BONuS12 Analysis Review Update

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(On behalf of the CLAS Collaboration)

2026 CLAS12 Collaboration Meeting, JLab, July 1st, 2026

Outline

- Physics Motivations
- Experimental Setup & Recoil Detector
- Updated analysis & Preliminary Results
  - Backgrounds
  - RTPC Efficiency
- Summary

Physics Motivations

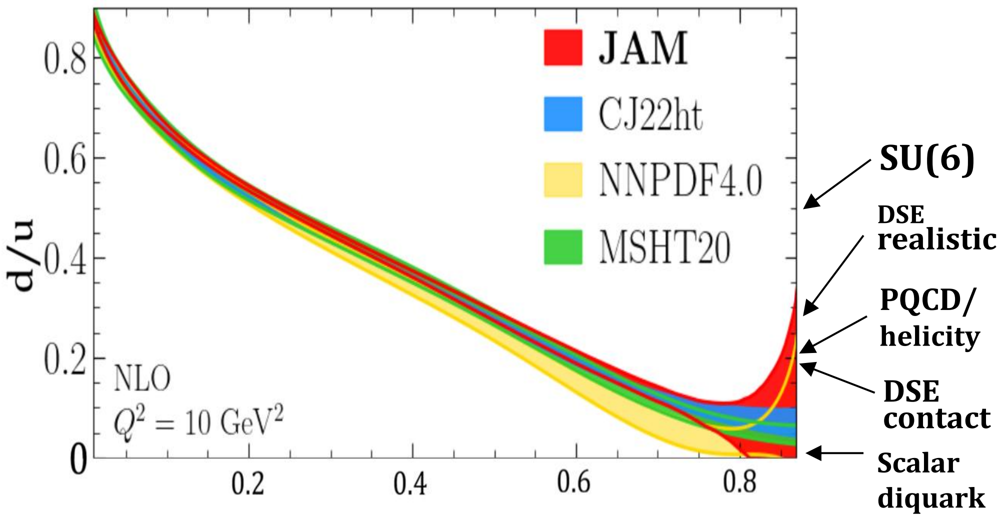
- There are many experiments provide precise measurements on F_2^p and F_2^d, but less precise for F_2^n, especially at large x, where different theoretical models have different predictions
- As it is difficulty to prepare free neutron in the experiment, F_2^n would be obtained from bound neutron inside the nucleus. 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 deuteron, could reduce the model dependency by constraining the kinematic.

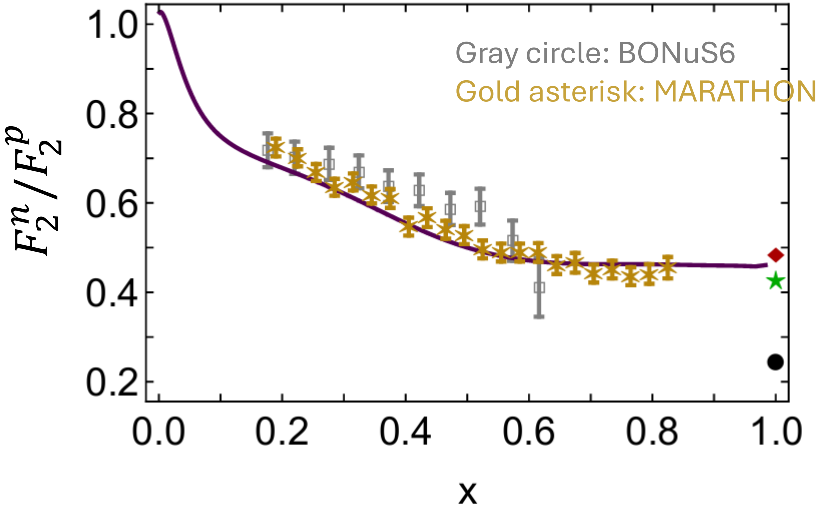
$$F_{2p}(x) = x\sum_q e_q^2(q(x) + \bar{q}(x)) \approx x\left(\frac{4}{9}u(x) + \frac{1}{9}d(x)\right)$$

$$F_{2n}(x) \approx x\left(\frac{4}{9}d(x) + \frac{1}{9}u(x)\right)$$

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

JAM 2026: JLAB-THY-26-4687, ADP-26-11/T1308

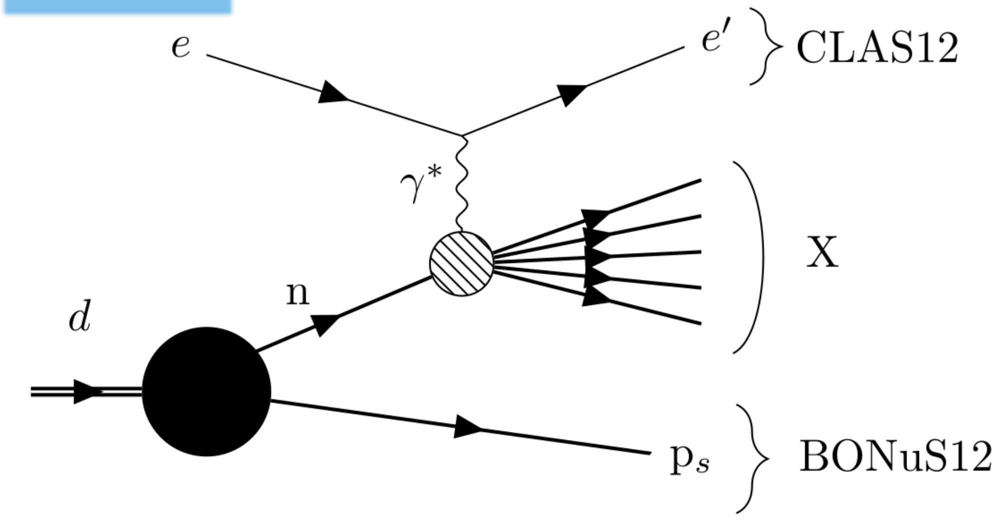


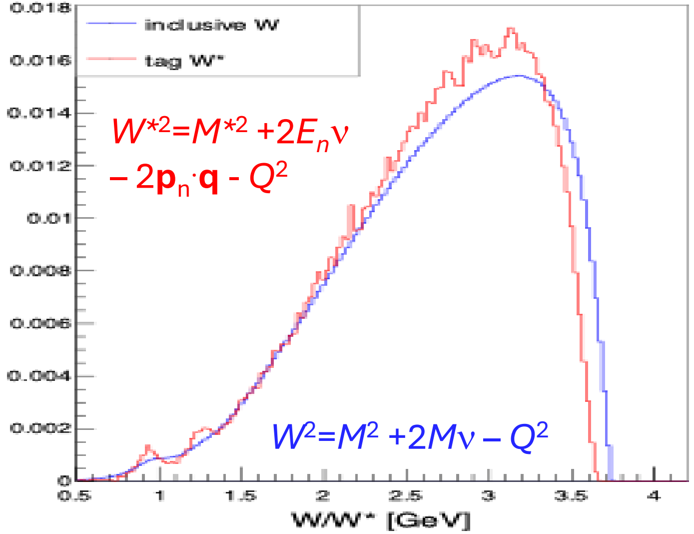


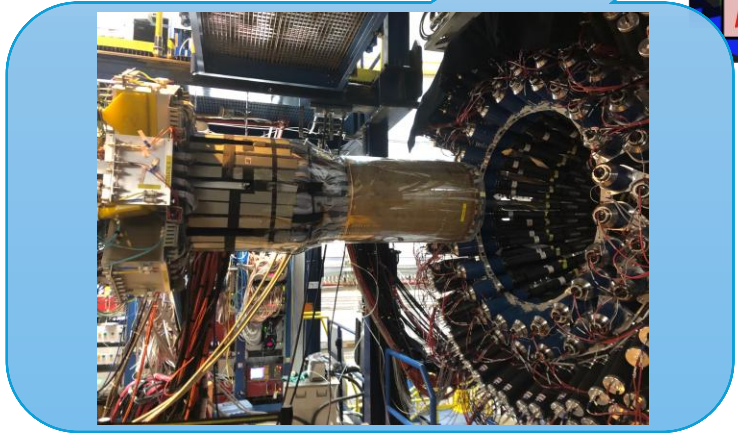
Y.Lu,L.Chang, K.Raya, C.D.Roberts, J.Rodríguez-Quintero, Proton and pion distribution functions in counterpoint, Phys. Lett. B**830** (2022)137130.

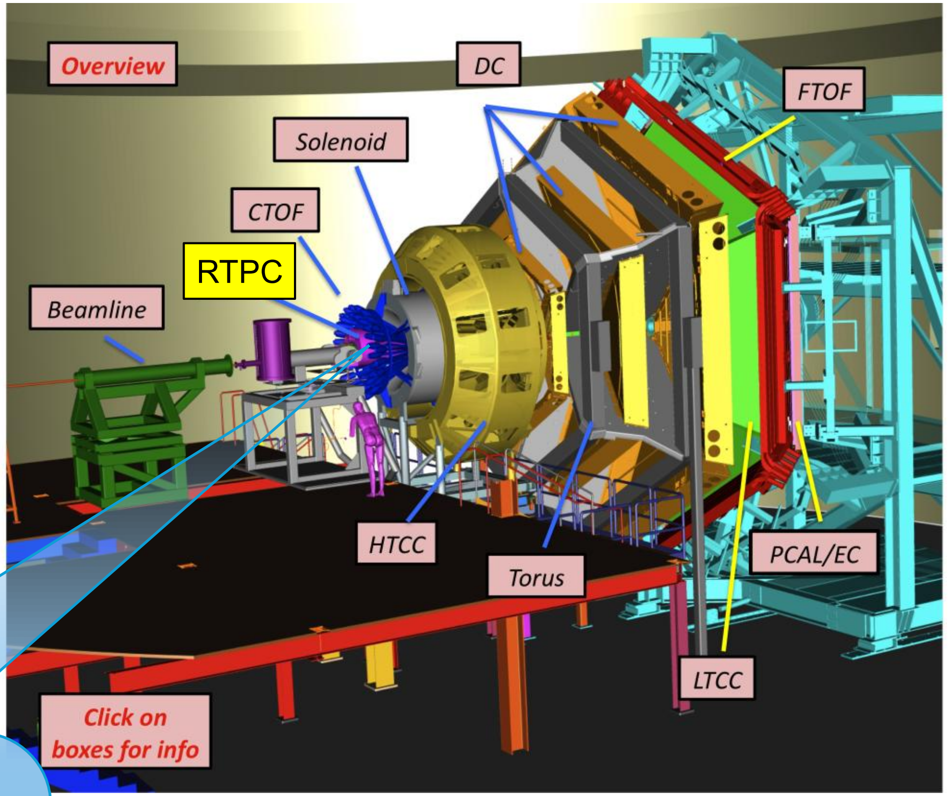
BONuS12 Experimental Setup

10.4 GeV





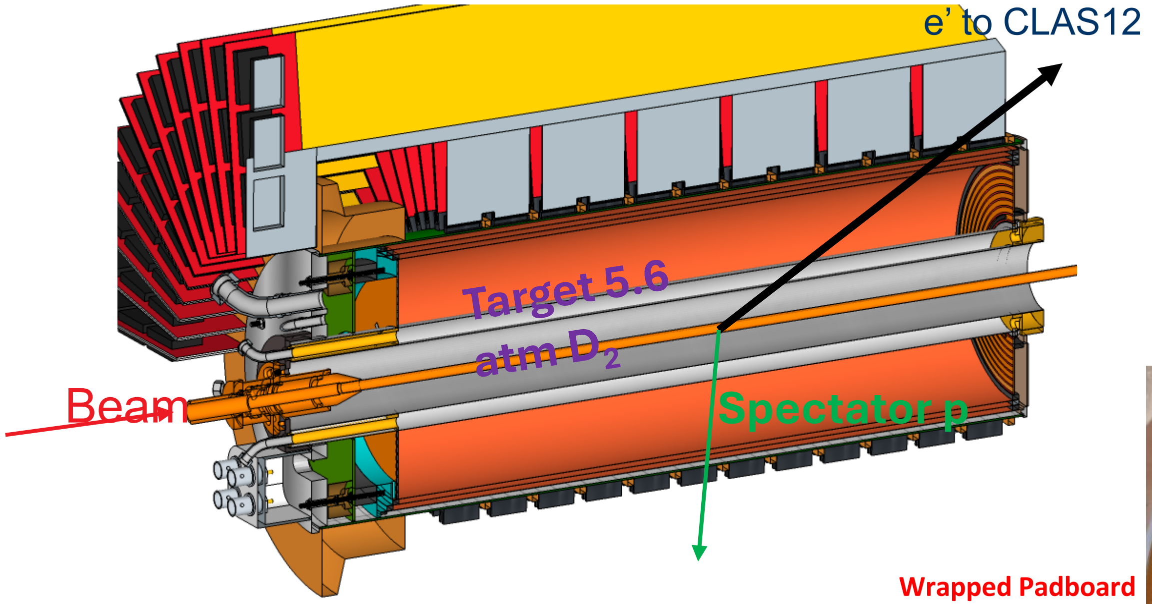




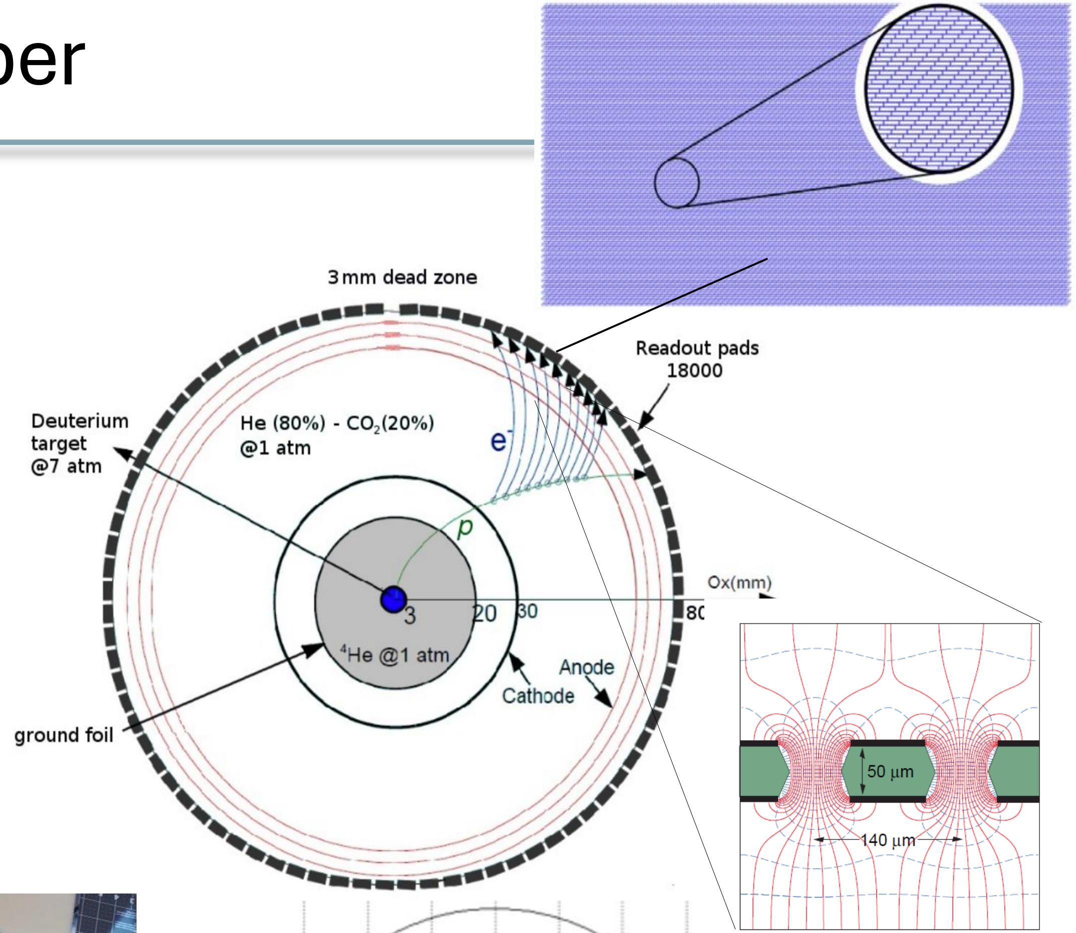
Beam Energy	Target	Spring 2020	Summer 2020
1 Pass Data	H2	81M	185M
	D2	37M	45M
	4He	19M	44M
	Empty	1M	22M
	Total	138M	296M
5 Pass Data	H2	151M	266M
	D2	2275M	2355M
	4He	77M	51M
	Empty	21M	45M
	Total	2524M	2717M

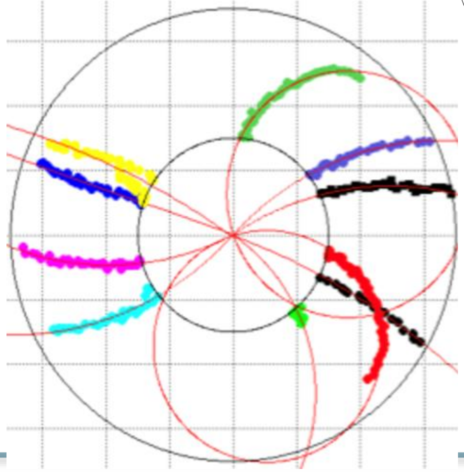
BONuS12 Radial Time Projection Chamber

- 40 cm long , and 16 cm in diameter, gaseous-type detector
- Ionized electron inside the drift region, between cathode (3 cm) to 1st GEM layer (7 cm)
- Ionization electrons drifted to the readout padboard (7.9cm), which can be reconstructed as a track.



Wrapped Padboard inner surface

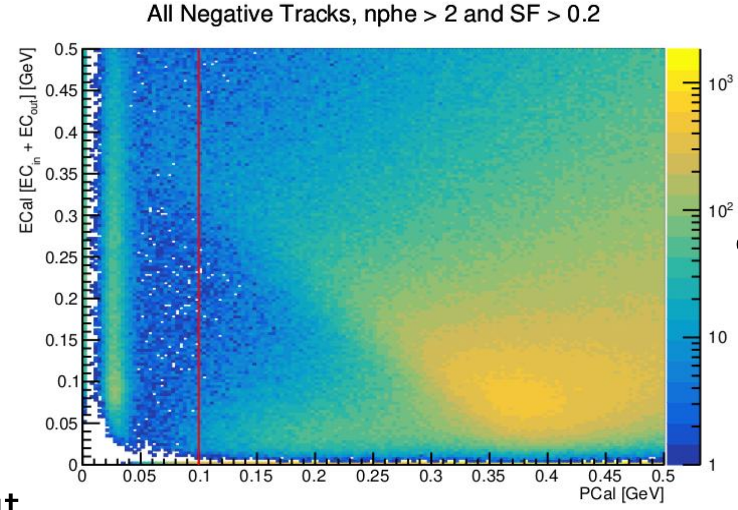


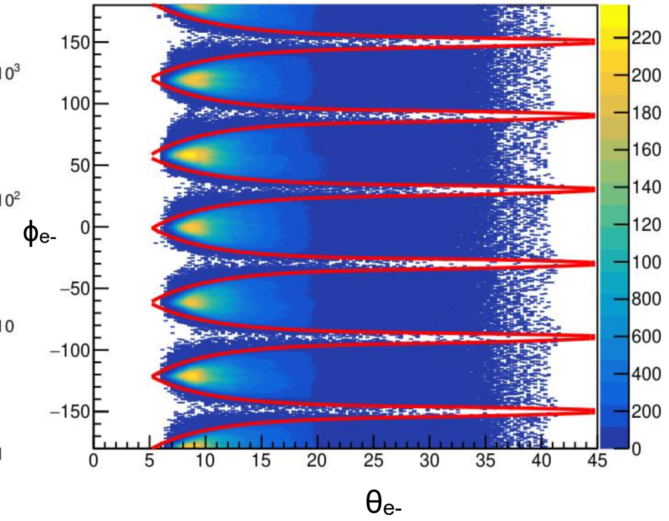


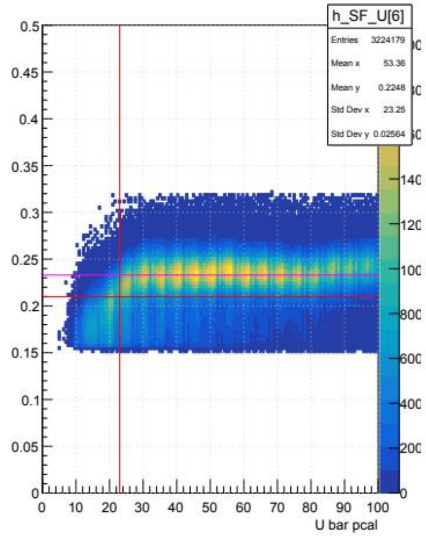
Event selection — DIS Electron at 10.4 GeV for D_2 target

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:

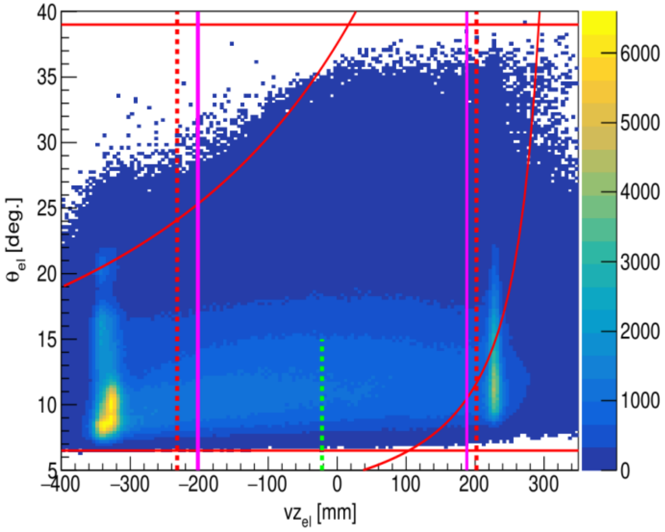


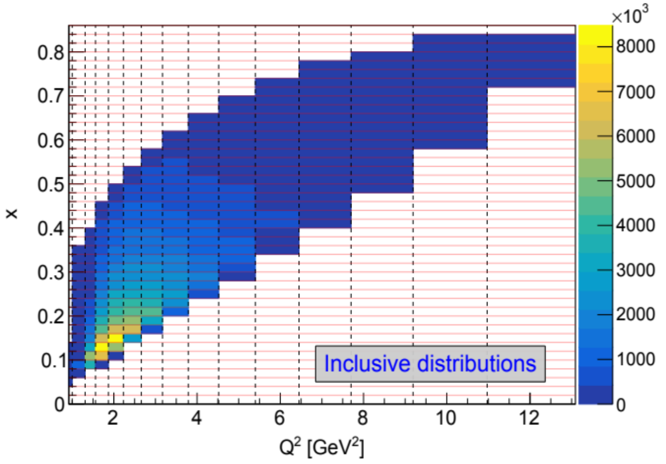




Additional DIS cuts

- 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])
- Fiducial cut of $\cos\theta_p$ vs. vz

PID Cuts:

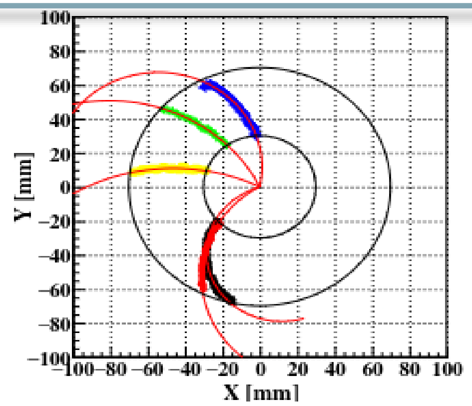
- Run-dependent Cuts on dEdx vs. p/q band for proton selection

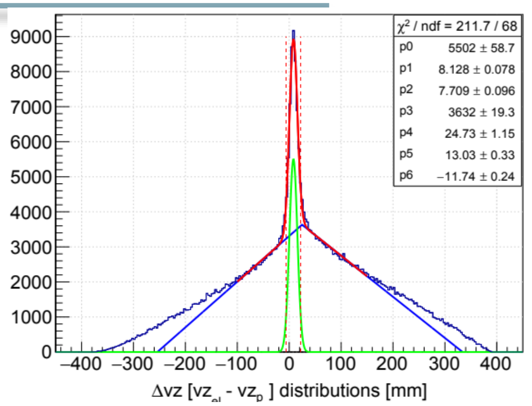
ep Coincidence cuts

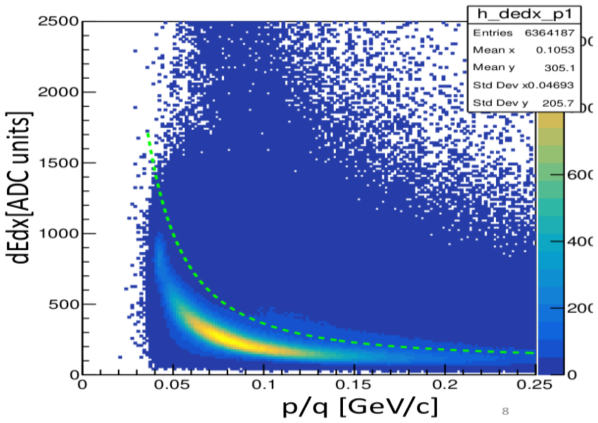
- Vertex coincidence cuts
- Timing coincidence

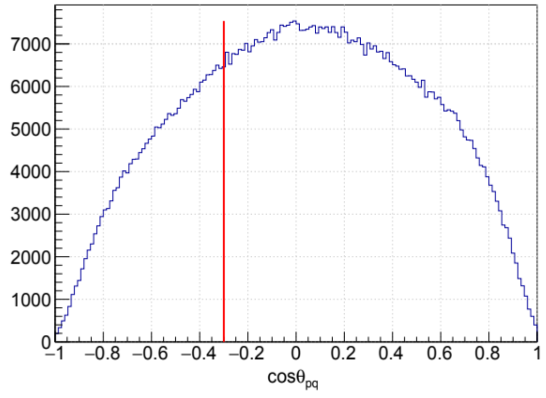
DIS & VIP cuts — To minimize the nuclear uncertainties (e.g. FSIs, Target Fragmentation, etc.)

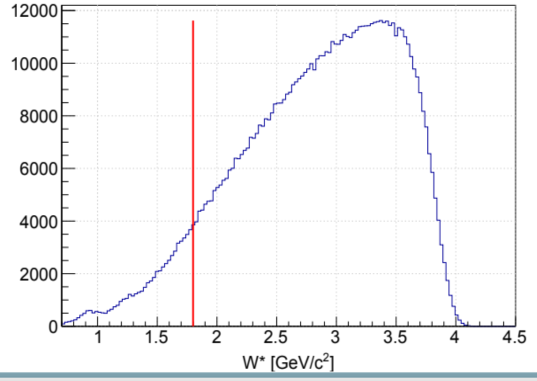
- W* > 1.8 [GeV]
- 0.075 < p_ps < 0.1 [GeV/c]
- $35^o < \theta_{ps} < 145^o$
- $\cos(\theta_{pq}) < -0.3$ (?)

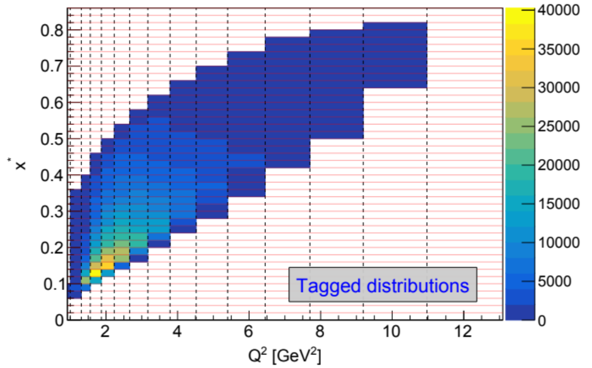












Event selection — Fiducial cut of $\cos\theta_p$ vs. vz

- Remove the distorted part of the stripes around 90 degrees → Both the end points and starting points of the tracks are within the drift volume.

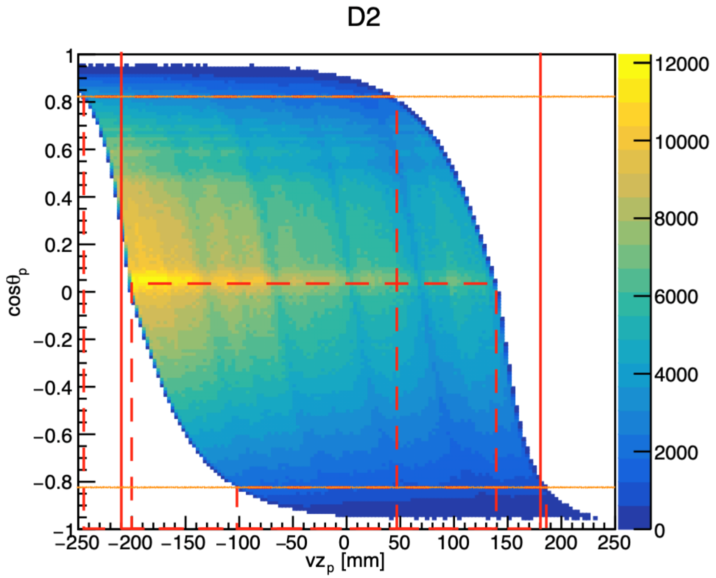
- Fiducial cut of $\cos\theta_p$ vs. $vz_{p,corr}$:

$-200 < vz_{p,corr1}$ & $vz_{p,corr2} < 140$, if $\cos\theta_p > 0$

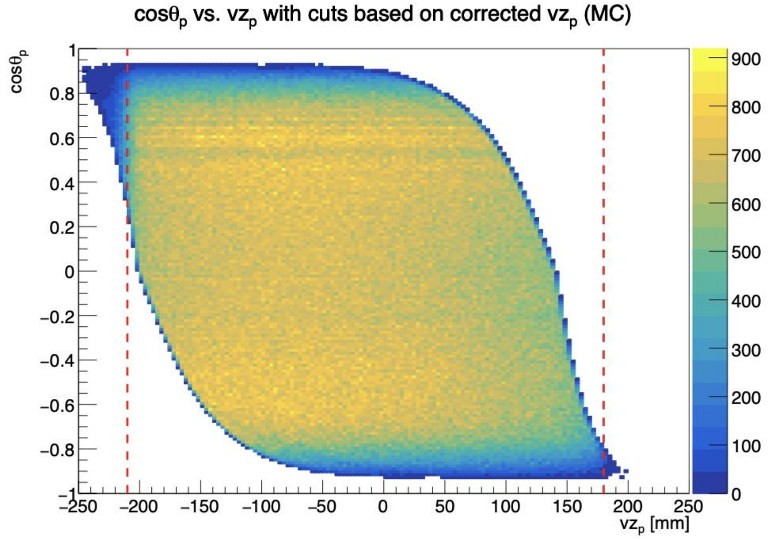
$vz_{p,corr1} < 140$ & $vz_{p,corr2} > -200$, others

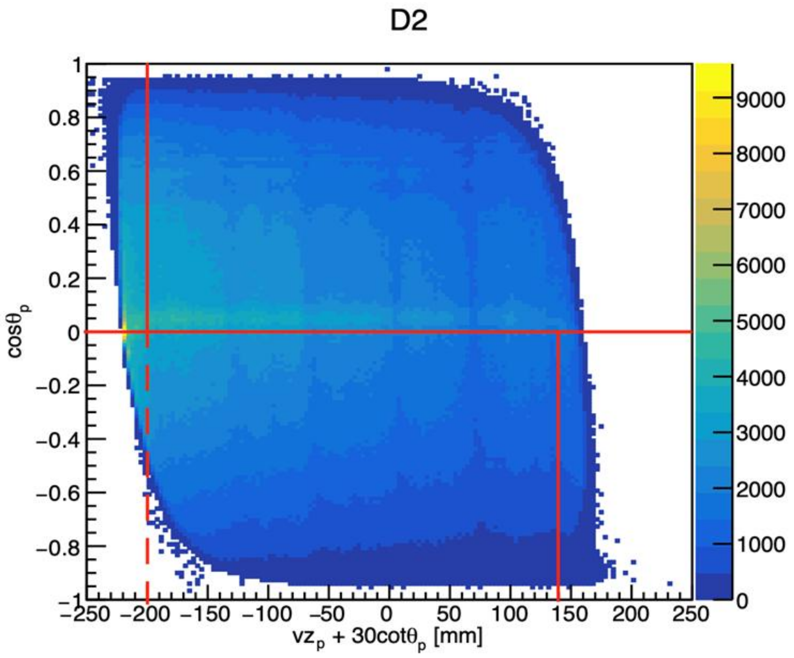
$vz_{p,corr1} = vz_p + 30\cot\theta_p$, $vz_{p,corr2} = vz_p + 70\cot\theta_p$ [mm]

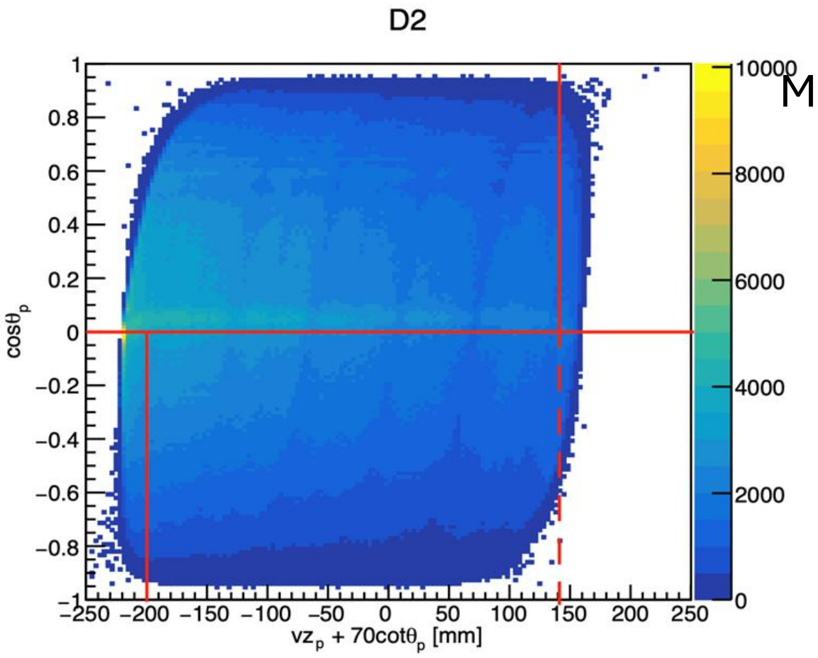
DATA



MC





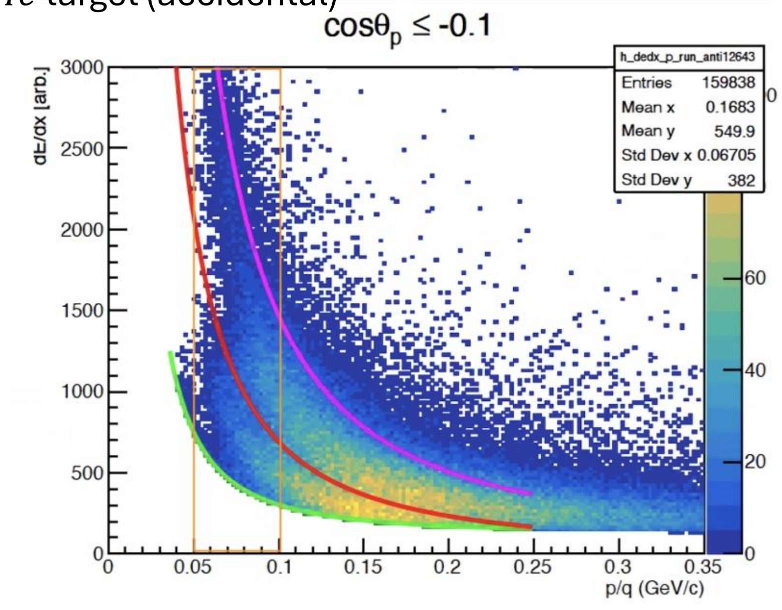


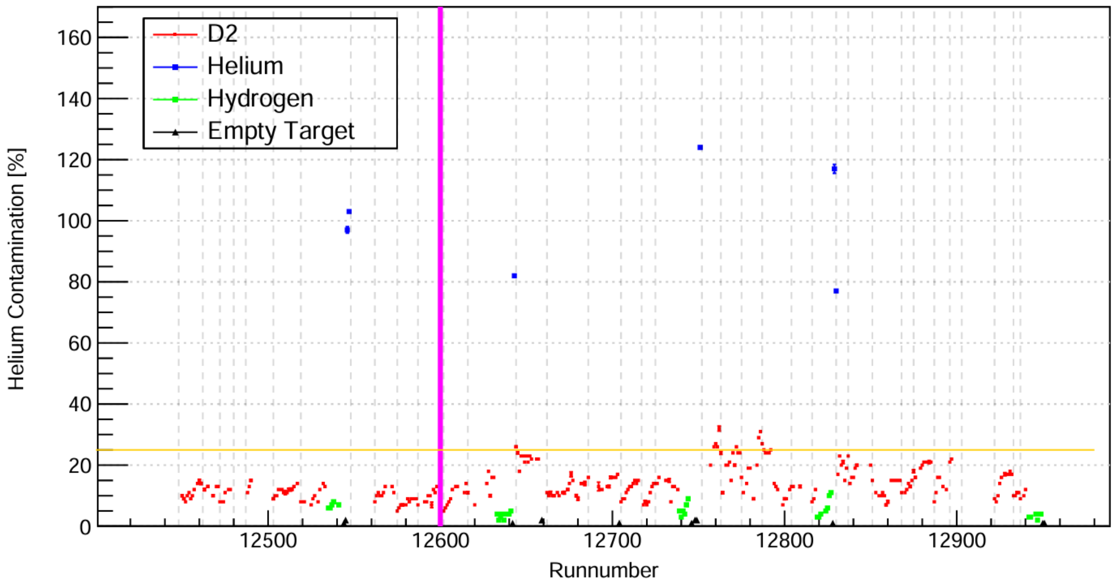
Background evaluation for experimental data — ^{4}He Contamination

Proton

- Deuterium Target Contamination
  - ^{4}He could diffuse into the target straw from the surrounding buffer gas region
  - Improve triton/ ^{3}He selection and using the accidental events
  - Discarded runs with contamination > 25%
  - Direct subtract the ^{4}He background

Run 12643: ^{4}He target (accidental)



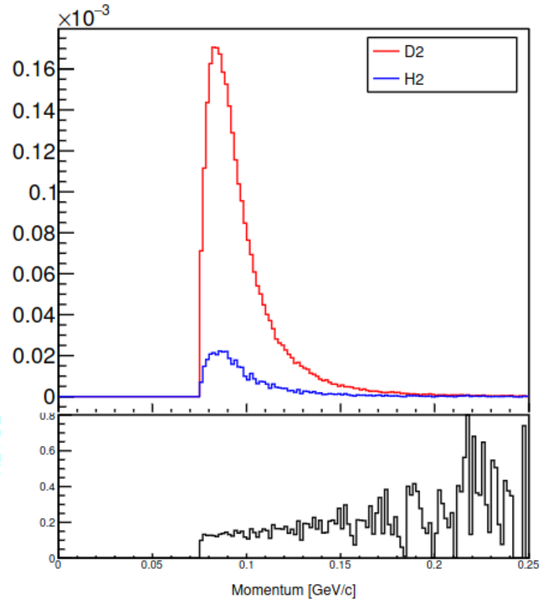


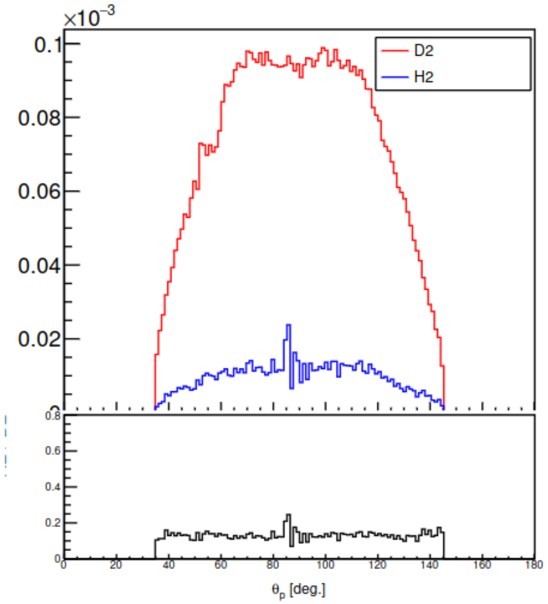
courtesy of Madhusudhan Pokhrel

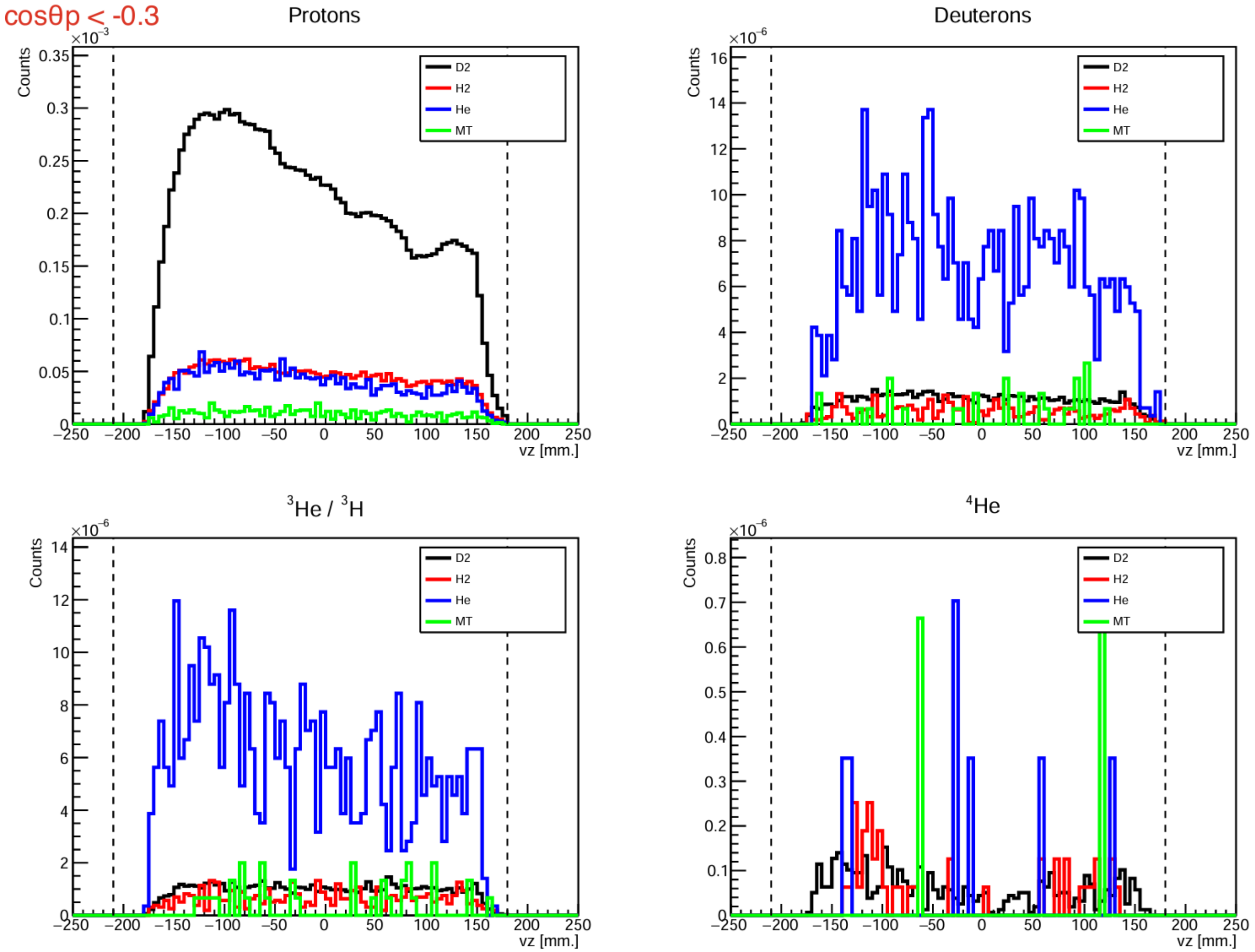
Background evaluation for experimental data — other Contamination

After subtracting the ^4He backgrounds, analyzed the H_2 data using same cuts and criteria as the D_2 data

→15% of the H_2 has a backward recoiling proton.
→No momentum or v_z structure.







courtesy of Madhusudhan Pokhrel

Background evaluation for experimental data — other Contamination?

Table of numerically evaluating the accidental particles in different type of targets

- All species heavier than p in all targets after subtracting the contribution from ^4He are small.
- Explanation: Backward-going p background in H_2→ due to D_2 contamination from the gas panel.

subtract ^4He Contamination

with cut cos(θ_p)<-0.3)

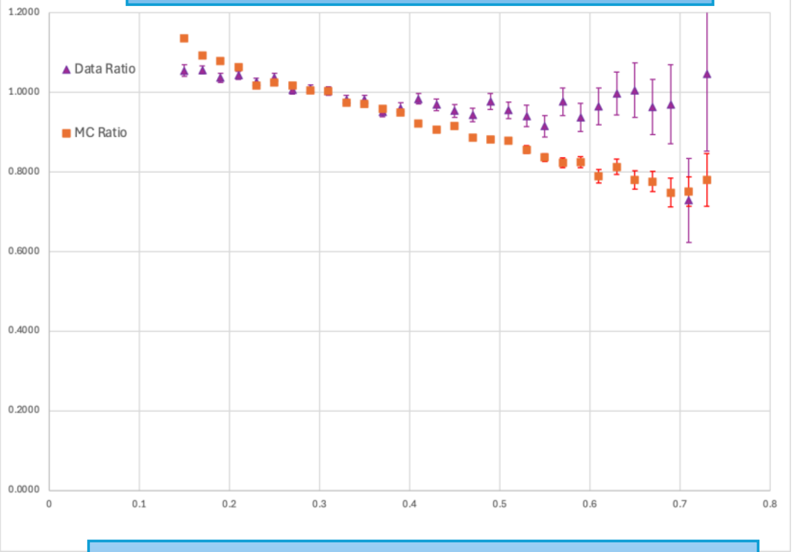
accidental coincidences particles

	Target	Counts	cts/1M e-	Normalisation	4He gas frac	minus 4He	unc	frac from 4He	inferred D2
Protons	D2	2.31E+06	14665	1.57E+08	16.2%	14236	11	3%	100%
	H2	49659	3130	1.59E+07	10.2%	2859	14	9%	20%
	He	7539	2650	2.84E+06	100.0%	0		100%	0%
	MT_D2	411	2031	2.02E+05	1.2%	2000	100	2%	14%
	MT_H2	593	455	1.30E+06	6.5%	283	19	38%	2%
Deuterons	D2	12448	79	1.57E+08	16.2%	5	2	94%	
	H2	641	40	1.59E+07	10.2%	-6	2	116%	
	He	1302	458	2.84E+06	100.0%	0		100%	
	MT_D2	4	20	2.02E+05	1.2%	14	10	27%	
	MT_H2	26	20	1.30E+06	6.5%	-10	4	149%	
Tritions	D2	10840	69	1.57E+08	16.2%	0		100%	
	H2	690	43	1.59E+07	10.2%	0		100%	
	He	1211	426	2.84E+06	100.0%	0		100%	
	MT_D2	1	5	2.02E+05	1.2%	0		100%	
	MT_H2	36	28	1.30E+06	6.5%	0		100%	
Alphas	D2	646	4	1.57E+08	16.2%	4	0	10%	
	H2	47	3	1.59E+07	10.2%	3	0	8%	
	He	7	2	2.84E+06	100.0%	0		100%	
	MT_D2	1	5	2.02E+05	1.2%	5	5	1%	
	MT_H2	1	1	1.30E+06	6.5%	1	1	21%	

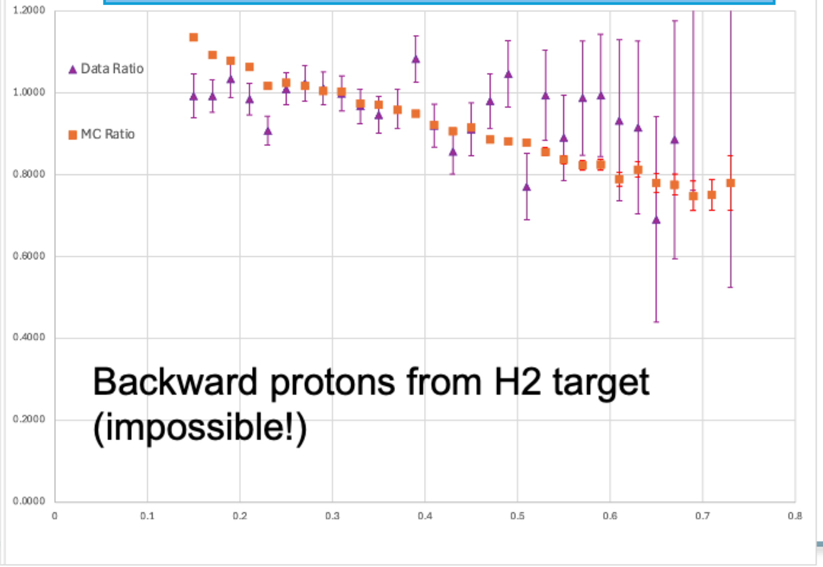
MT_D2/MT_H2:
empty target runs right after D2/H2 runs

Potential misidentified tritons/helions

tag/inclusive ratio in D_2 target

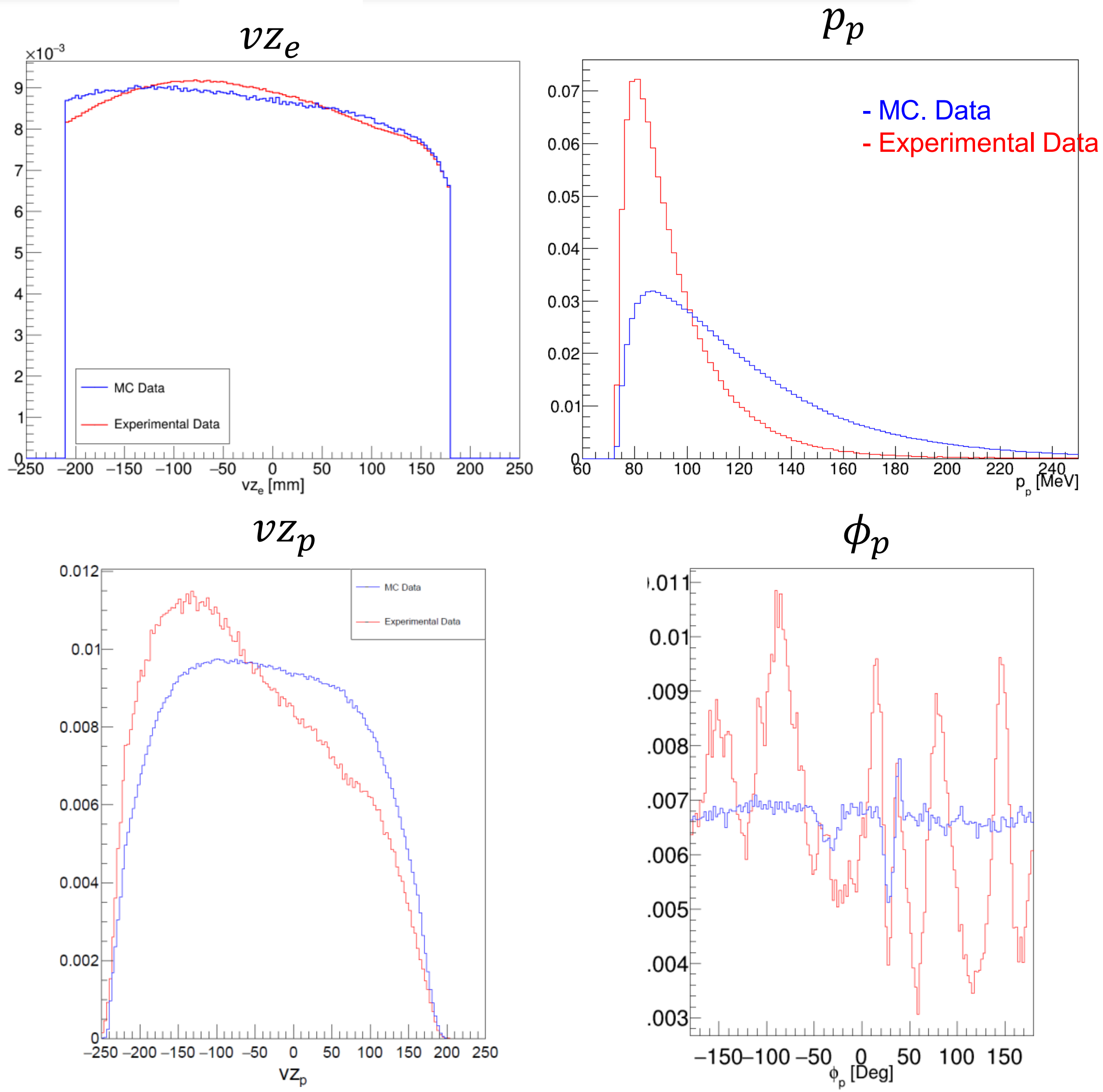


tag(from H_2 target)/inclusive ratio



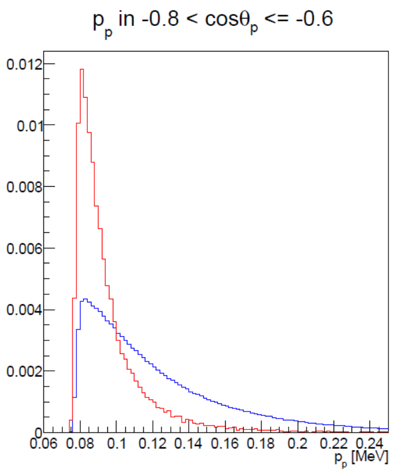
Simulation for BONuS12

- Generator: PWIA spectator model with 2014 Bosted/Christy fit to world data for F_2^n and F_2^d, 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 needed to implement into the simulation.
- Introduce the weighting factors to each selected event so that the final distributions can match the real data.

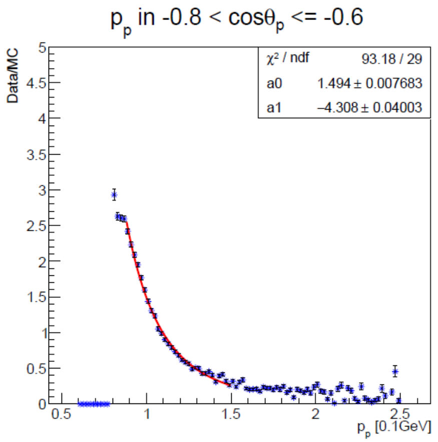


vz_e and p_p weighting on MC

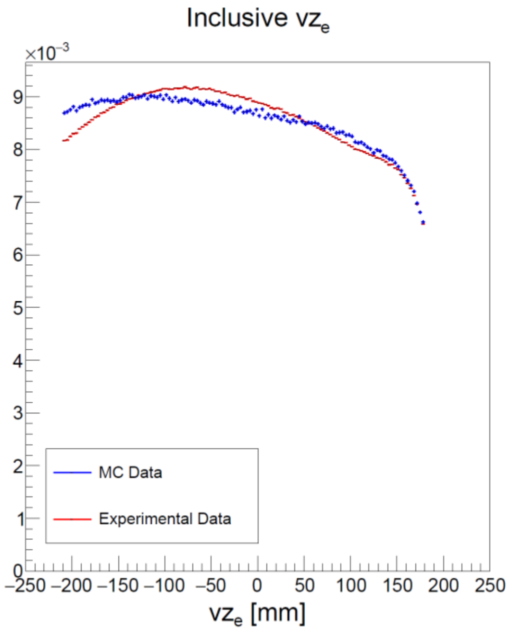
- Evaluating the p_p weighting by fitting the Data/MC ratio in 8 $\cos\theta_p$ regions, from -0.8 ~ 0.8.
- Extract the a_0& a_1 by fitting with a fourth-order polynomial.

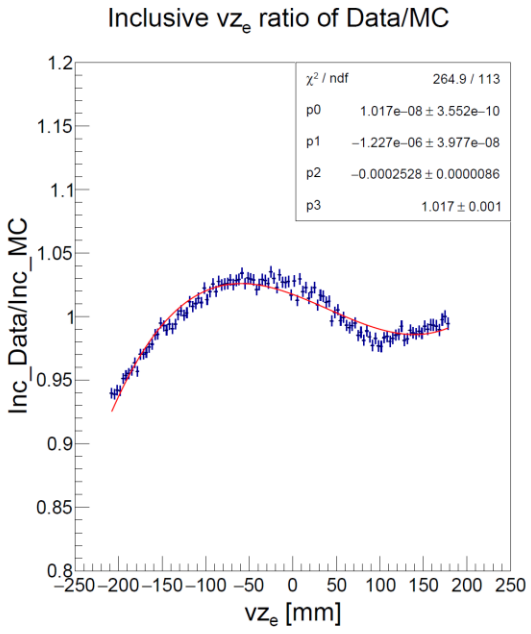


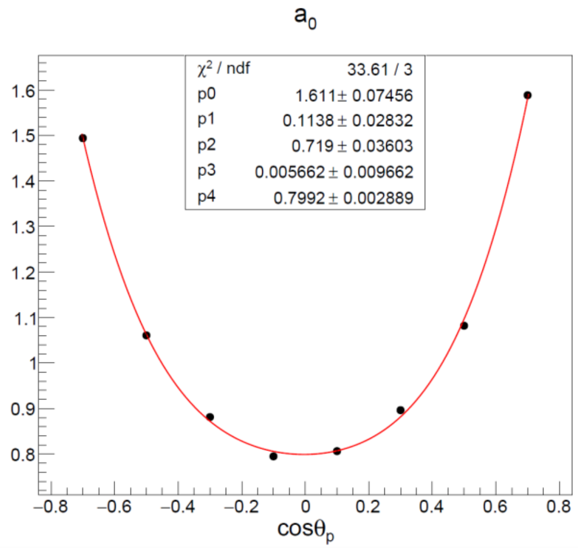
fitting form: $a_0 * {p_p}^{a_1}$

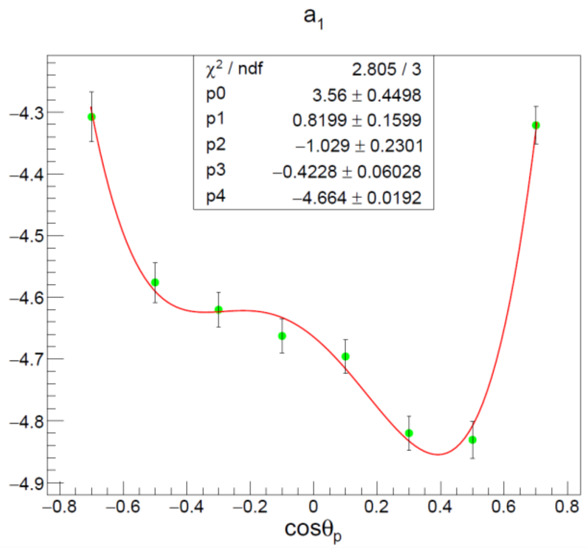


- Evaluating the vz_e weighting from the inclusive case.
- Fit the Data/MC ratio with a third-order polynomial.

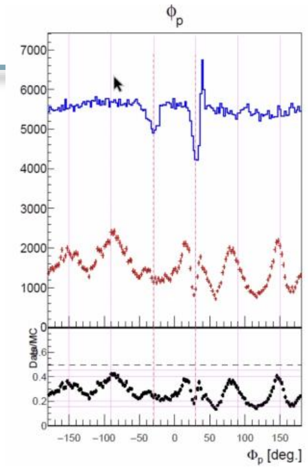


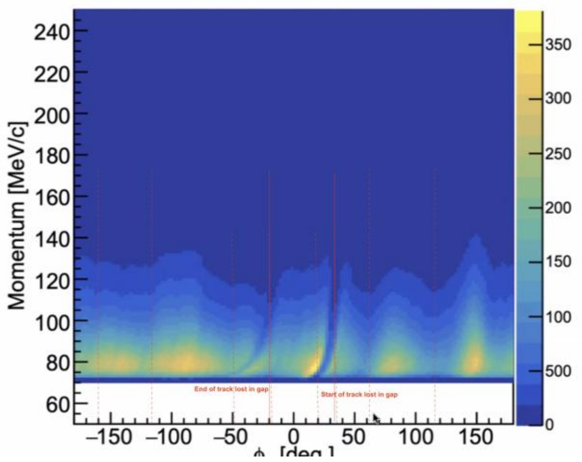




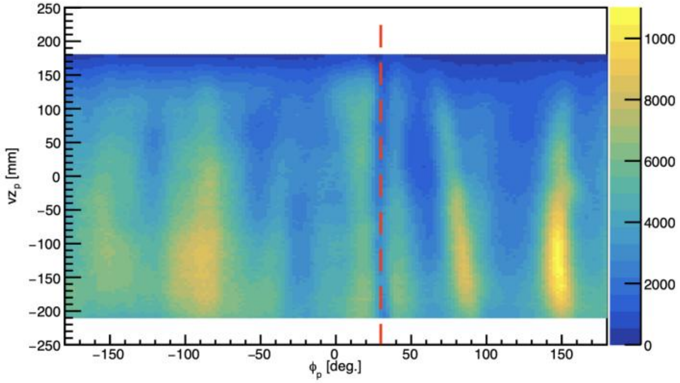


Causes of vz_p, ϕ_p Inefficiency of RTPC

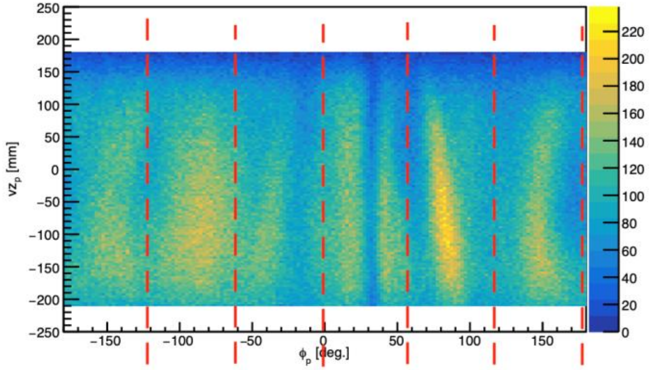




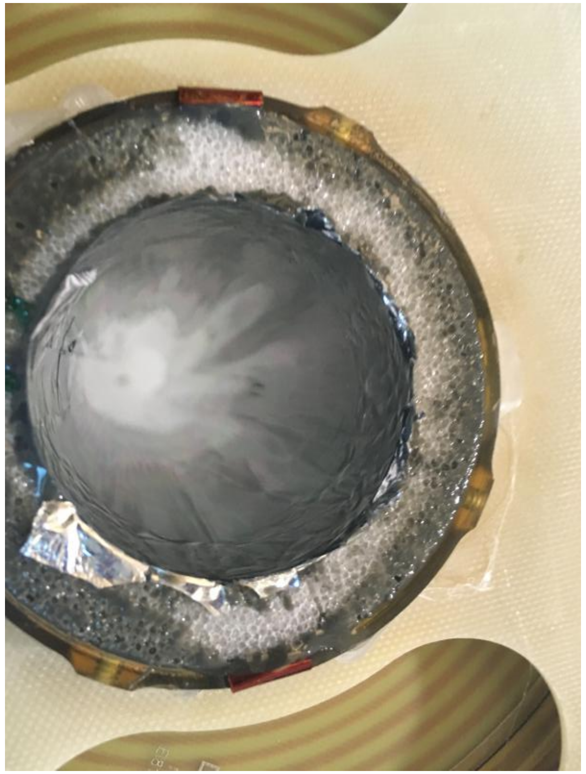
No coincident cuts



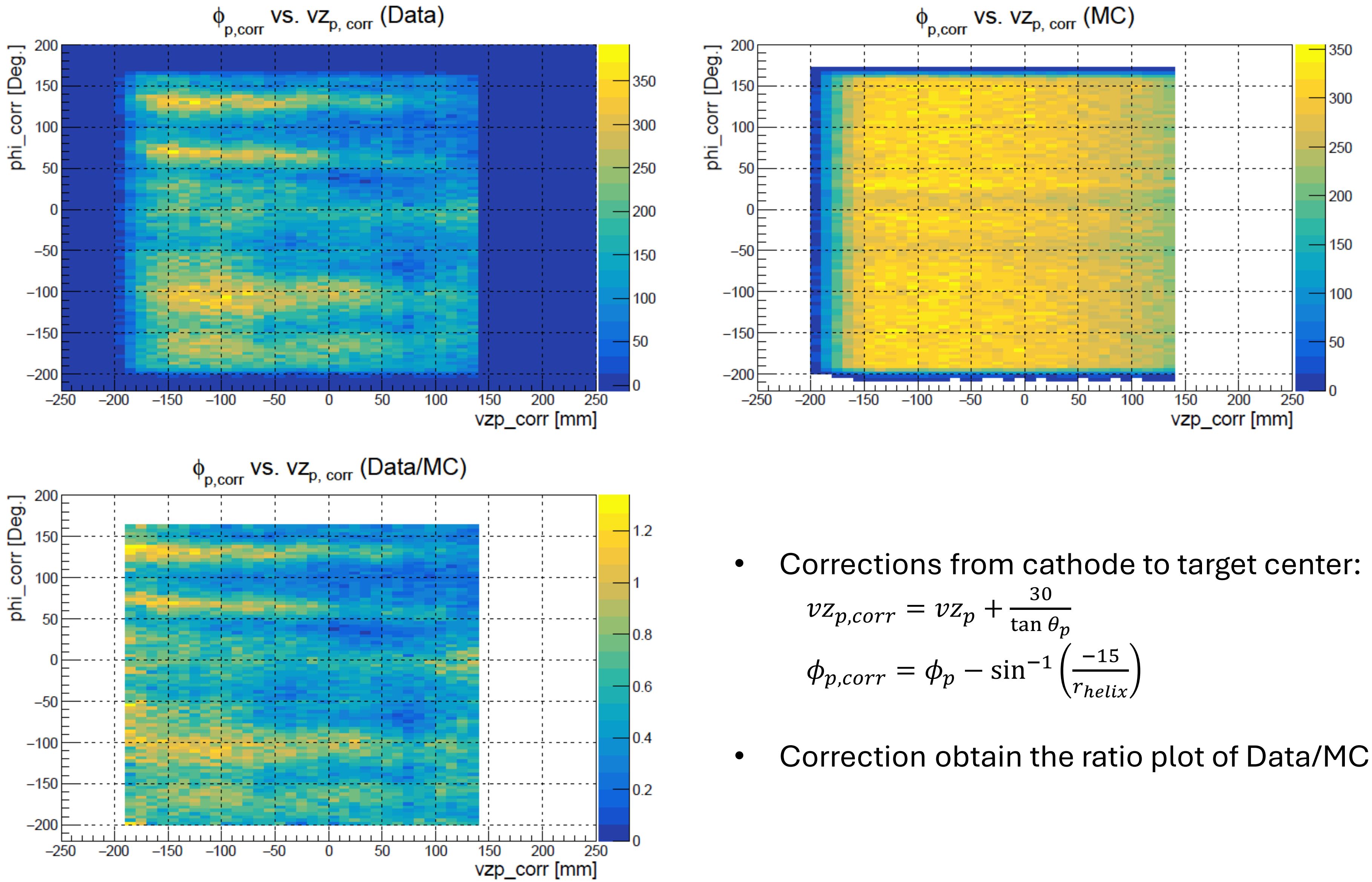
With coincident cuts [tdiff and Δvz cuts]



- Dead regions: tracks start or end in a phi-region that is projected on the seam in GEMs/Padout by e- drift
- Signal size at hairy edge for higher p_p
- Inefficient GEM regions, pads, readout electronics… → Should NOT affect ϕ_{recon}
- INDEPENDENT of scattered e^- → Distortions of field and foil geometry could affect reconstruction reliability and efficiency



2D $vz_p vs. \phi_p$ weighting on MC



- Corrections from cathode to target center:

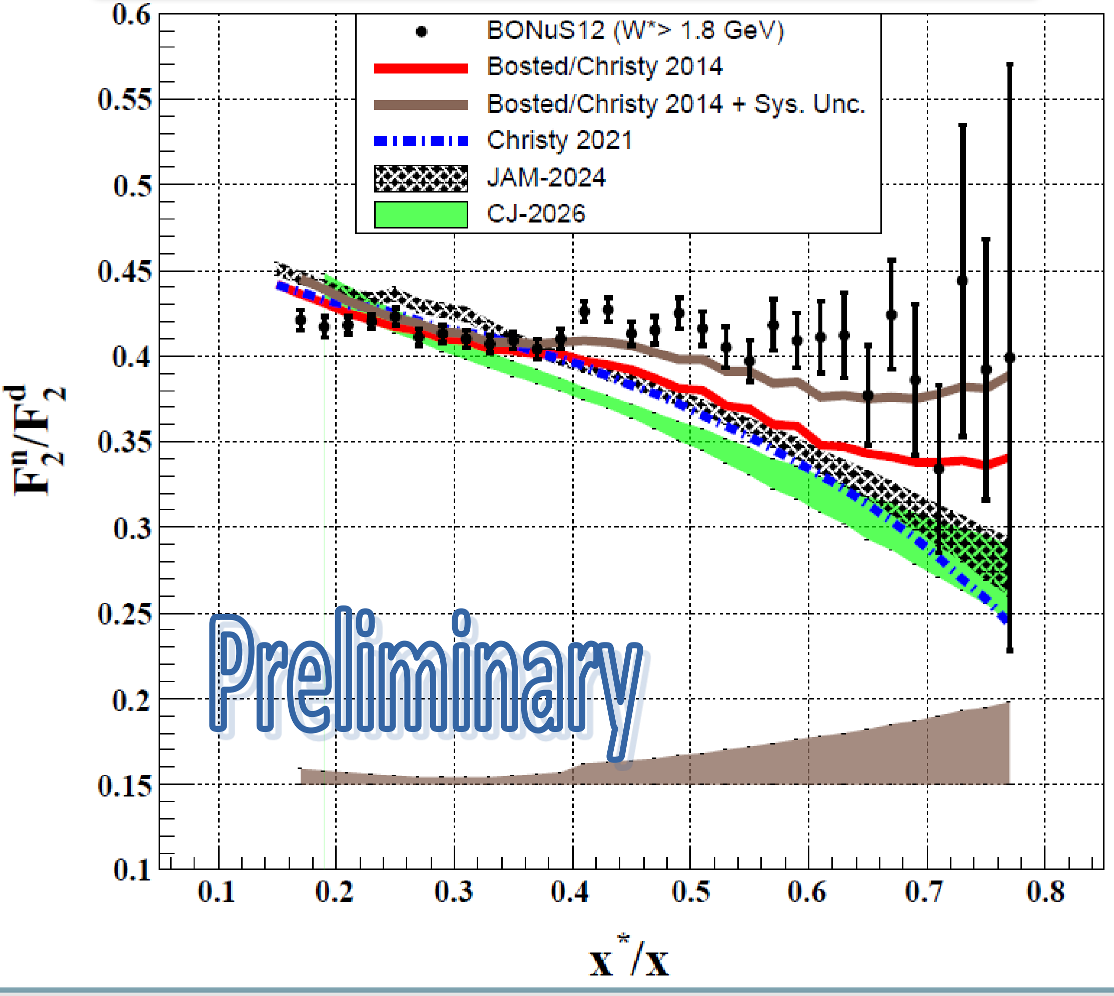
$$vz_{p,corr} = vz_p + \frac{30}{\tan\theta_p}$$

$$\phi_{p,corr} = \phi_p - \sin^{-1}\left(\frac{-15}{r_{helix}}\right)$$

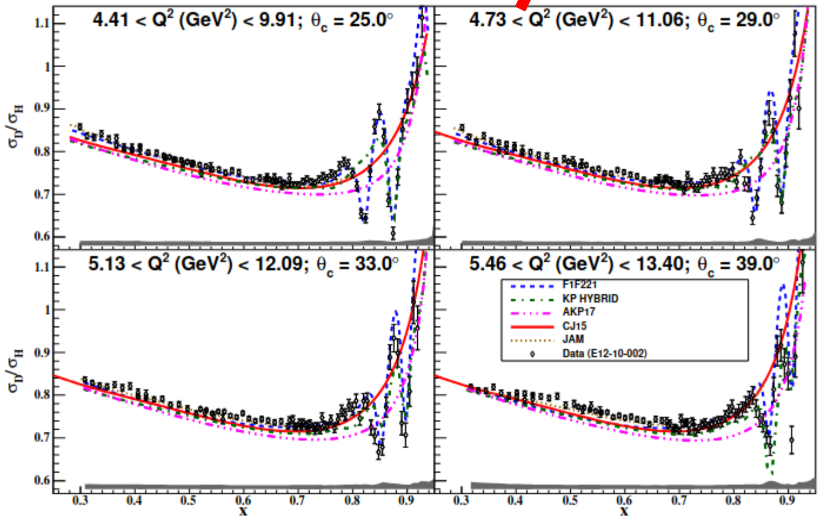
- Correction obtain the ratio plot of Data/MC

BONuS12 Preliminary Results — F_2^n/F_2^d

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



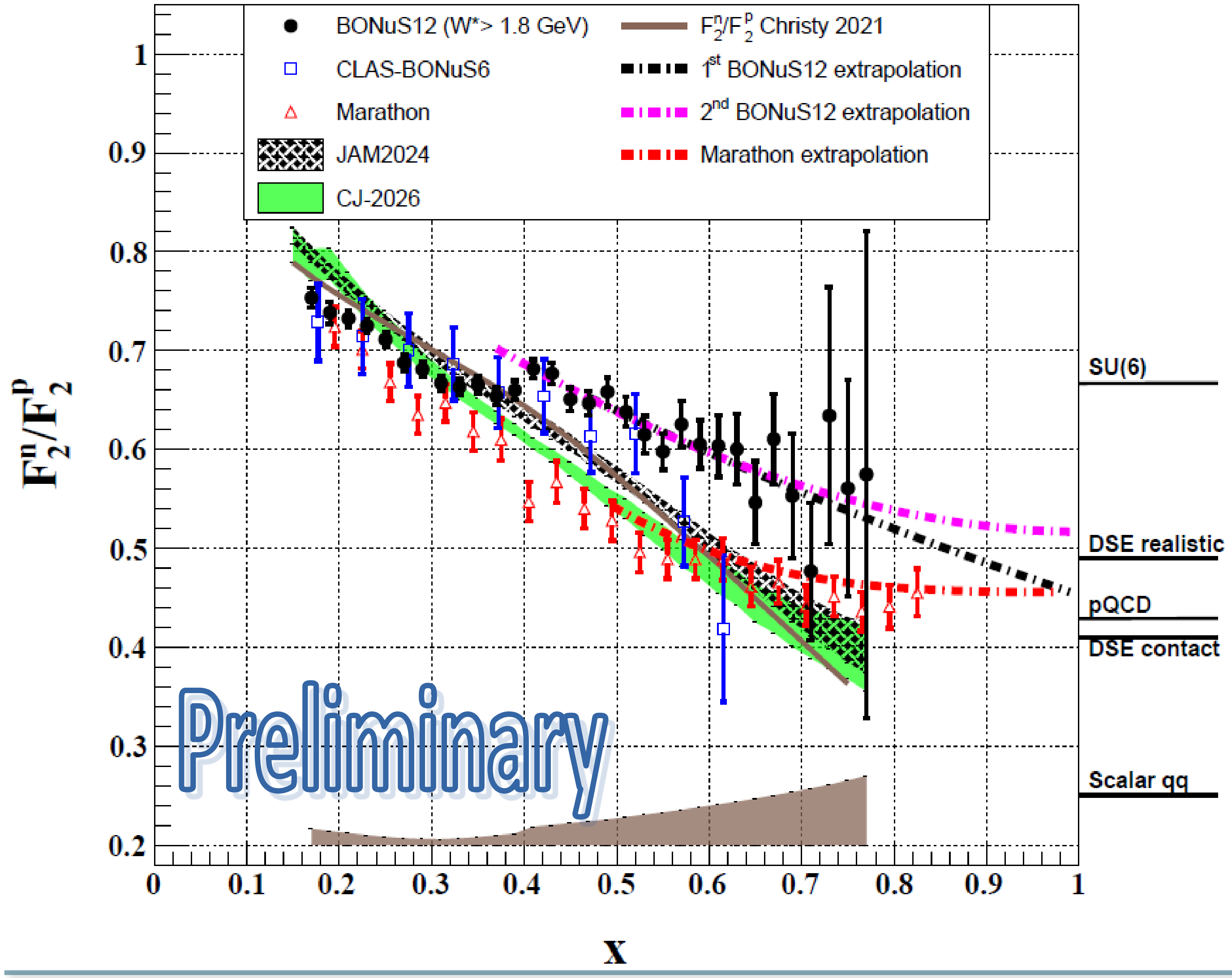
$$\left(\frac{F_2^n}{F_2^p}\right)^{\text{true}} = \left(\frac{F_{2n}}{F_{2d}}\right)^{\text{true}} * \left(\frac{F_{2d}}{F_{2p}}\right)^{\text{fit}}$$

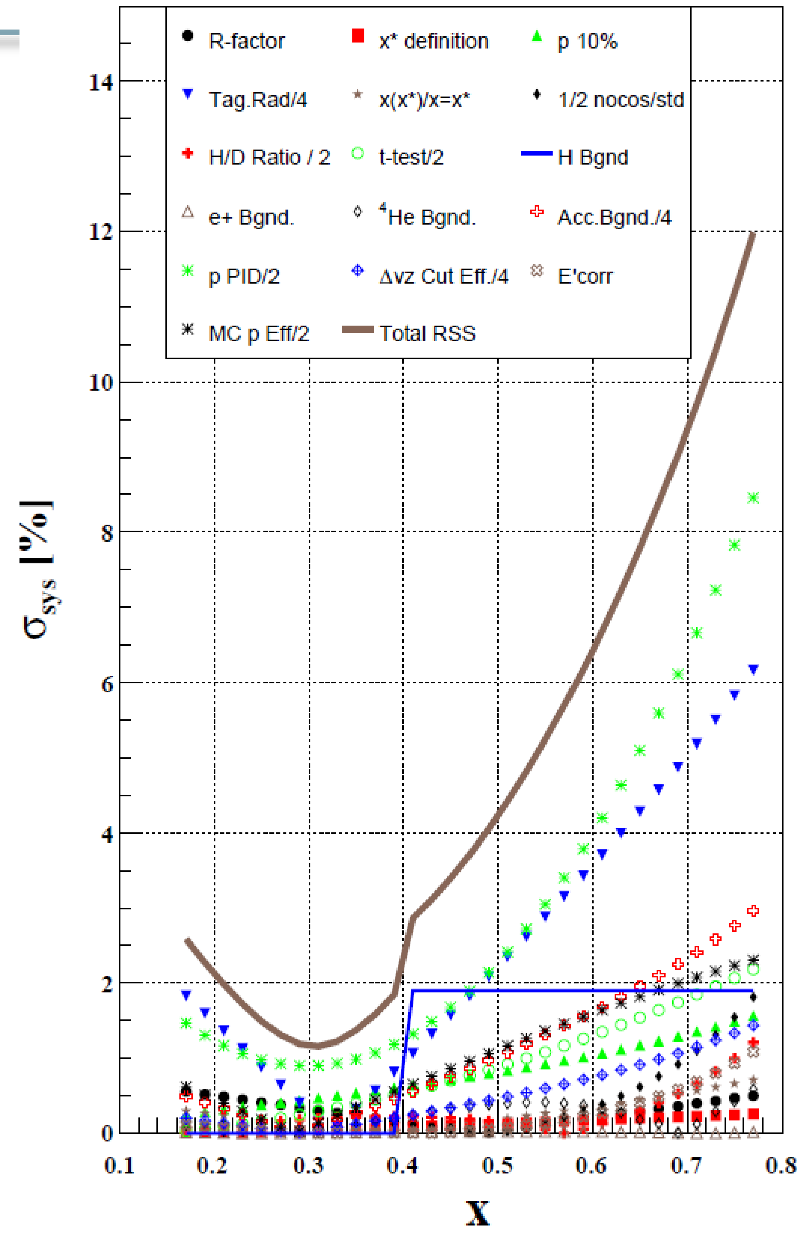


D. Biswas et al., arXive hep-ex 2409.15236

PHYSICAL REVIEW LETTERS 135, 151902 (2025)

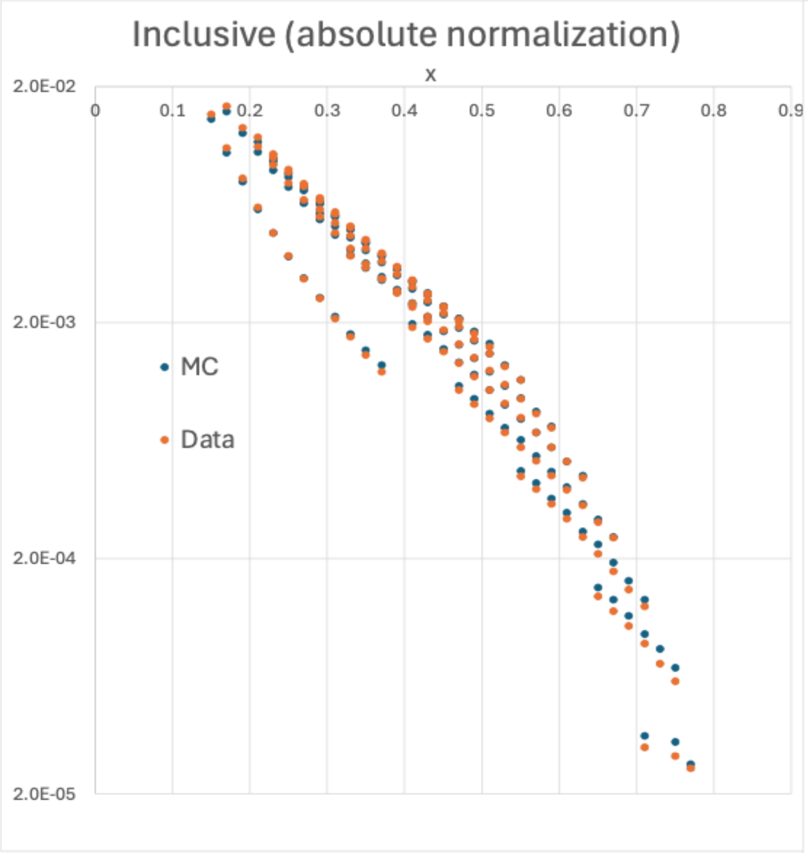
BONuS12 Preliminary Results — F_2^n / F_2^p

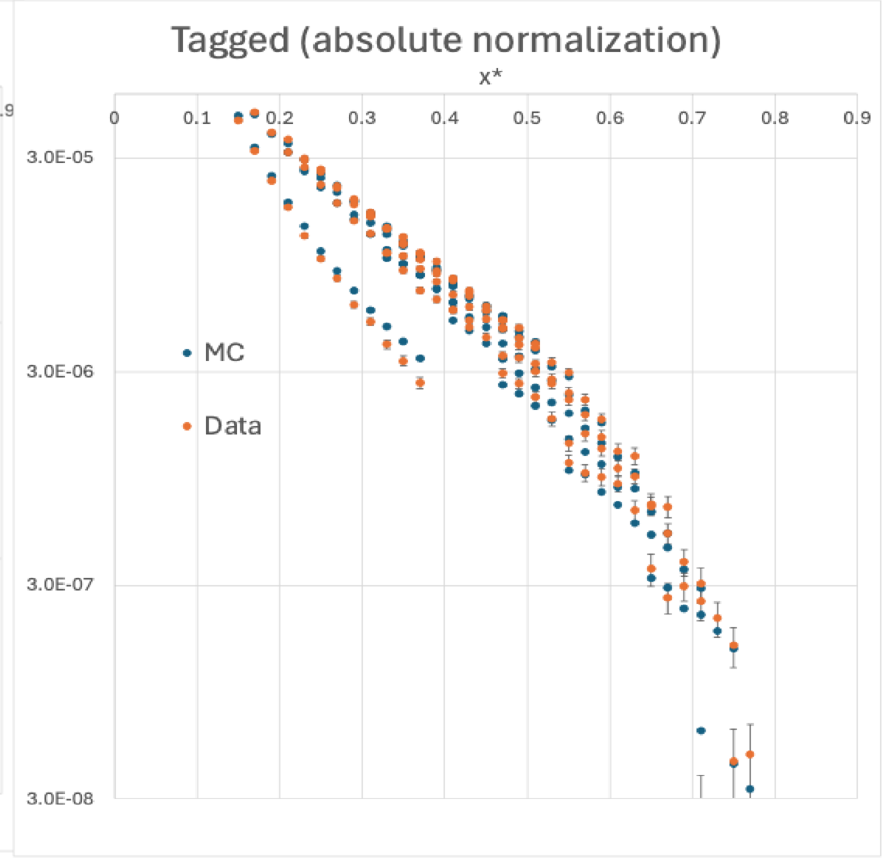




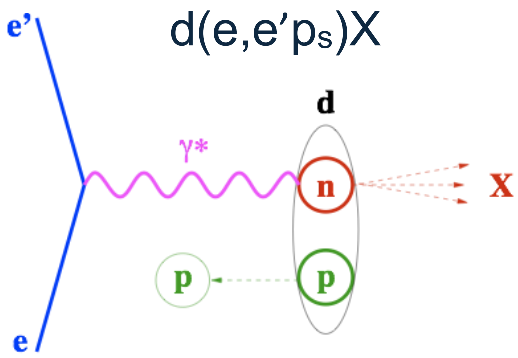
Yield results in absolute normalization

- The tagged/inclusive method does not rely on absolute efficiency
- The entire efficiency correction affects the final result by only up to 2%
- After correction, simulated and measured data agree well in absolute magnitude





Modifications to Simple Spectator Picture

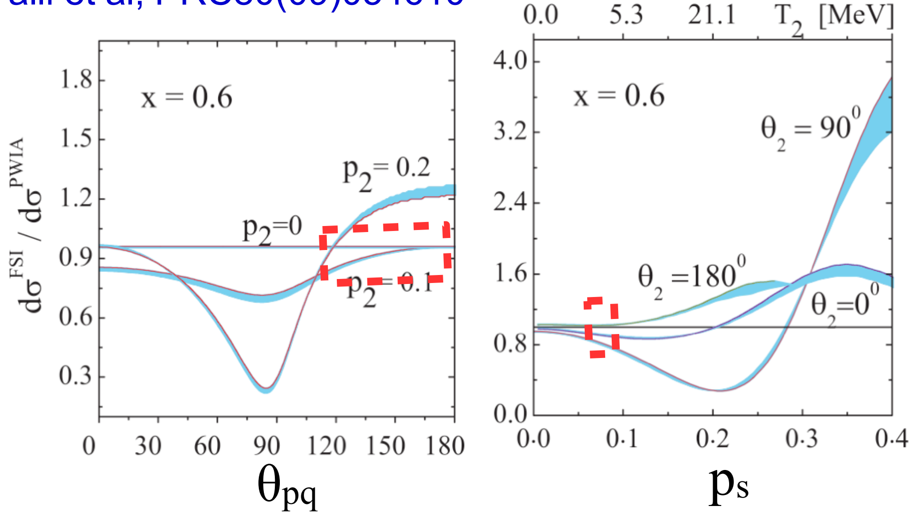


- Final State Interaction
  - Struck neutron interacts with the spectator p
  - Proton momentum is enhanced
  - FSIs are small at low p_s and large θ_{pq}

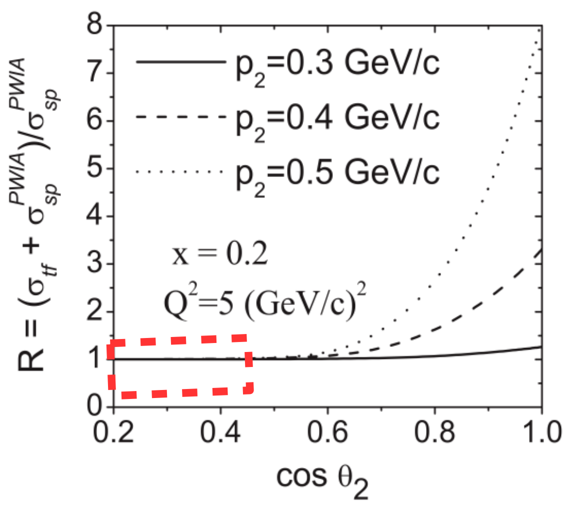
- Target Fragmentation
  - e n → e p X (where n → π- p) and
    e p → e p X (where p → π0 p).
  - TF enhances the proton yield only at forward angles ($\cos\theta_{pq}$ >0.6)

- Off-Shell Corrections
  - Due to the neutron is bound in the deuteron
  - Less than 2% in our region

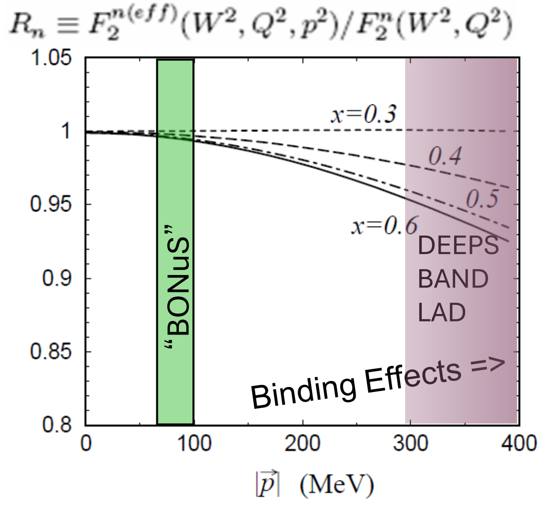
Palli et al, PRC80(09)054610



Palli et al, PRC80(09)054610



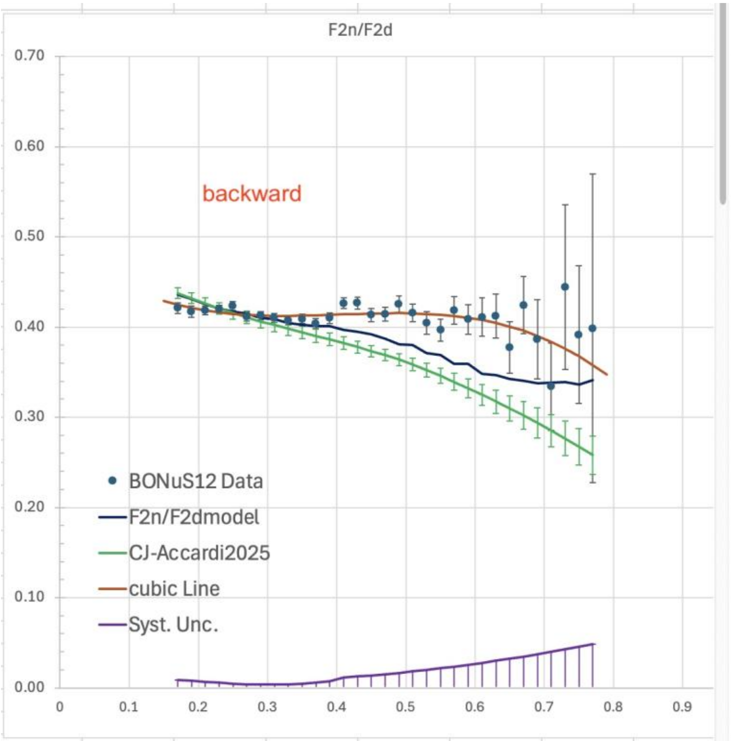
W. Melnitchouk, A.W. Schreiber and A.W. Thomas, Phys. Lett. B335, 11 (1994); Phys. Rev. D 49, 1183 (1994).



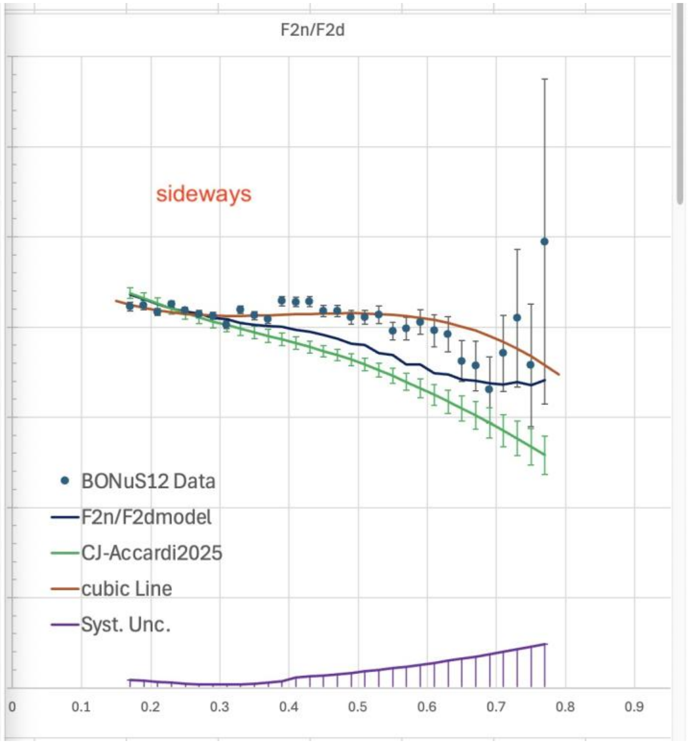
Different angle ranges of the spectator proton

- Nuclear effects dependence on proton angle seemed small in the proton momentum range we selected.
- Calculate the super-ratio in three different $\cos\theta_{pq}$ ranges.

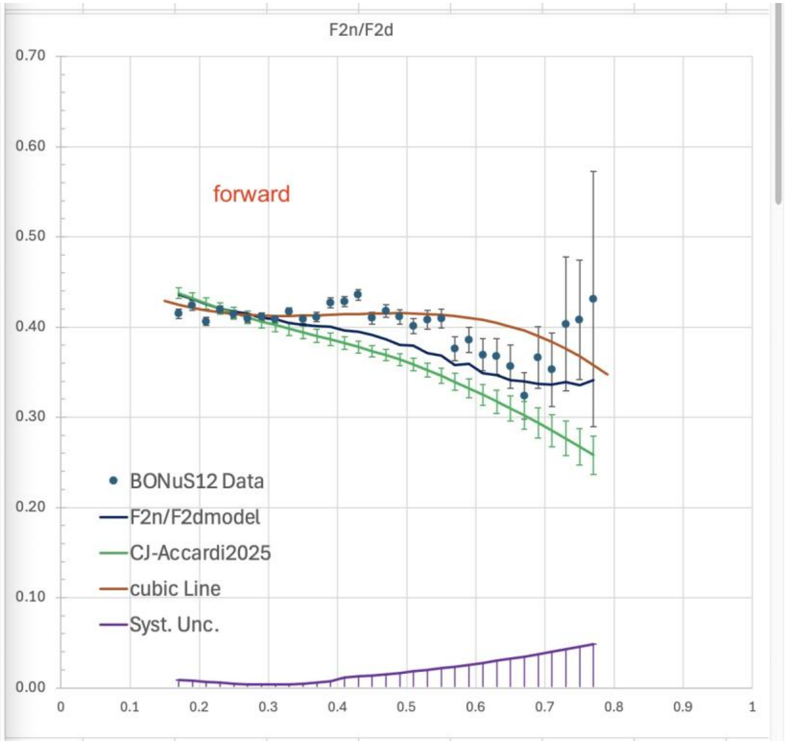
$\cos\theta_{pq}$ < -0.3



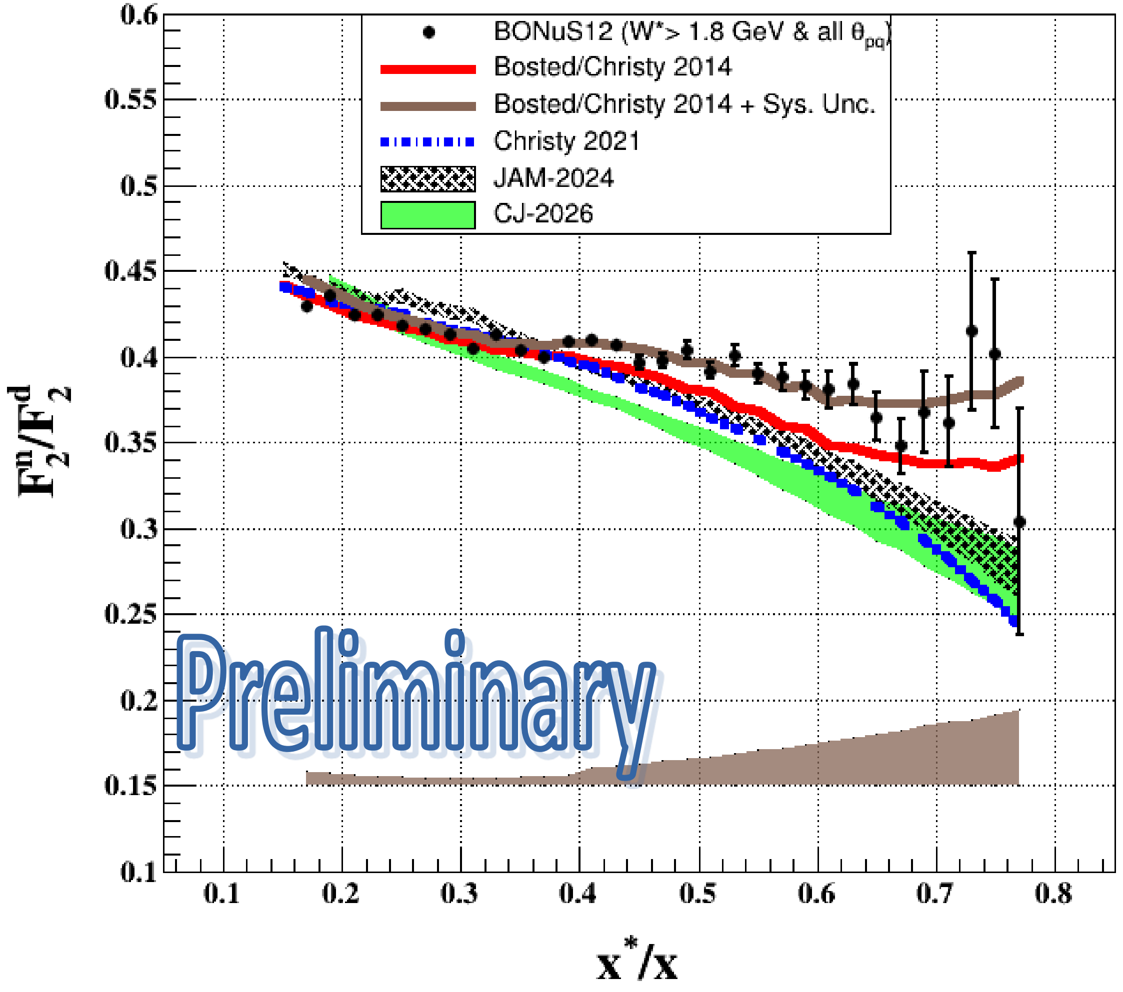
-0.3 < $\cos\theta_{pq}$ < 0.3

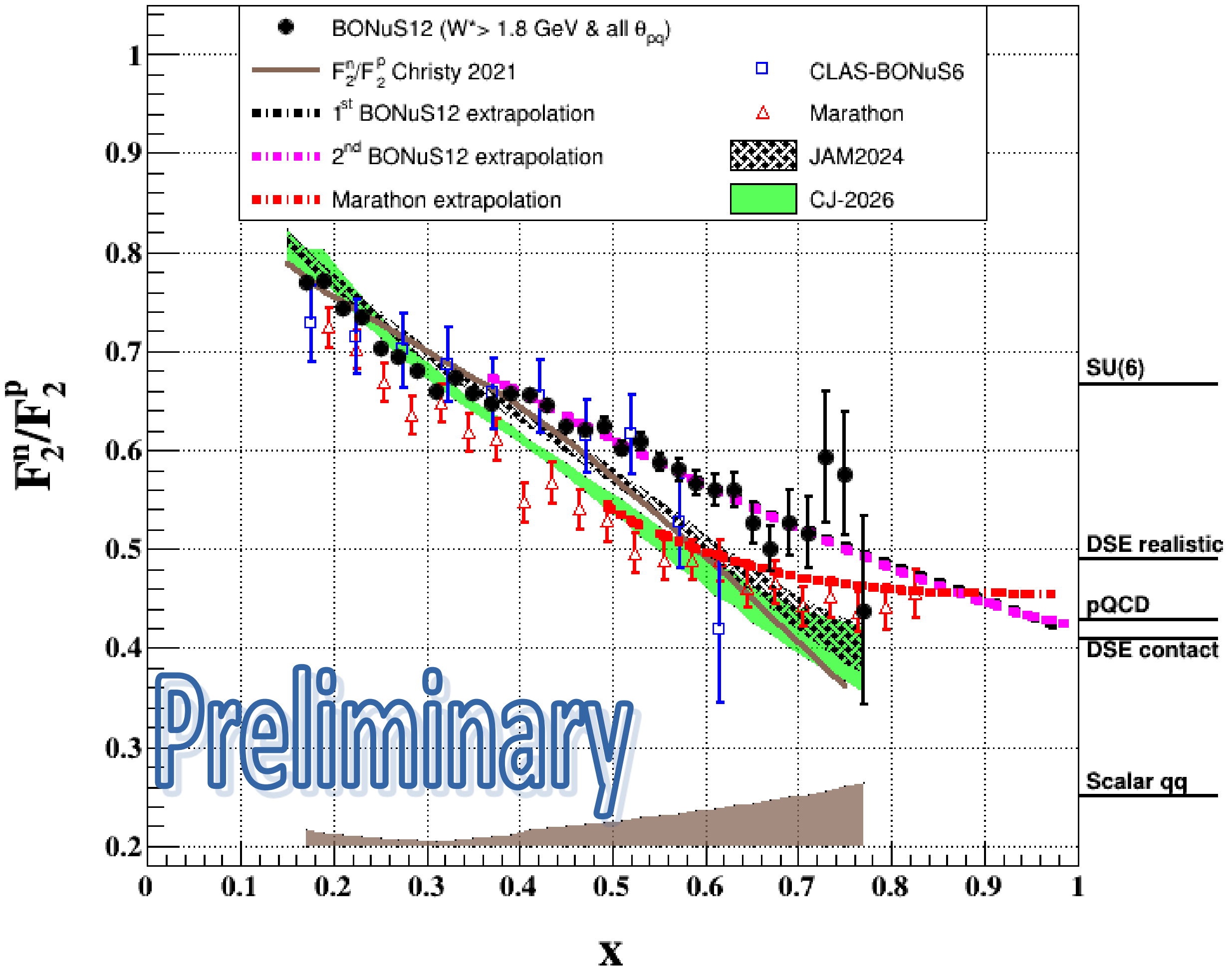


0.3 < $\cos\theta_{pq}$



Results for super-ratio in full angle ranges of the spectator proton





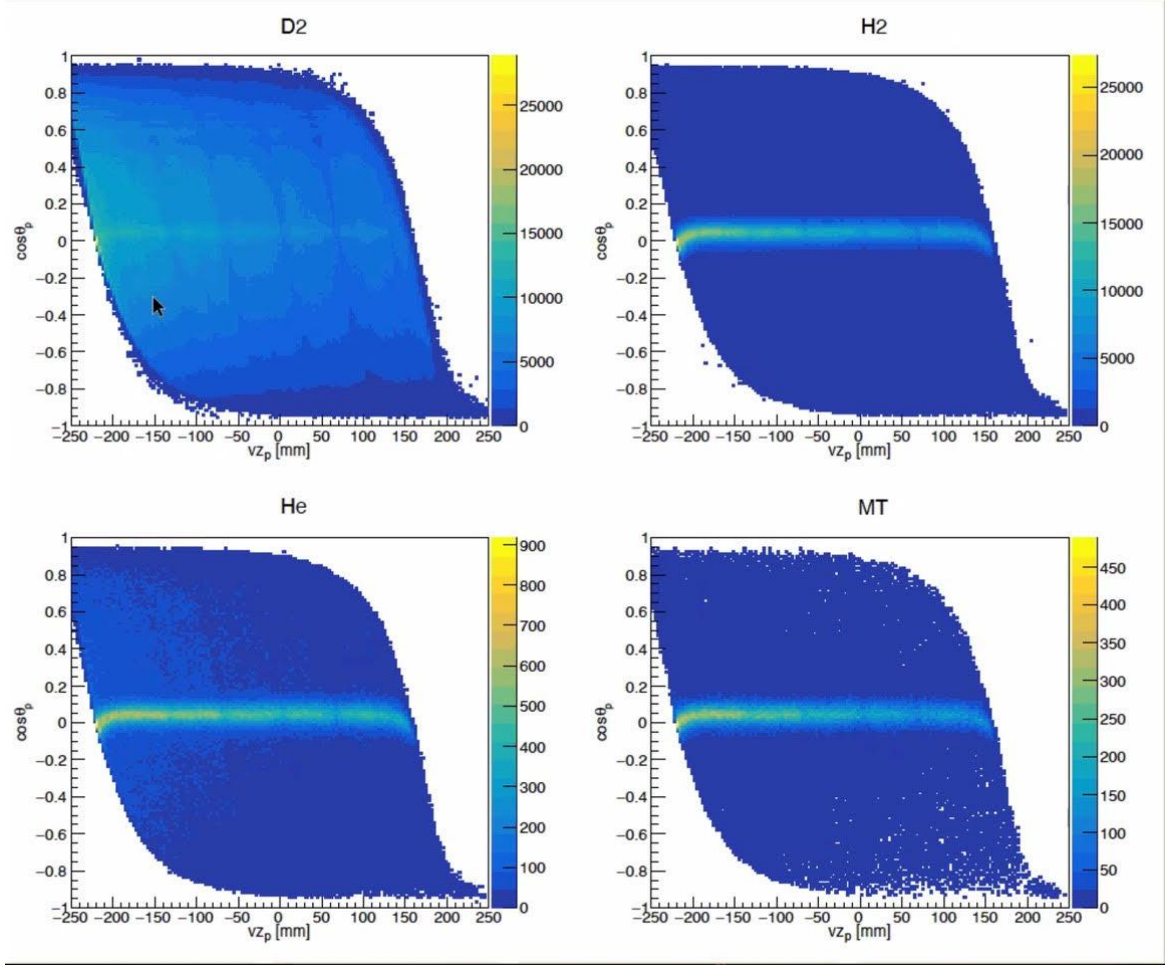
Summary

- BONuS12 extends the measurement of the spectator-tagged neutron structure functions over a larger kinematic range, with much improved statistics.
- Re-evaluated the background for the experimental data, and the efficiency corrections on the simulation.
- All the improvements seemed not change the final F_2^n/F_2^p ratios significantly.
- Results for different angle ranges of the Spectator proton are similar. Consider to get the final result in full $\cos\theta_{pq}$ ranges.

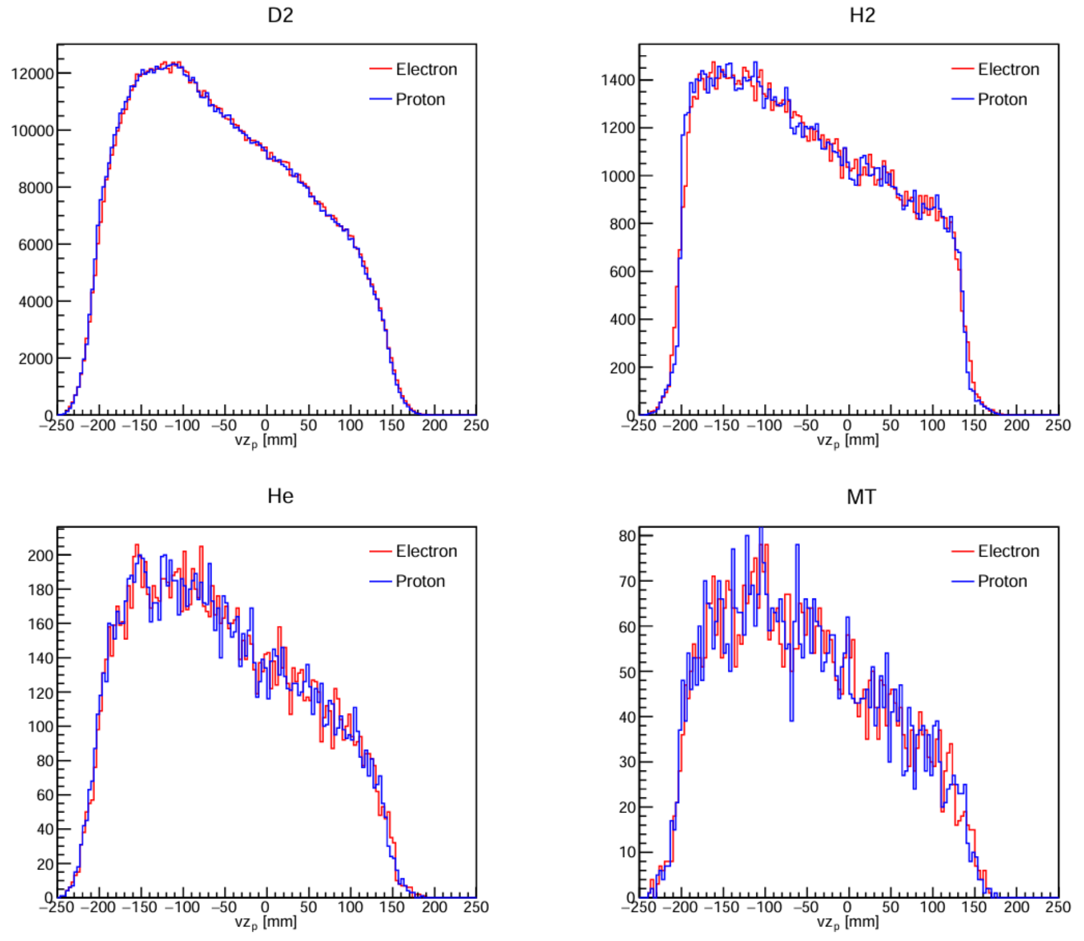
Backup

Backup — Fiducial cut of $\cos\theta_p$ vs. vz

- The distorted part of the stripes around 90 degrees are more significant on the other targets.



- z-vertex distribution for the electron and protons passed all VIP and coincidence cuts with additional fiducial cut.

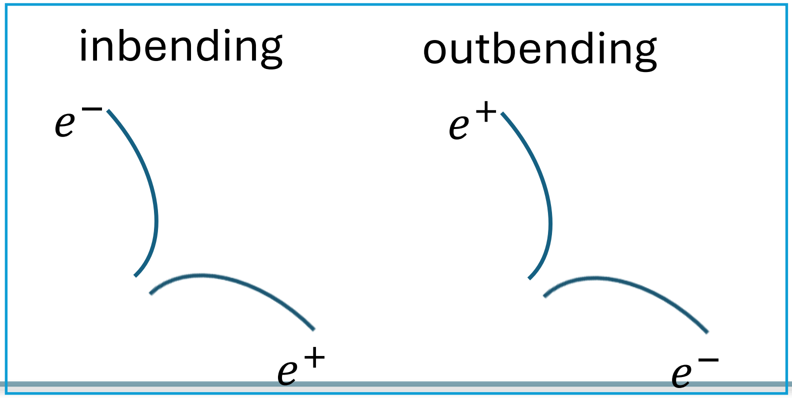


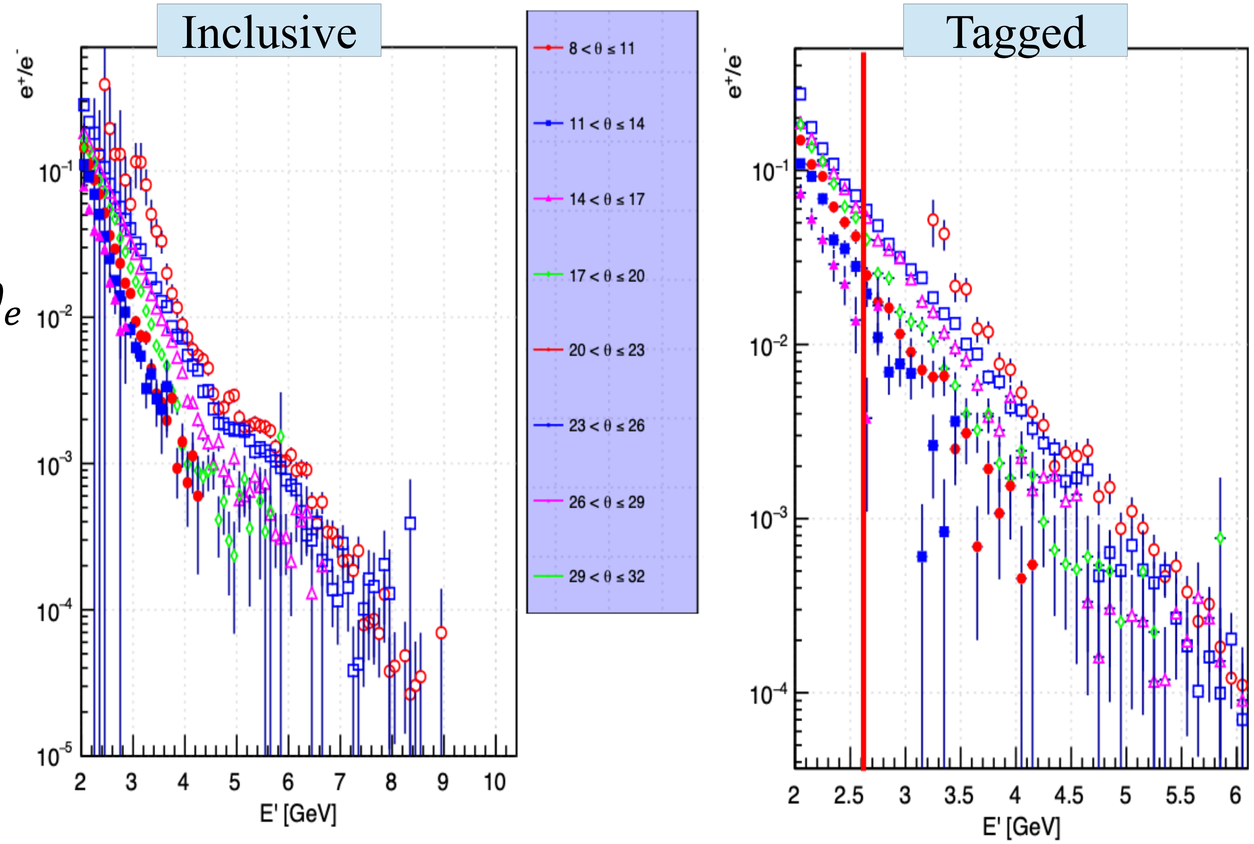
Background evaluation for experimental data — Pair Symmetric Background

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

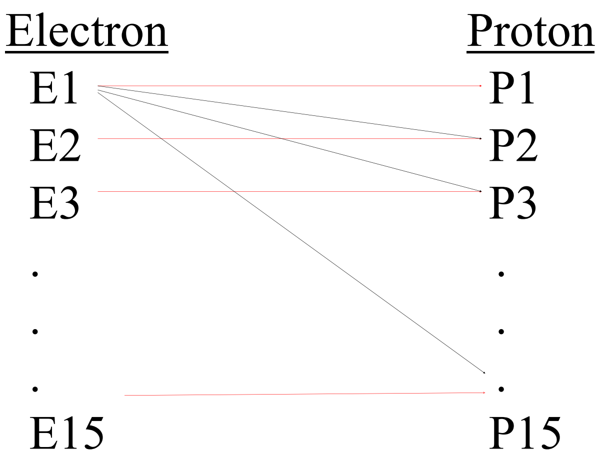


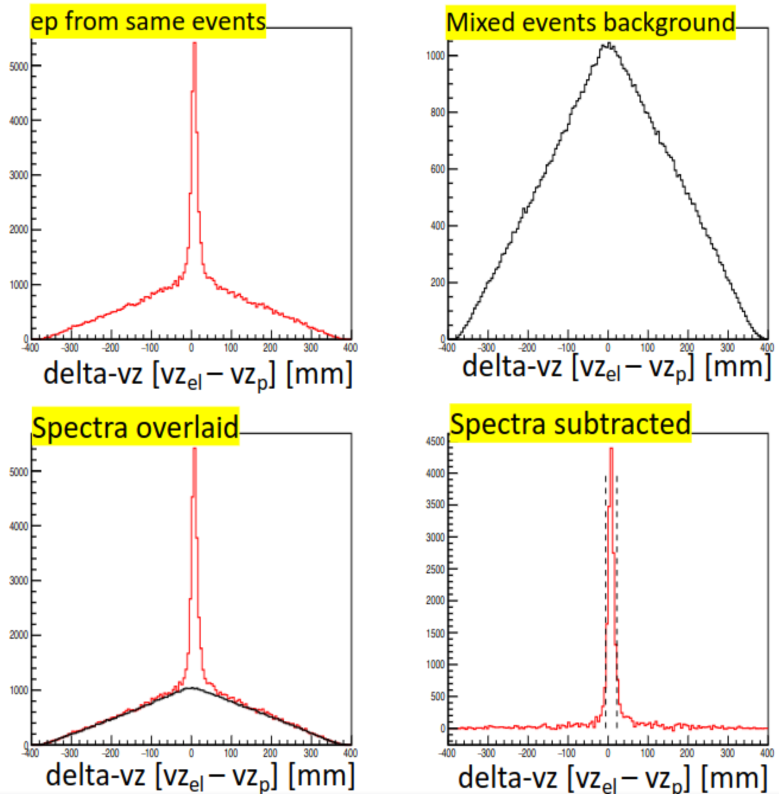


Background evaluation for experimental data — Accidentals

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**.

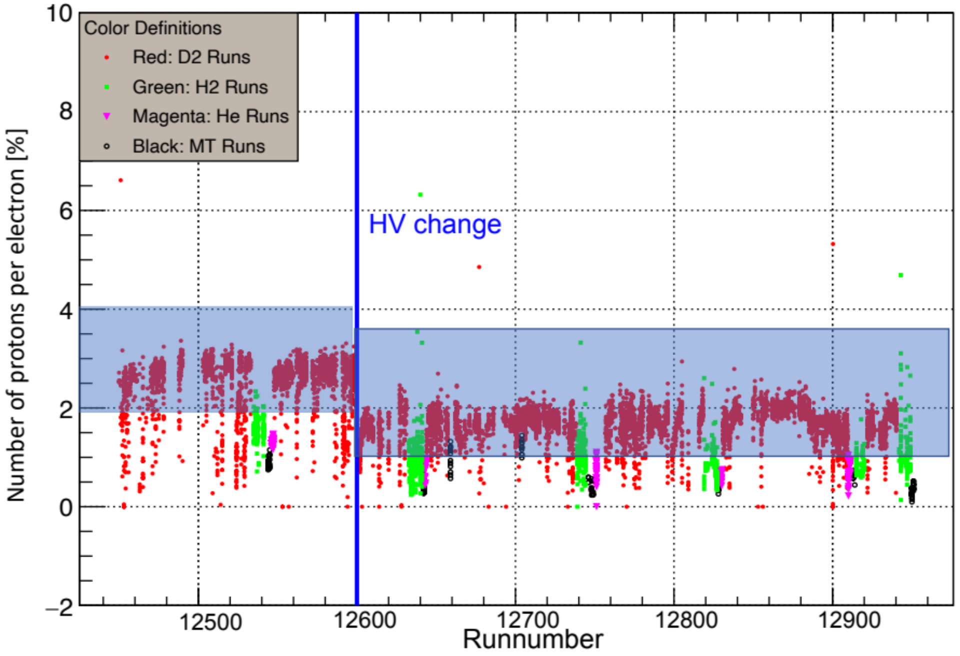


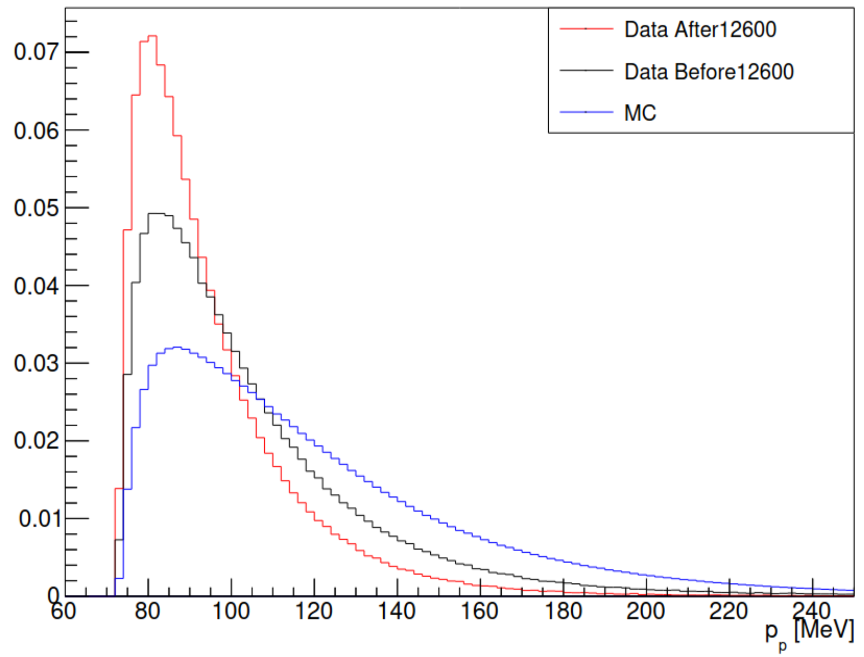


GEMs HV reduced of in RTPC after run 12600

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

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

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

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

Acceptance and efficiencies

$D(e,e')X$

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

$D(e,e'p_s)X$

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

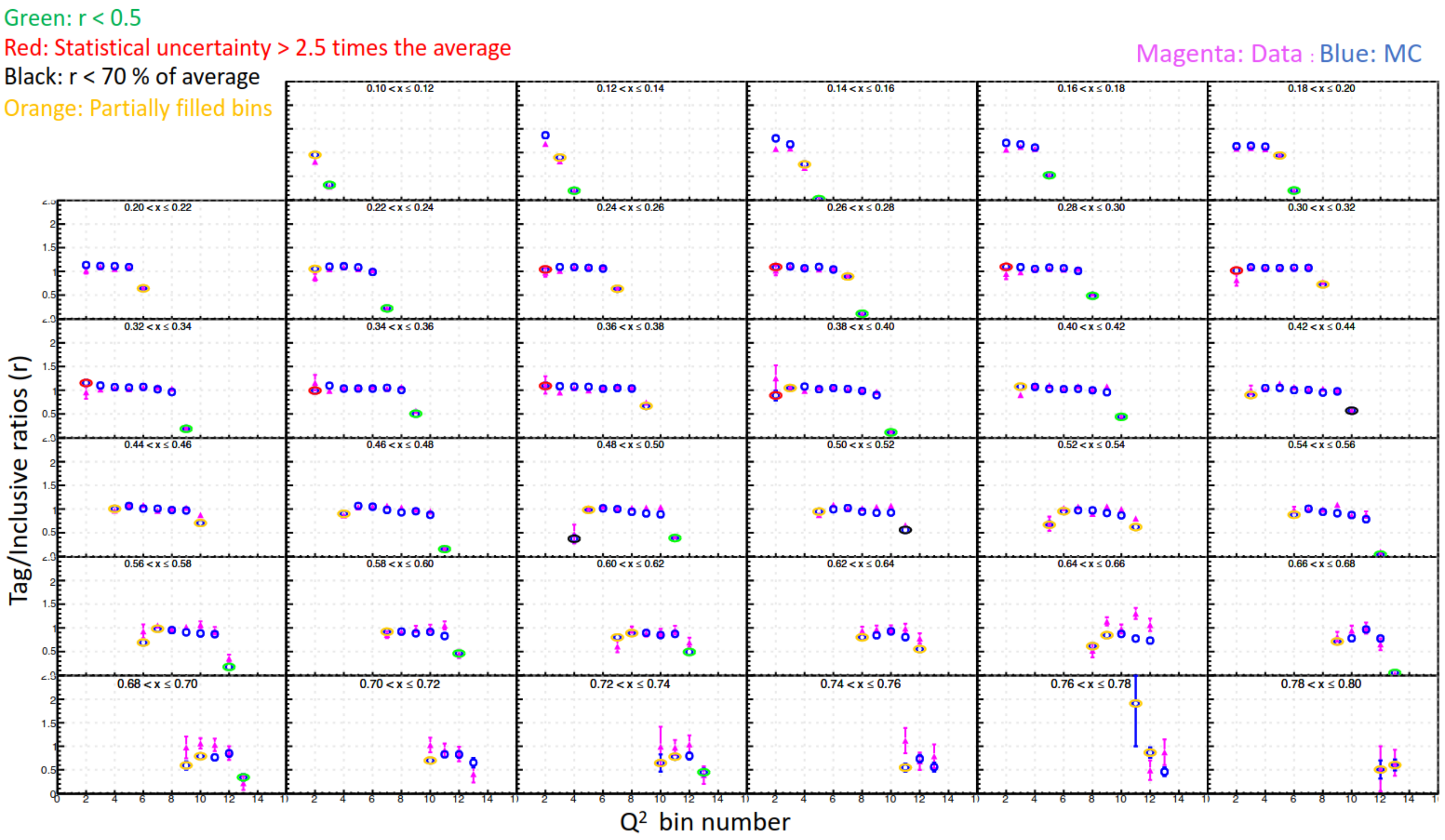
$$SR = \frac{R_{\text{tag}}(x',Q^2)}{R_{\text{inc}}(x,Q^2)} = \frac{\left(Y_{\text{tag}}^{\text{Data}}/Y_{\text{tag}}^{\text{MC}}\right)}{\left(Y_{\text{inc}}^{\text{Data}}/Y_{\text{inc}}^{\text{MC}}\right)} = \frac{\left(Y_{\text{tag}}^{\text{Data}}/Y_{\text{inc}}^{\text{Data}}\right)}{\left(Y_{\text{tag}}^{\text{MC}}/Y_{\text{inc}}^{\text{MC}}\right)}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

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

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

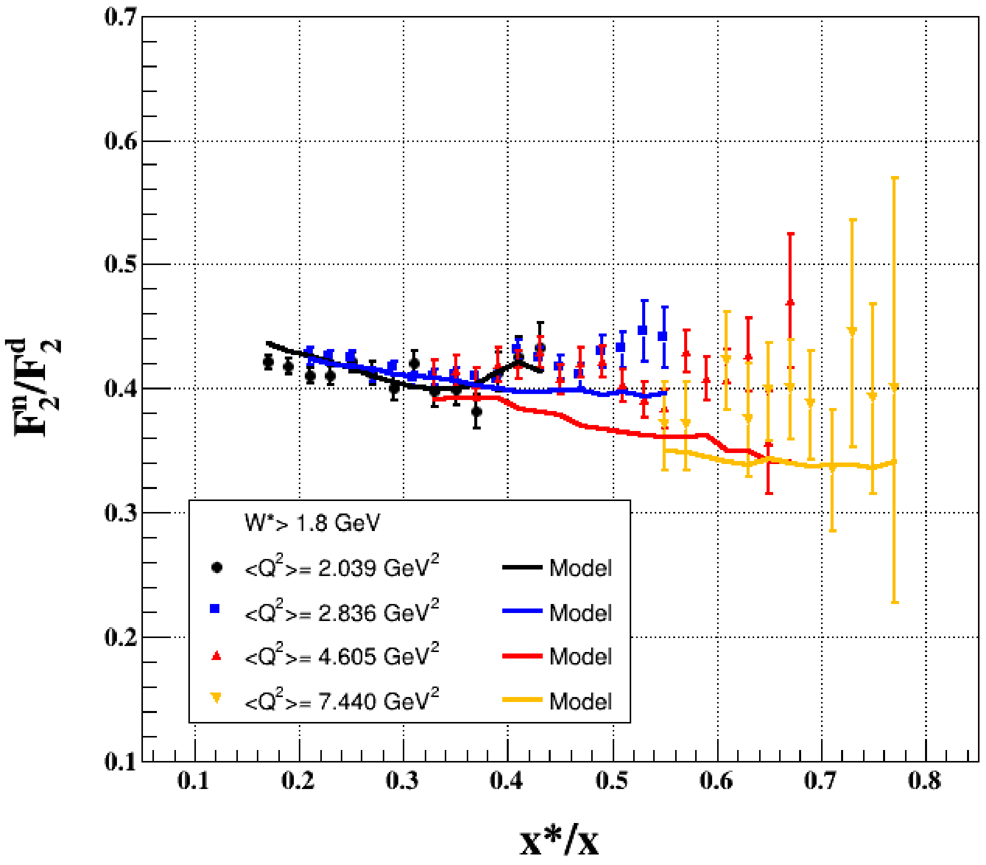
BONuS12 Corr. V: Culling Partially Filled Bins

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…



Results of F_2^n/F_2^d in four Q^2 bins

$\cos\theta_{pq}$ < -0.3



full $\cos\theta_{pq}$ ranges