MEG II 陽電子スペクトロメータにおける飛跡パターン認識への機械学習の活用

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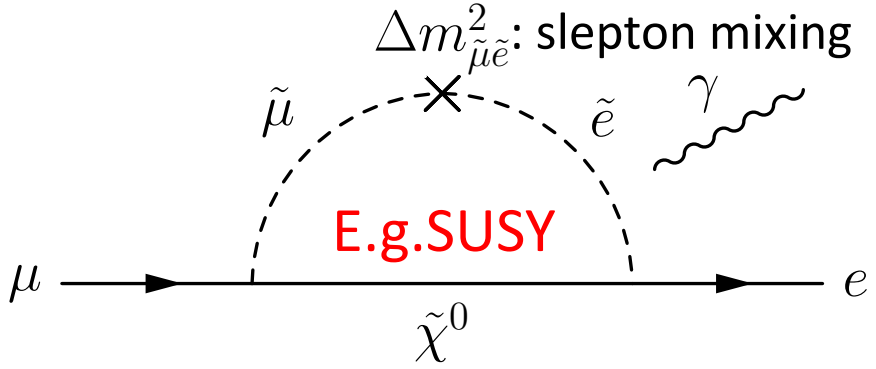
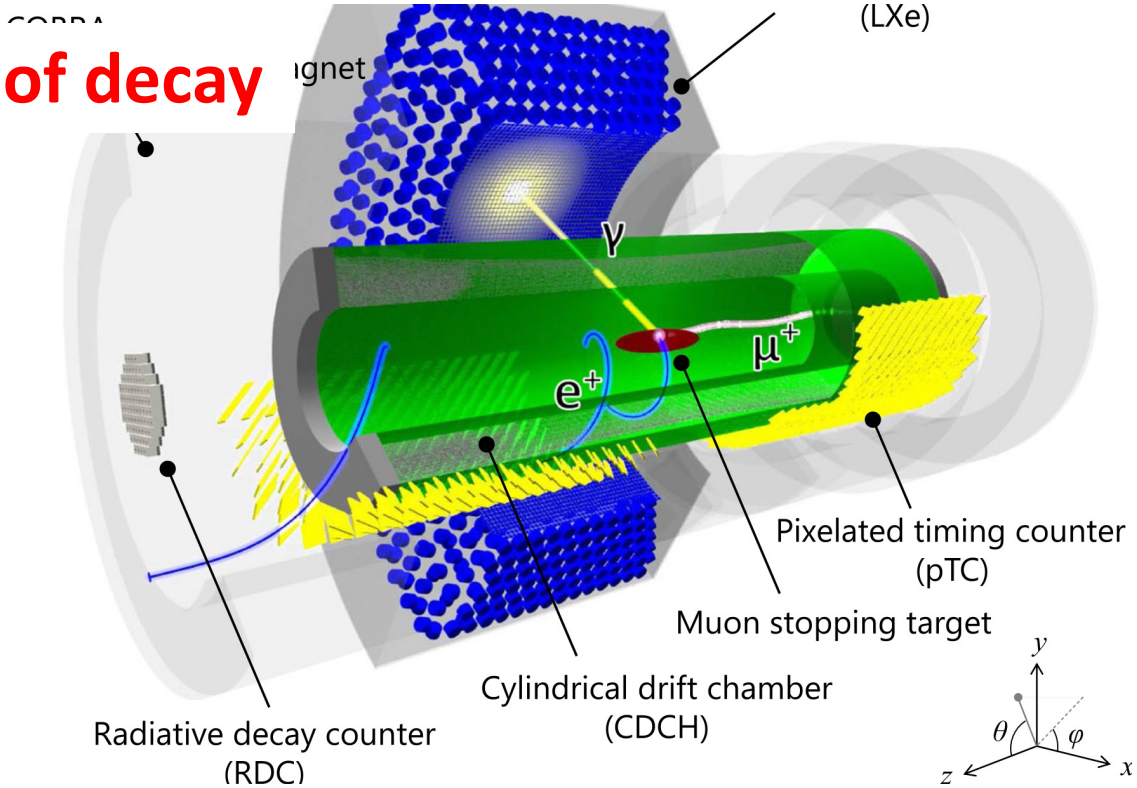
$\mu \to e\gamma$ search @MEG II experiment

- $\mu \to e\gamma$ search by MEG II
  - $\mu \to e\gamma$: CLFV decay, forbidden in SM
  - Target sensitivity: Br($\mu \to e\gamma$) ~ $\mathbf{6\times10^{-14}}$
  - DAQ start in 2021, planned till 2026



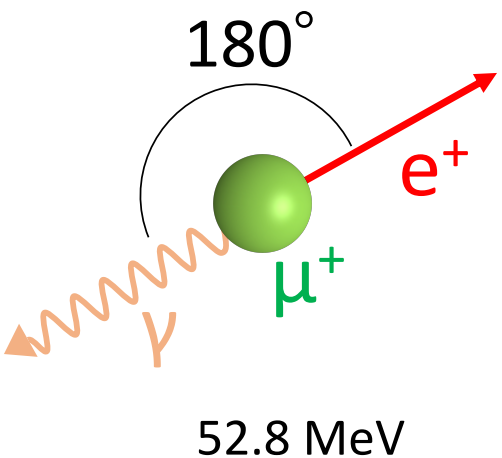
MEG II detector, designed for $\mu\to e\gamma$



- **Strategy: Precise & efficient measurement of decay**

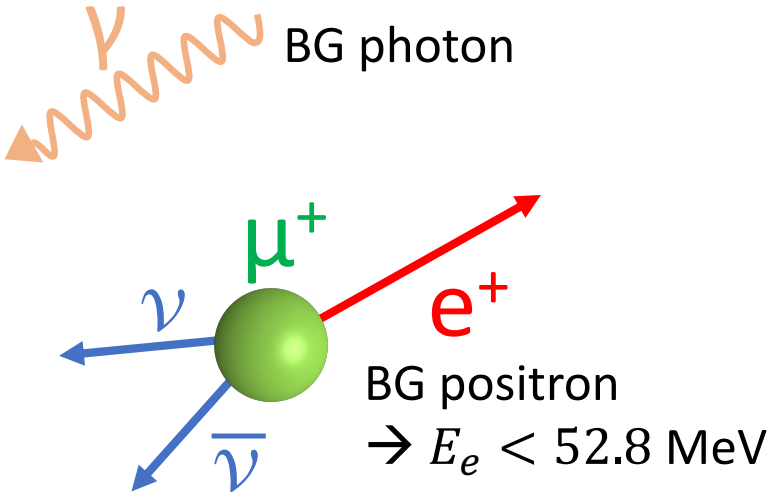
Signal

2-body kinematics

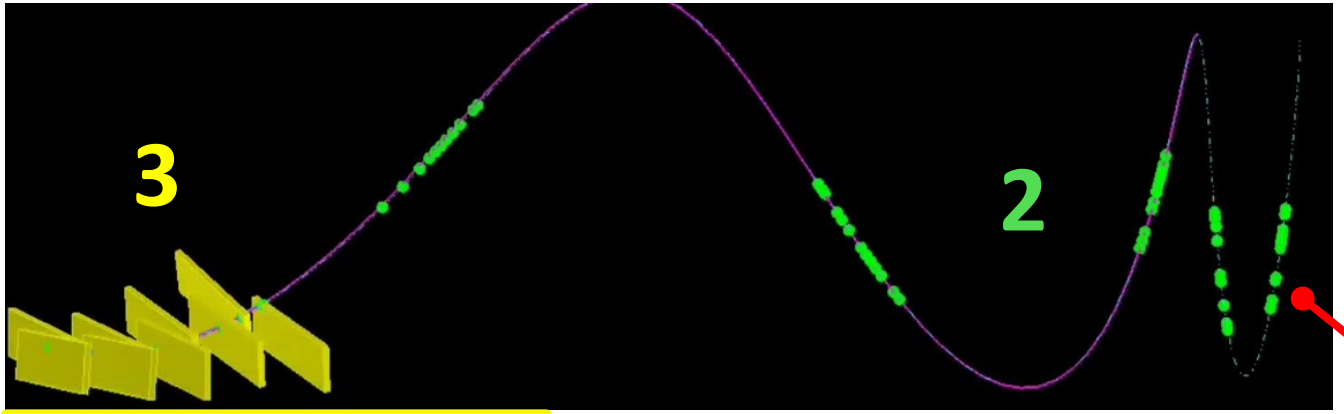


Background

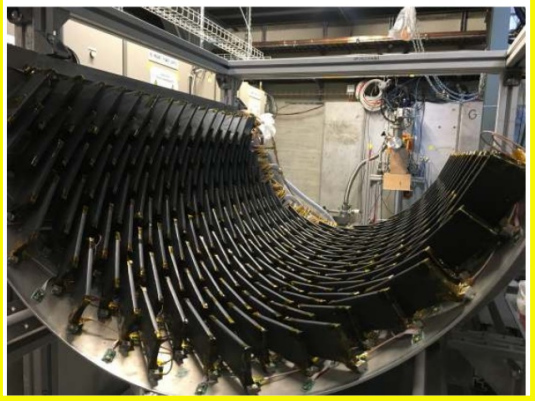
Accidental coincidence



MEG II positron spectrometer



1. Gradient magnetic field
2. Drift chamber for tracking
3. Scintillation counter for timing



- 512 plastic counters in total
- 110 ps resolution / hit
- 9 hits (average) / signal track

- Wire chamber w/ stereo geometry
- High-density readout (2 – 3 cells / cm^2)
- Reduced material ($1.6\times10^{-3}\ X_0$)

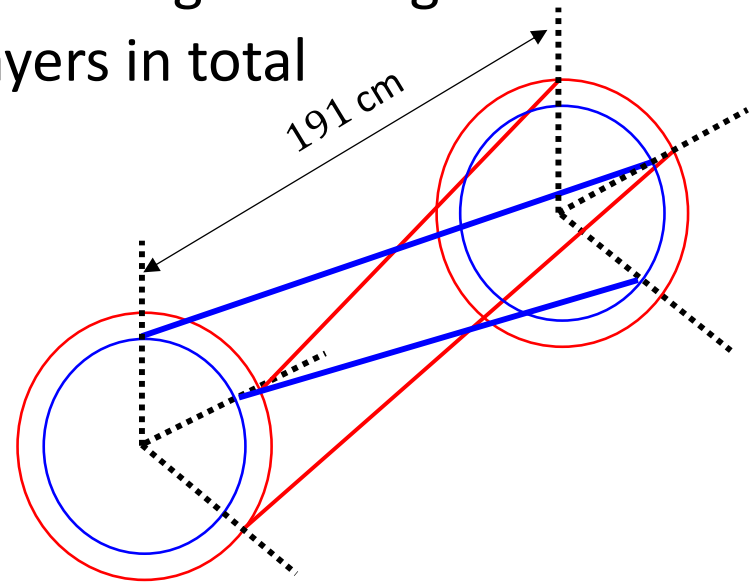
Tracking Challenge

- Connection of distant turn segments
- High pileup probability (30 – 50% occupancy in 300 ns)

Aim of this talk: Improve tracking algorithm

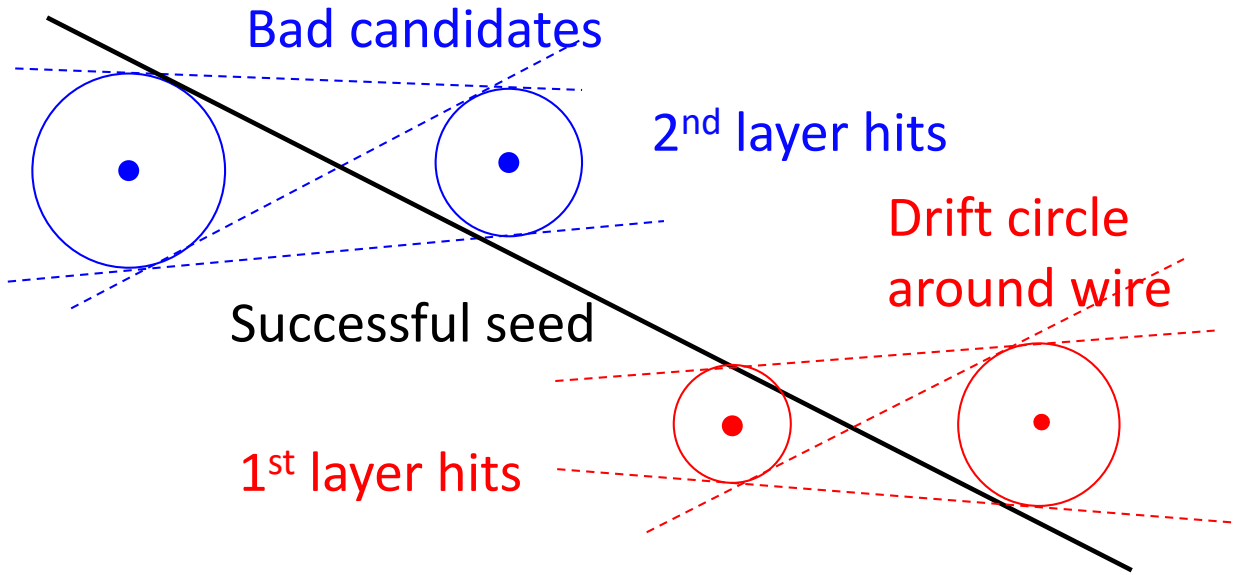
Tracking condition

- Chamber geometry
  - Alternating wire angle
  - 9 layers in total



- Hit resolution
  - 200 μm drift distance resolution
  - 15 cm position resolution along wire

- Current track pattern recognition
  - Local seeding + prolongation

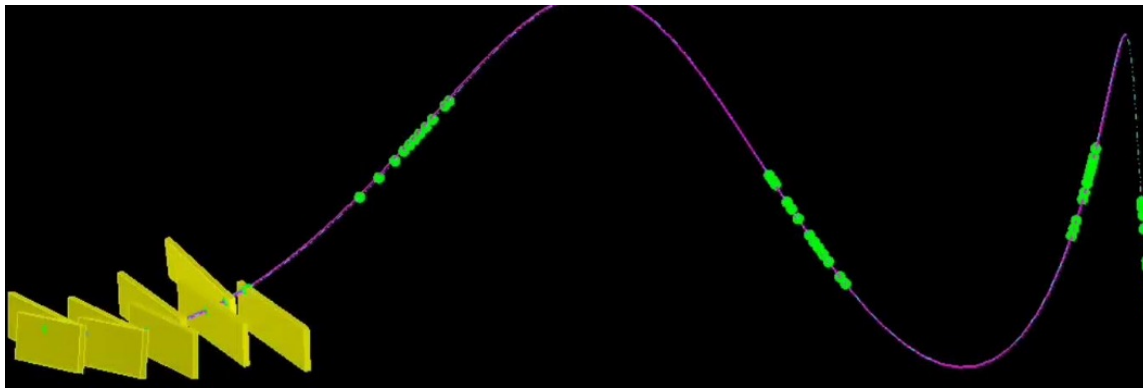


Limitations of current PR

- Sensitive to impurities in seeding
  → Not robust against pileup. Worse @high rate
- Local seeding cannot connect distant turns

Global approach

- Quest for global approach
  1. Can we connect all track hits at once?
  2. Can we even connect timing counter? (Enough resolution to separate pileup)



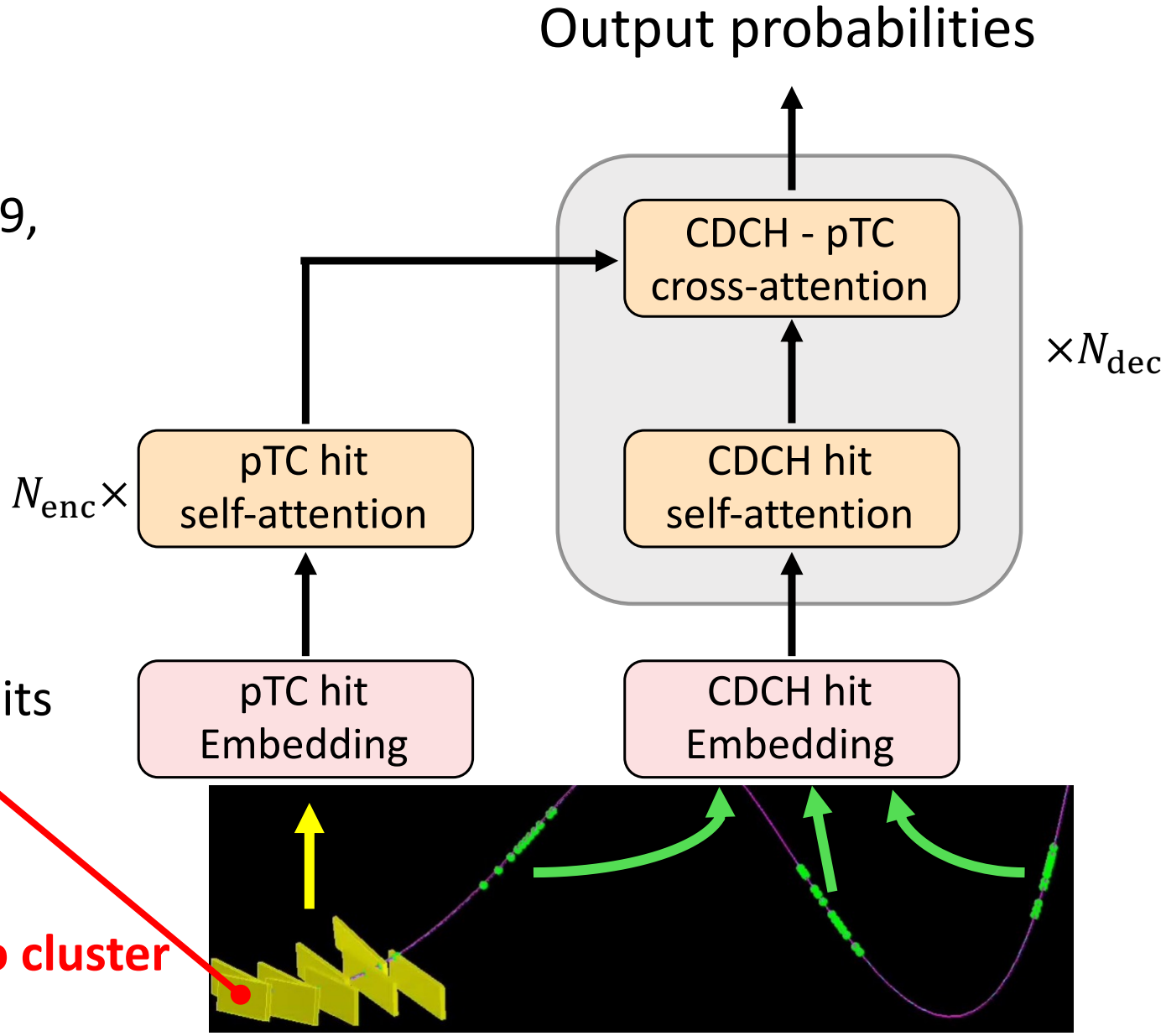
- Known global algorithms
  - Conformal mapping, Hough transform, etc.

- But, non-trivial for MEG II tracking
  - Use of gradient field
  - Multi-turn structure

Approach in this work:
ML for global pattern recognition

ML of choice: Transformer

- Transformer:
  - Relies on Attention mechanism
  - This work inspired by arxiv:2411.07149, application to collider tracking
- Model for MEG II
  - Predict probability for each CDCH hit to be connected with counters
  - Input on right side: All CDCH hits
  - Input on left side: Clustered counter hits



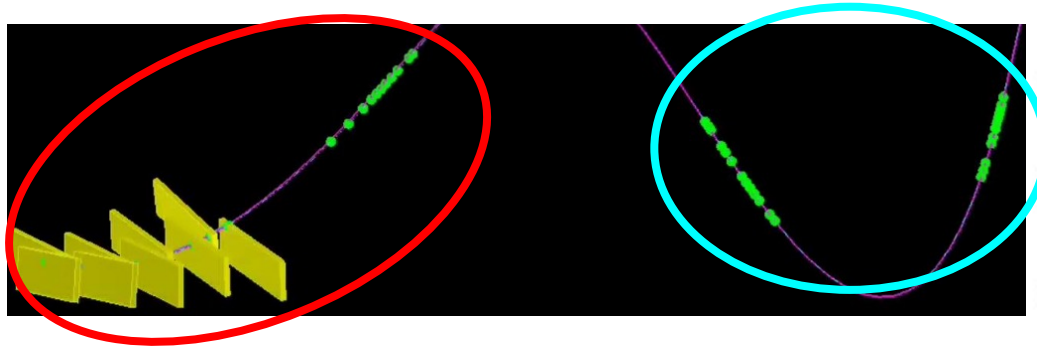
Clustering separates pileup beforehand
→ ML predicts if CDCH hit is connected to cluster

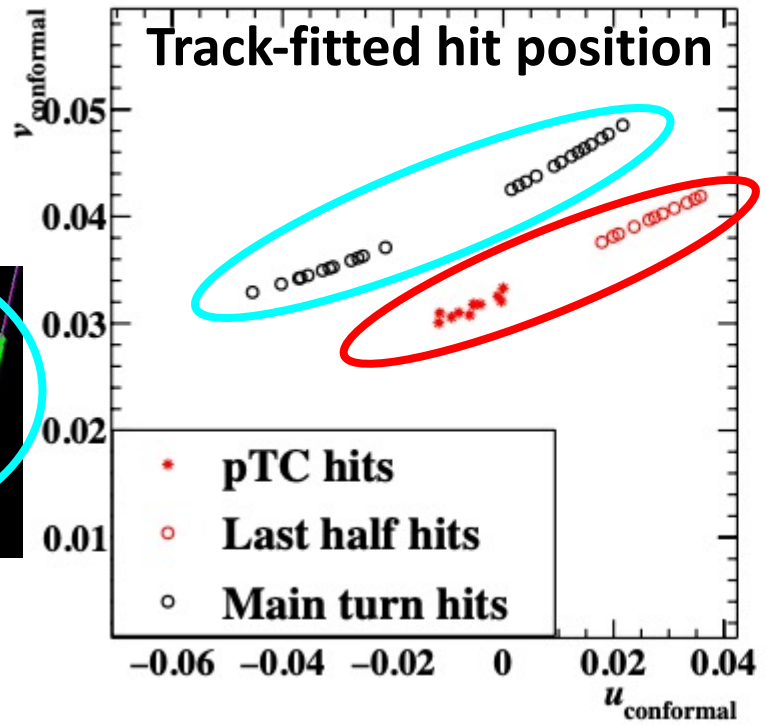
Feature inputs (1/2)

- Conformal mapping
  - Mapping of perfect circle in (x,y) → linear line in (u, v)
  - Different lines in conformal coordinate corresponding to different turn segment

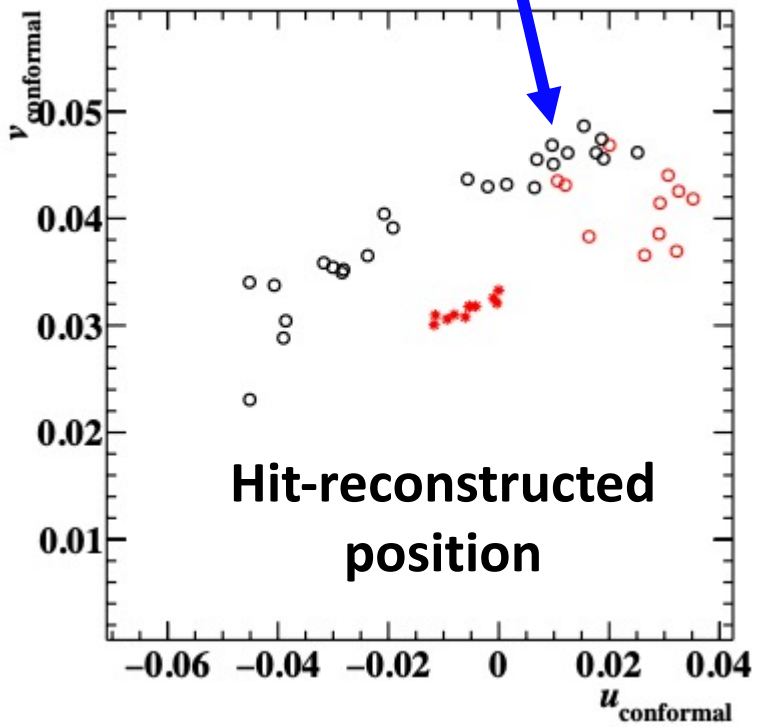
Conformal mapping

$$(u, v) = \left(\frac{x}{x^2 + y^2}, \frac{y}{x^2 + y^2}\right)$$





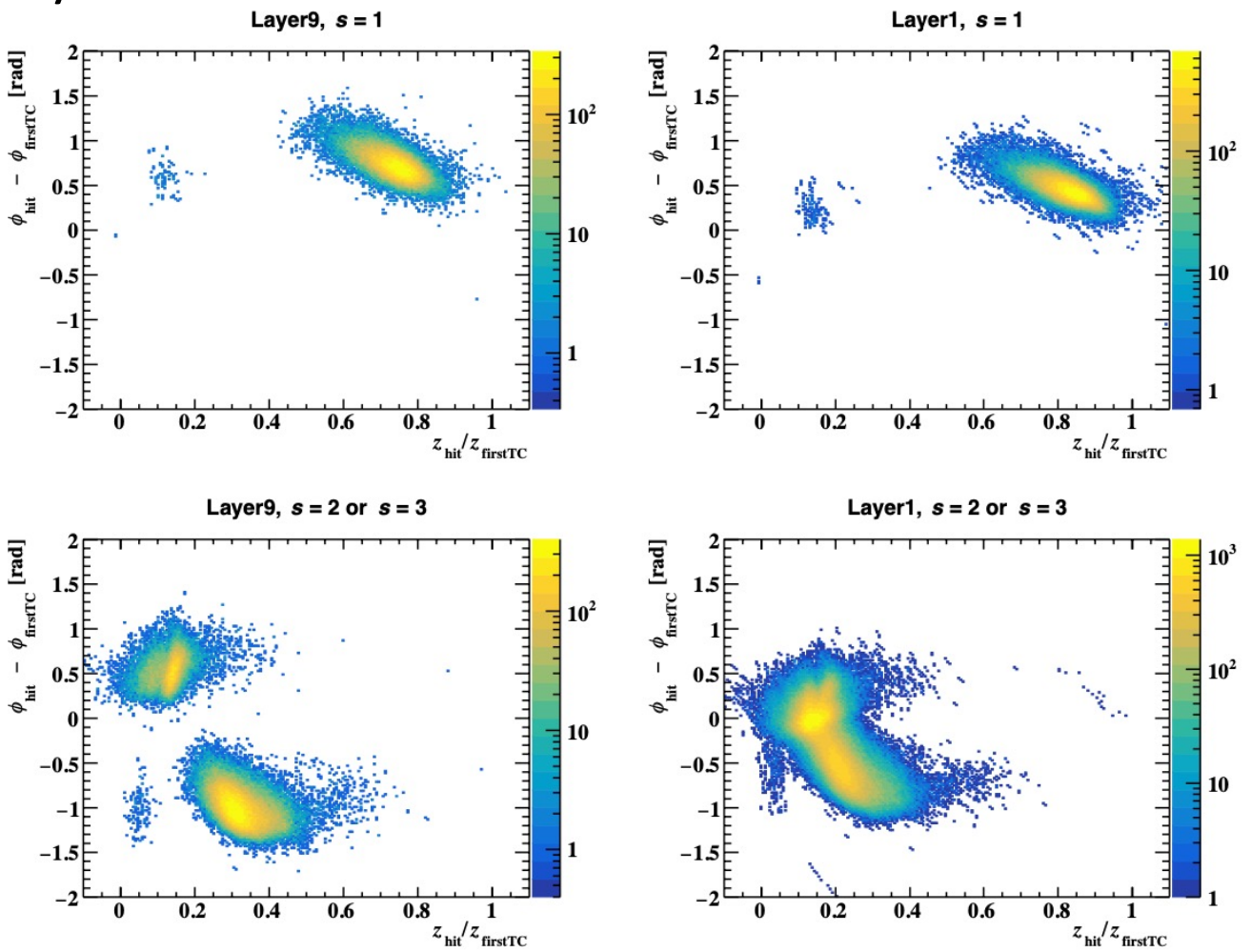
Variation due to limited z_{hit} resolution in reconstruction



Feature inputs (2/2)

- Explicit representation of turn-by-turn pattern
  - (z, ϕ) depends on turn segments & wire layer
  - (z, ϕ)-correction estimated for different turn segments
  - Different (z, ϕ)-corrected coordinates are concatenated to get feature input

Chamber hit feature: 47-dim vector (including others, conformal coordinate, etc.)

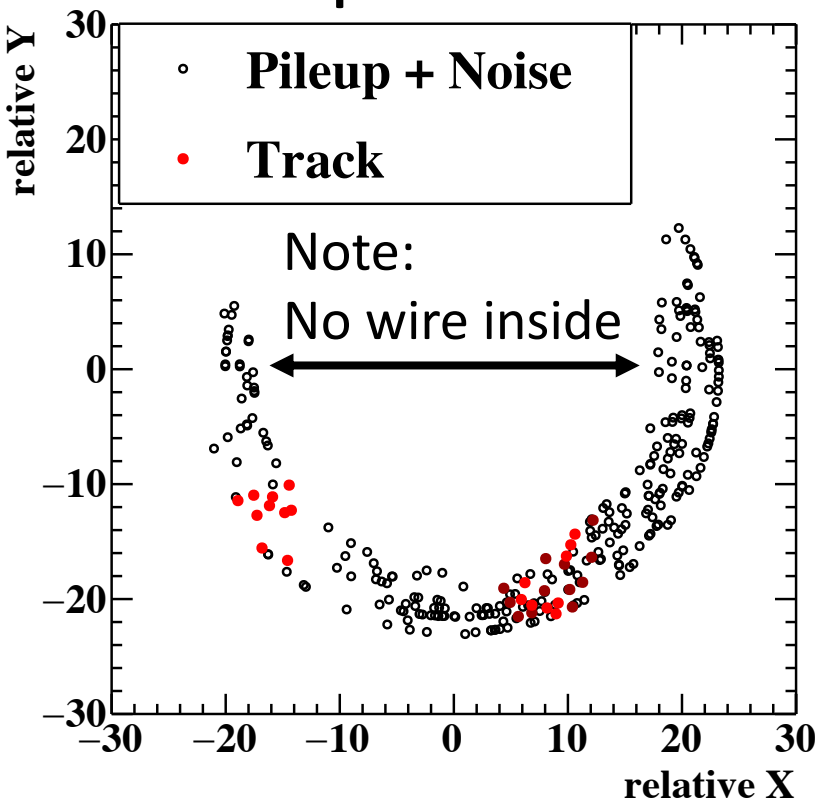


Training & example inference

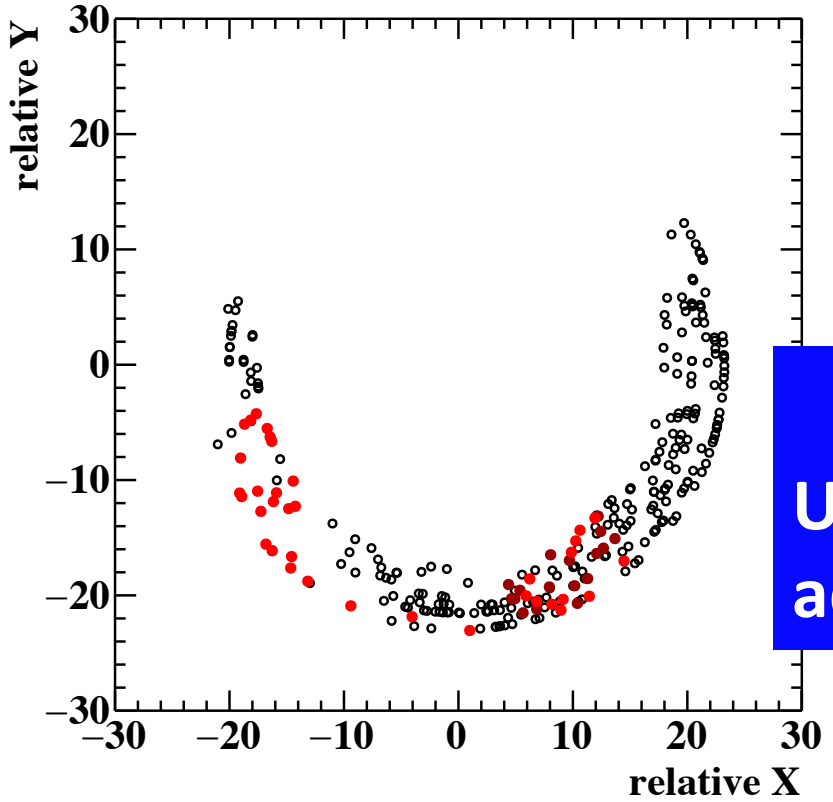
- Training samples: Mainly MC tracks (both 52.8 MeV & $\mu \rightarrow e\nu\nu$)
  - Training first with no-pileup samples (Likely learned track geometry)
  - Then, training with samples with pileup

Pre-training without pileup made the main training more efficient (3M samples, 3 days to train)

Sample from MC



ML inference



Tracking strategy

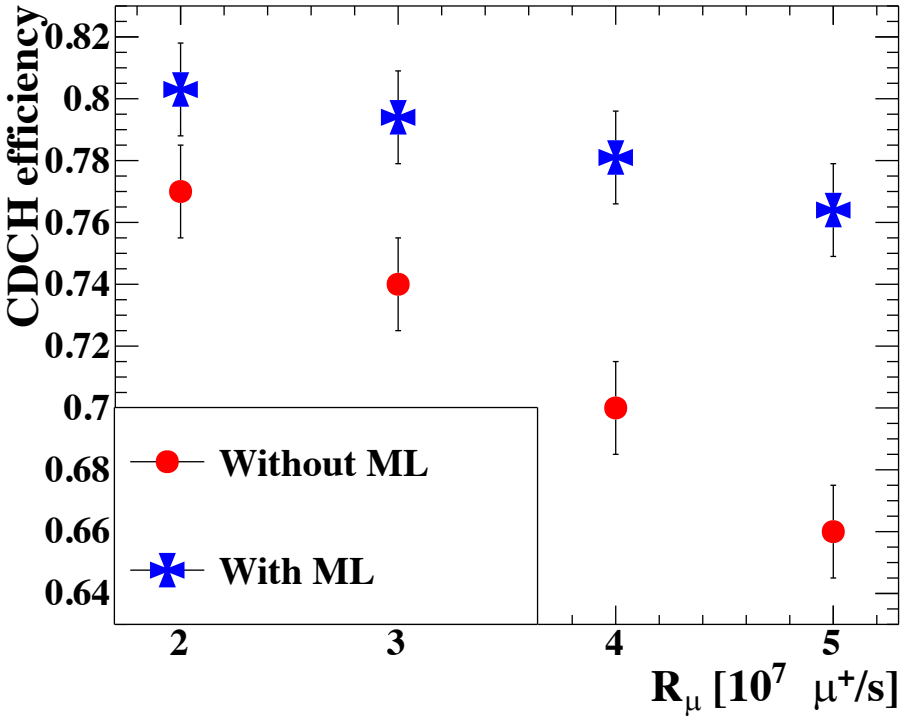
Use of existing PR, but take advantage of higher purity

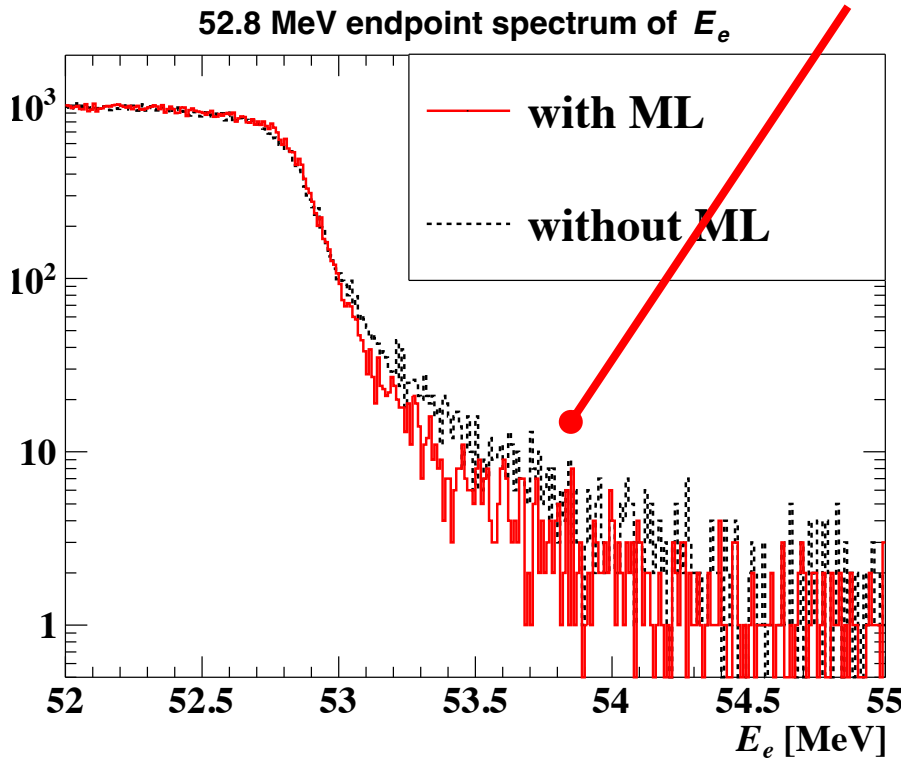
Result: Performance improvement

- Performance evaluated with MEG II data
  - Efficiency improvement by O(10%) (Especially, at higher rate)
  - Resolution improvement by ~5%
  - CPU cost reduced by $\times 0.8$

$\mu \to e\nu\nu$ spectrum bounded $E_e < 52.8$ MeV:
High energy tail caused by E_e error.
→ Reduction of tail means better resolution

Tracking efficiency





Discussion

- Impact on MEG II experiment
  - Improved efficiency & resolution will be applied to already taken data
  - In addition, we decided to increase muon rate: $4\times10^7 \rightarrow 5\times10^7$ μ/sec
    (Before, 4×10^7 was best because of low efficiency @5×10^7)

  → Would improve $\mu \rightarrow e\gamma$ sensitivity by ~10%

- Prospects
  - Now, ML implemented as classifier to filter out pileup hits
  - Possible extension of model to directly estimate track parameter
    (Hoping to further reduce CPU time & find tracks missed by local algorithm)

Summary

- Transformer-based model developed for MEG II positron tracking
  - Classifier to filter out pileup hits
  - Filtered hits fed into conventional track pattern recognition
  - Observed tracking performance improvement thanks to improved purity

- Significant improvement of the experiment
  - Not just improved the analysis of existing data
  - Also, decided to increase the muon stopping rate