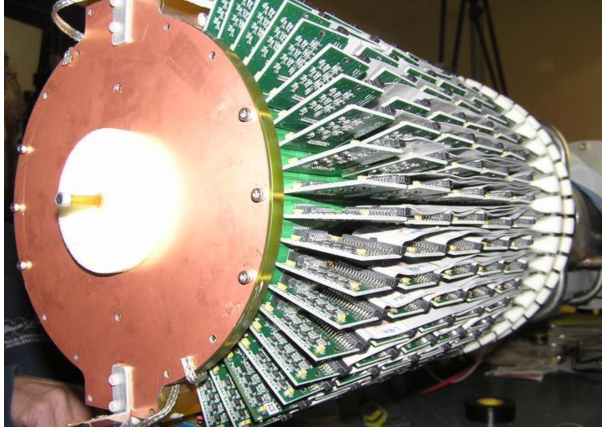
BoNuS Program at CLAS and CLAS12:



BoNuS=Barely off-shell Nuclear Structure

measurement of the free neutron structure function at large *x* in deuterium via spectator tagging

Jixie Zhang （张机械）

Jefferson Lab

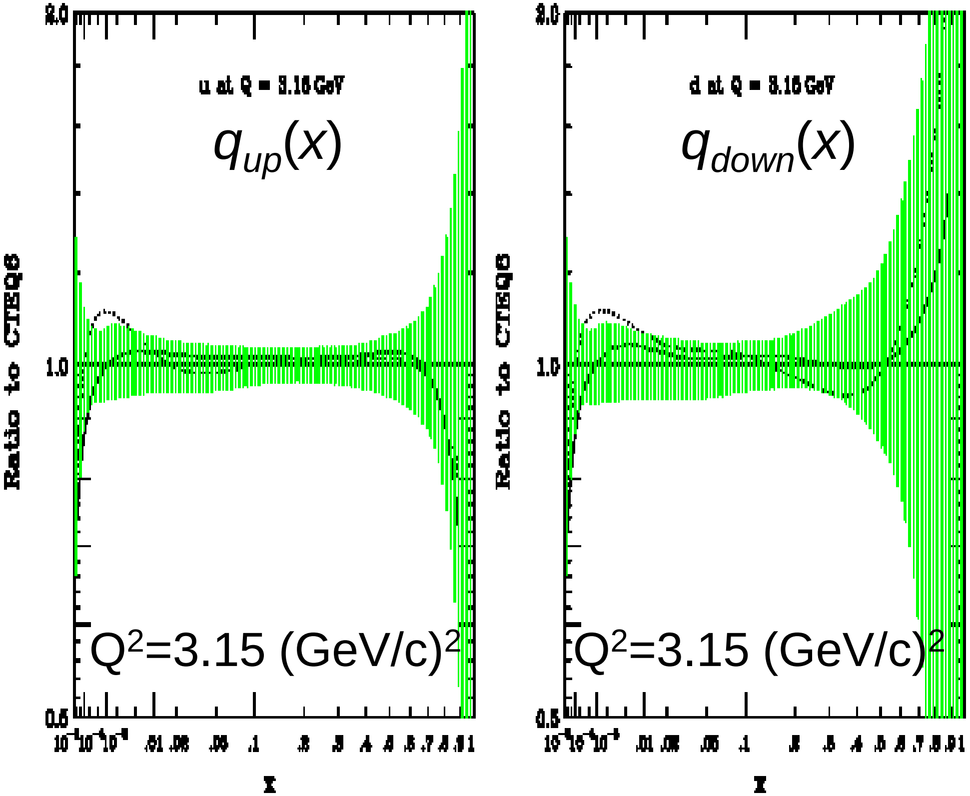
for the CLAS Collaboration

2nd Workshop on Hadron Physics in China, July 30, 2010

Structure Functions and Moments

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left(2\tan^2\frac{\theta}{2}\frac{F_1(x)}{M} + \frac{F_2(x)}{\nu}\right)$$

$$F_2(x,Q^2) = x \sum_{f=up,down,\ldots} z_f^2(q_f(x,Q^2)+\bar{q}_f(x,Q^2))$$

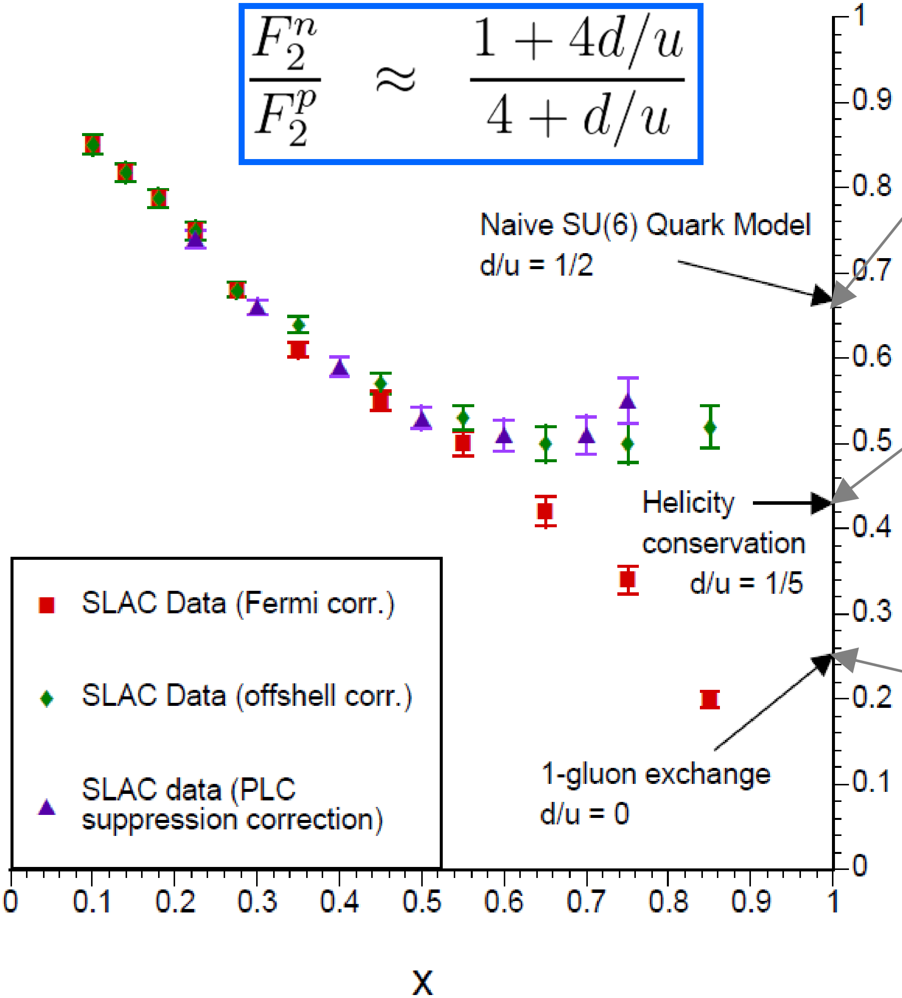


Ratio to CTEQ6

- Precise PDFs at large x needed as input for LHC
  - Large x, medium Q^2 evolves to medium x, large Q^2
- Moments can be directly compared with OPE (twist expansion), Lattice QCD and Sum Rules
  - All higher moments are weighted towards large x

Nucleon Structure Functions

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



SLAC E139 (*L. W. Whitlow, et al.*), and E140 (*J. Gomez, et al.*)

$$\frac{F_2^n}{F_2^p} = \frac{2}{3}, \qquad \frac{d}{u} = \frac{1}{2}$$

SU(6) symmetry **$u_v(x) = 2d_v(x)$**

$$\frac{F_2^n}{F_2^p} \rightarrow \frac{3}{7}, \qquad \frac{d}{u} \rightarrow \frac{1}{5}$$

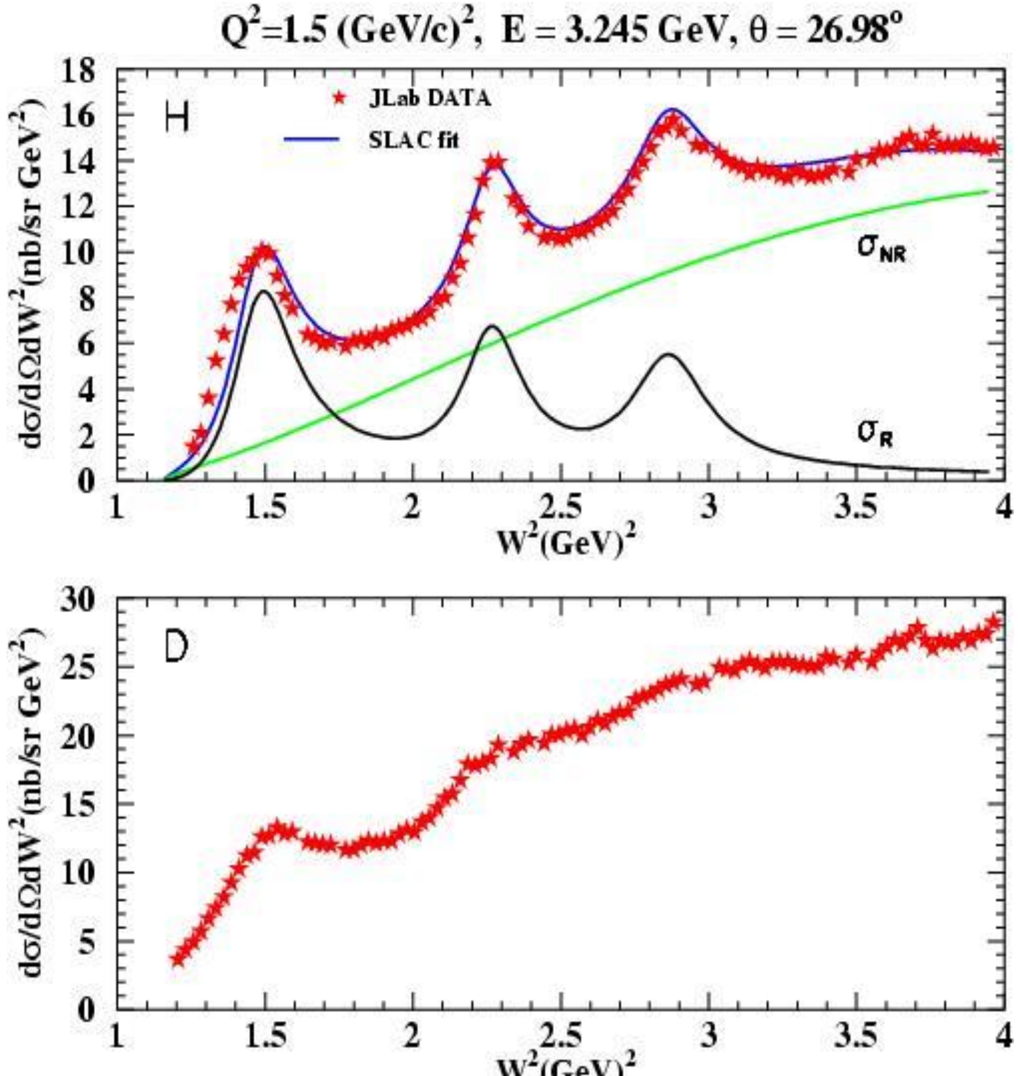
$S_z = 0$ dominant, helicity conservation
Farrar and Jackson, *Phys Rev Lett* **35** (1975)
Brodsky, Burkardt and Schmidt, *Nuc Phys* **B441** (1995)

$$\frac{F_2^n}{F_2^p} \rightarrow \frac{1}{4}, \qquad \frac{d}{u} \rightarrow 0$$

S = 0 dominant, one-gluon exchange
Close, *Phys Lett* **B43** (1973)
Carlitz, *Phys Lett* **B58** (1975)
Close and Thomas *Phys Lett* **B212** (1988)
Isgur, *Phys Rev* **D59** (1999), *Phys Rev Lett* **41** (1978)

Inclusive Cross Section

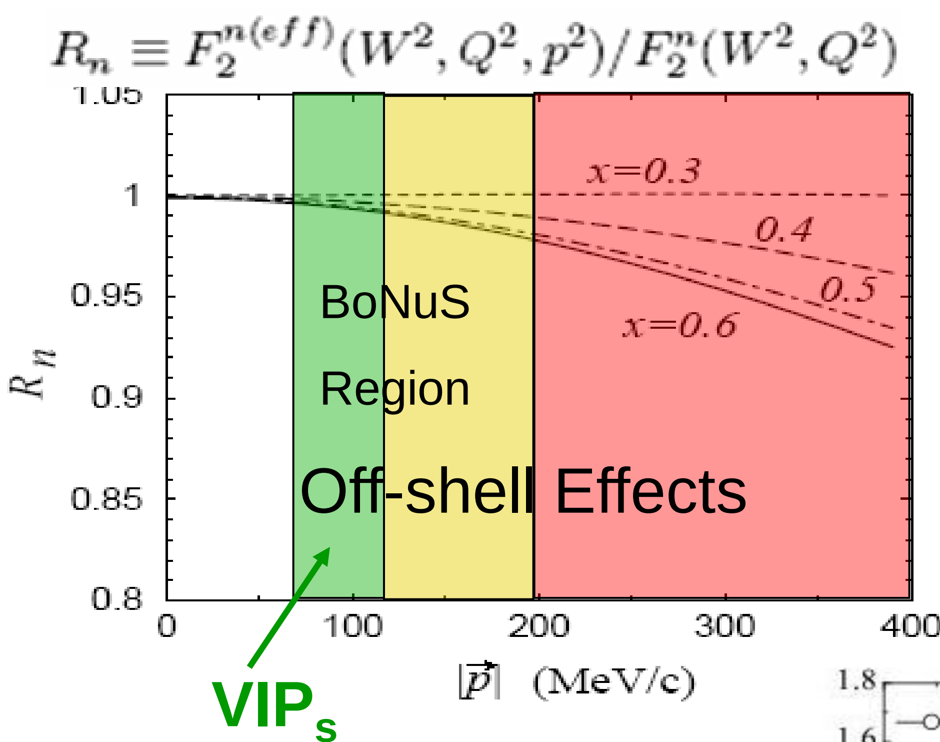
- Data on the Proton: Clear resonant structure, separation from the non-resonant background is possible
- Data on the deuteron: Kinematically smeared due to binding, off-shell, final state interactions (FSI), etc.



L.W. Whitlow *et al.*, Phys. Lett. **B282**, 475 (1992).

P. Amaudruz *et al.*, Phys. Lett. **B295**, 159 (1992).

Off-Shell and FSI for $D(e,e'p_s)X$



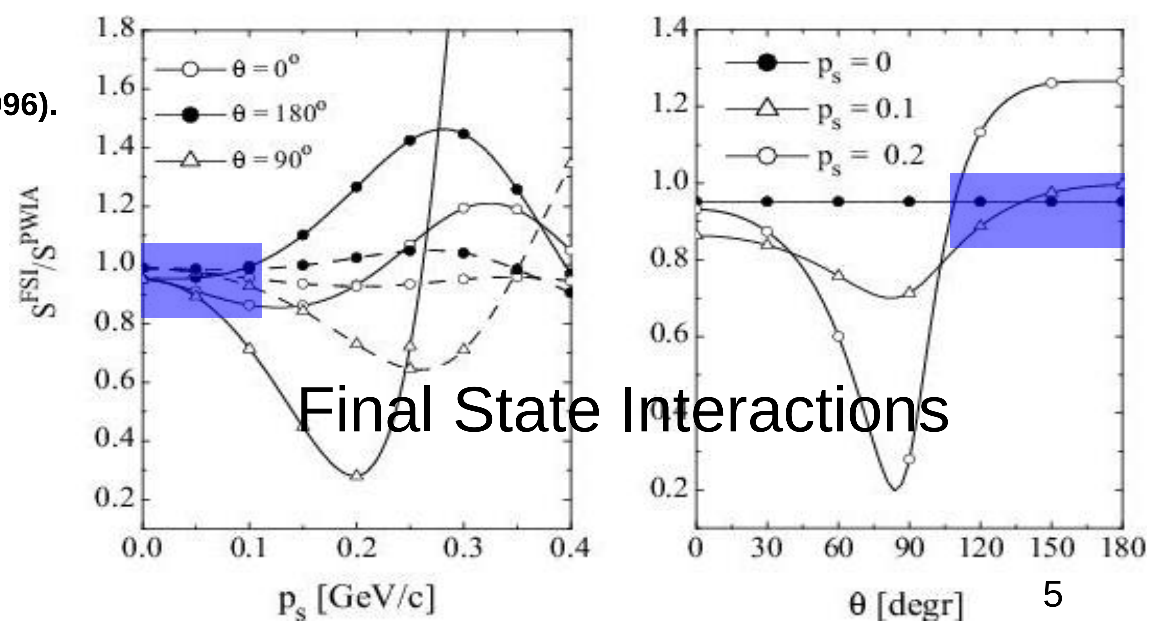
W. Melnitchouk *et al*, Phys. Lett. B377, 11 (1996).

↑

Off-shell effects are negligible for small P_s. Choose P_s<120 MeV/c as Very Important Spectator Protons (VIP)

Select low P_s (<120 MeV/c) and large backward θ_{pq} (>100°), angle between P_s and virtual photon, to minimize FIS.

↓



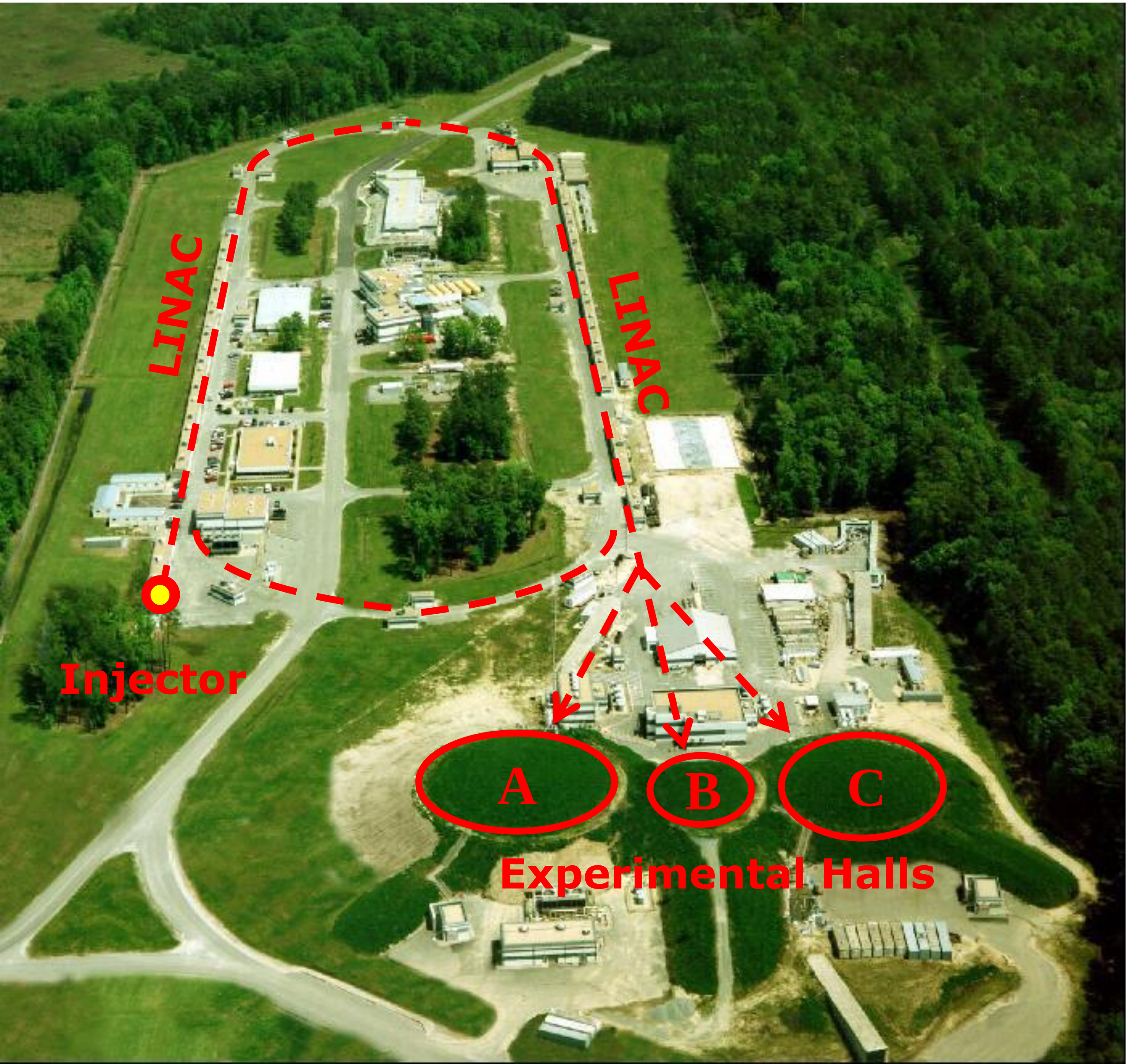
C. Ciofi degli Atti *et al*, Eur. Phys. J. A 19,133-137 (2004).

Jefferson Lab Experiment E03-012

Barely off-shell Nucleon Structure

- Electron beam energies: 2.1, 4.2, 5.3 GeV
- Spectator protons were detected by the newly built Radial Time Projection Chamber (RTPC)
- Scattered electrons and other final state particles were detected by CEBAF Large Acceptance Spectrometer (CLAS)
- Target: 7 atm D_2 gas, 20 cm long
- Data were taken from Sep. to Dec. in 2005

Jefferson Lab

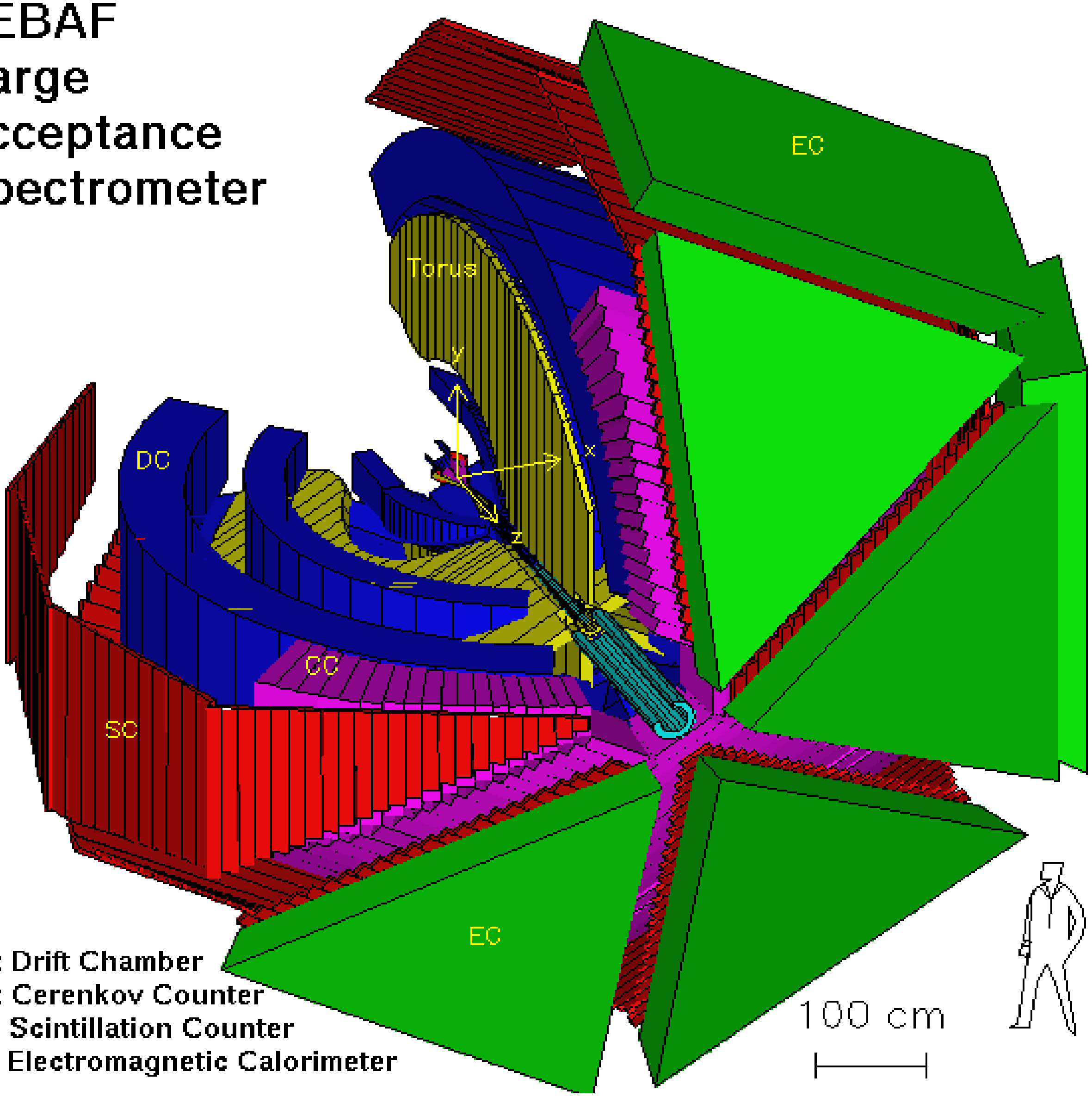


Continuous
Electron
Beam
Accelerator
Facility

- → **E: 0.75 –6 GeV**
- → **I_{max}: 200μA**
- → **RF: 1499 MHz**
- → **Duty Cycle: ~ 100%**
- → **$\sigma(E)/E$: ~ 10^{-4}**
- → **Polarization: 85%**
- → **Simultaneous distribution to 3 experimental Halls**

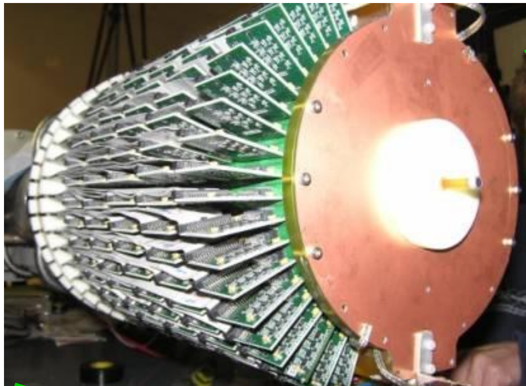
CLAS in Jefferson Lab, Hall B

CEBAF
Large
Acceptance
Spectrometer

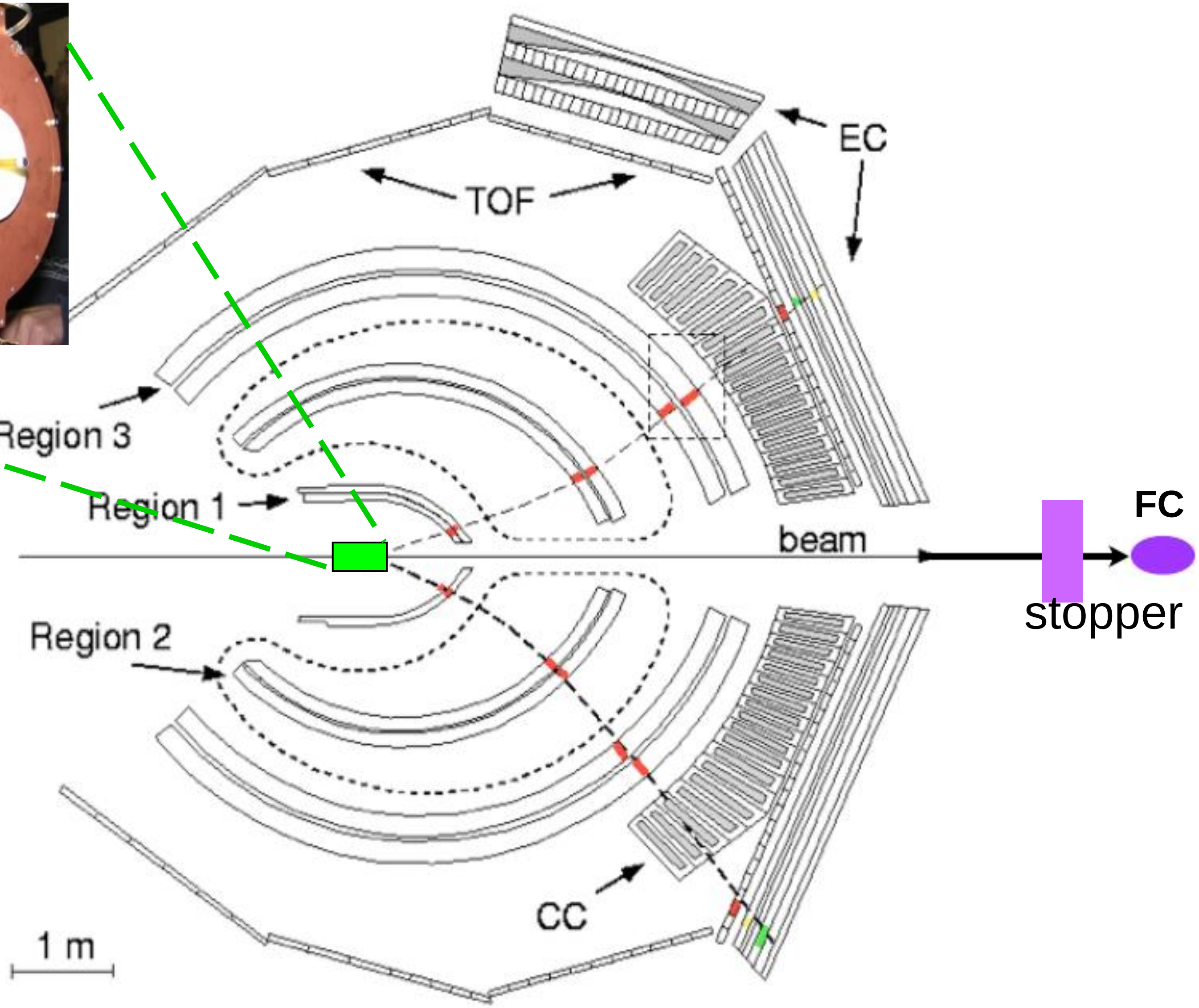


DC: Drift Chamber
CC: Cerenkov Counter
SC: Scintillation Counter
EC: Electromagnetic Calorimeter

RTPC Sits in the Center of CLAS

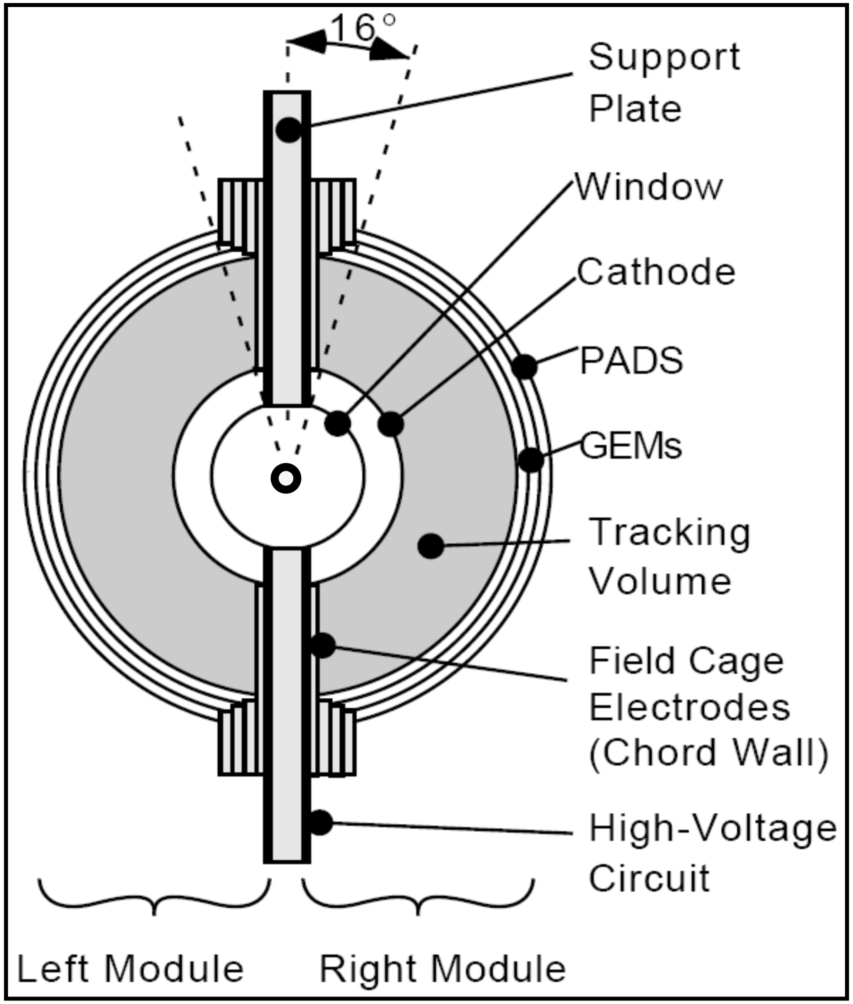


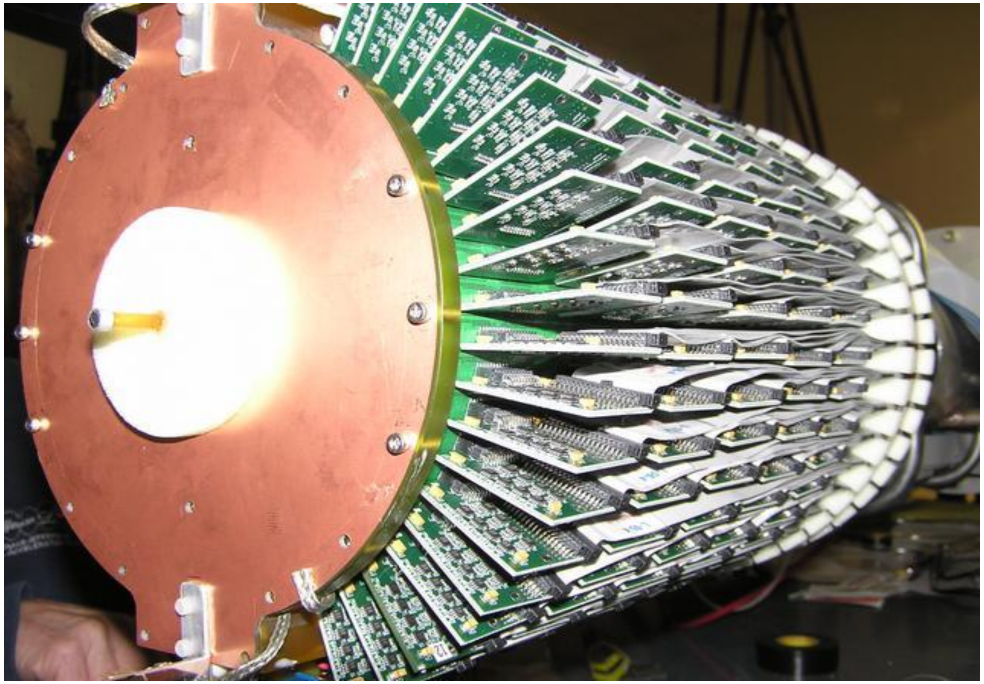
BoNuS RTPC



CLAS

Radial Time Projection Chamber (RTPC)





Radial Time Projection Chamber (RTPC)

Sensitive to protons with momenta of 67-250 Mev/c

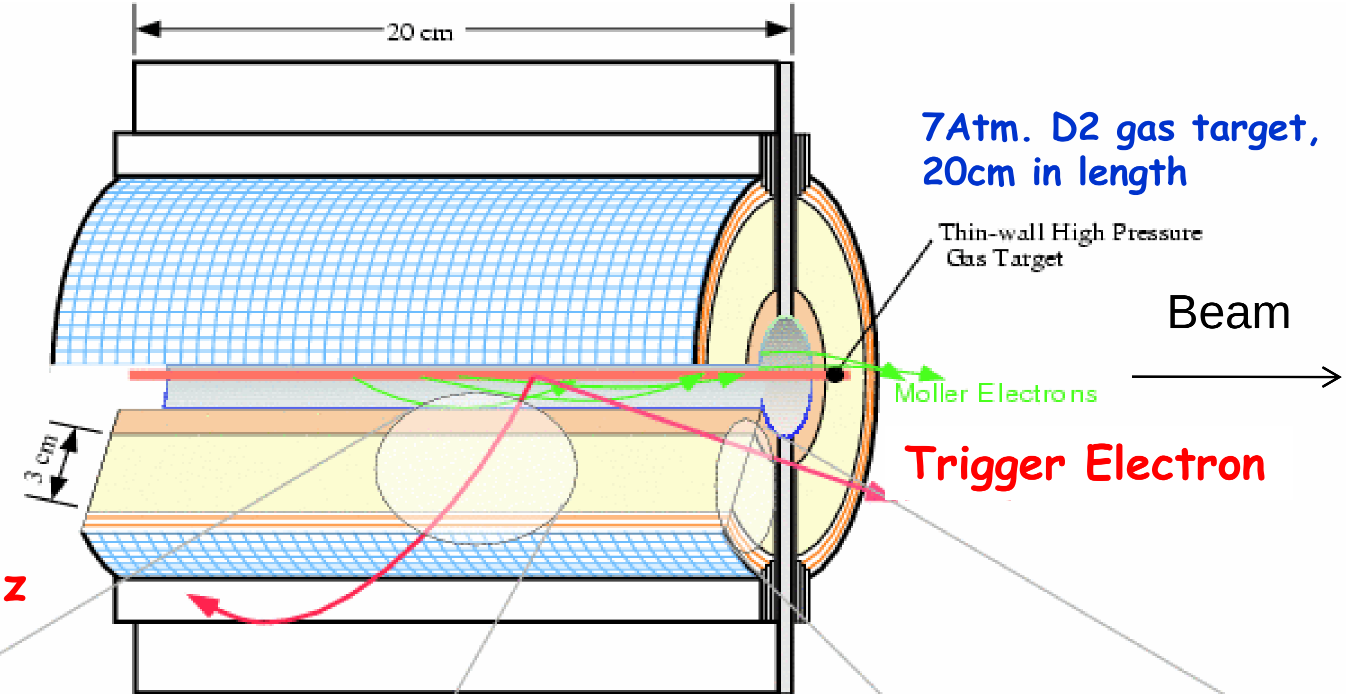
3 layers of GEM

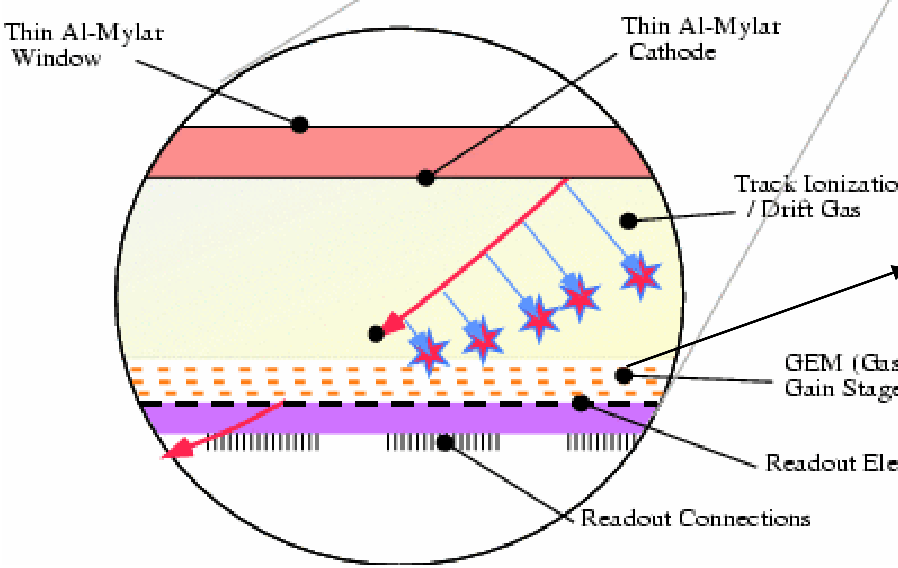
3200 pads (channels)

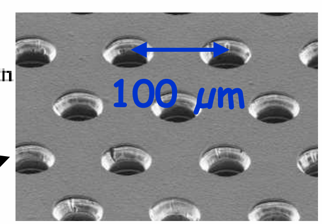
5 Tesla B field

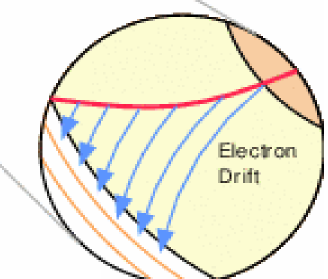
Particles ID by dE/dx

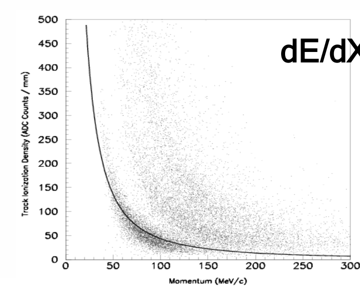
3-D tracking:
time of drift -> r
pad position -> ϕ, z





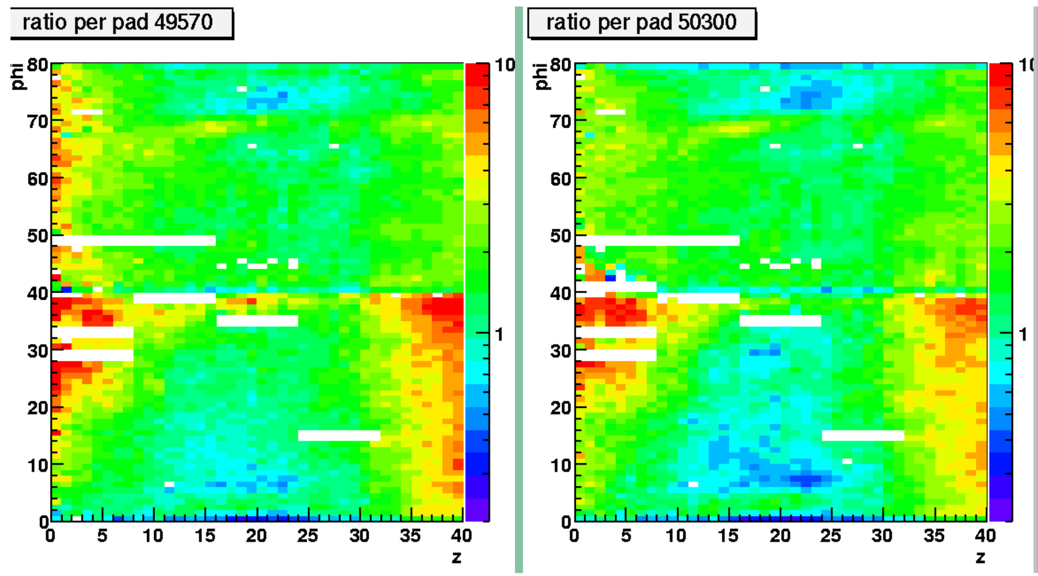




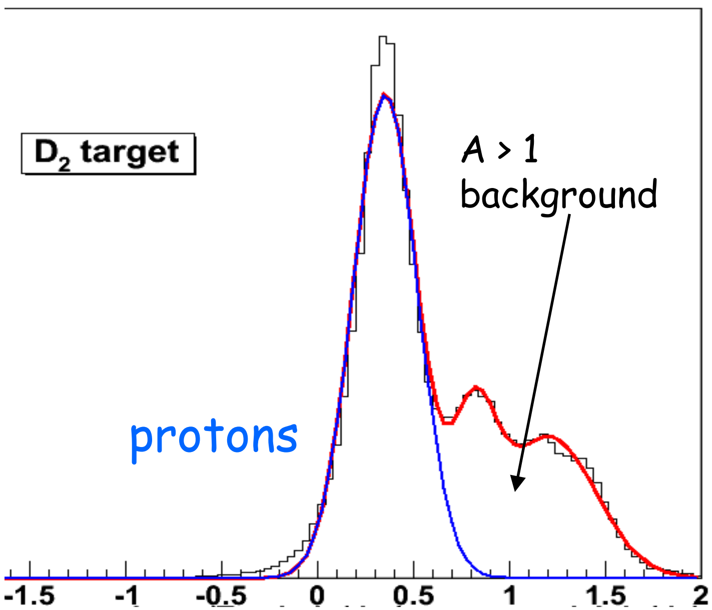


RTPC Particle Identification

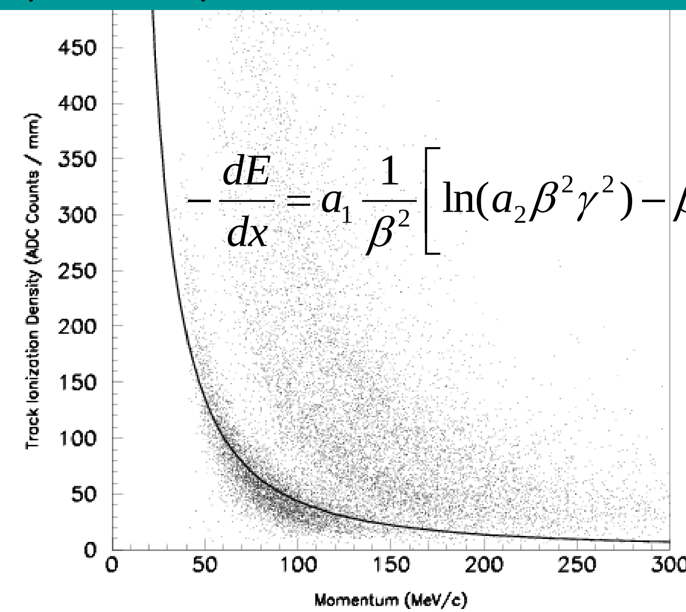
Channel by Channel gain multipliers can be determined for each run by comparing the track's expected energy loss to the measured value. After applying these gain corrections, a clear separation of protons and heavier particles through dE/dx has been achieved.



Gain constants (vs phi and z) detemined independently for two different runs.

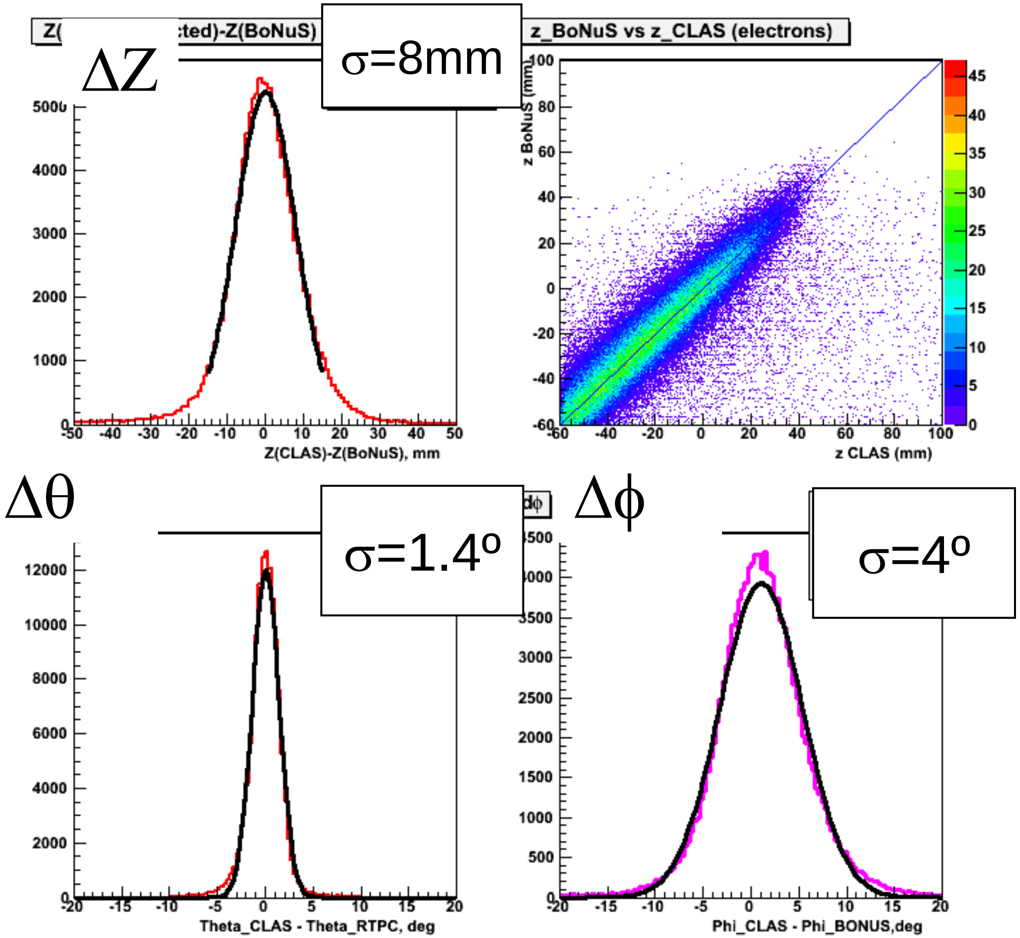


$$\log_{10}\left[\frac{dQ/dx_{\exp}}{dQ/dx_{calc}}\right]$$

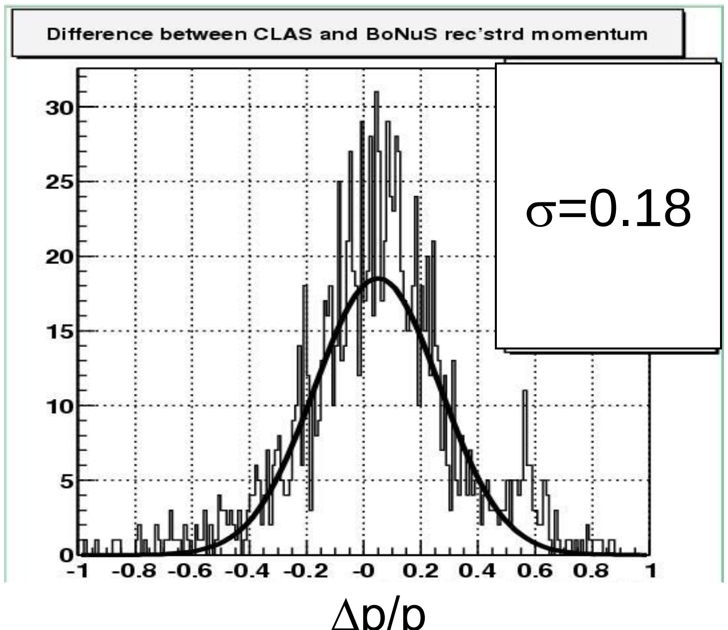


$$-\frac{dE}{dx} = a_1 \frac{1}{\beta^2}\left[\ln(a_2\beta^2\gamma^2) - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

RTPC Resolution



Trigger electrons measured by CLAS are compared to the same electrons measured in BoNuS during High Gain Calibration runs.

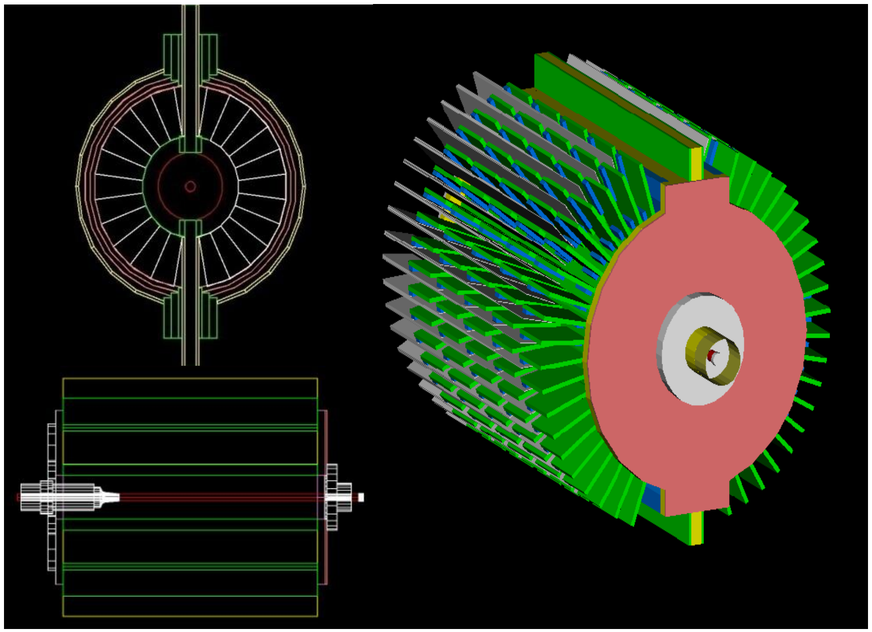


H. Fenker, et.al. **Nucl.Instrum. Meth. A592:273-286,2008**

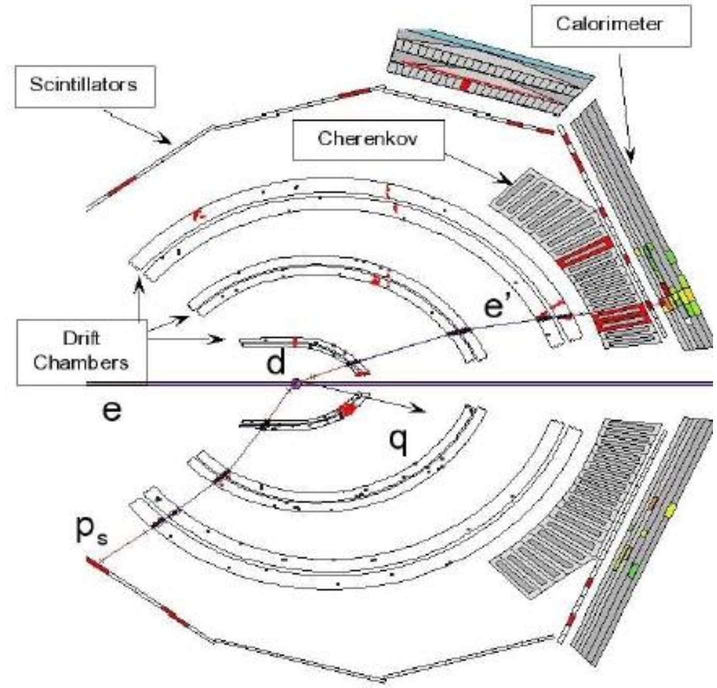
Proton momentum measured in RTPC and inferred from CLAS

Simulation Overview

RTPC(Geant4) → CLAS(geant3) → Reconstruction → Analysis



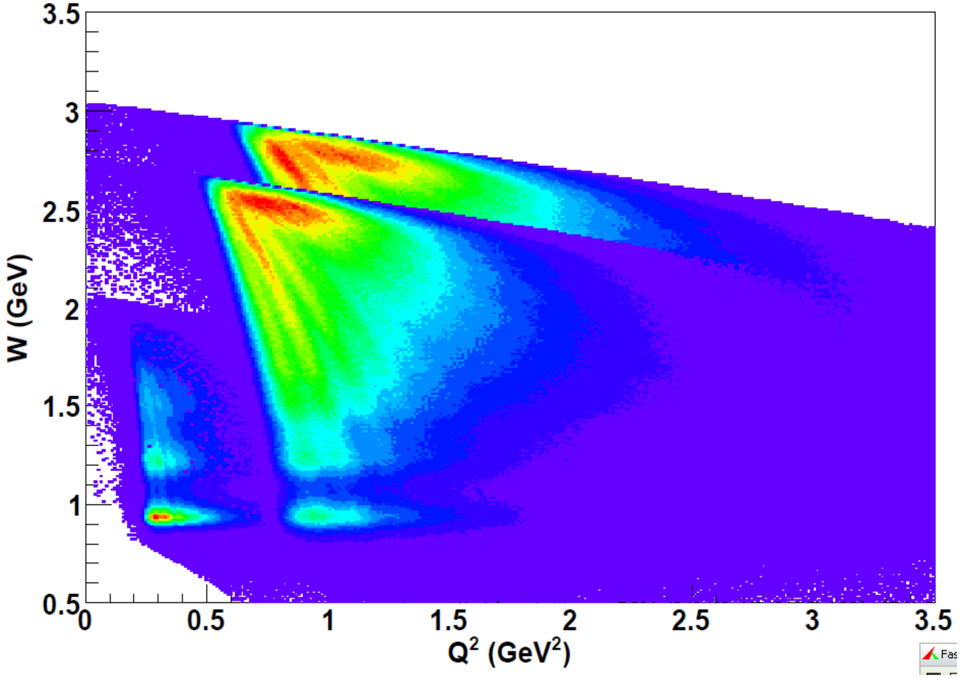
→

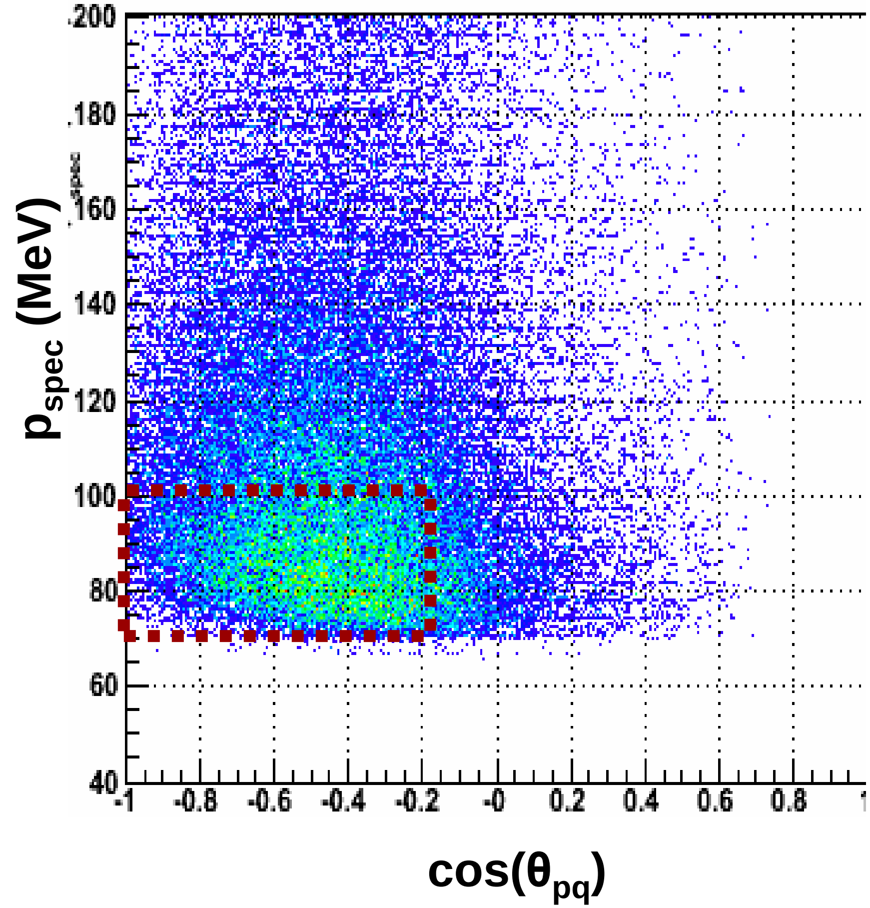


What have been done with simulation?

- Debug/optimize RTPC reconstruction packages
- Generate energy loss correction tables, radiation length tables
- Study Detector's acceptance for various reacctions
- Study particle detection efficiency
- Model the background…

BoNuS6 Data Volume and Kinematic Coverage

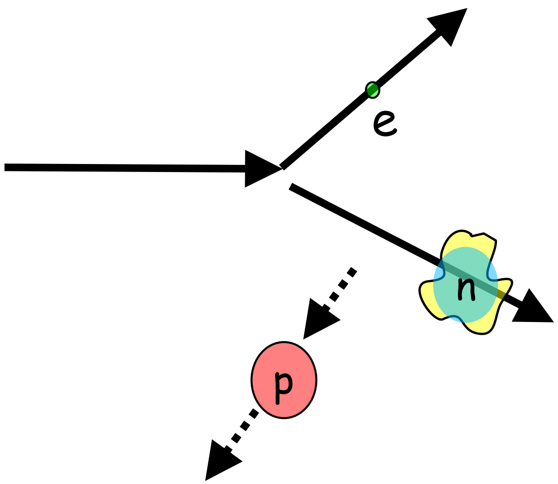




- 5.262 GeV : 456 M (D_2) and 64 M (H_2)
- 4.223 GeV : 306 M (D_2) and 11 M (H_2)
- 2.140 GeV : 91 M (D_2) and 15 M (H_2)
- Overall tagged count on D_2 is ~ 2%
- I = 35 nA, target = D_2:   L = 4.3 x 10^{33} g s^{-1} cm^{-3}

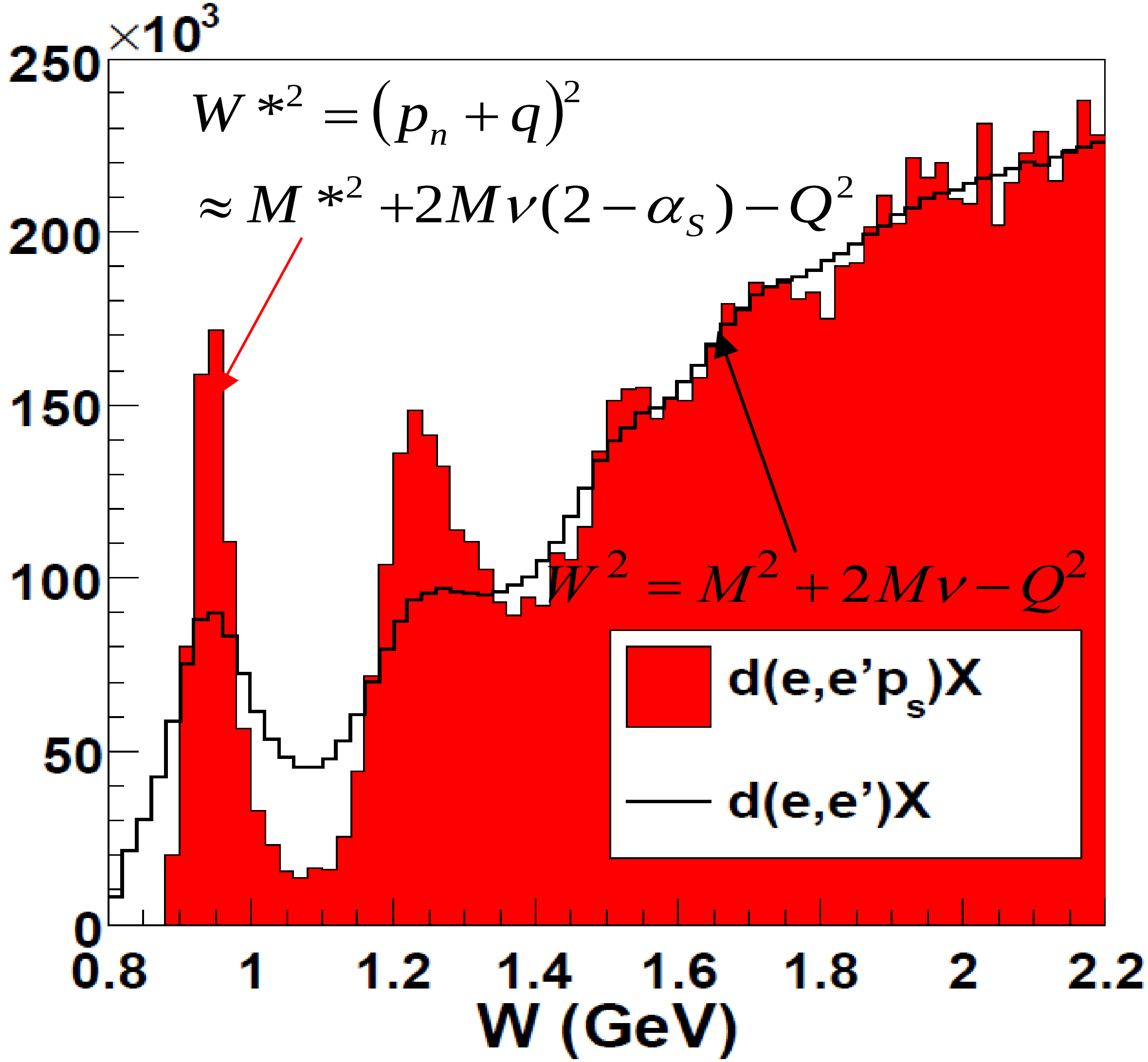
Spectator Tagging

E_{beam} = 4.223 GeV
$\langle Q^2 \rangle$ = 1.19 $(GeV/c)^2$

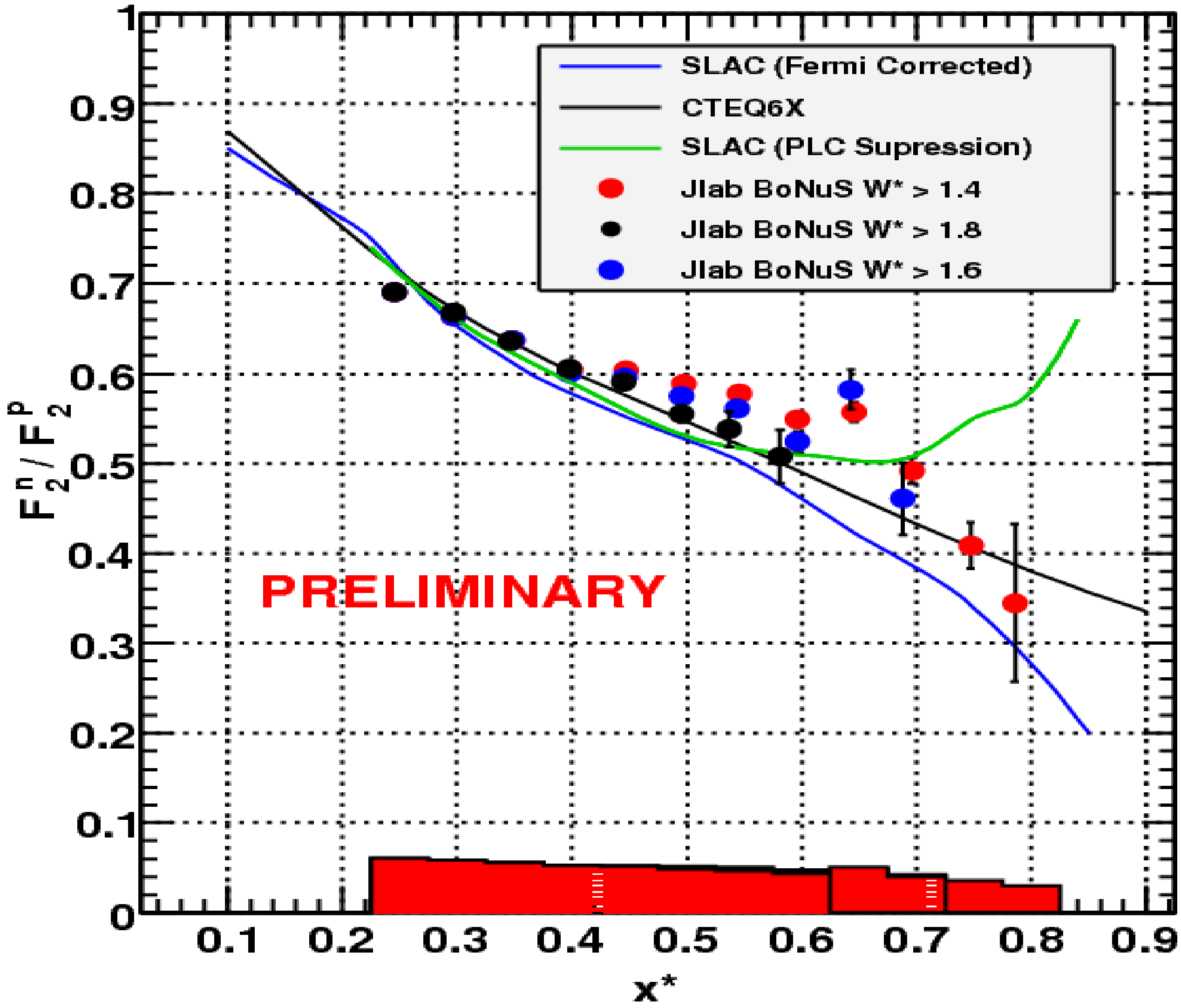


$$p_S = (E_S, \vec{p}_S); \quad \alpha_S = \frac{E_S - \vec{p}_S \cdot \hat{q}}{M_D/2}$$

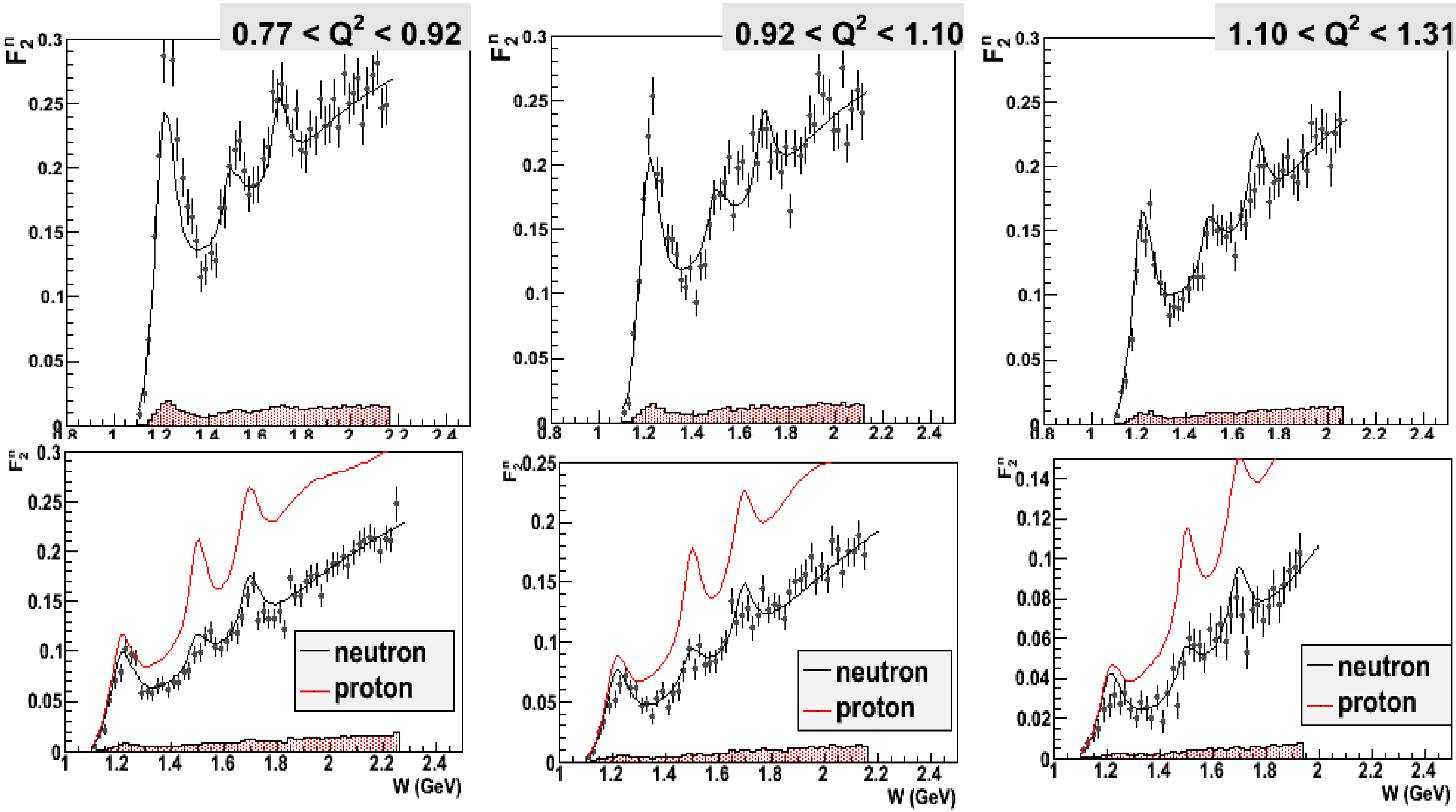
$$p_n = (M_D - E_S, -\vec{p}_S);$$
$$\alpha_n = 2 - \alpha_S$$



BoNuS Extracted F_2^n/F_2^p



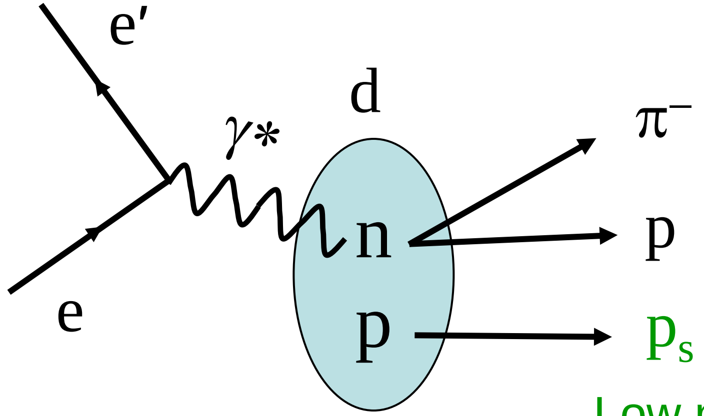
BoNuS Extracted F_2^n



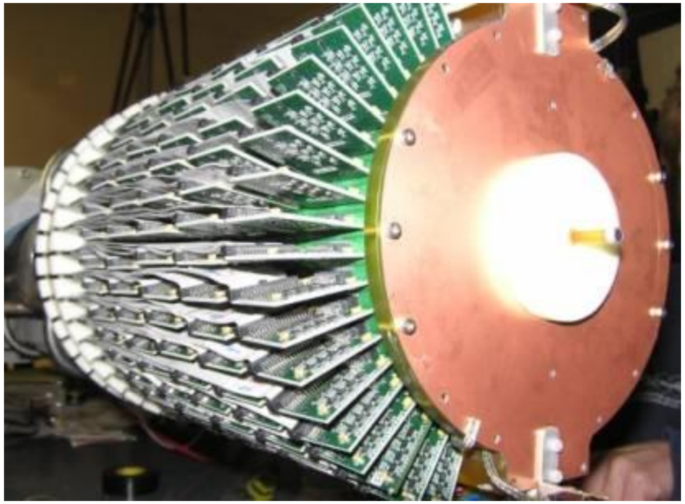
"Free" neutron structure function compared with a model by P. Bosted, Phys. Rev. C77 (2008) 065206

What else we can do?
Exclusive π^- electro-production

Detect e′, π^- and at least ONE of the two final state protons in $D(e,e`\pi^- p)p$ to ensure exclusivity and select events where the "spectator" proton has low, backwards momentum. Conservation of energy and momentum allows to determine the initial state of the neutron.

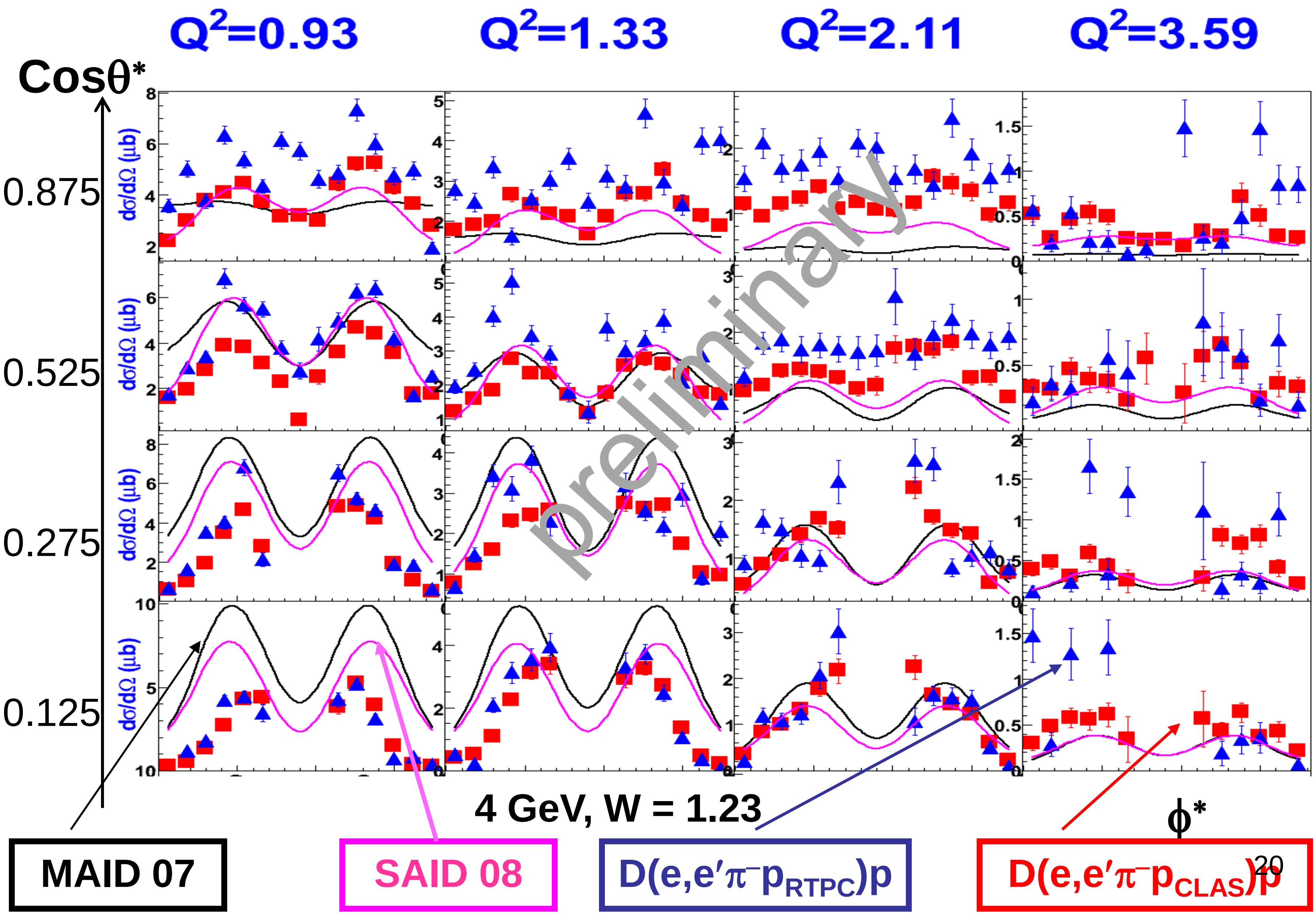


Low momentum spectator proton

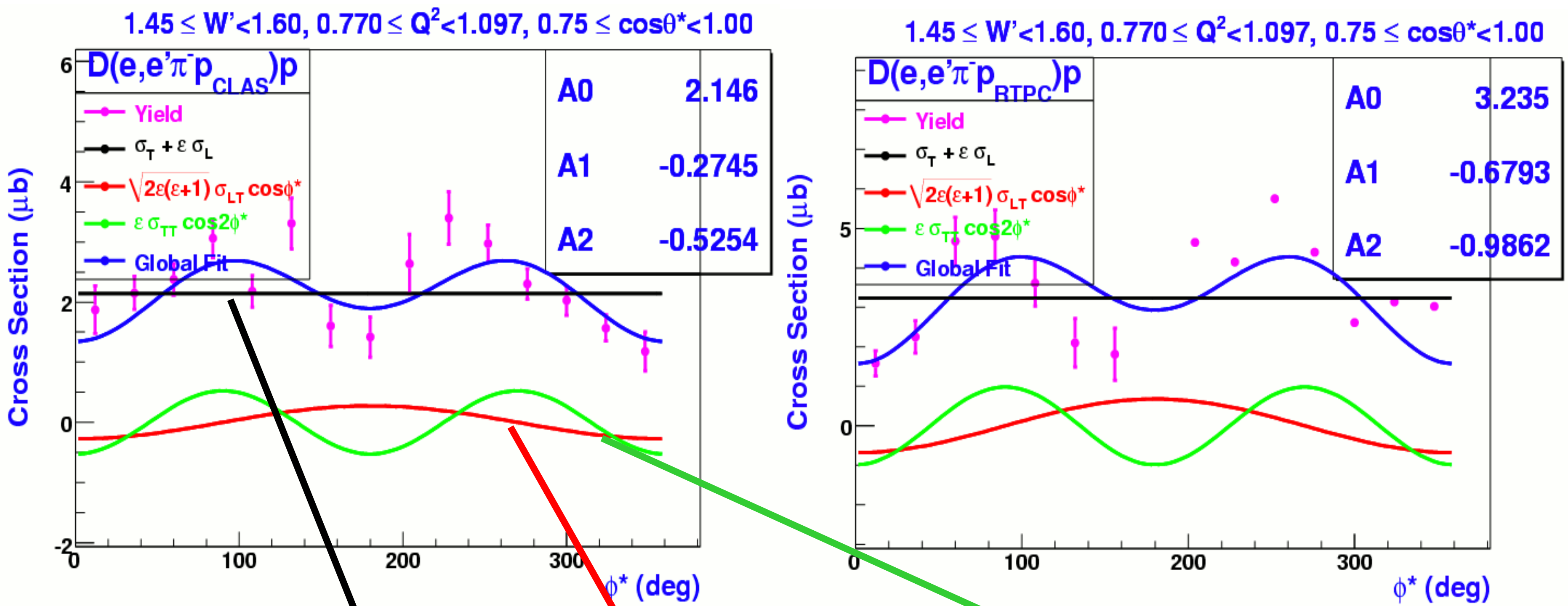


Novel approach by the BoNuS collaboration: detect the spectator proton directly.

Cross Section: BoNuS Vs MAID and SAID



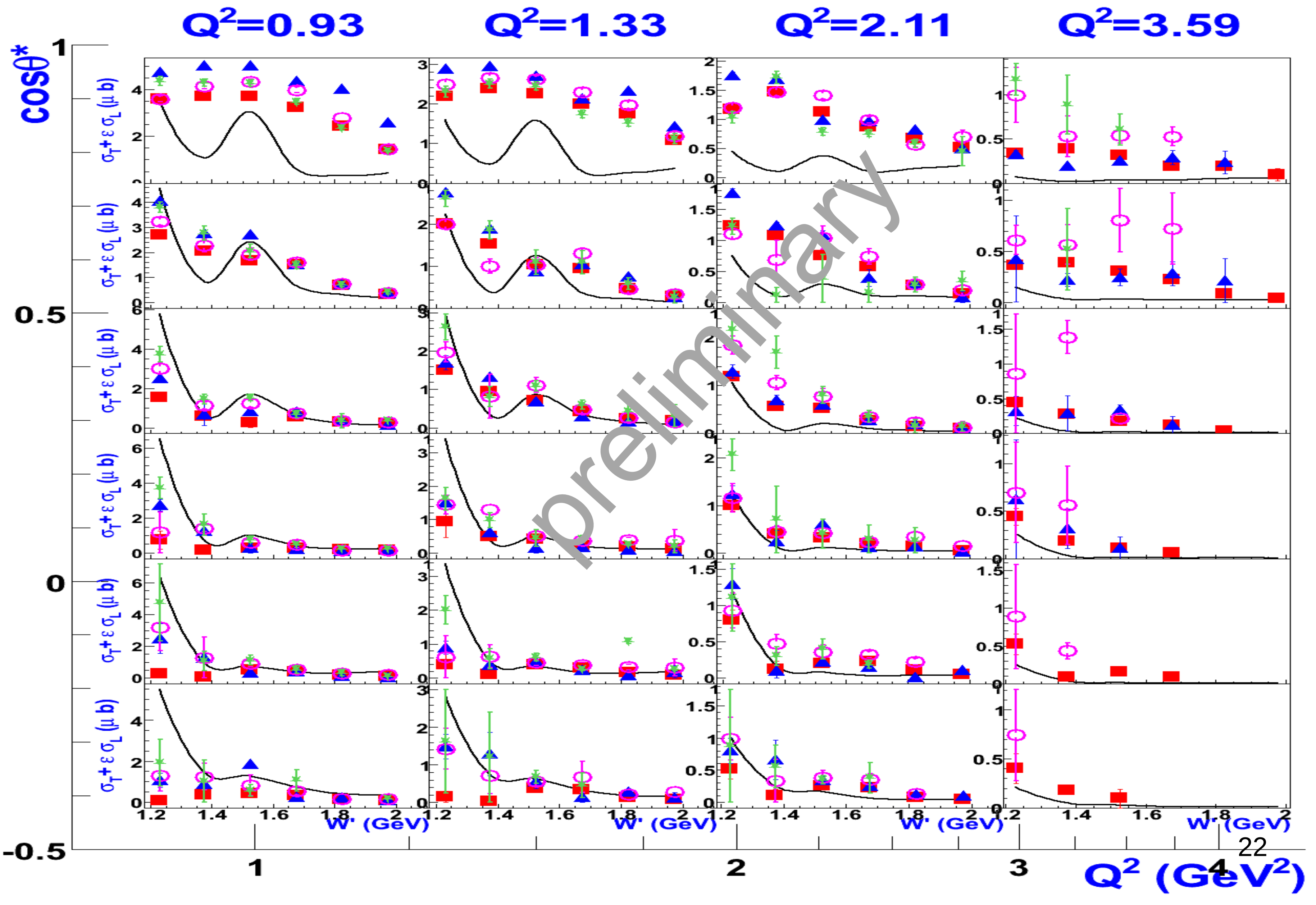
Cross Section Fitting



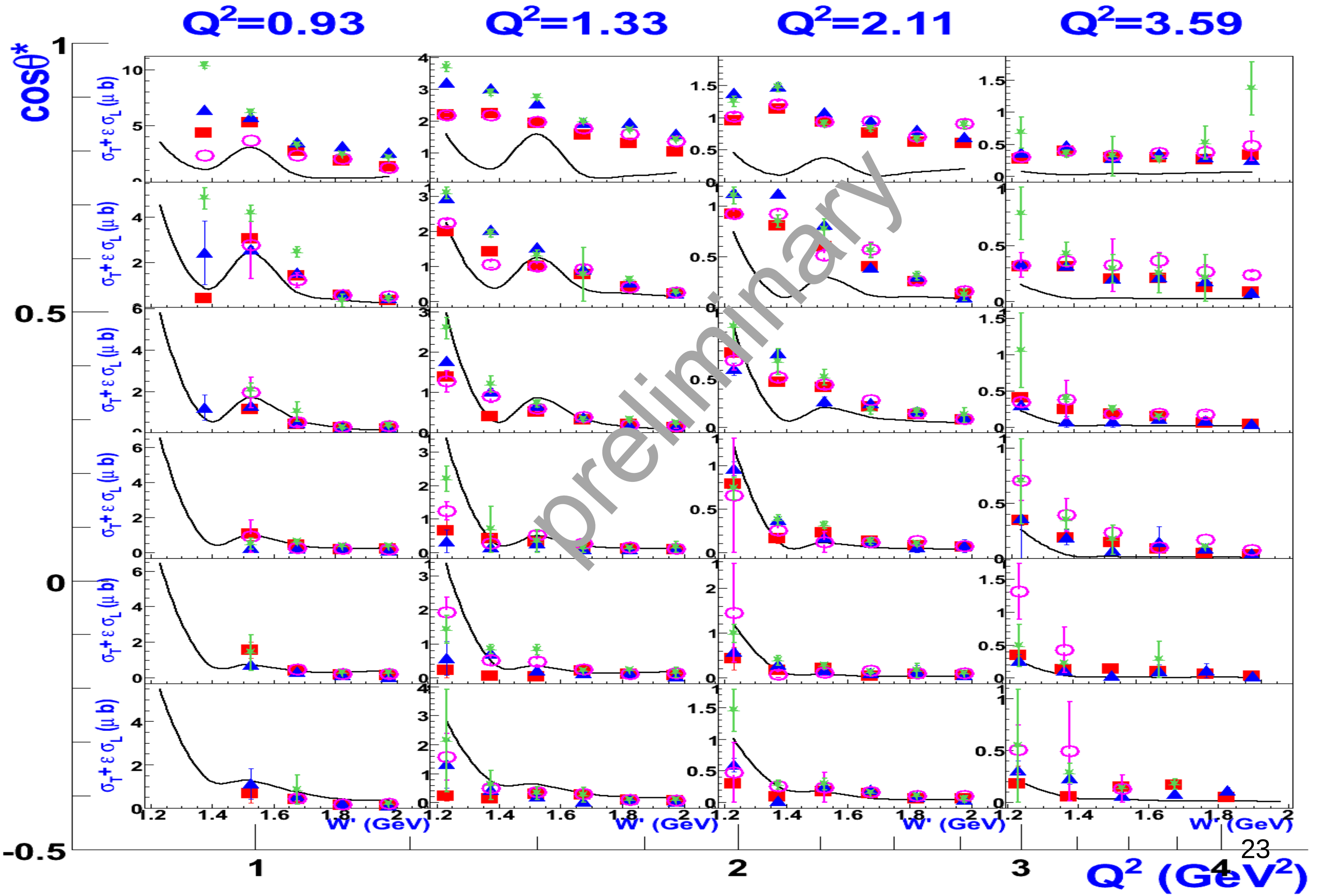
$$\frac{\partial^2\sigma}{\partial\Omega^*_\pi} = \boxed{\sigma_T + \varepsilon\sigma_L} + \boxed{\sqrt{2\varepsilon(1+\varepsilon)}\sigma_{LT}cos\phi^*_\pi} + \boxed{\varepsilon\sigma_{TT}cos2\phi^*_\pi}$$

$$= \boxed{A0} + \boxed{A1\ Cos\phi^*} + \boxed{A2\ Cos2\phi^*}$$

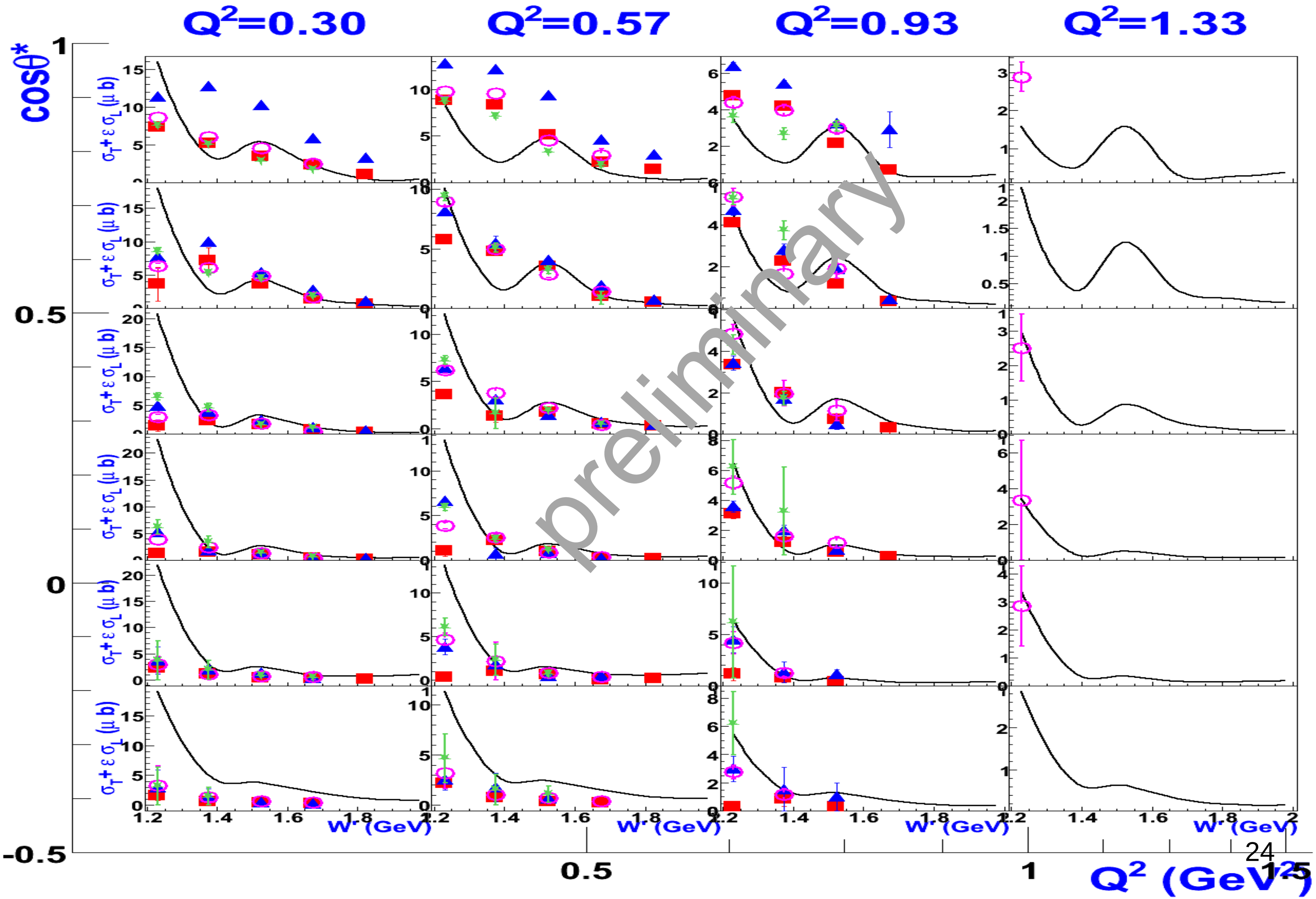
A_0: BoNuS VIP Vs MAID, 4 GeV



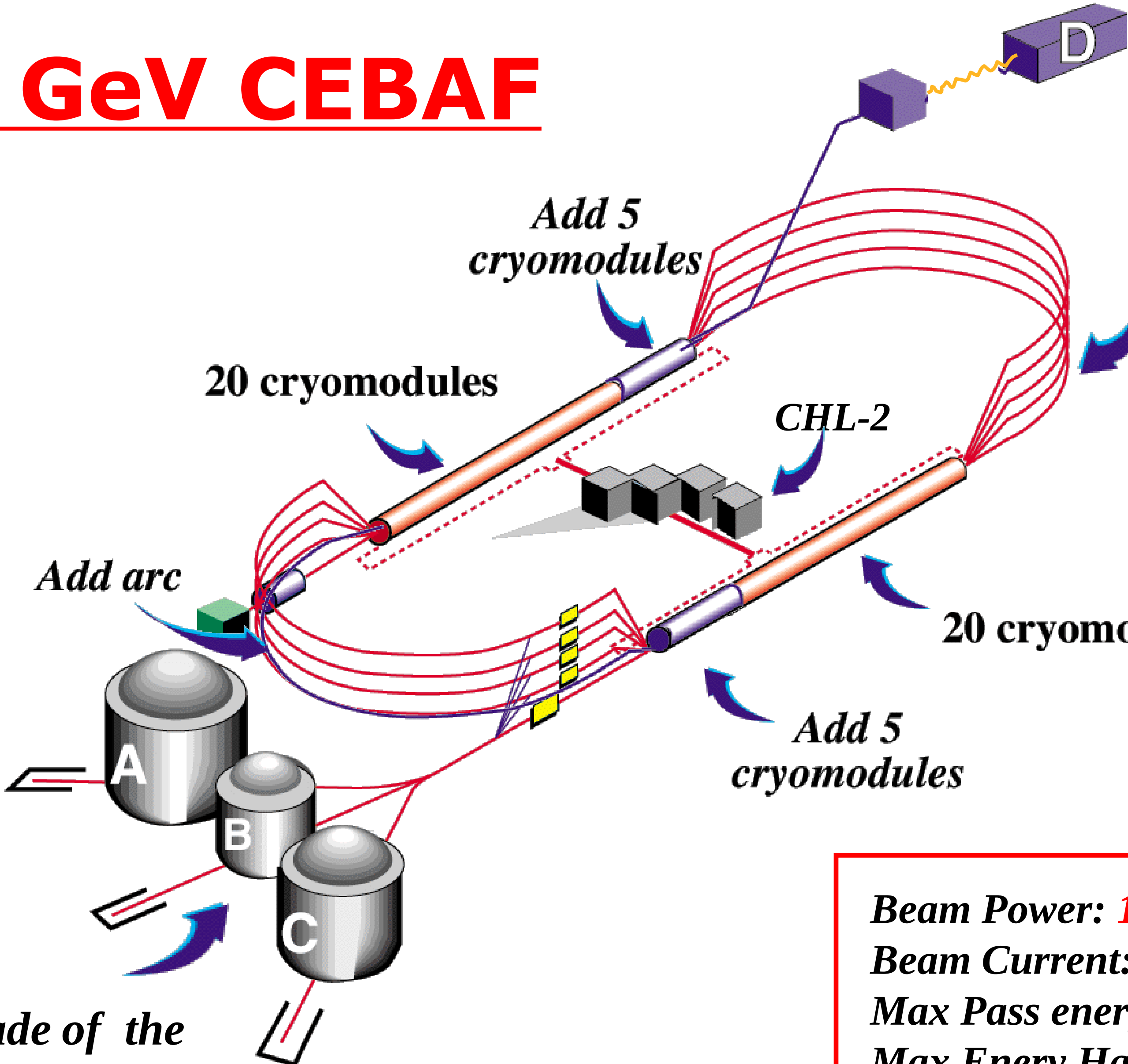
A_0: BoNuS VIP Vs MAID, 5 GeV



A_0: BoNuS VIP Vs MAID, 2 GeV



12 GeV CEBAF



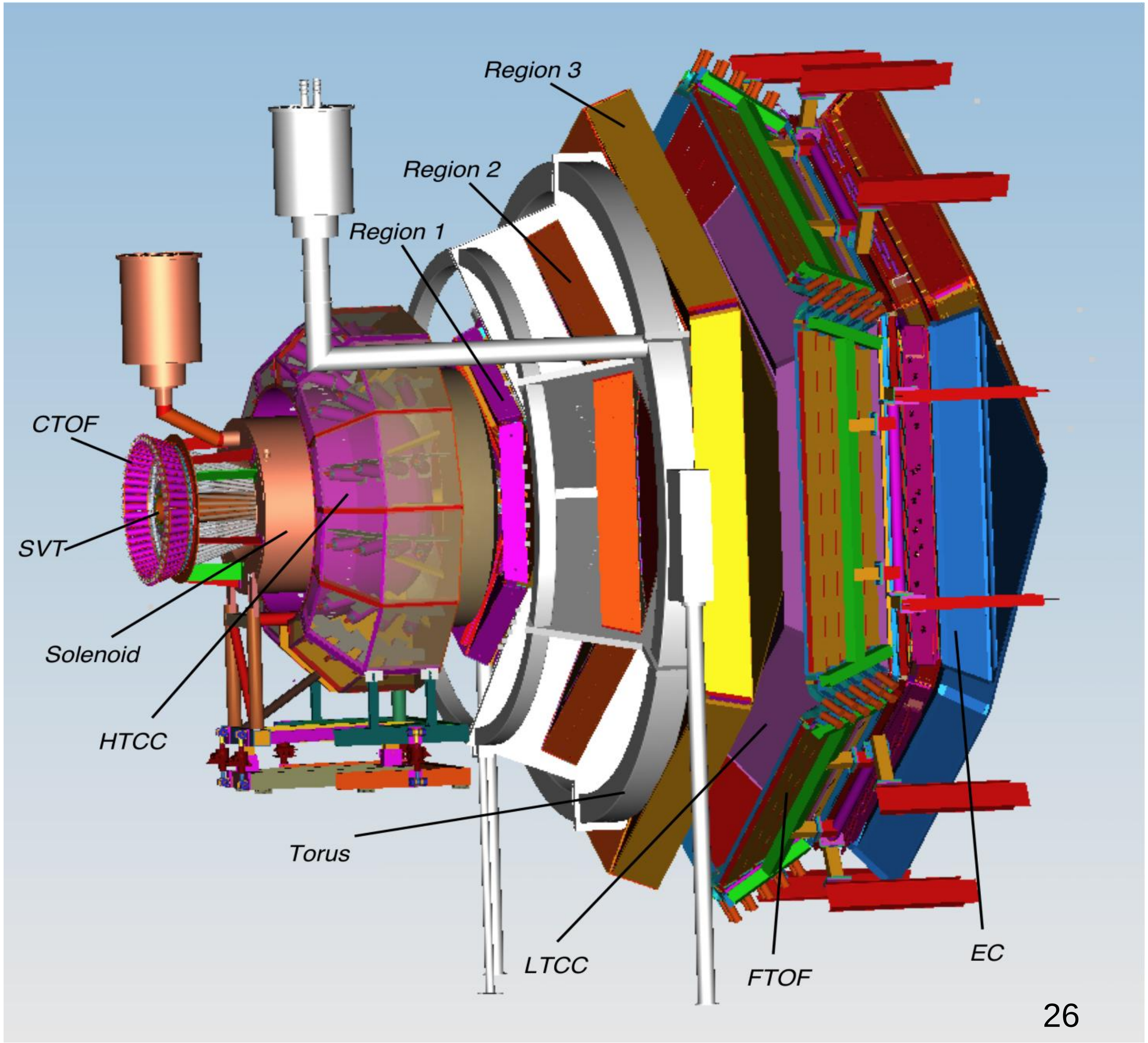
Beam Power: ***1MW***
Beam Current: ***90 μA***
Max Pass energy: ***2.2 GeV***
Max Enery Hall A-C: ***10.9 GeV***
Max Energy Hall D: ***12 GeV***

CLAS12

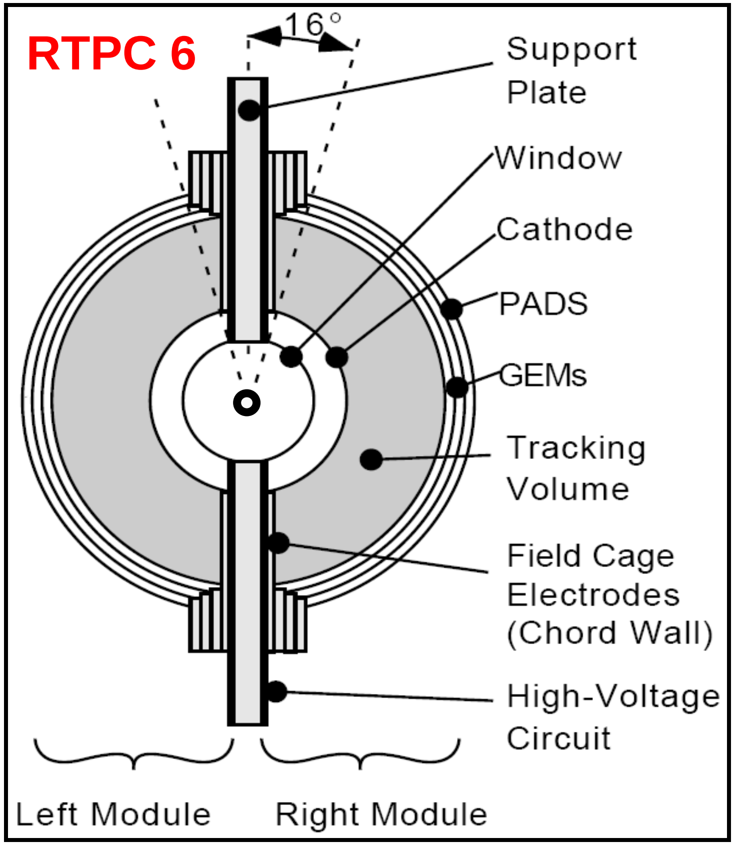
Forward Detector:
- *TORUS magnet*
- *Forward SVT tracker*
- *HT Cherenkov Counter*
- *Drift chamber system*
- *LT Cherenkov Counter*
- *Forward ToF System*
- *Preshower calorimeter*
- *E.M. calorimeter (EC)*

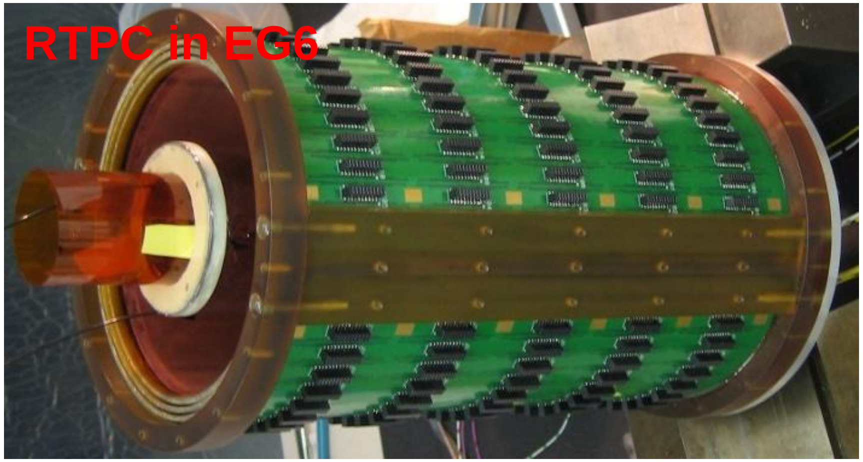
Central Detector:
- *SOLENOID magnet*
- *Barrel Silicon Tracker*
- *Central Time-of-Flight*

Proposed upgrades:
- *Micromegas (CD)*
- *Neutron detector (CD)*
- *RICH detector (FD)*
- *Forward Tagger (FD)*



RTPC 12





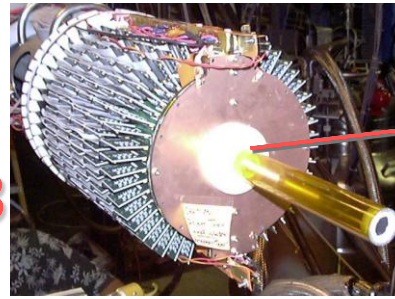
RTPC 12

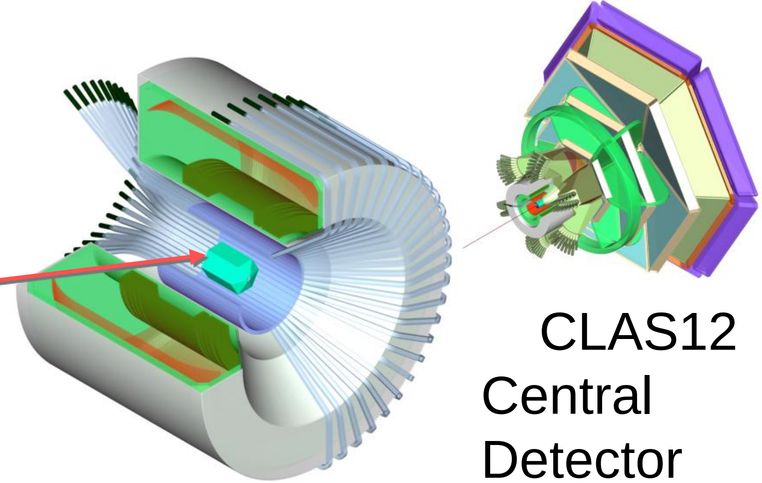
- Remove support spikes
- Expanse drift region by 1 cm in radius
- Double the length
- More channels
- Read out hardare upgrade

Plans for 12 GeV

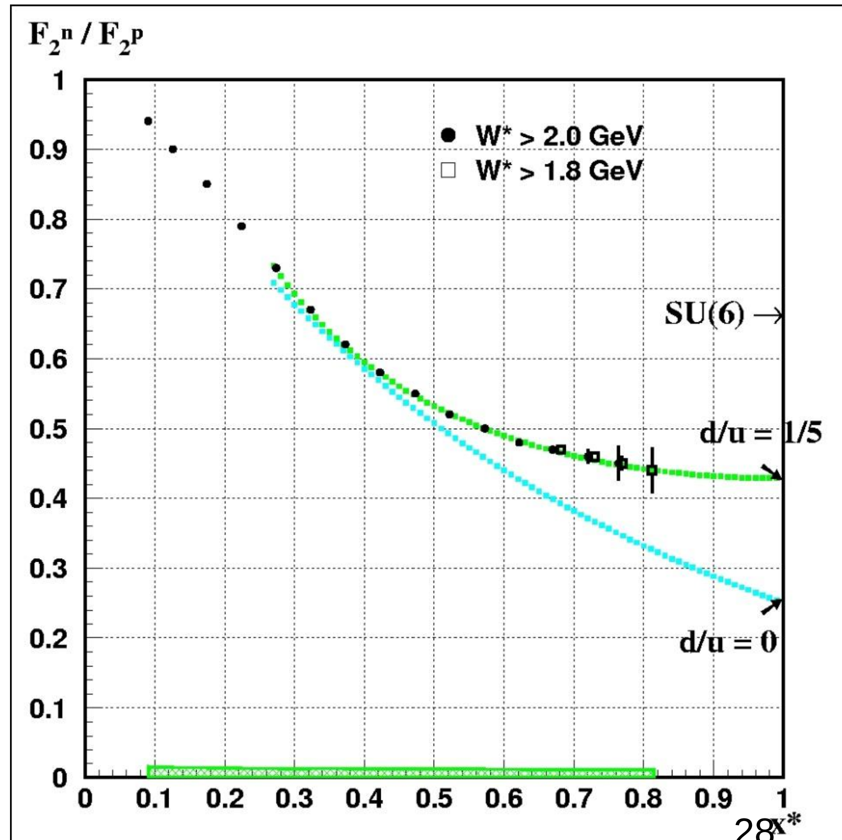
BoNuS

E12-06-113





- Data taking of 35 days on D_2 and 5 days on H_2 with $L = 2 \cdot 10^{34}\ cm^{-2}\ sec^{-1}$
- **Planned** BoNuS detector DAQ and trigger **upgrade**
- DIS region with
  - $Q^2 > 1\ GeV^2/c^2$
  - $W^* > 2$ GeV
  - $p_s < 100$ MeV/c
  - $\theta_{pq} > 110^\circ$
- Largest value for $x^* = 0.80$ (bin centered $x^* = 0.76$)
- Relaxed cut of $W^* > 1.8$ GeV gives max. $x^* = 0.83$



Summary and Outlook

- Neutron structure is of high interest, but hard to access reliably at high *x* and in the resonance region.
- BoNuS RTPC detector works well. Another RTPC has also been successfully used in a second experiment already - EG6.
- Spectator tagging technique works. BoNuS provides nearly model-independent results (Will settle d/u question at 12 GeV).
- Neutron structure function extracted and under review. Analysis note and paper are underway.
- Measured absolute cross sections for $D(e,e'\pi^{-}p)p$ reaction over a wide kinematic range. Huge increase in available data for neutron channel. These data will be used to improve our understanding of neutron structure, as part of fits to world data (SAID, MAID…)
- BoNuS12 proposal re-submission in preparation.

Thank you!

Outline

- Motivation
- Experiment setup
- Data Analysis
- BoNuS6 Result
- BoNuS12
- Summary

d(x) and u(x) as $x \to 1$

- Valence structure of the nucleon - sea quarks and gluons don't contribute
- SU(6)-symmetric wave function of the proton in the quark model:

$$\frac{1}{\sqrt{18}}\left(3\bar{u}[ud]_{s=0}+\bar{u}[ud]_{s=1}-\sqrt{2}\bar{u}[ud]_{s=1}-\sqrt{2}\bar{d}[uu]_{s=1}-2\bar{d}[uu]_{s=1}\right)$$

- In this model: d/u = 1/2, Δu/u*) = 2/3, Δd/d = -1/3 for all x
- Hyperfine structure effect (1-gluon exchange): S=1 suppressed $\Rightarrow$ d/u = 0, Δu/u = 1, Δd/d = -1/3 for $x \to 1$
- pQCD: helicity conservation (q$\uparrow\uparrow$p) $\Rightarrow$ d/u = 1/5, Δu/u = 1, Δd/d = 1 for $x \to 1$
- Wave function of the neutron via isospin rotation: replace u $\to$ d and d $\to$ u => using experiments with protons and neutrons one can extract information on u, d, Δu and Δd in the valence quark region.

*) helicity $\Delta q = (q\uparrow - q\downarrow)$ for Nucleon N$\Uparrow$

Why nuclear structure from DIS on a neutron target

✓ **Need proton *and* neutron targets to pin down u/d PDFs from DIS**

At leading order

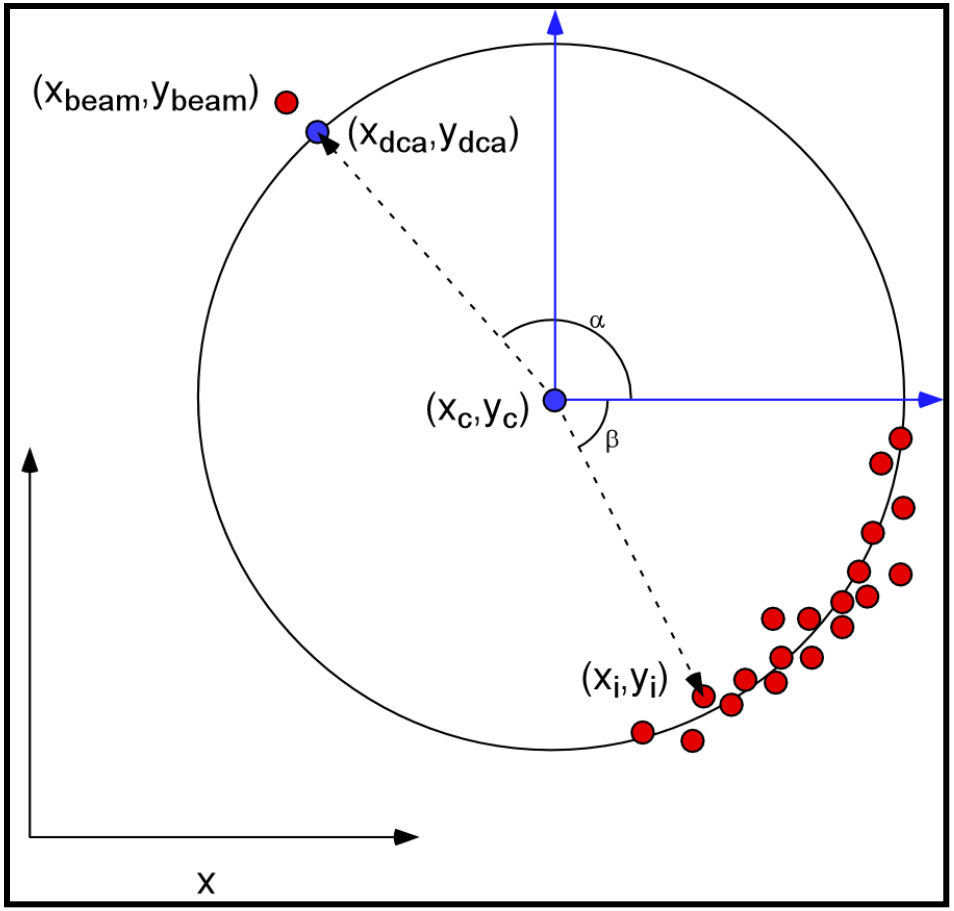
$$F_2^p(x) = x\sum_q e_q^2\left(q(x)+\bar{q}(x)\right) \underset{x\to 1}{\approx} x\left(\frac{4}{9}u(x)+\frac{1}{9}d(x)\right)$$

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

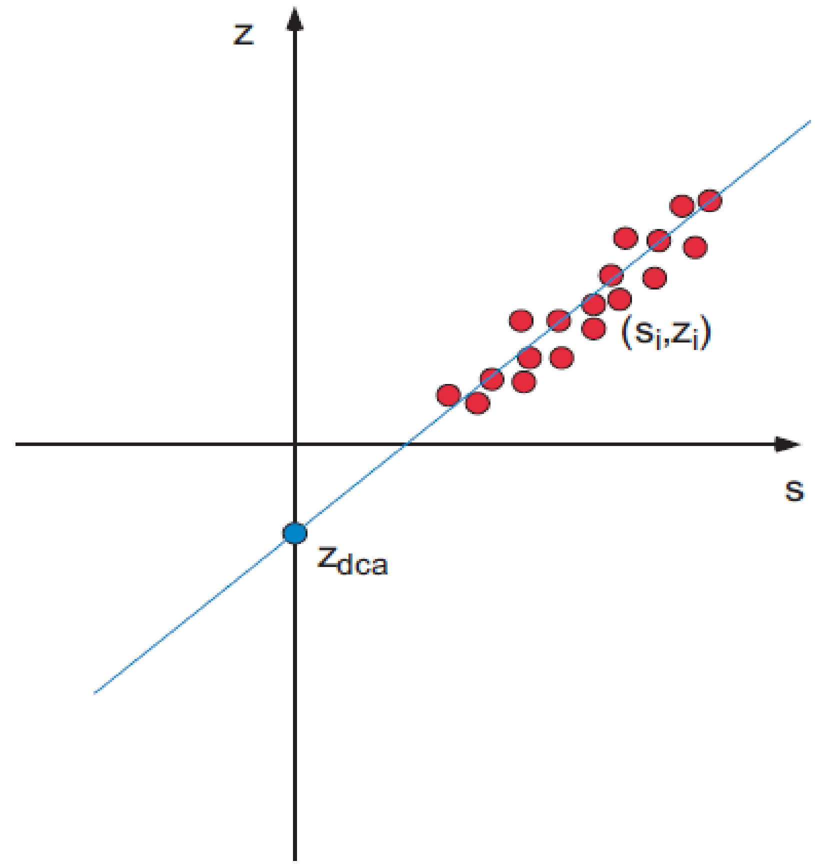
At large *x* proton dominated by *u(x)* and neutron by *d(x)* due to charge weighting.

✓ **Proton minus neutron can determine non-singlet (valence) contributions to structure functions at all *x***

Fit Helix to the Chains

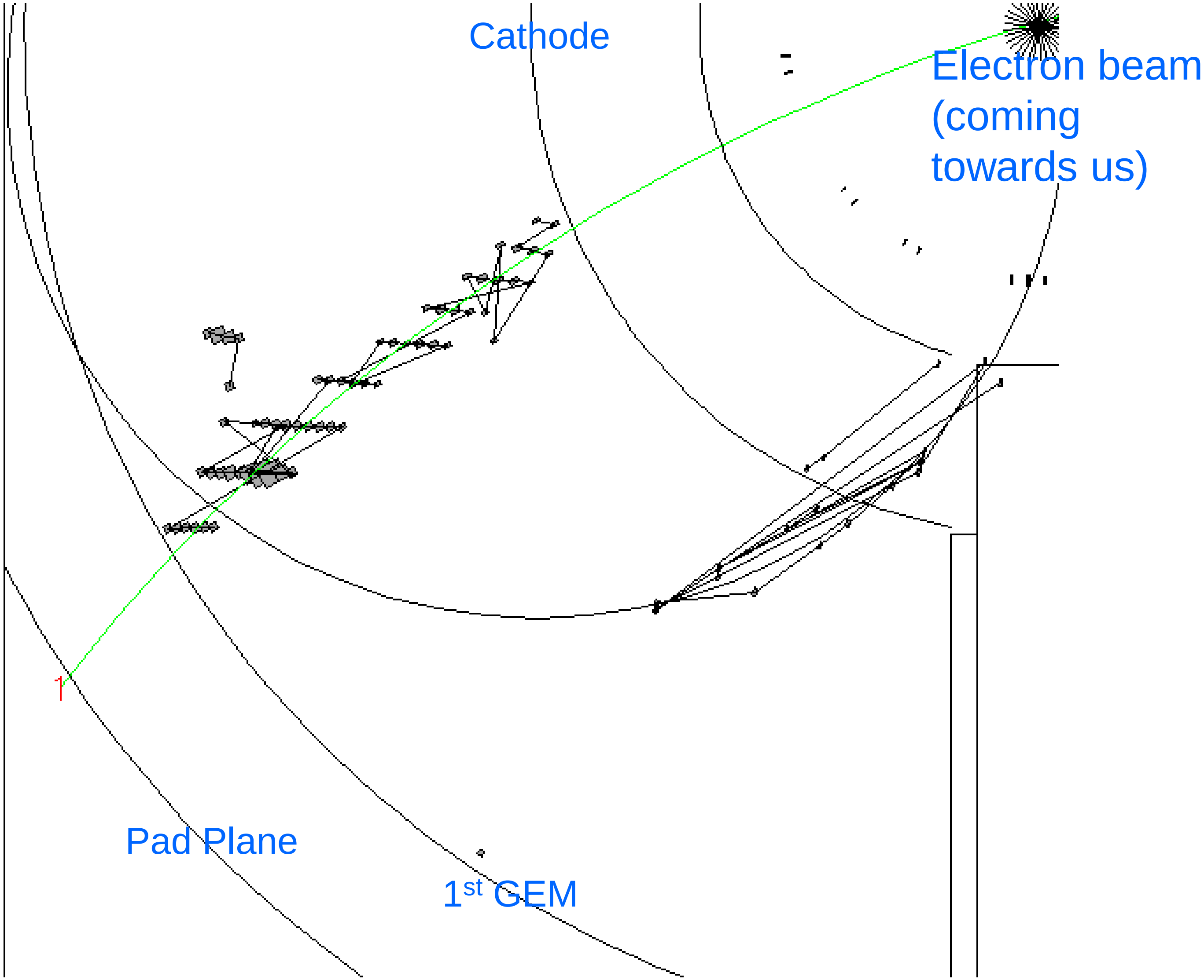


Momentum from Curvature



Pitch and z-vertex position

Reconstructed Points (x-y plane)



Extraction of Structure Function Ratios

Now that we've identified spectator proton candidates we can take the ratio of tagged events (contain a spectator) to untagged (inclusive scattering on deuteron), apply a few standard corrections, and have a measurement of the structure function ratios.

$$\frac{F_2^n}{F_2^d} = (R_{corr})(C_{e^+})(C_\pi)(r_{rc})(n)$$

tagged/untagged counts, corrected for accidental backgrounds and CLAS acceptance

corrections to the ratio from pion background and electrons from pair production

radiative correction

overall normalization to the world's data at low x. Accounts for overall RTPC efficiency

$$\frac{F_2^n}{F_2^p} = \left(\frac{F_2^n}{F_2^d}\right)\left(\frac{F_2^d}{F_2^p}\right)_{\text{model}}$$

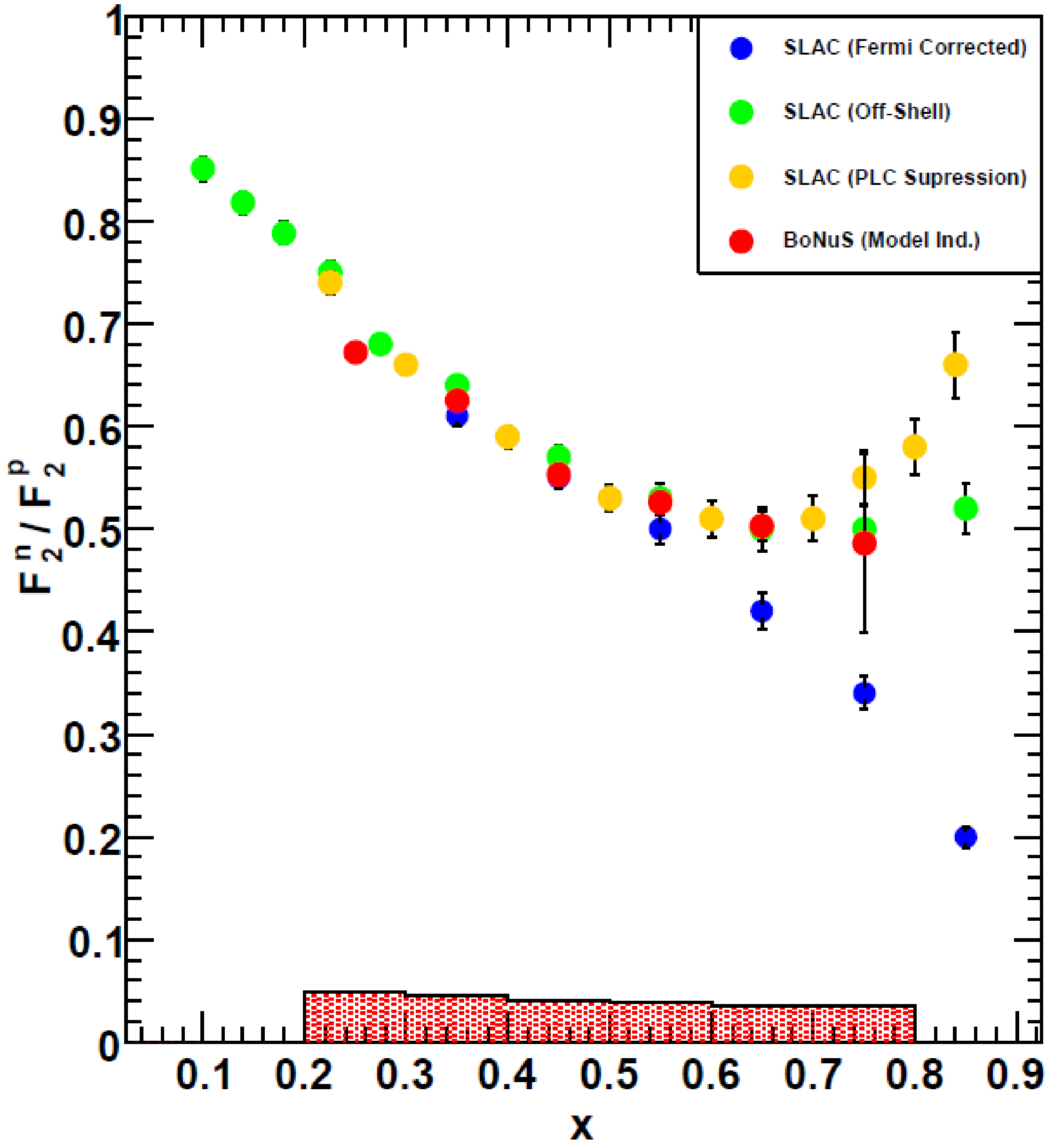
Status of BoNuS Analysis

Cut $Q^2 > 1.0\ (GeV/c)^2$,

W > 1.6 GeV but with the further requirement that $Q^2 > 2.0\ (GeV/c)^2$ if

W = 1.6 - 2.0 GeV to extend our coverage into the resonance region.

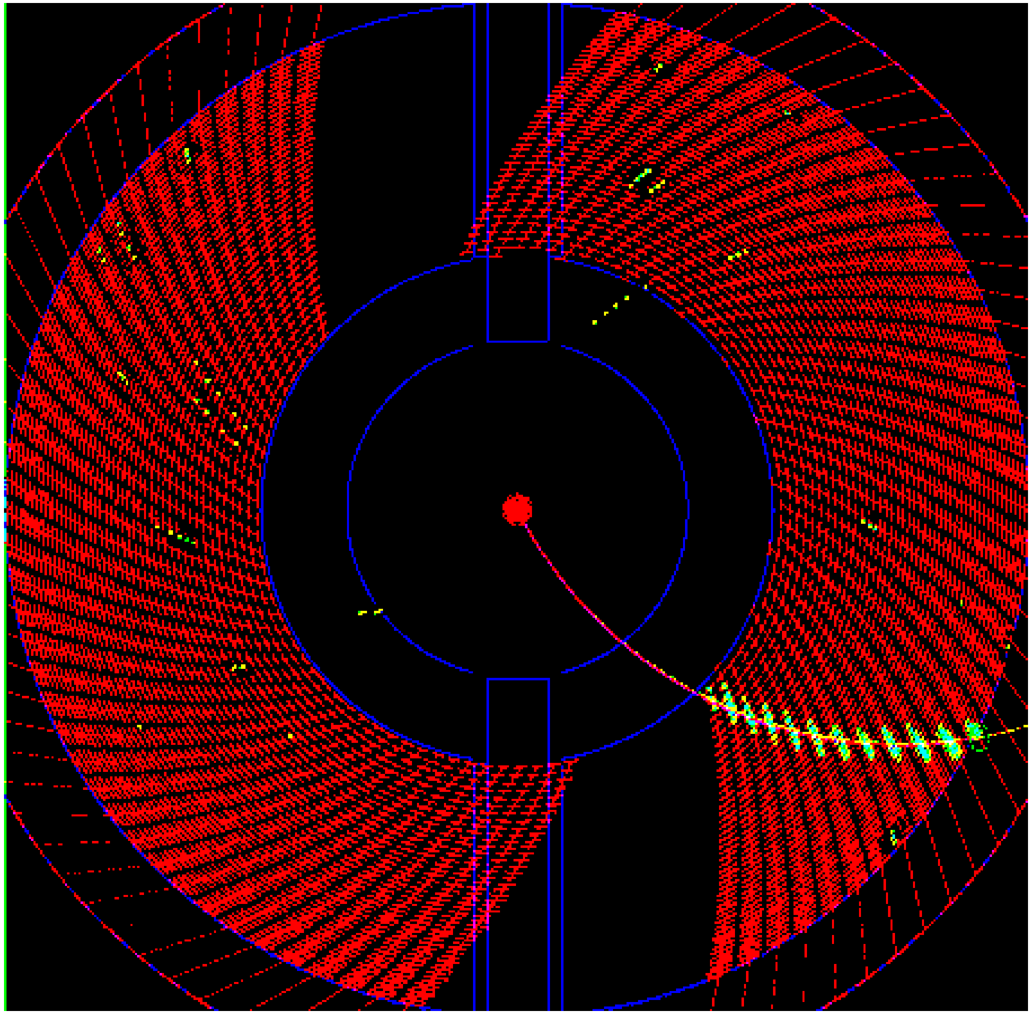
Data normalized so that tagged/untagged ratio agrees with the world's data below x = 0.5



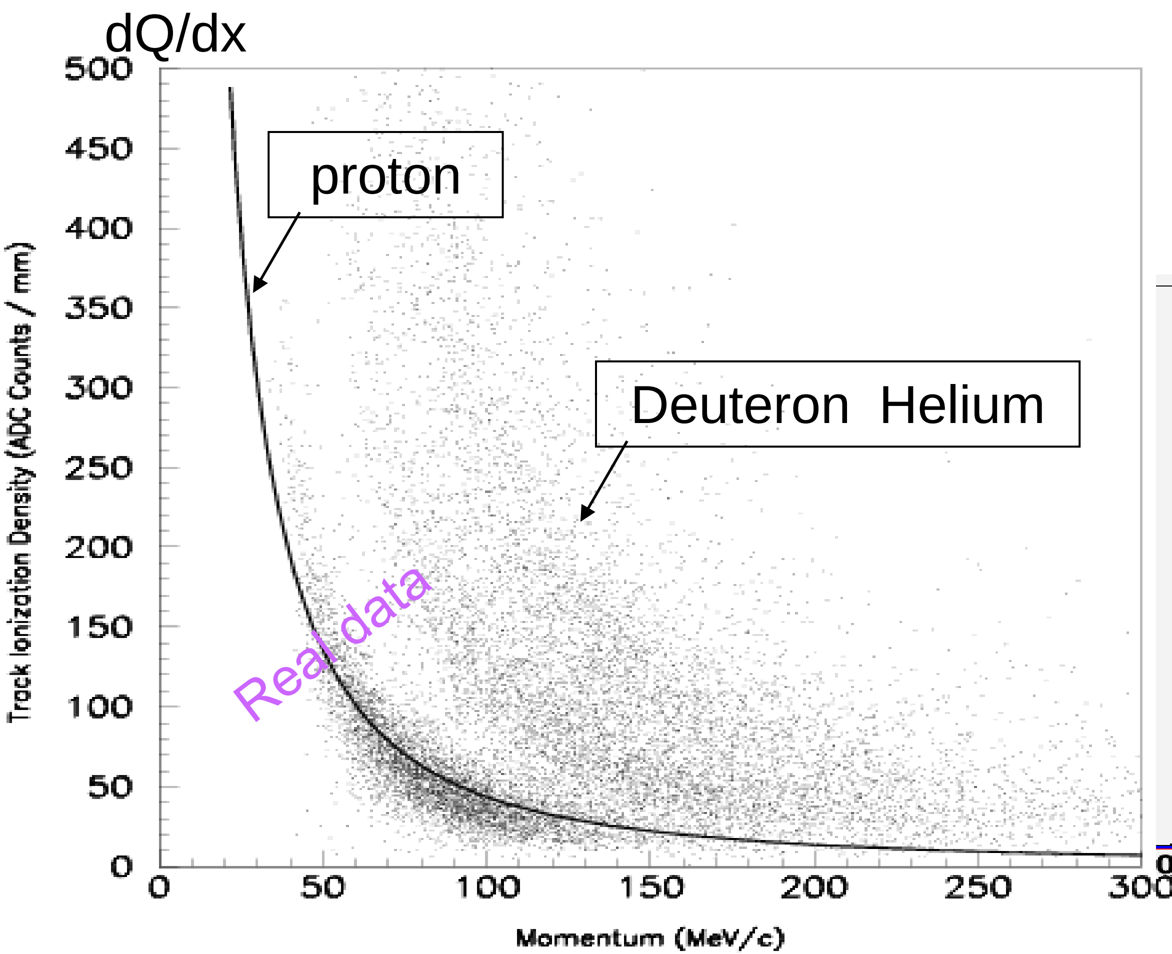
The Drift Path of An Ionized Electron

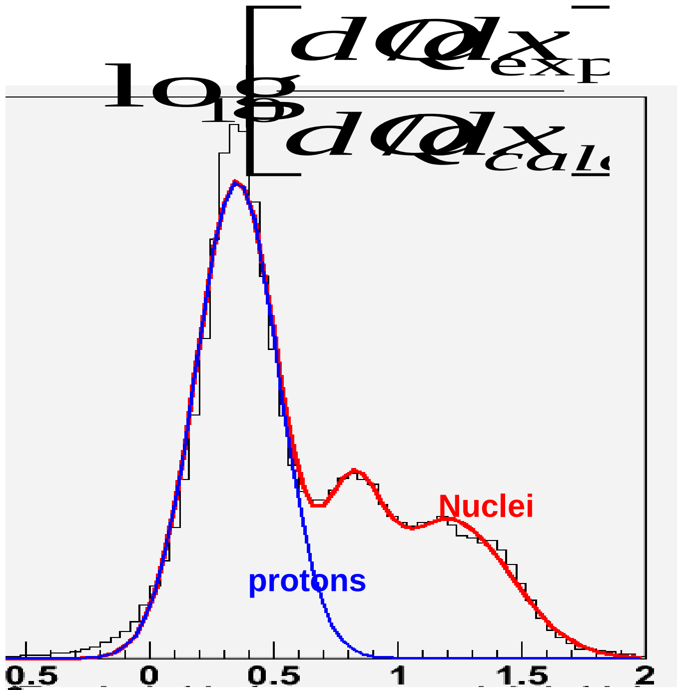
A MAGBOLTZ simulation of the crossed E and B fields, together with the drift gas mixture, determines the drift path and the drift velocity of the electrons.

- The red lines show the drift path of each ionization electron that would appear on a given channel.
- In green is the spatial reconstruction of where the ionization took place.
- In reconstruction, hits which are close to each other in space are linked together and fit to a helical trajectory.
- This resulting helix tells us the vertex position and the initial three momentum of the particle.



RTPC Proton Identification

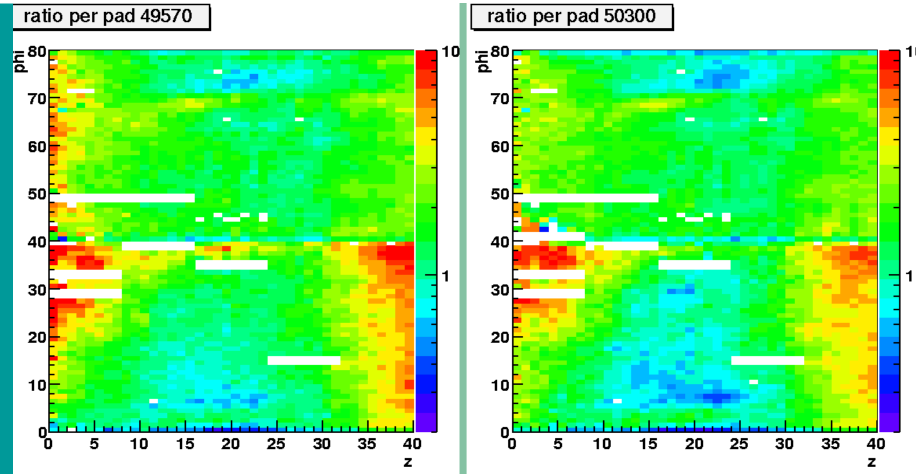




RTPC Gain Calibration

Channel by Channel gain multipliers can be determined for each run by comparing the track's expected energy loss to the measured value.

After applying the gain corrections, a clear separation of protons and heavier particles through dE/dx has been achieved.



Gain constants (vs phi and z) determined independently for two different runs.

Before and After Gain Calibration