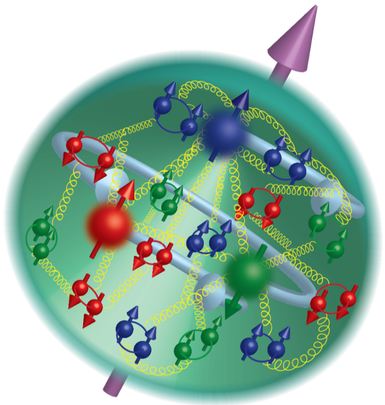
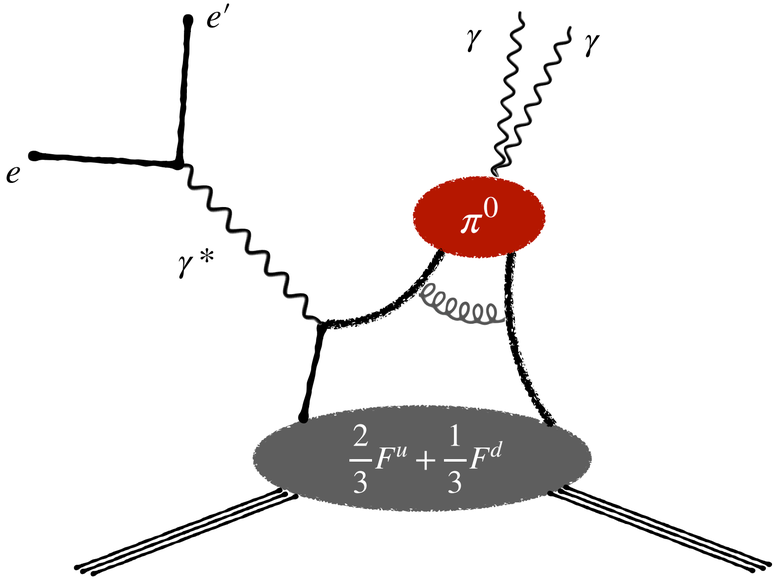
Exclusive π^0 Production : RGK Fa18 $\gamma^* p \rightarrow \pi^0 p$ cross-section extractions

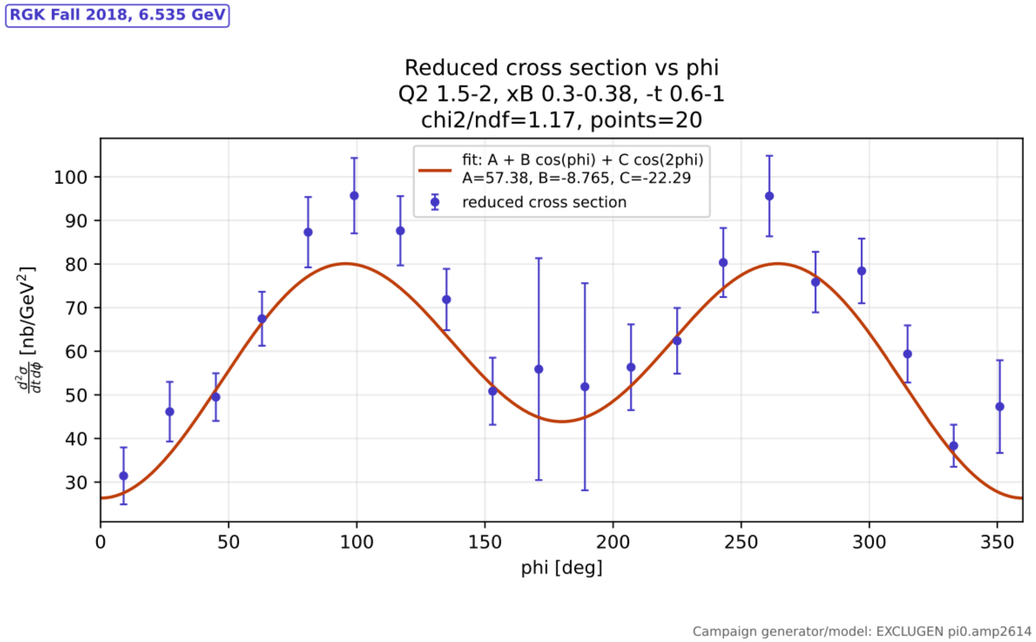
11.18.26 CLAS12 Collaboration Meeting



nucleon: NP QCD bound state

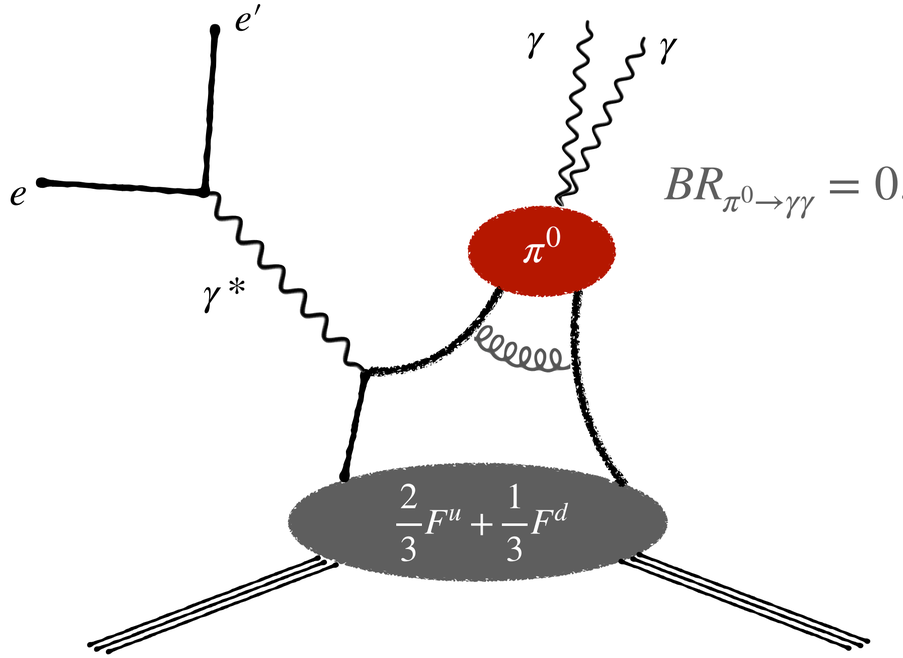


DVπ^0P schematic in GPD framework



$d^2\sigma\left(\gamma^* p \rightarrow \pi^0 p\right)\Big|_{6.5GeV}$ fit to $A + Bcos(\phi) + Ccos(2\phi)$

DVπ^0P: $ep \to e'p'\pi^0 \to e'p'\gamma\gamma$

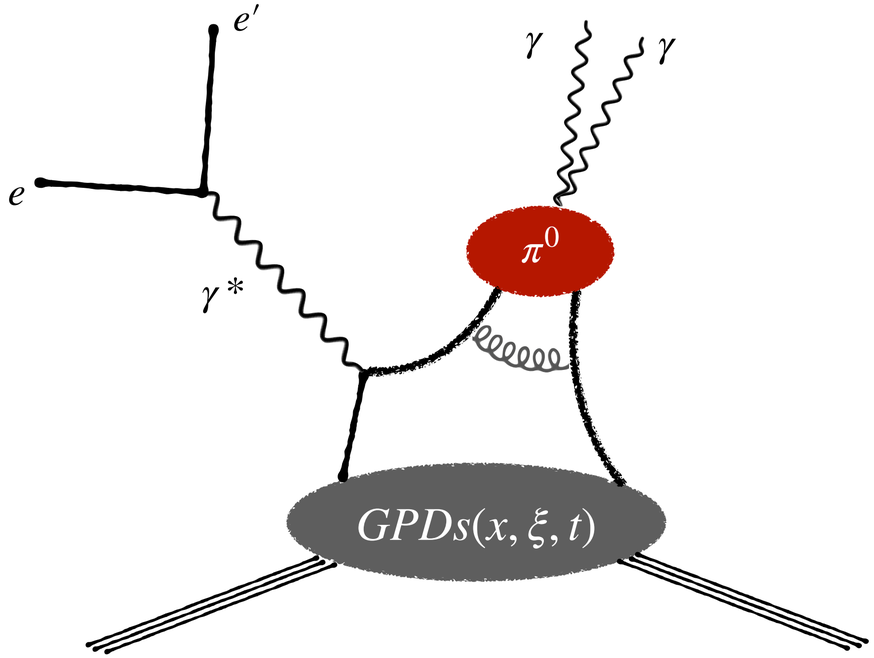


$$BR_{\pi^0\to\gamma\gamma} = 0.988$$

virtual photon flux — unpolarized structure function — Photon interference structure functions

$$\frac{d^4\sigma_{ep\to ep'\pi^0}}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}\left\{\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos(2\phi)\frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)\frac{d\sigma_{LT}}{dt}\right\}$$

DVπ^0P: $ep \to e'p'\pi^0 \to e'p'\gamma\gamma$



CFF equivalents

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{kQ^2}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2\Re\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$$

$$\frac{d\sigma_T}{dt} = \frac{2\pi\alpha\mu_\pi^2}{kQ^4}\left\{(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2\right\}$$

$$\frac{d\sigma_{LT}}{dt} = \frac{4\pi\alpha\mu_\pi}{\sqrt{2}kQ^3}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\Re\left\{\langle H_T\rangle^*\langle\tilde{E}\rangle\right\}$$

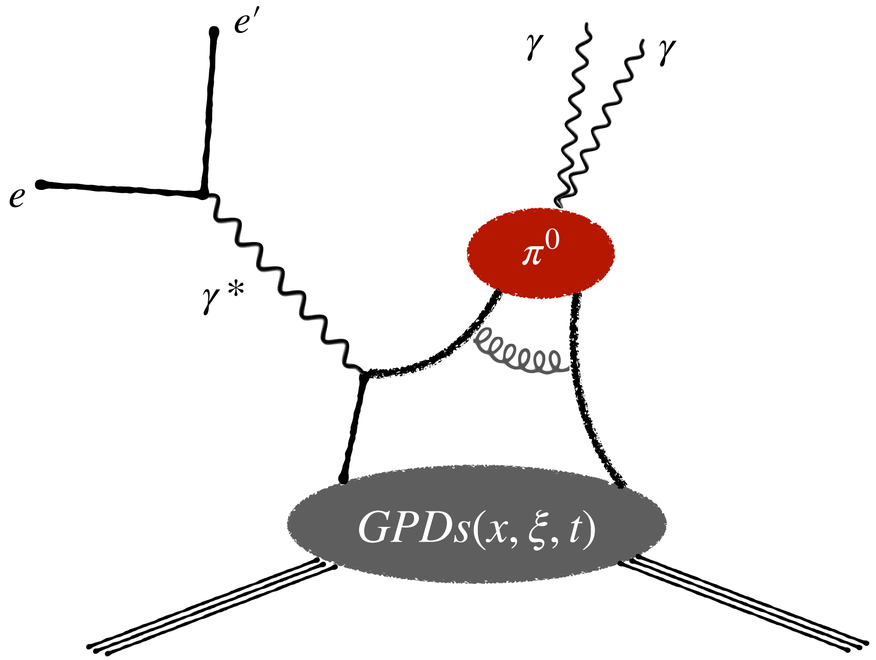
$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha\mu_\pi^2}{kQ^4}\frac{-t'}{16m^2}\langle\bar{E}_T\rangle^2$$

chiral-odd GPD sensitivity

virtual photon flux | unpolarized structure function | Photon interference structure functions

$$\frac{d^4\sigma_{ep\to ep'\pi^0}}{dQ^2dx_Bdtd\phi_\pi} = \Gamma(Q^2,x_B,E)\frac{1}{2\pi}\left\{\left(\frac{d\sigma_T}{dt}+\epsilon\frac{d\sigma_L}{dt}\right)+\epsilon\cos(2\phi)\frac{d\sigma_{TT}}{dt}+\sqrt{2\epsilon(1+\epsilon)}\cos(\phi)\frac{d\sigma_{LT}}{dt}\right\}$$

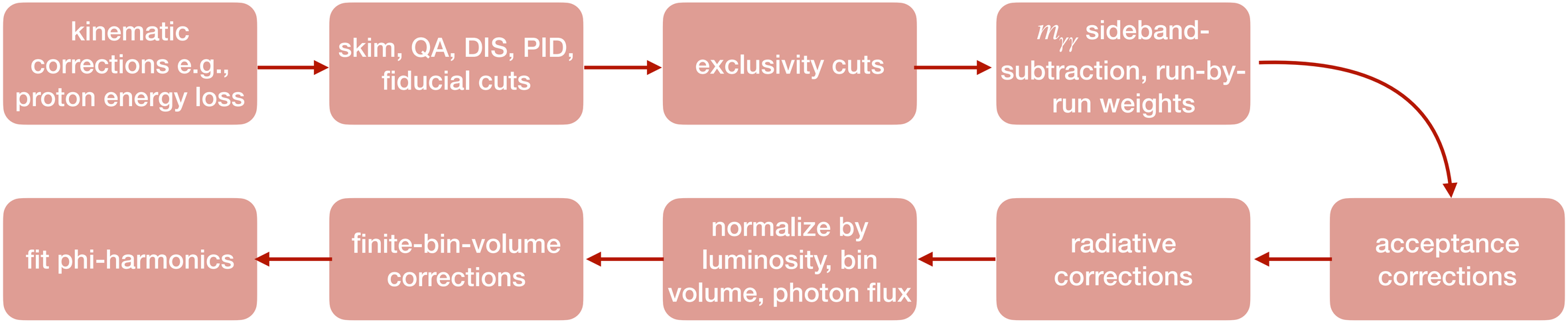
DVπ^0P: $ep \to e'p'\pi^0 \to e'p'\gamma\gamma$



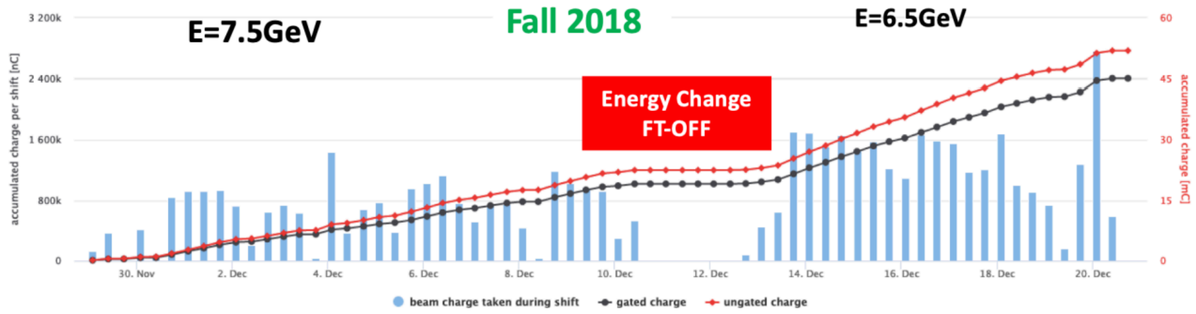
- flavor filter for light quarks
- no enhancement from pion pole, so $\sigma_L^{\pi^0} \sim \sigma_T^{\pi^0}$
- sizable twist-3 contributions at valence kinematics
- separation of σ_U can isolate transversity contribution
- [in review] *I. Korover et al.* : first CLAS12 extraction of unpolarized DVπ^0P cross section and structure functions using a 10.6 GeV longitudinally polarized beam incident on a hydrogen target (RGA Fa18)
- [in-progress] BSA, cross-section analysis underway for complementary RGK Fa18, Sp24 data sets, hopefully support Rosenbluth separation

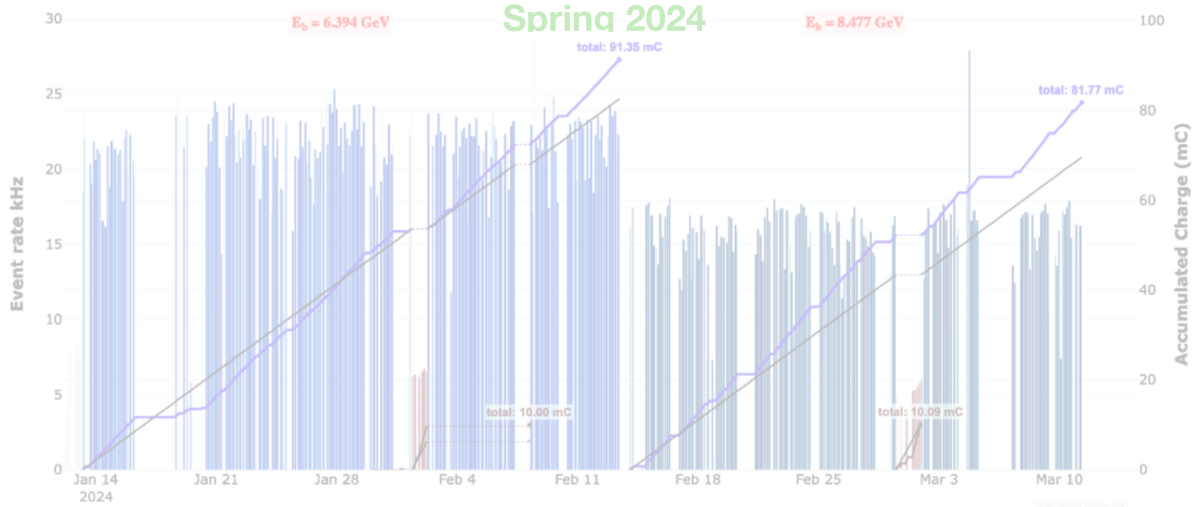
methodology / analysis workflow

$$\left.\frac{d^2\sigma_{\gamma^* p\to\pi^0 p}}{dt\,d\phi}\right|_b = \frac{\frac{1}{\varepsilon_b\,\delta_{A,b}}\left[\sum_{e\in b}^{\text{sig}} w_{r(e)} - \sum_g \alpha_g \sum_{e\in b}^{\text{side},\,g} w_{r(e)}\right]}{\mathcal{L}_{\text{int}}\;\mathcal{B}(\pi^0\to\gamma\gamma)\;\Delta V_{\text{phys},b}\;\Gamma_v\left(Q^2_{\text{ref}}, x_{B,\text{ref}}\right)\;C_{\text{BC,b}}} = \frac{Y_{\text{corr}}}{\mathcal{L}_{\text{int}}\;\mathcal{B}(\pi^0\to\gamma\gamma)\;\Delta V_{\text{phys}}\;\Gamma_v\;C_{\text{BC}}},$$



Run Group K: longitudinal beam, unpolarized LH_2 target





- 6.5 GeV : 18 mC , torus+1 , FT-out
- 7.5 GeV: 10 mC , torus+1 , FT-in

- 6.4 GeV : 91 mC , torus+1 , FT-out
- 7.5 GeV: 82 mC , torus+1 , FT-out

ExcluGen event generator (V. Kubarovsky)

EXCLUGEN: an event generator for exclusive π^0 and η electroproduction with exact first-order radiative corrections

Design, validation and first productions

V. Kubarovsky
Jefferson Lab

August 7, 2026

Abstract

EXCLUGEN is an event generator for exclusive meson electroproduction $ep \to e'p'\pi^0(\eta)$ with exact first-order QED radiative corrections, built directly on the EXCLURAD framework of Afanasev, Akushevich, Burkert and Joo. Unlike peaking-approximation generators (aao_rad), EXCLUGEN samples the radiated photon from the exact one-photon emission matrix element, including both collinear peaks and their interference, with no ISR/FSR separation. Events are generated "measured-variables-first": the sampled kinematics are exactly those in which the analysis bins and in which EXCLURAD defines $\sigma_{\rm obs} = \sigma_{\rm Born}(1+\delta)$, so the generated event density reproduces the exact radiative correction bin by bin, by construction. The generator is validated by closure against EXCLURAD at the 1% level, independent of the internal soft-photon cutoff over three orders of magnitude, for both channels. We describe the algorithm, the absolute normalization, the validation suite, and the first large-scale productions: $4 \times (30\text{–}40)$M events at the four π^0 grid points of the CLAS $ep \to e'p'\pi^0$ analysis (5.75 GeV), and the first η productions, including a direct comparison with the published η radiative-correction curve. All plots produced by the production pipeline are collected here.

- *full* LO radiative kernel
- tuned to world data at amplitude level
- documented, accessible, user-friendly
- *significant* π^0 GEMC production underway for RGAFA18, RGKFA18
- …but not in time for this presentation

RGK Fall 2018, 7.546 GeV

Data: 152,997 final candidates

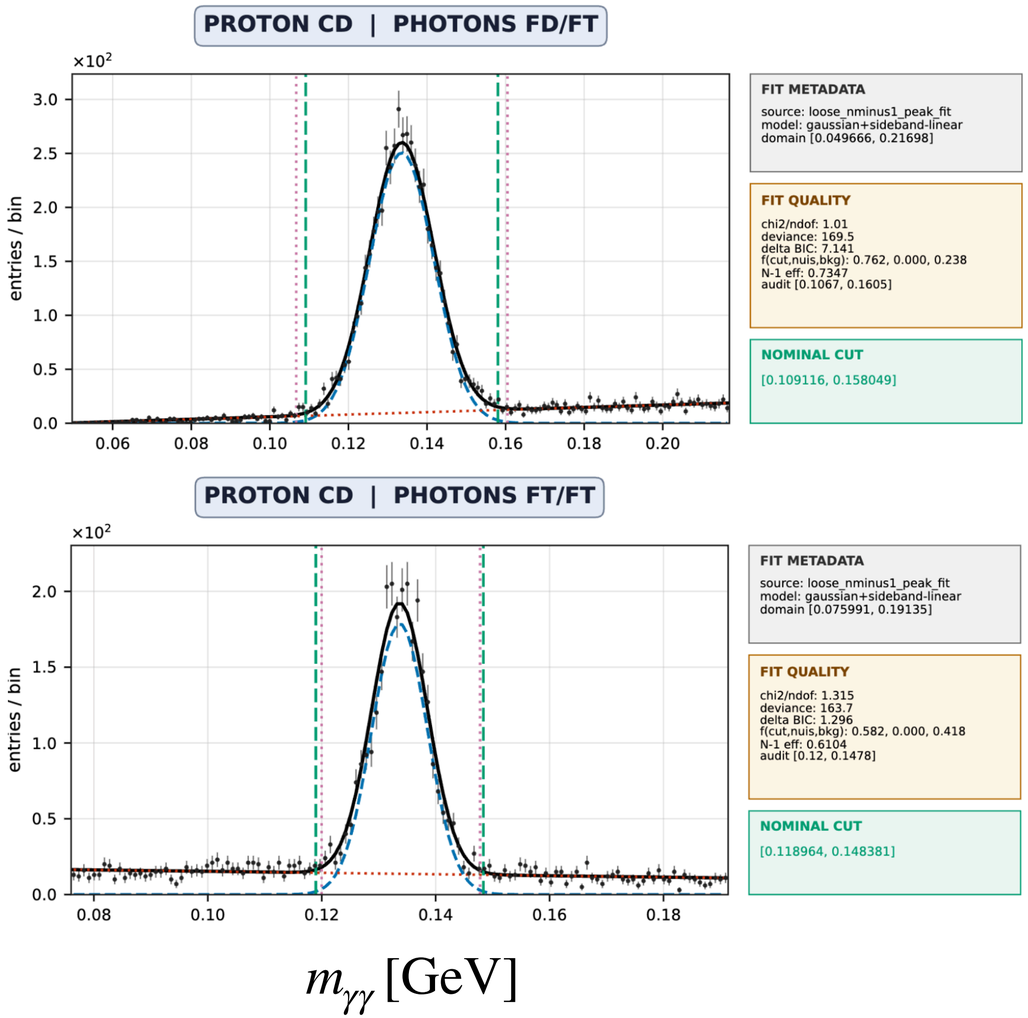
Production GEMC: 258,731 final candidates

event selection I : event-builder, fiducial cuts, PID cuts

Category	Selection Criteria
Skim and phase space	• $0 < m_{\gamma\gamma} < 0.35$ GeV (converter skim) • Data filtered by QADB • $Q^2 \geq 1\,\text{GeV}^2$, $W \geq 2$ GeV, $p_e \geq 1$ GeV
Electron (FD)	• First PID-11 particle, $p \geq 1$ GeV • $E_{PCAL} > 0.07$ GeV • SF within $\mu \pm 3.5\sigma$ per sector • DC + ECAL RGA fiducials
Proton (FD or CD)	• PID 2212, $p \geq 0.3$ GeV • $\lvert z_p - z_e \rvert \leq 20$ cm • DC (FD) or CVT (CD) RGA fiducials
Photons ≥ 2	• PID 22, $p \geq 0.4$ GeV, $0.9 \leq \beta \leq 1.1$ • ECAL RGA fiducials (FD photons) • FT photons admitted at 7.546 GeV (FT RGA fiducial ring + holes)
One candidate per event	• $\gamma\gamma$ pair closest to the π^0 mass, $\lvert \Delta m \rvert < 0.15$ GeV
Loose post-processing guards	• $\lvert E_{miss} \rvert < 2$ GeV • $\theta_{e\gamma} > 4°$, $\theta_{\gamma\gamma} > 1°$ • π^0 cone angle $< 4°$

DATA

event selection II : refine π^0 signal region, subtract background



1. fit conservative windows for $m_{\gamma\gamma}, p_T^{miss}, M^2_{miss}(ep\gamma\gamma X)$
2. single contour-cut on correlated $(E_{miss}, M_{e\gamma\gamma X}, M^2_{epX})$
3. refit $m_{\gamma\gamma}$, estimate background from sidebands

Within each topology, the fitted $m_{\gamma\gamma}$ signal interval defines the signal events and the remainder of the fitted mass domain defines the sideband. The fitted nonnegative linear-background shape supplies the transfer factor

$$\alpha_g = \frac{\text{fitted background integral in signal window}}{\text{fitted background integral in sideband}} \tag{24}$$

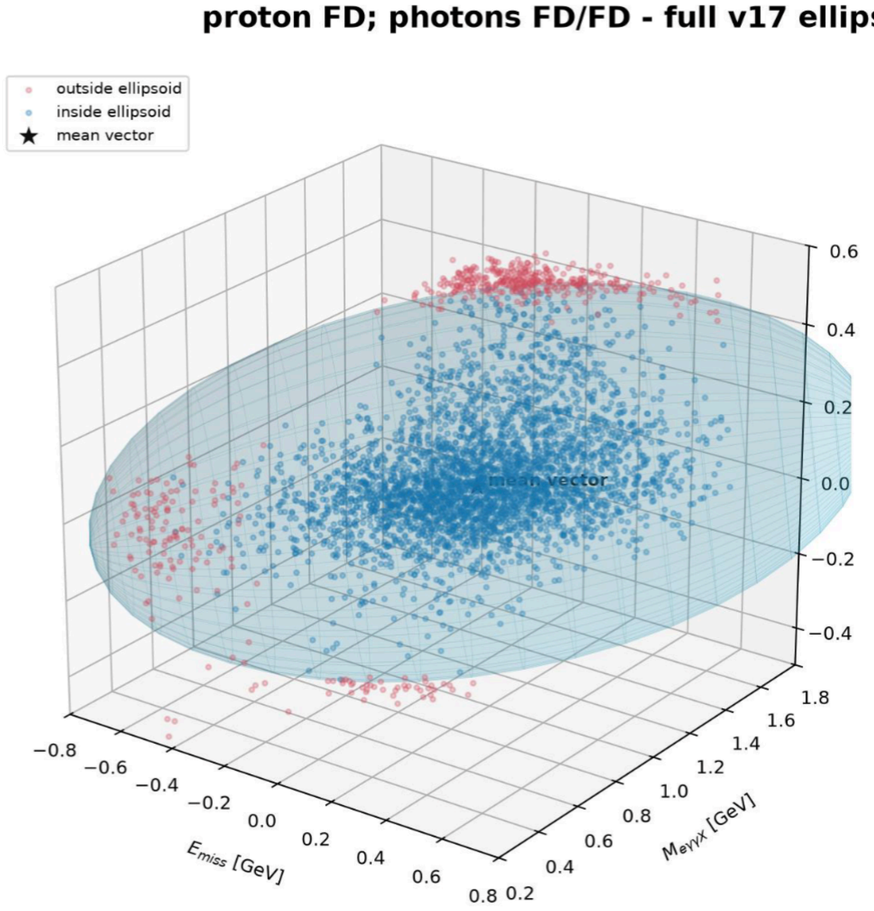
for topology g. In every reconstructed analysis bin,

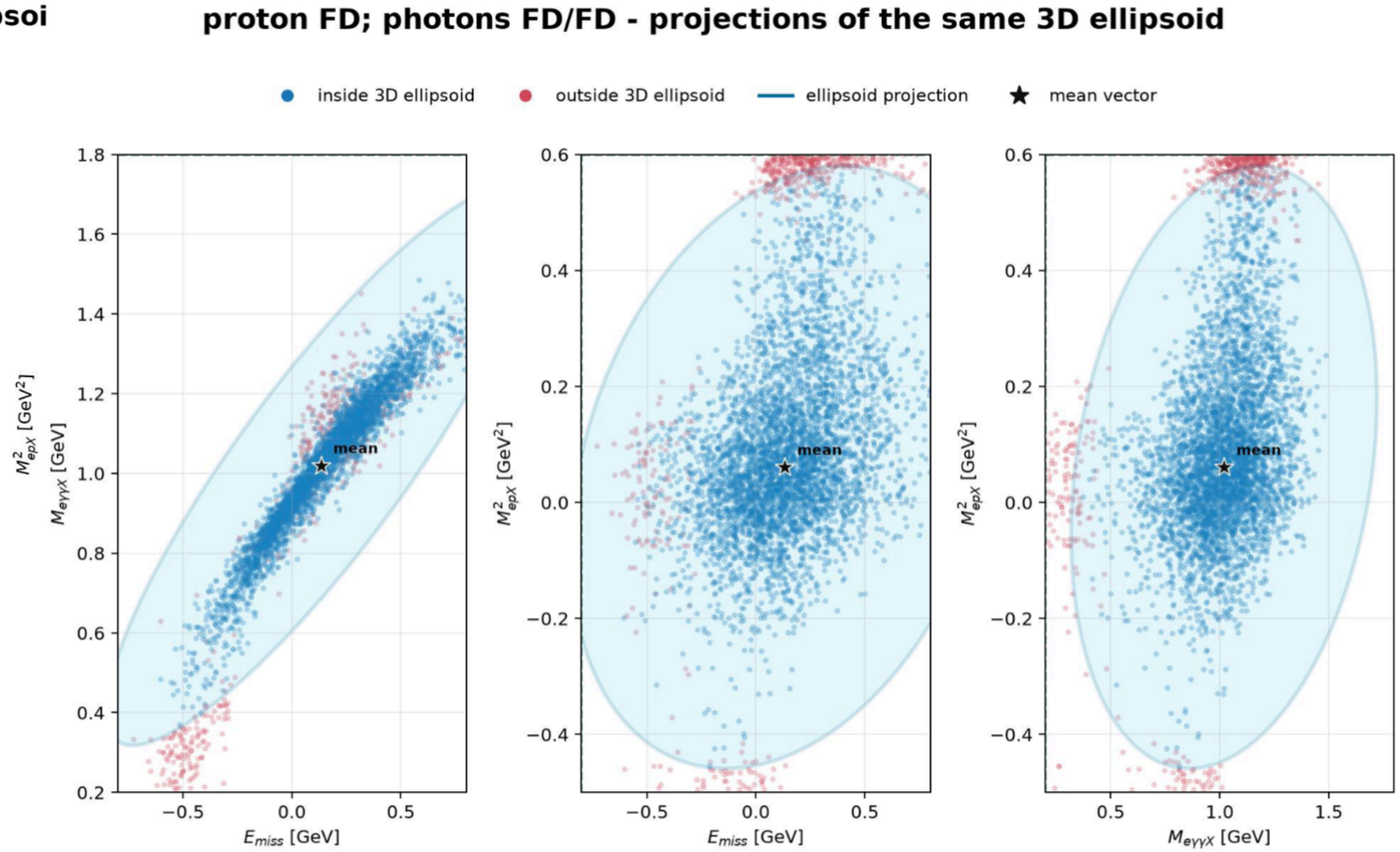
$$Y_i^{\text{net}} = N_{i,\text{sig}} - \sum_g \alpha_g N_{ig,\text{side}}. \tag{25}$$

Event-level current weights are applied to both signal and sideband events. Counting variance is $\sum w^2$ in the signal plus $\alpha_g^2 \sum w^2$ in the sideband; bootstrap uncertainty in α_g is recorded as correlated systematic information and is not added independently to every run-fit point. Bins that become slightly negative are clipped only under the explicit conservative policy and the clipped total is logged: 9 bins/5.44 events at 6.535 GeV and 25 bins/11.70 events at 7.546 GeV.

DATA

$(E_{miss}, M_{e\gamma\gamma X}, M^2_{epX})$ 99% contour cut: $d_i^2 = (x_i - \mu)^T \Sigma^{-1} (x_i - \mu) \leq q^2$





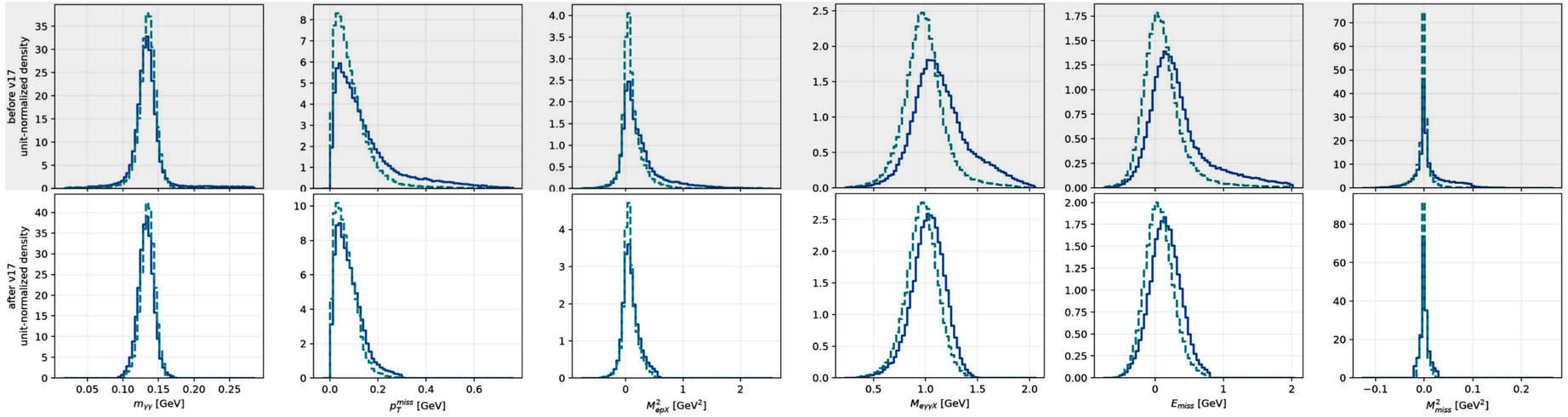
done separately for GEMC

Story Frantzen | Jefferson Lab

$m_{\gamma\gamma}$ p_T^{miss} M_{epX}^2 $M_{e\gamma\gamma X}$ E_{miss} M_{miss}^2

$p_{FD} : \gamma_{FD}\gamma_{FD}$

$(\approx 33\%)$

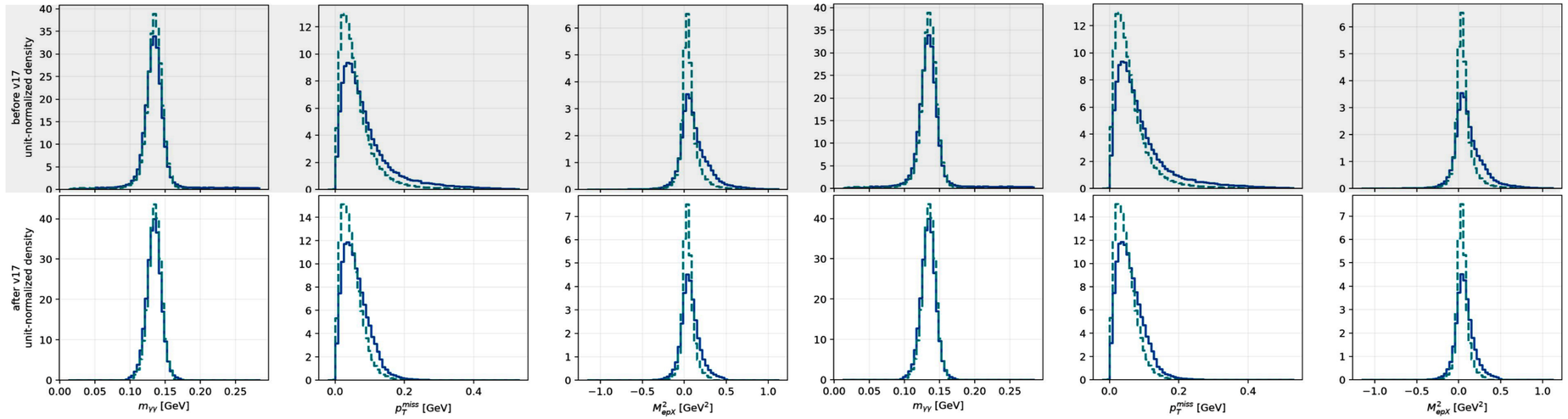


before cuts

after cuts

$p_{CD} : \gamma_{FD}\gamma_{FD}$

$(\approx 62\%)$



before cuts

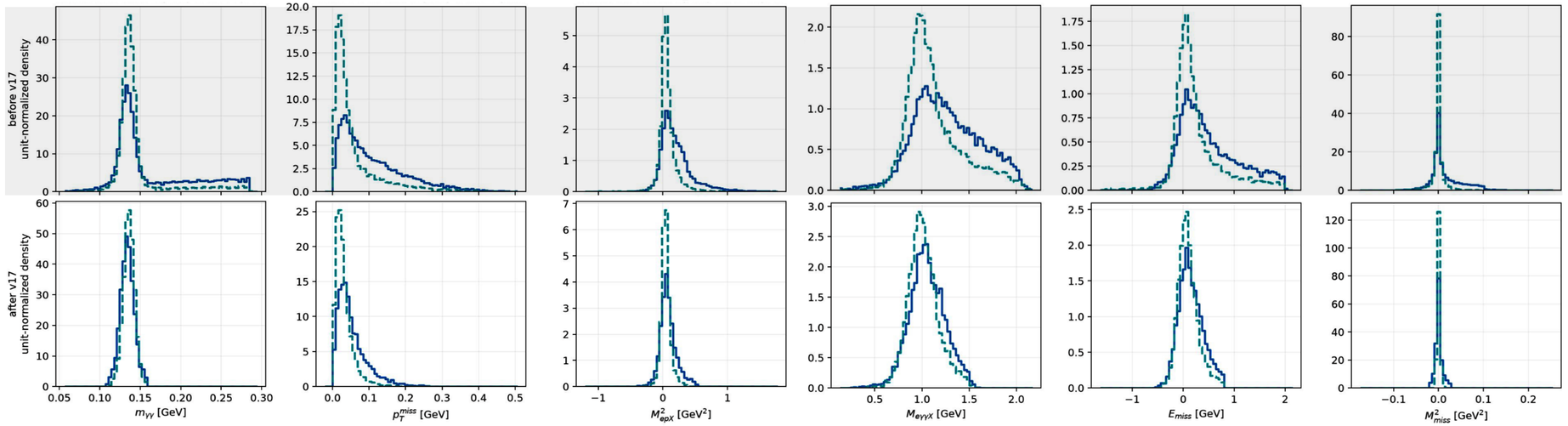
after cuts

production data nominal GEMC

$m_{\gamma\gamma}$ p_T^{miss} M^2_{epX} $M_{e\gamma\gamma X}$ E_{miss} M^2_{miss}

$p_{CD} : \gamma_{FT}\gamma_{FD}$

$(\approx 3\%)$

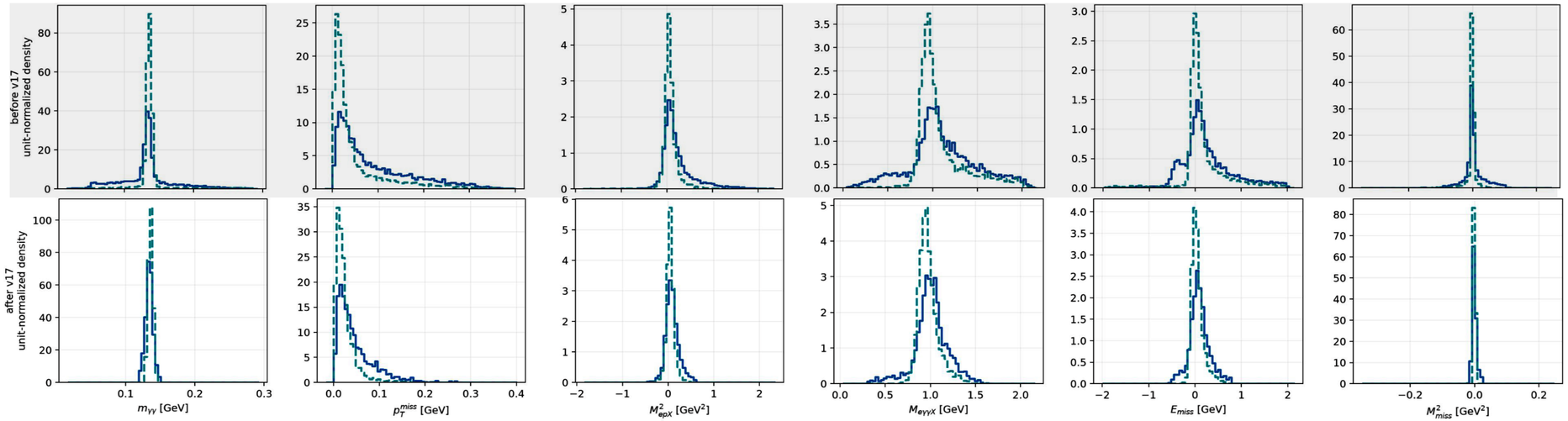


before cuts

after cuts

$p_{CD} : \gamma_{FT}\gamma_{FT}$

$(\approx 2\%)$



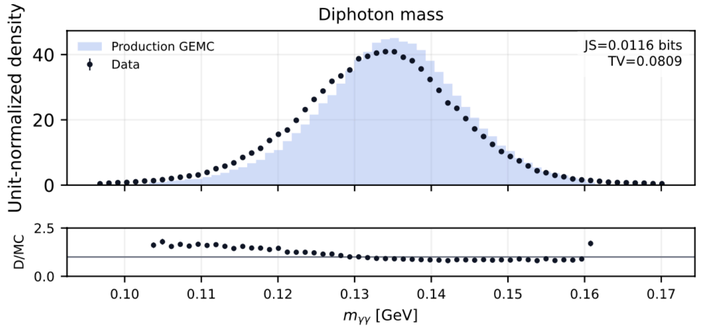
before cuts

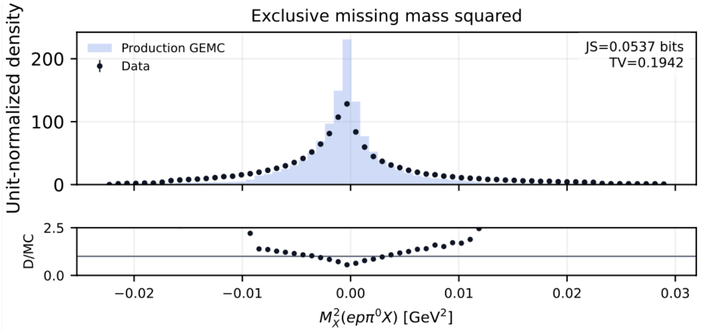
after cuts

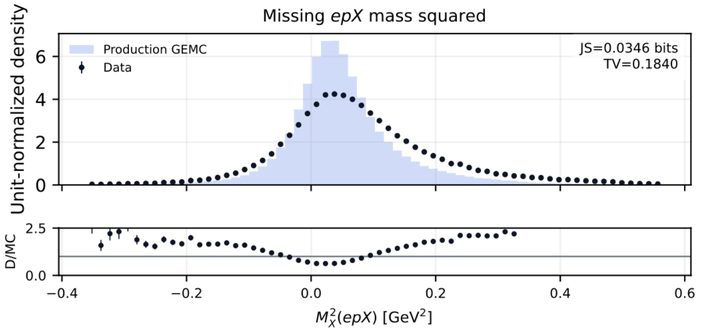
production data nominal GEMC

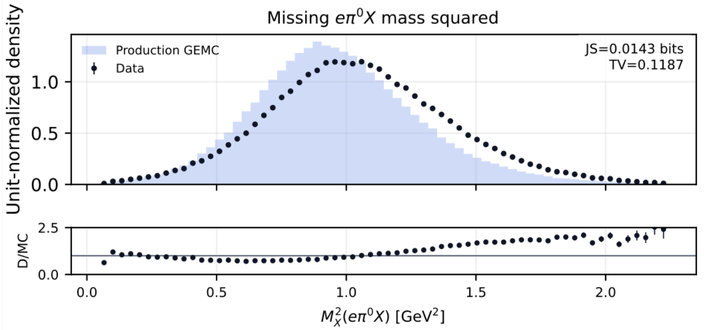
Story Frantzen | Jefferson Lab

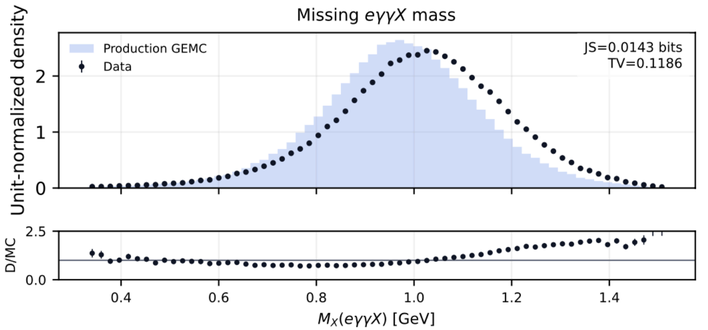
exclusivity distributions: data vs. GEMC (topology integrated)

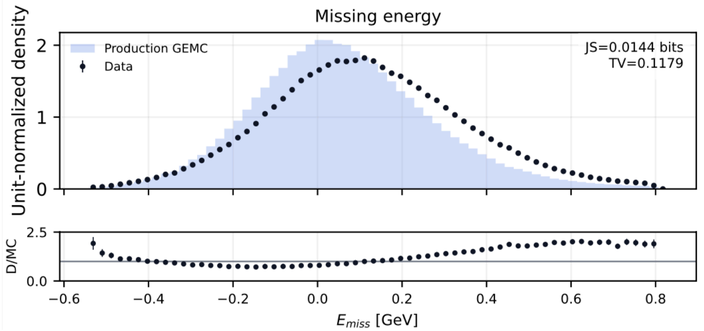


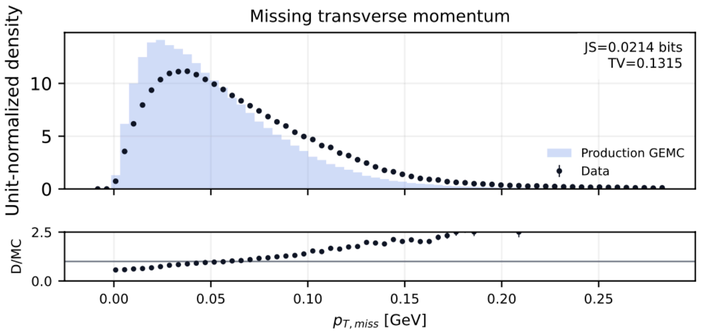






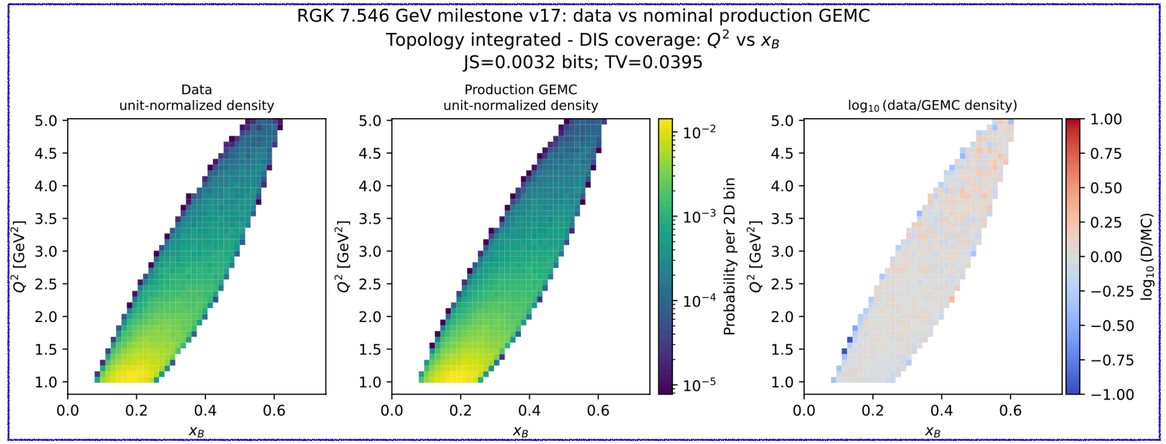


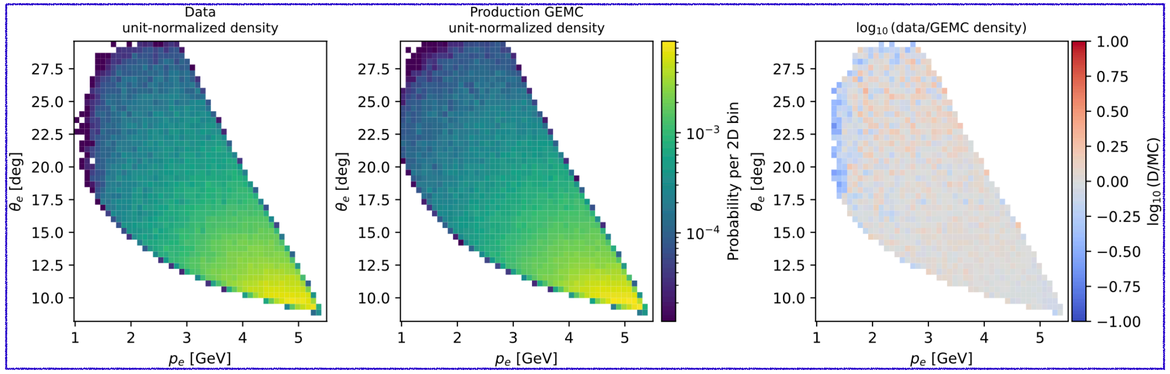


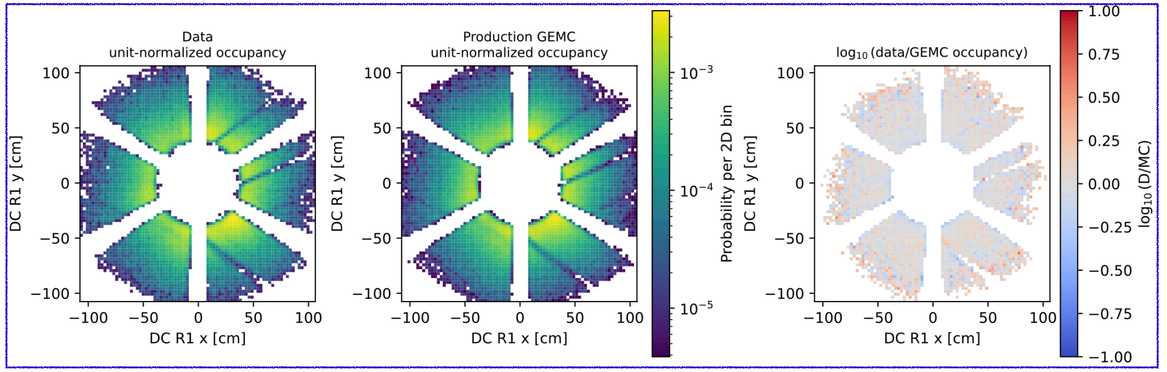


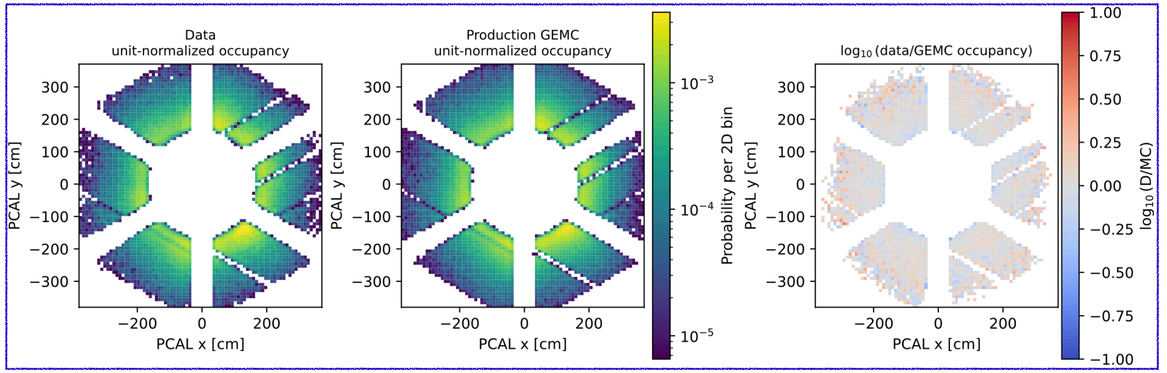
Story Frantzen | Jefferson Lab

selected-event kinematics: electrons

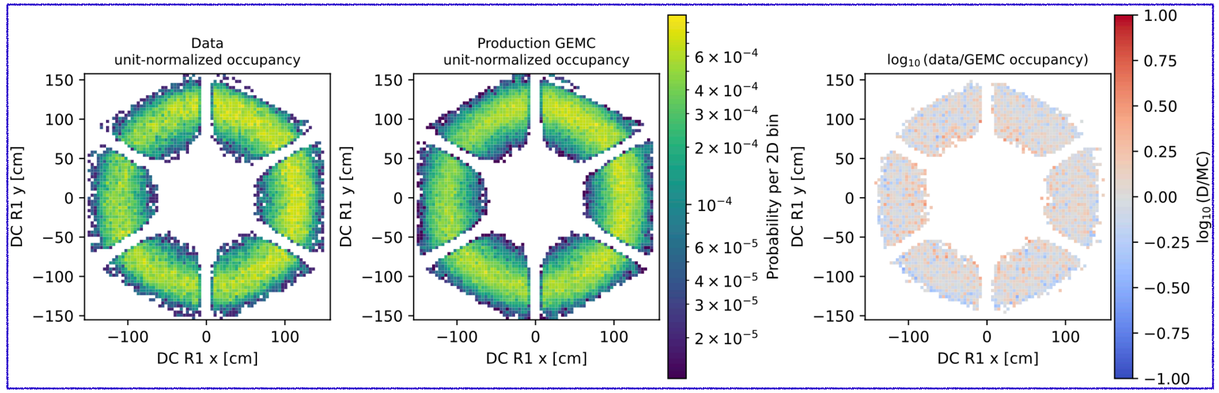


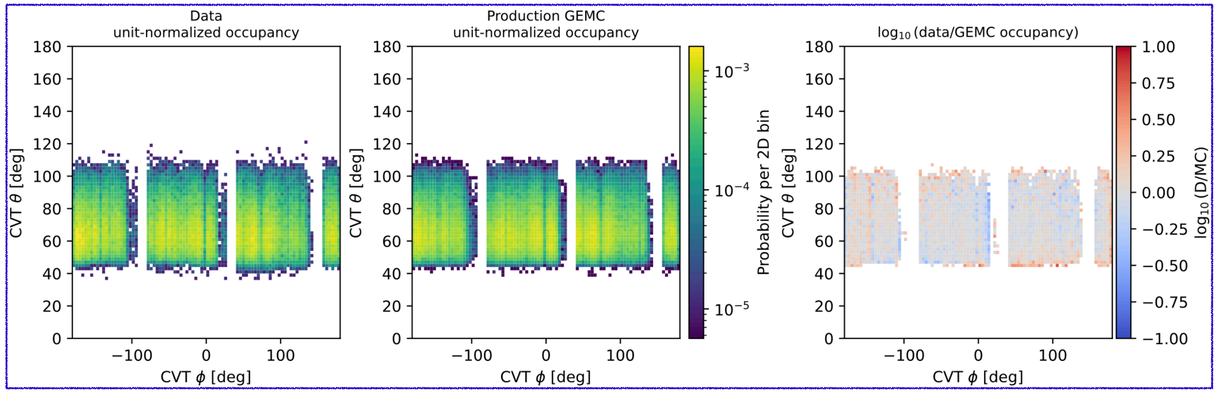


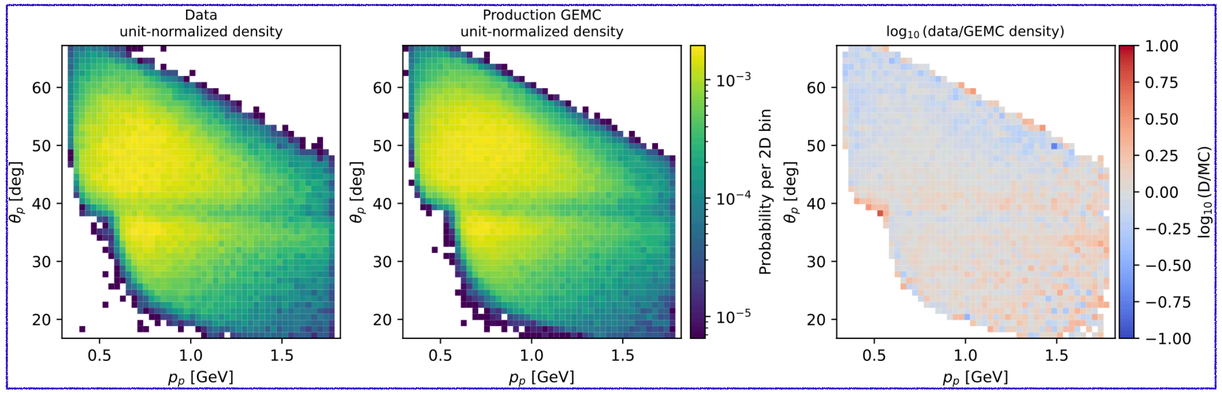


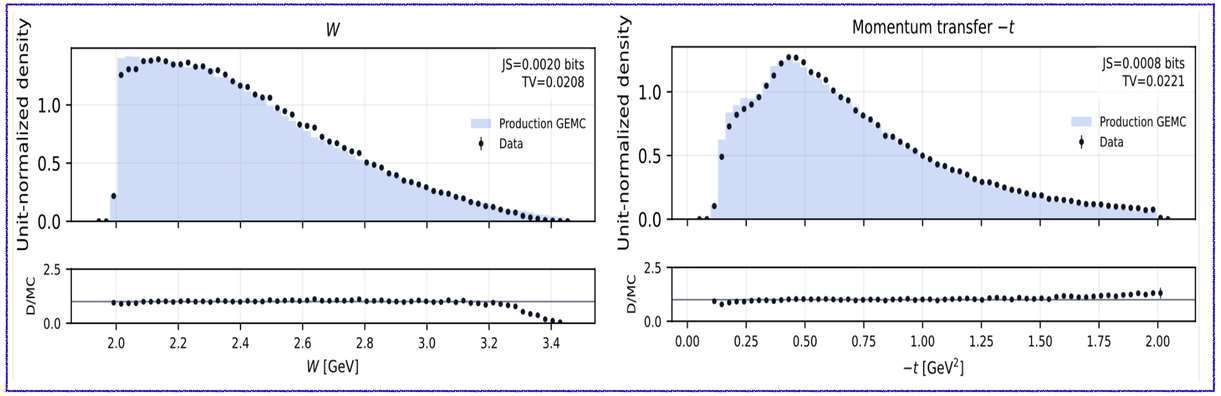


selected-event kinematics: protons



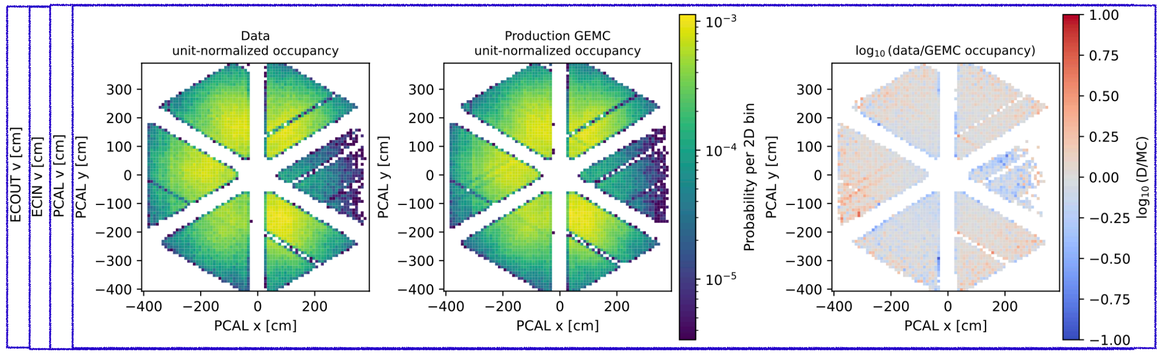


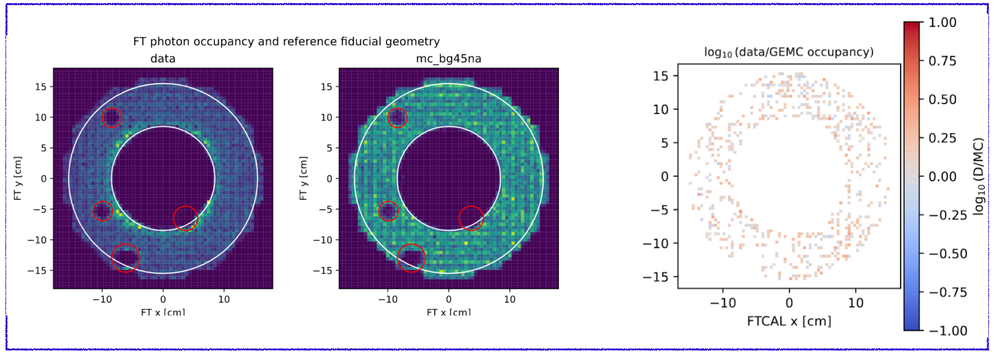


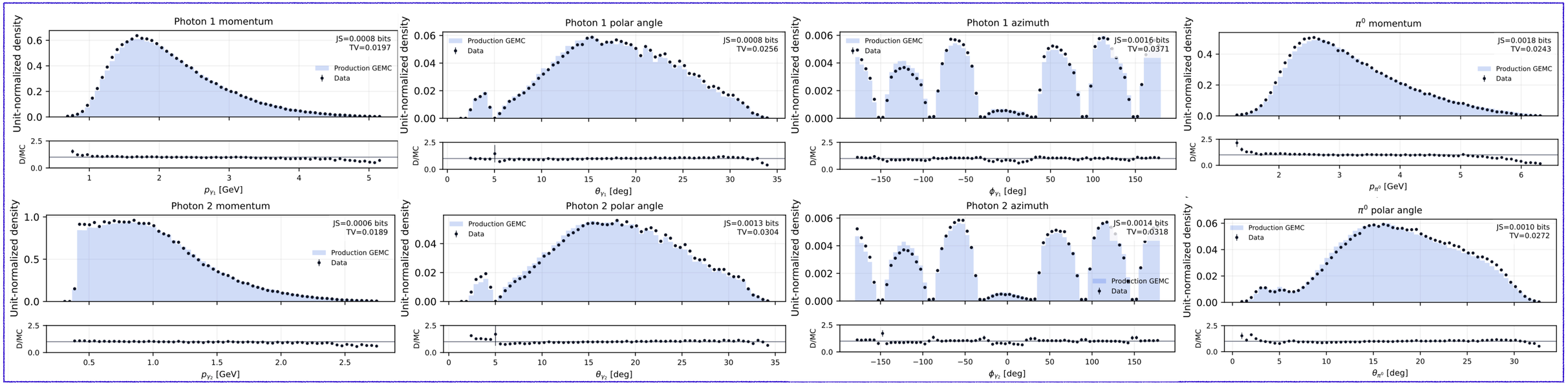


Story Frantzen | Jefferson Lab

selected-event distributions: photons



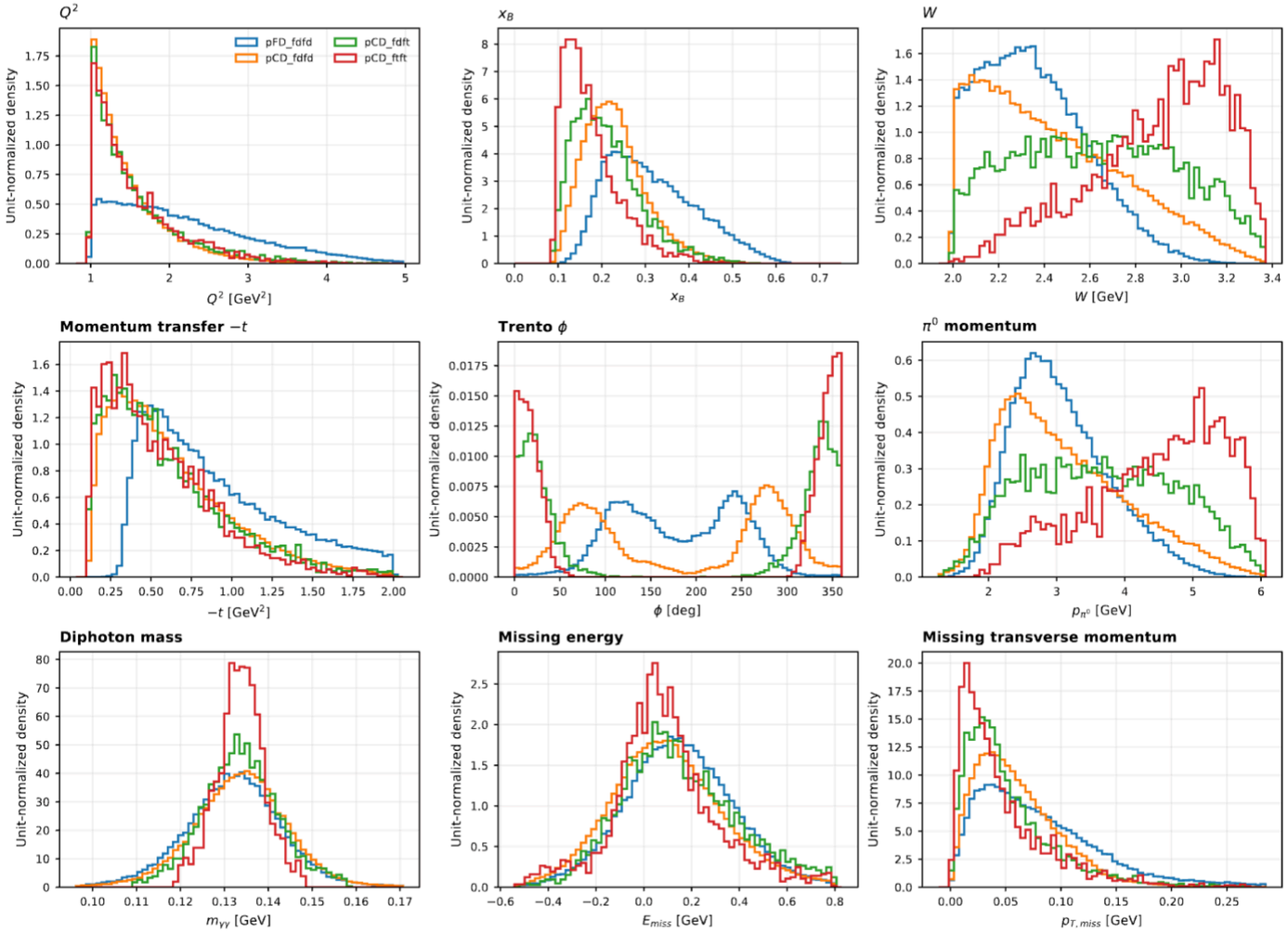




DATA

post-selection distributions: by topology

pFD_fdfd
pCD_fdfd
pCD_fdft
pCD_ftft



GEMC

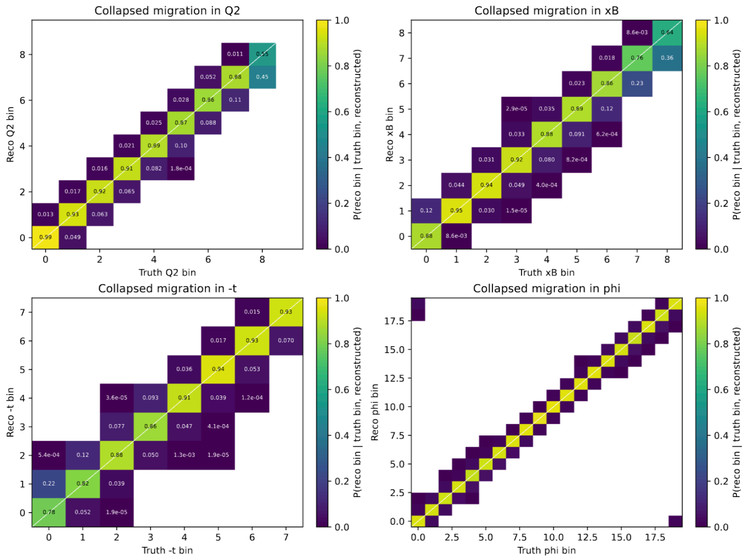
acceptance studies via 45nA-merged radiative ExcluGen

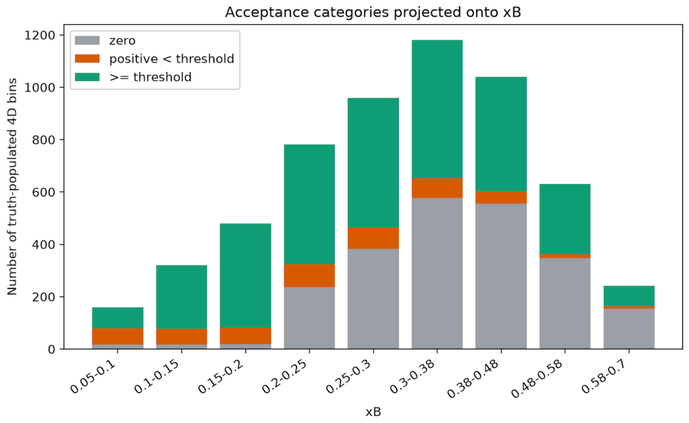
$$N_j^{\text{truth}} = \text{all generated events in truth bin } j,$$

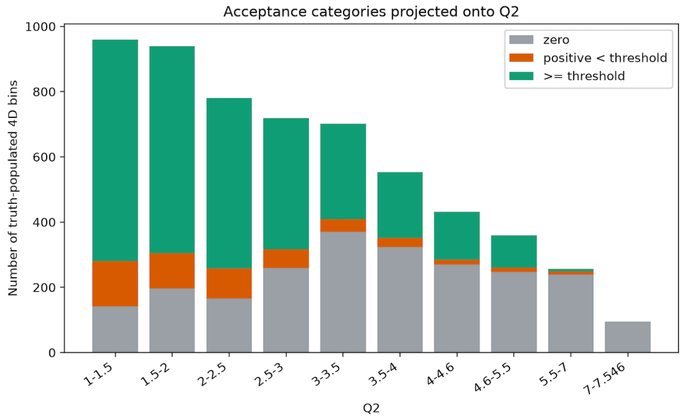
$$N_{ij}^{\text{mig}} = \text{events generated in } j \text{ and reconstructed/selected in } i,$$

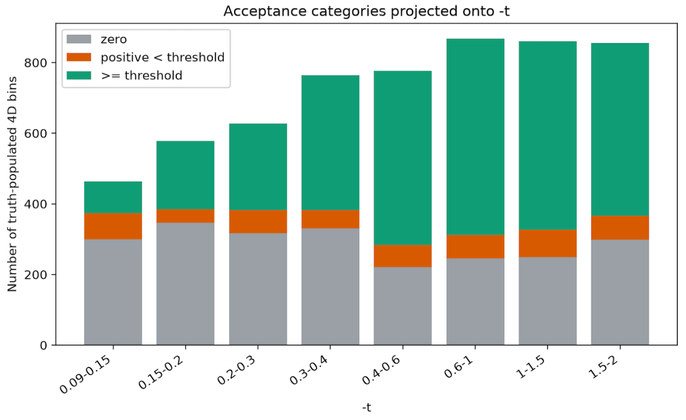
$$R_{ij} = \frac{N_{ij}^{\text{mig}}}{N_j^{\text{truth}}}, \qquad \epsilon_j = \sum_i R_{ij} = \frac{N_j^{\text{accepted}}}{N_j^{\text{truth}}}$$

- impose threshold $\epsilon_j \geq 0.005$









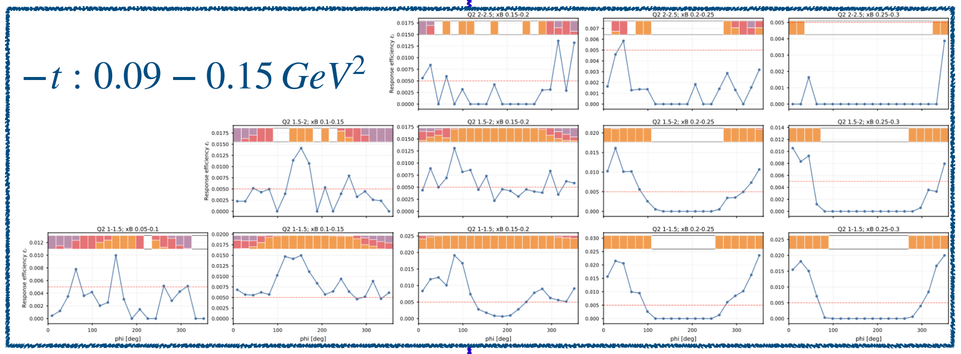
Story Frantzen

GEMC

acceptance studies via 45nA-merged radiative ExcluGen

	min.	10	med.	90	max.
epsilon	0	0	0.006	0.05	0.21
+/-	0.024	0.07	0.21	0.71	1.00

$-t$: 0.09 – 0.15 GeV^2



$-t$: 0.6 – 1.0 GeV^2

epsilon_i total efficiency
p FD; gamma gamma FD/FD
p CD; gamma gamma FD/FD
p CD; gamma gamma FD/FT
p CD; gamma gamma FT/FT

radiative corrections

For analysis bin B and reconstruction kernel $K_B(x)$,
integrate over acceptance x to obtain measured cross section I :

$$I_m^{\mathcal{B}} = \int dx\; K_{\mathcal{B}}(x)\, \sigma_m(x), \qquad \delta_{\mathcal{B}} = \frac{I_{\mathrm{rad}}^{\mathcal{B}}}{I_{\mathrm{Born}}^{\mathcal{B}}}.$$

2 methods to compute Born denominator of the correction

- unbiased method **B** requires Born GEMC

$$\hat{I}_m^{\mathcal{B}} = \frac{\sigma_m}{N_m^{\mathrm{gen}}} N_{m,\mathcal{B}}^{\mathrm{rec}}, \qquad \delta_B^{\mathcal{B}} = \frac{N_{\mathrm{rad}}^{\mathrm{rec}}\, \sigma_{\mathrm{rad}} / N_{\mathrm{rad}}^{\mathrm{gen}}}{N_{\mathrm{Born}}^{\mathrm{rec}}\, \sigma_{\mathrm{Born}} / N_{\mathrm{Born}}^{\mathrm{gen}}}$$

- “quick” method **A** used here :

$$\eta(x; v_{\mathrm{cut}}) = \frac{\sigma_{\mathrm{obs}}(x; v_{\mathrm{cut}})}{\sigma_{\mathrm{Born}}(x)}. \qquad \delta_A^{\mathcal{B}}(v_{\mathrm{cut}}) = \left[\frac{1}{N_{\mathrm{rad}}^{\mathrm{rec}}} \sum_{i \in \text{accepted rad}} \frac{1}{\eta(x_i; v_{\mathrm{cut}})} \right]^{-1}$$

GEMC

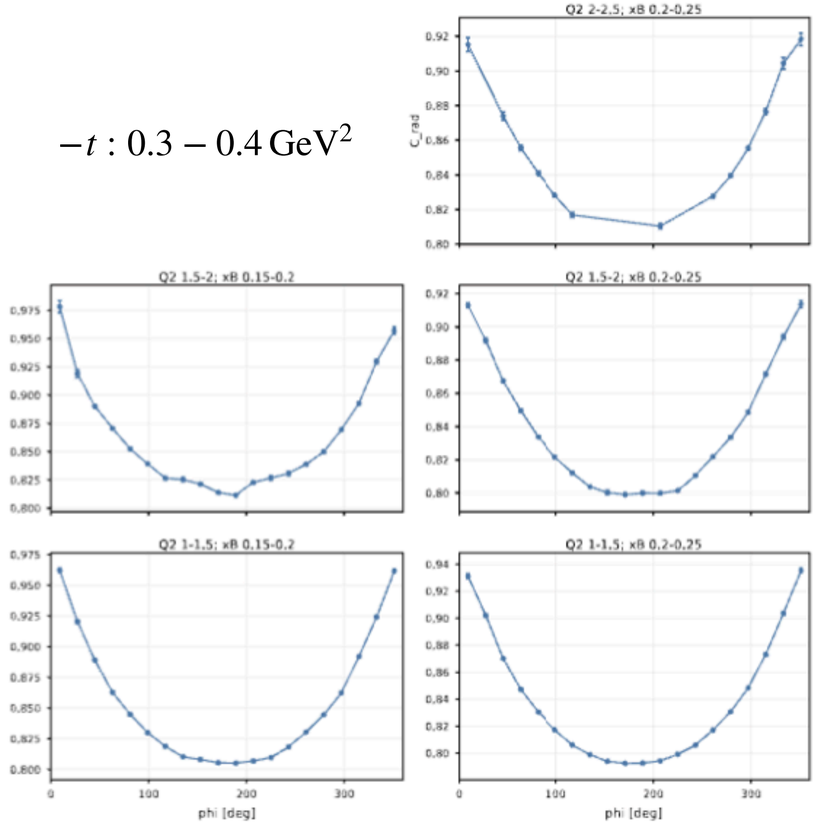
radiative corrections

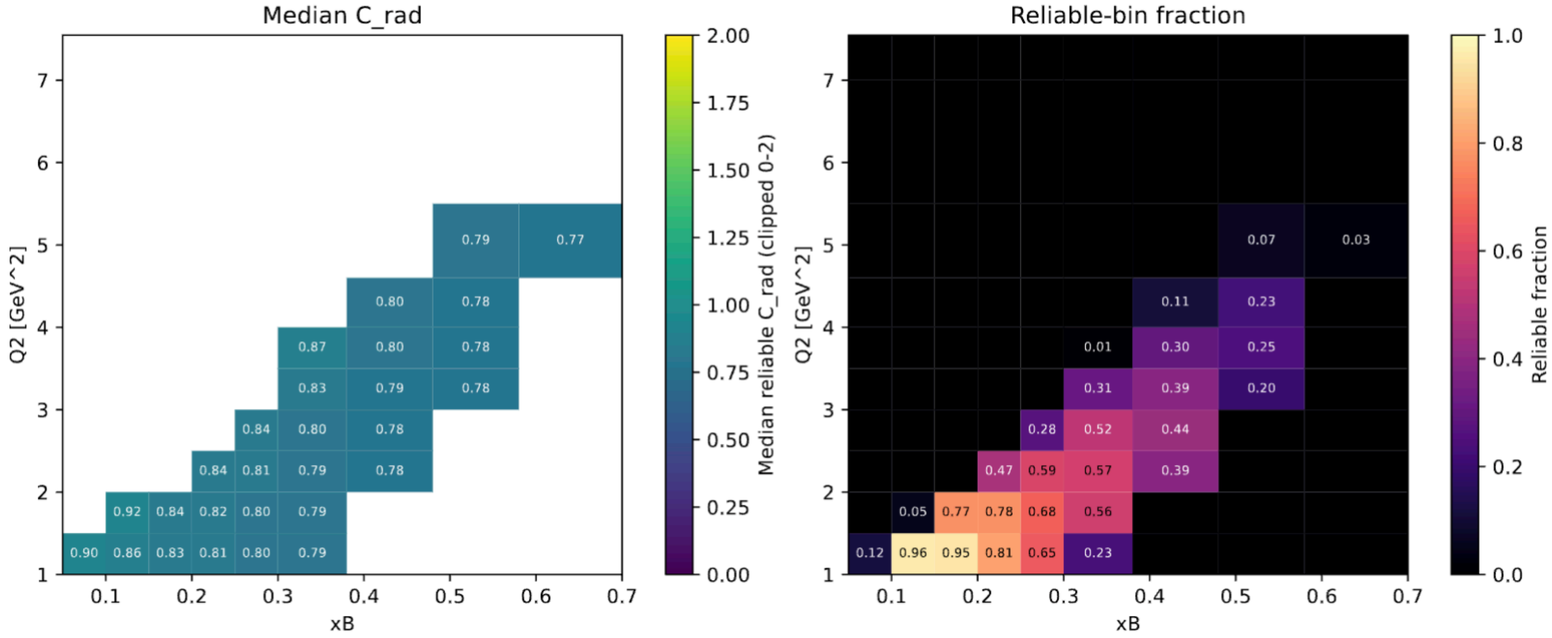
- “quick” method **A** used here :

$$\delta_A^{\mathcal{B}}(v_{\text{cut}}) = \left[\frac{1}{N_{\text{rad}}^{\text{rec}}} \sum_{i \in \text{accepted rad}} \frac{1}{\eta(x_i; v_{\text{cut}})} \right]^{-1}$$

$$Y_b^{\text{Born}} = Y_b^{\text{rad}} / \delta_A(b)$$

$-t : 0.3 - 0.4\,\text{GeV}^2$



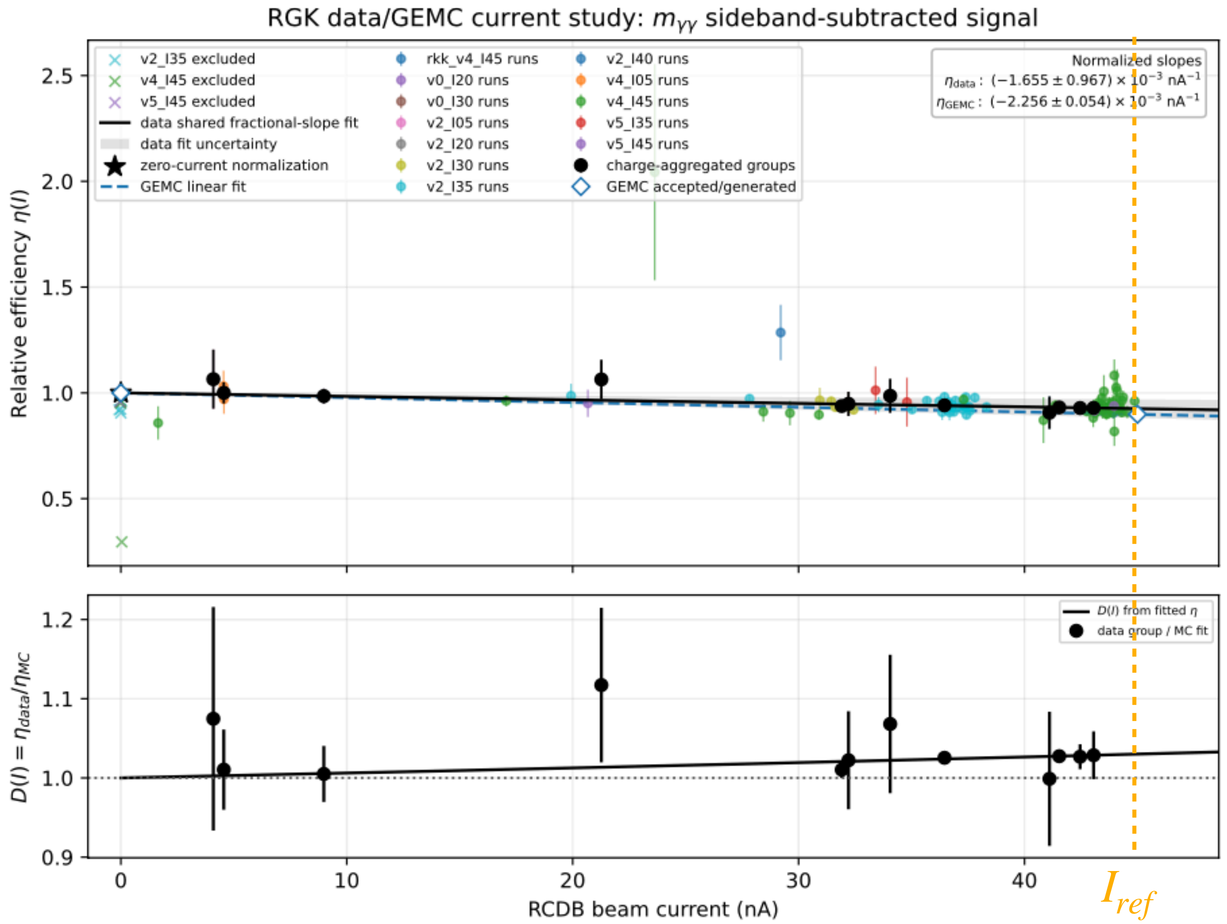


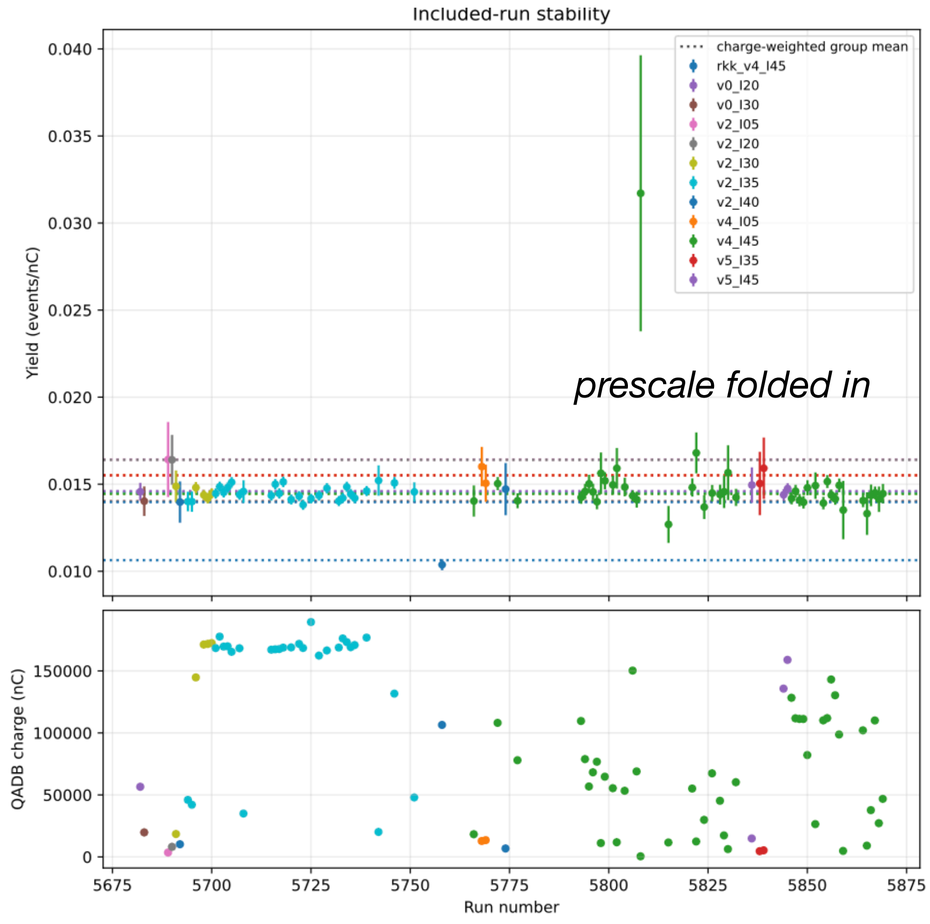
Story Frantzen | Jefferson Lab

tracking efficiency

Current/occupancy run weight

$$w_r = \frac{\eta_{\mathrm{MC}}(I_{\mathrm{ref}})}{\eta_{\mathrm{data}}(I_r)}, \quad \eta_{\mathrm{data}}(I) = 1 + s_{\mathrm{data}}\, I, \quad \eta_{\mathrm{MC}}(I) = \frac{a_{\mathrm{MC}} + b_{\mathrm{MC}} I}{a_{\mathrm{MC}}}, \quad w_r = 0 \text{ for excluded runs}$$



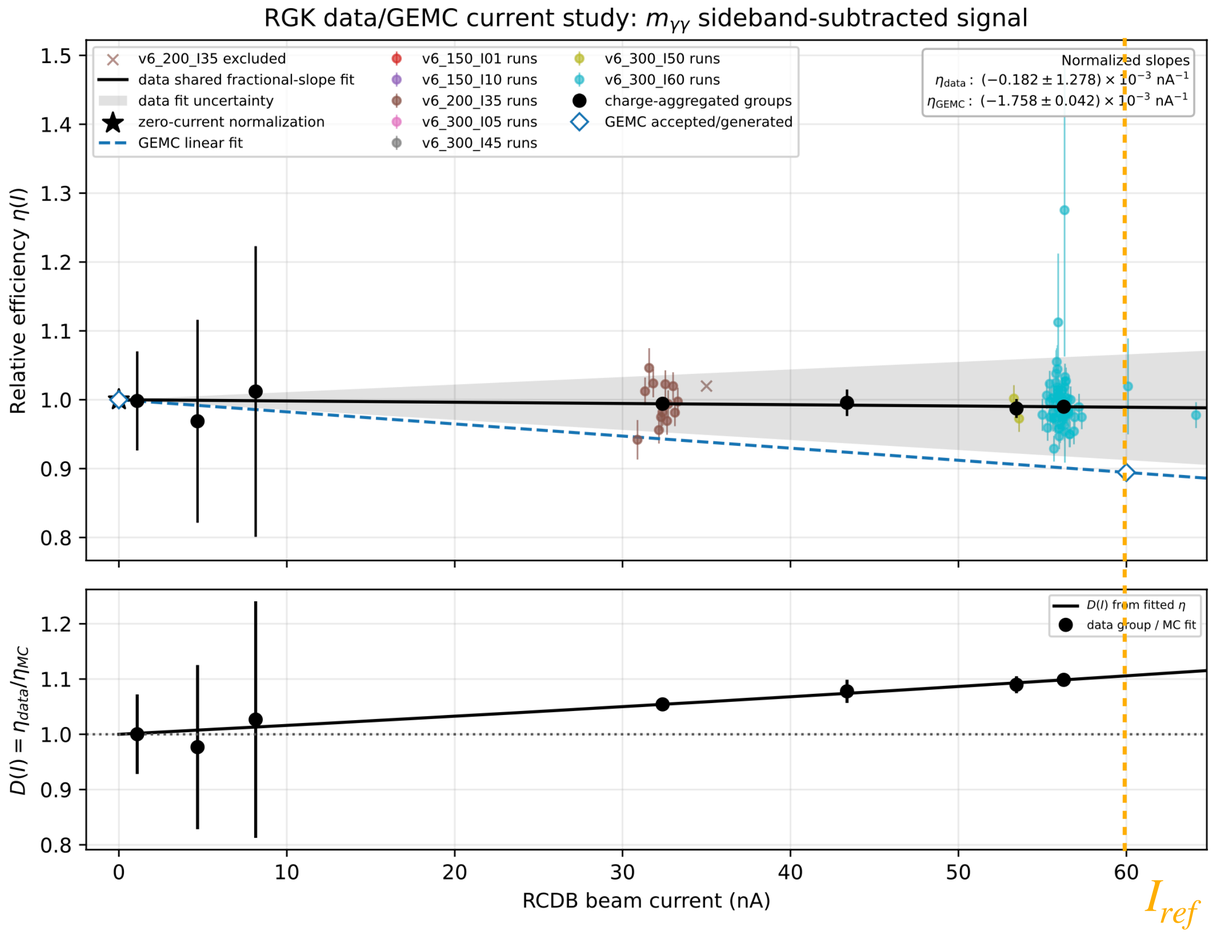


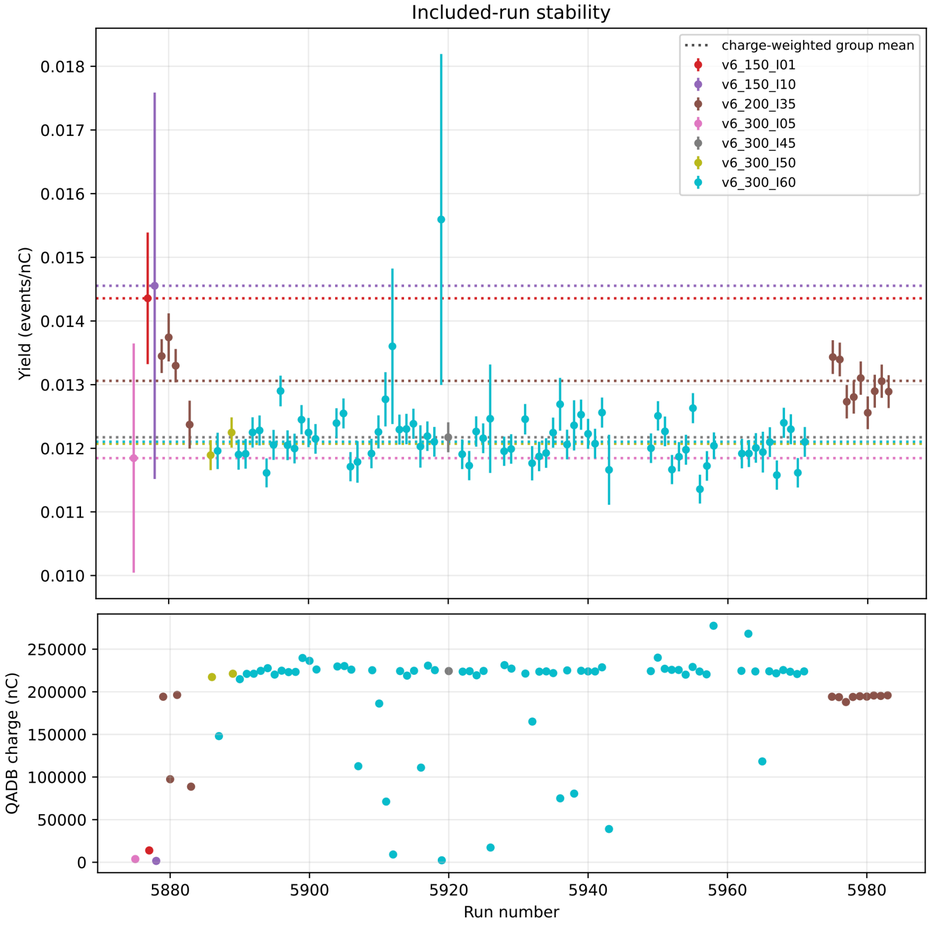
Story Frantzen | Jefferson Lab

tracking efficiency

Current/occupancy run weight

$$w_r = \frac{\eta_{\mathrm{MC}}(I_{\mathrm{ref}})}{\eta_{\mathrm{data}}(I_r)}, \quad \eta_{\mathrm{data}}(I) = 1 + s_{\mathrm{data}}\, I, \quad \eta_{\mathrm{MC}}(I) = \frac{a_{\mathrm{MC}} + b_{\mathrm{MC}} I}{a_{\mathrm{MC}}}, \quad w_r = 0 \text{ for excluded runs}$$





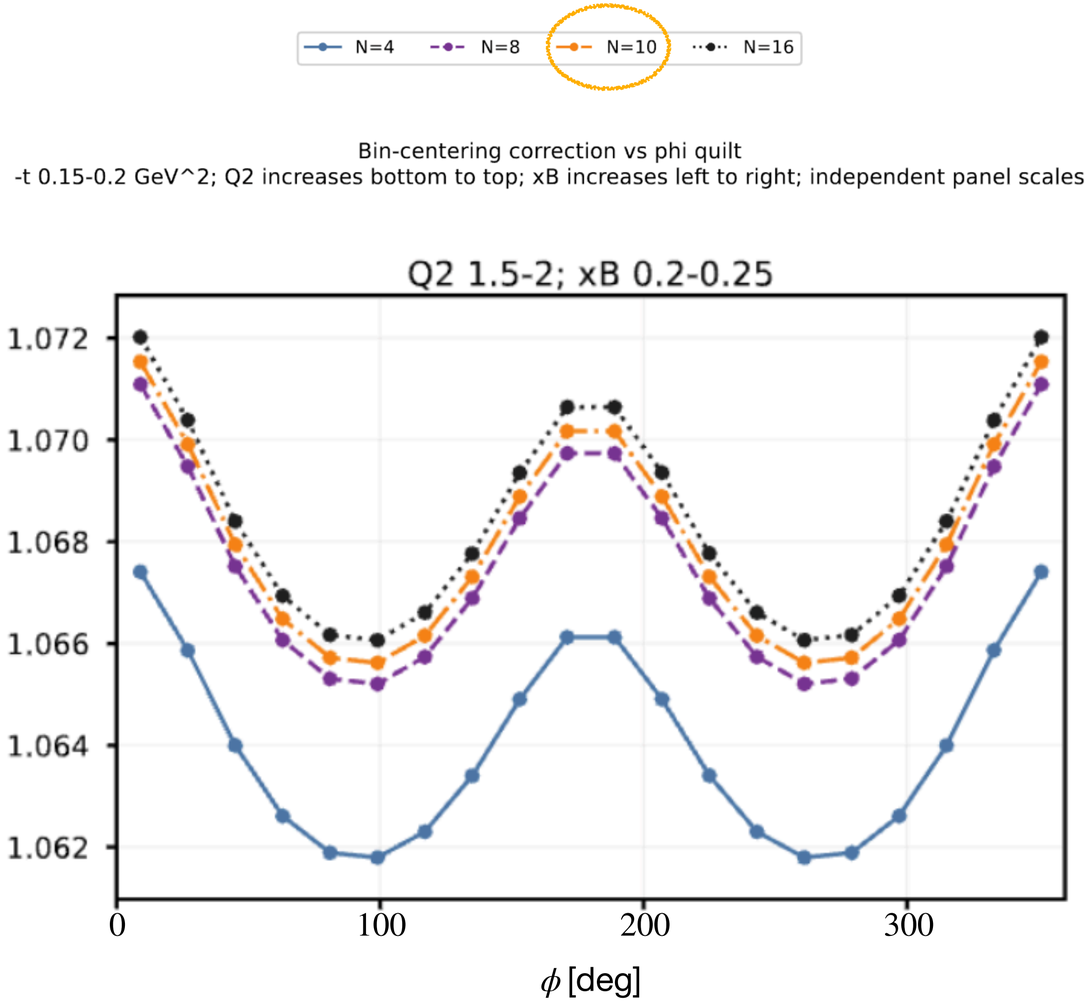
finite-bin volume corrections via ExcluGen

$$C_{\mathrm{BC}}(b) = \frac{\left\langle \Gamma_v(Q^2, x_B)\, \sigma_{\mathrm{red}}^{\mathrm{model}}(Q^2, x_B, t, \phi) \right\rangle_{b,\mathrm{phys}}}{\Gamma_v(Q^2_{\mathrm{ref}}, x_{B,\mathrm{ref}})\, \sigma_{\mathrm{red}}^{\mathrm{model}}(Q^2_{\mathrm{ref}}, x_{B,\mathrm{ref}}, t_{\mathrm{ref}}, \phi_{\mathrm{ref}})}$$

for bin b, scale bin-averaged (measured) value to a reference value, e.g., physical bin centroid

evaluate Born model on N^4 physical midpoint grid ($N = 10$ in what follows)

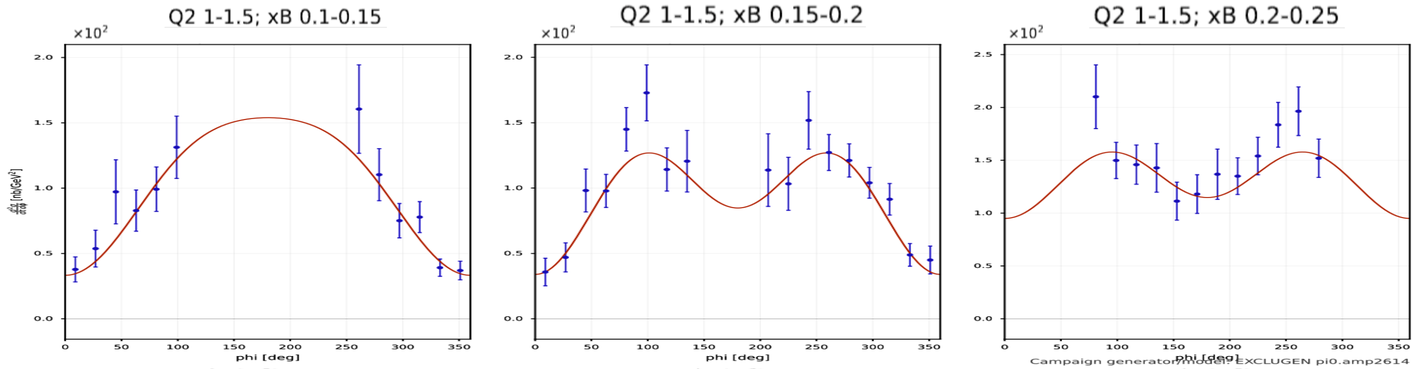
min.	10	med.	90	max.
0.975	1.00	1.03	1.12	1.25



preliminary results

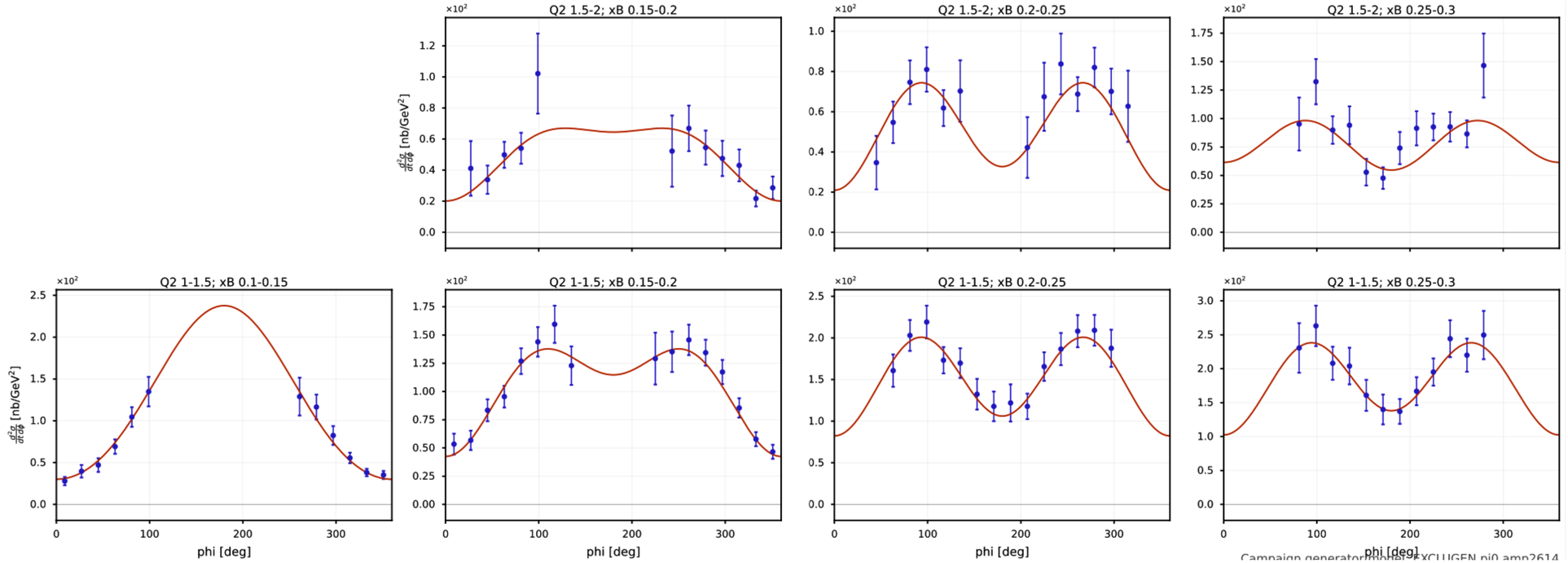
$$\frac{\mathrm{d}^2\sigma_{\gamma^* p\to\pi^0 p}}{\mathrm{d}t\,\mathrm{d}\phi}$$

$-t : 0.15 - 0.2\,GeV^2$

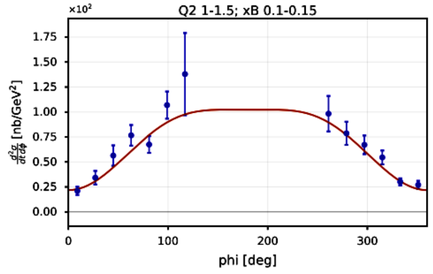


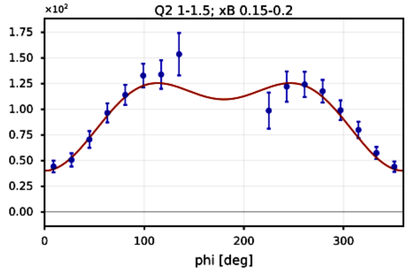
$$\frac{\mathrm{d}^2\sigma_{\gamma^* p\to\pi^0 p}}{\mathrm{d}t\,\mathrm{d}\phi}$$

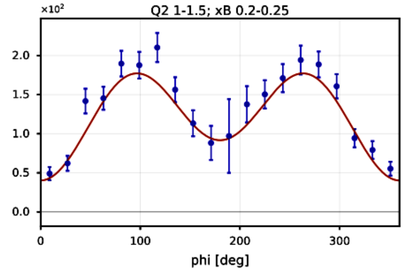
$-t : 0.2 - 0.3\,GeV^2$

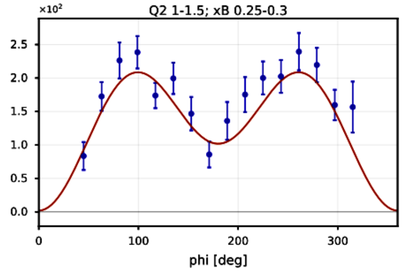


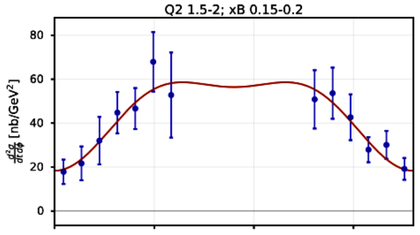
$$\frac{\mathrm{d}^2\sigma_{\gamma^* p\to\pi^0 p}}{\mathrm{d}t\,\mathrm{d}\phi} \qquad -t : 0.3 - 0.4\,GeV^2$$

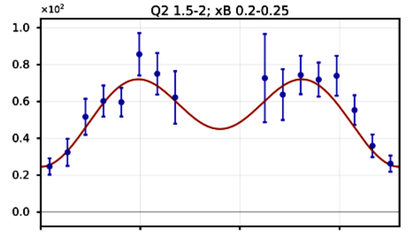


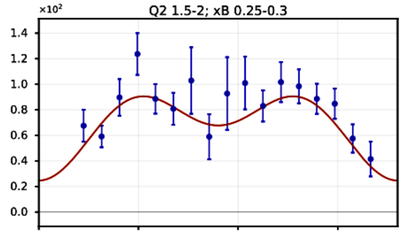


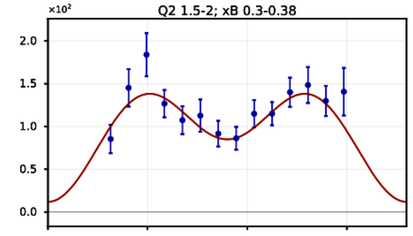


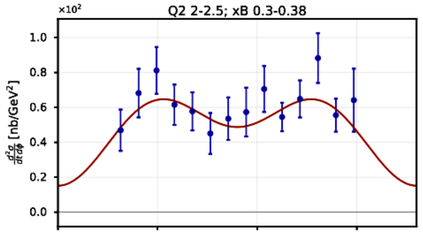


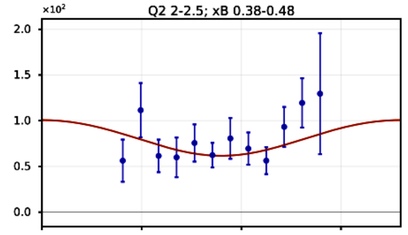






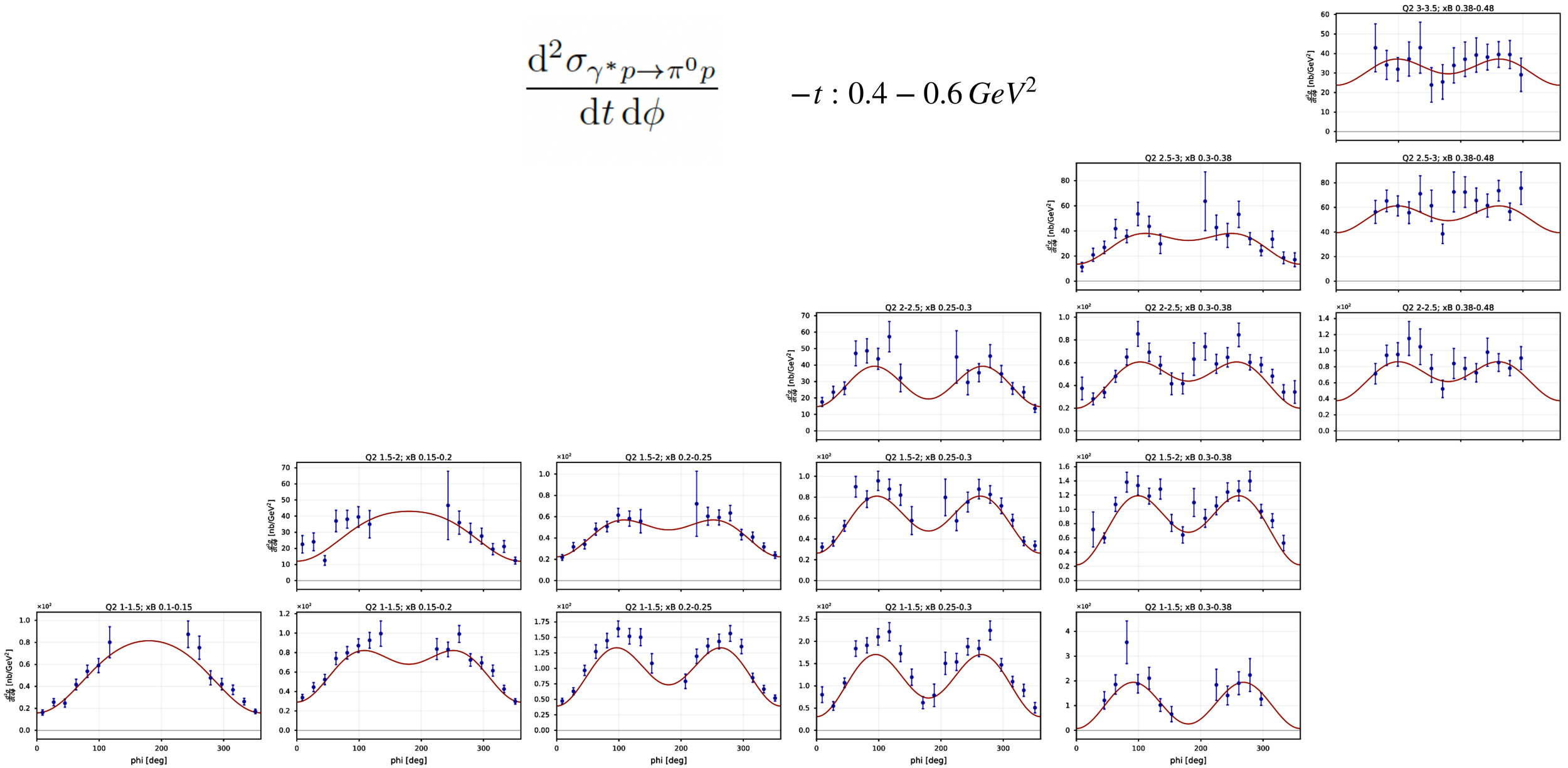




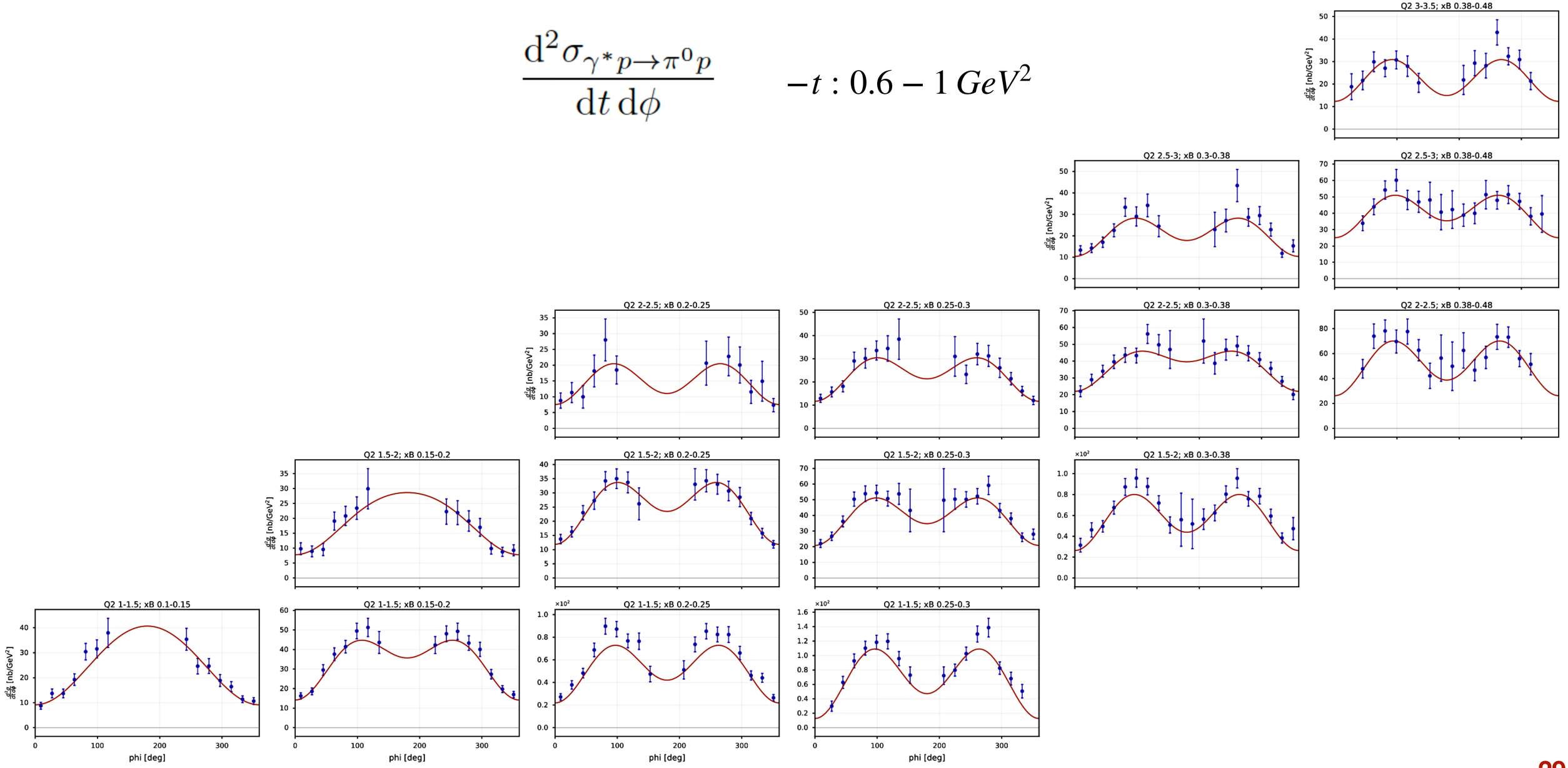


Campaign generator/model: EXCLUGEN pi0.amp2614

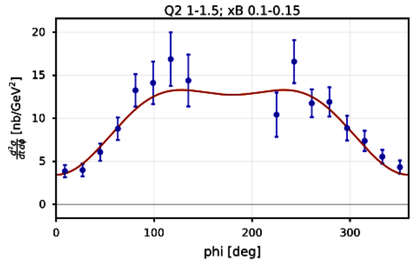
$$\frac{\mathrm{d}^2\sigma_{\gamma^* p\to\pi^0 p}}{\mathrm{d}t\,\mathrm{d}\phi} \qquad -t : 0.4 - 0.6\,GeV^2$$

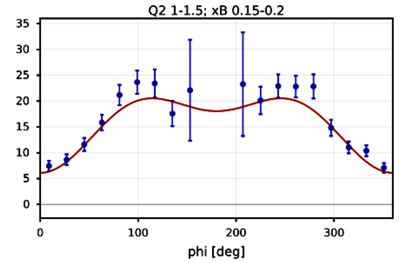


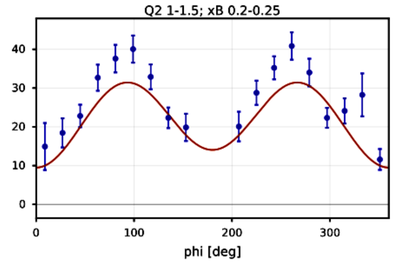
$$\frac{\mathrm{d}^2\sigma_{\gamma^* p\to\pi^0 p}}{\mathrm{d}t\,\mathrm{d}\phi} \qquad -t : 0.6 - 1\,GeV^2$$

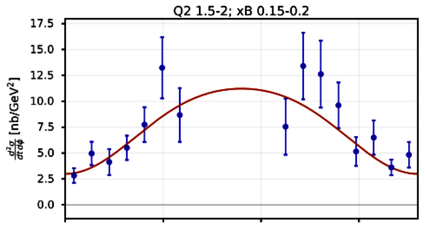


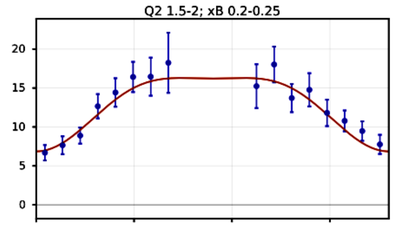
$$\frac{\mathrm{d}^2\sigma_{\gamma^* p\to\pi^0 p}}{\mathrm{d}t\,\mathrm{d}\phi} \qquad -t : 1 - 1.5\,GeV^2$$

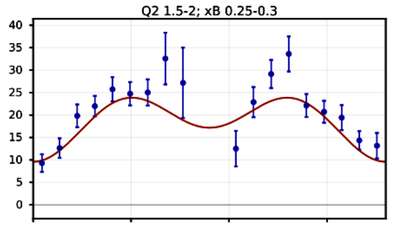


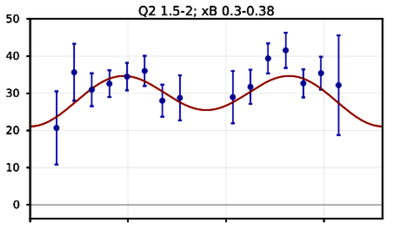


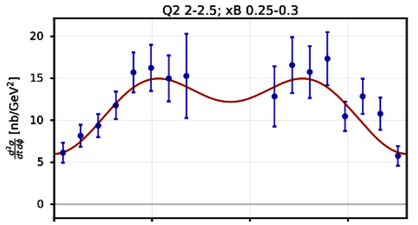


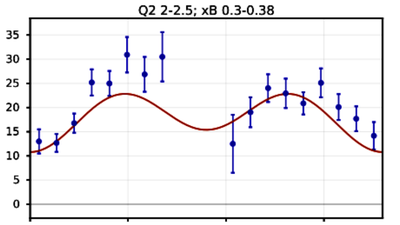


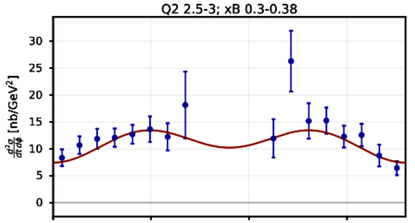


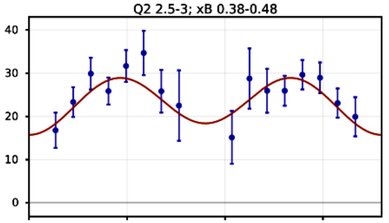


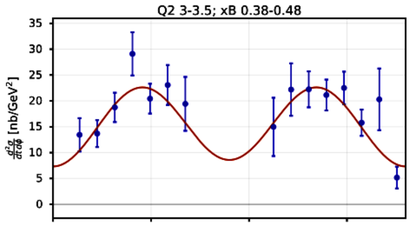




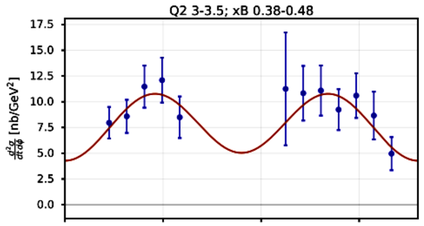


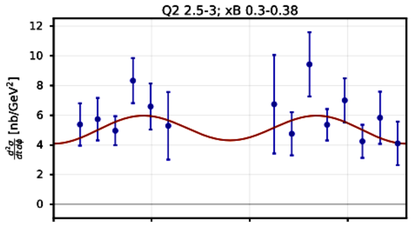


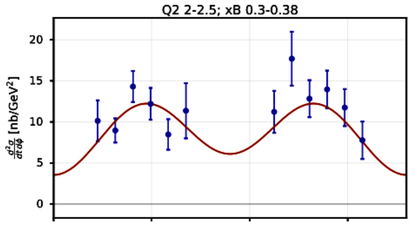


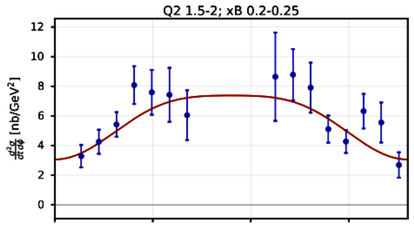


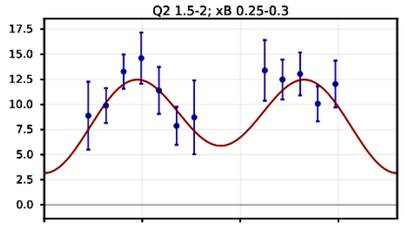
$$\frac{\mathrm{d}^2\sigma_{\gamma^* p\to\pi^0 p}}{\mathrm{d}t\,\mathrm{d}\phi} \qquad -t : 1.5 - 2\,GeV^2$$

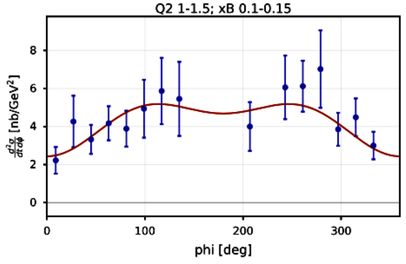


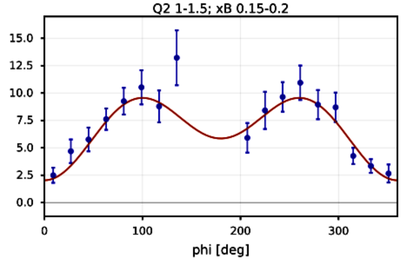






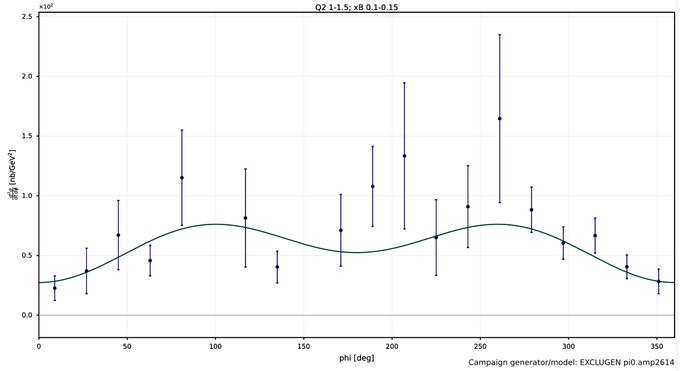






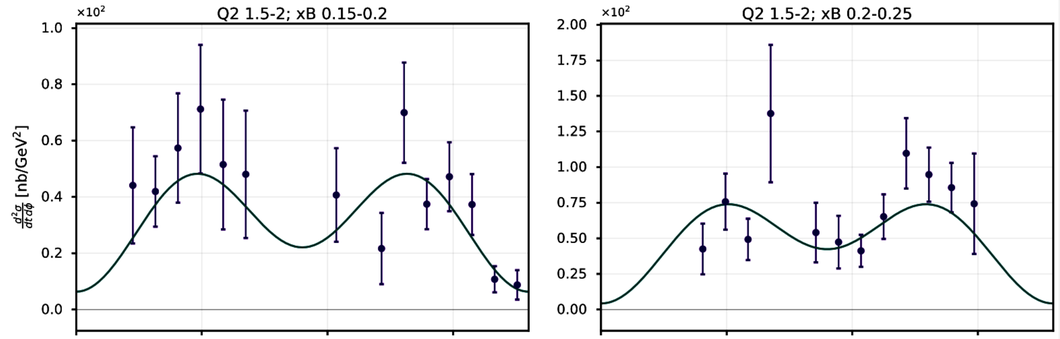
$$\frac{\mathrm{d}^2\sigma_{\gamma^* p\to\pi^0 p}}{\mathrm{d}t\,\mathrm{d}\phi}$$

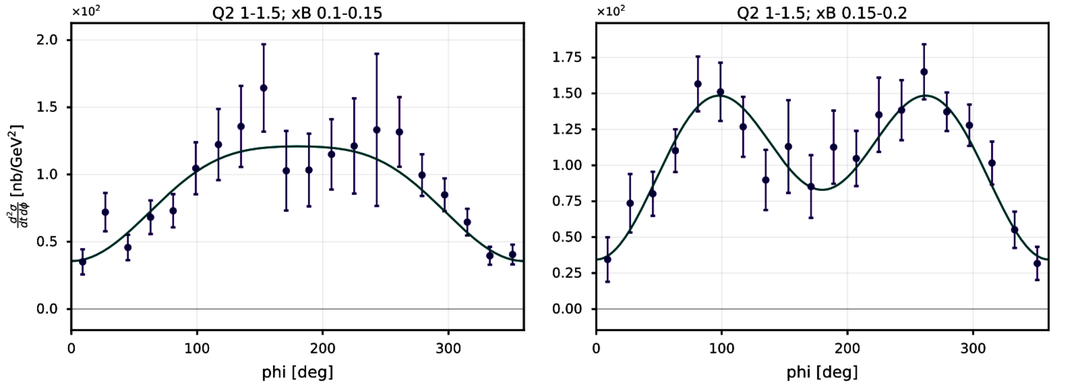
$-t : 0.09 - 0.15\,GeV^2$



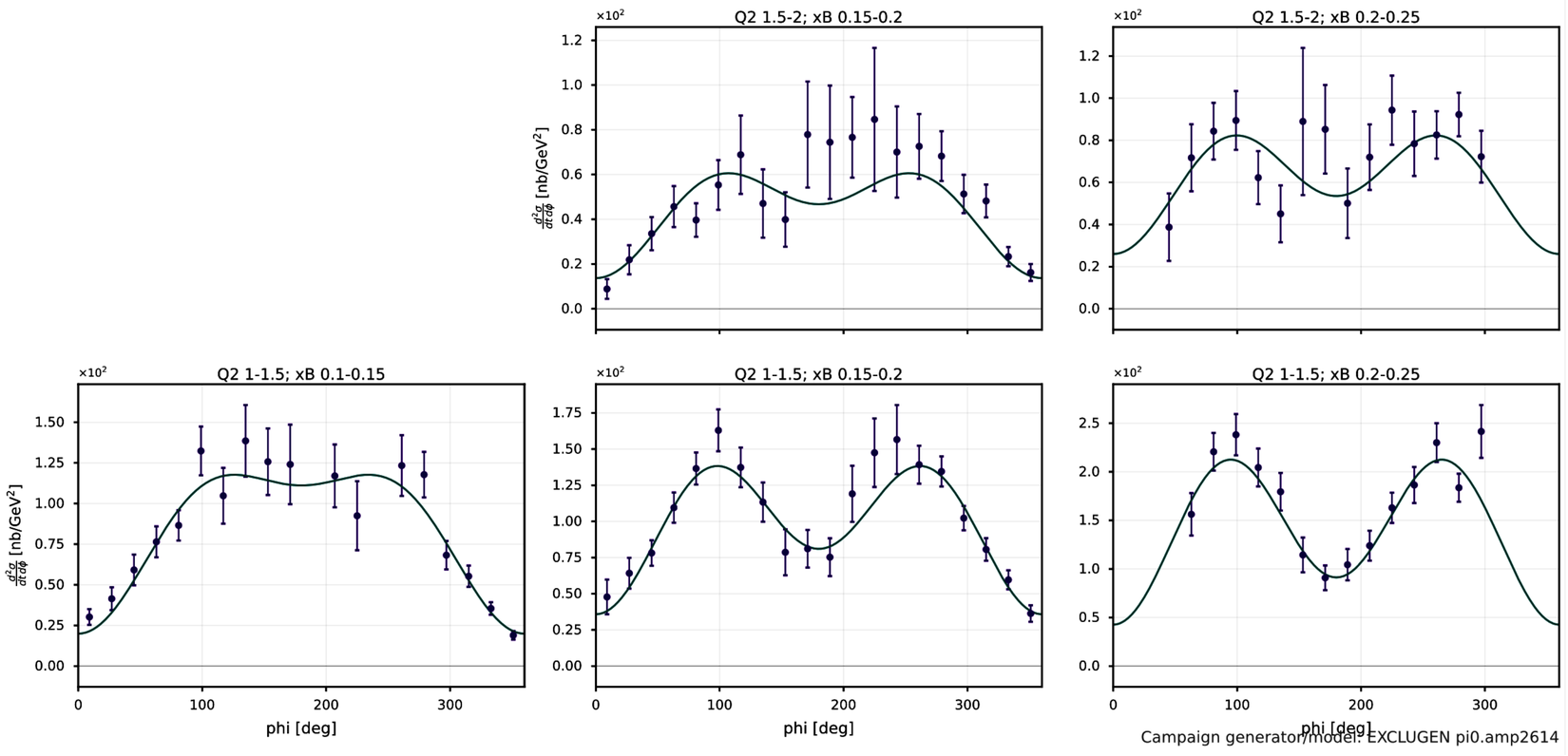
$$\frac{\mathrm{d}^2\sigma_{\gamma^* p\to\pi^0 p}}{\mathrm{d}t\,\mathrm{d}\phi}$$

$-t : 0.15 - 0.2\,GeV^2$



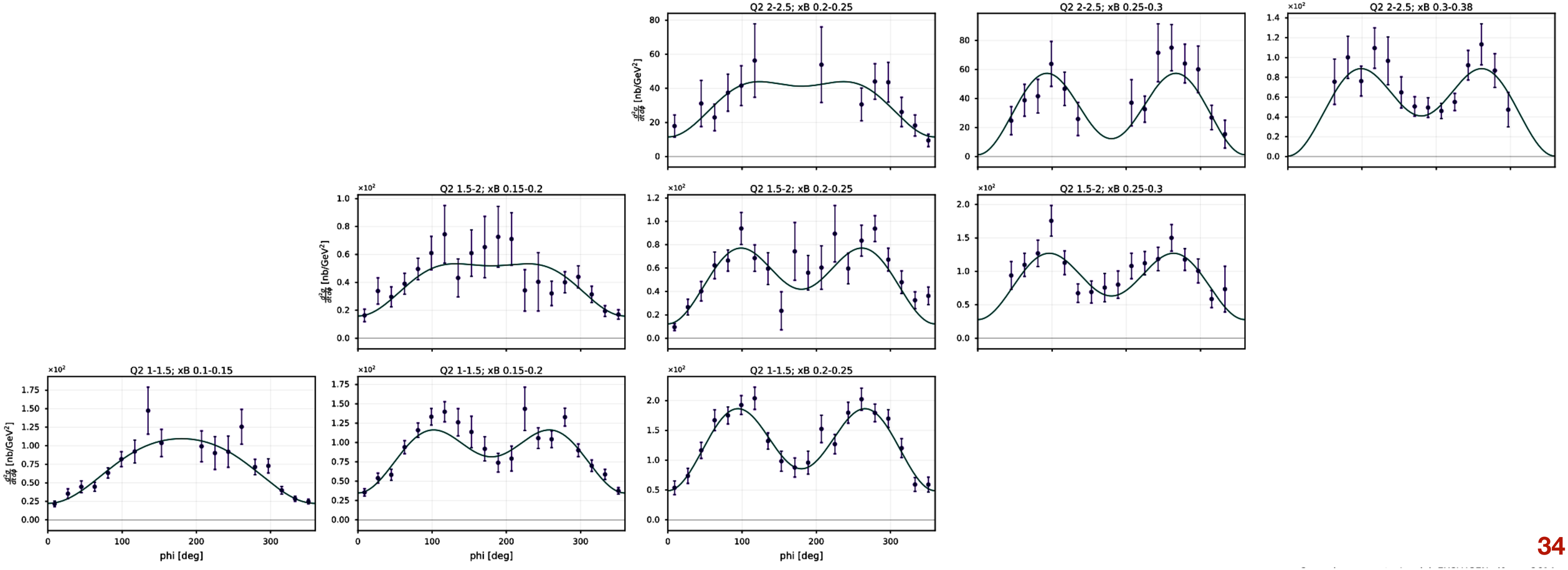


$$\frac{\mathrm{d}^2\sigma_{\gamma^* p\to\pi^0 p}}{\mathrm{d}t\,\mathrm{d}\phi} \qquad -t : 0.2 - 0.3\,GeV^2$$

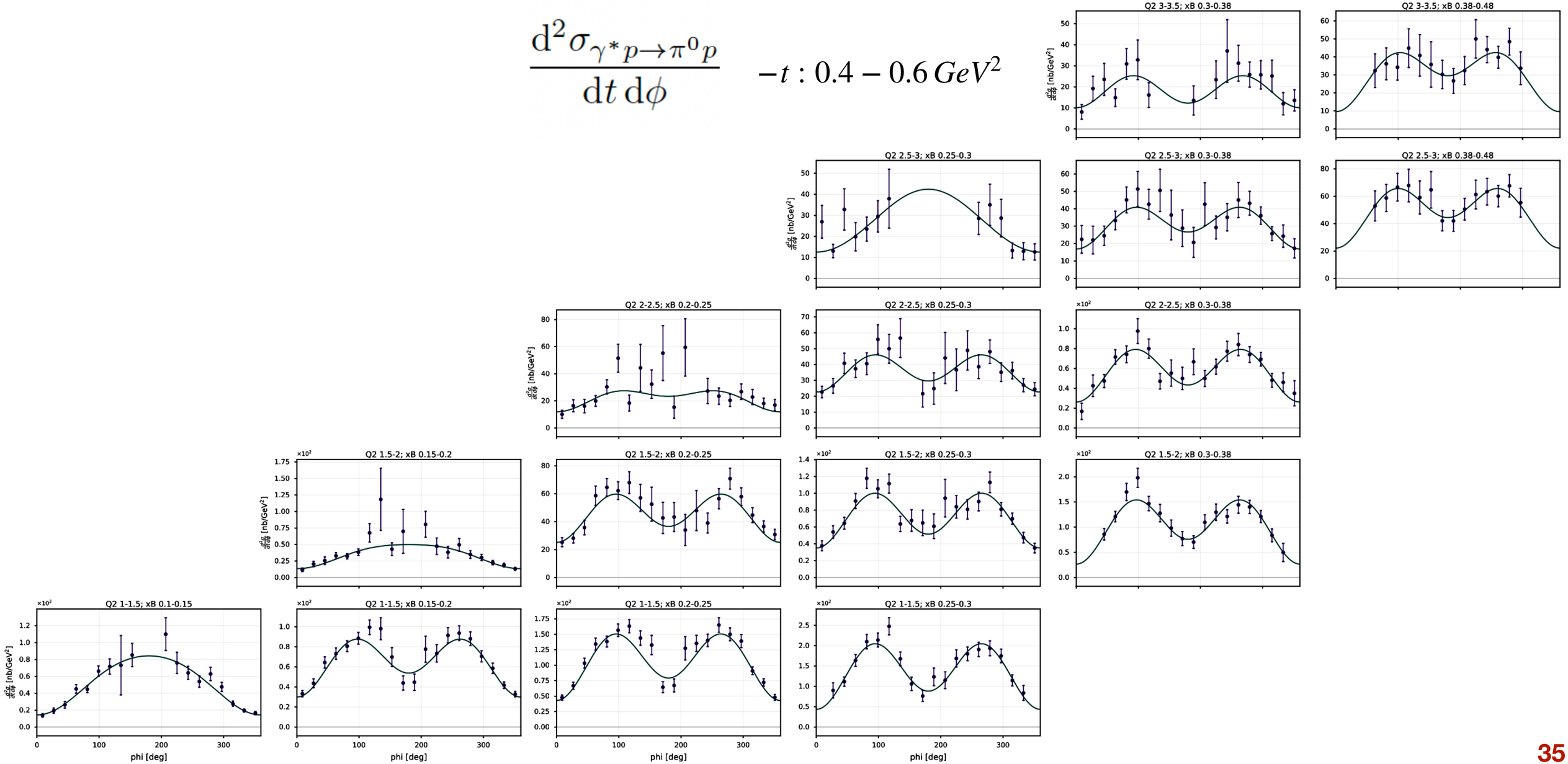


Campaign generator/model: EXCLUGEN pi0.amp2614

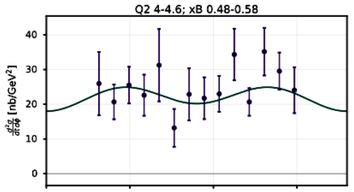
$$\frac{\mathrm{d}^2\sigma_{\gamma^* p\to\pi^0 p}}{\mathrm{d}t\,\mathrm{d}\phi} \qquad -t : 0.3 - 0.4\,GeV^2$$

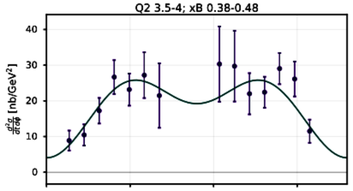


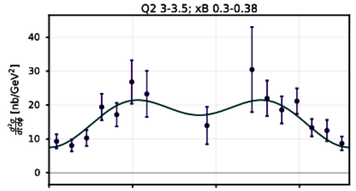
$$\frac{\mathrm{d}^2\sigma_{\gamma^* p\to\pi^0 p}}{\mathrm{d}t\,\mathrm{d}\phi} \qquad -t : 0.4 - 0.6\,GeV^2$$

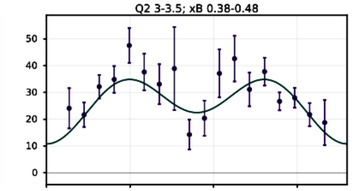


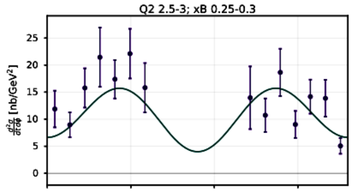
$$\frac{\mathrm{d}^2\sigma_{\gamma^* p\to\pi^0 p}}{\mathrm{d}t\,\mathrm{d}\phi} \qquad -t : 0.6 - 1\,GeV^2$$

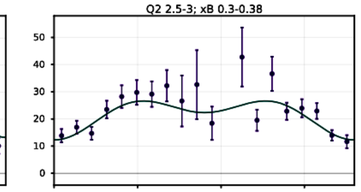


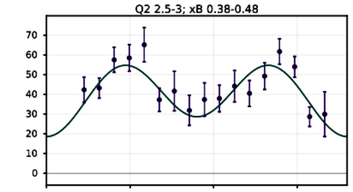


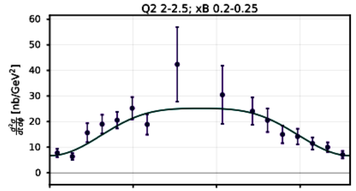


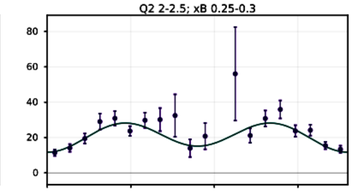


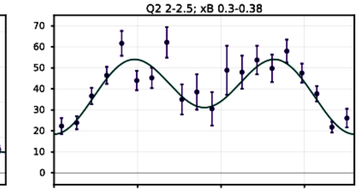


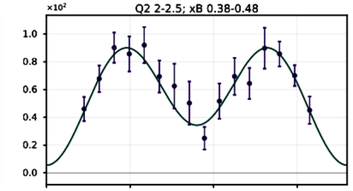


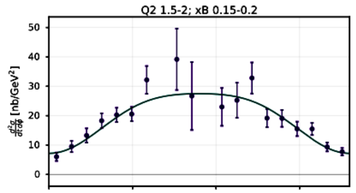


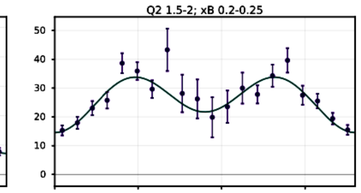


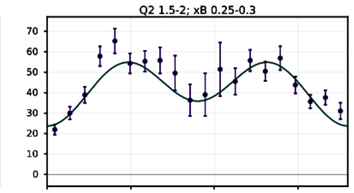


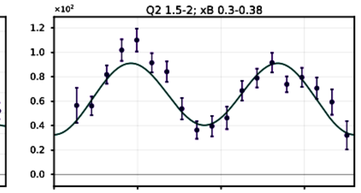


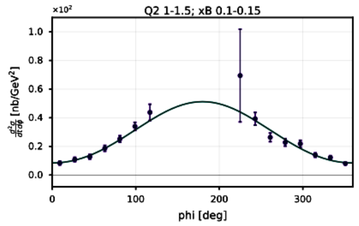


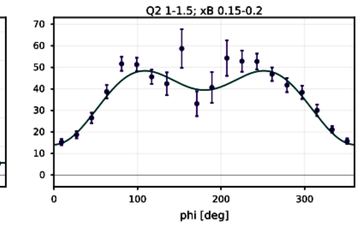


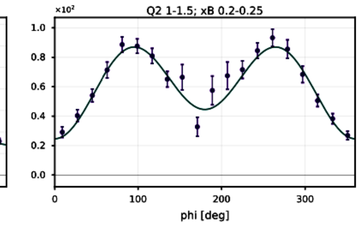


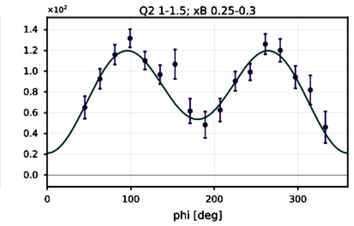




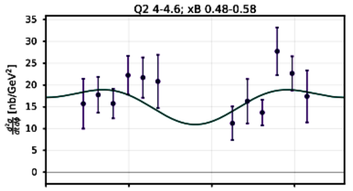


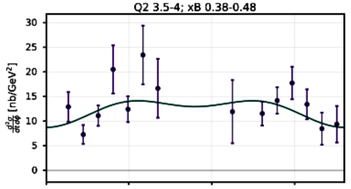


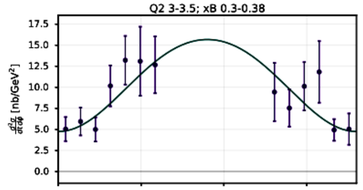


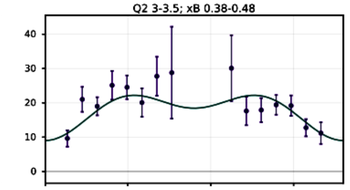


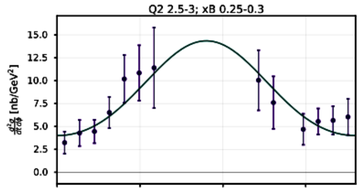
$$\frac{\mathrm{d}^2\sigma_{\gamma^* p\to\pi^0 p}}{\mathrm{d}t\,\mathrm{d}\phi} \qquad -t : 1 - 1.5\,GeV^2$$

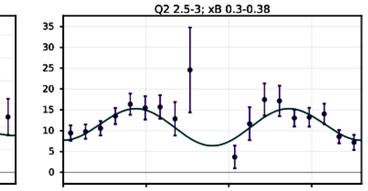


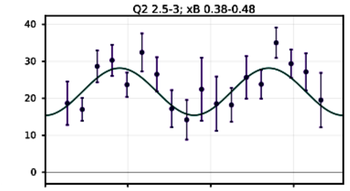


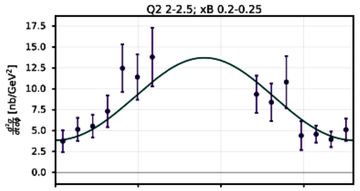


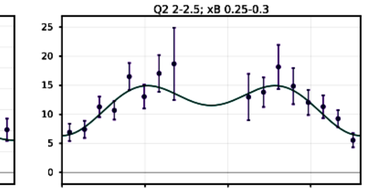


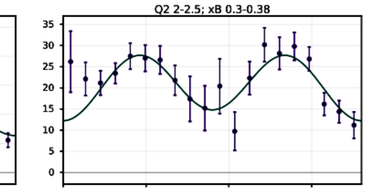


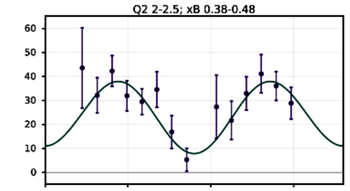


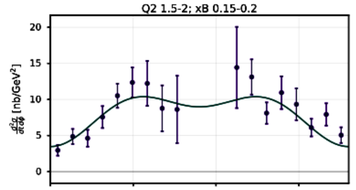


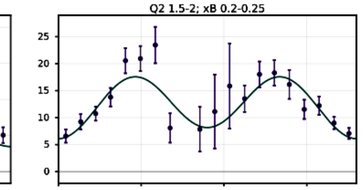


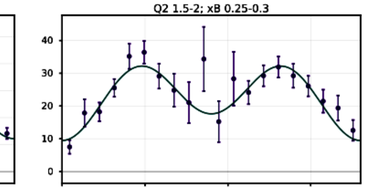


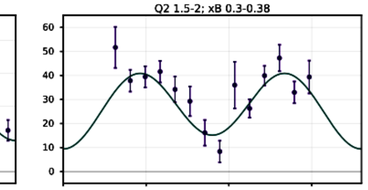


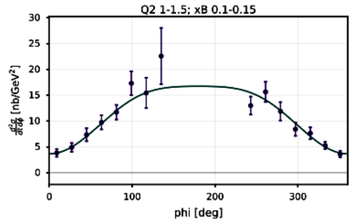


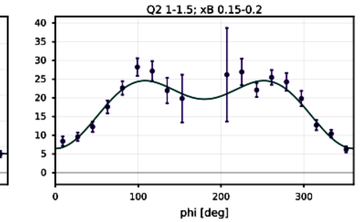


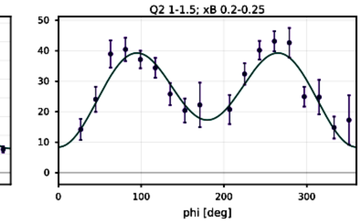


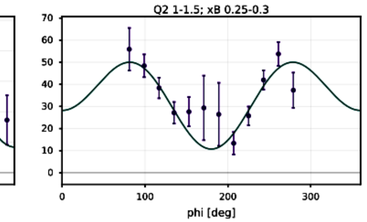




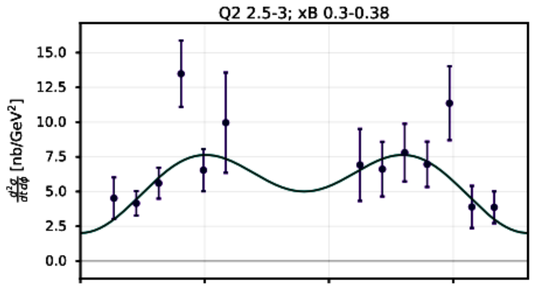


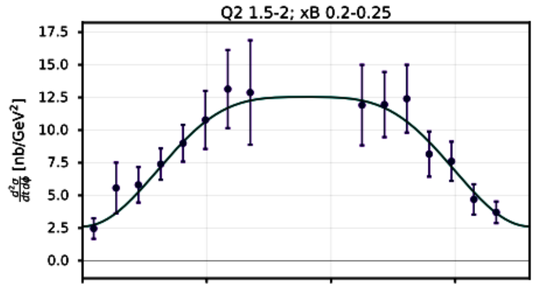


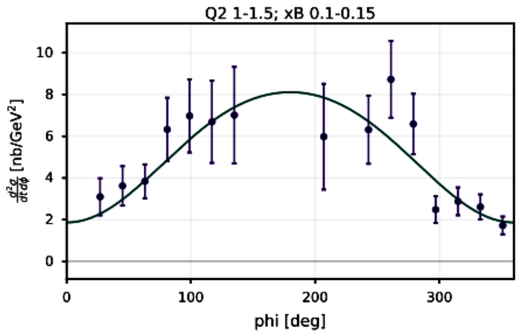


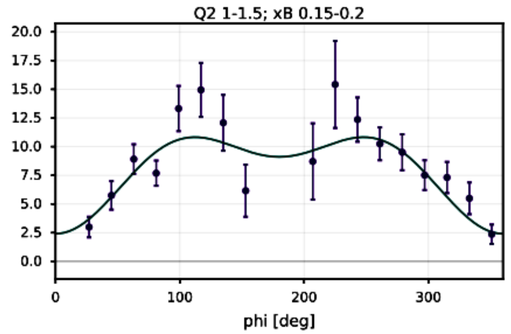


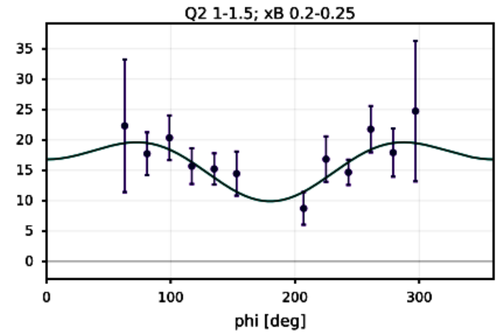
$$\frac{\mathrm{d}^2\sigma_{\gamma^* p\to\pi^0 p}}{\mathrm{d}t\,\mathrm{d}\phi} \qquad -t : 1.5 - 2\,GeV^2$$











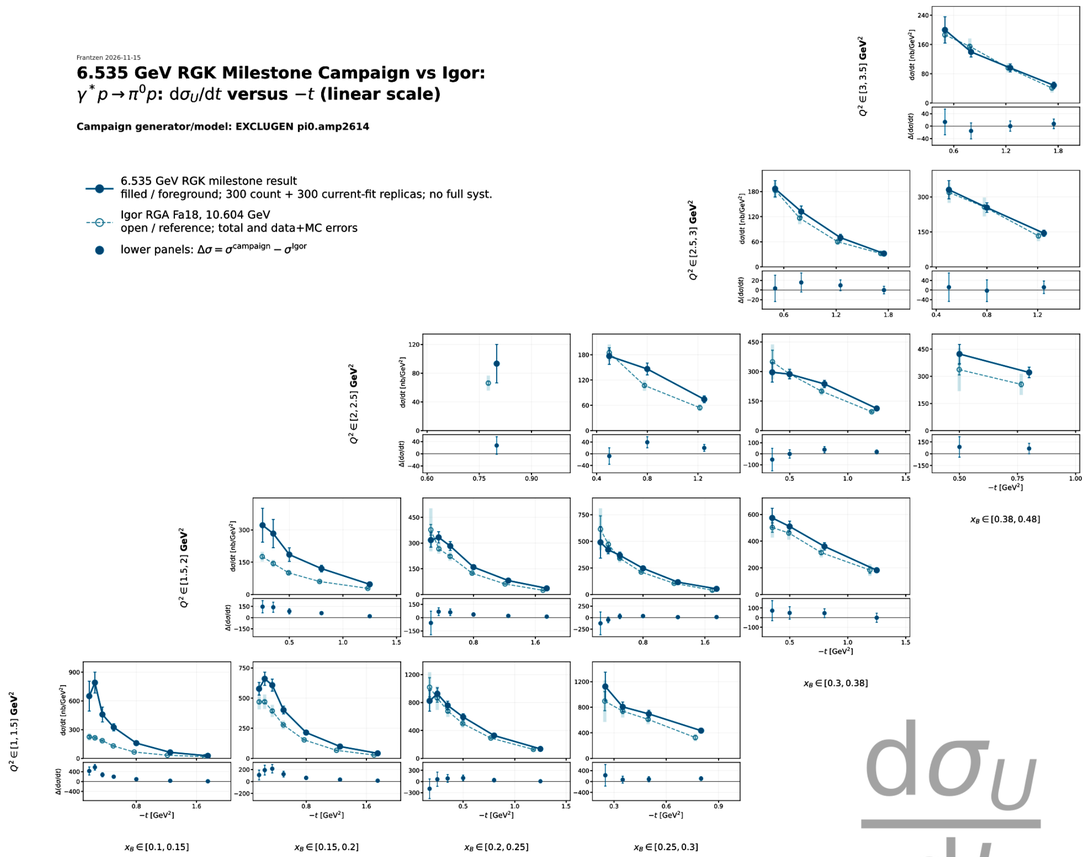
RGK Fall 2018, 6.535 GeV

Frantzen 2026-11-15

6.535 GeV RGK Milestone Campaign vs Igor:
$\gamma^* p \to \pi^0 p$: $d\sigma_U/dt$ versus $-t$ (linear scale)

Campaign generator/model: EXCLUGEN pi0.amp2614

- 6.535 GeV RGK milestone result
  filled / foreground; 300 count + 300 current-fit replicas; no full syst.
- Igor RGA Fa18, 10.604 GeV
  open / reference; total and data+MC errors
- lower panels: $\Delta\sigma = \sigma^{\text{campaign}} - \sigma^{\text{Igor}}$



$$\frac{d\sigma_U}{dt}$$

RGK Fall 2018, 7.546 GeV

Story Frantzen

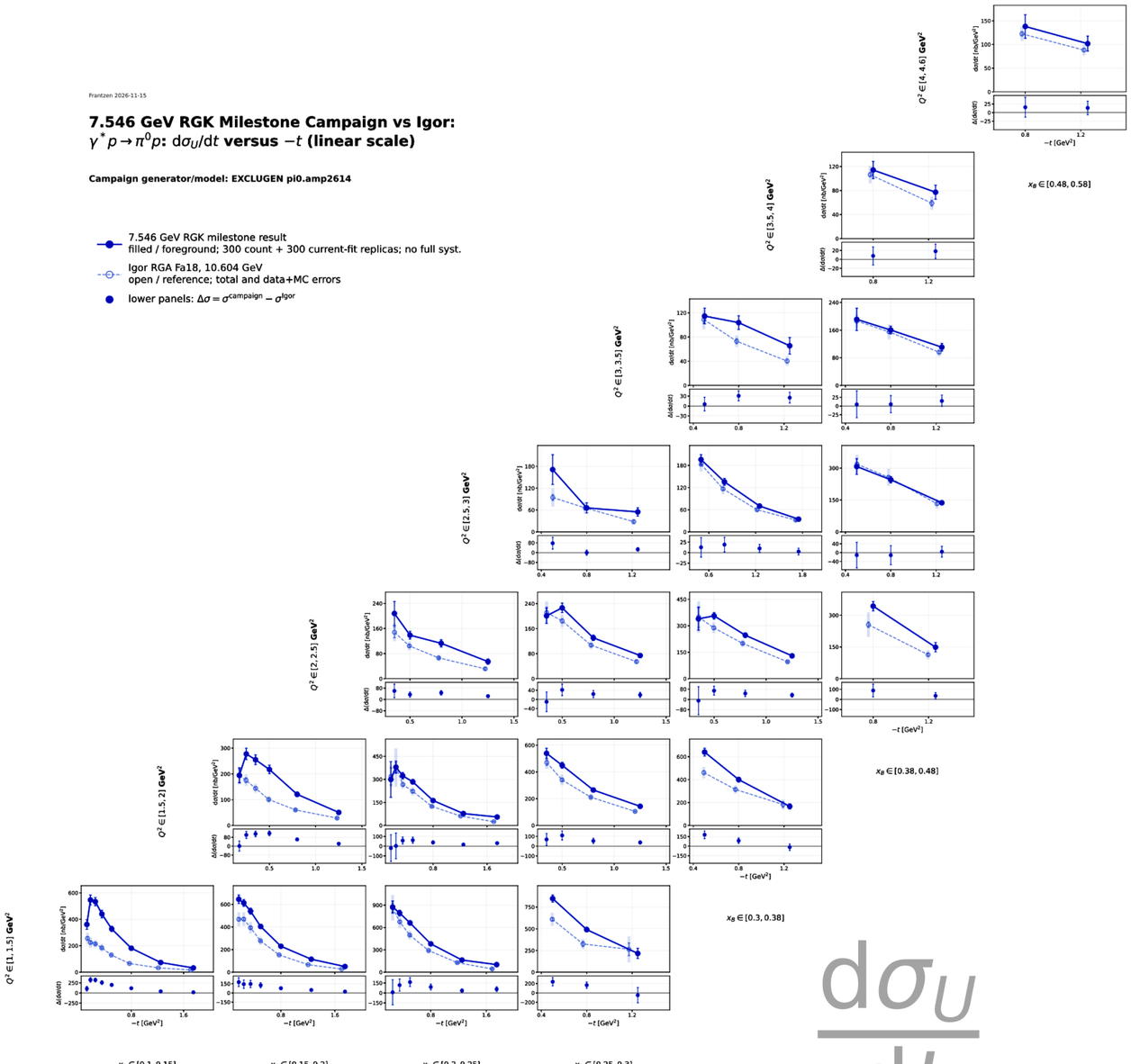
Jefferson Lab

Frantzen 2026-11-15

7.546 GeV RGK Milestone Campaign vs Igor:
$\gamma^* p \to \pi^0 p$: $d\sigma_U/dt$ versus $-t$ (linear scale)

Campaign generator/model: EXCLUGEN pi0.amp2614

- 7.546 GeV RGK milestone result
  filled / foreground; 300 count + 300 current-fit replicas; no full syst.
- Igor RGA Fa18, 10.604 GeV
  open / reference; total and data+MC errors
- lower panels: $\Delta\sigma = \sigma^{\text{campaign}} - \sigma^{\text{Igor}}$



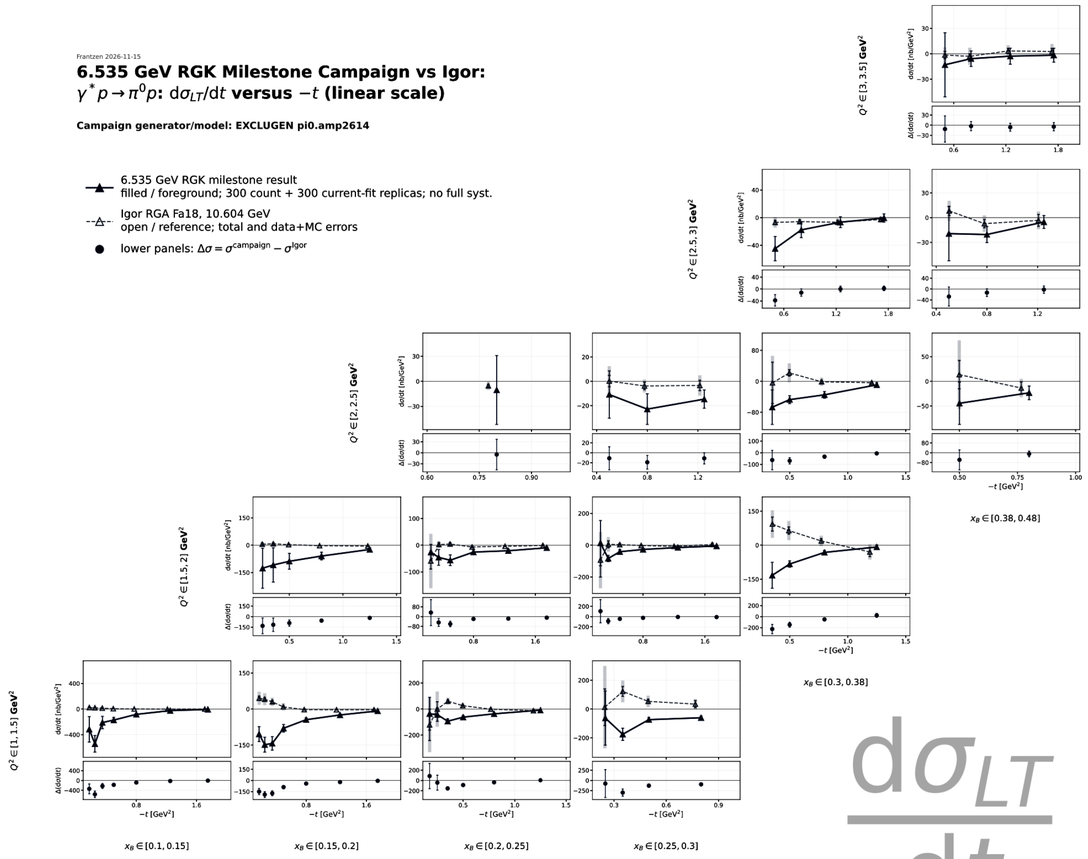
$$\frac{d\sigma_U}{dt}$$

Frantzen 2026-11-15

6.535 GeV RGK Milestone Campaign vs Igor:
$\gamma^* p \to \pi^0 p$: $d\sigma_{LT}/dt$ versus $-t$ (linear scale)

Campaign generator/model: EXCLUGEN pi0.amp2614

- 6.535 GeV RGK milestone result
  filled / foreground; 300 count + 300 current-fit replicas; no full syst.
- Igor RGA Fa18, 10.604 GeV
  open / reference; total and data+MC errors
- lower panels: $\Delta\sigma = \sigma^{\text{campaign}} - \sigma^{\text{Igor}}$



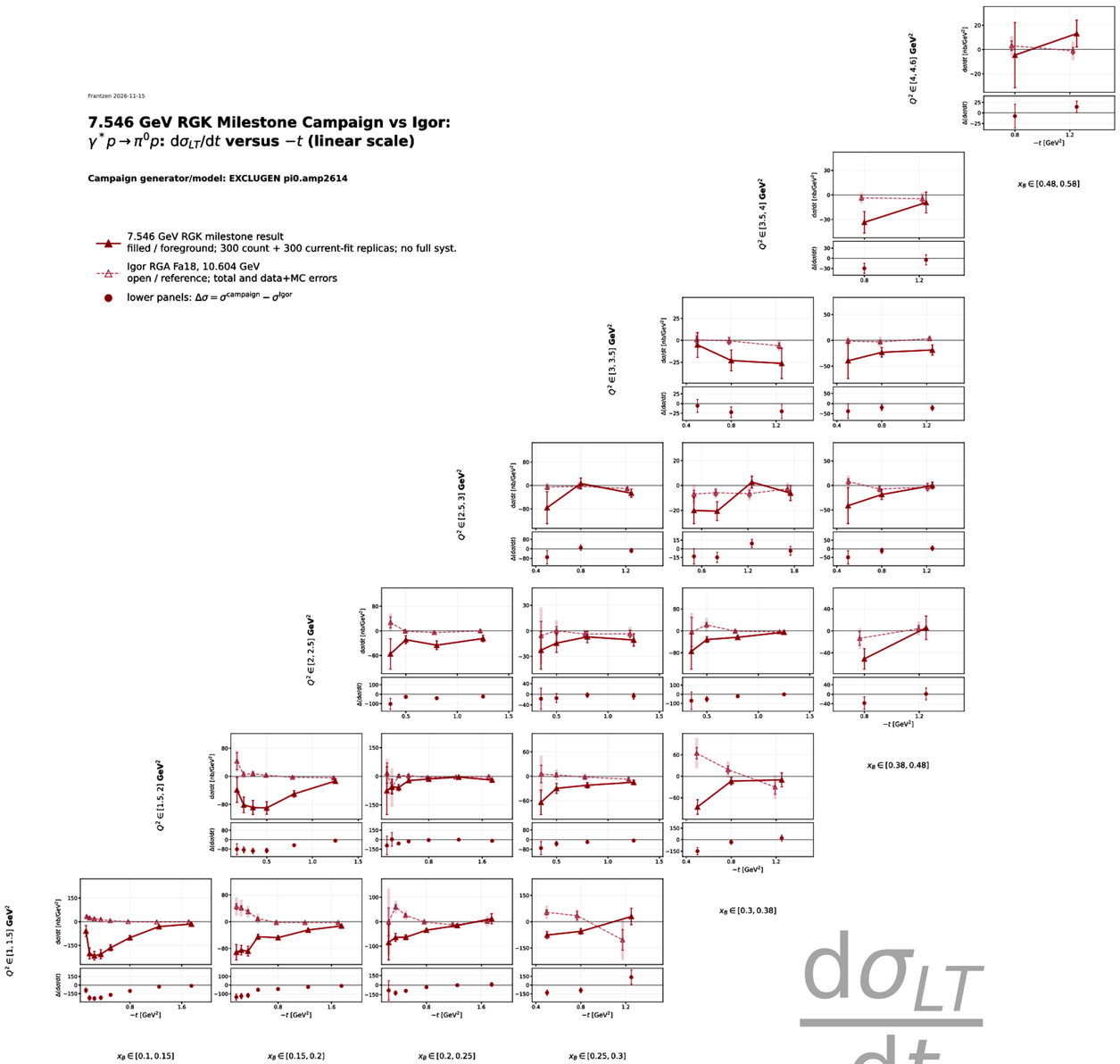
$$\frac{d\sigma_{LT}}{dt}$$

Frantzen 2026-11-15

7.546 GeV RGK Milestone Campaign vs Igor:
$\gamma^* p \to \pi^0 p$: $d\sigma_{LT}/dt$ versus $-t$ (linear scale)

Campaign generator/model: EXCLUGEN pi0.amp2614

- 7.546 GeV RGK milestone result
  filled / foreground; 300 count + 300 current-fit replicas; no full syst.
- Igor RGA Fa18, 10.604 GeV
  open / reference; total and data+MC errors
- lower panels: $\Delta\sigma = \sigma^{\text{campaign}} - \sigma^{\text{Igor}}$



$$\frac{d\sigma_{LT}}{dt}$$

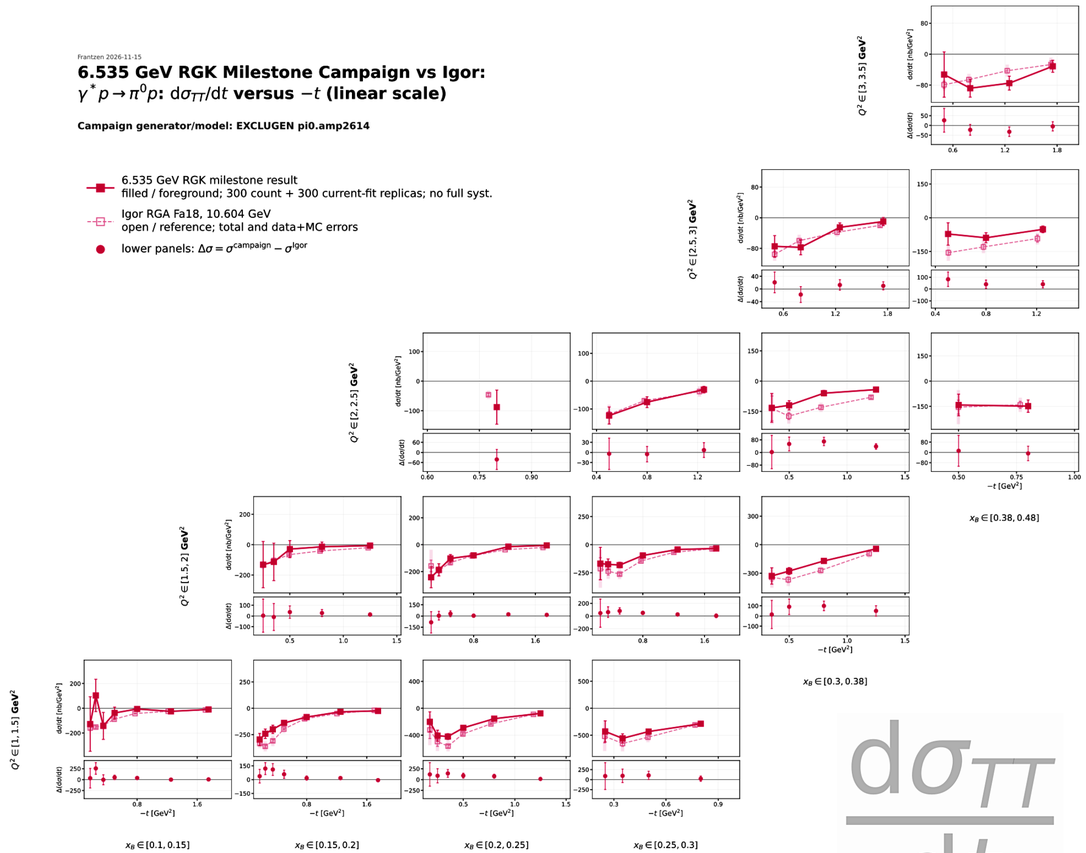
RGK Fall 2018, 6.535 GeV

Frantzen 2026-11-15

6.535 GeV RGK Milestone Campaign vs Igor:
$\gamma^* p \to \pi^0 p$: $d\sigma_{TT}/dt$ versus $-t$ (linear scale)

Campaign generator/model: EXCLUGEN pi0.amp2614

- 6.535 GeV RGK milestone result
  filled / foreground; 300 count + 300 current-fit replicas; no full syst.
- Igor RGA Fa18, 10.604 GeV
  open / reference; total and data+MC errors
- lower panels: $\Delta\sigma = \sigma^{\text{campaign}} - \sigma^{\text{Igor}}$



$$\frac{d\sigma_{TT}}{dt}$$

RGK Fall 2018, 7.546 GeV

Story Frantzen

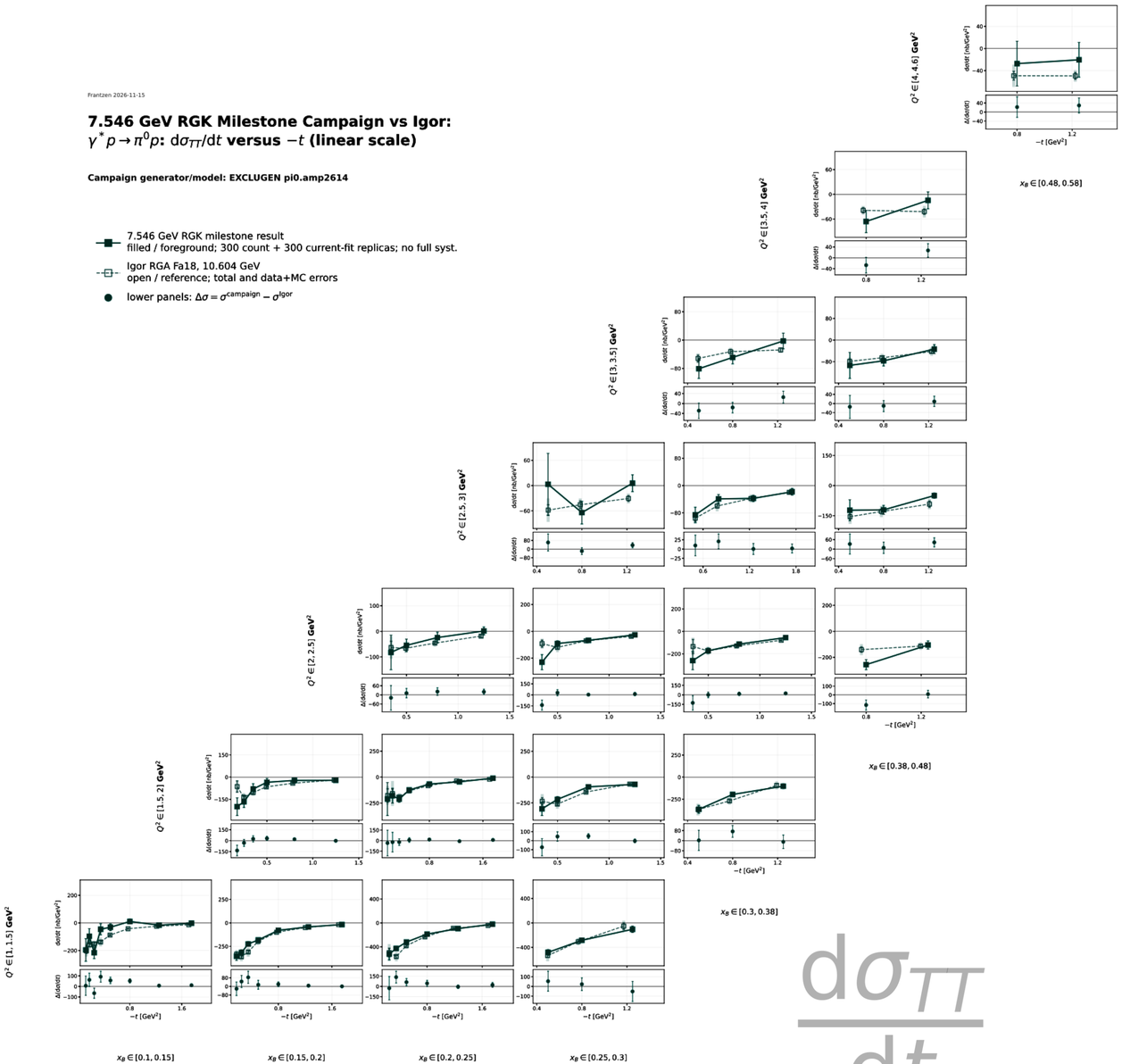
Jefferson Lab

Frantzen 2026-11-15

7.546 GeV RGK Milestone Campaign vs Igor:
$\gamma^* p \to \pi^0 p$: $d\sigma_{TT}/dt$ versus $-t$ (linear scale)

Campaign generator/model: EXCLUGEN pi0.amp2614

- 7.546 GeV RGK milestone result
  filled / foreground; 300 count + 300 current-fit replicas; no full syst.
- Igor RGA Fa18, 10.604 GeV
  open / reference; total and data+MC errors
- lower panels: $\Delta\sigma = \sigma^{\text{campaign}} - \sigma^{\text{Igor}}$



$$\frac{d\sigma_{TT}}{dt}$$

full event selection

Table 5: 6.535-GeV event-level selection flow.

Sample	Stage	Entered	Removed	Retained
Data	Reconstructed event input	2,205,202	0	2,205,202
Data	Deterministic post-processing candidate	2,205,202	1,871,368	333,834
Data	Supported topology and physical analysis range	333,834	13,963	319,871
Data	Final owner-specific v17 selection	319,871	98,983	220,888
Nominal GEMC	Reconstructed event input	2,226,158	0	2,226,158
Nominal GEMC	Deterministic post-processing candidate	2,226,158	1,927,379	298,779
Nominal GEMC	Supported topology and physical analysis range	298,779	4,465	294,314
Nominal GEMC	Final owner-specific v17 selection	294,314	54,704	239,610

Table 6: 6.535-GeV primitive-cut rejection occurrences.

Category	Implemented requirement	Data	Nominal GEMC	Counter meaning
π^0 candidate	candidate ranking domain $\lvert m_{\gamma\gamma} - m_{\pi^0}\rvert \leq 0.15$ GeV	212,082	93,228	rejected candidate occurrence
Electron	electron in FD/ECAL detector assignment	0	718	rejected candidate occurrence
Electron	standard-RGA DC and ECAL fiducials	378,721	444,941	rejected candidate occurrence
Electron	$p_e \geq 1.0$ GeV	3,000	4,614	rejected candidate occurrence
Electron	$E_{\mathrm{PCAL}} \geq 0.07$ GeV	343	628	rejected candidate occurrence
Electron	ECAL diagonal sampling-fraction requirement	32	105	rejected candidate occurrence
Electron	sector-dependent sampling fraction within 3.5σ	29,690	50,003	rejected candidate occurrence
Electron	first reconstructed PID-11 particle	6,811	8,778	rejected candidate occurrence
Loose tuple guard	broad tuple guard $\lvert E_{\mathrm{miss}}\rvert < 2$ GeV	14,740	14,128	rejected candidate occurrence
Loose tuple guard	$\theta(\pi^0, X_{ep}) < 4^\circ$	179,074	88,183	rejected candidate occurrence
Loose tuple guard	$\theta(e, \gamma_1) > 4^\circ$	4,123	6,754	rejected candidate occurrence
Loose tuple guard	$\theta(e, \gamma_2) > 4^\circ$	5,469	7,230	rejected candidate occurrence
Loose tuple guard	$\theta(\gamma_1, \gamma_2) > 1^\circ$	637	1,927	rejected candidate occurrence
Photon pair	each photon $0.9 \leq \beta \leq 1.1$	384,068	242,513	rejected candidate occurrence
Photon pair	allowed photon detector assignment	239,226	246,411	rejected candidate occurrence
Photon pair	FD-ECAL or FT standard-RGA fiducial	2,137,504	1,716,093	rejected candidate occurrence
Photon pair	each photon $p_\gamma \geq 0.4$ GeV	2,211,441	1,586,155	rejected candidate occurrence
Proton	CD-proton ϕ veto: 143°–158°	42,351	49,518	rejected candidate occurrence
Proton	CD-proton ϕ veto: 25°–40°	47,401	59,817	rejected candidate occurrence
Proton	CD-proton ϕ veto: 265°–280°	50,239	56,543	rejected candidate occurrence
Proton	FD-DC or CD-CVT standard-RGA fiducial	430,741	480,940	rejected candidate occurrence
Proton	$p_p \geq 0.3$ GeV	59	63	rejected candidate occurrence
Proton	$\lvert z_p - z_e\rvert \leq 20$ cm	16,079	11,077	rejected candidate occurrence

Table 8: 7.546-GeV event-level selection flow.

Sample	Stage	Entered	Removed	Retained
Data	Reconstructed event input	1,643,885	0	1,643,885
Data	Deterministic post-processing candidate	1,643,885	1,393,452	250,433
Data	Supported topology and physical analysis range	250,433	13,508	236,925
Data	Final owner-specific v17 selection	236,925	83,928	152,997
Nominal GEMC	Reconstructed event input	2,439,362	0	2,439,362
Nominal GEMC	Deterministic post-processing candidate	2,439,362	2,107,586	331,776
Nominal GEMC	Supported topology and physical analysis range	331,776	5,685	326,091
Nominal GEMC	Final owner-specific v17 selection	326,091	67,360	258,731

Table 9: 7.546-GeV primitive-cut rejection occurrences.

Category	Implemented requirement	Data	Nominal GEMC	Counter meaning
π^0 candidate	candidate ranking domain $\lvert m_{\gamma\gamma} - m_{\pi^0}\rvert \leq 0.15$ GeV	208,440	160,079	rejected candidate occurrence
Electron	electron in FD/ECAL detector assignment	85,337	30,867	rejected candidate occurrence
Electron	standard-RGA DC and ECAL fiducials	272,250	470,975	rejected candidate occurrence
Electron	$p_e \geq 1.0$ GeV	36,709	10,403	rejected candidate occurrence
Electron	$E_{\mathrm{PCAL}} \geq 0.07$ GeV	277	549	rejected candidate occurrence
Electron	ECAL diagonal sampling-fraction requirement	18,536	20,391	rejected candidate occurrence
Electron	sector-dependent sampling fraction within 3.5σ	22,031	54,113	rejected candidate occurrence
Electron	first reconstructed PID-11 particle	89,933	39,655	rejected candidate occurrence
Loose tuple guard	broad tuple guard $\lvert E_{\mathrm{miss}}\rvert < 2$ GeV	20,414	30,170	rejected candidate occurrence
Loose tuple guard	$\theta(\pi^0, X_{ep}) < 4^\circ$	139,227	106,842	rejected candidate occurrence
Loose tuple guard	$\theta(e, \gamma_1) > 4^\circ$	3,584	10,686	rejected candidate occurrence
Loose tuple guard	$\theta(e, \gamma_2) > 4^\circ$	5,222	12,268	rejected candidate occurrence
Loose tuple guard	$\theta(\gamma_1, \gamma_2) > 1^\circ$	735	2,530	rejected candidate occurrence
Photon pair	each photon $0.9 \leq \beta \leq 1.1$	292,985	279,480	rejected candidate occurrence
Photon pair	allowed photon detector assignment	193,935	270,896	rejected candidate occurrence
Photon pair	FD-ECAL or FT standard-RGA fiducial	1,620,992	1,963,232	rejected candidate occurrence
Photon pair	each photon $p_\gamma \geq 0.4$ GeV	1,752,575	1,776,498	rejected candidate occurrence
Proton	CD-proton ϕ veto: 143°–158°	34,112	57,257	rejected candidate occurrence
Proton	CD-proton ϕ veto: 25°–40°	37,814	66,527	rejected candidate occurrence
Proton	CD-proton ϕ veto: 265°–280°	39,470	63,238	rejected candidate occurrence
Proton	FD-DC or CD-CVT standard-RGA fiducial	318,906	523,816	rejected candidate occurrence
Proton	$p_p \geq 0.3$ GeV	64	72	rejected candidate occurrence
Proton	$\lvert z_p - z_e\rvert \leq 20$ cm	12,555	12,627	rejected candidate occurrence

RGK Fall 2018, 7.546 GeV

```
# RGK 7.546 GeV milestone trigger-prescale promotion

Status: **promoted**

- Raw converter charge: 15.045509 mC
- Effective charge before current-metadata exclusions: 10.435417 mC
- Effective analysis charge: 9.308040 mC
- Prescaled charge-bearing runs: 78
- Applied prescale 2 to the late v4 trigger family (`rkk_v4.cnf`, `rgk_v4.cnf`, and `rgk_v5.cnf`).
- Reused charge-independent selection, response/closure, Method A, and bin-centering artifacts.
- Rebuilt current efficiency, unfolding, final extraction, and both campaign comparisons.
```


```
"Q2_min": 1.0,
"W_min": 2.0,
"beamEnergy": 7.546,
"diphotonMassSkim": {
  "enabled": true,
  "maxGeV": 0.35,
  "minGeV": 0.0
},
"electron_p_min": 0.3,
"enableSkim": true,
"fillMC": false,
"finalState": [
  { "count": 1, "mode": "atleast", "pid": 11 },
  { "count": 1, "mode": "atleast", "pid": 2212 },
  { "count": 2, "mode": "atleast", "pid": 22 }
],
"inclusive": true,
"inputValidation": {
  "enabled": true,
  "skipMalformed": true
},
"kinematicCorrections": "/work/clas12/storyf/rgk_fa18/20261109_exclusive_eppi0_7546MeV_torus+1_r
"outputFile": "7.546_rgk_fa18_eppi0_data_ftin_fullstats_production_limited_calibrated.root",
"qadb": {
  "allowMiscRuns": [],
  "database": "latest",
  "enabled": true,
  "rejectDefects": [
    "MarginalOutlier",
    "TerminalOutlier",
    "TotalOutlier",
    "SectorLoss",
    "LowLiveTime"
  ]
},
"torus": 1
```

backup slides

Fully explicit cross-section expression (RGK $ep \to e'p'\pi^0$)

Master equation (bin b; result quoted at the reference point)

$$\left.\frac{d^2\sigma_{\gamma^* p\to\pi^0 p}}{dt\,d\phi}\right|_b = \frac{\dfrac{1}{\varepsilon_b\,\delta_{A,b}}\left[\sum_{e\in b}^{\text{sig}} w_{r(e)} \;-\; \sum_g \alpha_g \sum_{e\in b}^{\text{side},\,g} w_{r(e)}\right]}{\mathcal{L}_{\text{int}}\;\mathcal{B}(\pi^0\to\gamma\gamma)\;\Delta V_{\text{phys},b}\;\Gamma_v\big(Q^2_{\text{ref}},x_{B,\text{ref}}\big)\;\;C_{\text{BC,b}}}$$

Variable	Edges
x_B	0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.38, 0.48, 0.58, 0.70
$-t$ [GeV^2]	0.09, 0.15, 0.20, 0.30, 0.40, 0.60, 1.00, 1.50, 2.00
ϕ [deg]	0 to 360 in 18-degree steps (20 bins)
Q^2, 6.535 GeV	1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.6, 5.5, 6.535
Q^2, 7.546 GeV	1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.6, 5.5, 7.0, 7.546

Current/occupancy run weight

$$w_r = \frac{\eta_{\text{MC}}(I_{\text{ref}})}{\eta_{\text{data}}(I_r)}, \quad \eta_{\text{data}}(I) = 1 + s_{\text{data}}\,I, \quad \eta_{\text{MC}}(I) = \frac{a_{\text{MC}} + b_{\text{MC}} I}{a_{\text{MC}}}, \quad w_r = 0 \text{ for excluded runs}$$

Sideband transfer factor (per topology g)

$$\alpha_g = \frac{\int_{\text{sig}} B_g(m_{\gamma\gamma})\,dm_{\gamma\gamma}}{\int_{\text{side}} B_g(m_{\gamma\gamma})\,dm_{\gamma\gamma}}, \qquad B_g = \text{fitted linear background}$$

Acceptance from the nominal-GEMC response

$$R_{ij} = \frac{N_{ij}^{\text{mig}}}{N_j^{\text{truth}}}, \qquad \varepsilon_j = \sum_i R_{ij} = \frac{N_j^{\text{acc}}}{N_j^{\text{truth}}}, \qquad \varepsilon_b > 0.005$$

Luminosity

$$\mathcal{L}_{\text{int}}[\text{fb}^{-1}] = 10^{-39}\,\frac{Q_{\text{eff}}}{e}\,N_A\frac{\rho\,L}{M}, \qquad Q_{\text{eff}} = \sum_{r\in\text{incl}} \frac{Q_r}{P_r}, \qquad \mathcal{B} = 0.988$$

Physical 4D bin volume

$$\Delta V_{\text{phys},b} = \Delta\phi \int_{Q^2_{\text{lo}}}^{Q^2_{\text{hi}}} dQ^2 \int_{x_{B,\text{lo}}}^{x_{B,\text{hi}}} dx_B \left[\min\big(|t|_{\text{hi}},\,|t|_{\max}(Q^2,x_B)\big) - \max\big(|t|_{\text{lo}},\,|t|_{\min}(Q^2,x_B)\big)\right]_+ \Theta(W\geq 2)\,\Theta(p_{e'}\geq 1)$$

Virtual-photon flux (Hand-like)

$$\Gamma_v = \frac{\alpha}{8\pi}\,\frac{Q^2(1-x_B)}{(M_pE)^2\,x_B^3\,(1-\varepsilon_\gamma)}, \qquad y = \frac{Q^2}{2M_p x_B E}, \qquad \varepsilon_\gamma = \frac{1-y-\dfrac{Q^2}{4E^2}}{1-y+\dfrac{y^2}{2}+\dfrac{Q^2}{4E^2}}$$

Bin-centering correction

$$C_{\text{BC,b}} = \frac{\Big\langle \Gamma_v(Q^2,x_B)\,\sigma_{\text{red}}^{\text{model}}(Q^2,x_B,t,\phi)\Big\rangle_{b,\text{phys}}}{\Gamma_v(Q^2_{\text{ref}},x_{B,\text{ref}})\,\sigma_{\text{red}}^{\text{model}}(Q^2_{\text{ref}},x_{B,\text{ref}},t_{\text{ref}},\phi_{\text{ref}})}$$

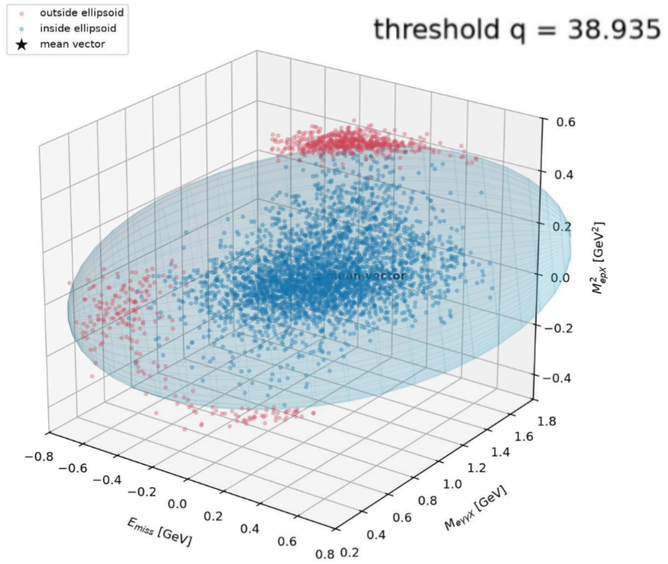
6.5 GeV appendix

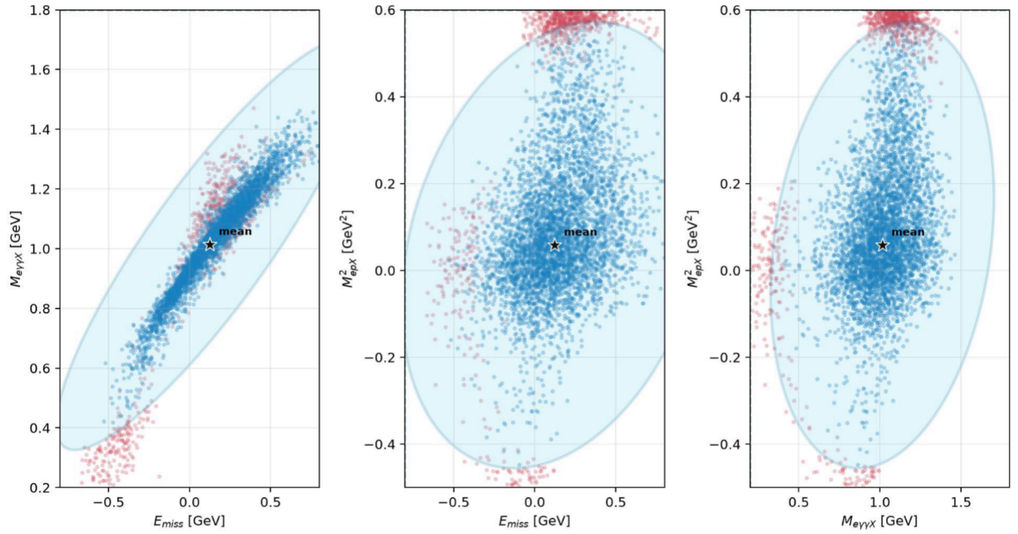
DATA

$$d^2 = (z-\mu)^T \Sigma^{-1} (z-\mu) \leq q$$

Story Frantzen | Jefferson Lab

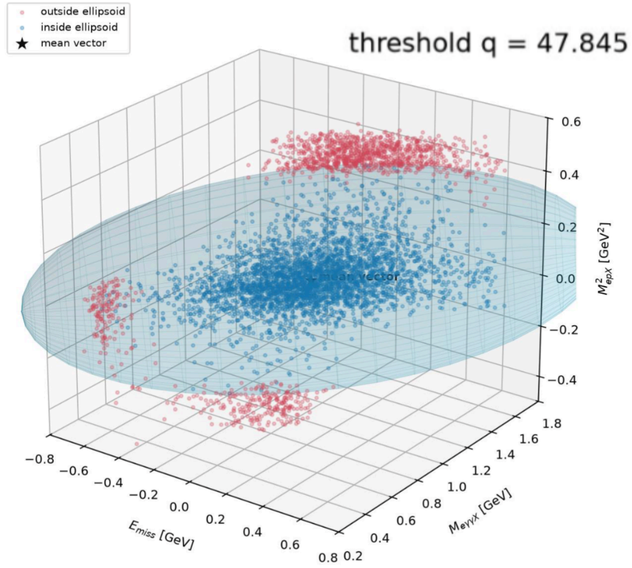
pFD

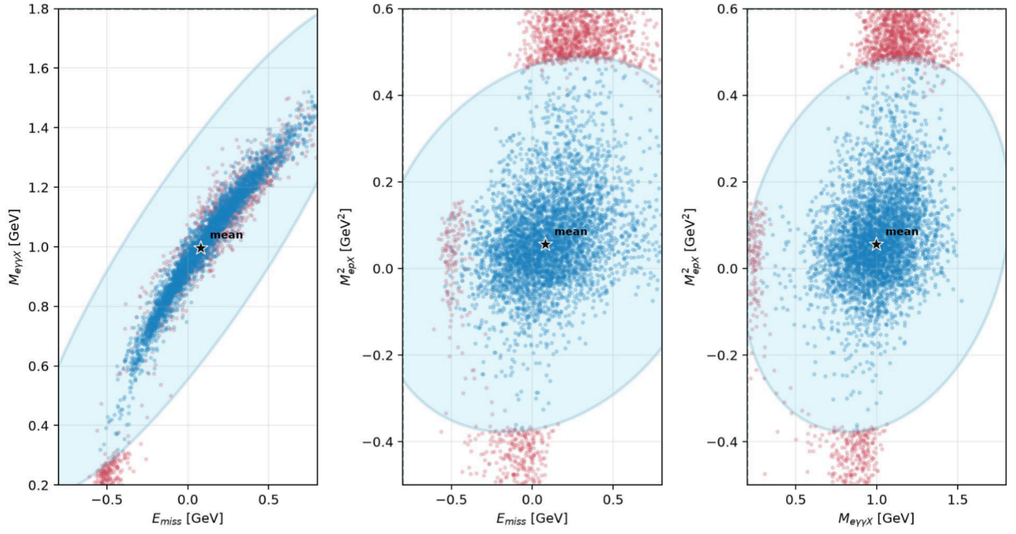




pre-ellipsoid candidates: 79,734
inside: 78,936
outside: 798
retention: 0.9900

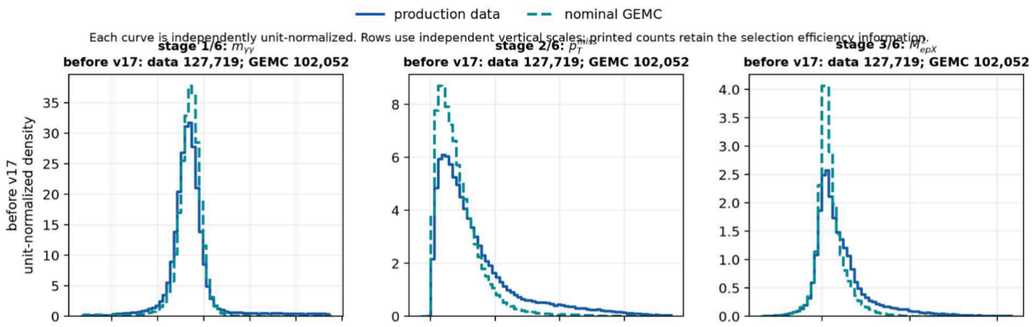
pCD



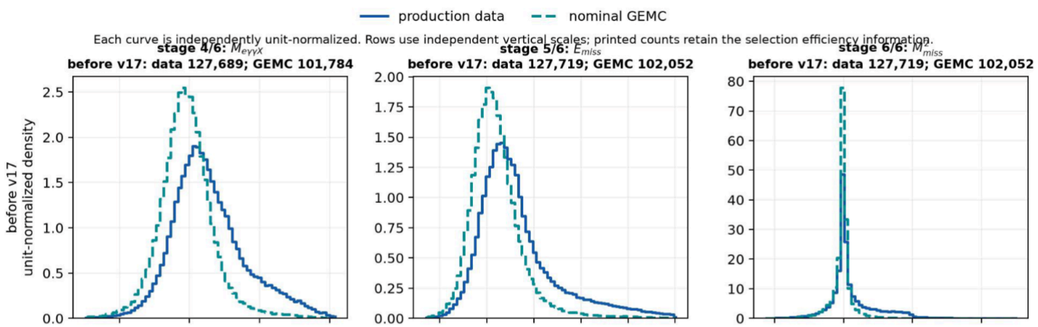


pre-ellipsoid candidates: 142,961
inside: 141,531
outside: 1,430
retention: 0.9900

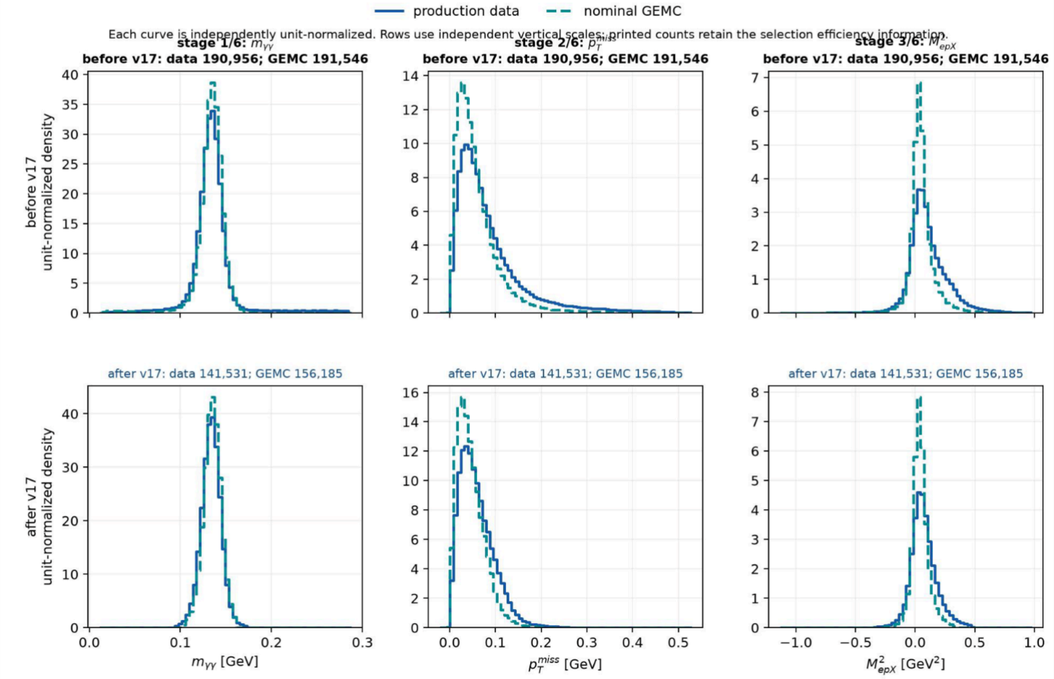
RGK 6.535 GeV milestone v17: normalized shapes before and after v17 proton FD; photons FD/FD (1/2)



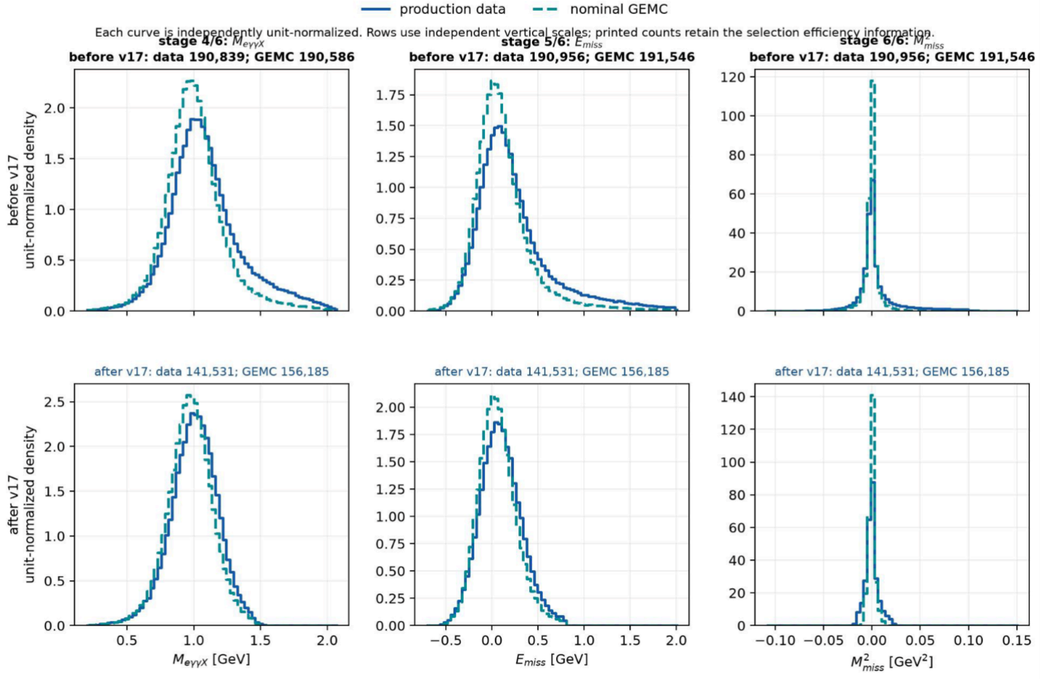
RGK 6.535 GeV milestone v17: normalized shapes before and after v17 proton FD; photons FD/FD (2/2)



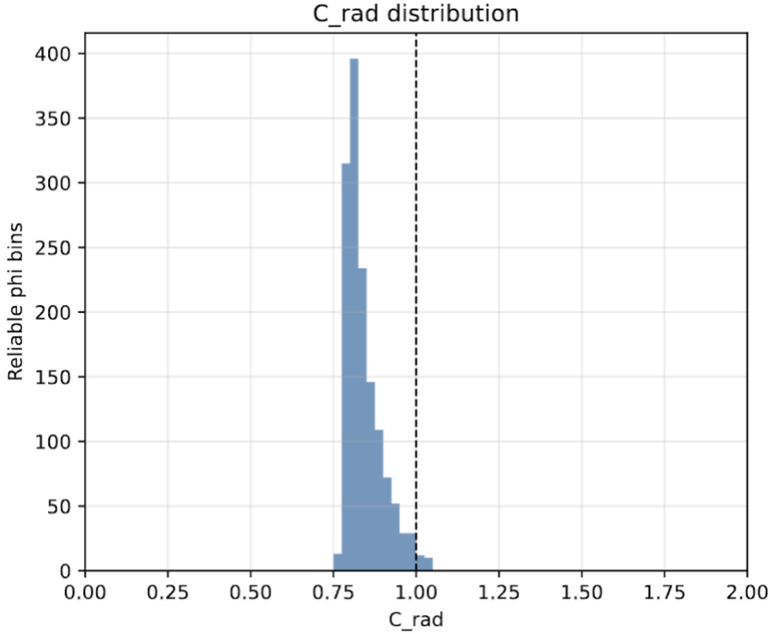
RGK 6.535 GeV milestone v17: normalized shapes before and after v17 proton CD; photons FD/FD (1/2)

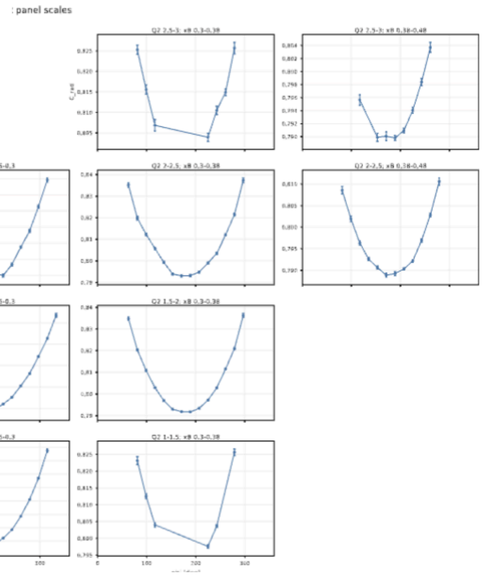


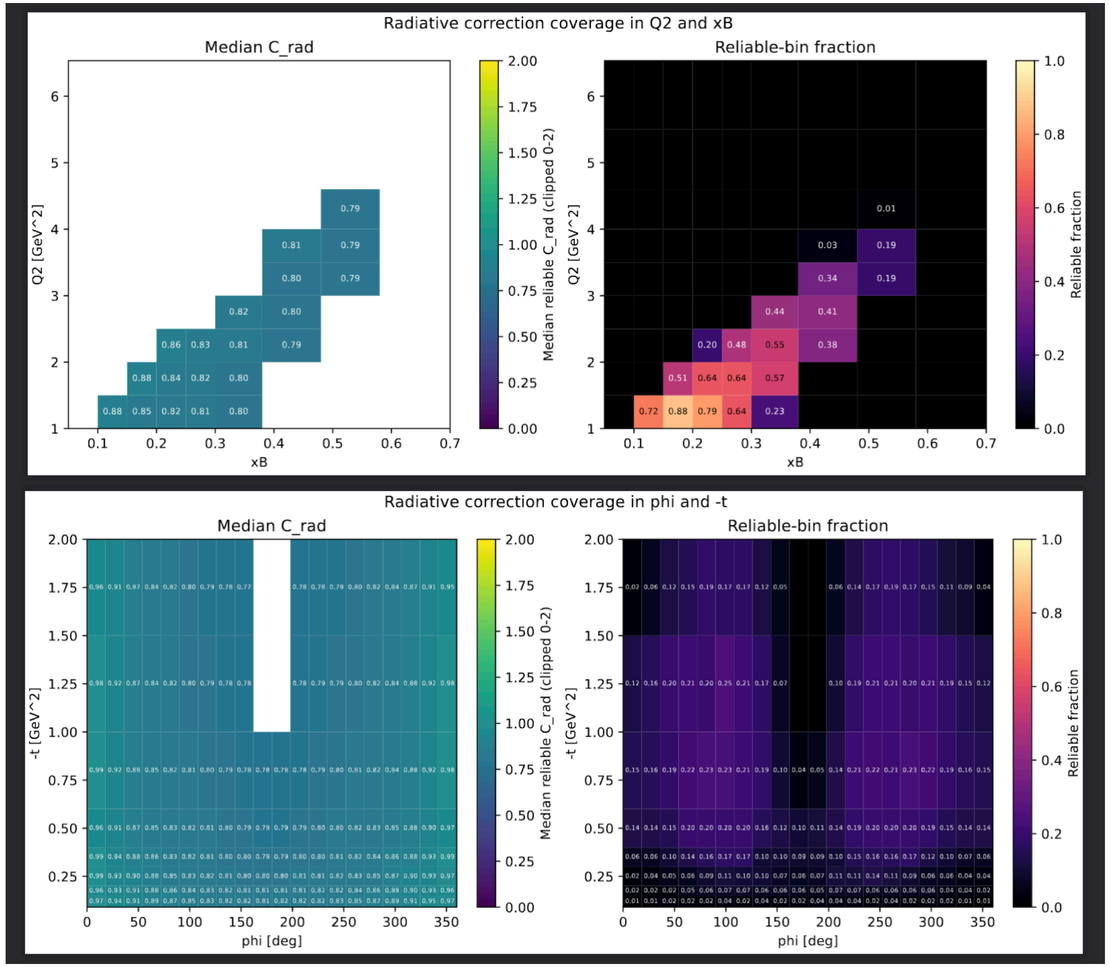
RGK 6.535 GeV milestone v17: normalized shapes before and after v17 proton CD; photons FD/FD (2/2)



RGK Fall 2018, 6.535 GeV







proton energy loss

$$\Delta q(p,\theta) = \sum_{m \in M_q} p^m \, P_{qm}(\theta),$$

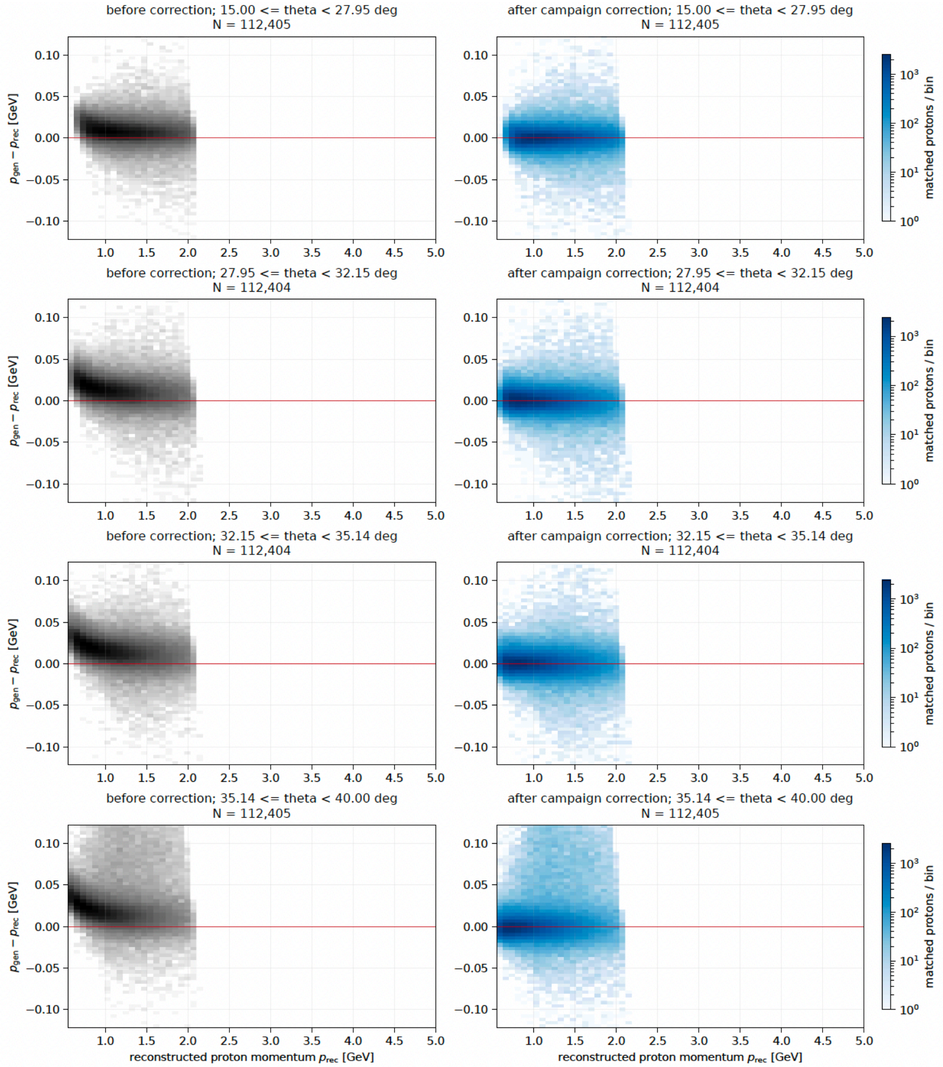


Figure 6: 6.535 GeV FD proton momentum residual versus reconstructed momentum, before and after correction in four equal-occupancy θ_p slices.

pFD

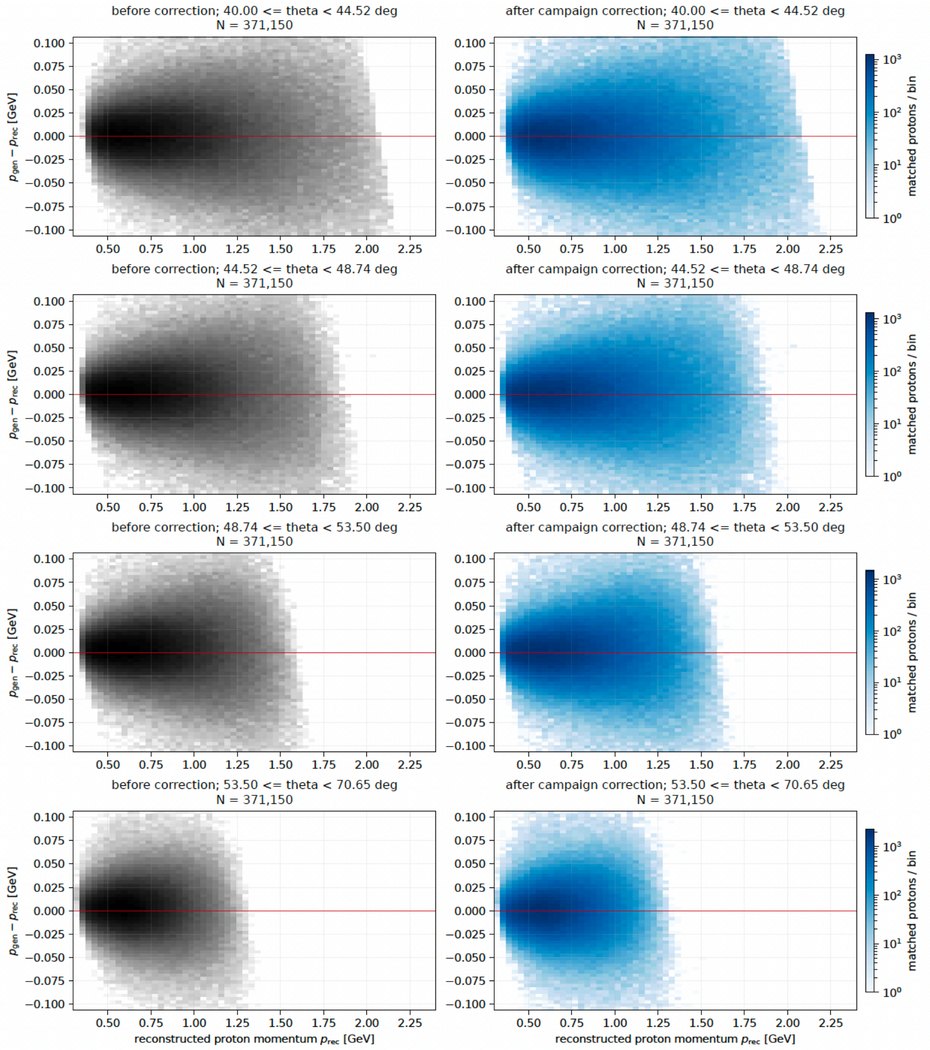


Figure 9: 6.535 GeV CD proton momentum residual versus reconstructed momentum, before and after correction in four equal-occupancy θ_p slices.

pCD

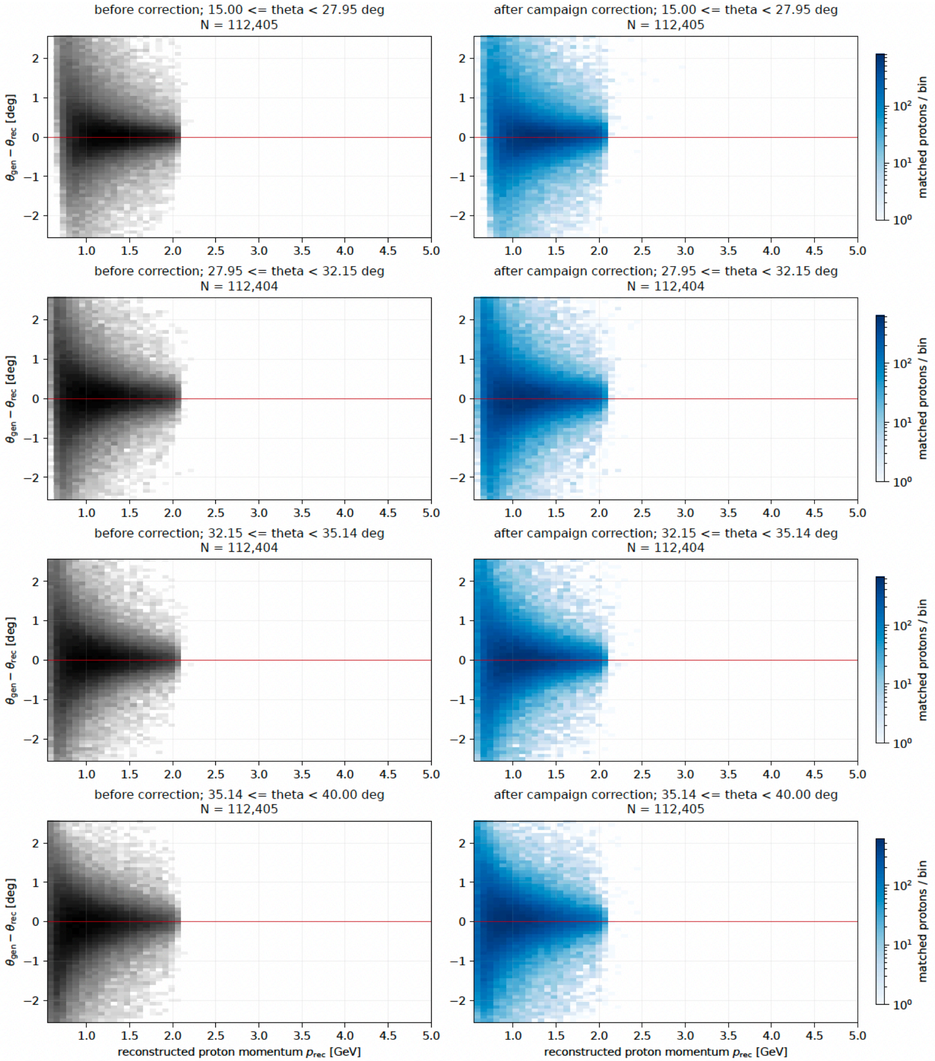


Figure 7: 6.535 GeV FD proton polar-angle residual versus reconstructed momentum, before and after correction in four equal-occupancy θ_p slices.

pFD

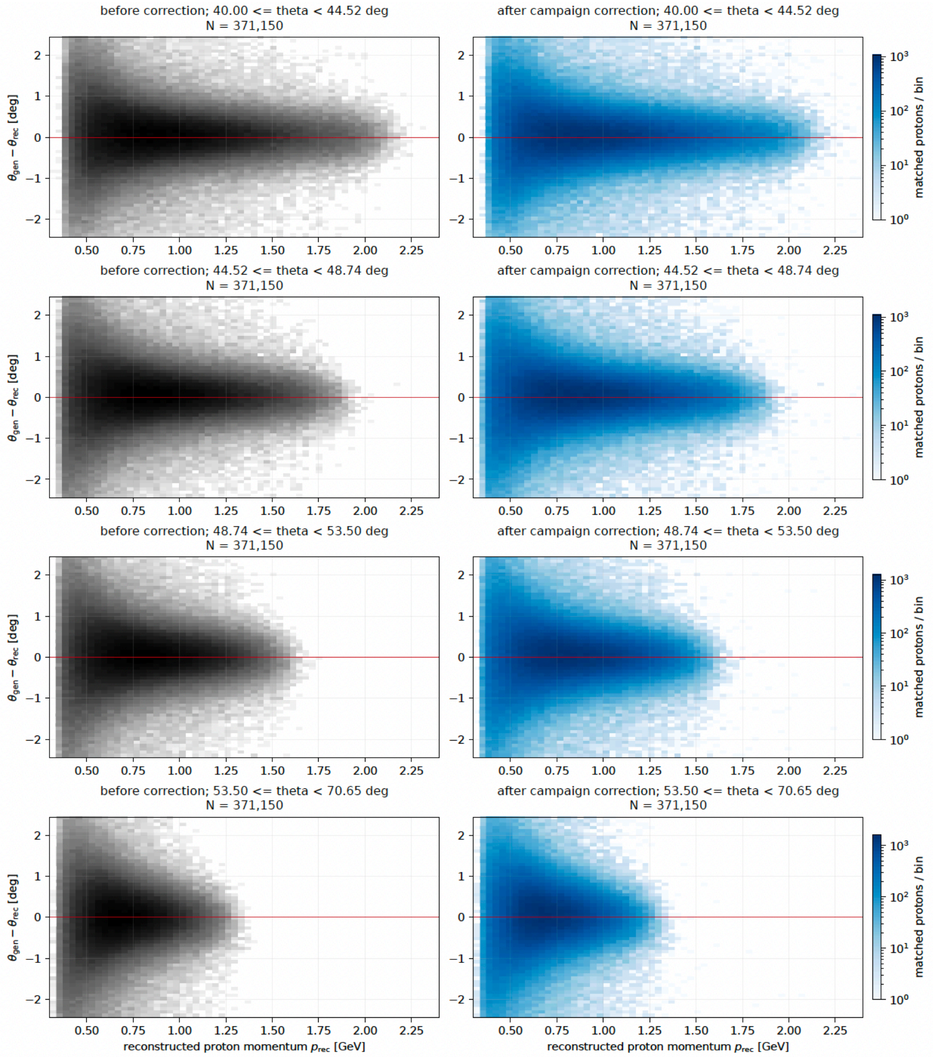


Figure 10: 6.535 GeV CD proton polar-angle residual versus reconstructed momentum, before and after correction in four equal-occupancy θ_p slices.

pCD

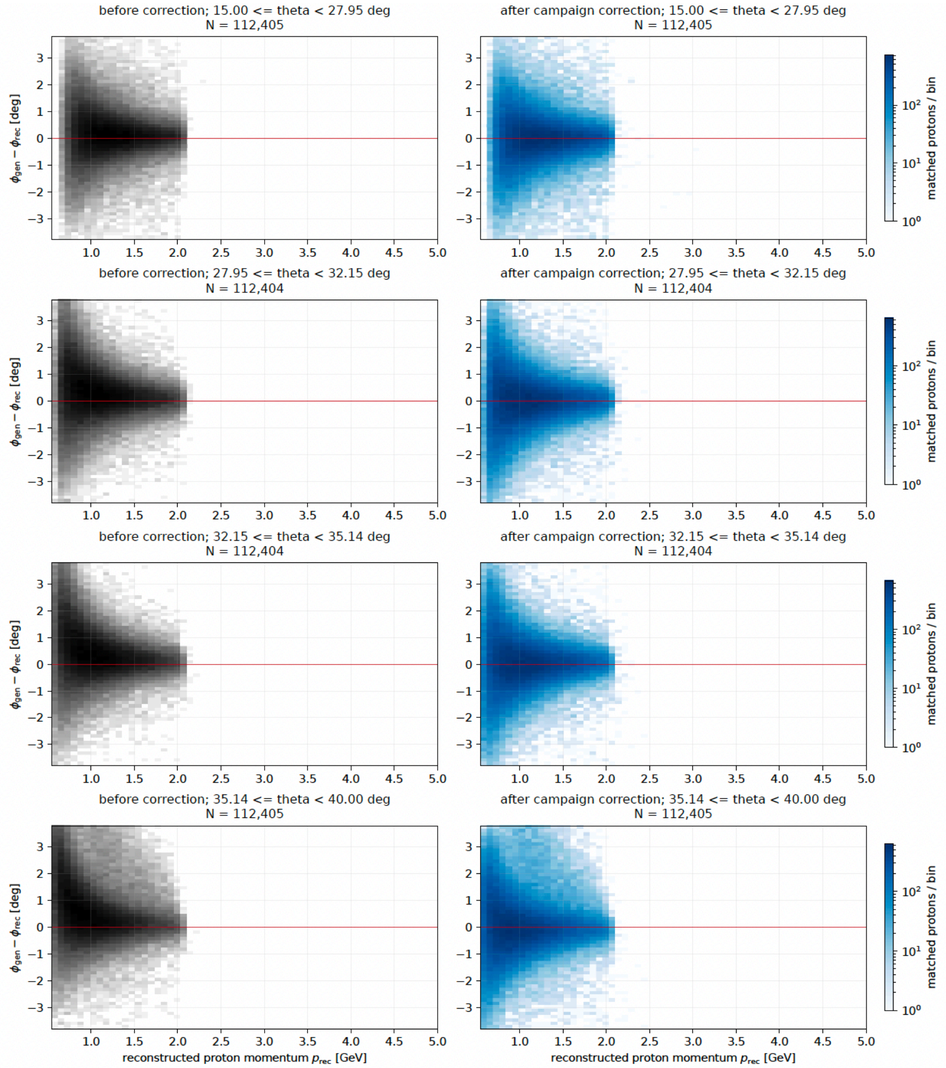


Figure 8: 6.535 GeV FD proton azimuthal residual versus reconstructed momentum, before and after correction in four equal-occupancy θ_p slices.

pFD

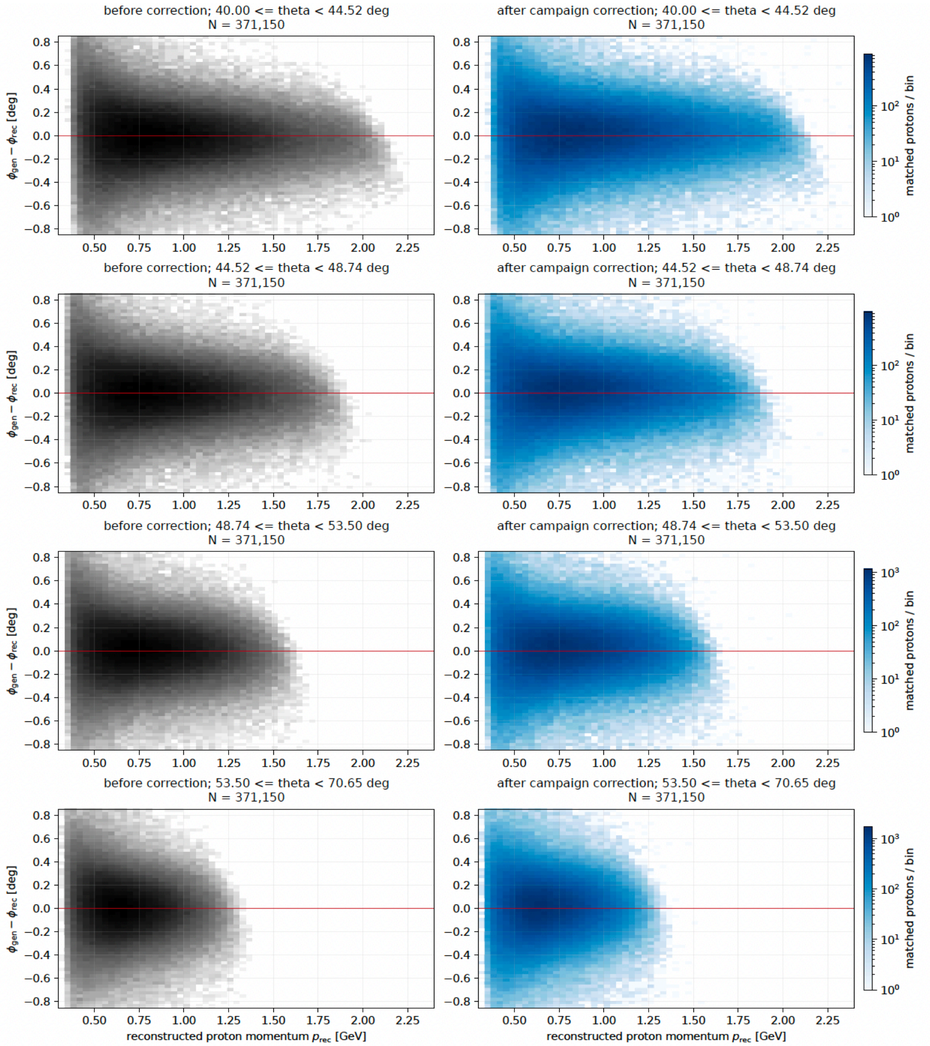


Figure 11: 6.535 GeV CD proton azimuthal residual versus reconstructed momentum, before and after correction in four equal-occupancy θ_p slices.

pCD

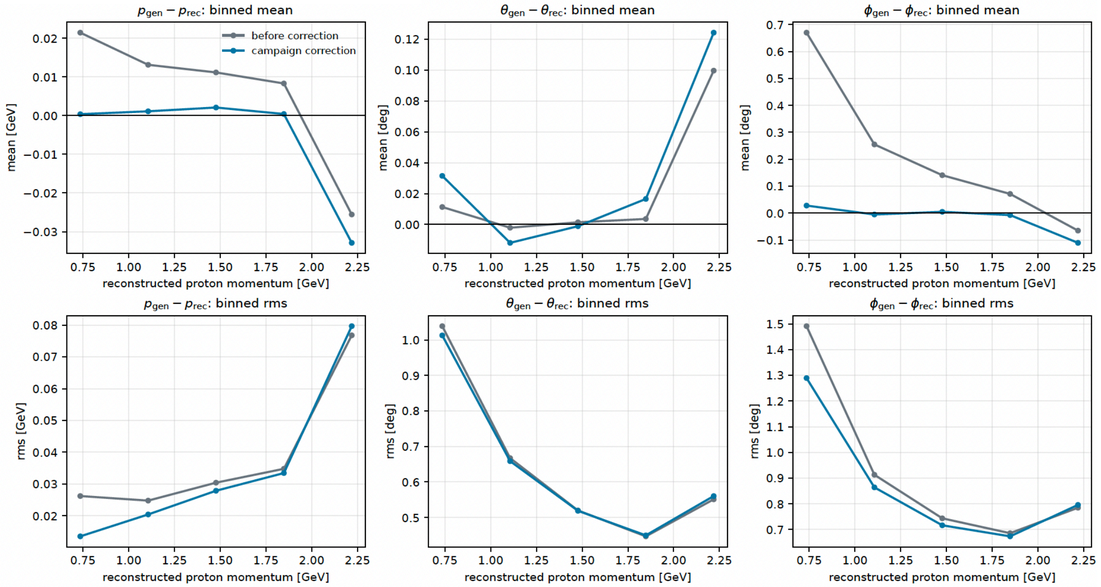


Figure 2: 6.535 GeV FD proton residual means and RMS values versus reconstructed momentum.

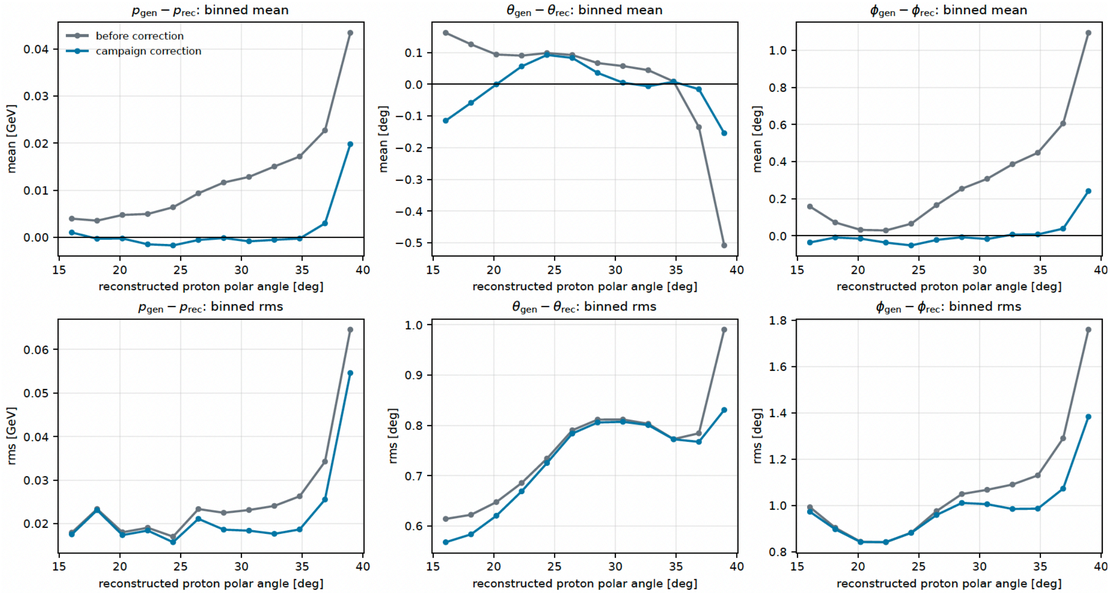


Figure 3: 6.535 GeV FD proton residual means and RMS values versus reconstructed polar angle.

pFD

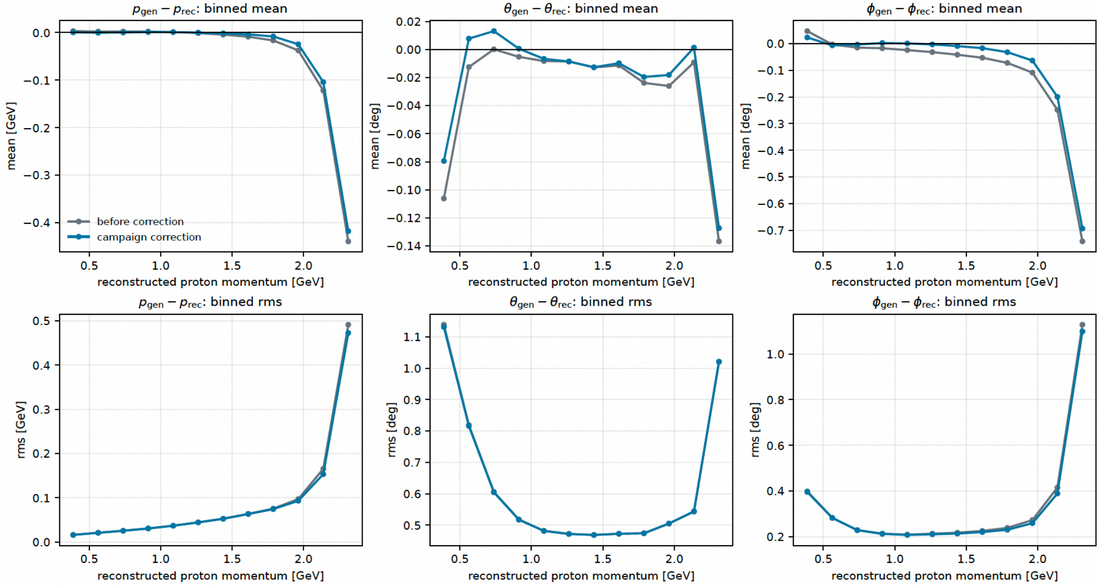


Figure 4: 6.535 GeV CD proton residual means and RMS values versus reconstructed momentum.

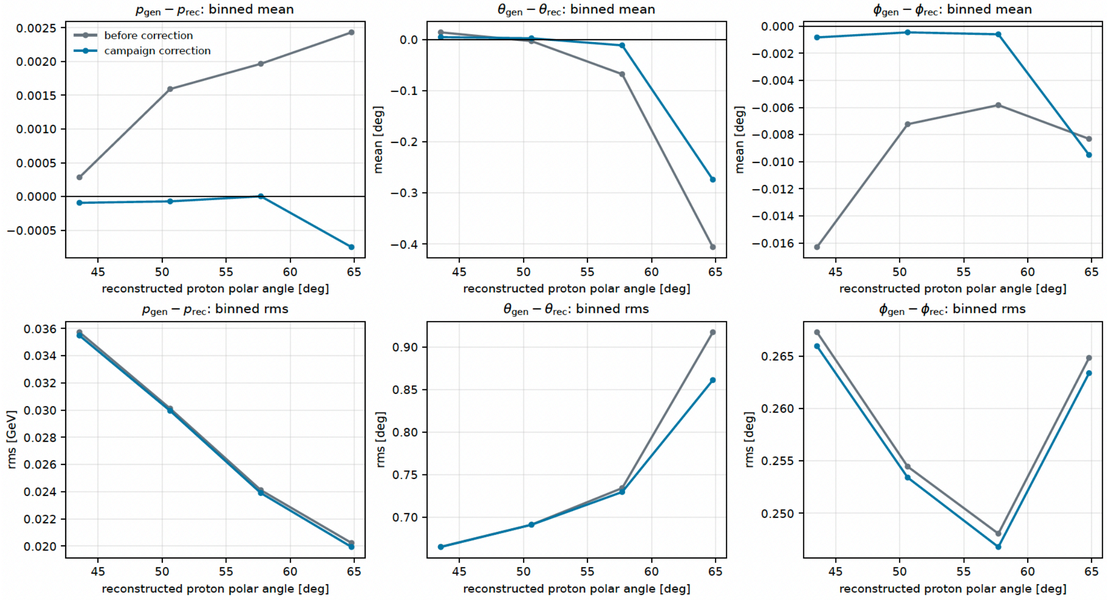


Figure 5: 6.535 GeV CD proton residual means and RMS values versus reconstructed polar angle.

pCD

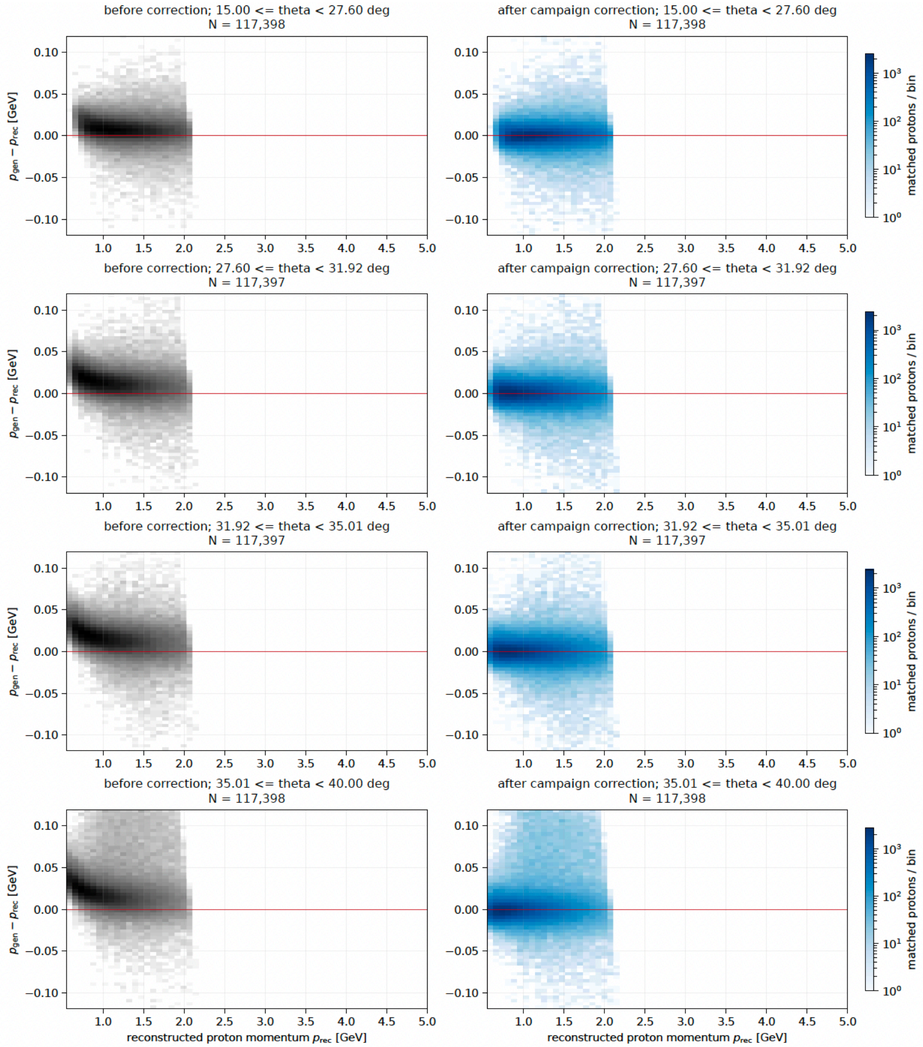


Figure 17: 7.546 GeV FD proton momentum residual versus reconstructed momentum, before and after correction in four equal-occupancy θ_p slices.

pFD

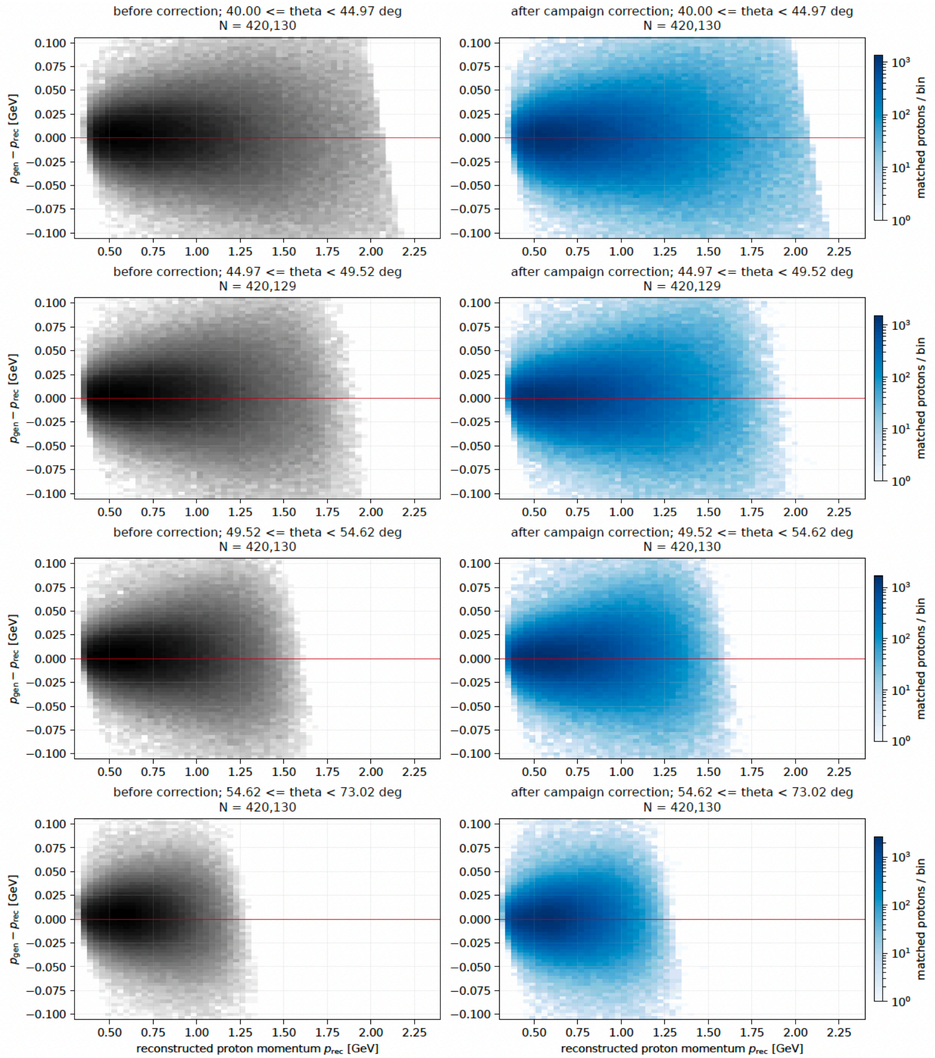


Figure 20: 7.546 GeV CD proton momentum residual versus reconstructed momentum, before and after correction in four equal-occupancy θ_p slices.

pCD

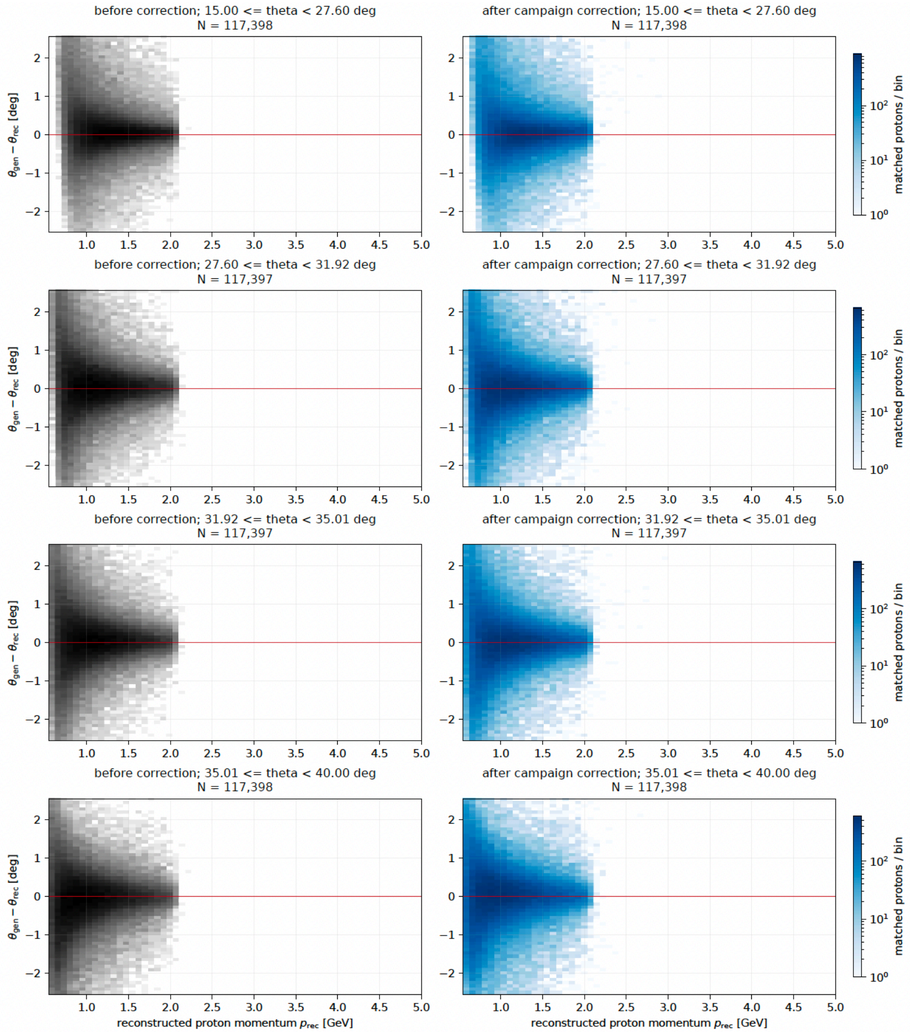


Figure 18: 7.546 GeV FD proton polar-angle residual versus reconstructed momentum, before and after correction in four equal-occupancy θ_p slices.

pFD

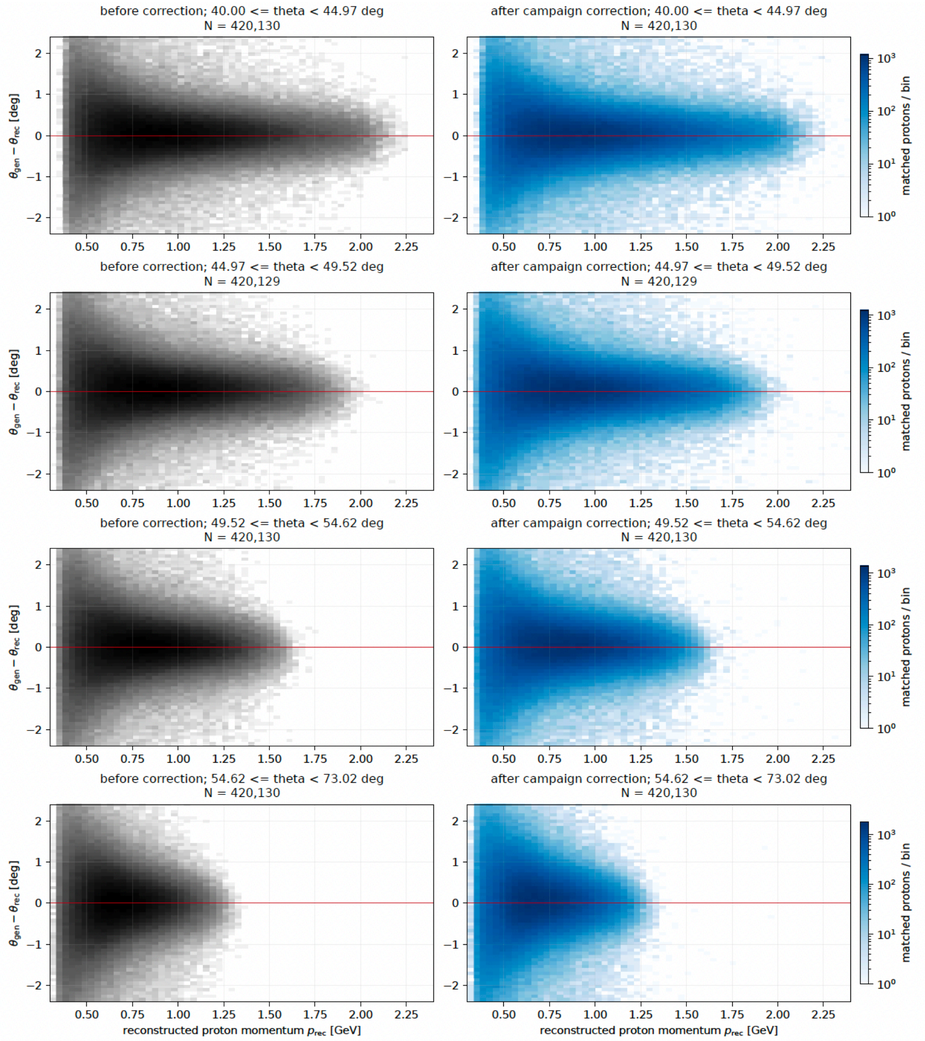


Figure 21: 7.546 GeV CD proton polar-angle residual versus reconstructed momentum, before and after correction in four equal-occupancy θ_p slices.

pCD

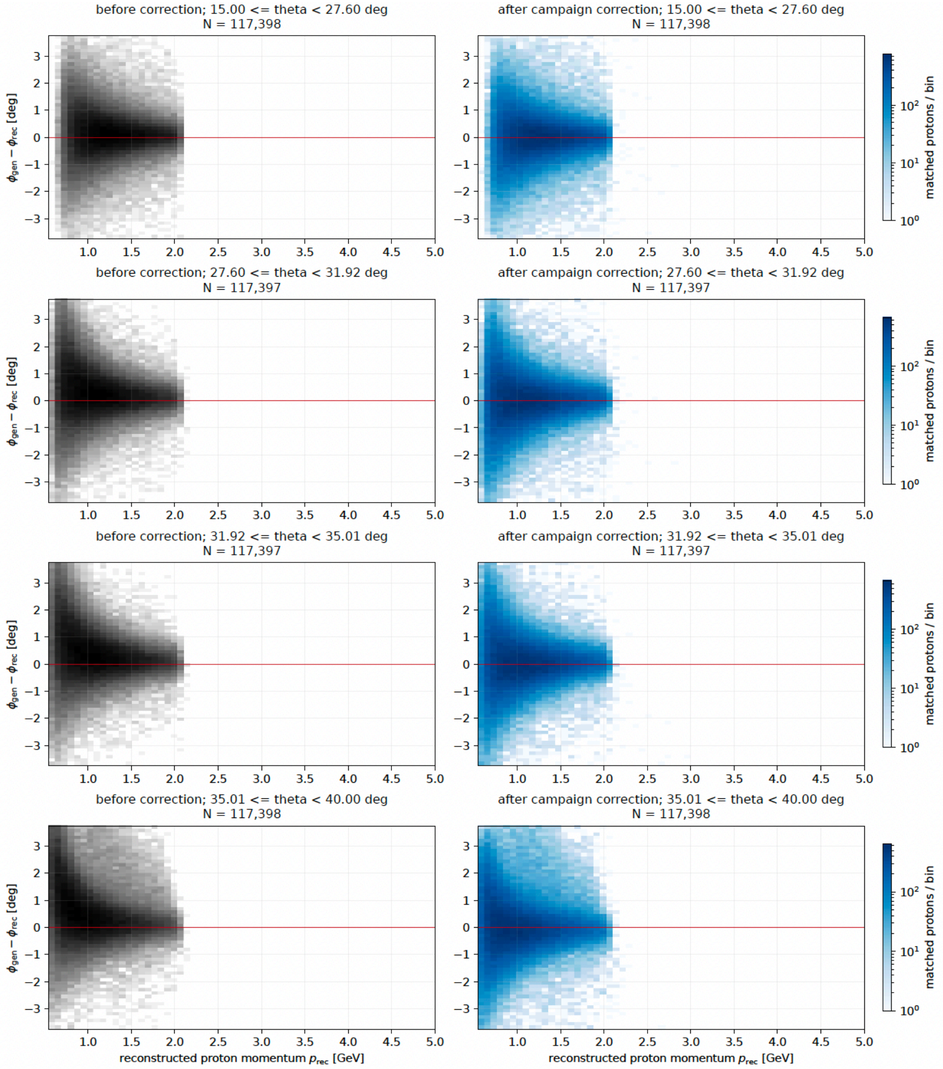


Figure 19: 7.546 GeV FD proton azimuthal residual versus reconstructed momentum, before and after correction in four equal-occupancy θ_p slices.

pFD

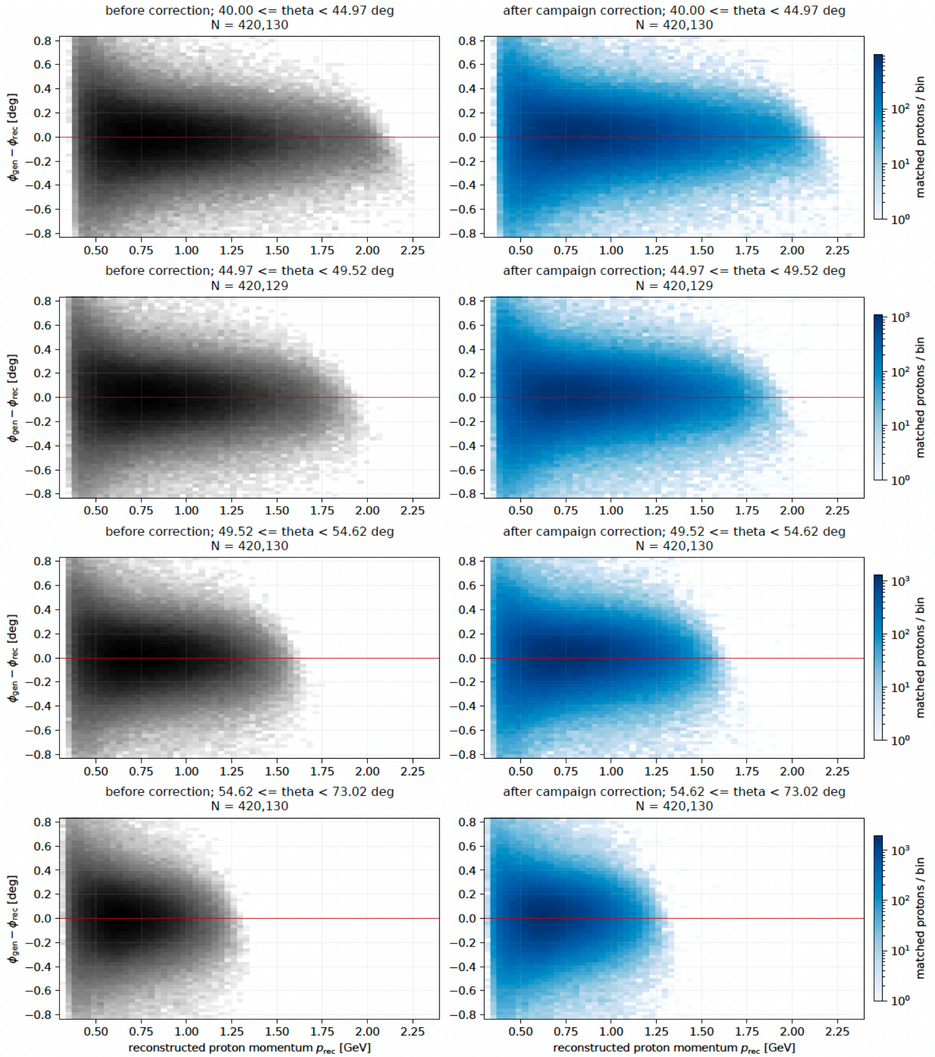


Figure 22: 7.546 GeV CD proton azimuthal residual versus reconstructed momentum, before and after correction in four equal-occupancy θ_p slices.

pCD

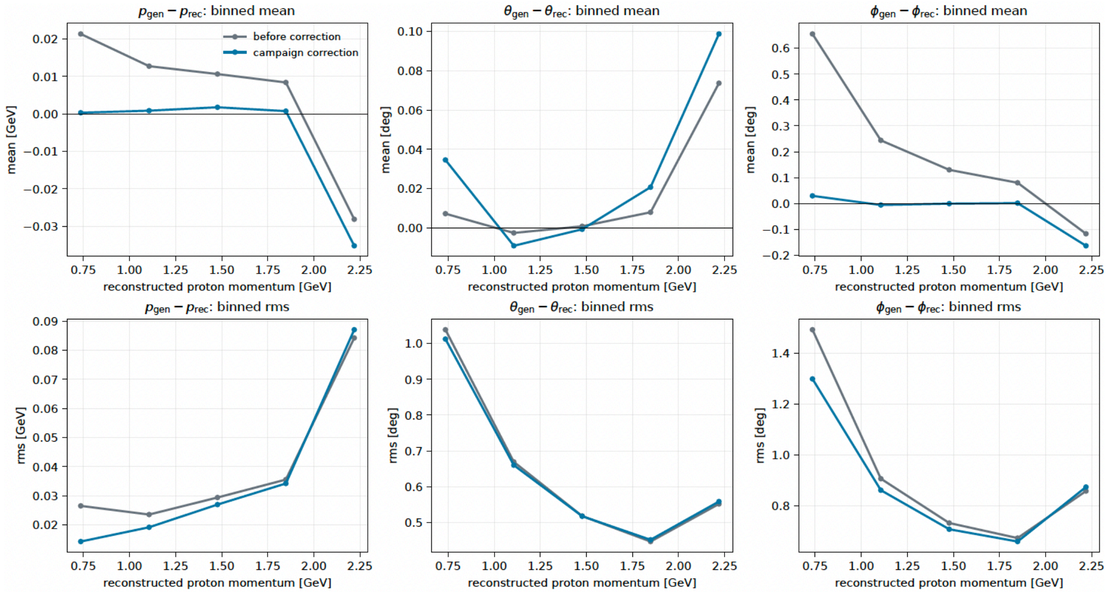


Figure 13: 7.546 GeV FD proton residual means and RMS values versus reconstructed momentum.

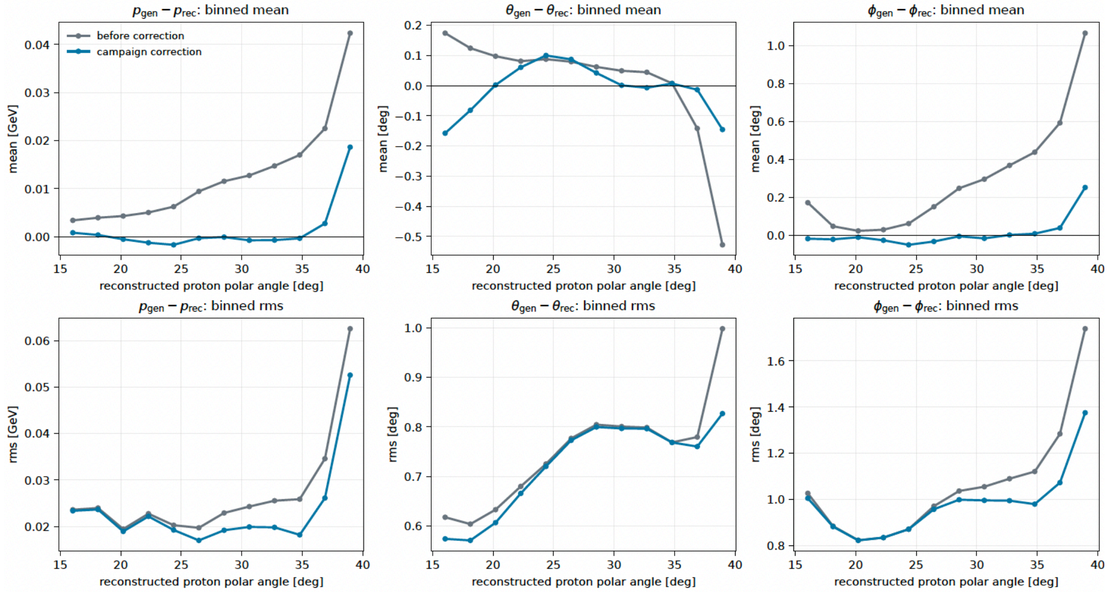


Figure 14: 7.546 GeV FD proton residual means and RMS values versus reconstructed polar angle.

pFD

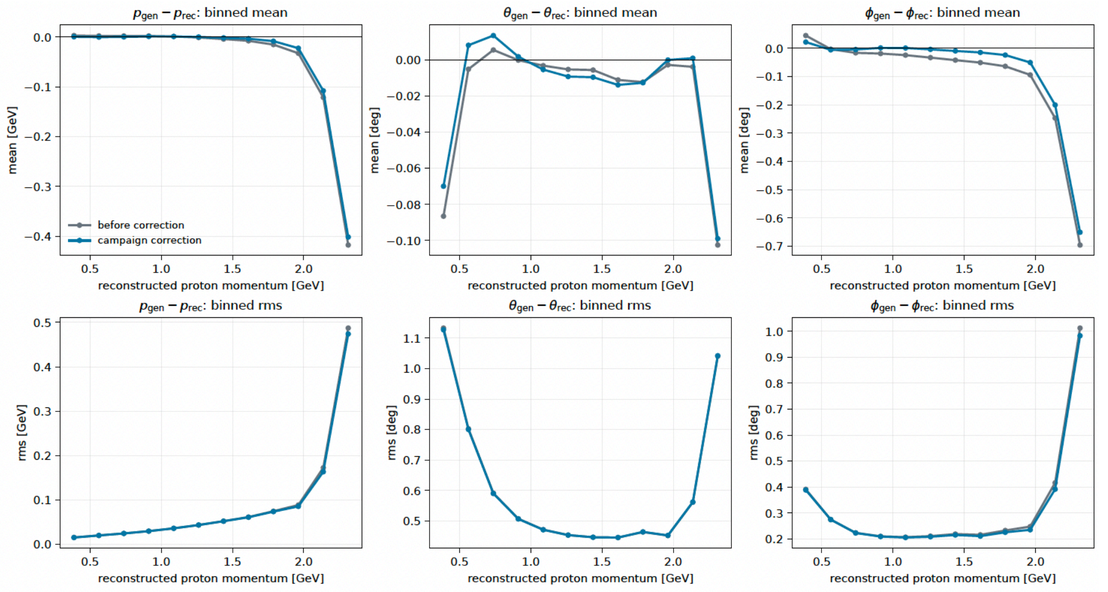


Figure 15: 7.546 GeV CD proton residual means and RMS values versus reconstructed momentum.

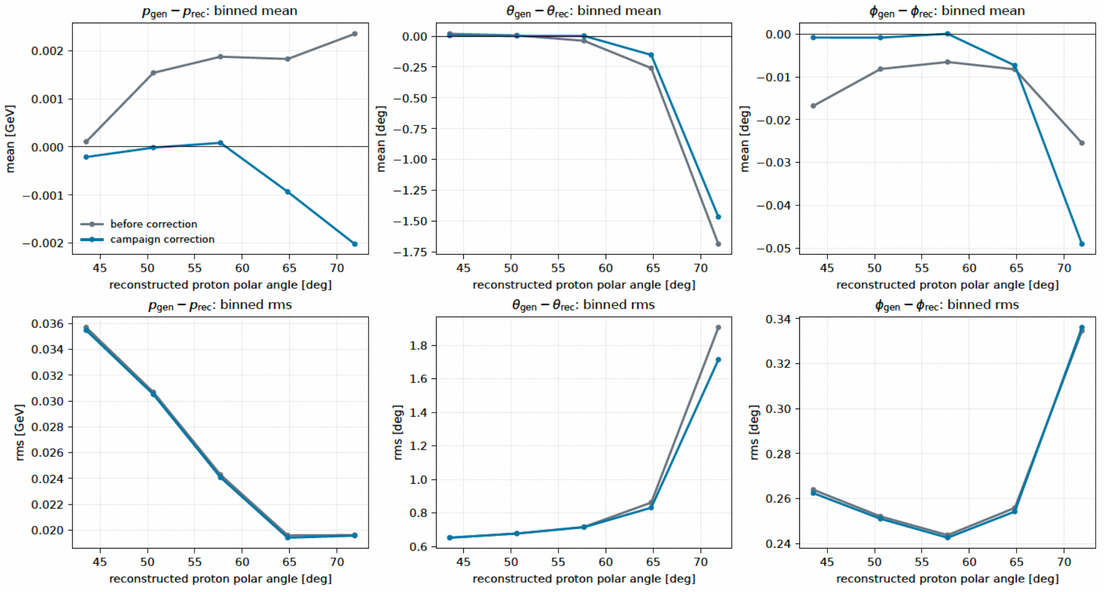


Figure 16: 7.546 GeV CD proton residual means and RMS values versus reconstructed polar angle.

pCD

electron SF diagnostics

*inclusive skim/GEMC should and will ultimately be used; these are placeholders for this presentation

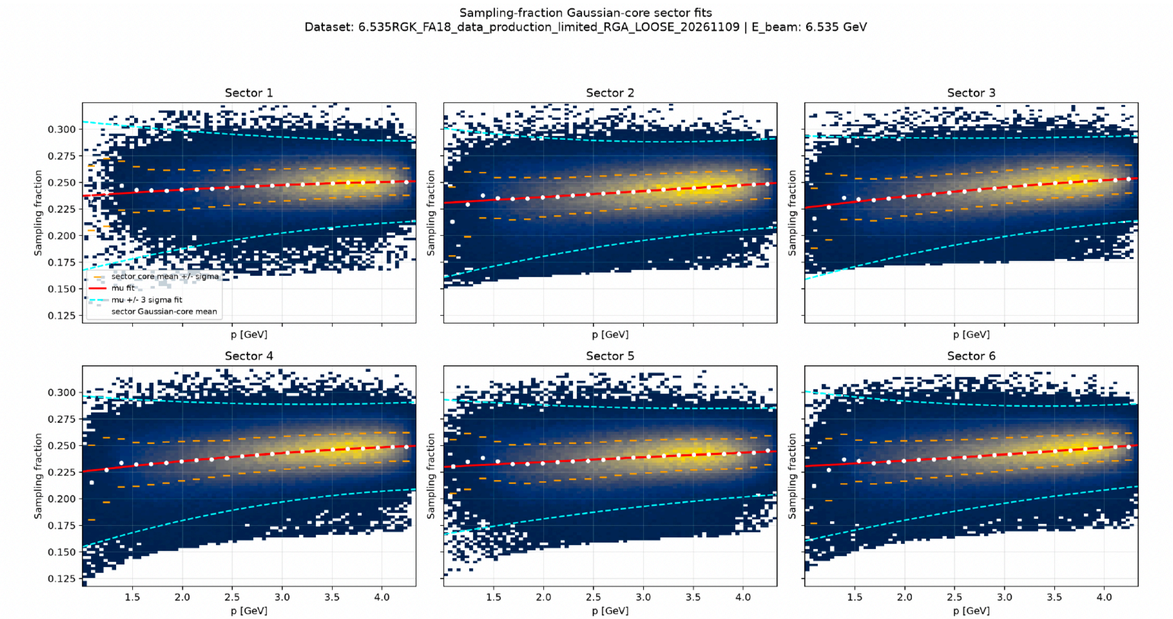


Figure 23: 6.535 GeV production-data sampling-fraction profiles and sector fits. The displayed bands are the actual polynomial $\mu_s(p) \pm 3.5\sigma_s(p)$ definitions consumed by post-processing.

DATA

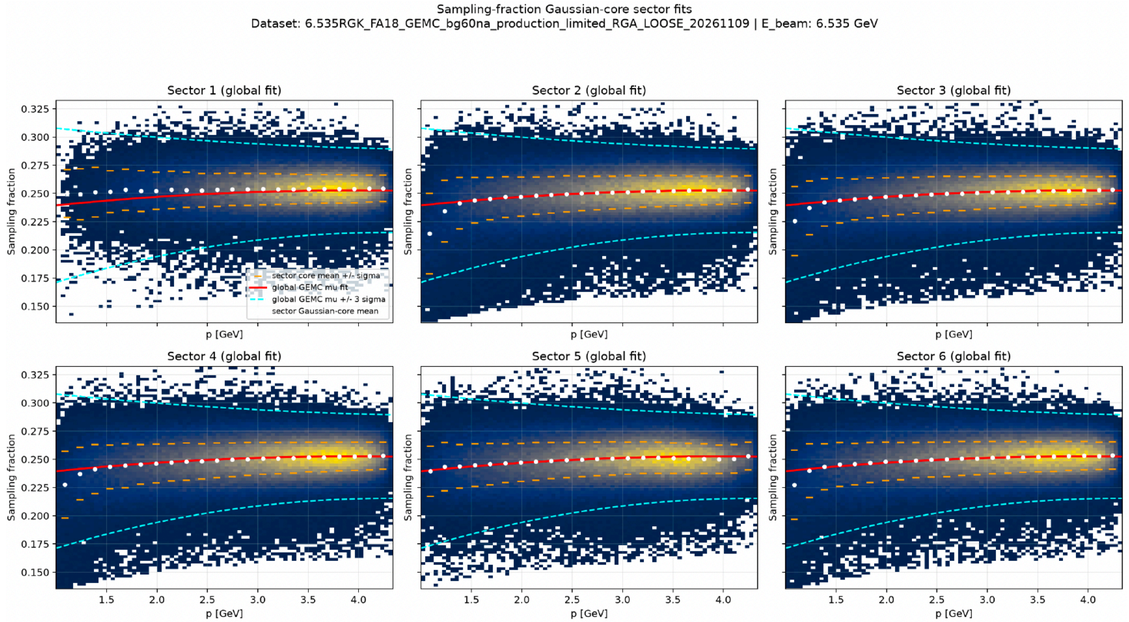


Figure 24: 6.535 GeV 60 nA production-GEMC sampling-fraction profiles and sector fits.

GEMC

*inclusive skim/GEMC should and will ultimately be used; these are placeholders for this presentation

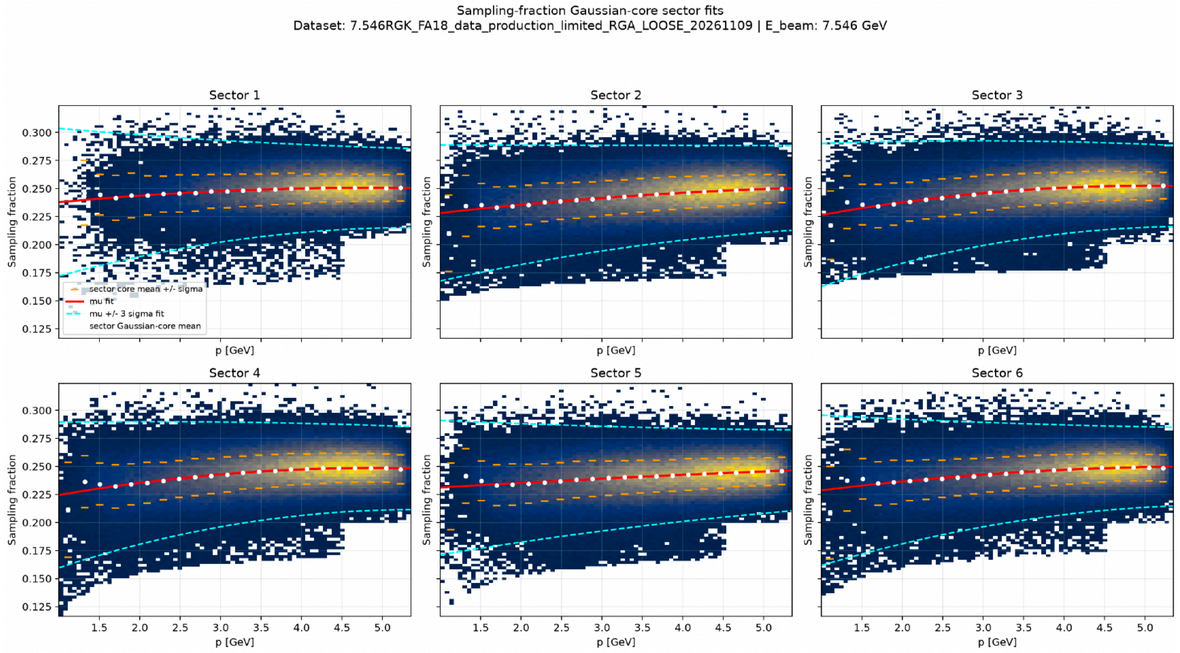


Figure 25: 7.546 GeV production-data sampling-fraction profiles and sector fits.

DATA

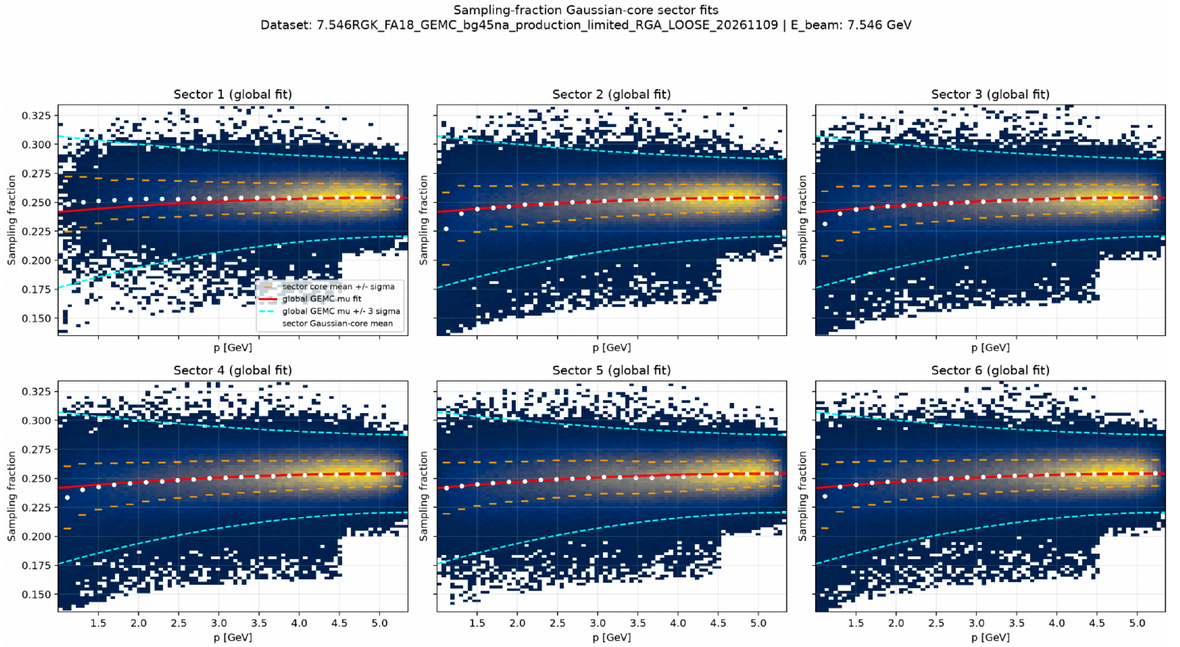


Figure 26: 7.546 GeV 45 nA production-GEMC sampling-fraction profiles and sector fits.

GEMC

radiative corrections

$$I_m^{\mathcal{B}} = \int dx\; K_{\mathcal{B}}(x)\,\sigma_m(x), \qquad \delta_{\mathcal{B}} = \frac{I_{\rm rad}^{\mathcal{B}}}{I_{\rm Born}^{\mathcal{B}}}.$$

2 methods “A” and “B” for radiative correction

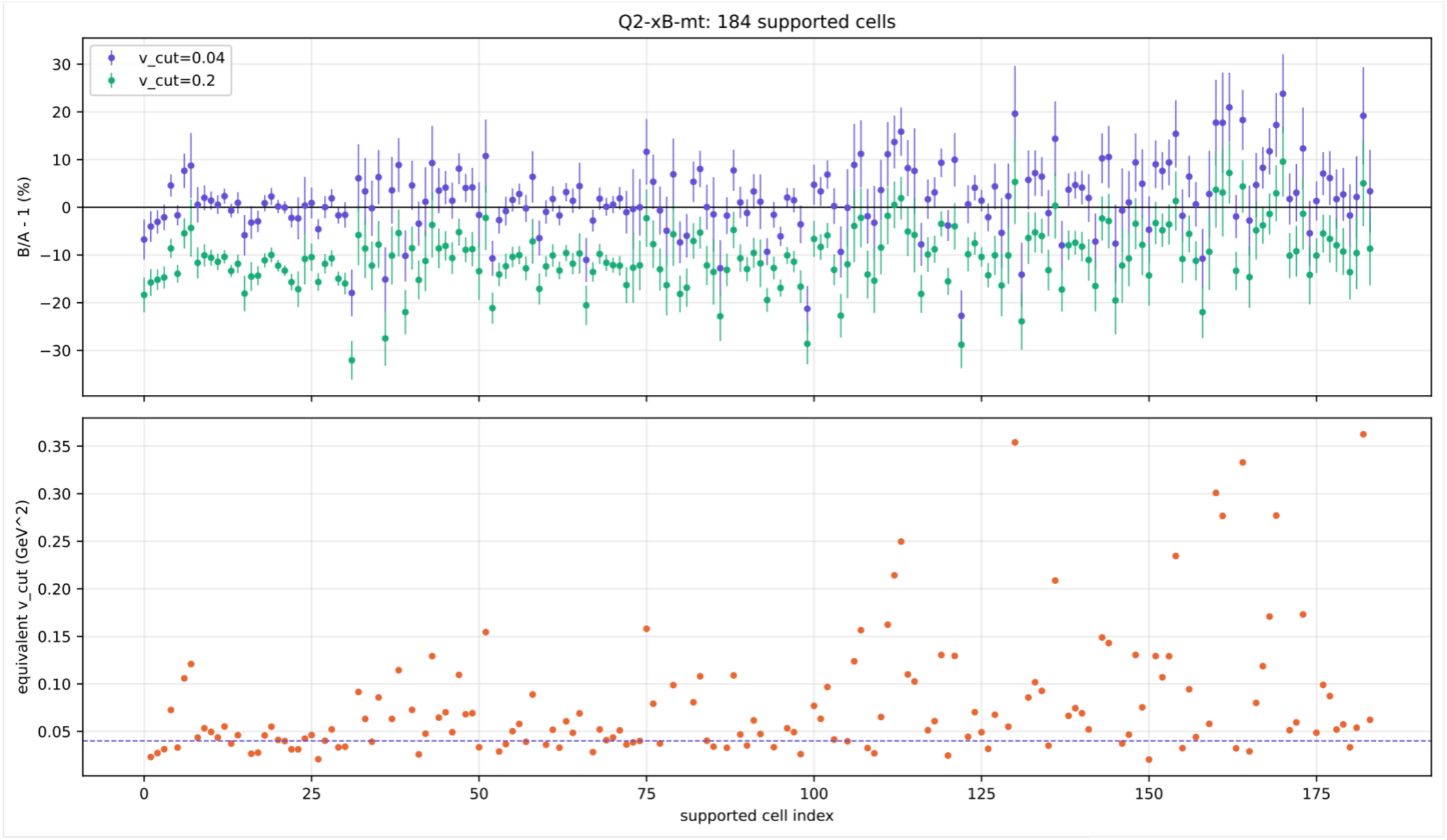
For analysis bin B and reconstruction kernel $K_B(x)$,

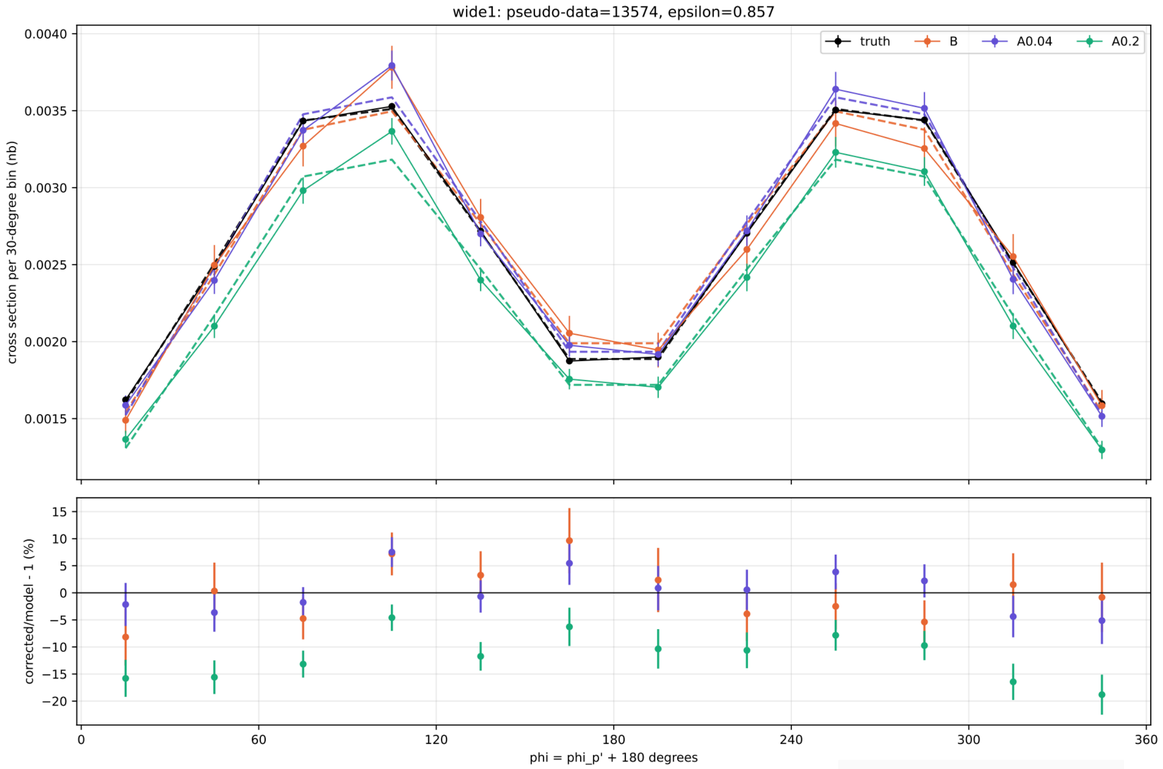
integrate over acceptance x to obtain measured cross section I :

$$I_m^{\mathcal{B}} = \int dx\; K_{\mathcal{B}}(x)\, \sigma_m(x), \qquad \delta_{\mathcal{B}} = \frac{I_{\text{rad}}^{\mathcal{B}}}{I_{\text{Born}}^{\mathcal{B}}}.$$

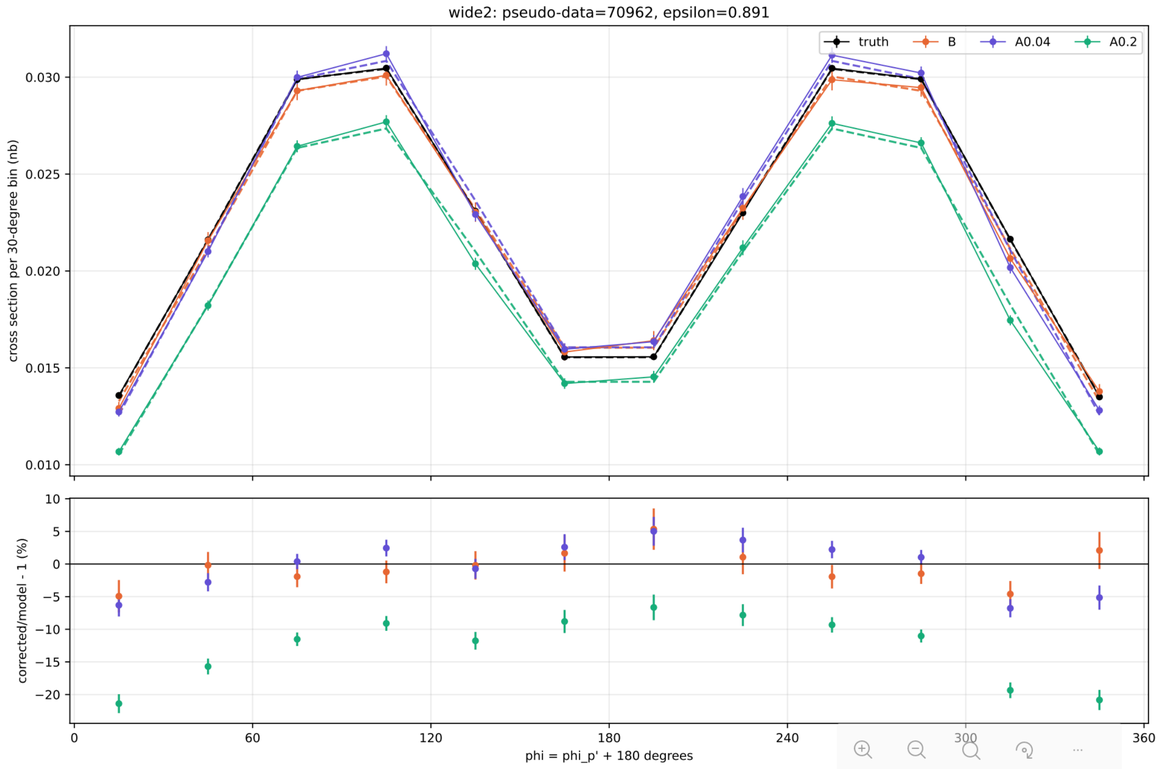
2 methods to compute Born denominator of the correction

- “rec-side” method **B** used by *Korover et al.* $\hat{I}_m^{\mathcal{B}} = \dfrac{\sigma_m}{N_m^{\text{gen}}} N_{m,\mathcal{B}}^{\text{rec}},$ $\delta_B^{\mathcal{B}} = \dfrac{N_{\text{rad}}^{\text{rec}}\, \sigma_{\text{rad}} / N_{\text{rad}}^{\text{gen}}}{N_{\text{Born}}^{\text{rec}}\, \sigma_{\text{Born}} / N_{\text{Born}}^{\text{gen}}}$
- “gen-side” method **A** used here : $\eta(x; v_{\text{cut}}) = \dfrac{\sigma_{\text{obs}}(x; v_{\text{cut}})}{\sigma_{\text{Born}}(x)}.$ $\delta_A^{\mathcal{B}}(v_{\text{cut}}) = \left[\dfrac{1}{N_{\text{rad}}^{\text{rec}}} \sum_{i \in \text{accepted rad}} \dfrac{1}{\eta(x_i; v_{\text{cut}})} \right]^{-1}$


Q2-xB-mt: 184 supported cells
v_cut=0.04
v_cut=0.2
B/A - 1 (%)
30
20
10
0
−10
−20
−30
equivalent v_cut (GeV^2)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
25
50
75
100
125
150
175
supported cell index



Wide 3D bin, ~10k events



Wide 3D bin, ~70k events

extractions

RGK Fall 2018, 6.535 GeV

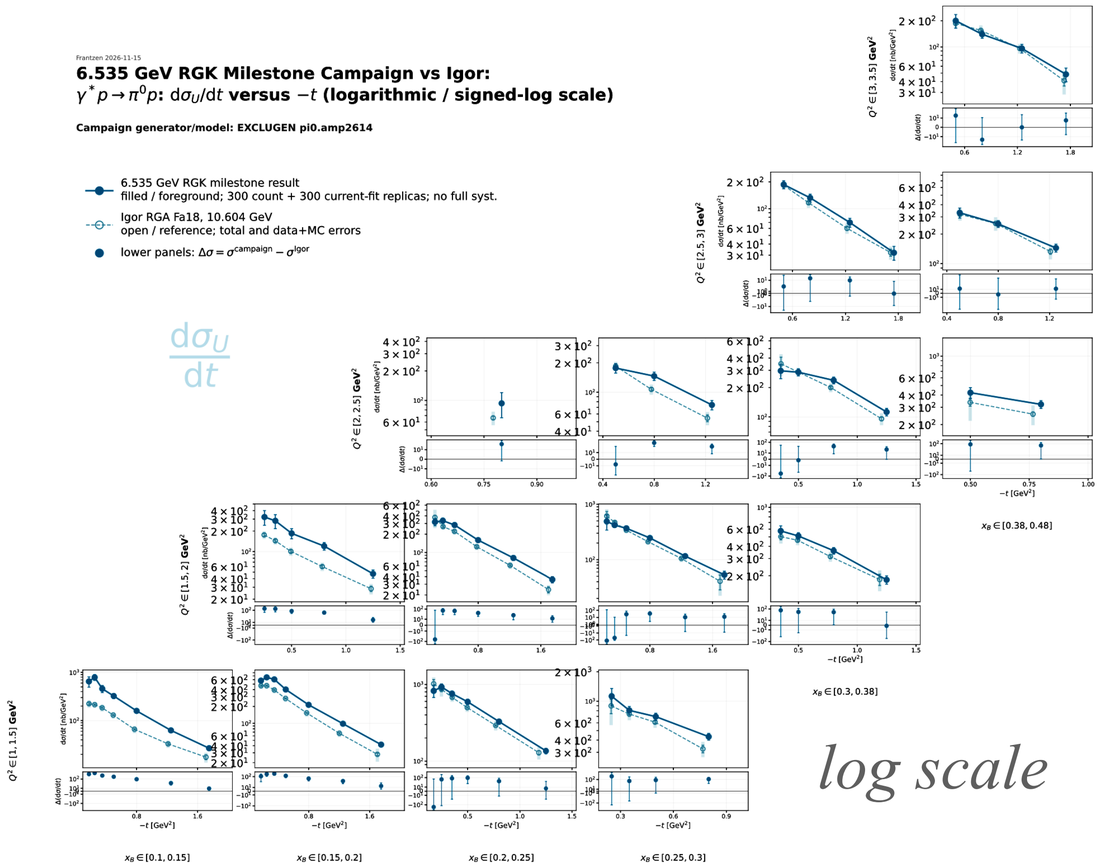
Frantzen 2026-11-15

6.535 GeV RGK Milestone Campaign vs Igor:
$\gamma^* p \to \pi^0 p$: $d\sigma_U/dt$ versus $-t$ (logarithmic / signed-log scale)

Campaign generator/model: EXCLUGEN pi0.amp2614

- 6.535 GeV RGK milestone result
  filled / foreground; 300 count + 300 current-fit replicas; no full syst.
- Igor RGA Fa18, 10.604 GeV
  open / reference; total and data+MC errors
- lower panels: $\Delta\sigma = \sigma^{\text{campaign}} - \sigma^{\text{Igor}}$

$\frac{d\sigma_U}{dt}$



log scale

RGK Fall 2018, 7.546 GeV

Story Frantzen

Jefferson Lab

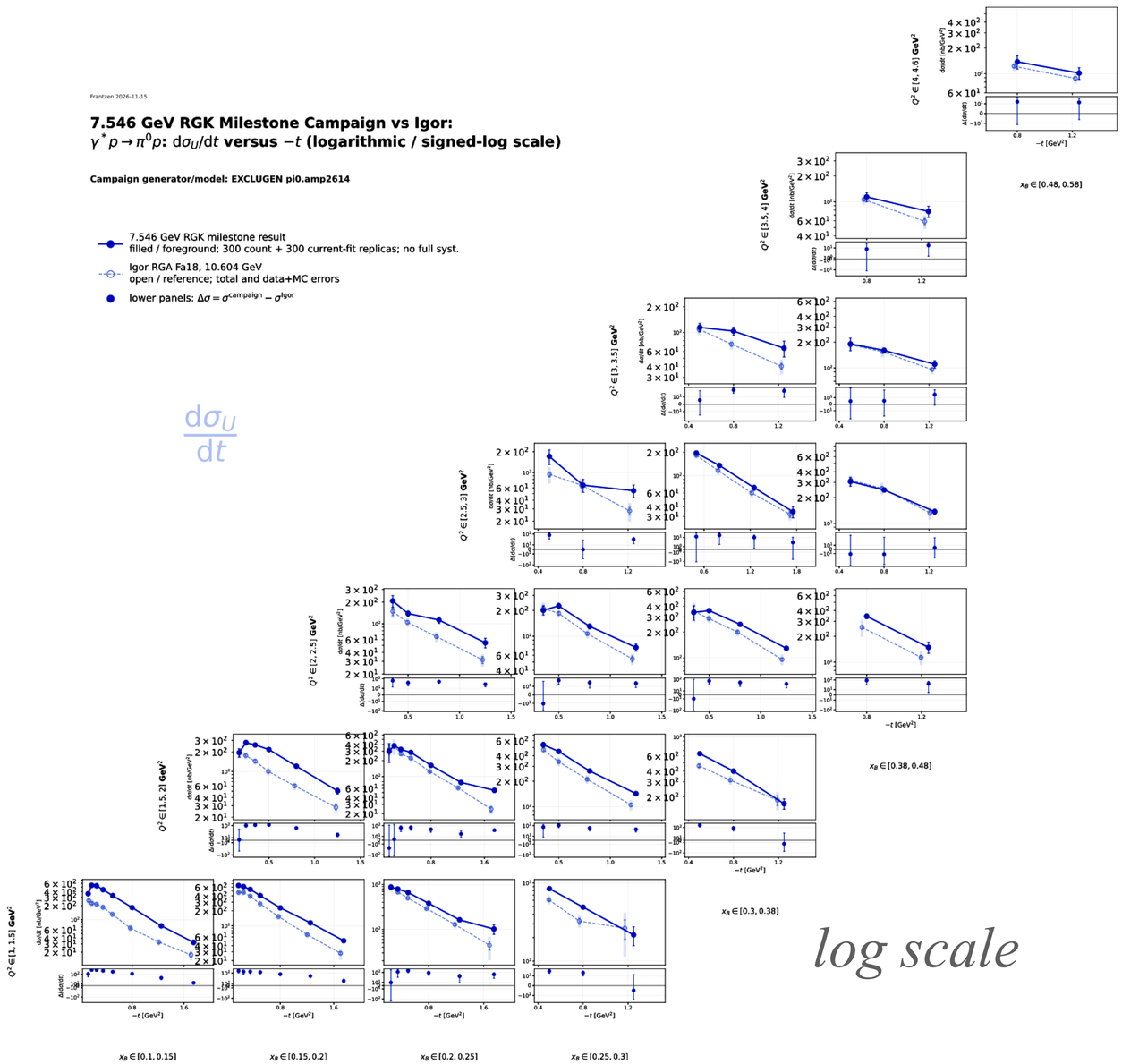
Frantzen 2026-11-15

7.546 GeV RGK Milestone Campaign vs Igor:
$\gamma^* p \to \pi^0 p$: $d\sigma_U/dt$ versus $-t$ (logarithmic / signed-log scale)

Campaign generator/model: EXCLUGEN pi0.amp2614

- 7.546 GeV RGK milestone result
  filled / foreground; 300 count + 300 current-fit replicas; no full syst.
- Igor RGA Fa18, 10.604 GeV
  open / reference; total and data+MC errors
- lower panels: $\Delta\sigma = \sigma^{\text{campaign}} - \sigma^{\text{Igor}}$

$\frac{d\sigma_U}{dt}$



log scale

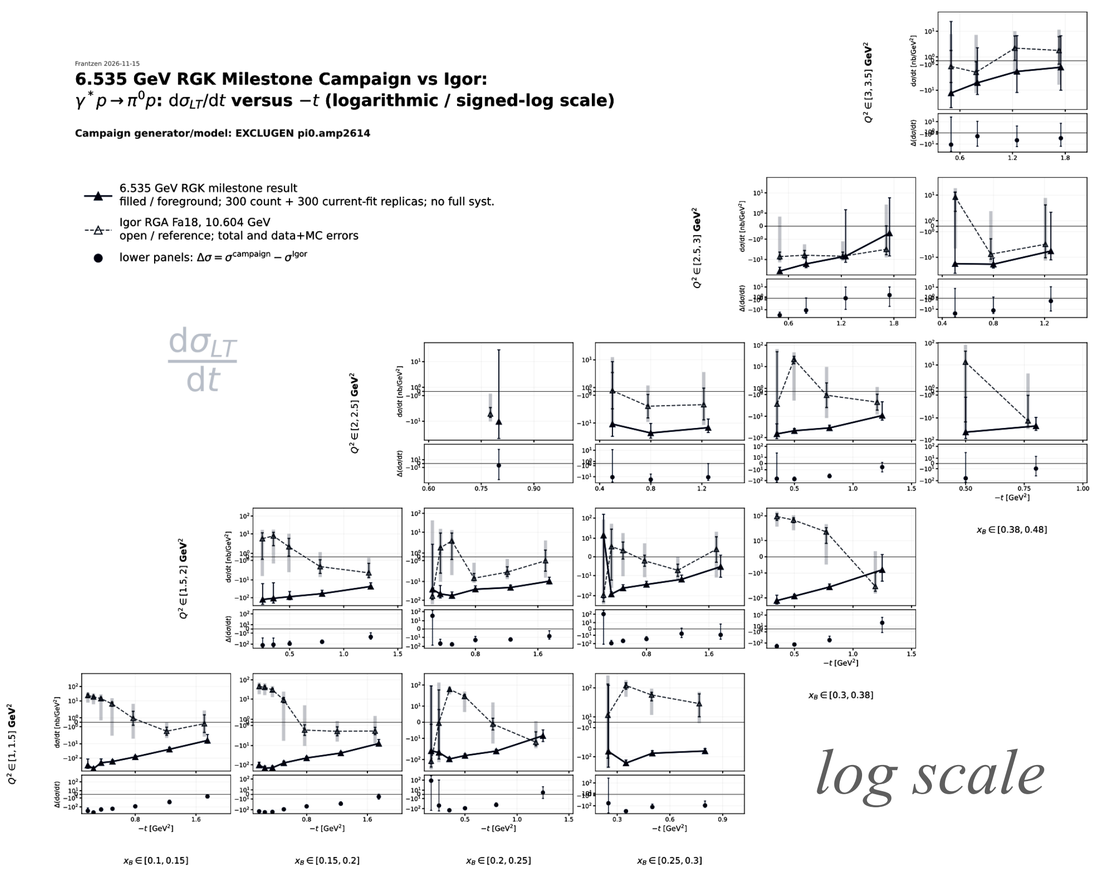
Frantzen 2026-11-15

6.535 GeV RGK Milestone Campaign vs Igor:
$\gamma^* p \to \pi^0 p$: $d\sigma_{LT}/dt$ versus $-t$ (logarithmic / signed-log scale)

Campaign generator/model: EXCLUGEN pi0.amp2614

- 6.535 GeV RGK milestone result
  filled / foreground; 300 count + 300 current-fit replicas; no full syst.
- Igor RGA Fa18, 10.604 GeV
  open / reference; total and data+MC errors
- lower panels: $\Delta\sigma = \sigma^{\text{campaign}} - \sigma^{\text{Igor}}$

$$\frac{d\sigma_{LT}}{dt}$$



log scale

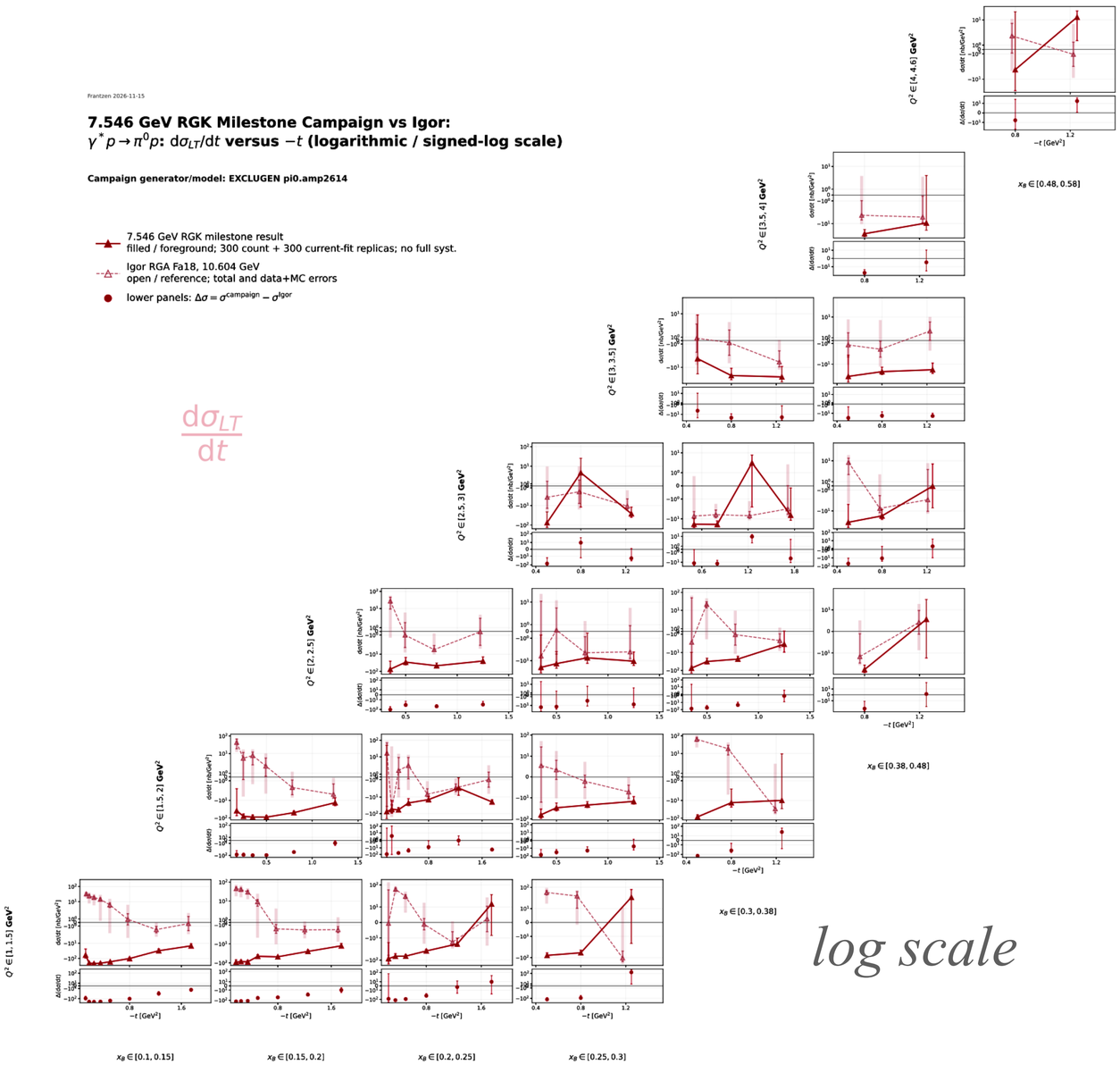
Frantzen 2026-11-15

7.546 GeV RGK Milestone Campaign vs Igor:
$\gamma^* p \to \pi^0 p$: $d\sigma_{LT}/dt$ versus $-t$ (logarithmic / signed-log scale)

Campaign generator/model: EXCLUGEN pi0.amp2614

- 7.546 GeV RGK milestone result
  filled / foreground; 300 count + 300 current-fit replicas; no full syst.
- Igor RGA Fa18, 10.604 GeV
  open / reference; total and data+MC errors
- lower panels: $\Delta\sigma = \sigma^{\text{campaign}} - \sigma^{\text{Igor}}$

$$\frac{d\sigma_{LT}}{dt}$$



log scale

Frantzen 2026-11-15

6.535 GeV RGK Milestone Campaign vs Igor:
$\gamma^* p \to \pi^0 p$: $d\sigma_{TT}/dt$ versus $-t$ (logarithmic / signed-log scale)

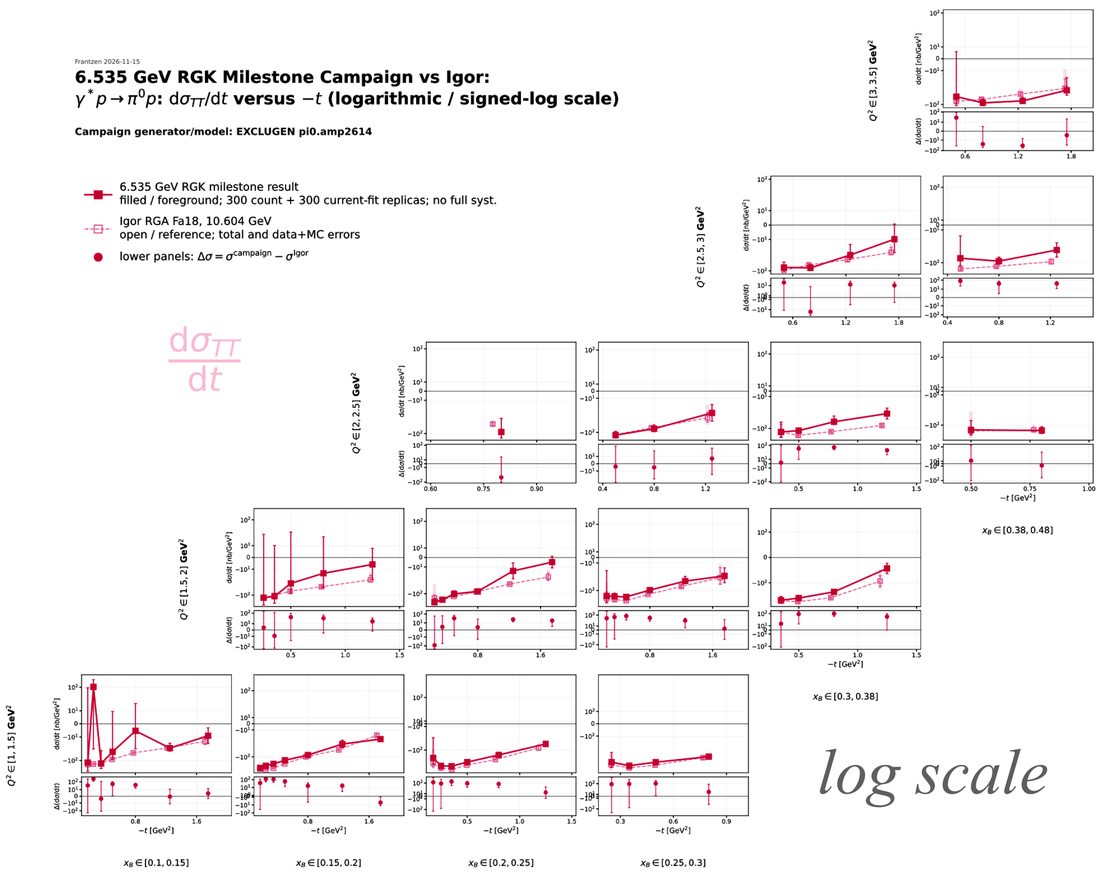
Campaign generator/model: EXCLUGEN pi0.amp2614

6.535 GeV RGK milestone result
filled / foreground; 300 count + 300 current-fit replicas; no full syst.

Igor RGA Fa18, 10.604 GeV
open / reference; total and data+MC errors

lower panels: $\Delta\sigma = \sigma^{\text{campaign}} - \sigma^{\text{Igor}}$

$\frac{d\sigma_{TT}}{dt}$



log scale

Story Frantzen

Jefferson Lab

Frantzen 2026-11-15

7.546 GeV RGK Milestone Campaign vs Igor:
$\gamma^* p \to \pi^0 p$: $d\sigma_{TT}/dt$ versus $-t$ (logarithmic / signed-log scale)

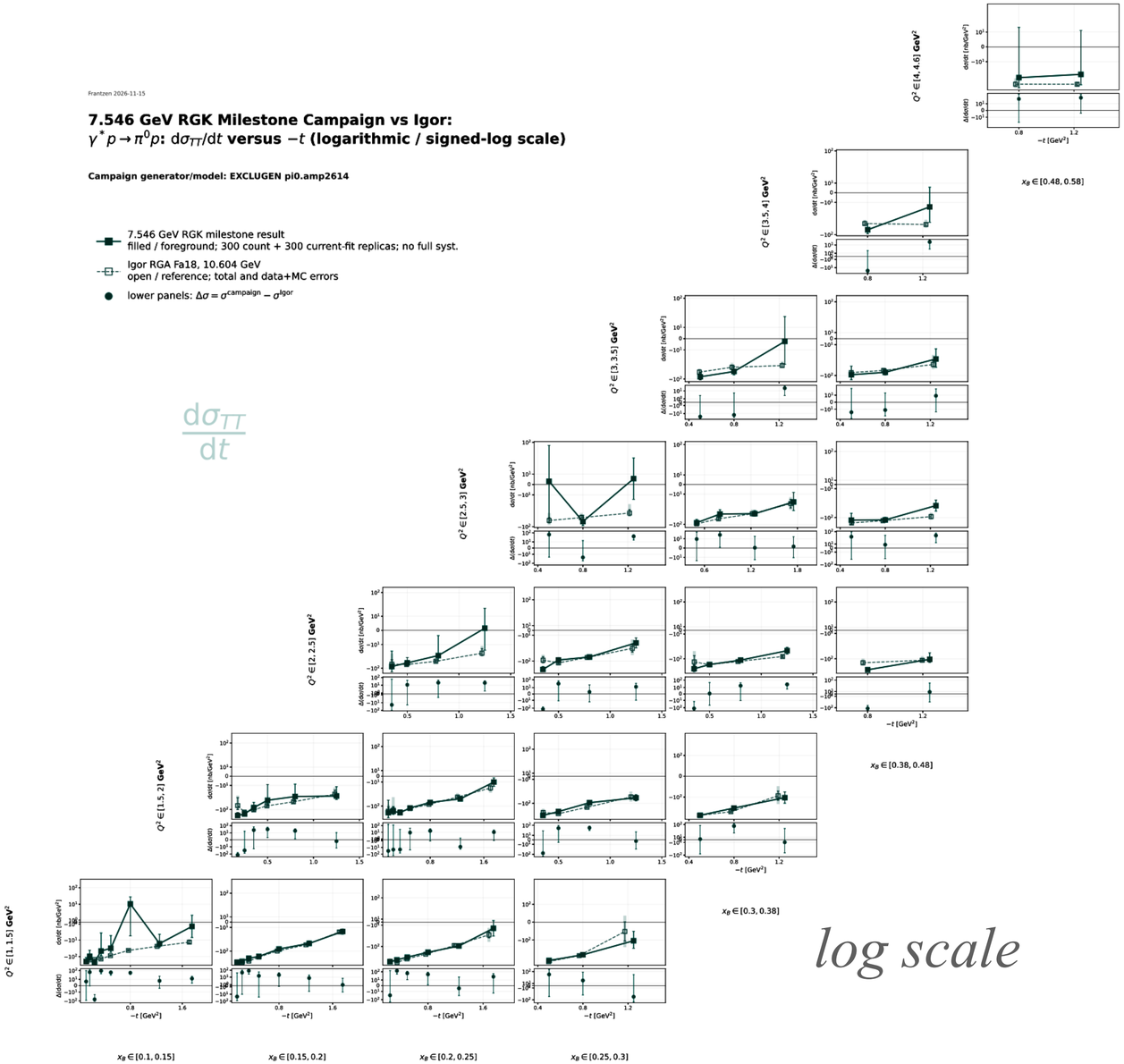
Campaign generator/model: EXCLUGEN pi0.amp2614

7.546 GeV RGK milestone result
filled / foreground; 300 count + 300 current-fit replicas; no full syst.

Igor RGA Fa18, 10.604 GeV
open / reference; total and data+MC errors

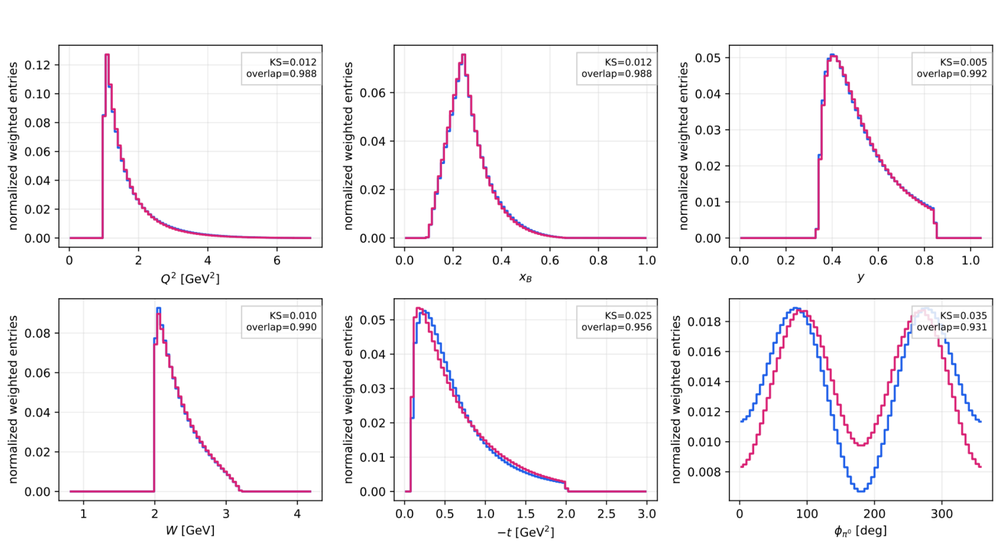
lower panels: $\Delta\sigma = \sigma^{\text{campaign}} - \sigma^{\text{Igor}}$

$\frac{d\sigma_{TT}}{dt}$

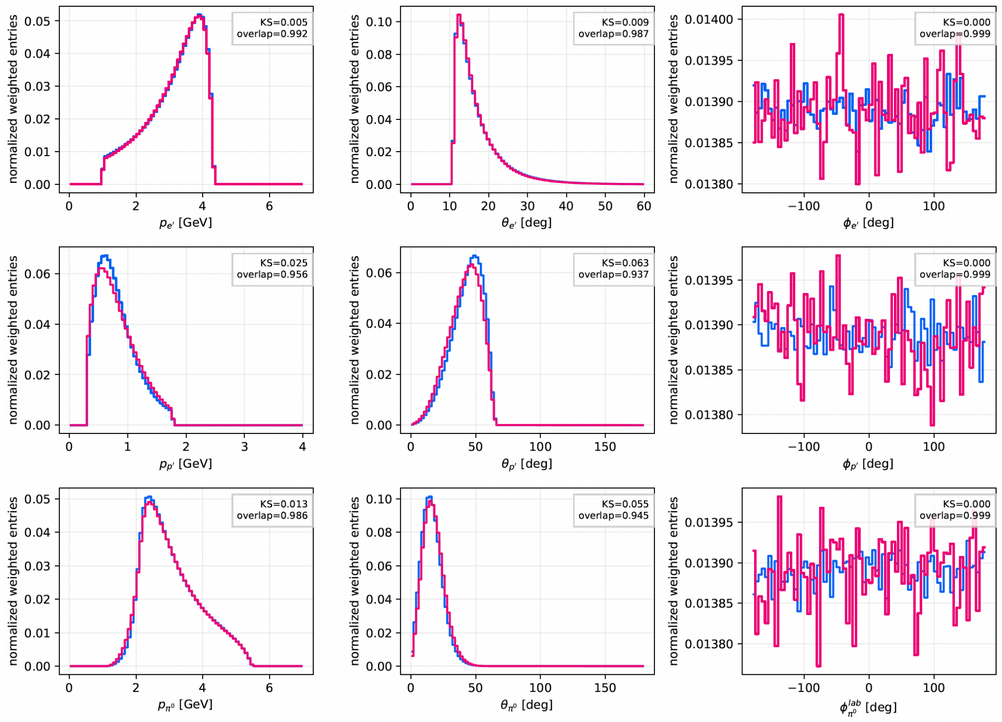


log scale

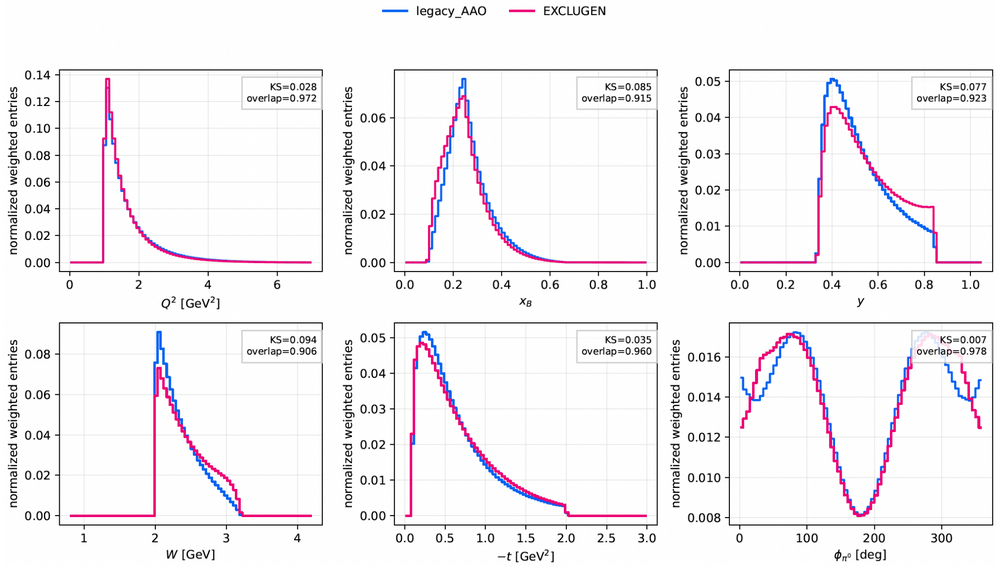
Born generators on the common analysis truth definition



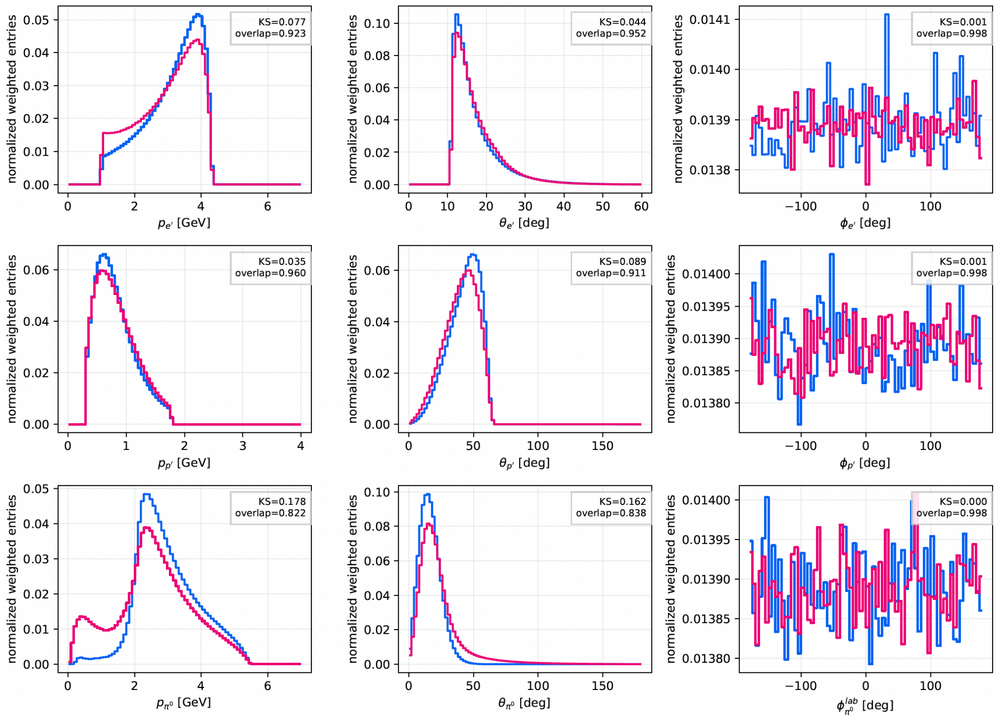
BORN



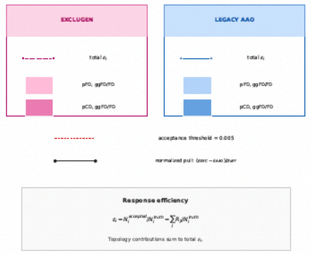
Radiative generators on the common analysis truth definition



RAD



6.535 GeV response acceptance: legacy AAO vs EXCLUGEN



$-t = 0.4 - 0.6\ \text{GeV}^2$