Experimental Search for LFV Muon Decay

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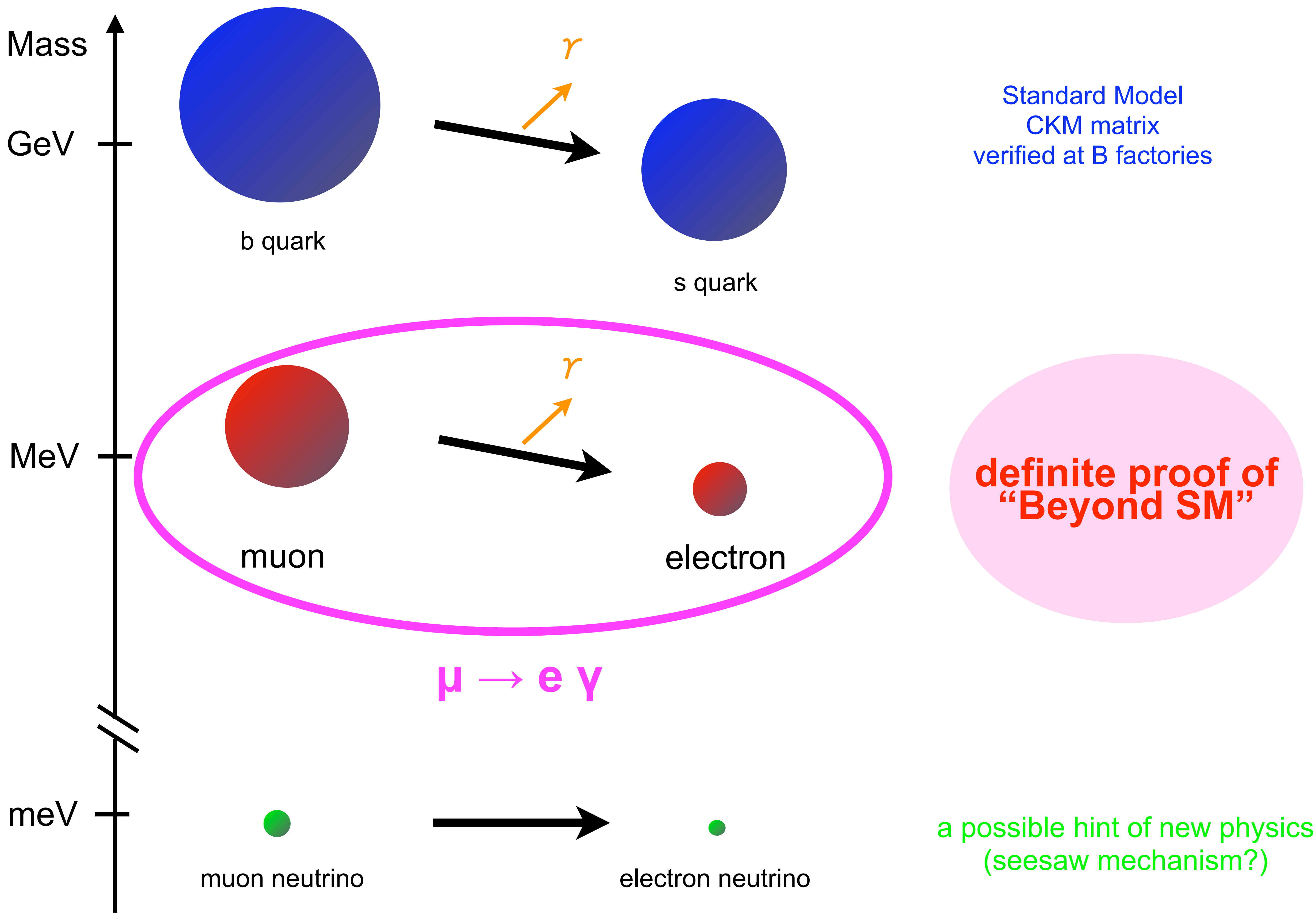
Topics to Cover

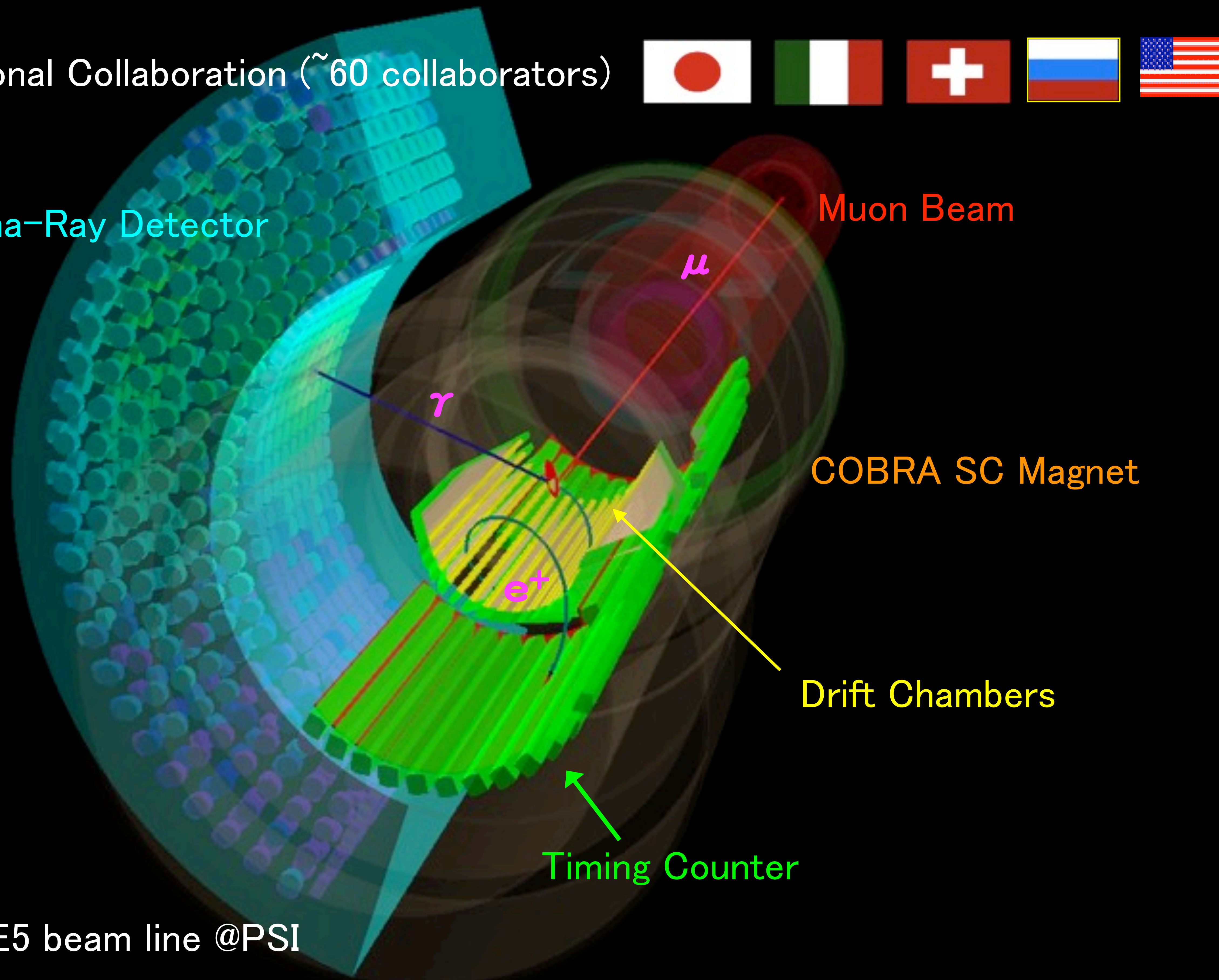
- No Experimental Program exists for $\mu^+ \rightarrow \mathrm{e}^+\mathrm{e}^-\mathrm{e}^+$
- $\mu^+ \rightarrow \mathrm{e}^+\gamma$: The MEG Experiment

Transitions Between Generations



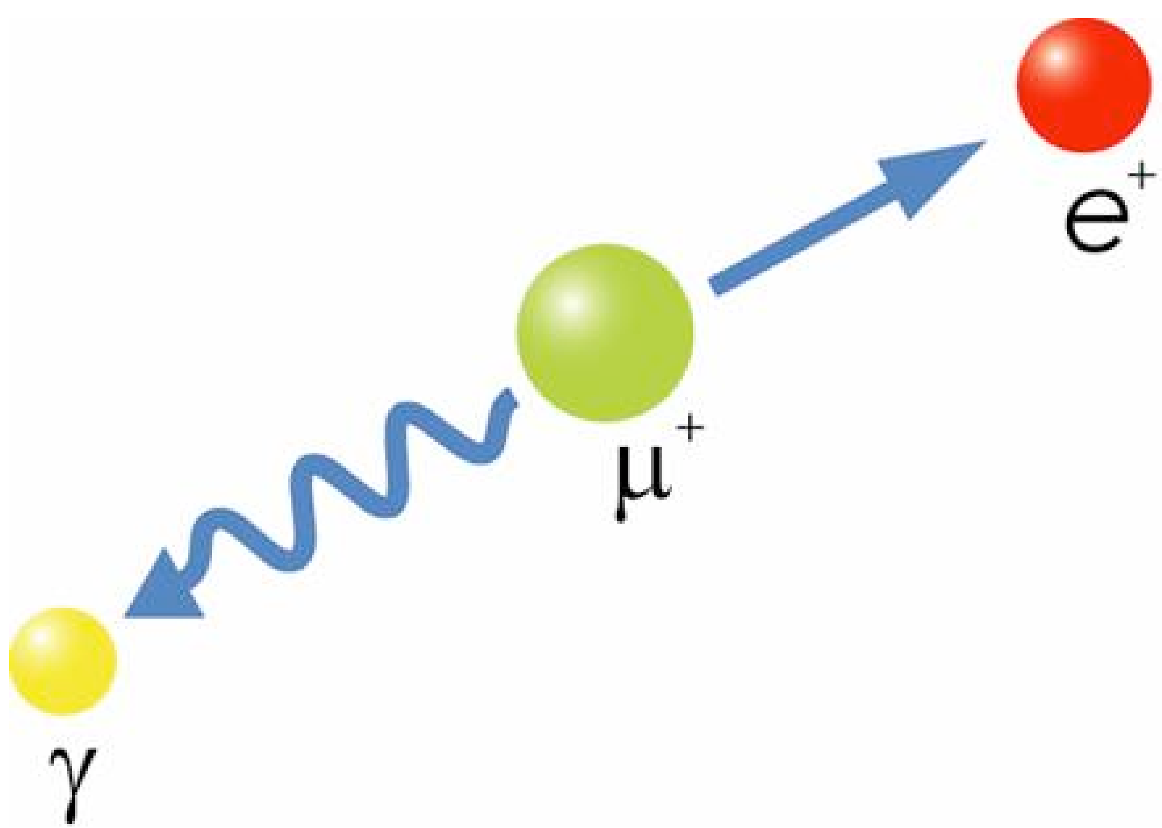
The MEG Experiment

International Collaboration (~60 collaborators)



π E5 beam line @PSI

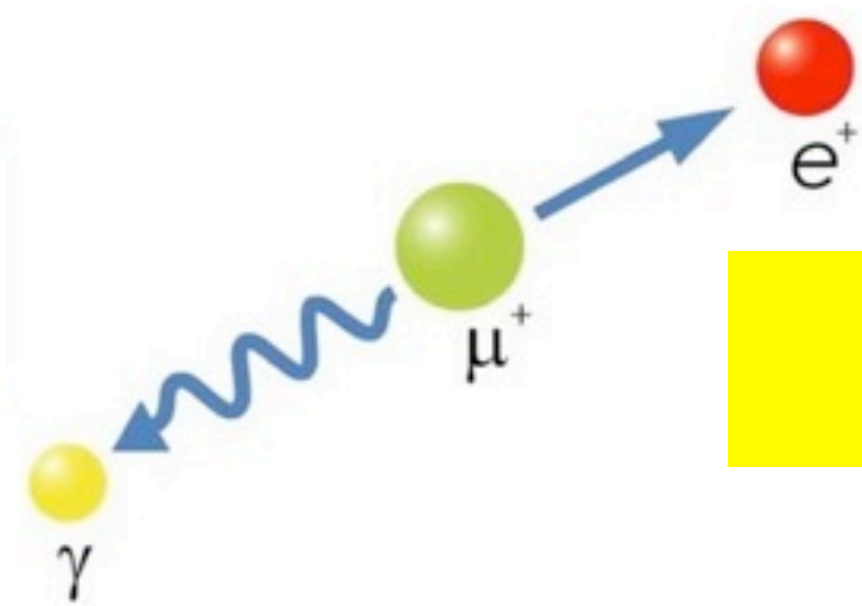
The $\mu^+ \to e^+\gamma$ process



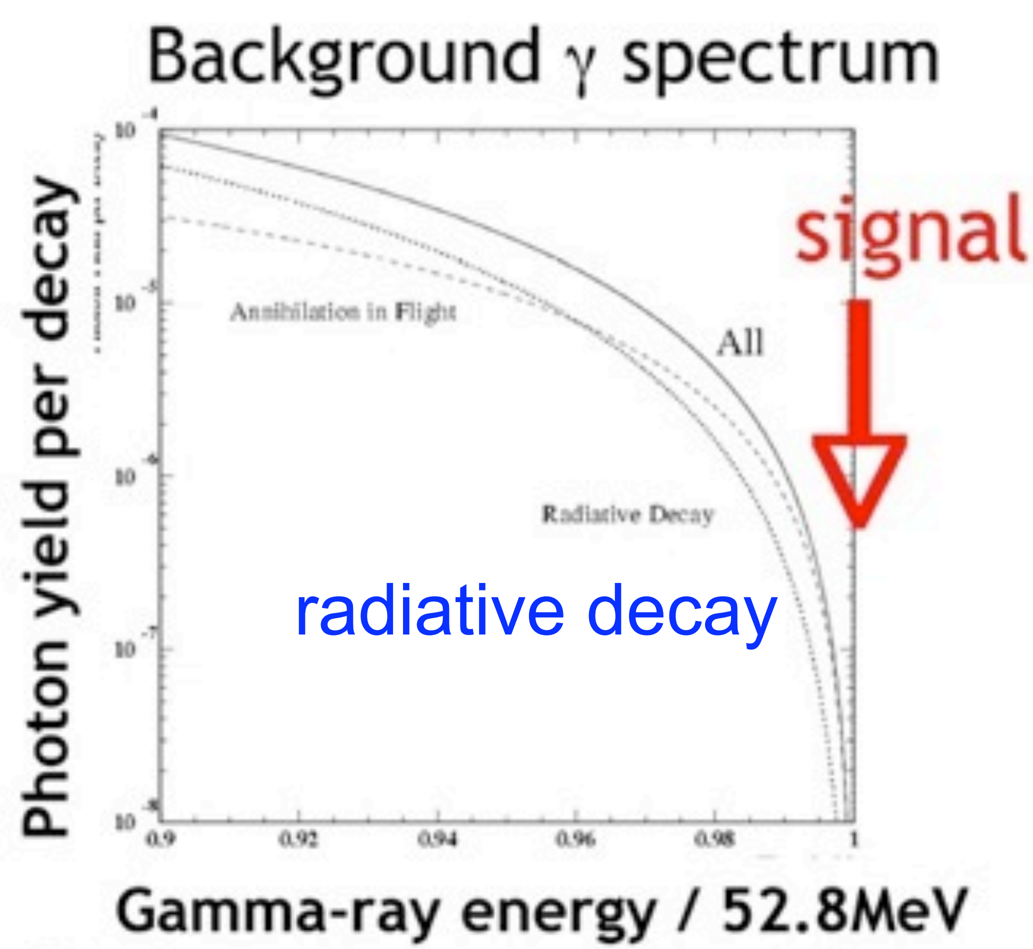
- clear 2-body kinematics
- need **positive muons** to avoid formation of muonic atoms
- **accidental background** limits the experiment
  - **DC beam**, rather than pulsed beam, gives lowest instantaneous rate and thus lowest background

Accidental coincidence of γ and e⁺ is the main background

γ ray measurement
Is most important!



must manage
high rate e+



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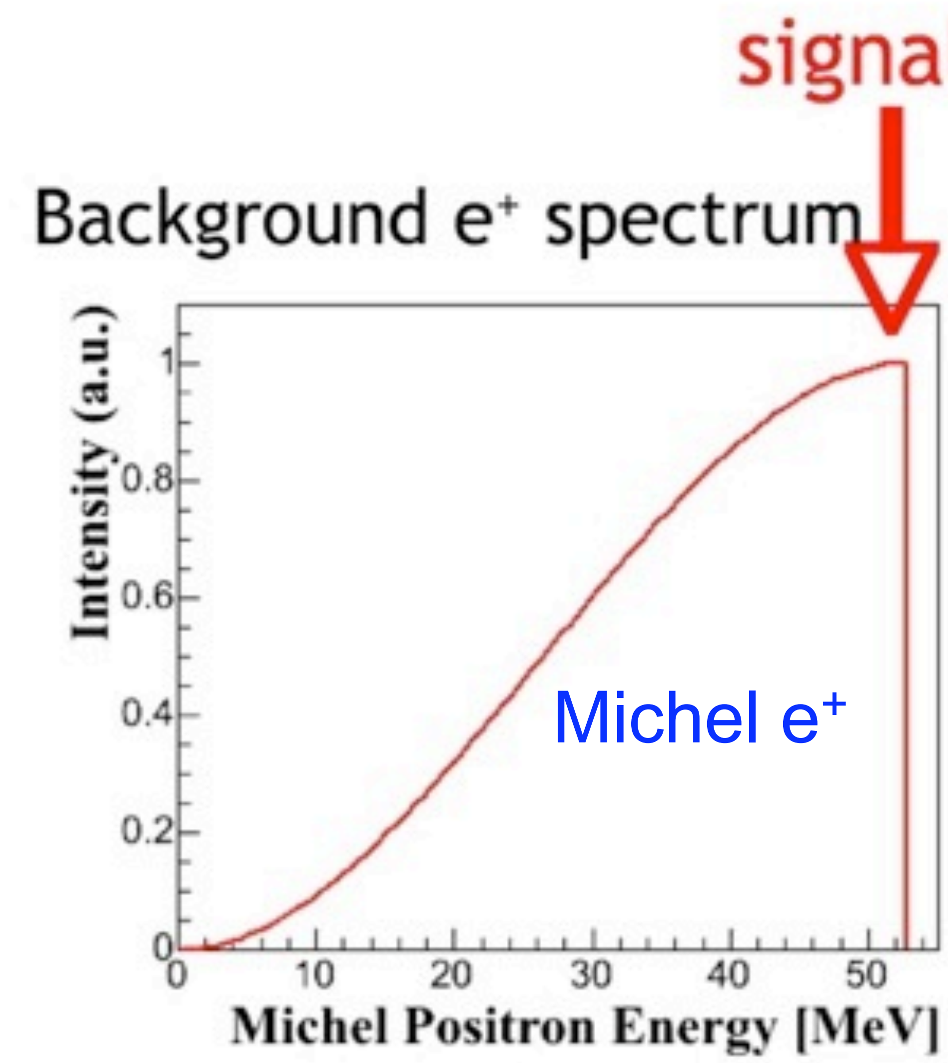
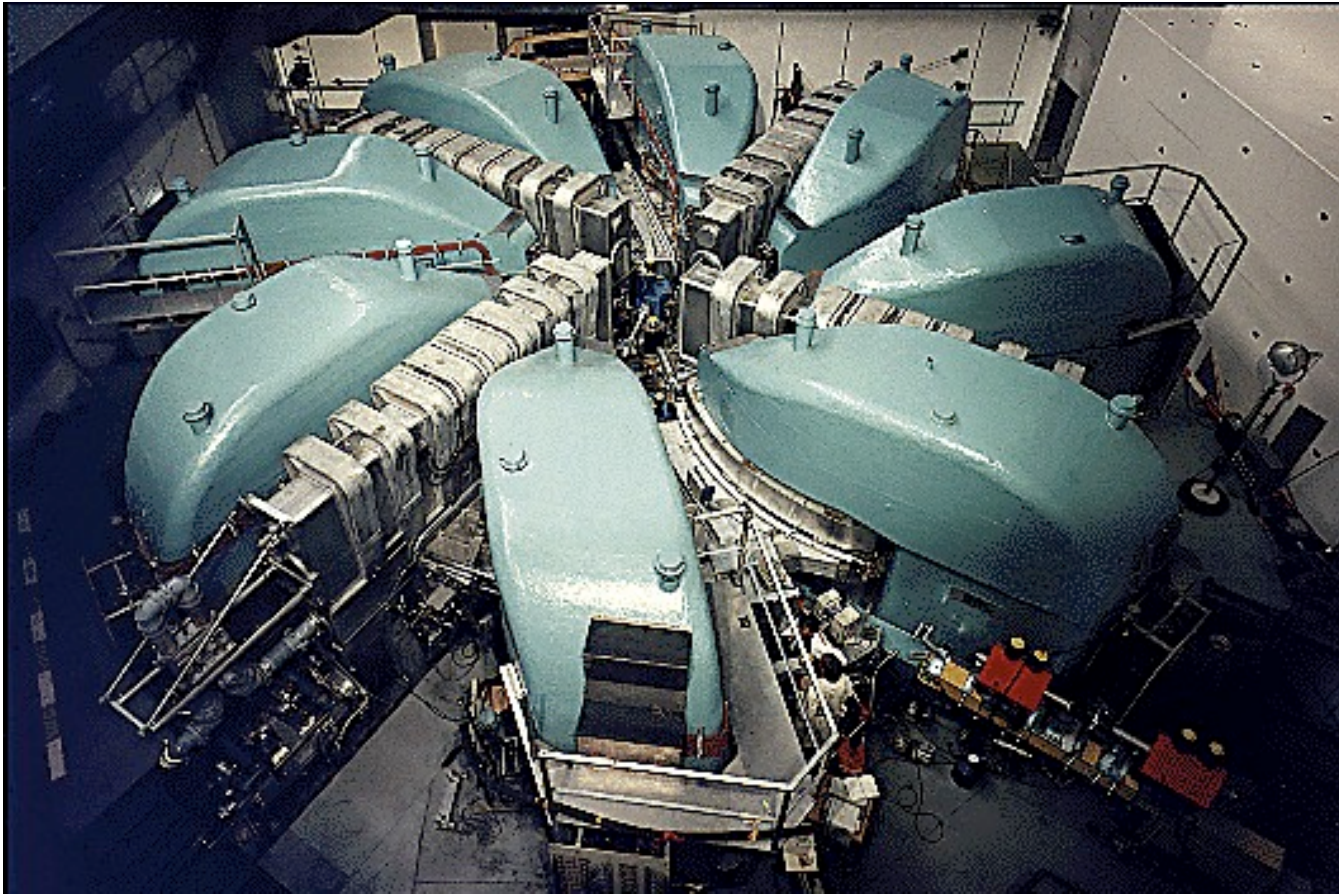
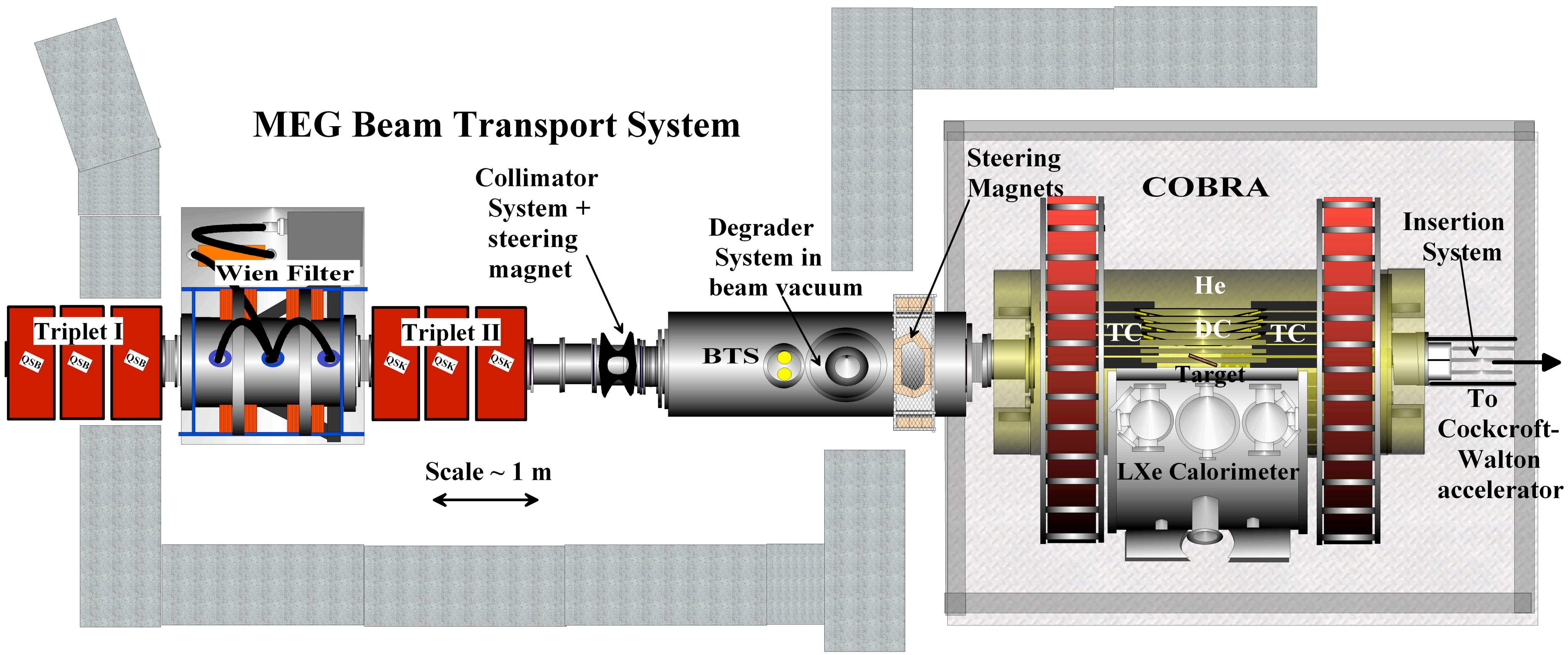


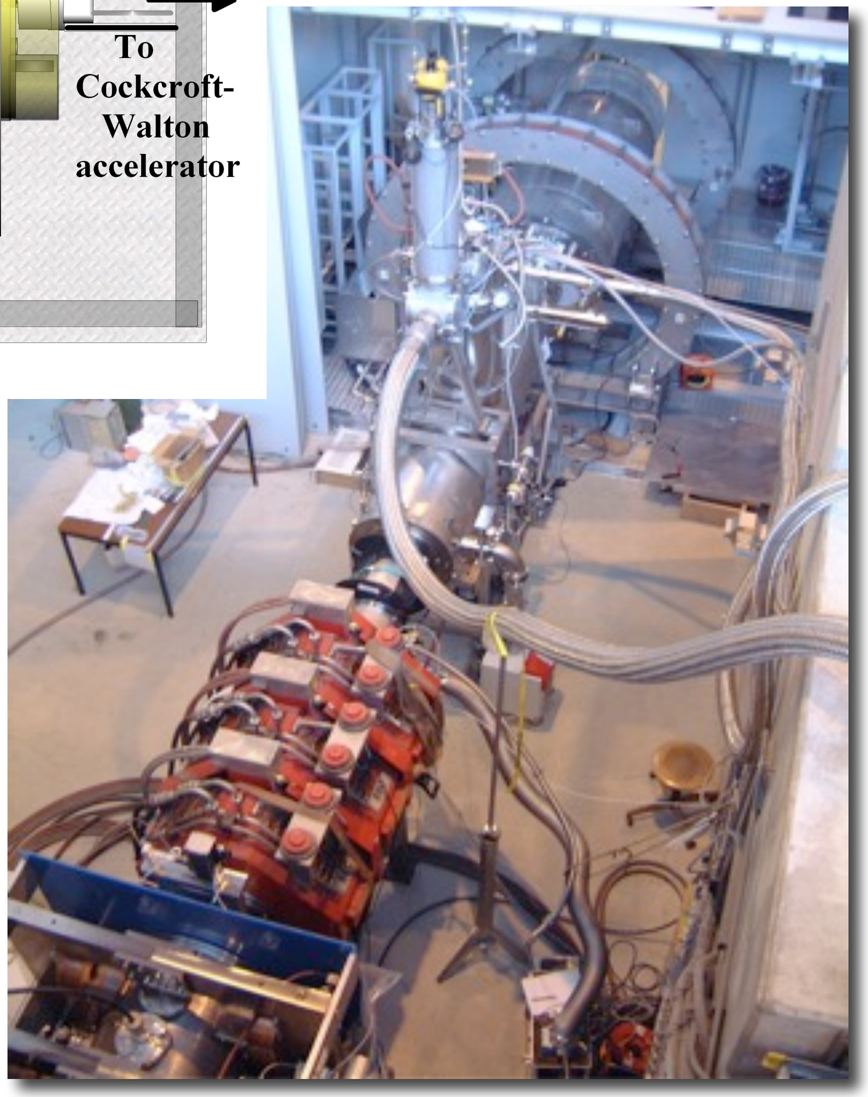
1.2MW Proton Cyclotron at PSI



Provides world's most powerful DC muon beam

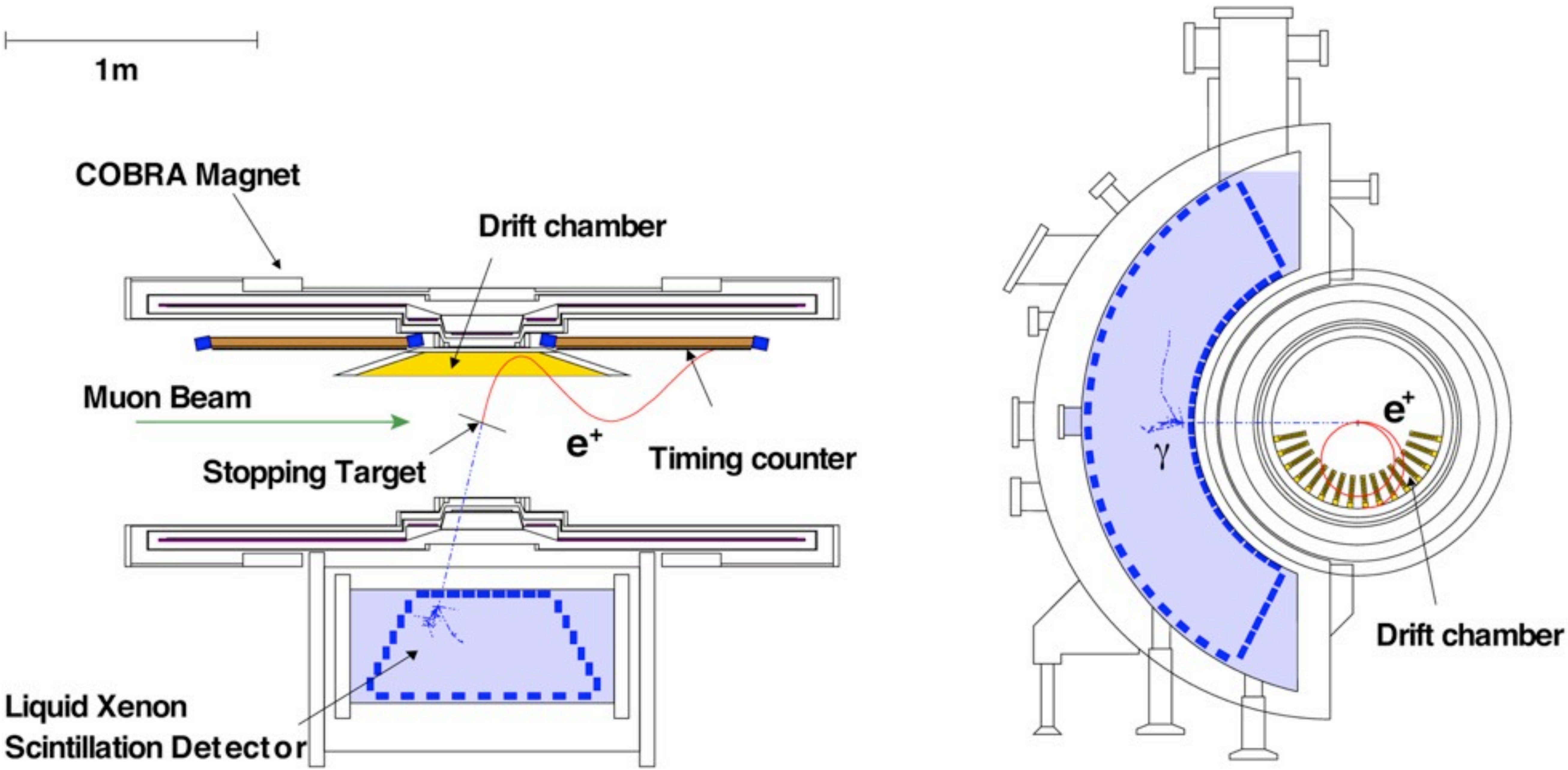
"Surface Muon" Beam Transport System





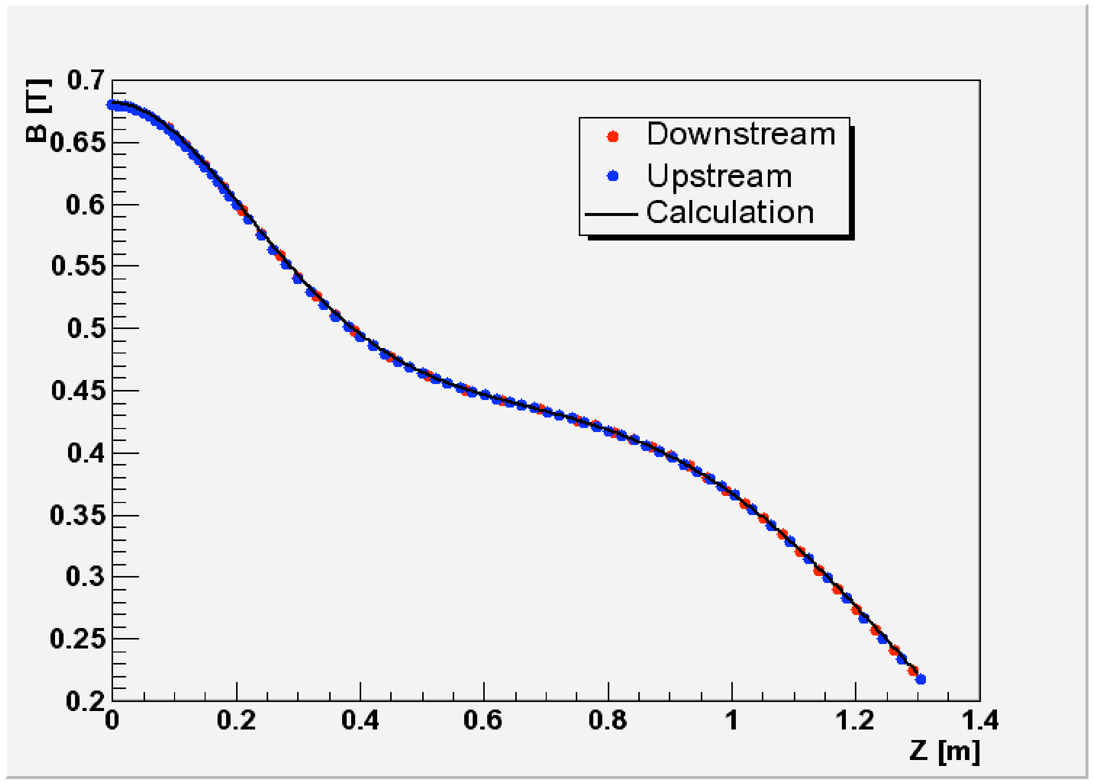
- 3×10^7 muons/sec stopped in 18mg/cm2 polyethylene target (slanted by 20.5^o from the beam) with 10mm spot size at the center of the spectrometer
- He environment inside the spectrometer to minimize scattering and background

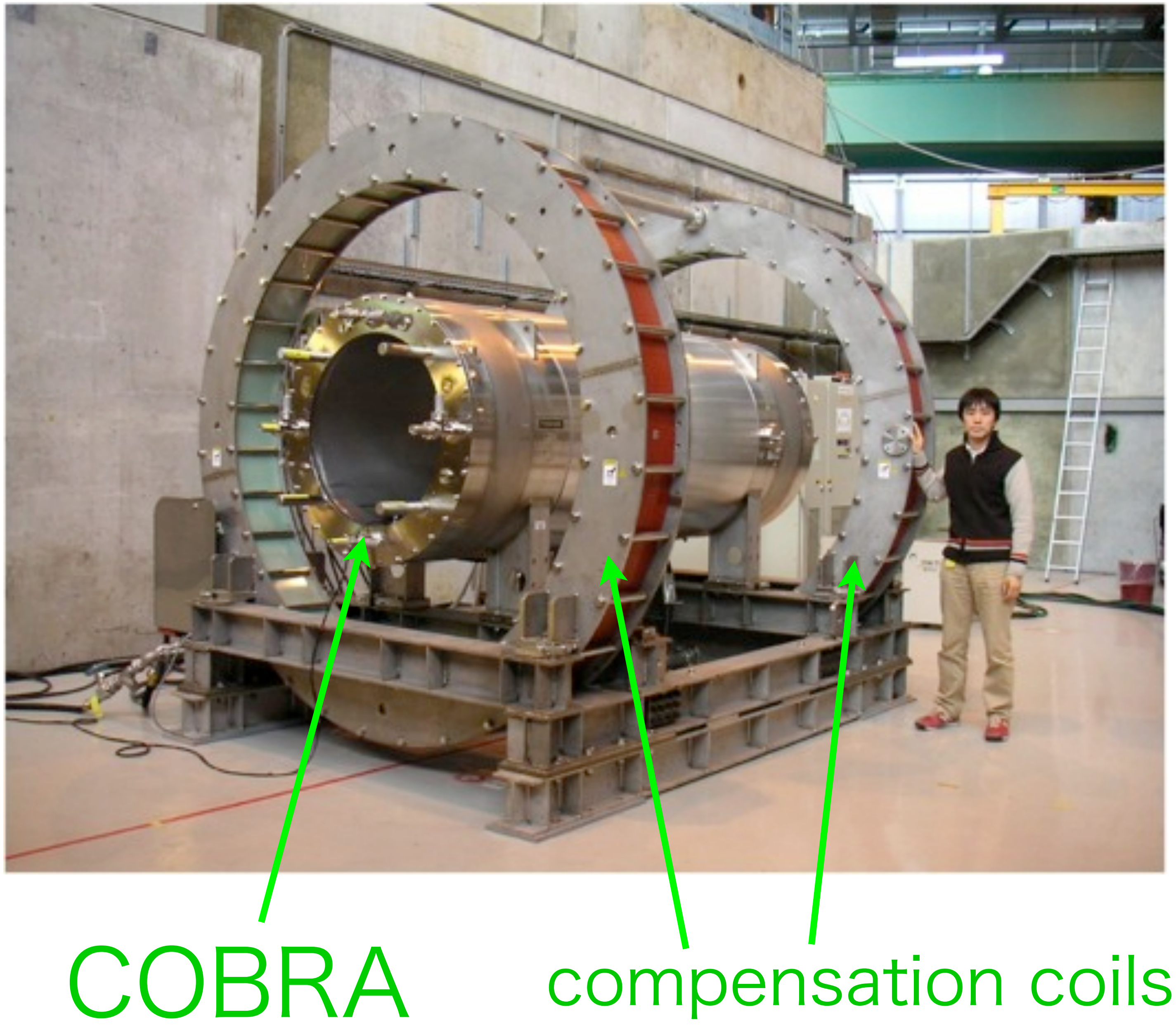
The MEG Experiment

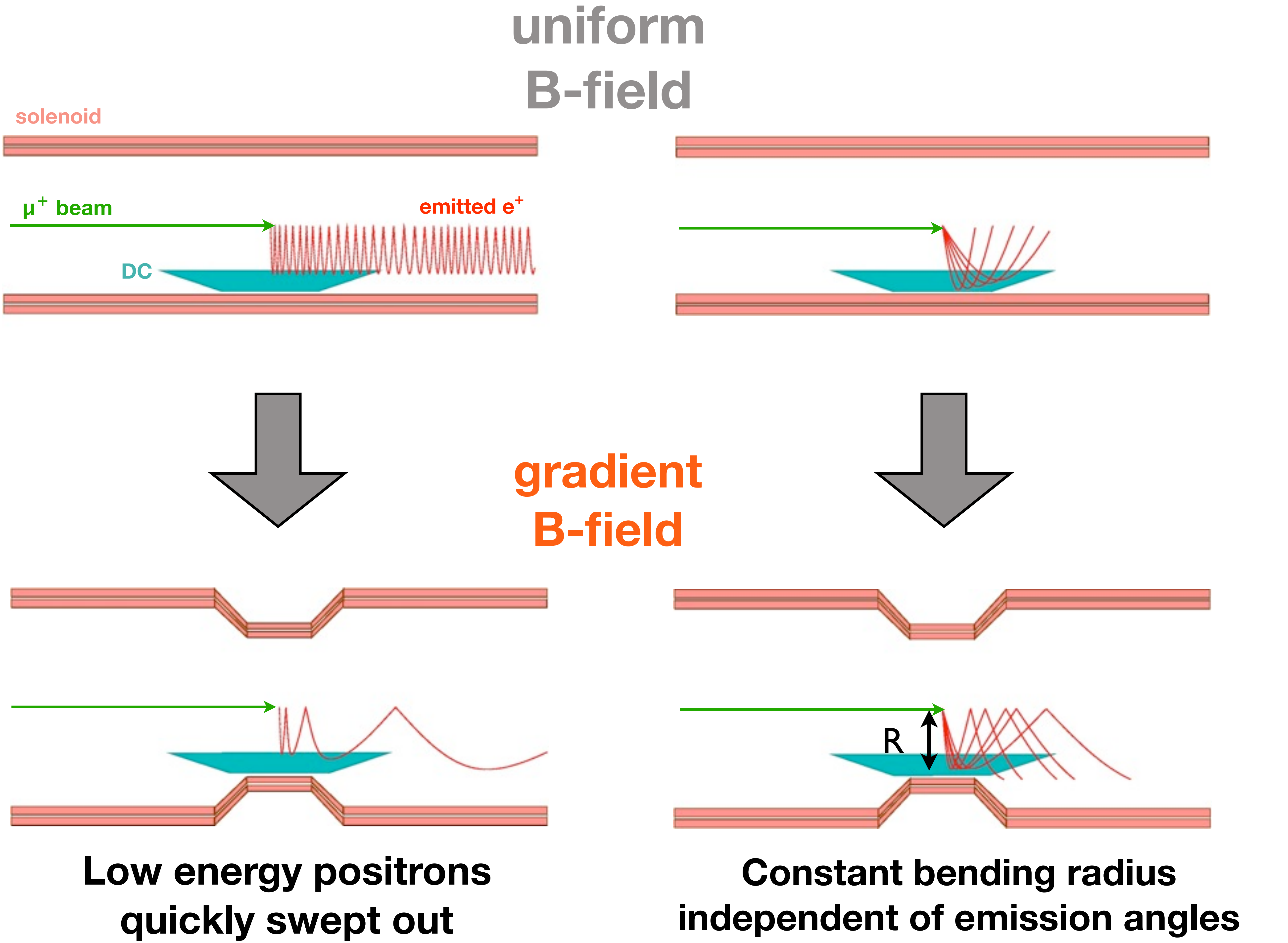


COBRA Positron Spectrometer

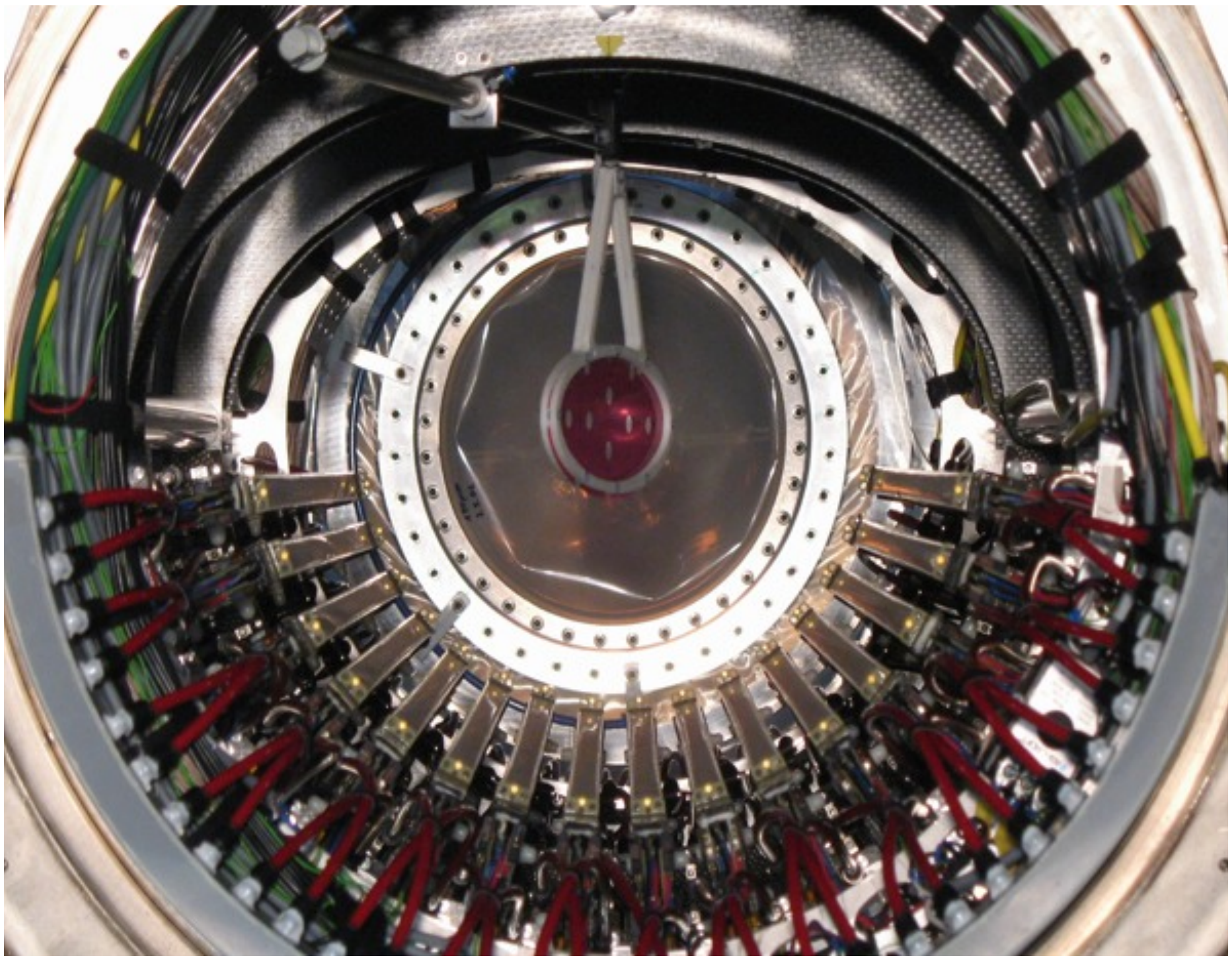
- thin-walled SC solenoid with a gradient magnetic field: 1.27 - 0.49 Tesla





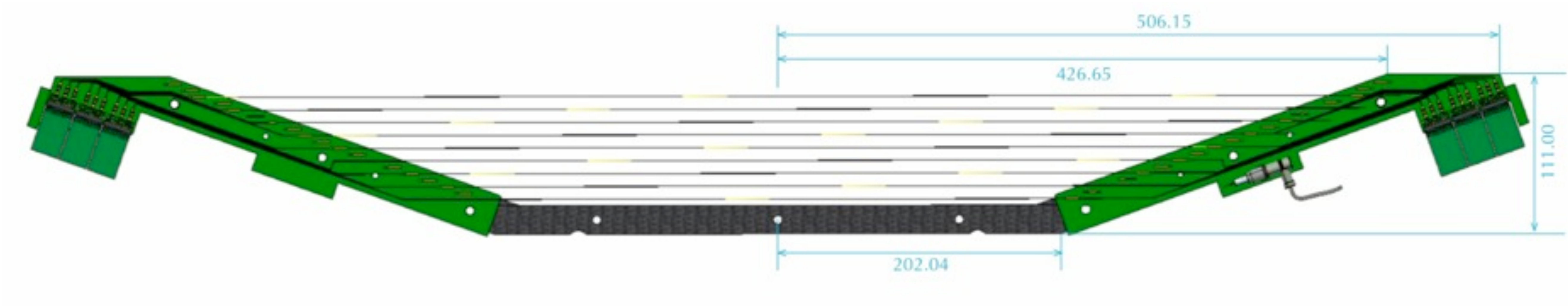

uniform
B-field
solenoid
μ+ beam
emitted e+
DC
gradient
B-field
R
Low energy positrons
quickly swept out
Constant bending radius
independent of emission angles

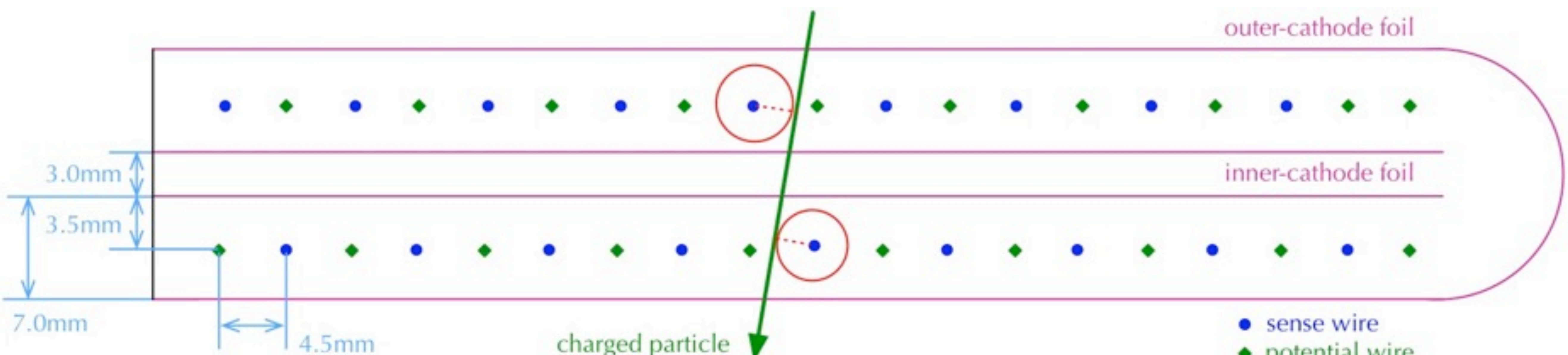
Low-Mass Drift Chambers (DC)



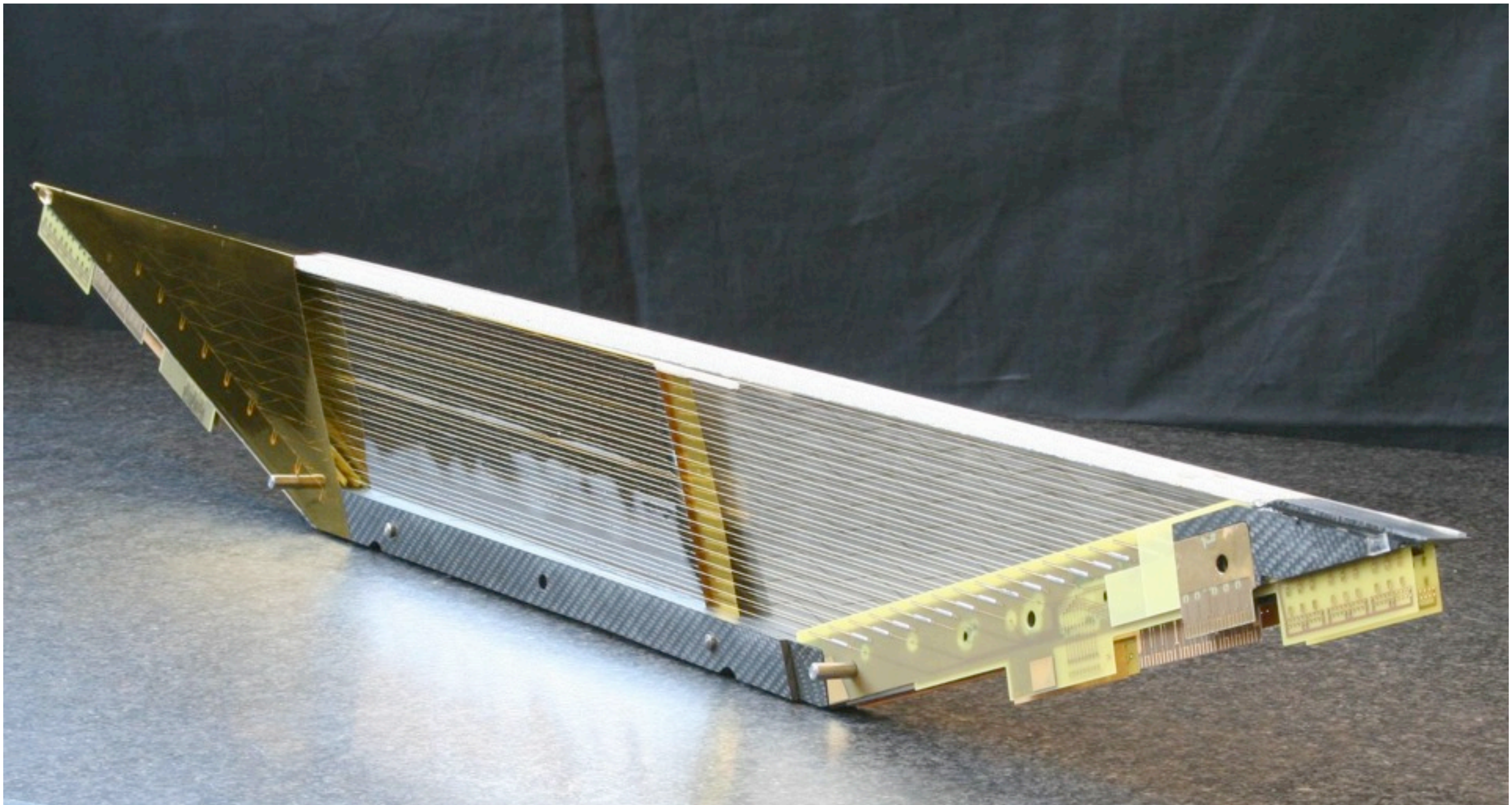
- 16 radially aligned modules, each consists of two staggered layers of wire planes
- 12.5um thick cathode foils with a Vernier pattern structure
- He:ethane = 50:50 differential pressure control to COBRA He environment
- ~2.0×10^{-3} X_0 along the positron trajectory

A Drift Chamber Module



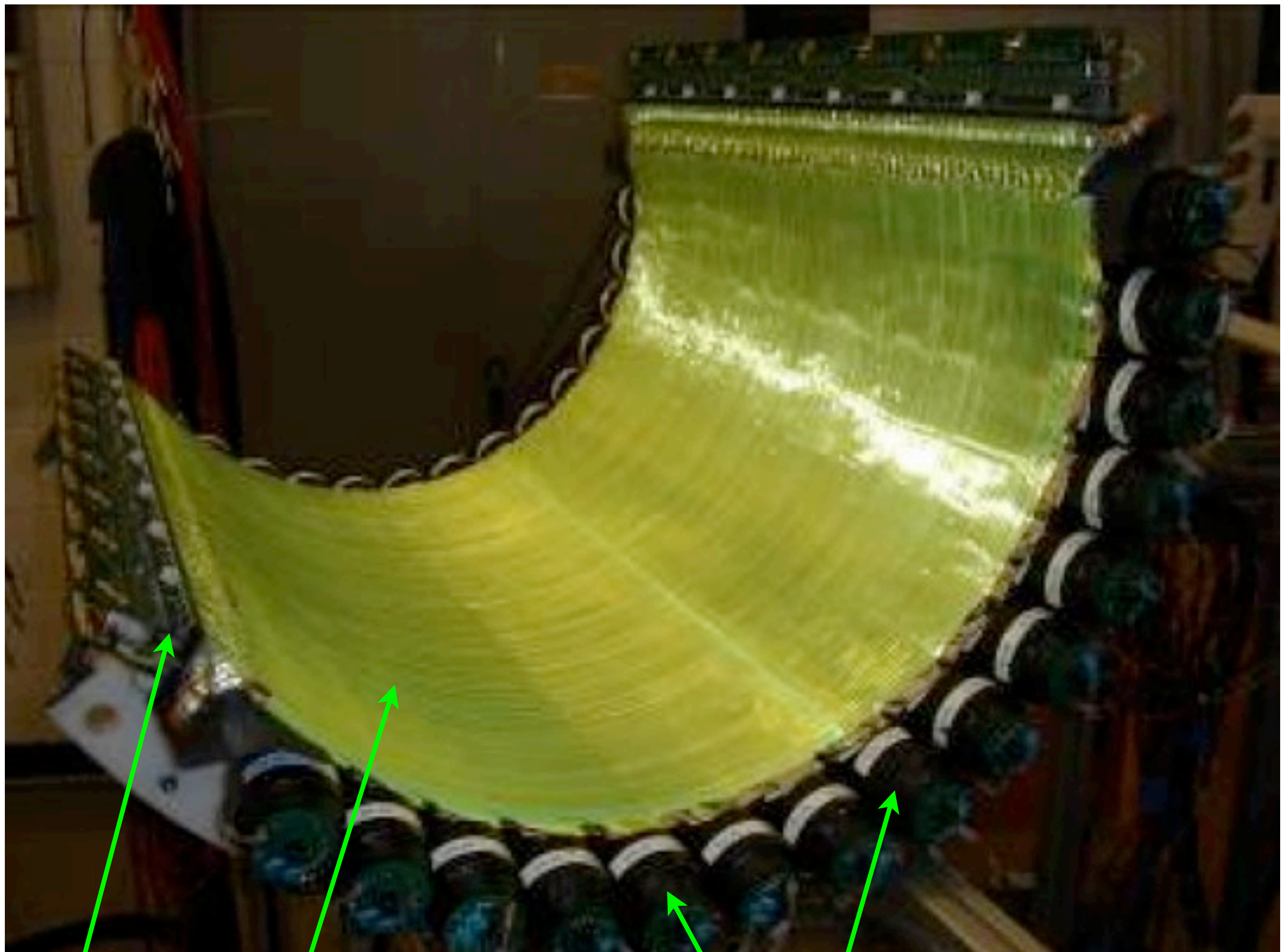


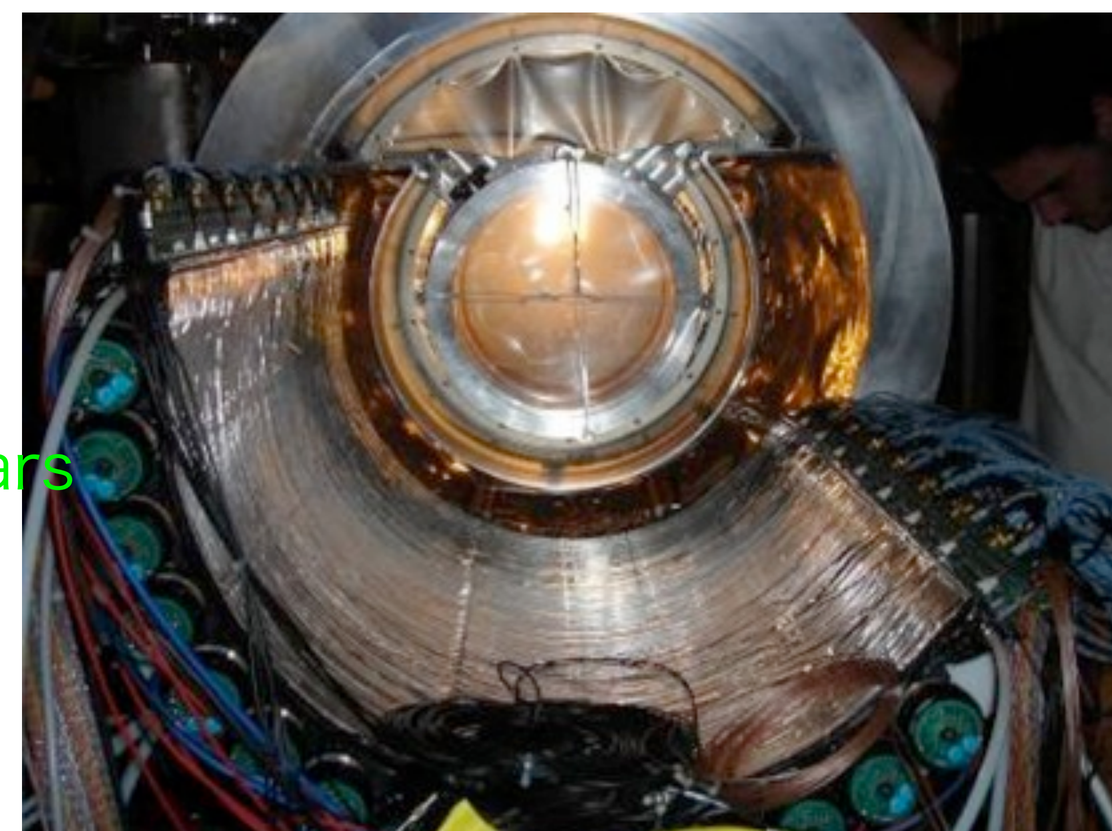
A DC Module



Timing Counters

- Scintillator arrays placed at each end of the spectrometer
- Measures the impact point of the positron to obtain precise timing





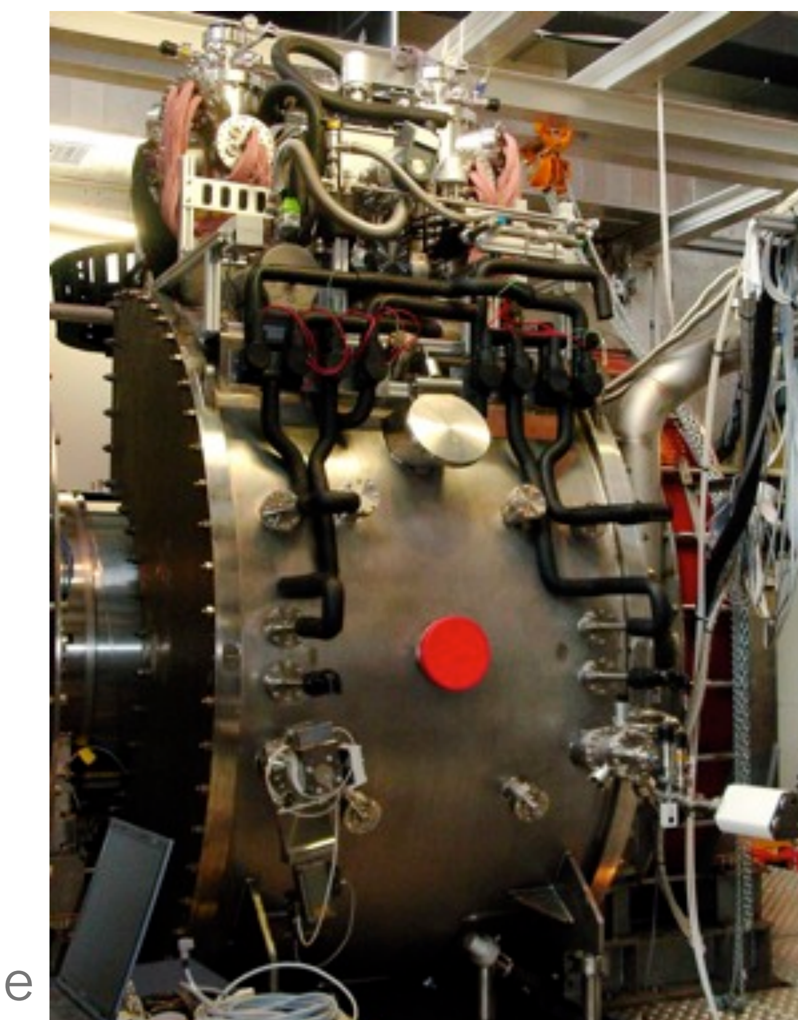
installing inside COBRA

Liquid Xenon Photon Detector

- Scintillation light from 900 liter liquid xenon is detected by 846 PMTs mounted on all surfaces and submerged in the xenon
- fast response & high light yield provide good resolutions of E, time, position
- kept at 165K by 200W pulse-tube refrigerator
- gas/liquid circulation system to purify xenon to remove contaminants

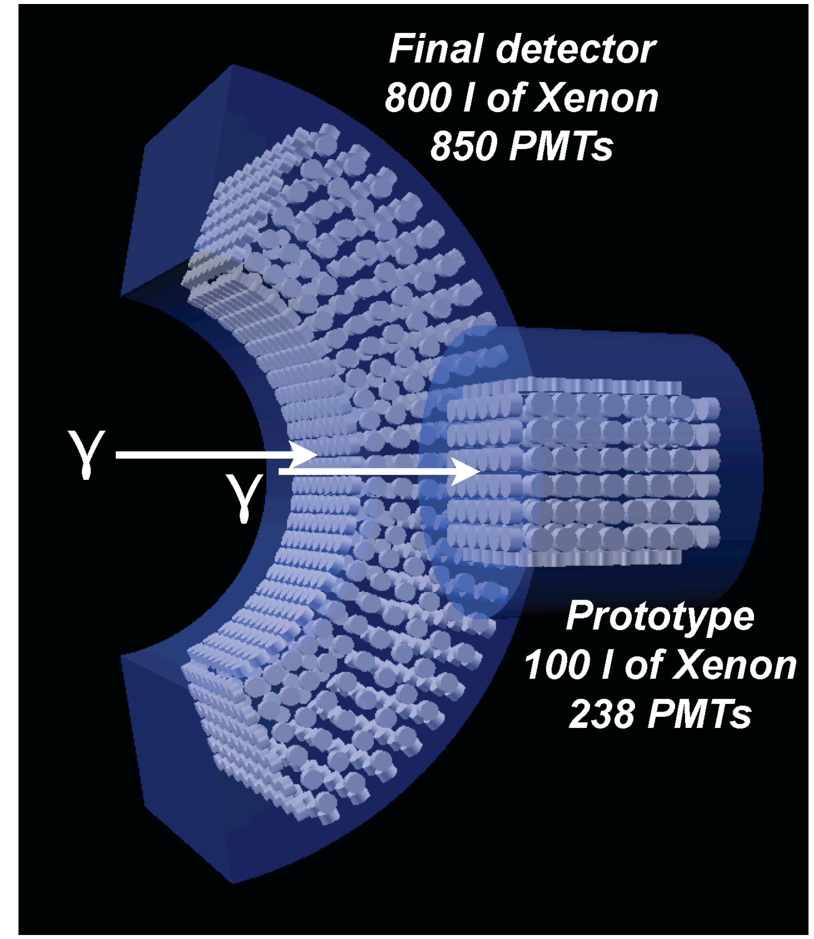
assembling the detector

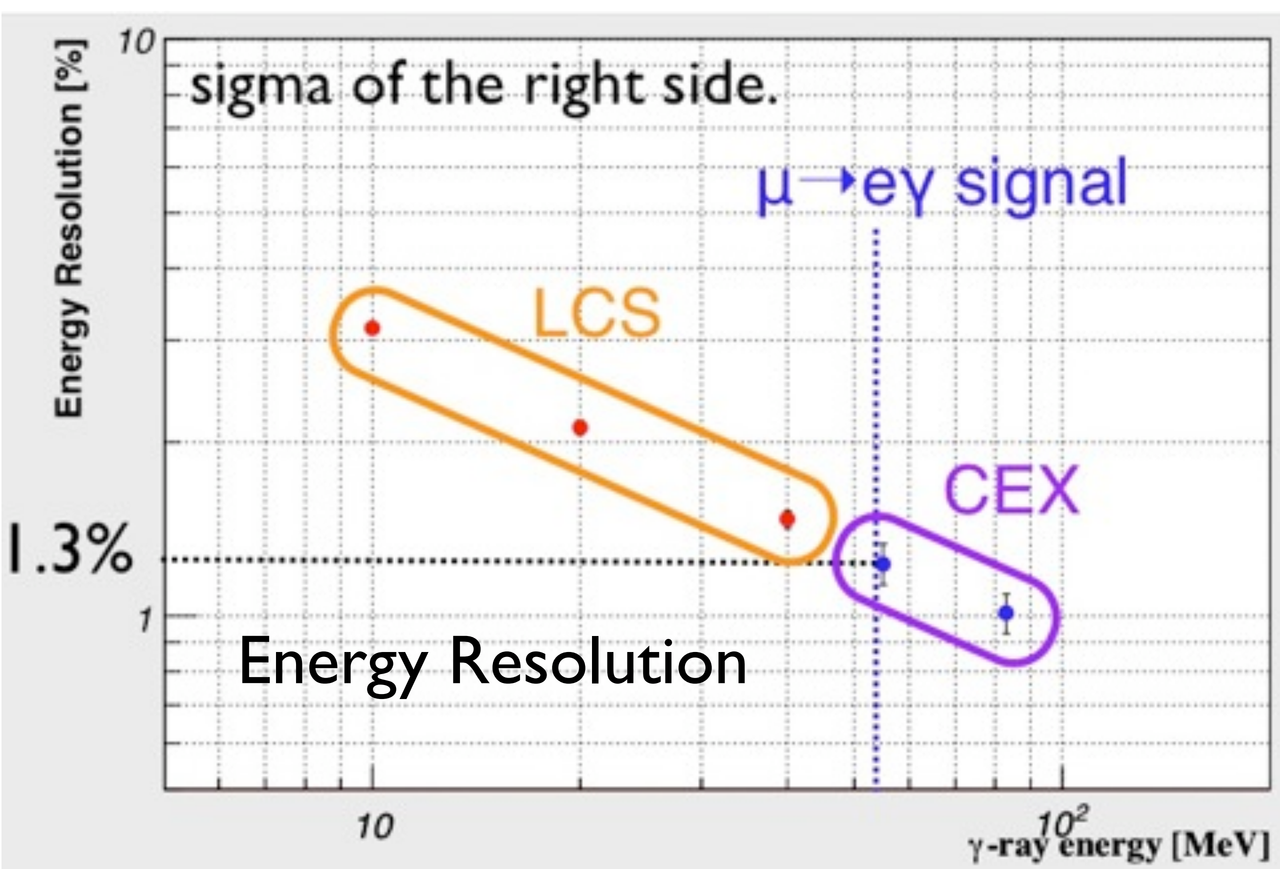
placed at the beam line

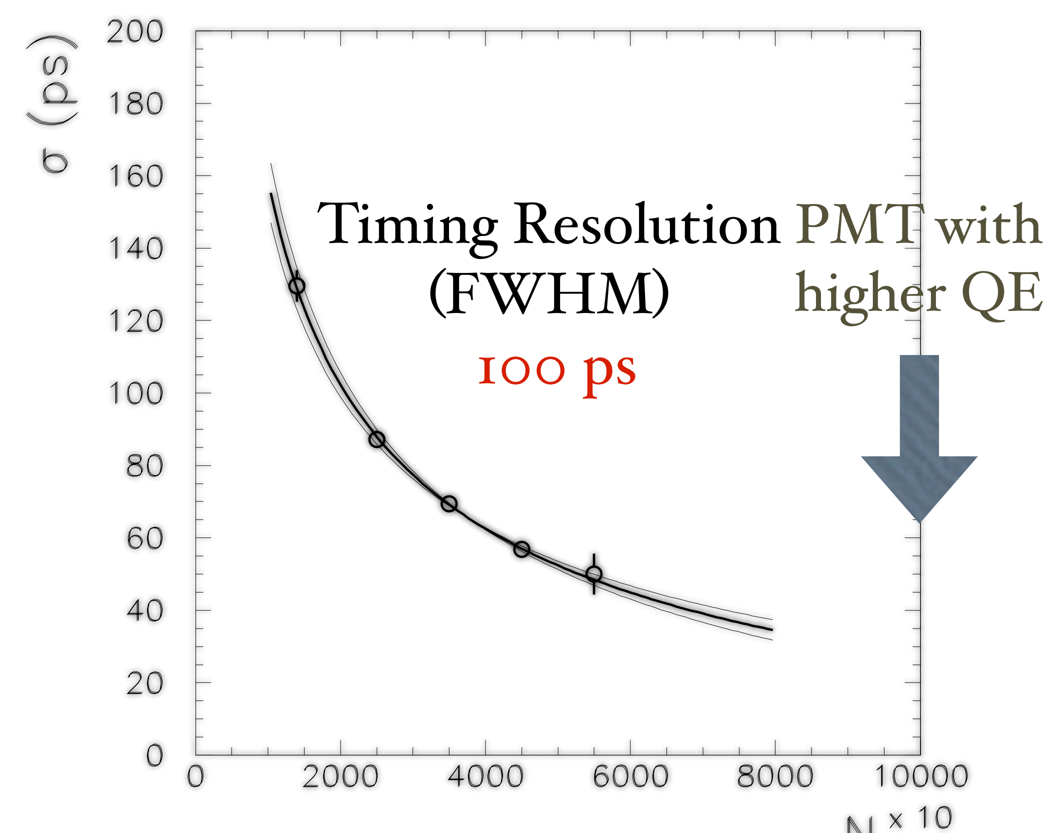


Detector Performance Verified by Prototype

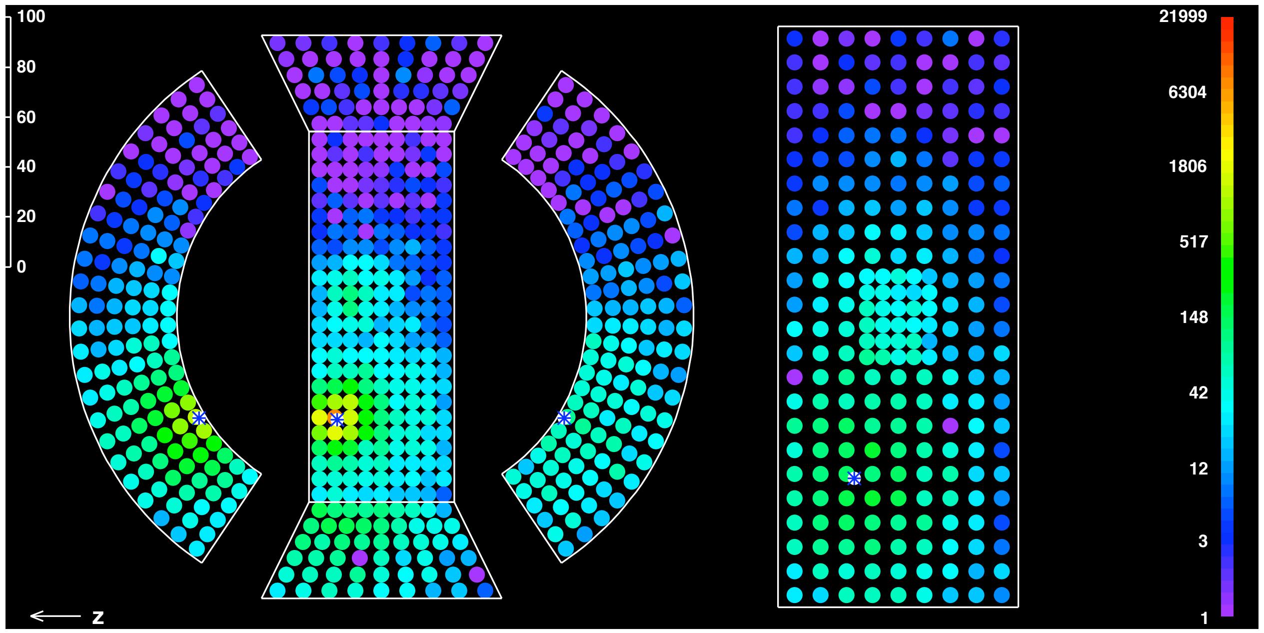
Position Resolution (σ in mm)



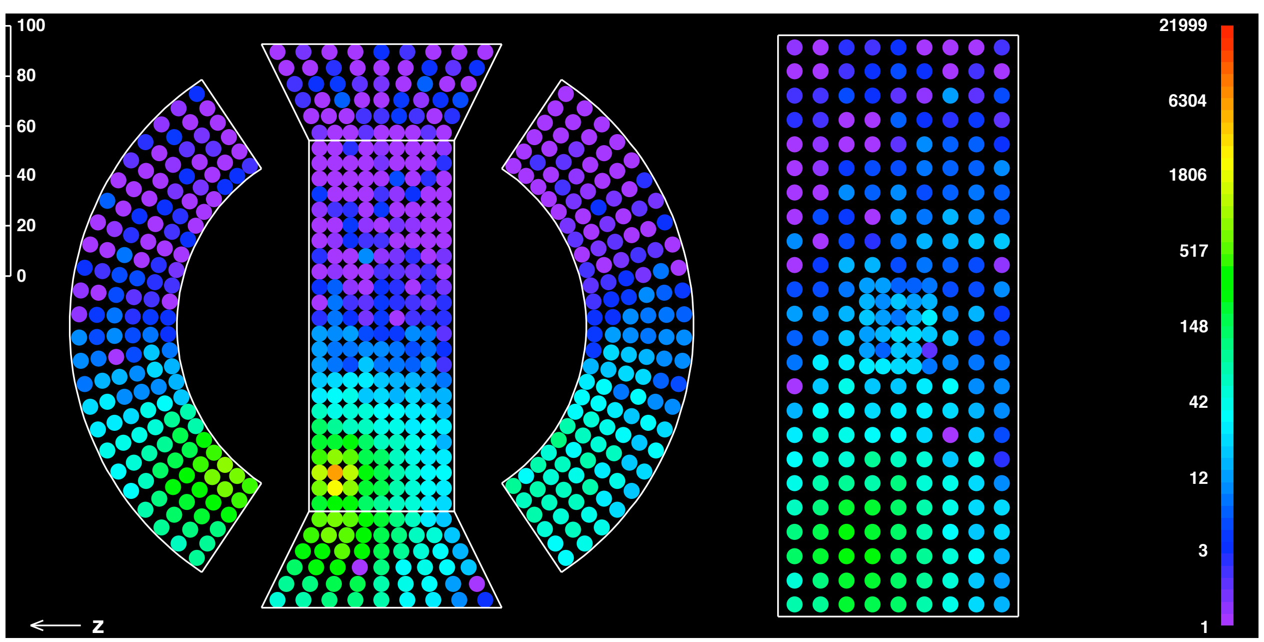




Pile-up Photon Removal

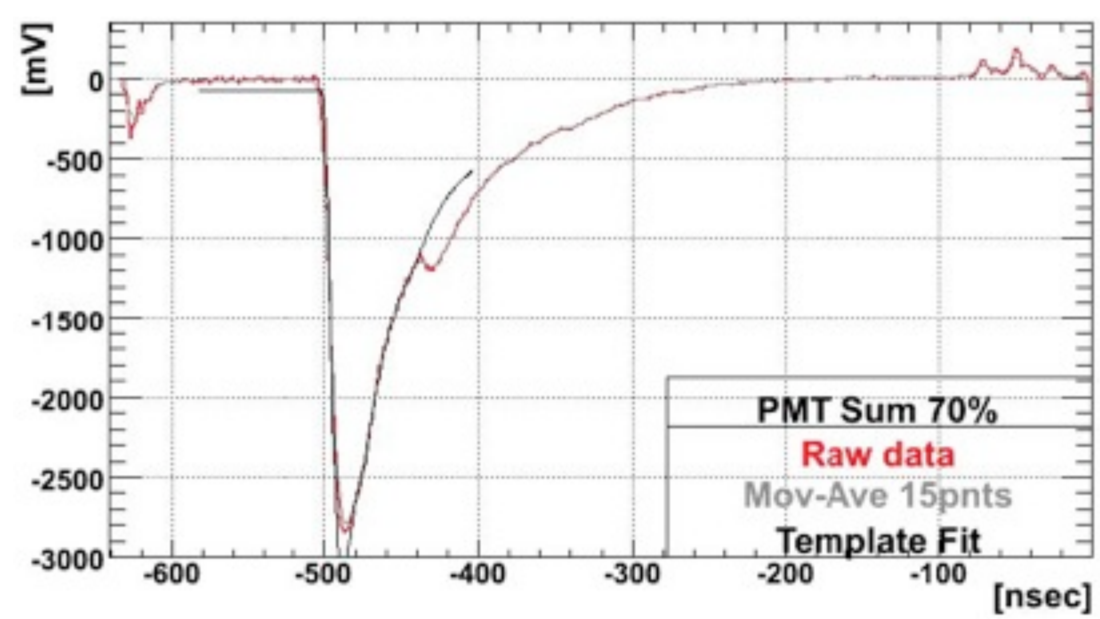


before



after

- Good position/timing resolutions enable to remove pile-up photons
- All the PMTs are read out by waveform digitizers (DRS2)



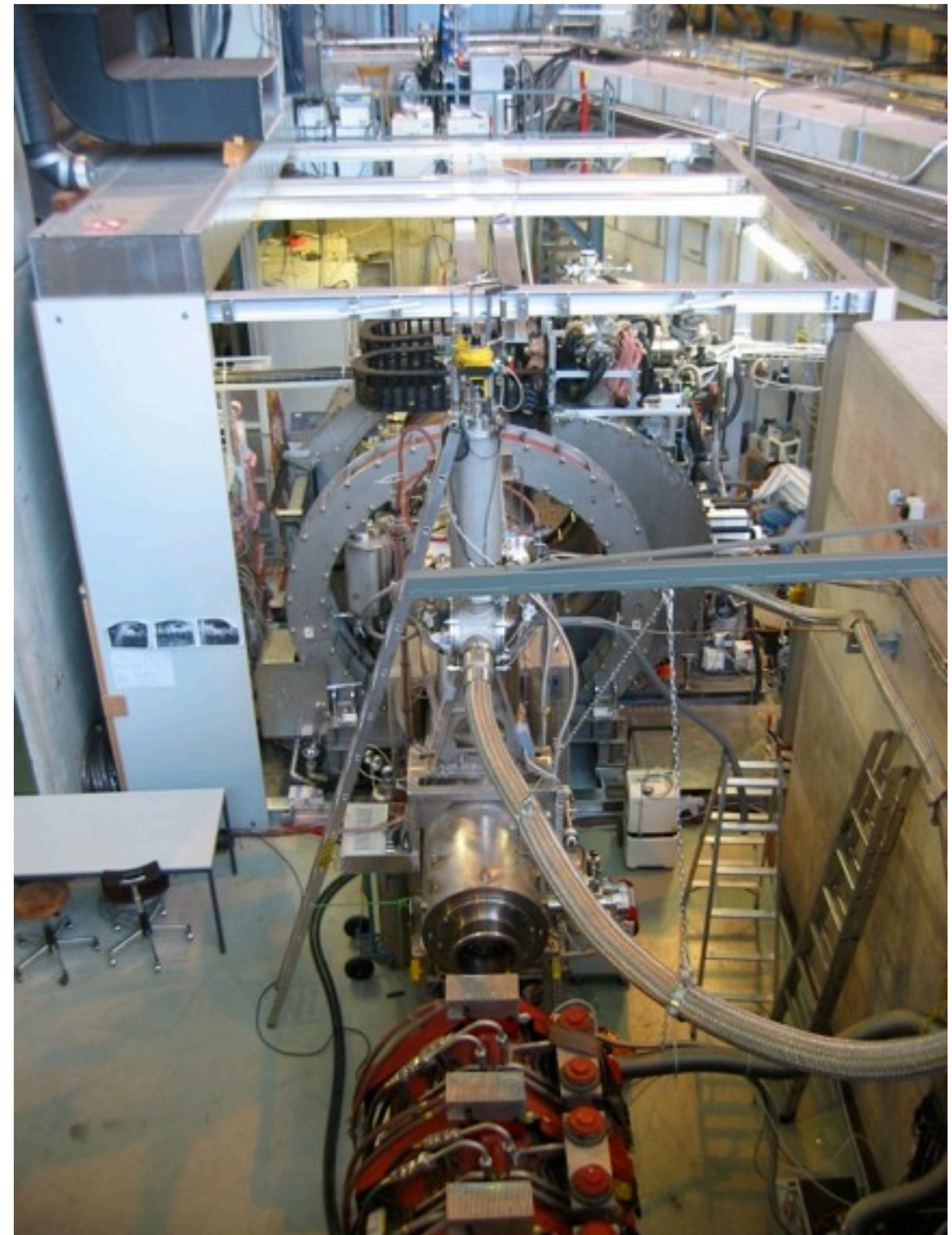
The 2008 Physics Run

- After the successful commissioning run at the end of 2007, the MEG detectors were started up again after the winter accelerator shut down.

- Physics run started in September after a long calibration run using pion charge-exchange reaction (CEX) in the summer.

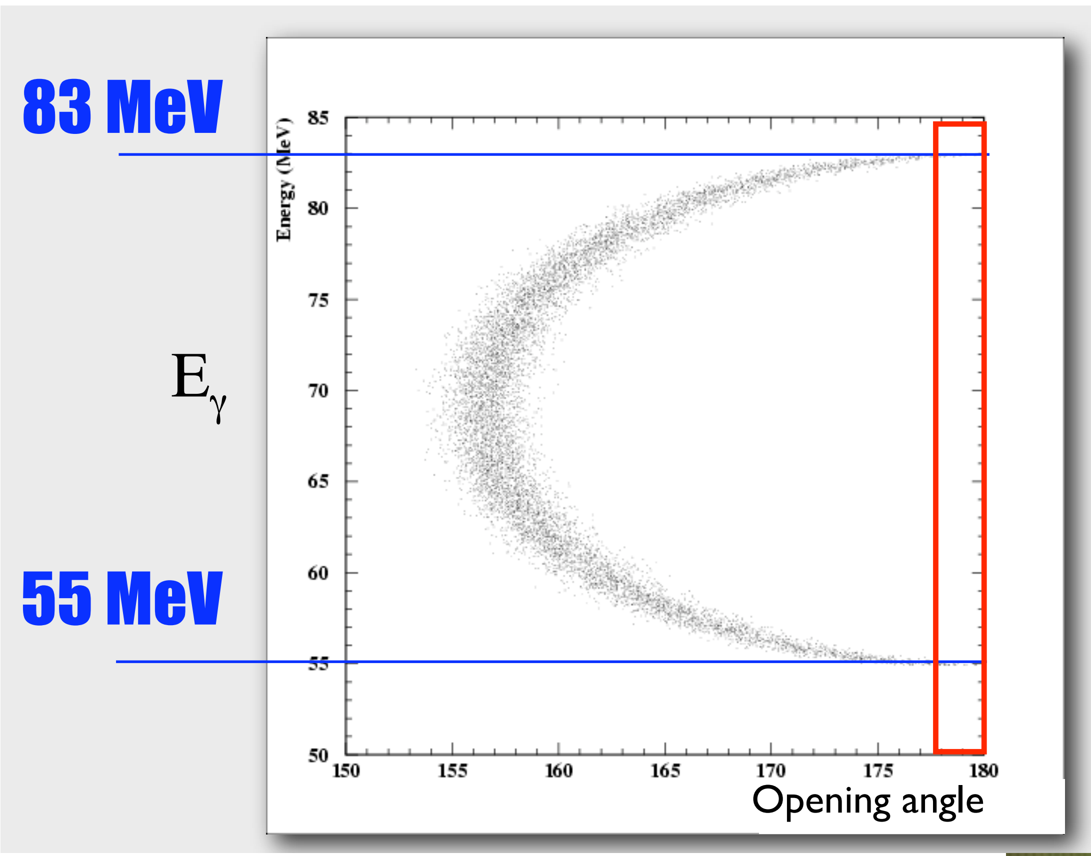
- During physics run, special runs were frequently conducted to monitor and calibrate the detectors (CW, RMD).

- Another CEX calibration run was performed in December.



Pion Charge Exchange Reactions (CEX)

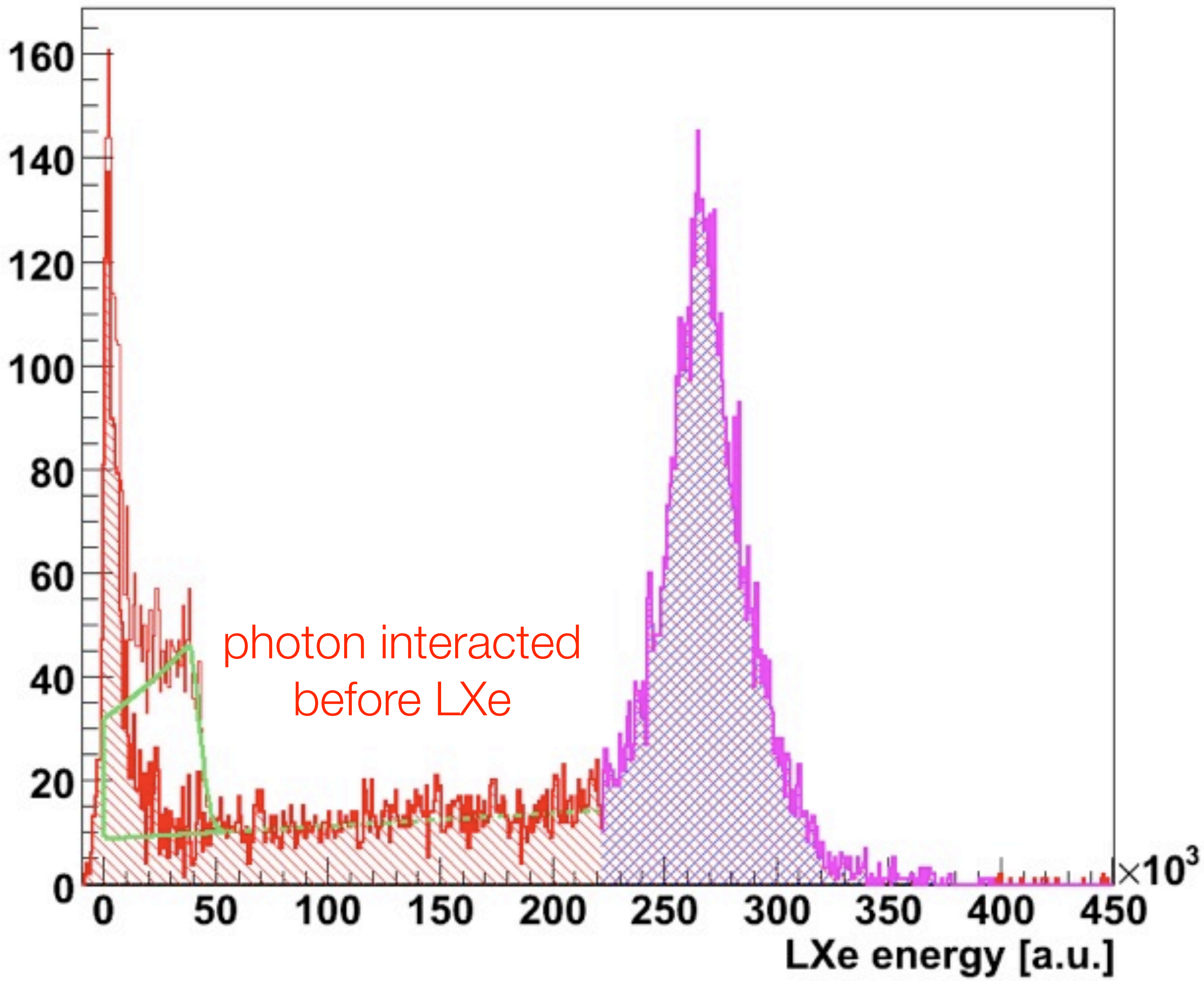
$$\pi^- p \rightarrow \pi^0 n \rightarrow \gamma\gamma n$$



NaI crystal array on a movable stand to tag the other photon

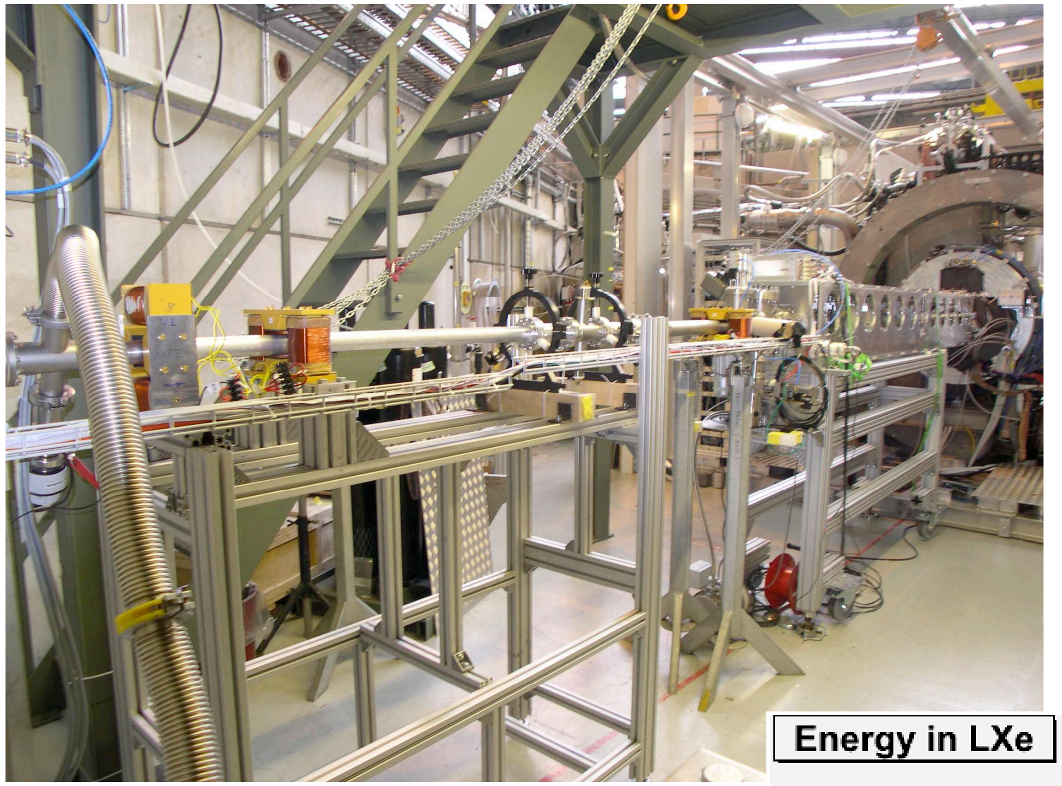
- negative pions stopped in liquid hydrogen target
- Tagging the other photon at 180° provides monochromatic photons
- Dalitz decays were used to study positron-photon synchronization and time resolution: $\pi^0 \rightarrow \gamma e^+ e^-$
- Conducted in August and December

Photon Detection Efficiency

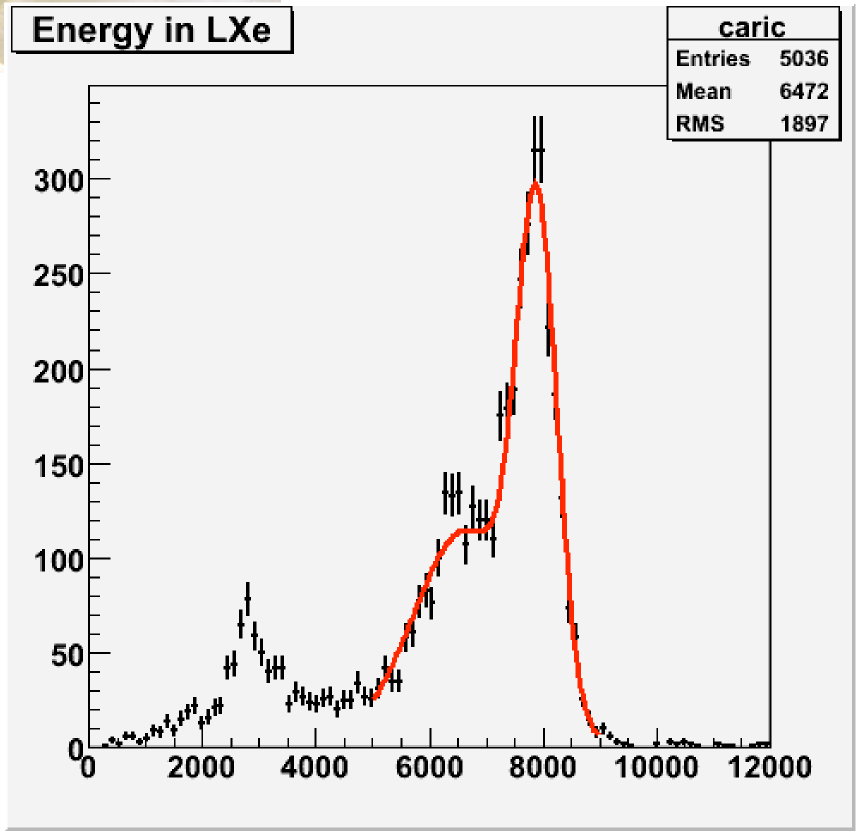


- ~55MeV photon tagged by another photon measured by NaI on the opposite side
- agree well with simulation < 5%
- 66% within positron acceptance for 46 - 60 MeV
- CR/pile-up selection -9%

Monochromatic Photons from Nuclear Reactions



remotely extendable beam pipe of CW proton beam (downstream of muon beam line)



17.67MeV Li peak

- sub-MeV proton beam produced by a dedicated Cockcroft-Walton accelerator (CW) are bombarded on $Li_2B_4O_7$ target.
- 17.67MeV from ^{7}Li
- 2 coincident photons (4.4, 11.6) MeV from ^{11}B: synchronization of LXe and TC
- Short runs three times a week

Drift Chamber Instability

- DC started to show frequent HV trips after 2-3 months of operation

  ➡ Increasing # DCs had to be operated with reduced HV settings

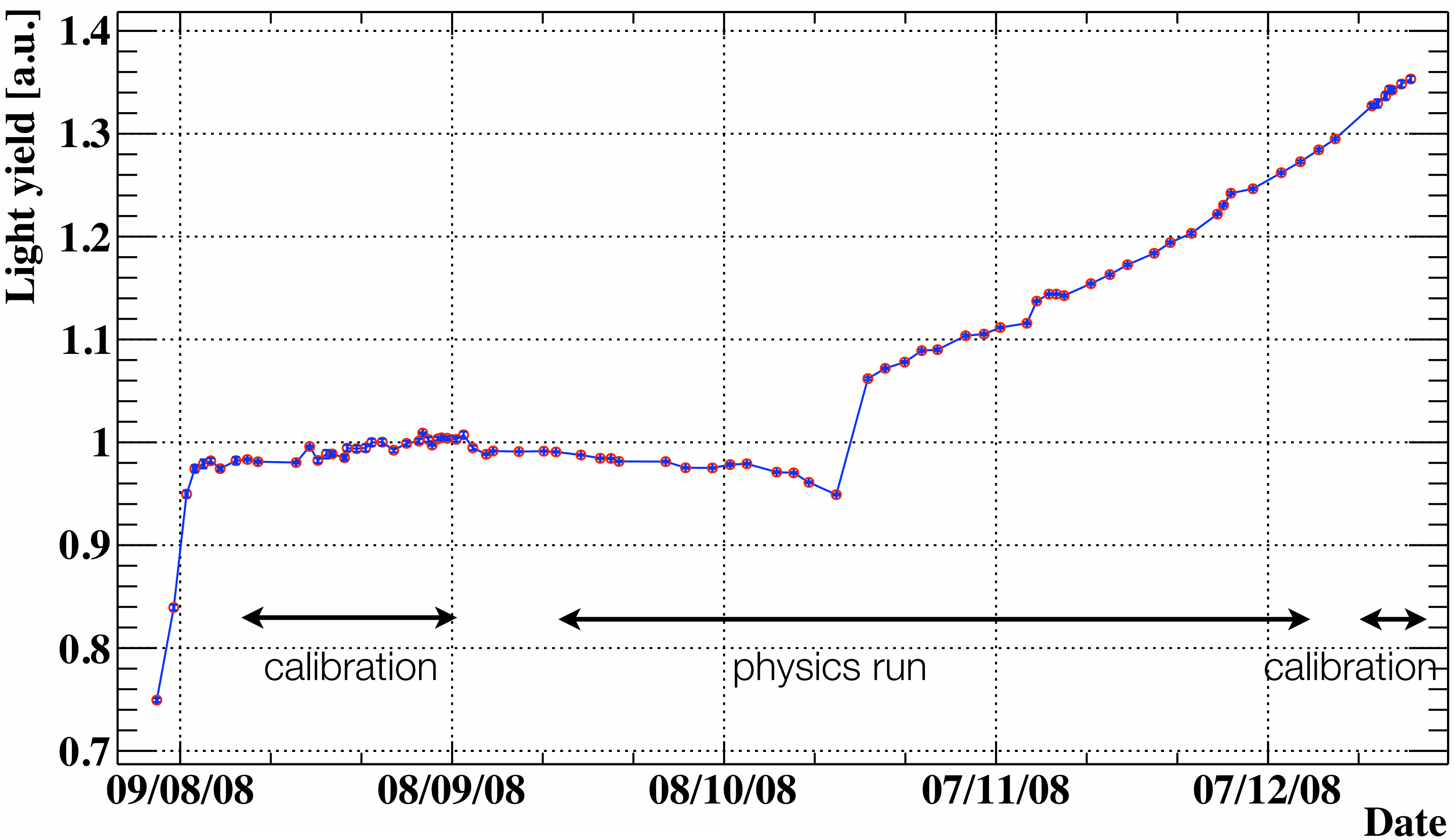
  - Reduced efficiency & resolution for positron measurement
  - Problem due to long-term exposure to helium (no gas aging)

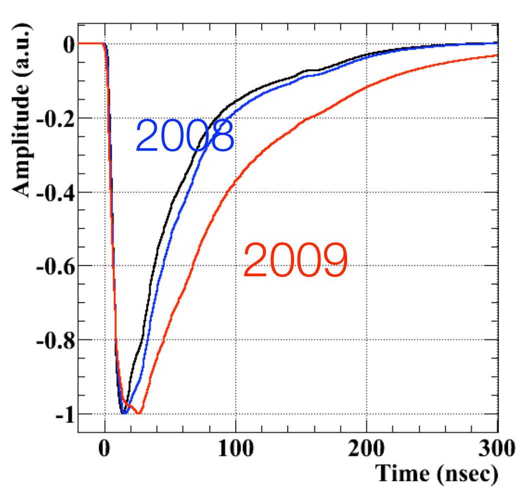
- The DC instability uncertainty cancels out in the $\mu^+ \to e^+\gamma$ analysis:
  BR = # $\mu^+ \to e^+\gamma$ / # Michel

- The DC modules have now been modified and showed no problem; two of them have been successfully operated for 6 months

HV trip reproduced in the lab

Light Yield of Liquid Xenon Detector

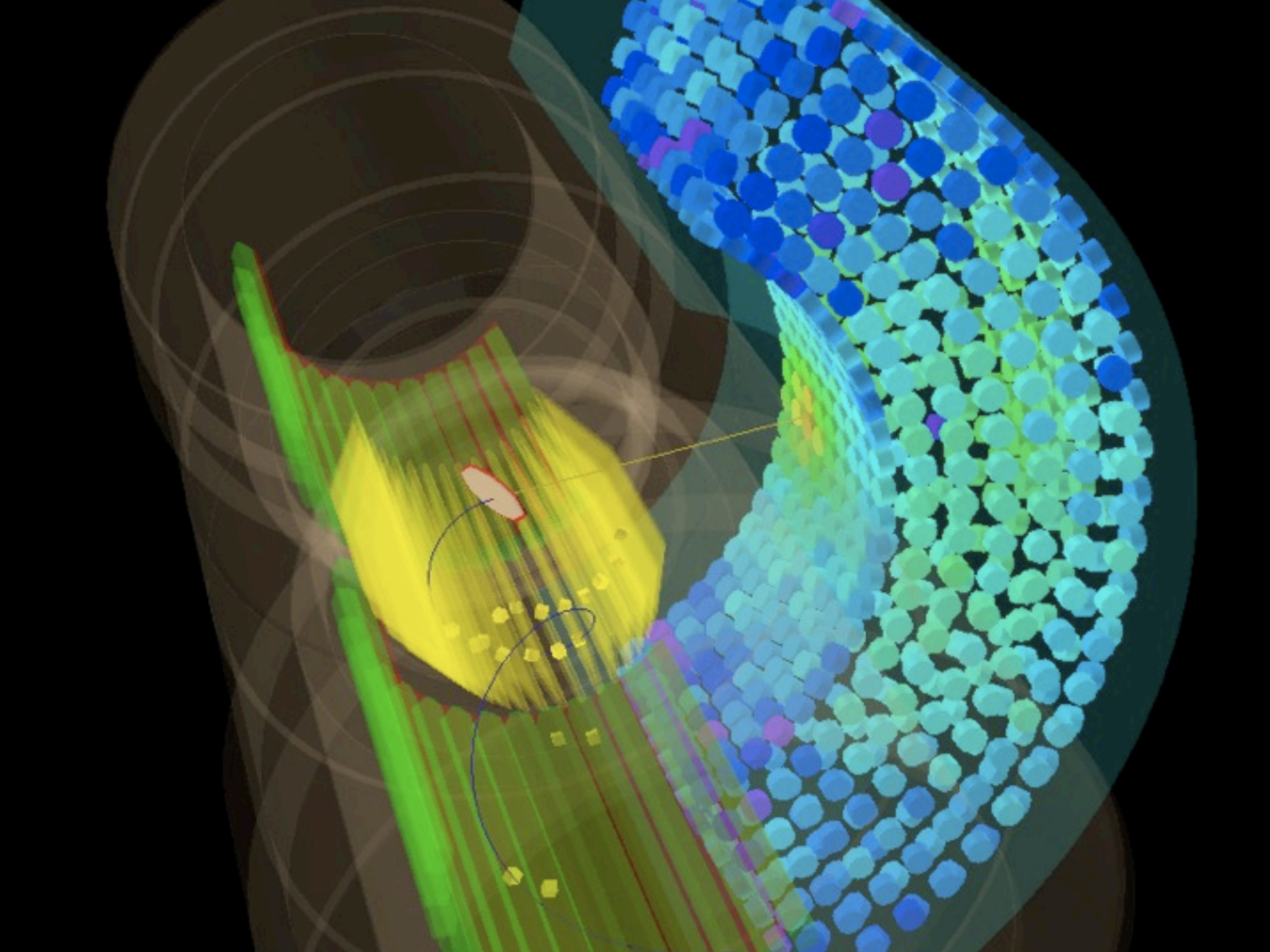


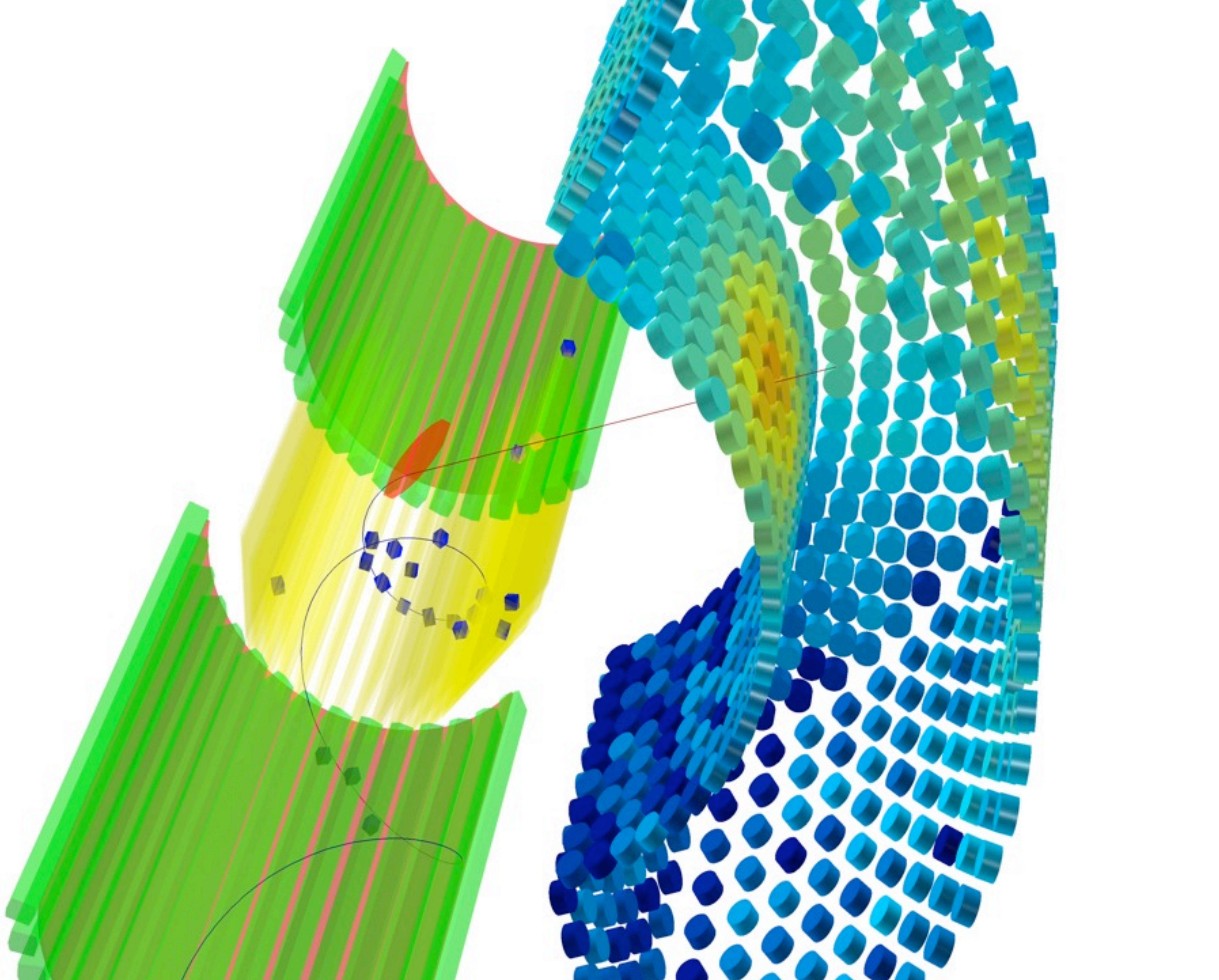


A longer tail of the waveform has also recovered

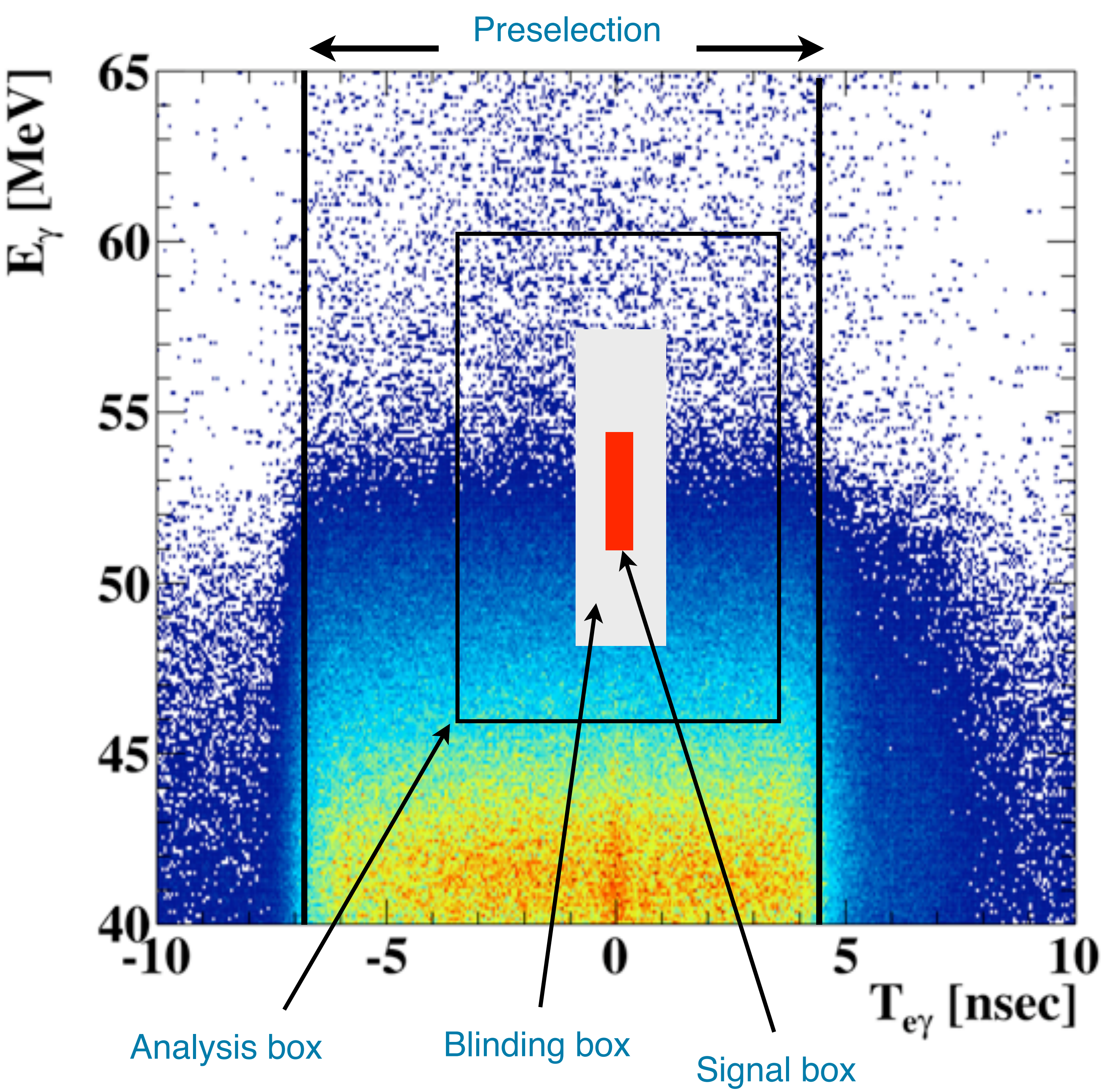
(amplitudes normalized)

- We continued to purify the LXe during the run, carefully monitoring the increasing light yield with various calibration tools (CW, alpha sources, LED, cosmic ray).
- Resulting overall energy scale uncertainty during the whole run period: ~0.4%
- The light yield at the end of run was still ~70% of the expectation. (Fully recovered this year)





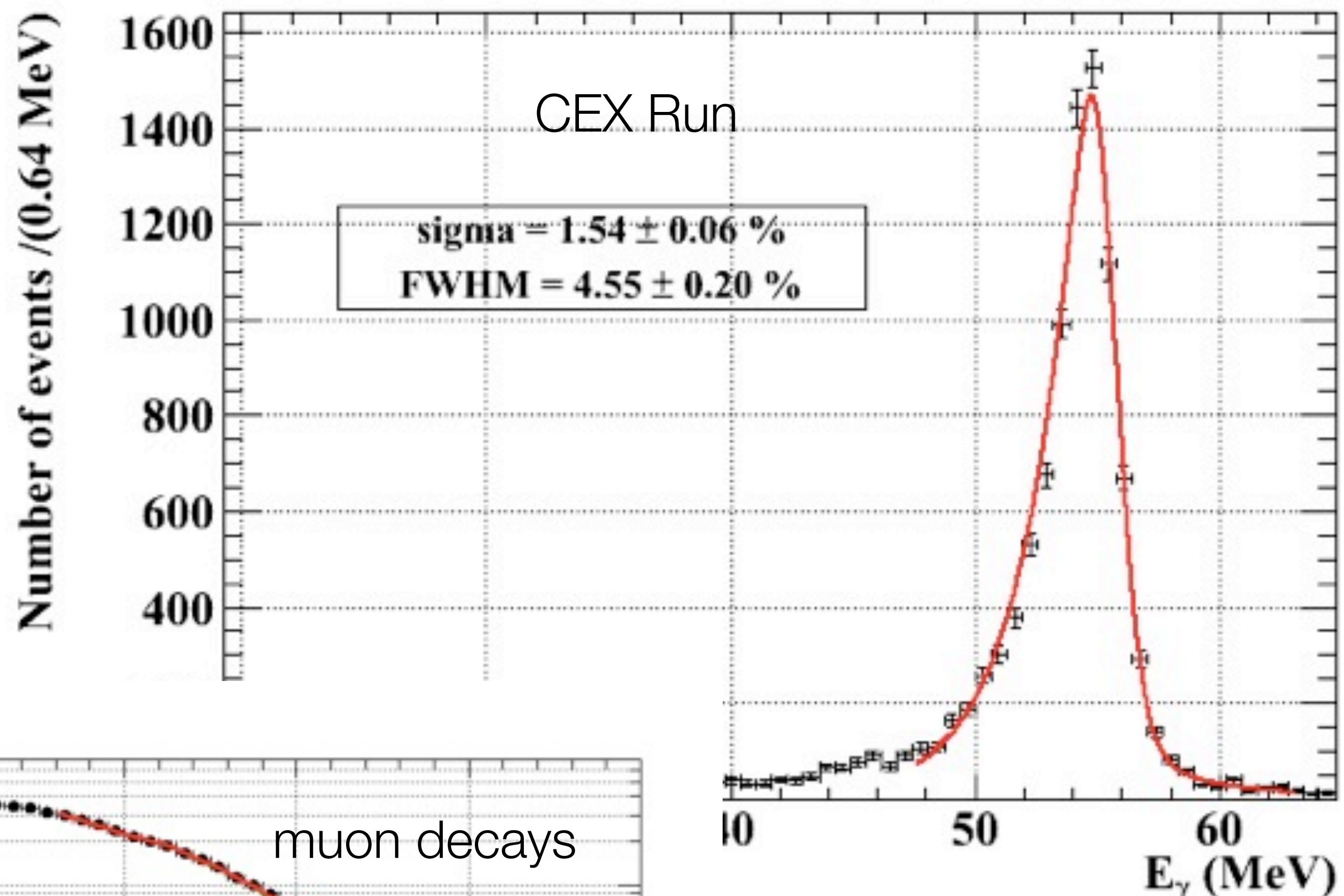
Blind & Likelihood Analysis

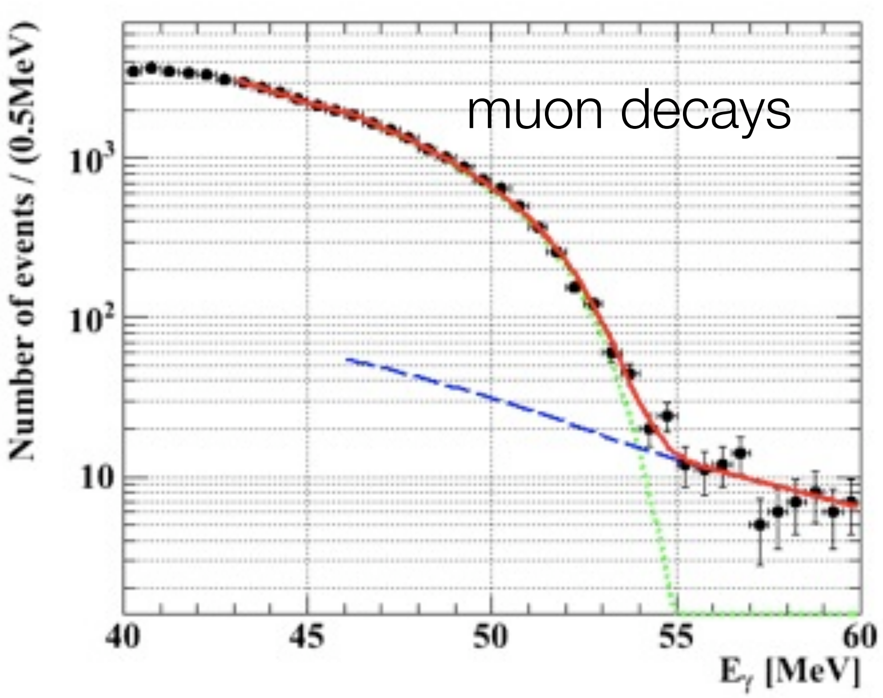


All the preselected events are shown

- Events falling into a pre-defined "Blinding Box" were written to a separate stream and not used to study the background and optimize analysis.
- "Analysis Box" was also defined for likelihood analysis.

Photon Energy





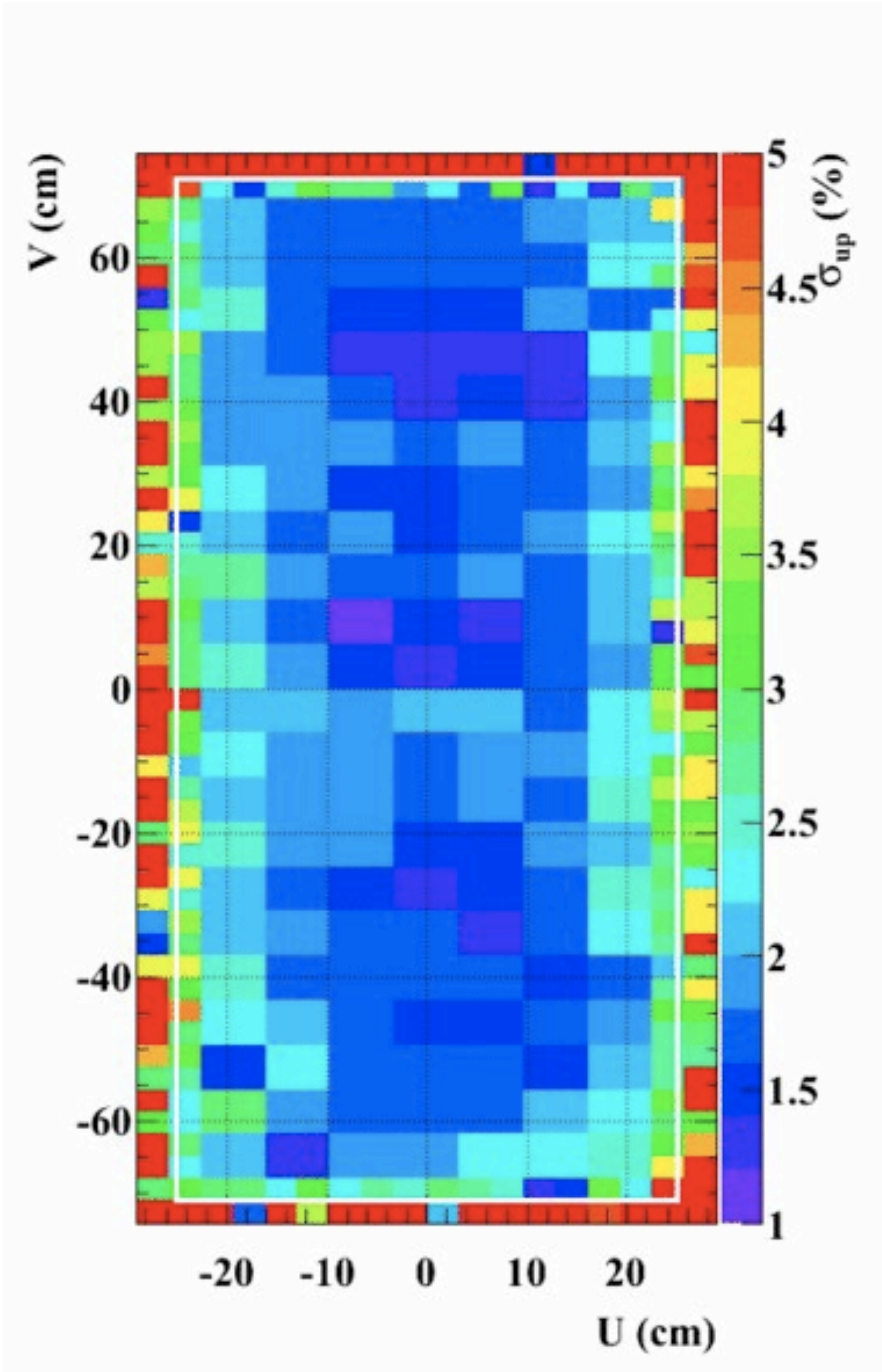
scale & resolutions verified by RMD (+AIF) spectrum

- absolute energy scale determined by CEX runs (55MeV photons)
- average upper tail resolution for deep conversions (> 2cm):

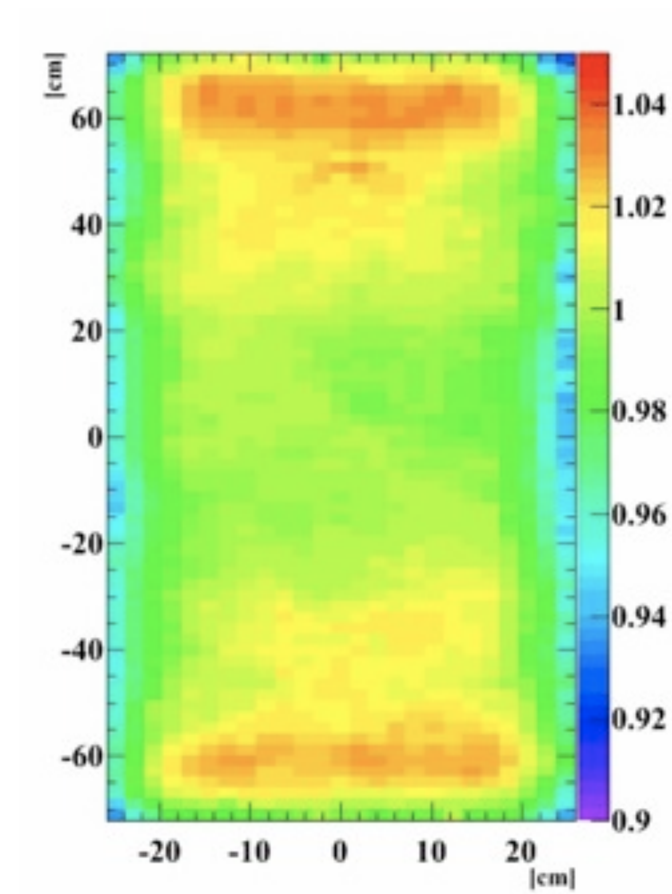
$$\sigma_R = 2.0 \pm 0.15\%$$

- systematic uncertainty on energy scale: 0.5%

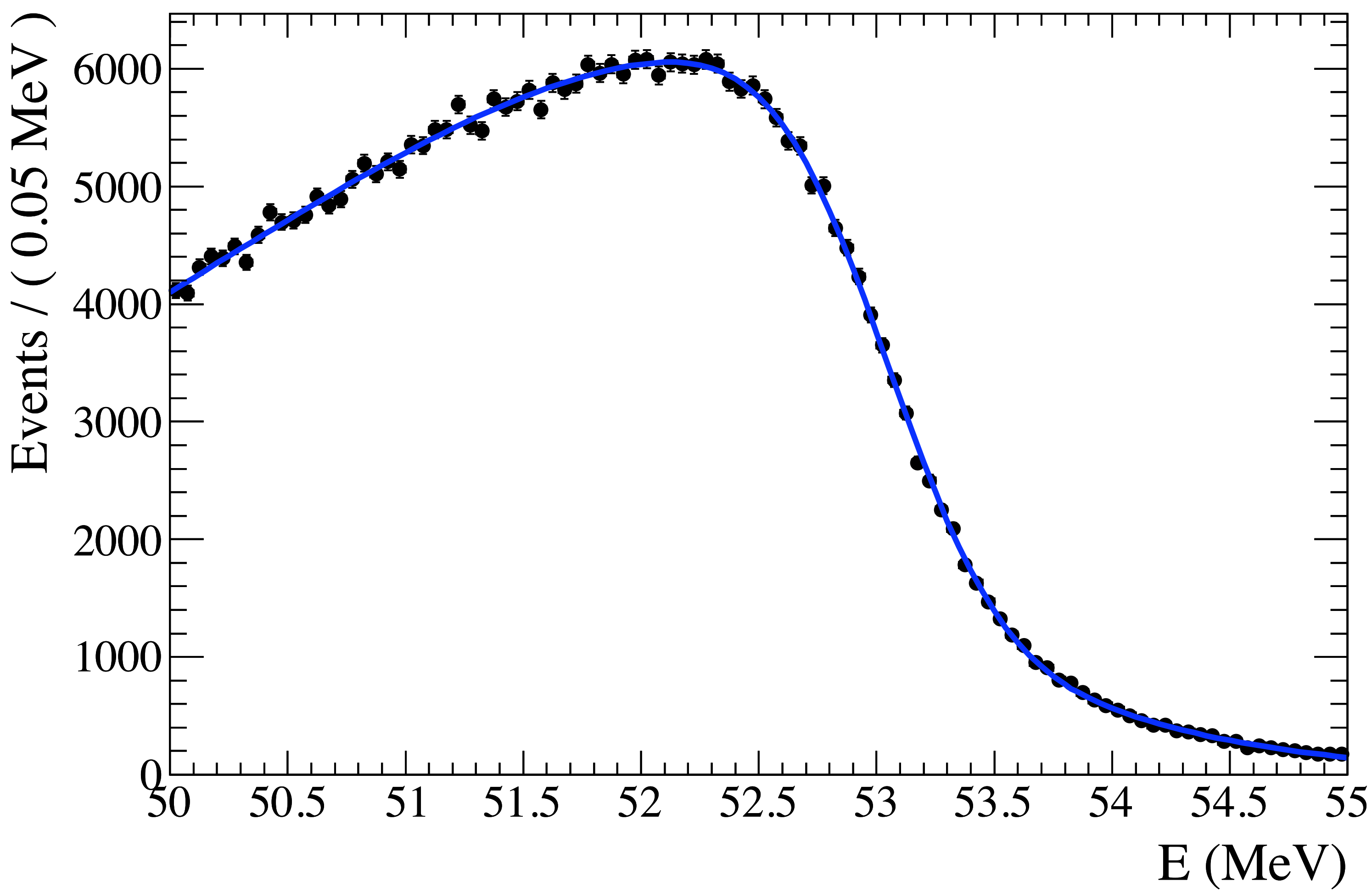
Position Dependence of Energy Resolution



position dependent response
before calibration



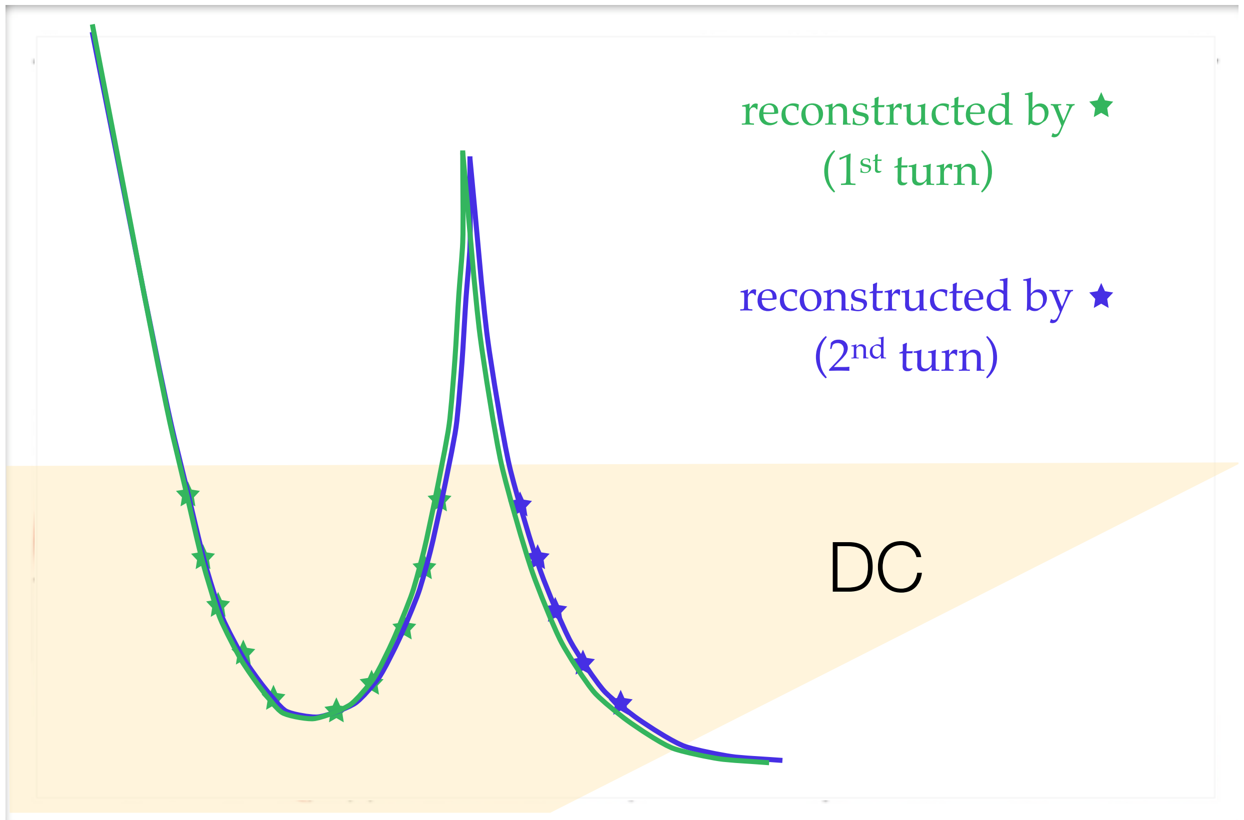
Positron Momentum



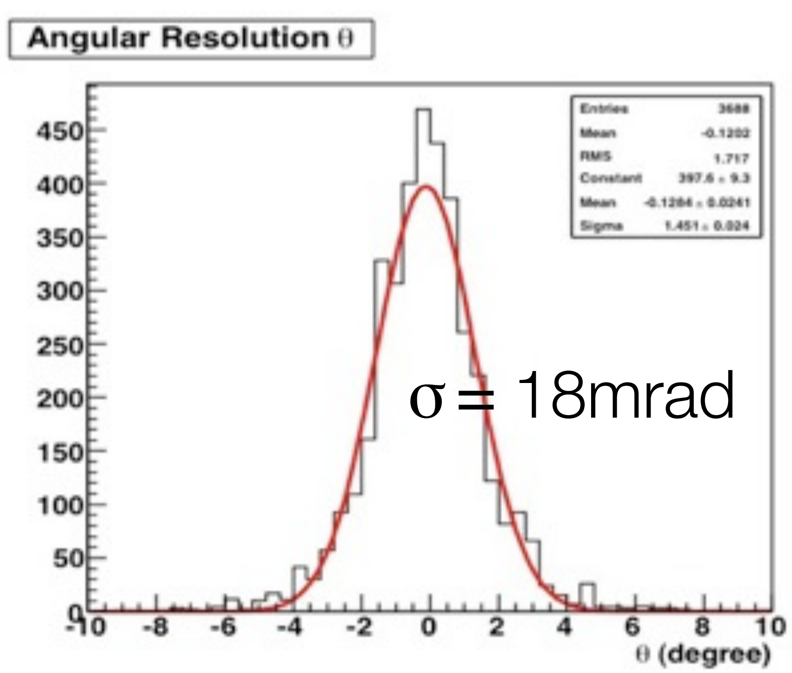
- Positron energy scale and resolution are evaluated by fitting the kinematic edge of the Michel positron spectrum at 52.8MeV

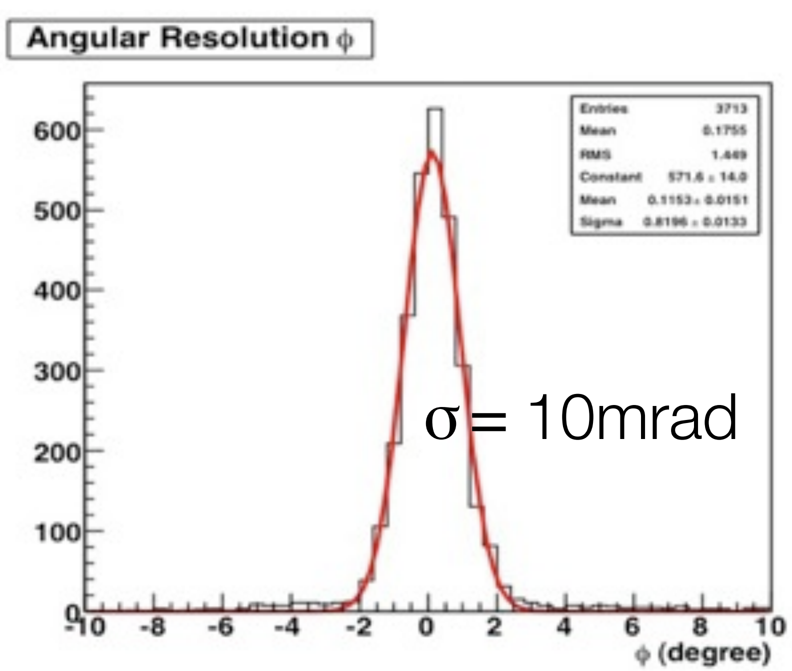
- Resolution function of core and tail components:
  core = 374keV (60%)
  tail = 1.06MeV (33%),
  2.00MeV (7%)

Positron Angle

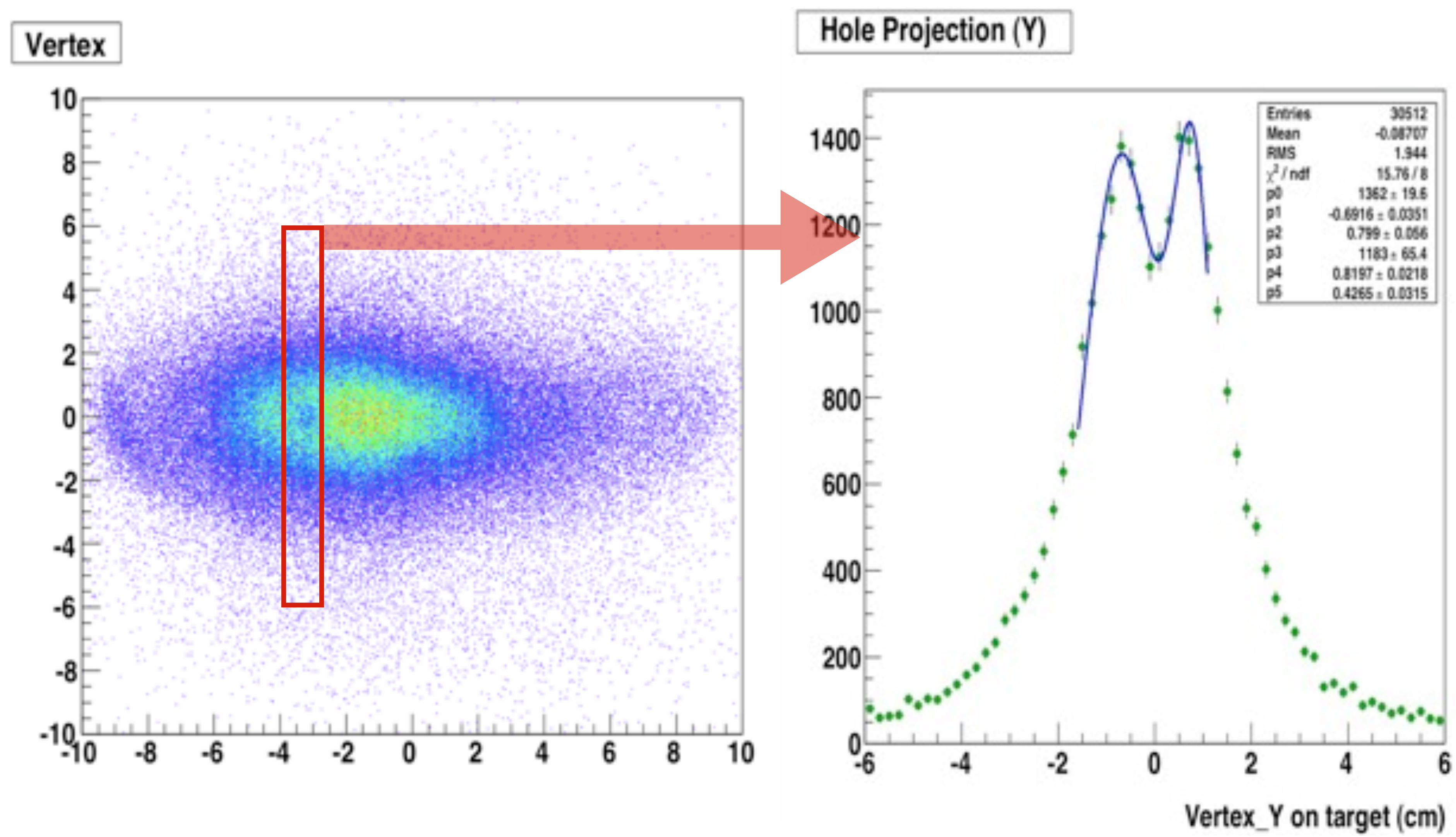


- Angular resolutions were evaluated by the double turn tracks inside the DC



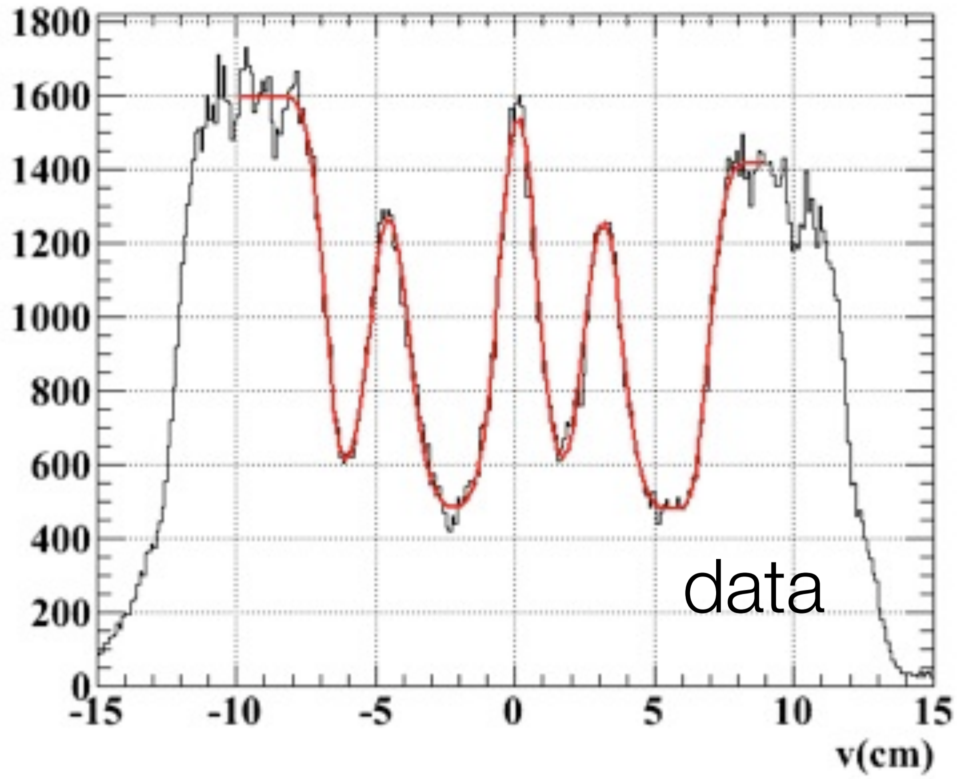


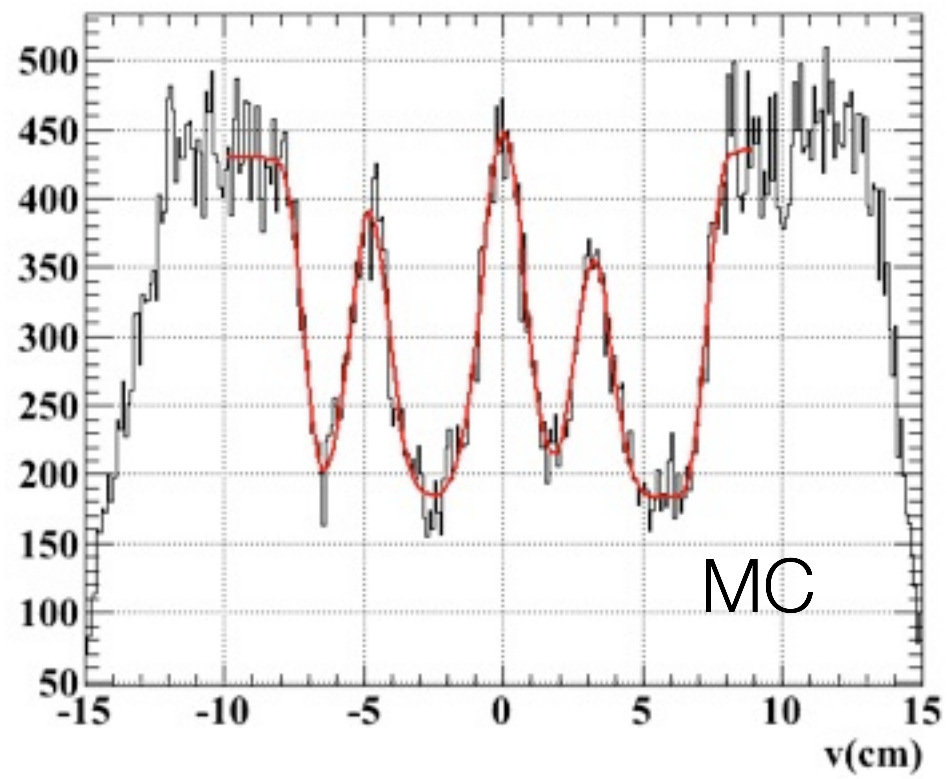
Muon Decay Position



- Evaluated by the holes of the muon stopping target and the double-turn tracks: 3.2 - 4.5 mm

Photon Conversion Position

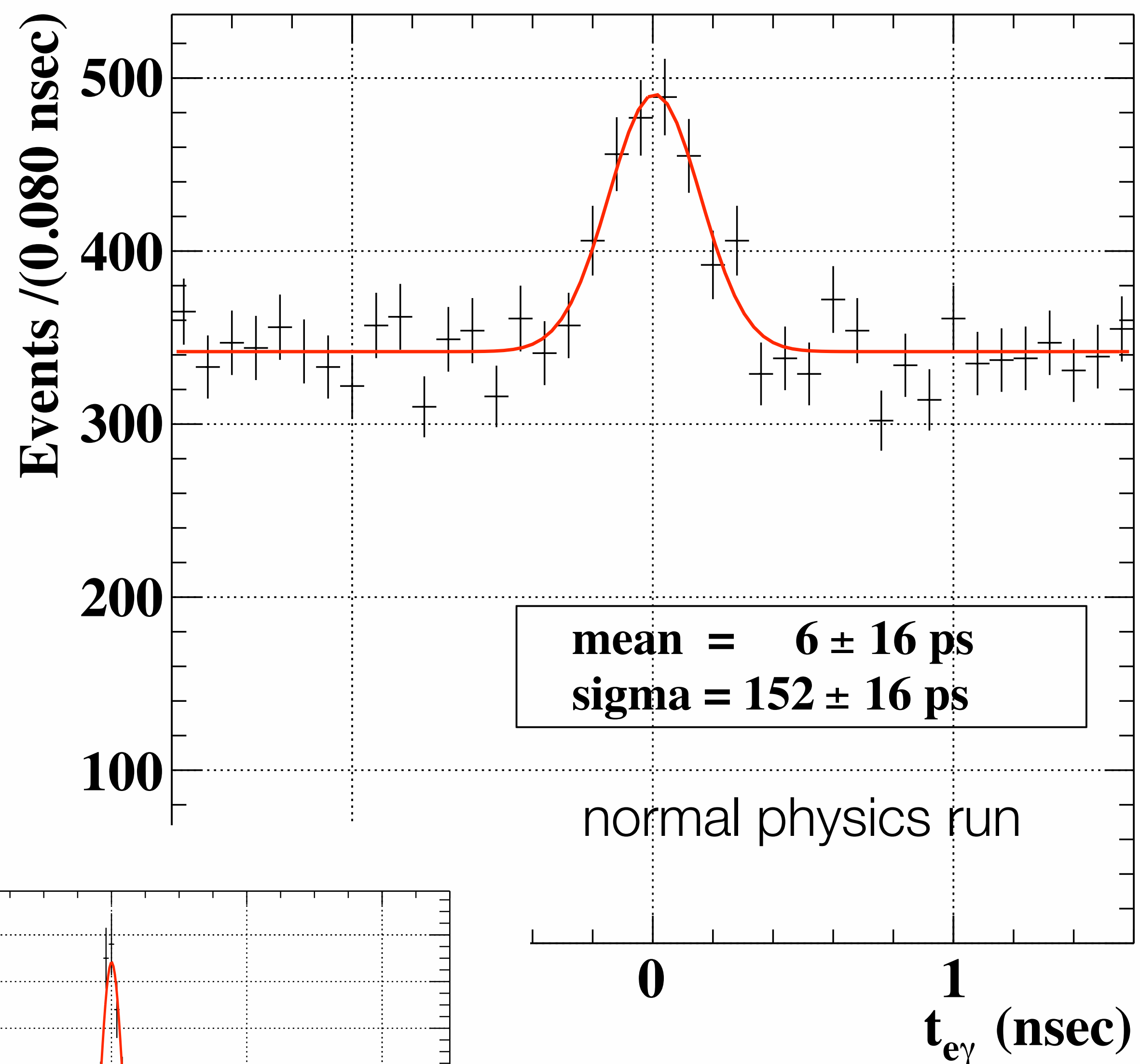




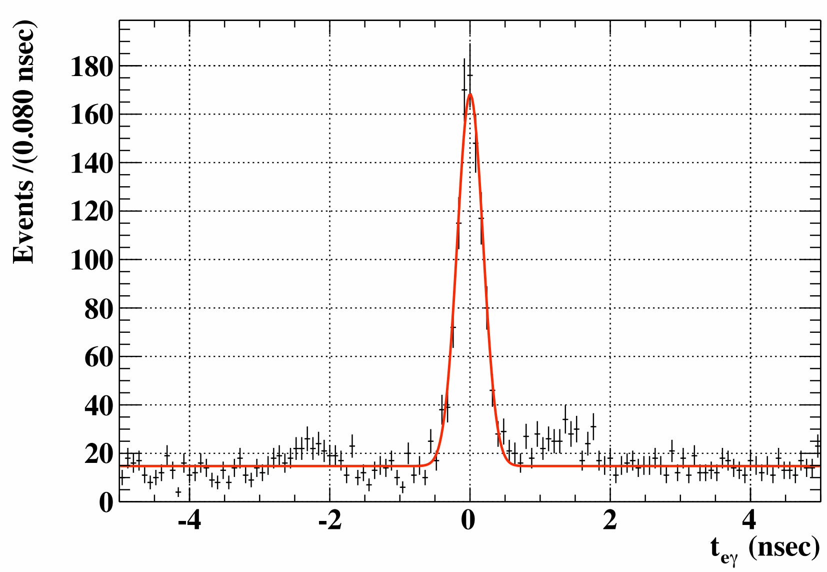
Pb collimator

- Resolution for photon conversion position was evaluated by CEX run with PB collimators
- ~ 5mm

Positron - Photon Timing



normal physics run



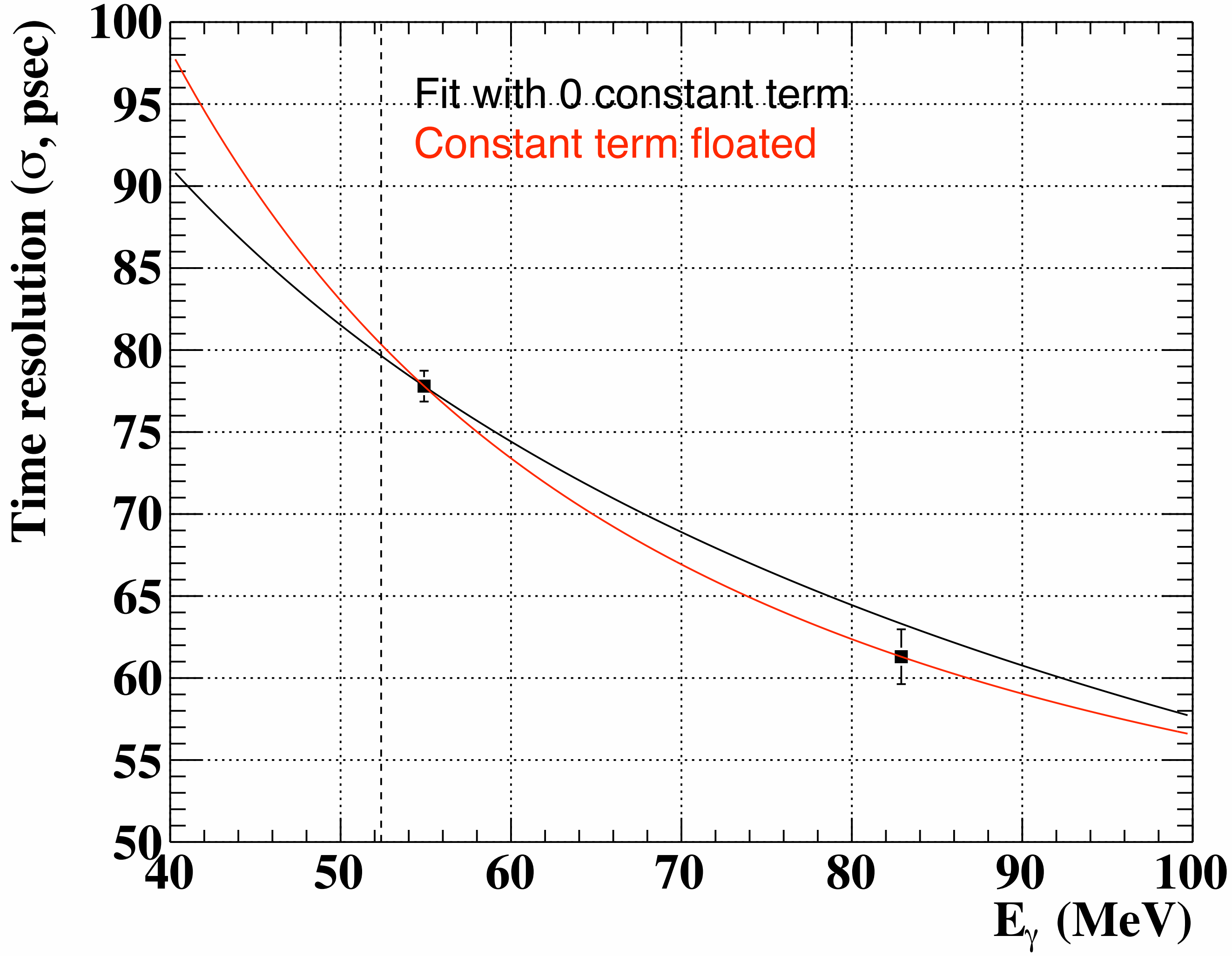
peak in the RMD run

- Positron time measured by TC and corrected by ToF (DC trajectory)
- LXe time corrected by ToF to the conversion point
- RMD peak in a normal physics run corrected by small energy dependence:

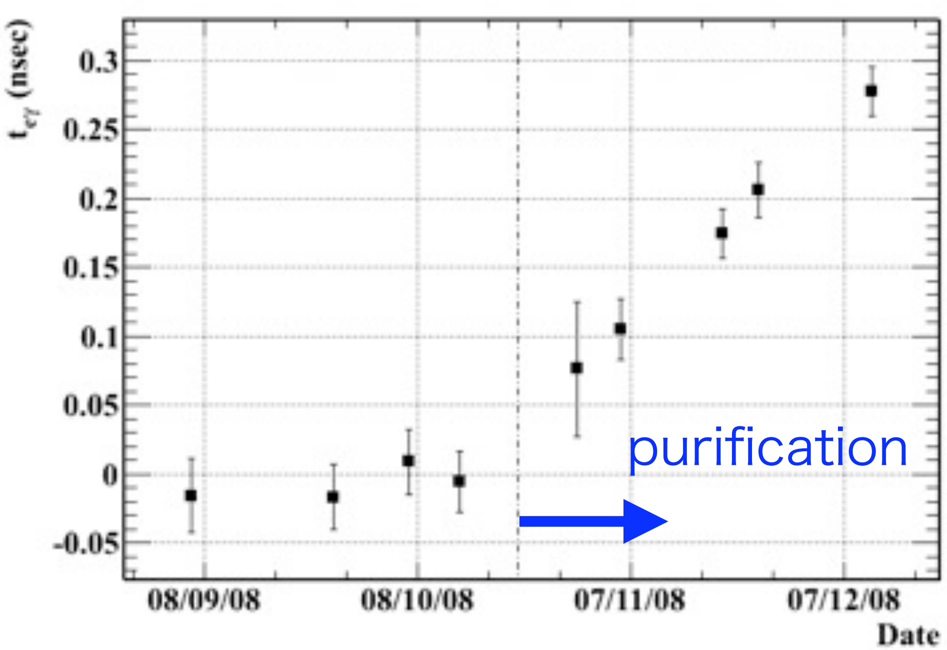
$$\sigma_{t_{e\gamma}} = 148 \pm 17\text{ps}$$

stable < 20ps

Time Resolution of LXe Detector



- Dependent on the light yield (~energy)
- Has improved during the 2008 run.



Blinding Box was Opened on July 30th

- Several systematic checks are still being carried out - So the following results should be regarded as preliminary.

- "Feldman-Cousins" approach was adopted for likelihood analysis.

    - The average expected 90% CL upper limit on BR assuming no signal: $\sim 1.3 \times 10^{-11}$

    - The 90% CL UL obtained for the side-band data (no signal): $(0.9 - 2.1) \times 10^{-11}$

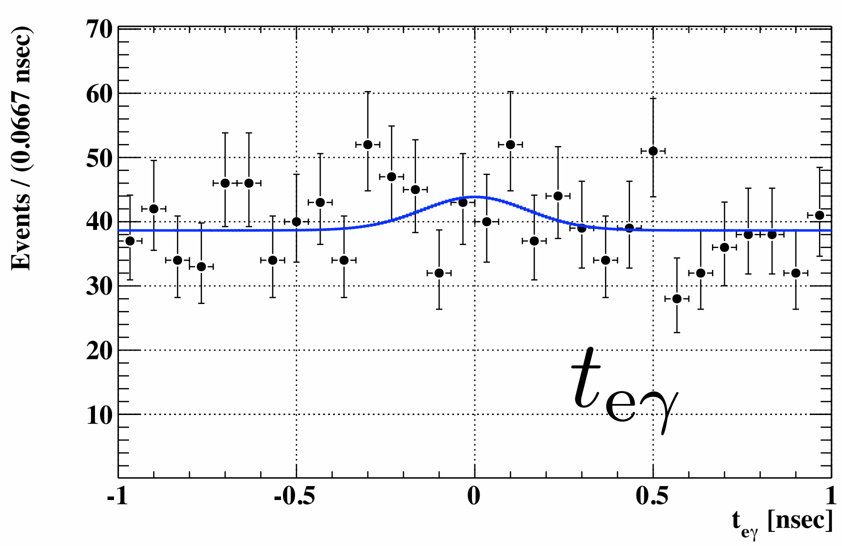
    - sensitivity limited by the data statistics: ~5 times more data expected for data taking 2009

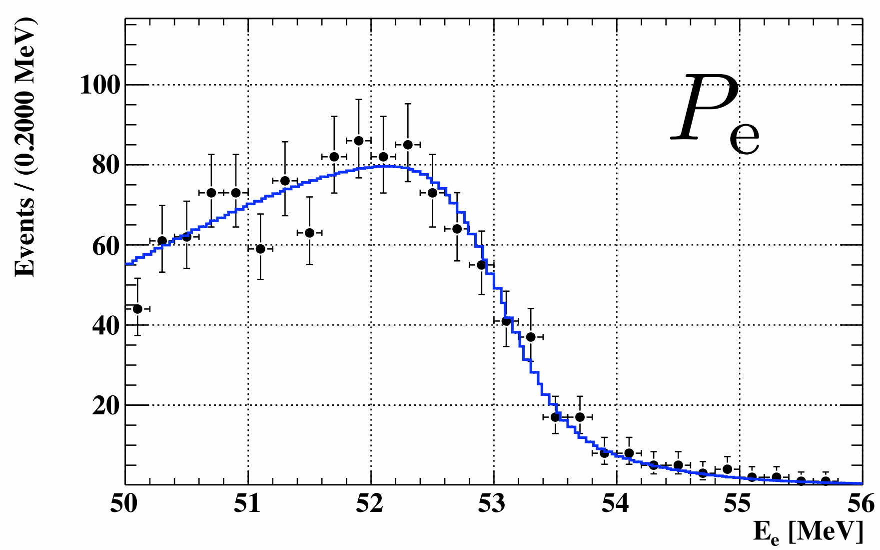
cf. The present 90% CL UL by MEGA is 1.2×10^{-11}

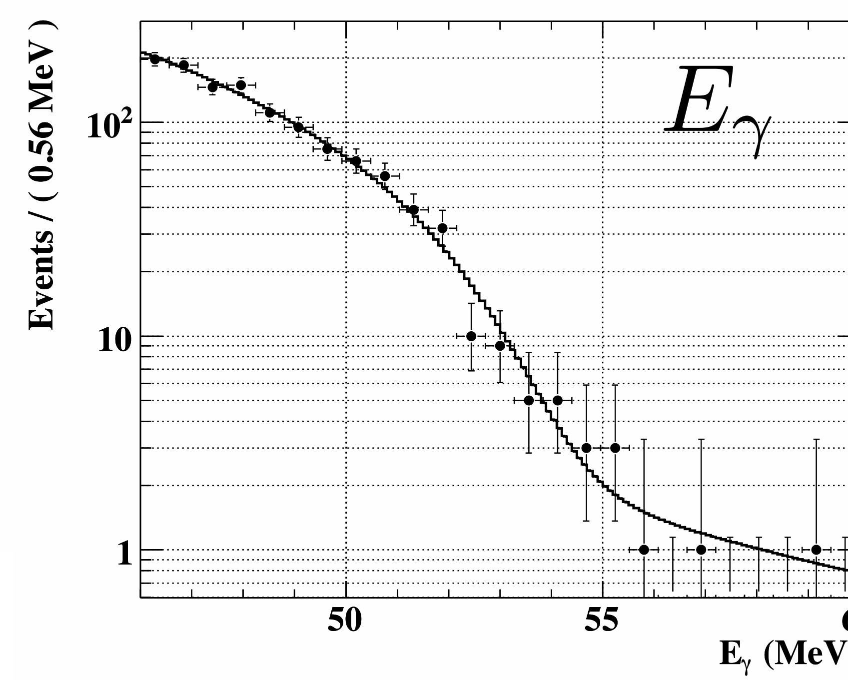
Maximum Likelihood Fit

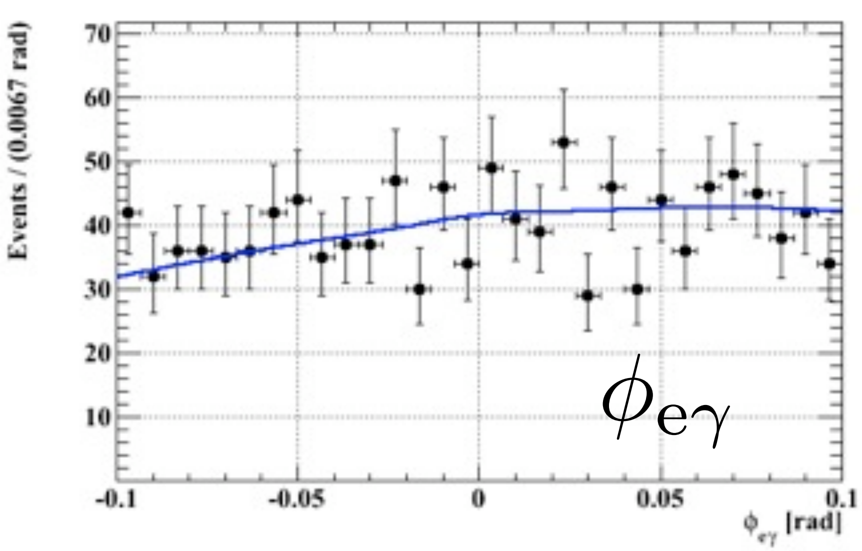
$$\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}) = \frac{N^{N_{\rm obs}} \exp^{-N}}{N_{\rm obs}!} \prod_{i=1}^{N_{\rm obs}} \left[\frac{N_{\rm sig}}{N} S + \frac{N_{\rm RMD}}{N} R + \frac{N_{\rm BG}}{N} B \right]$$

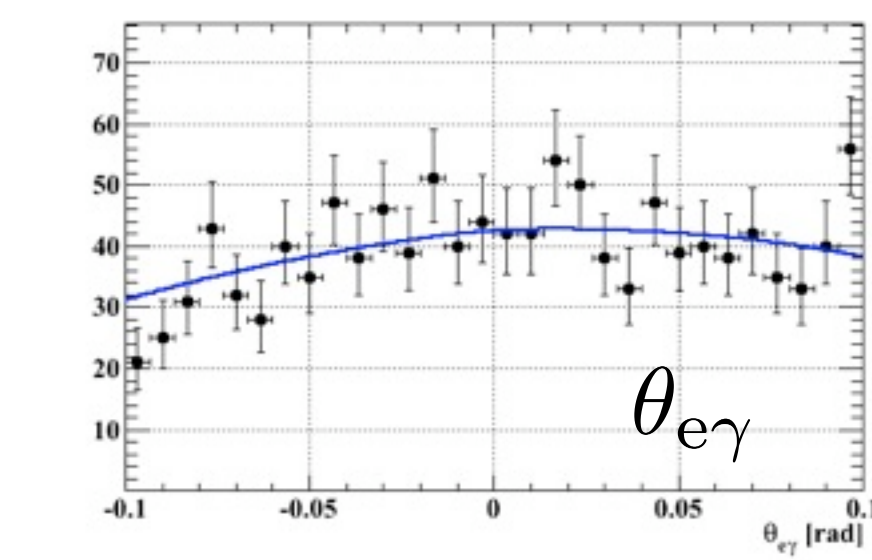
$N_{\rm obs} = 1189$









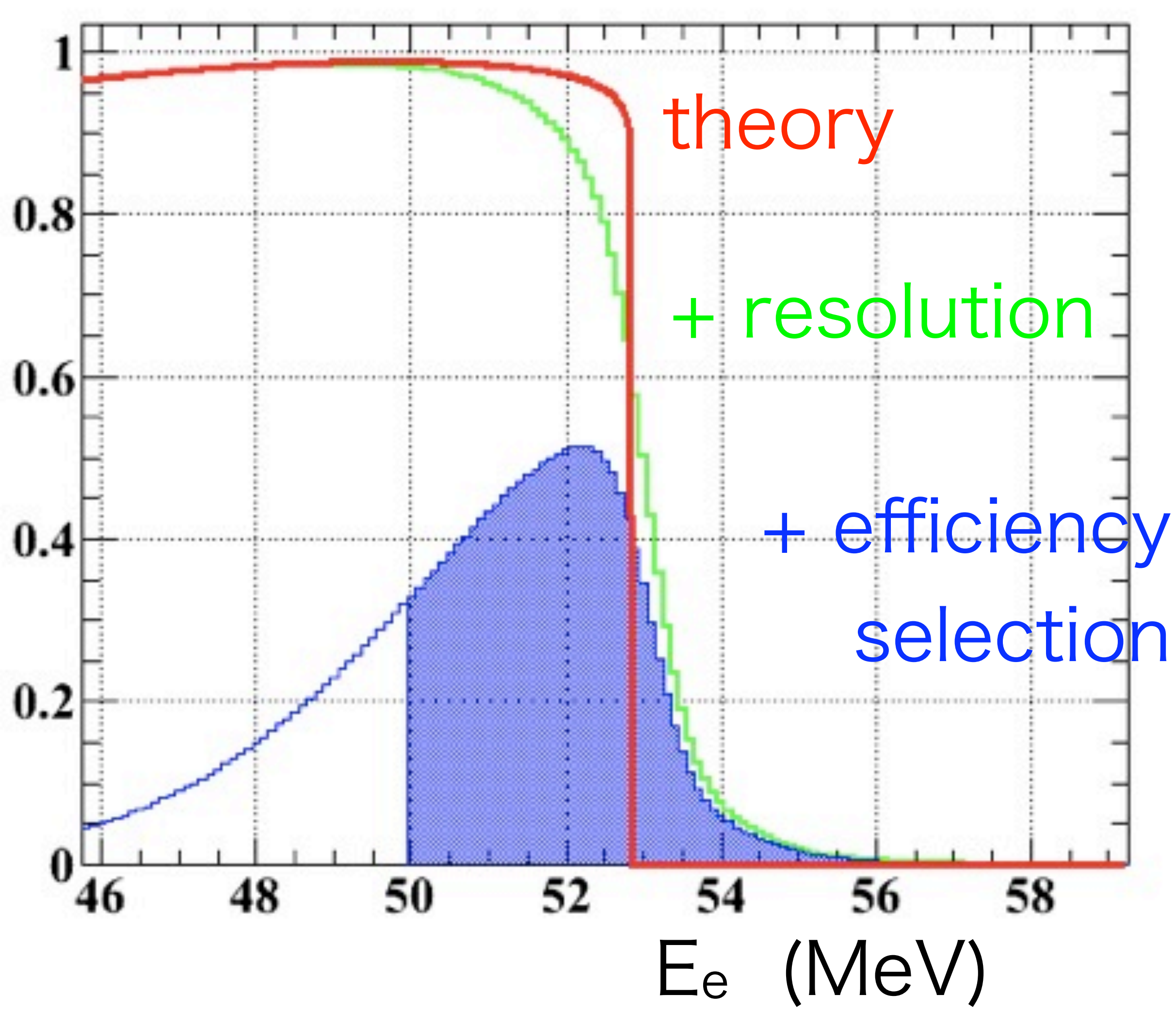


$N_{\rm sig} < 14.7$ @90% CL

$N_{\rm RMD}$ consistent with sideband estimate: 25^{+17}_{-16}

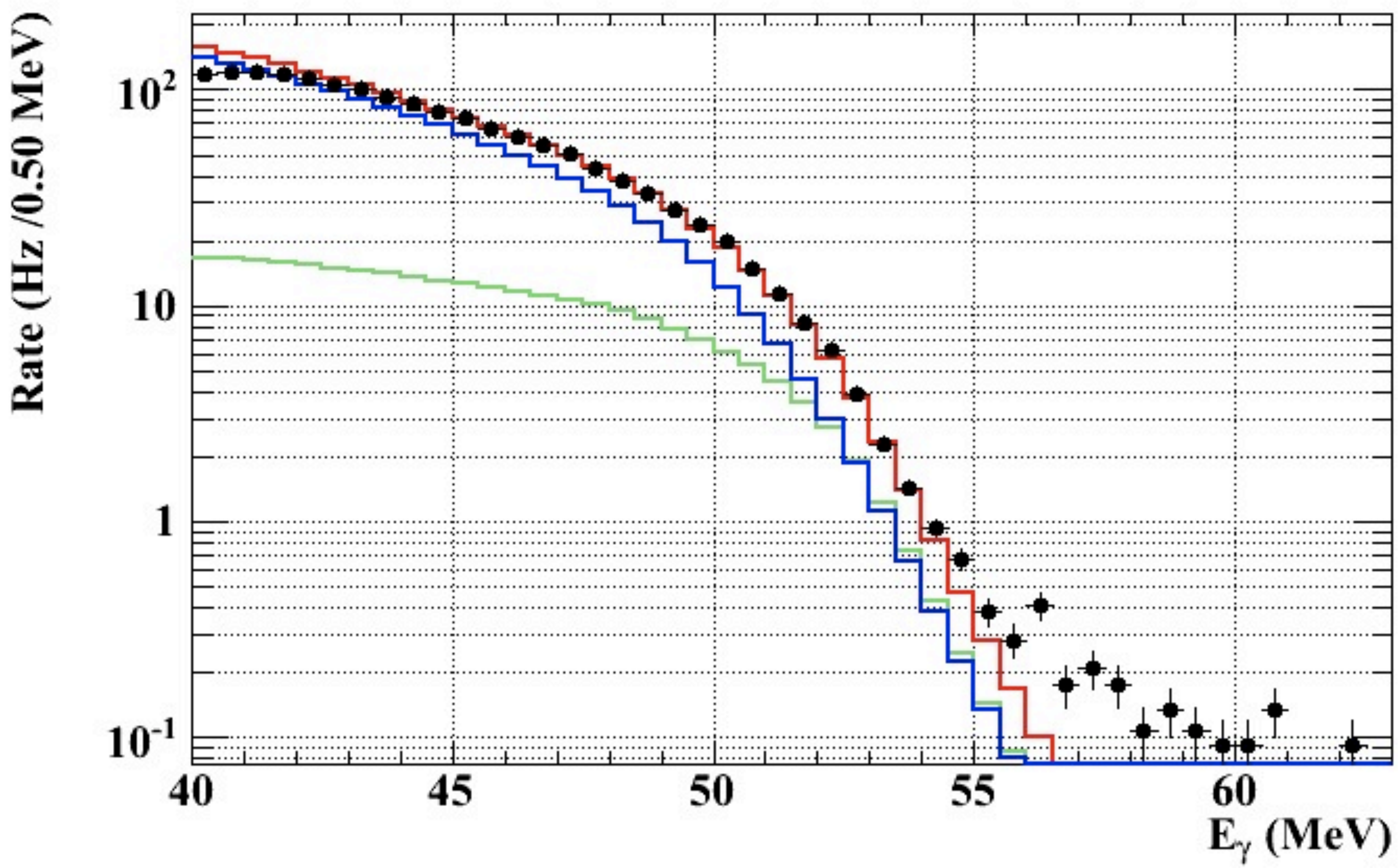
Normalization to Observed # Michel Decays

$$\mathrm{BR}(\mu^+ \to \mathrm{e}^+\gamma) = \frac{N_{\mathrm{sig}}}{N_{e\nu\bar{\nu}}} \times \frac{f^E_{e\nu\bar{\nu}}}{P} \times \frac{\epsilon^{trig}_{e\nu\bar{\nu}}}{\epsilon^{trig}_{e\gamma}} \times \underbrace{\frac{A^{TC}_{e\nu\bar{\nu}}}{A^{TC}_{e\gamma}} \times \frac{\epsilon^{DC}_{e\nu\bar{\nu}}}{\epsilon^{DC}_{e\gamma}}}_{=\sim 1} \times \frac{1}{A^{LXe}_{e\gamma}} \times \frac{1}{\epsilon^{LXe}_{e\gamma}}$$



- Nsig normalized to Michel positrons counted simultaneously with the signal.
- Independent of instantaneous beam rate and insensitive to positron acceptance and efficiency

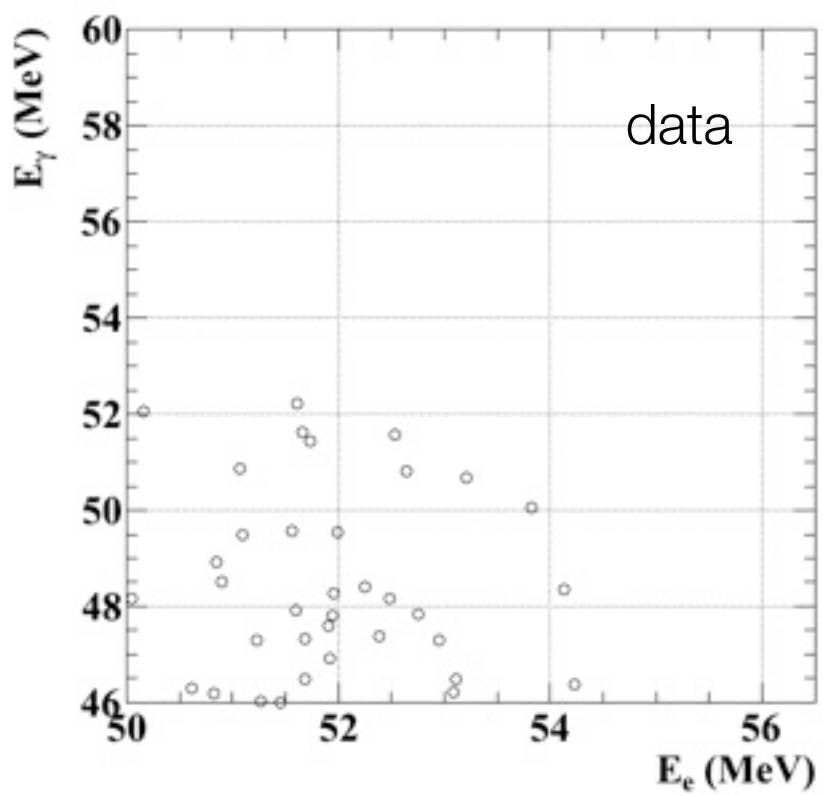
Various Checks on Normalization

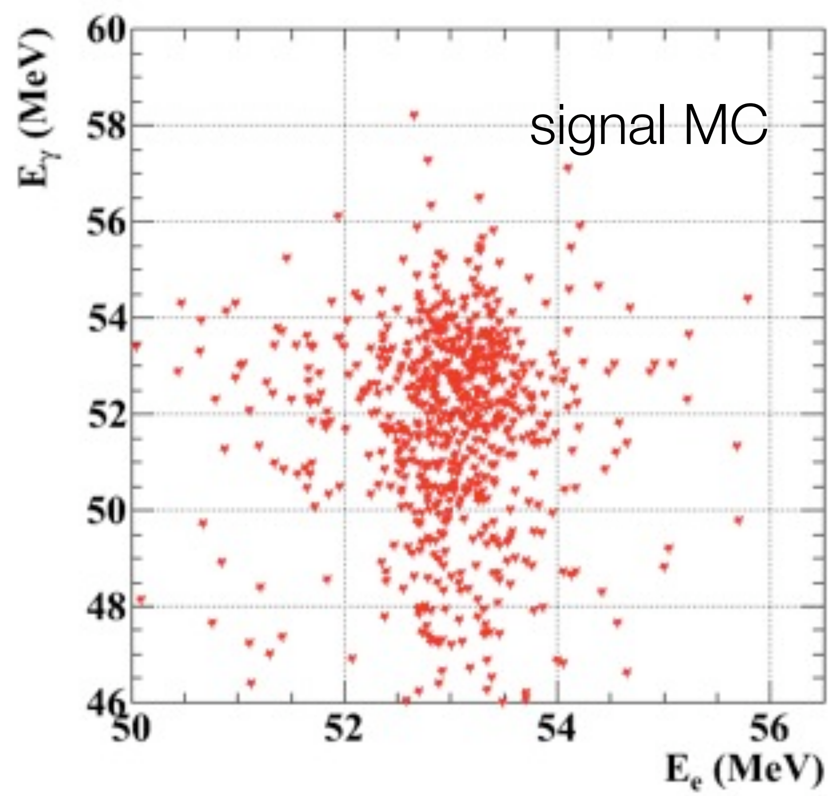


- Expected vs. measured rate of the background photons

The Preliminary 2008 Data Result

$$\mathrm{BR}(\mu^+ \to \mathrm{e}^+\gamma) < 3.0 \times 10^{-11}$$





After the selection cuts on the other variables where 90% of the signal events remain after each cut.

Prospects for the 2009 Run

- Sensitivity is limited by data statistics with the expected detector performance

- Up to 5 times more data expected => up to 5 times better sensitivity

  - Positron efficiency: the DC modules operating for 6 months - no problem

  - Trigger efficiency: TC fiber detector with improved electronics

  - More DAQ live time and less time needed for calibration

  - Better performance expected also for LXe with the increased light yield and the new wave form digitizer (DRS4)

Summary and Prospects of MEG

- Data taken during the first startup period in 2008 have yielded a 90% CL upper limit $\mathrm{BR}(\mu^+ \to \mathrm{e}^+\gamma) < 3.0 \times 10^{-11}$ while the expected 90% sensitivity was 1.3×10^{-11}.
- The drift chambers have now been modified to solve the problems and two of them have been successfully operated for 6 months. Following minor maintenance, the LXe detector is now operating and shows improved light yield (x ~1.4).
- MEG will resume data taking in late September; It is expected to reach a ~5 times better sensitivity ($\sim 2.4 \times 10^{-12}$) by the end of the year. Two more years will be required to accomplish a 10^{-13} sensitivity goal.