Analysis Status of the BONuS12 Experiment [RG-F]

CLAS Collaboration Meeting
March 12 – 15, 2024

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BONuS: "Barely Off-Shell Neutron Structure"

In Deep Inelastic Scattering (DIS), the unpolarized scattering cross section is,

$$\frac{d\sigma}{dxdQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[(1-y)\frac{F_2(x,Q^2)}{x} + y^2 F_1(x,Q^2)\right]$$

In partonic model,

$$F_2(x,Q^2) = 2x\, F_1(x,Q^2) = x \sum_q z_q^2 \,.q(x).$$

$q_i(x)$: PDFs provide information on longitudinal momentum distributions.

In Valence region

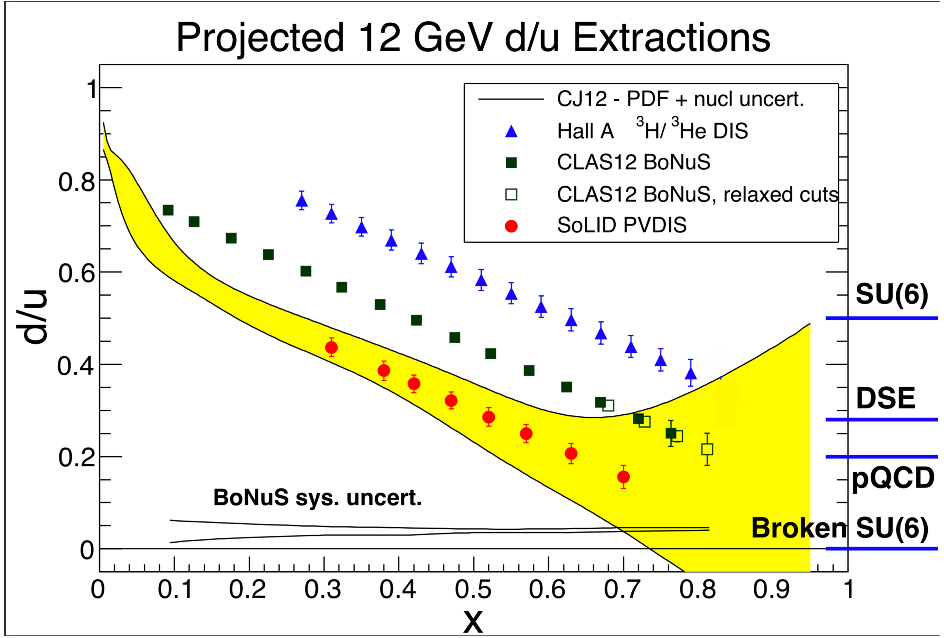
For proton,

$$F_2^p \approx \; x\left[\frac{4}{9}u(x) + \frac{1}{9}d(x)\right] \; : \text{dominated by } u(x)$$

For neutron,

$$F_2^n \approx \; x\left[\frac{4}{9}d(x) + \frac{1}{9}u(x)\right] \; : \text{dominated by } d(x)$$

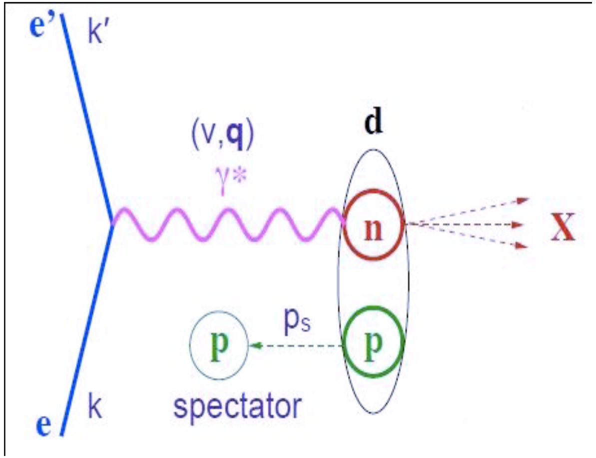
Fig from 2015 LRP for Nuclear Physics



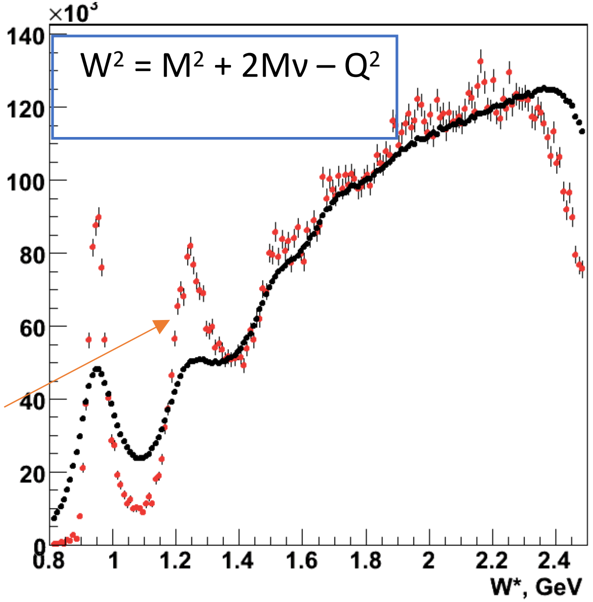
- DIS on protons gives constraints on $u(x)$
- We need measurements on neutrons to extract $d(x)$ precisely.

- Free neutron decays in just under 15 mins
- It is difficult to form a dense neutron target because it is chargeless

Spectator Tagging and BONuS12 Experiment:



$$W^{*2} = (p_n + q)^2$$
$$= p^{\mu} p_{\mu} + 2((M_D - E_s)\nu - \bar{p}_n . \bar{q} - Q^2$$
$$\approx M^{*2} + 2M\nu(2-\alpha_s) - Q^2$$



Kinematically minimize nuclear effects

- VIP protons: $P_s < 100$ MeV/c
- Backward Moving Protons: $\theta_{pq} > 100$ [spectator angle relative to virtual photon exchange]

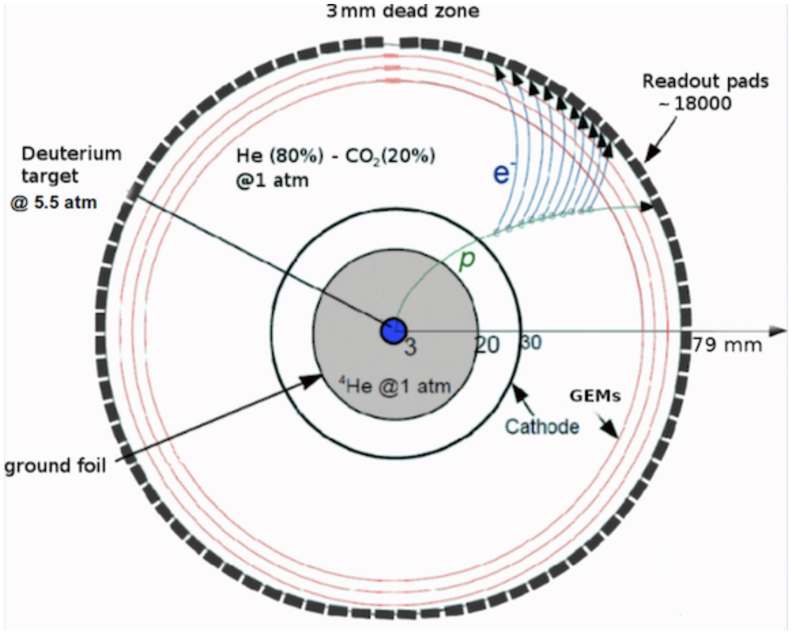
→ scattering from "nearly" free neutron

→ use proton momentum to correct for the initial state neutron

$$p_n = (M_D - E_s, -\vec{p_s})$$
$$p_s = (E_s, \vec{p_s})$$
$$\alpha_s = \frac{2(E_s - \vec{p_s} \cdot \vec{q})}{M_D}$$
$$x^* \approx \frac{Q^2}{2M\nu(2 - \alpha_s)}$$

BONuS12 RTPC:

A Gas Electron Multiplier(GEM) based detector was built to measure spectator protons



Run Conditions

E_b = 10.4 GeV, 2.1 GeV (calibrations)

Target = D_2 /He-4 / H_2/ Empty

Target Pressure: 5.5 atm, 293 K

L = $2 \cdot 10^{34} cm^{-2} s^{-1}$

Nuclear Instruments and Methods in Physics Research A 1062 (2024) 169190

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

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Full Length Article

Design, construction, and performance of the GEM based radial time projection chamber for the BONuS12 experiment with CLAS12

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ARTICLE INFO

Keywords:
Time projection chamber
Gas electron multiplier
Spectator-tagging
BONuS12 experiment
Nuclear physics
CLAS12 spectrometer

ABSTRACT

A new radial time projection chamber based on Gas Electron Multiplier amplification layers was developed for the BONuS12 experiment in Hall B at Jefferson Lab. This device represents a significant evolutionary development over similar devices constructed for previous experiments, including cylindrical amplification layers constructed from single continuous GEM foils with less than 1% dead area. Particular attention had been paid to producing excellent geometric uniformity of all electrodes, including the very thin metalized polyester film of the cylindrical cathode. This manuscript describes the design, construction, and performance of this new detector.

1. Introduction

The BONuS12 experiment was carried out in Hall B at Jefferson Lab in 2020. The goal of the experiment was to measure the F_2 structure function from a *nearly* free neutron at large Bjorken x via inclusive electron scattering, where x is the fraction of the momentum carried by the struck quark inside the nucleon. This experiment utilized the recently upgraded CEBAF accelerator, which nearly doubled the beam energy compared to the previous BONuS experiment [1,2]. This allowed the experiment to reach larger values of both Bjorken x in the deep inelastic scattering (DIS) region, as well as the 4-momentum transfer Q^2. Due to the lack of high density neutron targets, the experiment utilized a pressurized gas target filled with deuterium gas. In order to ensure that the electron scattered off a weakly-bound neutron inside the deuterium, a low momentum spectator proton was tagged in a Radial Time Projection Chamber (RTPC) in coincidence with the scattered electron. The scattered electrons, as well as other particles, were detected with the CLAS12 spectrometer in Hall B.

For this RTPC, the gas electron amplification relied on three concentrically stacked layers of Gas Electron Multiplier (GEM) foils [3]. Its design is a significant improvement over earlier GEM based RTPCs utilized in Hall B for both, the original BONuS experiment [4], and for a later experiment [5] designed to tag alpha particles. Much of the design improvements were due to progress in the production of large area GEMs, which allowed the production of cylindrical GEM layers made from single GEM foils without the need to splice multiple foils together. This significantly reduced the inactive area of the RTPC from 30% in the previous RTPCs to 3% in this unprecedented detector.

The BONuS12 RTPC replaced the central tracker of the CLAS12 spectrometer [6], which is situated inside the solenoid of the CLAS12 Central Detector. Compared to a more typical "axial" TPC, an RTPC has several advantages in view of the needs of this experiment. A larger number of readout pads to improve the spatial resolution and to accommodate larger multiplicity rates. Reduced drift time of the ionization electrons inside the active detector region, making an RTPC a comparatively faster detector. It also allows for a somewhat simpler gas system.

There were several motivations in designing this new detector.

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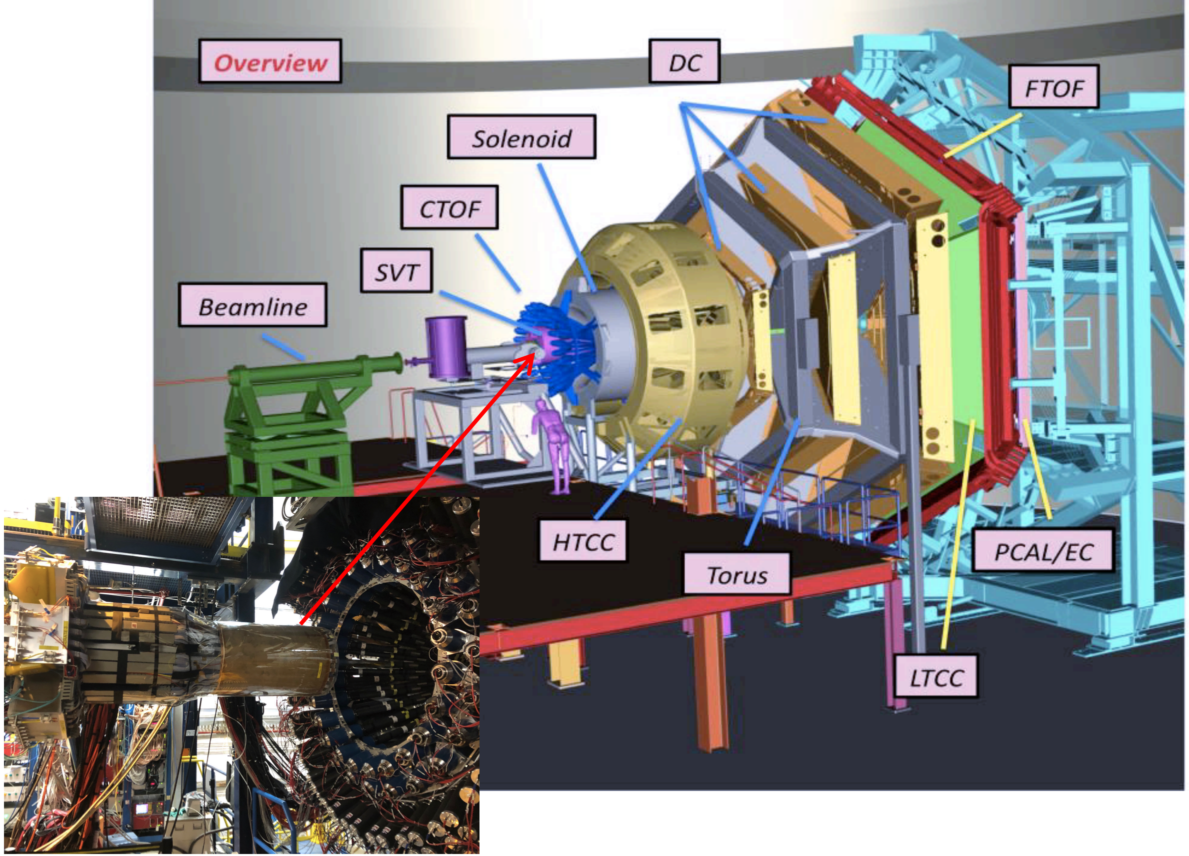
BONuS12 RTPC in CLAS12

CLAS12 forward detectors:

- Superconducting torus magnet ($\pm$ polarity)
- 6 independent sectors
- HTCC
- 3 regions of DCs
- LTCC /RICH
- FTOF counters
- PCAL and ECs

Central:

- BONuS12 RTPC
- FMT (3 layers)
- Solenoid (3.8 T)
- CTOF, and CND



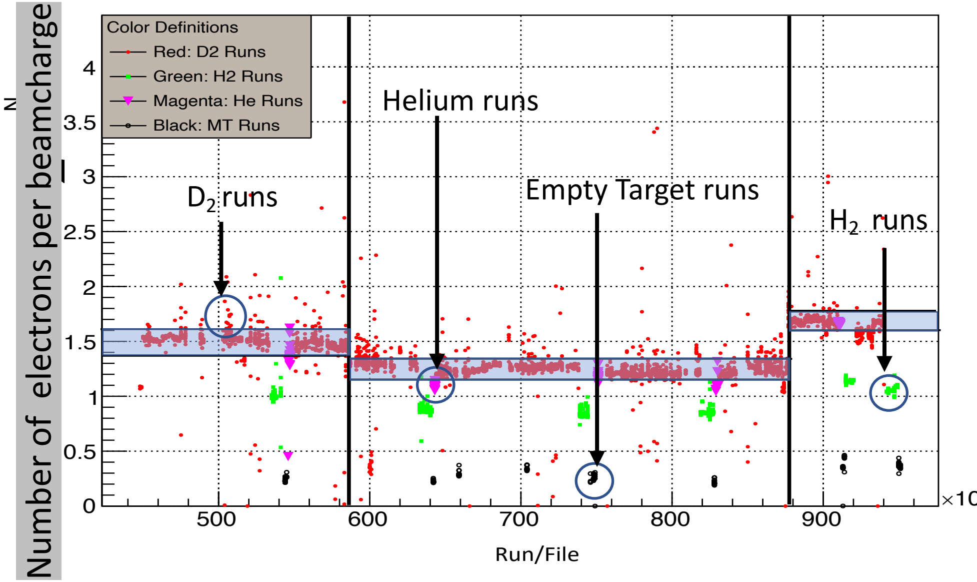
Collected ~ 3.5 billion triggers in the Summer 2020 run

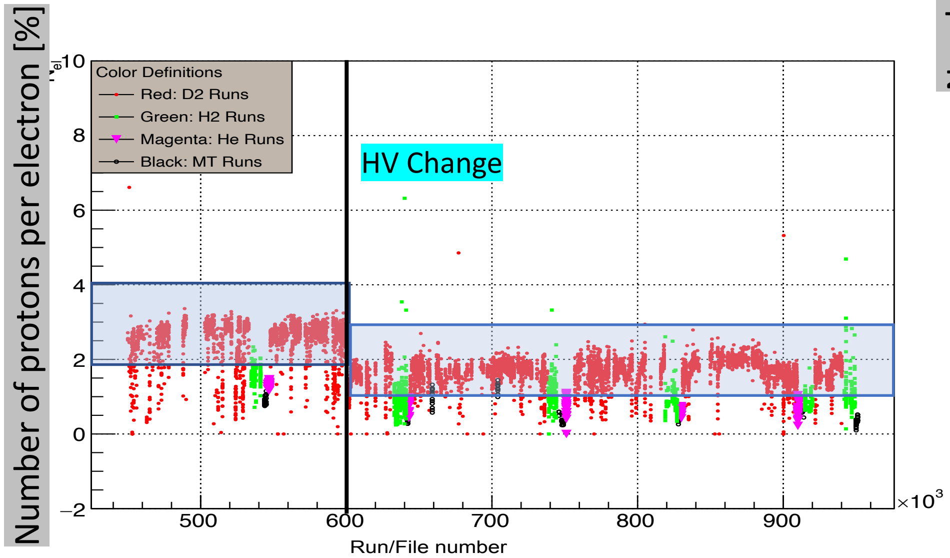
The Pass1 review has been completed. Since then, all Summer 2020 data has been decoded and cooked. All results are based on this version.

Good run/ file selection

Normalized electron yield

- Select a good run/file for final analysis.
- Extracted the electron yield normalized to beamcharge.
- Expect this quantity to be stable and consistent for runs with similar run conditions.





Proton yield per electron

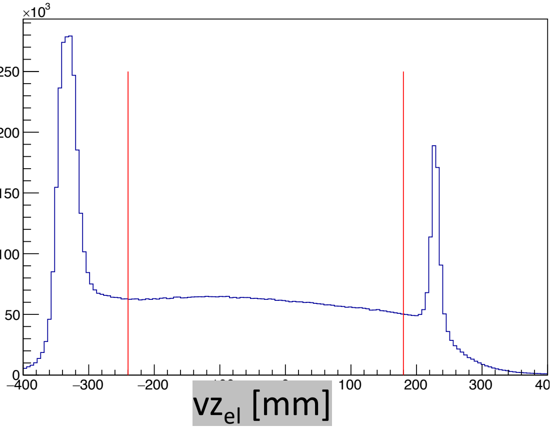
- Additional cut for good file selection based on the number of proton tracks in RTPC per electron.

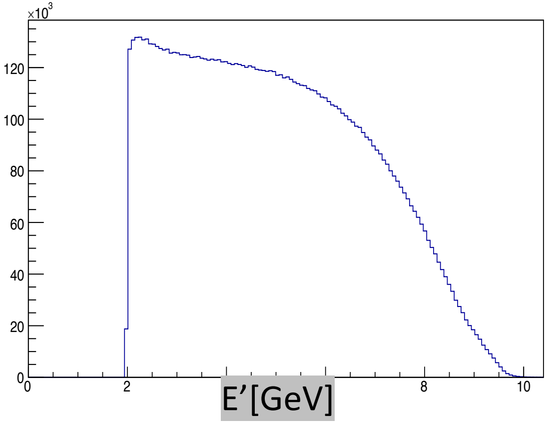
Electron selection for analysis

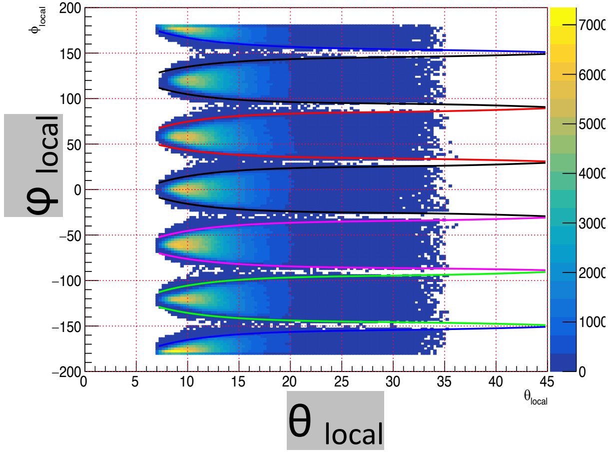
- PID = 11
- Nphe > 2
- Sampling fraction > 0.2
- EC_{in} > 10 MeV
- EPCal > 100 MeV
- DC fiducial cuts
- E' > 2 GeV

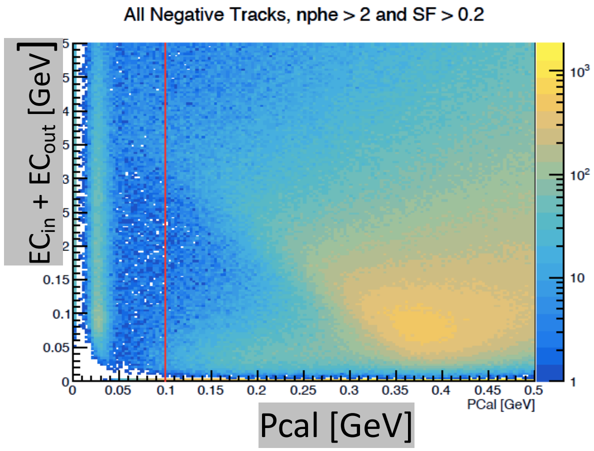
Additional DIS cuts

- W > 1.8
- Q^2 > 0.92









Spectator Proton selection cuts for analysis

Quality of tracks

- 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 < rmax < 72 mm
  [Distance of farthest hit from beamline]

Coincidence cuts

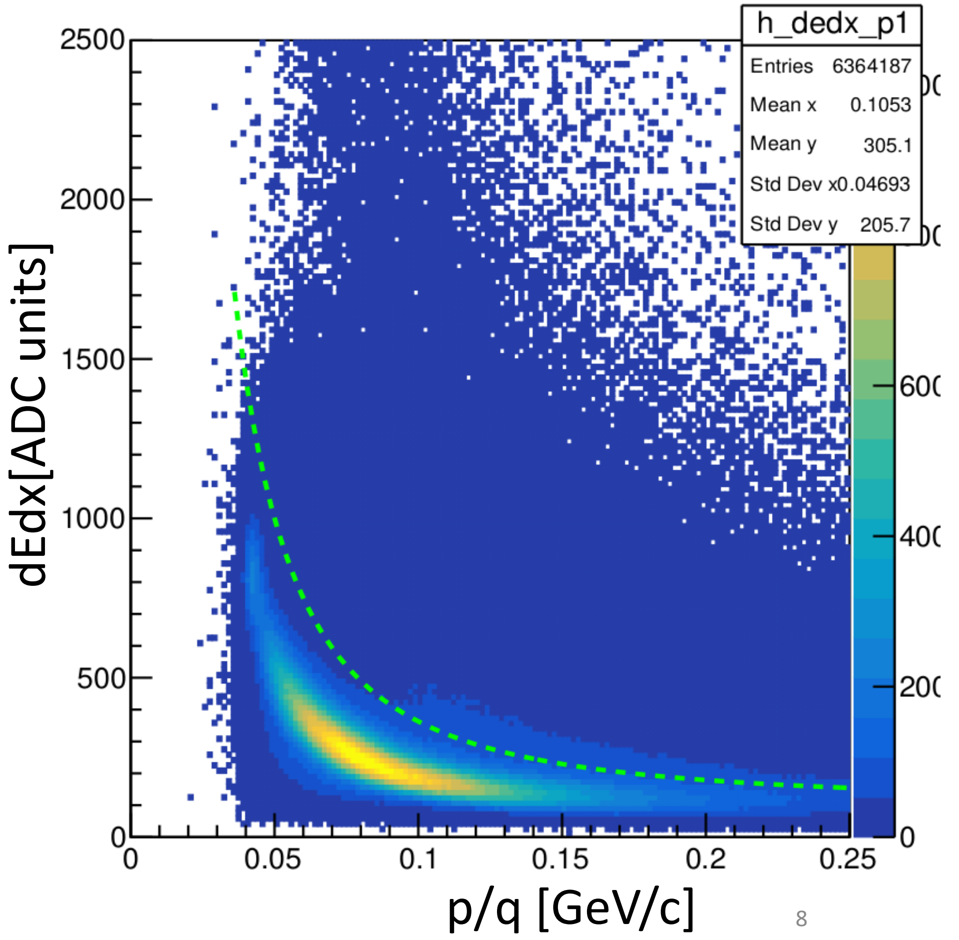
- Vertex coincidence cuts
- Timing coincidence

PID Cuts:

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

Spectator Cuts and DIS cuts

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

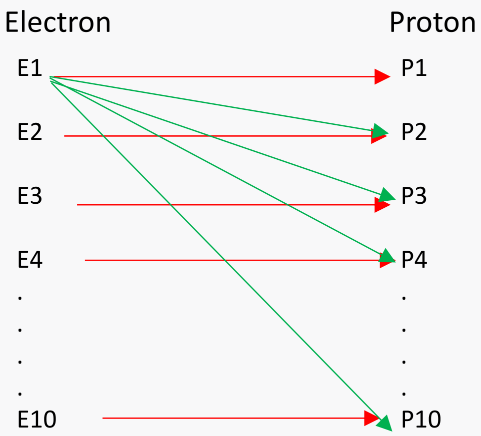


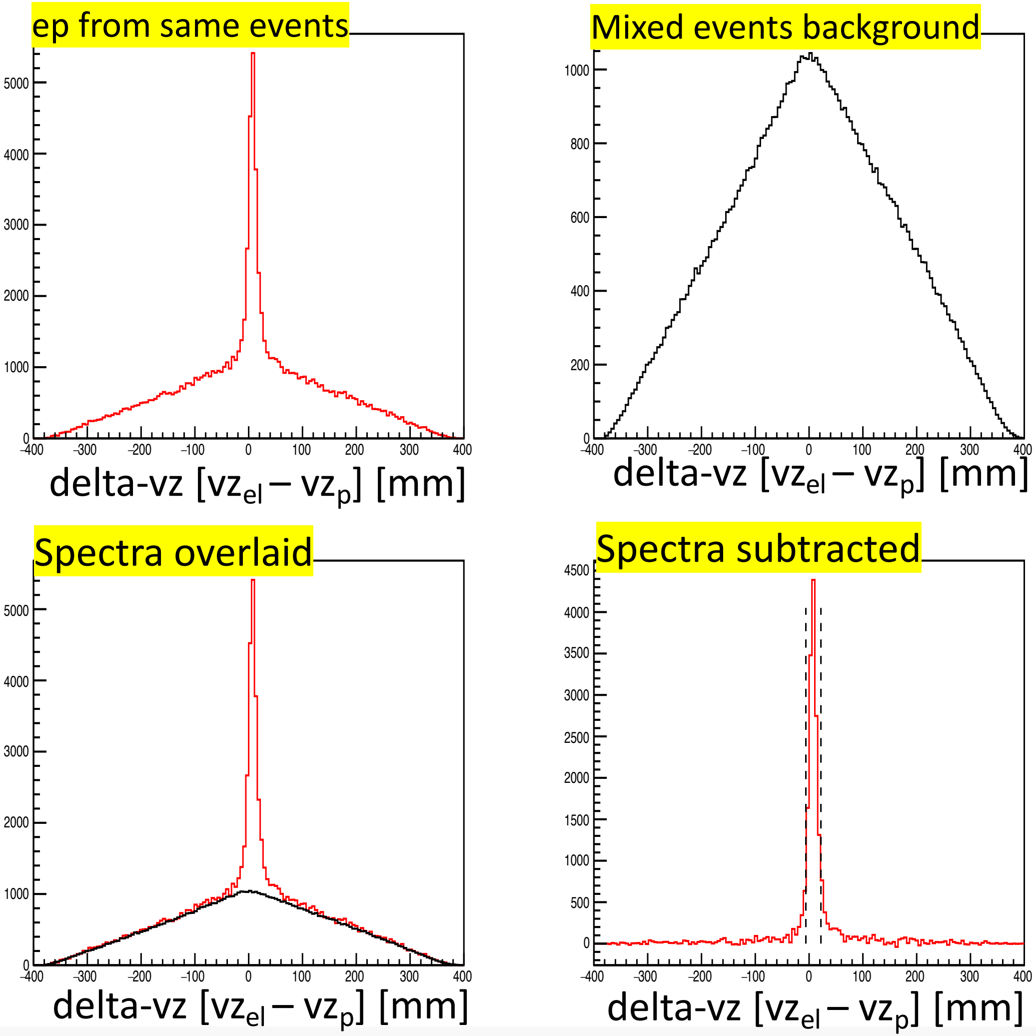
Accidental Backgrounds in BONuS12

To get better statistics on accidental backgrounds

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

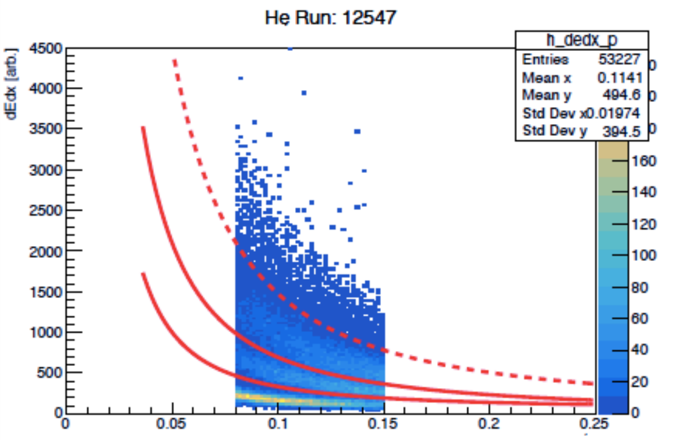
- We did event mixing
- Form 100 ep pairs
- 10 ep pairs [Red in fig.] from the same event
- 90 combinatorics backgrounds [Green in fig.].
- Scale background count by 9.

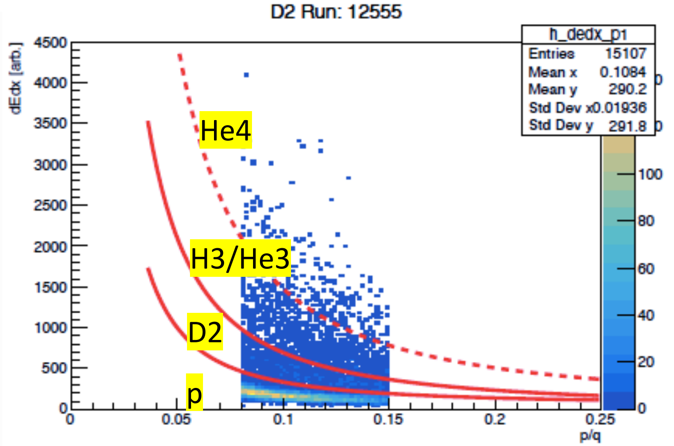




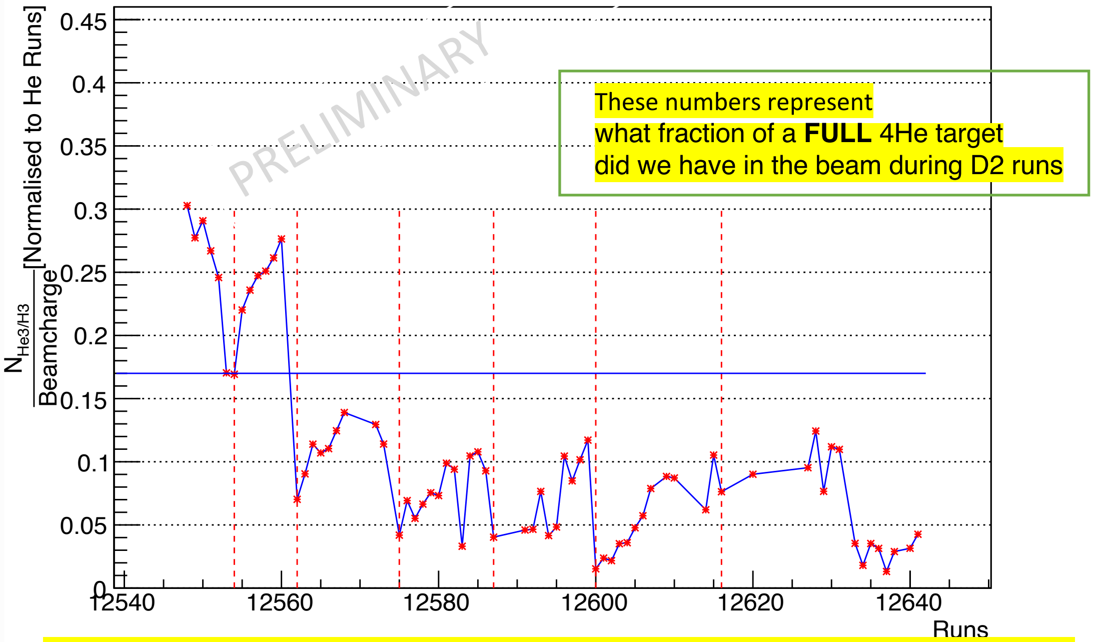
Deuterium Target Contamination

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





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



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

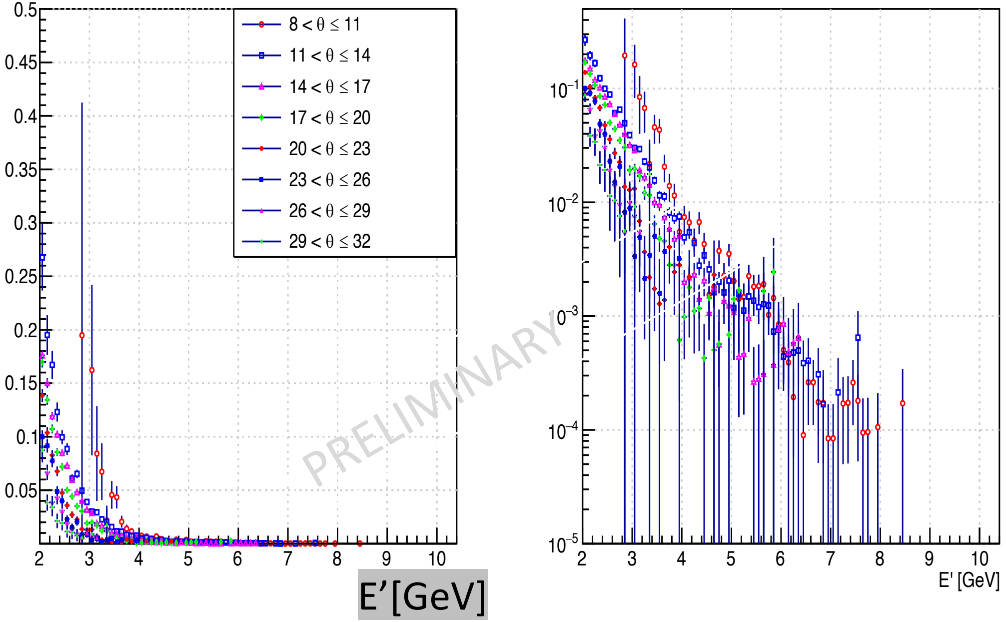
Pair Symmetric Background Correction: Inclusive Data

Primary sources of electron background are:

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

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

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



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

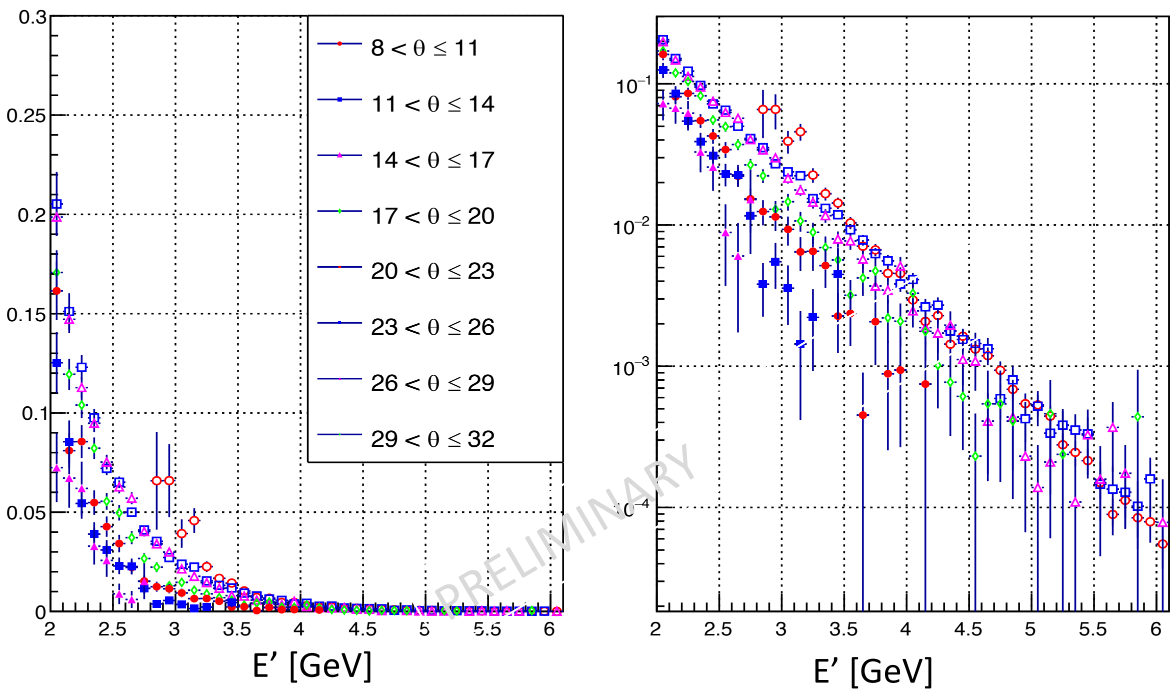
Pair Symmetric Background Correction: Tagged Data

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

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

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

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



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

Ratios results:

Our Final observable is

- the ratio of tagged to inclusive counts of events in a kinematical bin

The ratio of tagged to inclusive events

$$\left(\frac{N_{tag}^{exp}}{N_{inc}^{exp}}\right)_{data} \Big/ \left(\frac{N_{tag}^{MC}}{N_{inc}^{MC}}\right)_{MC} = \text{Constant.} \left(\frac{F_{2n}}{F_{2d}}\right)_{true} \Big/ \left(\frac{F_{2n}}{F_{2d}}\right)_{Gen}$$

BONuS12 Data | BONuS12 MC | BONuS12 Generator

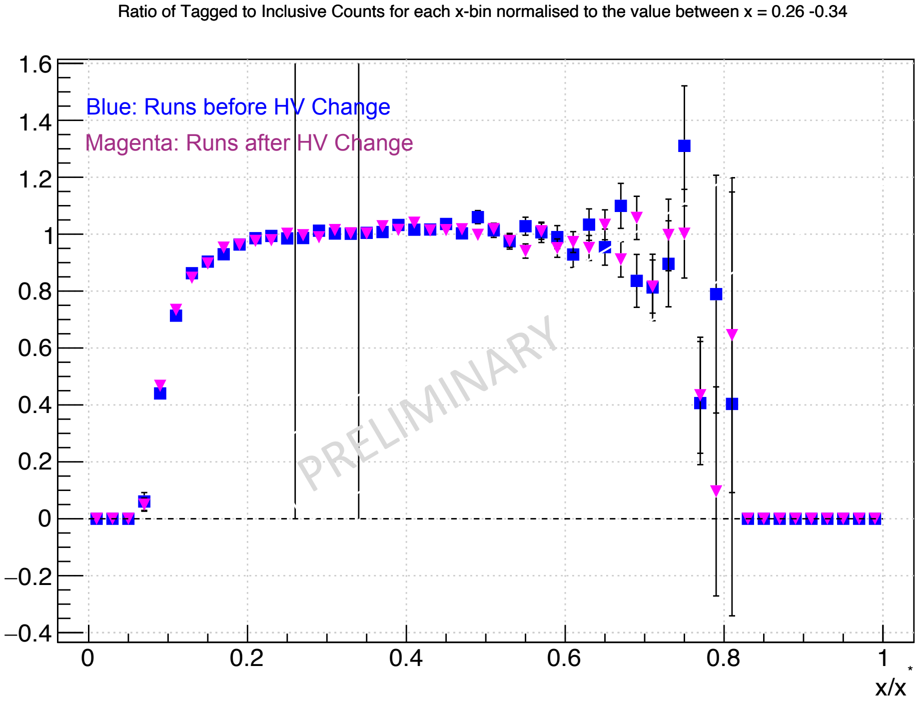
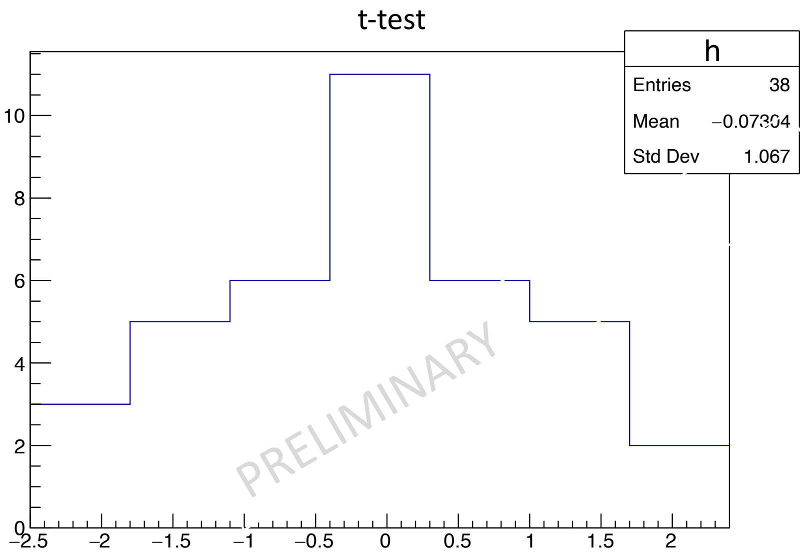


Fig: Normalized ratio of tagged to inclusive counts for each x/x' bin

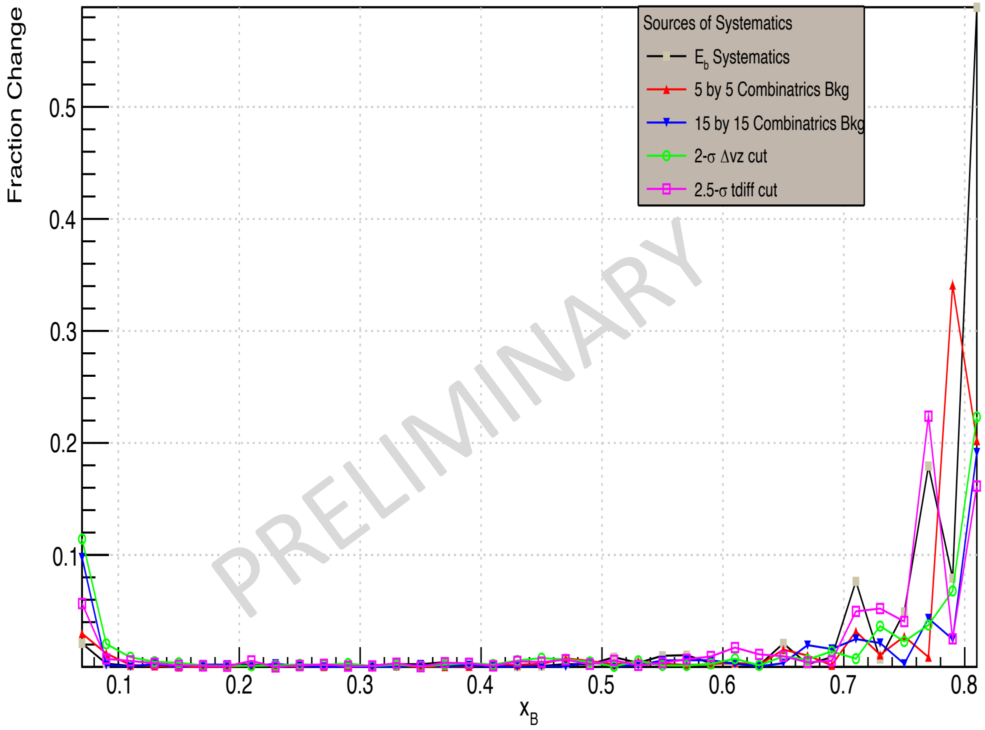


$$\frac{X_1 - X_2}{\sqrt{\sigma_1^2 + \sigma_2^2}}$$

X_1 and X_2 are tagged to inclusive ratios

Systematics Uncertainties

- Systematics studies are done by varying different cuts and variables used in our dataset.
- The new result compared to the nominal result
- The relative difference compared to the original is calculated



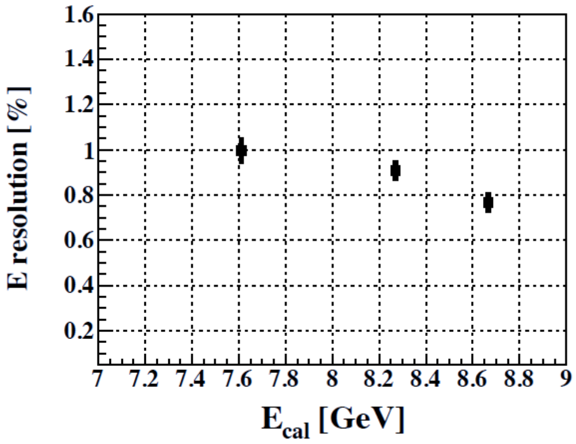
$$\text{Systematic fraction change} = \frac{\text{Ratio}_{\text{nom}} - \text{Ratio}_{\text{var}}}{\text{Ratio}_{\text{nom}}}$$

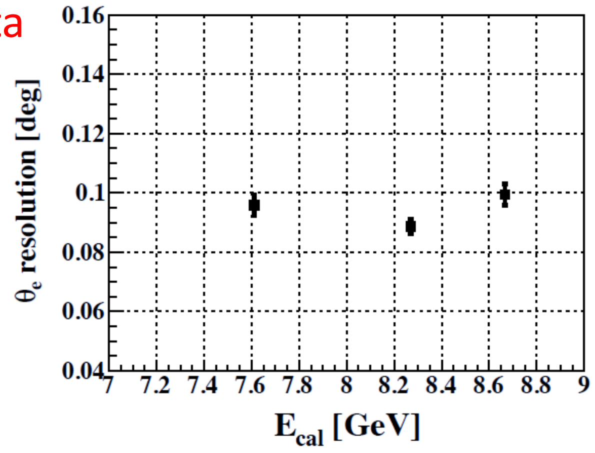
Work on progress !!

Resolutions:

- Elastic ep using 10 GeV data
- Both ep in the forward detector

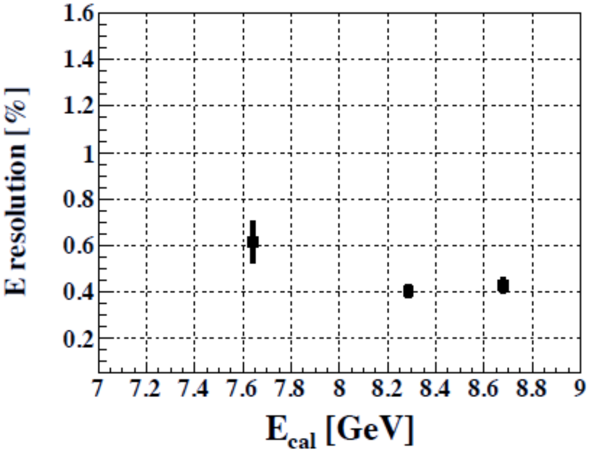
Data

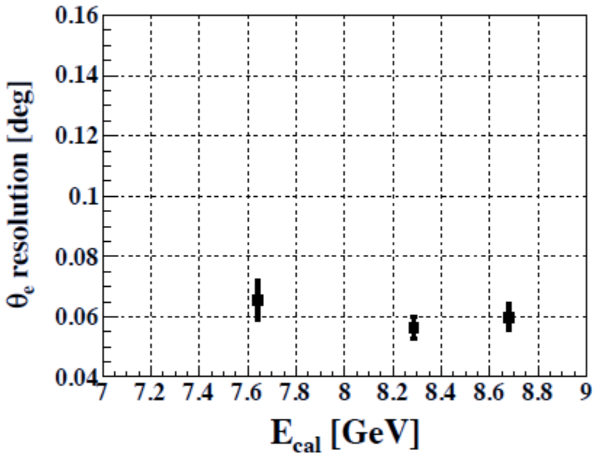




- Observed resolution in MC is nearly half of the real data

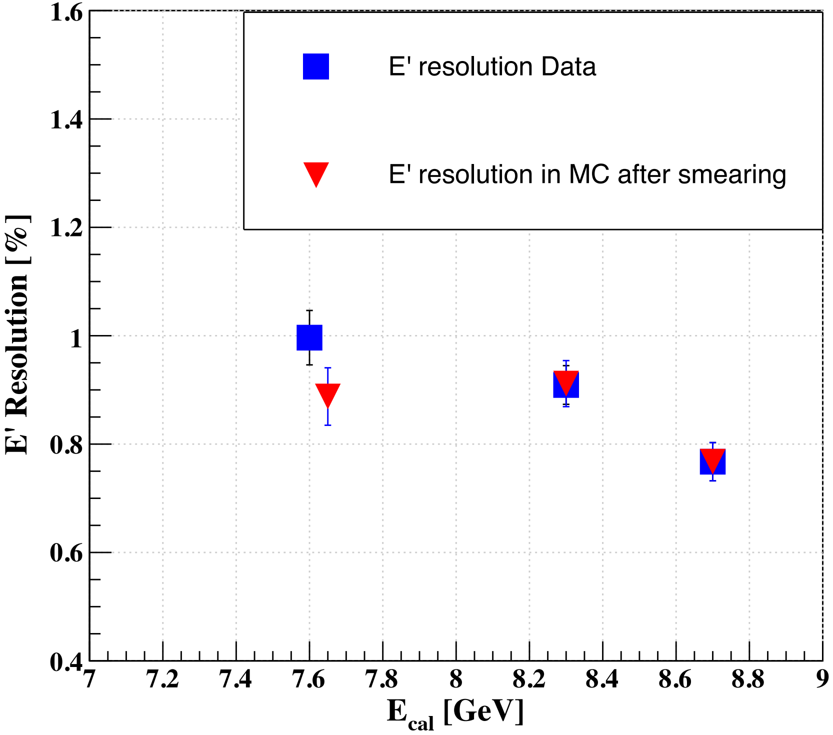
MC

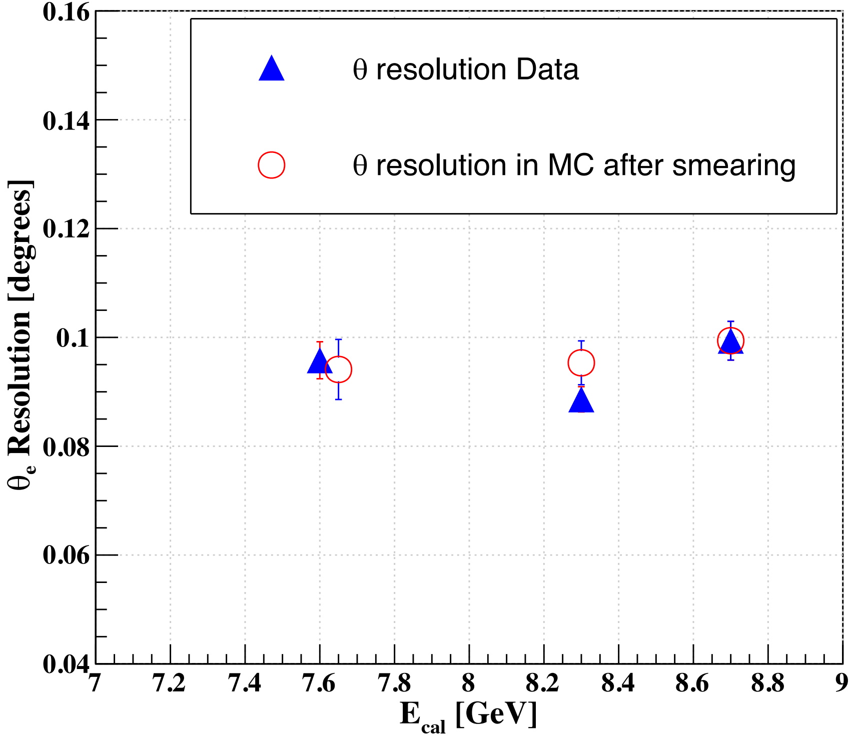




- So, we needed to implement additional smearing in reconstructed MC data

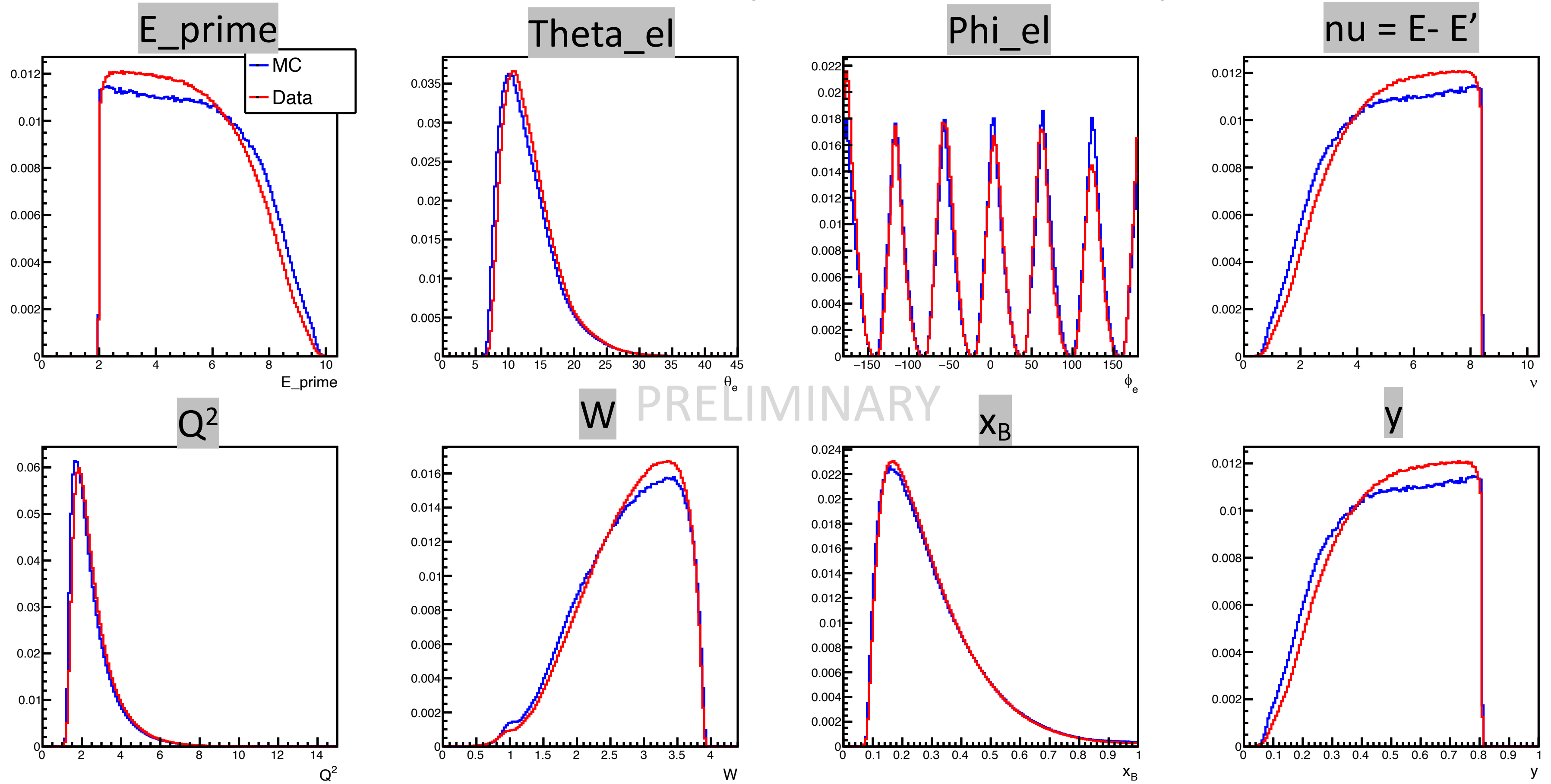
MC Resolutions after applying the additional smearing function

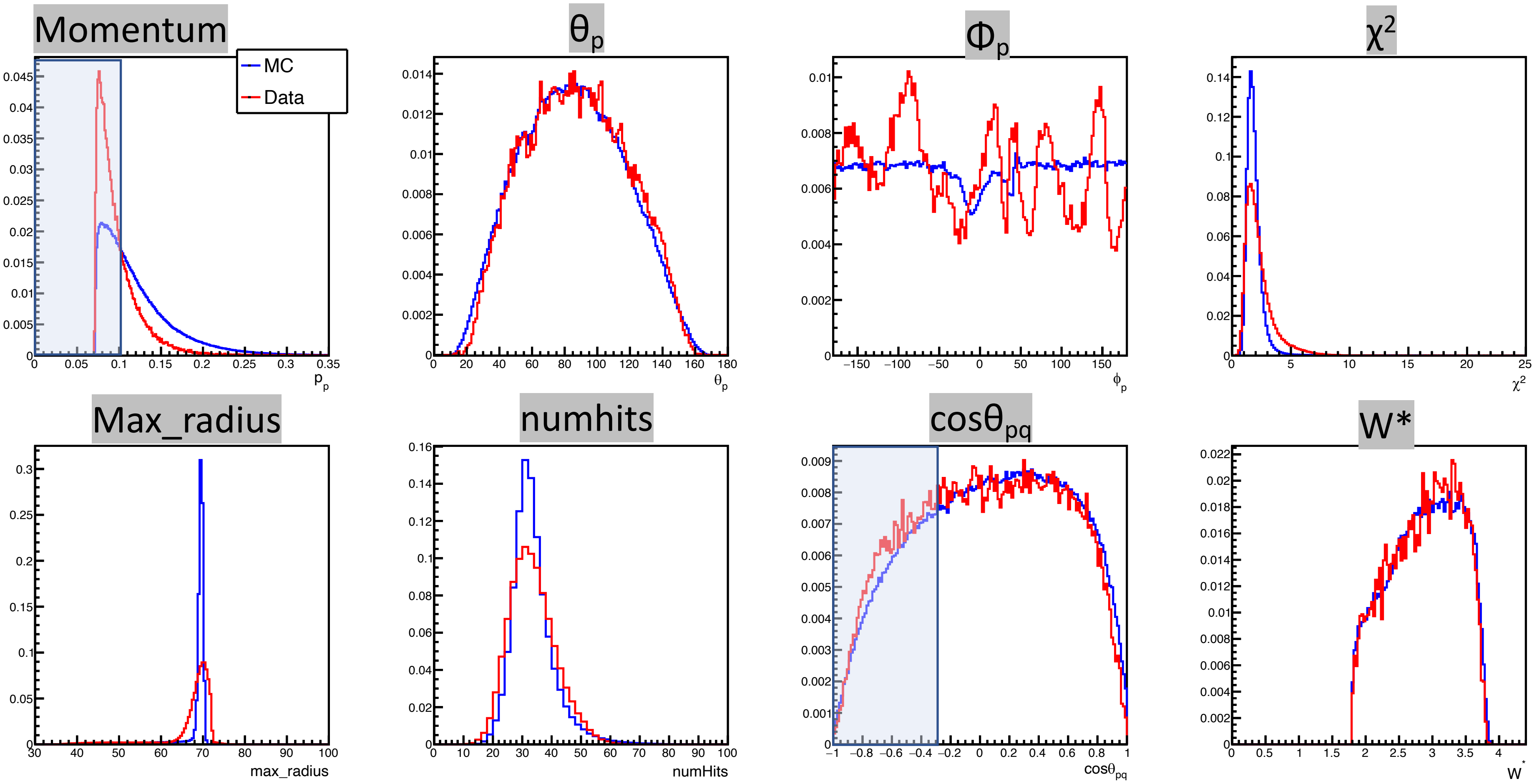




Updates on Simulation

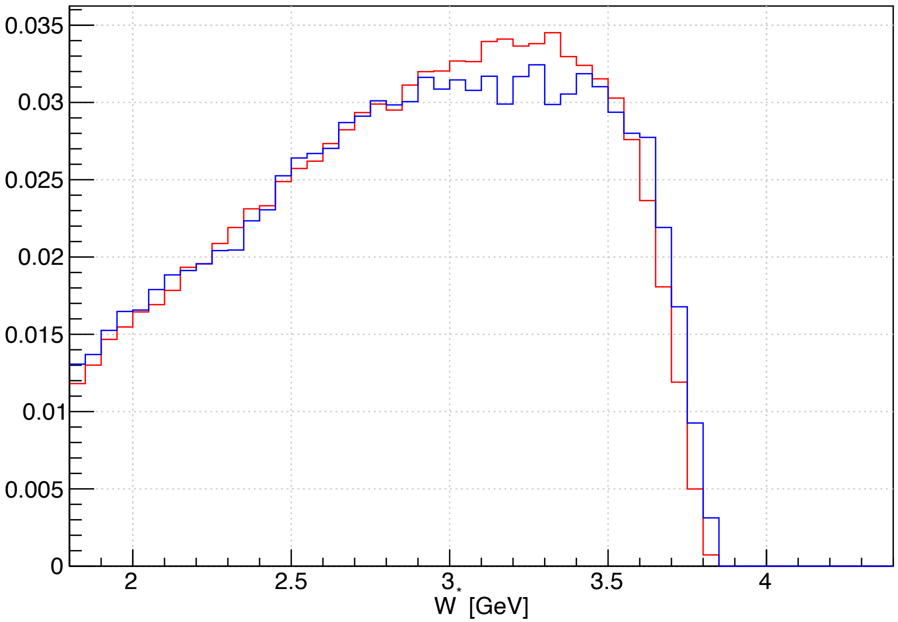
Generator: Updated version of Generator already used in the BONuS6 experiment

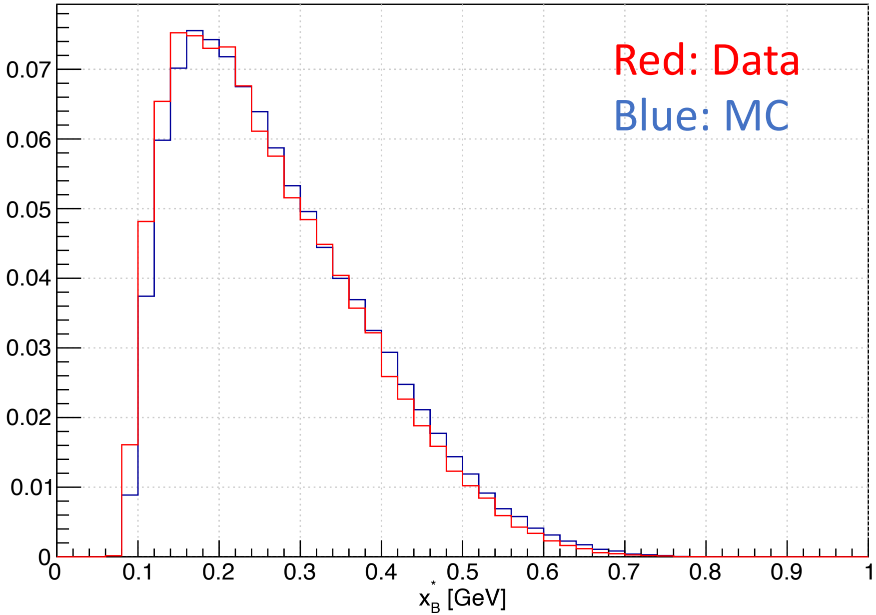



Momentum
MC
Data
p_p
θp
θ_p
Φp
φ_p
χ2
χ2
Max_radius
max_radius
numhits
numHits
cosθpq
cosθ_pq
W*
W*

Comparison: DIS Events

- $W^* > 1.8$
- $0.07 < p_s < 0.1$ GeV/c
- $\cos\theta_{pq} < -0.3$
- Accidental background subtracted
- Helium contamination subtracted
- Pair symmetric background contamination corrected





Conclusions and Perspectives

- RTPC NIM paper has been published
- All ingredients for the final physics analysis are ready
- Systematics study is in progress.
- The group has started writing analysis note for nDIS analysis.
- Stay tuned for physics result: F_{2n}/F_{2p} and d/u

BONuS12 Nuclear Uncertainties

Final State Interactions:

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

Target Fragmentation:

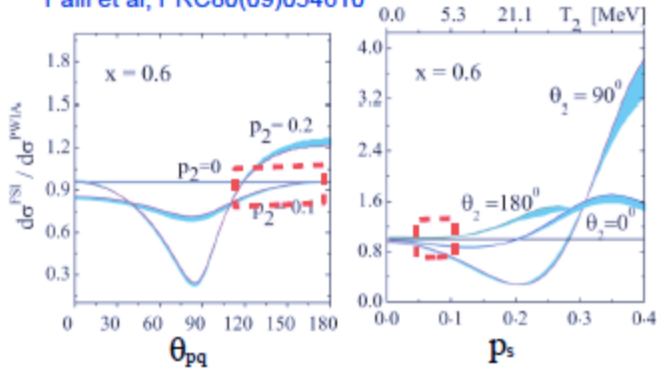
- $e\, n \rightarrow e\, p\, X$ (where $n \rightarrow \pi^- p$) and
  $e\, p \rightarrow e\, p\, X$ (where $p \rightarrow \pi^0 p$).
- TF enhances the proton yield only at forward angles ($\cos\theta_{pq} > 0.6$).

Off-Shell Corrections:

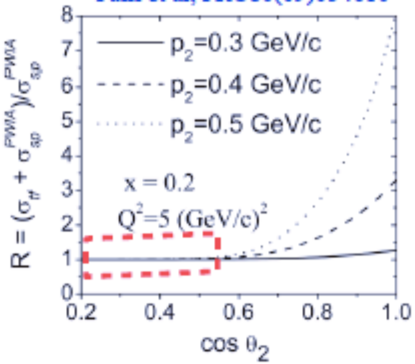
- Less than 2% in our region.

Overall systematic uncertainities will be less than 6%

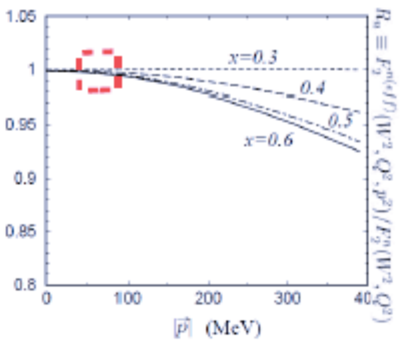
Palli et al, PRC80(09)054610



Palli et al, PRC80(09)054610



Melnitchouk et al, PRL B335,11(1994)

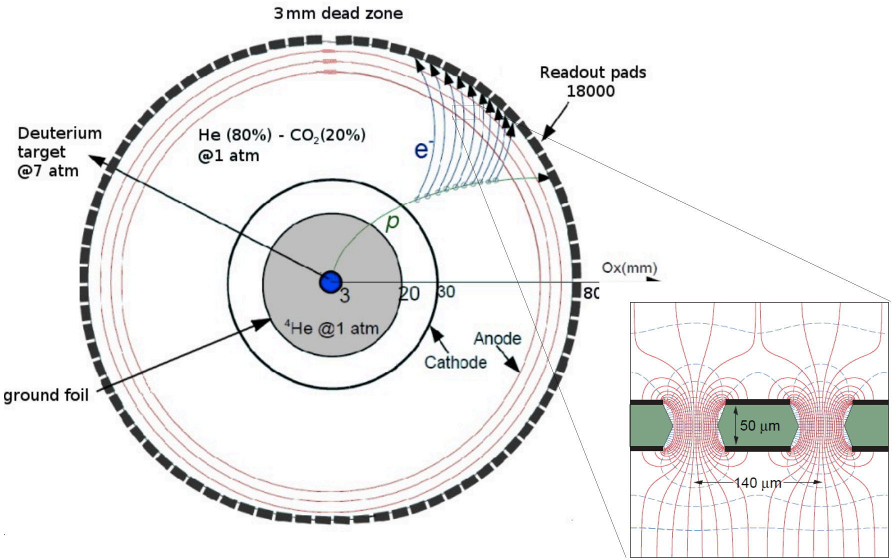


BONuS12 RTPC:

A Gas Electron Multiplier(GEM) based RTPC will measure protons between 70 MeV/c and 150 MeV/c .

Design

- 400 mm long cylindrical Detector.
- 360° Azithumal coverage
- Target gas is inside a 50 µm Kapton tube placed along axis at center of detector
- Consists a cathode foil at 4.3 kV
- 4 cm drift region
- Uniform E = 500V/cm and B = 3.78T
- 3 GEM's layers
- 17280 readout elements (2.7 mm x 3.9 mm)



RTPC with 3 Layers of GEM amplification

Advantages:

- Momentum threshold around 70 MeV/c
- Reduced quantity of material in forward part

BONuS12 Run Summary

- Feb 11 -2020 : Official start of experiment
- March 24 – June 08 -2020 Experiment halted due to MEDCON6 [Due to covid outbreak]
- Sep 21 -2020: End of experiment

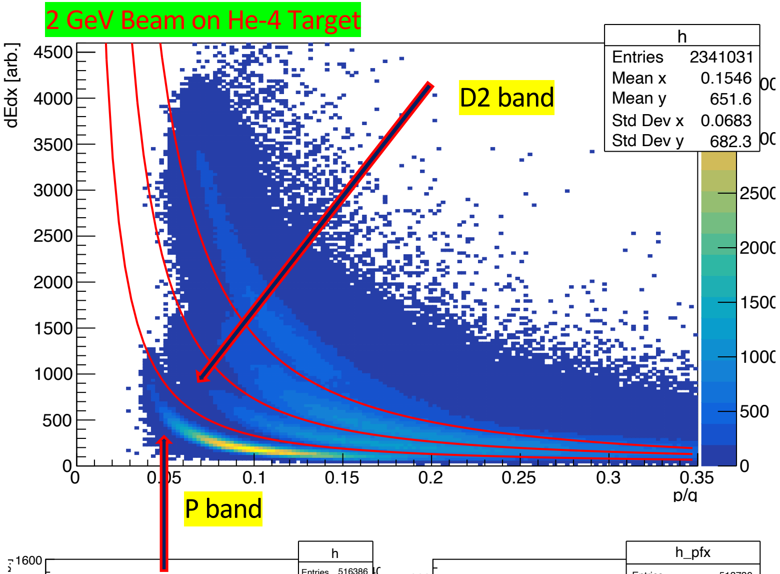
Beam Energy:
- 2.18 GeV (1 pass)
- 10.4 GeV (5 pass)

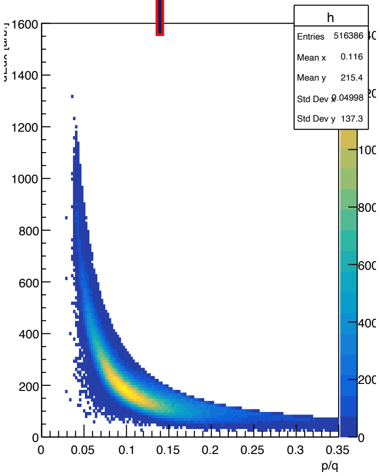
Target Gas :
- H_2
- He
- D_2
- Empty

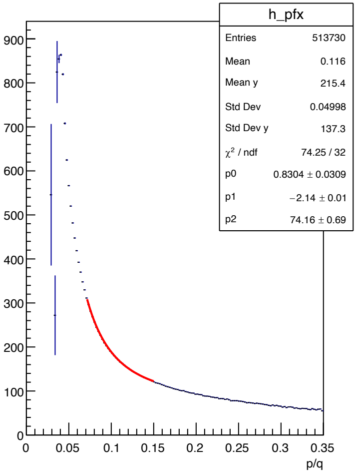
Target Pressure:
- 68 psi

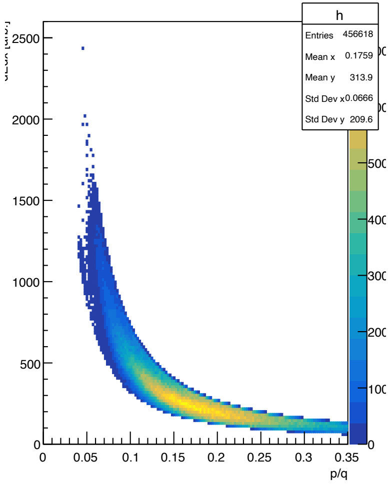
Beam Energy	Target	Spring - 2020	Summer - 2020
1 Pass	H2	81 M	185 M
	D2	37 M	45 M
	4He	19 M	44 M
	Empty	1 M	22 M
5 Pass	H2	151 M	266 M
	D2	2275 M	2355 M
	4He	77 M	51 M
	Empty	21 M	45 M

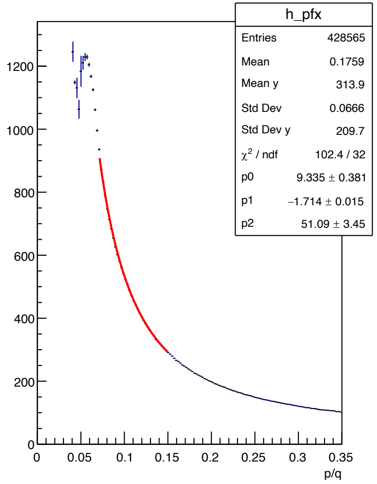
PID cuts for separating proton/deuteron from other particles in dEdx band

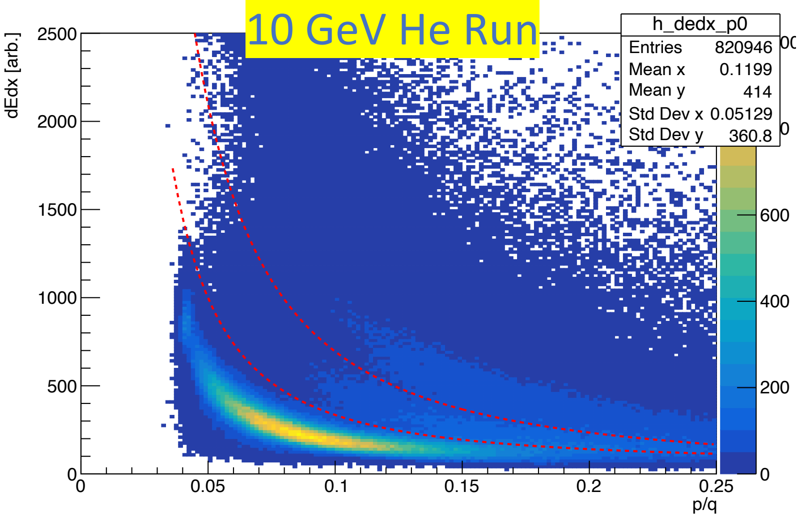










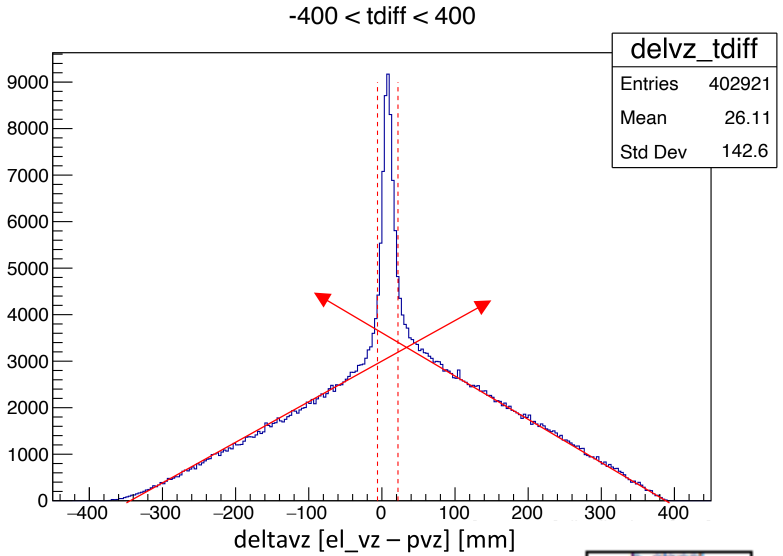


For spectator ep events selection we apply several quality cuts on the tracks.

For true coincidences following 2 cuts are further applied

- Δv_z cut: $< \Delta v_z > \pm 1.7\ \sigma$
- tdiff cut: <tdiff > $\pm$ 1.9 σ

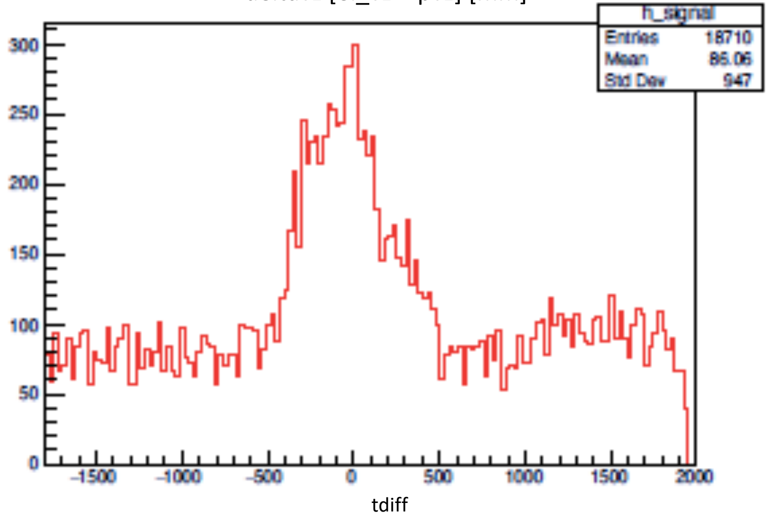
Even after these cuts total accidental background is over 72 % of signal



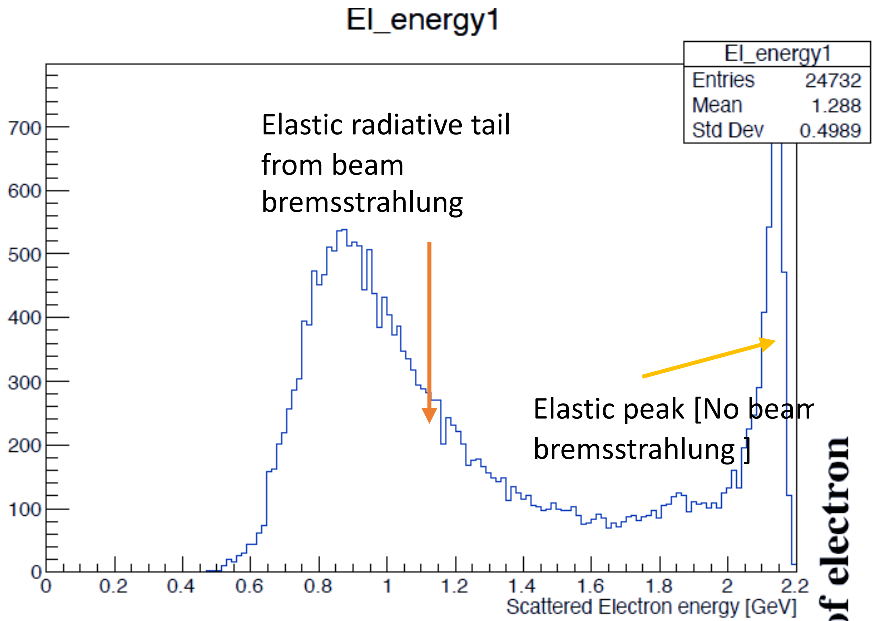
Background sampling

Could be done by extrapolating the side wing outside to inside of the wing. But

- ➢ The Δv_z distributions are not flat because,
- for a given Δv_z contributions can only come from some fraction of target length.
- It makes extrapolation uncertain and lowers statistics.

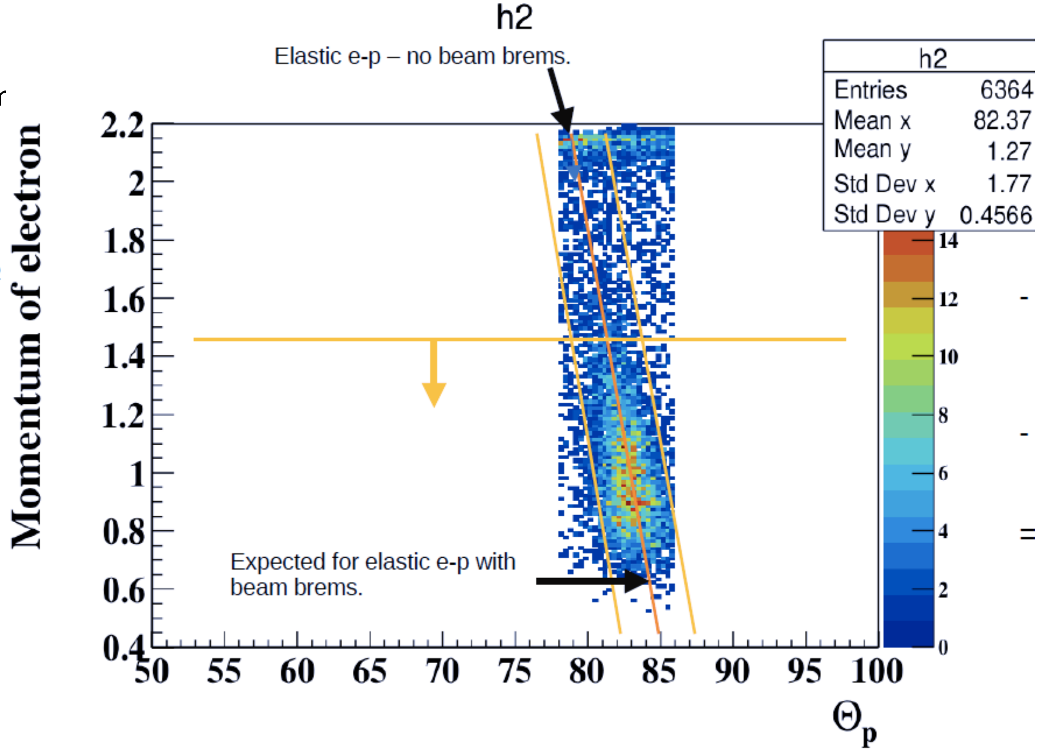


Momentum Calibration
Beam energy 2.18 GeV , Target H_2 gas



We used radiative ep scattering events:

- $E_{el} < 1.5$
- Theta_el : 5 – 8.6
- Apply del-phi and del-vz cuts
- Assuming event was elastic we calculate corrected beam energy at vertex using measured scattered electron energy [using elastic kinematics]
- Modify Lorentz drift angle until best agreement is reached between calc. and measured kinematics



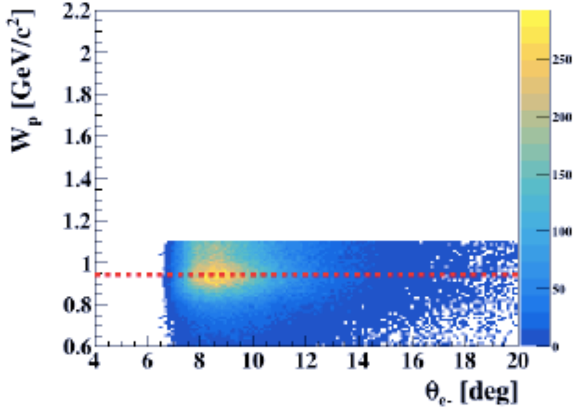
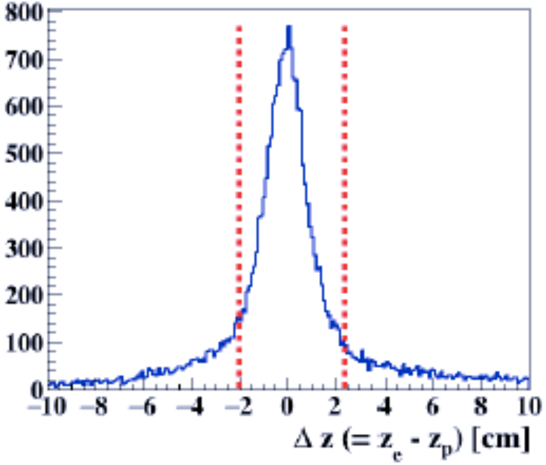


Figure 6: The correlation between the elastic peak in Wp and θ_e.

Data



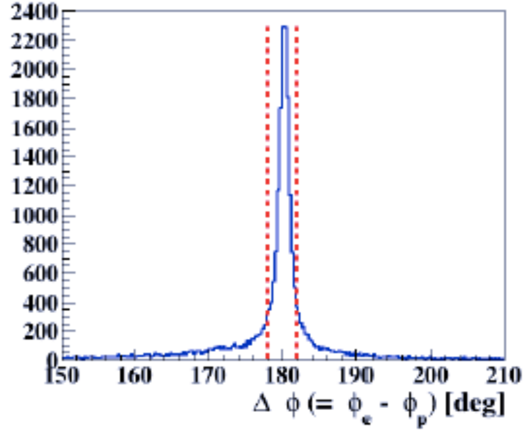
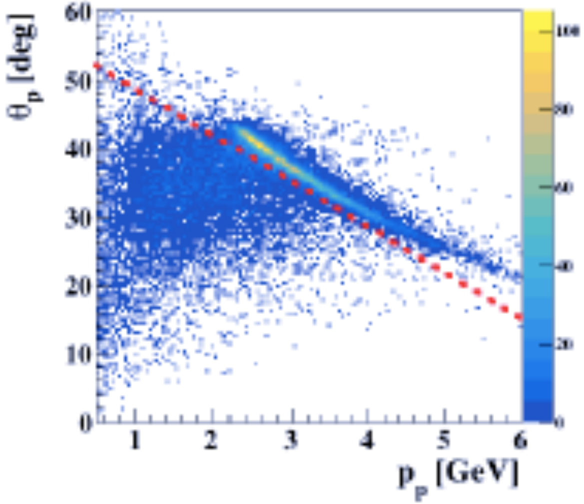
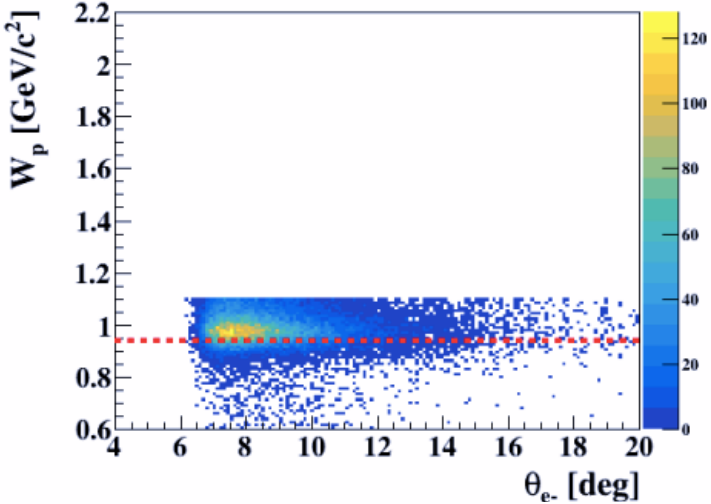
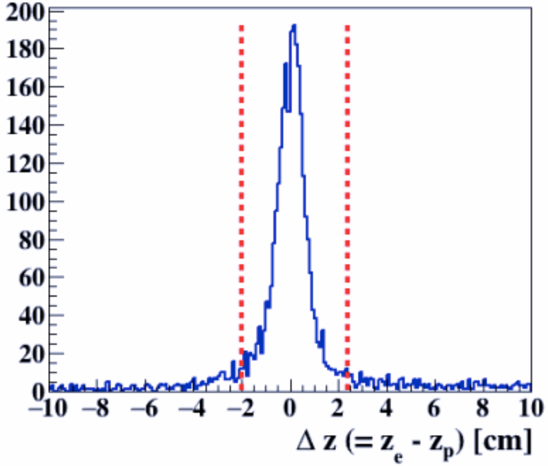


Figure 9:

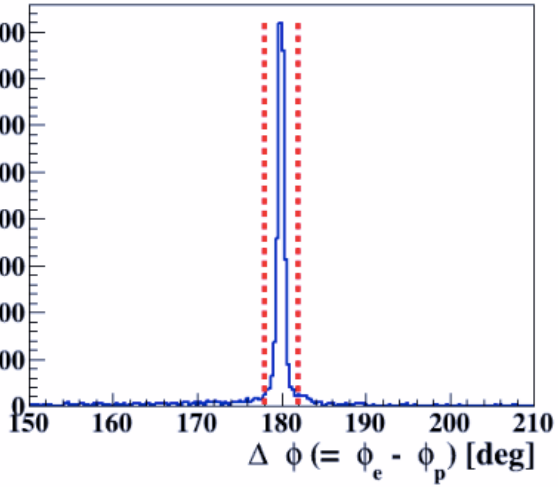




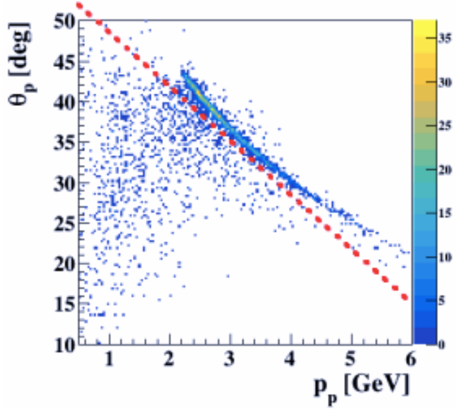
W_p [GeV/c^2]
θ_{e-} [deg]



Δz (= z_e - z_p) [cm]



$\Delta\ \phi$ (= ϕ_e - ϕ_p) [deg]



θ_p [deg]
p_p [GeV]