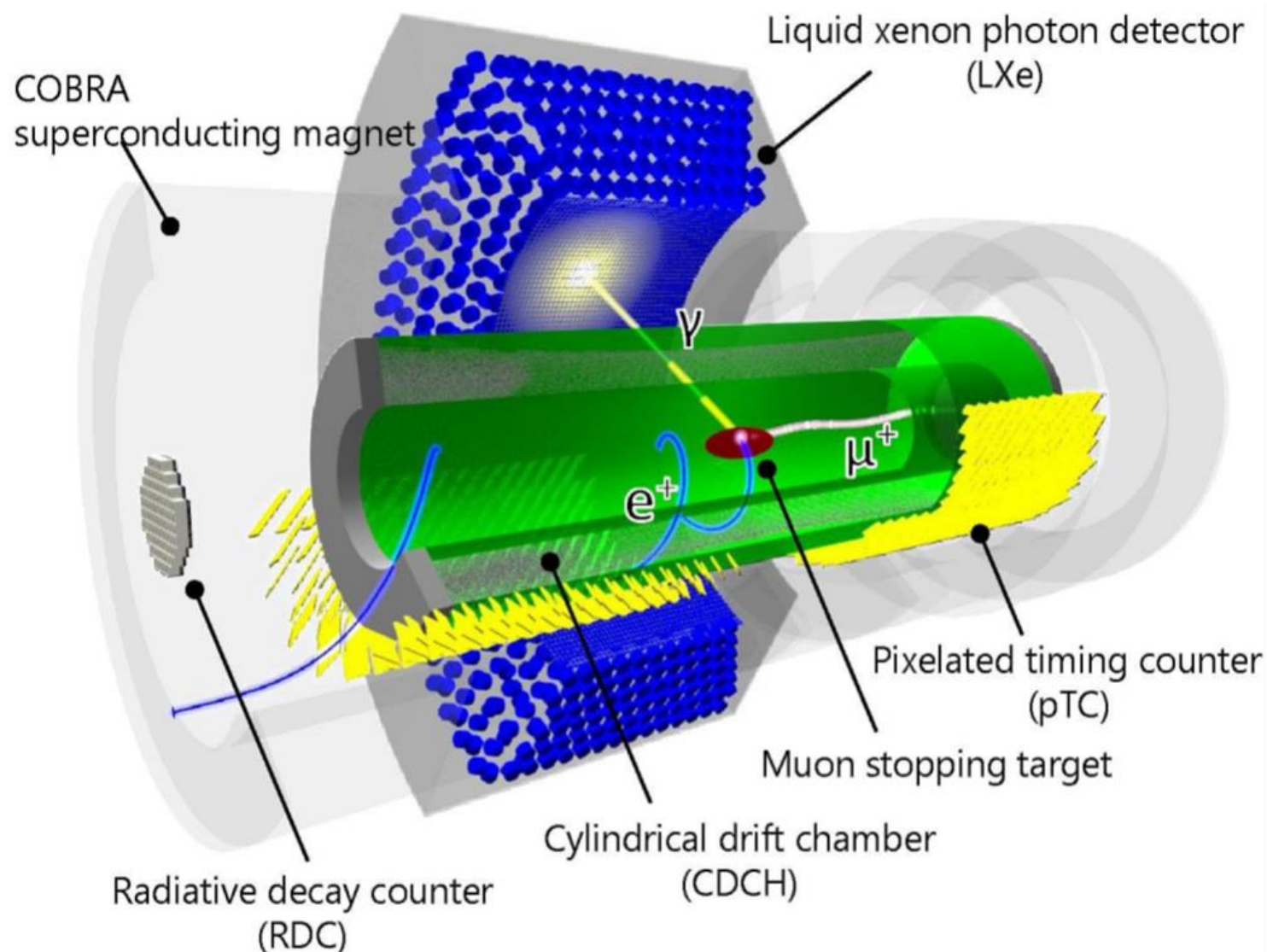




MEG II Experiment: Search for $\mu^+ \rightarrow e^+ \gamma$

Dylan Palo

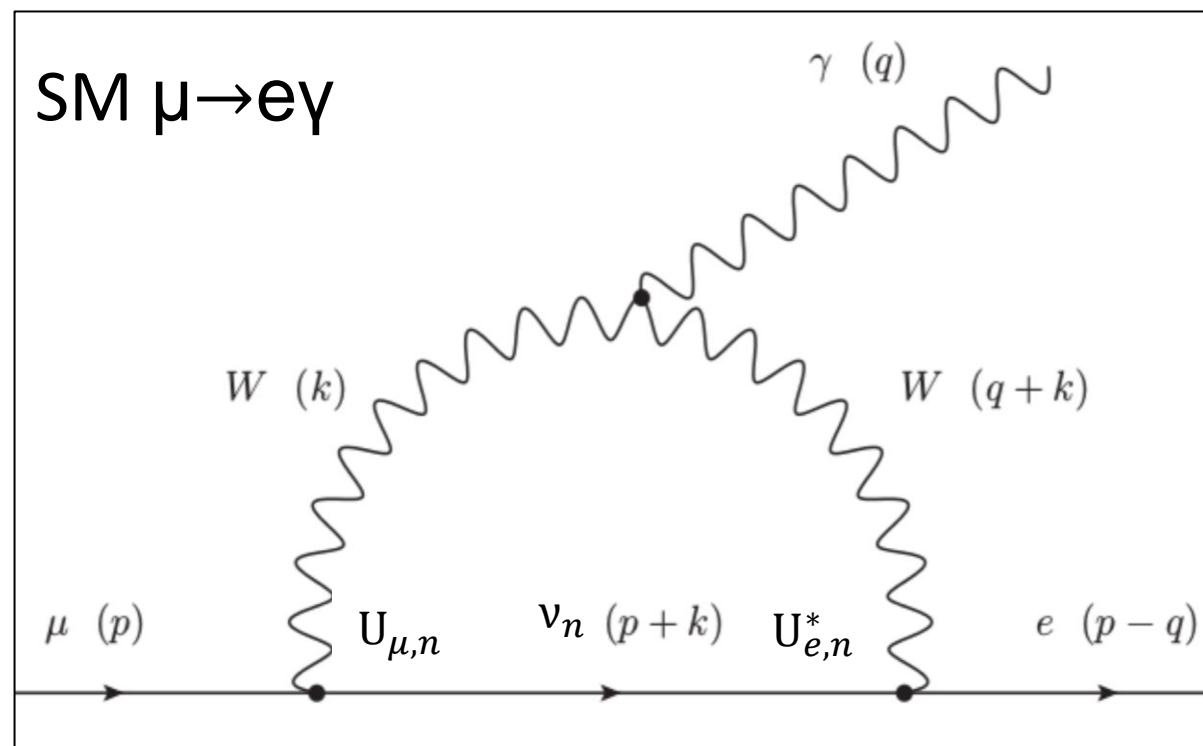
- Goal:
 - Describe the MEG II experimental technique and its data analysis
- Discuss:
 - Charged Lepton Flavor Violation (CLFV)
 - MEG II experimental overview
 - MEG II data analysis



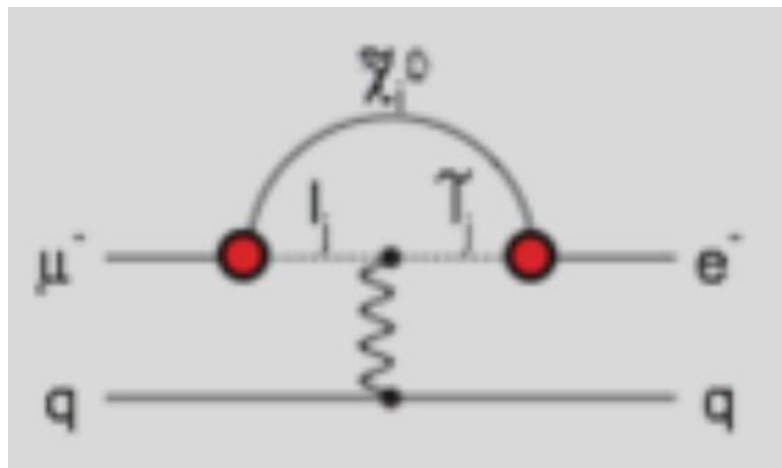


Charged Lepton Flavor Violation

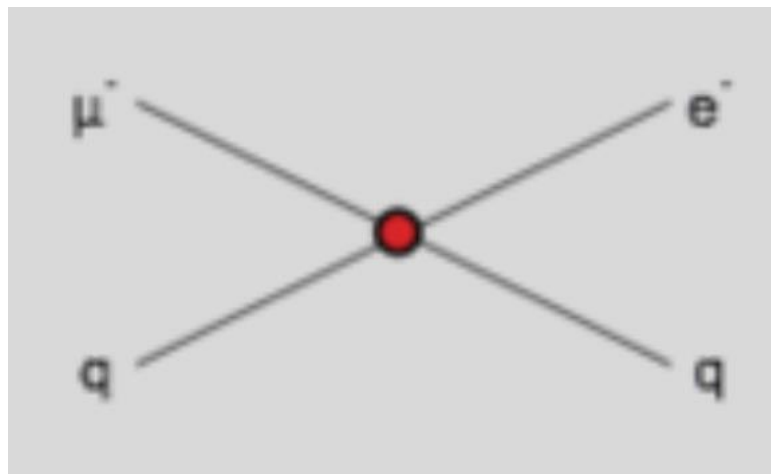
- No instance of charged lepton flavor violation has been observed
- e.g. $\mu \rightarrow e \gamma$ decay:
SM BR is **negligible** $\sim 10^{-54}$; $\propto [\frac{\Delta(m_\nu^2)}{m_W^2}]^2$
- $\mu \rightarrow e \gamma$ observation would be clear sign of new physics
- Many SM extensions allow for other $\mu \rightarrow e \gamma$ decays at significantly higher, detectable rates



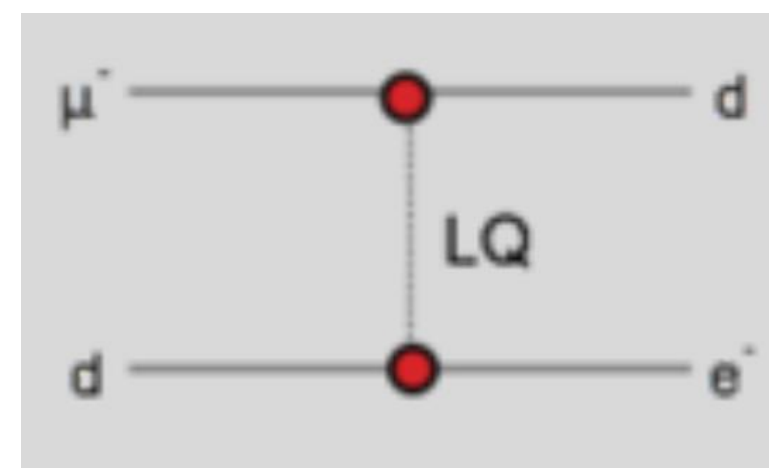
Supersymmetry



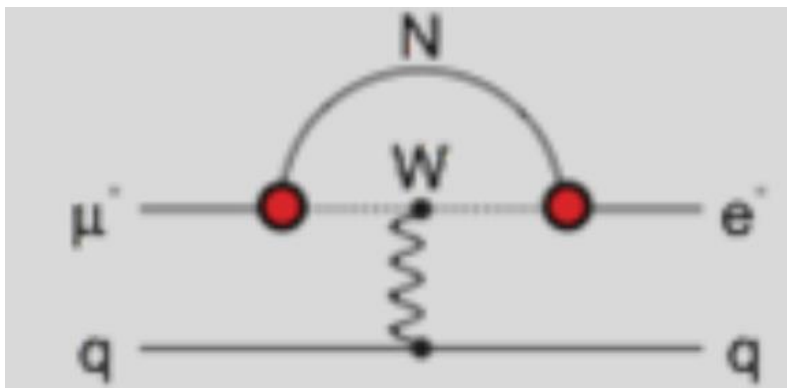
Compositeness



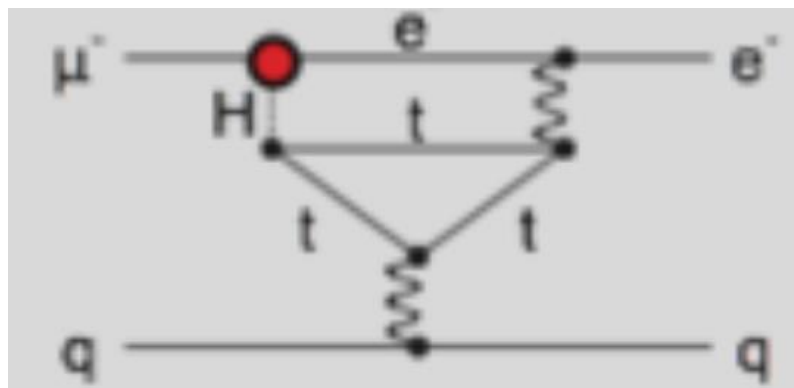
Leptoquark



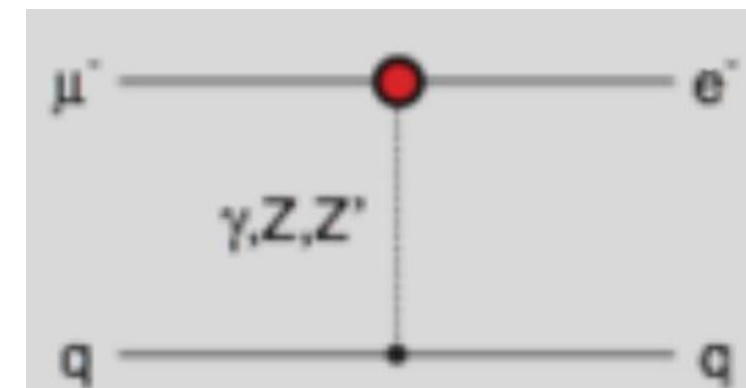
Heavy Neutrinos



Second Higgs Doublet



Heavy Z' Anomal. Z Coupling

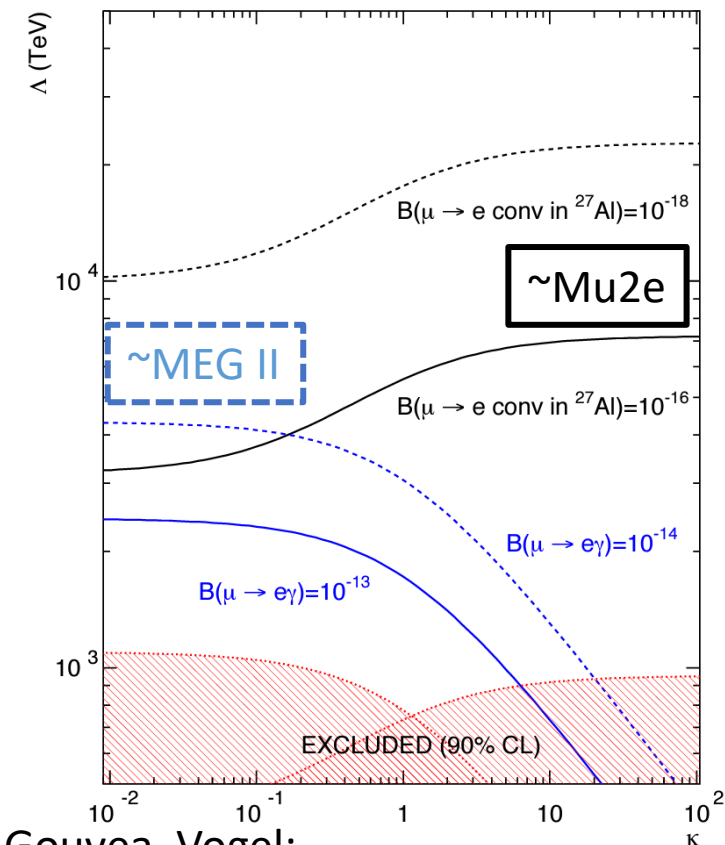


Slide originally by Marciano

- Model-independent effective Lagrangian with two types of theoretical models
- If (e.g. SUSY, $\kappa \ll 1$):

$$\text{BR}(\mu \rightarrow e\gamma) \sim \text{BR}(\mu N \rightarrow e N)/\alpha$$
- If (e.g. leptoquarks, $\kappa \gg 1$):
 $\mu N \rightarrow e N$ at tree level and $\mu \rightarrow e\gamma$ at loop level
- If MEG II sees a signal, likely indicates a signal for Mu2e in $\kappa \ll 1$ space
- Similar relationship between MEG II and Mu3e at PSI

$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + h.c. + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L) + h.c..$$



de Gouvea, Vogel:

<https://doi.org/10.1016/j.pnpnp.2013.03.006>

- The final MEG result cited in ~500 theory papers with >100 in 2022
- The results of MEG II and CLFV experiments in general are strongly motivated by current interest in the theory community

The screenshot shows the INSPIRE HEP website interface. On the left, under the 'Subject' section, 'Phenomenology-HEP' is selected with a red box around it, showing 537 results. Below it, other subjects like 'Experiment-HEP' (117), 'Astrophysics' (30), 'Theory-HEP' (12), etc., are listed. The 'arXiv Category' section shows 'hep-ph' with 524 results. The main content area displays a list of search results, including:

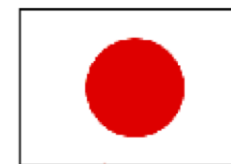
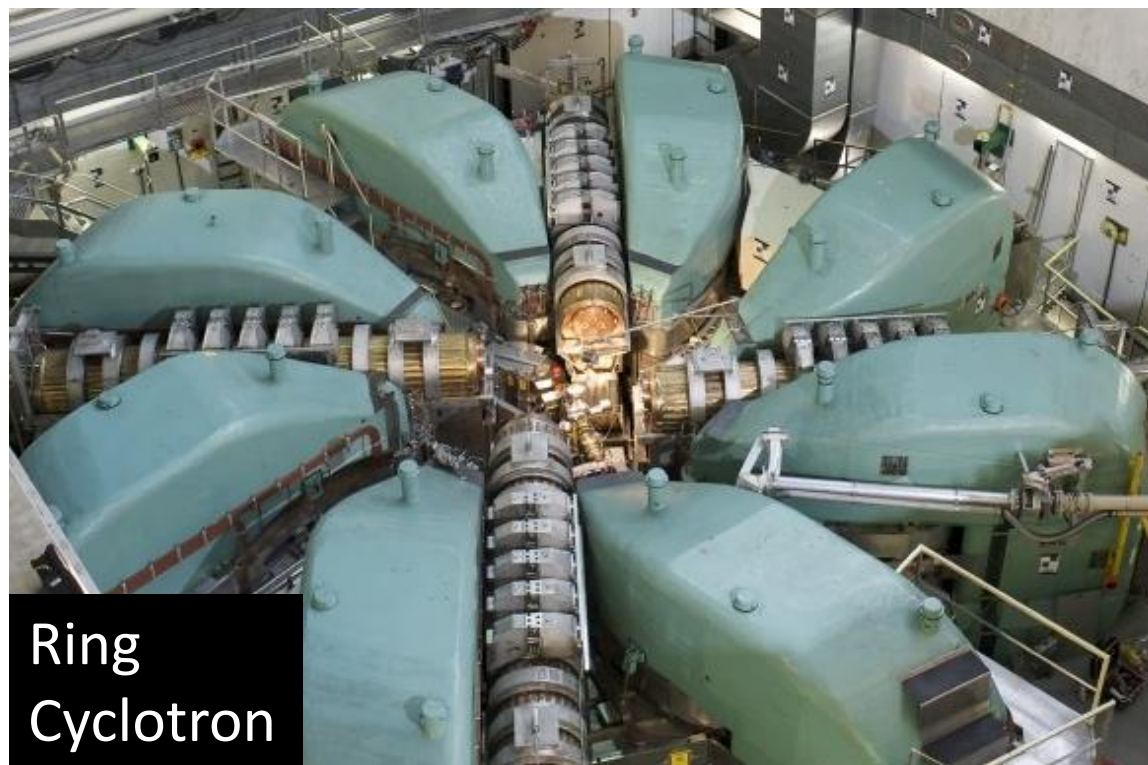
- Indirect upper limits on $\ell_i \rightarrow \ell_j \gamma \gamma$ from $\ell_i \rightarrow \ell_j \gamma$** (#7) by Fabiola Fortuna, Alejandro Ibarra, Xabier Marciano, Marcela Marín, and Pablo Roig (Oct 11, 2022).
- Lepton Flavour Violation tests of Type II Seesaw Leptogenesis** (#8) by N.D. Barrie, S.T. Petcov, and others (Oct 5, 2022).
- Type II Dirac seesaw portal to the mirror sector: Connecting neutrino masses and a solution to the strong CP problem** (#9) by Maximilian Berbig (Sep 28, 2022).
- Relic challenges for vector-like fermions as connectors to a dark sector** (#10) by Alexandre Carvunis, Navin McGinnis, and David E. Morrissey (Sep 28, 2022).
- A two-component vector WIMP — fermion FIMP dark matter model with an extended seesaw mechanism** (#11) by Francesco Costa, Sarif Khan, and Jinsu Kim (Sep 27, 2022).



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:
Stop rate $\approx 7 \times 10^7$ Hz,
28 MeV muons



UTokyo
KEK
Kobe



INFN Genoa
INFN Lecce
INFN Pavia
INFN Pisa
INFN Roma



UC Irvine

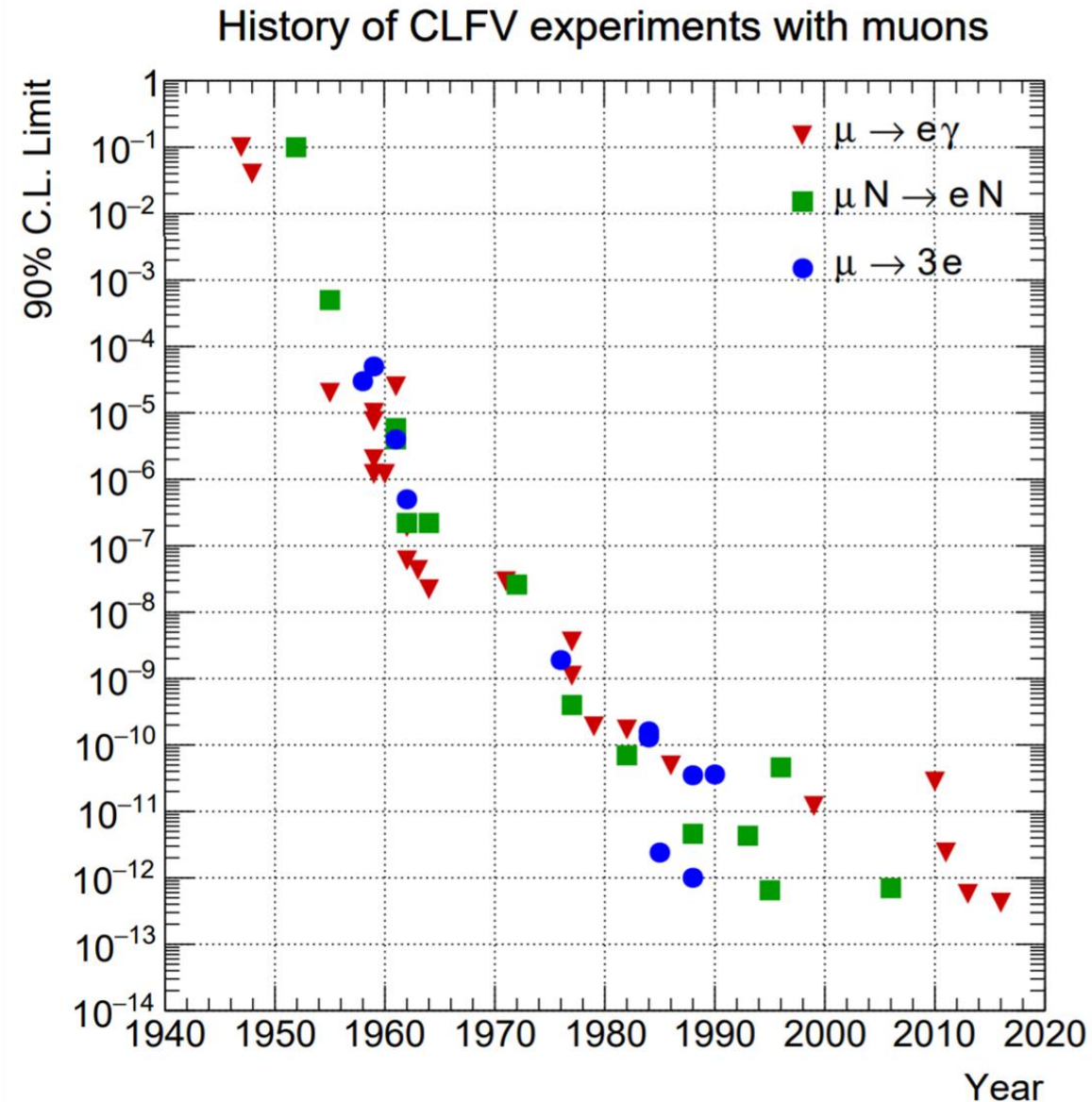


BINP
JINR

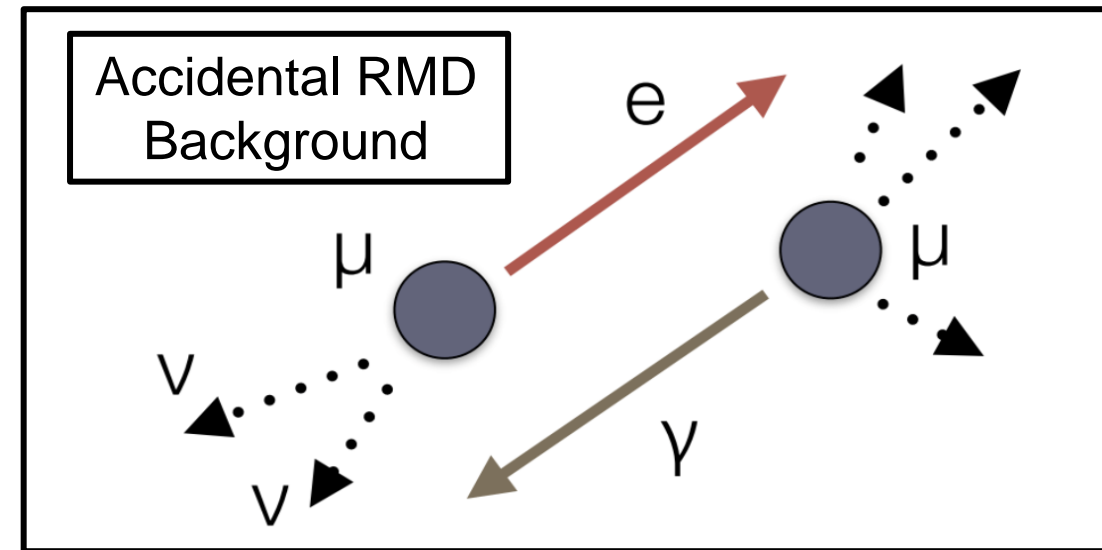
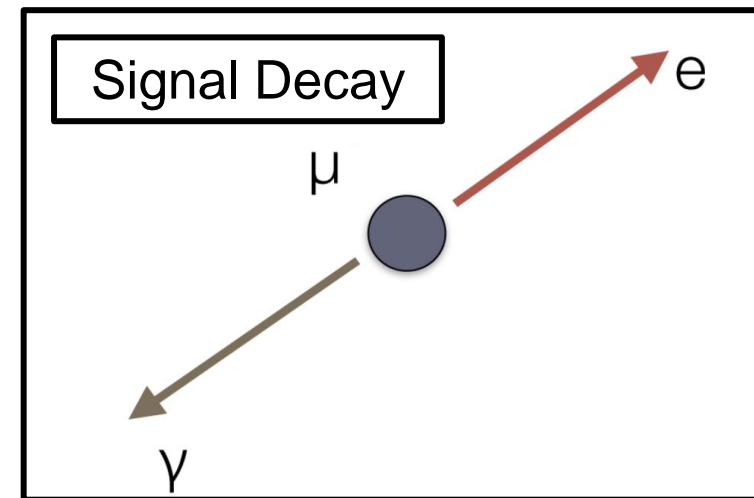


PSI
ETHZ

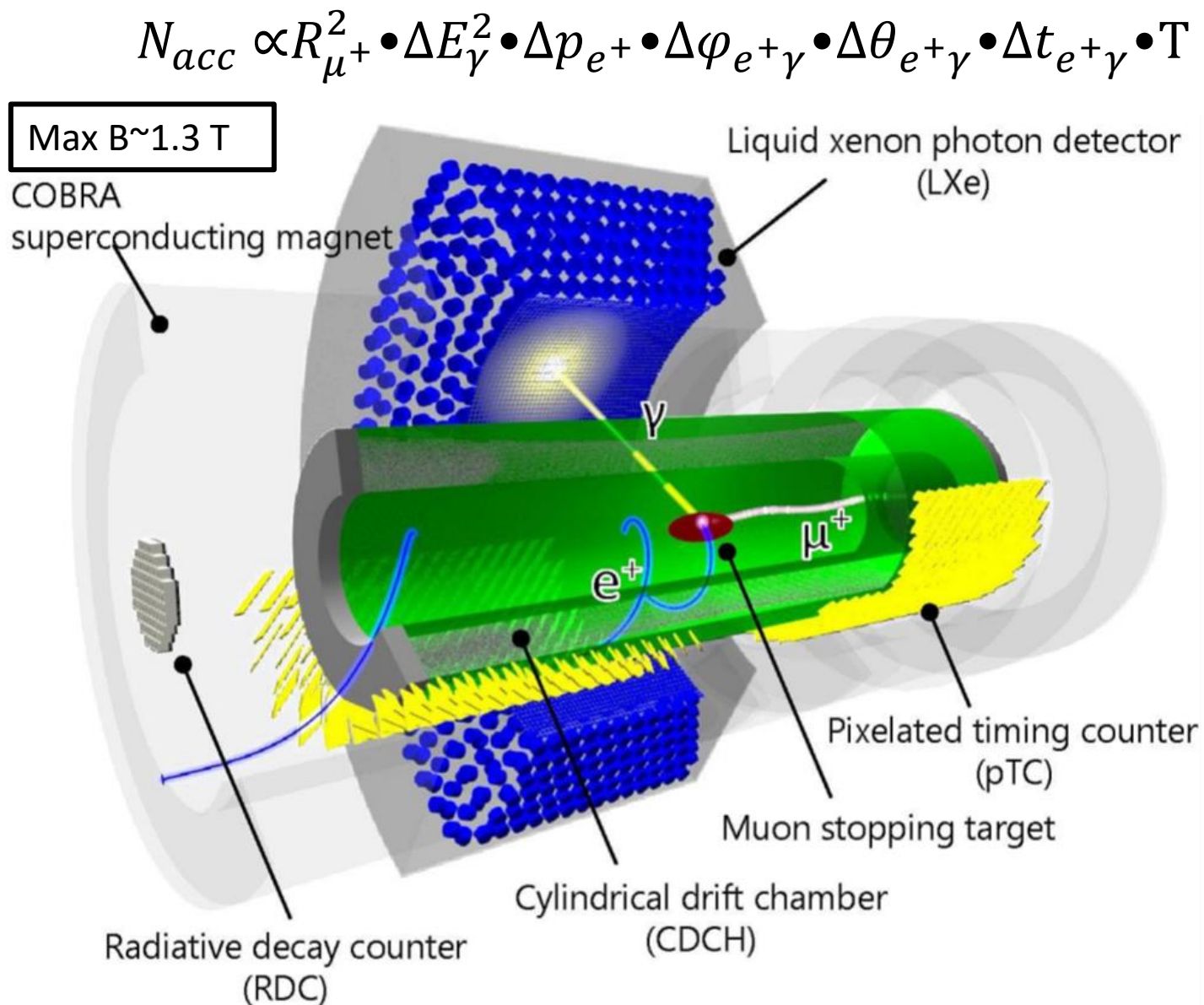
- The current $\mu \rightarrow e\gamma$ decay sensitivity is 4.2×10^{-13} (90% Confidence Level), set by MEG I
- The MEG II collaboration aims to increase the sensitivity by an order of magnitude.



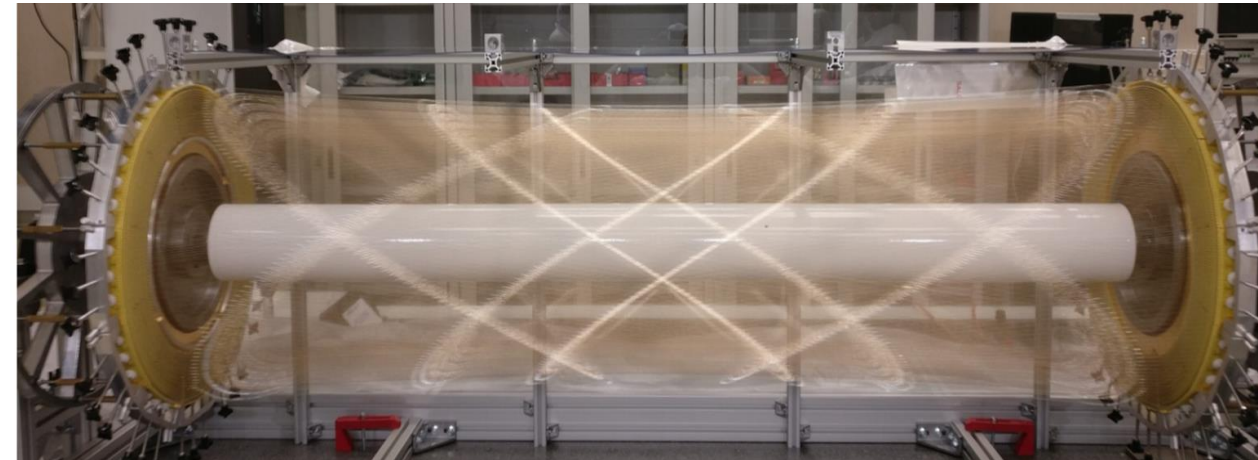
- The $\mu \rightarrow e \gamma$ signal is a two-body decay at rest, signal e/γ have equal and opposite momentum ($m_\mu/2$)
- Background does not have these characteristics:
 - RMD (radiative muon decay) : $\mu^+ \rightarrow \gamma e^+ \nu_\mu \bar{\nu}_e$ (small $E_{\nu_\mu \bar{\nu}_e}$)
 - **Accidental background**: high p_{e^+} coincident with γ from RMD, AIF ($e^+ e^- \rightarrow \gamma \gamma$), etc.
- The experiment requires **precise kinematic measurements of the decay products** to distinguish between signal/background decays



- 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 propagating e^+ to the target, then projecting γ to e^+ target vertex ($\Delta\theta_{e+\gamma}$, $\Delta\varphi_{e+\gamma}$, $\Delta t_{e+\gamma}$, ΔE_γ , Δp_{e^+})



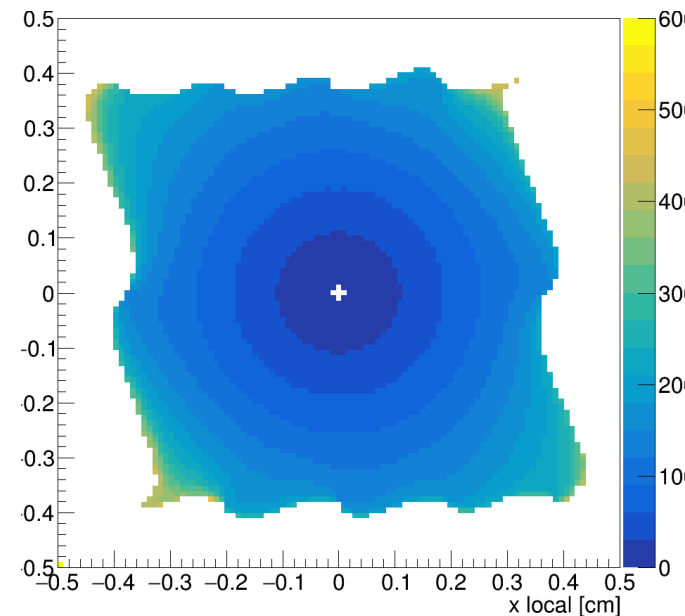
- Upgrades:
 - New ultra-light stereo open-cell drift chamber to improve efficiency and resolution
 - More track space points in drift chamber to improve resolution (1150 readout drift cells)
- In 2021, the chamber was filled with He: C₄H₁₀: C₃H₈O: O₂ (88.2:9.8:1.5:0.5)



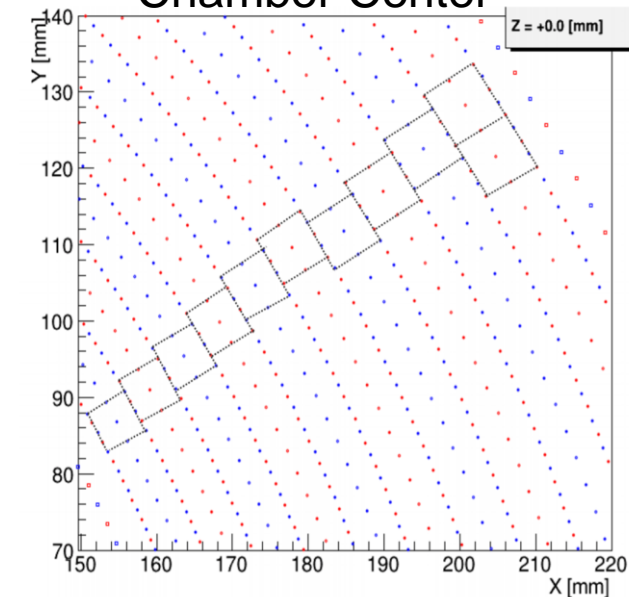
Kinematic Core σ	MEG I	MEG II Goal
p_{e^+} (keV)	380	130
θ_{e^+}/ϕ_{e^+} (mrad)	9.4 / 8.7*	5.3/3.7*
t_{e^+} (ps)	70	30
z_{e^+}/y_{e^+} (mm)	2.4/1.2	1.6/0.7
e+ Efficiency	30	70

* ϕ_{e^+} estimated at plane perpendicular to track

Time-Distance Isochrones[ns]

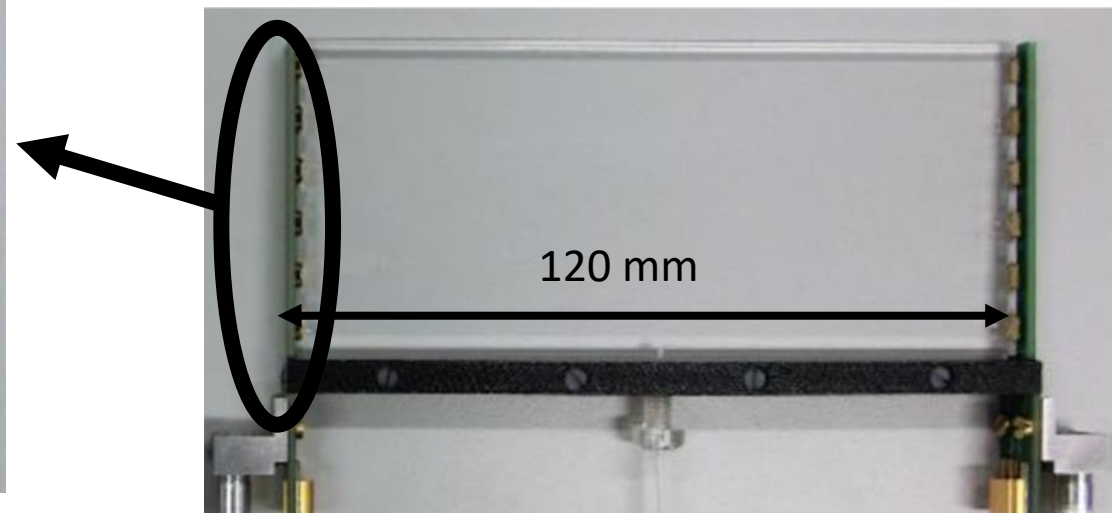
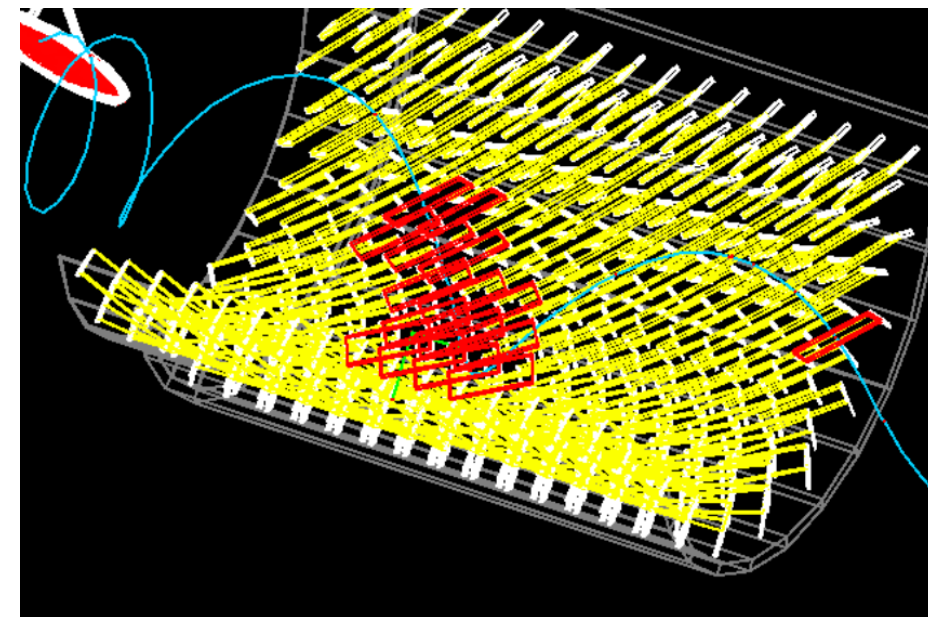


Wire Positions at Chamber Center

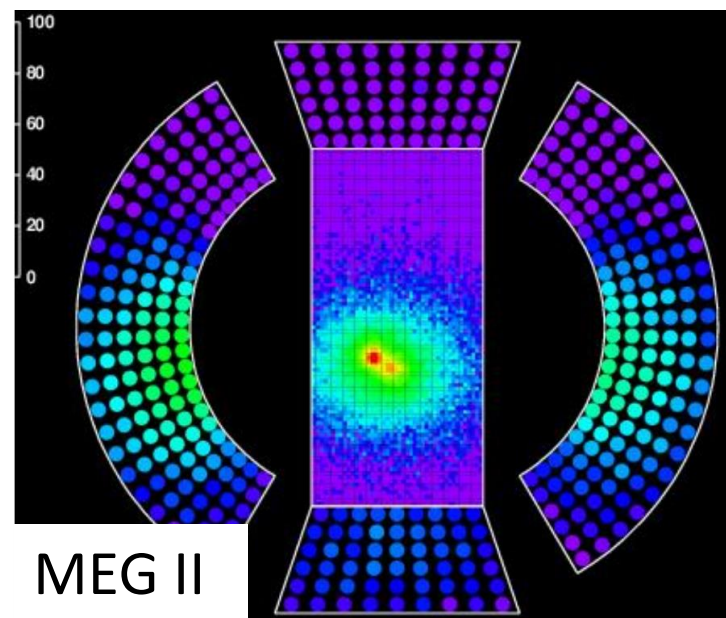


- Upgrade: new design with **higher hit multiplicity**
- Two semi-cylindrical modules, each consisting of 256 timing counters
- Counter consists of a scintillation tile with double-sided SiPM readout
- Individual counter timing precision ~ 90 ps
- Signal $e^+ \langle N_{TC} \rangle \sim 9$; $\sigma_{t_{e^+}} = 30$ ps

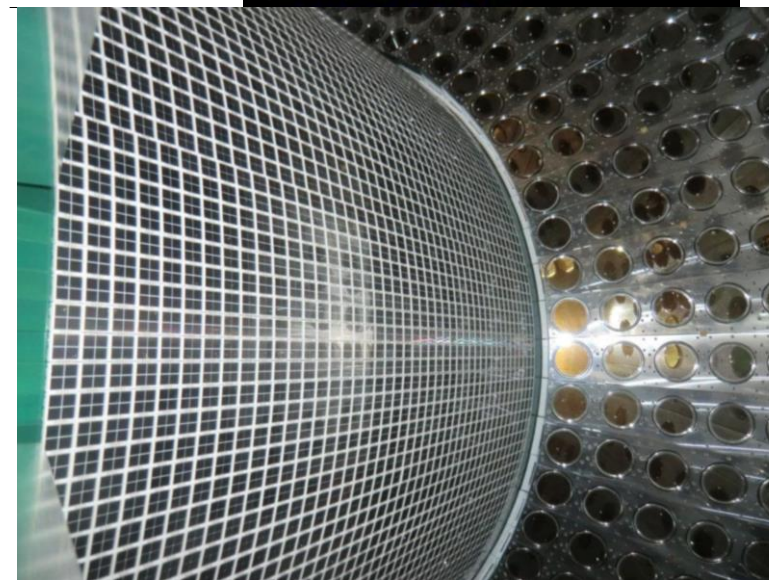
Kinematic Core σ	MEG I	MEG II Goal
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e^+ Efficiency	30	70



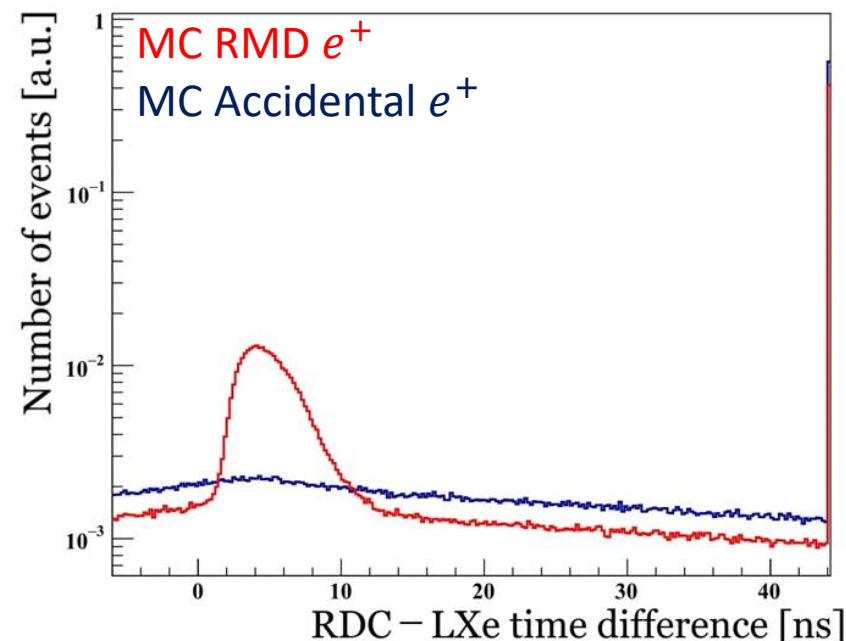
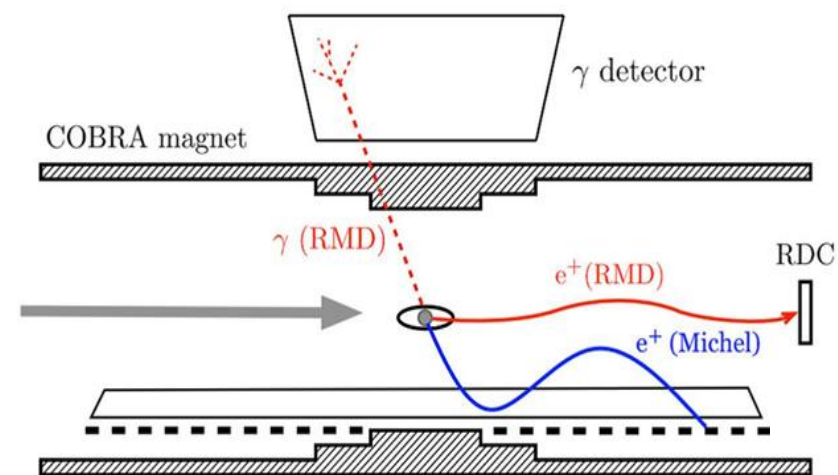
- One of world's largest liquid Xe detector
- Upgrade: inner face is now covered by 4092 MPPCs (Multi-Pixel Photon Counters)
- Other 5 sides covered by PMTs



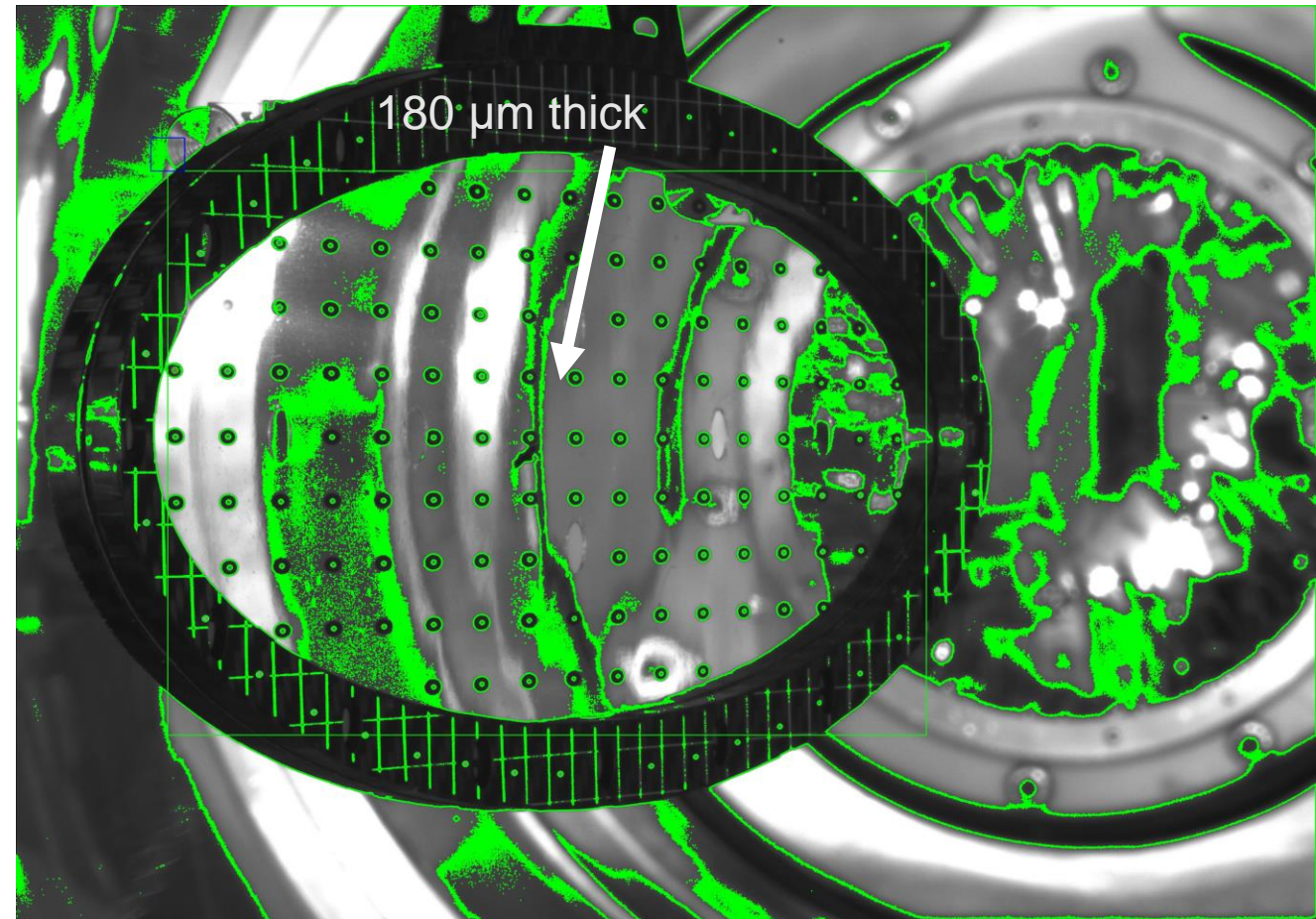
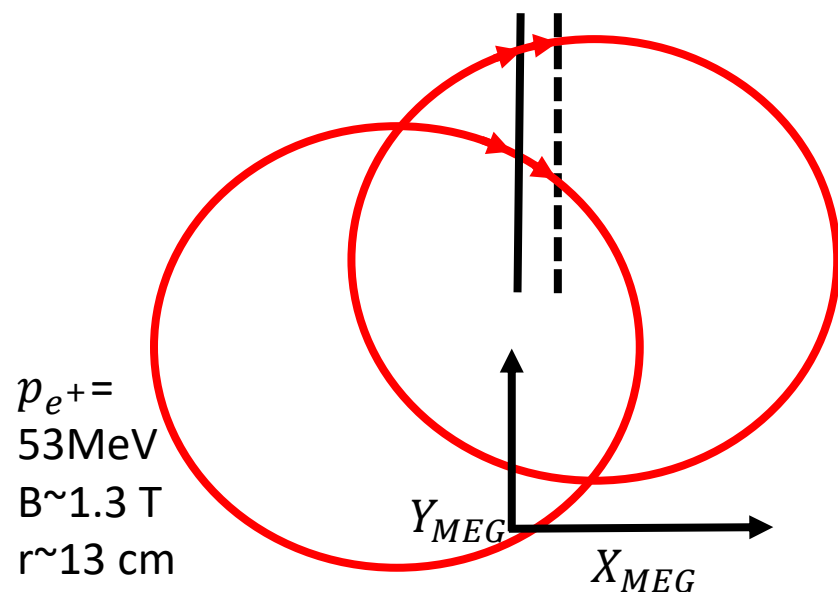
Kinematic Core σ	MEG I	MEG II Goal
E_γ (%)	2.4	1.1
u_γ (z_γ) (mm)	5	2.6
v_γ ($R\phi_\gamma$) (mm)	5	2.2
w_γ (R_γ) (mm)	6	5
t_γ (ps)	60	60



- RDC eliminates RMD some accidental events using LXe/RDC time-matched γ/e^+
- Remove events based on:
 - γ/e^+ relative timing (scintillator)
 - e^+ energy (RMD~low p_{e^+}) (LYSO)
- MC predicts MEG II sensitivity improvement of ~15%



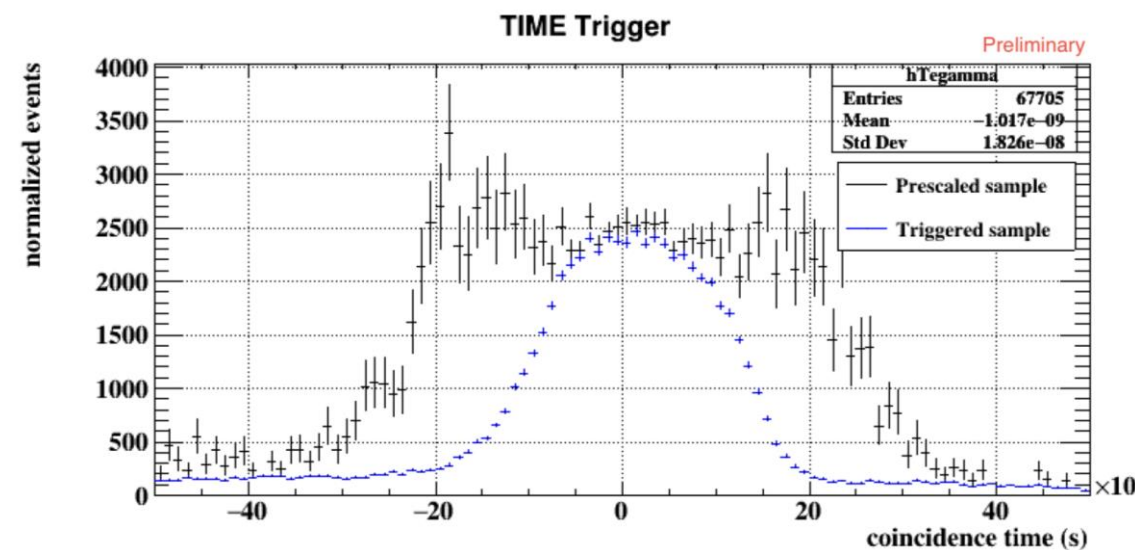
- **Target position error was of the main sources of uncertainty in MEG I**
- Target 0.5 mm normal error
→ 5 mrad φ_e error
- Monitor the target motion using a photographic camera analysis
- ‘Hole Analysis’: image holes in target by lack of positrons originating from the hole position



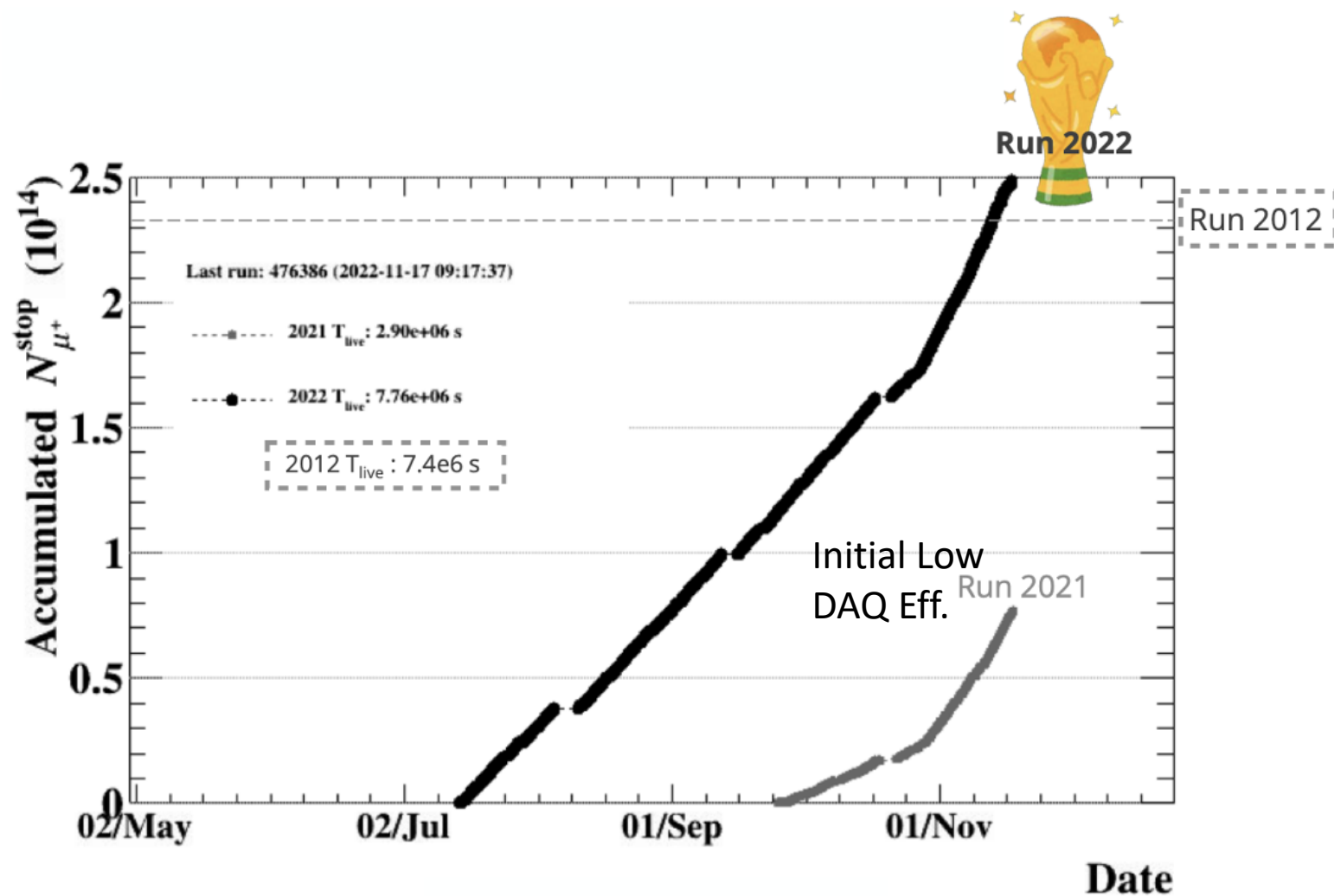
- All detectors use custom WaveDREAM (Waveform Domino REAdout Module) electronics boards
- O(10k) channels contain 1024 ‘sample-and-hold’ cells that sample and temporarily store detector signal (1.4 GHz)
- MEG Trigger Conditions:
 - LXe $E_\gamma > E_{\text{Threshold}}$ (40-45 MeV)
 - Time Match: pTC/LXe $|T_{e^+/\gamma}| < 12.5$ ns
 - Spatial Match: pTC/LXe based on $\mu \rightarrow e\gamma$ decays simulated in Geant4
- Trigger rate of ~ 10 Hz at $4 \times 10^7 \mu/\text{s}$



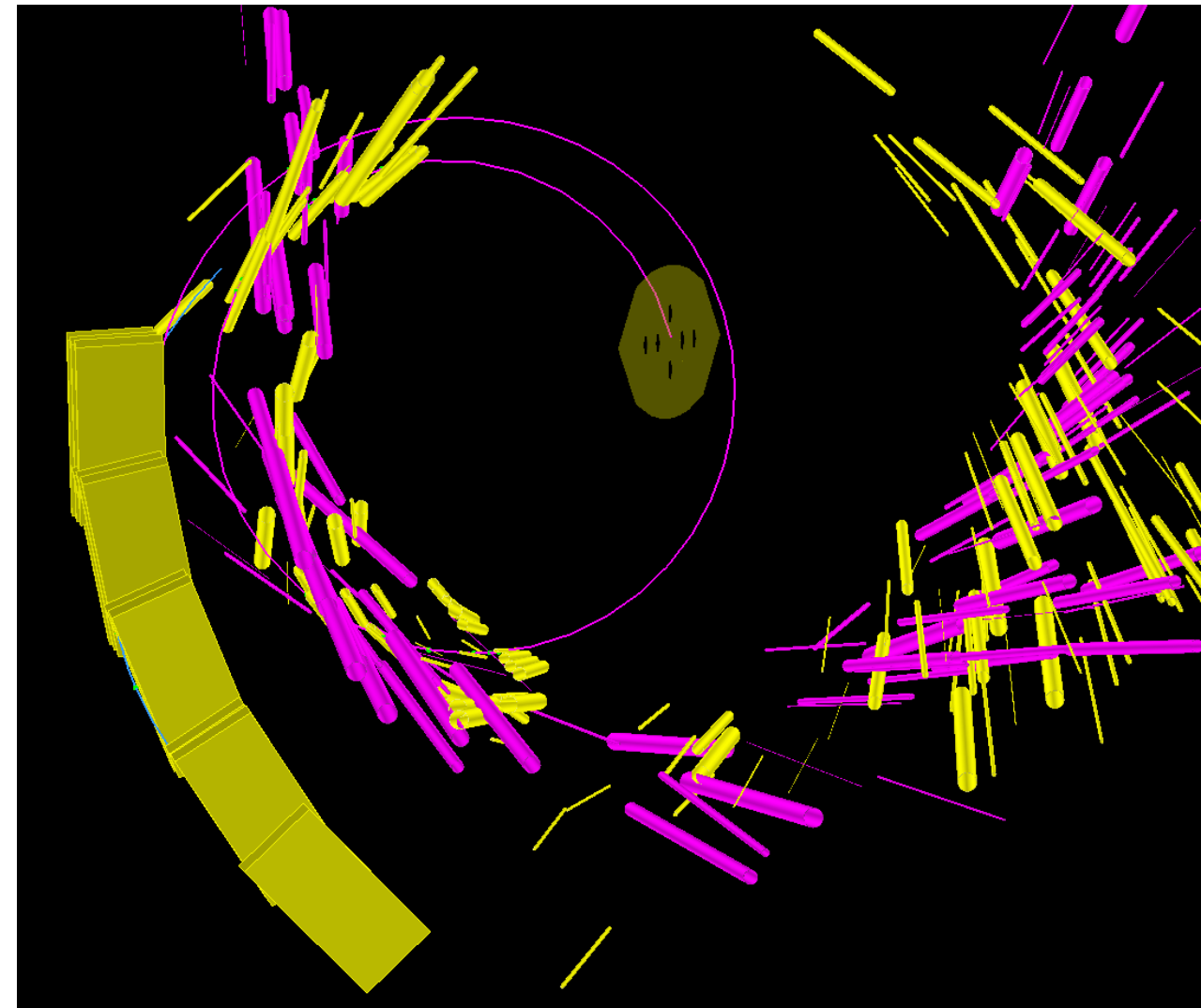
Ritt: <https://doi.org/10.1016/j.nima.2003.11.059>



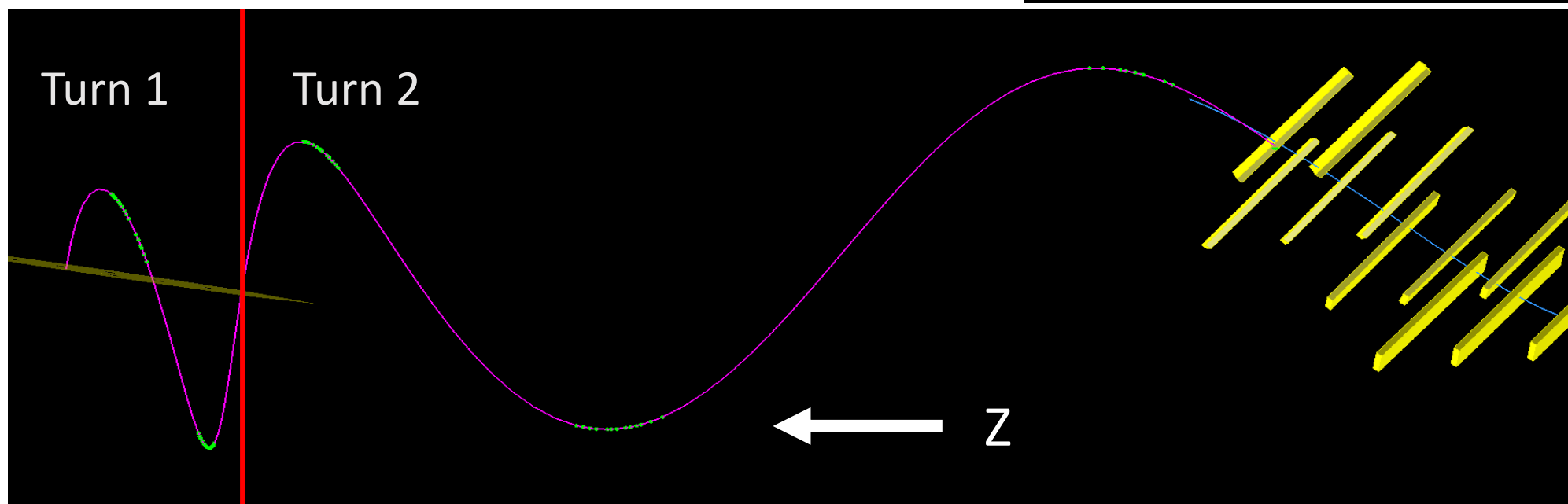
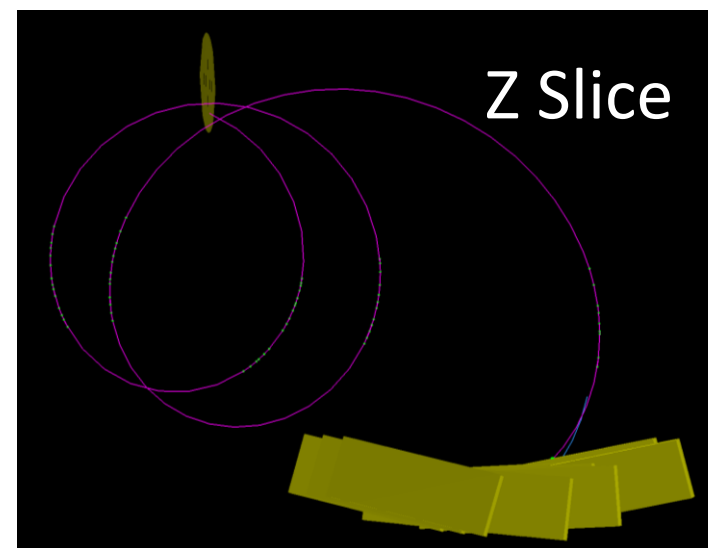
- 2021 dataset consisted of ~24M MEG triggers at varying beam rates ($2,3,4,5 \cdot 10^7 \mu/s$)
- 2022 accumulated more stops than any MEG run to date!



- **Optimizing resolutions/efficiency is critical to achieve the optimal sensitivity and ultimately detect $\mu \rightarrow e\gamma$**
- Data analysis:
 - Positron analysis:
CDCH+SPX waveform data $\rightarrow e^+$ kinematics
 - Photon Analysis:
MPPC+PMT waveform data $\rightarrow \gamma$ kinematics
 - Target analysis: tracking target position, orientation, shape
 - RDC analysis: matching low momentum e^+ with LXe γ
 - Physics analysis: optimizing data selection, kinematic resolution estimates, kinematic correlation, etc.
- Will highlight some kinematic resolution measurements in next few slides



- 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



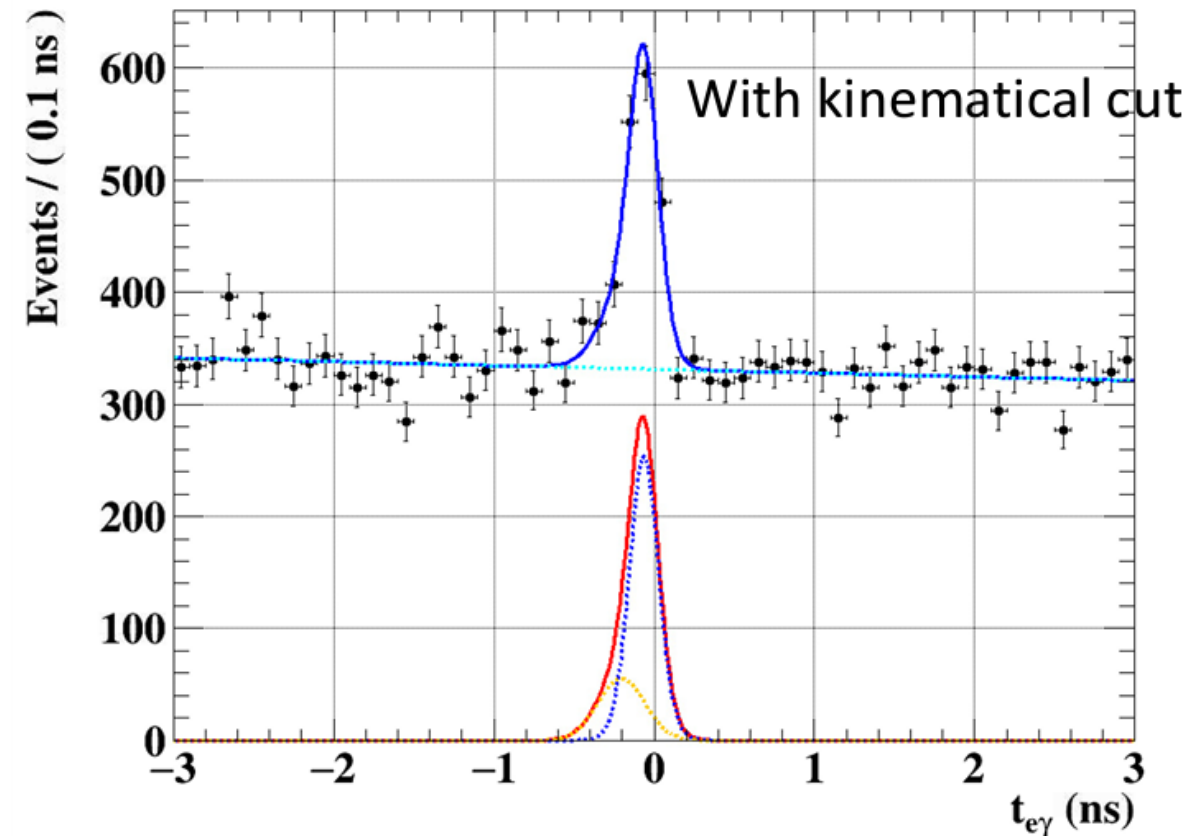
- **Preliminary** double turn (DT) resolution estimates are all improved with respect to MEG I
- Improving single hit resolution, magnetic field map, etc. aim to achieve the MEG II goal resolutions
- ***Goal resolutions are based on signal e_+ ; double turn resolutions are corrected by MC $\sigma_{signal}/\sigma_{michel}$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

3 • 10 ⁷ μ/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
$\theta_{e_+}/\varphi_{e_+}^*$ (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
 **based on early CDCH track fitting algorithms

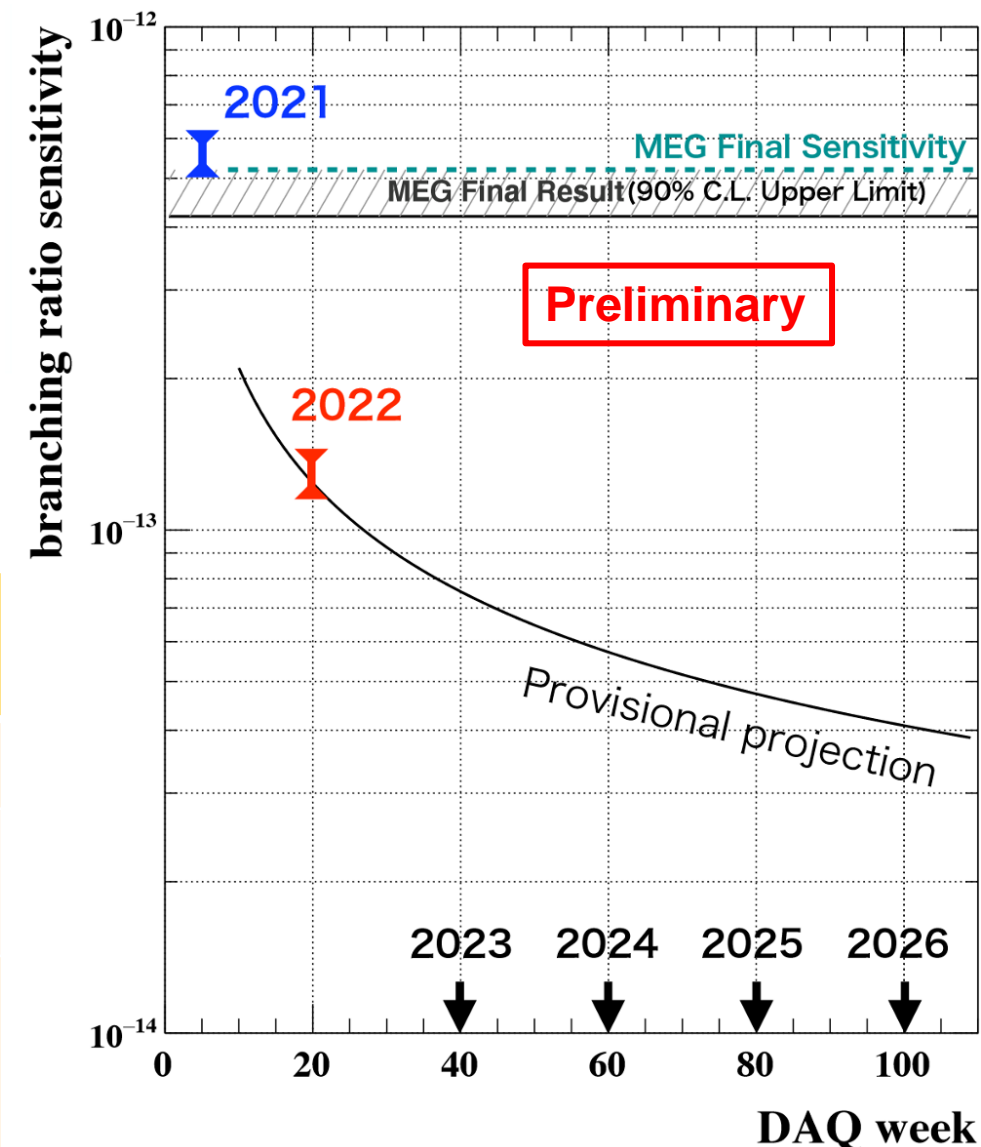
- Use true non-accidental RMD e^+/γ pairs at standard beam intensity to estimate $\sigma_{t_{e^+\gamma}}$
- Direct measurement of $\sigma_{t_{e^+\gamma}}$
- For events with 9 N_{TC} ($\langle N_{TC} \rangle$ for signal):
 $\sigma_{t_{e^+\gamma}} \sim 83$ ps
- Comparable to MEG II goal

RMD $t_{e^+\gamma}$ with TC per-event Errors



- Maximum likelihood analysis
- 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 here hasn't yet been updated to reflect updated resolutions
- **Single event sensitivity is the branching fraction that would result in 1 signal event in the dataset

Dataset	Sensitivity (10^{-13}) 90% CL	Single Event Sensitivity (10^{-13})
MEG I Sensitivity	5.3	0.58
MEG II Preliminary 2021 Sensitivity Estimate	5.3-6.1	3.85
MEG II Preliminary 2021+ 2022 Sensitivity Estimate	1.2-1.4	0.81





Summary of Current Status



- In 2021, the experiment had its first physics run, achieving resolutions comparable to the MEG II design (e.g. $\sigma_{p_{e^+}}, \sigma_{t_{e^+\gamma}}, \sigma_{Z, Y_{e^+}}$). Finalizing algorithms for the 2021 physics analysis (CDCH alignment, LXe calibration, tuning likelihood PDFs, etc.)
- Now the 2021+2022 dataset is expected to achieve the most stringent limit on the CLFV $\mu \rightarrow e\gamma$ decay.
- Plan to publish 2021 results in June and 2021+2022 at the end of 2023



Summary of Future Work



- Data analysis upgrades:
 - Optimize the magnetic field calculation/measurements (improve resolutions)
 - Alternate LXe energy calculations ($\sigma_{E_\gamma} \sim 1.8\%$ with goal of 1.1%)
 - Alternate CDCH track finders (higher efficiency)
- Beam intensity optimization for 2023+. Dependencies:
 - LXe MPPC quantum efficiency degradation (annual annealing post-run)
 - Out-of-time 'pileup' in CDCH and LXe
 - Resolution/efficiency
- Hardware:
 - Drift chamber with additional layer designed with new material to avoid high current issues for 2024+
 - Work on upstream RDC counter
- DAQ:
 - Comparable DAQ weeks in 2023, plan to share beamtime with Mu3e in 2024+ until shutdown



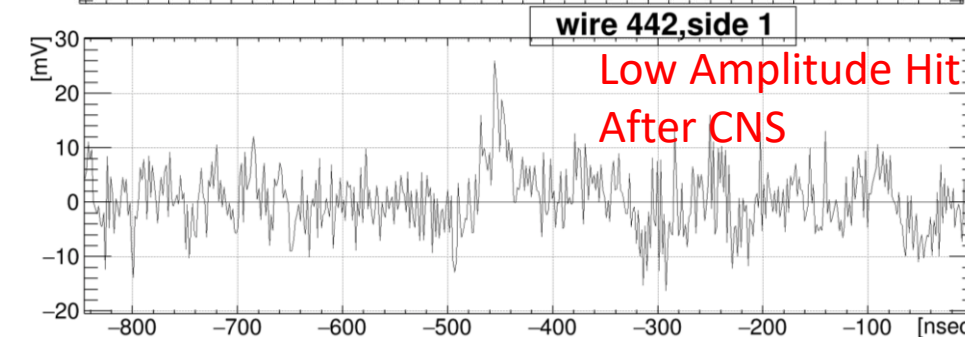
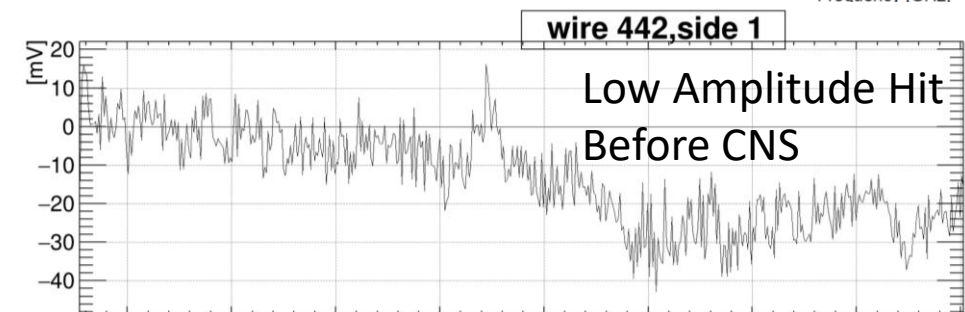
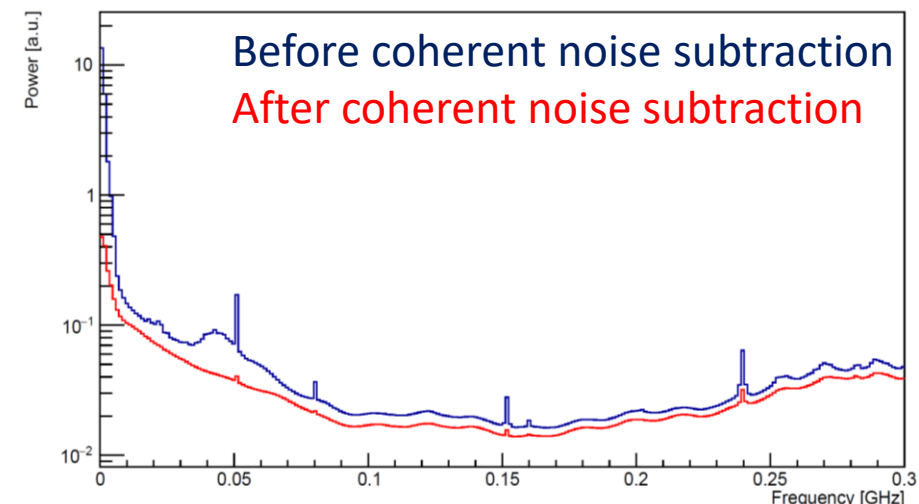
Backup Slides



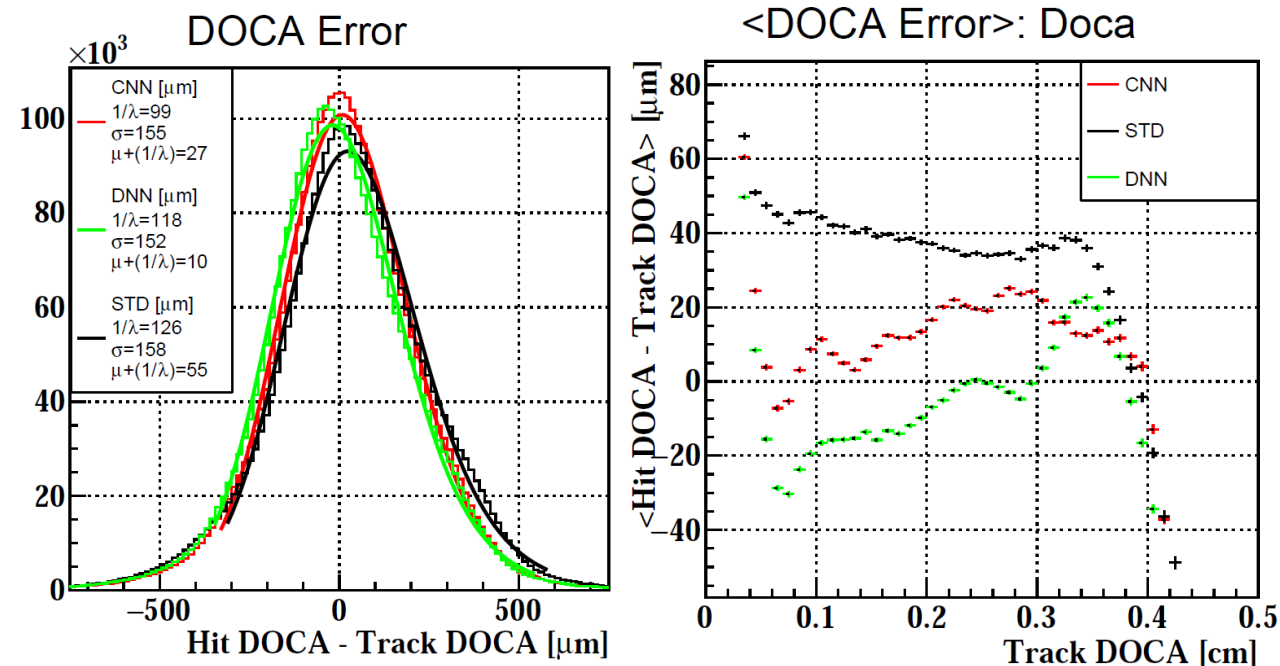
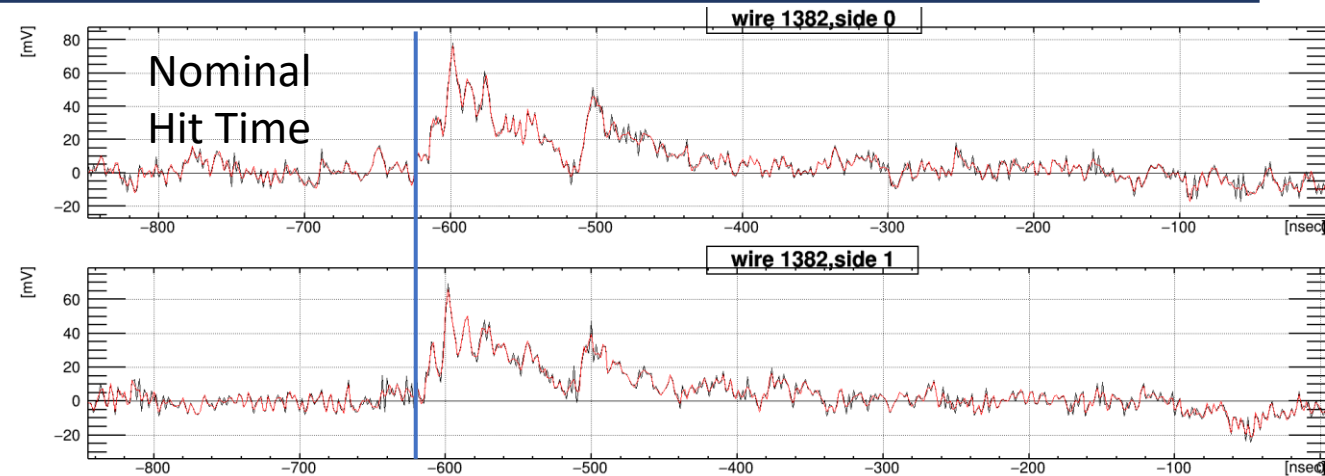
Thanks!

- Observed low frequency noise on the CDCH waveforms coherent over entire electronics chips
- Developed algorithms to suppress noise by averaging the voltage bin-by-bin/chip away from signals
- Noise suppression is critical to improving hit efficiency and improving track space-point measurements

Noise Spectra With/Without CNS



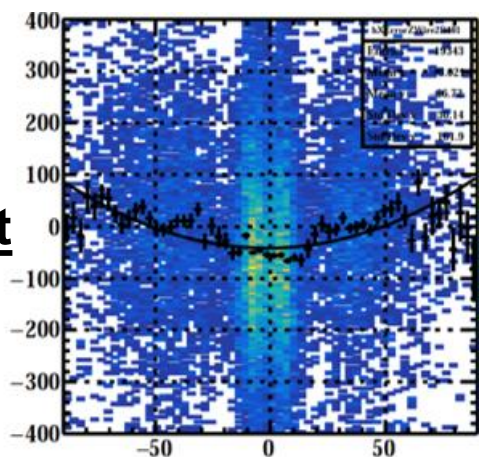
- Primary CDCH measurement is the track's distance of closest approach (DOCA) to a wire's center
- Waveform analysis results in estimated hit time. Combine with track T0 (from pTC), yields a drift time
- **Requires time-distance relationship to estimate the hit DOCA.** Conventionally calculated by Garfield
- Replaced by convolutional neural network (CNN) approach offers a data-driven approach by training on tracks in MEG data
- Improves DOCA resolution, reduces DOCA bias produced by ionization statistics, and improves kinematic resolutions



- Align the wires by calculating residuals as a function of position along the wire axis
- Iteratively correct the wire by applying translations, rotations, and a wire sagitta (electrostatic)
- Improves kinematic resolutions and biases in the kinematic resolutions

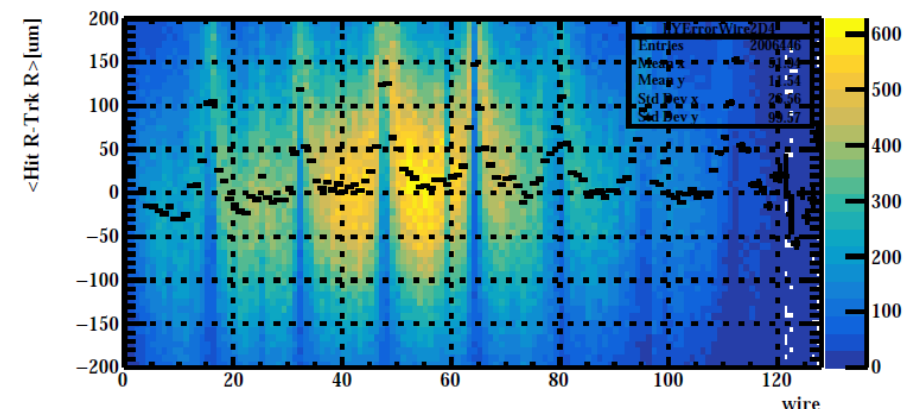
Survey Alignment

X Error on Wire 401[μm]



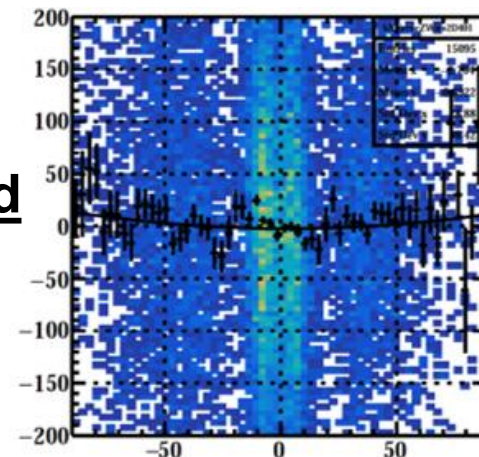
Axial Coordinate [cm]

Average Y Error for Layer 4 Wires [μm]



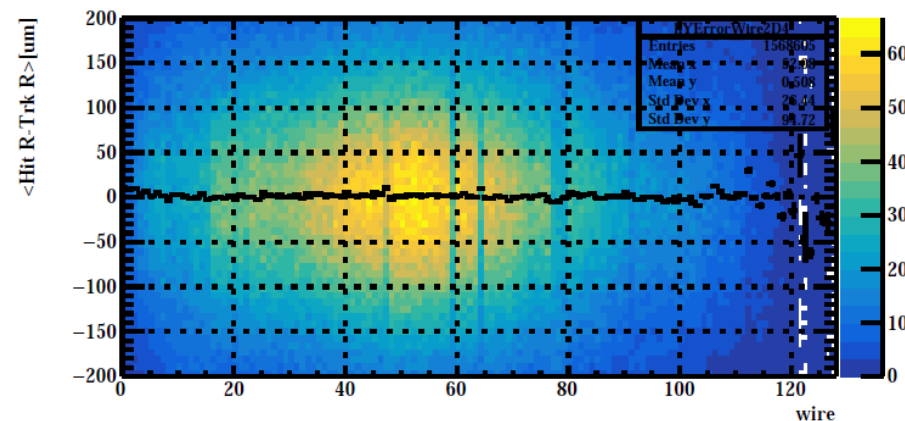
Track-Based Alignment

X Error on Wire 401[μm]

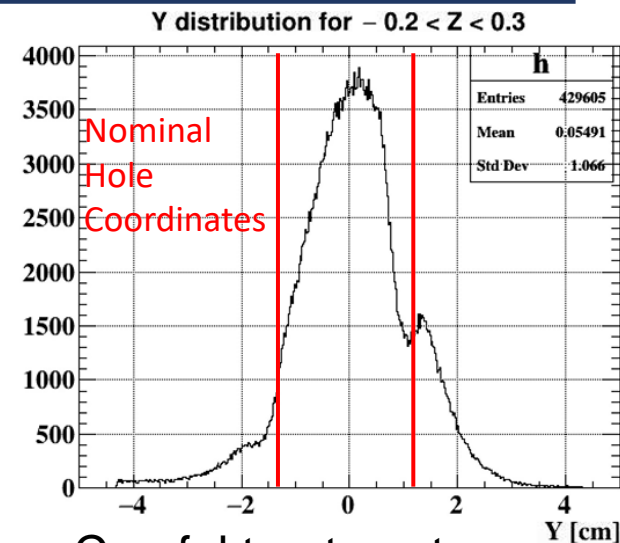
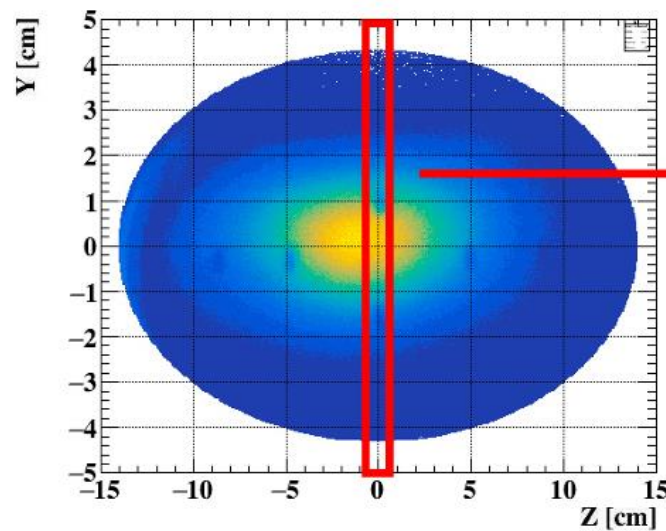


Axial Coordinate [cm]

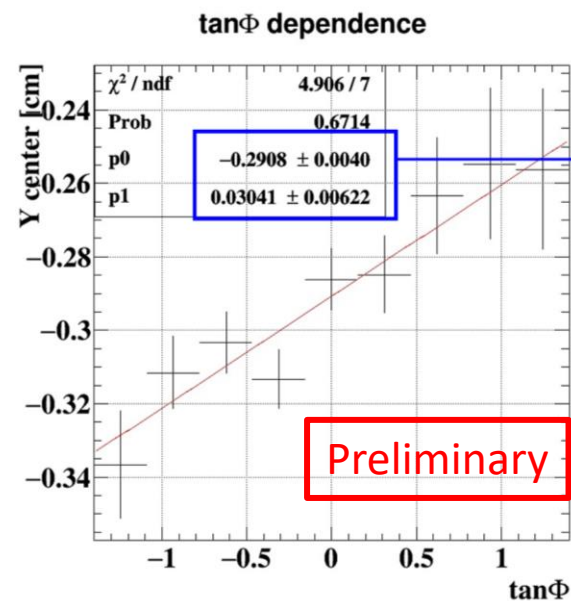
Average Y Error for Layer 4 Wires [μm]



- 6 holes in the target foil
- Calculating hole's 3D coordinate using e^+ vertex distribution
- Yields absolute CDCH/target position
- Parallel coordinates estimated using vertex slice (no effect on kinematics)
- Normal coordinate estimated by calculating apparent hole coordinate VS. φ_{e^+}



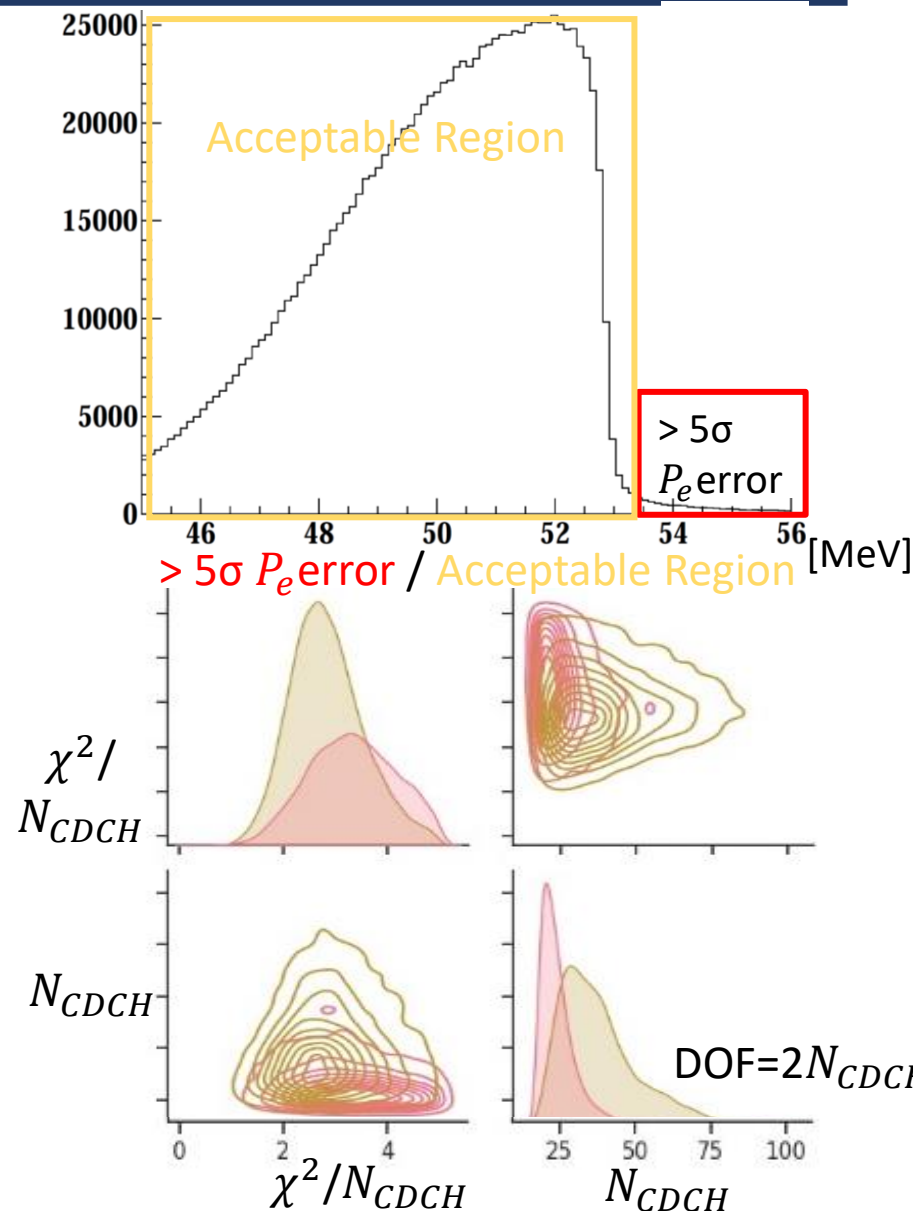
Careful treatment to avoid fit errors!
(e.g. use MC)



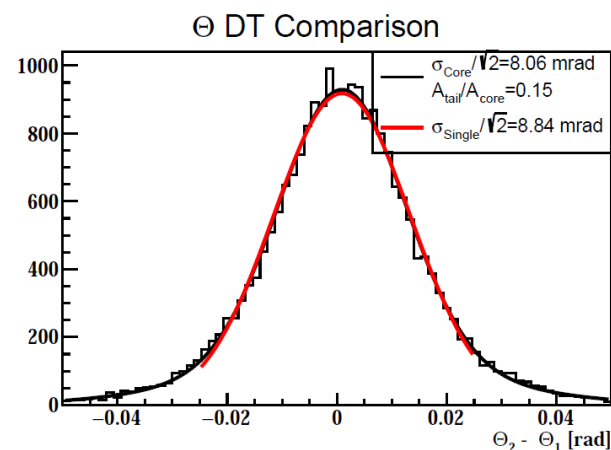
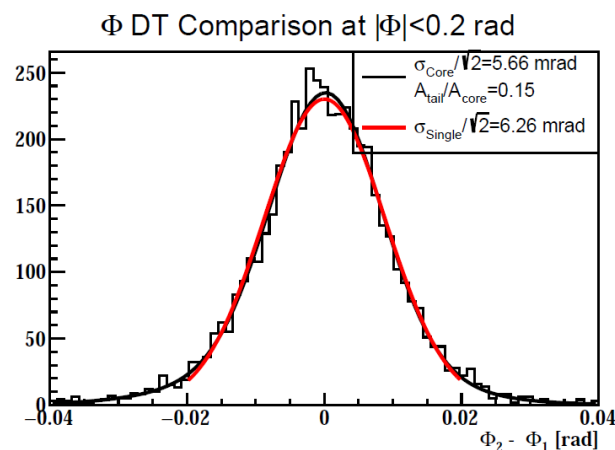
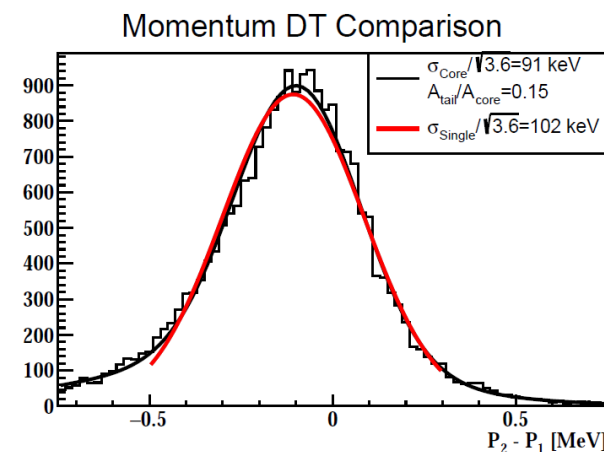
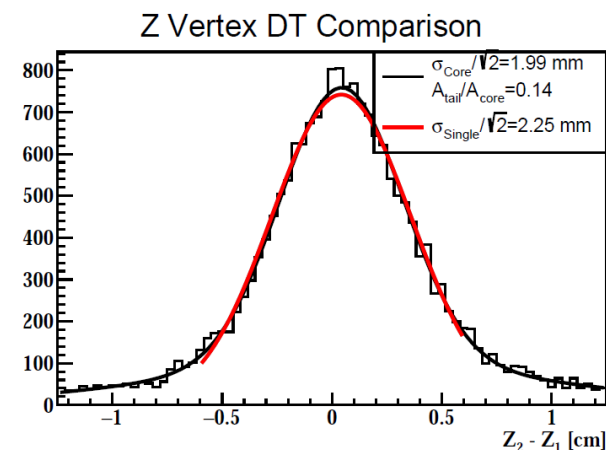
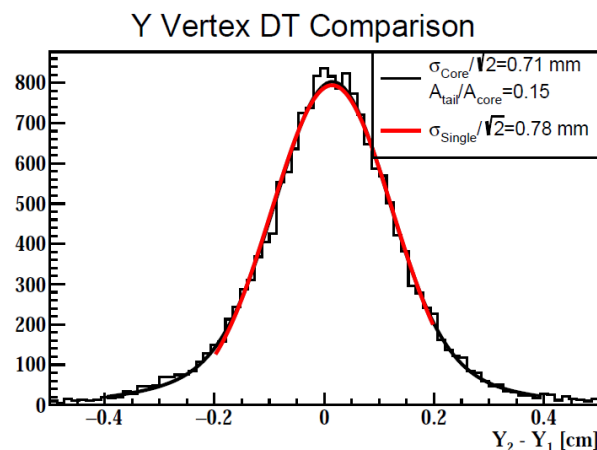
X: 0.03 ± 0.006 cm away from nominal plane
Y: -0.291 ± 0.004 cm

Preliminary

- Track selection is implemented to achieve an appropriate positron sample
- Poorly measured tracks contribute a small amount to the maximum likelihood and require significantly more complicated PDFs.
- Identify function that eliminates mismeasured tracks while preserving quality tracks
- Data-driven example:
 - $p_{e^+} > 52.8$ MeV is unphysical. $p_{e^+} > 53.5$ MeV is mismeasured by $>5\sigma$
 - Compare measurables in $p_{e^+} > 53.5$ MeV / $p_{e^+} < 53.5$ MeV regions
 - e.g., Mismeasured tracks have large χ^2/N_{CDCH} and small N_{CDCH}
 - Apply machine learning to perform binary categorization using measurables (e.g., covariance, χ^2 , N_{CDCH})
 - Dense neural network achieves improved categorization with respect to box cuts. Removes bad tracks over all p_{e^+}

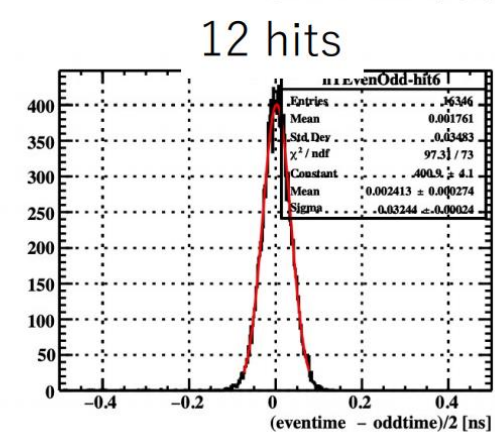
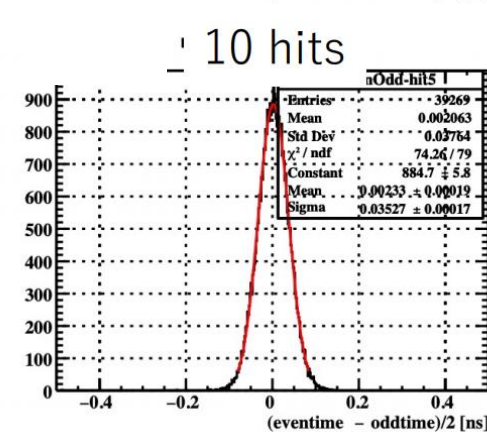
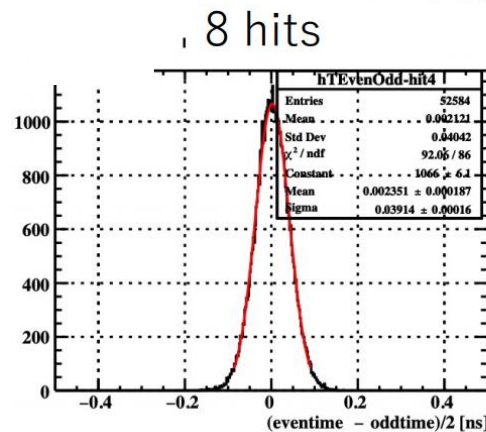
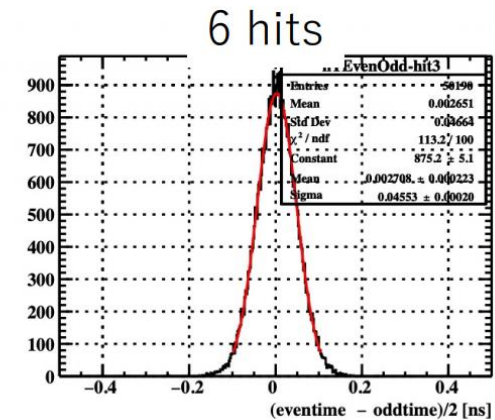
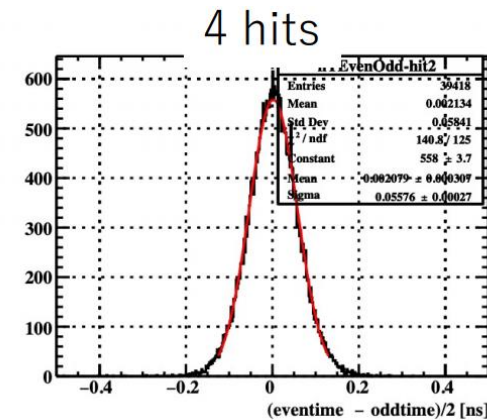
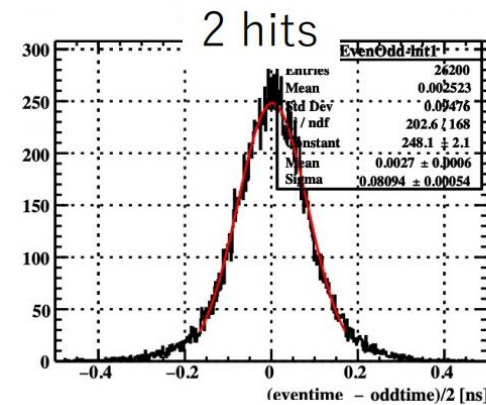


- Turn kinematic comparison at target plane
- $\sigma_{\Delta A}^2 = \sigma_{Turn\ 2}^2 + \sigma_{Turn\ 1}^2$
- $\langle P_2 - P_1 \rangle \sim -100$ keV, still under investigation... suspect magnetic field systematics



ϕ_{e^+} estimated at plane perpendicular to track

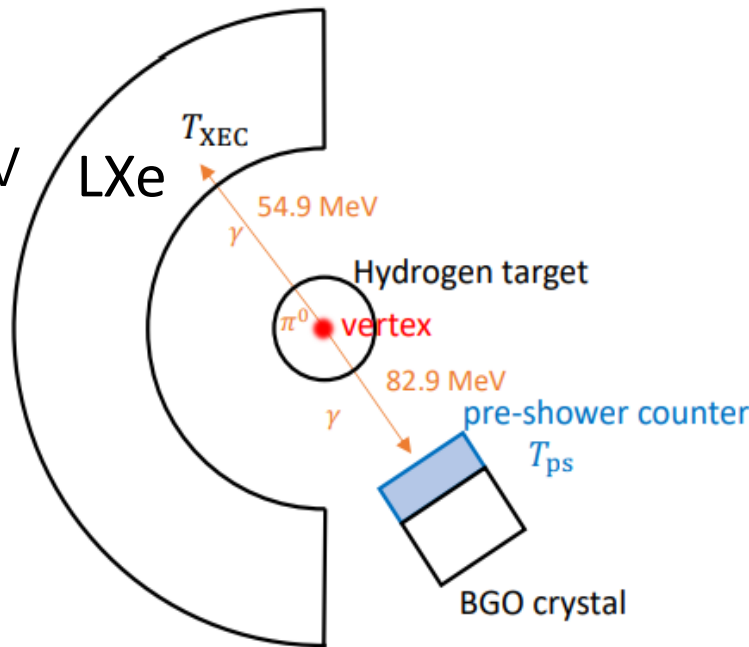
- pTC $\sigma_{t_{e^+}}$ estimated by comparing time of even/odd ordered hits in the same “cluster” of SPX hits
- Fit for $\sigma_{t_{e^+}}(N_{TC}) = \frac{112}{\sqrt{N_{TC}}}$
- Signal $e^+ <N_{TC}> \sim 9$



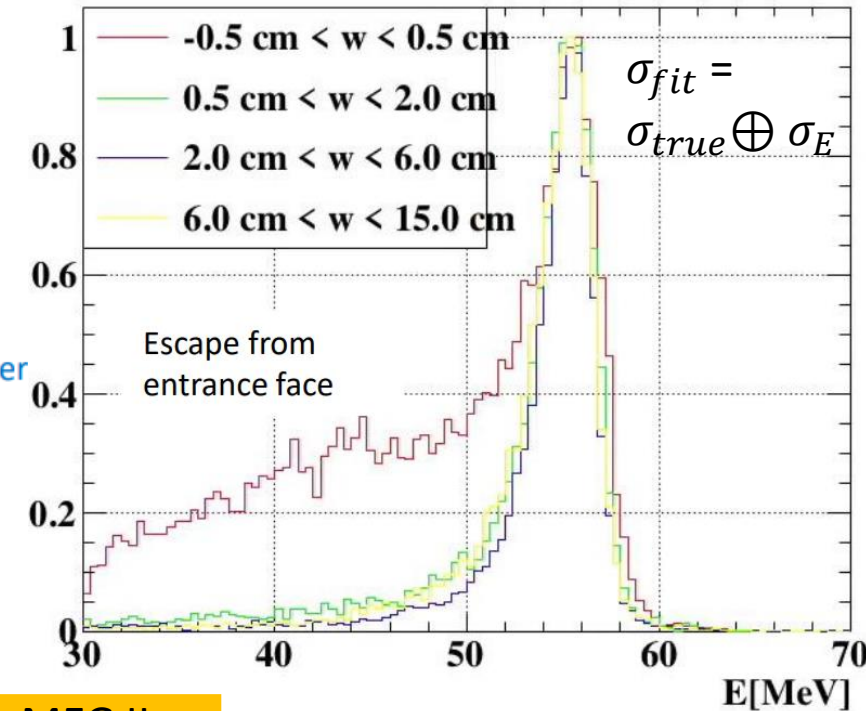
Kinematics/ Core σ	MEG I	MEG II Goal	MEG II Preliminary 2021
t_{e^+} (ps)	70	30	37

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

LXe CEX Setup

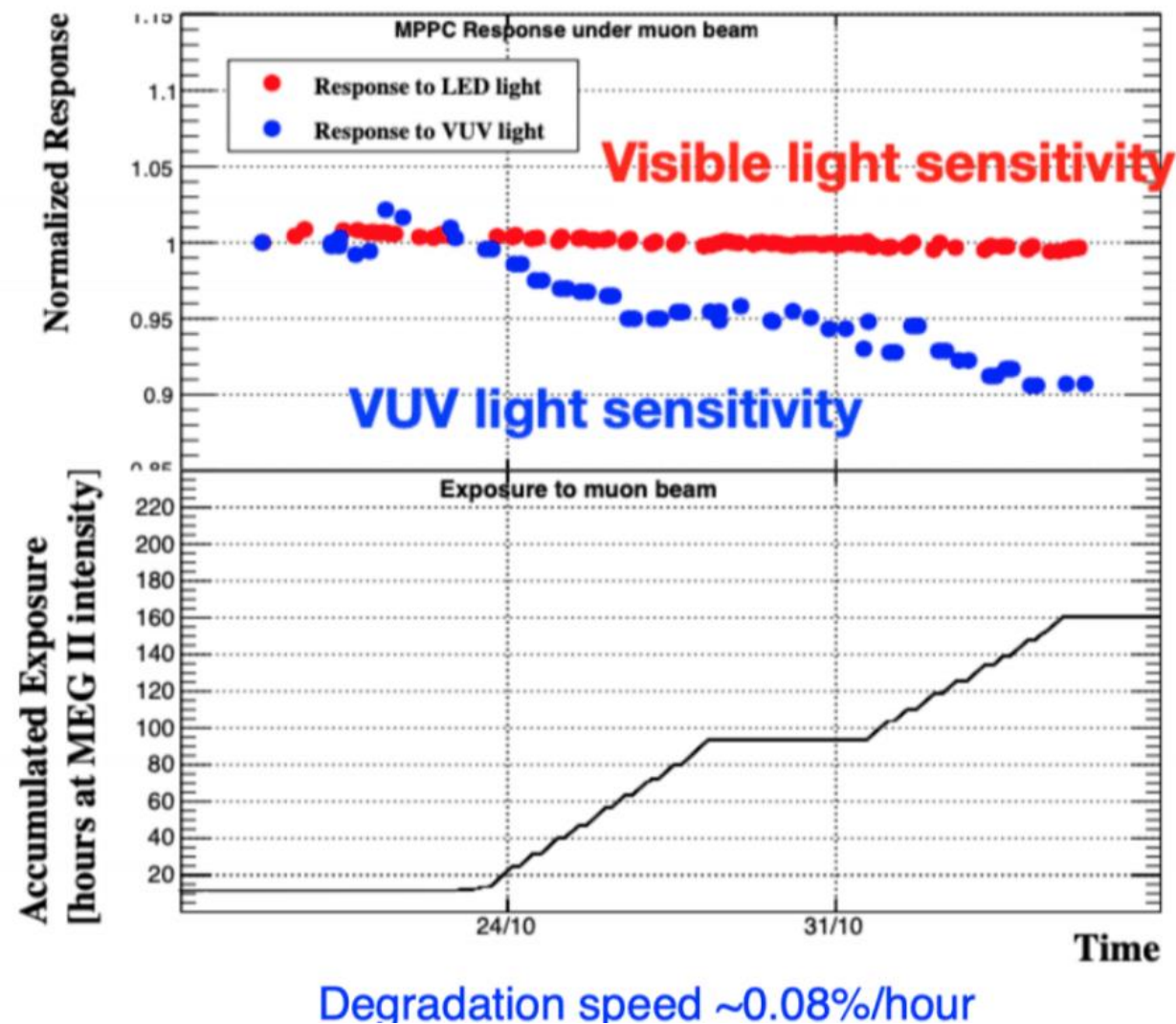


LXe CEX Energy Distribution with Varying Depth (w)

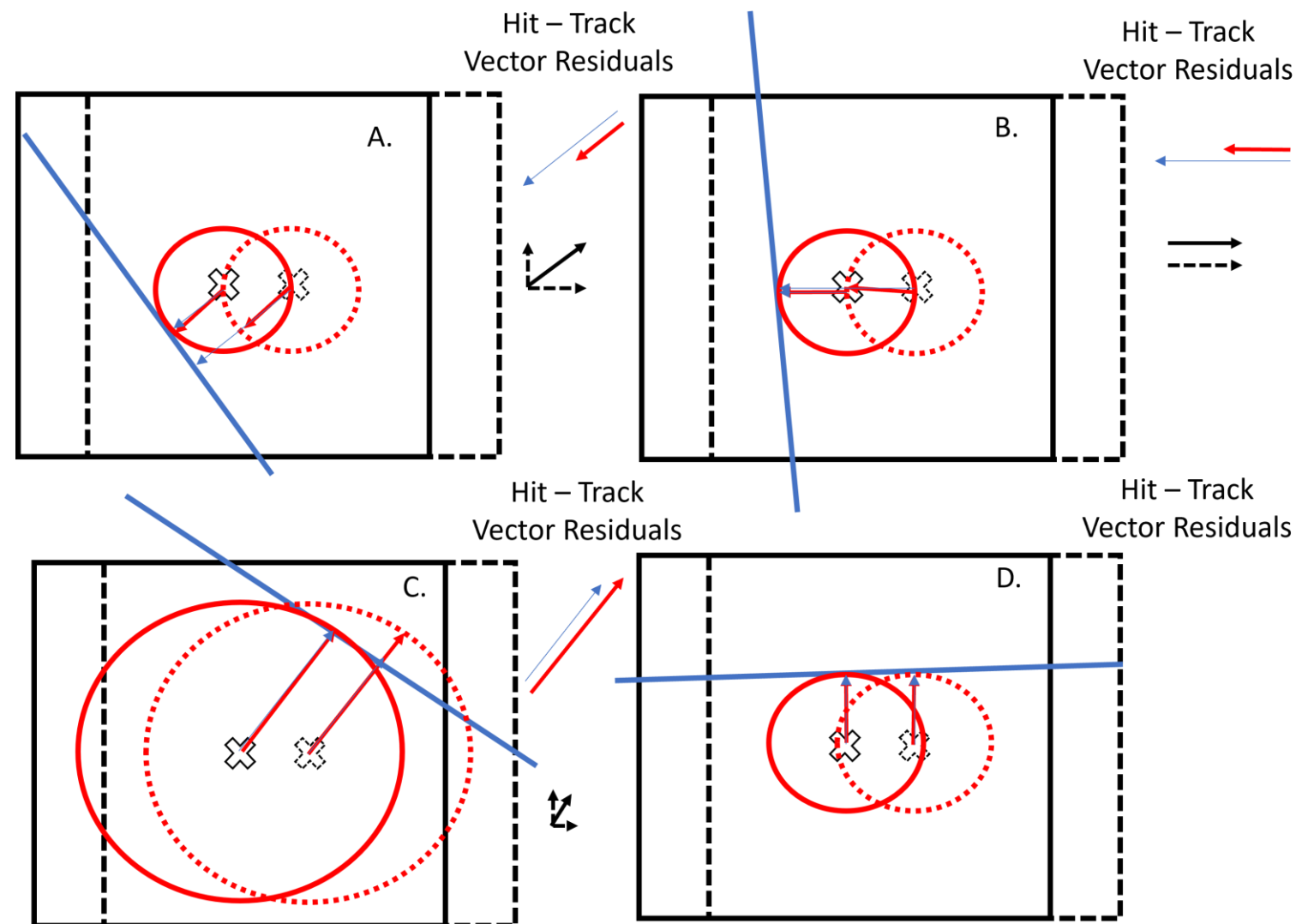


Kinematic Resolution	MEG I	MEG II Goal	MEG II Preliminary 2021
E_γ (%)	2.4	1.1	1.8
t_γ (ps)	60	60	70

- Anneal MPPCs every year in order to recover MPPC quantum efficiency
- Quantum efficiency and therefore the signal/noise degrades with beam exposure
- Anneal using Joule method: i.e. high current



- Motivation: observed systematic mean residuals perpendicular to the wire axis. Causes biases observed in kinematic resolution checks
- Graphic shows how tracks can align the anode wires.
- Dotted vs. solid lines represent the true/incorrect drift cell
- Hit vector is aligned based on the track doca
- In all cases, $\text{hit } X - \text{track } X \geq 0$
- Clear that information is maximal (minimal) if track is perpendicular (parallel) to the alignment error



- Sensitivity is the average upper-limit based on many pseudo-experiments run with a null hypothesis

