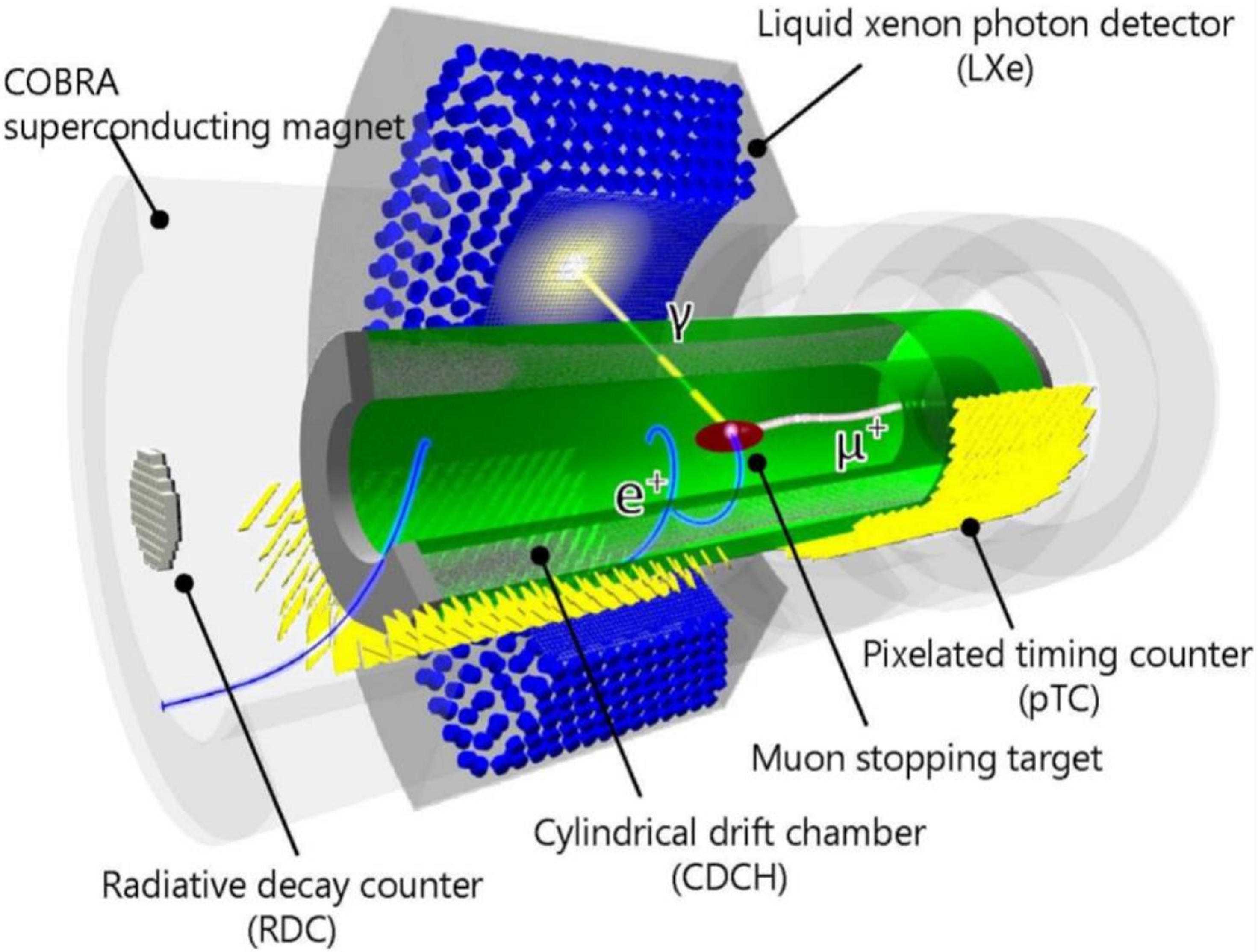
Status of the MEG II Experiment

Dylan Palo – On Behalf of the MEG II Collaboration

Overview

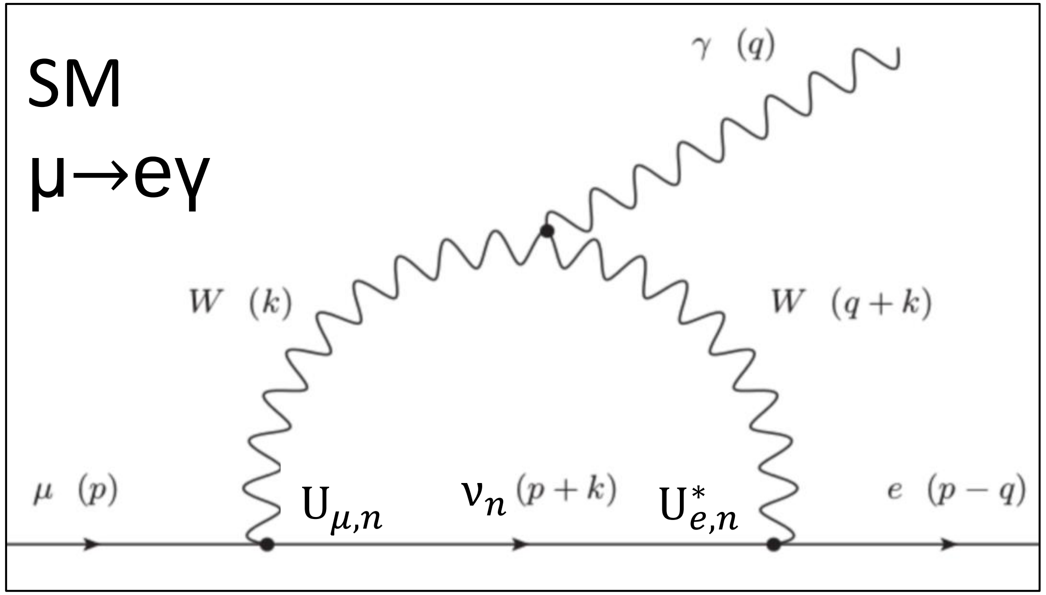
- Goal:
  - Describe MEG II experimental technique and show results from the first MEG II run
- Discuss:
  - Charged Lepton Flavor Violation (CLFV) background
  - MEG II experimental overview
  - MEG II physics data
    - Detector resolutions
    - Sensitivity projections

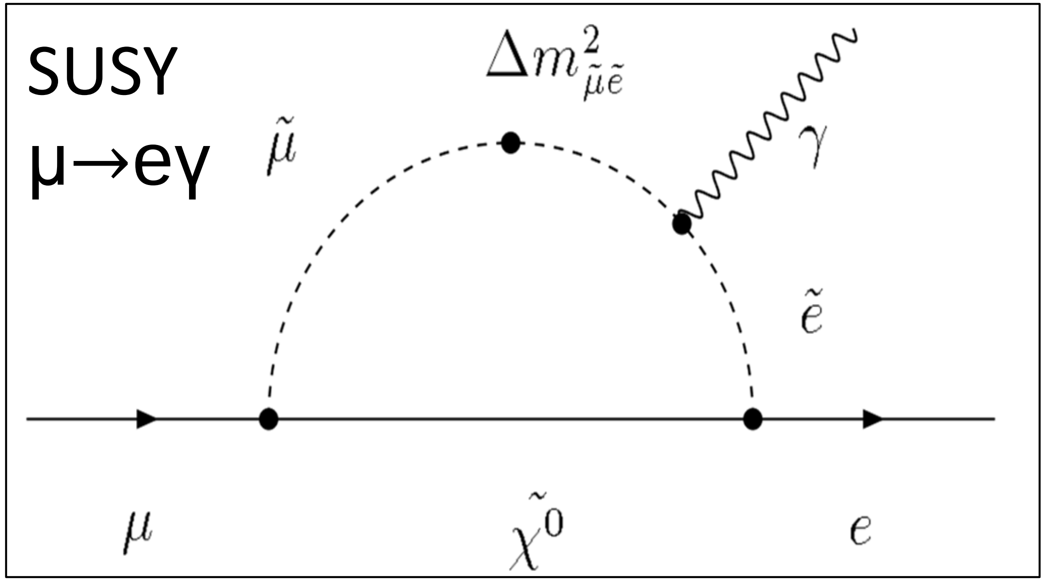


Charged Lepton Flavor Violation

μ→eγ Decay

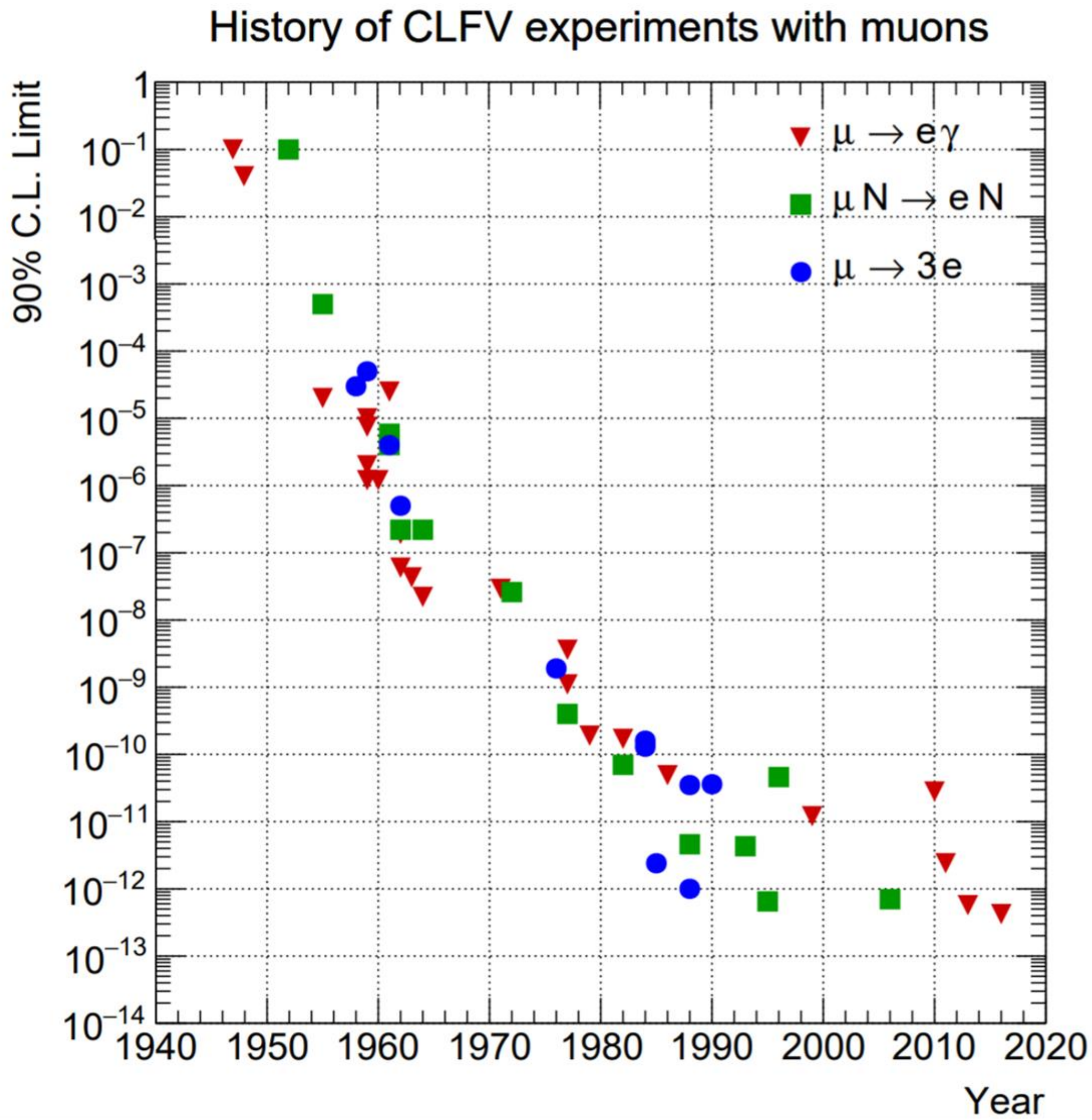
- μ→eγ decay is an example of charge lepton flavor violation (CLFV)
- The SM μ→eγ BR is **negligible**: ~ 10^{-54}; proportional to $[\frac{\Delta(m_\nu^2)}{m_W^2}]^2$
- SM extensions (e.g. SUSY) allow for other μ→eγ decay channels
- Theorized SUSY μ→eγ is detectable (BR~ 10^{-11}: 10^{-15}) since the mass splittings can be comparable to masses
- **Detecting μ→eγ would be a clear indication of new physics**





CLFV History

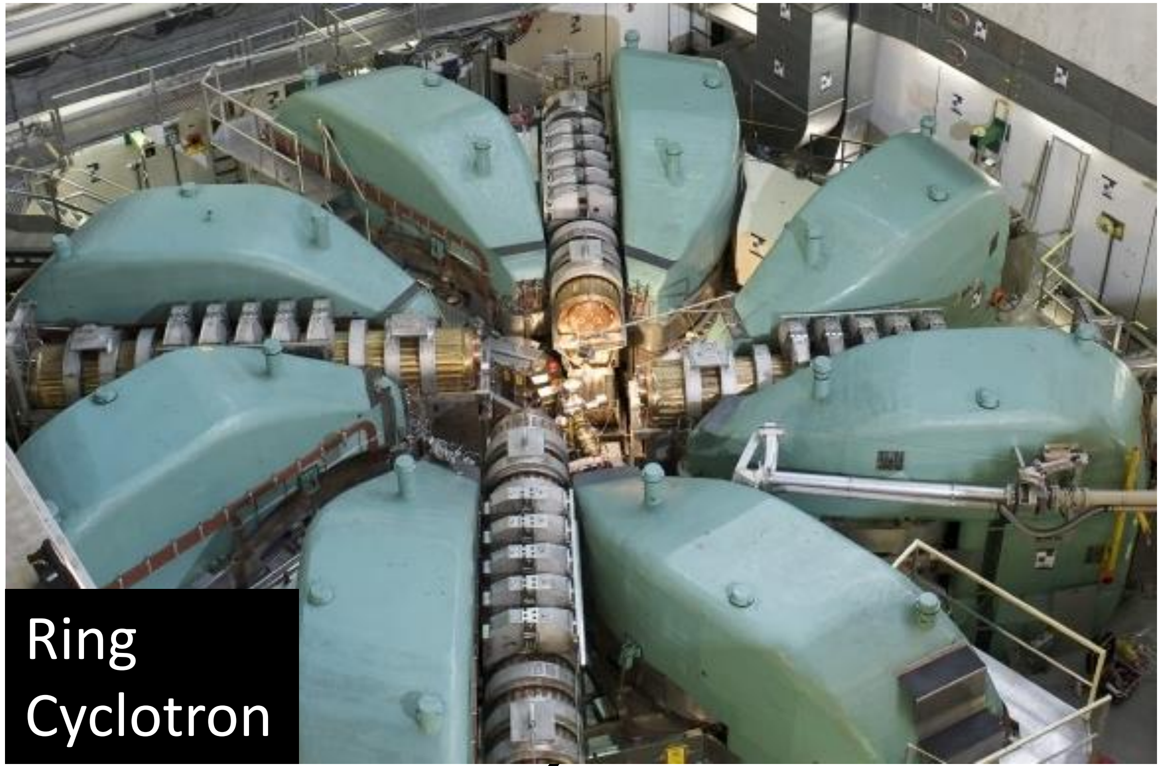
- The MEG II collaboration searches for the μ→eγ decay; one of several ongoing searches for charged lepton flavor violation (CLFV)
- The current μ→eγ decay sensitivity is 4.2x10^{-13} (90% Confidence Level), set by MEG I
- The MEG II collaboration aims to increase the sensitivity by an order of magnitude.



MEG II Experimental Overview

MEG II Experiment

- International collaboration of ~ 60 physicists
- Based at Paul Scherrer Institut located in Villigen, CH near Zurich
- Uses the PSI proton ring cyclotron
  - 590 MeV protons
  - Unbunched surface muon beam produced: $R_\mu \approx 7 \times 10^7$ Hz



UTokyo
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INFN Lecce
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INFN Pisa
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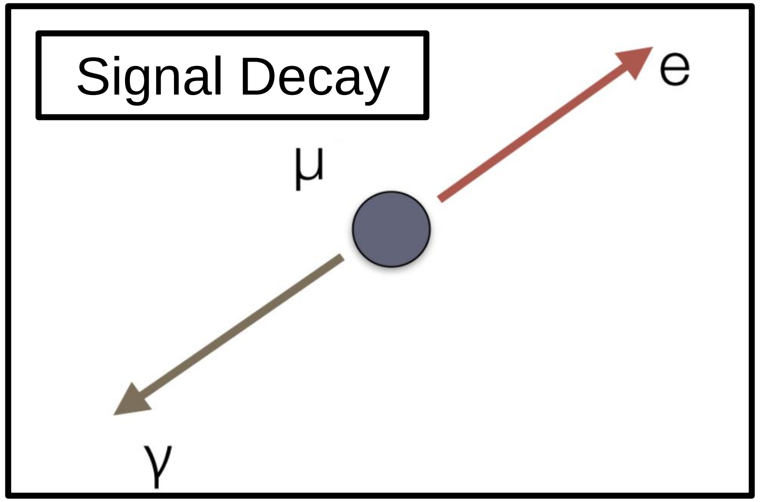
UC Irvine

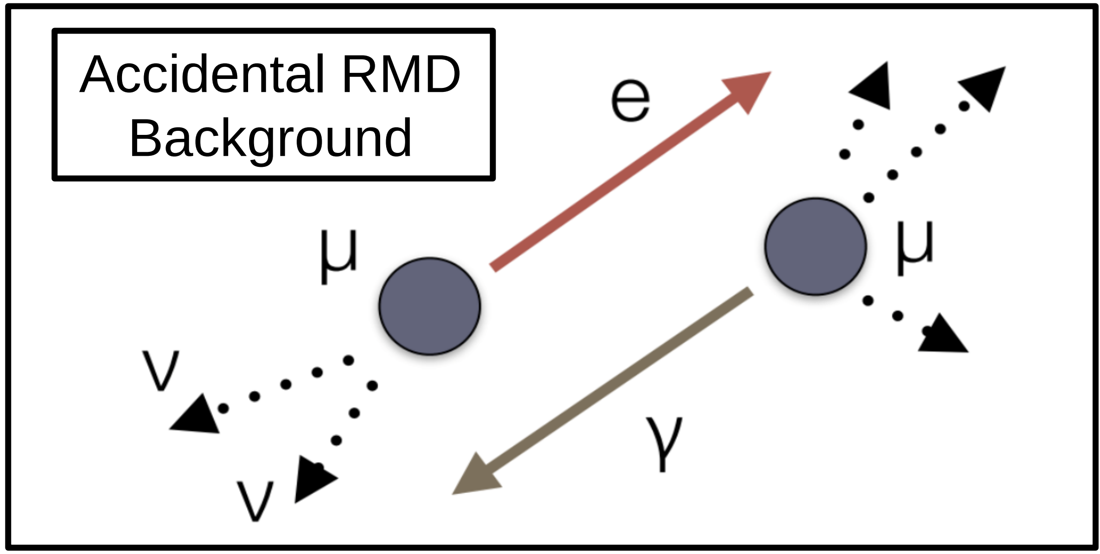
BINP
JINR

PSI
ETHZ

MEG II Experiment: Signal/Background

- The experiment relies **on precise kinematic measurements of the decay products** to distinguish between signal/background decays
- The μ→eγ signal is a two-body decay at rest, signal e/γ have equal and opposite momentum (m_μ/2)
- Background does not have these characteristics:
  - RMD (radiative muon decay) **:**
    $\mu^+ \rightarrow \gamma\, e^+ \nu_\mu \overline{\nu_e}$ (small E $\nu_\mu \overline{\nu_e}$)
  - Accidental background: high p_{e_+} coincident with γ from RMD (**dominant background**), AIF ($e^+ e^- \rightarrow \gamma\gamma$) or bremsstrahlung

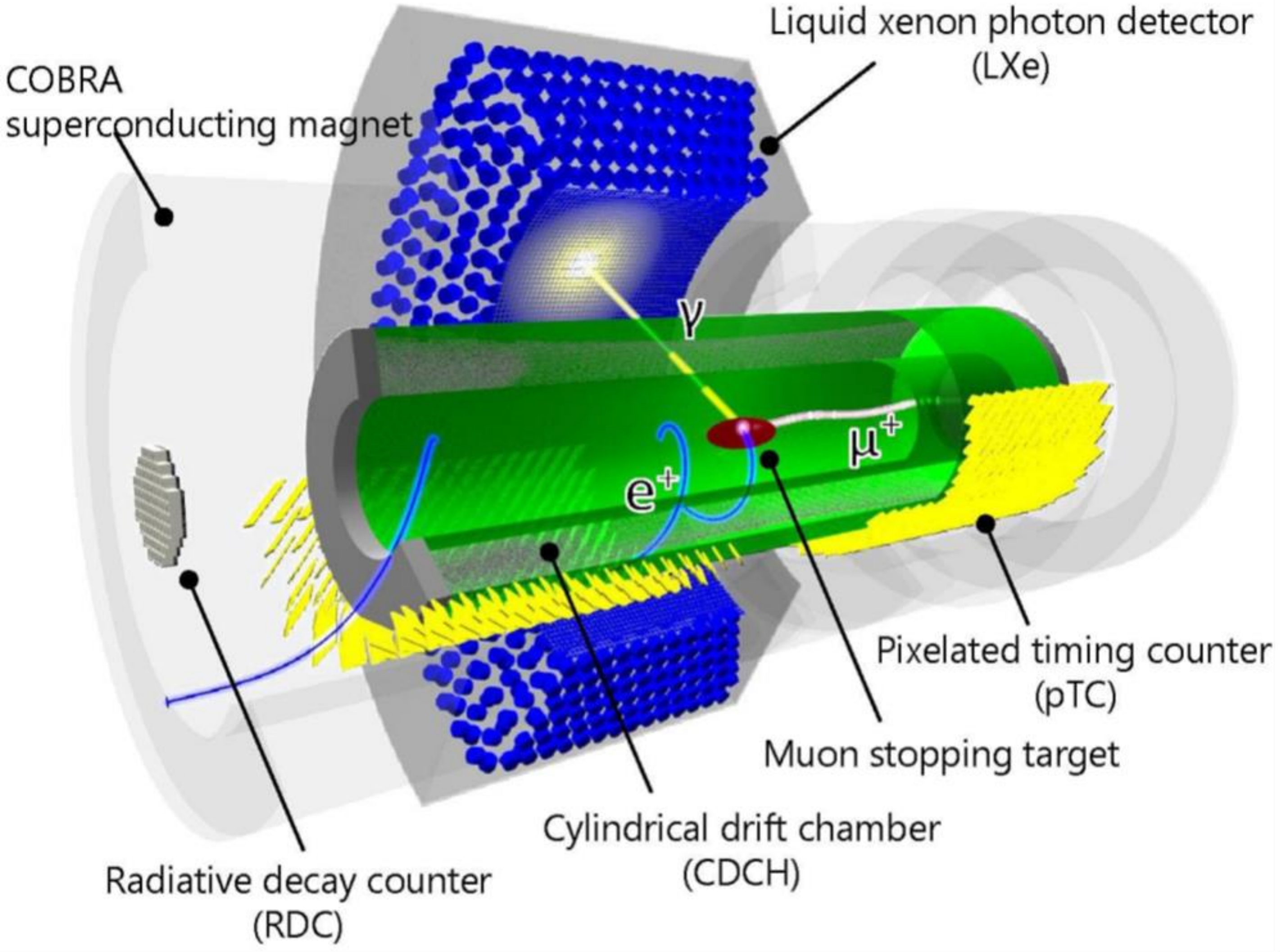




MEG II Experiment: Apparatus

- The experiment stops μ^+in a thin film target ($R_\mu \sim 7 * 10^7$ Hz)
- Stopped μ^+ decay in target; decay products (e, γ) are measured in various detectors
- Similar design to MEG I, but all detectors have been upgraded
- Kinematic estimates at target by e^+ Kalman propagation to target, then γ propagation to e^+ target vertex $(\Delta\theta_{e^+\gamma}, \Delta\varphi_{e^+\gamma}, \Delta t_{e^+\gamma}, \Delta E_\gamma, \Delta p_{e^+})$

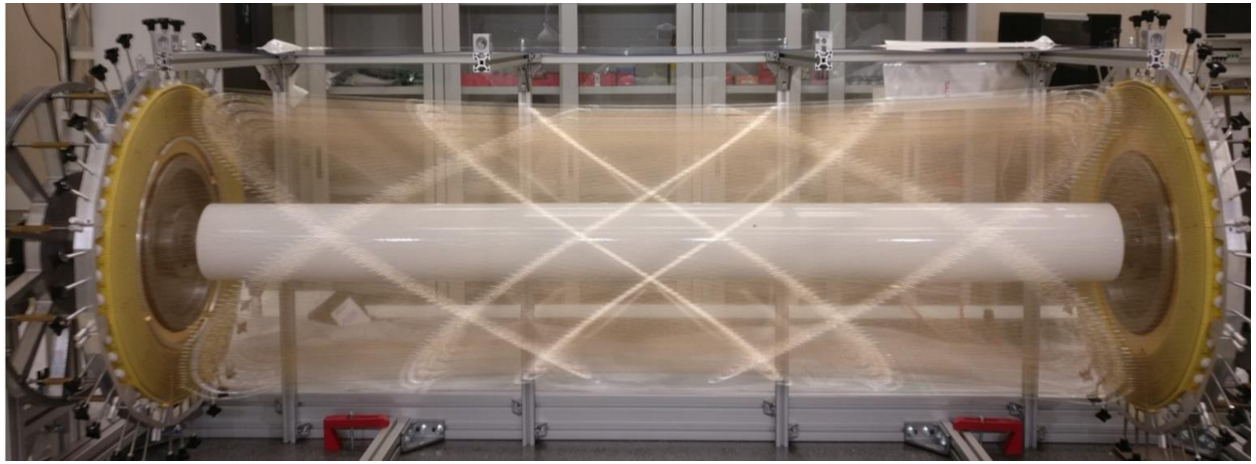
$$N_{acc} \propto R_{\mu^+}^2 \bullet \Delta E_\gamma^2 \bullet \Delta p_{e^+} \bullet \Delta\varphi_{e^+\gamma} \bullet \Delta\theta_{e^+\gamma} \bullet \Delta t_{e^+\gamma} \bullet \mathrm{T}$$



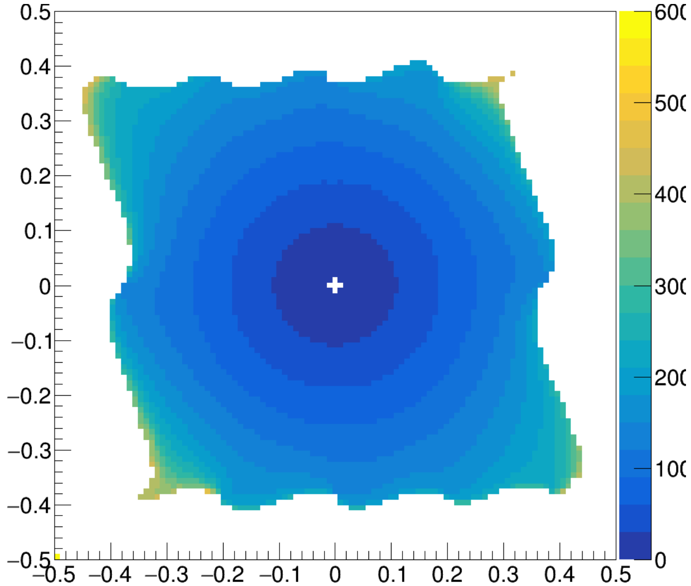
CDCH Detector

- Upgrades:
  - New ultra-light stereo drift chamber to improve efficiency and resolution
  - More track space points in drift chamber to improve resolution (1150 readout drift cells)
- In 2021, the chamber was filled with $He: C_4H_{10}: C_3H_8O: O_2$ (88.2: 9.8: 1.5: 0.5)
- High voltage wires surrounding sense wire creates drift cell geometry

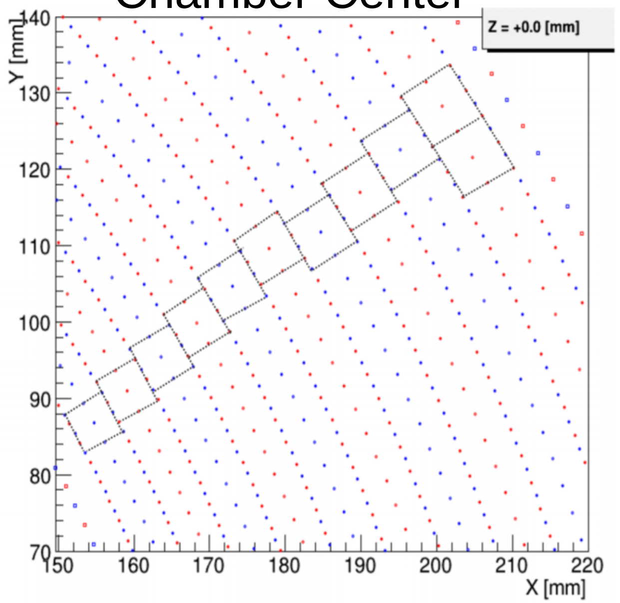
Kinematic Core σ	MEG I	MEG II Goal
p_{e_+}(keV)	**380**	**130**
θ_{e+} /φ_{e+} (mrad)	**9.4 / 8.7**	**5.3/3.7**
t_{e+} (ps)	70	30
z_{e+} /y_{e+} (mm)	**2.4/1.2**	**1.6/0.7**
e+ Efficiency	**30**	**70**



Time-Distance Isochrones



Wire Positions at Chamber Center



pTC Detector

- Upgrade: higher hit multiplicity
- Two semi-cylindrical modules, each consisting of 256 timing counters
- Counter consists of a scintillation tile with double-sided SiPM readout
- Individual counter timing precision ~90 ps
- Signal e_+ <n counters> ~9; $\sigma_{t_{e^+}}$=30 ps

Kinematic Core σ	MEG I	MEG II Goal
p_{e_+}(keV)	380	130
θ_{e+} /φ_{e+} (mrad)	9.4 / 8.7	5.3/3.7
t_{e+} (ps)	**70**	**30**
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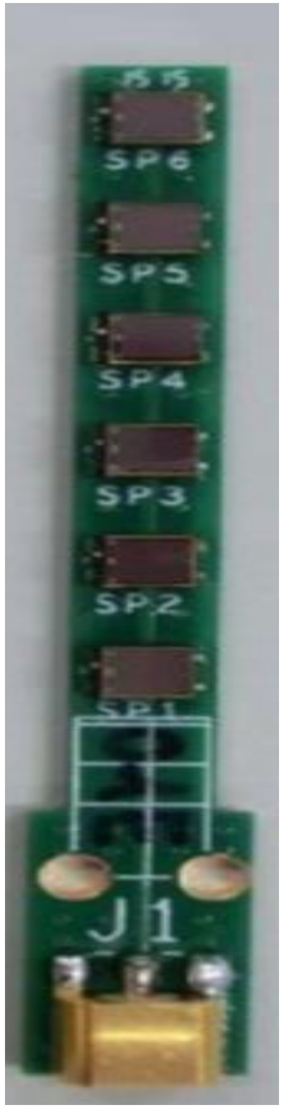
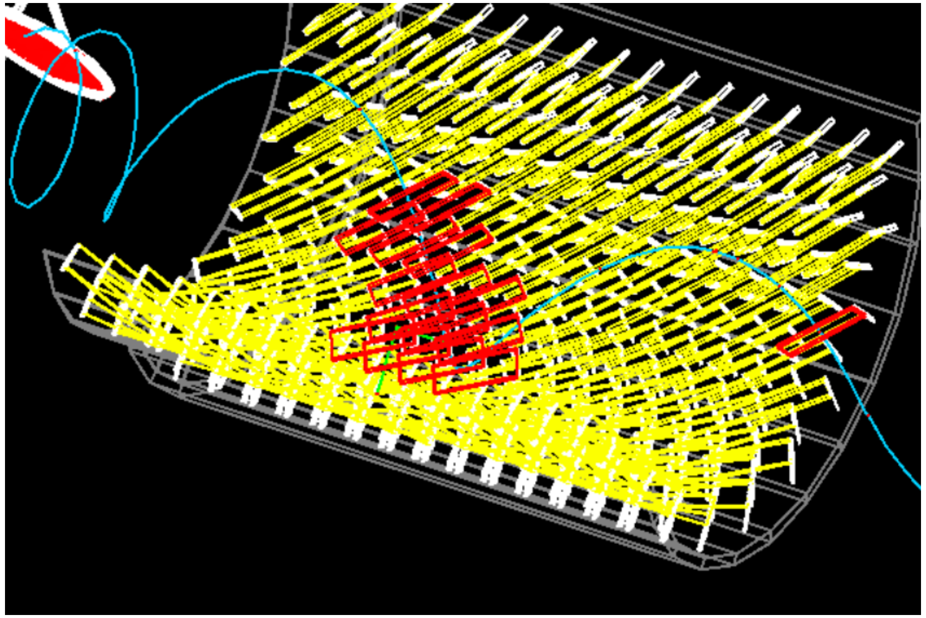
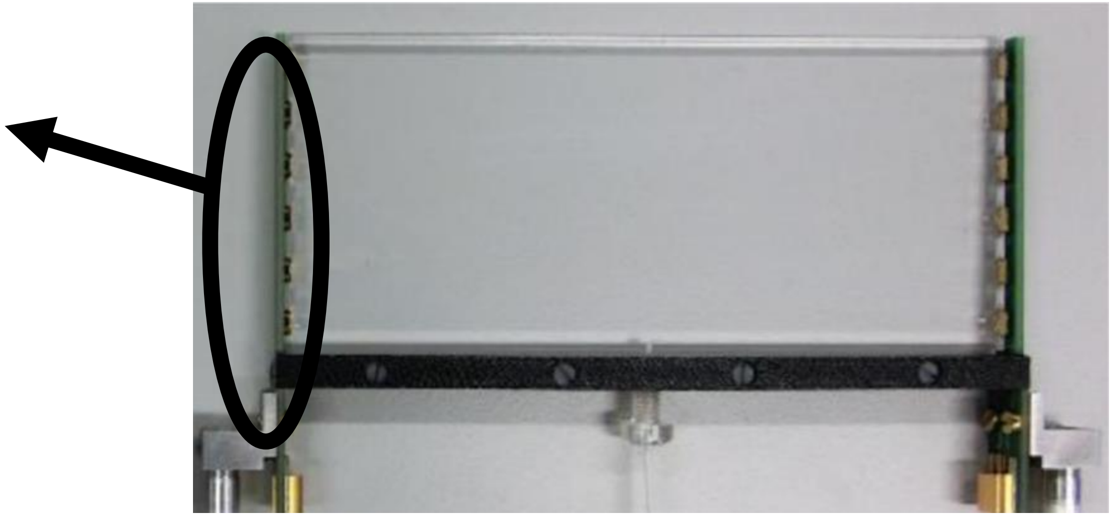
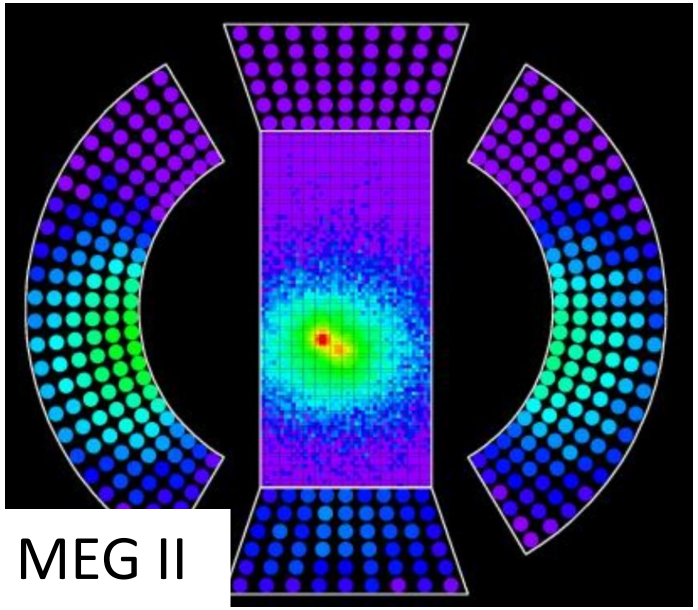




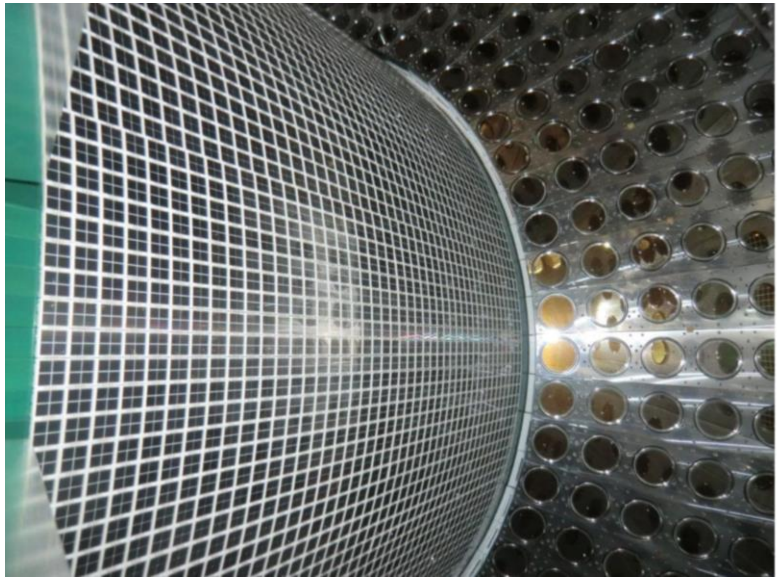


LXe Detector

- One of world's largest liquid Xe detector
- Upgrade: inner face is now covered by 4092 MPPCs (Multi-Pixel Photon Counters)
- Other 5 sides covered by PMT photon counters



Kinematic Core σ	MEG I	MEG II Goal
E_γ (%)	**2.4**	**1.1**
u_γ (mrad)	**5**	**2.6**
v_γ (mrad)	**5**	**2.2**
w_γ (mm)	**6**	**5**
t_γ (ps)	**60**	**60**



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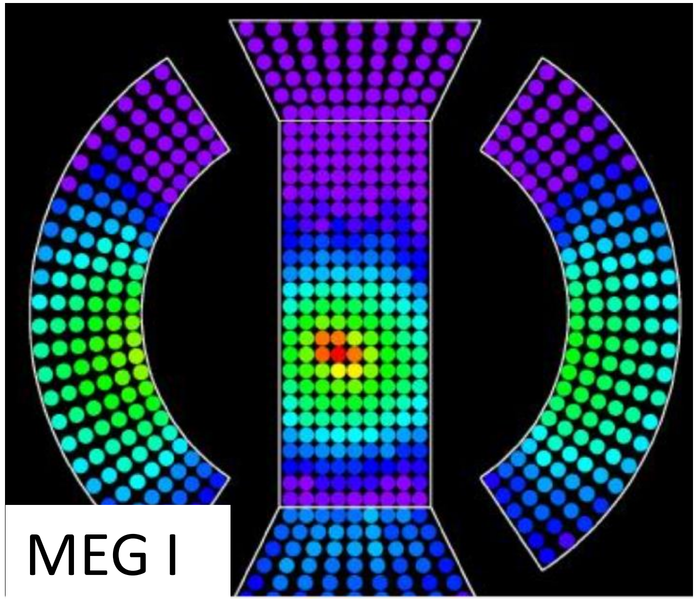

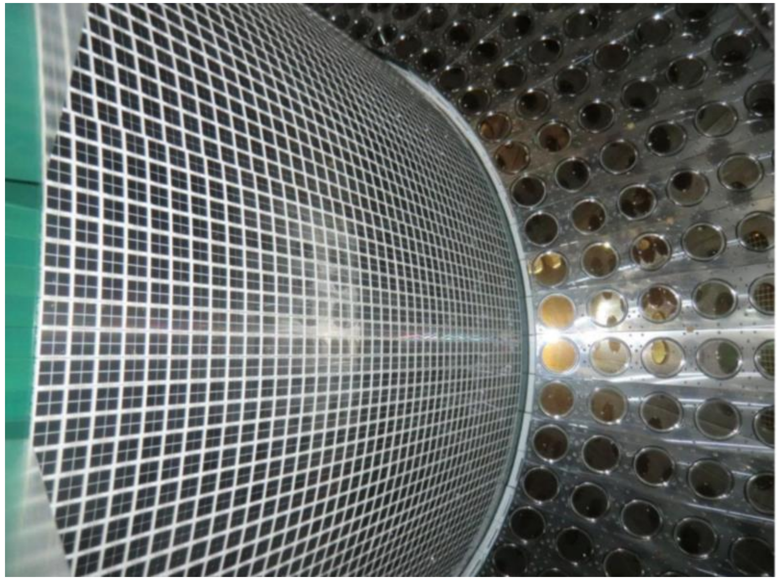

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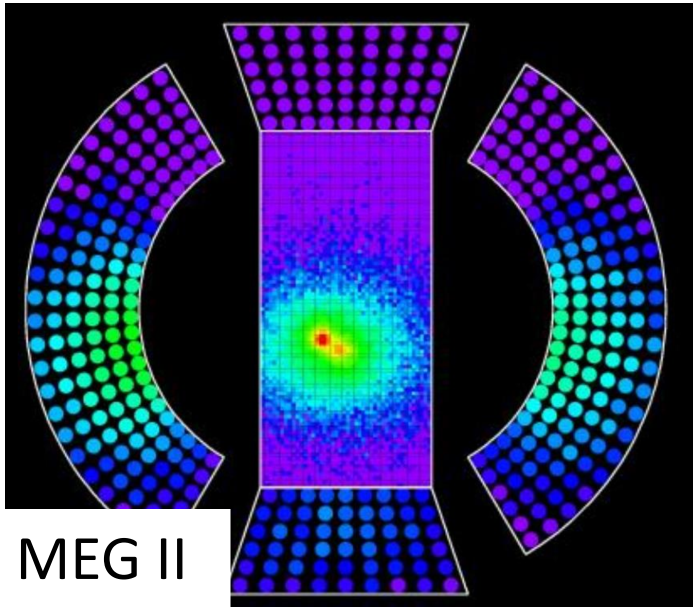

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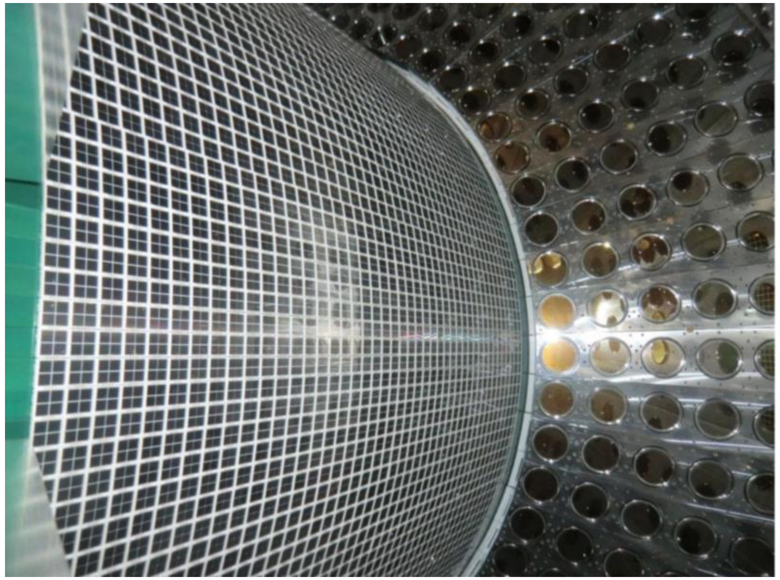
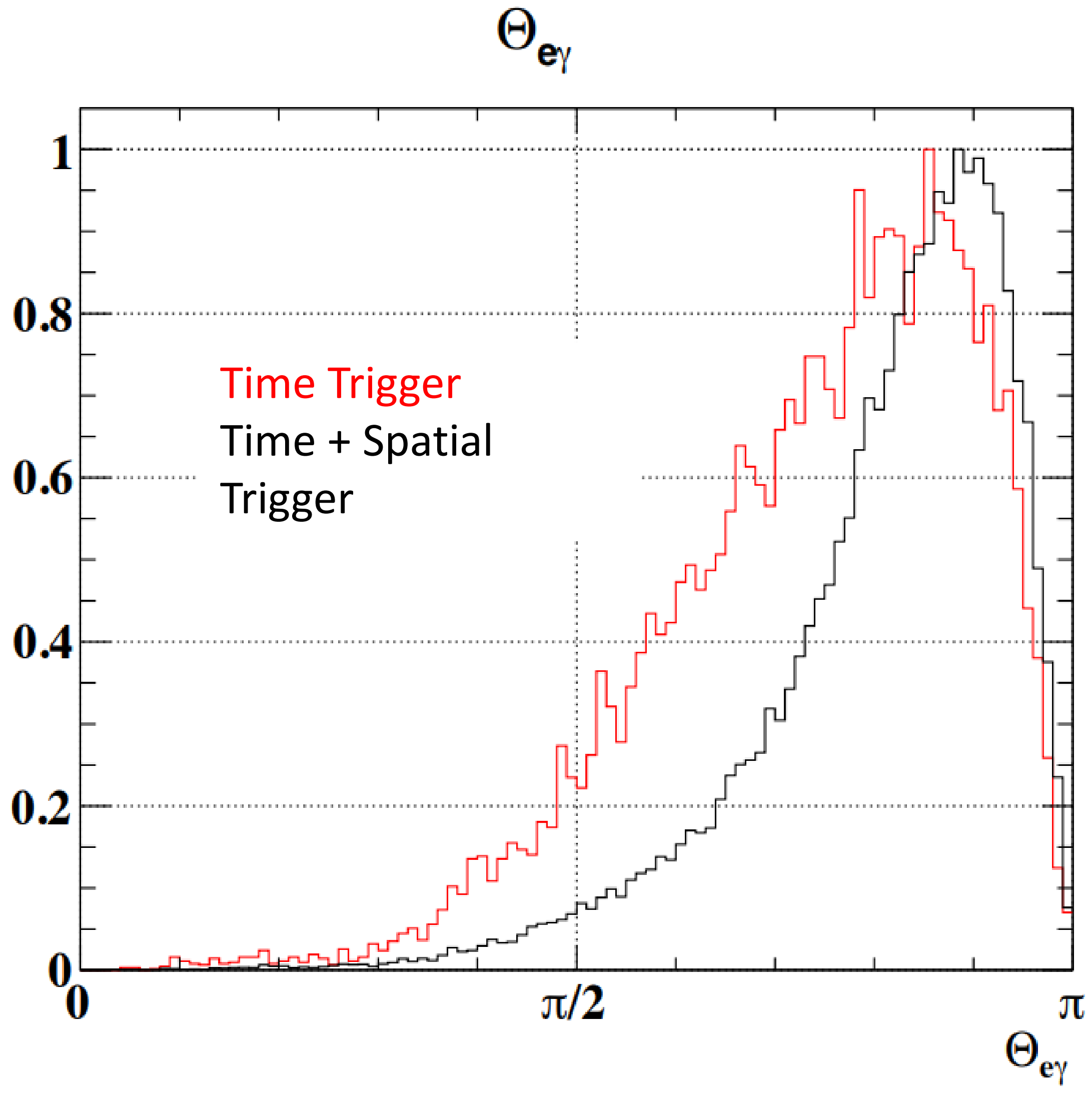


MEG II 2021 Physics Run

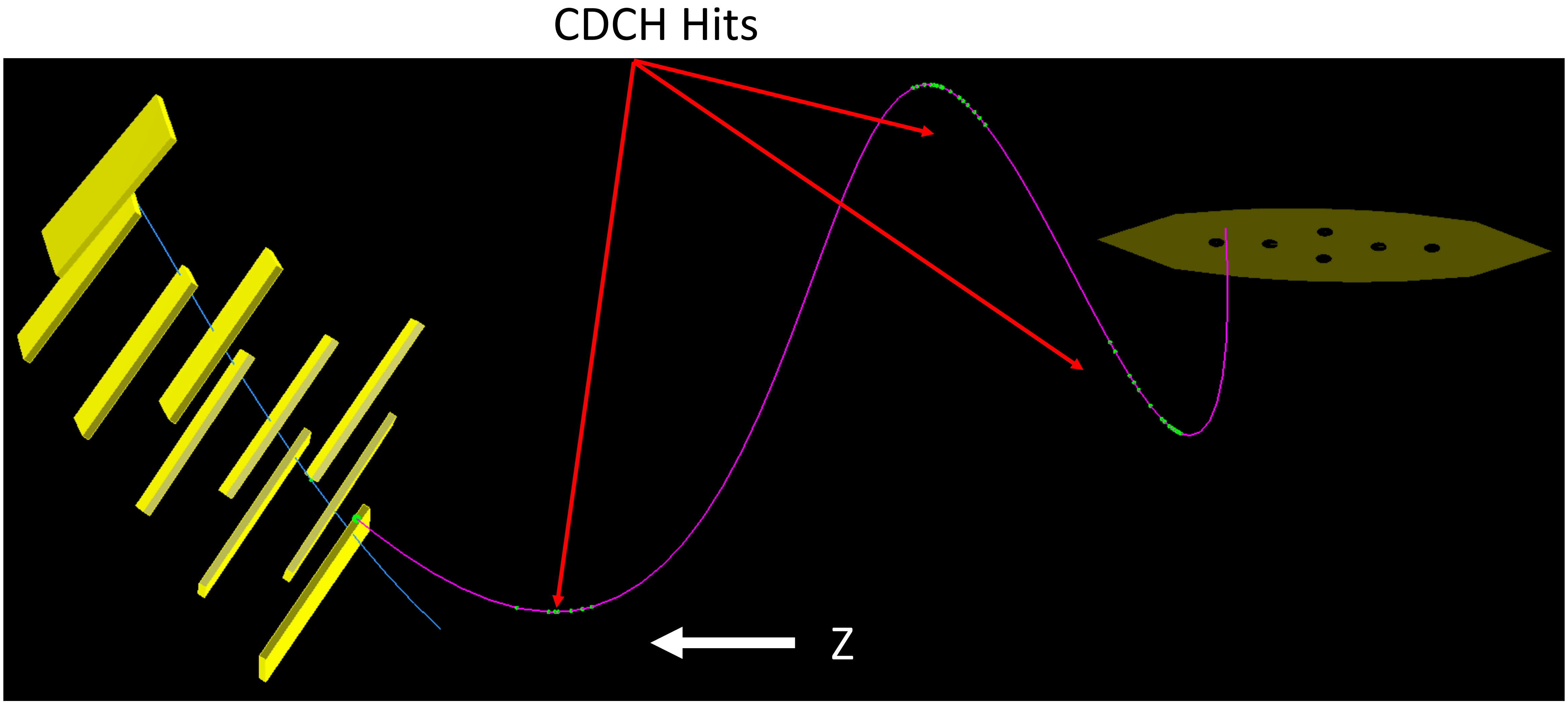
MEG II 2021 Physics Run/Trigger

- First MEG II physics run with a complete set of instrumented electronics
- Dataset:
  - 3.4 M @ $2 * 10^7$ μ/s
  - 8.8 M @ $3 * 10^7$ μ/s
  - 5.7 M @ $4 * 10^7$ μ/s
  - 6.2 M @ $5 * 10^7$ μ/s
  - 24M Total
- Trigger Conditions:
  - LXe $E_\gamma > E_{\text{Threshold}}$ (40-45 MeV)
  - Time Match: pTC/LXe $|T_{e+/\gamma}|$ < 12.5 ns
  - Spatial Match: pTC/LXe based on μ→eγ decays simulated in Geant4



MEG II 2021 Positron Analysis

2021 Positron Tracks



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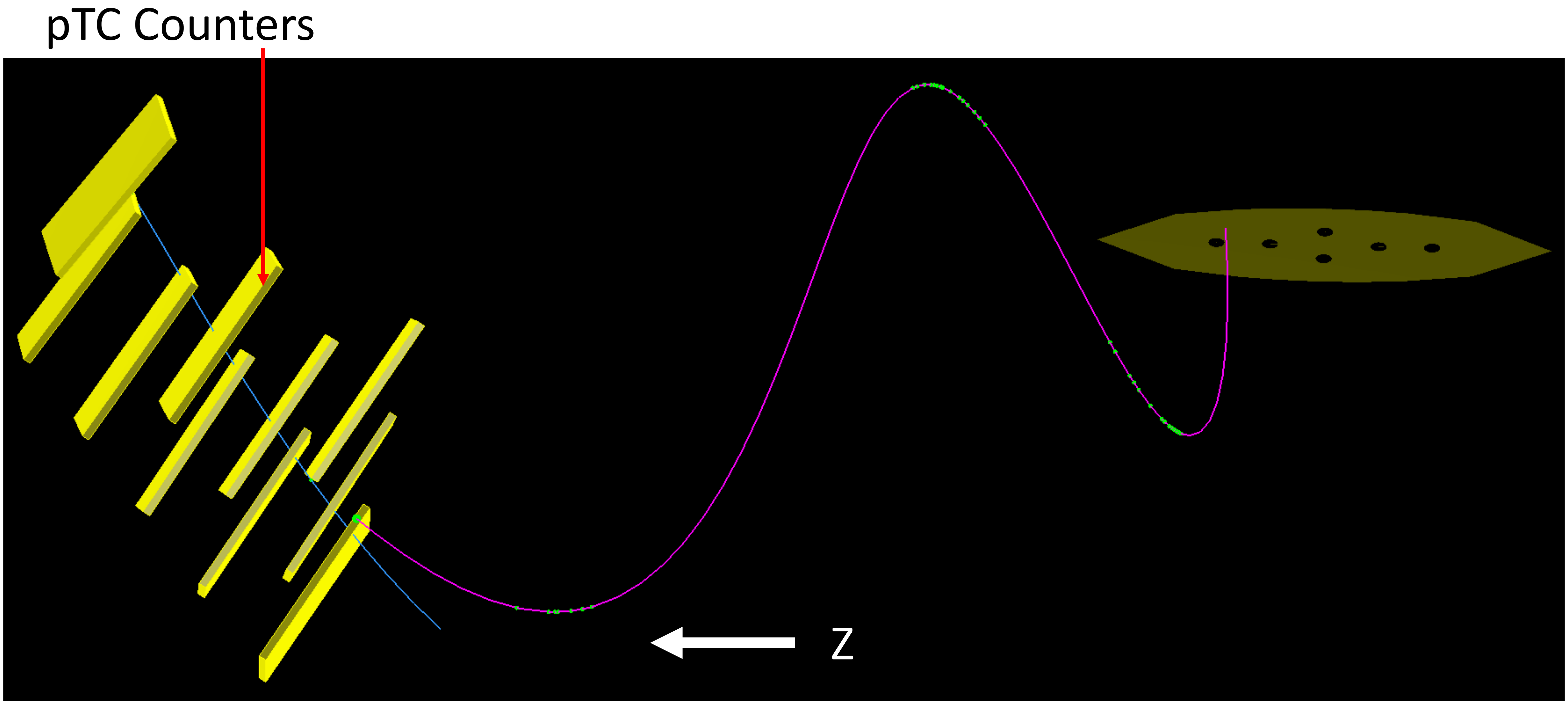
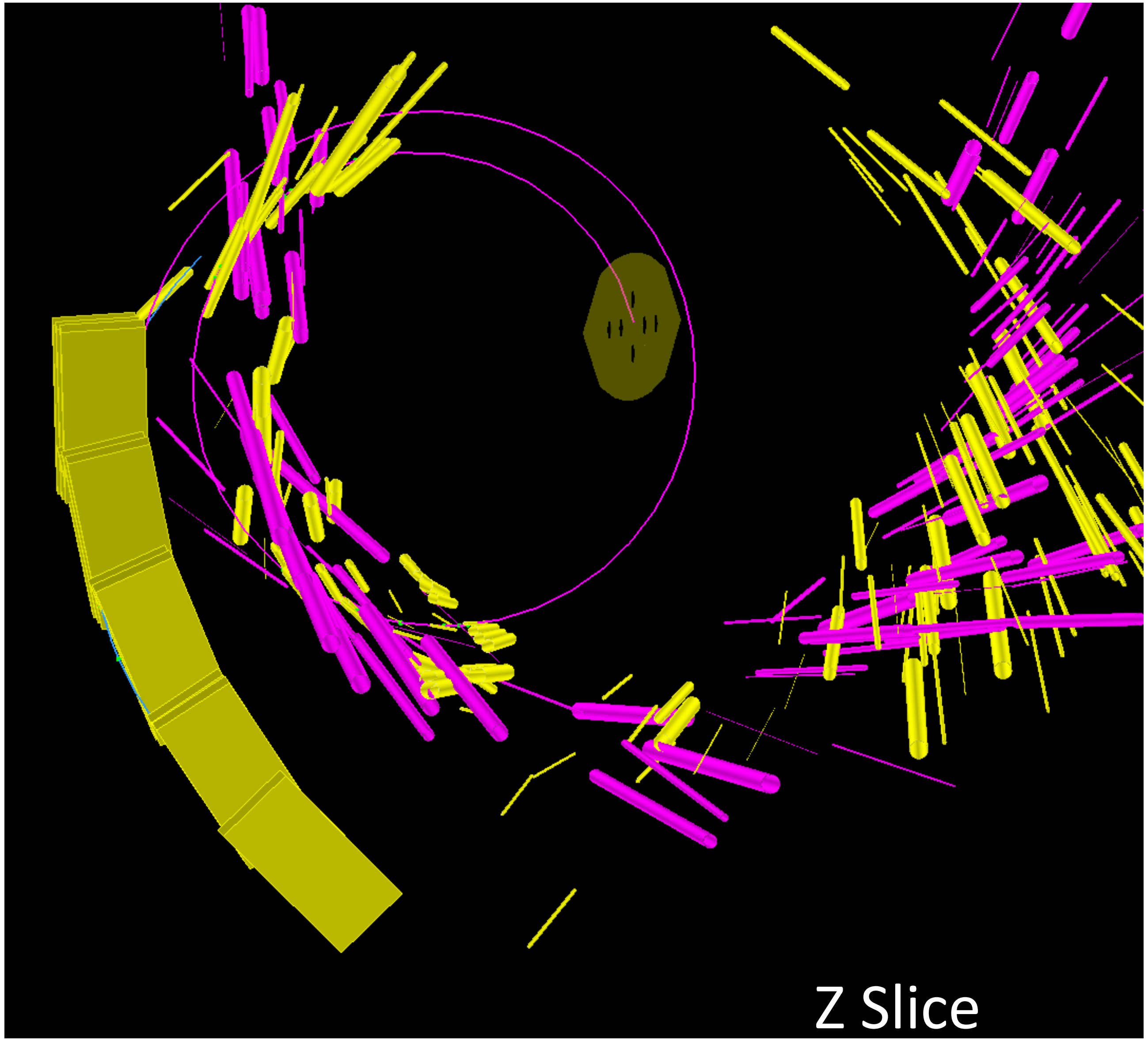
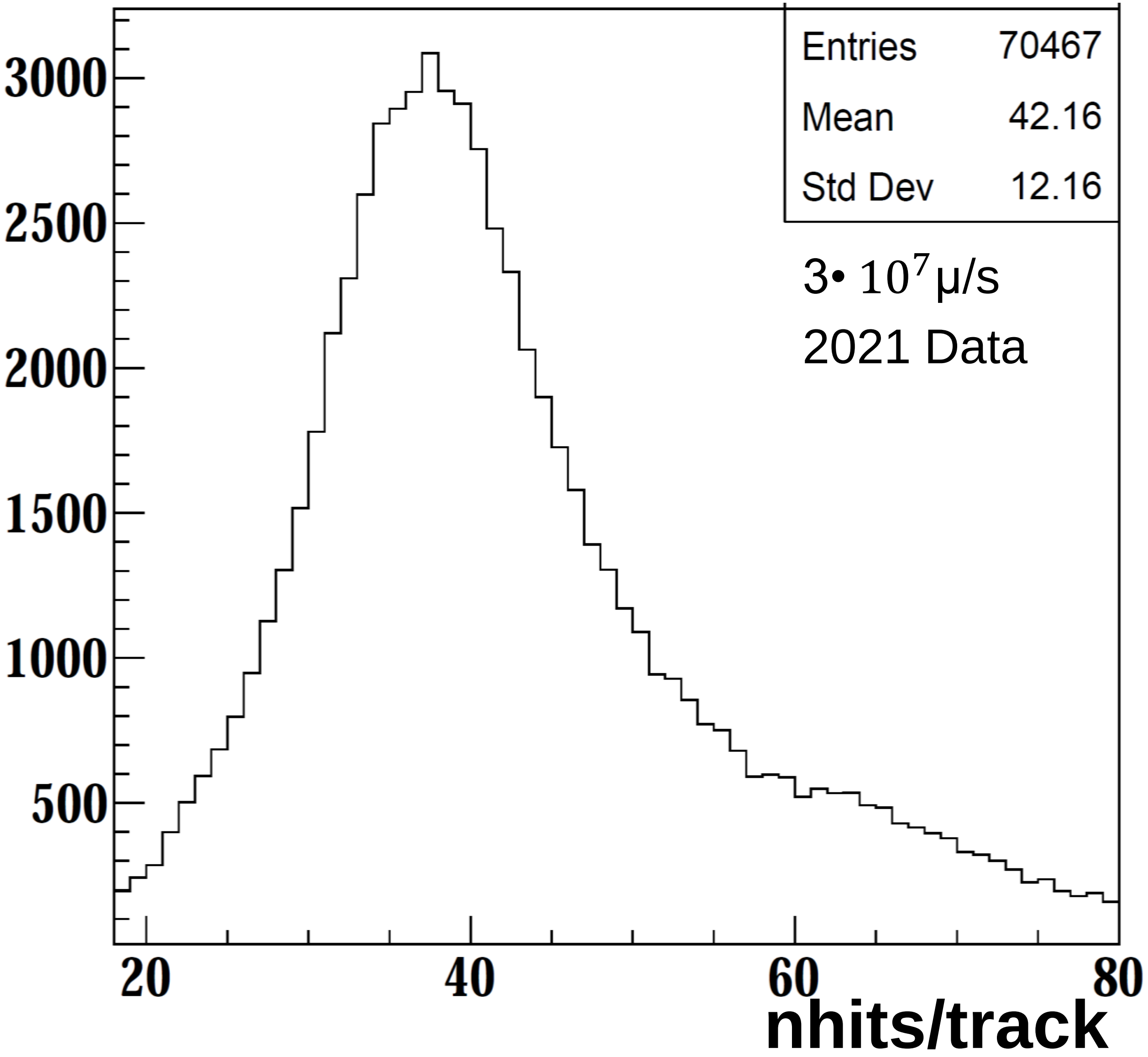


2021 Positron Tracks



2021 CDCH Tracking Status

- On-going work to improve tracking efficiency, **nhits/track**, hit residuals (distance of closest approach/B), etc.
- e.g. CNN (Convolutional Neural Network) model using CDCH digitized voltages to improve DOCA residuals (B)
- Still require optimization of CDCH wire alignment/ optimal magnetic field map



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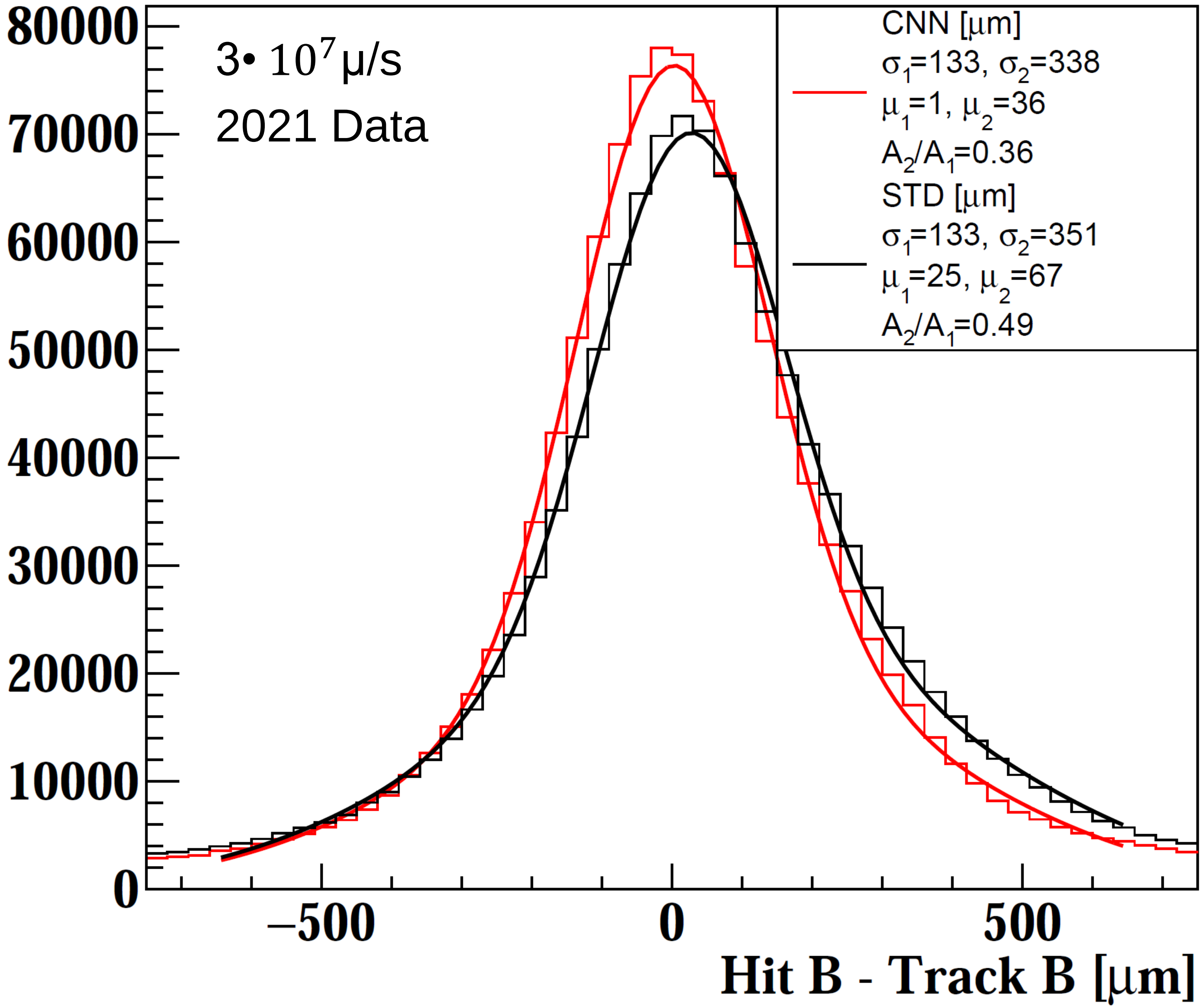
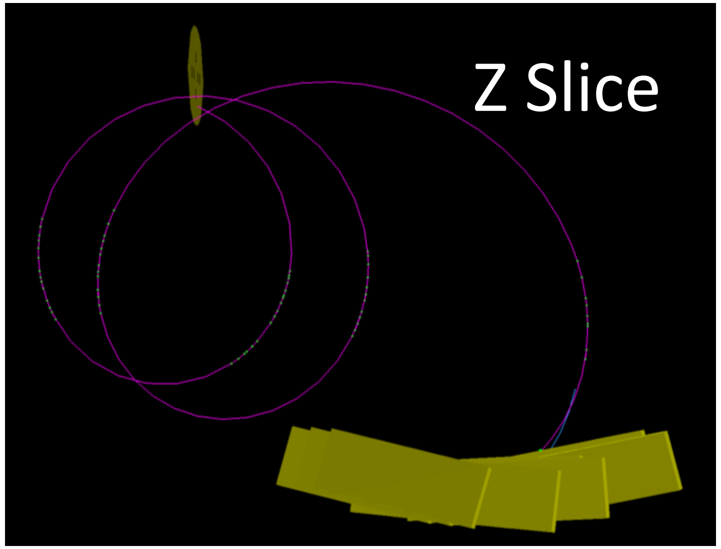
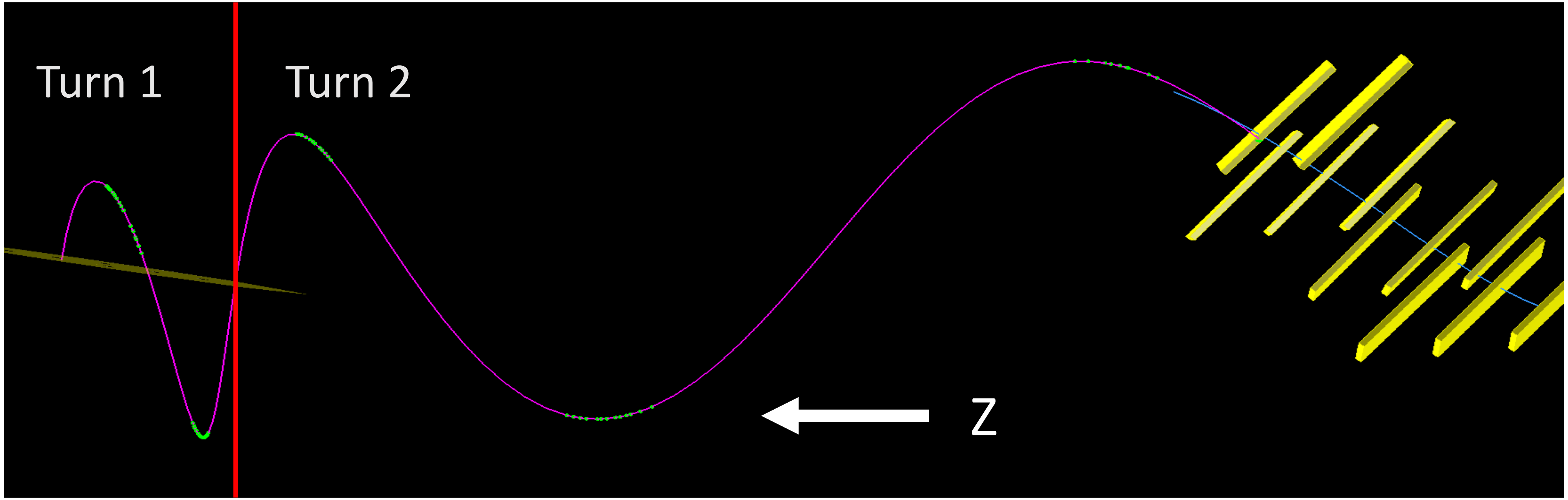


2021 Double Turn Analysis

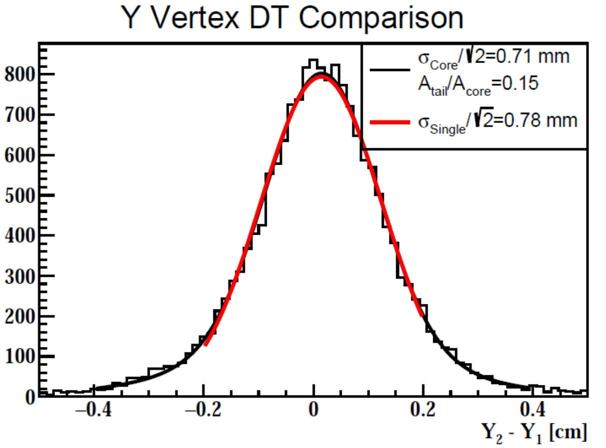
- e.g. data-driven e^+ kinematic resolution estimate compares two independently measured/fit turns on a single e^+ track
- Compare kinematics at a common plane between the turns

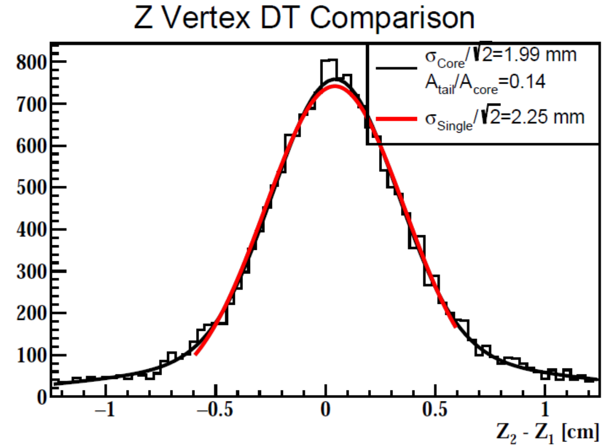


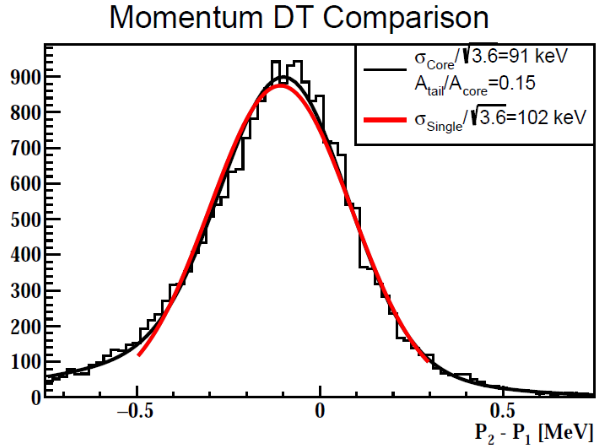


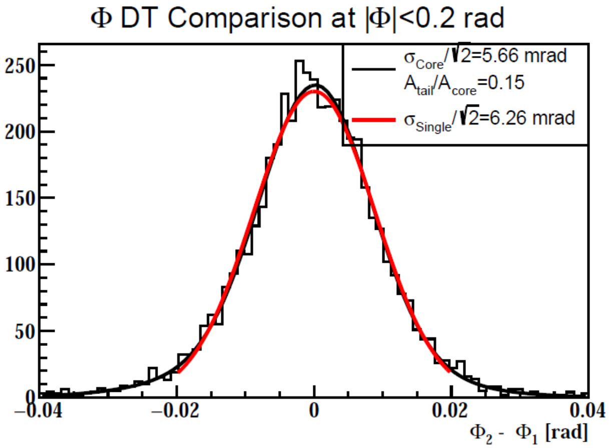
Double Turn Analysis

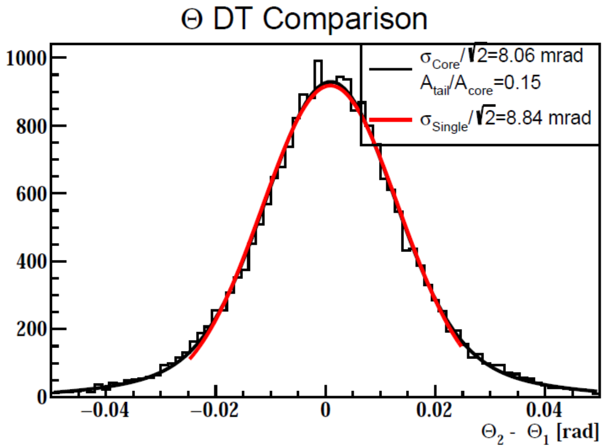
- Turn kinematic comparison at target plane
- $\sigma^2_{\Delta A} = \sigma^2_{Turn\ 2} + \sigma^2_{Turn\ 1}$
- $<P_2\text{-}P_1>\sim$ -100 keV, still under investigation… suspect alignment or magnetic field











ϕ_{e+} estimated at plane perpendicular to track

Double Turn Analysis

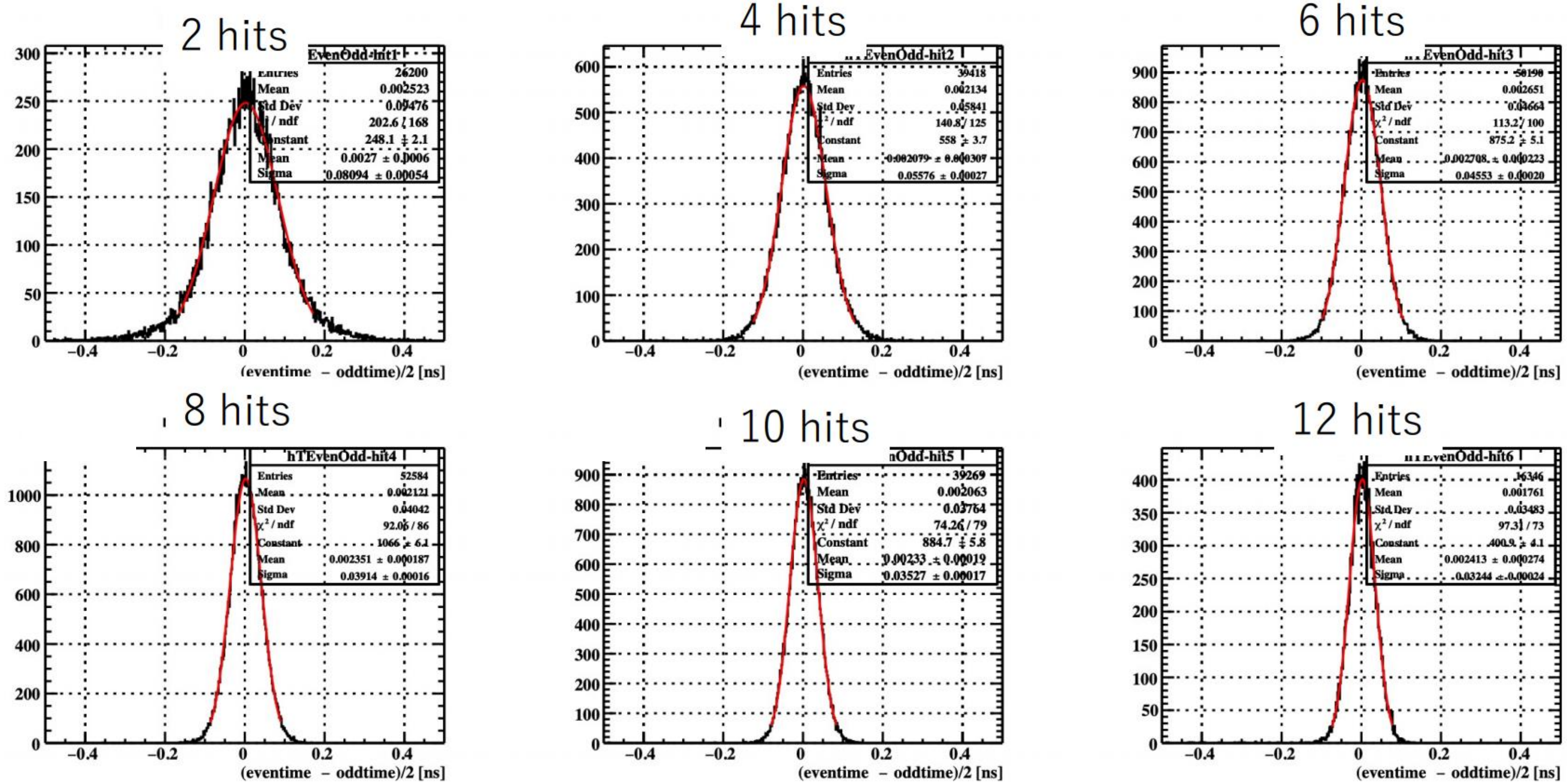
- **Preliminary** double turn (DT) resolution estimates are all improved with respect to MEG I
- Improving single hit resolution, wire alignment, magnetic field map, etc. aim to achieve the MEG II goal resolutions
- *Goal resolutions are based on signal e_+; double turn resolutions are corrected by MC $\sigma_{signal}/\sigma_{michel}$ ratio

			$3 \cdot 10^7 \mu/s$	
Kinematic Resolution	MEG I Core σ	MEG II Goal Core σ	MEG II 2021 Preliminary DT Core σ	MEG II 2021 Preliminary DT Single σ
p_{e_+} (keV)	380	130	94	105
θ_{e+}/φ_{e+} (mrad)	9.4 / 8.7	5.3/ 3.7	7.4/ 5.3	8.1/ 5.9
z_{e+}/y_{e+} (mm)	2.4/ 1.2	1.6/ 0.7	1.9/ 0.7	2.1/ 0.8

φ_{e+} estimated at plane perpendicular to track

2021 pTC Time Resolution

- pTC $\sigma_{t_{e_+}}$ estimated by comparing time of even/odd hits in the same “cluster” of SPX hits
- Signal e_+ <n hits> ~9

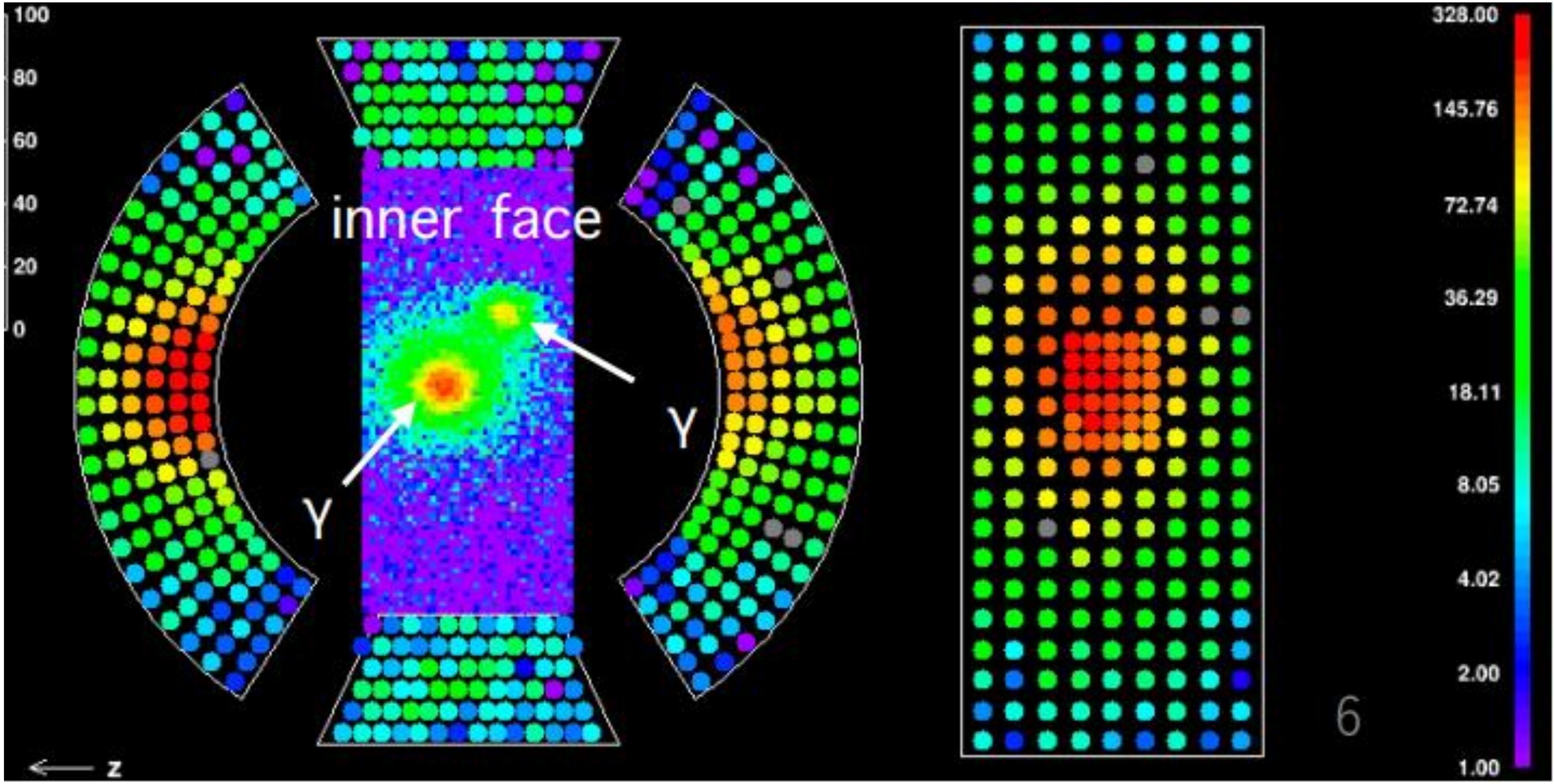


Kinematics/ Core σ	MEG I	MEG II Goal	MEG II Preliminary 2021
t_{e+} (ps)	70	30	35

MEG II 2021 Photon Analysis

Example Pileup Event

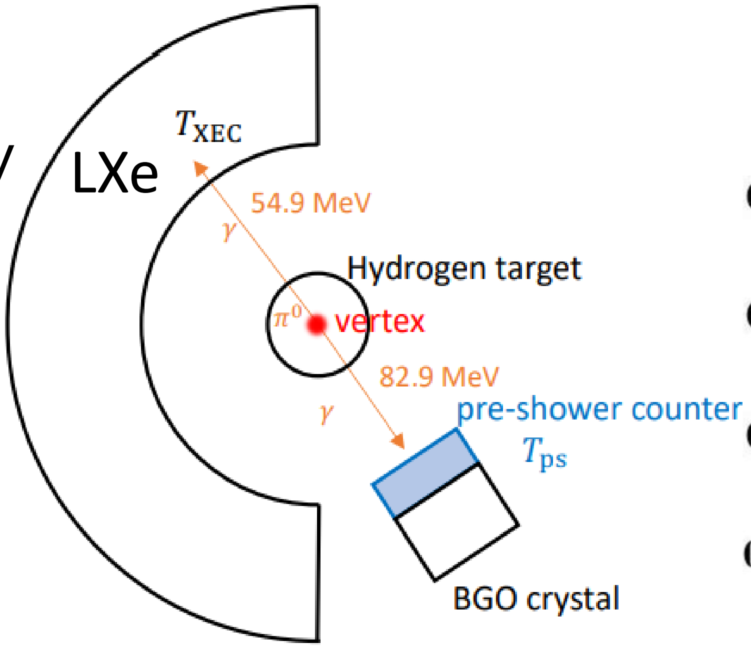
- Image highlights the LXe detector's ability to discriminate between two time-coincident γ using the inner face



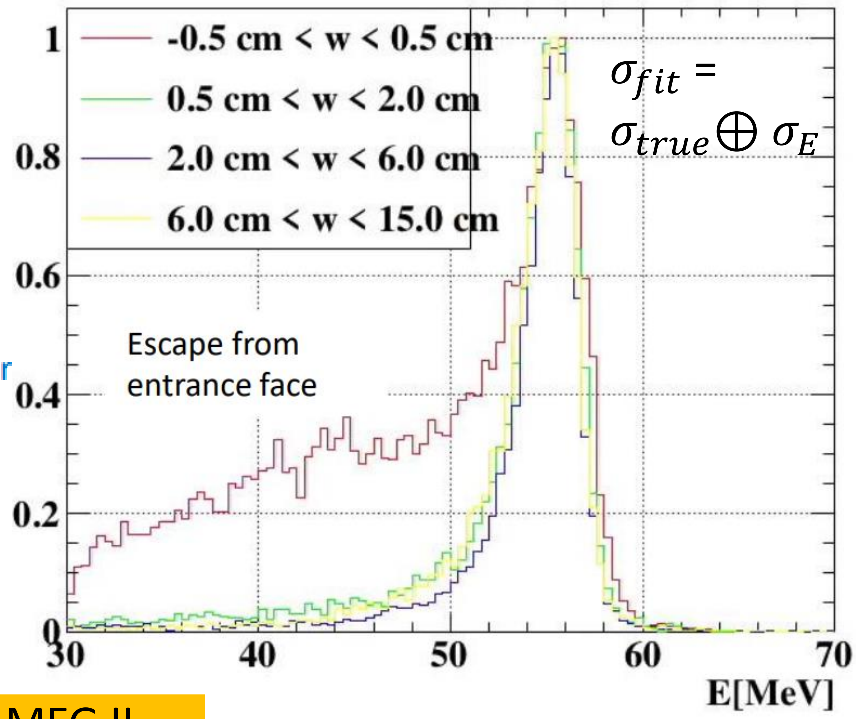
2021 XEC Resolutions

- CEX Reaction:
  - $\pi^- p \rightarrow \pi^0 n;\ \pi^0 \rightarrow \gamma\gamma$
  - $E_\gamma = 0.5 m_{\pi_0}\gamma(1 \pm \beta\cos\theta_{rest})$
  - $\theta_{rest} = 0; \beta \sim 0.2; E_\gamma = 55/83$ MeV
- Separate detector (BGO) selects back-to-back γ pair ($dt_{BGO-LXe}$, E_{BGO}, Opening angle > 170 deg)
- CEX reaction used to
  - Calibrate E_γ, t_γ
  - Estimate σ_{E_γ}, σ_{t_γ}
- Still much ongoing work to calibrate LXe to achieve MEG II goal resolutions

LXe CEX Setup



LXe CEX Energy Distribution with Varying Depth (w)

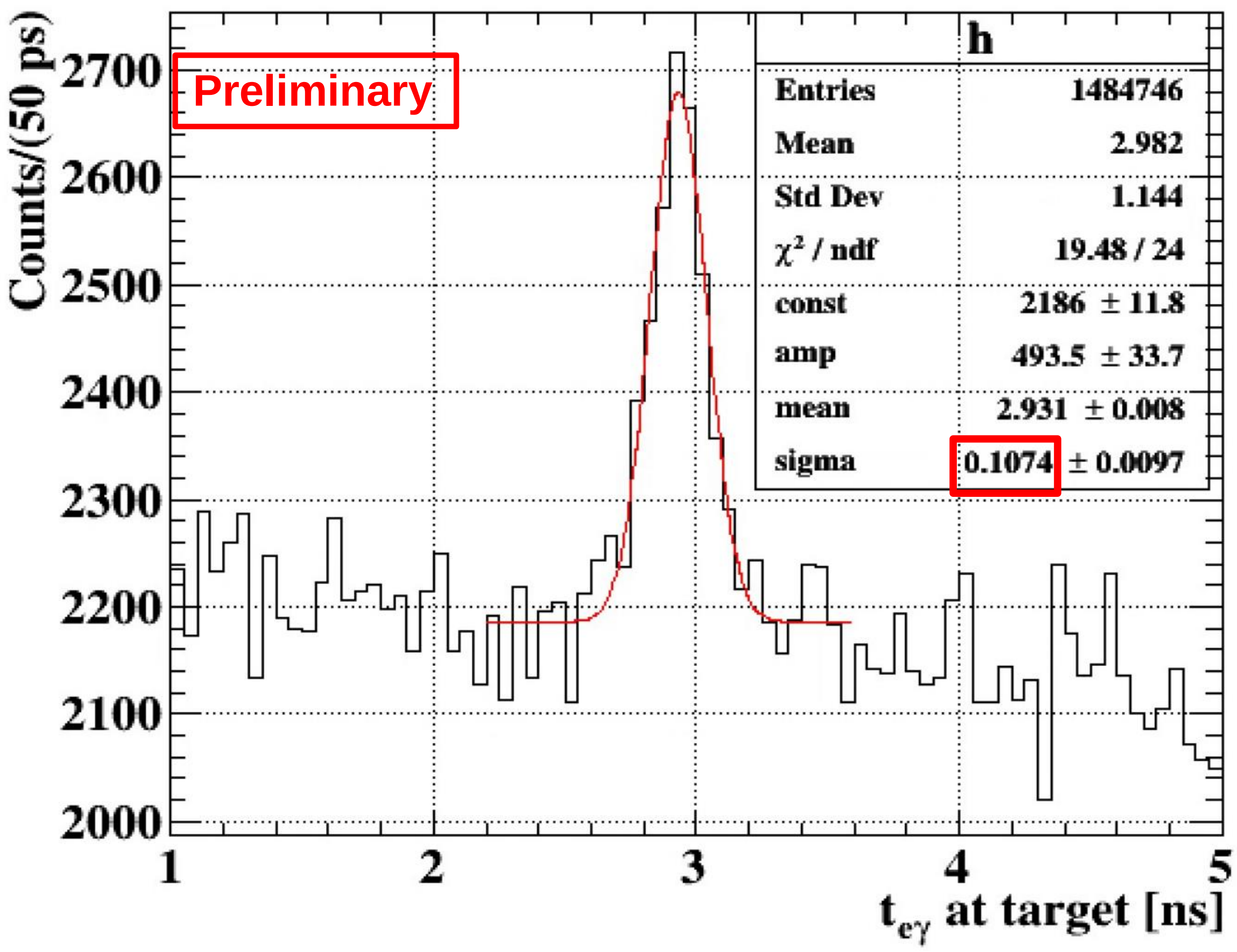


Kinematic Resolution	MEG I	MEG II Goal	MEG II Preliminary 2021
E_γ (%)	2.4	1.1	1.8
t_γ (ps)	60	60	85

2021 RMD Timing Peak

- Use true non-accidental RMD e^+/γ pairs at standard beam intensity to estimate $\sigma_{t_{e^+\gamma}}$~107 ps
- Direct measurement of signal $\sigma_{t_{e^+\gamma}}$ with small corrections (γ energy, number of pTC hits)
- Already improved with respect to MEG I
- Timing calibration/ optimization is still ongoing to improve resolution

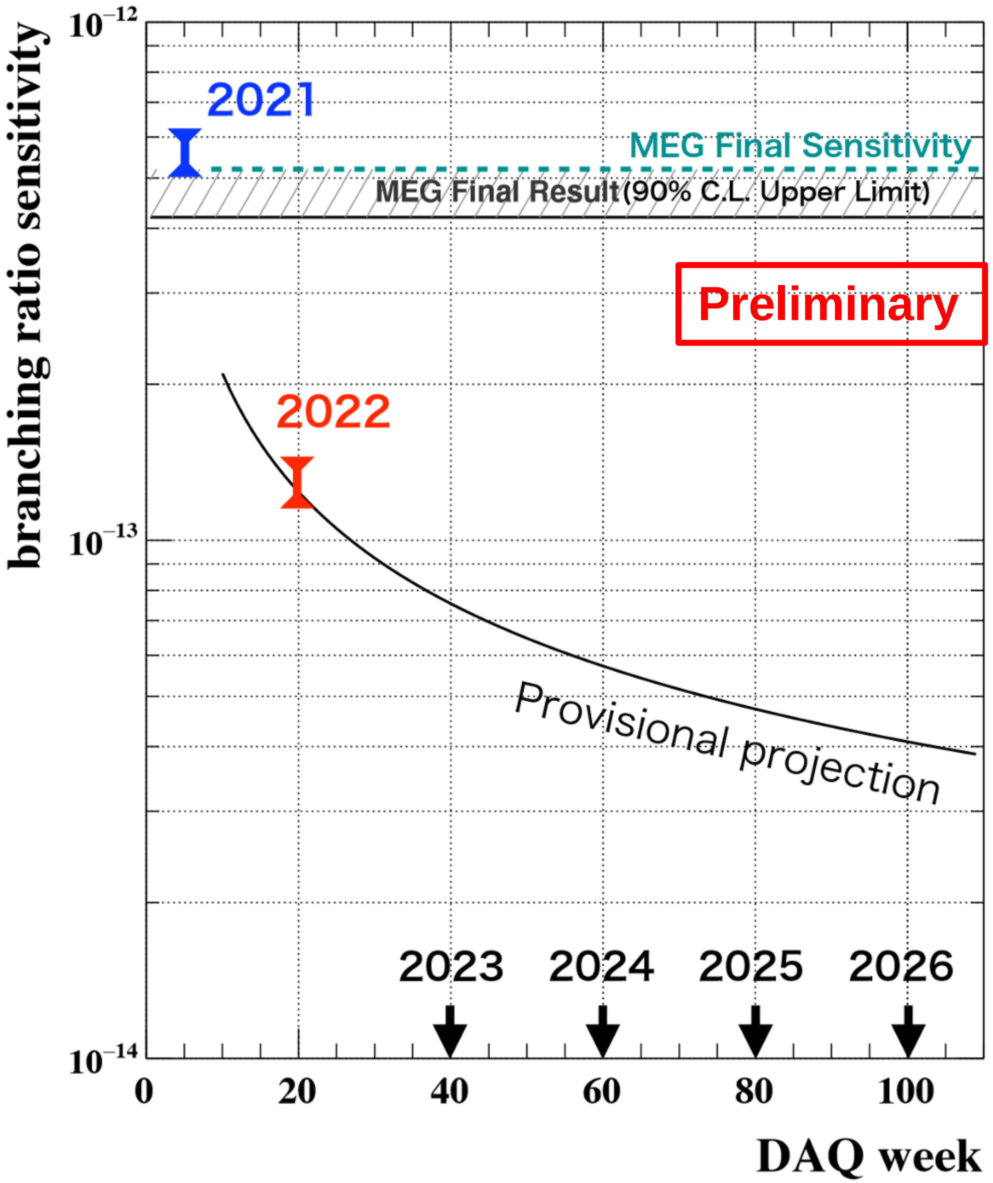
Target $t_{e_+\gamma}$



Preliminary Sensitivity Estimates

- MEG II 2021 dataset expected to approach the sensitivity limit set by MEG I
- MEG II 2021+2022 expected to surpass MEG I by a factor of ~4
- *Sensitivity hasn't yet been updated to reflect updated resolutions

Dataset	Sensitivity (10^{-13})
MEG I Sensitivity	5.3
MEG II Preliminary 2021 Sensitivity Estimate	5.3-6.1
MEG II Preliminary 2021+ 2022 Sensitivity Estimate	1.2−1.4

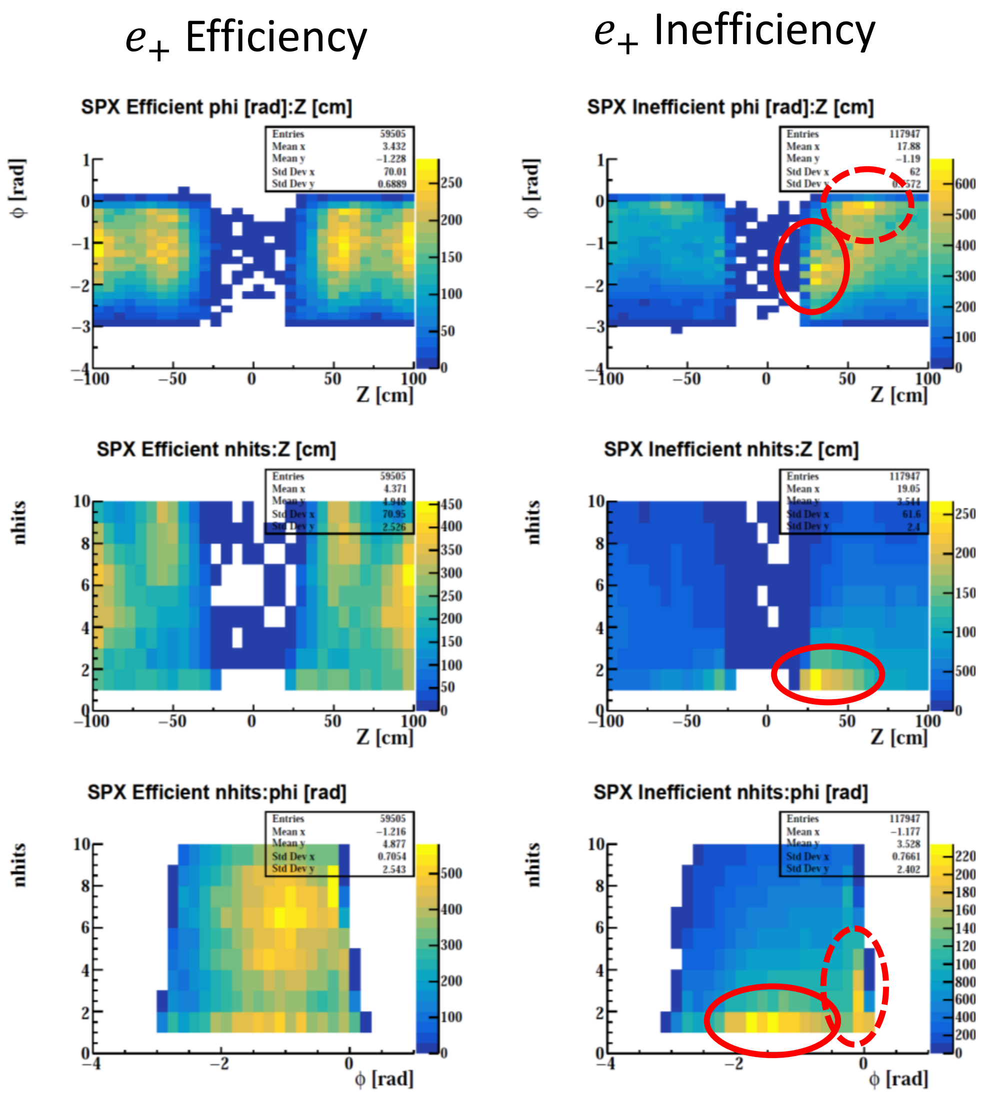


Conclusions

- Much work ongoing to improve detector resolution (CDCH wire alignment, magnetic field, LXe calibration, algorithm optimization, etc.). The mentioned improvements aim to achieve MEG II goal resolutions (some already achieved e.g. $\sigma_{p_{e_+}}$)
- MEG II 2021 dataset expected to approach the $\mu \to e\gamma$ decay sensitivity limit originally set by MEG I
- MEG II 2021+2022 expected to achieve the most stringent limit on the CLFV $\mu \to e\gamma$ decay

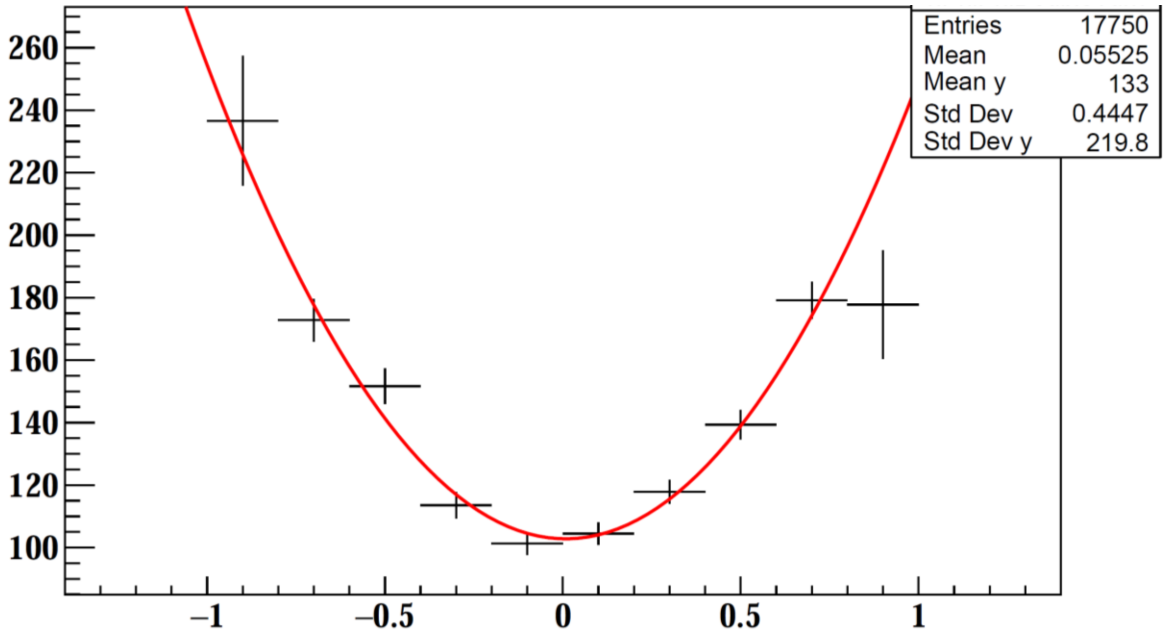
Backup: 2021 Trigger Comment

- Unexpected events cause higher rate of e_+ inefficiency in some phase space regions
- Events cluster into two categories:
  - ~0 < Z < 50 cm, SPX hits <=2
  - ~40< Z < 75 cm, φ ~0 rad
- These inefficient events are not observed in the MC
- Results in a lower “purity” i.e. % events with a reconstructed e_+
- Relevant when discussing the single event sensitivity or the efficiency



Backup: Double Turn Analysis

- σ_φ degraded at large φ
- Track continues propagating (and curving due to B Field);
- Easier to get a larger φ error in case 2
- e.g. energy error causes φ error; magnified by plane !⊥ to track

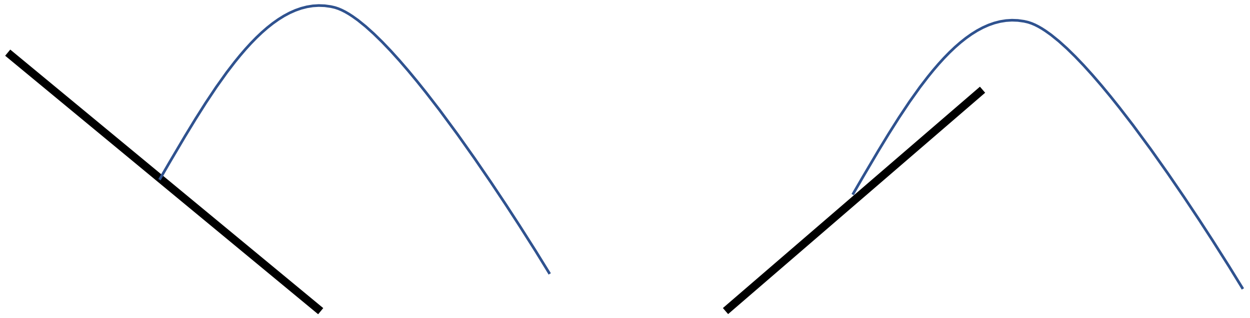


$\langle\varphi_1 - \varphi_0\rangle^2$ [mrad^2]

φ_{e+} [rad]

Case 1

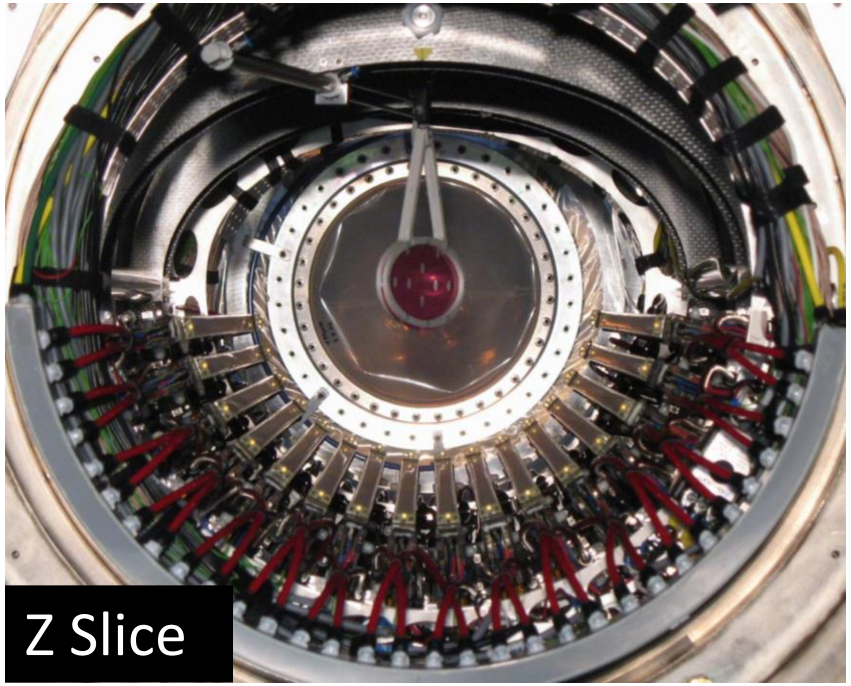
Case 2



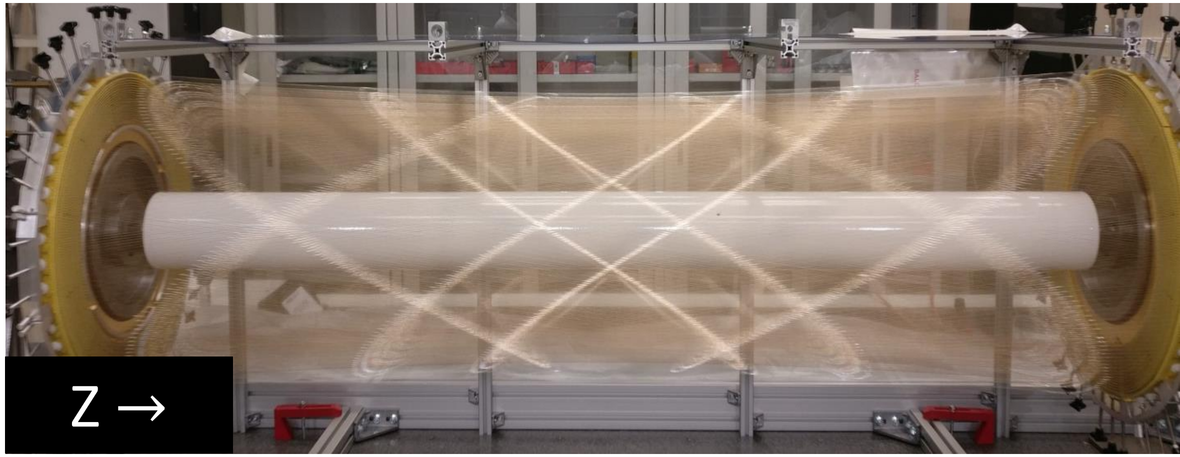
Backup: MEG II Experiment Upgrade

- MEG II upgrade based on MEG I experiment limitations
  - **Ultra-light drift chamber to improve efficiency and resolution**
  - **More track space points in drift chamber to improve e^+resolution**
  - New e^+ timing counter design with higher hit multiplicity to improve e^+ timing
  - Upgraded LXe inner-face with improved granularity for improved γ resolution
  - Higher beam intensity
  - Target position monitoring
  - RMD counter
  - Improved trigger DAQ

MEG I



MEG II



Backup: MEG II Experiment Upgrade

- MEG II upgrade based on MEG I experiment limitations
  - Ultra-light drift chamber to improve efficiency and resolution
  - More track space points in drift chamber to improve e^+resolution
  - **New e^+ timing counter design with higher hit multiplicity to improve e^+ timing**
  - Upgraded LXe inner-face with improved granularity for improved γ resolution
  - Higher beam intensity
  - Target position monitoring
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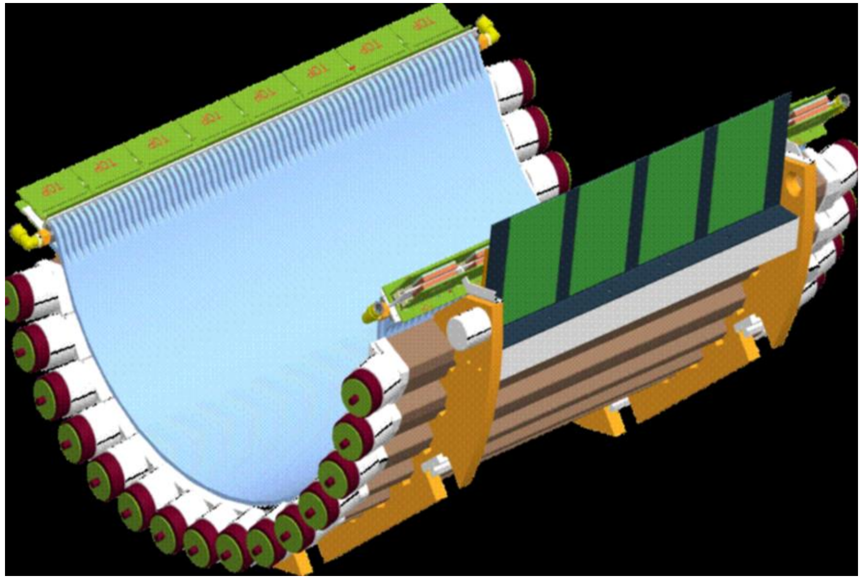
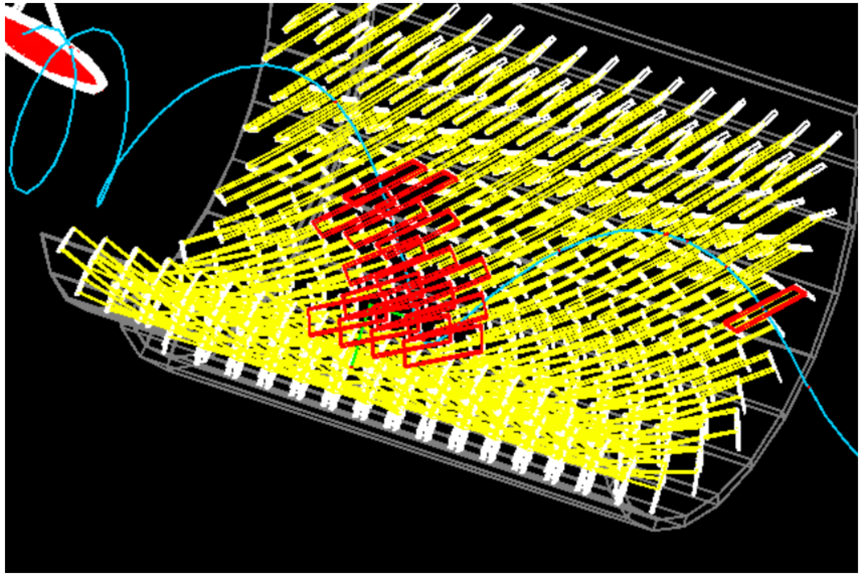


MEG II



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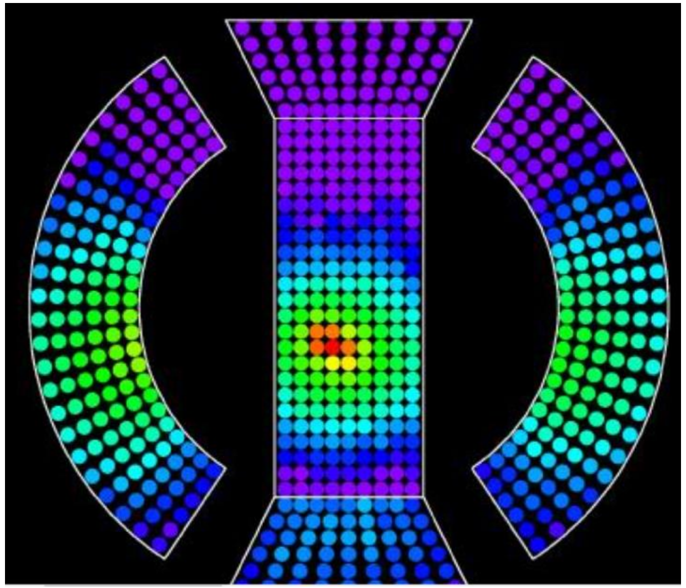
MEG I



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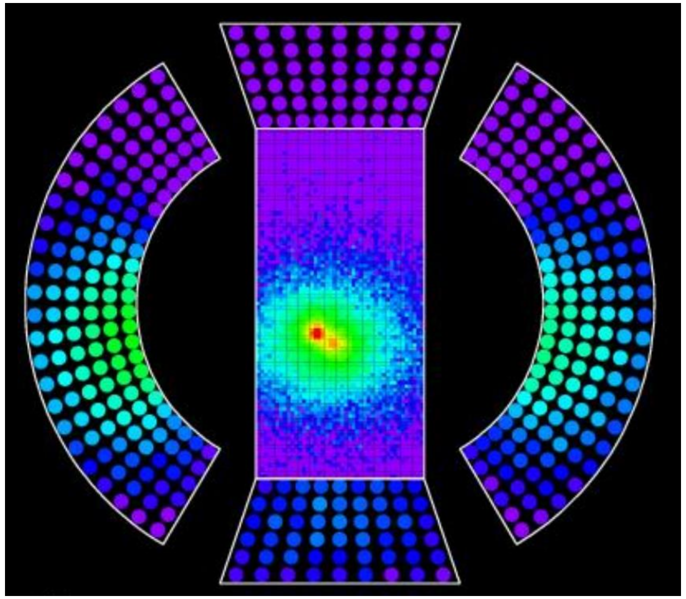
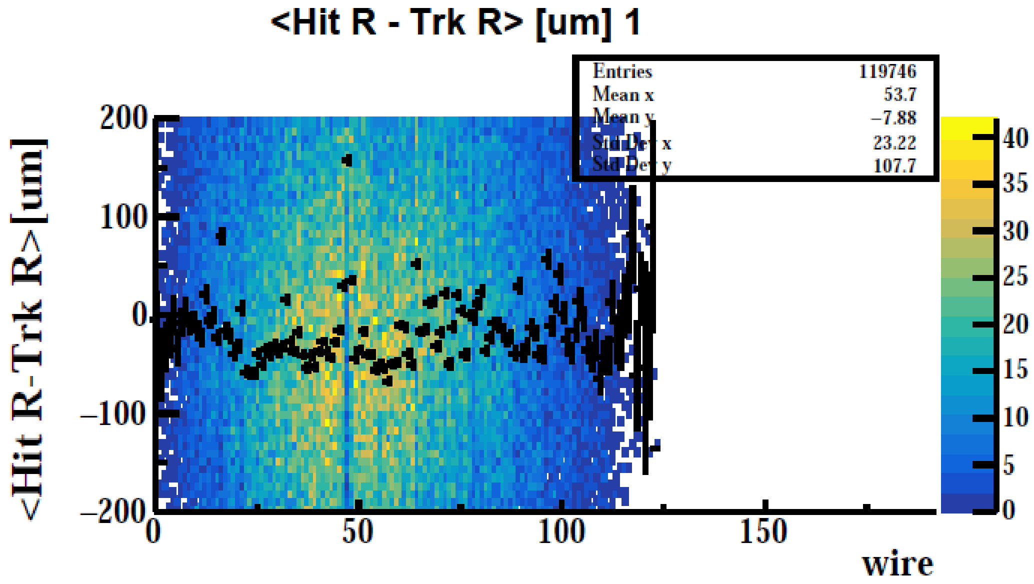
MEG II



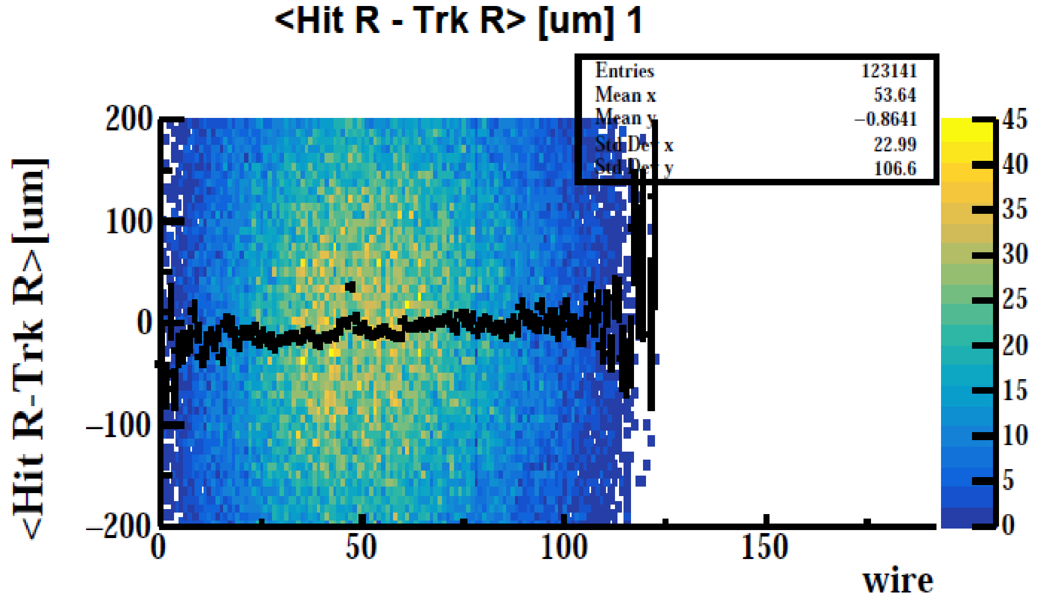
Backup: 2021 CDCH Track Properties

- Preliminary track properties for $3 \cdot 10^{7}$ μ/s
- On-going work to improve tracking efficiency, nhits/track, hit residuals (B), etc.
- e.g. CNN (Convolutional Neural Network) model using CDCH digitized voltages to improve DOCA residuals (B)
- Still require optimized tuning of **CDCH wire alignment**/ improve upon magnetic field map

Survey Alignment



Track-Based Alignment



Backup: Double Turn Analysis Signal/Michel

- Here, we show the ratio of the MC resolutions for signal/Michel e_+
- Fit (Reconstructed - MC) to a single gaussian in a truncated region
- Older analysis code, not as optimized

Kinematic Resolution	MEG II MC Signal/ Michel
p_{e_+} (keV)	1.03
θ_{e+} /φ_{e+} (mrad)	0.92/ 0.94
z_{e+} /y_{e+} (mm)	0.94/ 1.0