Simulation & Development of the RTPC for the BONuS12 Experiment in CLAS12

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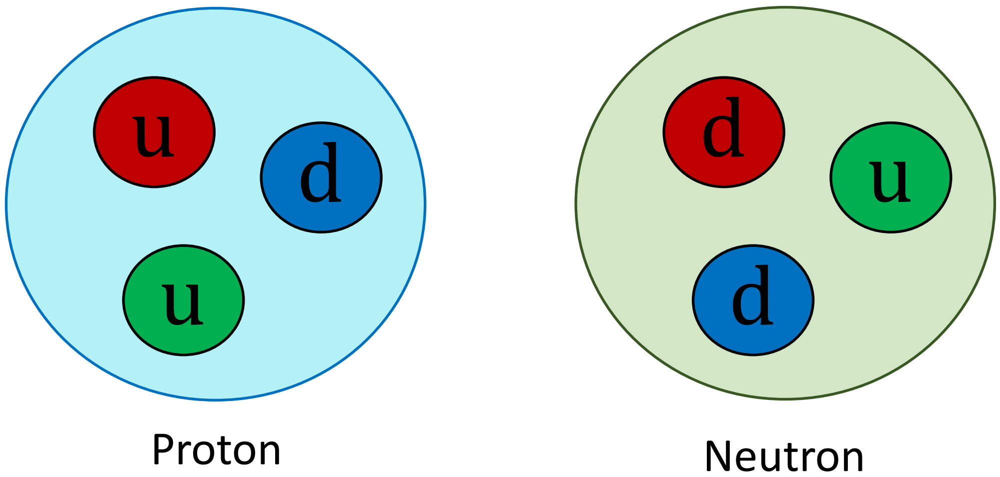
Dissertation defense - 07 May 2019

BONuS12 MOTIVATION

Nucleon Structure

Protons and neutrons (nucleons) both contain 3 valence quarks



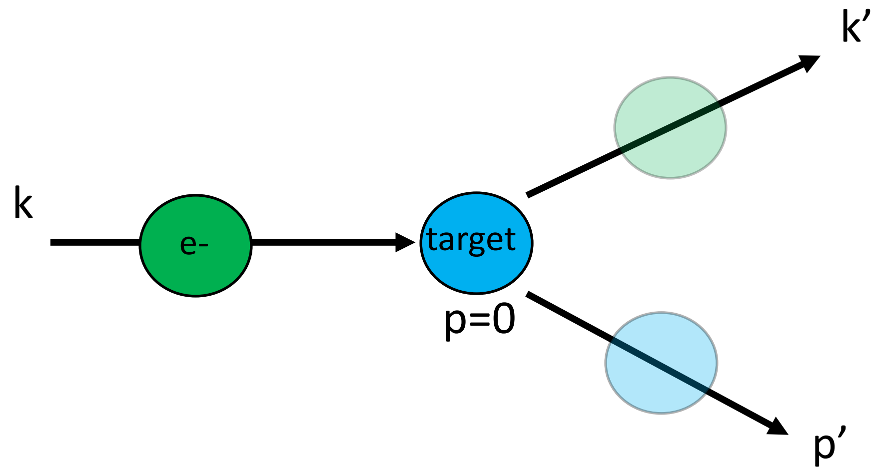
These nucleons also contain quark-antiquark pairs in a constant state of creation and annihilation. These are called “sea quarks”.

The valence quarks all have momentum within the confines of the nucleon. The fraction of the total momentum carried by a single quark is called the Bjorken-x (or just x).

BONuS12 MOTIVATION

Electron scattering experiments

One of the purposes of scattering experiments is to probe a target in order to determine its structure.



momentum before = momentum after

$$k + 0 = k' + p'$$

By detecting particles in the final state and using conservation laws we can study the probability of a particular reaction, which leads to increased understanding of the underlying nuclear physics.

BONuS12 MOTIVATION

Deep Inelastic Scattering Kinematics

Deep inelastic scattering is when scattering occurs off a constituent particle within a nucleon, breaking the nucleon into other particles.

k	Initial electron momentum
k'	Final electron momentum
p	Initial nucleon momentum
X	Nucleon debris

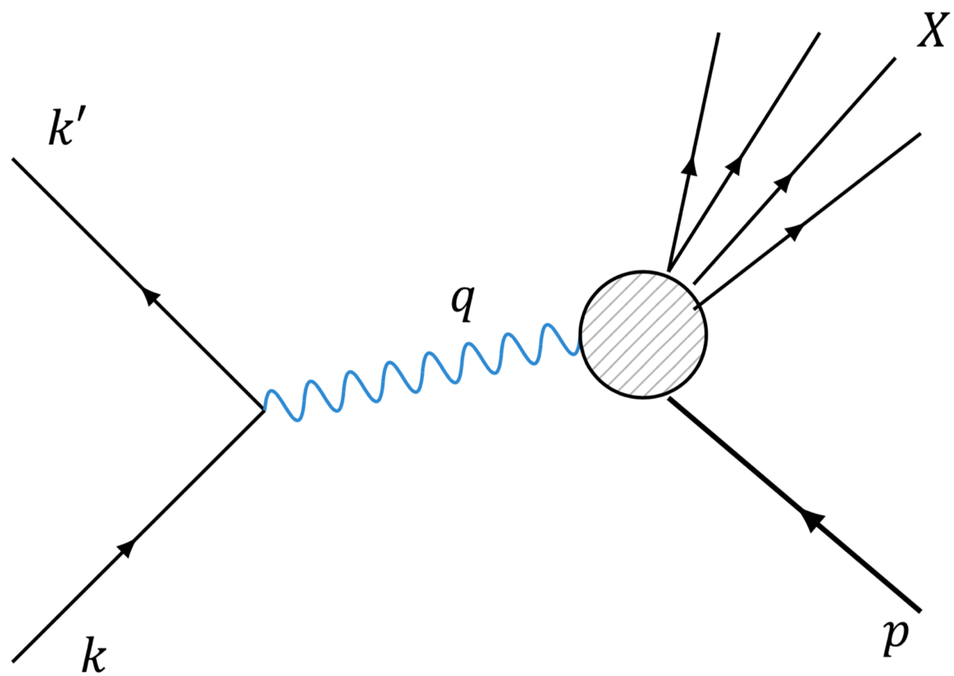
Four-momentum transfer

$q = k - k'$

$$Q^2 = -q^2 = (k - k')^2 \approx 4EE'\sin^2\frac{\theta}{2}$$

Four-momentum transfer

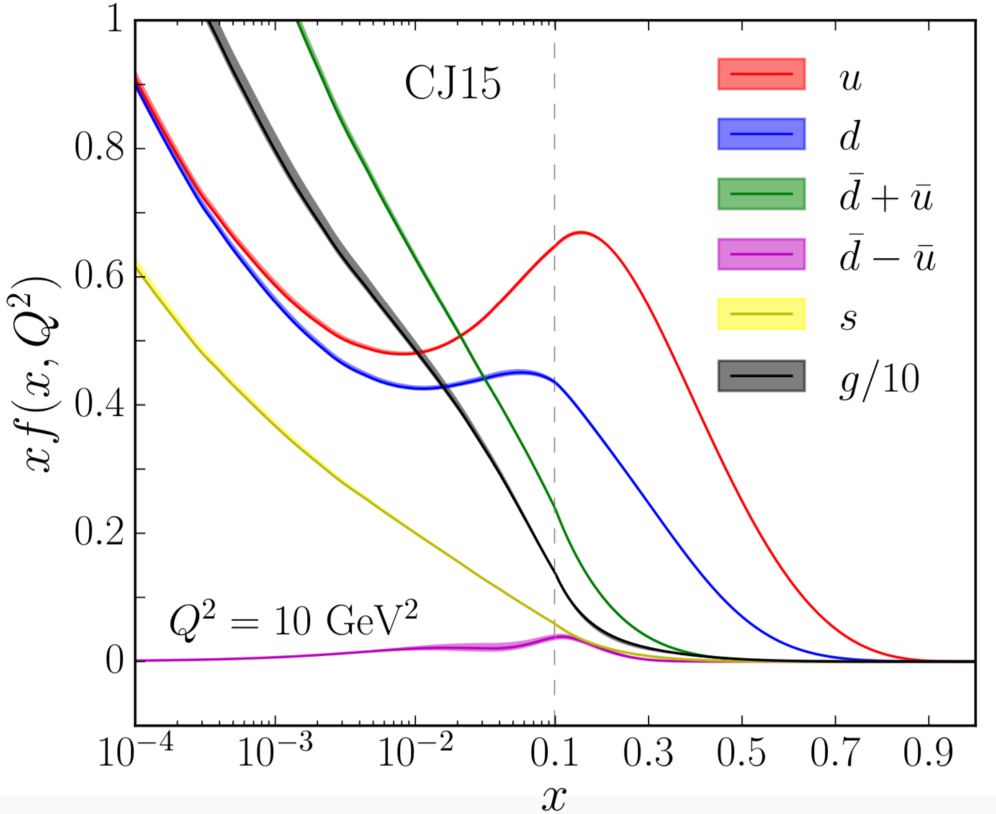
$$x_B = x = \frac{Q^2}{2M(E - E')}$$



BONuS12 MOTIVATION

Nucleon Structure Function at Large x

Valence quarks dominate above x~0.4



S. Tkachenki, *et al*. Phys. Rev. D, **93**, (2016).

The parton distribution function or PDF $f(x, Q^2)$ is the longitudinal momentum distribution of quarks and gluons (or partons) inside the nucleon.

The structure function is given by

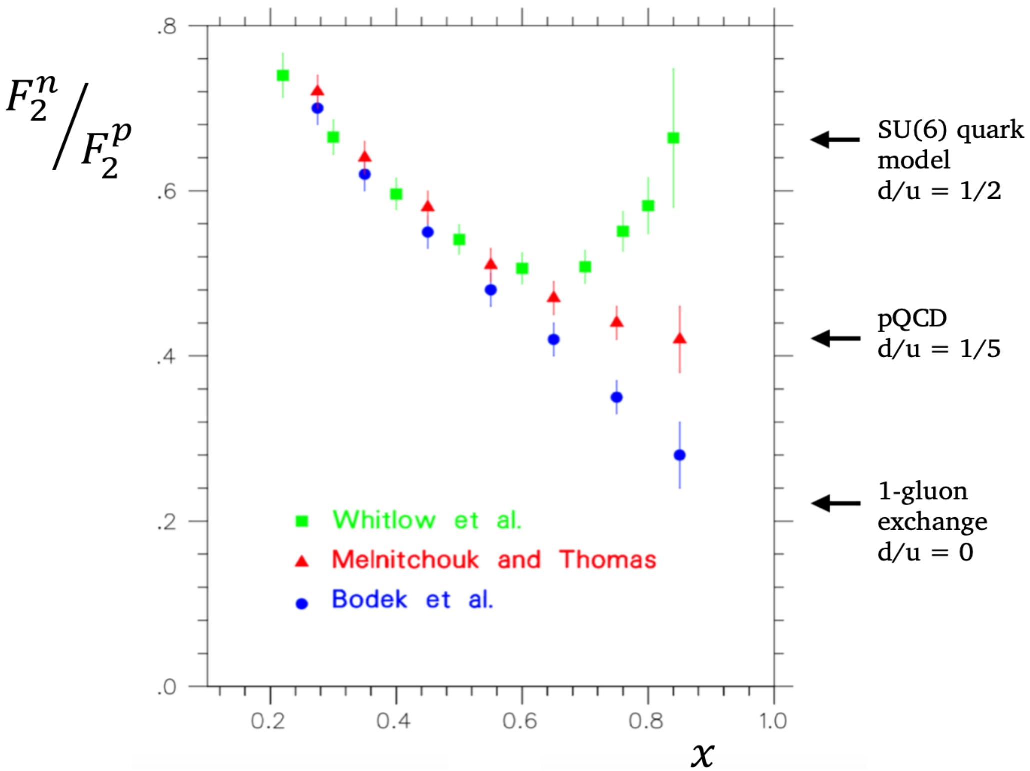
$$F_2(x) = x \sum_q e_q^2 f_q(x)$$

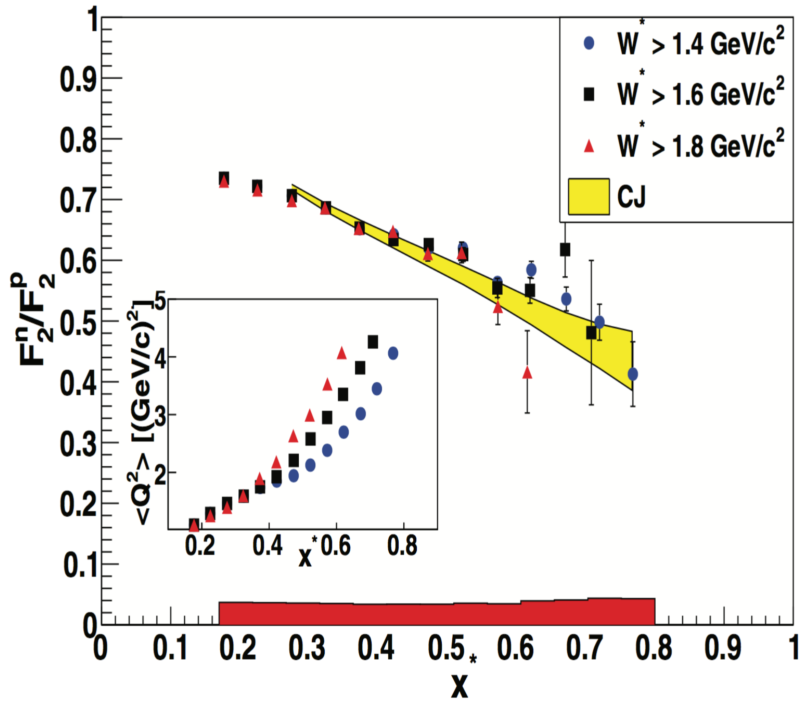
$x > 0.5$ allows for the approximation of the F_2^n/F_2^p ratio to

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

BONuS12 MOTIVATION

Nucleon Structure Function at Large x





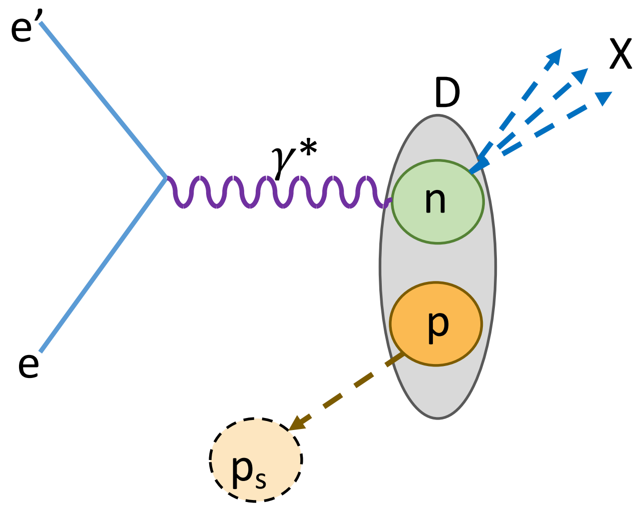
S. Tkachenki, *et al.* Phys. Rev. C **89**, 045206 (2014).

At large x, previous extractions of the F_2^n/F_2^p ratio have been model dependent. Model-independent measurements first occurred in 2005, but end at x∼0.8 and have large uncertainties.

BONuS12 MOTIVATION

Spectator Proton Tagging

The purpose of spectator tagging is to select events that involve the scattering of the electron off of the neutron in deuterium.



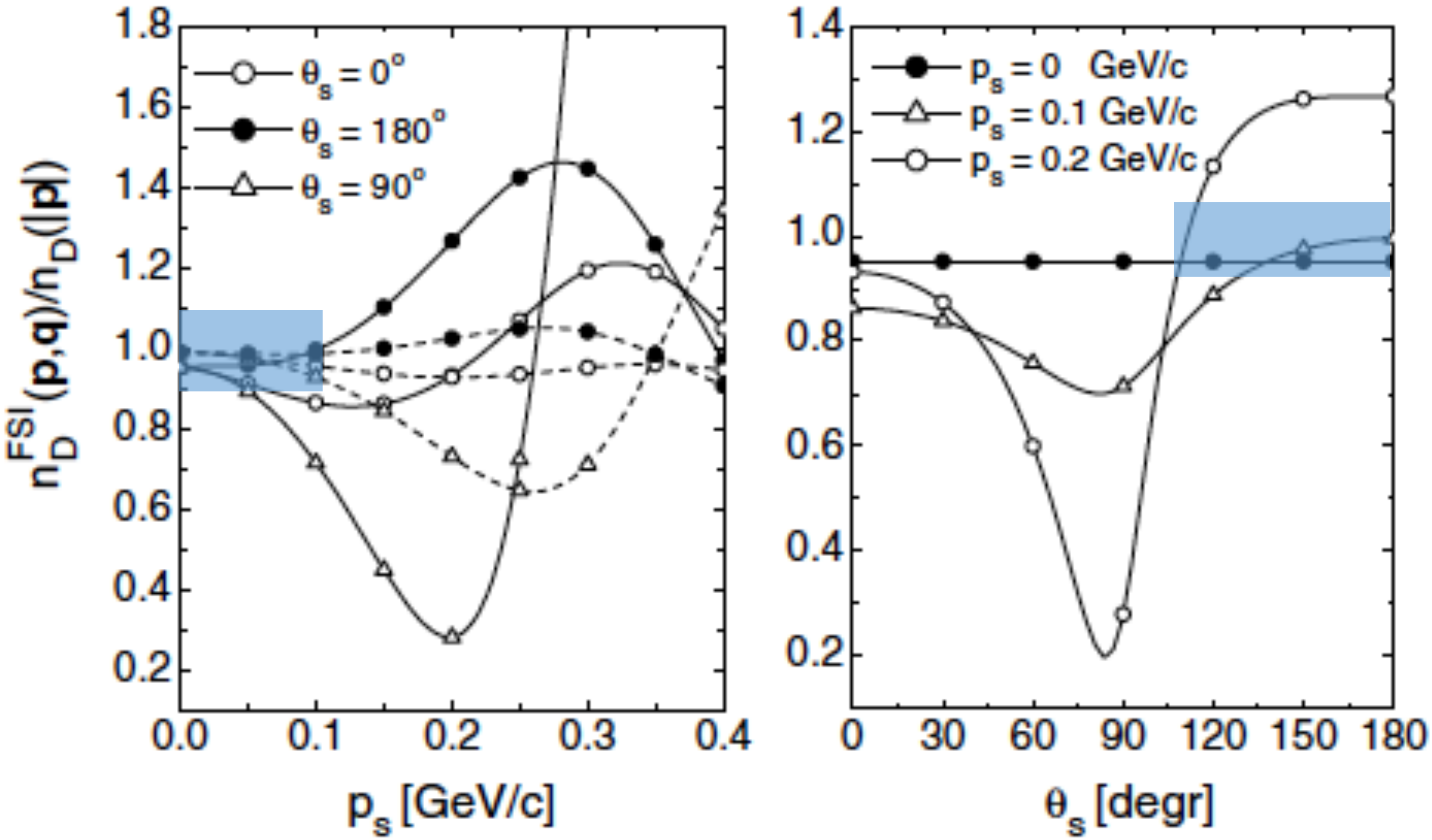
$$e + D \rightarrow e' + p_s + X$$

By detecting low-momentum, backward-going protons that result from the scattering, we minimize significant final state interactions between the debris from the neutron and the spectator proton.

BONuS12 MOTIVATION

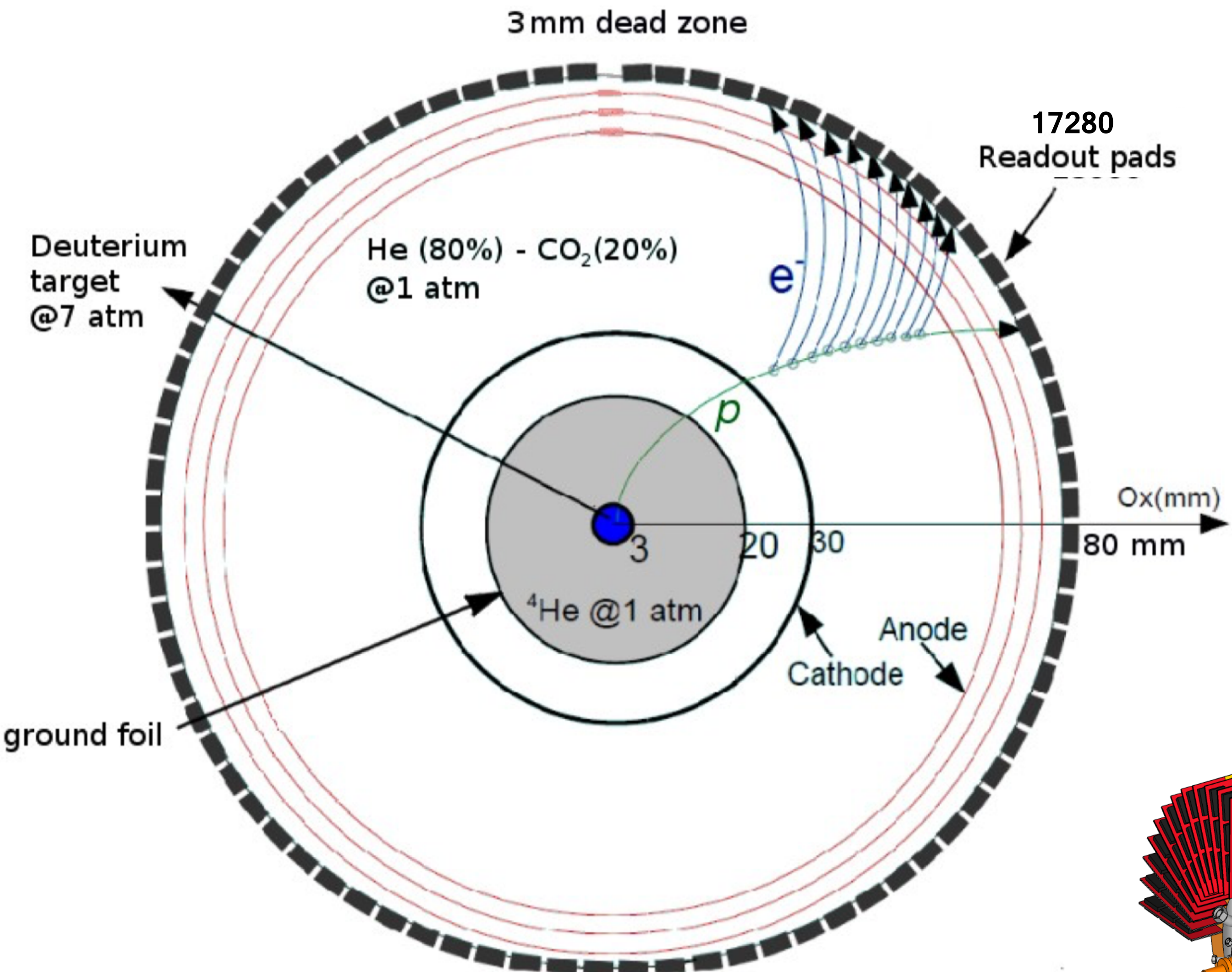
Reducing Final State Interactions

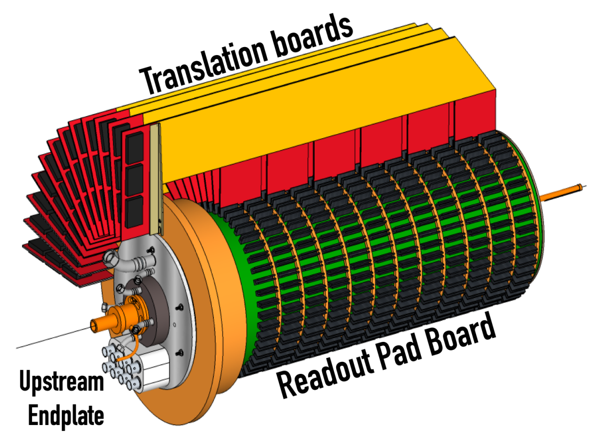
FSI are minimized for $p_s < 100$ MeV/c and $\theta_{pq} > 100°$



C. degli Atti *et al*, Eur. Phys. J. A 19,145 (2004).

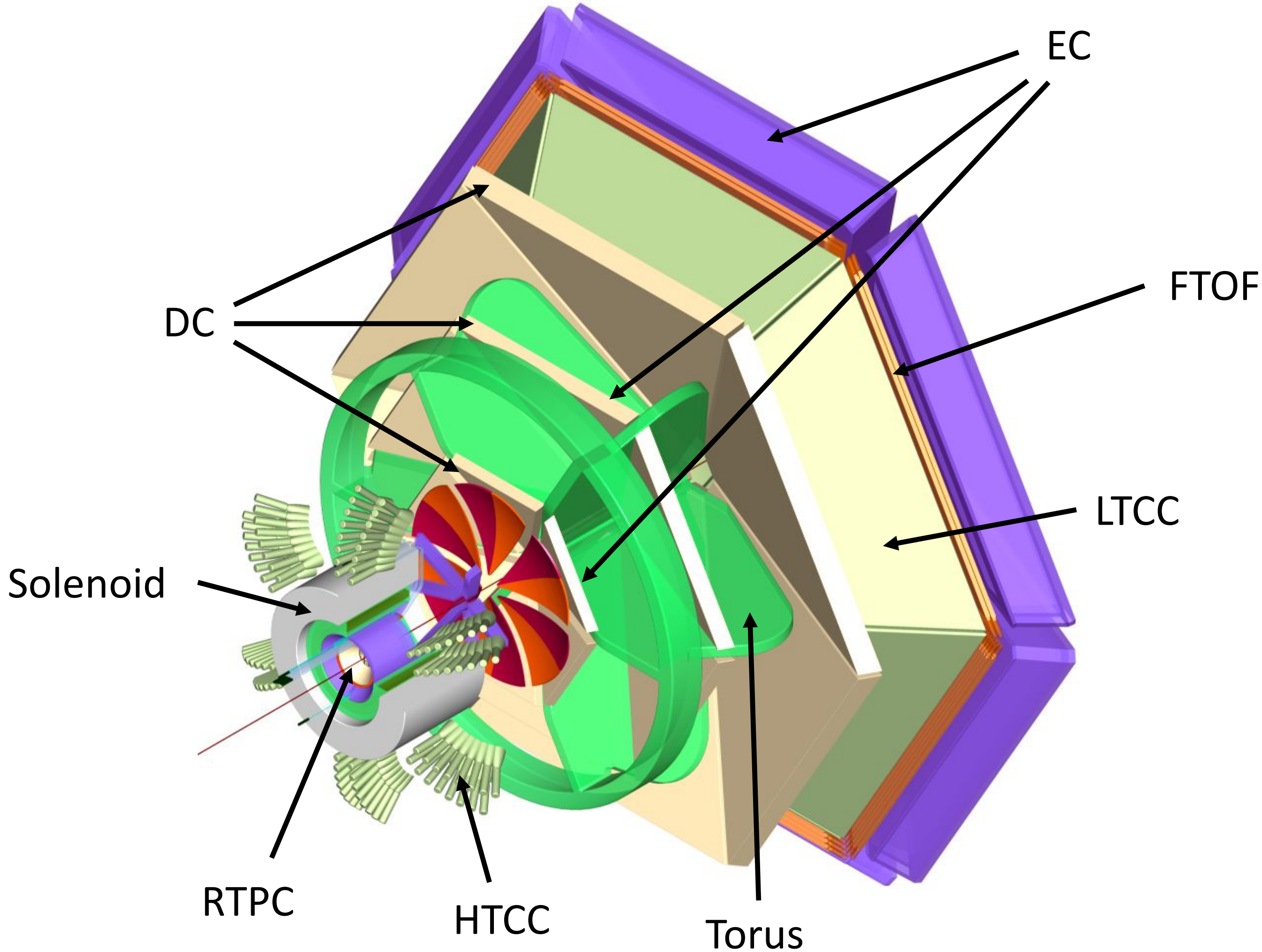
Radial Time Projection Chamber





CEBAF Large Acceptance Spectrometer

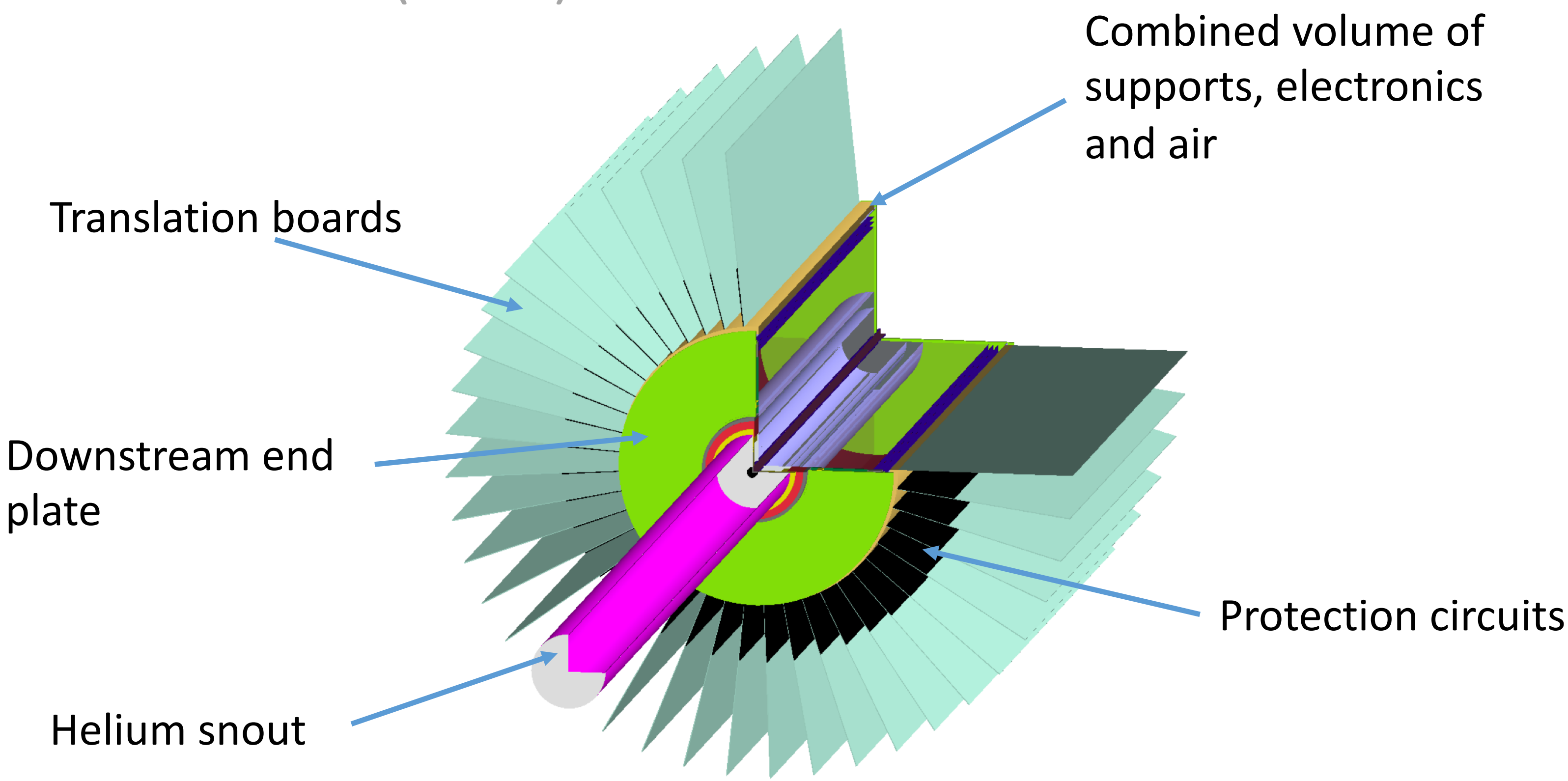
CLAS12 Detectors



The BONuS12 RTPC will be installed in the CLAS12 in Hall B.

Simulation

GEant4 Monte Carlo (GEMC)

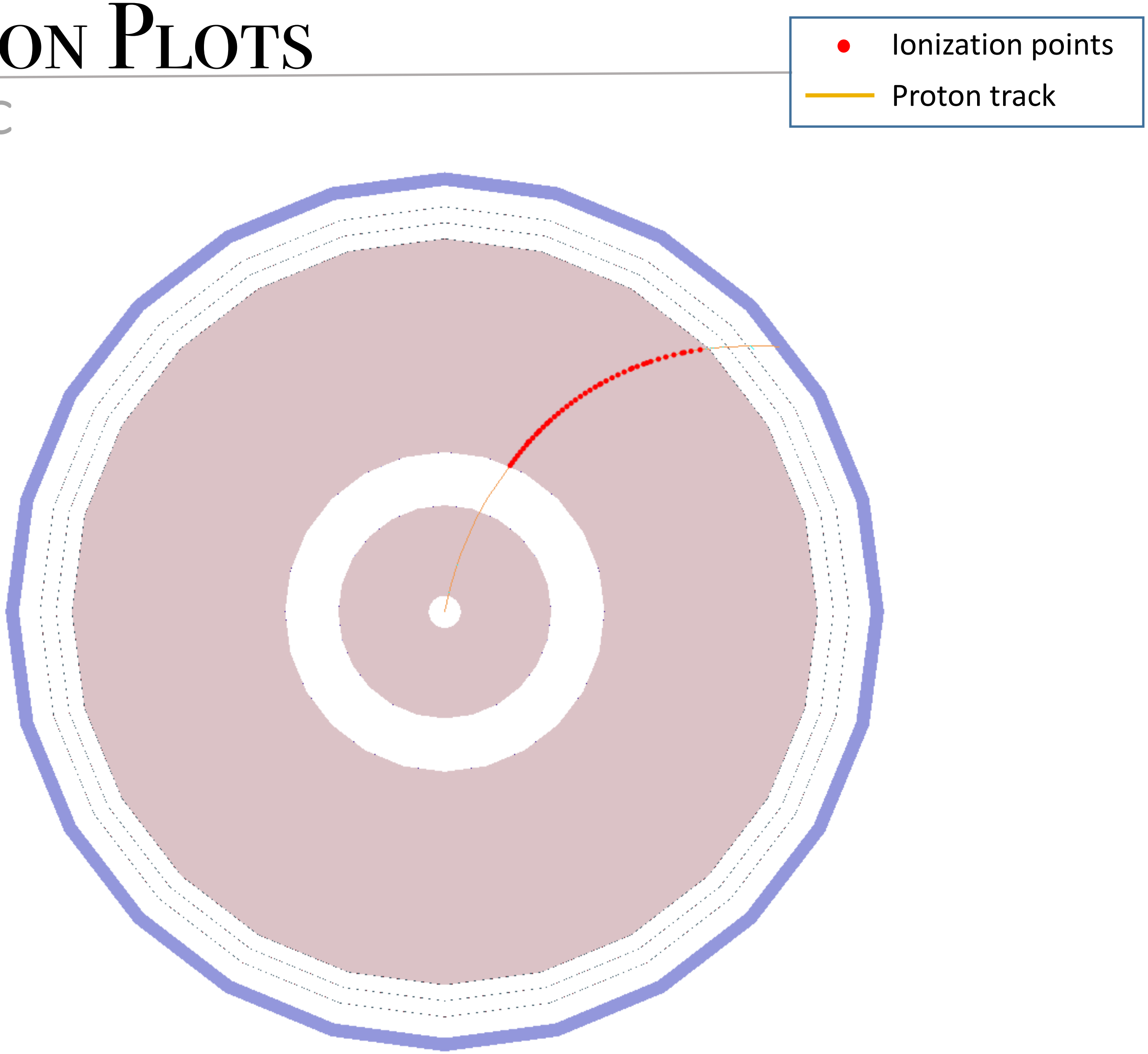


GEMC is a Monte-Carlo based package of Geant4 used primarily for CLAS12.

Geant4 is a toolkit used to simulate particles passing through and interacting with matter.

Simulation Plots

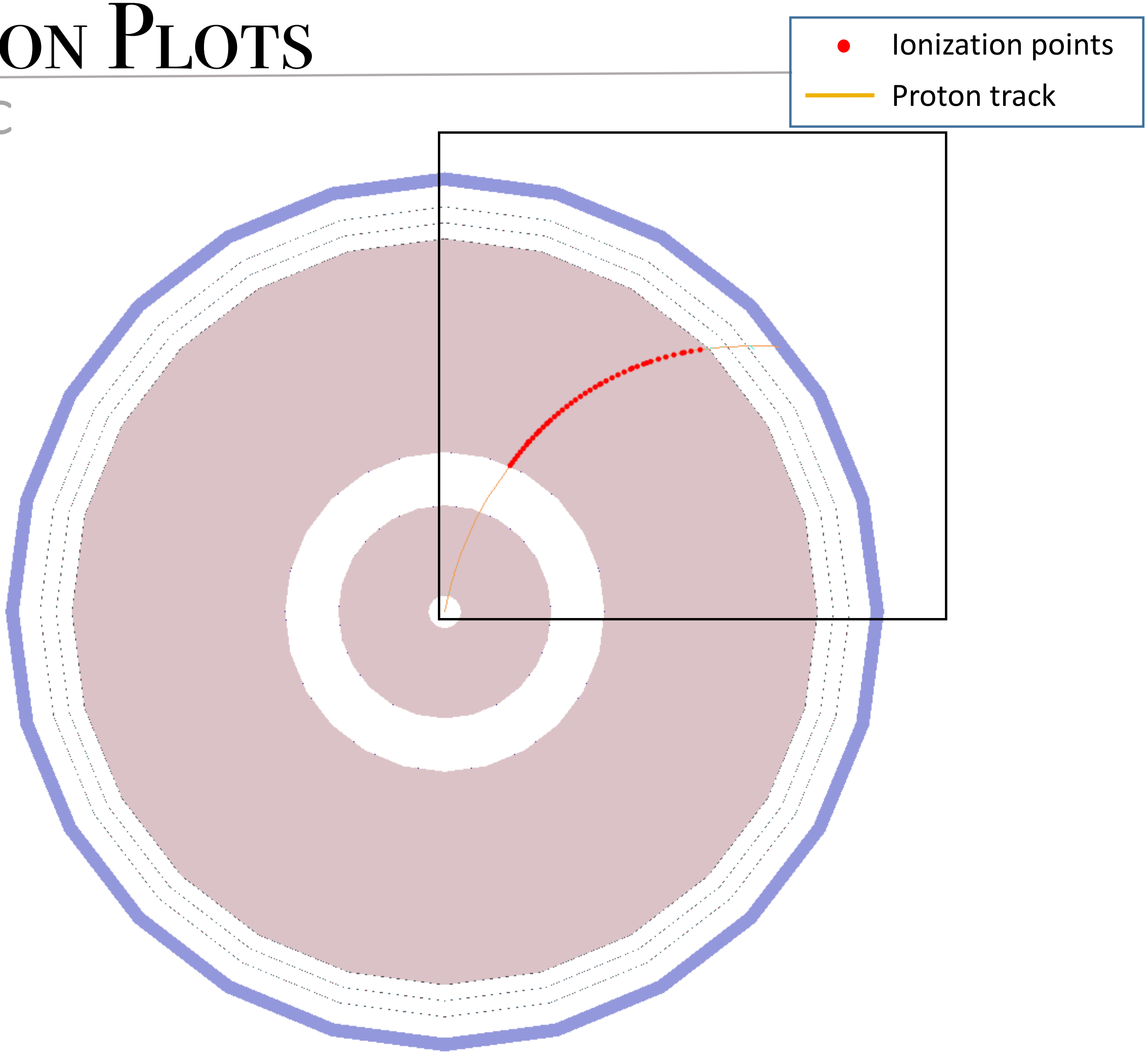
SOURCE: GEMC



5T magnetic field along z-axis

Simulation Plots

SOURCE: GEMC



Simulation Plots

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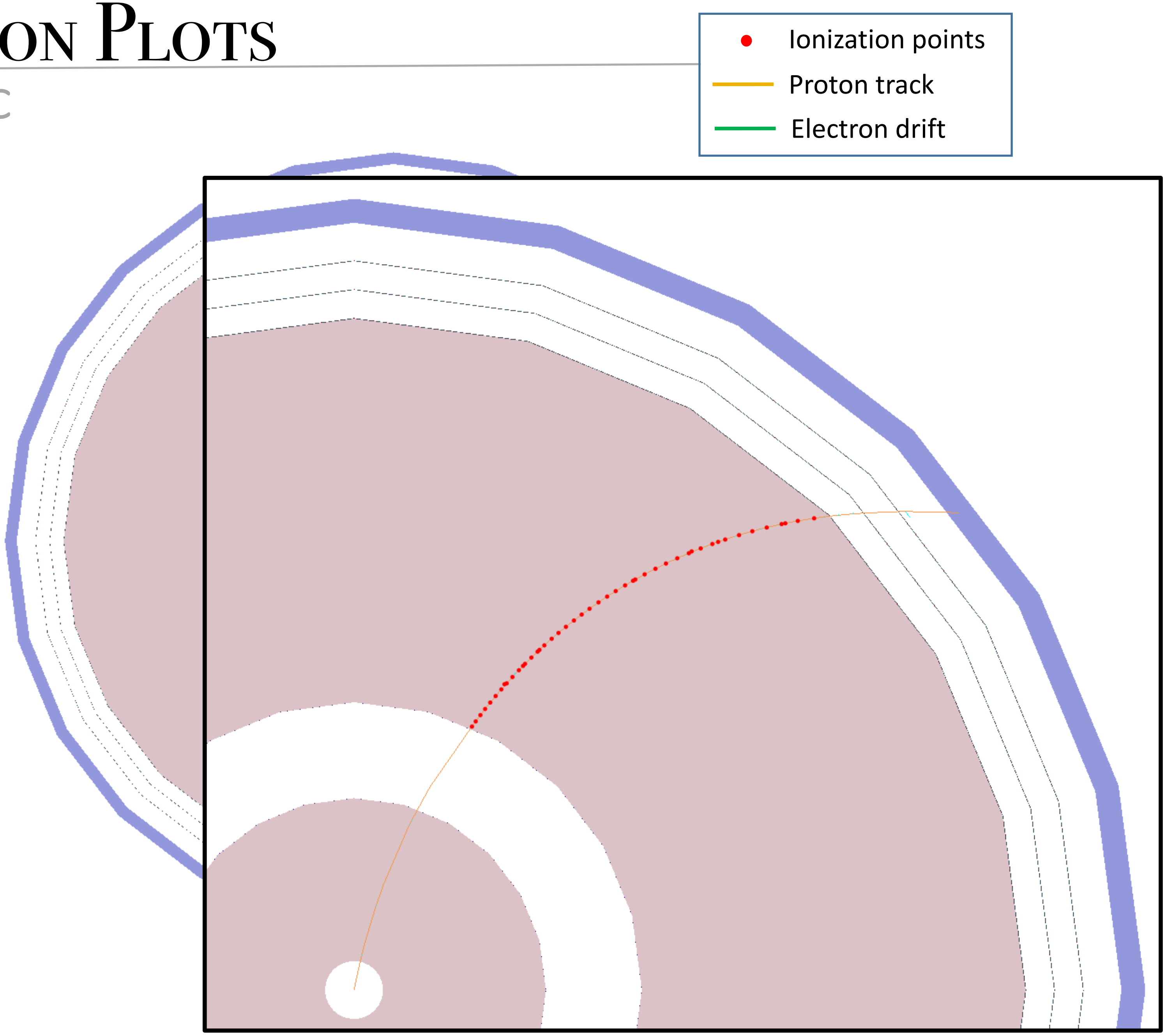
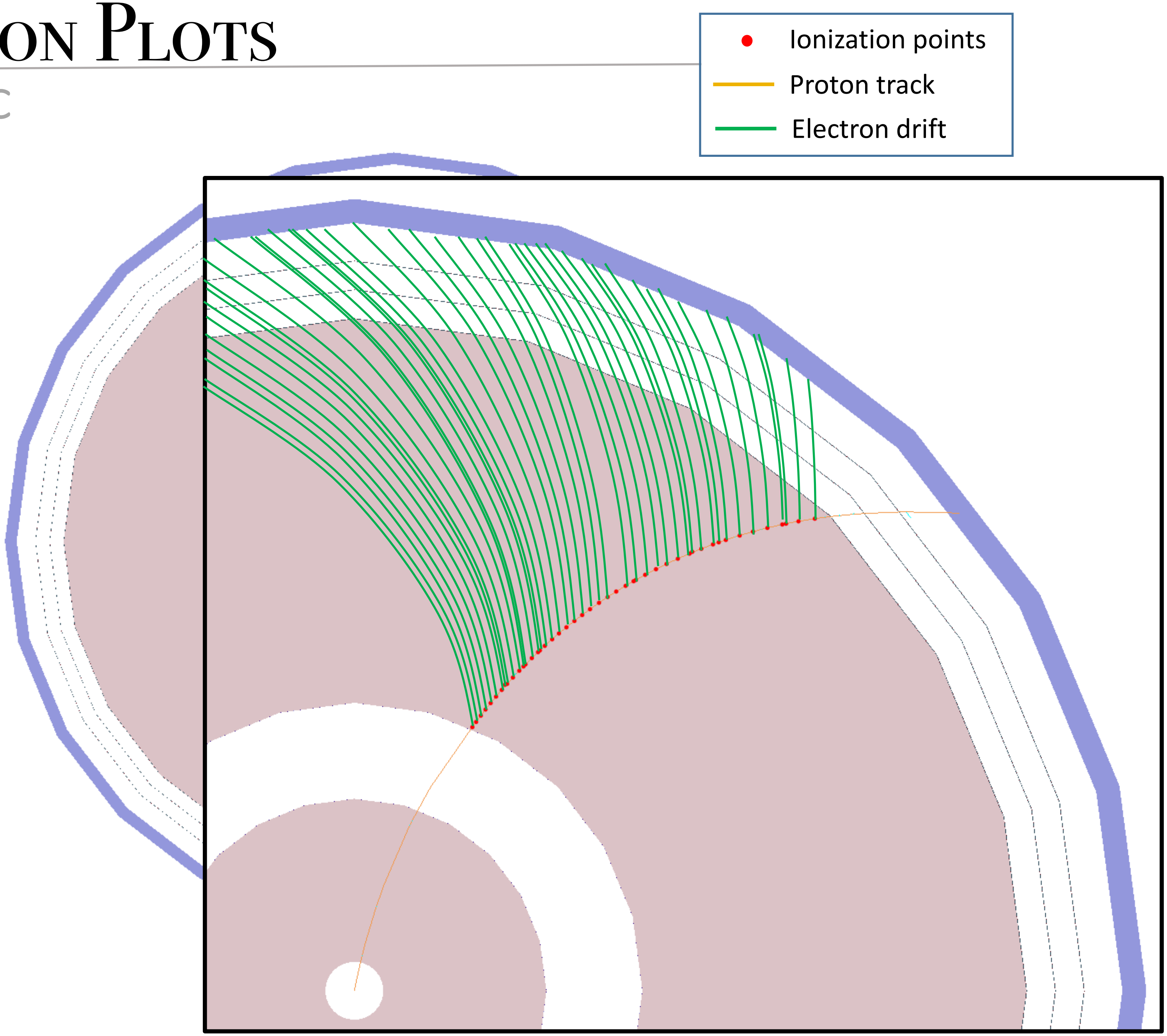


Simulation Plots

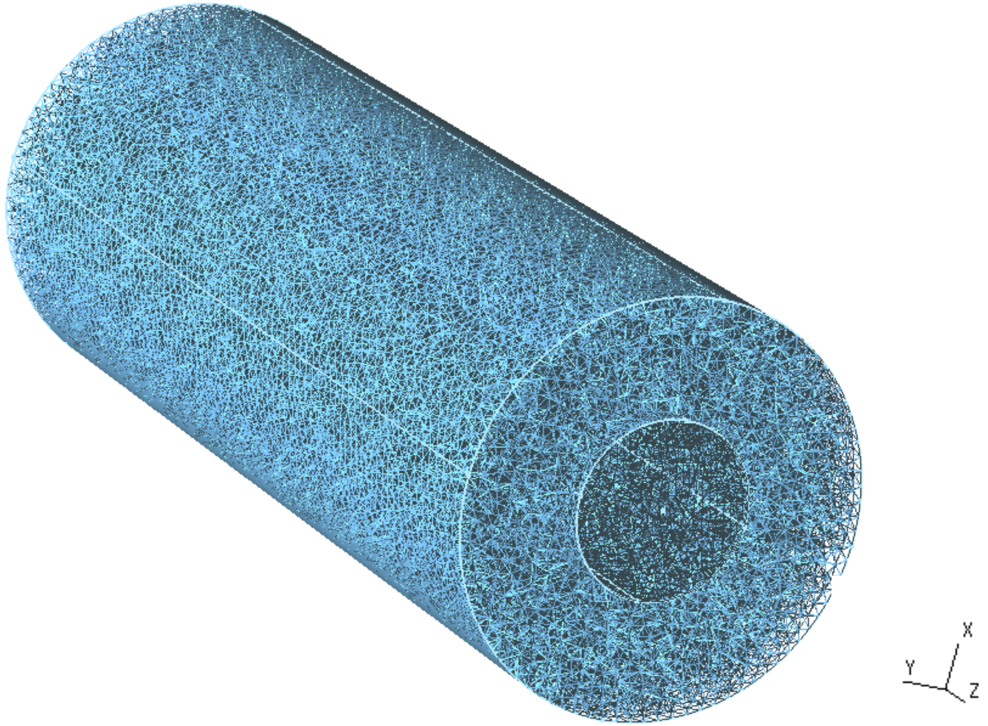
SOURCE: GEMC



Operation/Purpose

Creates gas property files that reflect the gas mixtures, electric and magnetic fields.

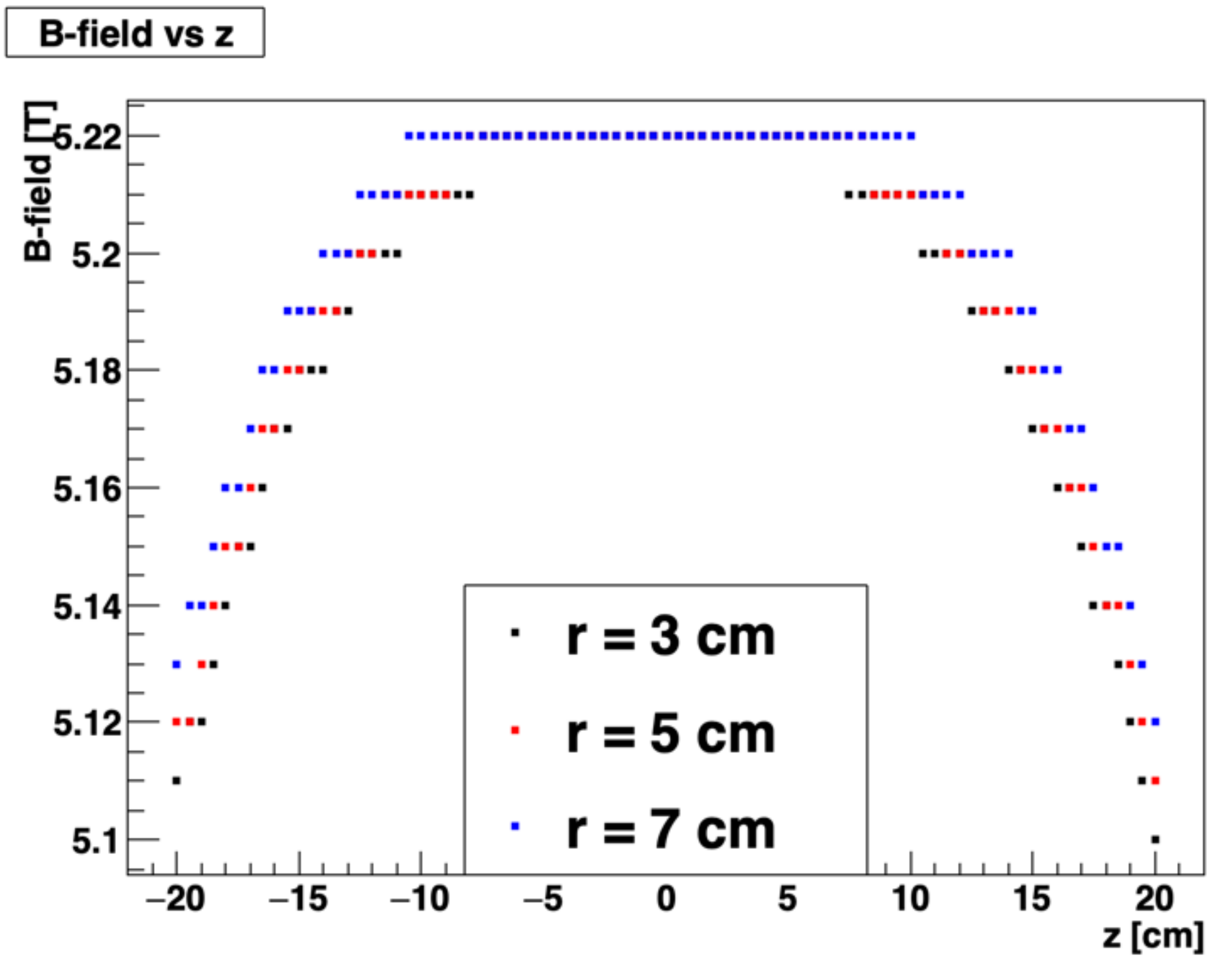
Uses Magboltz, which solves the Boltzmann transport equations for electrons in gas mixtures under the influence of electric and magnetic fields.



Drift-electron Analysis

Solenoid Magnetic Field Map

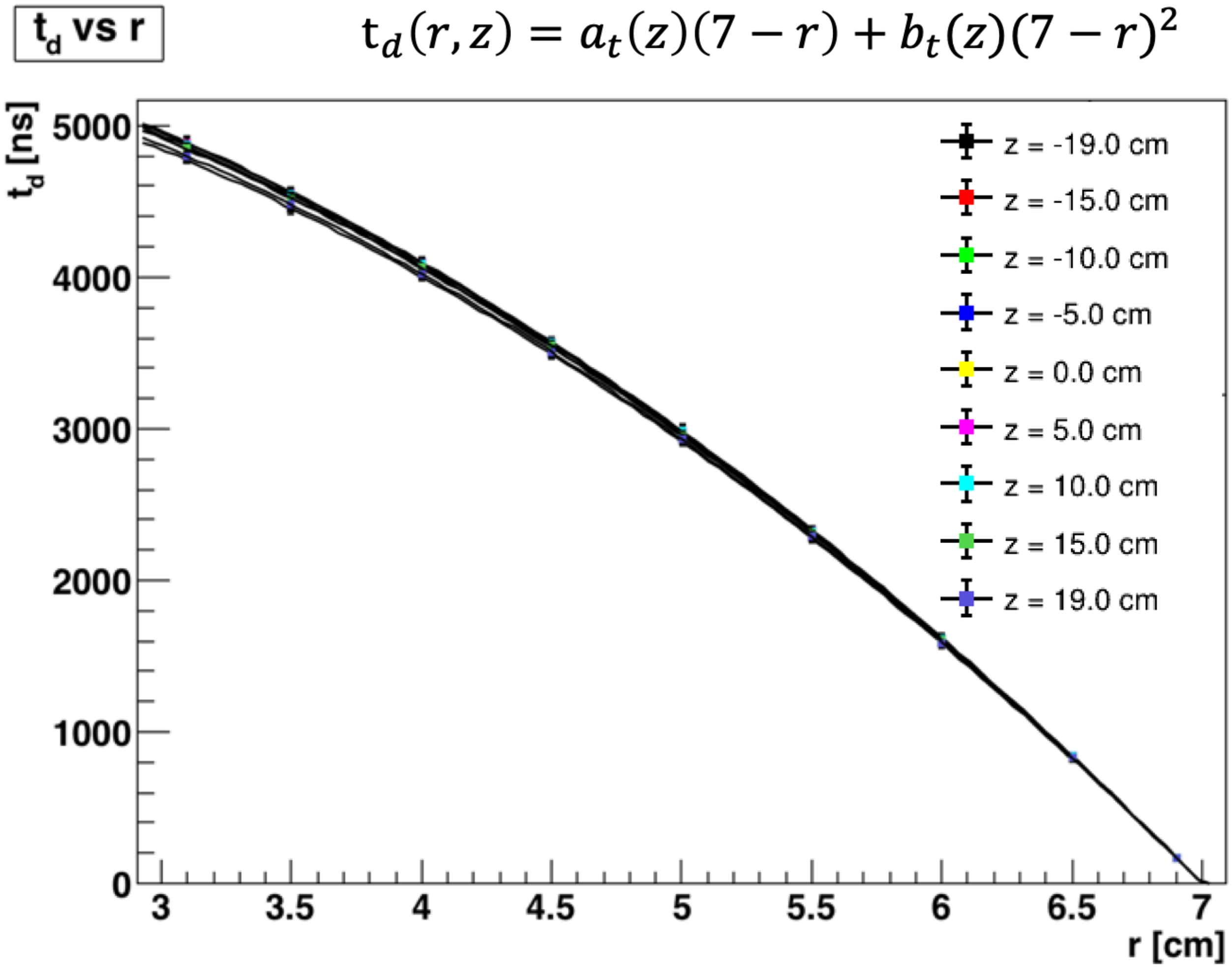
As $z \rightarrow 0$, the strength of the field increases symmetrically from locations upstream and downstream of the target center (z=0).



Drift-electron Analysis

Garfield++

$$t_d(r,z) = a_t(z)(7-r) + b_t(z)(7-r)^2$$

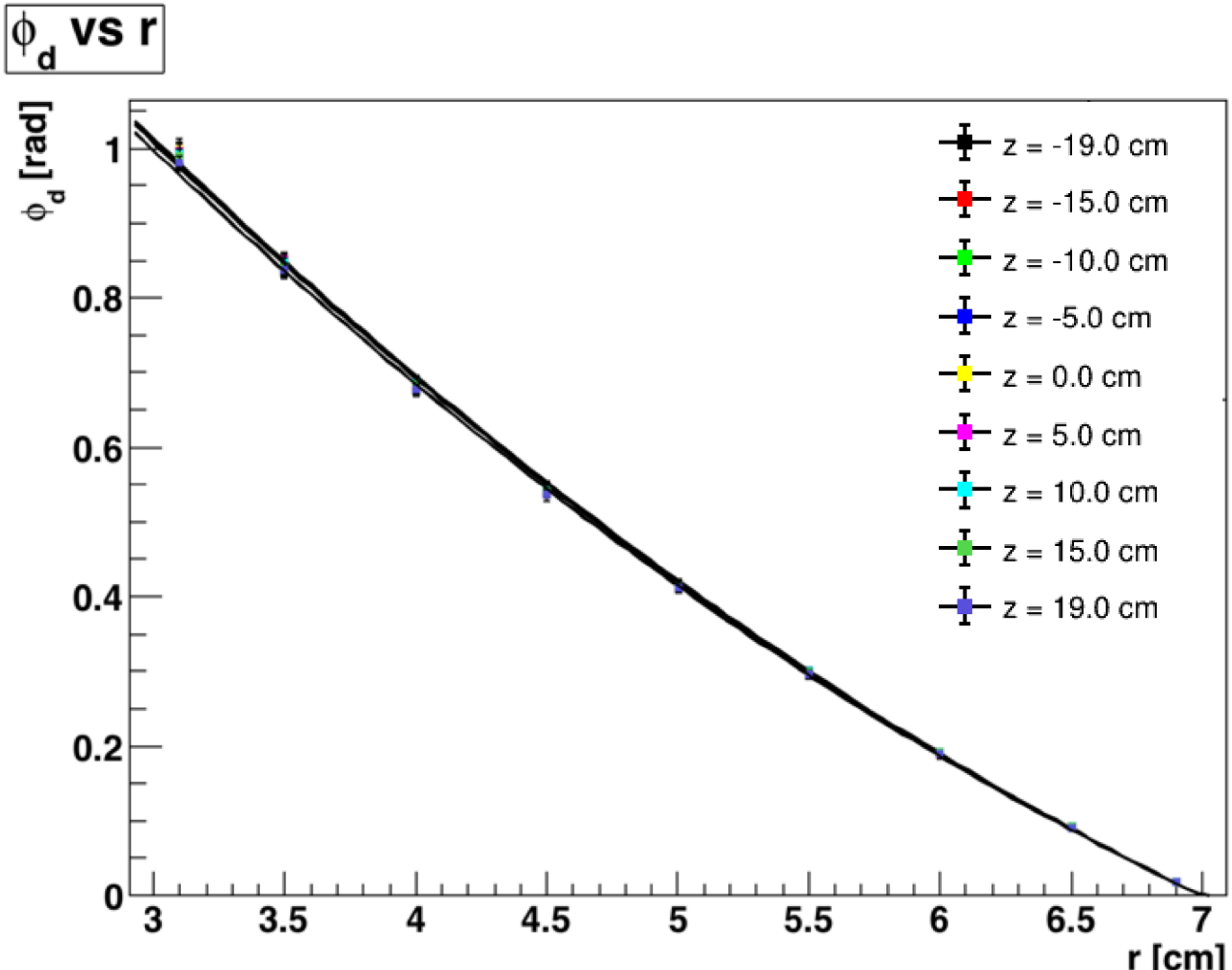


The drift time (t_d) at points along the radius of the drift region (r) decreases to zero as r goes to 7 cm.

Drift-electron Analysis

Garfield++

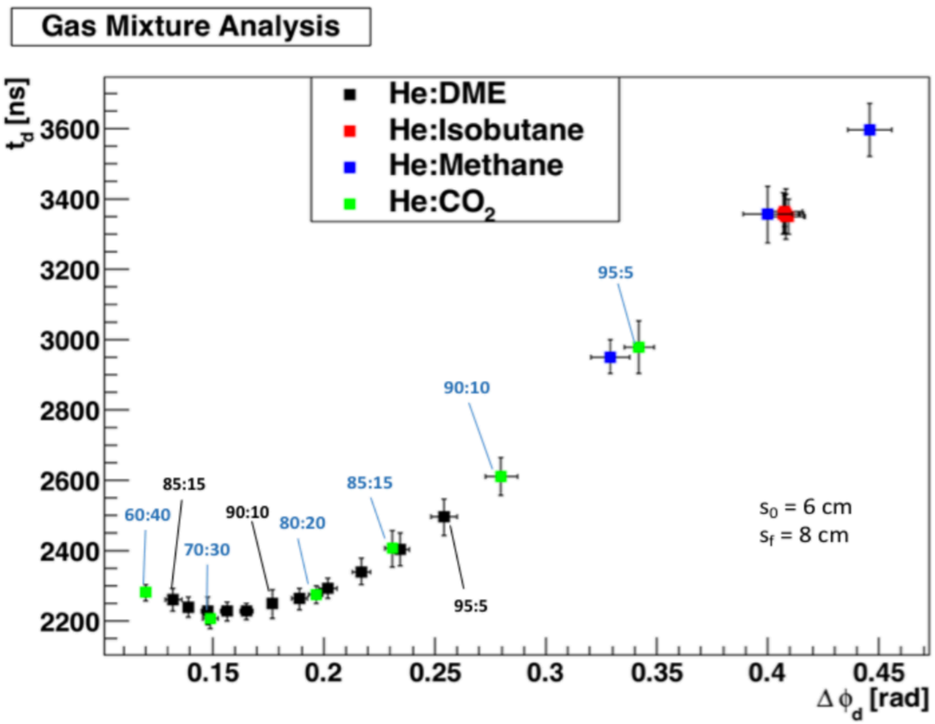
The drift angle (ϕ_d) at points along the radius of the drift region (r) decreases to zero as r goes to 7 cm.

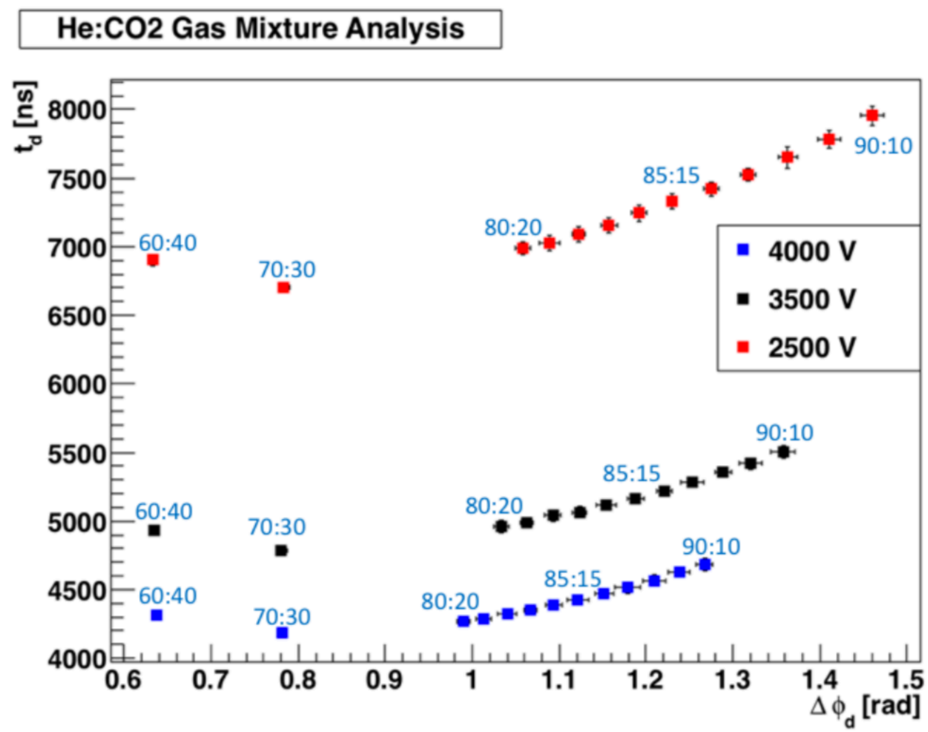


$$\phi_d(r,z) = a(z)(7-r) + b(z)(7-r)^2$$

Drift-electron Analysis

E-field and Gas mixture variations



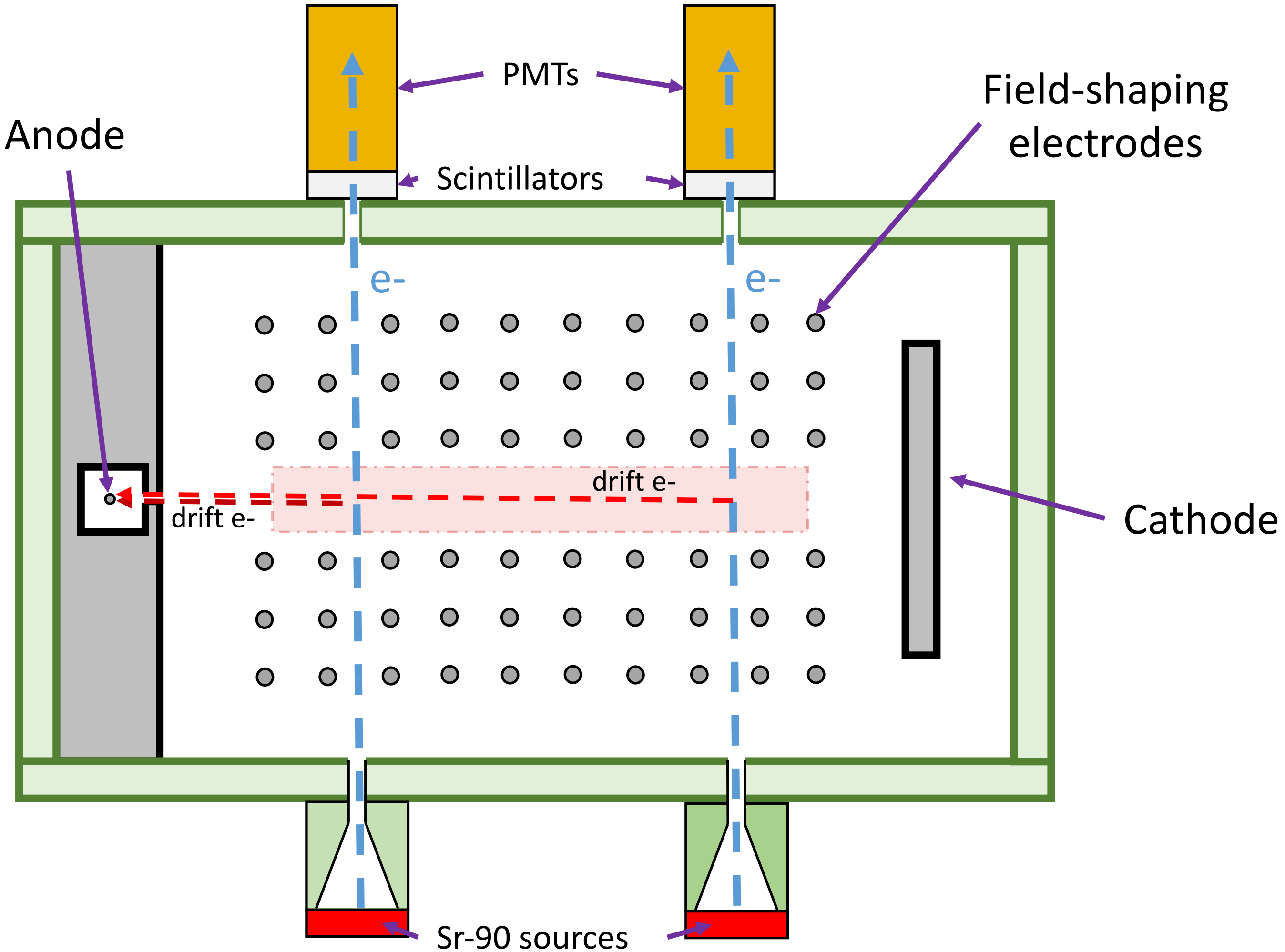


Variations in electric field, gas mixture, temperature and pressure have dramatic effects on the electron drift times and drift angles.

Drift-gas Monitoring System

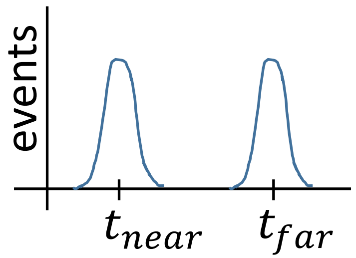
Operation/Purpose

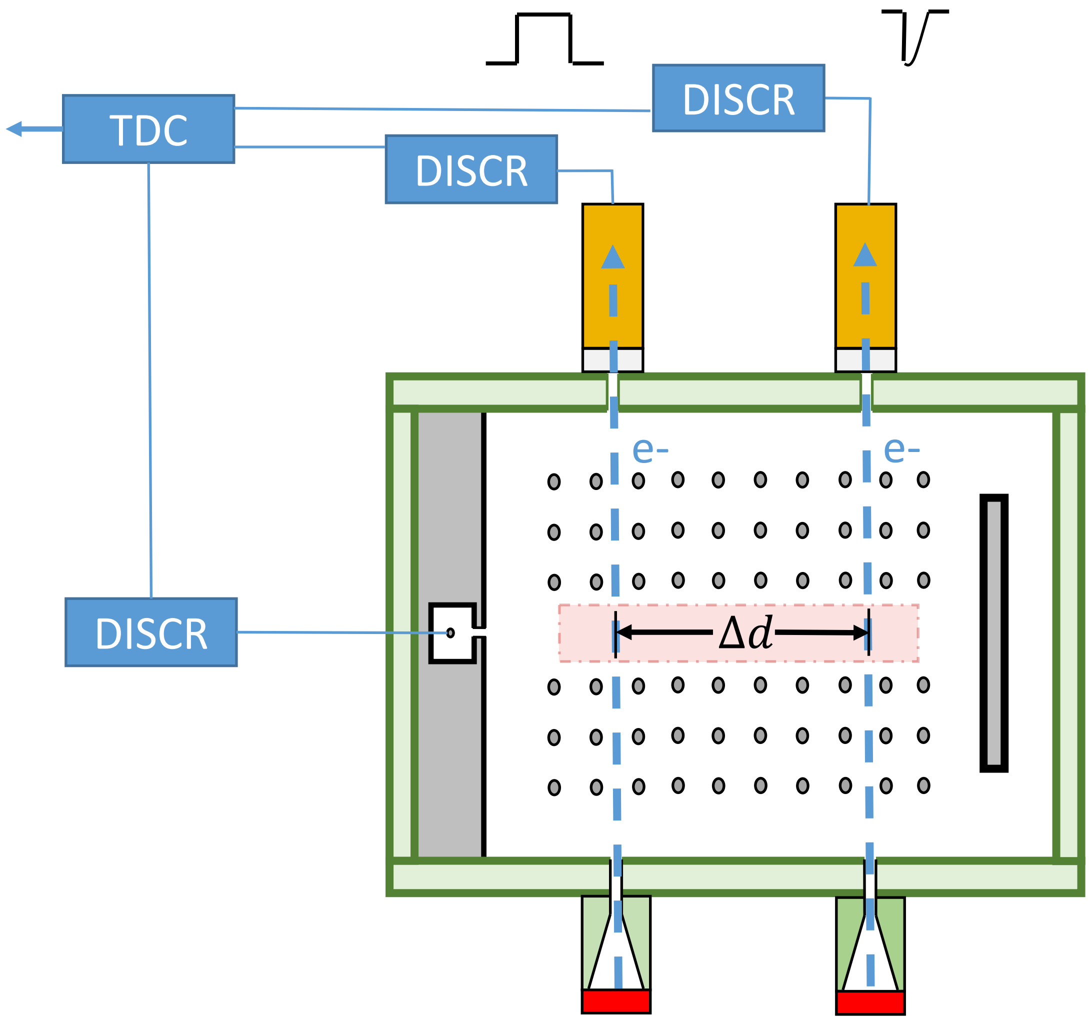
A drift chamber that measures the drift velocity of electrons for a given gas mixture, electric field, temperature and pressure.



Drift-gas Monitoring System

Concept





$$\Delta t = t_{far} - t_{near}$$

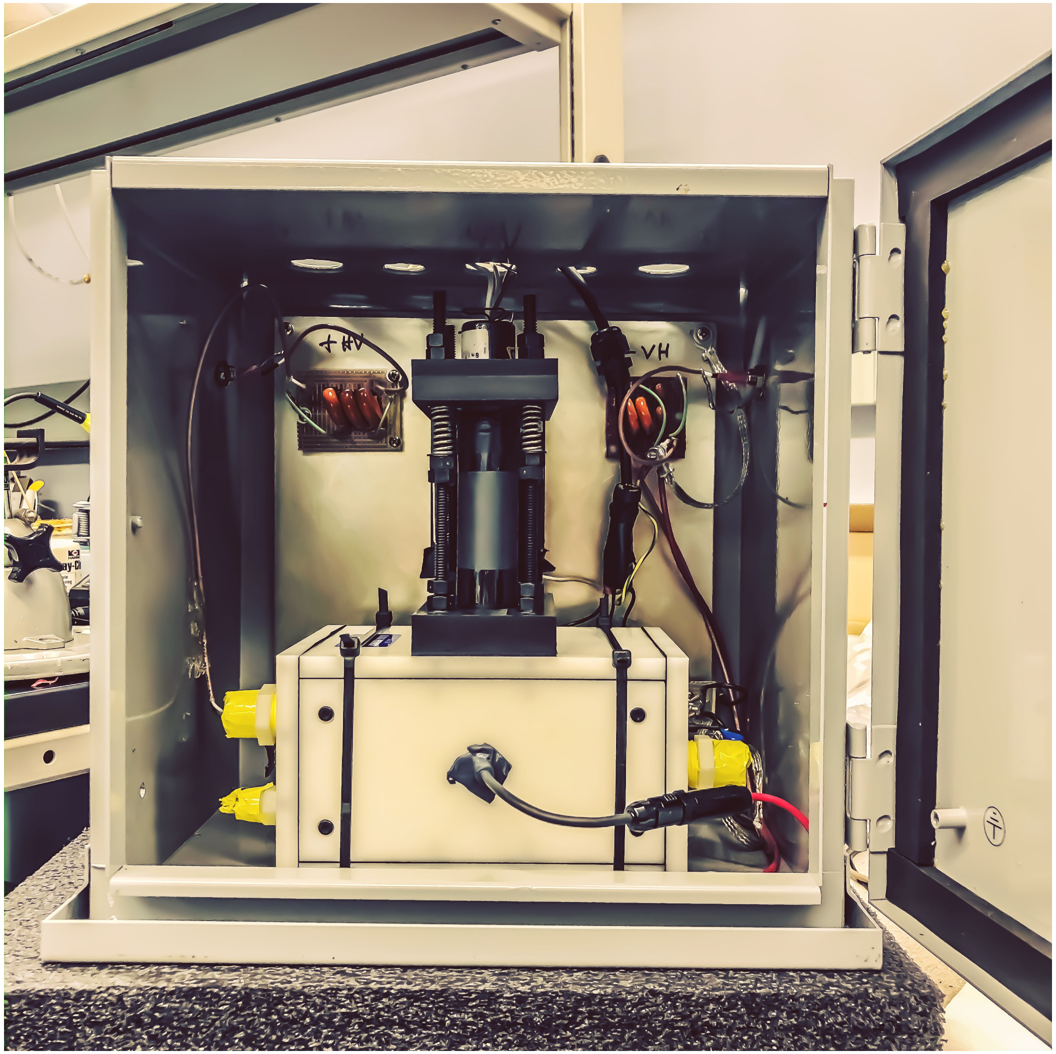
$$\Delta d = 4 \text{ cm}$$

Drift velocity

$$v_d = \frac{\Delta d}{\Delta t}$$

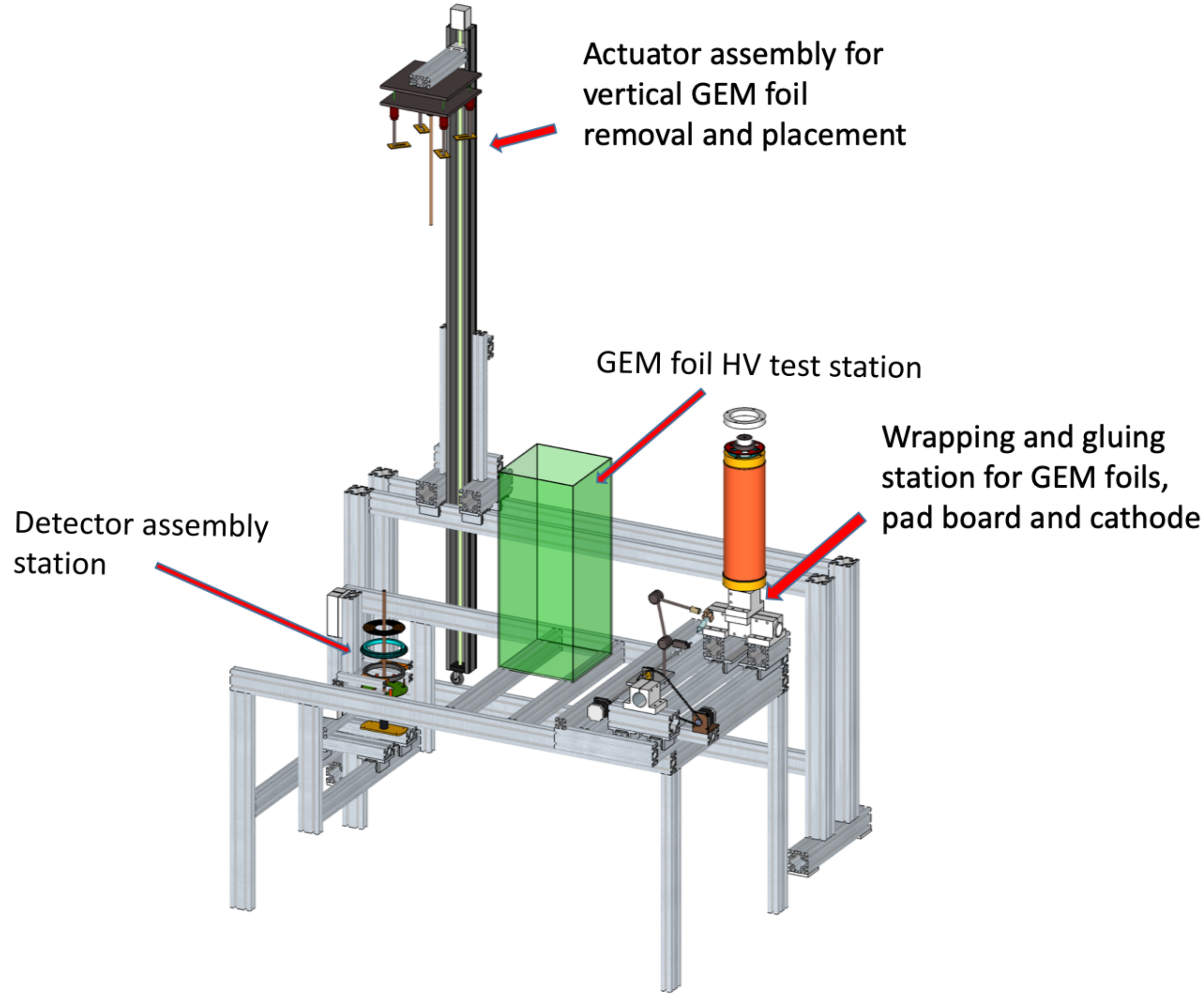
Drift-gas Monitoring System

Fully Constructed



RTPC Construction

Assembly Station



RTPC Construction

Fully Assembled

BONuS12 EXPERIMENTAL RUN

The BONuS12 experiment ran in the Spring 2020 for 36 days and collected 3.3 billion triggers.

RTPC1 ran for 33 days at about 50% efficiency.

5 days to swap from RTPC1 to RTPC3.

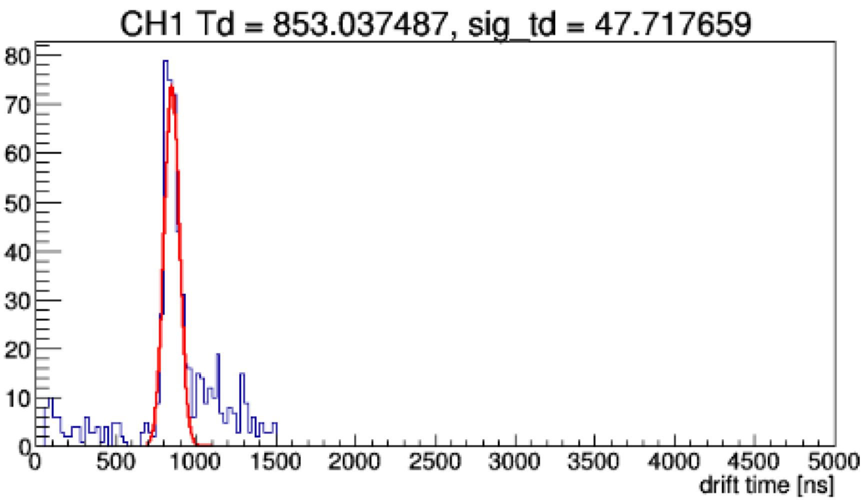
RTPC3 ran for 3 days also at about 50% efficiency.

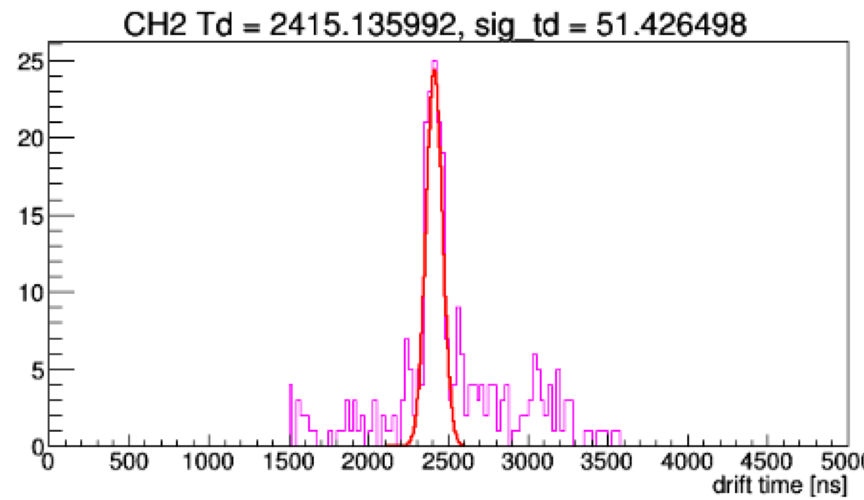
2.8 billion of the 3.3 billion triggers included the RTPC.

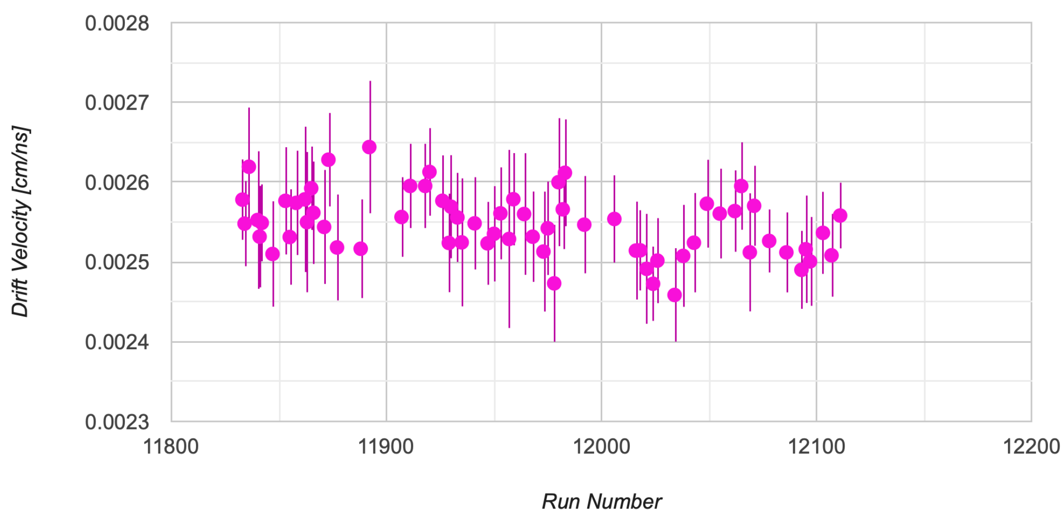
The run was cut short by about half of the scheduled days by the COVID19 pandemic.

Data Analysis – Run Group F

Drift-gas Monitoring System

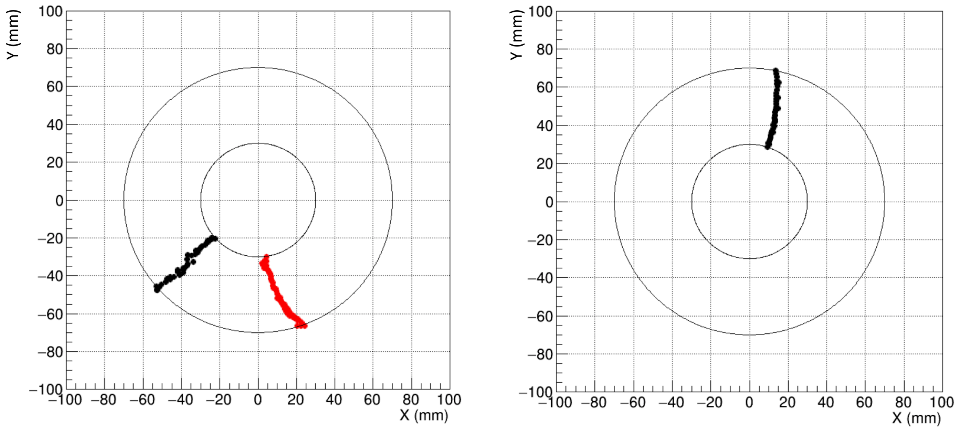






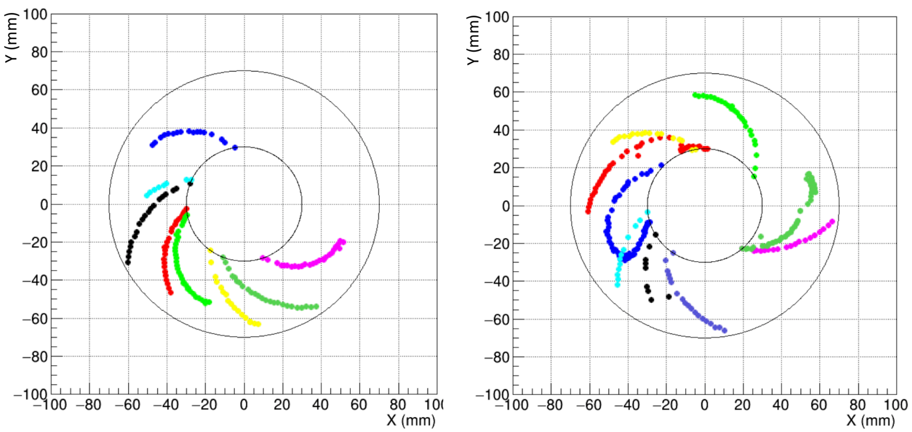
Data Analysis – Run Group F

First RGF data analysis



Run 11637
2.14 GeV
5 nA

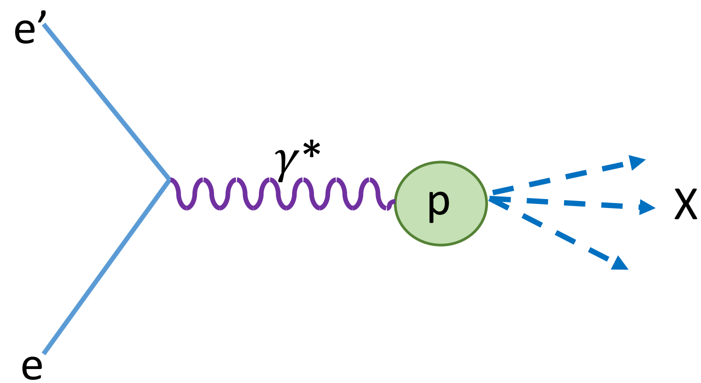
Run 12240
10.4 GeV
240 nA

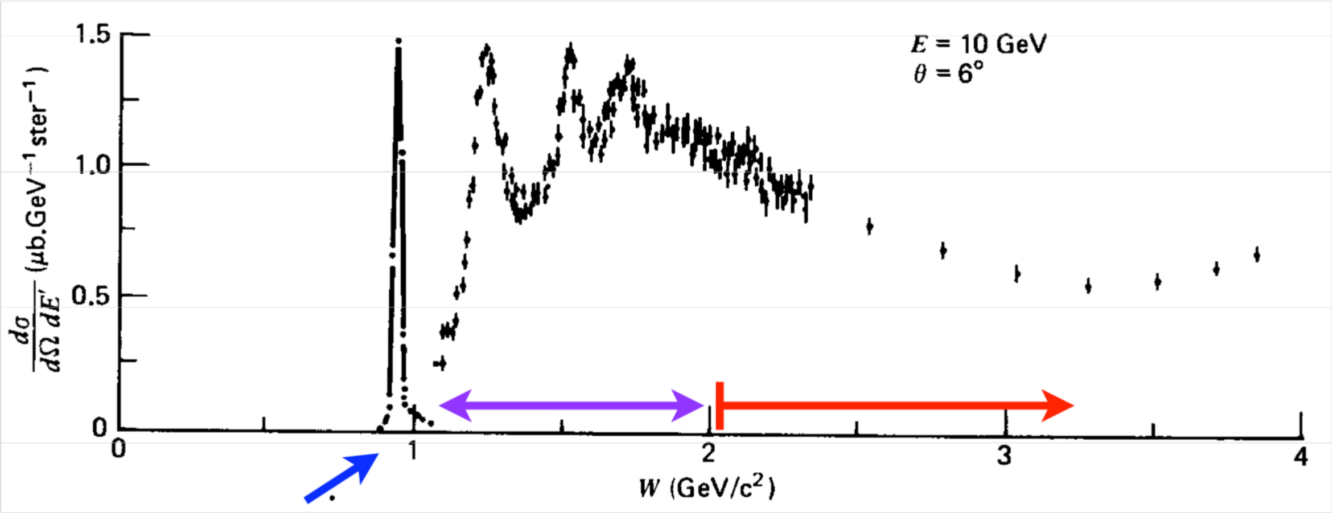


Courtesy D. Payette

Data Analysis – Run Group A

Inclusive Deep Inelastic Scattering Differential Cross Section





elastic scattering
ep → ep

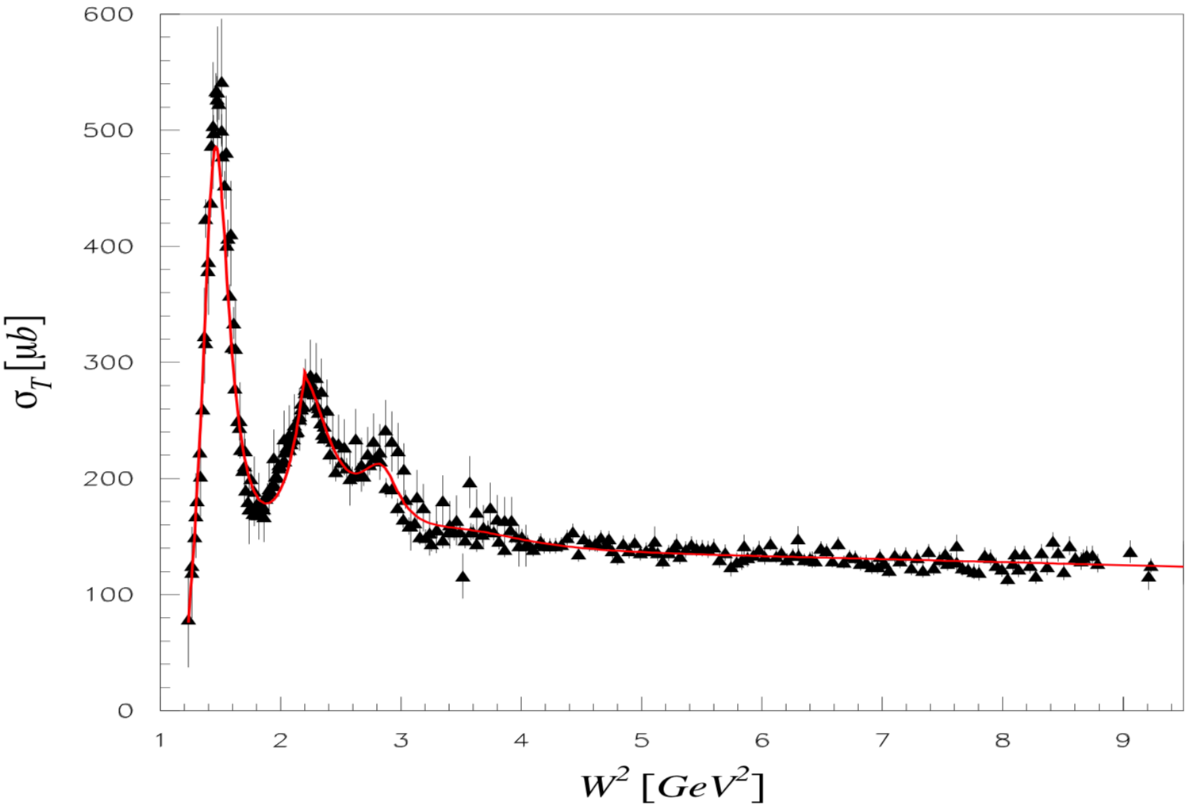
resonance region
ep → eΔ, eN*, ...

DIS regime: W > 2 GeV
ep → e(X = many hadrons)

Data Analysis – Run Group A

Monte-Carlo Data

$$\frac{d^2\sigma}{dxdy} = \frac{4\pi\alpha_{em}S}{Q^4}\left[xyF_1^p(x,Q^2) + \left(1 - y - xy\frac{M^2}{S}\right)F_2^p(x,Q^2)\right]$$



$\frac{d^2\sigma}{dxdy}$: inclusive DIS differential cross section

α_{em} : fine structure constant

M : proton mass

S$= 2ME$

$y = (E - E')/E$

M.E. Christy and P.B. Bosted. Phys. Rev. C, **81**, p. 055213, (2010).

RGA Analysis Cuts

Summary of cuts

DIS Kinematics

- $W > 2$ GeV
- $Q^2 > 1$ GeV^2

Fiducial

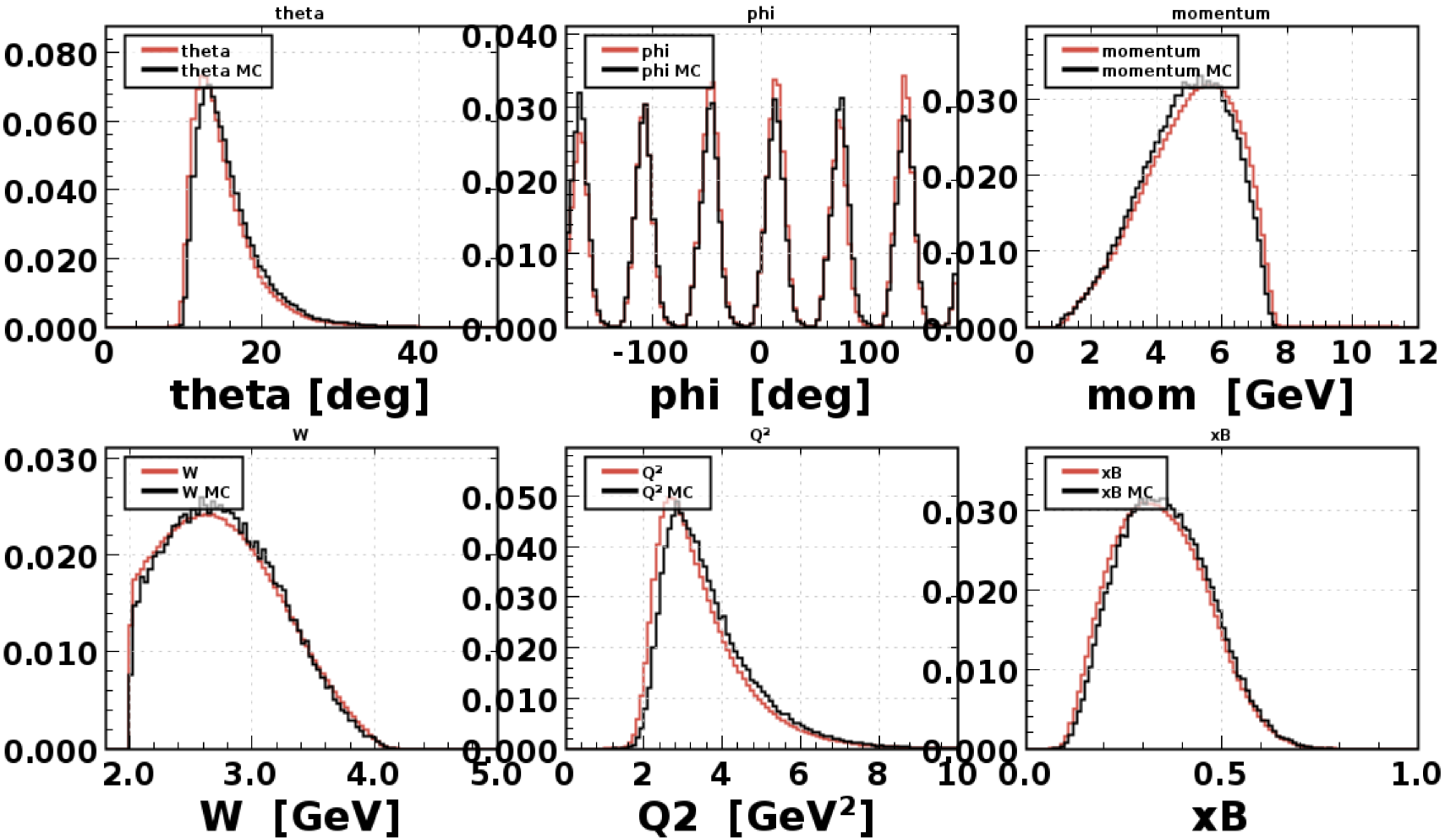
- PCAL cuts: U > 30 cm, 30 < V < 390 cm, and 30 < W < 390 cm
- $-10 < v_z < 10$ cm
- $5^\circ < \theta < 40^\circ$

Particle ID (e^- selection)

- 5σ cut on EC E_{tot}/p vs p
- HTCC cut: nphe > 5
- EC energy cuts: $E_{PCAL} > 0.06$ GeV, $E_{ECin} > 0.025$ GeV, $E_{ECout} > 0.05$ GeV

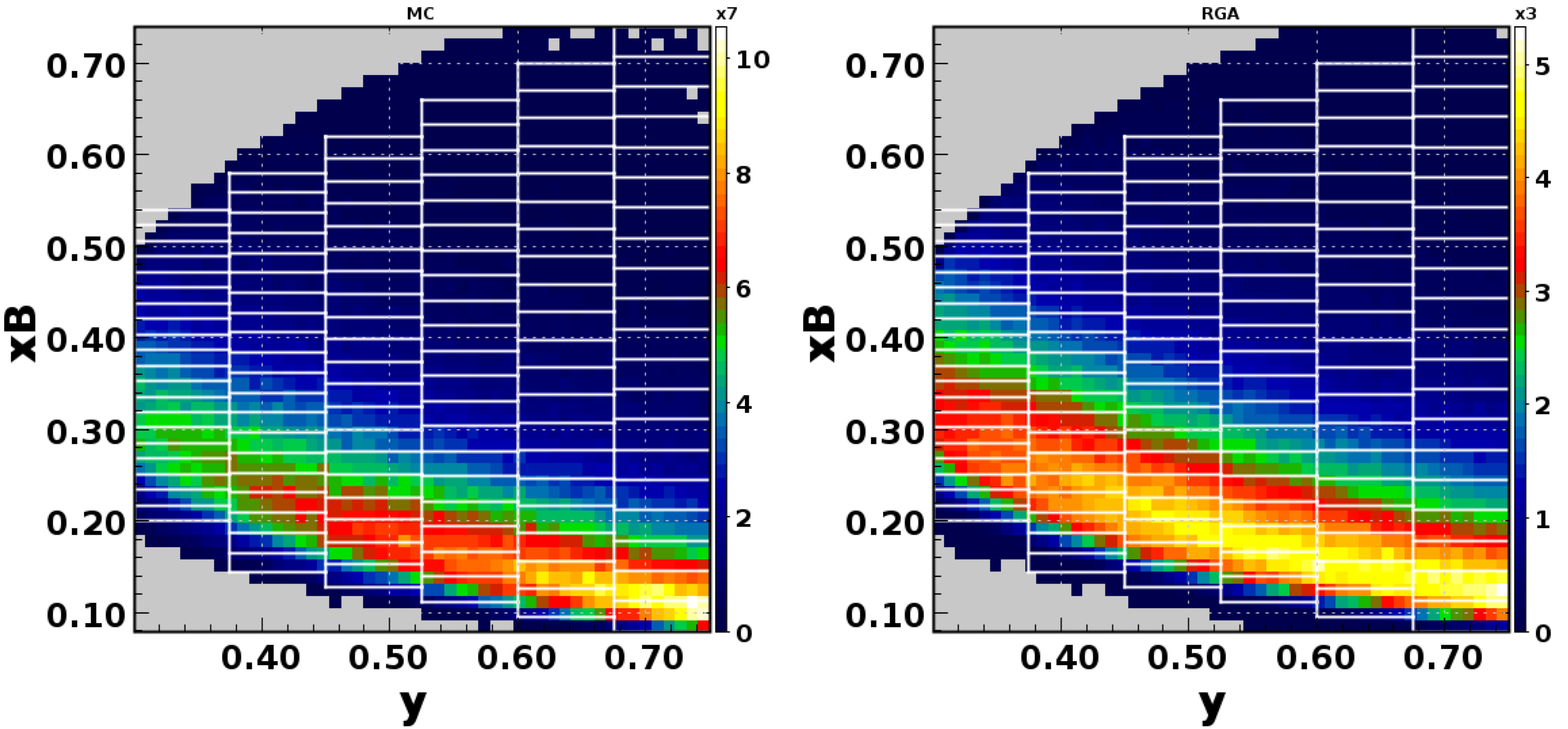
Data Analysis – Run Group A

Comparison of MC and RGA kinematics



DATA ANALYSIS – RUN GROUP A

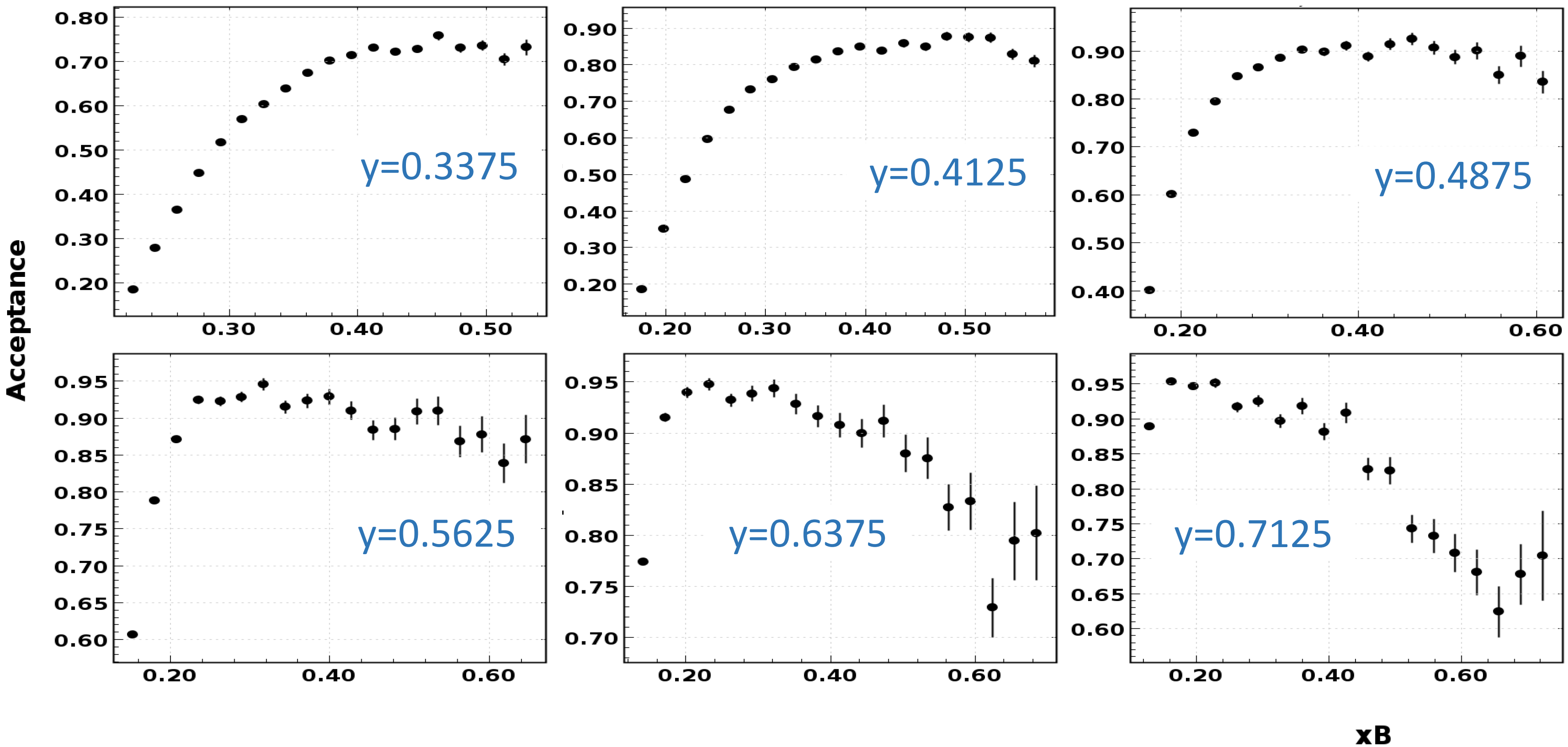
Binning in x and y



6 bins in y and 20 x-bins in each y-bin to cover the kinematic range of the y vs x distribution.

Data Analysis – Run Group A

Bin Acceptance



$$A(x,y) = \frac{N_{rec}}{N_{gen}} \qquad \delta A(x,y) = \frac{A(x,y)}{\sqrt{N_{rec}}}$$

Data Analysis – Run Group A

RGA Inclusive DIS Differential Cross Section Calculation

$$\frac{d^2\sigma}{dxdy} = \frac{N(x,y)}{\mathcal{L}_{int}A(x,y)\Delta x\Delta y}$$

$$\delta\left(\frac{d^2\sigma}{dxdy}\right) = \frac{d^2\sigma/dxdy}{\sqrt{N(x,y)}}$$

$\frac{d^2\sigma}{dxdy}$: inclusive DIS differential cross section

$N(x,y)$: number of reconstructed DIS events in the x,y bin

$\mathcal{L}_{int}$: time integrated luminosity

$A(x,y)$: acceptance of the x,y bin

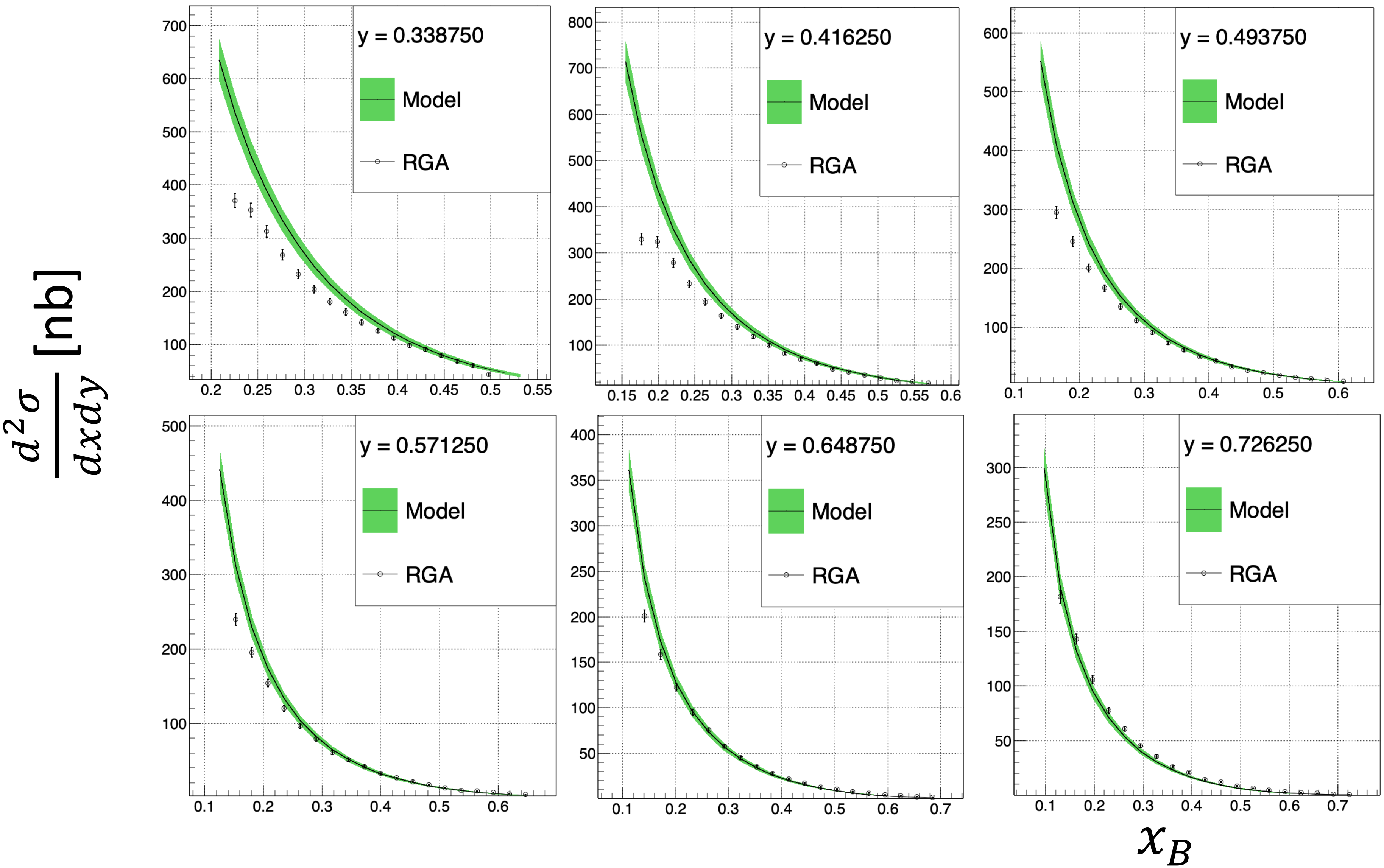
Δx : x bin size

Δy : y bin size

$\delta\left(\frac{d^2\sigma}{dxdy}\right)$: uncertainty on the cross section

Data Analysis – Run Group A

Inclusive DIS differential cross section



Conclusions

The extracted inclusive DIS differential cross sections from Run Group A data were consistent with fits to existing data.

The simulation and development of the BONuS12 RTPC was successful.

The DMS worked successfully and helped to determine variations in the drift-gas parameters that it was meant to monitor during the BONuS12 experiment.

The BONuS12 RTPC worked relatively well during its 36 day run. There was a substantial amount of data collected that will be calibrated and analyzed for years to come.

References

Beringer et al., Phys. Rev. **D86**, 010001 (2012).

Ciofi degli Atti and Kopeliovich, Eur. Phys. J. **A17** (2003) 133.

E.D.Bloon et.al, Phys. Rev. Lett **23** (1969) 930

H1 Collab., I. Abt et al.,Nucl. Phys. **B407** (1993) 515.

M. Sargsian and M. Strikman, Phys. Lett. **B639** (2006) 223.

S. Tkachenko et al. Phys. Rev. **C89** (2014) 045206.

W. Melnitchouk, M. Sargsian and M.I. Strikman, Z. Phys. **A359** (1997) 99.

ZEUS Collab., M. Derrick et al., Phys. Lett. **B316** (1993) 412.

M.E. Christy and P.B. Bosted, Phys. Rev. C, **81**, (2010) 055213.

Backups

RGA Analysis

Summary of Systematic Errors

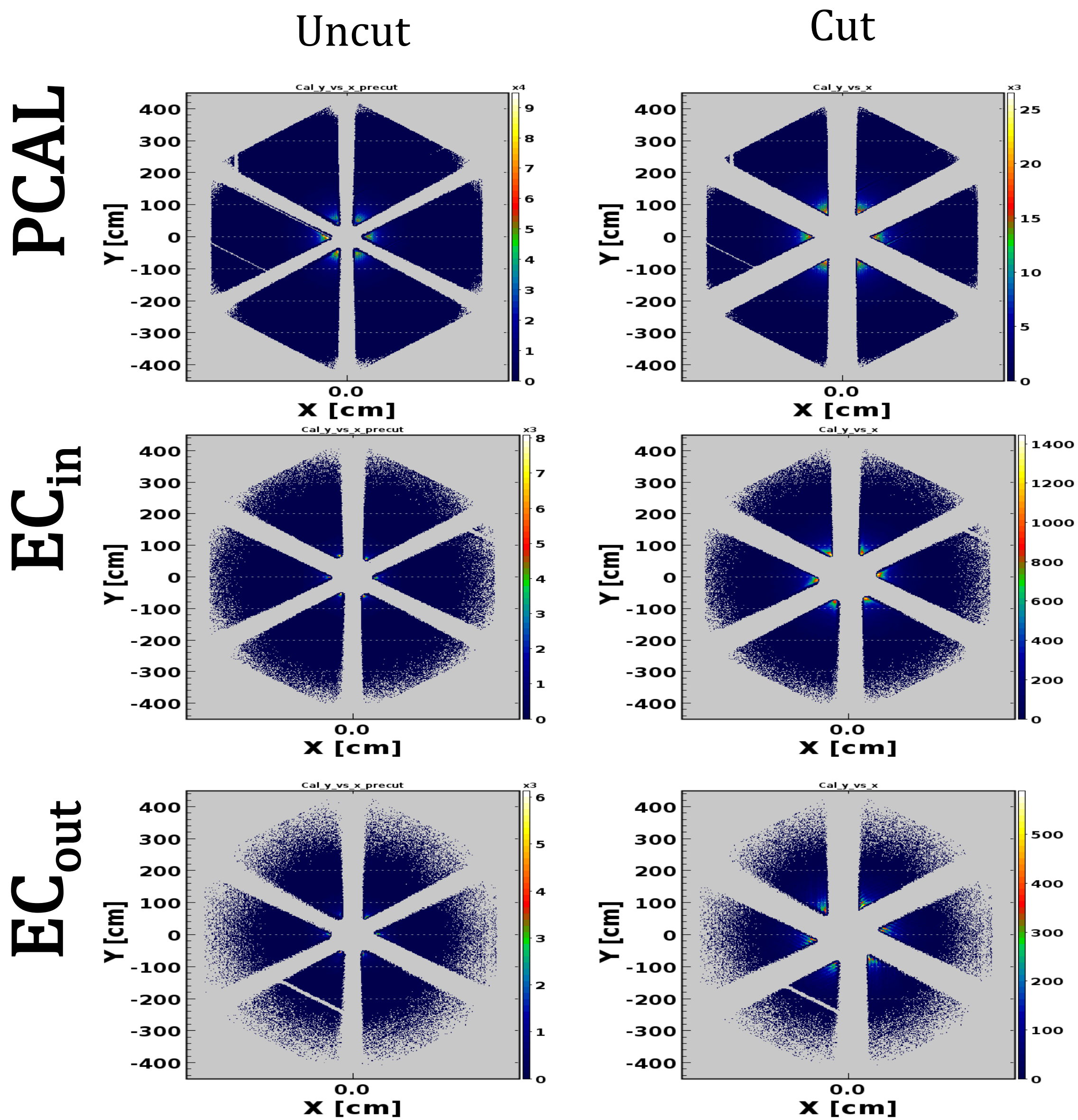
Source	Systematic Uncertainty (%)	Explanation
e^+	1.0	Effect of pair-symmetric contamination
π^-	1.0	Effect of pion contamination
MC	3.0	Combined uncertainty due to Monte-Carlo statistics and systematics
TOTAL	3.32	Added in quadrature

RGA Analysis Cuts

EC

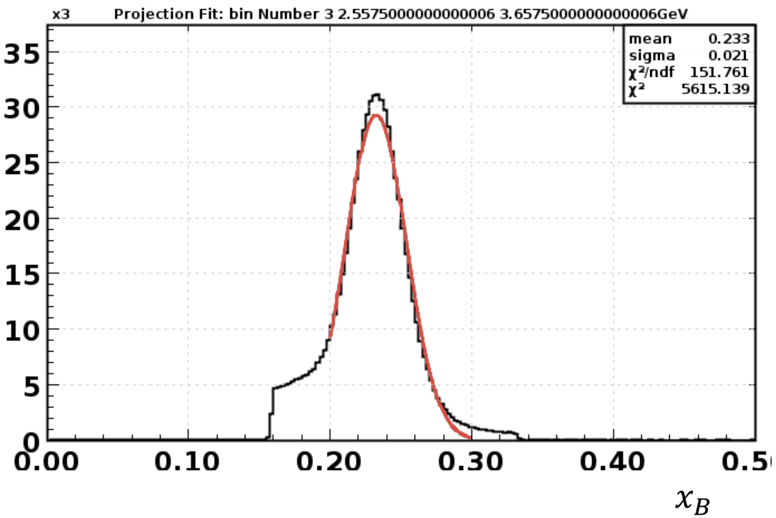
U > 30 cm
30 < V < 390 cm
30 < W < 390 cm

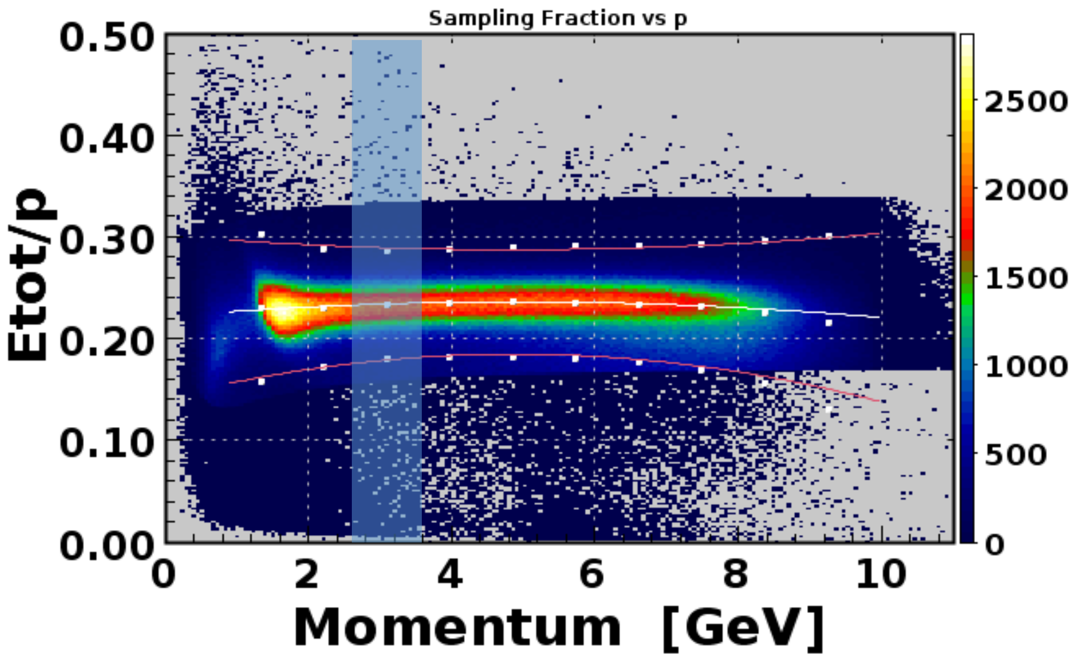
$E_{PCAL} > 0.06$ GeV
$E_{ECin} > 0.025$ GeV
$E_{ECout} > 0.05$ GeV



RGA Analysis Cuts

Sampling fraction





$$\left(\frac{E_{tot}}{p}\right)_{+2.5\sigma} = 0.008p^2 - 0.0112p + 0.3137$$

$$\left(\frac{E_{tot}}{p}\right)_{-2.5\sigma} = -0.0017p^2 + 0.0228p + 0.1397$$

BONuS12 Analysis

Off-shell corrections

Neutron off-shell mass squared

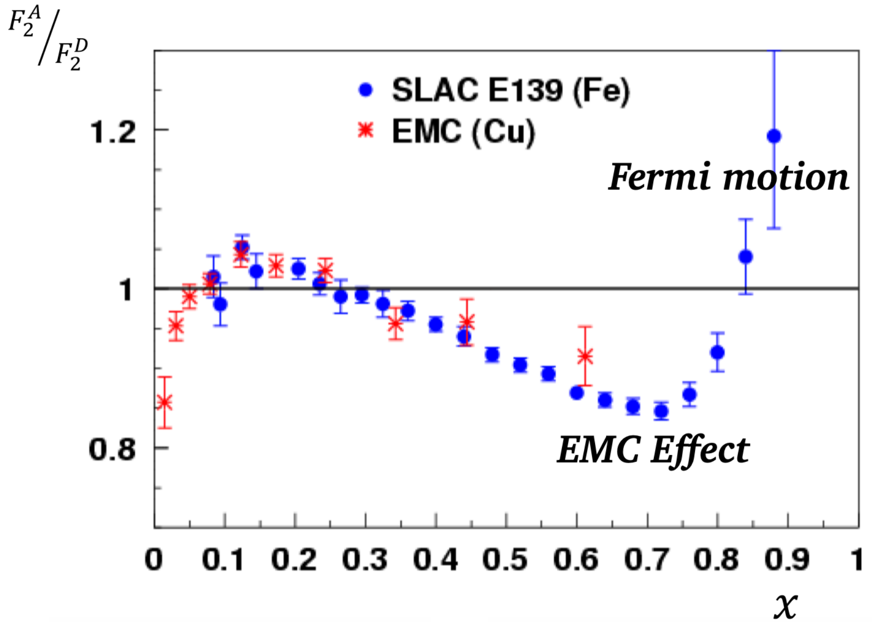
$$p^2 \approx M^2 + 2M\epsilon_d - 2p_s^2$$

The bound neutron structure functions depend on this off-shell mass squared and can introduce deviations of the extracted structure functions to their on-shell values.

Restricting the detection of only low momentum protons reduces this dependence to a few percent around $p \approx 100$ MeV/c and less than a percent $p \approx 70$ MeV/c.

BONuS12 Analysis

EMC effect and nuclear corrections



Bound nucleons do not behave the same as free protons and neutrons. Between $0.3 < x < 0.8$ the EMC effect must be a correction to the ratio. For $x > 0.8$, Fermi motion, which describes the movement of the nucleons within the nucleus dominates.

Drift-gas Monitoring System

Expected rate assuming point source

$$\tan \gamma = \frac{d}{2b}$$

Solid angle element

$$\Omega_f = \pi \gamma^2 = \pi \left(\tan^{-1} \frac{d}{2b} \right)^2$$

Fraction of solid angle

$$f = \frac{\Omega_f}{\Omega_{tot}} = \frac{\Omega_f}{4\pi} = \frac{1}{4} \left(\tan^{-1} \frac{d}{2b} \right)^2$$

$d = 0.65\ cm$
$b = 13\ cm$

$f = 0.000156$
$A = 2\ uCi = 74000$ decays per sec

$$a = fA \approx 12\ Hz$$