RGH Recoil Detector Event Reconstruction & PID

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CEBAF Large Acceptance Spectrometer

Background and Motivations

Generalized Parton Distributions of the Proton

- Generalized parton distributions (GPDs) contain elusive three-dimensional information on nucleon structure
  1. ***Chiral even GPDs***, H, E, $\tilde{H}$, $\tilde{E}$ → DVCS is "golden channel"
     - H → best probed with unpolarized target (RG-A/B/K @ CLAS12)
     - $\tilde{H}$ → best probed with longitudinally polarized target (RG-C @ CLAS12)
     - E → **best probed with transversely polarized target (RG-H @ CLAS12)**
  2. ***Chiral odd GPDs***, H_T, E_T, $\tilde{H}_T$, $\tilde{E}_T$ → DVMP
- GPDs H and E enter into Ji's sum rule for both quarks and gluons, which provides a hypothesis for obtaining the proton's intrinsic spin-1/2
- Additionally GPDs H and E probe gravitational form factors (GFFs), which encode nucleon mechanical properties
- Access to properties of GPD H from CLAS12 unpolarized pDVCS, so contribution of access to GPD E from RGH would be very complementary!

		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	H		$2\tilde{H}_T + E_T$
	L		$\tilde{H}$	$\tilde{E}_T$
	T	E	$\tilde{E}$	$H_T, \tilde{H}_T$

Ji's Sum Rule

$$\int_0^1 dx x \left(H_{q,g}(x,\xi,t=0) + E_{q,g}(x,\xi,t=0) \right) = 2J_{q,g}$$

$$\frac{1}{2} = \sum_q J_q + J_g = \frac{1}{2}\Delta\Sigma(\mu) + L_q^z(\mu) + J_g^z(\mu)$$

X. Ji and Y. Zhao, 10.1142/S2010194516600016 (2016)

X. Ji, 10.1103/PhysRevLett.78.610 (1997)

Measurement of GPD E

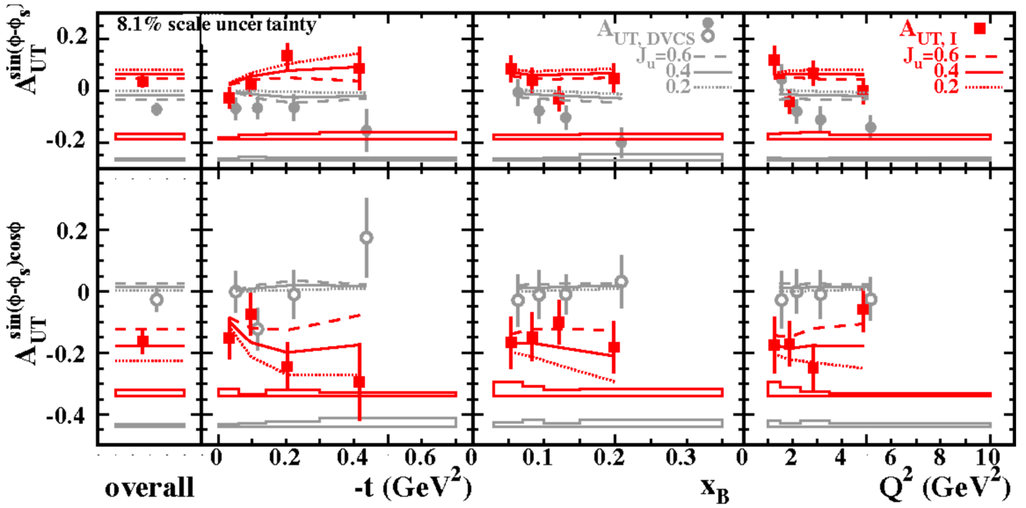
- GPD E currently very poorly constrained … transversely polarized target is much more difficult to measure experimentally!
  - HERMES pDVCS from transversely polarized target
  - CLAS12 nDVCS from unpolarized target
- In our DVCS experiments, we are sensitive to a convolution of the GPD E with respect to longitudinal quark momentum, x, as it is not experimentally accessible

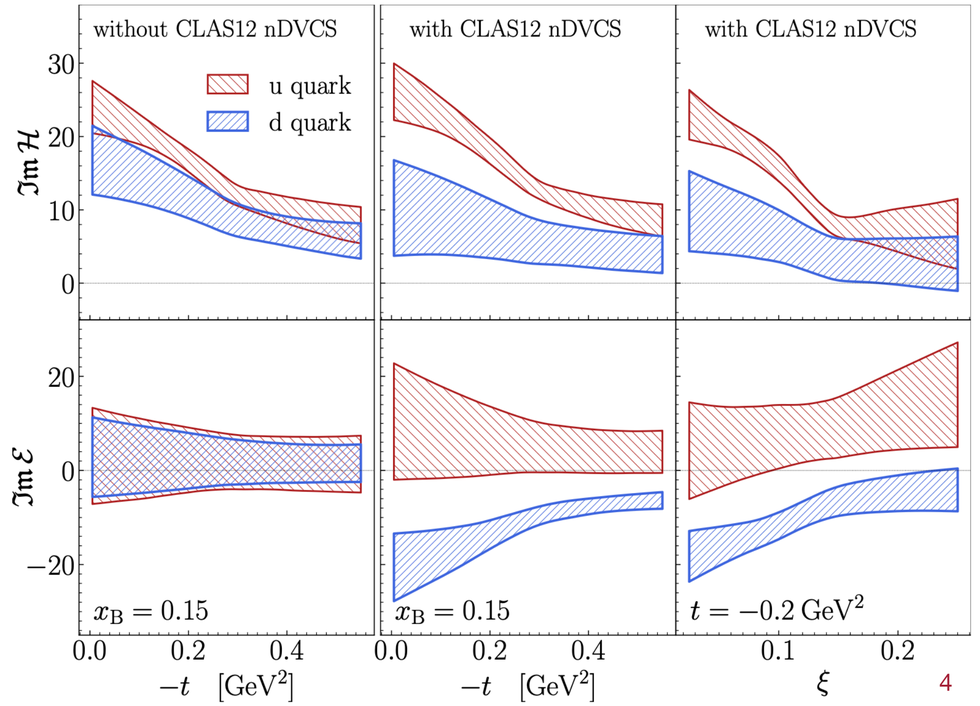
$$\mathcal{E}(\xi,t) = \int_0^1 dx \left[\frac{1}{x-\xi+i\epsilon} - \frac{1}{x+\xi+i\epsilon}\right] E(x,\xi,t)$$

$$\mathcal{E}(\xi,t) = \mathrm{Re}\mathcal{E} + i\mathrm{Im}\mathcal{E}$$

$$\mathrm{Re}\mathcal{E}(\xi,t) = \mathcal{P}\int_0^1 dx \left[\frac{1}{x-\xi} + \frac{1}{x+\xi}\right] \left[E(x,\xi,t) - E(-x,\xi,t)\right]$$

$$\mathrm{Im}\mathcal{E}(\xi,t) = E(\xi,\xi,t) - E(-\xi,\xi,t)$$





HERMES Collaboration, 10.1088/1126-6708/2008/06/066 (2008)

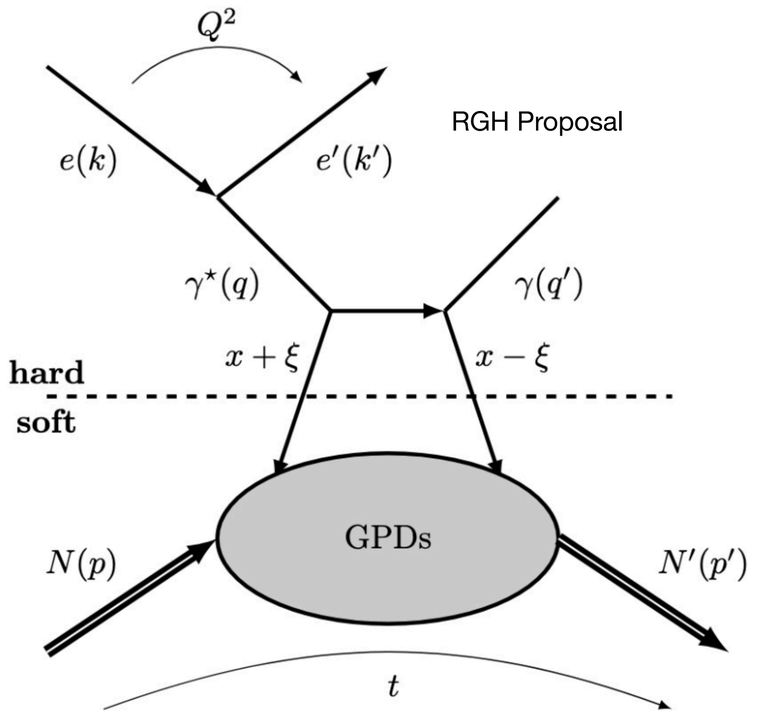
A. Hobart, *et al*. (CLAS Collaboration), 10.1103/PhysRevLett.133.211903 (2024)

Deeply Virtual Compton Scattering on a Transversely Polarized Target

- Sensitive to Im$\mathcal{E}$ through (transversely polarized) ***target spin asymmetry*** measurement

$$A_{UT} \propto \frac{d\sigma_{UT}^{\uparrow} - d\sigma_{UT}^{\downarrow}}{d\sigma_{UT}^{\uparrow} + d\sigma_{UT}^{\downarrow}}$$

Need to account for different target polarizations and charge accumulations in each configuration, dilution factor, etc. (similar to RGC)

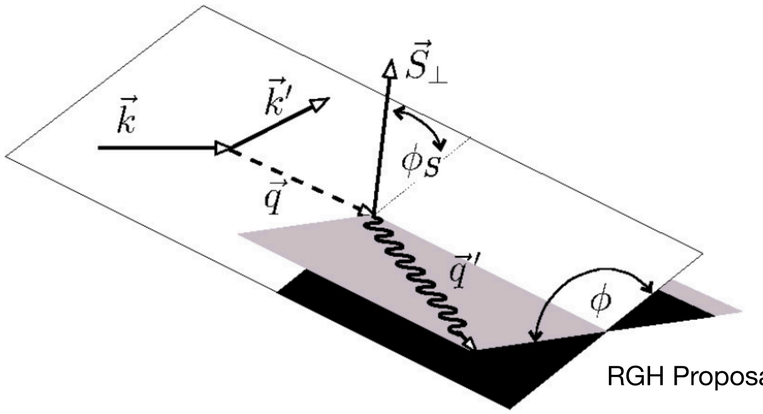


RGH Proposal

- At leading order,

$$A_{UT} \propto c_1^{UT} \sin(\phi - \phi_S)\cos\phi \propto f(CFFs, FFs)$$

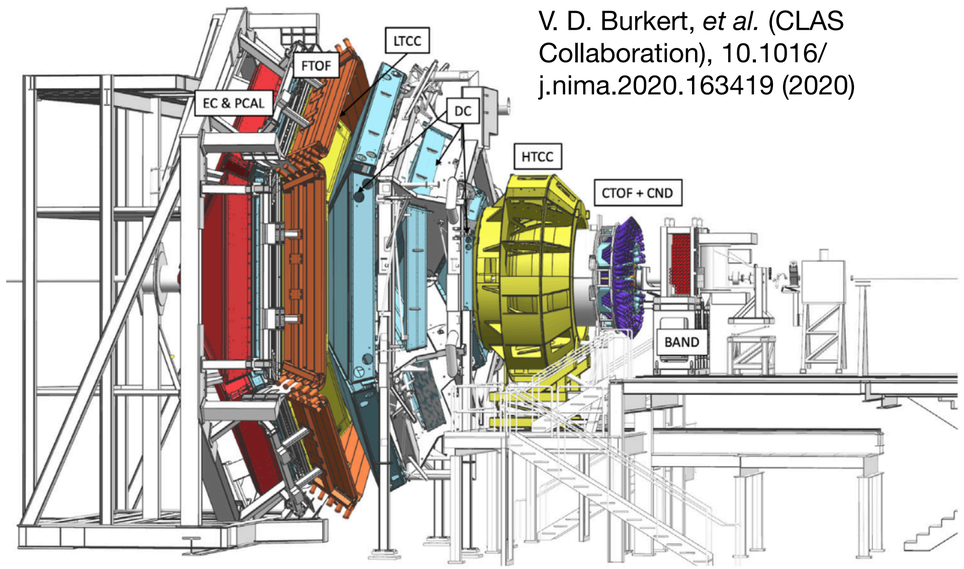
where strongest CFF sensitivity is to Im$\mathcal{E}$.



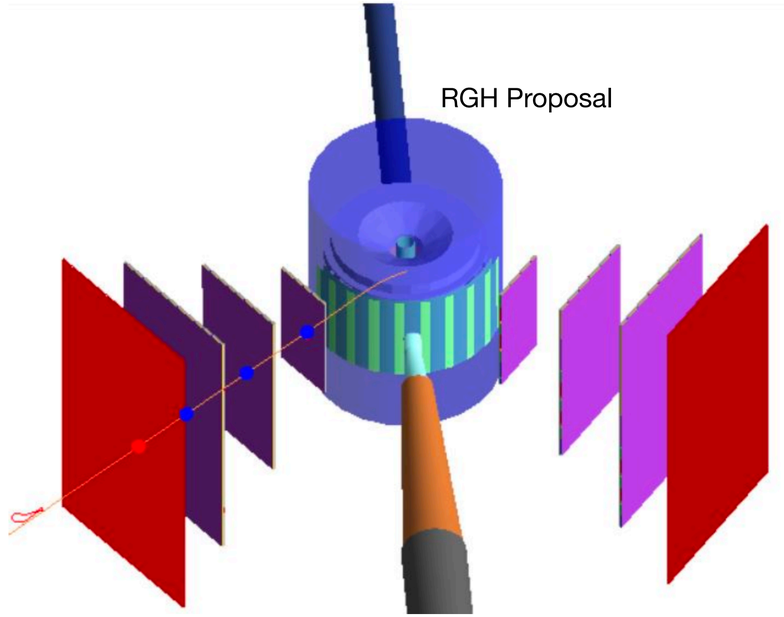
RGH Proposal

Motivation for Recoil Detector

See S. Niccolai's talk for more information on the recoil detector!



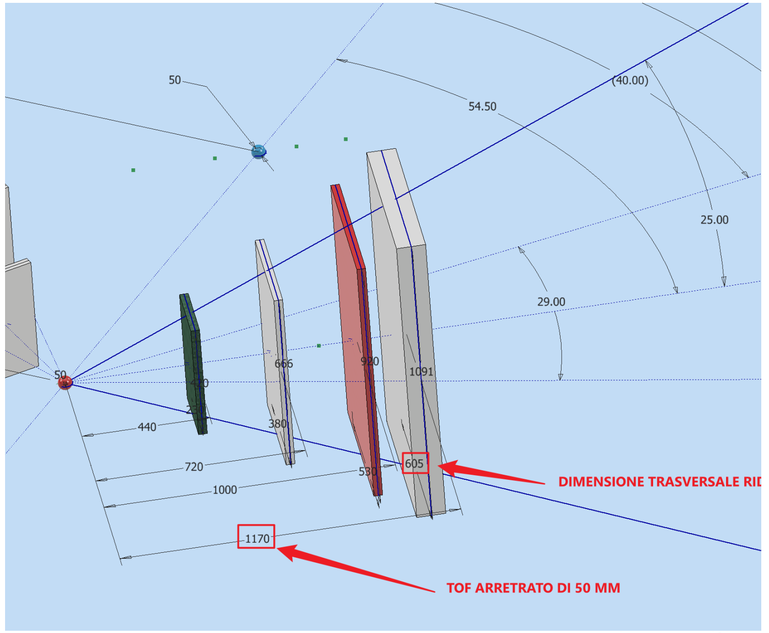
V. D. Burkert, *et al.* (CLAS Collaboration), 10.1016/j.nima.2020.163419 (2020)



- In order to install equipment to transversely polarize target for RGH, Central Detector (CD) must be removed
- However, CD provides extremely valuable detection of slower moving protons for pDVCS → ~ half of DVCS protons end up in this region!
- To recover majority of these protons: new ***recoil detector system*** (REC) for RGH

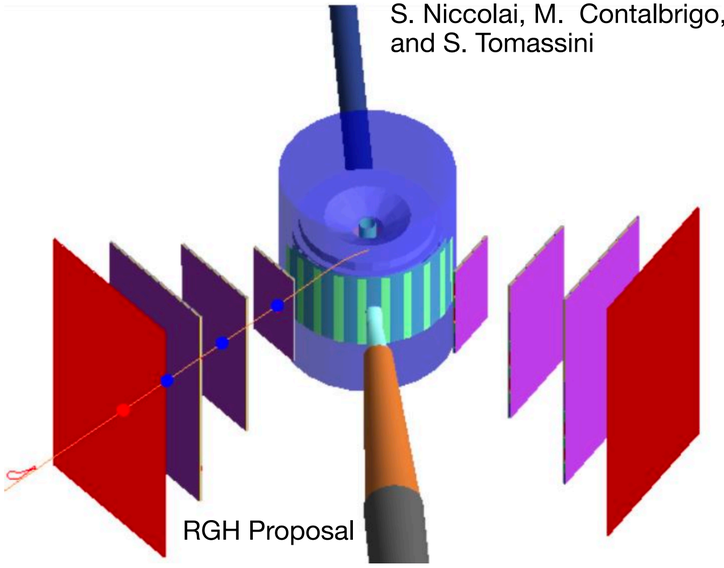
Recoil Detector Parameters

- REC involves tracking and time of flight for protons
  - REC-TRK: 3 tracking detectors for position reconstruction
    - μR well trackers; $O(100\mu\text{m})$ spatial resolution
  - REC-TOF: 1 time of flight detector for β reconstruction
    - plastic scintillation; $O(<100\text{ps})$ timing resolution
- REC originally has “starting angle” (relative to beamline) of 40°, “horizontal opening angle” of 29°, “vertical opening angle” of 50°



From correspondence with S. Niccolai, M. Contalbrigo, and S. Tomassini

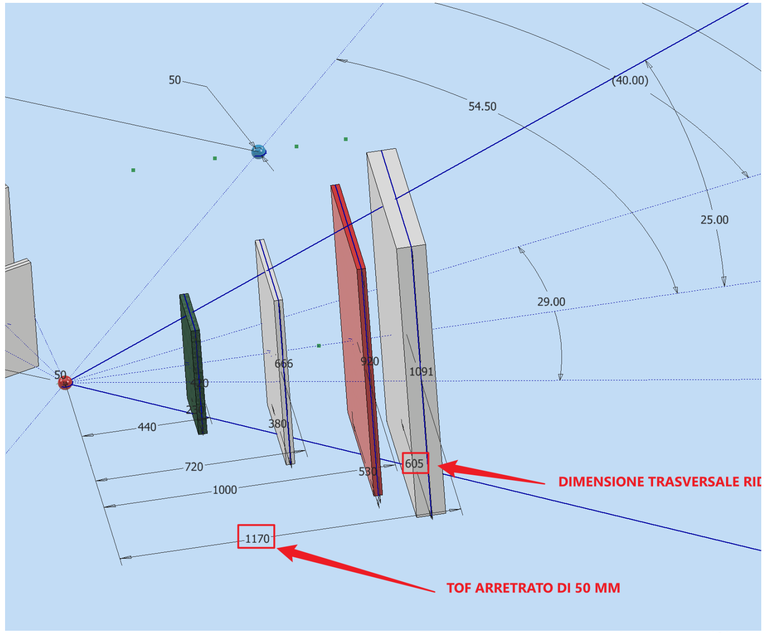
	Tracker Region 1	Tracker Region 2	Tracker Region 3	TOF
Radius (from Target)	44.00 cm	72.00 cm	100.00 cm	122.00 cm
Height	41.04 cm	67.15 cm	93.26 cm	113.78 cm
Width	22.76 cm	37.24 cm	51.72 cm	63.10 cm



RGH Proposal

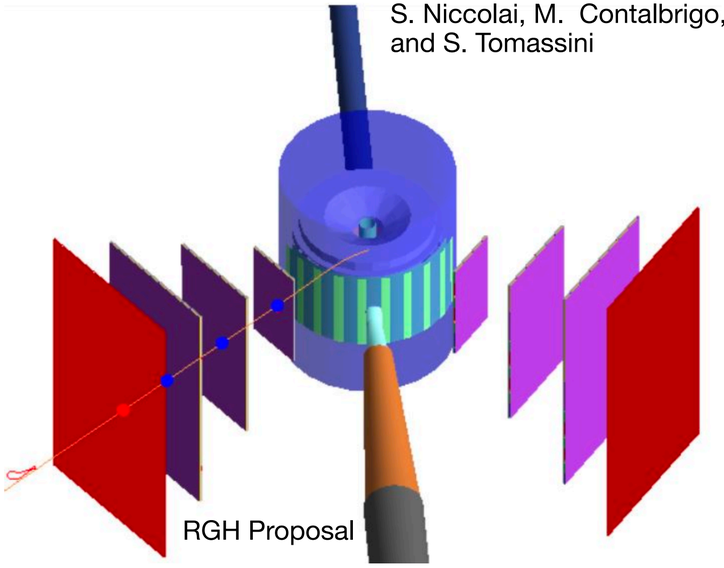
Recoil Detector Parameters

1. **Can we improve acceptance by adjusting angular configuration of the recoil detector?**
   - Opening angle limited to be in (40˚, ~48˚) range given other beamline requirements
   - Possible asymmetric opening angle?
2. **What is optimal way to reconstruct hits in the recoil detector?**
   - Initial polynomial χ^2 reconstruction
   - New MLP reconstruction technique
3. **Can we perform any sort of PID with this detector setup, given limited magnetic field exposure?**
   - Typically expect to detect mostly protons and neutrons in CD region, but would be good to *know* we are detecting protons



From correspondence with S. Niccolai, M. Contalbrigo, and S. Tomassini

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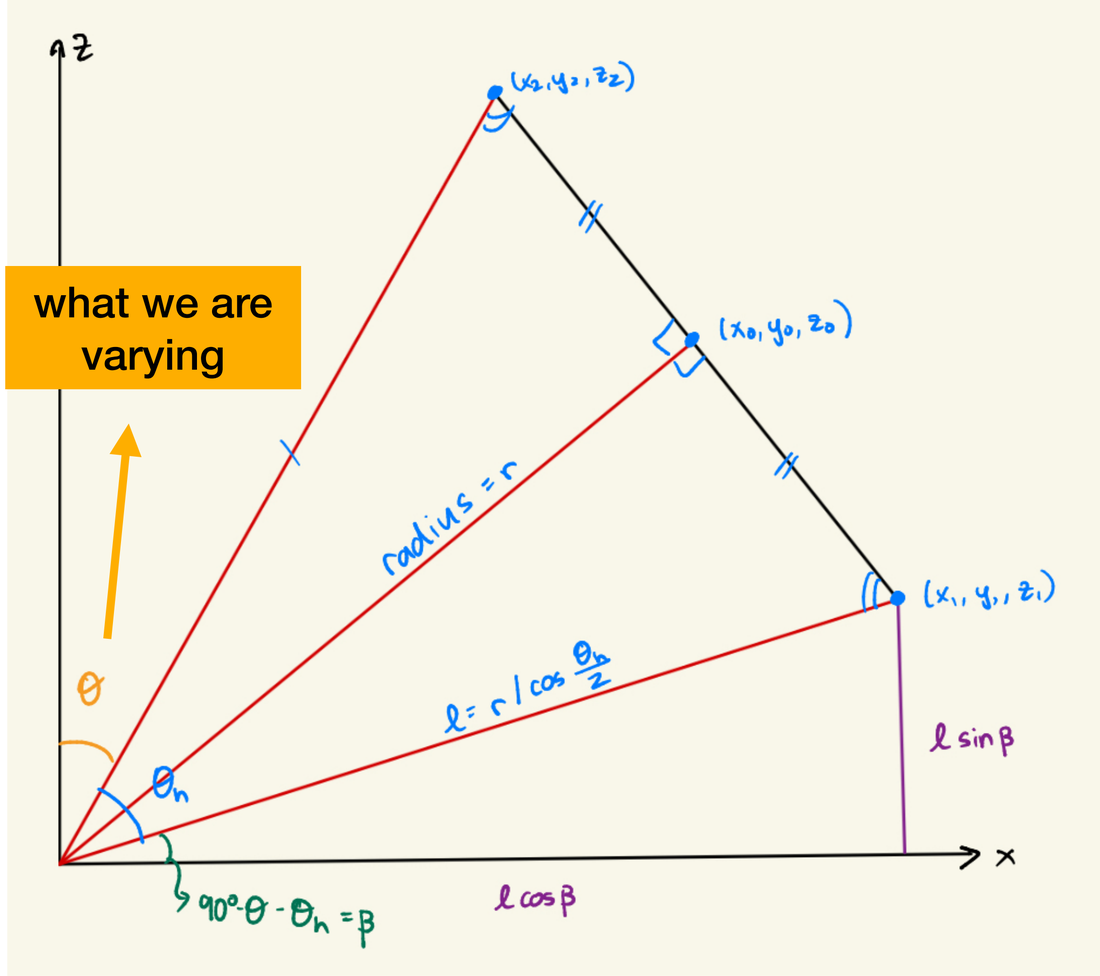


RGH Proposal

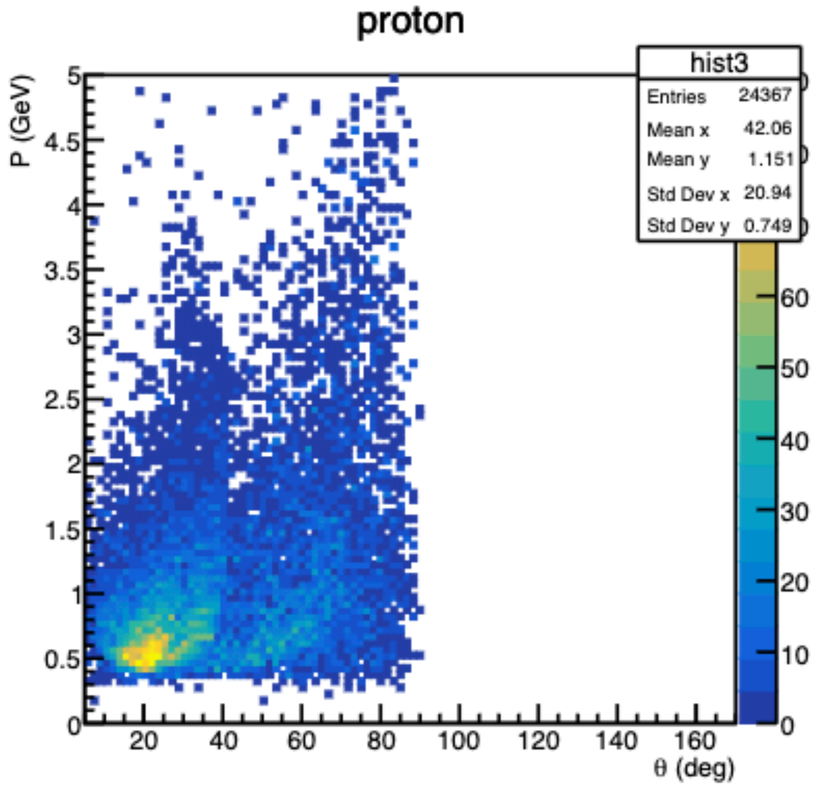
Starting Angle Optimization

Optimizing Starting Angle

- ***Can an adjusted starting angle offer increased acceptance for DVCS protons?***
- ***Will using a symmetric or asymmetric configuration for the two recoil sectors affect outcomes?***
  - Since the beam is transversely polarized, maybe there is asymmetric azimuthal preference?
- Limited range to vary the starting angle to avoid interference with other components of the CLAS12 beamline (HTCC, target polarization apparatus)
- We adjusted the geometry of the recoil detector system design and tested yields of same MC pDVCS event sample, generated with ***genepi***
  - ~1000 files, ~3 million generated pDVCS events
  - Beam energy of 10.6 GeV
  - Emulating NH_3 target
  - Wide x_B, Q^2, t range



Symmetric Reconstruction Example: $40^\circ/40^\circ$ Configuration



Multiple reconstruction techniques:

- 4-point reconstruction (x,y,z of crosses in 3 REC-TRK detector regions + x,y,z of REC-TOF cluster → developed by S. Niccolai
- 3-point reconstruction (x,y,z of crosses in 3 REC-TRK detector regions + e^- vertex → developed by J. S. Alvarado) used in proposal
- Both involve χ^2 fits to hit points.

For $40^\circ/40^\circ$ configuration, 24367 events.

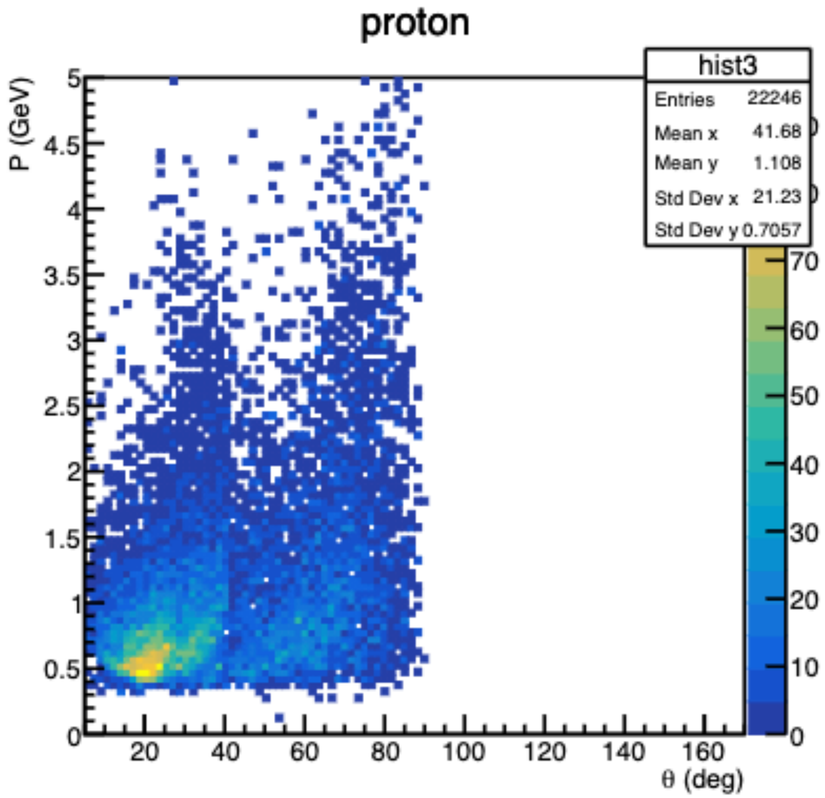
← 3 point reconstruction, made using code of J. S. Alvarado

Other symmetric yields tested:

- $44^\circ/44^\circ$: 25124 events (1.0311x initial yield)
- $45^\circ/45^\circ$: 25495 events (1.0463x initial yield)
- $47^\circ/47^\circ$: 25721 events (1.0556x initial yield)

Opening angle changed in geometry and MC re-“cooked” (*work of K. Neupane)*.

Asymmetric Reconstruction Example: 41°/45° Configuration



To allow for asymmetric opening angles, adjusted GEMC coatjava definitions for recoil geometry to allow for each sector to have a different opening angle.

For 41°/45° configuration, 22246 events (0.9130x initial yield).

← 3 point reconstruction, made using code of J. S. Alvarado

Other symmetric yields tested:

- 45°/41°: 21787 events (0.8941x initial yield)
- 45°/47°: 22439 events (0.9209x initial yield)

Opening angles changed in geometry and MC re-“cooked”.

Summary of Linear Reconstruction

- Multiple methods of performing reconstruction using linear fit to crosses and clusters
- However, not fully accounting for magnetic field despite minimal effects
- Difficult to model particles “swimming” in field, especially as proton vertex is difficult to reconstruct, and we don’t want to rely on the vertex of another particle to determine it, as this could introduce systematic issues
- New modeling method?

Overall results with linear reconstruction:

- 40°/40°: 24367 events
- 44°/44°: 25124 events (1.0318x initial yield)
- 45°/45°: 25495 events (1.0463x initial yield)
- 47°/47°: 25721 events (1.0556x initial yield)
- 41°/45°: 22246 events (0.9130x initial yield)
- 45°/41°: 21787 events (0.8941x initial yield)
- 45°/47°: 22439 events (0.9209x initial yield)

Reconstruction with MLP-Assisted Tracking

MLP-Assisted Tracking Overview

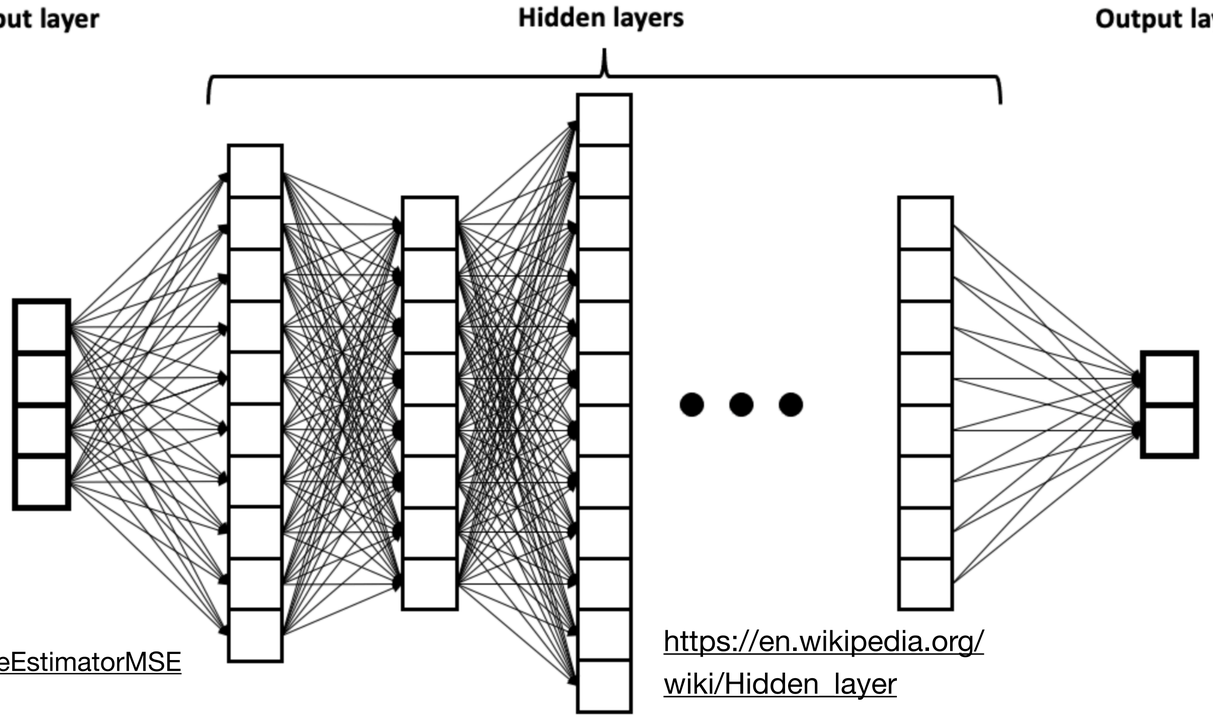
See T. Cao's talk for more information on the development of the reconstruction MLP!

- Brief summary of (initial) MLP features:
  - Nine "input dimensions" → (x, y, z) position of "clustered" hits in three recoil tracking layers → $(x_1, y_1, z_1, x_2, y_2, z_2, x_3, y_3, z_3)$
  - Three "state dimensions" →(p, θ, ϕ)
  - Arbitrarily "training set" selected from total Monte Carlo sample (80% of sample) develops MLP parameterization and tests modeling on remaining Monte Carlo events as a "validation set" (20% of sample)
- Developed from a similar model used for μCLAS12 reconstruction

MLP hyper-parameters:

- 64 hidden dimensions
- 3 layers
- Learning rate of 10^{-3}
- Dropout of 0.1
- 50 training epochs

https://github.com/tongtongcao/rghTrackStateEstimatorMSE

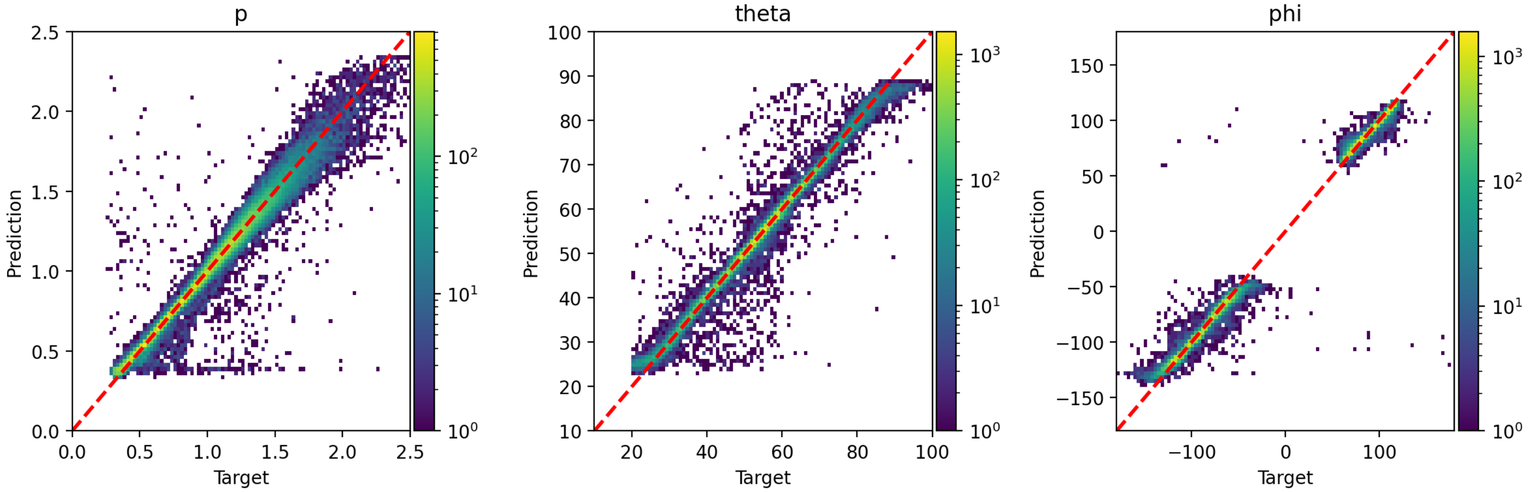


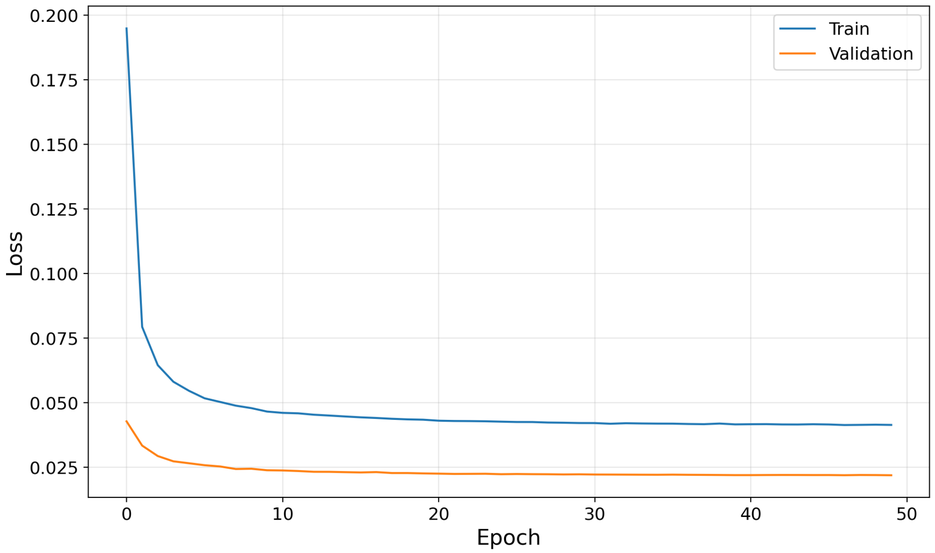
https://en.wikipedia.org/wiki/Hidden_layer

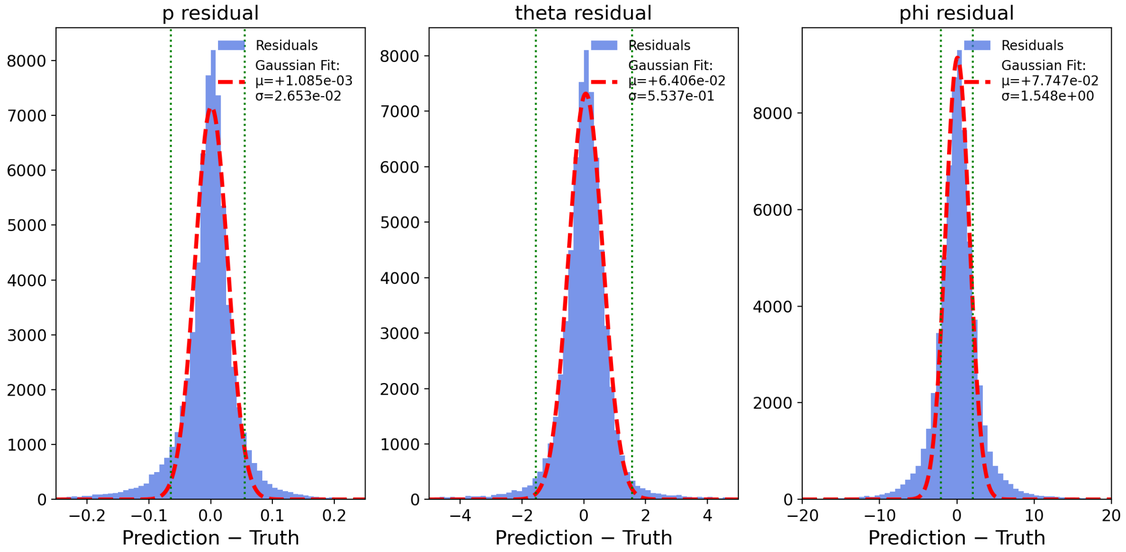
Monte Carlo Quality Cuts:

- $0.1 \text{ GeV} \leq p < 3.5 \text{ GeV}$
- $1 \text{ ns} \leq \text{tof} < 20 \text{ ns}$
- $20^\circ \leq \theta < 100^\circ$
- We also shifted the azimuthal angle distributions to make them "smooth" for MLP to interpret more easily

MLP Symmetric Reconstruction Example: 40°/40° Configuration

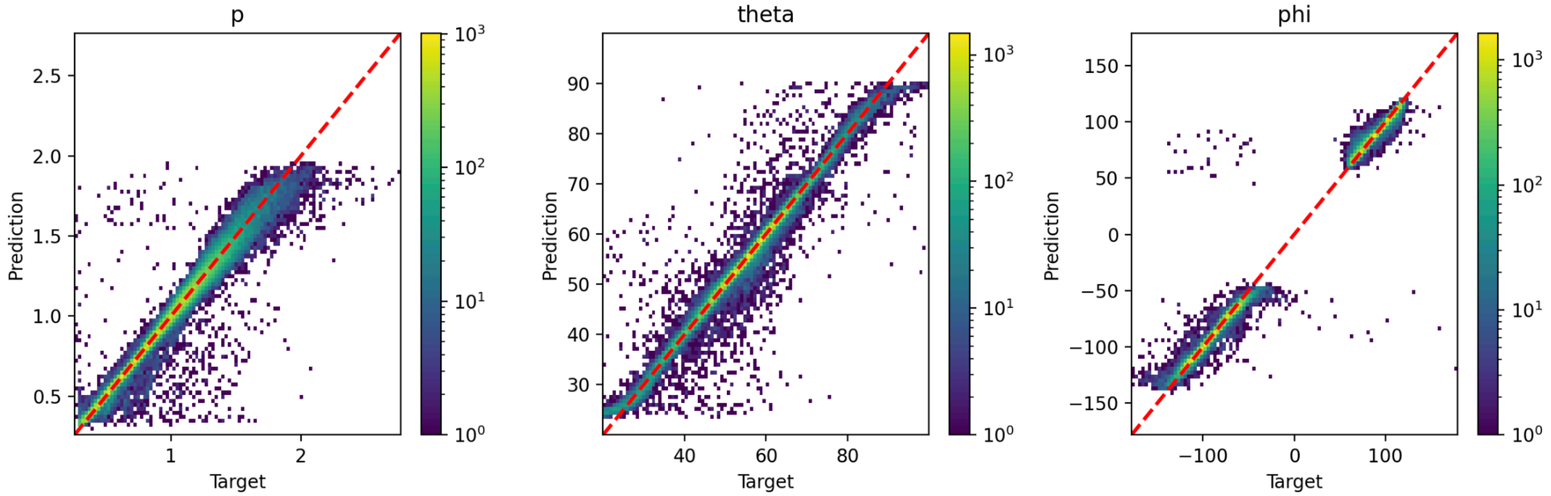


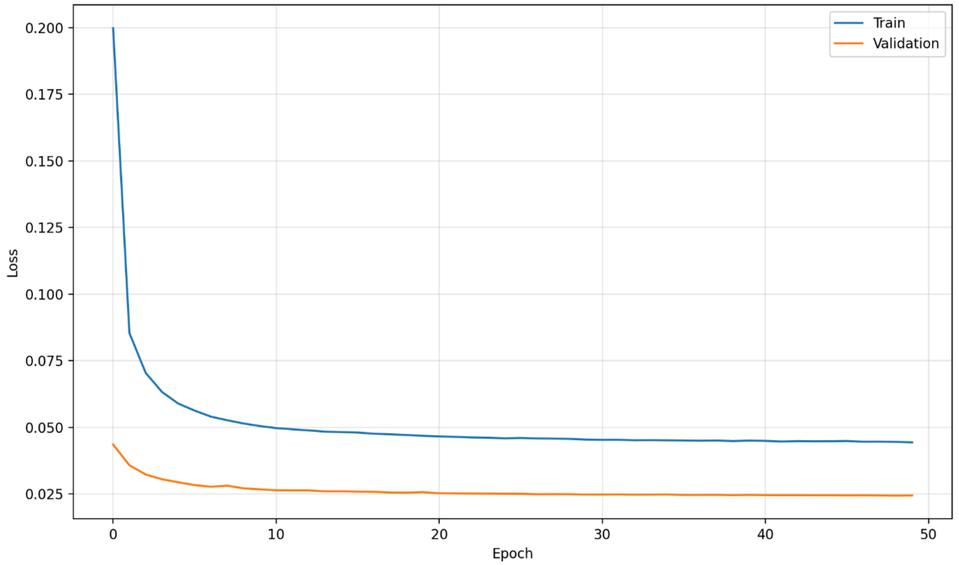


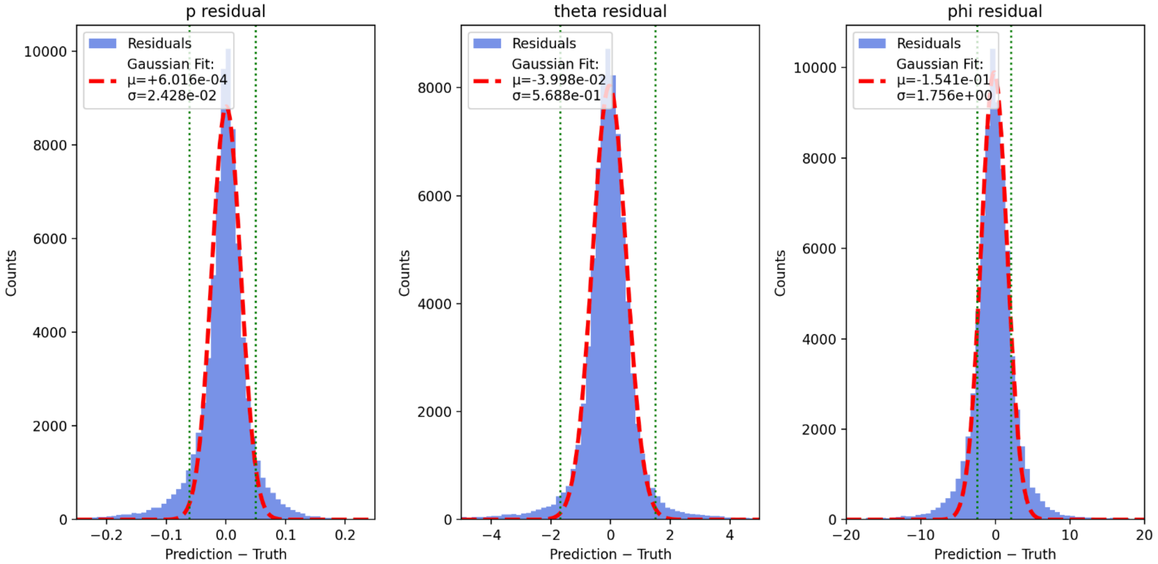


- Δp: 0.0011 GeV $\pm$ 0.0265 GeV
- $\Delta\theta$: 0.0064° $\pm$ 0.5537°
- $\Delta\phi$: 0.0775° $\pm$ 1.5480°

MLP Asymmetric Reconstruction Example: 40°/48° Configuration

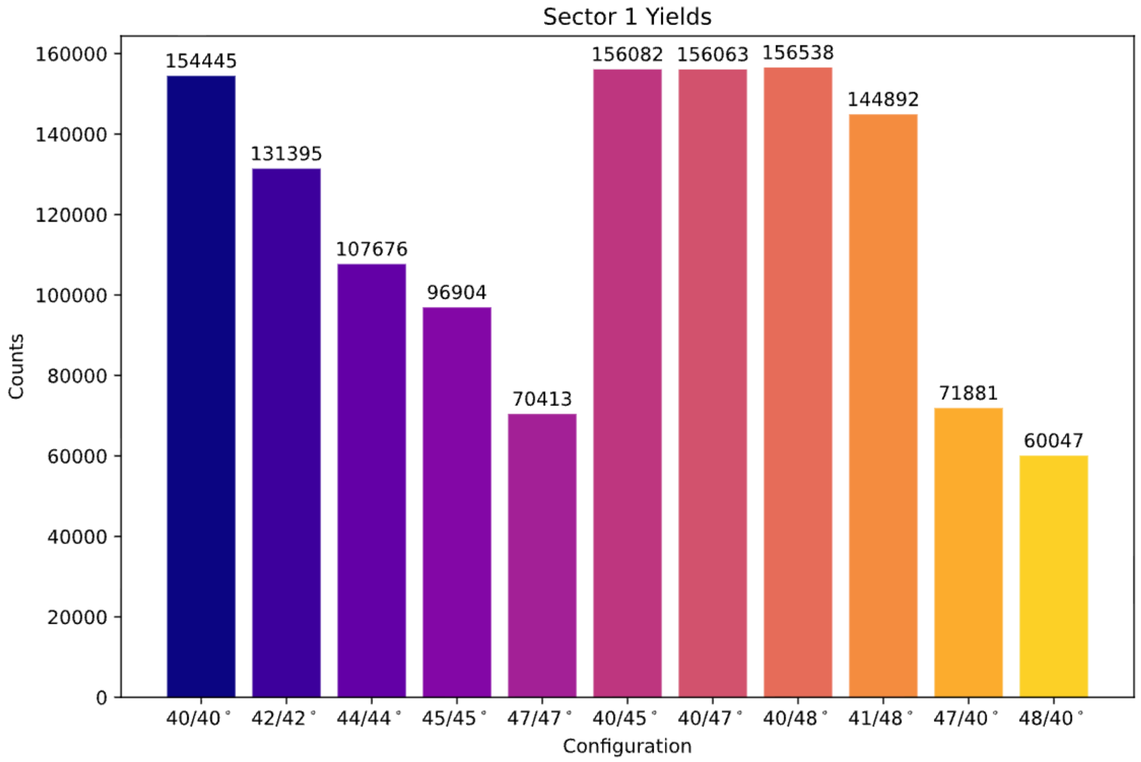


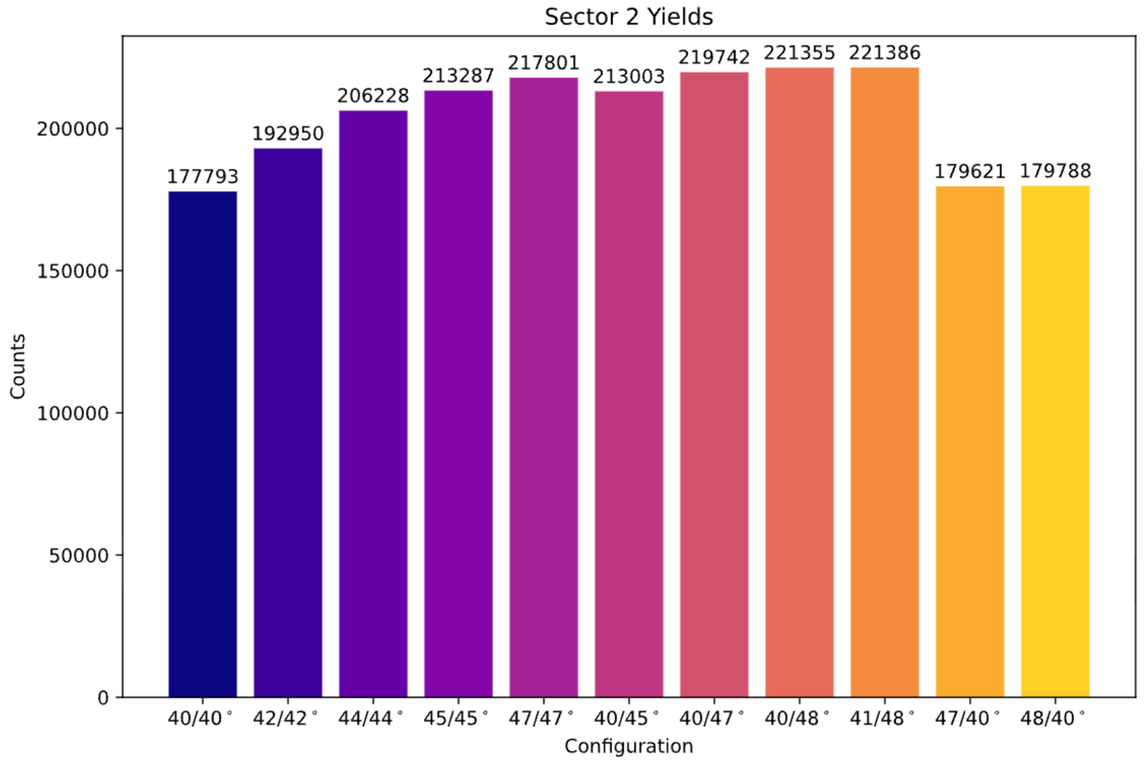




- Δp: 0.0006 GeV $\pm$ 0.0243 GeV
- $\Delta\theta$: $-0.0400^\circ \pm 0.5688^\circ$
- $\Delta\phi$: $-0.1541^\circ \pm 1.7560^\circ$

Summary of Sector Dependent Yields

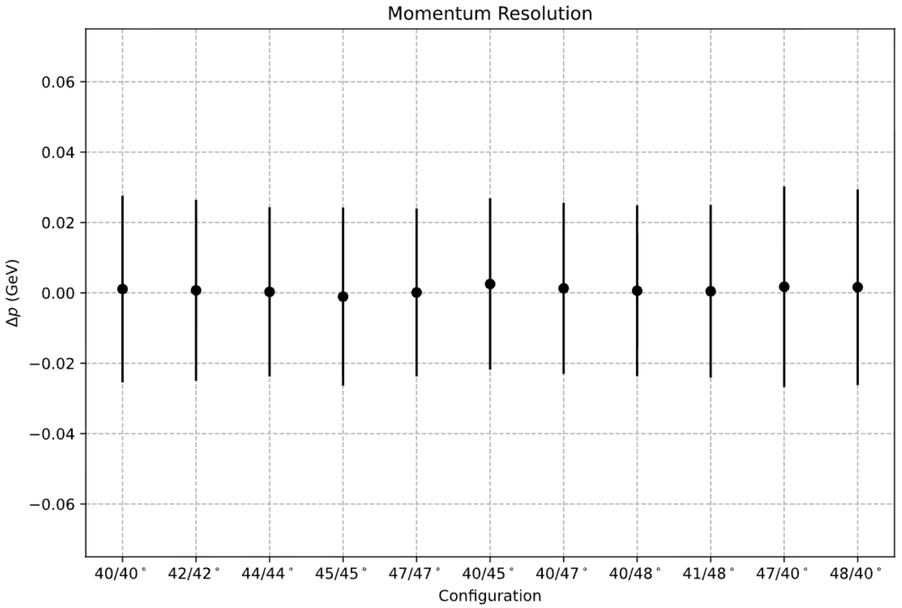




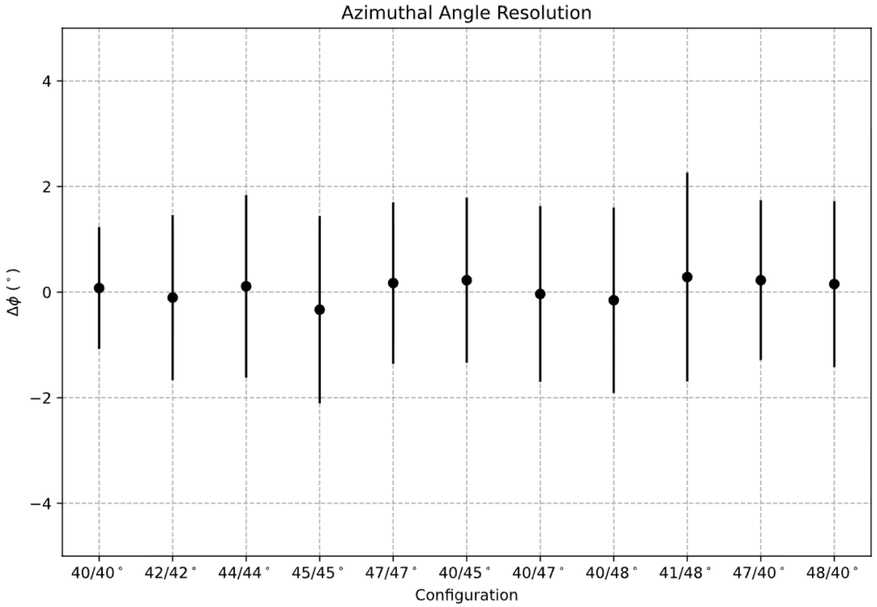
Yields seem to favour an asymmetric configuration with smaller starting angle for sector 1 and larger starting angle for sector 2 → best configuration is $40°/48°$! But not a big difference between multiple of best configurations.

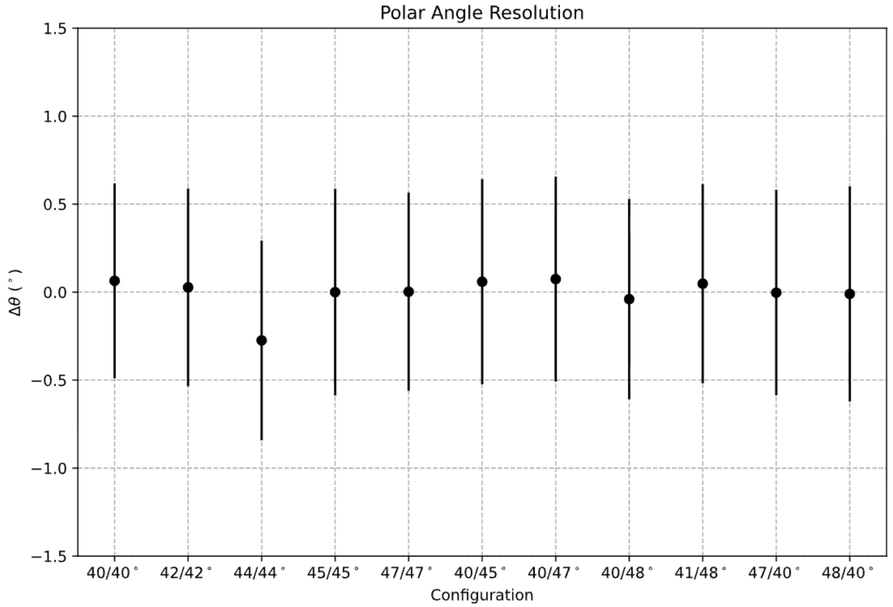
This is a different result from the χ^2 linear reconstruction fits; but it should also be noted that more configurations were tested with this version of the reconstruction and $40°/48°$ has not yet been tested with the original reconstruction method of the proposal.

Summary of Configuration Resolutions



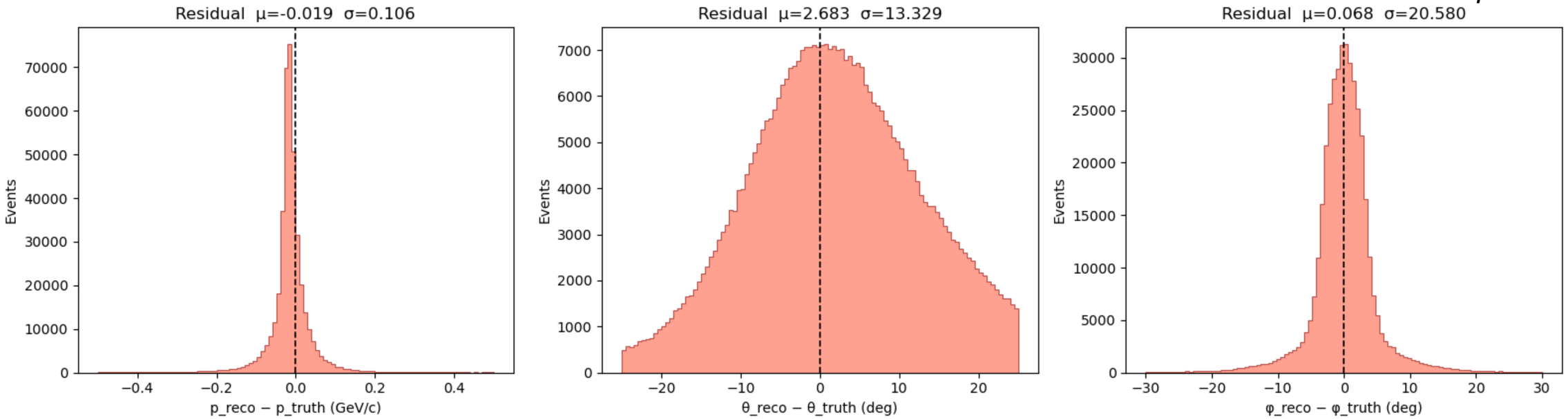
Remarkable momentum, θ, and ϕ reconstruction agreement between different configurations!





Comparison to Earlier Reconstruction Method

Plot from K. Neupane



(Using results from $40/40°$ configuration)

- $\sigma_{\chi^2,p}/\sigma_{MLP,p} = 3.9955$
- $\sigma_{\chi^2,\theta}/\sigma_{MLP,\theta} = 24.0726$
- $\sigma_{\chi^2,\phi}/\sigma_{MLP,\phi} = 13.2946$

→

Significantly higher resolution on reconstruction on momentum, θ, and ϕ when using MLP compared to earlier χ^2 method

Adding PID to MLP-Assisted Tracking

Adding PID to MLP

- MLP package developed μCLAS12 momentum/position *reconstruction*, not for PID $\rightarrow$ $\mu^{\pm}$ PID enters as a known variable
- We currently do not have a method of performing PID for the particles interacting with the recoil detector system: because of limited exposure to magnetic field, we expect REC-TRK charged particle tracks to be in straight lines, so we only have β from REC-TOF
  - Could MLP "learn" the particle species from β and small adjustments to path from small magnetic field exposure?
- Majority of particles in CD/Recoil Detector region are heavy (proton/neutron), so a reasonable assumption that a charged particle interacting with REC-TRK/TOF would be a proton, particularly with other kinematic cuts in analysis
  - Still always better to know for sure! :)
- From discussion with experts:
  - Assign PID number as another target variable, specifically 0, 1 for ease of result interpretation (for convenience, 1 was assigned to the heavier particle, or the positively charged particle in the case of testing PID between positively and negatively charged particles of the same species)
  - Second option of the targets being "proton" or "not proton", in which case the training data sets for several particles species were combined
- Features of MLP adjusted: thirteen "input dimensions" (x_1, y_1, z_1, x_2, y_2, z_2, x_3, y_3, z_3, x_{tof}, y_{tof}, z_{tof}, tof), four "state dimensions" (p, θ, ϕ, PID value)

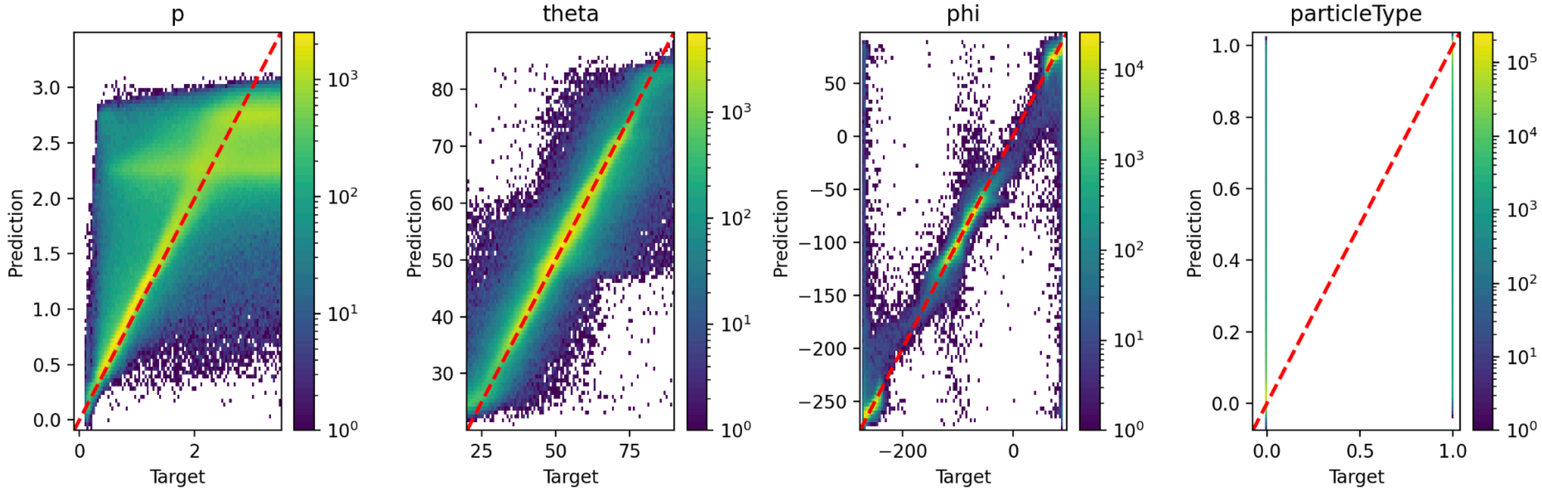
Generating Training Sample

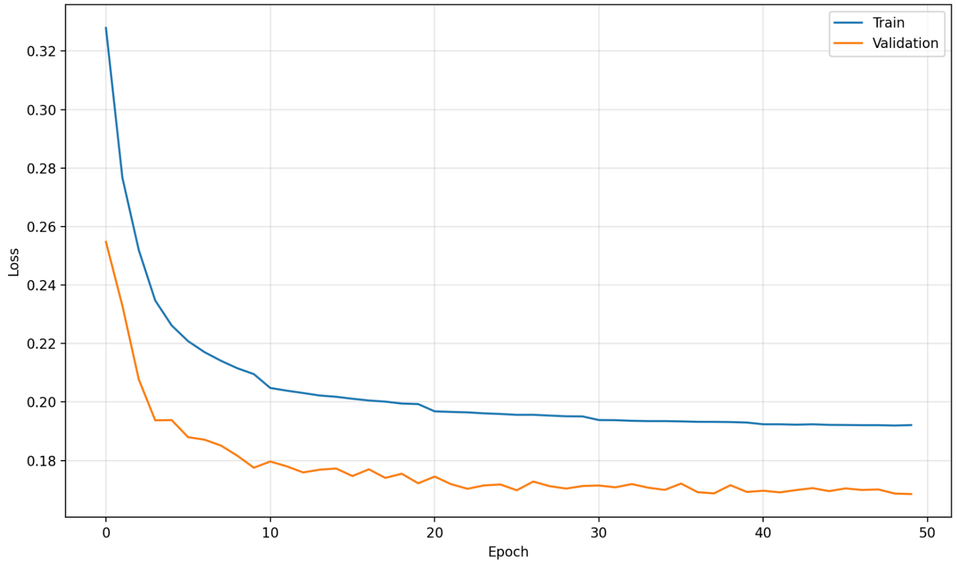
- Using GEMC “particle gun” to simulate event samples of a particular particle
  - 1000 files, each with 50000 events
- Starting with proton, π^+, π^- beams & adding K^+ and K^- particles
- Using initial symmetric (40˚x40˚) starting angle configuration for recoil detector to begin

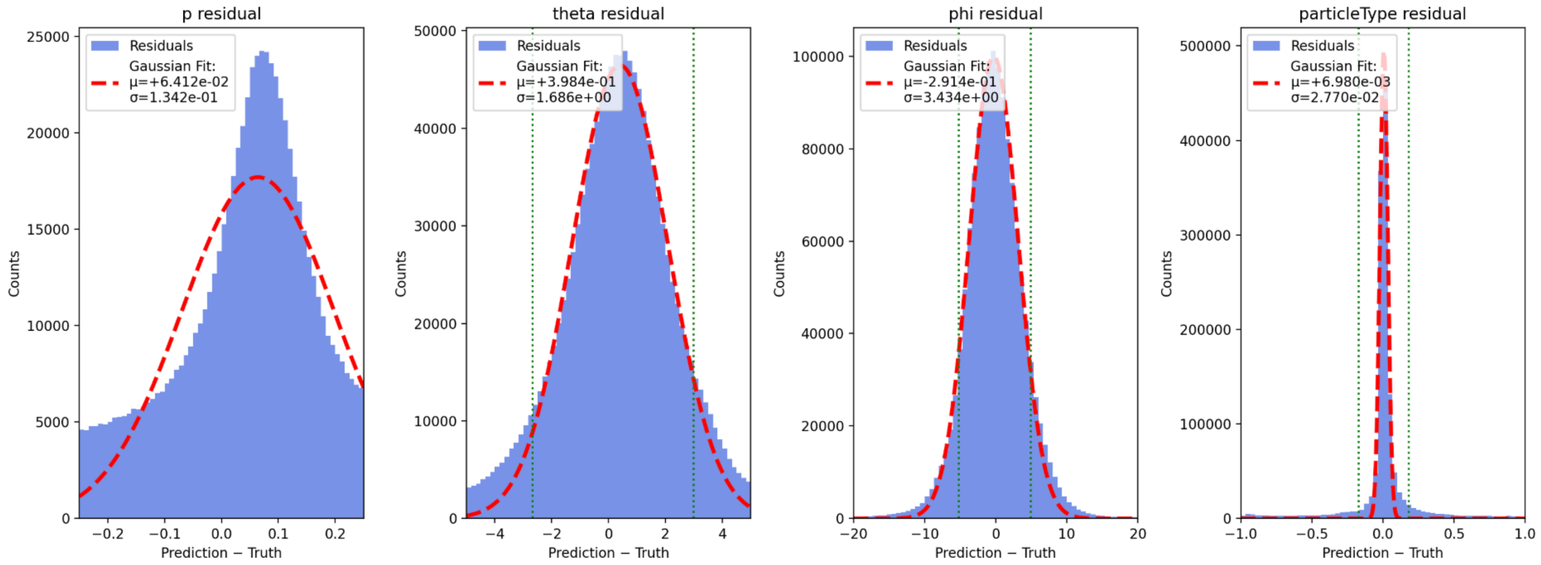
```
# -------- GEMC --------
/work/clas12/silvia/source_nilanga/gemc \
  rgh_marco_new_asym_rtrk_rtof.gcard \
  -USE_GUI=0 -RUNNO=11 \
  -BEAM_P="proton, 2.5*GeV, 45*deg, 0*deg" -SPREAD_P="2.5*GeV,45*deg,180*deg" \
  -BEAM_V="(0,0,-3.25)cm" -SPREAD_V="(0,5)cm" \
  -N=50000 -OUTPUT="hipo, out.hipo"
```

- Similarly to initial case, go through generated samples, retaining x, y, z, positions of all recoil detector layer and recoil tof layer, tof, momentum, lab θ, lab ϕ + *PDG PID number*
- Some loose quality cuts:
  - 0.1 GeV $\leq p < 3.5$ GeV
  - 1 ns $\leq$ tof < 20 ns
  - $20^\circ \leq \theta < 100^\circ$

p versus π^+

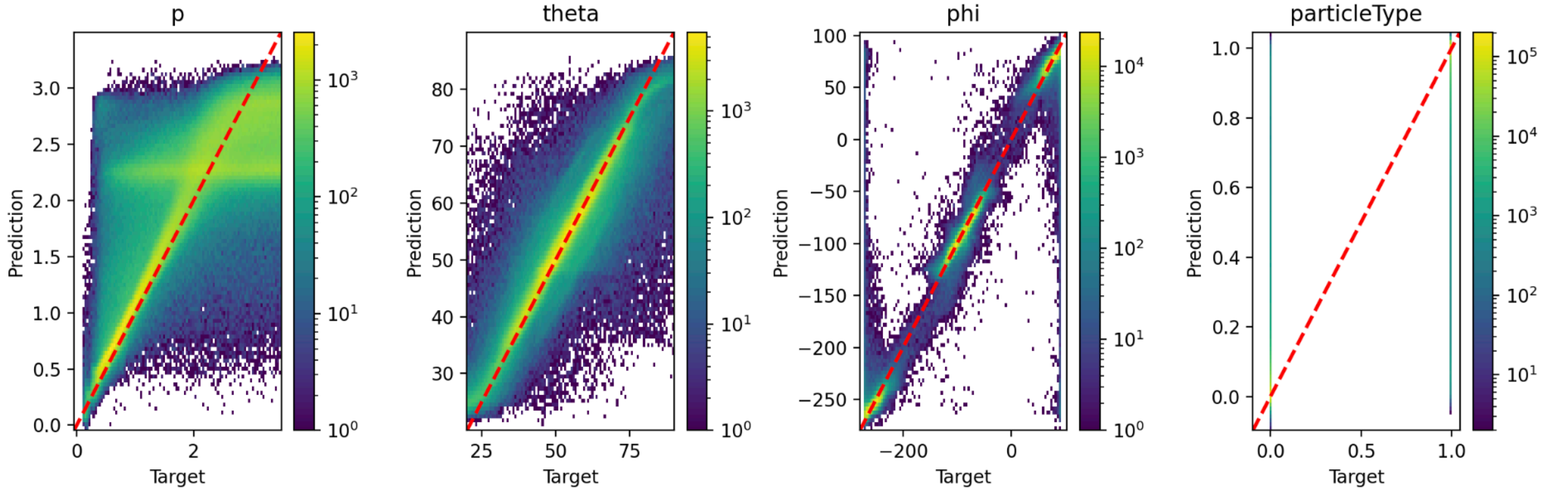


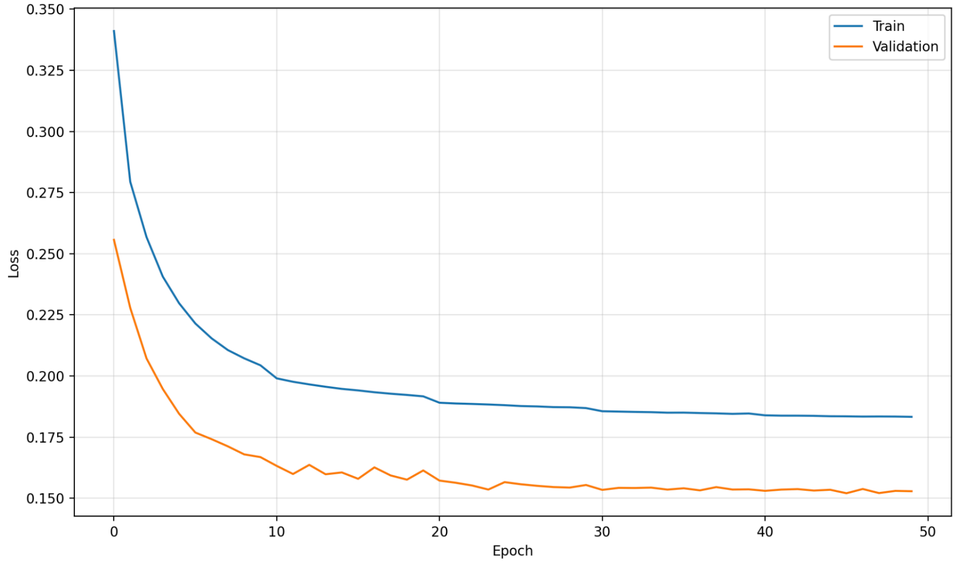


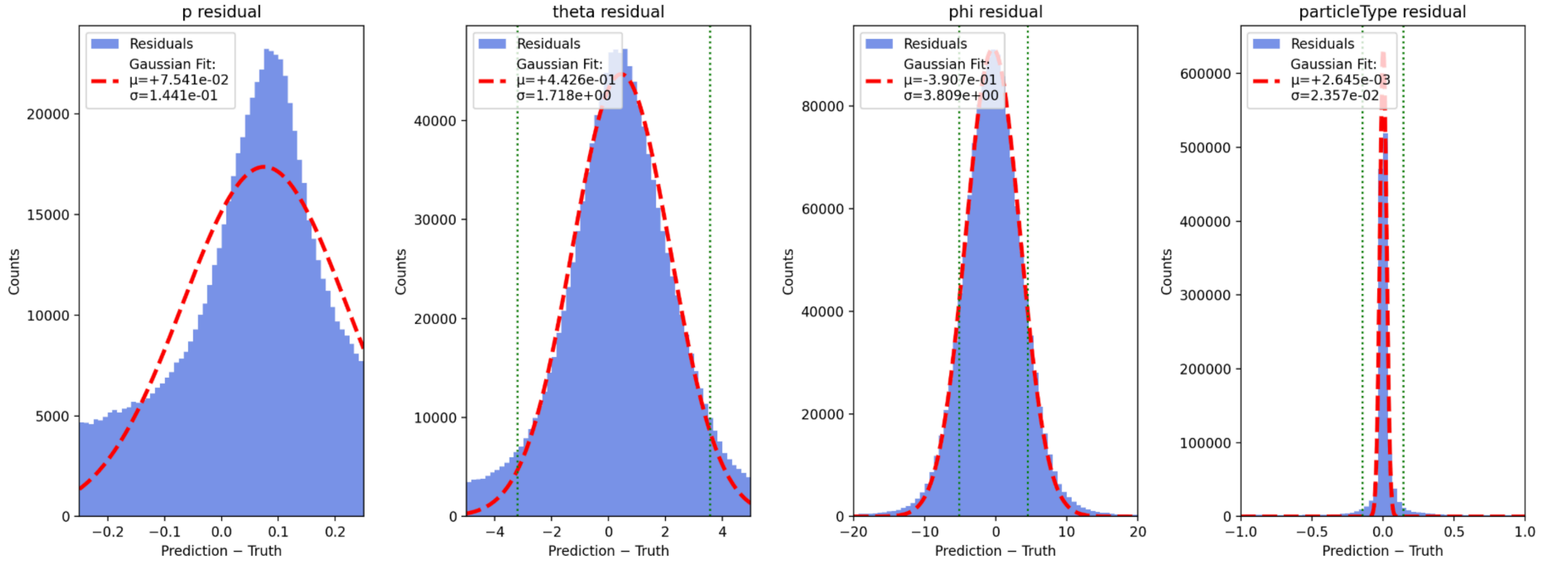


- Δp: 0.0641 GeV ± 0.1342 GeV
- $\Delta\theta$: $0.3984^\circ \pm 1.6862^\circ$
- $\Delta\phi$: $-0.2914^\circ \pm 3.4345^\circ$
- ΔPID: 0.0070 ± 0.0277 (proton assigned 1, π^+ assigned 0)

p versus π^-

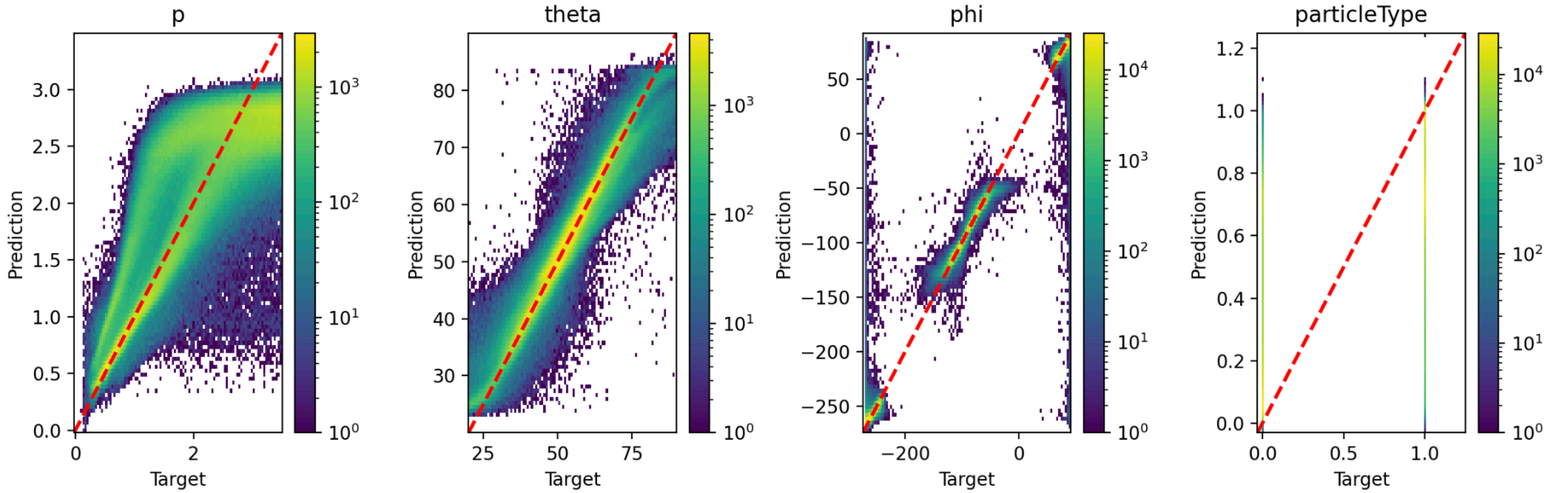


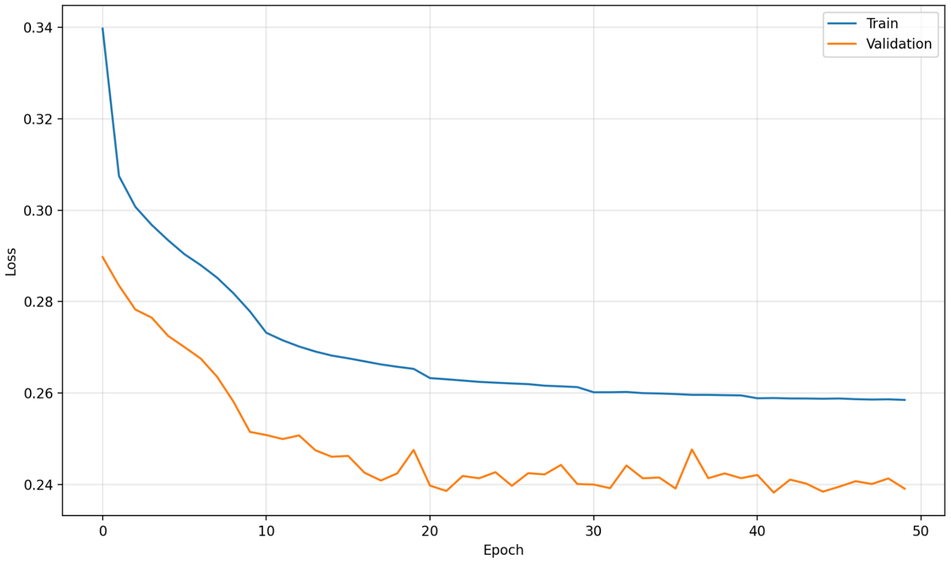


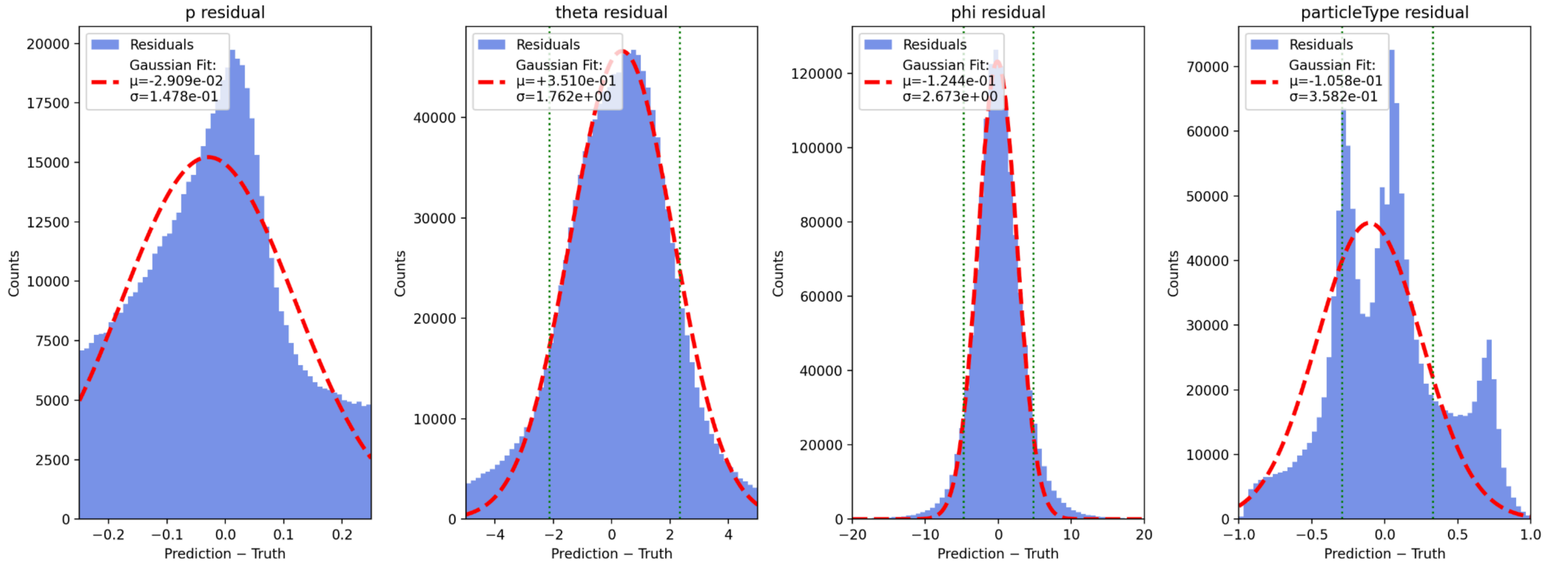


- Δp: 0.0754 GeV ± 0.1441 GeV
- $\Delta\theta$: $0.4426^\circ \pm 1.7180^\circ$
- $\Delta\phi$: $-0.3907^\circ \pm 3.8091^\circ$
- ΔPID: 0.0026 ± 0.0236 (proton assigned 1, π^- assigned 0)

p versus K^+

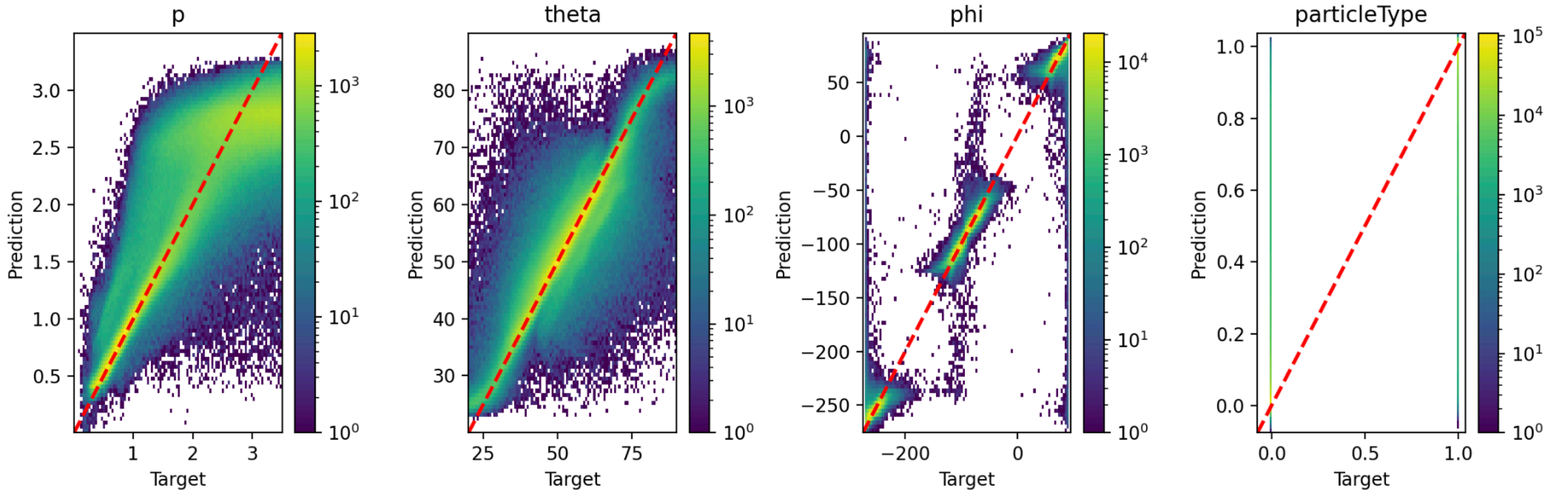


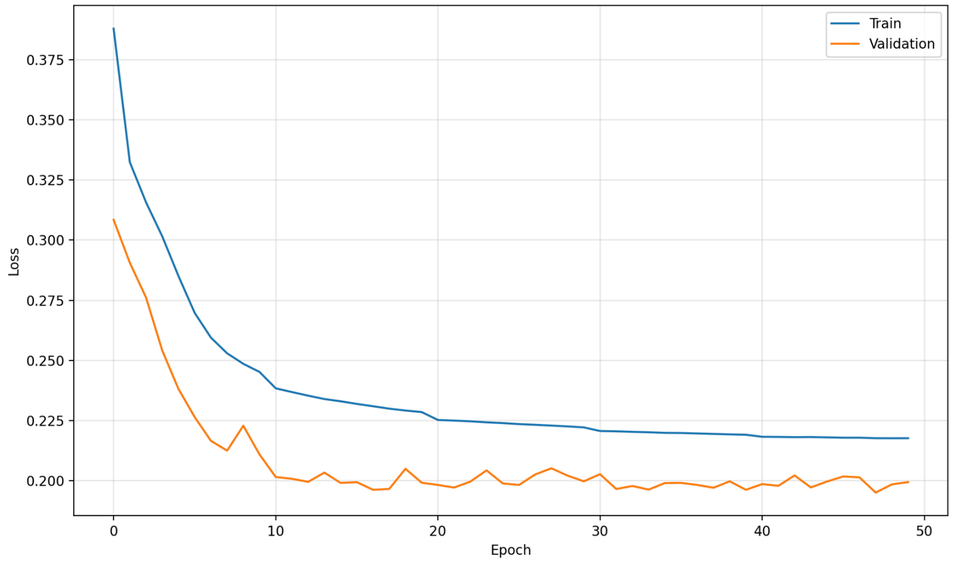


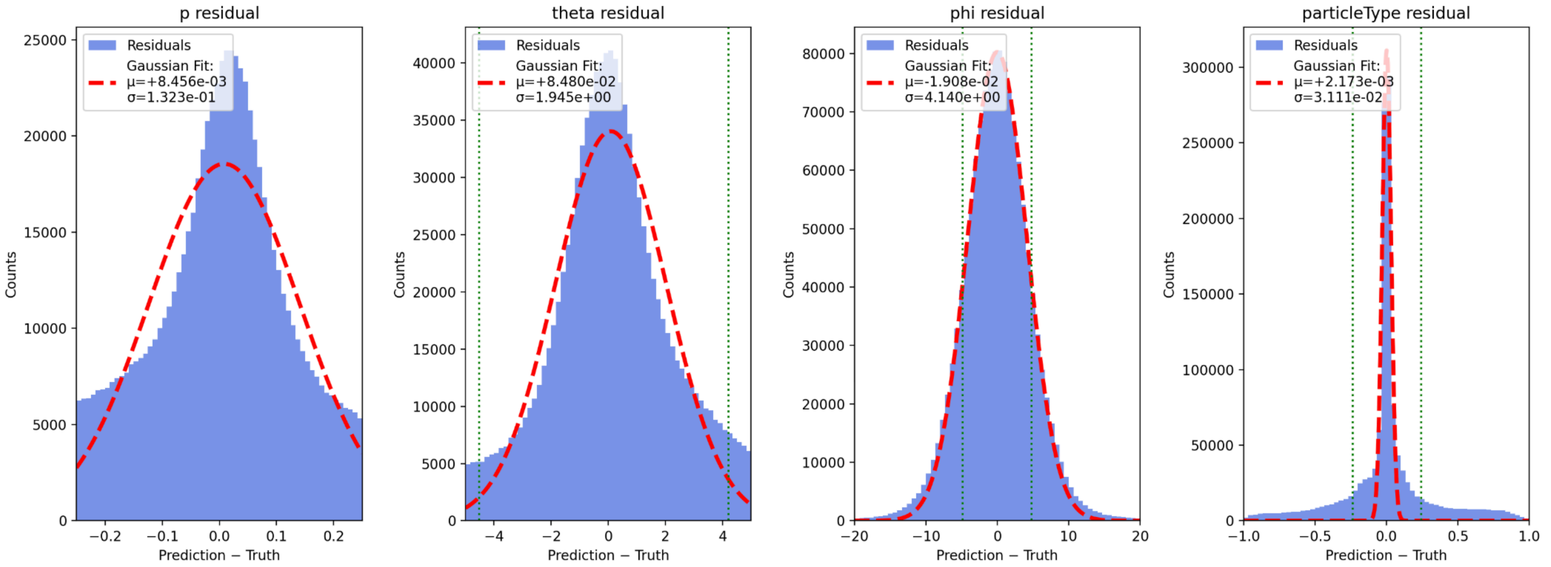


- Δp: 0.0291 GeV ± 0.1478 GeV
- $\Delta\theta$: $0.3510^\circ \pm 1.7620^\circ$
- $\Delta\phi$: $-0.1244^\circ \pm 2.6730^\circ$
- ΔPID: -0.1058 ± 0.3582 (proton assigned 1, K^+ assigned 0)

p versus K^-

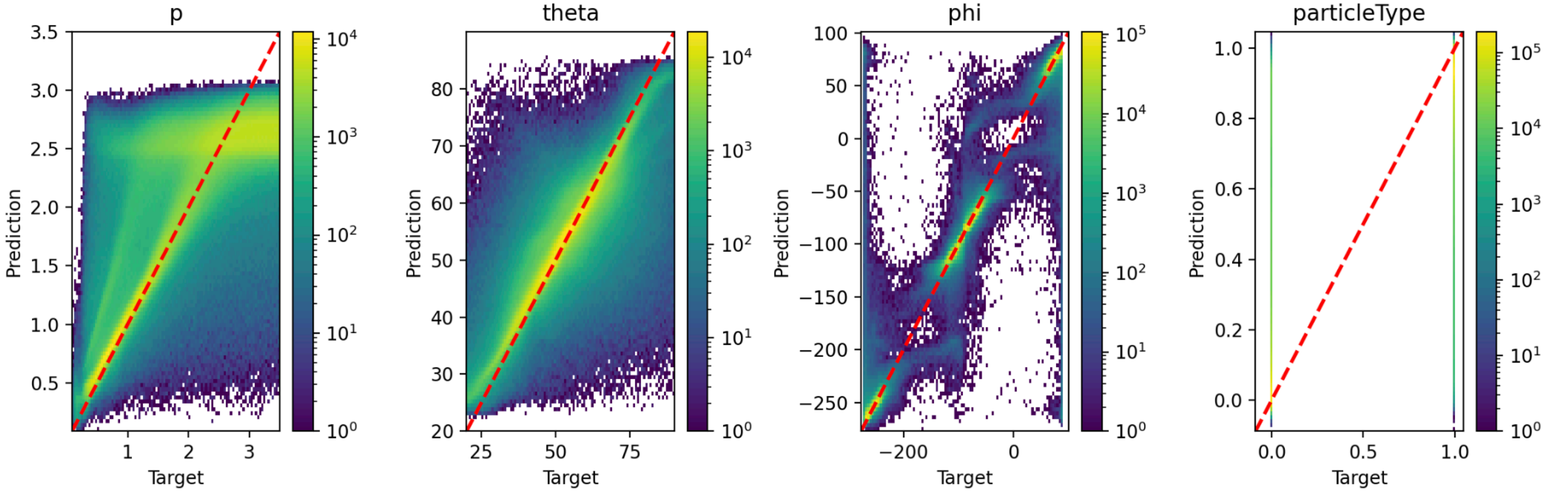


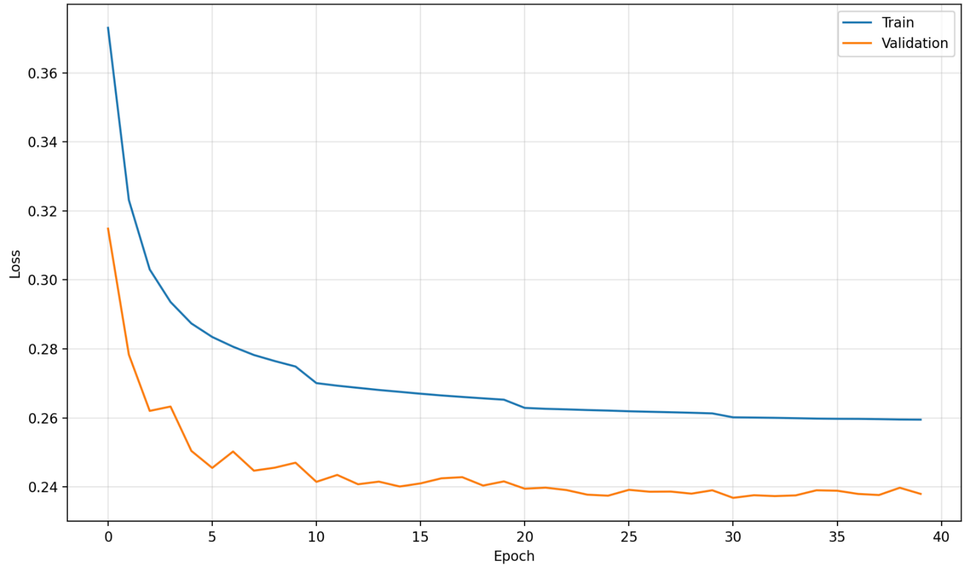


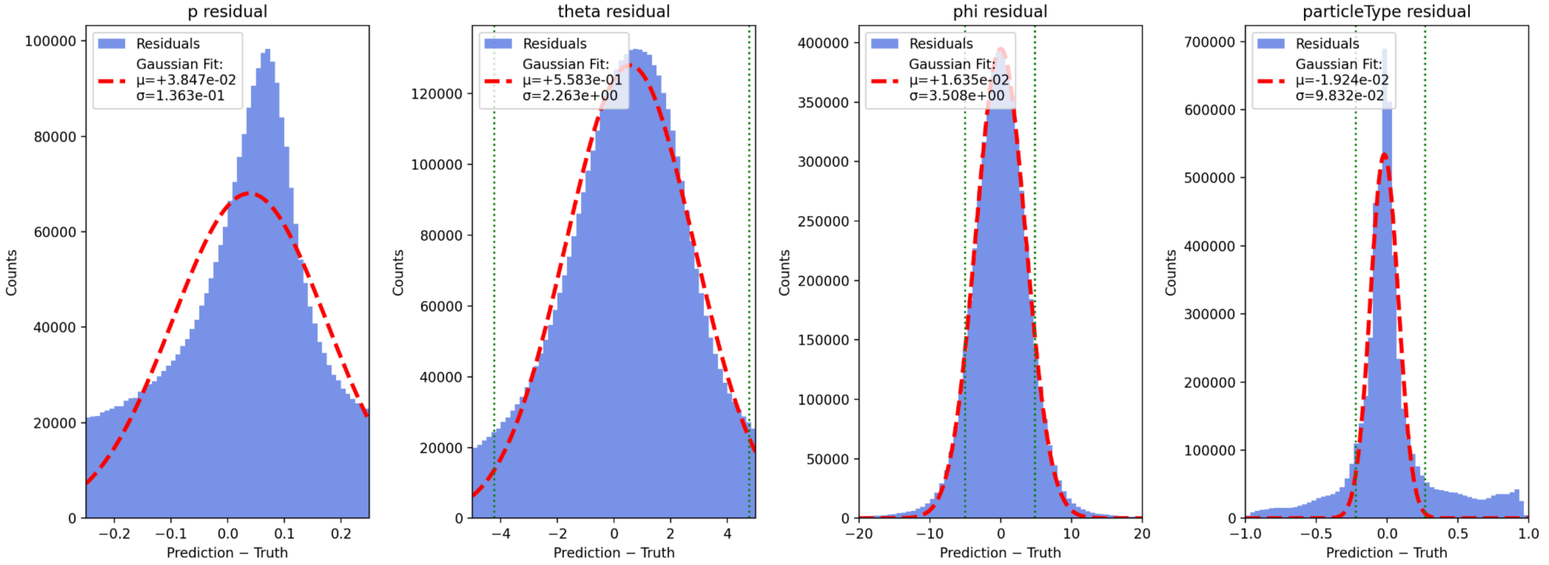


- Δp: 0.0846 GeV ± 0.1323 GeV
- $\Delta\theta$: $0.0085^\circ \pm 1.9450^\circ$
- $\Delta\phi$: $-0.0191^\circ \pm 4.1400^\circ$
- ΔPID: 0.0022 ± 0.0311 (proton assigned 1, K^- assigned 0)

p versus $\pi^{\pm}$ & $K^{\pm}$ (combined data sample)







- Δp: 0.0385 GeV $\pm$ 0.1363 GeV
- $\Delta\theta$: $0.5583^{\circ} \pm 2.2630^{\circ}$
- $\Delta\phi$: $0.0164^{\circ} \pm 3.5080^{\circ}$
- ΔPID: -0.0192 ± 0.0983 (proton assigned 1, all others assigned 0)

Current Reco+PID Outcomes

Comparison Particles	Δp (GeV)	$\Delta\theta$ (°)	$\Delta\phi$ (°)	ΔPID	$1-4\sigma$
p vs. π^+	0.0641 ± 0.1342	0.3984 ± 1.6862	-0.2914 ± 3.4345	0.0070 ± 0.0277	0.8892
p vs. π^-	0.0754 ± 0.1441	0.4426 ± 1.7180	-0.3907 ± 3.8091	0.0026 ± 0.0236	0.9056
p vs. K^+	0.0291 ± 0.1478	0.3510 ± 1.7620	-0.1244 ± 2.6730	-0.1058 ± 0.3582	-0.4328
p vs. K^-	0.0846 ± 0.1323	0.0085 ± 1.9450	-0.0191 ± 4.1400	0.0022 ± 0.0311	0.8756
p vs. others	0.0385 ± 0.1363	0.5583 ± 2.2630	0.0164 ± 3.5080	-0.0192 ± 0.0983	0.6068

- All but one of the particles (K^+) well distinguished from protons by preliminary MLP, with 4σ PID uncertainty well still within range of proton (>0.5)
- However, fits to kinematics are less convincing than with only genepi DVCS events, with larger uncertainties on kinematics and distributions visibly less Gaussian
- Possible dual phase reconstruction?
    1. *PID*
    2. *Reconstruction with remaining events*
- In future, smear vertex for more realistic reconstruction

Summary

- The Recoil Detector System is an invaluable component of the RGH experiment design, particularly for pDVCS analysis goals
- Recoil detector will recover statistics from CD region lost because of target polarization equipment installation
- There is no clear consensus on an optimal angular configuration for the Recoil Detector
- Using AI-assisted methods (MLP neural network) for particle track reconstruction has been shown to offer significant improvements to resolution of momentum, polar, and azimuthal angles of DVCS protons
- Additions to MLP model can provide some degree of p/π, p/K separation for particle identification
- Further phenomenology studies can use Recoil Detector model to provide estimations of RGH sensitivity to pDVCS across kinematic regions

Thank you, questions?

Backup Slides

Deeply Virtual Compton Scattering on a Transversely Polarized Target

From RGH Proposal:

The contribution to the total cross section coming from the BH-DVCS interference is given, in the case of a transversely polarized target, by:

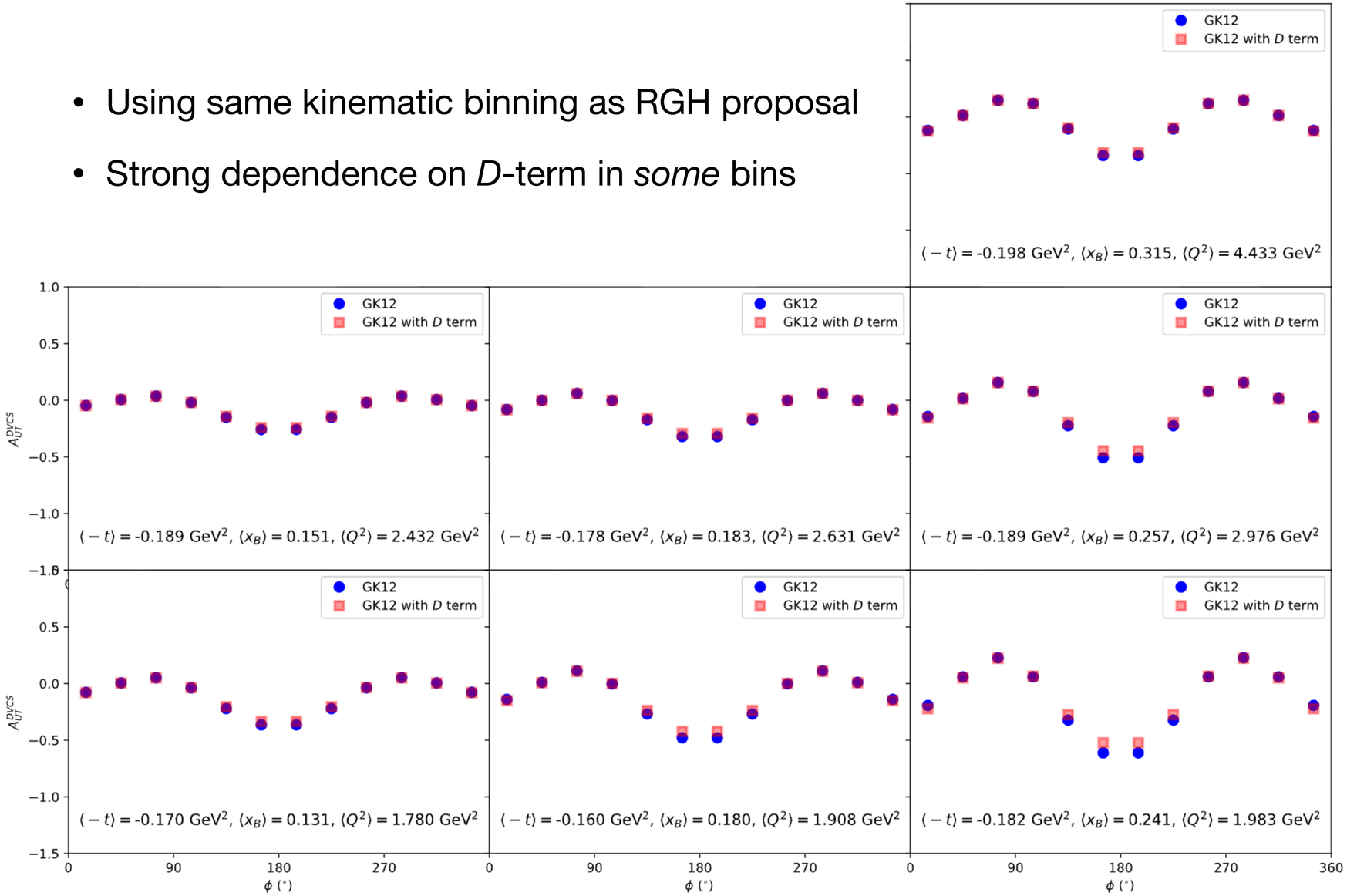
$$d\sigma^{\mathrm{I}}_{UT} = \frac{-K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left\{\sum_{n=0}^{3} c^{\mathrm{I}}_{n,\mathrm{TP}-}\sin(\phi-\phi_S)\cos(n\phi) + \sum_{n=1}^{3} s^{\mathrm{I}}_{n,\mathrm{TP}+}\cos(\phi-\phi_S)\sin(n\phi)\right\}, \tag{10}$$

The extraction of A^{I}_{UT} gives access to the leading Fourier coefficient in Equation 11, which, in turn, relates to the CFF as

$$c^{\mathrm{I}}_{1,\mathrm{TP}-} \propto -\frac{M}{Q}\Im\mathrm{m}\left\{\frac{t}{4M^2}\left[(2-x_B)F_1\mathcal{E} - 4\frac{1-x_B}{2-x_B}F_2\mathcal{H}\right] + x_B\xi\left[F_1(\mathcal{H}+\mathcal{E}) - (F_1+F_2)(\tilde{\mathcal{H}}+\frac{t}{4M^2}\tilde{\mathcal{E}})\right]\right\}, \tag{11}$$

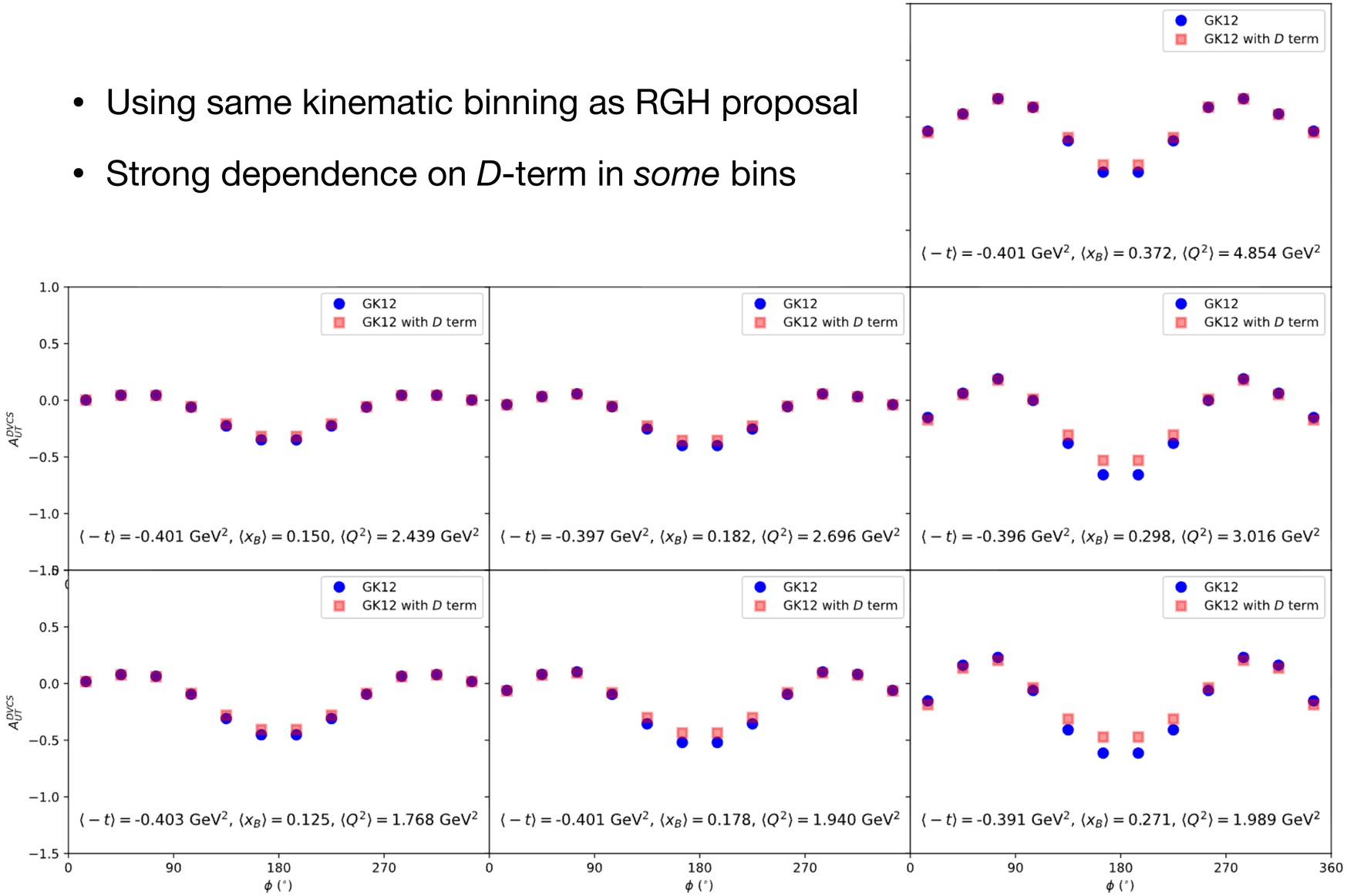
GK Model of pDVCS A_{UT}

- Using same kinematic binning as RGH proposal
- Strong dependence on *D*-term in *some* bins



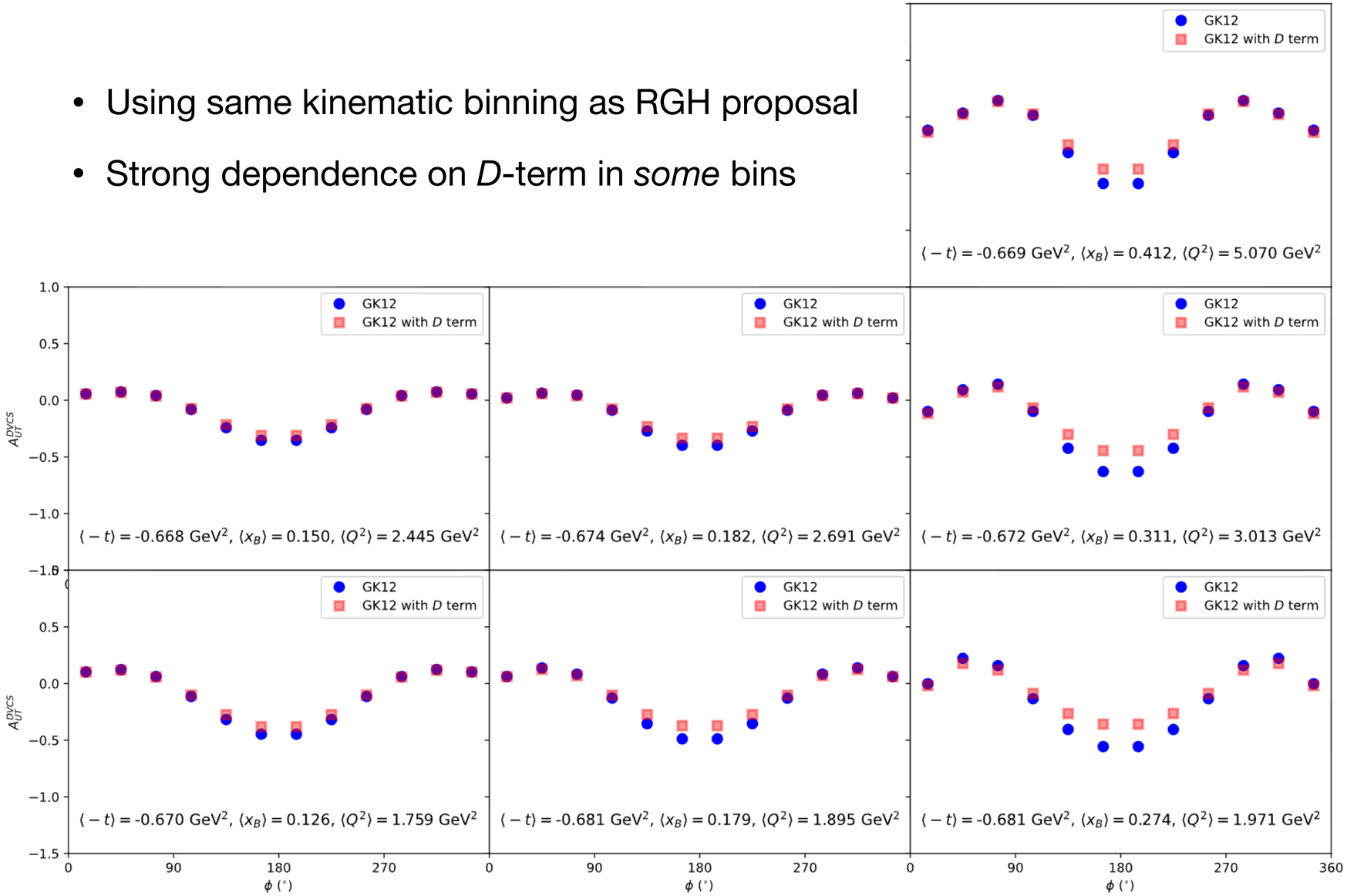
GK Model of pDVCS A_{UT}

- Using same kinematic binning as RGH proposal
- Strong dependence on *D*-term in *some* bins



GK Model of pDVCS A_{UT}

- Using same kinematic binning as RGH proposal
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GK Model of pDVCS A_{UT}

- Using same kinematic binning as RGH proposal
- Strong dependence on *D*-term in *some* bins

