Measurement of Deeply Virtual Compton Scattering on the Proton at Multiple Beam Energies with the CLAS12 Detector

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clas

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Way to Understand Proton's Structure

Generalized Parton Distribution

GPDs encode the correlated momentum and spatial structure of quarks and gluons inside hadrons. Each term is a complex function.

Measurable variables are Compton Form Factor:

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

CFF GPD

With polarized electron beam and proton, we can have access to CFFs' $\mathrm{Im}(\mathcal{H})$ and $\mathrm{Re}(\mathcal{H})$.

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

Way to Understand Proton's Structure

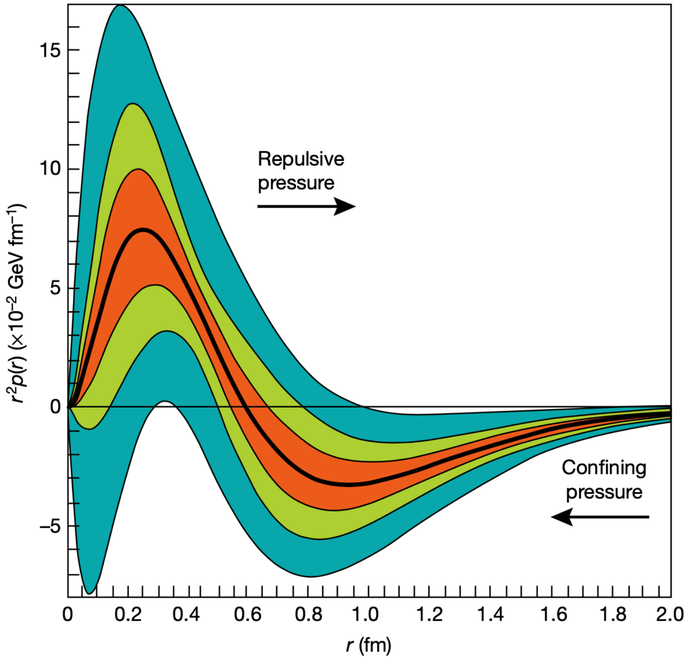
Gravitational Form Factor

- Mass/energy distribution
- Angular momentum distribution
- Shear forces and pressure distributions

$$\langle p' | T^{\mu\nu} | p \rangle = \bar{u}(p') \left[A(t)\,\gamma^{(\mu} P^{\nu)} + B(t)\,\frac{i\sigma^{(\mu\alpha}\Delta_\alpha P^{\nu)}}{2M} + D(t)\,\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{4M} \right] u(p)$$

$$\int_{-1}^{1} dx\, x\, H(x,\xi,t) = A(t) + \xi^2 D(t) \qquad \int_{-1}^{1} dx\, x\, E(x,\xi,t) = B(t) - \xi^2 D(t)$$

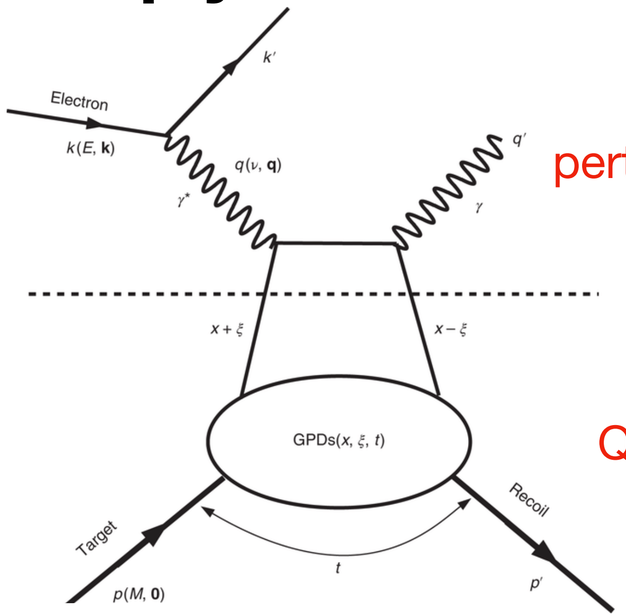
$$p(r) = \frac{1}{6M}\nabla^2 \widetilde{D}(r) \qquad s(r) = -\frac{1}{4M}\, r \frac{d}{dr}\left(\frac{1}{r}\frac{d}{dr}\widetilde{D}(r)\right)$$



Burkert, V. D., Elouadrhiri, L., & Girod, F. X. (2018). The pressure distribution inside the proton. *Nature*, *557*(7705), 396-399.

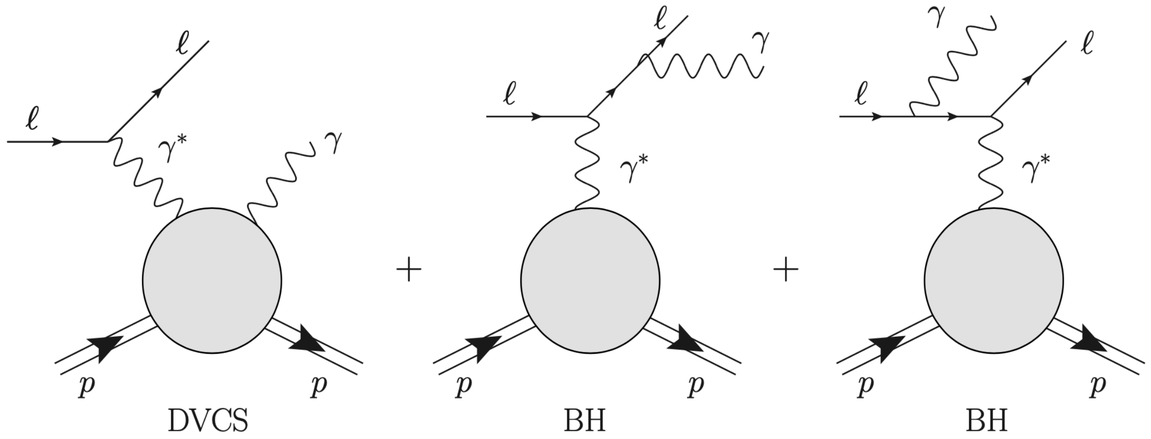
Physics Processes

Deeply Virtual Compton Scattering $ep \rightarrow ep\gamma$



perturbative QED

QCD

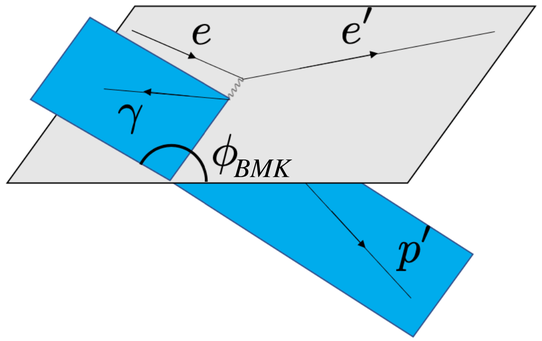


Cross Section of BH-DVCS

$$\frac{d^5\sigma}{dx_B dQ^2 d|t| d\phi d\phi_S} = \frac{\alpha^3 x_B}{16\pi^2 Q^4 \sqrt{1+\epsilon^2}} |\mathcal{T}|^2$$

$$|\mathcal{T}|^2 = \left|\mathcal{T}_{\mathrm{BH}} + \mathcal{T}_{\mathrm{DVCS}}\right|^2 = \left|\mathcal{T}_{\mathrm{BH}}\right|^2 + \left|\mathcal{T}_{\mathrm{DVCS}}\right|^2 + \mathcal{I}$$

$\mathcal{I}$ and $\mathcal{T}$ are functions of CFF



DVCS at Multiple Beam Energies

Deeply Virtual Compton Scattering $ep \rightarrow ep\gamma$

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Different beam energies give different y at same (x_B, Q^2, t) *point*

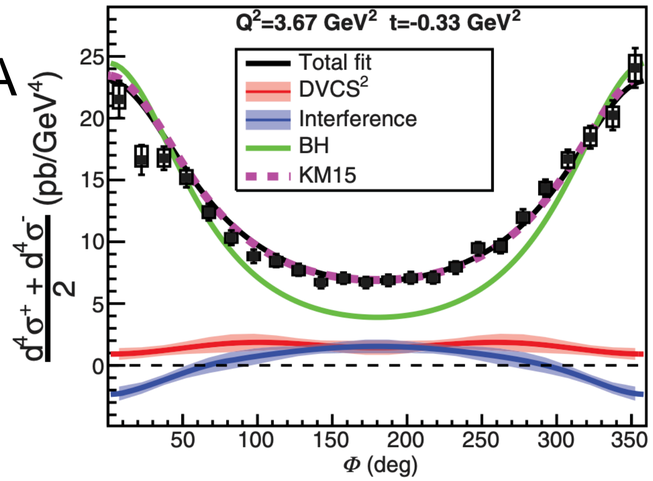
$$\mathcal{I} \sim 1/y^3$$

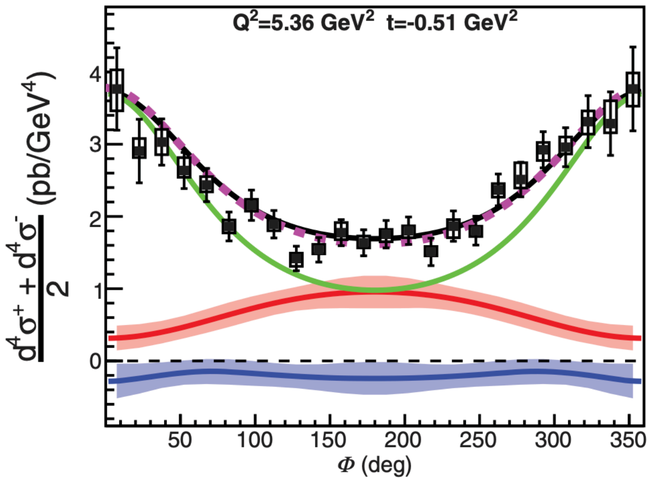
$$\left|\mathcal{T}^{\mathrm{DVCS}}\right|^2 \sim 1/y^2$$

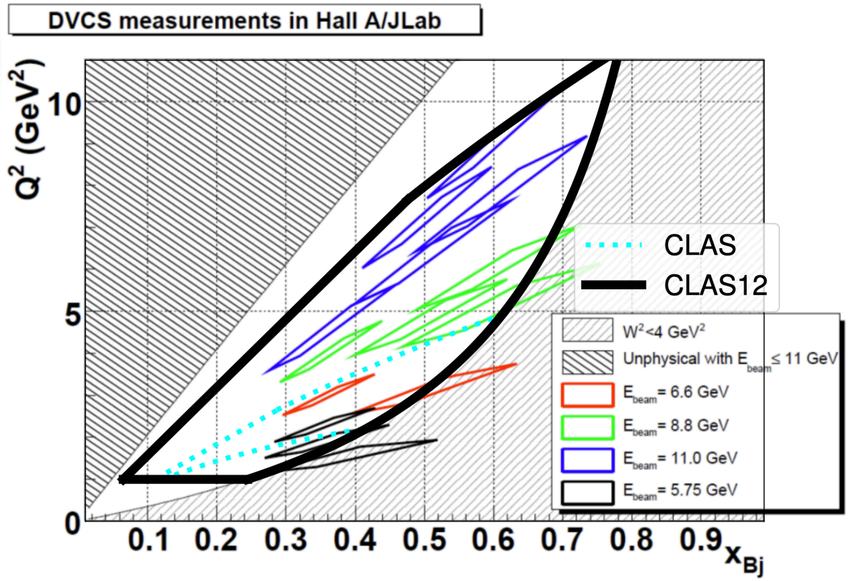
Separate DVCS and interface term!

Previous Hall A Result

Georges, F., Rashad, M. N. H., Stefanko, A., Dlamini, M., Karki, B., Ali, S. F., ... & Urciuoli, G. M. (2022). Deeply virtual compton scattering cross section at high Bjorken x B. *Physical review letters*, *128*(25), 252002.







DVCS at Multiple Beam Energies

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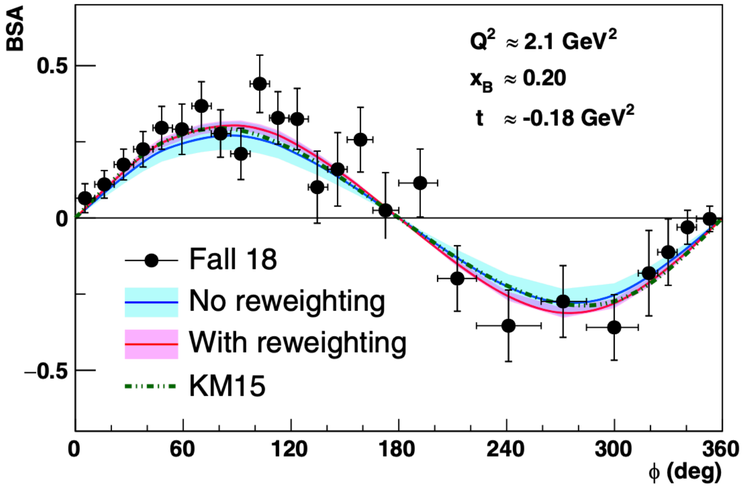
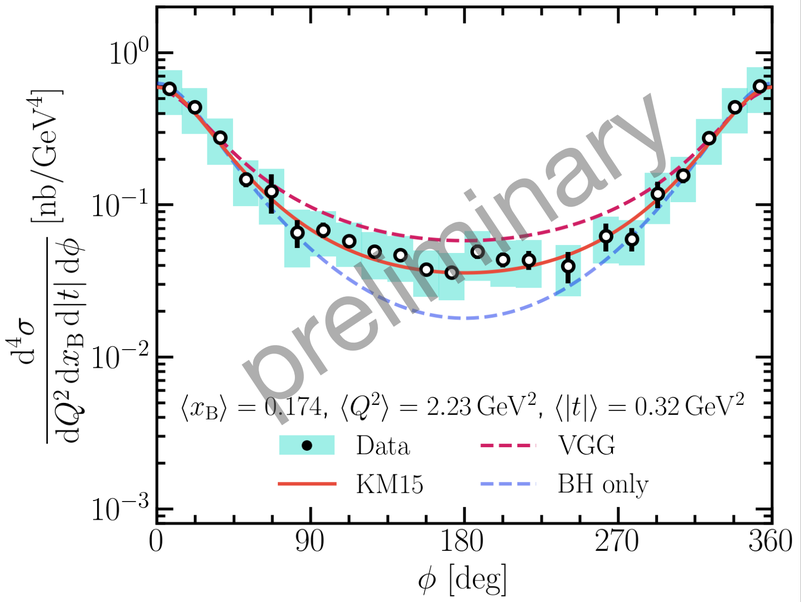
Separate DVCS and interface term!

RGA Pass1 Result

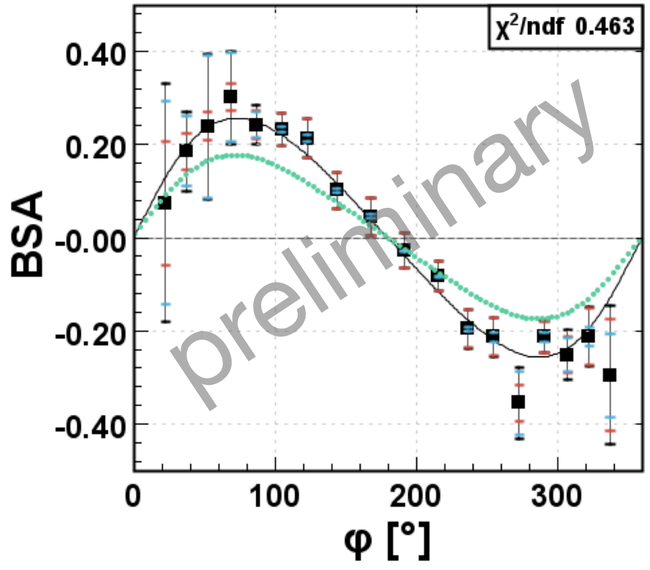


Christiaens, G., et al. "First CLAS12 measurement of deeply virtual Compton scattering beam-spin asymmetries in the extended valence region." *Physical Review Letters* 130.21 (2023): 211902.



Sangbaek Lee, et al, Submitted to collaboration review

RGK Pass2
6.5 GeV & 7.5 GeV Result

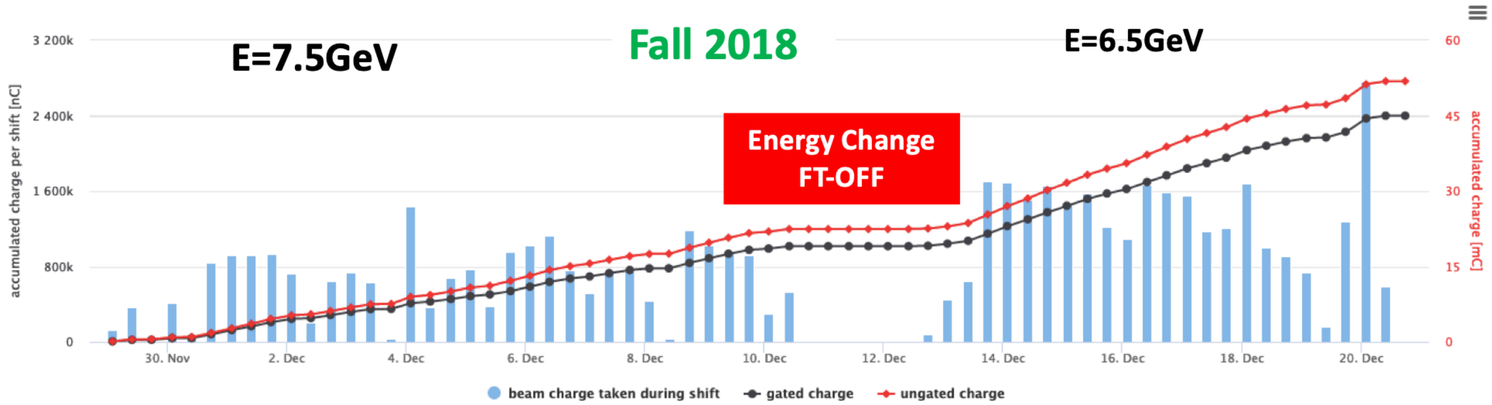


Joshua Artem Tan, et al, Submitted to collaboration review

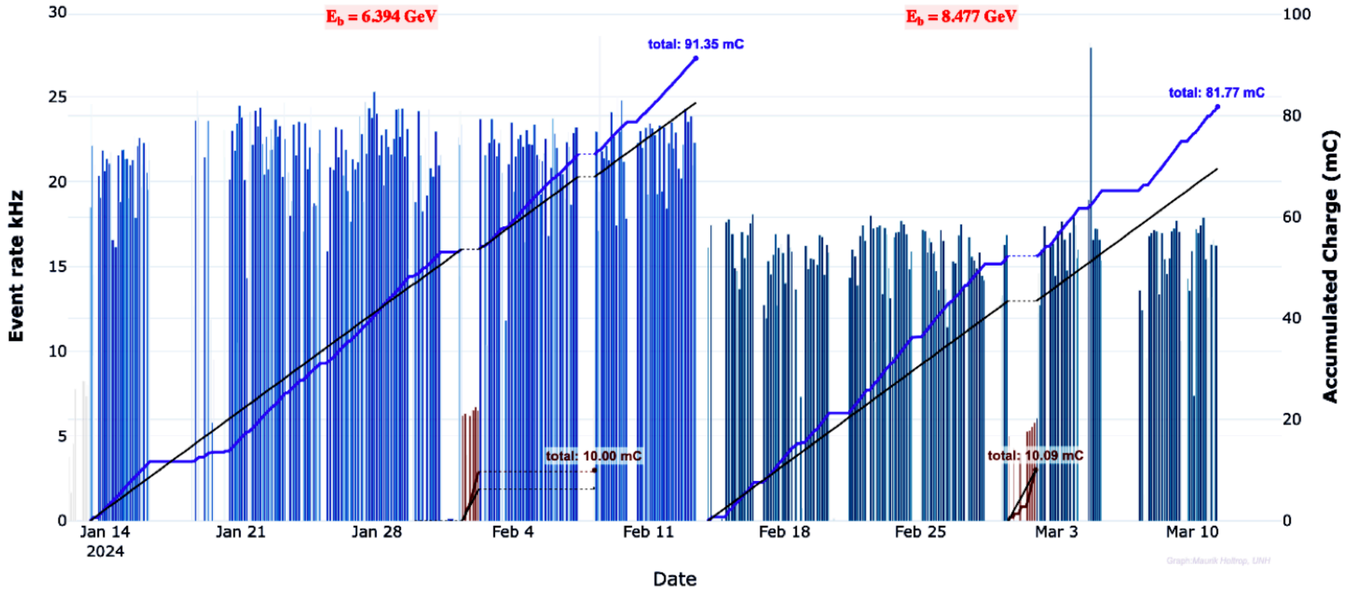
Run Group K

LH2 Target

RGK Fall2018

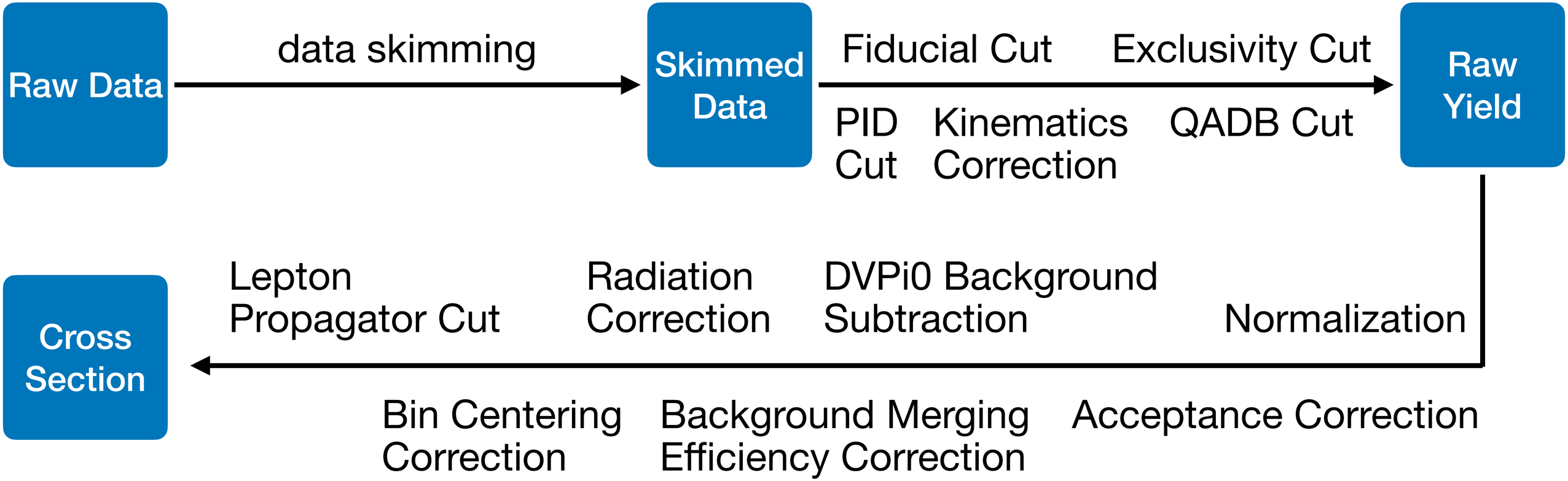


RGK Spring2024



Beam Energy/GeV	Accumulated Charge/mC
6.4	~90
6.5	~10
7.5	~10
8.5	~80

Analysis Method

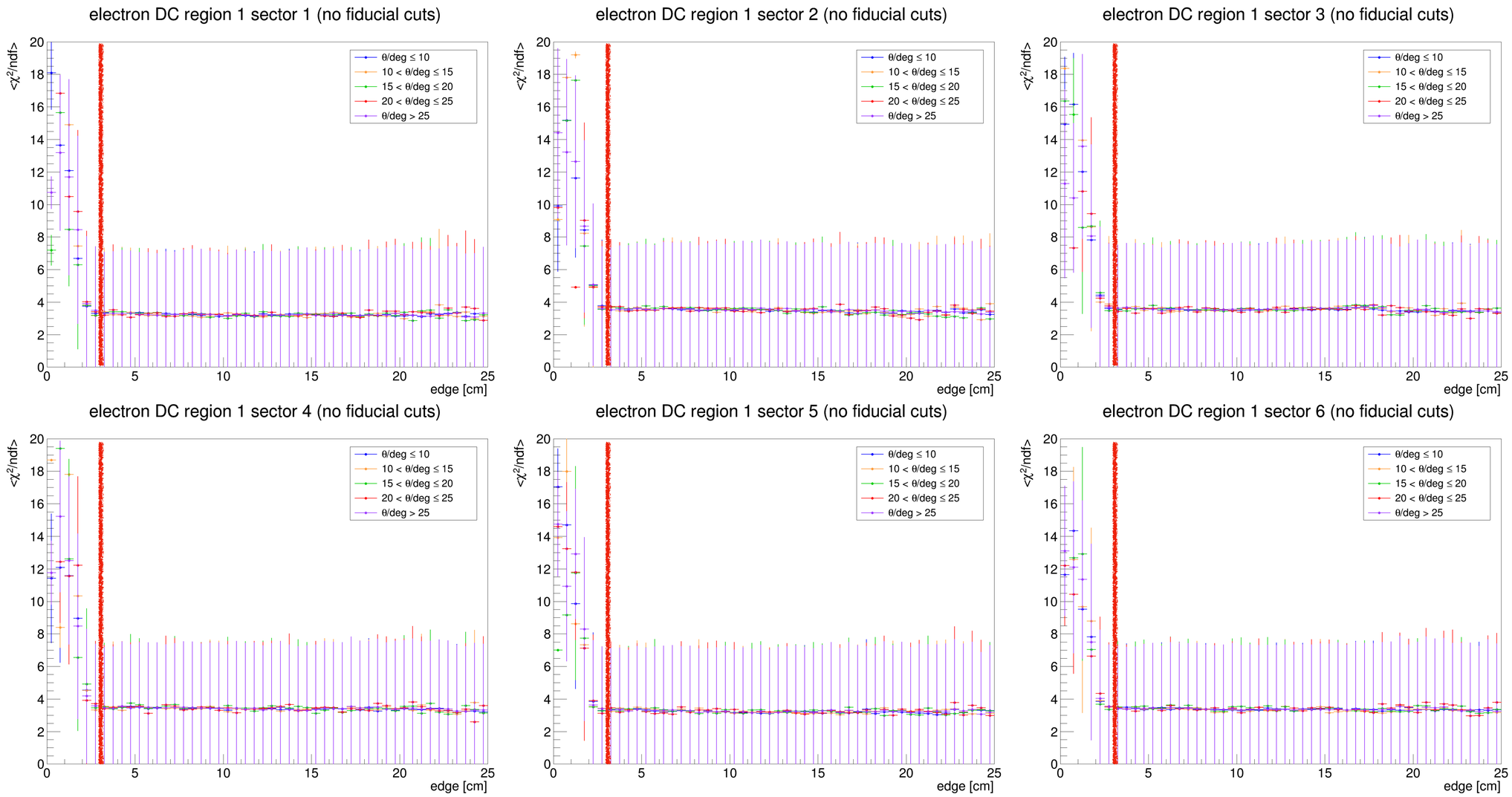


Fiducial Cut

Electron

DC, R1

$edge > 3$ cm

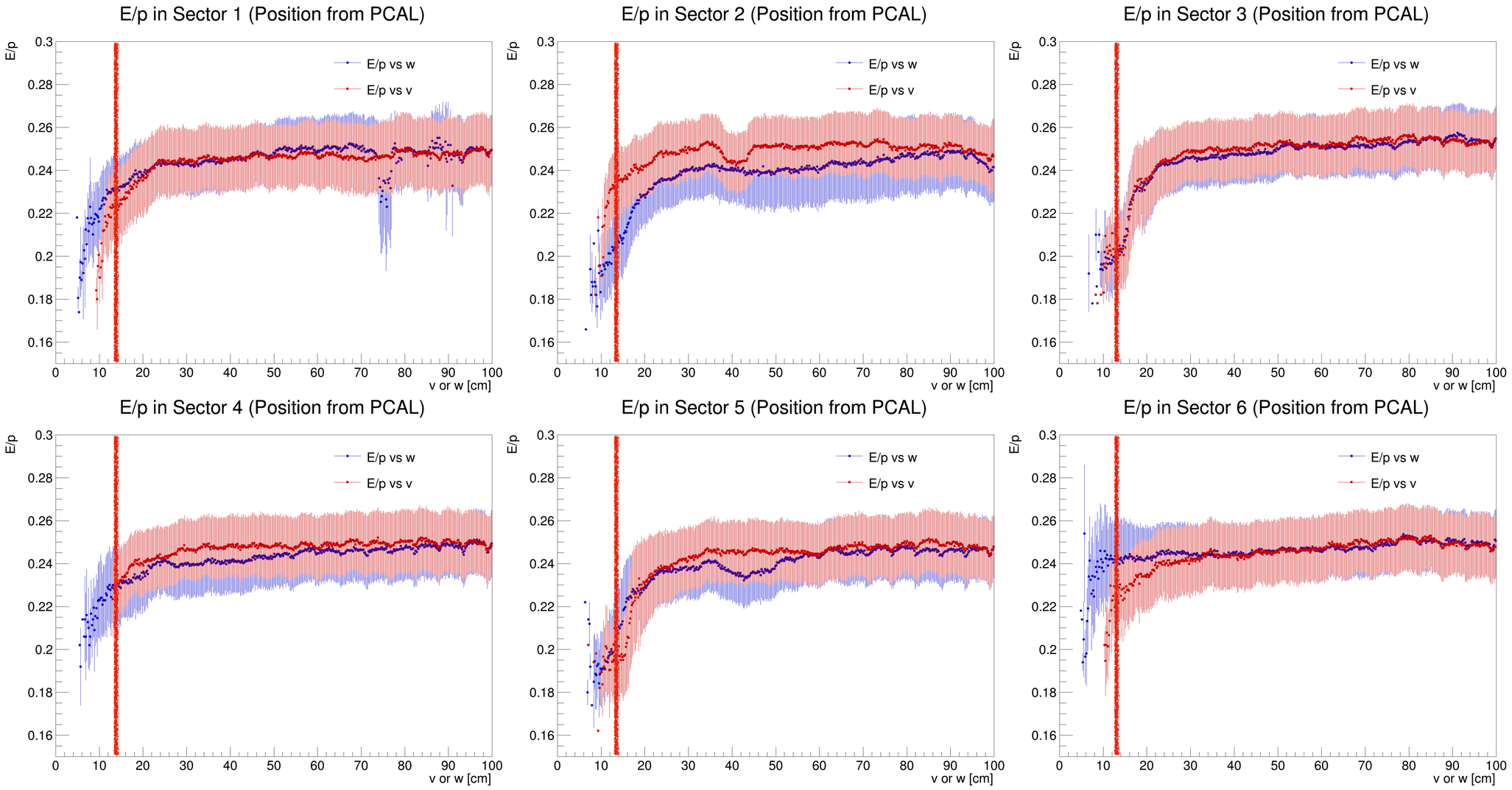


Fiducial Cut

Electron

ECAL, deposited energy

$v, w > 13.5$ cm

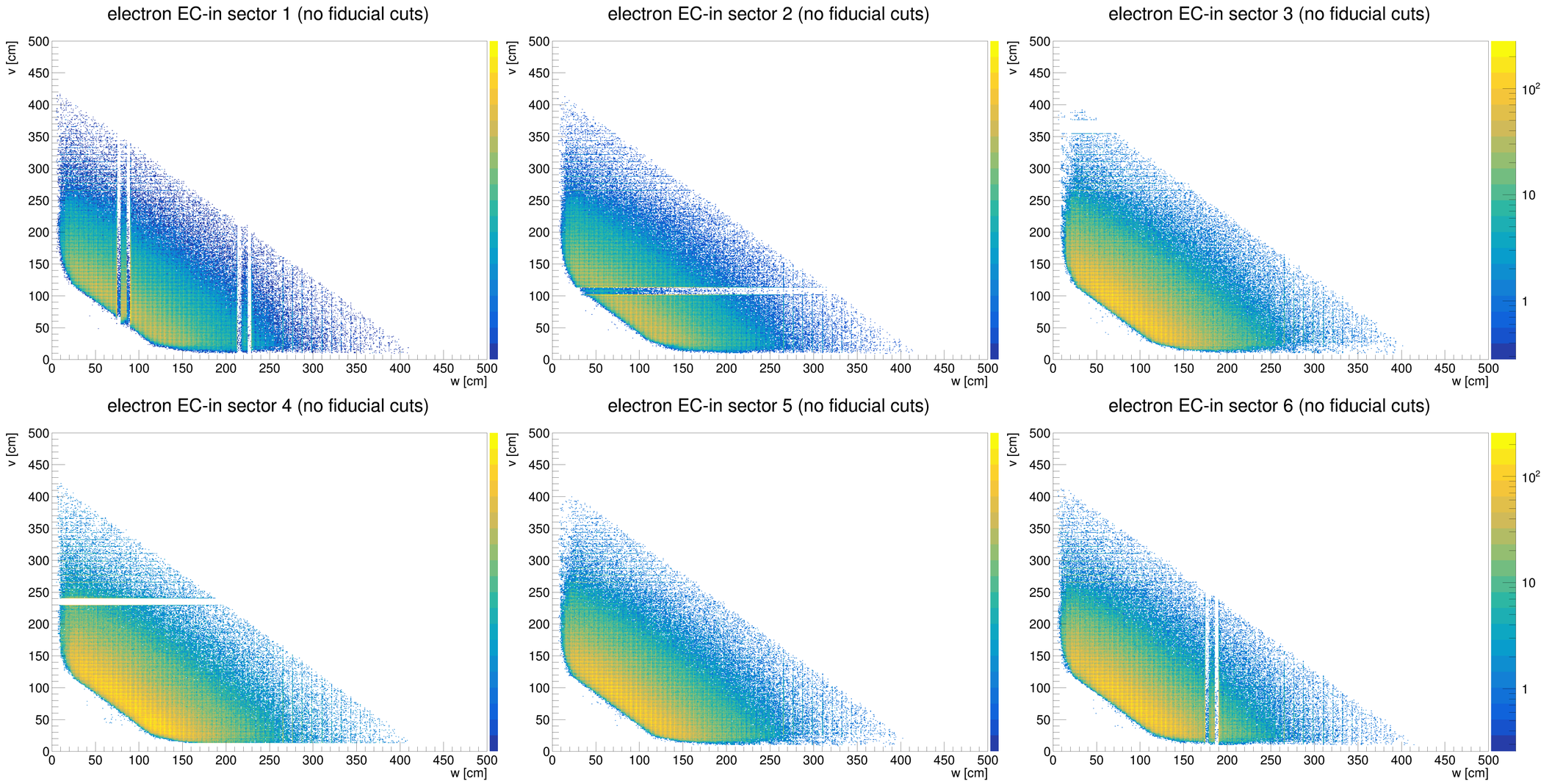


Fiducial Cut

Electron

ECAL, EC-in as Example

remove bad strips

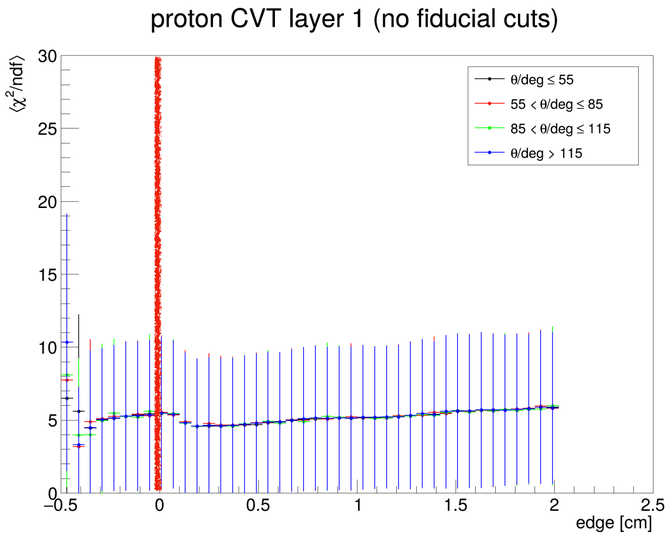


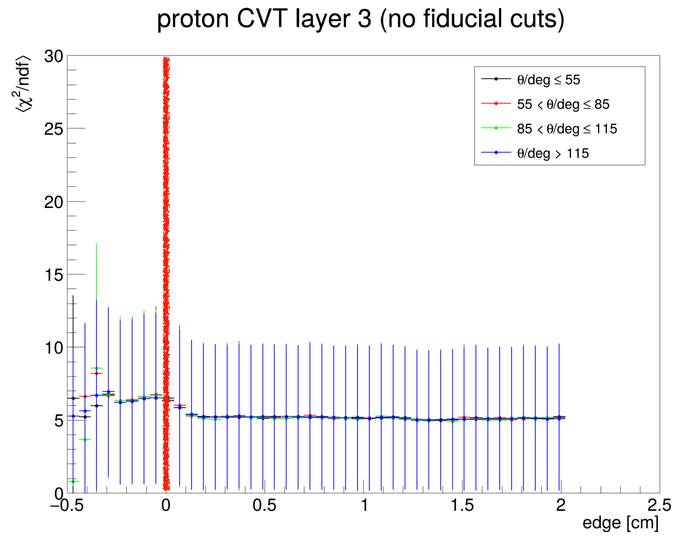
Fiducial Cut

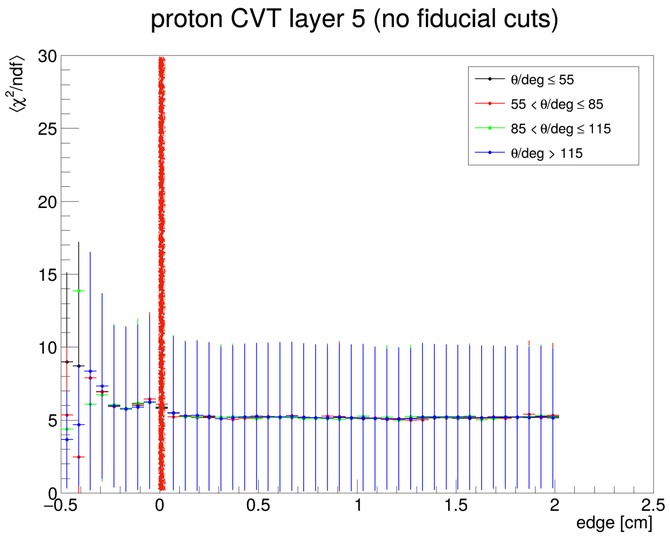
Proton

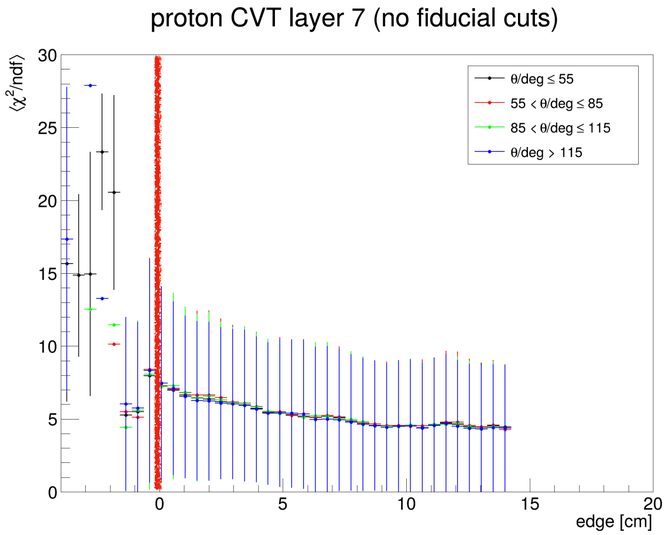
CVT

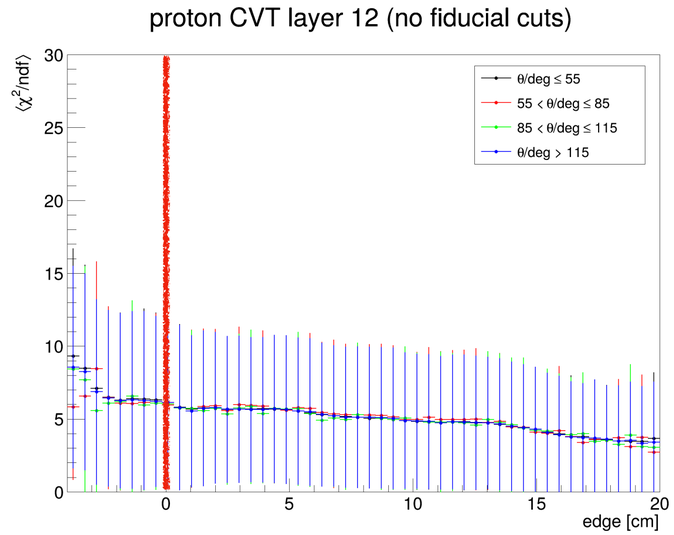
$edge > 0$ cm









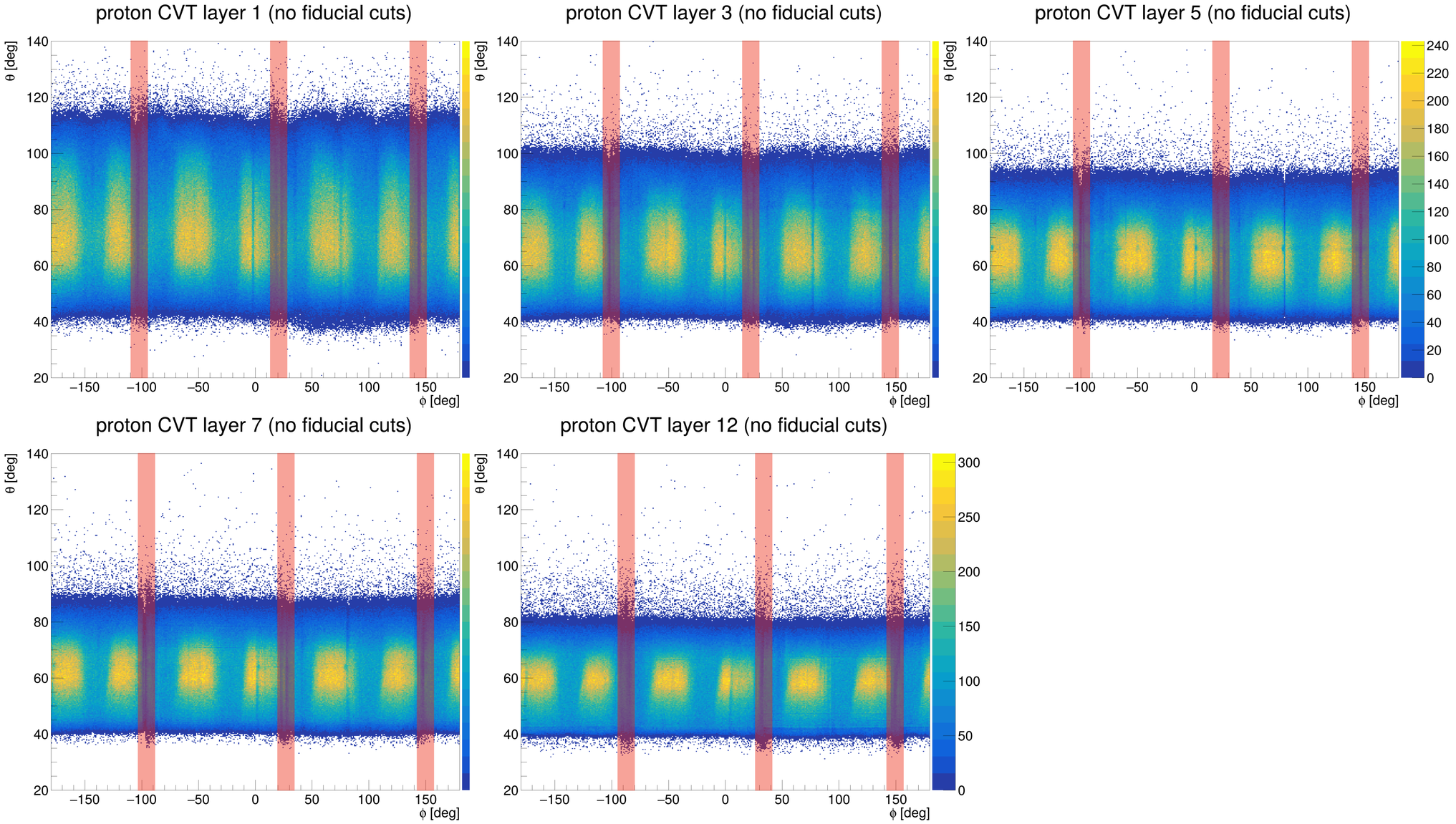


Fiducial Cut

Proton

CVT

remove support bands

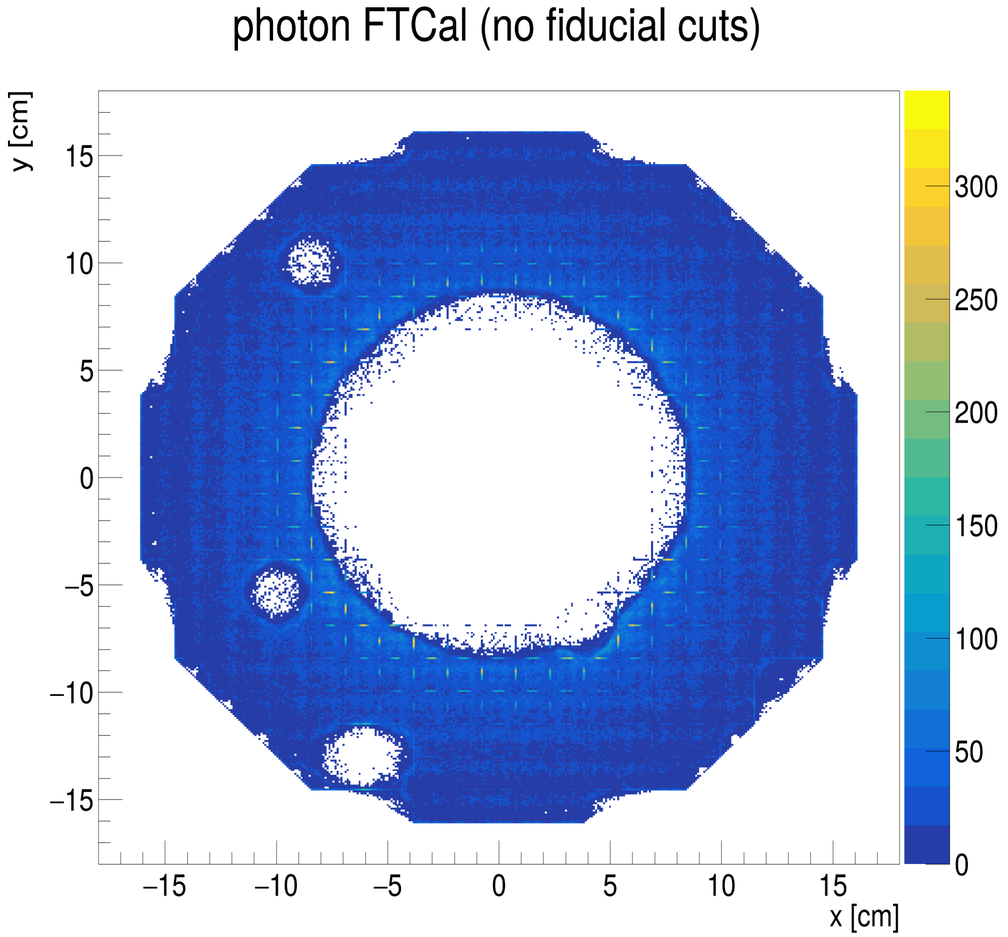


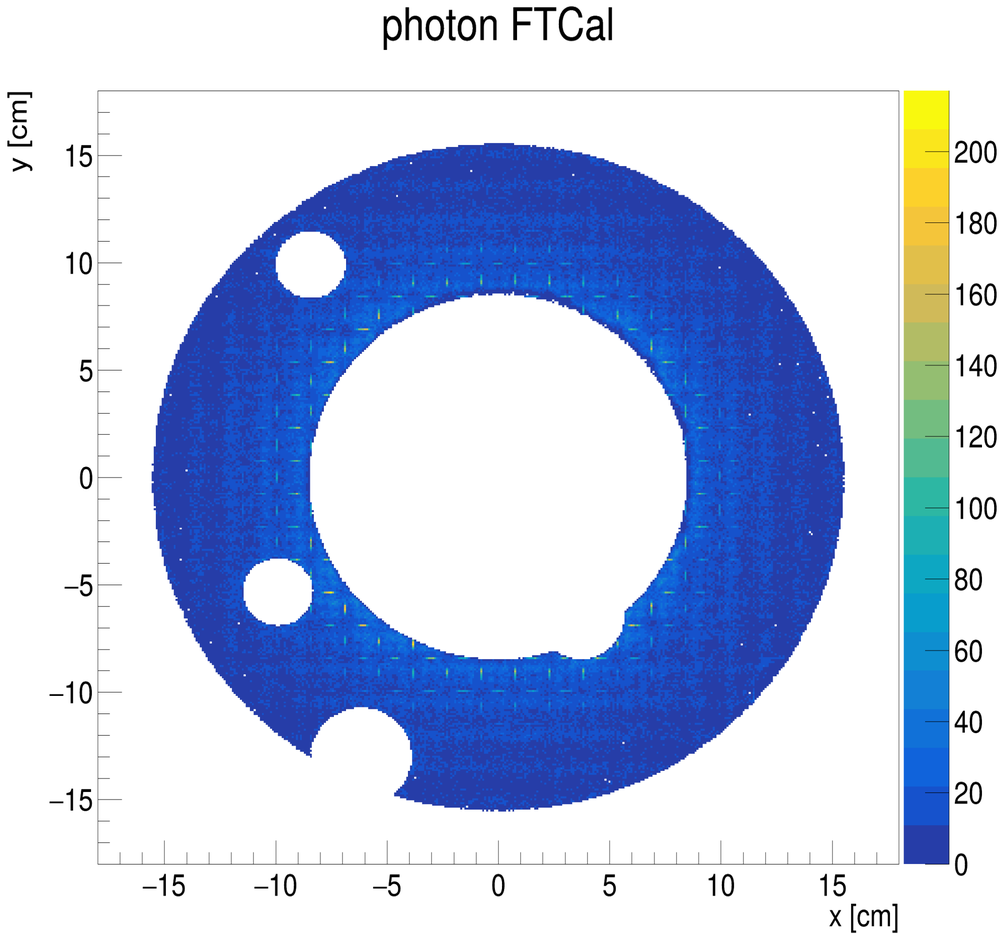
Fiducial Cut

Photon

FT

remove bad circles

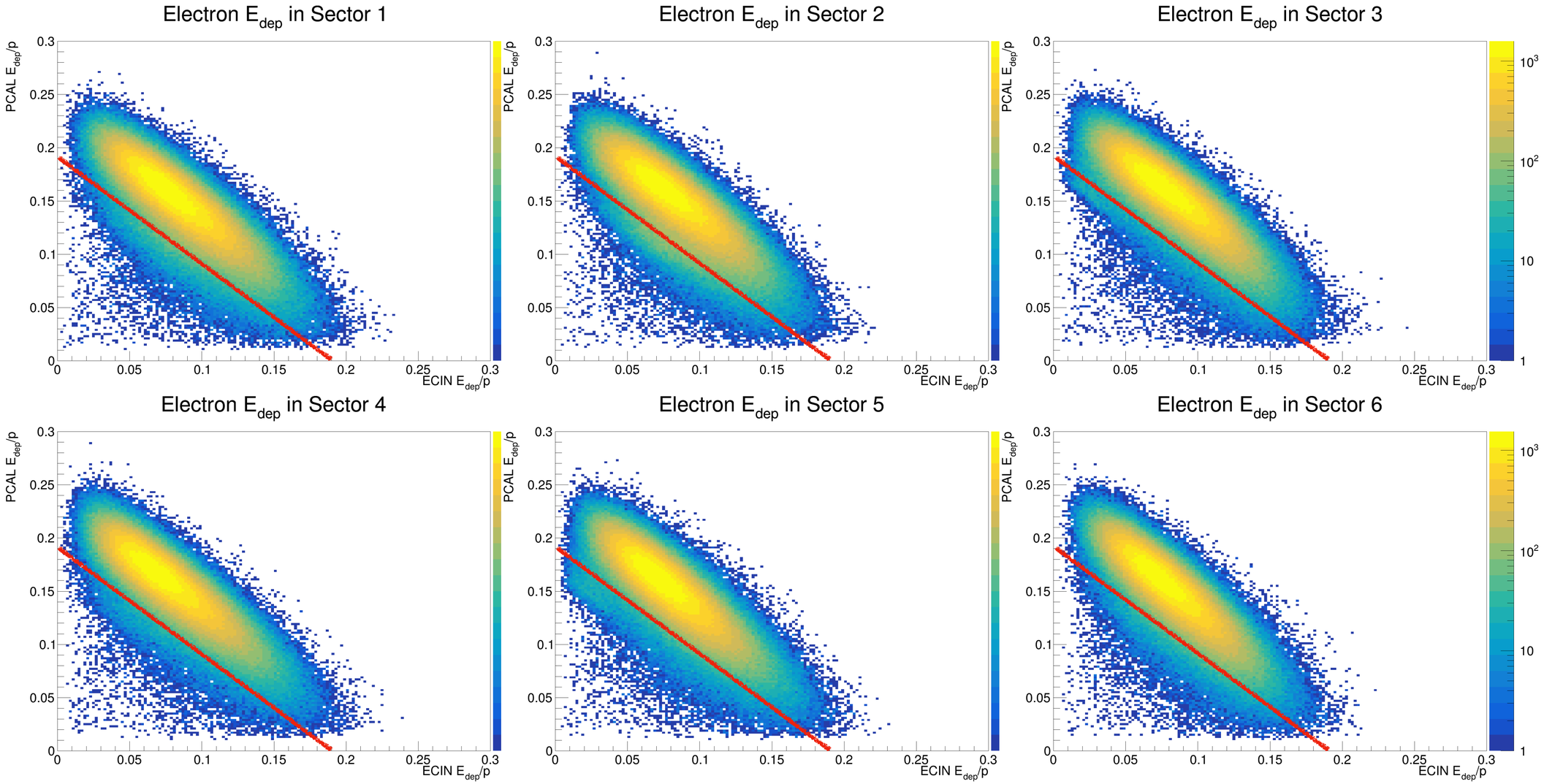




PID Cut

Electron

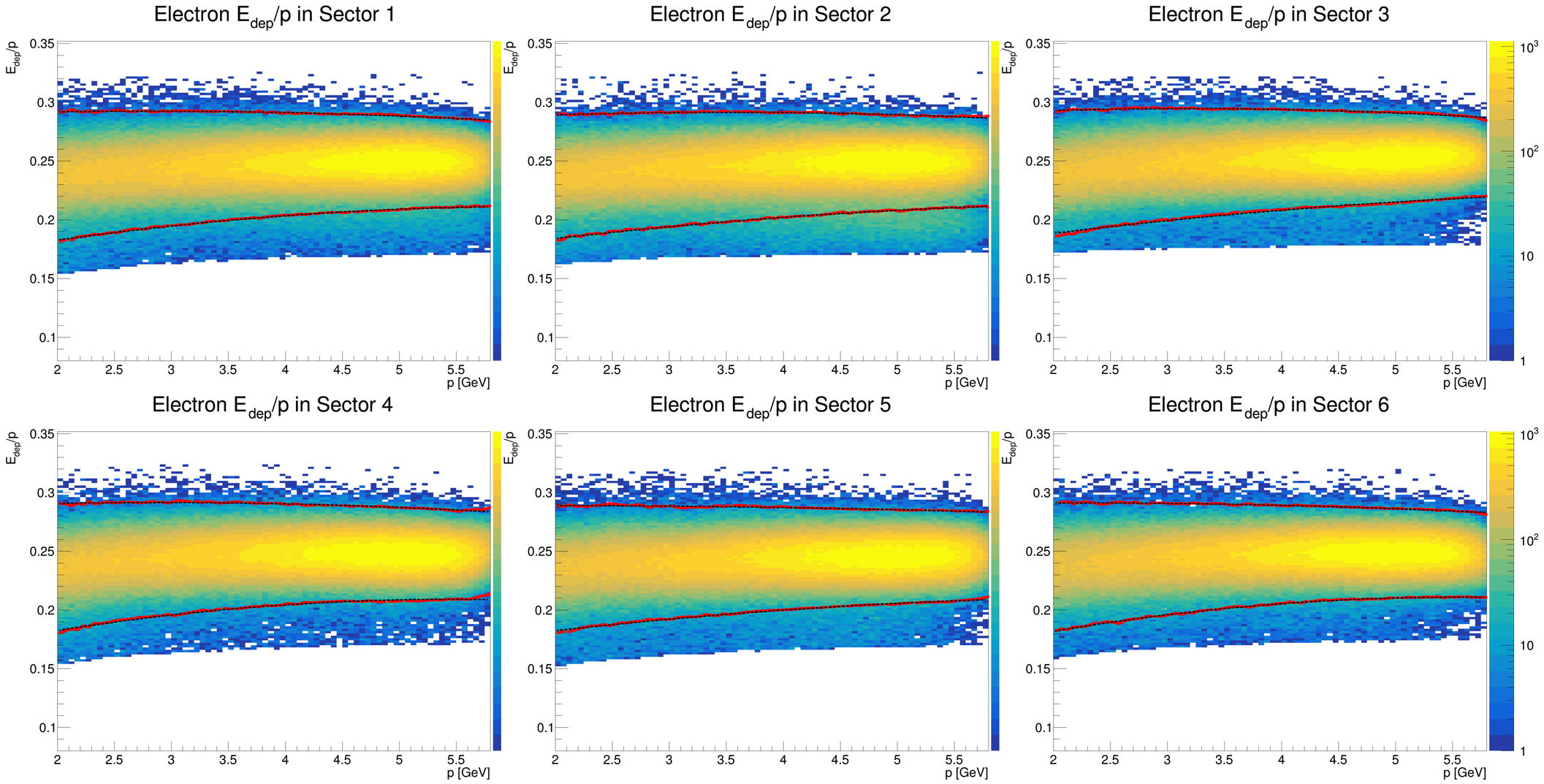
Triangle Cut



PID Cut

Electron

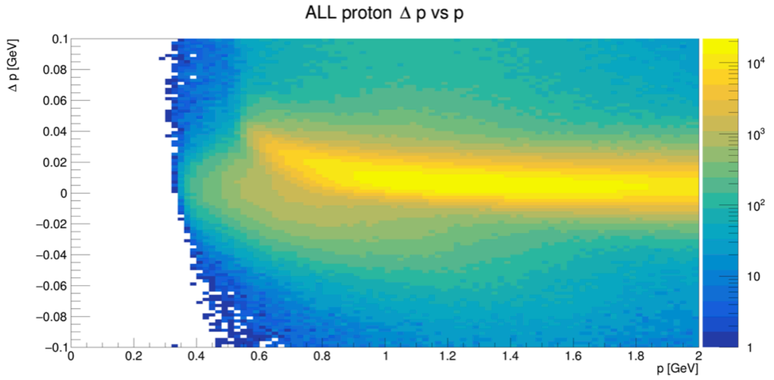
Sampling Fraction Cut



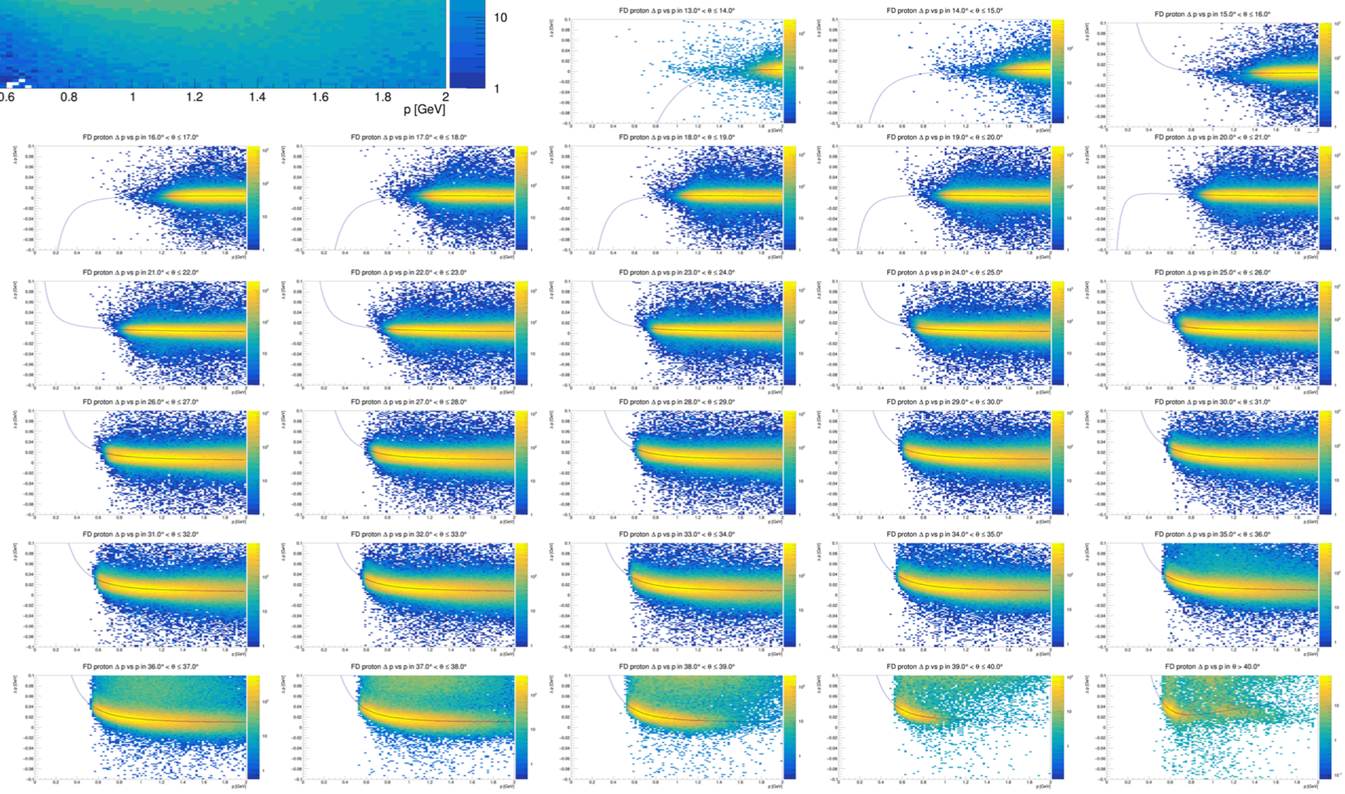
Energy Loss Correction

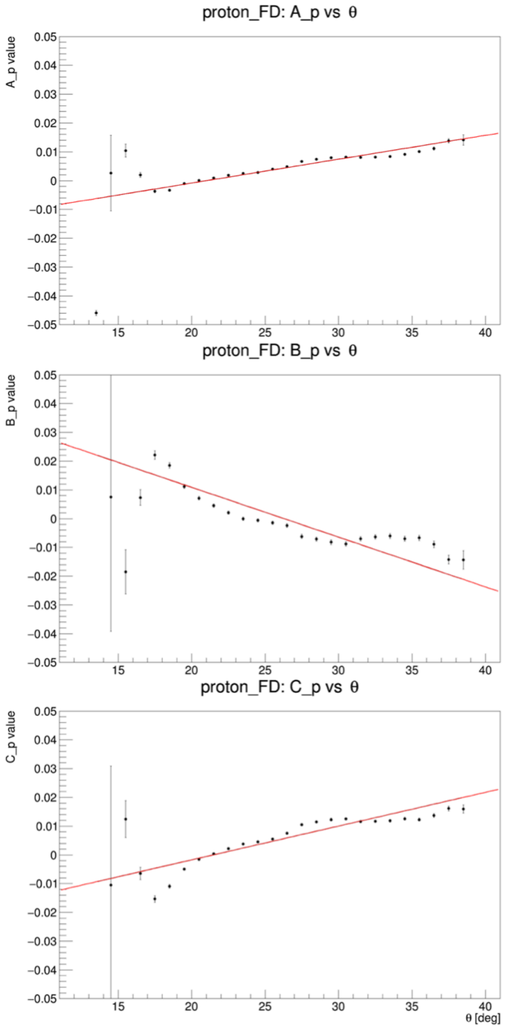
Proton

FD



$$\Delta p = A(\theta) + B(\theta)/p + C(\theta)/p^2$$

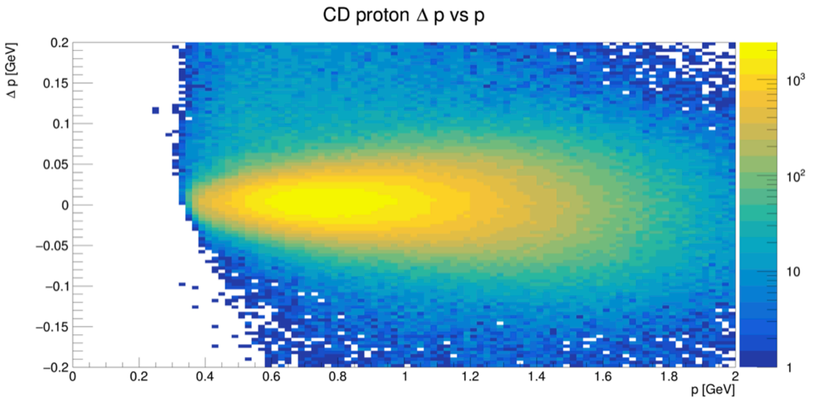




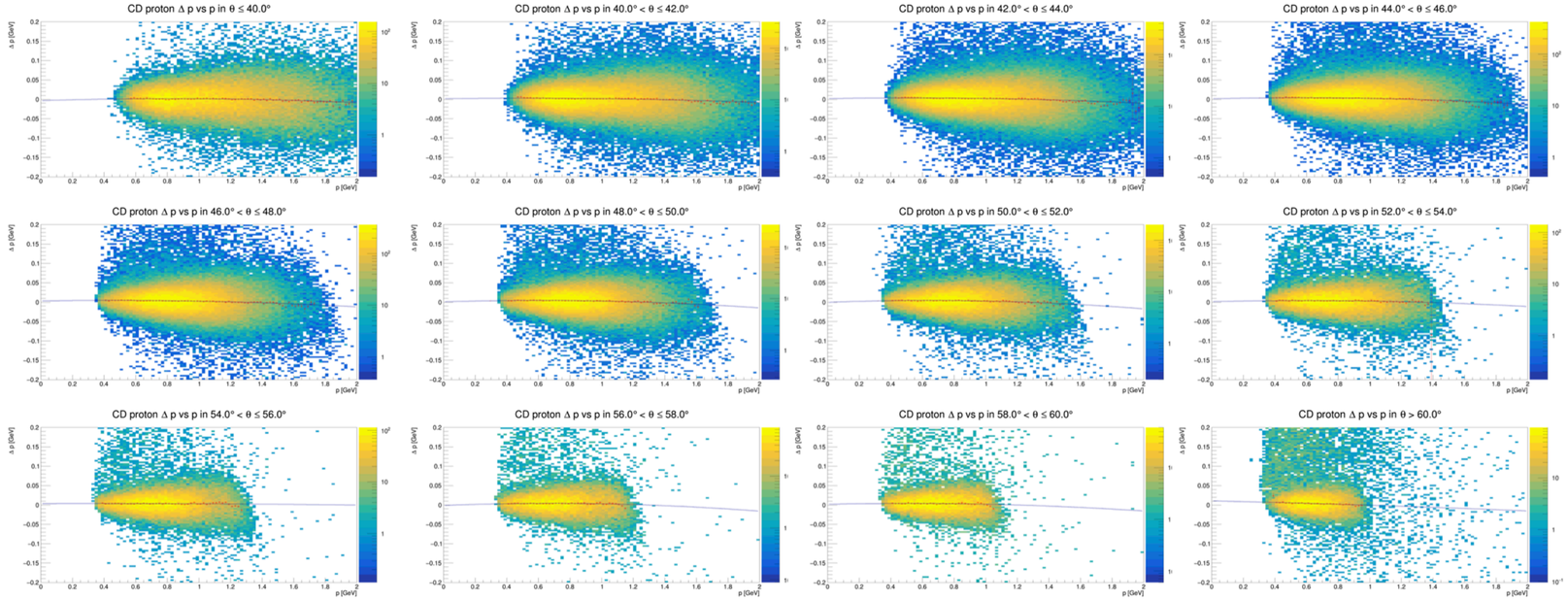
Energy Loss Correction

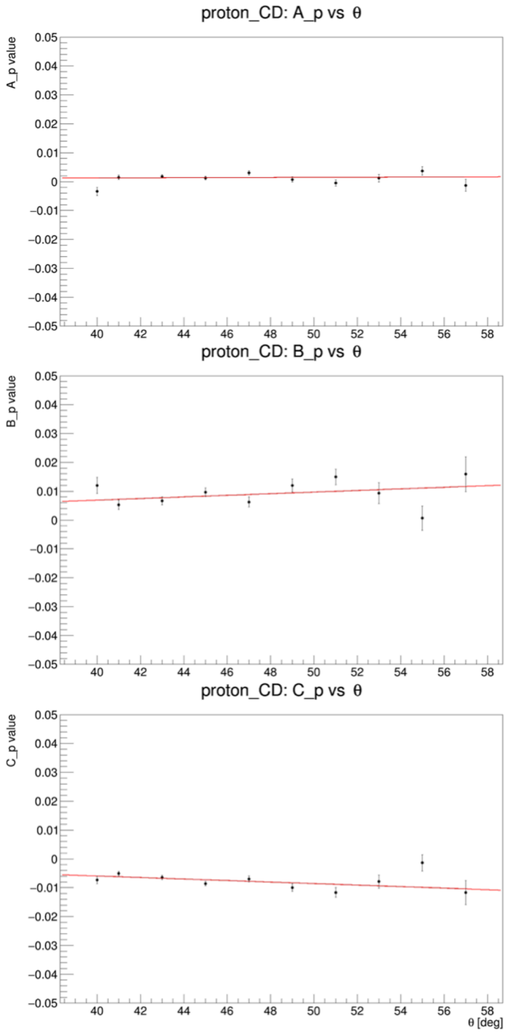
Proton

CD



$$\Delta p = A(\theta) + B(\theta) \cdot p + C(\theta) \cdot p^2$$

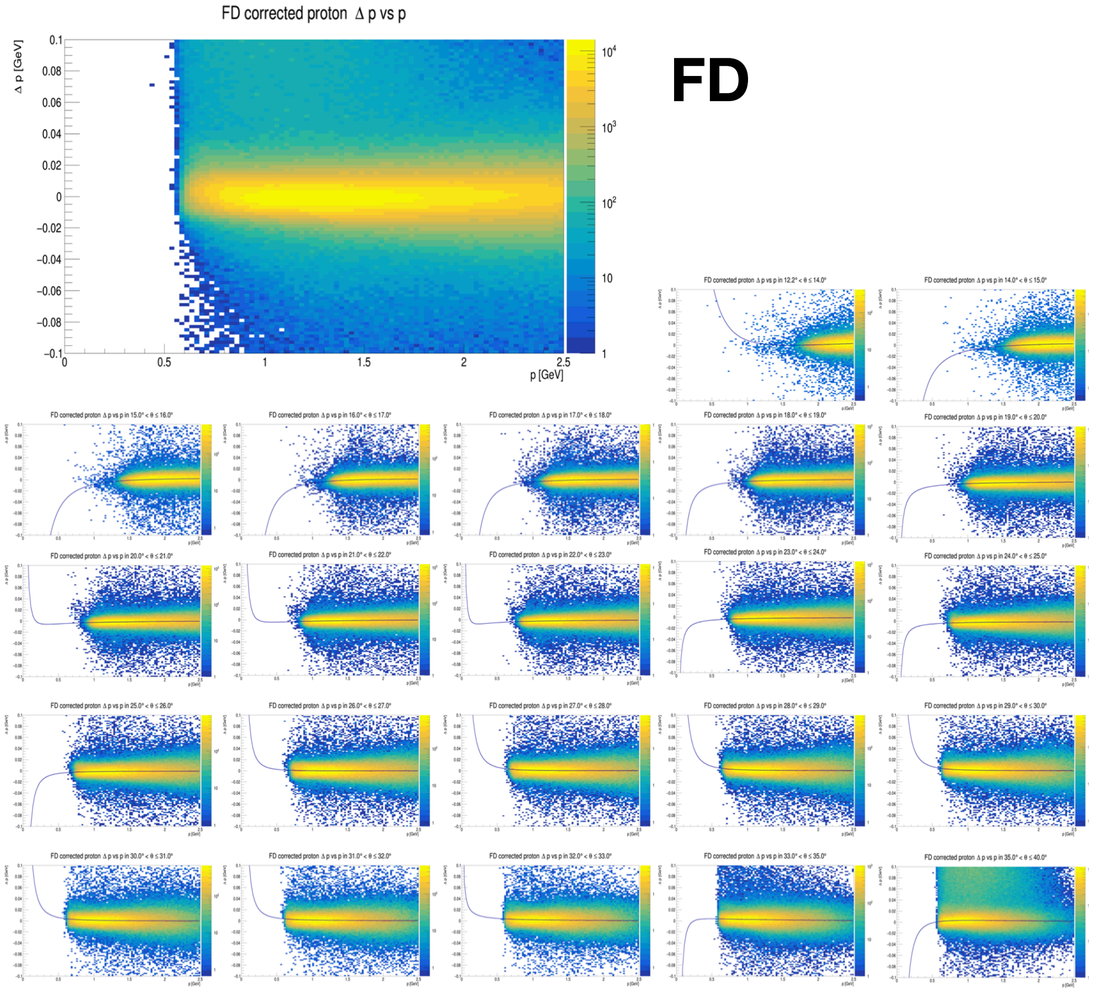




Energy Loss Correction

Proton After Correction

FD



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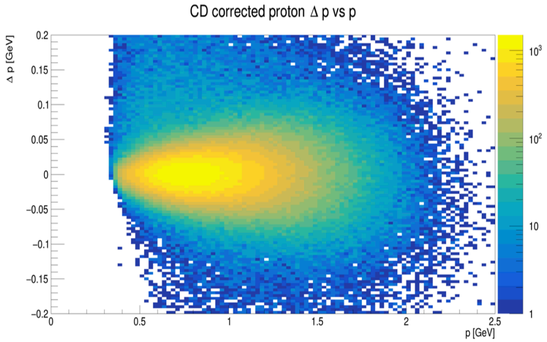
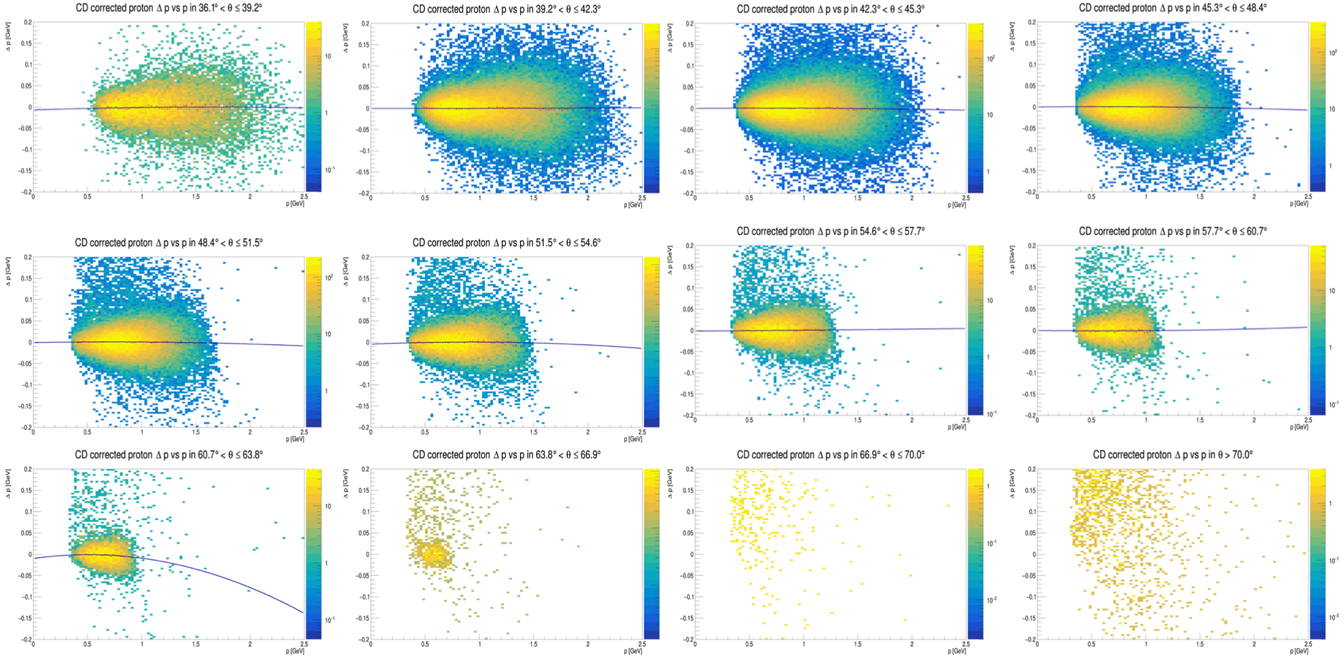


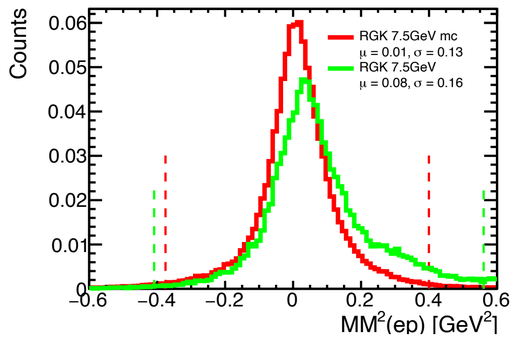


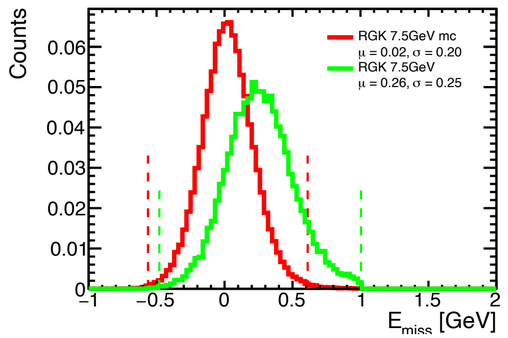
Exclusivity Cut

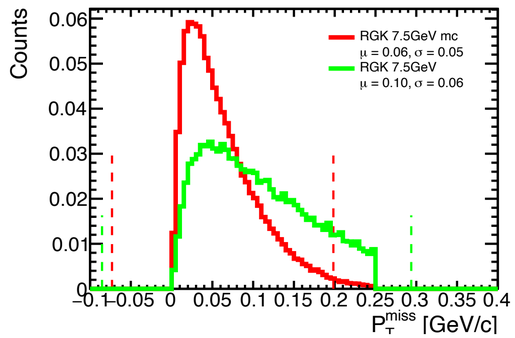
Exclusivity Cut

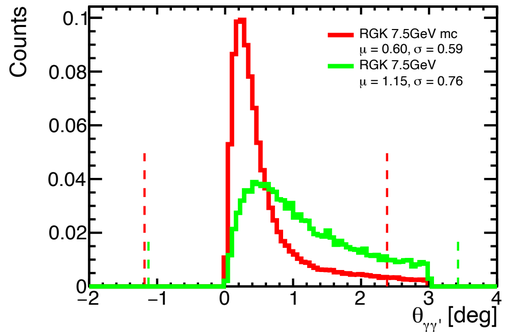
(FD,FD) as an Example

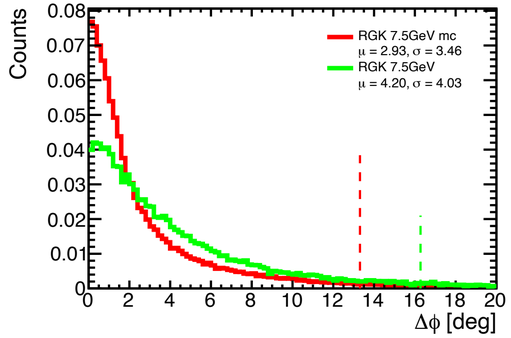
Variable	Definition
MM^2_{ep}	Missing mass squared of the ep system
$\mathrm{MM}^2_{ep\gamma}$	Missing mass squared of the $ep\gamma$ system
$\mathrm{MM}^2_{e\gamma}$	Missing mass squared of the $e\gamma$ system
E_{miss}	Missing energy of the $ep\gamma$ system
P_T^{miss}	Missing transverse momentum of the $ep\gamma$ system
$\theta_{\gamma\gamma'}$	Angle between the measured photon and the photon reconstructed from the ep kinematics
$\theta_{e\gamma}$	Opening angle between the scattered electron and photon
ΔE	Energy imbalance of the $ep\gamma$ system
$\Delta\phi$	Coplanarity angle between the photon plane and the recoil-proton plane

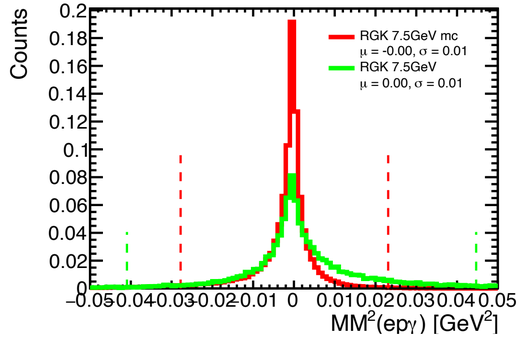


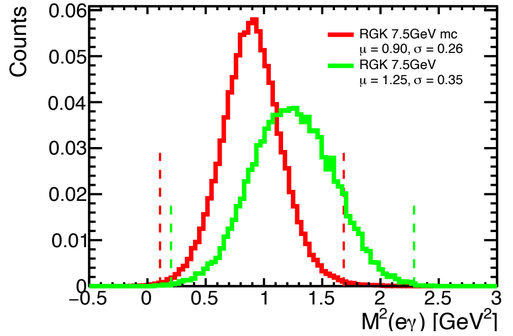


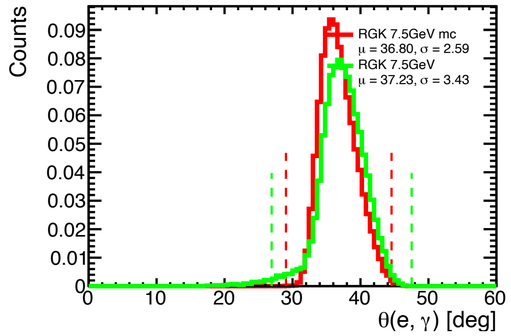












Exclusivity Cut

First Selection Cut

(FD,FD) as an Example

$$Q^2 > 1\ \text{GeV}^2$$

$$-t < 1\ \text{GeV}^2$$

$$W > 2\ \text{GeV}$$

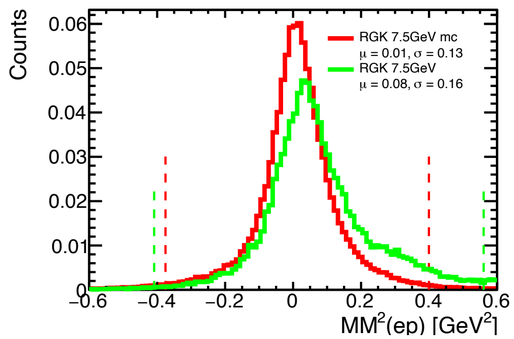
$$|MM^2(ep)| < 1.5\ \text{GeV}^2$$

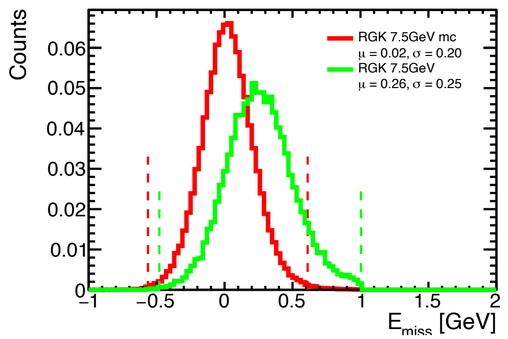
$$E_{miss} < 1\ \text{GeV}$$

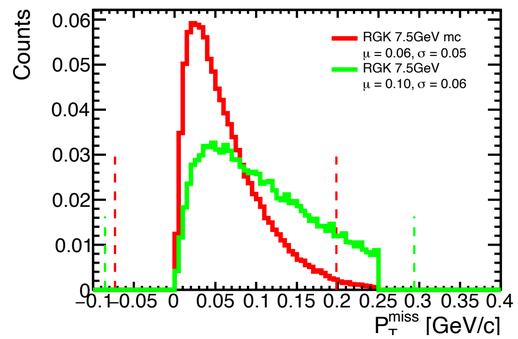
$$P^T_{miss} < 0.25\ \text{GeV}$$

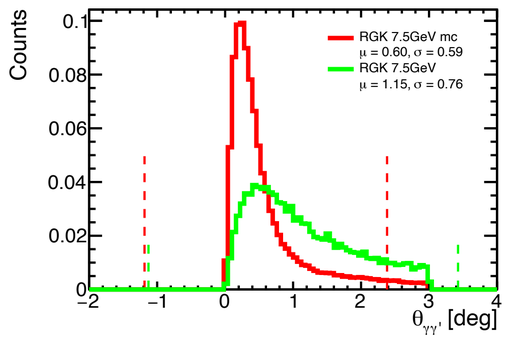
$$\theta(e,\gamma) > 5^\circ$$

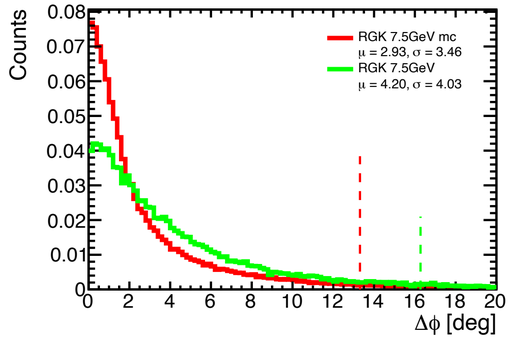
$$\theta(\gamma,\gamma') < 3^\circ$$

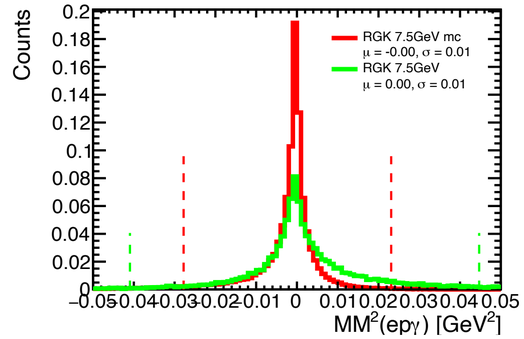


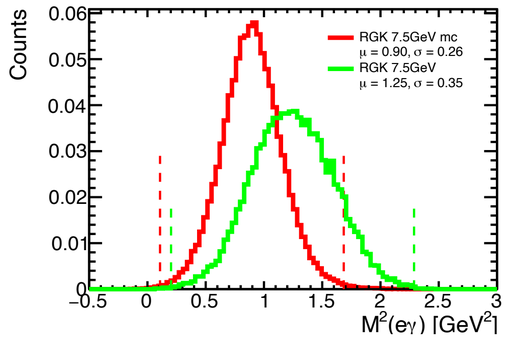


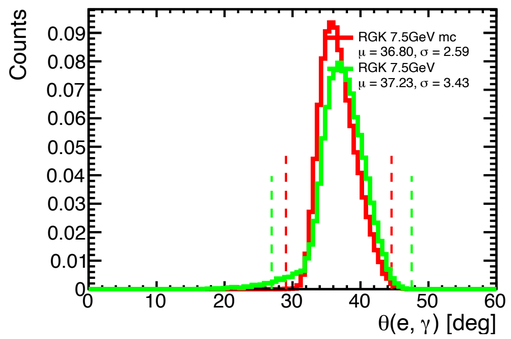








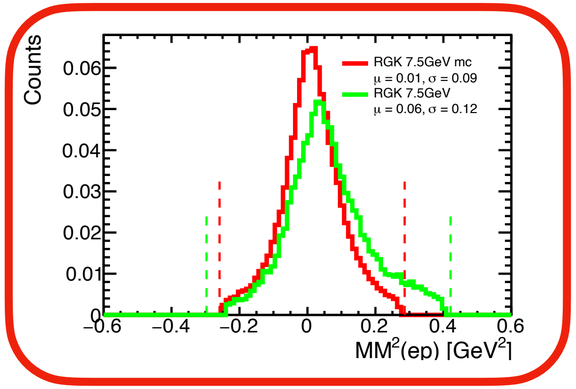


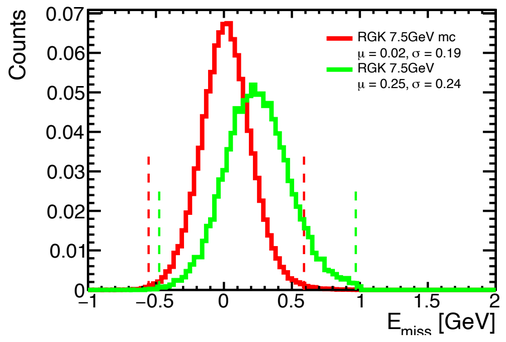


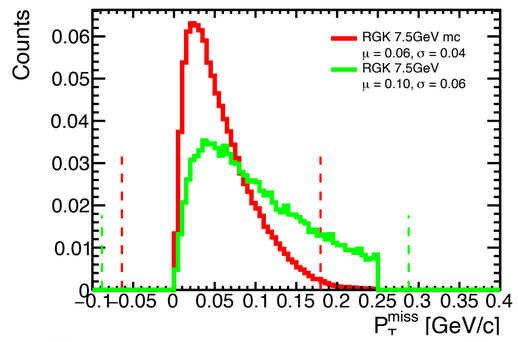
Exclusivity Cut

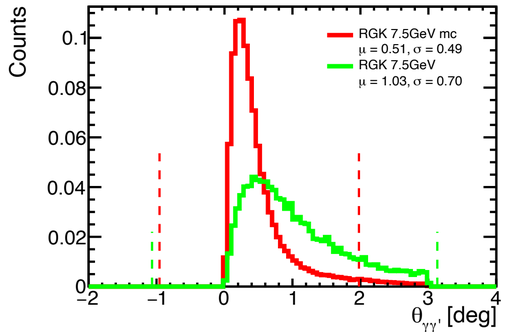
Exclusivity Cut 1

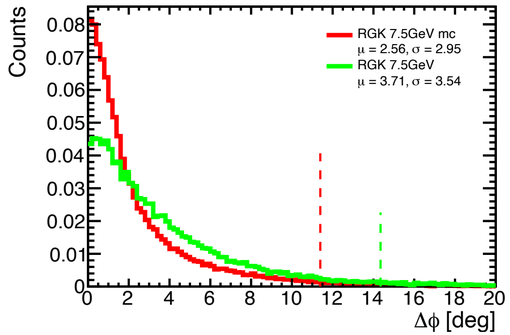
$MM^2(ep)$ *cut*
$MM^2(ep\gamma)$ *cut*

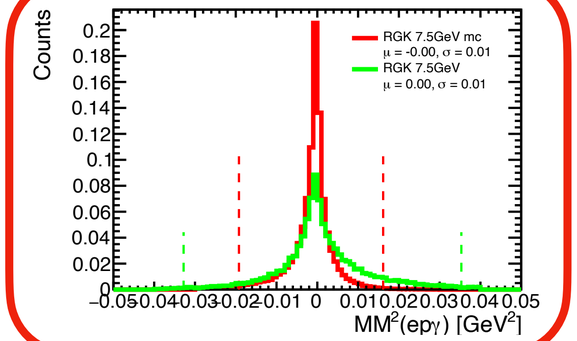


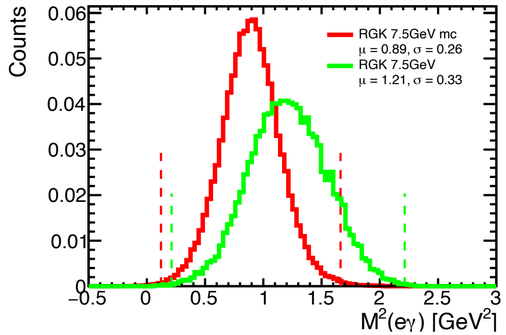


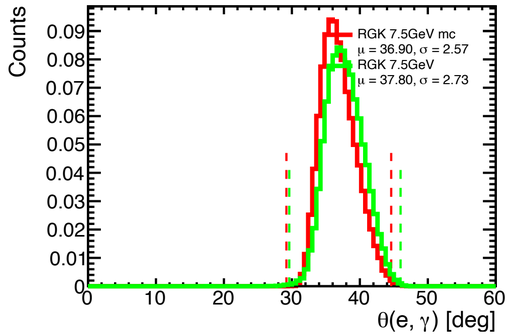










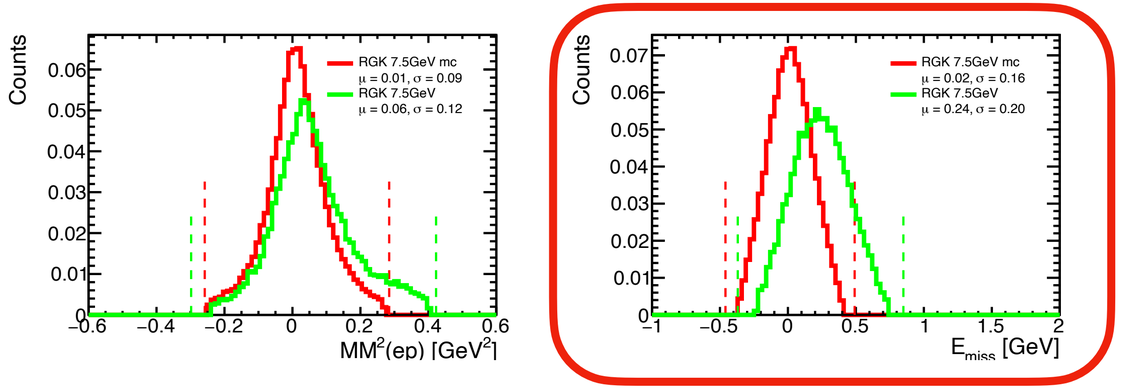


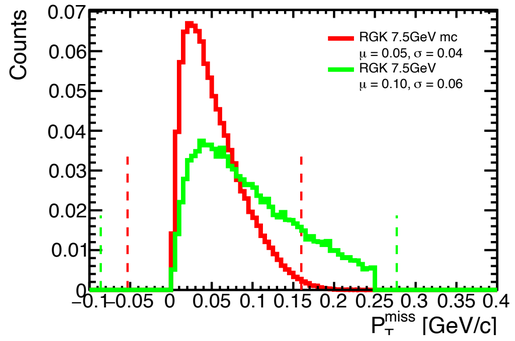
Exclusivity Cut

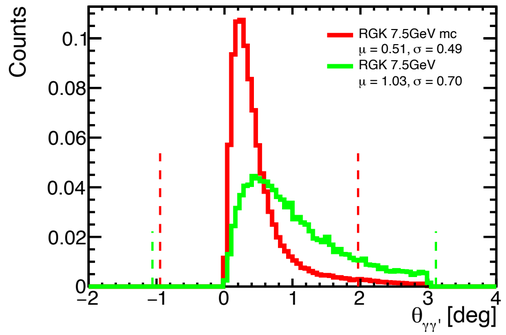
Exclusivity Cut 2

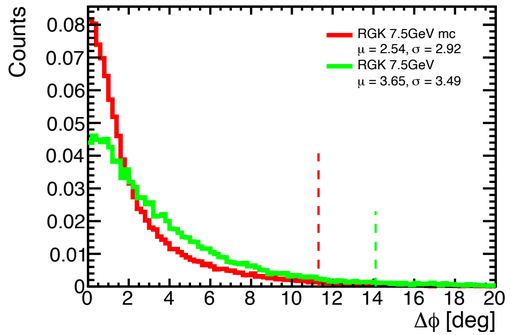
$MM^2(e\gamma)$ *cut*

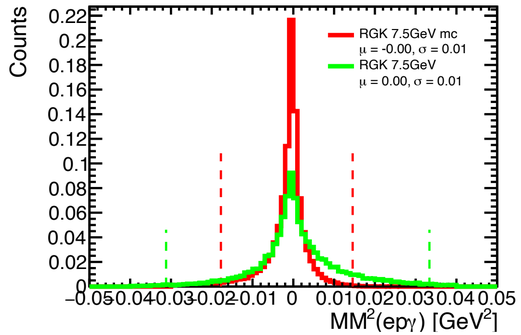
E_{miss} *cut*

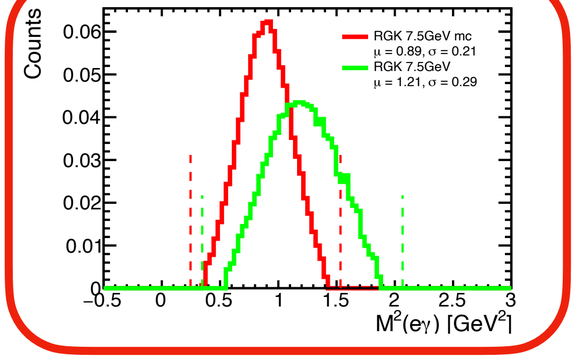


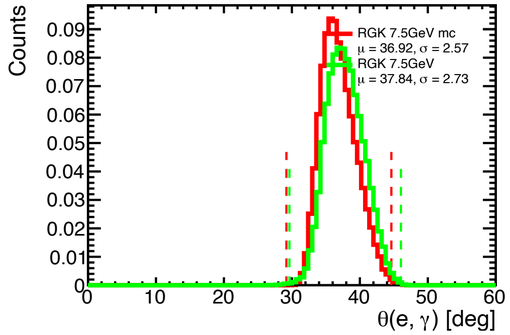












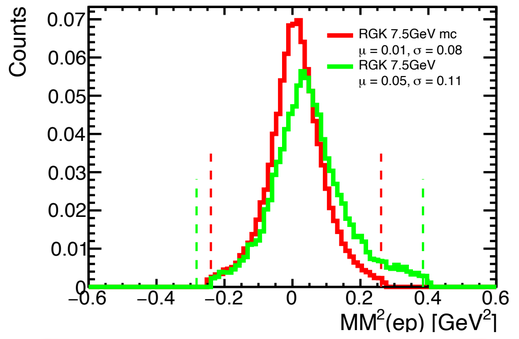
Exclusivity Cut

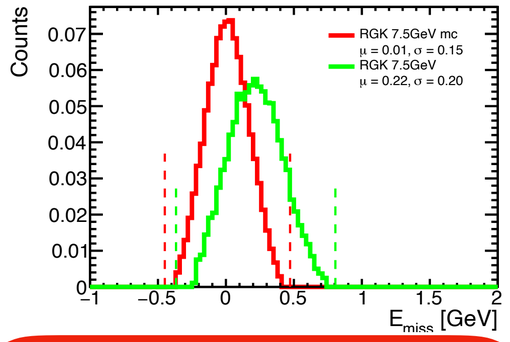
Exclusivity Cut 3

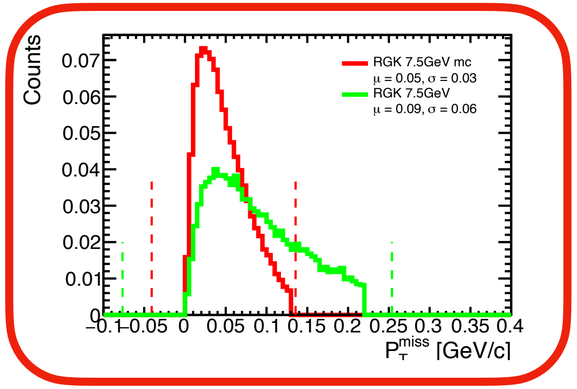
P^{T}_{miss} *cut*

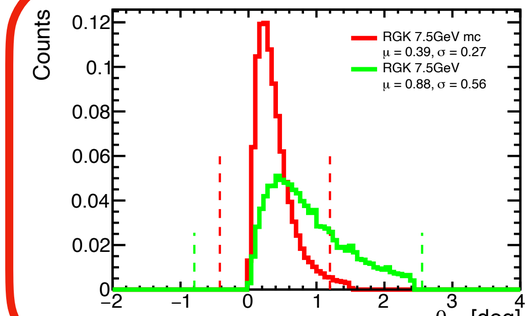
$\theta(\gamma, \gamma')$ *cut*

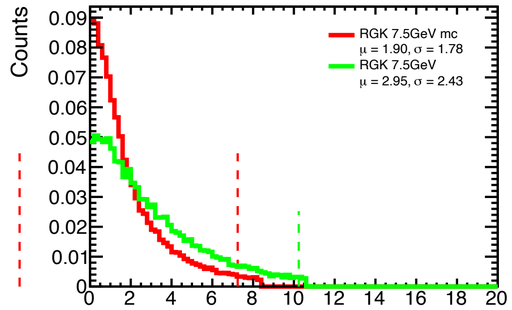
$\Delta\phi$ *cut*

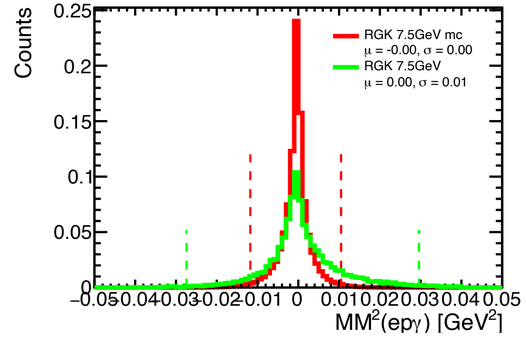


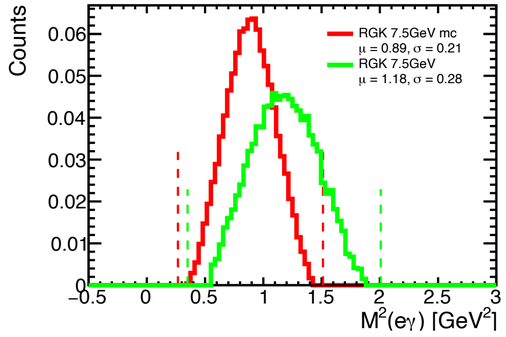


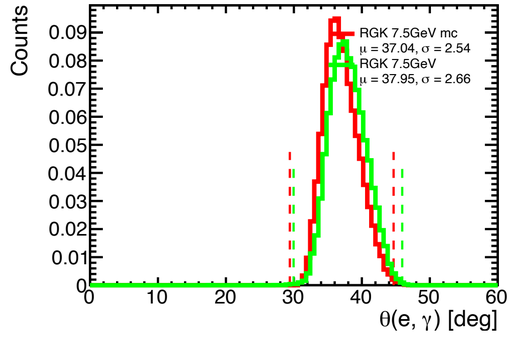






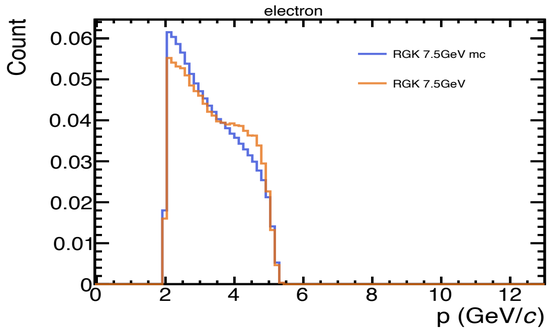


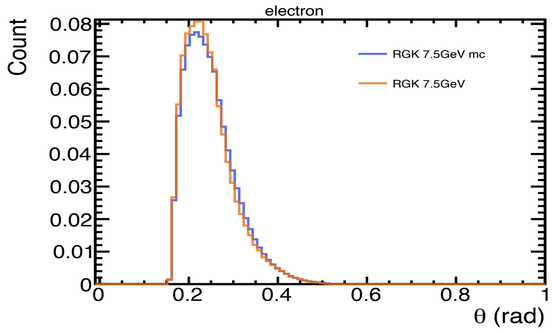


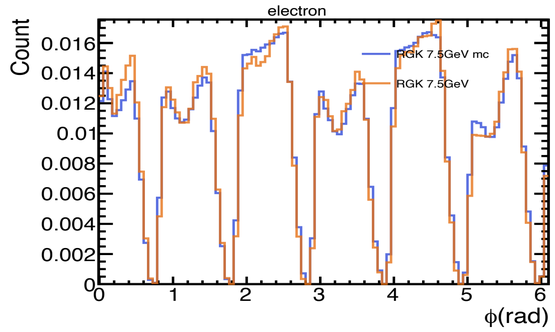


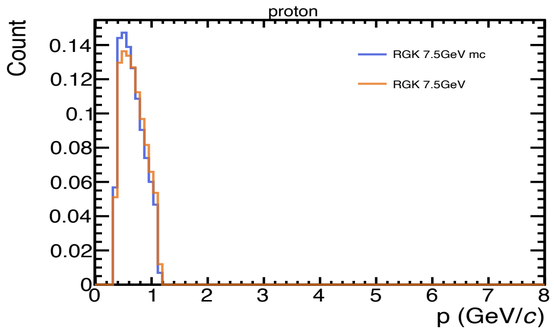
Exclusivity Cut

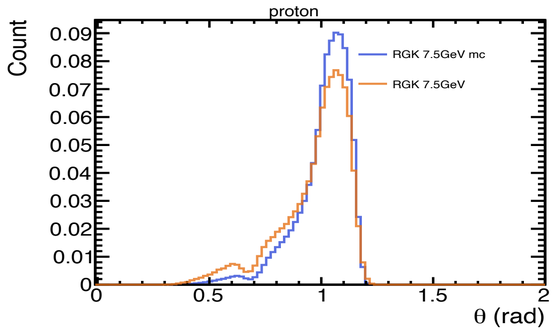
After Exclusivity Cut

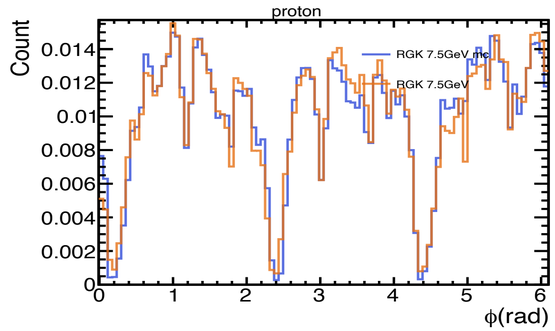


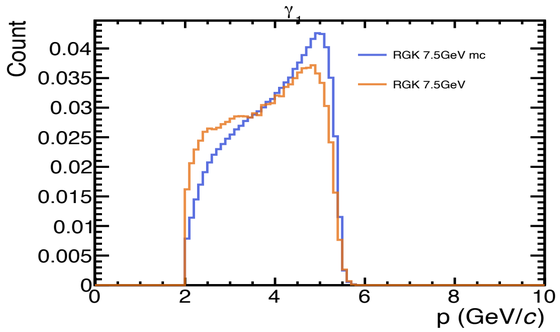


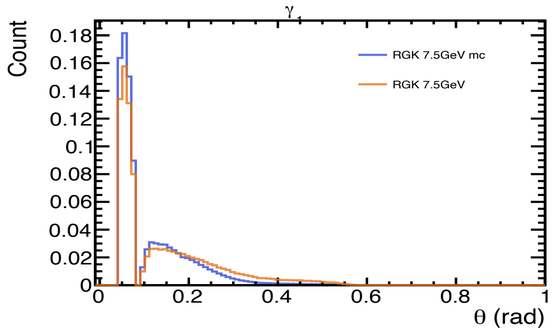


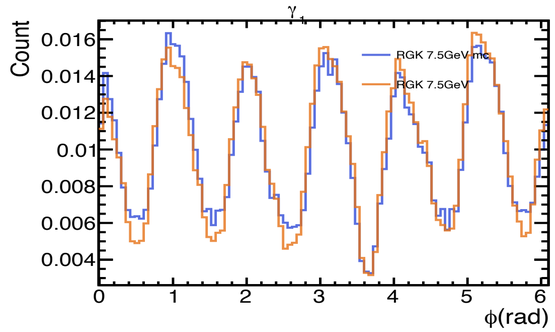








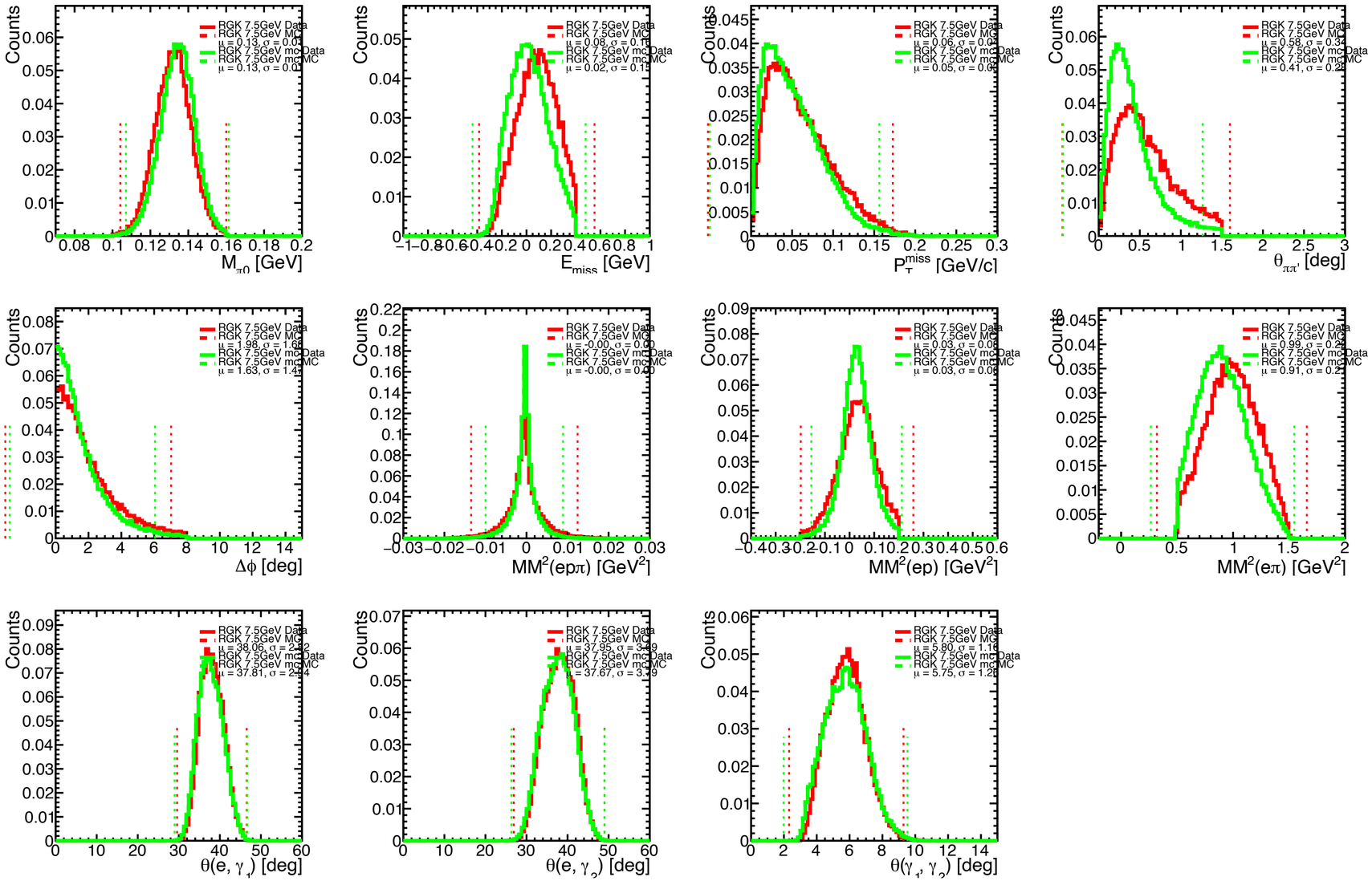




DVπ^0P Background Exclusivity Cut

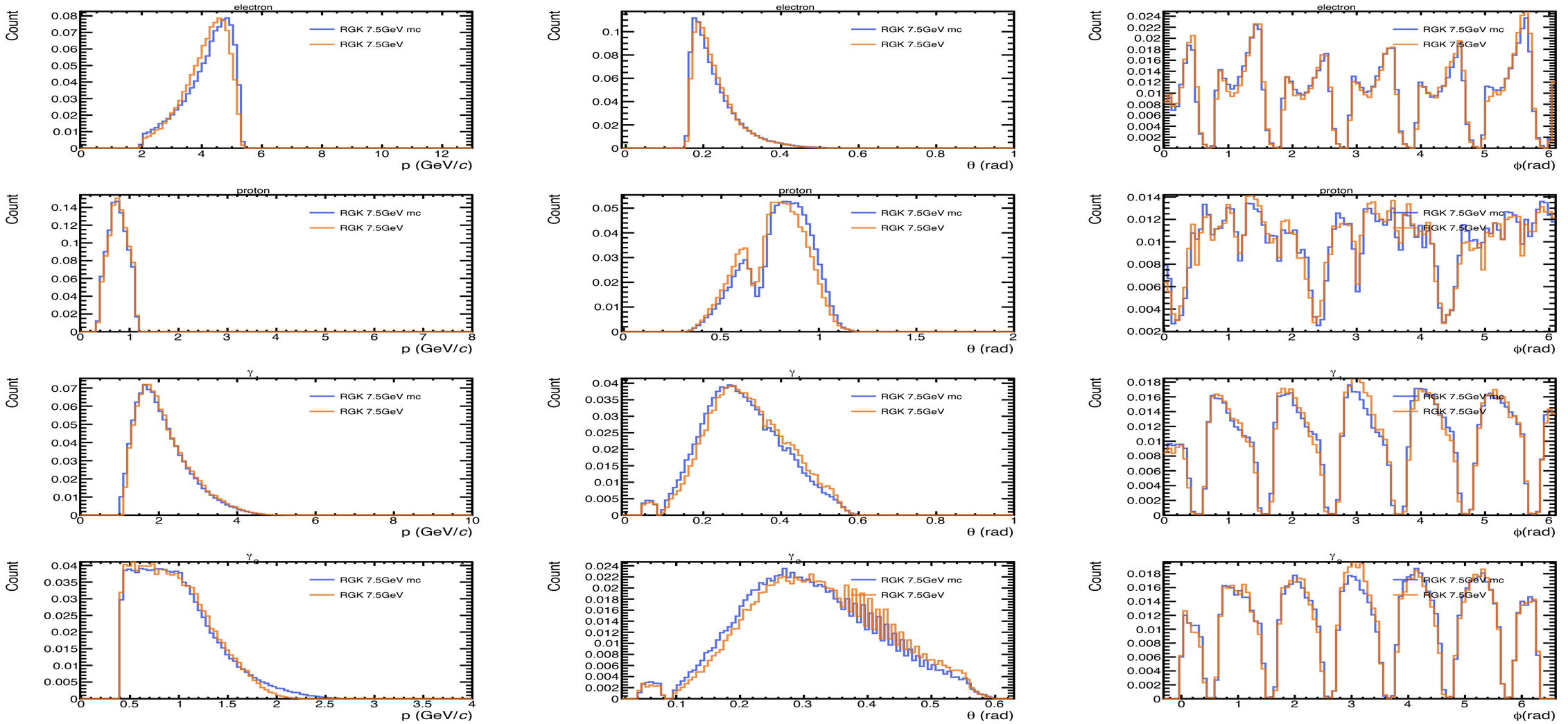
Exclusivity Cut

Variable	Definition
M_{π^0}	Invariant mass of the two-photon system
$\mathrm{MM}^2_{ep\pi^0}$	Missing mass squared of the $ep\pi^0$ system
MM^2_{ep}	Missing mass squared of the ep system
$\mathrm{MM}^2_{e\pi^0}$	Missing mass squared of the $e\pi^0$ system
$E^{\pi^0}_{\mathrm{miss}}$	Missing energy of the $ep\pi^0$ system
$P^{\pi^0}_{T,\mathrm{miss}}$	Missing transverse momentum of the $ep\pi^0$ system
$\theta_{\pi^0\pi^{0\prime}}$	Angle between the π^0 reconstructed from $\gamma\gamma$ kinematics and the π^0 reconstructed from ep kinematics
$\Delta\phi_{\pi^0}$	Coplanarity angle between the π^0 plane and the recoil-proton plane
$\theta_{e\gamma_1}$, $\theta_{e\gamma_2}$	Opening angles between the scattered electron and each decay photon
$\theta_{\gamma_1\gamma_2}$	Opening angle between the two decay photons



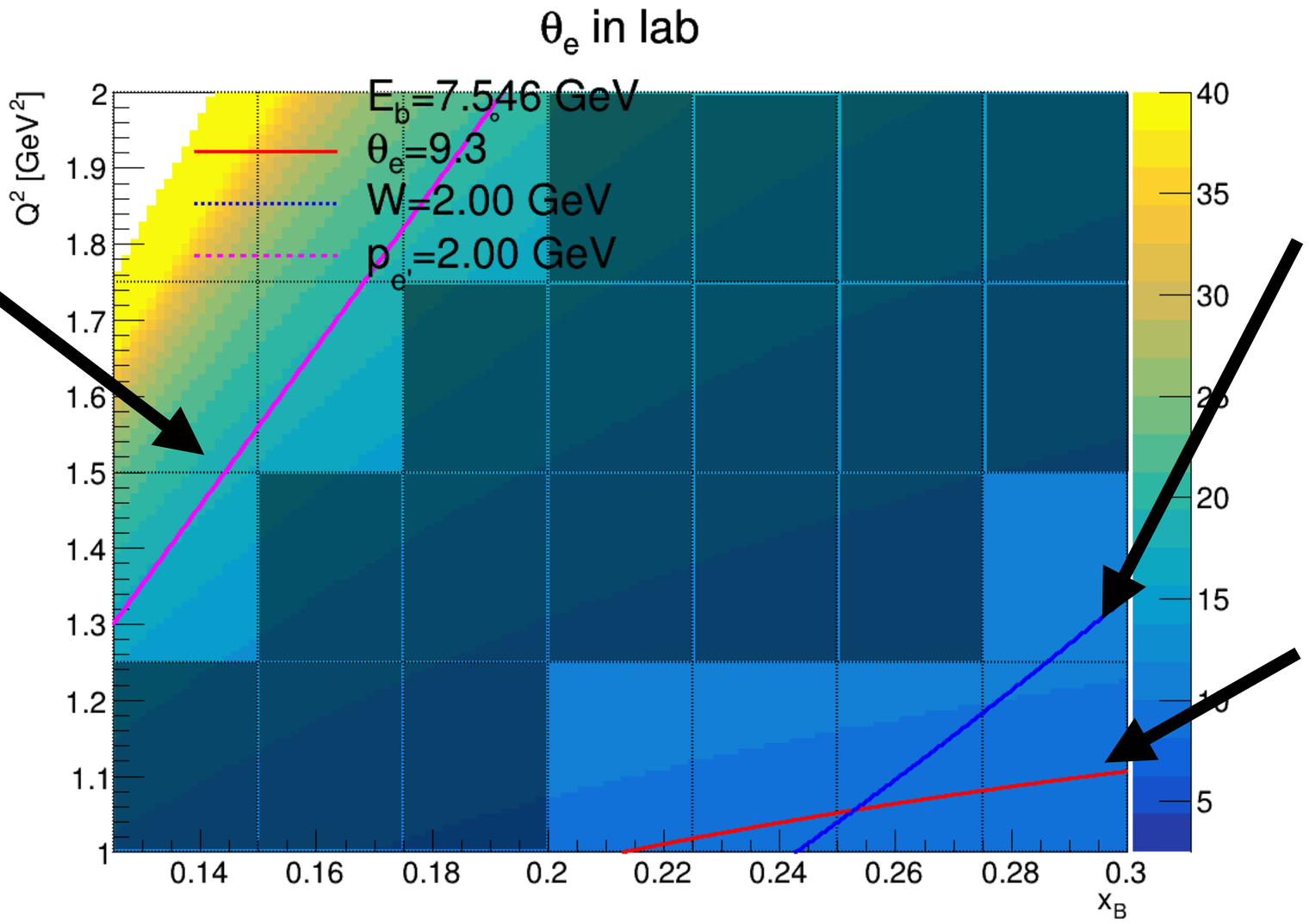
DVπ^0P Background Exclusivity Cut

After Exclusivity Cut



Data Binning

Boundary from the minimum electron energy cut

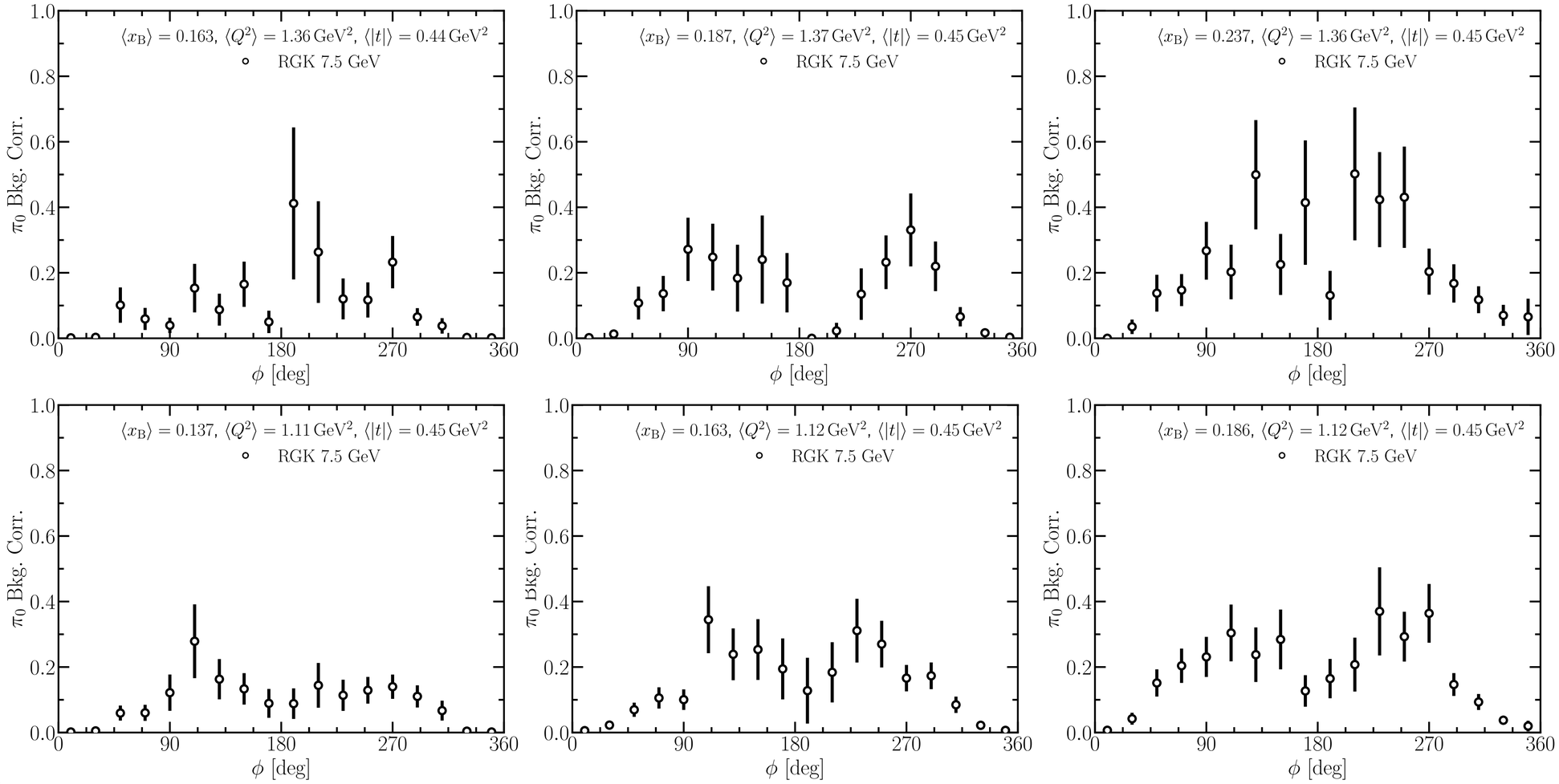


Boundary from the minimum W cut

Boundary from the minimum electron angle cut

DVπ^0P Background Subtraction

$$B_{\pi^0} = \frac{N^{DVCS,rec}_{DV\pi^0P,sim}(x_B, Q^2, t, \phi)}{N^{DV\pi^0P,rec}_{DV\pi^0P,sim}(x_B, Q^2, t, \phi)} \cdot \frac{N^{DV\pi^0P,rec}_{exp}(x_B, Q^2, t, \phi)}{N^{DVCS,rec}_{exp}(x_B, Q^2, t, \phi)}$$

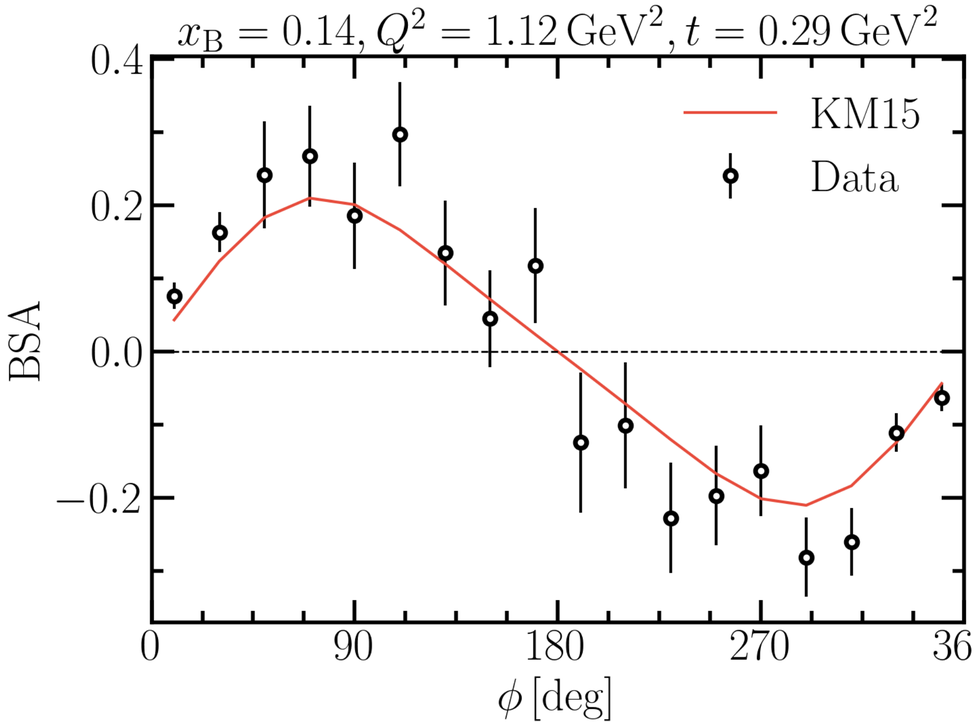


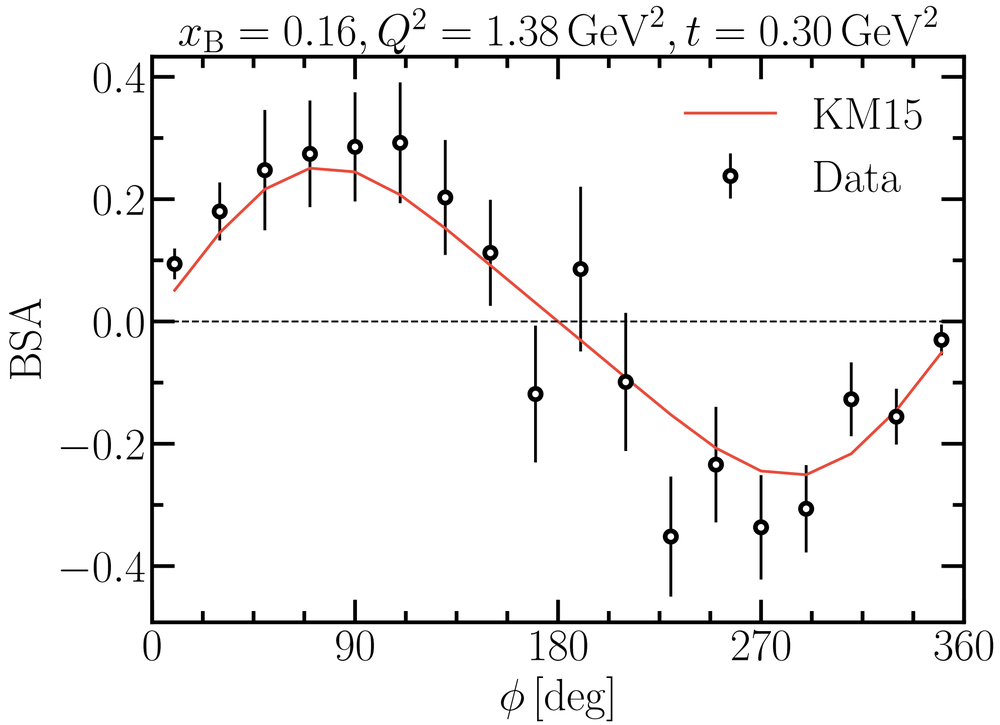
BSA Extraction

RGK Fall18 Pass2 7.5GeV BSA

$$A_{LU,\mathrm{DVCS}}^{\mathrm{corr}} = \frac{A_{LU,\mathrm{DVCS}} - A_{\pi^0} \cdot A_{LU,DV\pi^0P}}{1 - A_{\pi^0}}$$

Beam Energy/GeV	Accumulated Charge/mC
6.4	~90
6.5	~10
7.5	~10
8.5	~80





RGK Fall18 Pass2 7.5GeV Integrated Charge

Integrated Charge

Trigger Config:

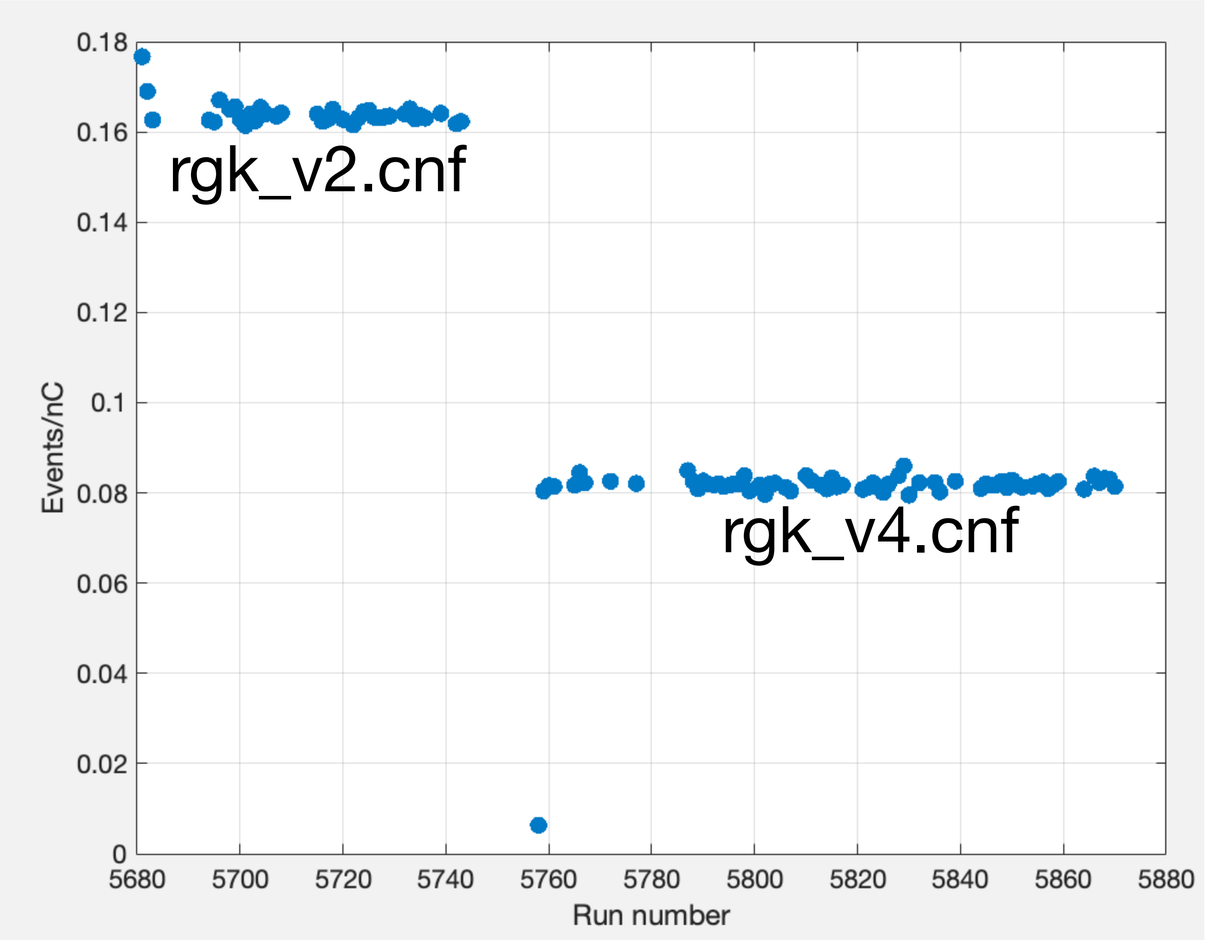
1) electron in ECAL
or electron in FT & 1 forward hadron

2) electron in ECAL, pre-scale by **2**
or electron in FT & 1 forward hadron

Thus, the effective charge is:

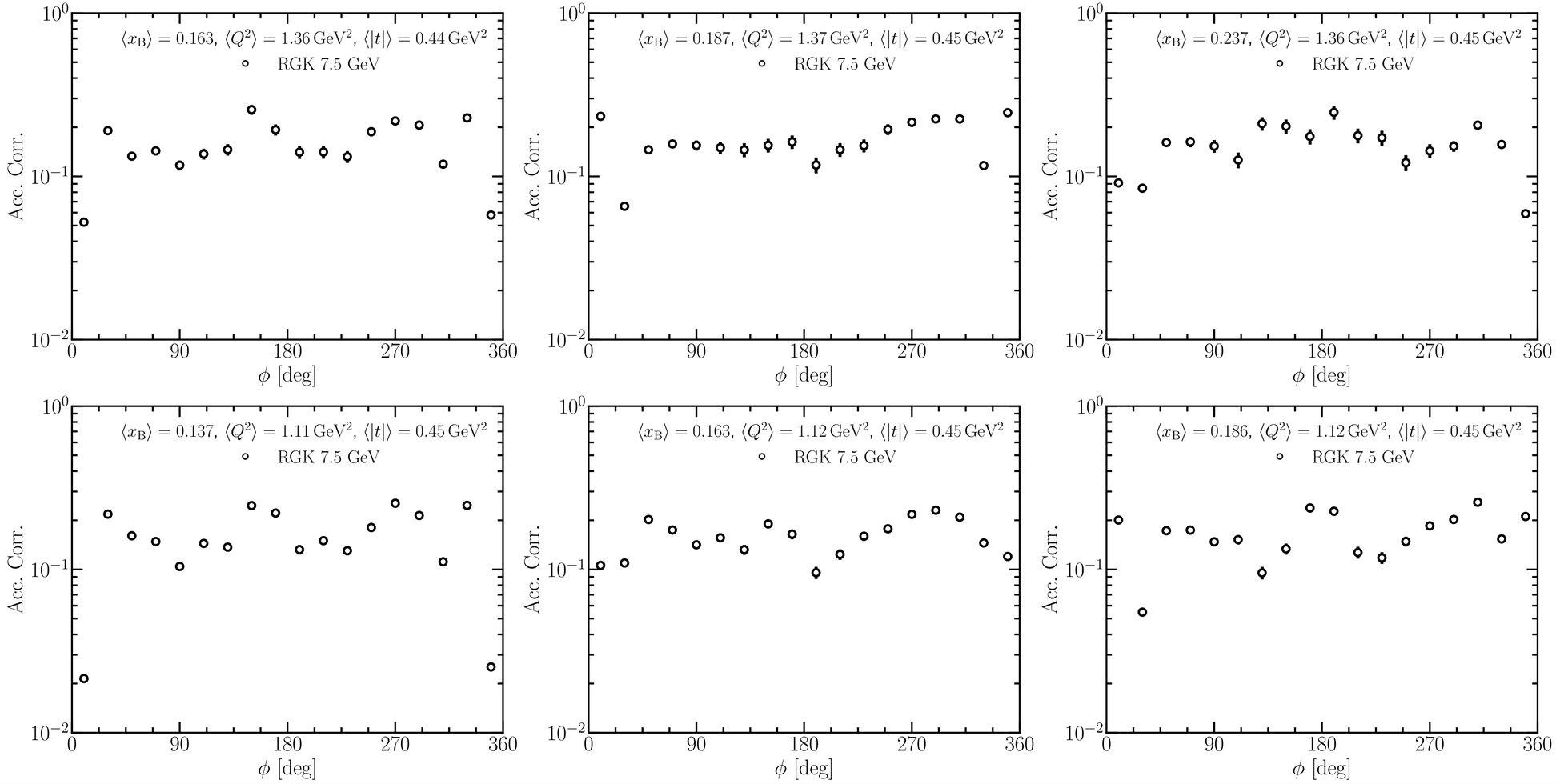
$$Q = Q_{v2} + Q_{v4} \cdot \frac{1}{2} = 9.14996 \text{ mC}.$$

Not 13.69730 mC !



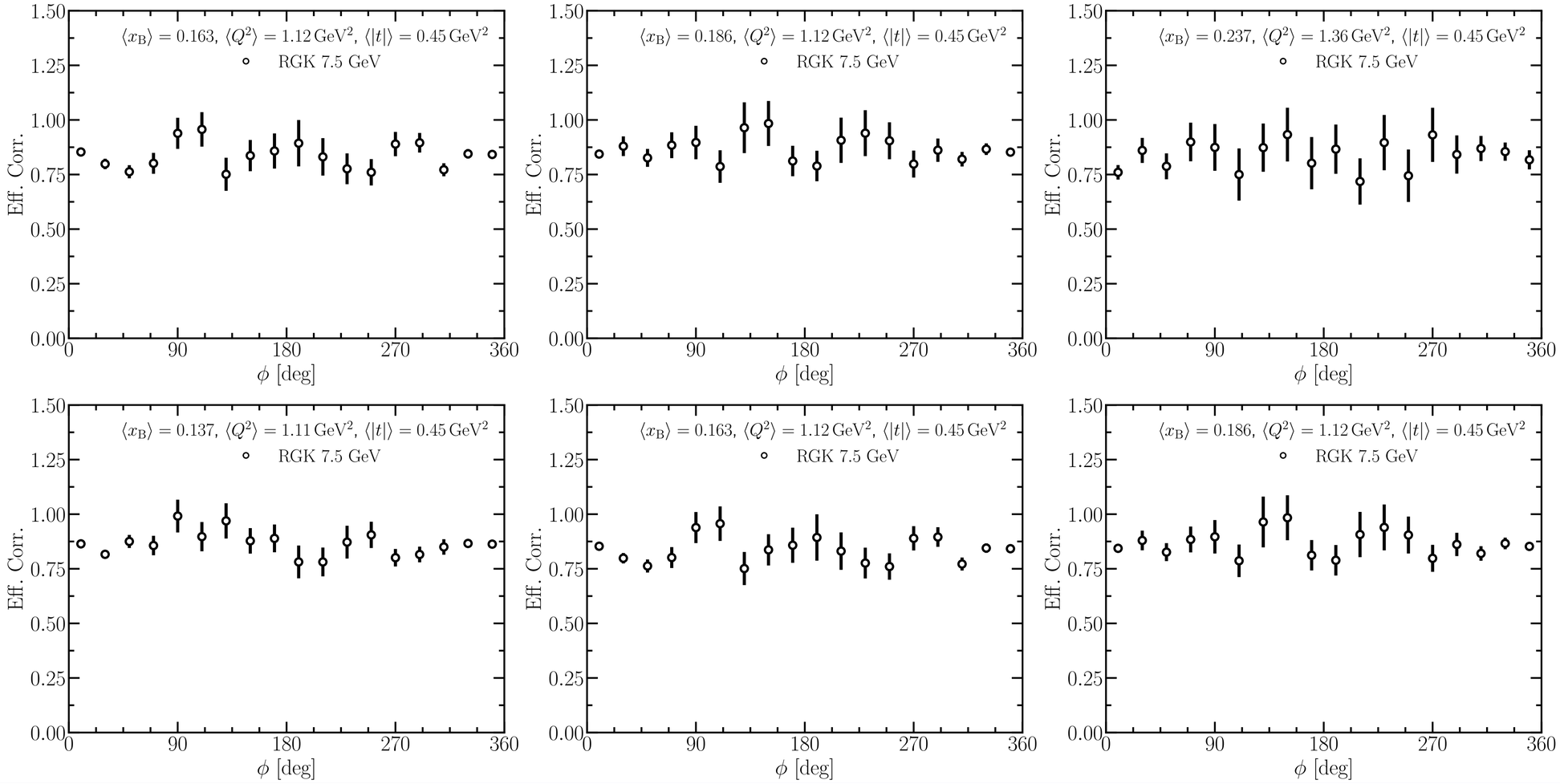
Acceptance Correction

$$A_{acc} = \frac{N_{rec}(x_B, Q^2, t, \phi)}{N_{gen}(x_B, Q^2, t, \phi)}$$



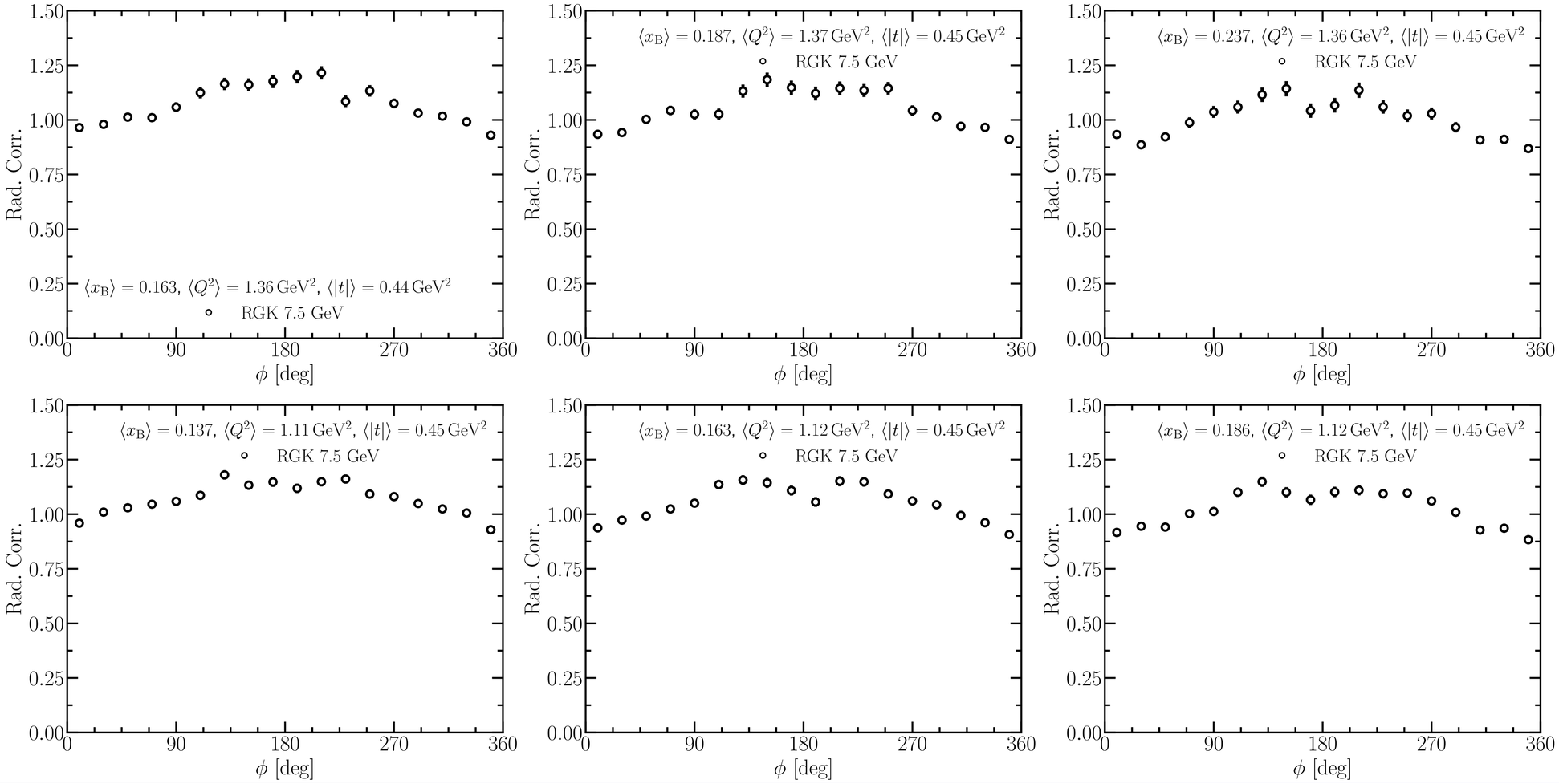
Background Merging Efficiency Correction

$$A_{eff} = 1 + \frac{I}{45\text{nA}}(-1 + \frac{N_{bkg}(x_B, Q^2, t, \phi)}{N_{no\ bkg}(x_B, Q^2, t, \phi)})$$



Radiation Correction

$$A_{rad} = \frac{N_{rad}(x_B, Q^2, t, \phi)}{N_{no\ rad}(x_B, Q^2, t, \phi)}$$



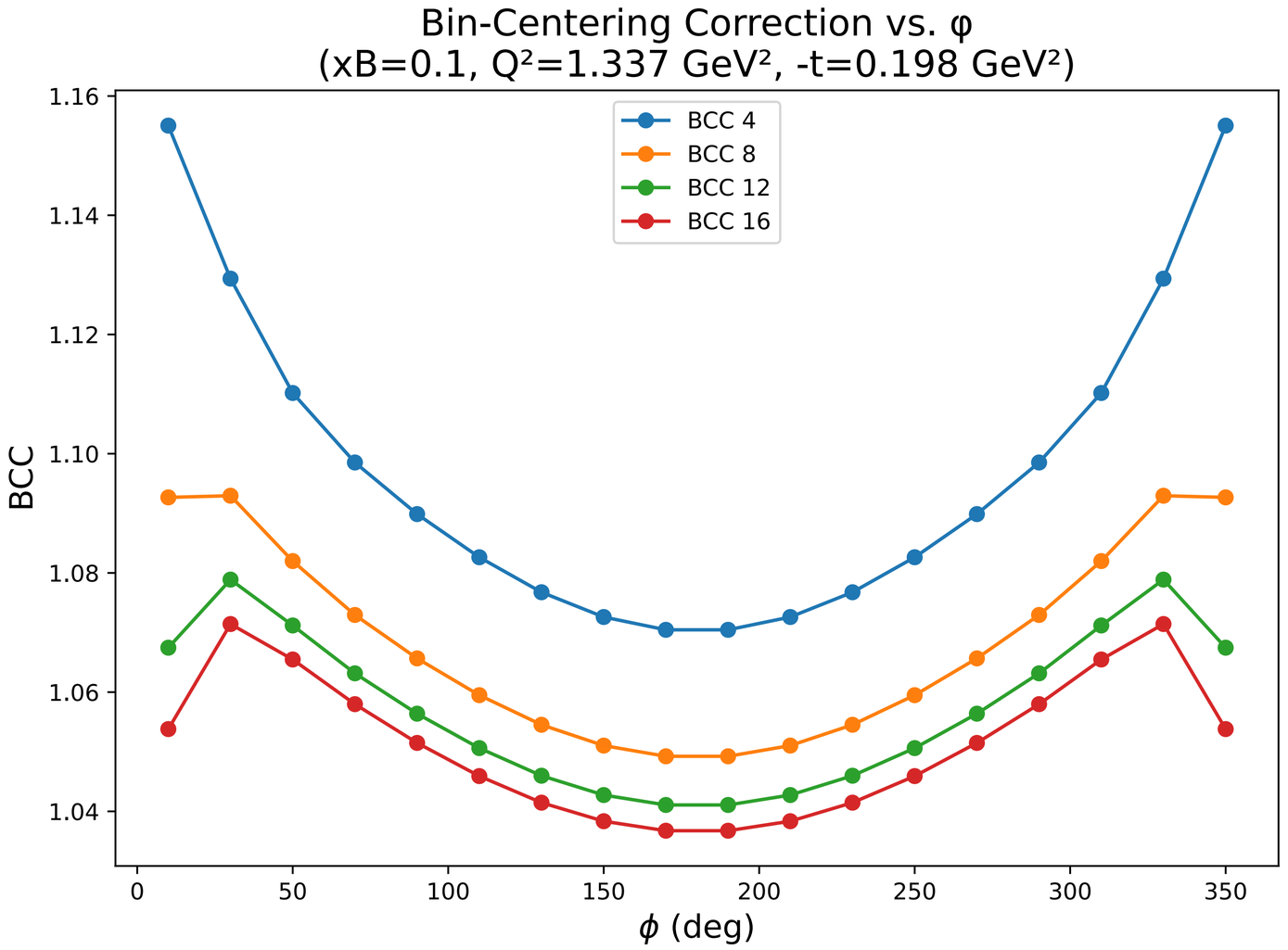
Bin Centering Correction

$$A_{bcc} = \frac{d\sigma}{< d\sigma >}$$

Evenly distributed grid in x_B, Q^2, t, ϕ 4D space

Size : $n \times n \times n \times n$

Final Choice: n = 20



Lepton Propagator Cut

$$d\sigma_{\mathrm{BH}^2} = \Gamma \frac{1}{x_B^2 y^2 (1+\epsilon^2)^2 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} (c_0^{\mathrm{BH}} + c_1^{\mathrm{BH}} \cos(\phi) + c_2^{\mathrm{BH}} \cos(2\phi))$$

$$d\sigma_{\mathrm{DVCS}^2} = \Gamma \frac{1}{y^2 Q^2} (c_0^{\mathrm{DVCS}} + c_1^{\mathrm{DVCS}} \cos(\phi) + c_2^{\mathrm{DVCS}} \cos(2\phi))$$

$$d\sigma_{\mathcal{I}} = \Gamma \frac{1}{x_B y^3 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} (c_0^{\mathcal{I}} + c_1^{\mathcal{I}} \cos(\phi) + c_2^{\mathcal{I}} \cos(2\phi) + c_3^{\mathcal{I}} \cos(3\phi))$$

$$P_1 = -\frac{1}{y(1+\epsilon^2)} (J + 2K \cos\phi_{\mathrm{BMK}})$$

Can reach 0 at collinear limit —> Diverge

dvcsgen require $|P_1| > P_1^c$ default $P_1^c = 0.005$ set another $P_1^c = 0.00005$

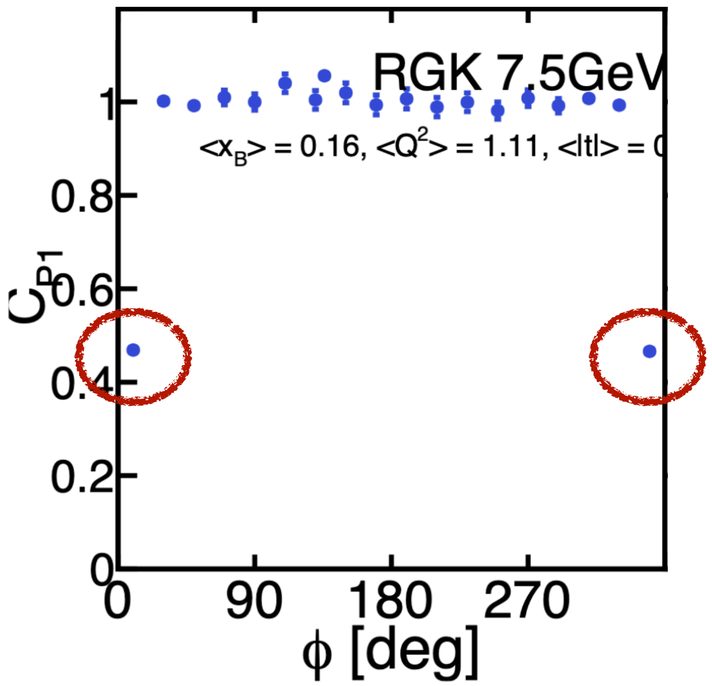
When P_1 is far away from 0, $\mathrm{d}\sigma(|P_1| > 0.005)/\mathrm{d}\sigma(|P_1| > 0.00005) = 1$

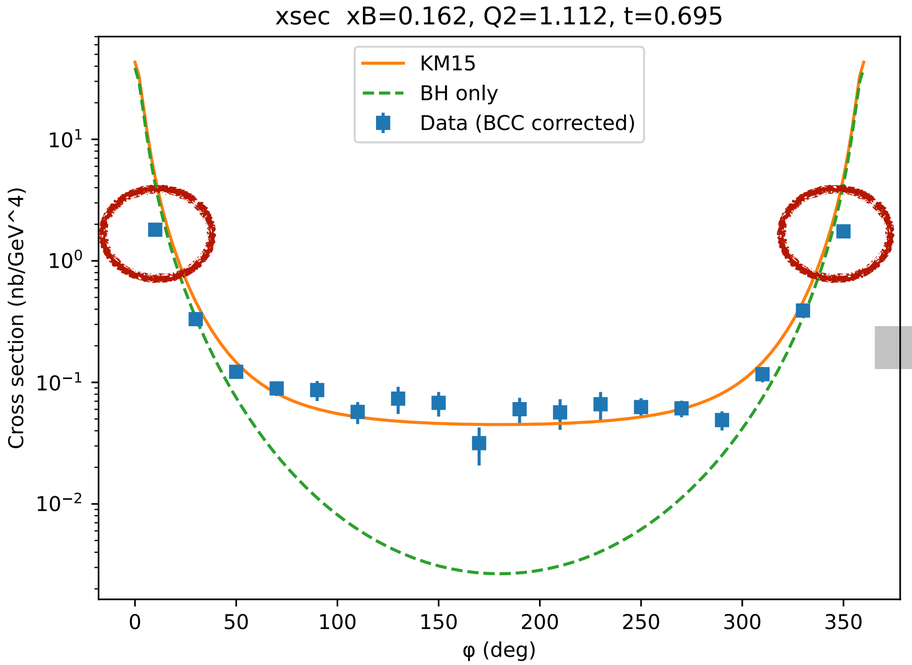
When $P_1 \sim 0$, $\mathrm{d}\sigma(|P_1| > 0.005)/\mathrm{d}\sigma(|P_1| > 0.00005) < 1$

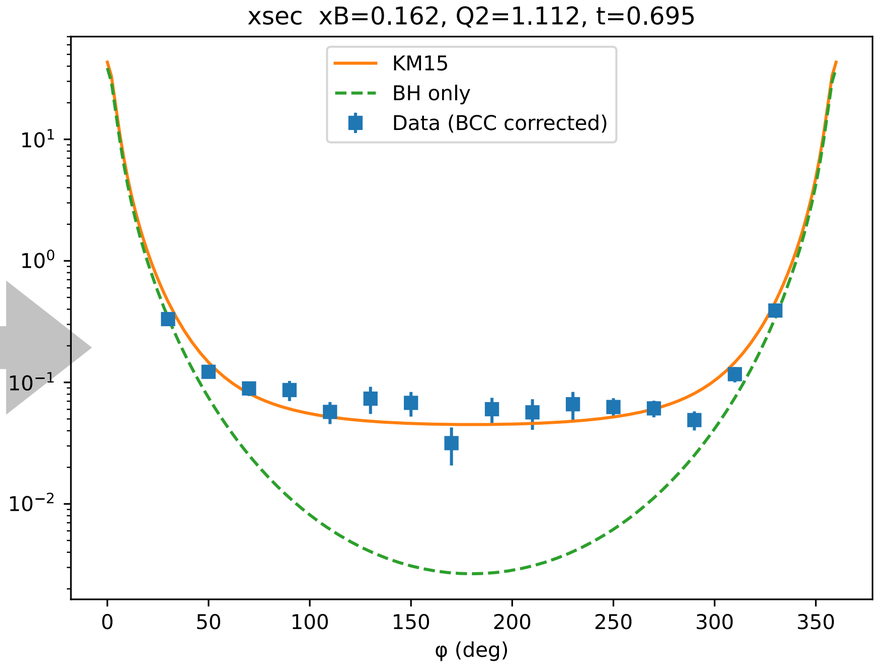
Lepton Propagator Cut

Thus, define $C_{P_1} = \mathrm{d}\sigma(|P_1| > 0.005)/\mathrm{d}\sigma(|P_1| > 0.00005)$

When C_{P_1} < Certain Value, we reject that data point.





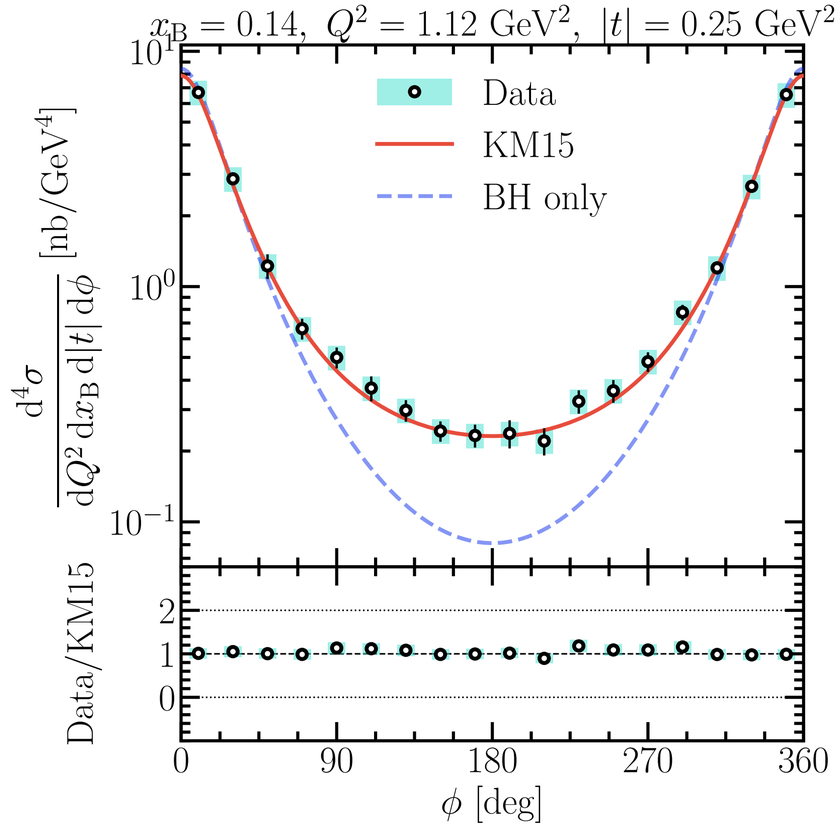


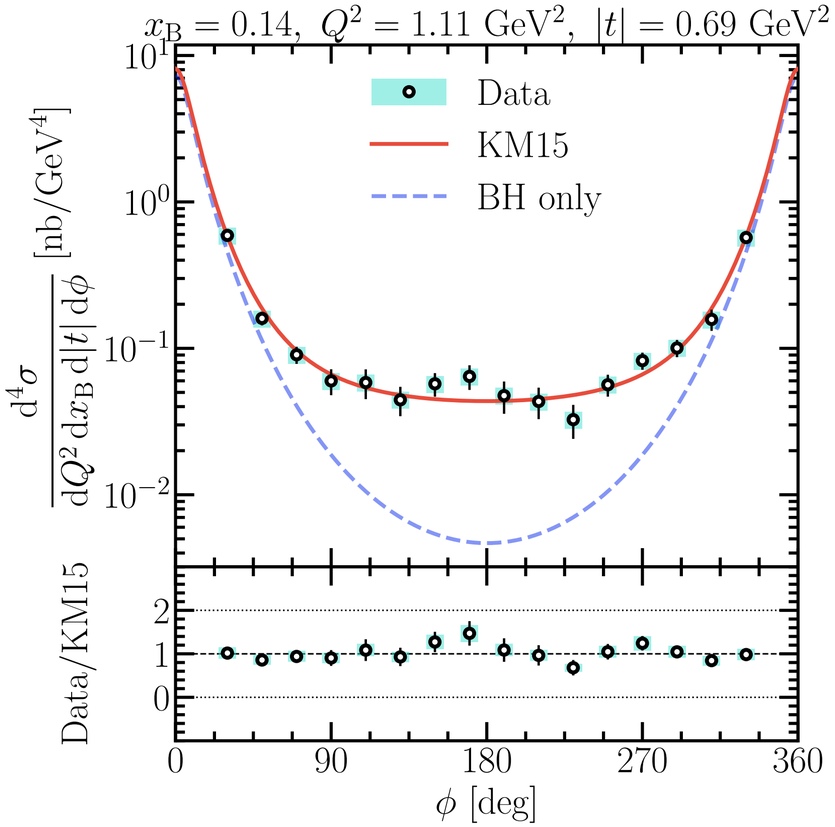
Cross Section Extraction

RGK Fall18 Pass2 7.5GeV Unpolarized Cross Section

$$\mathrm{d}\sigma = \frac{N}{\mathscr{L}\,\Delta V} \cdot \frac{1 - B_{\pi_0}}{A_{acc}\,A_{eff}\,A_{rad}} \cdot A_{bcc}$$

Beam Energy/GeV	Accumulated Charge/mC
6.4	~90
6.5	~10
7.5	~10
8.5	~80



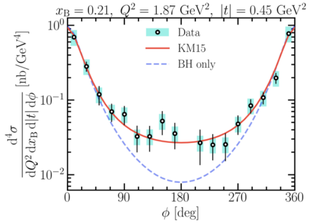


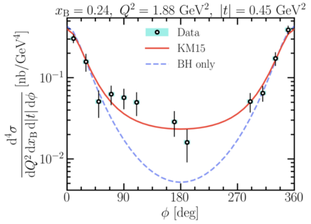
Cross Section Extraction

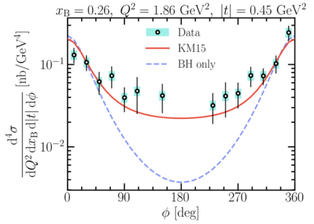
RGK Fall18 Pass2 7.5GeV Unpolarized Cross Section $0.4\ \mathrm{GeV}^2 < |t| < 0.5\ \mathrm{GeV}^2$

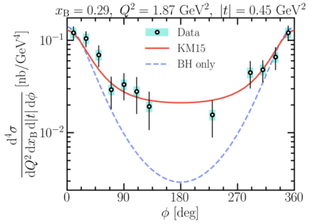
$$d\sigma = \frac{N}{\mathscr{L}\,\Delta V} \cdot \frac{1 - B_{\pi_0}}{A_{acc}\,A_{eff}\,A_{rad}} \cdot A_{bcc}$$

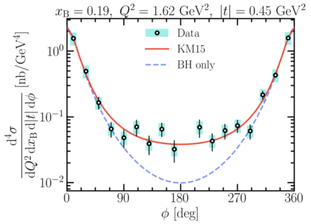
Beam Energy/GeV	Accumulated Charge/mC
6.4	~90
6.5	~10
7.5	~10
8.5	~80

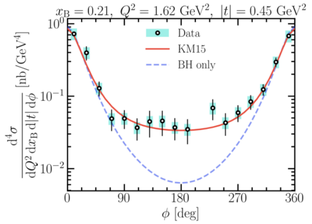


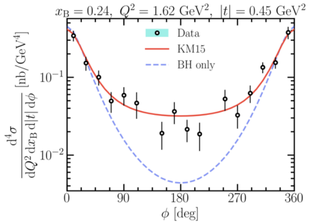


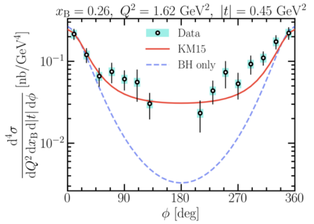


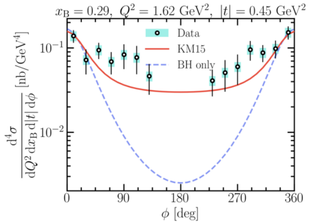


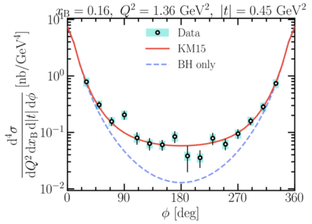


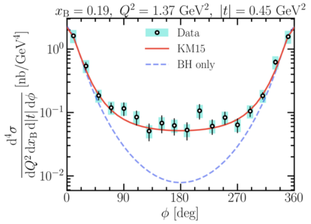


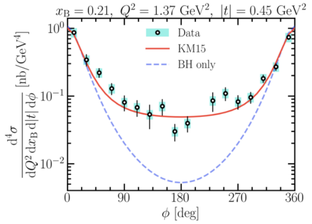


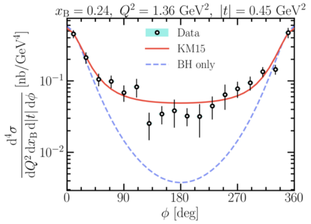


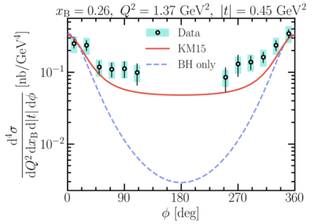


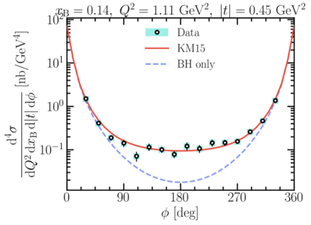


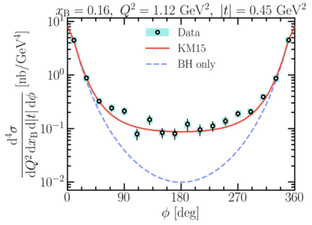


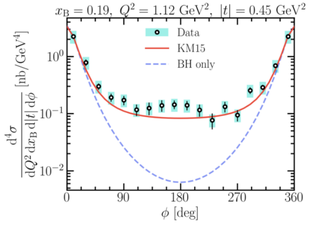












Cross Section Extraction

RGK Fall18 Pass2 7.5GeV Polarized Cross Section

$$\mathrm{d}\sigma = \frac{N}{\mathscr{L}\,\Delta V} \cdot \frac{1 - B_{\pi_0}}{A_{acc}\,A_{eff}\,A_{rad}} \cdot A_{bcc}$$

Beam Energy/GeV	Accumulated Charge/mC
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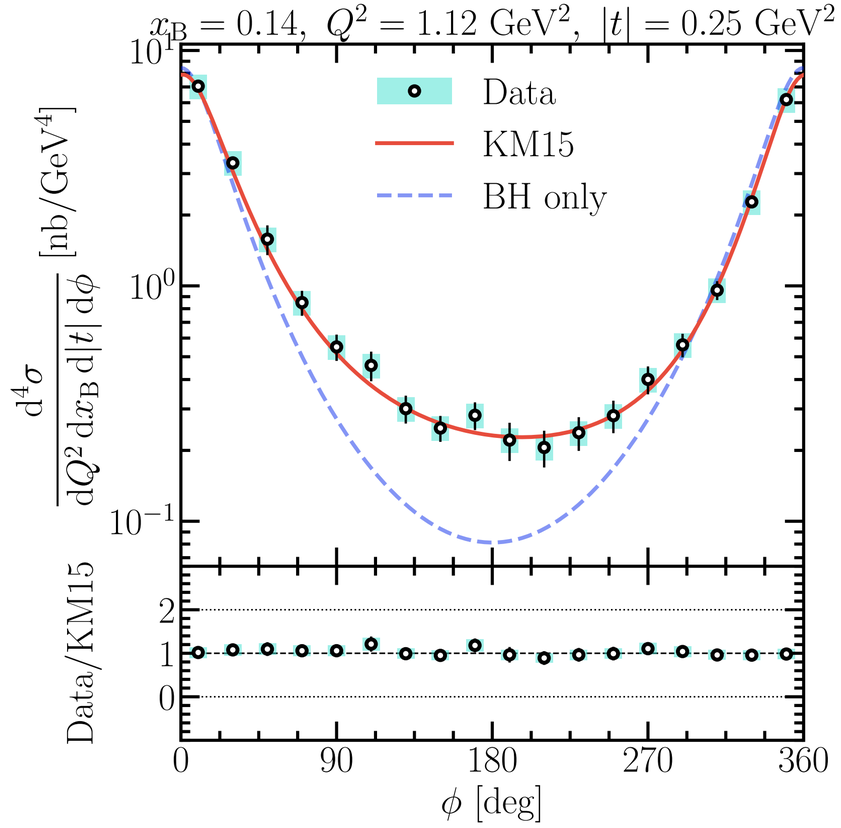

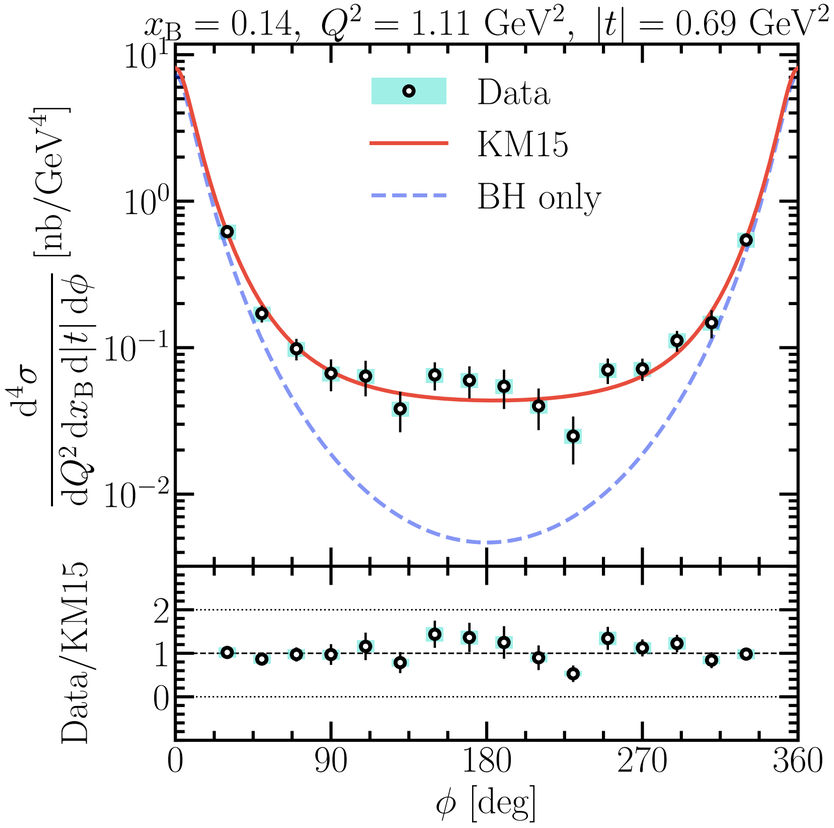

Cross Section Extraction

RGK Fall18 Pass2 7.5GeV Polarized Cross Section $0.4\ \mathrm{GeV}^2 < |t| < 0.5\ \mathrm{GeV}^2$

$$\mathrm{d}\sigma = \frac{N}{\mathscr{L}\,\Delta V} \cdot \frac{1 - B_{\pi_0}}{A_{acc}\,A_{eff}\,A_{rad}} \cdot A_{bcc}$$

Beam Energy/GeV	Accumulated Charge/mC
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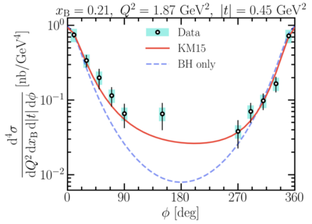
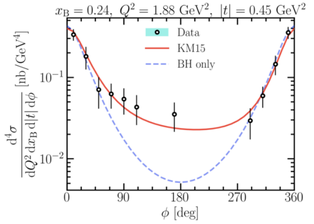
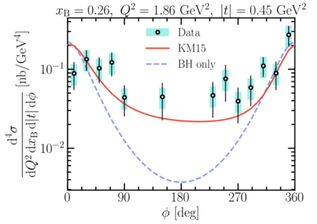
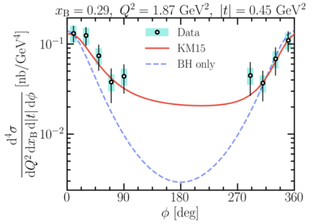
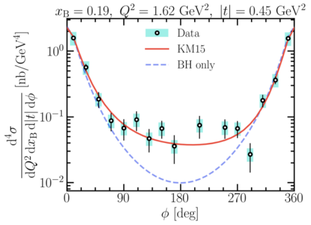
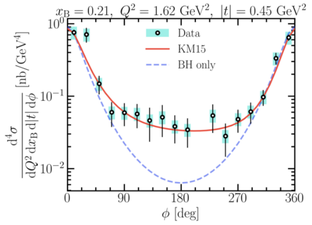


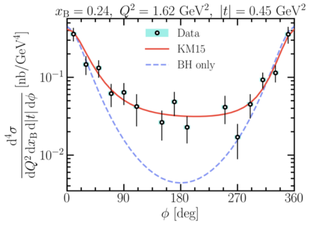


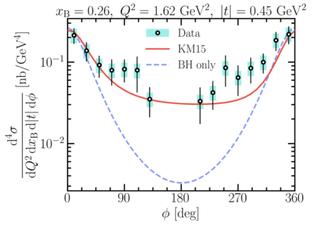


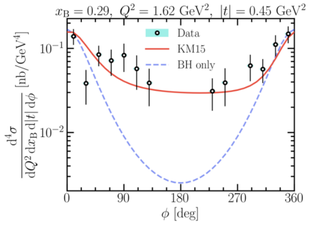


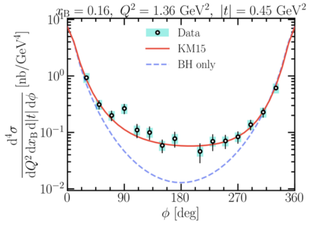


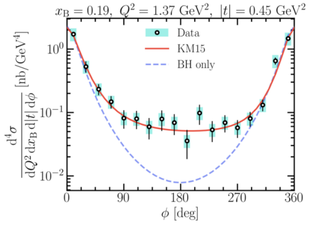


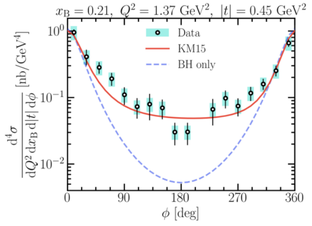


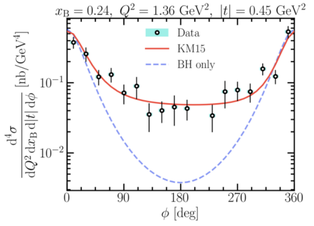


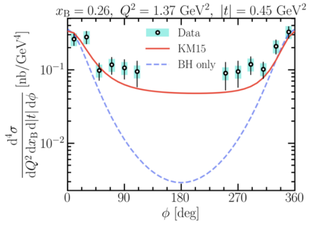


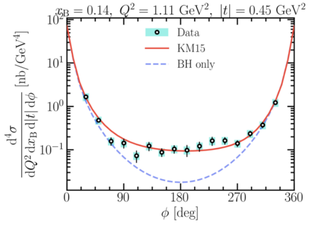


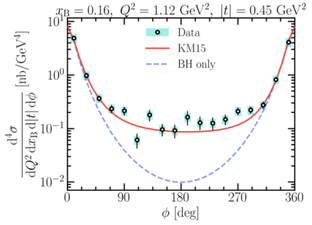


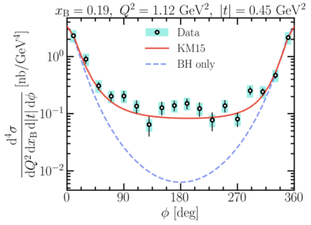










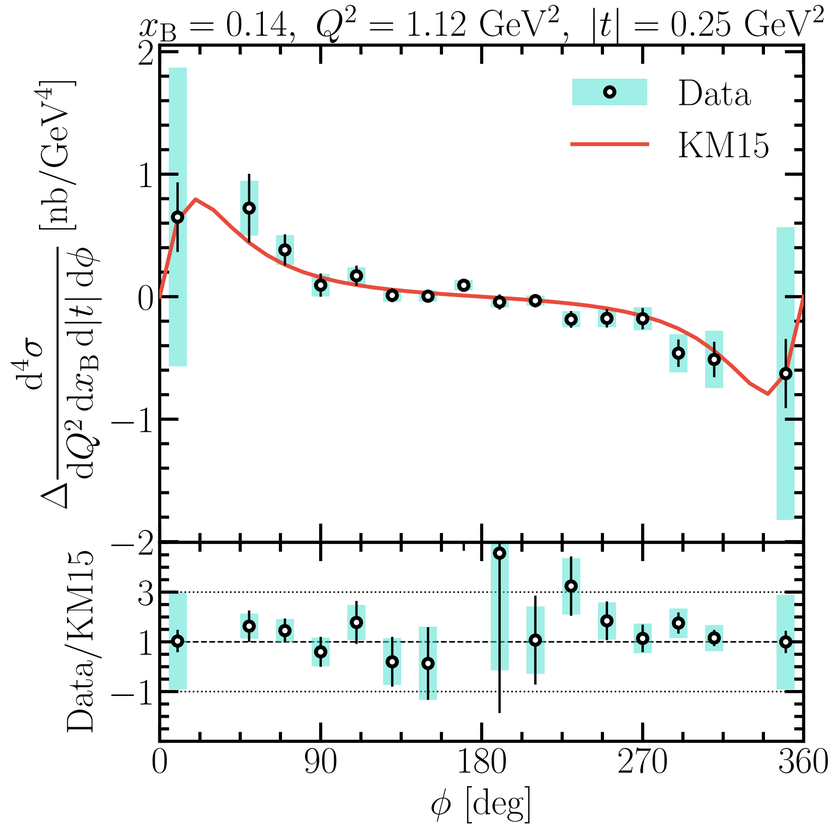


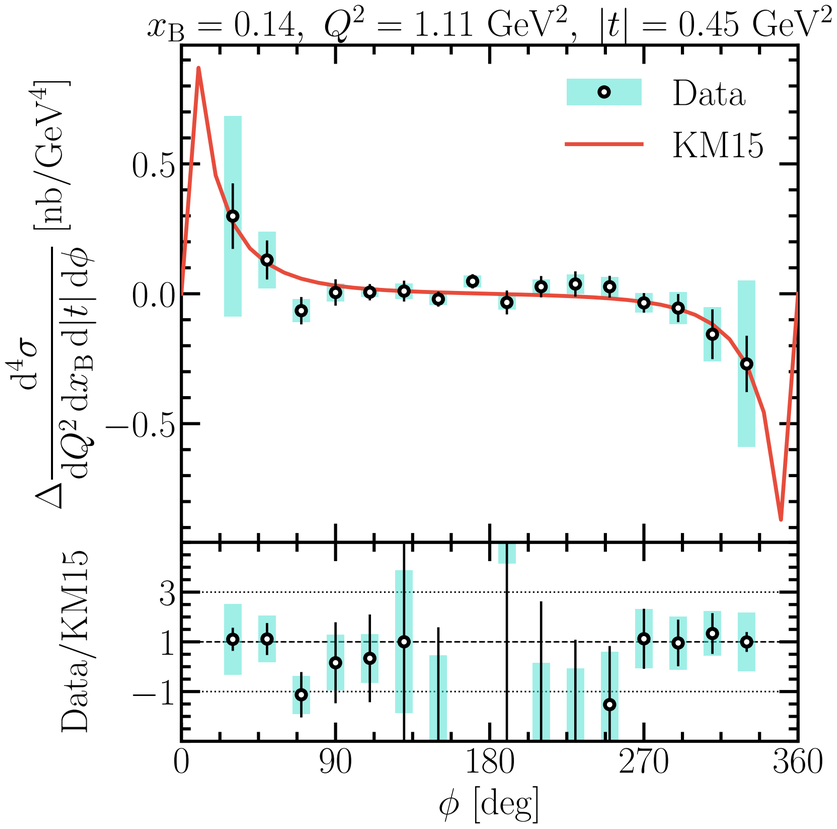
Cross Section Extraction

RGK Fall18 Pass2 7.5GeV Cross Section Difference

$$\Delta\sigma = \mathrm{d}\sigma_{\rightarrow} - \mathrm{d}\sigma_{\leftarrow}$$

Beam Energy/GeV	Accumulated Charge/mC
6.4	~90
6.5	~10
7.5	~10
8.5	~80





Cross Section Extraction

RGK Fall18 Pass2 7.5GeV Cross Section Difference $0.4\ \mathrm{GeV}^2 < |t| < 0.5\ \mathrm{GeV}^2$

$$\Delta\sigma = \mathrm{d}\sigma_{\rightarrow} - \mathrm{d}\sigma_{\leftarrow}$$

Beam Energy/GeV	Accumulated Charge/mC
6.4	~90
6.5	~10
7.5	~10
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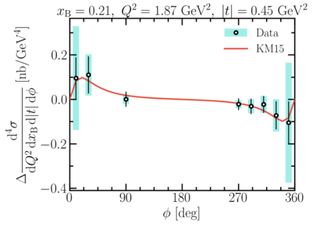
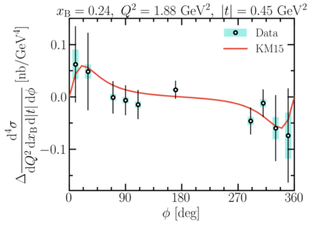
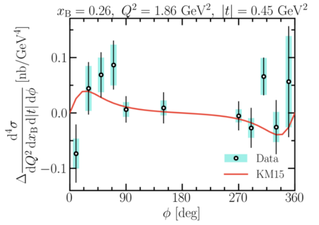
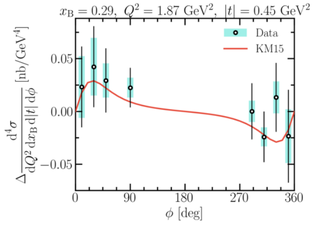
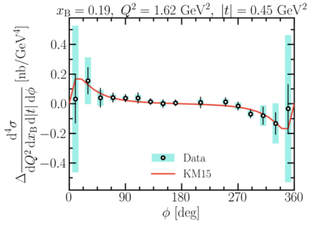
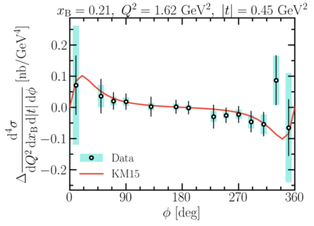


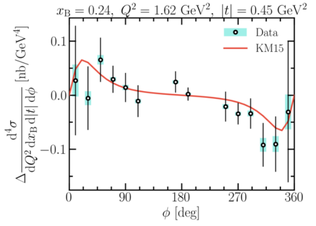


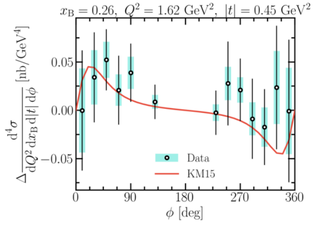


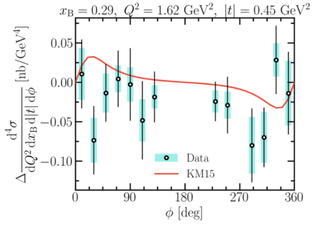


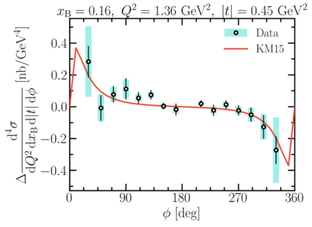


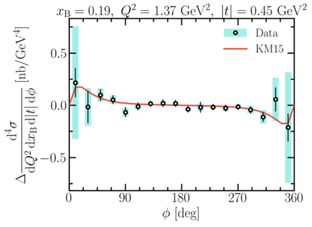


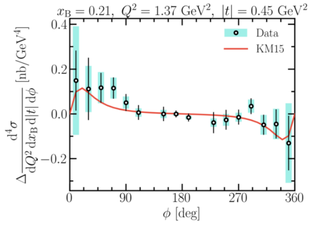


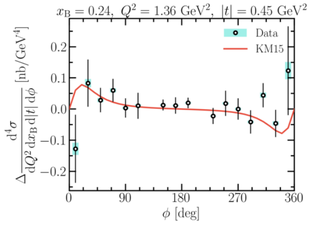


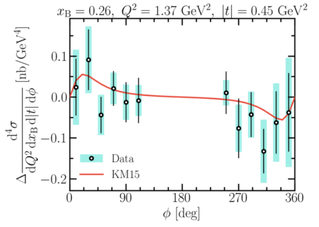


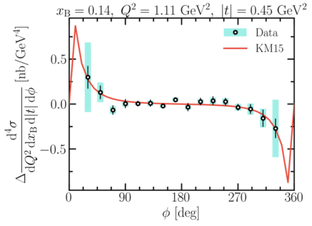


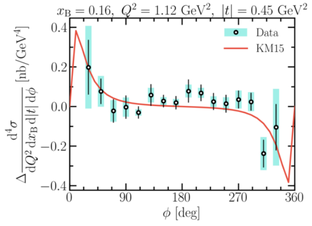


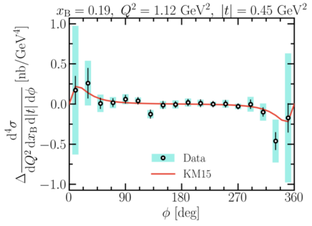












Rosenbluth Separation

$$\frac{d^5\sigma}{dx_B dQ^2 d|t| d\phi d\phi_S} = \frac{\alpha^3 x_B}{16\pi^2 Q^4 \sqrt{1+\epsilon^2}} |\mathcal{T}|^2 \qquad |\mathcal{T}|^2 = \left|\mathcal{T}_{\mathrm{BH}} + \mathcal{T}_{\mathrm{DVCS}}\right|^2 = \left|\mathcal{T}_{\mathrm{BH}}\right|^2 + \left|\mathcal{T}_{\mathrm{DVCS}}\right|^2 + \mathcal{I}$$

Different beam energies give different y at same (x_B, Q^2, t) *point*

$$\mathcal{I} \sim 1/y^3$$
$$\left|\mathcal{T}^{\mathrm{DVCS}}\right|^2 \sim 1/y^2$$

Separate DVCS and interface term!

Fitting Formular:

$$\begin{pmatrix} b_{UU} \\ b_{LU} \end{pmatrix} = \begin{pmatrix} A_0(y) & A_1(y,\phi) & A_2(y,\phi) & A_3(y,\phi) & 0 \\ 0 & 0 & 0 & 0 & y(2-y)K\Gamma_I(\phi)\sin(\phi) \end{pmatrix} \begin{pmatrix} C^{DVCS} \\ \mathrm{Re}C^{INT} \\ \mathrm{Re}C^{INT,V} \\ \mathrm{Re}C^{INT,A} \\ F_\Delta \end{pmatrix}$$

σ Degree of Freedom : 4

A_{LU} Degree of Freedom : 1

Beam Energy/GeV	Accumulated Charge/mC
6.4	~90
6.5	~10
7.5	~10
8.5	~80

Too close, consider as one beam energy.

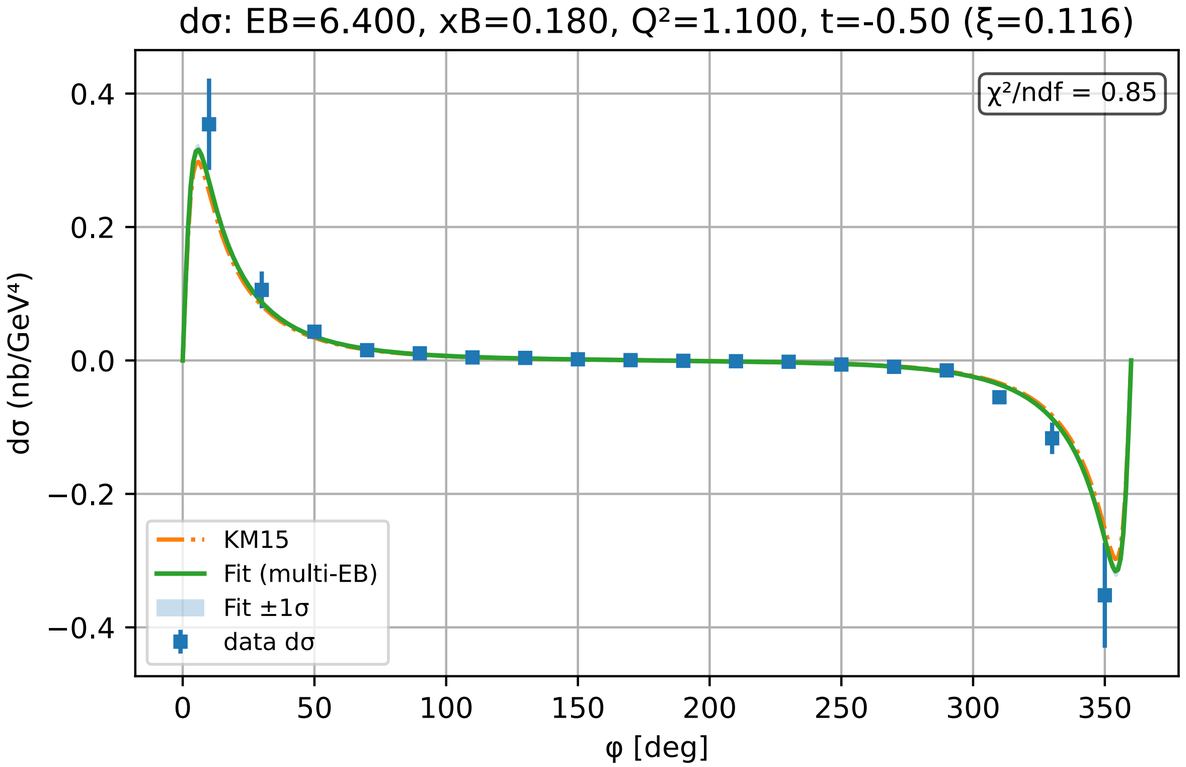
\+

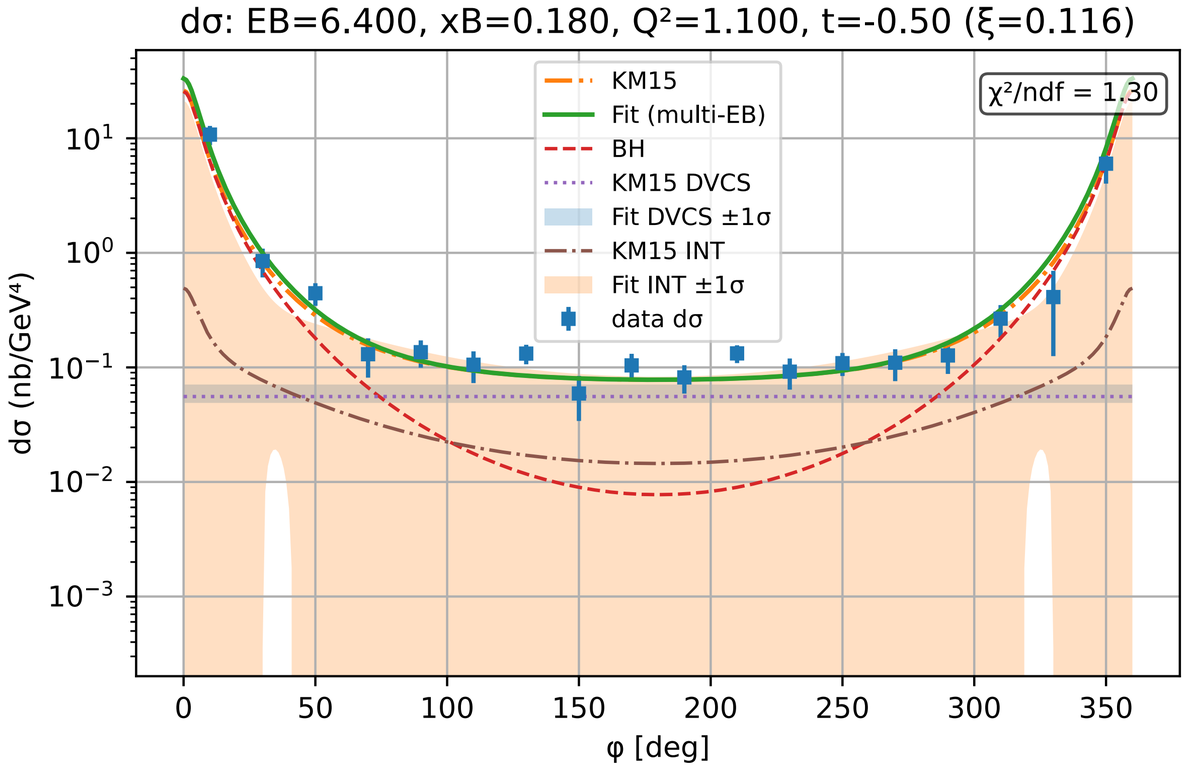
RGA: 10.6 GeV

All beam energies from RGK are crucial!

Rosenbluth Separation

Pseudo Data Test (~ 20% uncertainty)





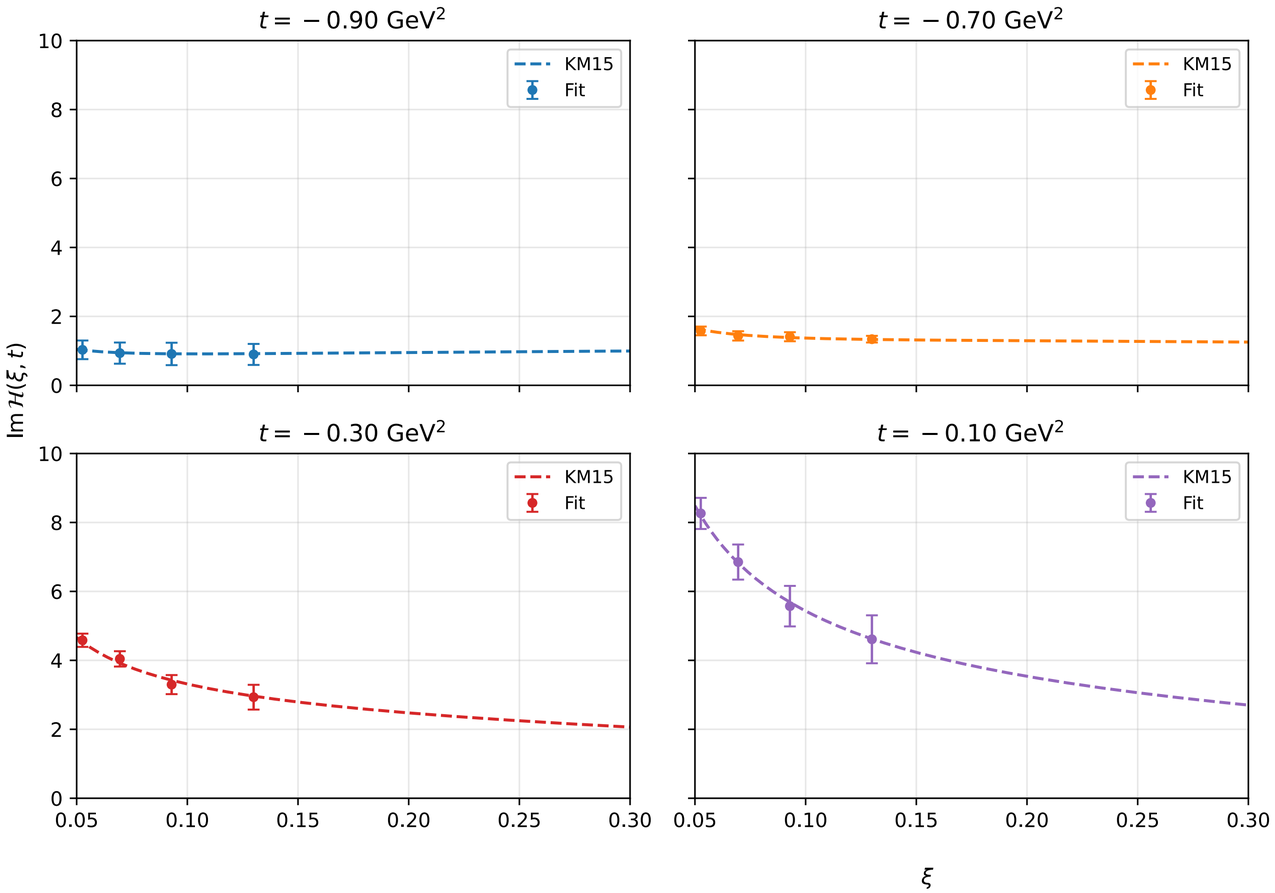
Twist-2 DVCS Amplitude separated!

Agree with true(generated) value

Rosenbluth Separation

Estimated Experiment Test — CFF Extraction

Im $\mathcal{H}$ vs ξ $(Q^2 = 1.10\ \mathrm{GeV}^2)$



Conservative Systematic Uncertainty

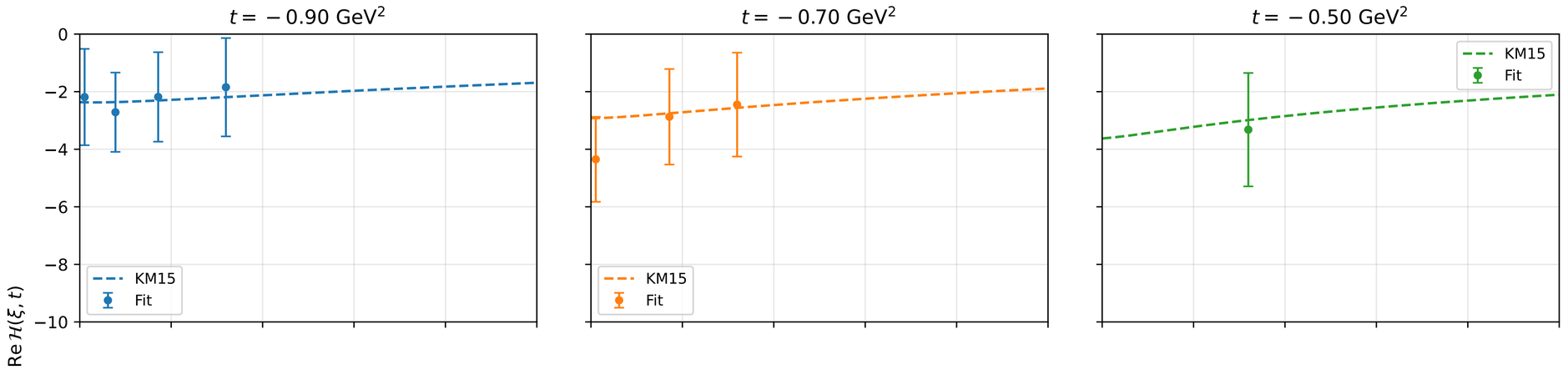
$$\sigma_{sys} = (\sigma_{fit,0\mathcal{F}} - \sigma_{fit,\mathcal{F}})$$

$$\sigma = \sqrt{\sigma_{fit}^2 + \sigma_{sys}^2}$$

Rosenbluth Separation

Estimated Experiment Test — CFF Extraction

Re $\mathcal{H}$ vs ξ $(Q^2 = 1.10\ \mathrm{GeV}^2)$

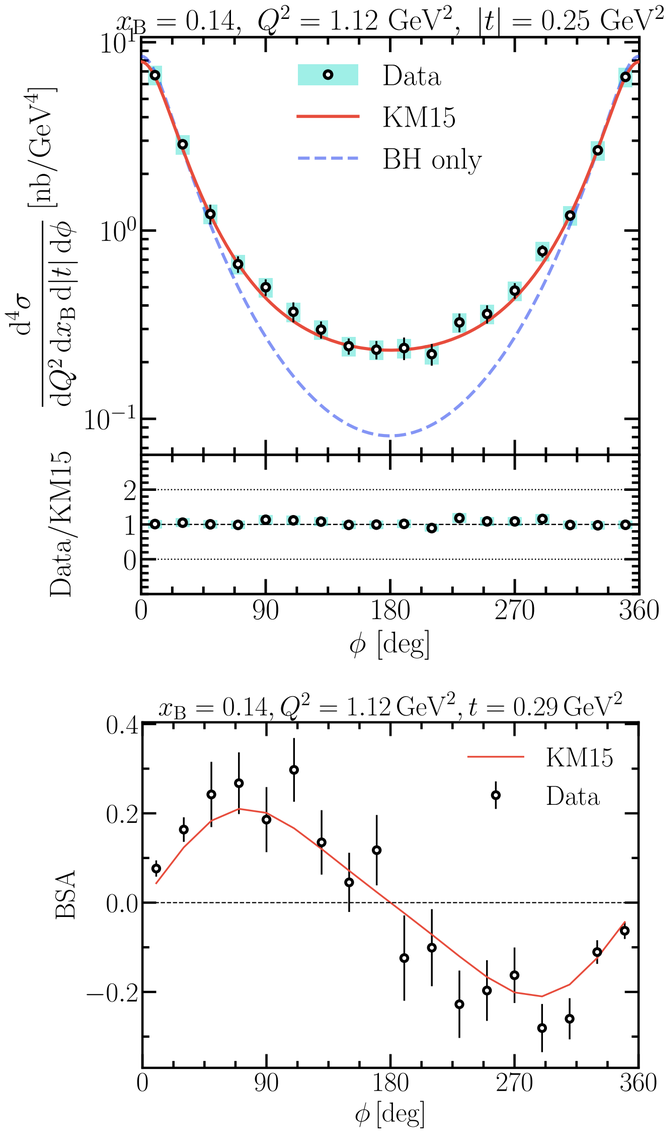


Conservative Systematic Uncertainty

$$\sigma_{sys} = (\sigma_{fit,0\mathcal{F}} - \sigma_{fit,\mathcal{F}})$$

$$\sigma = \sqrt{\sigma_{fit}^2 + \sigma_{sys}^2}$$

Status & Summary



We have successfully extracted the beam spin asymmetry (BSA) as well as the unpolarized and polarized cross sections from the RGK 7.5GeV data. The Rosenbluth separation procedure is currently being refined using simulations.

Next Steps:

- Evaluate full systematic uncertainties.
- Analyze the full RGK data set as soon as it becomes available.
- Perform Rosenbluth separation to disentangle the various contributions, combining results across all RGK beam energies (6.4, 6.5, 7.5, and 8.4 GeV) and RGA data sets (10.2 and 10.6 GeV) to improve coverage, statistical precision, and control of systematics of extracted physics quantities.

Building on the previous studies of the proton's gravitational structure with CLAS data, this work using CLAS12 data with **multiple beam energies** will enable high-resolution imaging to map the proton's internal pressure and force distributions.

Thank you for your listening!

Yijie Wang, Volker Burkert, Latifa Elouadrhiri,
Richard G. Milner, Bhawani Singh

Run Group K

Massachusetts Institute of Technology

Jefferson Lab

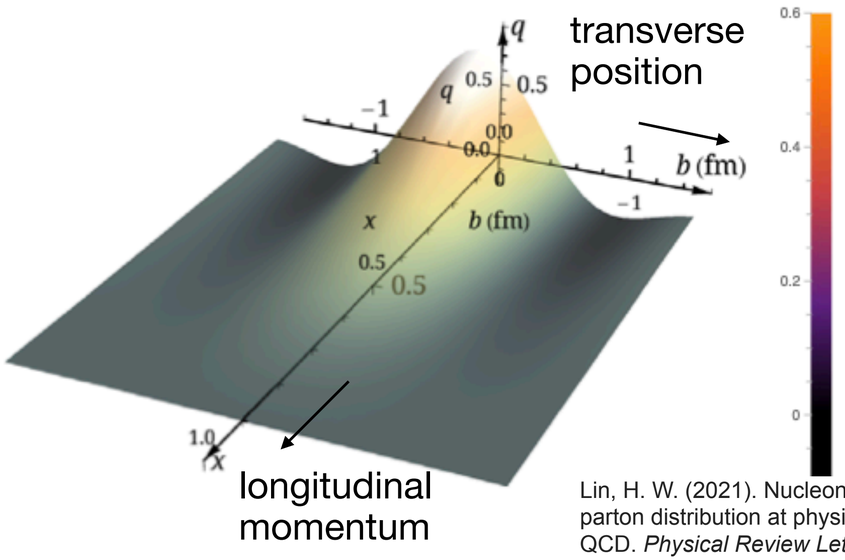
clas

Mar, 2026

Backup: Way to Understand Proton's Structure

Generalized Parton Distribution

3D Imaging of proton



Lin, H. W. (2021). Nucleon tomography and generalized parton distribution at physical pion mass from lattice QCD. *Physical Review Letters*, *127*(18), 182001.

Spin & Angular Momentum

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \mathrm{L}_q + J_g$$

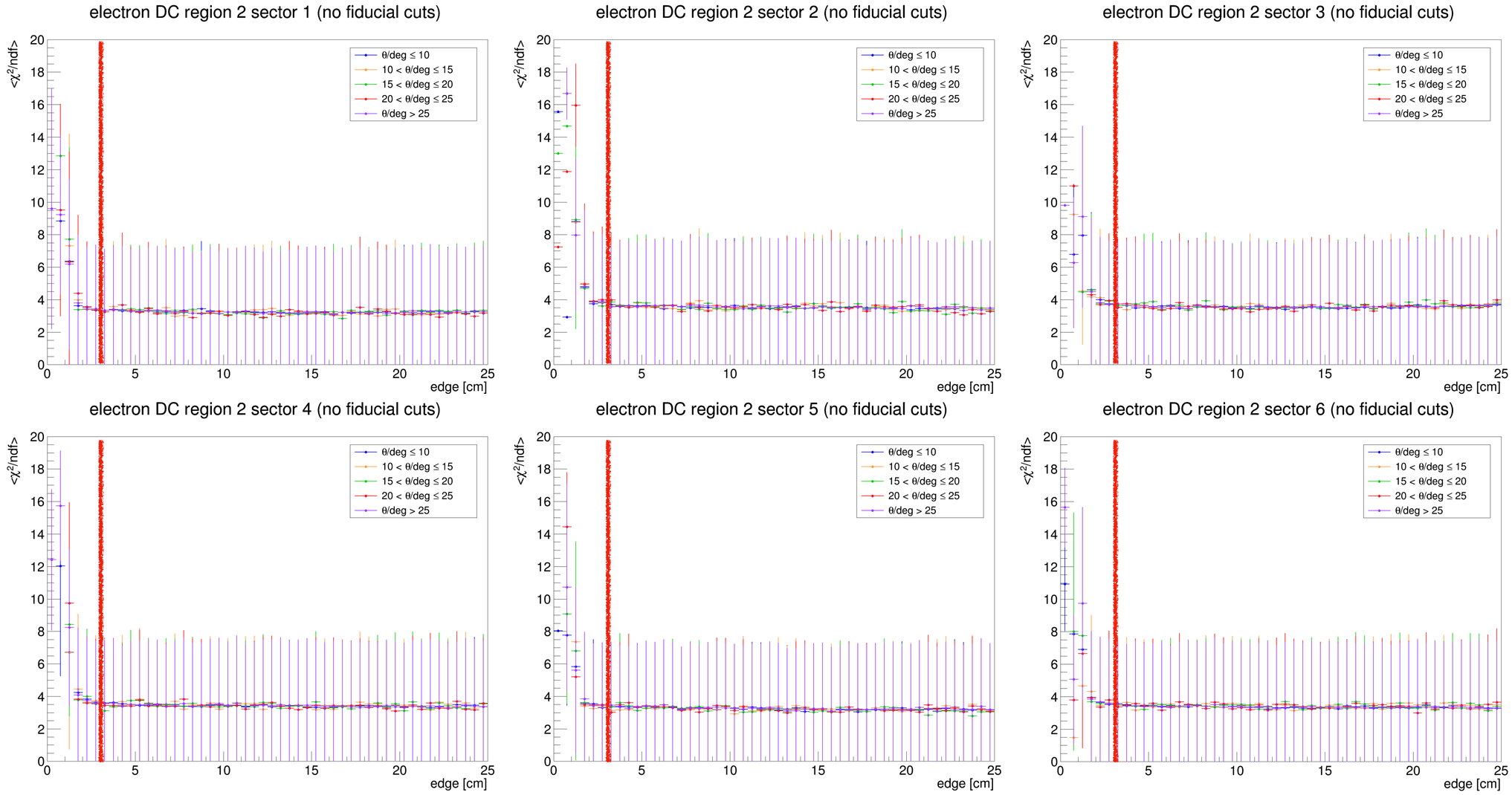
$$J_{q/g} = \lim_{t,\xi\to 0} \frac{1}{2} \int x dx \left[H^{q/g}(x,\xi,t) + E^{q/g}(x,\xi,t) \right]$$

Backup: Fiducial Cut

Electron

DC, R2

$edge > 3$ cm

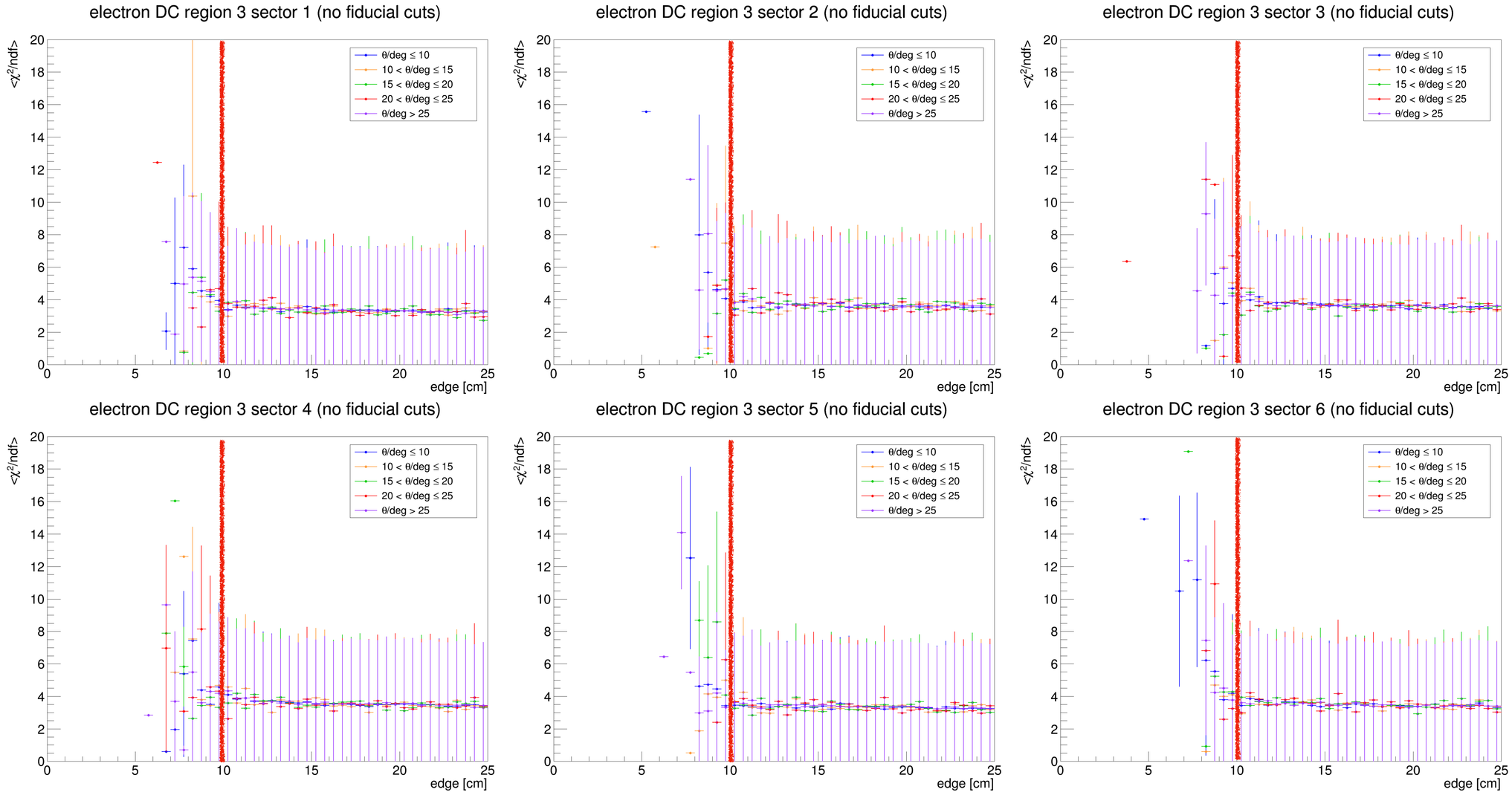


Backup: Fiducial Cut

Electron

DC, R3

$edge > 10$ cm

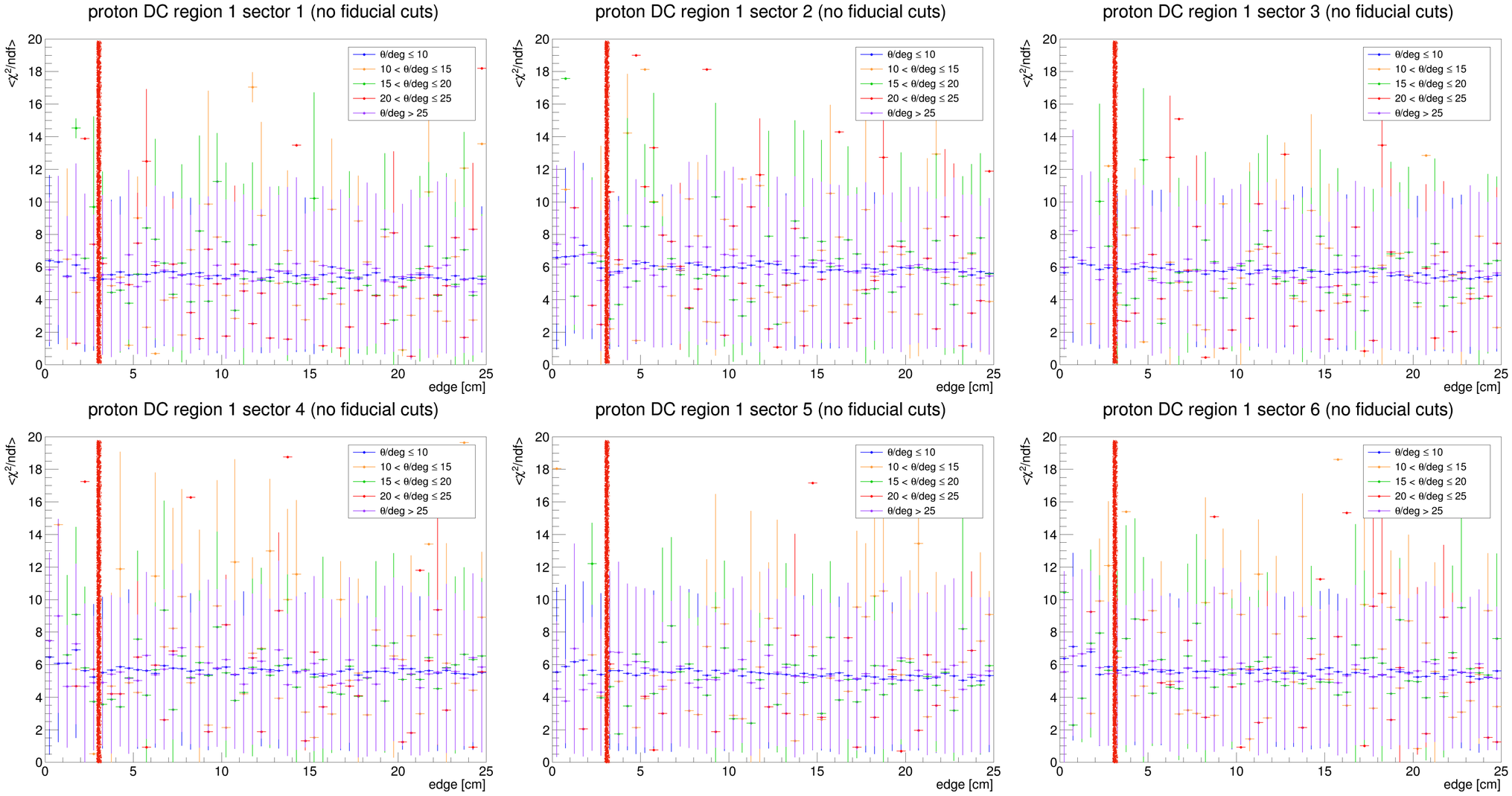


Backup: Fiducial Cut

Proton

DC, R1

$edge > 3$ cm

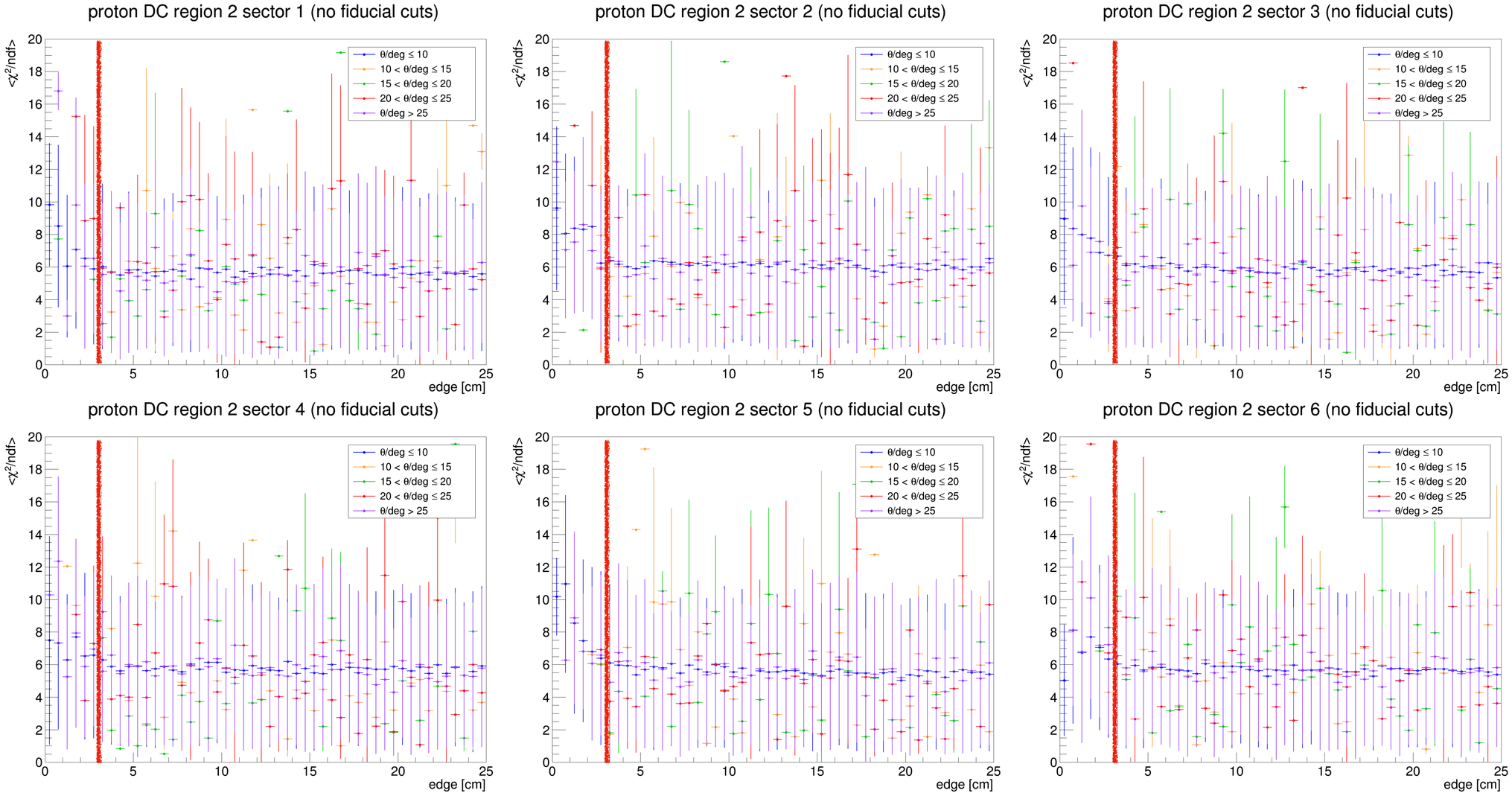


Fiducial Cut

Proton

DC, R2

$edge > 3$ cm

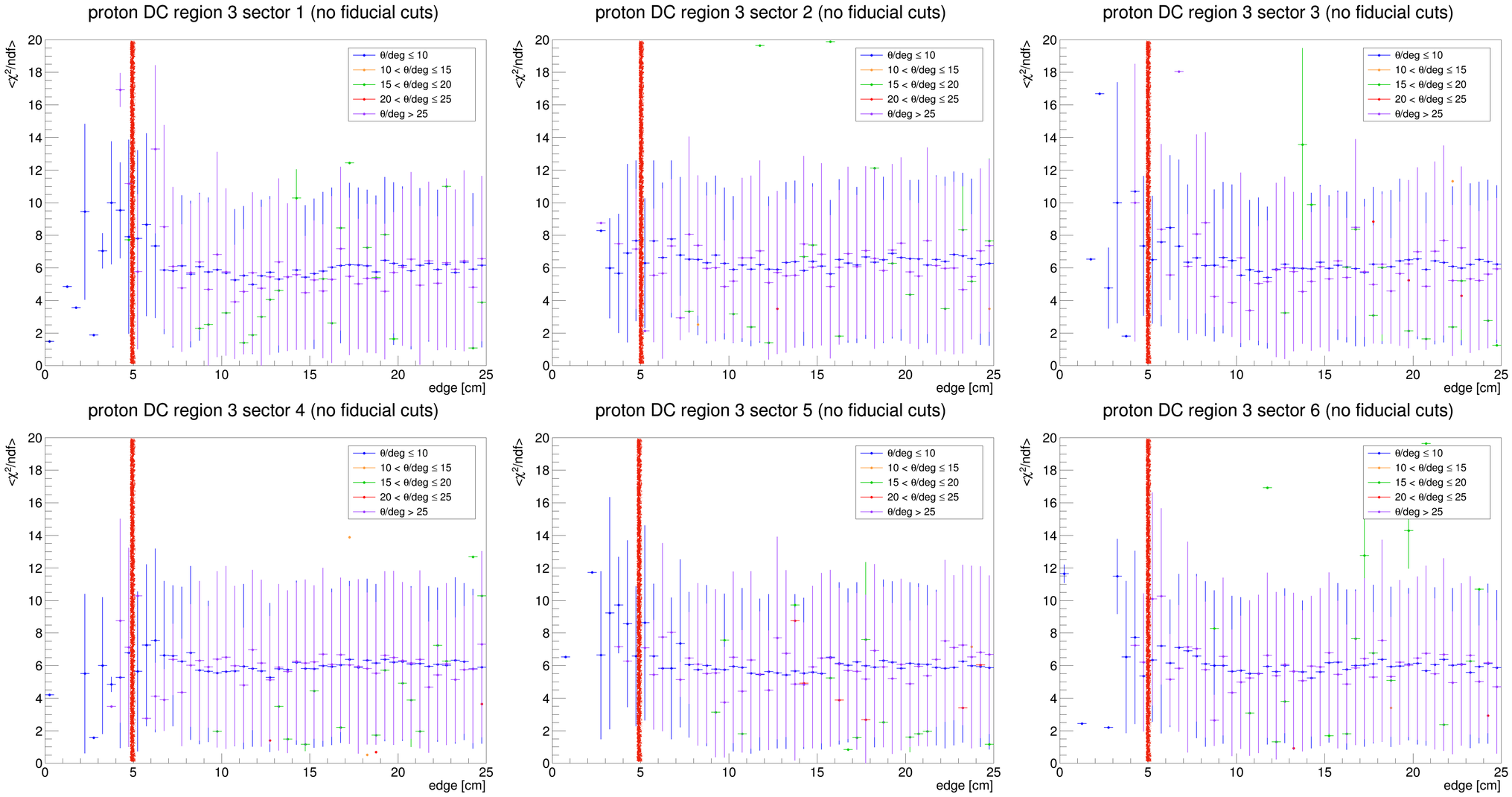


Fiducial Cut

Proton

DC, R3

$edge > 5$ cm

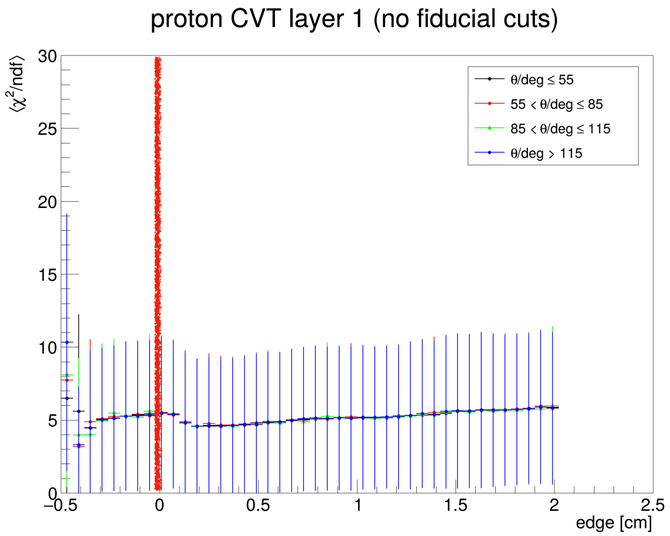


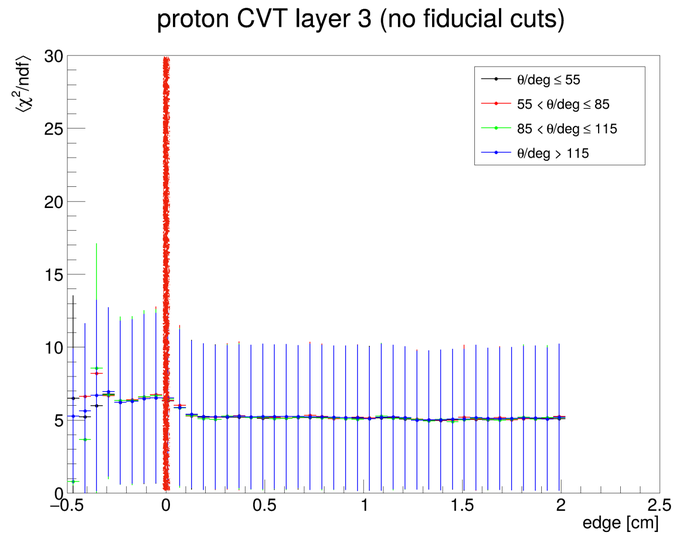
Backup: Fiducial Cut

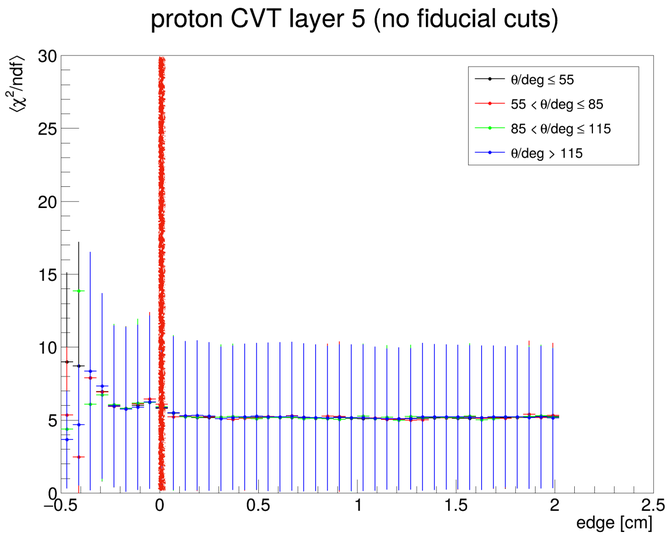
Proton

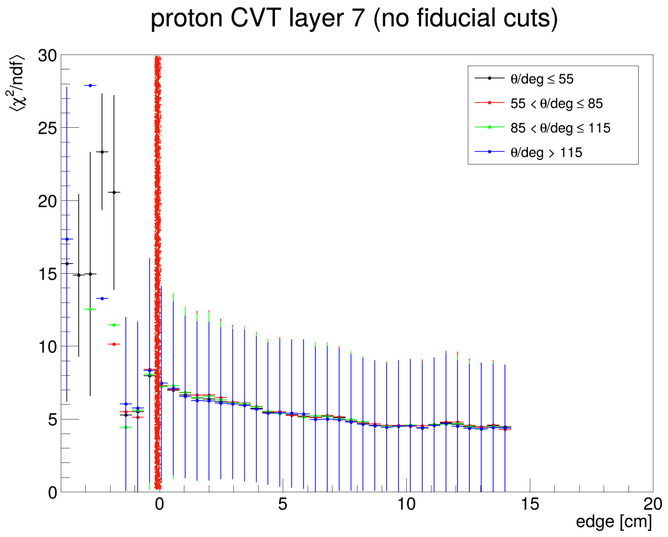
CVT

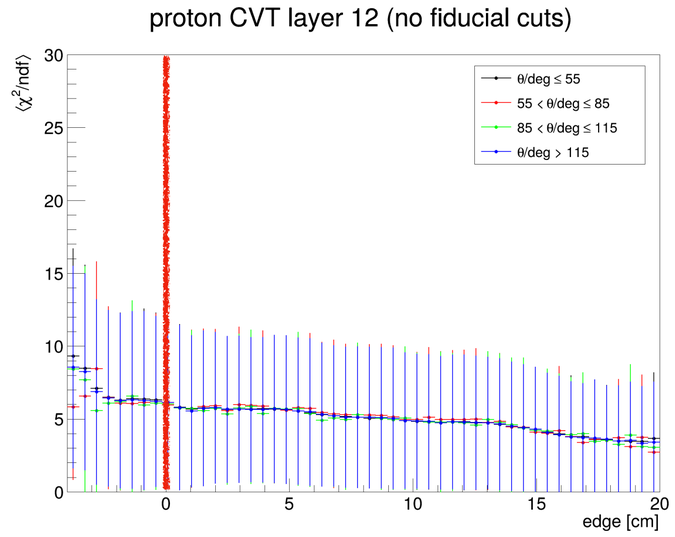
$edge > 5$ cm









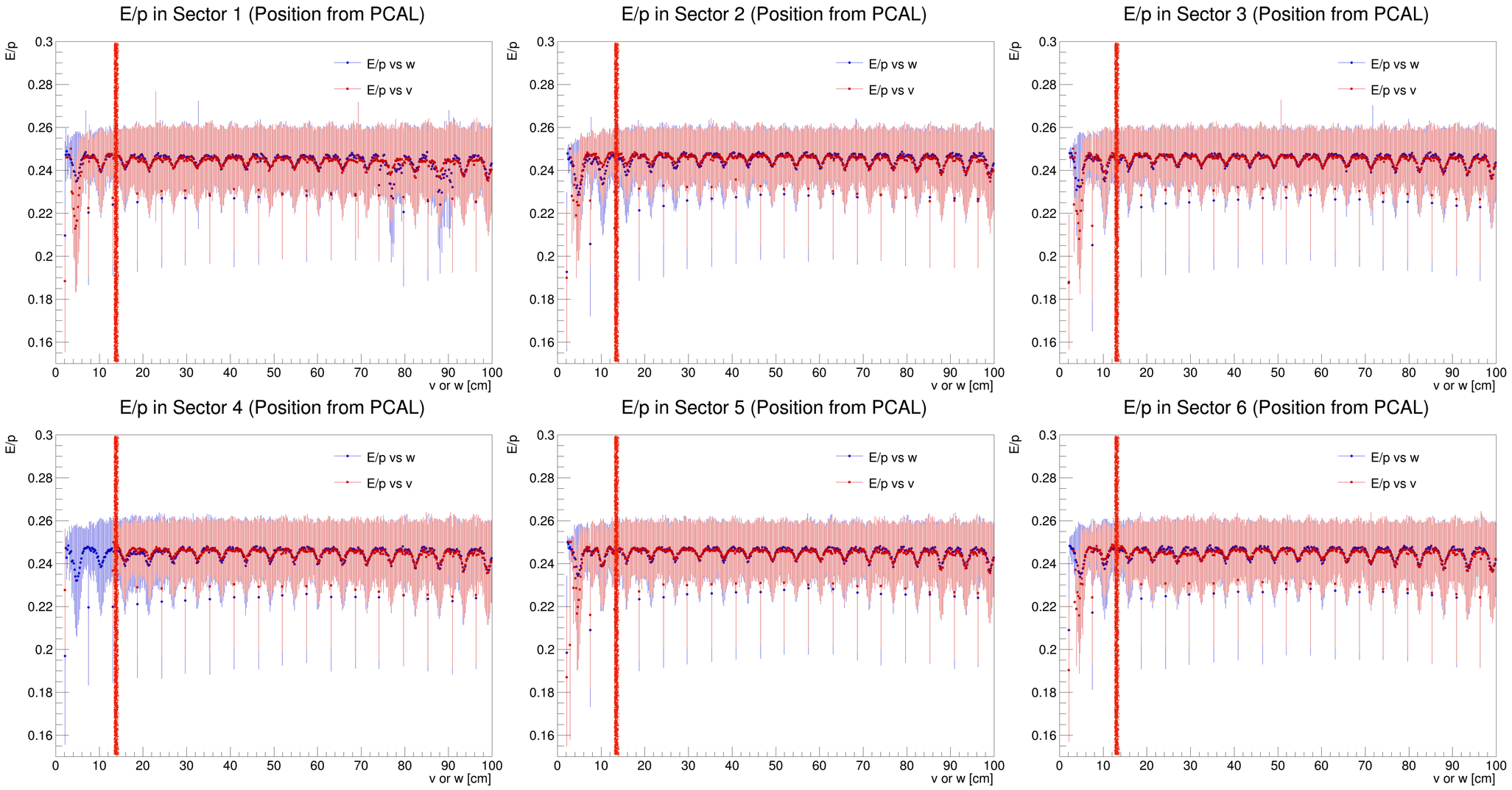


Backup: Fiducial Cut

Photon

ECAL, deposited energy

$v, w > 13.5$ cm

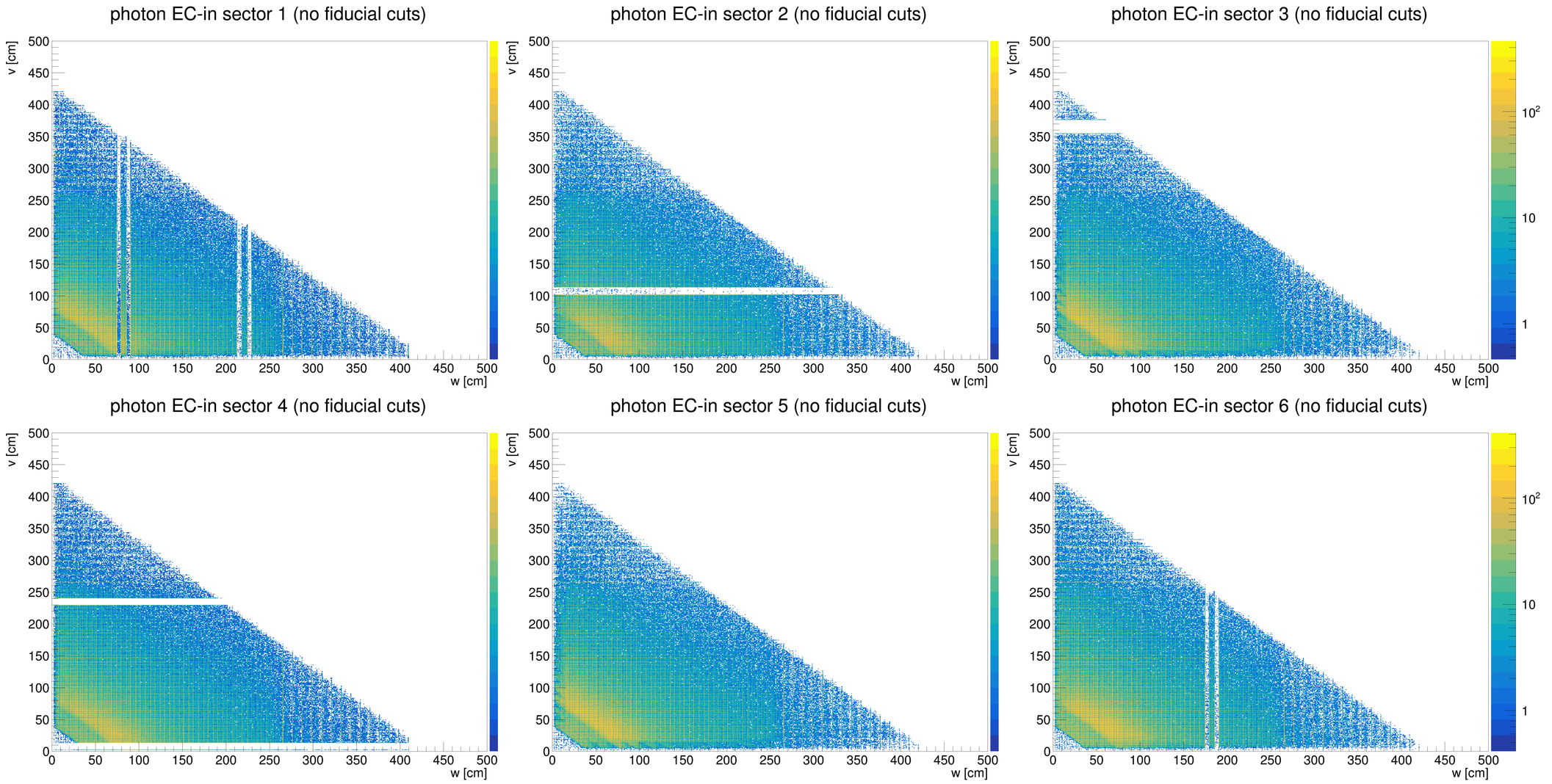


Backup: Fiducial Cut

Photon

ECAL, EC-in as an Example

remove bad strips



Backup: Data Skimming

Event Selection Criteria (DVCS analysis)

- ≥1 electron detected in FD
- ≥1 photon detected in FT or FD
- ≥1 proton detected in FD or CD

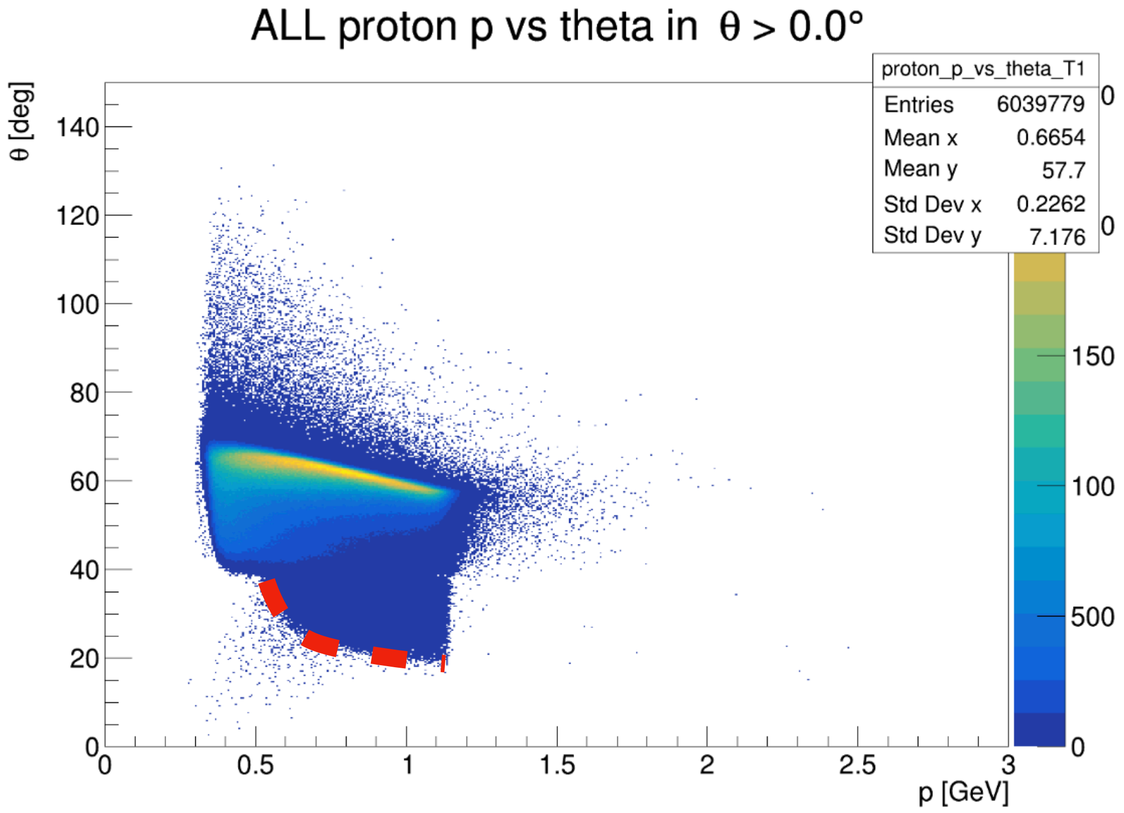
Kinematic cuts:

- $E_e > 0.1\, E_{beam}$
- $E_p > M_p + 5\,\mathrm{MeV}$
- $P_\gamma > 0.15\, E_{beam}$
- $Q^2 > 0.8\,\mathrm{GeV}^2$
- $W > 1.8\,\mathrm{GeV}$

Exclusivity cuts:

- Missing energy: $-1 < E_{miss} < 2\,\mathrm{GeV}$
- Proton missing mass²: $0.25 < MM_p^2 < 2.0\,\mathrm{GeV}^2$
- System missing mass²: $-0.1 < MM_{ep\gamma}^2 < 0.1\,\mathrm{GeV}^2$
- Transverse missing momentum: $P_T^{miss} < 0.75\,\mathrm{GeV}$
- Photon–missing photon angle: $\theta_{\gamma\gamma'} < 7.5^\circ$

Backup: Data Kinematics Coverage Constrained by Proton



Boundary From Proton:

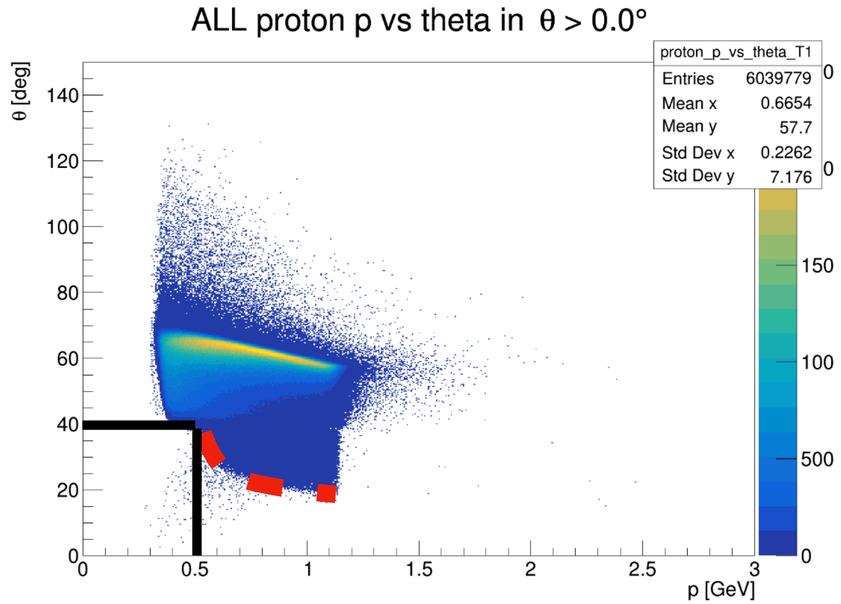
1. Strong boundary in FD, due to bending of low momentum protons
2. Boundary depends on p and θ

Proton momentum is equivalent to t

For Example:

$t = 0.25\ \mathrm{GeV}^2$ <=> $p = 0.51\ \mathrm{GeV}$

Backup: Data Kinematics Coverage Constrained by Proton



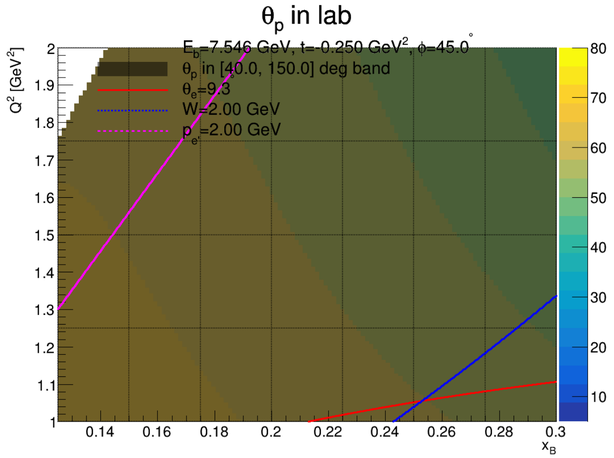
For Example:

$t = 0.25\ \mathrm{GeV}^2$ <=> $p = 0.51\ \mathrm{GeV}$

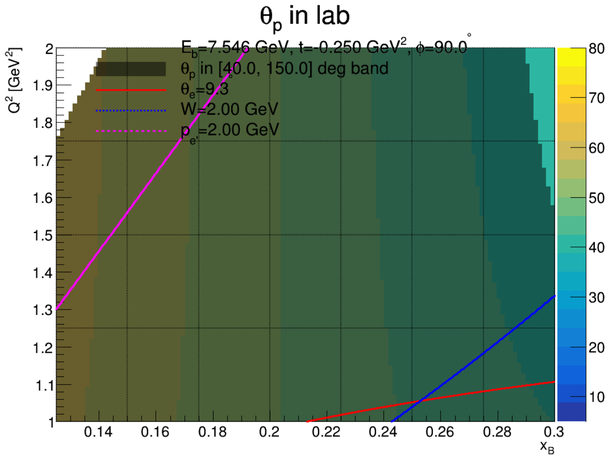
Read from the left plot: only $\theta > 40°$ proton is within boundary

This boundary depends on ϕ_{BMK}

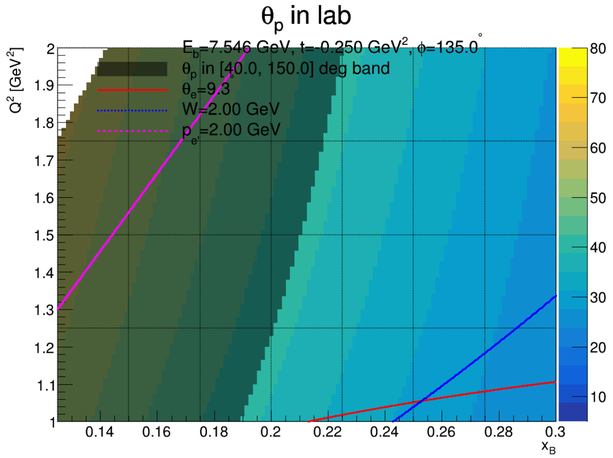
$\phi_{BMK} = 45°$



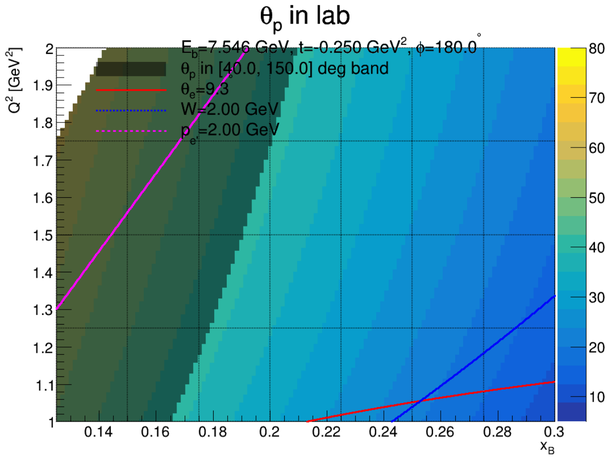
$\phi_{BMK} = 90°$



$\phi_{BMK} = 135°$

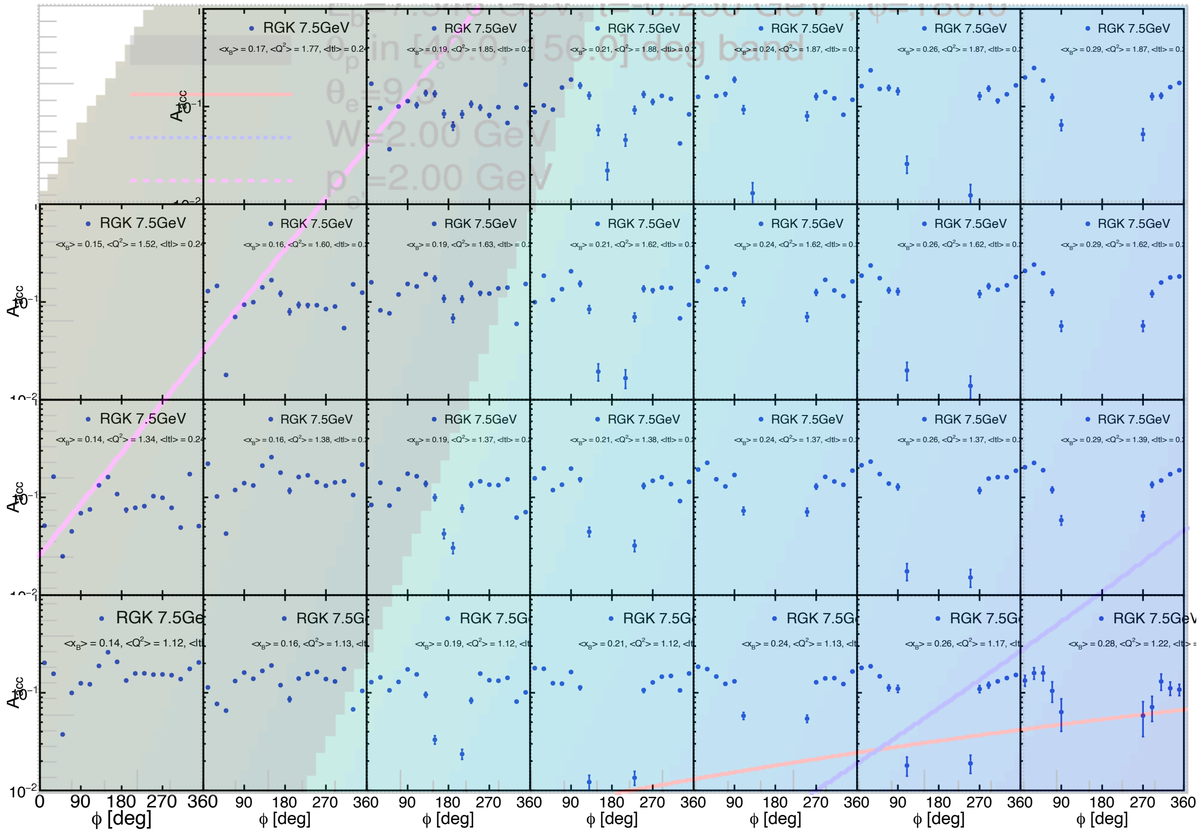


$\phi_{BMK} = 180°$

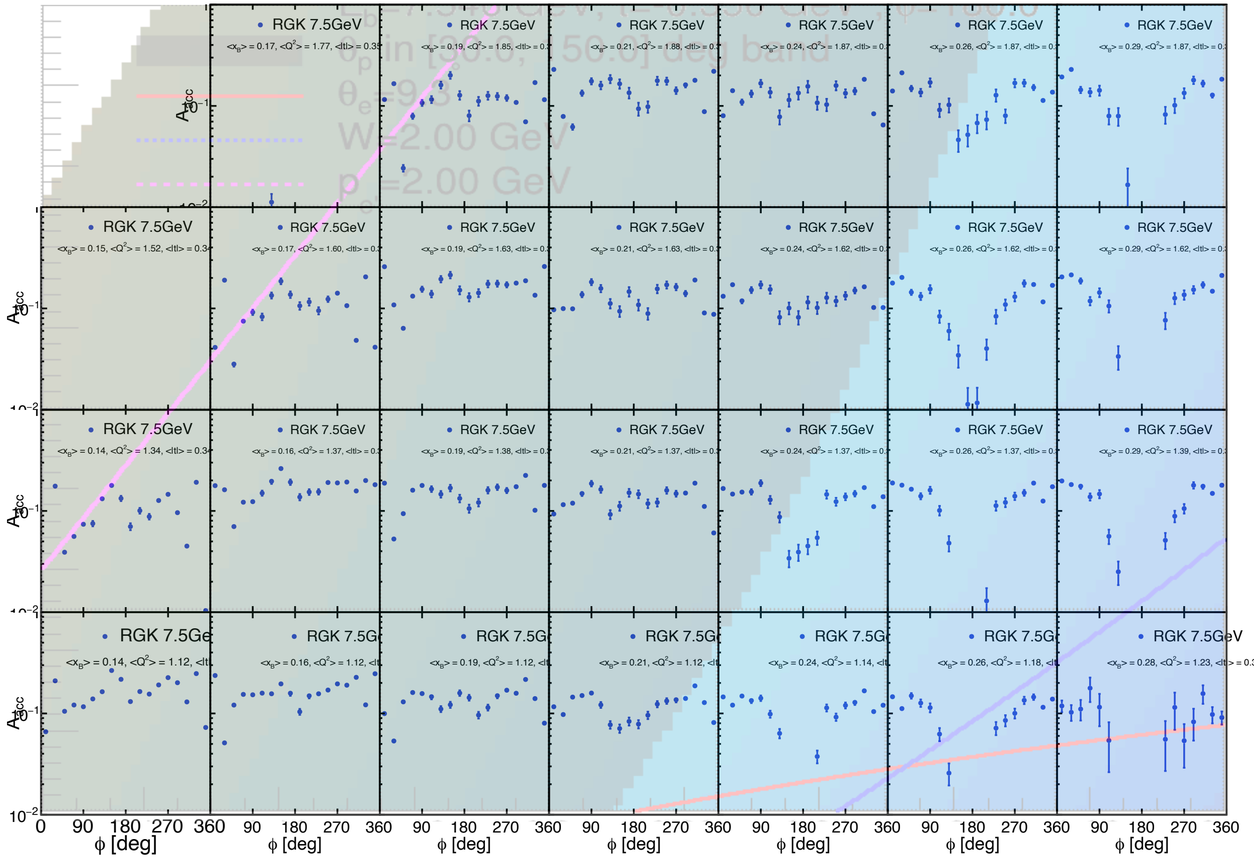


Backup: Data Kinematics Coverage Constrained by Proton

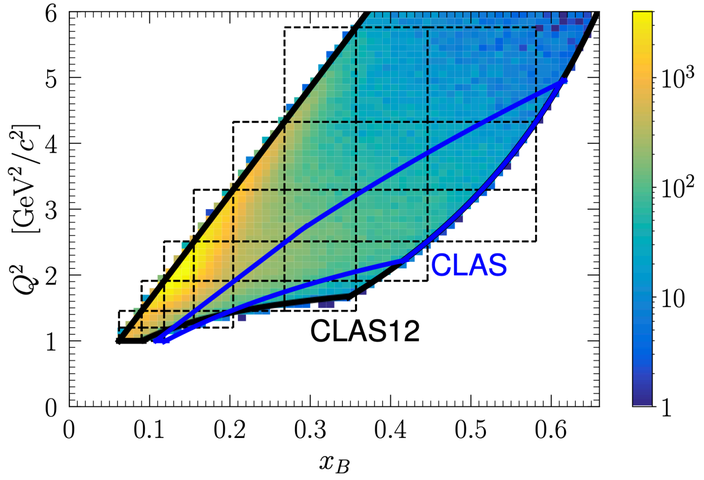
$t = 0.25\ \mathrm{GeV}^2$

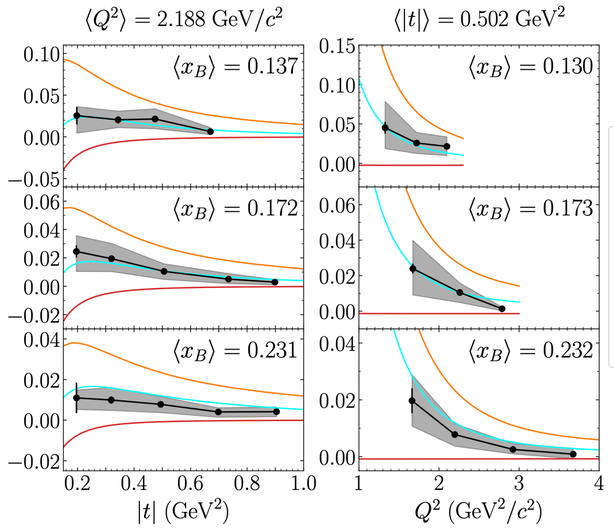


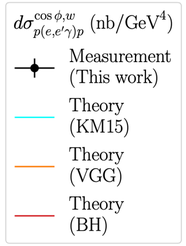
$t = 0.35\ \mathrm{GeV}^2$

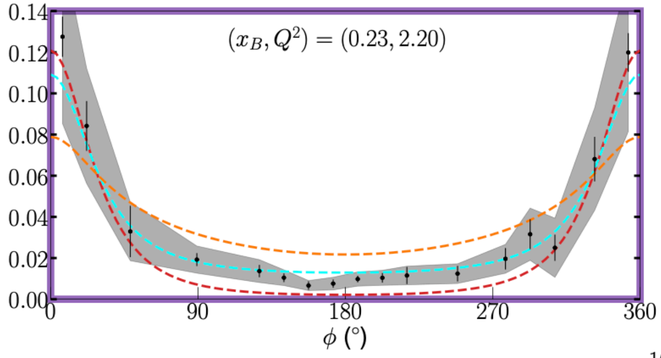


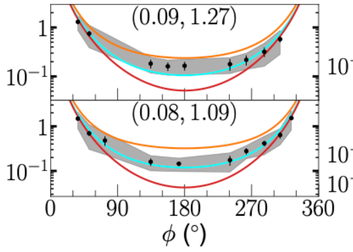
Backup: RGA — DVCS @ 12GeV

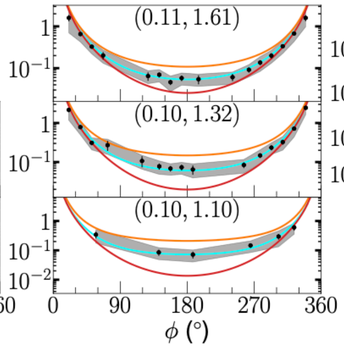


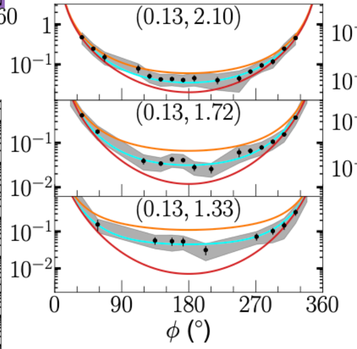


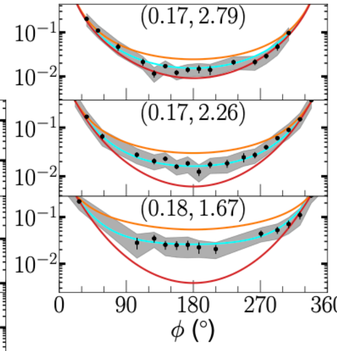


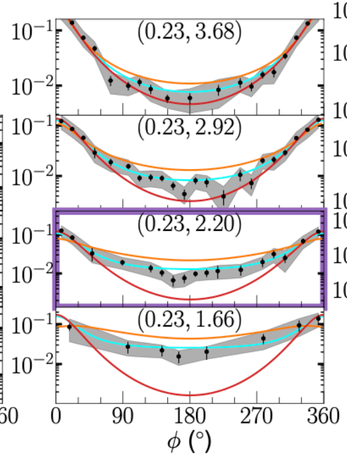


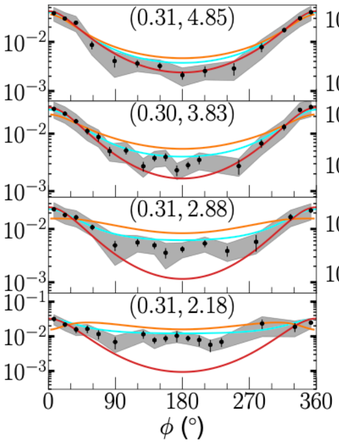


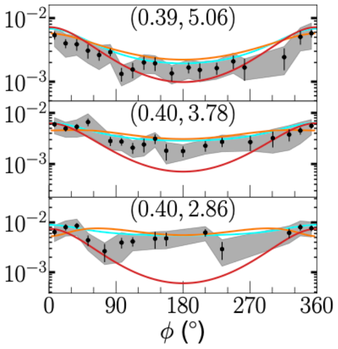


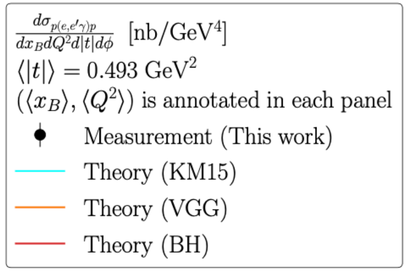












Sangbaek Lee