BONuS12 Analysis Status Update

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(On behalf of the CLAS Collaboration)

2025 CLAS12 Collaboration Meeting, CNU, July 9th, 2025

Outline

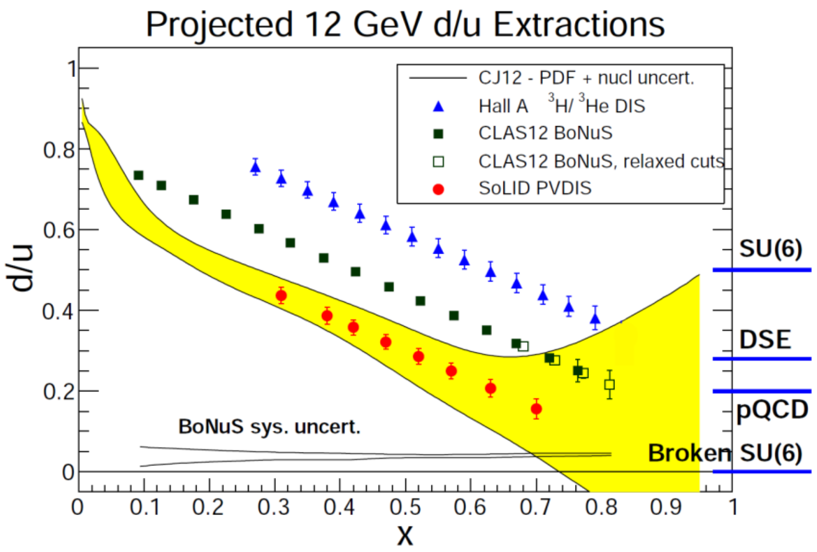
- Physics Motivations
- Experimental Setup & Recoil Detector
- Data analysis & Preliminary Results
- Summary

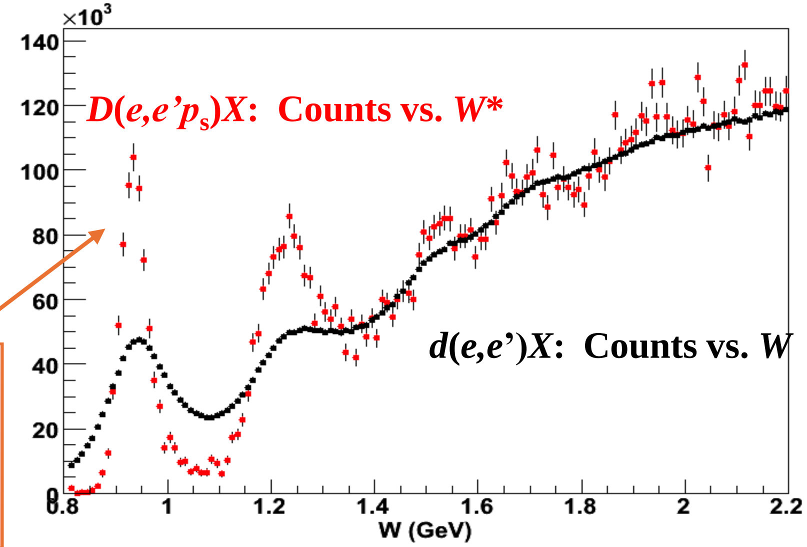
Physics Motivations

- There are many experiments provide precise measurements on F_2^p and F_2^d, but less precise for F_2^n, especially at large x, where different theoretical models have different predictions
- As it is difficulty to prepare free neutron in the experiment, F_2^n would be obtained from bound neutron inside the nucleon. Yet, the nuclear corrections will have theoretical model dependence at large Bjorken-x
- BONuS12 : By using the spectator tagging technique, which measure the spectator-proton bound in the nucleon, could reduce the model dependent by constraining the kinematic.

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

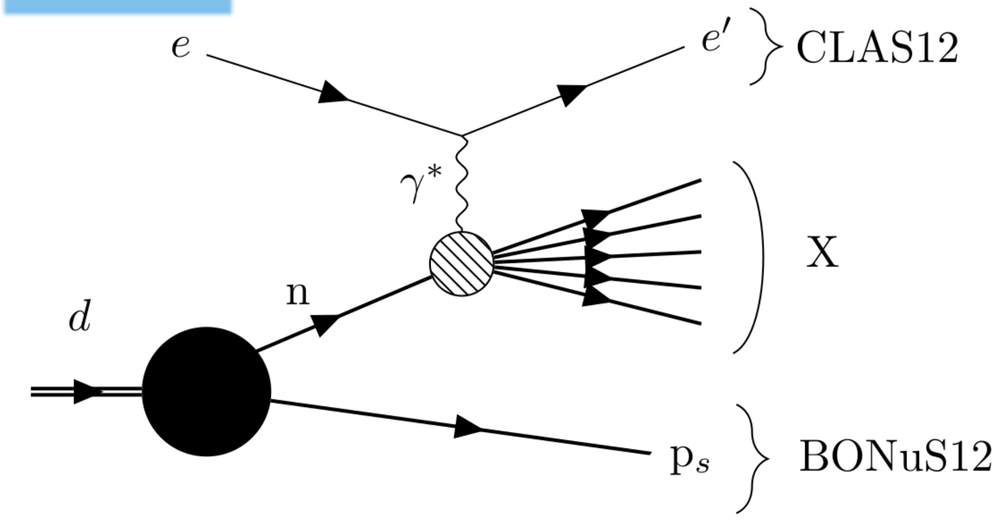
$$M^{*2} = (M_d - E_s)^2 - |\vec{p}_s| \qquad \alpha_s = \frac{E_s - \vec{p}_s \cdot \hat{q}}{M_s}$$

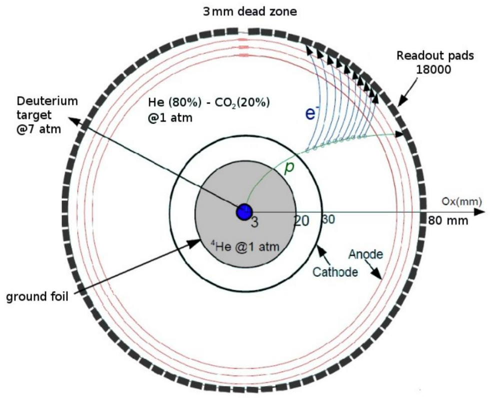


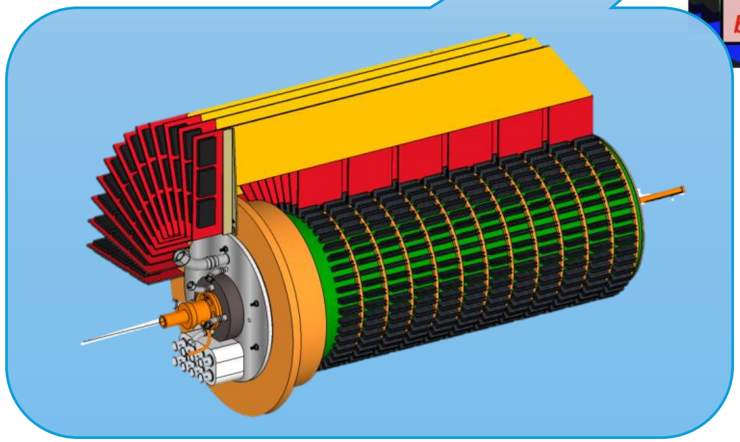


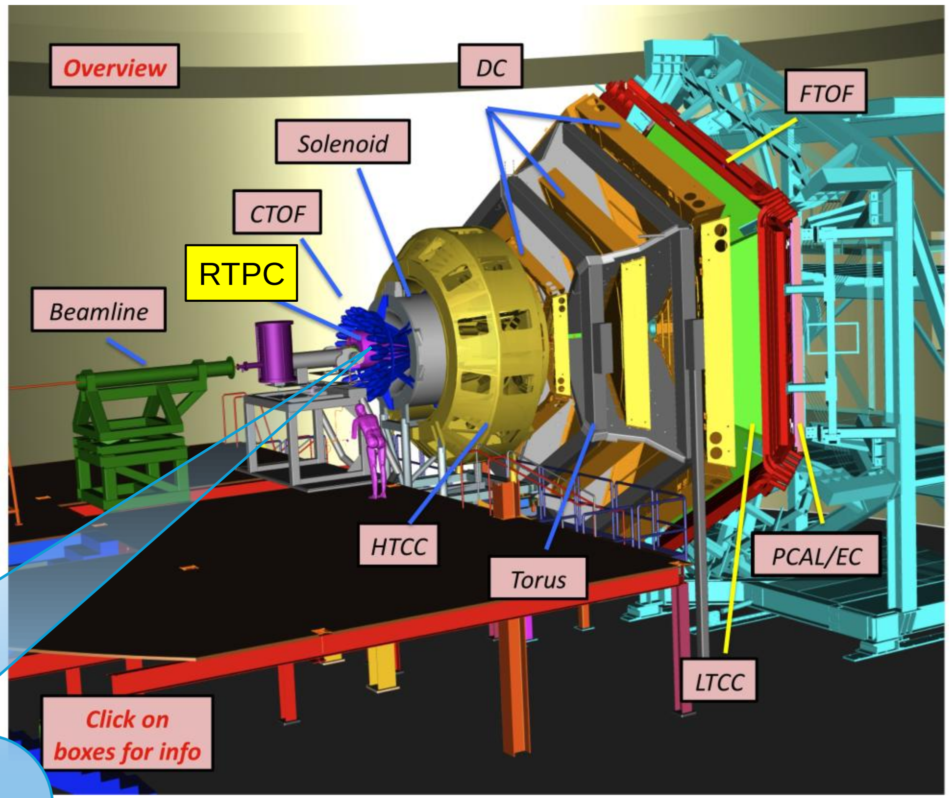
BONuS12 Experimental Setup

10.4 GeV









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

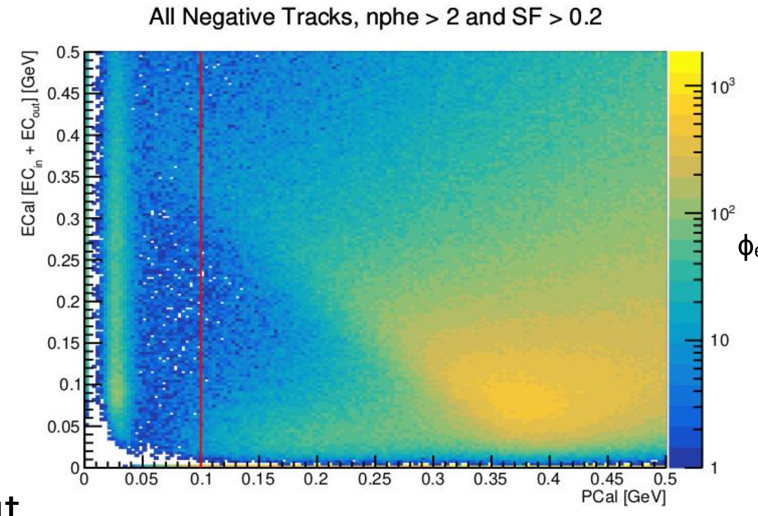
Event selection — DIS Electron at 10.4 GeV for D_2 target

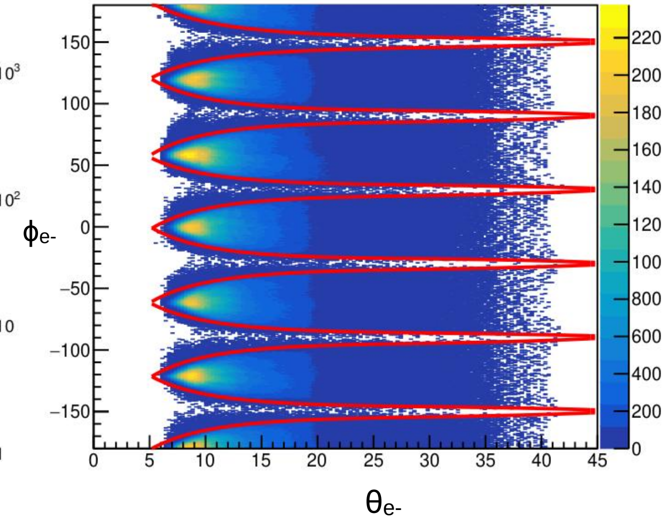
Electron selection cuts

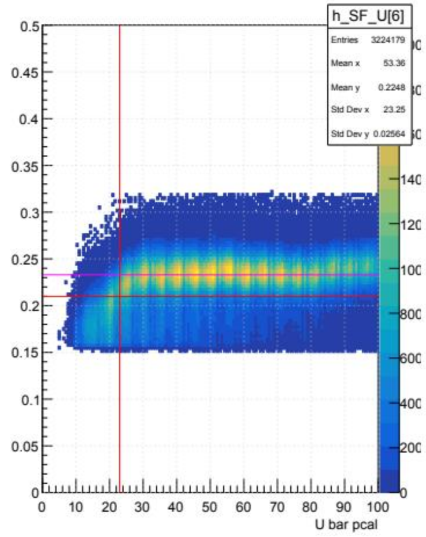
- PID = 11
- nphe > 2
- EC_{in} > 10 [MeV]
- E_{PCal} > 100 [MeV]
- DC fiducial cuts
- E' > 2.6 [GeV]
- vz_{e-}
- vz_{e-} & θ_{e-} 2D geometric cut
- θ_{e-}^{local} > 7.0 [Deg.]
- PCal SF and Fiducial cuts:

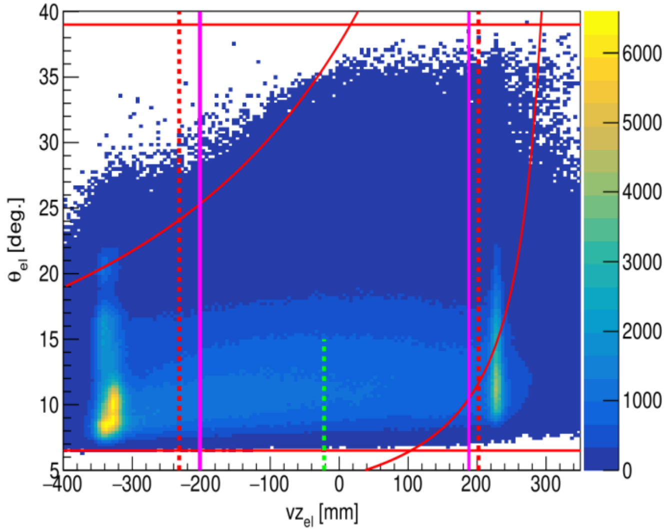
Additional DIS cuts

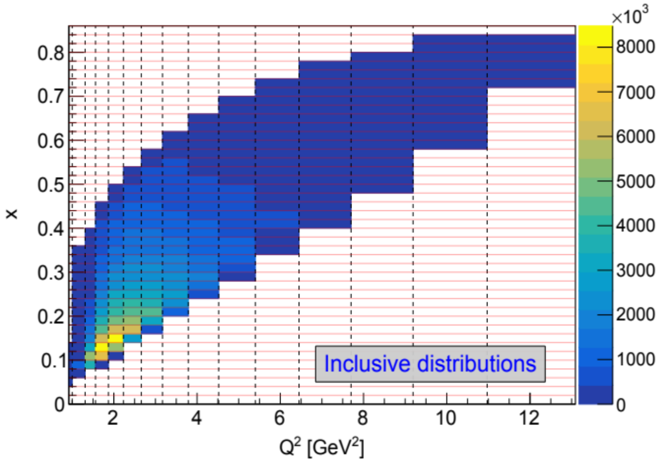
- W > 1.8 [GeV] (for Exp. And Sim.)
- Q^2 > 1.56 [GeV^2]











Event selection — Spectator Proton in nDIS at 10.4 GeV for D_2 target

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])

PID Cuts:

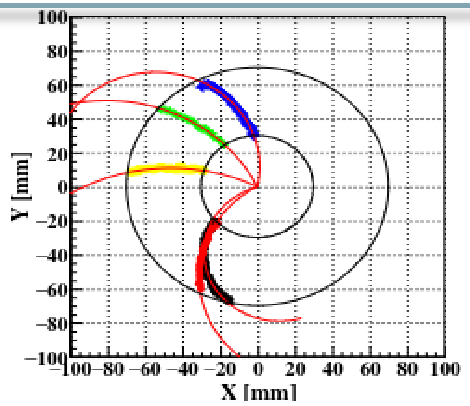
- Run-dependent Cuts on dEdx vs. p/q band for proton selection

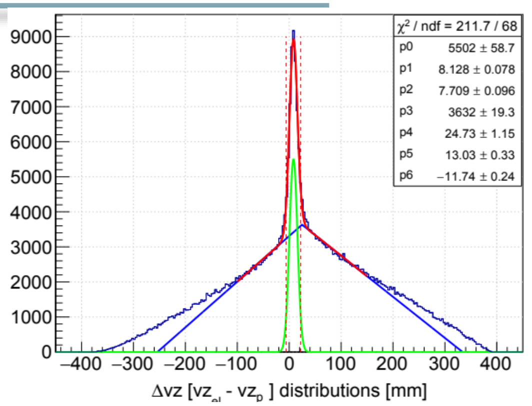
ep Coincidence cuts

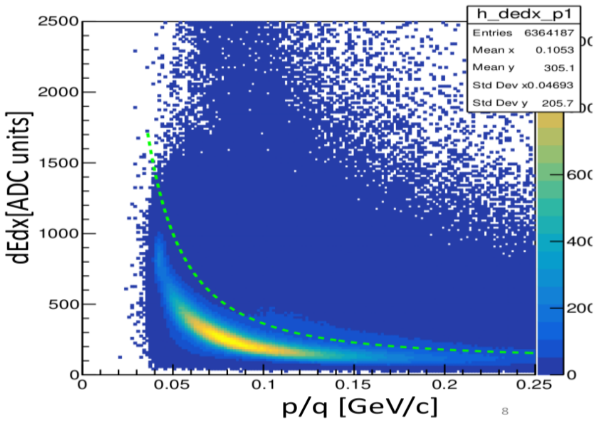
- Vertex coincidence cuts
- Timing coincidence

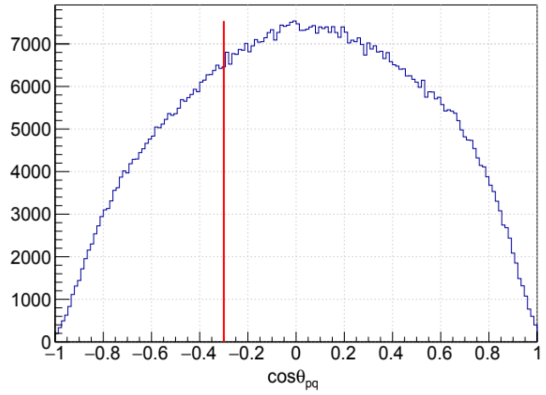
DIS & VIP cuts — To minimize the nuclear uncertainties (e.g. FSIs, Target Fragmentation, etc.)

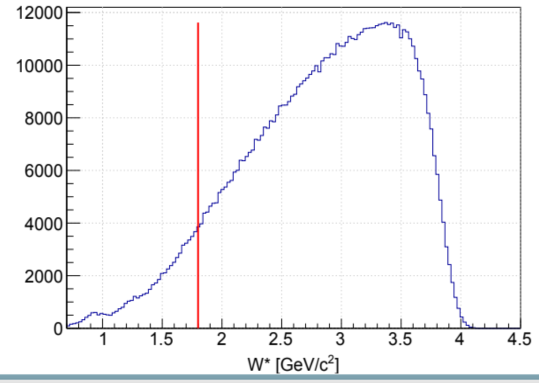
- W* > 1.8 [GeV]
- 0.075 < p_ps < 0.1 [GeV/c]
- $35^o < \theta_{ps} < 145^o$
- $\cos(\theta_{pq}) < -0.3$

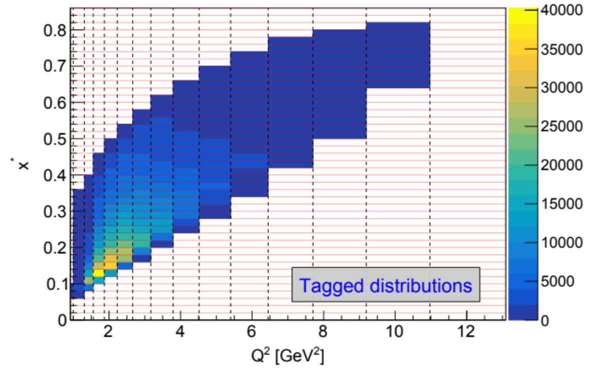




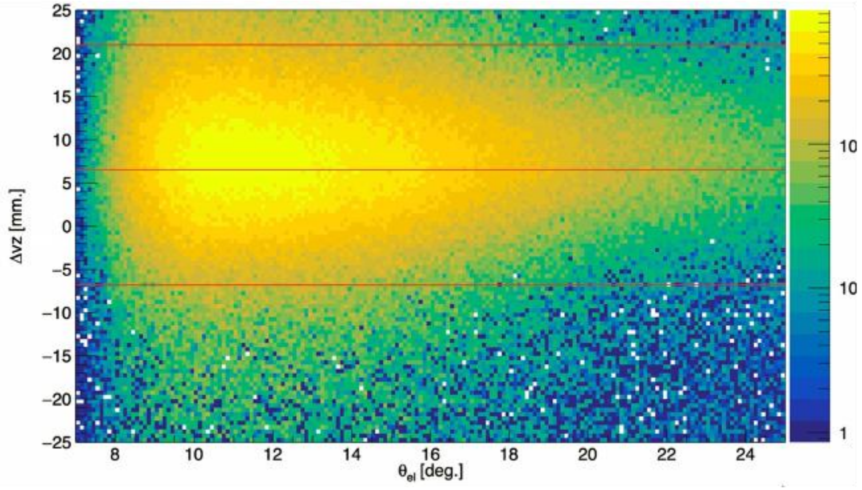








Event selection — Vertex coincidence cuts ($\Delta v_z = v_{z,e} - v_{z,p}$)



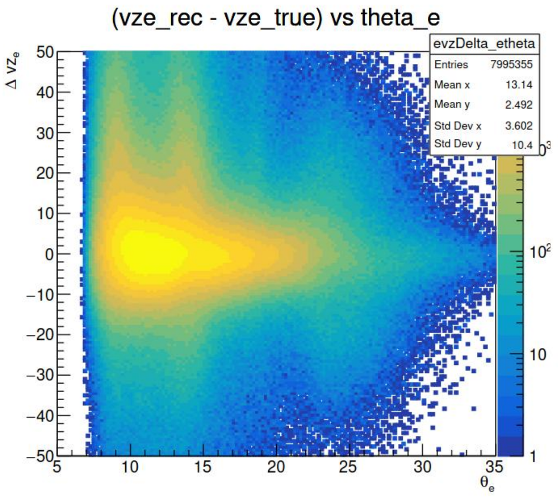
Δv_z cut for **data** is 2σ around μ, separately for each sector →

θ-dependence of μ and σ leads to θ-dependent inefficiency (Gaussian tails outside the cut)

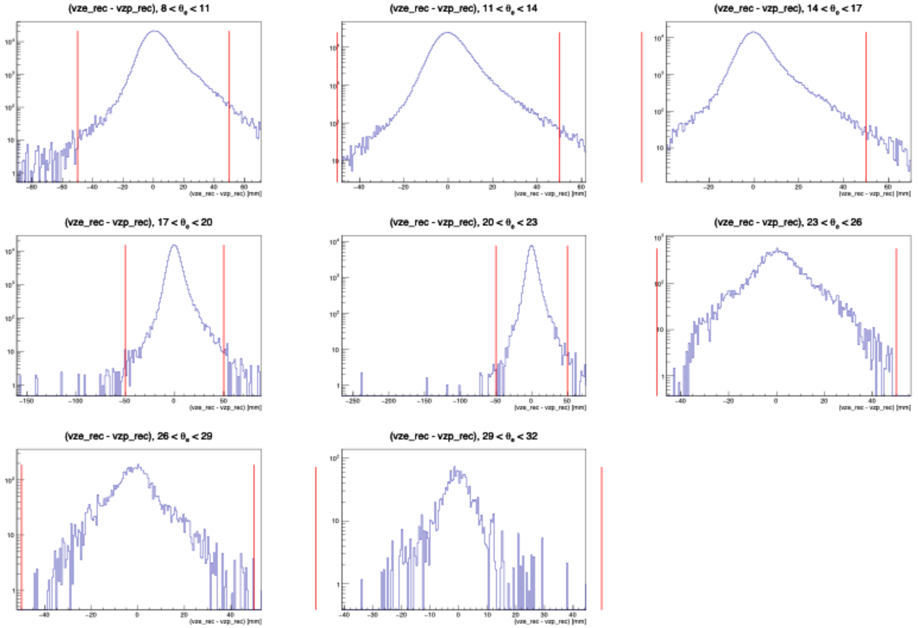
→ Correct yield for the cut efficiency

For **MC**, we had to use much wider Δv_z cuts (+/- 5 cm) due to distortion in tracking leading to mis-reconstructed θ_e and Δv_z.

→ Remaining inefficiency is small (< 0.45%) but also corrected for.



Δv_z in different θ_e bins

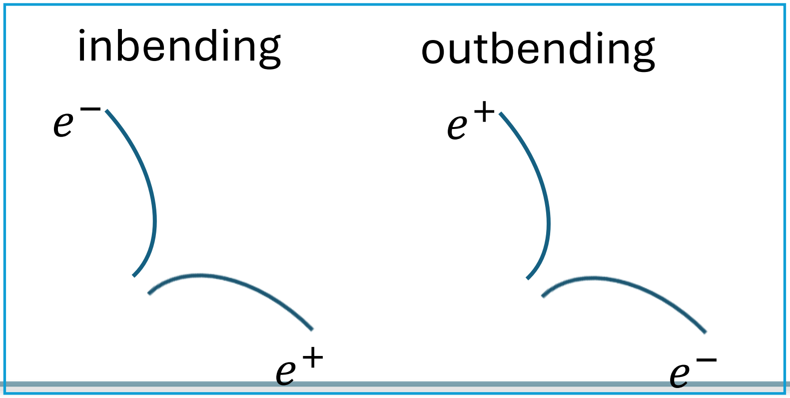


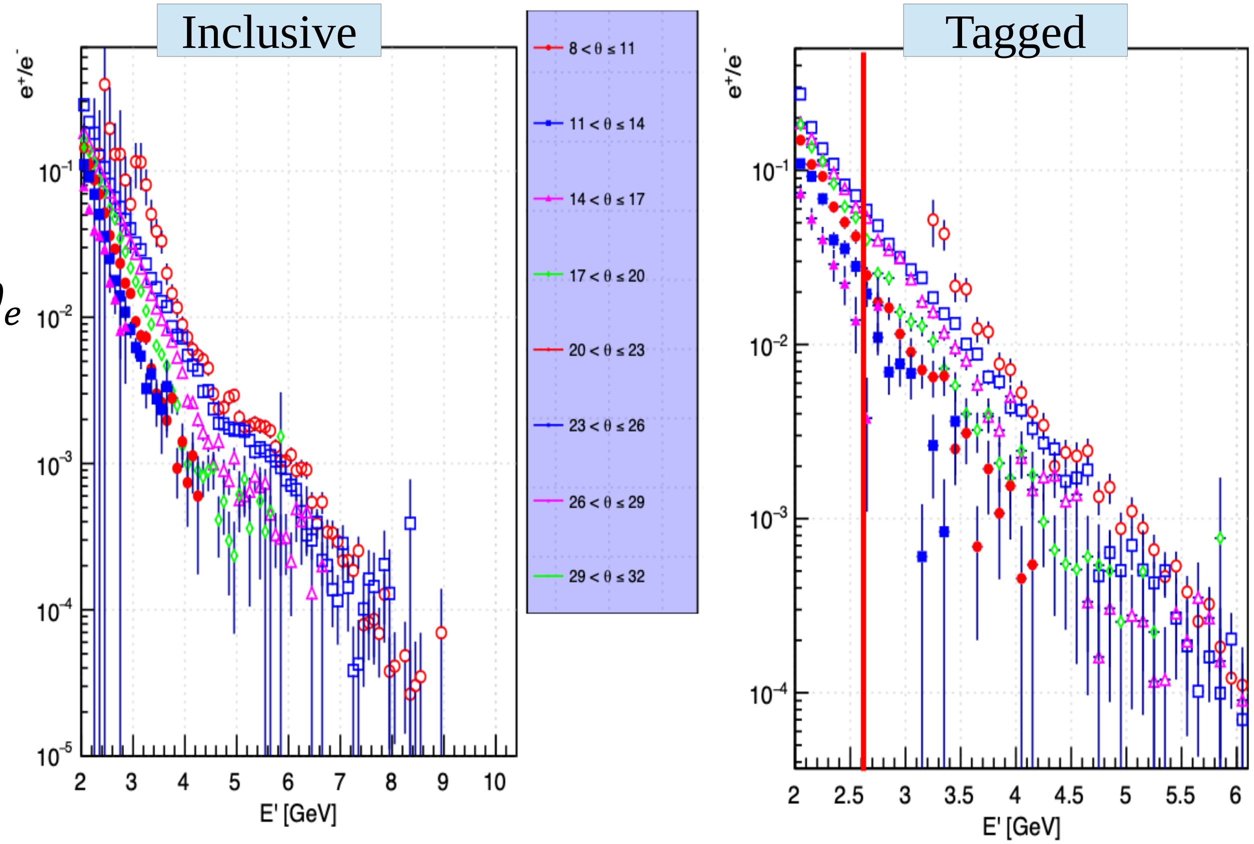
Background evaluation for experimental data — Pair Symmetric Background

There are still a number of events, but not the true ones, that passed the criteria as the background.

Electron

- Pair Symmetric Background: $\pi^0 \rightarrow e^+ e^- \gamma$
    - Secondary electron as trigger particle
    - Electron and positron have same behavior in the opposite direction of the magnetic field
    - Look at the ratio of the outbending position to the inbending electron $\frac{e^+}{e^-}$ as function of E' in different θ_e bins.
    - $N_{e-,scattered} = N_{e-,measured}\left(1 - \frac{N_{e+,measured}}{N_{e-,measured}}\right)$

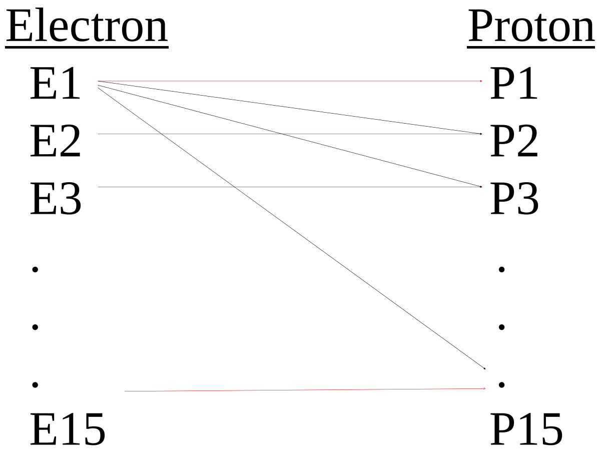


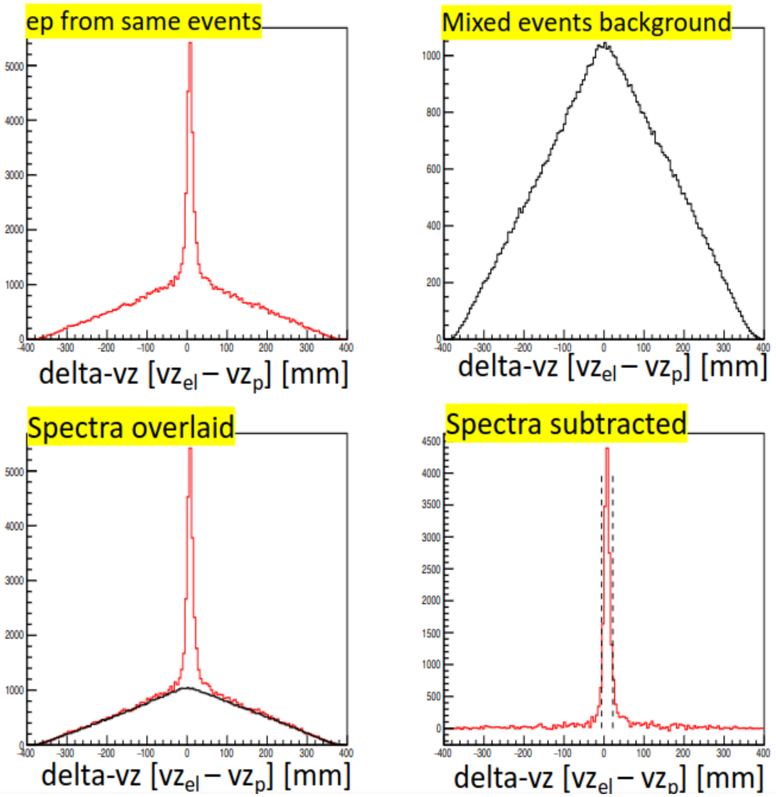


Background evaluation for experimental data — Accidentals

Proton

- Accidental Background
  - Due to ionization electron inside RTPC drift slowly, the coincidence cuts are wider
    → A significant number of accidental coincidence is included
  - Procedure: For every **15 consecutive events** passing all selection criteria:
    - Perform event mixing and form 15x15 ep pairs
    - **15 ep pairs** [Red in fig.] from the same event
      210 combinatorics backgrounds [Black in fig.].
    - Scale background count by **14**.

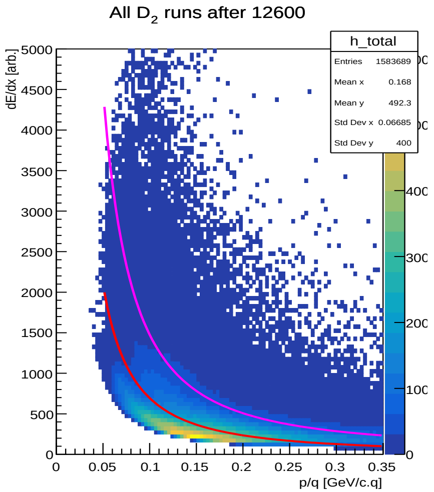


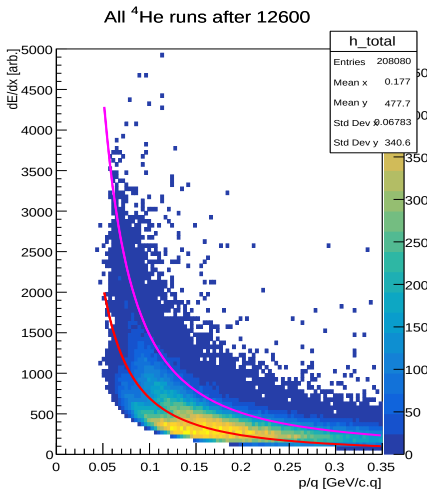


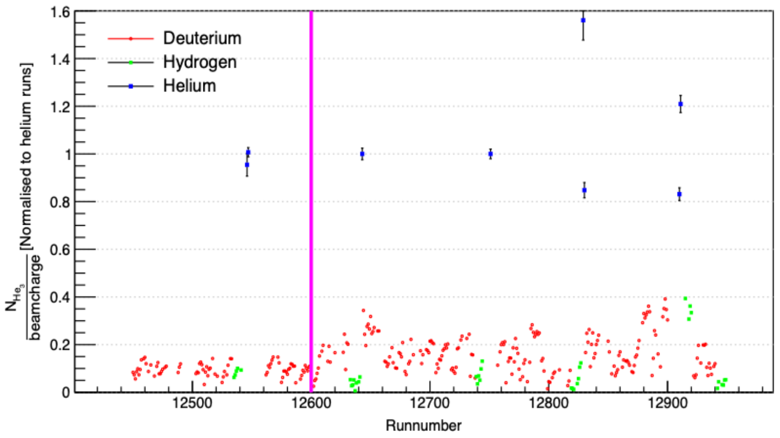
Background evaluation for experimental data — ^4He Contamination

Proton

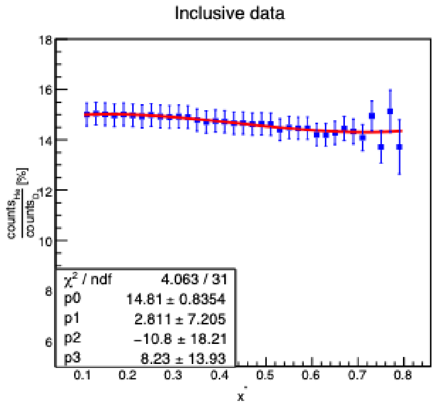
- Deuterium Target Contamination
  - ^4He could diffuse into the target straw from the surrounding buffer gas region
  - Estimated using ^{3}H/^{3}He band in dE/dx vs. p/q from D_2 runs and ^4He runs.

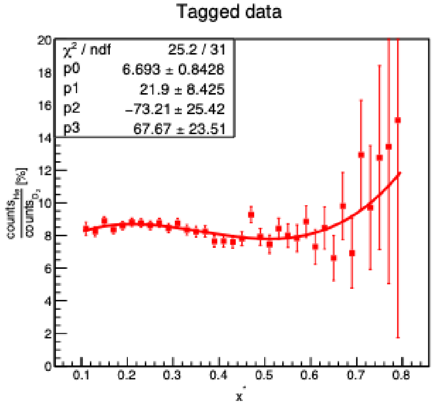






- VIP fraction coming from ^{4}He corrected using polynomial fit.



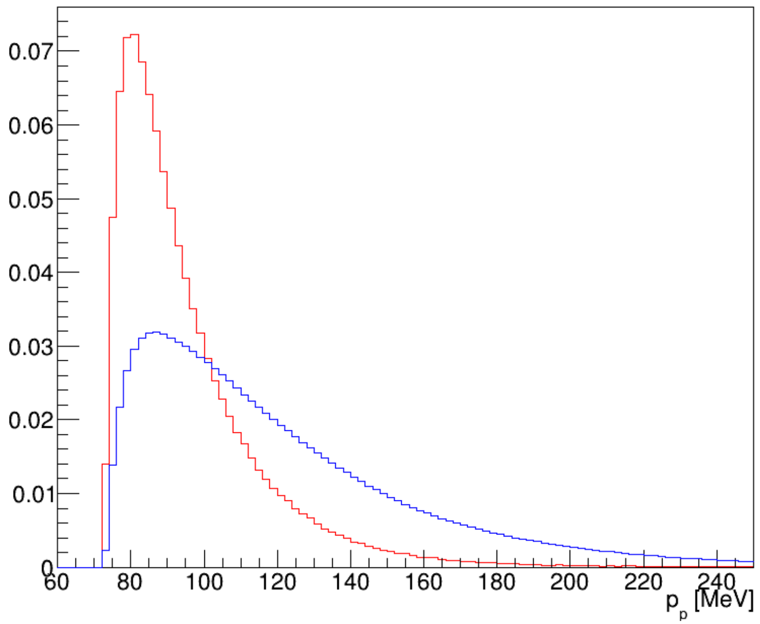


Dr. M.Pokhrel's Thesis

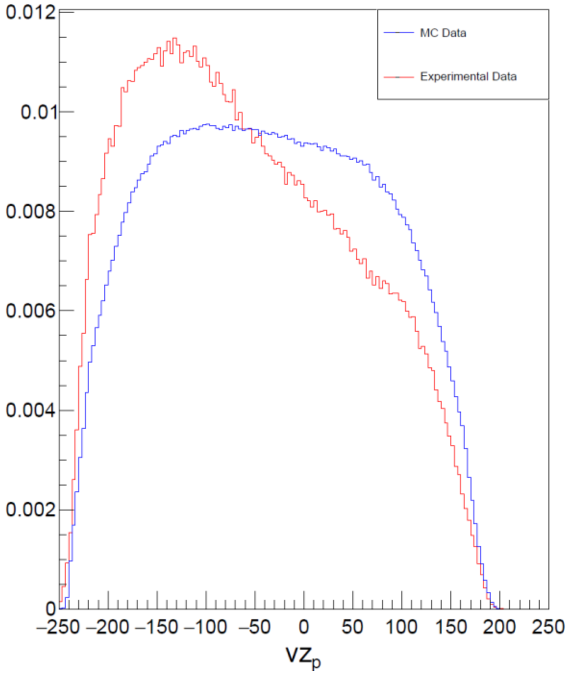
Simulation for BONuS12

- Generator: PWIA spectator model with 2014 Bosted/Christy fit to world data for F2n and F2d, AV14 D wave function, relativistic motion of struck nucleon, and equivalent radiator method for internal rad. Effects.
- Full GEMC simulation chain for both tagged and inclusive spectra with RTPC implement
- A realistic efficiency of RTPC is still needed to implement into the simulation.
- Introduce the weighting factors to each selected event so that the final distributions can match the real data.
- The weight factors are evaluated from proton momentum, vz, and ϕ_p
- The total weight factor = weightInP*weightInVZ*weightInPhi;

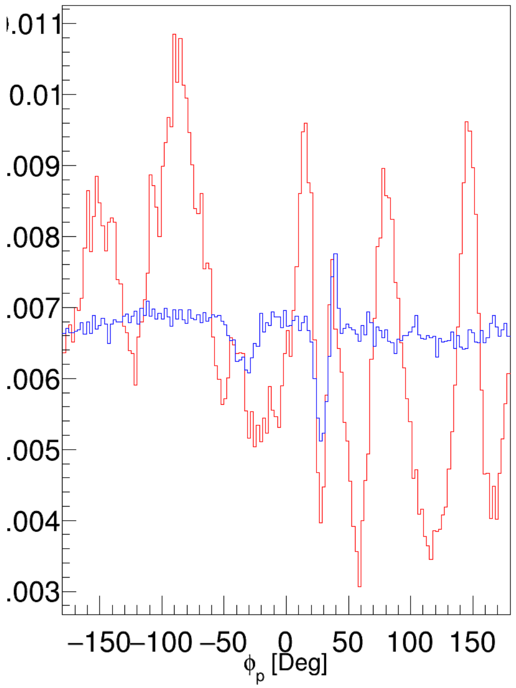
p_p



vz_p



ϕ_p



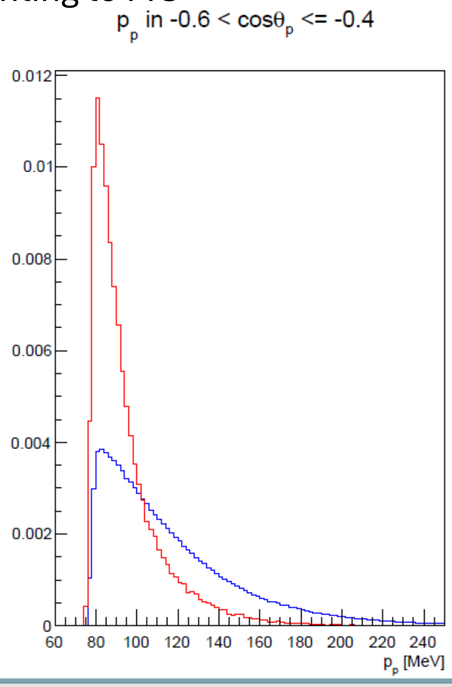
- MC. Data
- Experimental Data

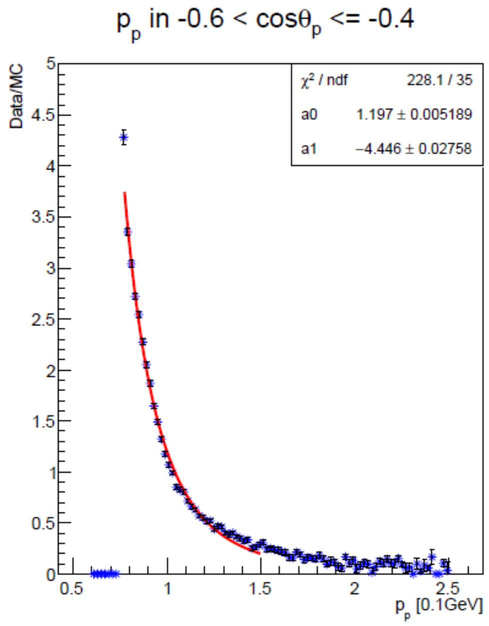
Momentum weighting on MC

Procedures

- Divided the tagged data in 10 $\cos\theta_p$ bins
- Calculate the Data/MC ratio, made plots as function of p
- Fit the Data/MC vs. p
- Extract the fitting parameters in the individual θ_p bins and fit them as a function of $\cos\theta_p$.
- Implement the weighting on MC to Match experimental data

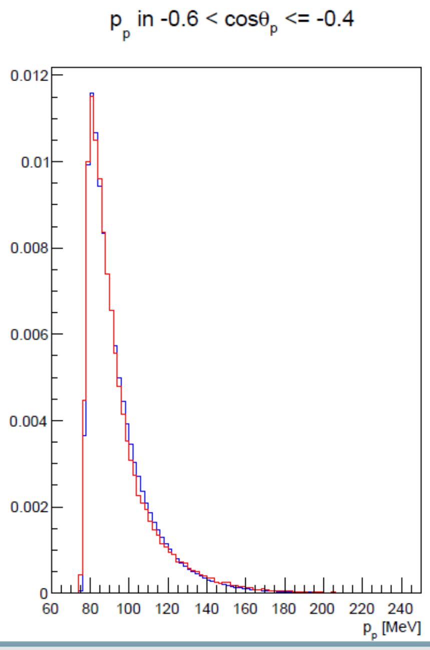
Before weighting to MC



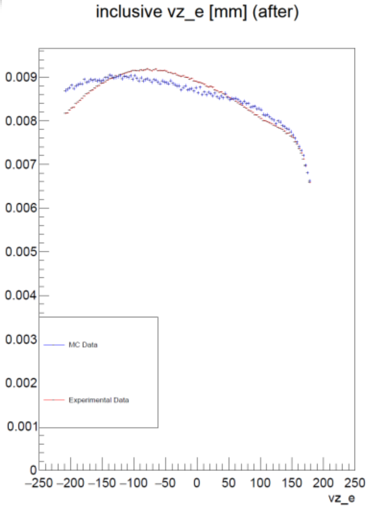


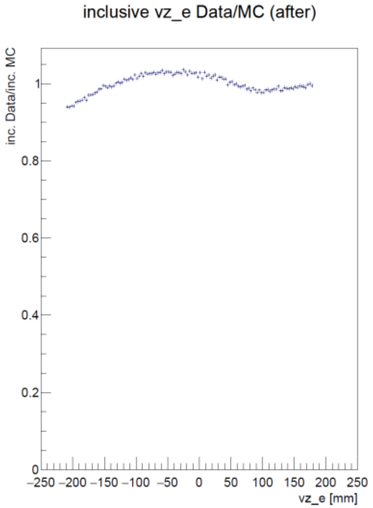
After weighting to MC

- MC. Data
- Experimental Data



z-vertex weighting on MC

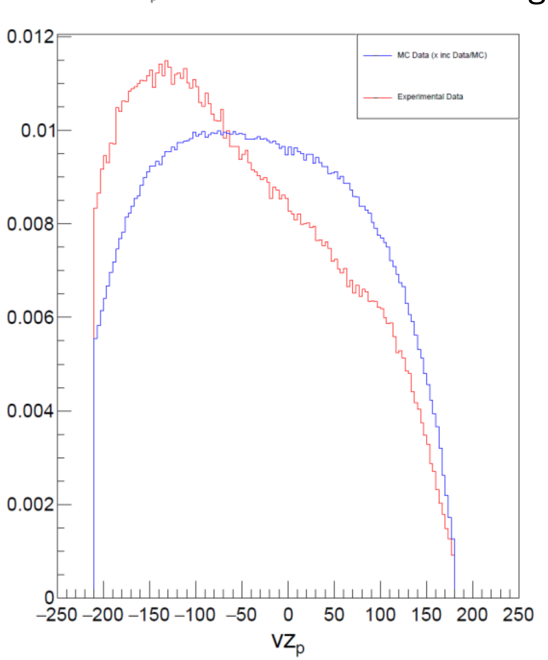


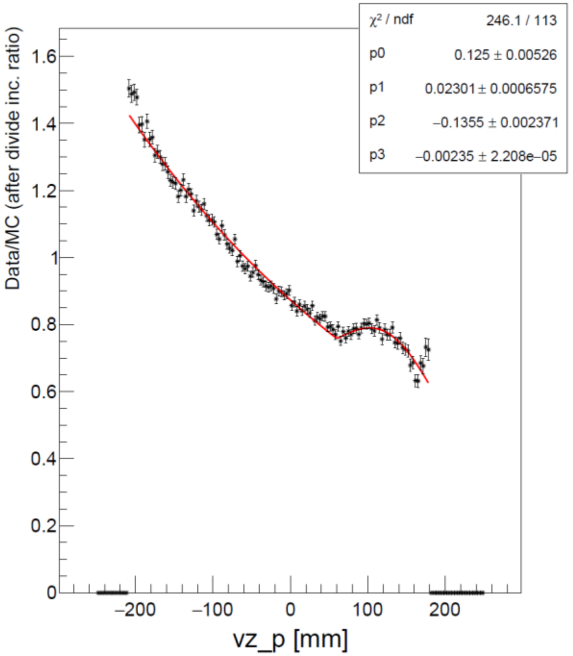


Procedures

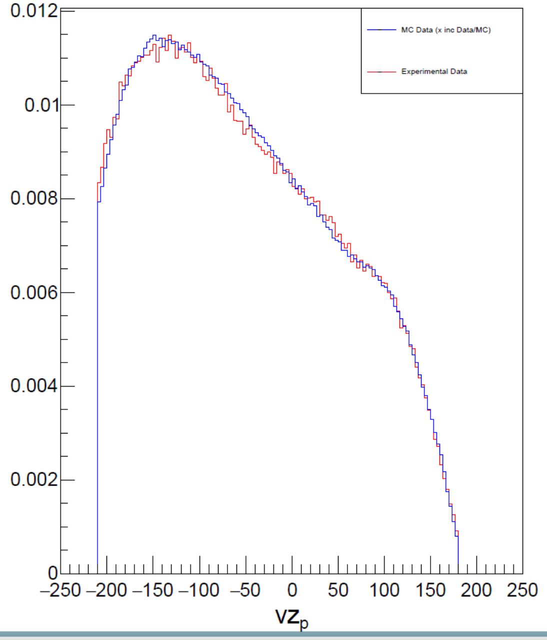
- Calculate the Data/MC ratio of vz_p, with eliminating the affect come from vz_e by dividing the inclusive vz_e ratio
- Fit the Data/MC vs. vz_p
- Parameterize the weight factor as a function of vz_p.

Before weighting to MC





After weighting to MC



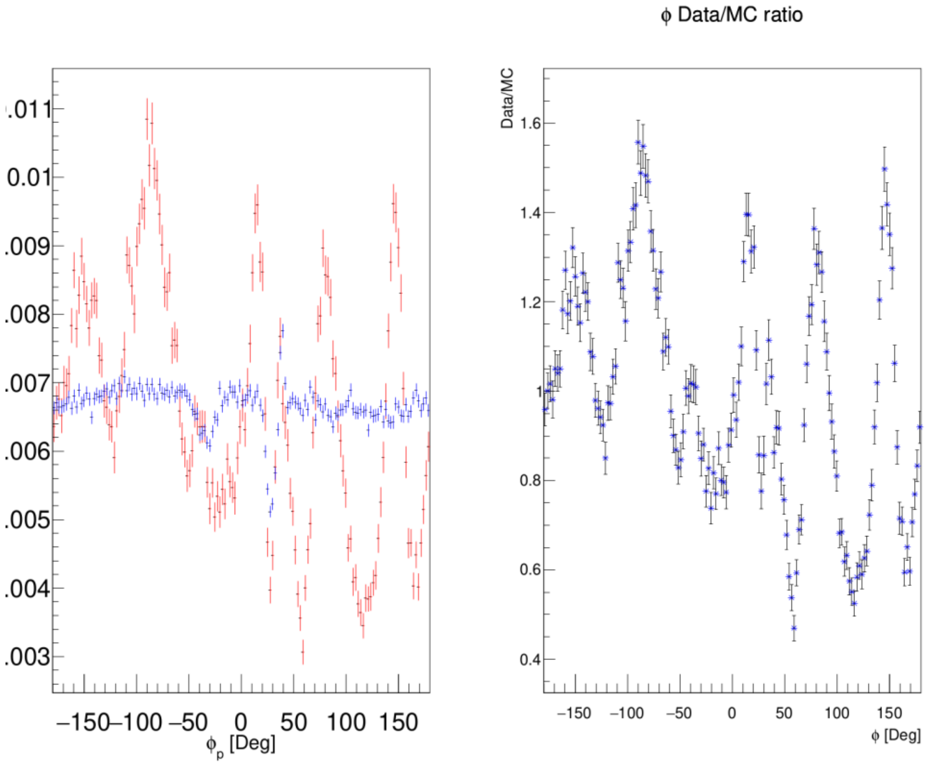
- MC. Data
- Experimental Data

ϕ_p weighting on MC

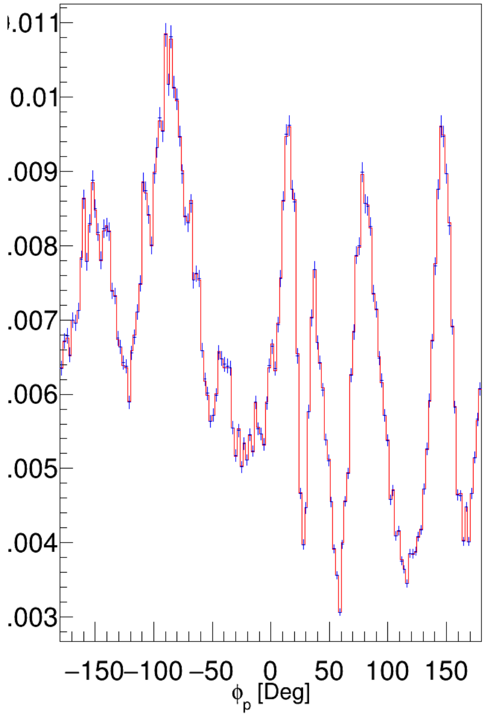
Procedures

- Calculate the Data/MC ratio for each bin from the histogram, made a table of the ratio in ϕ_p
- The weight factor is the ratio if ϕ_p is filled within that bin.

Before weighting to MC



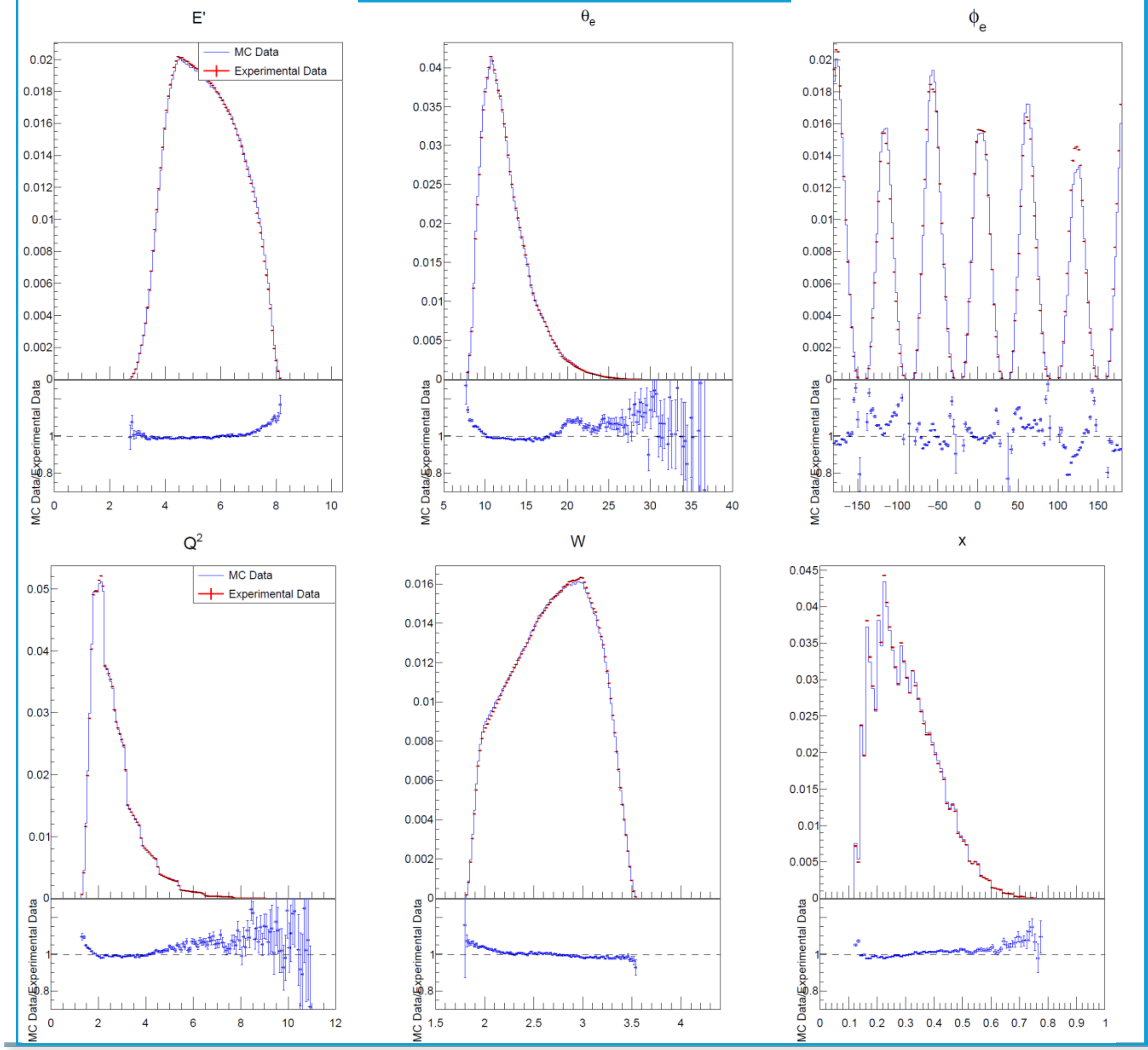
After weighting to MC



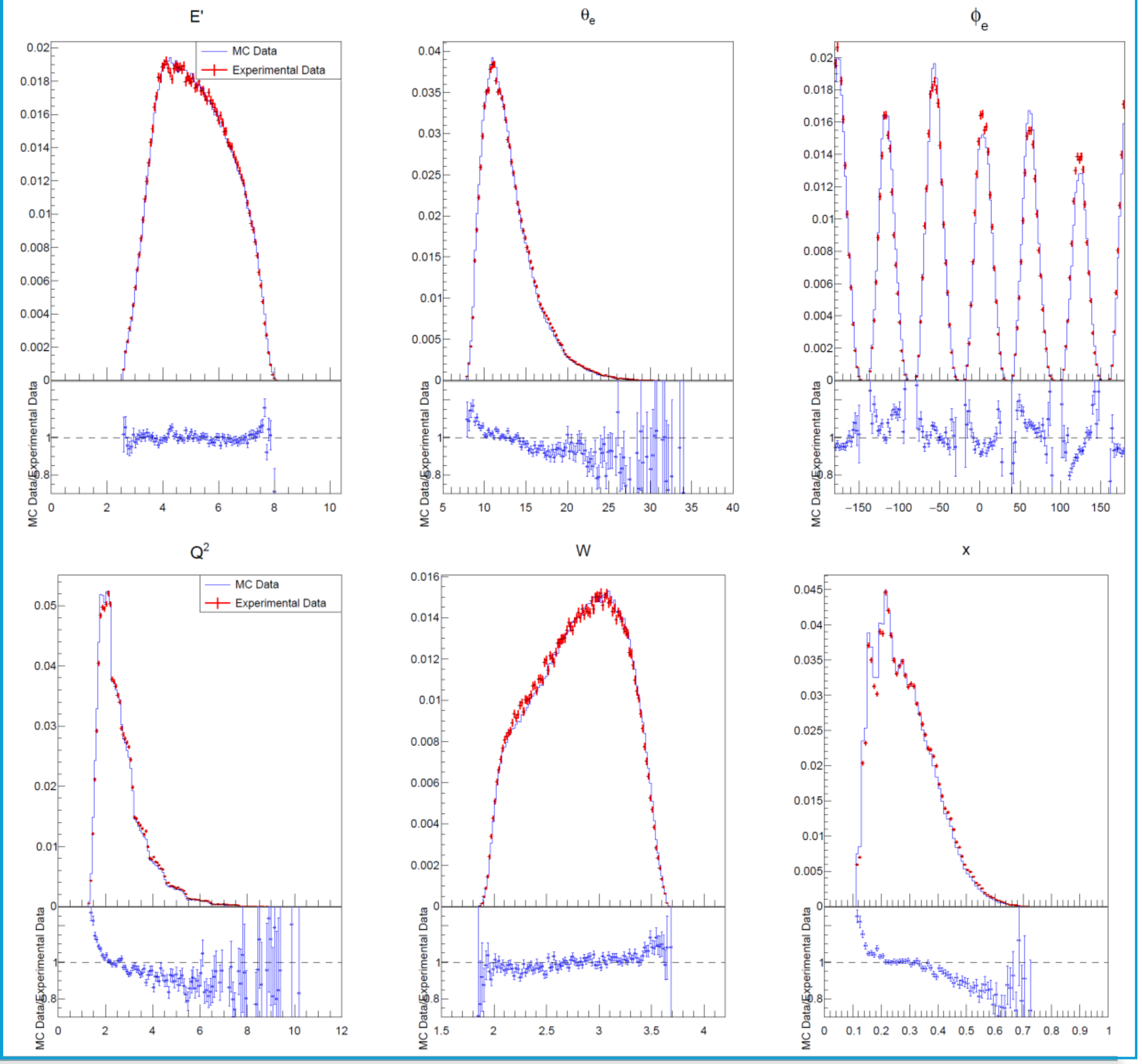
- MC. Data
- Experimental Data

Data & MC comparison — Electron

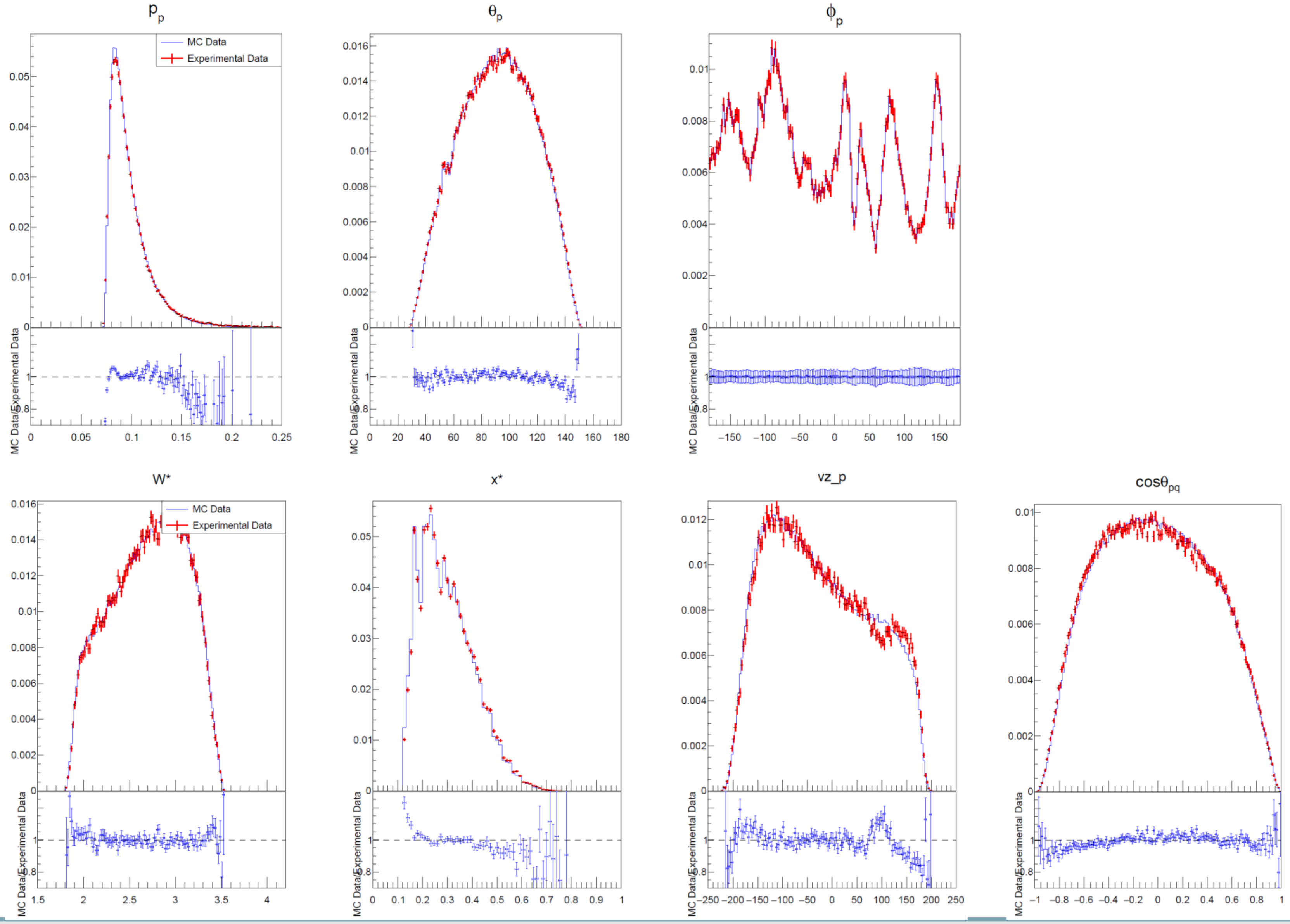
Inclusive



Tag



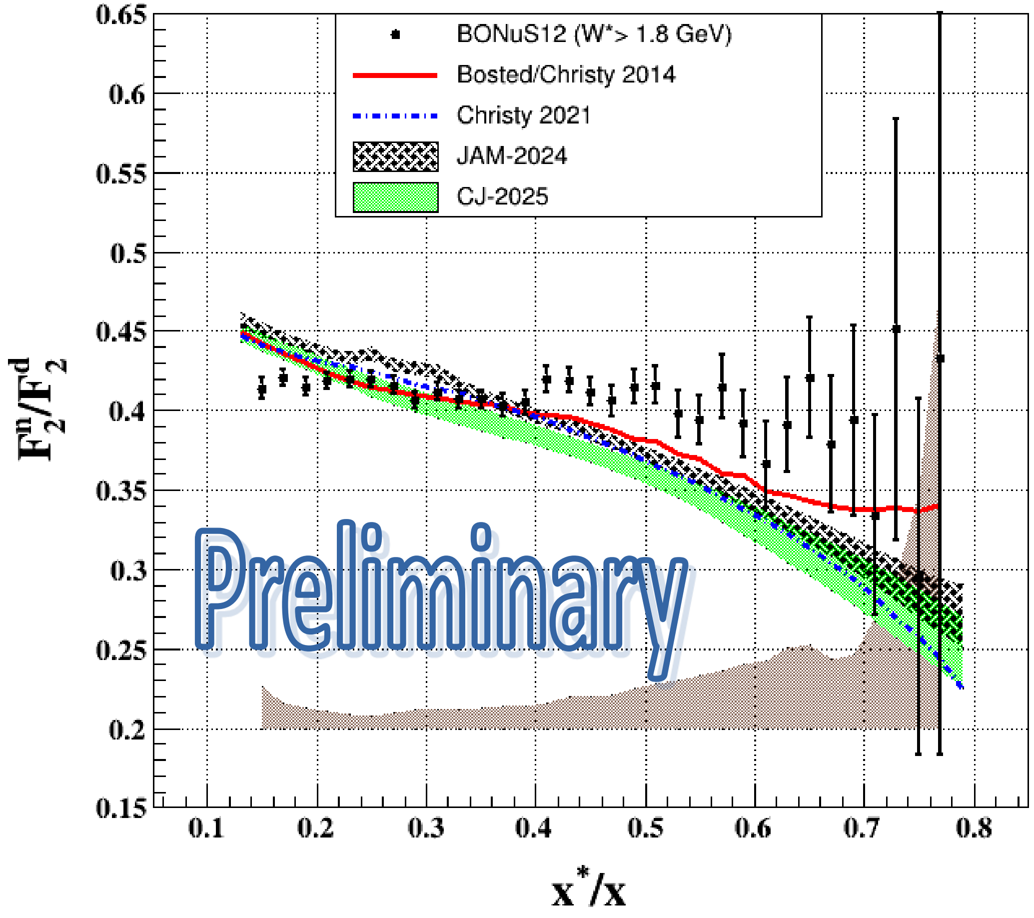
Data & MC comparison — Proton

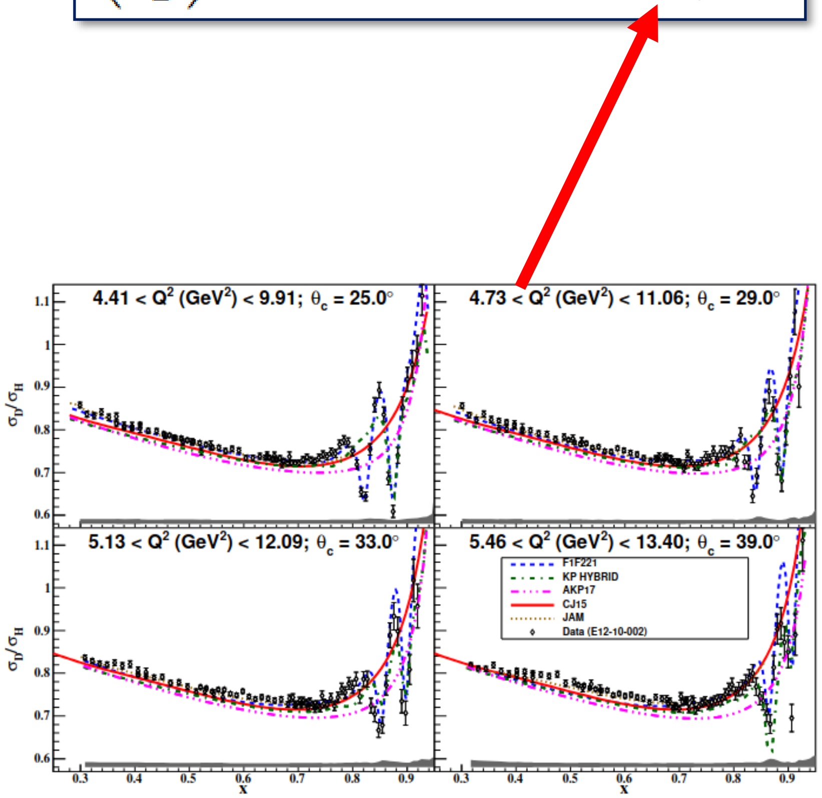


BONuS12 Preliminary Results — F_2^n/F_2^d

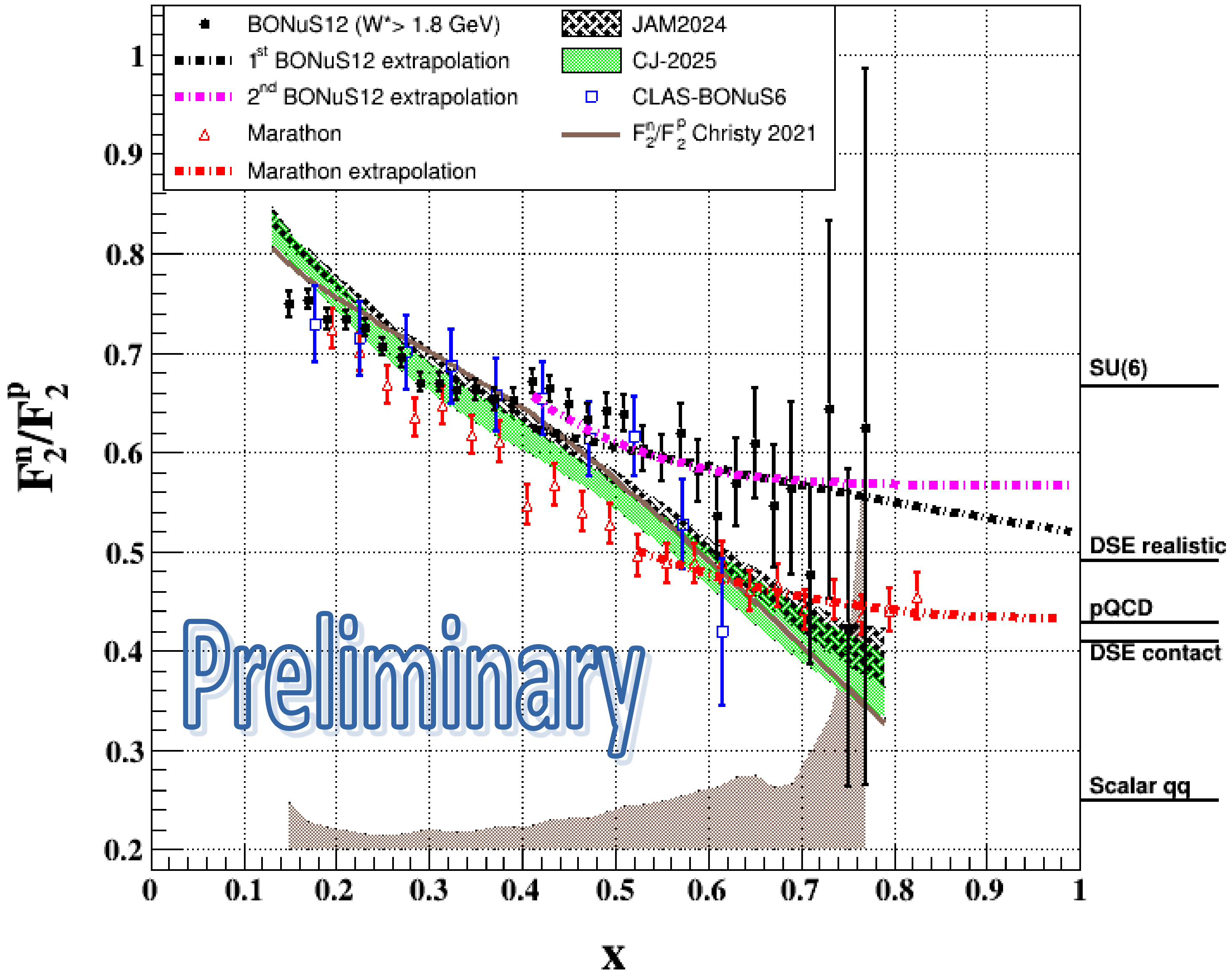
$$\left(\frac{F_{2n}}{F_{2d}}\right)^{\text{true}} = \text{Constant} \cdot \left(\frac{F_{2n}}{F_{2d}}\right)^{\text{Gen}} * \frac{\left(Y_{\text{tag}}^{\text{Data}}/Y_{\text{inc}}^{\text{Data}}\right)}{\left(Y_{\text{tag}}^{\text{MC}}/Y_{\text{inc}}^{\text{MC}}\right)}$$

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





BONuS12 Preliminary Results — F_2^n / F_2^p



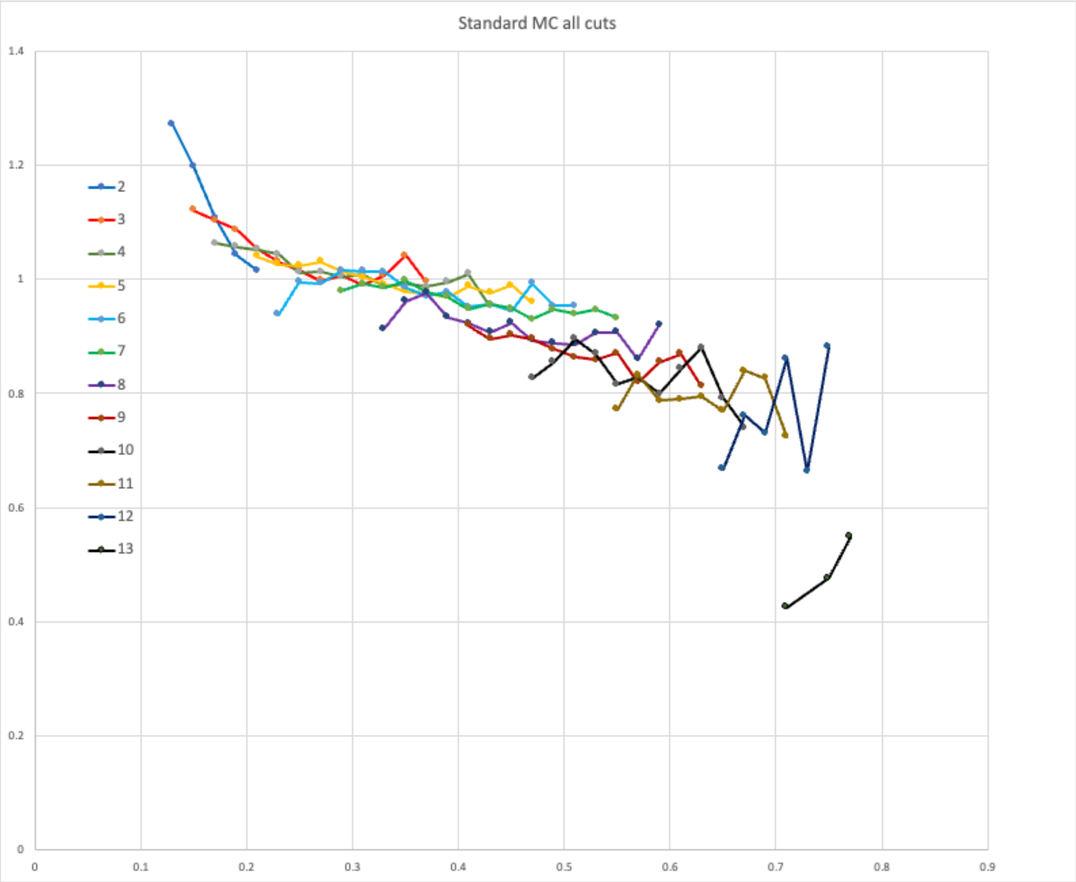
Summary

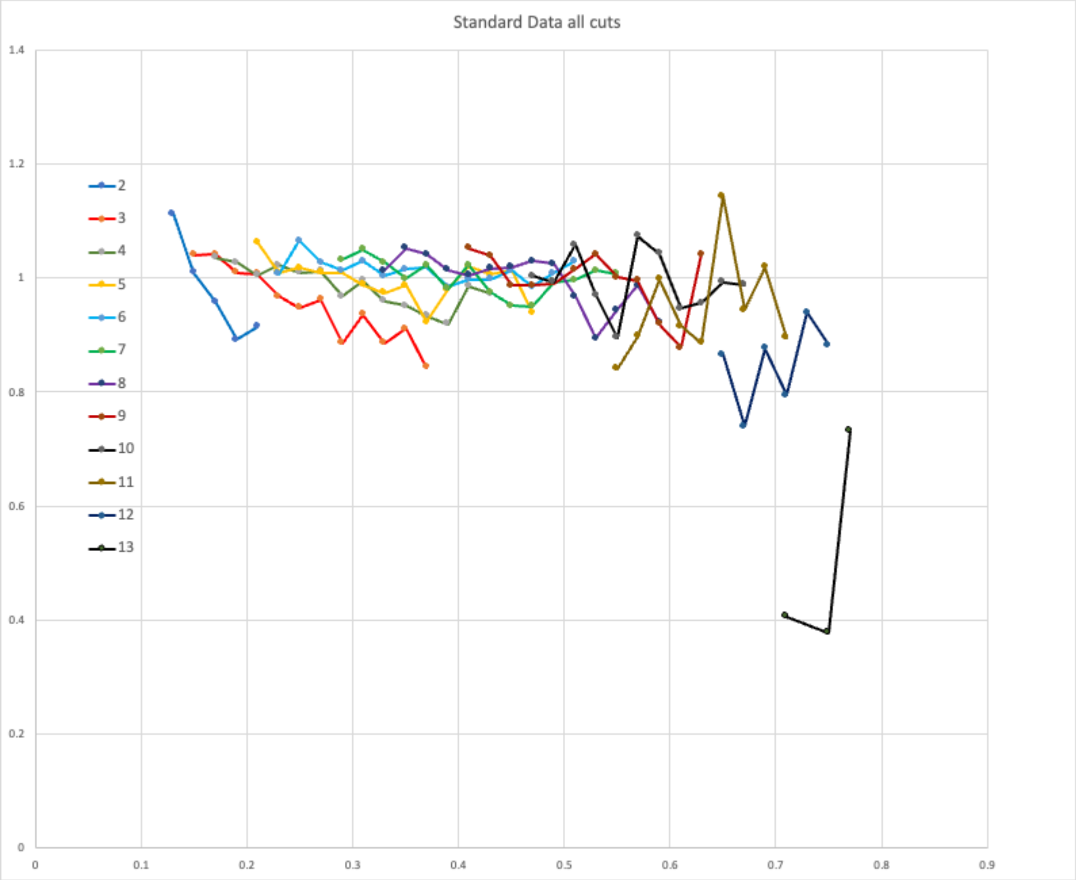
- BONuS12 extends the measurement of the spectator-tagged neutron structure functions over a larger kinematic range, with much improved statistics.
- Particle identification and all selection cuts have been tuned and are now finalized. All known backgrounds have been thoroughly studied and corrected for, with many checks showing minimal systematic uncertainty.
- MC Simulation has been tuned to reproduce the detector response of both CLAS12 and RTPC over the entire phase space. Generally, very good agreement between data and MC.
- Analysis based on Summer 2020 data is complete and preliminary results for F2n/F2d and F2n/F2p are available. A more detailed assessment of all systematic uncertainties is underway. Disagreement between extracted F2n/F2d and expected trend is still unexplained — some more studies are underway.

Backup

Backup — Check between MC and Experimental data

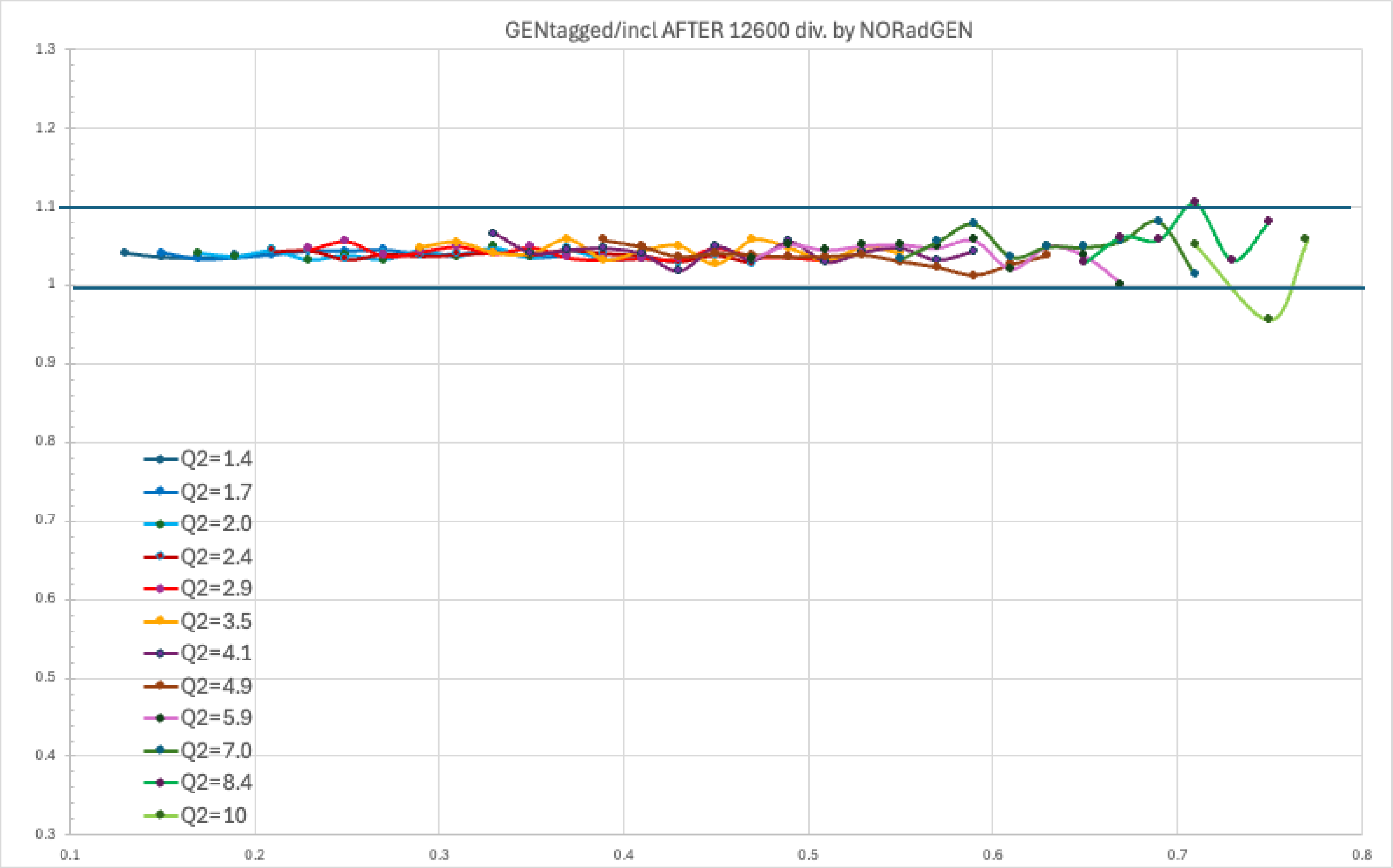
- Individual ratio of the MC and data
- These two plots show where the discrepancy comes from: The MC (left) shows the fall-off for tagged/inclusive with x expected from the F2n/F2d ratio, consistent over all Q2 bins. The DATA (right) show how each consecutive Q2 bin starts too high relative to the previous one (F2n/F2d depends only very mildly on Q2).





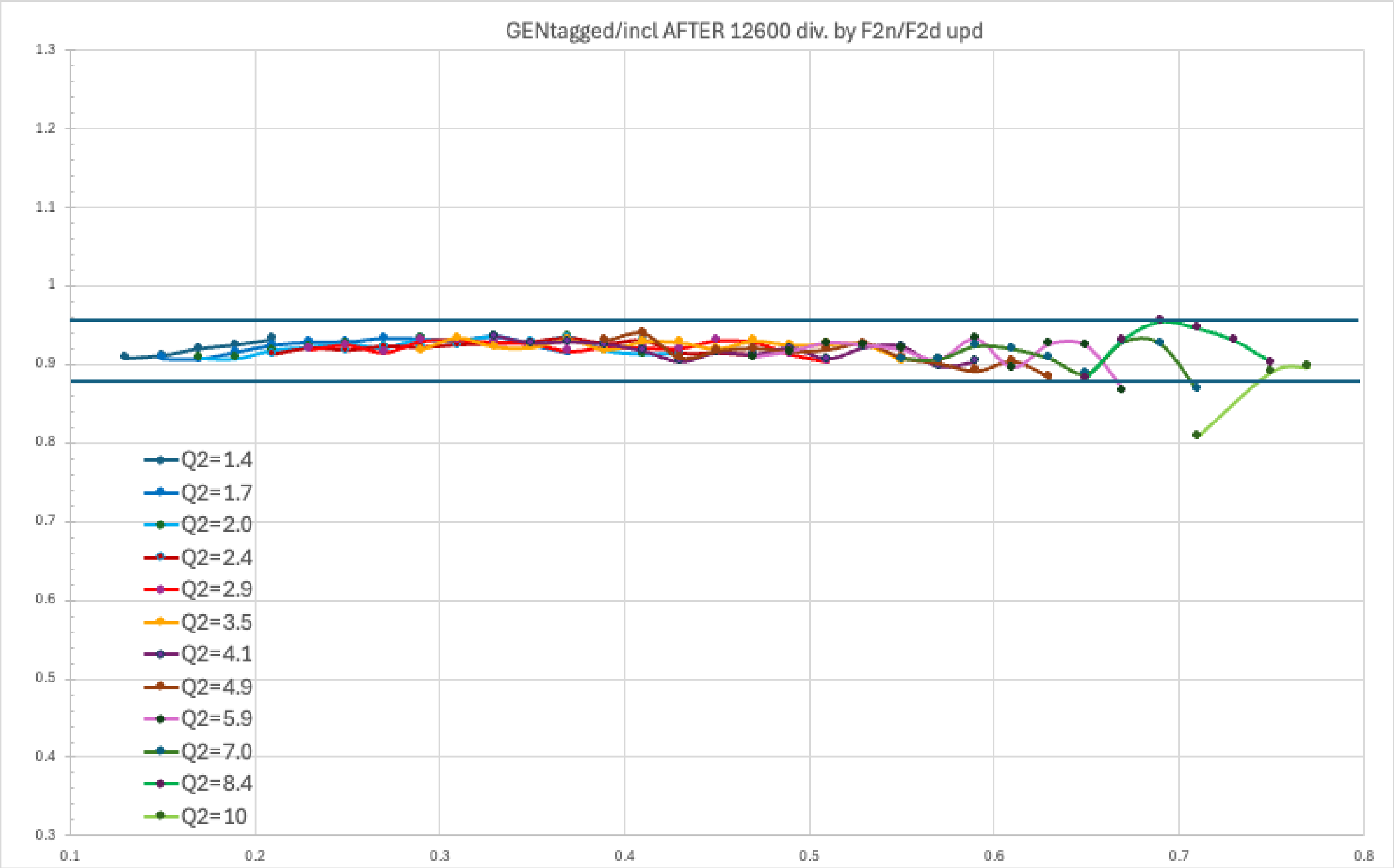
Backup — Check ratio from rad.&non-rad. events

- Perform the same analysis to standard MC (with internal radiation) and MC with radiation turn-off and calculate the ratio between them
- This plot shows that the internal (and pre-scattering) radiative effects encoded in the generator largely cancel in the ratio tagged/inclusive, except for an overall factor of 1.05 increase of the radiated tagged/incl vs. not radiated tagged/incl



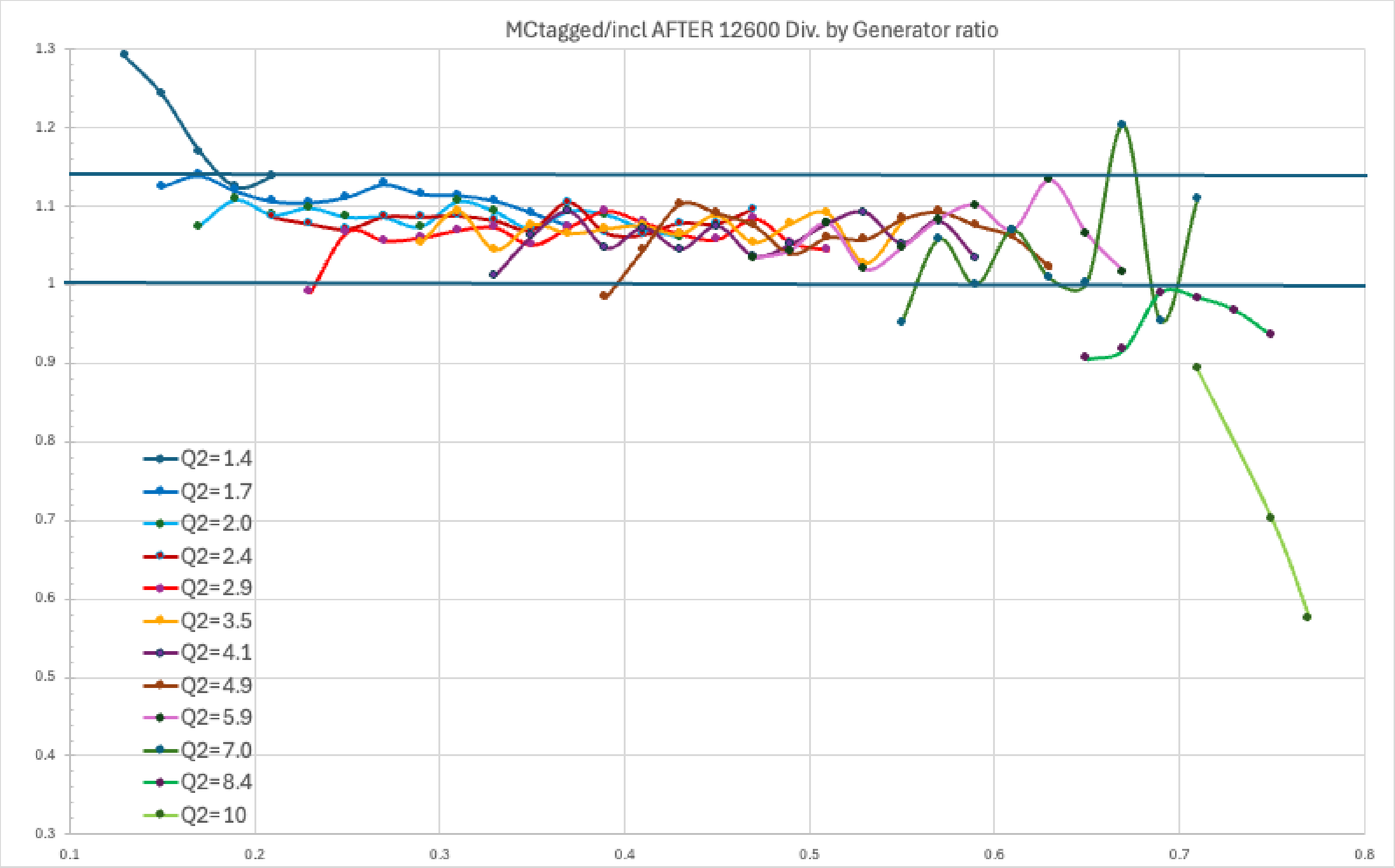
Backup — Check the MC ratio with theoretical model

- The ratio of the generated events divided by the theoretical model
- This plot shows that the output from the generator for the ratio tagged/incl counts follows VERY closely the input model for F2n/F2d
- the overall normalization is arbitrary.



Backup — Check the acceptance effect from MC

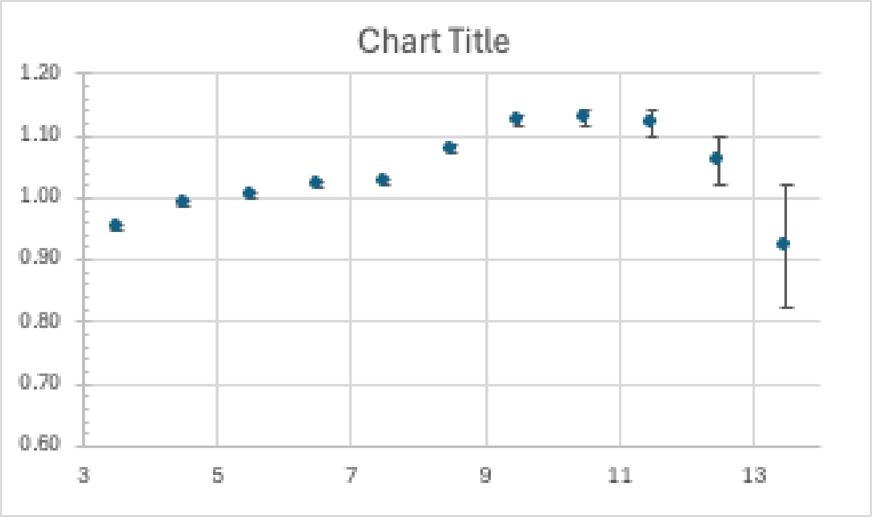
- The ratio of the reconstructed events divided by the generated events
  → nearly constant, with the exception of the lowest Q2 bin (is discard) and the highest 1-2 Q2 bins which are only partially filled.
- This plot shows that the acceptance effects for tagged vs. inclusive also cancel to a very good extent



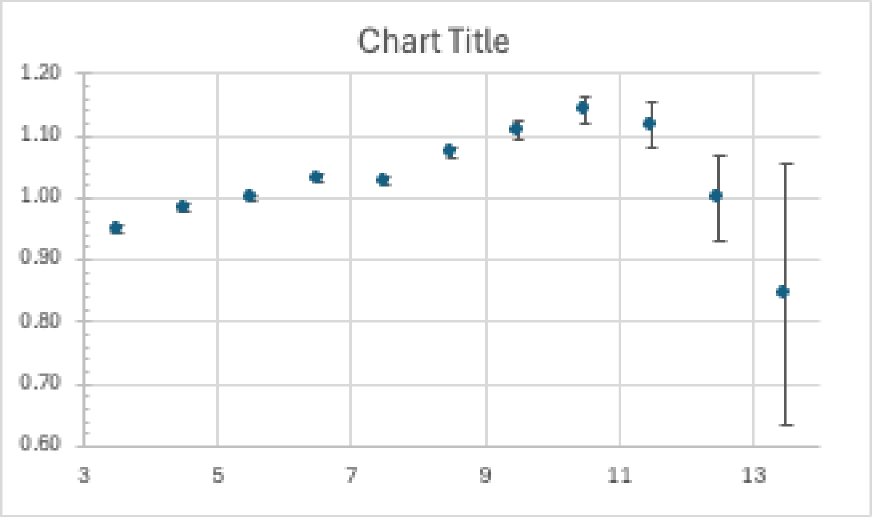
Backup — Check the Background subtraction to data

- Extensive tests for the background evaluations on data
  - Model the 4He background → No, the ratios behave roughly the same for D and 4He runs)
  - Pair-symmetric background → No change on the ratio if we ignore it). It is also not due to our
  - Accidental background subtraction → Negative results with many tests.
  - Potential miscalculation of x* or W* → No significant effect when removing our cut on backwards-going protons, we are averaging out the effect of kinematic corrections

without the cut on cos(theta_pq)



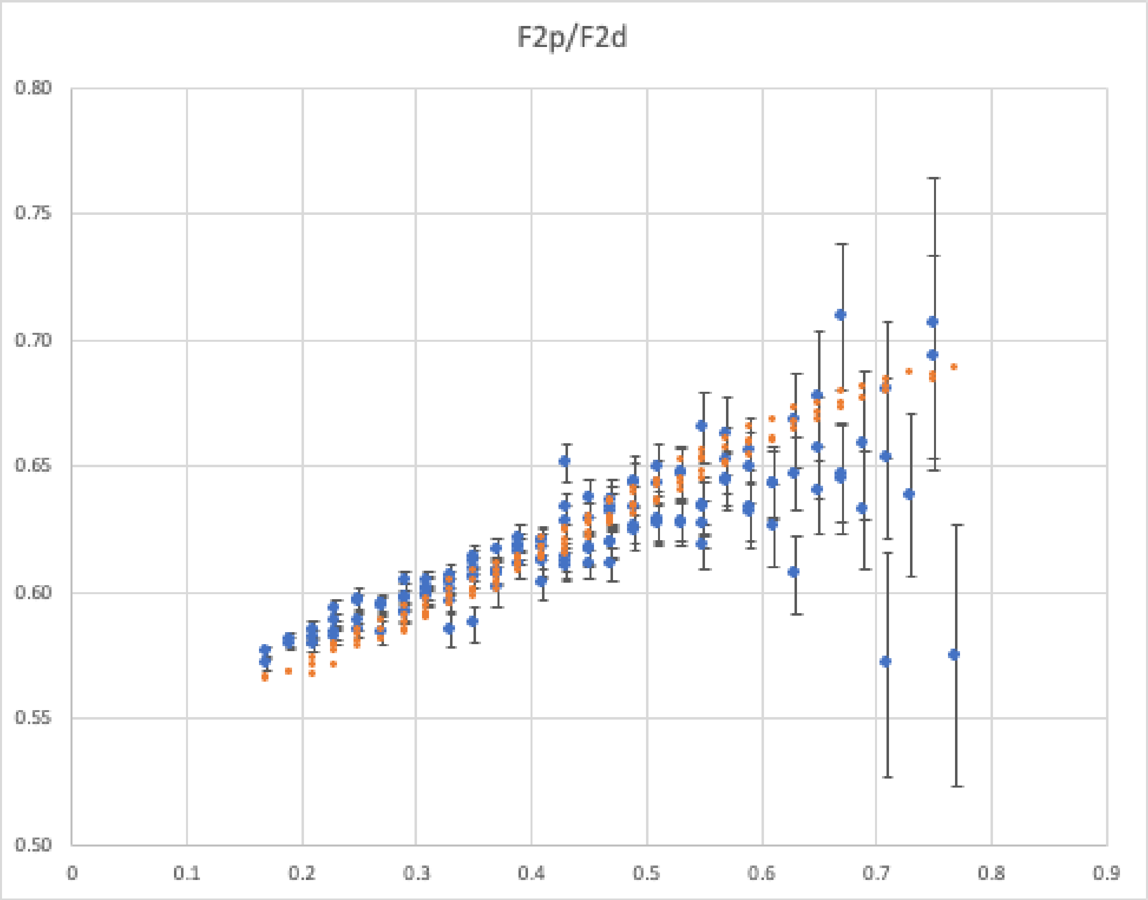
with the cut on cos(theta_pq)



(plotted the ratio vs. Q2 bin)

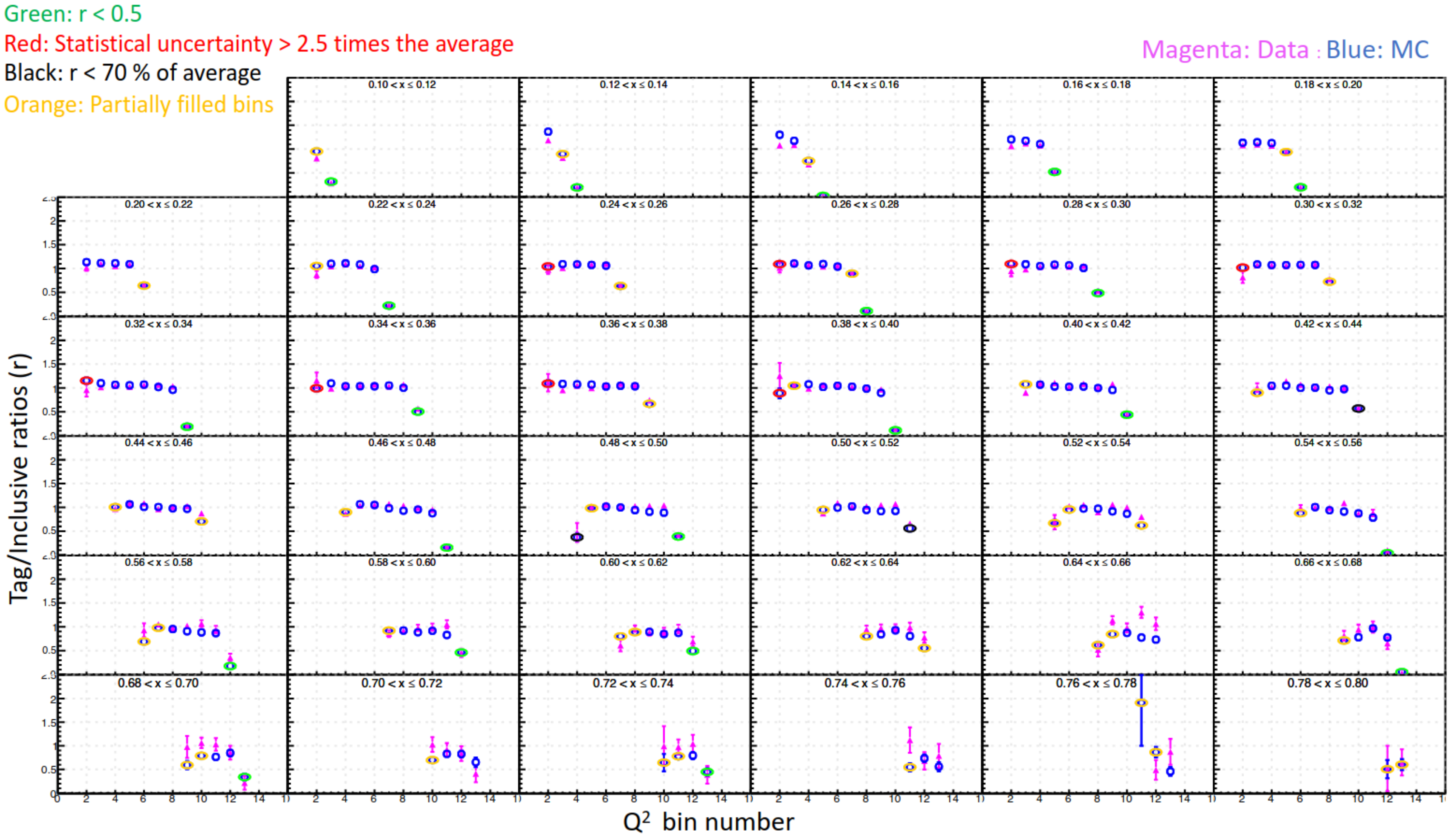
Backup — Check the H/D ratio

- Extract F2p/F2d from our data and MC using the same approach (superratio data/MC for inclusive H/D):
- The plot shows the result for all our bins vs. x, while the orange points are Eric Christy's up-to-date fit for F2p/F2d. Not a PERFECT agreement, but shows that the method is valid in principle.



BONuS12 Corr. V: Culling Partially Filled Bins

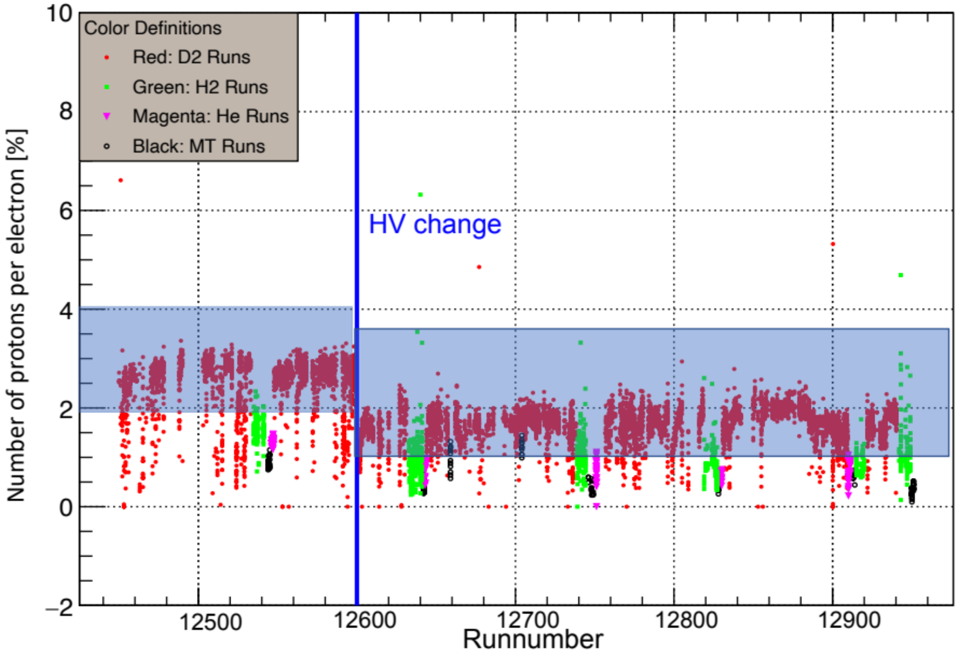
Ratio Tagged/Inclusive from MC show smooth dependence on x and Q^2 except for a few bins at the edge of the acceptance (very sensitive to precise simulation of physical boundaries), as well as bins only partially filled due to W* / W cut => These bins have been removed from final results…

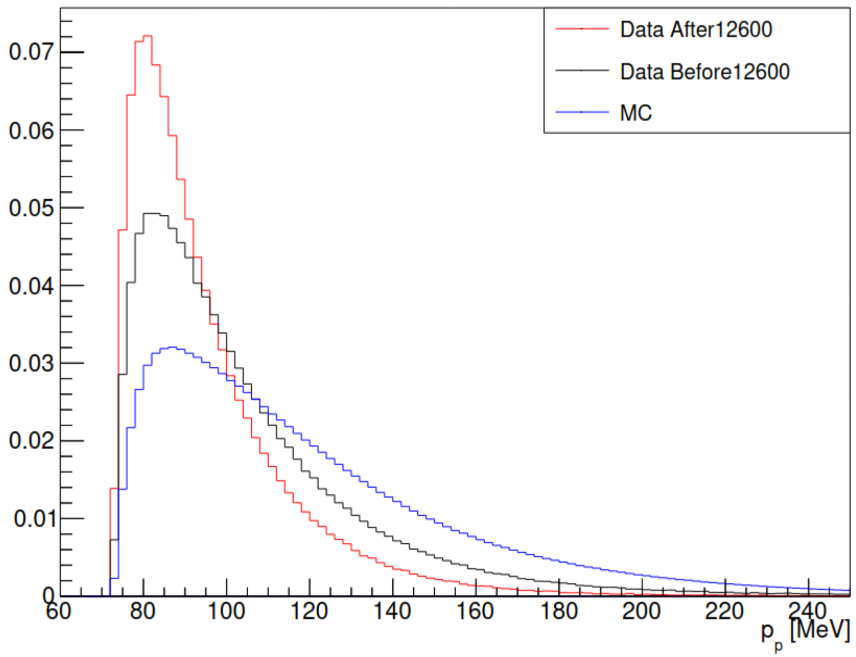


GEMs HV reduced of in RTPC after run 12600

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.





Extract the physics

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

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

# of counts, with the assumption that $\Delta\sigma \propto F_2^d$

Acceptance and efficiencies

$D(e,e')X$

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

$D(e,e'p_s)X$

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

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

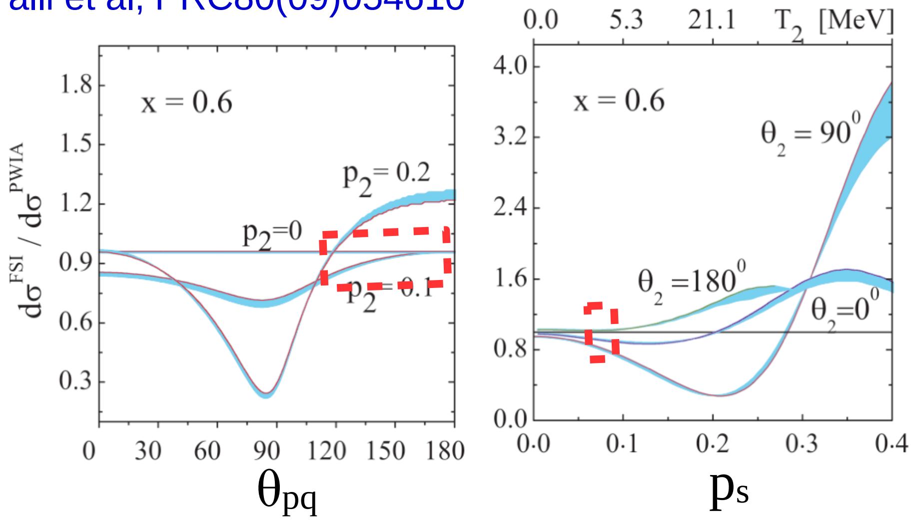
$$\left(\frac{F_{2n}}{F_{2d}}\right)^{\text{true}} = \text{Constant}\cdot\left(\frac{F_{2n}}{F_{2d}}\right)^{\text{Gen}} * \frac{\left(Y^{\text{Data}}_{\text{tag}}/Y^{\text{Data}}_{\text{inc}}\right)}{\left(Y^{\text{MC}}_{\text{tag}}/Y^{\text{MC}}_{\text{inc}}\right)}$$

$$\left(\frac{F_2^n}{F_2^p}\right)^{\text{true}} = \left(\frac{F_{2n}}{F_{2d}}\right)^{\text{true}} * \left(\frac{F_{2d}}{F_{2p}}\right)^{\text{fit}} \quad \& \quad \boxed{\frac{d}{u} \approx \frac{4F_{2n}/F_{2p} - 1}{4 - F_{2n}/F_{2p}}}$$

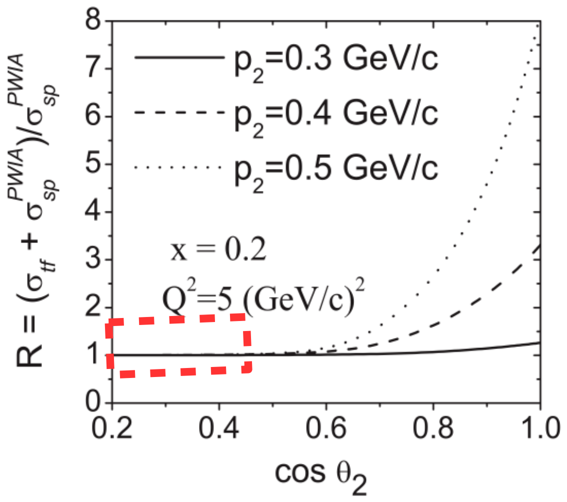
Event selection — VIP(Very Important Proton) cuts

- Final State Interaction
  - ➢ 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 → e p X (where n → π- p) and
    e p → e p X (where p → π0 p).
  - ➢ TF enhances the proton yield only at forward angles ($\cos\theta_{pq}$ >0.6)
- Off-Shell Corrections
  - ➢ Due to the neutron is bound in the deuteron
  - ➢ Less than 2% in our region

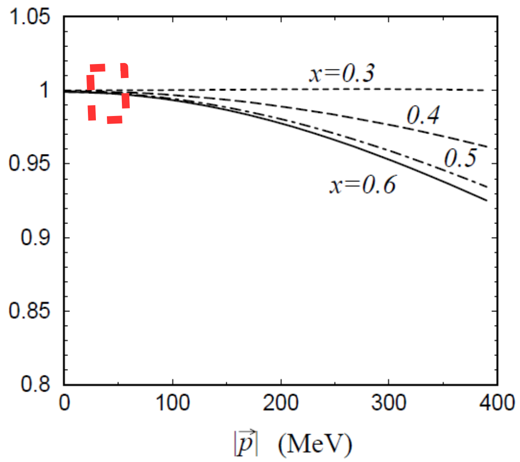
Palli et al, PRC80(09)054610



Palli et al, PRC80(09)054610

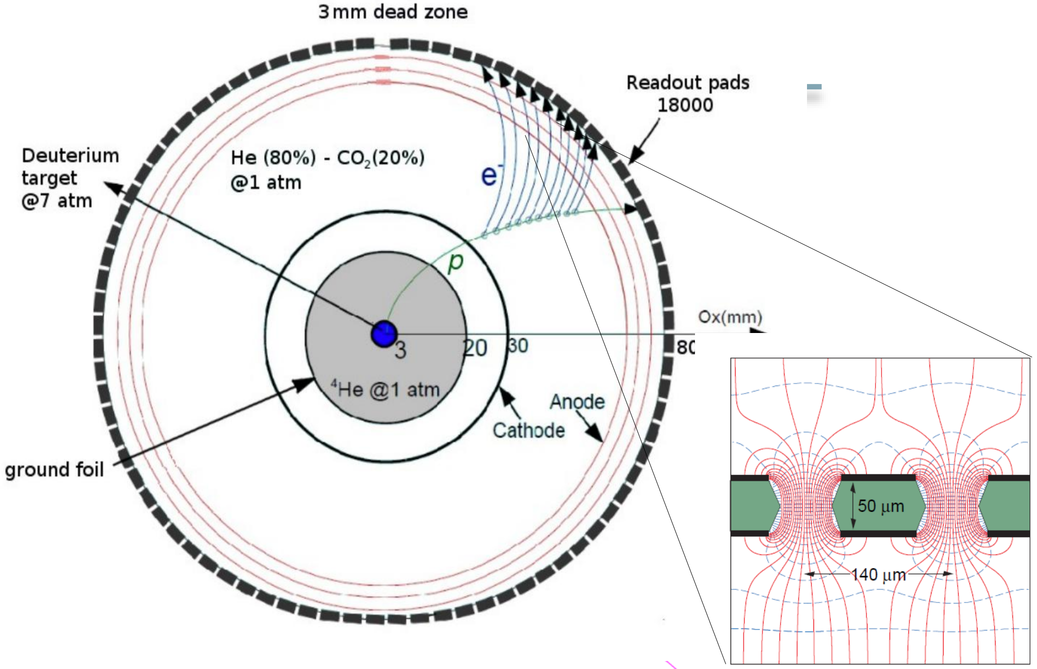


Melnitchoul et al, PRL B335,11(1994)

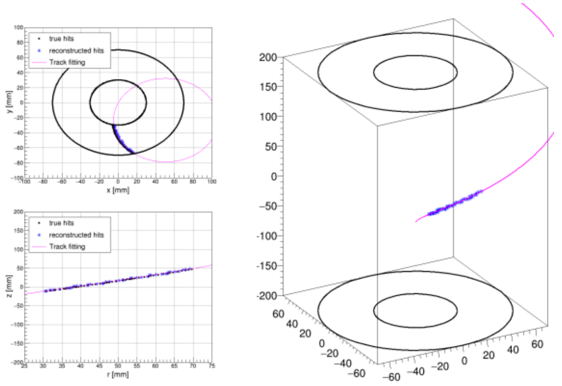


RTPC (Radial Time Projection Chamber)

- detector geometry and gas
  - 40 cm long , and 16 cm in diameter
  - He/CO_2 (80/20) gas mixture
  - Drift region (3 cm to 7 cm) and Transfer region (from 7 cm to 7.9 cm, 3mm space by the GEMs)
  - GEM (Gas Electron Multiplier): amplified the ionization electron.
  - 4π angle coverage, 17,280 readout pads at outermost cylindrical surface



- Work principle
  - Charged particle ionizes the gas atoms
    → Under EM field, released electrons follow their drift paths at a certain drift speed
    →Amplifications via the 3 GEM layers
    →Readout board → MVT FEU electronics → Signal height vs. Time bin
  - Construct 3D trajectory in the detector.



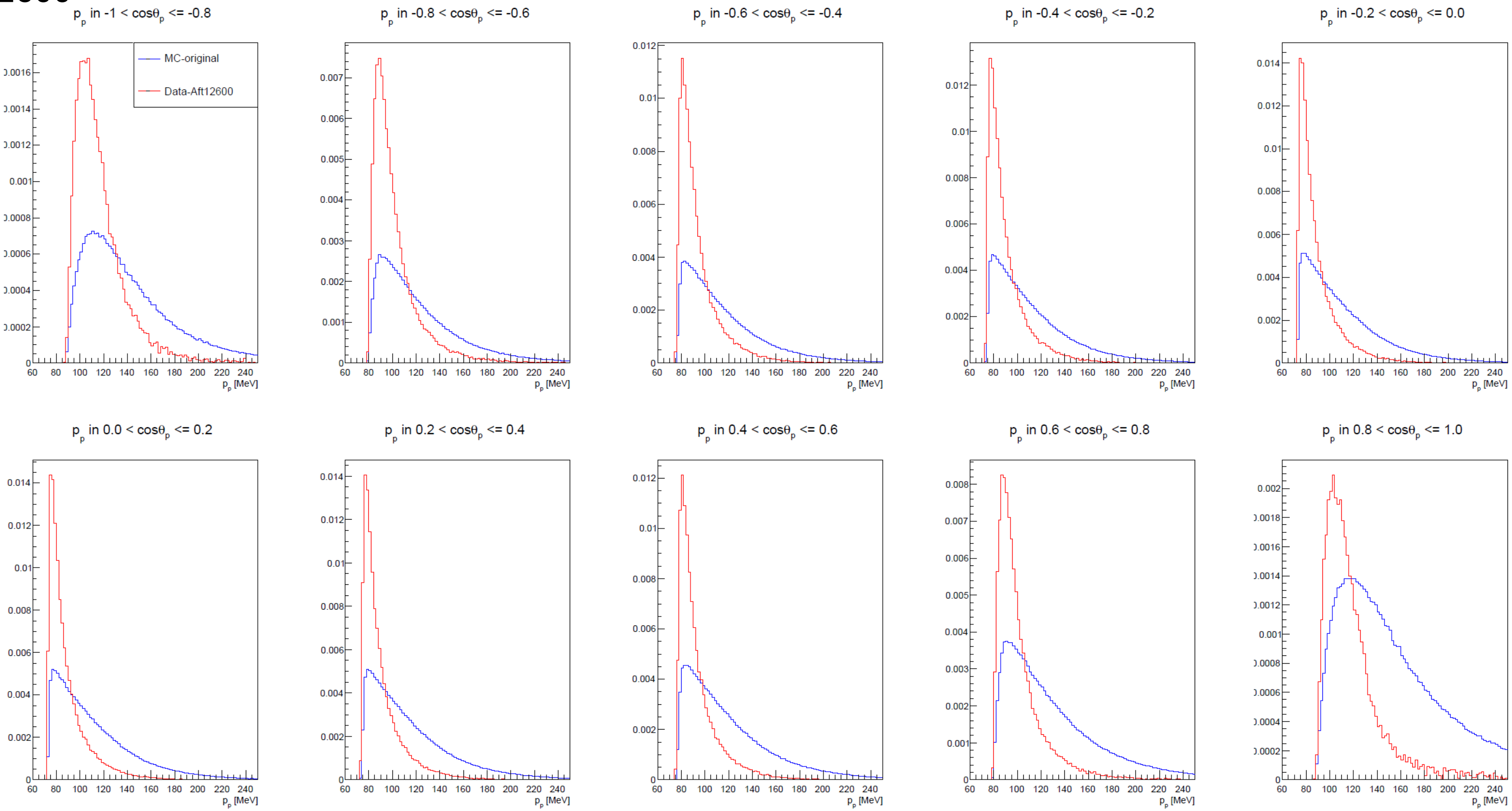
Signal height —Pads' gains (Gi)→ $\left\langle \frac{dE}{dX} \right\rangle = \frac{\sum_i \frac{ADC_i}{Gi}}{vtl}$

Time and Pad location → 3D reconstruction of track → vector p/q, vz, vertex time

} **PID**

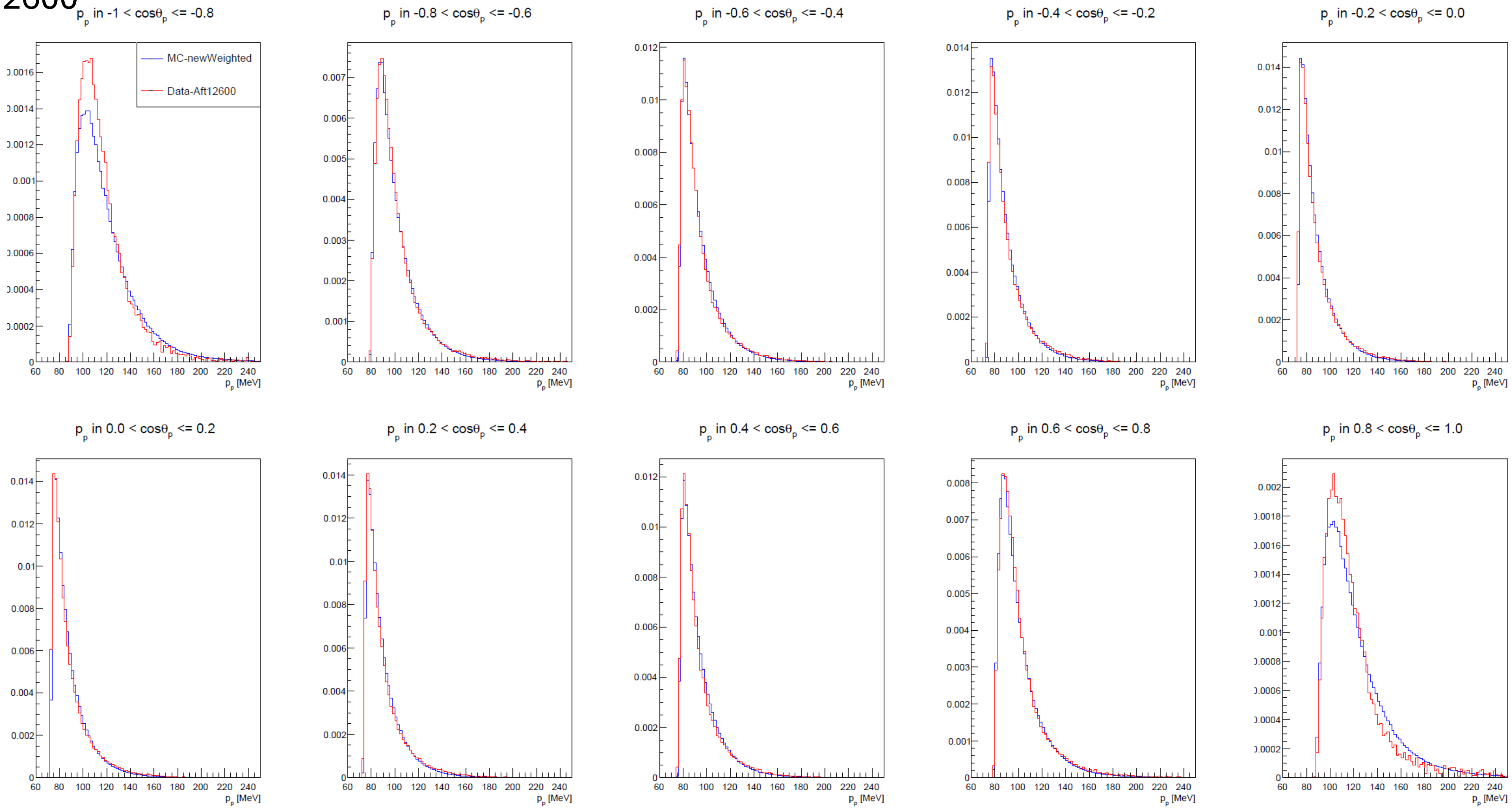
Backup

After 12600



Backup

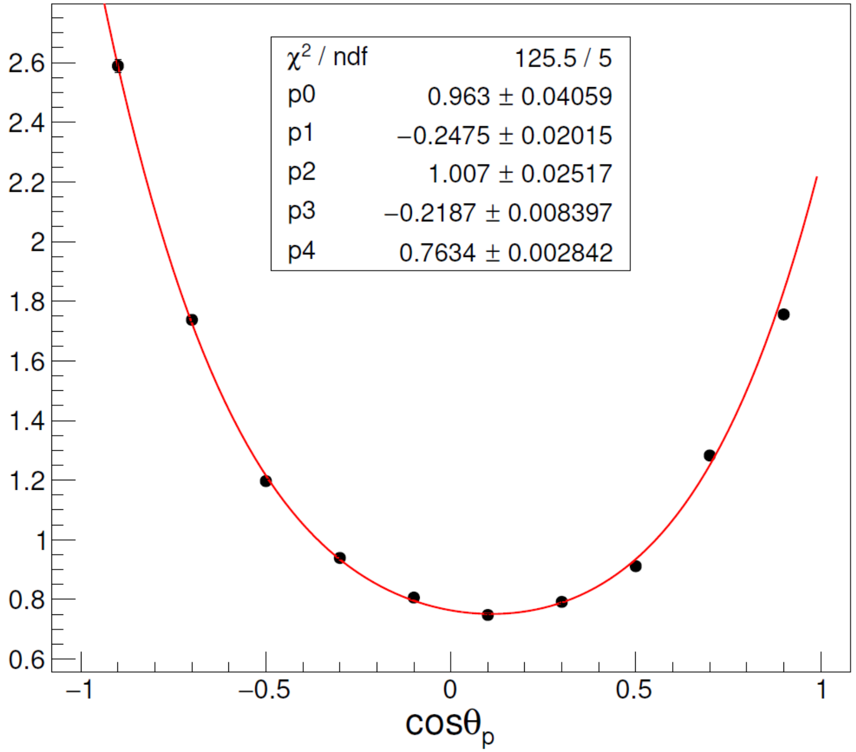
After 12600



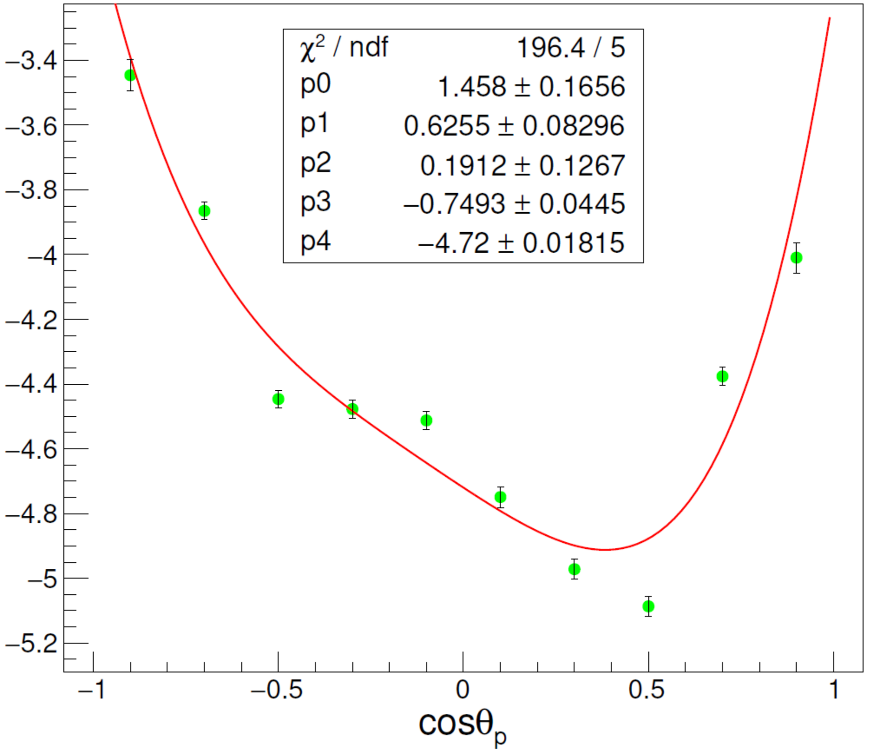
Momentum weighting on MC

After 12600

para0



para1



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

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

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