MEG I final result and MEG II

Ryu Sawada
ICEPP, The University of Tokyo

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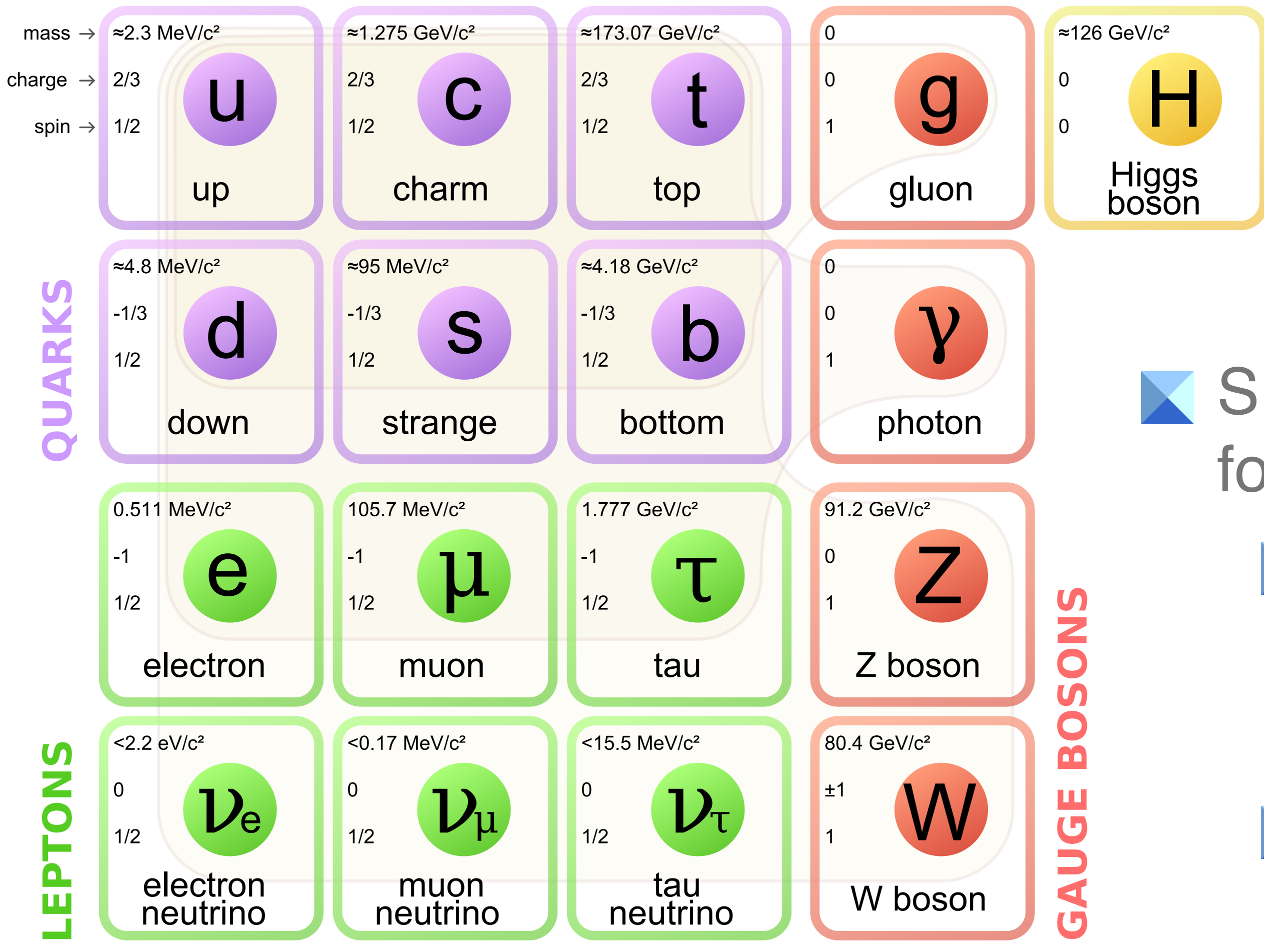
Standard Model



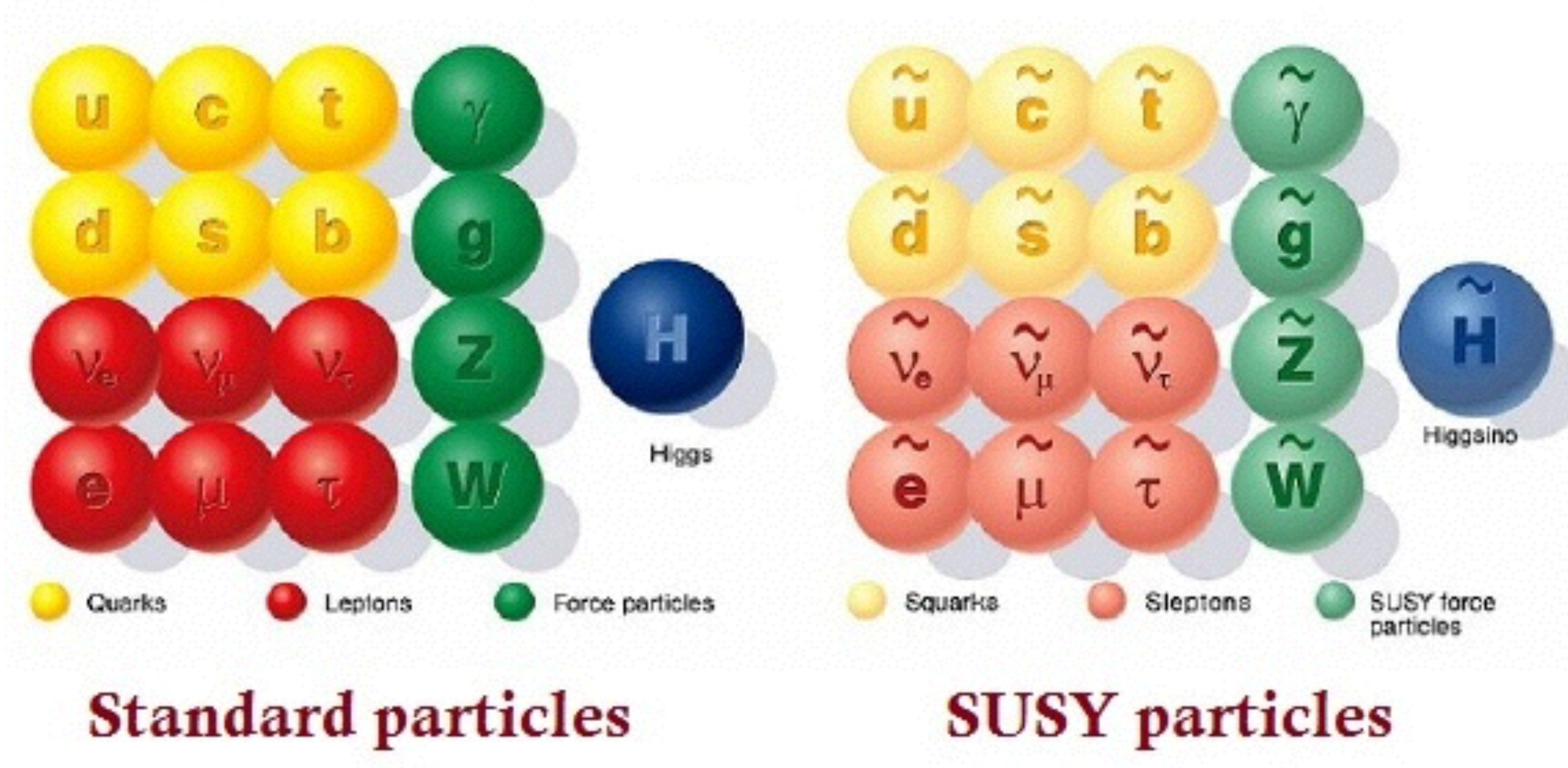
from wikipedia

- SM is a very successful theory of the matter and force.
  - Compatibility with many experiment results with very high precision.
    - No significant deviations were observed.
  - All the fundamental particles are already found (Higgs in 2012)

- But, there are some problems,
  - Hierarchy problem
  - Dark matter and dark energy
  - Gravity is not in the theory
  - …

SM can be a low-energy approximation of new physics

Supersymmetry

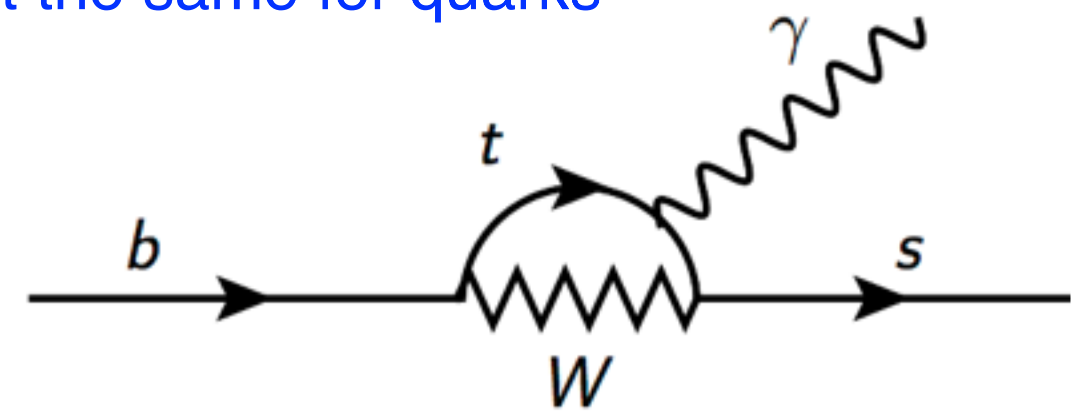


(Illustration: CERN & IES de SAR)

- Spacetime symmetry which relates bosons and fermions
- Solves problems of SM
- Another set of particles with 1/2 spin difference
  - squarks (stop, sbottom etc), sleptons, chargenos, neutralinos and higgsino

Flavor Mixing in SM

- Mass eigenstates and flavor eigenstates are not the same for quarks and neutrinos



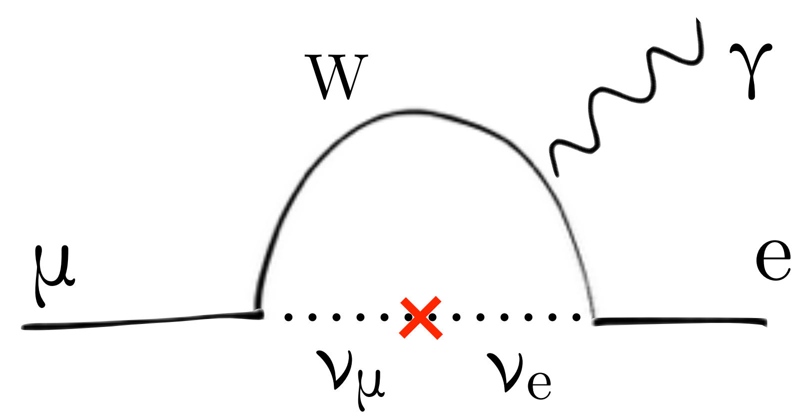
  - Flavor mixing
    - Quarks : CKM matrix
    - Neutrinos : PMNS matrix

      Neutrino oscillation

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

$l_i \rightarrow l_j$ transitions through W-ν mediation is suppressed (GIM)

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W} \right|^2 \simeq 10^{-54}$$



LFV in charged sector is forbidden because it is not observed

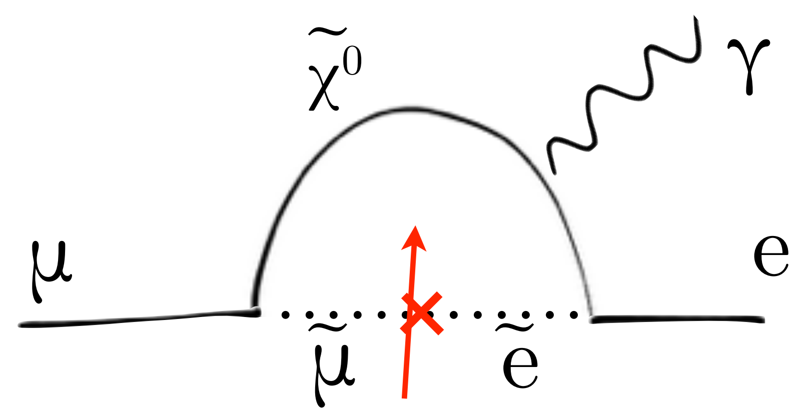
CLFV and Physics beyond SM

In many new theories beyond the SM, LF conservation is naturally violated.

SUSY-GUT
SUSY-Seesaw
Extra dimension
...

Several observations which suggests large lepton flavor violation in charged sector (CLFV) signal

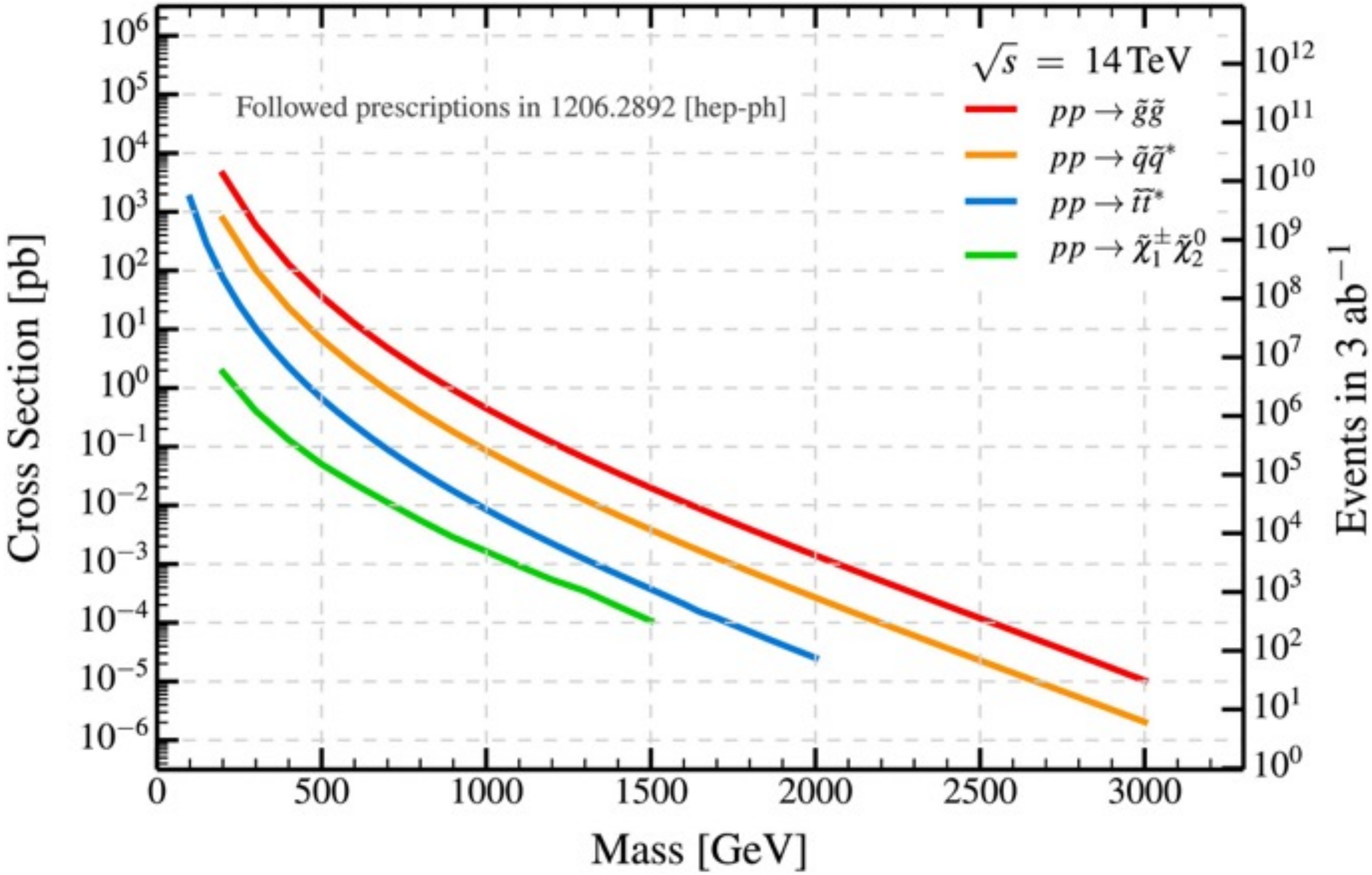
- 3.3—3.6 σ deviation of observed **muon g-2** (anomalous magnetic dipole moment)
  - can be a hint of new physics which relates to muon
- Large **neutrino mixing angle θ_{13}** : 9 deg
  - Large CLFV in new physics
- Discovered **Higgs** is light : 125 GeV
  - Higgs is likely to be elementary
- Excess of **LFV Higgs decay** : 2.4σ excess of $h \rightarrow \mu\tau$ by CMS

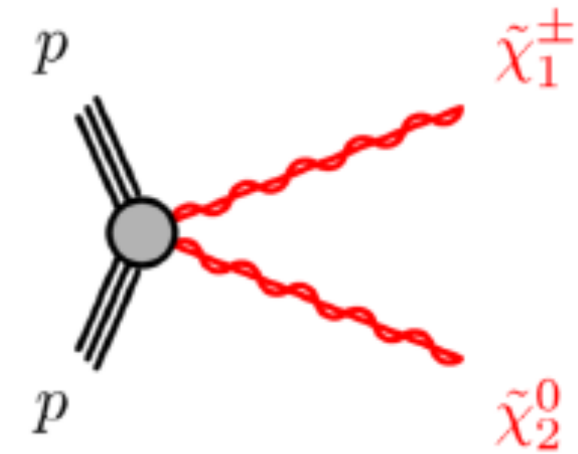


New physics at very high energy scale

An observation of CLFV would be a clear evidence of the new physics

CLFV and LHC

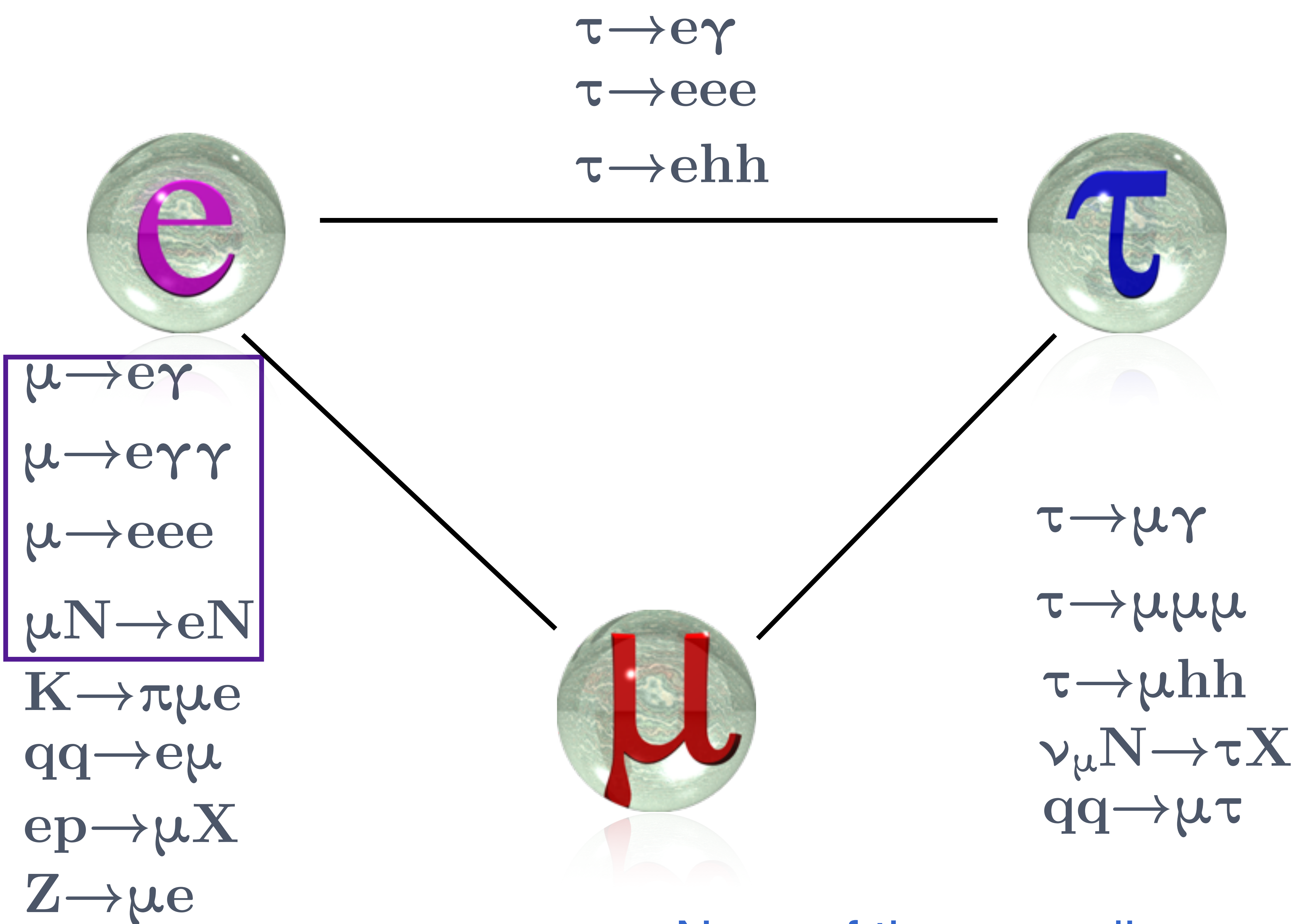




Paul de Jong, Experimental challenges for SUSY (and other new physics) searches at the LHC 13/14

CLFV rare decay searches are complementary to direct searches in LHC

CLFV channels



None of them are discovered

Ratio of channels

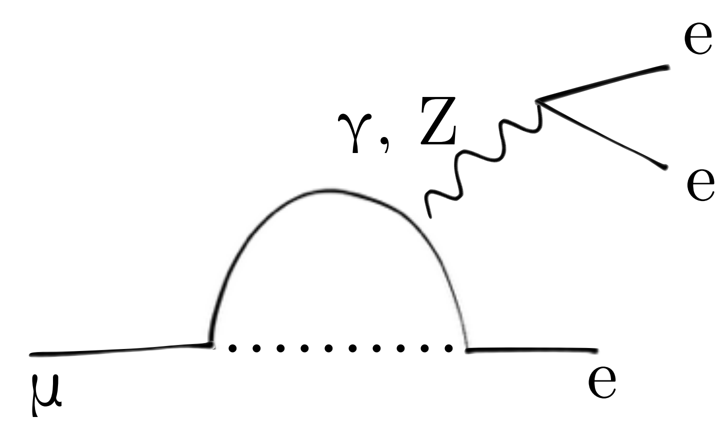
ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)}$	$0.02 \ldots 1$	$\sim 6 \cdot 10^{-3}$	$\sim 6 \cdot 10^{-3}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.4$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.4$	$\sim 2 \cdot 10^{-3}$	$0.06 \ldots 0.1$
$\frac{Br(\tau^- \to e^- \mu^+ \mu^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.3$	$\sim 2 \cdot 10^{-3}$	$0.02 \ldots 0.04$
$\frac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.3$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau^- \to e^- \mu^+ \mu^-)}$	$0.8 \ldots 2.0$	~ 5	$0.3 \ldots 0.5$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau^- \to \mu^- e^+ e^-)}$	$0.7 \ldots 1.6$	~ 0.2	$5 \ldots 10$
$\frac{R(\mu\mathrm{Ti} \to e\mathrm{Ti})}{Br(\mu \to e\gamma)}$	$10^{-3} \ldots 10^{2}$	$\sim 5 \cdot 10^{-3}$	$0.08 \ldots 0.15$

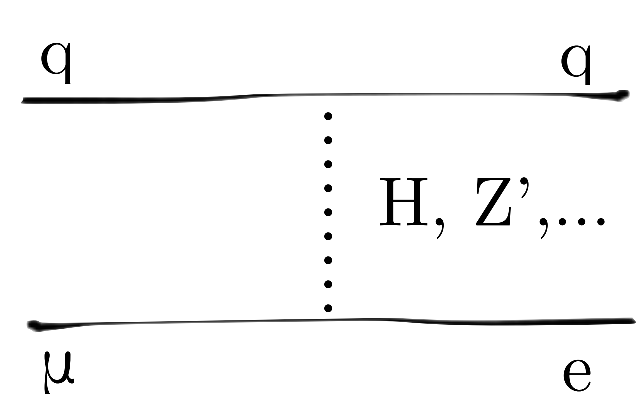
M.Blanke et al., Acta Phys.Polon.B41(2010)657

e.g.

Only loop effects are relevant to $\mu \to e\gamma$

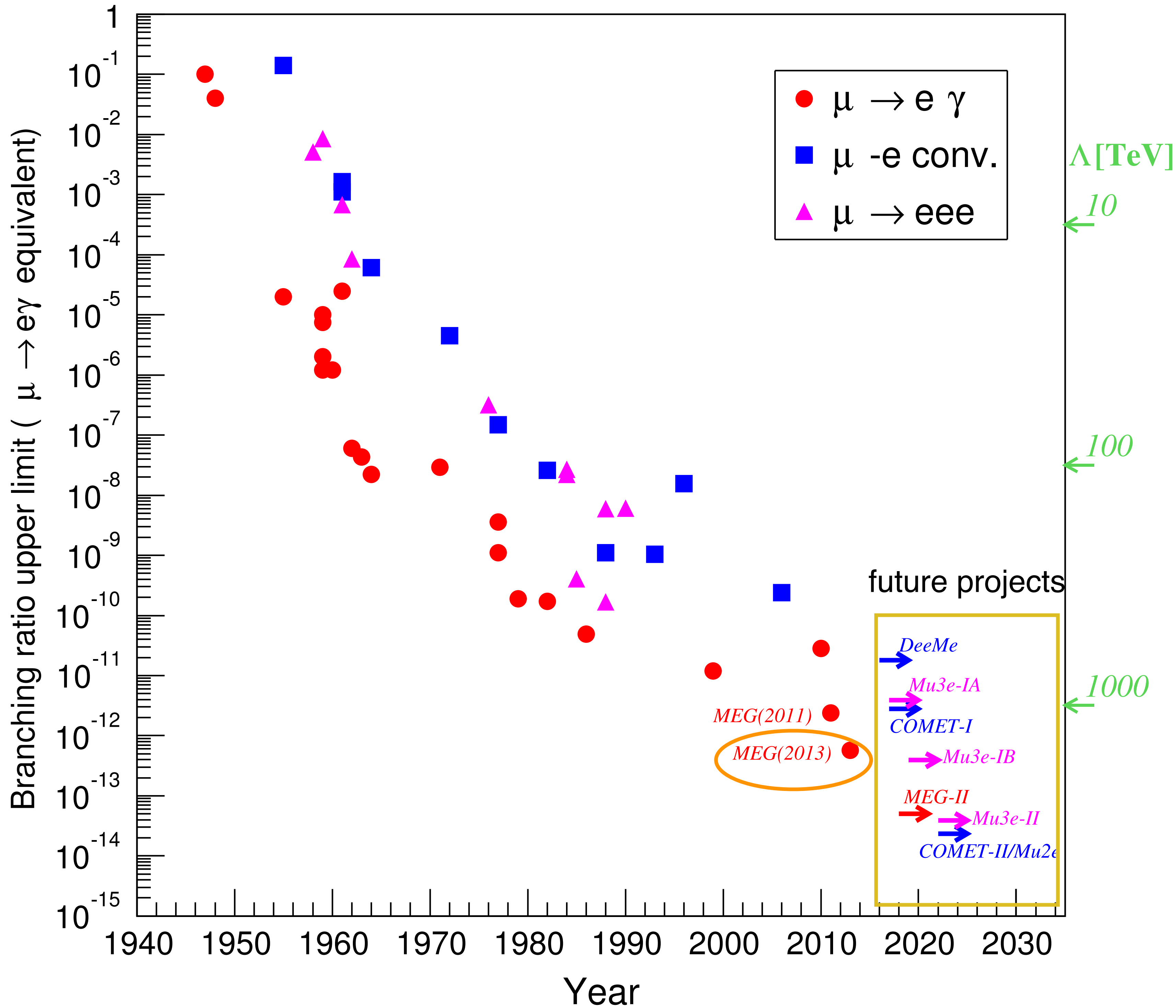
μ-e conversion, $\mu \to eee$ can be mediated by tree-level couplings





Searches for different channels are complementary.

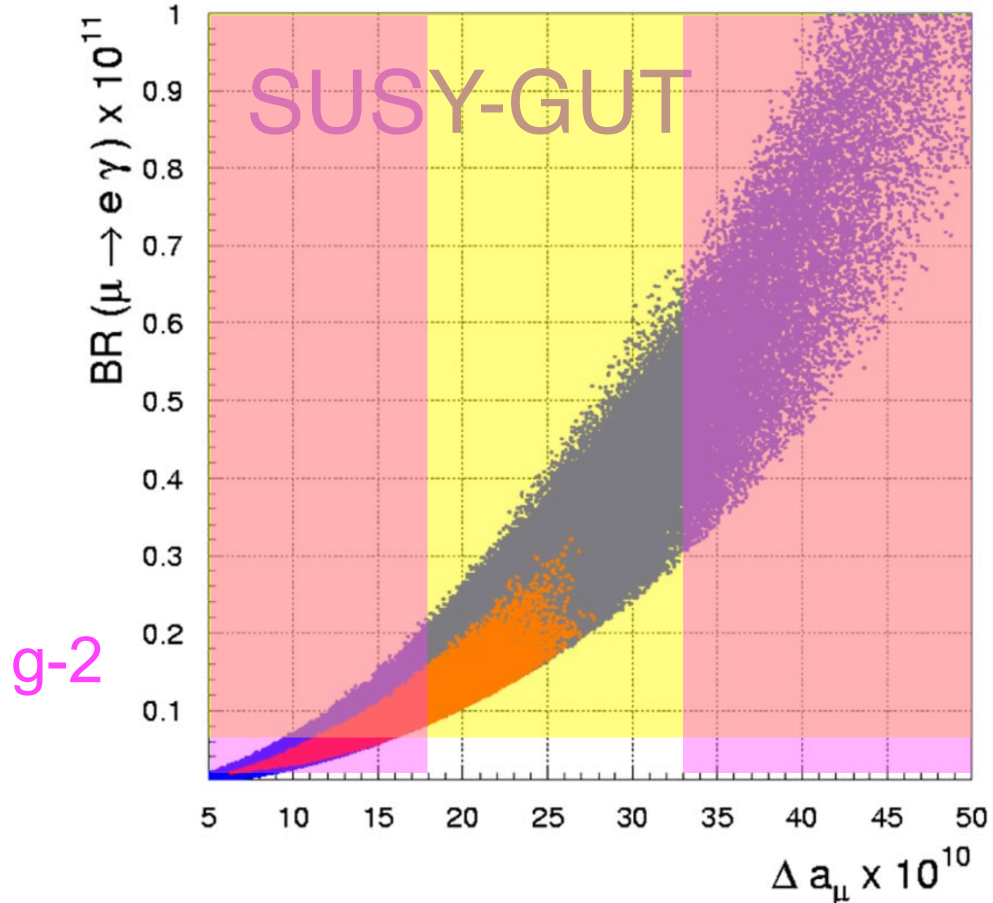
Current status of CLFV experiments



T. Mori and W. Ootani, Prog. Part. Nucl. Phys. 79, 57 (2014).

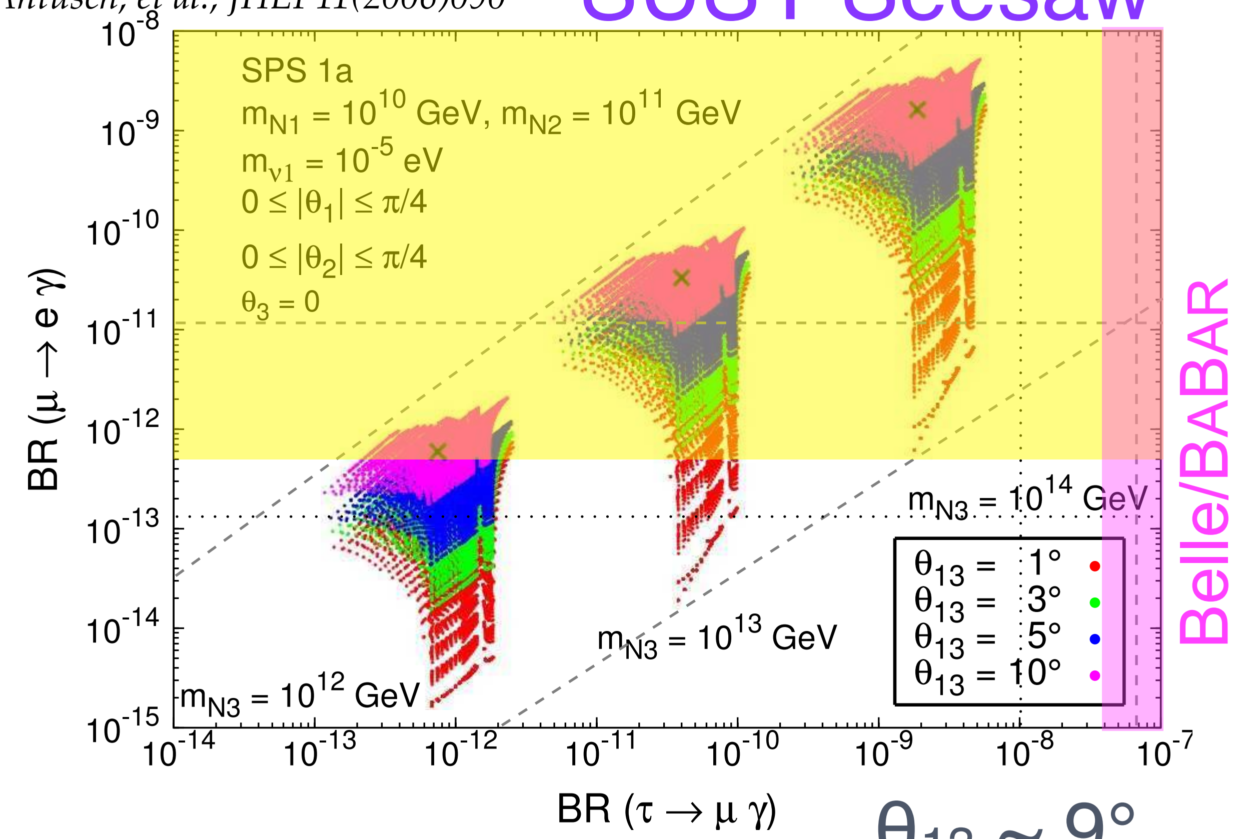
New physics models and CLFV

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



S. Antusch, et al., JHEP11(2006)090

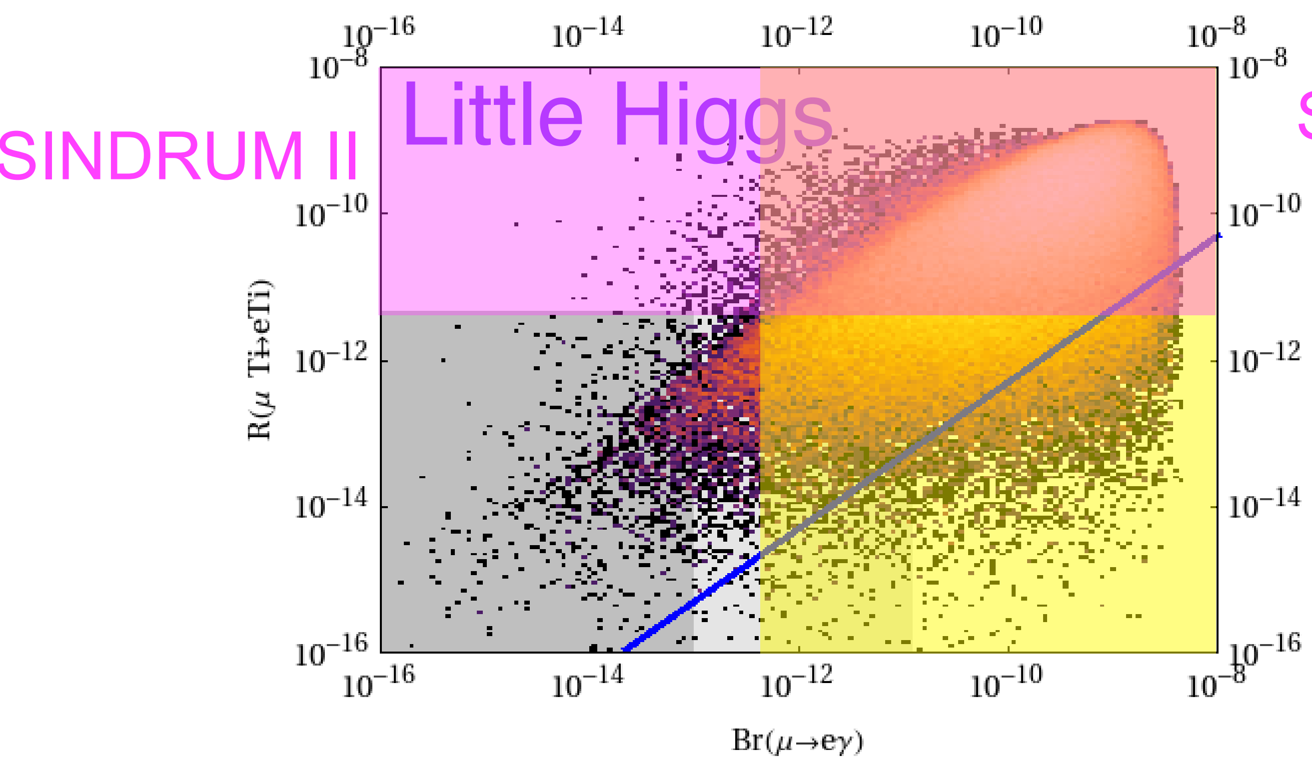
SUSY-Seesaw



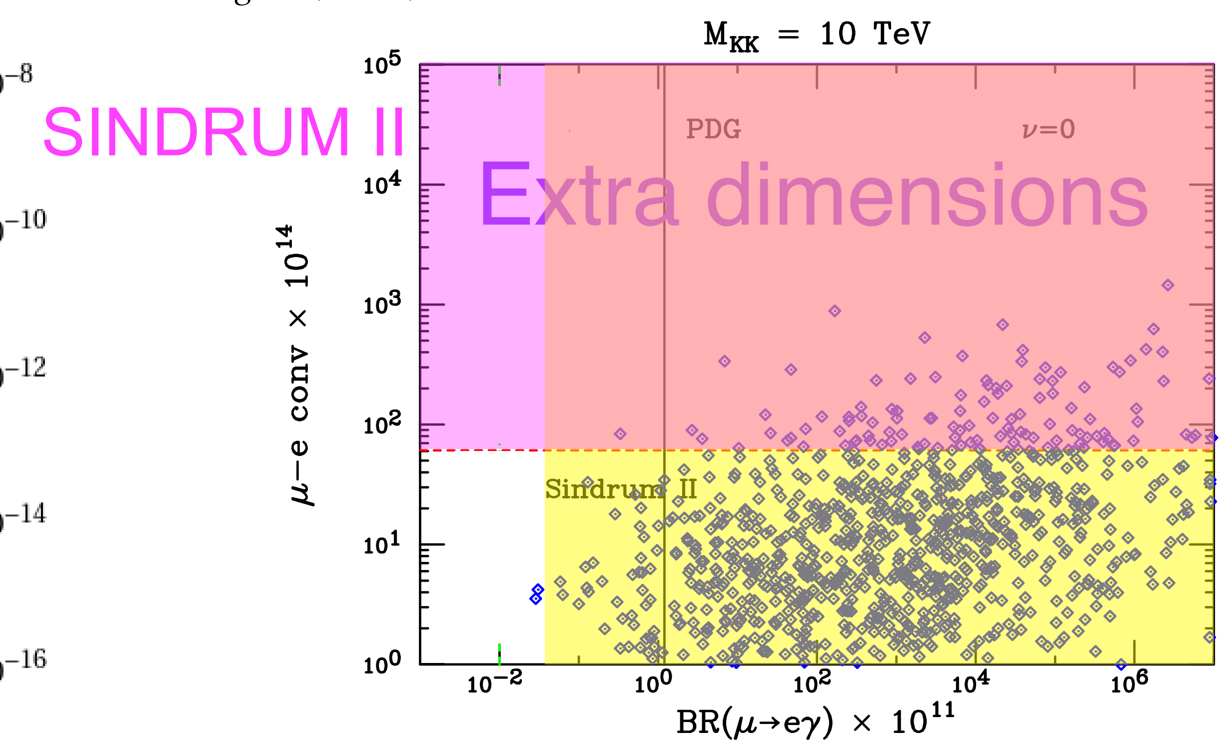
$\theta_{13} \sim 9°$

(Daya Bay, RENO, Double Chooz, T2K, MINOS)

M.Blanke et al., Acta Phys.Polon.B41(2010)657



K.Agashe, et al., PRD74(2006)053011



- CLFV is forbidden in SM
- Strong signals are predicted by new physics
  - A discovery of CLFV is a clear evidence of new physics
- There are several observations which suggest the existence of CLFV
- CLFV searches are complementary to the high-energy frontier
- Several CLFV searches are complementary to understand new physics

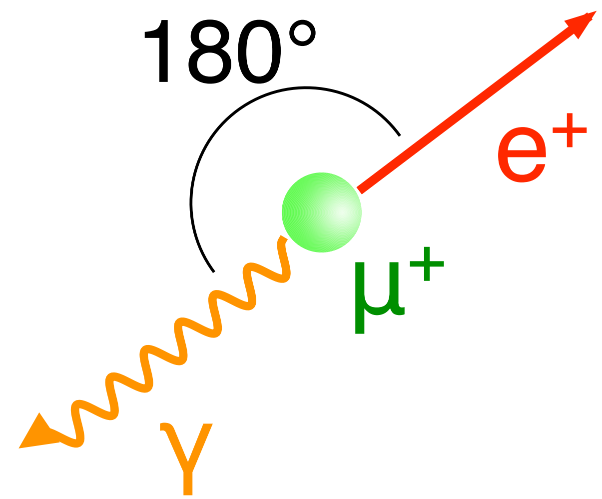
- $\mu \to e\gamma$ has been a leading channel of CLFV searches
  - The most stringent limit given by the MEG experiment
    - $Br < 5.7 \times 10^{-13}$ in previous result published in 2013 (Phys. Rev. Lett. **110**, 201801)
    - New results will be presented in this talk.

MEG

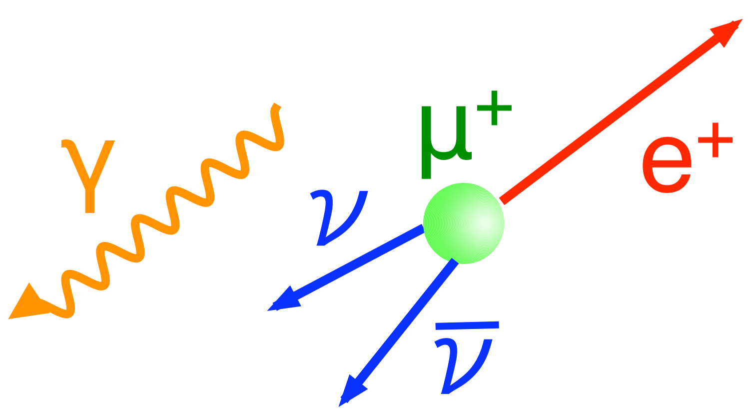
$\mu \to e\gamma$

Signal & Background

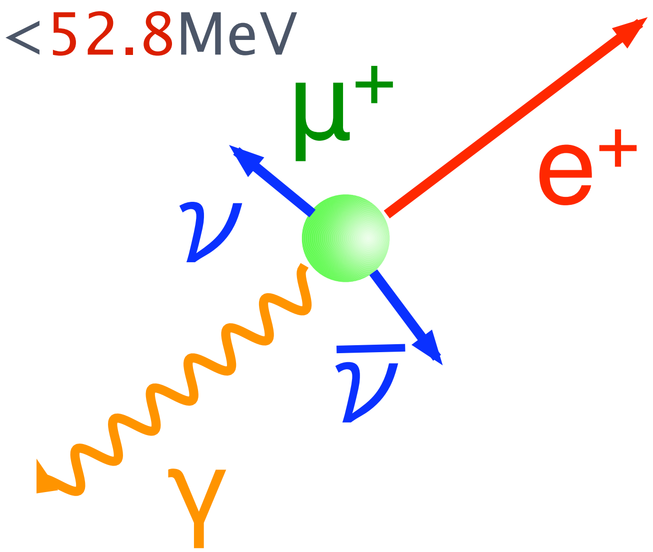
- Signal
  - μ^+ decay at rest
  - 52.8MeV (half of M_μ) (E_γ,E_e)
  - Back-to-back ($\theta_{e\gamma}$,$\varphi_{e\gamma}$)
  - Timing coincidence ($T_{e\gamma}$)



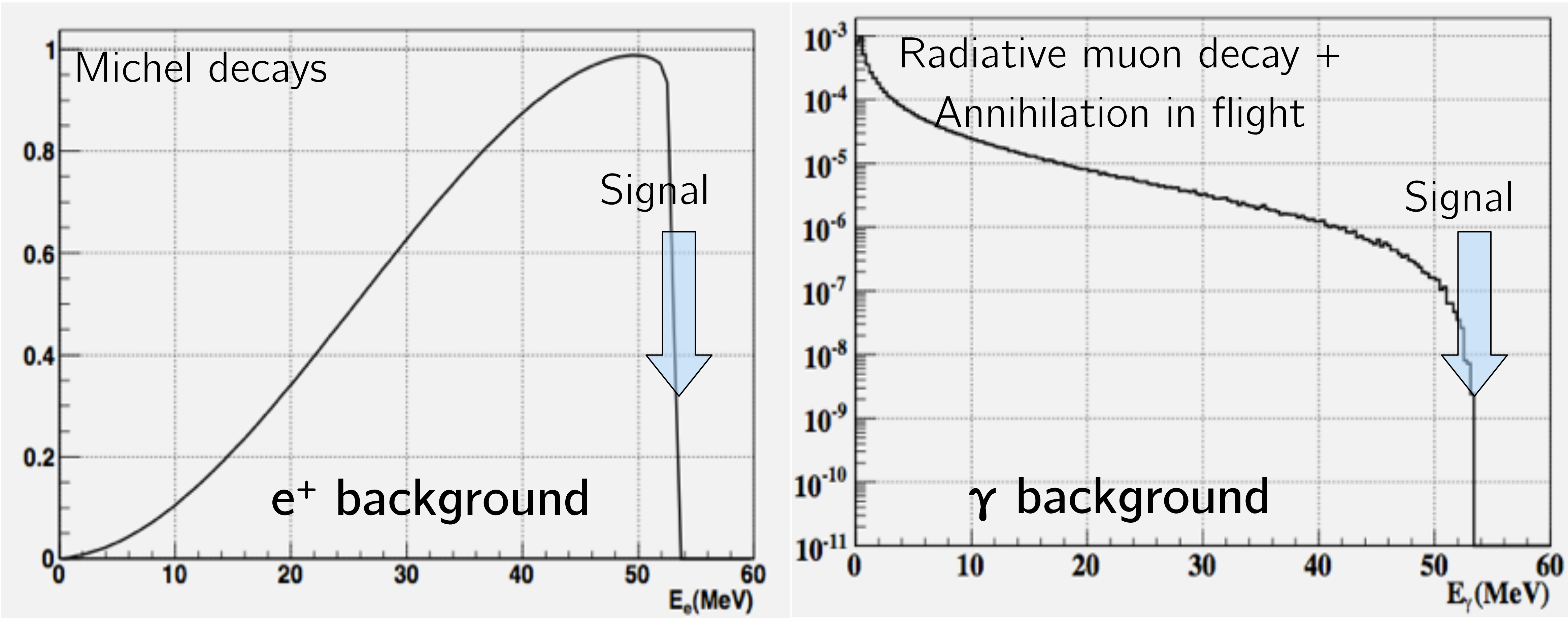
- Accidental background
  - Michel decay e^+ + random γ
  - γ from RMD or annihilation in flight (AIF) of positrons
  - Random timing, angle, <52.8MeV



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



Background spectra



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

Key items for μ→eγ experiments

High statistics

- Very high rate μ beam and stopping efficiency on target
- Large acceptance and high detection efficiency of the detector

Resolution

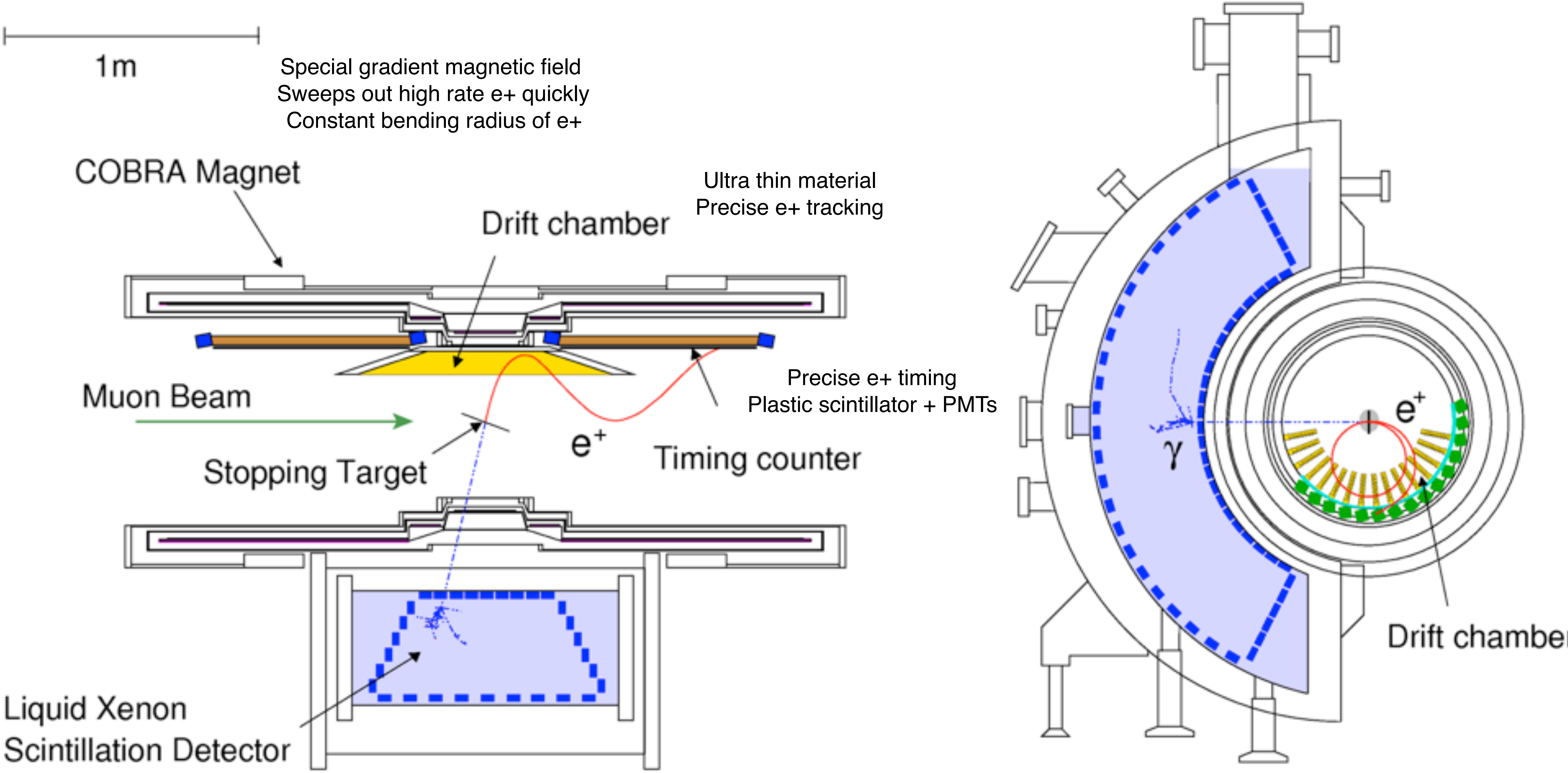
- Good resolution for relatively low (52.8 MeV) energy particles

low Background rate

- Low material budget hit by positrons

MEG Experiment

The most intense DC muon beam, 3×10^7 μ/s @ PSI, Switzerland

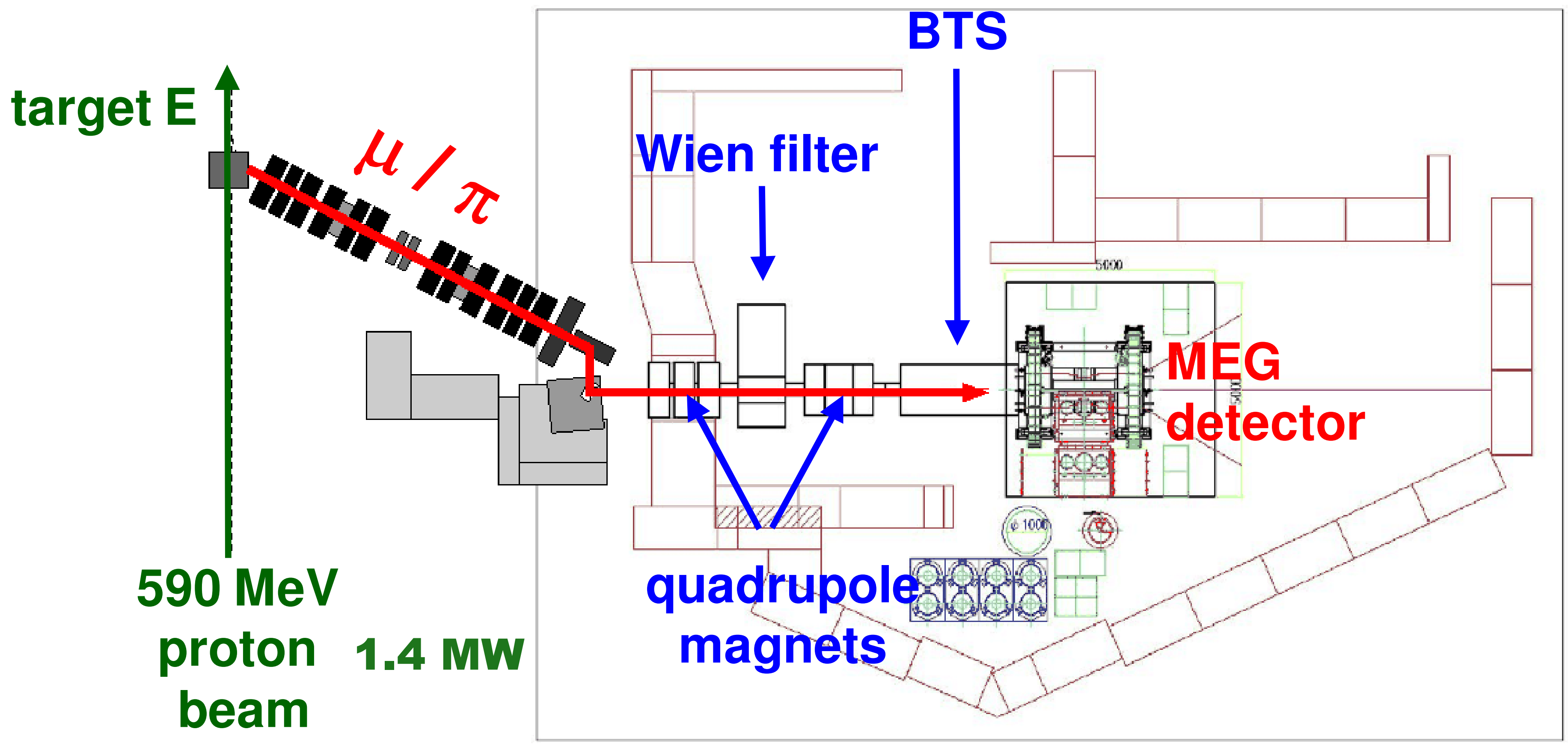


2.7 ton of liquid xenon
Homogeneous detector
Good time, position, energy resolution

Waveform digitizer for all detectors

Beam and target

PSI
πE5



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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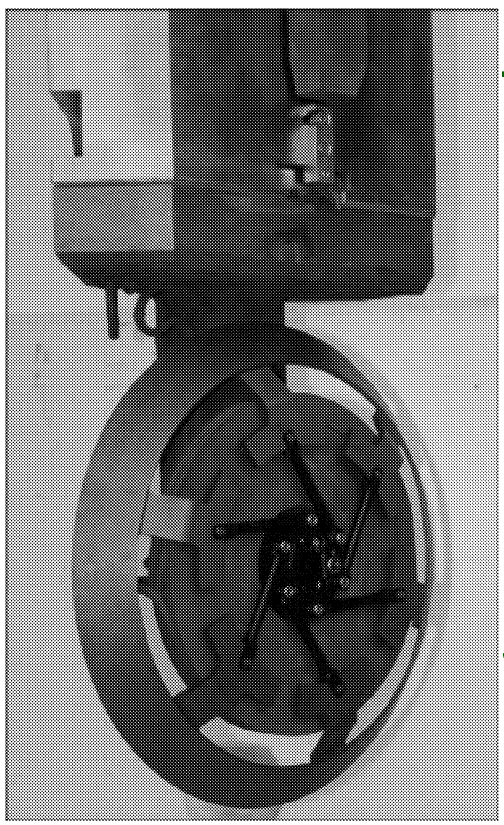

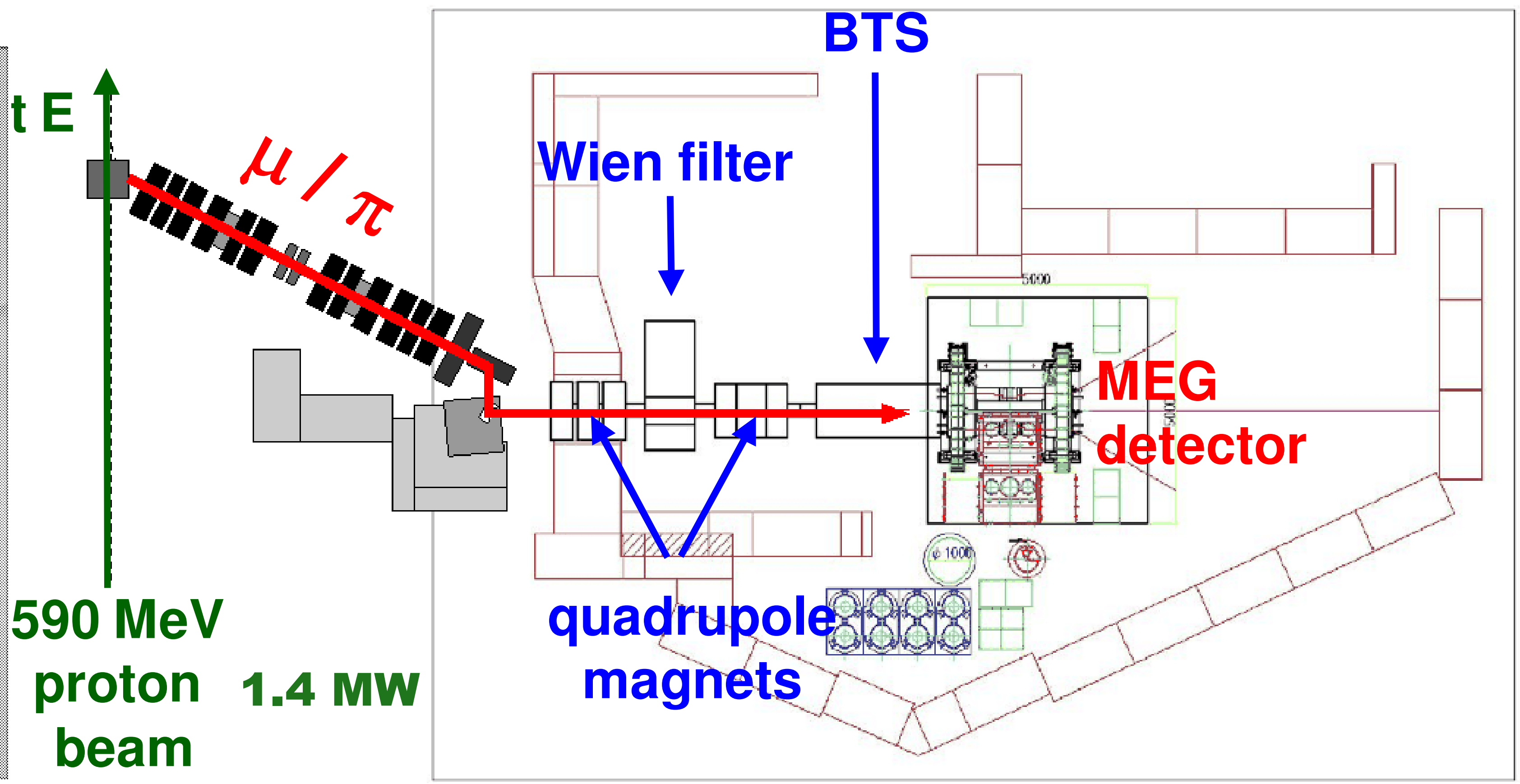

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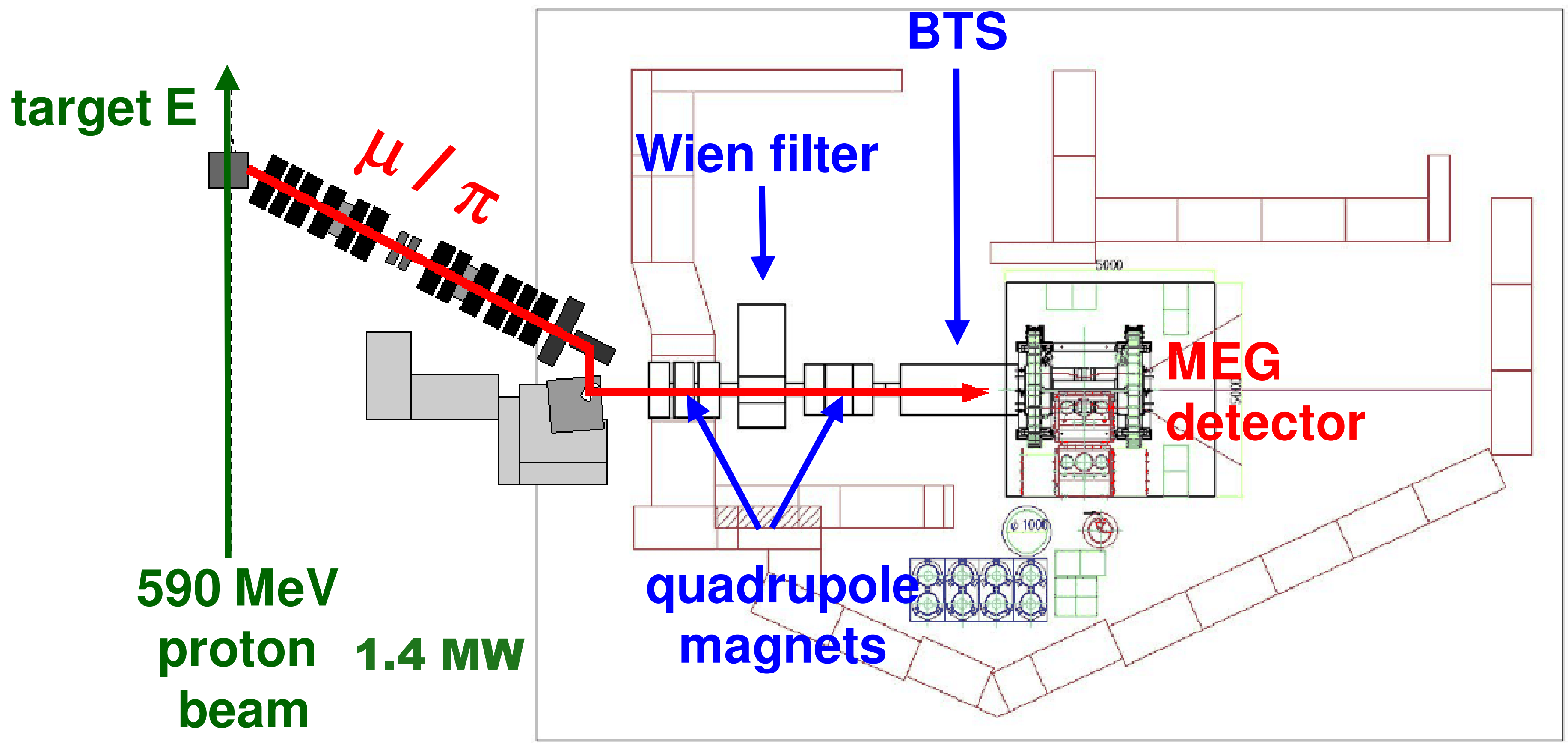

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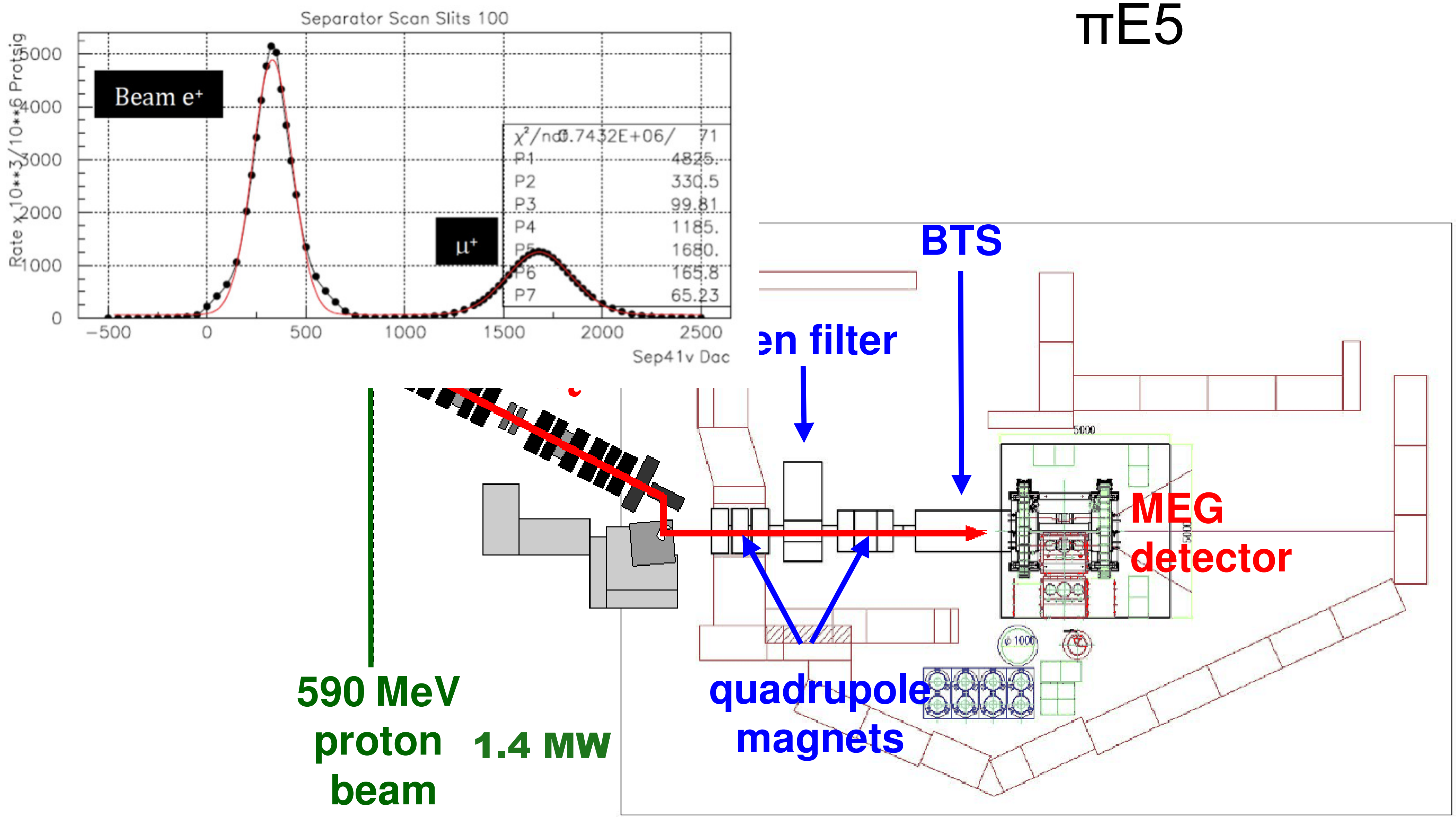

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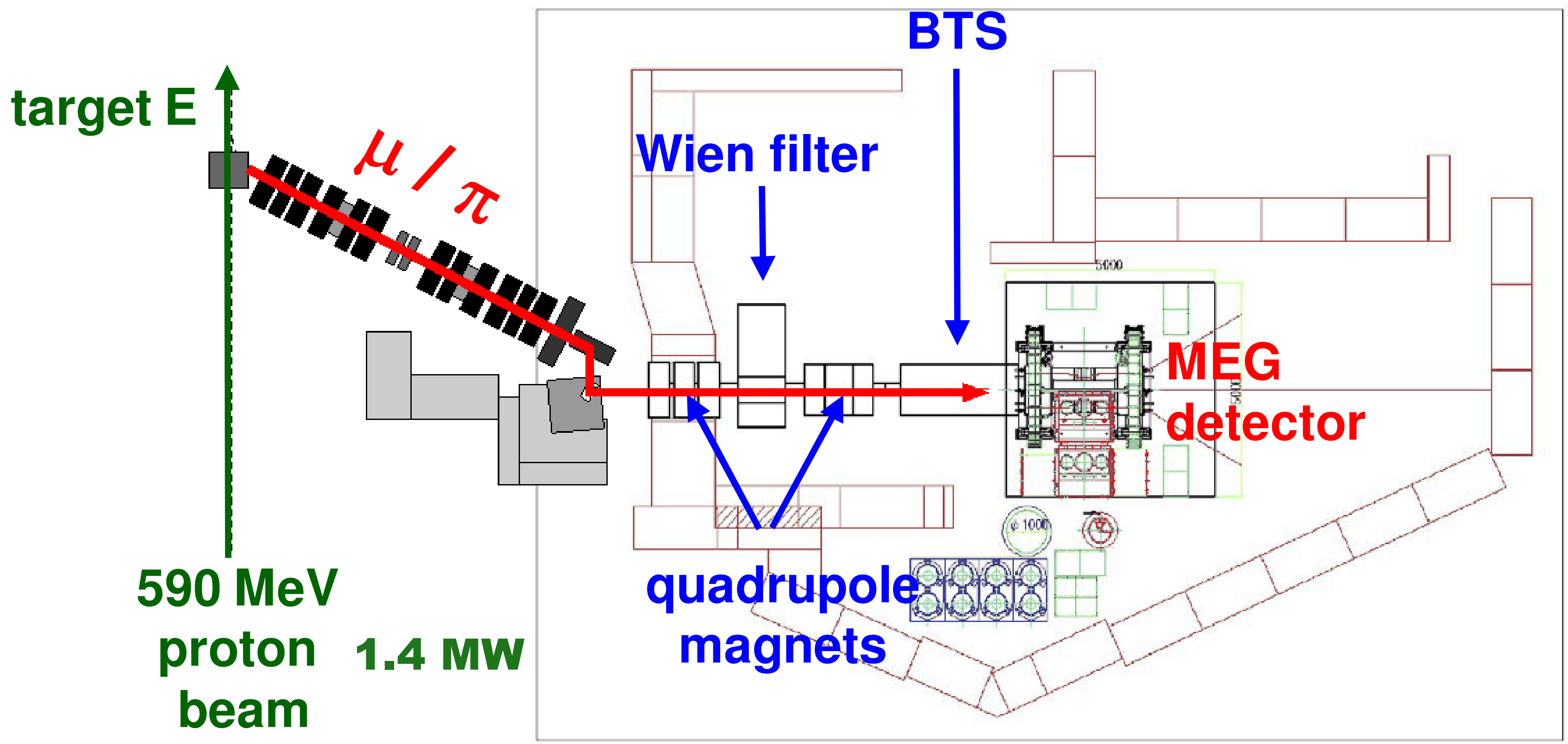

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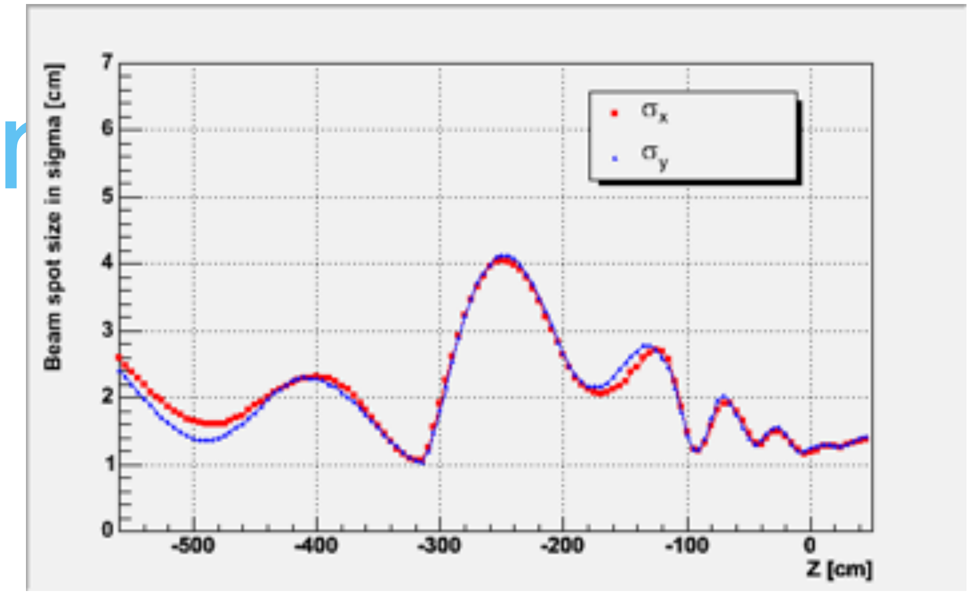

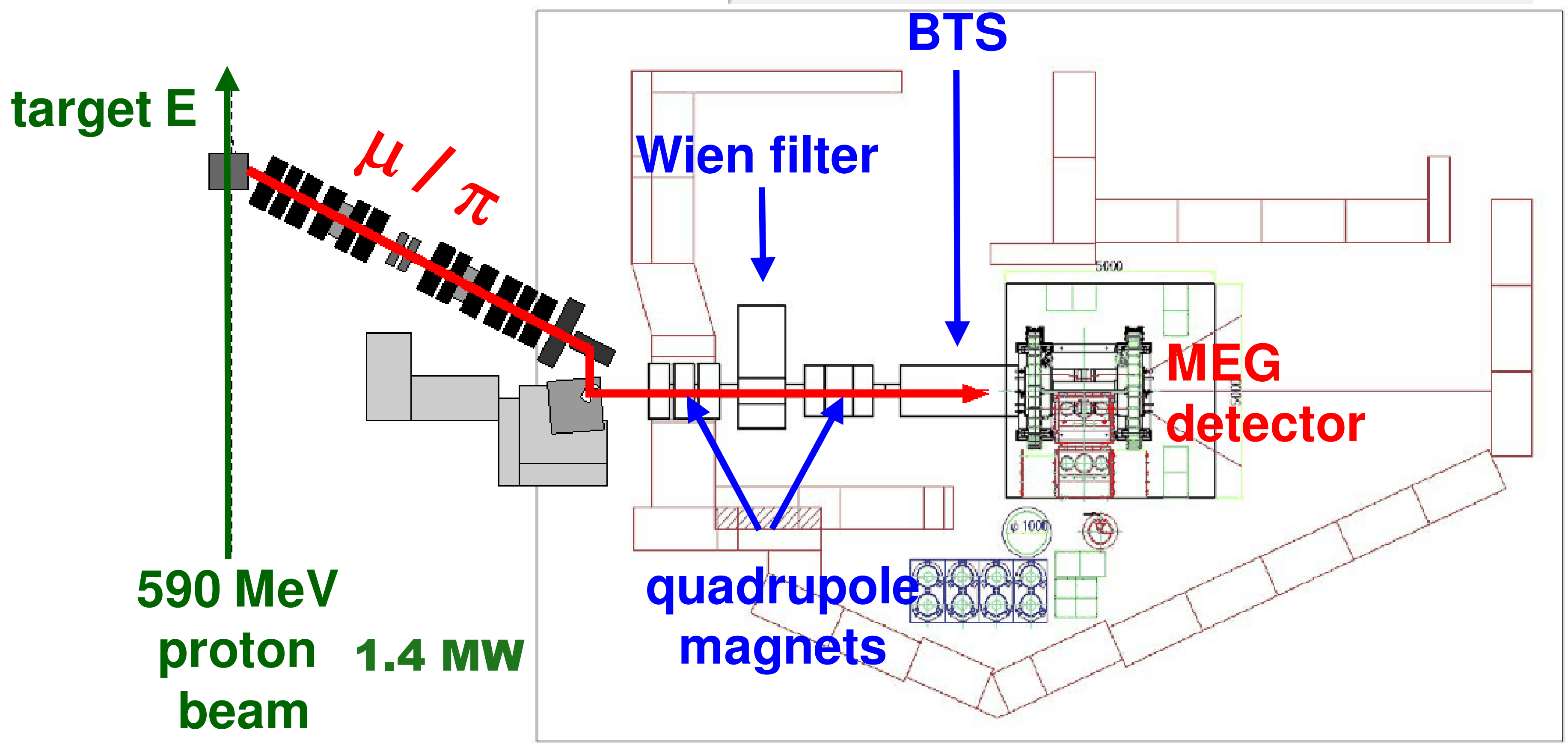

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PSI
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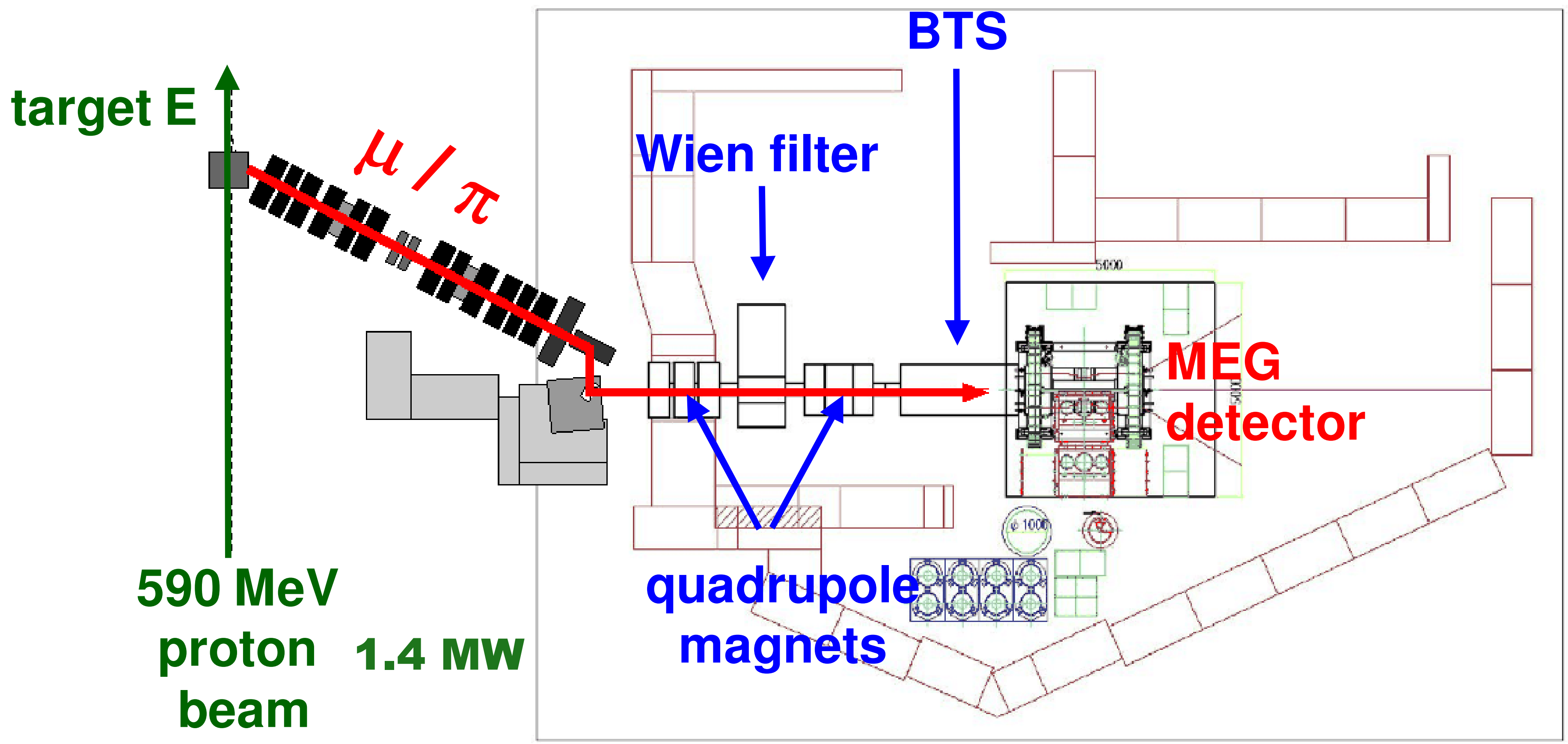

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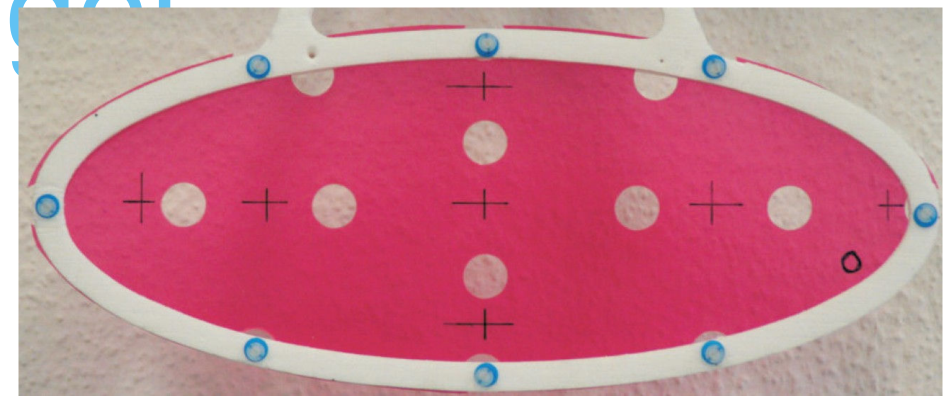

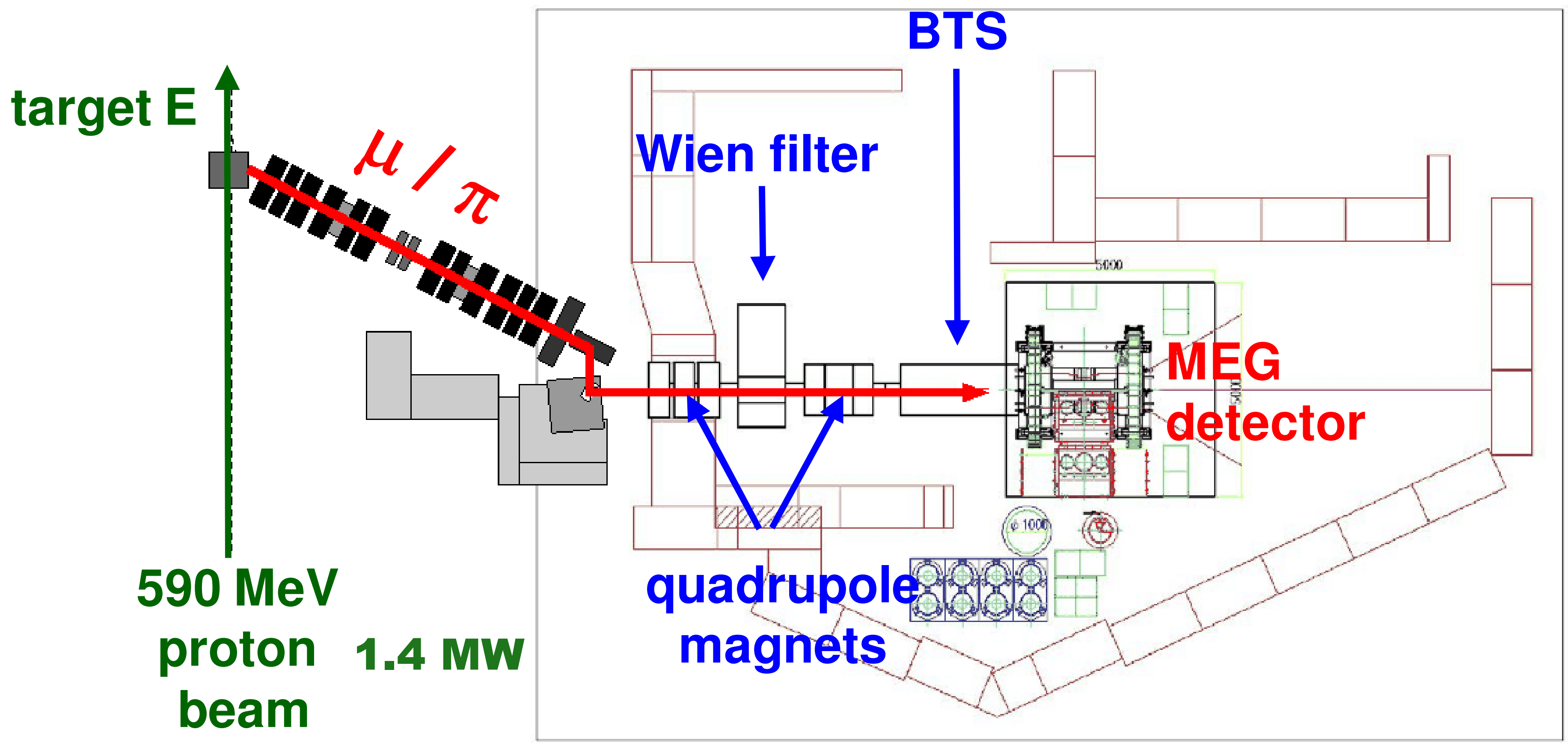

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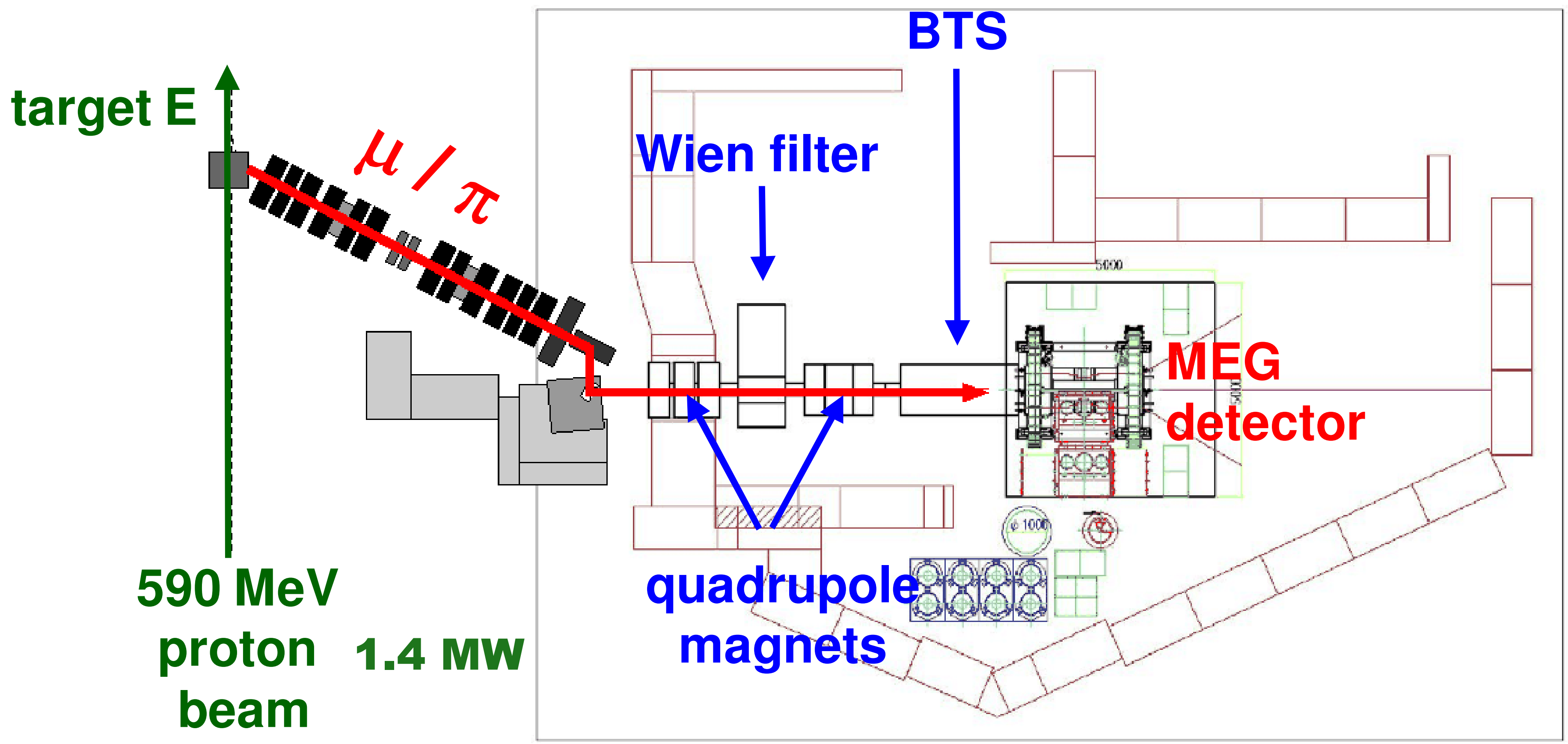
205 μm thick polyethylene plate
Slanted angle of 20.5°
79.8×200.5 mm
Stopping efficiency : 82%

Beam and target

PSI
πE5



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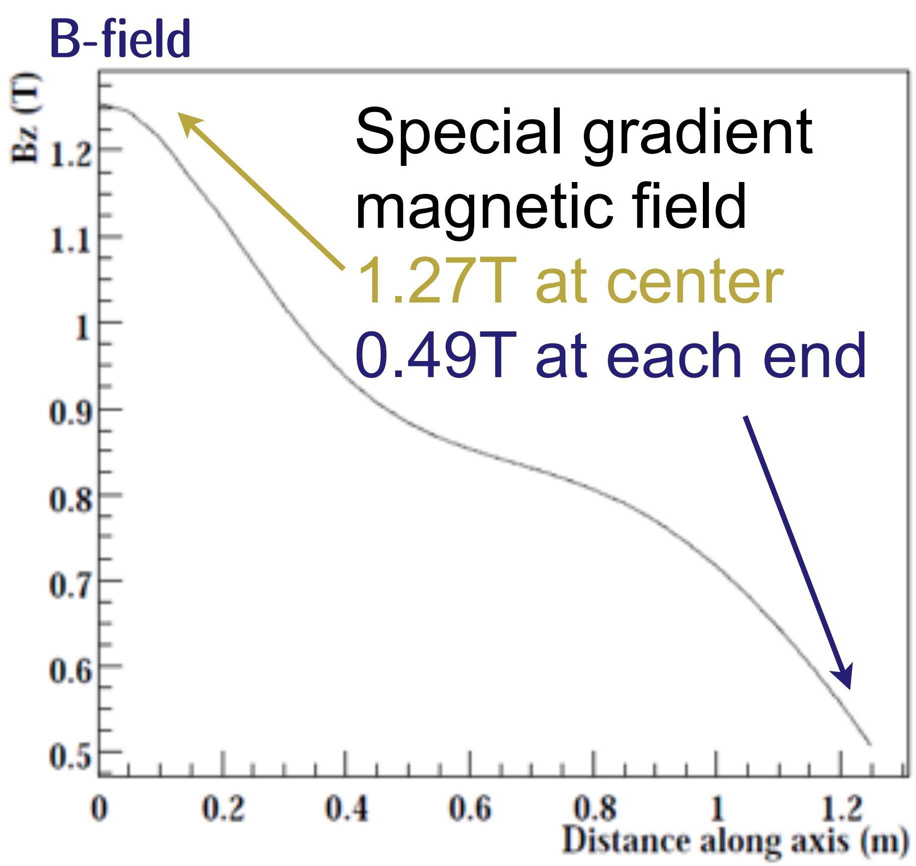
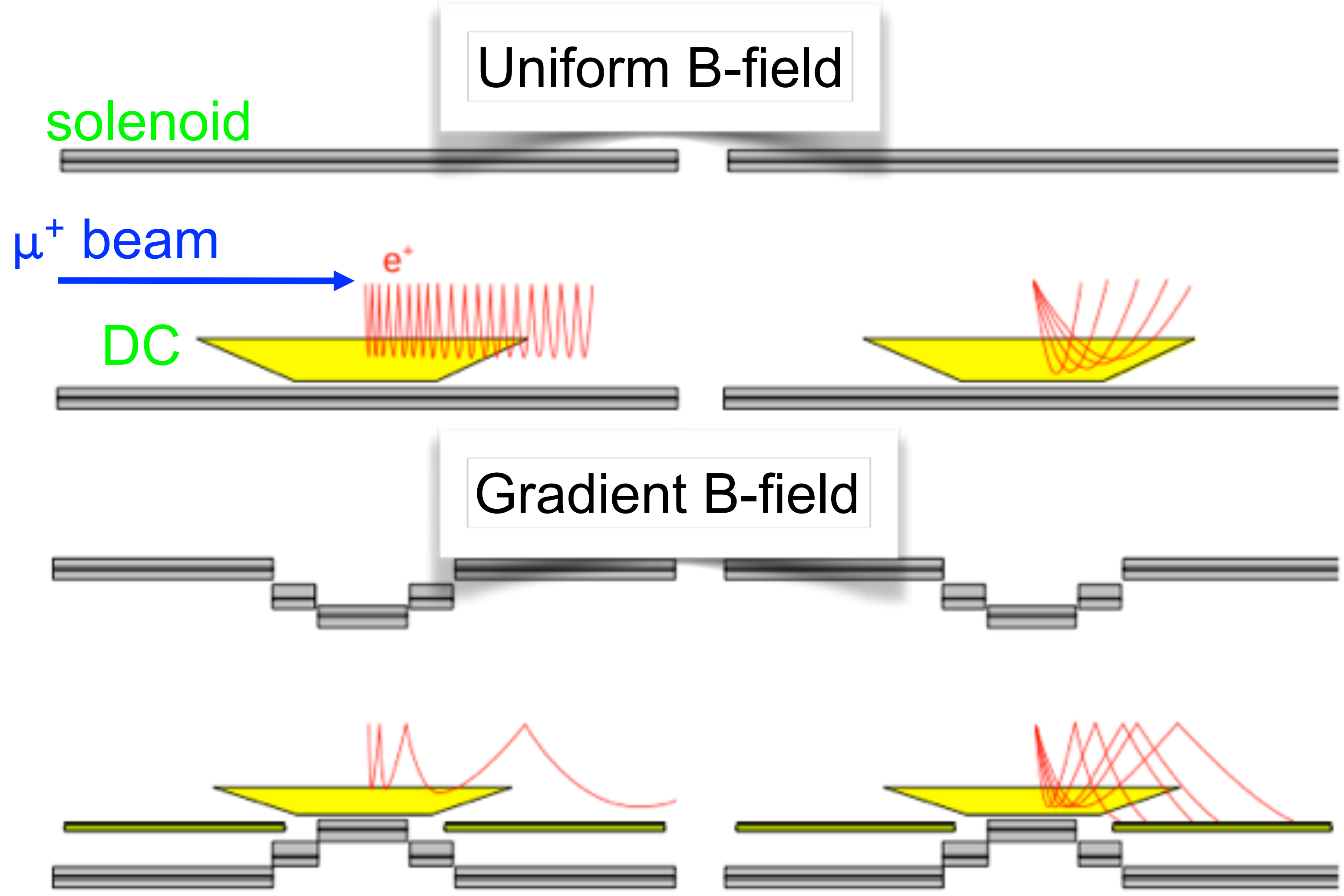
Positron spectrometer magnet



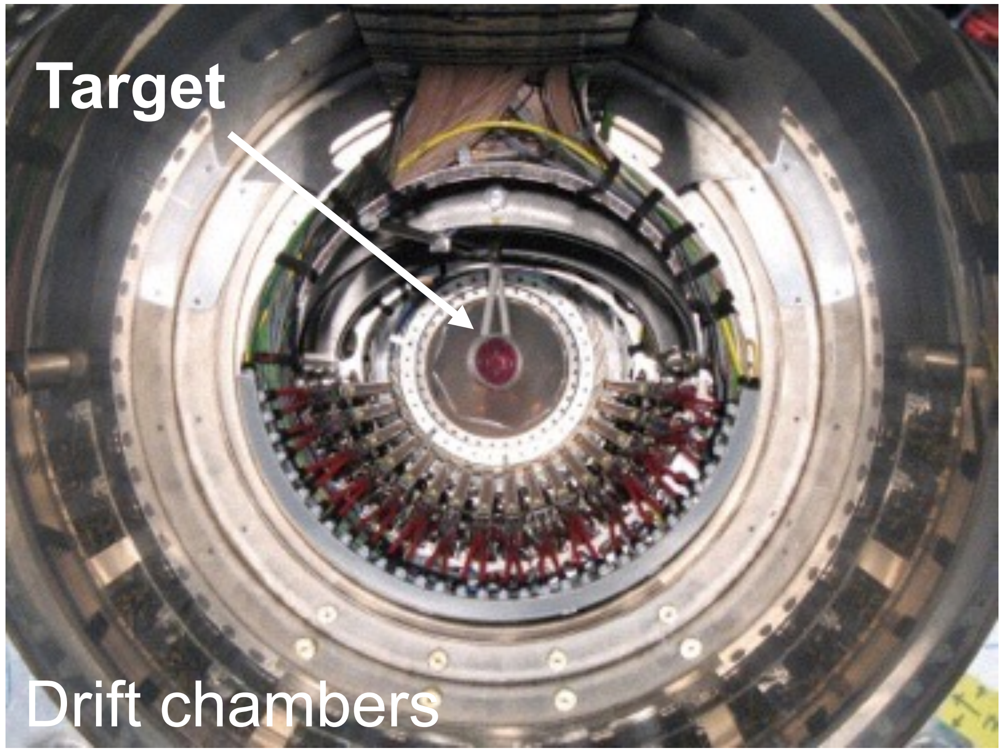


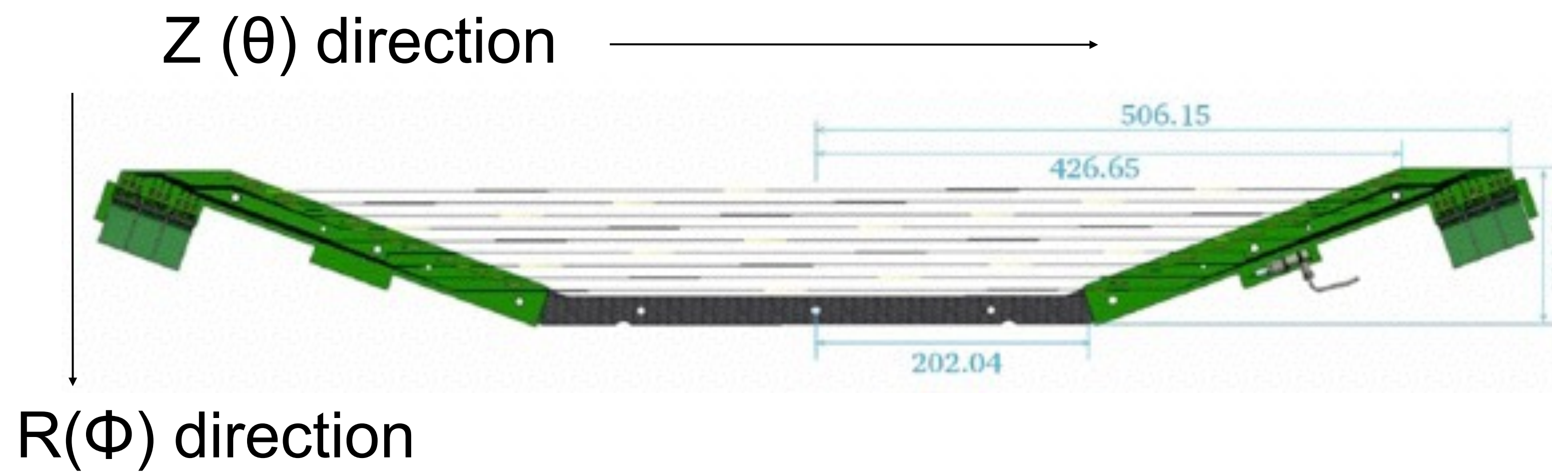
Low energy positron quickly swept away

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

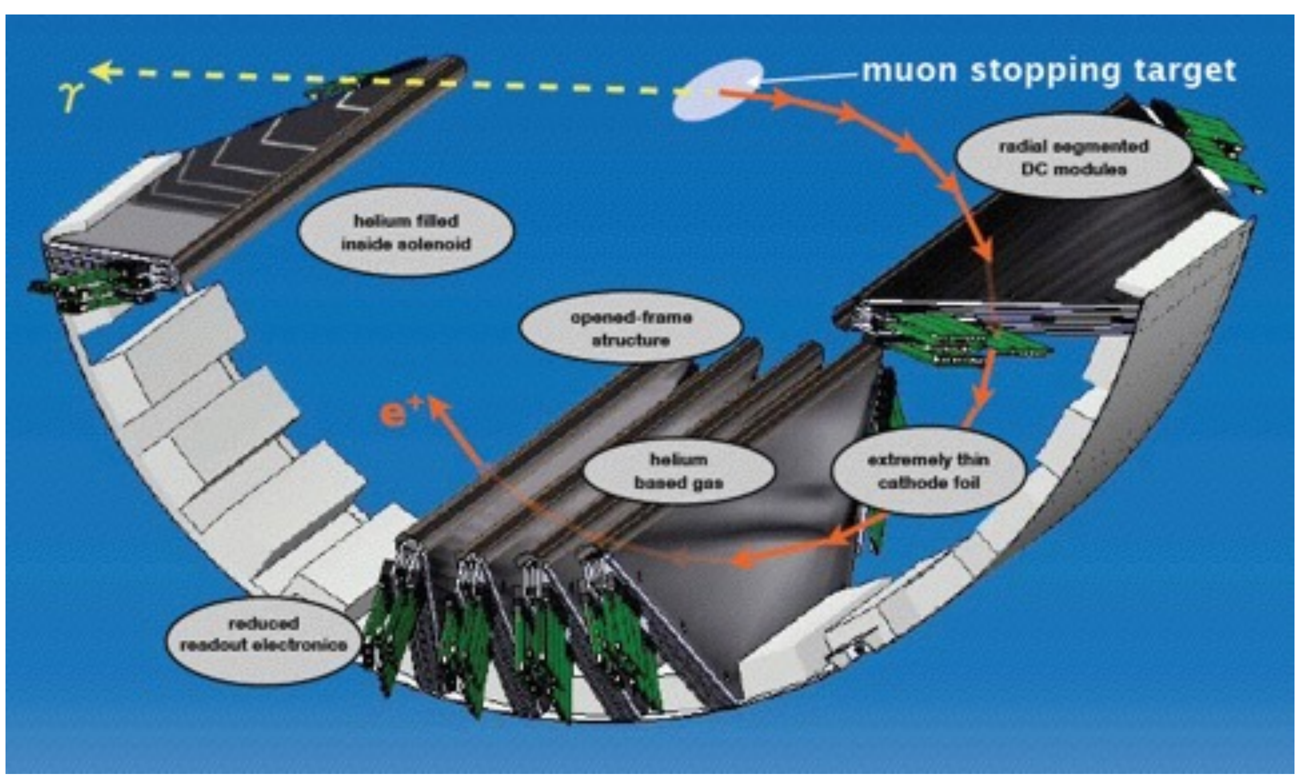
- Made of thin materials ($0.2X_0$)
- Precise 3D field mapping
- Positrons do not hit magnet walls

Drift chambers



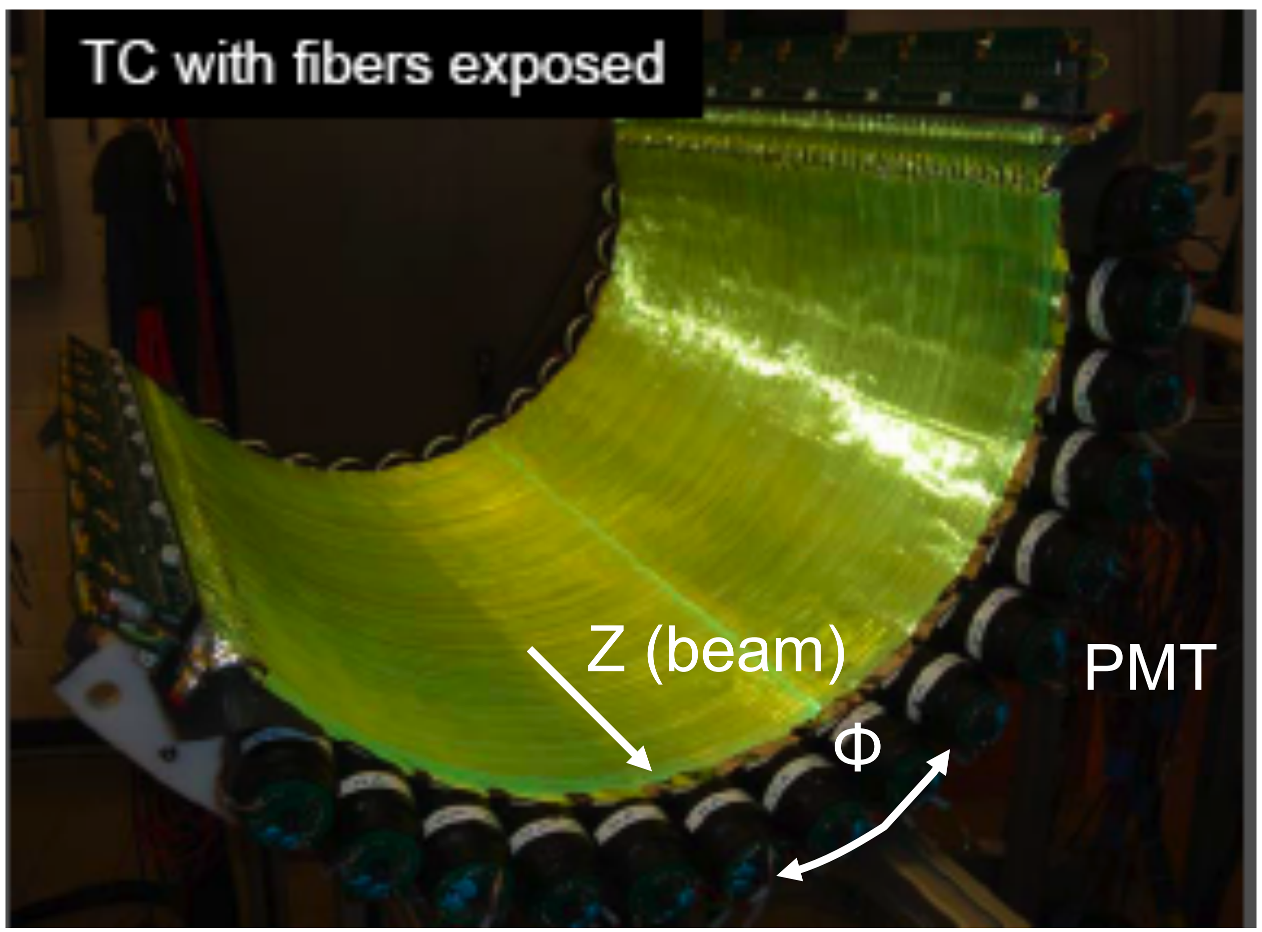


- 16 radial drift chambers
  - Only high momentum e^+ (>40MeV, 19.3cm<r<27.9cm)
- Chamber gas He:C_2H_6 = 50:50
- Low material budget (~$2\times10^{-3}X_0$ for one turn of e^+ trajectory)
  - Open frame at the target side
  - Low MS, low γ background

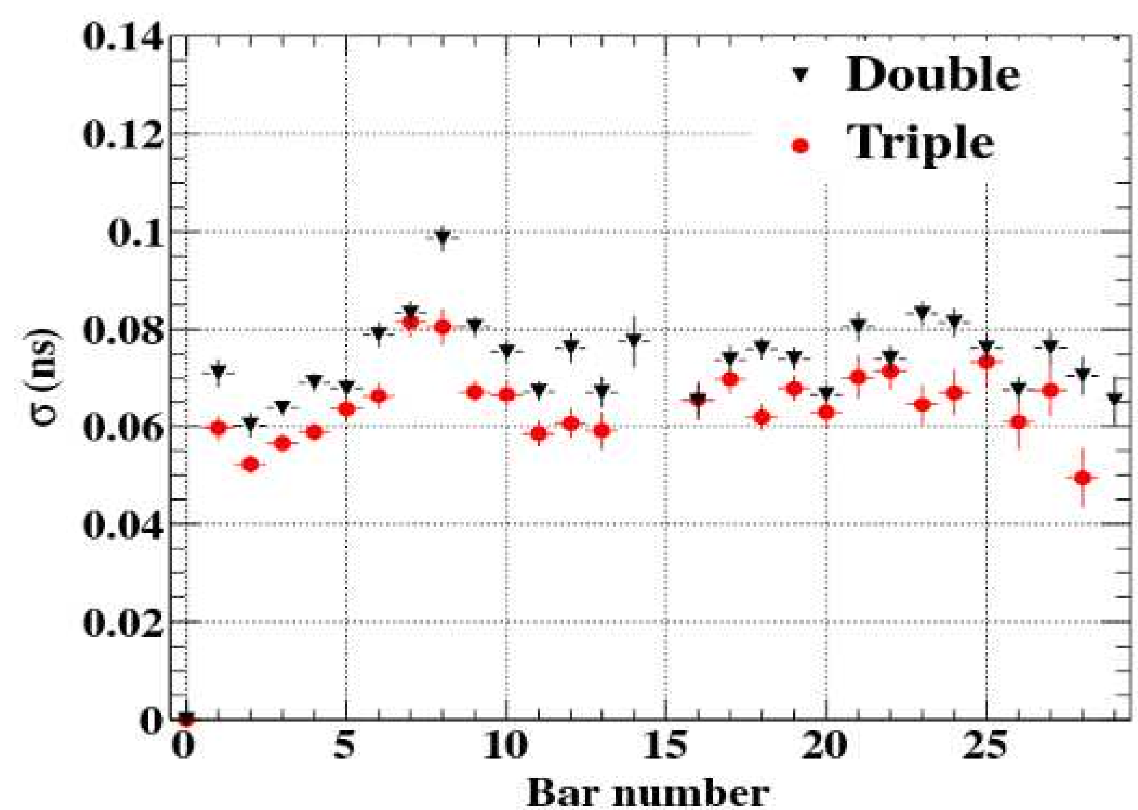


Timing counter

- 15×2(Upstream/Downstream) plastic scintillator bars (4×4×80cm³)
  - Fine mesh PMTs at both ends, positron timing measurement
  - Positron ϕ, z position reconstruction using charge-ratio (online) or time-difference (offline).



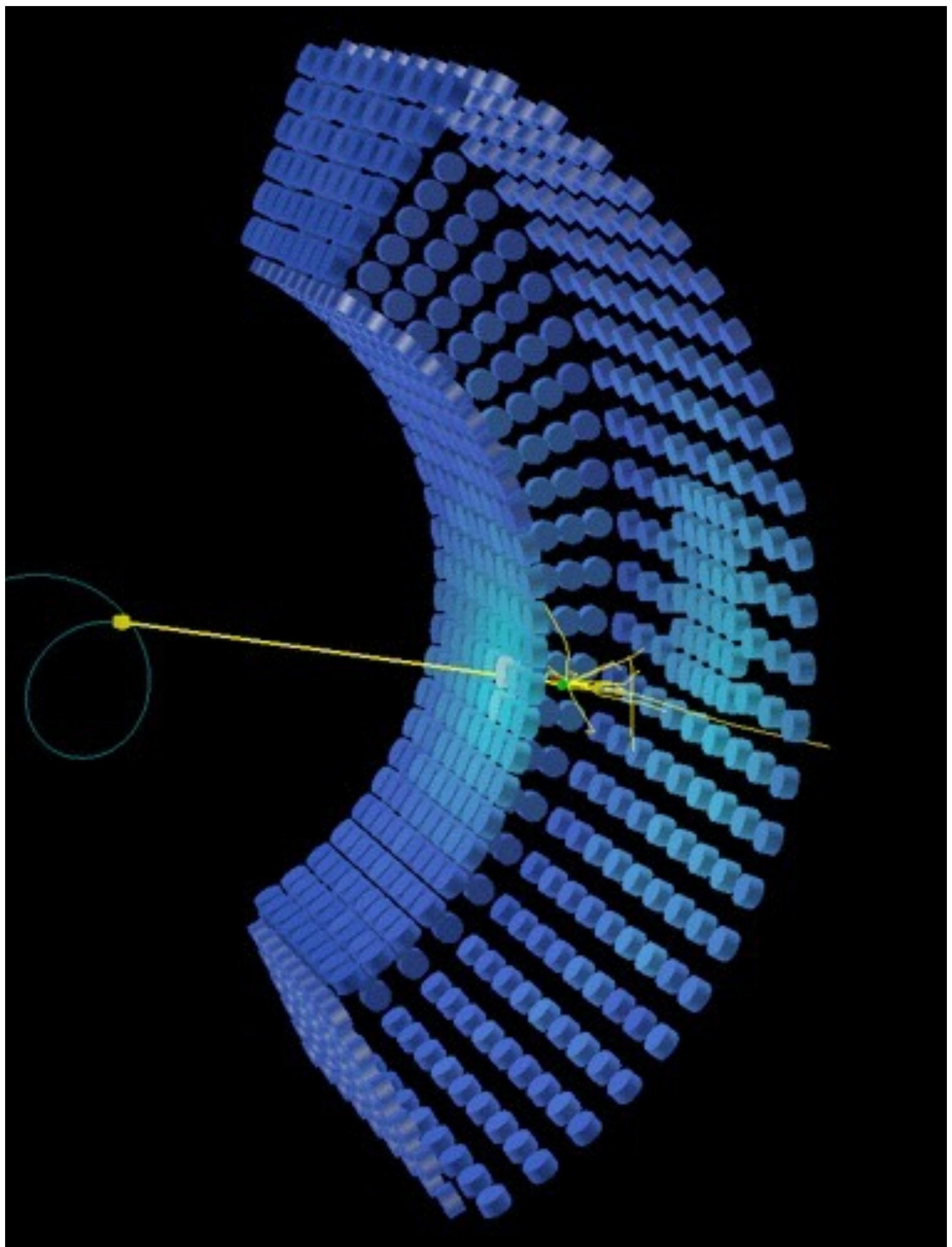
Time resolutions



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



- 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

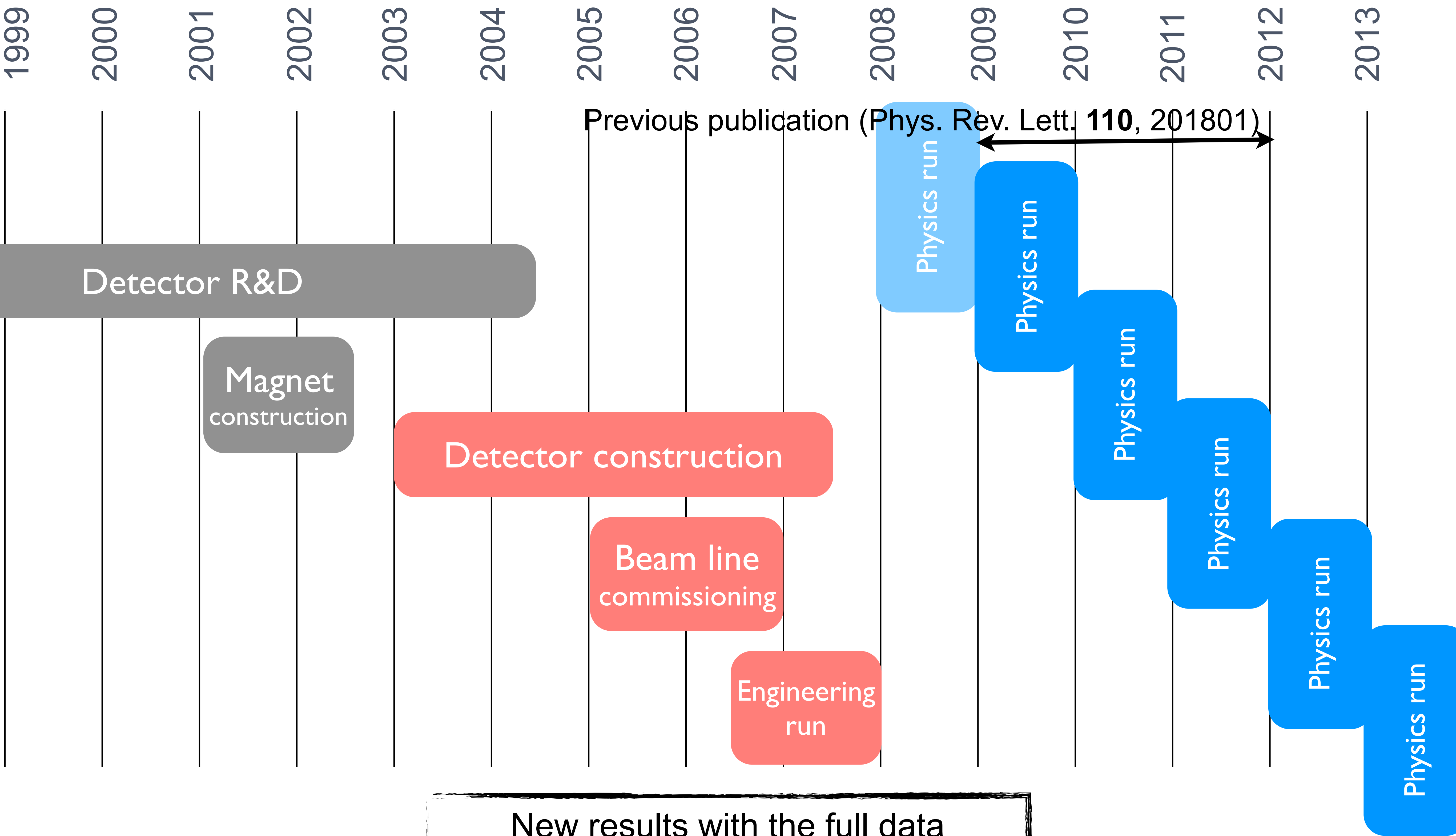
Analysis Software

- MEG analysis software is based on ROME (http://midas.psi.ch/rome)
  - The same analyzer is used for the online monitor and for offline analysis (reconstruction and physics analysis)
- ROME
  - Experiment independent software generator
    - Also used in other experiments (e.g. g-2 group in Fermilab)
  - Users define the structure of the software (data structure, tasks, steering parameters etc.); then ROME prepare C++ code to be ready for the implementation of algorithms.
  - The generated code can be executed out of package just after ‘make’
  - The software is ROOT based; users can implement analysis algorithm using ROOT classes.
  - Significant reduction of hand-written code, therefore the time for the coding and the probability of having bugs.

Detector performance summary

Resolutions	
e^+ energy (keV)	306 (core)
e^+ θ (mrad)	9.4
e^+ ϕ (mrad)	8.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7
γ position (mm) $u/v/w$	5 / 5 / 6
γ-e^+ timing (ps)	122
Efficiency (%)	
trigger	$\approx$ 99
γ	63
e^+	40

Time Line



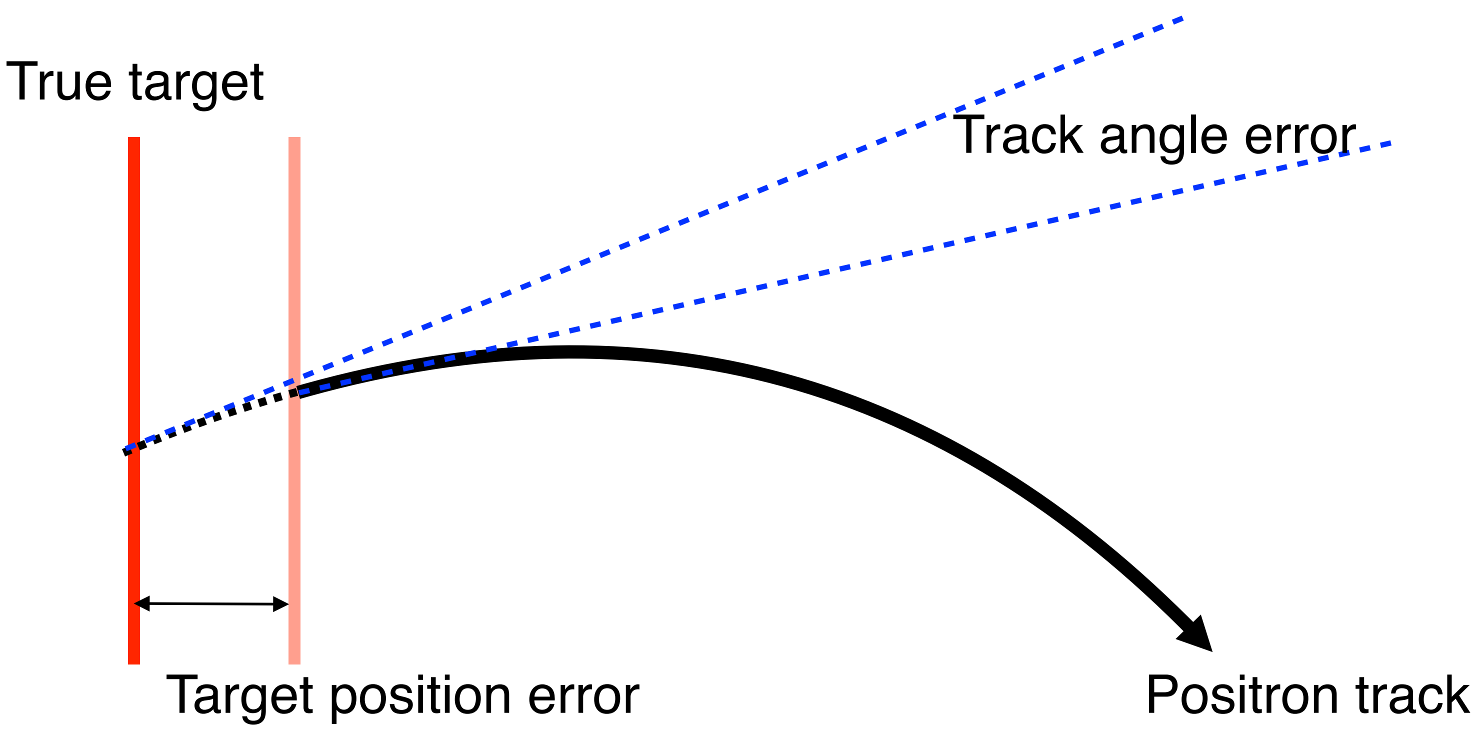
New results with the full data

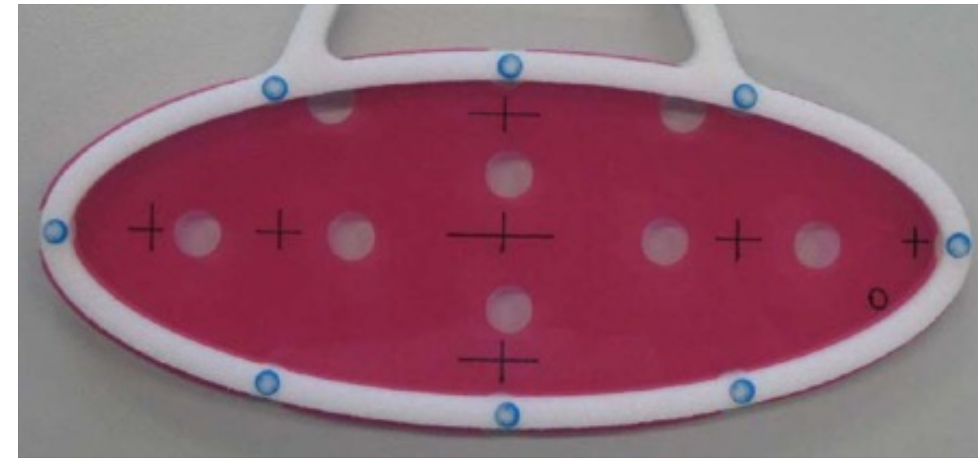
New analysis

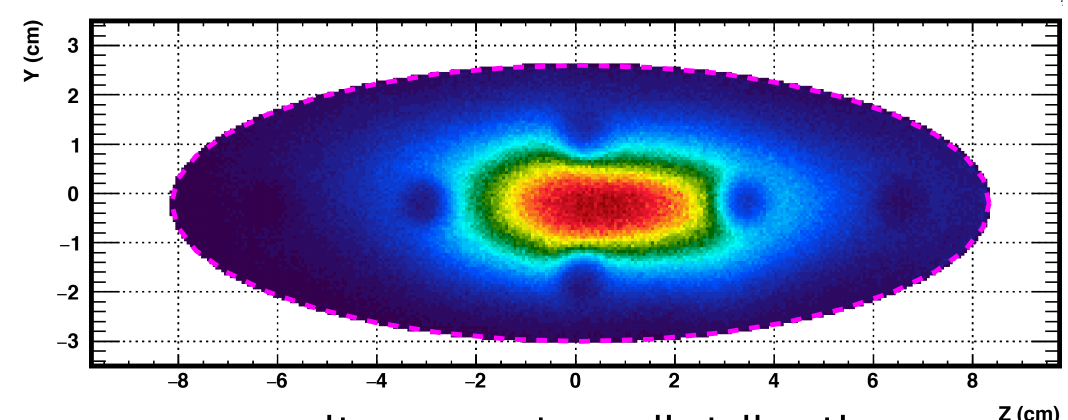
- All data (including 2009-2012) were analyzed with new analysis
  - Target alignment
  - Positron missing turn recovery
  - AIF event veto
  - Photon detector alignment
    - Precise laser survey was done for the structure to support PMTs
    - Thermal shrink is taken into account

Target alignment

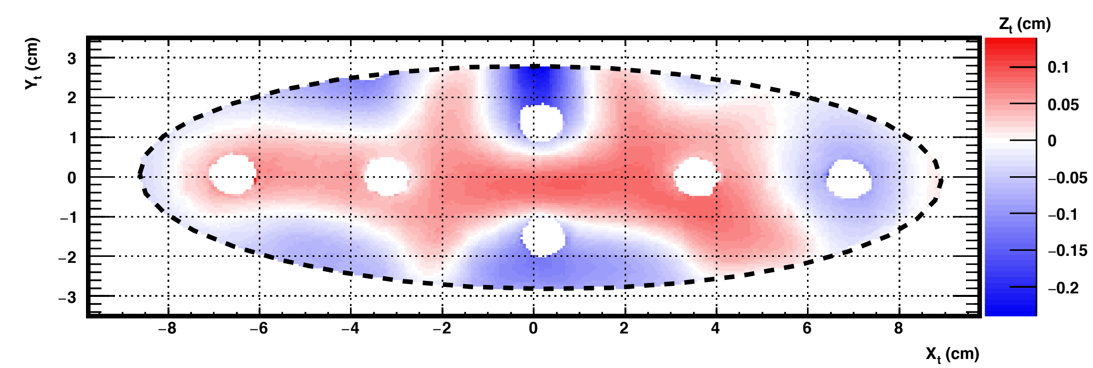
- The target position and shape are measured by
  - Positron data : hole position reconstruction
    - Approximation as paraboloid
  - 3D scanner survey done in 2013
- The position uncertainty (0.3—0.5 mm) and the deformation uncertainty (difference of the two measurements) **included as a systematic uncertainty as nuisance parameter**.
  - e.g. 0.5 mm position error ~ 4 mrad error in the eγ angle







positron vertex distribution

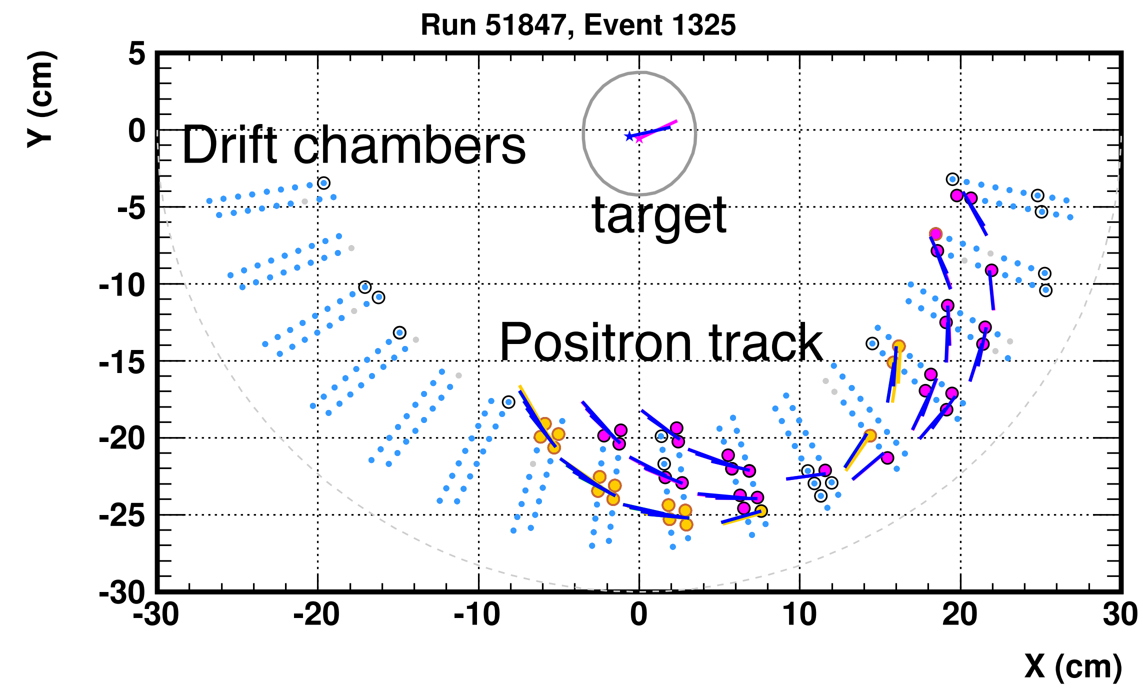


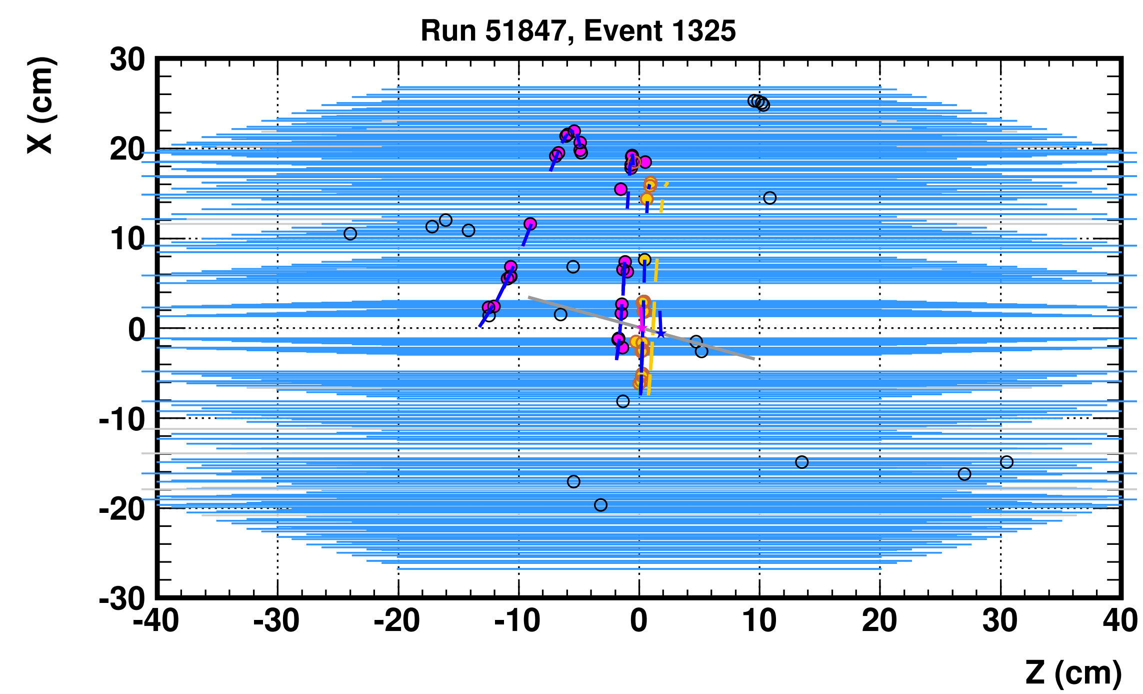
deformation measured by 3D scanner

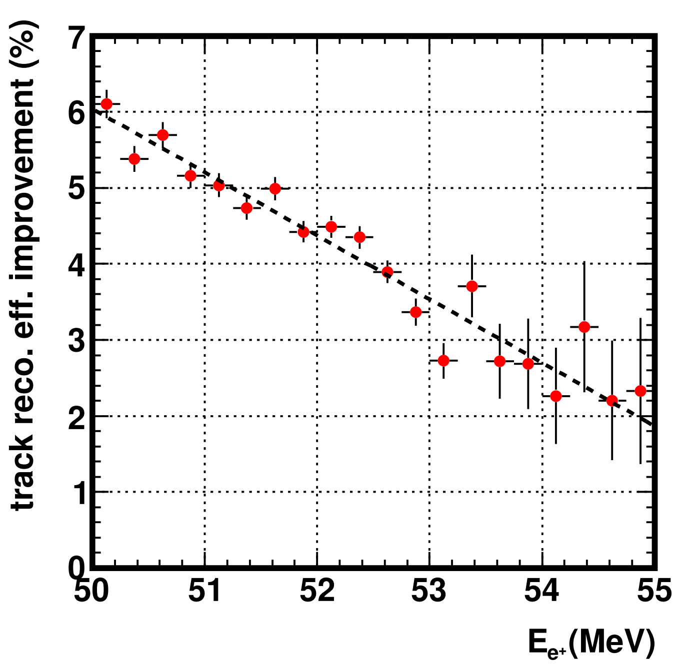
13% degradation in sensitivity

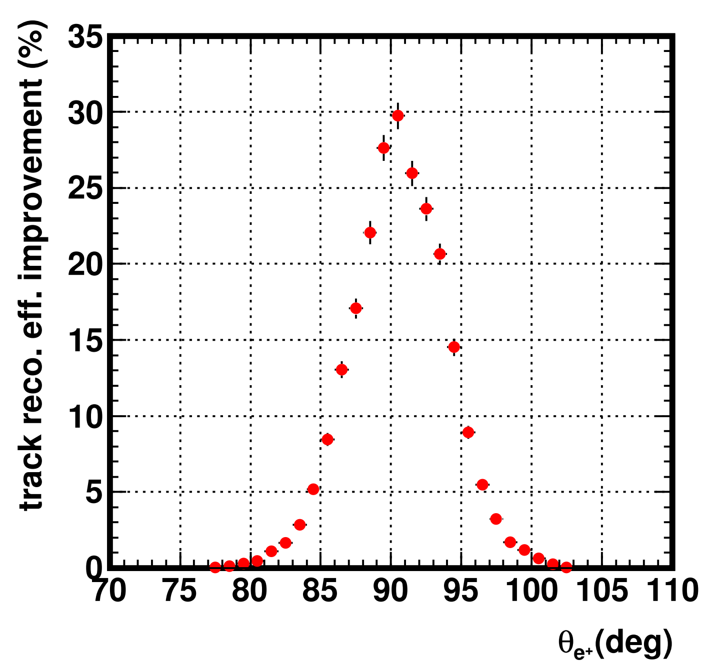
Positron missing turn recovery

- When track-segments are close (= emission angle is close to 90 degrees), the connection of them were easily failed.
  - The emission time is shifted by ~2 nsec
  - Loss of signal efficiency
- The merging algorithm was improved.
  - **Signal efficiency recovered by ~4%**



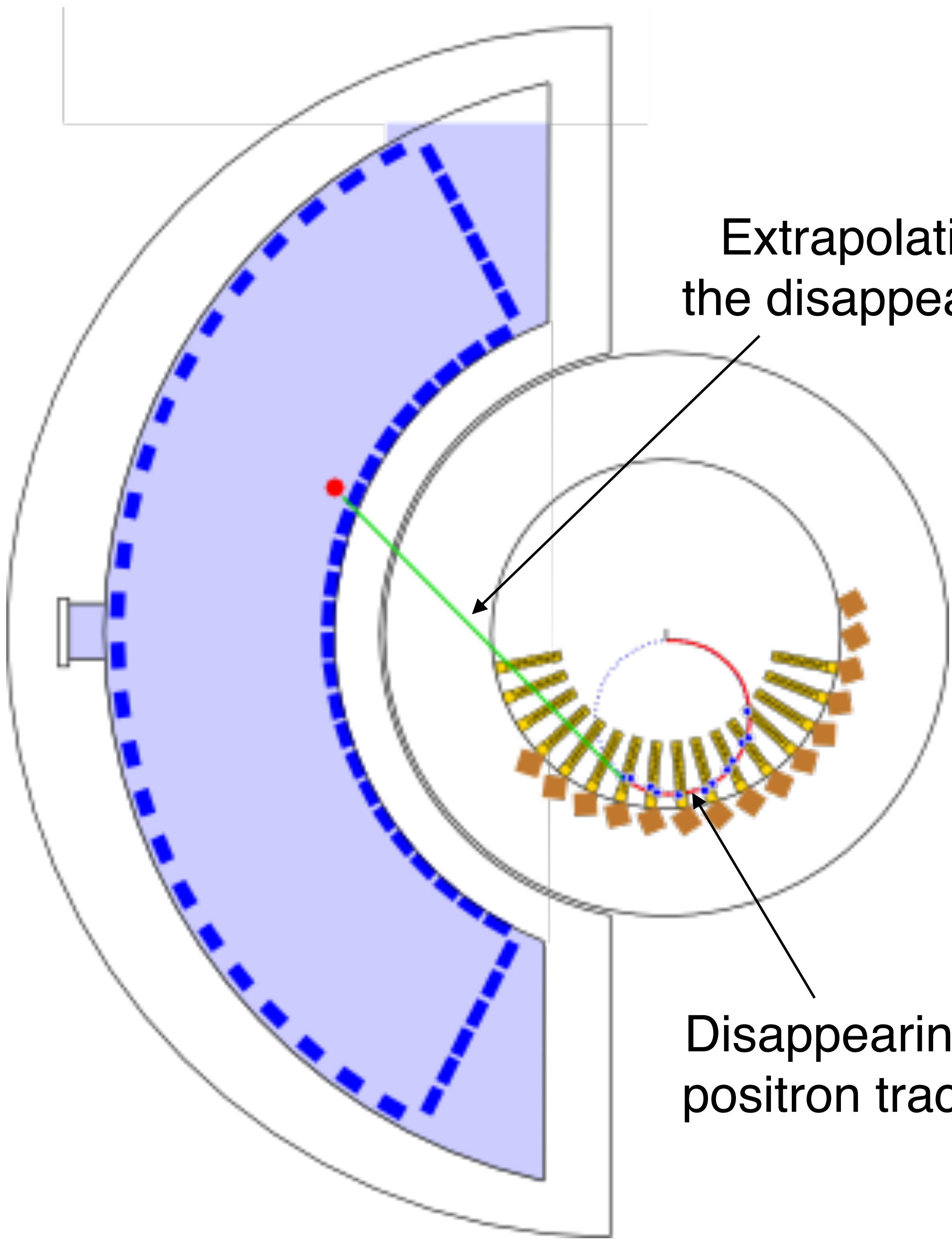




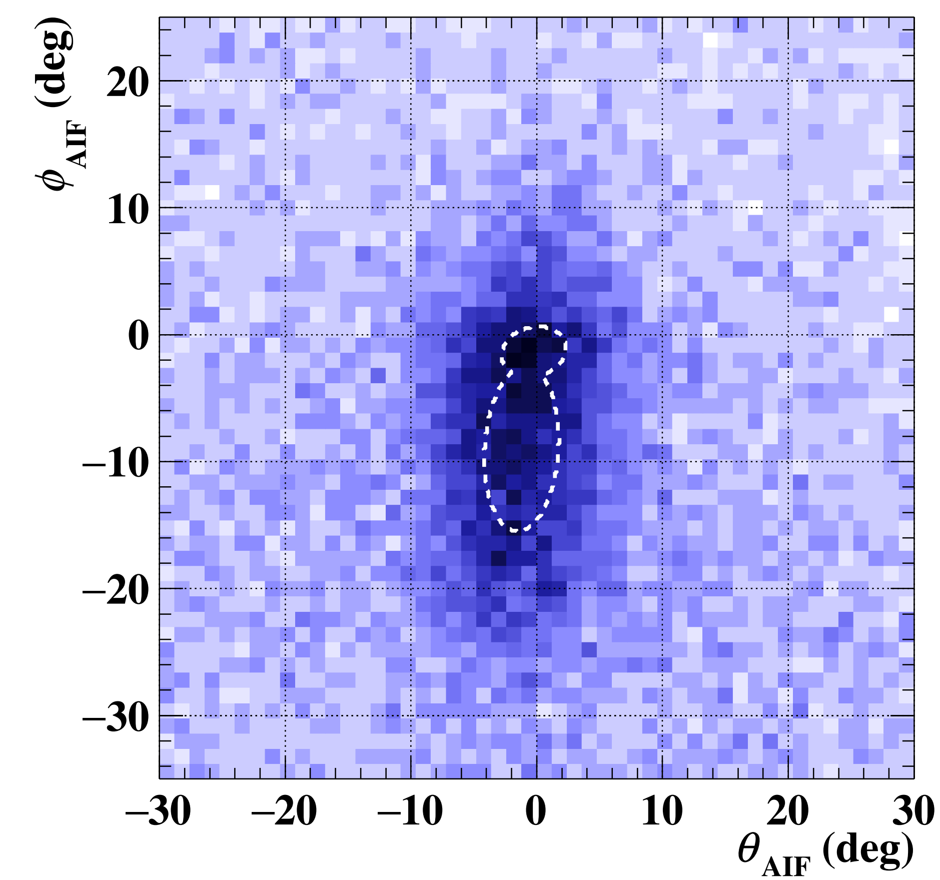


Annihilation-in-flight event veto

Very AIF BG like events are excluded from the analysis.



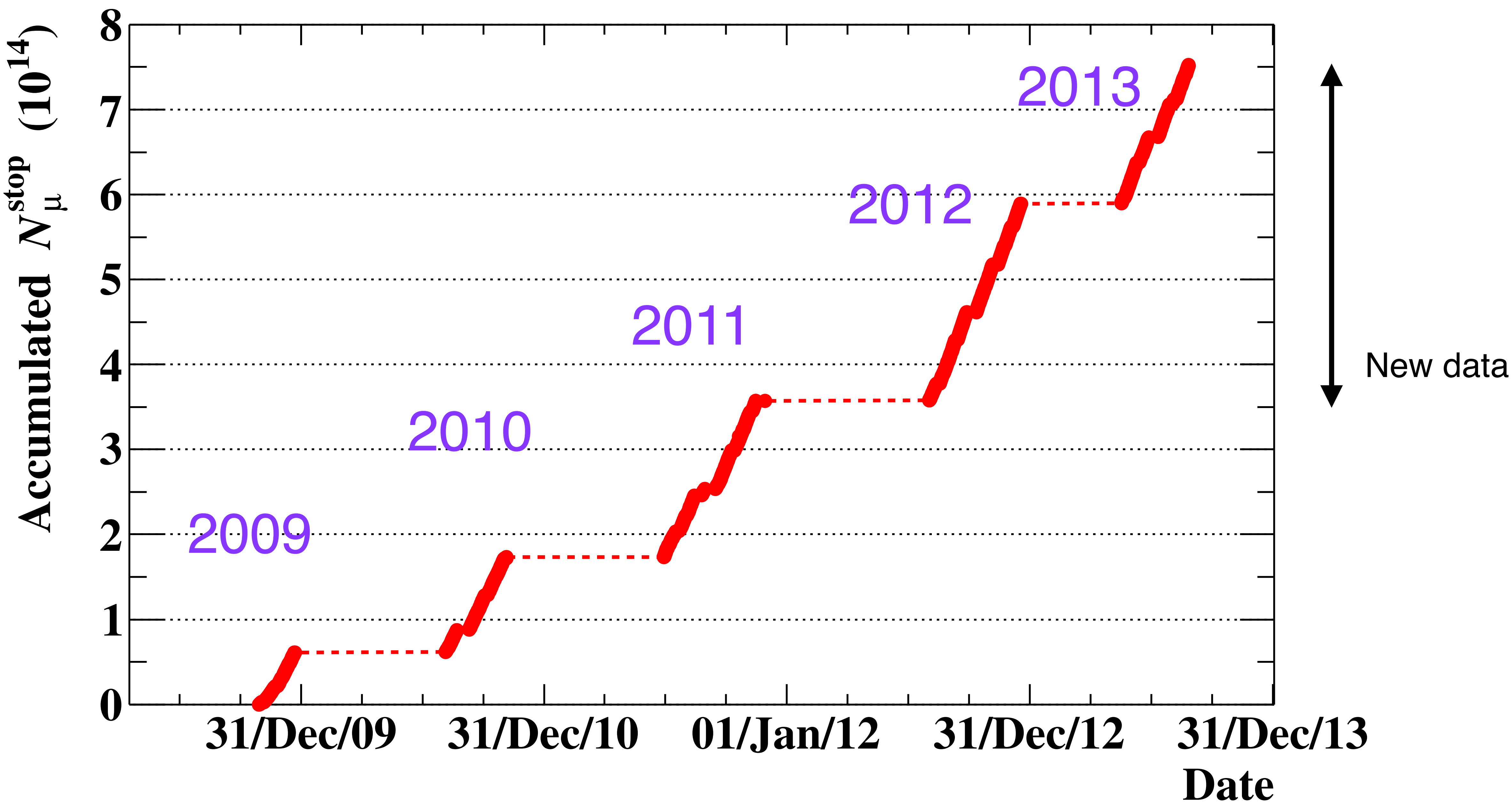
"Distance" from
the photon detector hit position
and
the expected position from the extrapolation



- Overall BG rejection 1.9%
- Signal Inefficiency 1.1%

Two peak structure because of ambiguity of the disappearing point (entering or exiting point from a chamber)

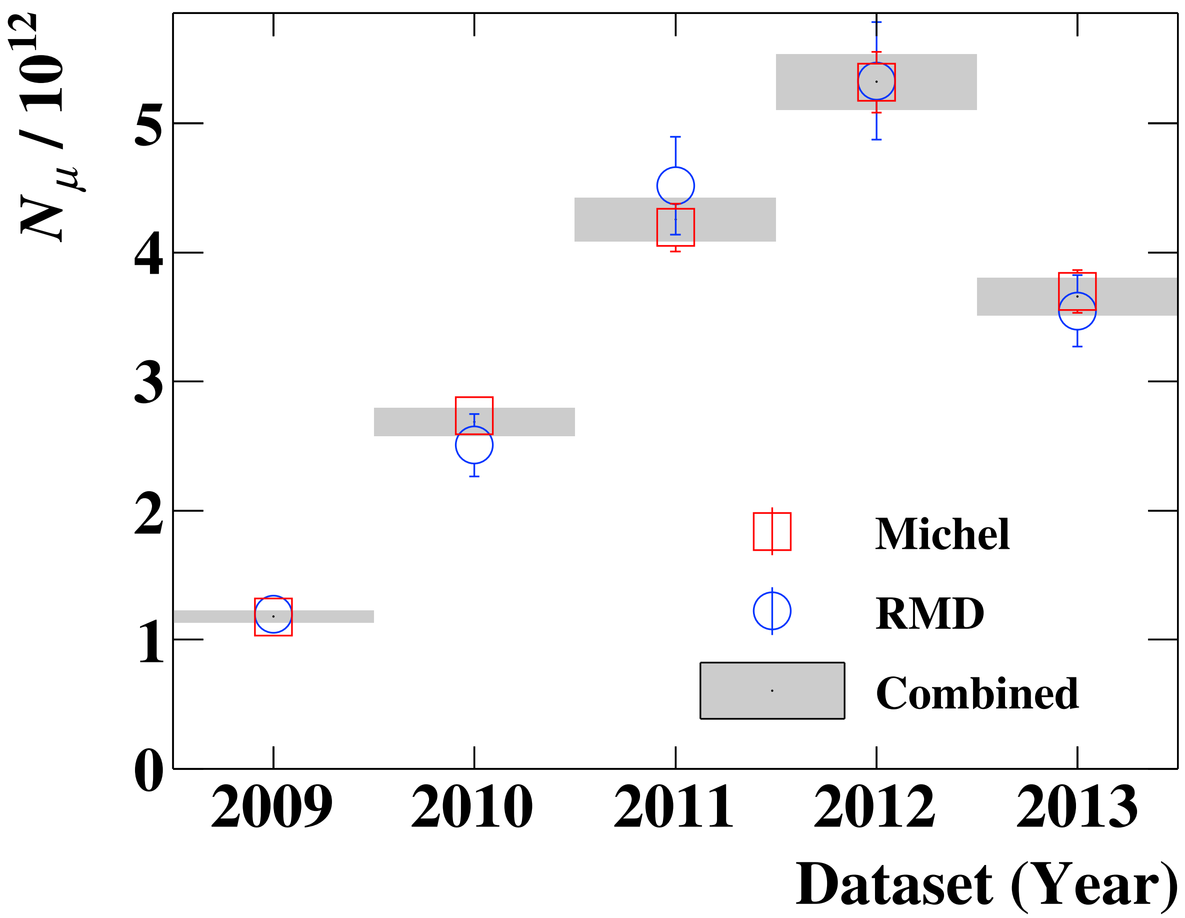
Data Statistics



Normalization

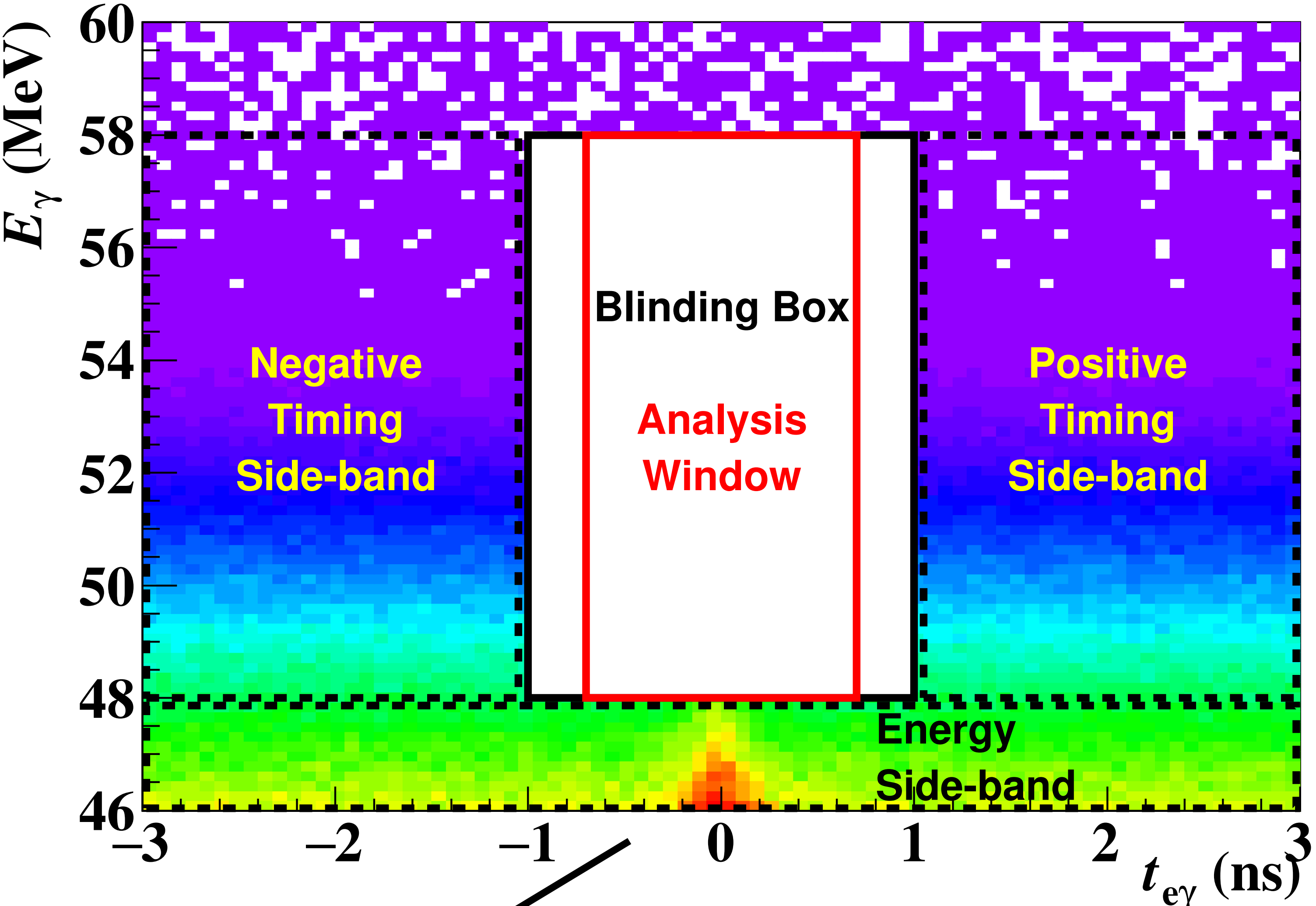
- Normalization factor (conversion from N_{sig} to Br) is calculated with two independent methods,
  - Counting number of positrons from muon decays (pre-scaled positron trigger data).
  - Counting radiative muon decay events
- Combined result:

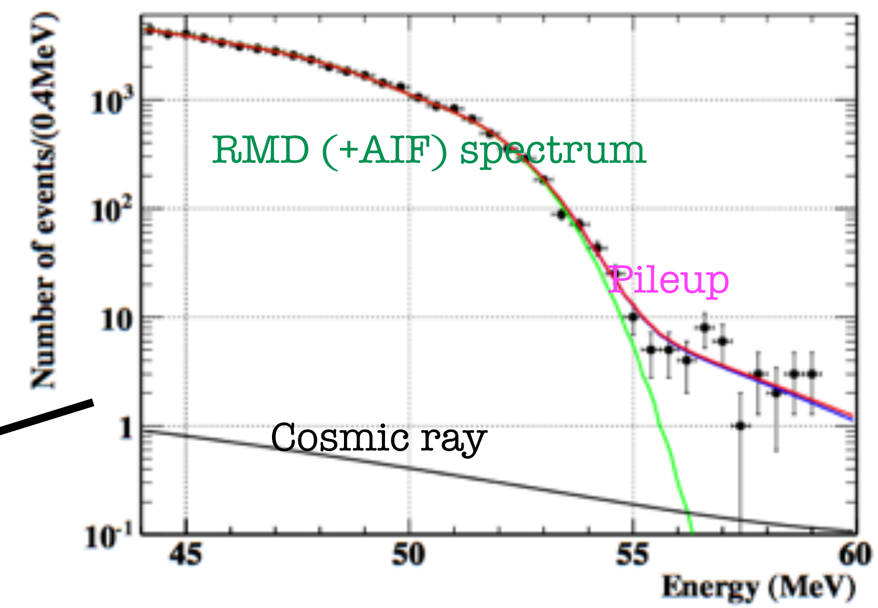
$$(5.84 \pm 0.21) \times 10^{-14}$$

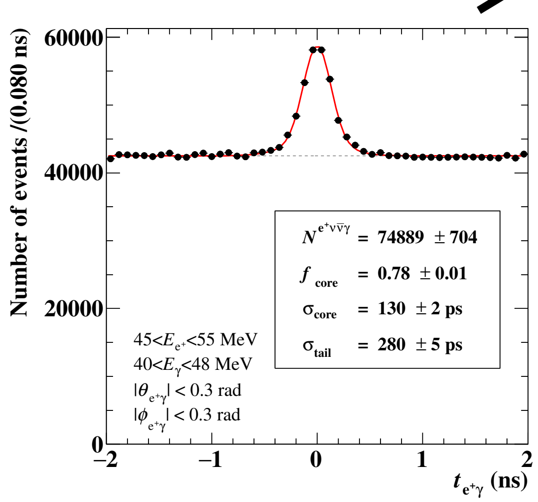


Analysis method

E_γ vs T distribution without any selection.







- Sidebands used for optimizing algorithms and for building PDFs.
- Analysis region hidden until the algorithms and PDF are finalized
- Likelihood fit with BG + signal PDFs in the wide analysis window (5—20 σ on each observable)

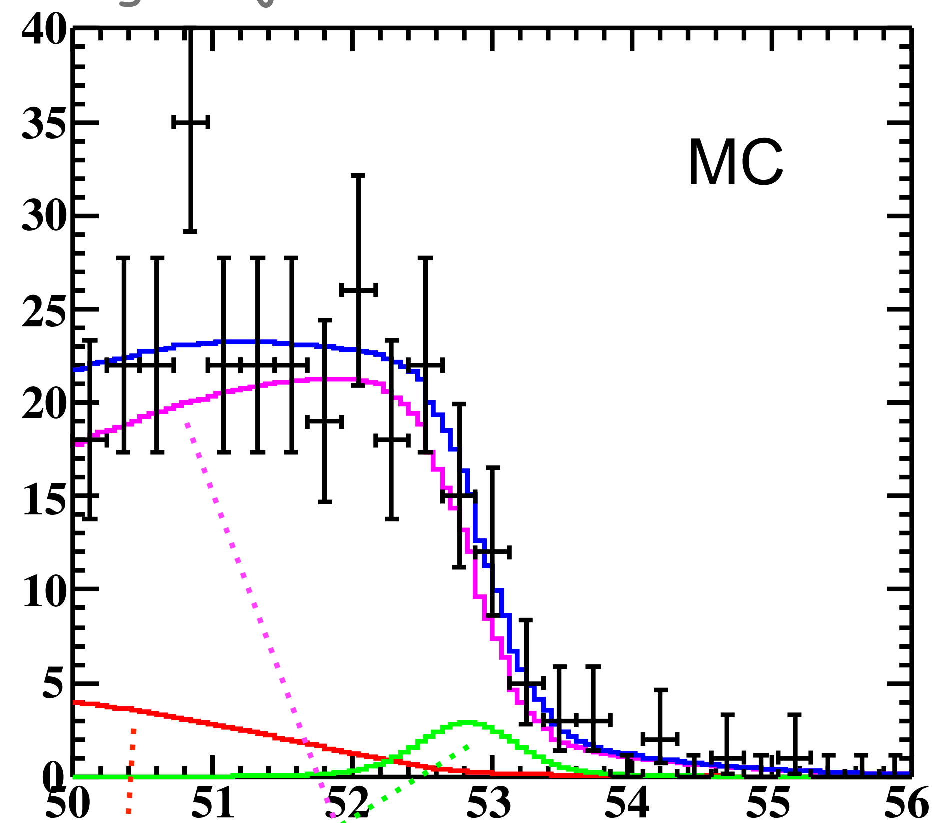
Likelihood function

Likelihood fitting with 5 observables

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

t : Target position and shape parameters

e.g. Projection to E_e



Unbinned likelihood fitting

$$\mathcal{L}\left(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{ACC}}, \boldsymbol{t}\right) =$$

$$\frac{e^{-N}}{N_{\text{obs}}!} C(N_{\text{RMD}}, N_{\text{ACC}}, \boldsymbol{t}) \times$$

$$\prod_{i=1}^{N_{\text{obs}}} \left(N_{\text{sig}} S(\boldsymbol{x}_i, \boldsymbol{t}) + N_{\text{RMD}} R(\boldsymbol{x}_i) + N_{\text{ACC}} A(\boldsymbol{x}_i)\right)$$

Constraint term

Limits calculated with profile likelihood ordering
Feldman-Cousins approach

BG : Accidental
RMD : Radiative muon decay

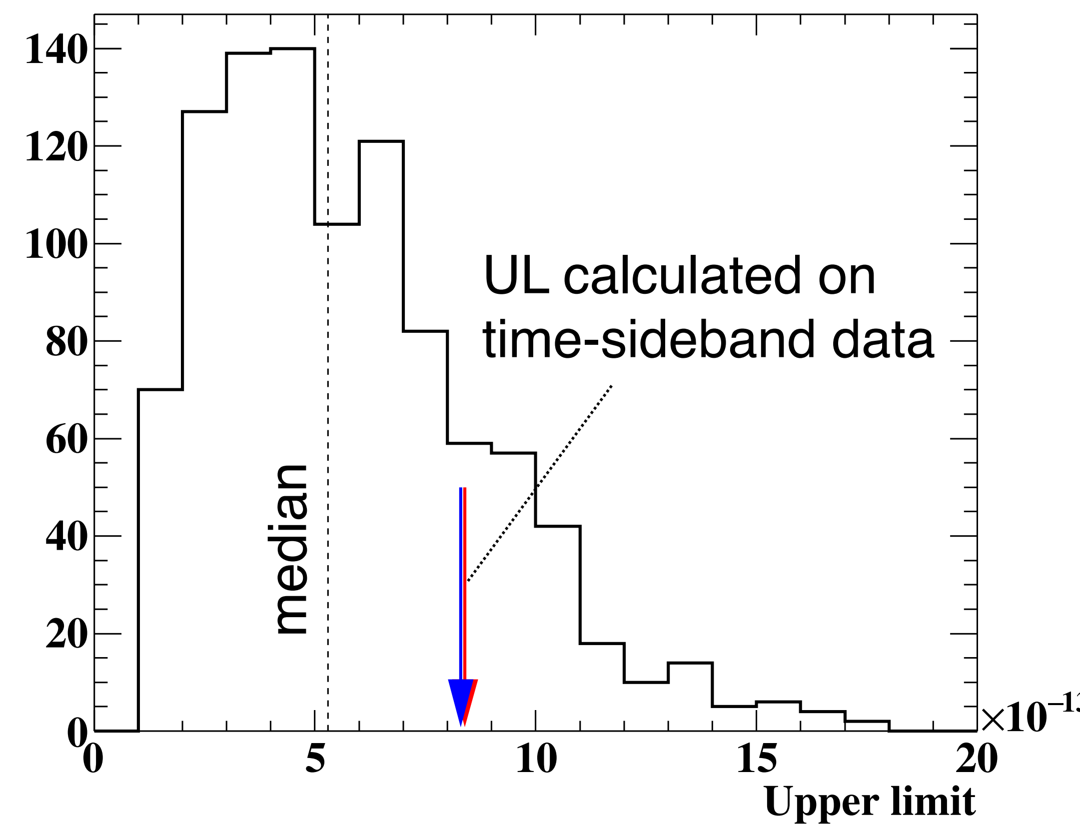
Sensitivity

- Sensitivity is the median upper limit of pseudo experiments (MC) with assuming null signal.
  - Effect of the background events fluctuation is included in the MC

5.3×10^{-13} for all data

(8.0×10^{-13} for 2009-2011 data)

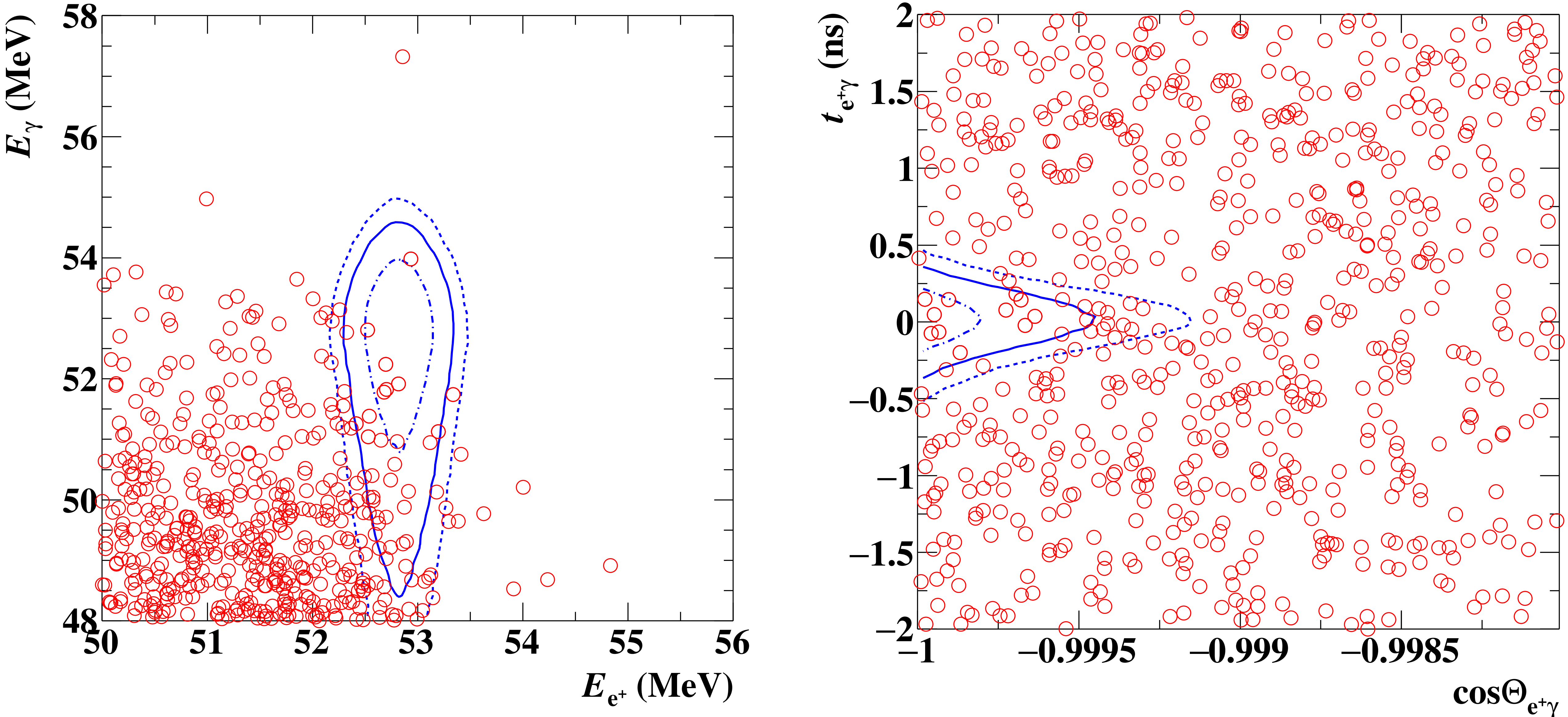
UL of MC experiments



•Sensitivity of the previous result = 7.7×10^{-13}

Blind box opened in Dec. 2015

Blue contour : signal PDF contours (1σ, 1.64σ and 2σ)



No visible excess in signal region

$\cos\Theta_{e^+\gamma} < -0.99963$ and $|t_{e^+\gamma}| < 0.24$ ns
90% efficiency for each variable

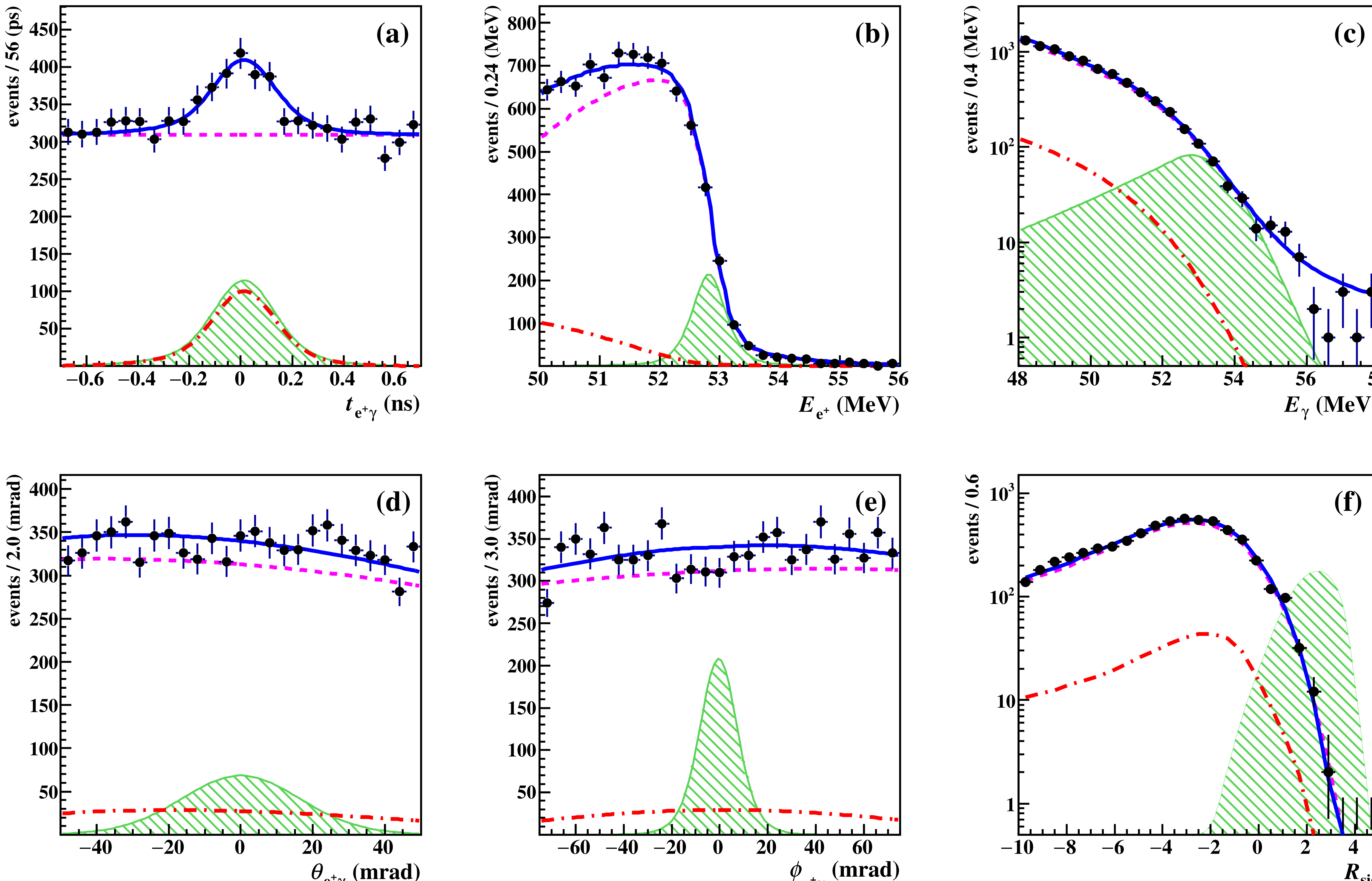
$51.0 < E_\gamma < 55.5$ MeV and $52.4 < E_{e^+} < 55.0$ MeV
74% and 90% efficiency respectively.

Accidental BG

RMD

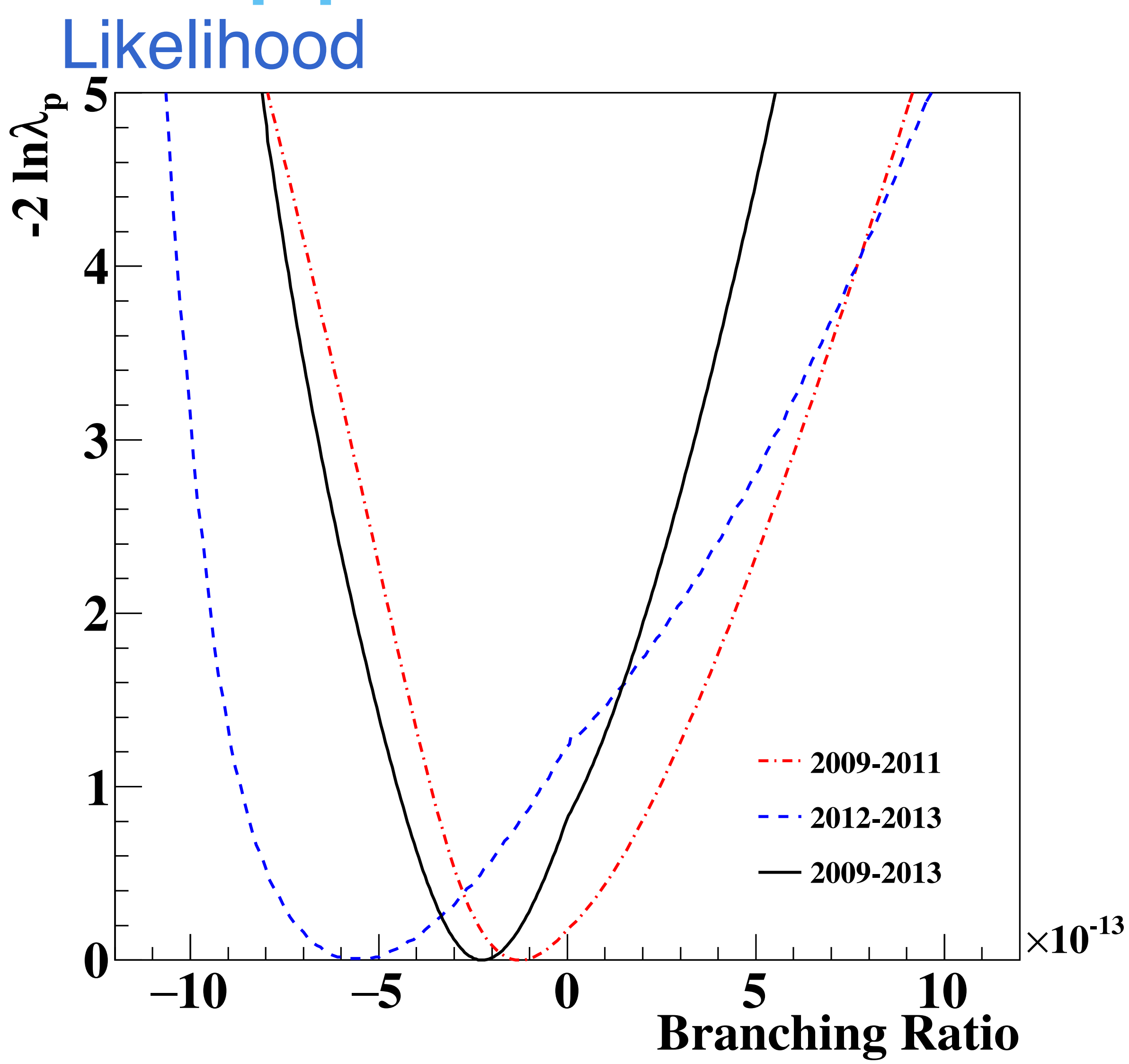
100× signal upper limit

Fit Result (projections)



$$= \log_{10}\left(\frac{S(\boldsymbol{x}_i)}{f_R R(\boldsymbol{x}_i) + f_A A(\boldsymbol{x}_i)}\right)$$

Upper limit



$\mathcal{B}(\mu \to e\gamma) <$ 4.2 ×10^{-13} @ 90% C.L.

Systematic uncertainties
UL increase by
- 5% by target position/shape uncertainties
- <1% by other systematic uncertainties

- Previous limit 5.7×10^{-13}

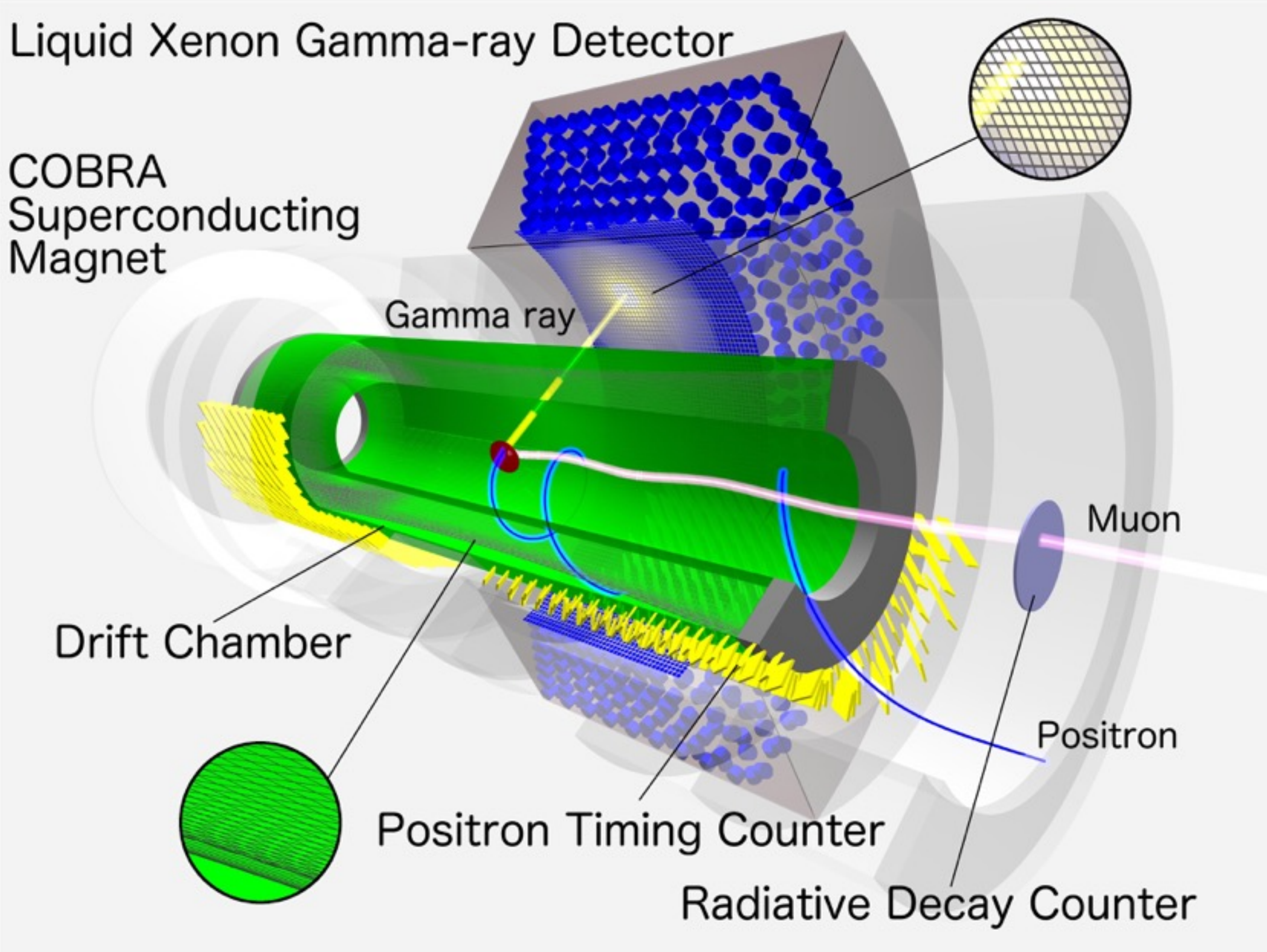
* this curve is not directly used for setting limits

Result summary

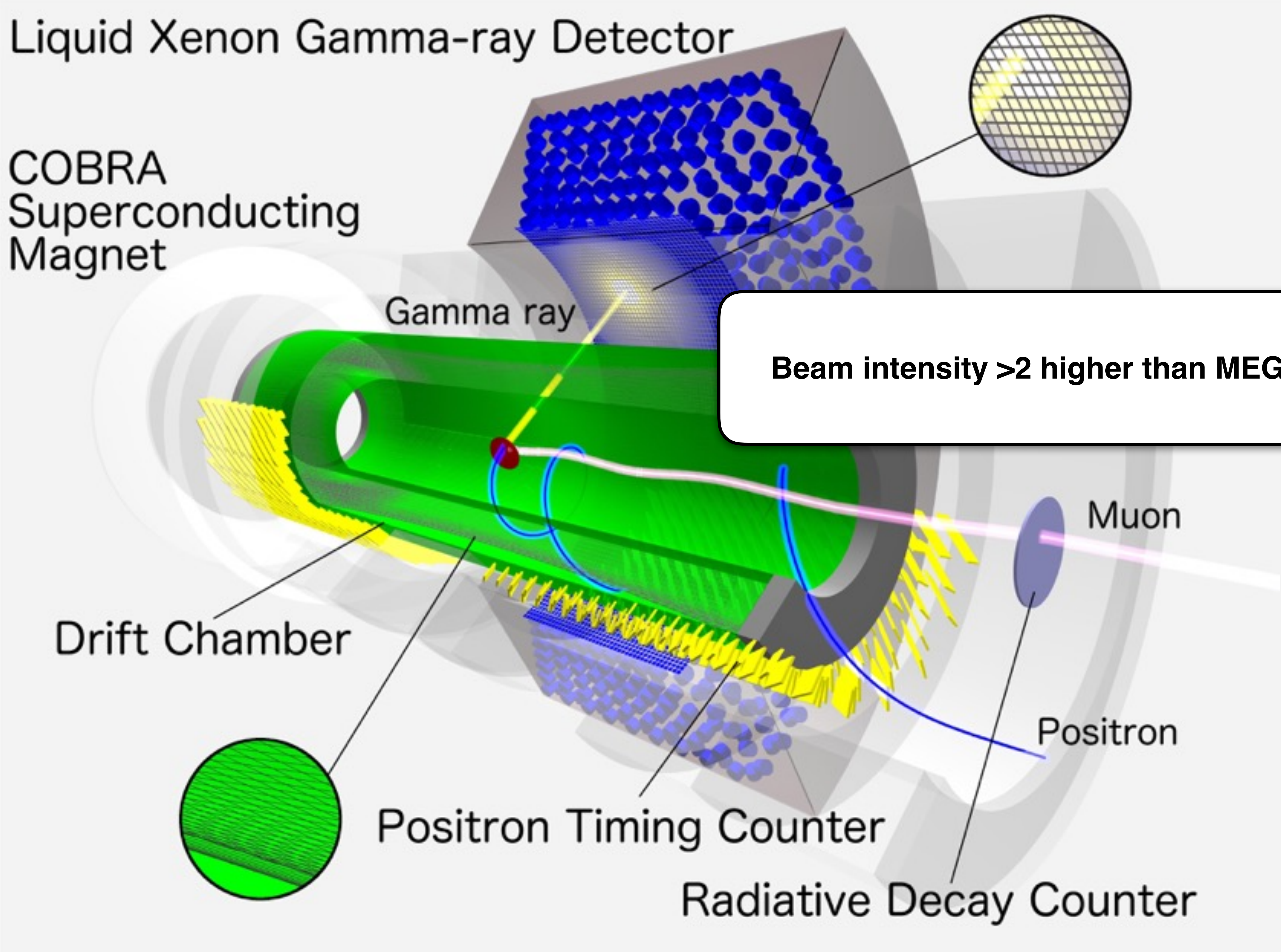
	dataset	2009–2011	2012–2013	2009-2013
Best fit Br	$\mathcal{B}_{\mathrm{fit}} \times 10^{13}$	-1.3	-5.5	-2.2
Br UL@90%CL	$\mathcal{B}_{90} \times 10^{13}$	6.1	7.9	$\boxed{4.2}$
90%CL Sensitivity	$\mathcal{S}_{90} \times 10^{13}$	8.0	8.2	5.3

- No excess of the signal was observed
- MEG updated the most stringent upper limit
    - 30 times more stringent than the previous experiment (MEGA)
    - Paper will be uploaded to arXiv soon (this week ?)

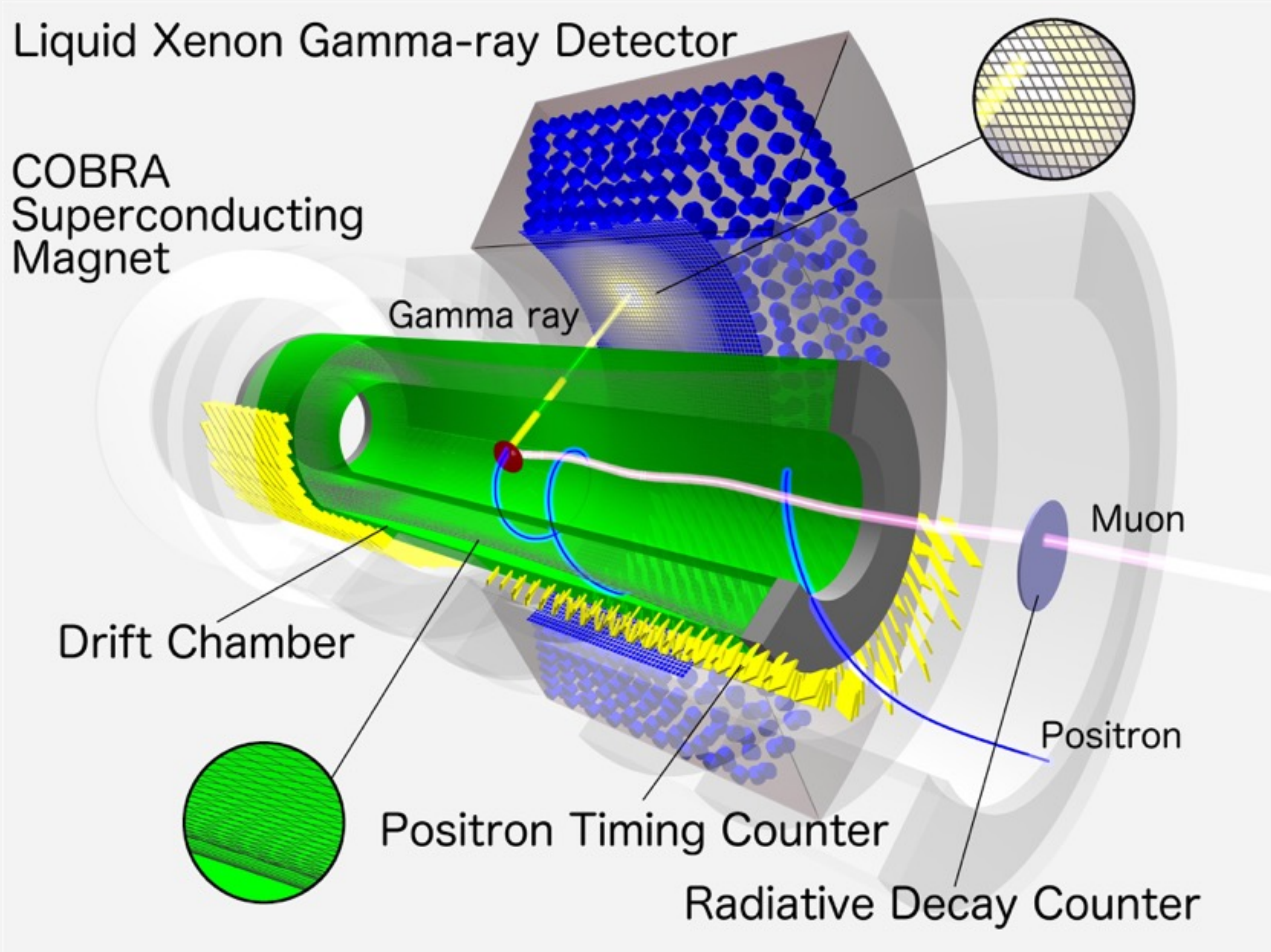
MEG II

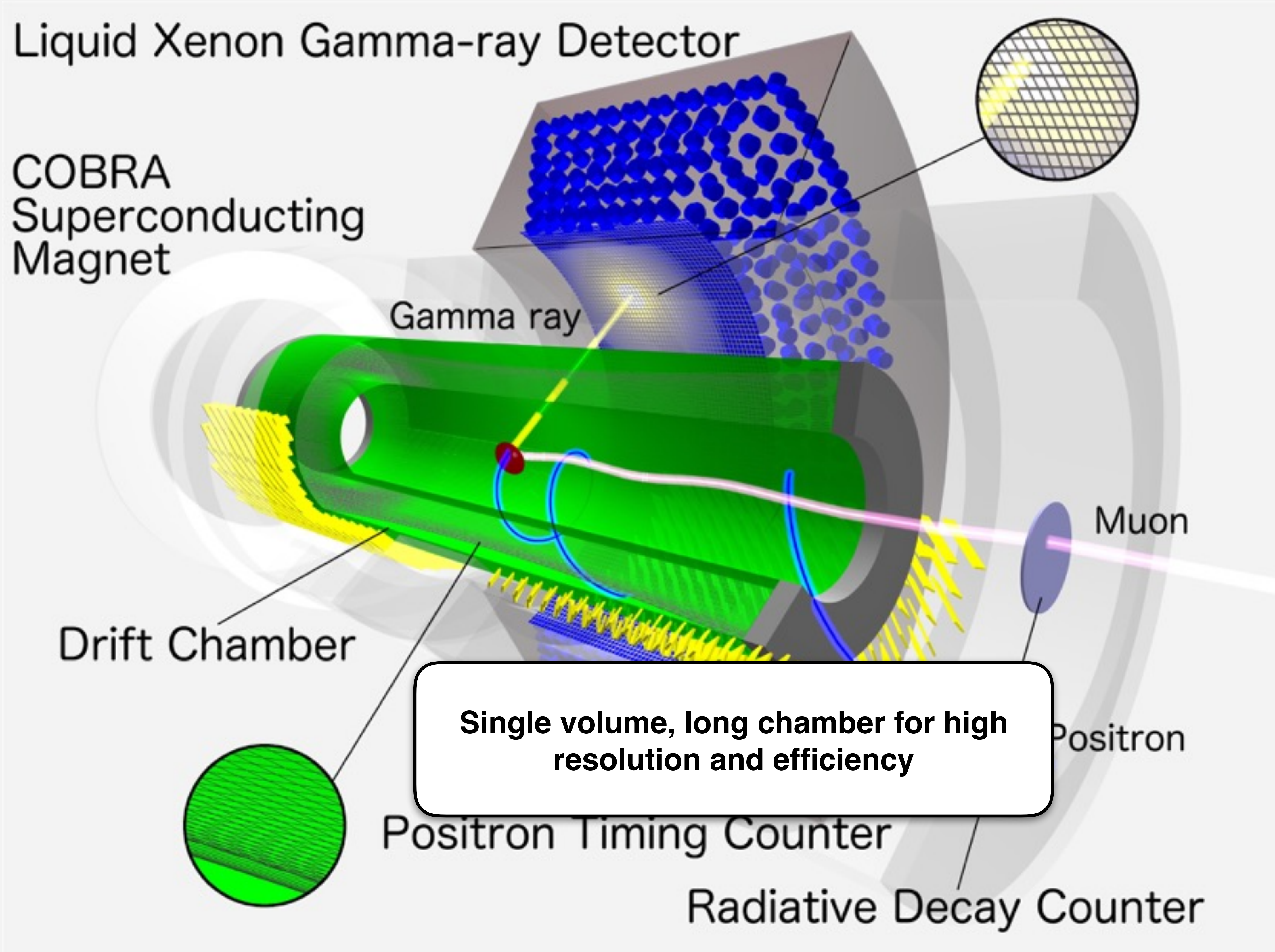


Liquid Xenon Gamma-ray Detector
COBRA
Superconducting
Magnet
Gamma ray
Muon
Drift Chamber
Positron
Positron Timing Counter
Radiative Decay Counter

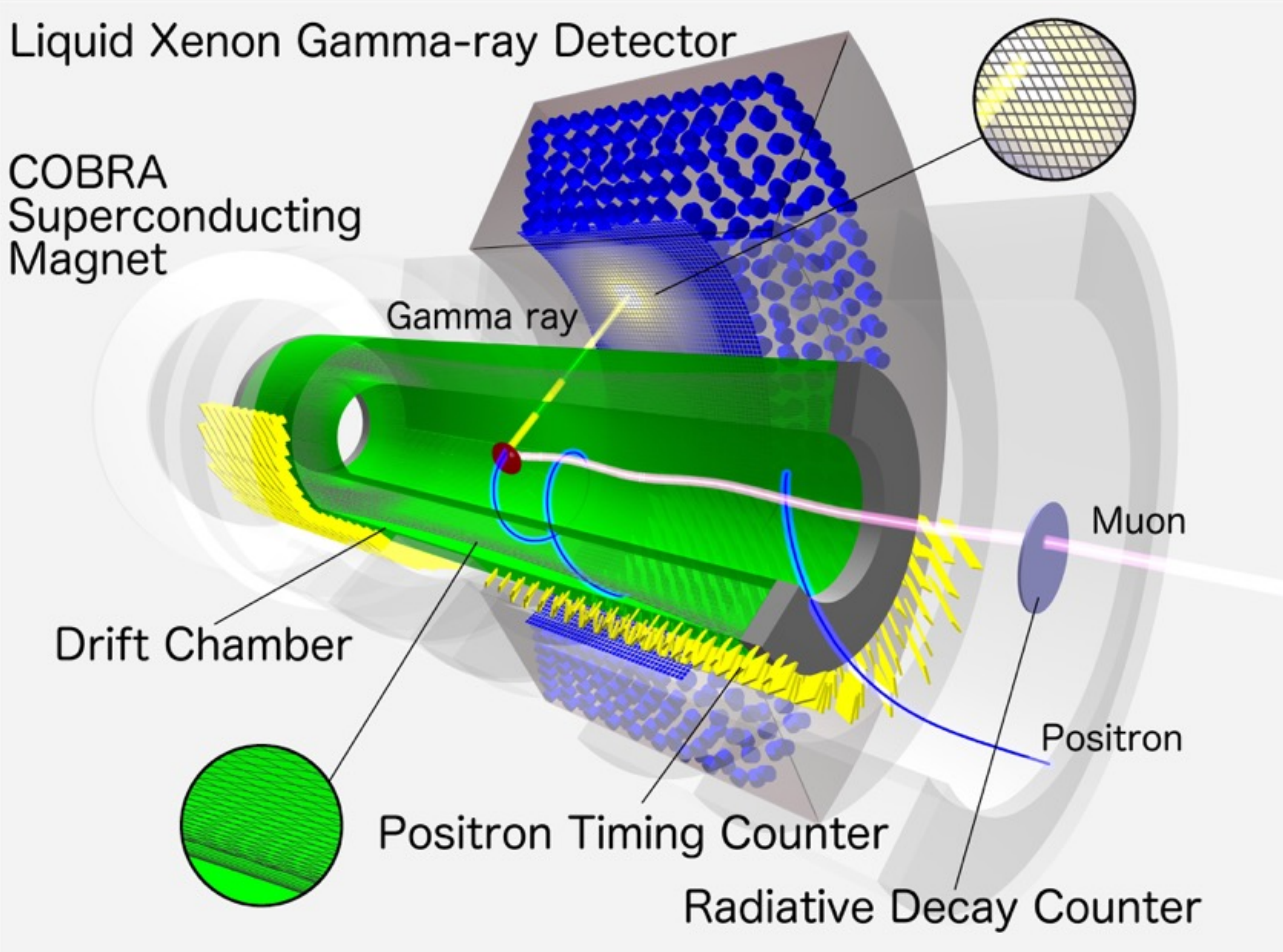


Beam intensity >2 higher than MEG I


Liquid Xenon Gamma-ray Detector
COBRA
Superconducting
Magnet
Gamma ray
Muon
Drift Chamber
Positron
Positron Timing Counter
Radiative Decay Counter



Single volume, long chamber for high resolution and efficiency


Liquid Xenon Gamma-ray Detector
COBRA
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Gamma ray
Muon
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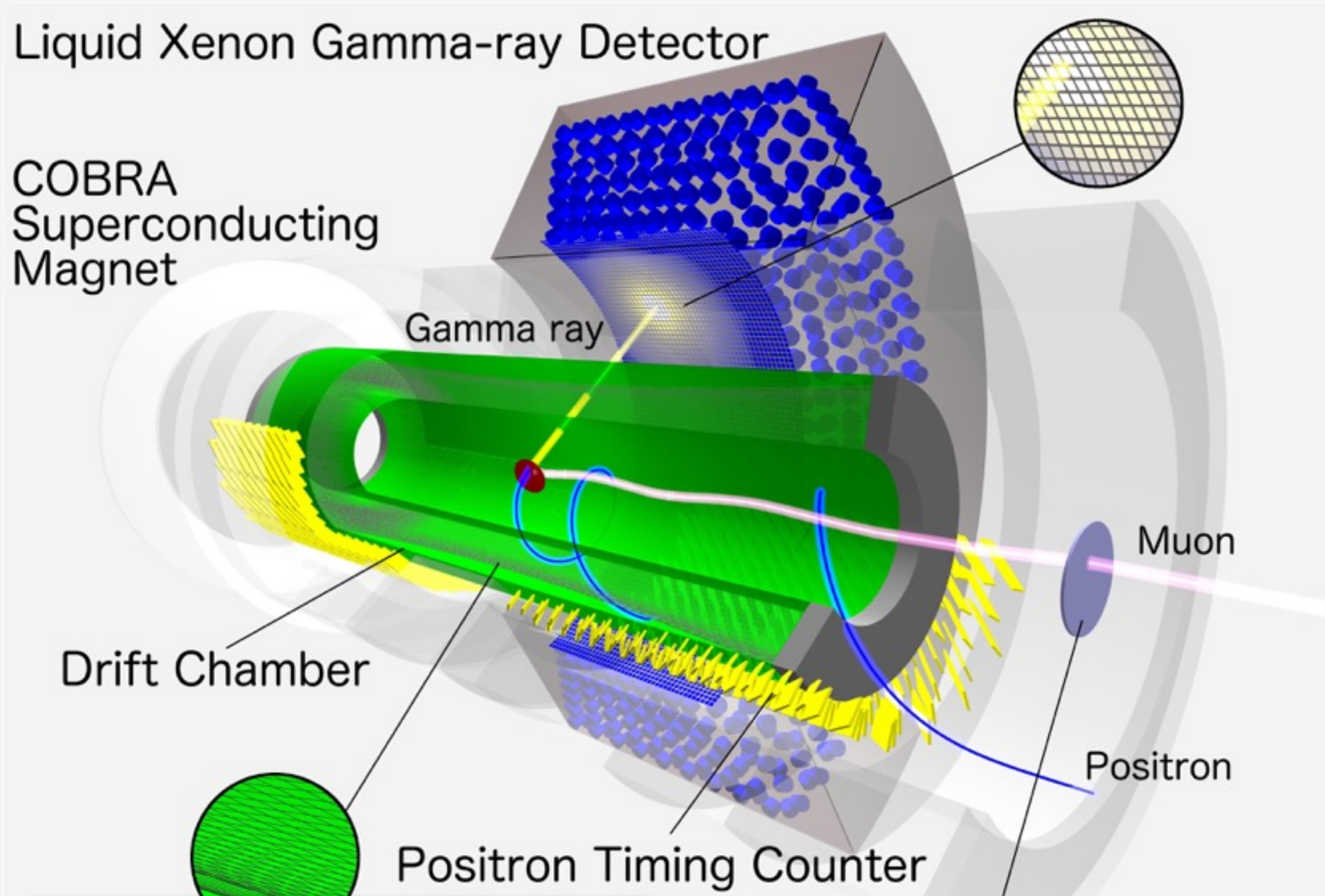
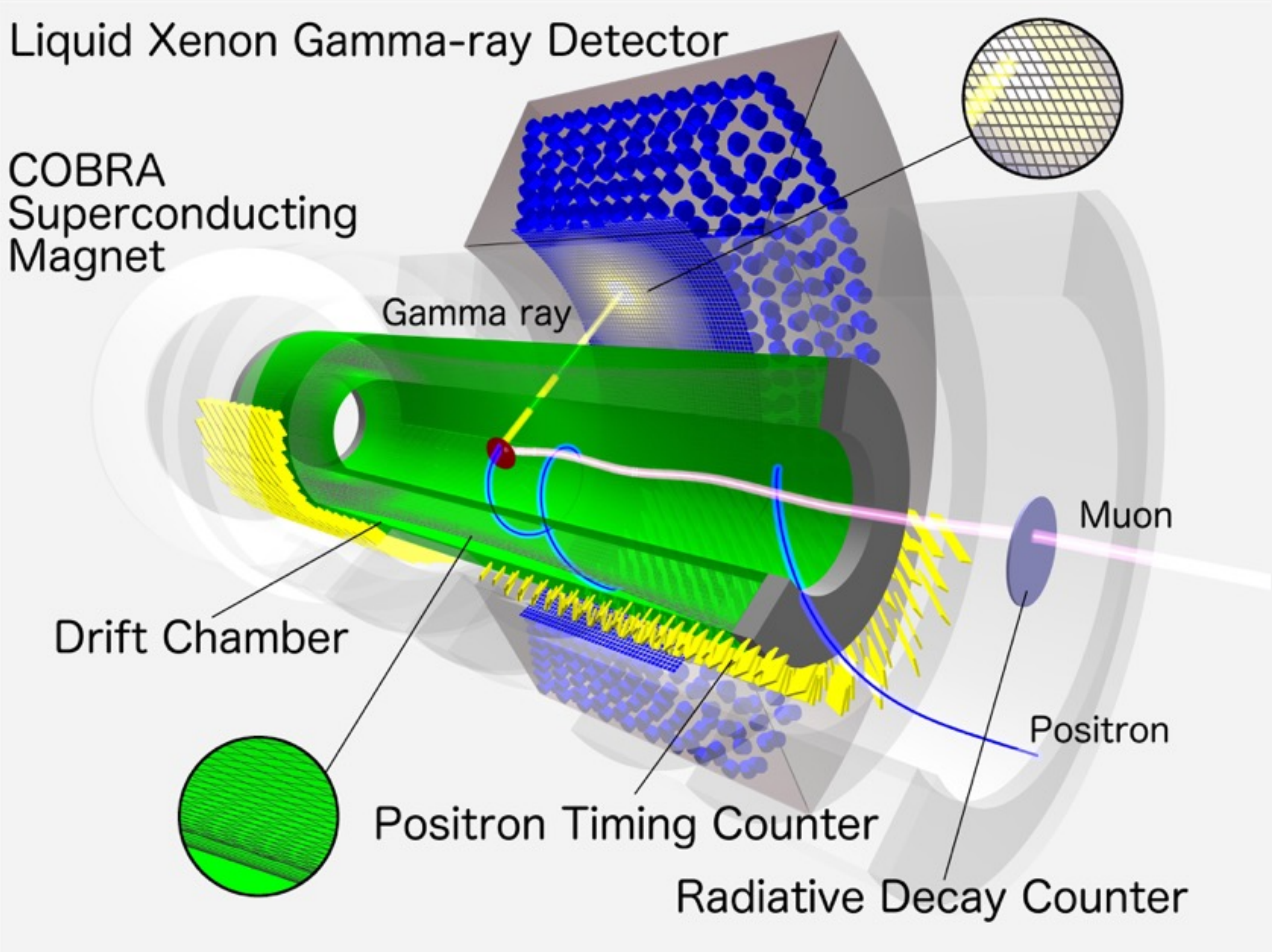
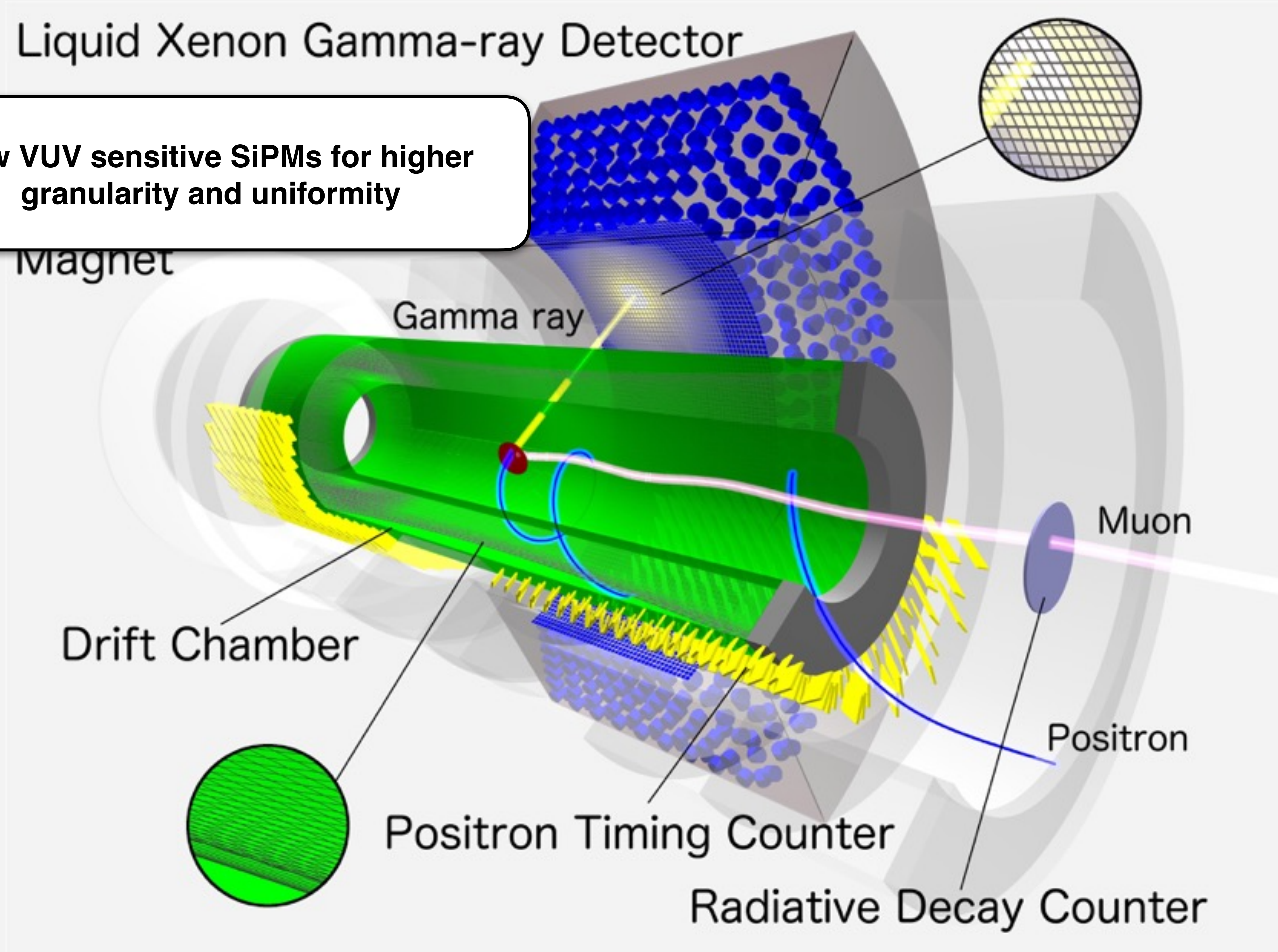
Positron
Positron Timing Counter
Radiative Decay Counter

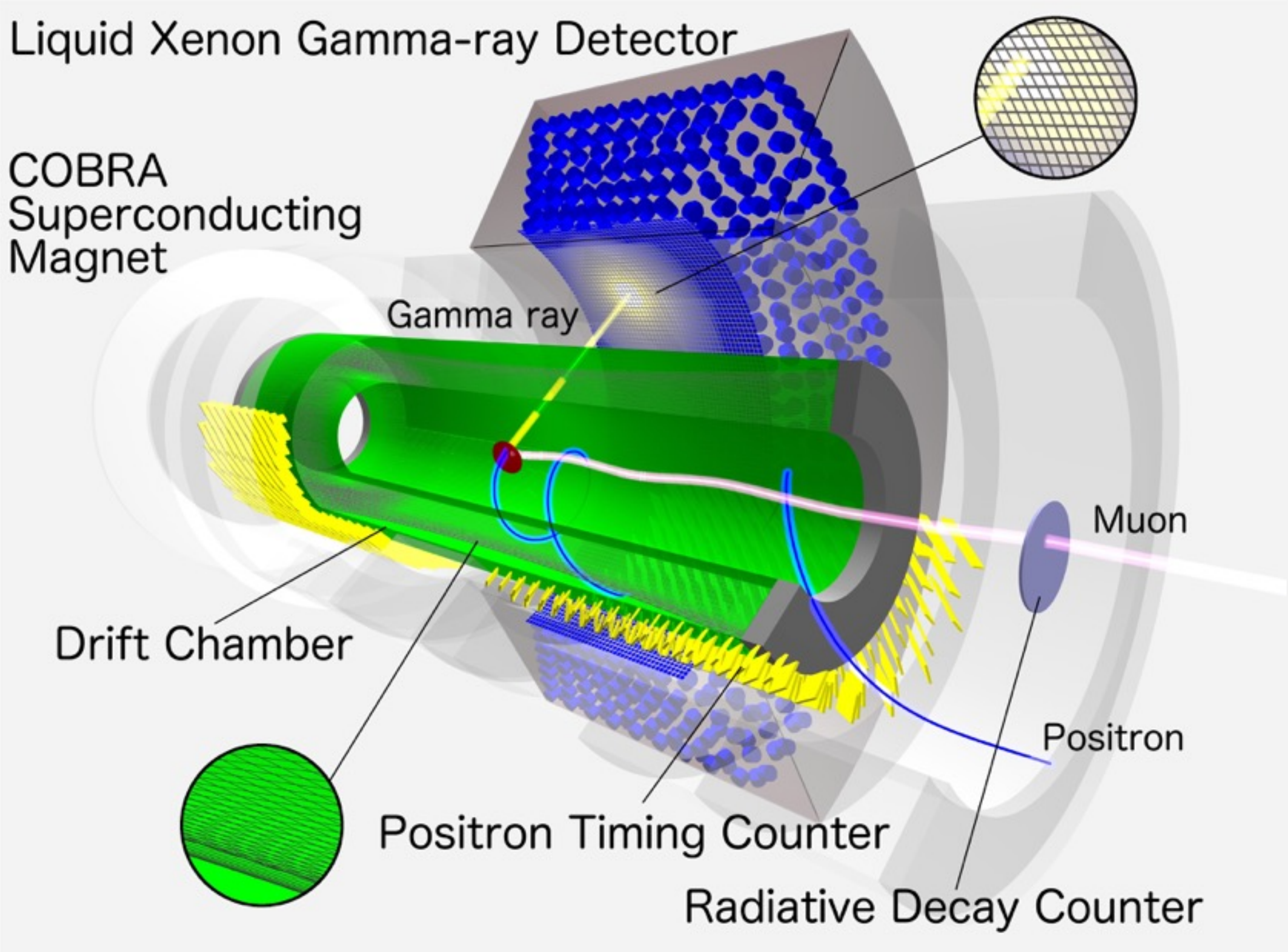


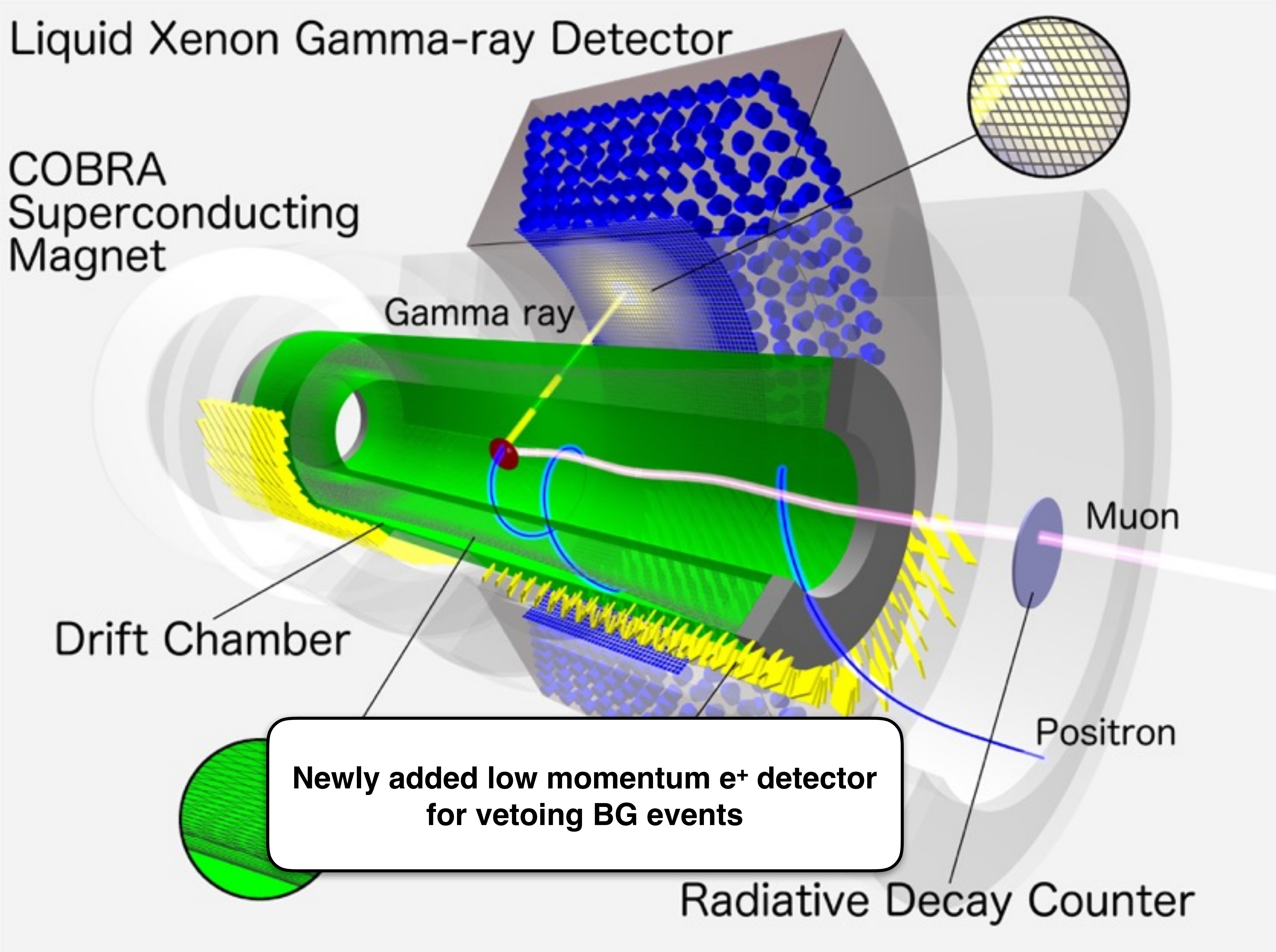
High resolution e^+ timing with highly segmented plastic counters


Liquid Xenon Gamma-ray Detector
COBRA
Superconducting
Magnet
Gamma ray
Muon
Drift Chamber
Positron
Positron Timing Counter
Radiative Decay Counter

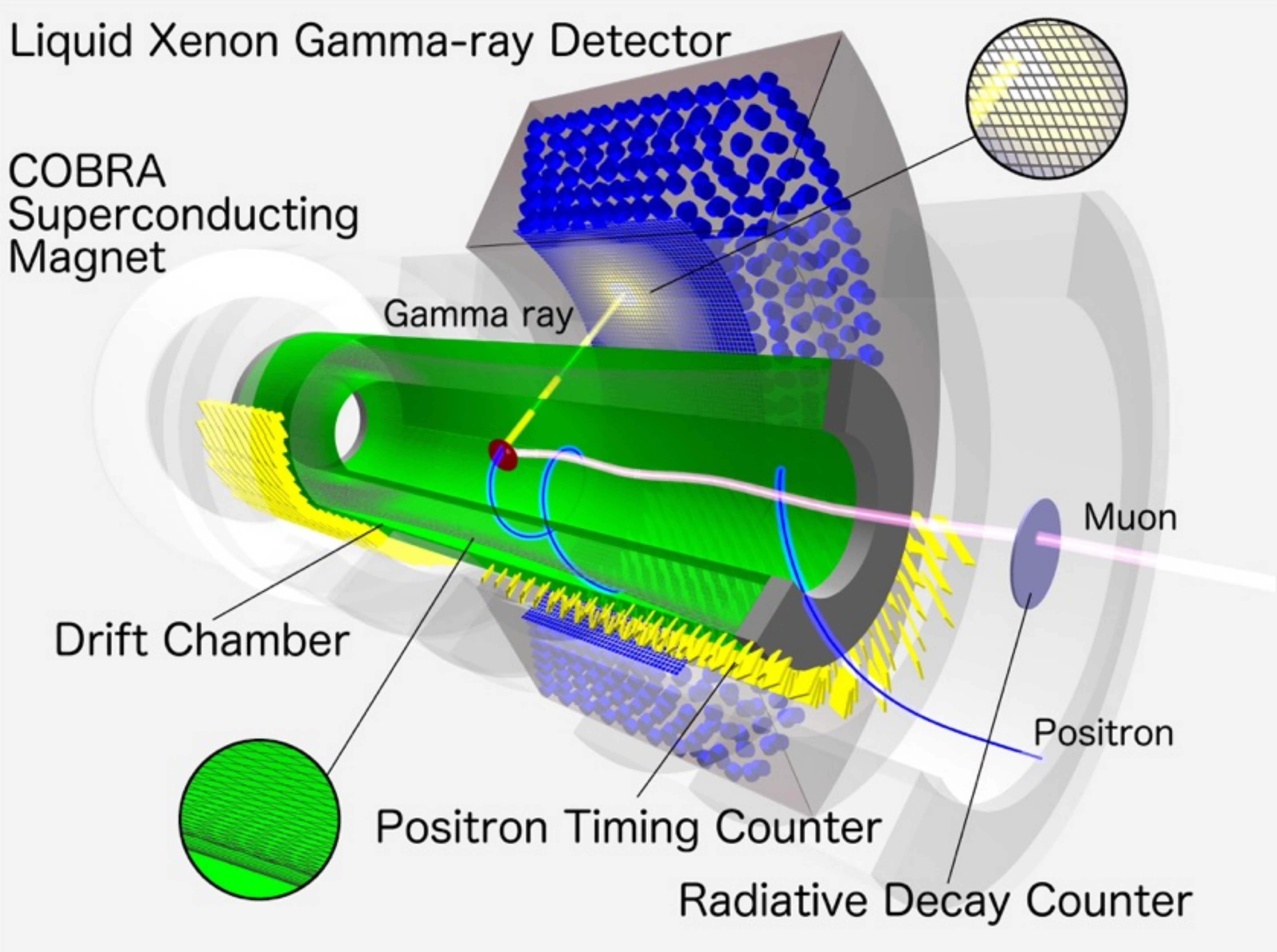
New VUV sensitive SiPMs for higher granularity and uniformity



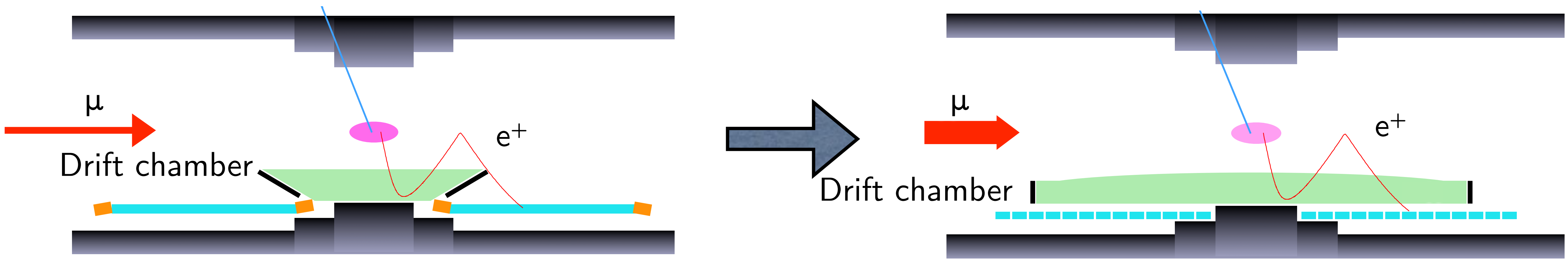

Liquid Xenon Gamma-ray Detector
COBRA
Superconducting
Magnet
Gamma ray
Muon
Drift Chamber
Positron
Positron Timing Counter
Radiative Decay Counter



Liquid Xenon Gamma-ray Detector
COBRA
Superconducting
Magnet
Gamma ray
Muon
Drift Chamber
Positron
Newly added low momentum e+ detector
for vetoing BG events
Radiative Decay Counter


Liquid Xenon Gamma-ray Detector
COBRA
Superconducting
Magnet
Gamma ray
Muon
Drift Chamber
Positron
Positron Timing Counter
Radiative Decay Counter

Cylindrical drift chamber



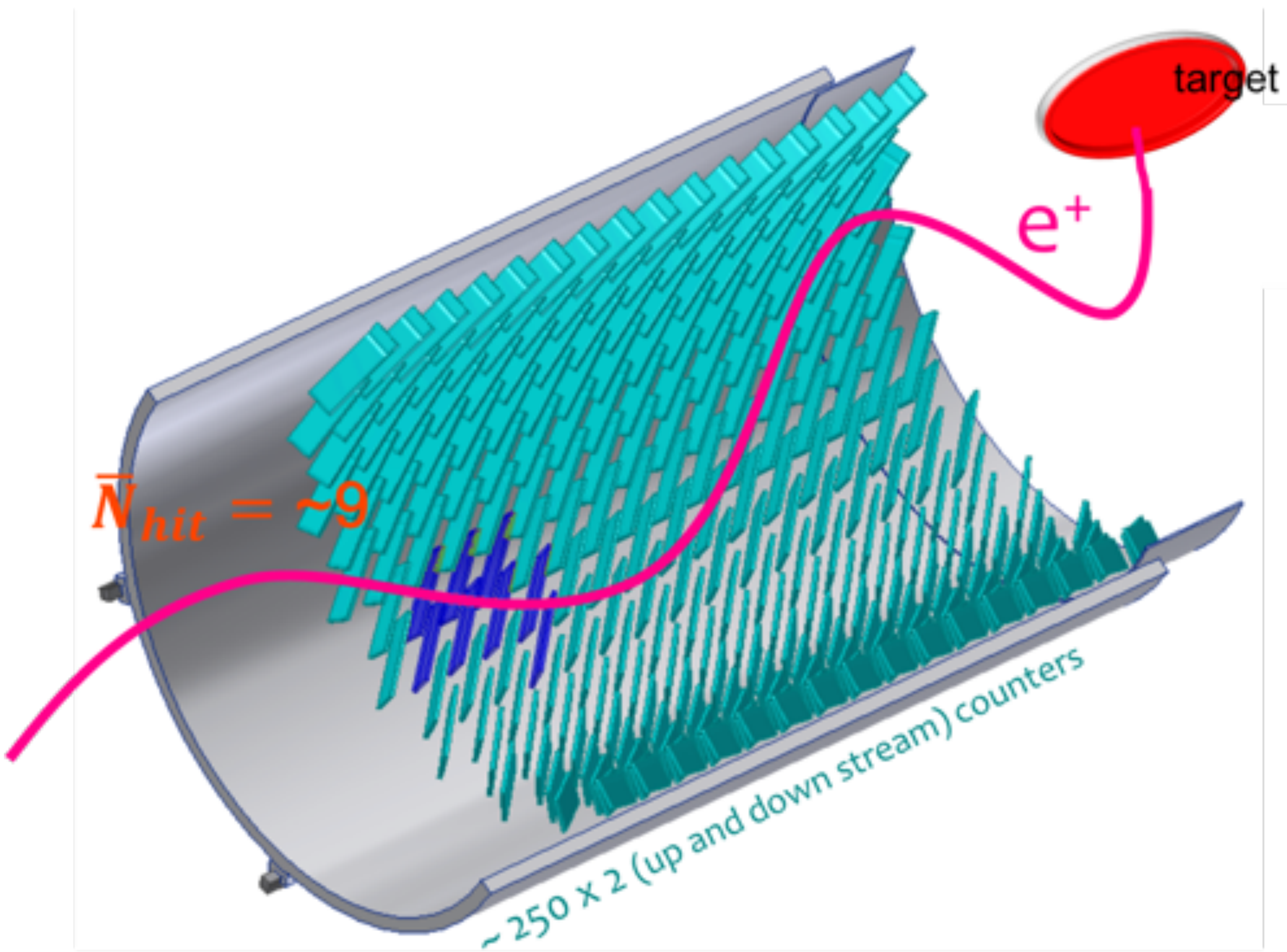
Expected performance

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

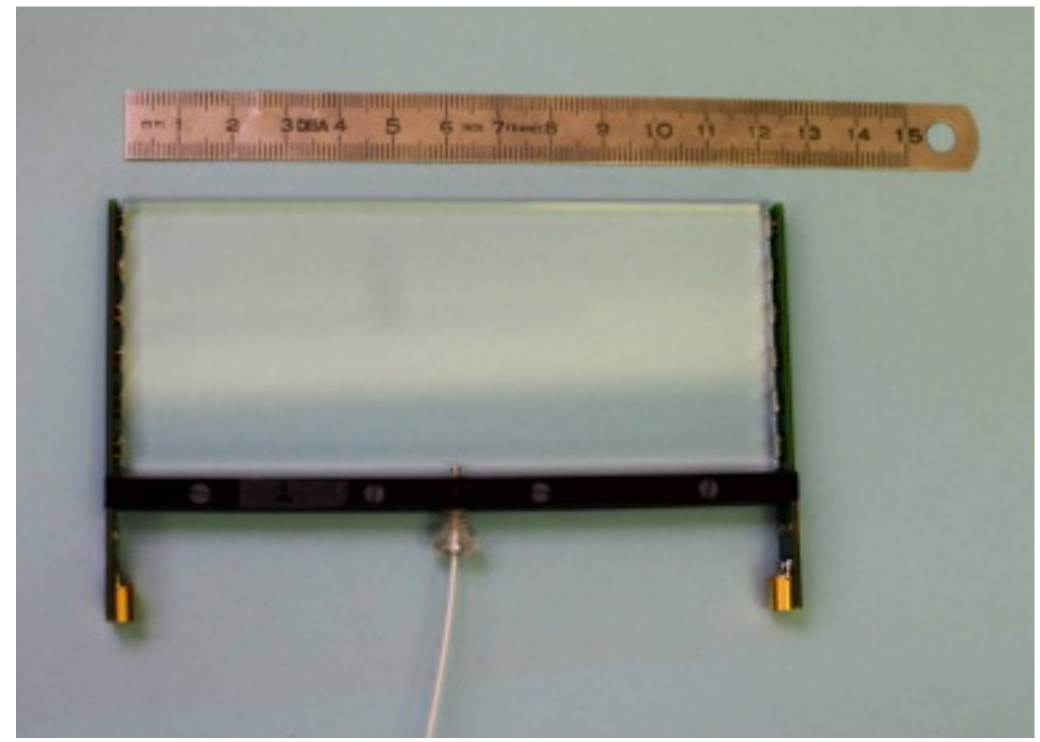
Efficiency	: >**85**%
Hit resolution	: **120** μm
Momentum resolution	: **130** keV
Angular resolution	: **3.7** mrad (φ), **5.3** mrad (θ)

Double the efficiency, and **half the resolutions** compared to MEG I spectrometer

Pixelated timing counter



9 counter-hits in average



4–5 cm wide, 12 cm long, 5 mm thick
Laser for time-offset calibration

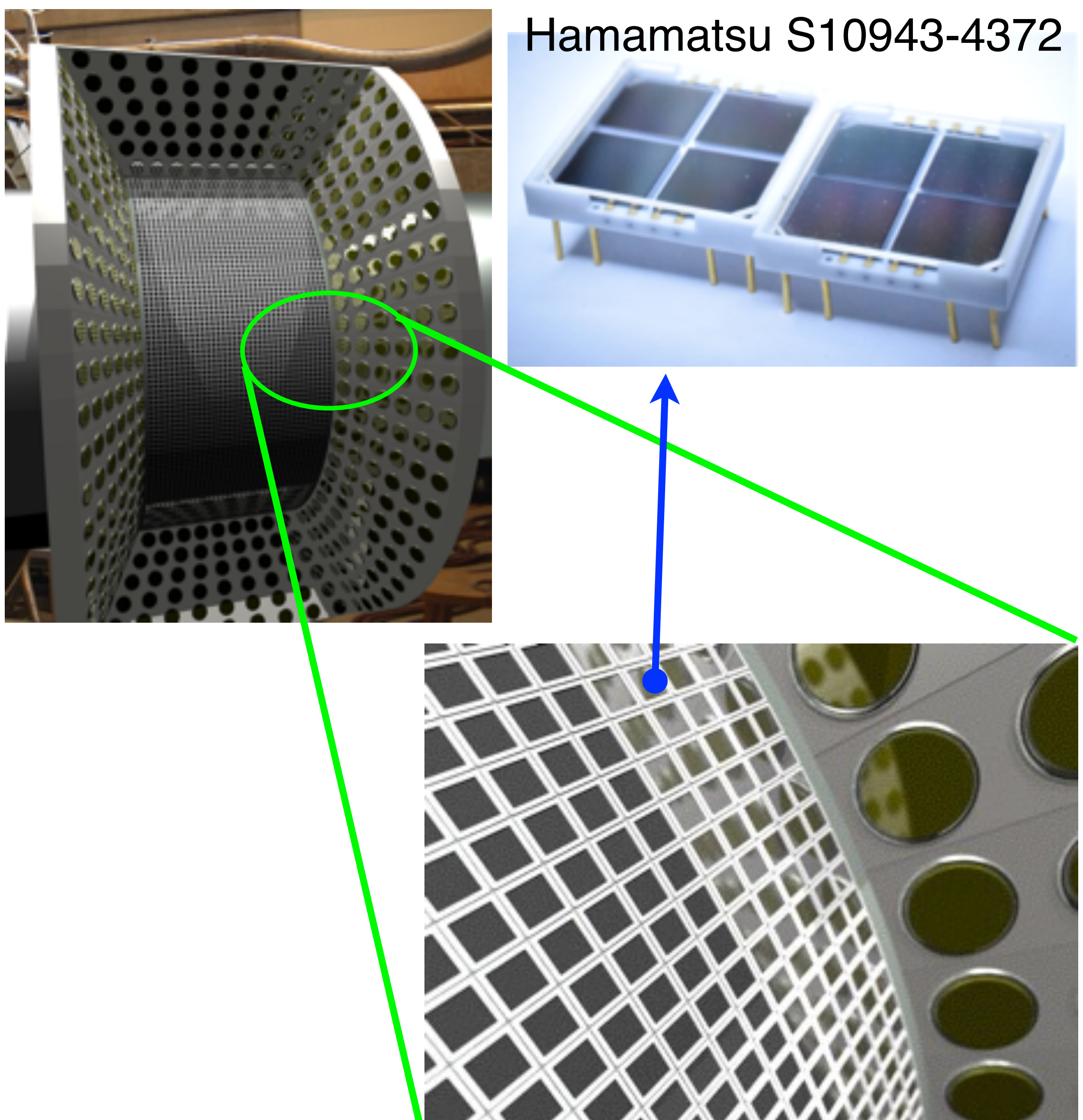
6 SiPMs in series

Single counter resolution : ~70 psec
Overall time resolution : **30** psec

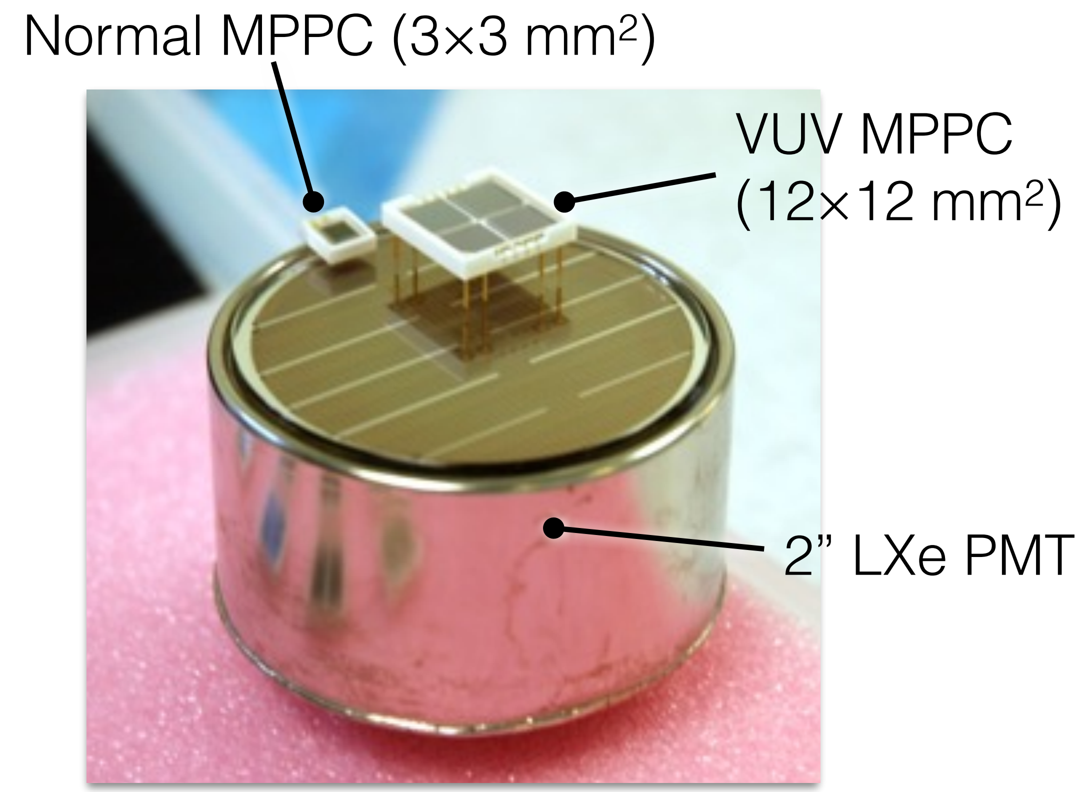
About **half the resolutions** compared to MEG I timing-counter

LXe Photon Detector

12×12mm² SiPMs sensitive to LXe scintillation lights



Computer graphics

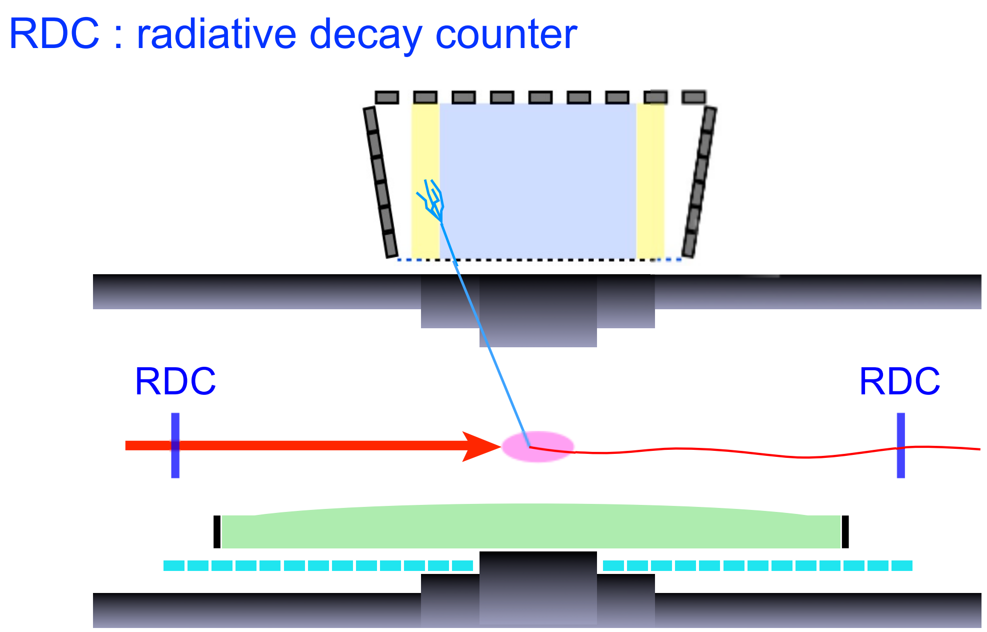


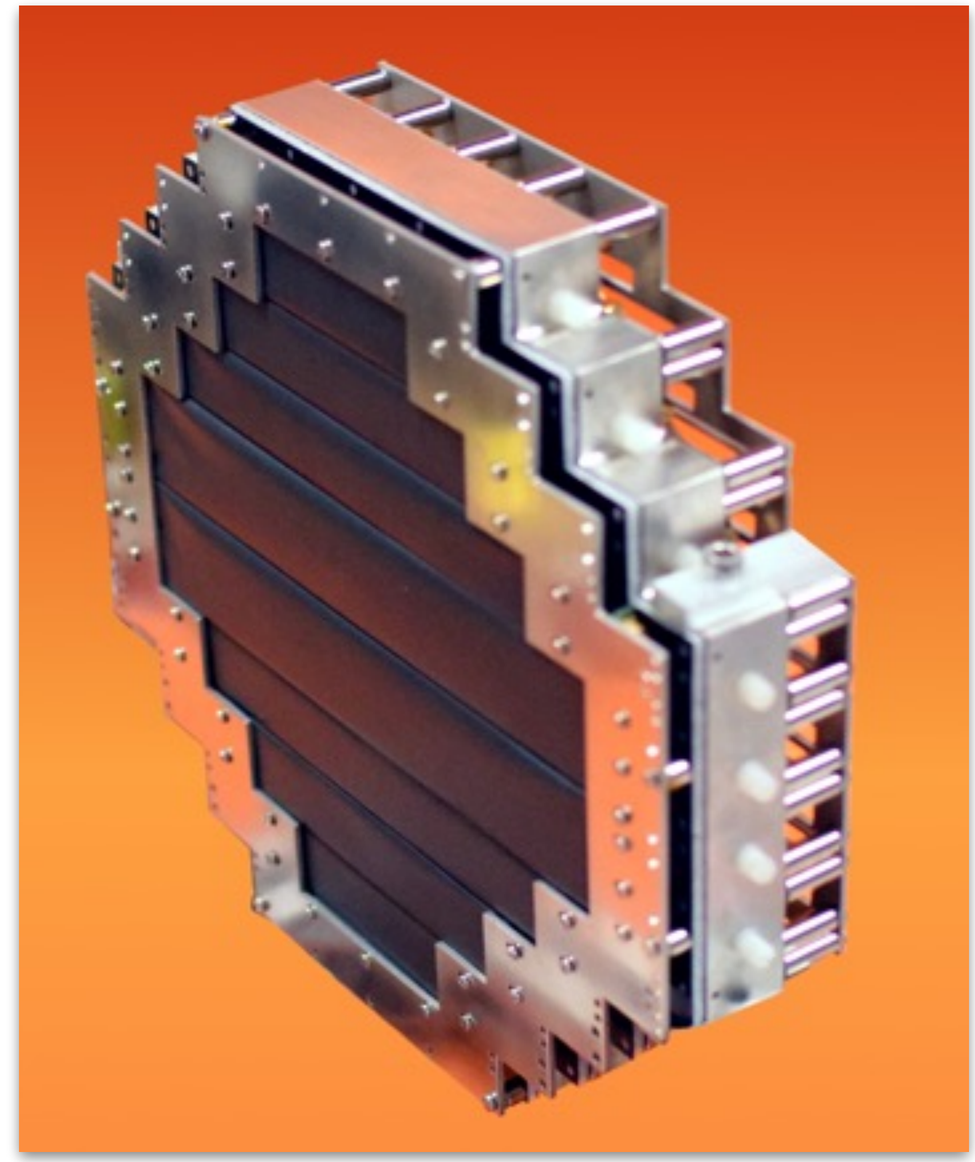
- Twice better energy and position resolutions
- Time resolution can be better (40–60 psec) because of the more photoelectrons and the better position resolution.
- ~10% improvement of detection efficiency due to less amount of material on the inner face

Radiative Decay Counter

Low momentum e+ detector

- Identify background γ from radiative muon decay
- 16—28 % improvement of sensitivity



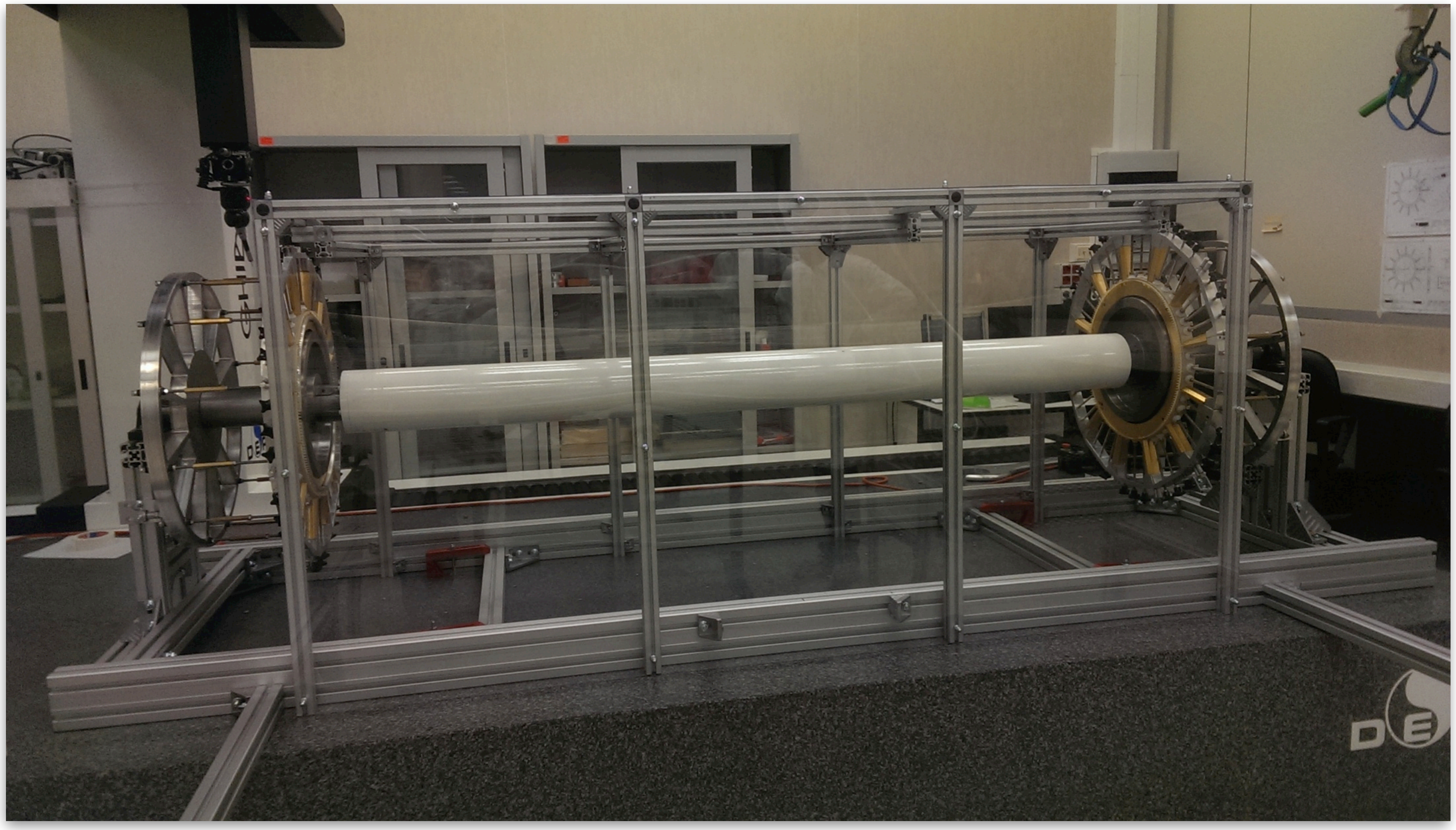


The detector was already built

Upstream (optional) : 250μm fibers
Downstream : Plastic scintillators for timing and LYSO for energy measurement

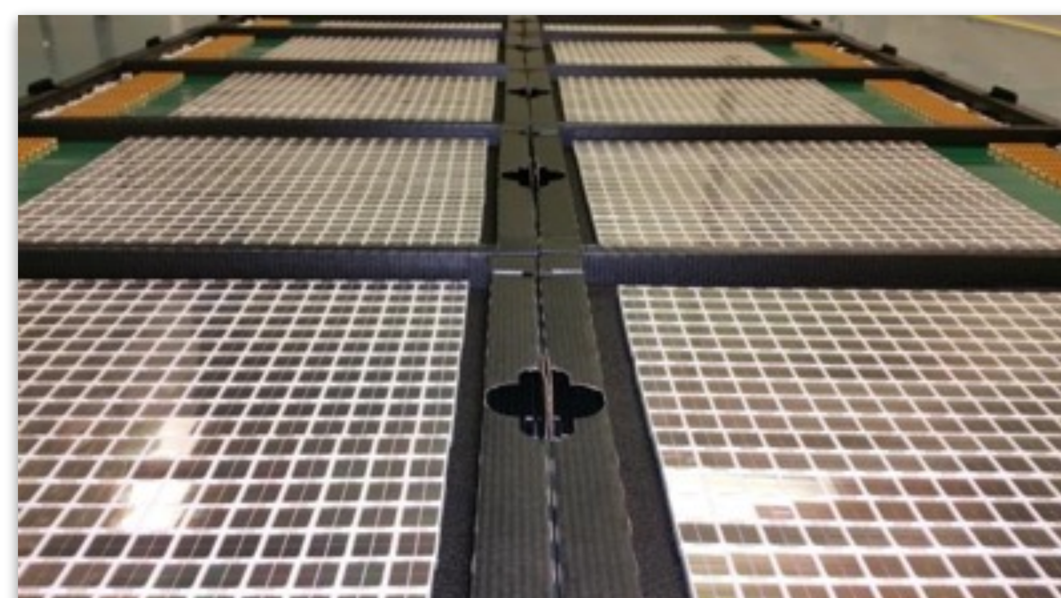
Construction

Drift chamber



LXe detector in a clean room

All LXe SiPMs produced



New waveform readout board (WaveDREAM)

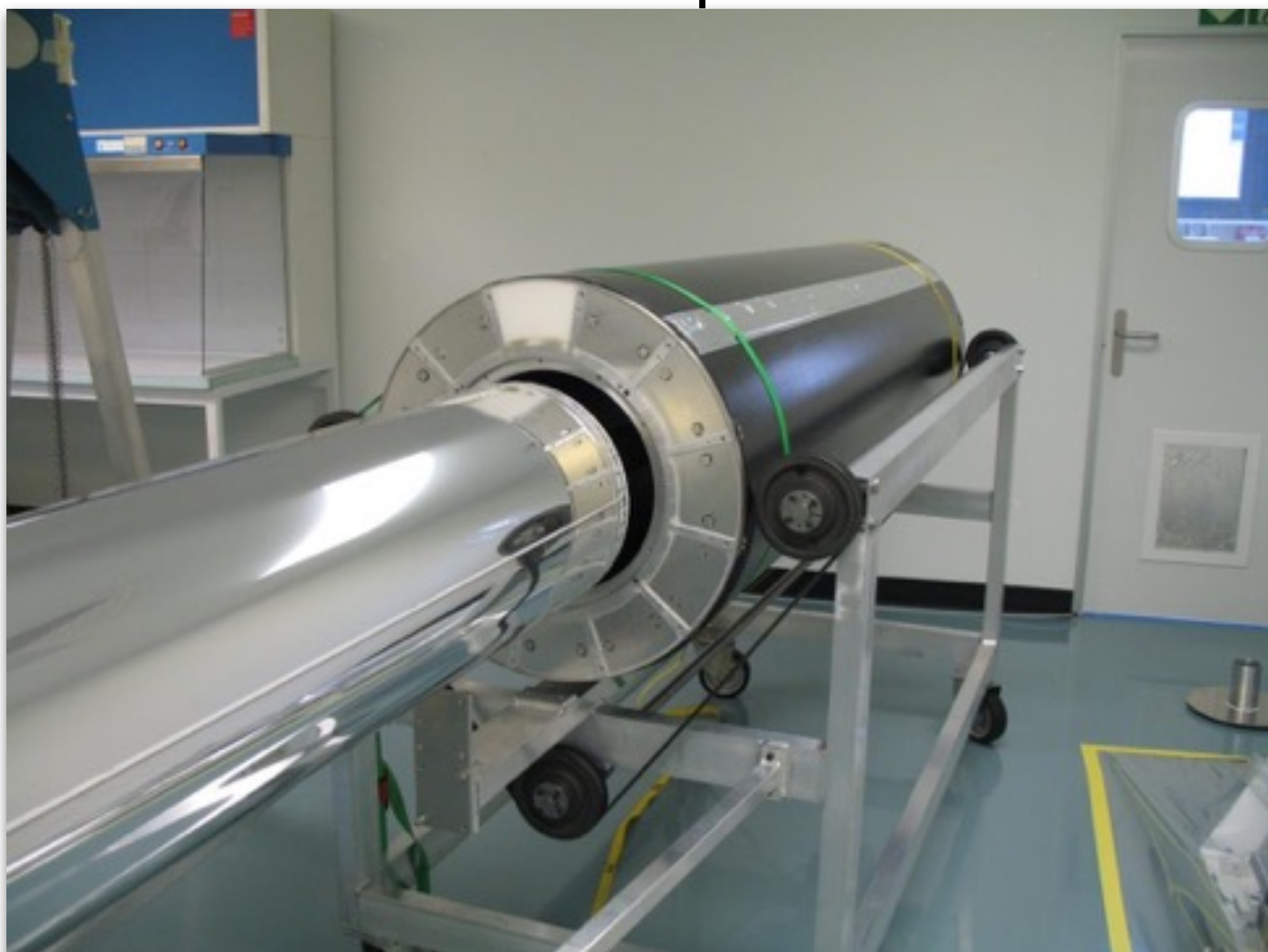
TC in 2015 is shown later

2015 pre-engineering run

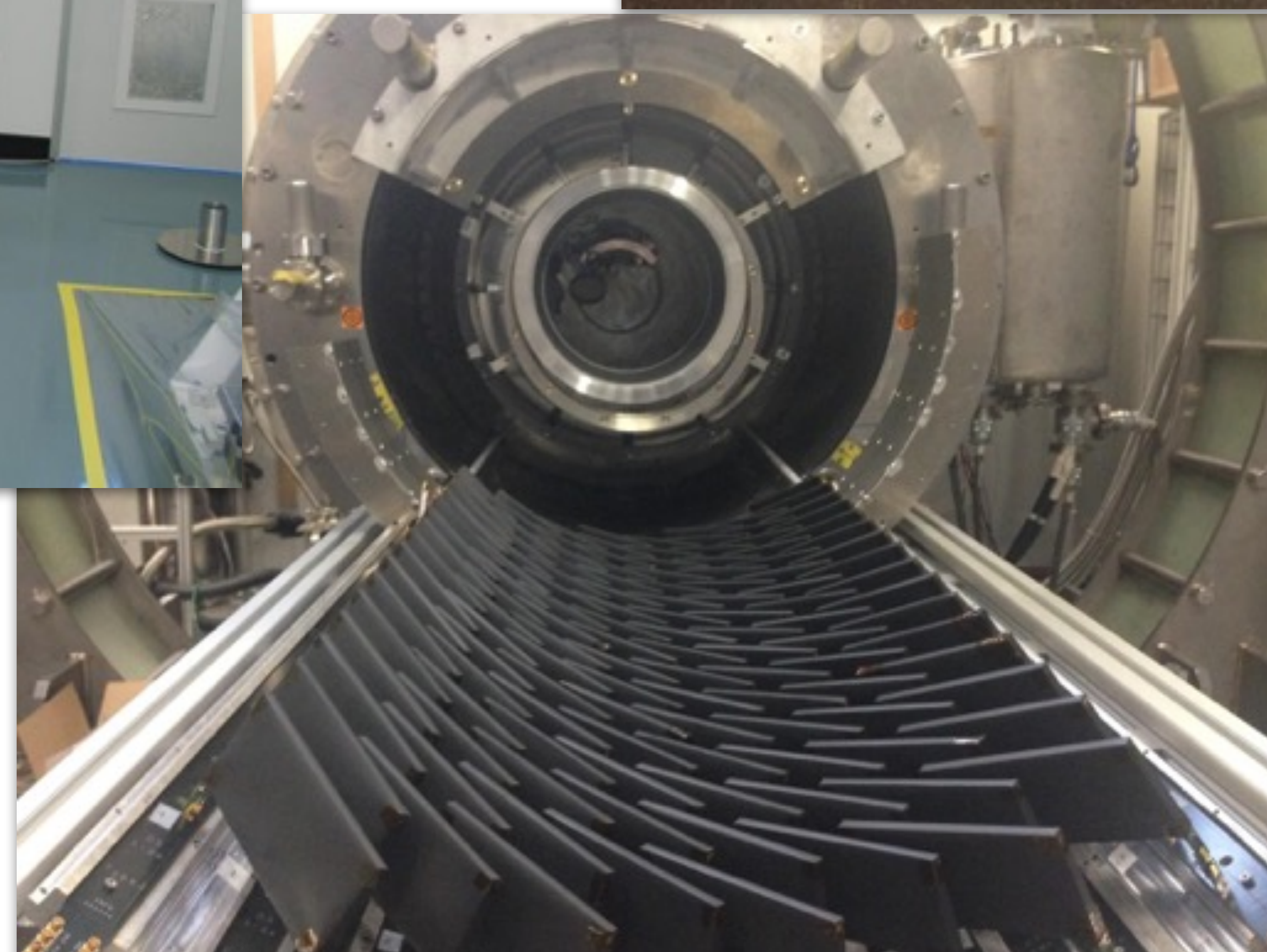
- In Oct—Dec 2015, we tested several parts in PSI with high rate muon beam
  - Same muon intensity with MEG II
  - 1/4 scale timing counter and a mockup drift-chamber were installed
- Goals
  - Mechanical tests
    - Mechanical integrity of sub-detectors, target insertion system etc.
  - Beam optimization
    - New thin target + degrader combination
    - Check how the upstream RDC affects the beam emittance with using a dummy US RDC
    - Test further monitoring tools,
      - Luminophor Foil (Plastic substrate + CsI) + CCD
      - Thin plastic scintillator as a muon stopping target
  - Electronics
    - New readout system (WaveDREAM)
    - New trigger and DAQ
  - Timing counter tests
    - The number of scintillation counters is 1/4 of the final one.
    - Laser calibration system partially installed.

2015 pre-engineering run

Drift chamber mockup and inner foil



New target



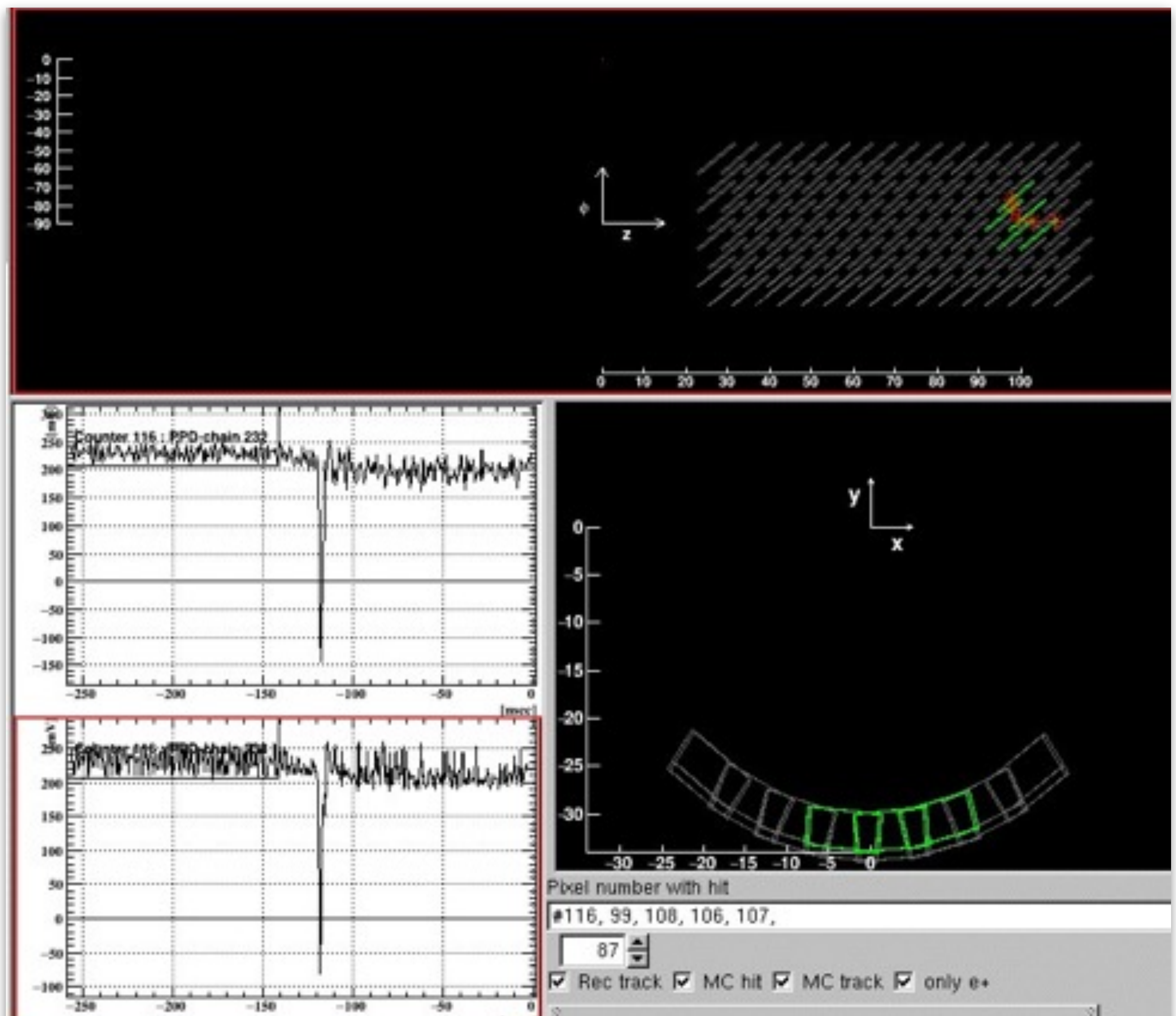
1/4 (=128) counters installed in the downstream side

pre-engineering run results

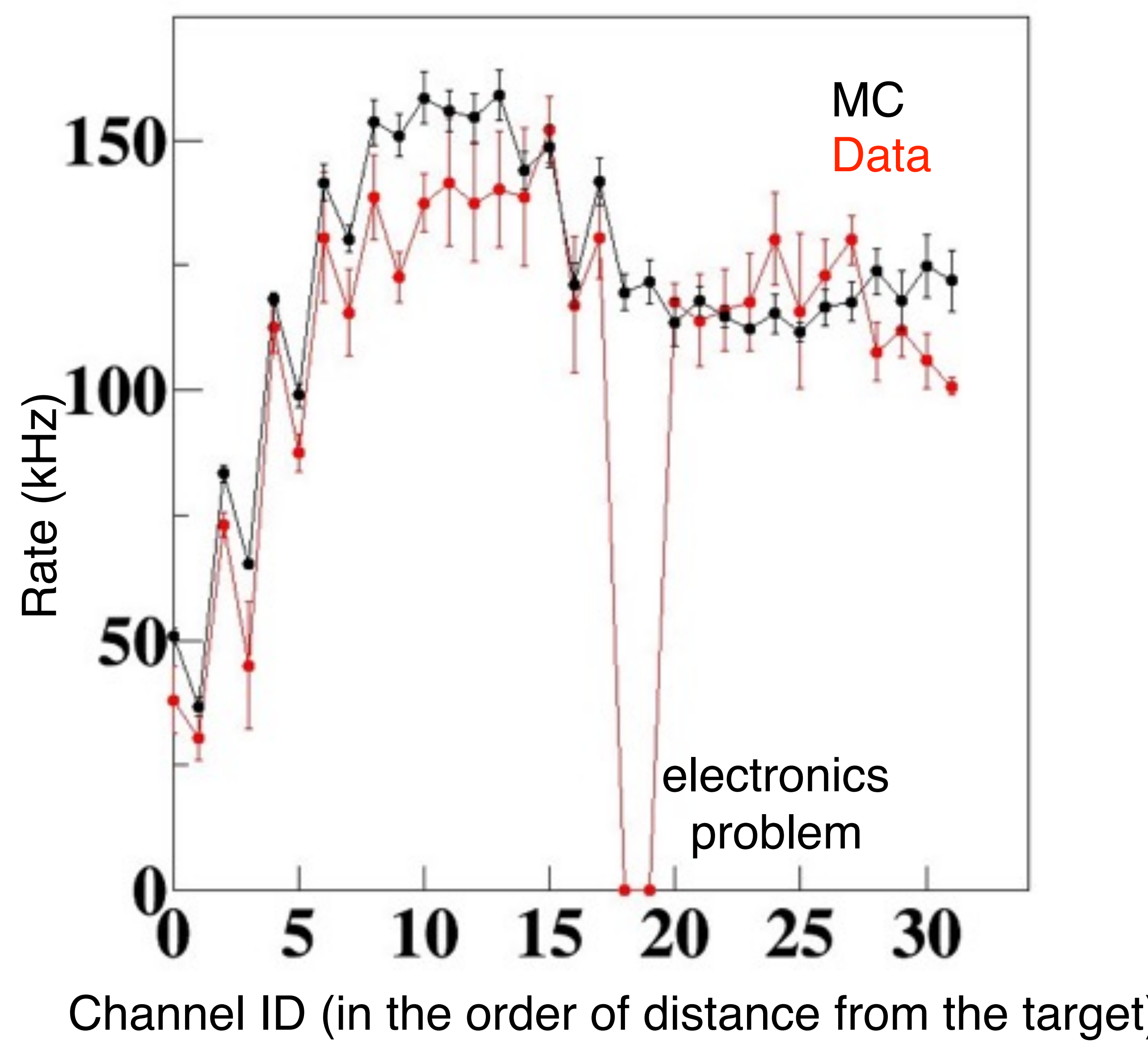
- Most of the goals achieved
  - All the mechanical parts were successfully installed with minor adjustments
  - Intensity of muon beam meets the requirements with some contingency.
    - Rate at Target 9×10^{7}
    - Target stopping efficiency ~85%
    - Beam size ~10 mm
  - The influence of US RDC to the beam emittance is little.
  - Successful muon data acquisition.
    - Trigger-DAQ chain was tested. Several issues (e.g. high noise level) found that need addressing.
    - All timing counters were functional
      - Resolutions were worse than expectation probably due to electronics problems.

Highlight of TC pilot data

TC event display showing a hits by a Michel positron



Hit rate on timing counters consistent with MC

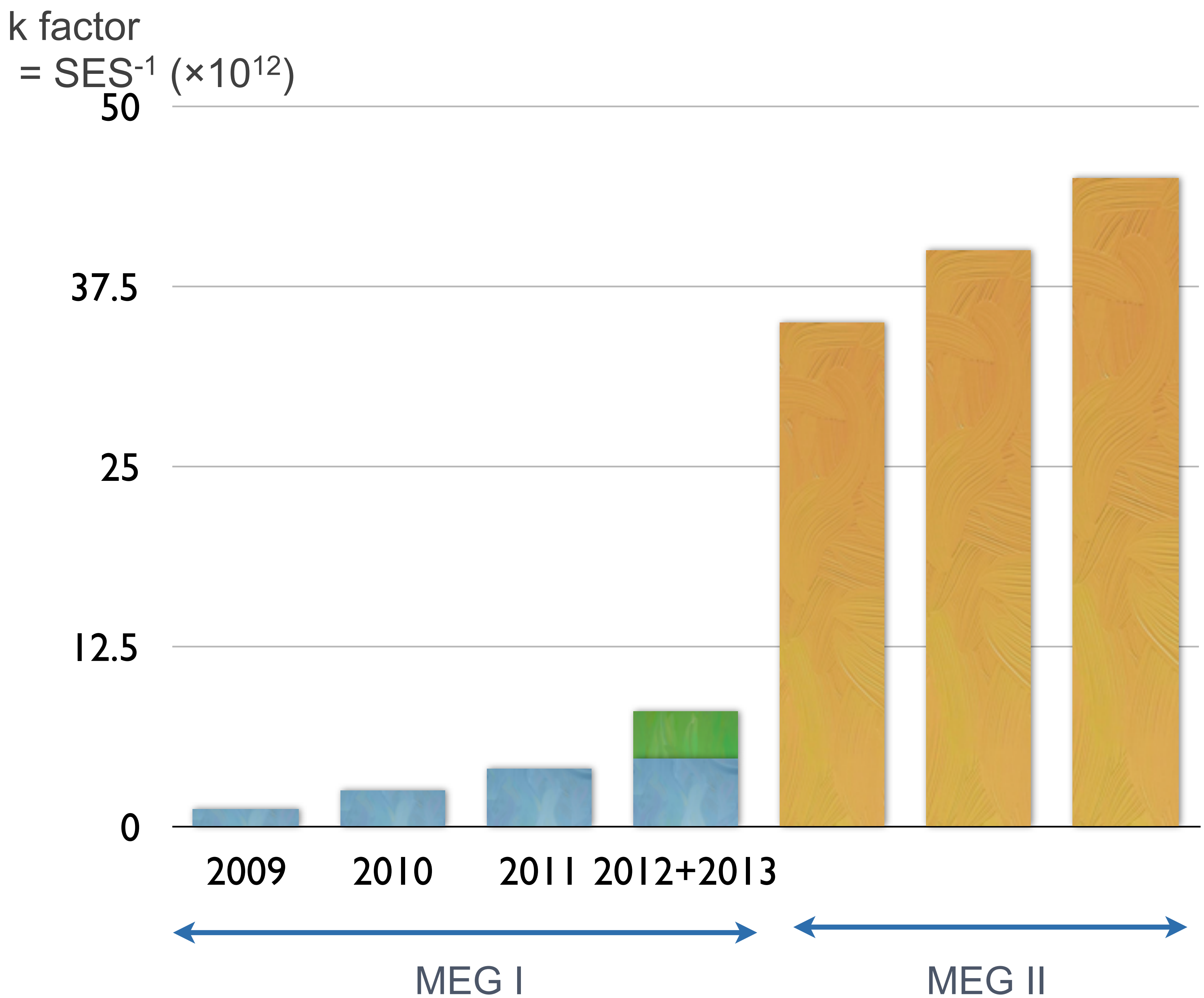


Data-MC difference may be due to imperfect implementation of chamber geometry in MC

Plan for 2016

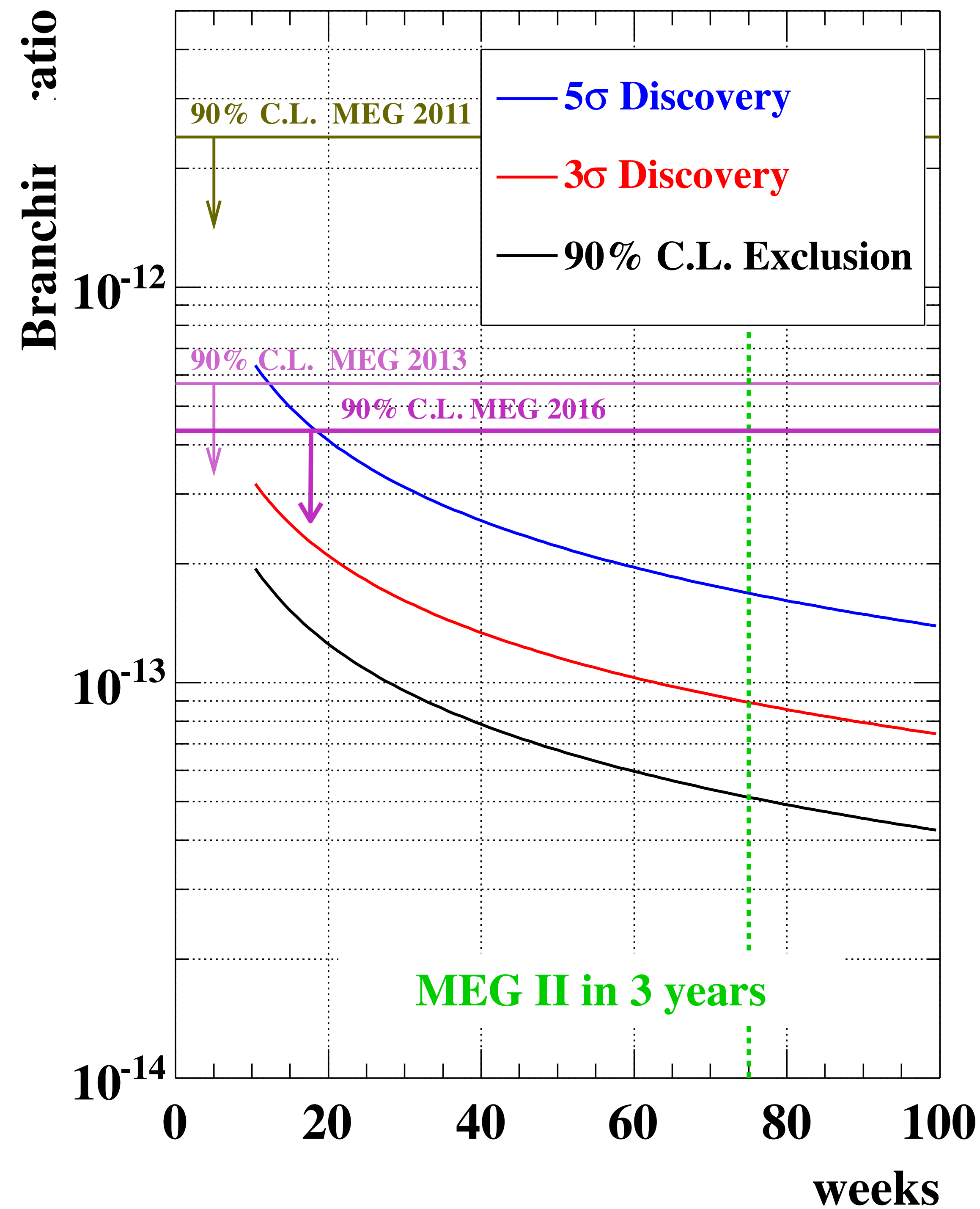
- Spring beam time (June — July)
    - TC pilot run with improved electronics
    - Downstream RDC beam test
- B-field mapping in the solenoid
- Construction of the photon detector followed by performance test with reduced number of electronics channels.
- Construction of the drift chamber

MEG II data statistics



Expected performance and Sensitivity

Resolutions	MEG I	MEG II
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 of DAQ : ~5×10^{-14}

(In the curve, an improvement by RDC is not included)

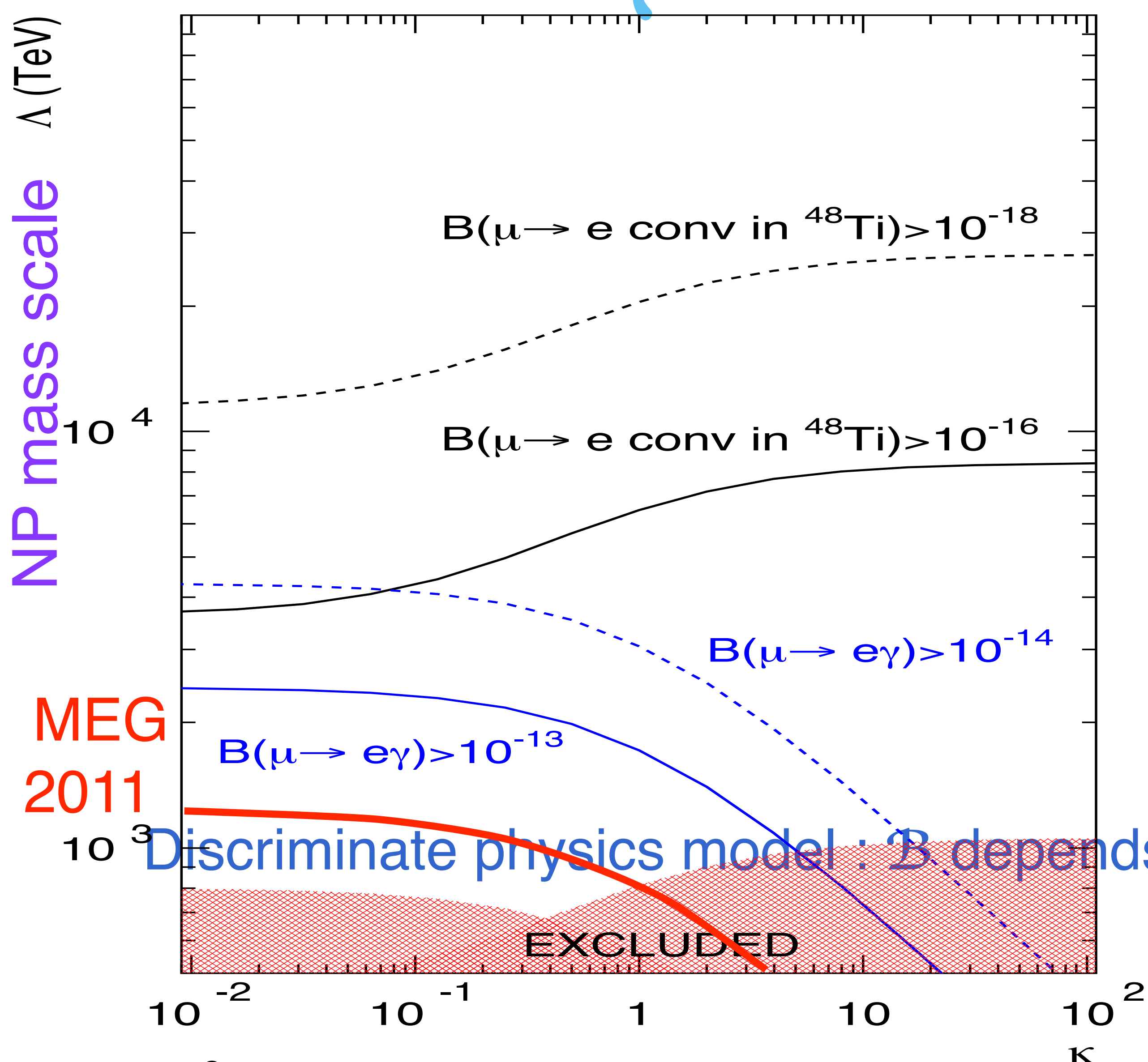
Conclusions

- Final result of MEG I
  - Sensitivity : 5.3×10^{-13}
  - No excess was found
  - 30 times stringent new limit : $\mathcal{B}$ **< 4.2×10^{-13}** @ 90% C.L. from the previous experiment (MEGA)
- MEG II
  - More intense beam, double the efficiency and half the resolutions.
  - Expected sensitivity : **~5×10^{-14}** in 3 years of DAQ
  - Construction of the detector is ongoing.

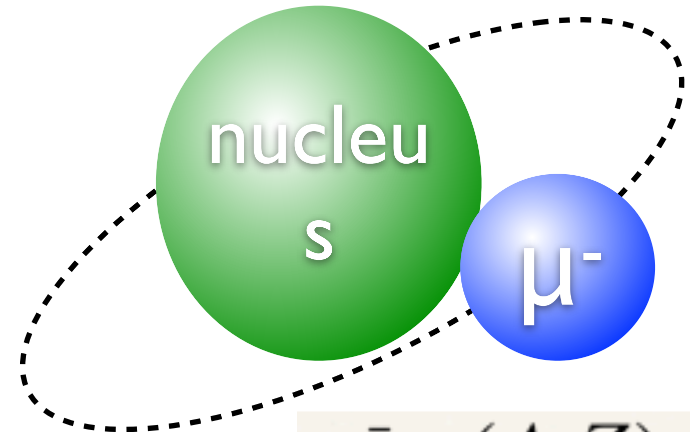
Backup

Present limit : **4.3×10⁻¹²** (SINDRUM II, Ti)

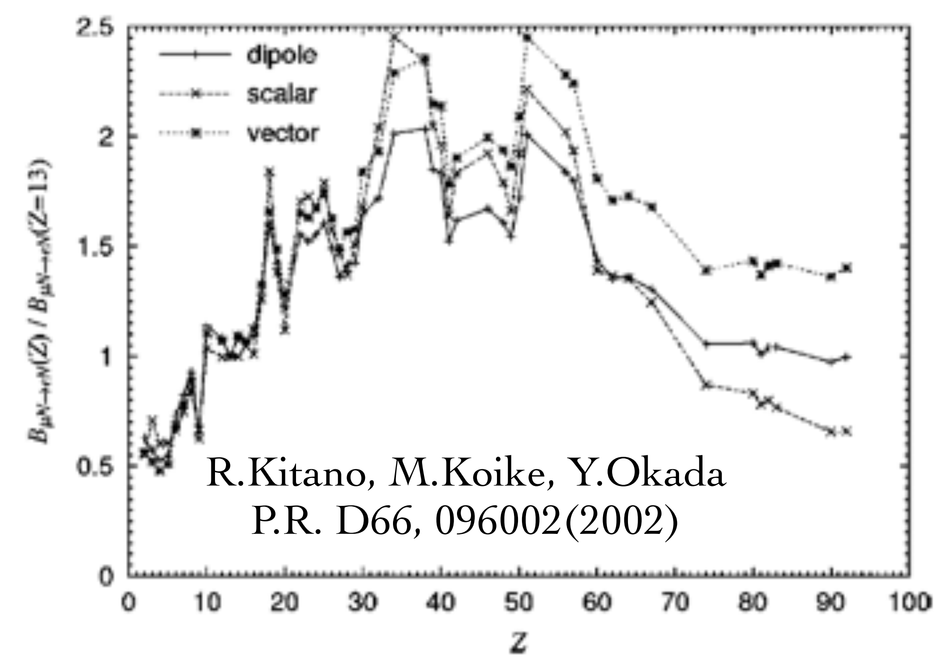
μ-e conversion



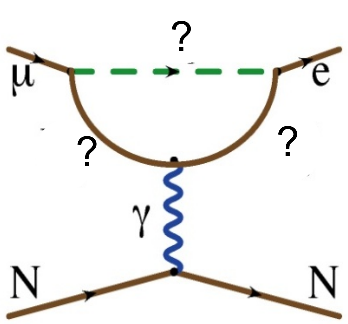
Discriminate physics model : $\mathcal{B}$ depends on the

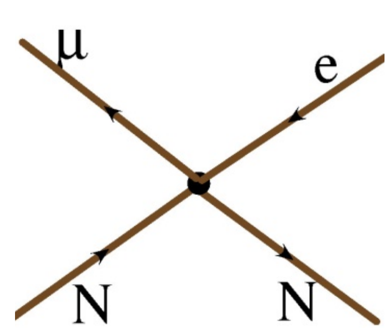


$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$



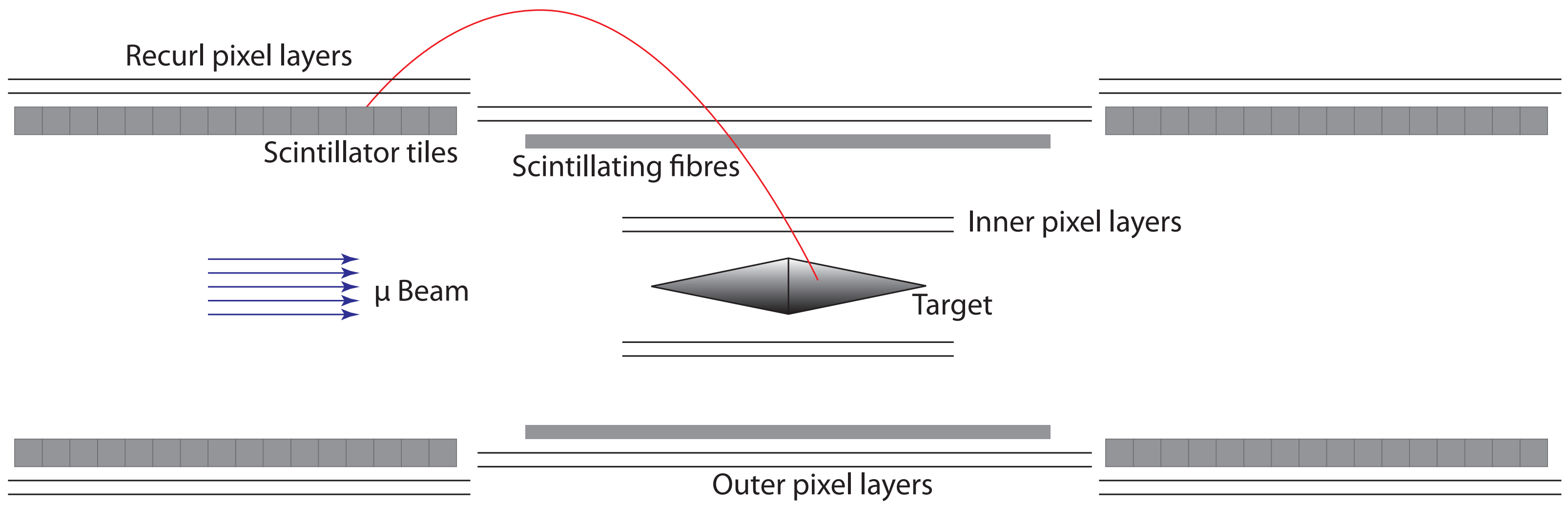
R.Kitano, M.Koike, Y.Okada
P.R. D66, 096002(2002)

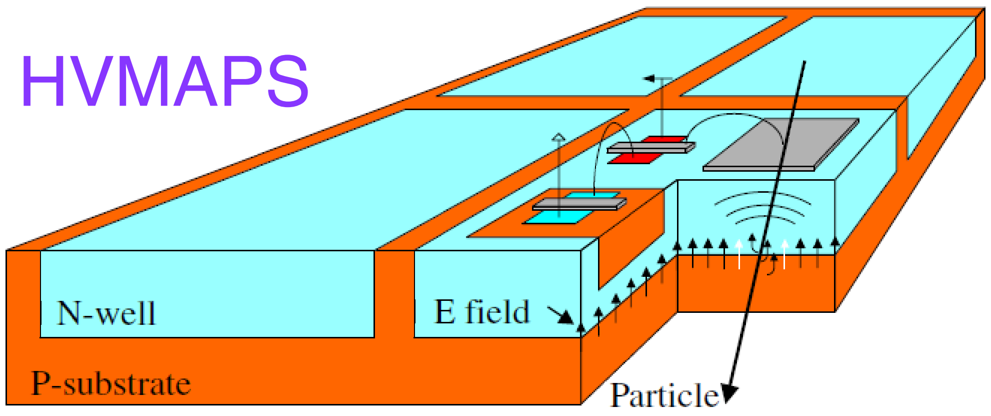


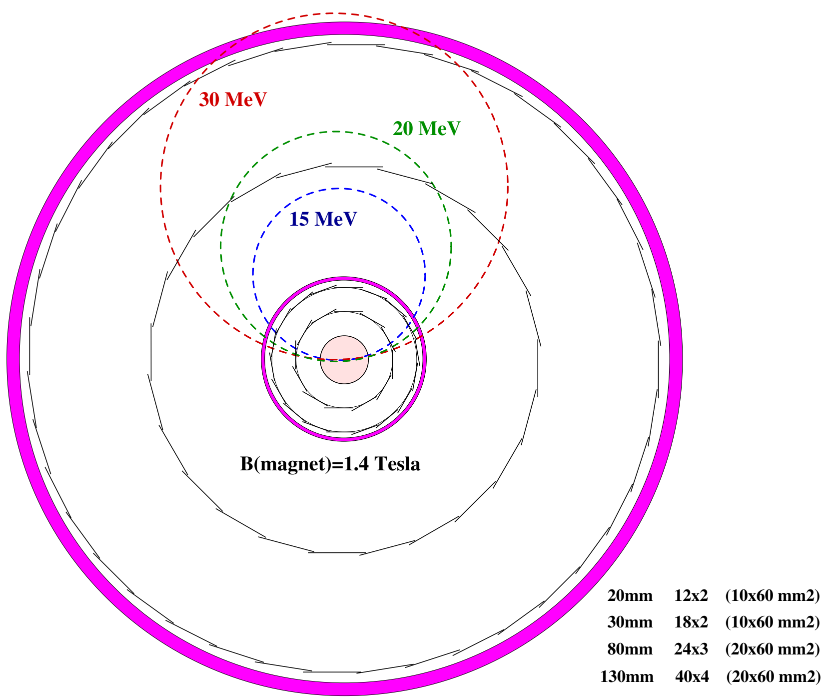


$$L_{LFV} = \boxed{\frac{m_\mu}{(\kappa+1)\Lambda^2}\,\overline{\mu_R}\sigma^{\mu\nu}e_L F_{\mu\nu}} + \boxed{\frac{\kappa}{(\kappa+1)\Lambda^2}\,\left(\overline{\mu_L}\gamma^\mu e_L\right)\left(\overline{e_L}\gamma_\mu e_L\right)}$$

Mu3e experiment







- Need excellent resolutions to get rid of backgrounds
  - Accidental BG : Vertex and timing
  - eeeνν decays : Momentum
- The detector
  - Scintillating fiber timing detector
    - 100 ps resolution on average one electron
  - Thin pixel silicon tracker
    - High voltage monolithic active pixel (HVMAPS)
      - Implement logic directly in N-well in the pixel
      - Use a high voltage commercial process
      - Small active region, fast charge collection
      - Can be thinned down to <50 μm
      - Low power consumption

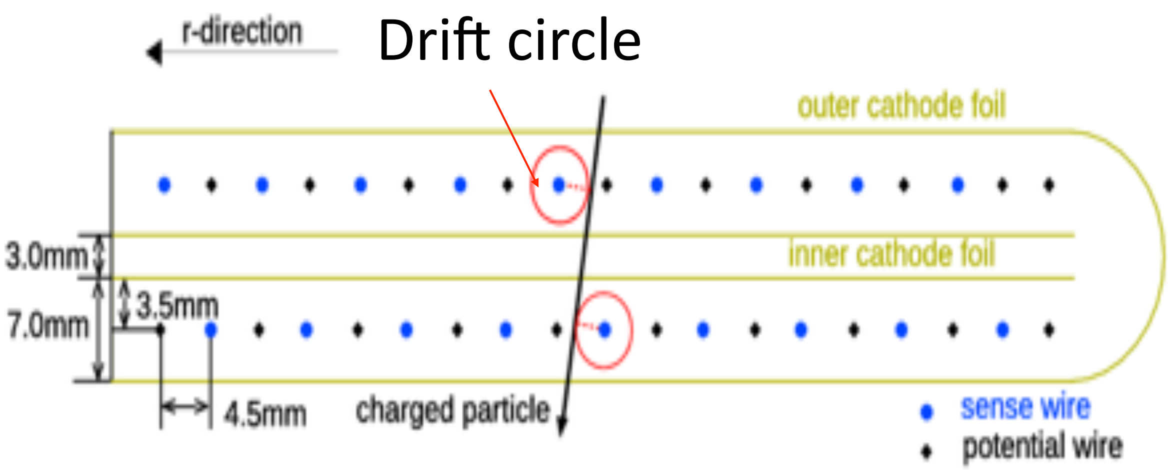
(I.Peric, P. Fischer et al., NIM A 582 (2007) 876 (ZITI Mannheim, Uni Heidelberg))

CLFV decay limits

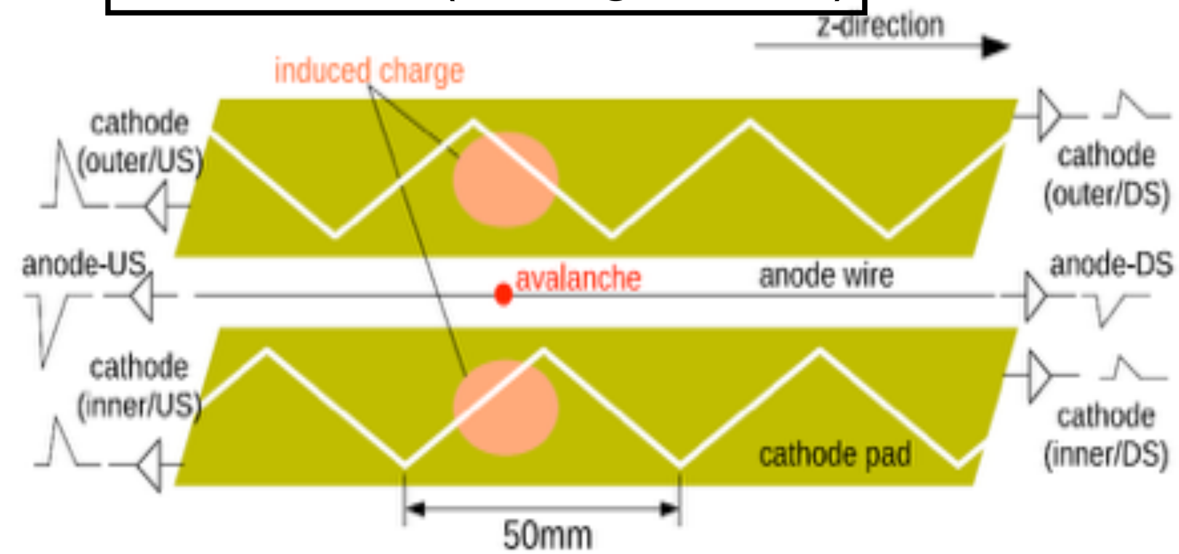
Process	Present UL	Future UL
$\mu \to e\gamma$	2.4×10^{-12}	$\mathcal{O}(10^{-14})$, MEG upgrade
$\mu \to eee$	1.0×10^{-12}	$\mathcal{O}(10^{-16})$, Mu3e
$\mu + \mathrm{Ti} \to e + \mathrm{Ti}$	4.3×10^{-12}	$\mathcal{O}(10^{-17})$, COMET/Mu2e
$\tau \to e\gamma$	3.3×10^{-8}	$\mathcal{O}(10^{-9})$, Future B-factories
$\tau \to eee$	2.7×10^{-8}	$\mathcal{O}(10^{-10})$, Future B-factories
$\tau \to e\mu\mu$	2.7×10^{-8}	$\mathcal{O}(10^{-10})$, Future B-factories
$\tau \to \mu\gamma$	4.4×10^{-8}	$\mathcal{O}(10^{-9})$, Future B-factories
$\tau \to \mu\mu\mu$	2.1×10^{-8}	$\mathcal{O}(10^{-10})$, Future B-factories
$\tau \to \mu ee$	1.8×10^{-8}	$\mathcal{O}(10^{-10})$, Future B-factories
$K \to \pi\mu e$	1.3×10^{-11}	
$K \to e\mu$	4.7×10^{-12}	

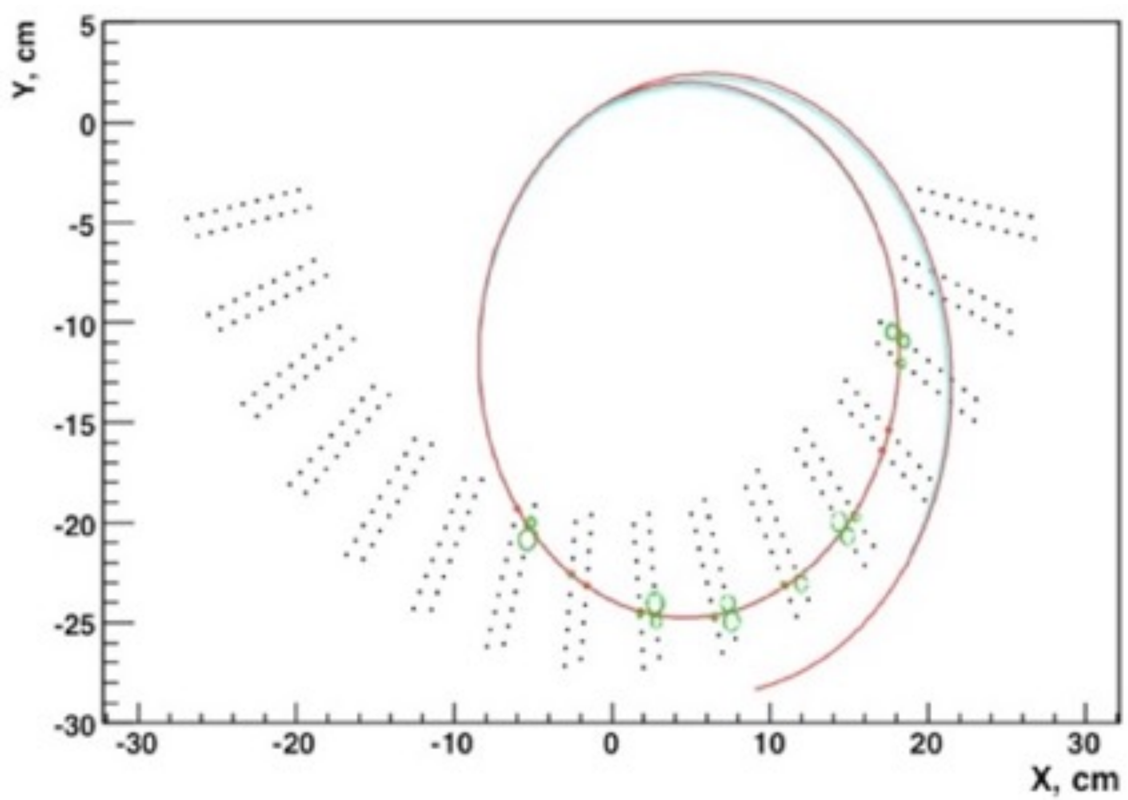
Track reconstruction

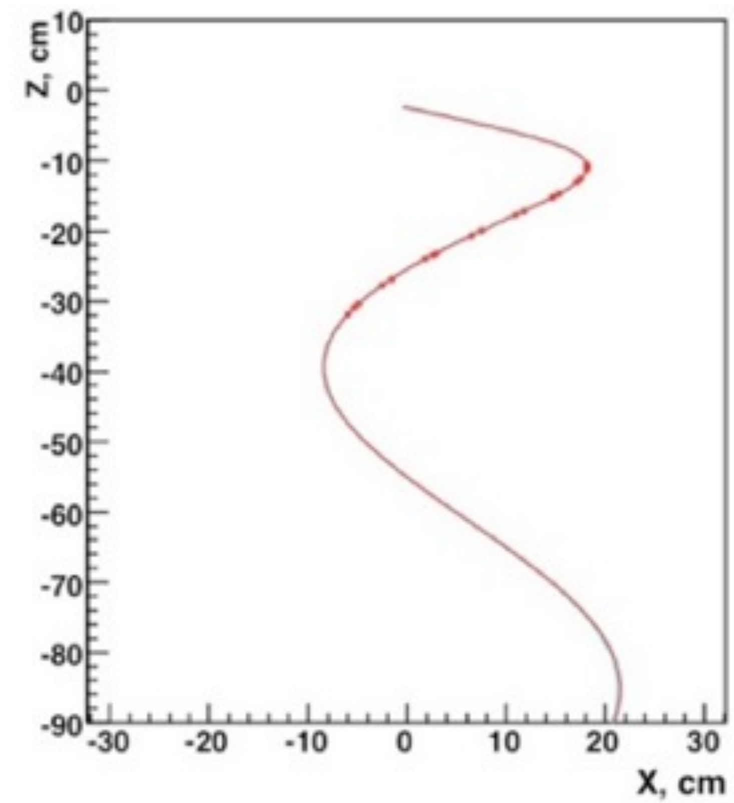
R direction (drift time)



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

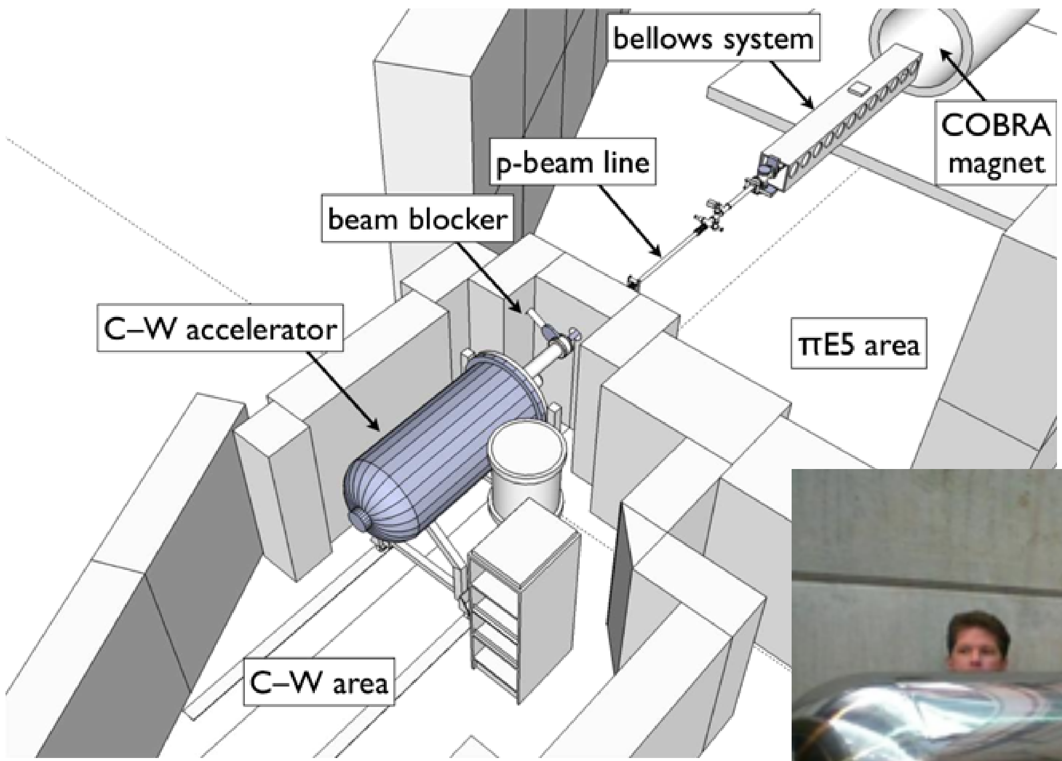
LED
Alpha source (5.5 MeV)

Energy

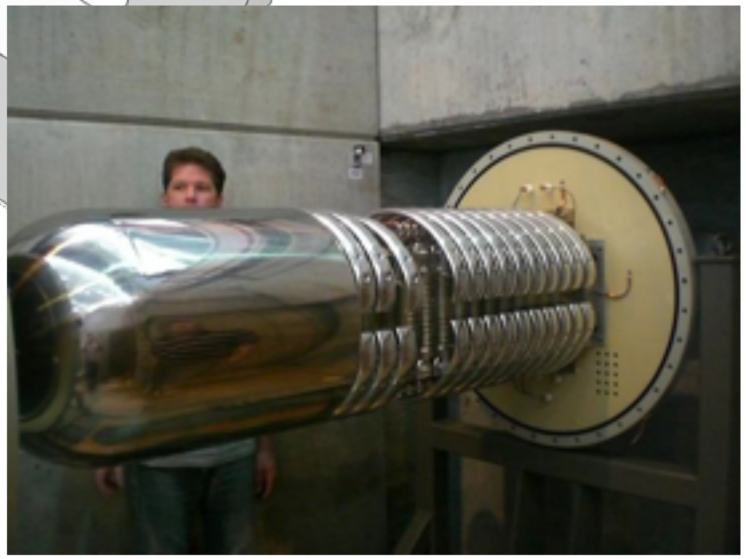
AmBe (4.4MeV)
Neutron capture (9MeV)
Li(p,γ)Be (17.6 MeV)
$\pi0 \to \gamma\gamma$ (55, 83 MeV)
Cosmic ray (160 MeV)

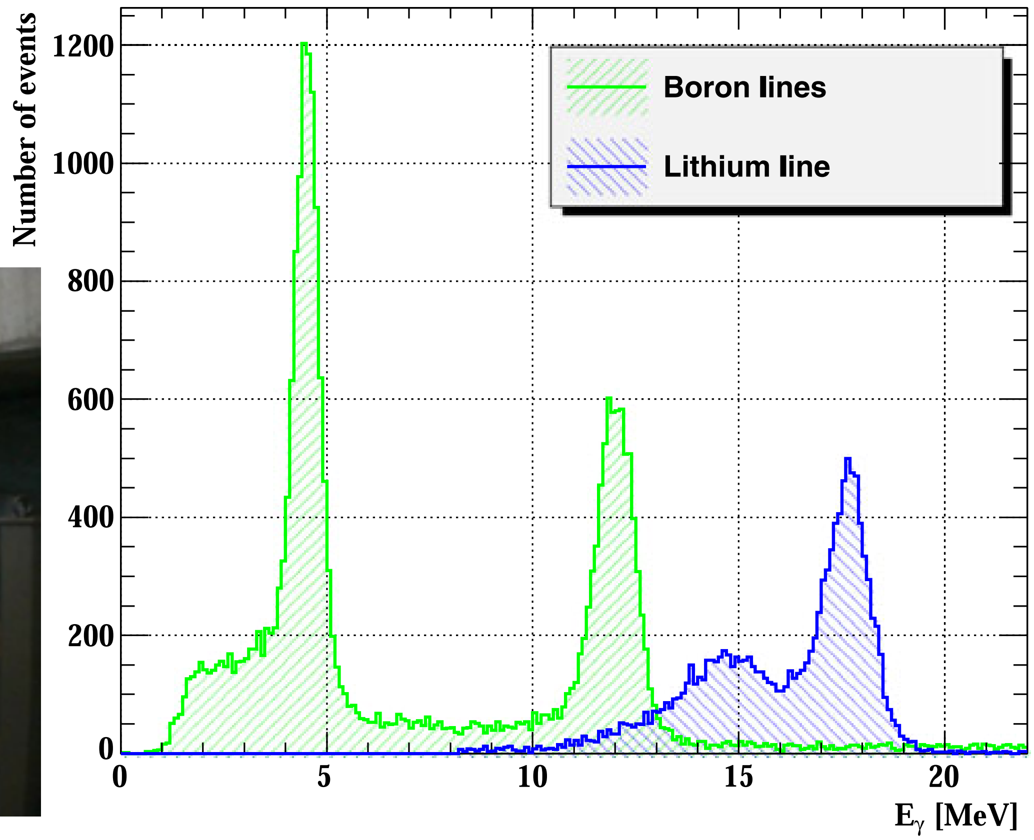
Time

B(p,γ) (4.4+11.7 MeV)
$\pi0 \to e^+e\gamma$ (55-83 MeV)
Muon radiative decay



Weekly energy and time calibration

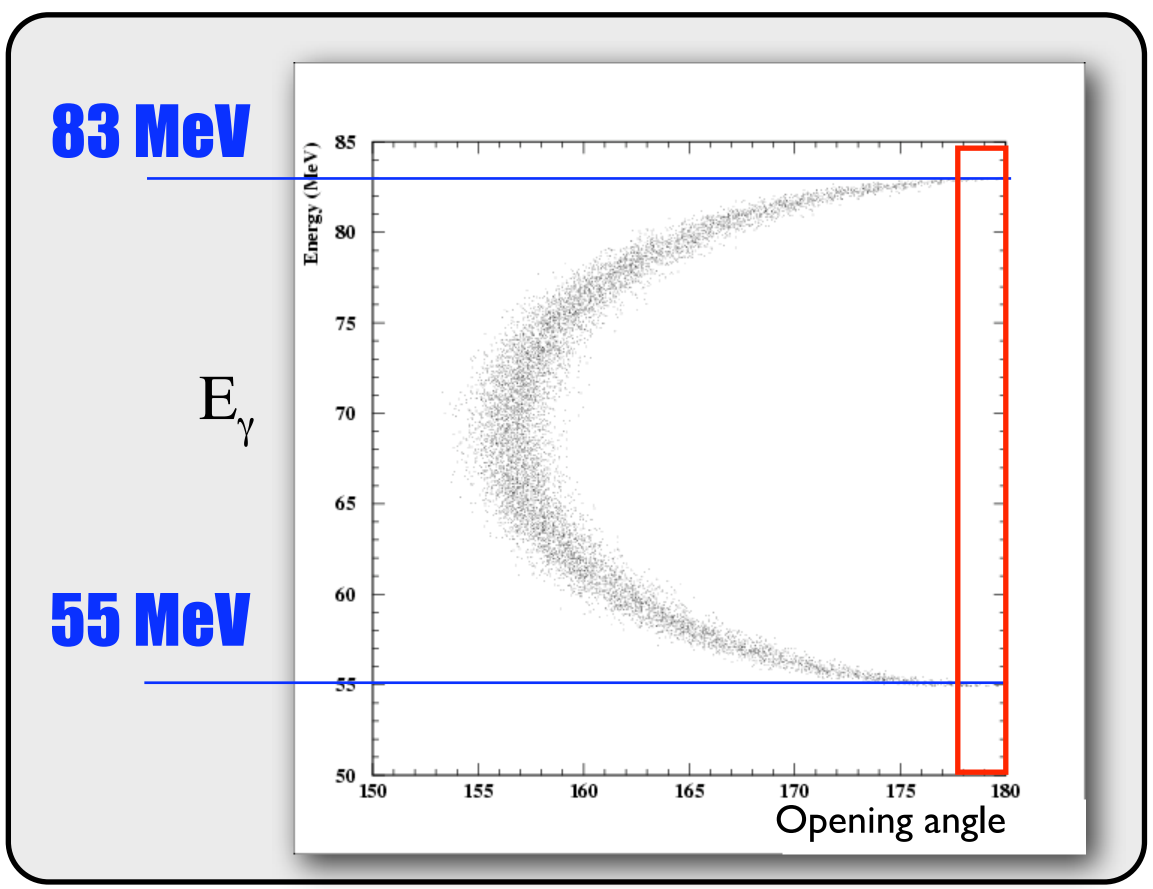




MEG Cockcraft-Walton(C.W.) proton accelerator

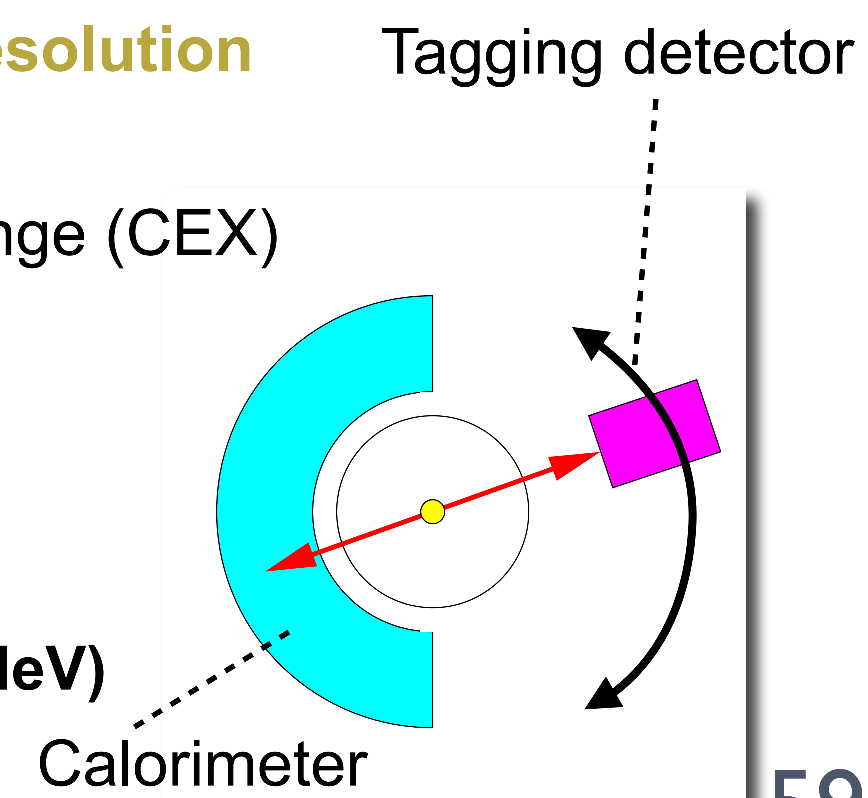
Calibration and monitoring

PMT	Energy	Time
LED Alpha source (5.5 MeV)	AmBe (4.4MeV) Neutron capture (9MeV) Li(p,γ)Be (17.6 MeV) $\pi0 \rightarrow \gamma\gamma$ (55, 83 MeV) Cosmic ray (160 MeV)	B(p,γ) (4.4+11.7 MeV) $\pi0 \rightarrow e^+e\gamma$ (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)



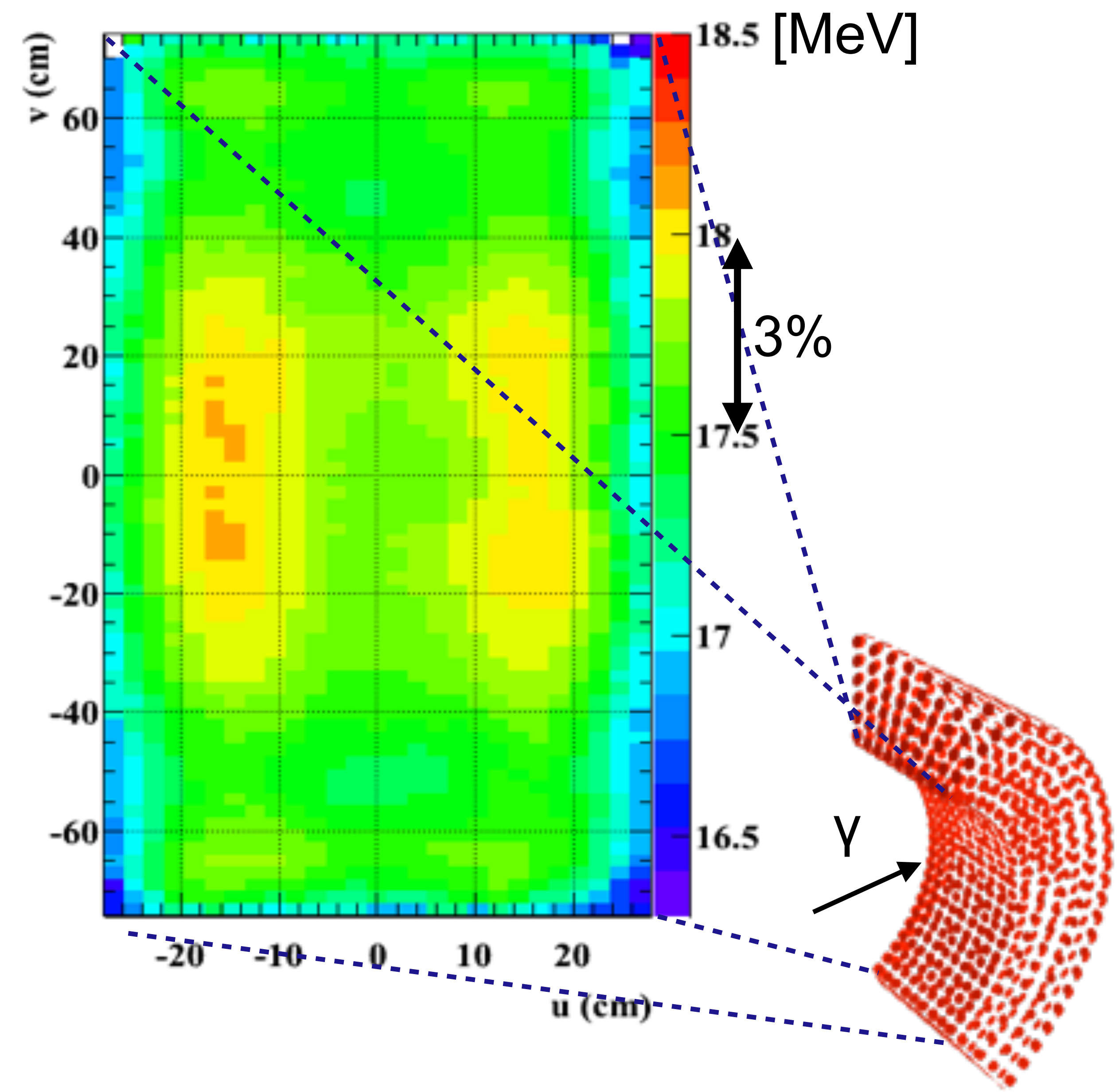
$\pi^- + p \rightarrow \pi^0 + n$
$\pi^0 \rightarrow \gamma\gamma$ (55MeV, 83MeV)
LH_2 target

Energy Scale Uniformity

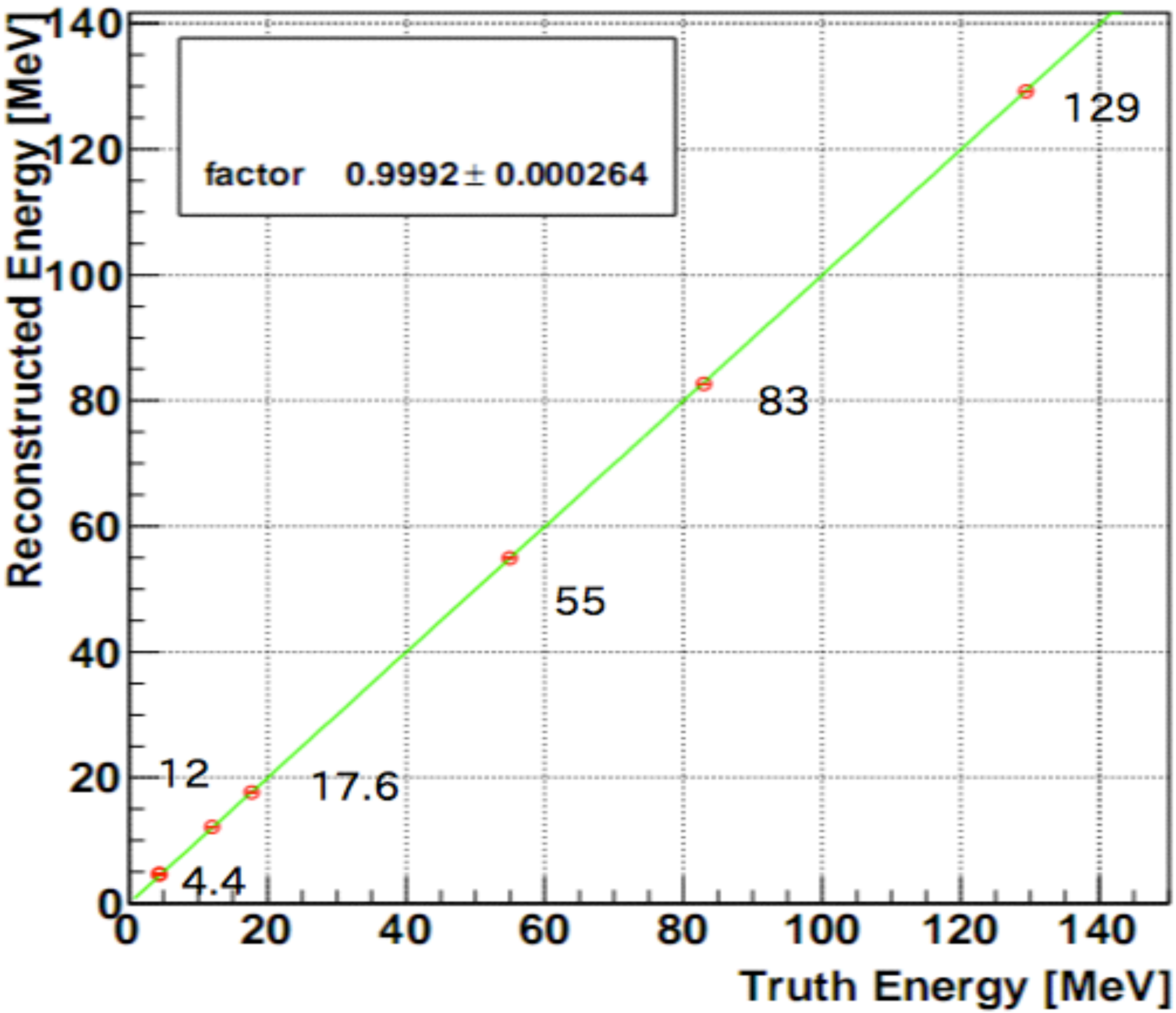
- Non-uniformity due to
  - Geometry
  - Reconstruction algorithm
- Correction using
  - 17.6 MeV CW gamma for position
    - Monitored weekly
  - 55 MeV CEX gamma for depth (energy dependent)
- Checked using background gamma spectrum during physics run

After correction : ~0.2 % uniform

17.6 MeV CW data
uniformity before correction



Linearity

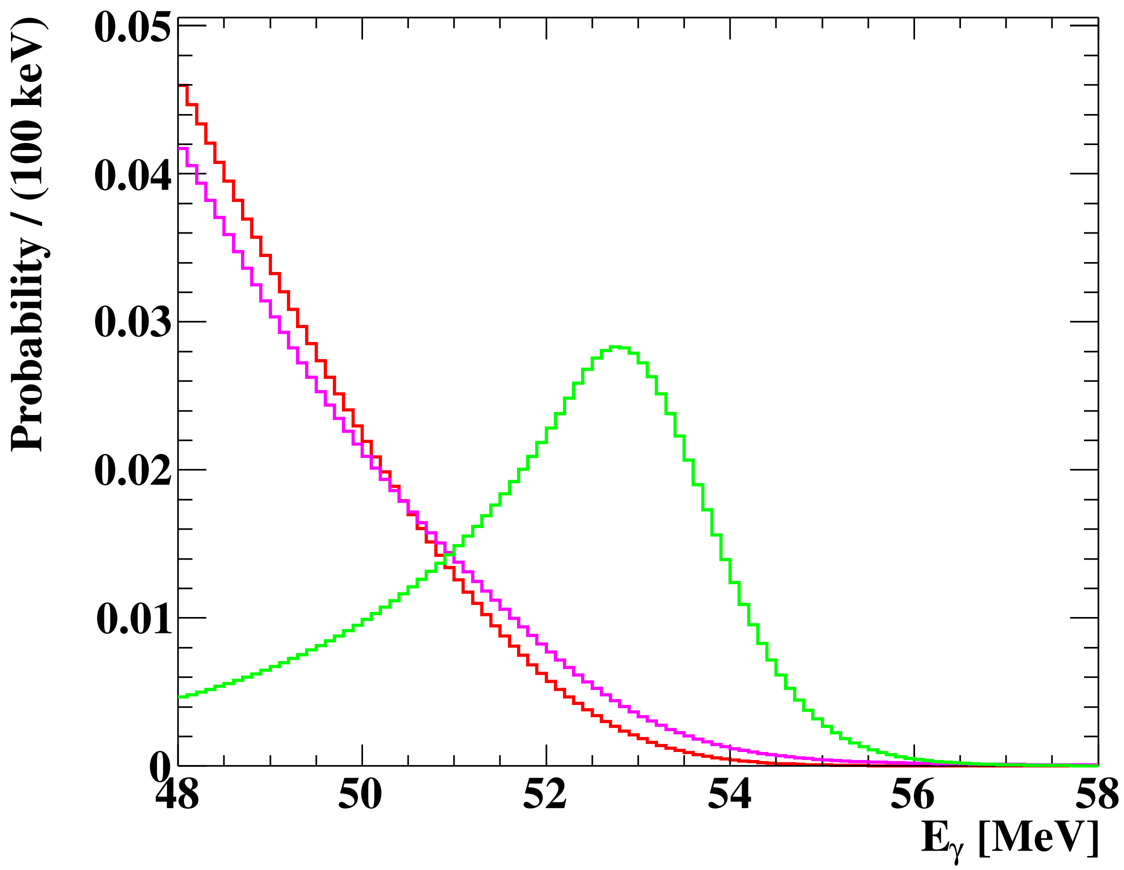


factor 0.9992 ± 0.000264
129
83
55
12
17.6
4.4
Reconstructed Energy [MeV]
Truth Energy [MeV]
0
20
40
60
80
100
120
140

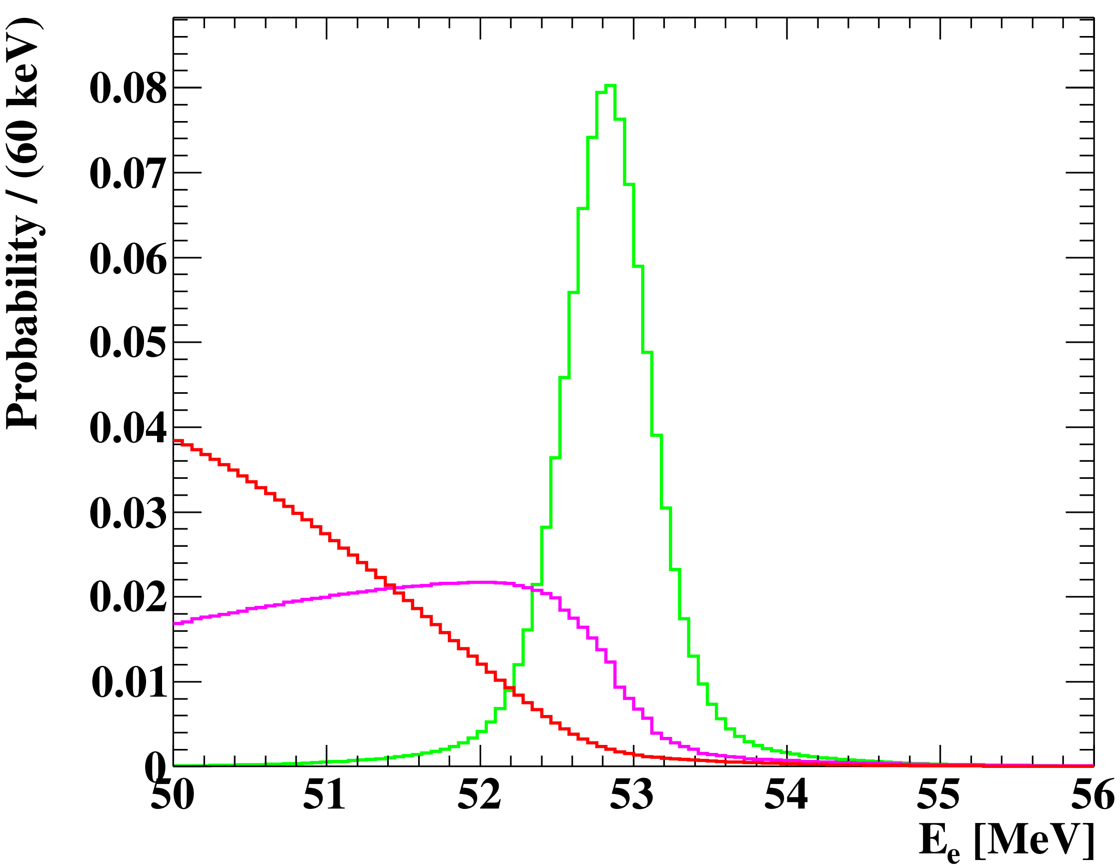
Probability density functions (PDF)

Signal RMD BG

E_γ



E_e



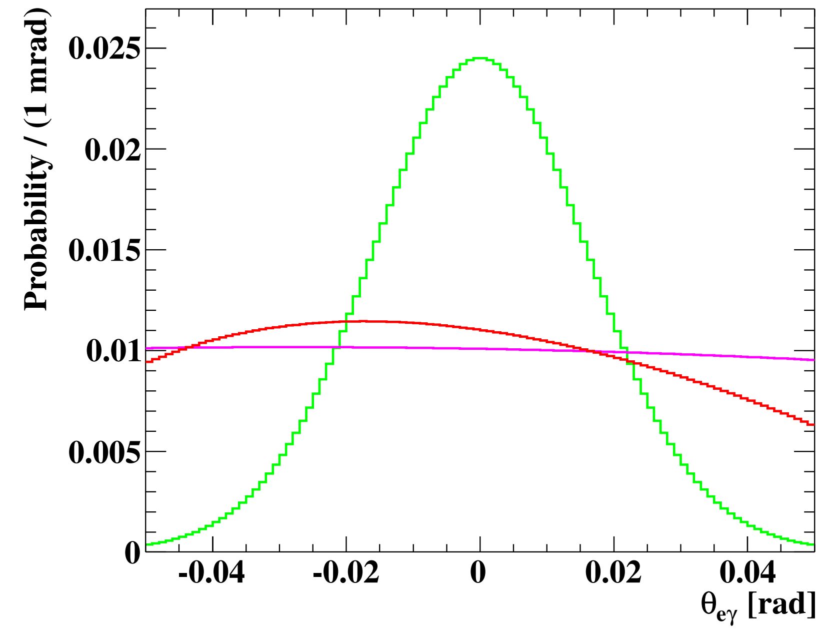
Signal : CEX data
BG : Sideband data
RMD : SM + detector response

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

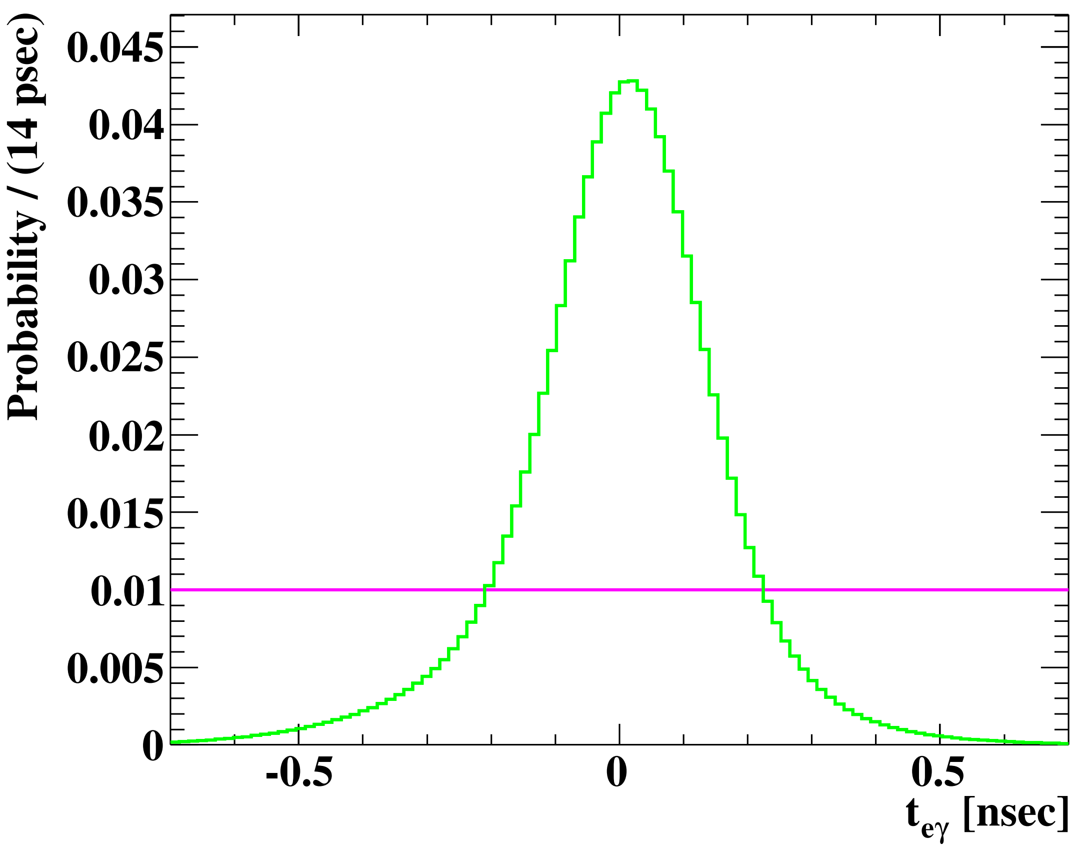
Probability density functions (PDF)

Signal RMD BG

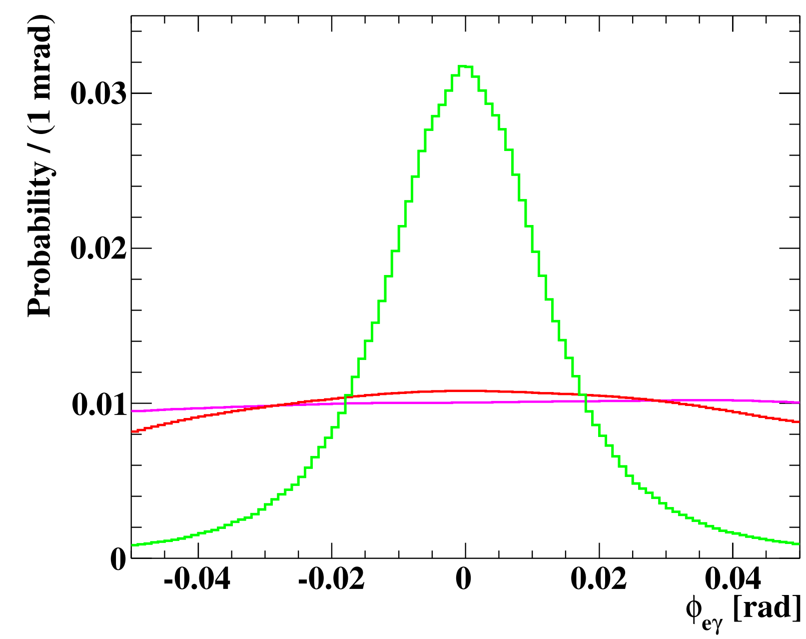
$\vartheta_{e\gamma}$



$T_{e\gamma}$



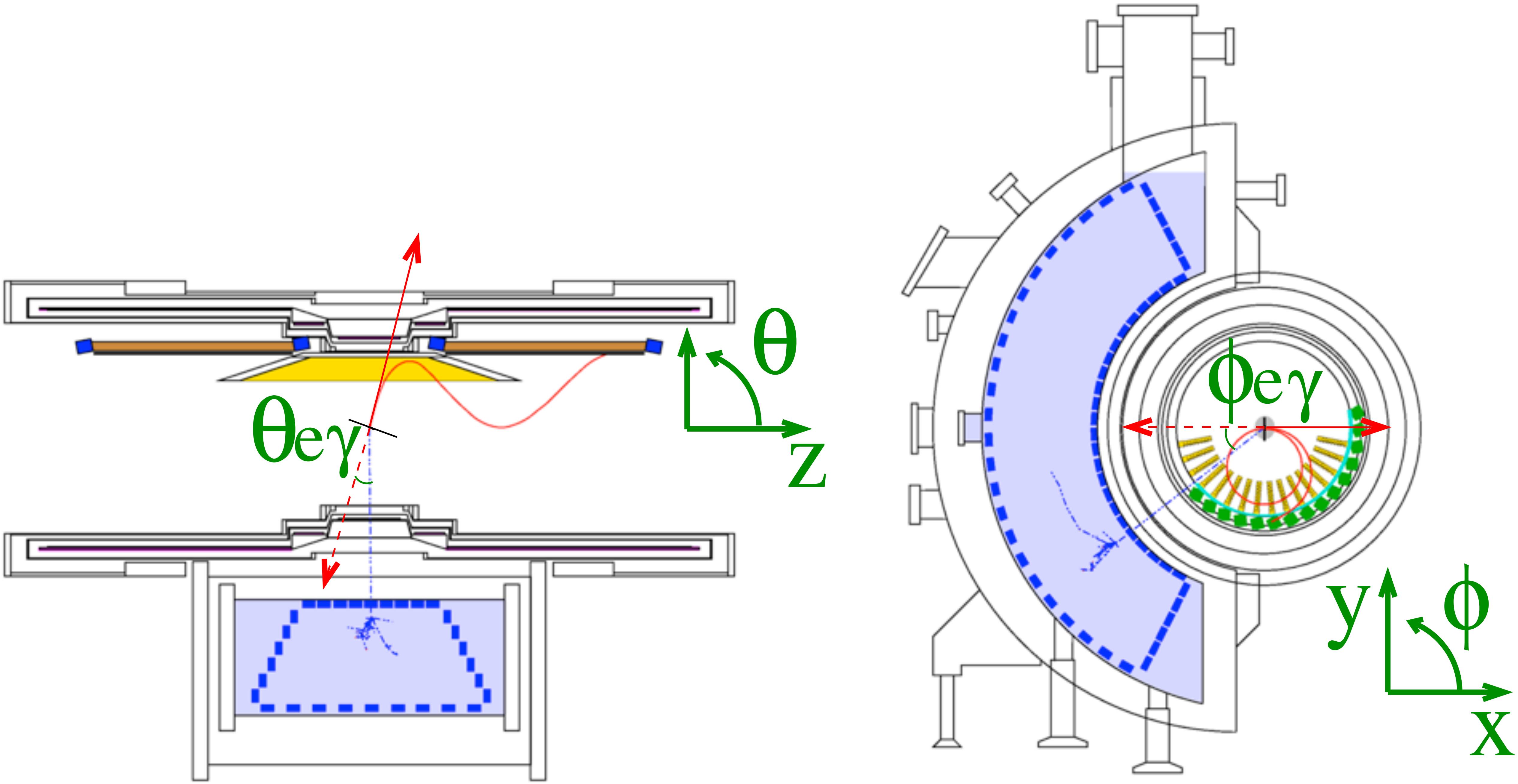
$\varphi_{e\gamma}$



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

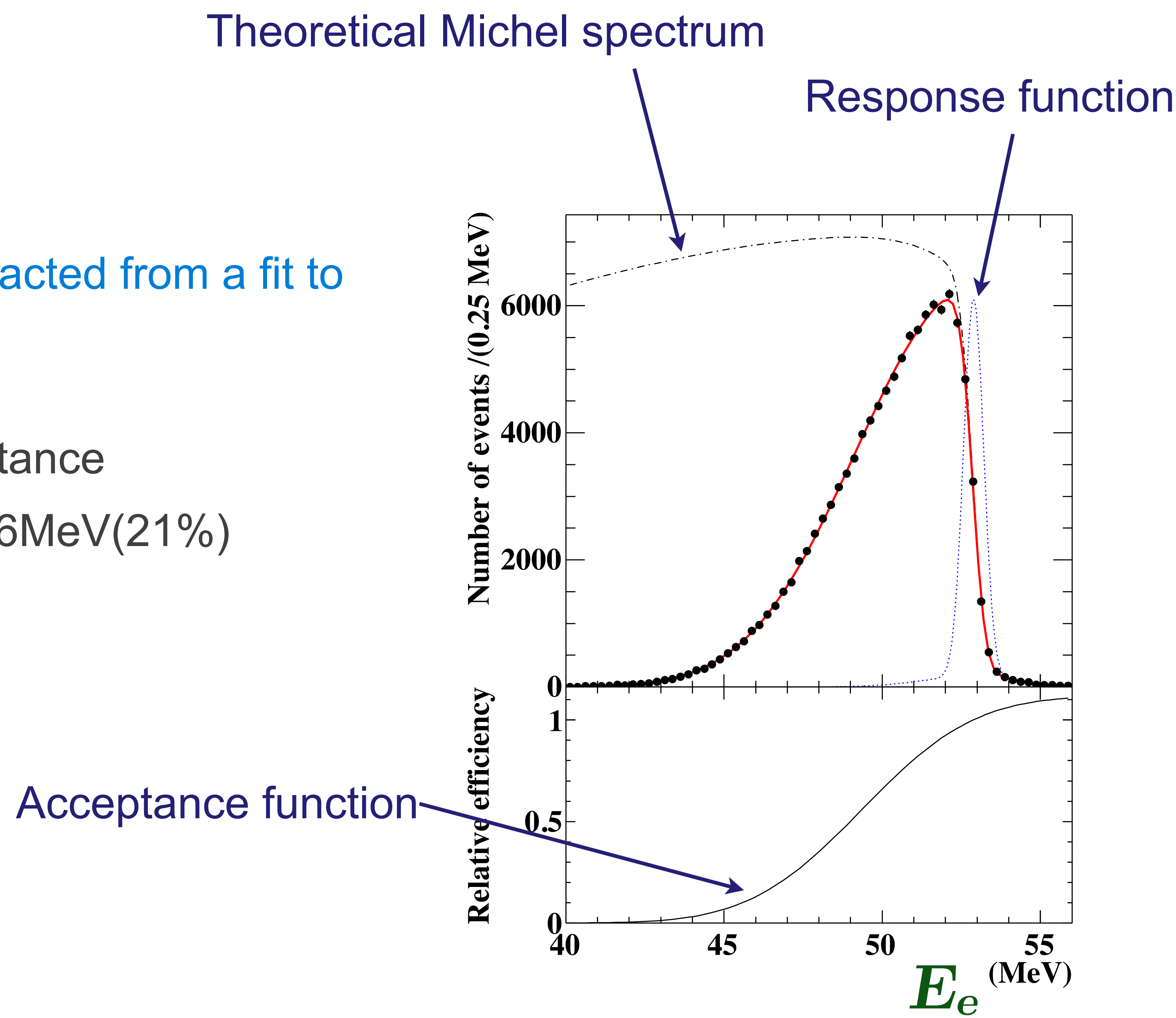
Signal : MC+CEX (γ), two turn (e^+)
BG : Sideband data
RMD : SM + detector response

Coordinate system

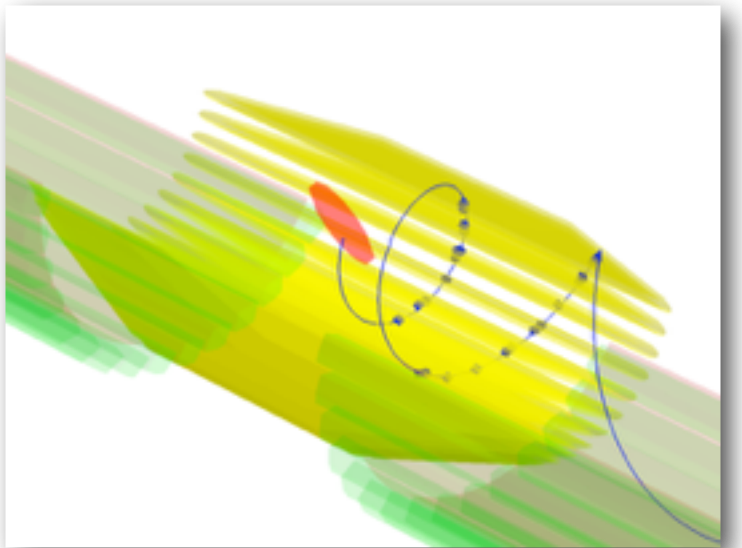


Positron spectrometer performance

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

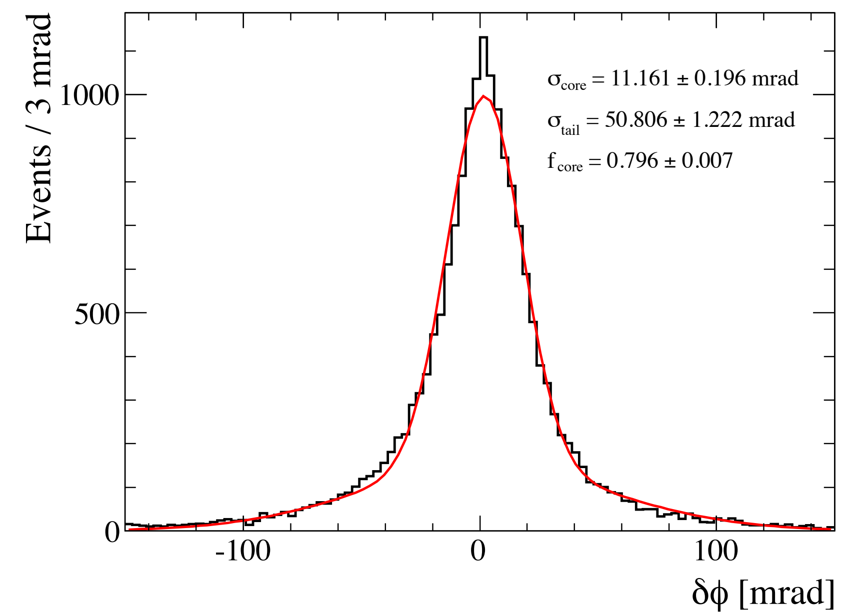


Positron spectrometer performance, cont.

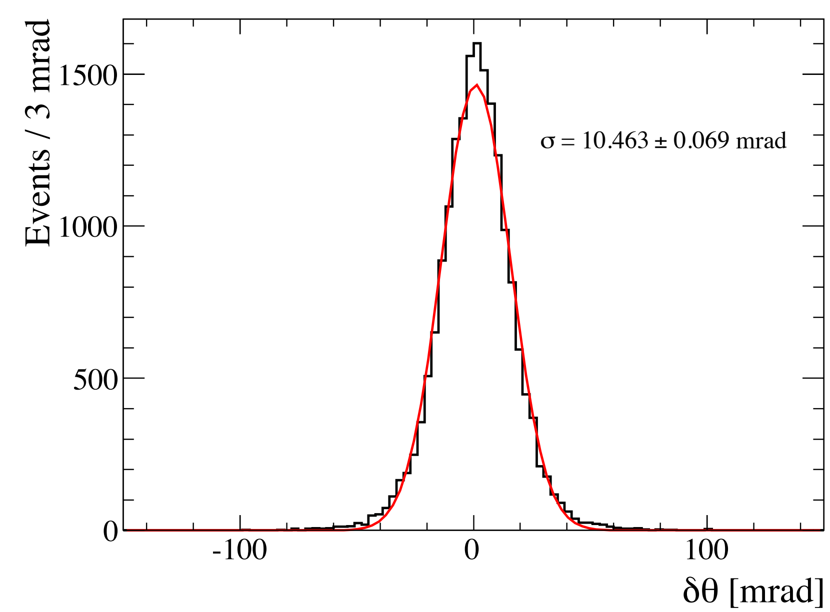


Angular resolutions measured comparing two-segments of 2-turn tracks

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

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)

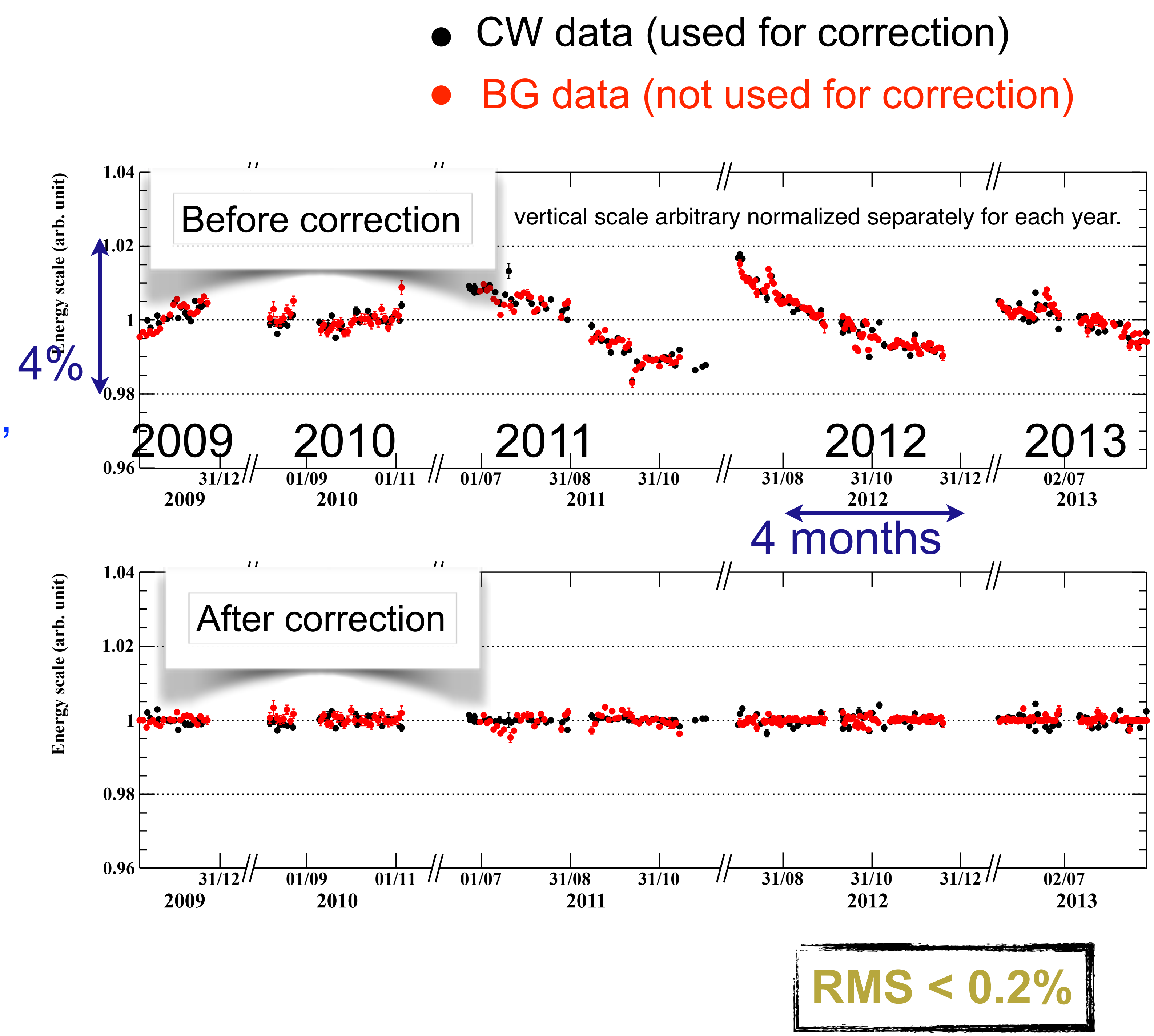
Time

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

Process		Energy	Main Purpose	Frequency
Charge exchange	$\pi^- p \rightarrow \pi^0 n$ $\pi^0 \rightarrow \gamma\gamma$	55, 83, 129 MeV photons	LXe energy scale/resolution	annually
Proton accelerator	$^{7}\mathrm{Li}(p,\gamma)^{8}\mathrm{Be}$	14.8, 17.6 MeV photons	LXe uniformity/purity	weekly
	$^{11}\mathrm{B}(p,\gamma)^{12}\mathrm{C}$	4.4, 11.6, 16.1 MeV photons	LXe–TC timing	weekly
Neutron generator	$^{58}\mathrm{Ni}(n,\gamma)^{59}\mathrm{Ni}$	9 MeV photons	LXe energy scale	weekly
Radioactive source	$^{241}\mathrm{Am}(\alpha,\gamma)^{237}\mathrm{Np}$	5.5 MeV α's	LXe PMT calibration/purity	weekly
Radioactive source	$^{9}\mathrm{Be}(\alpha_{^{241}\mathrm{Am}},n)^{12}\mathrm{C}^{\star}$ $^{12}\mathrm{C}^{\star}(\gamma)^{12}\mathrm{C}$	4.4 MeV photons	LXe energy scale	on demand
LED			LXe PMT calibration	continuously

Energy Scale Stability

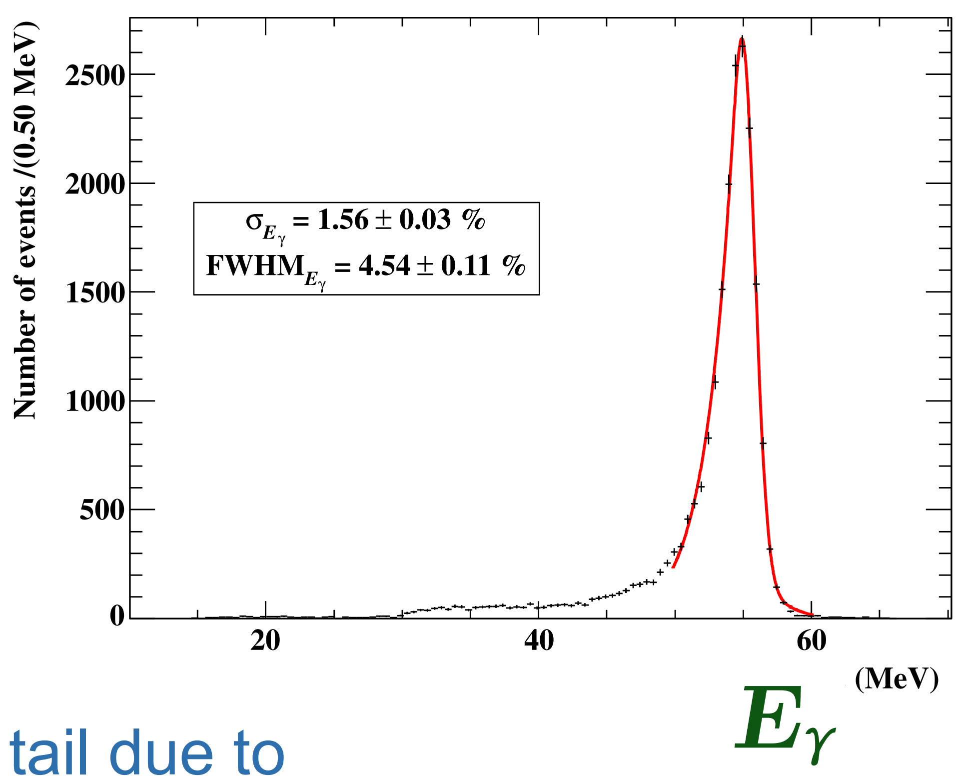
- Energy scale is monitored with several calibration sources as well as BG shape
- Each of these shows very good stability (<0.2%RMS) by themselves.
- However, they show same trend, and indicate real variation of the scale.
- Introduce time-dependent correction by combination of calibrations
  - Not use BG fit variation, but use it as a cross check
- Uncertainty is evaluated (later) 0.3-0.35%.



Energy resolution

Measured using 55 MeV CEX gamma rays

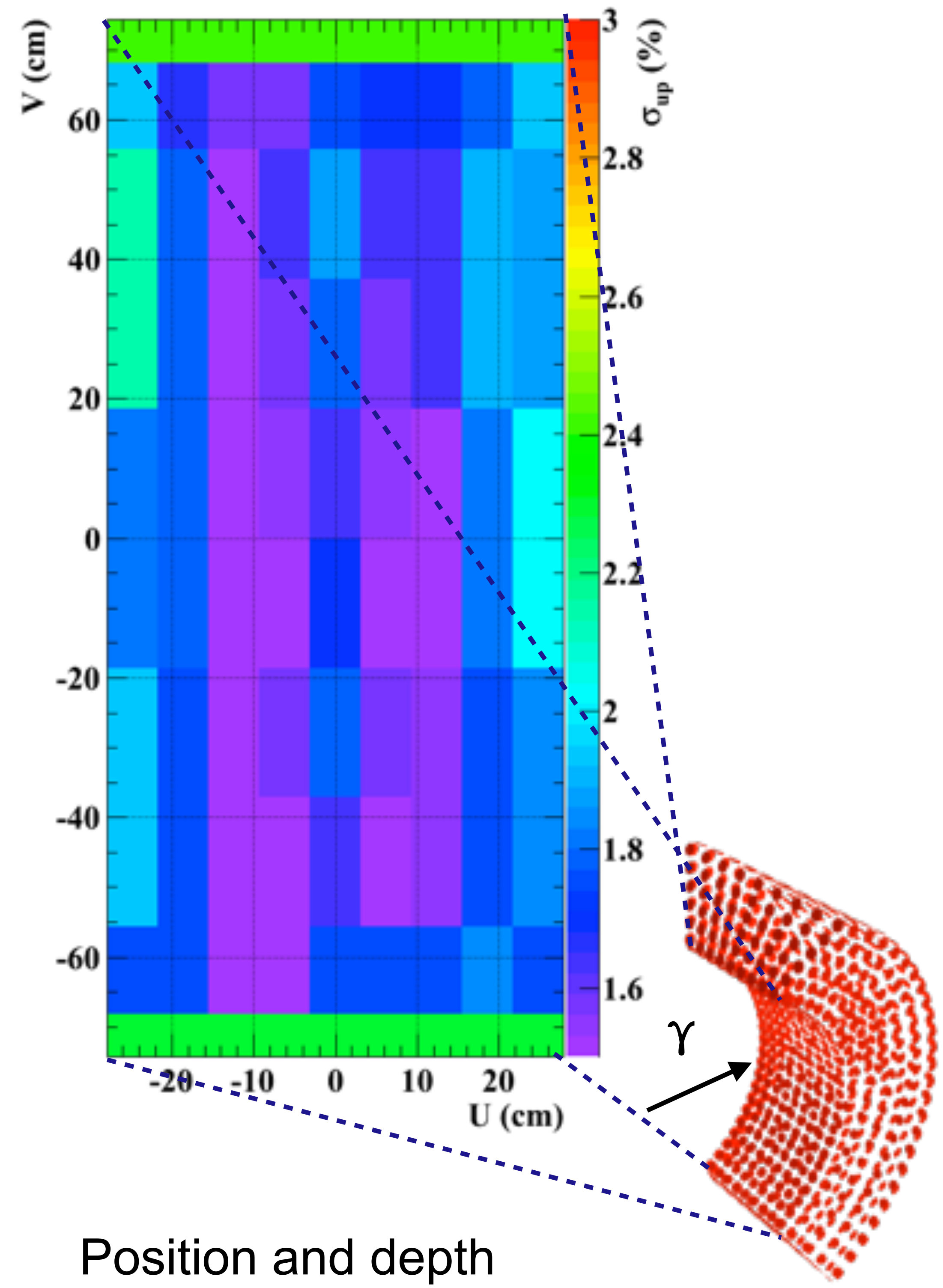
Typical 55 MeV CEX spectrum



Lower tail due to

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

Resolution map

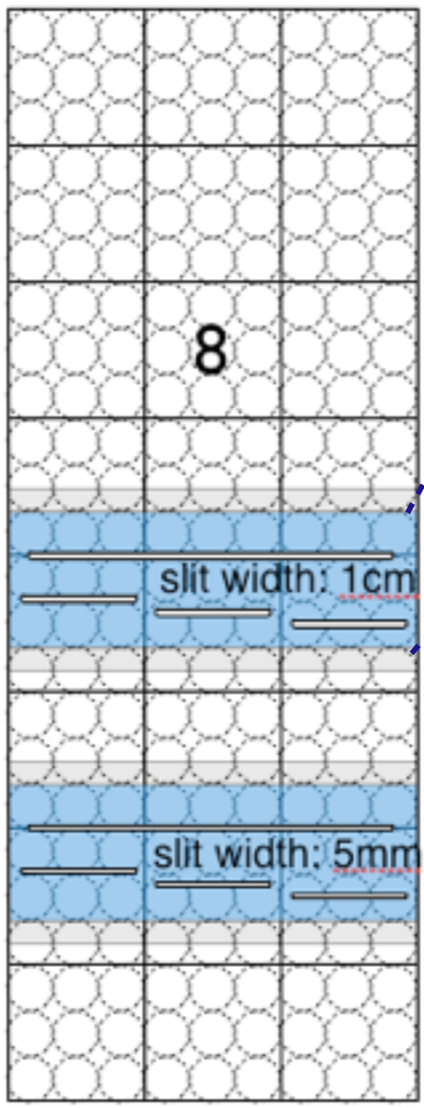


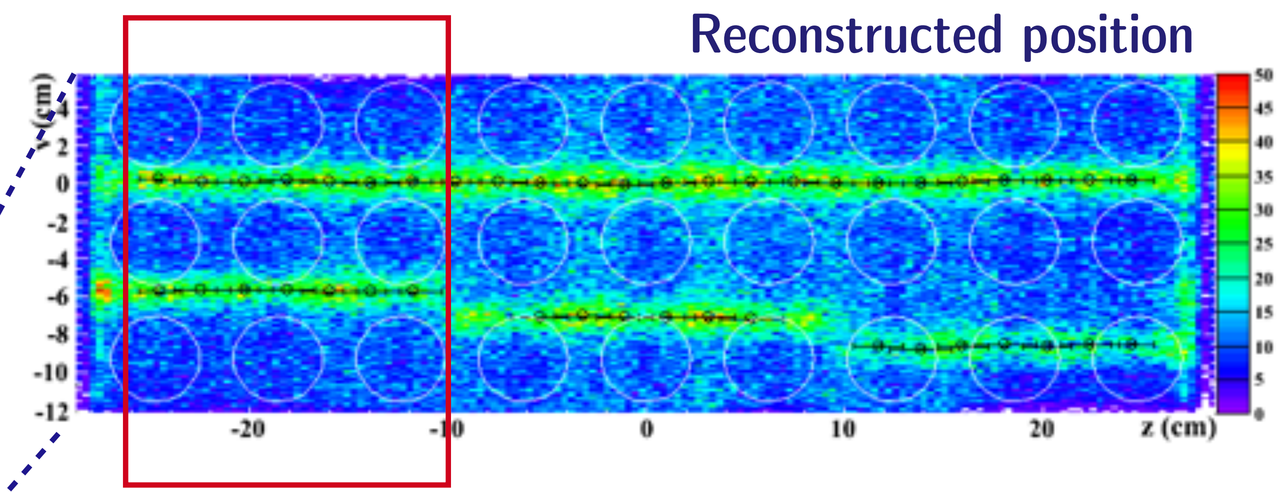
Position and depth dependences are measured

Average resolutions
1.6% (depth>2cm), 2.3% (depth<2cm)

Position resolution

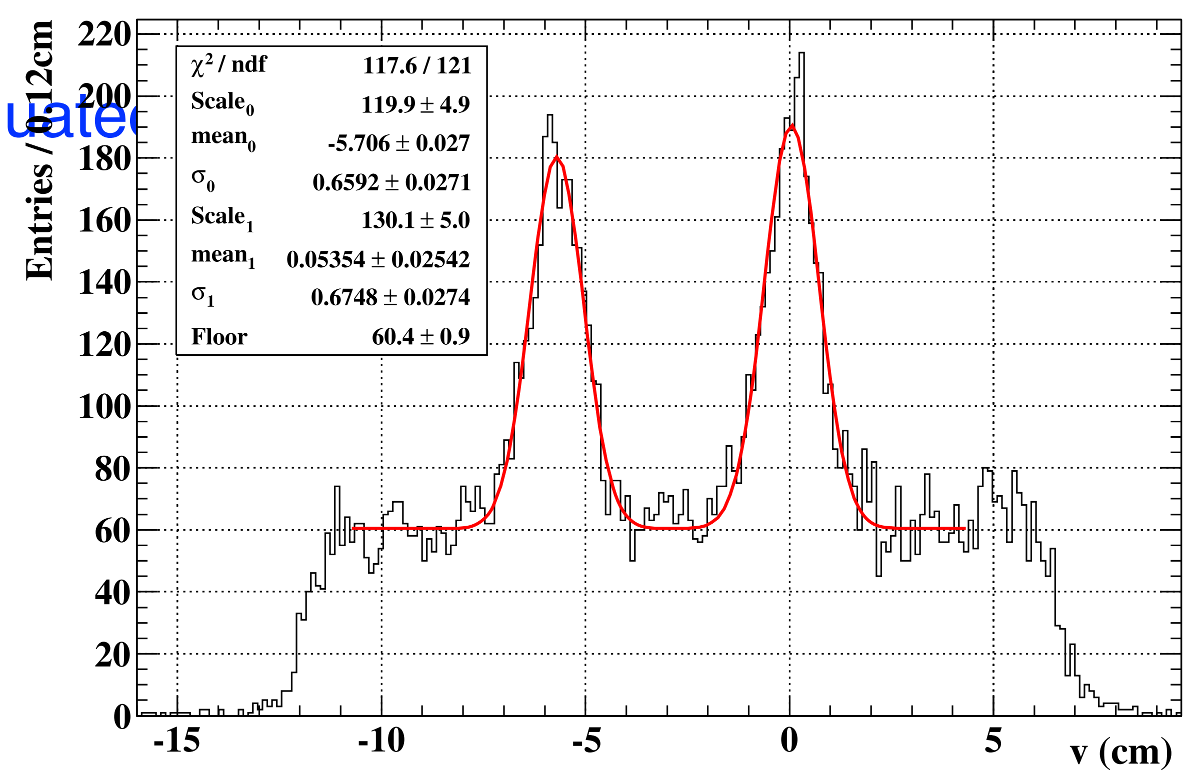
Measured using lead collimators with CEX data





Projection

on resolution is evaluated

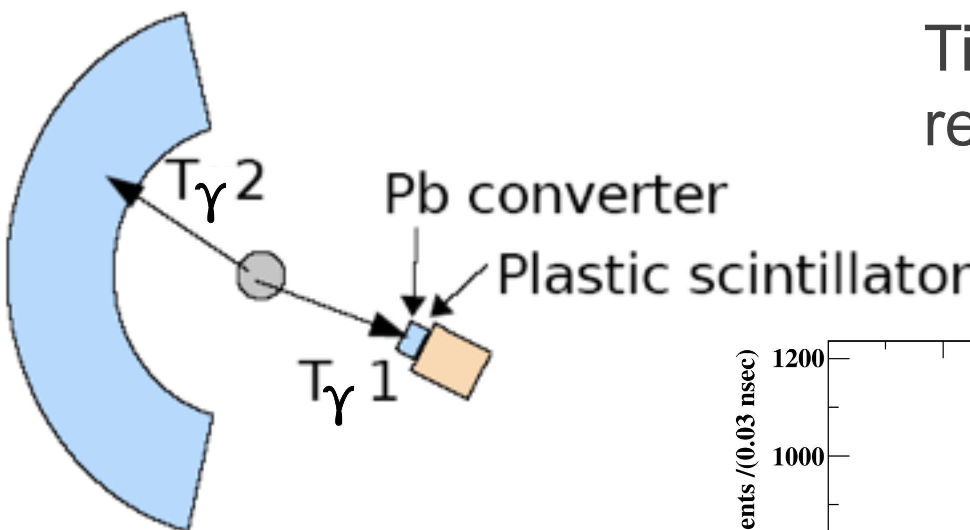


Position resolution : 5 mm

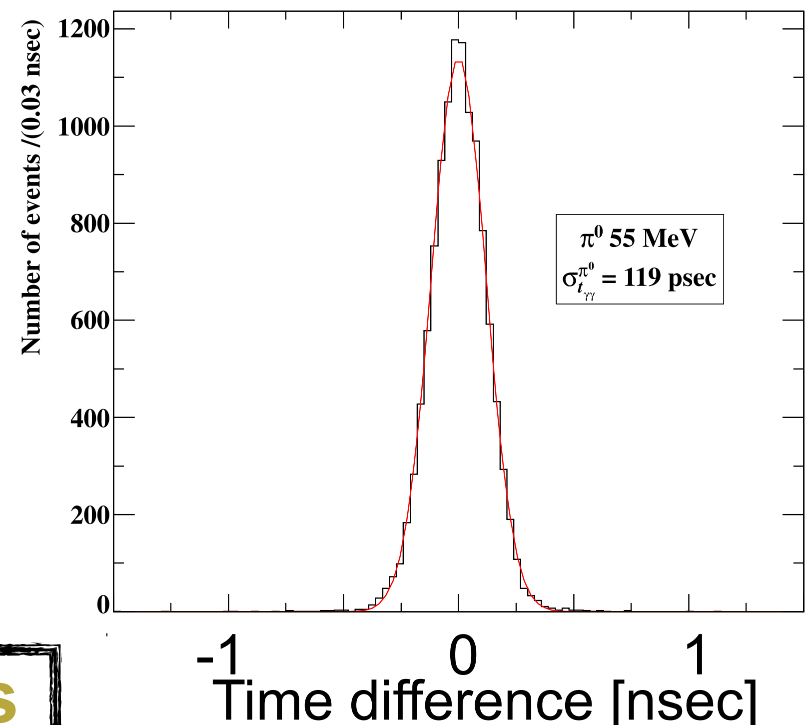
Width is compared with MC

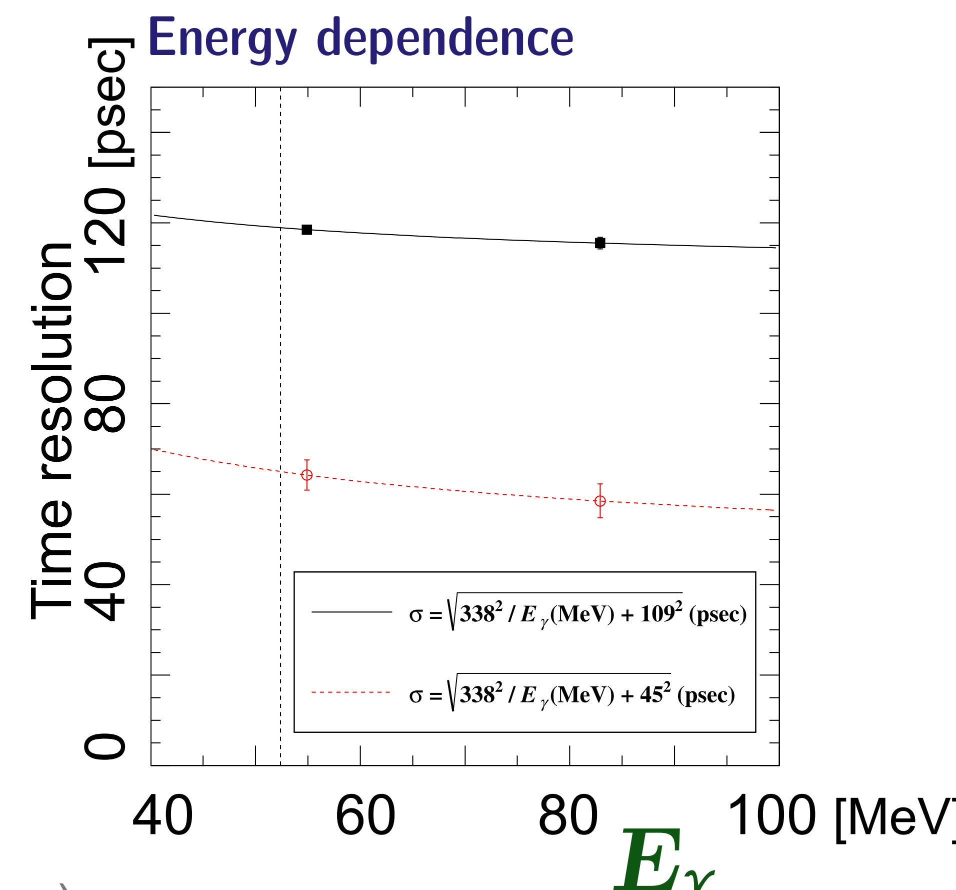
Timing resolution

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



Time difference between calorimeter and pre-shower



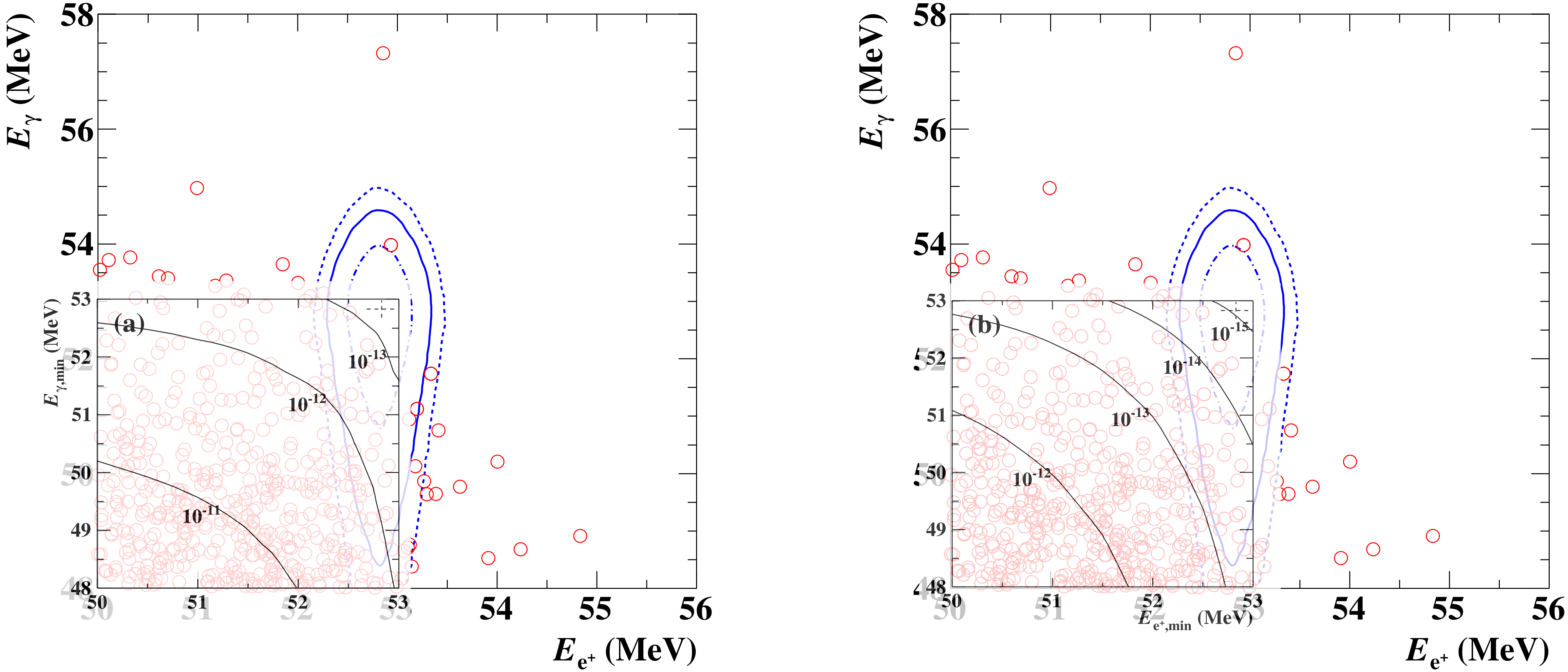


Time resolution : 67 ps

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

Breakdown

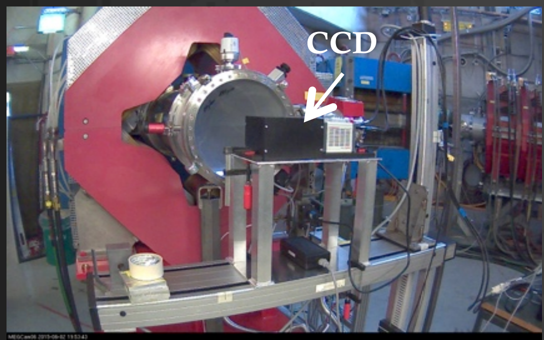
Intrinsic	36 ps
ToF (depth)	20 ps
Electronics	24 ps
Position resolution and shower fluctuation	46 ps



(a)
(b)
E_γ (MeV)
E_{e^+} (MeV)
$E_{\gamma,\mathrm{min}}$ (MeV)
$E_{e^+,\mathrm{min}}$ (MeV)
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}

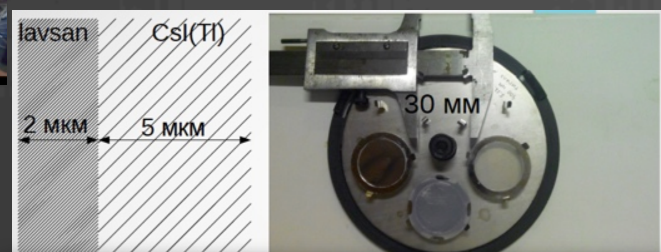
Further Beam Studies

High-intensity non-invasive Beam Monitoring



Luminophor Foil + CCD

(Work undertaken together with our Novosibirsk colleagues)



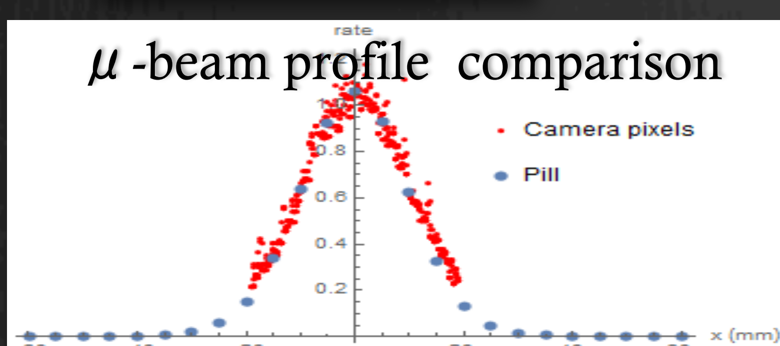
Foils = 2 μm Plastic Substrate + 5 μm CsI(Tl)

Foil+ Beam-spot

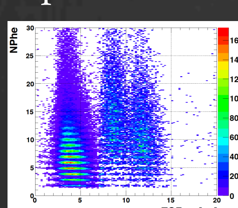
Logo in solder

Luminorphor Foil 40 mm dia.

μ-Radiography



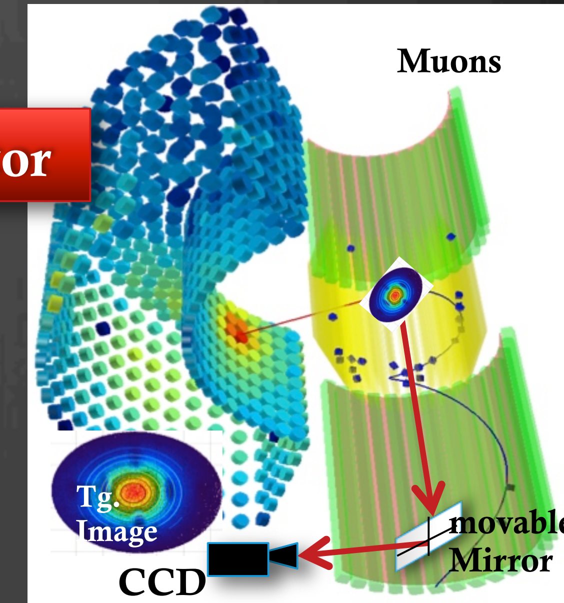
from just 1-row of pixels at centre potential much better if uses all pixels
1 pixel = 16 bit depth

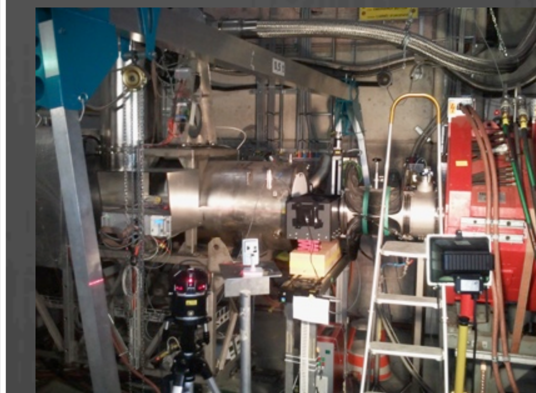


SciFi methods with Particle_ID also being pursued

MEG II Target Centring Monitor

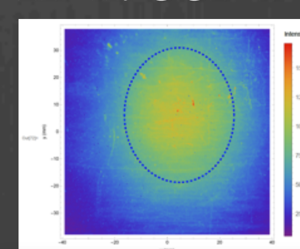
- Use Scintillation Target for MEG II
- View with movable mirror system in RDC flange with fix CCD on flange side





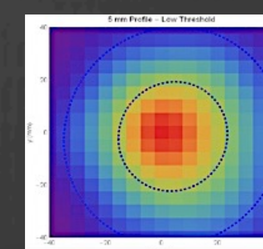
- Test setup collimator system 150 μm BC404B scintillator
- Compare to 2D pill scan

2D-fit CCD Data



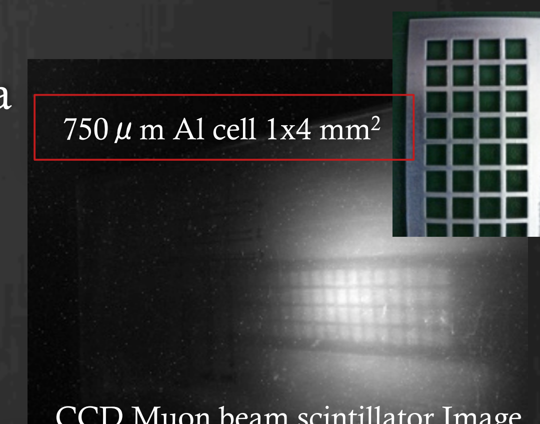
(σ_X = 21 mm, σ_Y =25 mm)
(MS not accounted for more material)

2D-fit Pill scan Data



(σ_X = 19 mm, σ_Y =21 mm)

750 μm Al cell 1x4 mm²



CCD Muon beam scintillator Image

μ-Radiography Target resolution with muons < 1mm

- Light intensity tested over long distance COBRA Equivalent 1.8 m using telephoto
  -> Still sufficient light
  -> Looks Promising use Scint. Target in COBRA for next Run

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

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

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

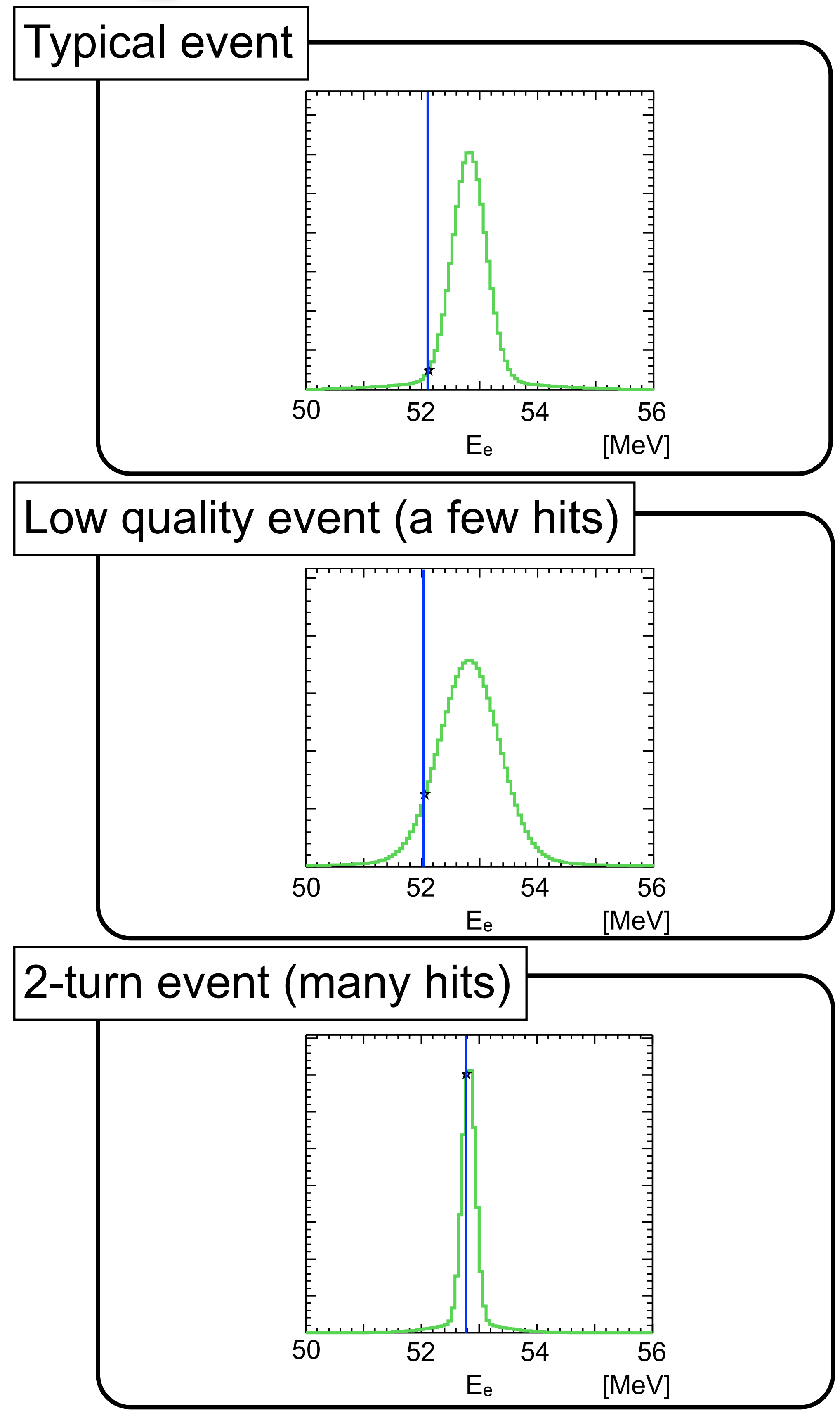
Correlation parameters extracted from data and MC

Sensitivity improved by **10%**

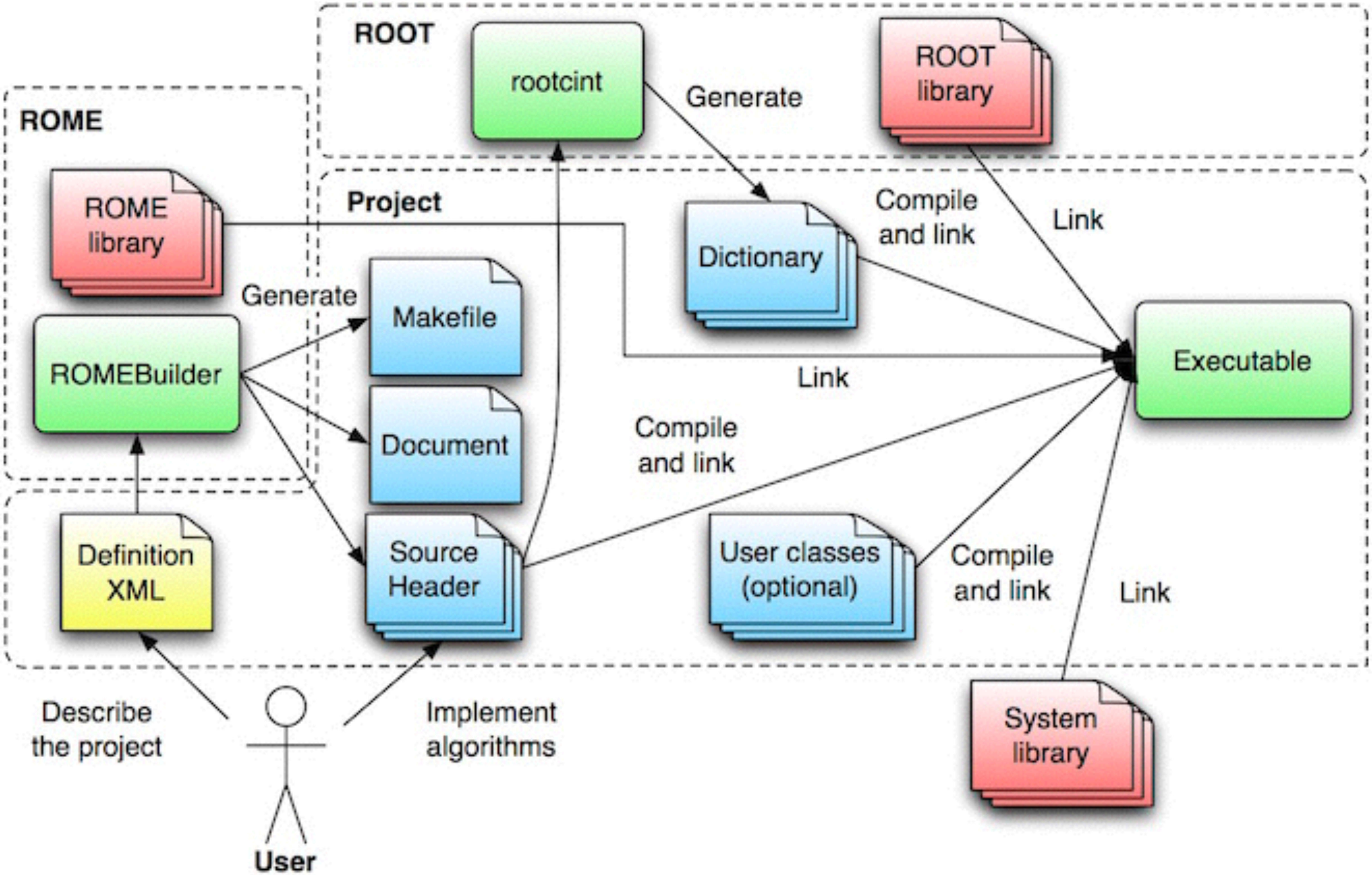
Examples

Signal PDF
Data

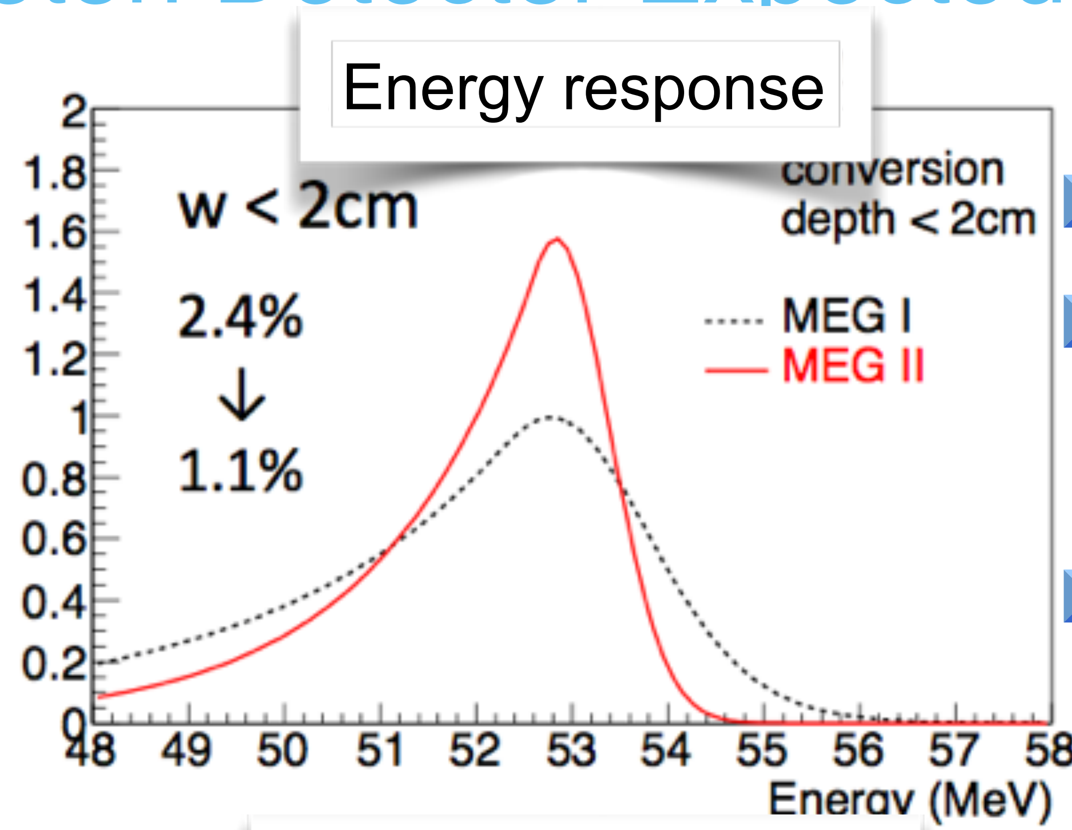
E_e



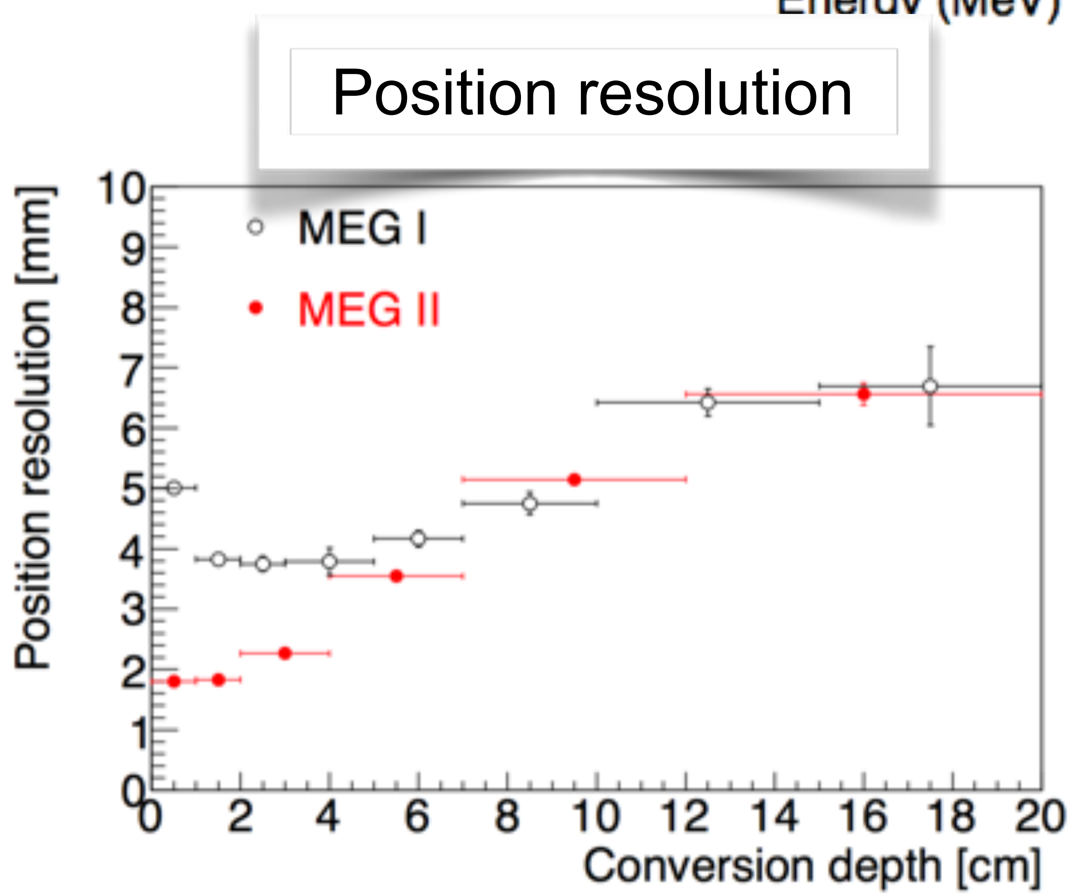
ROME

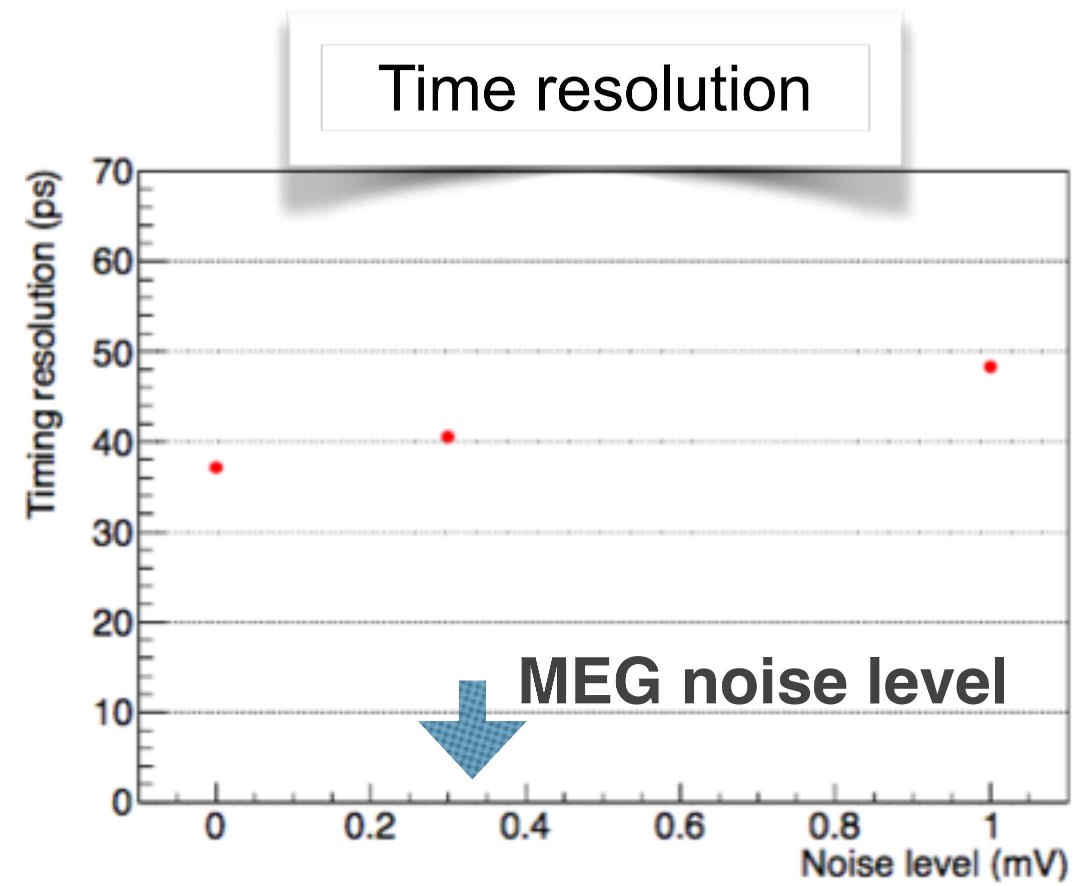

ROOT
rootcint
Generate
ROOT library
ROME
Project
ROME library
Dictionary
Compile and link
Link
Generate
Makefile
ROMEBuilder
Executable
Link
Document
Compile and link
Definition XML
Source Header
User classes (optional)
Compile and link
Link
System library
Describe the project
Implement algorithms
User

Photon Detector Expected Performance (MC)



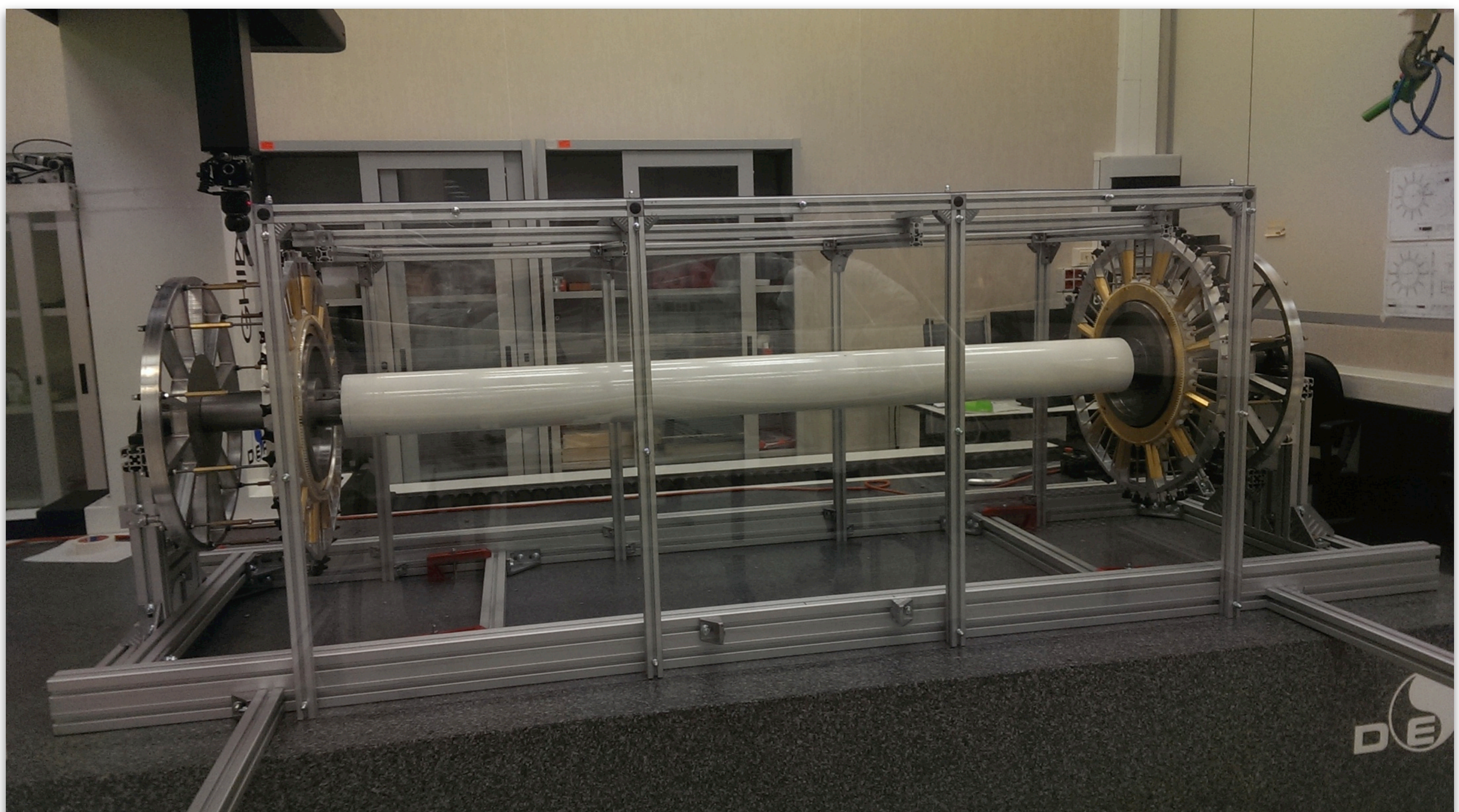
- Twice better energy and position resolutions
- Time resolution can be better (40–60 psec) because of the more photoelectrons and the better position resolution.
- ~10% improvement of detection efficiency due to less amount of material on the inner face

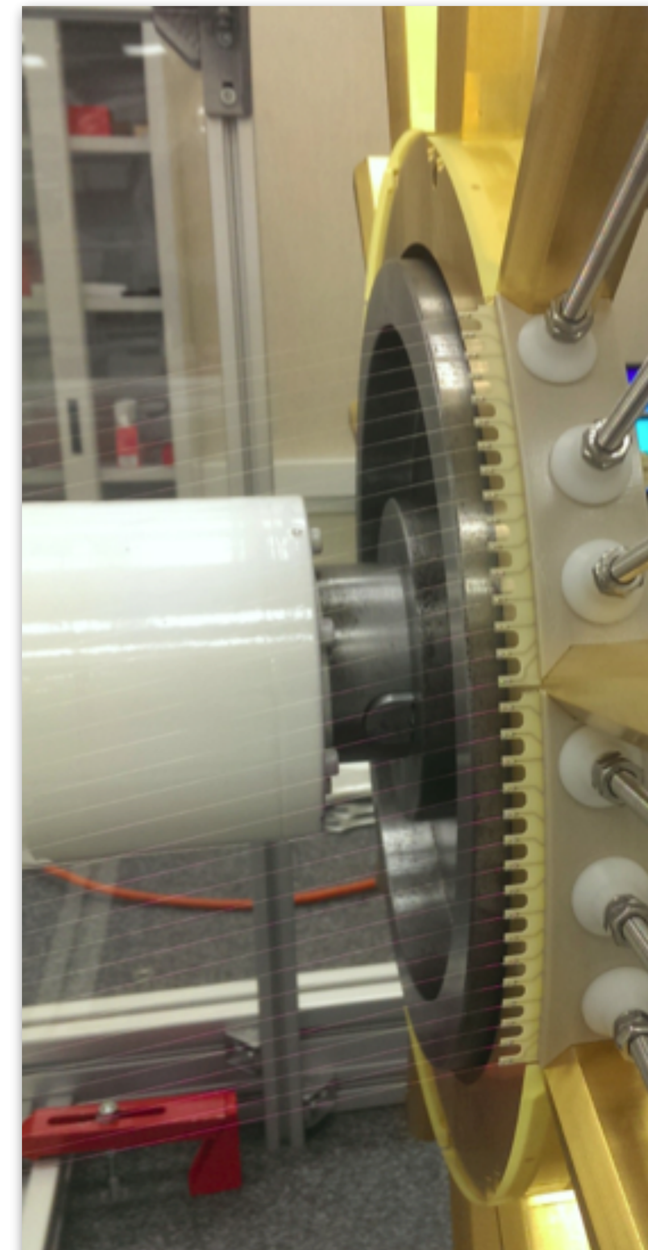




Construction of Drift Chamber

- Design and production of the parts (endcap, PCB, support structure, wires etc.) were completed
- Wiring in ongoing with using a wiring machine produce in house.

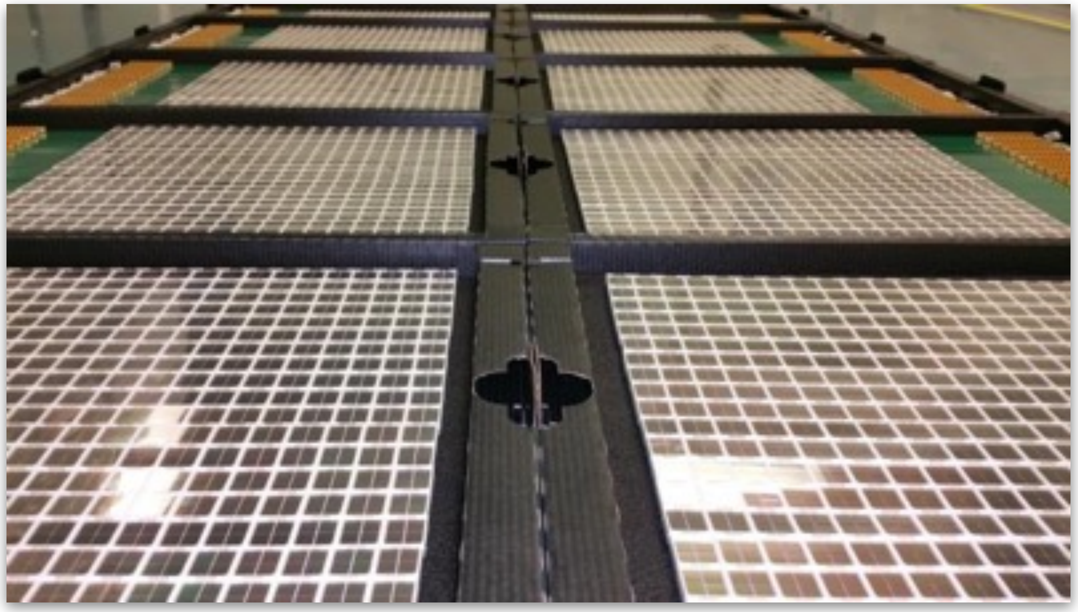




Construction status of photon detector

- All the SiPMs were produced and delivered
- We are mounting SiPMs and PMTs in the cryostat

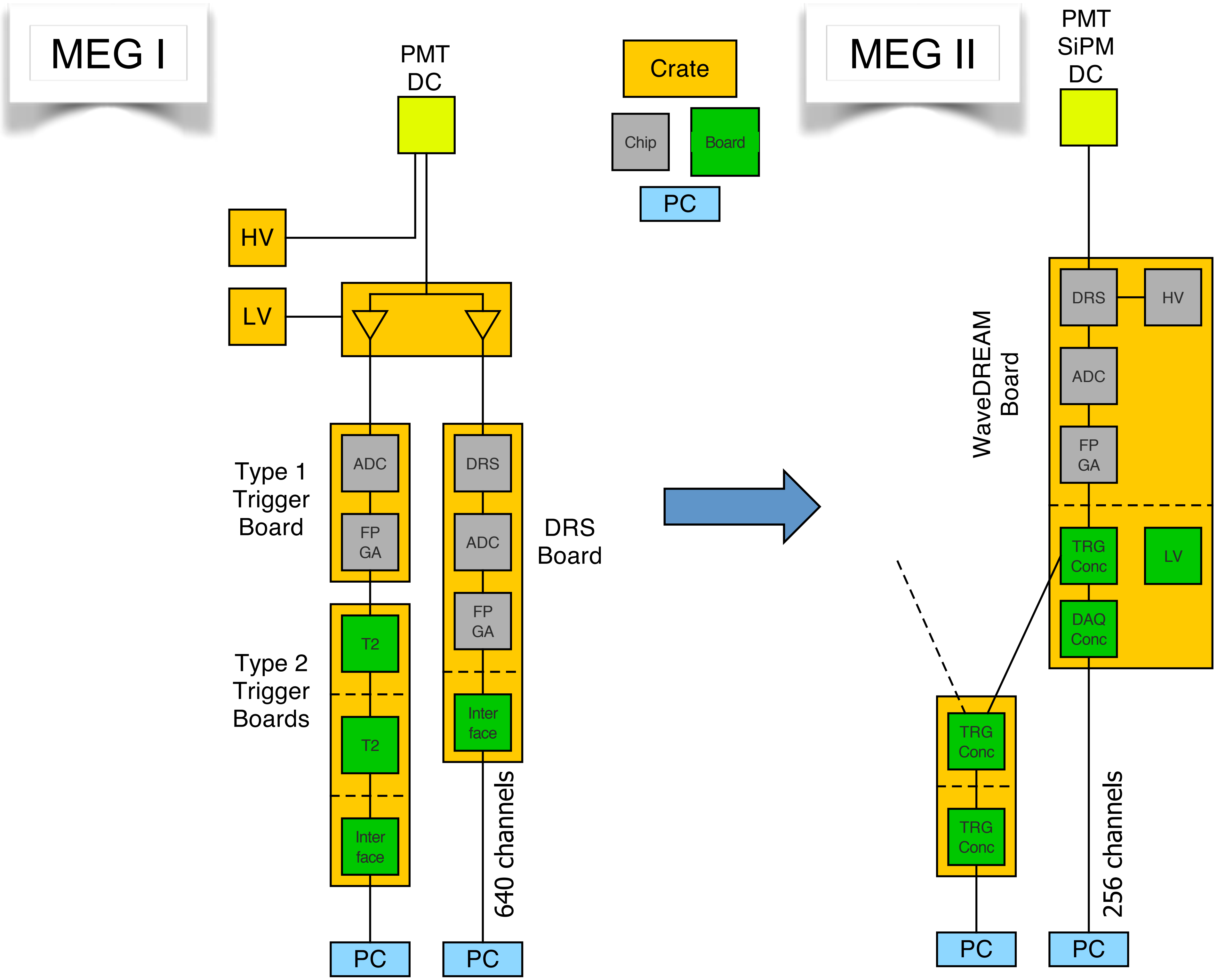
~4000 SiPMS delivered to PSI



A slab of SiPM on a readout PCB

Cryostat (re-used) in a clean room

New Electronics (WaveDREAM)

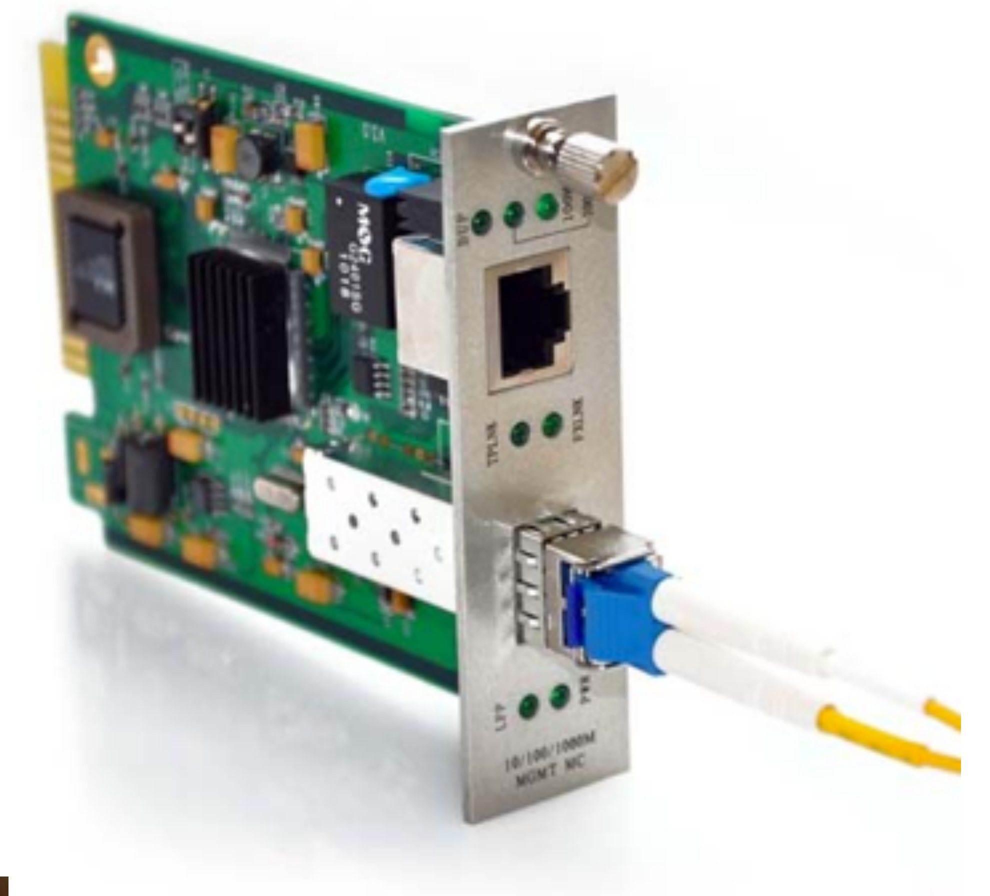


Readout, HV and trigger are integrated on same board.

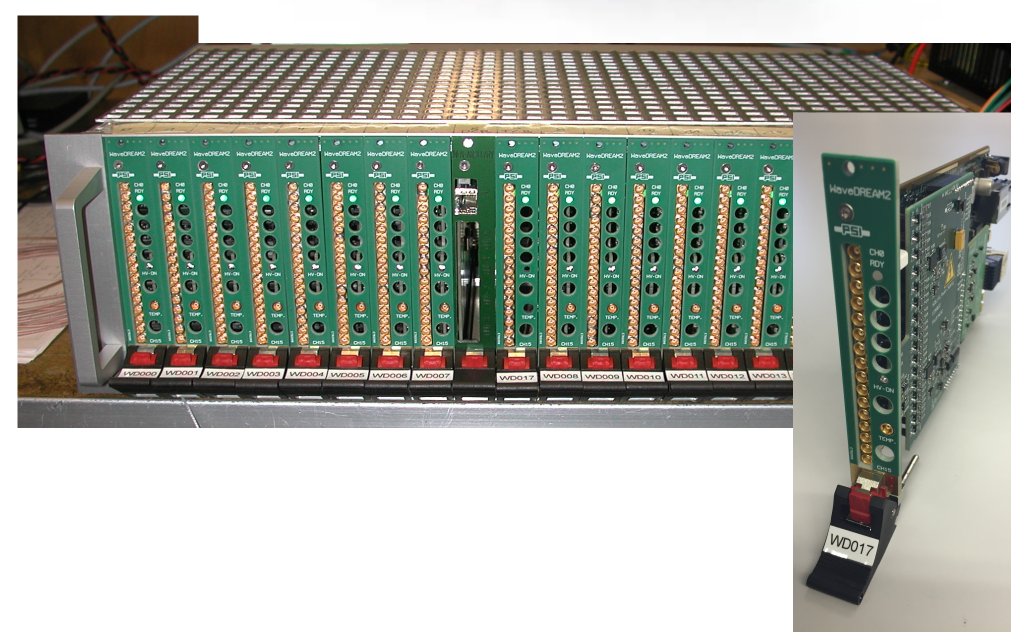
Electronics and trigger status

- One crate of WaveDREAM boards were produced and tested
  - Full production will be done after the test with actual detectors.
- Trigger preparation is ongoing. Higher online resolutions are expected
- Some problems (noise-level etc.) need to be solved.

Data concentration board

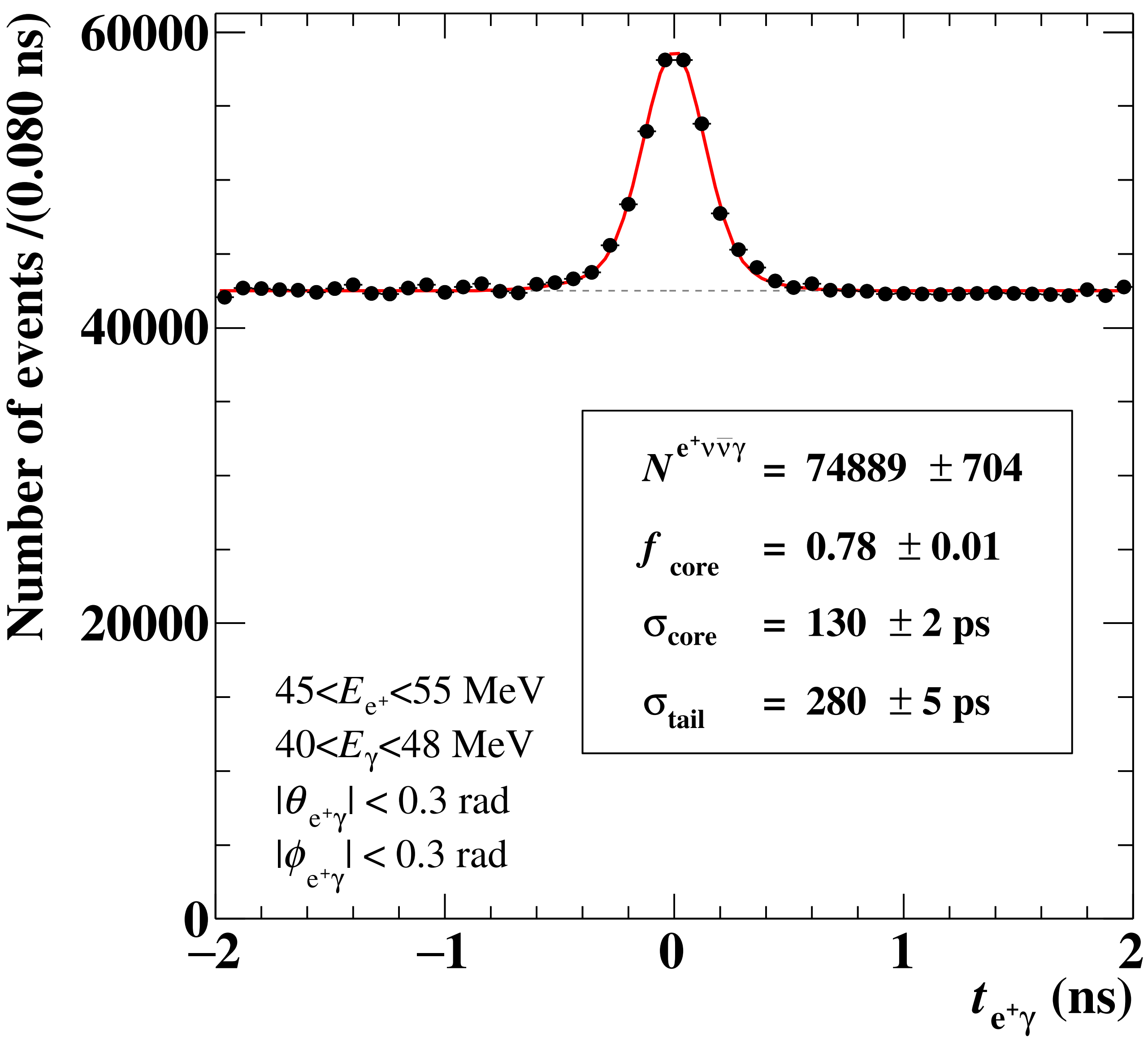


WaveDREAM



Positron - photon timing

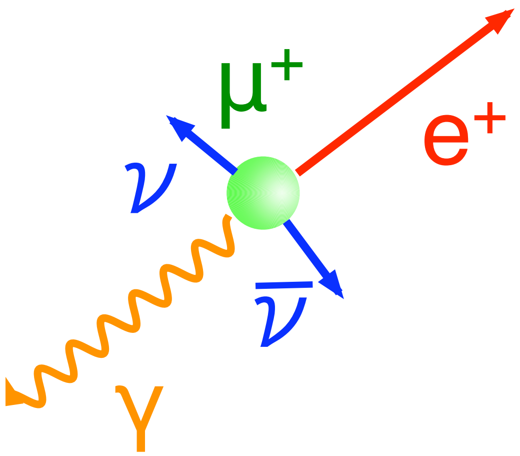
Time difference between gamma and positron



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

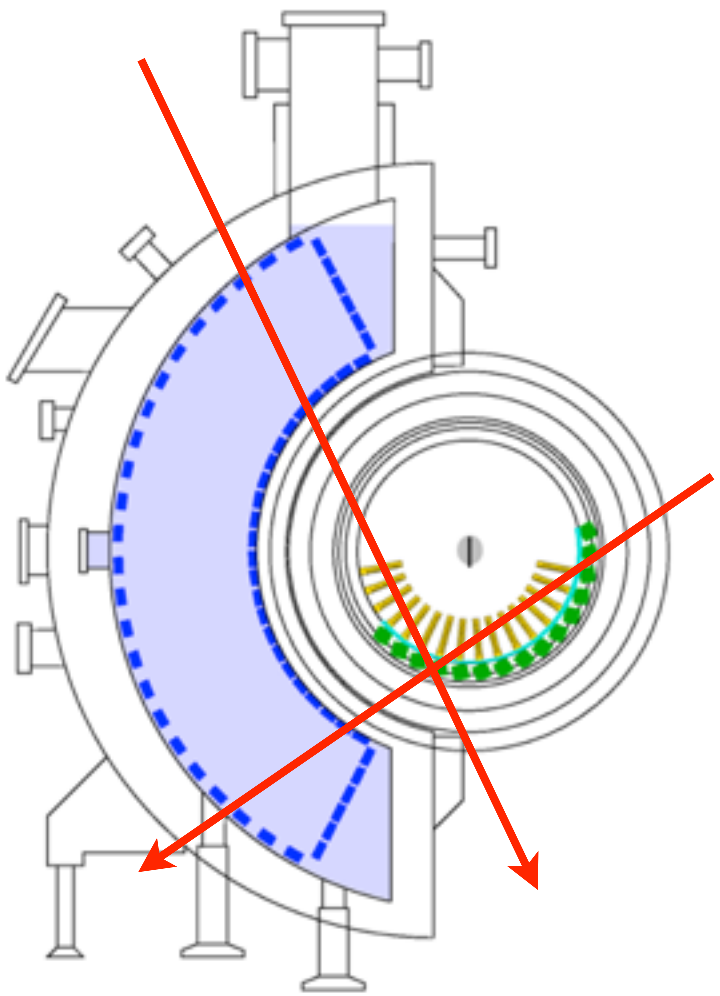
Timing resolution for signal is **122** ps

taking into account the energy dependence

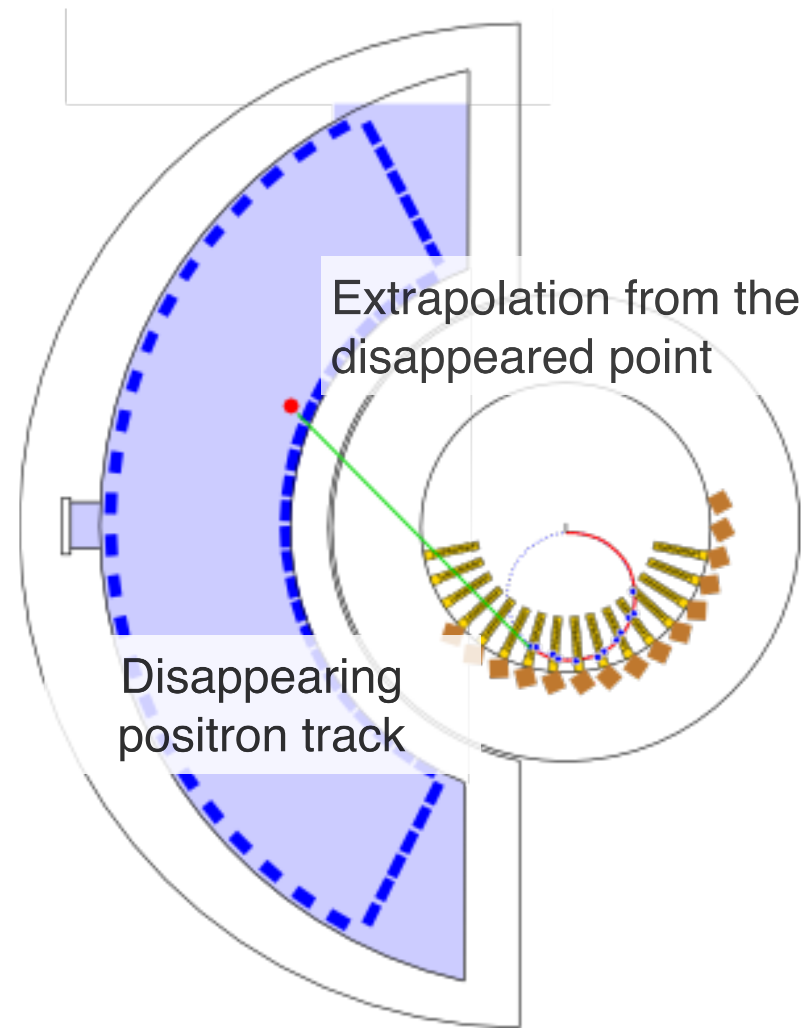


Alignment between detectors

Cosmic ray



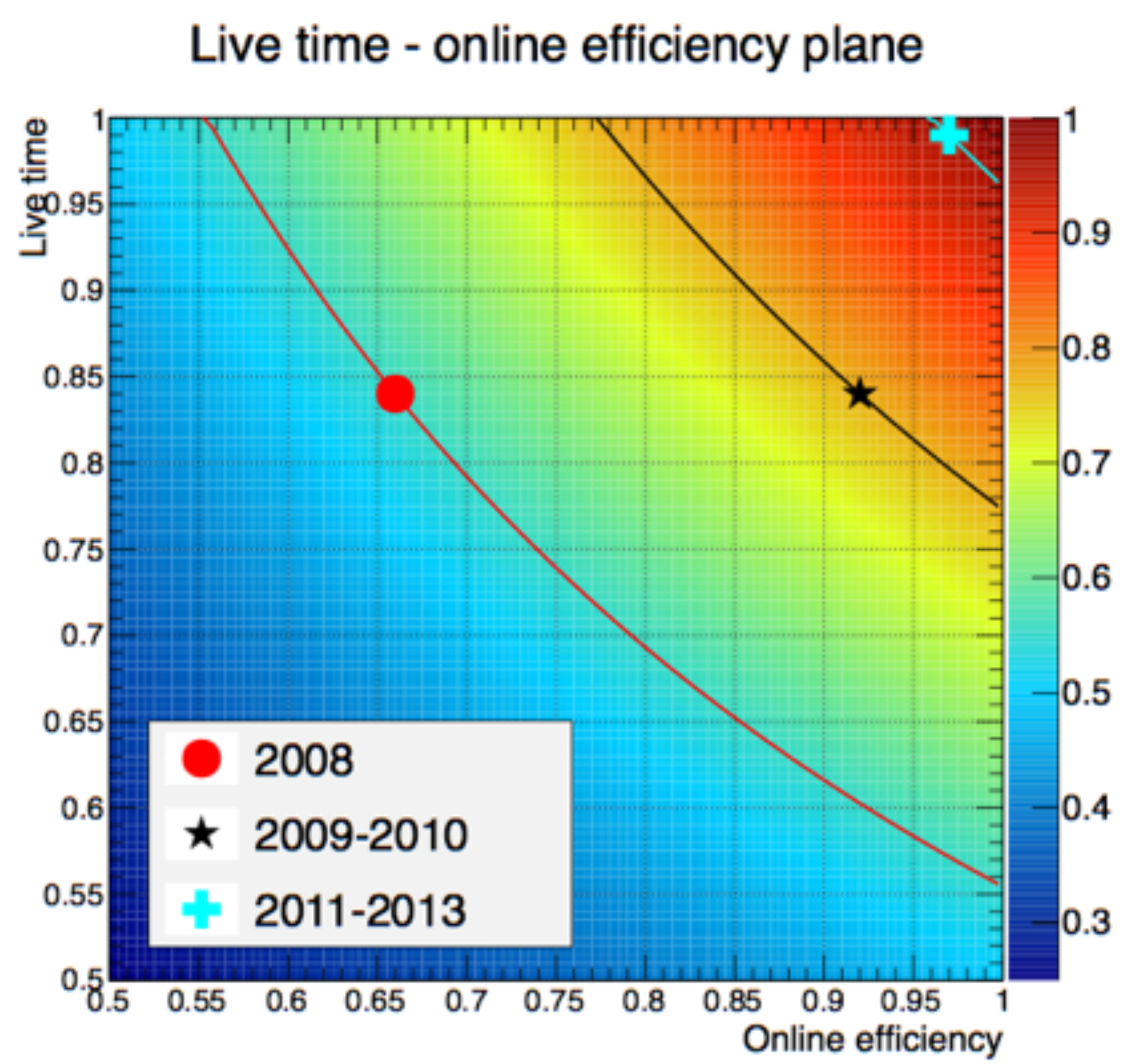
AIF



- Relative position measurements
  - Position of the sub-detectors were measured with laser-survey
  - The alignment is checked by the cosmic ray data and AIF (positron Annihilation-in-flight) events
- The difference of two method is included as a systematic uncertainty (1 mm) in the physics analysis

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

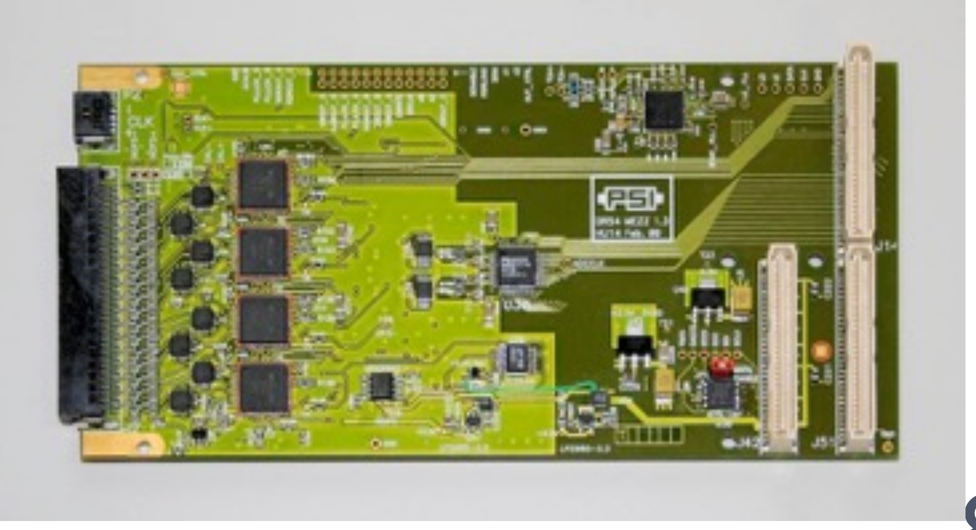


2008 → 2009 : direction-match and γ energy resolution improvement
2010 → 2011 : multiple-buffer readout

- 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