Lepton Flavour Violating Muon Decay at MEG

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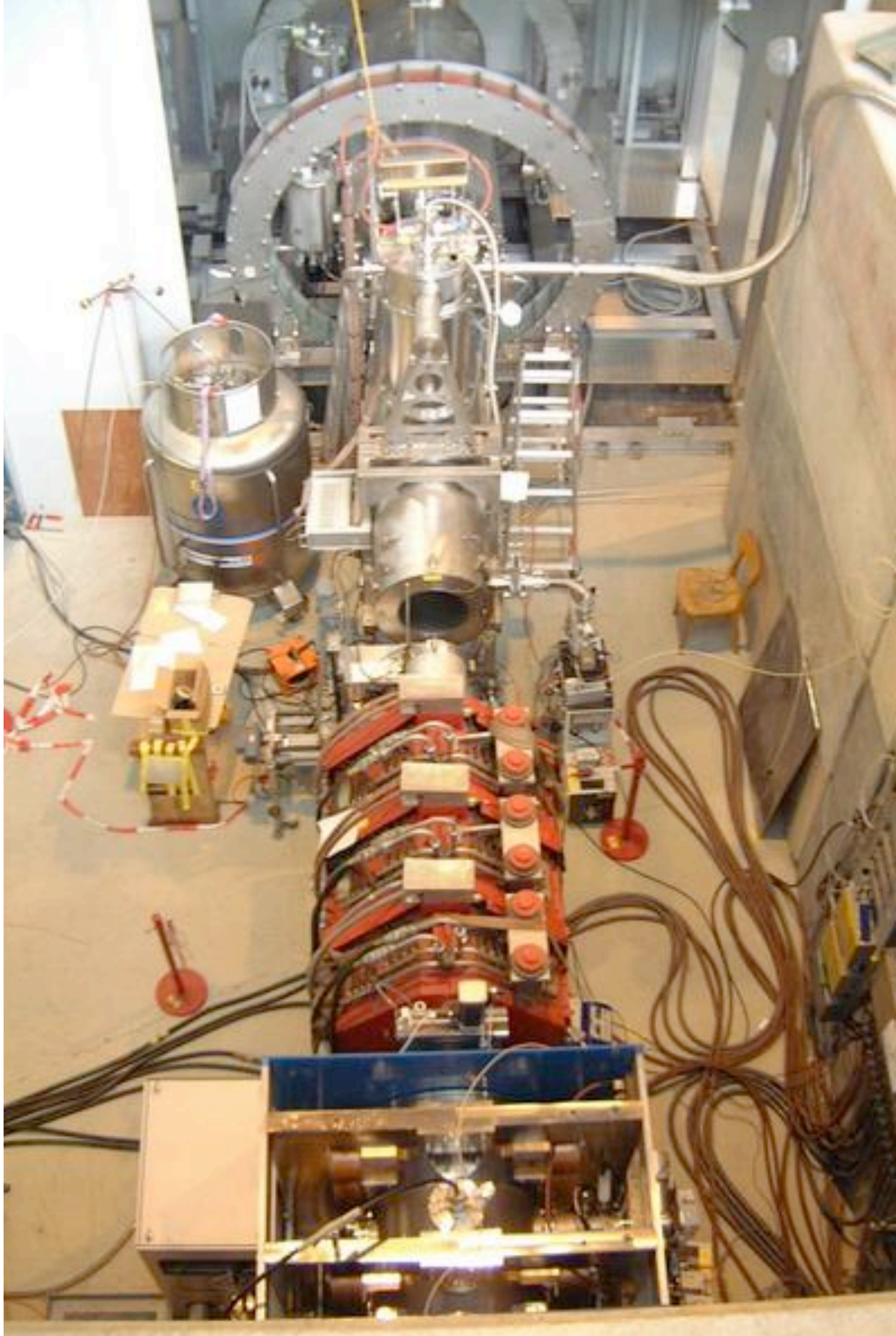
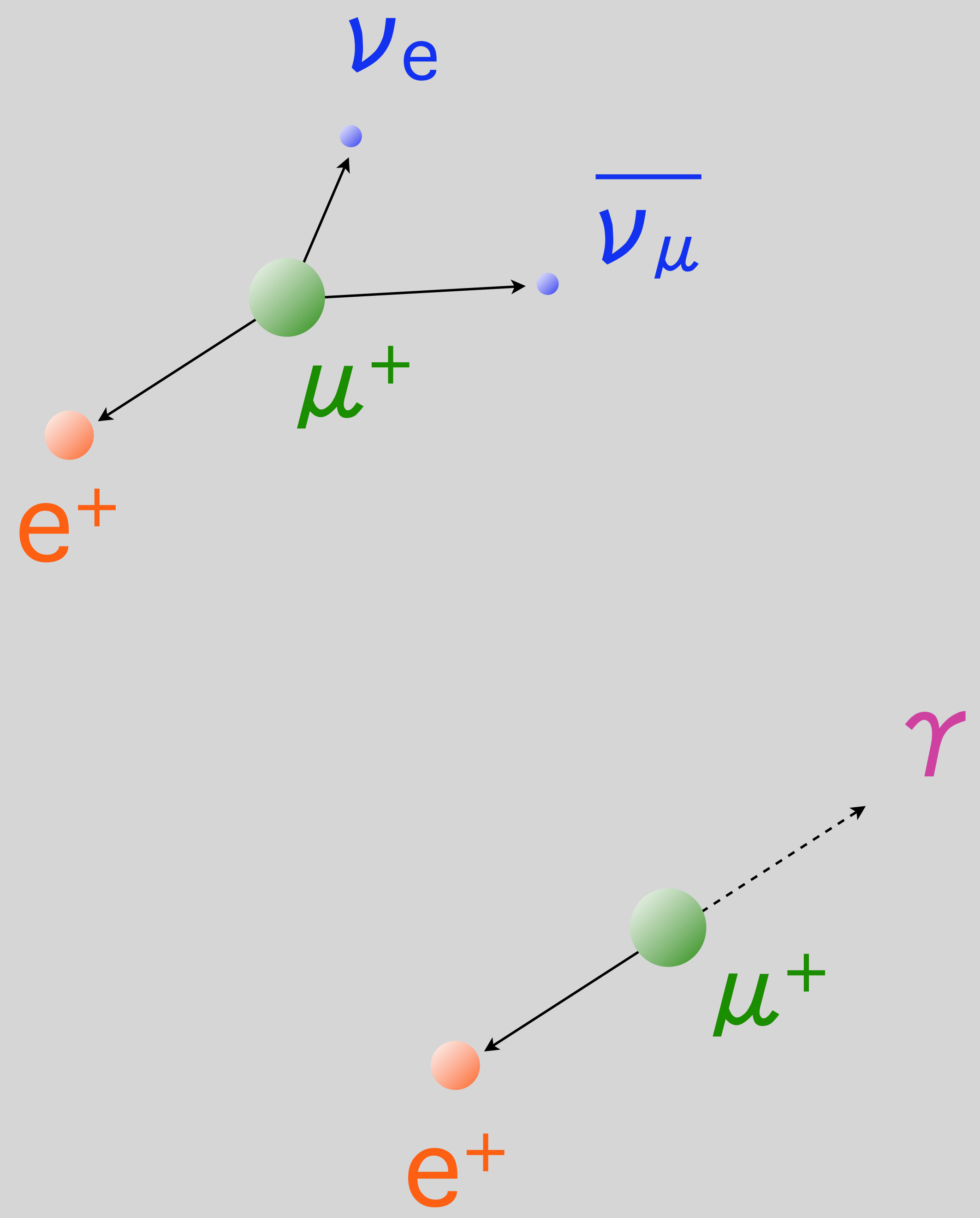
University of Tokyo
on behalf of the MEG collaboration

CONTENTS

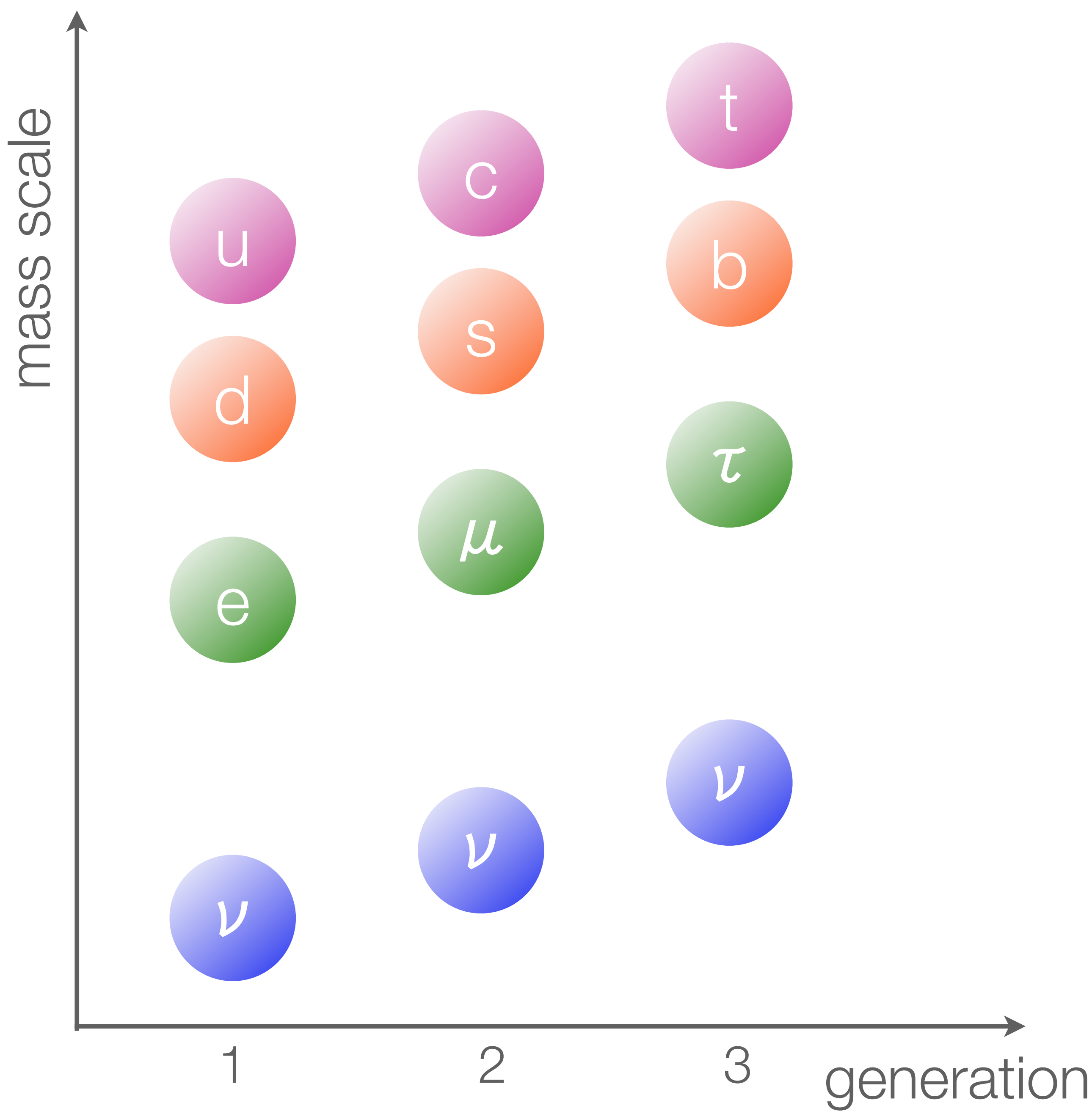
- Lepton Flavor Violation @ Muon
- MEG Experiment
  - Beam and Detector
  - Engineering Run 2007
  - Physics Run 2008
- Conclusion



Lepton Flavor Violation @ Muon



A Still Missing Piece in Flavour Physics



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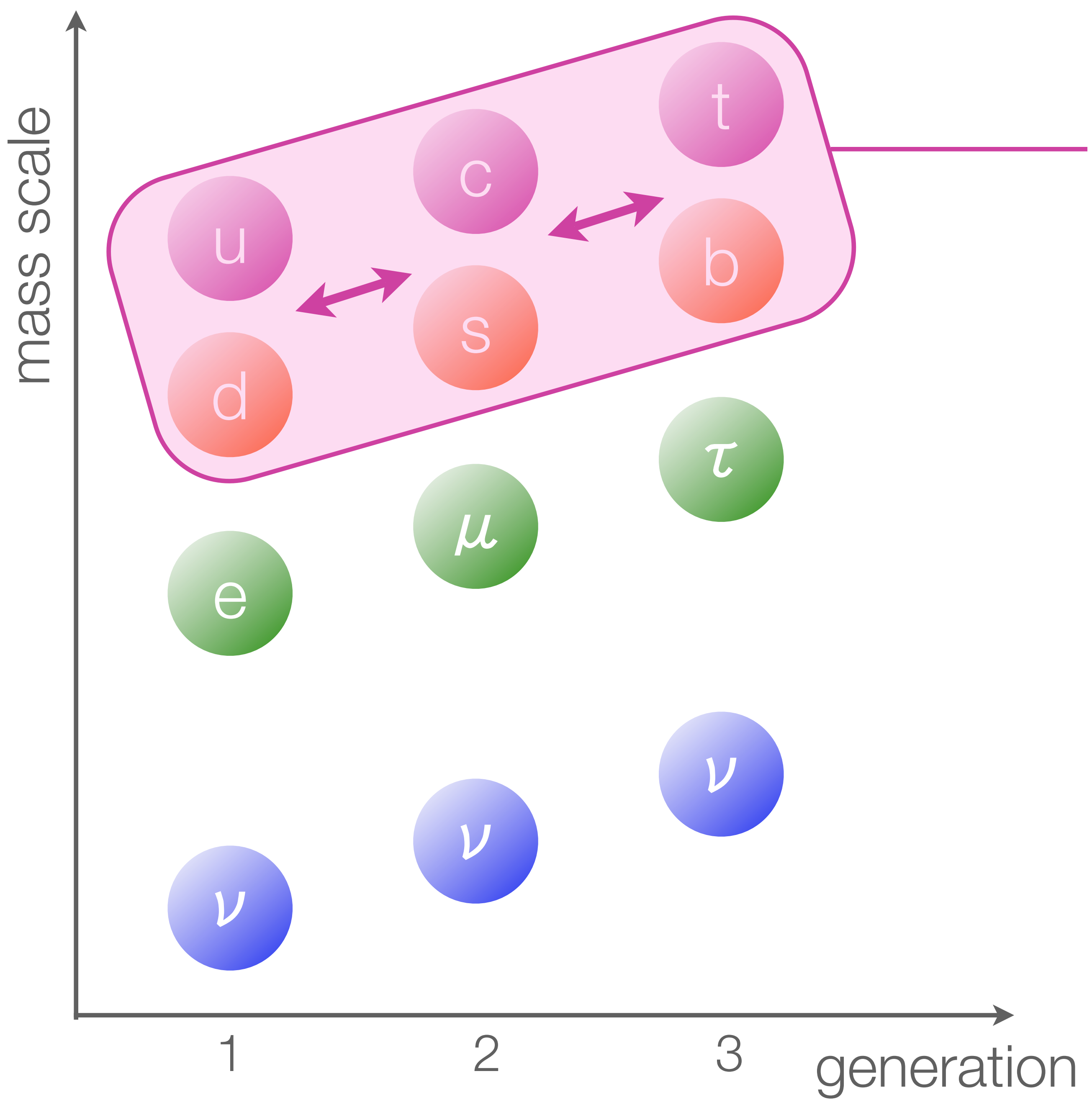
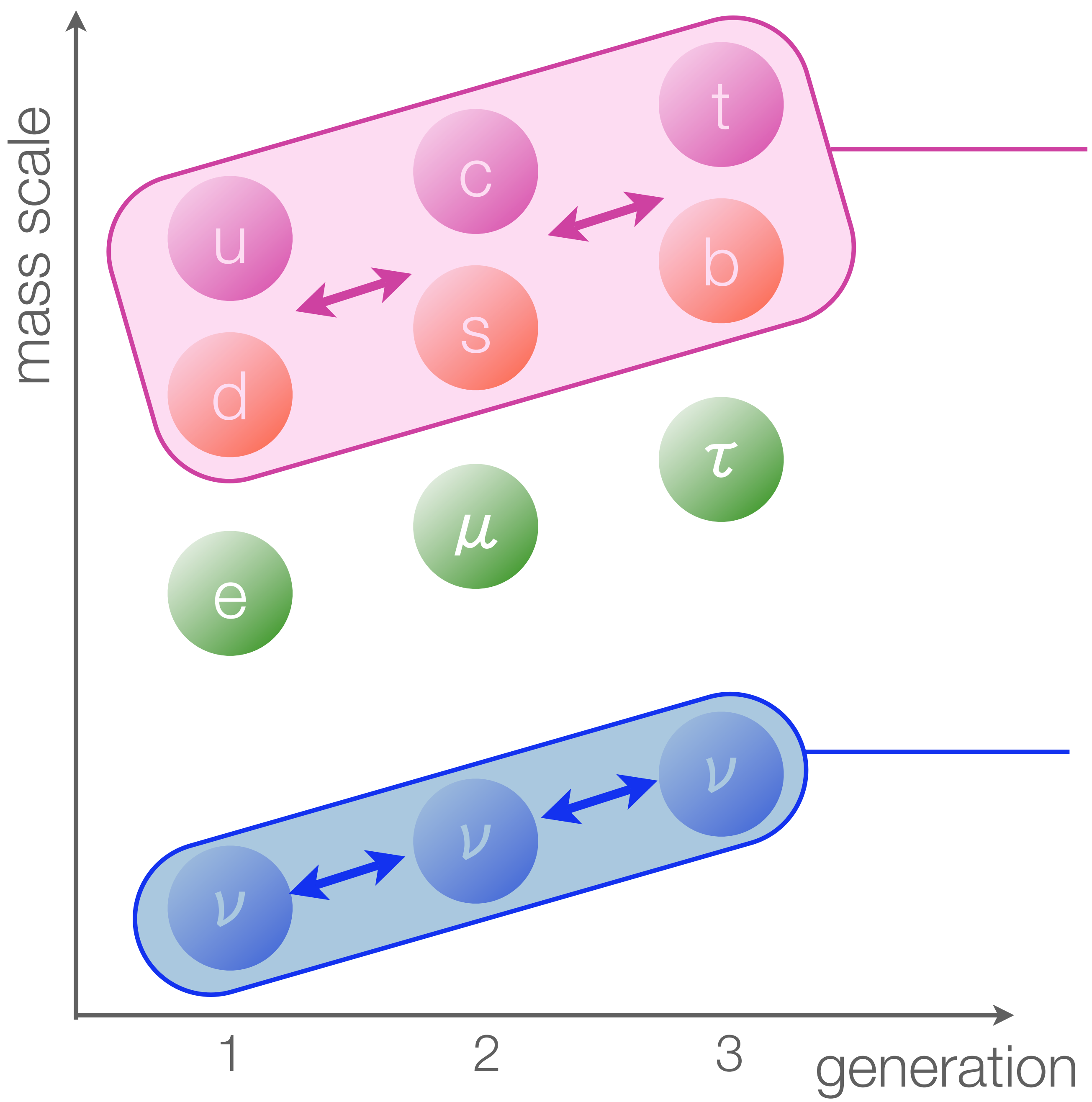


Quark Sector

- Mixed by CKM mechanism
- Experimentally Verified
  - ➡ B factories

A Still Missing Piece in Flavour Physics



Quark Sector

- Mixed by CKM mechanism
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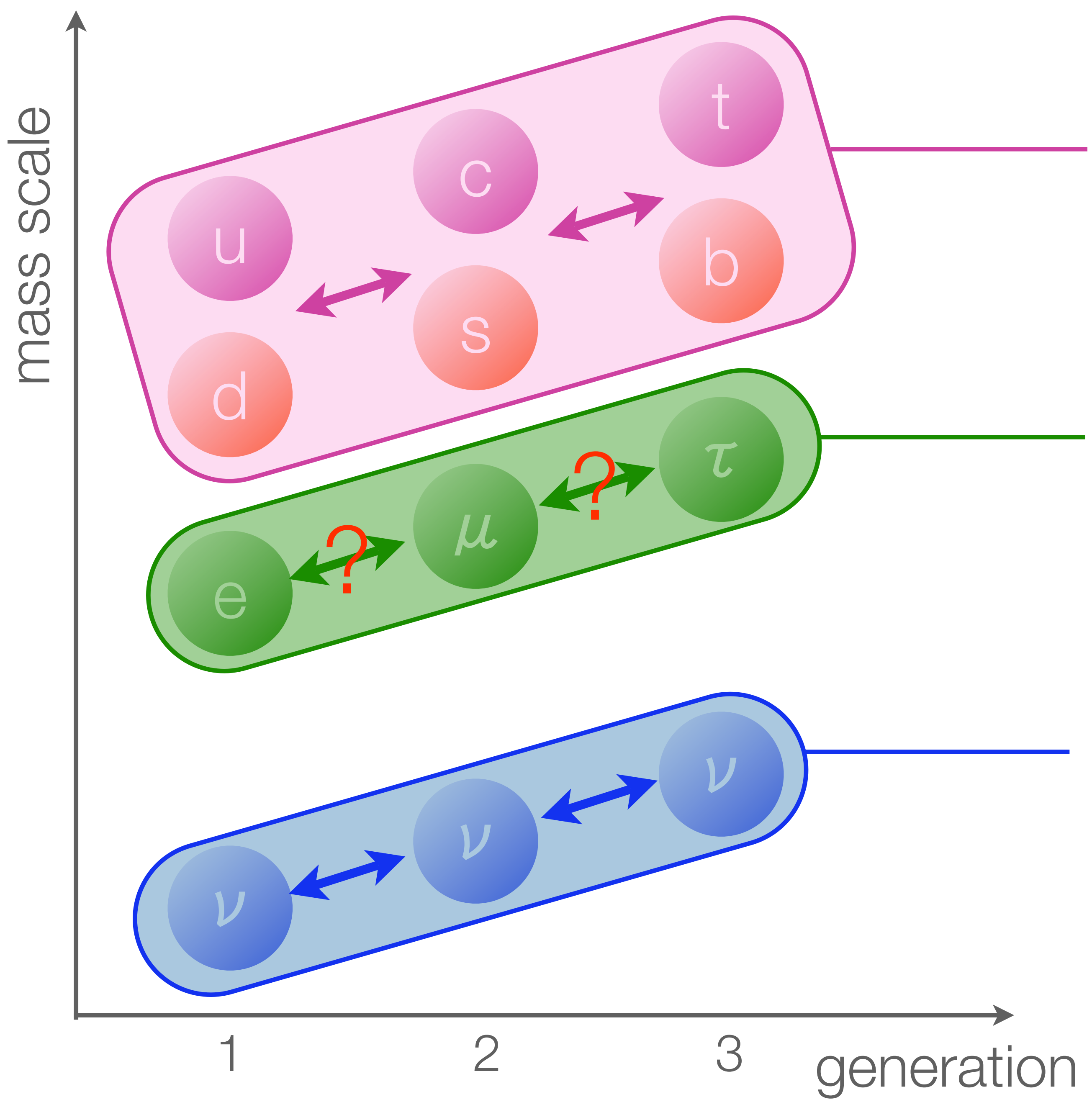
neutral Lepton Sector

- Neutrino Oscillation
- Experimentally Verified
  - ➡ SK, SNO, KamLAND, etc.

A Still Missing Piece in Flavour Physics



Quark Sector

- Mixed by CKM mechanism
- Experimentally Verified
  - ➡ B factories

charged Lepton Sector

- source from beyond SM ??
- never observed yet !!

neutral Lepton Sector

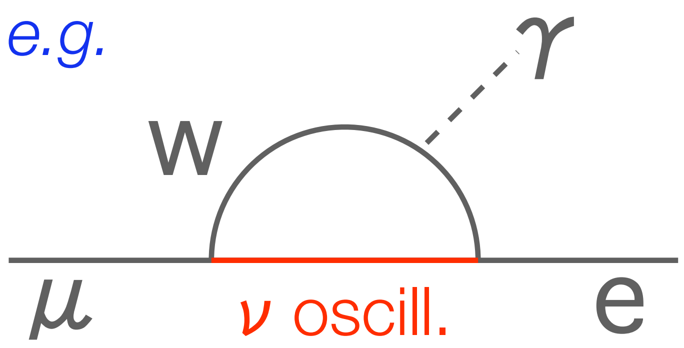
- Neutrino Oscillation
- Experimentally Verified
  - ➡ SK, SNO, KamLAND, etc.

Why charged LFV has never been observed ?

SM + simple ν Oscillation

- charged LFV is possible

e.g.



- but extremely rare (small ν)

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \sum_i \left| U^*_{\mu i} U_{ei} \frac{m^2_{\nu i}}{m^2_W} \right|^2$$

- $B(\mu \to e\gamma) = 10^{-50} \sim 10^{-40}$!!!

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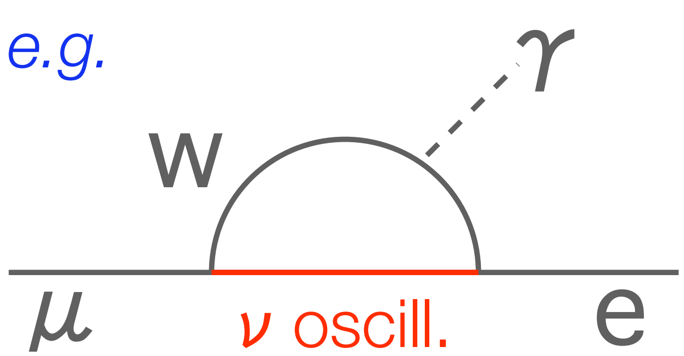

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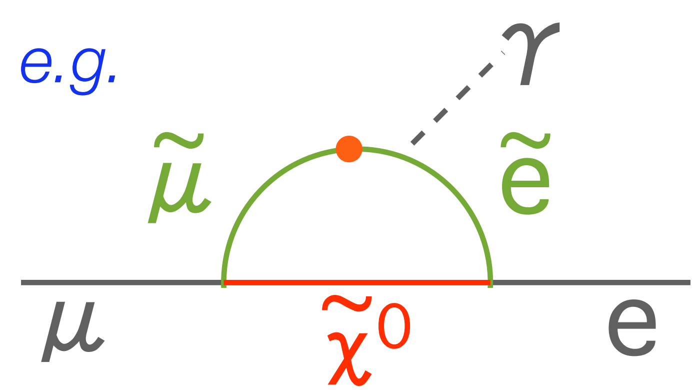
beyond SM (SUSY-GUT etc.)

- charged LFV is largely enhanced

e.g.



- still rare but observable level

$$\mathcal{B}(\mu \to e\gamma) \simeq \frac{\alpha^3 \pi \theta^2_{\tilde{e}\tilde{\mu}}}{G_F^2 \tilde{m}^4}$$

- B($\mu \to e\gamma$) = $10^{-15} \sim 10^{-11}$!!!

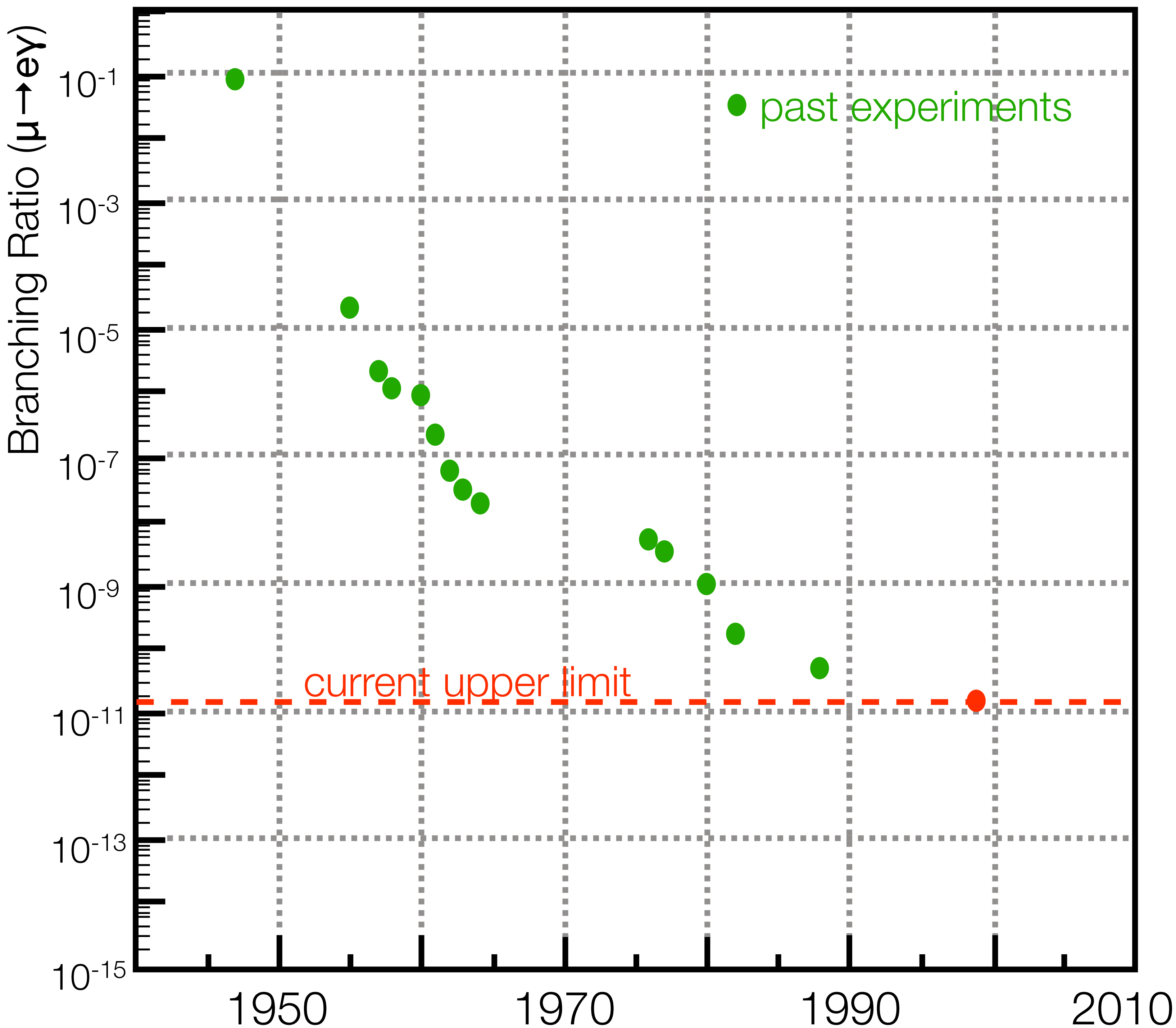
Why Charged LFV is Interesting ?

- Only charged LFV has never been observed
- Neutrino Oscillation is possible by “SM + ν mass”
- Quark Mixing is generally contaminated by SM

➡ charged LFV **is** “NEW PHYSICS”

- Experimental Upper Limit is already sensitive to predicted region
- *e.g.* <u>$\mu \to e\gamma$ is the most sensitive mode to search for charged LFV</u>

History of $\mu \to e\gamma$ Search Experiment



- current experimental limit : $Br(\mu \to e\gamma) = 1.2 \times 10^{-11}$
  - ➡ by MEGA, *PRL* ***83*** (1999) 1521
- $Br(\mu \to e\gamma) = 10^{-11} \sim 10^{-15}$ are predicted by theories
- predicted branching ratios are within the reach of the next experiments

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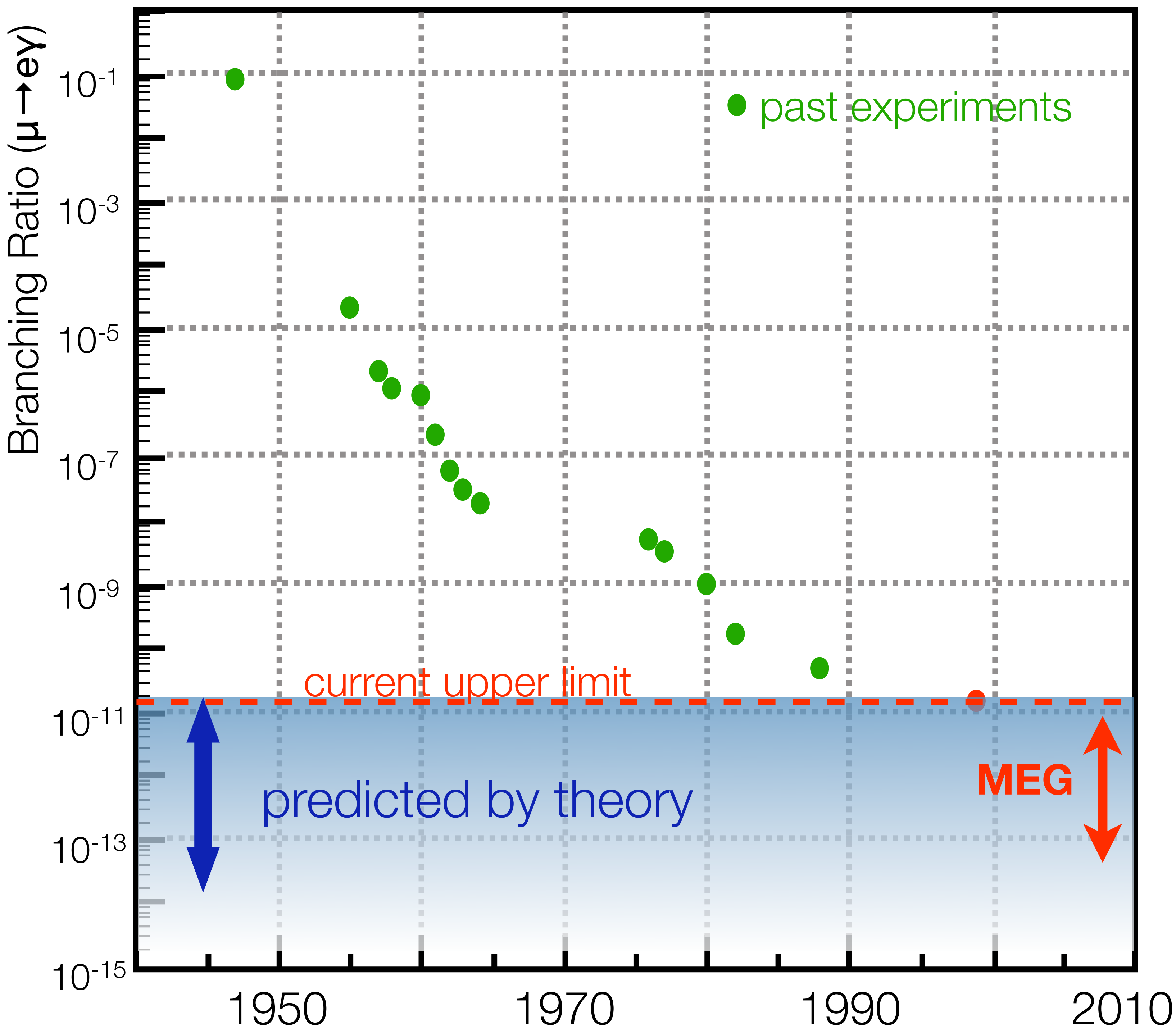

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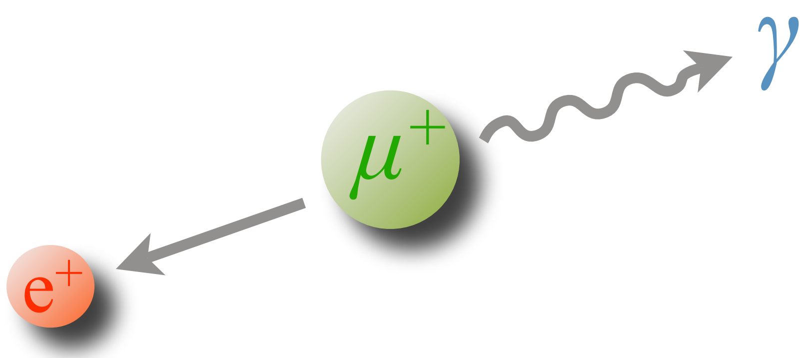
MEG Starts

$\mu \to e\gamma$ Signature & Background

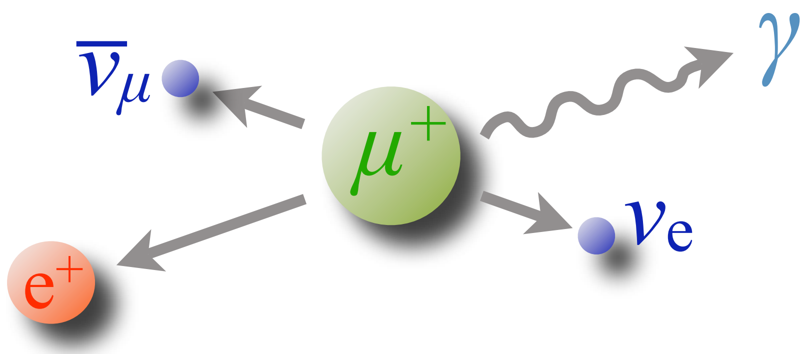
- Signal



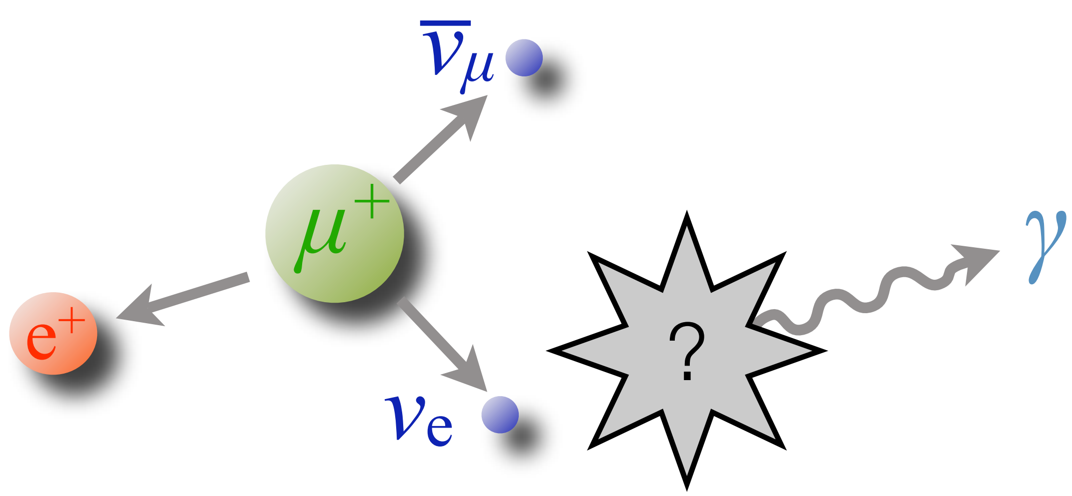
- $E_e = E_\gamma = m_\mu/2 = 52.8$MeV
- $\theta = 180$deg.
- time coincidence

Clear 2-body kinematics
use μ^+ to avoid capture inside stopping target
Background dominated by Accidental overlap
- lower muon beam rate is better
- DC muon beam is the best

- Background
  - radiative muon decay



  - accidental overlap



Requirements for $\mu \rightarrow e\gamma$ Search

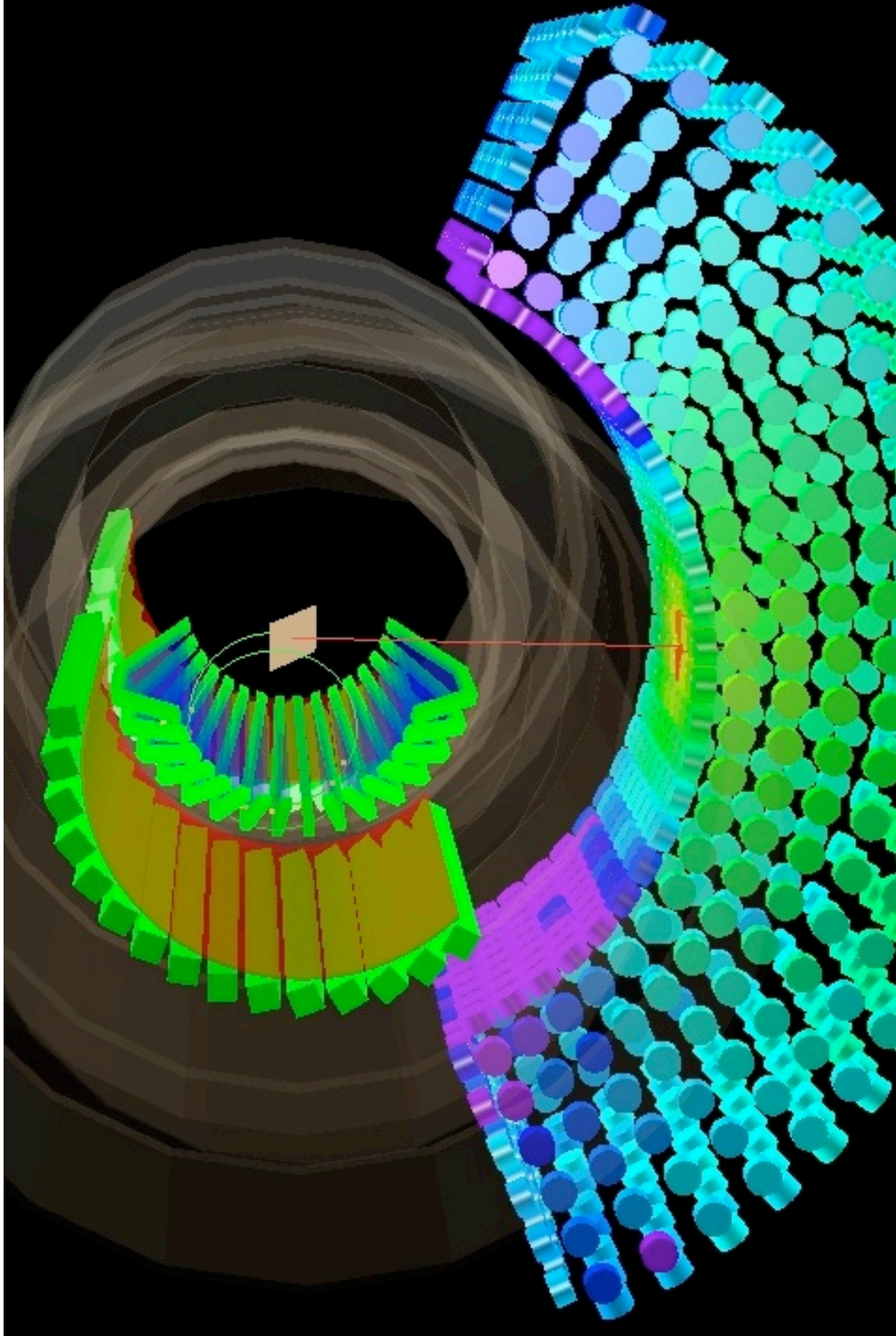
- High Intensity & DC Muon Source
- Good Energy/Angle/Timing Resolution
- Operational in High Rate

Requirements for $\mu \rightarrow e\gamma$ Search

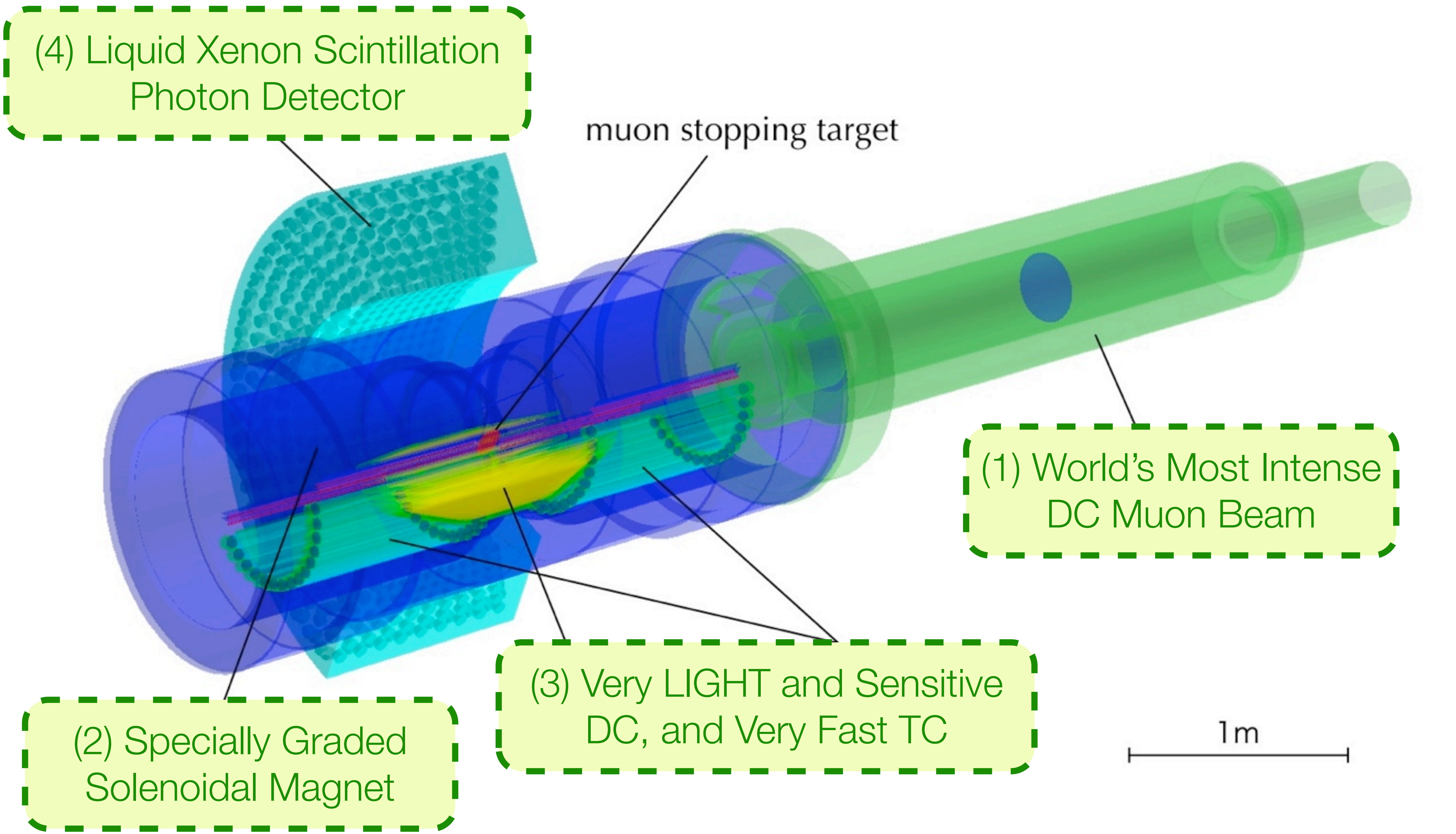
MEG

- High Intensity & DC Muon Source — PSI muon beam
- Good Energy/Angle/Timing Resolution — Liquid Xenon γ Detector
- Operational in High Rate — e^+ spectrometer with Specially Graded B-field

MEG Experiment



MEG Concept and Detector Apparatus

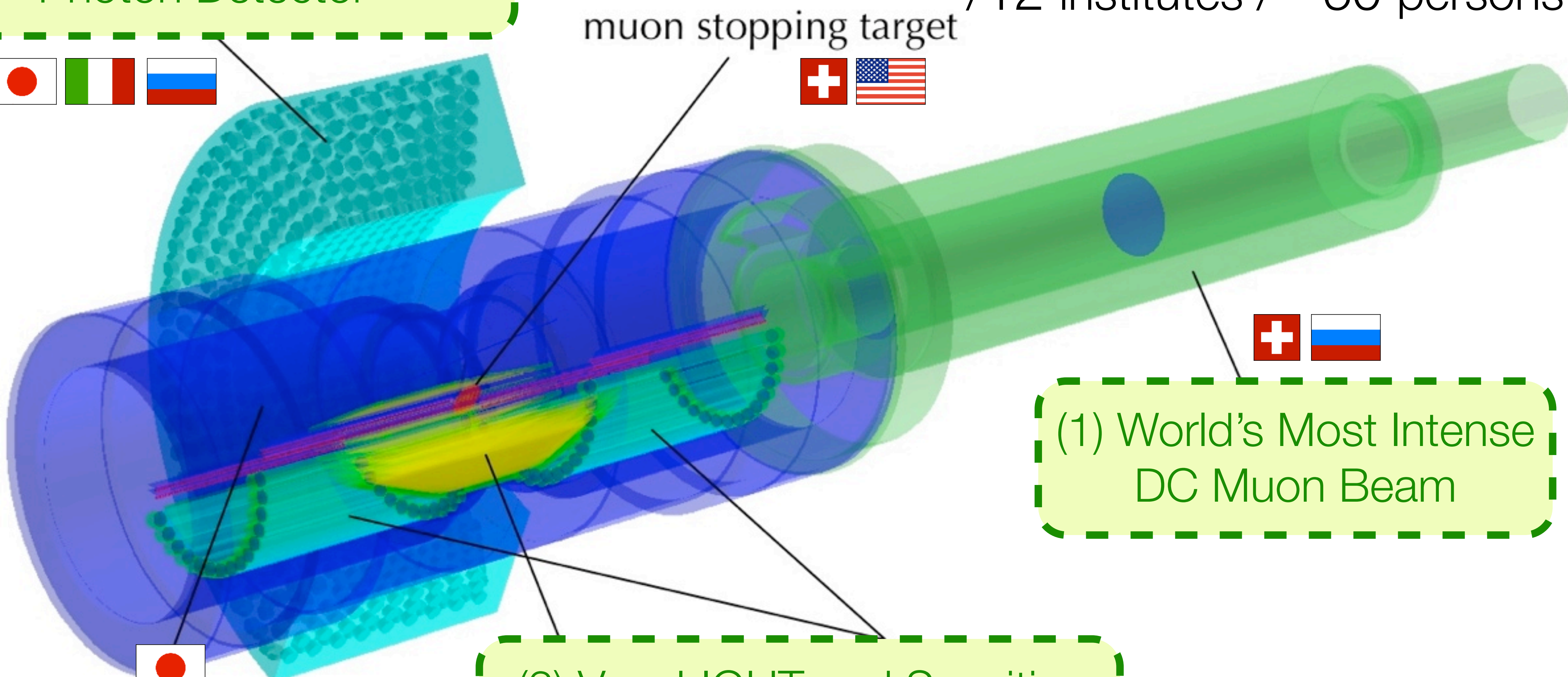


MEG Concept and Detector Apparatus

The MEG Collaboration

(5 countries ,
/12 institutes / ~60 persons)

(4) Liquid Xenon Scintillation Photon Detector



(1) World's Most Intense DC Muon Beam

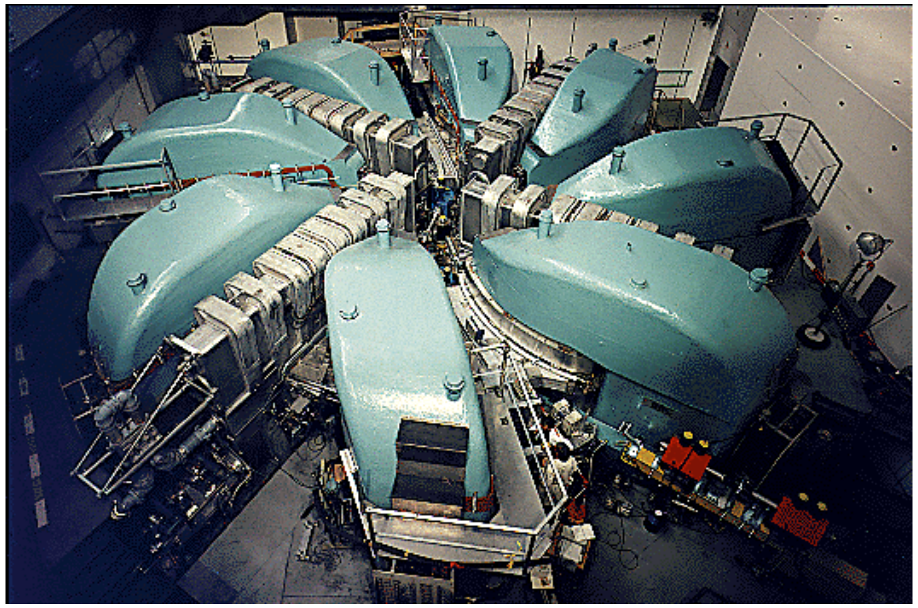
(2) Specially Graded Solenoidal Magnet

(3) Very LIGHT and Sensitive DC, and Very Fast TC

1m

Muon Beam

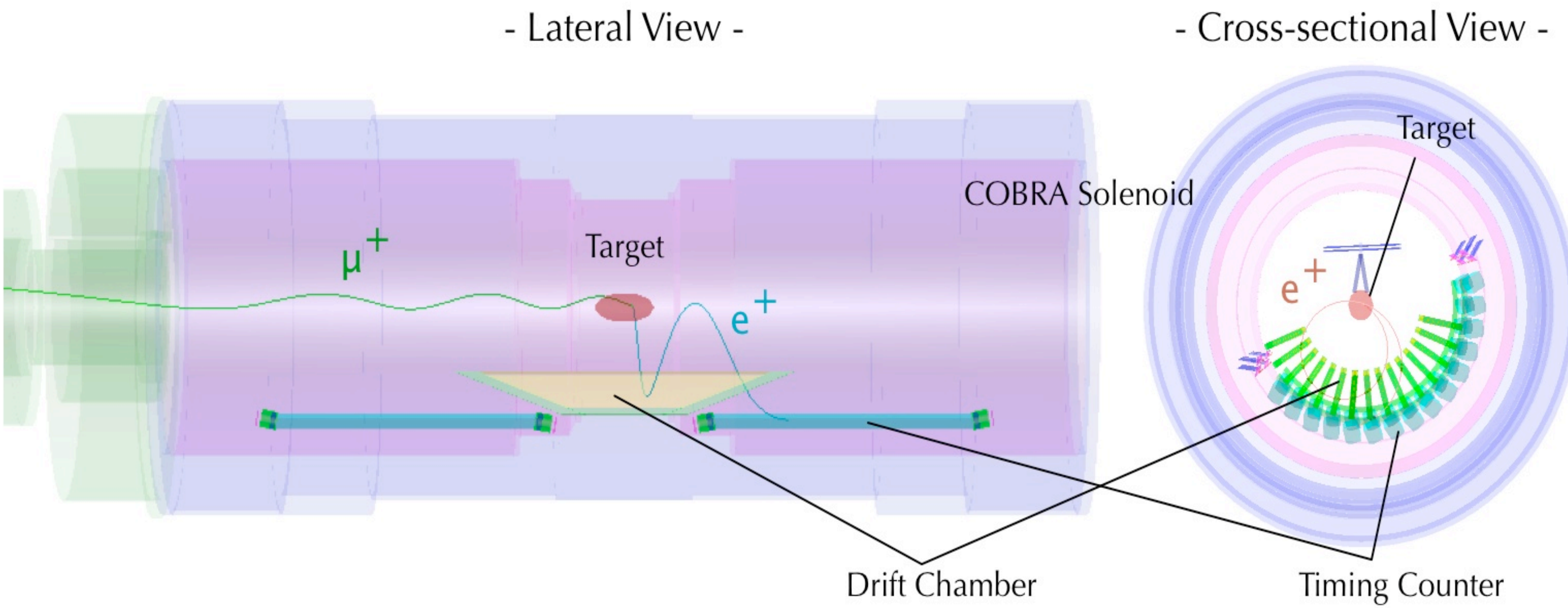
- Requirements
  - Powerful Proton Driver
  - DC Beam is Better than Pulsed
  - Surface Muon is Better than Cloud
- Paul Scherrer Institut (PSI) is the Best
  - World Most Powerful Proton Cyclotron
    - 590 MeV, >2mA
  - Surface Muon , DC Beam
  - πE5 Beam-line is setup for MEG
    - Up to 10^8 μ^+/sec is Available



590 MeV Ring Cyclotron @ PSI

production target

Positron Spectrometer - Overview



Solenoid

superconducting solenoid
gradient B-field (0.5-1.7 T)
very thin conductor and
cryostat wall ($0.2X_0$)

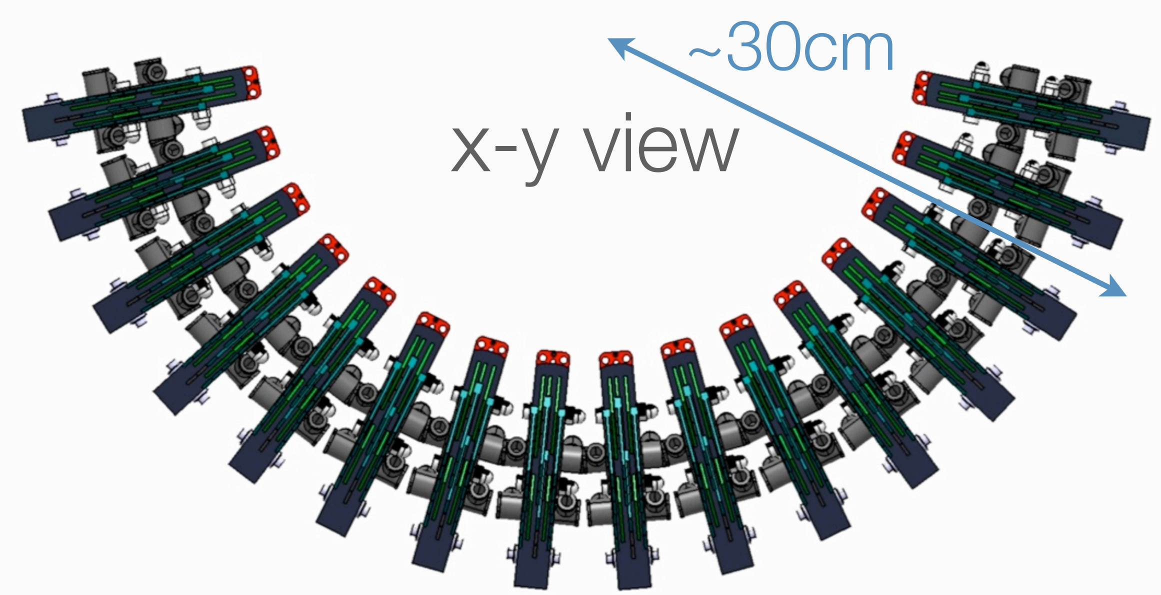
Drift Chamber

segmented radially (16 sectors)
helium:ethane (50:50)
opened-frame
very thin cathode foil with pads

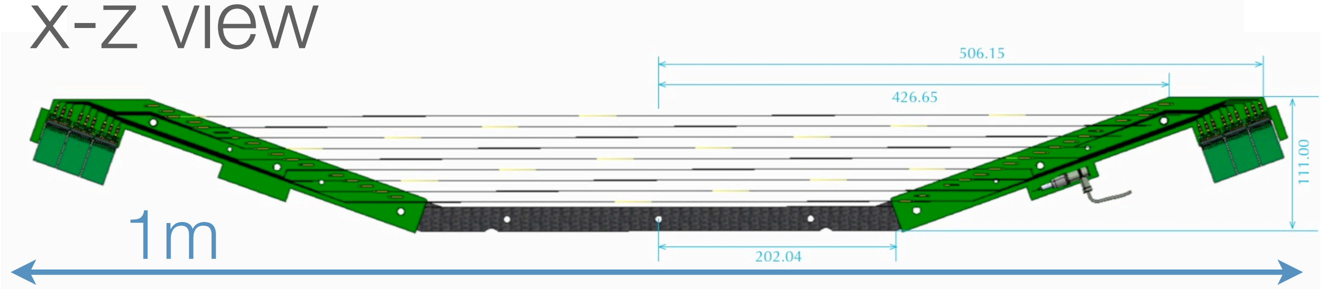
Timing Counter

2-layers of scintillators
- scintillator bars (outer)
- scintillator fibres (inner)

Drift Chamber - Overview



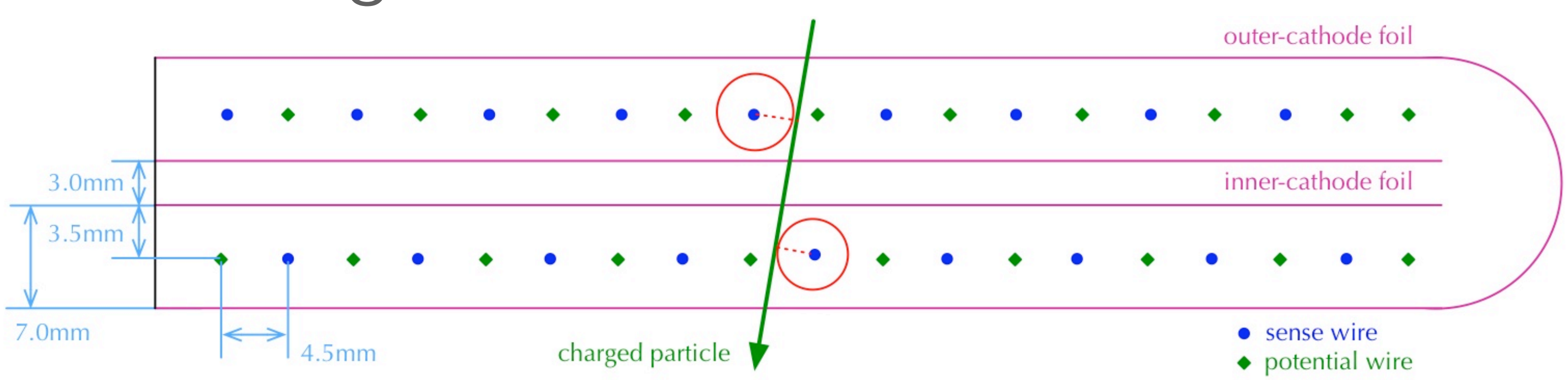
x-z view



- 16 Segmented Module Structure
- Helium-Ethane gas mixture (50:50)
- 2 Layers of axial wires
  - staggered sense and potential
  - small cell (4.5 mm pitch)
- carbon-fibre frame
  - open-structure
  - trapezium shape
- ultra-thin cathode foil
  - vernier-pad method

} critical

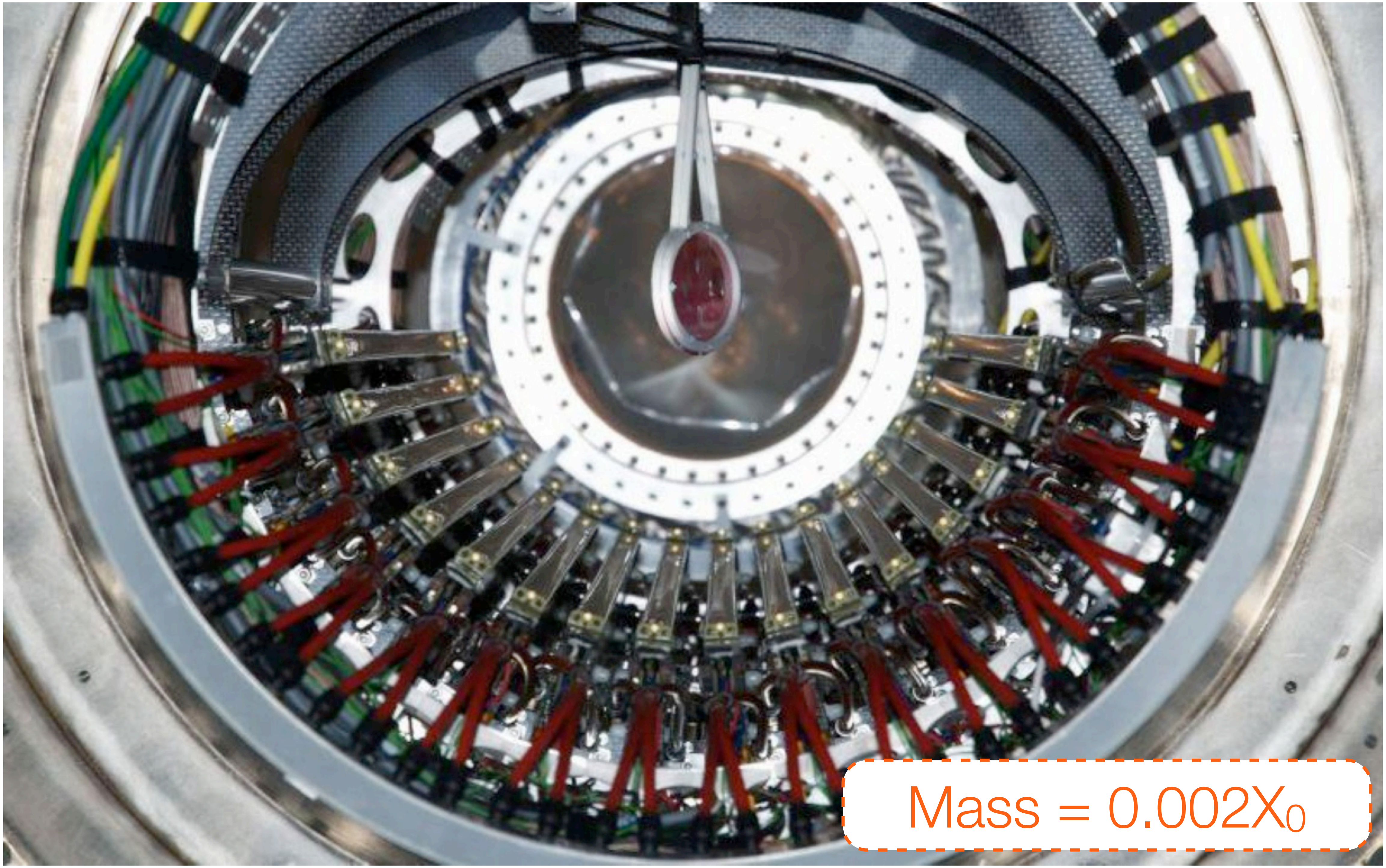
cell configuration



specially designed *zig-zag* cathode pads; σ_Z~500 μm is possible w/o increasing # of Ch.

Completed Drift Chamber System

Completed Drift Chamber System

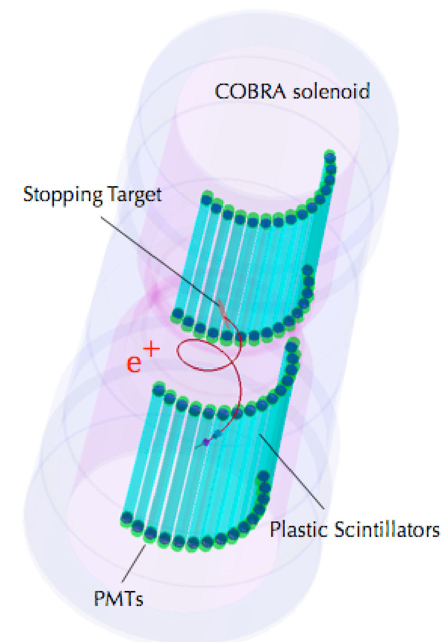


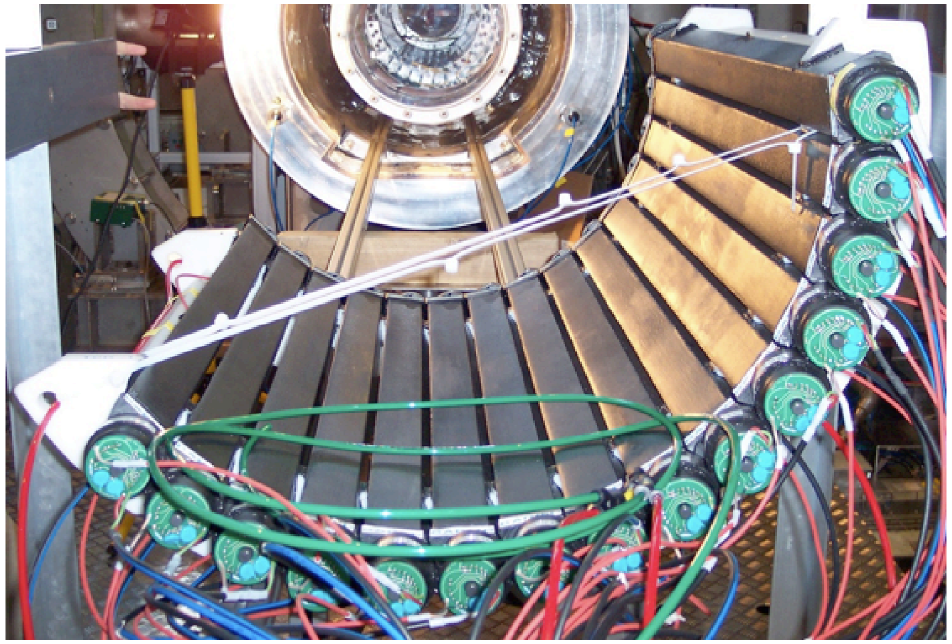
Mass = $0.002X_0$

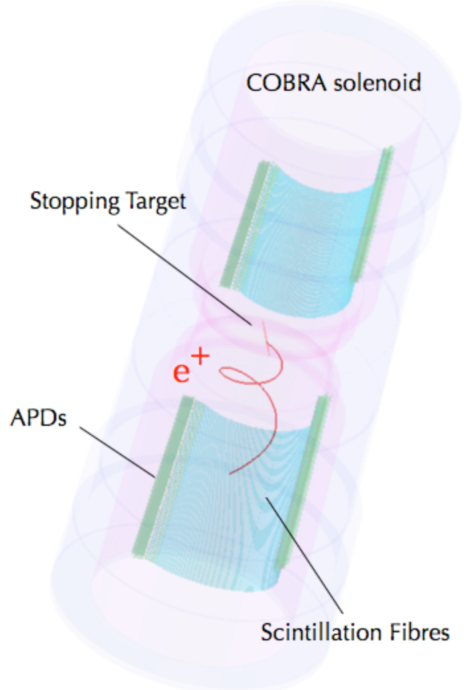
Timing Counter

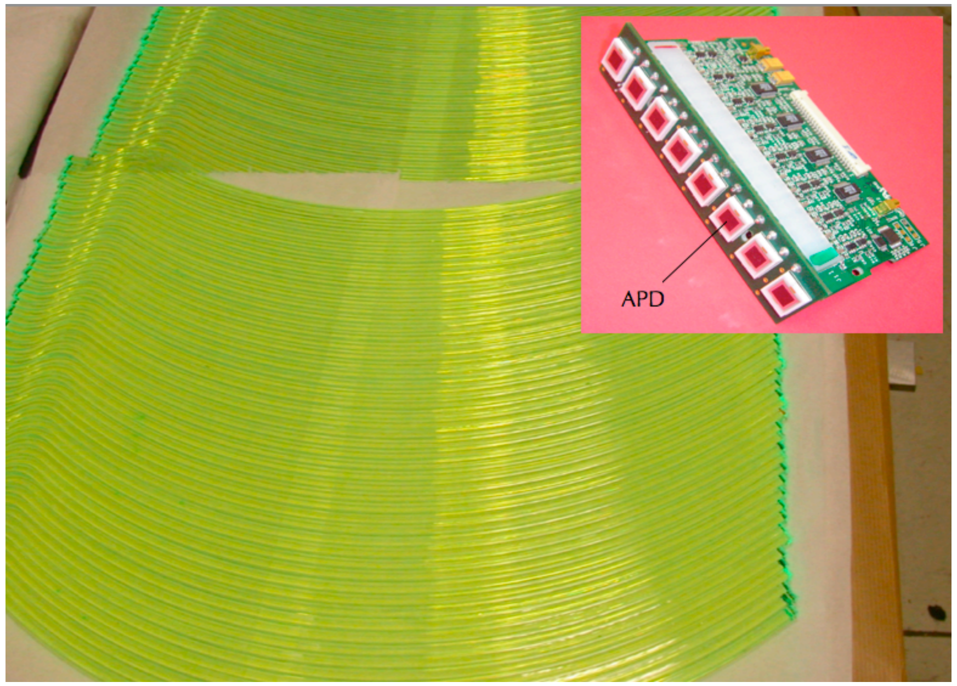
- 2-layers of scintillators
  - Scintillator bars (outer layer), read out by PMTs for timing
    - 30 bars with 2” PMTs at both ends
  - Scintillator fibres (inner layer), read out with APDs for z-trigger
    - 256 fibres with APDs at both ends
- Goal : $\sigma_T \sim 40$ ps

verified by testbeam



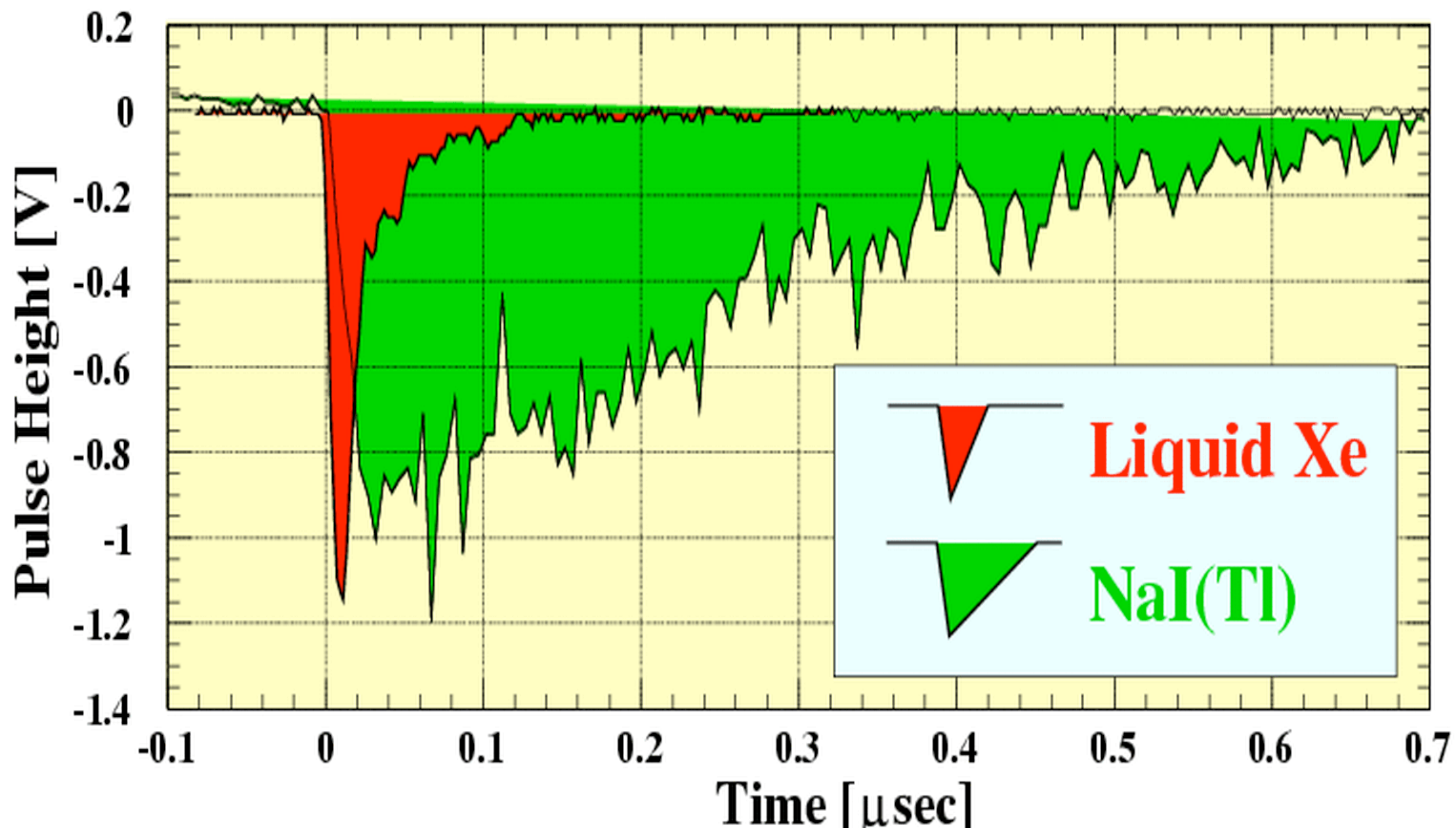






Liquid Xenon Photon Detector - Why Liquid Xe ?

- Good Resolutions
  - Large Light Yield (80% of NaI)
    - W_{ph} = 22.4 eV
- Pile-up Event Rejection
  - Fast Response
  - Short Decay
    - τ_S=4.2ns, τ_T=45ns
- Good Uniformity

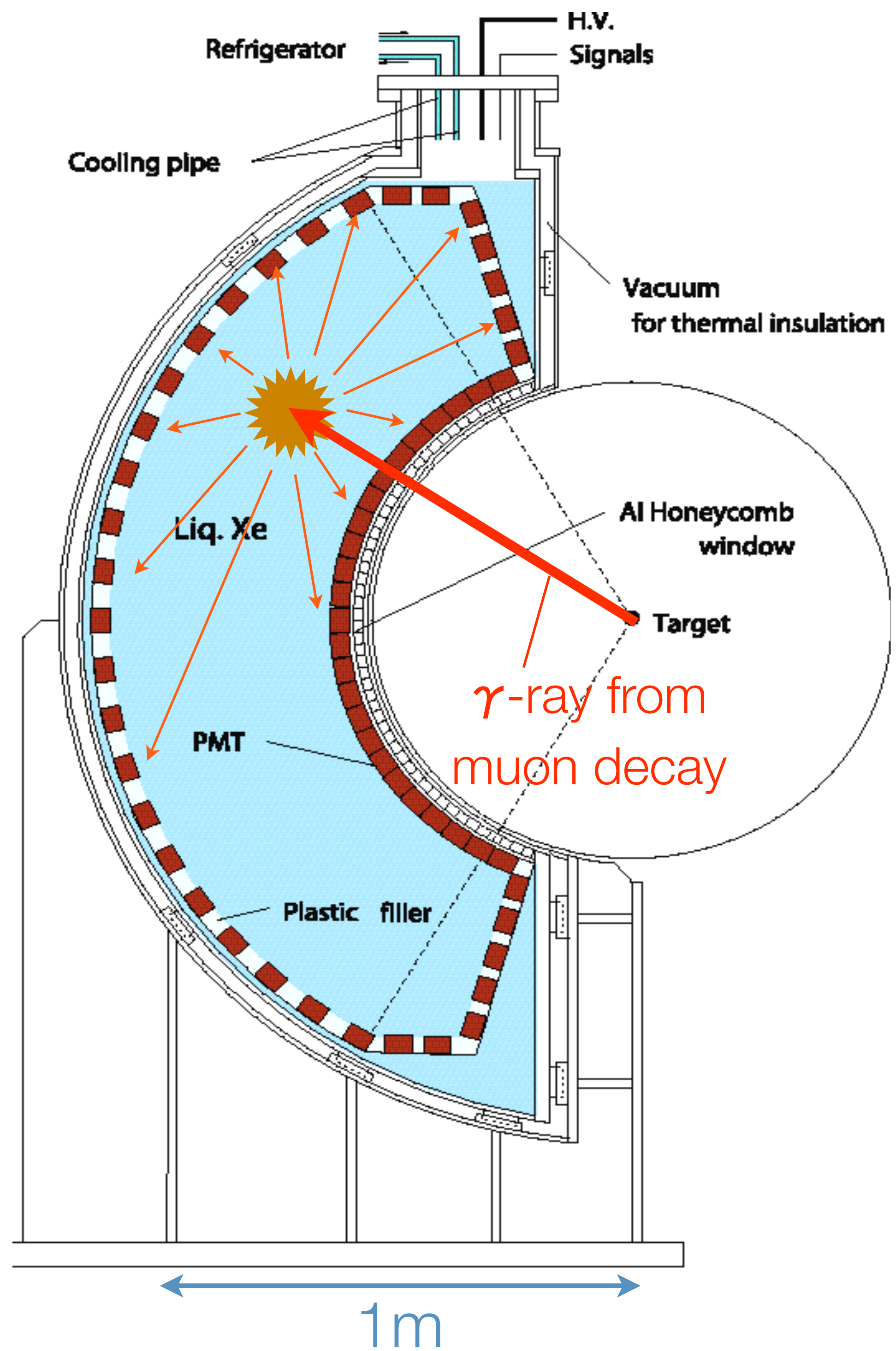


	NaI	BGO	GSO	Liq. Ar	Liq. Xe
effective Atomic Number	50	73	58	18	54
Density (g/cm³)	3.7	7.1	6.7	1.4	3.0
Relative Light Output (%)	100	15	20-40	67	80
Decay Time (ns)	230	300	60	6 / 1000	4 / 22

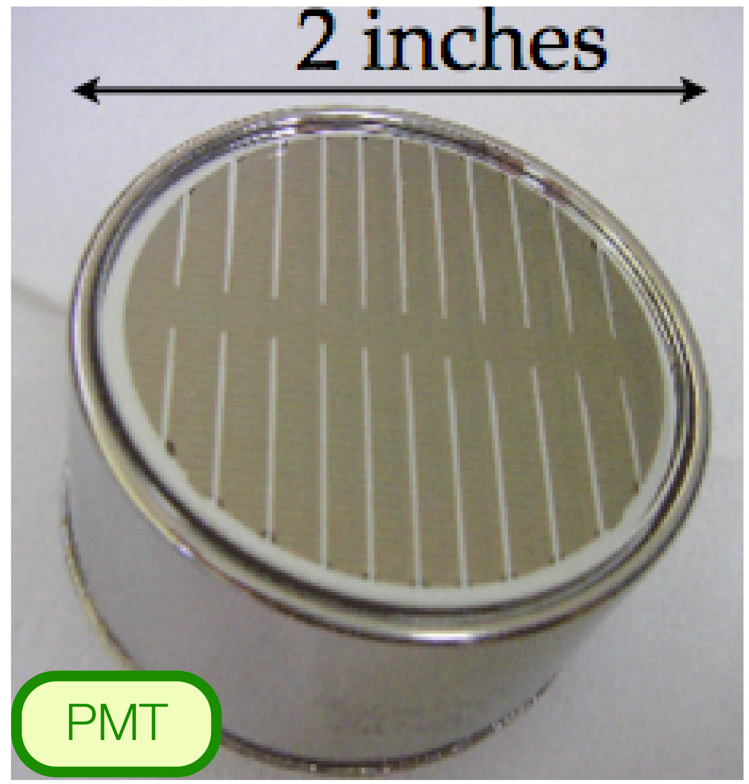
MEG Liquid Xe Detector

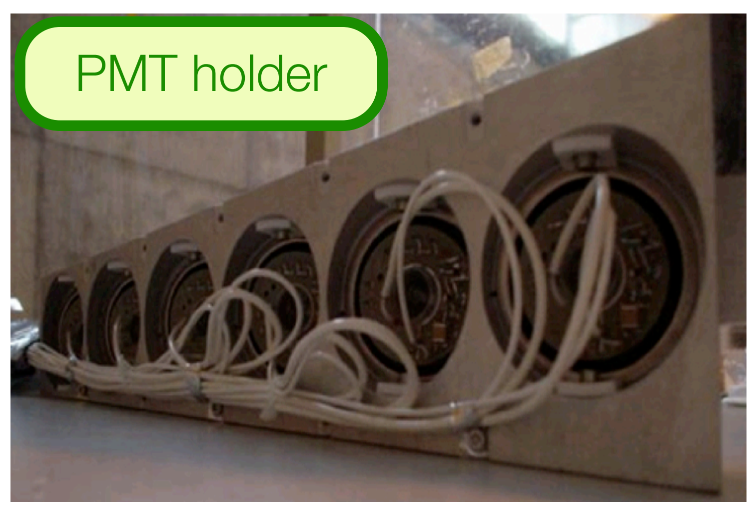
- Active Volume ~ 800 l is surrounded by PMTs on all faces
- 846 PMTs in the liquid
- No segmentation
- Energy
  - All PMT outputs
  - σ_E/E = 2 % (@52.8MeV)
- Position
  - PMTs on the inner face
  - σ_x = 4~5 mm (@52.8MeV)
- Timing
  - Averaging of signal arrival time of selected PMTs
  - σ_T = 65 ps (@52.8MeV)

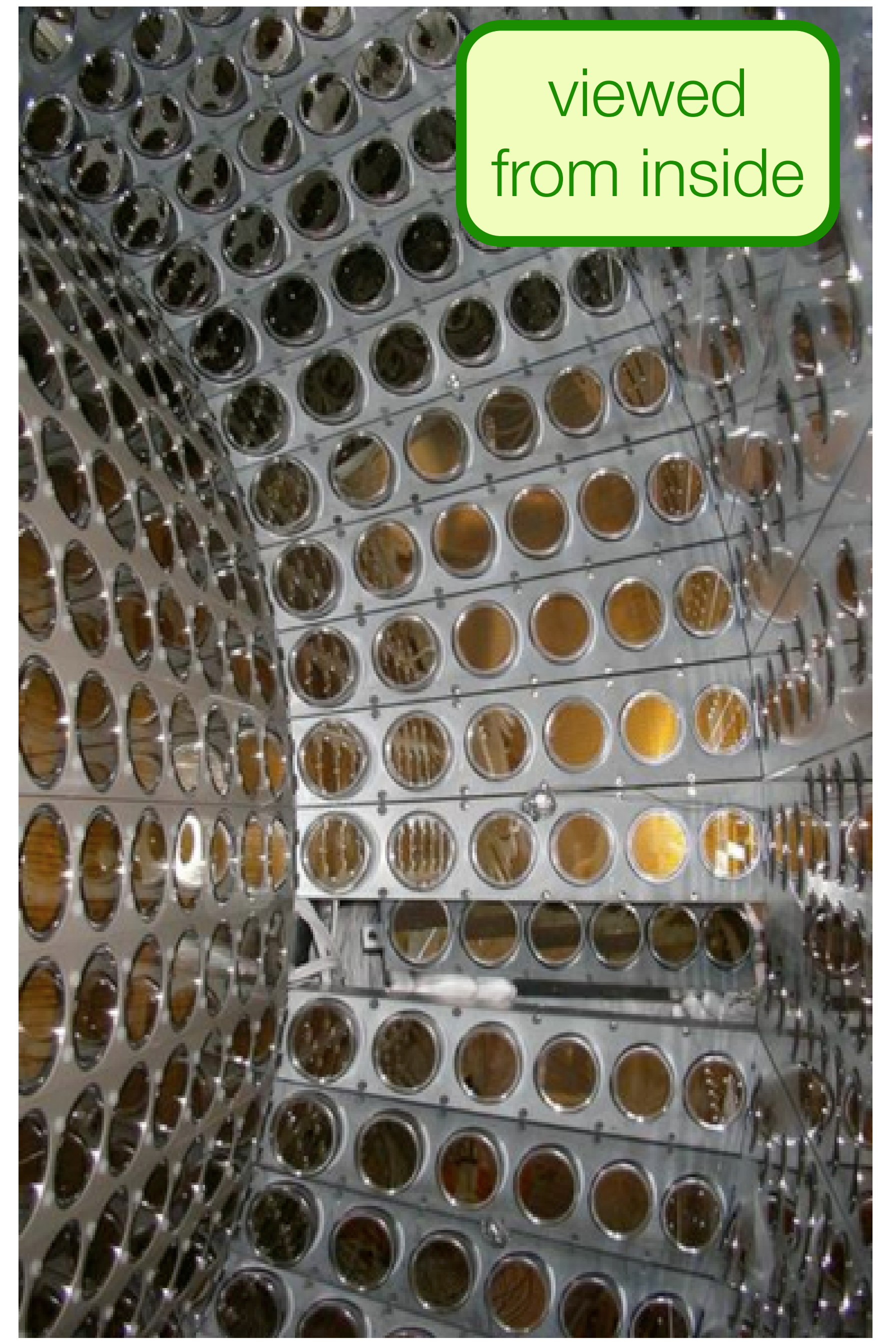
verified by prototype



MEG Liquid Xe Detector - Assembly







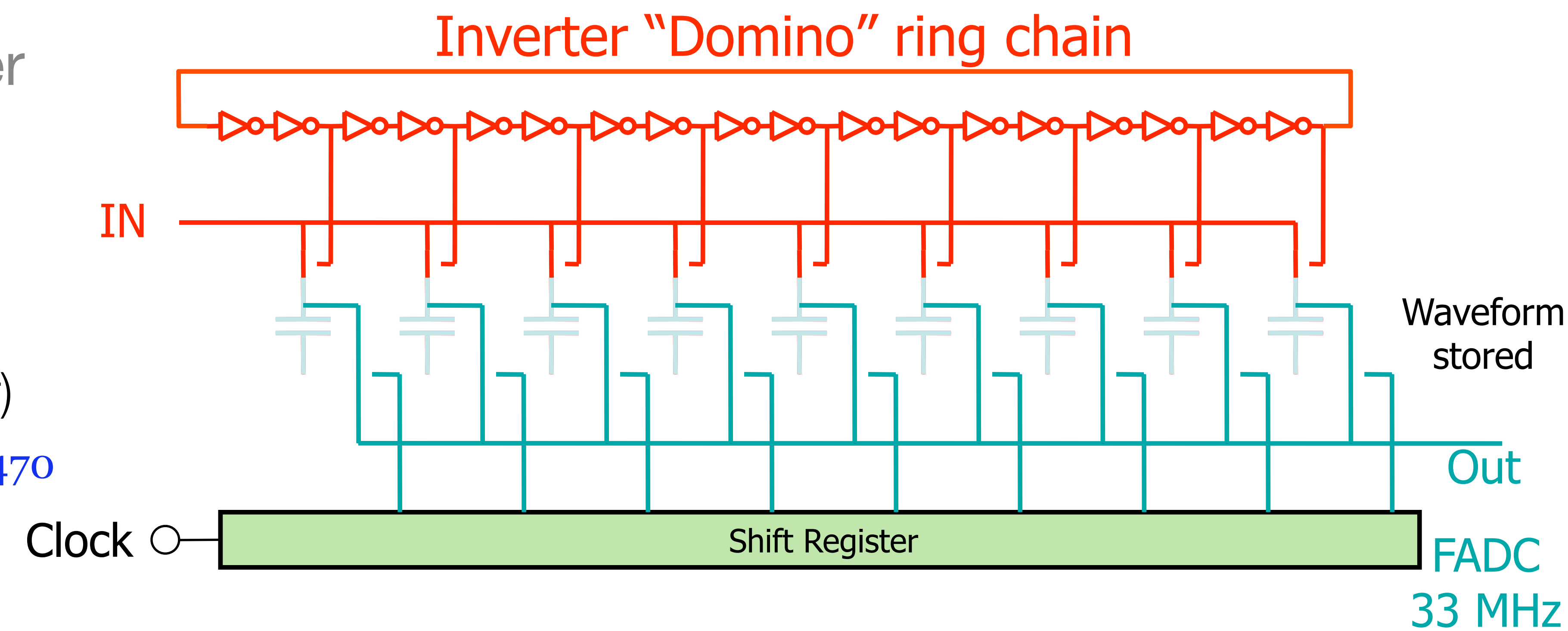
DAQ - Waveform Sampler

- Waveform Digitizer

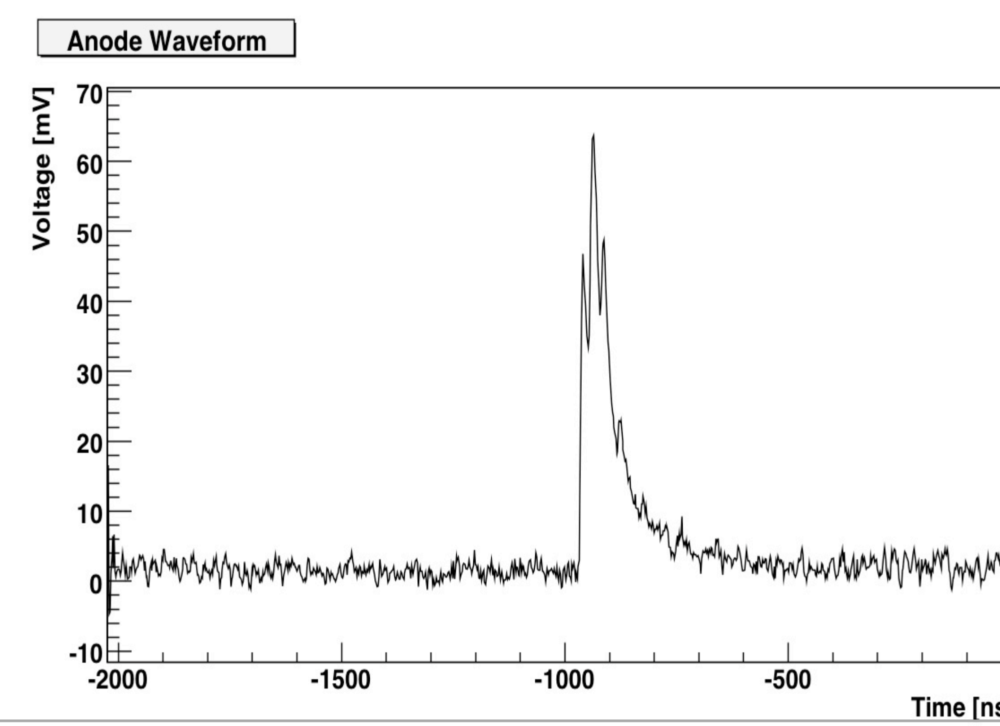
DRS

(Domino Ring Sampler)

➡S.Ritt *NIM* ***A518*** (2004) 470



- <u>ALL OUTPUTS are Recorded in Sampler</u>
- 1024 capacitive sampling cells
- 1024 cells SCA
- 0.5 - 4 GHz sampling is available
- 1.8GHz for Xenon/TC and 500MHz for DC

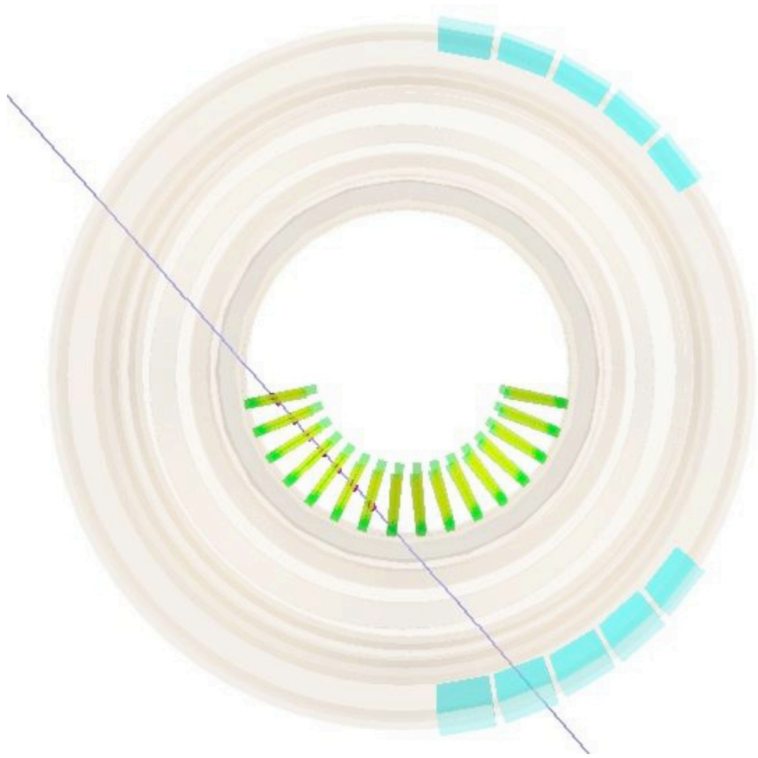


MEG Engineering Run 2007

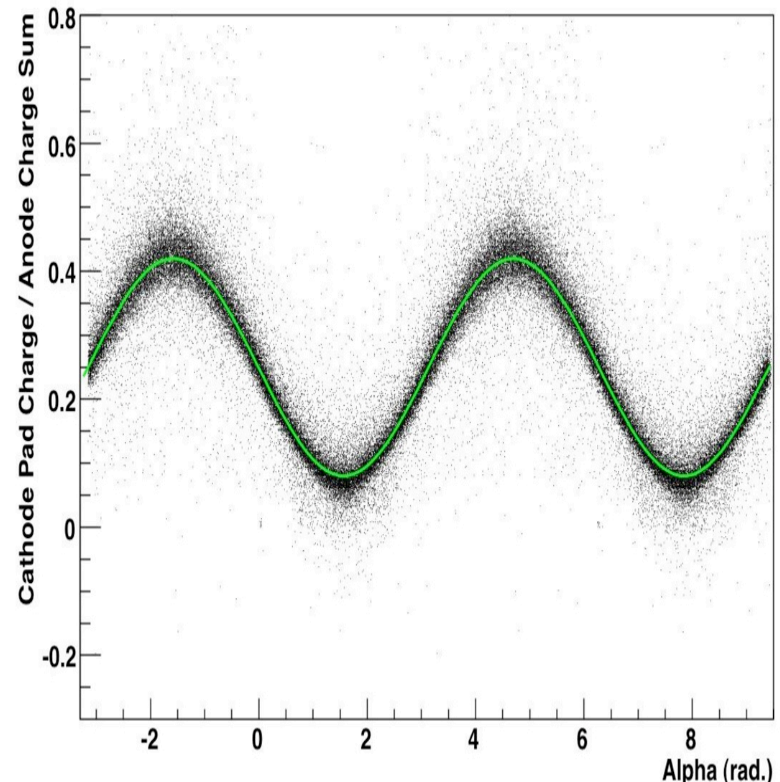
MEG 2007

- All the detector components were installed in summer 2007
- Engineering Run started (Conditioning + Calibration + Commissioning)
  - September
    - Spectrometer Conditioning with Cosmic-ray
    - Xenon Liquefaction and Liquid Transfer
  - October
    - Muon Beam Commissioning
    - Timing Counter Calibration in COBRA with Cosmic-ray
    - DC wire alignment with Cosmic-ray w/o COBRA
  - November
    - Spectrometer Conditioning/Calibration Runs with Michel e^+ @ low/full intensity
    - Liquid Xenon Purification, Calibration Runs with α-ray, γ-ray from CW accelerator
  - December (~until Christmas)
    - “$\mu \to e\gamma$” Run (1.1 M triggers recorded, 25 h of live time)
    - $\pi^0 \to \gamma\gamma$ Run for Liquid Xenon Energy Calibration

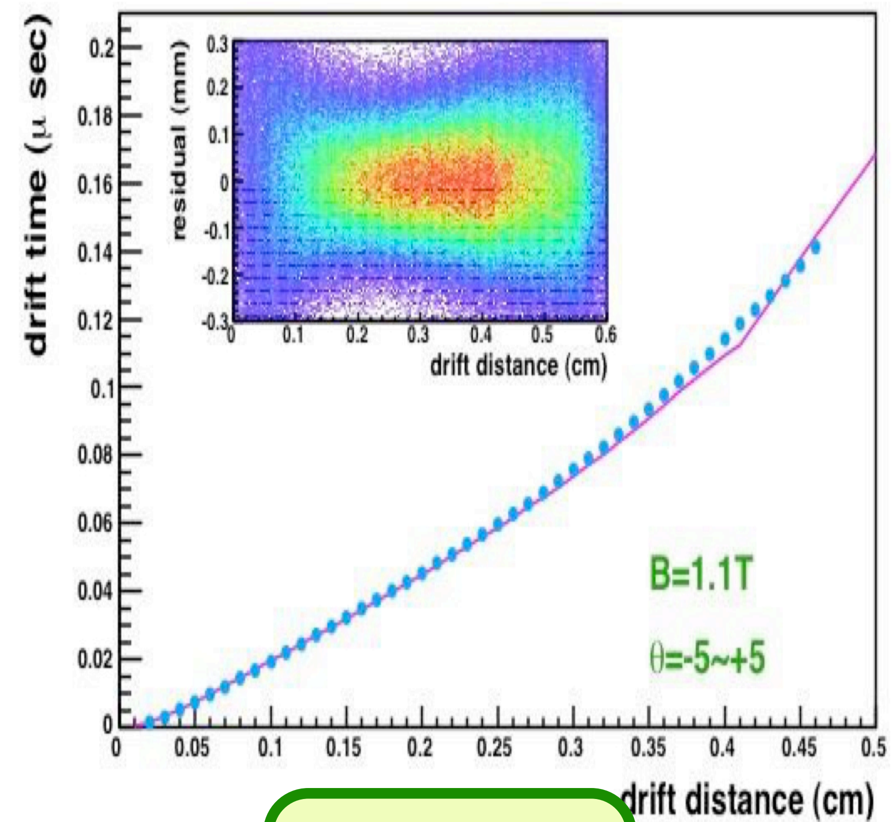
Spectrometer Calibrations



alignment



vernier calib.

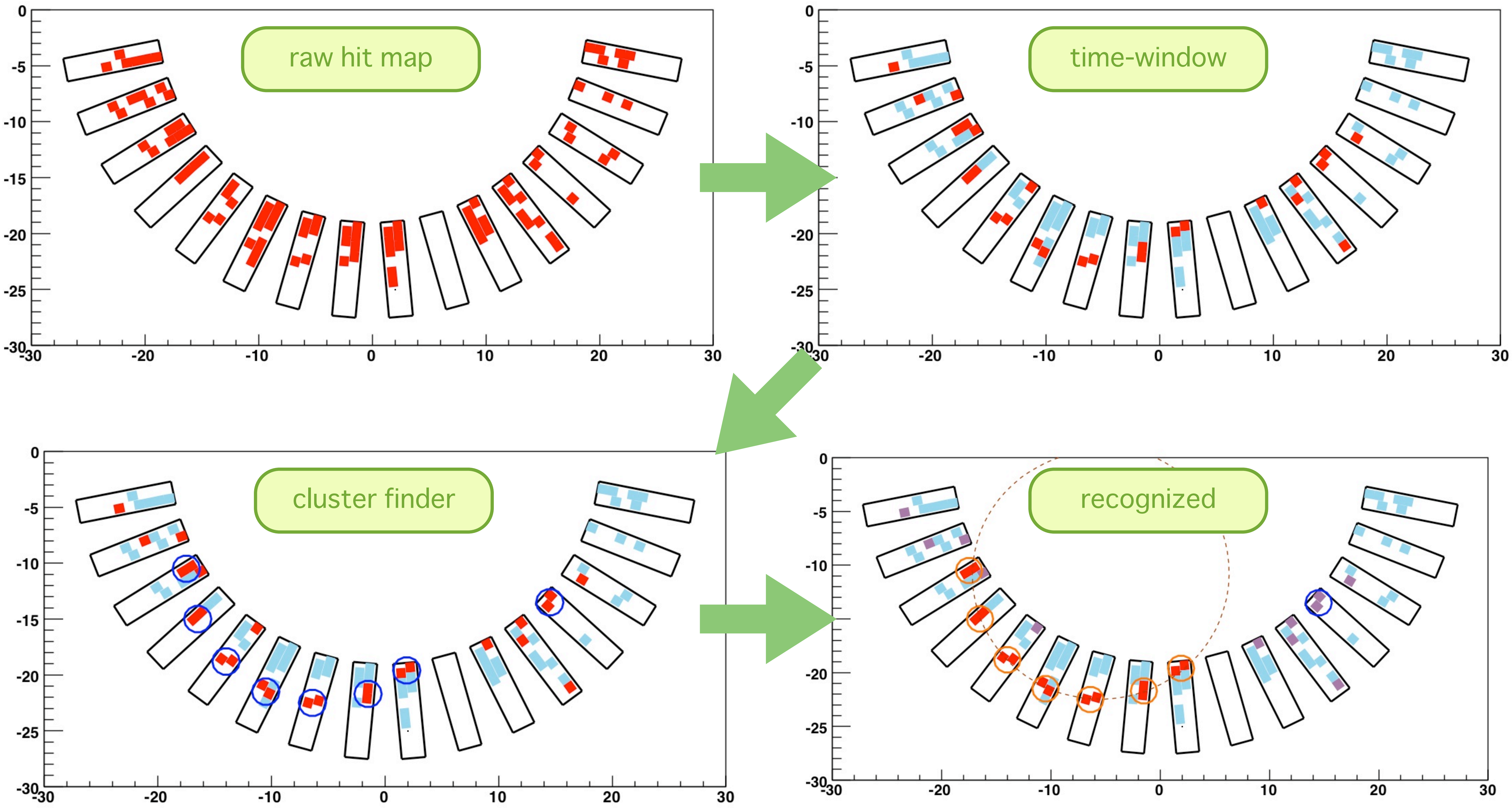


X-T calib.

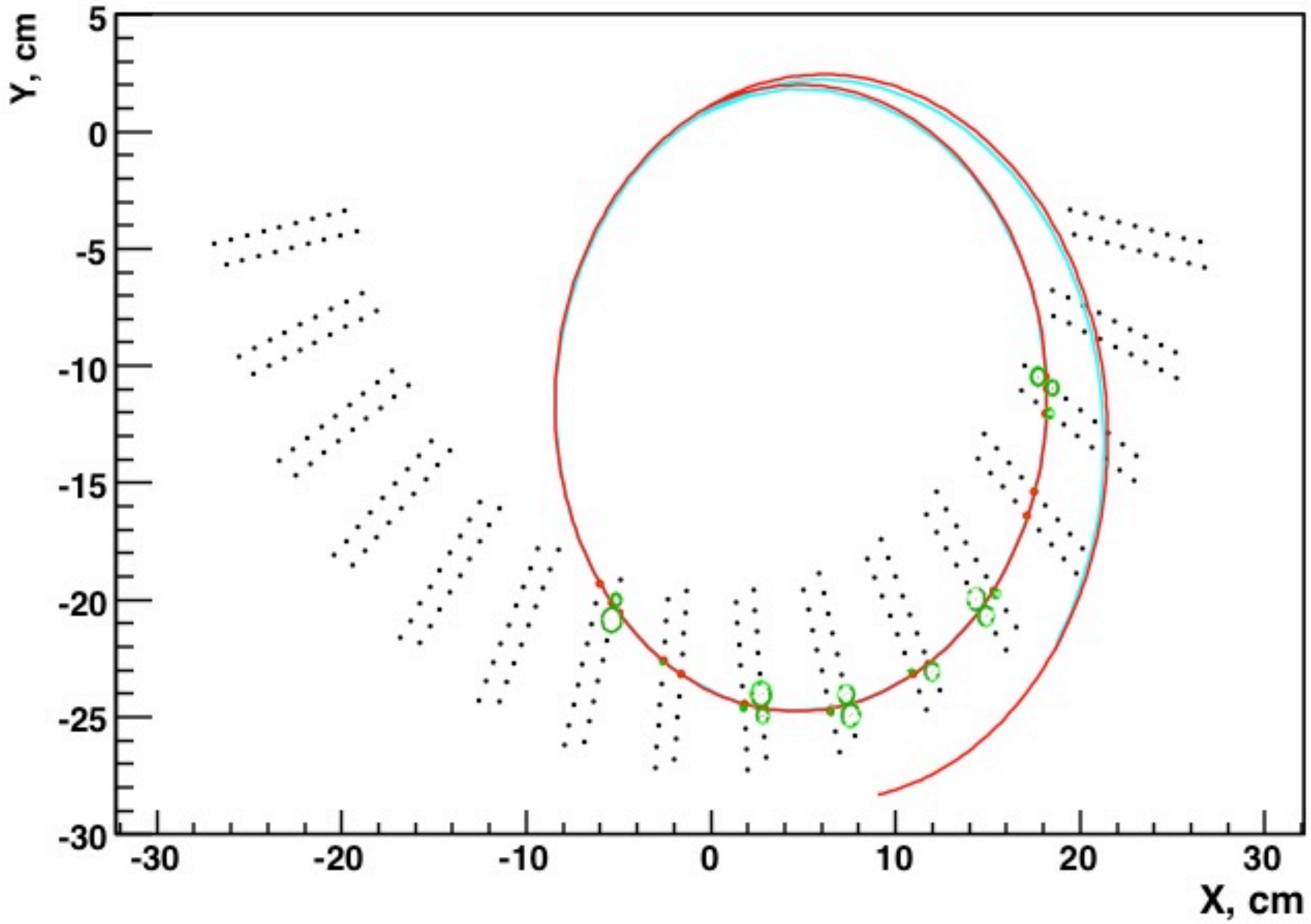
Calibration Procedures were established in Engineering Run 2007

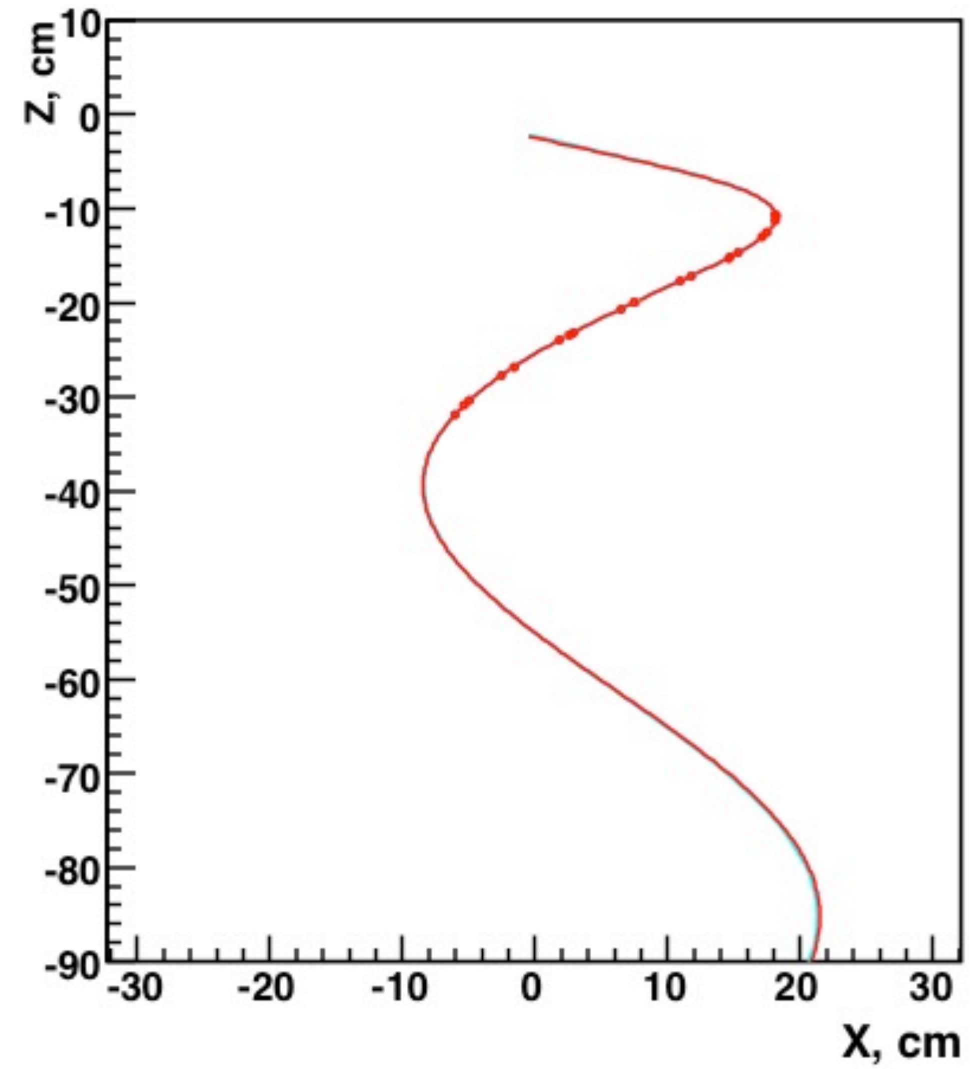
- DC Wire is relatively aligned by using Cosmic-ray straight track w/o B-field
- z-coordinate reconstruction is calibrated by using vernier pad zig-zag period
- XT-relation is calibrated by collecting tremendous Michel e^+ tracks (>5M trig.)

Track Finder



Track Fitting

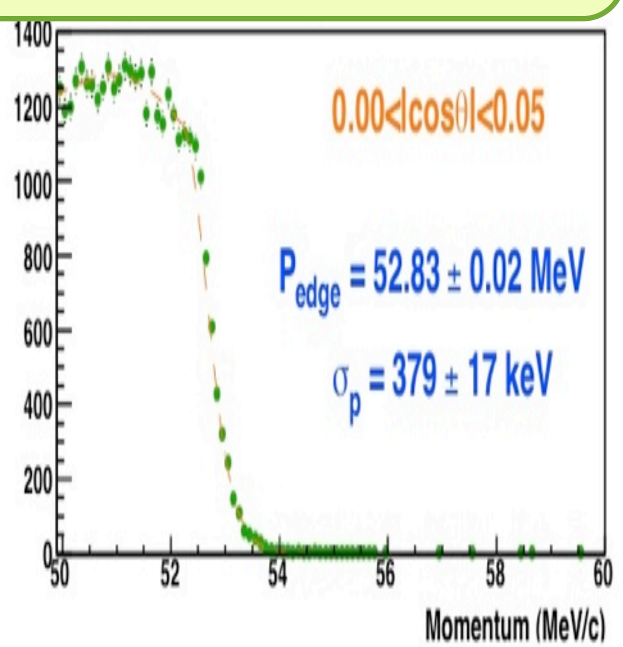


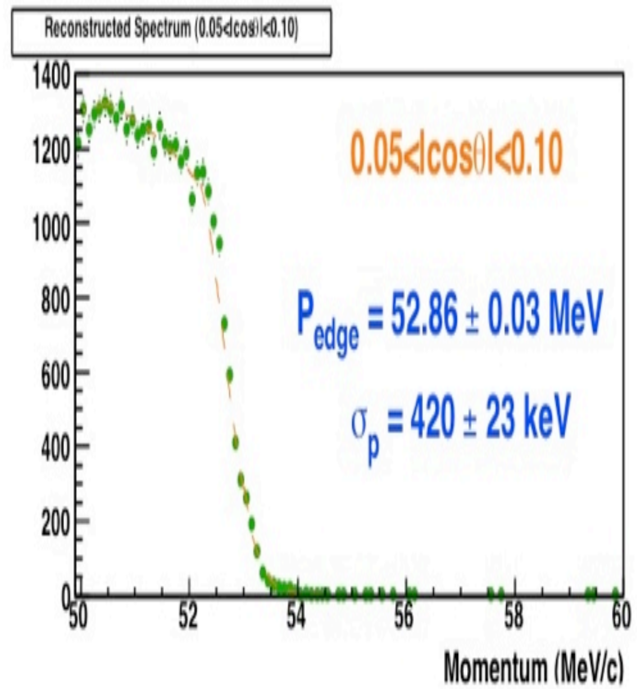


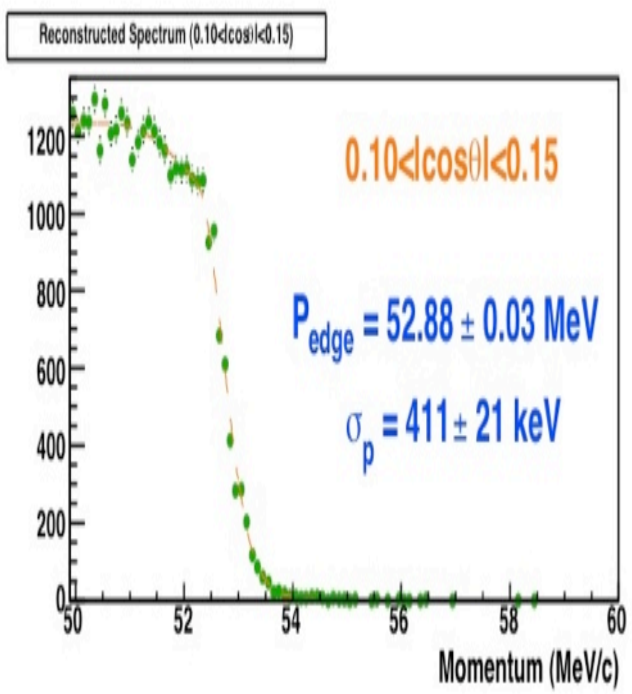
- Track Fitting is carried out based on Kalman filter technique
  - track interpolation is done by numerical integration
  - should be taken into account B-field map precisely (due to COBRA field)

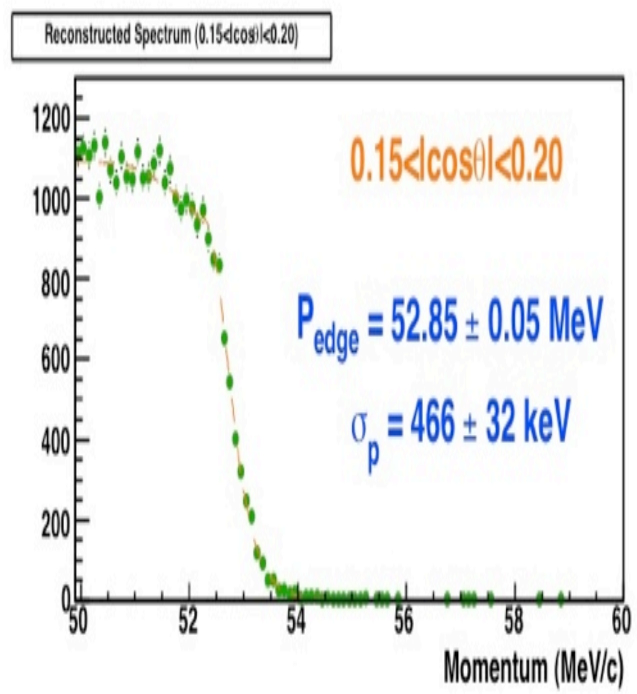
Spectrometer Performances

Momentum Resolution

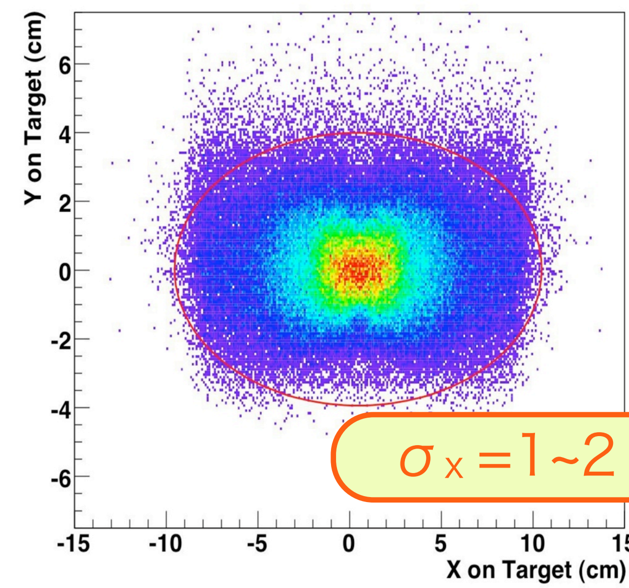


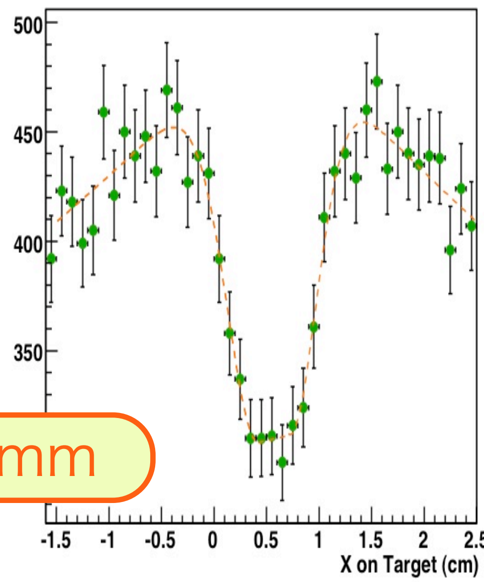






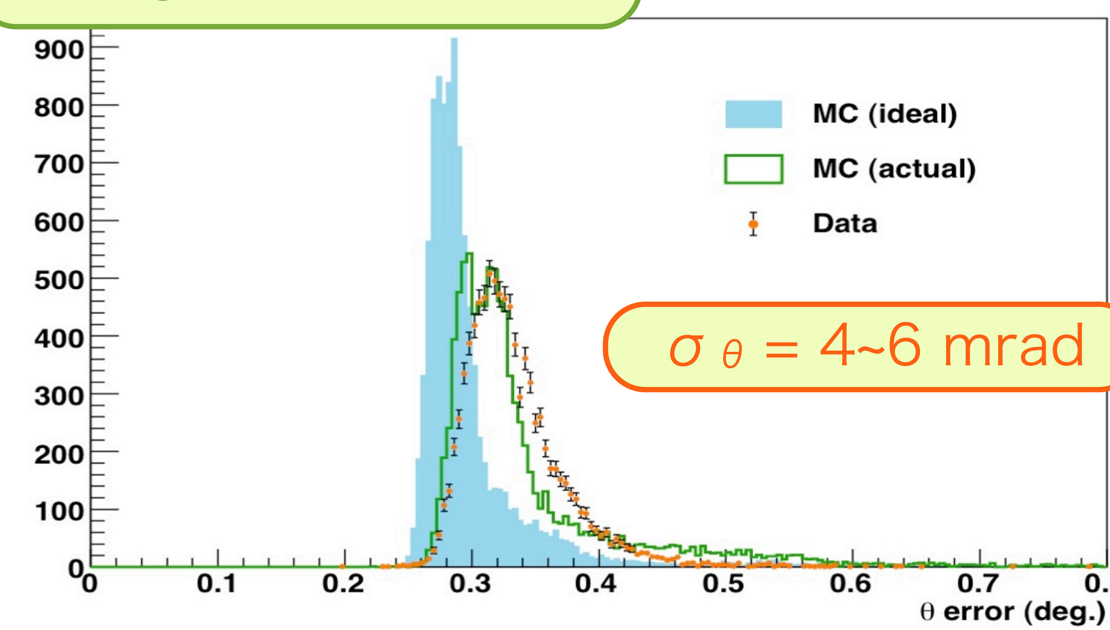
Vertex Resolution





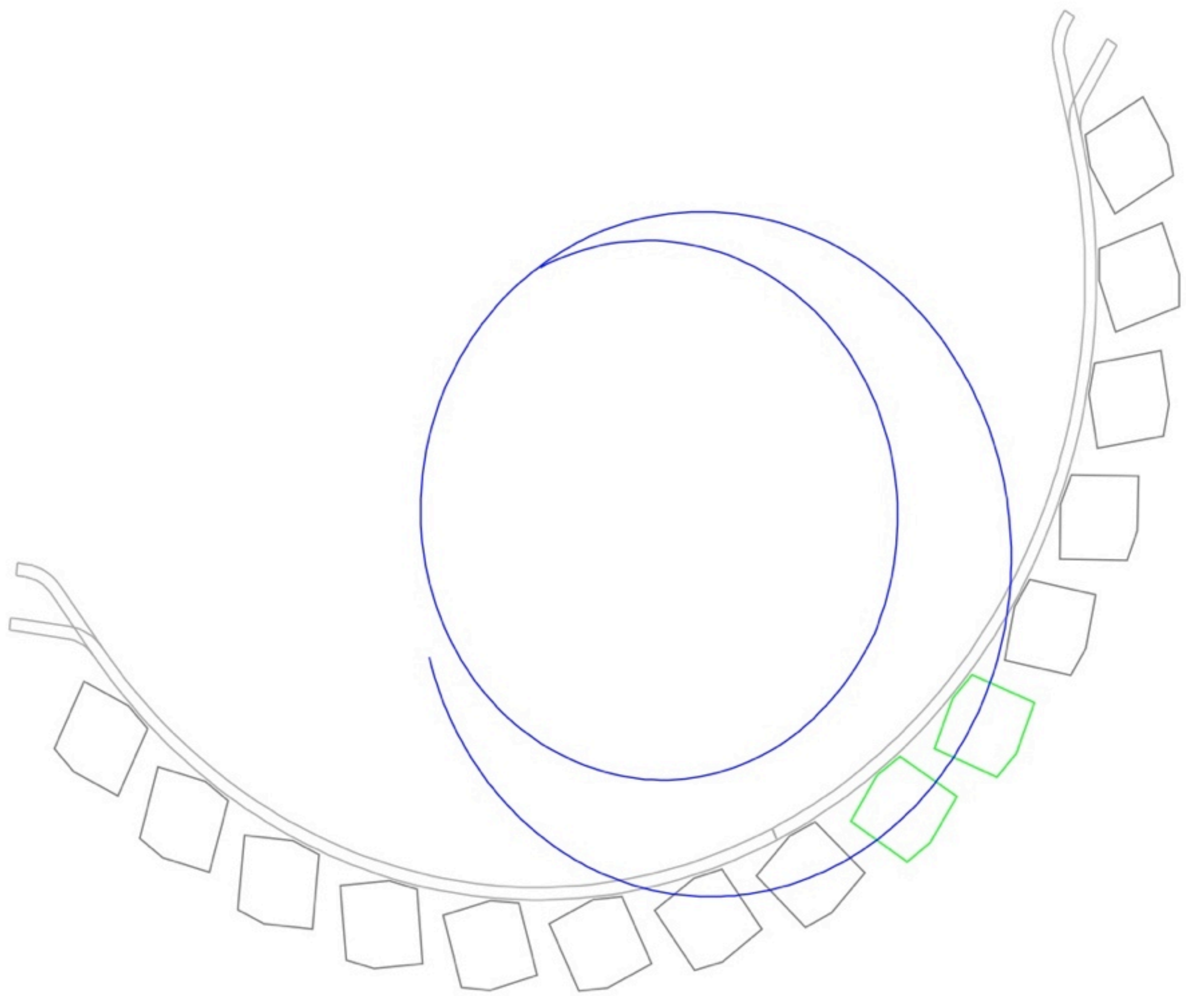
σ_x = 1~2 mm

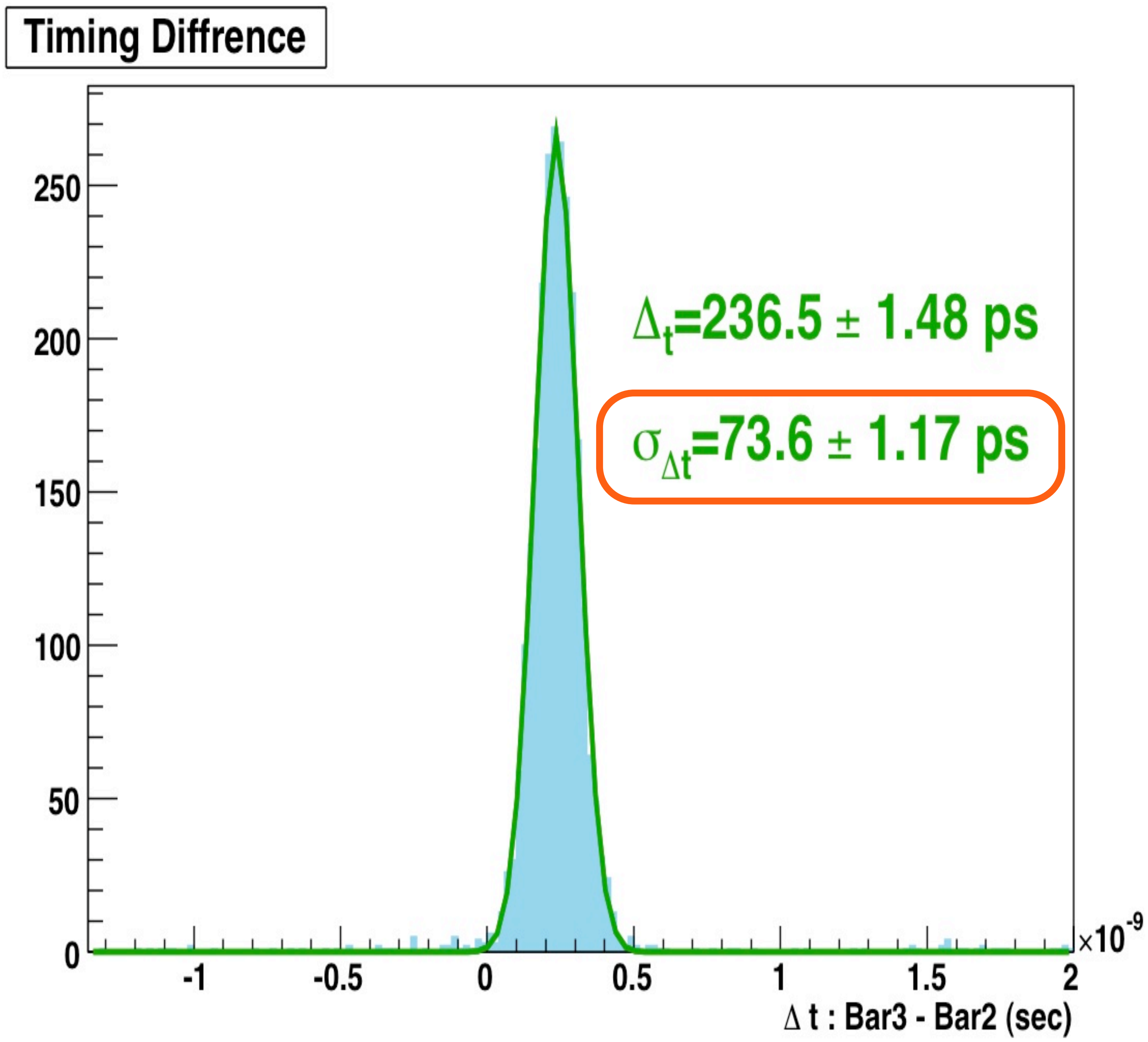
Angular Resolution



σ_θ = 4~6 mrad

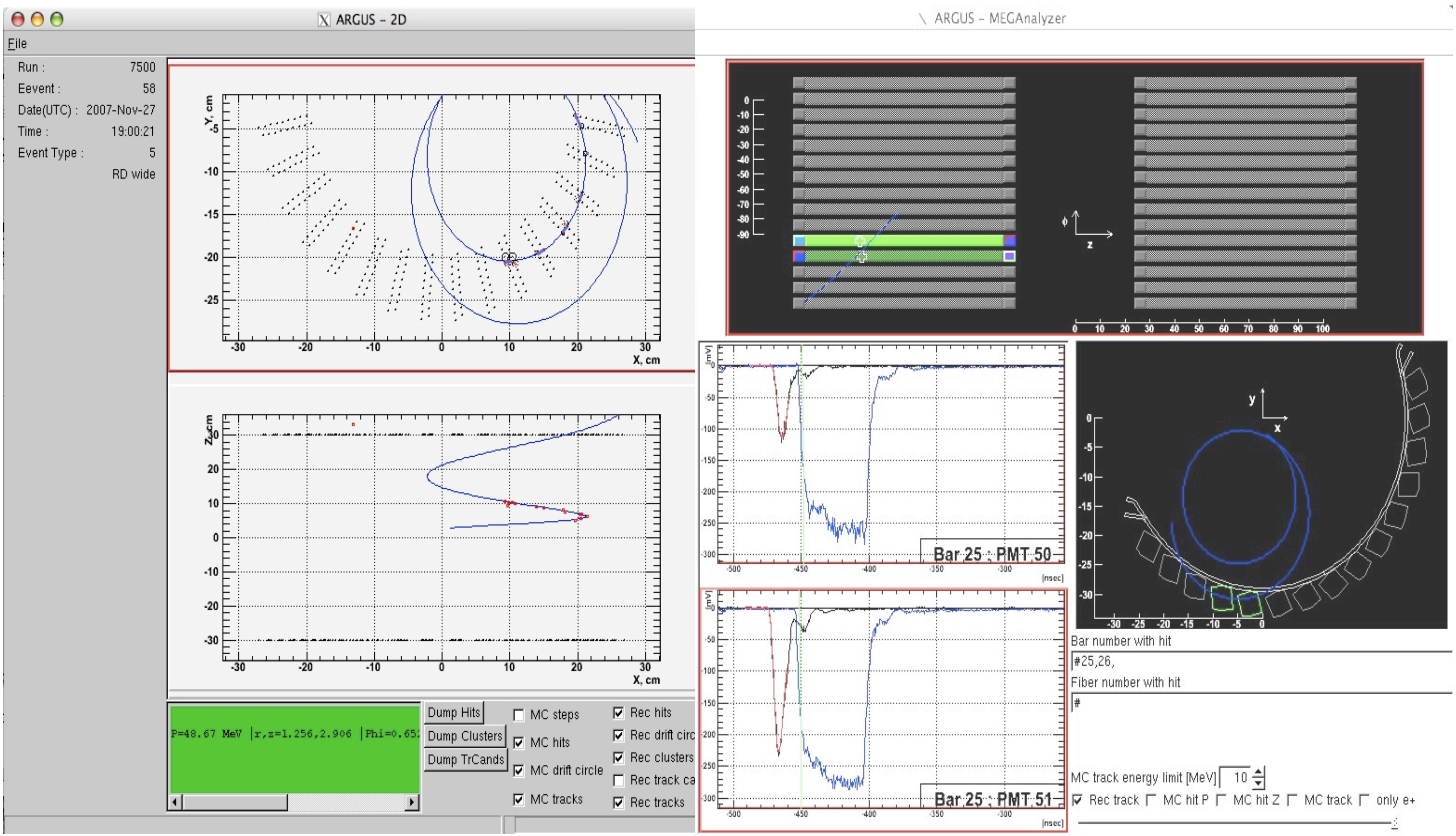
Timing Counter : *Intrinsic* Timing Resolution



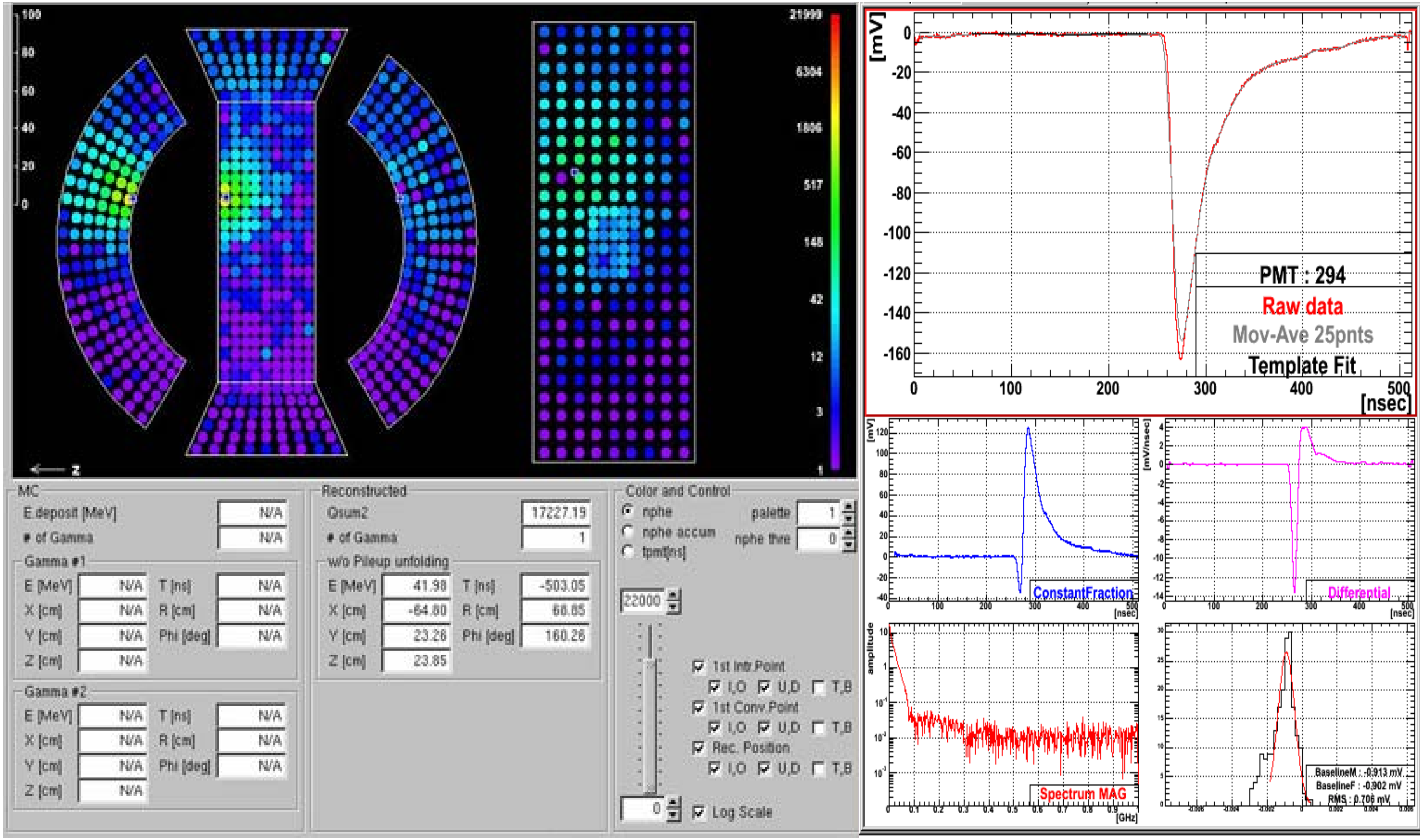


- Time Difference b/w two φ-counter
- 52 ps of timing resolution

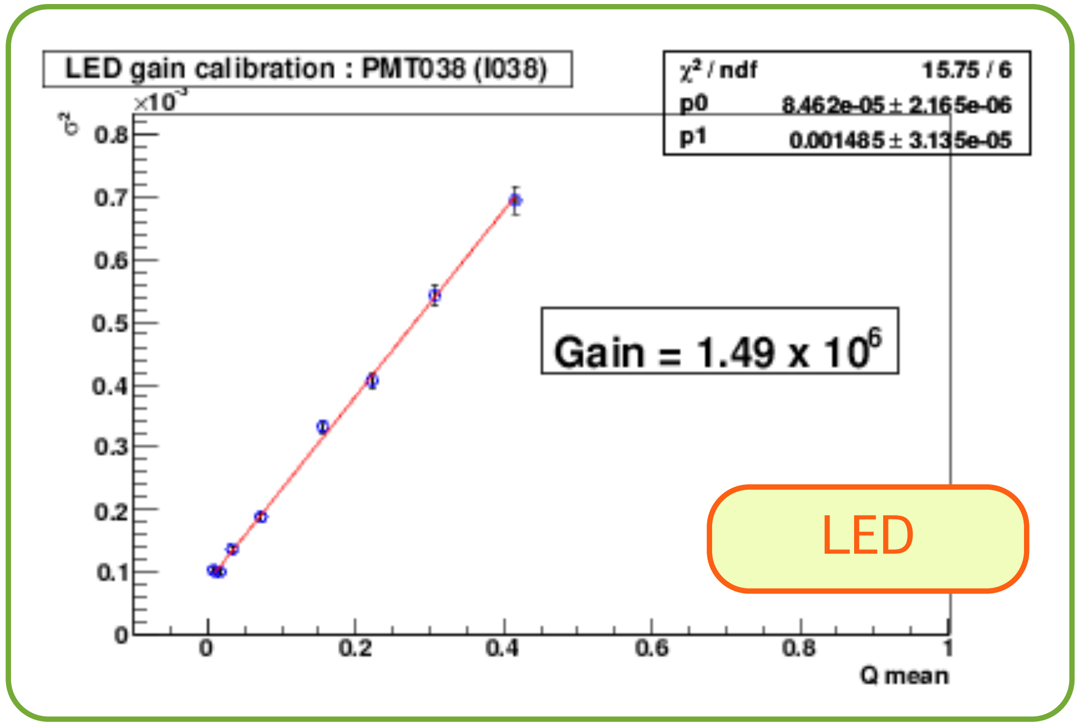
Sample Event Display (Spectrometer)

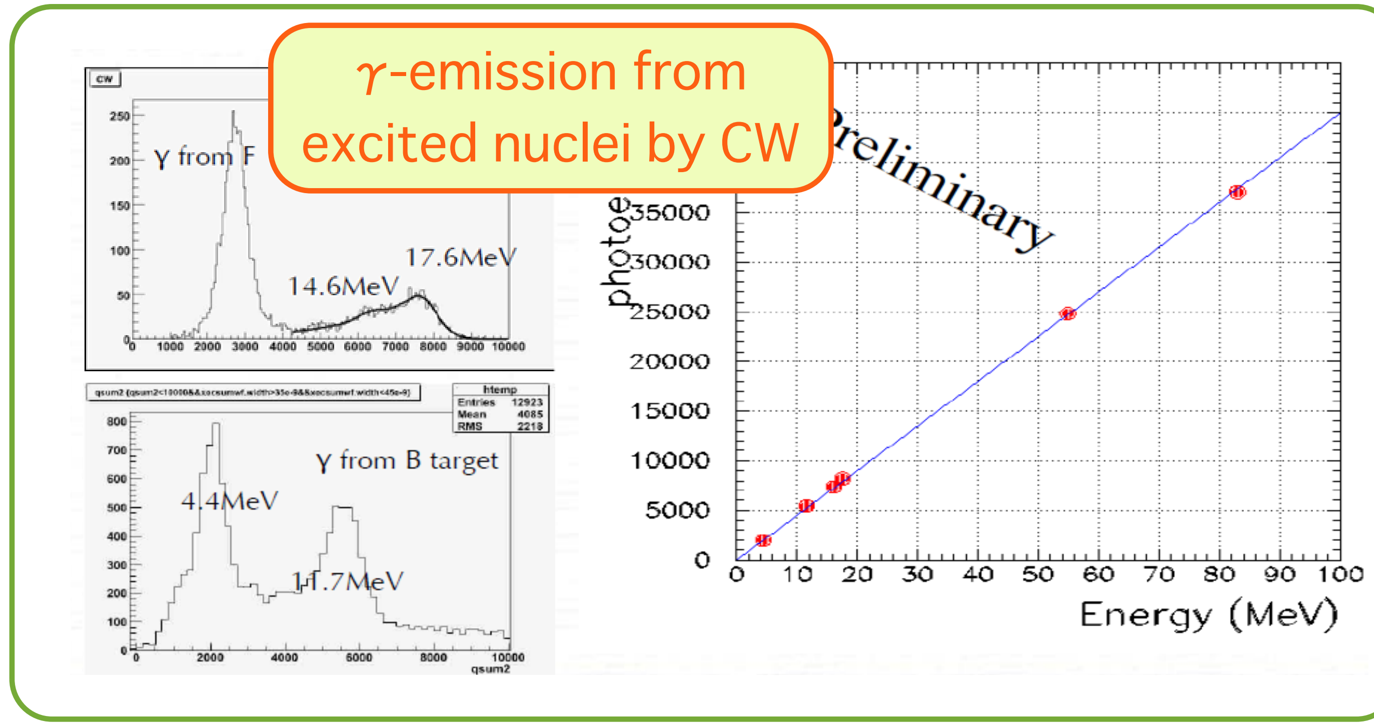


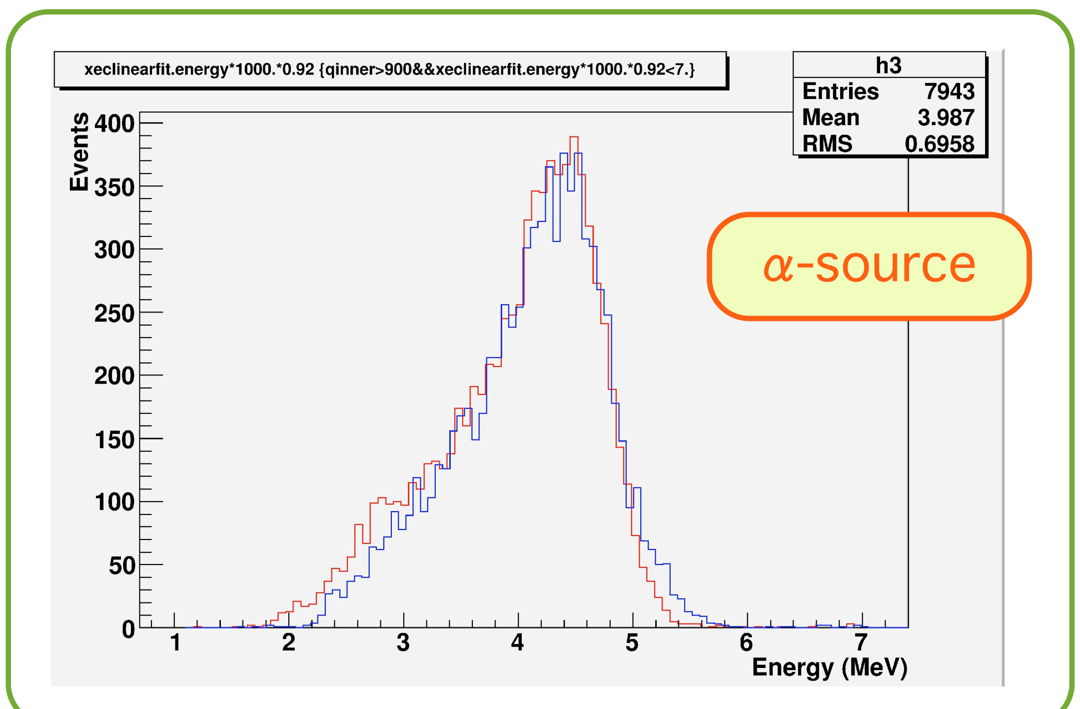
Sample Event Display (Liq.-Xenon Detector)

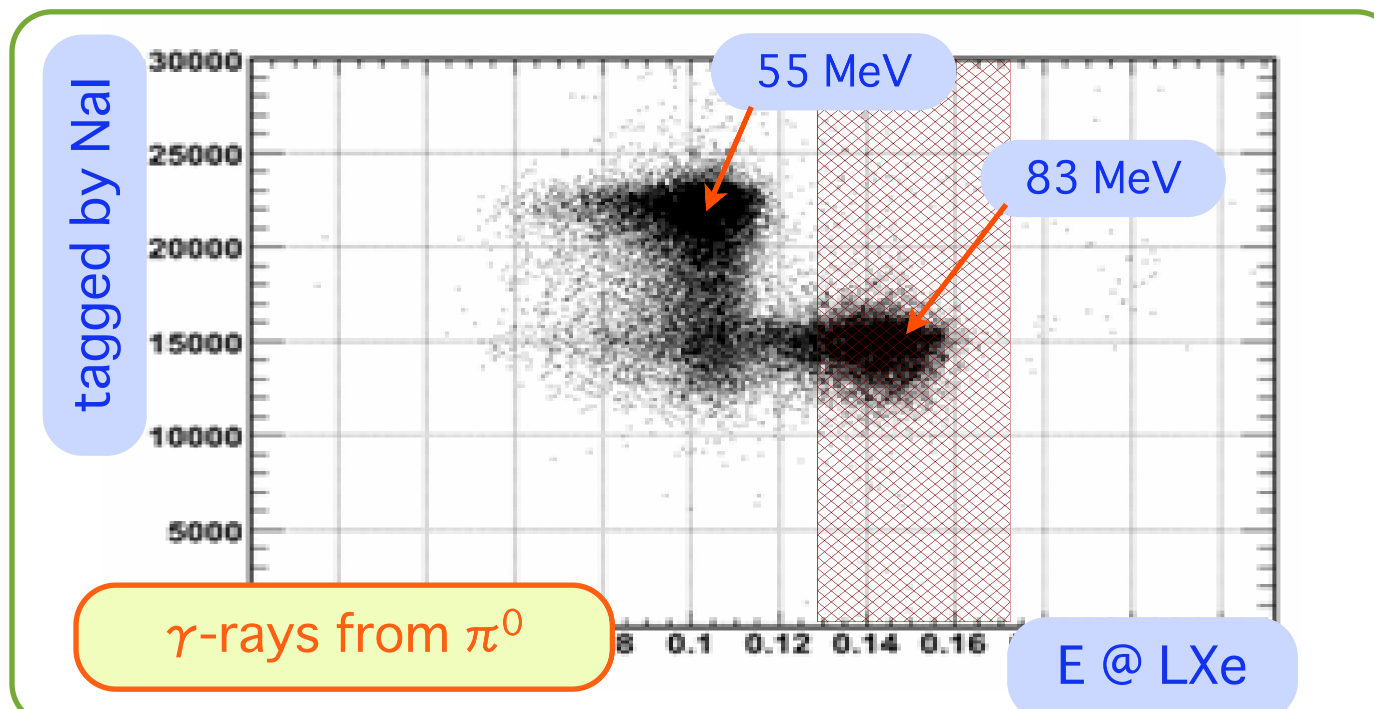


Four tools of Xenon Calibration



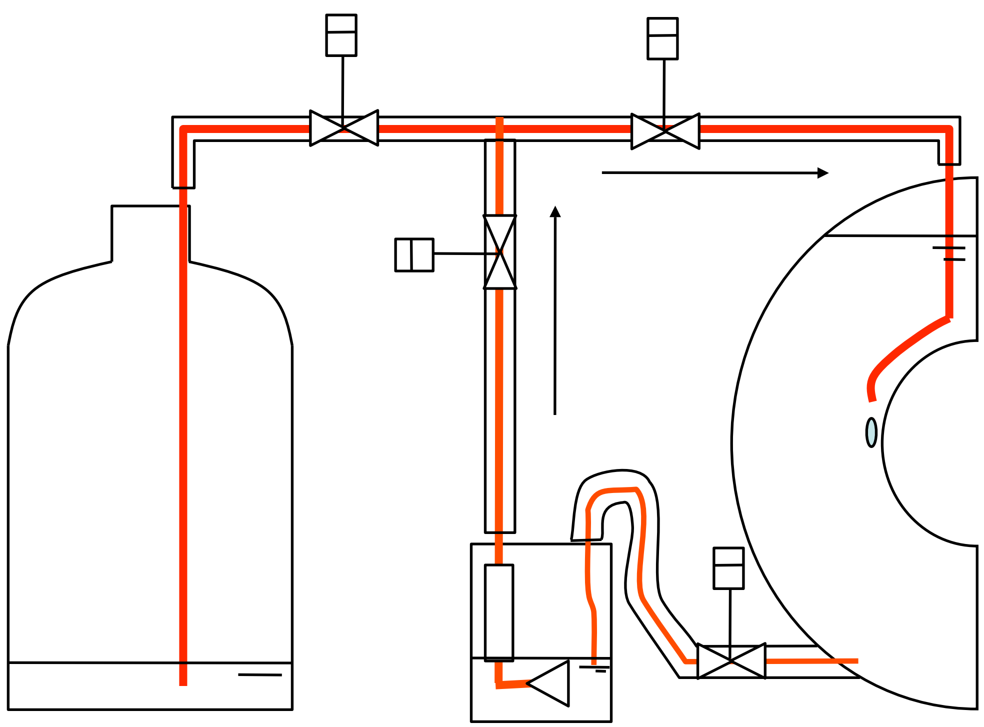




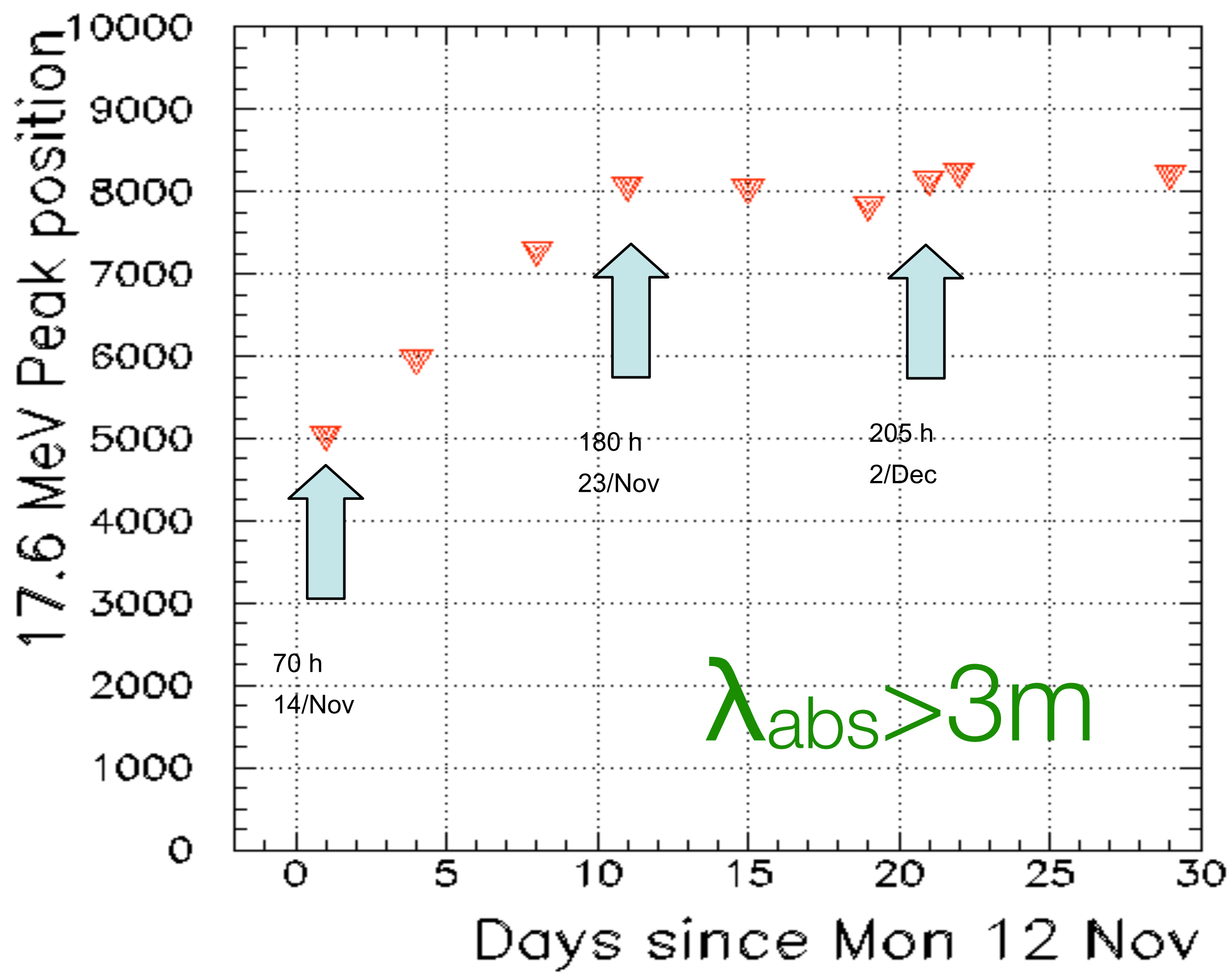


Xenon Purification

- Impurity contamination can cause absorption of scintillation light
  - H_2O, O_2 *etc*.
  - Circulation pump (100 liter/h) with Molecular sieves (>24g water absorption)
  - Light yield for 17.6 MeV γ is utilized to monitor



Xenon Circulation Scheme



Summary of Obtained Performances in 2007

- In 2007, several problems were found and repaired during shutdown.

	Run 2007	Can be improved ?
γ-Energy Resolution (%)	6.5	yes (noise/impurity)
γ-Timing Resolution (ns)	0.27	yes (clock for DRS)
γ-Position Resolution (mm)	15	yes (noise/impurity)
γ-Detection Efficiency (%)	>40	no
e^+ Momentum Resolution (%)	2.1	yes (missing channel/noise)
e^+ Timing Resolution (ns)	0.12	yes (clock for DRS)
e^+ Angle Resolution (mrad)	17	yes (missing channel/noise)
e^+-Detection Efficiency (%)	39	yes (missing channel/noise)

MEG Physics Run 2008

MEG 2008

- Jan.-Apr.
  - Detector Maintenances and Repairs were done
    - Bad Components (PMT, DC, *etc.*) were replaced
    - Better Molding for DC to avoid discharge
    - New Purification System for Liquid Xenon Detector
- Apr.-May.
  - Detector Re-Installation was Completed
  - Xenon Purification Started
  - Spectrometer Conditioning Started
- May.-Jul.
  - Engineering Run 2008 (Conditioning + Calibration + Commissioning)
- Aug.-Dec.
  - “MEG Physics Run 2008” will start in August
  - 20 Beam-Weeks of Data Acquisition is scheduled
  - DRS Upgrade is planed

Prospects for MEG Physics Run 2008

	2007 (Measured)	2008 (Prospects)
γ-Energy Resolution (%)	6.5	
γ-Timing Resolution (ns)	0.27	
γ-Position Resolution (mm)	15	
γ-Detection Efficiency (%)	>40	
e^+ Momentum Resolution (%)	2.1	
e^+ Timing Resolution (ns)	0.12	
e^+ Angle Resolution (mrad)	17	
e^+-Detection Efficiency (%)	39	
Muon Stopping Rate (10^7 /sec)	3	
Running Time (week)	8	
Single Event Sensitivity (10^{-13})	-	
Accidental Rate (10^{-13})	-	
Number of Expected Background	-	
90 % C.L. Limit (10^{-13})	-	

(* very pessimistic, possibly improved)

Prospects for MEG Physics Run 2008

	2007 (Measured)	2008 (Prospects)
γ-Energy Resolution (%)	6.5	5.0
γ-Timing Resolution (ns)	0.27	0.15 *
γ-Position Resolution (mm)	15	9.0
γ-Detection Efficiency (%)	>40	>40
e^+ Momentum Resolution (%)	2.1	1.1
e^+ Timing Resolution (ns)	0.12	0.12 *
e^+ Angle Resolution (mrad)	17	17. *
e^+-Detection Efficiency (%)	39	65
Muon Stopping Rate (10^7 /sec)	3	3
Running Time (week)	8	20
Single Event Sensitivity (10^{-13})	-	
Accidental Rate (10^{-13})	-	
Number of Expected Background	-	
90 % C.L. Limit (10^{-13})	-	

(* very pessimistic, possibly improved)

Prospects for MEG Physics Run 2008

	2007 (Measured)	2008 (Prospects)
γ-Energy Resolution (%)	6.5	5.0
γ-Timing Resolution (ns)	0.27	0.15 *
γ-Position Resolution (mm)	15	9.0
γ-Detection Efficiency (%)	>40	>40
e^+ Momentum Resolution (%)	2.1	1.1
e^+ Timing Resolution (ns)	0.12	0.12 *
e^+ Angle Resolution (mrad)	17	17. *
e^+-Detection Efficiency (%)	39	65
Muon Stopping Rate (10^7 /sec)	3	3
Running Time (week)	8	20
Single Event Sensitivity (10^{-13})	-	2.6
Accidental Rate (10^{-13})	-	1.0 *
Number of Expected Background	-	0.4
90 % C.L. Limit (10^{-13})	**-**	**7.2**

(* very pessimistic, possibly improved)

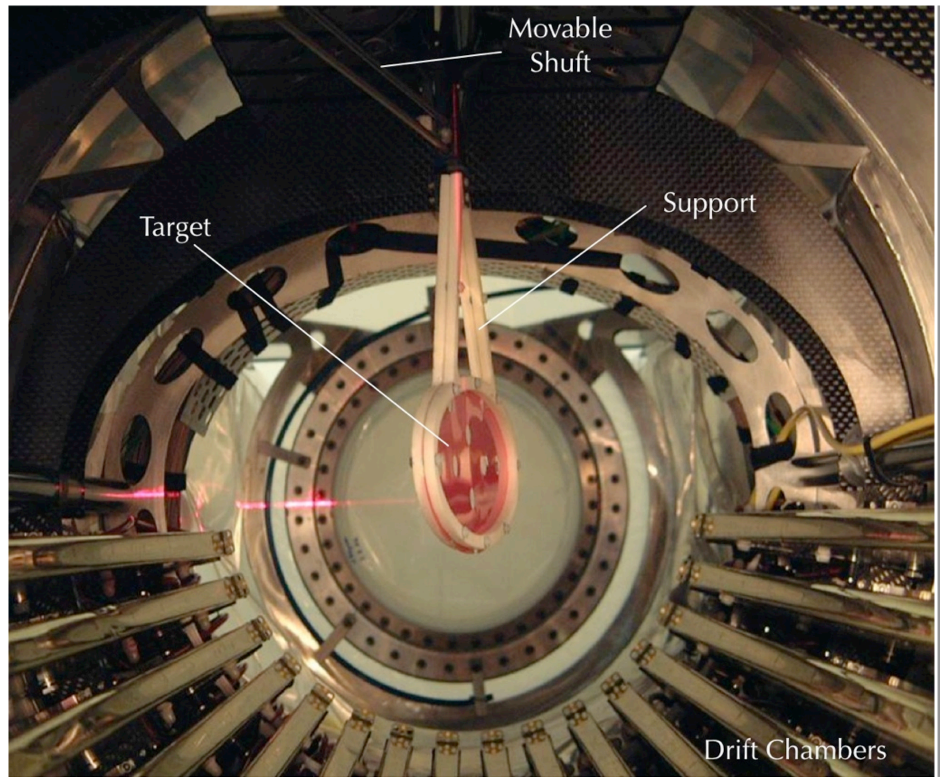
Conclusion

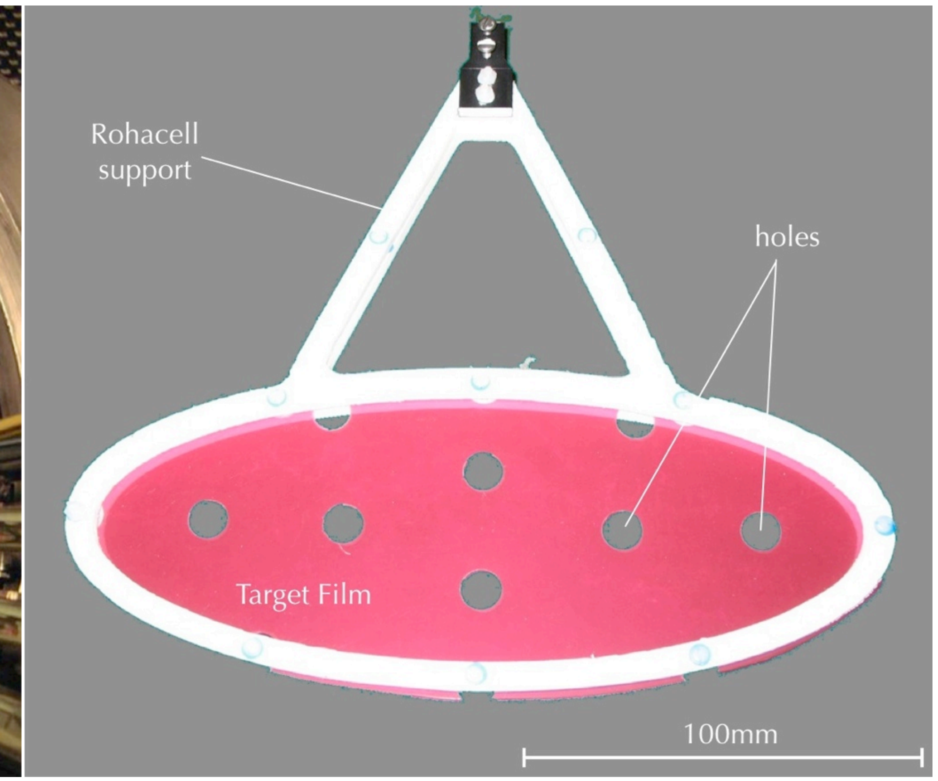
- The MEG Experiment searches for LFV in muon with 10^{-13} sensitivity
  - With this Sensitivity, MEG Can Probe the Most Promising Parameter Region Predicted by Many Models
  - Discovery of $\mu \rightarrow e\gamma$ = New Physics Beyond SM
- Construction of the MEG-Apparatus was Completed in 2007
  - Engineering Run 2007 was carried out, Calibration Procedure was Established
  - Successful Data Acquisition in 2007
  - 2×10^{12} Muons Stopped on the Target
  - All Detector Worked Fine, But Several Problems Also Found
- In 2008, MEG will Start Physics Run in August !!
  - Detector Upgrade/Repair and Re-Installation Completed
  - Engineering Run is Starting
  - 20 weeks of Data Acquisition
  - $Br(\mu \rightarrow e\gamma)^{2008} < 7.2 \times 10^{-13}$ (90%C.L.) of sensitivity is conservatively expected

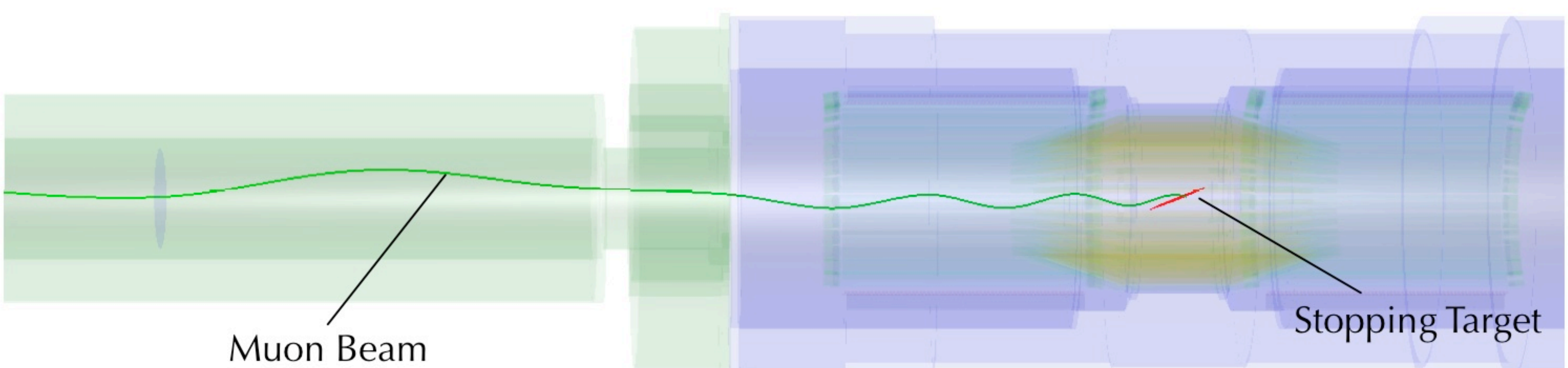
Backup Slides

Muon Stopping Target

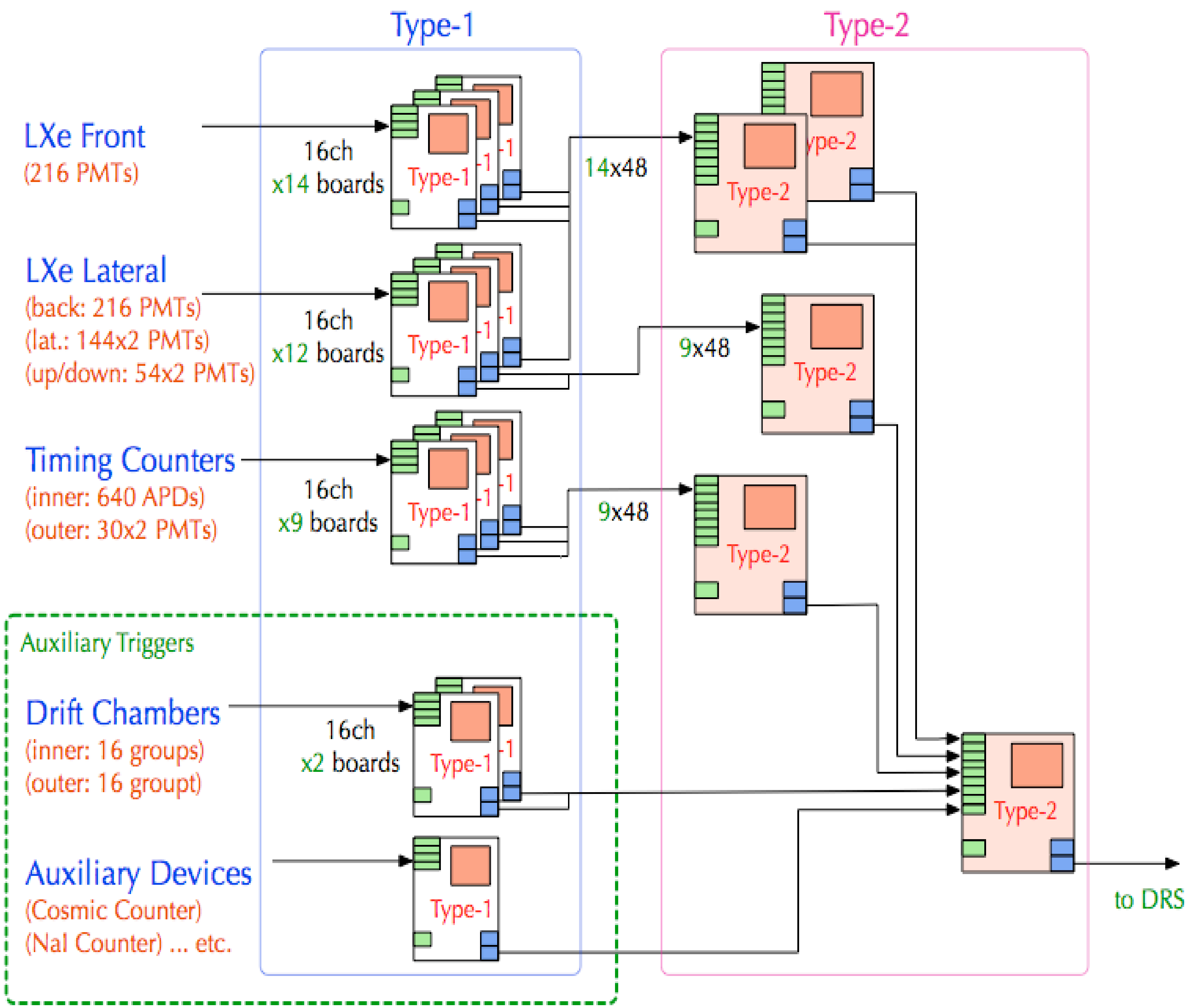
- Requirements
  - Light Material
  - Thin
  - (Plastic)







DAQ -Trigger



- Two-staged Trigger
  - Type-1 : 100MHz FADC
    - Q and T reconstruction
  - Type-2 : Online Reconst.

- E_γ : Q(LXe) > 40 MeV

&&

- Coinc. : $\Delta T_{e\gamma} < 10$ ns

&&

- Angle : $\Delta\theta_{e\gamma} < 1$ PMT

↓

- Acceptable DAQ Rate
  4~5 Hz @ $3\text{x}10^7$ μ/sec

- Auxiliary Triggers are equipped for detector calibrations

Positron Spectrometer

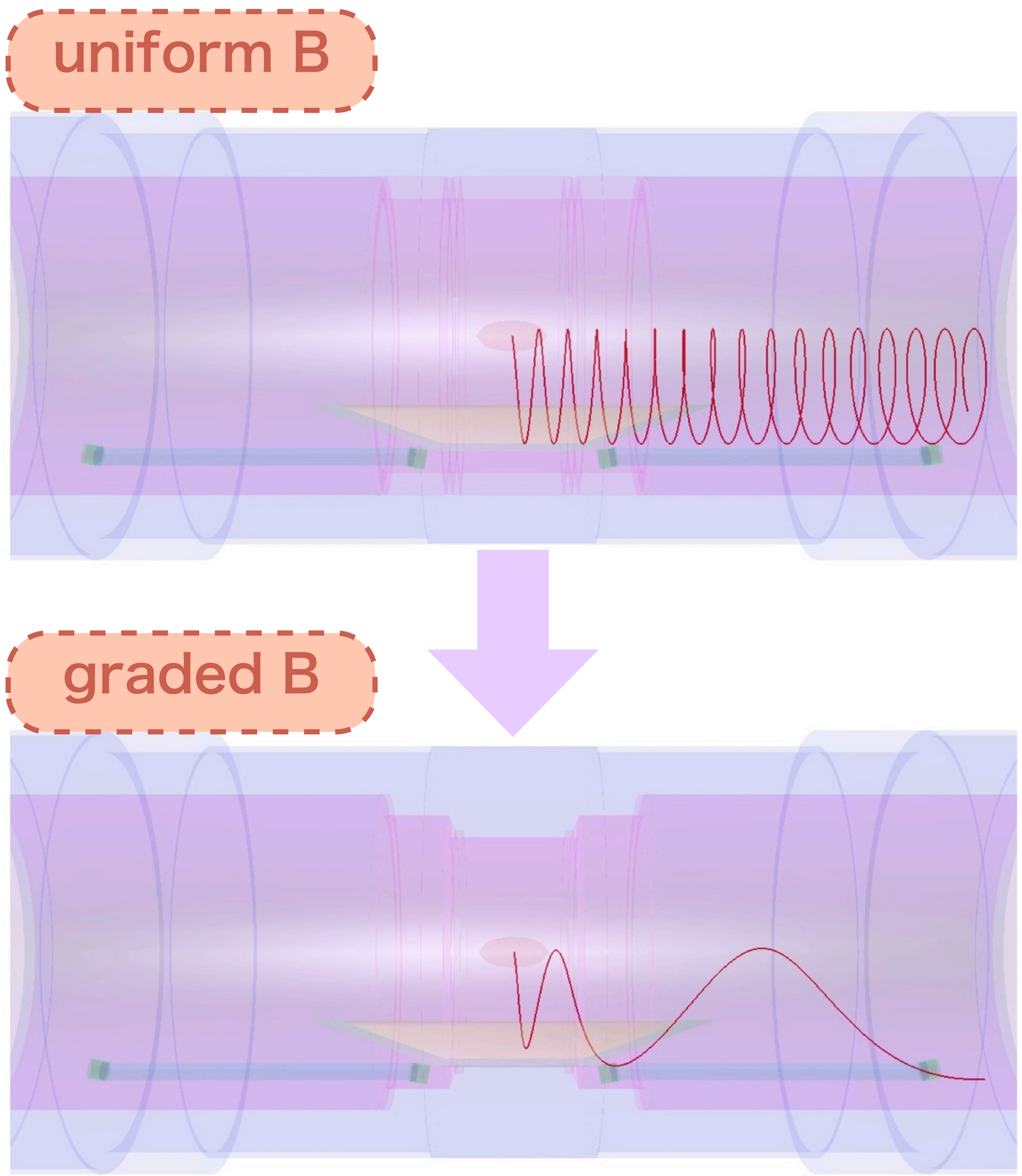
- **Very high counting rate**
  - the most intense DC muon beam in the world
  - muon stopping rate : 3×10^7 muon/sec

→ Special B-field

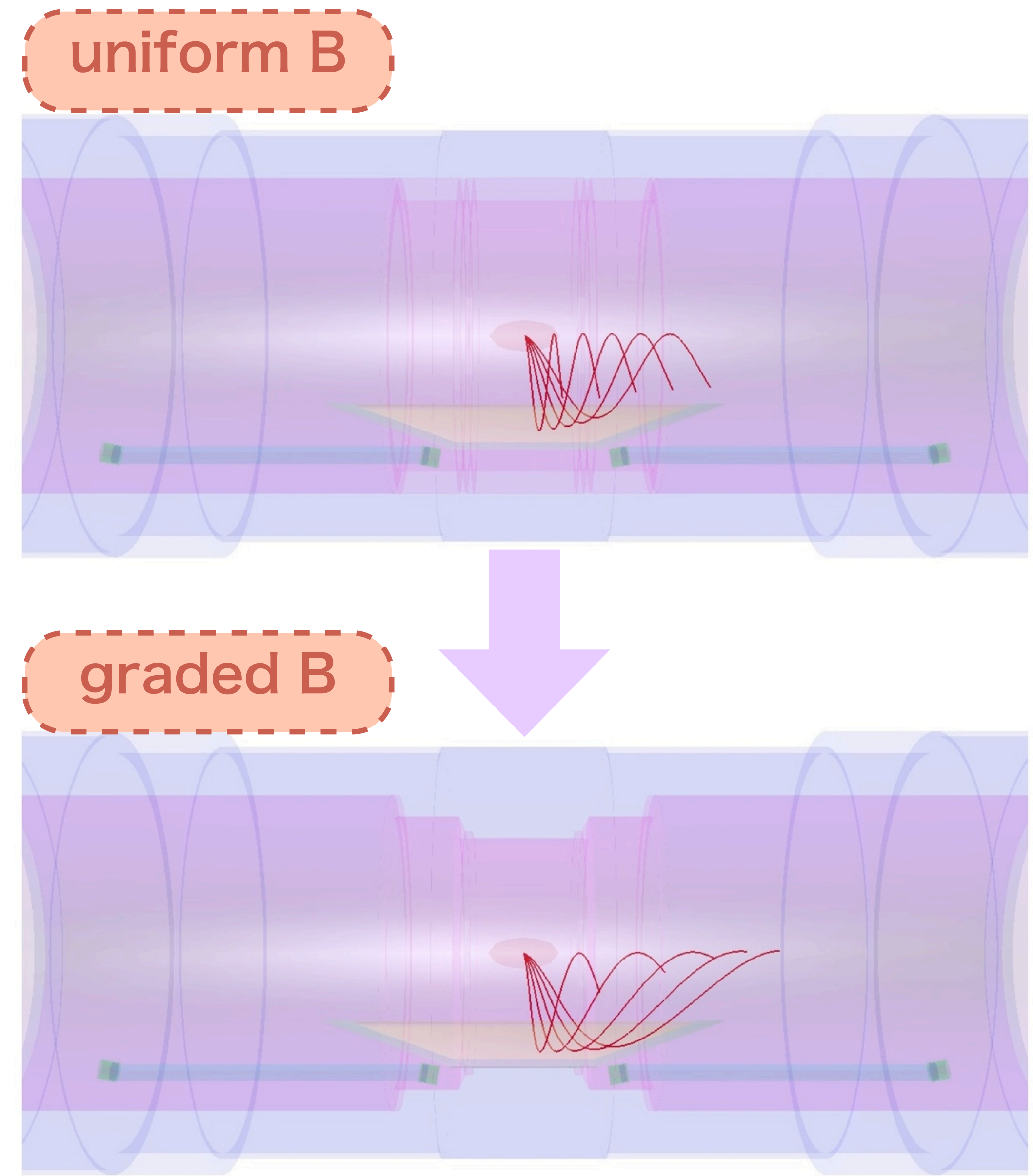
- **Good momentum/position/timing resolution**
  - aiming excellent sensitivity
  - 0.4% momentum resolution, 300μm position resolution for both direction(r,z) and 40 ps timing resolution
- **Low-mass material**
  - 52.8MeV positron can be affected by coulomb multiple scattering easily
  - γ background generation should be suppressed as much as possible

→ new sensitive & light DC

COBRA Solenoid

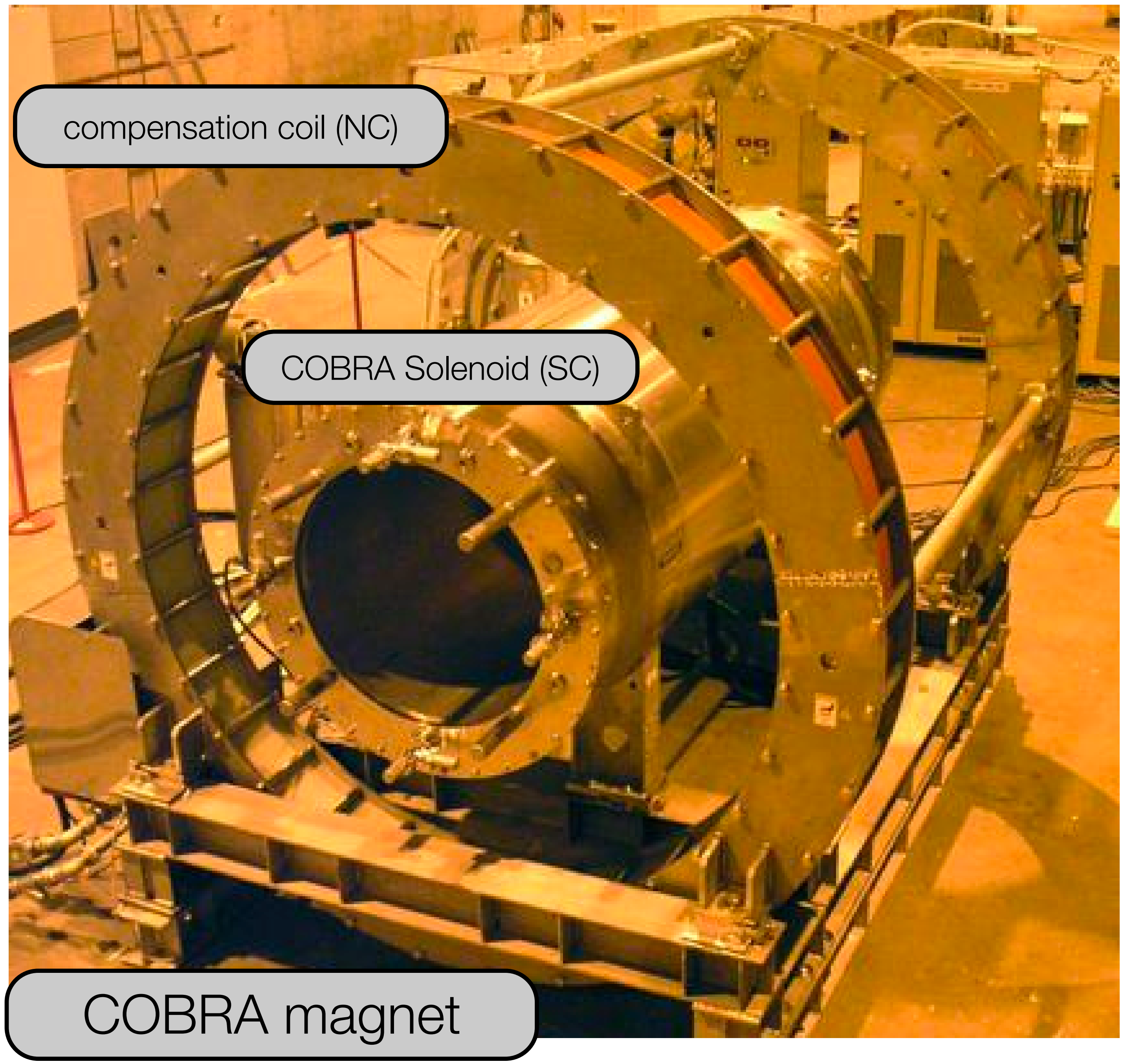


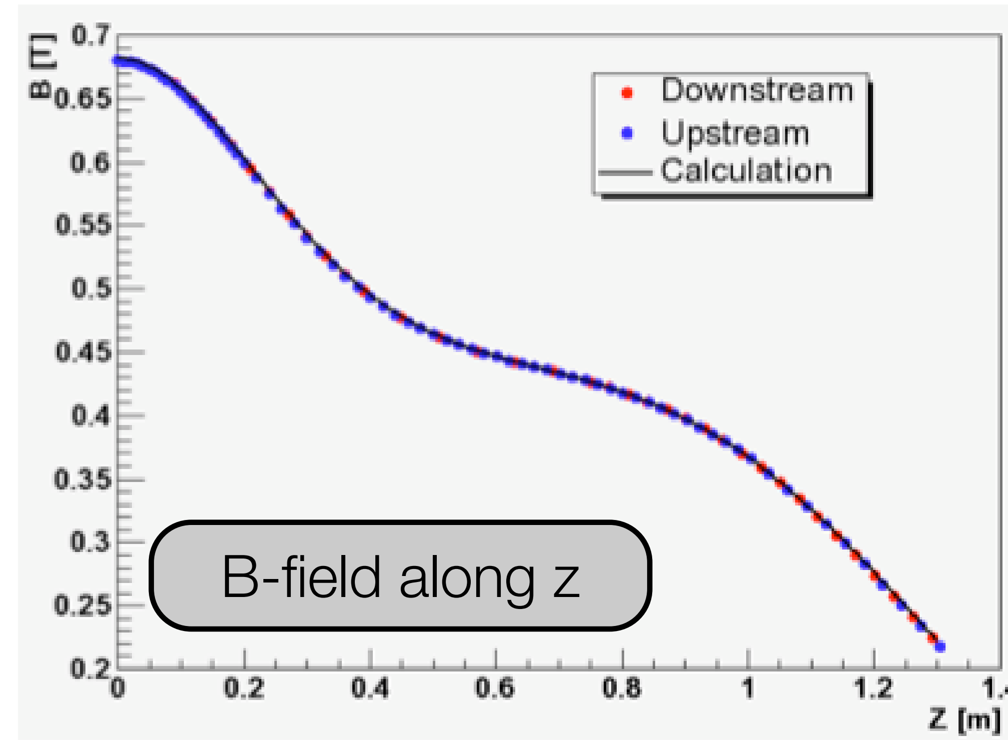
low energy e+ quickly swept out

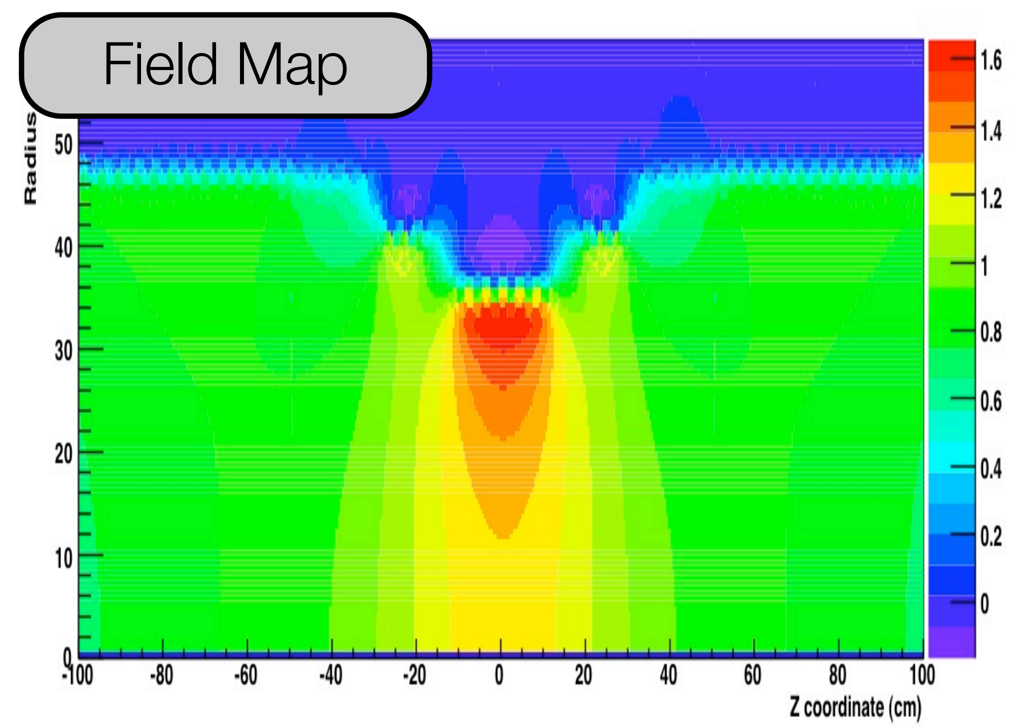


constant bending radius
independent of emission angles

COBRA Magnet and Special Gradient of B-field

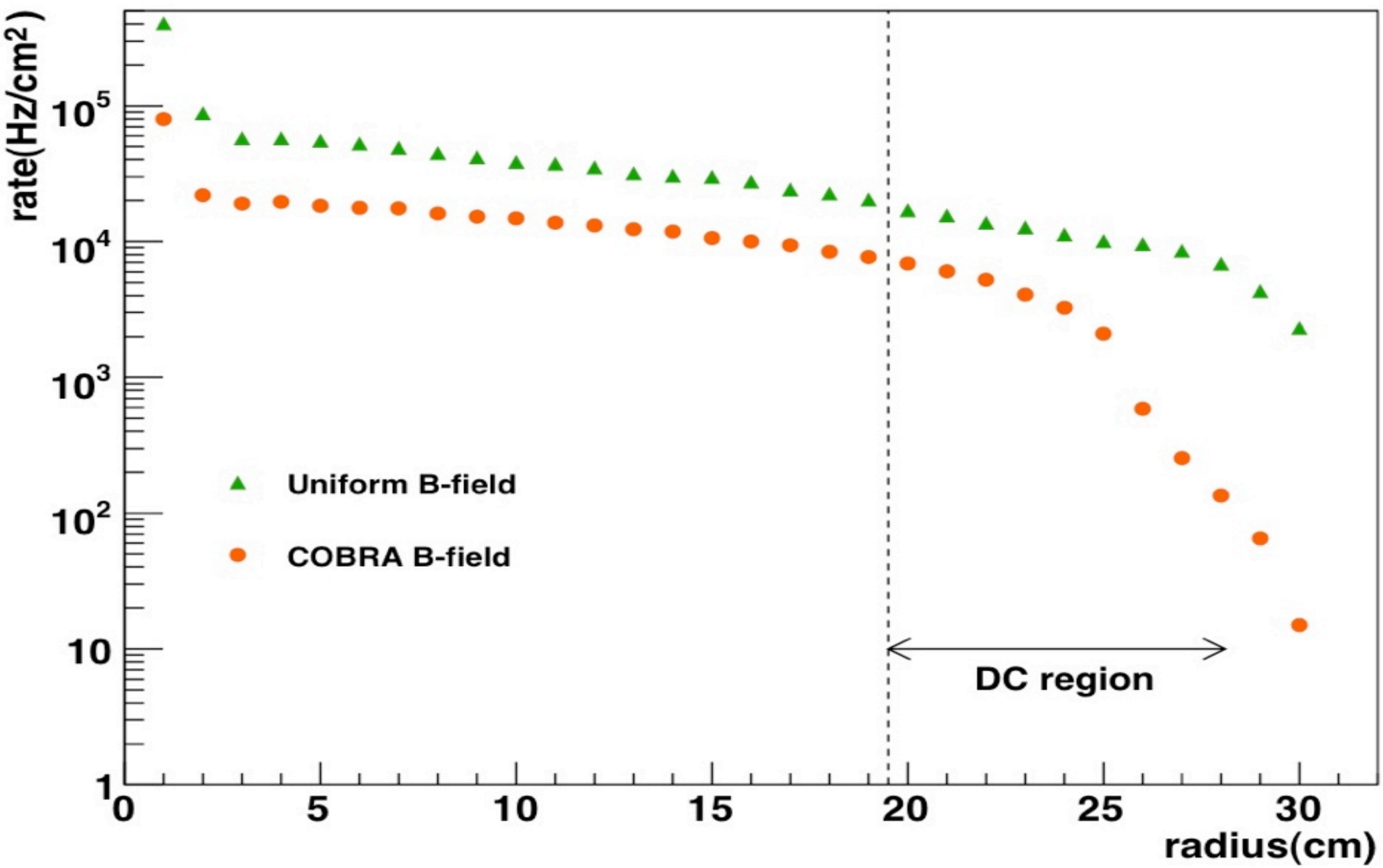




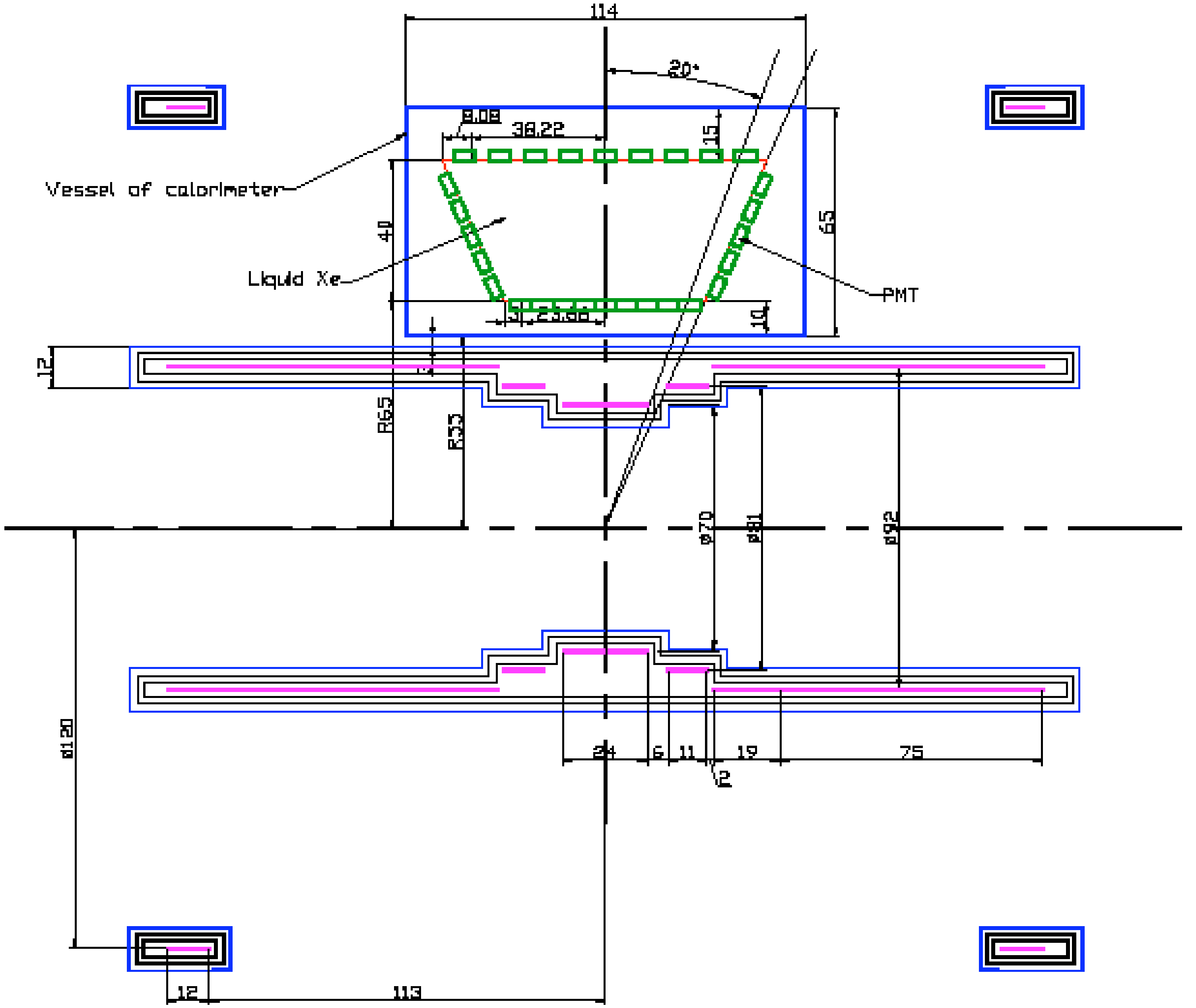


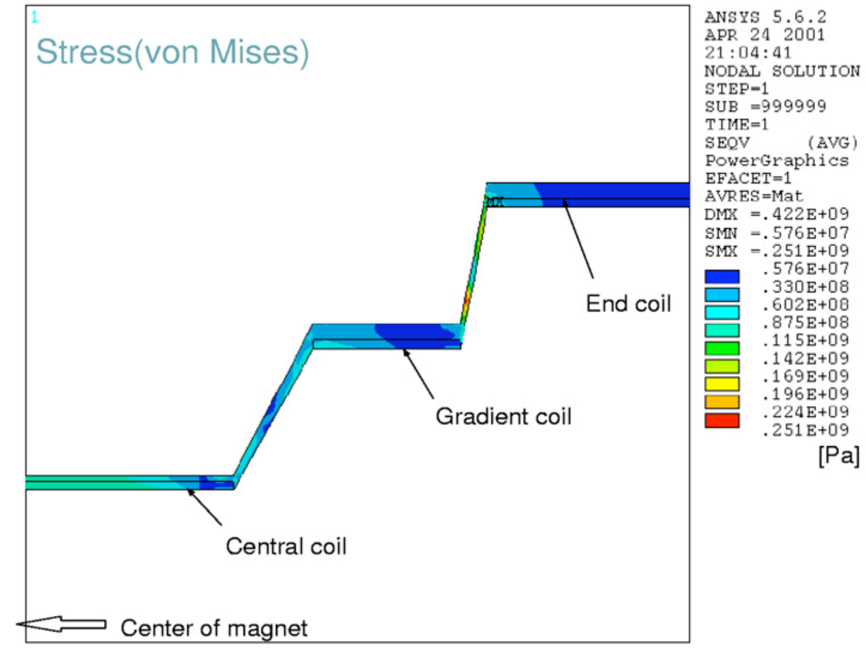
Benefit of COBRA field

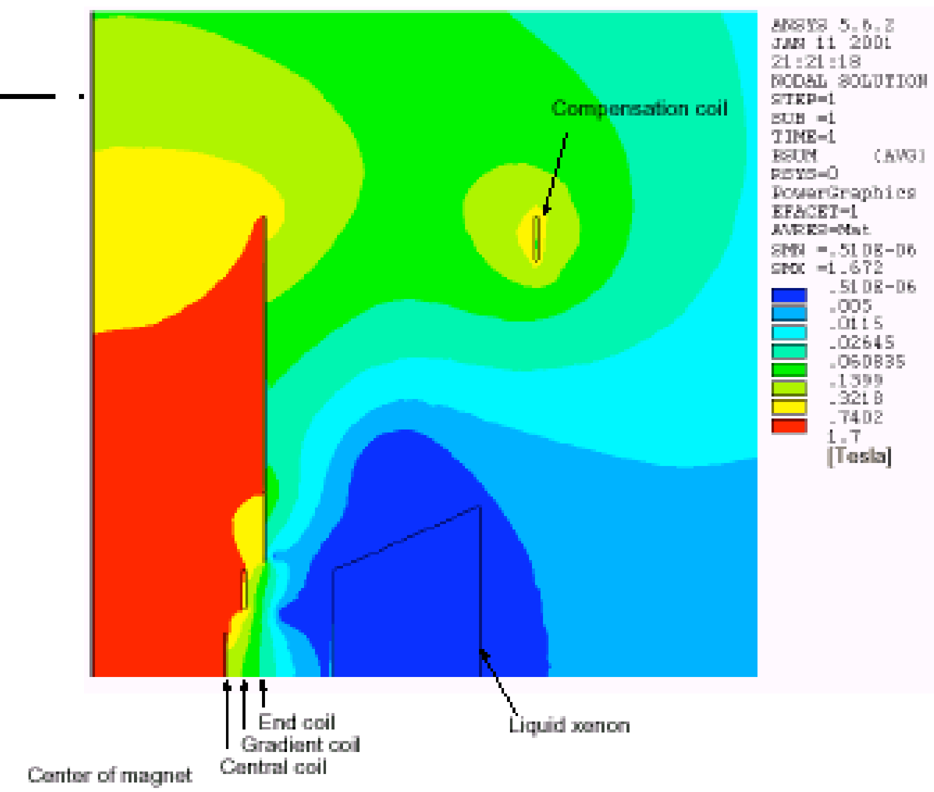
Benefit of COBRA field



Superconducting Solenoidal Magnet (Design)

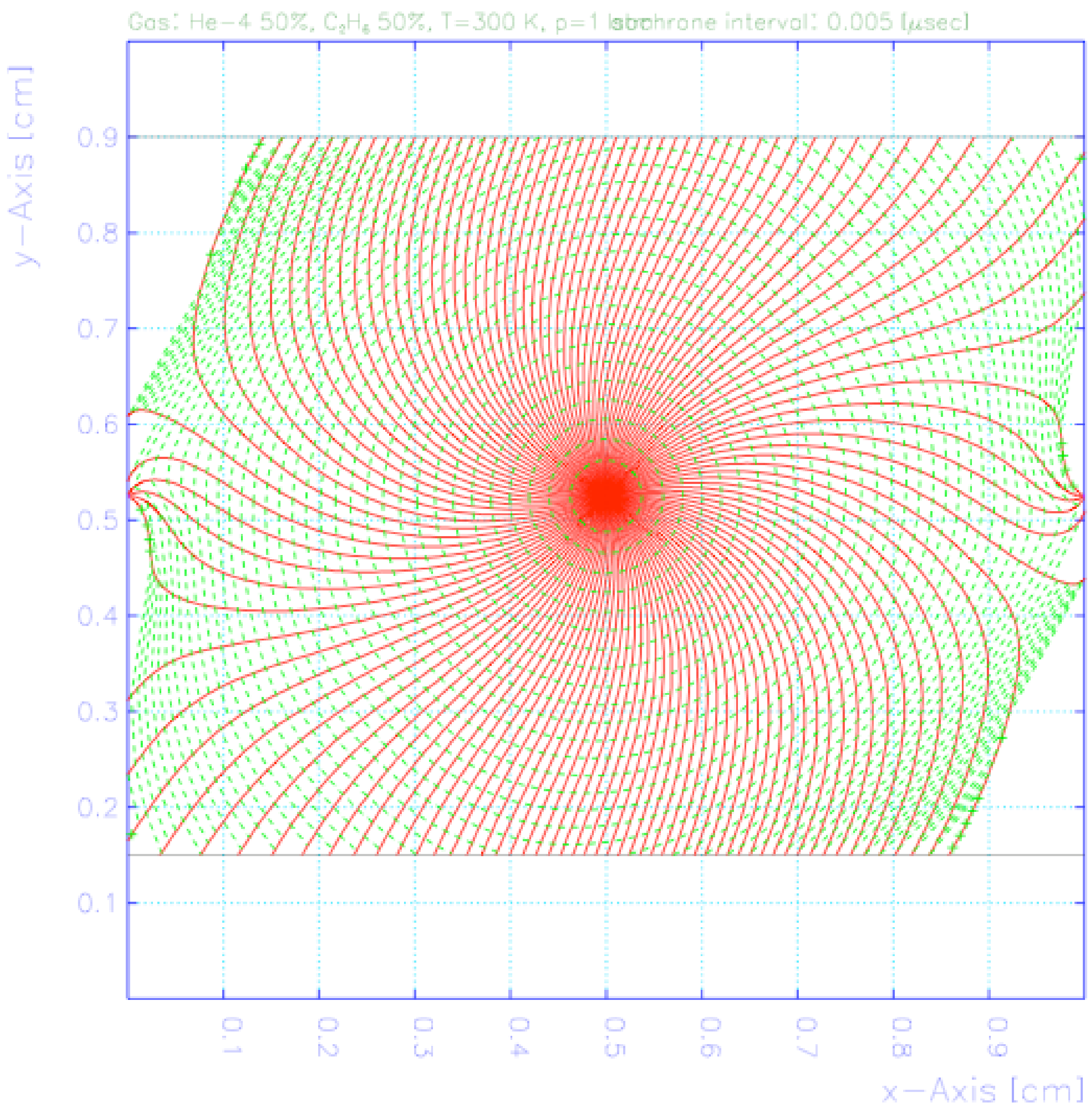




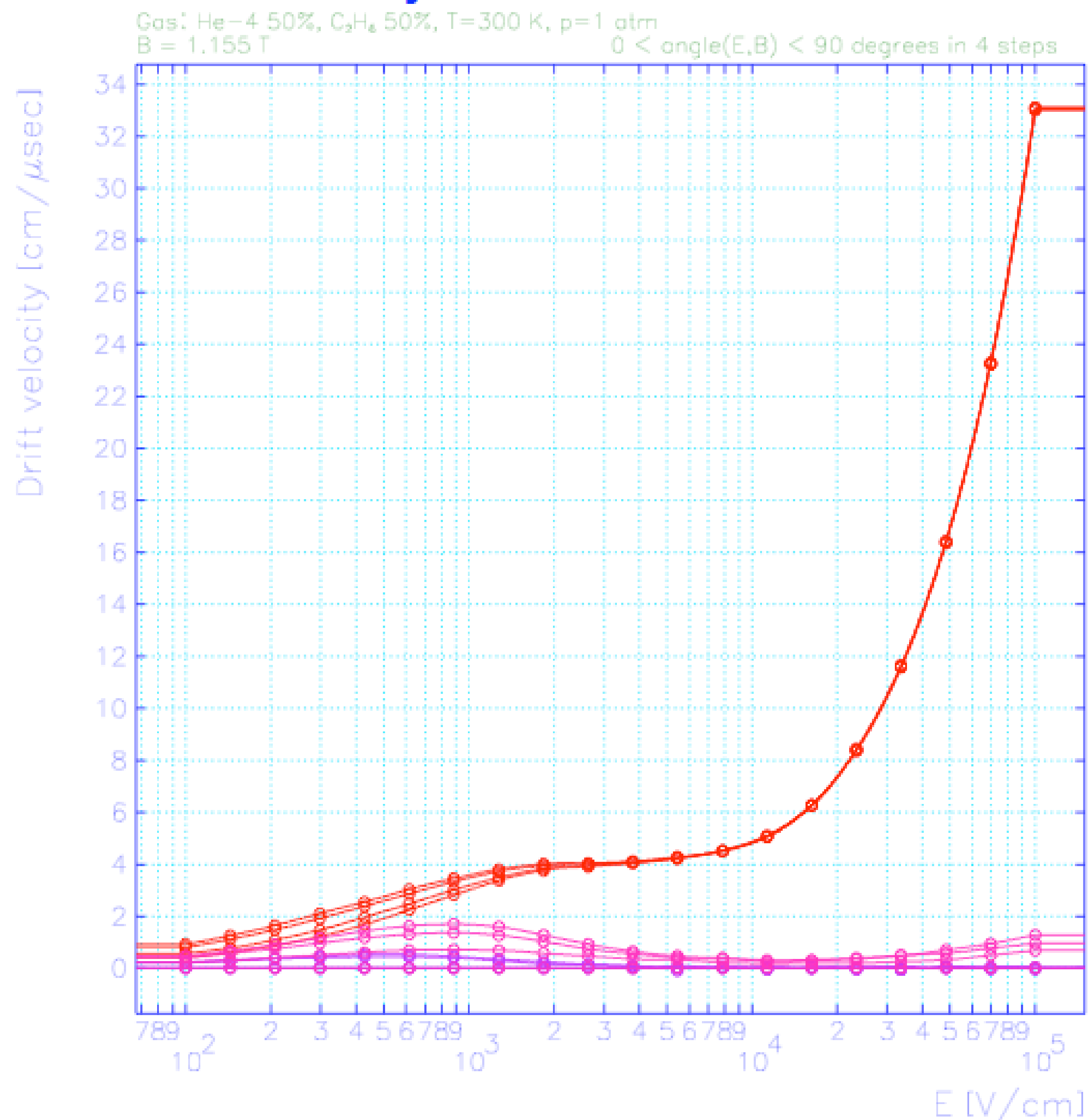


DC Characteristics Simulation (Garfiled)

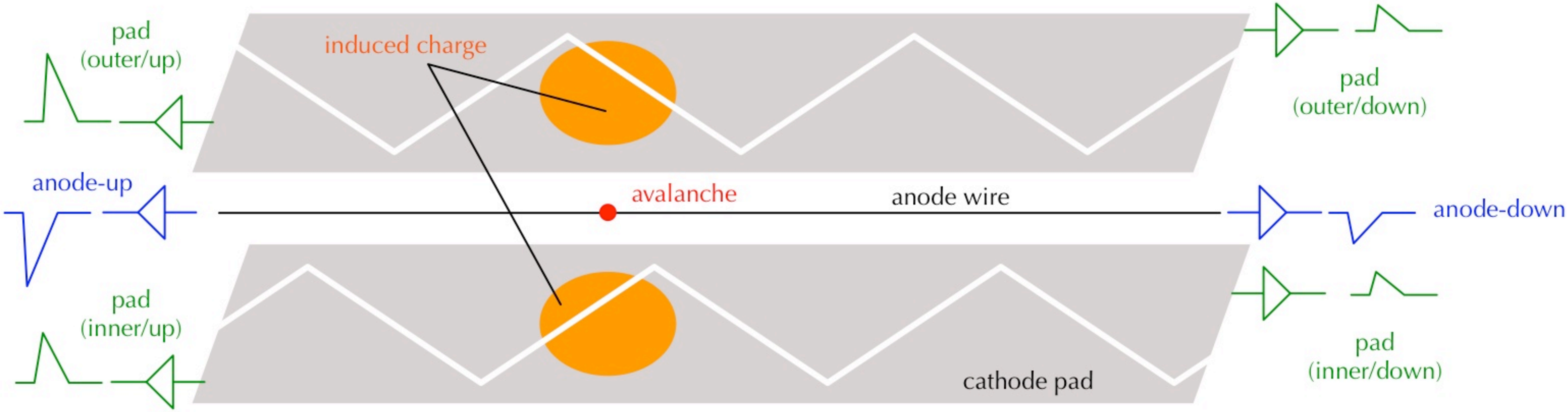
Electron drift lines from a wire



Drift velocity vs E



Vernier Pad Method

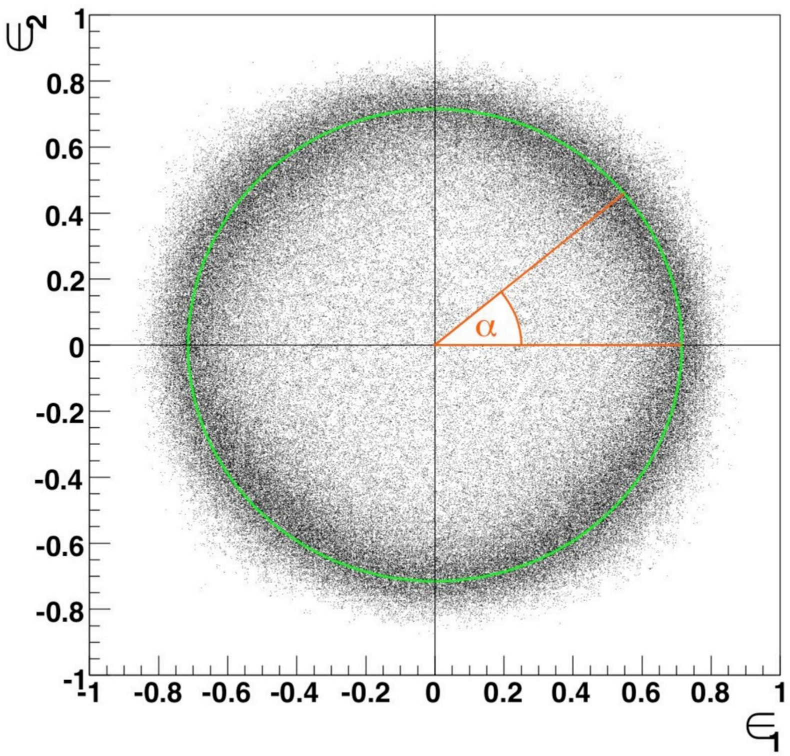


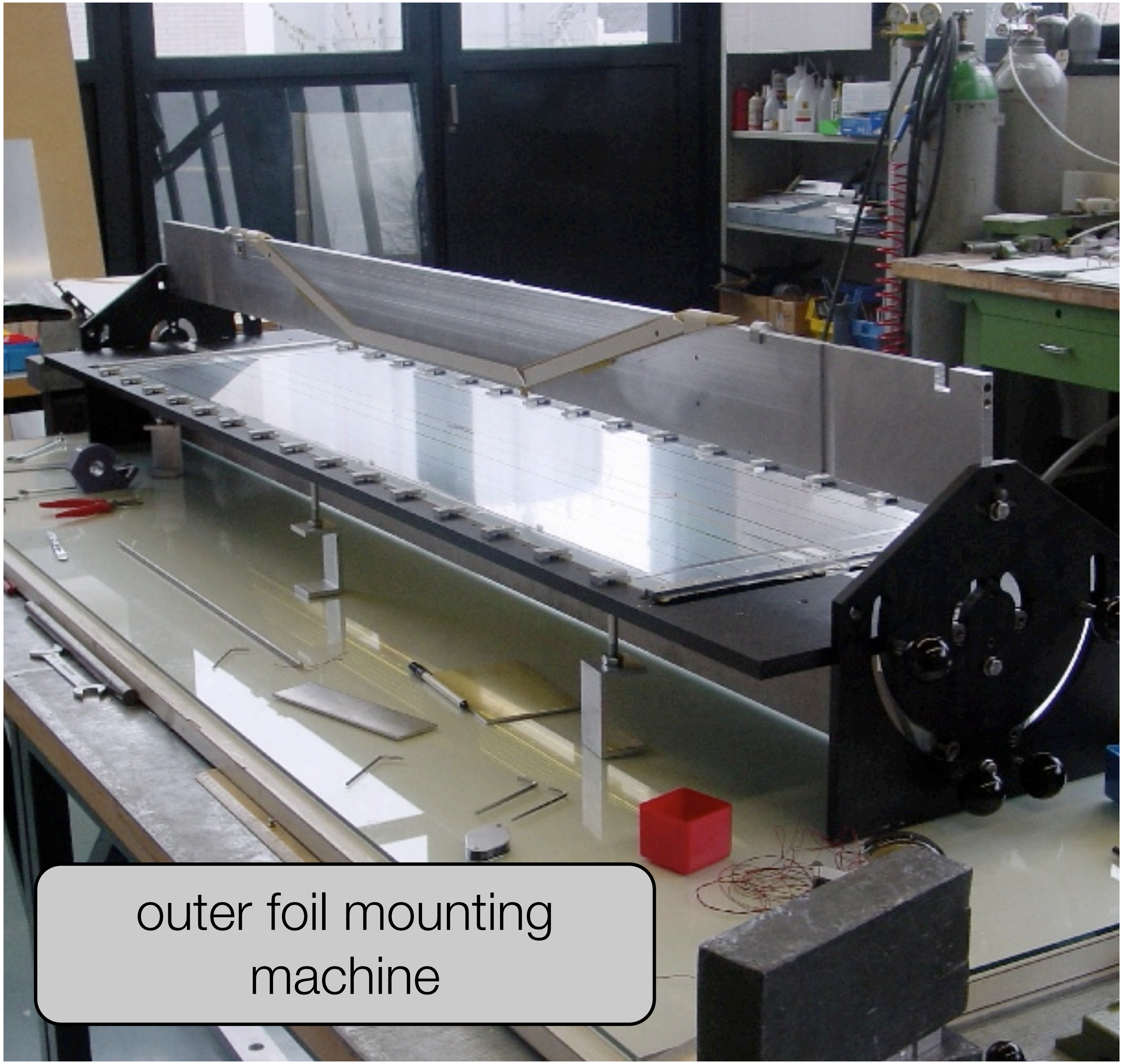
$$\epsilon_1 = \frac{Q_{iu} - Q_{id}}{Q_{iu} + Q_{id}}$$

$$\epsilon_2 = \frac{Q_{ou} - Q_{od}}{Q_{ou} + Q_{od}}$$

$$\alpha = \tan^{-1} \epsilon_2 / \epsilon_1$$

$\sigma_z \sim 500\mu m$ is available w/o increasing # of ch.

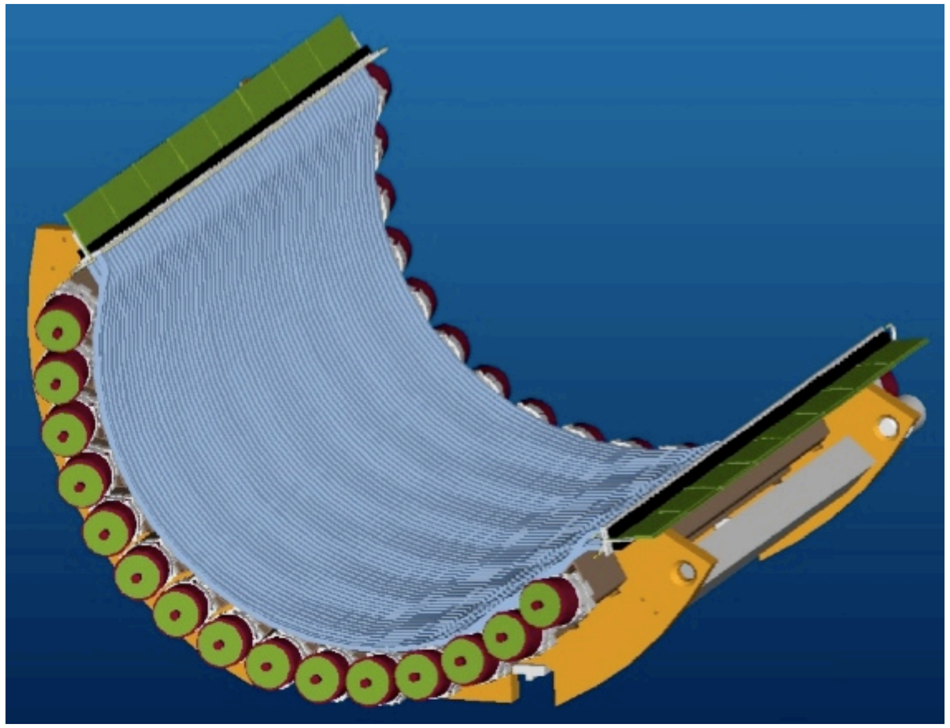


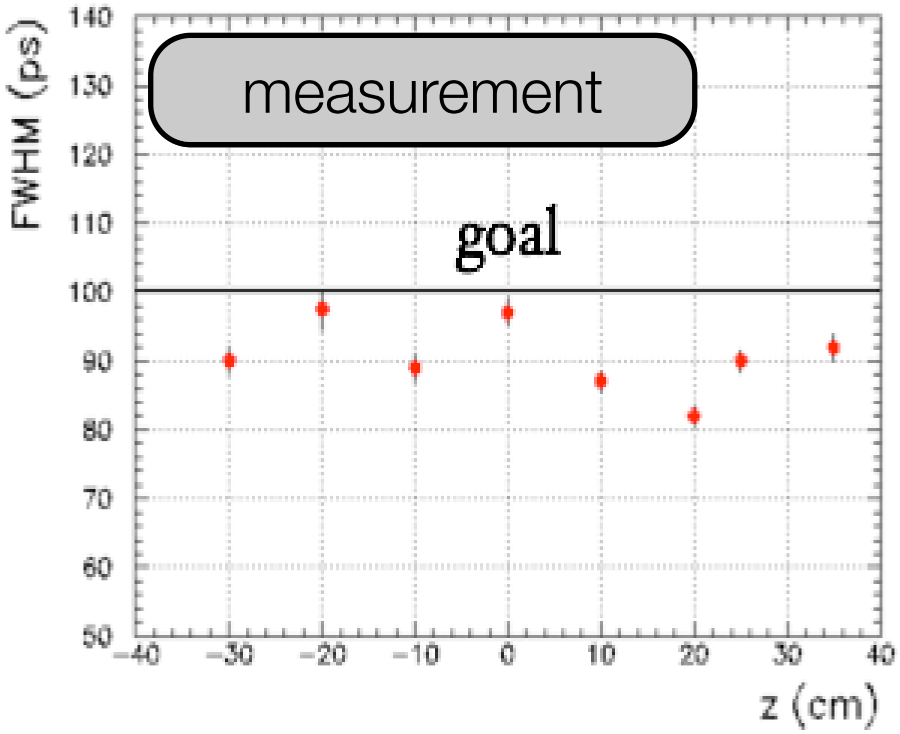


Making of MEG Drift Chamber

Timing Counter

- 2-layers of scintillators
  - Scintillator bars (outer layer), read out by PMTs for timing
  - Scintillator fibres (inner layer), read out with APDs for z-trigger
- Obtained goal σ_T ~ 40psec (100psec FWHM)
- This is Best existing Timing Counter

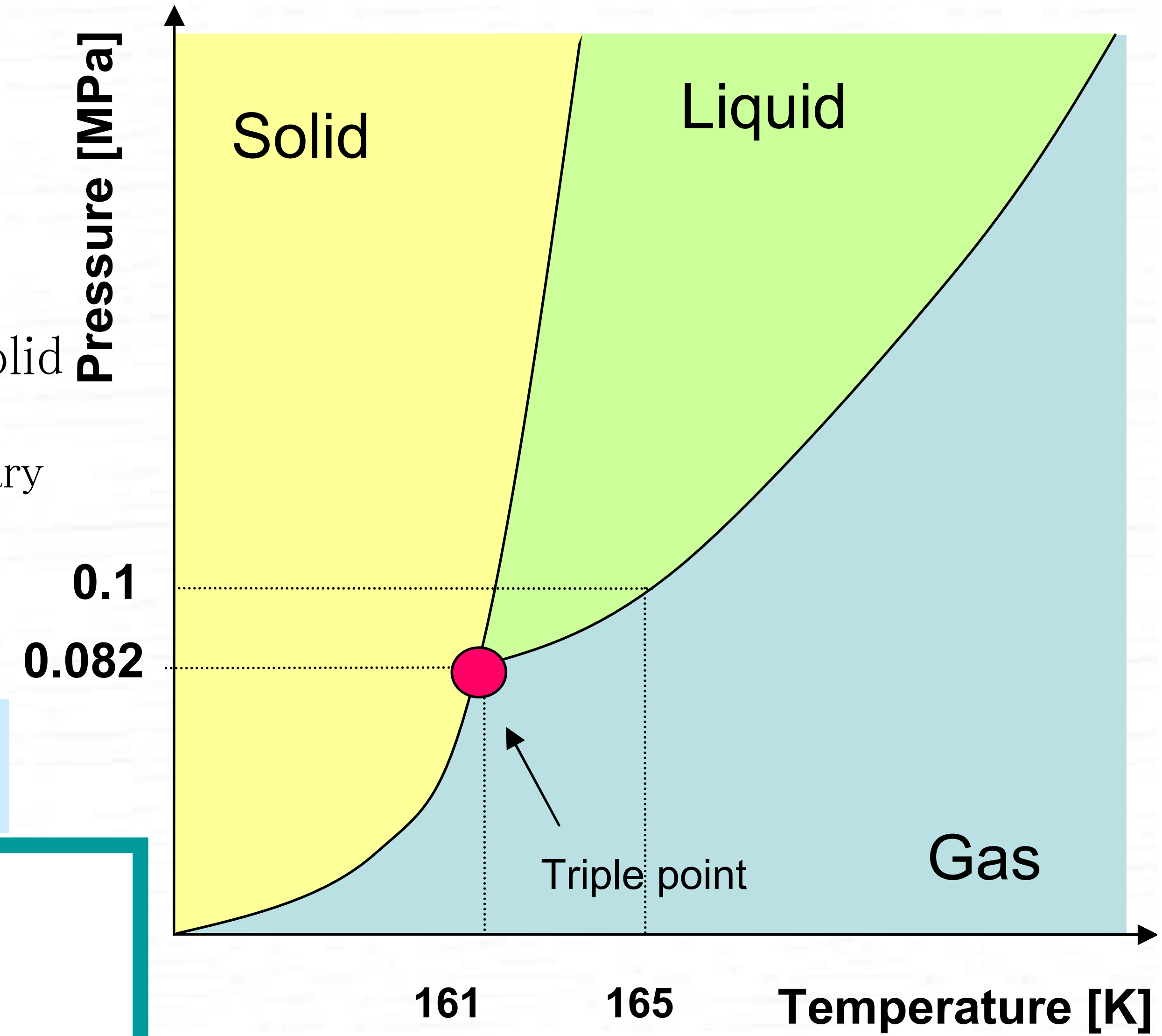




Expe. application	size(cm)	Scinti.	PMT	L(att) cm	σmeas)	σ(exp)
G.D.Agostini	3x15x100	NE114	XP2020	200	120	60
T.Tanimori	3x20x150	SCSN38	R1332	180	140	110
T.Sugitate	4x3.5x100	SCSN23	R1828	200	50	53
R.T.Gile	5x10x280	BC408	XP2020	270	110	137
TOPAZ	4.2x13x400	BC412	R1828	300	210	240
R.Stroynowski	2x3x300	SCSN38	XP2020	180	180	420
Belle	4x6x255	BC408	R6680	250	90	143
MEG	4x4x90	BC404	R5924	270	38	43

Liquid Xenon and Scintillation Light

- Density 3.0 g/cm^3
- Triple point 161K, 0.082MPa
- Normal operation at
  - T~167K P~0.12MPa
- Narrow temperature range between liquid and solid phases
  - Stable and reliable temperature control is necessary
- Scintillation light emission mechanism



Excitation

$$Xe + Xe^* \rightarrow 2Xe + h\nu$$

Recombination

$$Xe^+ + Xe \rightarrow Xe_2^+$$

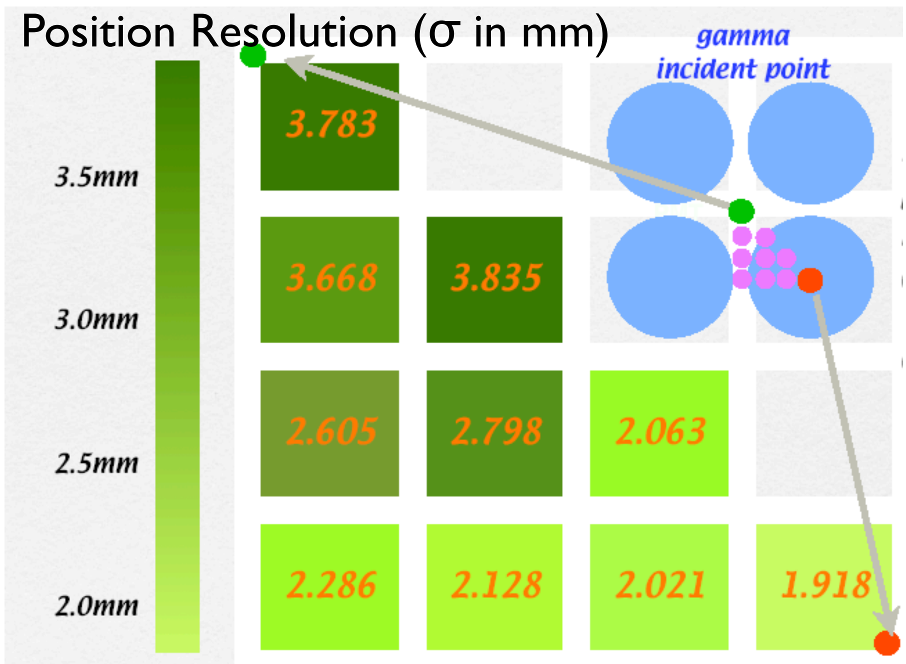
$$Xe_2^+ + e \rightarrow Xe^{**} + Xe$$

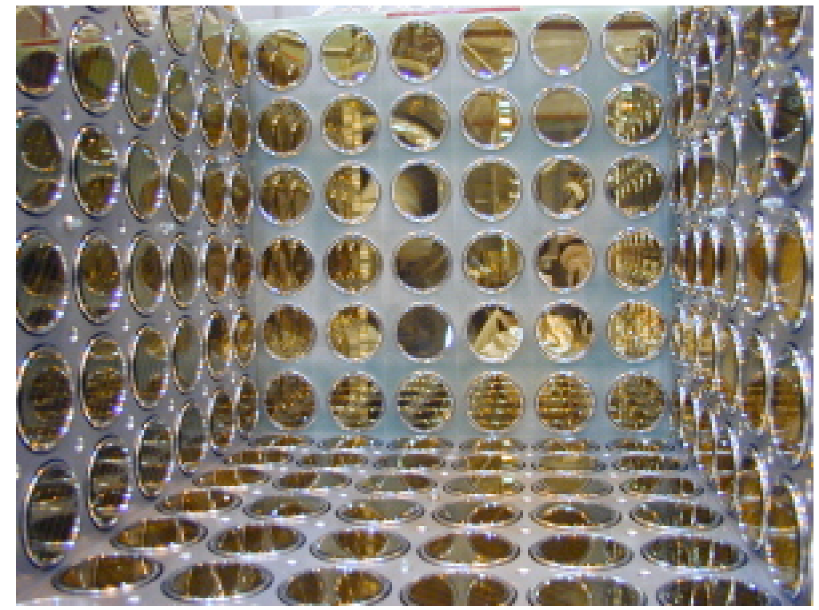
$$Xe^{**} \rightarrow Xe^*$$

$$Xe + Xe^* \rightarrow Xe_2^* \rightarrow 2Xe + h\nu$$

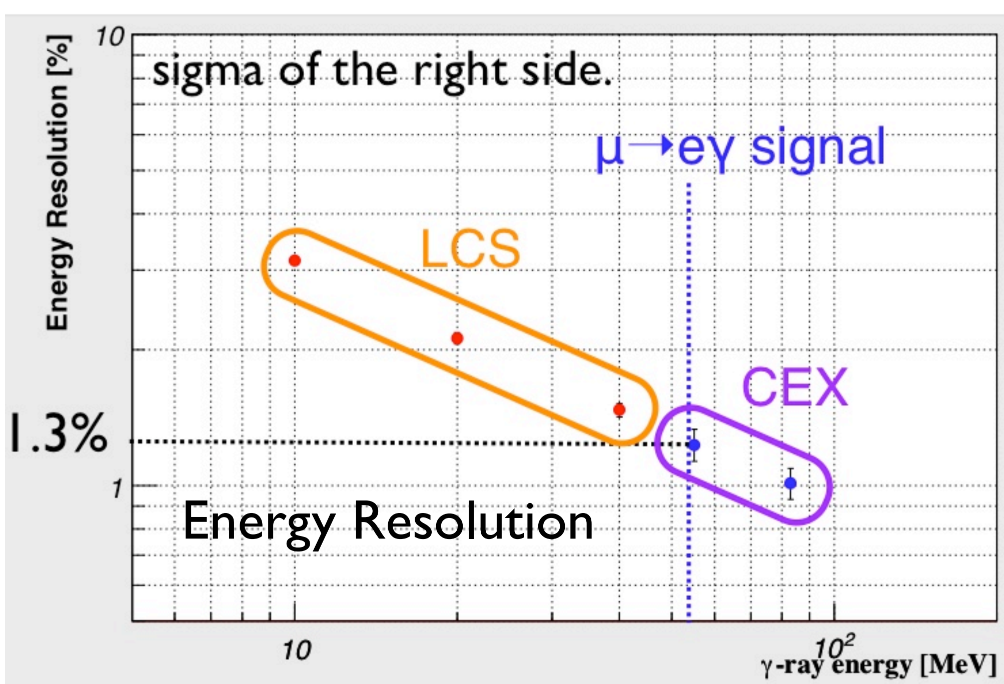
$$\lambda \sim 175 \pm 10\,nm$$

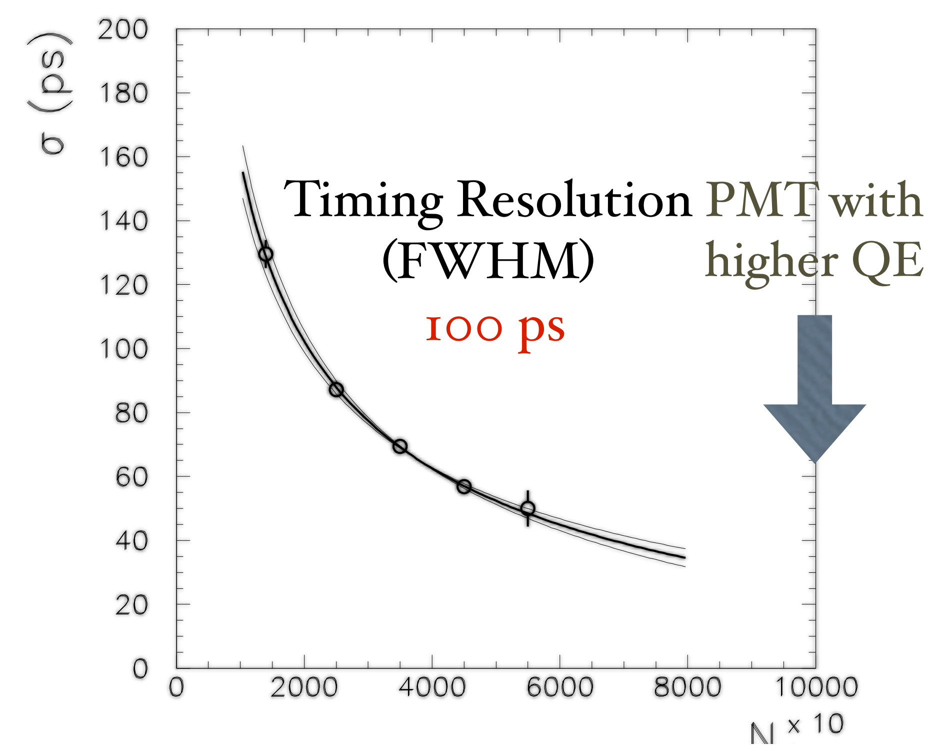
Results of Liquid Xenon Prototype



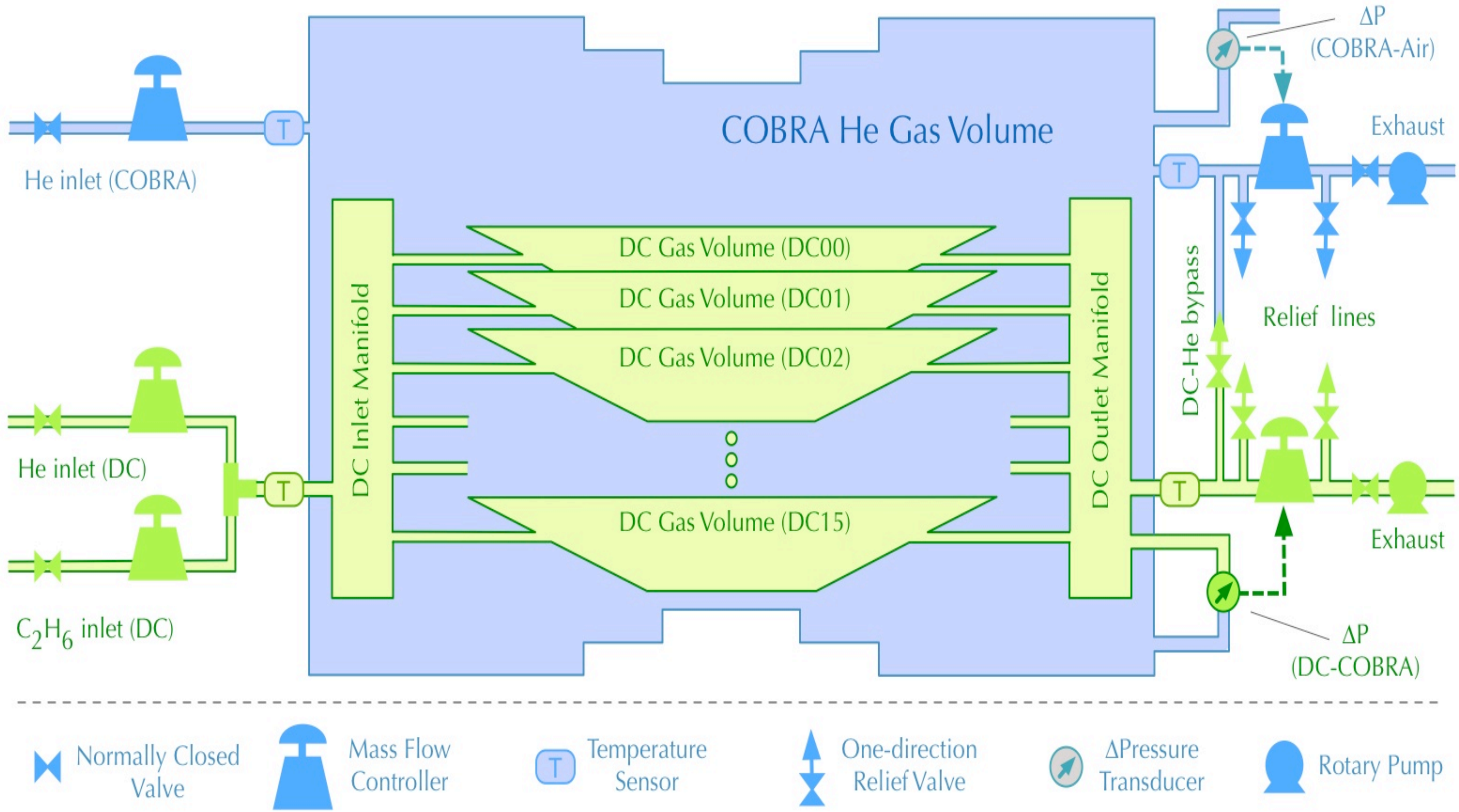


100 liter Prototype Detector

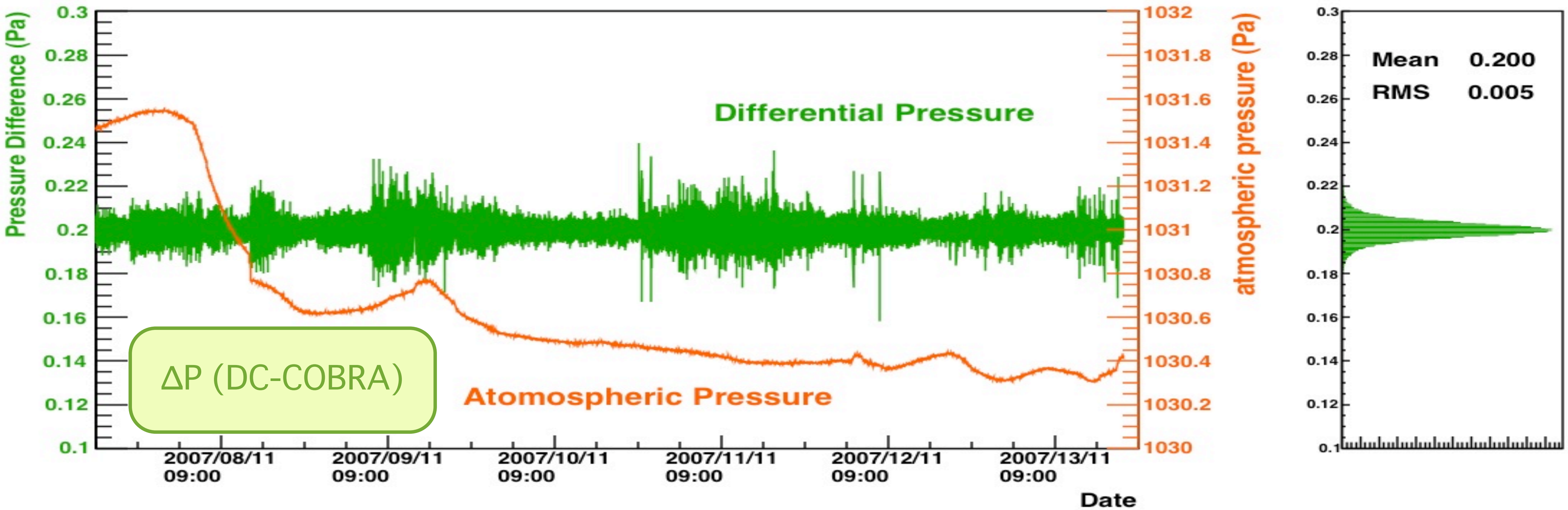


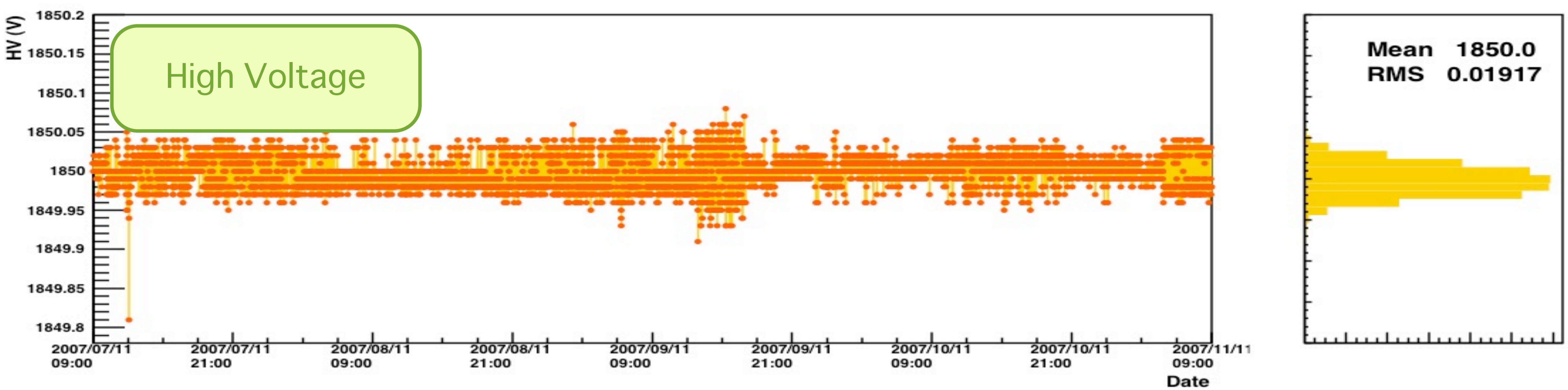


Drift Chamber Pressure Equalization System



Drift Chamber Stability

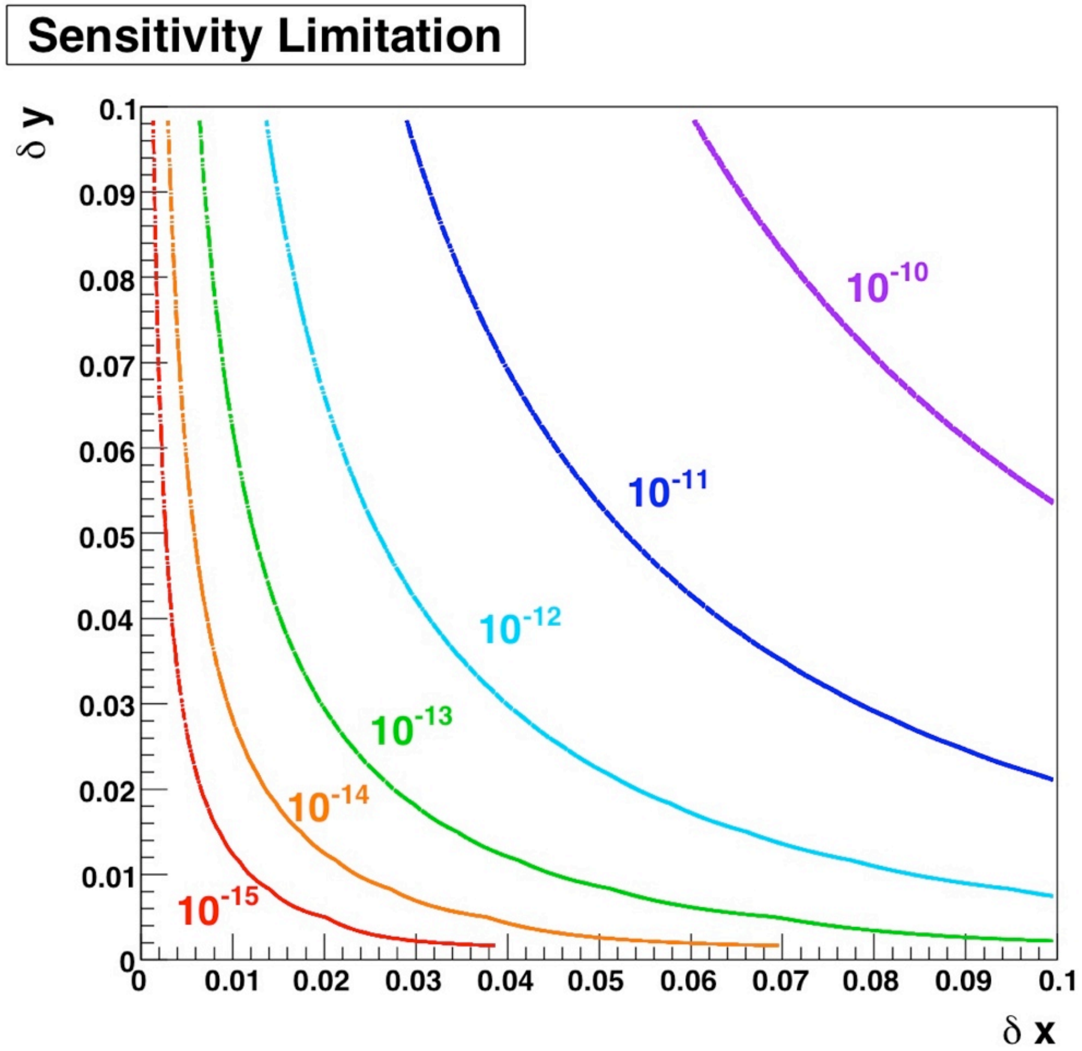


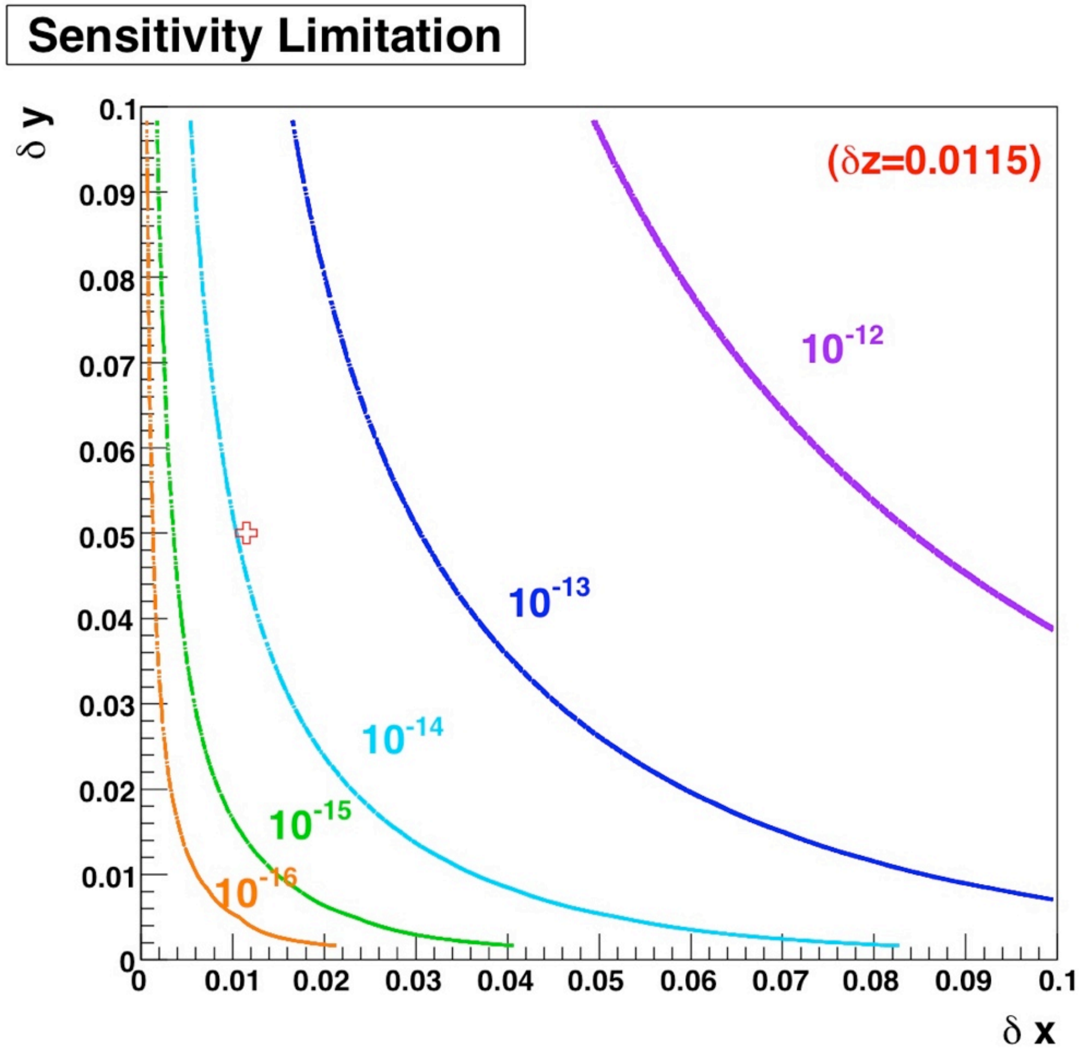


Physics Background Rate

- Physics Background (Radiative Muon Decay)

$$\mathrm{d}\mathcal{B}(\mu \to e\nu\bar{\nu}\gamma) = \frac{1}{\Gamma(\mu \to e\nu\bar{\nu})} \int_{1-\delta x}^{1} \mathrm{d}x \int_{1-\delta y}^{1} \mathrm{d}y \int_{0}^{\min\left[\delta z, 2\sqrt{(1-x)(1-y)}\right]} \mathrm{d}z \frac{\mathrm{d}\Gamma(\mu \to e\nu\bar{\nu}\gamma)}{\mathrm{d}x\mathrm{d}y\mathrm{d}z}$$



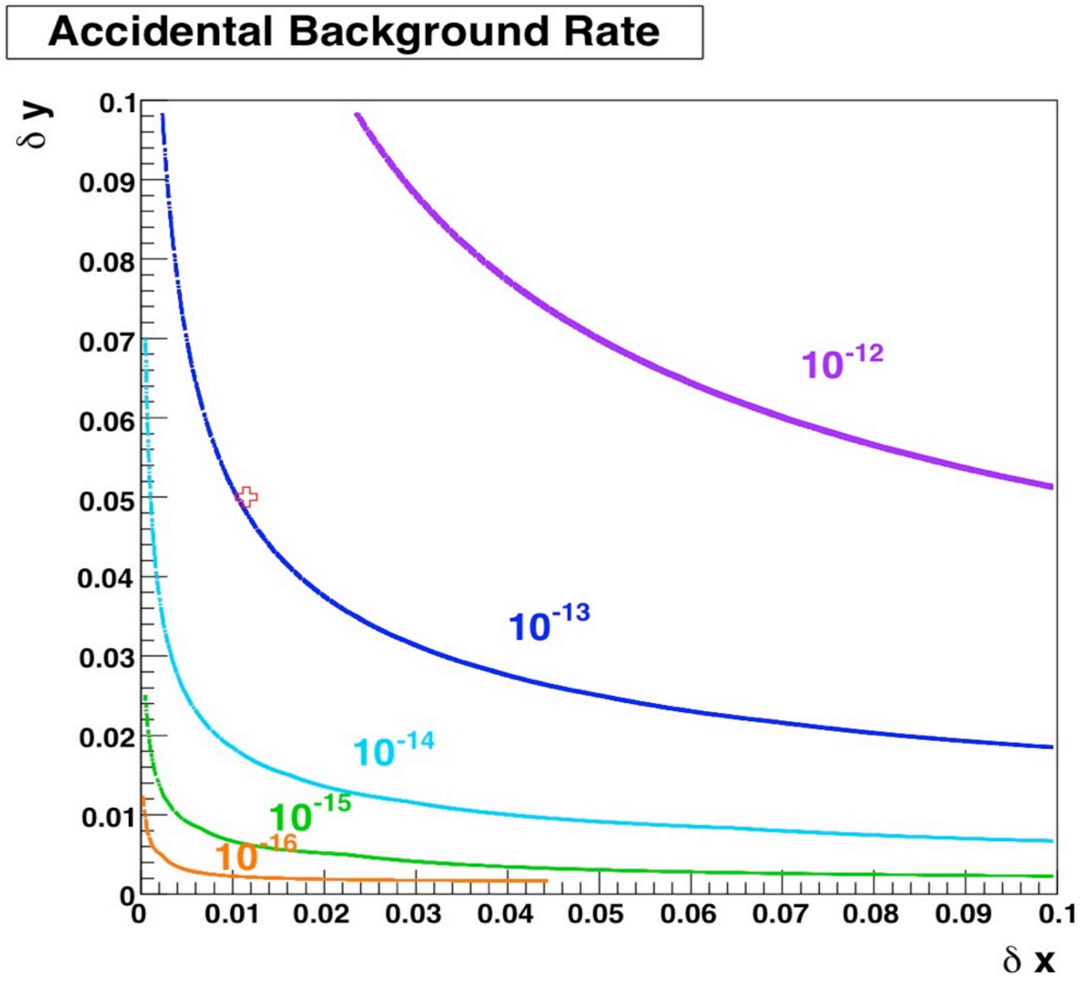


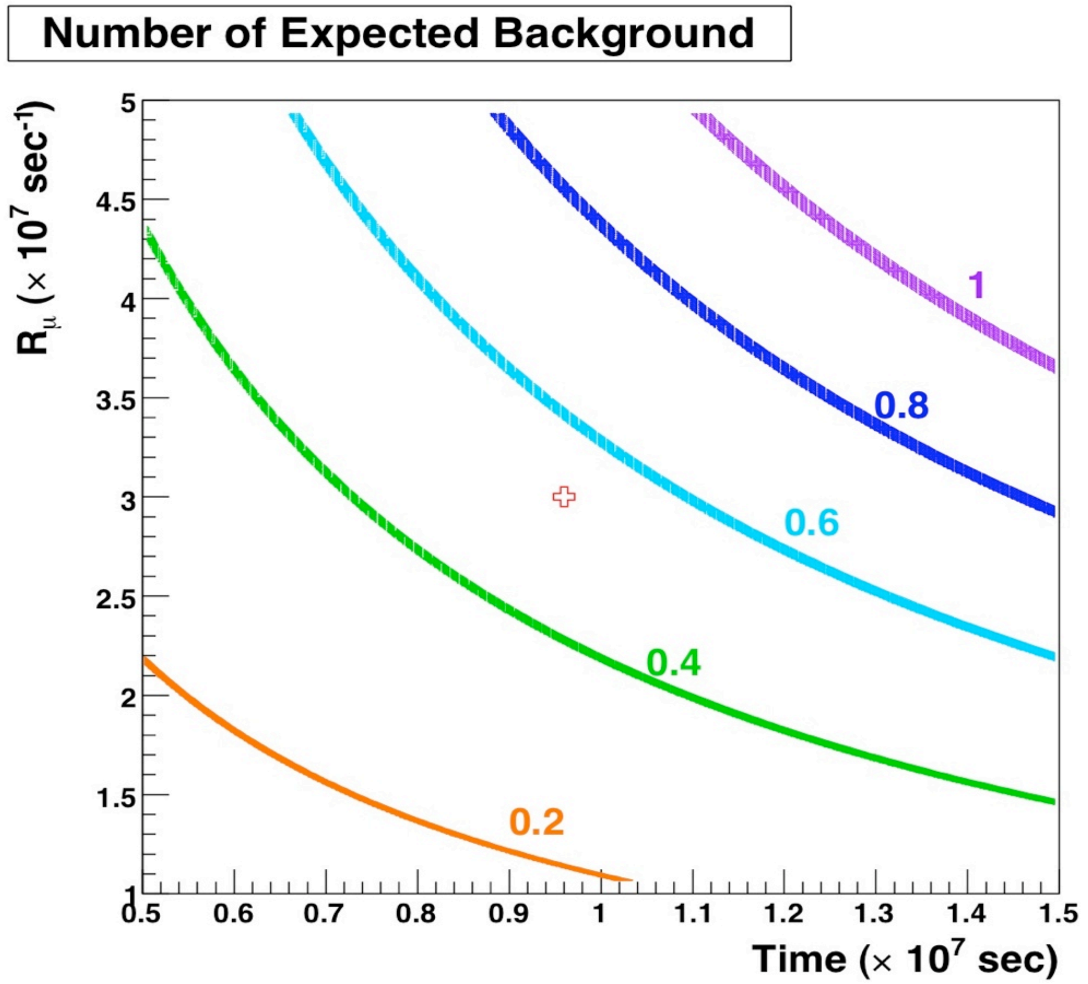
- For MEG 2008, Physics Background < 1.1×10^{-14}

Accidental Background Rate

- Accidental Background

$$\mathcal{B}_{acc} = \mathcal{R}_\mu \cdot (2\delta x) \cdot \left[\frac{\alpha}{2\pi}(\delta y)^2(\ln(\delta y) + 7.33)\right] \times \left(\frac{\delta\theta^2}{4}\right) \cdot (2\delta t).$$





- For MEG 2008, Physics Background < 1.0×10^{-13}
- For MEG 2008, Number of Expected Background Event = 0.5

MEG Sensitivity 2008 (assuming 24 weeks daq)

- Single Event Sensitivity

$$\mathcal{B}(\mu^+ \to \mathrm{e}^+\gamma) = \frac{1}{\mathcal{R}_\mu \cdot T \cdot (\Omega/4\pi)} \times \frac{1}{\epsilon_\mathrm{e} \cdot \epsilon_\gamma \cdot \epsilon_\mathrm{sel}},$$

- For MEG 2008, Single Event Sensitivity :

$$B^{2008}(\mu \to e\gamma) = 2.2 \times 10^{-13}$$

- For MEG 2008, Feasible Upper-limit

$$B^{2008}(\mu \to e\gamma) < 6.9 \times 10^{-13} \text{ (90\% C.L.)}$$