Search for the Lepton Flavor Violating Muon Decay $\mu^+ \rightarrow e^+\gamma$ with a Sensitivity below 10^{-12} in the MEG Experiment

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~~IHEP~~ → KEK

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Abstract

- Analysis on the data taken by MEG during 2009-2011 to search for $\mu^+ \to e^+\gamma$
  - Statistics are double by the previous results using 2009-2010 data
- Further improvements for the reconstruction and analysis methods
  - Pileup removal for gamma rays
  - Offline noise reduction for drift chamber waveforms
  - Revise the track fitting for positrons
  - Newly developed "Per-event" PDF
- The first search for the $\mu^+ \to e^+\gamma$ with a sensitivity below 10^{-12} order of magnitude
- The most stringent upper limit on search for $\mu^+ \to e^+\gamma$: **$B < 5.7 \times 10^{-13}$** @ 90% C.L.

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- ~~The most stringent upper limit~~ on search for $\mu^+ \to e^+\gamma$: **$B<5.7\times10^{-13}$** @ 90% C.L.

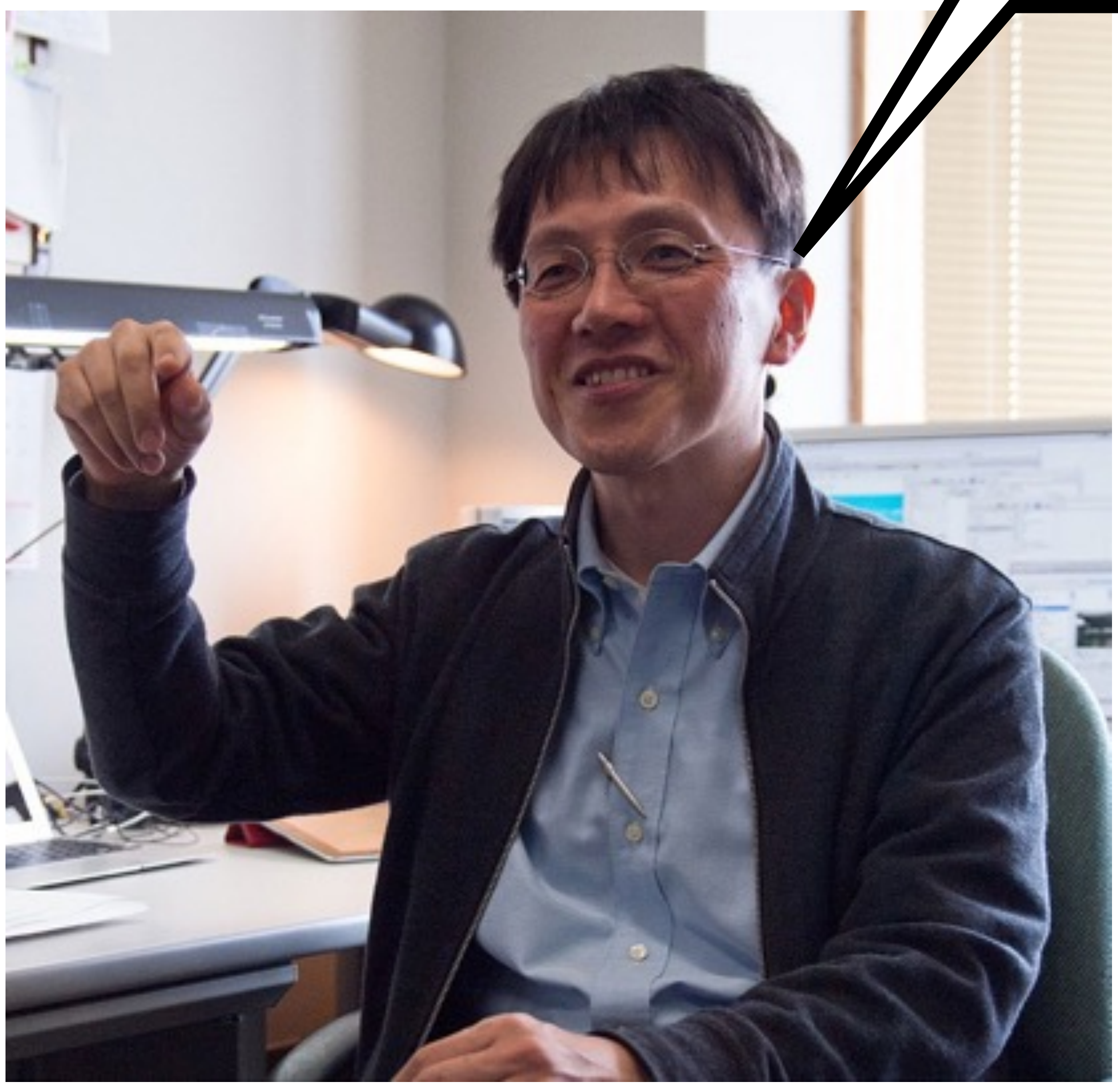
Final results is published in this month

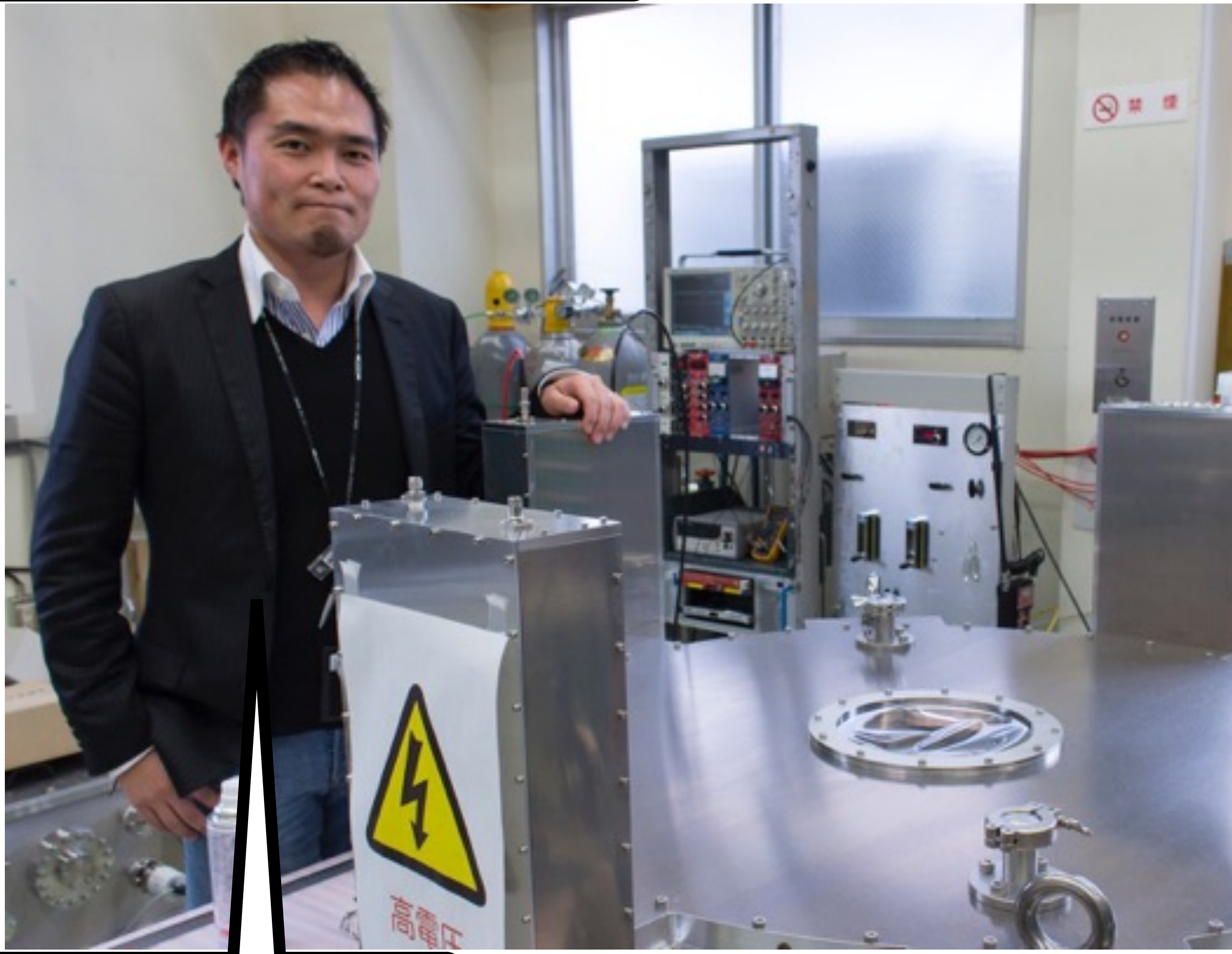
New upper limit: 4.2×10^{-13}

1st report @ La Thuile, 2nd one is in this meeting!

No positive signal found

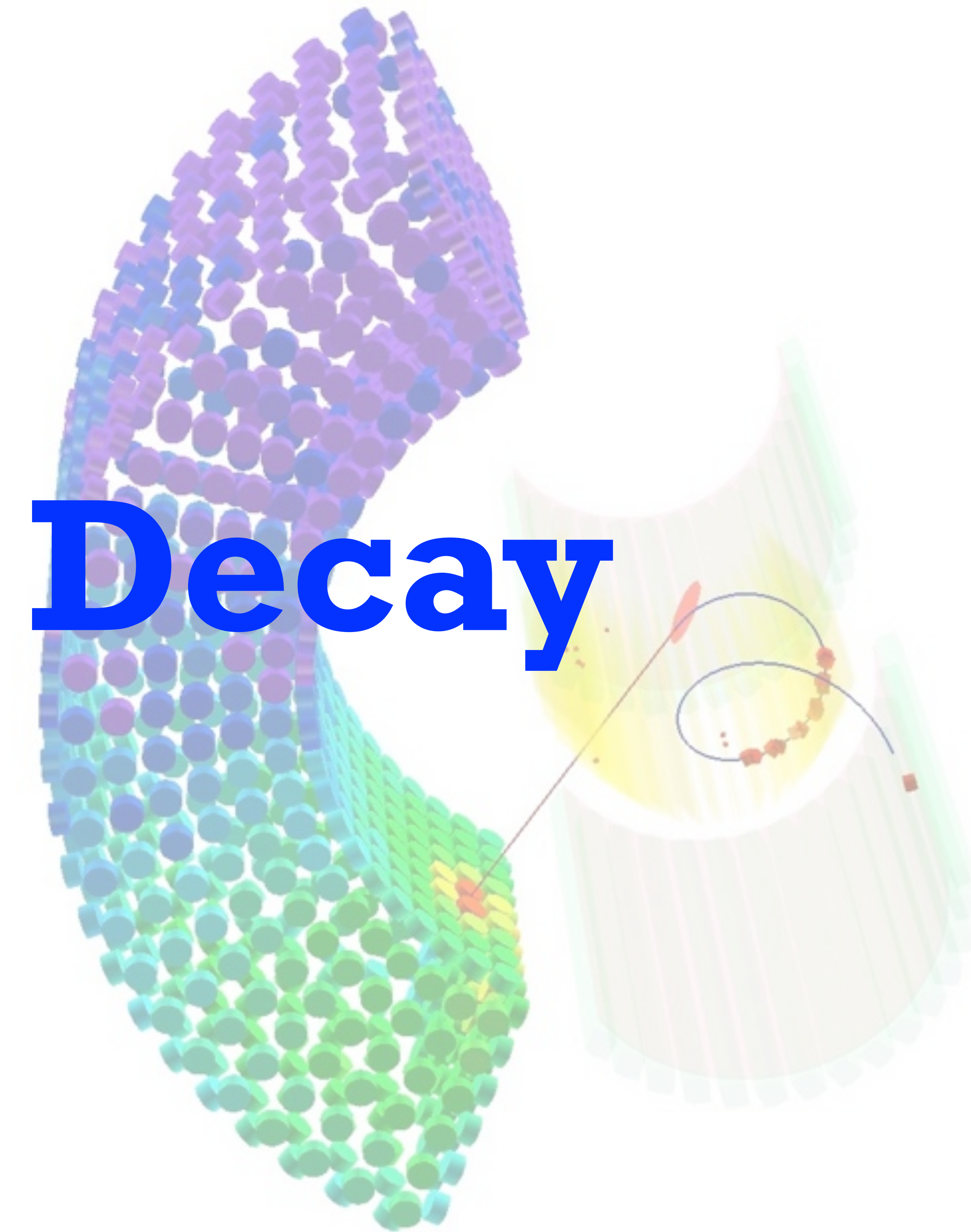
もっと面白い話をして下さい





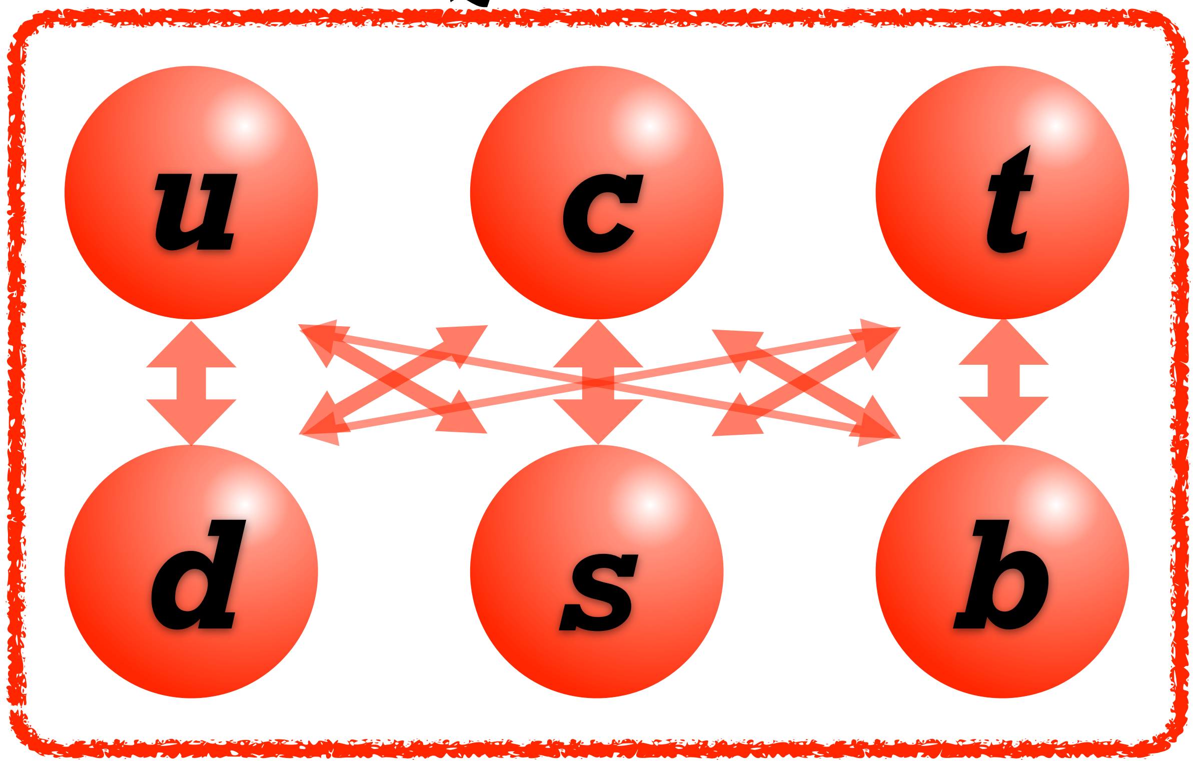
COMETの話を入れるように！

$\mu \rightarrow e\gamma$ Decay



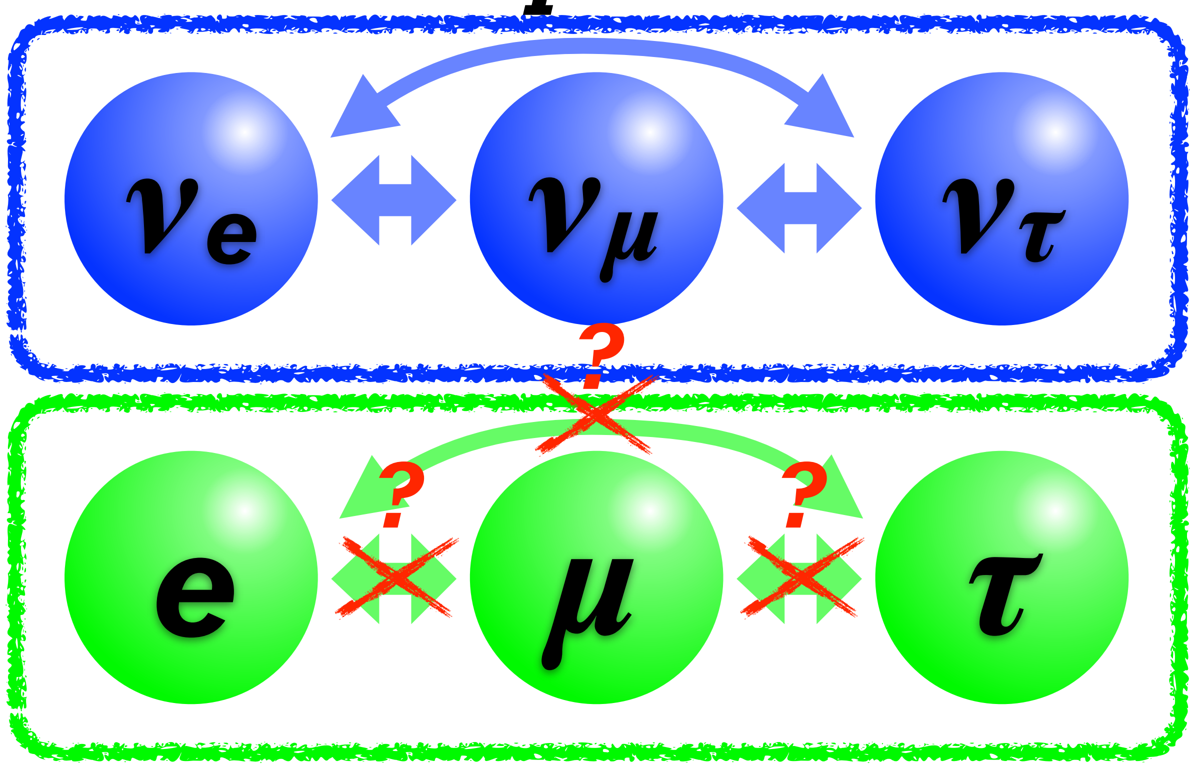
Lepton Flavor Violation

Quarks



Flavors are mixed through CKM matrix in the Standard Model,
Already confirmed

Leptons



Flavors are mixed through PMNS matrix,
Already confirmed (not included in SM)

Charged Lepton Flavor Violation (CLFV)
Forbidden in the Standard Model,
$B(\mu \to e\gamma) \sim O(10^{-50})$ for SM+ν oscillation,
Not observed yet

Lepton Flavor Violation

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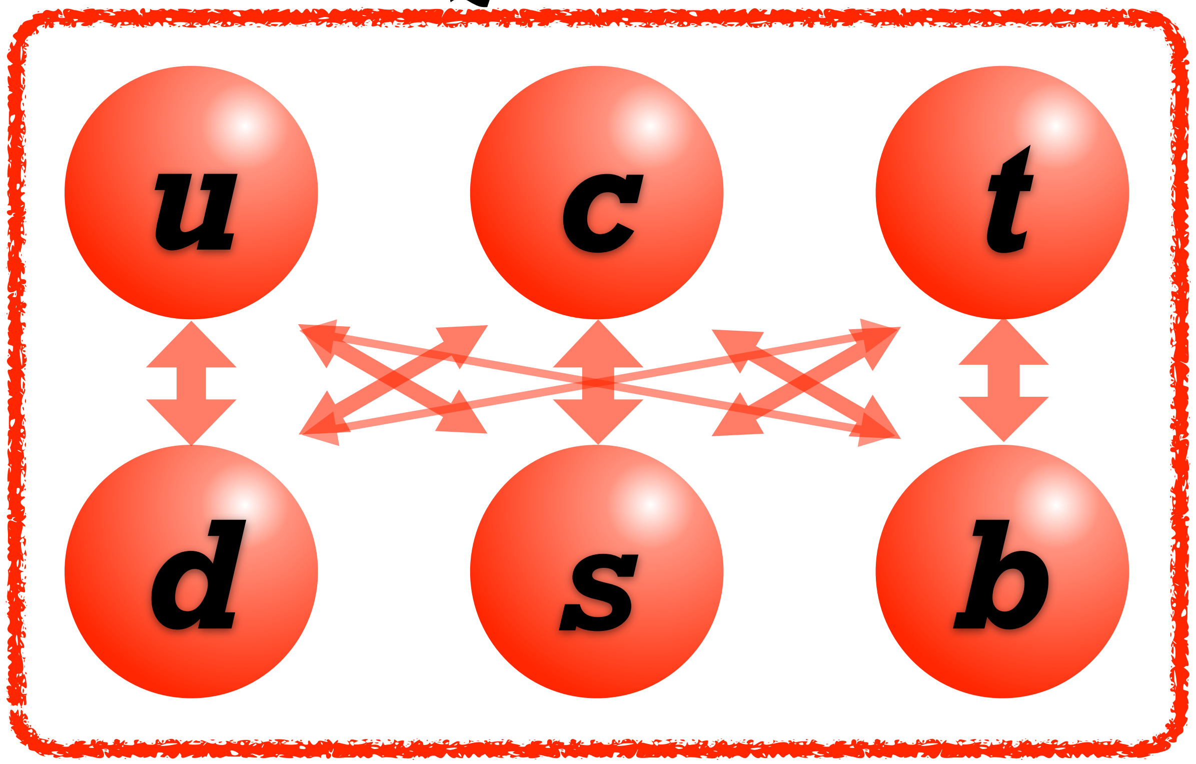

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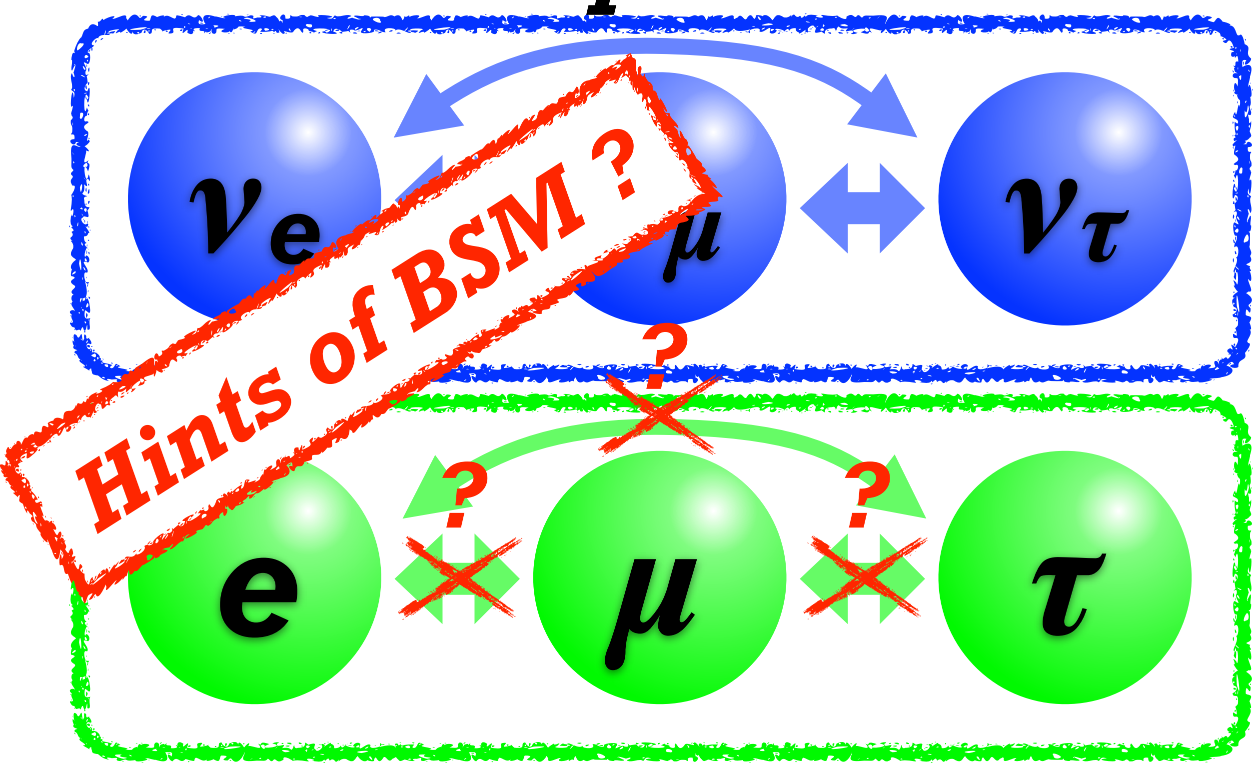

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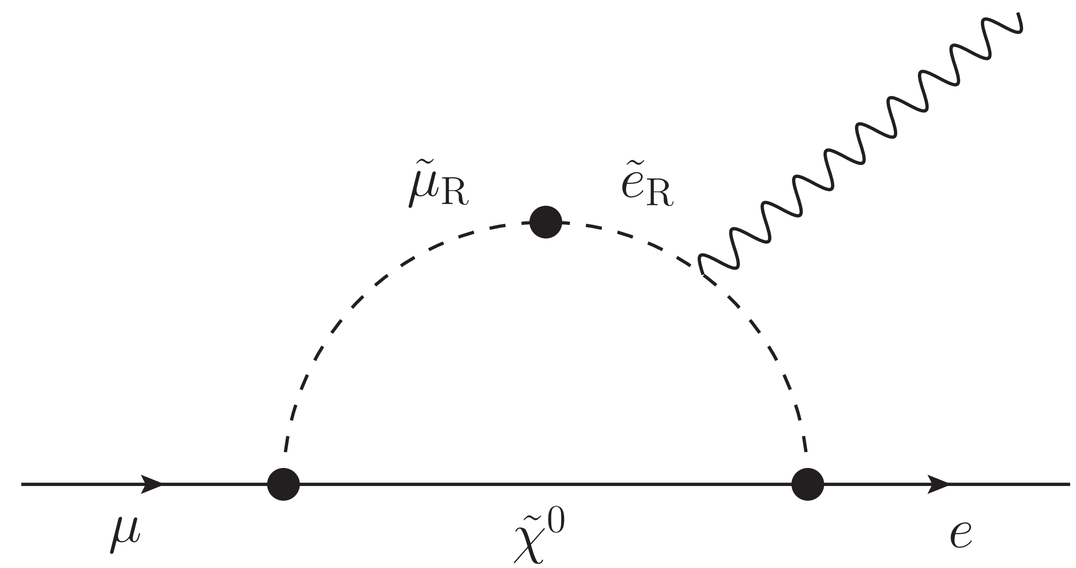
μ→eγ in BSM

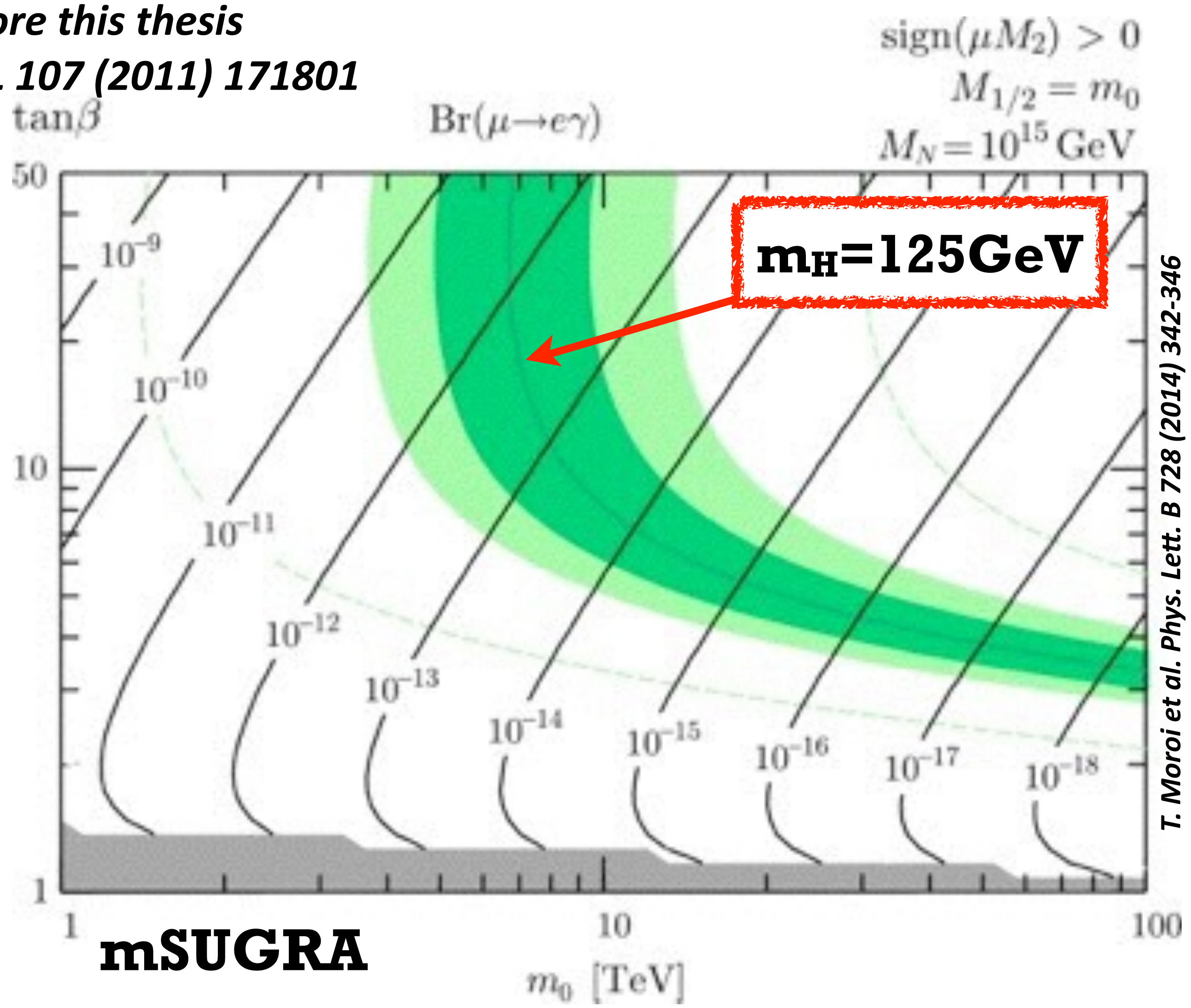
- Many BSMs predict the detectable B(μ→eγ) in between 10^{-11} and 10^{-15}
  - SUSY-GUT, SUSY-Seesaw, Extra dimension, etc.
- *Previous MEG results: ****2.4×10^{-12}** @ 90% C.L.
  - Already in the "BSM region" !
- Discovery of the μ→eγ decay should be the **clear evidence of BSM**
- Existence of the g-2 deviation, proton radius puzzle
  - **Something new in the muon sector??**
- CLFV searches can indirectly access the <u>higher mass scale than that of LHC</u>



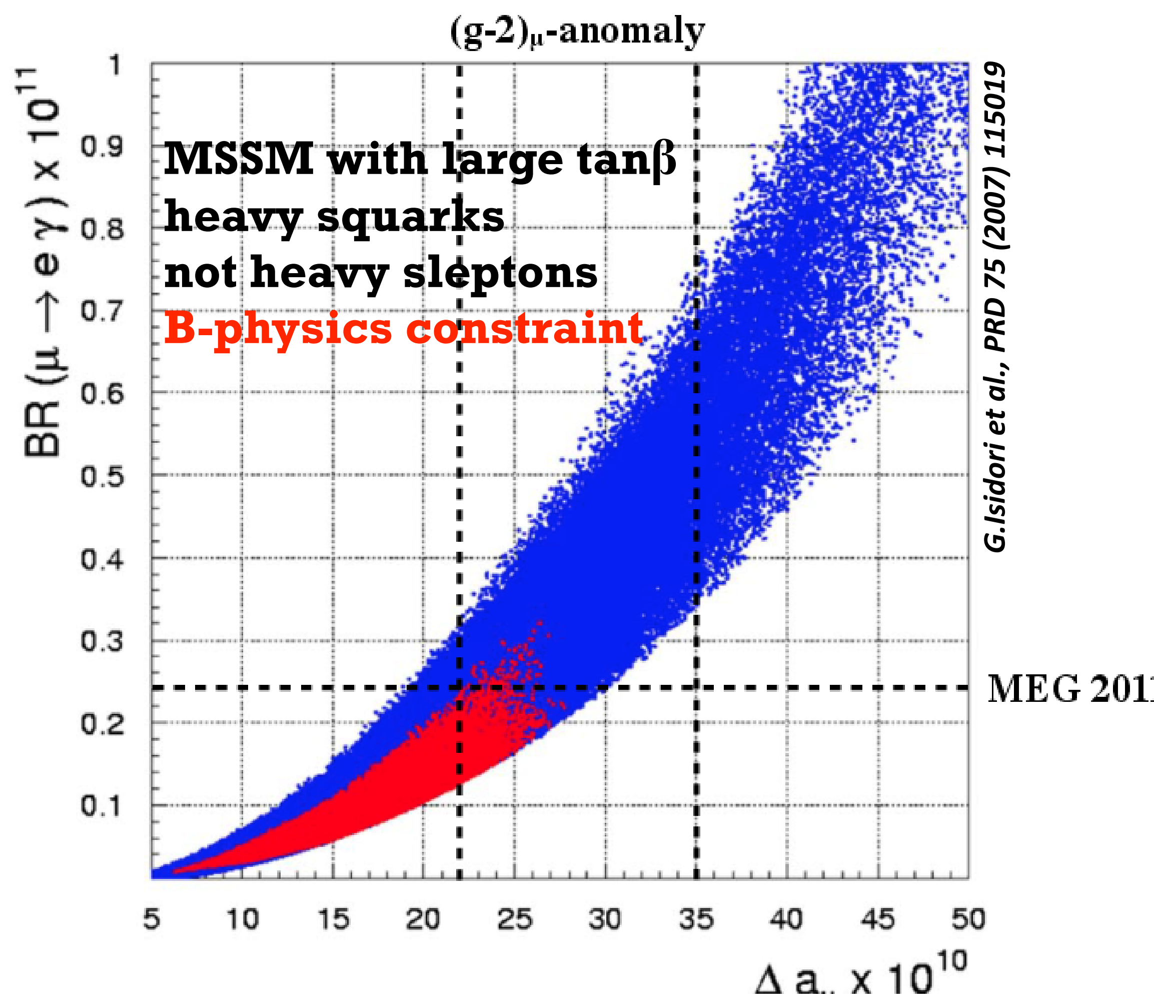
Example diagram of the μ→eγ decay in SUSY

Before this thesis

*****PRL 107 (2011) 171801***



mSUGRA



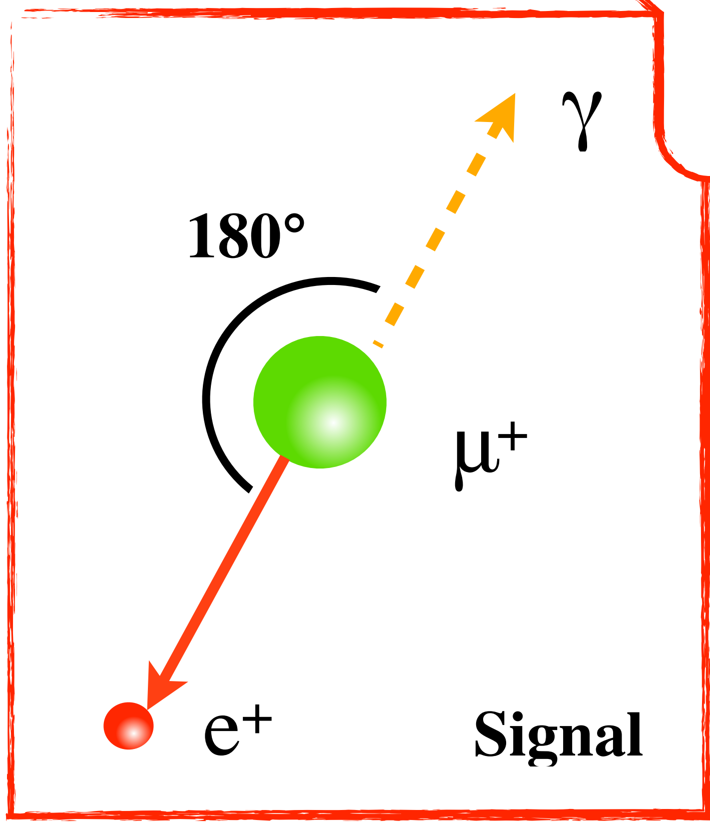
Signal / Background

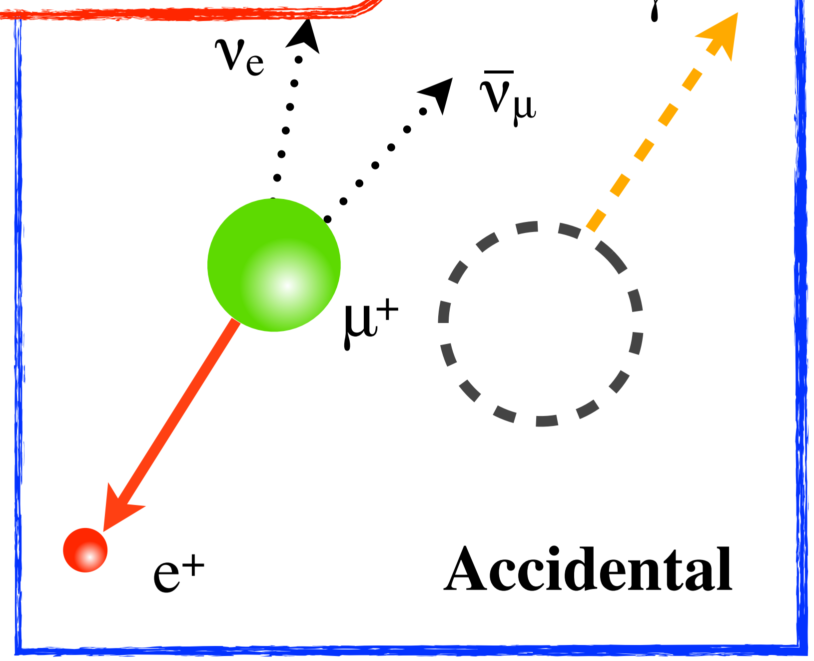
Back-to-back
$E_e = E_\gamma = 52.8$ MeV
$T_e = T_\gamma$

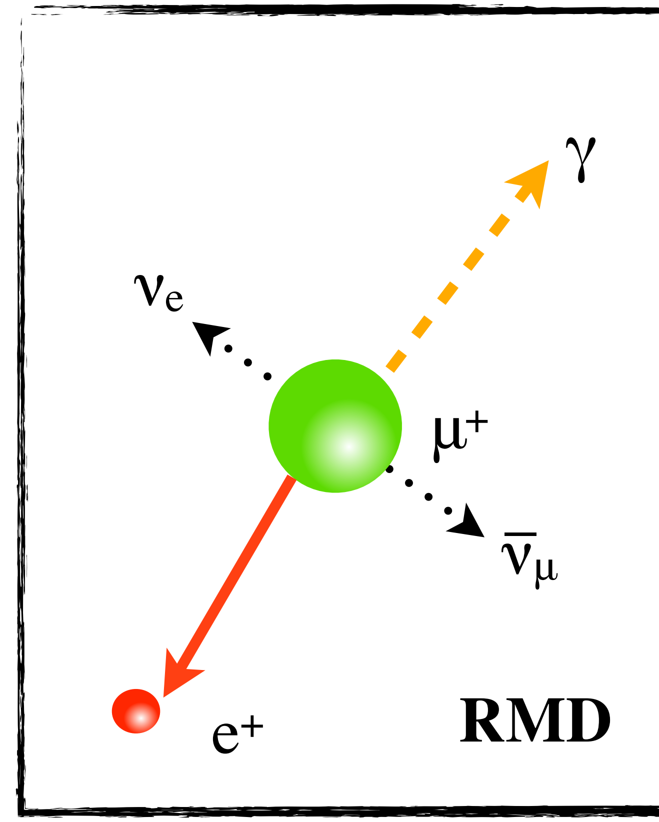
Dominant Background
$N_{acc.} \propto R^2_\mu$
R_μ: instantaneous μ^+ rate

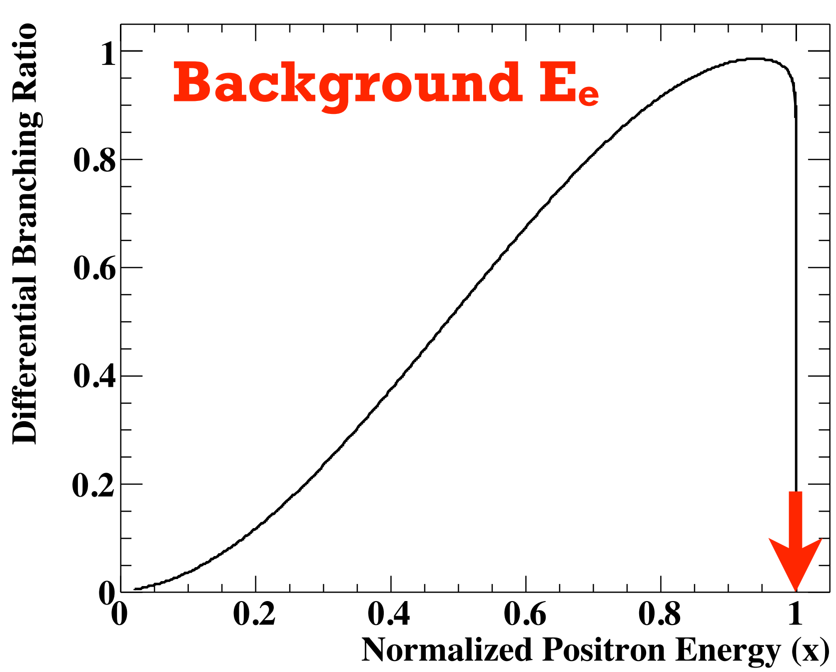
Radiative Muon Decay (RMD)
$N_{RMD} \fallingdotseq 0.1 \times N_{acc.}$

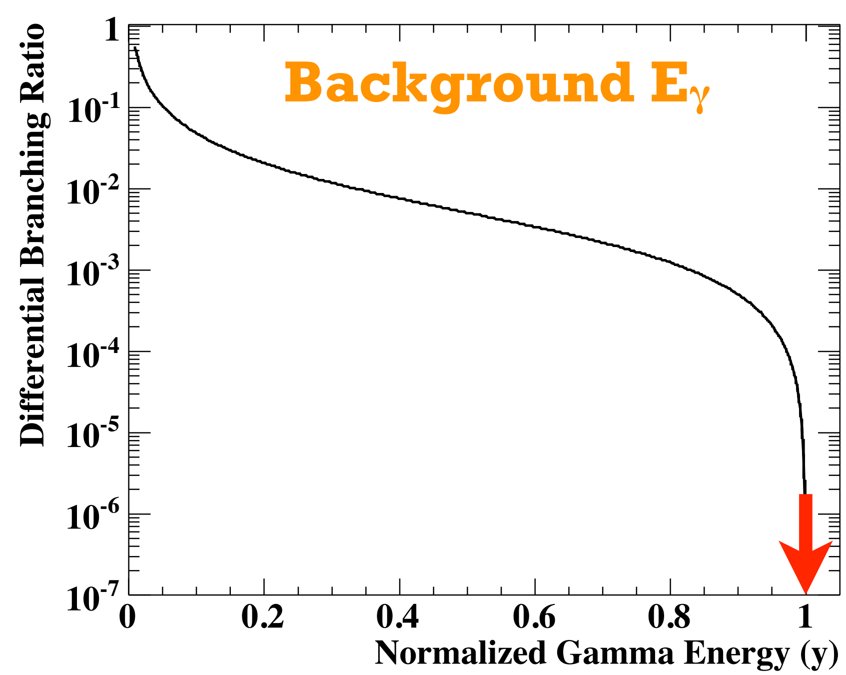
Very simple kinematics











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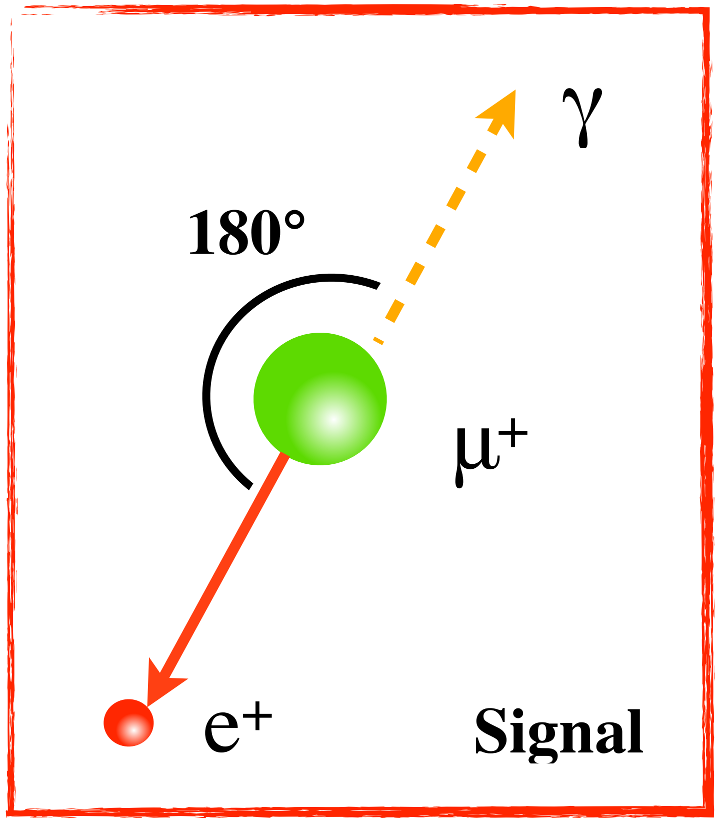
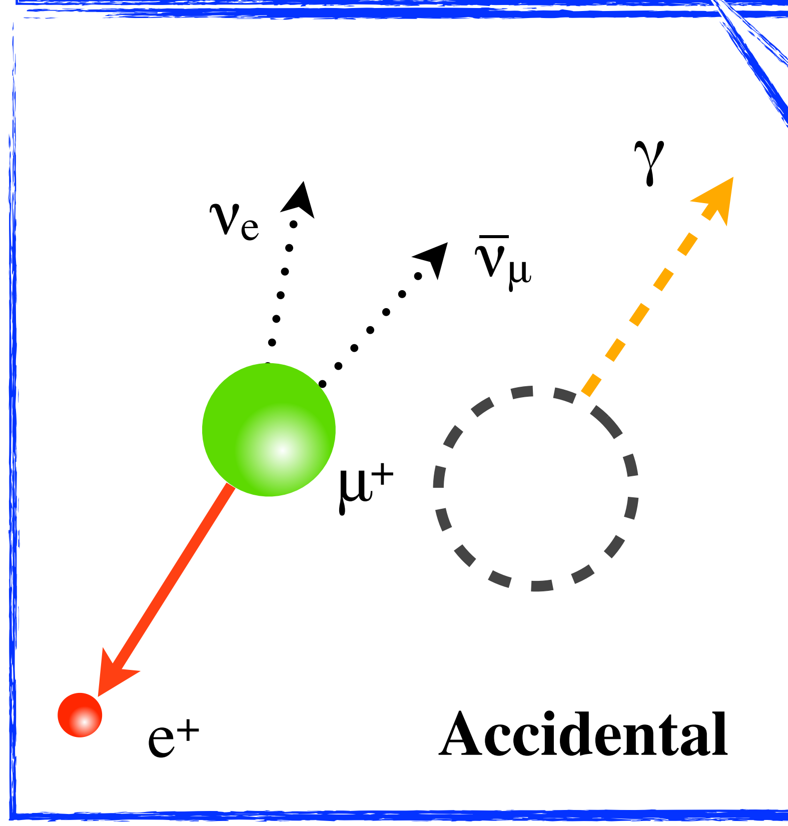
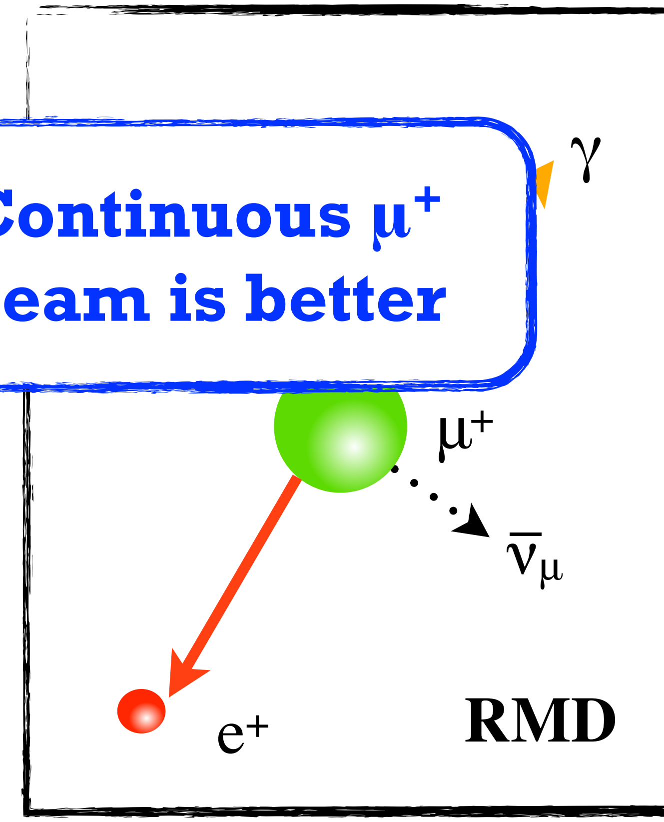
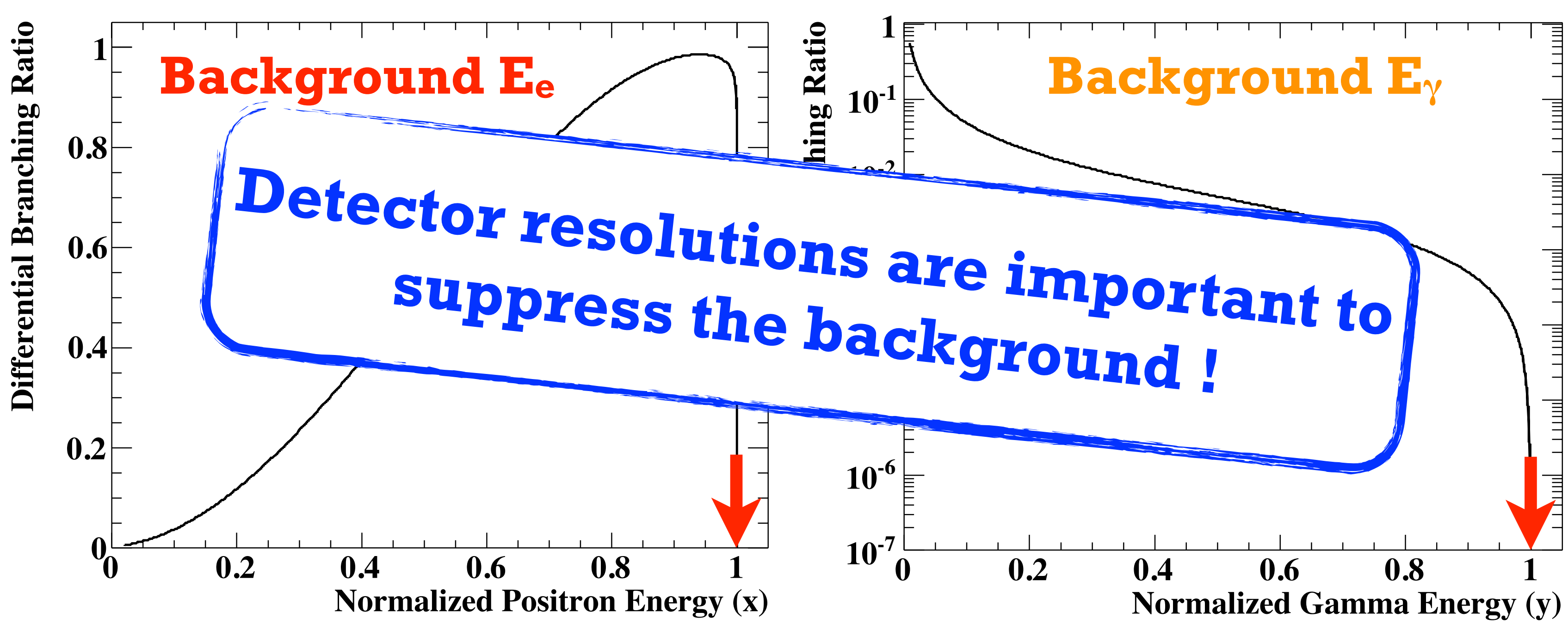




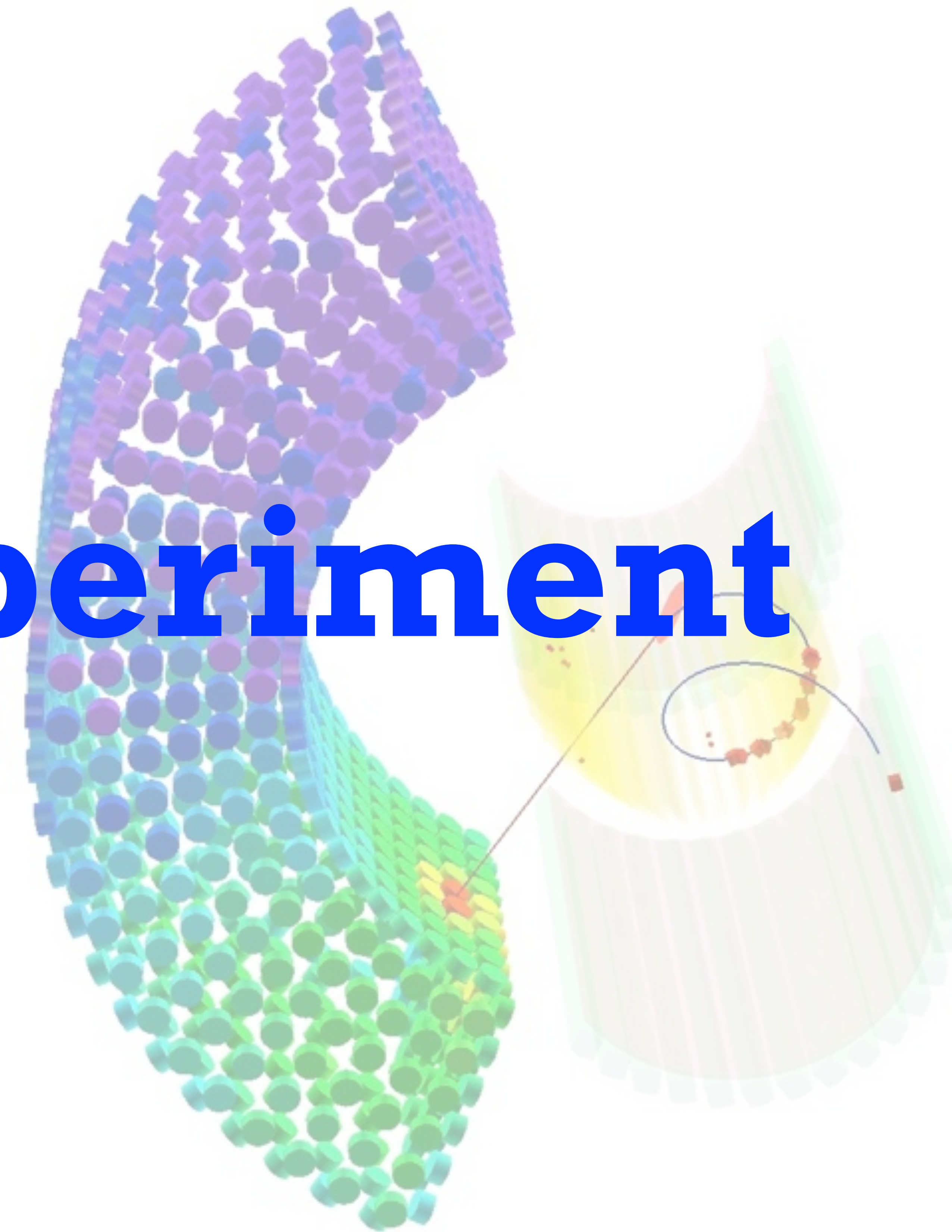
Continuous μ^+ beam is better



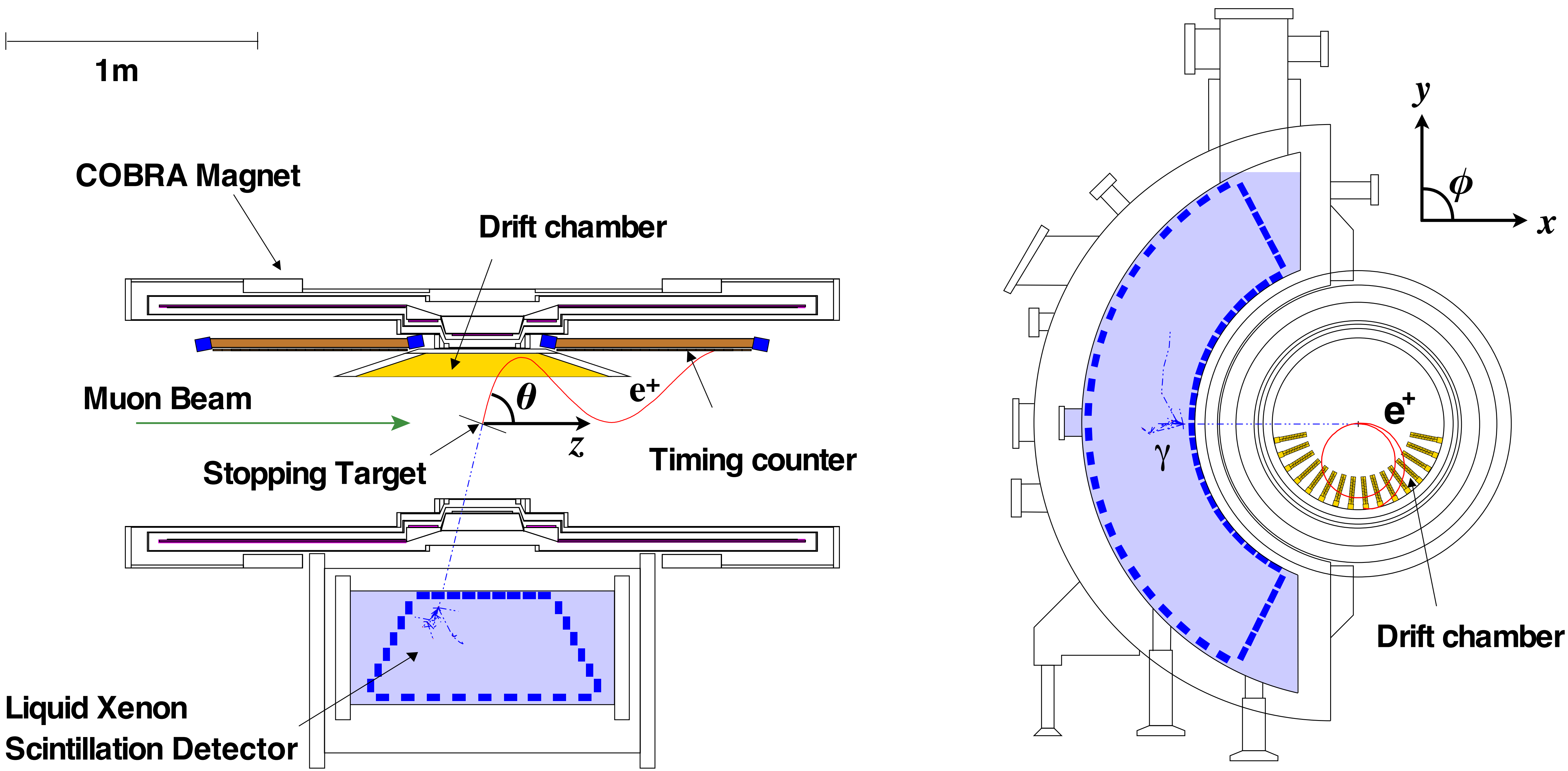


Detector resolutions are important to suppress the background !

MEG Experiment



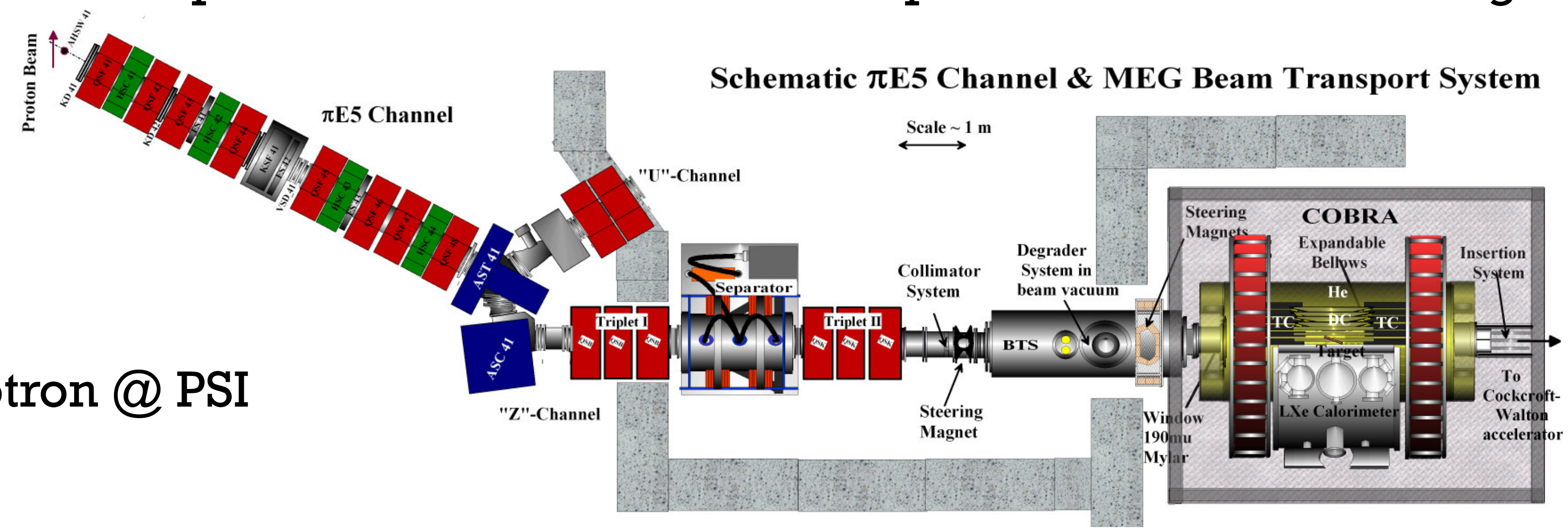
MEG Apparatus



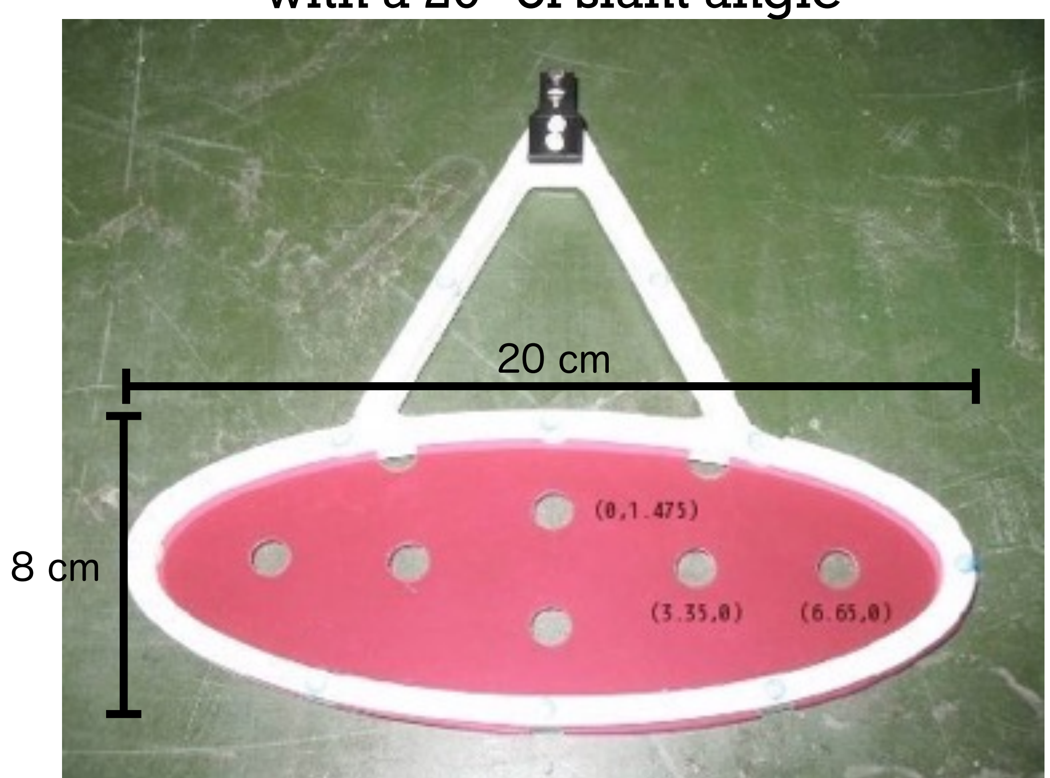
Beam & Target

The world most powerful proton ring cyclotron @ PSI
- 1.3 MW (2.2 mA) with a 590 MeV energy
- 50.6 MHz frequency

Muon beam transport solenoid (BTS)
- Select the surface (~30MeV/c) muon with a high purity
- Up to 8×10^8 muons can be transported at the detector region

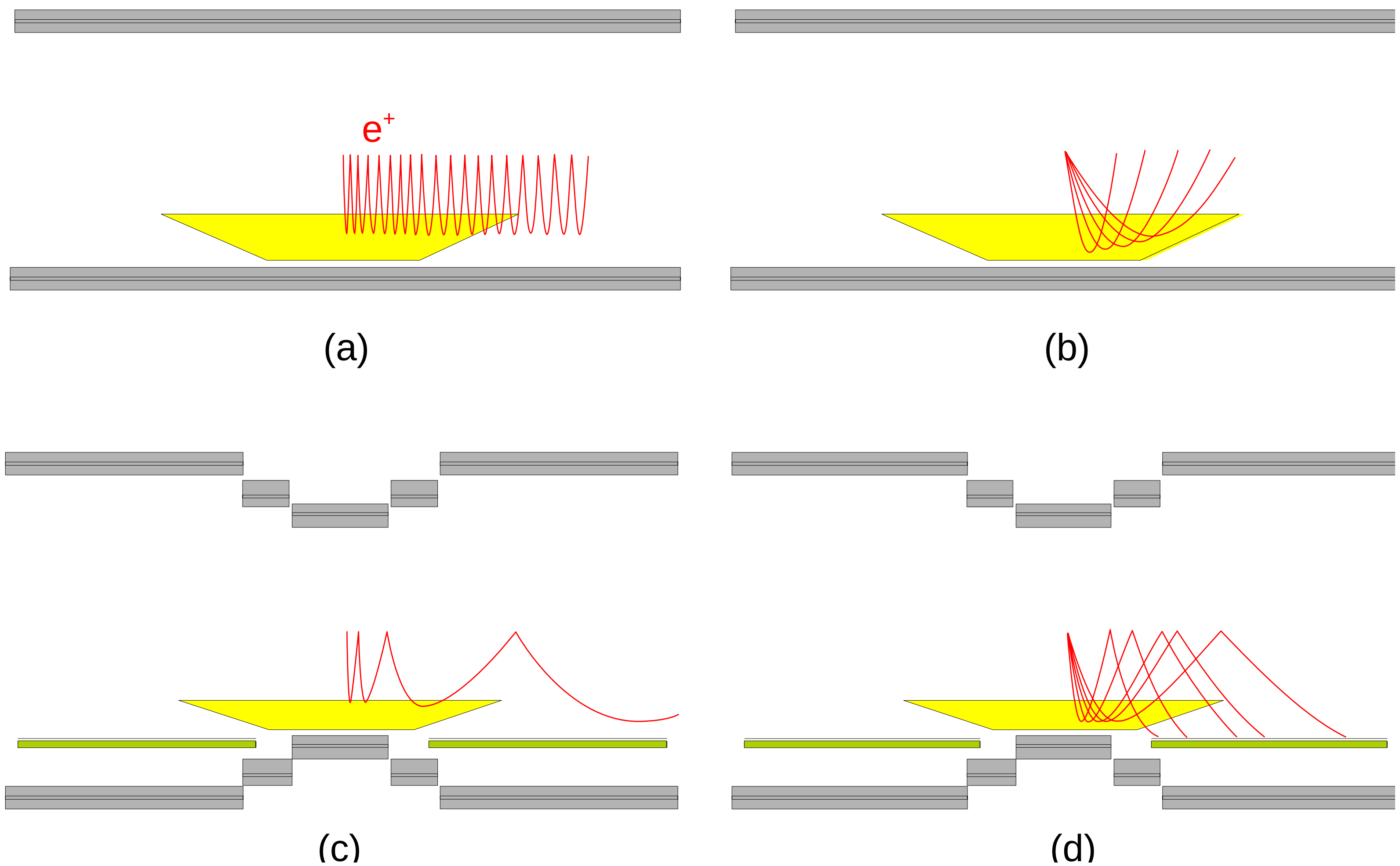


205 μm plastic target to stop muons
with a 20° of slant angle



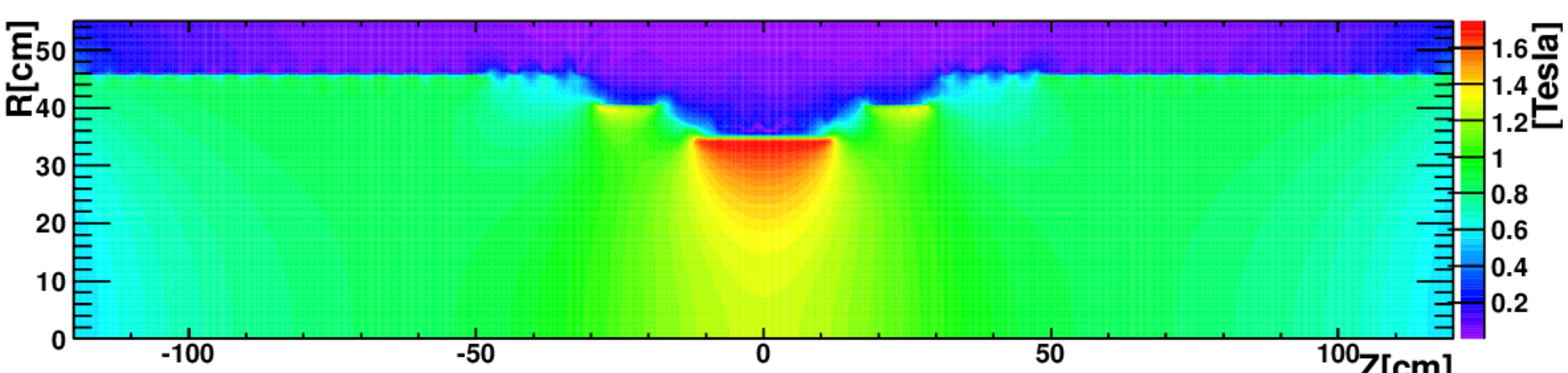
Muon stopping target mounted
inside the COBRA magnet

COBRA Magnet

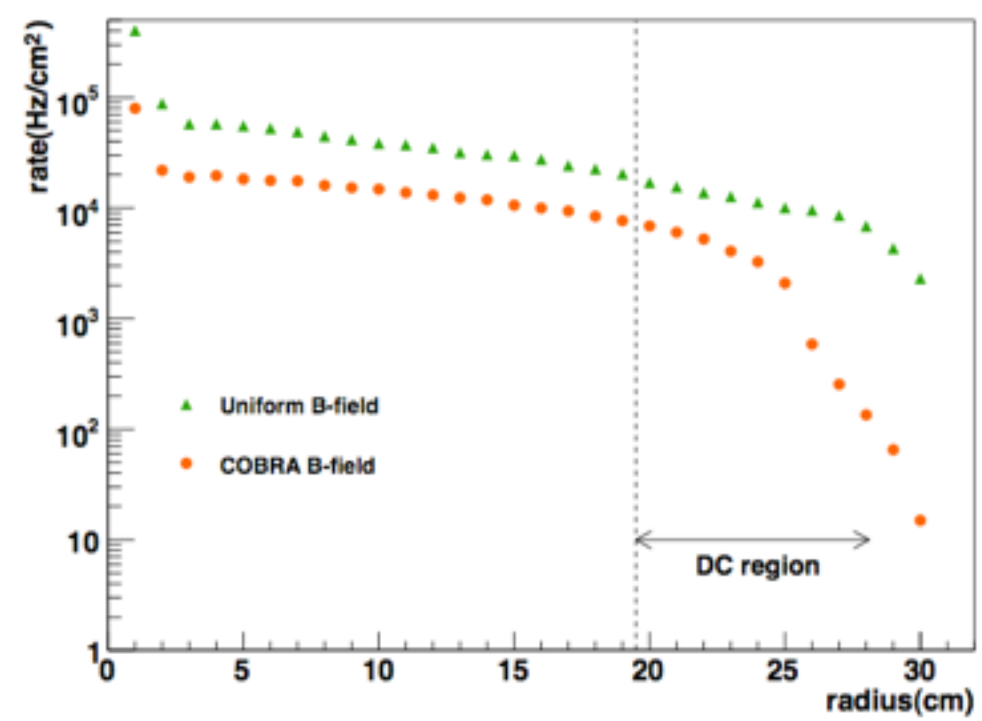


一様磁場(a),(b)とCOBRA磁場(c),(d)との比較

- Specially graded B field
  - Low momentum positrons are quickly swept out
    - → Low hit rate in the drift chambers
  - The curvature of signal positrons is almost independent on their emission angles

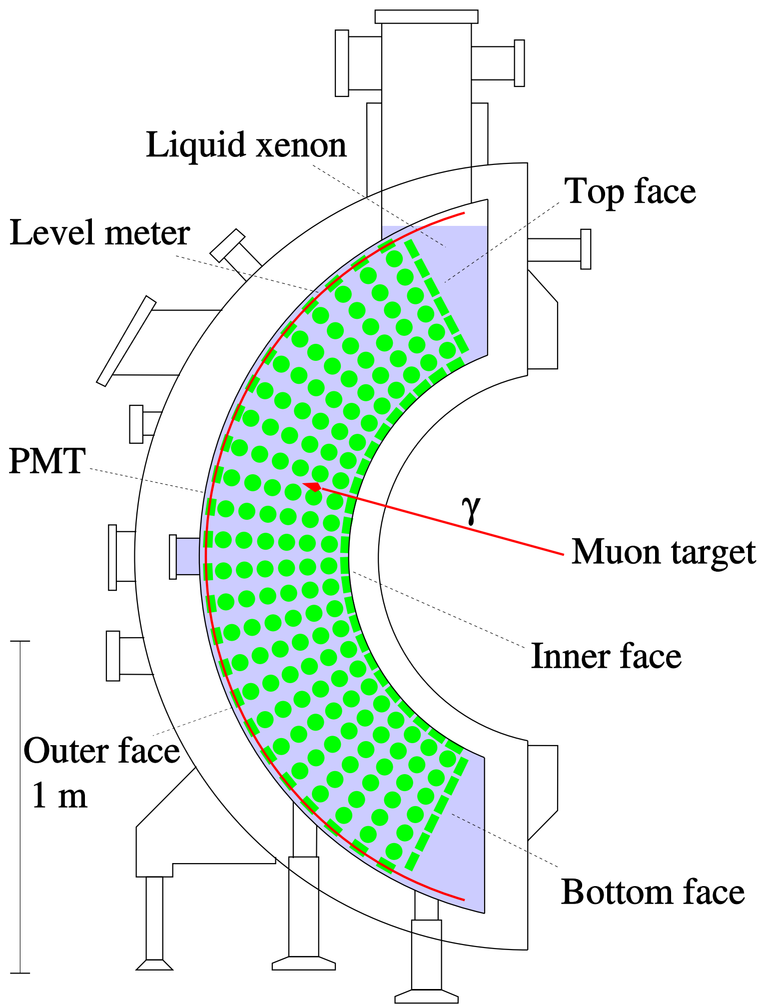


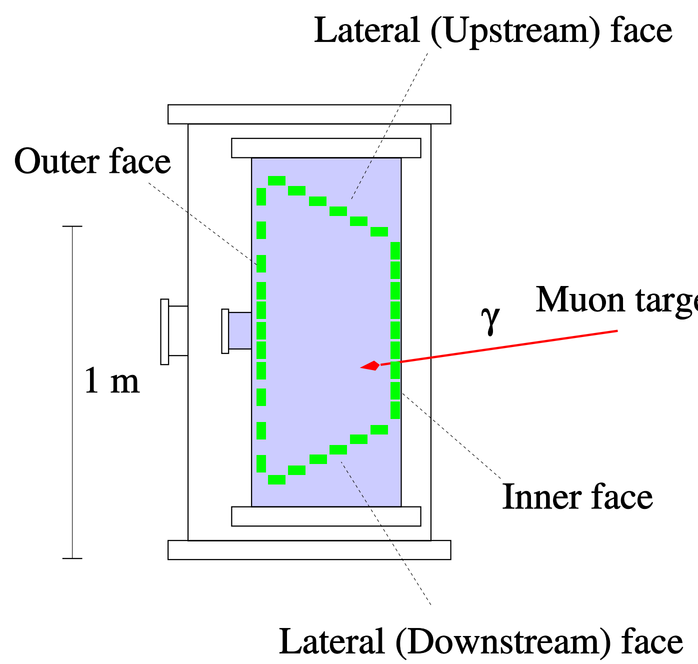
磁場の絶対値分布



ヒットレートのR依存性
(一様磁場との比較)

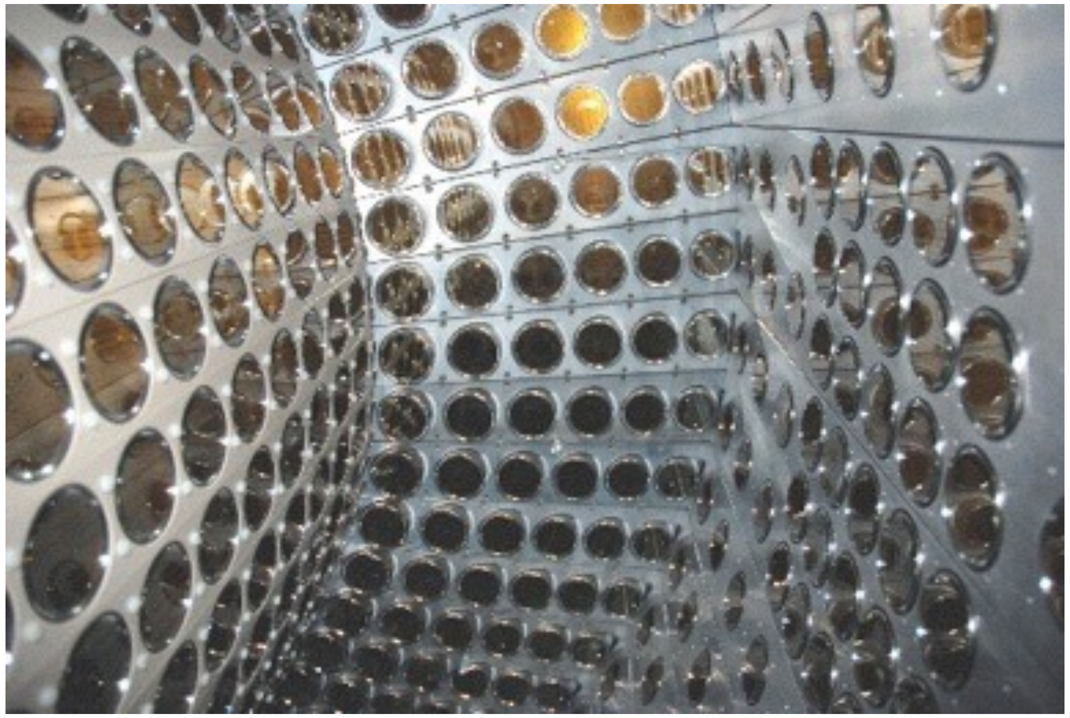
Liquid Xenon Detector



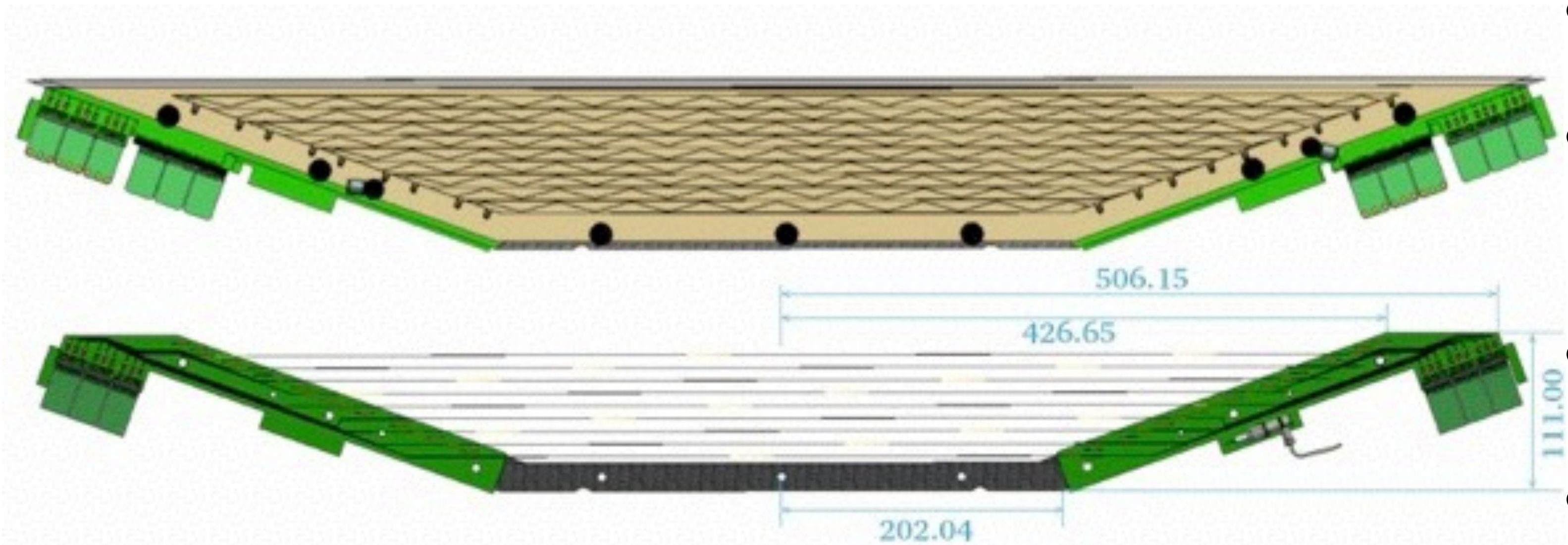


- Determine the timing/energy/position of γ rays
- Non-segmented calorimeter with 900 ℓ of liquid xenon
  - Good stopping power
    - High detection efficiency
  - Fast scintillation timing
    - Good at pileup separation
  - VUV-sensitive PMTs

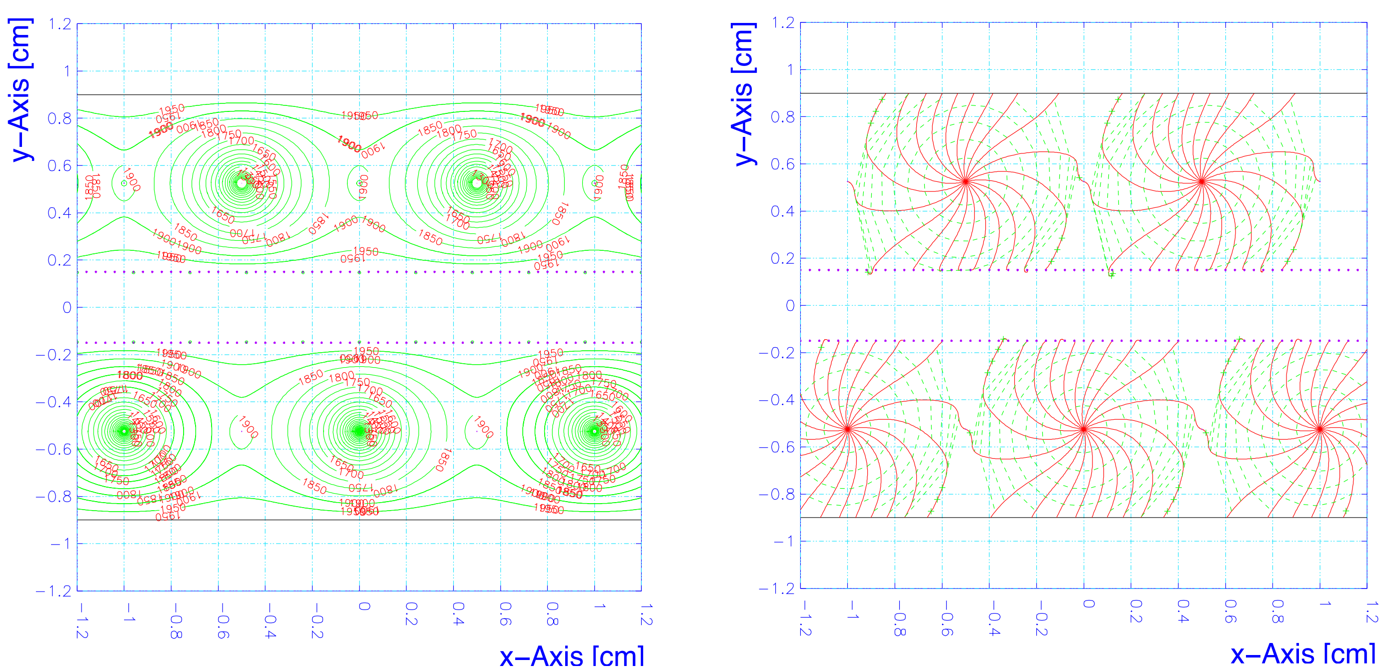
	LXe	LAr	NaI(Tl)	CsI(Tl)	BGO
Density (g/cm^3)	2.98	1.40	3.67	4.51	7.40
Radiation length (cm)	2.77	14	2.59	1.86	1.12
Moliere radius (cm)	4.2	7.2	4.13	3.57	2.23
Decay time (ns)	45	1620	230	1300	300
Wavelength (nm)	178	127	410	560	480
Relative light yield	75	90	100	165	21

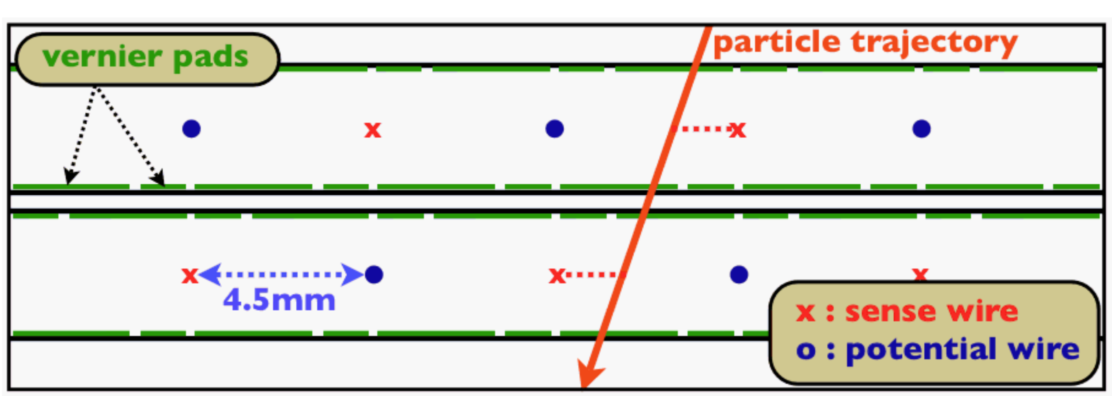


Drift Chamber

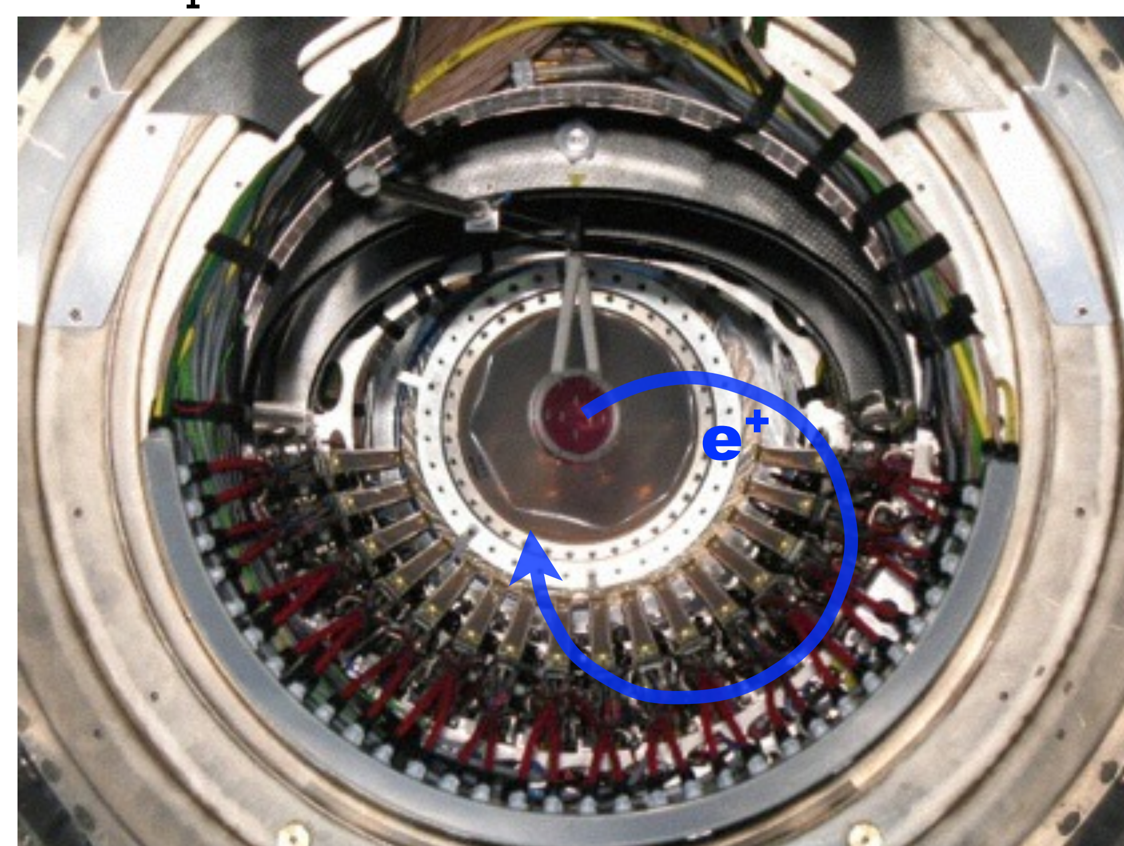


Schematics of the drift chamber module



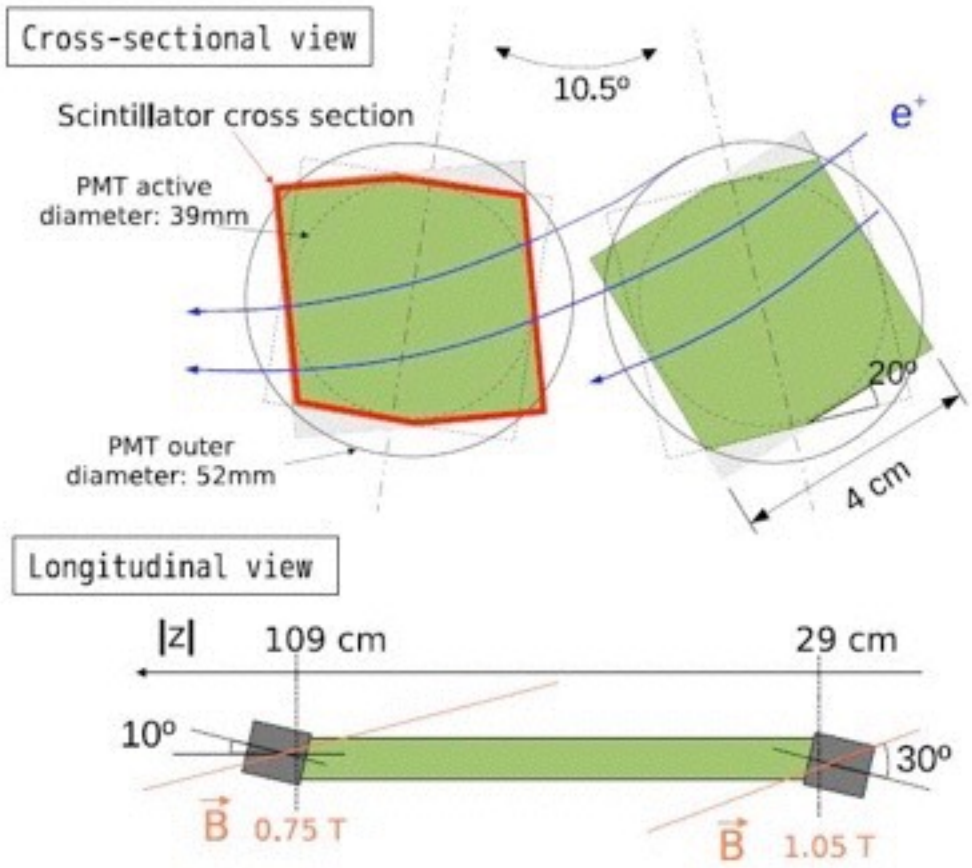


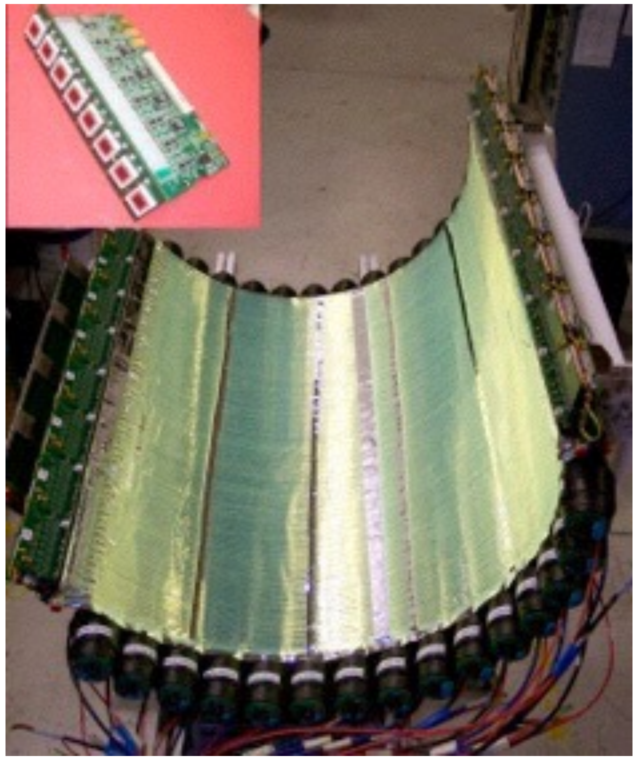
- Measure the momentum and vertex of positrons
- Made of ultra low mass materials
  - Minimize the multiple scattering
  - Suppress γ ray BG production
- 16 modules consist of two staggered layers
  - Reduce the L-R ambiguity
- Vernier method
  - Zig-zag pattern enables the precision measurement along z-axis less than 1mm
- He:C_2H_4=50:50 gas mixture
  - Short radiation length ~$2\times10^{-3}X_0$ for signal positrons



Drift chambers installed inside the COBRA magnet

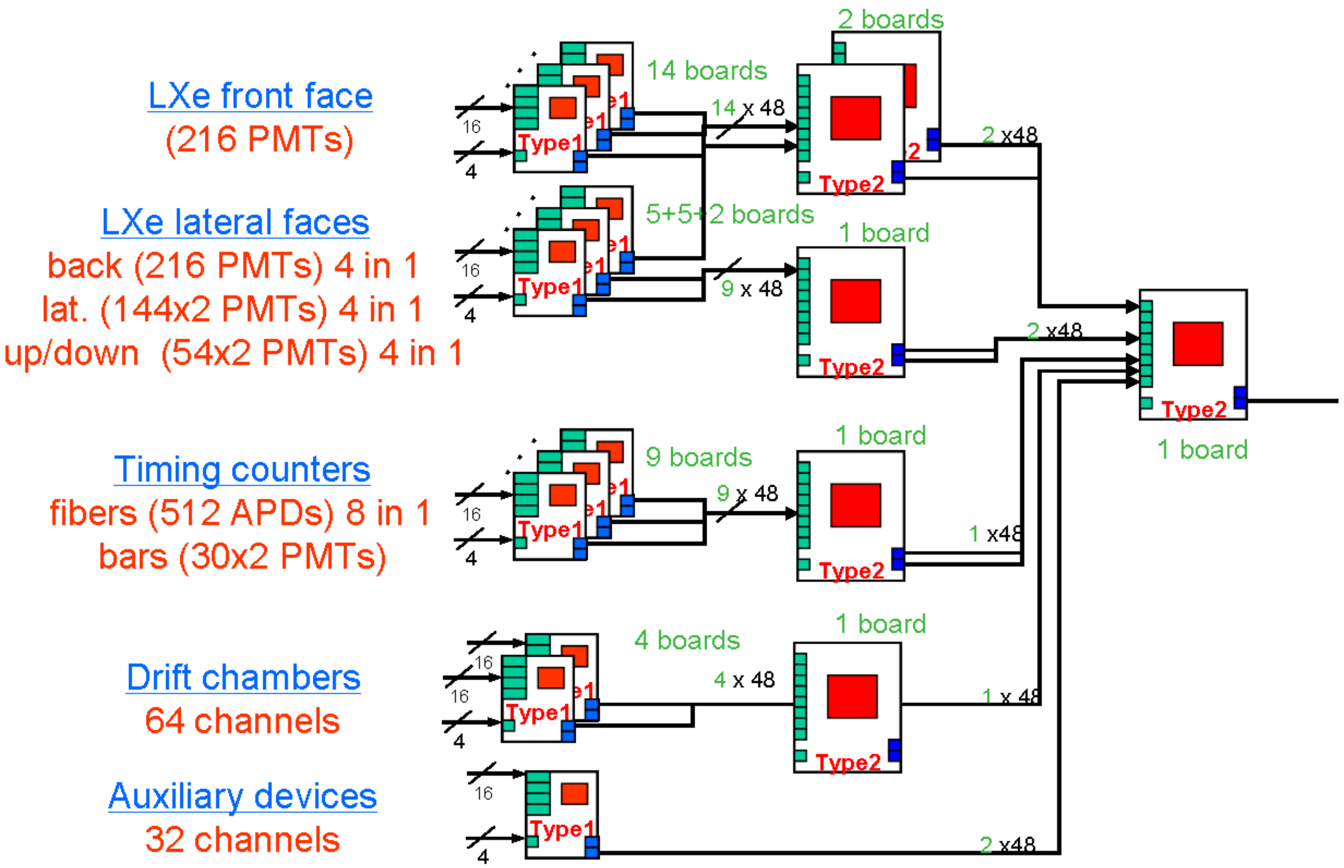
Timing Counter

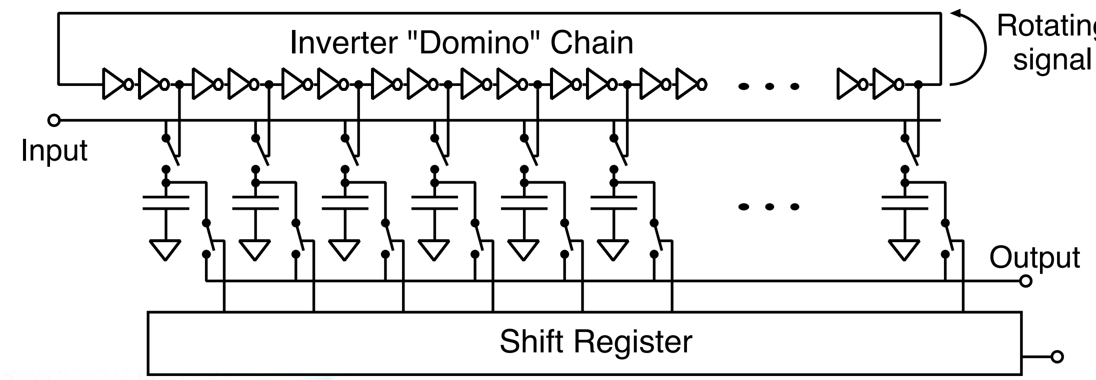


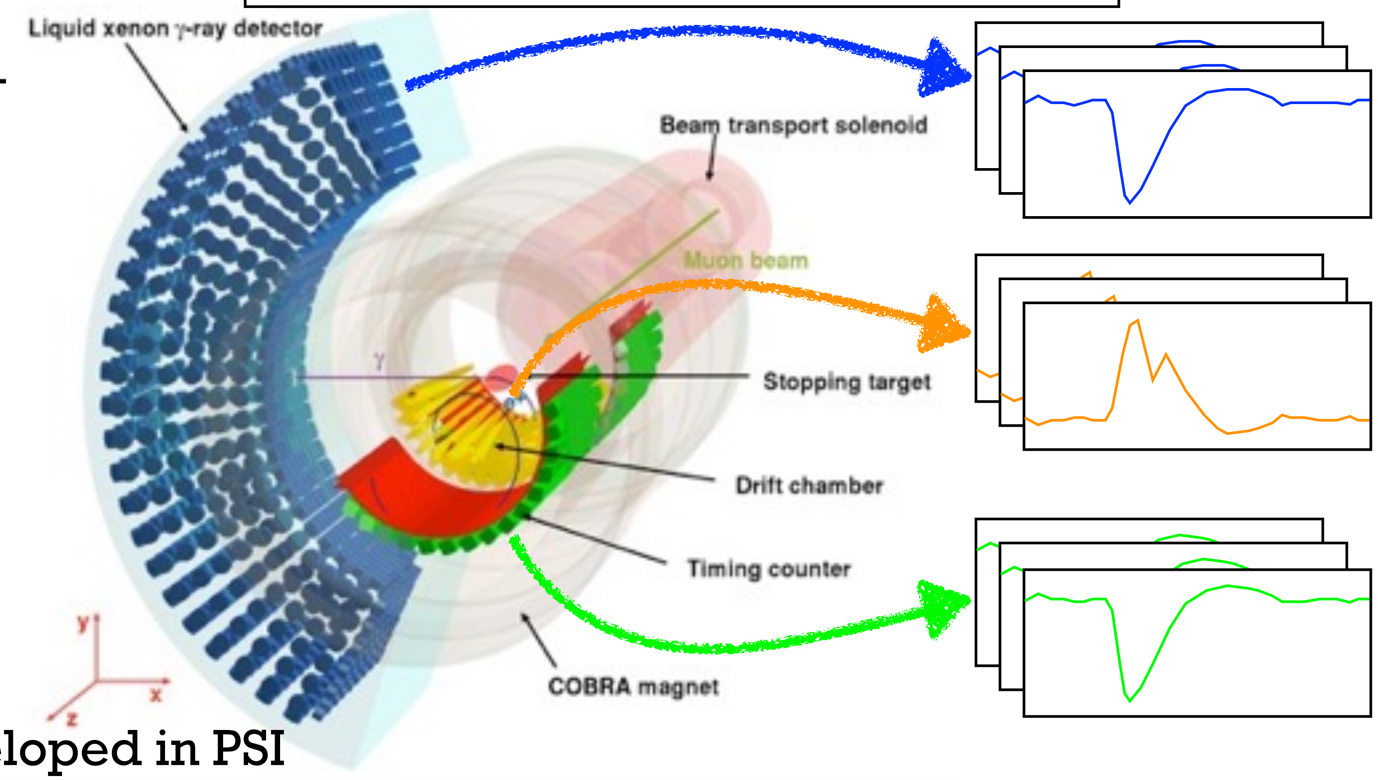


- Reconstruct the impact time of positrons
  - 15 of scintillator bars for both upstream and downstream
    - Timing and ϕ position measurement
    - Scintillation light are detected by using fine-mesh PMTs at both ends
  - Scintillating fibers are placed on the scintillator bars to measure the position along z-axis
    - Not used in the reconstruction/analysis because of unstable operation

Trigger & DAQ

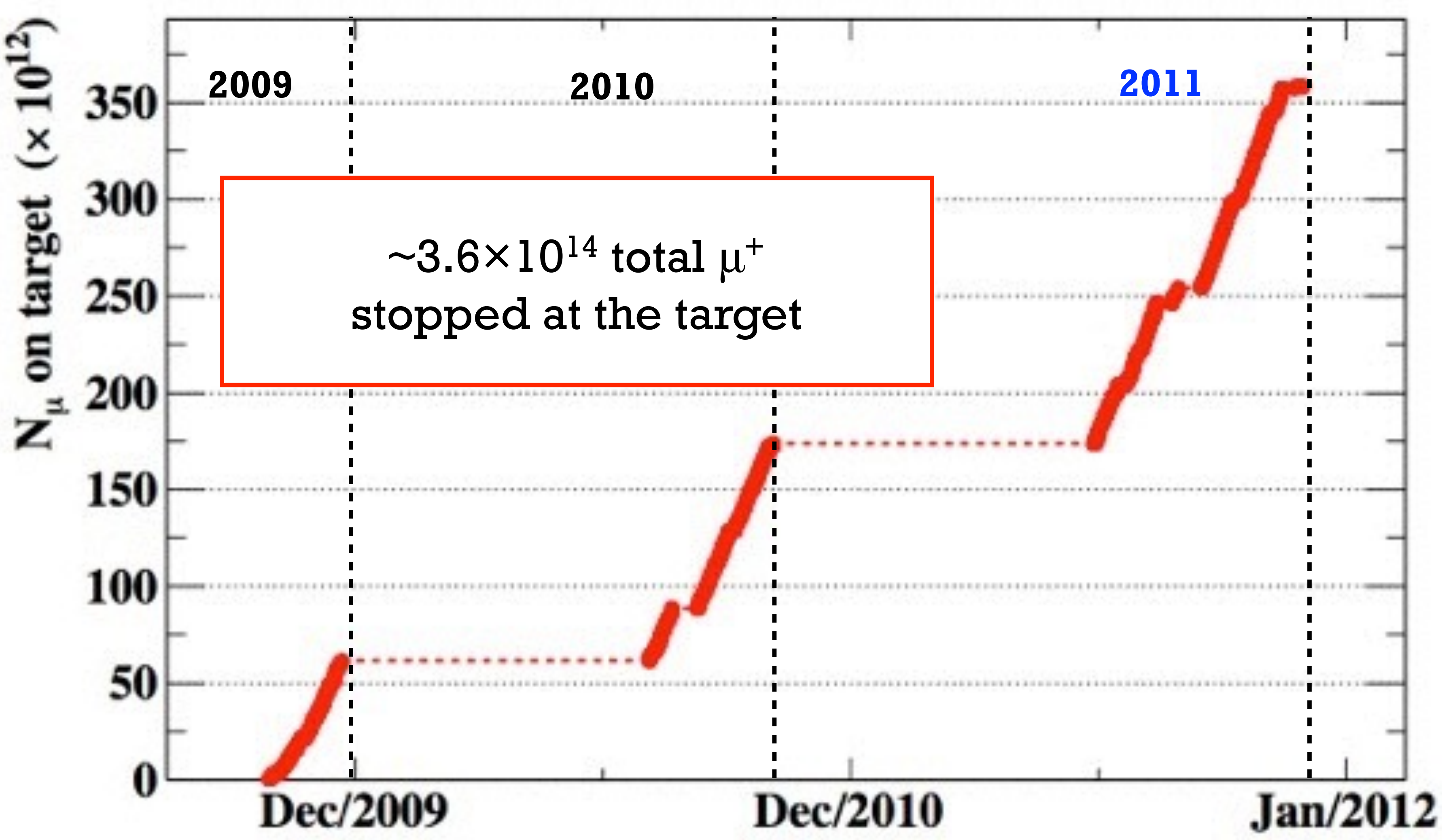






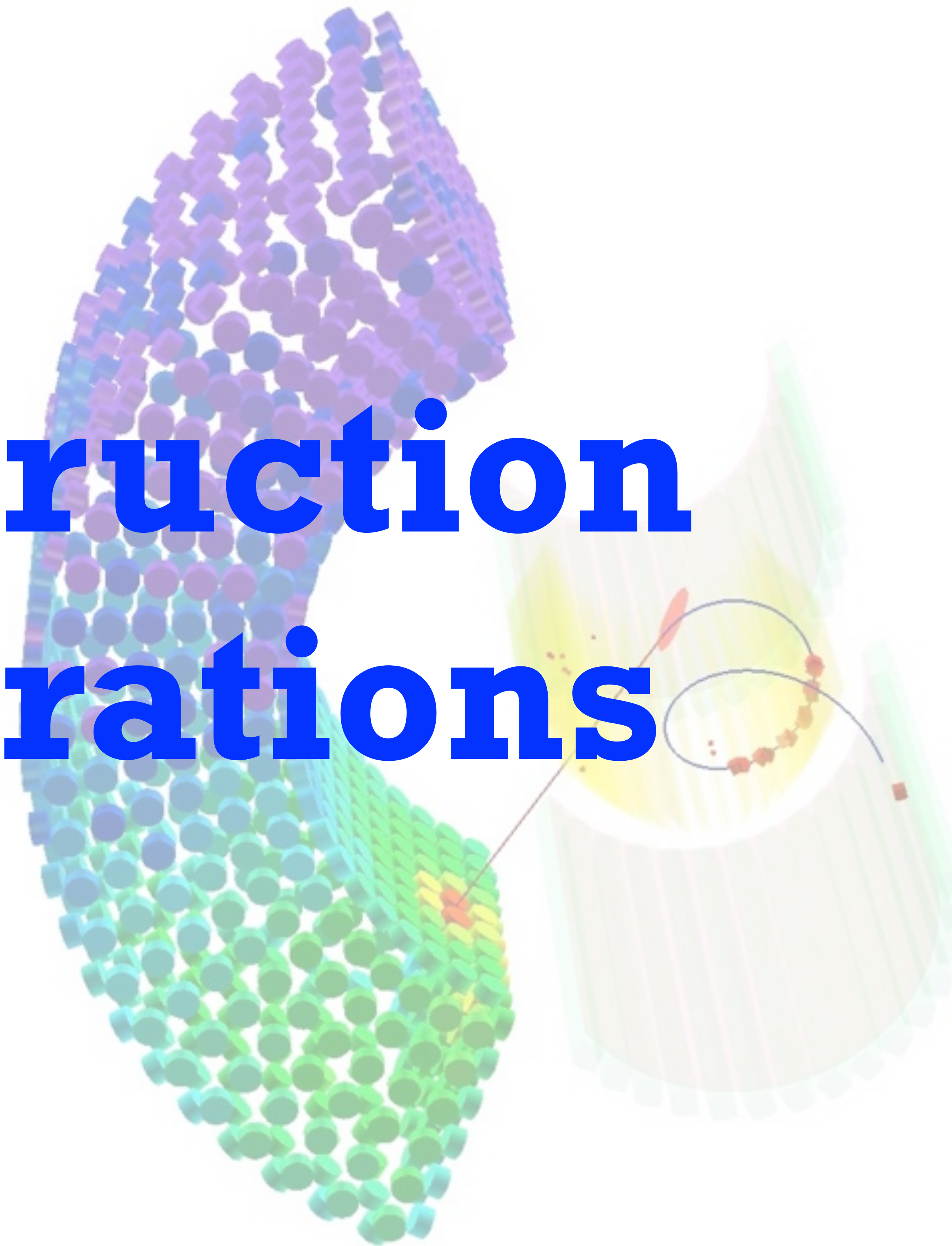
- **DRS4** (**D**omino **R**ing **S**ampler)
  - Kind of switched capacitor array specially developed in PSI
  - Enables to take the data from all detectors as waveforms
  - Adjustable sampling speed up to 5GHz, 1.6GHz for LXe, TC and 0.8GHz for DCH
- **Trigger**
  - Latency should be less than 700ns to trigger the data before DRS4 buffer becomes full
  - Need to suppress the DAQ rate less than 10Hz to read out the enough channels as waveforms
  - FPGA based trigger system is adopted
- **DAQ**
  - Based on the "MIDAS" developed in PSI and TRIUMF

Run Status

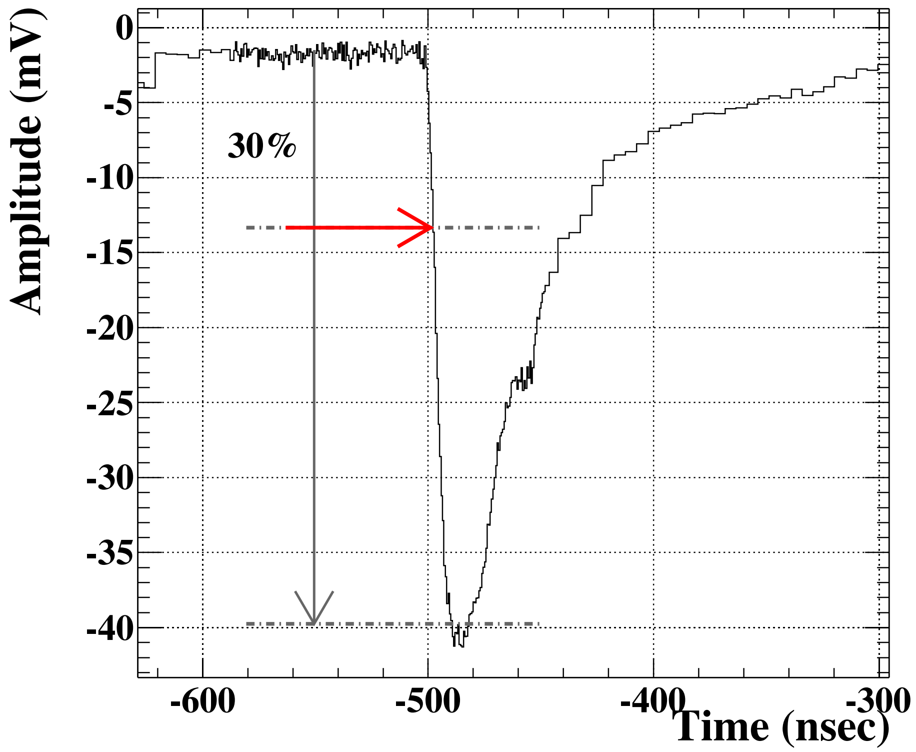


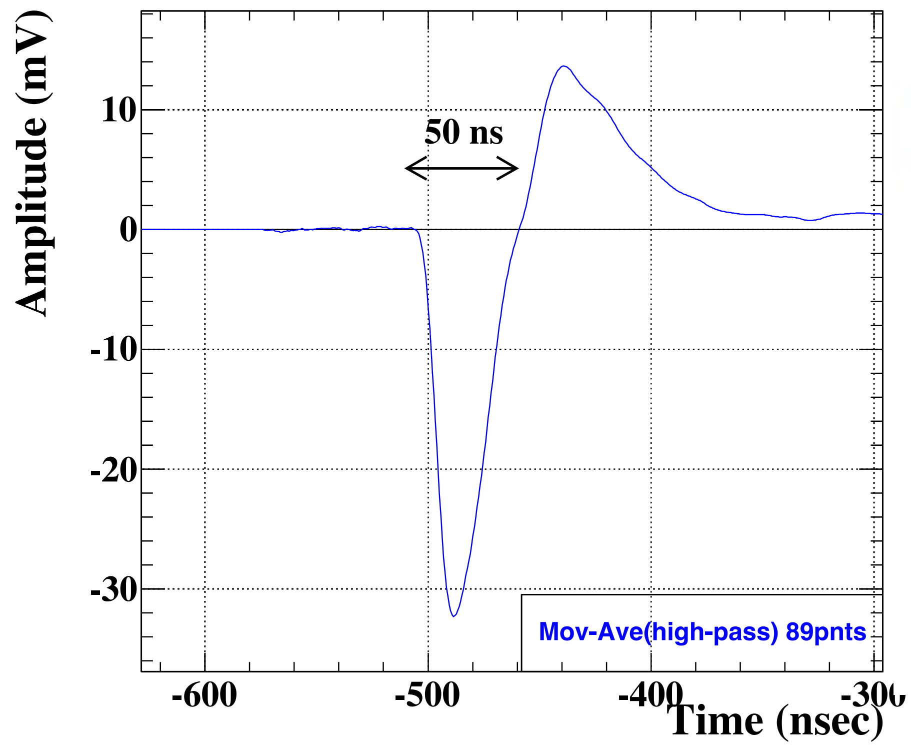
- **Statistics are almost doubled**
  - Improve the DAQ live time by introducing double-buffering method
  - Replace NaI to BGO crystals for CEX calibration
  - etc..
  - 2011 data taking: The longest and the most stable run period so far

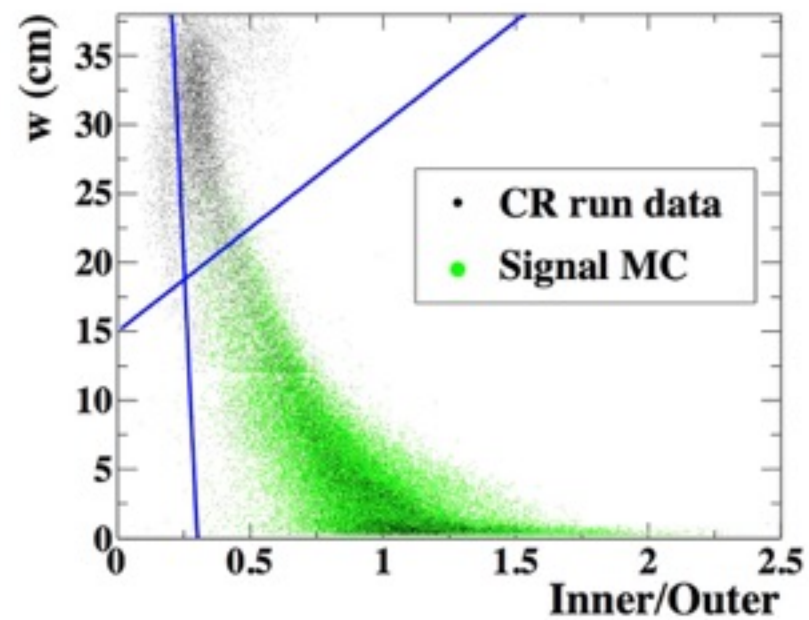
Reconstruction & Calibrations



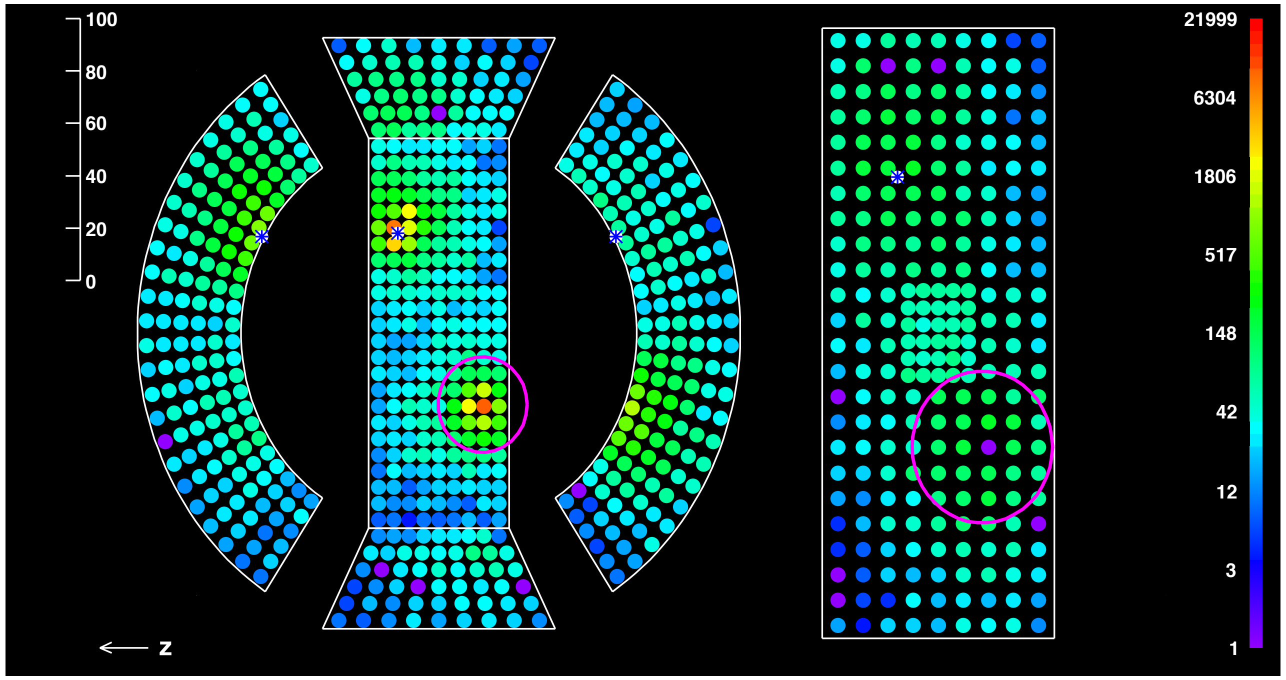
Gamma Reconstruction



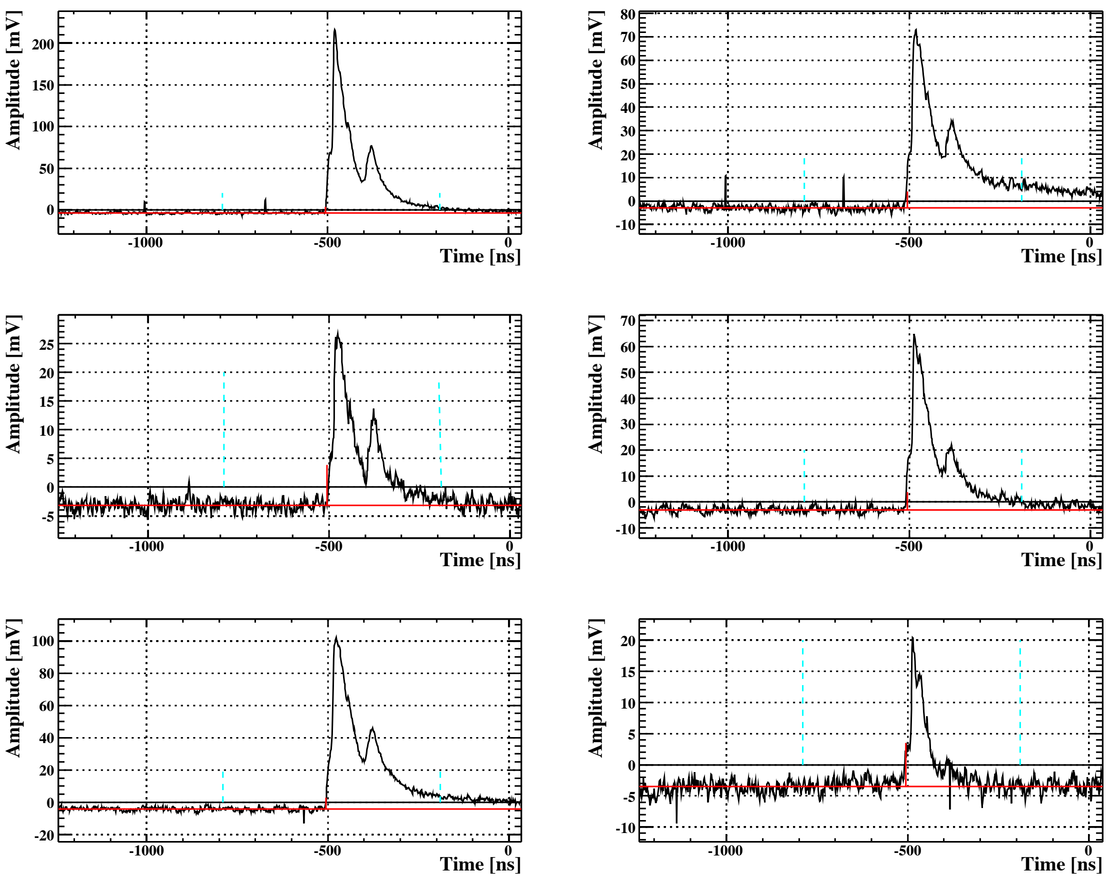




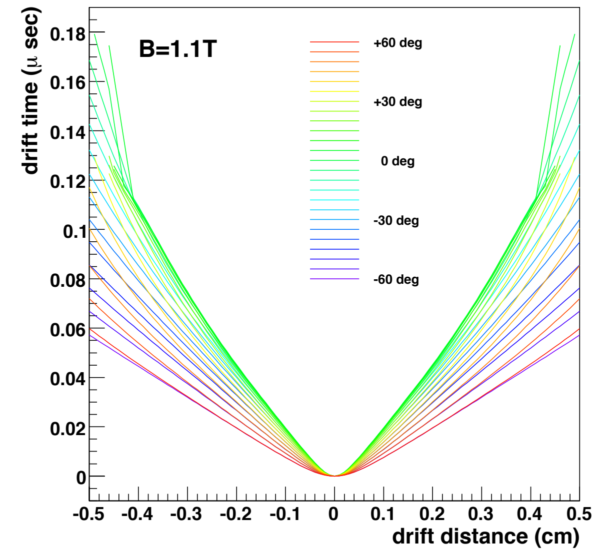
- E_γ, T_γ, γ position are reconstructed from all waveforms from LXe
    - Gain, Non-uniformity etc. are corrected
- Cosmic-rays are rejected topologically
- Pileup events are identified/rejected by searching the multi-peaks on the light yield distribution
- New waveform removal algorithm is implemented as well
    - Details will be described later



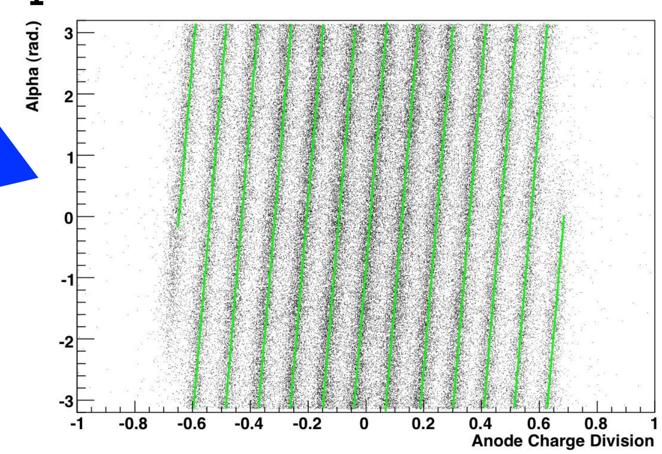
Positron Reconstruction



r pos recon. w/ drift time & TXY table

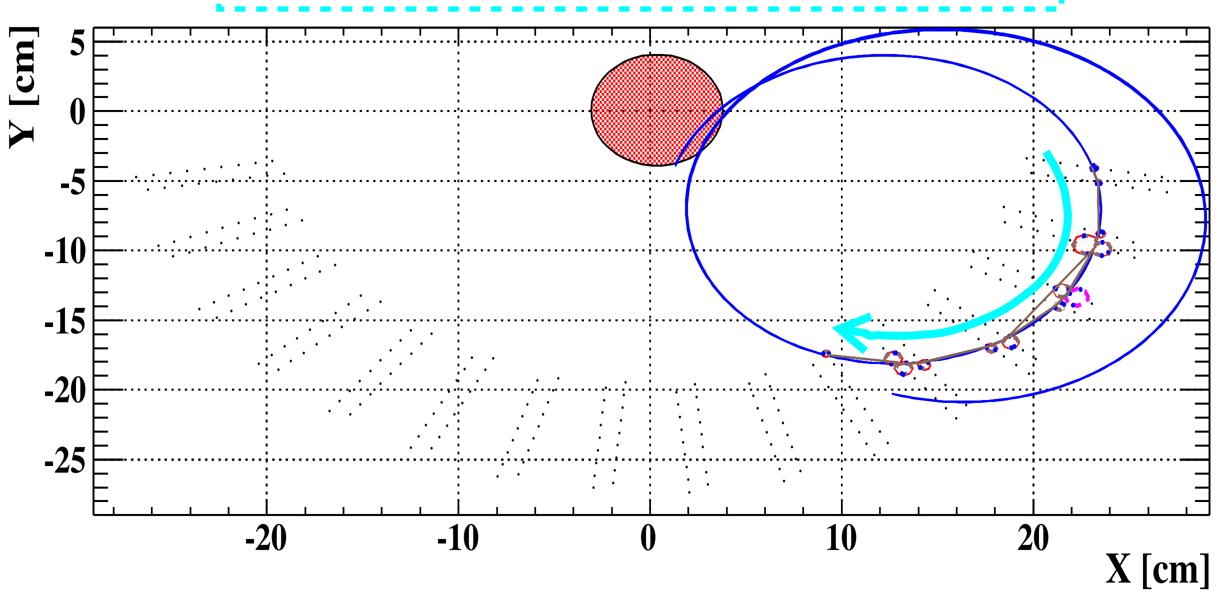


z pos recon. w/ **'vernier method'**

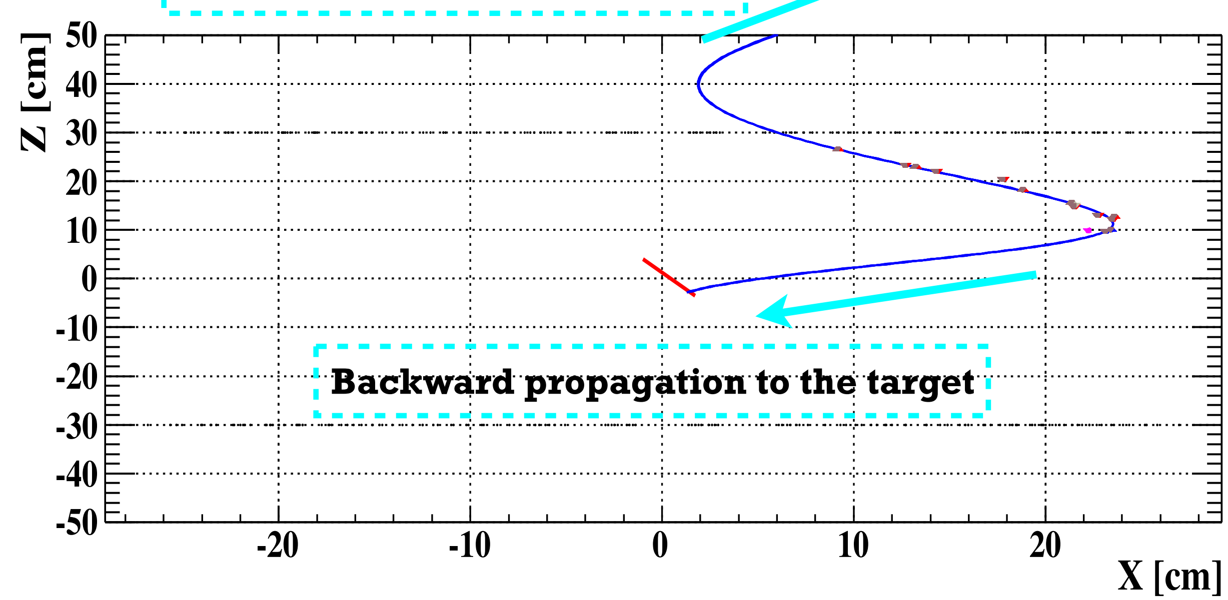


1. Hit reconstruction
   - Waveform analysis
2. Clustering
3. Track finding
   - Local pattern recognition
4. Track fitting
   - Kalman filter
5. DC-TC matching
   - Use TC Hit timing

Fitting by using the Kalman Filter technique



Forward propagation to the TC

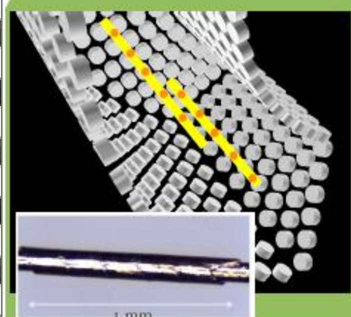


Backward propagation to the target

Calibration Methods

MEG Calibrations

Established



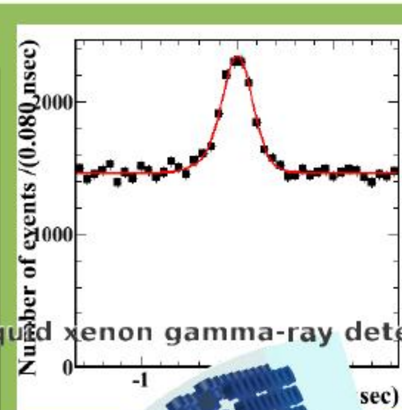
Am source on wire

LED

PMT Gain

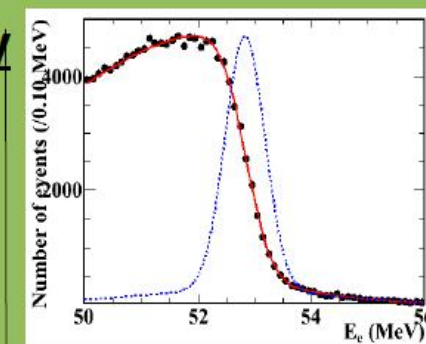
Alpha

PMT QE
Absorption



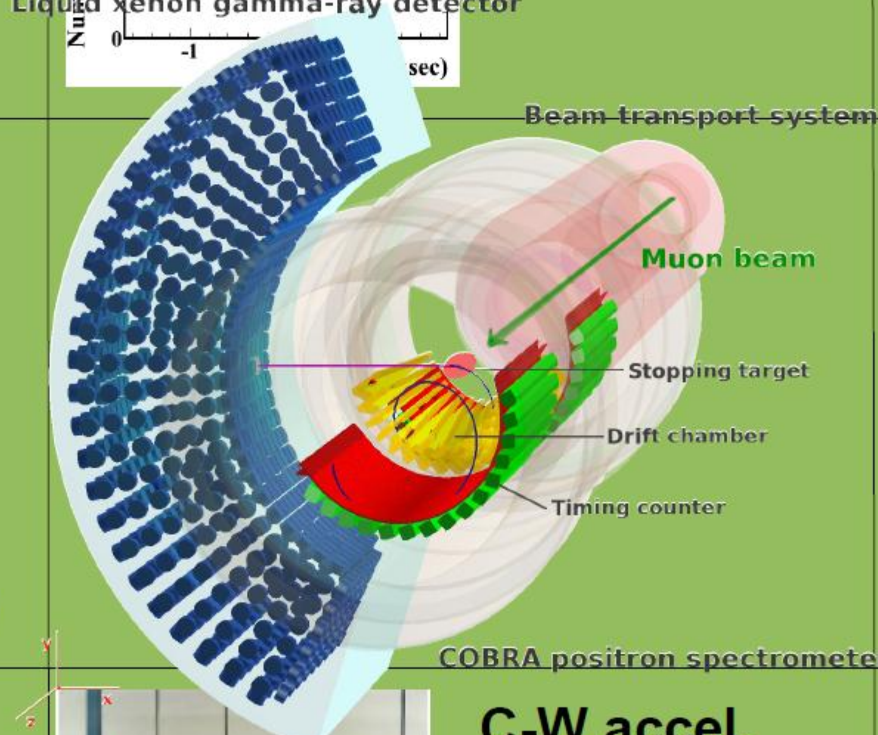
Radiative Decay

$\mu \to e\nu\nu\gamma$
Relative timing
Similar topology

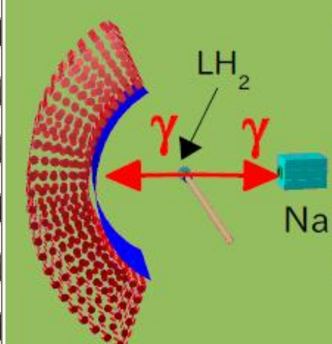


Michel Decay

$\mu \to e\nu\nu$



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

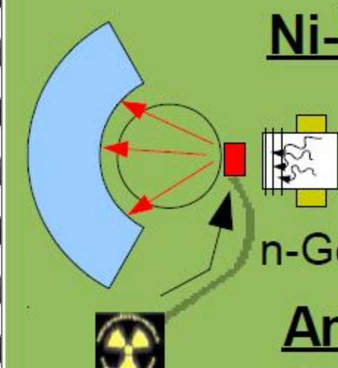


$\pi^0 \to \gamma\gamma$
55,83,129MeV
monochoro

$\pi^0 \to \gamma e^+ e^-$
Relative timing
Similar topology

e^+ Mott-scatter

Monochro, tunable momentum



Ni-n

9MeV γ source

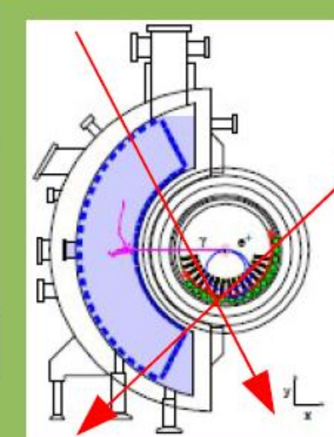
n-Generator

AmBe

AmBe source 4.4MeV γ source

C-W accel.

Li(p,γ)Be
– 18MeV γ
B(p,γ)C
– 4,11MeV 2γ



CosmicRay

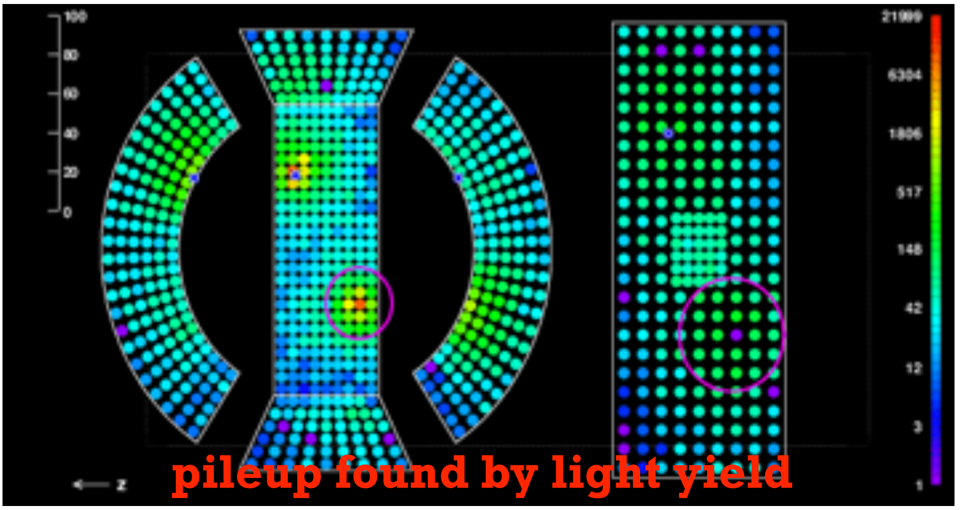
DC alignment

TC uniformity

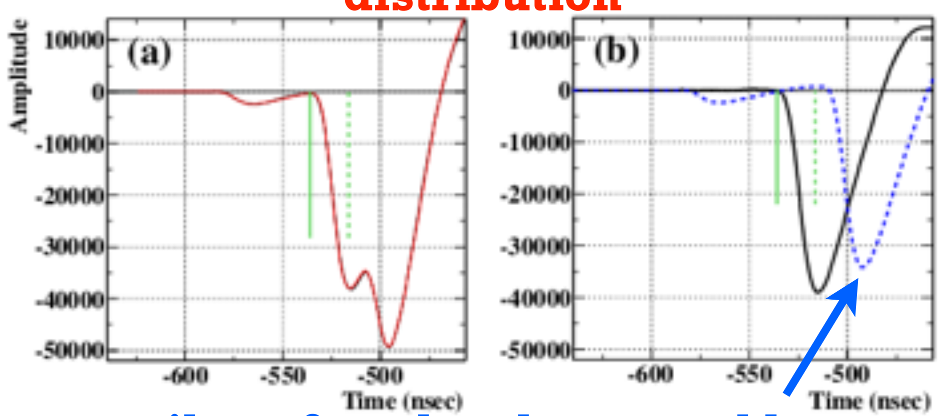
LXe monitor

JPS 2011 Autumn, 16/Sep/2011 Yusuke UCHIYAMA, the University of Tokyo 20

Reconstruction Updates

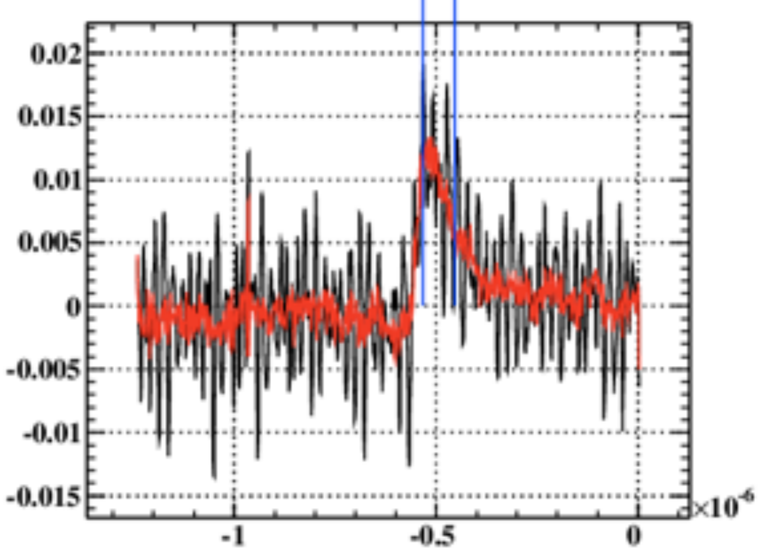


pileup found by light yield distribution

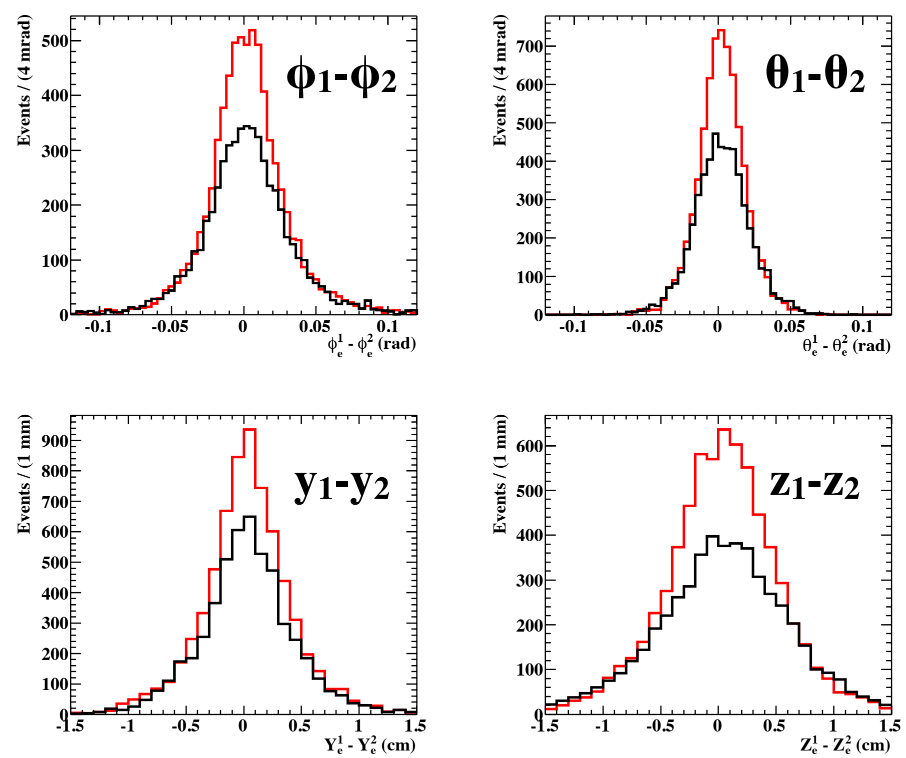


pileup found and removed by waveform analysis

- **Gamma pileup removal using waveforms**
  - 7% improvement in efficiency
- **Drift chamber offline noise reduction**
  - 6% efficiency recovery, resolutions improved as well
- **Revisited the track fitting method**
  - 6% efficiency improvement, reduce the momentum tail
  - Enable to use the event-by-event uncertainties for physics analysis

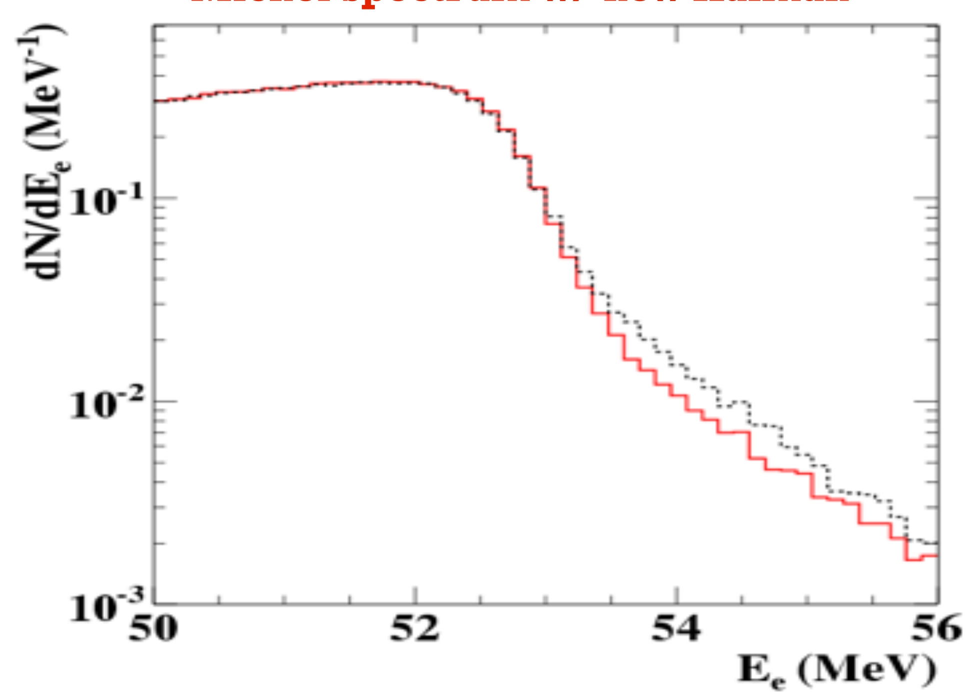


DCH waveform in noisy period



- Michel spectrum w/ old Kalman

- Michel spectrum w/ new Kalman



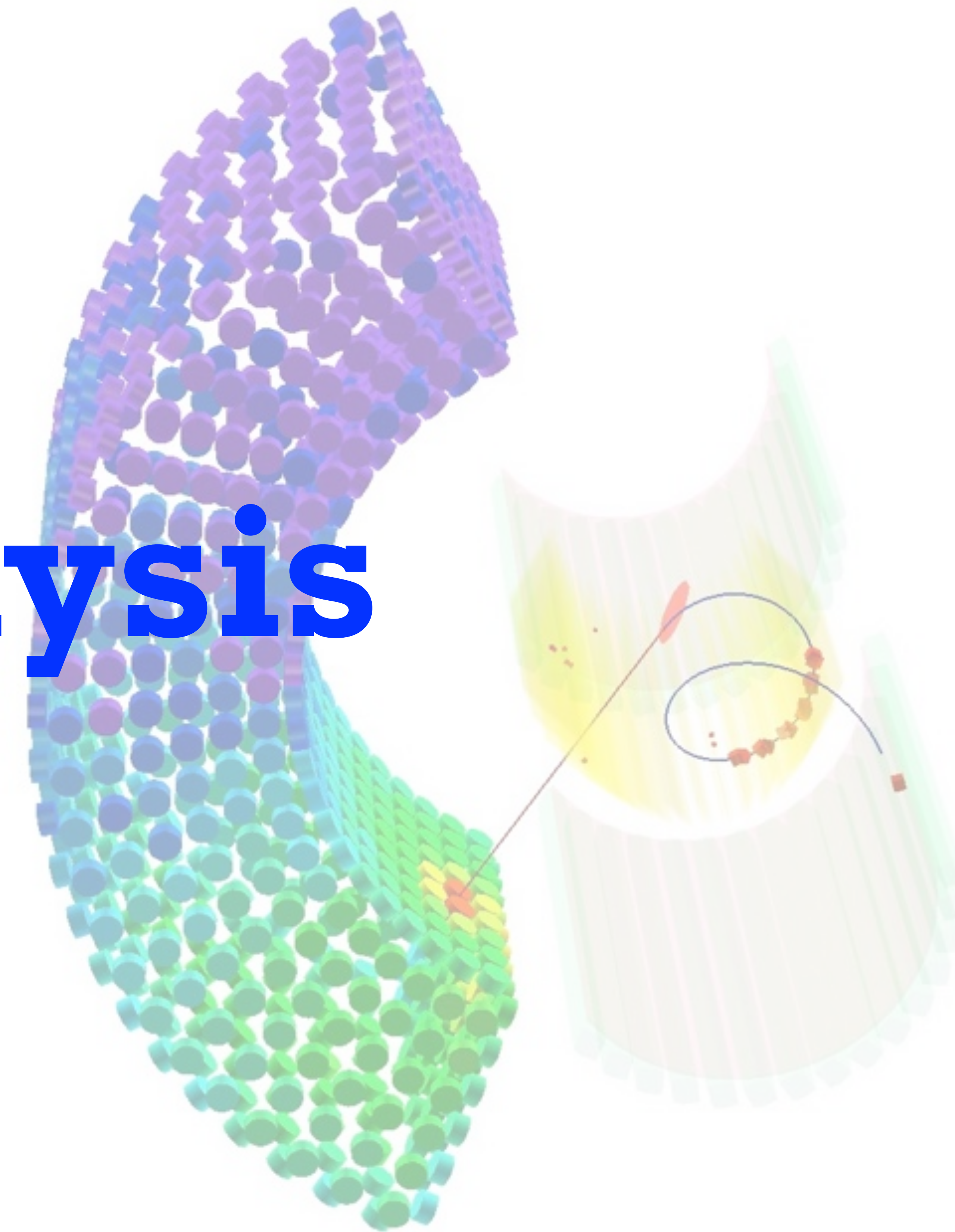
Performance Summary

Observables in Physics Analysis

Table 5.7: Performance summary.

Variable	2009	2010	2011
Gamma Resolutions			
E_γ (%)	1.9 ($w > 2$ cm), 2.4 ($w < 2$ cm)	1.9 ($w > 2$ cm), 2.4 ($w < 2$ cm)	1.7 ($w > 2$ cm), 2.4 ($w < 2$ cm)
u_γ,v_γ (mm)	5	5	5
w_γ (mm)	6	6	6
t_γ (ps)	96	67	67
Positron Resolutions			
E_{e} (MeV)	0.31	0.32	0.31
ϕ_{e} (mrad)	6.6	7.2	7.5
θ_{e} (mrad)	9.4	11.0	10.6
y_{e} (mm)	1.1 (core)	1.1 (core)	1.2 (core)
z_{e} (mm)	1.1	1.7	1.9
t_{e} (ps)	107	107	107
Combined Resolutions			
$\phi_{\mathrm{e}\gamma}$ (mrad)	8.9	9.0	8.9
$\theta_{\mathrm{e}\gamma}$ (mrad)	15.0	16.1	16.2
$t_{\mathrm{e}\gamma}$ (ps)	156	123	127
Efficiency			
ϵ_γ (%)	63	63	63
ϵ_{e} (%)	28	35	31
ϵ_{trg} (%)	91	92	97

*All resolutions are defined as σ



Analysis

Likelihood Analysis

- Maximum Likelihood Fitting is used to determine the values of N_{sig}, N_{RMD} and N_{BG}
- Parameters of PDFs are mostly determined by looking the data in sidebands
- Full frequentist approach to calculate the upper limit

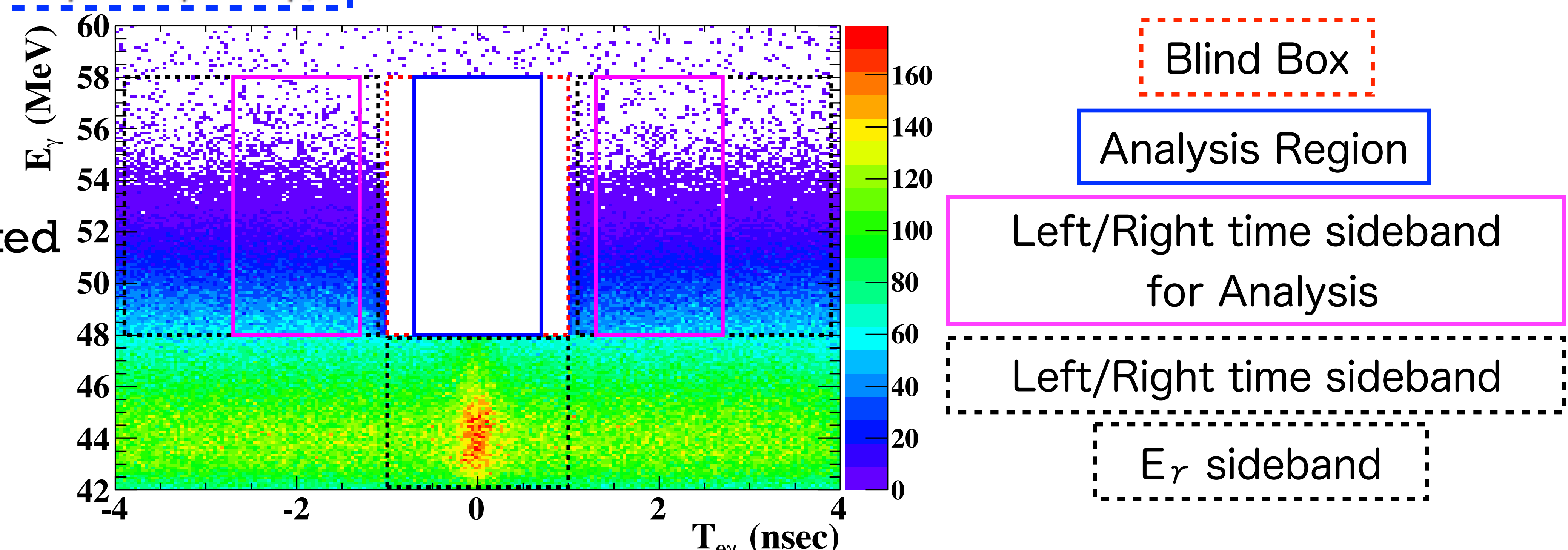
$$\mathcal{L}(N_{\mathrm{sig}}, N_{\mathrm{RMD}}, N_{\mathrm{BG}}) = \frac{e^{-N}}{N_{\mathrm{obs}}!} e^{-\frac{(N_{\mathrm{RMD}}-\langle N_{\mathrm{RMD}}\rangle)^2}{2\sigma_{\mathrm{RMD}}^2}} e^{-\frac{(N_{\mathrm{BG}}-\langle N_{\mathrm{BG}}\rangle)^2}{2\sigma_{\mathrm{BG}}^2}} \times \prod_{i=1}^{N_{\mathrm{obs}}} \left(N_{\mathrm{sig}} S(\overrightarrow{x_i}) + N_{\mathrm{RMD}} R(\overrightarrow{x_i}) + N_{\mathrm{BG}} B(\overrightarrow{x_i})\right) \qquad (6.1)$$

# of backgrounds are constrained from the observation in sidebands

Signal PDF **RMD PDF** **Accidental(BG) PDF**

$$\overrightarrow{x_i} = (E_\gamma, E_e, t_{e\gamma}, \phi_{e\gamma}, \theta_{e\gamma})_i$$

Blind analysis:
Signal region is masked until every PDF parameters are fixed



Per-Event PDF (1/2)

Resolutions :

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

Fully event-by-event, scaling factor determined by using sideband data

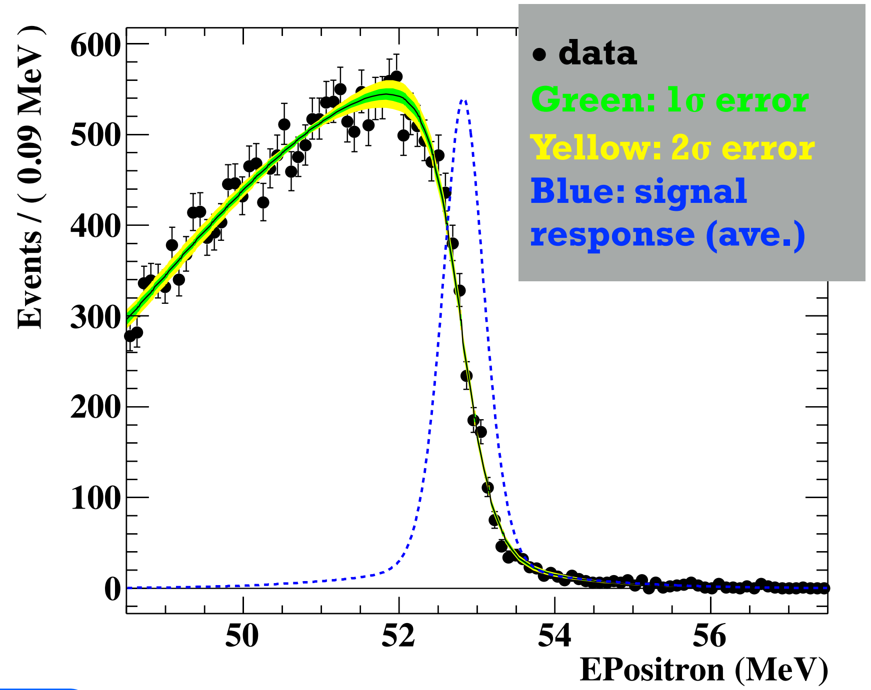
Correlations :

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

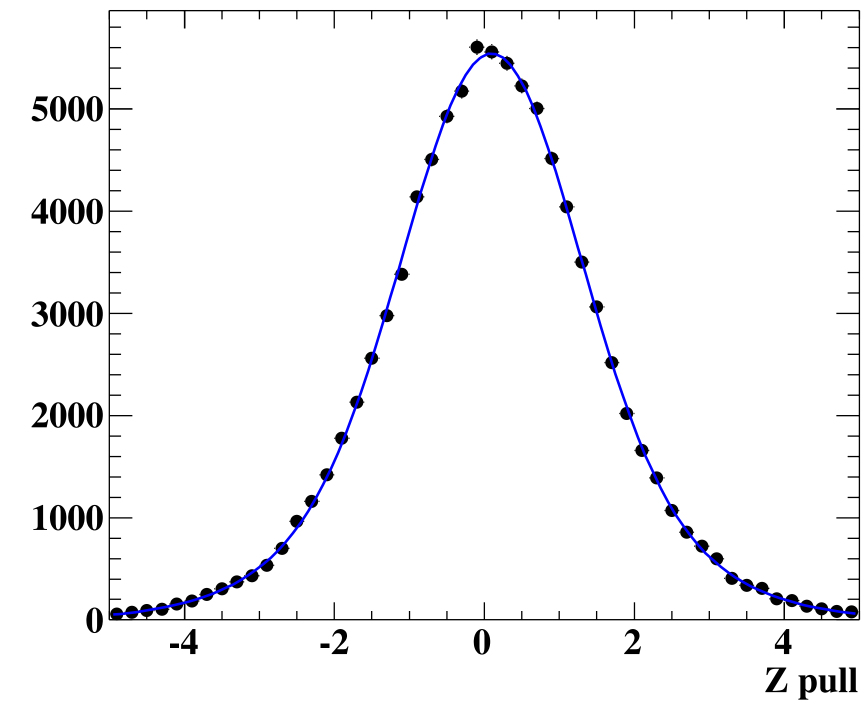
$$p_{xy} = p'_{xy} \times \frac{\sigma'_y}{\sigma'_x}$$

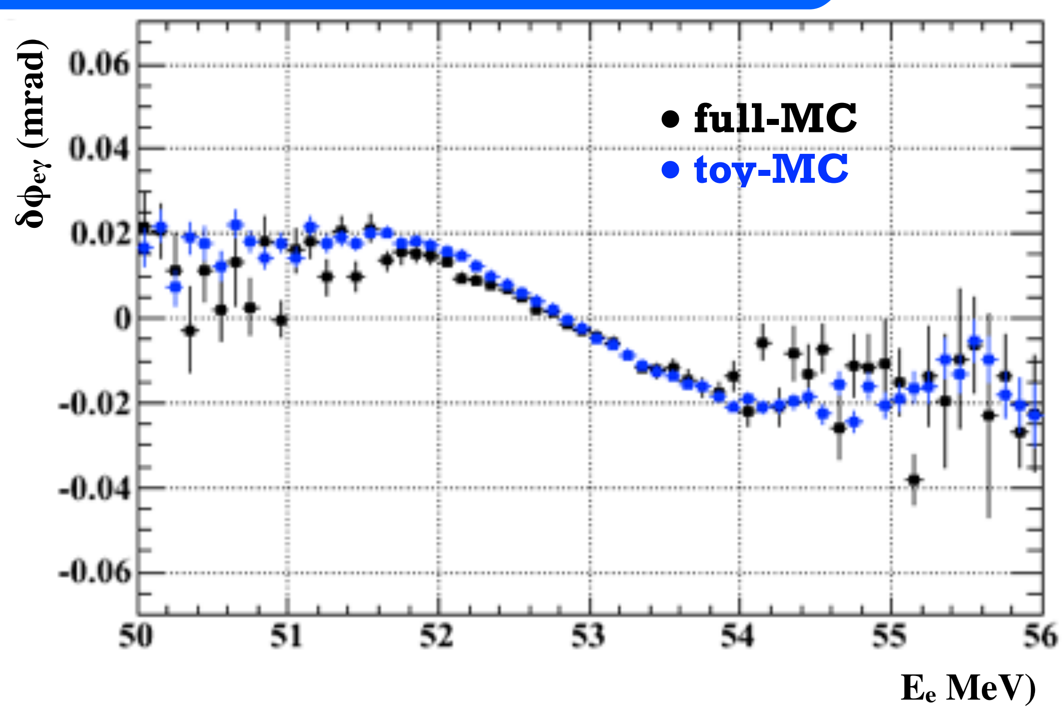
correlations are also event-by-event, evaluated by using MC and two-turn events

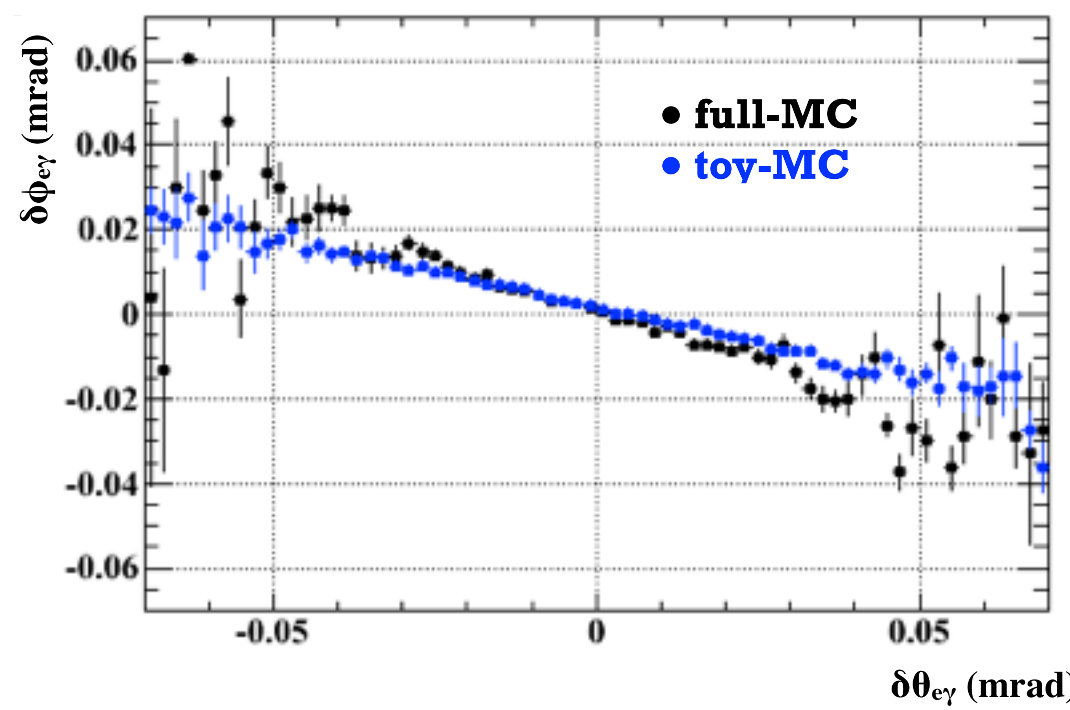
Michel Edge



Two-turn events





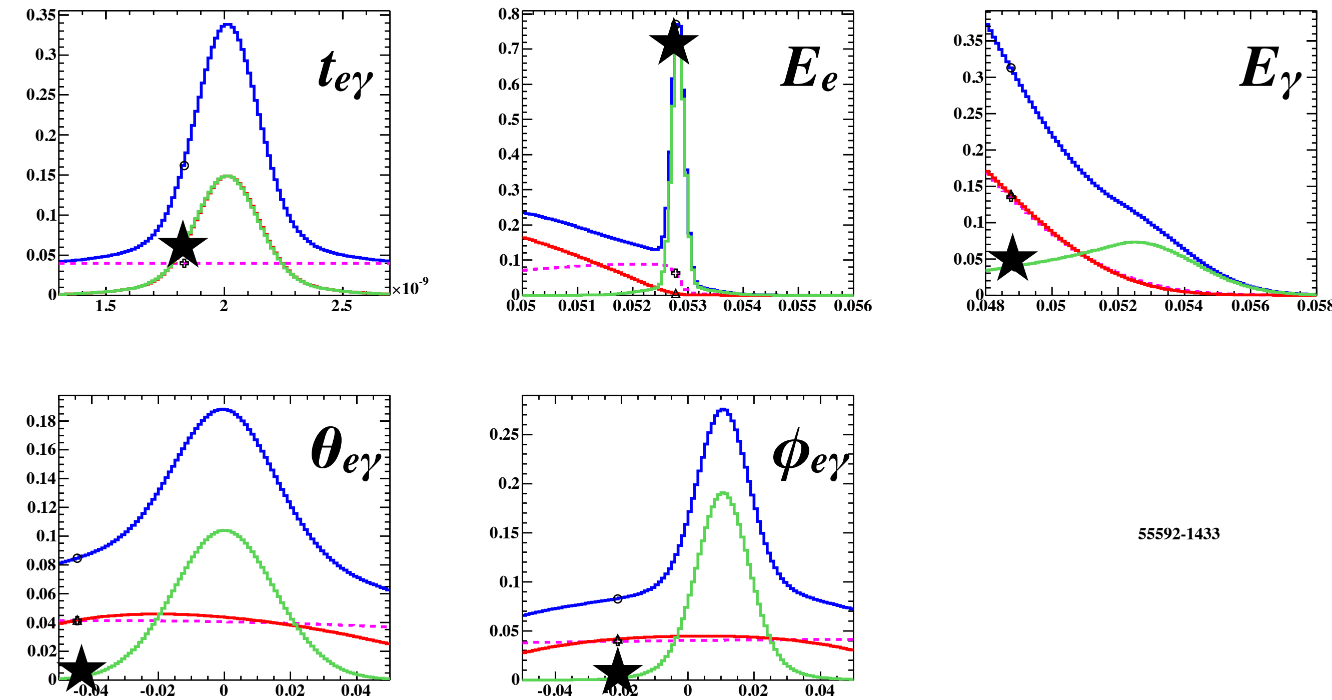


Per-Event PDF (2/2)

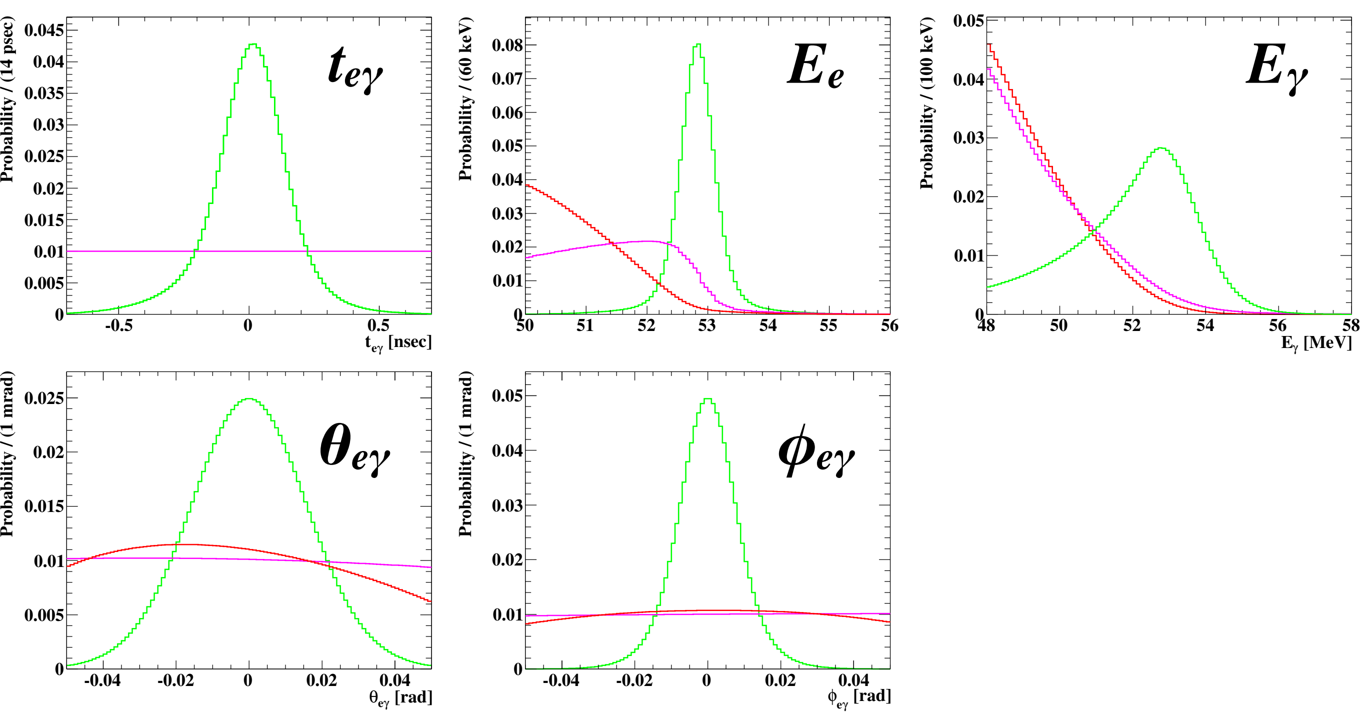
Event-by-event PDFs of typical 2 events in $t_{e\gamma}$ sideband
→ Per-event PDF gives **~10% better sensitivity** by taking into account the event-by-event difference of uncertainties in the likelihood fitting

Green: Signal PDF
Magenta: BG PDF
Red: RMD PDF
Blue: Total
★: Data

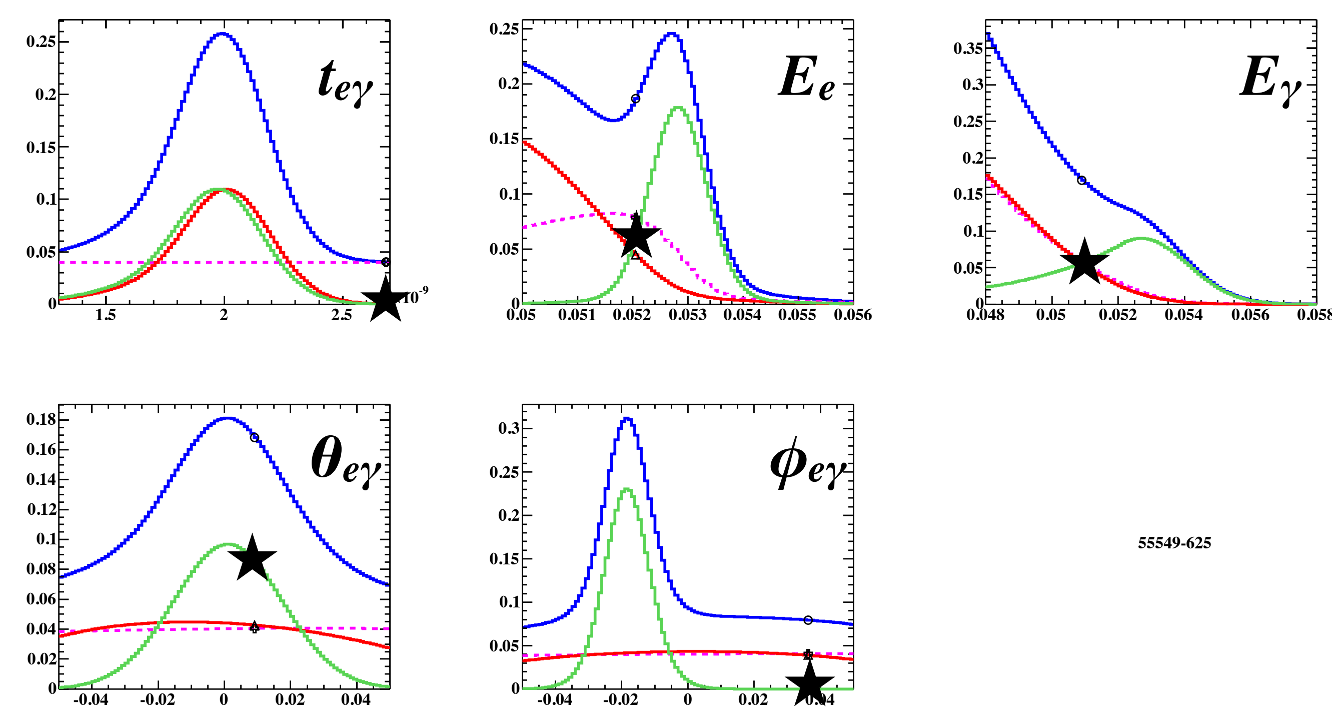
High quality track



Average PDF in 2009-2011 dataset

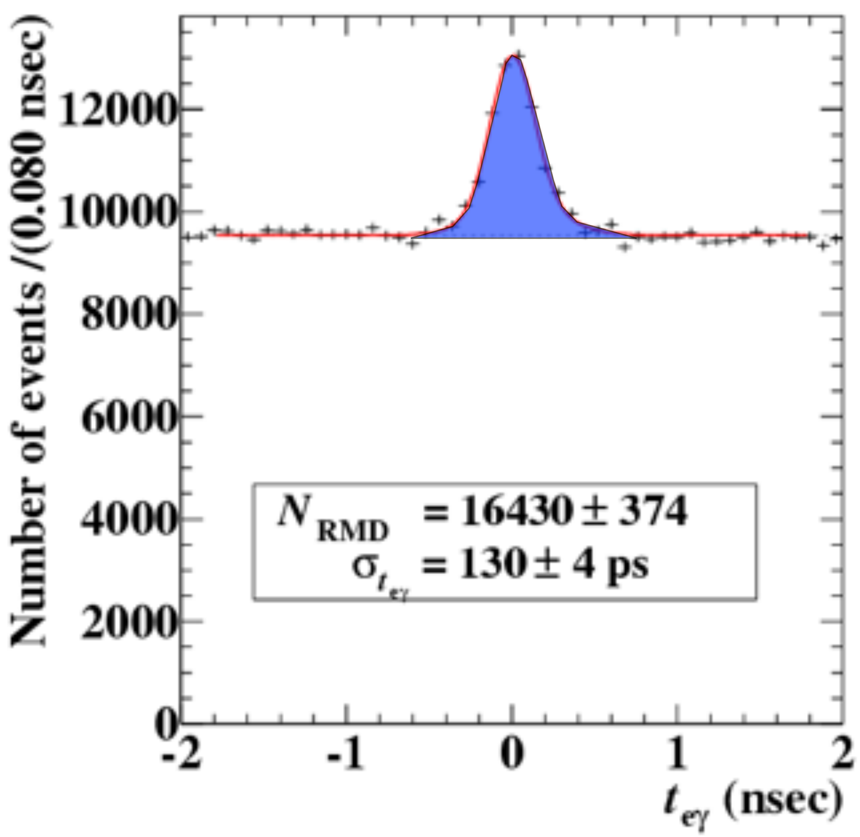


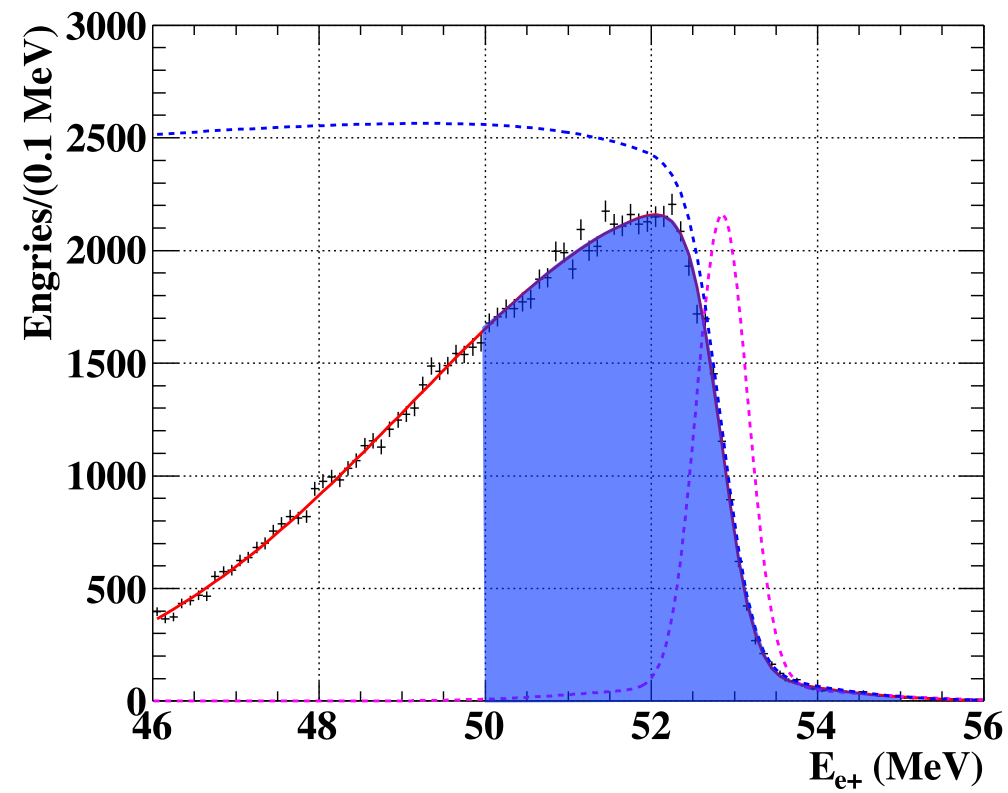
Low quality track



Normalization

- Normalization factor is defined as: **k = 1/(S.E.S.)** → **B(μ→eγ) = N_{sig}/k**
- The value is calculated by independent two methods
  - #of Michel positron using "Michel trigger" data taken w/o requiring γ-rays in LXe
  - # of RMD using MEG trigger
- Results of above 2 methods are combined to reduce the uncertainties

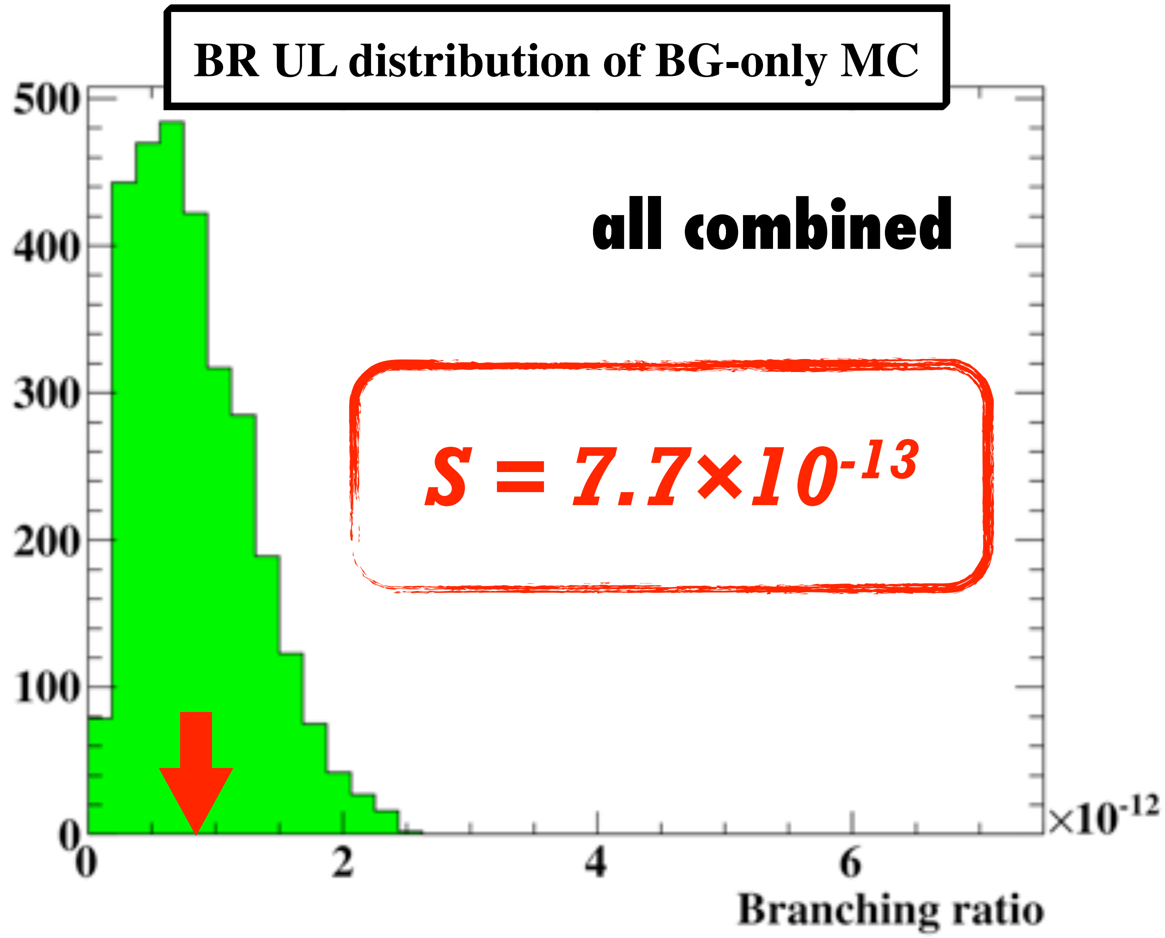


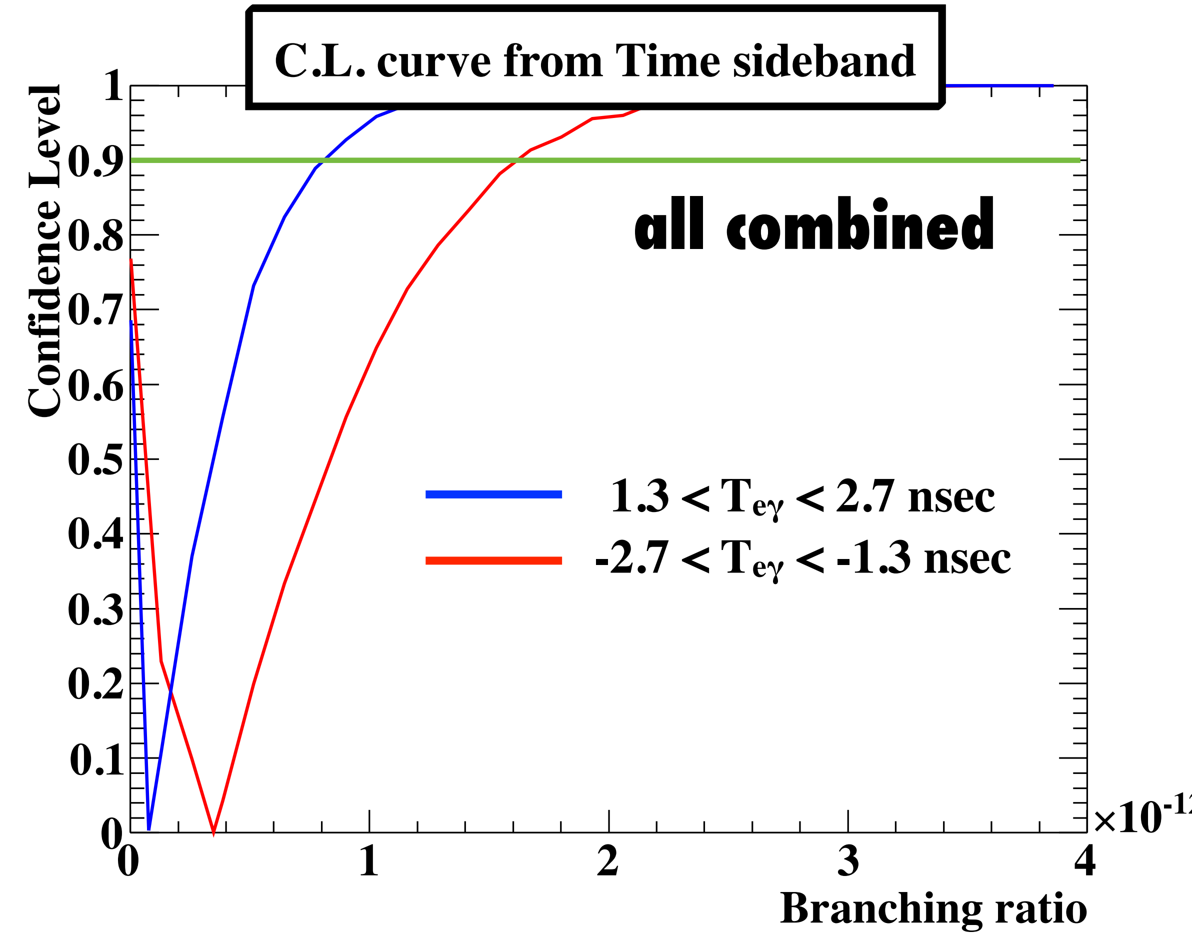


$$k^{2009+2010}_{\text{combined}} = (3.72 \pm 0.15) \times 10^{12}, \quad (6.37)$$

$$k^{2009+2010+2011}_{\text{combined}} = (7.77 \pm 0.31) \times 10^{12}. \quad (6.38)$$

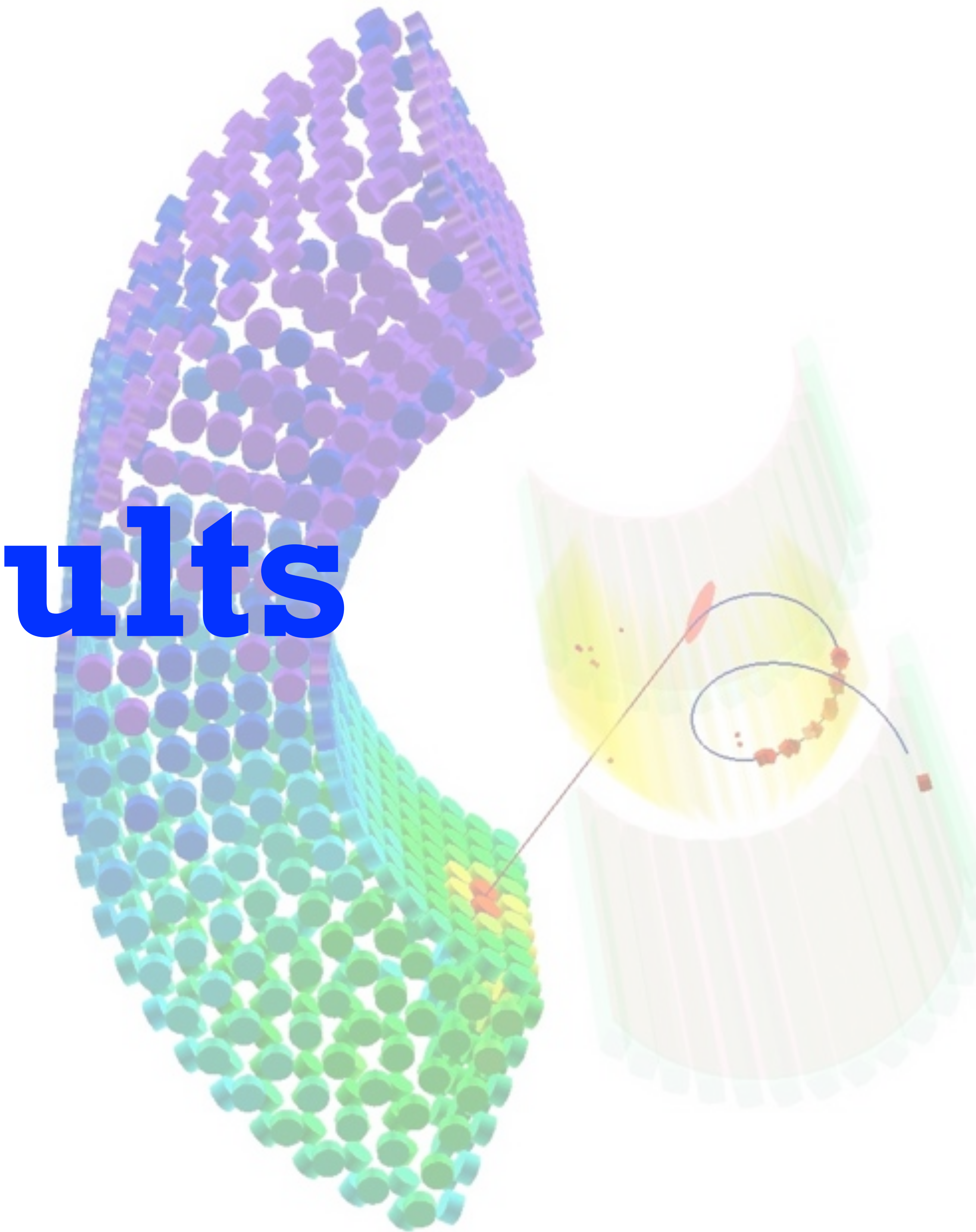
Sensitivity



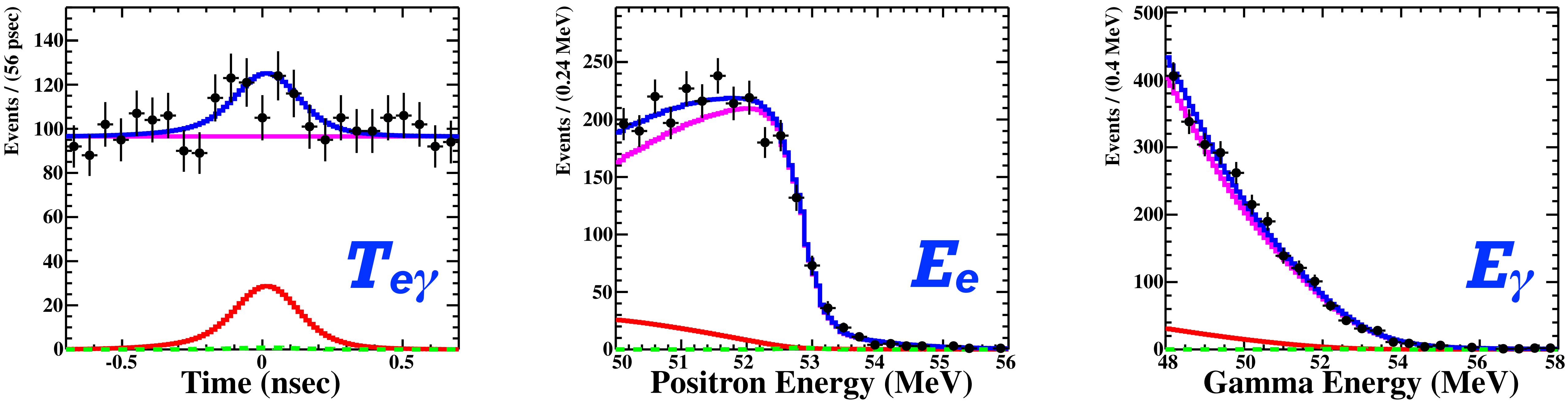


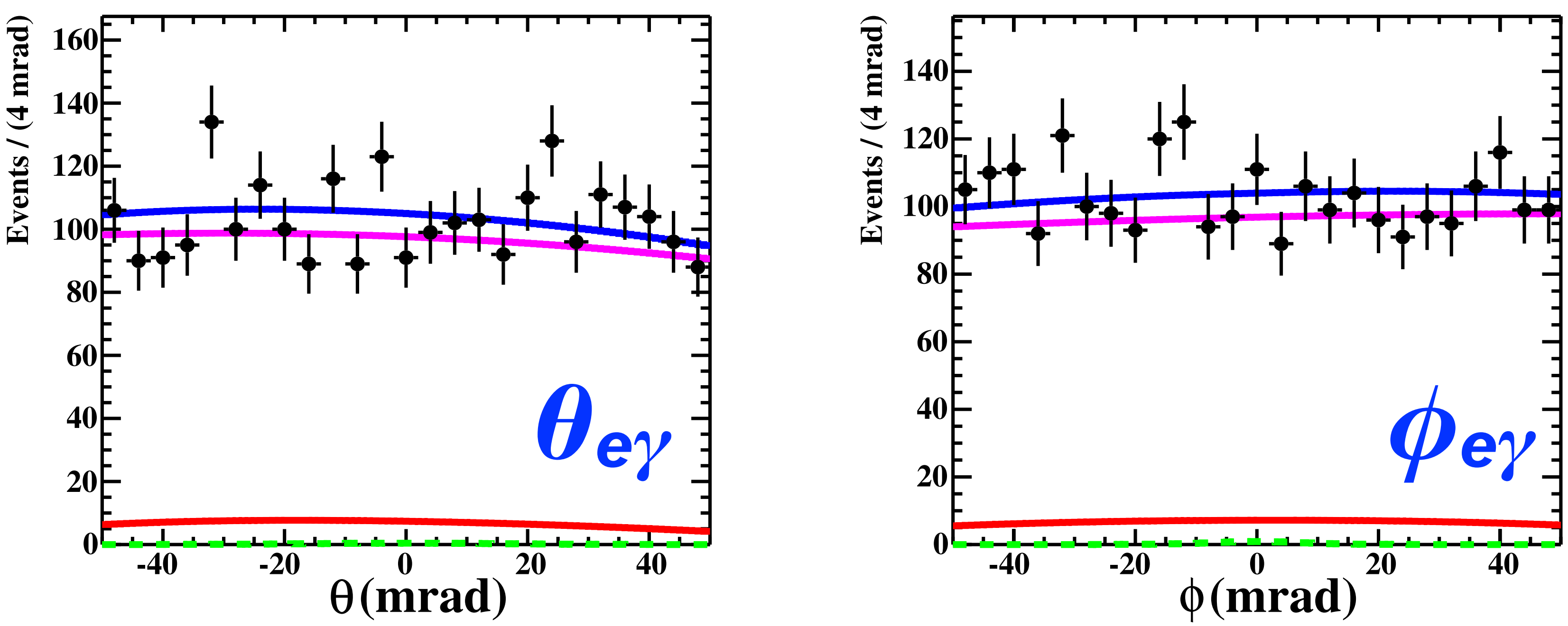
- Sensitivity ≡ Median of the 90% C.L. upper limits determined by generating the sizable toy-MC experiments with a NULL signal hypothesis
- Statistics, several reconstruction and analysis improvements give **twice better sensitivity** than before
    - **The first search of $\mu \to e\gamma$ down to 10^{-13} order of magnitude**
- All sidebands show the consistent results

Results



Likelihood Fit





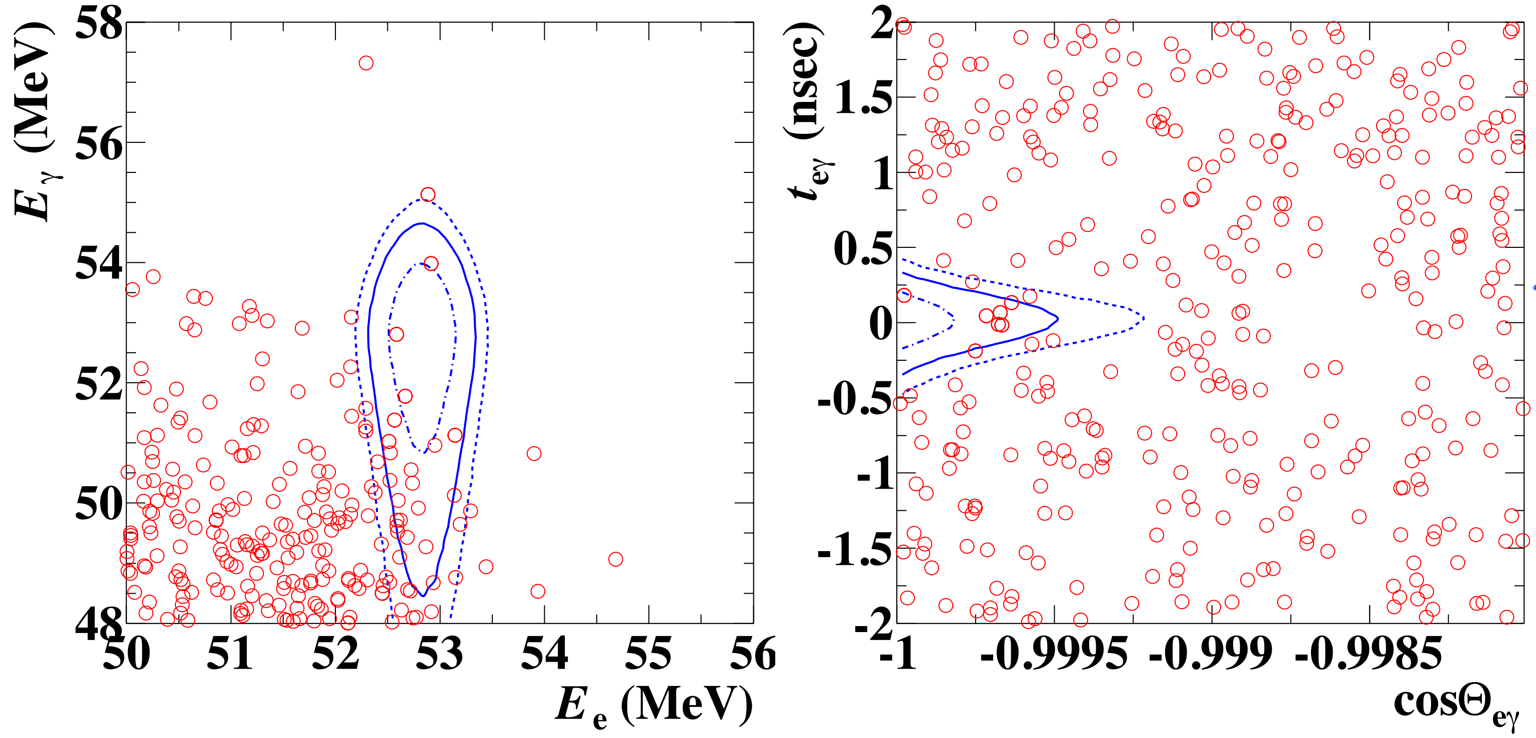
Blue: All
Magenta: Accidental
Red: RMD
Green: Signal

	Expected	Best Fit
N_{BG}	2415.0±25.0	$2413.6^{+37.1}_{-37.0}$
N_{RMD}	169.3±17.0	$167.5^{+24.2}_{-24.0}$
N_{signal}	-	$-0.4^{+4.8}_{-1.9}$

- No signal excess is found

Upper Limit

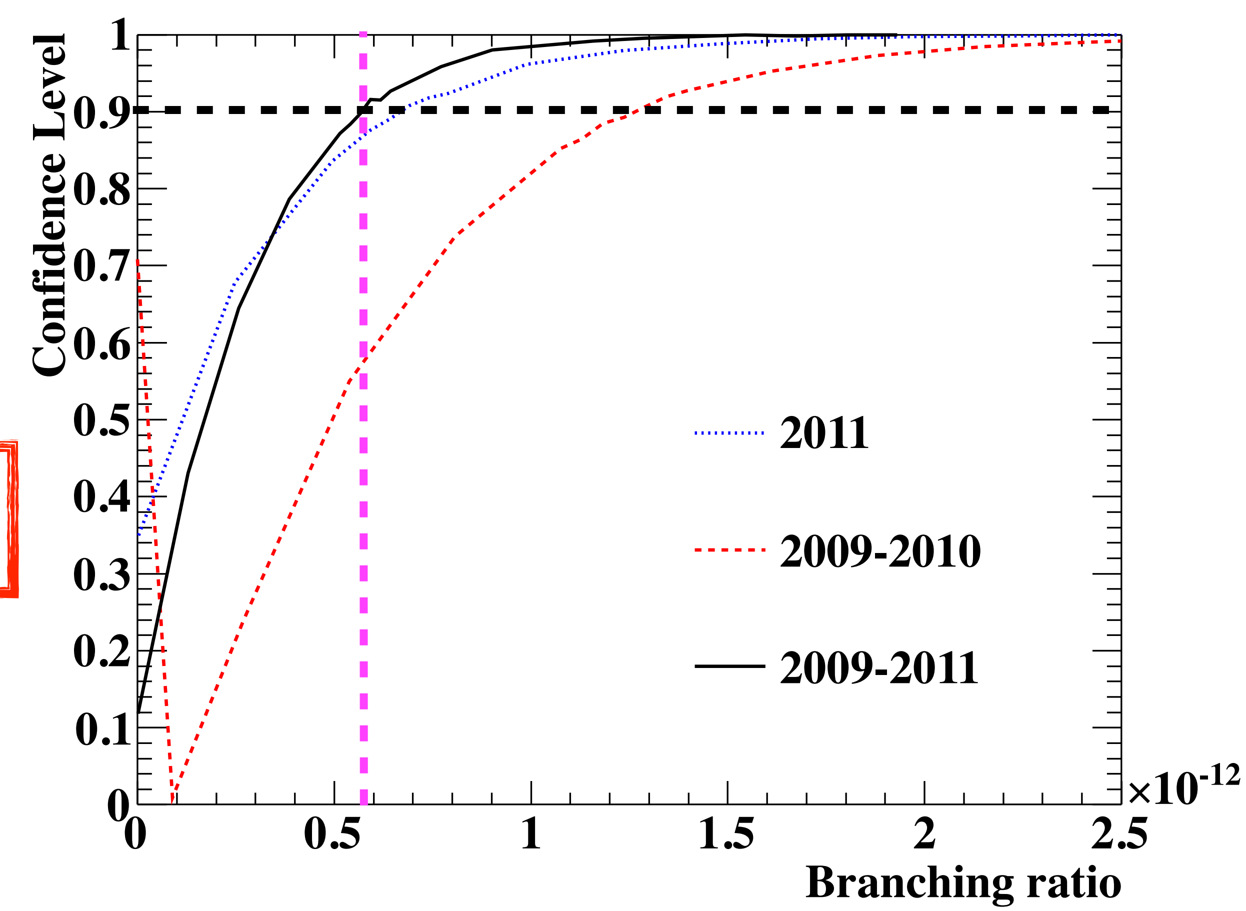
$|T_{e\gamma}| < 244.3$ psec, $\pi - \Theta_{e\gamma} < 27.3$ mrad	$51 < E_\gamma < 55.5$ MeV, $52.385 < E_e < 55$ MeV



2D event distribution w/ cuts
- data with 90% cut
- signal PDF

No signal excess is observed = consistent w/ BG only hypothesis

confidence level curve

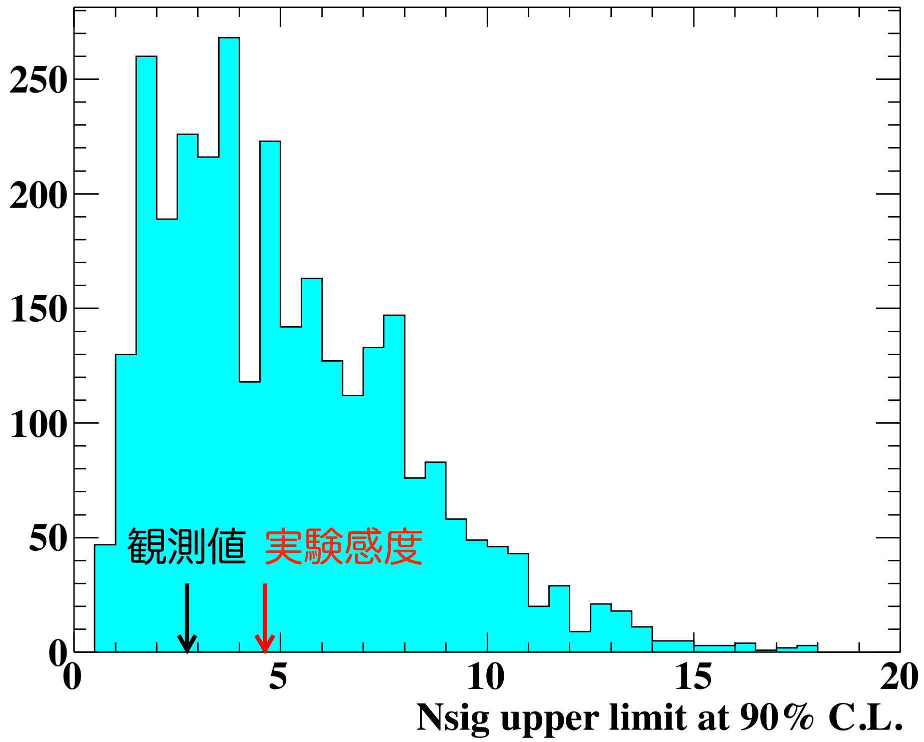


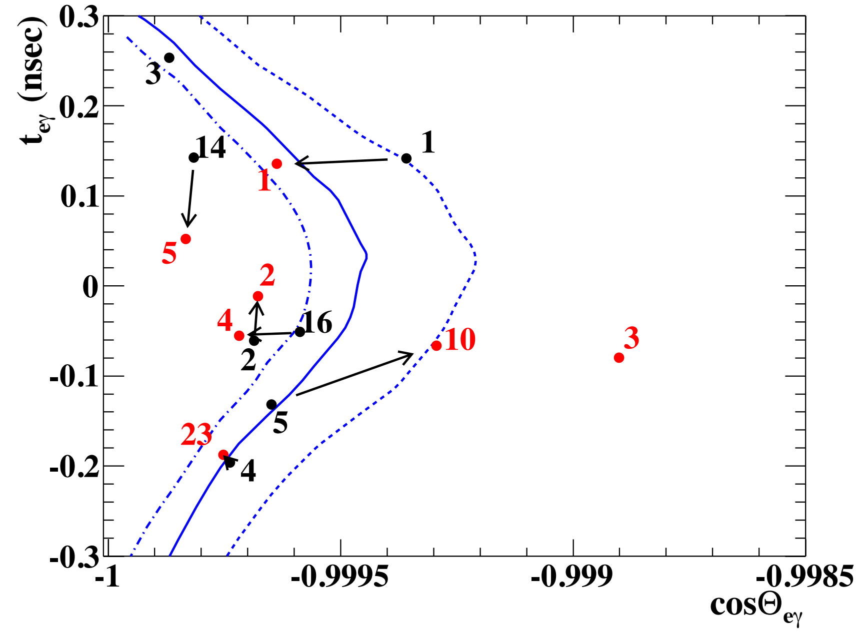
90% C.L. upper limit is calculated based on Feldman-Cousins' full-frequentist approach for 2009-2011 combined dataset:

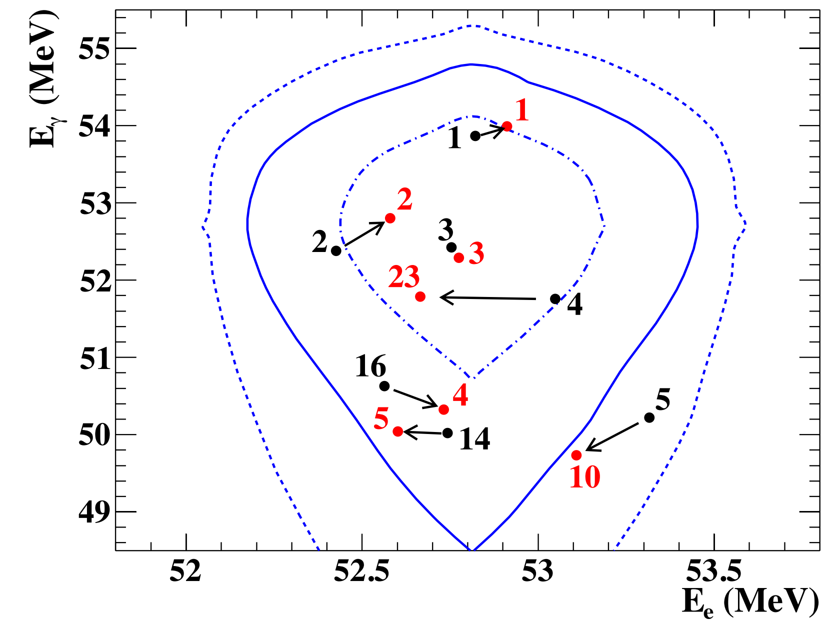
$$\mathcal{B}(\mu^+ \to e^+\gamma) < 5.7\times10^{-13} \text{ @ 90\% C.L.}$$

Details in J. Adam *et al.,* Phys. Rev. Lett. **110** 201801 (2013),
More details in my PhD thesis

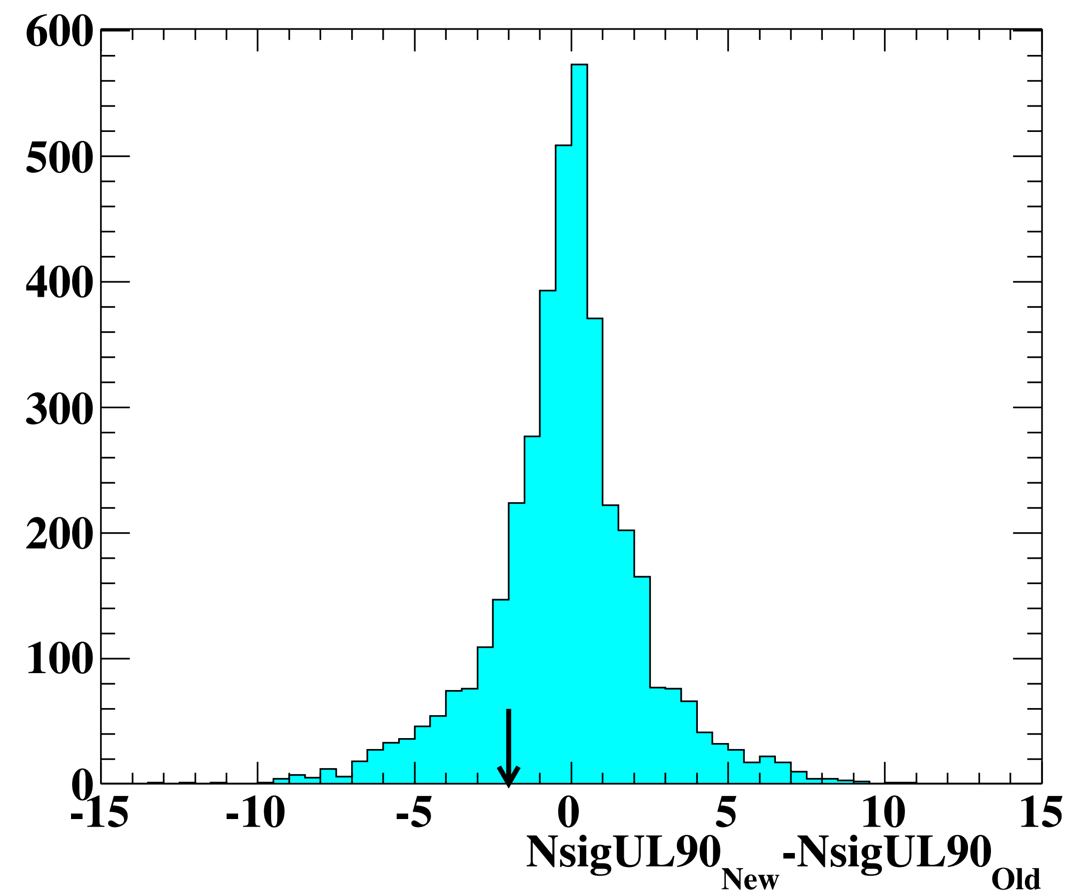
Consistency Checks





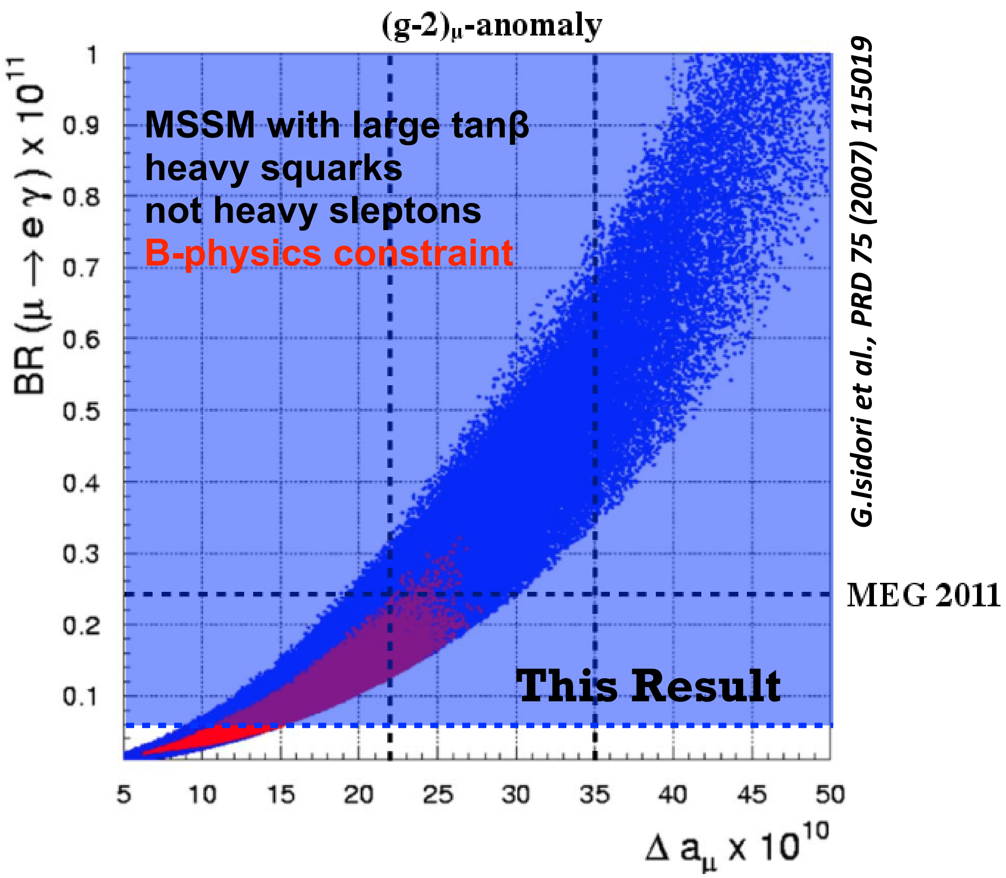


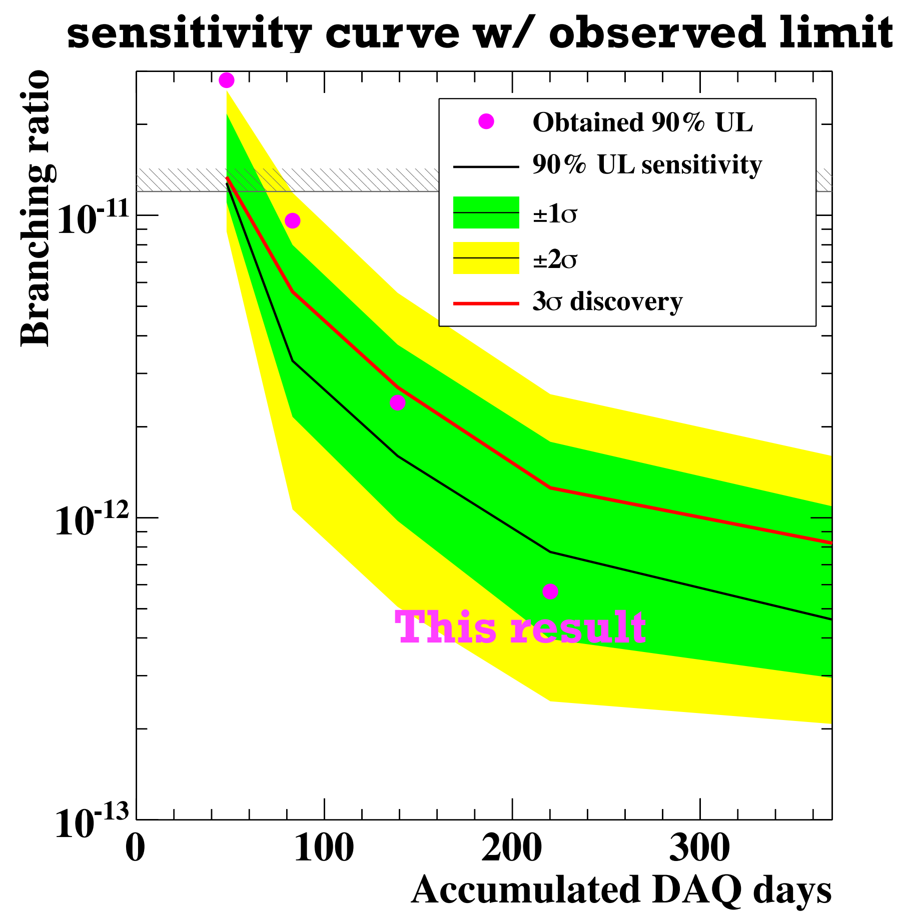
- Several consistency checks are done
  - For 2011 data, relatively large 'negative' fluctuation is observed
    - It can happen in 24% of probability
  - High signal-like events in the new/previous analysis are checked
    - All differences for high ranked events are within expectation
  - We also performed the physics analysis using the old PDF
    - The difference between old/new is not large



Conclusions & Remarks

- **The $\mu^+ \to e^+\gamma$ decay search using 2009-2011 data performed**
  - First $\mu^+ \to e^+\gamma$ search with a sensitivity below 10^{-12}
- **No signal excess is observed**
  - **$B(\mu^+ \to e^+\gamma) < 5.7\times10^{-13}$** (90% C.L.), with a sensitivity of 7.7×10^{-13}
  - Start exploring **"new physics region"** deeply
- **New results presented in this month using "FULL" data taken by MEG**
  - Final upper limit: 4.2×10^{-13} with a Sensitivity of $\mathbf{5.3\times10^{-13}}$, no signal excess observed
  - Details are presented by D. Kaneko (19aAH-3), will be published on arXiv soon

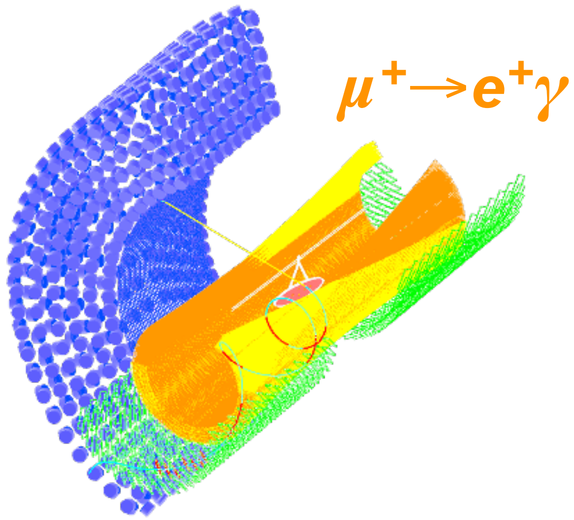




Don’t worry, it’s not the end!

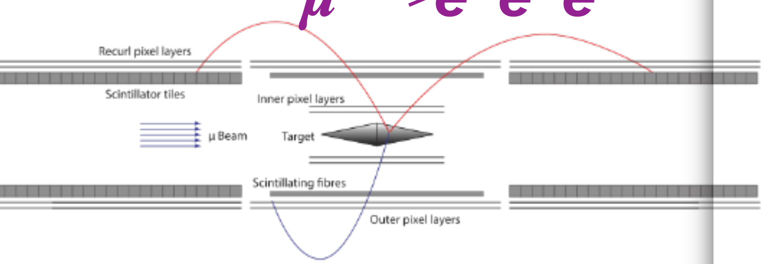
New Era of CLFV Searches

$\mu^+ \to e^+\gamma$

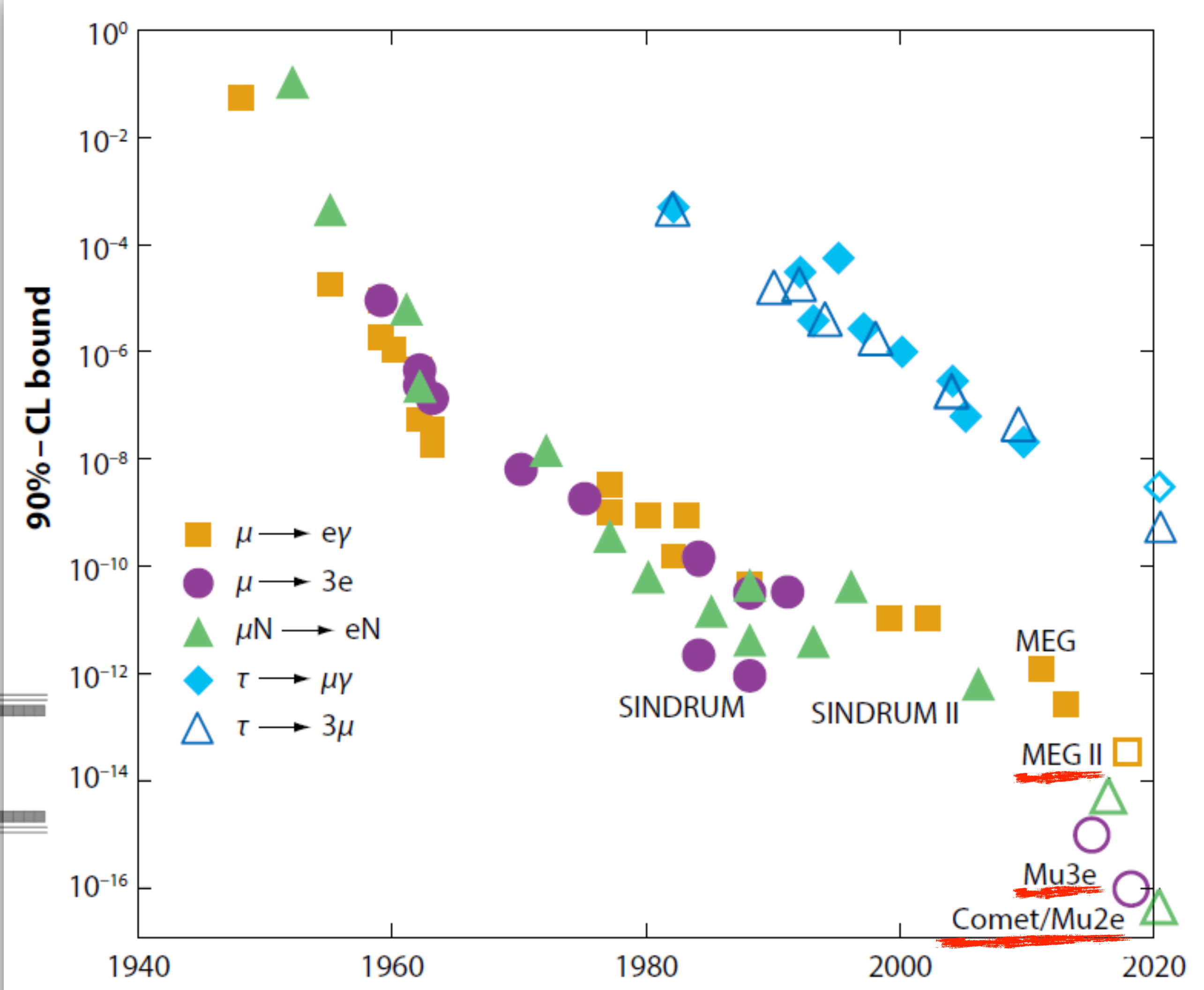


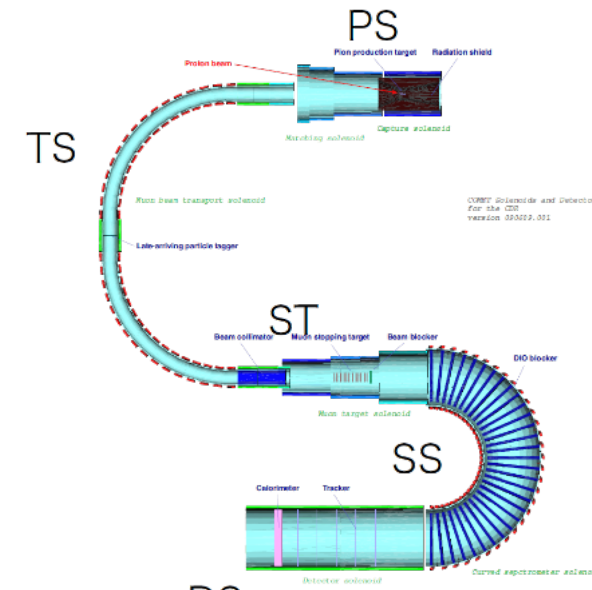
MEG II @ PSI

$\mu^+ \to e^+e^+e^-$



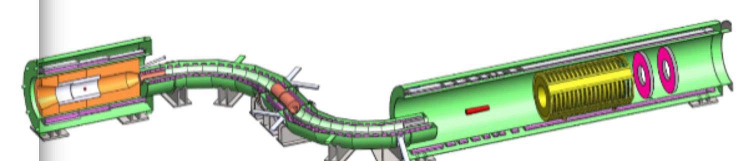
Mu3e @ PSI



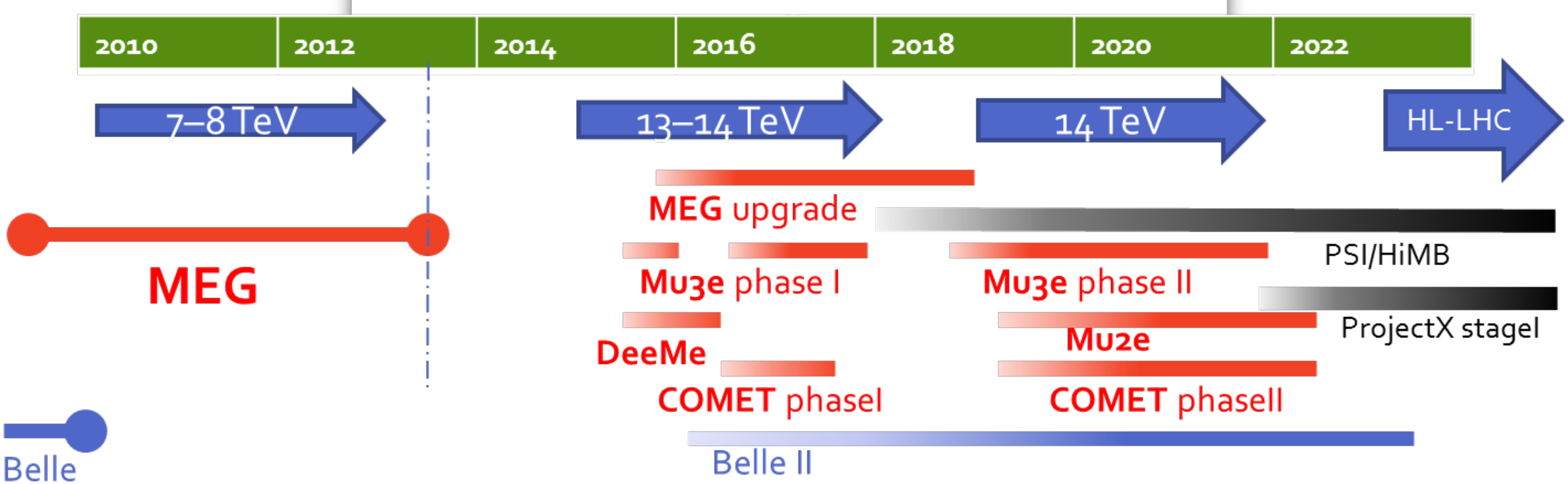


COMET @ J-PARC

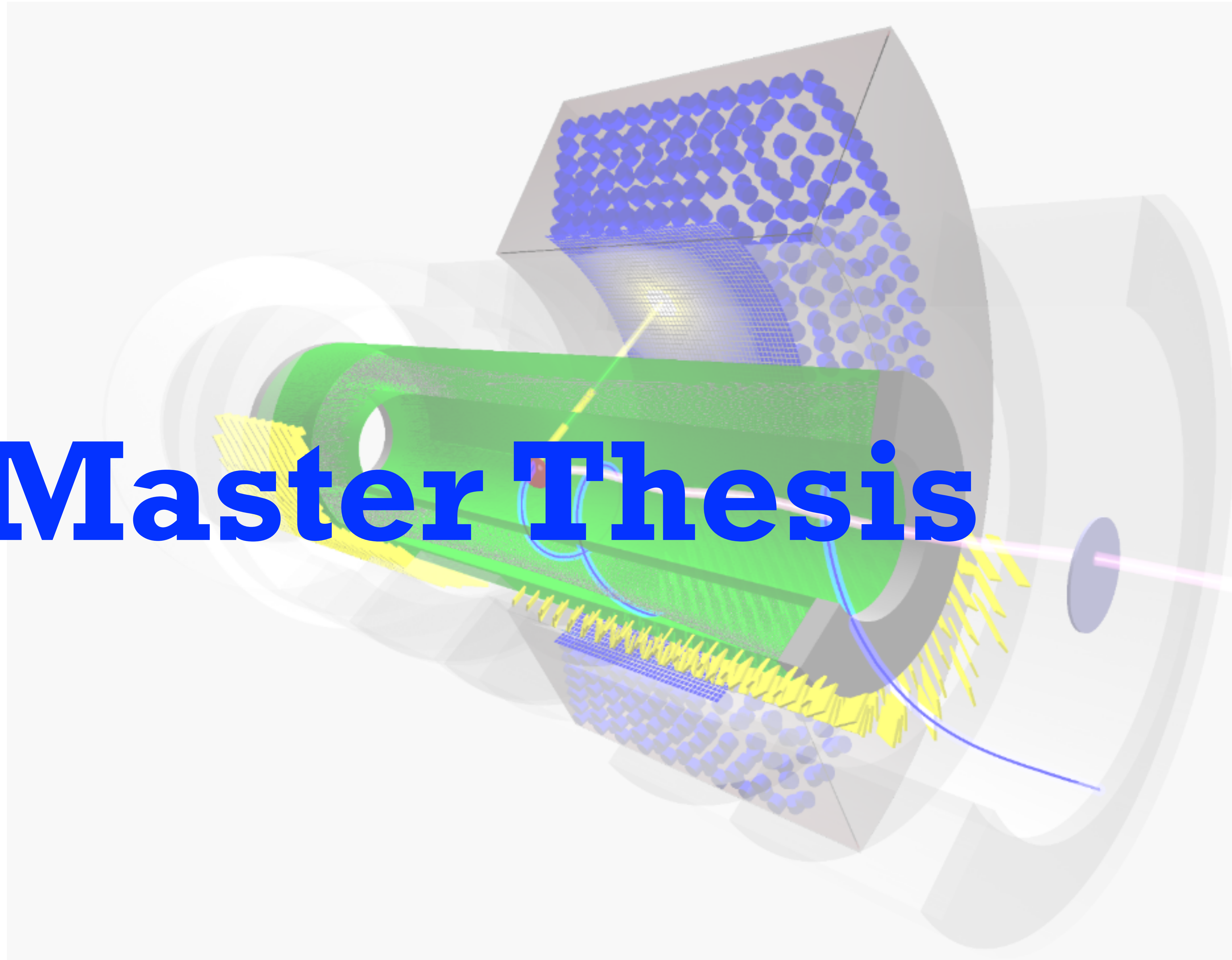
$\mu^- N \to e^- N$



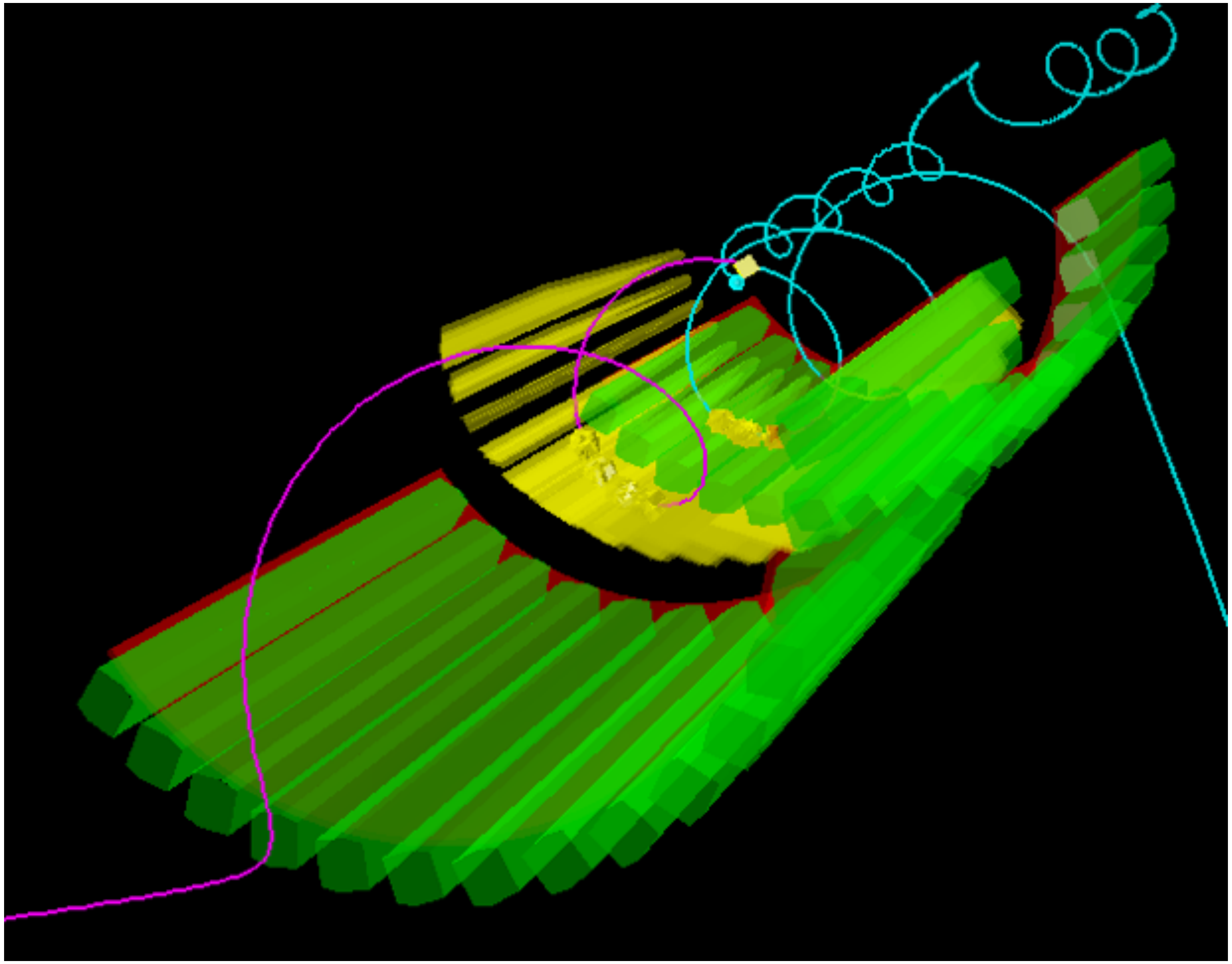
Mu2e @ Fermilab

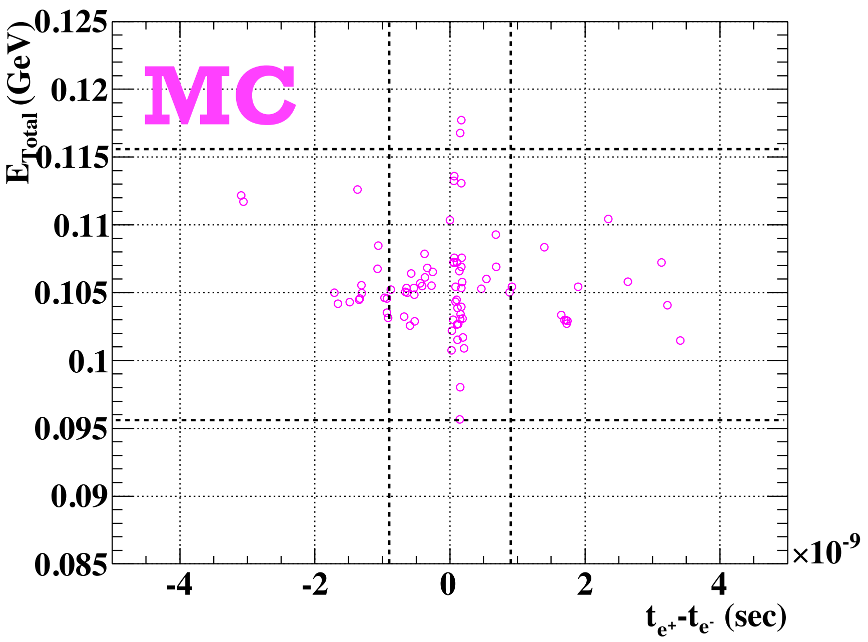


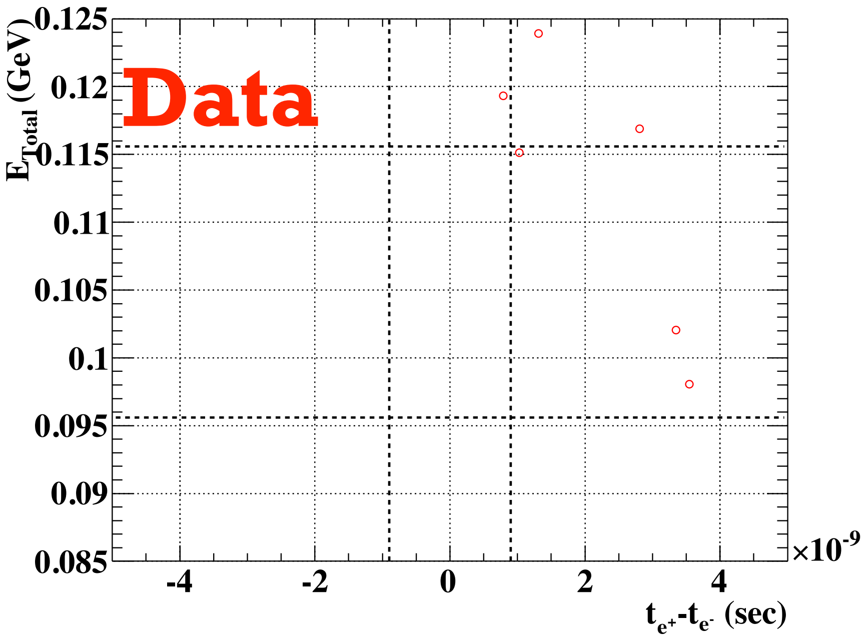
Master Thesis



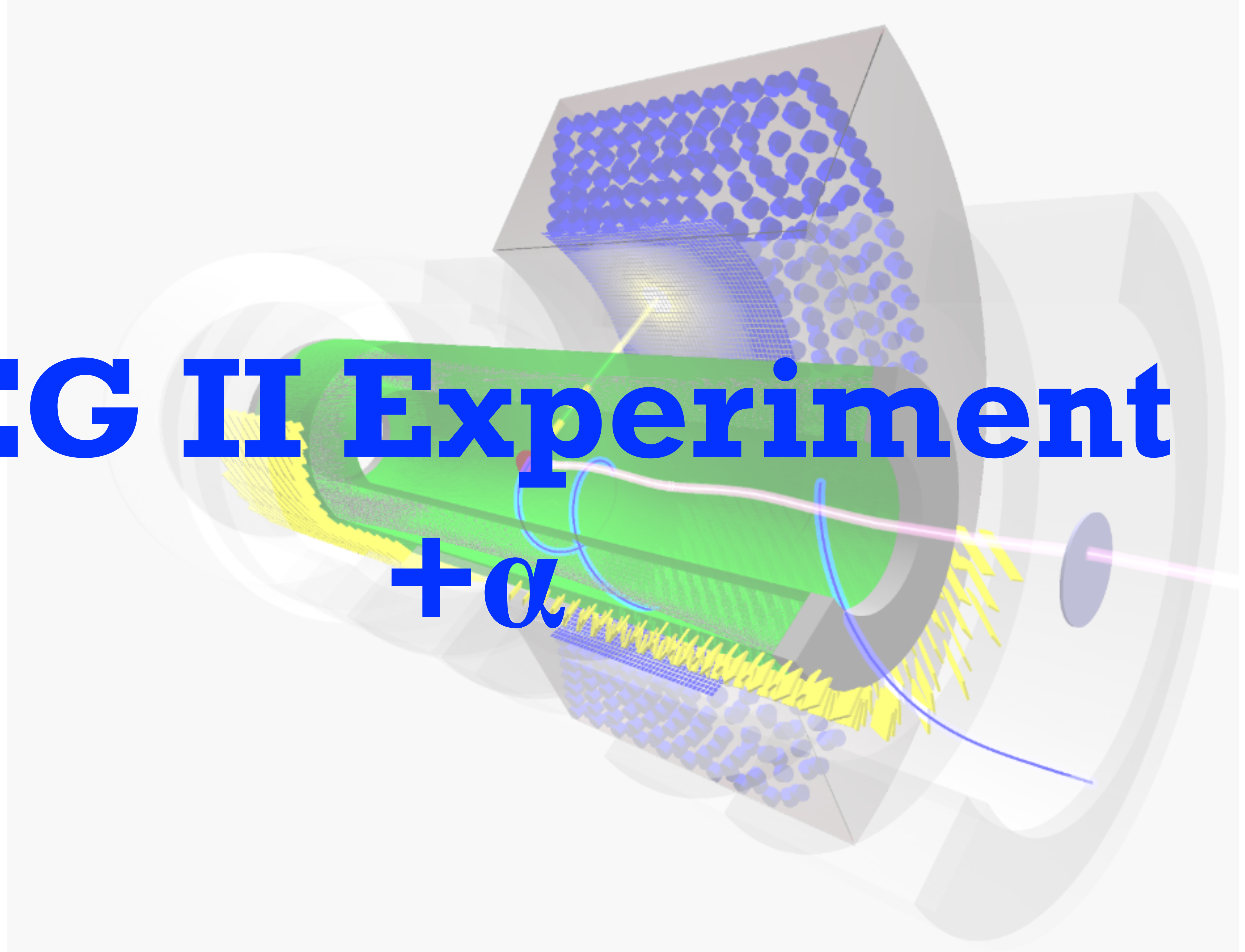
μ→eee Search







- Study the feasibility to search for μ→eee using the COBRA spectrometer
  - Confirmed that it is almost impossible to exceed the current upper limit
- In MEG II, I think it's possible at least to reach the current upper limit~10^{-12}



MEG II Experiment

+α

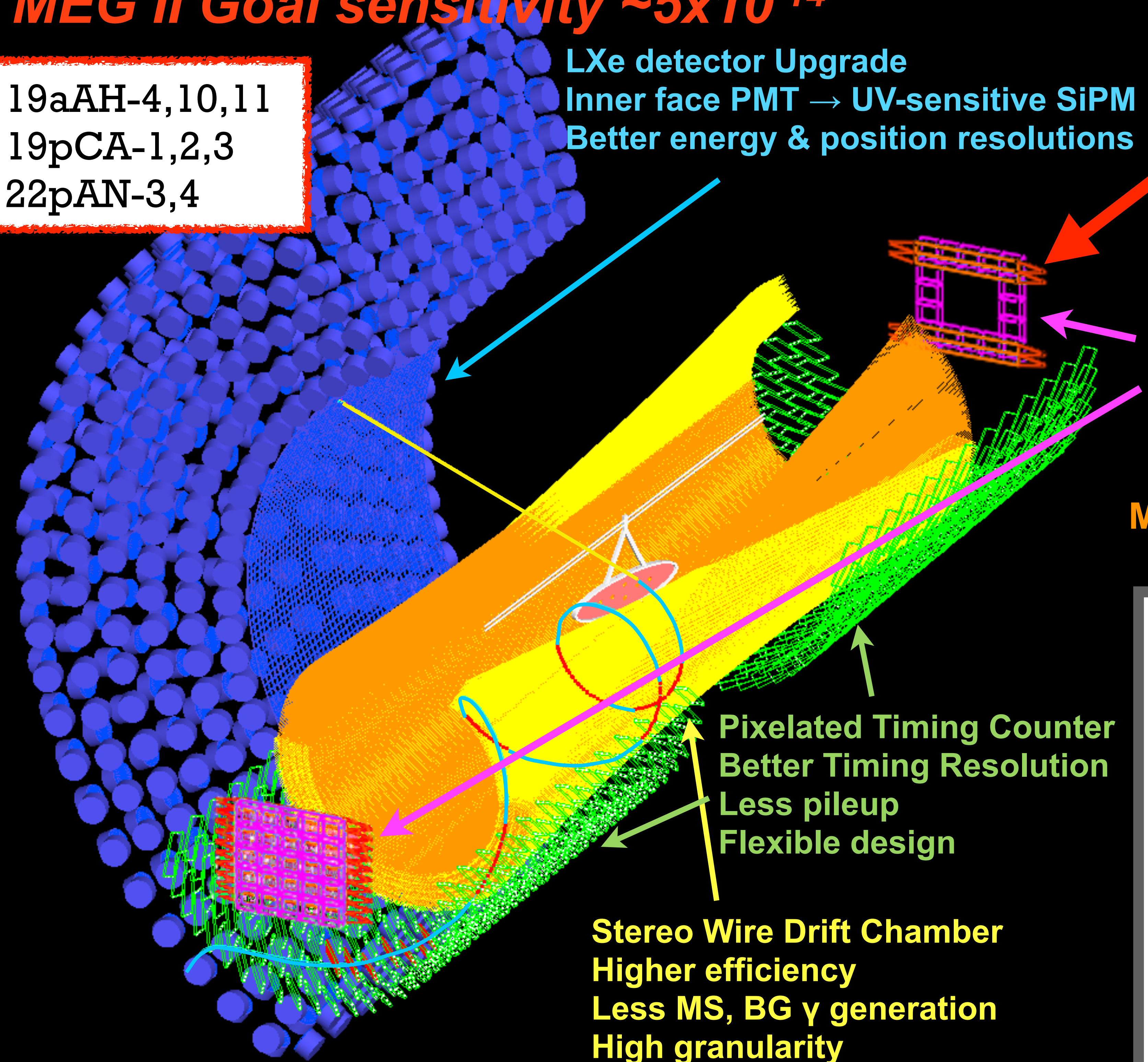
MEG II

MEG II Goal sensitivity ~5x10^{-14}

19aAH-4,10,11
19pCA-1,2,3
22pAN-3,4

$\sim 7\times10^{7}$ μ/s stopped on target
already available @ PSI

LXe detector Upgrade
Inner face PMT → UV-sensitive SiPM
Better energy & position resolutions

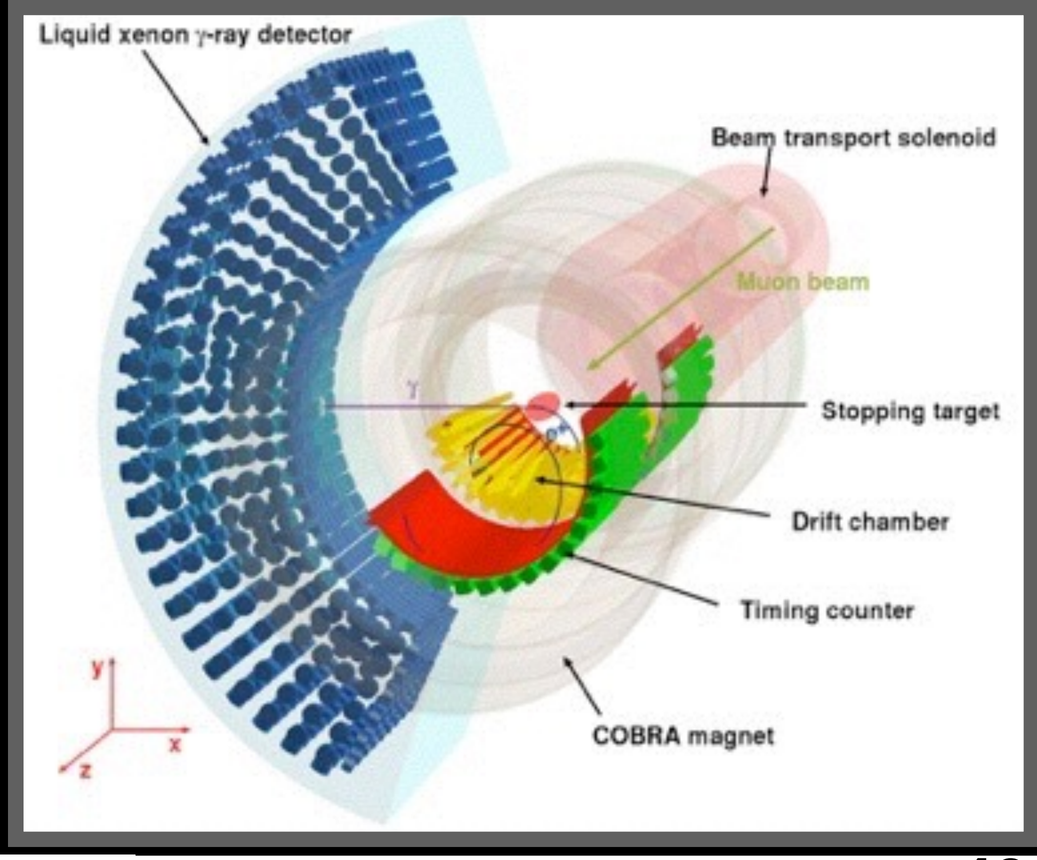


Radiative Decay Counter (RDC)
Tagging gamma BG from RMD
→ Active BG suppression

Pixelated Timing Counter
Better Timing Resolution
Less pileup
Flexible design

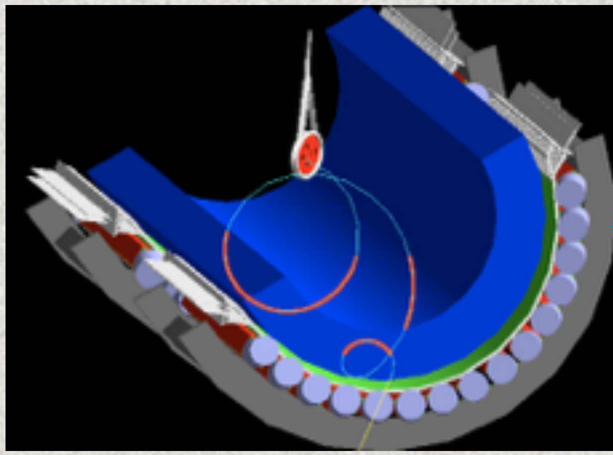
Stereo Wire Drift Chamber
Higher efficiency
Less MS, BG γ generation
High granularity

MEG
- Finished data taking in August 2013



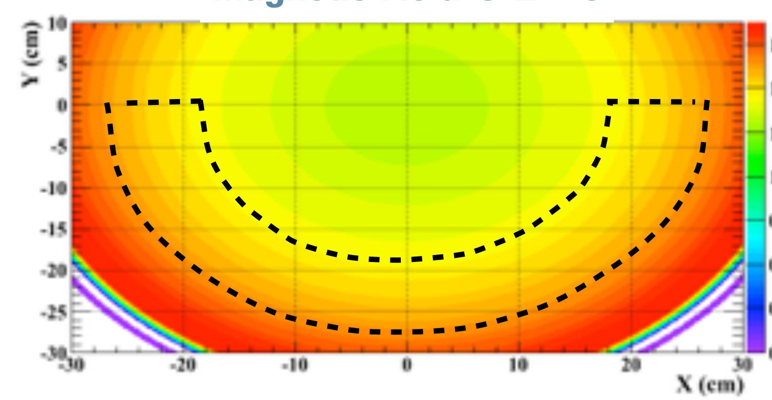
Upgrade proposal was already approved by
Paul Scherrer Institut (arXiv:1301.7225)

Simulation study

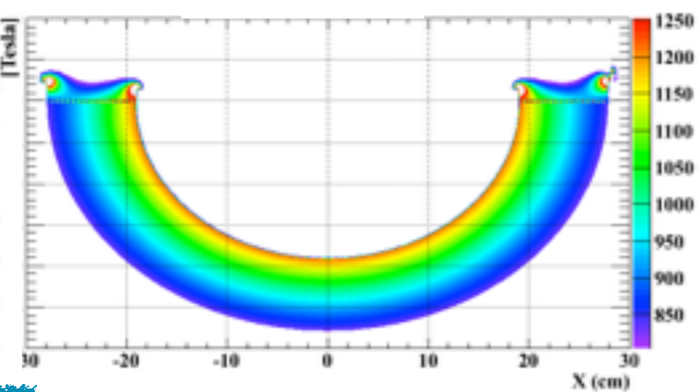


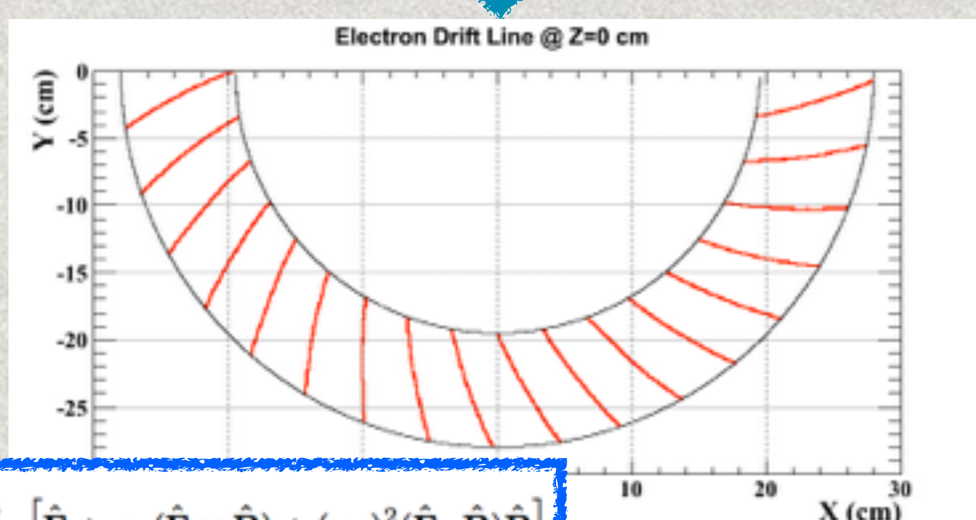
Geant4 simulation of signal e+ w/ TPC

Magnetic Field @ Z = 0



Electric Field



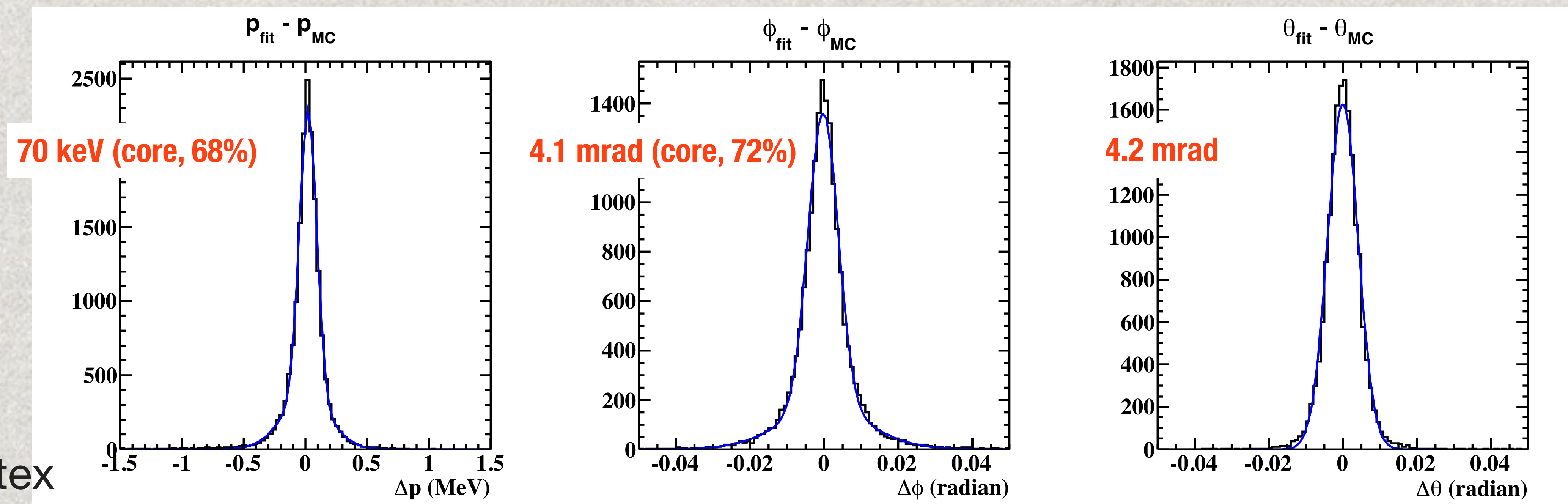


$$\mathbf{u} = \frac{eE\tau/m}{1+(\omega\tau)^2}\left[\hat{\mathbf{E}} + \omega\tau(\hat{\mathbf{E}}\times\hat{\mathbf{B}}) + (\omega\tau)^2(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}})\hat{\mathbf{B}}\right]$$

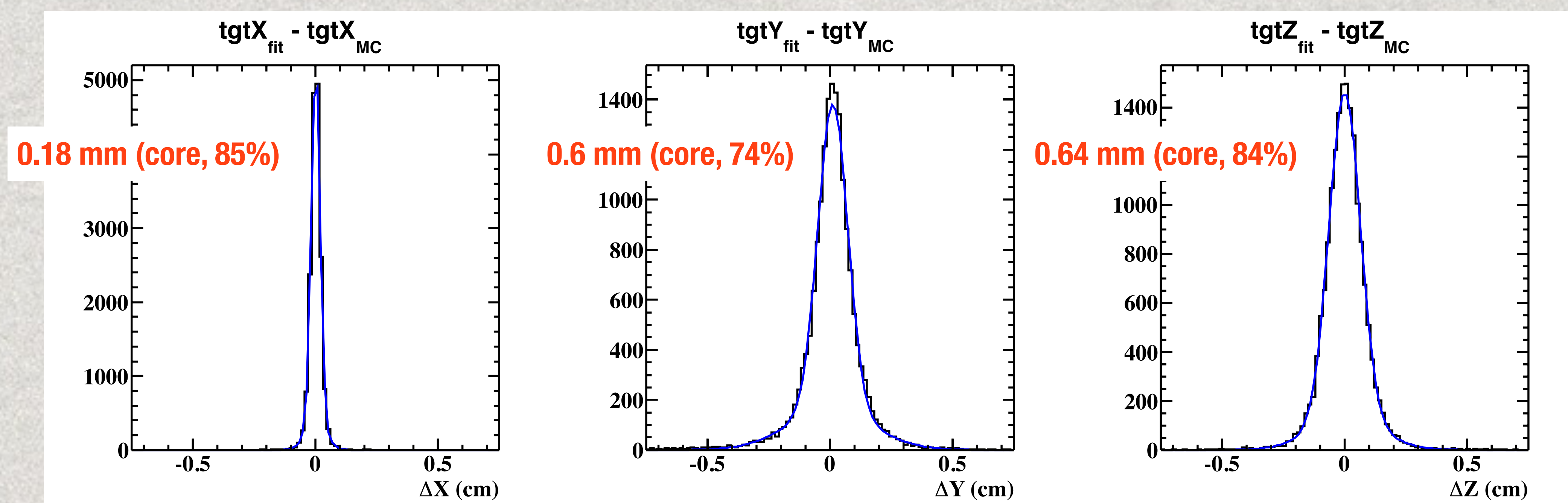
- There are 2 main simulation part
  - Event generation, Detector simulation and physics processes
    - Done by Geant4
  - Gas simulation
    - Drift part of ionized electron
      - E field is calculated by ANSYS (FEA)
      - Drift line of ionized electron is bent by magnetic field
        - 3D TXY table can be generated w/ Garfield++
    - Gas amplification
      - To be calculated w/ Garfield++

Performance evaluation

- Momentum & Angular resolutions (e.g. σ_{int} = 250μm, target thickness = 140μm)

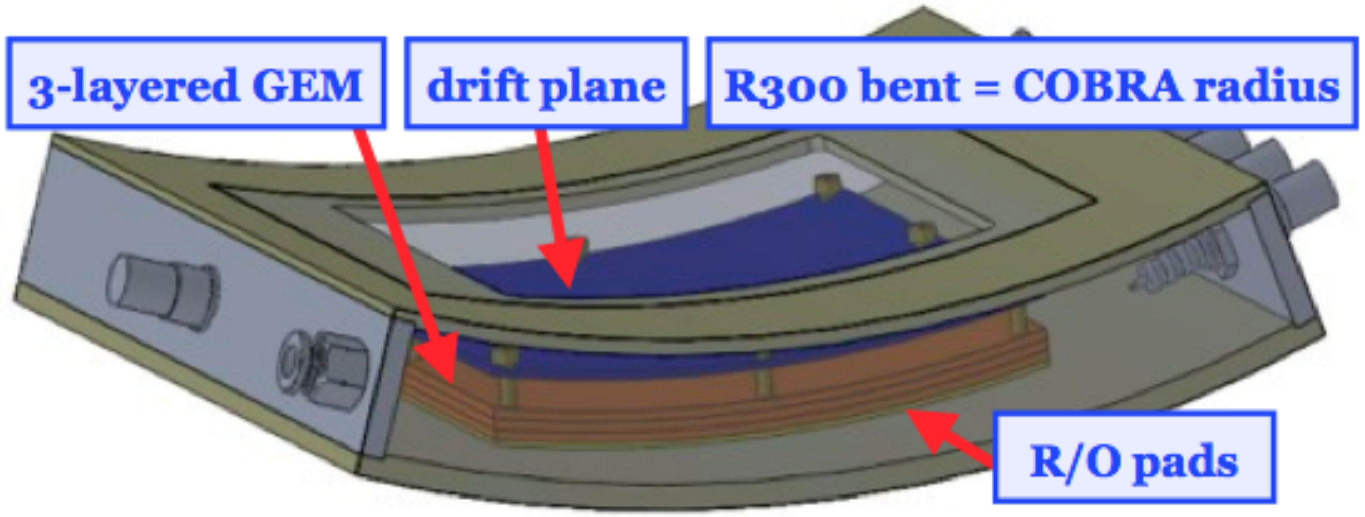


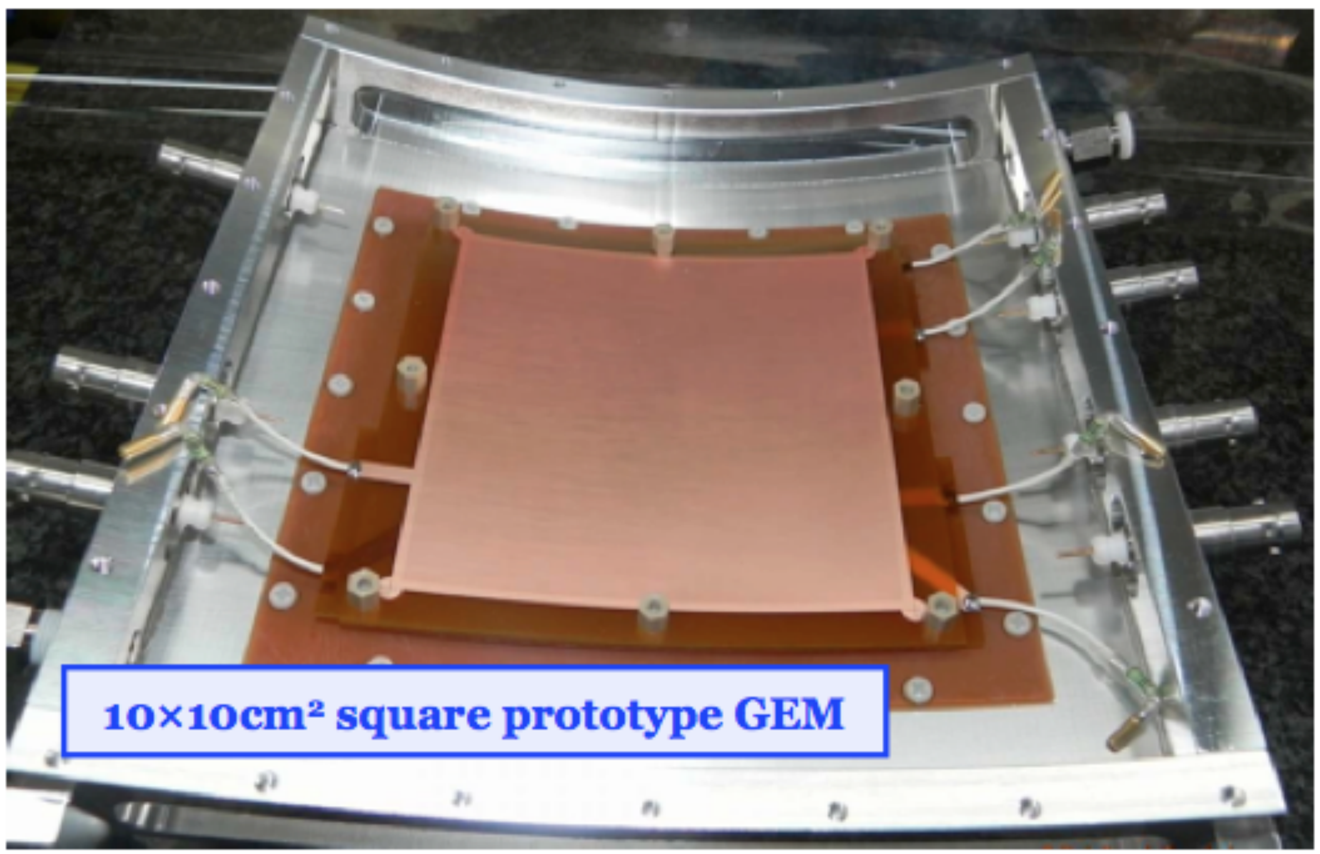
- Vertex

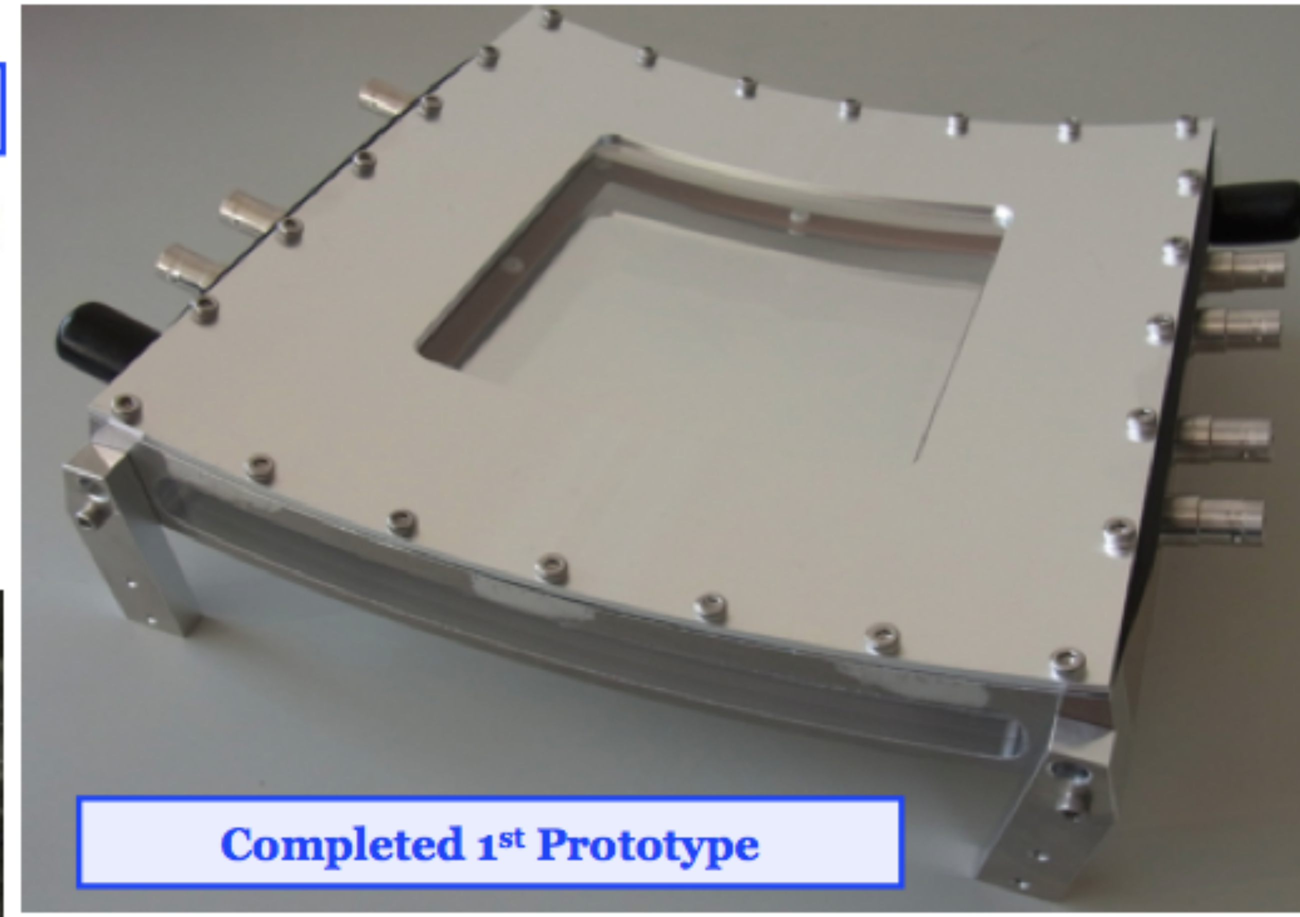


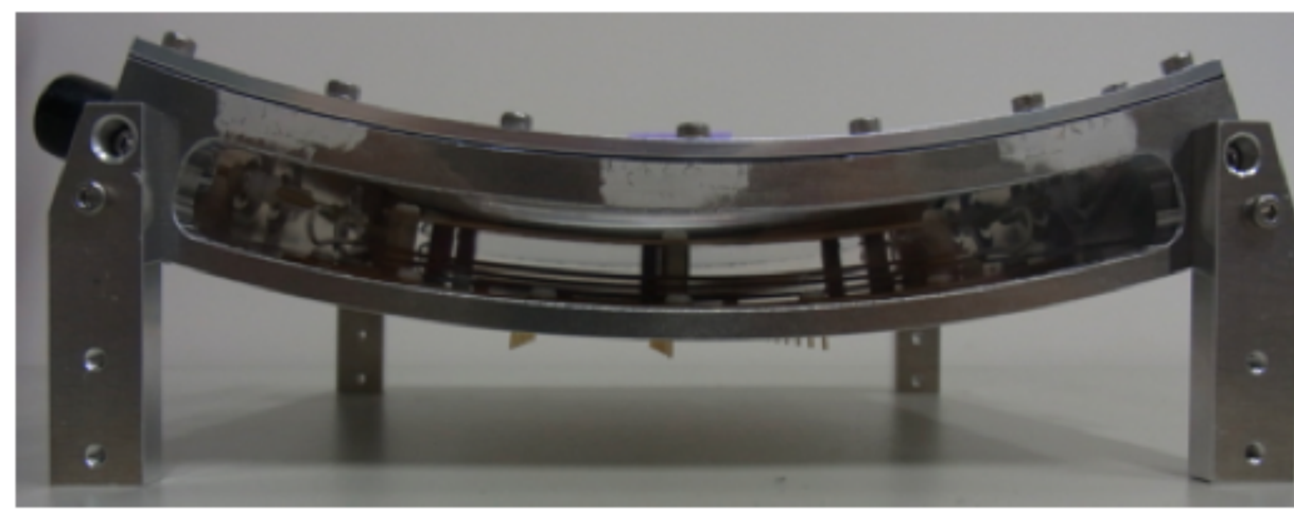
- Very good resolutions !

RTPC Prototype



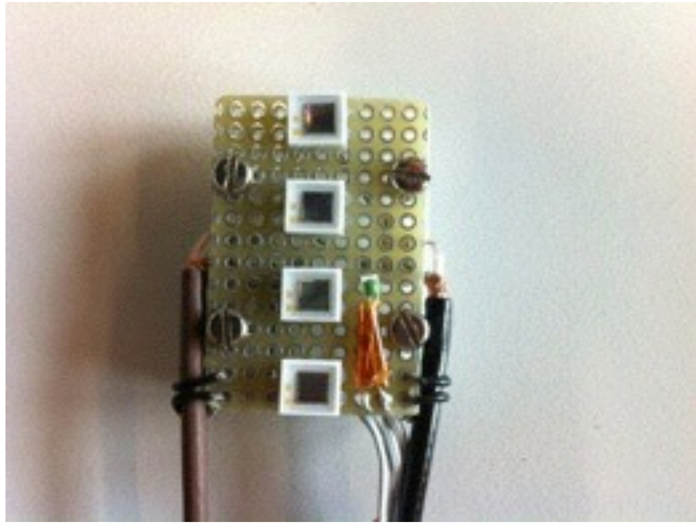
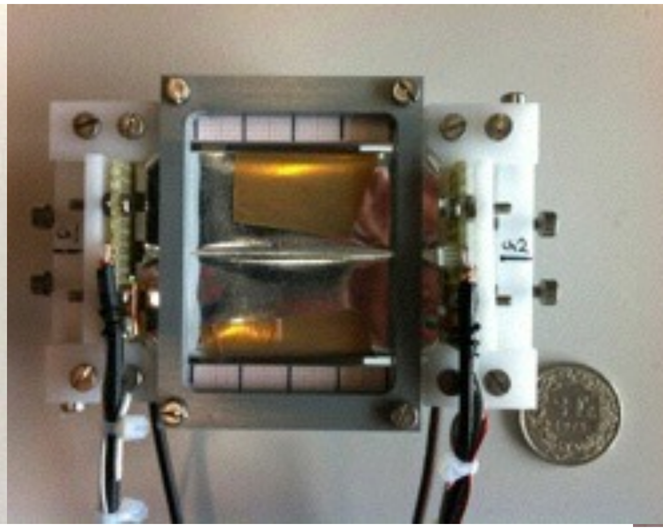


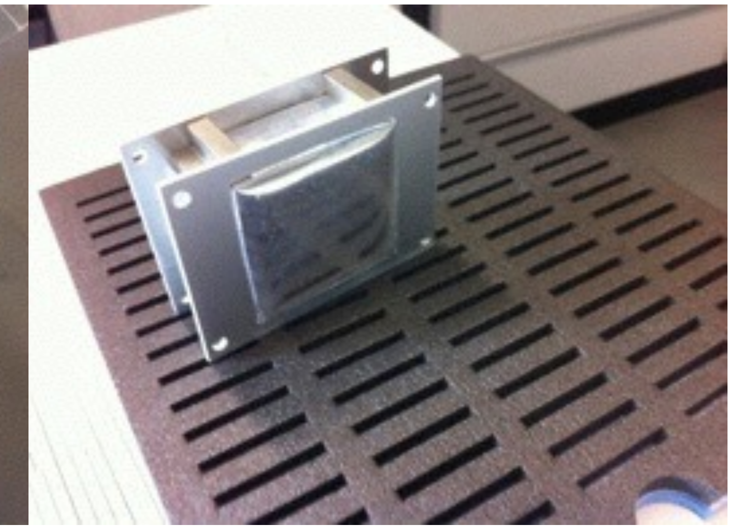
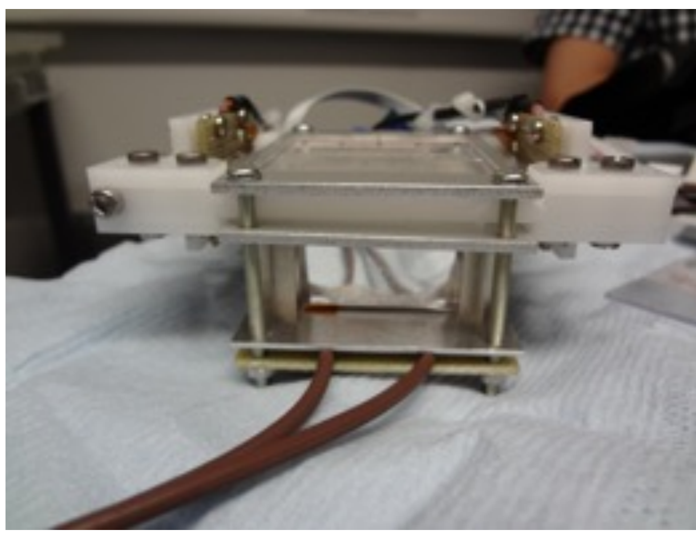


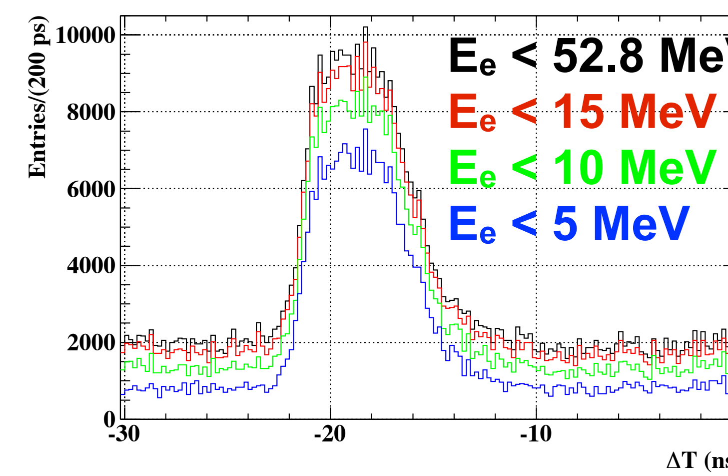


- Now this prototype is waiting for being tested @KEK…

RDC Development

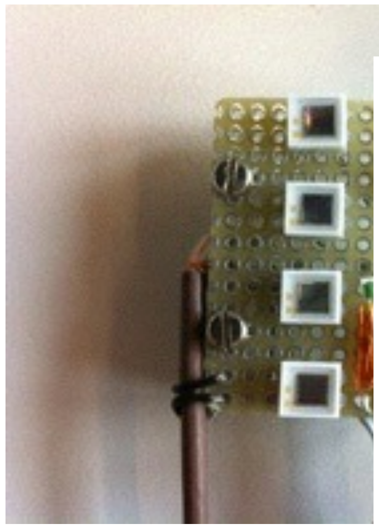



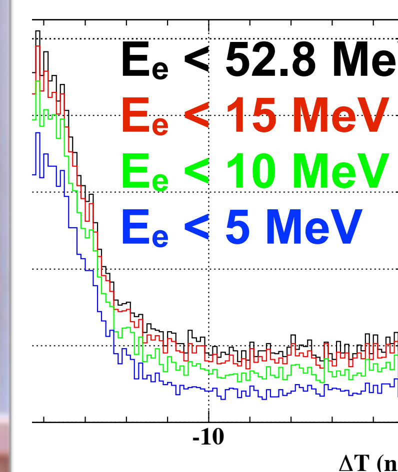



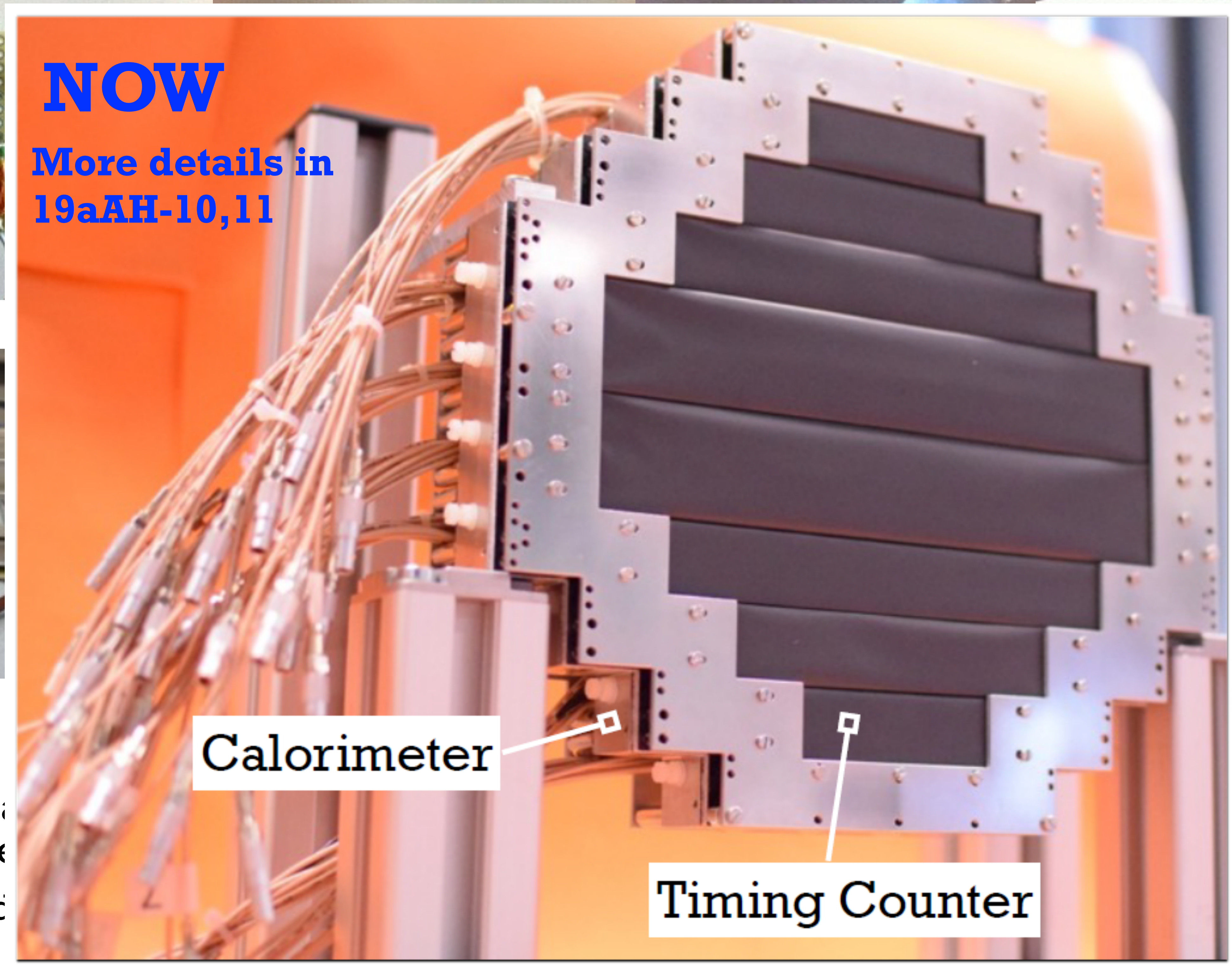



- **RDC** is an additional detector for MEG II to further suppress the gamma BG from radiative muon decay
  - The development just started from the coffer break conversation with Sawada-san…
  - Then the small prototype was produced and beam test was performed in 2013

RDC Development

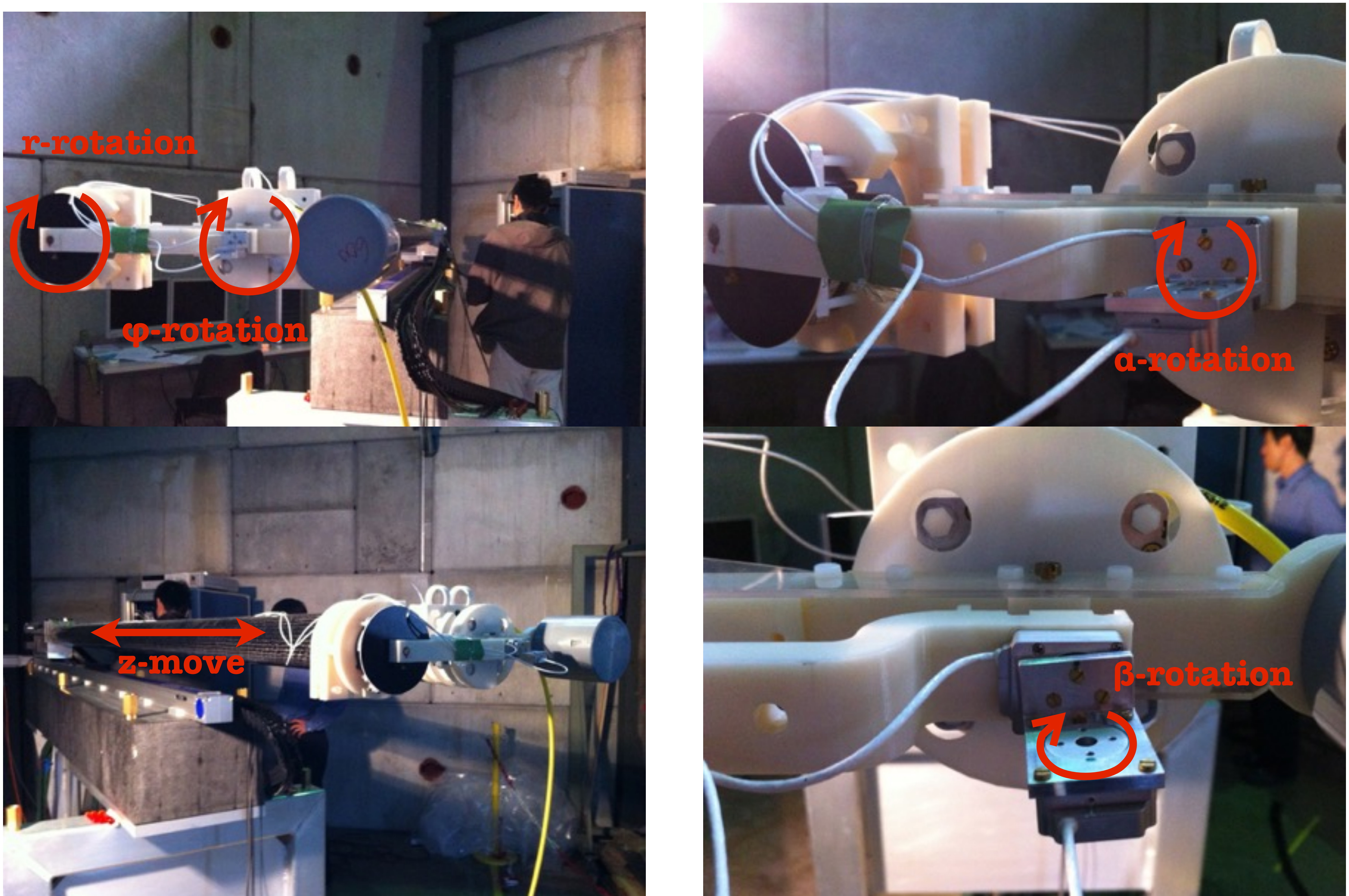






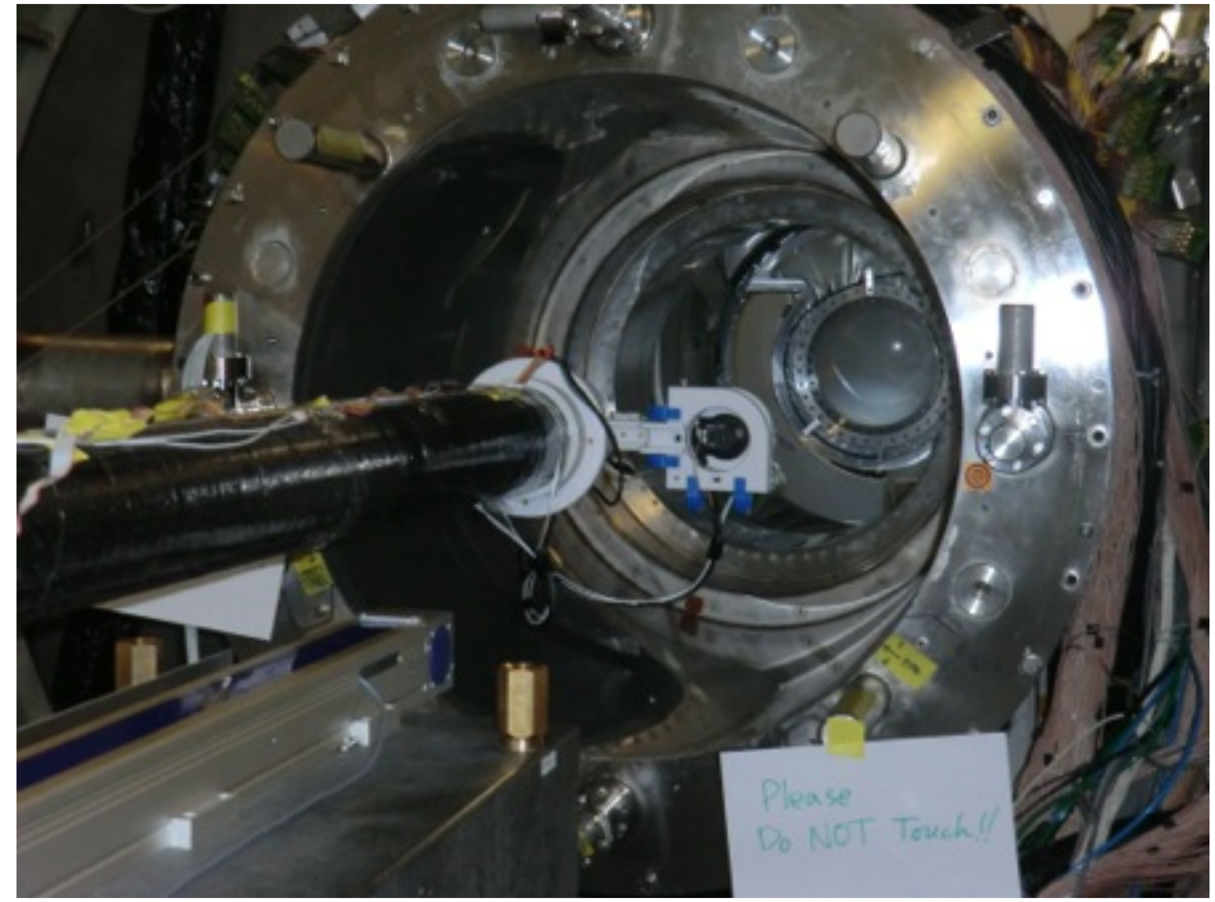
- **RDC** is ... G from radiative ...
  - The ... san…
  - Then the small prototype was produced and beam test was performed in 2015

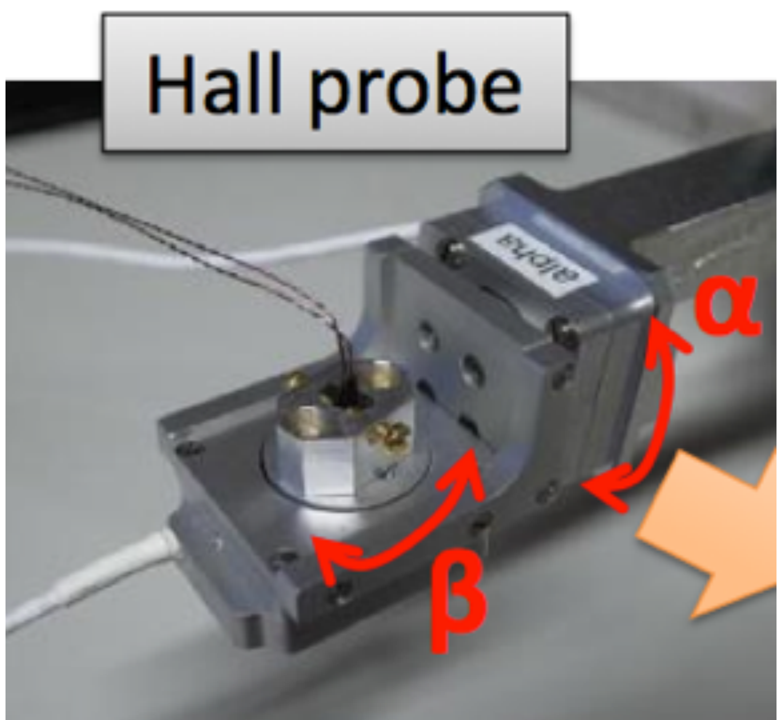
New Field Measurement Machine

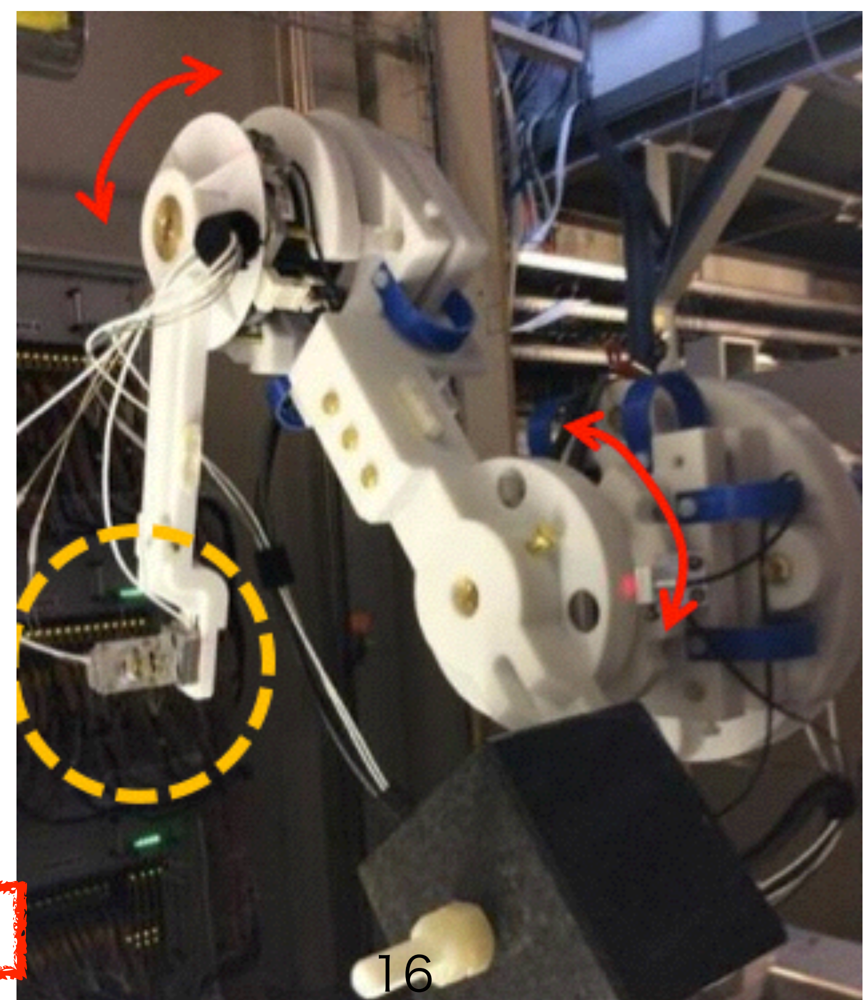


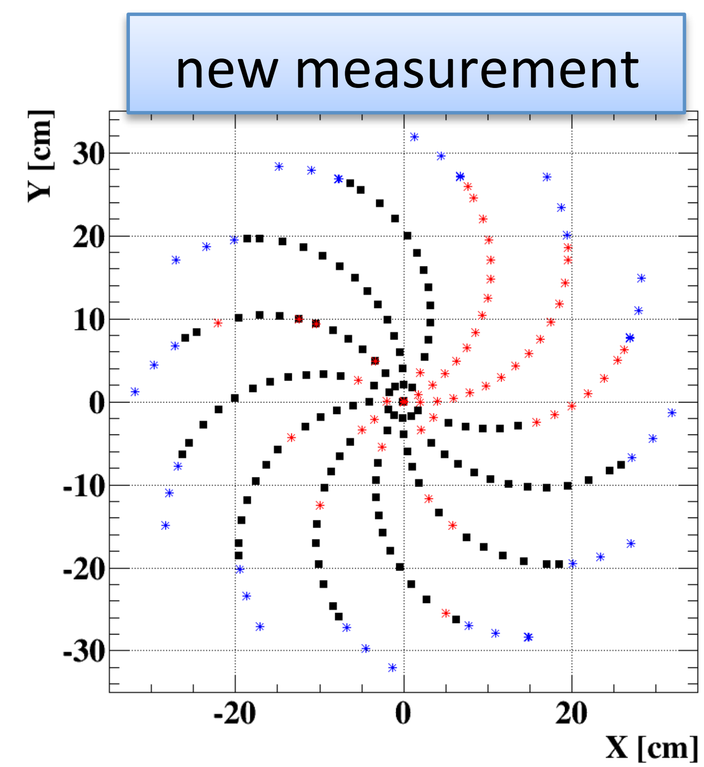
Magnetic field measurement

- 2006 magnetic field was measured with 0.2% precision (sensor position calibration ~800μm) ~ 150keV momentum resolution
- Momentum resolution in MEG II ~ 130keV, need to reduce the uncertainty of the magnetic field
- In July and August 2014, magnetic field measurements were performed with a new measurement machine which sensor position is more precisely calibrated (<300μm). If this new field map improves the momentum resolution of the current MEG data, this will be applied to them, too.





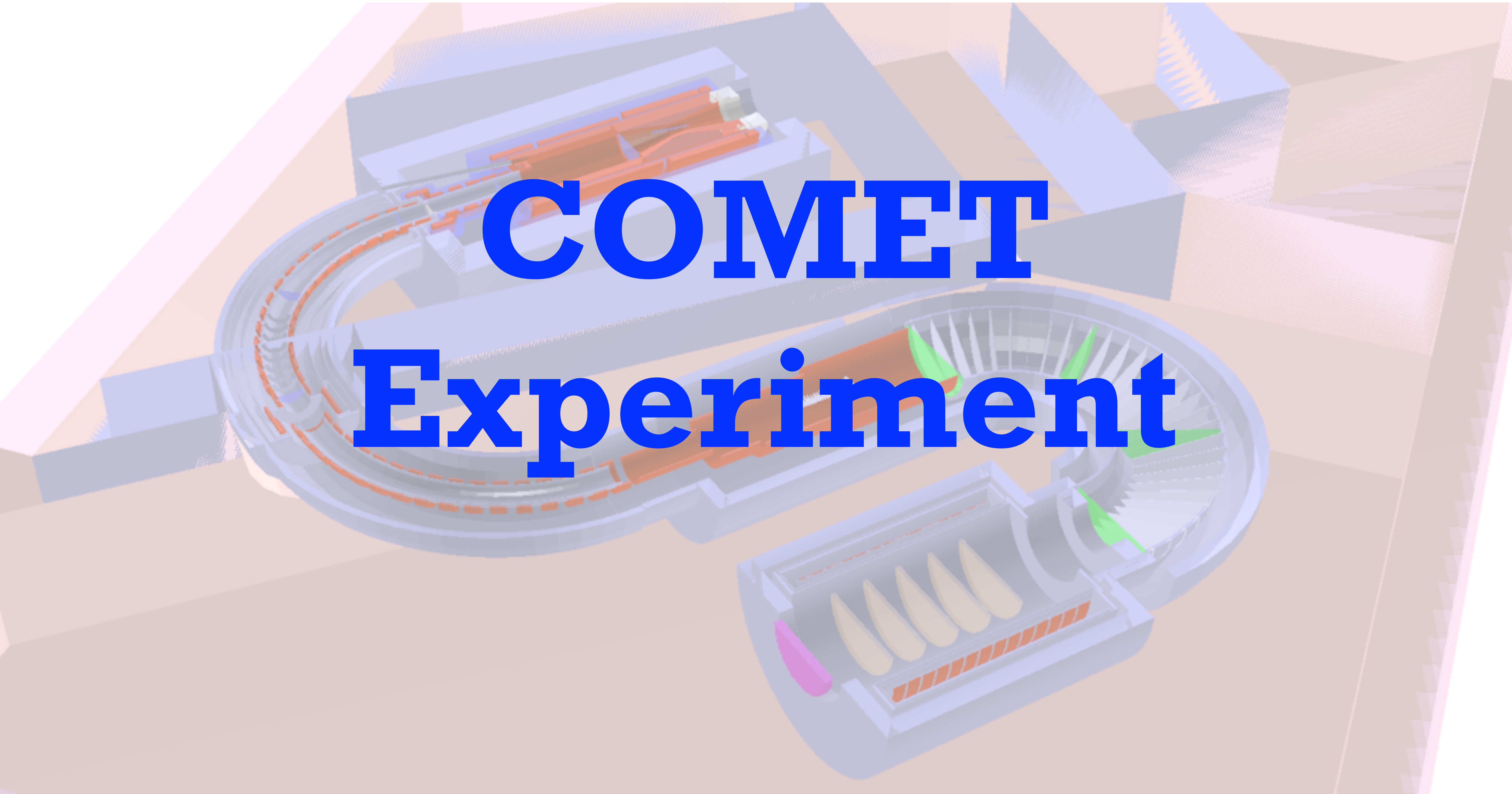




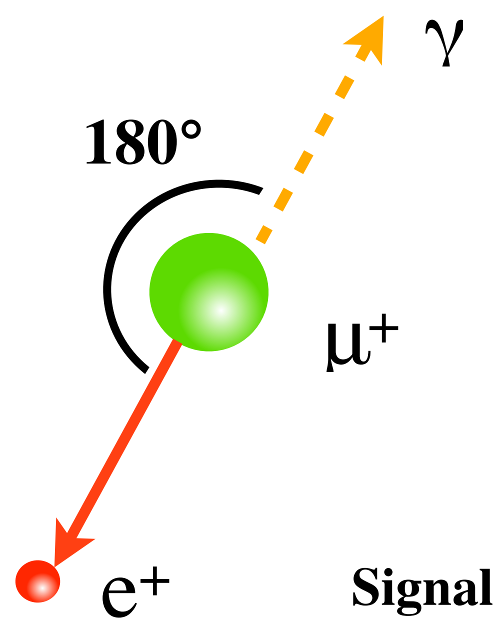
Z: ~4 mm step
R: 20 mm step
ϕ: 30 deg step

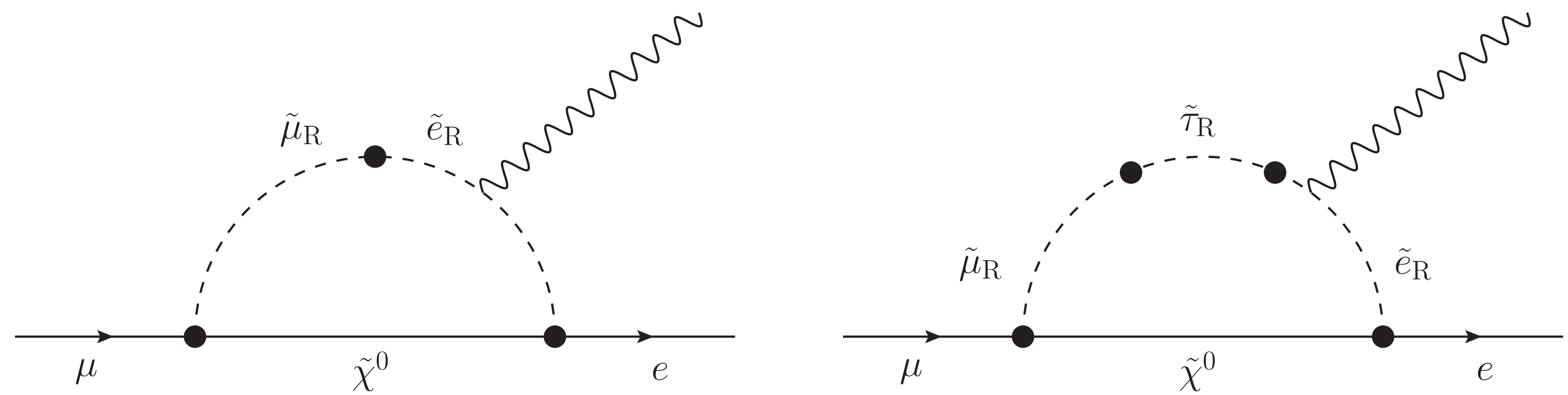
岩本敏幸氏 2014年秋季大会スライドより

COMET Experiment

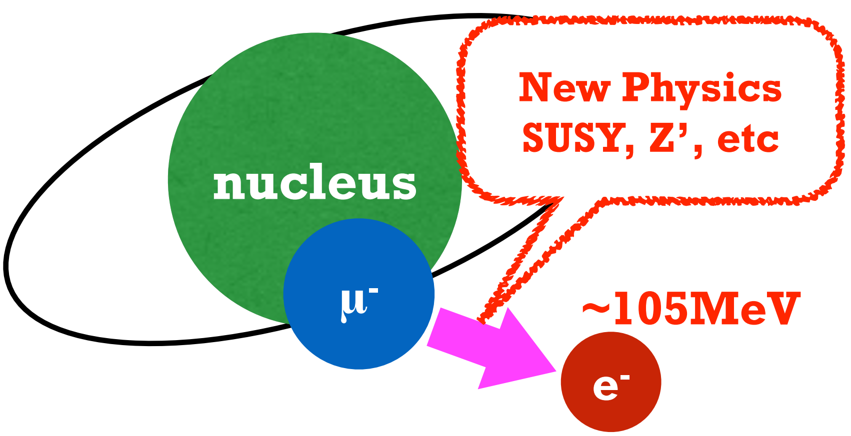


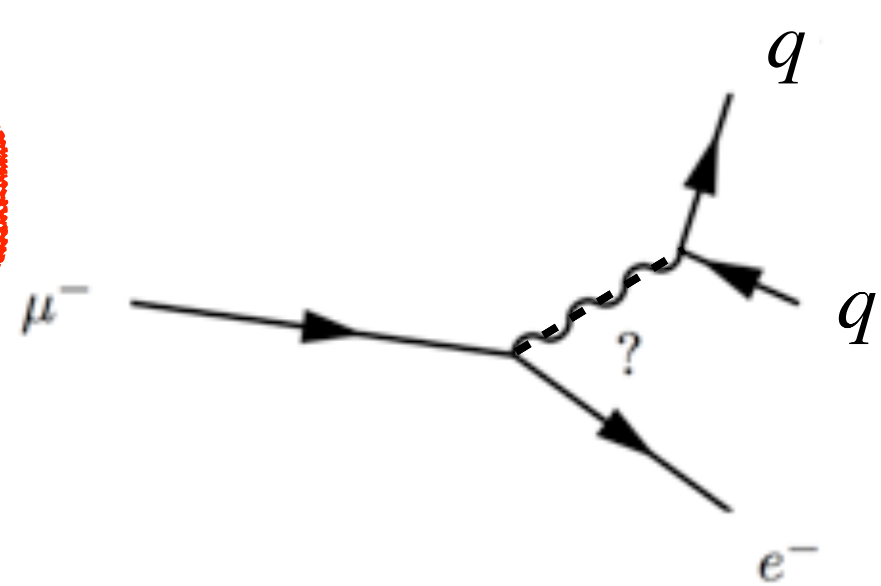
μ→eγ & μ-e conv.

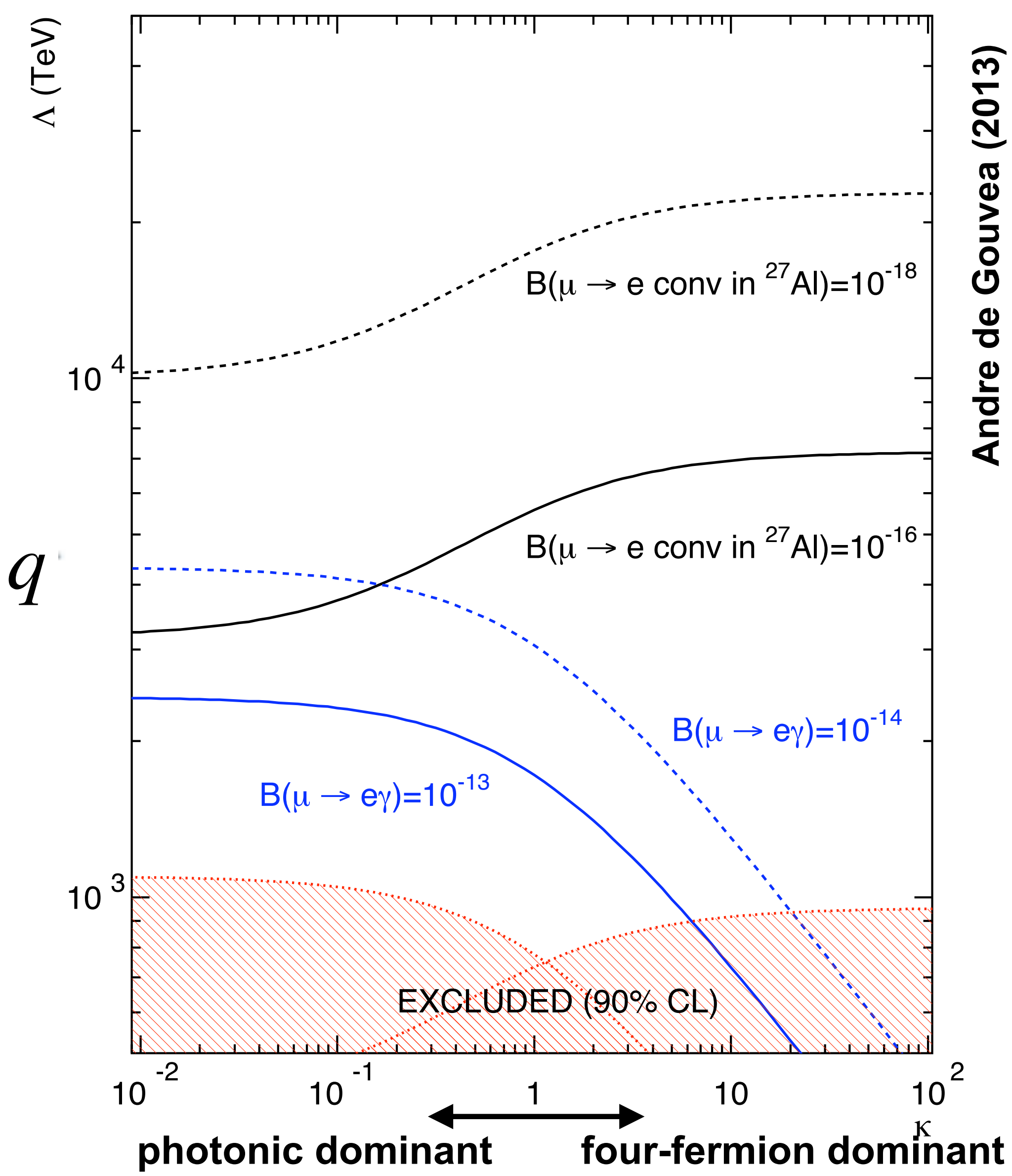




μ→eγ: Sensitive to the SUSY-like photon penguin diagrams







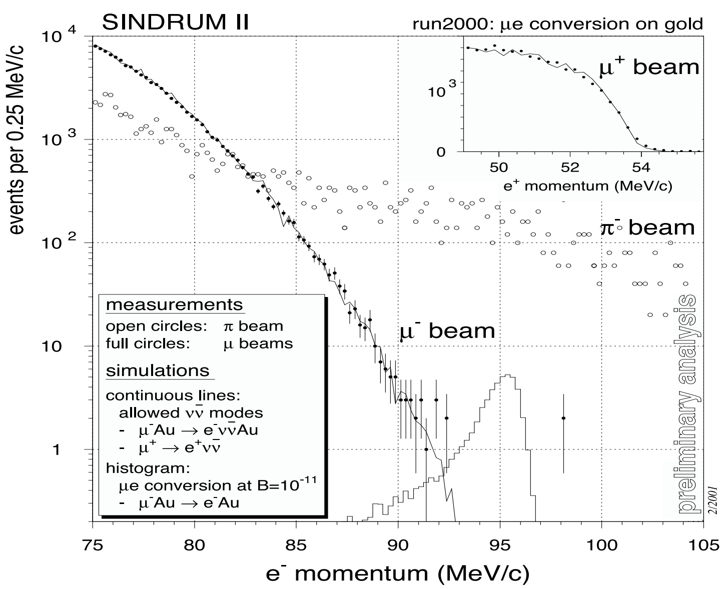
μ-e conv.: Sensitive to the tree-level four-fermion diagrams

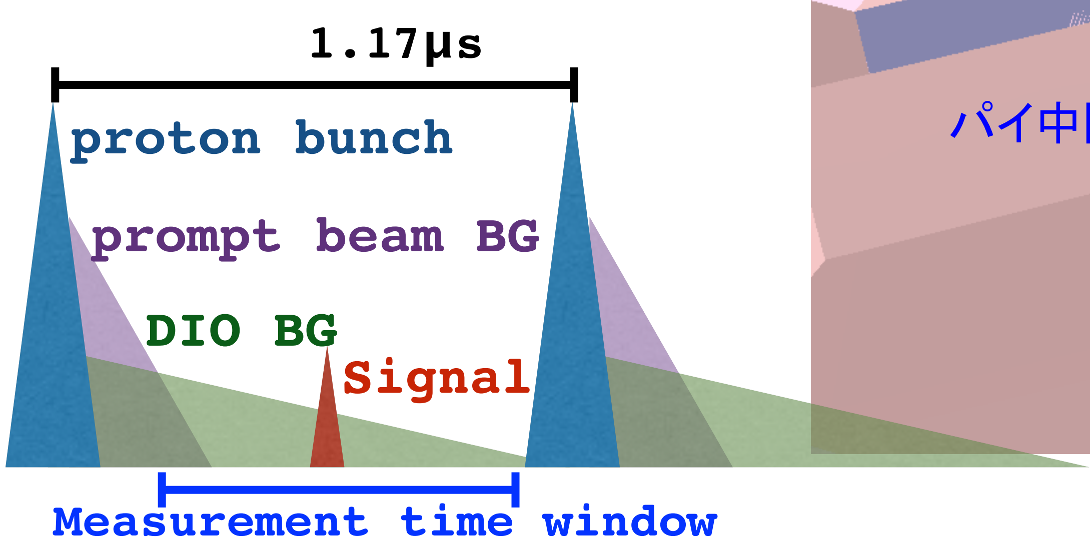
μ-e conversion has simple kinematics, too

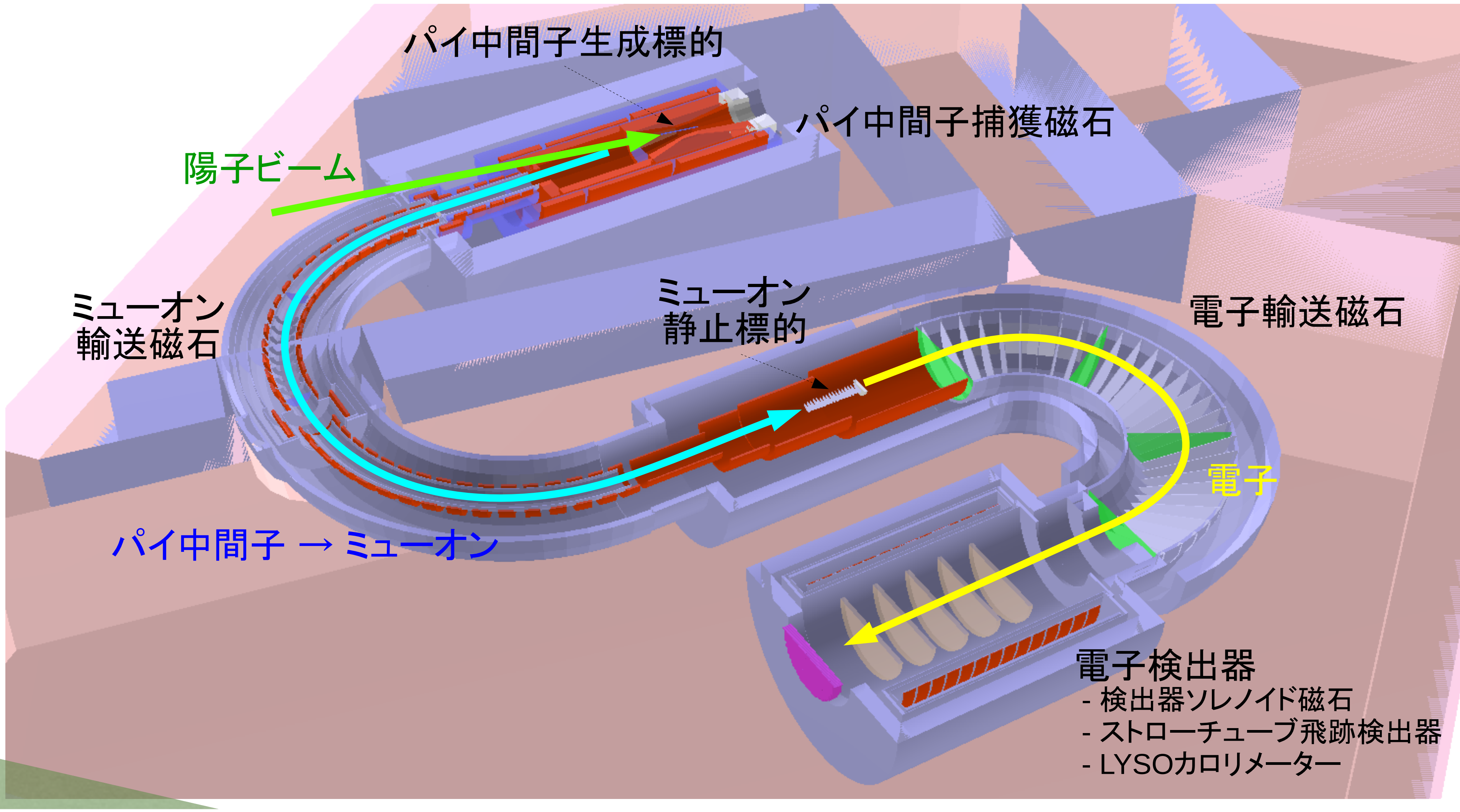
$E_{\mu e}=M_\mu-B_\mu$~105MeV/c, monochromatic electron

COMET Experiment

- Current upper limit: 7×10^{-13} @90% C.L. set by SINDRUM II
- COMET aiming goal: **10,000** times higher sensitivity, $O(10^{-17})$
  - Bunched slow extraction+delayed timing method highly suppress the prompt beam BG
    - SINDRUM II → continuous beam, suffered from the beam origin BG…
  - C-shaped muon transport solenoid further reduce beam origin BG
  - Another C-shaped electron transport solenoid enables the low occupancy @ detector region





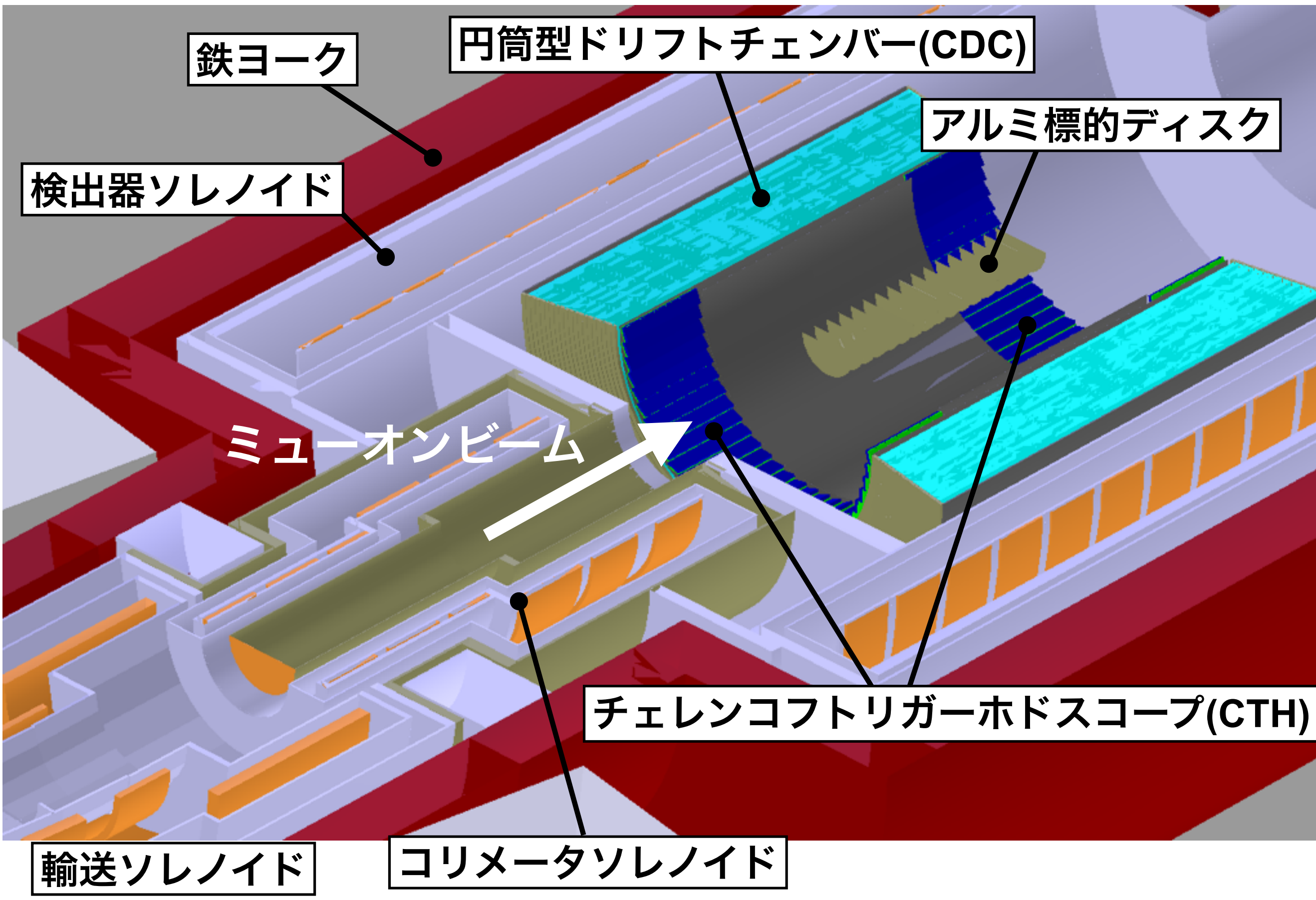


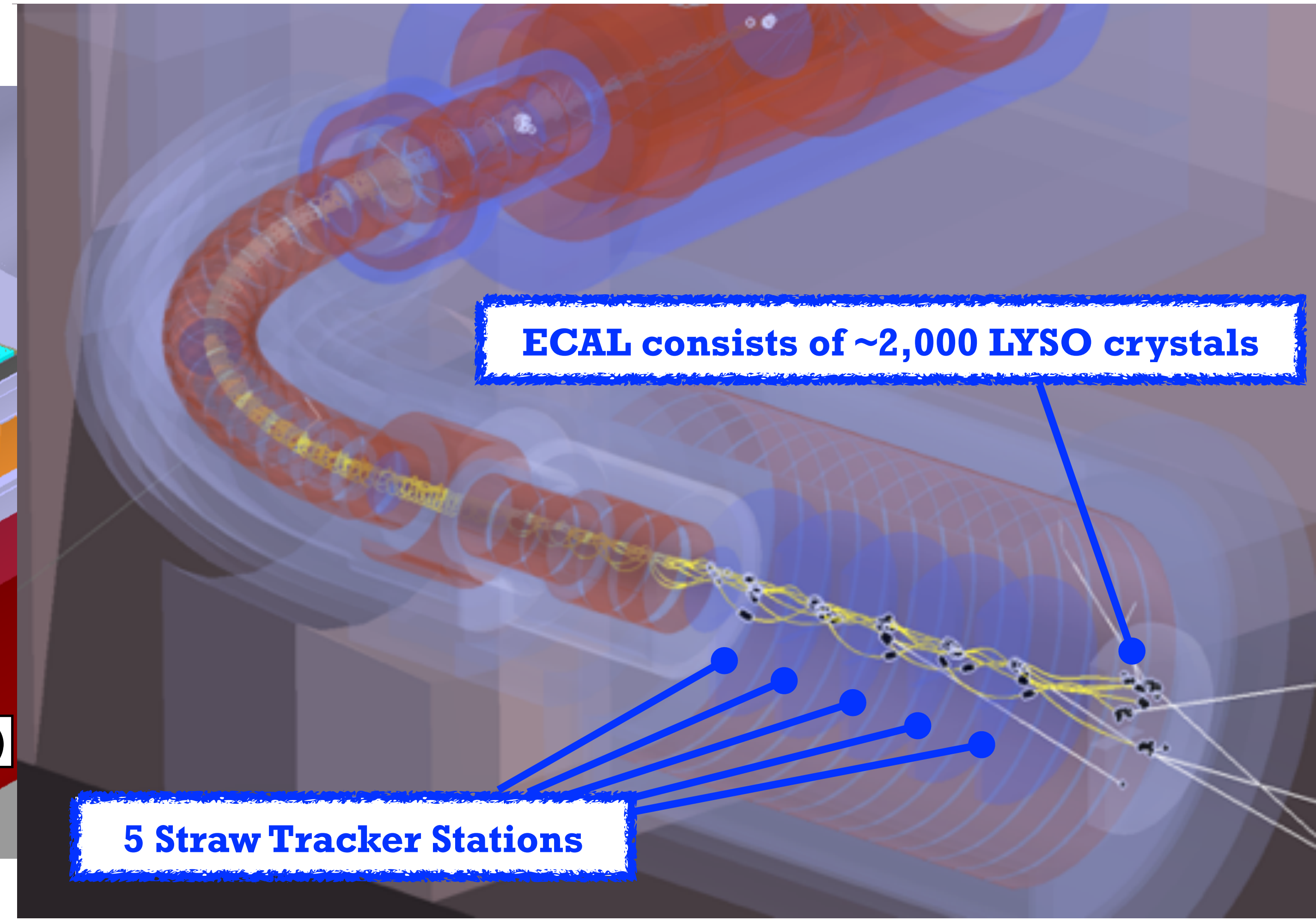
COMET Experiment

- **World Wide Collaboration**
  - ~150 people, 40 institutes in 15 countries

COMET Phase-I

Phase I CyDet Geometry



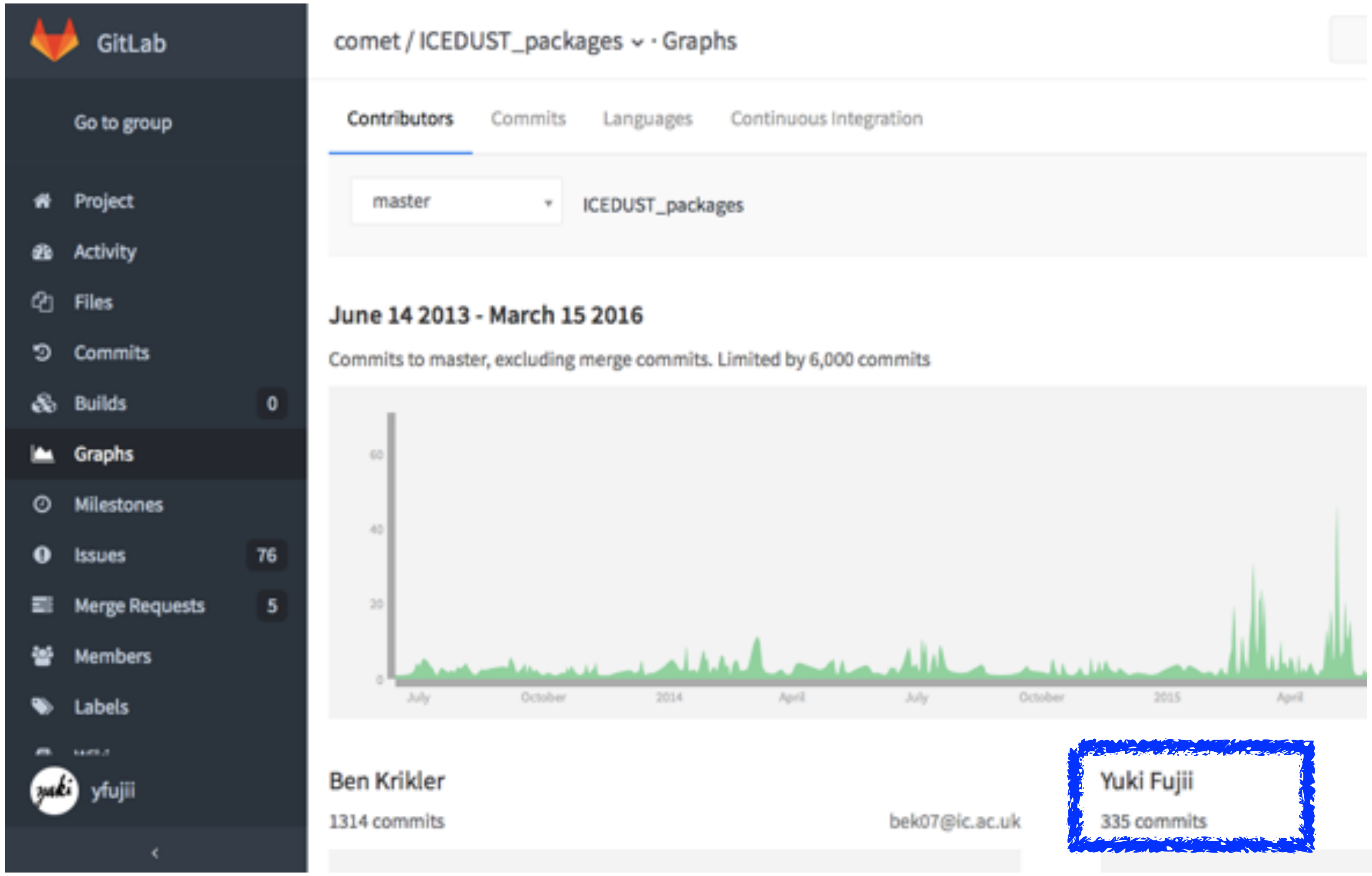


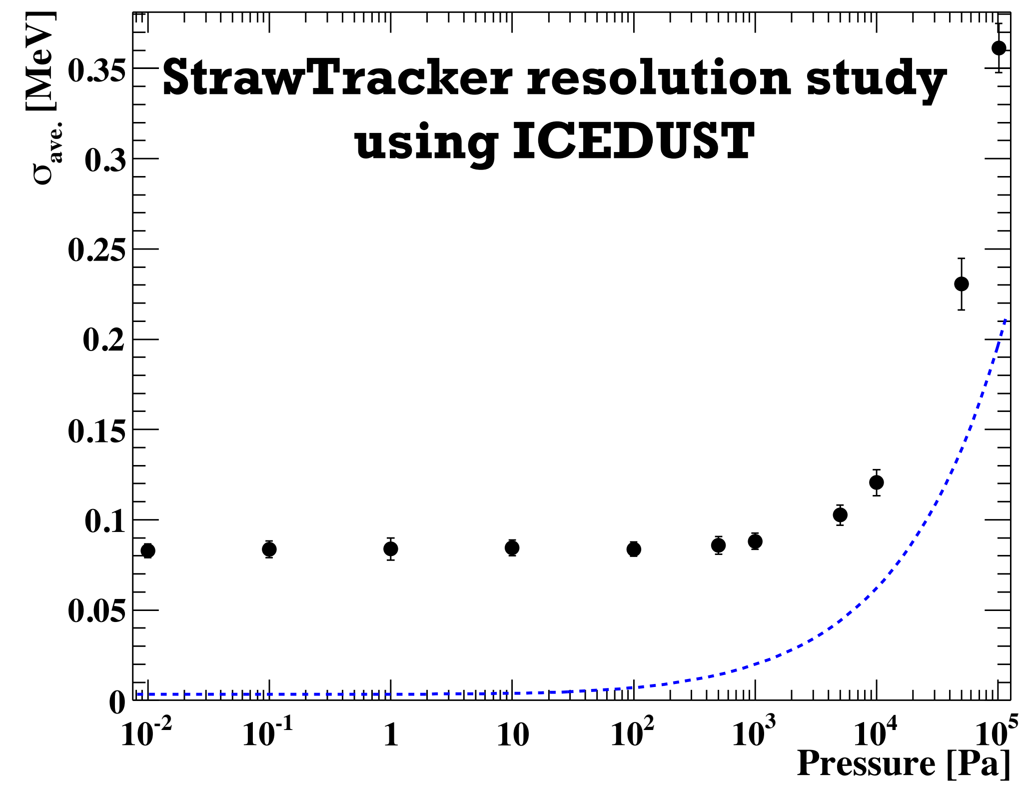
- COMET will start Phase-I experiment from **2018/2019**:
  - Construct the 1st 90° of the muon transport solenoid
  - **CyDet**: Physics measurement aiming to search for μ-e conv. w/ a sensitivity of 10^{-15}, Cylindrical Drift Chamber+Cherenkov Trigger Hodoscope
  - **StrawECAL**: Measure the beam particles and their timing precisely, alternatively search for μ-e conv. use Straw Tube Tracker+ECAL as Phase-II prototype detectors

CyDet
22aCA-8,9 Yamane, Y. Nakazawa
22pAH-4,5 H. Yoshida, T.S. Wong

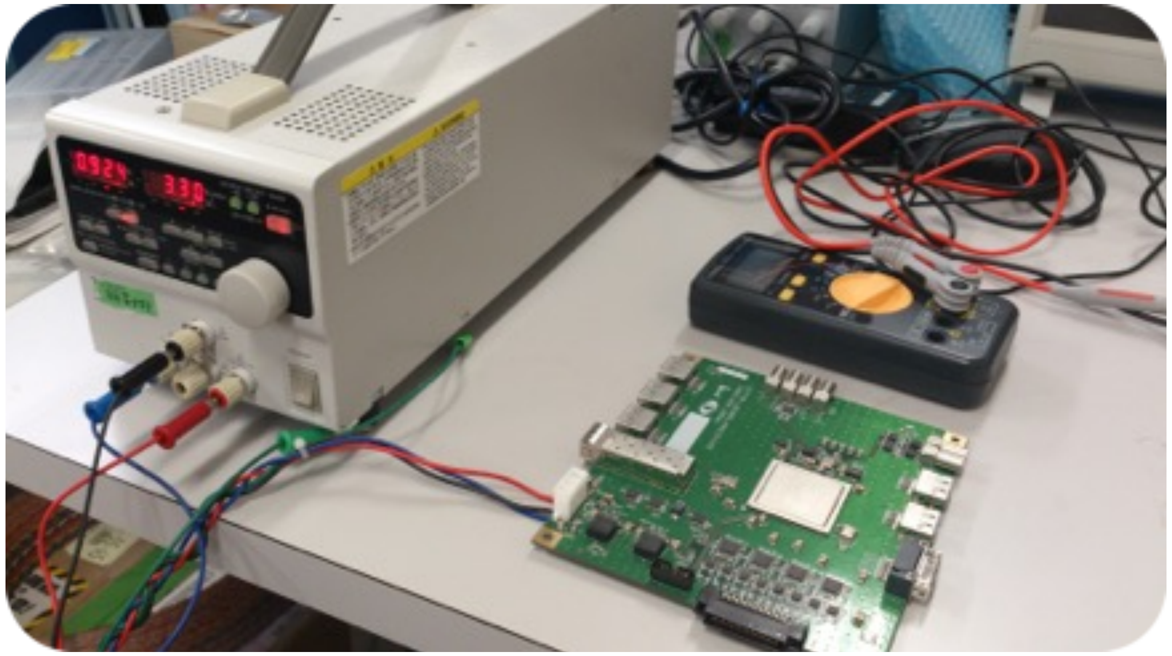
StrawECAL
20pAM-4 H. Yamaguchi
22pAH-3 S. Tanaka

Main Tasks in COMET



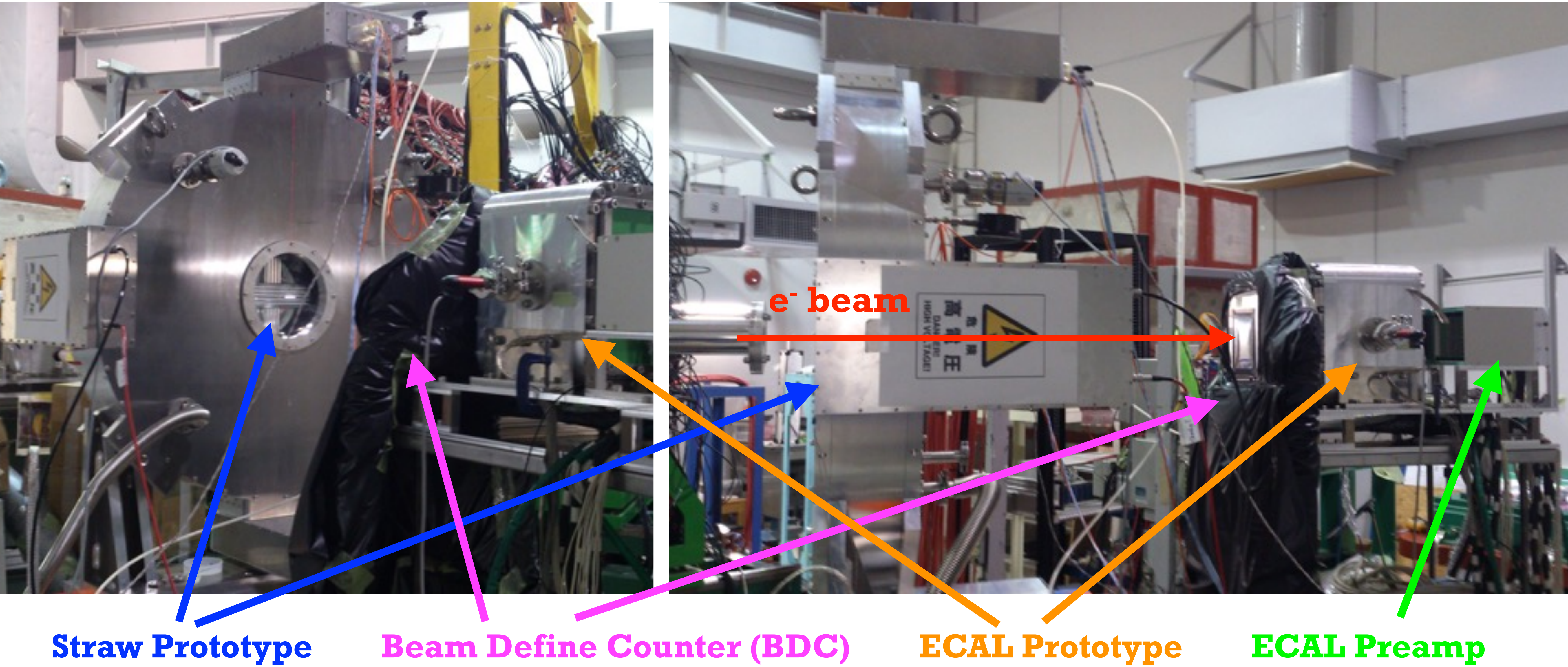


- **Software**
  - Development for the offline software "ICEDUST"
    - Simulation: Almost implemented
    - Reconstruction: Basic part established
- **Trigger**
  - Start the **COTTRI** (**CO**me**T TRI**gger) project as for the front-end trigger system
    - Design: 1st prototype was produced
    - Firmware Development: Ongoing



COTTRI Prototype in Lab

Beam Test @ELPH



- 1st Beam Test for Straw+ECAL
  - **During 4-13, March 2016**
  - The beam debut for COTTRI

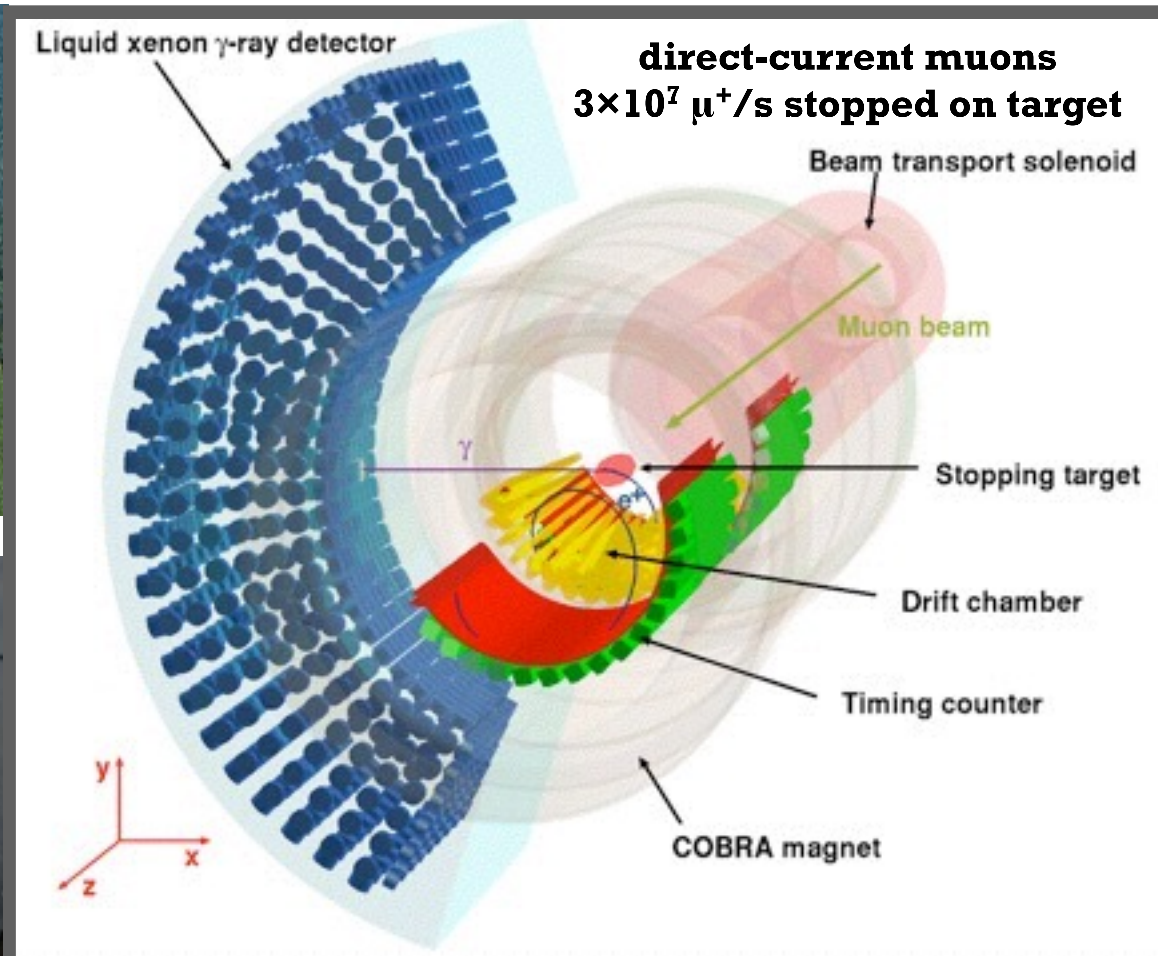
More details in 22aCA-7 Y. Fujii

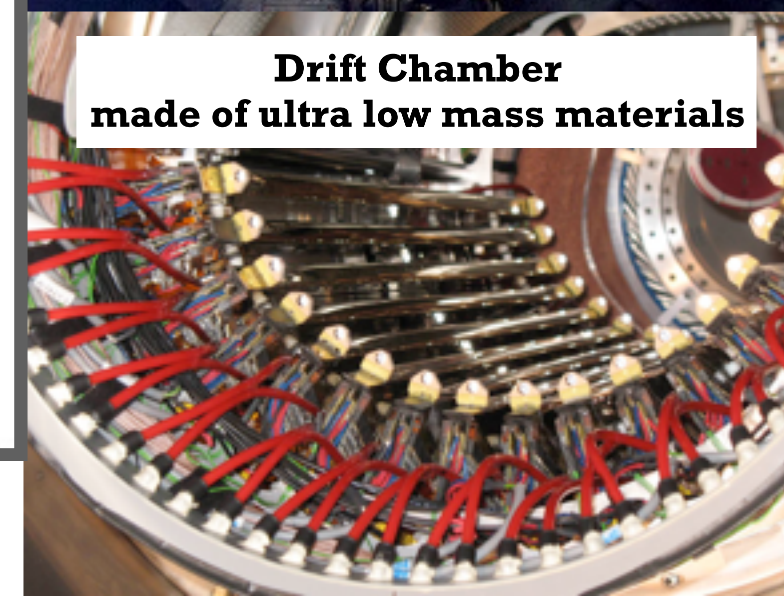
Summary

- **The $\mu^+ \rightarrow e^+\gamma$ decay is one of the powerful probes to investigate the BSM**
- **Most stringent upper limit on LFV processes is set by MEG**
  - ~~**$B(\mu \rightarrow e\gamma) < 5.7\times10^{-13}$**~~ **@ 90% C.L. → 4.2×10^{-13}** with a sensitivity of 5.3×10^{-13} including several updates
- **Preparations for MEG II is ongoing to start the data taking from 2017**
  - **Aiming to achieve 10 times higher sensitivity than that of MEG**
  - All detectors will be improved
    - LXe detector: Inner face PMTs ⇒ VUV-sensitive MPPCs
    - Drift chamber: 16 drift chamber modules ⇒ Stereo wire drift chamber with a single gas volume
    - Timing counter: Bar counter ⇒ Pixelated counter
    - Additional detectors are also being developed to further improve the sensitivity
- **Other muon CLFV searches will be started at the same period**
  - Complementary searches with comparable sensitivities as that of MEG II
  - The COMET experiment is searching for μ-e conversion with a sensitivity of 10^{-17}
    - Several detector R&Ds are ongoing now
    - **Very exciting stage!**

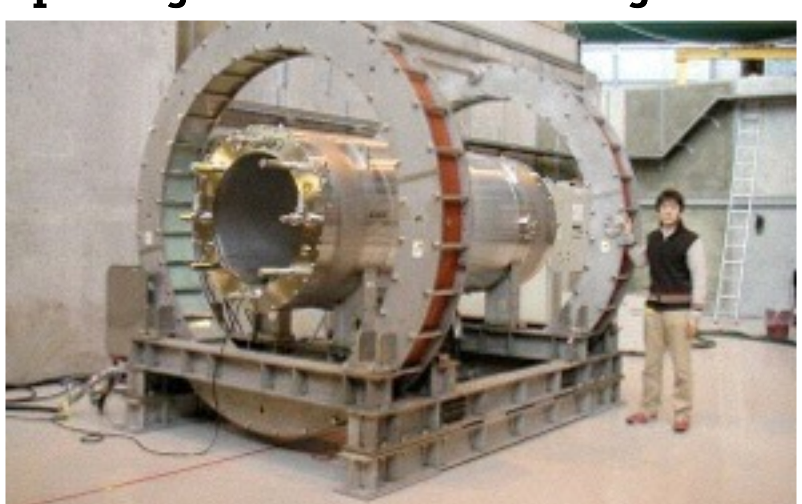
Backup

MEG Experiment

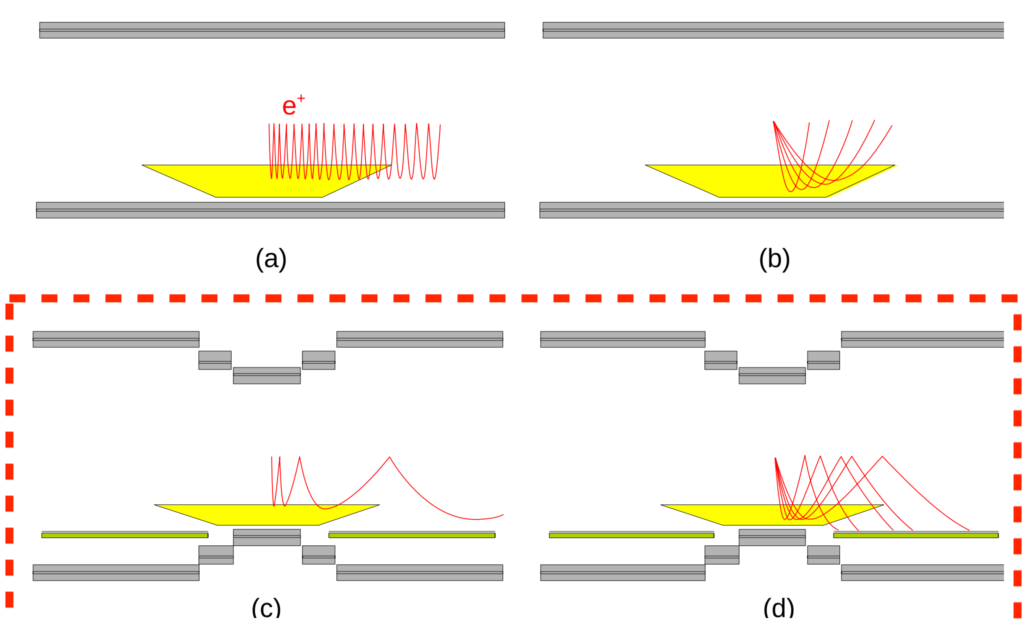


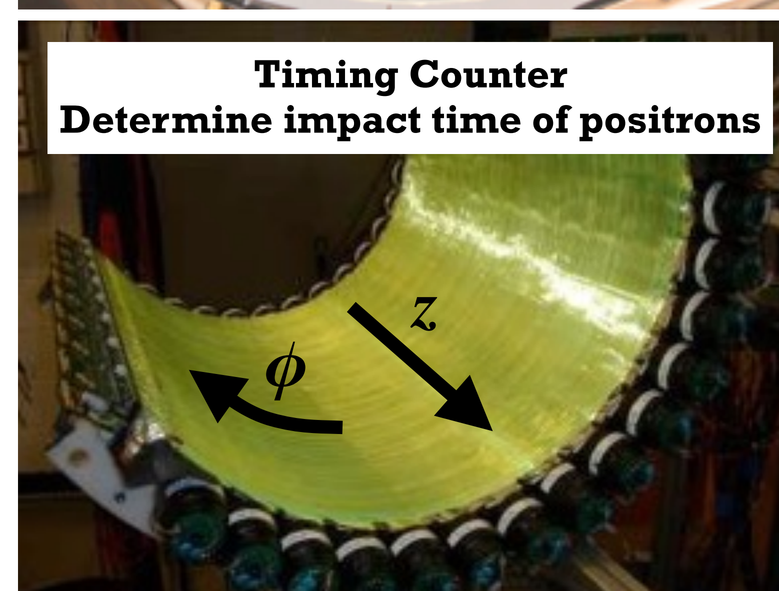


COBRA magnet
special graded field to detect signal e^+



COnstant Bending RAdius

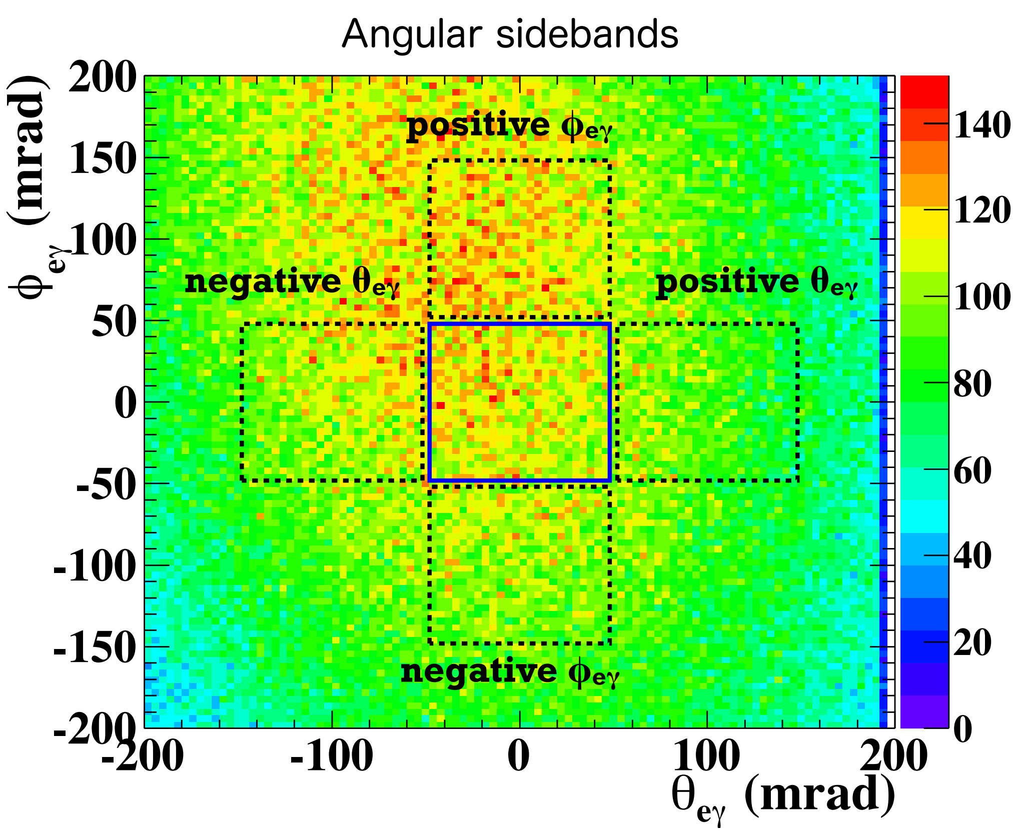




Datasets

- Signal Region
  - Use datasets of 2009-2010 combined, 2011 only and 2009-2011 combined
    - $48 \leq E_\gamma \leq 58$ MeV,
    - $50 \leq E_e \leq 56$ MeV,
    - $|\phi_{e\gamma}| \leq 50$ mrad and $|\theta_{e\gamma}| \leq 50$ mrad,
    - $|t_{e\gamma}| \leq 0.7$ ns,

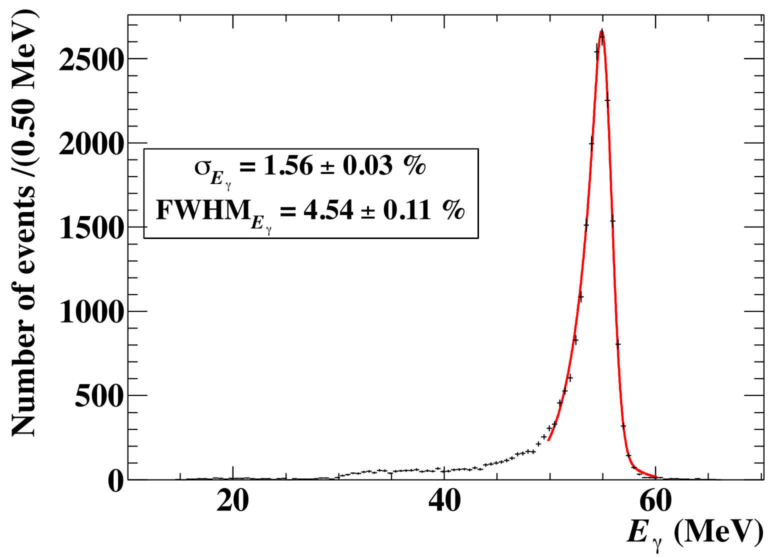
    + Select only a pair of e-γ
  - $\Rightarrow$ 86% of analysis efficiency
- Time sidebands
  - Check the reliability of acc. BG PDFs before unblind
  - Analyze the regions of $|t_{e\gamma} \pm 2\text{ ns}| < 0.7$ ns
- Angular sidebands
  - Check the reliability of RMD PDFs before unblind
  - Use 100 mrad off-axis regions for $\phi_{e\gamma}$ or $\theta_{e\gamma}$



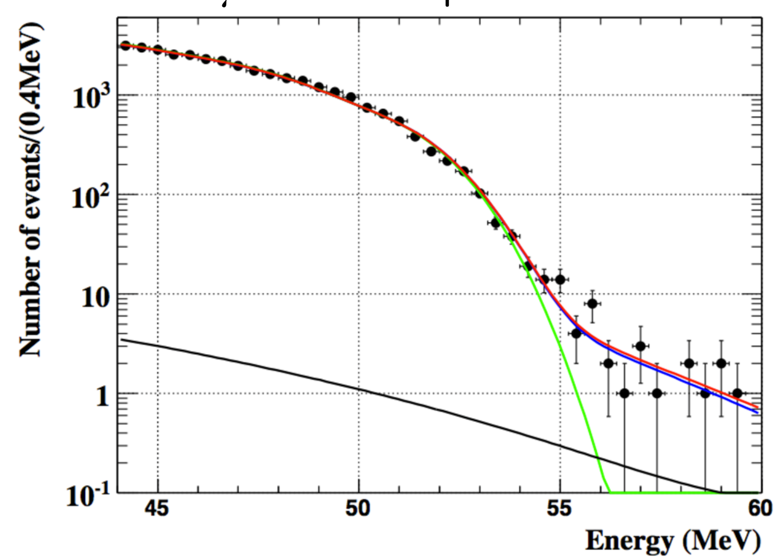
PDF

- E_γ PDF: signal ⇒CEX data, RMD ⇒ theoretical+measured detector response, accidental ⇒ sideband
- $T_{e\gamma}$ PDF: signal/RMD ⇒ measured RMD, accidental ⇒ flat

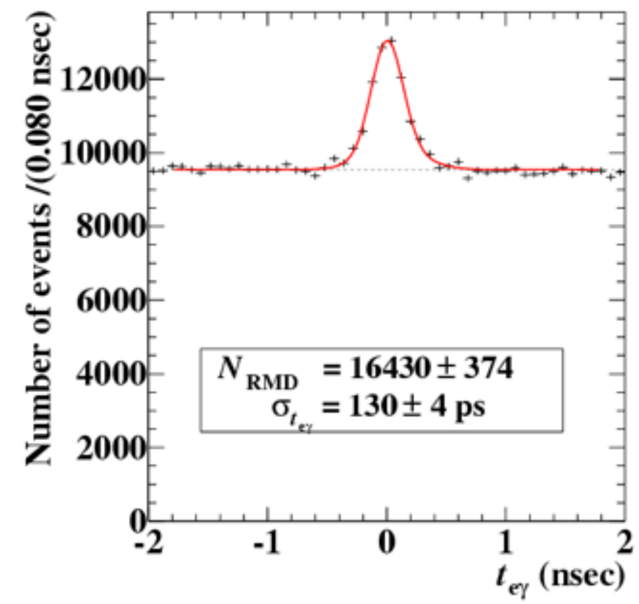
CEXラン55 MeVガンマのフィット結果



E_γ sideband spectrum



$T_{e\gamma}$ spectrum in E_γ sideband



- Old PDF for positron observables (category PDF)
  I. Positrons are divided by two category PDFs by their "quality" e.g. #of hits, Δt between DC/TC
  II. PDF parameters are determined for each category separately
- New PDF (per-event PDF)
  III. Determine the event-by-event uncertainties (σ'_x) using the error matrix provided by the fitting
  IV. Calculate the scaling parameters (s_x) to convert the per-event uncertainties to resolutions from sideband data
  V. Correlations are mostly calculated from the MC

Sideband Results

- Further check for sideband data

Table 7.2: Time sideband results without including systematic uncertainties.

Dataset	$\mathcal{B}$ best fit	$\mathcal{B}$ upper limit
2009-2010 negative	7.7×10^{-13}	3.1×10^{-12}
2009-2010 positive	-2.8×10^{-13}	1.1×10^{-12}
2011 negative	3.7×10^{-15}	1.7×10^{-12}
2011 positive	2.1×10^{-13}	1.4×10^{-12}
2009-2011 negative	3.5×10^{-13}	1.6×10^{-12}
2009-2011 positive	7.8×10^{-14}	8.1×10^{-13}

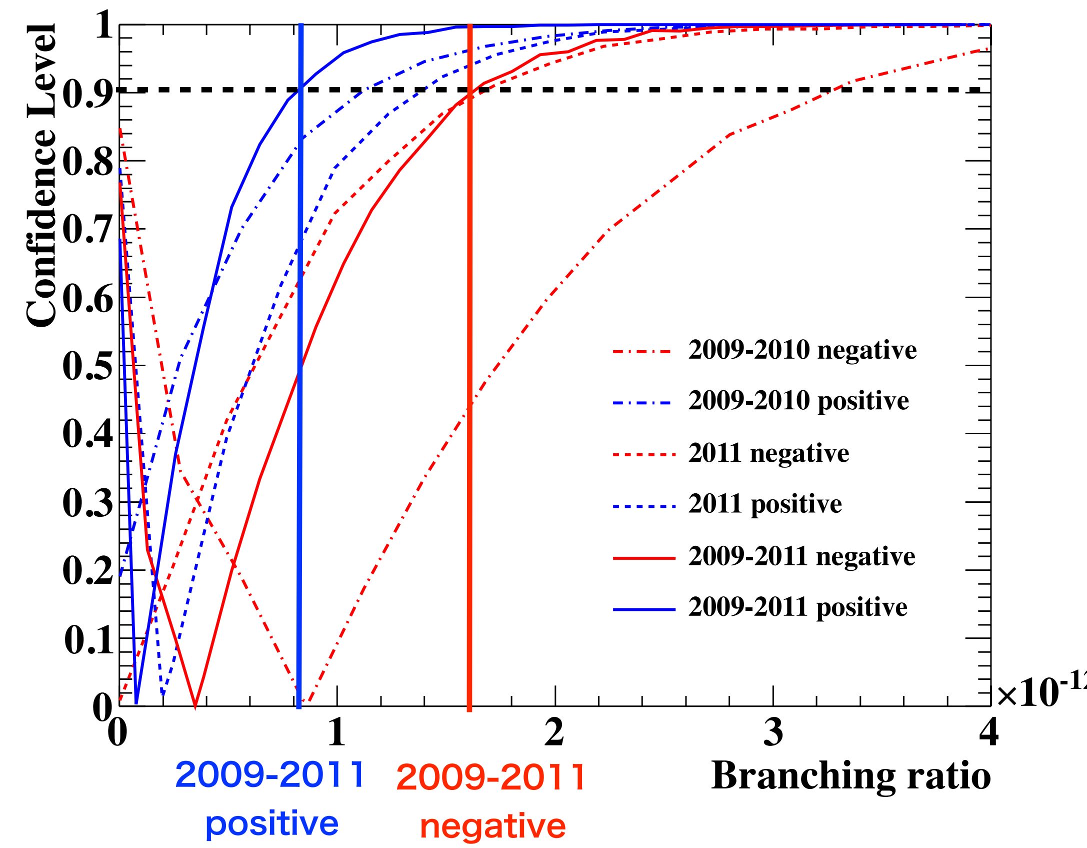


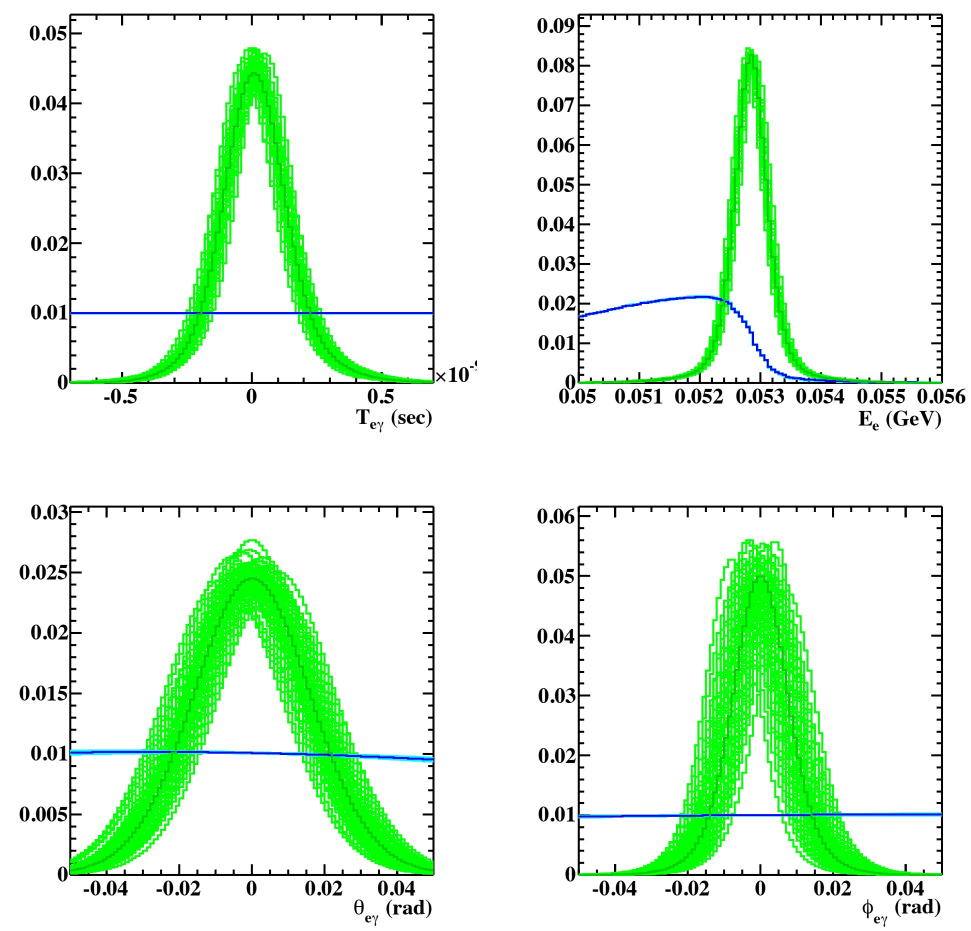
Table 7.4: Angle sideband results without constraints on the number of backgrounds (Uncertainties are in 1σ). N_{sig} = 0に固定

Dataset	$\langle N_{BG} \rangle$	$\langle N_{RMD} \rangle$	N_{obs}	$\hat{N}_{BG}$	$\hat{N}_{RMD}$
2009-2010 negative ϕ	1120 ± 17	34 ± 3	1120	1077 ± 35	40 ± 15
2009-2010 positive ϕ	1169 ± 17	36 ± 3	1247	1212 ± 39	46 ± 18
2009-2010 negative θ	1123 ± 17	39 ± 4	1120	1083 ± 36	35 ± 16
2009-2010 positive θ	877 ± 15	24 ± 2	962	963 ± 34	1 ± 12
2011 negative ϕ	1130 ± 18	35 ± 4	1163	1132 ± 37	27 ± 15
2011 positive ϕ	1189 ± 18	37 ± 4	1241	1195 ± 38	47 ± 16
2011 negative θ	1131 ± 18	41 ± 4	1233	1208 ± 38	27 ± 15
2011 positive θ	976 ± 17	25 ± 3	1016	979 ± 34	37 ± 14
2009-2011 negative ϕ	2228 ± 24	69 ± 7	2283	2210 ± 51	66 ± 21
2009-2011 positive ϕ	2365 ± 25	73 ± 7	2488	2404 ± 54	93 ± 24
2009-2011 negative θ	2251 ± 24	80 ± 8	2353	2292 ± 52	61 ± 22
2009-2011 positive θ	1855 ± 22	49 ± 5	1978	1939 ± 48	41 ± 18

- Signal, RMD無しのtime sidebandは実験感度と無矛盾な結果
  - BG PDFは問題無し
- Angle sidebandのフィット結果, RMD観測数は期待値とベストフィットで無矛盾
  - RMD PDFも問題無し

→ いよいよ信号領域を解析！

Systematics



Dark Green: signal PDF
Green: signal PDF w/ fluctuation
Blue: BG PDF
Cyan: BG PDF w/ fluctuation

陽電子とガンマ線相対角度の不定性
⇒ 検出器位置の不定性, 磁場の影響

パラメータ相関の不定性(ジオメトリー起源)

Relative contributions (RMS of ΔΔNLL) of uncertainties

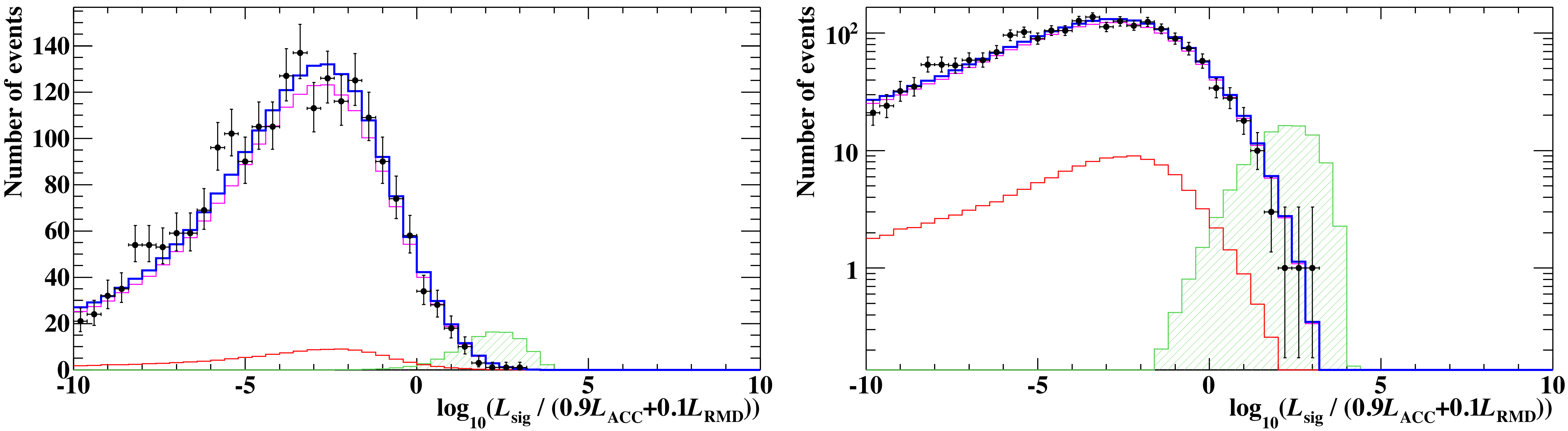
Center of $\theta_{e\gamma}$ and $\phi_{e\gamma}$	0.18
Positron correlations	0.11
E_γ scale	0.07
E_e bias	0.06
$t_{e\gamma}$ signal shape	0.06
$t_{e\gamma}$ center	0.05
Normalization	0.04
E_γ signal shape	0.03
E_γ BG shape	0.03
Positron angle resolutions (θ_e, ϕ_e, z_e, y_e)	0.03
γ angle resolution (u_γ, v_γ, w_γ)	0.03
E_e BG shape	0.01
E_e signal shape	0.01
Angle BG shape	0.00
Total	0.25

- バックグラウンドは高い精度でコントロールされており, 不定性が小さい
- Signal PDFの不定性は比較的大きいが, 観測されたN_{sig}が小さかったため, 崩壊分岐比の90%上限値に対する影響は少ない
  - 2009-2011データに対して数%程度の影響

R_{sig} Distribution

- Relative signal likelihood defined as follows: (Large R_{sig}=signal like events)

$$R_{\rm sig} = \log_{10} \frac{L_{\rm sig}}{0.1 \cdot L_{\rm RD} + 0.9 \cdot L_{\rm BG}}. \quad (7.1)$$



- **Data**

Magenta: toy-MC of BG PDF

- normalized to the expected N_{BG}

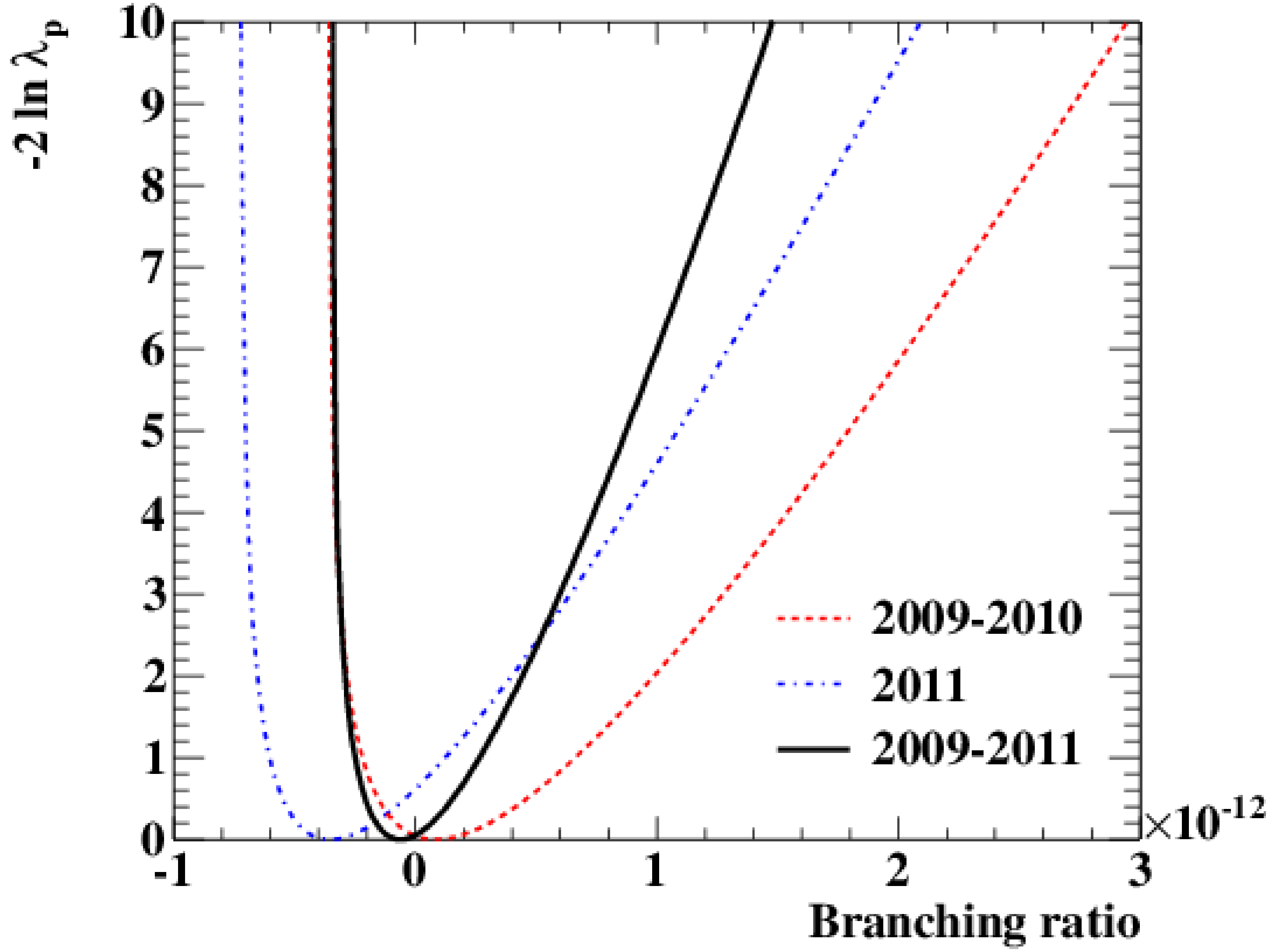
Red: toy-MC of RMD PDF

- normalized to the expected N_{RMD}

Green: toy-MC of signal

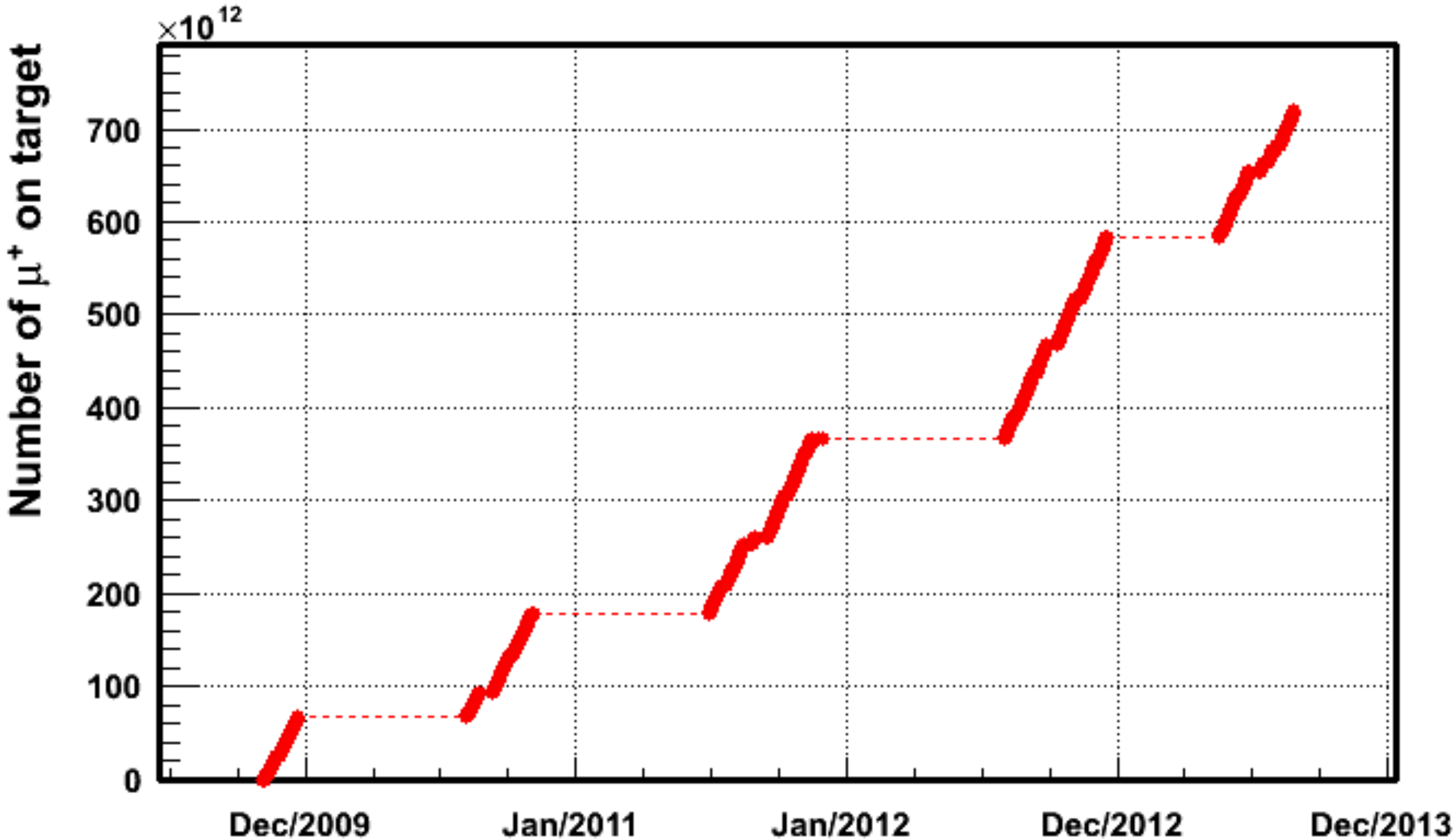
- normalized to N_{sig}=100

Likelihood Curve



$$\lambda_{\mathrm{p}} = \frac{\mathcal{L}(N_{\mathrm{sig}}^{\mathrm{fix}}, N_{\mathrm{RMD}}(N_{\mathrm{sig}}^{\mathrm{fix}}), N_{\mathrm{BG}}(N_{\mathrm{sig}}^{\mathrm{fix}}))}{\mathcal{L}(N_{\mathrm{sig}}, N_{\mathrm{RMD}}, N_{\mathrm{BG}})}$$

2009-2013


$\times 10^{12}$
Number of μ^+ on target
0
100
200
300
400
500
600
700
Dec/2009
Jan/2011
Jan/2012
Dec/2012
Dec/2013