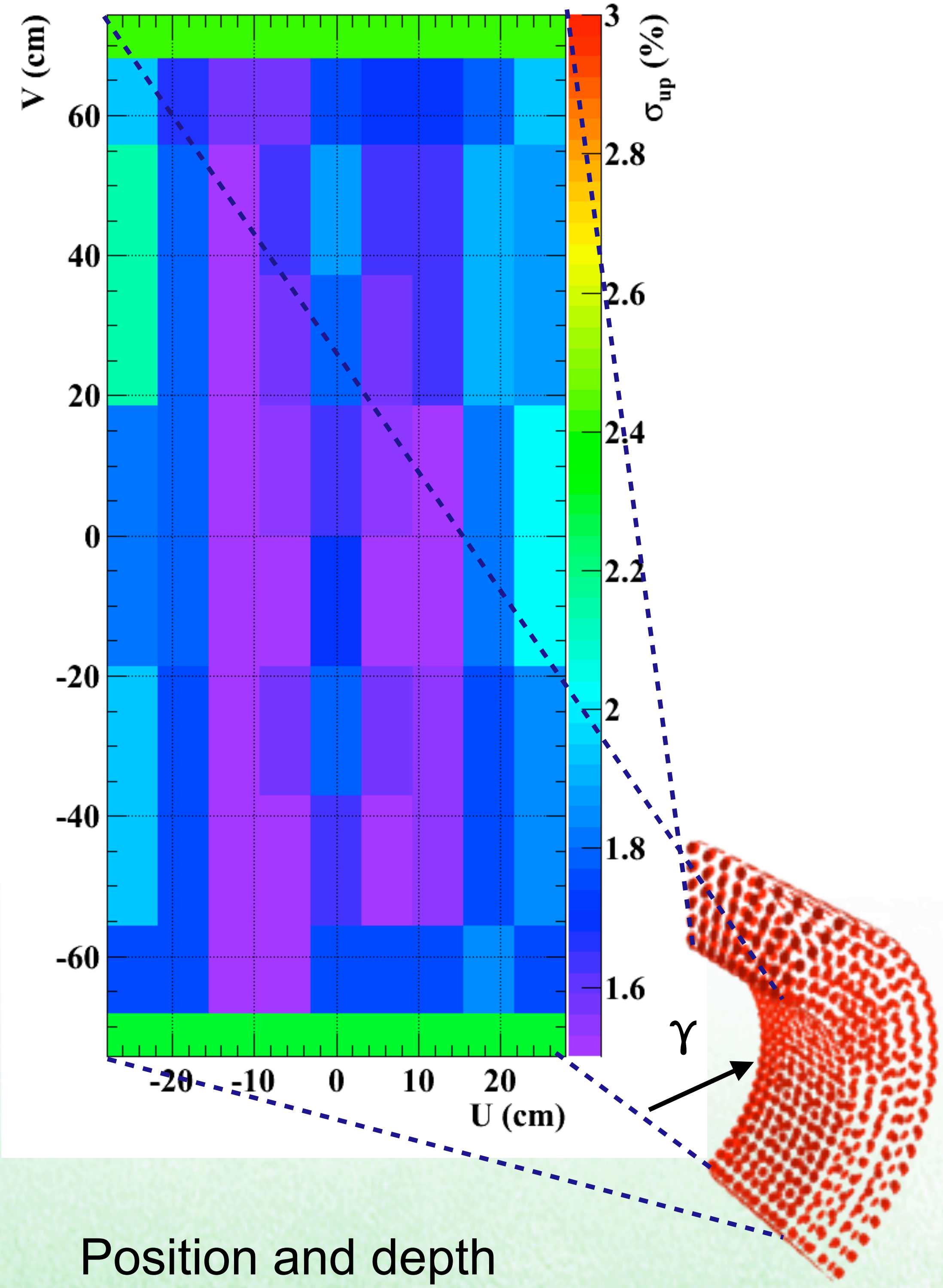
Energy resolution

Measured using 55 MeV CEX gamma rays

Typical 55 MeV CEX spectrum



Resolution map



Lower tail due to

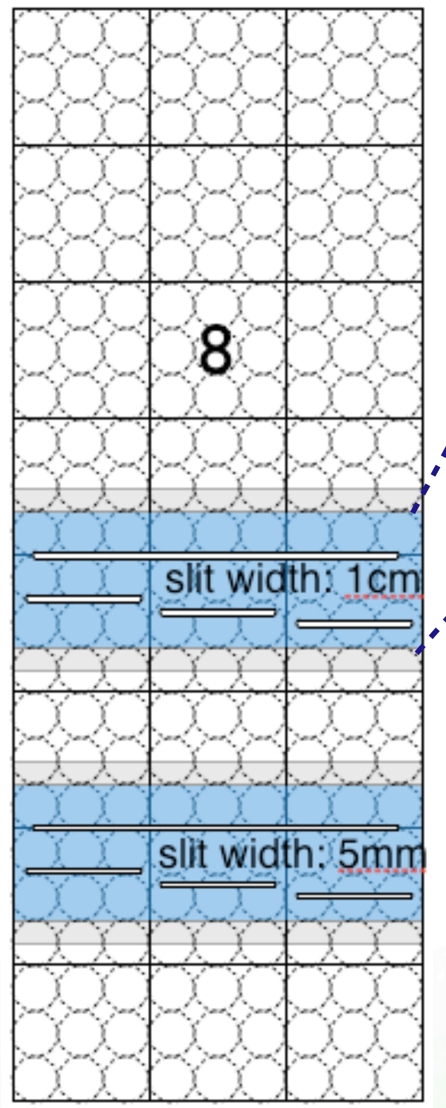
- Energy deposit in material before entering LXe (Magnet, cryostat, PMT holder etc.)
- Energy escape from LXe

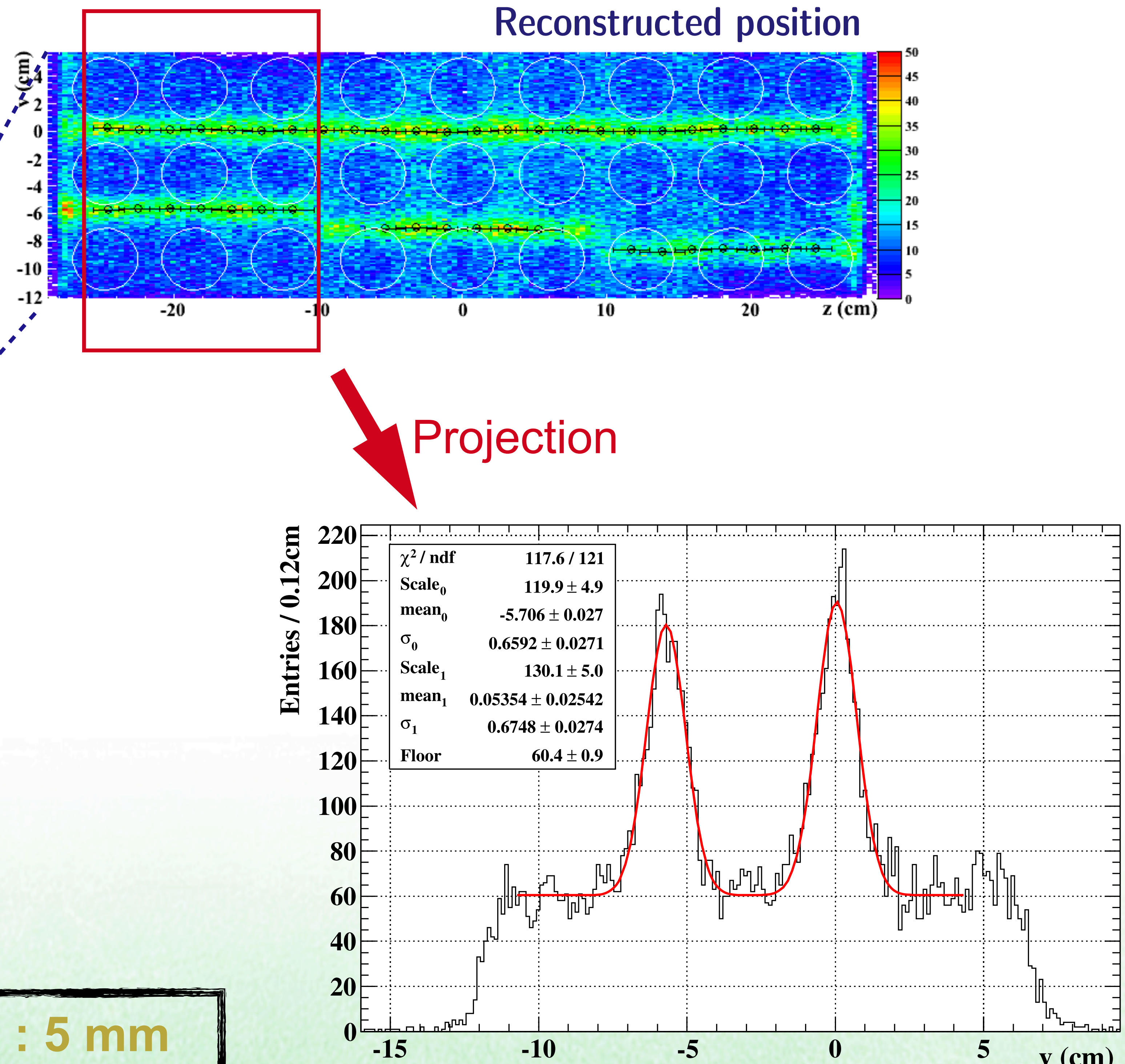
Average resolutions
1.7% (depth>2cm), 2.4% (depth<2cm)

Position and depth dependences are measured

Position resolution

Measured using lead collimators with CEX data



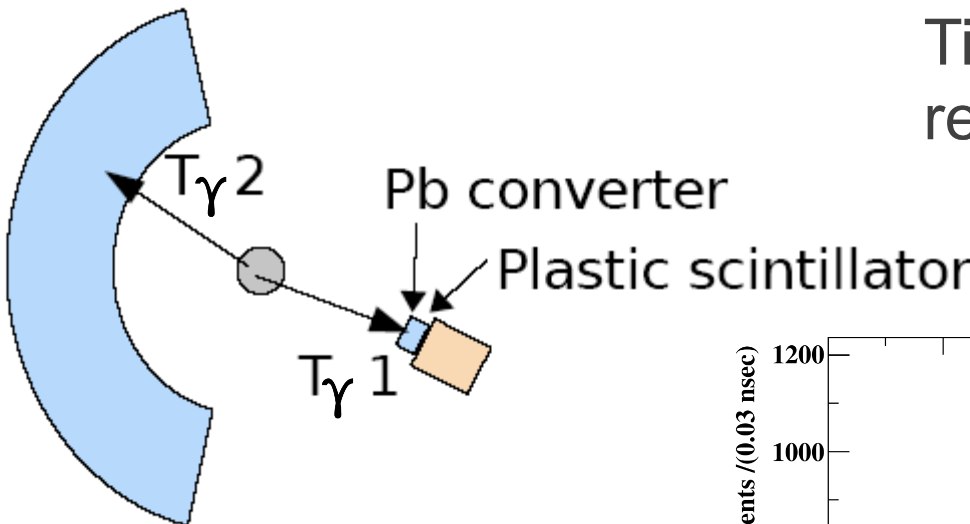


Position resolution : 5 mm

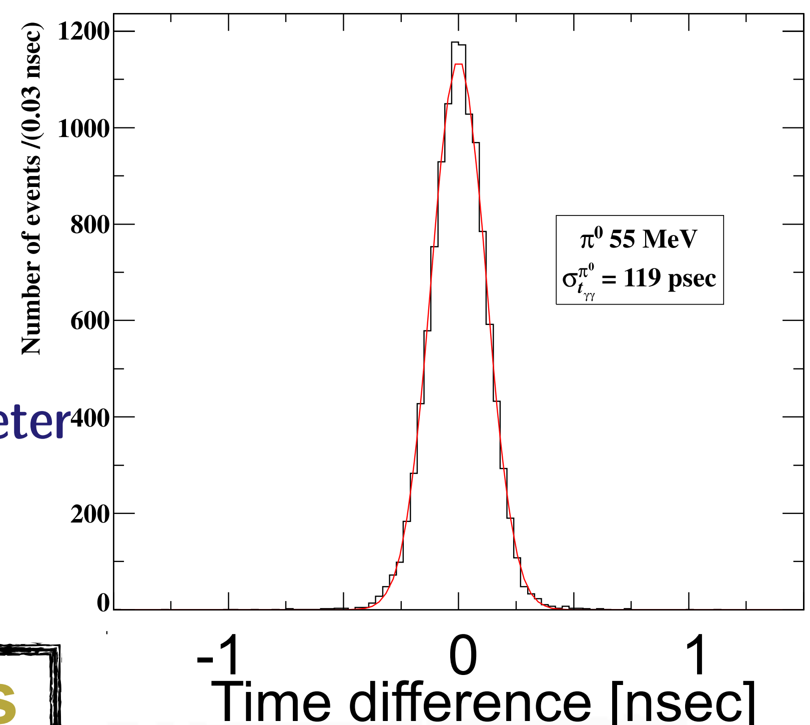
Width is compared with MC

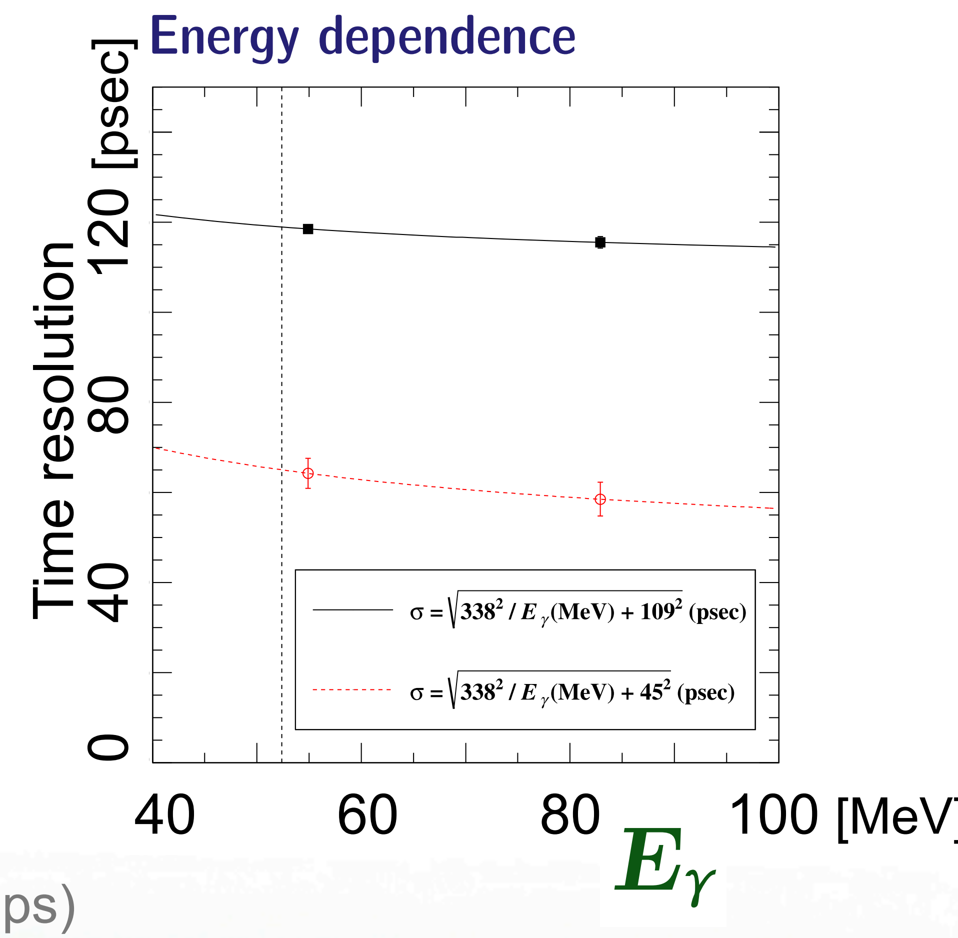
Timing resolution

Time difference between LXe calorimeter and a reference counter in CEX data



Time difference between calorimeter and pre-shower





Time resolution : 67 ps

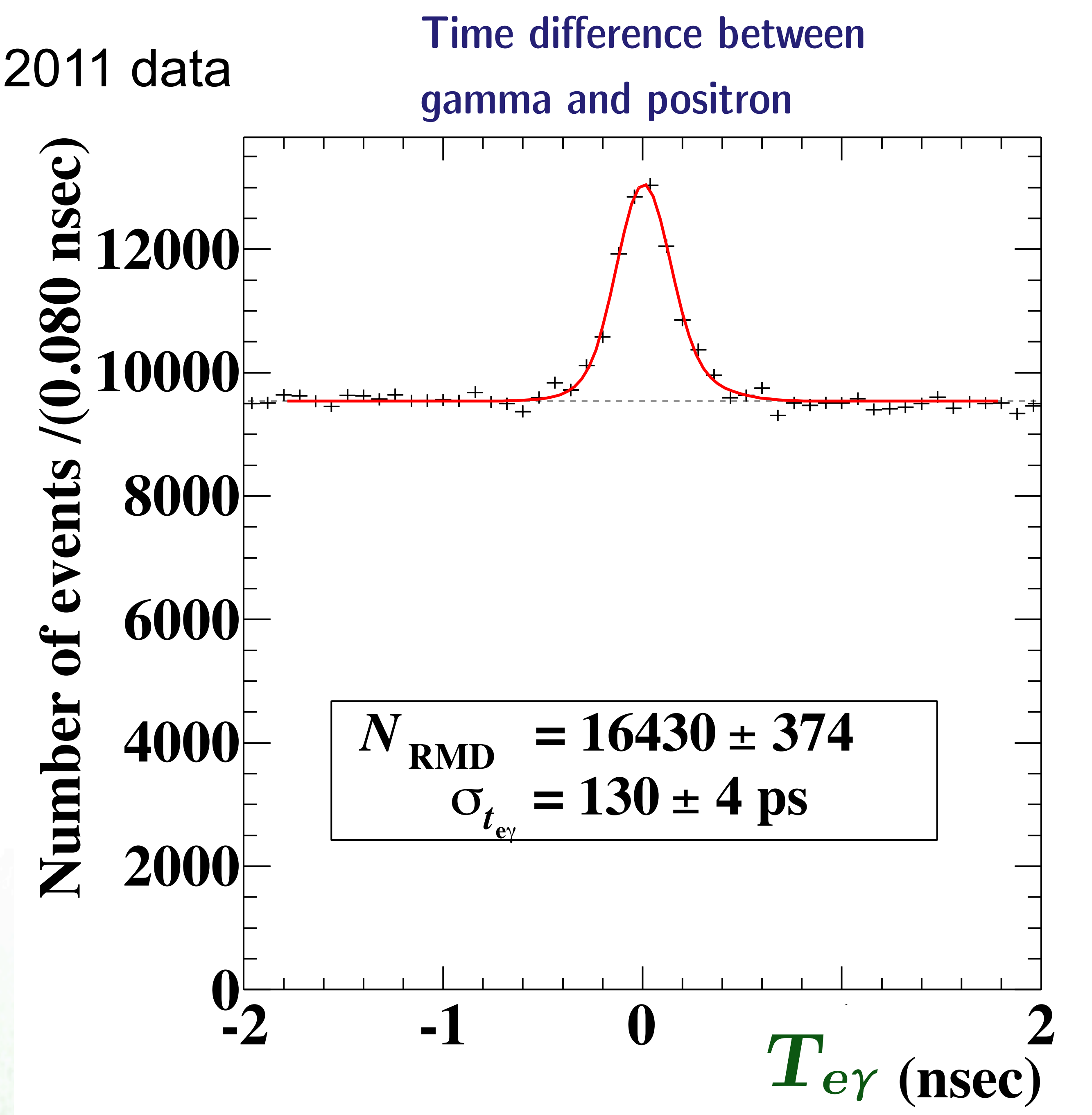
= 119ps - beam spread(58ps) - resolution of reference counter(81ps)

Breakdown

Intrinsic	36 ps
ToF (depth)	20 ps
Electronics	24 ps
Position resolution and shower fluctuation	46 ps

Positron - photon timing

2011 data



- Radiative muon decay peak
  - In normal physics run
  - Corrected by small energy dependence

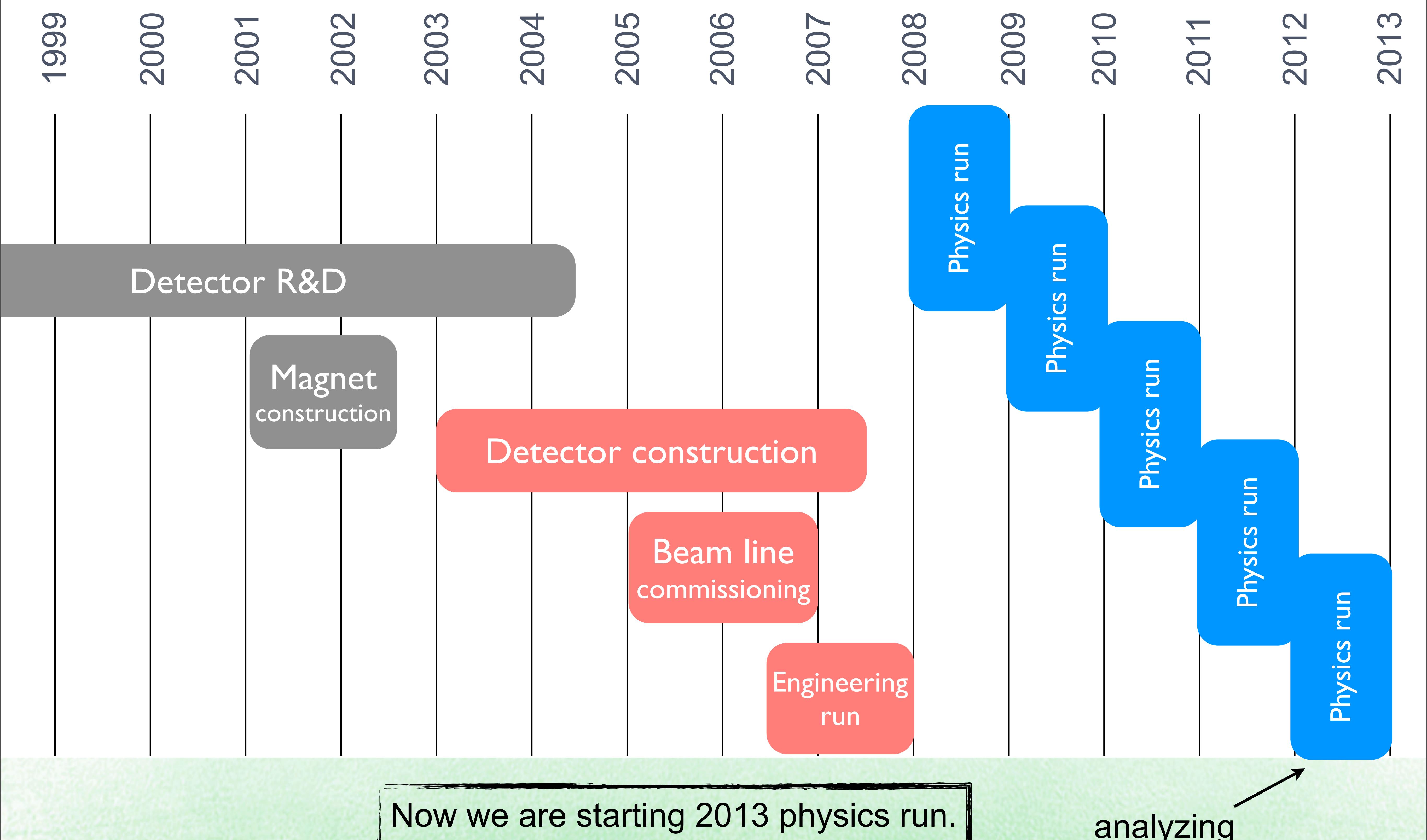
Timing resolution for signal is 122 ps

taking into account the energy dependence

Time Line

Previous publication (Phys. Rev. Lett. 107, 171801)

New publication

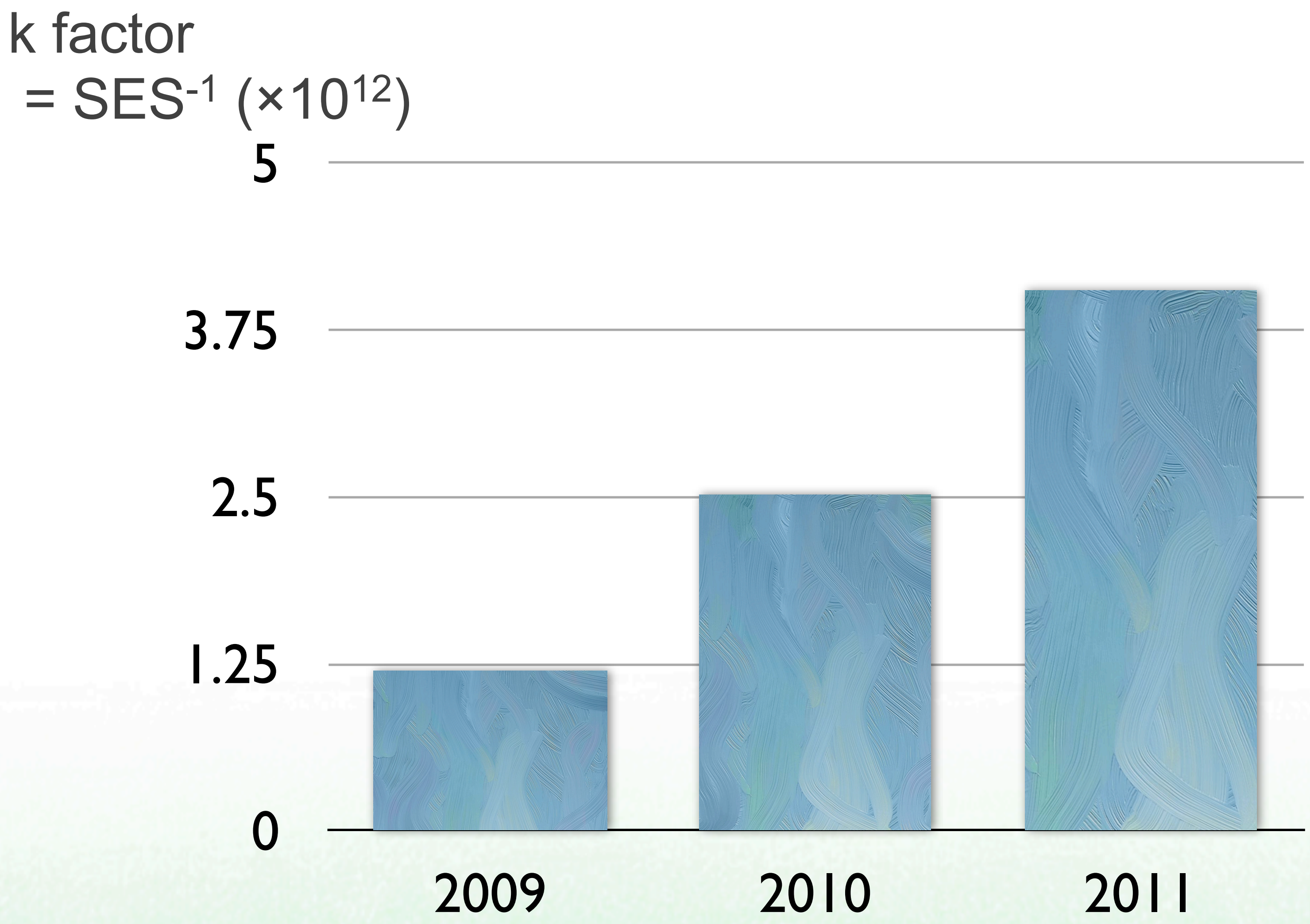


Now we are starting 2013 physics run.

New result from Run2009-2011

Data statistics

DAQ efficiency 87%→96% in 2011



Improvements for the new result

New

- 2011 data
  - Doubled the statistics
  - Hardware modifications
    - NaI detector used for calorimeter calibration run was replaced with BGO
    - Laser tracker system for target and drift chamber initial alignment
- Improvements of analysis, applied for 2009-2011 data
  - Reconstruction improvements (next slide)
  - Physics analysis
    - per-event PDF for e^+

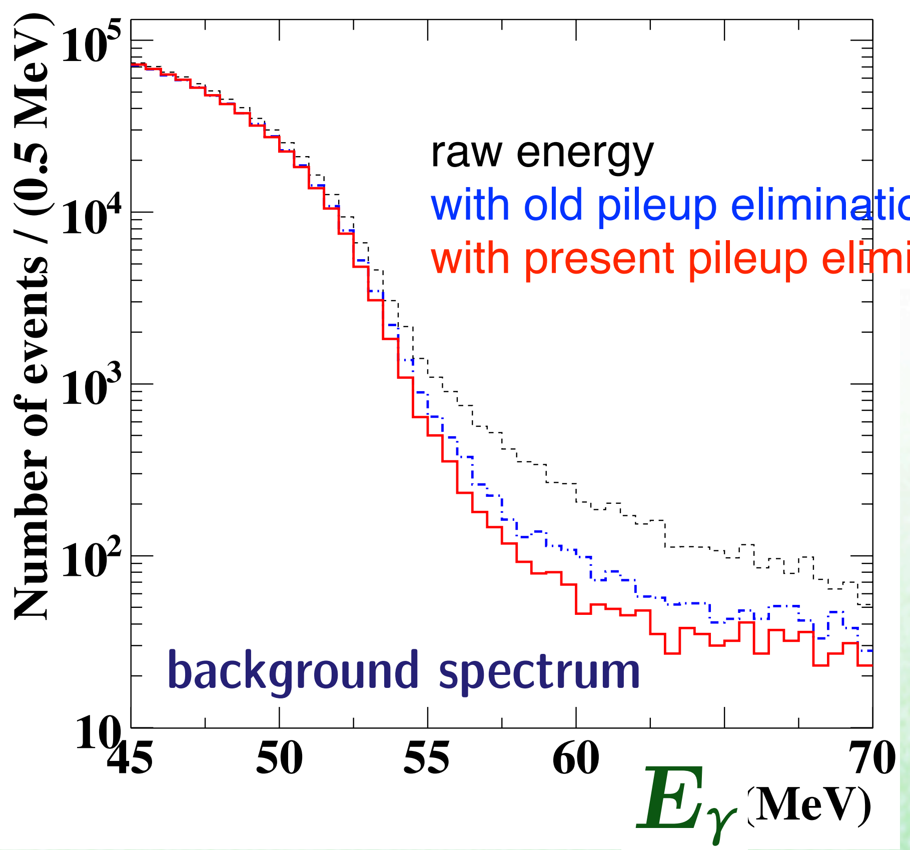
Reconstruction improvements

New

γ

Improved pileup unfolding using waveform

- **7%** higher signal efficiency
- Reduced tail component



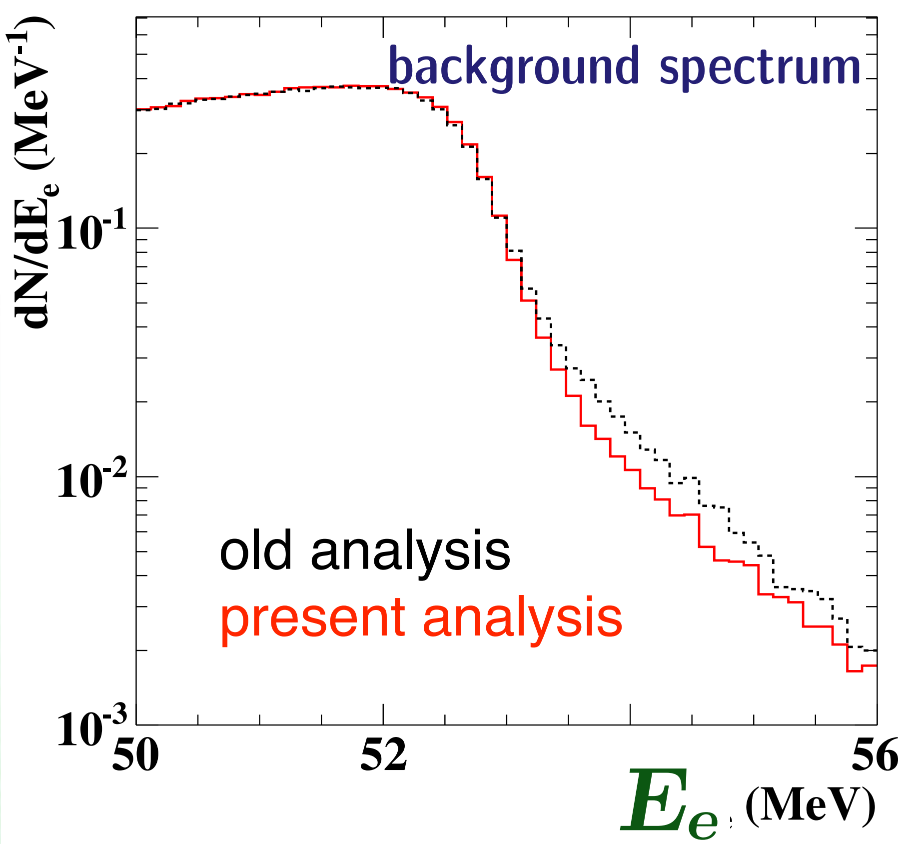
e+

FFT based offline noise reduction

- **6%** higher signal efficiency
- Angular resolution improved a few percent

Revised track-fitter

- **7%** higher efficiency
- Reduced tail component

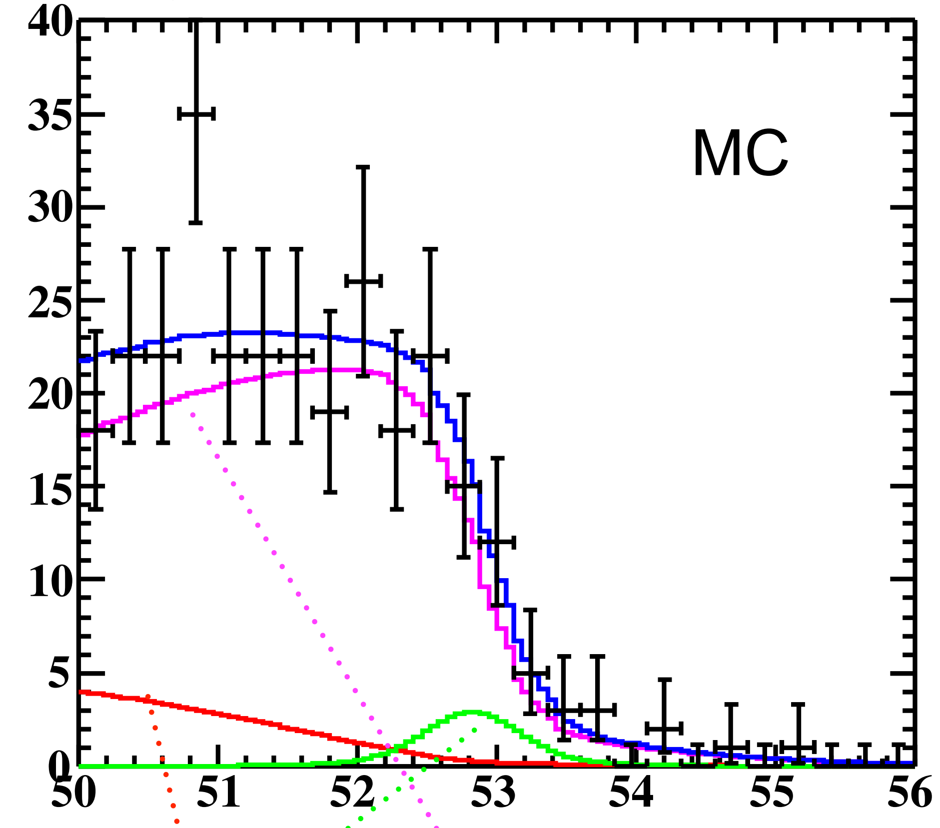


Analysis method

Likelihood fitting with 5 observables

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

Projection to E_e



Unbinned likelihood fitting

I will explain later...

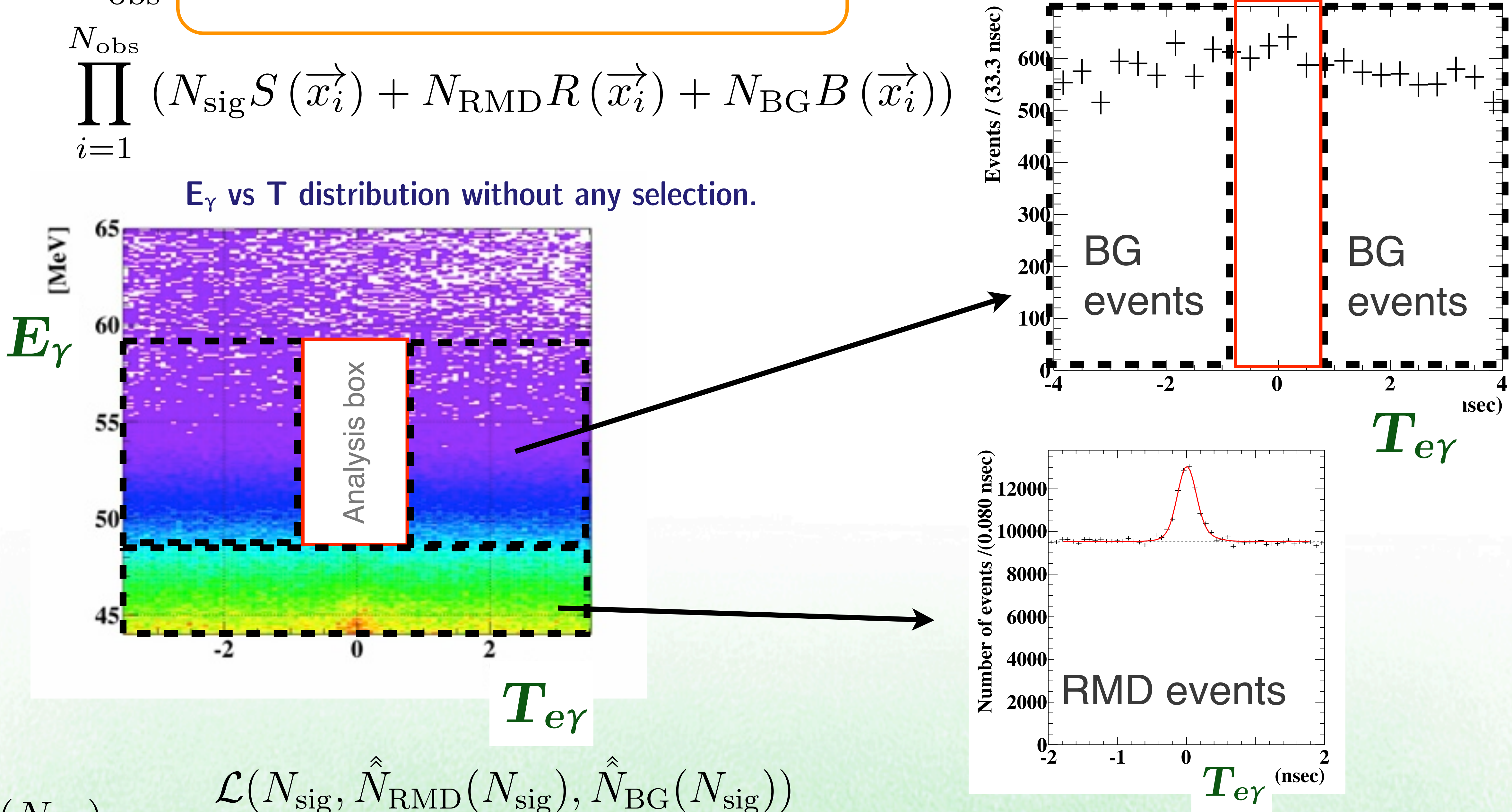
$$\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}) = f(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}) \times \prod_{i=1}^{N_{\rm obs}} \left(N_{\rm sig} S(\vec{x}_i) + N_{\rm RMD} R(\vec{x}_i) + N_{\rm BG} B(\vec{x}_i)\right)$$

BG : Accidental
RMD : Radiative muon decay

Likelihood and test-statistic

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

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

New

Per-event e+ PDF

Resolutions :

$$\sigma_x = s_x \times \sigma'_x$$

fitting error

Scaling factors extracted from
1) Michel spectrum : Momentum
2) 2-turn method : Angular & Vertex

Correlations : between observables

$$d\mu_y = p_{xy} \times dx$$

$$p_{xy} = p'_{xy} \times \frac{\sigma'_y}{\sigma'_x}$$

Correlation parameters extracted from data and MC

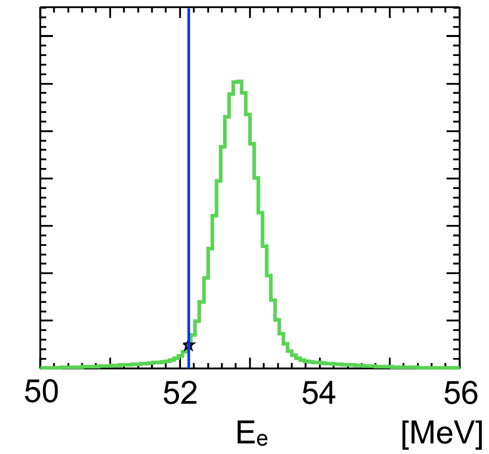
Sensitivity improved by **10%**

Examples

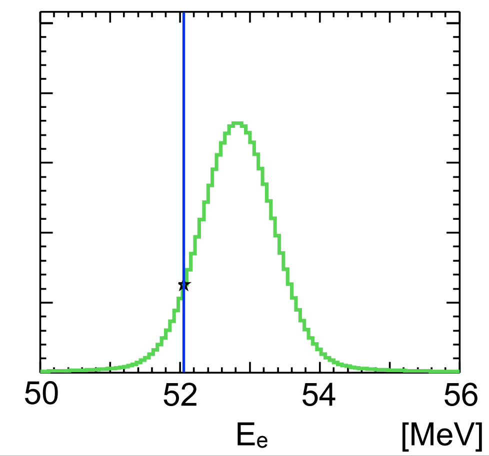
Signal PDF
Data

E_e

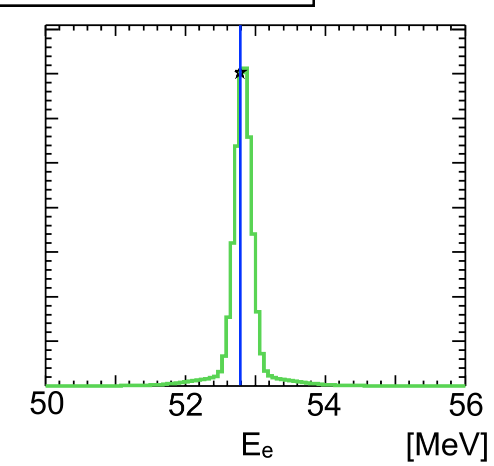
Typical event



Low quality event (a few hits)



2-turn event (many hits)



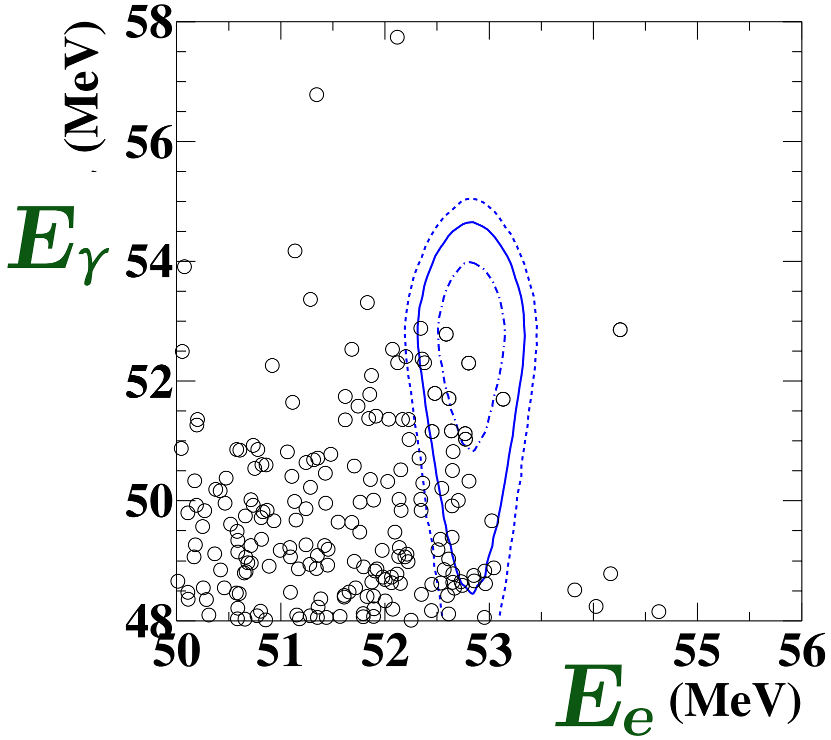
Time side-bands

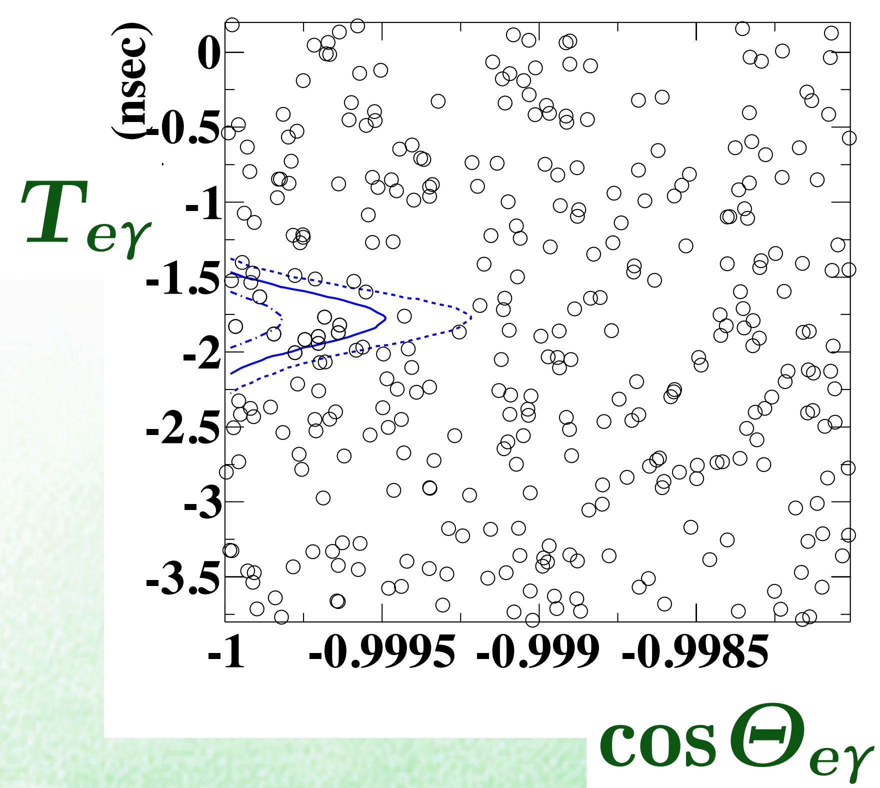
contour : signal PDF (39.3, 74.2, 86.5 %)

2009-2011 data

$T_{e\gamma}$ negative sideband

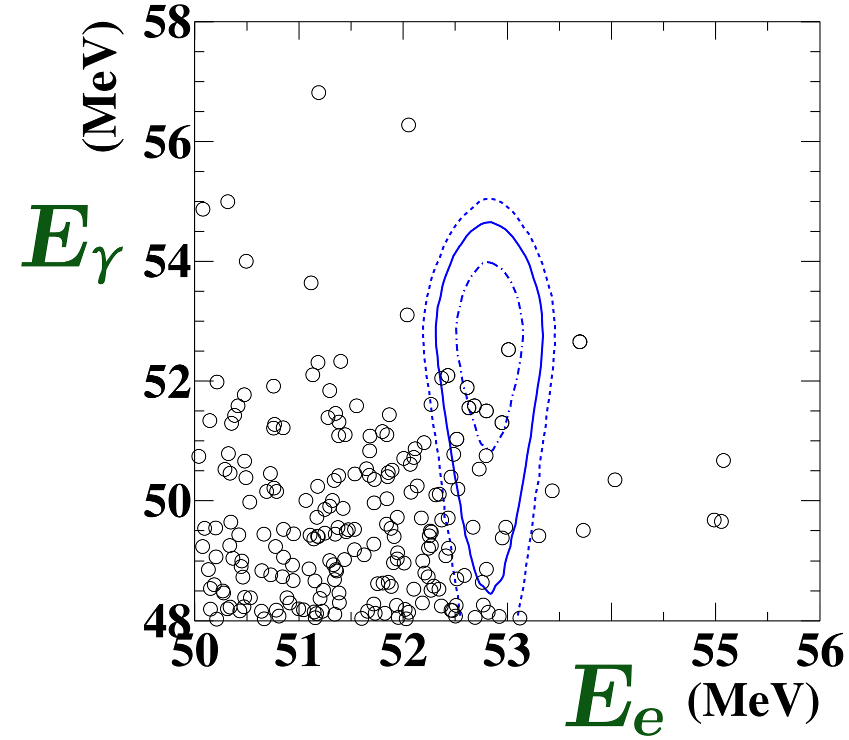
$\mathcal{B} < 1.6\times10^{-12}$

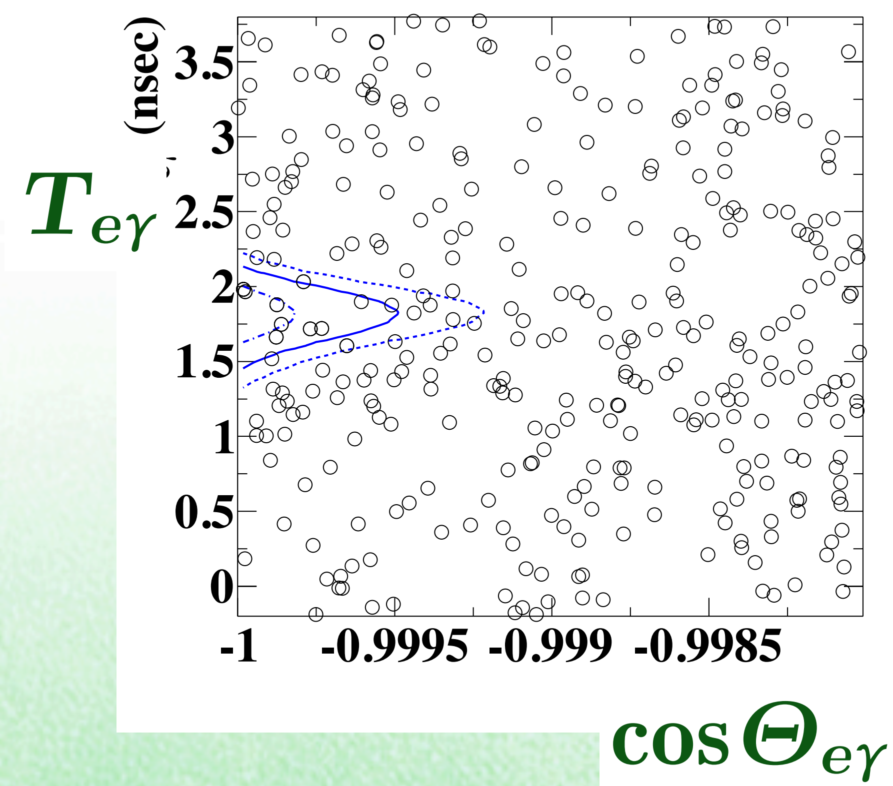




$T_{e\gamma}$ positive sideband

$\mathcal{B} < 8.1\times10^{-13}$

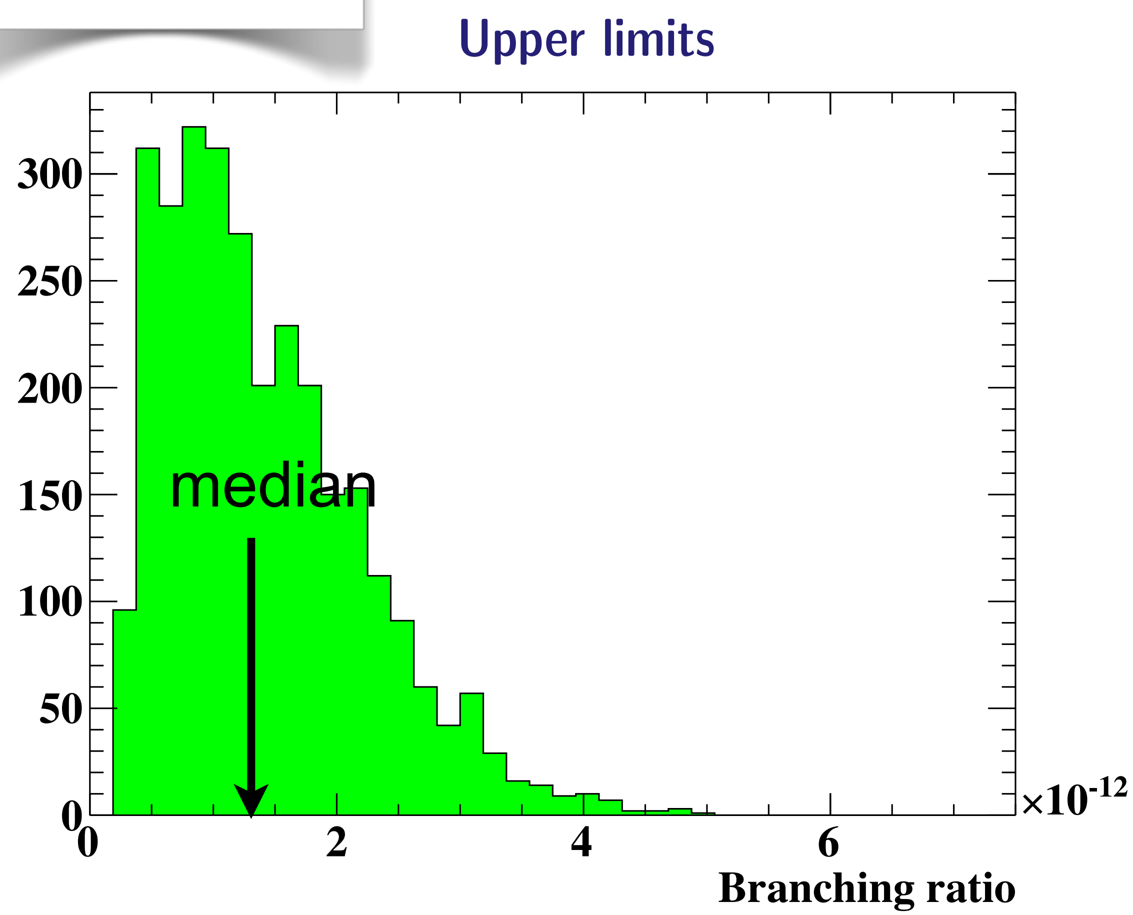




Sensitivity

Median upper limit of pseudo-experiments (MC) with background-only hypothesis

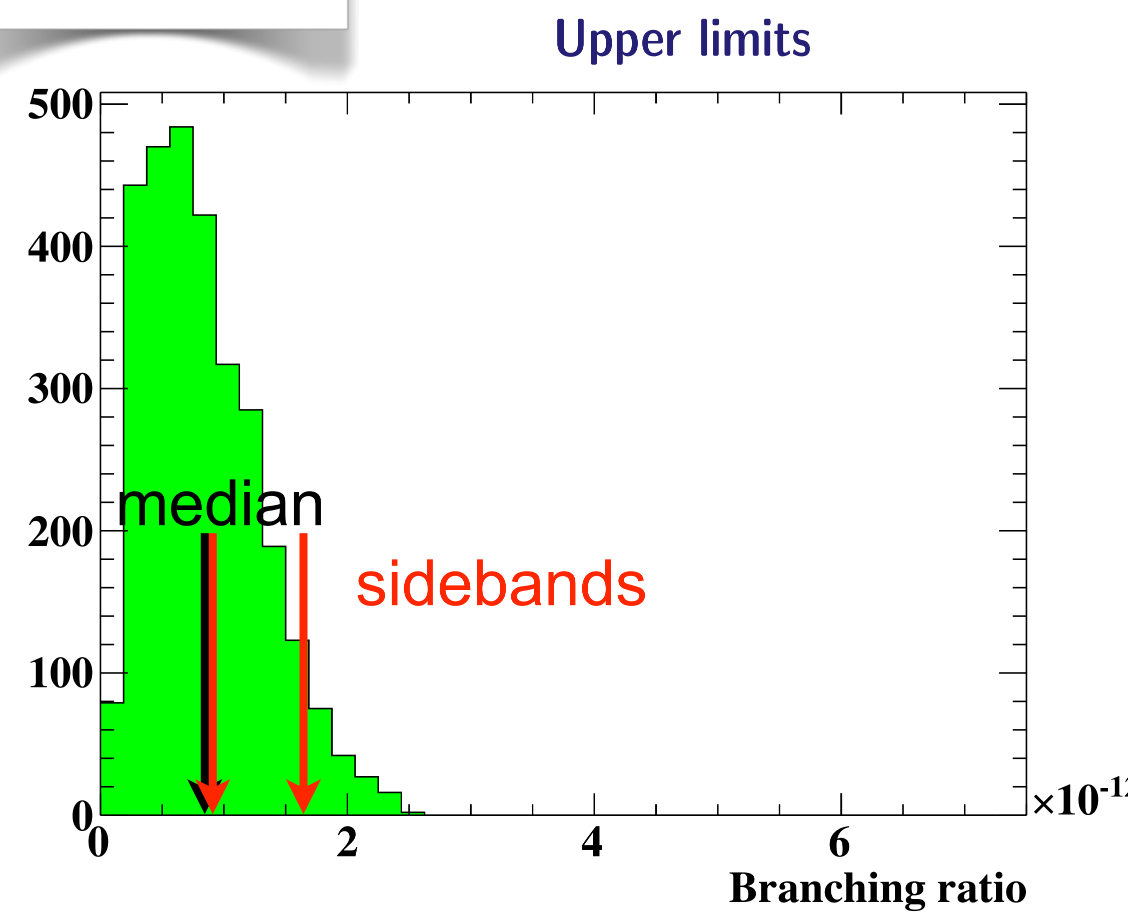
2009-2010



median = **1.3×10^{-12}**

c.f. 1.6×10^{-12} in previous publication (**20% improvement**)

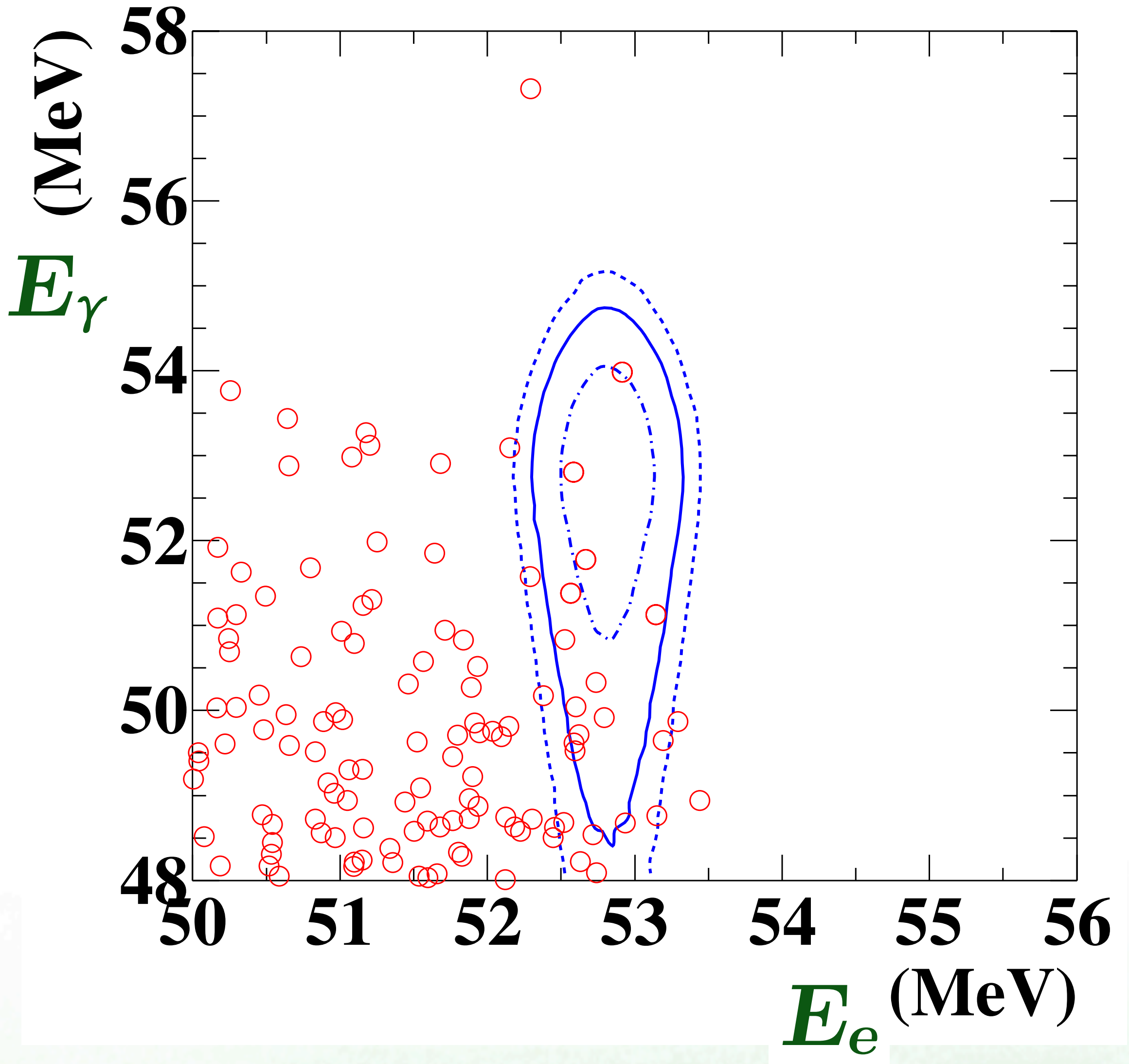
2009-2011

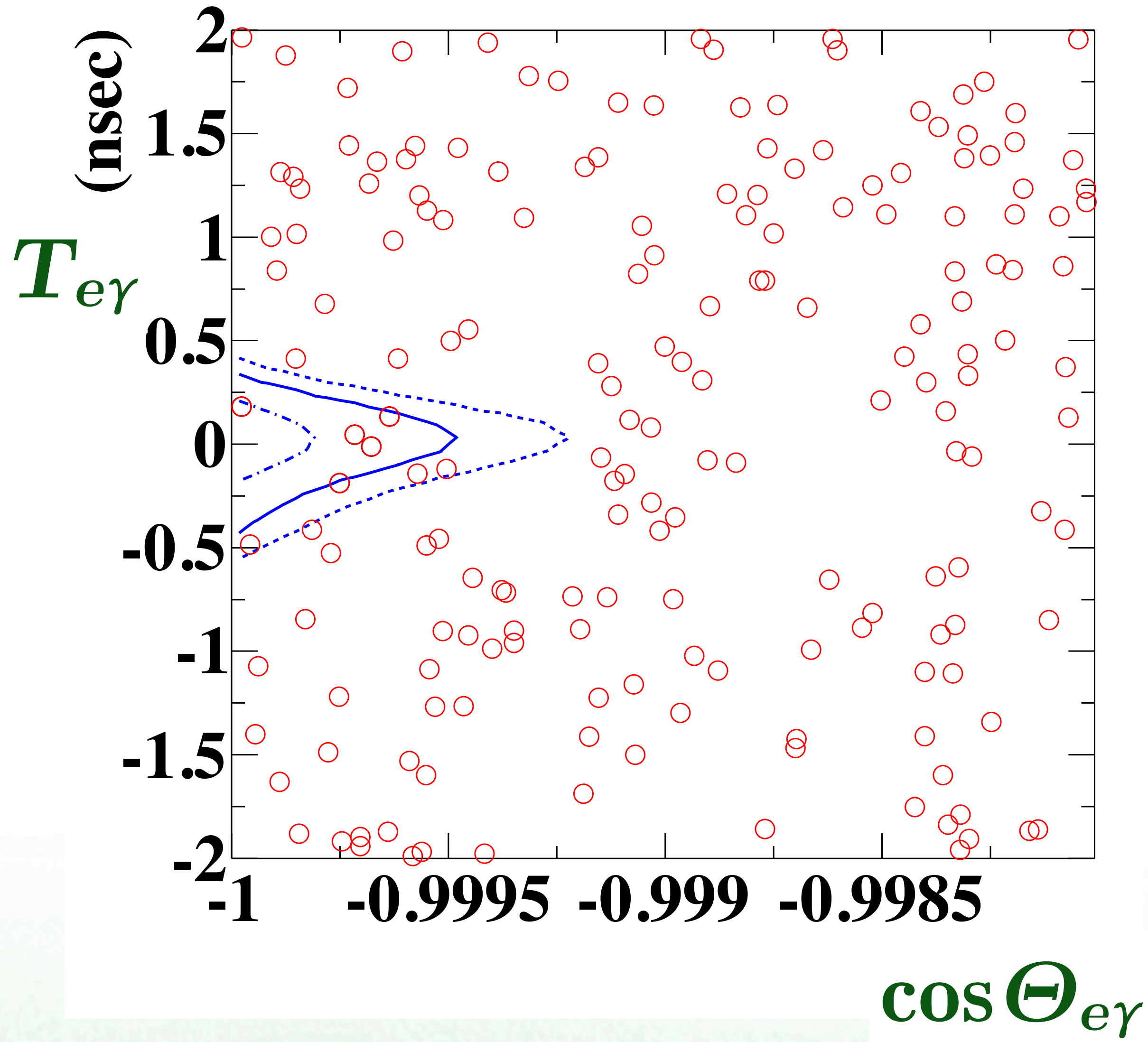


median = **7.7×10^{-13}**

First $\mu \to e\gamma$ search with O(10^{-13}) sensitivity

2009+2010 data





No excess: N_{signal} best fit is $0.3^{+4.1}_{-1.5}$

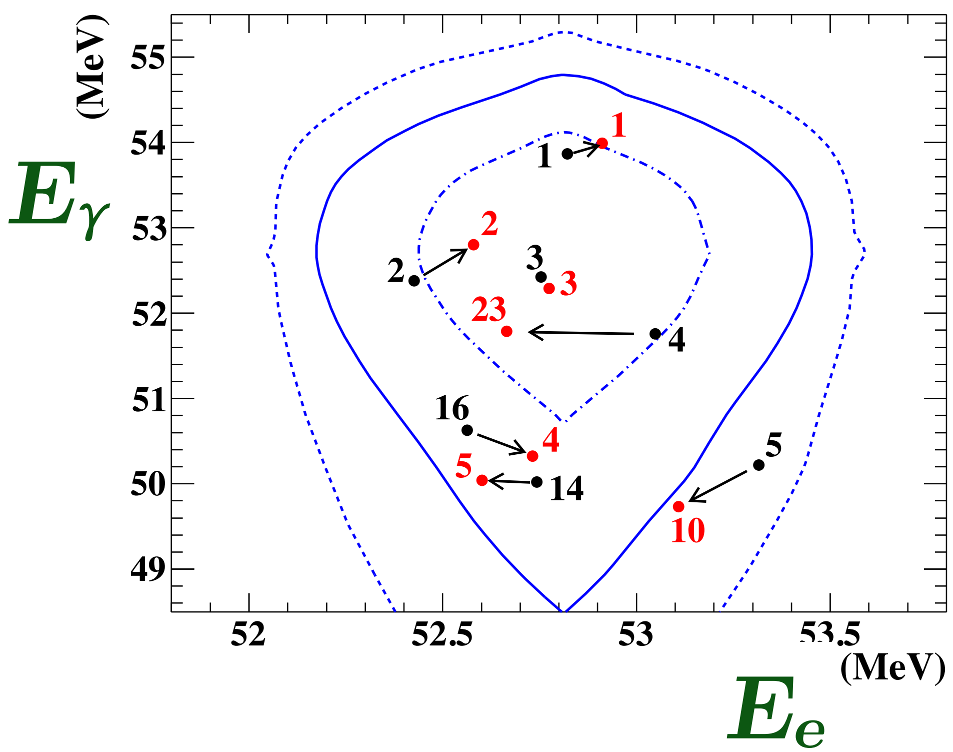
contour : signal PDF (39.3, 74.2, 86.5 %)

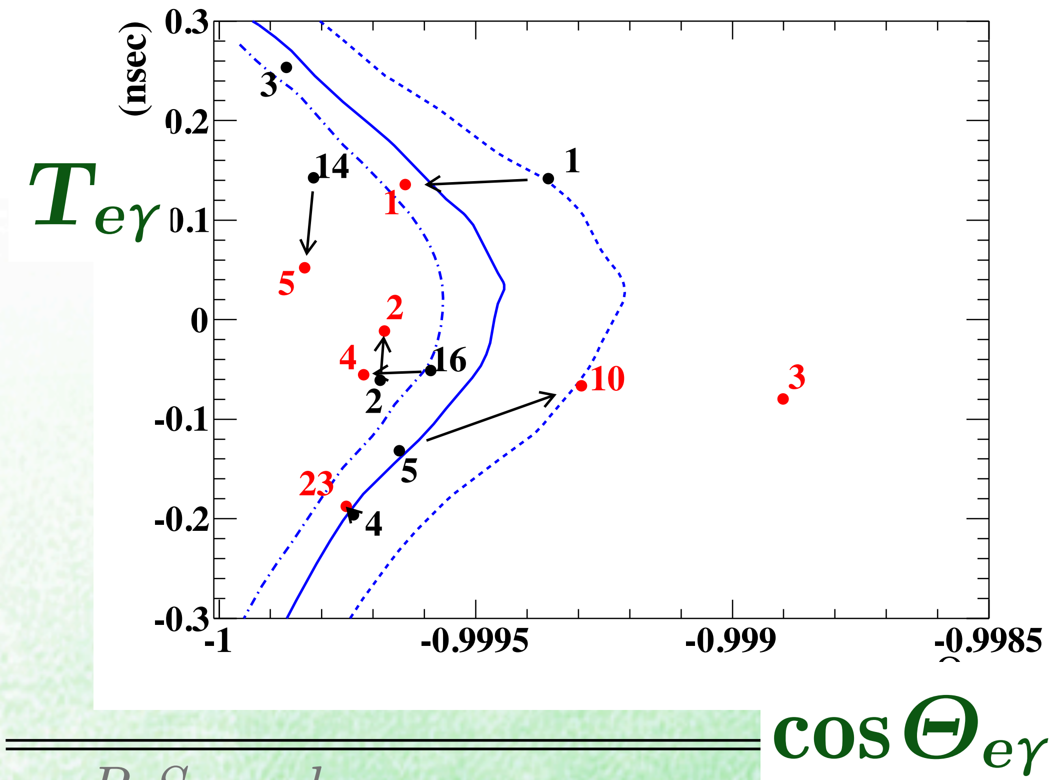
errors : MINOS 1.645σ

Comparison with previous analysis

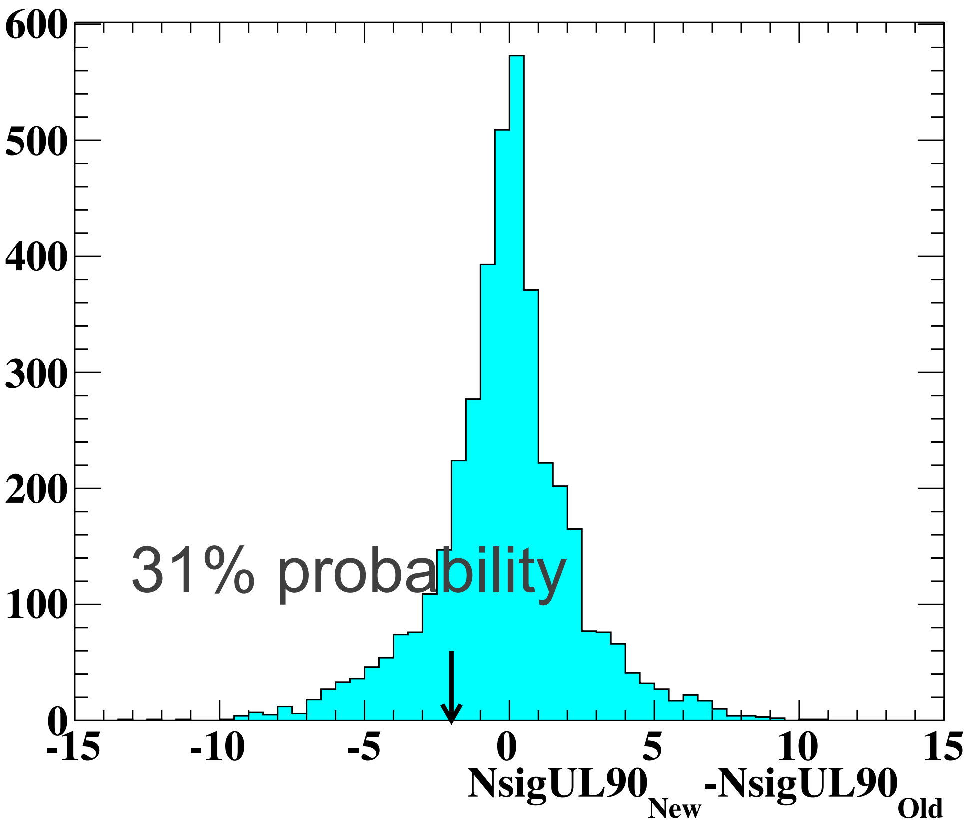
- Previous analysis
- New analysis

Numbers : rank in each dataset



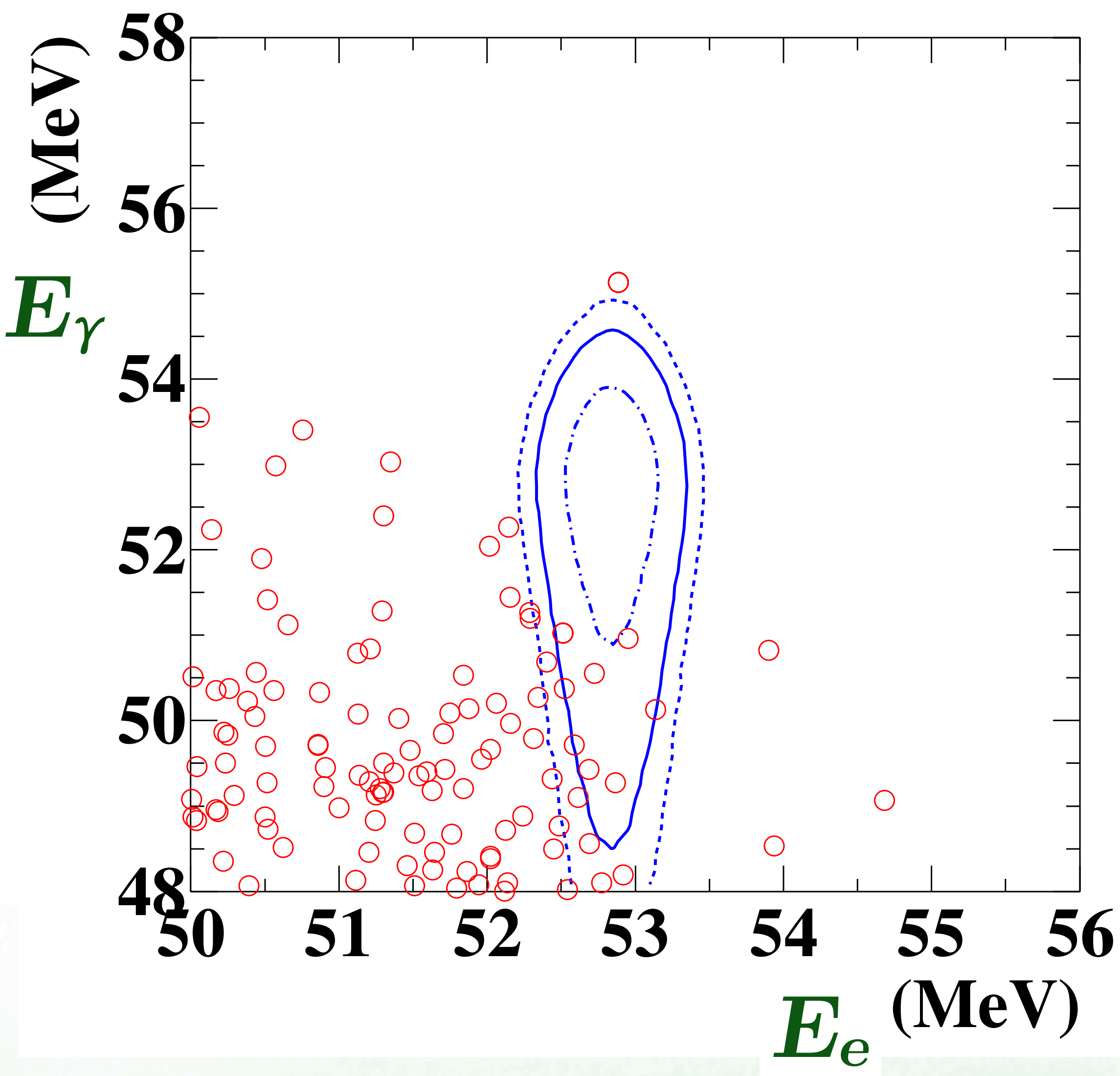


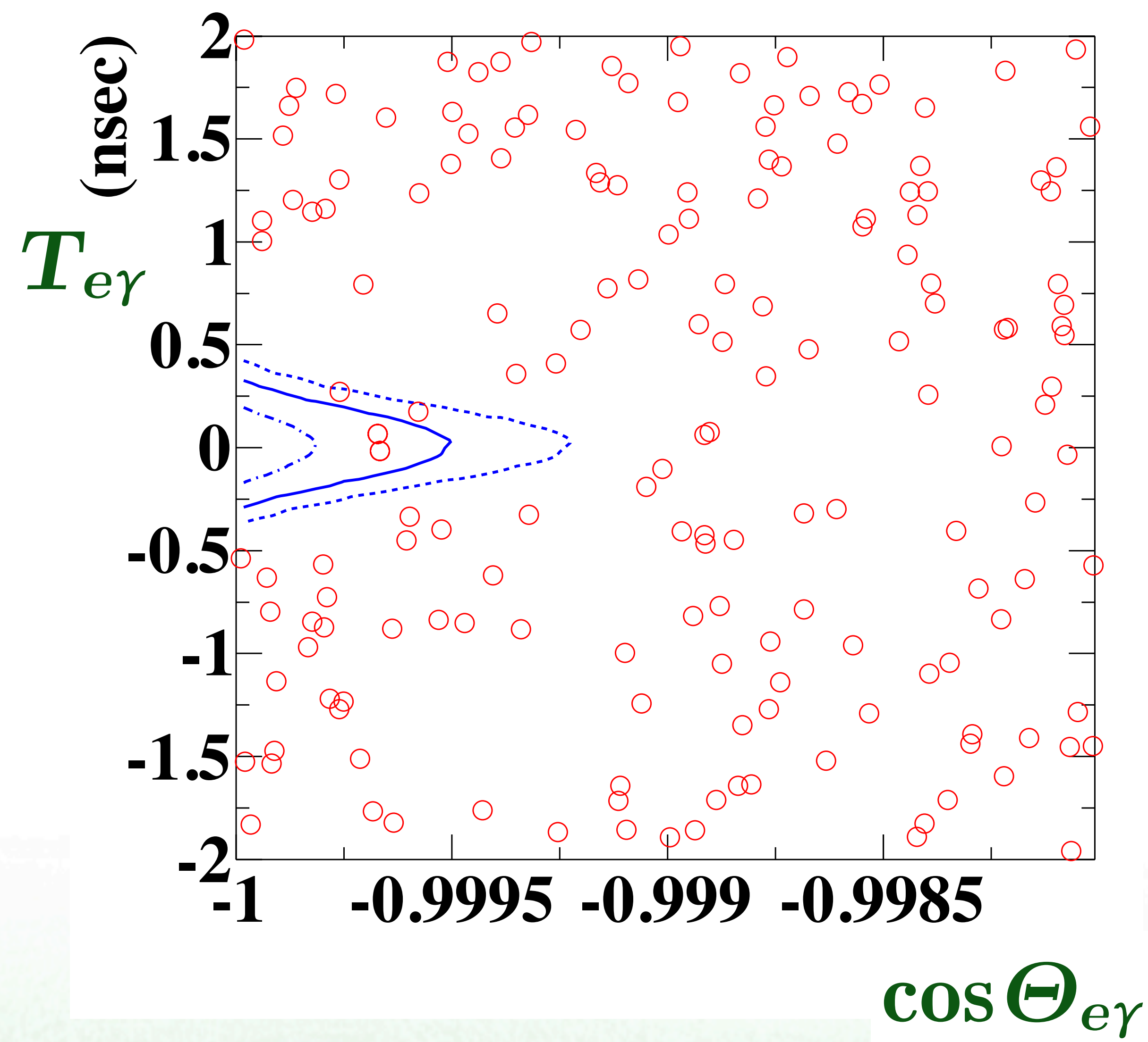
Change of UL by modifications of reconstruction algorithms. (MC)



- High ranked events are stable
- Differences of observables by modifications of reconstruction algorithms are smaller than resolutions.

2011 data



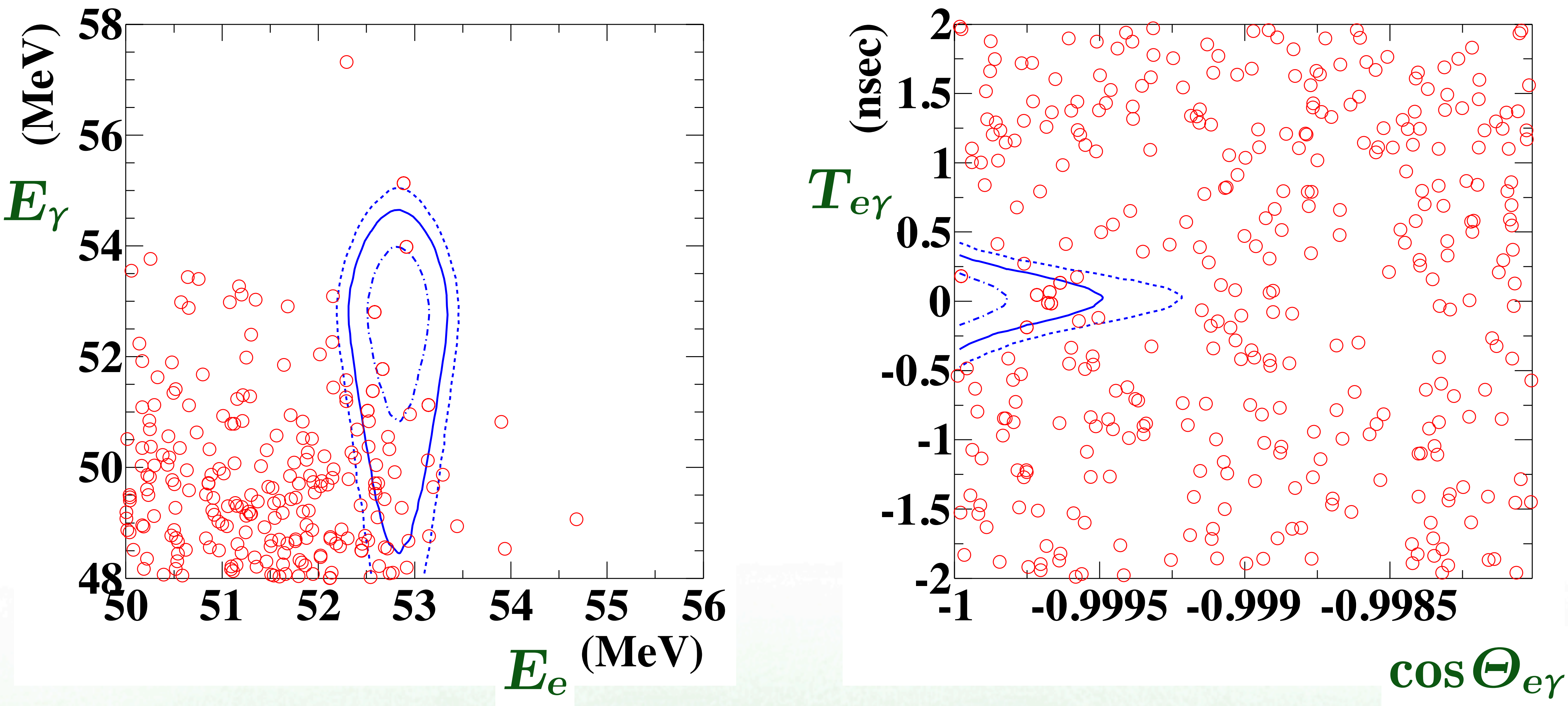


No excess: N_{signal} best fit is $-1.4^{+3.8}_{-1.3}$ (slight negative fluctuation)

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

errors : MINOS 1.645σ

2009-2011 data



No excess: N_{signal} best fit is $-0.4^{+4.8}_{-1.9}$

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

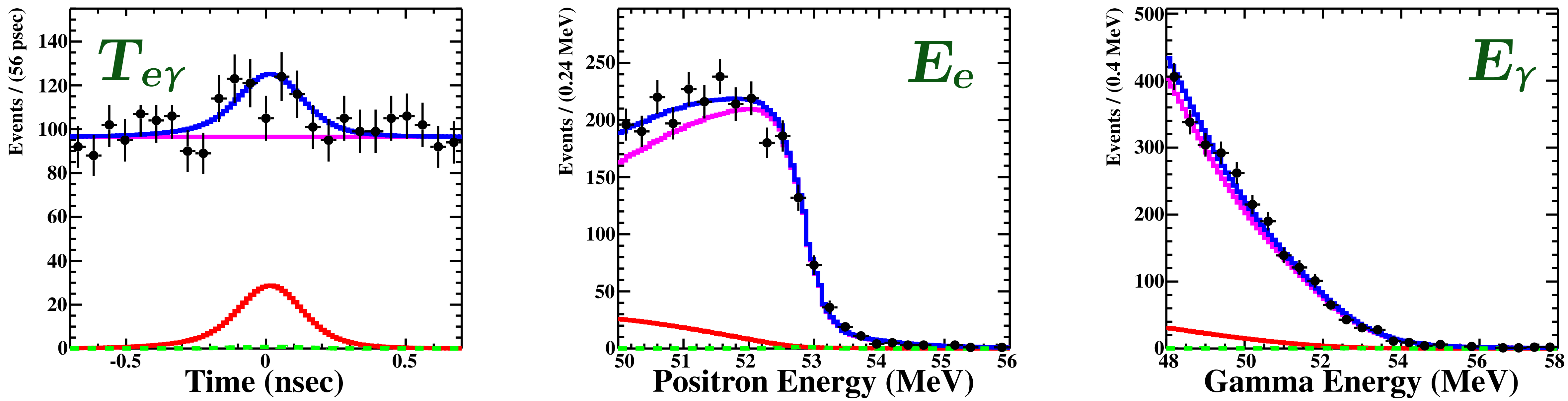
errors : MINOS 1.645σ

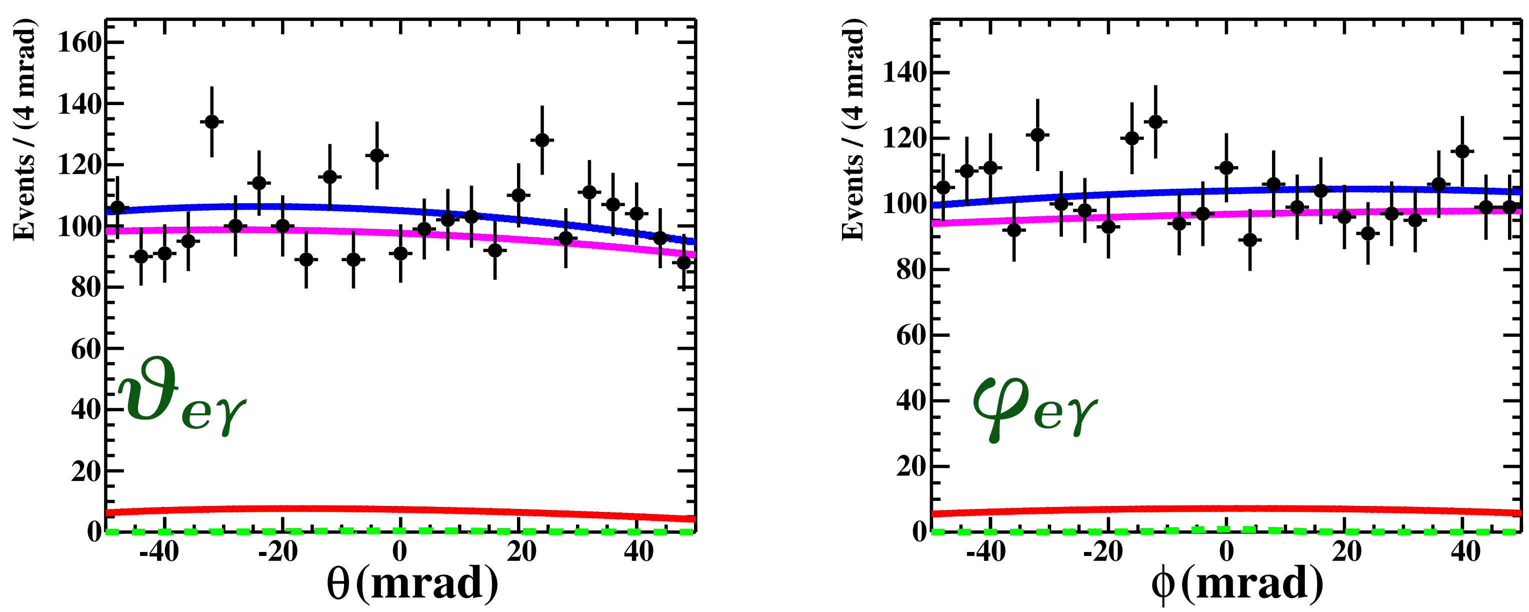
2009-2011 Fit Result

Signal
RMD
BG
Total

dotted line : 90% UL

Unbinned likelihood fitting on 5 dimension observable data





$N_{sig} = -0.4^{+4.8}_{-1.9}$

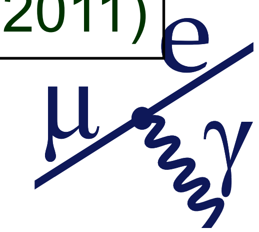
$N_{acc} = 2413.6 \pm 37$

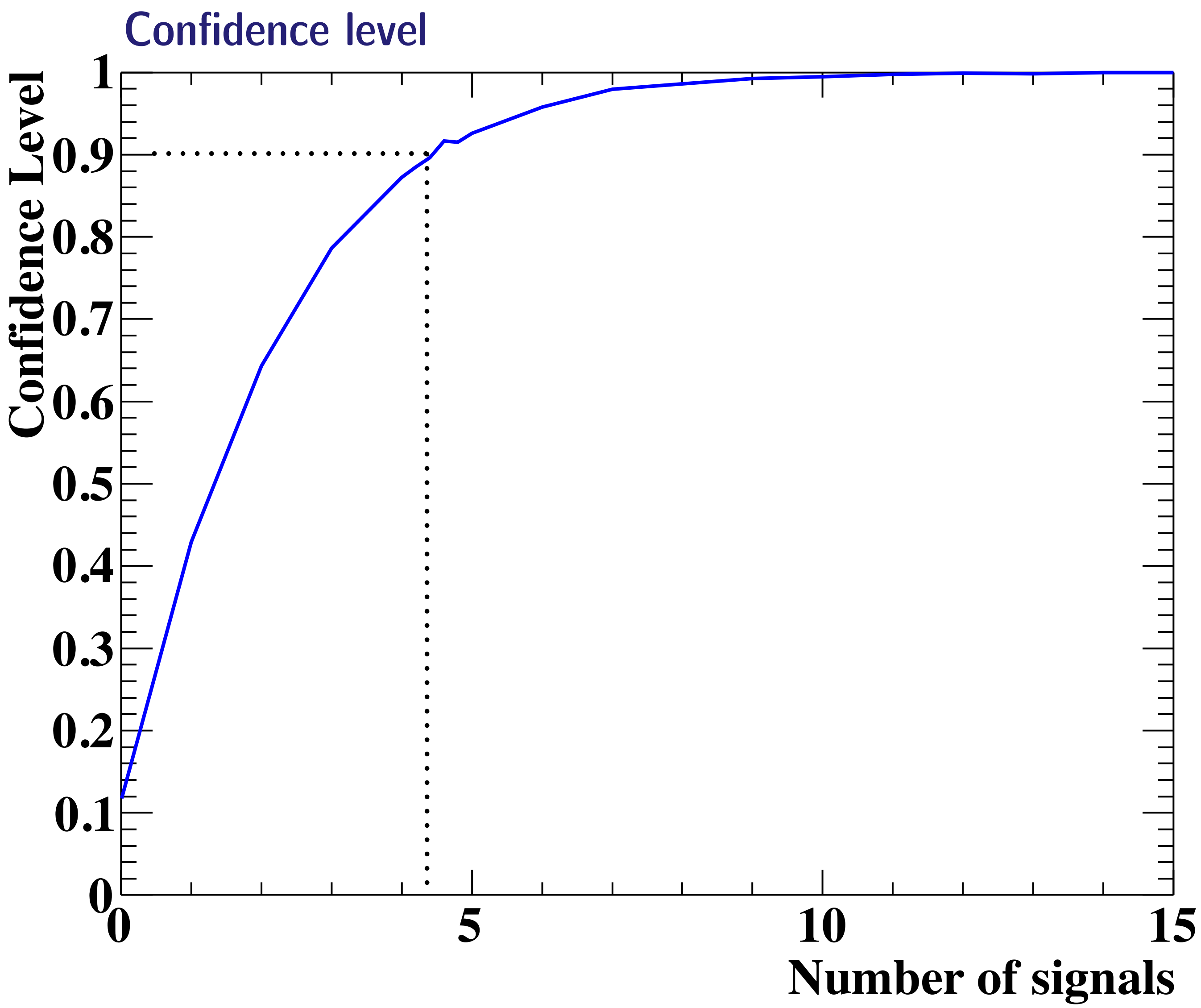
$N_{RMD} = 167.5 \pm 24$

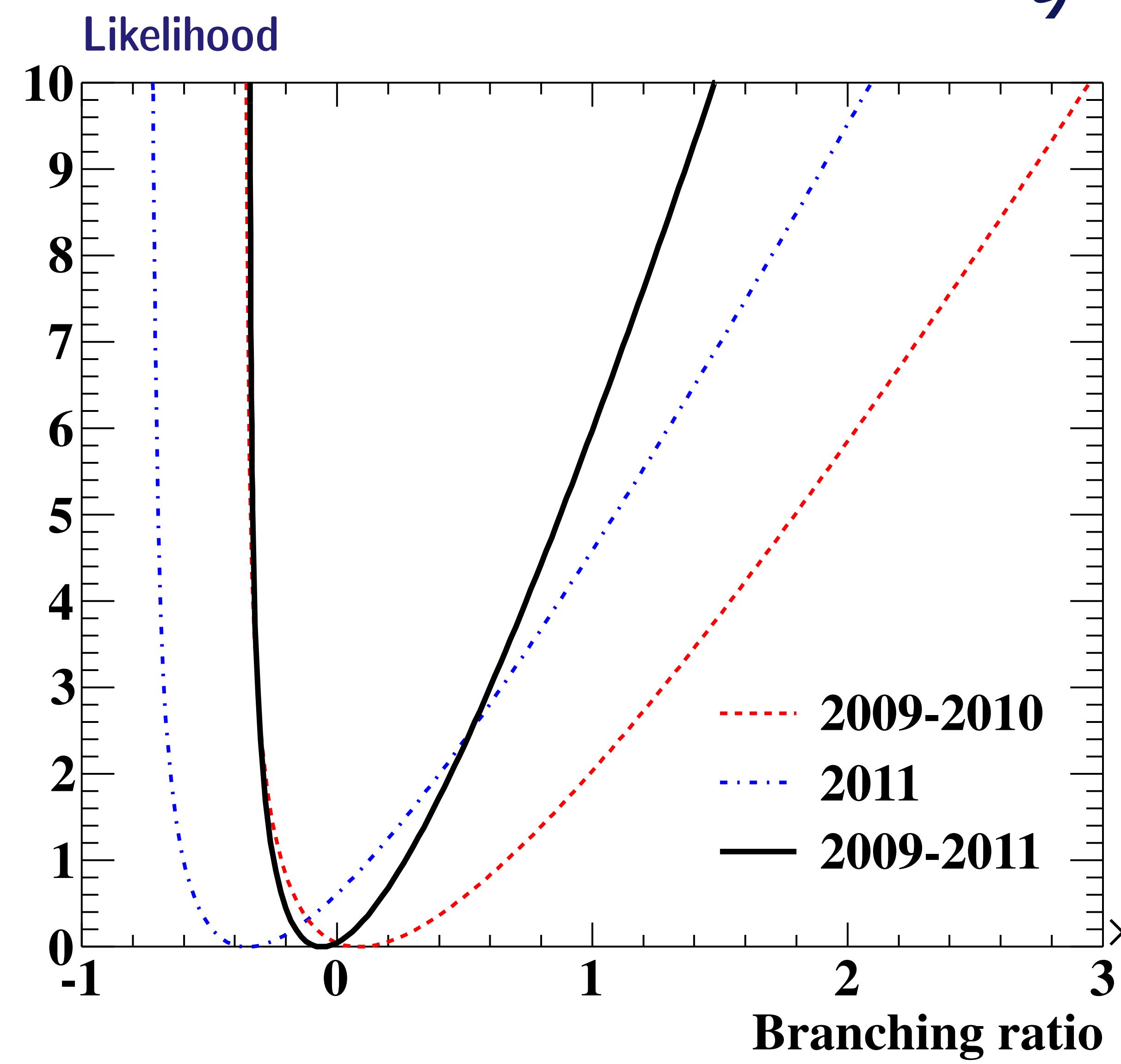
errors : MINOS 1.645σ

2009-2011 result

Previous limit : **2.4×10^{-12}** (MEG, 2011)







normalization : 7.77×10^{12}

$\mathcal{B} < 5.7\times10^{-13}$ @ 90% C.L.

Dataset	$\mathcal{B}_{\rm fit}\times10^{12}$	$\mathcal{B}_{90}\times10^{12}$	$\mathcal{S}_{90}\times10^{12}$
2009–2010	0.09	1.3	1.3
2011	−0.35	0.67	1.1
2009–2011	−0.06	0.57	0.77

arXiv:1303.0754 [hep-ex]
accepted by Phys. Rev. Lett.

Systematic uncertainties (in total 1% in UL)
- relative angle offsets
- correlations in e^+ observables

Likelihood curves are not directly used to calculate UL

Expected final sensitivity

Data taking will be done until Summer 2013

Since 2012, 15% higher beam rate is used

2009-2011 sensitivity

7.7×10^{-13}

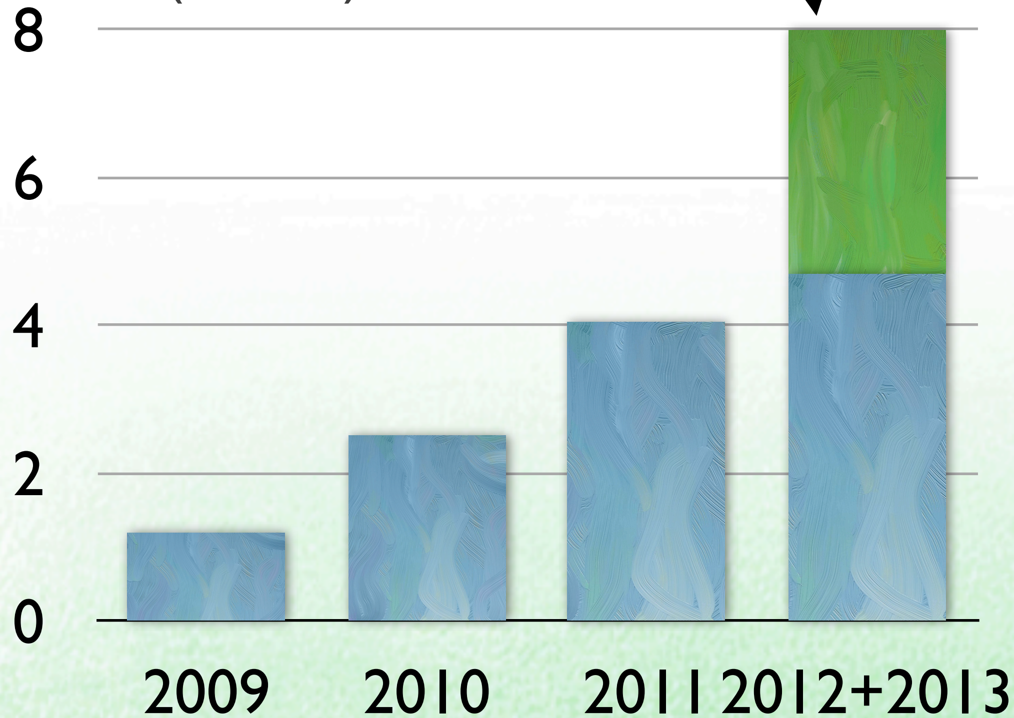
Expected 2009-2013 sensitivity

$\sim5\times10^{-13}$

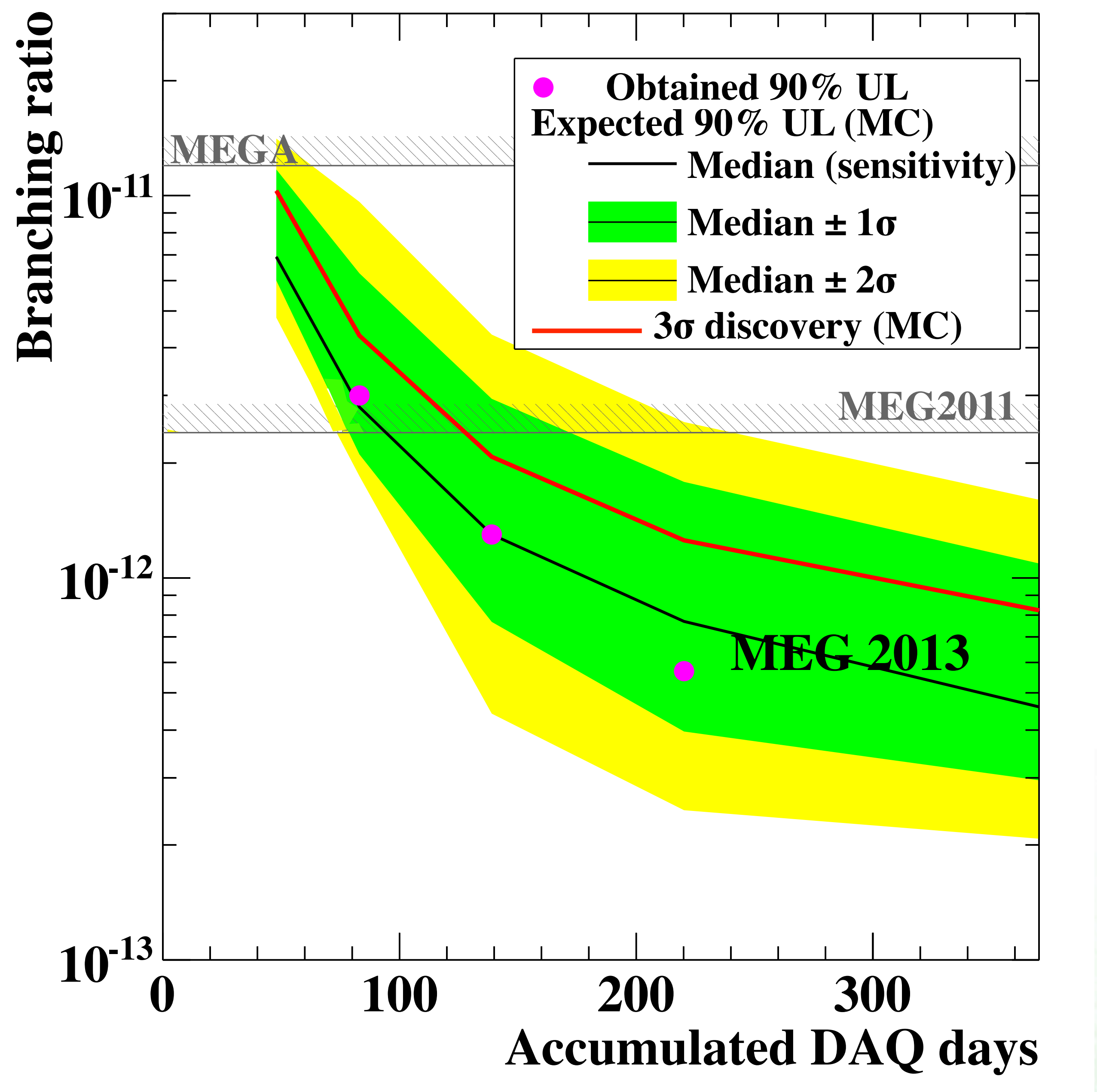
double the statistics

k factor

= SES^{-1} ($\times10^{12}$)



Observed limits and sensitivity

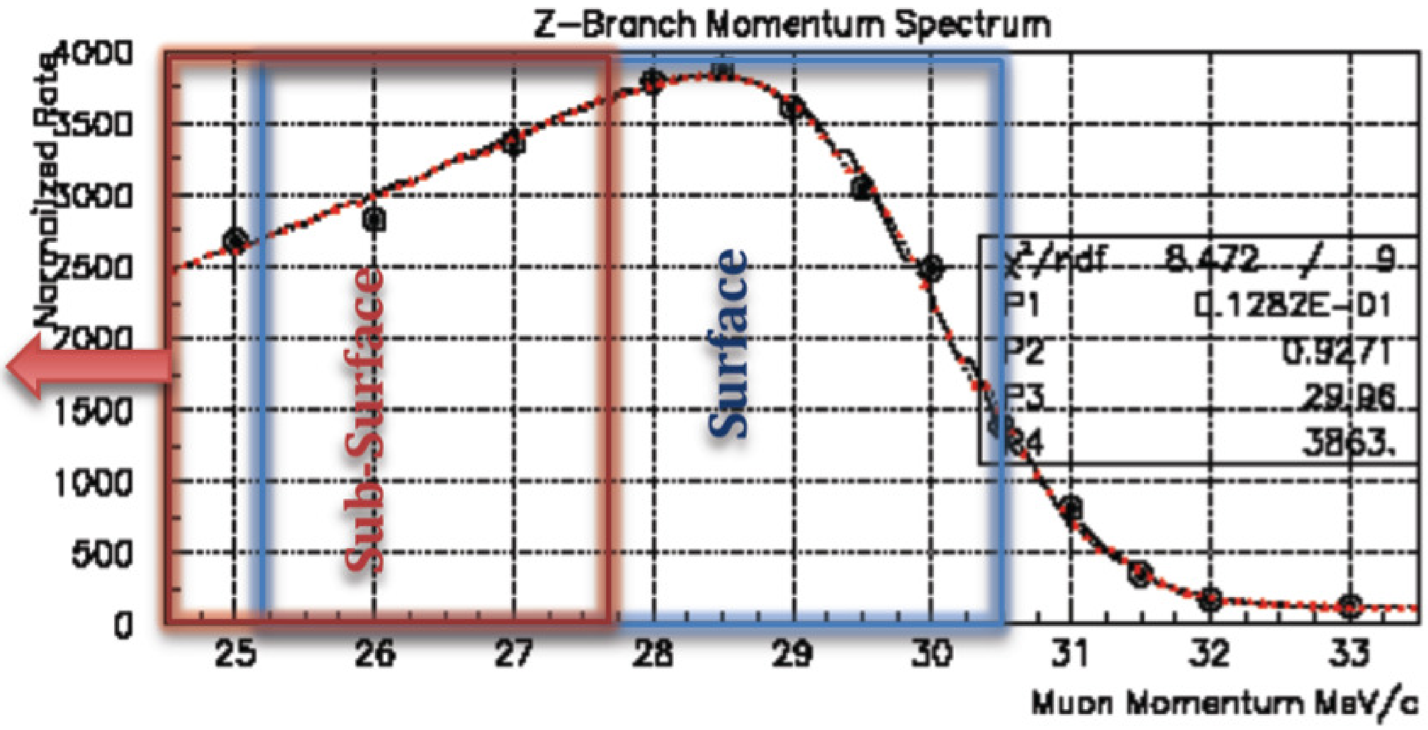


MEG Upgrade

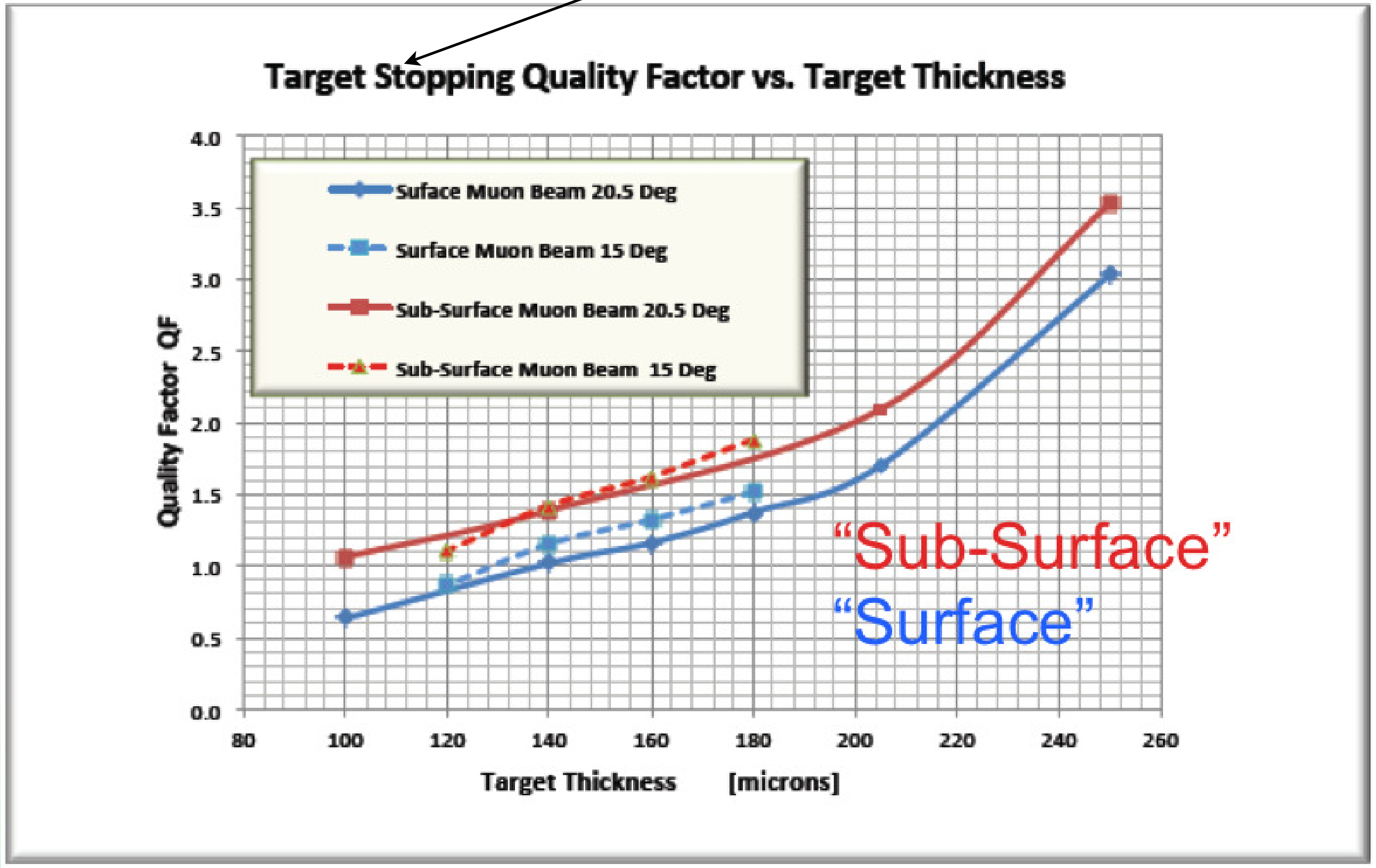
arXiv:1301.7225 [physics.ins-det]

The proposal was accepted by PSI

Beam and target



target stops versus ranging-out particles

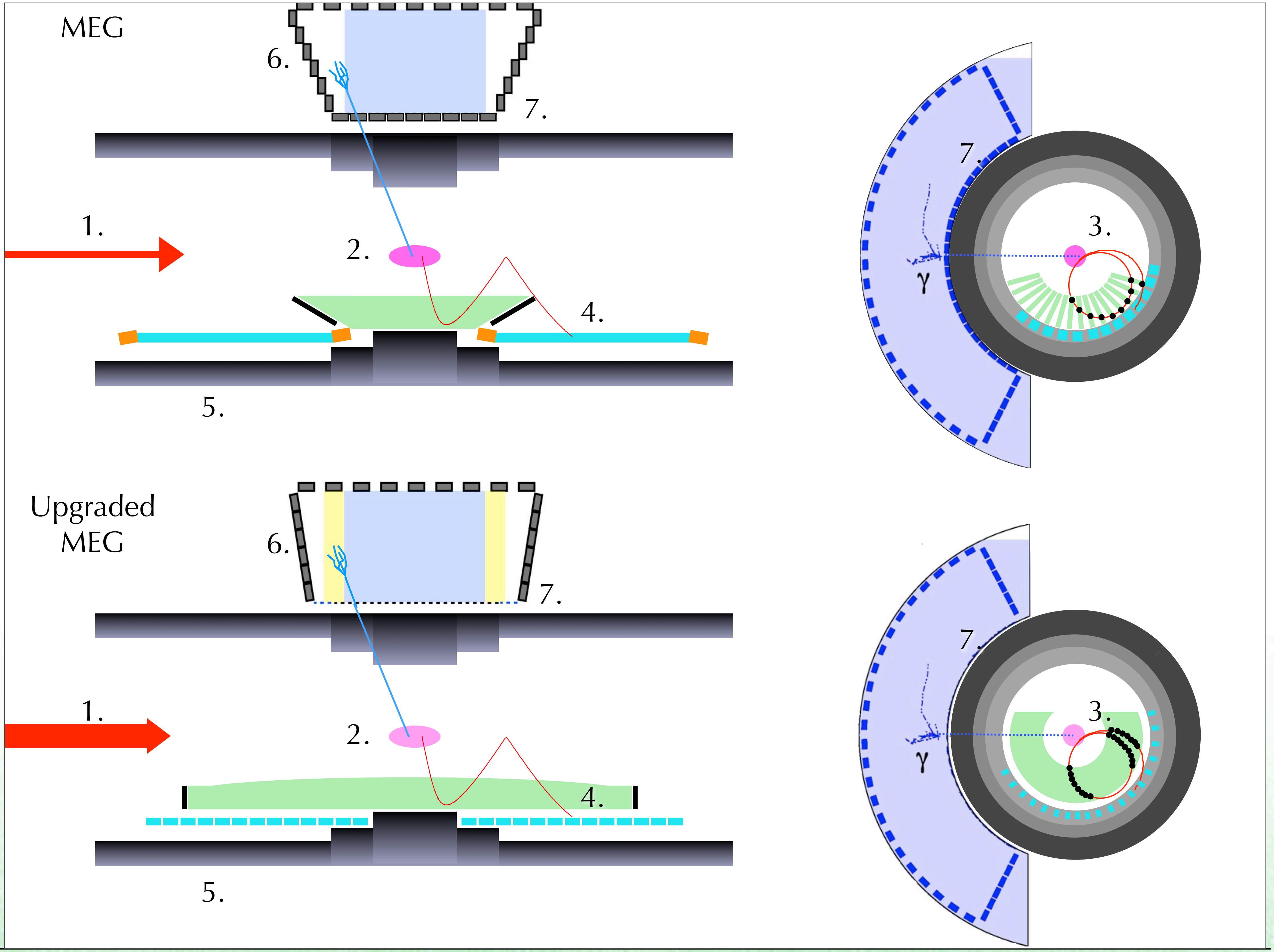


Baseline design

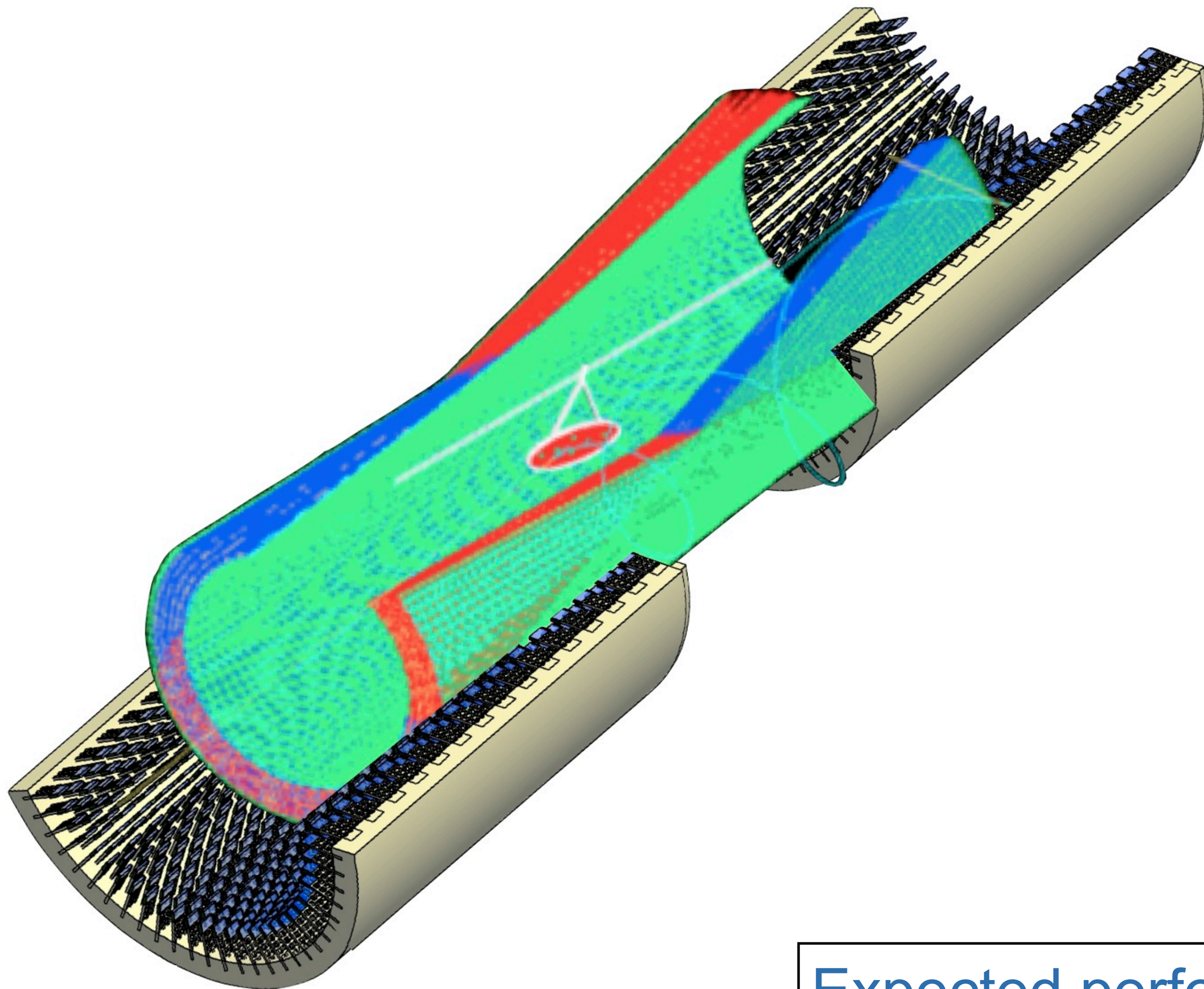
- *7×10^7* μ/s
- Surface beam
- 140 μm thick target, 15° slanted

>2 times higher beam rate

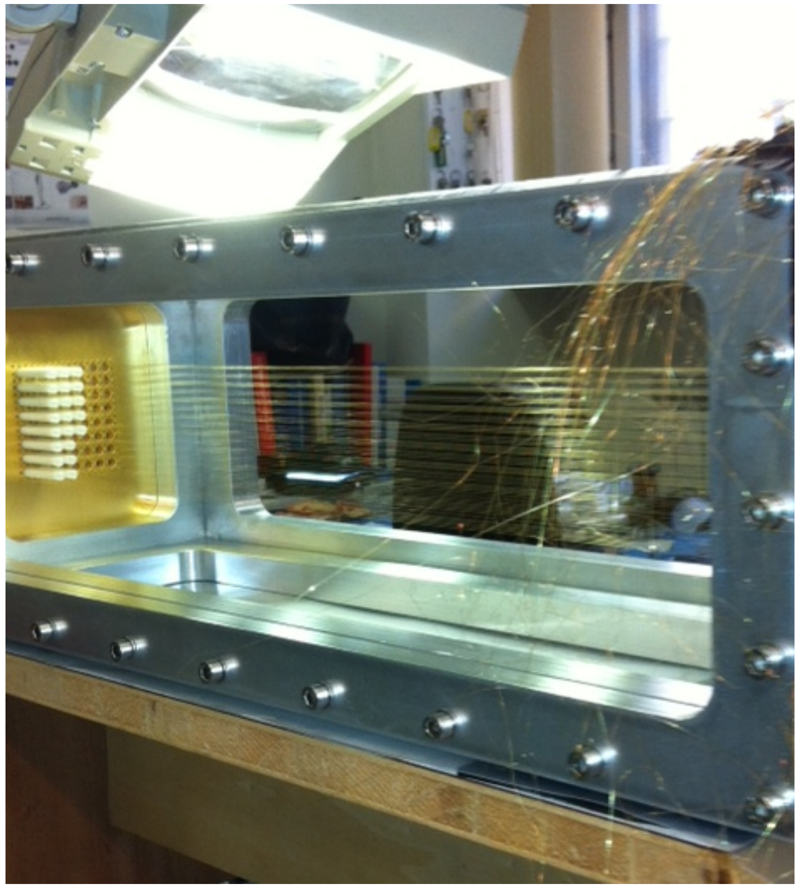
Detector



Spectrometer : Cylindrical drift chamber



Prototype



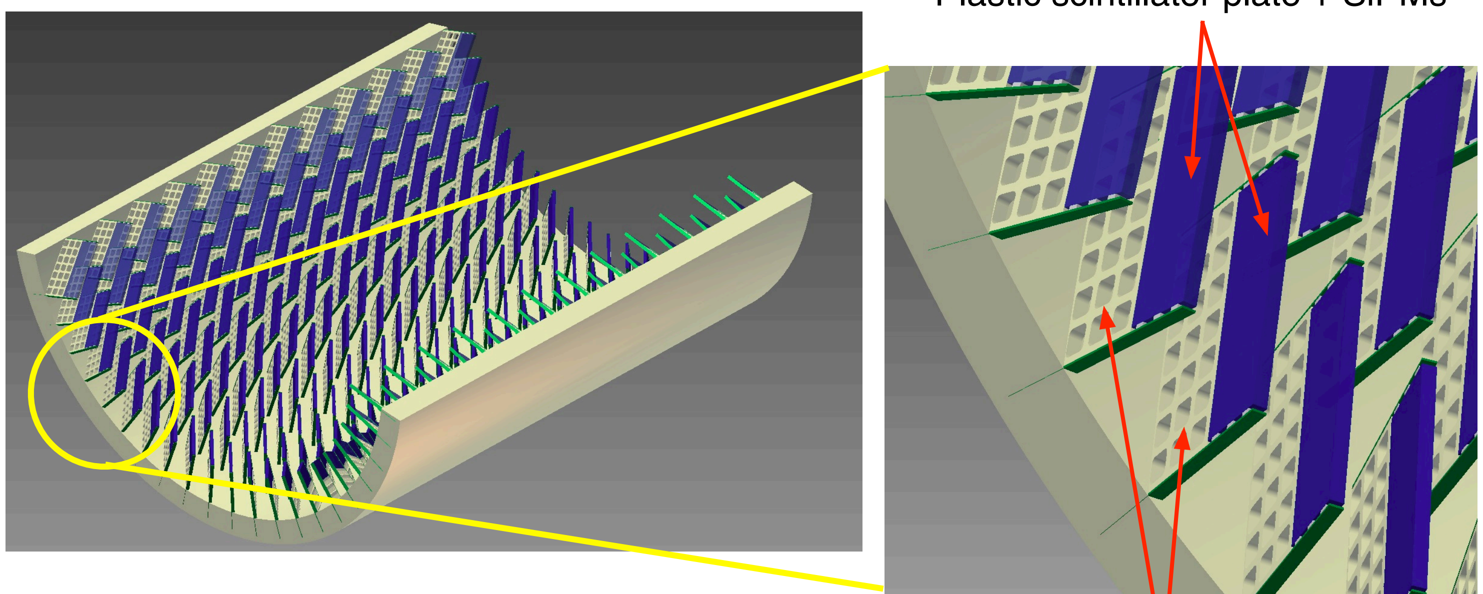
Expected performance

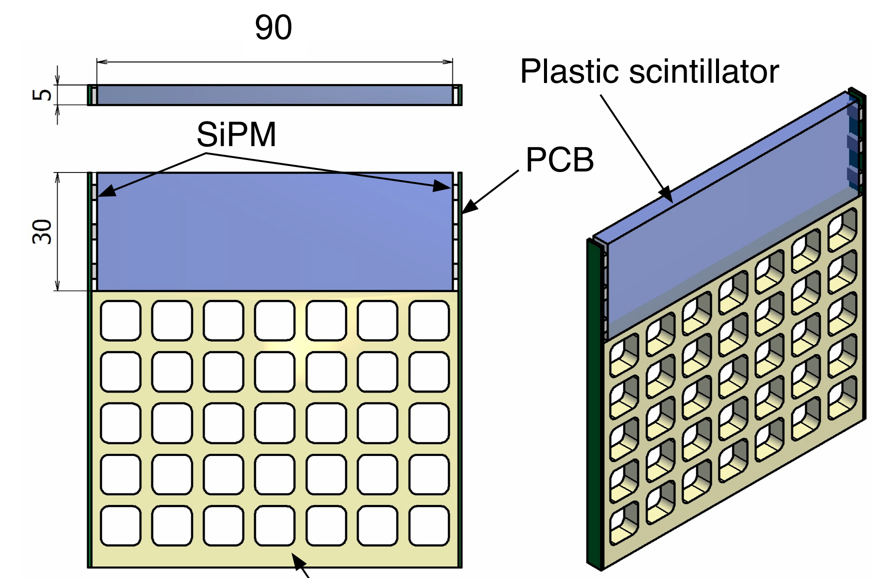
- Unique gas volume
- He/Isobutane 90:10
- Stereo angle (7-8°) wires
- ~1200 anode, ~6400 cathode wires
- Low material : 1.7×10^{-3} X_0

Efficiency : >**85**%
Hit resolution : **120** μm
Momentum resolution : **130** keV
Angular resolution : **3.7** mrad (φ), **5.3** mrad (θ)

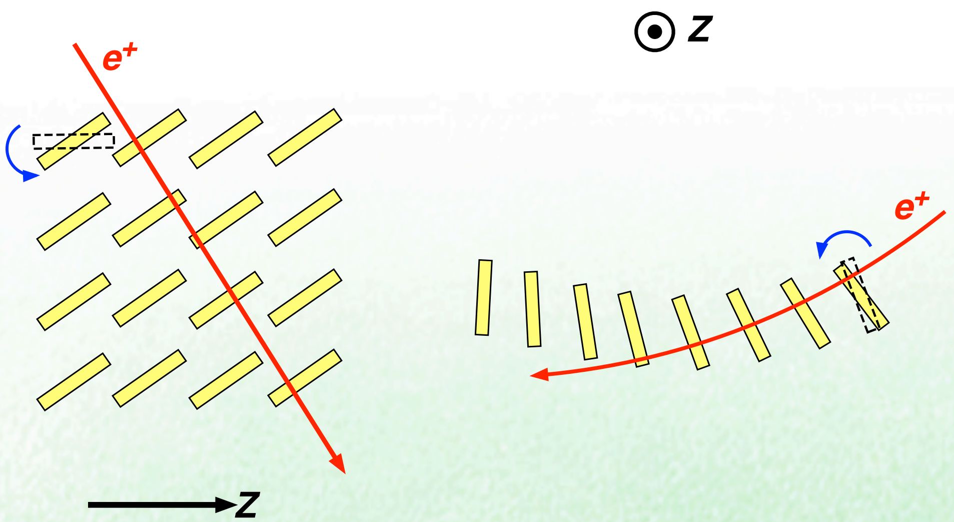
Double the efficiency, and **half the resolutions** compared to present spectrometer

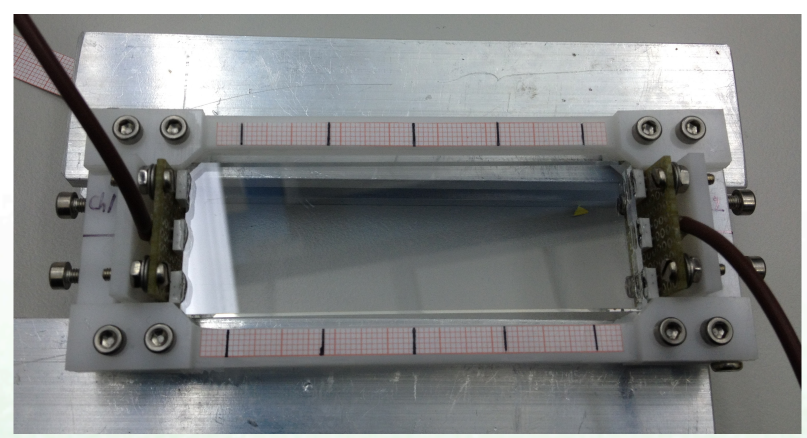
Pixelated timing counter

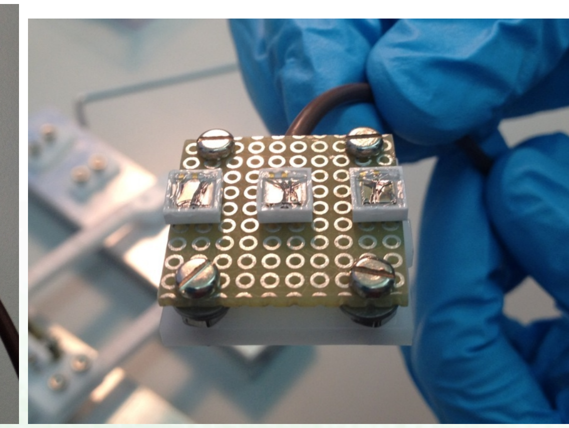




4.8 counter-hits in average







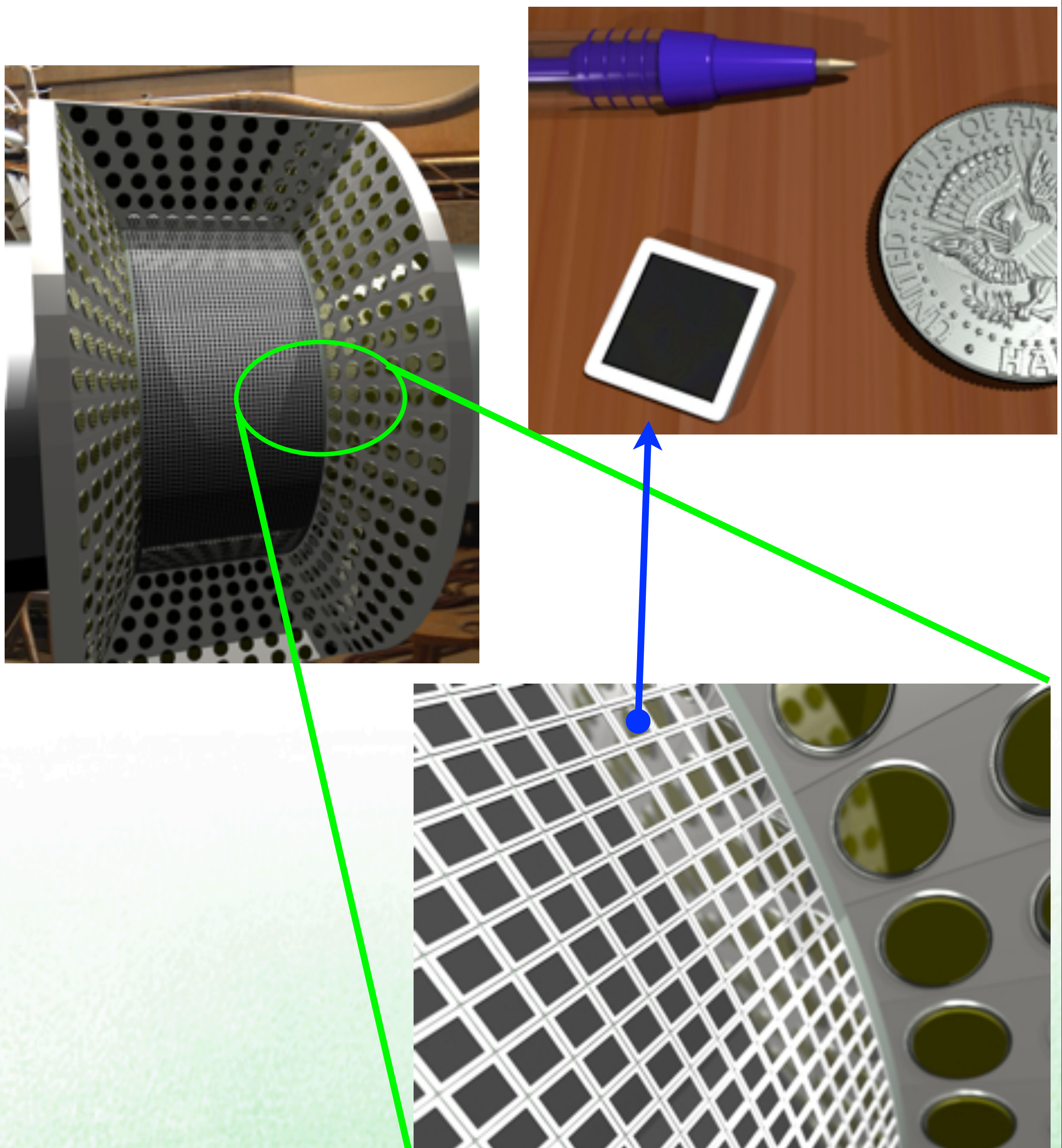
Overall time resolution : **35** psec

About **half the resolutions** compared to present timing-counter

LXe gamma detector

Present detector
Upgraded detector

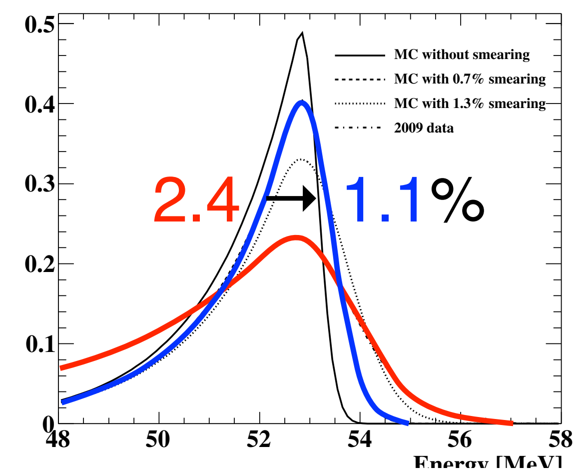
12×12mm^2 SiPMs sensitive to LXe scintillation lights
Development in progress



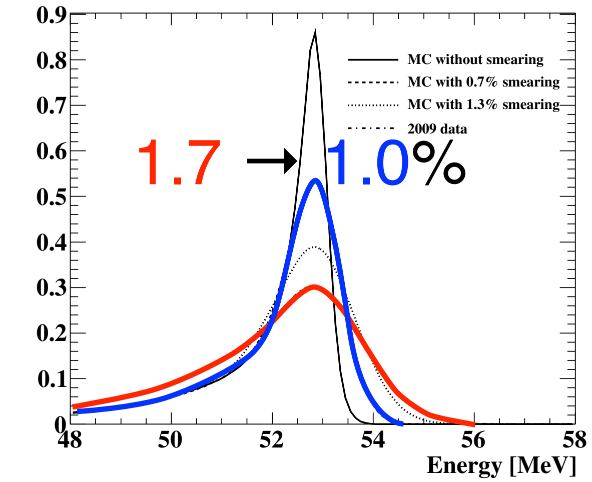
Computer graphics

Energy response

shallow conversion

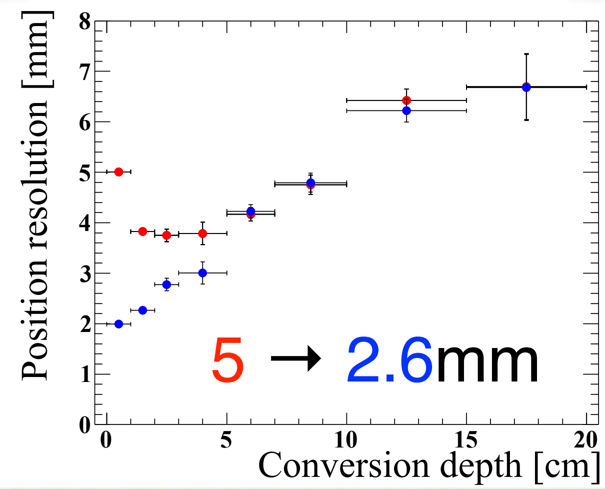


deep conversion

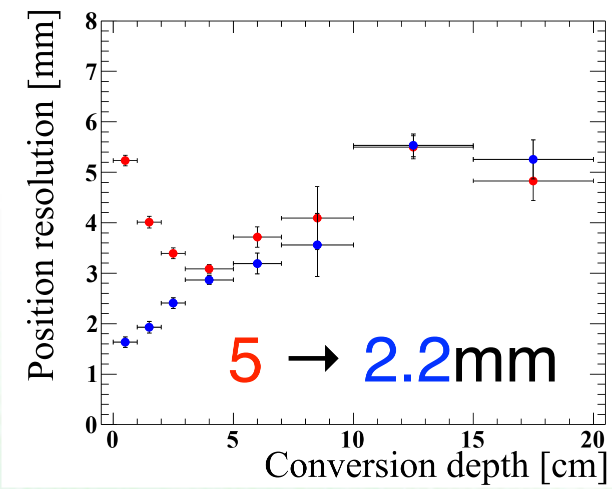


Position resolution

horizontal

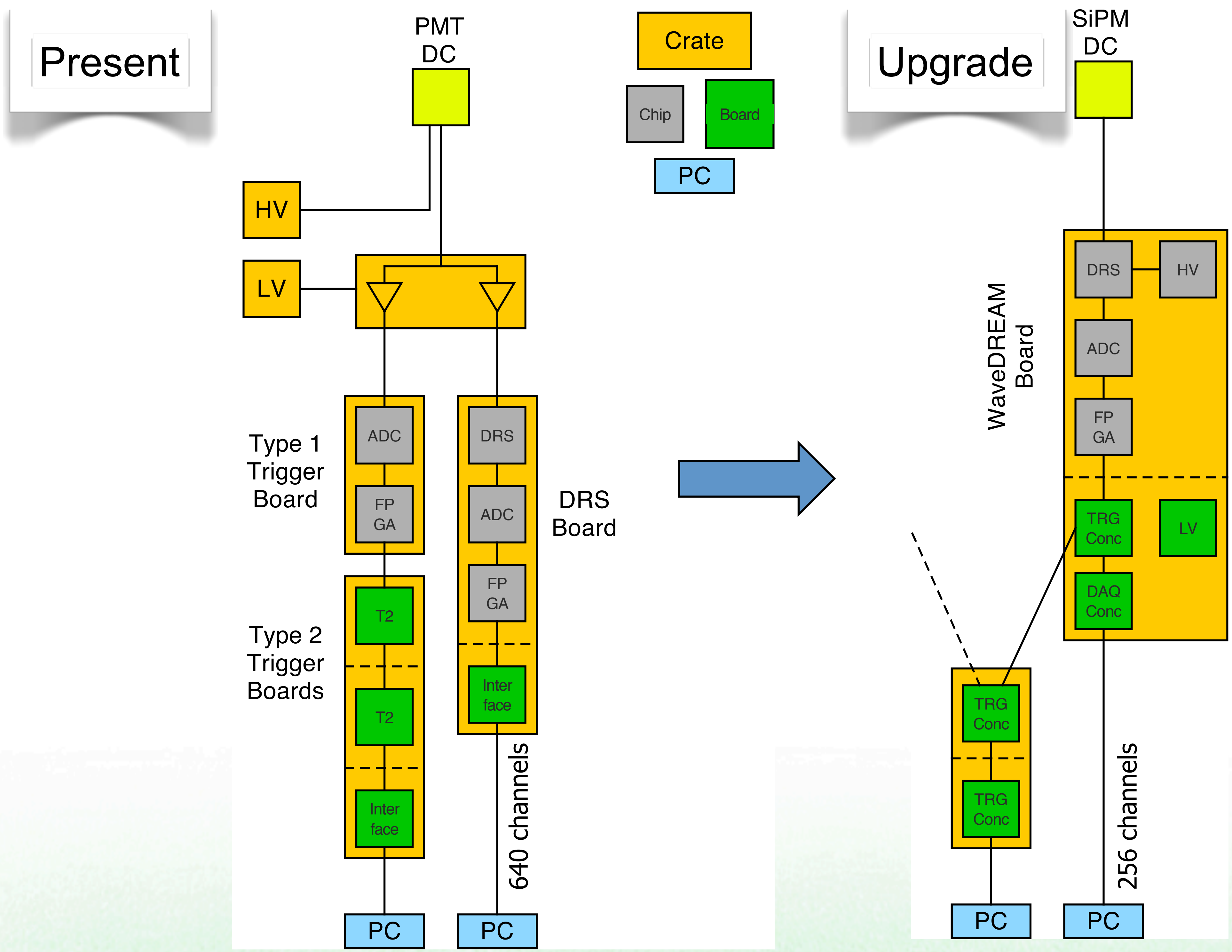


vertical



Half the position resolutions
About **Half the energy resolution**
compared to present calorimeter

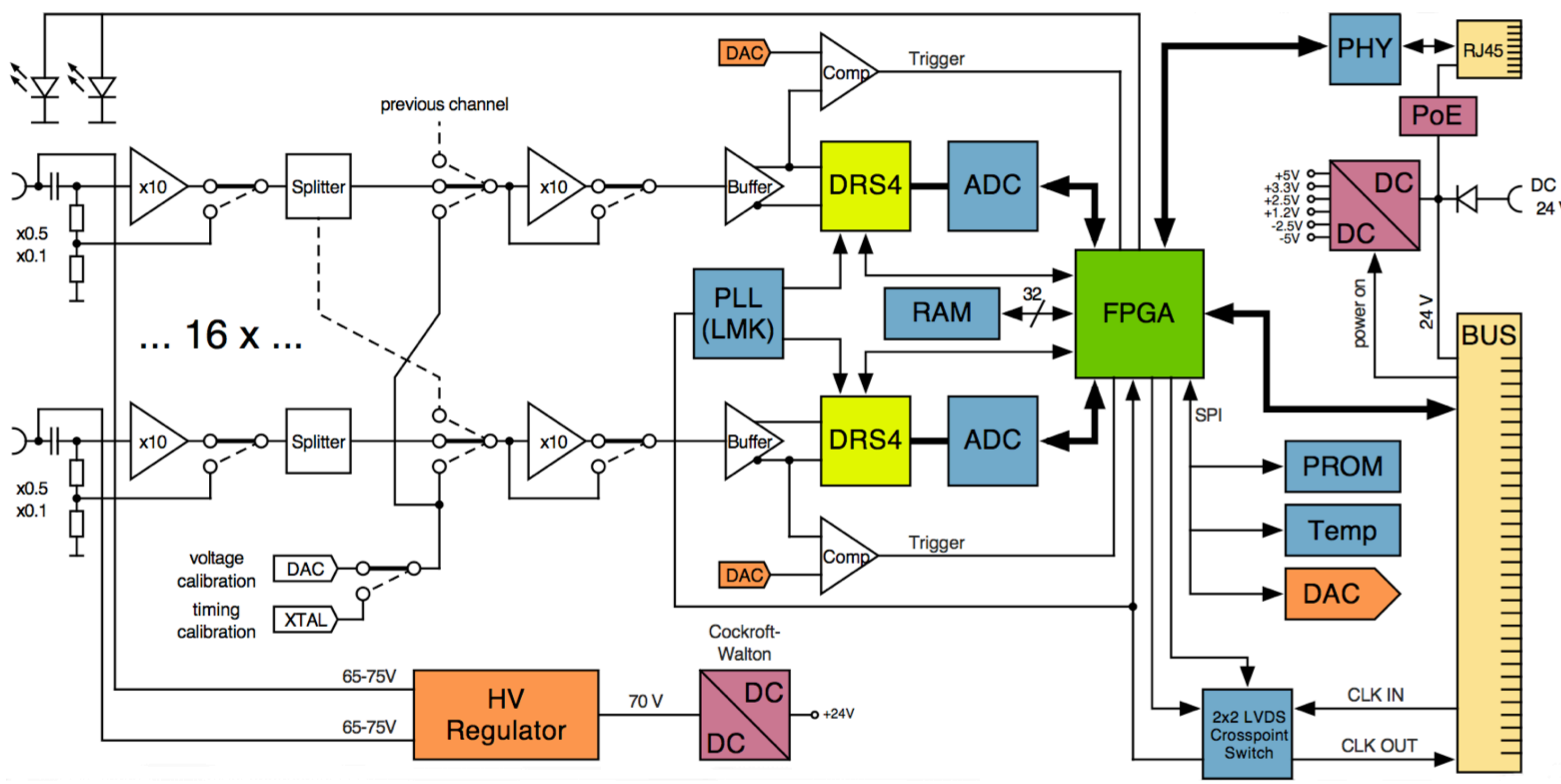
Electronics



Readout, HV and trigger are integrated on same board.

Electronics

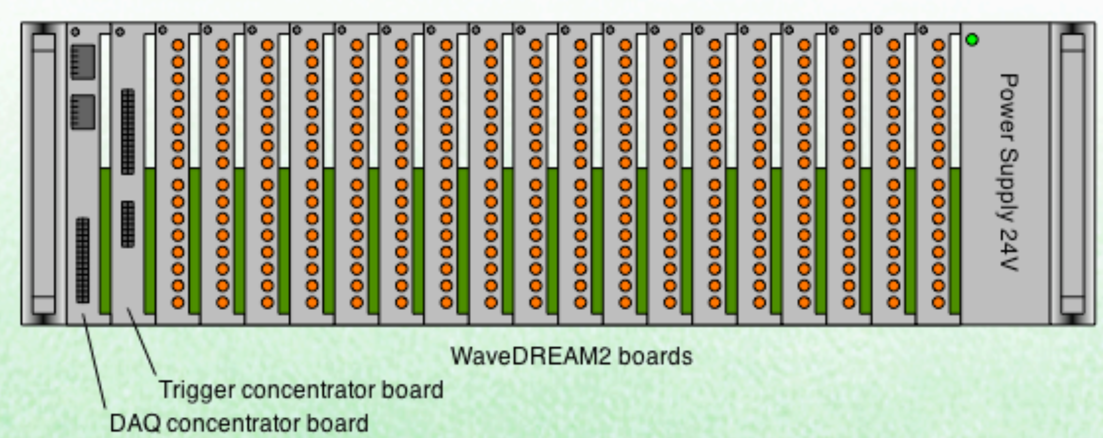
WaveDREAM board



- Put SiPM HV (70-210V) on boards
- Digitize all inputs continuously with 85 MHz/12 bit
- Upon trigger, read DRS through same ADC

- VME → 3 HE 19” crates
  - Higher density
  - Cheaper
  - Faster

256 Channels 5 GSPS/12 bits on a 3HE crate including trigger and SiPM high voltage

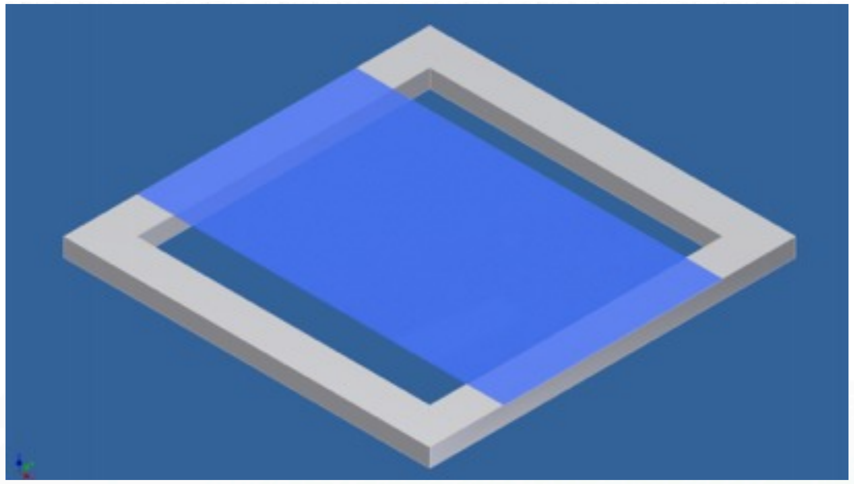


- “Added value” to DAQ boards
  - Switchable gain amplifiers
  - Second level trigger

Other possibilities

Active target

- Target made of 250μm plastic scintillation fibers
- Very precise measurements of muon decay position

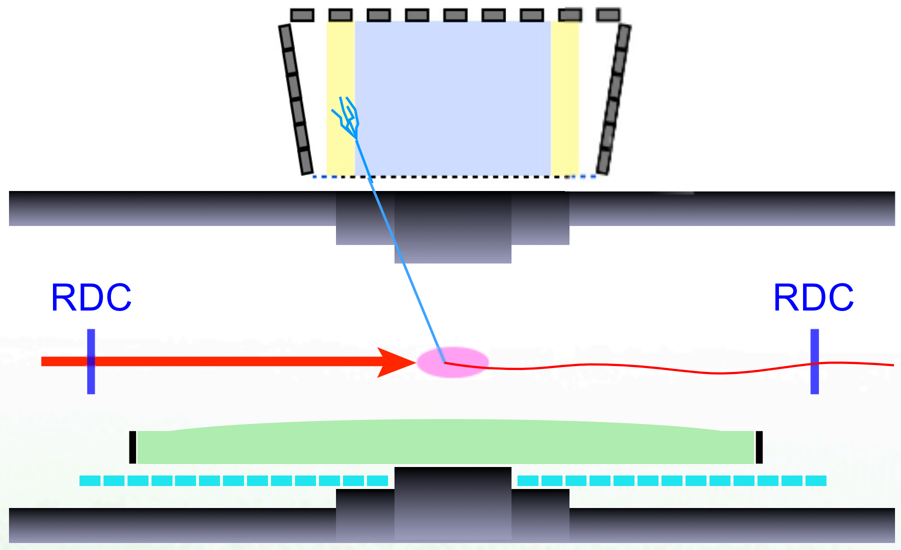


Further improvement of spectrometer performance

Low momentum e^+ detector

- Identify background γ from radiative muon decay
- Half of background γs are from radiative decays

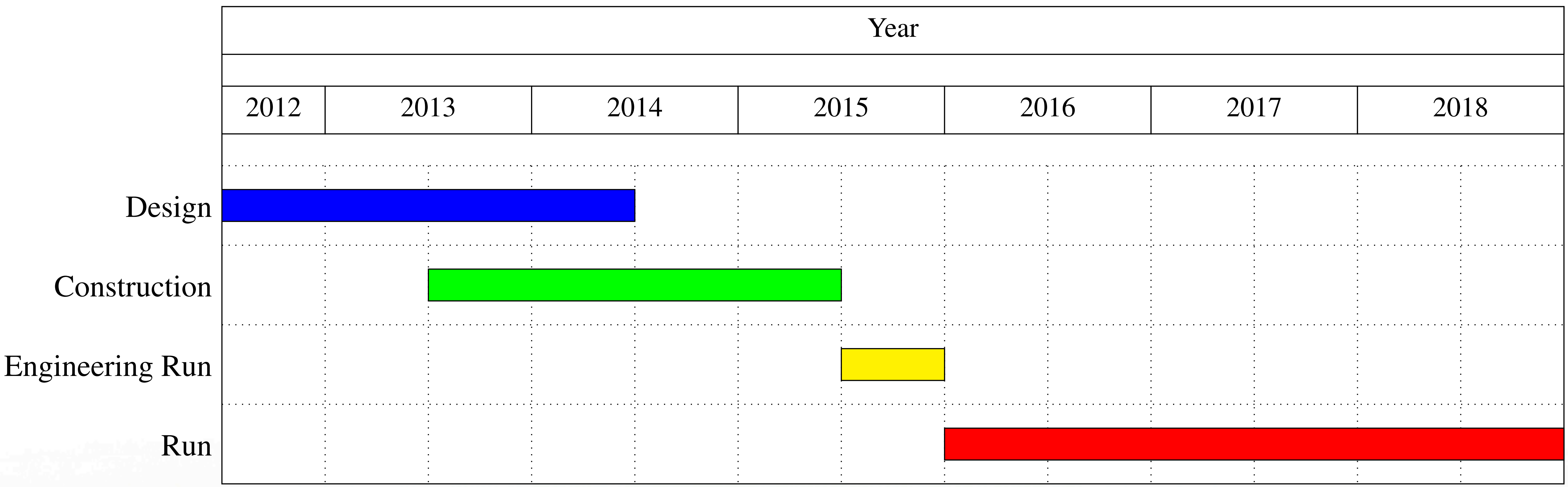
RDC : radiative decay counter



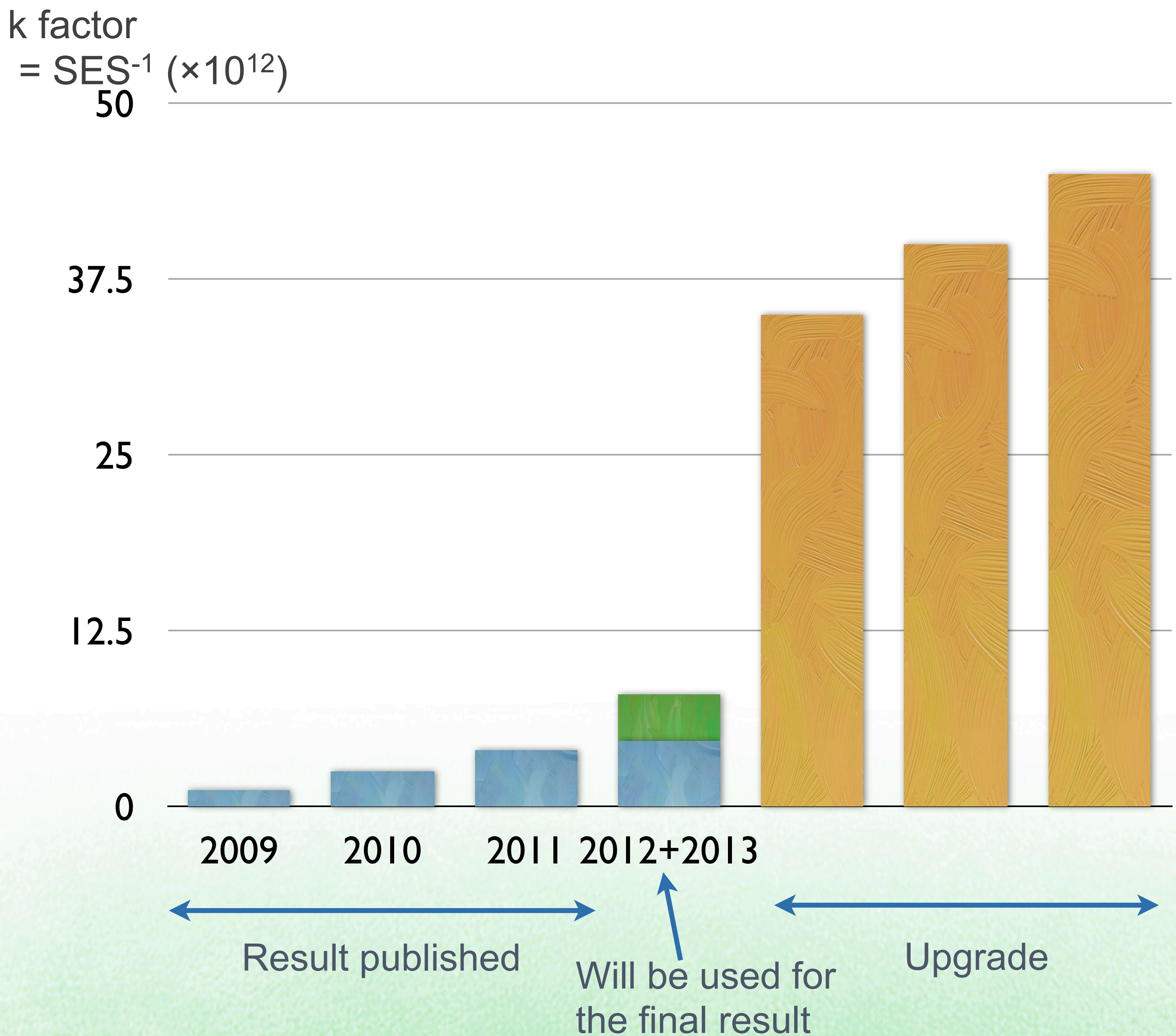
Further background reduction

Hardware development ongoing

Schedule


Year
2012
2013
2014
2015
2016
2017
2018
Design
Construction
Engineering Run
Run

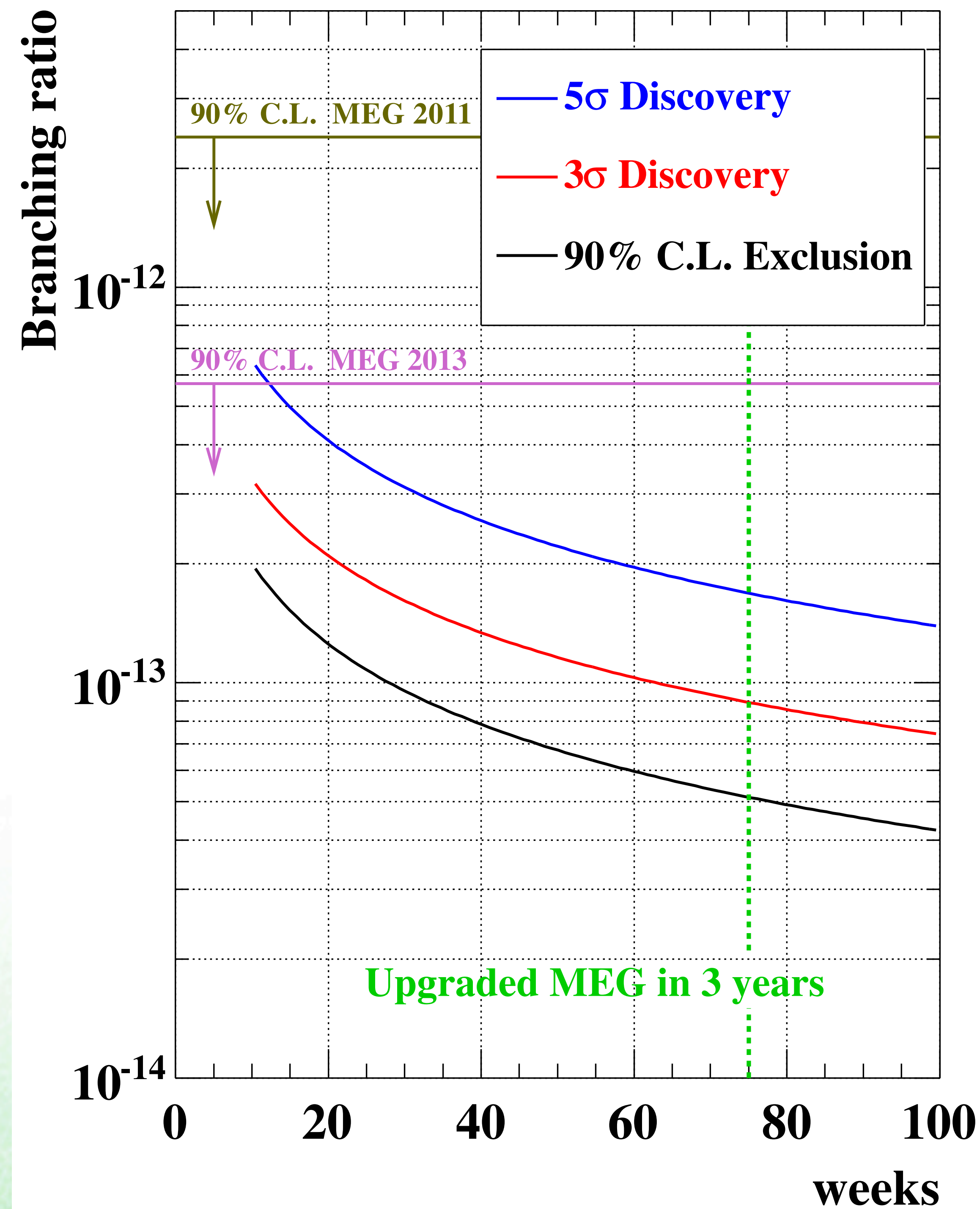
Data statistics in the future



Expected performance and Sensitivity

PDF parameters	Present MEG	Upgrade scenario
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad)	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency (%)		
trigger	≈ 99	≈ 99
γ	63	69
e^+	40	88

Sensitivity in three years : **~5×10^{-14}**



Conclusions

- First $\mu \to e\gamma$ search with $O(10^{-13})$ sensitivity
  - Sensitivity : 7.7×10^{-13}
  - No excess was found
  - 4 times stringent new limit : $\mathcal{B} < 5.7 \times 10^{-13}$ @ 90% C.L.

Related posters

"Measurement of inner Bremsstrahlung in polarized muon decay with MEG" by Y. Uchiyama

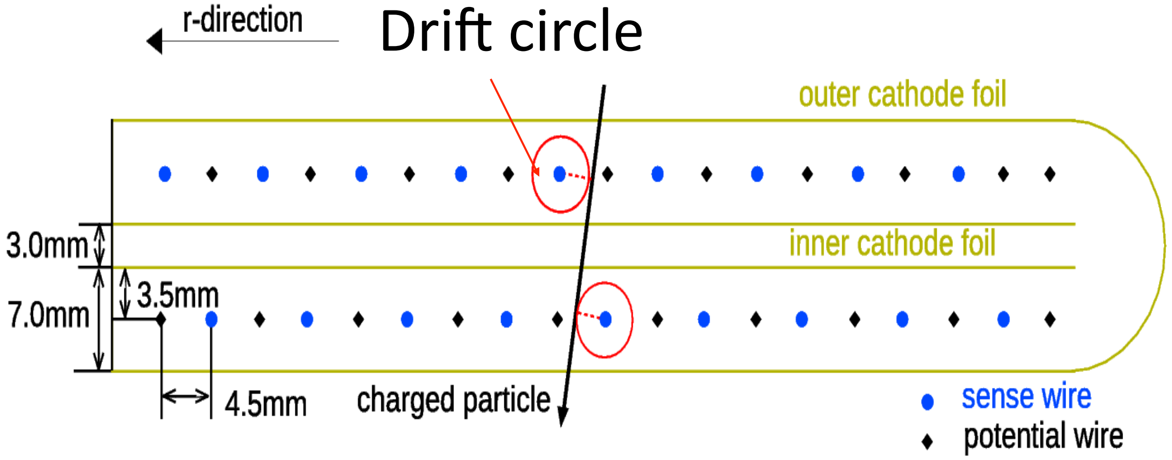
R&D on the drift chamber for MEG upgrade by L. Galli et al
Active target for MEG upgrade by A. Papa et al

- Data taking will be done until summer 2013
  - Double the statistics
  - Expected sensitivity : $\sim 5 \times 10^{-13}$
- Upgrade proposal was accepted, and R&D ongoing
  - More intense beam, double the efficiency and half the resolutions.
  - Expected sensitivity : $\sim 5 \times 10^{-14}$ in 3 years starting from 2016

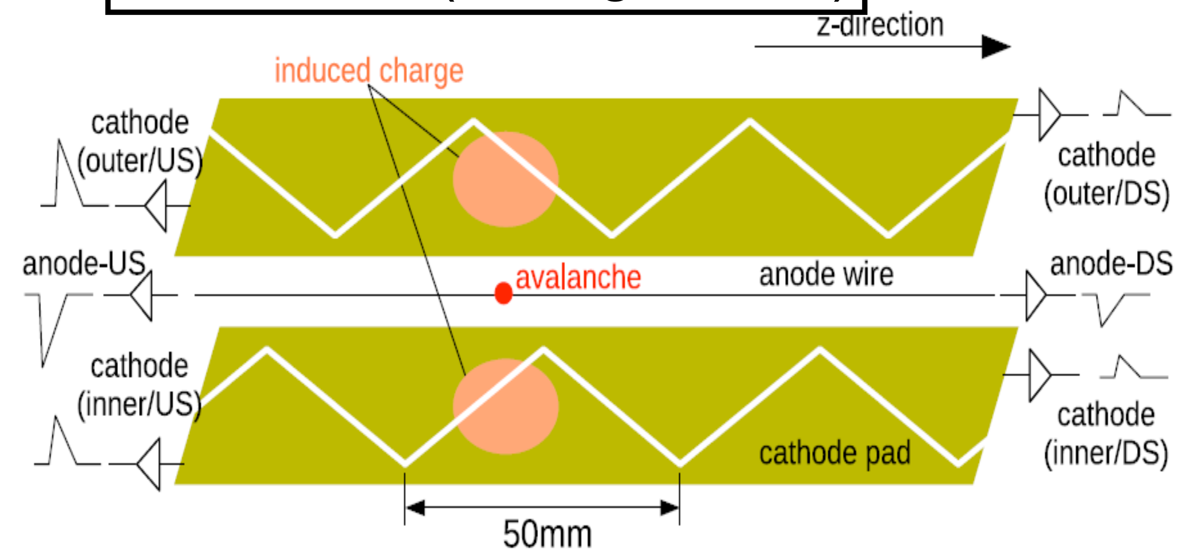
Back up

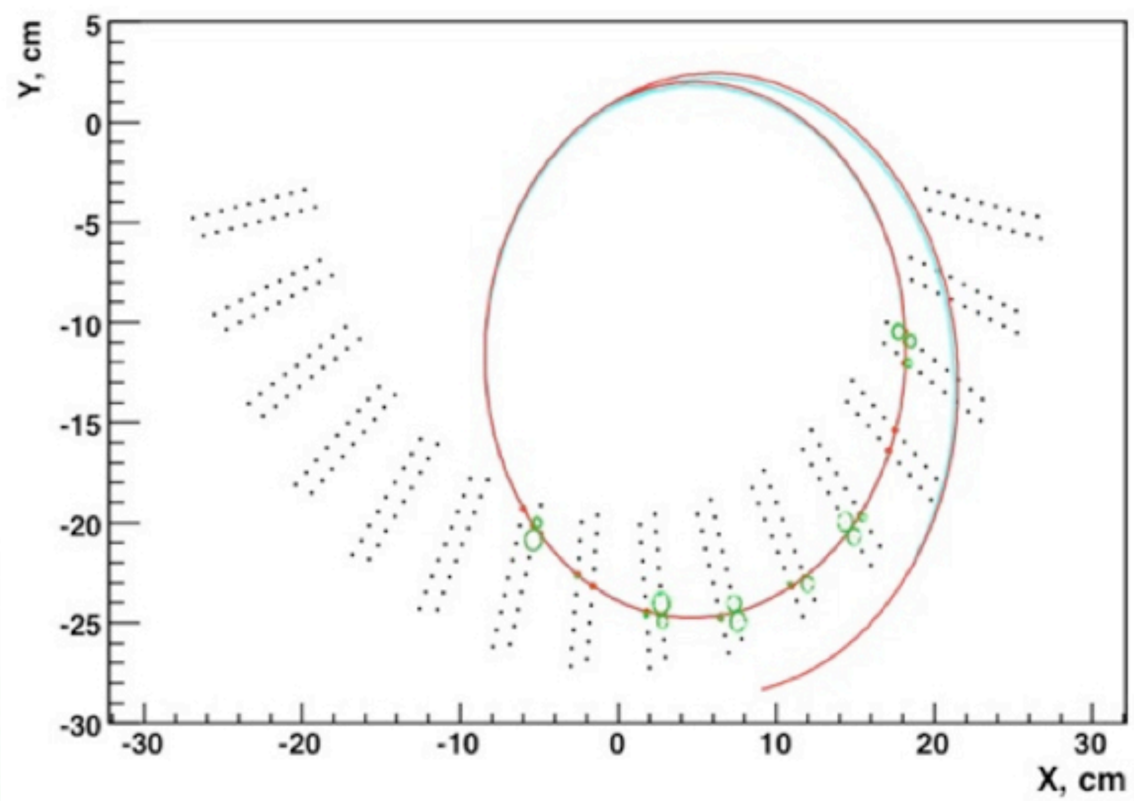
Track reconstruction

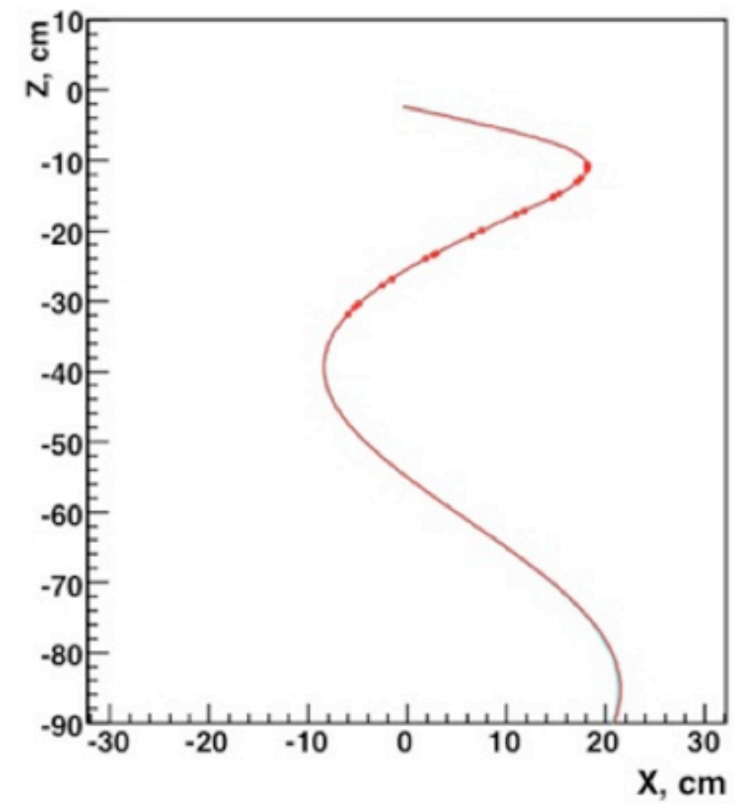
R direction (drift time)



Z direction (charge ratio)







Single hit intrinsic resolution

R : **210μm** (core, 87%), 780 μm (tail, 13%)
Z : **800μm** (core, 91%), 2.1 mm (tail, 9%)

Calibration and monitoring

PMT

LED
Alpha source (5.5 MeV)

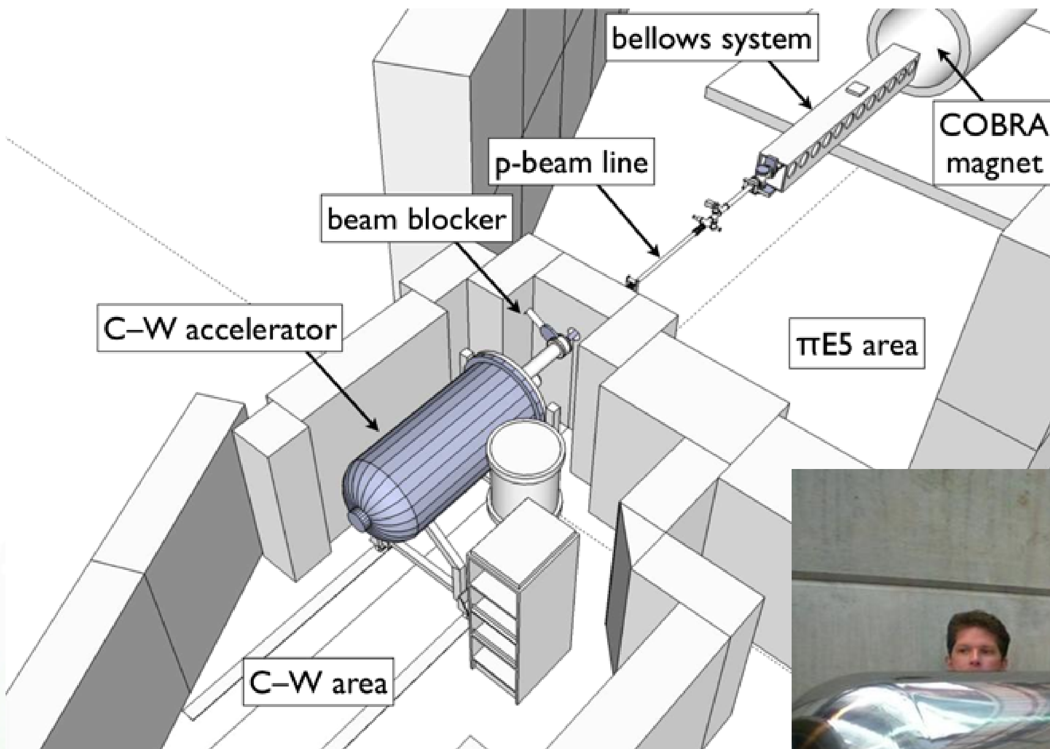
Energy

AmBe (4.4MeV)
Neutron capture (9MeV)
Li(p,γ)Be (17.6 MeV)
$\pi 0 \rightarrow \gamma\gamma$ (55, 83 MeV)
Cosmic ray (160 MeV)

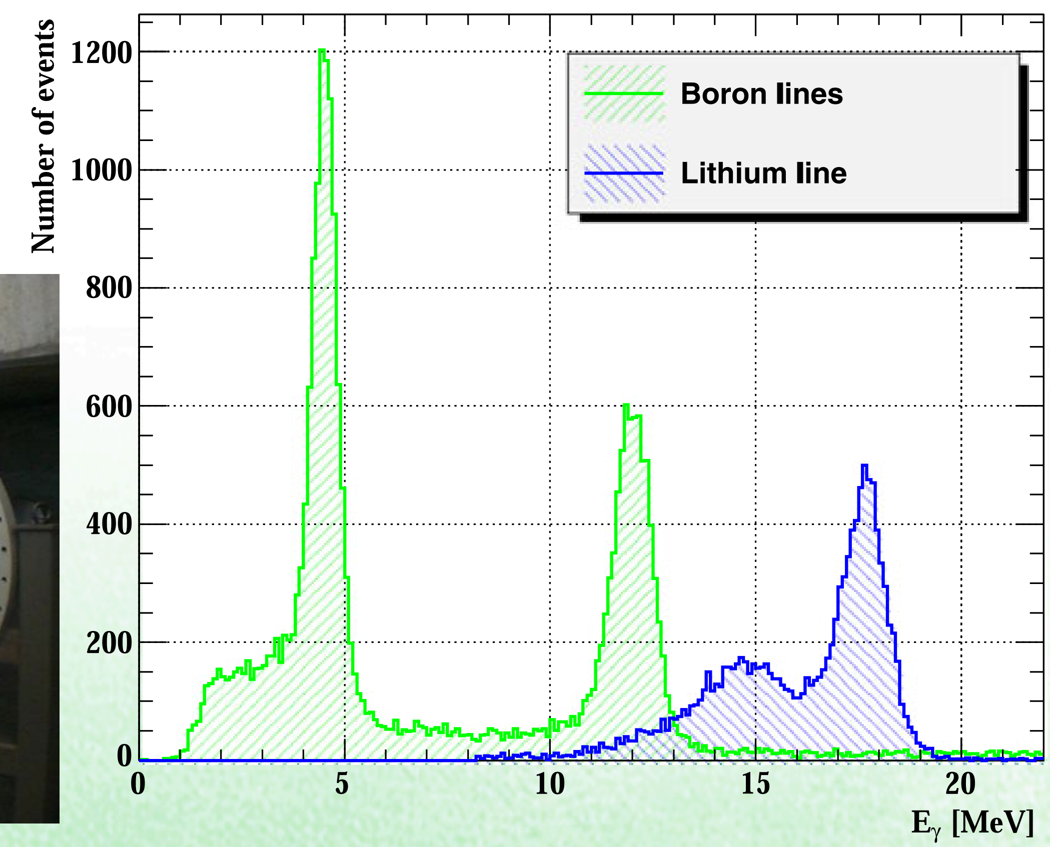
Time

B(p,γ) (4.4+11.7 MeV)
$\pi 0 \rightarrow e^+ e\gamma$ (55-83 MeV)
Muon radiative decay

Weekly energy and time calibration



MEG Cockcraft-Walton(C.W.)
proton accelerator

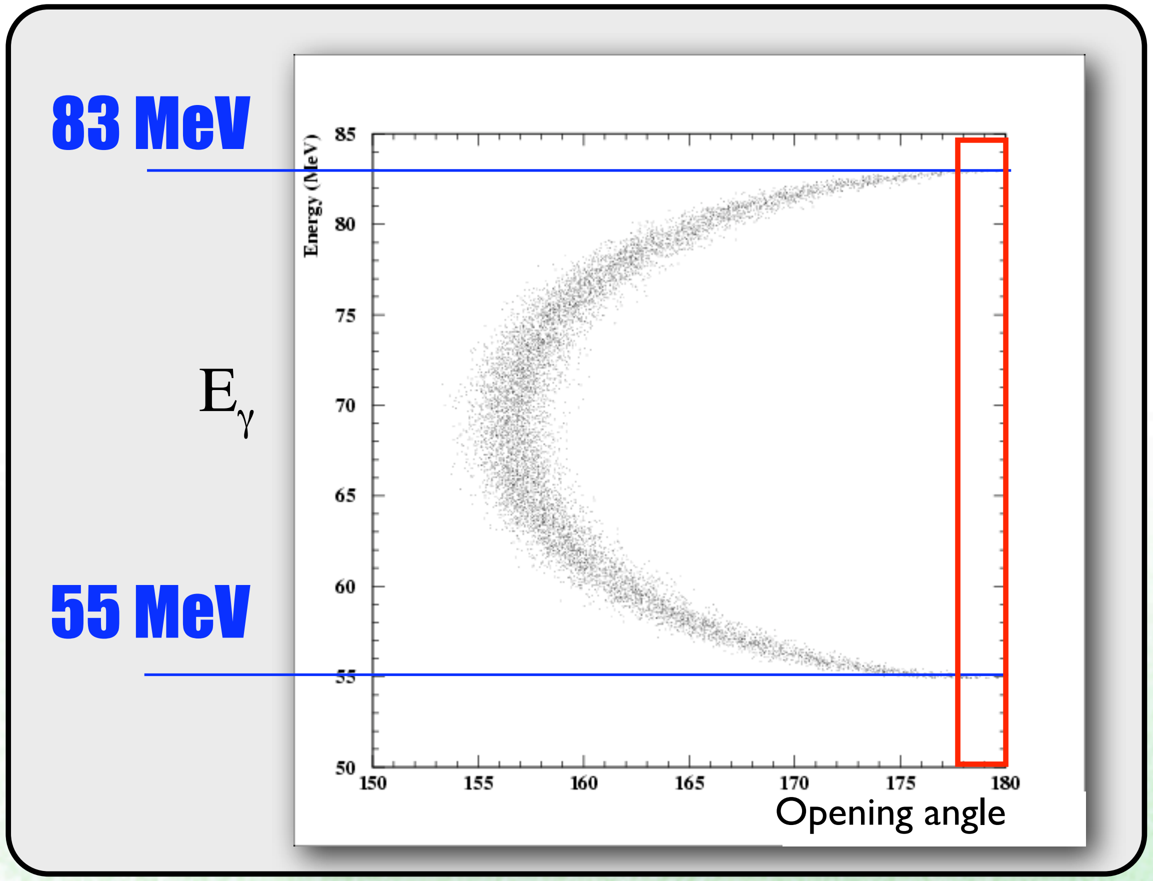


Calibration and monitoring

PMT
- LED
- Alpha source (5.5 MeV)

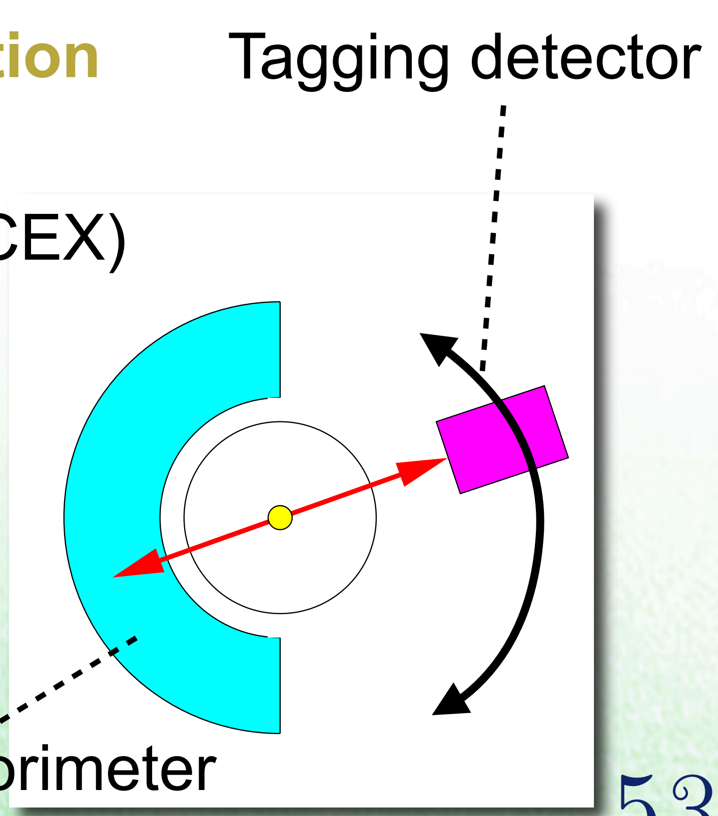
Energy
- AmBe (4.4MeV)
- Neutron capture (9MeV)
- Li(p,γ)Be (17.6 MeV)
- π0→γγ (55, 83 MeV)
- Cosmic ray (160 MeV)

Time
- B(p,γ) (4.4+11.7 MeV)
- π0→e⁺eγ (55-83 MeV)
- Muon radiative decay



Once (or twice) per year
Absolute energy calibration
PMT time calibration
Energy and time resolution

Pion **C**harge **EX**change (CEX)



π^- + p → π^0 + n

π^0→ γγ (55MeV, 83MeV)

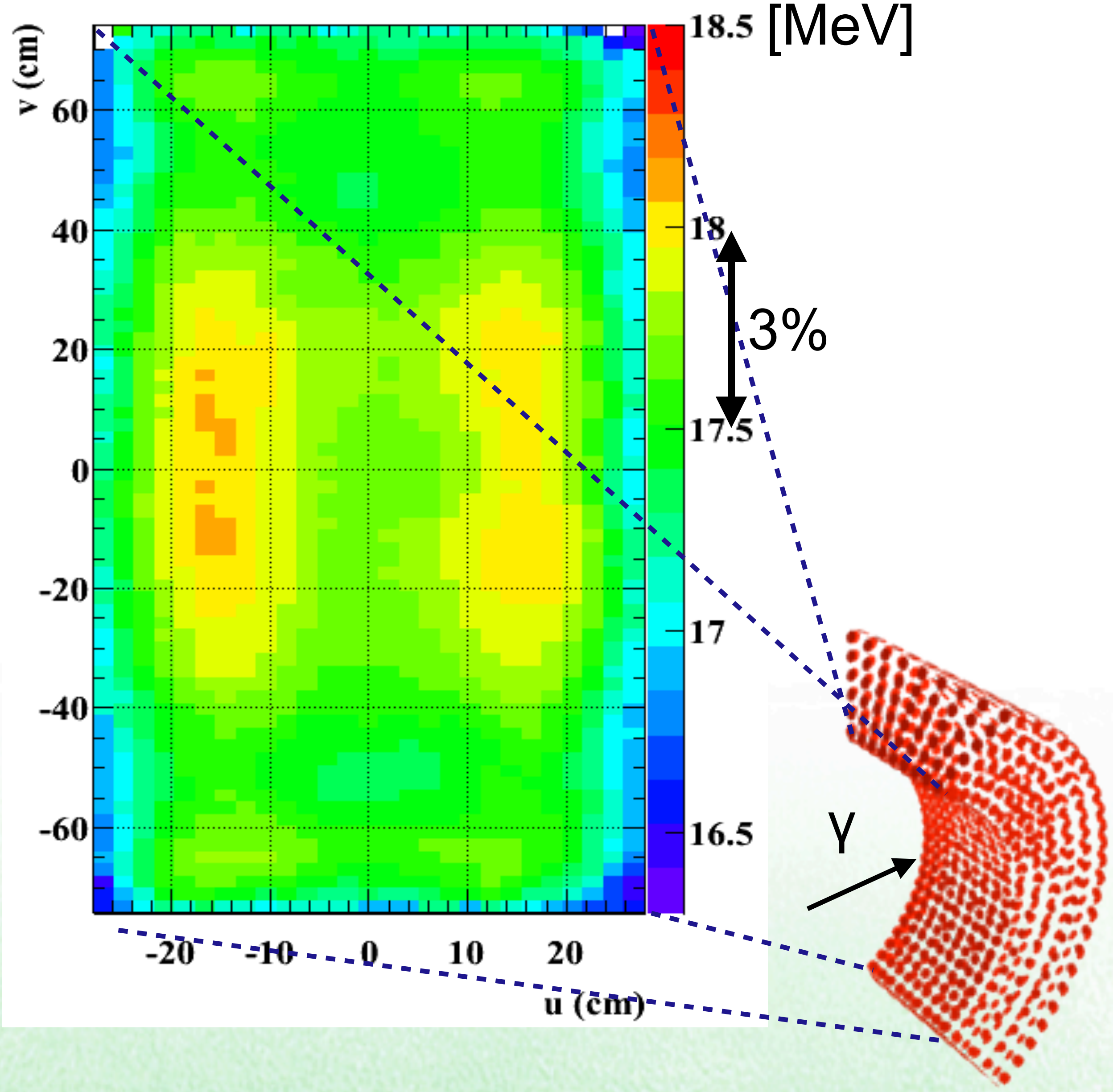
LH_2 target

Energy Scale Uniformity

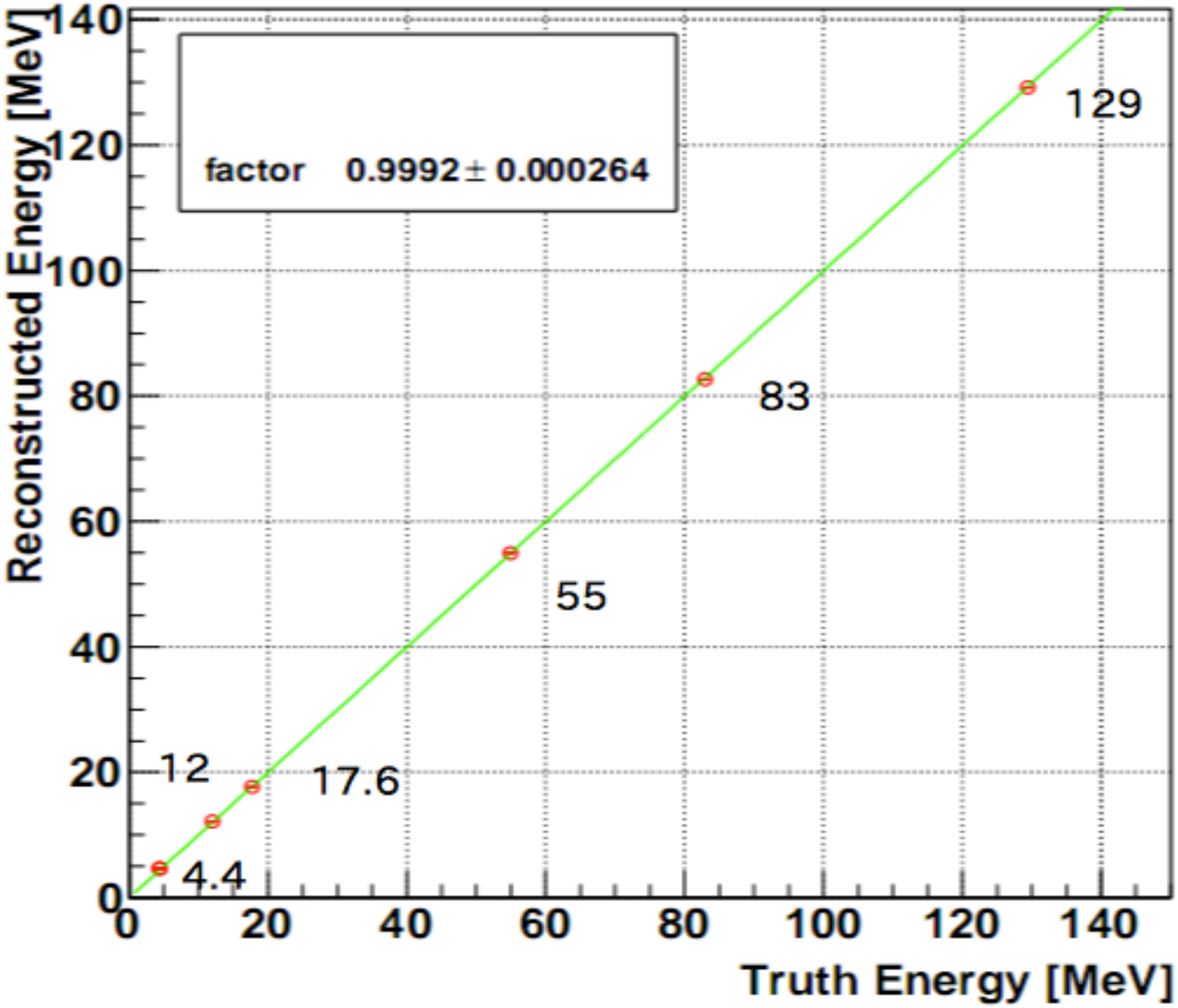
- Non-uniformity due to
  - Geometry
  - Reconstruction algorithm
- Correction using
  - 17.6 MeV CW gamma for position
    - Monitored weekly
  - 55 MeV CEX gamma for depth (energy dependent)
- Checked using background gamma spectrum during physics run

After correction : ~0.2 % uniform

17.6 MeV CW data
uniformity before correction



Linearity



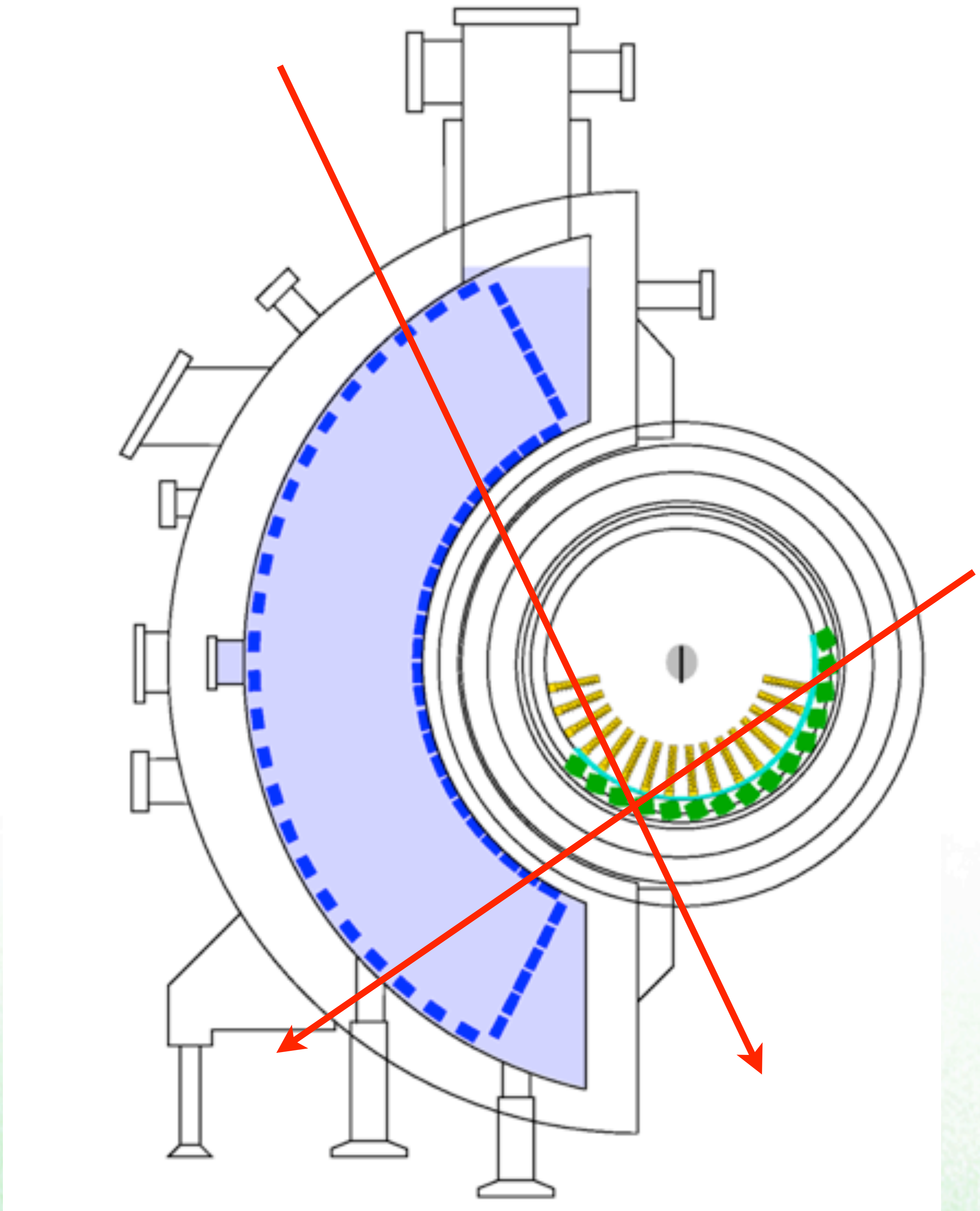
factor 0.9992 ± 0.000264
129
83
55
17.6
12
4.4
Reconstructed Energy [MeV]
Truth Energy [MeV]
0
20
40
60
80
100
120
140

Alignment between detectors

- Positron spectrometer
  - **Optical survey**
- Photon detector
  - PMT position scan using **AmBe source**
  - Calibration 17.6 MeV gamma, with **lead collimators**

Cosmic rays passing both systems

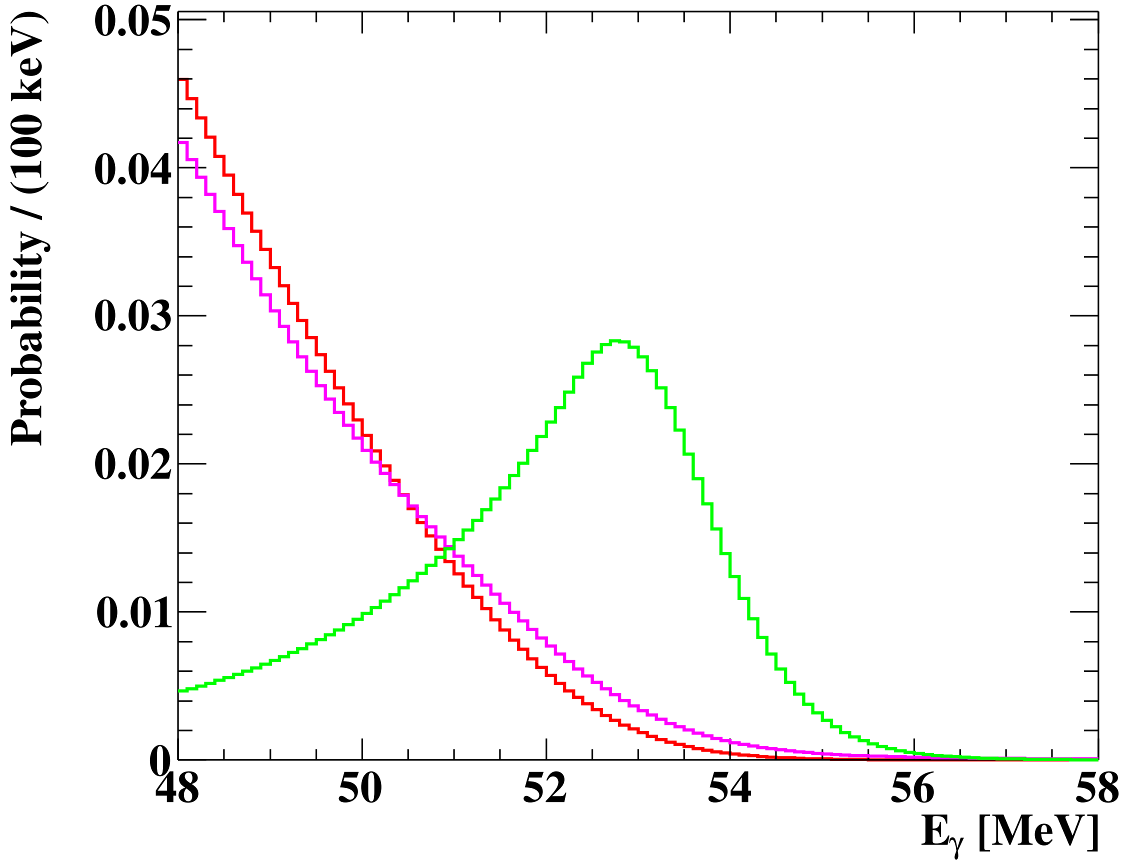
~1mm agreement in various methods

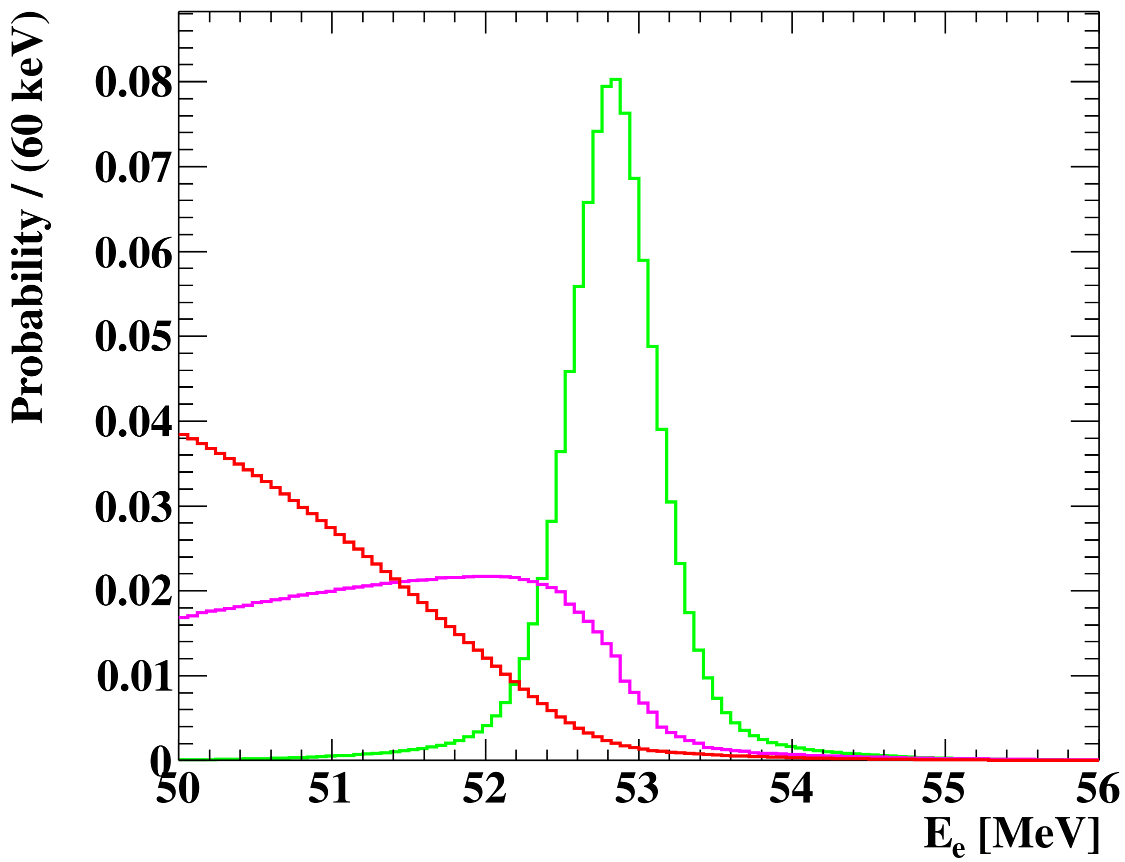


Probability density functions (PDF)

Signal RMD BG

E_γ E_e





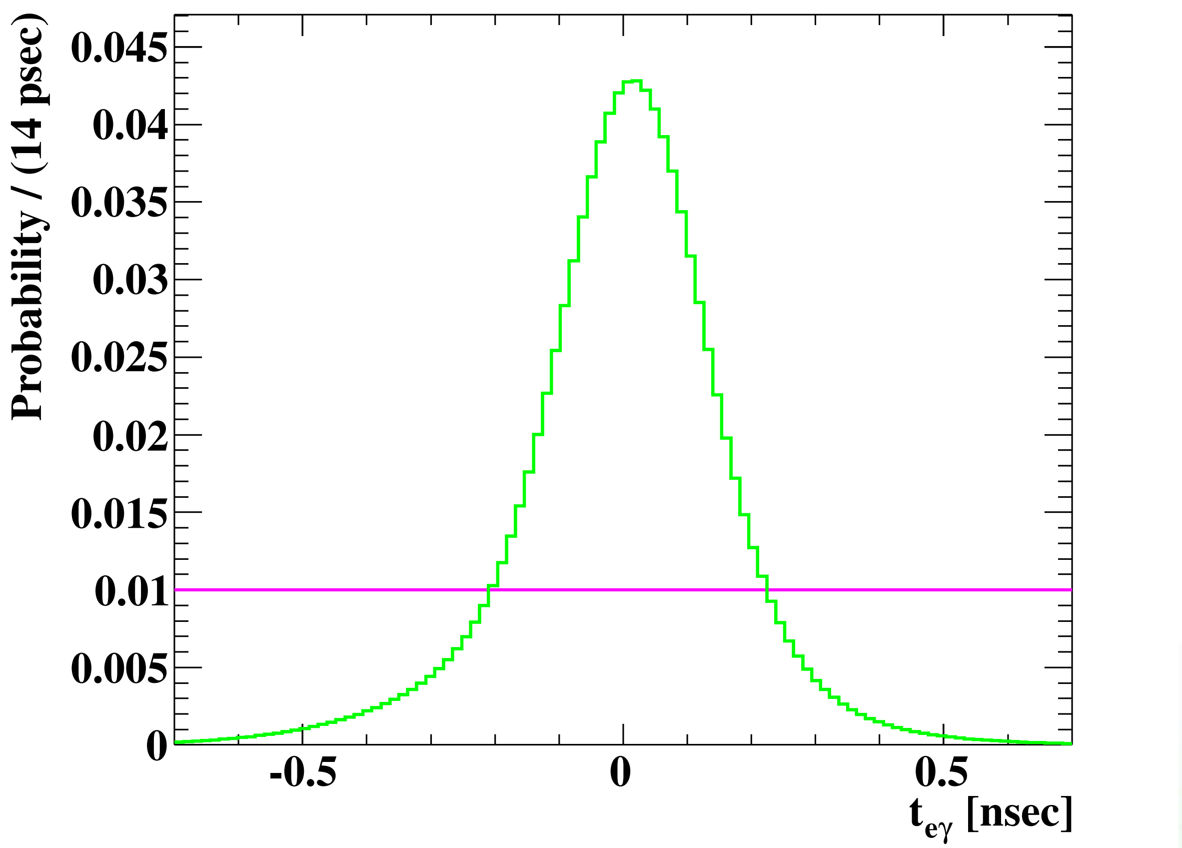
Signal : CEX data
BG : Sideband data
RMD : SM + detector response

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

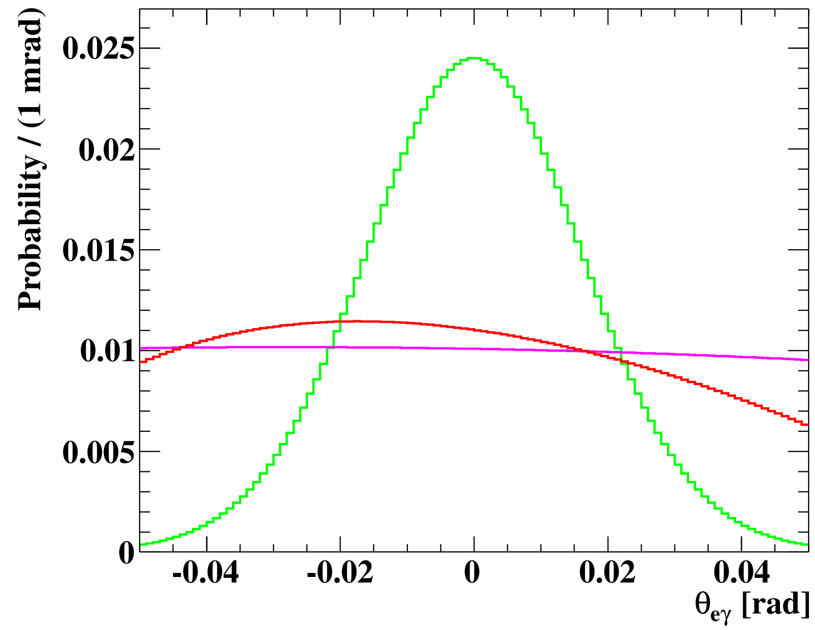
Probability density functions (PDF)

Signal RMD BG

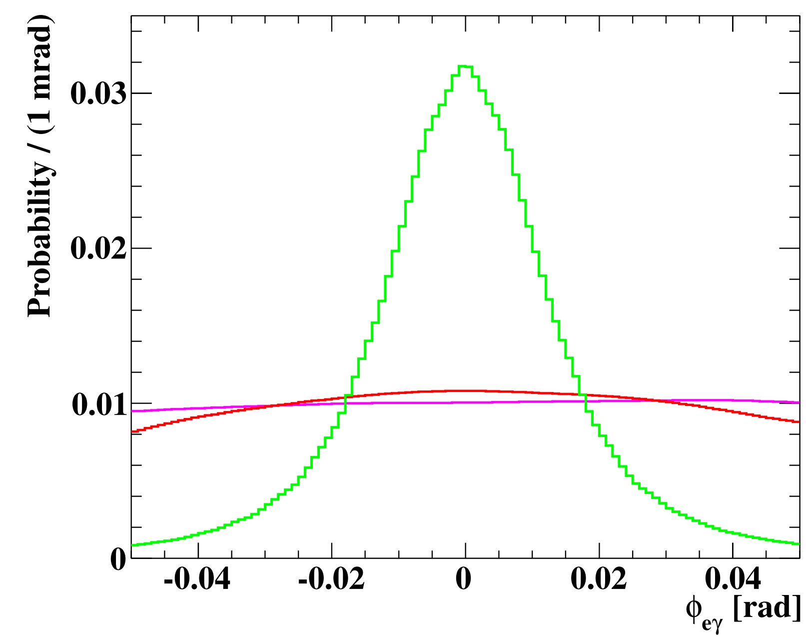
$T_{e\gamma}$



$\vartheta_{e\gamma}$



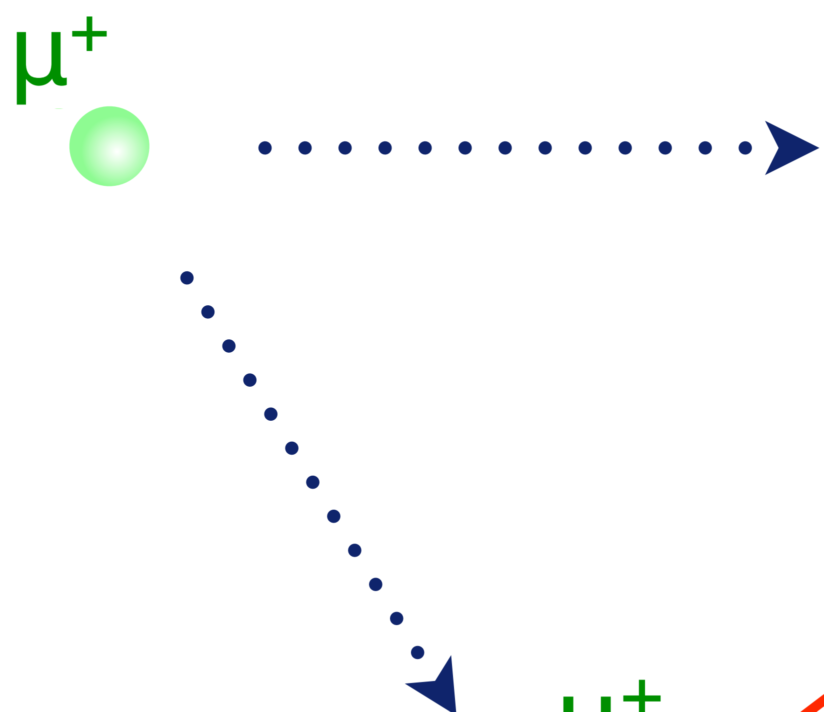
$\varphi_{e\gamma}$

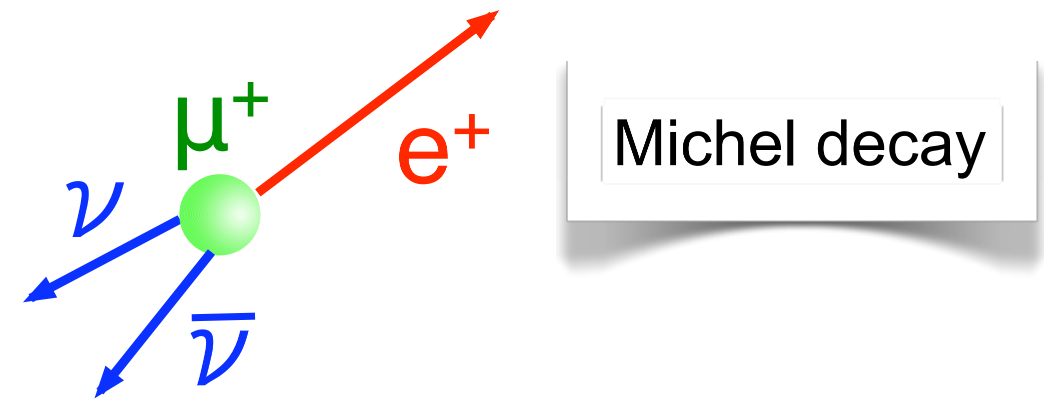


Signal : RMD data
BG : Flat
RMD : SM + detector response

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

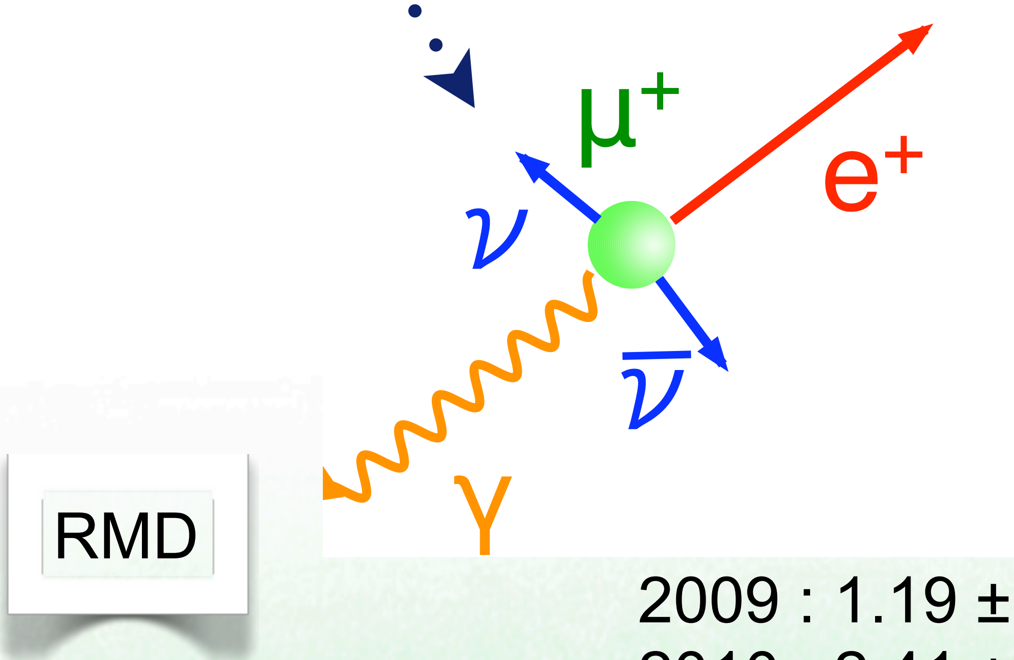
Normalization





2009 : 1.21 ± 0.07
2010 : 2.66 ± 0.13
2011 : 4.10 ± 0.20
$\times 10^{12}$

~ 5% Uncertainty



2009 : 1.19 ± 0.06
2010 : 2.41 ± 0.13
2011 : 3.96 ± 0.24
$\times 10^{12}$

~ 6% Uncertainty

2009 : 1.20 ± 0.06
2010 : 2.52 ± 0.09
2011 : 4.05 ± 0.16
$\times 10^{12}$

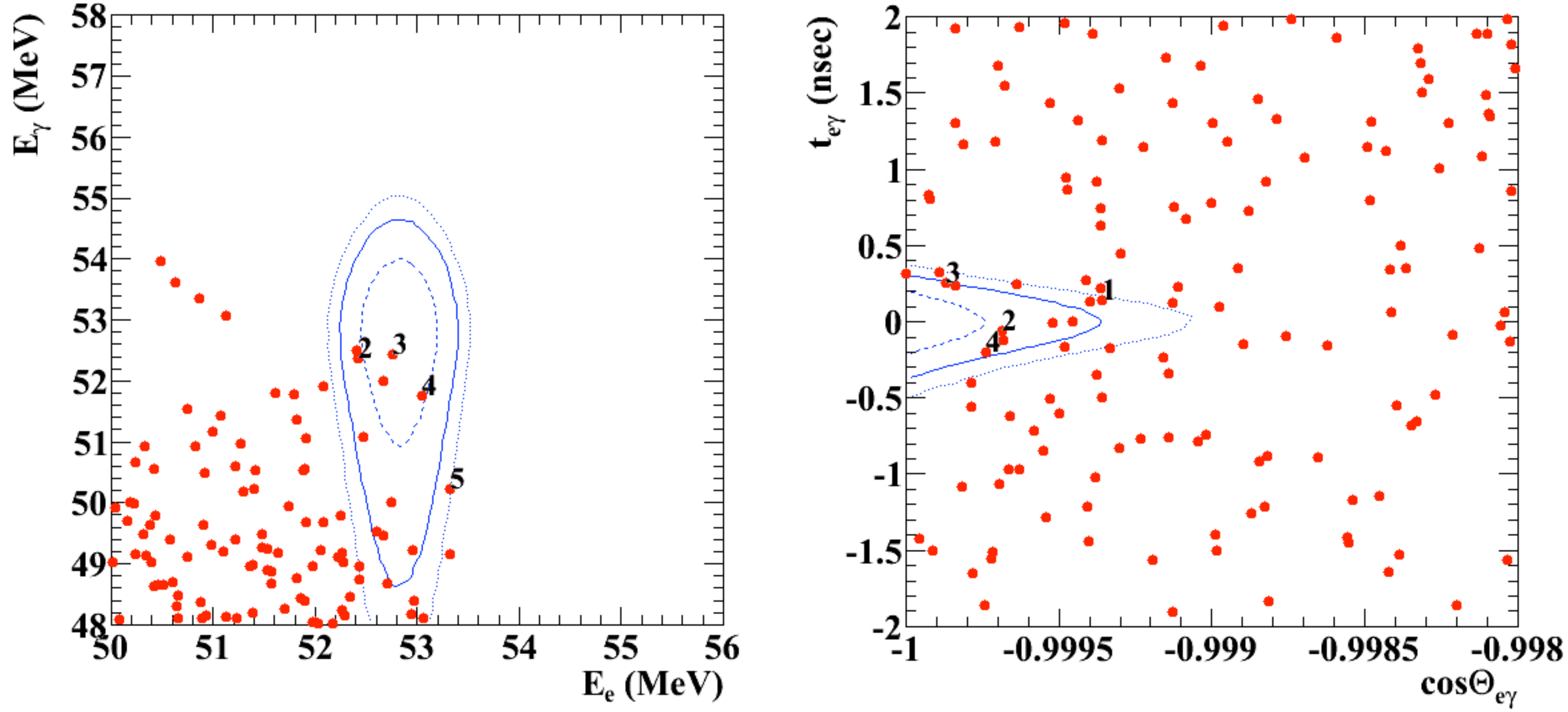
~ 4% Uncertainty

Event distribution (previous analysis)

2009+2010 data

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

Phys. Rev. Lett. 107 171801

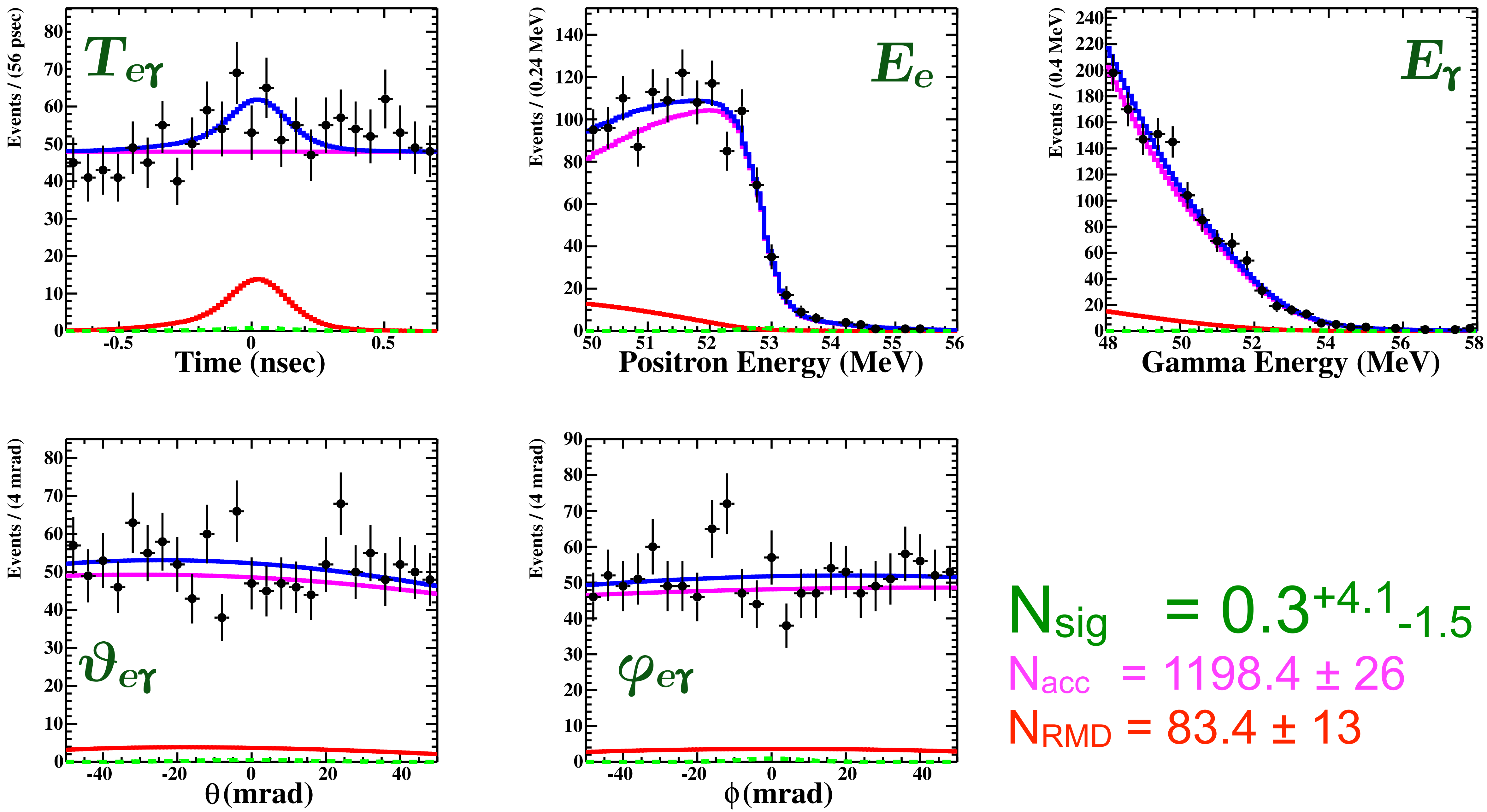


2009+2010 Fit Result

Signal
RMD
BG
Total

dotted line : 90% UL

Unbinned likelihood fitting on 5 dimension observable data



$N_{sig} = 0.3^{+4.1}_{-1.5}$

$N_{acc} = 1198.4 \pm 26$

$N_{RMD} = 83.4 \pm 13$

errors : MINOS 1.645σ