The structure function of the quasi-free neutron using spectator-tagging in deep-inelastic D(e,e`ps)X scattering with the CLAS12 Spectrometer

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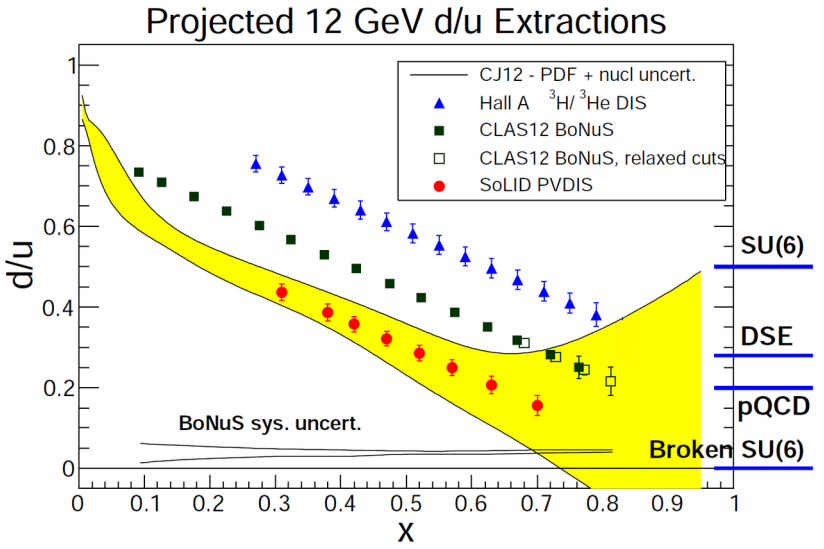
Old Dominion University

- **Physics Motivations**
- **Experimental Setup & Recoil Detector.**
- **Data Analysis & Preliminary Results.**
- **Conclusions & Perspectives.**

CLAS Collaboration Meeting, November 18th, 2026

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.

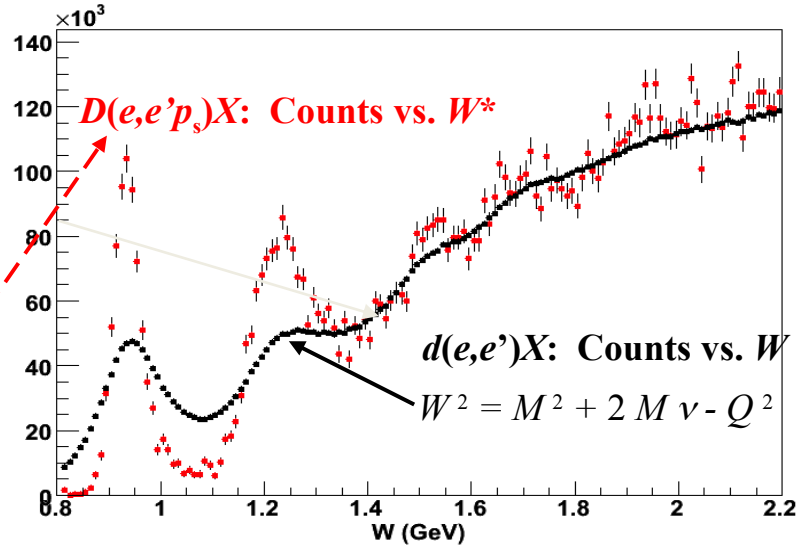


- F_2^n is obtained from measurements on bound neutrons, but F_2^n extraction at large *x* introduces theoretical model dependence on nuclear corrections (Fermi motion, nucleon off-shell corrections, FSI, .

- **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.

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

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

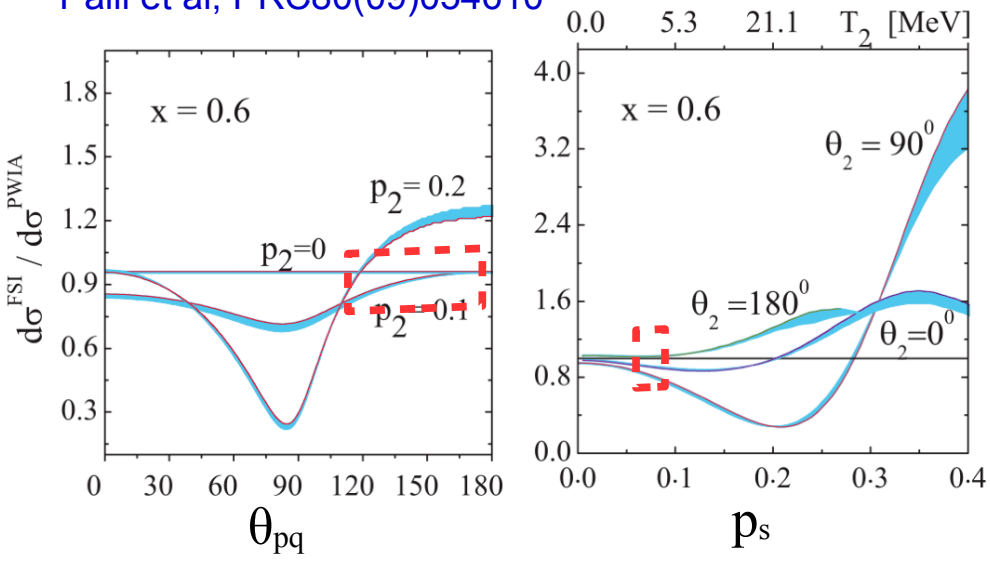


BONuS12 Nuclear Uncertainties

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}.

Palli et al, PRC80(09)054610

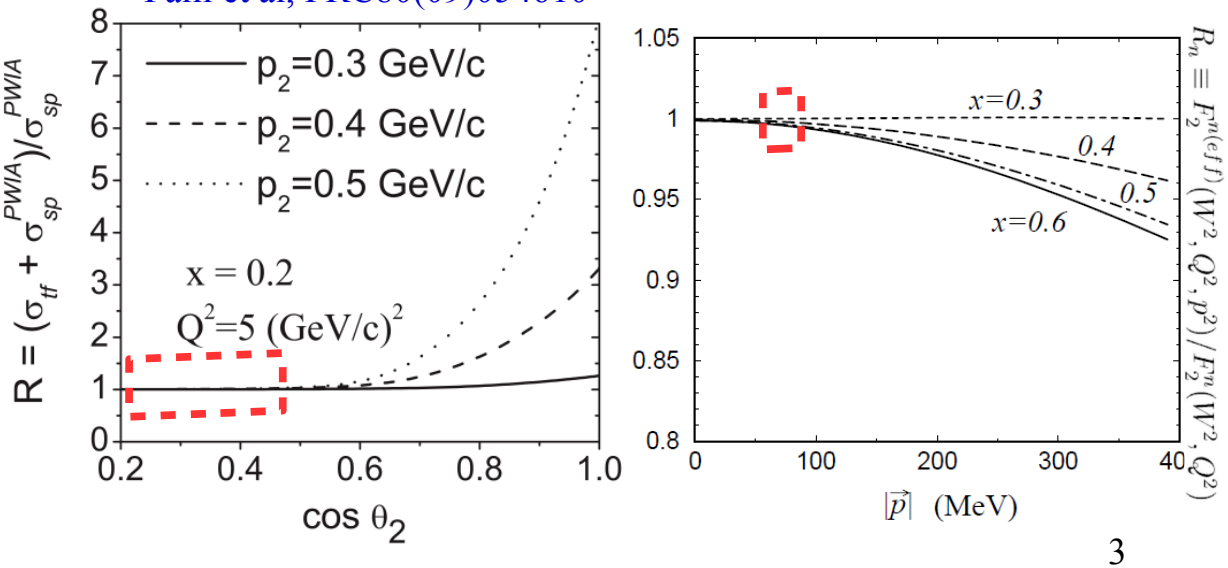


Target Fragmentation:

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

Palli et al, PRC80(09)054610

Melnitchoul et al, PRL B335,11(1994)



Off-Shell Corrections:

- Less than 2% in our region.

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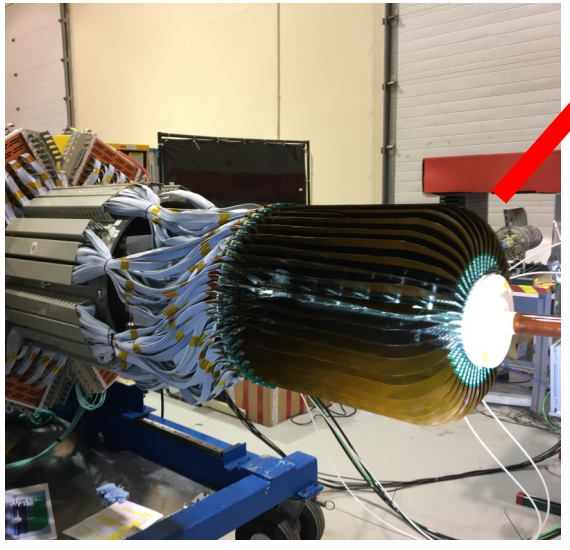
BONuS12 Experimental Setup

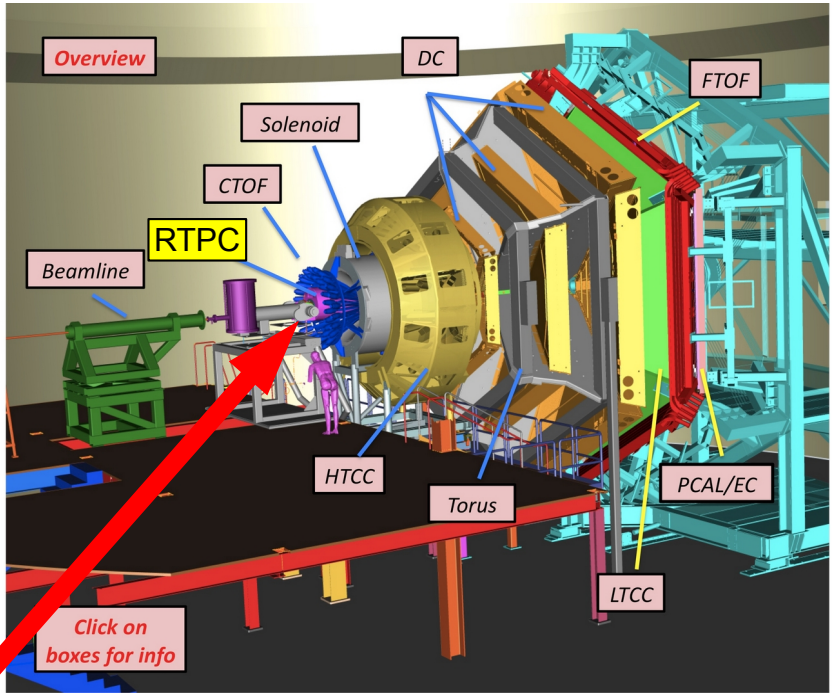
10.4 GeV

$e^- D \rightarrow e\ p\ \gamma\ (n)$

- **CLAS12 Forward Detector:**
  - → Superconducting Torus magnet.
  - → 6 independent sectors:
    - → HTCC: identifying e^- ($p < 5.0$ GeV/c).
    - → 3 regions of DCs: tracking charged particles.
    - → LTCC and RICH: π^- identification ($p > 3.0$ GeV/c).
    - → FToF Counters: identifying hadrons.
    - → PCAL and EC: detecting γ, e^- and n [5°,40°].

- **Central Detector:**
  - **Target:** D_2 gas @ 5.5 atm, 293 K
  - **BONuS12 RTPC:** Detects low energy recoils.
  - **Solenoid**
  - **CToF**
  - **CND**
  - **FMT**





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

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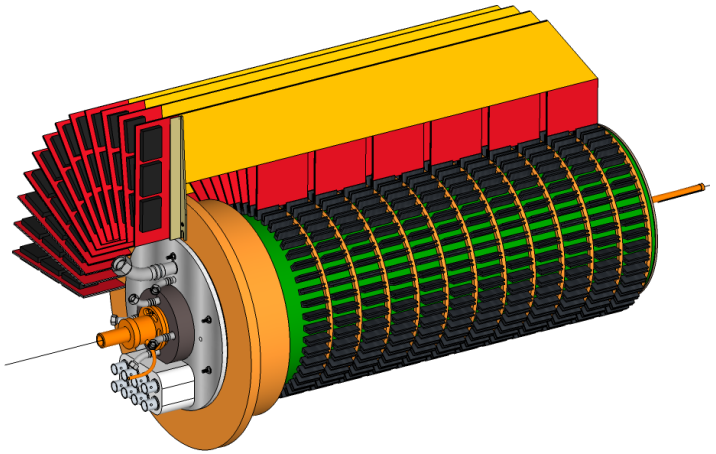
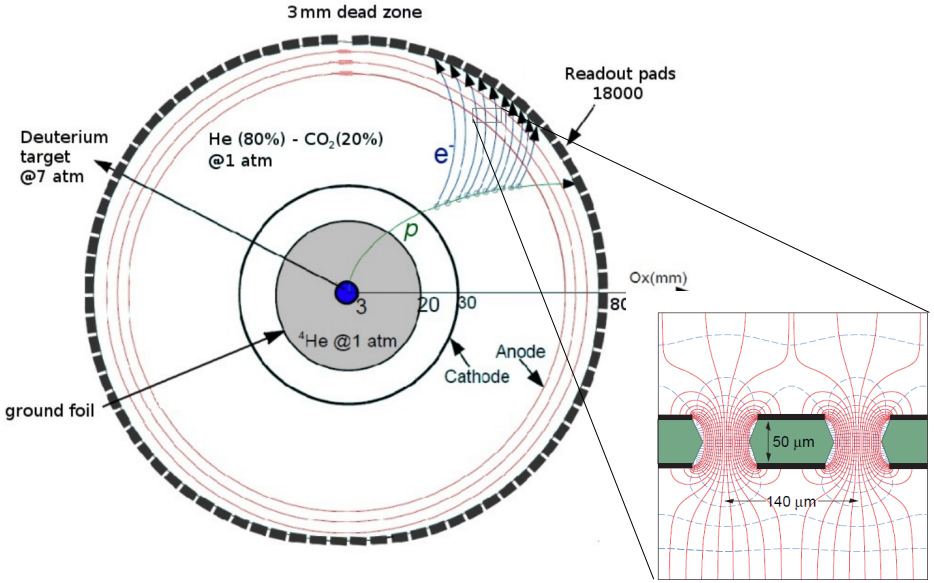
BONuS12 RTPC





[I. Albayrak, M. Hattawy et al., Nucl. Instrum. Meth. A 1062, 169190 (2024)]

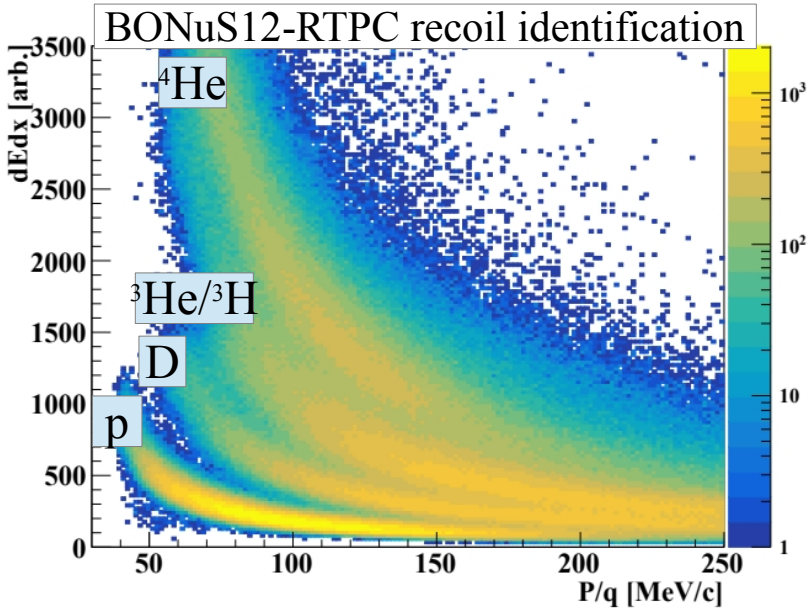
- Work principle:

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
→ Signal height vs. Time bin

- Offline reconstruction:

Time and Pad location → 3D reconstruction of track → p/q, vz, vtl

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



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DIS-Electron Identification @10.4 GeV

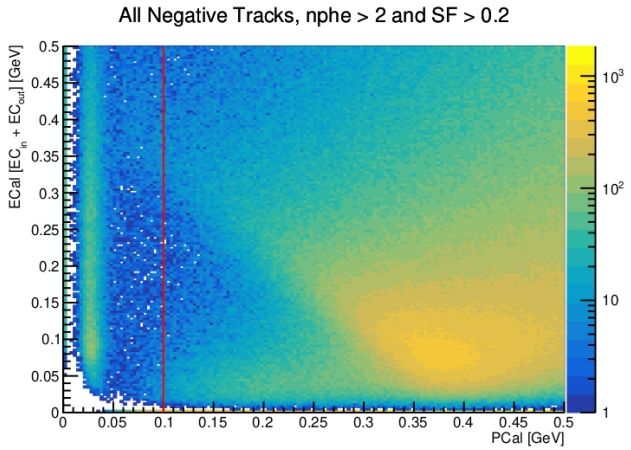
e- @10.4 GeV beam on D_2 target

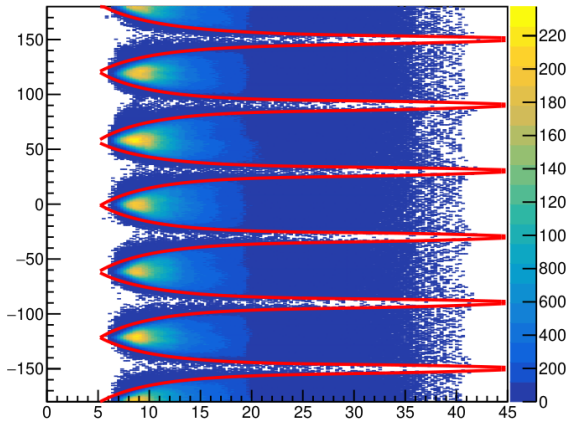
Electron selection cuts

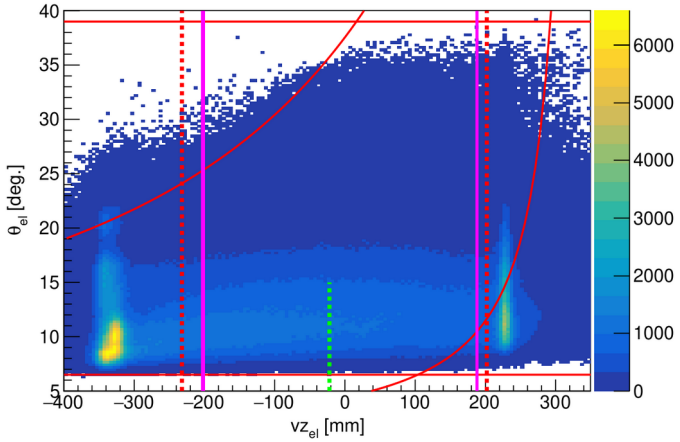
- PID = 11
- nphe > 2
- $E_{tot}/p > 0.2$
- $EC_{in} > 10$ MeV
- $E_{PCal} > 100$ MeV
- DC fiducial cuts
- E` > 2.6 GeV
- vz_{e-}
- PCal SF and Fiducial cuts:

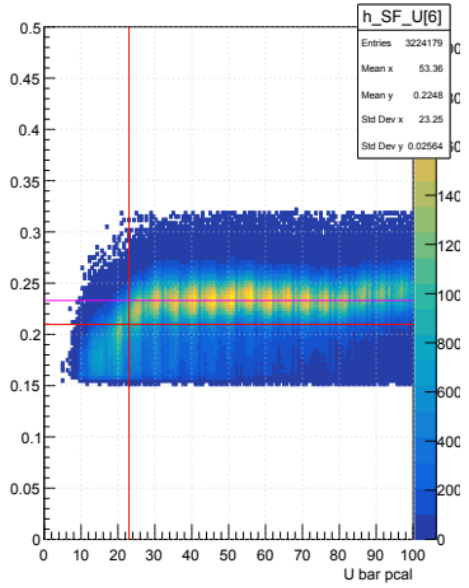
Additional DIS cuts

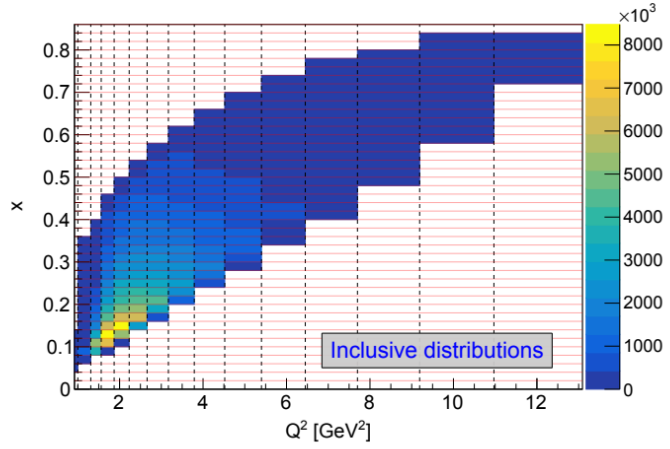
- W > 1.8 GeV (for Exp. And Sim.)
- $Q^2 > 1.56$ GeV^2











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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

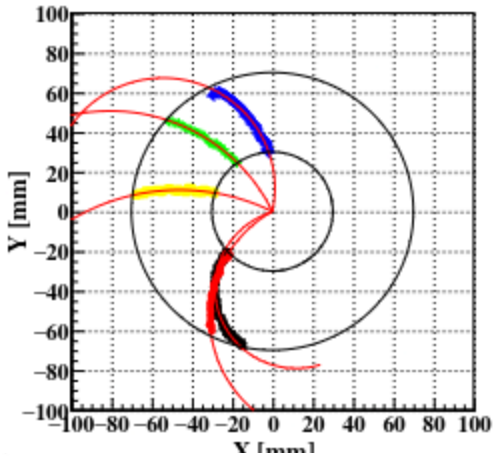
- Vertex coincidence cuts
- Timing coincidence

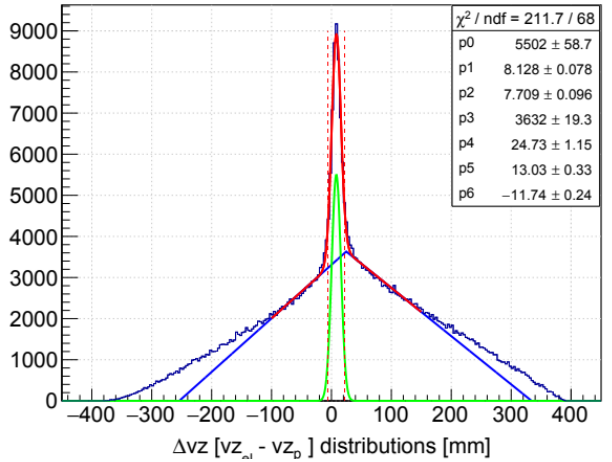
PID Cuts:

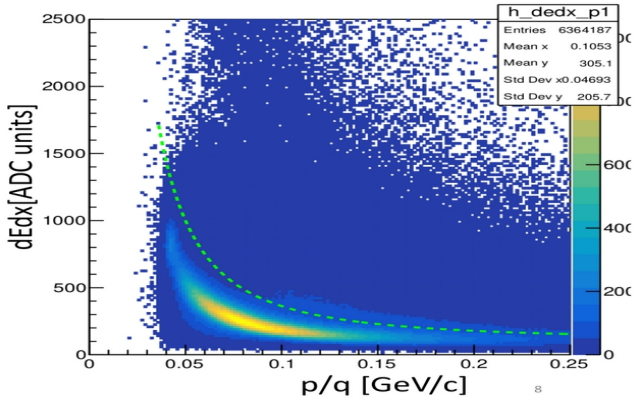
- Cuts on dEdx vs. p/q band for proton selection

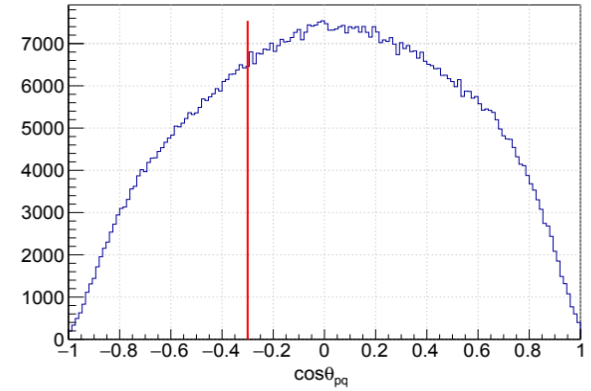
DIS & VIP cuts

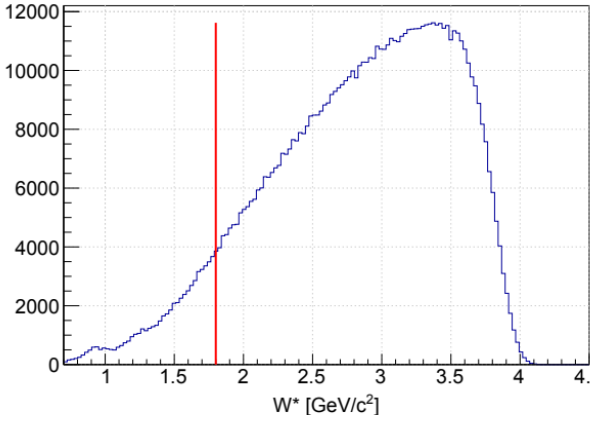
- W* > 1.8 GeV
- 0.075 < p_ps < 0.1 GeV/c
- 35° < θ_ps < 145°
- cos(θ_{pq})< -0.3

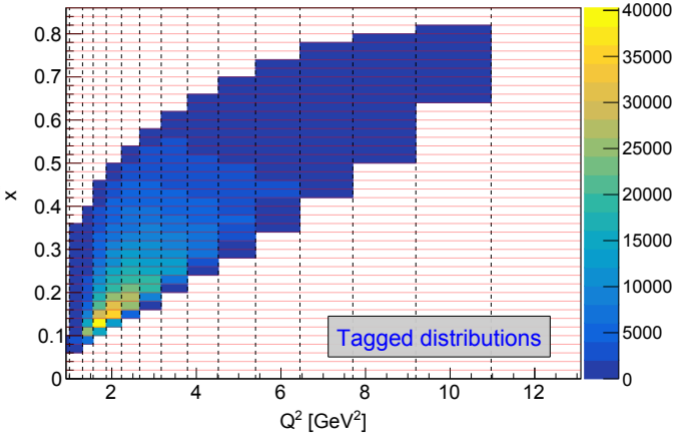












BONuS12 F_2^n/F_2^p Extraction Method

$\underline{D(e,e')X}$

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

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

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

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

$\underline{D(e,e'p_s)X}$

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

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

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

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

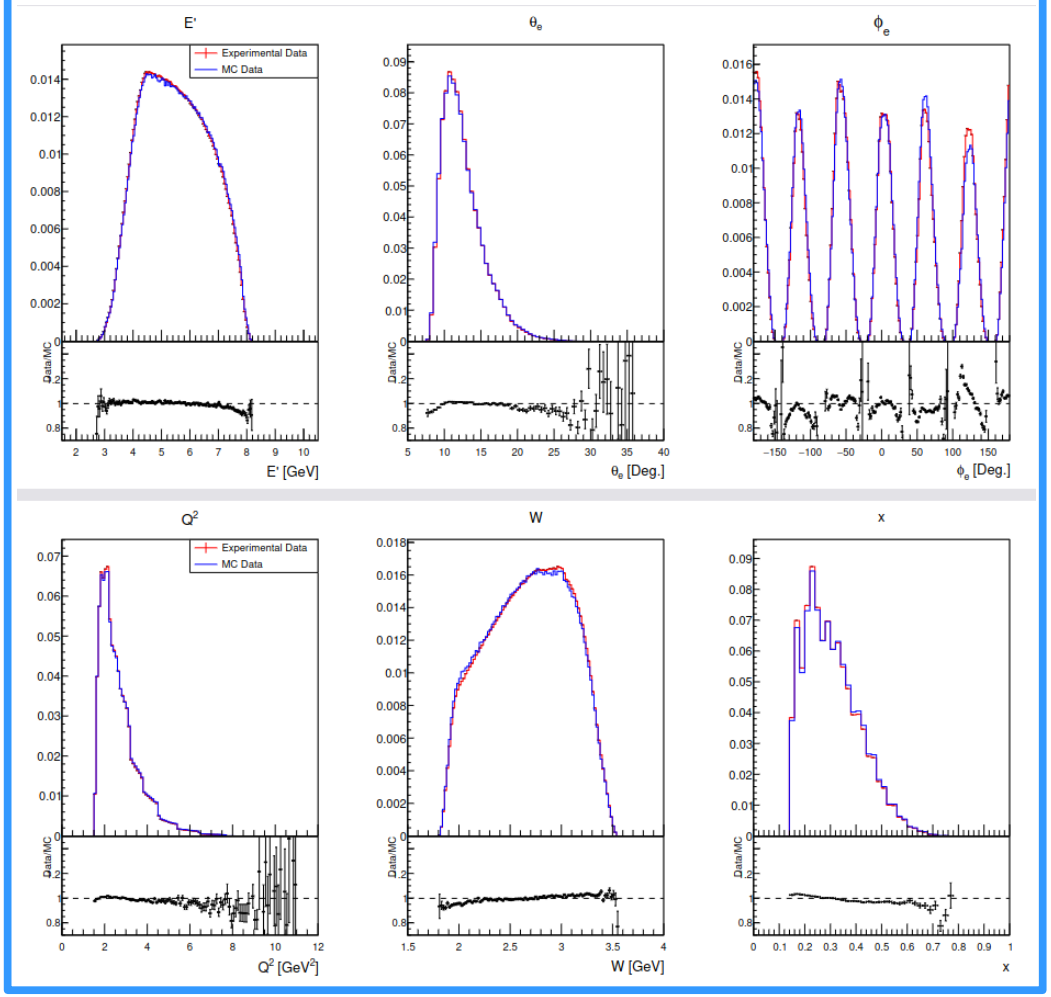
ODU

Data vs. MC: e^- kinematics

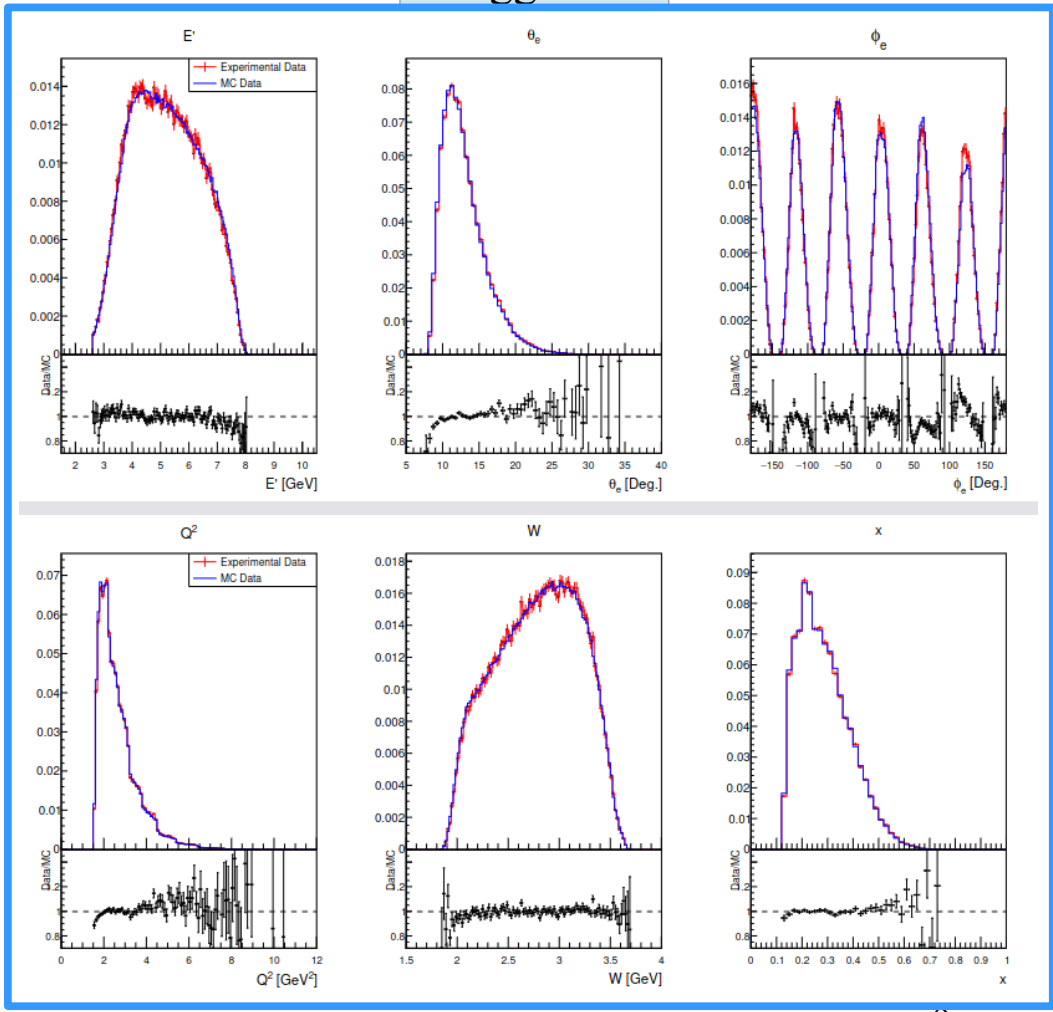
- **Full GEMC** simulation of both tagged and inclusive spectra with detailed implementation of the RTPC.
- **Generator:** PWIA spectator model with 2014 Bosted/Christy fit to world data for F_{2n} and F_{2d}, AV14 D wave function, relativistic motion of struck nucleon, and equivalent radiator method for internal rad. Effects.

-- MC
-- Exp.

Inclusive e^-



Tagged e^-



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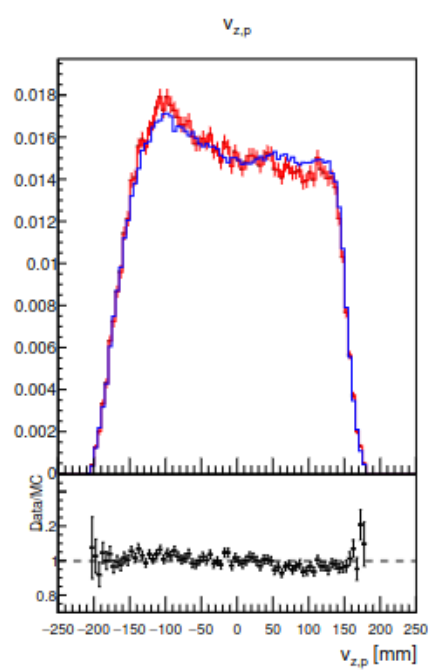
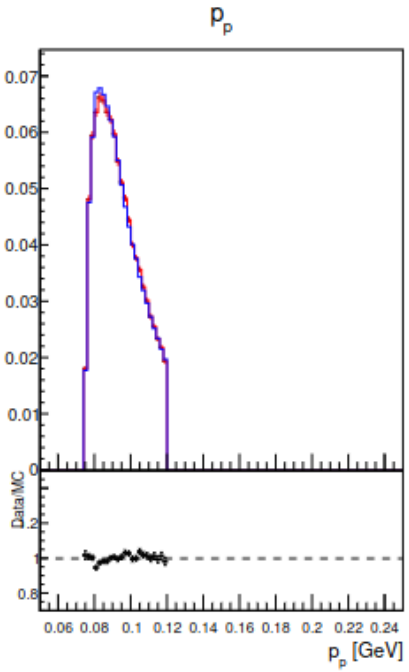
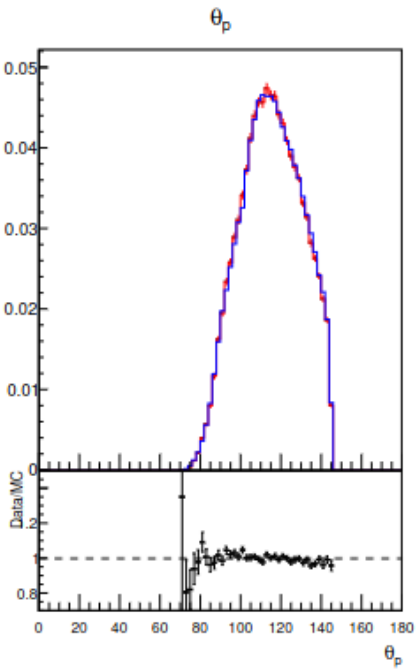
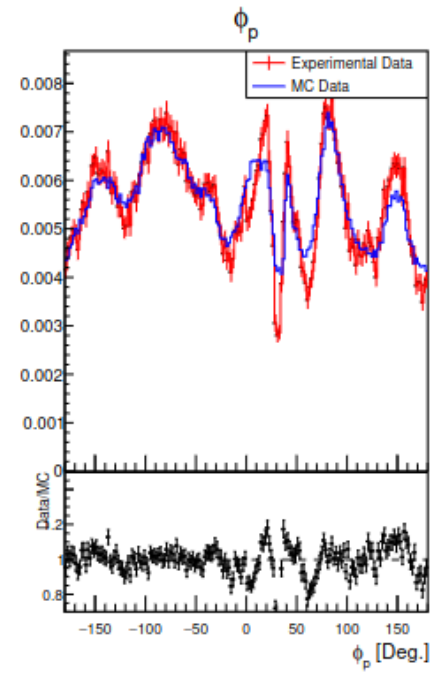
Data vs. MC : D(e,e'p_s)X : p_s kinematics

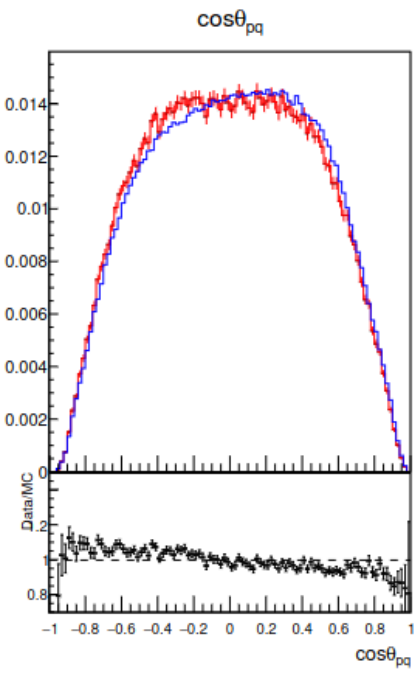


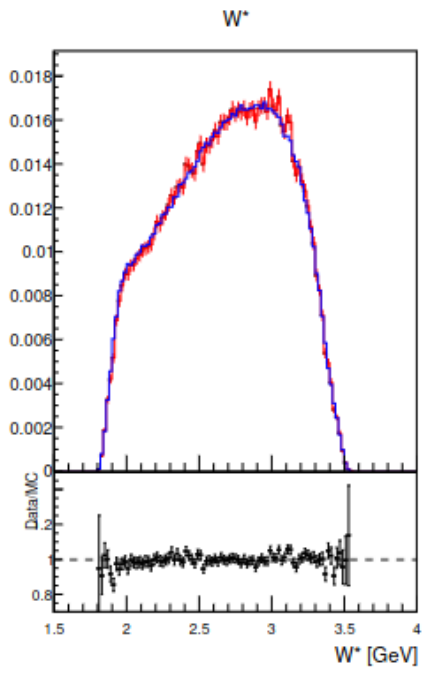


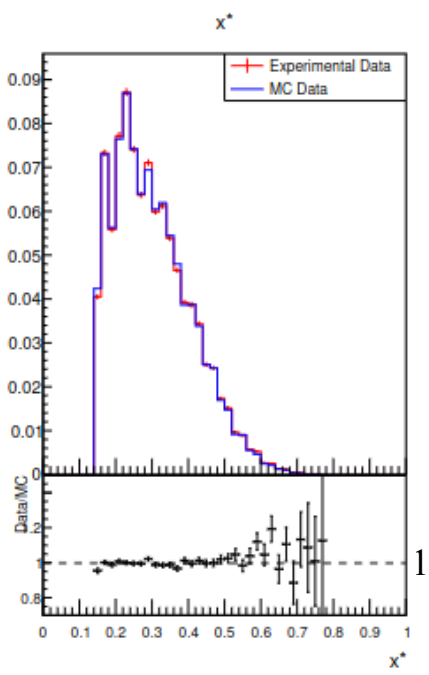


-- MC. Data
-- Exp. Data

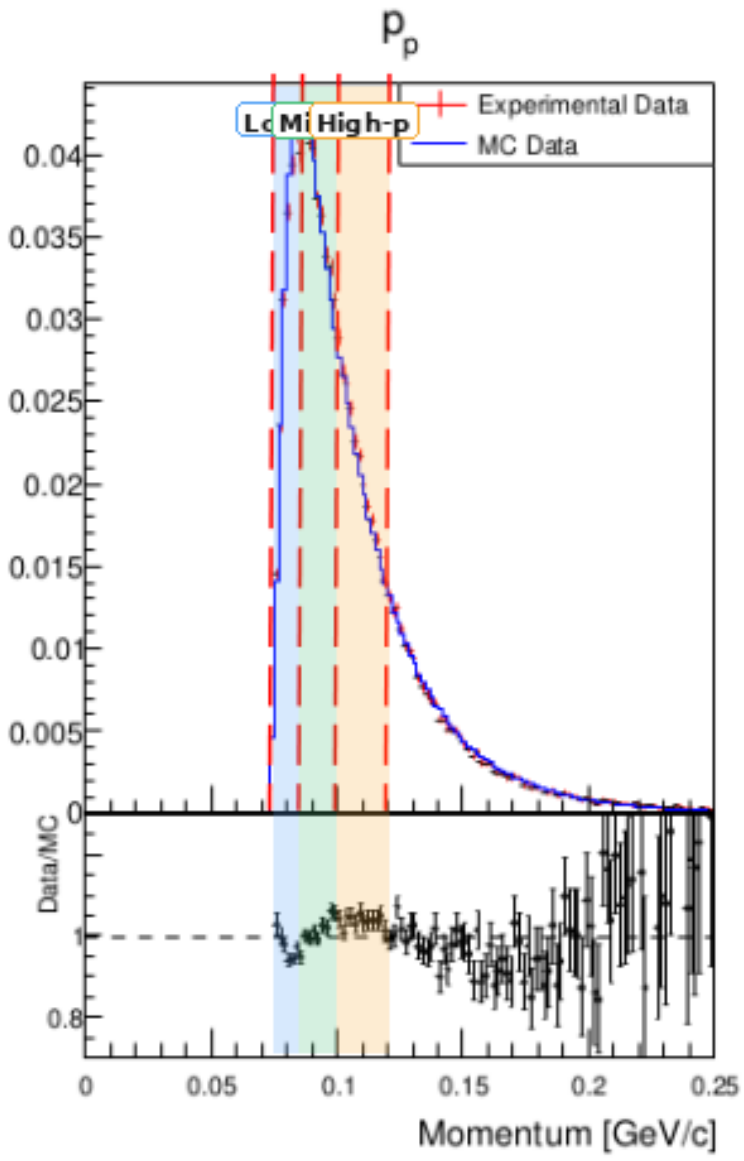


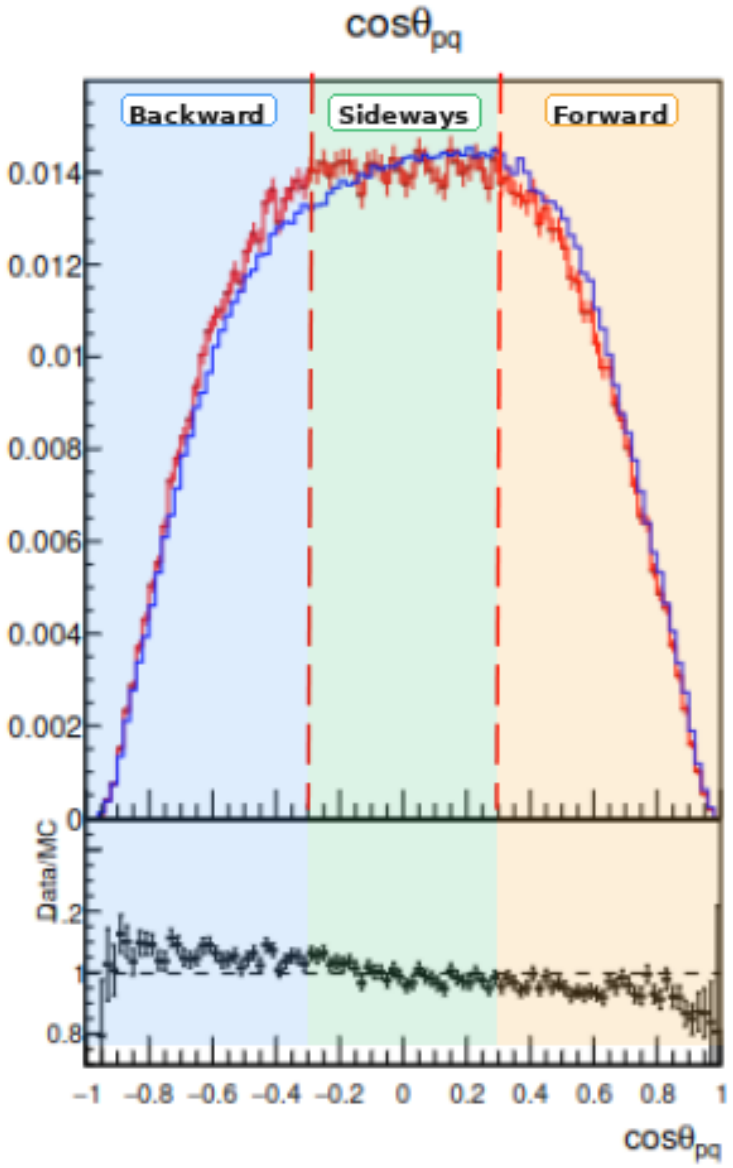






Testing the Sensitivity of the Spectator-Tagging (1/2)





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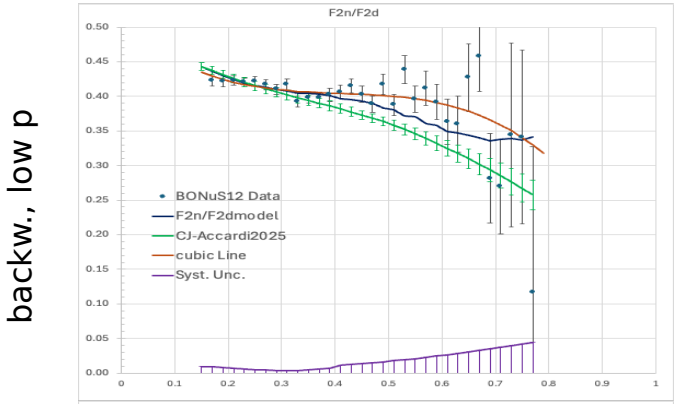
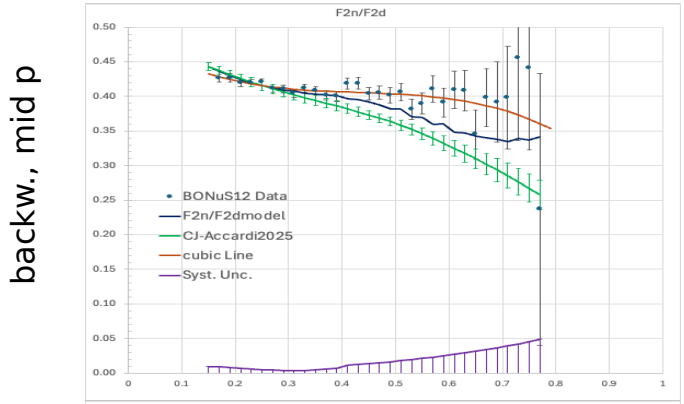
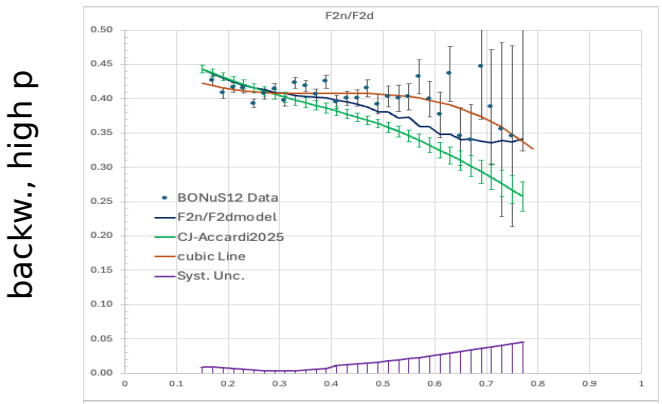
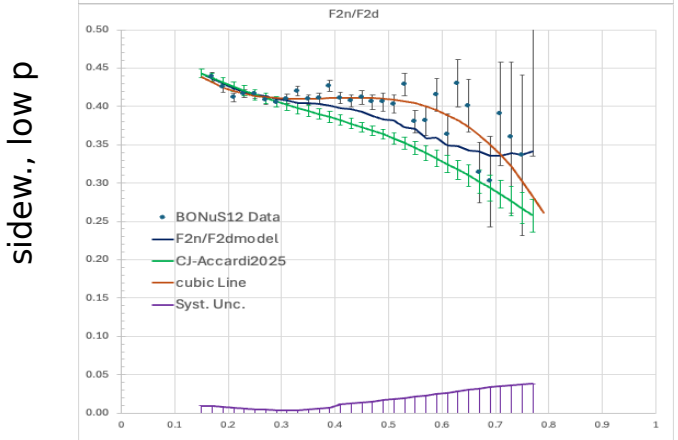
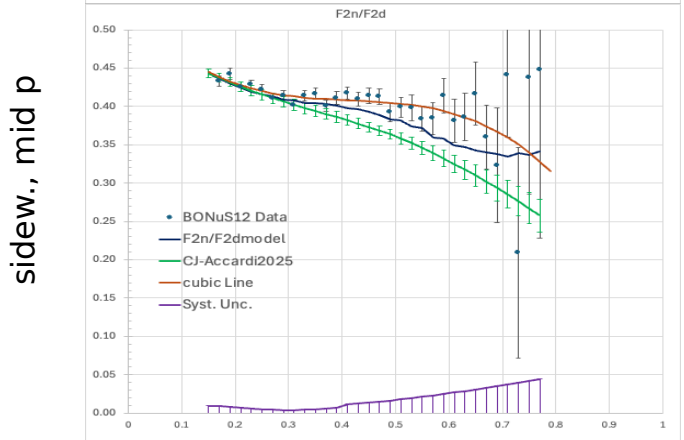
Testing the Sensitivity of the Spectator-Tagging (2/2)

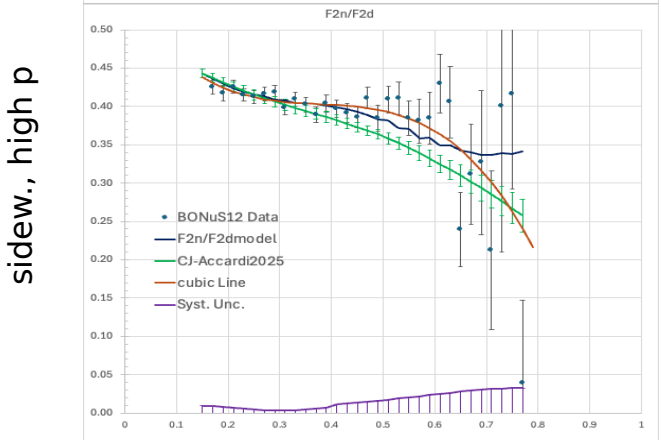


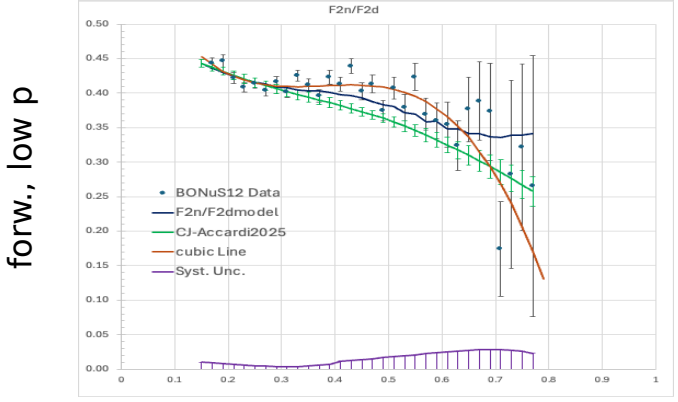


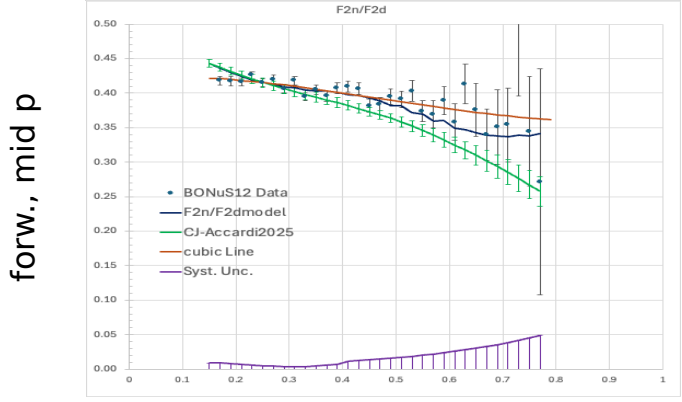


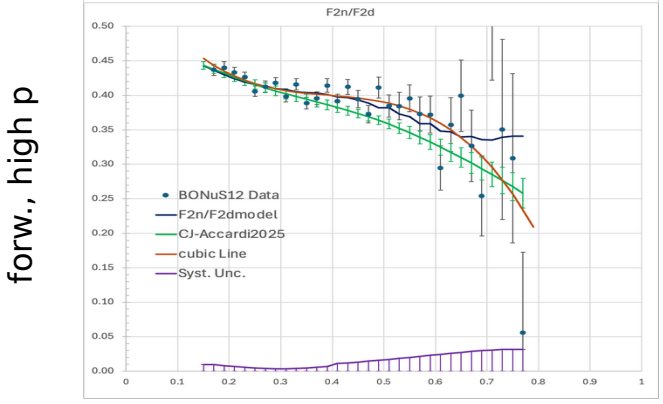












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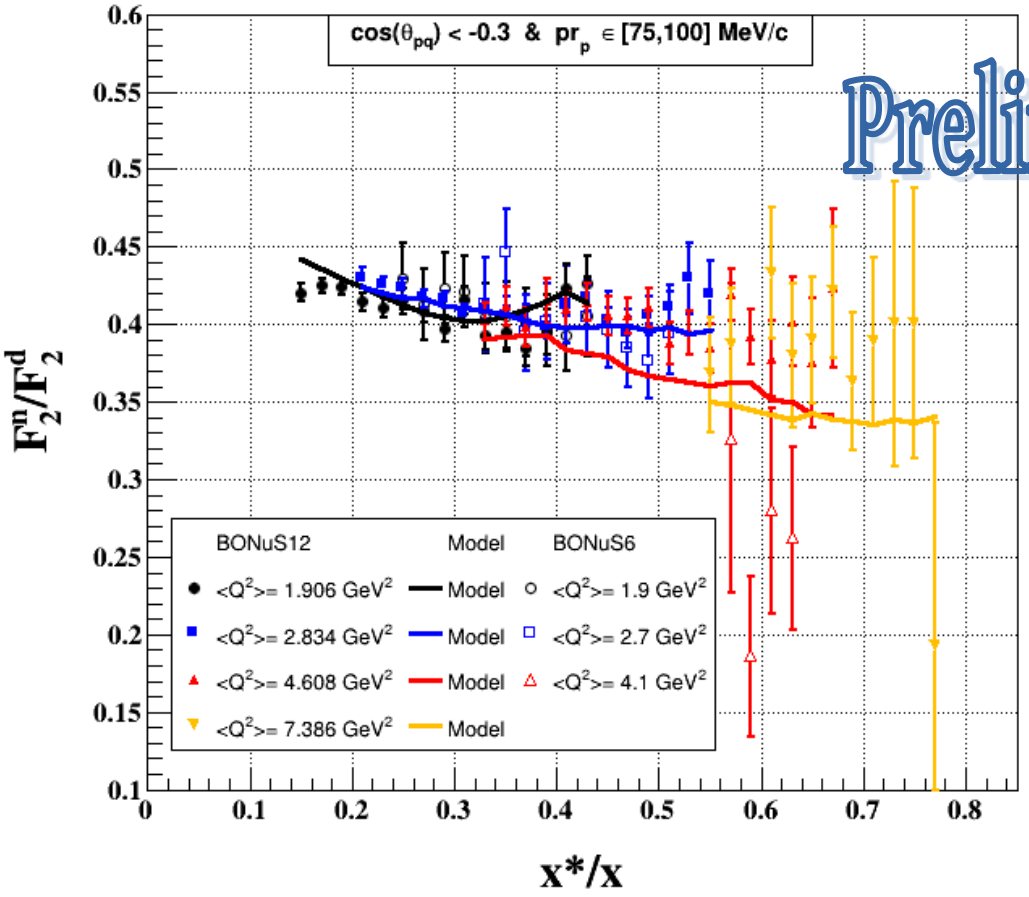
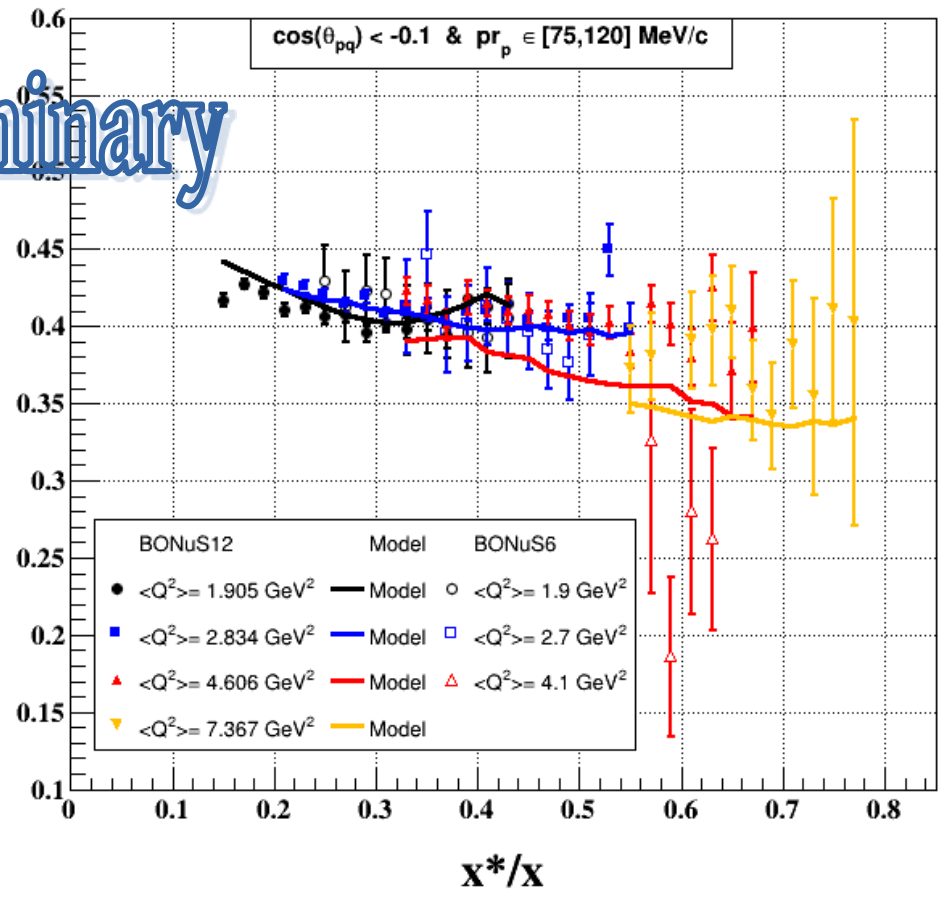
BONuS12 Preliminary Results (1/3)





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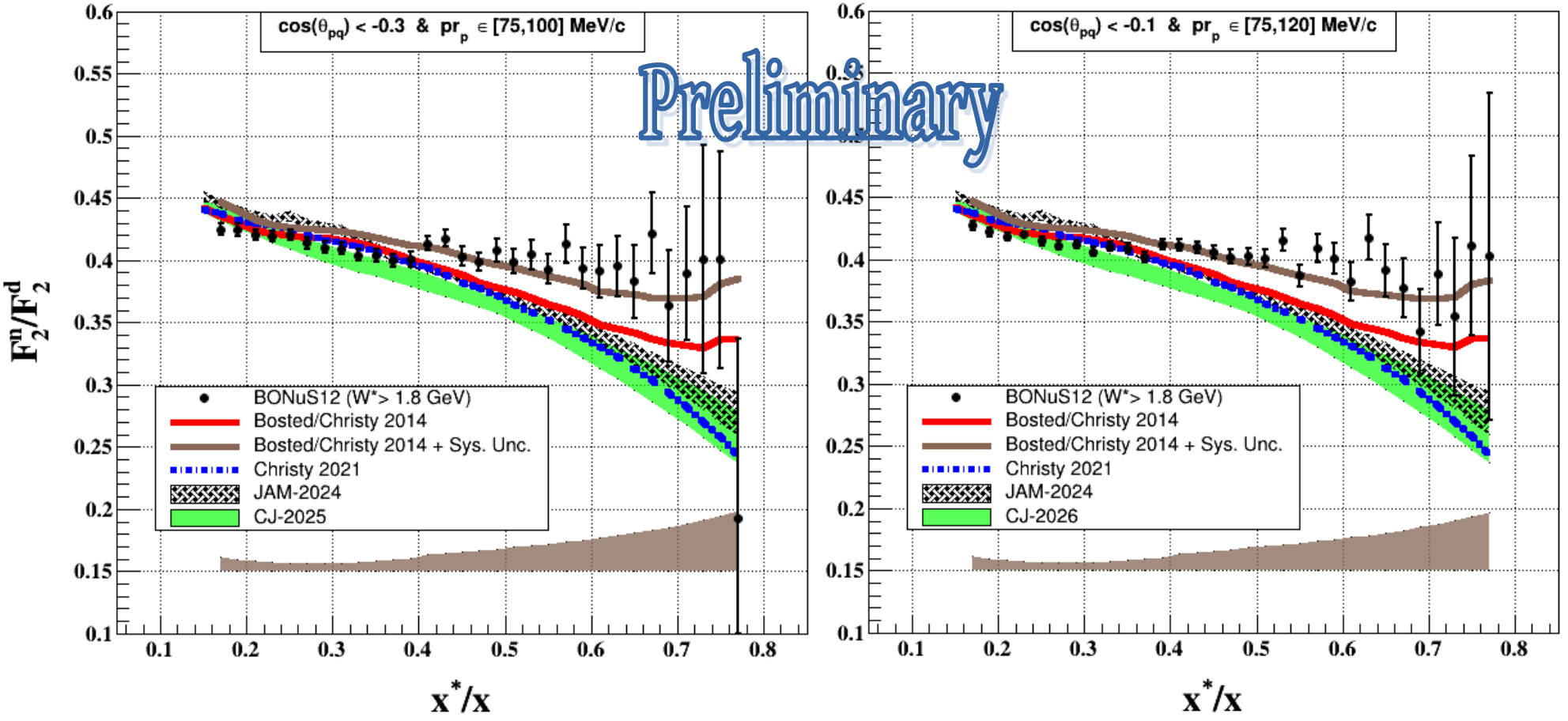
BONuS12 Preliminary Results (1/2)



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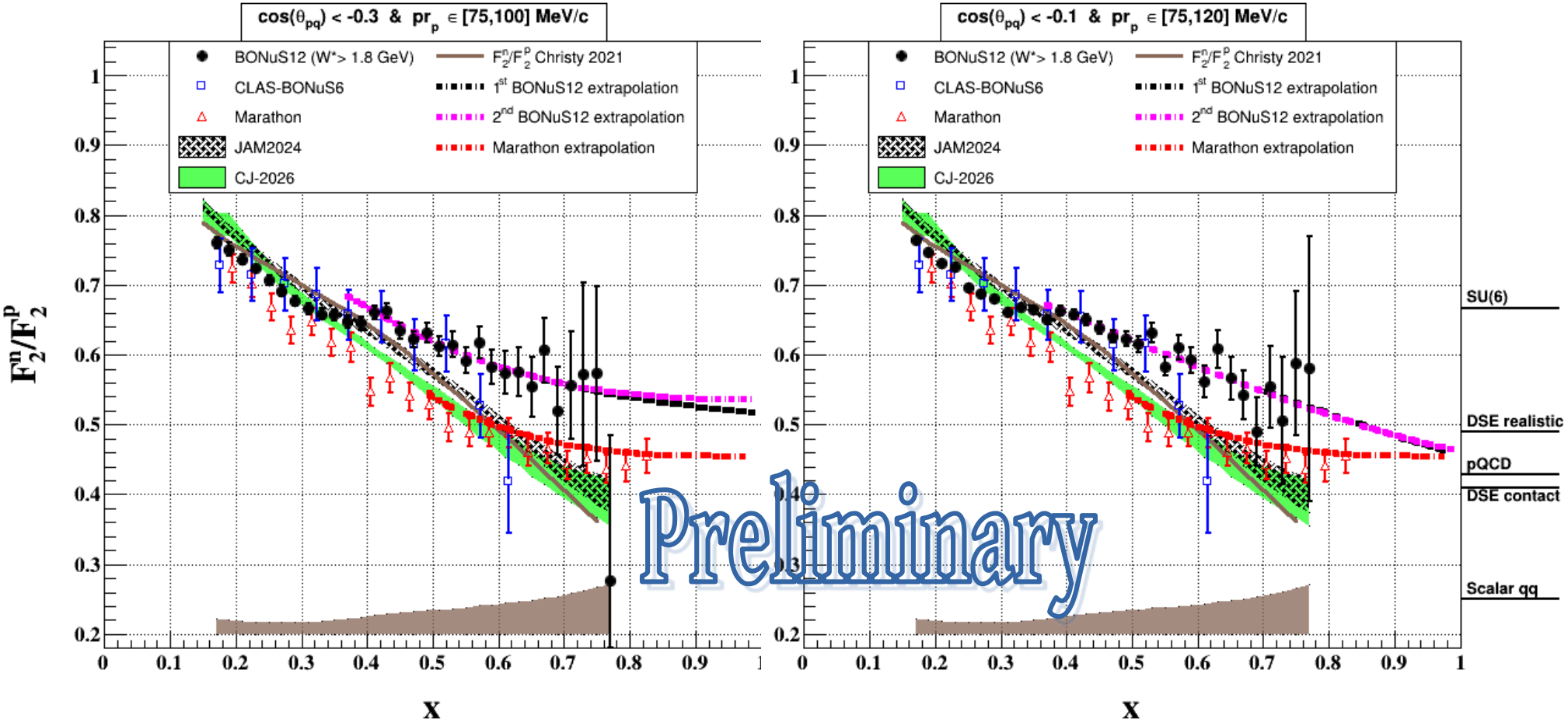
BONuS12 Preliminary Results (3/3)



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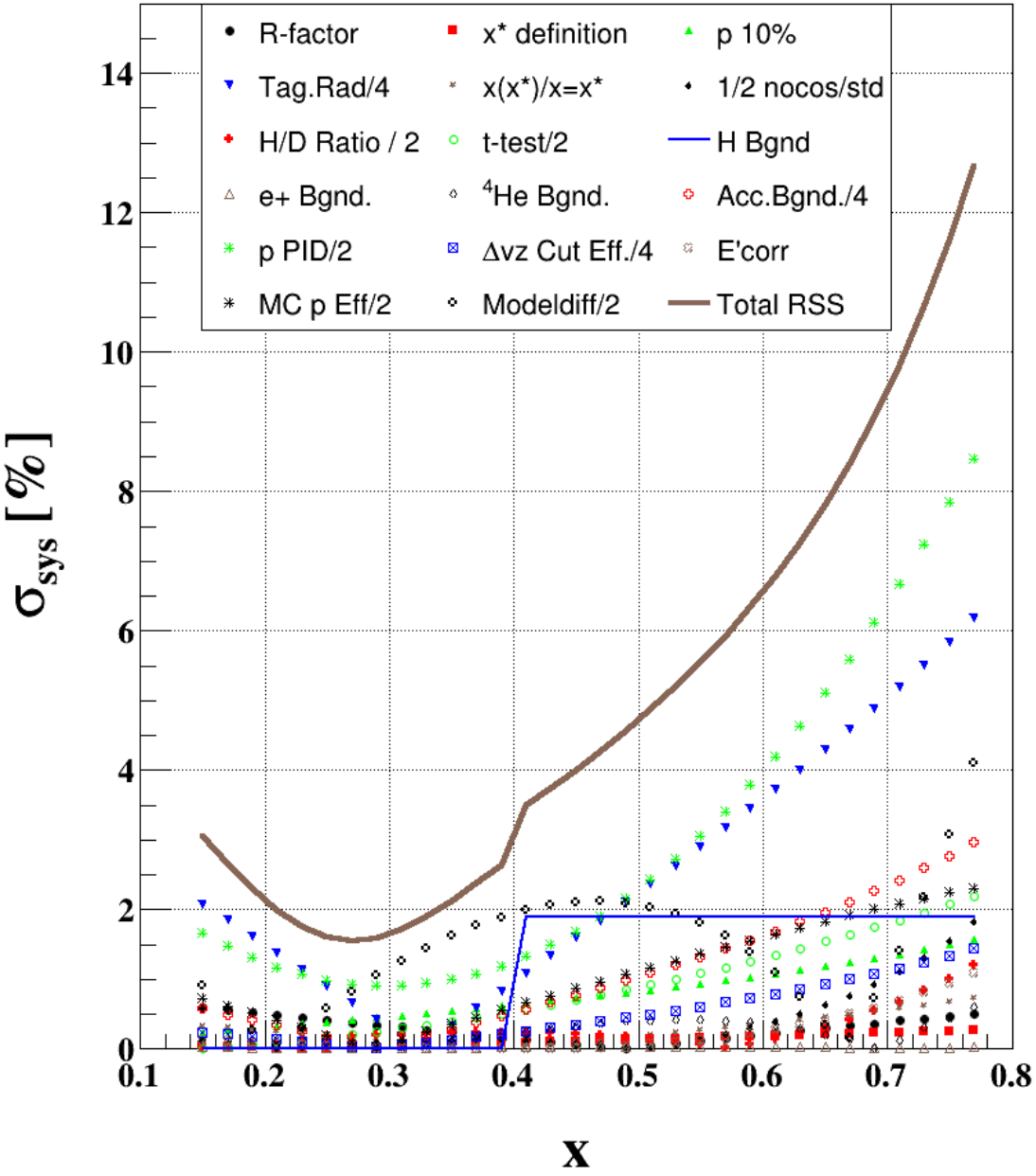
BONuS12 Systematic Uncertainties



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Conclusions

◊ **BONuS12** extends the measurement of **spectator-tagged neutron structure functions** over a **larger kinematic range**, with much improved statistics.

◊ The analysis is finalized and all systematic uncertainties have been concluded.

◊ The response to the 1st round comments on the analysis note is ongoing.

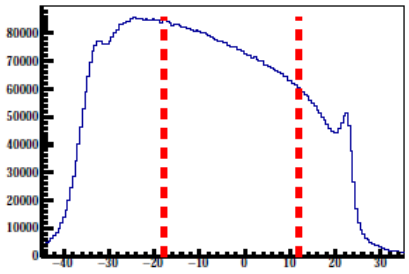
◊ More experiments at **12 GeV** – **ALERT**, **TDIS**, **BAND**, **…**

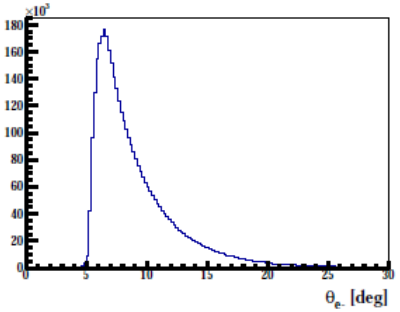
◊ Future of spectator tagging: **JLab 22 GeV** & **EIC**

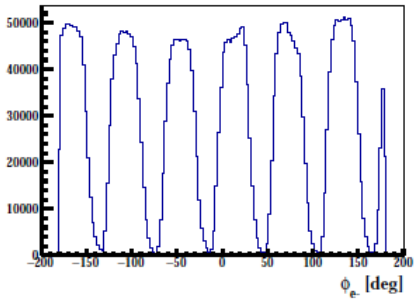
Backup Slides!

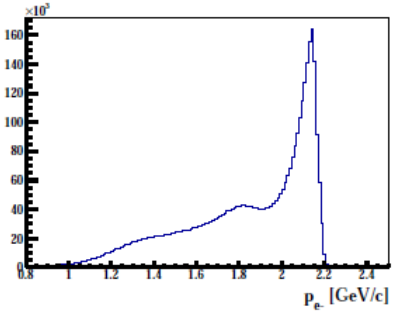
2.1 GeV Calibration Data

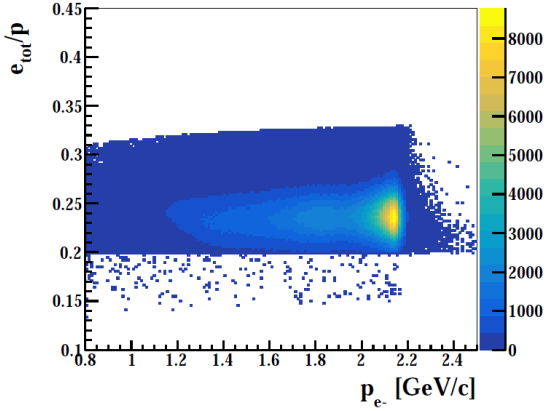
Electron Selection : 2.14 GeV on H_2 target



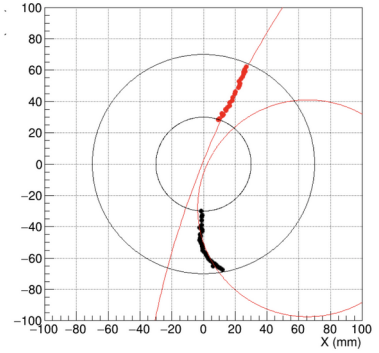


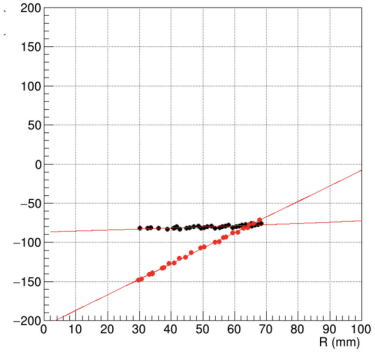


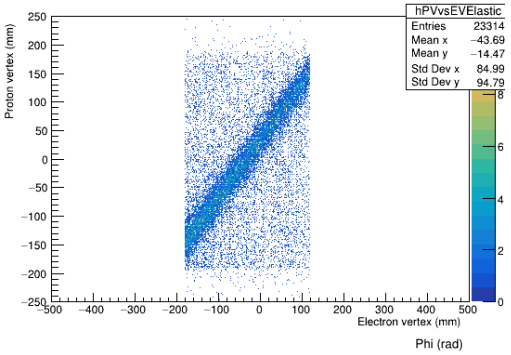


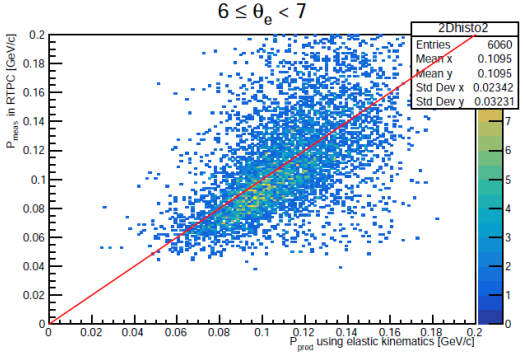


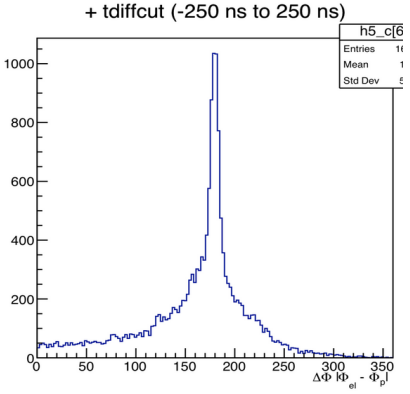
Radiative elastic e- in coincidence with good p tracks:

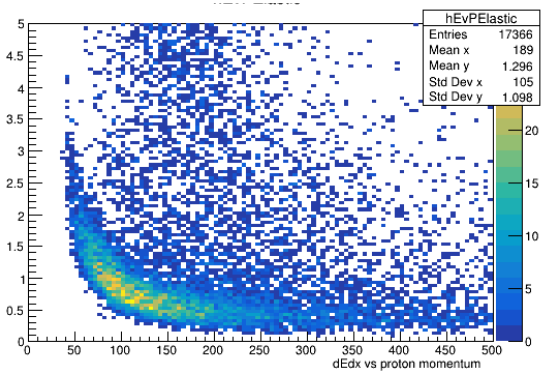












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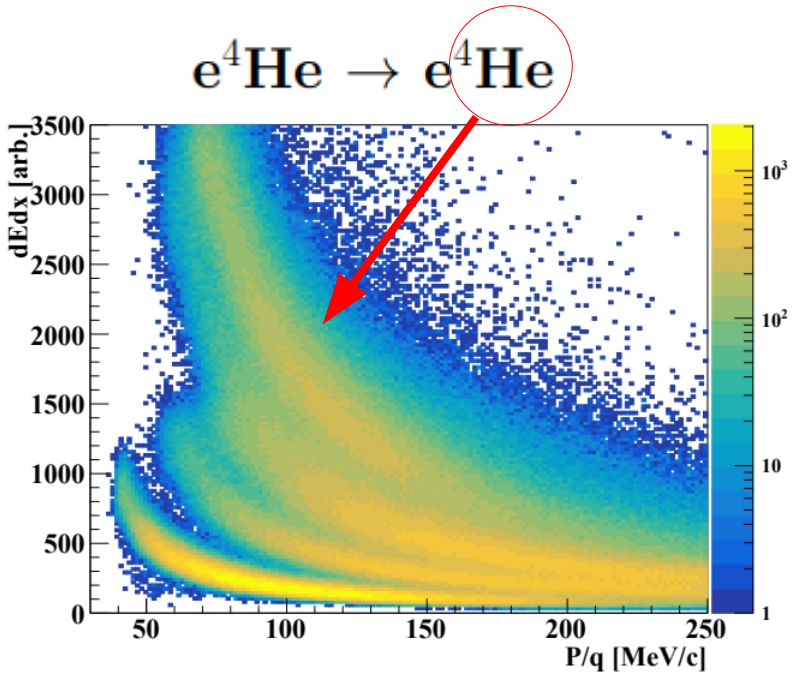
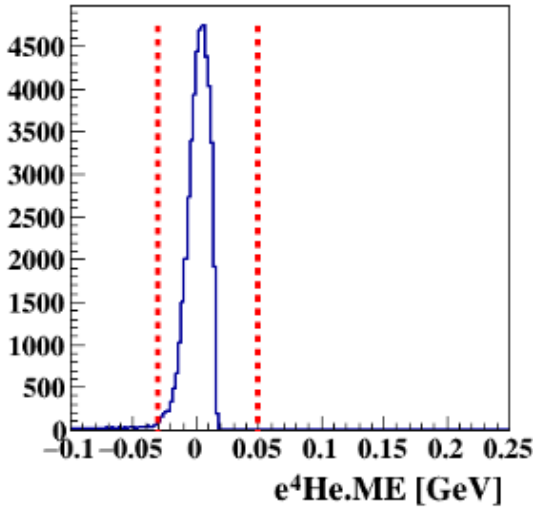
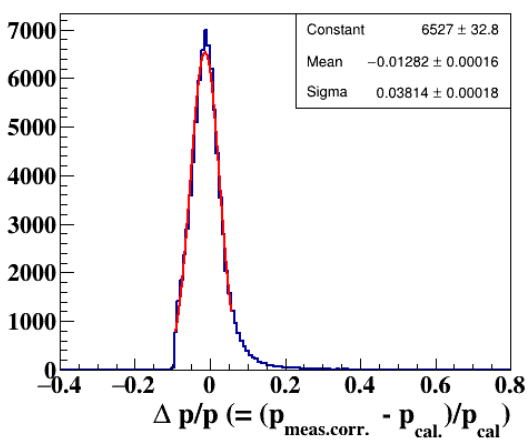
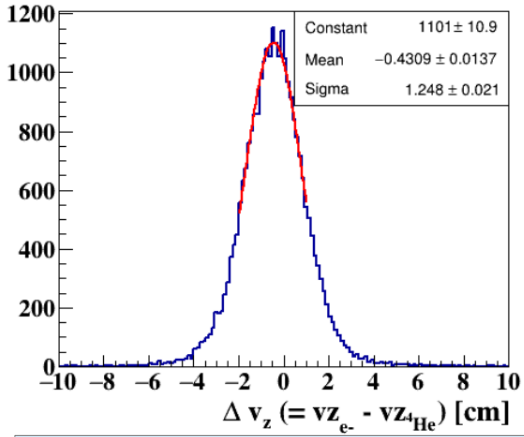
BONuS12 RTPC Performance

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



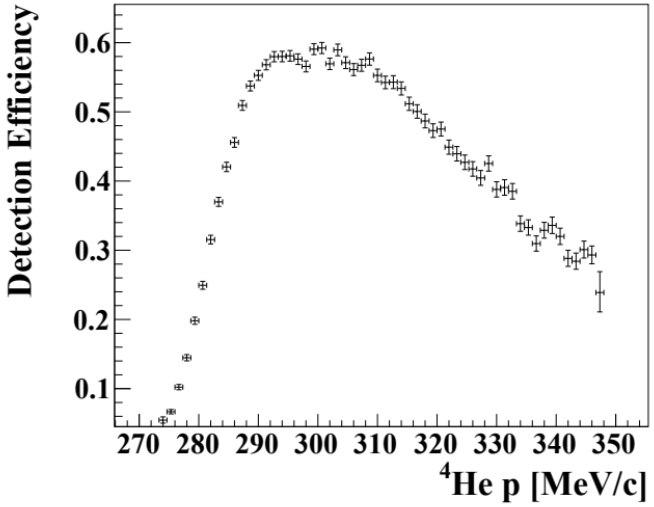


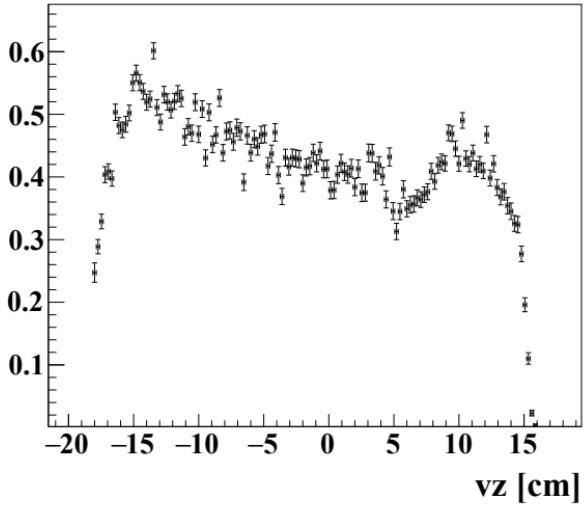




4% momentum resolution

1.2 cm combined CLAS12-RTPC vertex resolution





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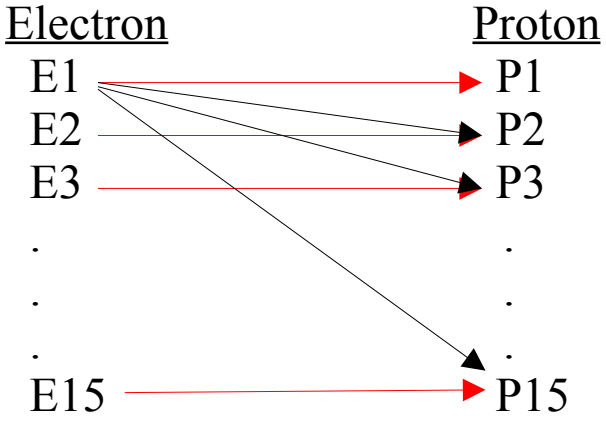
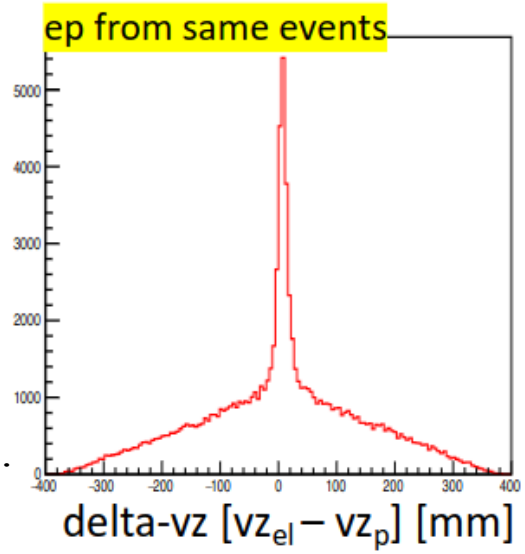
BONuS12 Corrections I: Accidentals

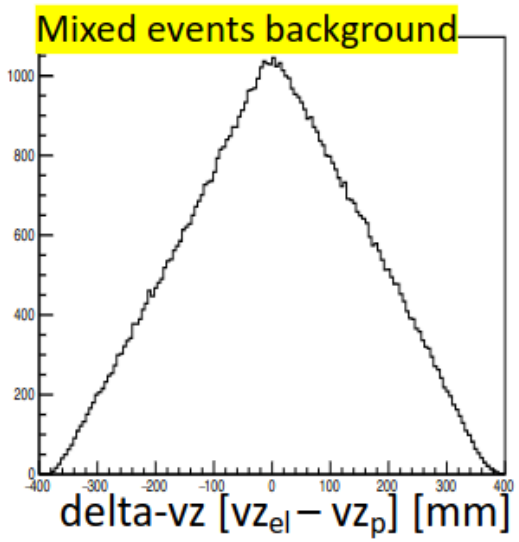
For better statistics on accidental backgrounds

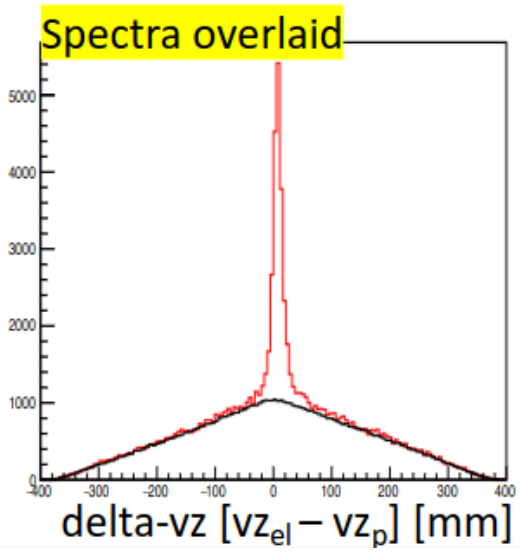
For every **15 consecutive events**
passing all selection criteria:

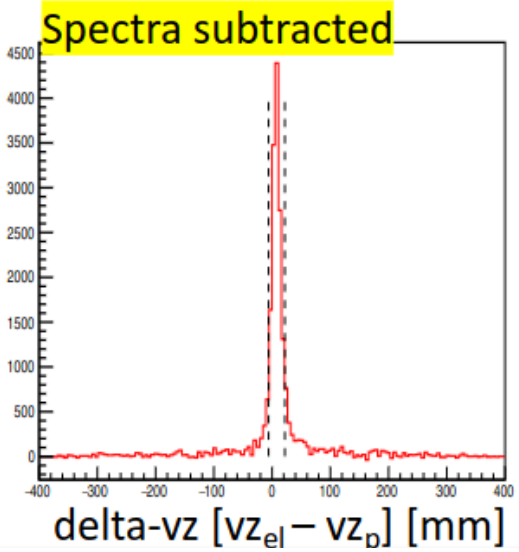
- We did event mixing
- Form **15x15 ep** pairs
- **15 ep pairs** [Red in fig.] from the same event
- **210 combinatorics backgrounds** [Black in fig.].
- Scale background count by **14**.











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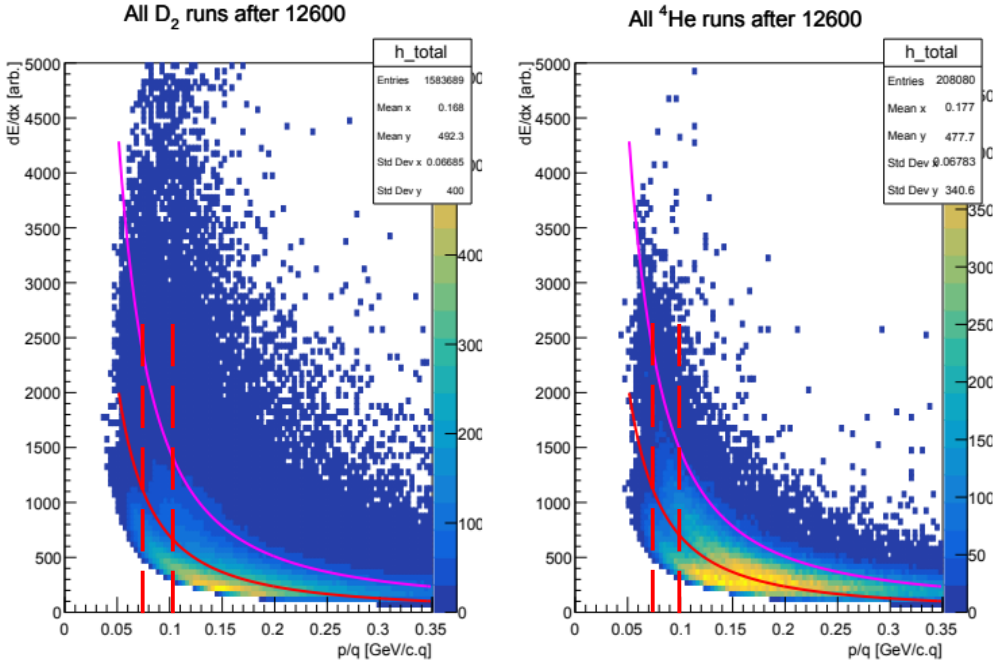
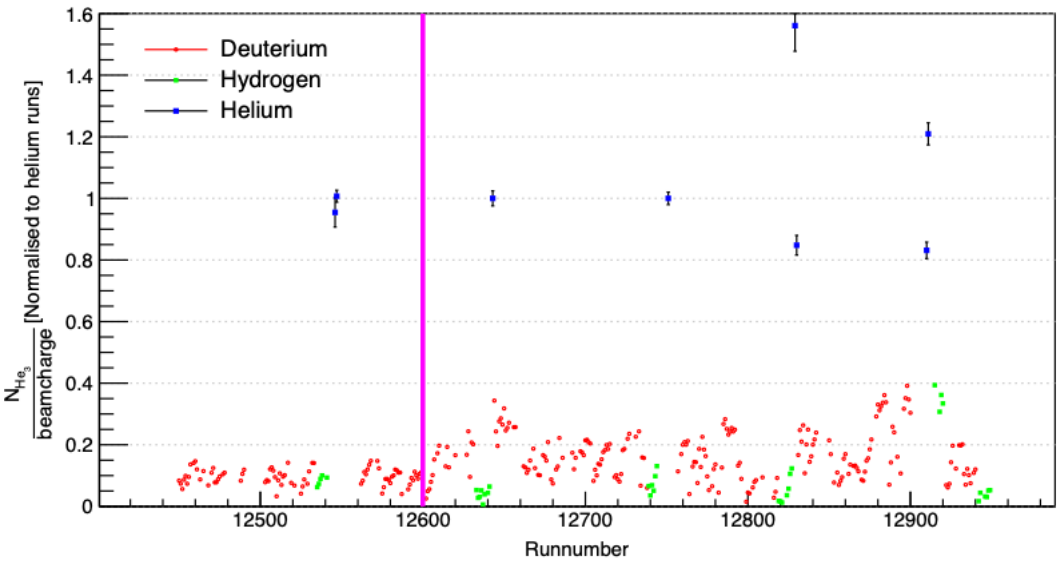
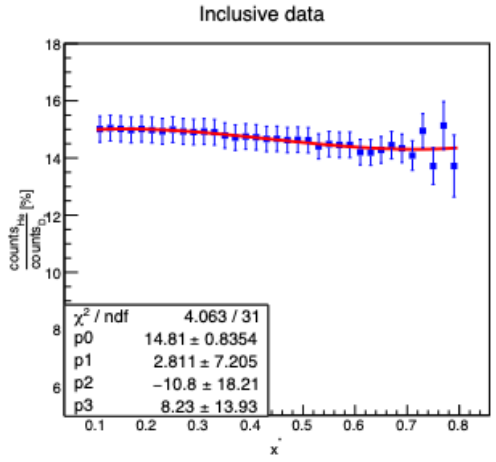
BONuS12 Corrections II: ^{4}He Contamination

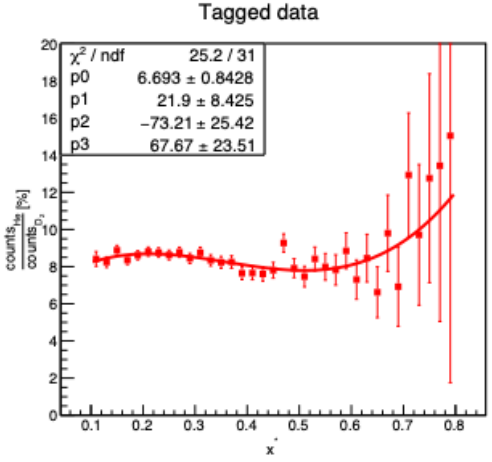
- Fraction of ^{4}He in D_2 target due to permeable target straw.
- Estimated using ^{3}H/^{3}He band in dE/dx vs. p/q.





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





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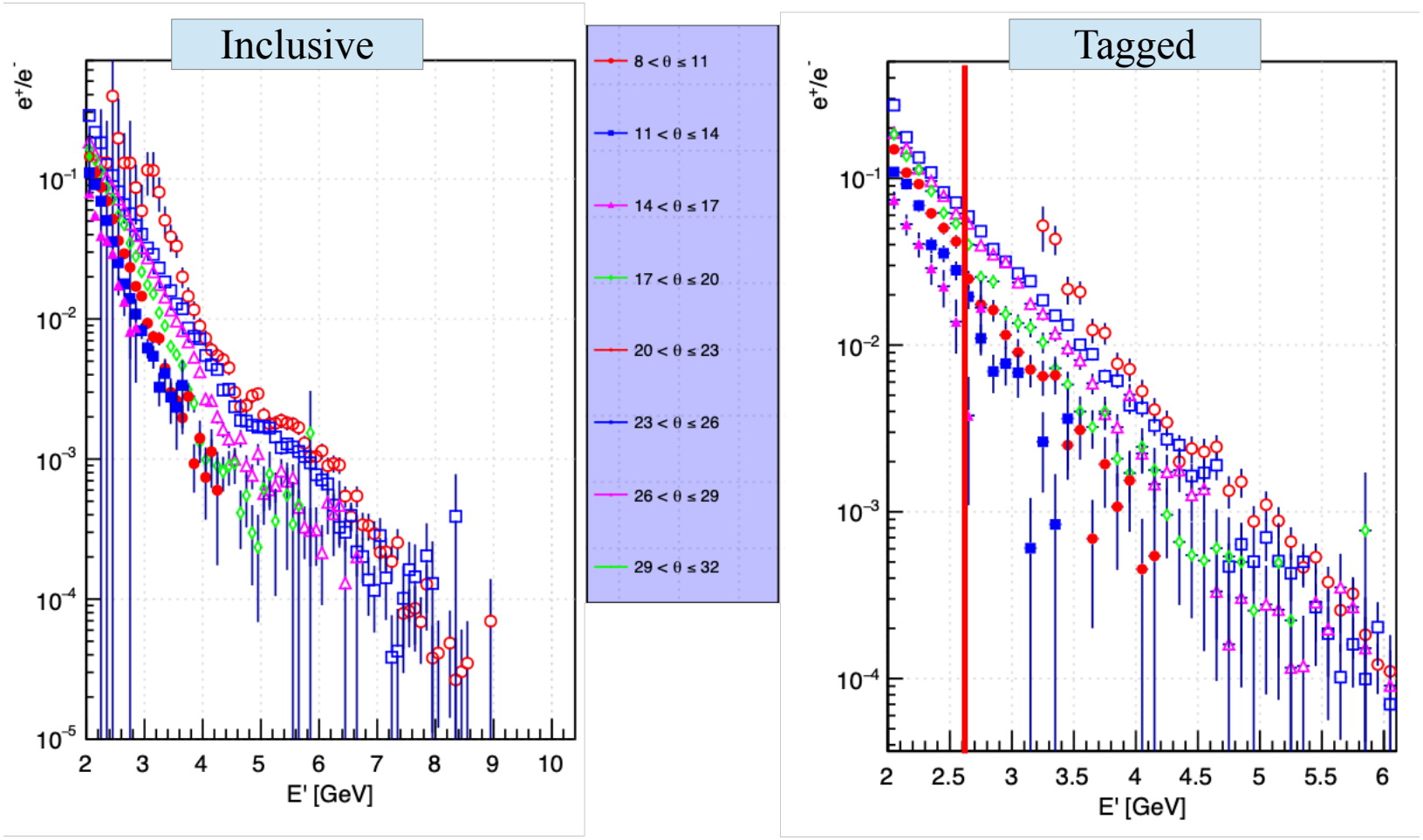
BONuS12 Corrections III: Pair-symmetric bgnd

- **For inclusive analysis:** e^+/e^- is measured by comparing e^+ from outbending torus runs with e^- from inbending torus runs (Winter2020 dataset).
- **For tagged analysis:** evaluated using e^+/e^- from tagged and inclusive events from Summer2020 dataset corrected by the inclusive e^+/e^- from Winter2020 data as:

$$R_{tag}(summer, true) = \frac{R_{tag}(summer)}{R_{inc}(summer)} R_{inc}(spring)$$



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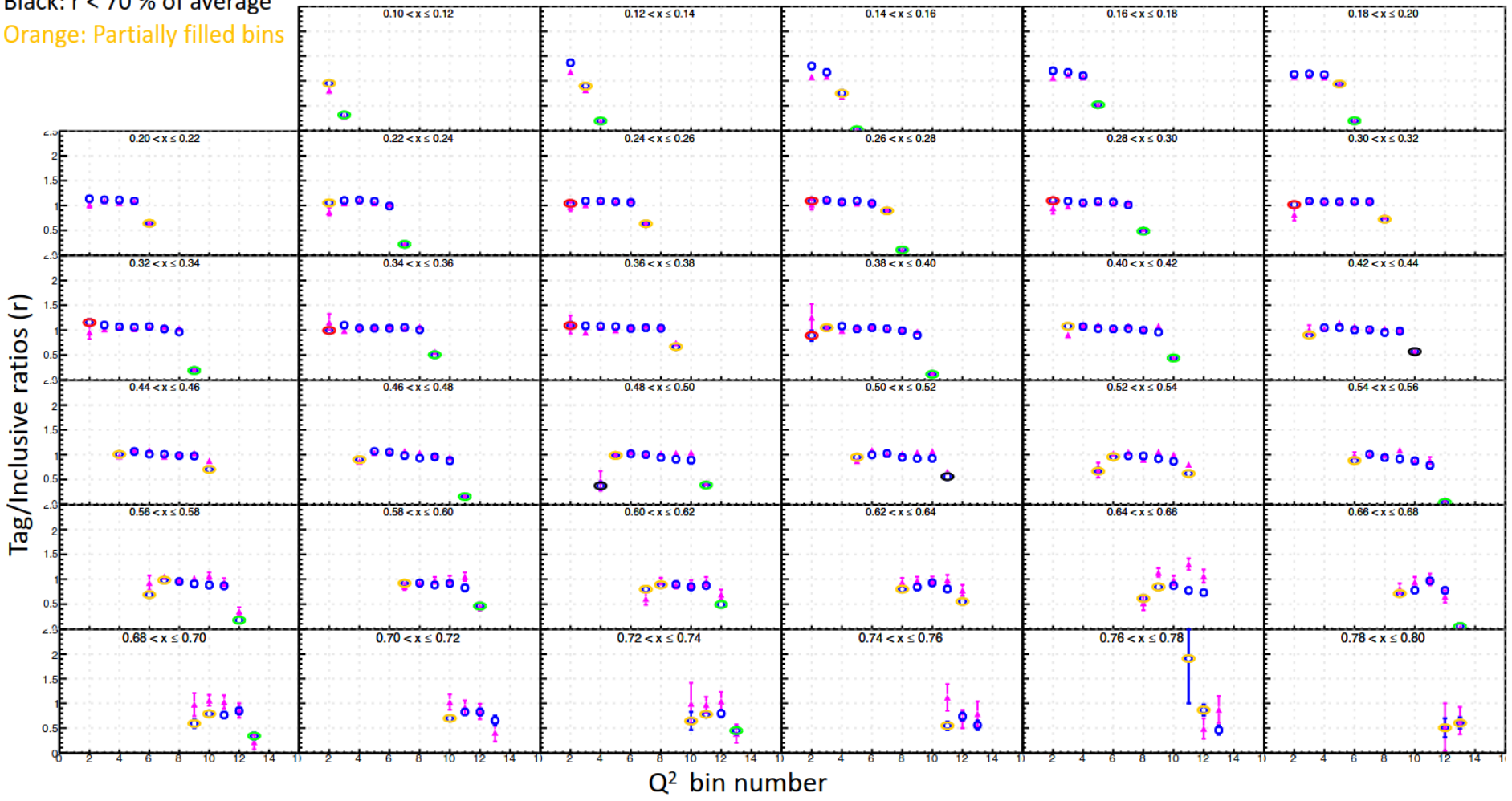
BONuS12 Corr. IV: Culling Partially Filled Bins

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.

Green: r < 0.5
Red: Statistical uncertainty > 2.5 times the average
Black: r < 70 % of average
Orange: Partially filled bins

Magenta: Data : Blue: MC



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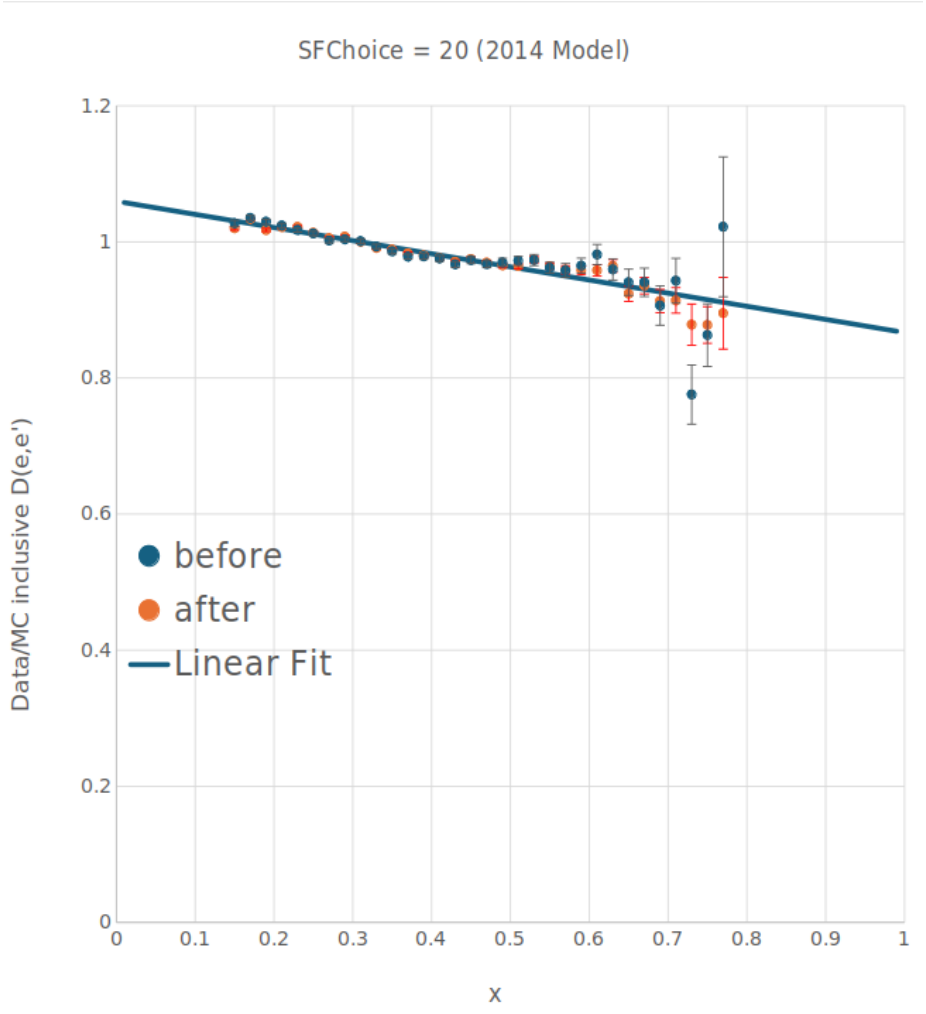
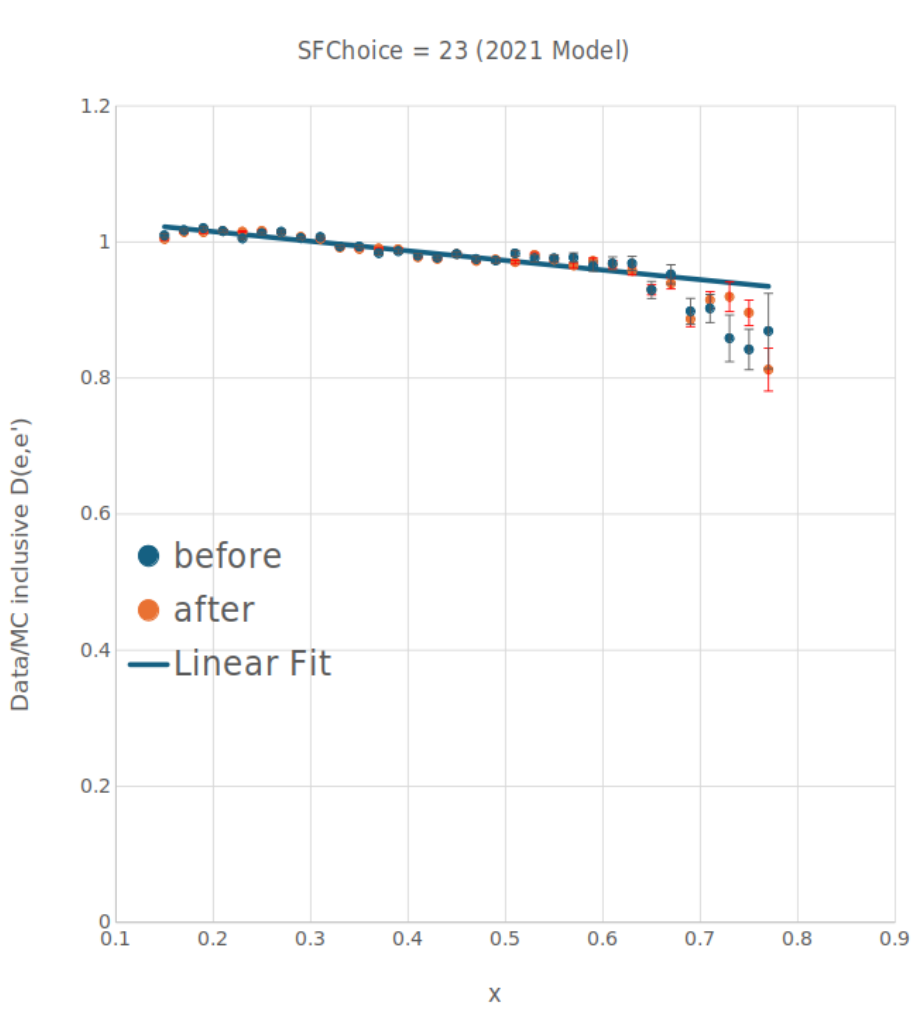
BONuS12 Model-Dependent MC Generation





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