The F_2^n / F_2^p measurement in the BONuS12 experiment

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Outline

- Physics Motivations
- BONuS12 experiment with CLAS12 at Jefferson Lab
  - Experimental Setup
  - RTPC features
- Data analysis & Preliminary Results
- Summary

Probing the inner structure particles

- Scattering/Collision → Probe the internal structure of patricles
- Elastic scattering:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E^2 \sin^4\left(\frac{\theta}{2}\right)} \frac{E'}{E} \left(\frac{G_E^2 + \tau G_M^2}{1+\tau} \cos^2\left(\frac{\theta}{2}\right) + 2\tau G_M^2 \, sin^2\left(\frac{\theta}{2}\right) \right) \qquad \tau = \frac{Q^2}{4m_p^2}$$

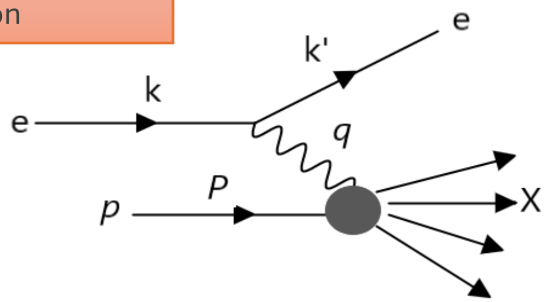
G_E: Electric form factor
→ charge distribution of the nucleon.

G_M: Magnetic form factor
→ magnetic moment distribution of the nucleon

- Deep Inelastic Scattering (DIS, large Q^2, large ν):

$$\frac{d\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2 \sin^4\left(\frac{\theta}{2}\right)} \left(\frac{F_2(x,Q^2)}{\nu} \cos^2\left(\frac{\theta}{2}\right) + \frac{2F_1(x,Q^2)}{M_p} sin^2\left(\frac{\theta}{2}\right) \right)$$

$F_1(x,Q^2)$, $F_2(x,Q^2)$ are structure functions



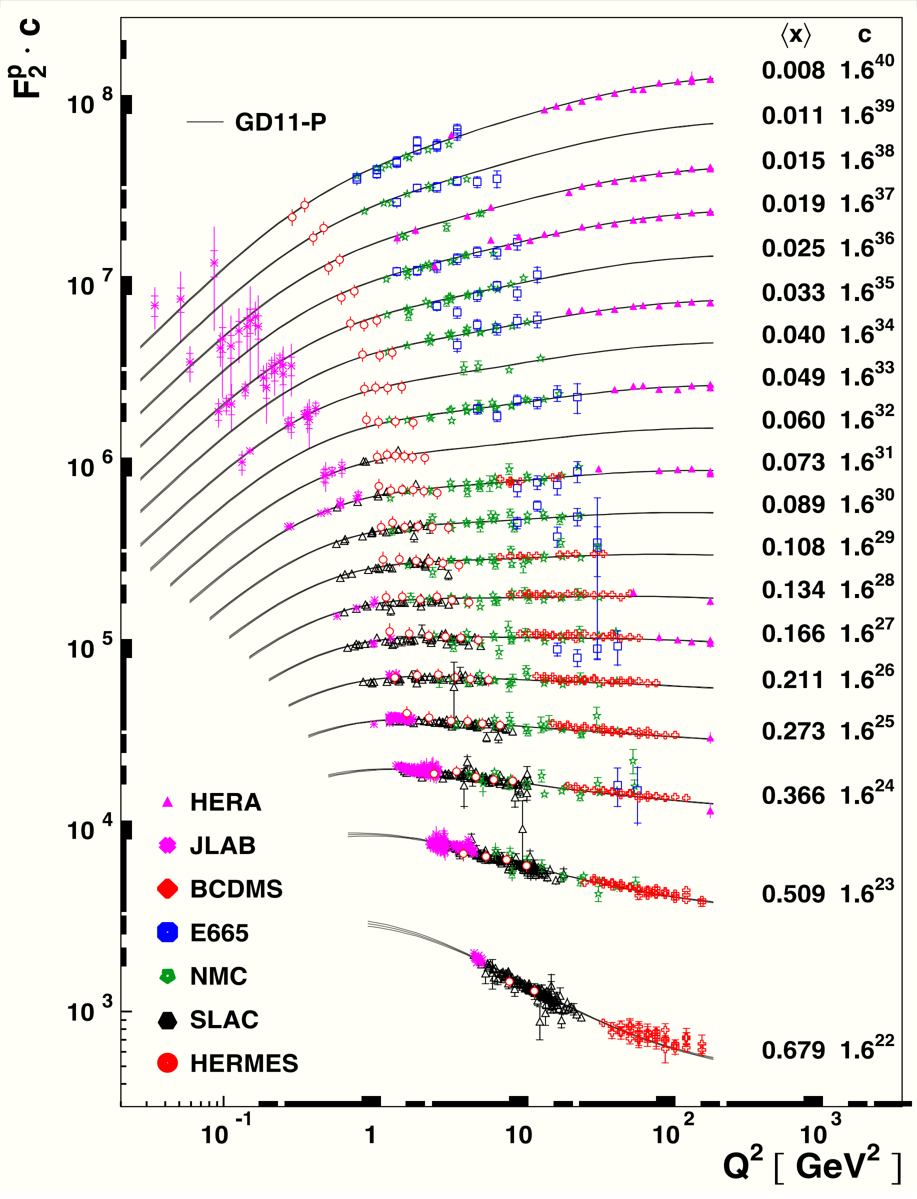
Electron scatter off a proton in DIS region

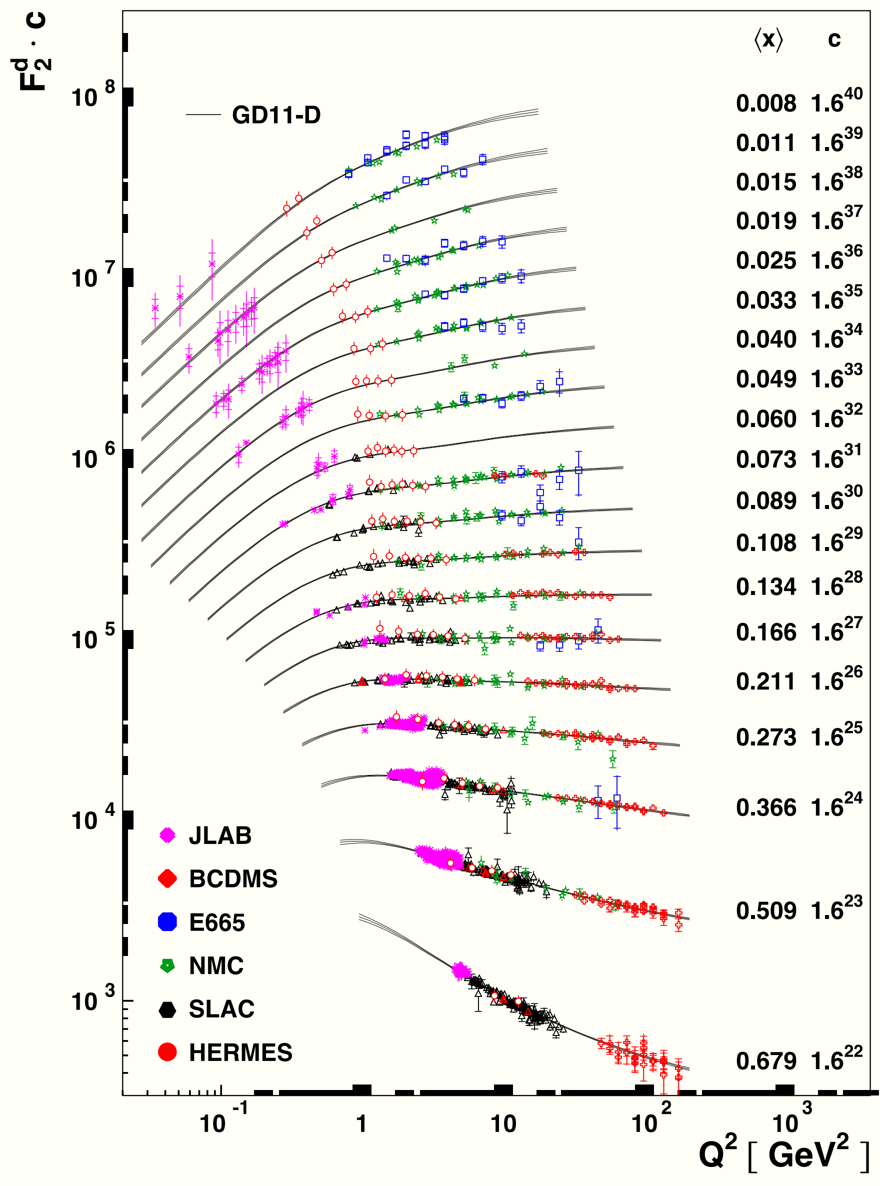
- Naïve Quark-Parton Model

$$F_1(x) = \frac{1}{2}\left(\frac{4}{9}\left[u(x) + \bar{u}(x)\right] + \frac{1}{9}\left[d(x) + \bar{d}(x) + s(x) + \bar{s}(x)\right] + \ldots \right)$$

$F_2(x) = 2xF_1(x)$ (Callan-Gross relation)

Structure Function — Existing data for p and D





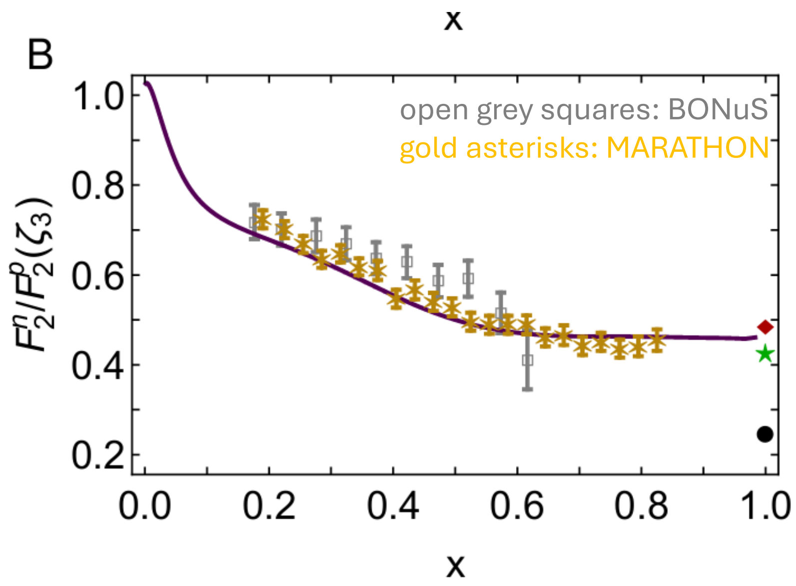
Rich results for F_2^p and F_2^d !

Structure Function — Existing data for n

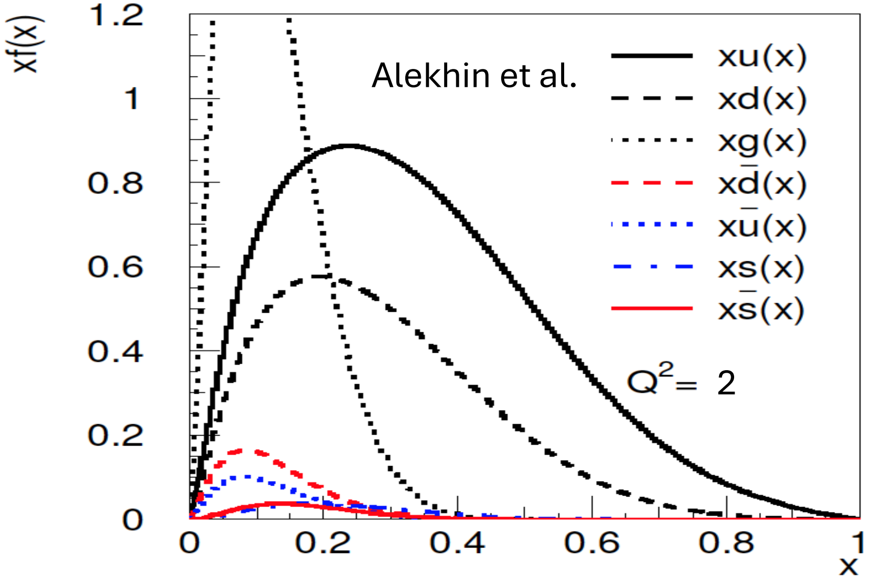
- There are many experiments provide precise measurements on F_2^p and F_2^d, but less precise for F_2^n, especially at large x, where different theoretical models have different predictions
- Neutron as the target
  → Decay in ~15 mins.

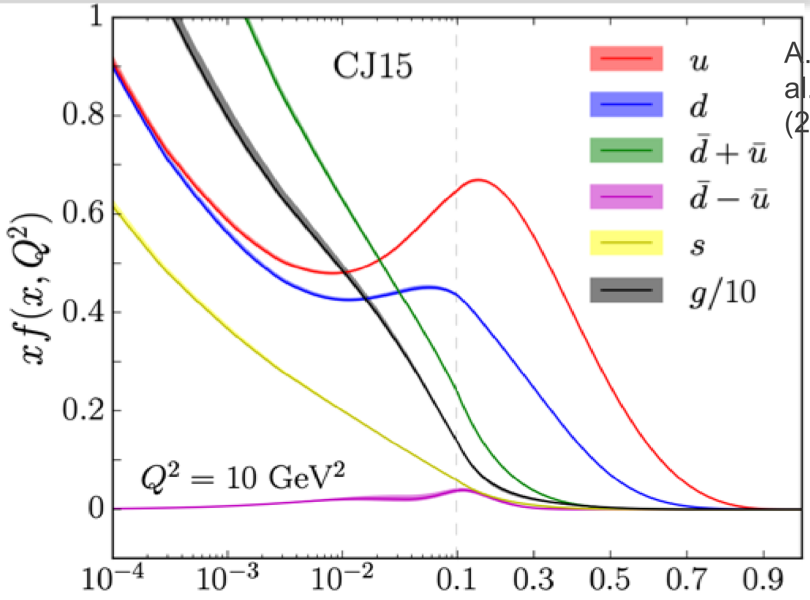
  →difficult to prepare a free neutron in the experiment
- Obtained F_2^n from a bound neutron inside the nucleon.

  →The nuclear corrections will have theoretical model dependence at large Bjorken-x

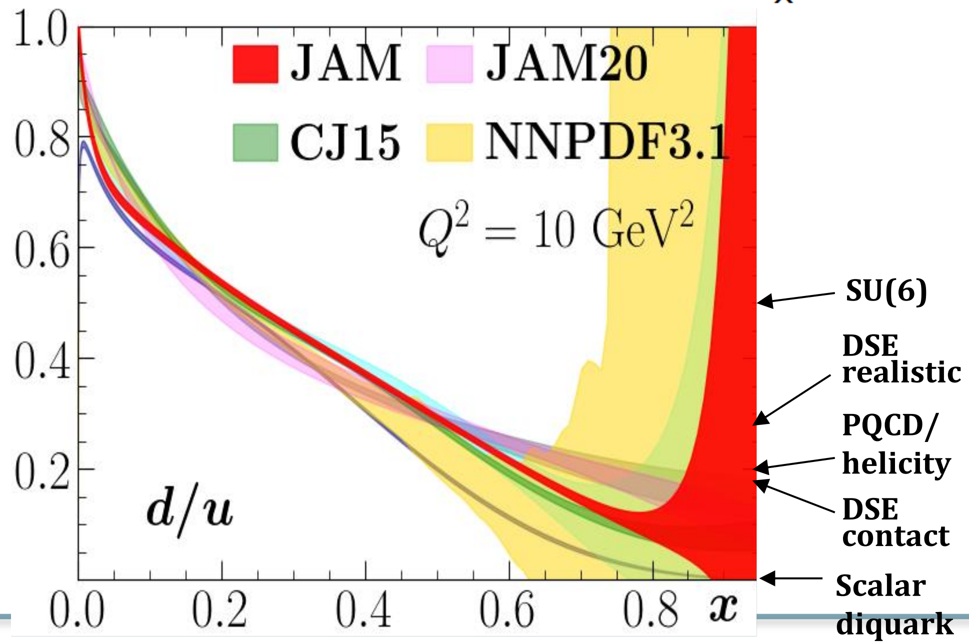


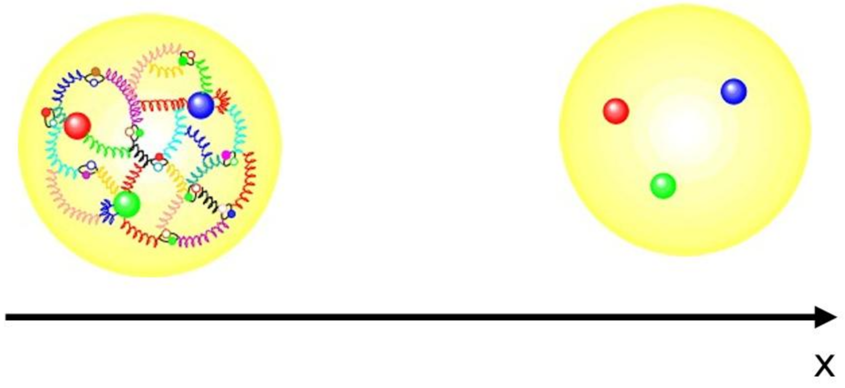
Unpolarized PDFs





A. Accardi, et al., PRD 93 (2016)





Valence Region: Structure Functions for $x \to 1$

*) Moments, quasi-PDFs, pseudo-PDFs

- Dominated by up and down valence quarks => quantum numbers of the nucleon
- Important for higher power x^n moments => Mellin Moments, LQCD
- Related to high-Q^2, moderate x through DGLAP => relevant for LHC Physics

- MANY predictions based on models, pQCD, DS equation and Lattice QCD *):

Nucleon Model	F_2^n/F_2^p $x \to 1$	d/u $x \to 1$
SU(6) Symmetry	2/3	0.5
Scalar diquark dominance	1/4	0
DSE contact interaction	0.41	0.18
DSE realistic interaction	0.49	0.28
PQCD (helicity conservation)	3/7	0.2

- With Isospin symmetry, at large x:

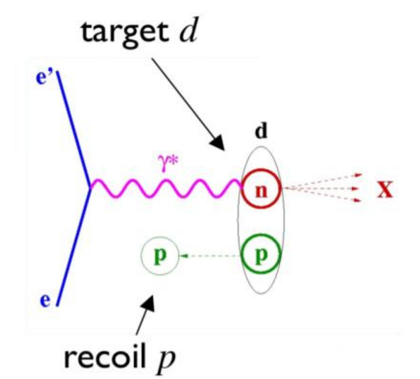
$$F_2^p \approx x\left(\frac{4}{9}u(x) + \frac{1}{9}d(x)\right)$$

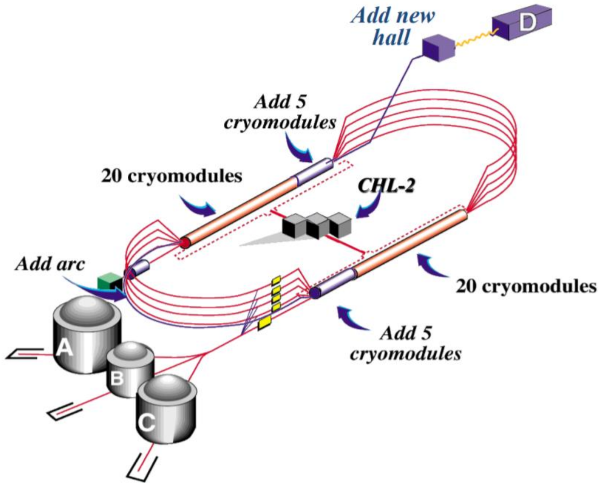
$$F_2^n \approx x\left(\frac{4}{9}d(x) + \frac{1}{9}u(x)\right)$$

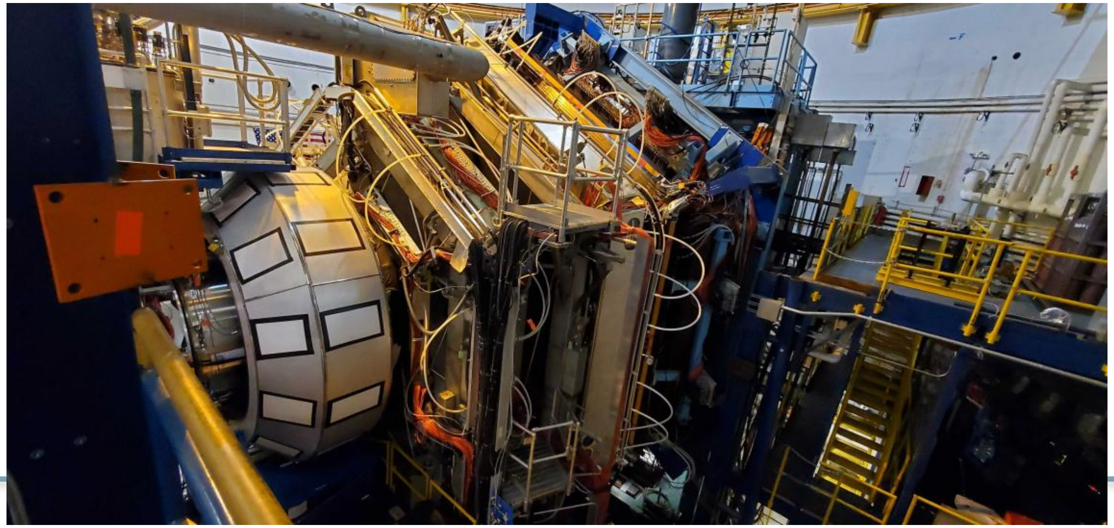
$$\rightarrow \frac{F_2^n}{F_2^p} \approx \frac{1+4d/u}{4+d/u}$$

BONuS12 Experiment at JLab

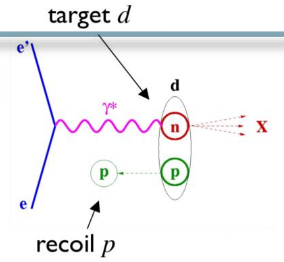
- BONuS12(Barely Offshell NUcleon Structure) is one of the experiments in the CLAS12 collaboration, completed at Jefferson Lab Hall B in 2020
- Extension program from previous BONuS with upgraded 12 GeV Continuous Electron Beam Accelerator Facility (CEBAF).
  - BONuS:
    - 5.3 GeV electron beam energy
    - DIS region: up to x=0.56 (at W > 2(GeV/c^2))
  - BONuS12:
    - 11 GeV electron beam energy
    - DIS region: x ~ 0.8 (at W > 1.8 (GeV/c^2))
- Use proton spectator tagging method which would reduce the model dependent of the $\frac{F_2^n}{F_2^p}$.





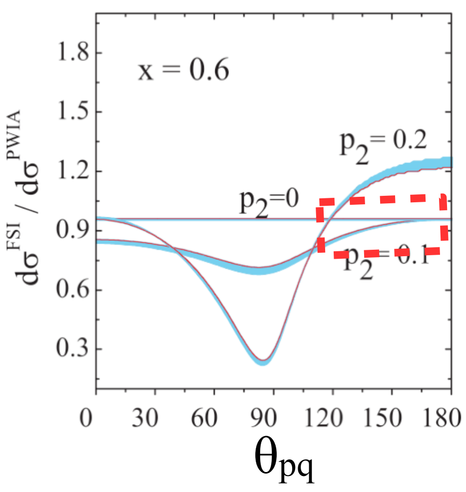


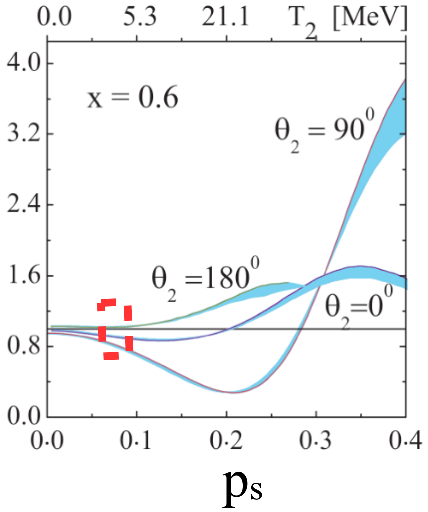
Nuclear Uncertainties in Deuteron



- 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}

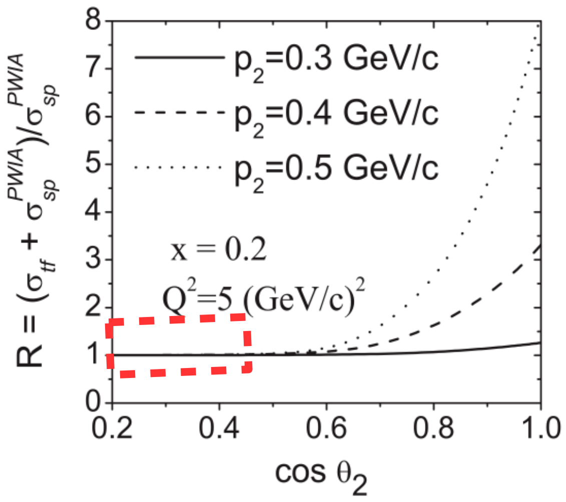
Palli et al, PRC80(09)054610



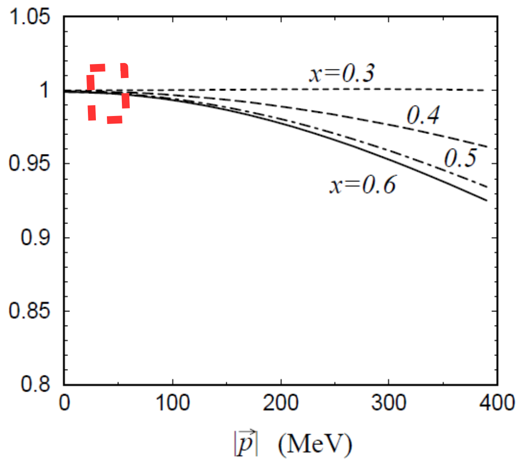


- Target Fragmentation
  - e n → e p X (where n → π- p) and e p → e p X (where p → π0 p).
  - TF enhances the proton yield only at forward angles (cos θ_{pq} >0.6)

Palli et al, PRC80(09)054610



Melnitchoul et al, PRL B335,11(1994)



- Off-Shell Corrections
  - Due to the neutron is bound in the deuteron
  - Low p_s selection reduces this effect →Less than 2% in our region

Extract the physics

$D(e,e')X$ $\quad R_{\mathrm{inc}}(x,Q^2) = \frac{Y^{\mathrm{Data}}_{\mathrm{inc}}}{Y^{\mathrm{MC}}_{\mathrm{inc}}} \propto \frac{F^{\mathrm{true}}_{2d}(x,Q^2)}{F^{\mathrm{Gen}}_{2d}(x,Q^2)}$

$D(e,e'p_s)X$ $\quad R_{\mathrm{tag}}(x',Q^2) = \frac{Y^{\mathrm{Data}}_{\mathrm{tag}}}{Y^{\mathrm{MC}}_{\mathrm{tag}}} \propto \frac{F^{\mathrm{true}}_{2n}(x',Q^2)}{F^{\mathrm{Gen}}_{2n}(x',Q^2)}$

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

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

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

Acceptance and efficiencies

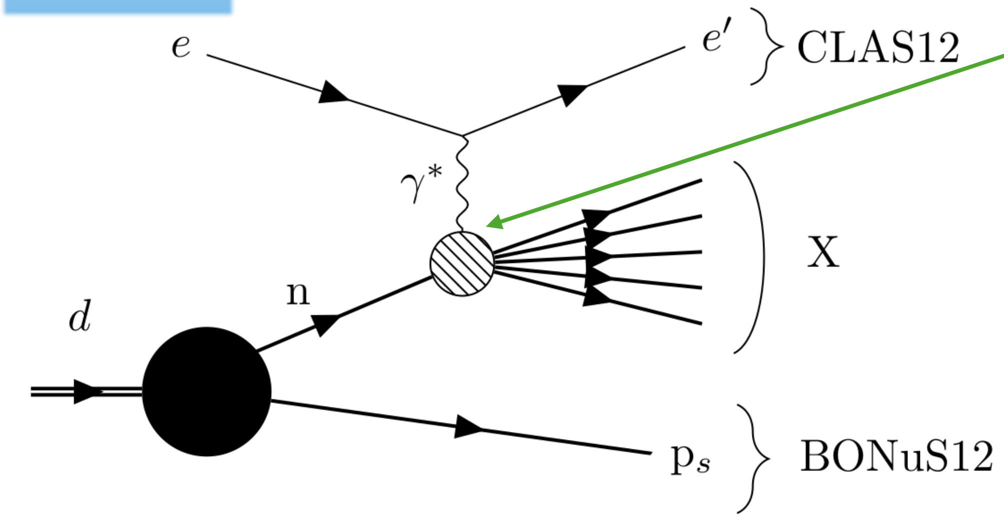
$$SR = \frac{R_{\mathrm{tag}}(x',Q^2)}{R_{\mathrm{inc}}(x,Q^2)} = \frac{\left(Y^{\mathrm{Data}}_{\mathrm{tag}}/Y^{\mathrm{MC}}_{\mathrm{tag}}\right)}{\left(Y^{\mathrm{Data}}_{\mathrm{inc}}/Y^{\mathrm{MC}}_{\mathrm{inc}}\right)} = \frac{\left(Y^{\mathrm{Data}}_{\mathrm{tag}}/Y^{\mathrm{Data}}_{\mathrm{inc}}\right)}{\left(Y^{\mathrm{MC}}_{\mathrm{tag}}/Y^{\mathrm{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

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

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

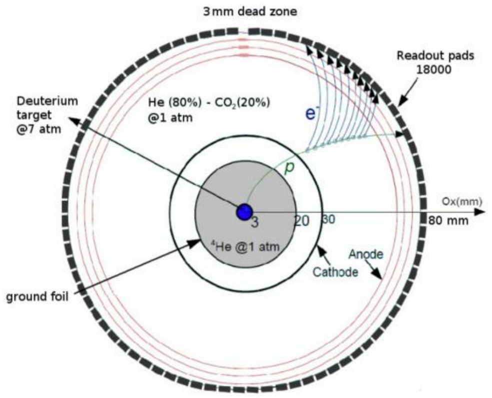
BONuS12 Experimental Setup with CLAS12

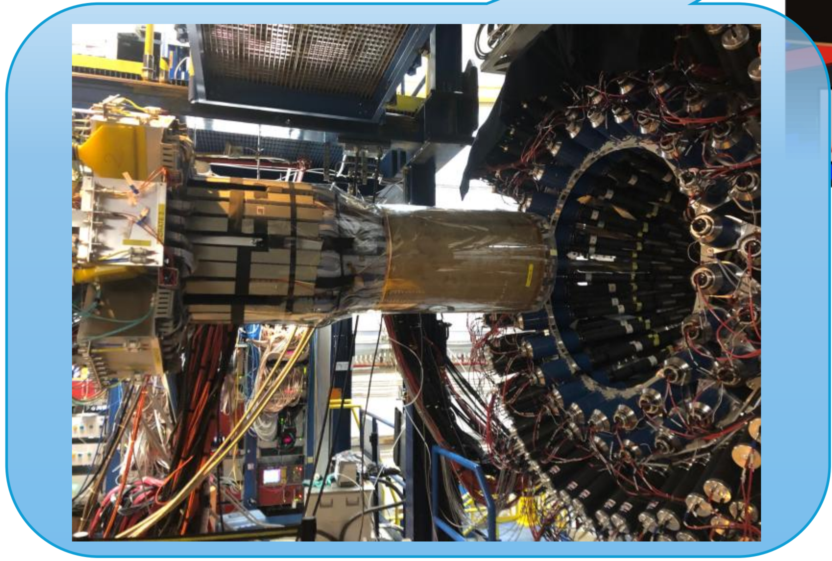
10.4 GeV

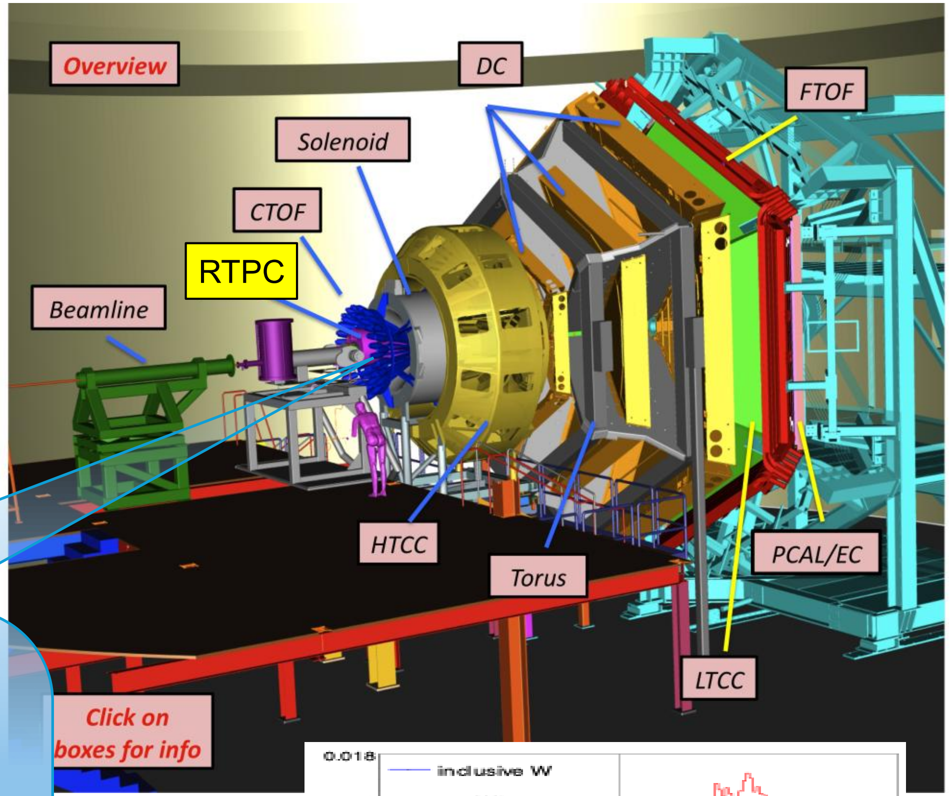


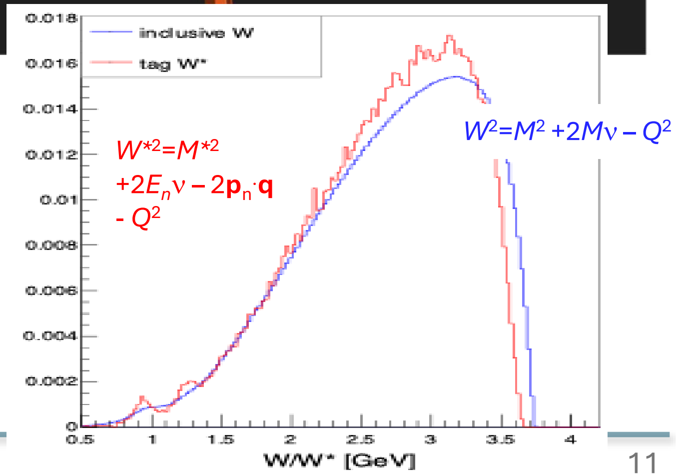
$E_n = M_D - E_s$
$\mathbf{p}_n = -\mathbf{p}_s$

$M^{*2} = E_n^2 - \mathbf{p}_n^2$







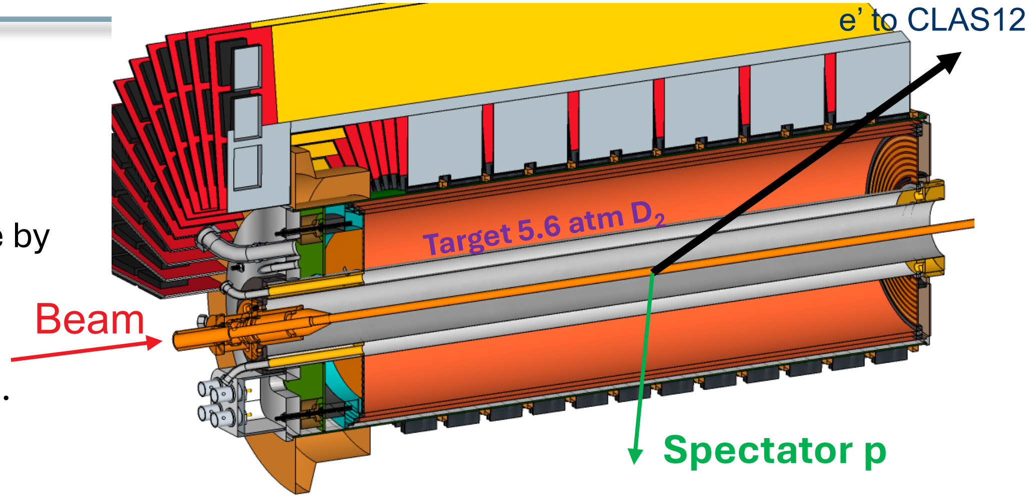


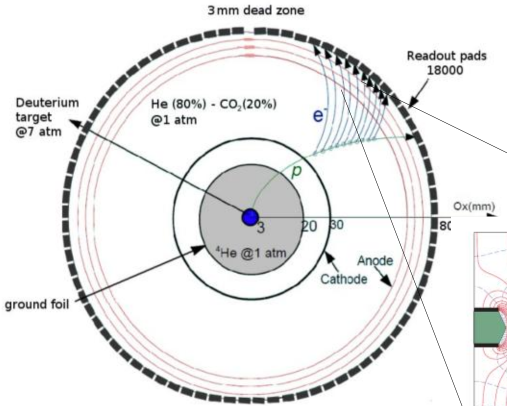
BONuS12 Radial Time Projection Chamber (RTPC)

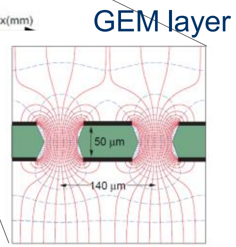
- Detector geometry and gas
  - 40 cm long , and 16 cm in diameter
  - He/CO_2 (80/20) gas mixture
  - Drift region (3 cm to 7 cm) and Transfer region (from 7 cm to 7.9 cm, 3mm space by the GEMs)
  - GEM (Gas Electron Multiplier): amplified the ionization electron.
  - Nearly 4π angle coverage, 17,280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

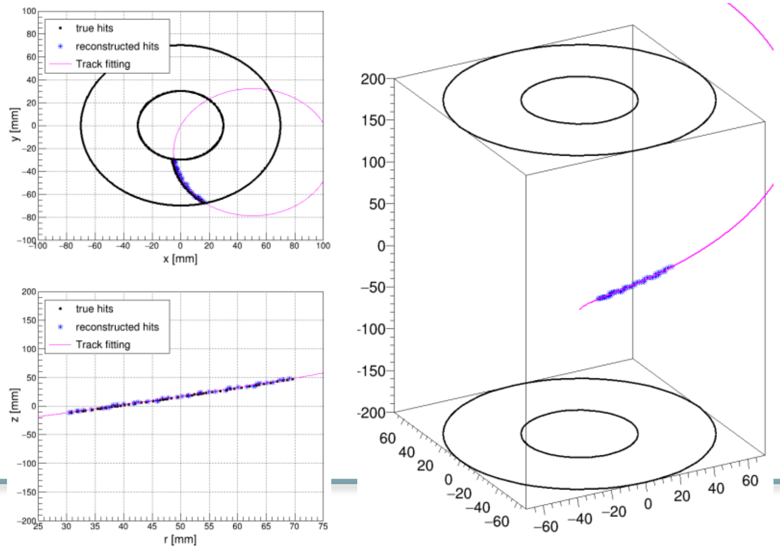
    →Amplifications via the 3 GEM layers

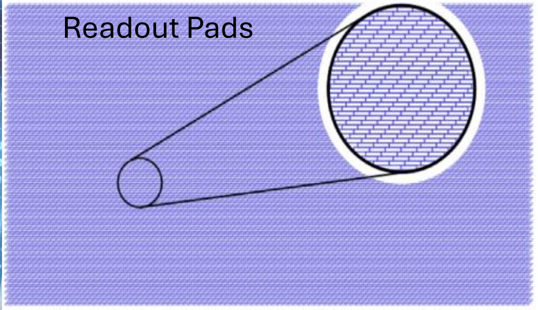
    →Readout board → MVT FEU electronics → Signal height vs. Time bin
  - Construct 3D trajectory in the detector.







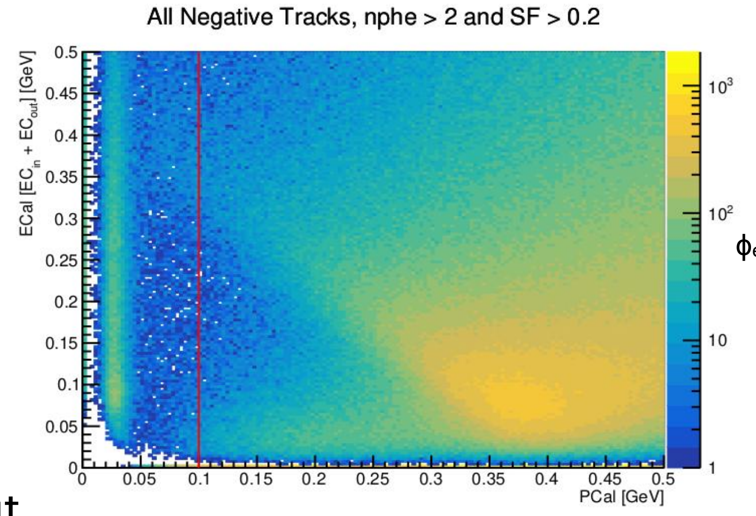


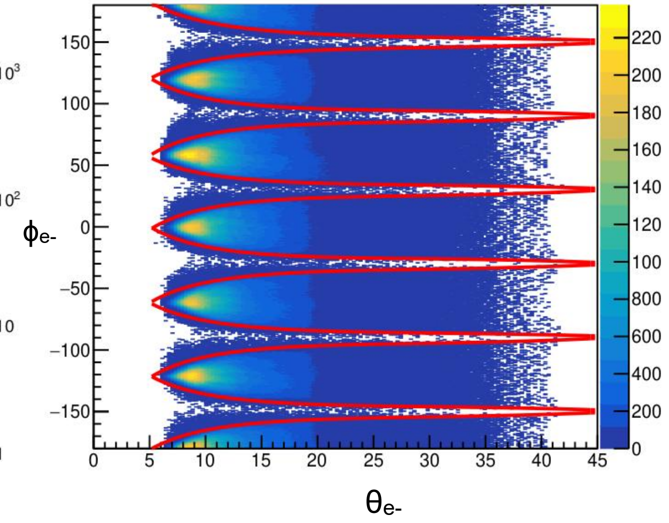


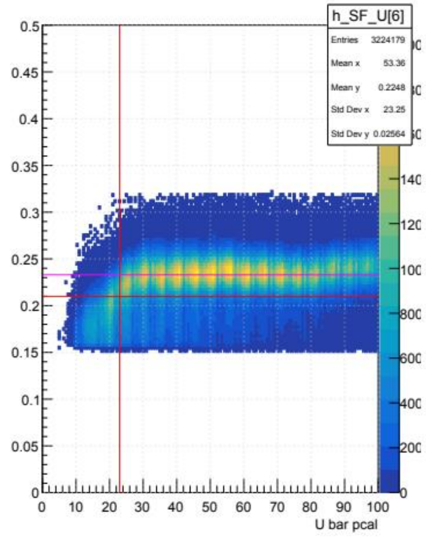
Event selection — DIS Electron at 10.4 GeV for D_2 target

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:

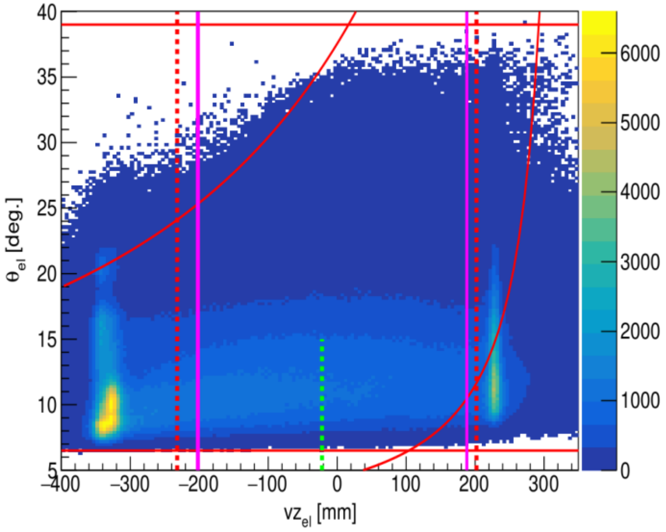


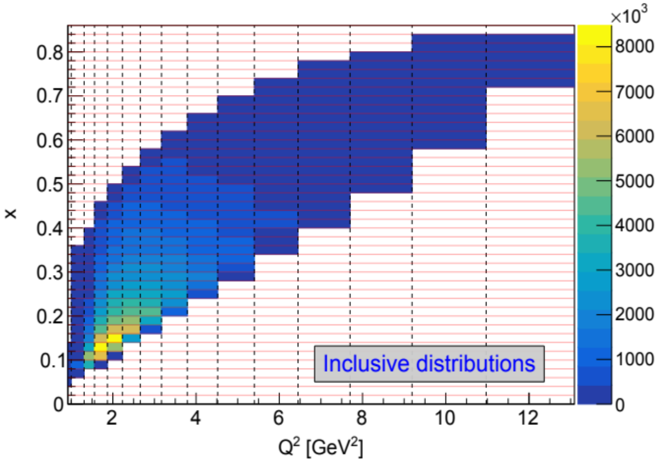




Additional DIS cuts

- 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])
- $35^o < \theta_{ps} < 145^o$

PID Cuts:

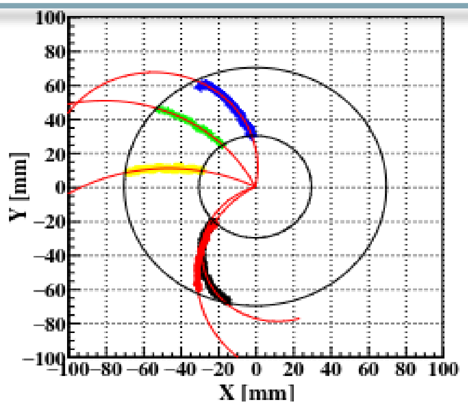
- Run-dependent Cuts on dEdx vs. p/q band for proton selection

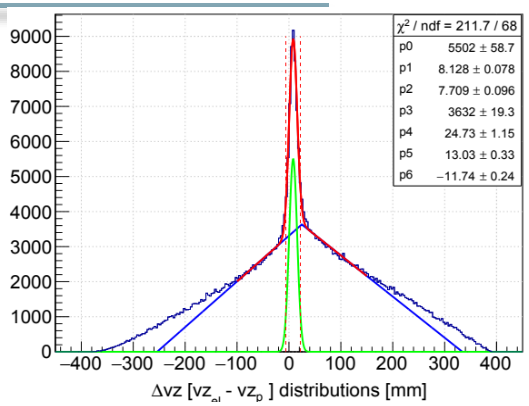
ep Coincidence cuts

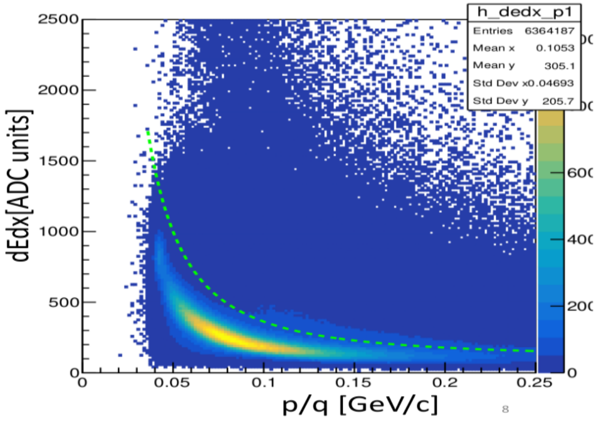
- Vertex coincidence cuts
- Timing coincidence

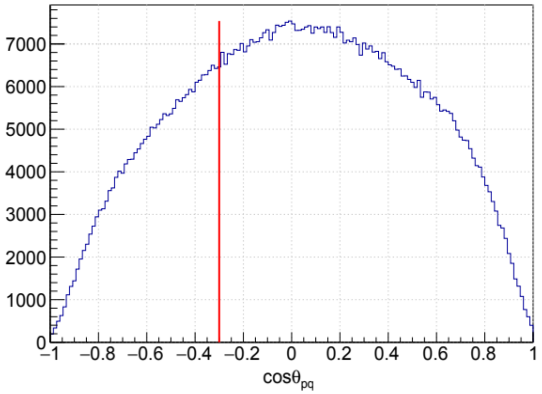
DIS & VIP cuts — To minimize the nuclear uncertainties (e.g. FSIs, Target Fragmentation, etc.)

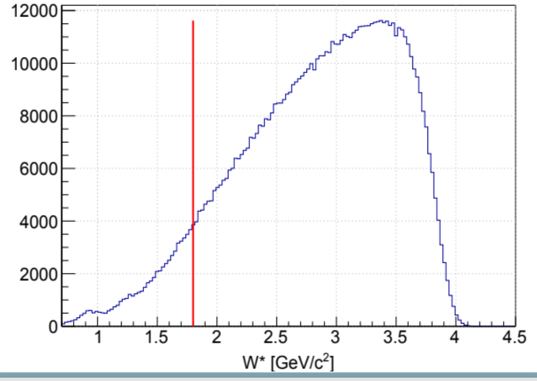
- W* > 1.8 [GeV]
- 0.075 < p_ps < 0.1 [GeV/c]
- $\cos(\theta_{pq}) < -0.3$

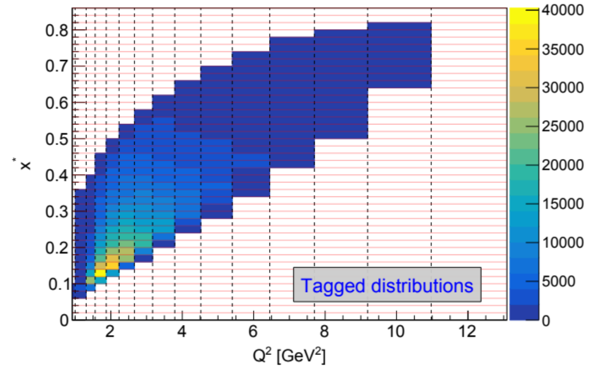








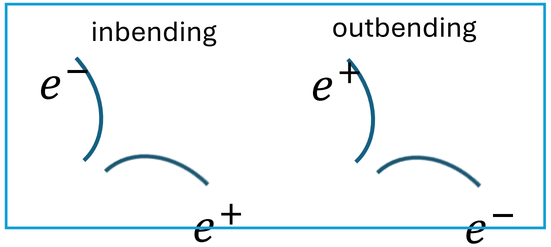


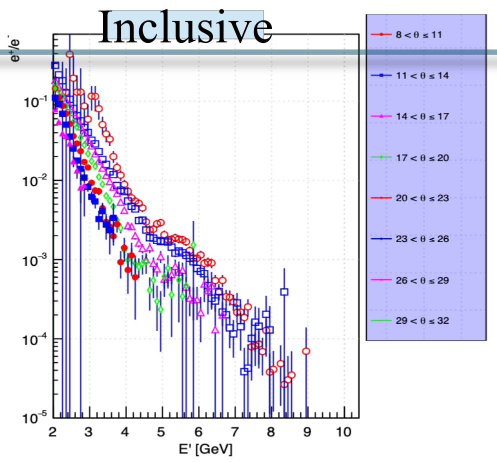


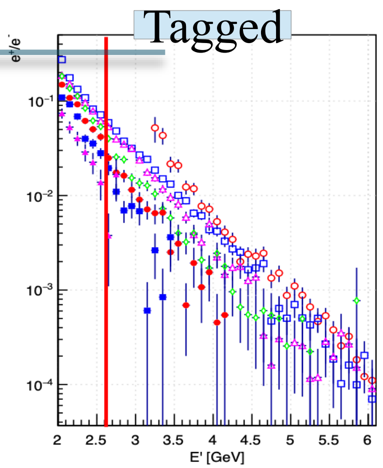
Background evaluation for experimental data

Electron

- Pair Symmetric Background: $\pi^0 \rightarrow e^+e^-\gamma$
  - Secondary electron as trigger particle

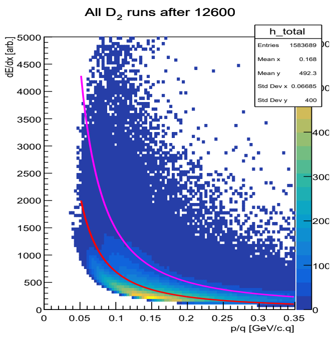


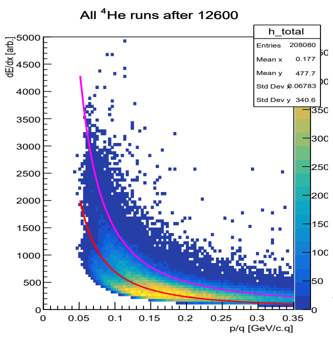


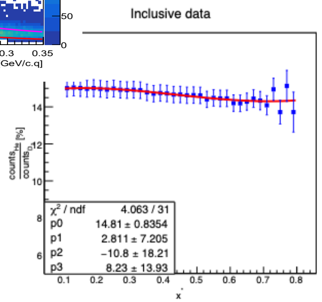


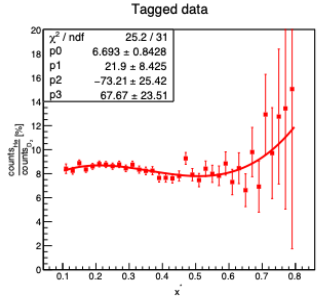
Proton

- Accidental Background
  - Due to ionization electron inside RTPC drift slowly, the coincidence cuts are wider
  - Evaluated the combinatorics backgrounds by event mixing
- Deuterium Target Contamination

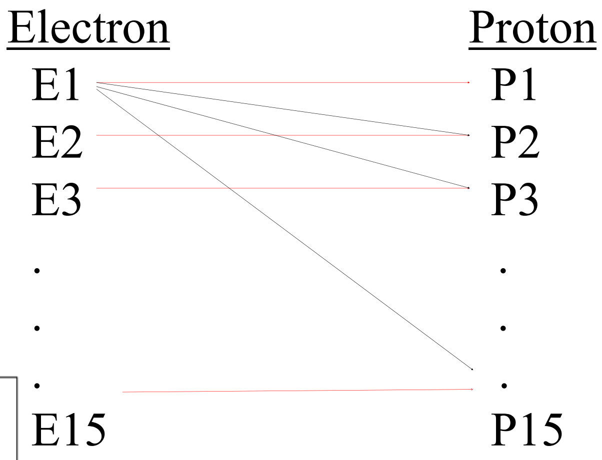


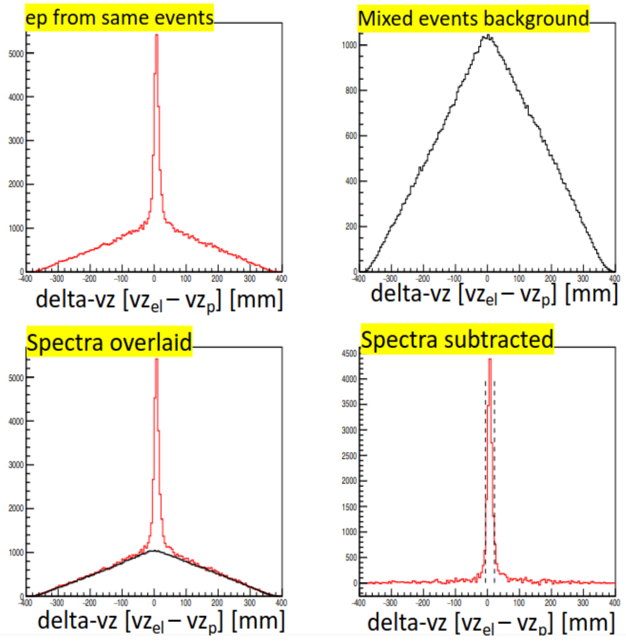






- VIP fraction coming from ^{4}He corrected using polynomial fit.

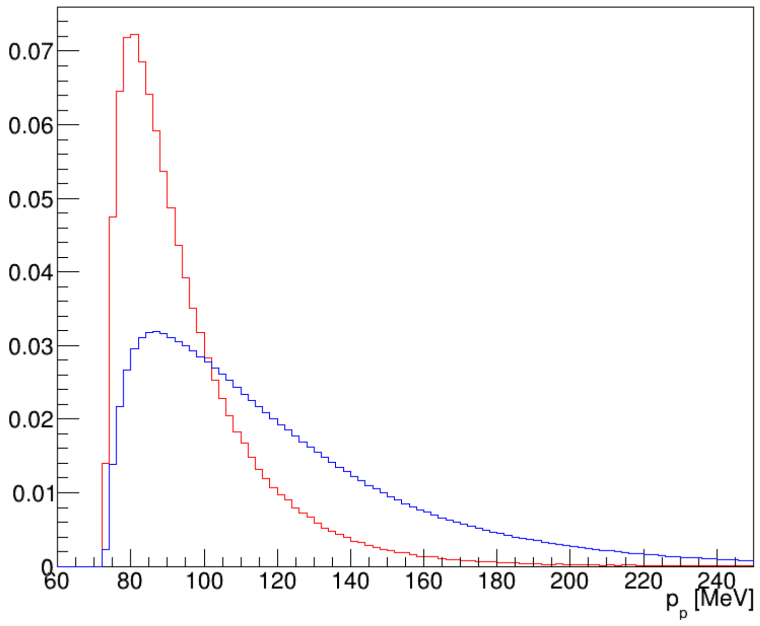




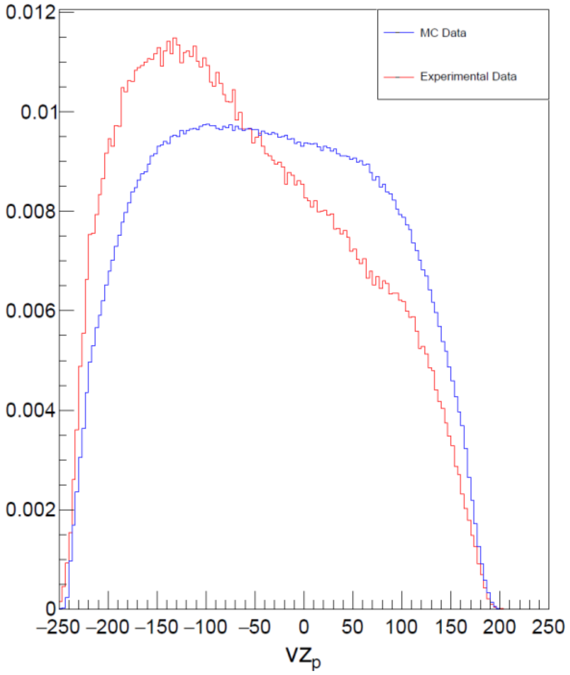
Simulation for BONuS12

- Generator: PWIA spectator model with 2014 Bosted/Christy fit to world data for F2n and F2d, AV18 D wave function, relativistic motion of struck nucleon, and equivalent radiator method for internal rad. Effects.
- Process the generated events through the full GEMC simulation chain with RTPC implementation and reconstruct them as real data. → For both tagged and inclusive cases.
- A realistic efficiency of RTPC is still needed to implement it into the simulation.
- Introduce weighting factors for each selected event to ensure the final distributions match the real data.
- The weight factors are evaluated from proton momentum, vz, and ϕ_p
- The total weight factor is the product of all individual weight factors.

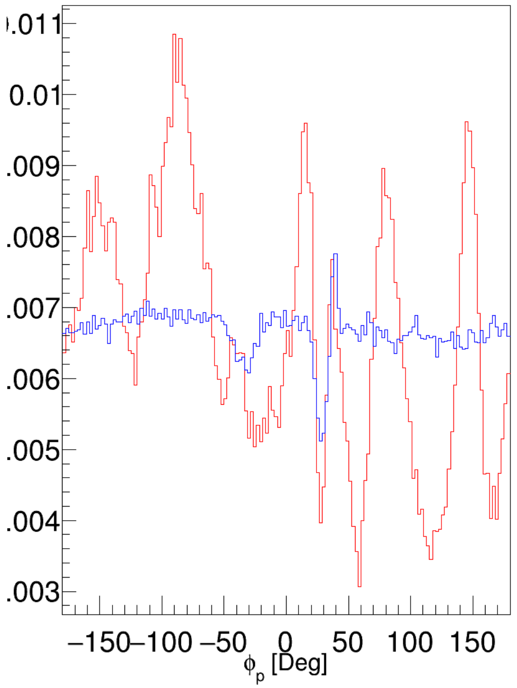
p_p



vz_p



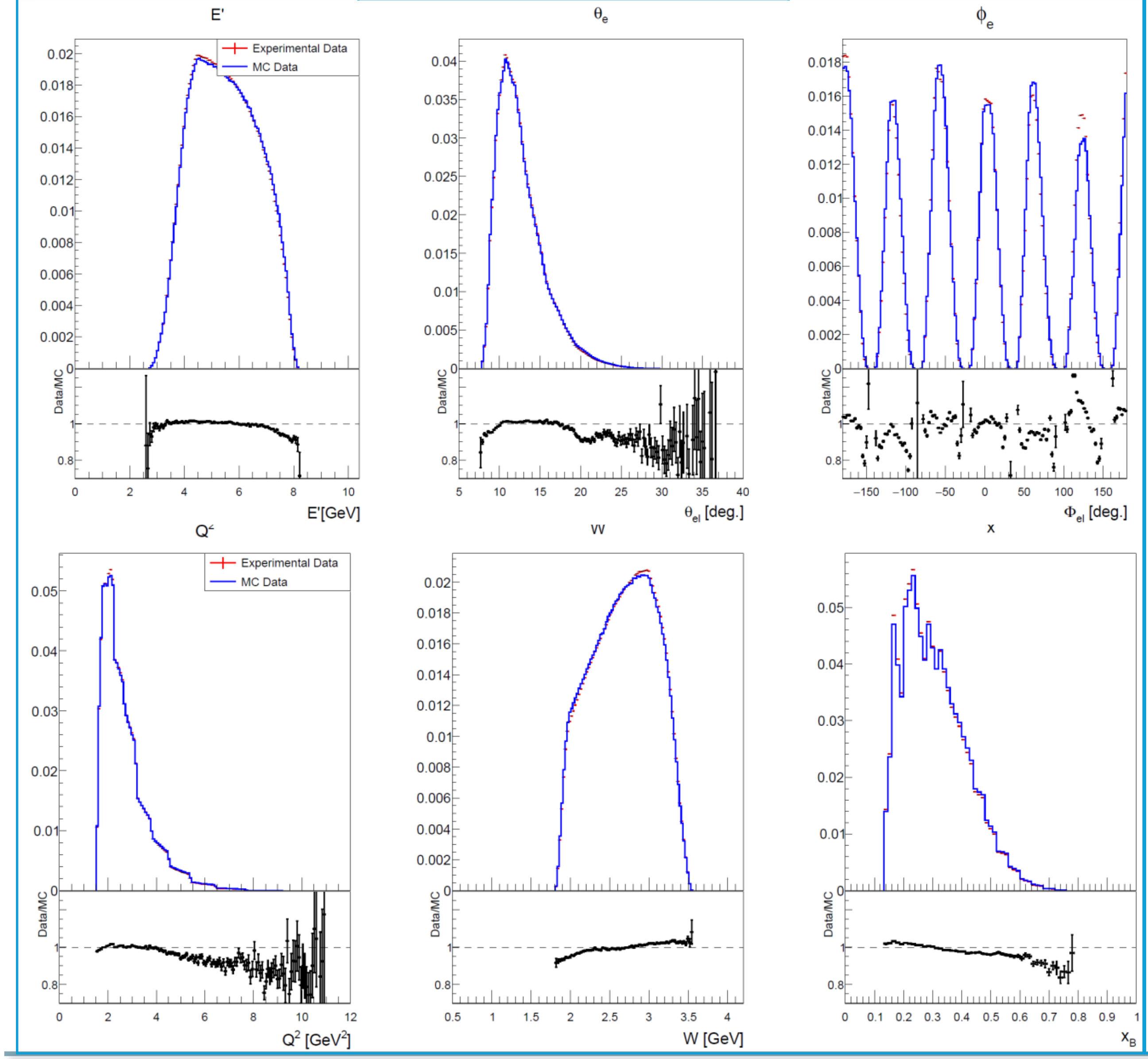
ϕ_p



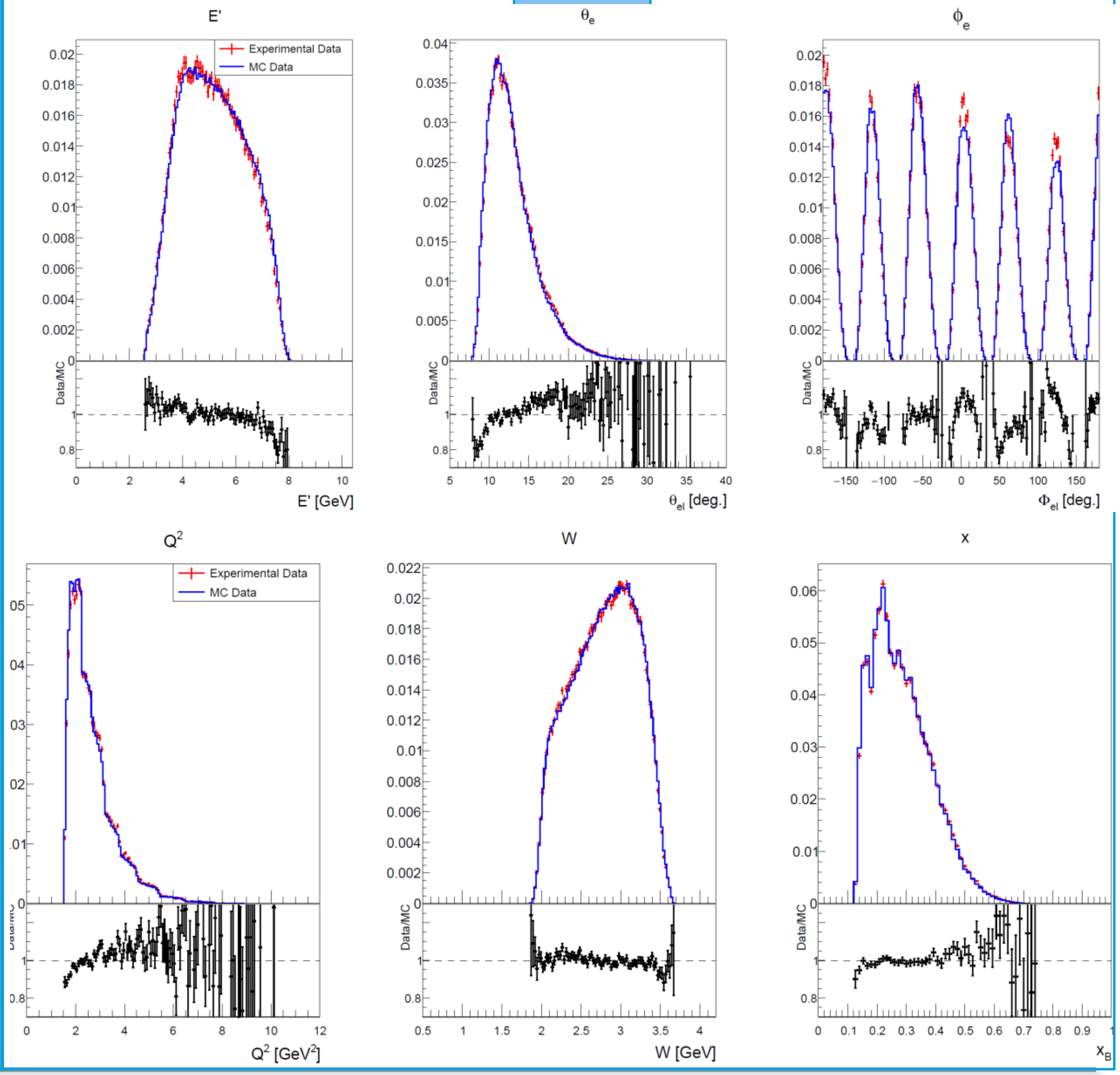
- MC. Data
- Experimental Data

Data & MC comparison — Electron

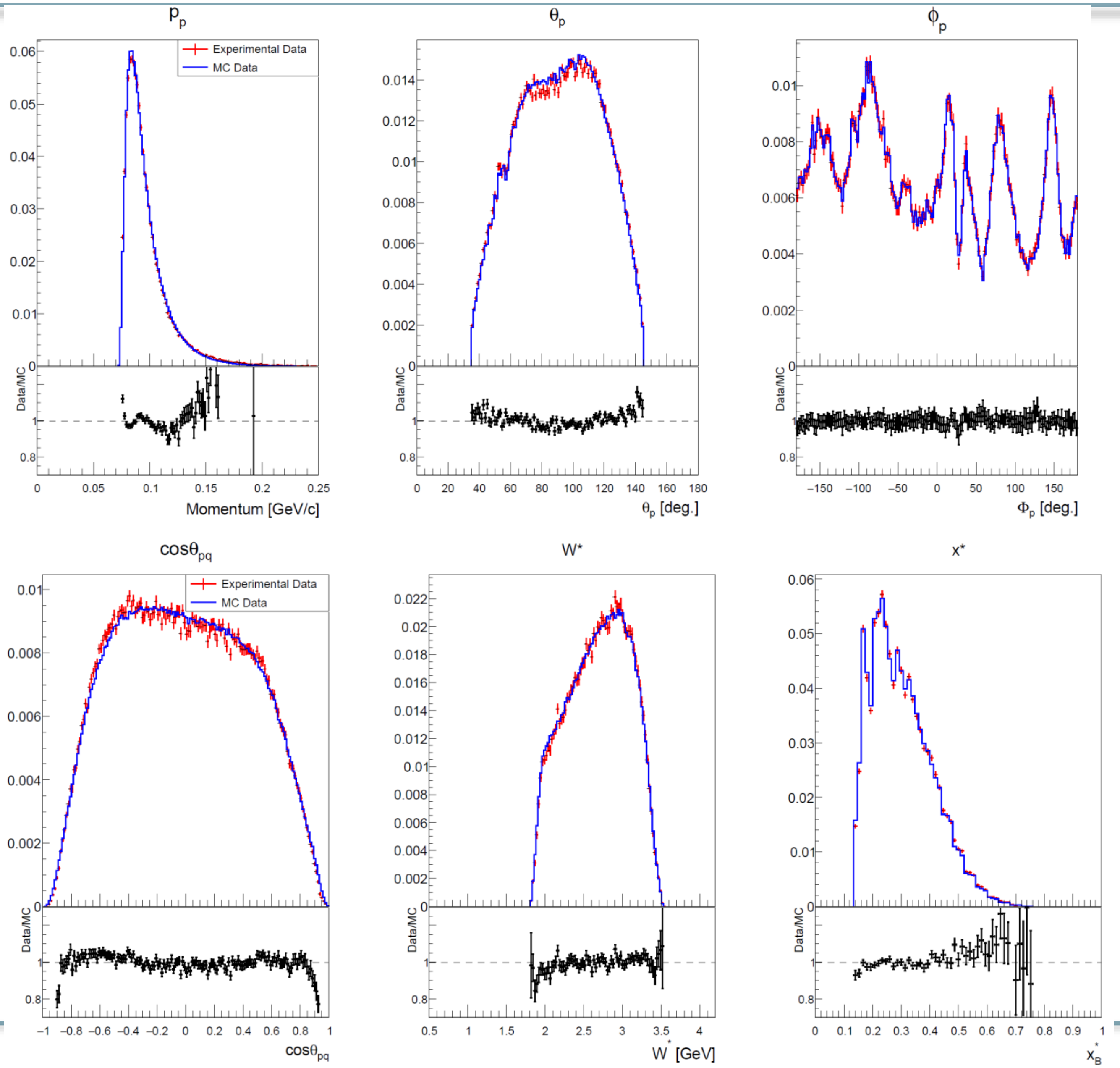
Inclusive



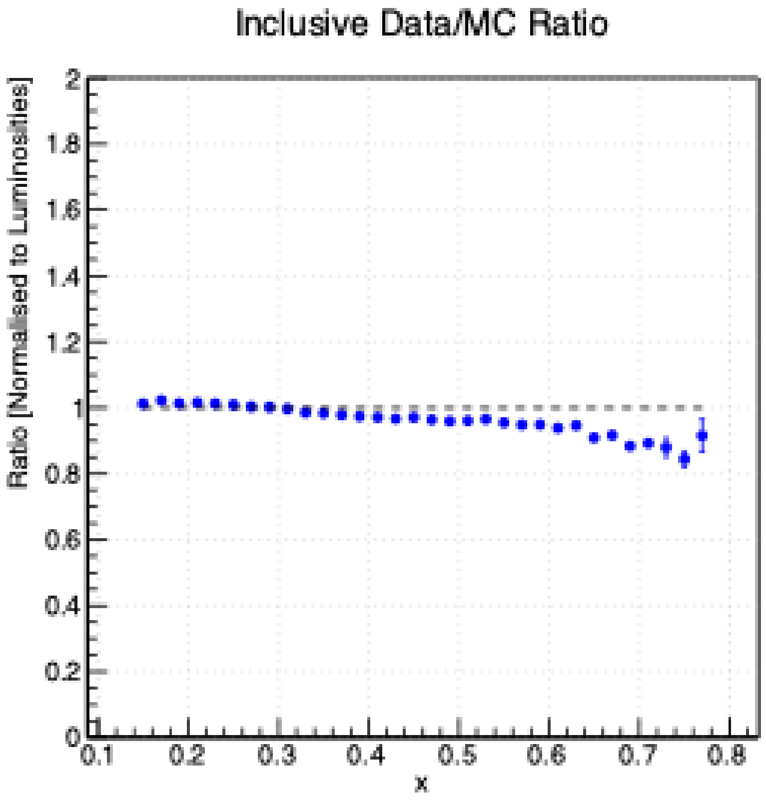
Tag

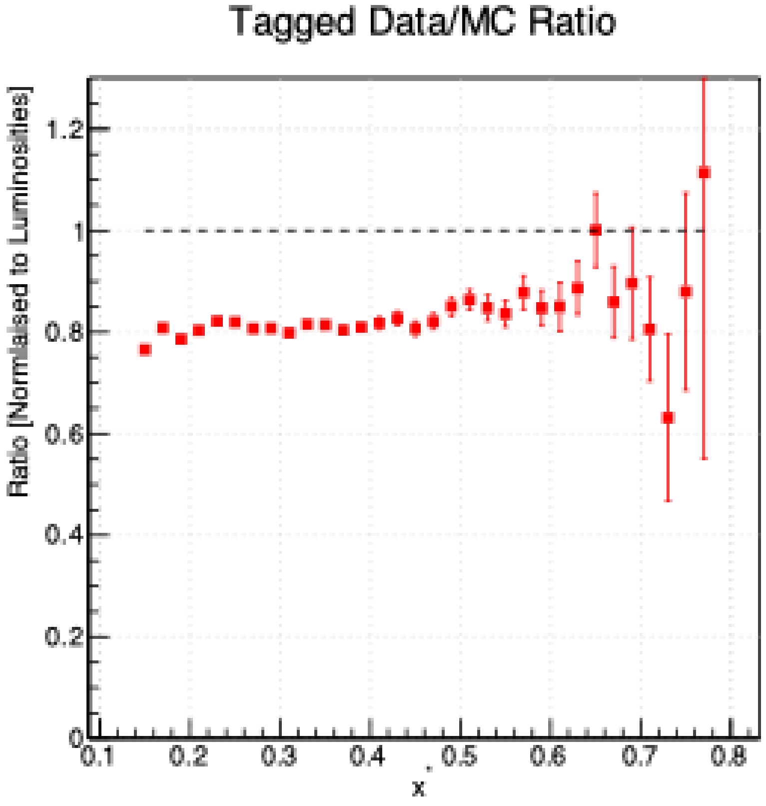


Data & MC comparison — Proton



Data/MC ratio with Normalized Luminosities — D(e, e')X and D(e, e'p_s)X

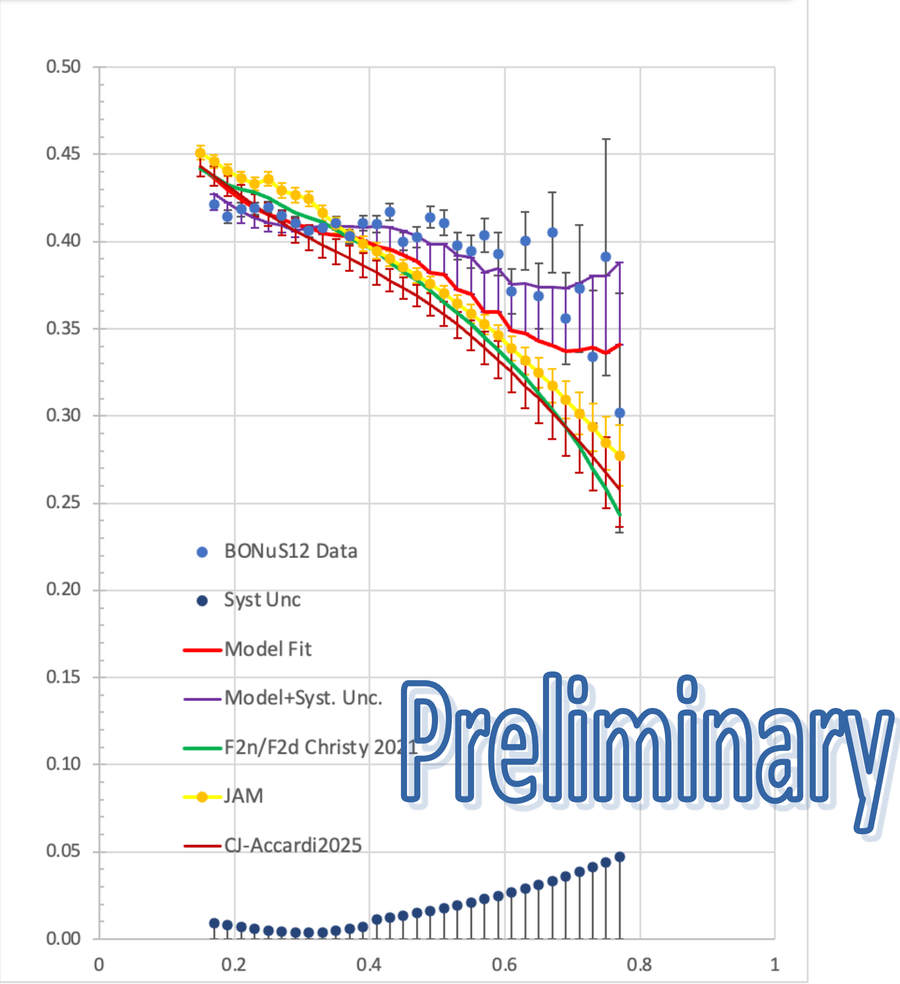


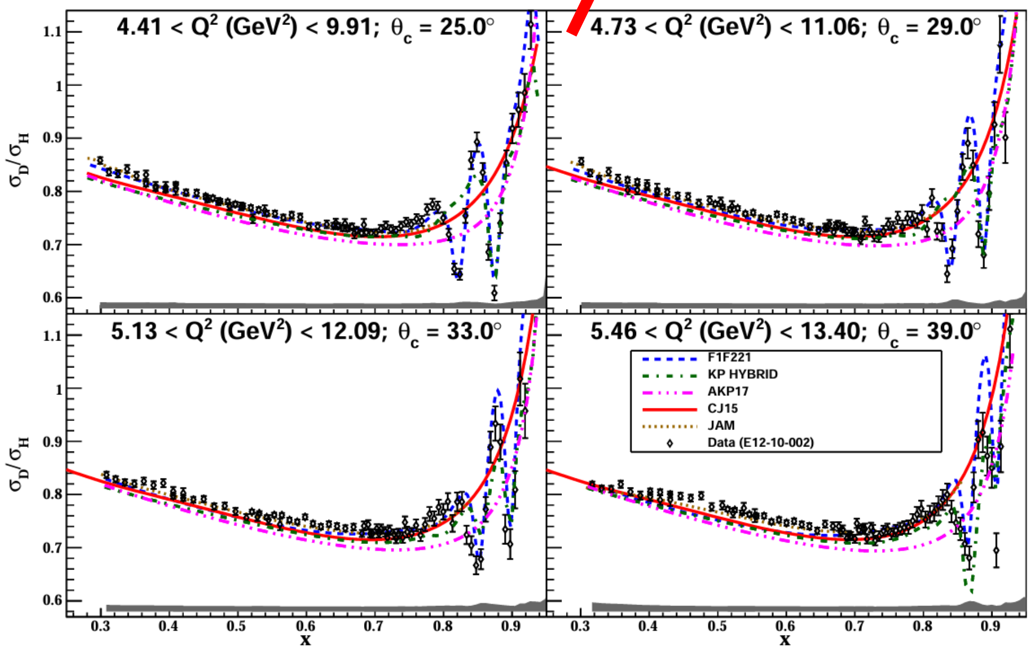


BONuS12 Preliminary Results — F_2^n / F_2^d

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

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

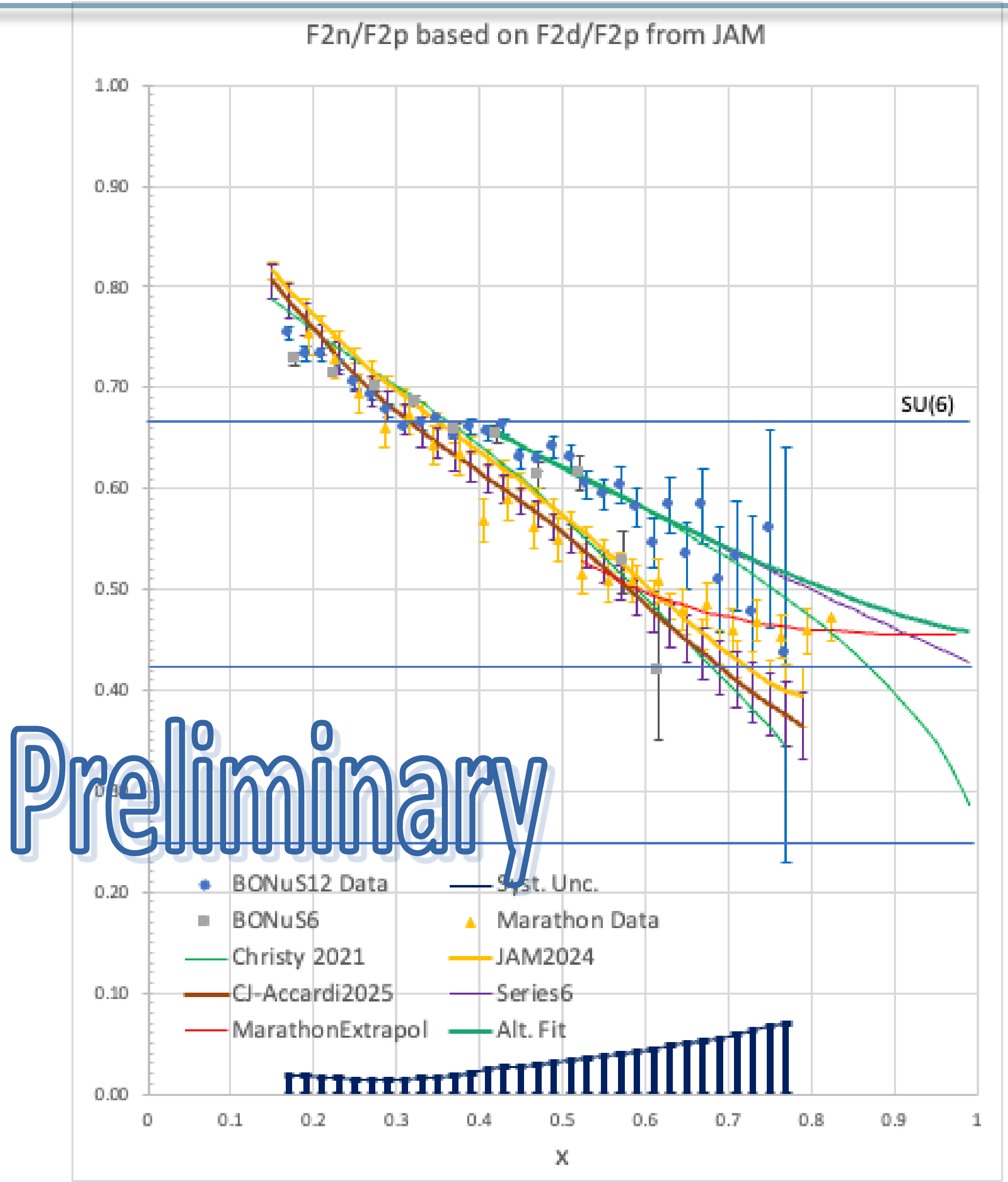




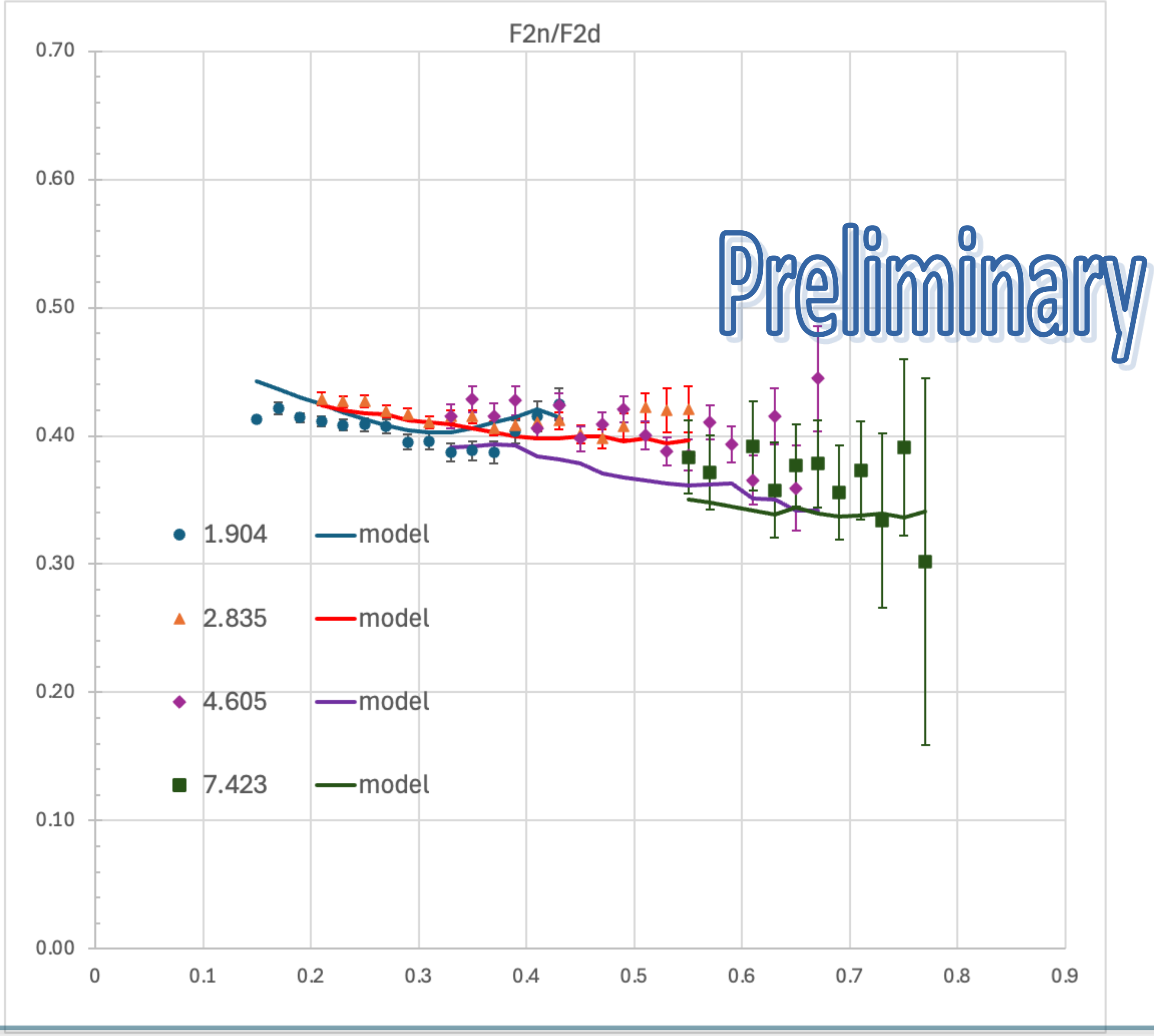
D. Biswas et al., arXive hep-ex 2409.15236

PHYSICAL REVIEW LETTERS 135, 151902 (2025)

BONuS12 Preliminary Results — F_2^n / F_2^p

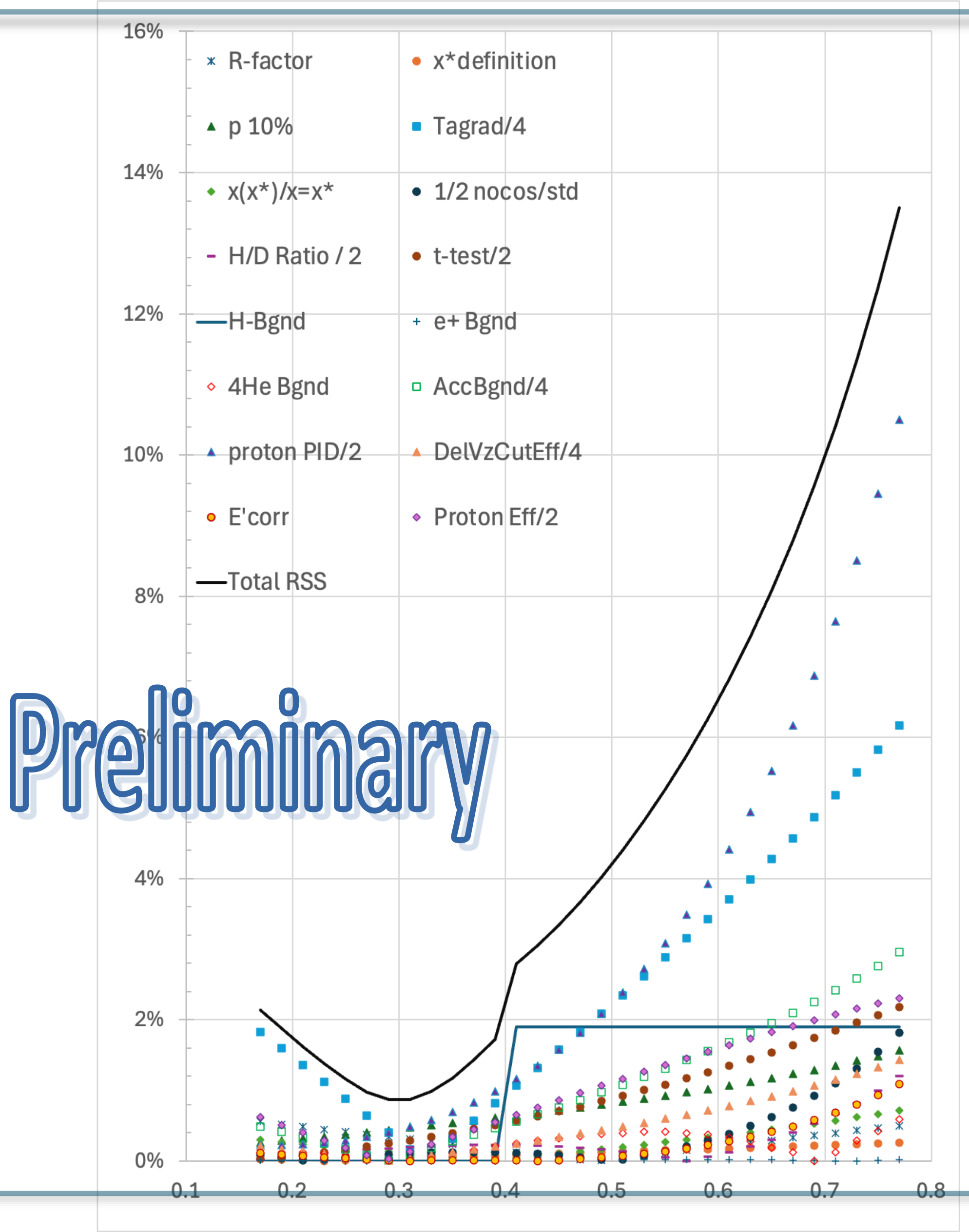


BONuS12 Preliminary Results — Q^2-dependence F_2^n/F_2^d



Systematic Uncertainty Budget

- Correction for R = σ_L / σ_T
- Ambiguity in definition of x* / n off-shellness
- Momentum misreconstruction
- **Radiative corrections**
- Mismatch between inclusive and tagged electron acceptance (different E', q if x* = x)
- Effect of dropping cos(θ_{pq}) VIP cut
- Sanity check: Can we extract F2p/F2D?
- Effect of different RTPC efficiency for 2nd half of run
- Background subtraction from tagged events:
  - "H background" (A > 4 target components)
  - Pair symmetric background
  - 4He background (A=4 target components)
  - Accidental background
- **Difference between low dE/dx and high dE/dx in the proton PID band**
- Coincidence cut efficiency
- E' correction in data and MC
- Efficiency correction for RTPC
- TOTAL RELATIVE SYSTEMATIC ERROR (Square root of sum of squares)



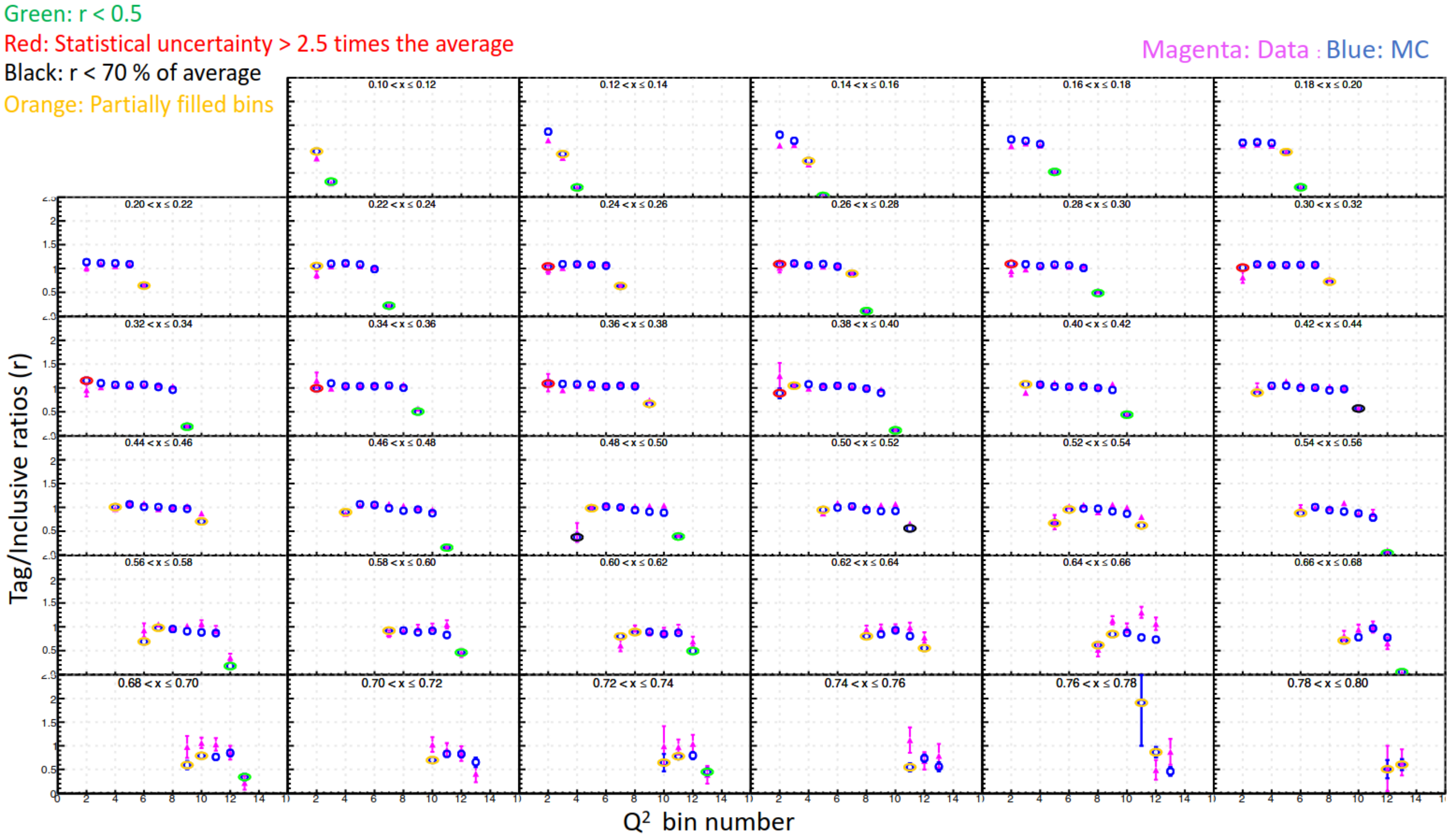
Summary

- Nucleon Structure functions provide fundamental information about bound-state QCD and continue to be actively studied (experimentally, theoretically, and phenomenologically)
- Structure functions in the valence region remain of high theoretical interest and provide crucial input to precision experiments (A1n, LHC,…)
- Results from MARATHON and, even more so, BONuS12 indicate higher than expected F2n/F2p ratio at large x
- Essential ingredient: To extract neutron (polarized) structure functions from measurements on nuclei (d, 3He) => we must understand the EMC effect in detail. Vice versa, only precise data on the free neutron can help us pin down nuclear binding effects across the table of isotopes
  => We need ALL the different data on F2n we can get

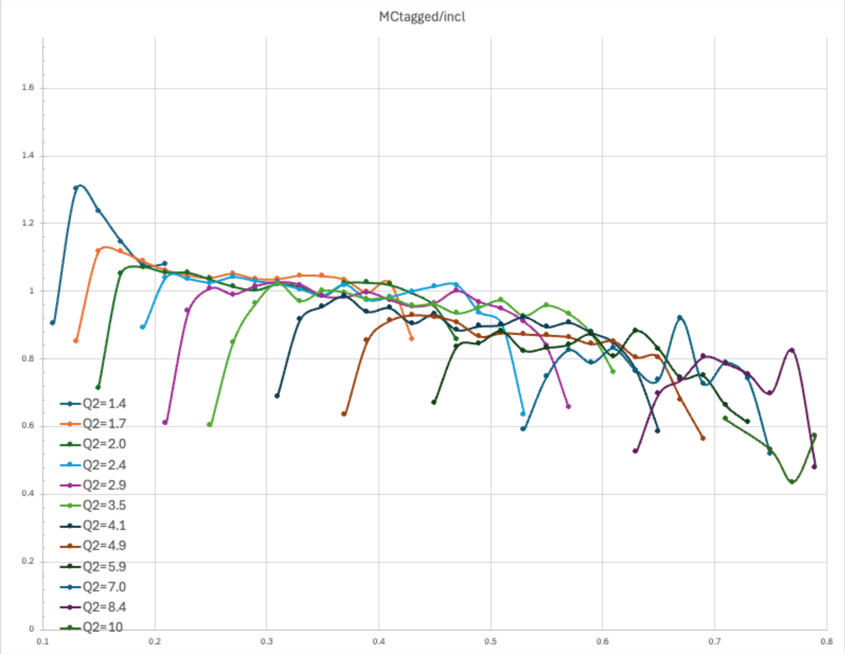
Backup

BONuS12 Corr. V: Culling Partially Filled Bins

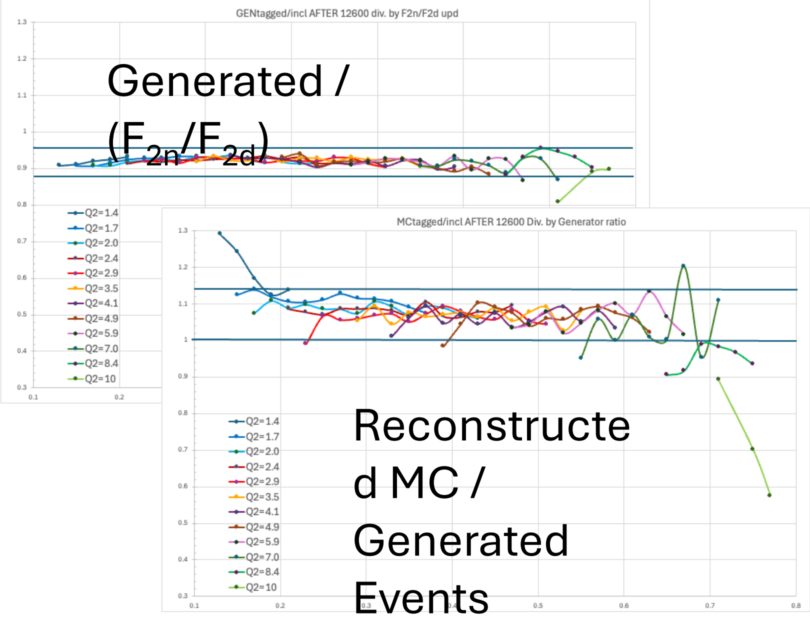
Ratio Tagged/Inclusive from MC show smooth dependence on x and Q^2 except for a few bins at the edge of the acceptance (very sensitive to precise simulation of physical boundaries), as well as bins only partially filled due to W* / W cut => These bins have been removed from final results…



BONuS12 Corr. V: Culling Partially Filled Bins

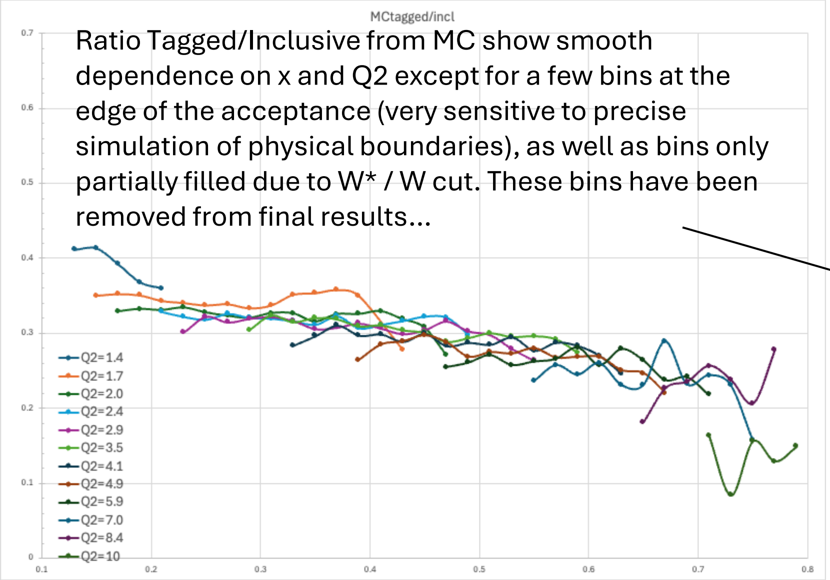


Sanity Checks:

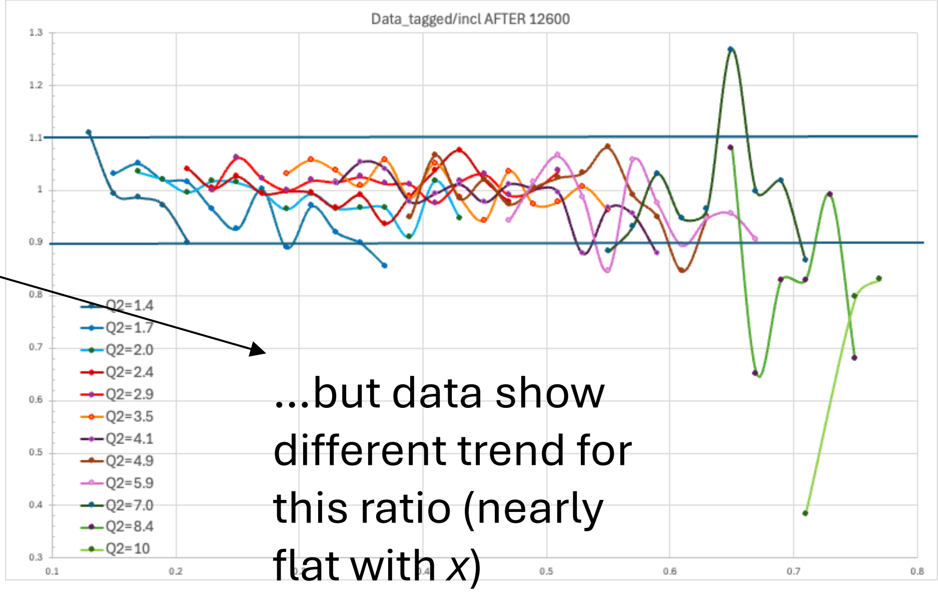


Generated / (F_{2n}/F_{2d})

Reconstructed MC / Generated Events



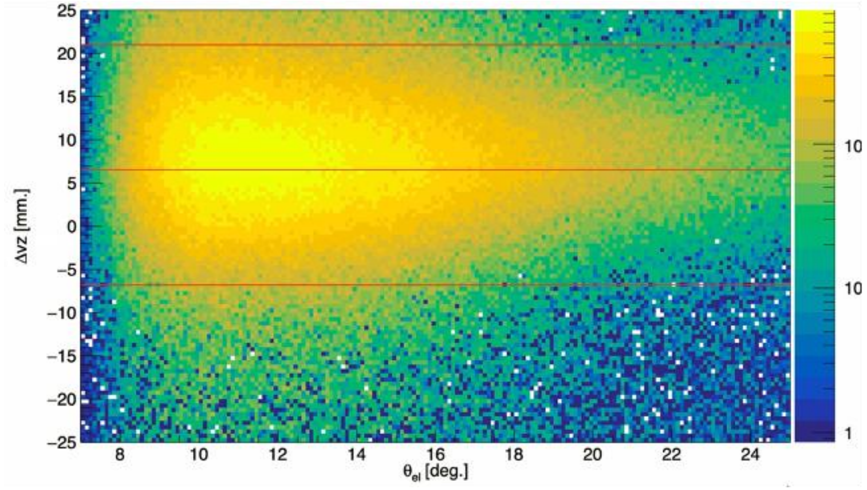
Ratio Tagged/Inclusive from MC show smooth dependence on x and Q2 except for a few bins at the edge of the acceptance (very sensitive to precise simulation of physical boundaries), as well as bins only partially filled due to W* / W cut. These bins have been removed from final results...



...but data show different trend for this ratio (nearly flat with *x*)

ODU

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



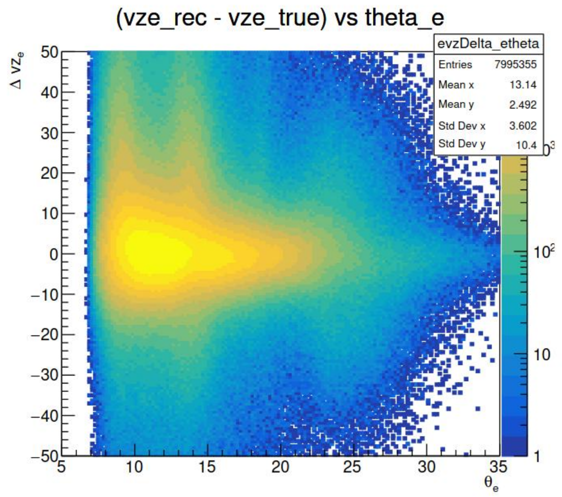
Δv_z cut for **data** is 2σ around μ, separately for each sector →

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

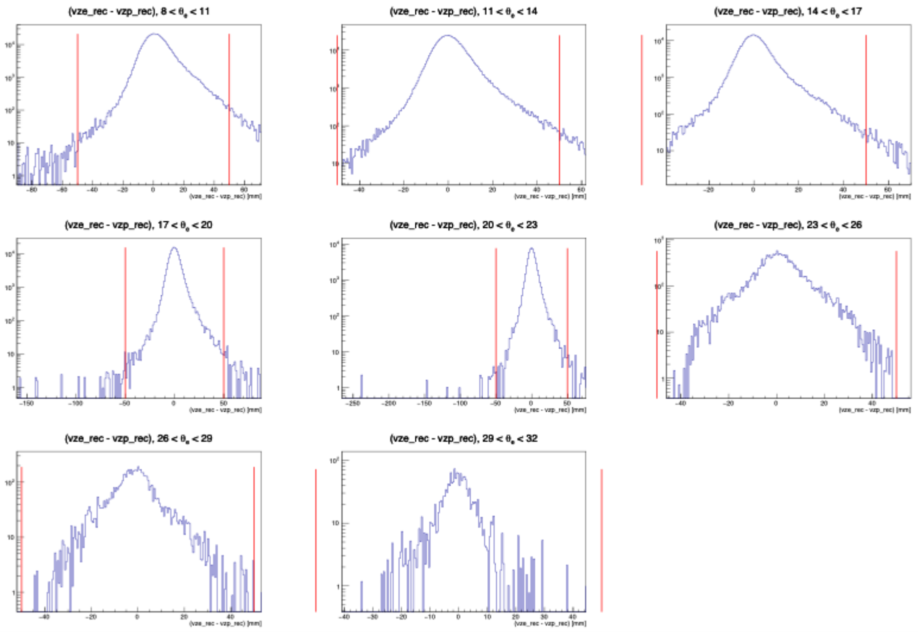
→ Correct yield for the cut efficiency

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.



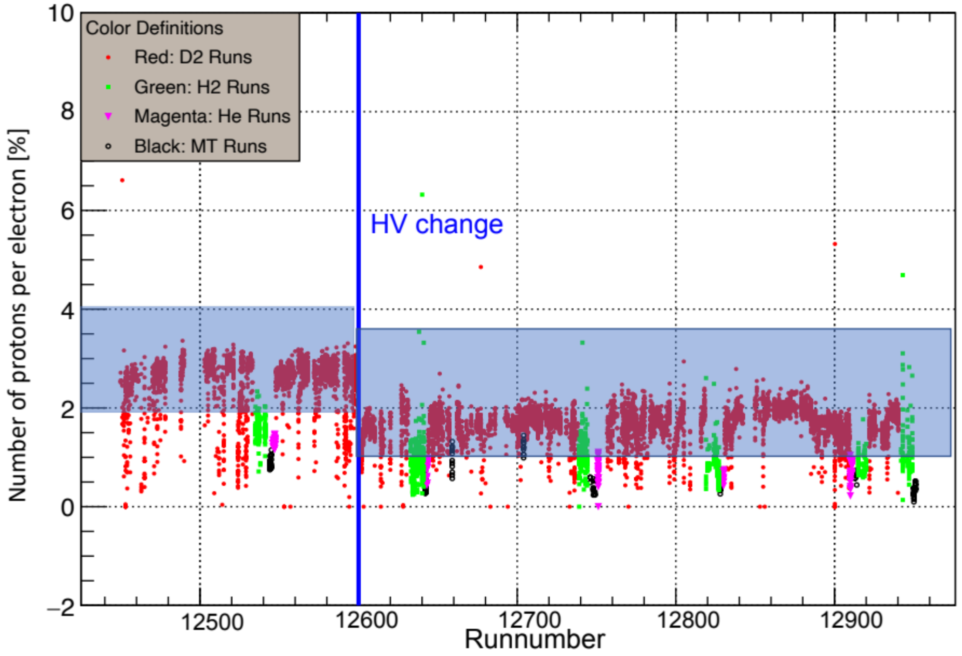
Δv_z in different θ_e bins

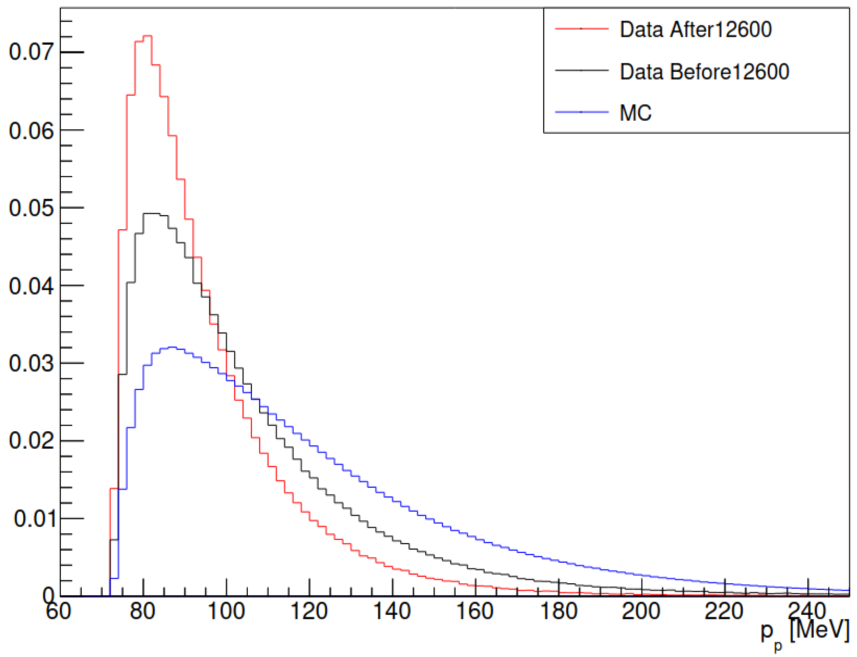


GEMs HV reduced of in RTPC after run 12600

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.



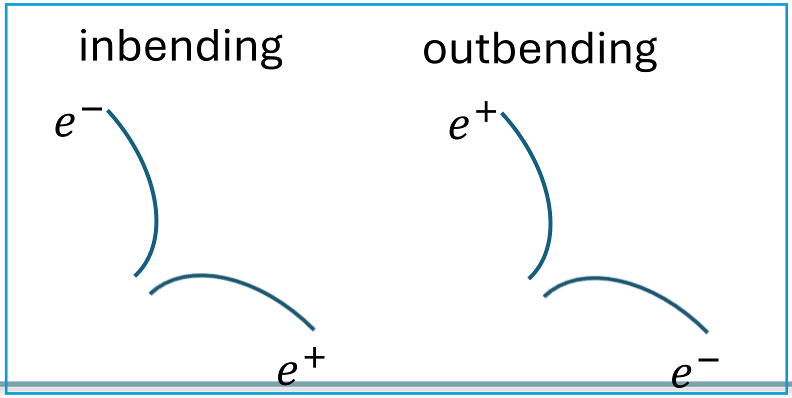


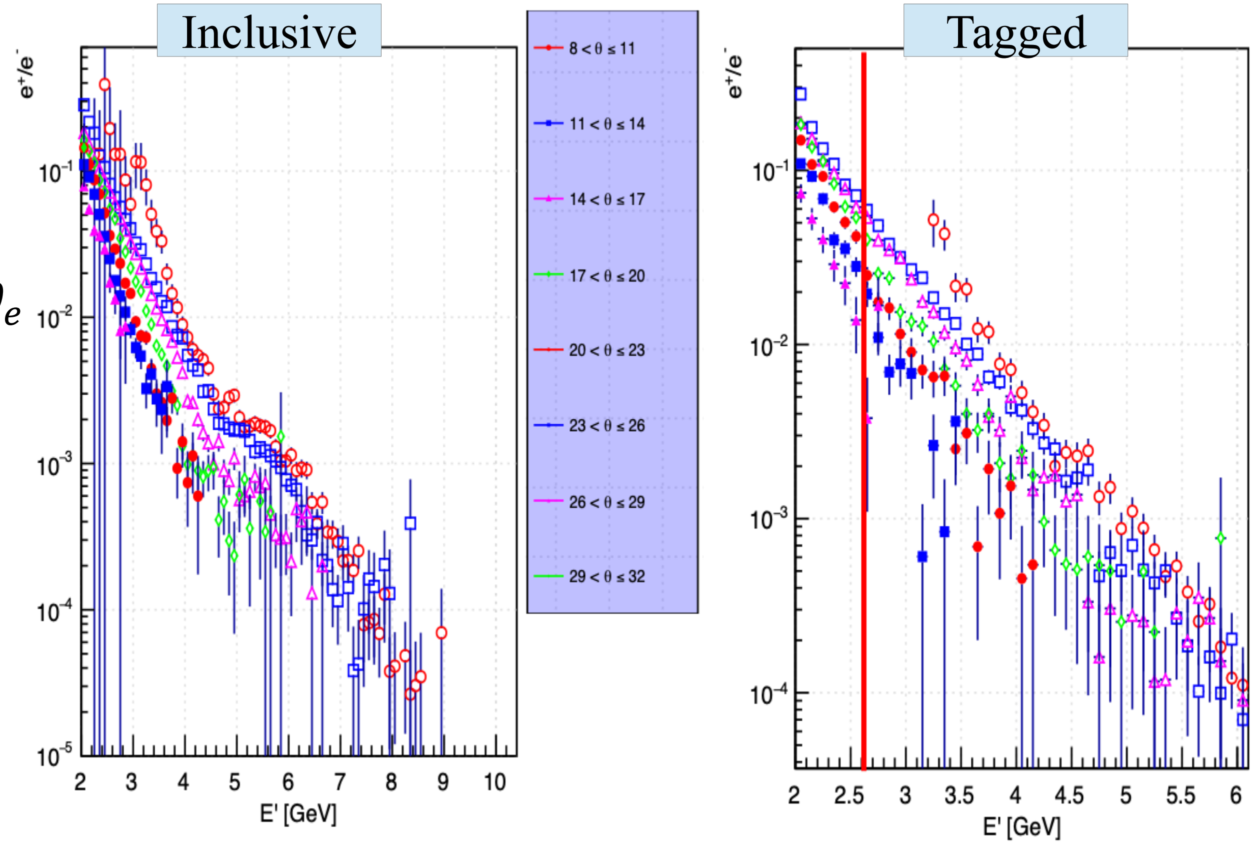
Background evaluation for experimental data — Pair Symmetric Background

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.
  - $N_{e-,scattered} = N_{e-,measured}\left(1 - \frac{N_{e+,measured}}{N_{e-,measured}}\right)$

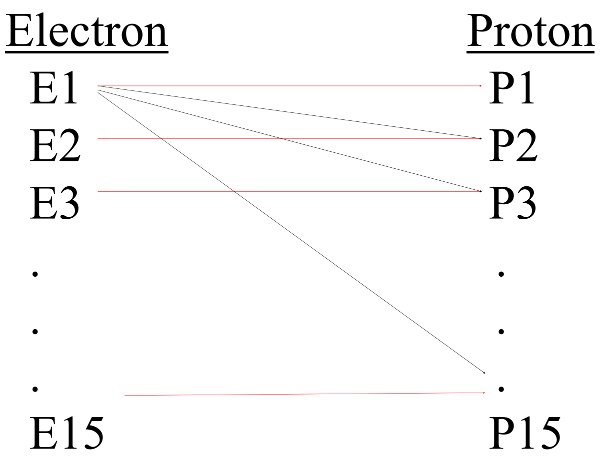


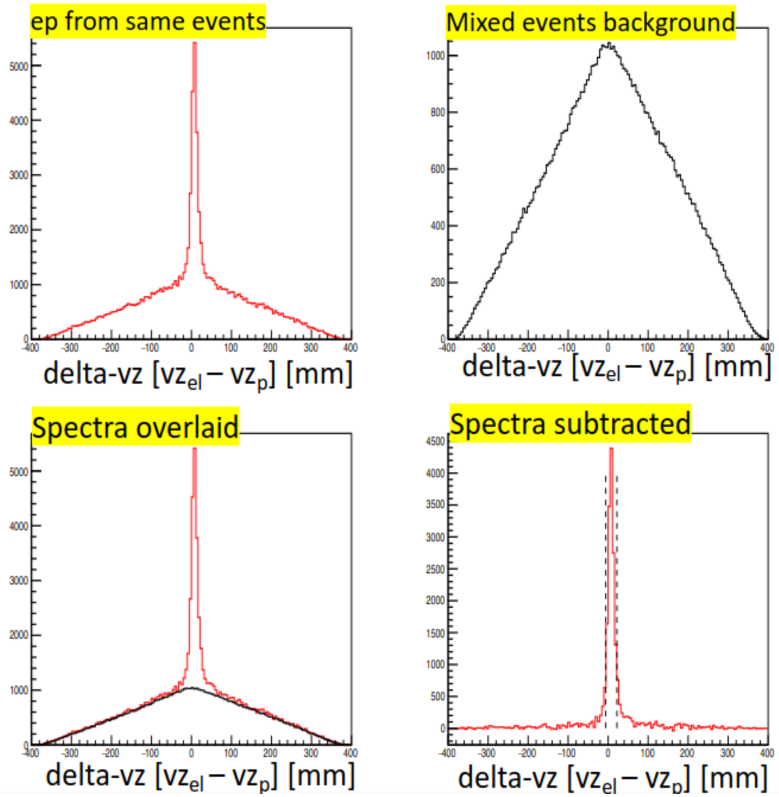


Background evaluation for experimental data — Accidentals

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**.

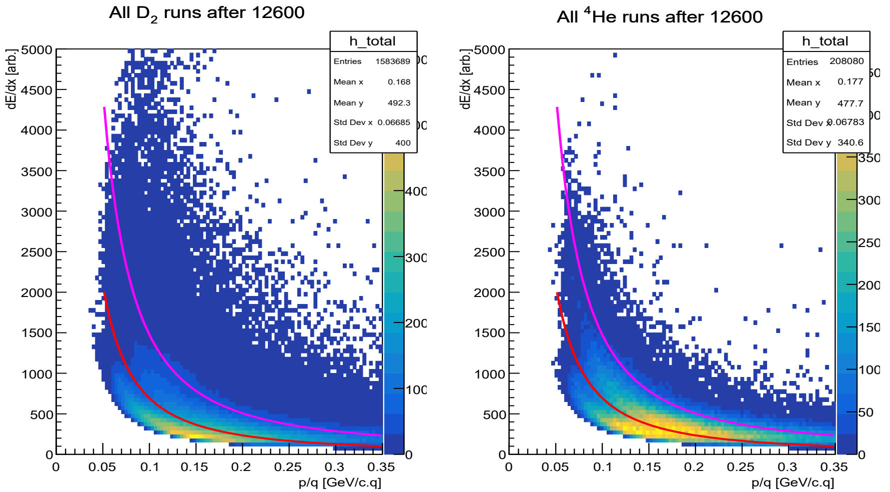


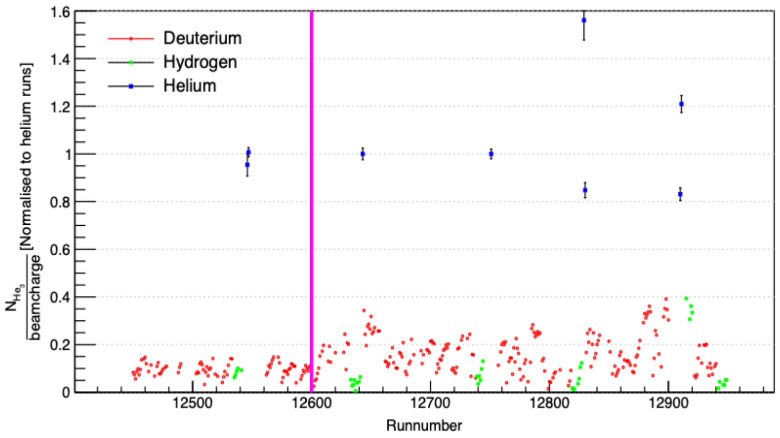


Background evaluation for experimental data — ^{4}He Contamination

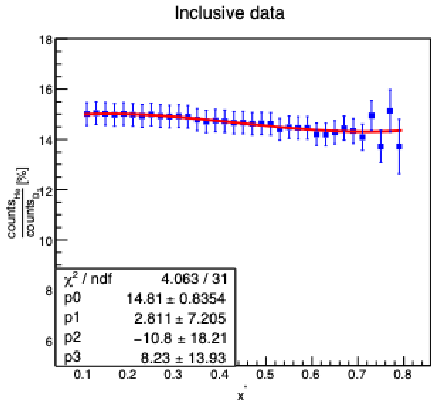
Proton

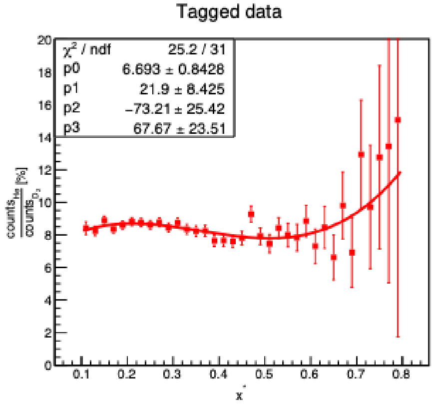
- Deuterium Target Contamination
  - ^{4}He could diffuse into the target straw from the surrounding buffer gas region
  - Estimated using ^{3}H/^{3}He band in dE/dx vs. p/q from D_2 runs and ^{4}He runs.





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





Dr. M.Pokhrel's Thesis

Background evaluation for experimental data — “H Background”

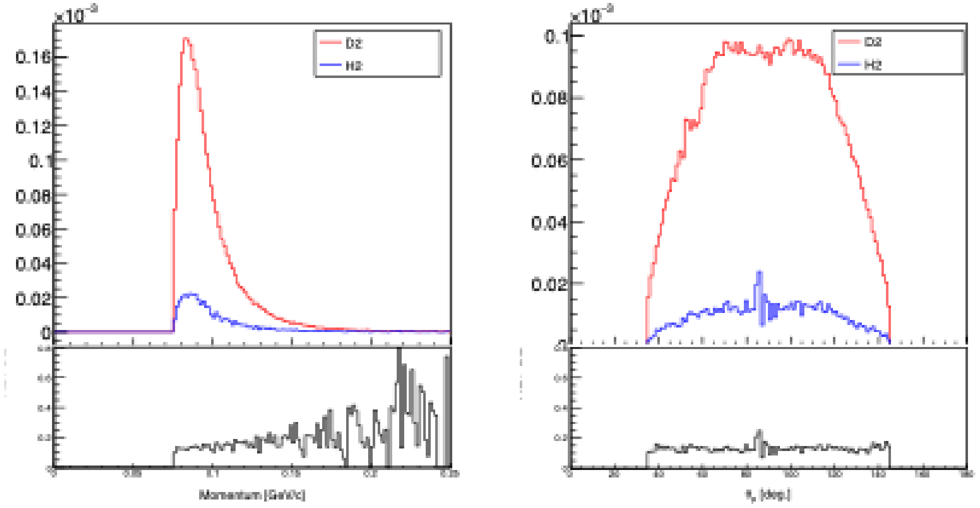
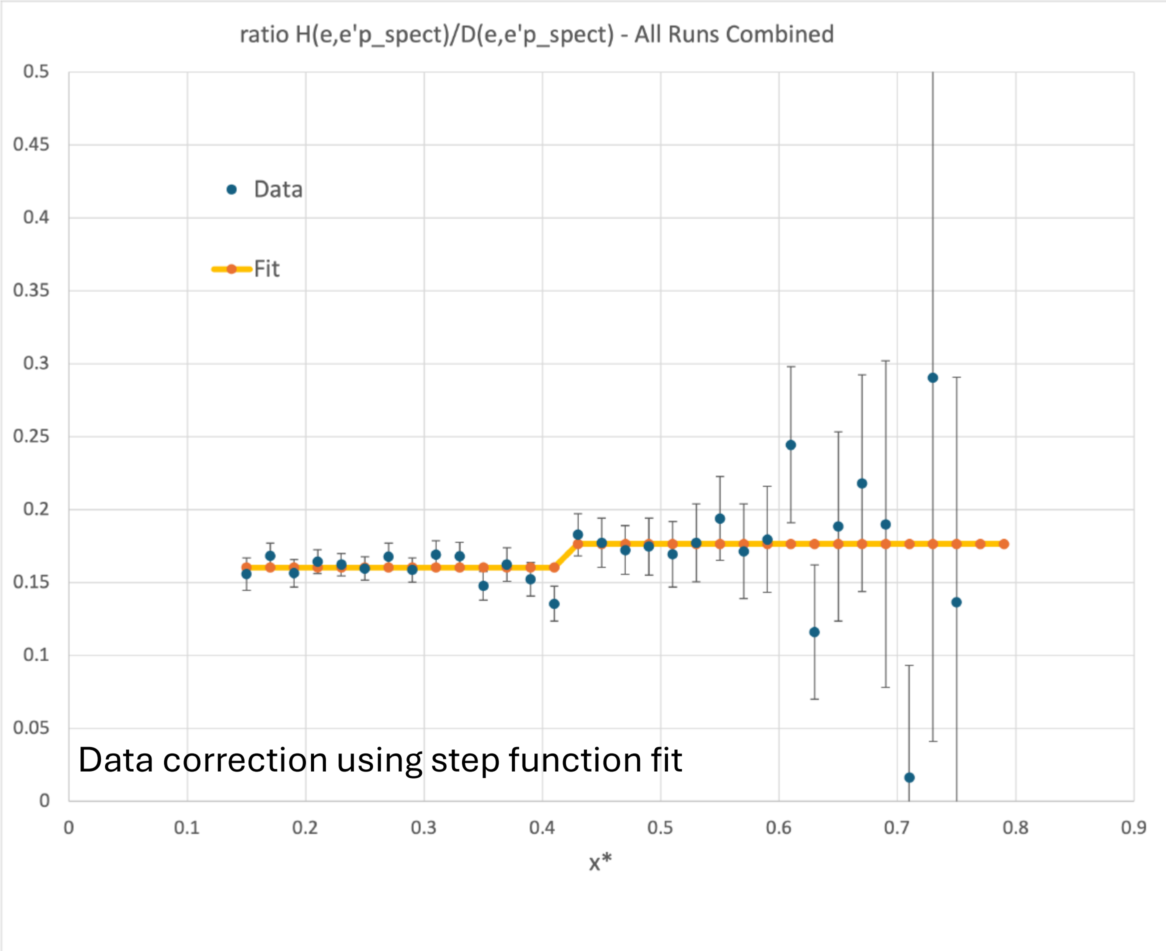


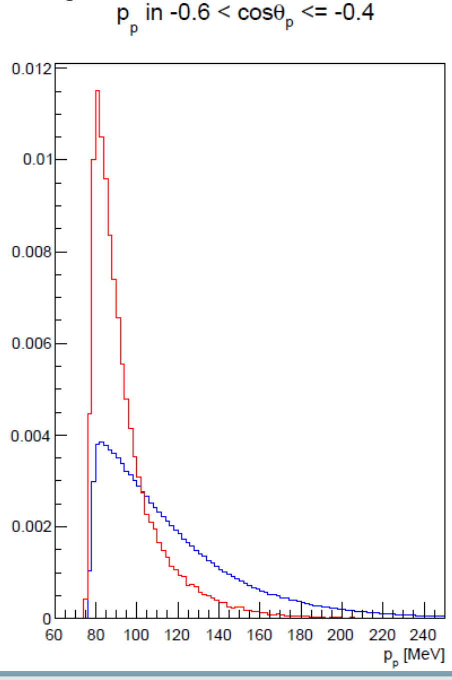
Figure 5.8: The distributions of momentum and θ_p for hydrogen and deuterium runs normalized to the beam charge after all backgrounds subtracted.

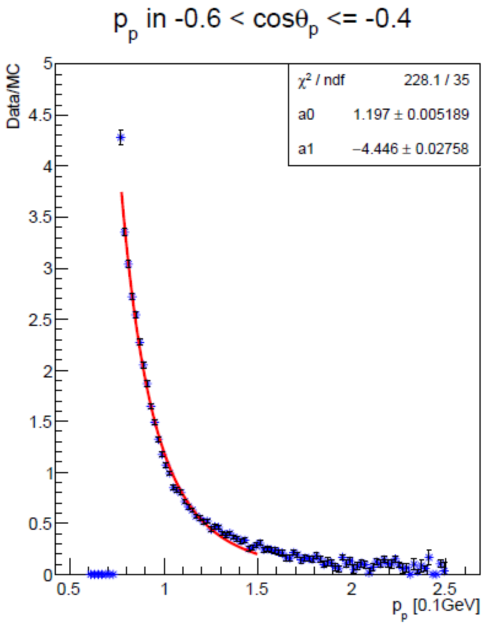


Momentum weighting on MC

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

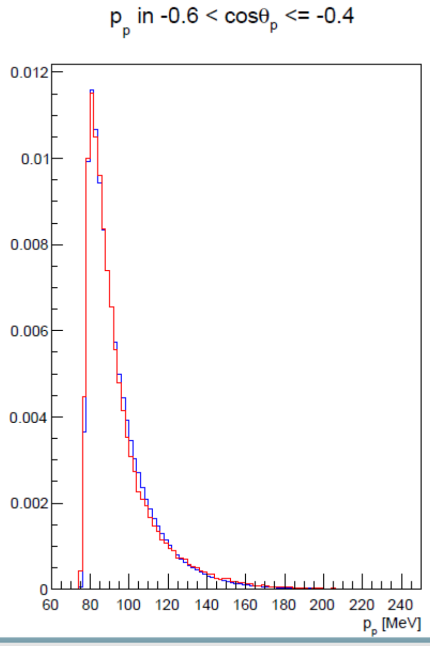
Before weighting to MC



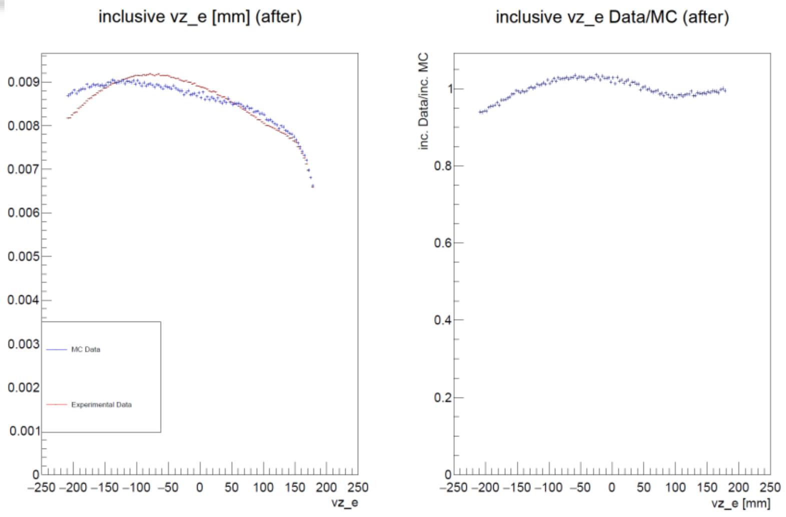


After weighting to MC

- MC. Data
- Experimental Data



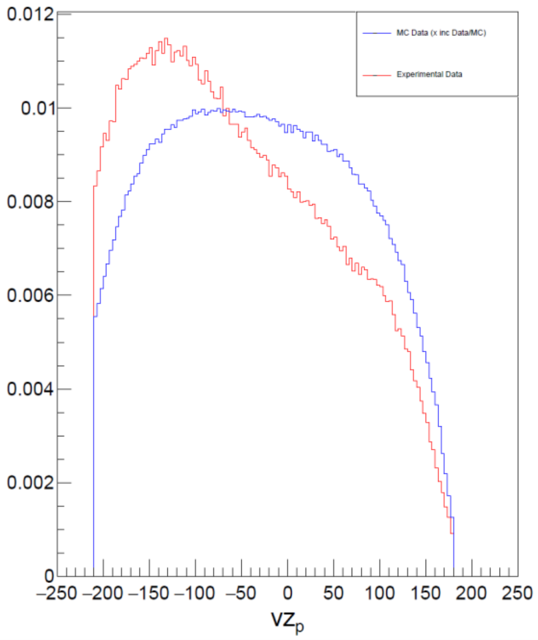
z-vertex weighting on MC

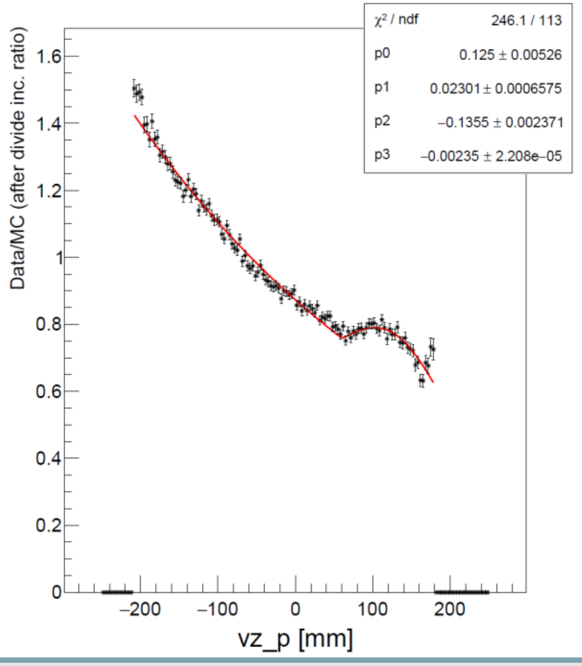


Procedures

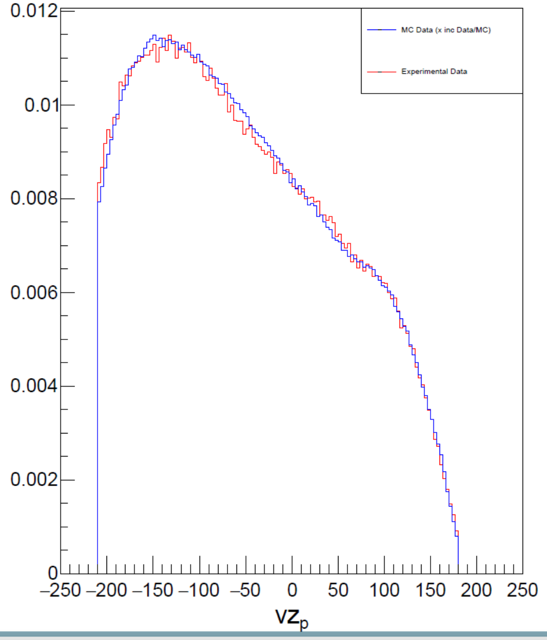
- Calculate the Data/MC ratio of vz_p, with eliminating the effect come from vz_e by dividing the inclusive vz_e ratio
- Fit the Data/MC vs. vz_p
- Parameterize the weight factor as a function of vz_p.

Before weighting to MC





After weighting to MC



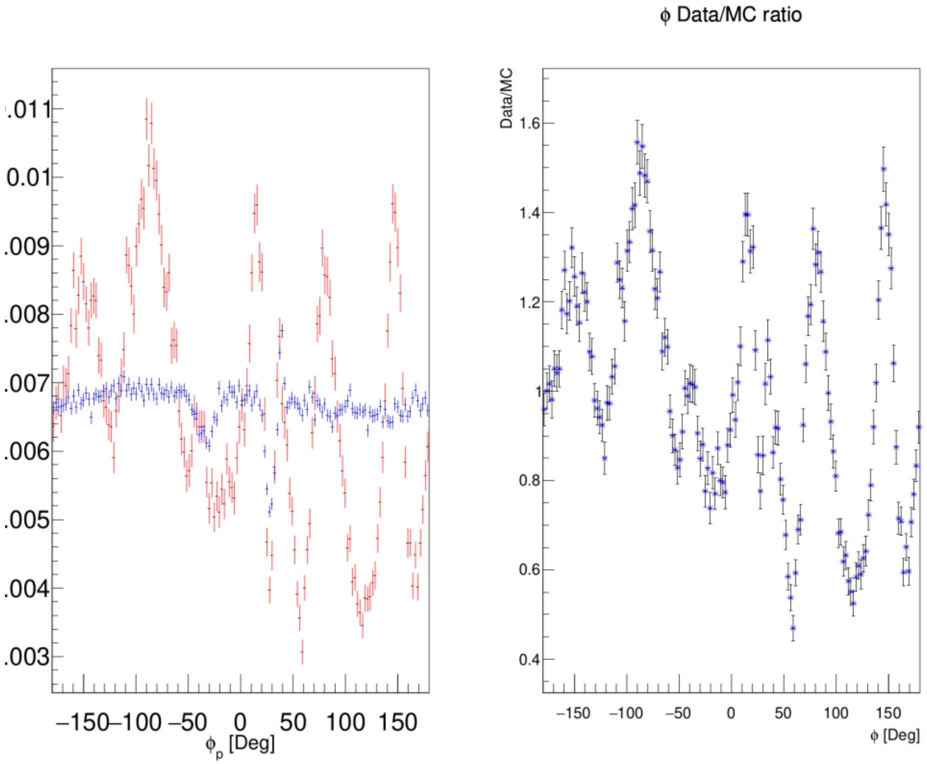
- MC. Data
- Experimental Data

ϕ_p weighting on MC

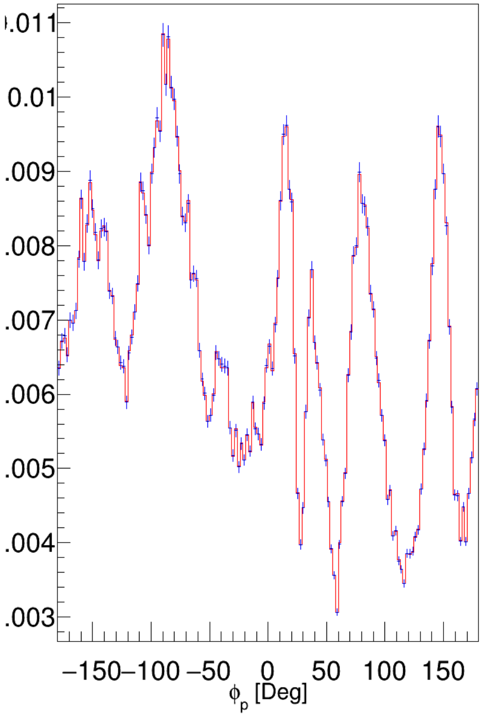
Procedures

- 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