BONuS12 Analysis Status Report

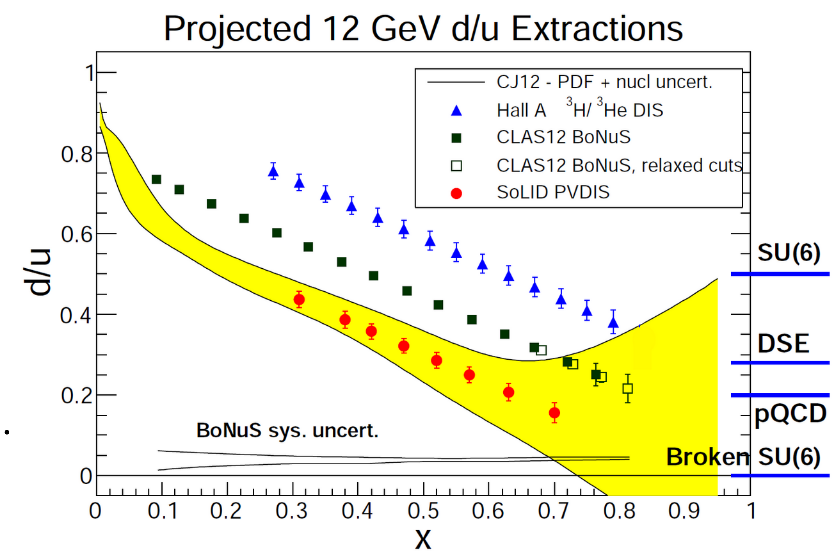
M. Hattawy
Old Dominion University

(On behalf of the CLAS Collaboration)

- **Physics Motivations.**
- **Experimental Setup.**
- **Status of Data Analysis.**
- **Conclusions.**

BONuS12: Spectator Tagging of Barely Off-Shell Neutrons in $D(e, e`p_s)X$

- DIS experiments have provided precise measurements on F_2^p, F_2^d up to fairly large x, but less precision on F_2^n specially at large x, where the theoretical modules have different predictions.

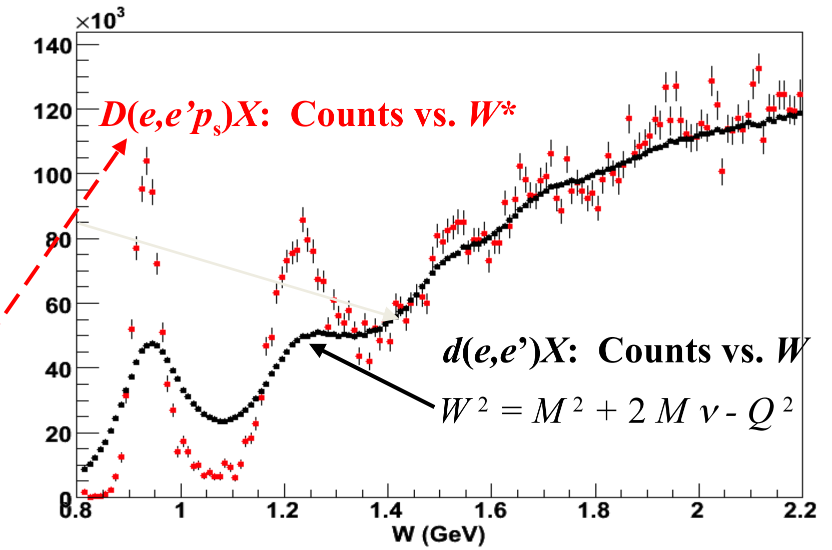


- F_2^n is obtained from measurements on bound neutrons, but F_2^n extraction at large *x* introduces theoretical model dependence on nuclear corrections (Fermi motion, nucleon off-shell corrections, FSI, .

- **BONuS12** constrains the nuclear uncertainties by using the **Spectator Tagging** technique, where correcting the neutron's kinematics implemented by measuring the spectator-proton results in improved resolution and constrains the kinematics of the knocked initial neutron to the phase-space where the nuclear uncertainties are minimized.

$$W^{*2} \approx M^{*2} - Q^2 + 2M\nu\,(2 - \alpha_s)$$

$$M^{*2} = (M_d - E_s)^2 - \vec{p}_s^{\,2} \qquad \alpha_s = \frac{E_s - p_{s_{||}}}{M_s}$$



BONuS12 Nuclear Uncertainties

Final State Interactions:

- Struck neutron interacts with the spectator p.
- Proton momentum is enhanced.
- FSIs are small at low p_s and large θ_{pq}.

Target Fragmentation:

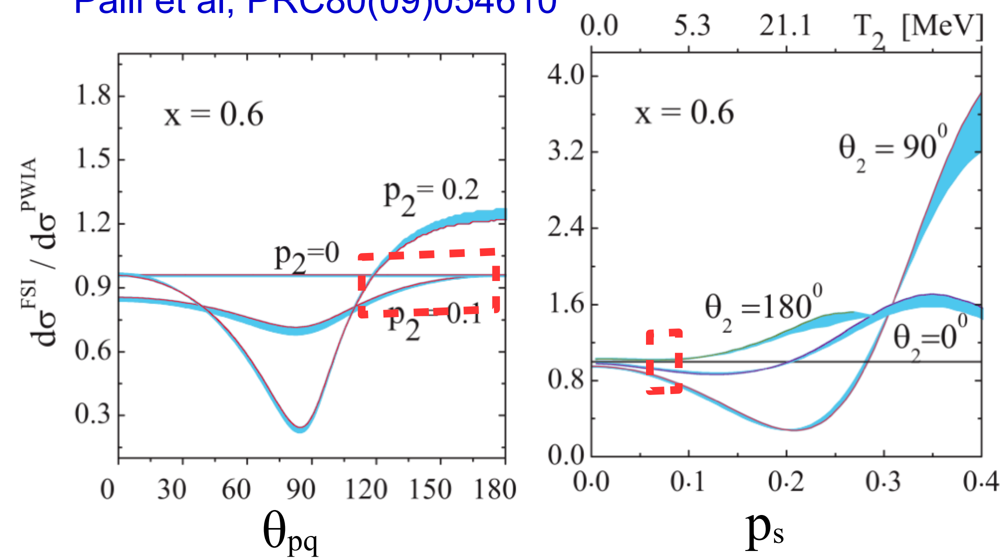
- $e\ n \rightarrow e\ p\ X$ (where $n \rightarrow \pi^- p$) and
  $e\ p \rightarrow e\ p\ X$ (where $p \rightarrow \pi^0 p$).
- TF enhances the proton yield only at forward angles ($\cos\theta_{pq} > 0.6$).

Off-Shell Corrections:

- Less than 2% in our region.

Overall systematic uncertainties will be less than 6%

Palli et al, PRC80(09)054610



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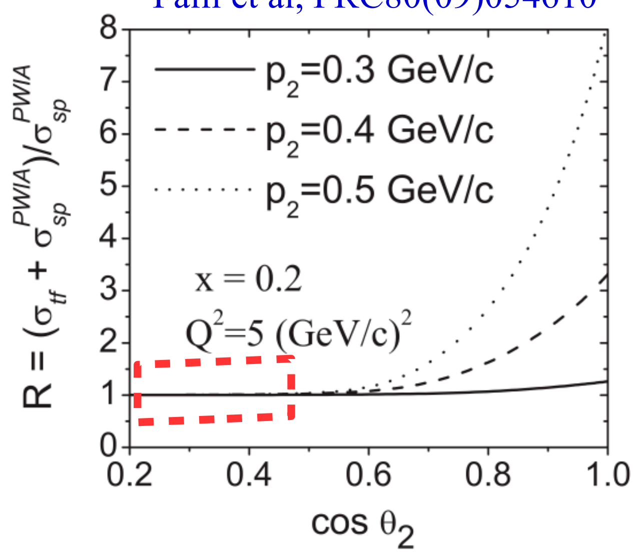
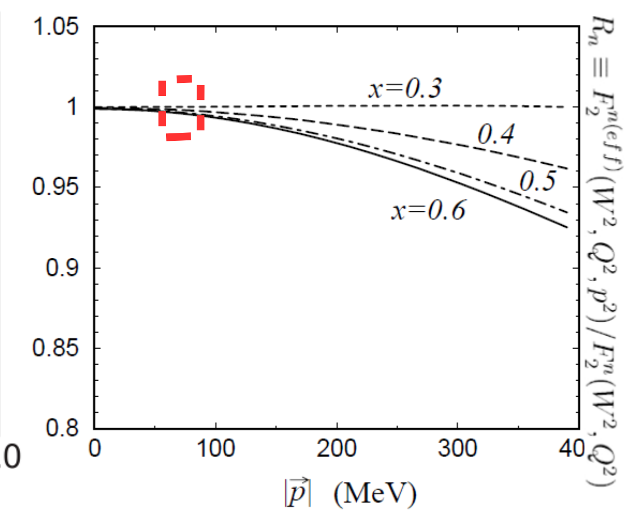


Melnitchoul et al, PRL B335,11(1994)



F_2^n / F_2^p Extraction Method

$D(e,e')X$

$$R_{\text{inc}}(x,Q^2) = \frac{Y_{\text{inc}}^{\text{Data}}}{Y_{\text{inc}}^{\text{MC}}} \propto \frac{F_{2d}^{\text{true}}(x,Q^2)}{F_{2d}^{\text{Gen}}(x,Q^2)}$$

$$Y_{\text{inc}}^{\text{Data}}(x,Q^2) \sim \mathcal{L} \cdot \text{A}(x,Q^2) \cdot \eta(x,Q^2) \cdot \Delta\sigma_{\text{inc}}(x,Q^2),$$

$$Y_{\text{inc}}^{\text{MC}}(x,Q^2) \sim \mathcal{L}_{\text{LUND}} \cdot \text{A}(x,Q^2) \cdot \eta(x,Q^2) \cdot \Delta\sigma_{\text{inc}}^{\text{Sim}}(x,Q^2),$$

With the assumption that $\Delta\sigma \propto F_{2d}$

$D(e,e'p_s)X$

$$R_{\text{tag}}(x',Q^2) = \frac{Y_{\text{tag}}^{\text{Data}}}{Y_{\text{tag}}^{\text{MC}}} \propto \frac{F_{2n}^{\text{true}}(x',Q^2)}{F_{2n}^{\text{Gen}}(x',Q^2)}$$

$$SR = \frac{R_{\text{tag}}(x',Q^2)}{R_{\text{inc}}(x,Q^2)} = \frac{\left(Y_{\text{tag}}^{\text{Data}}/Y_{\text{tag}}^{\text{MC}}\right)}{\left(Y_{\text{inc}}^{\text{Data}}/Y_{\text{inc}}^{\text{MC}}\right)} = \frac{\left(Y_{\text{tag}}^{\text{Data}}/Y_{\text{inc}}^{\text{Data}}\right)}{\left(Y_{\text{tag}}^{\text{MC}}/Y_{\text{inc}}^{\text{MC}}\right)} = \text{Constant} \cdot \frac{\left(\frac{F_{2n}}{F_{2d}}\right)^{\text{true}}}{\left(\frac{F_{2n}}{F_{2d}}\right)^{\text{Gen}}}$$

$$\left(\frac{F_{2n}}{F_{2d}}\right)^{\text{true}} = \text{Constant} \cdot \left(\frac{F_{2n}}{F_{2d}}\right)^{\text{Gen}} * \frac{\left(Y_{\text{tag}}^{\text{Data}}/Y_{\text{inc}}^{\text{Data}}\right)}{\left(Y_{\text{tag}}^{\text{MC}}/Y_{\text{inc}}^{\text{MC}}\right)}$$

$$\left(\frac{F_2^n}{F_2^p}\right)^{\text{true}} = \left(\frac{F_{2n}}{F_{2d}}\right)^{\text{true}} * \left(\frac{F_{2d}}{F_{2p}}\right)^{\text{fit}}$$

&

$$\frac{d}{u} \approx \frac{4F_{2n}/F_{2p} - 1}{4 - F_{2n}/F_{2p}}$$

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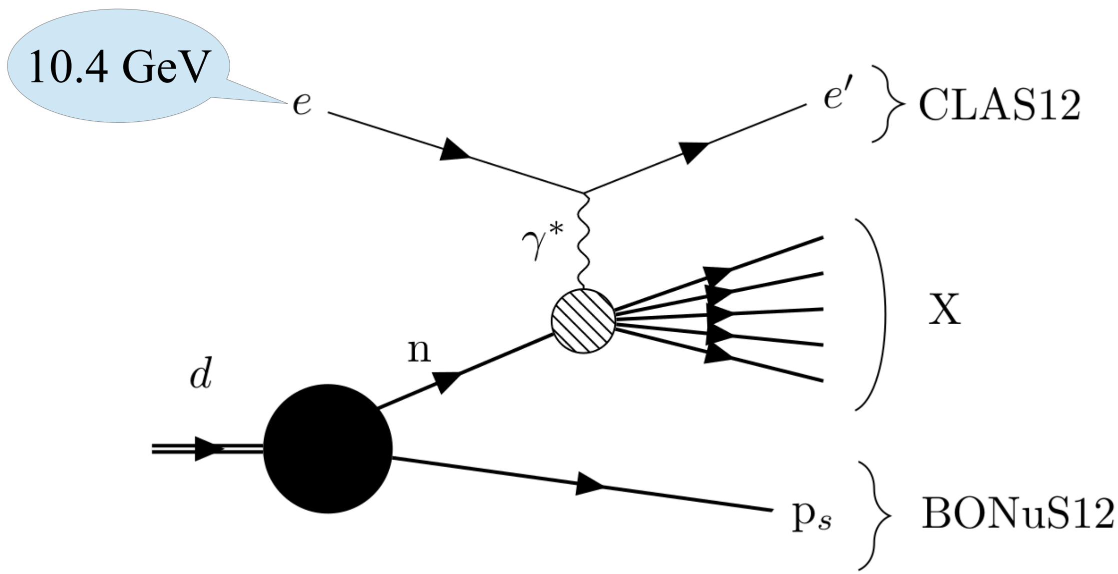
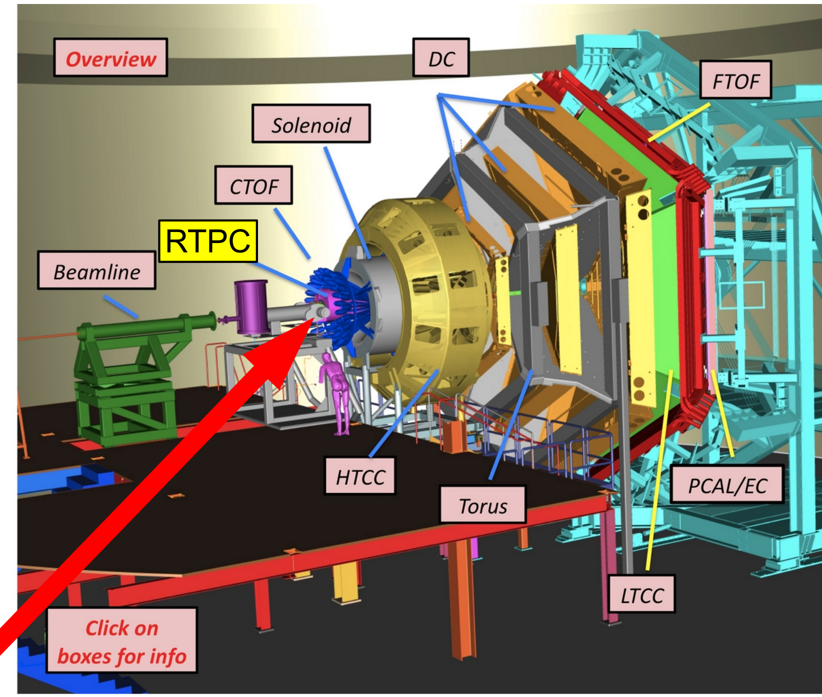
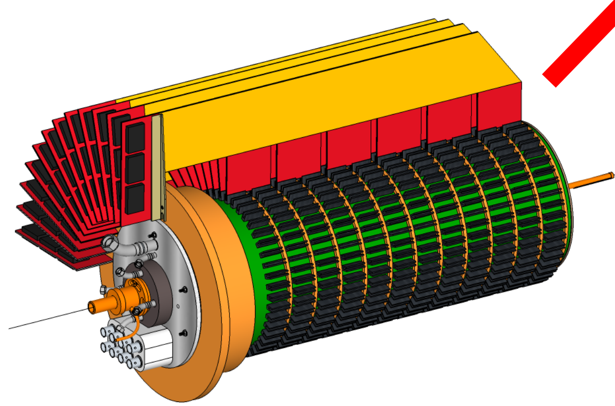
BONuS12 Experimental Setup







Beam Energy	Target	Spring 2020	Summer 2020
	H2	81M	185M
	D2	37M	45M
1 Pass Data	4He	19M	44M
	Empty	1M	22M
	Total	138M	296M
	H2	151M	266M
	D2	2275M	2355M
5 Pass Data	4He	77M	51M
	Empty	21M	45M
	Total	2524M	2717M

February – March 2020 | MEDCON6 | August-September 2020

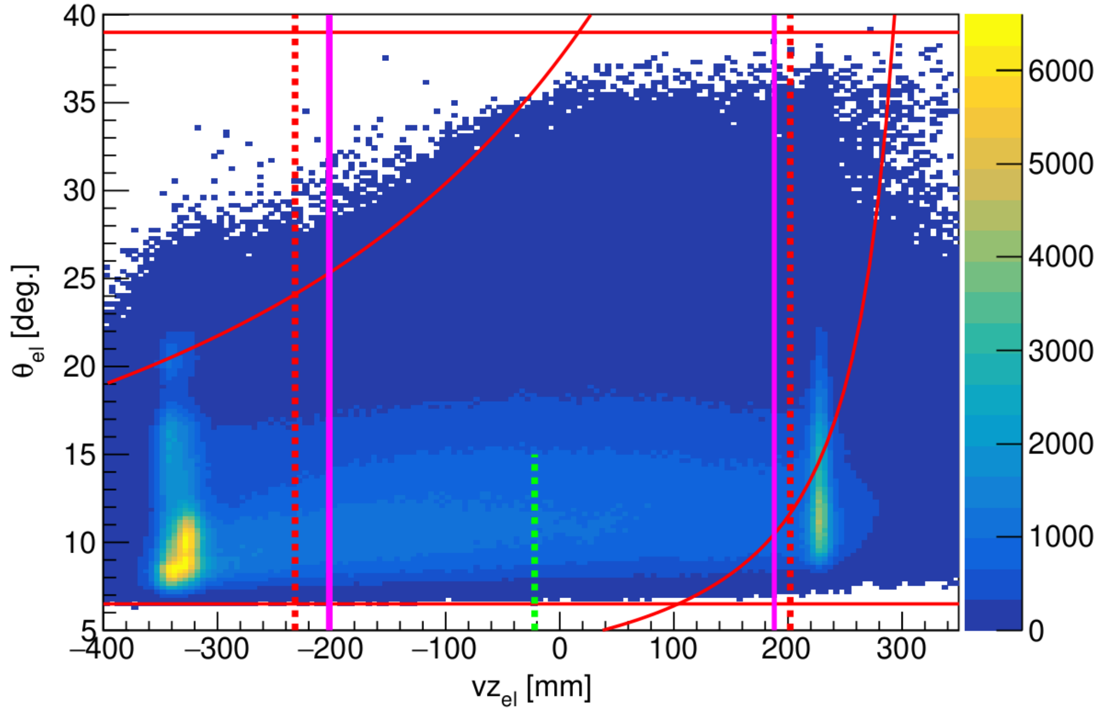
DIS-Electron Identification @10.4 GeV (1/2)

e- @10.4 GeV beam on D_2 target

BONuS12 Anaylsis Updates:
(Calibration, Simulation, PID, Resolutions, Efficiecies, backgrounds and accidentals, Data evaluation and Selection, ... etc):
- CLAS meeting on June 2024
- CLAS Meeting on March 2024

Electron selection cuts

- PID = 11
- nphe > 2
- $E_{tot}/p > 0.2$
- $EC_{in} > 10$ MeV
- $E_{PCal} > 100$ MeV
- DC fiducial cuts
- E` > 2 GeV
- vz_{e-} - Relaxed cut on the tagged events



DIS-Electron Identification @10.4 GeV (2/2)

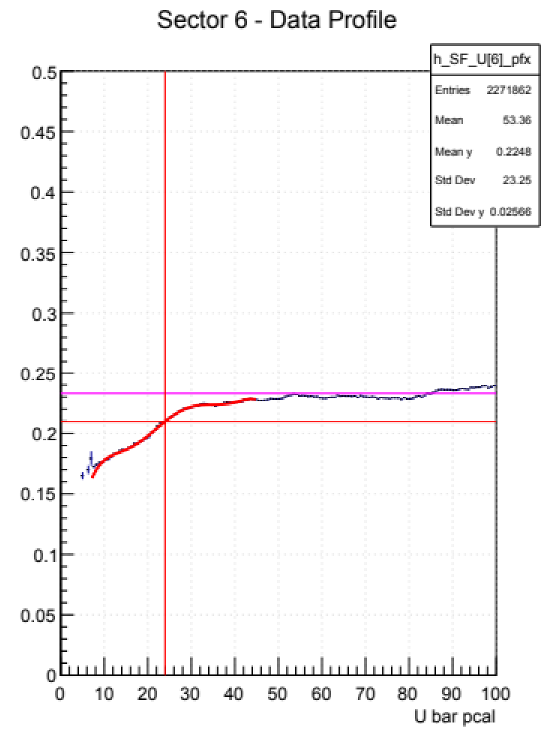
e- @10.4 GeV beam on D_2 target

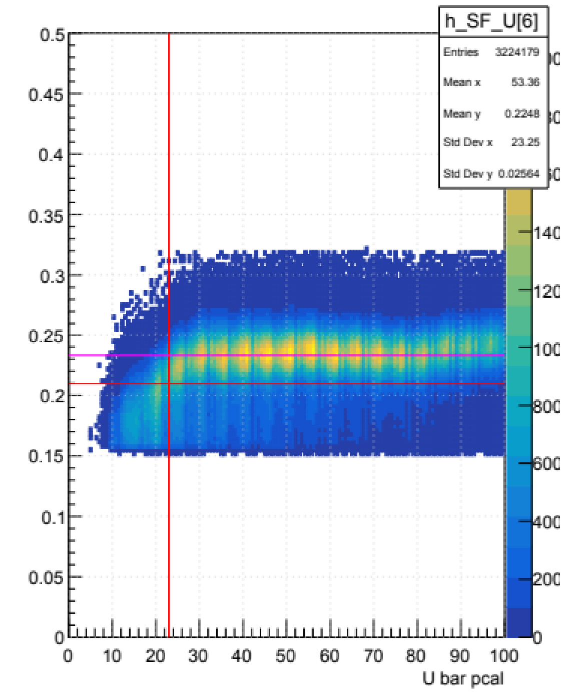
Electron selection cuts

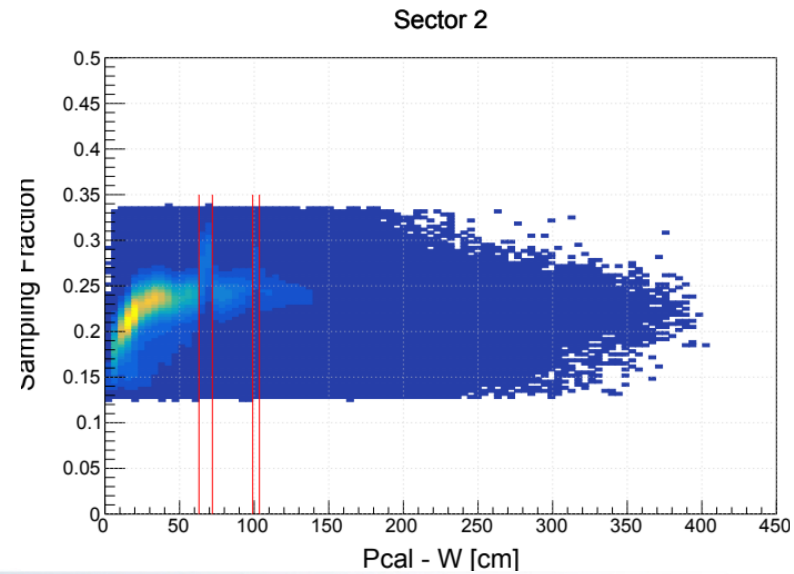
- PID = 11
- nphe > 2
- $E_{tot}/p > 0.2$
- $EC_{in} > 10$ MeV
- $E_{PCal} > 100$ MeV
- DC fiducial cuts
- E` > 2 GeV
- vz_{e-}
- PCal SF and Fiducial cuts:
  - SF in {U,V,W} vs. 6 Sectors:
    drop at 90%,
    18 function of mean and sigma for SF.
  - additional Fid. Cut on W in Sec.2
    (for both Exp. and Sim.)

Additional DIS cuts

- W cut (for Exp. And Sim.)
- $Q^2 > 1.0\ GeV^2$







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Tagged-Proton nDIS Selection @10.4 GeV

Tagged-Proton Selection from D_2 Data

RTPC track quality cuts:

- The radius of curvature of tracks (< 0)
- Cut on χ^2 of helix fitter (< 5)
- Number of hits in a track (> 10)
- Cut on the maximum radius (67-72) mm
- Fiducial cut (vz: (-210, 180)mm)

Coincidence cuts

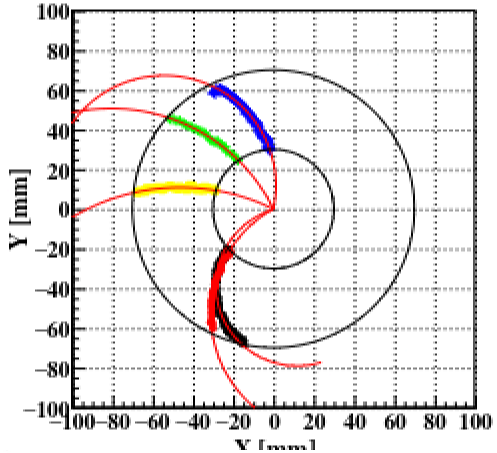
- Vertex coincidence cuts
- Timing coincidence

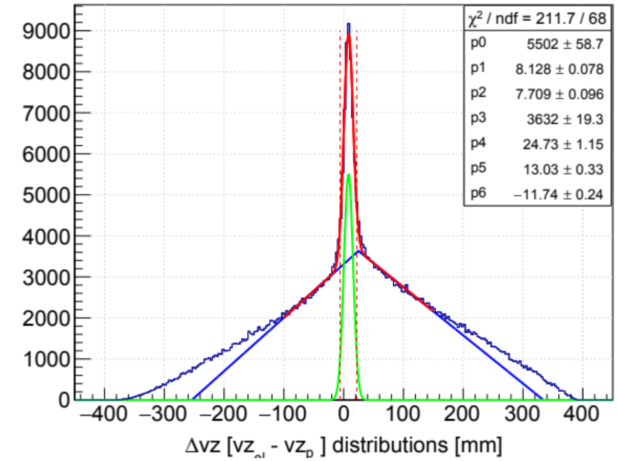
PID Cuts:

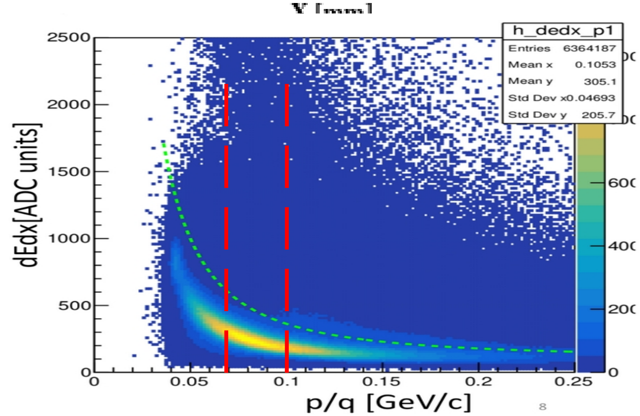
- Cuts on dEdx vs. p/q band for proton selection

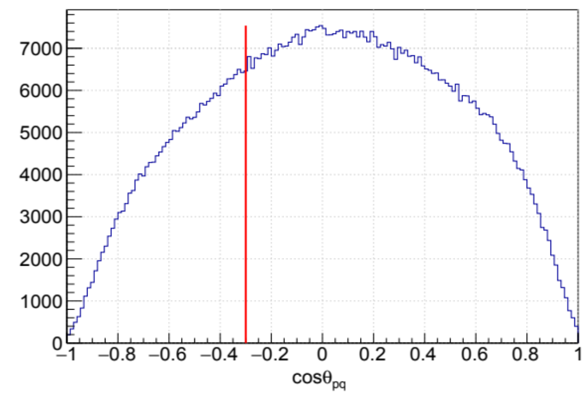
DIS & VIP cuts

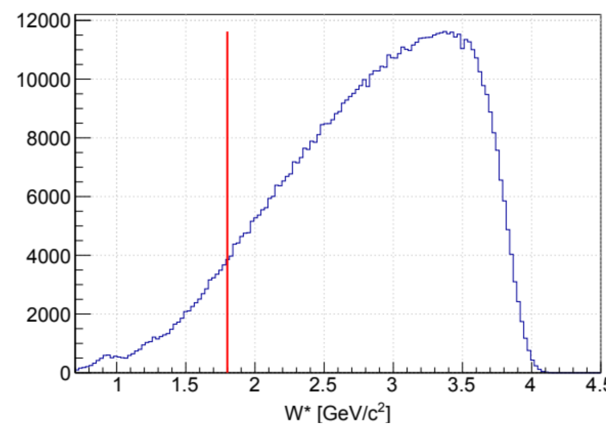
- W* > 1.8 GeV
- 0.07 < p < 0.1 GeV/c
- $\cos(\theta_{pq})$< -0.3











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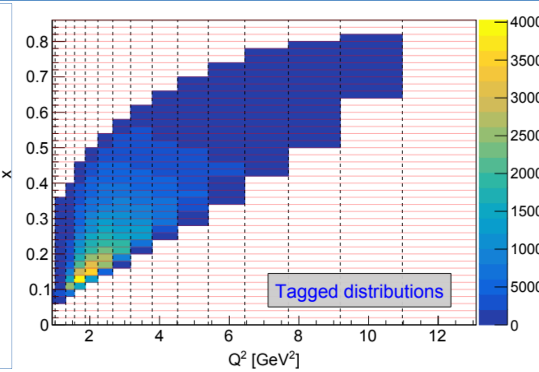
Matching the Inclusive to Tagged Data (1/3)

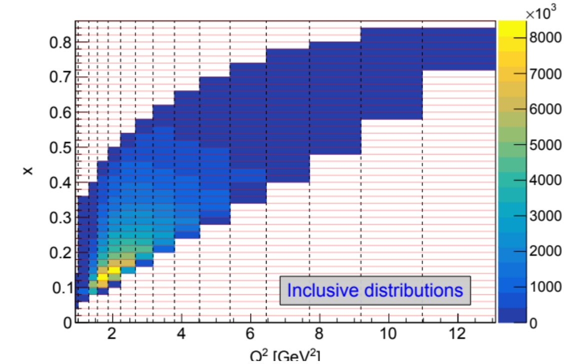
» Match the CLAS12 acceptance for the inclusive DIS events to that of the Tagged collected data.

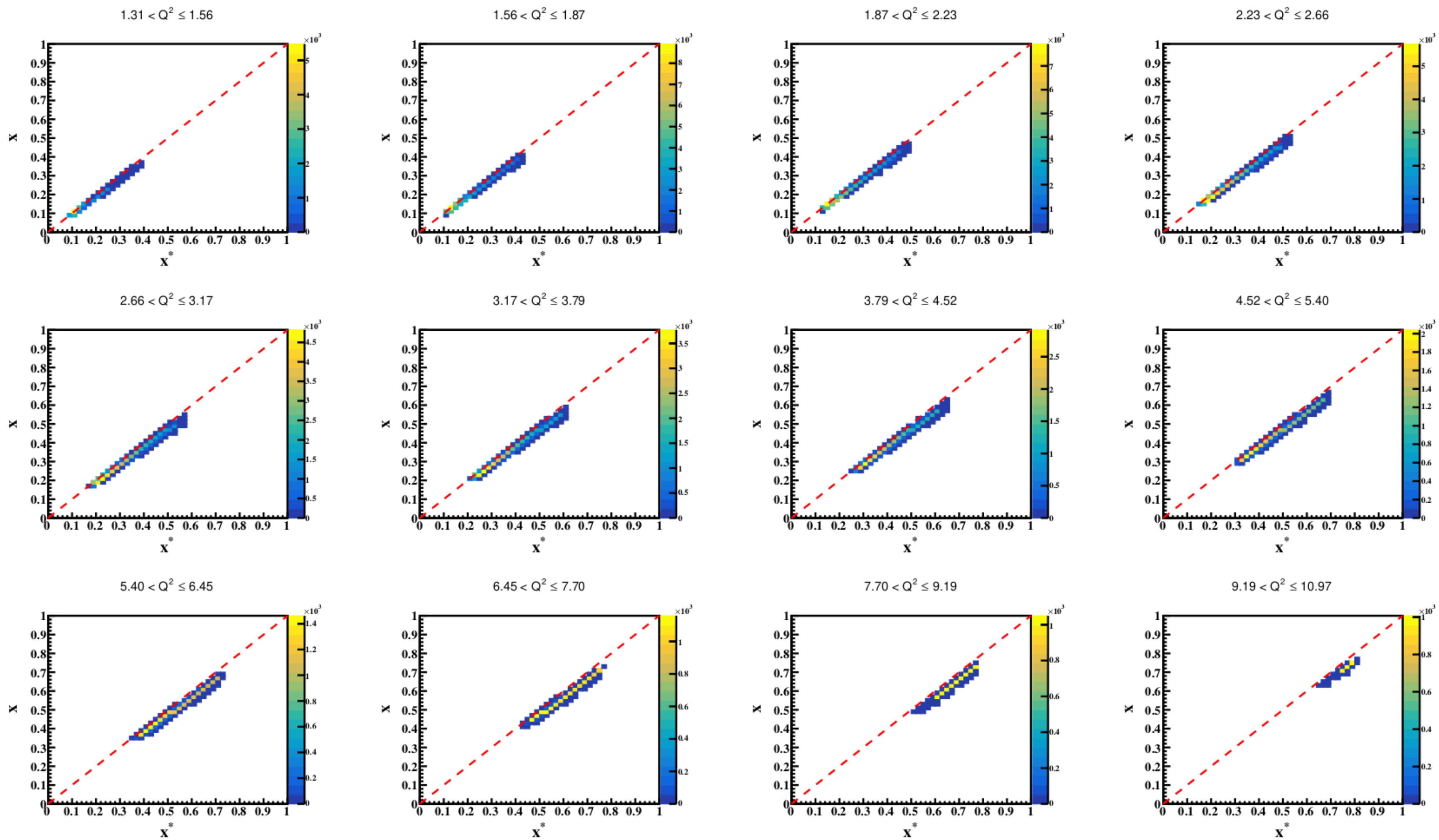
» Using the collected tagged nDIS events

→ Correlation of x vs. x*

→ Get x for every x*







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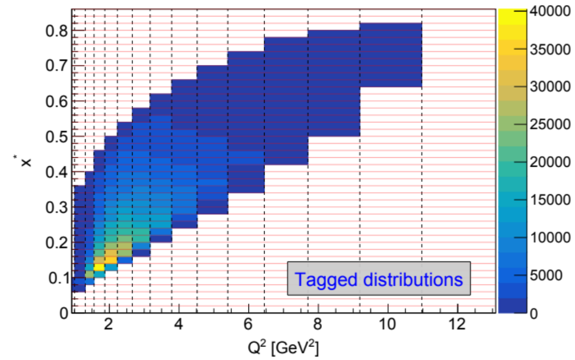
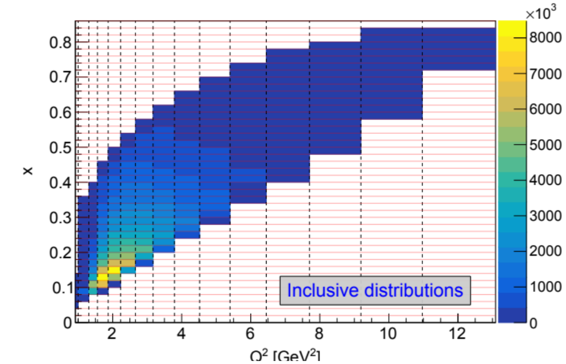
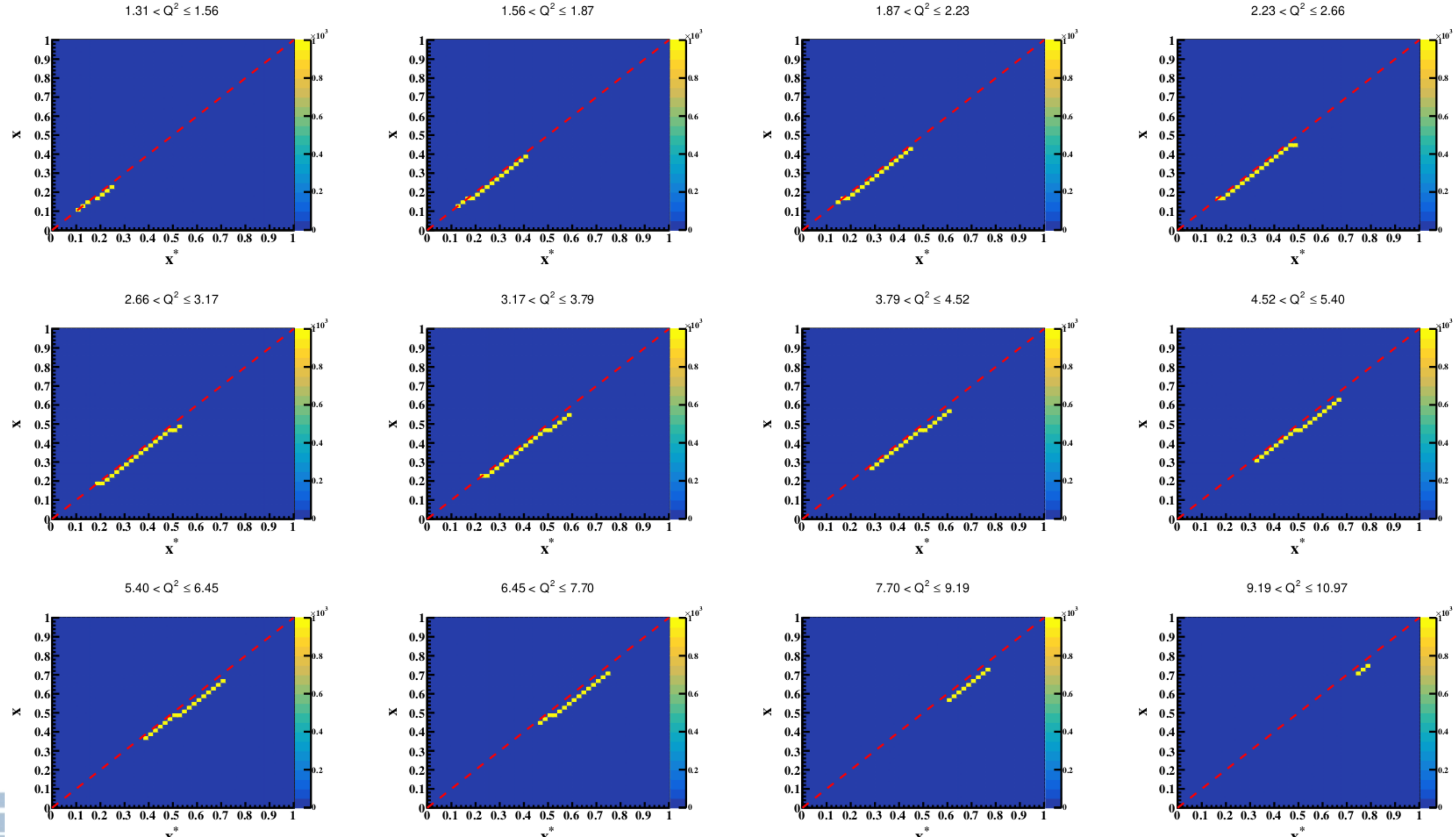
Matching the Inclusive to Tagged Data (2/3)

Match the CLAS12 acceptance for the inclusive DIS events to that of the Tagged collected data.

Total of 171 bins in Q2 vs. x(x*)



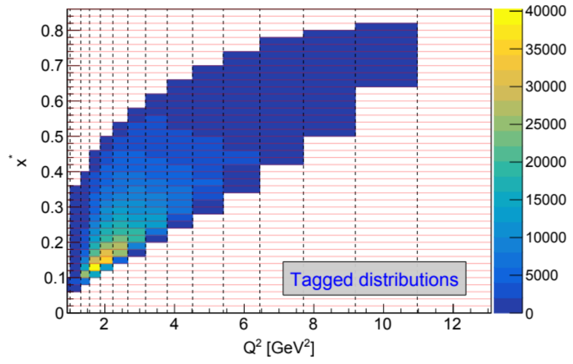


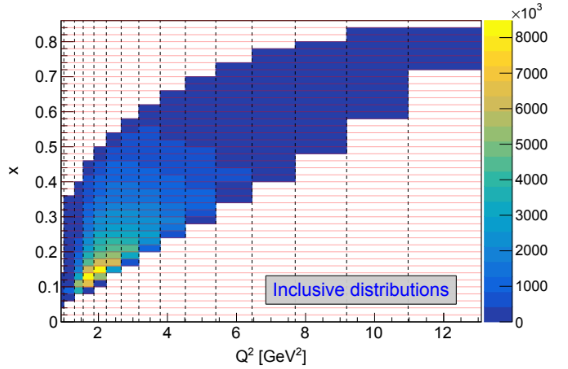


Matching the Inclusive to Tagged Data (3/3)

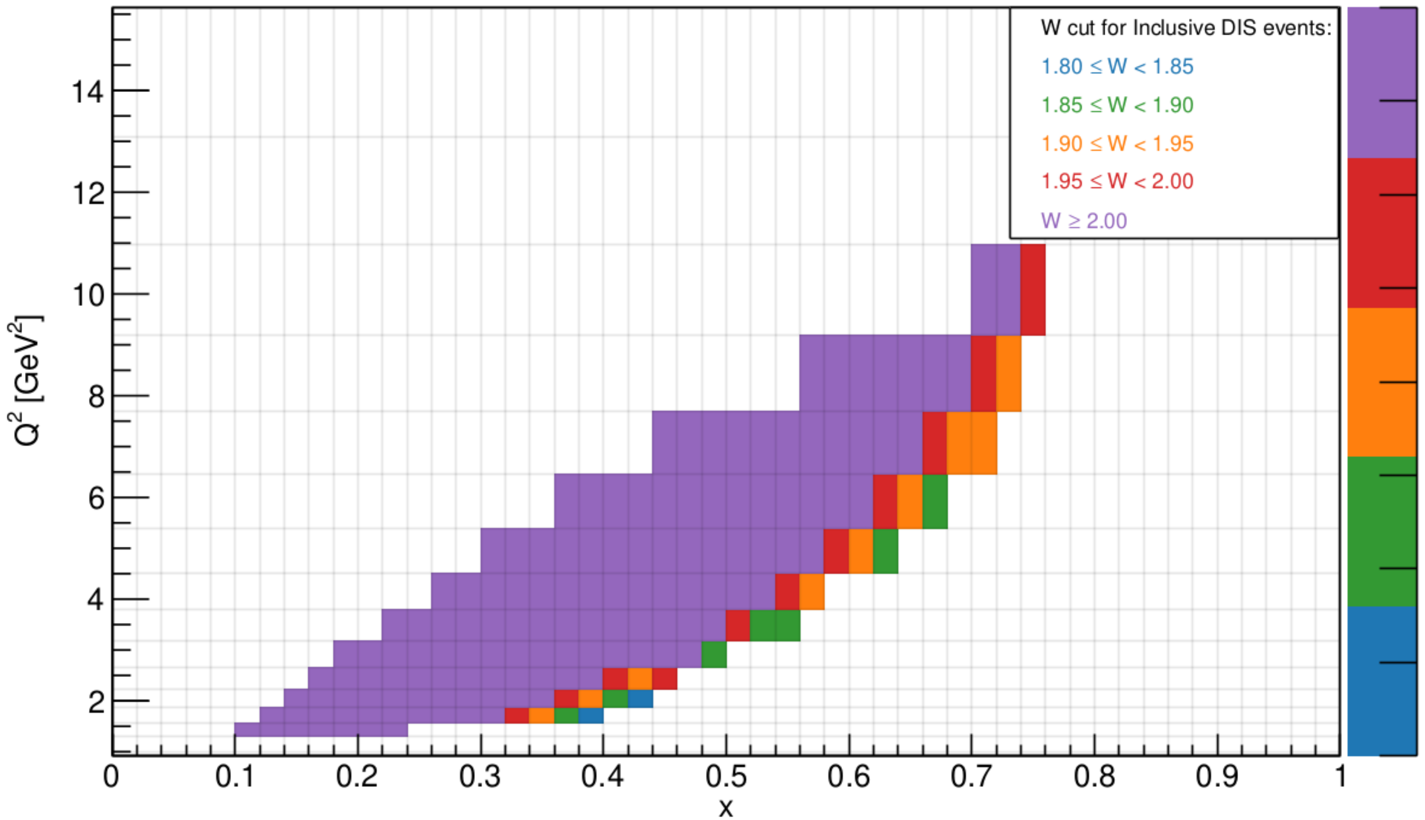
Match the CLAS12 acceptance for the inclusive DIS events to that of the Tagged collected data.

Total of 171 bins in Q2 vs. x(x*)





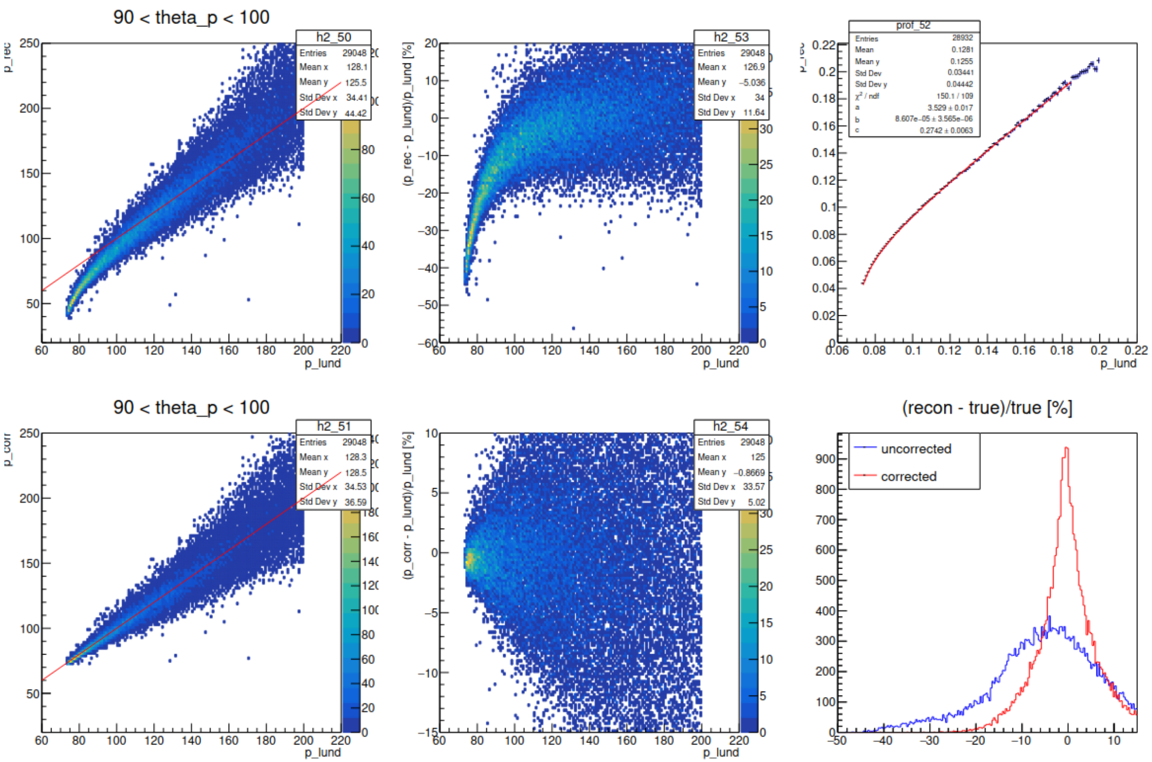
- x-dependent W cut (for Exp. And Sim.)



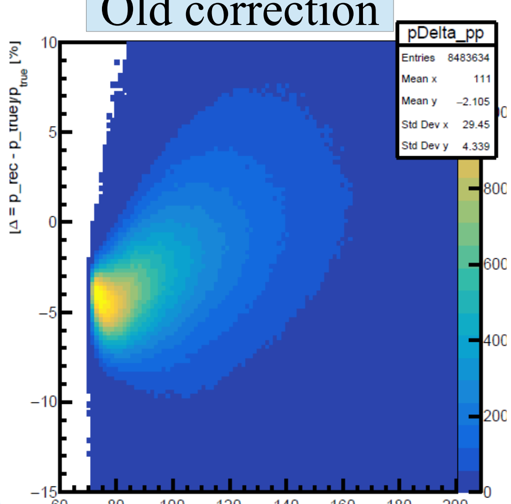
Improving the RTPC Momentum Correction (1/2)

- 1st RTPC momentum correction extracted using simulated radiative elastic events
→ Lake of statistics in the VIP region of interest (low momentum tail).

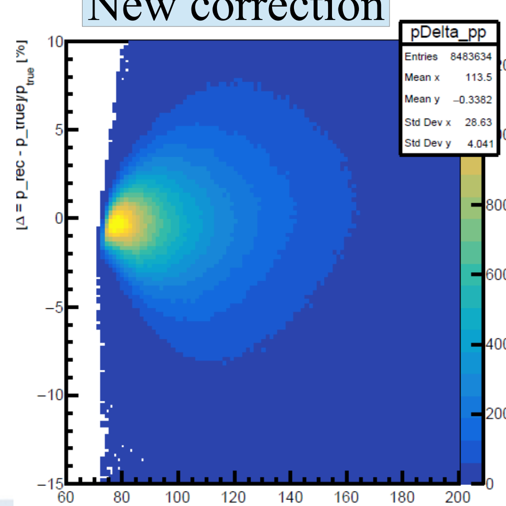
- New correction from flat phase-space simulated protons:
  - » precise p_rec vs. p_gen in all the phase-space.
  - » applied to both Exp. and Sim. data.



Old correction



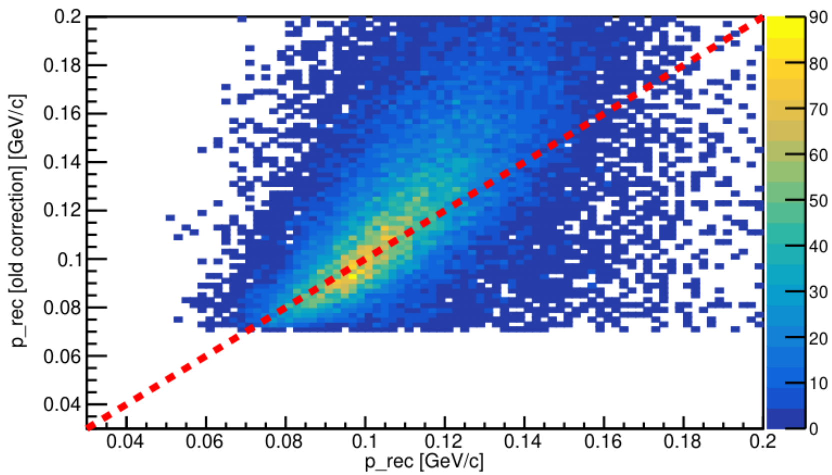
New correction

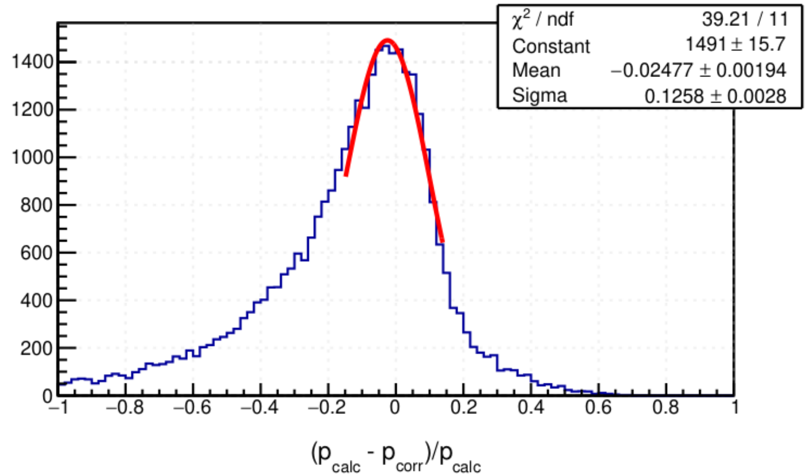


Improving the RTPC Momentum Correction (2/2)

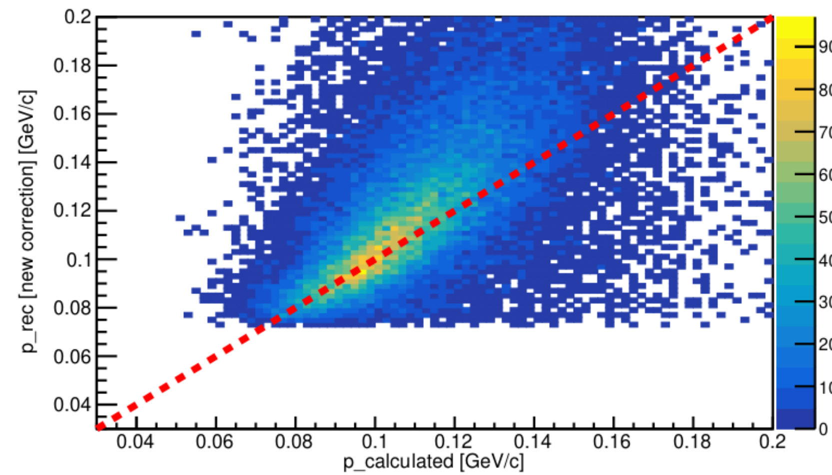
Testing the quality of the new momentum correction compared to the previous correction using the 2 GeV radiative elastic ep events.

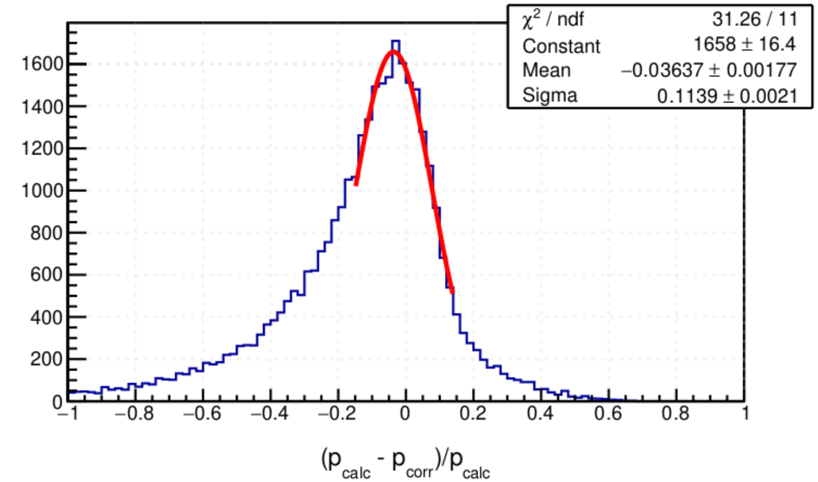
OLD momentum Correction





NEW momentum Correction





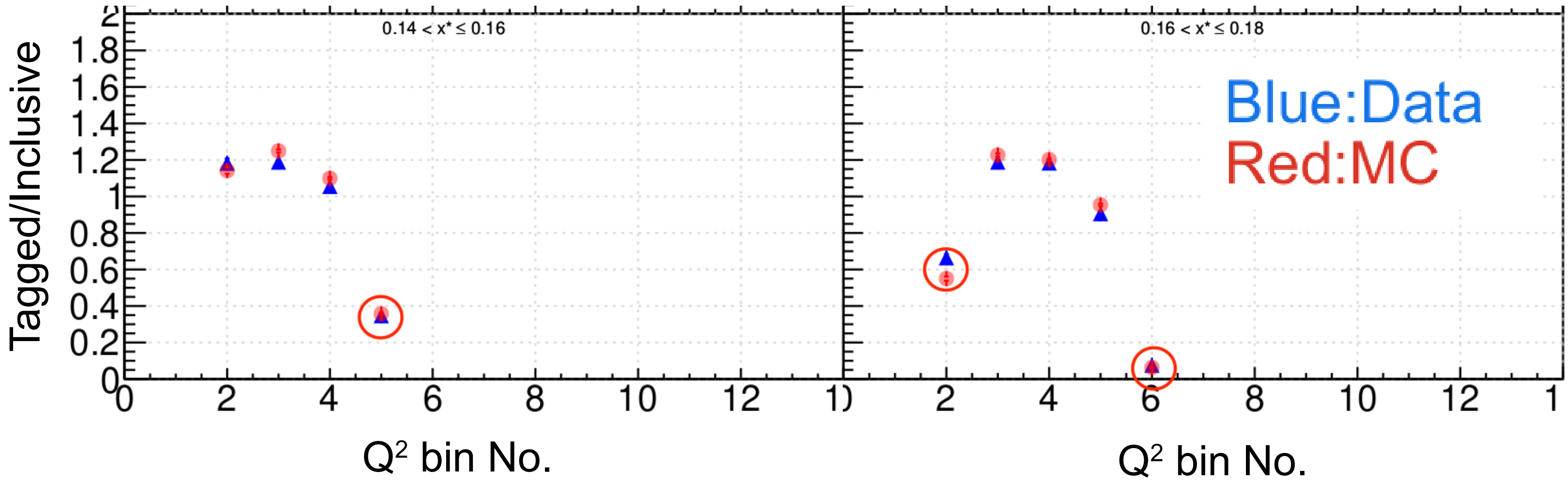
Data Filtration (1/2)

Minimizing the Statistical fluctuations on the Q^2-integrated yield ratios based on Simulation.

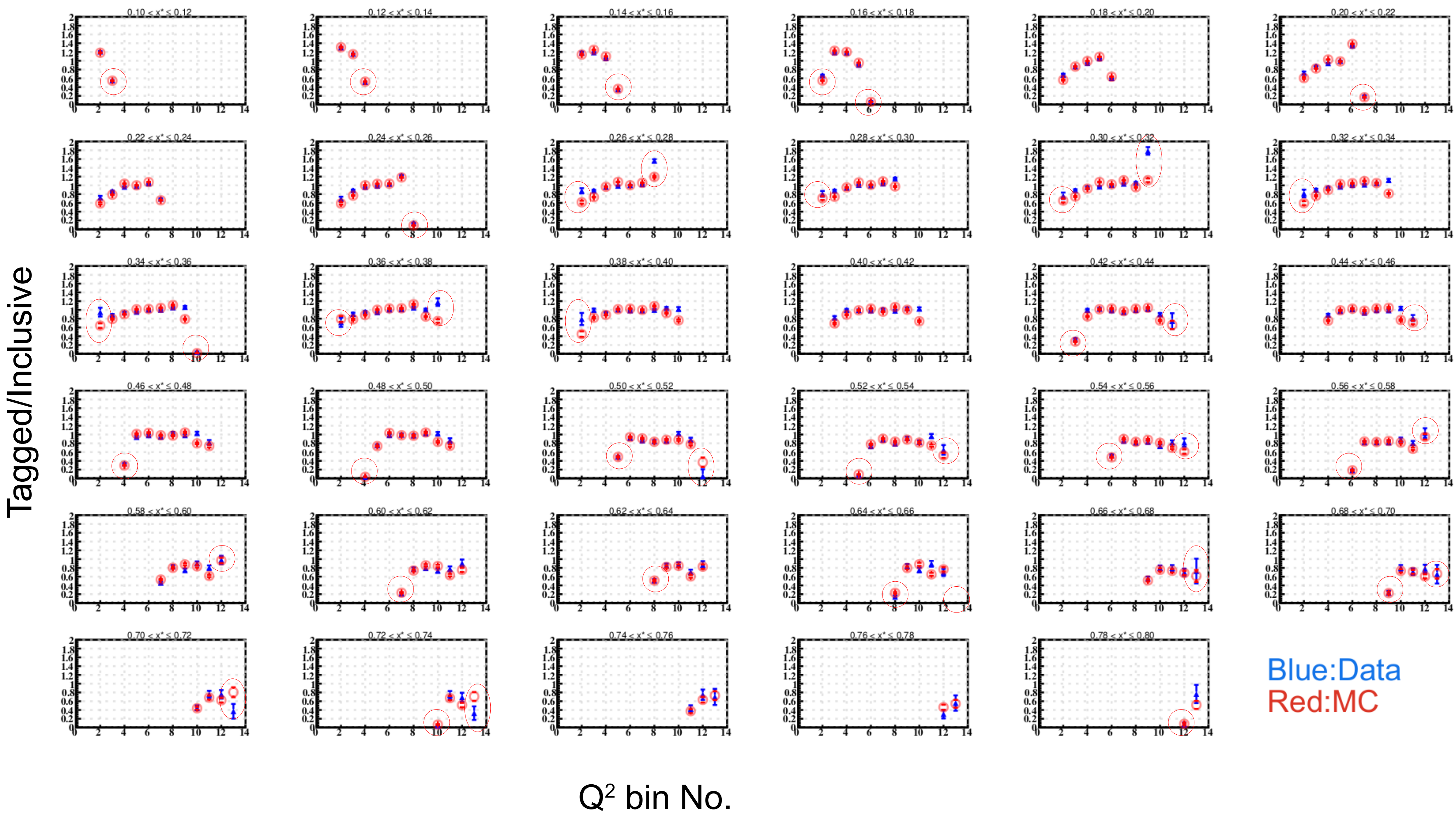
Criteria:

1) Simulated Tagged/Inclusive ratio is less than 60% of others in the same x-bin

2) Simulated Tagged/Inclusive ratio error bar is greater than 1.8x the average for the same x-bin



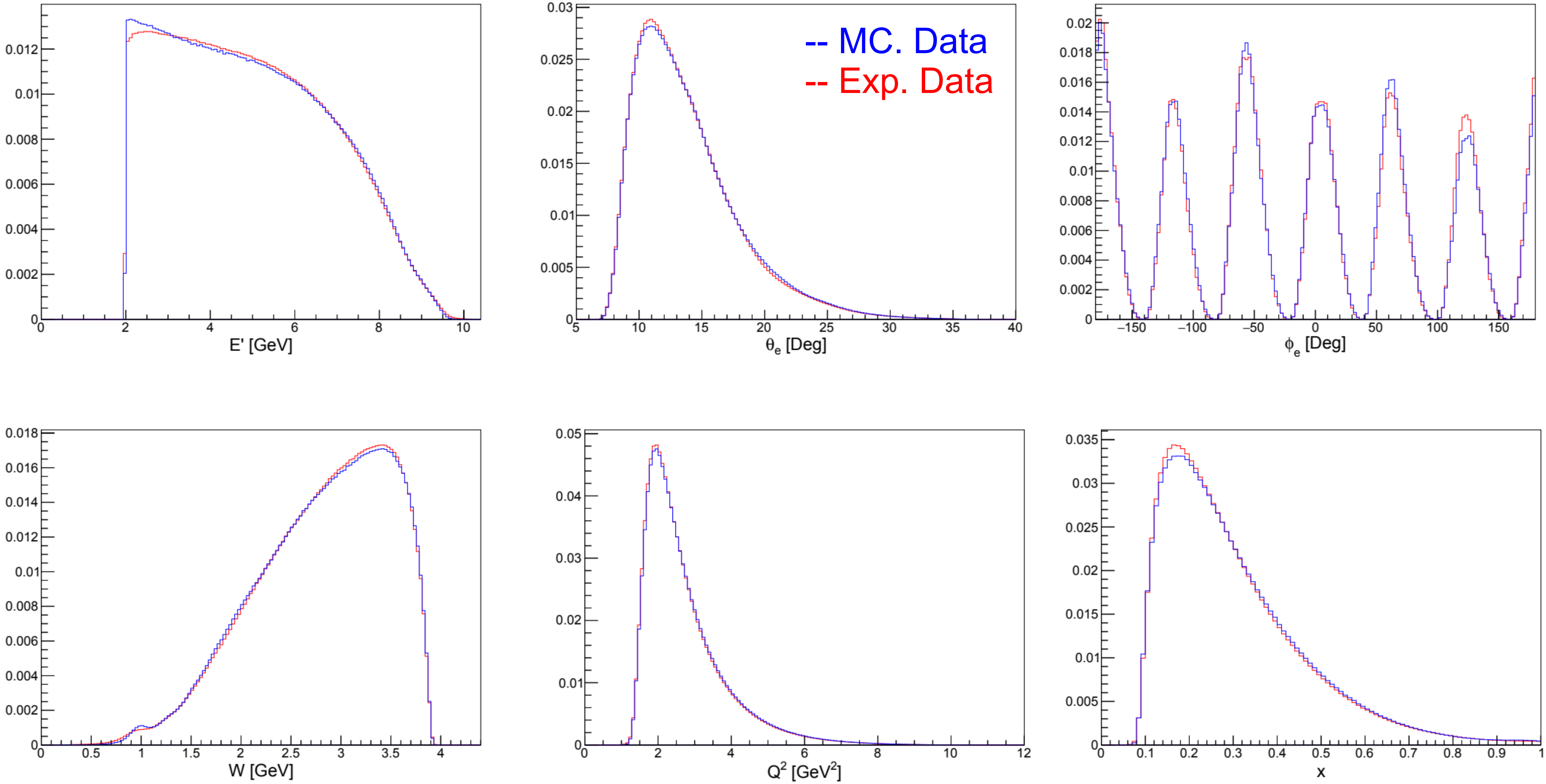
Data Filtration (2/2)



Data vs. MC : D(e,e')X

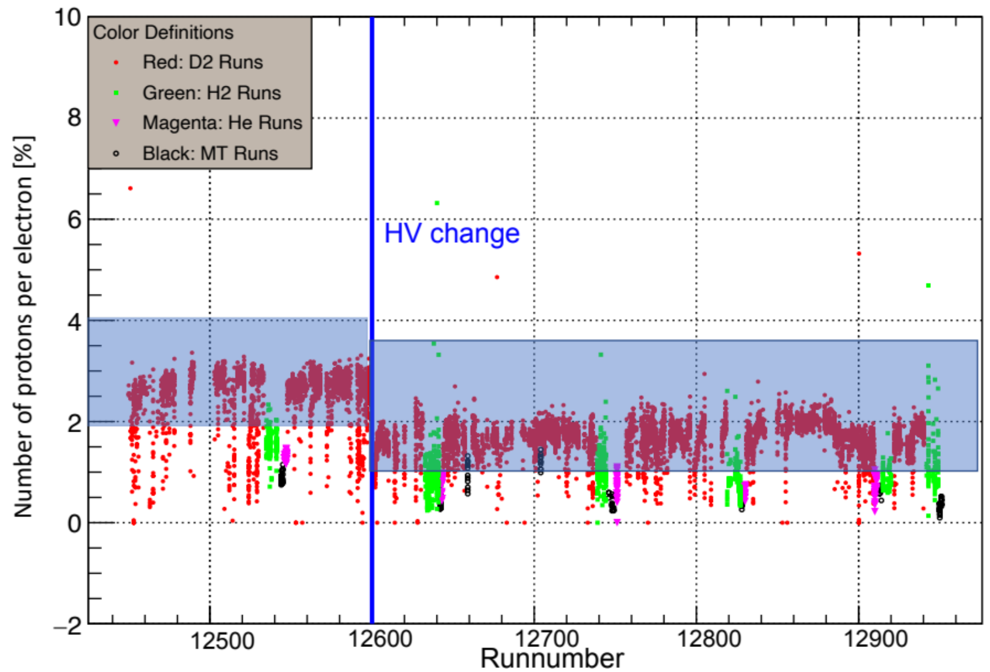
- Improved RTPC implementation in GEMC.
- **Generator**: An extension version from previous Bonus experiment that accommodates the higher beam energy.

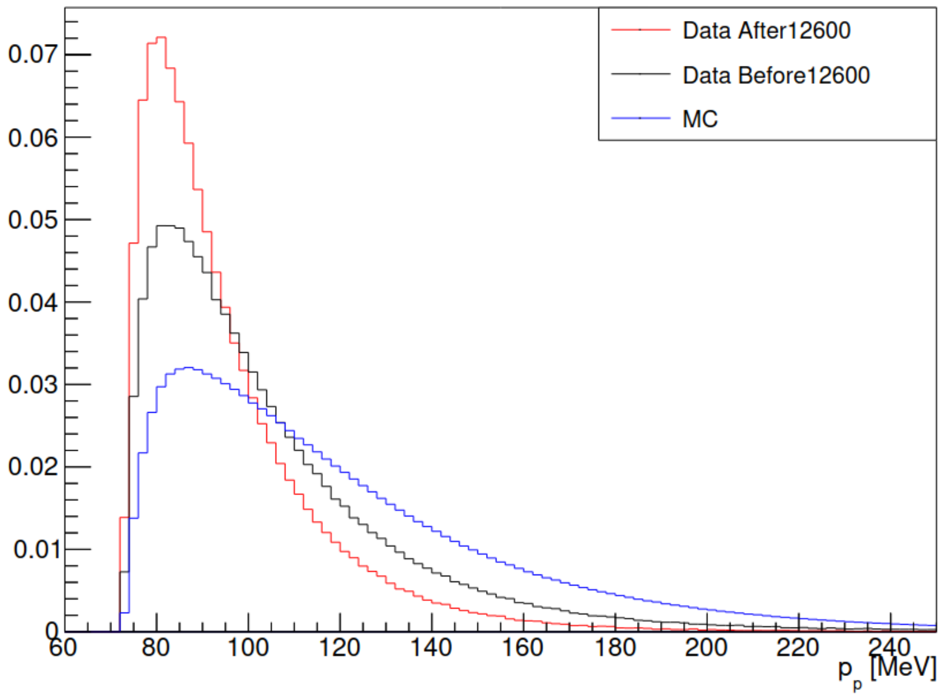
Inclusive e^- kinematics



Tagged-Proton nDIS Analysis

- In the middle of RGF-Summer2020 run, the RTPC GEMs HV were reduced from 385V to 375V.
- This change has made the RTPC blinder to the high-energy recoils and more sensitive to the low-energy recoils of interest.



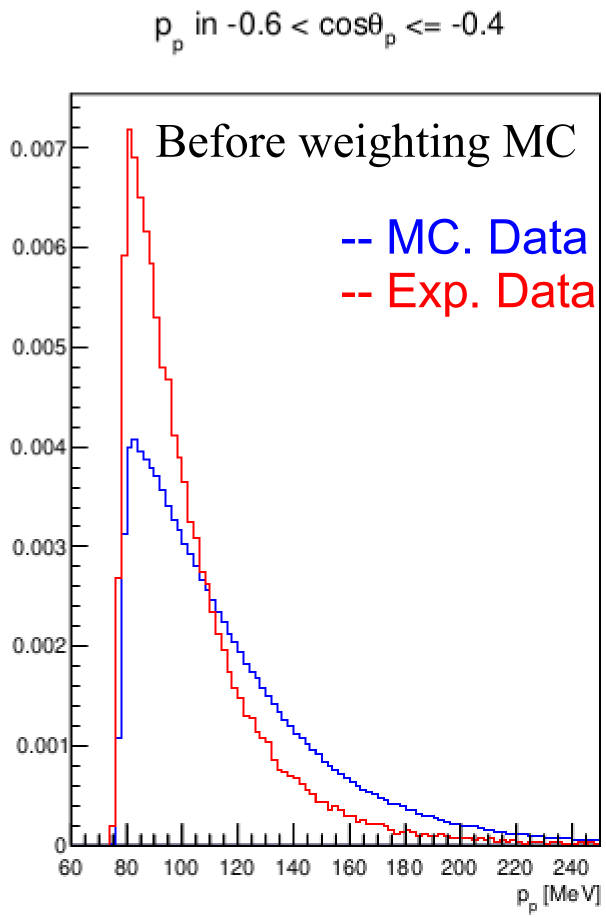


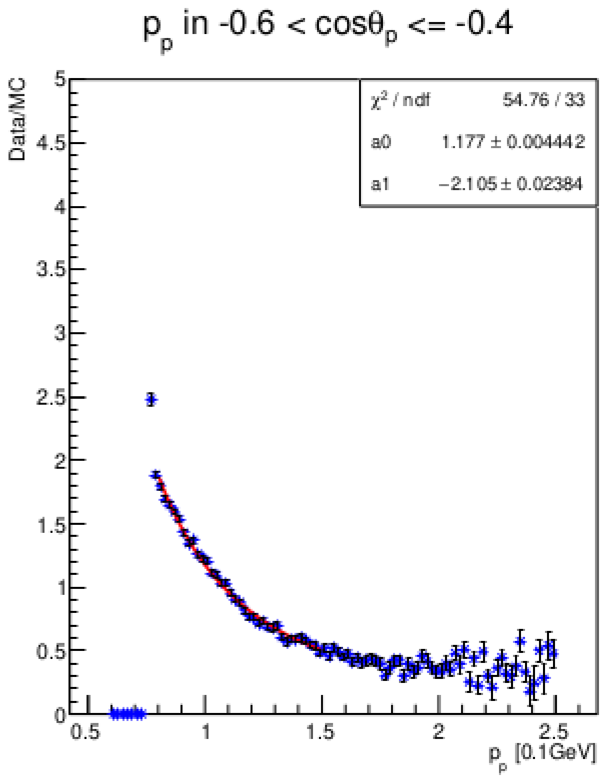
» **The two parts of the run have to be analyzed, compared to MC, and extract yield ratios separatly.**

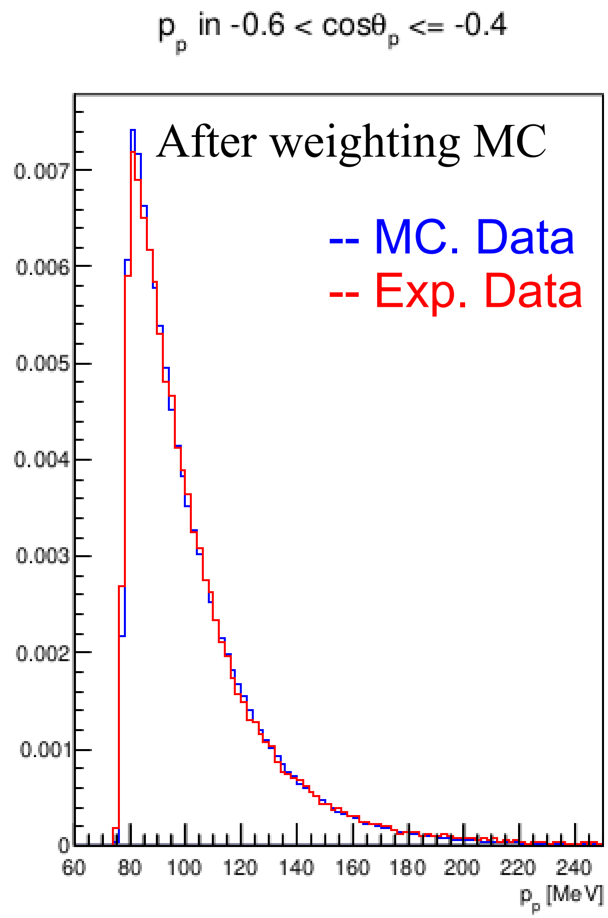
MC Proton Momentum Weighting

Procedures:

- Bin the collected tagged data in θ_p bins
- Construct the Data/MC ratio vs. p
- Fit the Data/MC
- Extract the fitting parameters in the individual θ_p bins and fit them as a function of θ_p.
- Implement the weighting on MC to Match Exp. data

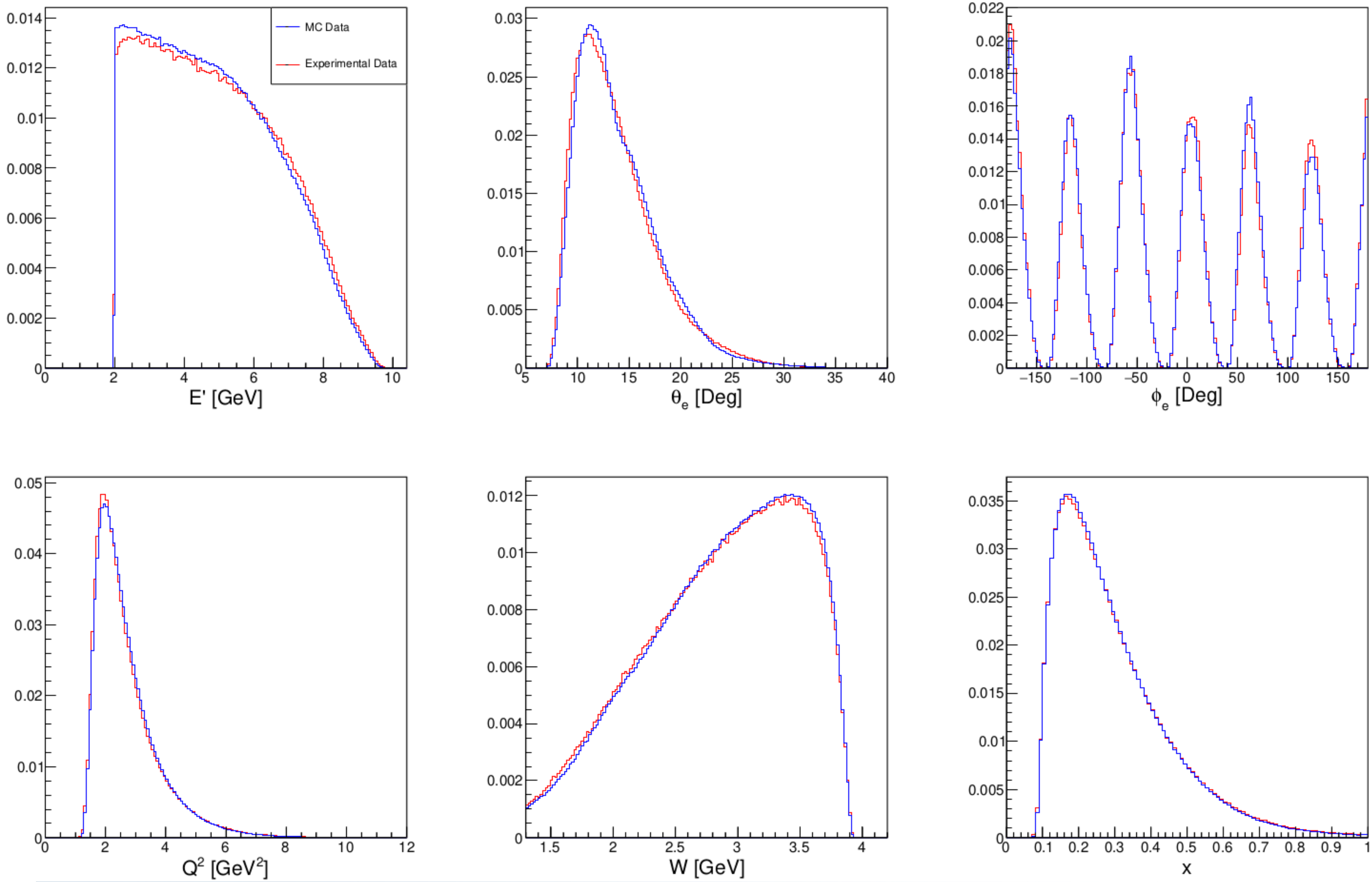






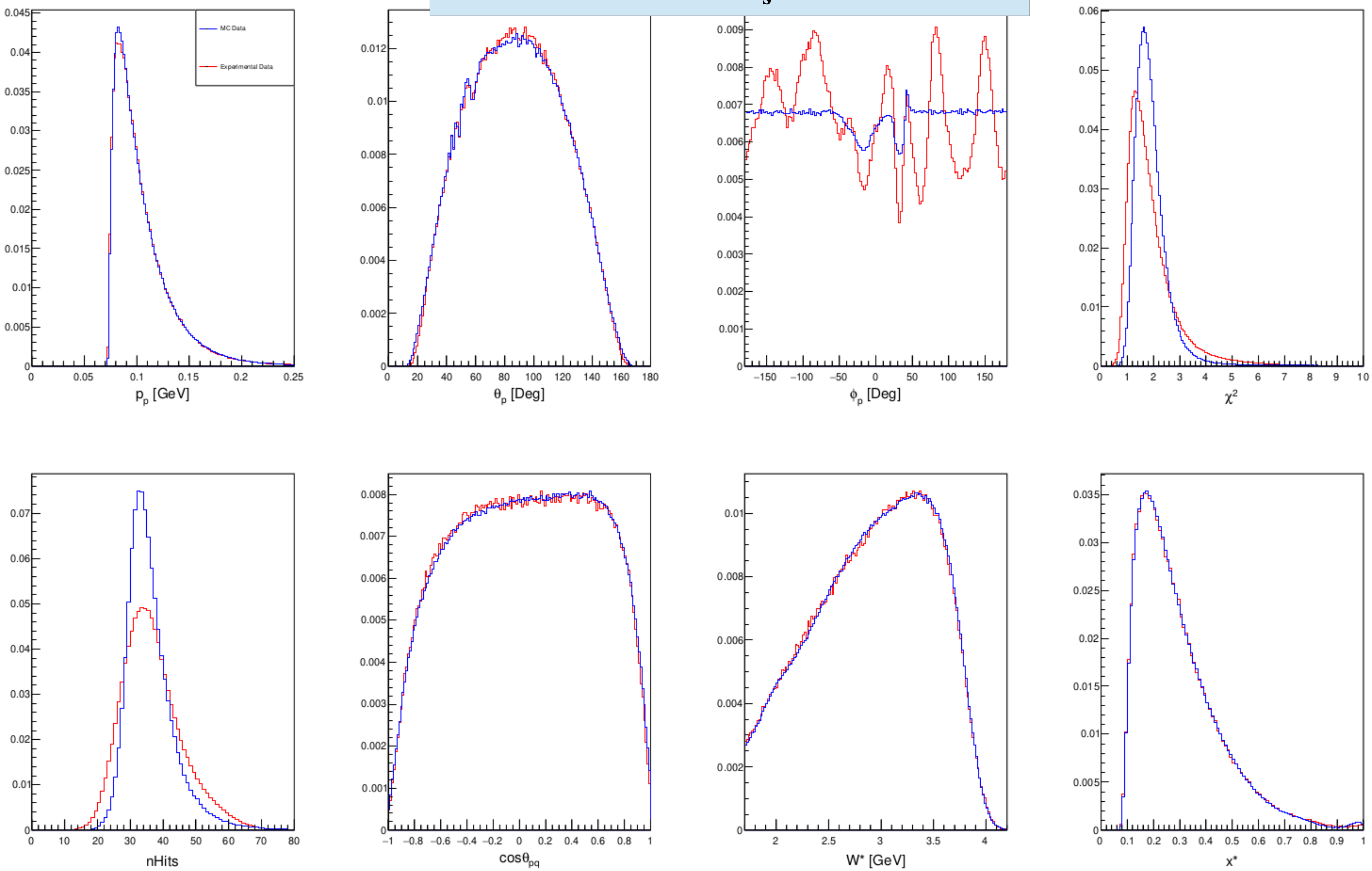
Data vs. MC: $D(e,e'p_s)X$

Before 12600: Tagged nDIS e⁻ kinematics



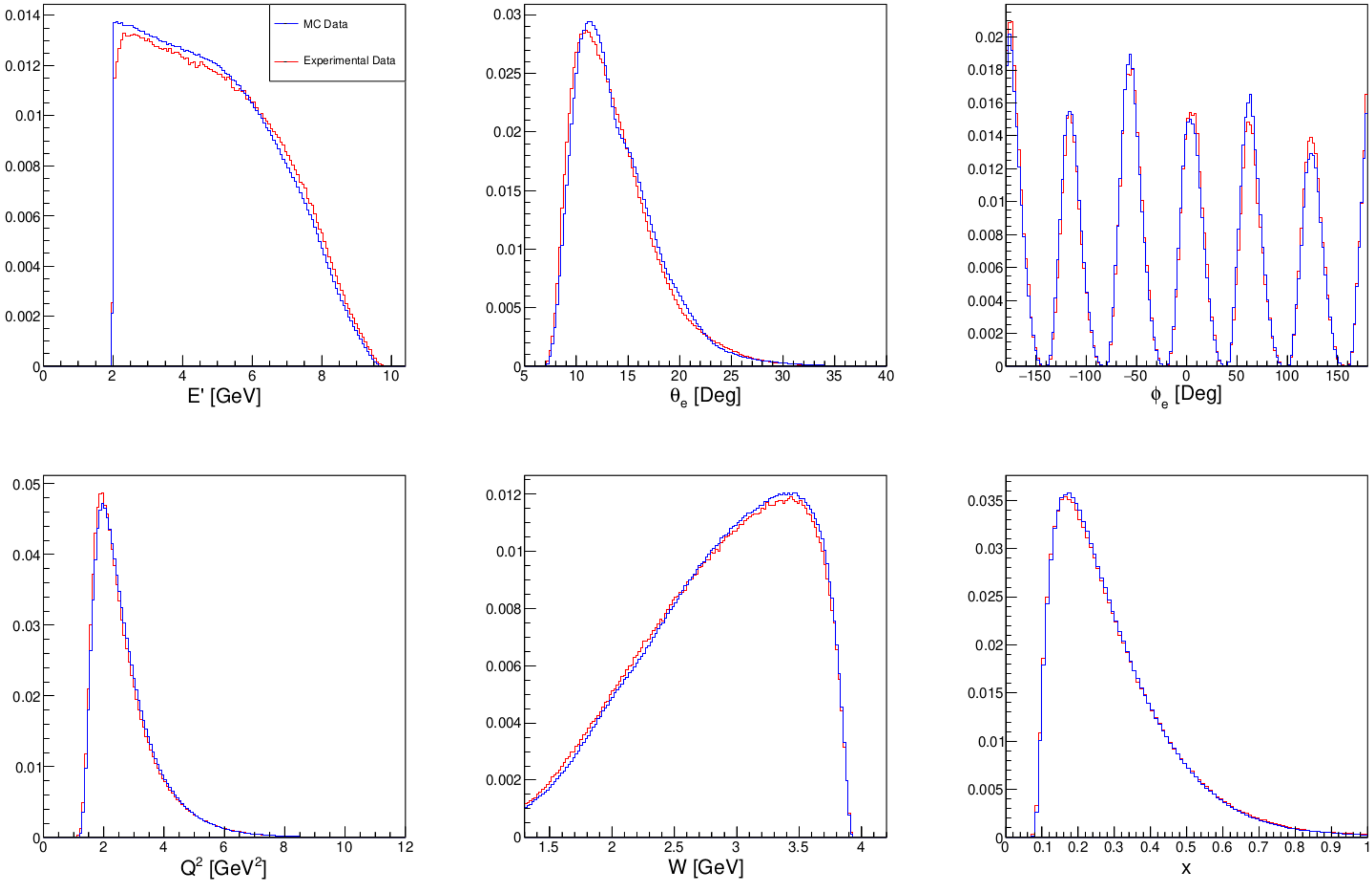
Data vs. MC: D(e,e'p_s)X

Before 12600: p_s kinematics



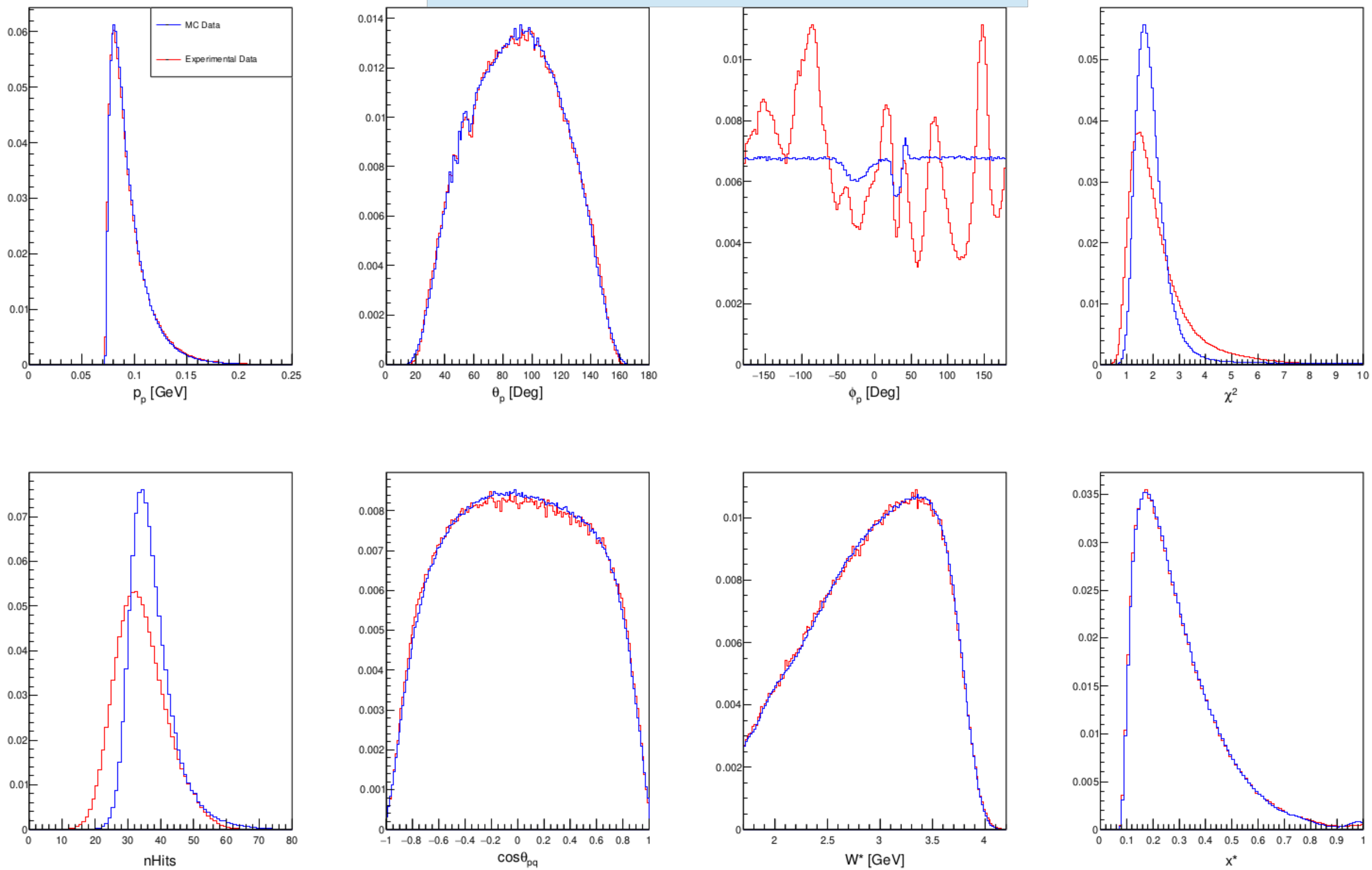
Data vs. MC: $D(e,e'p_s)X$

After 12600: Tagged nDIS e⁻ kinematics



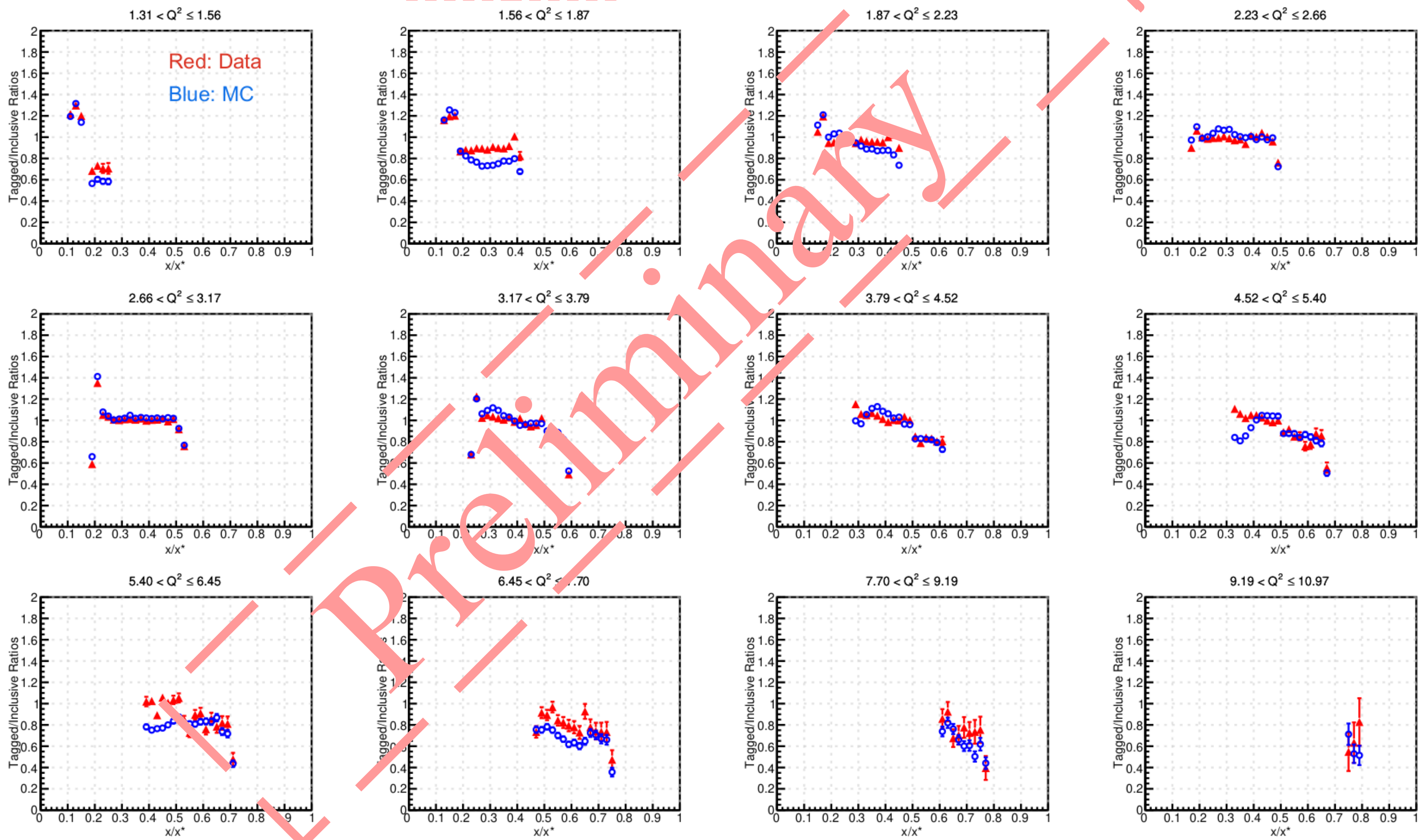
Data vs. MC: $D(e,e'p_s)X$

After 12600: p_s kinematics



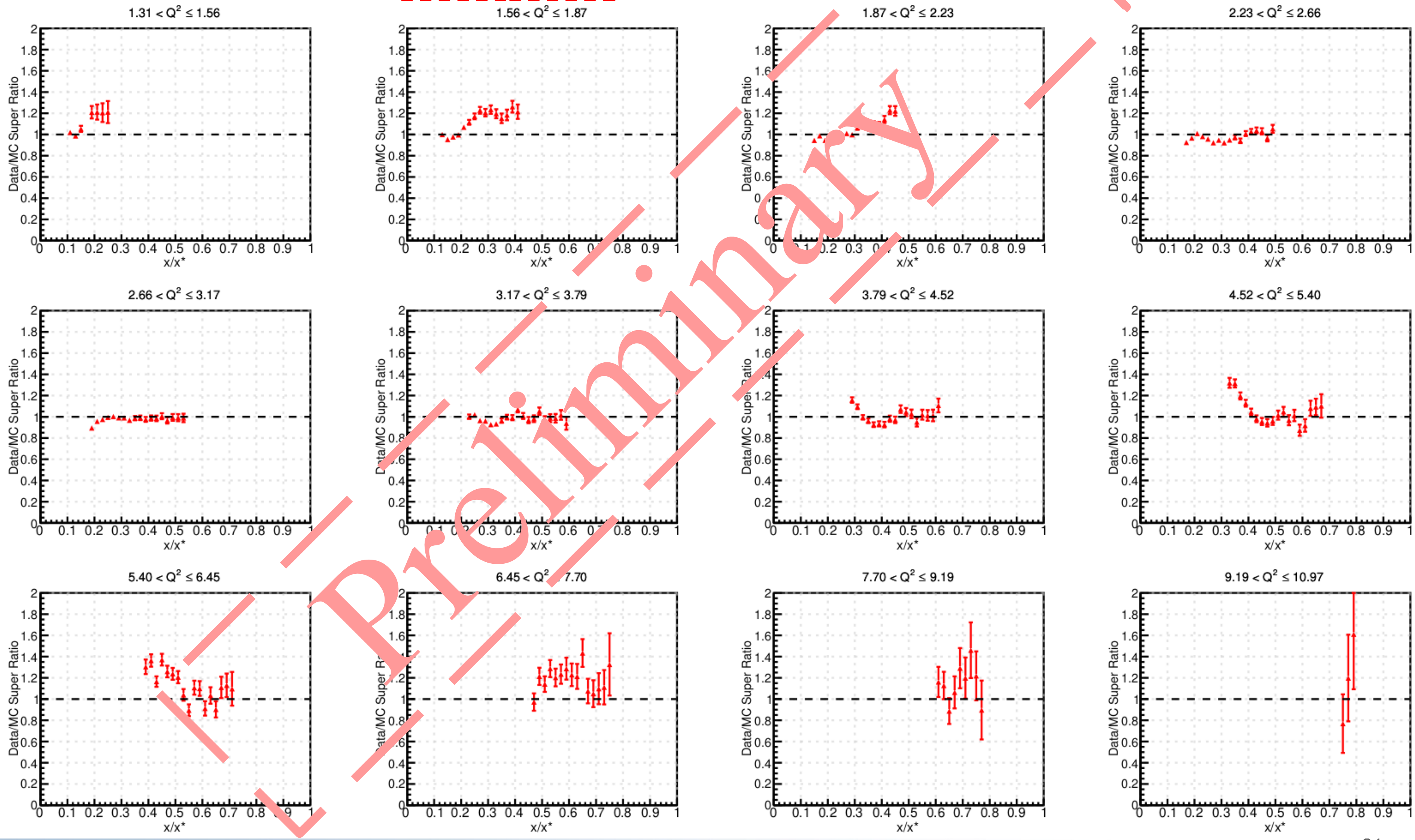
Data/MC Yield Ratios

$$\left(\frac{F_{2n}}{F_{2d}}\right)^{\text{true}} = \text{Constant} \cdot \left(\frac{F_{2n}}{F_{2d}}\right)^{\text{Gen}} * \frac{\left(Y_{\text{tag}}^{\text{Data}} / Y_{\text{inc}}^{\text{Data}}\right)}{\left(Y_{\text{tag}}^{\text{MC}} / Y_{\text{inc}}^{\text{MC}}\right)}$$



Data/MC Super Ratios

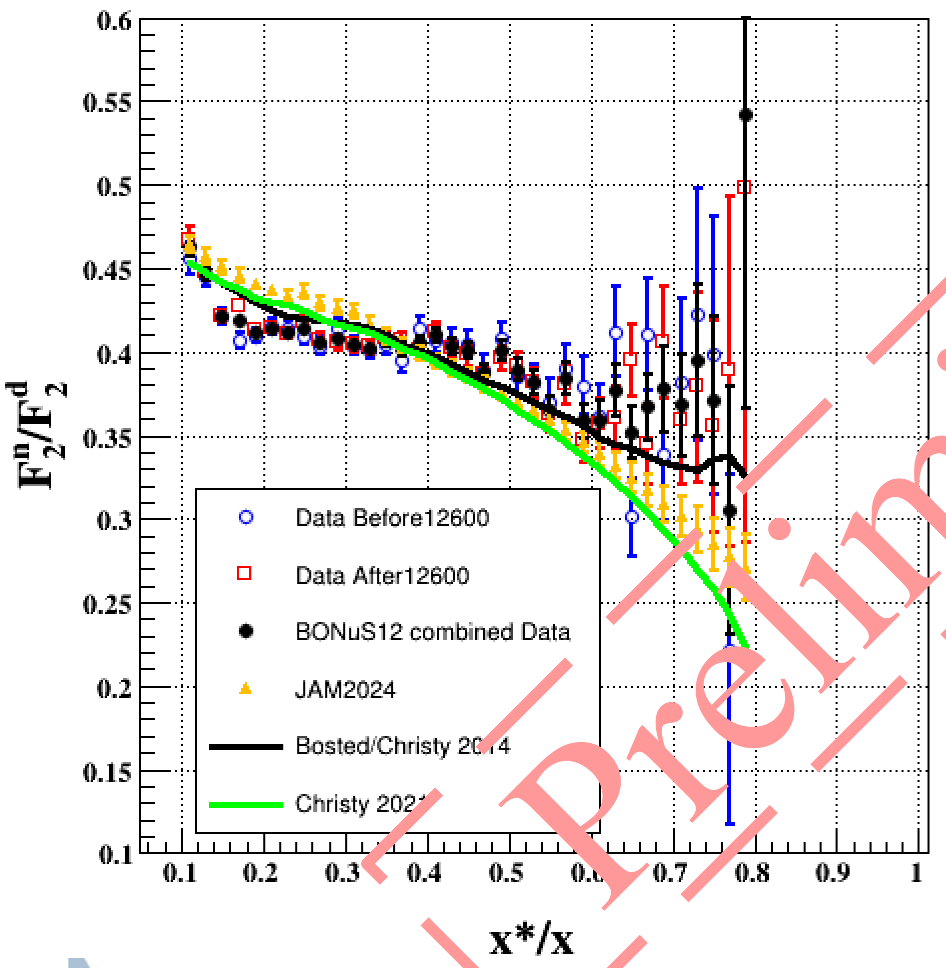
$$\left(\frac{F_{2n}}{F_{2d}}\right)^{\text{true}} = \text{Constant} \cdot \left(\frac{F_{2n}}{F_{2d}}\right)^{\text{Gen}} * \frac{\left(Y_{\text{tag}}^{\text{Data}} / Y_{\text{inc}}^{\text{Data}}\right)}{\left(Y_{\text{tag}}^{\text{MC}} / Y_{\text{inc}}^{\text{MC}}\right)}$$

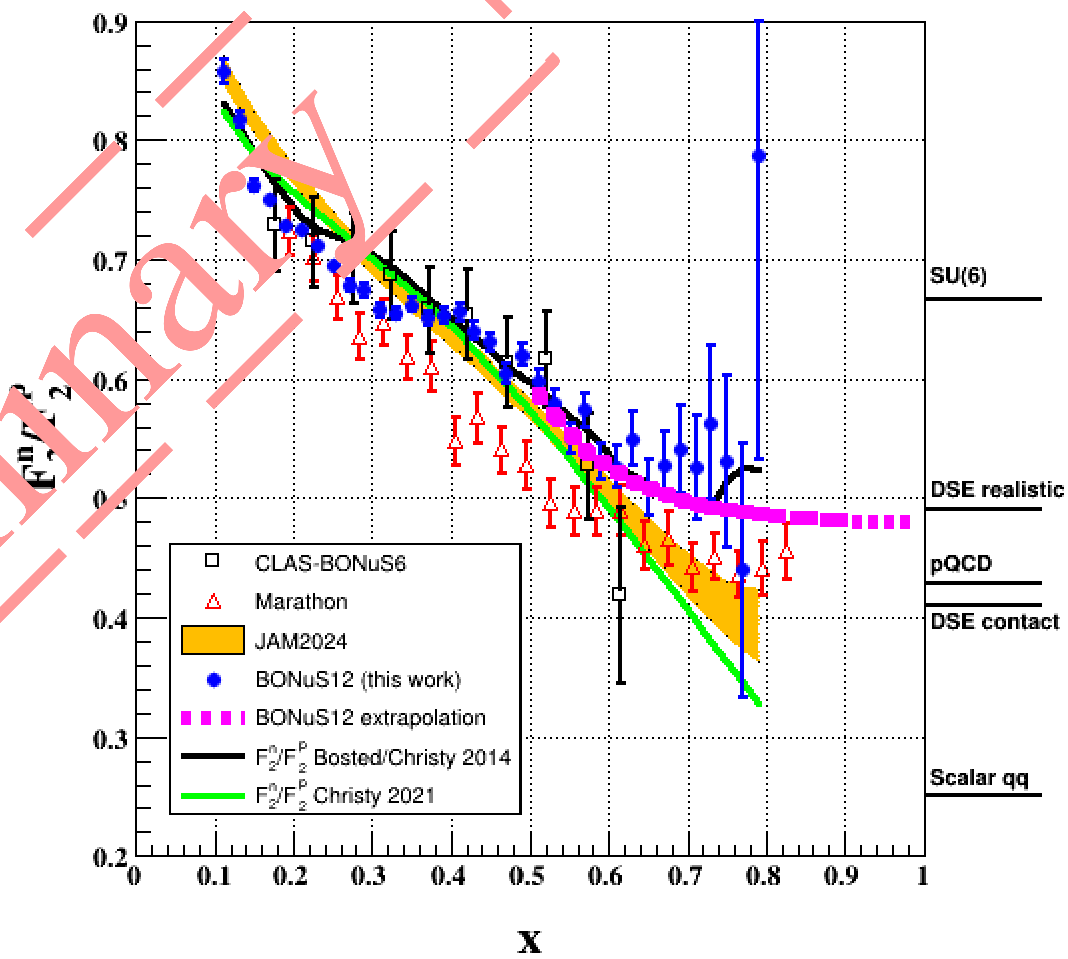


Q^2-Integrated Results

$$\left(\frac{F_{2n}}{F_{2d}}\right)^{true} = \text{Constant} \cdot \left(\frac{F_{2n}}{F_{2d}}\right)^{Gen} * \frac{\left(Y_{tag}^{Data} / Y_{inc}^{Data}\right)}{\left(Y_{tag}^{MC} / Y_{inc}^{MC}\right)}$$

$$\left(\frac{F_2^n}{F_2^p}\right)^{true} = \left(\frac{F_{2n}}{F_{2d}}\right)^{true} * \left(\frac{F_{2d}}{F_{2p}}\right)^{fit}$$

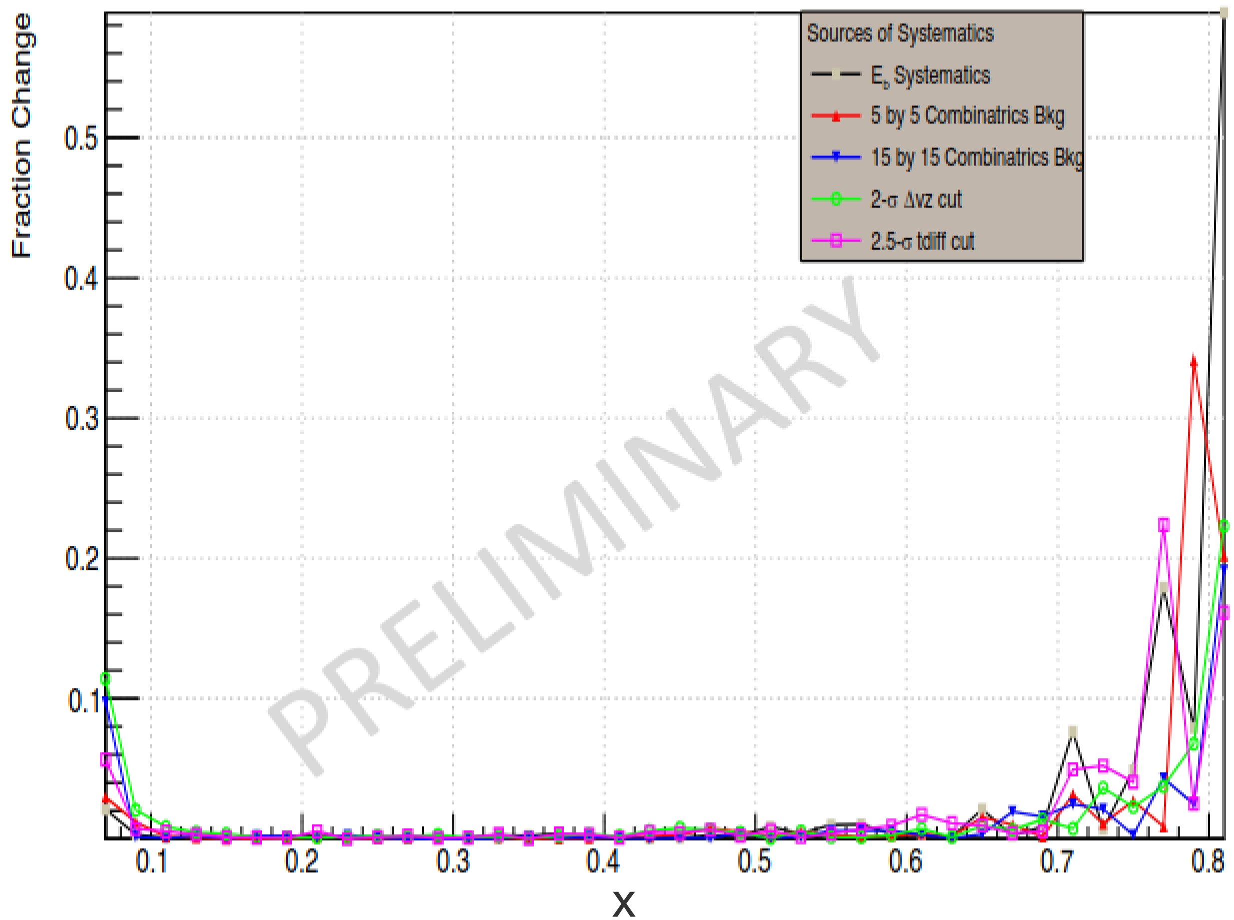




Ongoing Systematic Uncertainties

Systematics studies are done by varying the different cuts and calculate the super-ratio fraction change bin-by-bin:

- Beam Energy.
- Pair-Symmetric background correction.
- RTPC accidental background.
- RTPC fiducial cut.
- Electron-proton vertex correspondence.
- Electron-proton timing cut.
- Helium Conatmination correction.



Conclusions

◊ **BONuS12** extends the measurement of the **spectator-tagged neutron structure functions** over a **larger kinematic range**, with much improved statistics. Many additional physics topics can be explored.

◊ Particles identification has been carried out and tuned over the **Summer2020** dataset.

◊ **Event generator / simulation** have been tuned and reproducing the measured phase-space.

◊ **First results** have been extracted and will be submitted soon to the DPWG for an analysis review.

Other Physics Topics Accessible with BONuS12

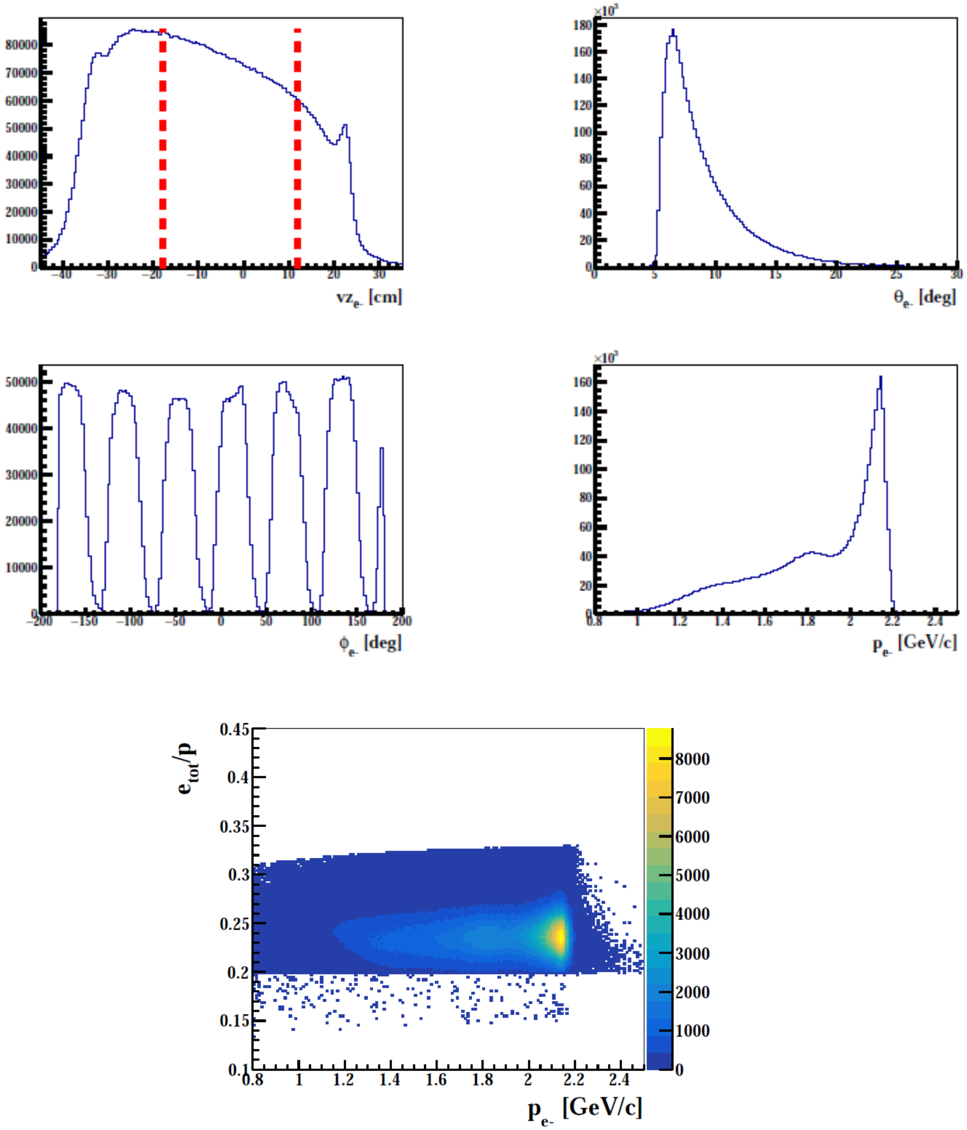
In addition to measuring **F_2^n**, the **BONuS12 dataset** is a golden dataset to study:

- Exclusive nDVCS $e^- D \rightarrow e^- n \gamma p$
- Tagged-p nDVCS $e^- D \rightarrow e^- p \gamma (n)$
- Neutron Elastic Scattering
- Coherent DVCS off D
- Coherent DVMP off D
- Semi-inclusive reaction p(e,e`p)X
- D(e, e`pp$_S$)X
- EMC effect in D
- SIDIS on the neutron
- Diffractive scattering off D

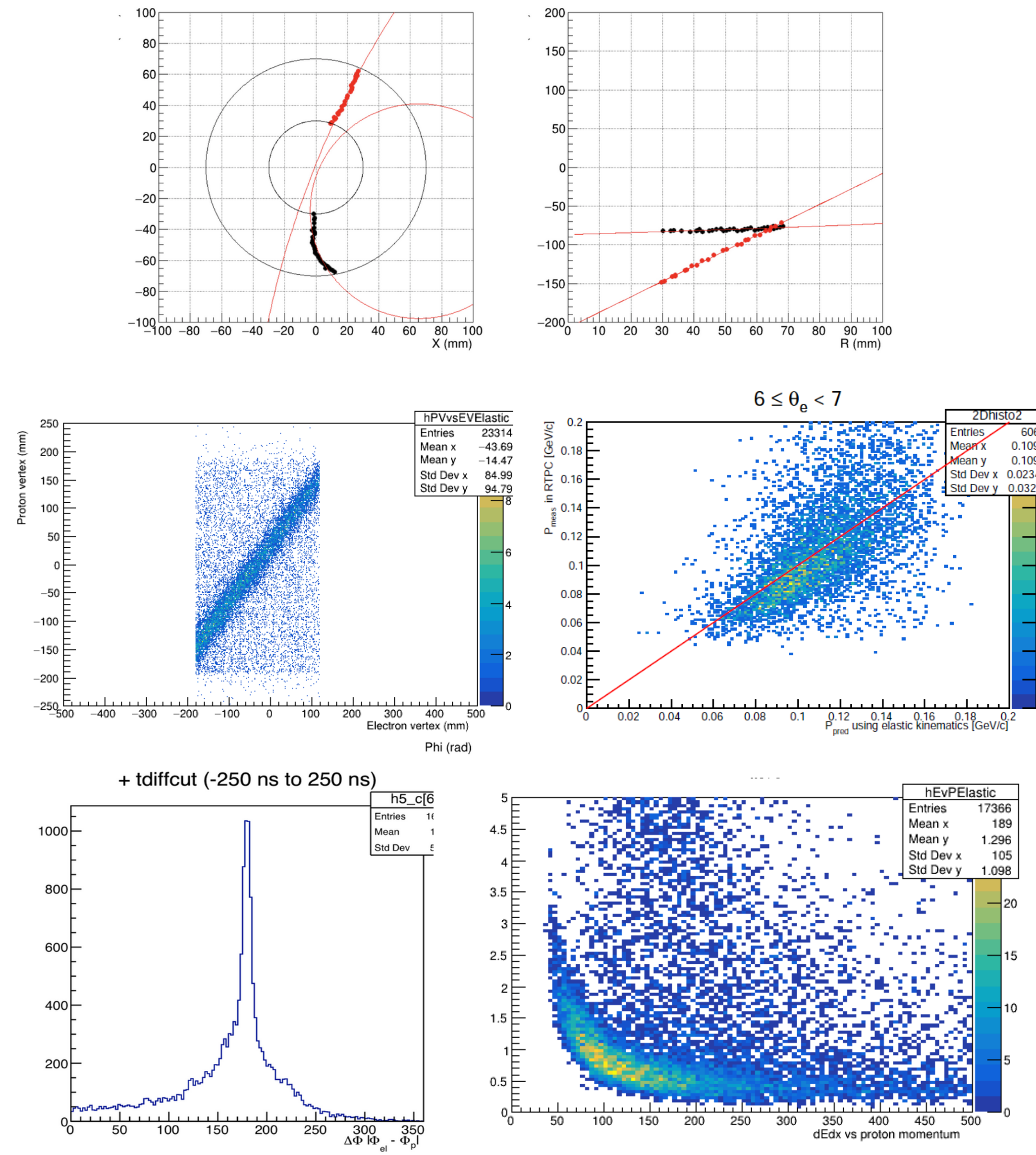
- More Physics:
  - DVCS off bound nucleons.
  - DVMP off bound nucleons.
  - The role of the final state interaction in hadronization and medium modified fragmentation functions.
  - The medium modification of the transverse momentum dependent parton distributions.
  - ... and more

2.1 GeV Calibration Data

Electron Selection : 2.14 GeV on H_2 target



Radiative elastic e- in coincidence with good p tracks:

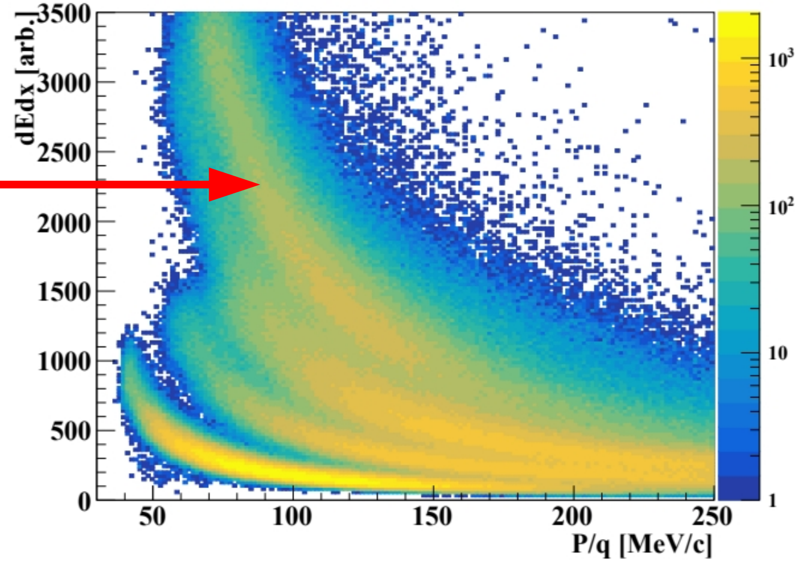


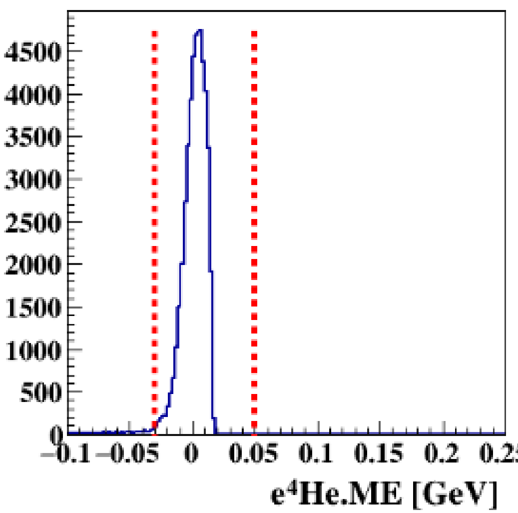
BONuS12 RTPC Resolutions

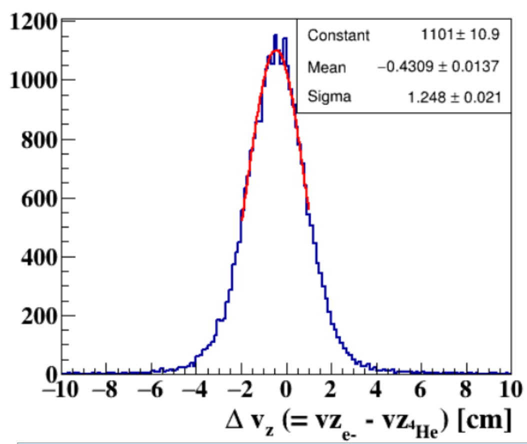
2.14 GeV e- beam on ^{4}He target

Elastic Events on ^{4}He:

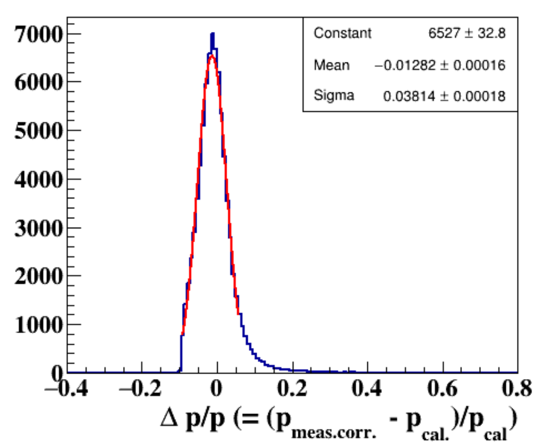
$$e^4He \rightarrow e^4He$$



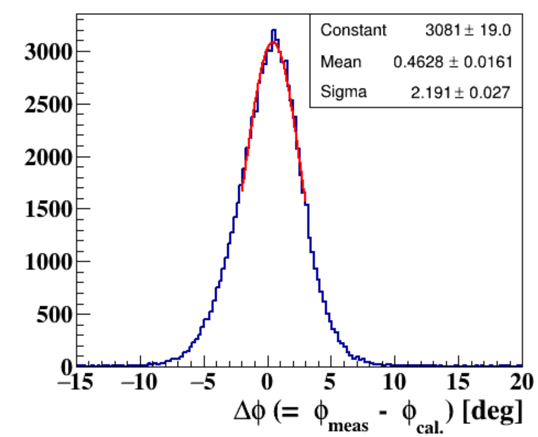




1.2 cm combined CLAS12-RTPC vertex resolution



4% momentum resolution



2° azimuthal angle resolution

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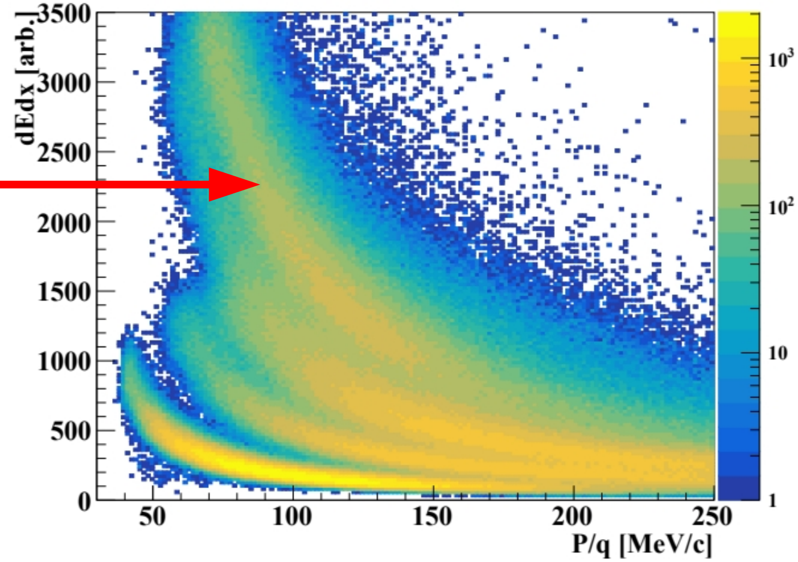
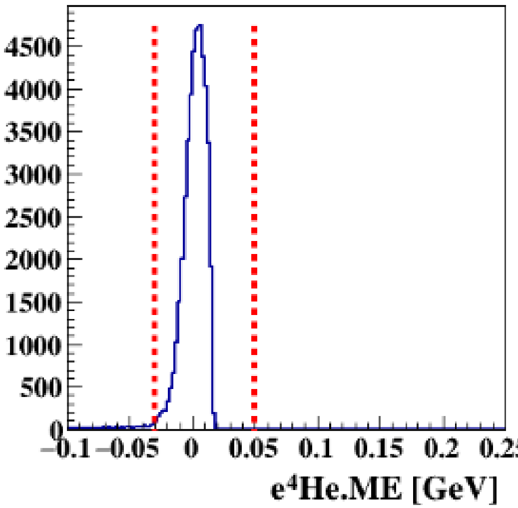
BONuS12 RTPC Detection Efficiency

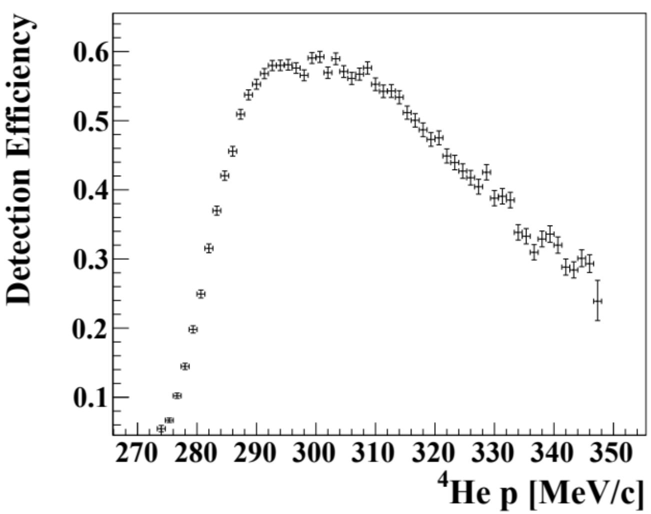
2.14 GeV e- beam on ^{4}He target

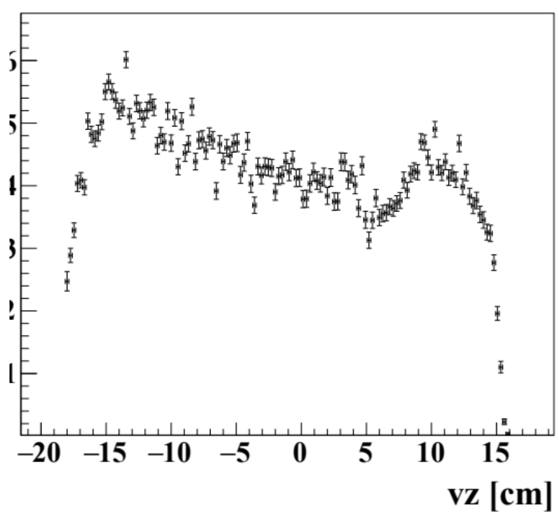
Elastic Events on ^{4}He:

$$e^4He \rightarrow e^4He$$









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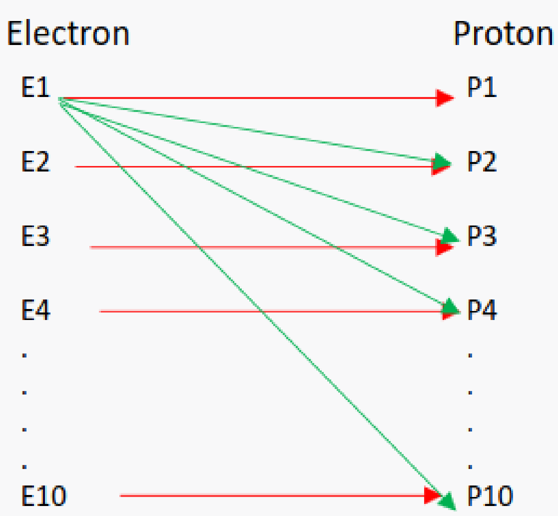
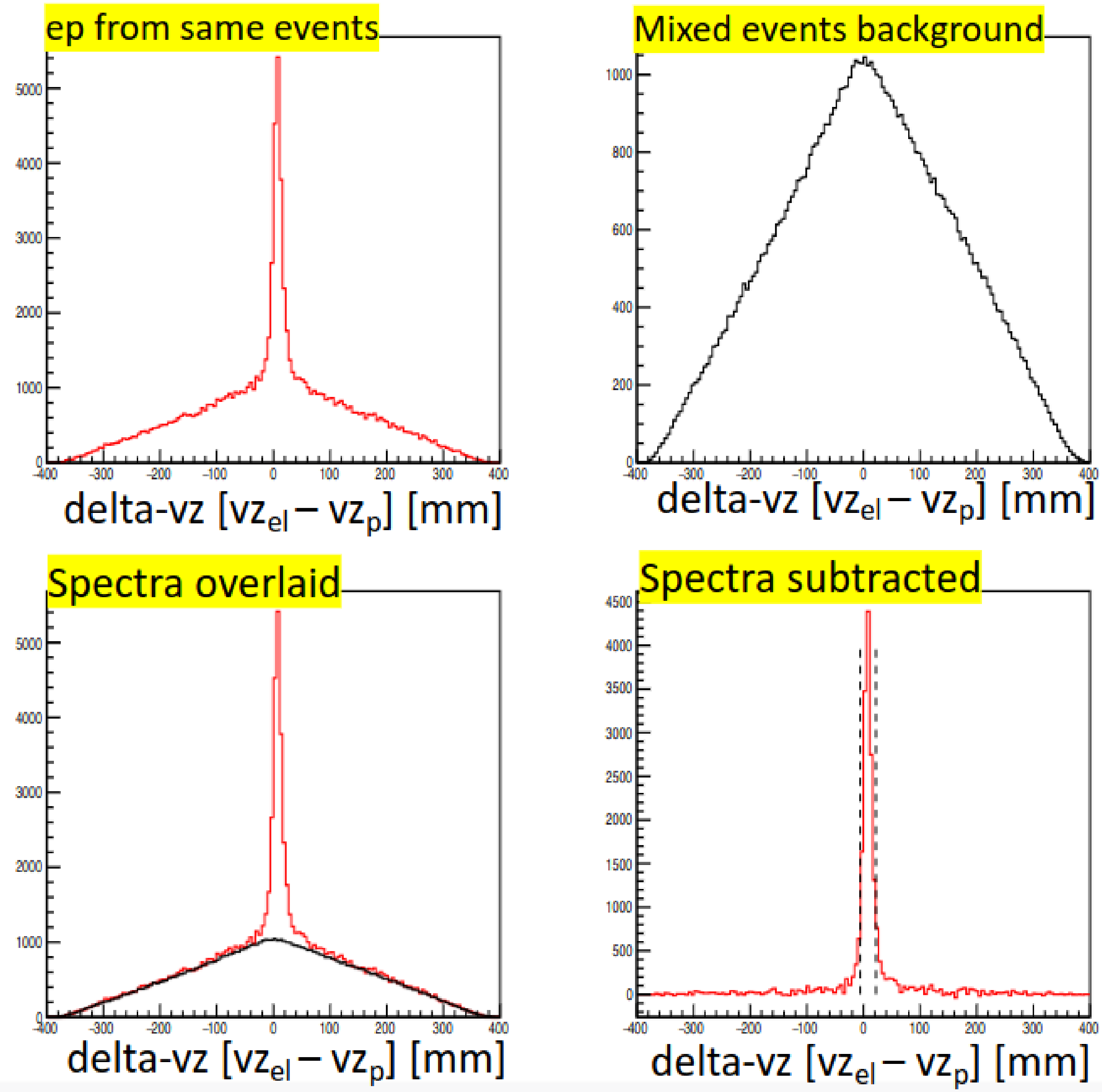
Accidental Backgrounds in BONuS12

To get better statistics on accidental backgrounds

For every 10 consecutive events with electrons satisfying all electron cuts:

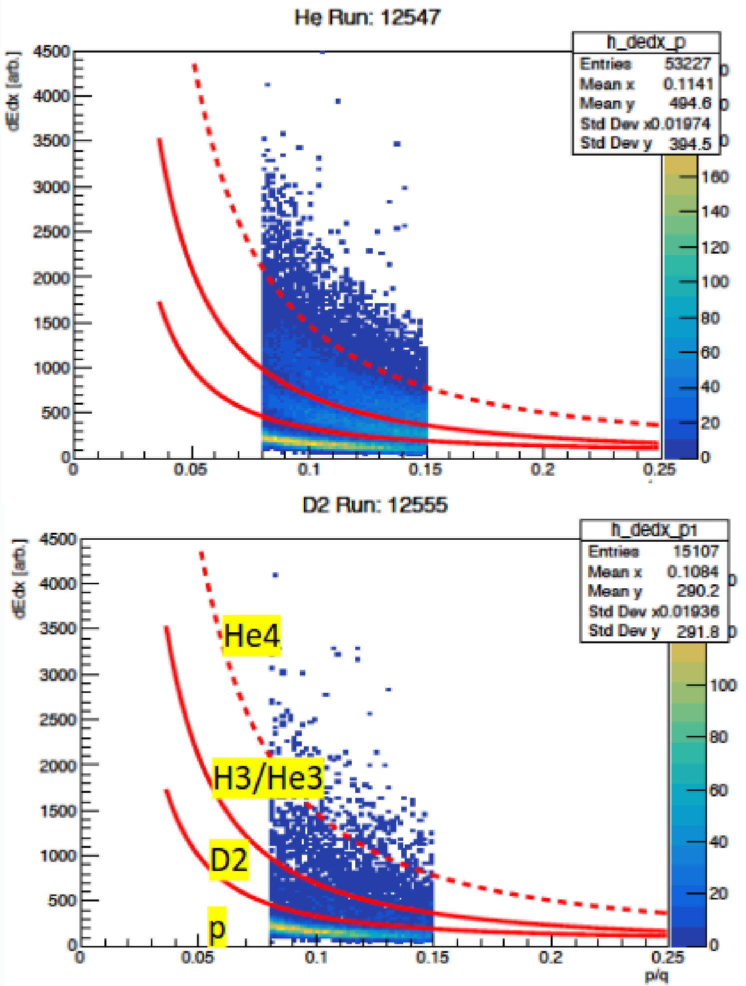
- We did event mixing
- Form 100 ep pairs
- 10 ep pairs [Red in fig.] from the same event
- 90 combinatorics backgrounds [Green in fig.].
- Scale background count by 9.



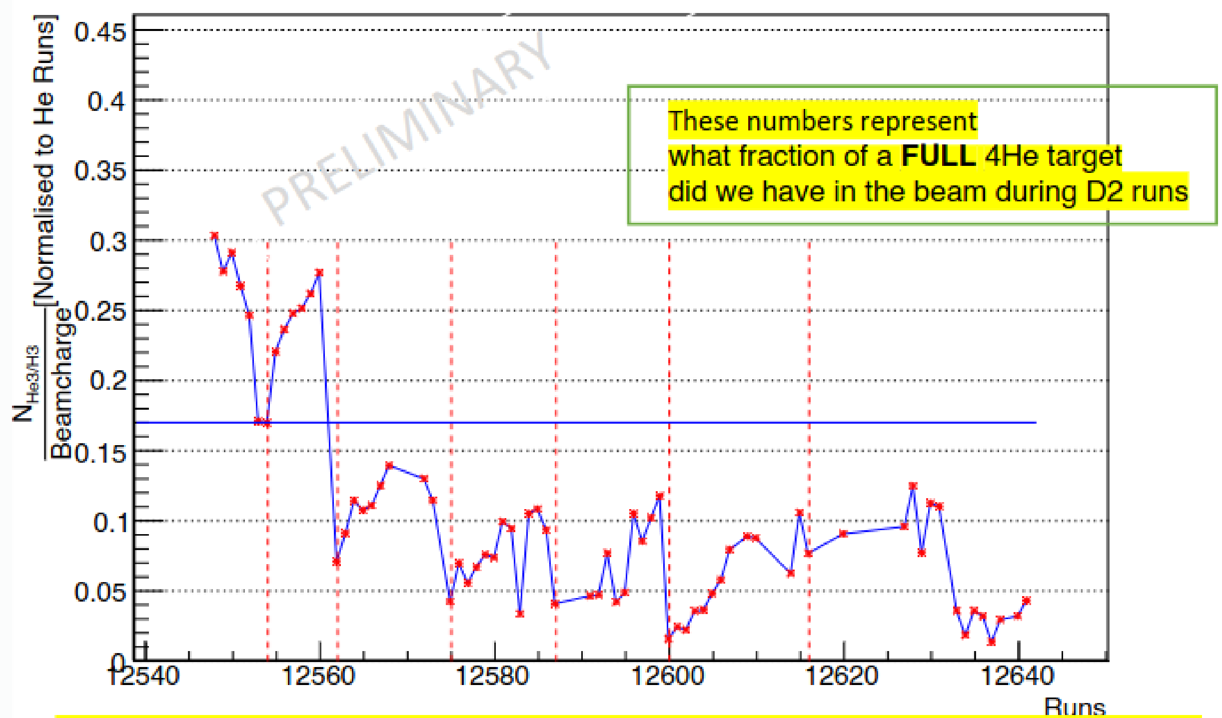


Deuterium Target Contamination

We need an estimate of a fraction of the higher-mass background in RTPC



- $^3H/^3He$ counts measured in all Targets
- Normalized to beamcharge for the run
- Further **Cross-Normalized** them to those measurements in He Runs



The vertical red lines represents runs where we did target flush. Hence, Minimum at those runs.

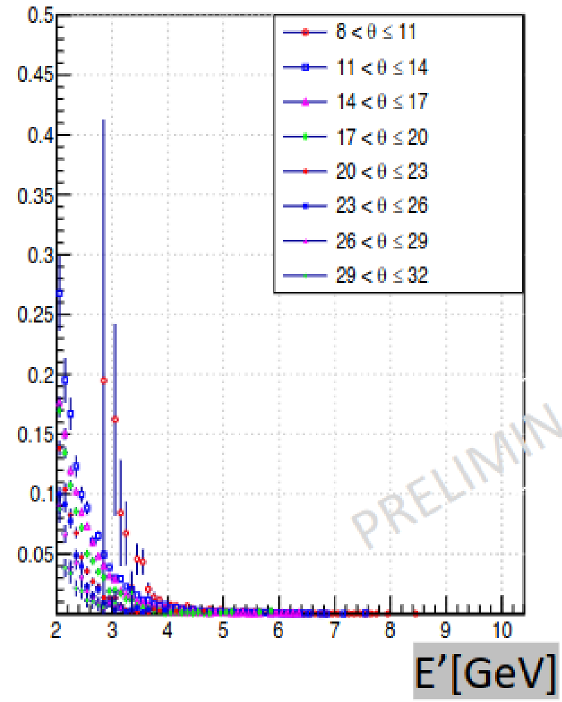
Pair Symmetric Background Correction: Inclusive Data

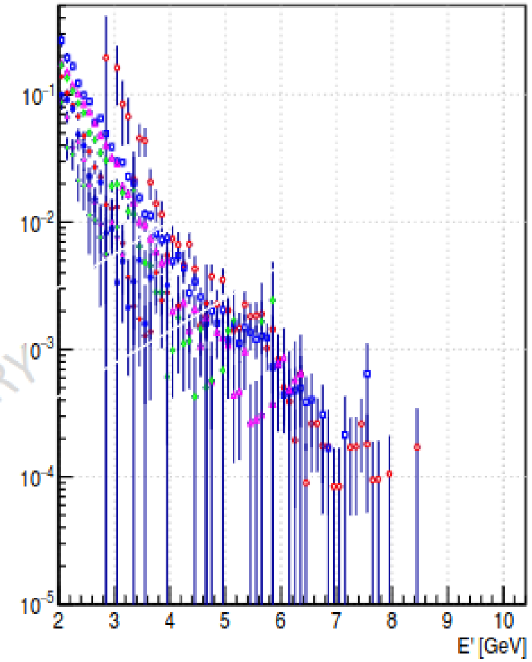
Primary sources of electron background are:

- Dalitz decay: $\pi^0 \rightarrow e^+e^-\gamma$ [1.2 % branching ratio]
- $\pi^0 \rightarrow \gamma\gamma \rightarrow e^+e^-\gamma$
- Other channels give non-significant contributions

Outbending and Inbending runs give pair of symmetric backgrounds to each other.

- We did not have Outbending runs in the Summer 2020 Run.
- So, we used the Spring 2020 run with Outbending Torus configuration for the "Pair Symmetric Background" study in Inclusive data.





- WE MONITOR POSITRON IN EACH KINEMATICAL BIN AND USE IT TO CORRECT FOR POSITRON CONTAMINATION

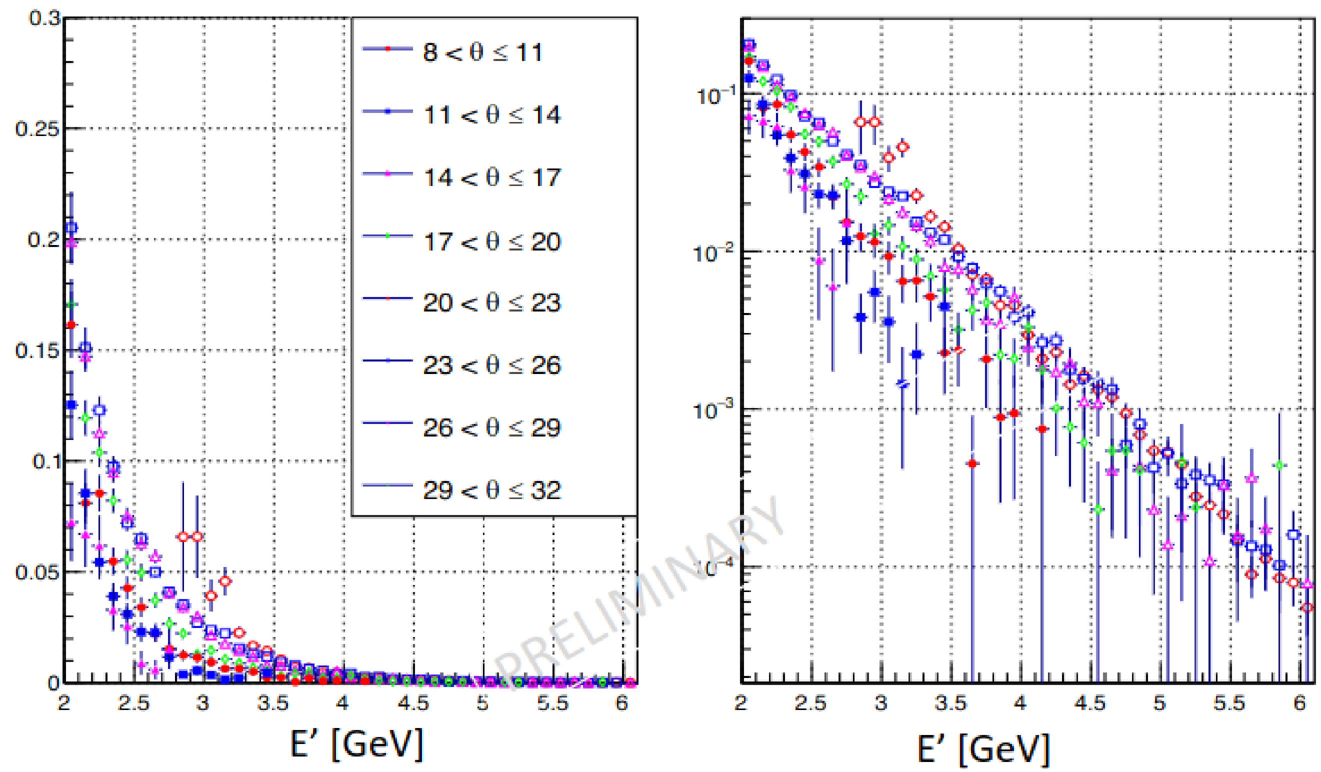
Pair Symmetric Background Correction: Tagged Data

We could do the same for tagged analysis but NO RTPC data for spring runs.

So, we had to estimate Positron correction from summer data alone.

Hence, we used summer data to study positron contamination and used Inclusive results from Spring to add additional corrections to summer results.

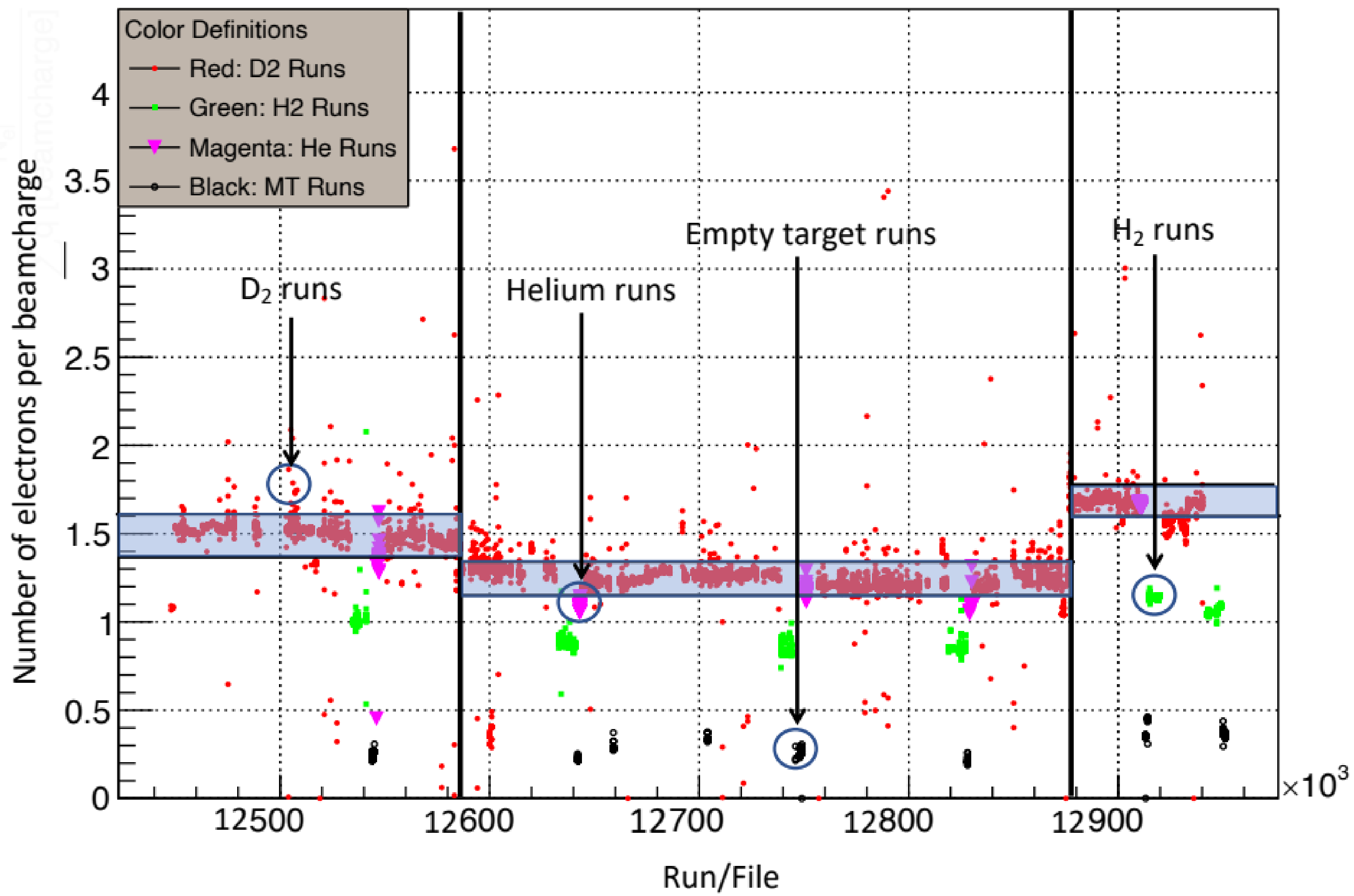
Fig: ratio of positron to electron counts in different theta bins



$$\text{Ratio}_{\text{tag}}\,(\text{true}) = \frac{\text{Ratio}_{\text{tag}}(\text{summer})}{\text{Ratio}_{\text{inc}}(\text{summer})}\ \text{Ratio}_{\text{inc}}\,(\text{spring})$$

Run/File Data Evaluation & Selection (1/2)

- Selected based on the normalized electron yield per beam-charge, which is expected to be stable for same the same run conditions.



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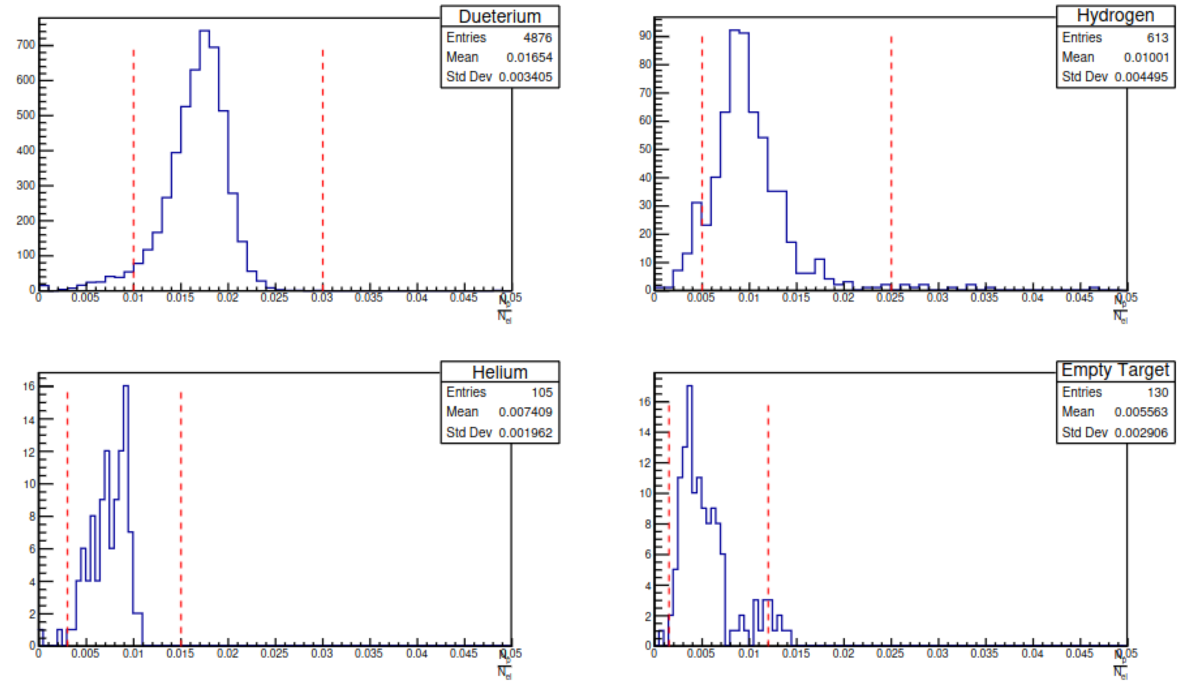
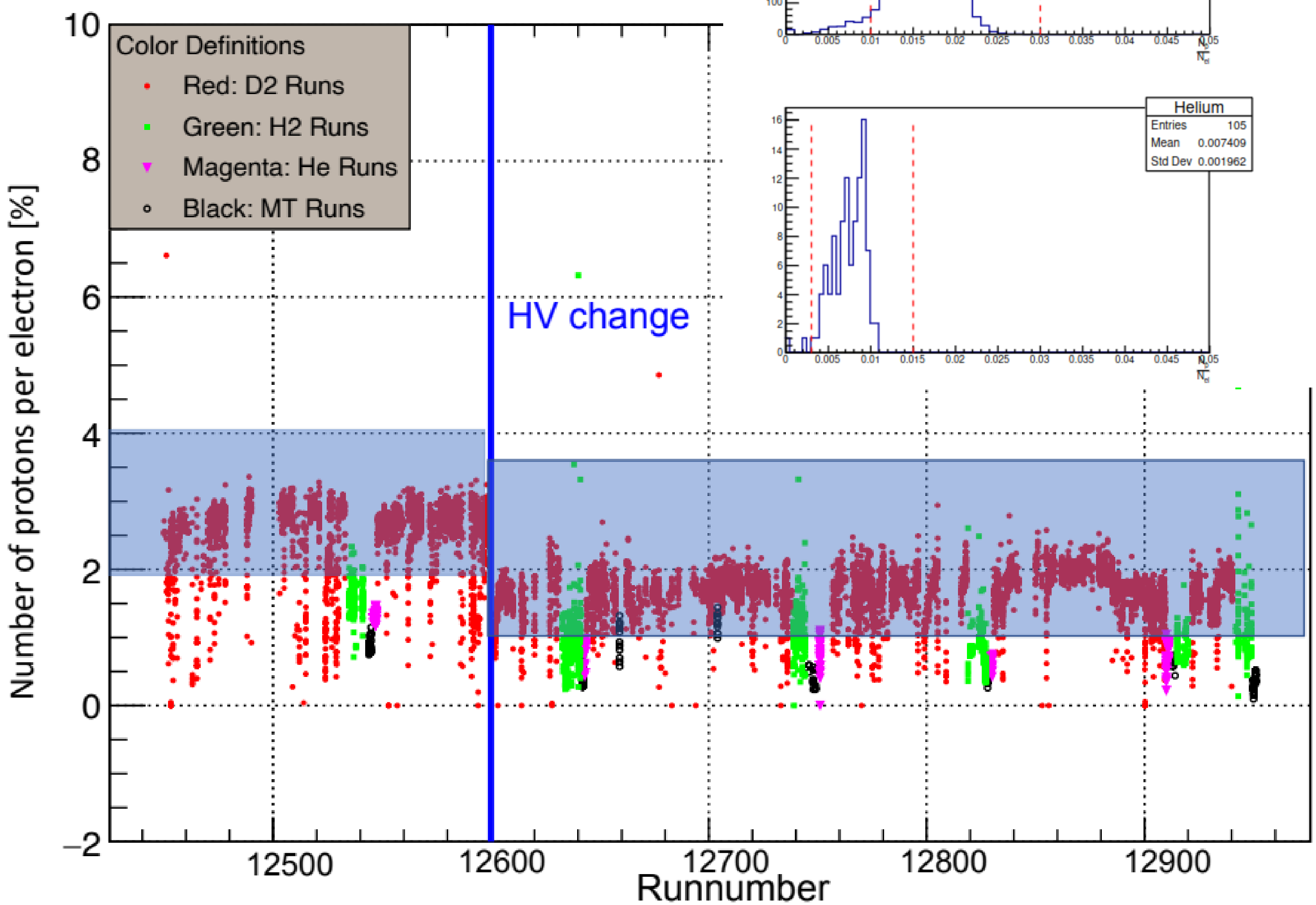
Run/File Data Evaluation & Selection (2/2)

- Selection based on the number of protons per trigger electron.

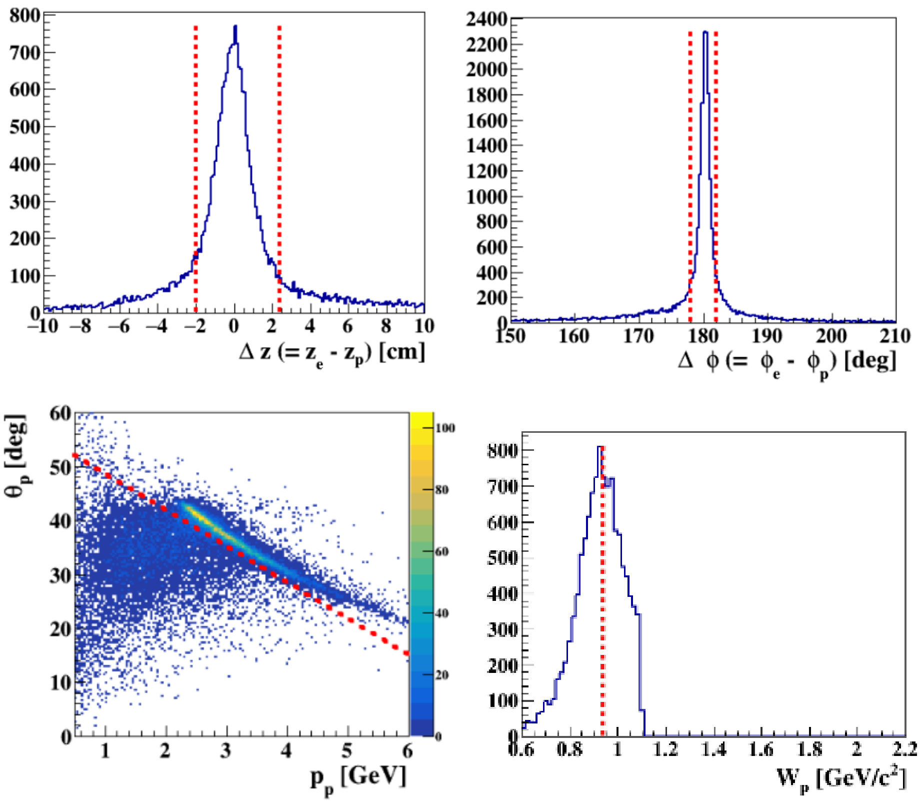


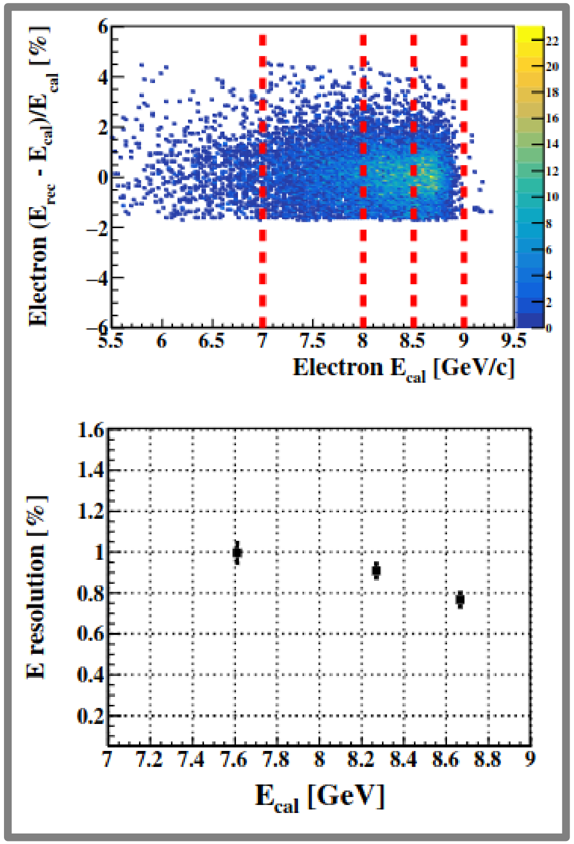


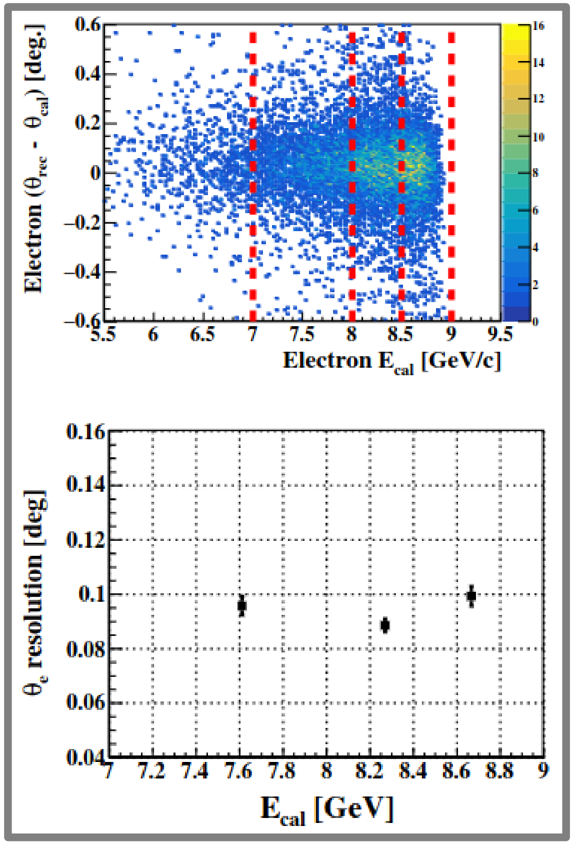
Data/MC Electron's Resolutions (1\2)

- Observed electron's E and θ resolutions from **Real Data** using the ep elastic events

$ep \rightarrow ep$ at 10GeV

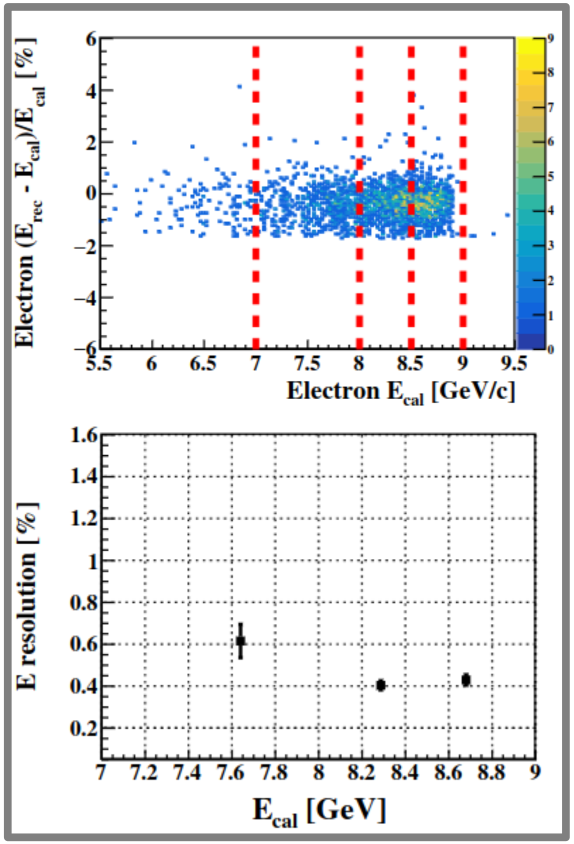


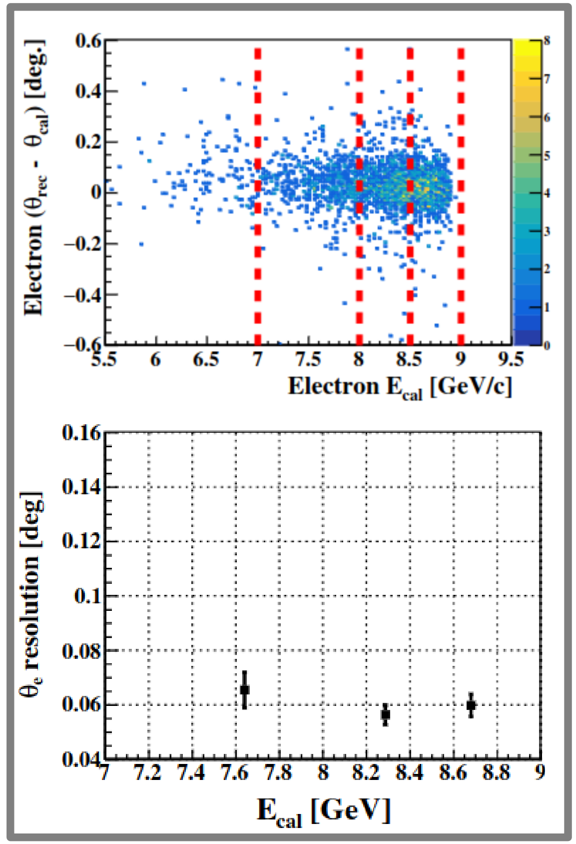




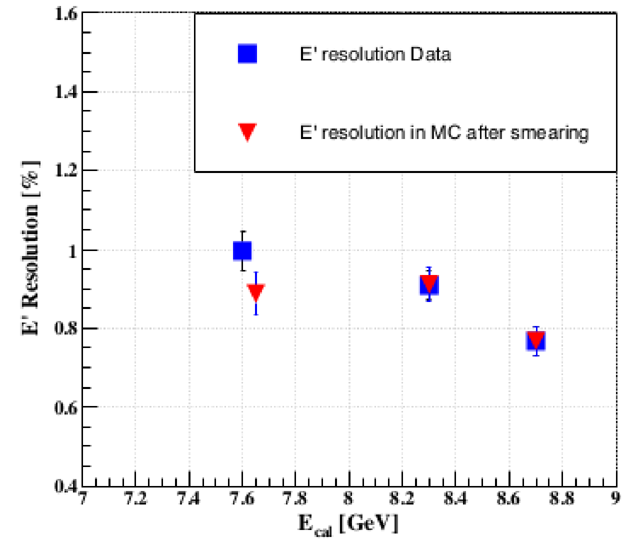
Data/MC Electron's Resolutions (2\2)

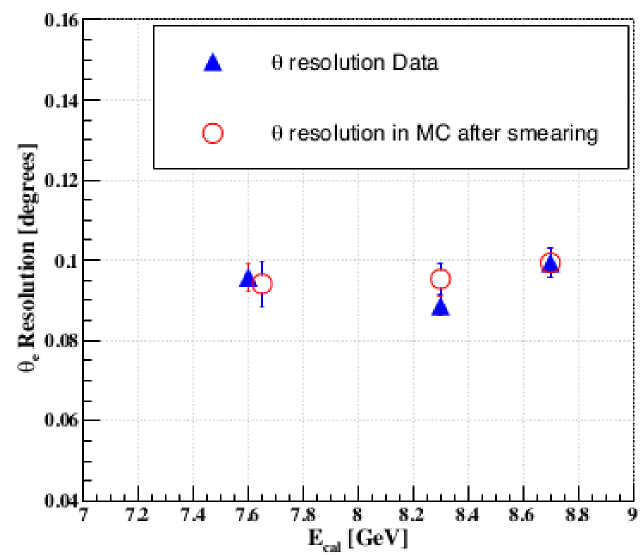
- Observed electron's E and θ resolutions from **GEMC** using the MC ep elastic events @ 10 GeV





- MC resolutions after applying an ad-hoc smearing to the electron's E & θ:





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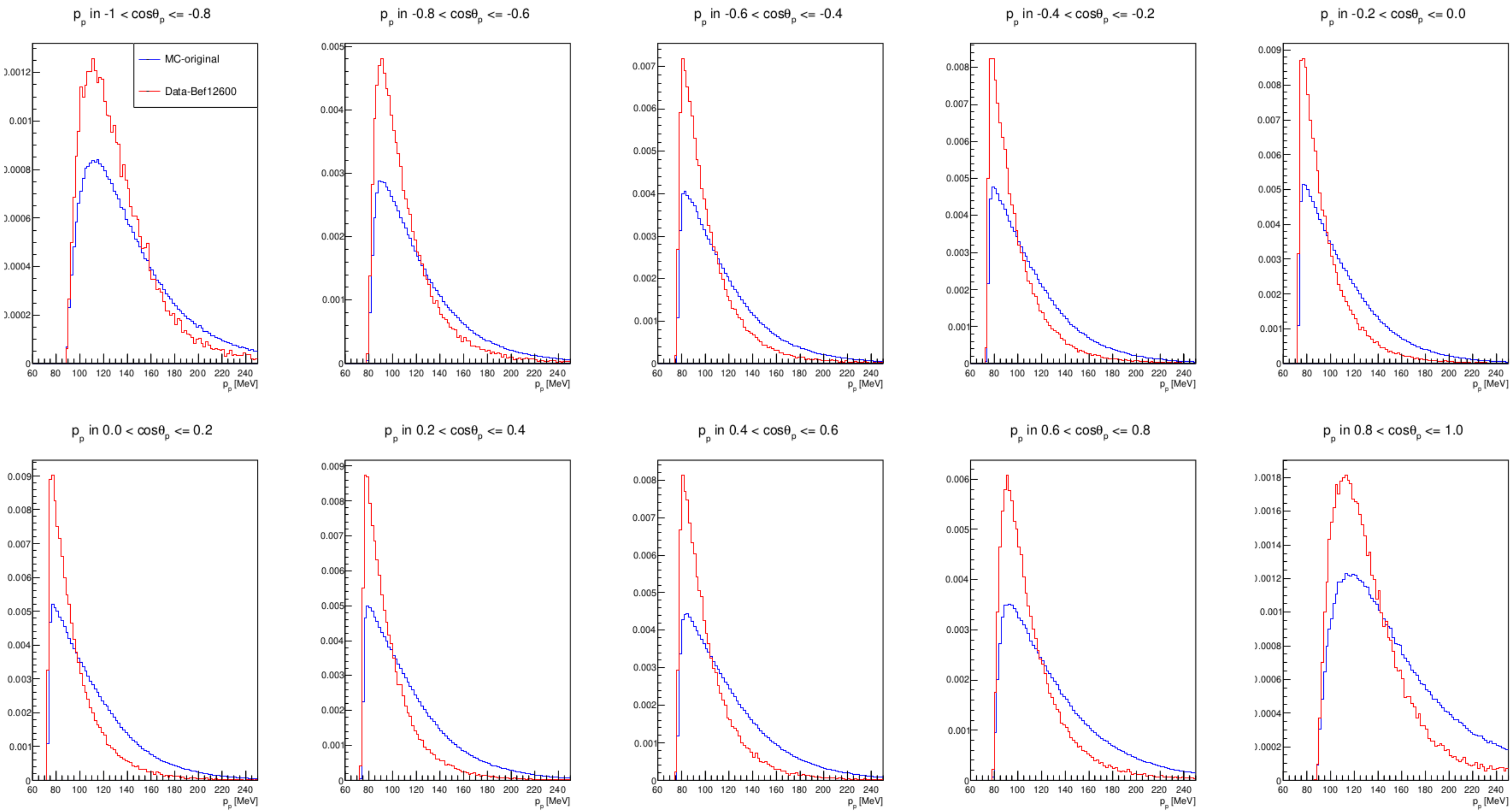
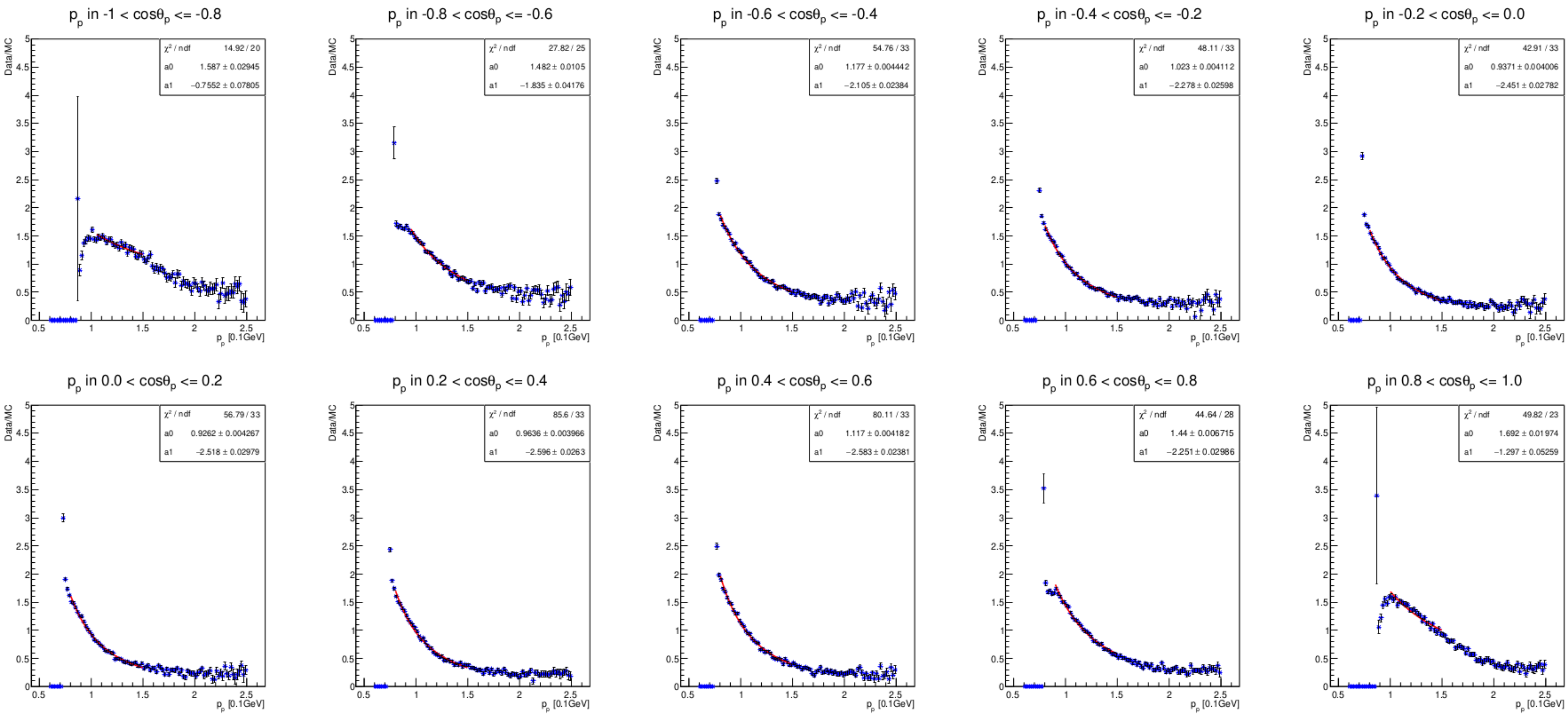
nDIS Analysis

MC Momentum Weighing (¼) – Before 12600



MC Momentum Weighing (2/4) – Before 12600



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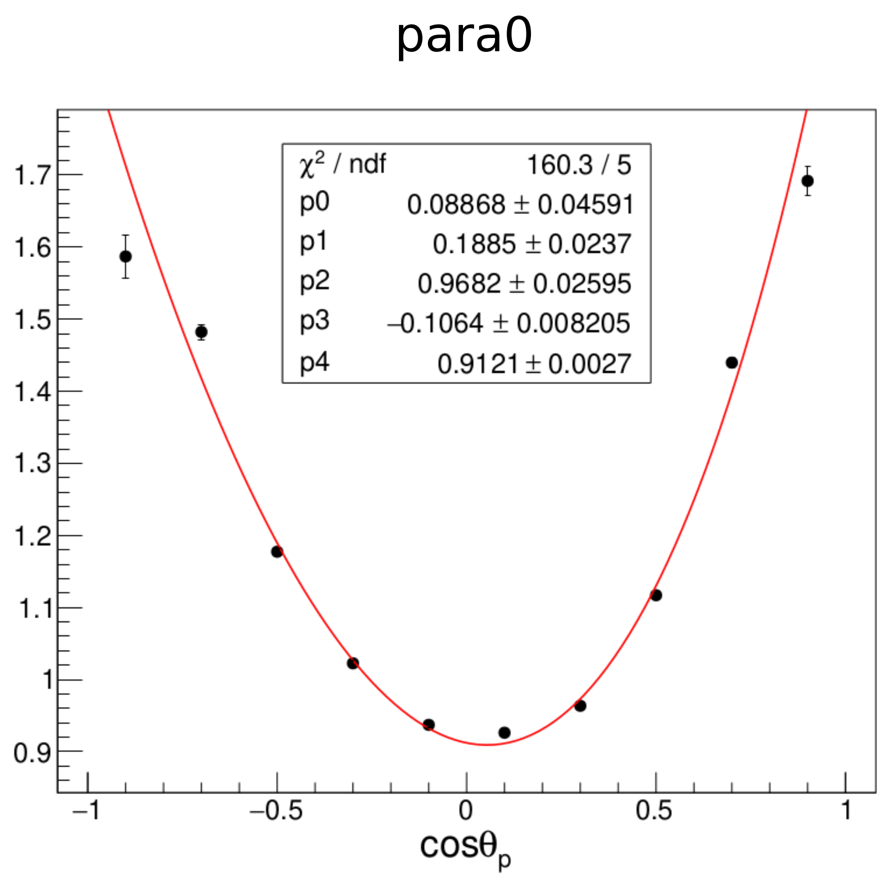
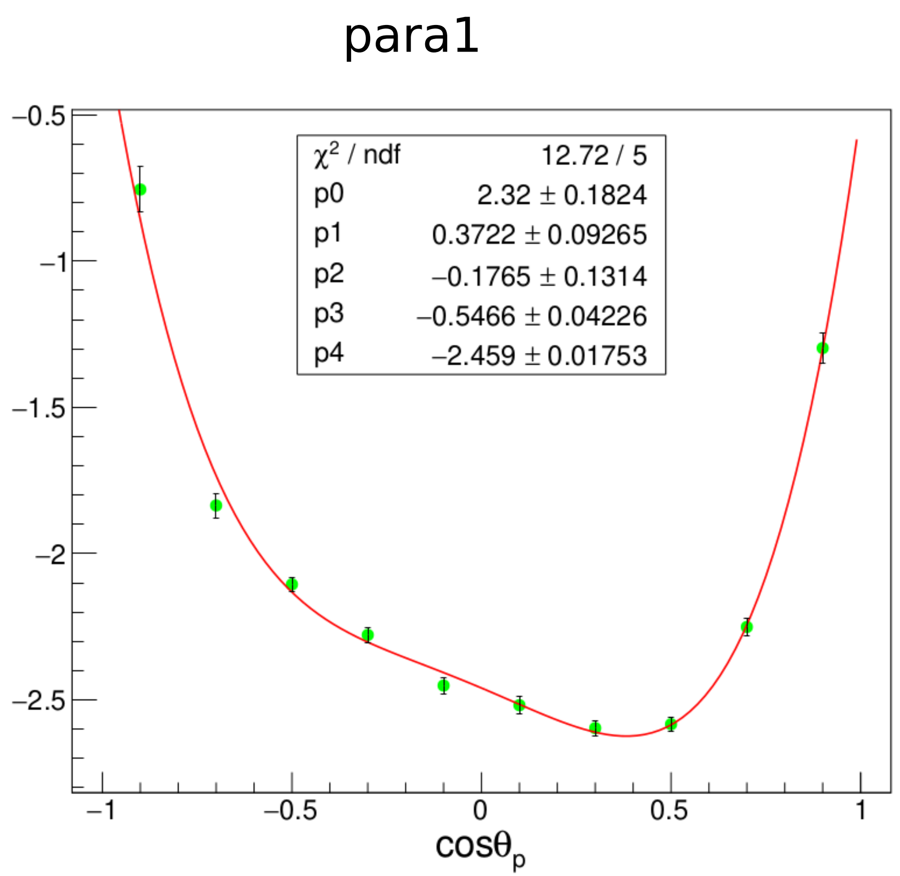
MC Momentum Weighing (¾) – Before 12600





weightFactor = para0*pow(p_{corr}/100., para1);   [p_corr in unit MeV]

With, $para0 = p_0*\cos^4(\theta) + p_1*\cos^3(\theta) + p_2*\cos^2(\theta) + p_3*\cos(\theta) + p_4$ (left)

$para1 = p_0*\cos^4(\theta) + p_1*\cos^3(\theta) + p_2*\cos^2(\theta) + p_3*\cos(\theta) + p_4$ (right)

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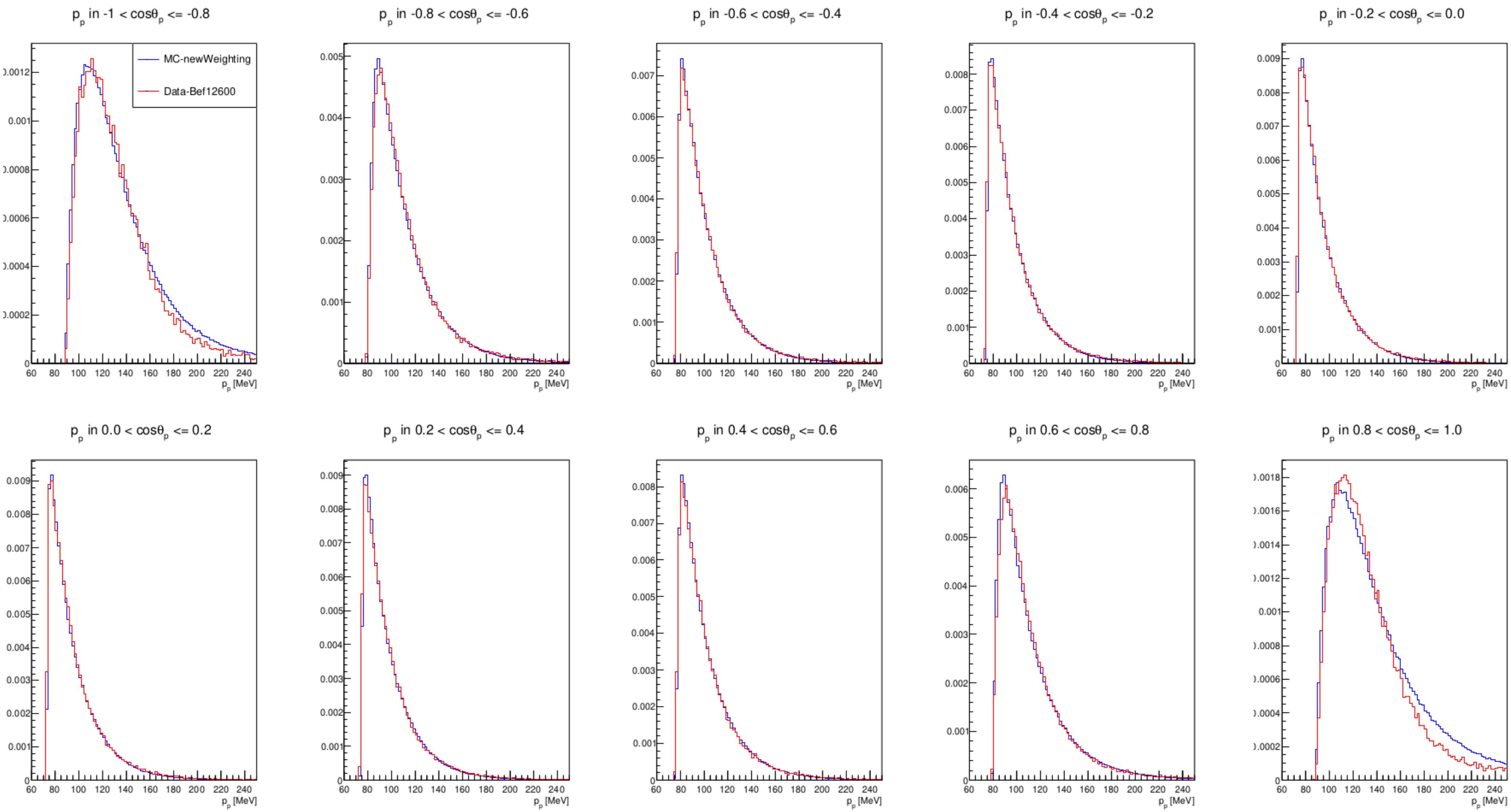
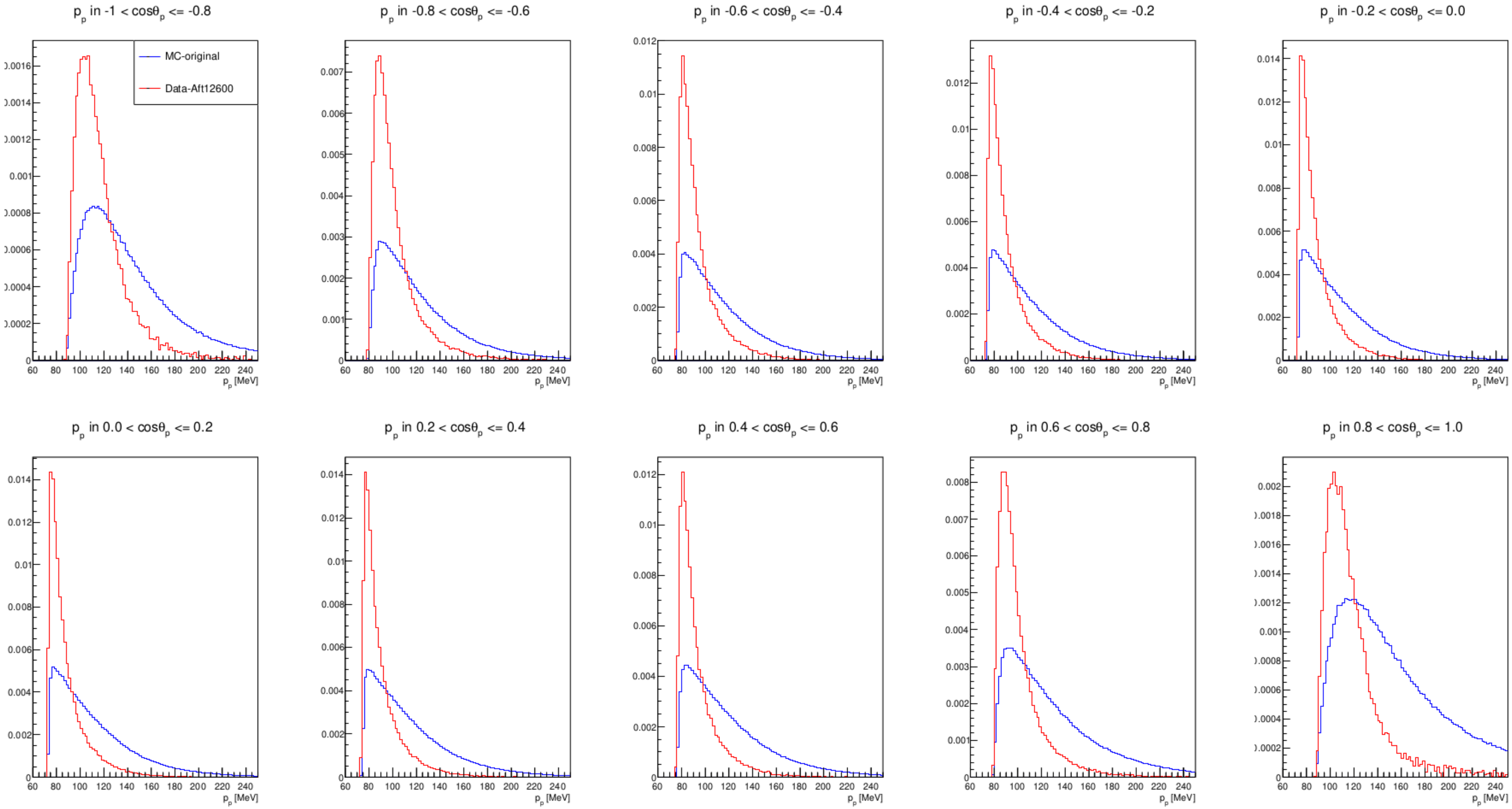
MC Momentum Weighing (4/4) – Before 12600



MC Momentum Weighing (¼) – After 12600



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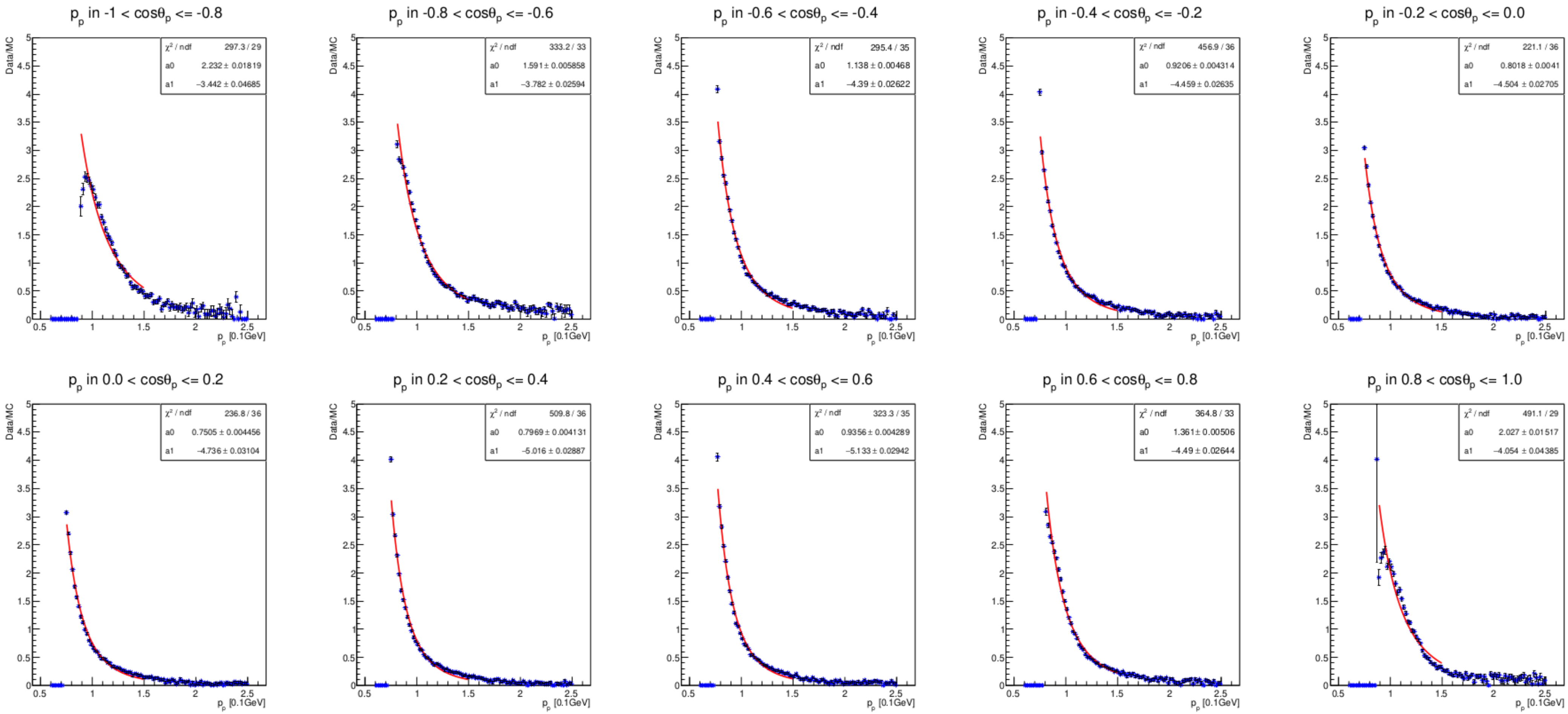
MC Momentum Weighing (2/4) – After 12600



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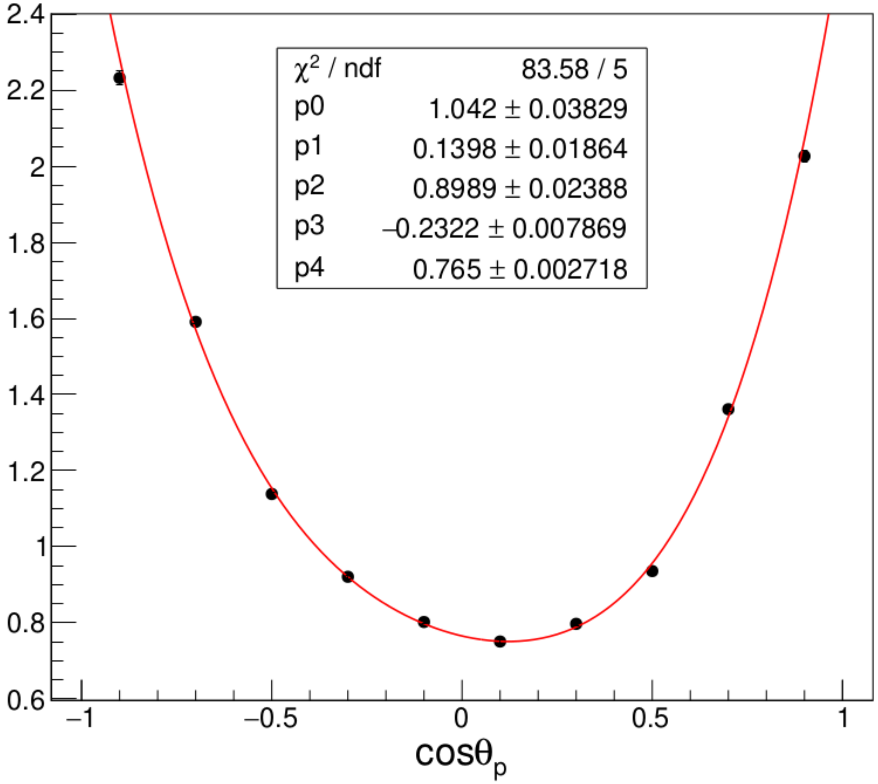
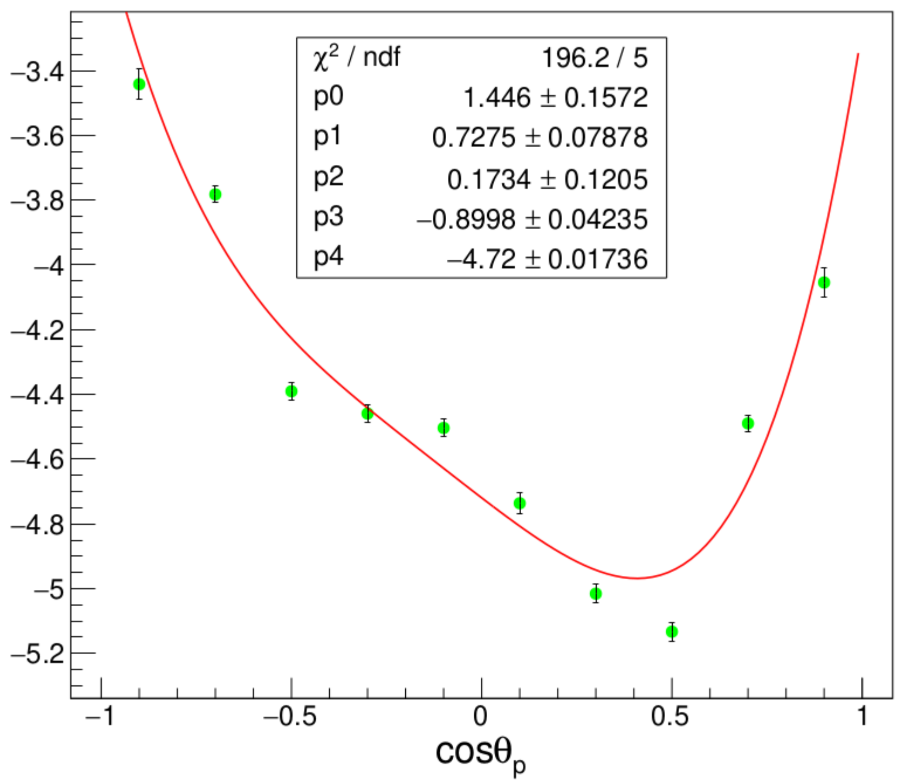
MC Momentum Weighing (¾) – After 12600

para0



para1

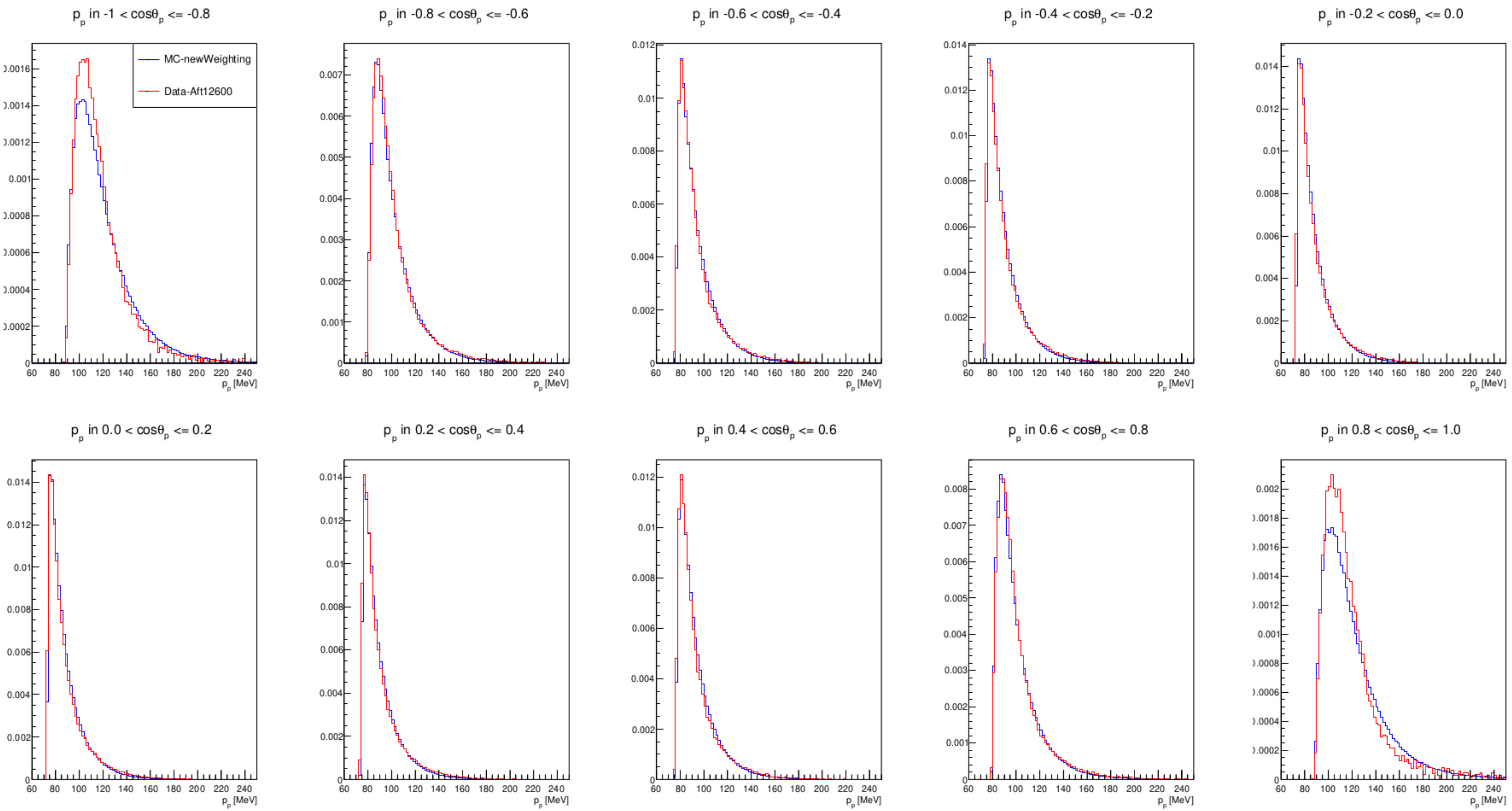


weightFactor = para0*pow(p_{corr}/100., para1); [p_corr in unit MeV]

With, para0 = $p_0*\cos^4(\theta) + p_1*\cos^3(\theta) + p_2*\cos^2(\theta) + p_3*\cos(\theta) + p_4$ (left)

para1 = $p_0*\cos^4(\theta) + p_1*\cos^3(\theta) + p_2*\cos^2(\theta) + p_3*\cos(\theta) + p_4$ (right)

MC Momentum Weighing (4/4) – After 12600



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nDIS Analysis