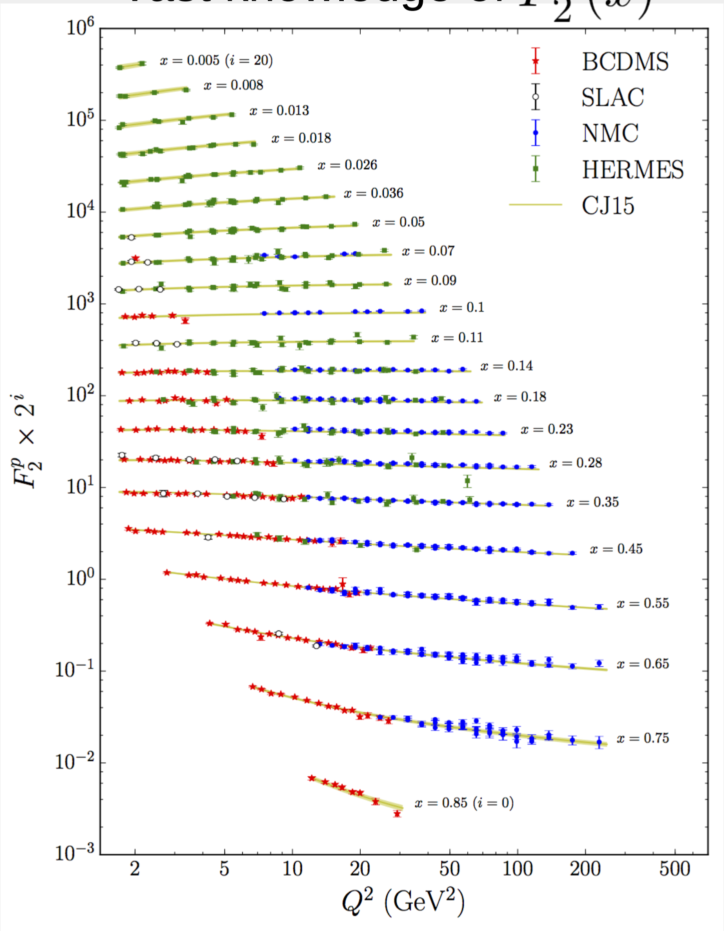
# The neutron structure function $F_2$ at high-$x$ with BONuS at CLAS12


C. Ayerbe Gayoso

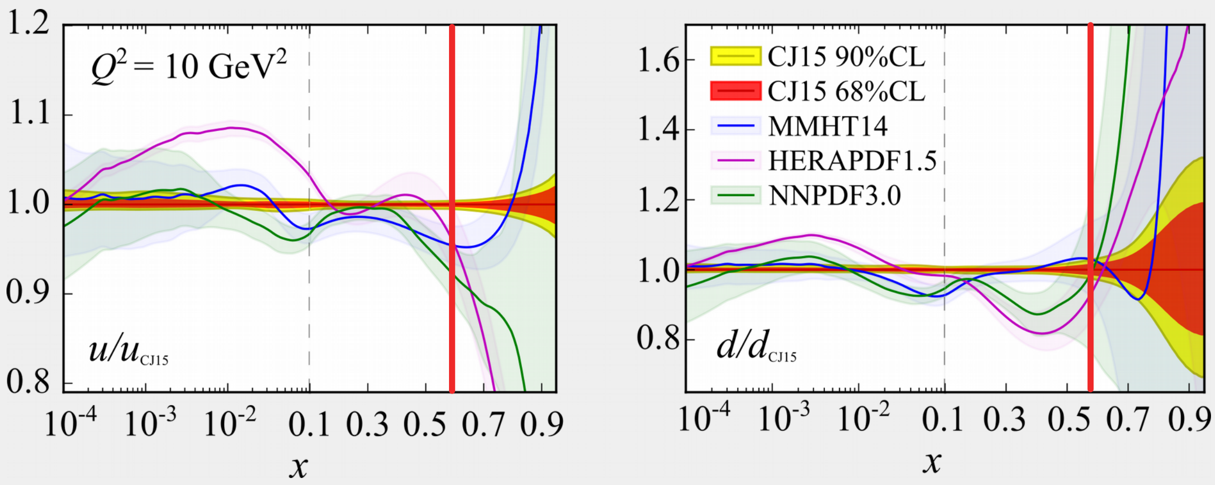
The College of William and Mary
on behalf of the BONuS collaboration

# Motivation I

Vast knowledge of $F_2^p(x)$




Global PDF fits normalized to CJ15




A. Accardi, L. T. Brady, W. Melnitchouk, J. F. Owens and N. Sato, Phys. Rev. D 93, 114017 (2016)

LO and $s(x) \approx 0$

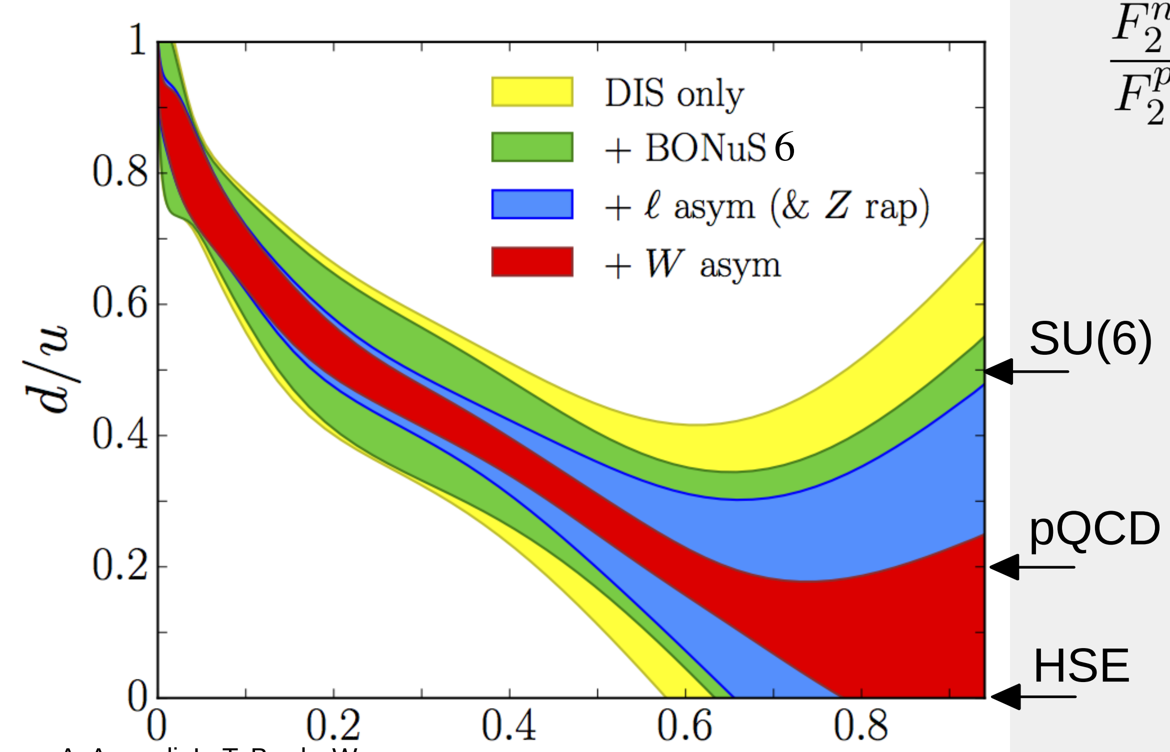
$$\frac{F_2^p(x)}{x} = \left[\frac{4}{9}u(x) + \frac{1}{9}d(x)\right]$$

*u(x)* is dominant → well determined from proton data

$$\frac{F_2^n(x)}{x} = \left[\frac{4}{9}d(x) + \frac{1}{9}u(x)\right]$$

Lack of free neutron data → *d(x)* larger uncertainties

# Motivation II




A. Accardi, L. T. Brady, W. Melnitchouk, J. F. Owens and N. Sato, Phys. Rev. D 93, 114017 (2016)

$$\frac{F_2^n(x)}{F_2^p(x)} \approx \frac{1+4d/u}{4+d/u} \Rightarrow \frac{d}{u} \approx \frac{4F_2^n/F_2^p - 1}{4 - F_2^n/F_2^p}$$

Data from neutron $F_2$ comes primarily from inclusive scattering off deuterium → theoretical uncertainties led to ambiguities

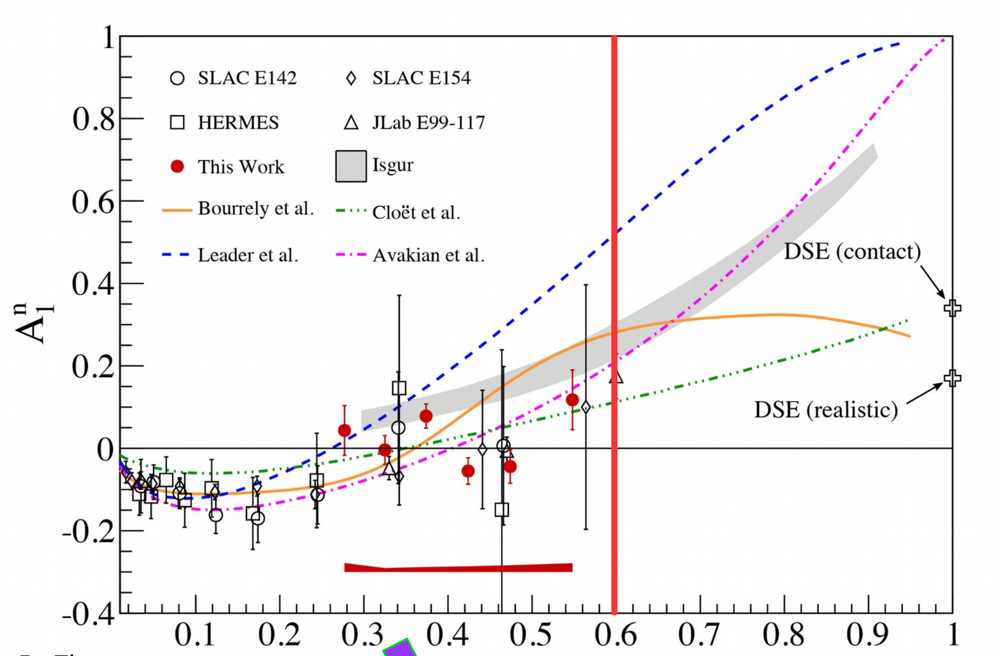
Representative predictions of $d/u$ at $x \to 1$ :

- SU(6): 1/2
- pQCD: 1/5
- Hyperfine Structure Effect: 0

# Motivation III

- the *d/u* ratio as $x \to 1$ is crucial to interpret *A1n* and *A1p* measurements for information on SU(6) symmetry breaking:

| | $A_1^p$ | $A_1^n$ | $\Delta u/u$ | $\Delta d/d$ |
|---|---|---|---|---|
| SU(6) | 5/9 | 0 | 2/3 | -1/3 |
| HFSE | 1 | 1 | 1 | -1/3 |
| pQCD | 1 | 1 | 1 | 1 |




D. Flay et at
Phys. Rev. D 94, 052003 (2016)

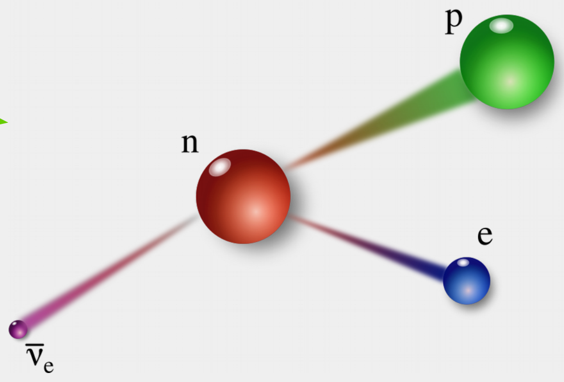
- Neutron $F_2$ is needed in general to extract neutron spin structure functions from measured asymmetries on nuclei like D and $^3$He

$$F_2(x) = 2xF_1(x) \rightarrow A_1^n \approx g_1^n / F_1^n$$

unpolarized

# Neutron sources

- Free neutrons decay in 15 minutes

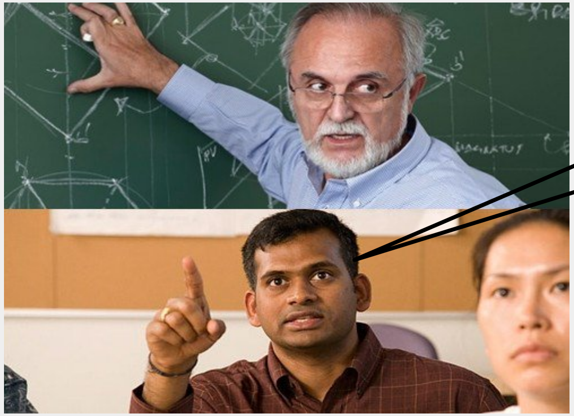



- Difficulty to make a dense target

S.Materne, NIMA 611, 2-3 (2009)

  - ✗ Magnetic bottle ~$10^6$ n/cm$^2$(PENeLOPE TU München)
  - ✔ Typical proton target ~$10^{23}$ p/cm$^2$ (10 cm LH)

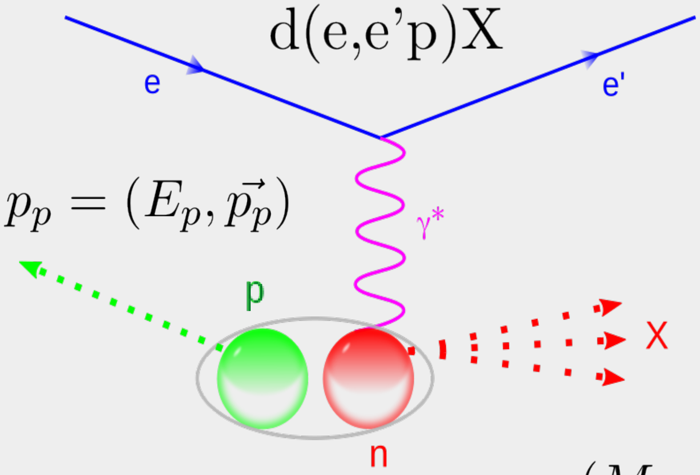
- Neutron sources solution: Deuterons and $^3$He
  - But... Nuclear model dependence:
    - Fermi motion
    - Off-shell effects
    - EMC effect
    - Final State interactions
    - ...



Is there any way to reduce uncertainties?

YES

# Spectator Tagging I




$$p_p = (E_p, \vec{p_p})$$

Plane-wave impulse approximation (PWIA)

Measuring the proton (spectator) we can infer the motion of the struck neutron

$$W^{*2} = (p_n + q)^2 = p_n^2 - Q^2 + 2(M_d - E_p)\nu - \vec{p}_n\vec{q}$$

$$\approx M^{*2} - Q^2 + 2M_p\nu(2 - \alpha_p)$$

$$p_n = (M_d - E_p, -\vec{p_p})$$

$$M_d = E_n + E_p$$

$$E_n = M_d - \sqrt{M_p^2 + p_p^2}$$

$$\alpha_p = \frac{E_p - \vec{p}_p\hat{q}}{M_p}$$

deuteron light cone momentum fraction carried by spectator proton

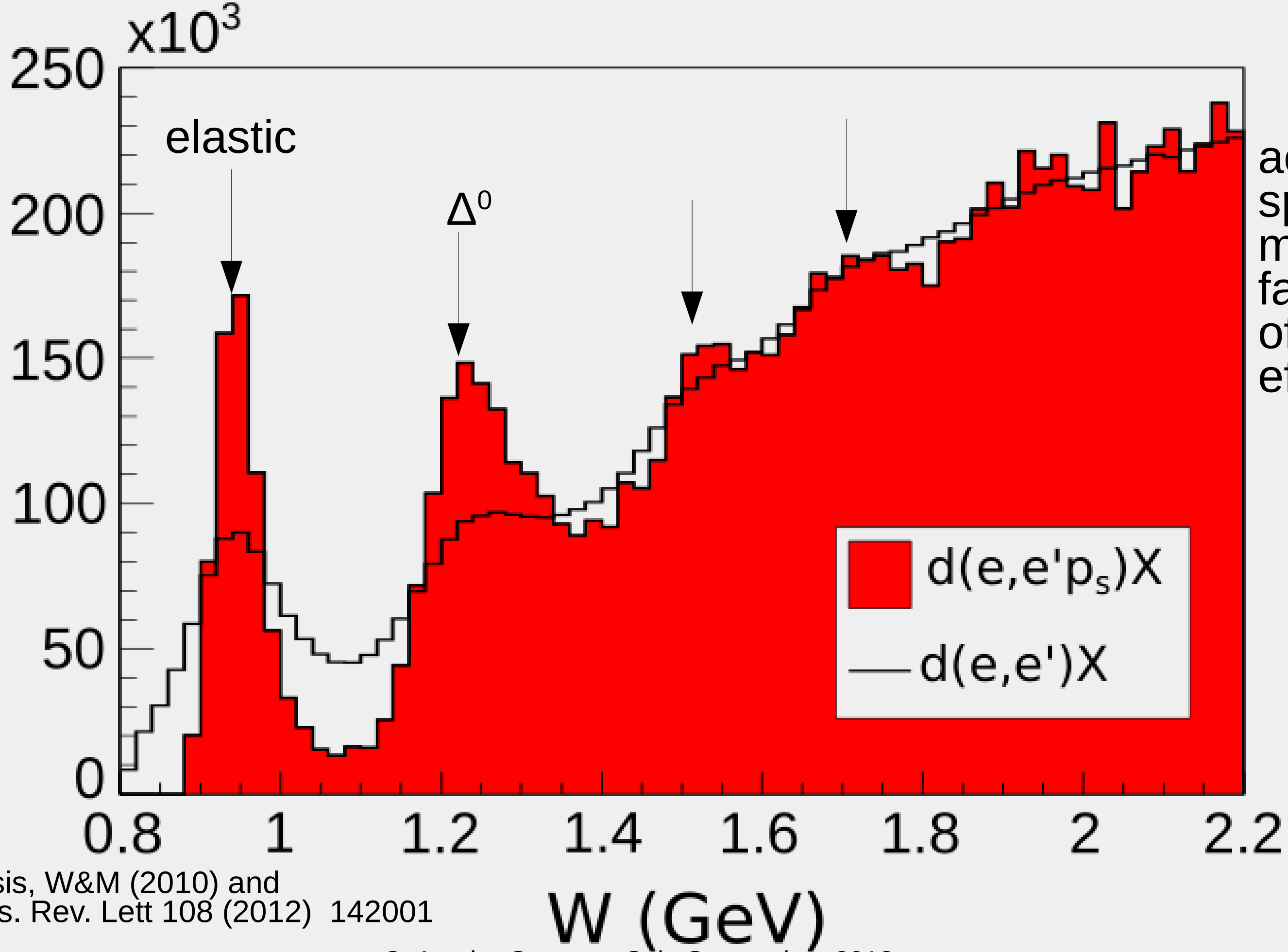
$$M^{*2} = (M_d - E_p)^2 - \vec{p_p}^{\,2}$$

invariant mass squared of the off-shell nucleon

$$x^* = \frac{Q^2}{2p_n\,q} \approx \frac{Q^2}{2M_p\nu(2 - \alpha_p)} = \frac{x}{2 - \alpha_p}$$

# Spectator Tagging II

Elastic and Δ peaks better resolved




access to spectator momentum facilitates removal of smearing effects

N. Baillie PhD Thesis, W&M (2010) and
N. Baillie et al, Phys. Rev. Lett 108 (2012) 142001

# The BONuS experiment

- The **B**arely **O**ff-shell **Nu**cleon **S**tructure experiment* BONuS12 (E12-06-113) at CLAS12 is the dedicated experiment to measure the neutron structure function making use of the tagged structure functions technique .
  - It is the successor of the successful experiment with the same name (E03-012) which ran in 2005.

- BONuS12 kinematics:
  - $0.1 < x < 0.8$
  - over a $Q^2$ range of $1\text{-}14\,\mathrm{GeV^2/c^2}$
  - $W$ up to $4\,\mathrm{GeV}$
  - Luminosity up to $2 \cdot 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$
  - 35 days on $D_2$ and 5 days on $H_2$ with an energy beam of $11\,\mathrm{GeV}$

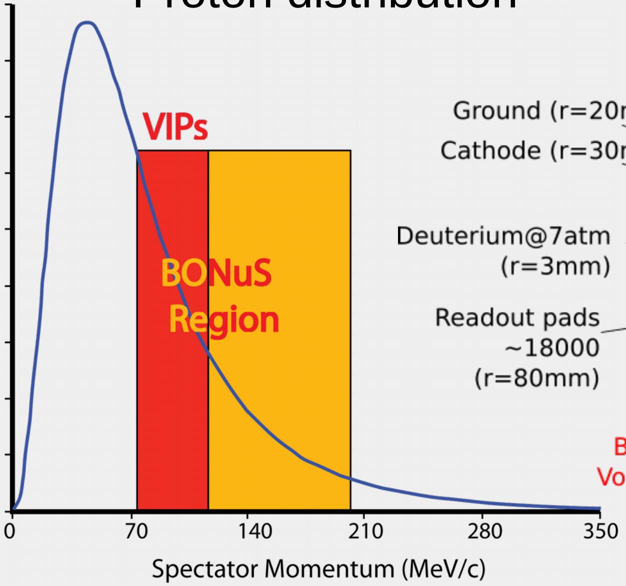
- The heart of the experiment is a 3rd generation state-of-the-art **R**adial **T**ime **P**rojection **C**hamber (RTPC).

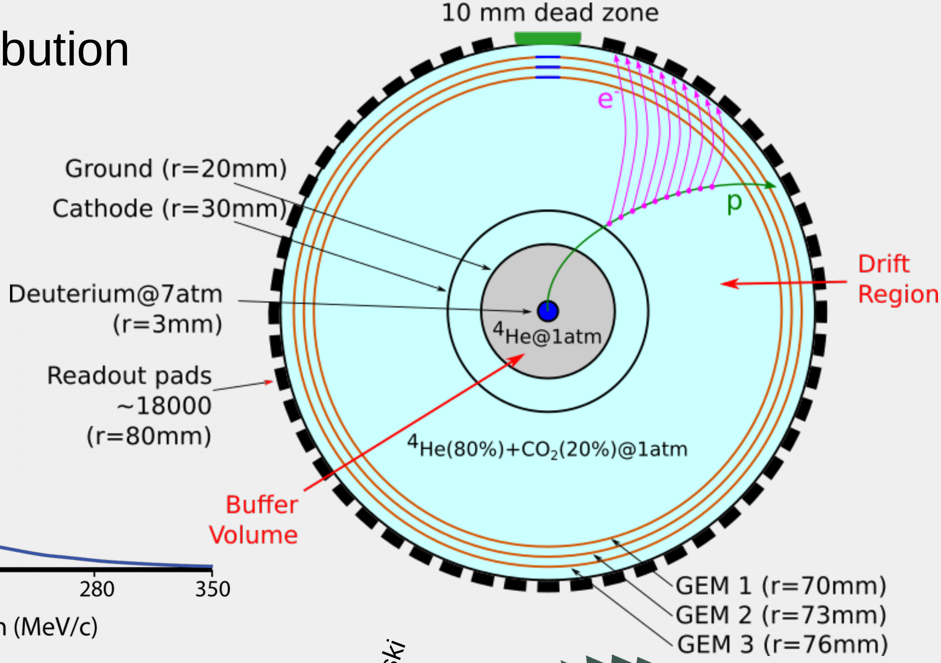
*aka **Bo**und **Nu**cleon **S**tructure

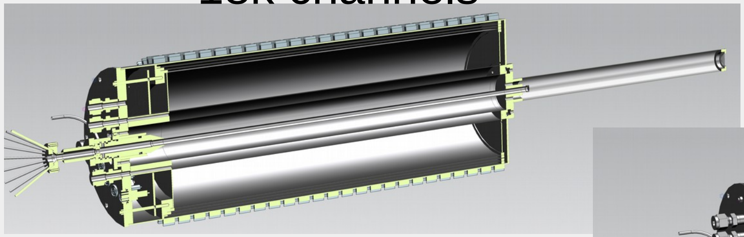
# BONuS12 RTPC

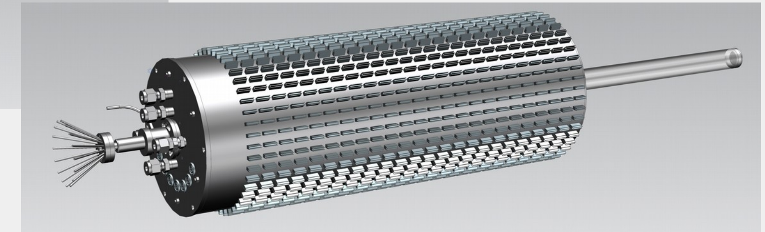
- Active length:  40 cm
- Radial drift distance:  4 cm
- Radial |E| = 1000 V/cm
- Axial |B| = 5 T
- Drift gas He/CO2  (80/20)
- 3 GEM amplification layers
  - → 16 HV sectors per GEM
- Pad readout: 2.8 mm x 4 mm
  - → ~18k channels

Proton distribution



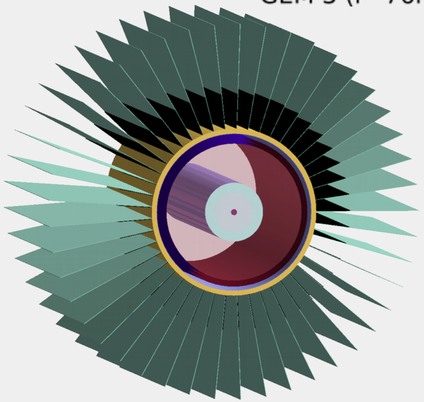





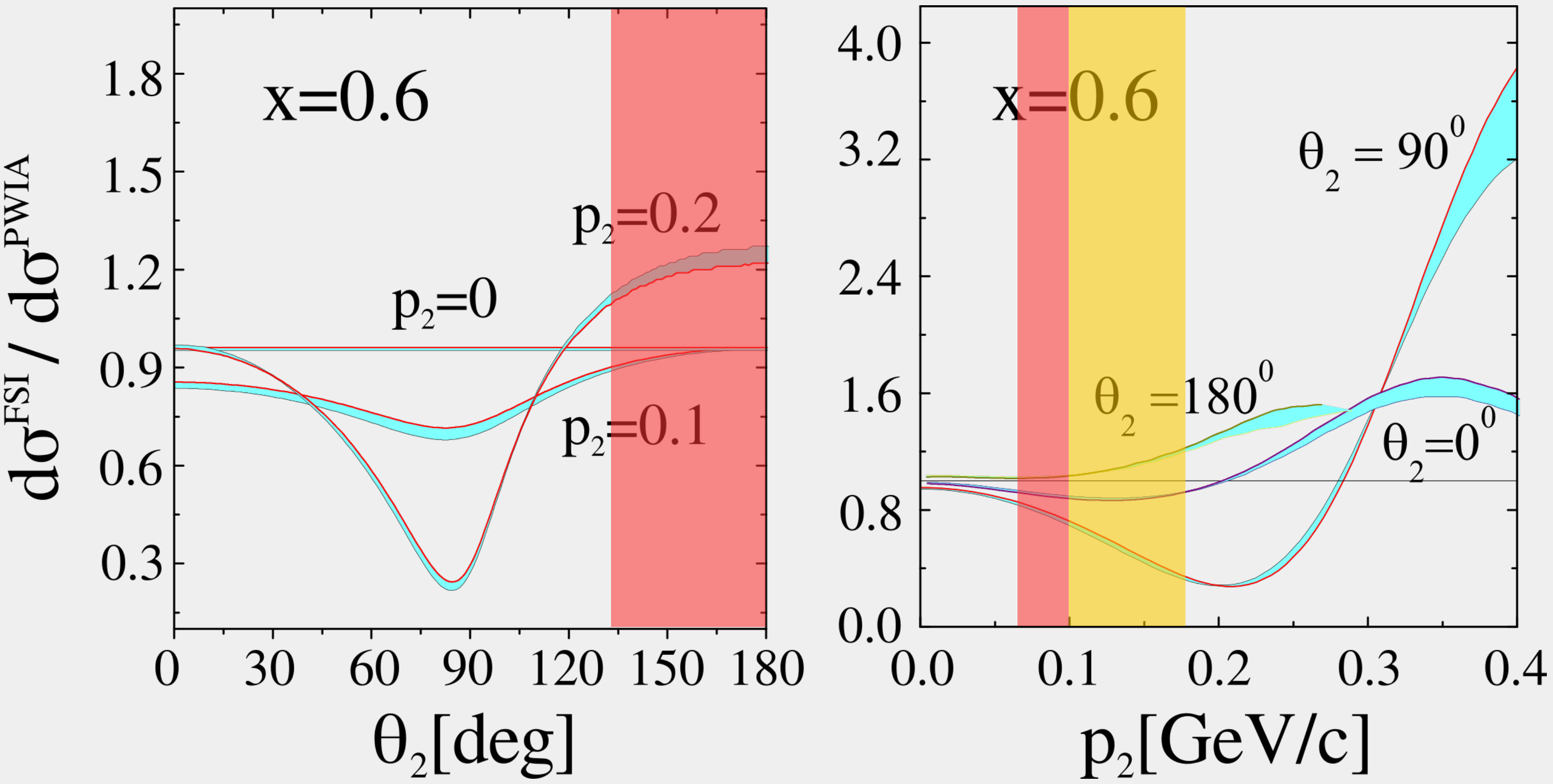
JLab Designer M. Zarecky

Simulation by Nathan Dzbenski
<ndzbe001@odu.edu>



# Final State Interactions

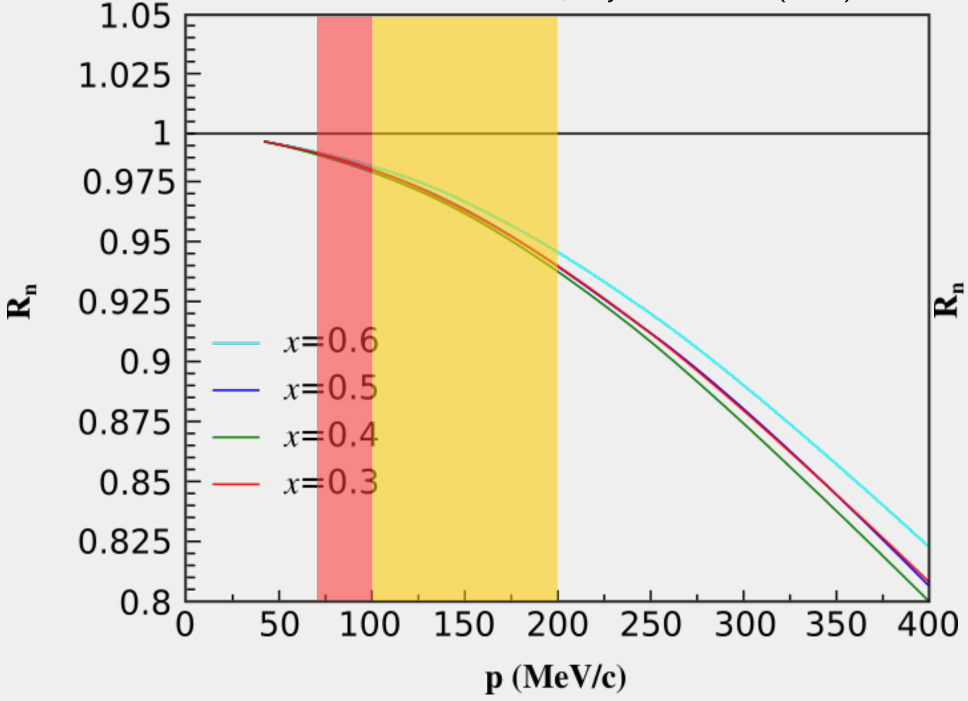
V. Palli et al, Phys. Rev. C 80(2009) 054610



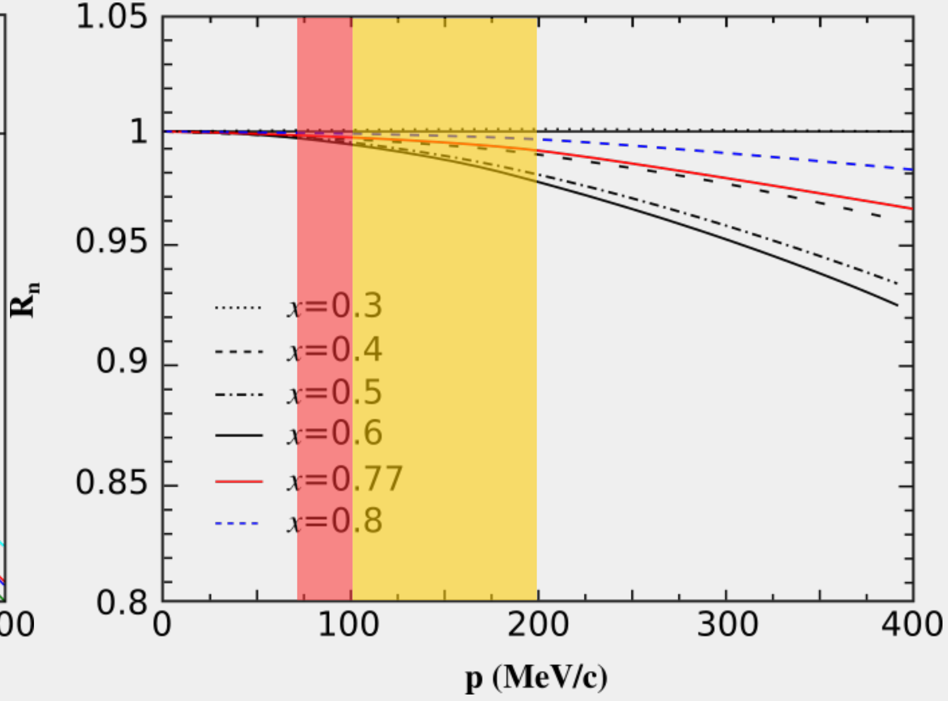
# Off-Shell Effects

$$R_n \equiv F_2^{n(\mathrm{eff})} / F_2^n$$

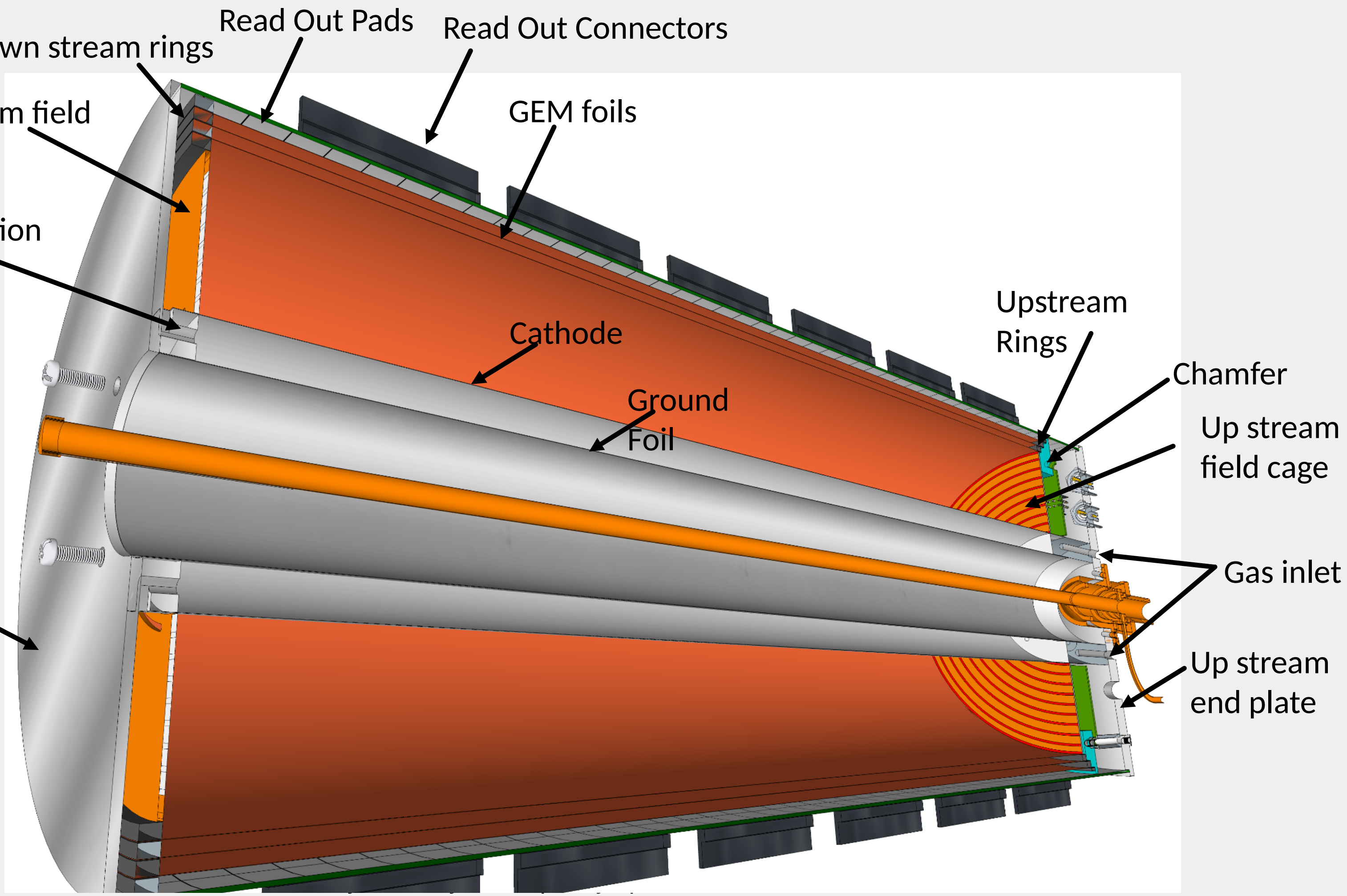
S. Liuti et al, Phys. Lett. B 356(1995) 157




W. Melnitchouk et al, Phys. Lett. B 335(1994) 11
updated (2010)



# RTPC design

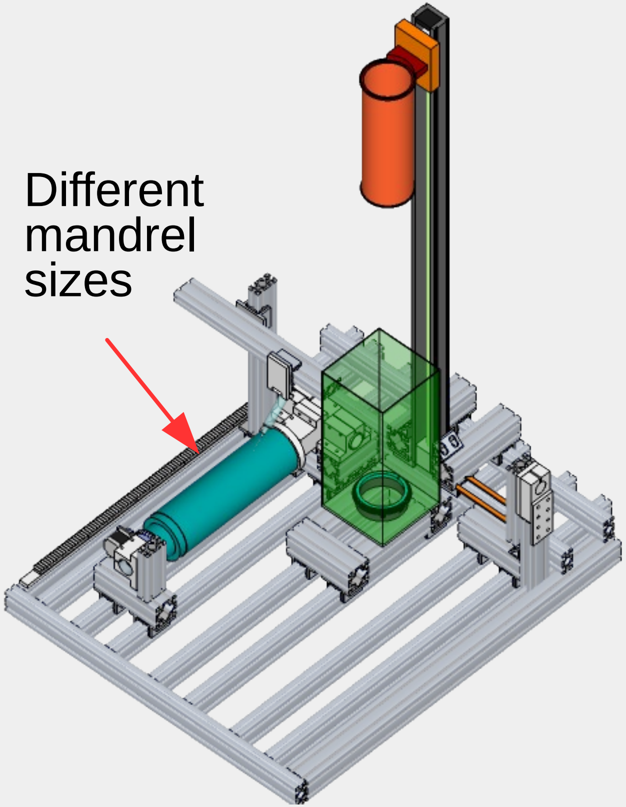


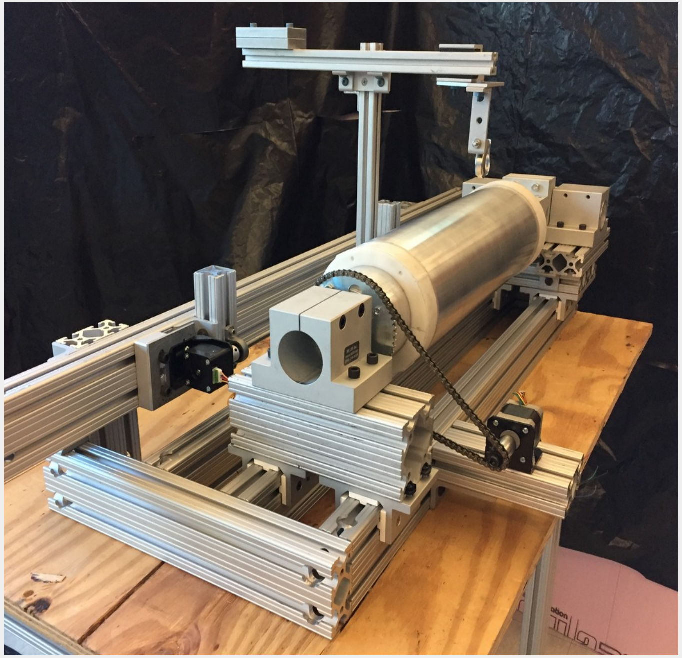

Design by I. Albayrak
<albayrak@jlab.org>

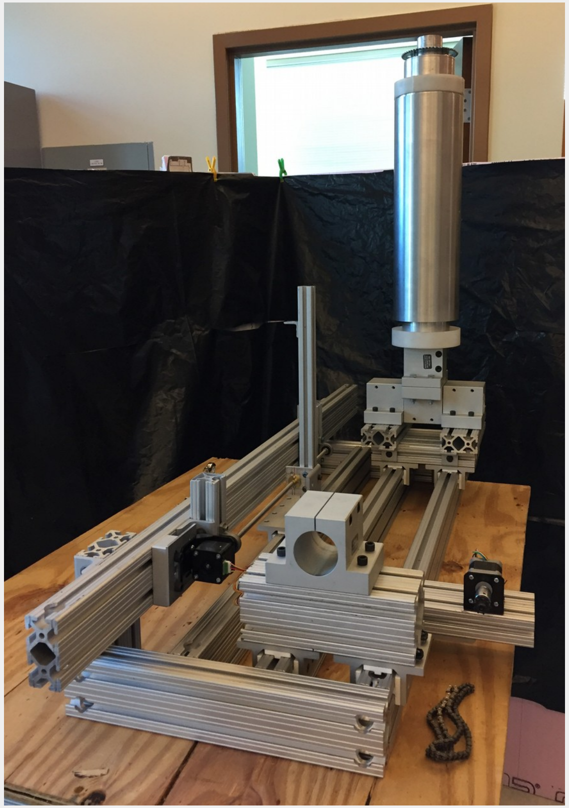
# RTPC assembly

Assembly station built in Hampton University

Different mandrel sizes





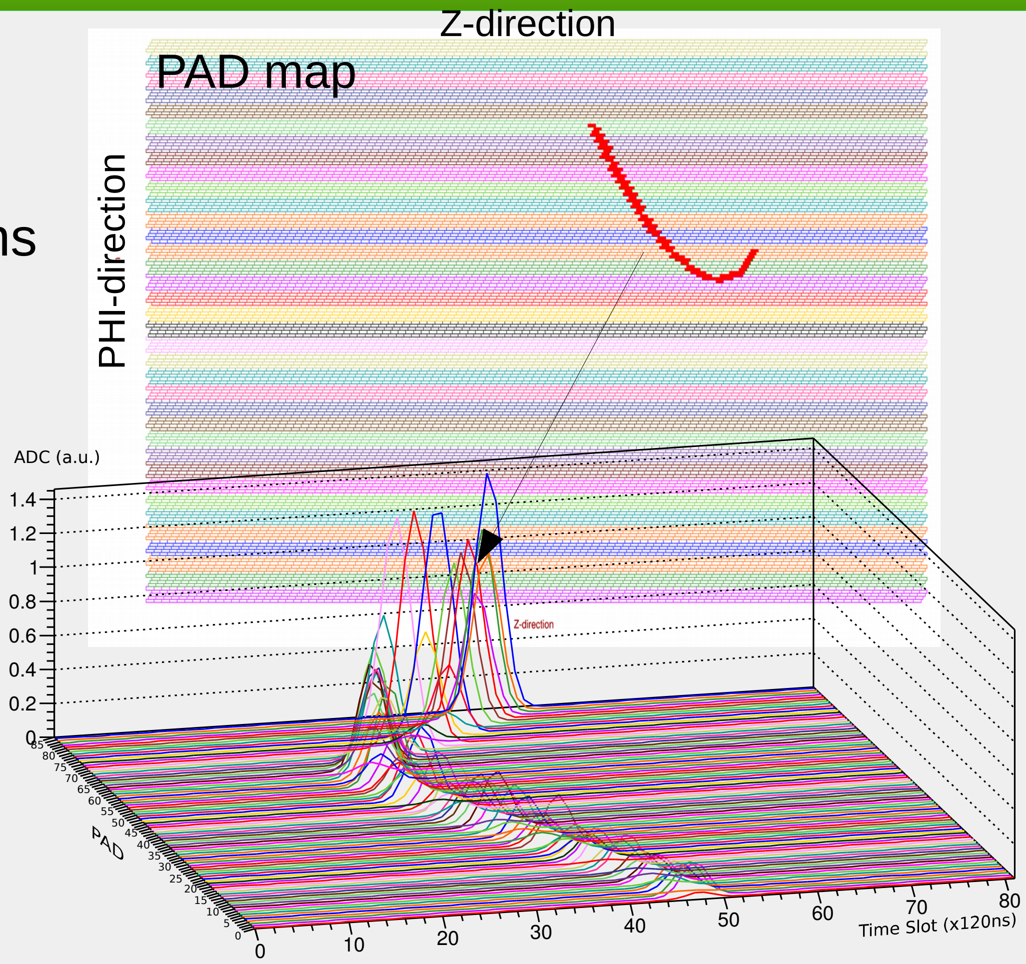


Pictures courtesy of:
I. Albayrak <albayrak@jlab.org>
A. Nadeeshani <arunin@jlab.org>
E. Christy <christy@jlab.org>

# RTPC read out

- Maximum drift time: 5 µs
- Read out time: 10 µs
- Collected charge integrated over40 ns every 120 ns
- Each track will hit 40 to 50 pads
- Read out by Micromegas DREAM electronics

- Trigger determined by CLAS12
- Max BONuS trigger rate ~2kHz

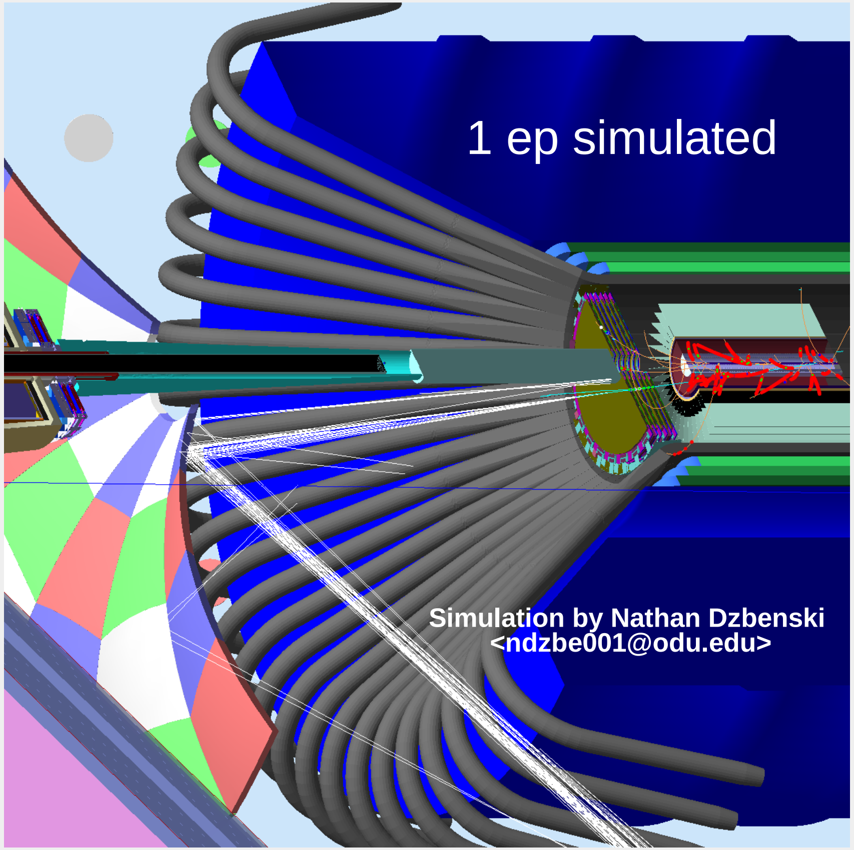


# BONuS12 Simulation

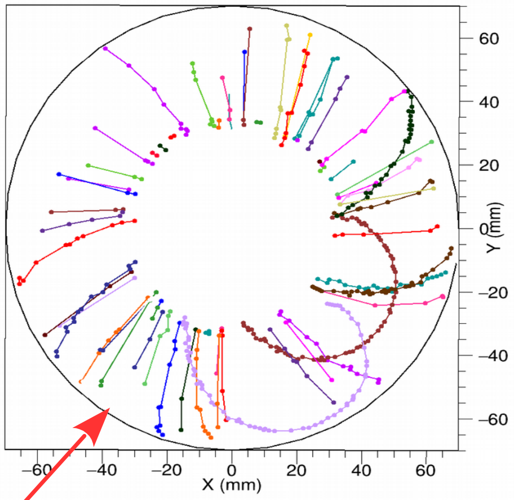
BONuS12 makes use of GEMC*, Coatjava** as well as two specific codes: the Track finder (TF) and the Kalman Filter (KF).

*GEant4 MonteCarlo

**CLAS Offline Analysis Tools Java

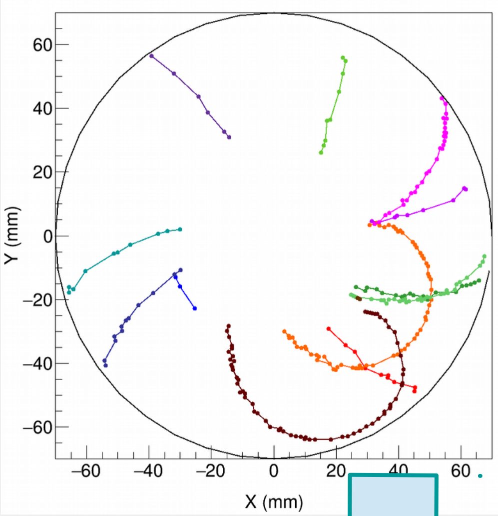



**1 EVENT → many particles**




Color and lines just for visual help

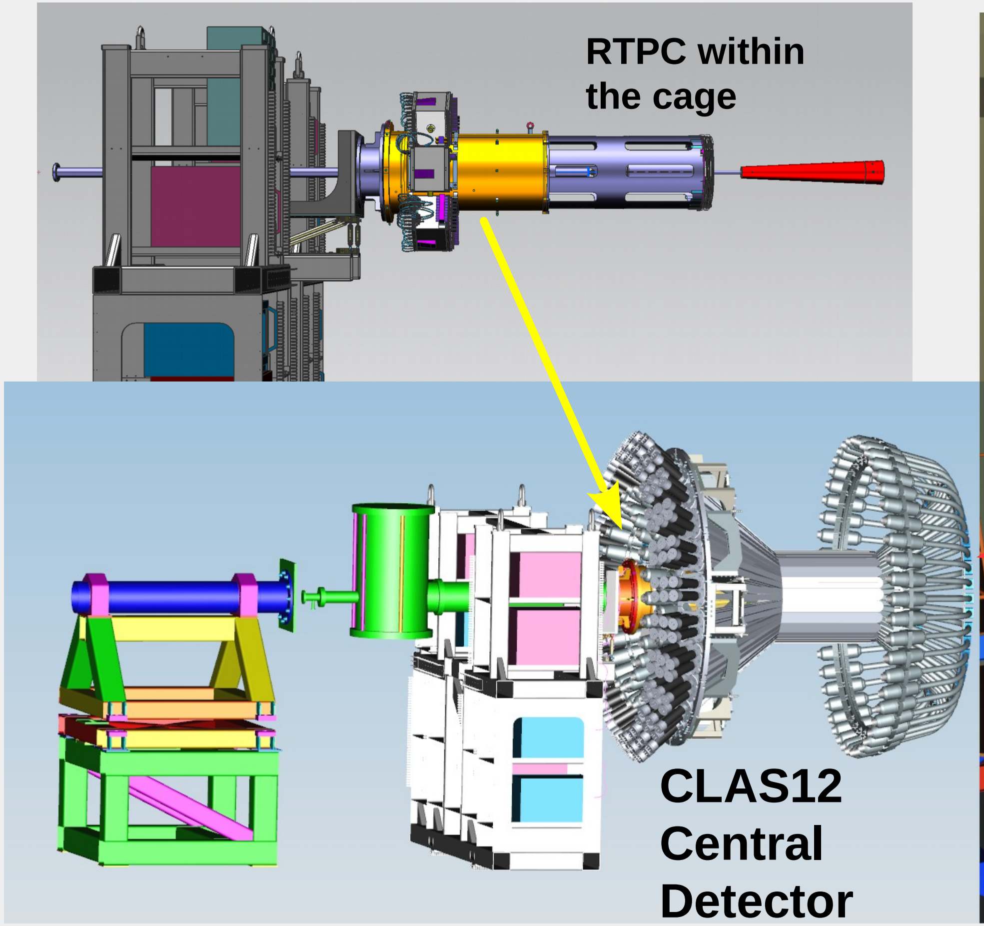
**Each color → one track**

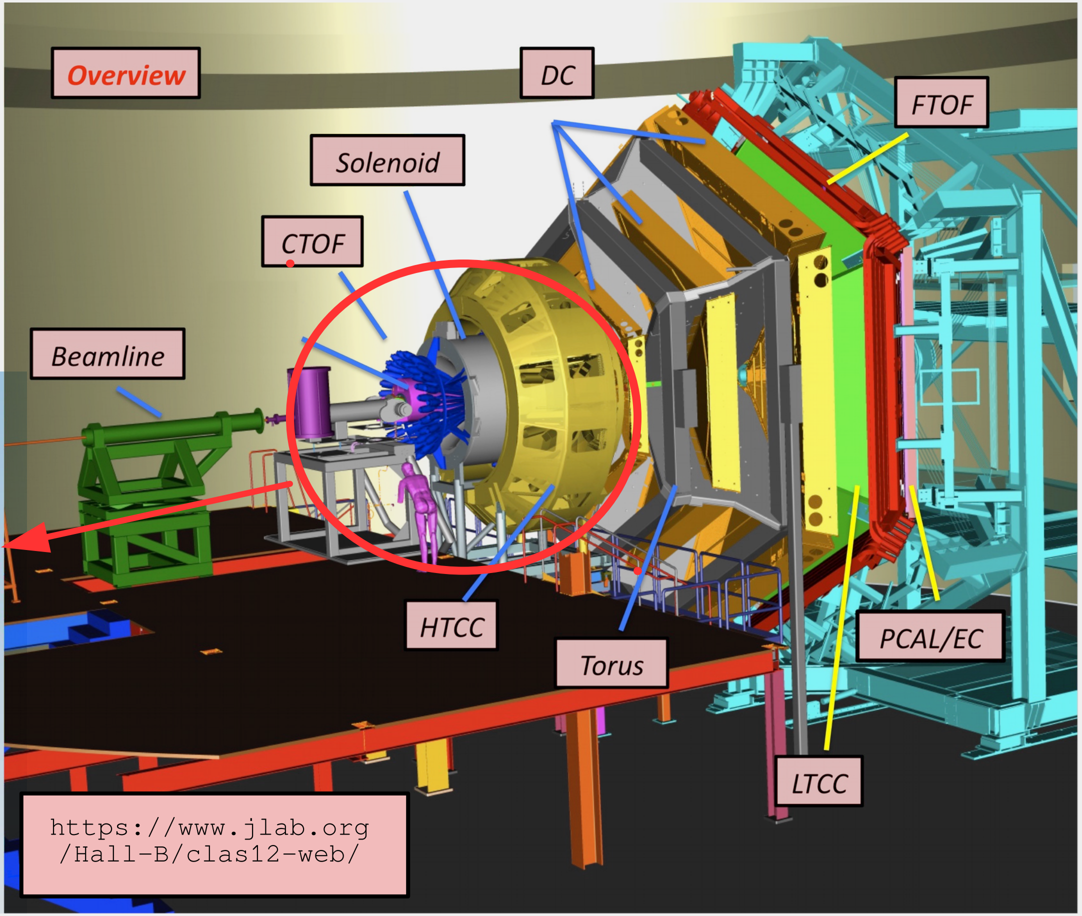



KALMAN FILTER
Will extract vertex and momentum

New track finder under development by David Payette <dpaye001@odu.edu>

# BONuS RTPC at CLAS12



# Expected Results

**Dark Symbols:**

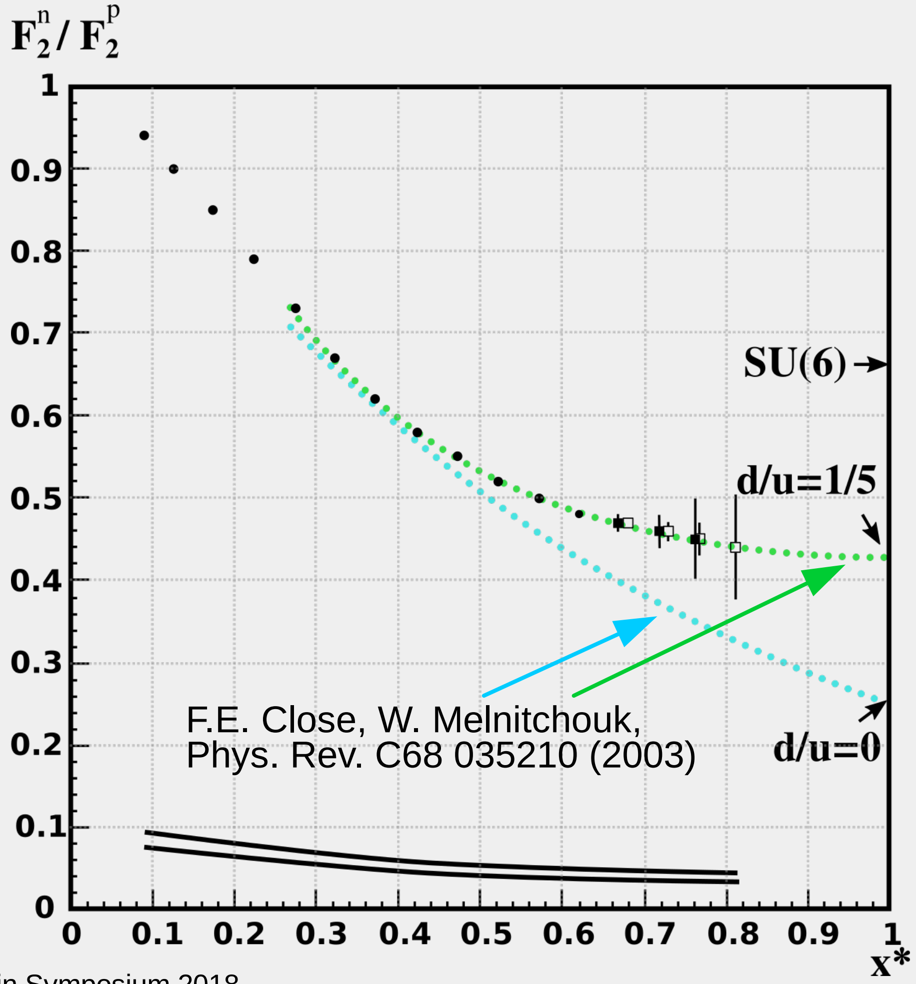
W* > 2 GeV

(x* up to 0.8, bin centered x* = 0.76)

**Open Symbols:**

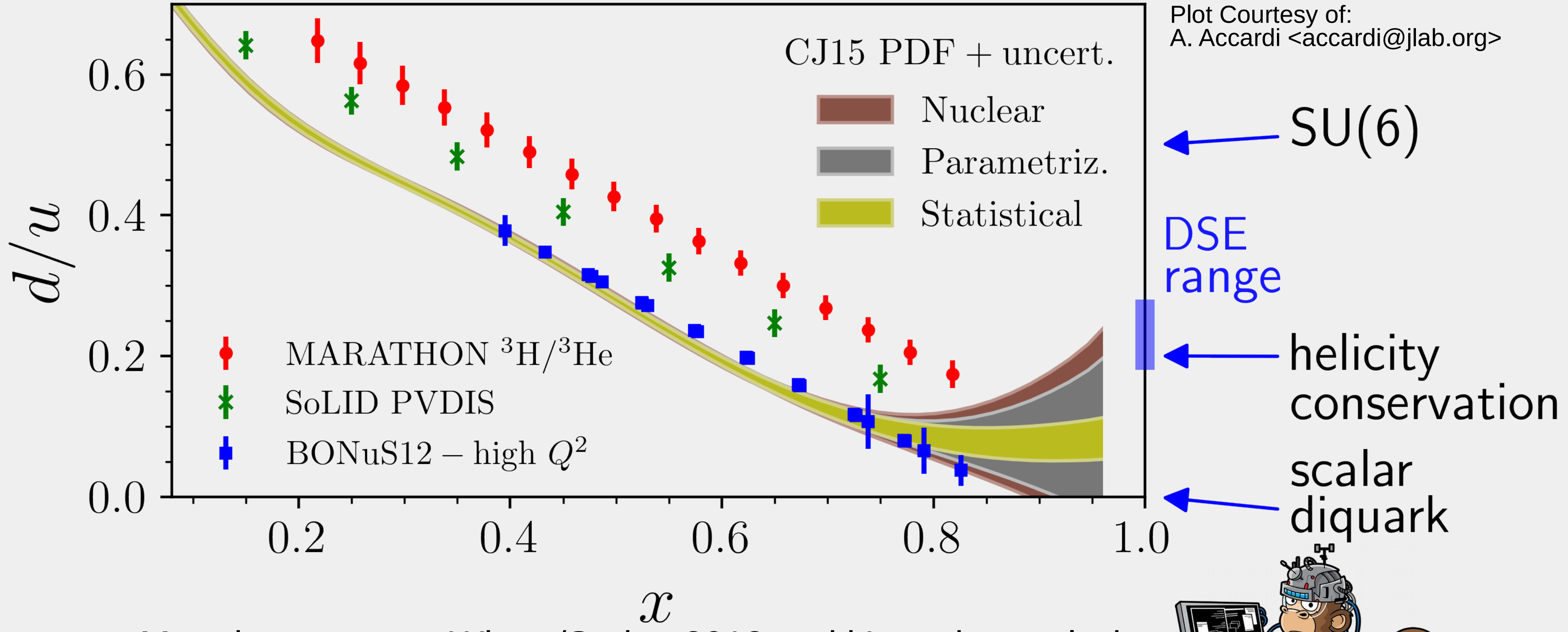
"Relaxed cut" W* > 1.8 GeV

(x* up to 0.83)



# Bonus (but not BONuS)

Plot Courtesy of:
A. Accardi <accardi@jlab.org>




Marathon ran past Winter/Spring 2018 and it's under analysis
SoLID under development

# Collaboration summary

- **Simulation,Tracking and Analysis Group**
  S. Kuhn, J. Zhang, C. Ayerbe, G. Charles,N. Dzbenski, D. Payette, G. Dodge, M. Hattawy.
- **Prototyping, Target, HV, DAQ and testing group**
  S. Kuhn, S. Bültmann, J. Poudel, G. Dodge, N. Dzbenski, D. Payette, G. Charles, M. Hattawy, P. Pandey, I. Neththikumara.
- **Detector Design group**
  E. Christy, A. Nadeeshani, I. Albayrak, K. Griffioen, S. Bültmann, M. Hattawy, S. Kuhn, N. Kalantarians, H. Fenker, C. Wiggins, B. Miller, D. Kashy, C. Cuevas, M. Taylor, N. Liyanage, K. Gnanvo, S. Covrig
- **Gas and slow controls group**
  C. Ayerbe, N. Kalantarians, K. Griffioen, N. Dzbenski, S. Bültmann, I. Niculescu, Y. Prok, W. Moore
- **CLAS12 Integration group**
  S. Kuhn, S. Bültmann, M. Hattawy, R. Miller, C. Wiggins, S. Stepanyan, C. Cuevas

# Summary/Outlook

- ✔ The neutron longitudinal structure information is not accurate as the proton.
  - ✔ Information of $d(x)$ distribution less known than $u(x)$
- ✔ The tagging spectator technique has shown to be a powerful tool in order to extract information from bound neutrons.
- ✔ BONuS 12 will measure the Structure Function $F_2$ at $x$ up to 0.85 at CLAS12.
- ✔ The recoil proton will be detected with a state-of-the-art Radial Time Projection Chamber (under construction).

  - ➔ The first BONuS 12 RTPC is expected to be ready by the end of 2018.
  - ➔ A second BONuS 12 RTPC will be delivered by March/April 2019.
  - ➔ The installation of the detector in Hall B is expected by Nov 2019.
  - ➔ The experiment is tentatively scheduled for data taking in the spring of 2020.

# Grazie per la vostra attenzione

# BACKUP SLIDES

# Ratio Method to extract $F_2$

$$R_{\text{exp}} = \frac{N_{\text{tagged}}(\Delta Q^2,\, \Delta W^*, \Delta p_s^{(\text{VIP})})}{N_{\text{inc}}(\Delta Q^2,\, \Delta W)} \times \frac{A_e(Q^2, W)}{A_e(Q^2, W^*)}$$

Experimental ratio (tagged/untagged) corrected by CLAS acceptance

$$R_{\text{exp}} = \frac{F_2^n(Q^2, W^*)}{F_2^d(Q^2, W)} \times I_{\text{VIP}}$$

Spectator approximation

$$I_{\text{VIP}} = \int_{\text{VIP}} d\alpha_s dp_s^{\perp} A_p(\alpha_s, p_s^{\perp}) S(\alpha_s, p_s^{\perp})$$

Spectral function

Proton acceptance of the RTPC

$$\left(\frac{F_2^n}{F_2^d}\right)_{\text{exp}} = \frac{R_{\text{exp}}}{I_{\text{VIP}}}$$

Well-measured values parametrized by:

$$\frac{F_2^n}{F_2^p} = \left(\frac{F_2^n}{F_2^d}\right)_{\text{exp}} \left(\frac{F_2^d}{F_2^p}\right)_{\text{model}} \quad \Rightarrow \quad \frac{F_2^n}{F_2^p} = \frac{R_{\text{exp}}}{I_{\text{VIP}}} \left(\frac{F_2^d}{F_2^p}\right)_{\text{model}}$$

P. E. Bosted and M. E. Christy, Phys. Rev. C 77, 065206 (2008)
M. E. Christy and P. E. Bosted, Phys. Rev. C 81, 055213 (2010).

To obtain F2n, just multiply the final expression by the values of F2p from the parametrization from Bosted/Christy

# Polarized quark distributions

The EMC Effect and The Quest to High x Quark Distributions

**Patricia Solvignon**
Argonne National Laboratory

Hall C seminar
Jefferson Lab
April 9 2009

In the parton model:

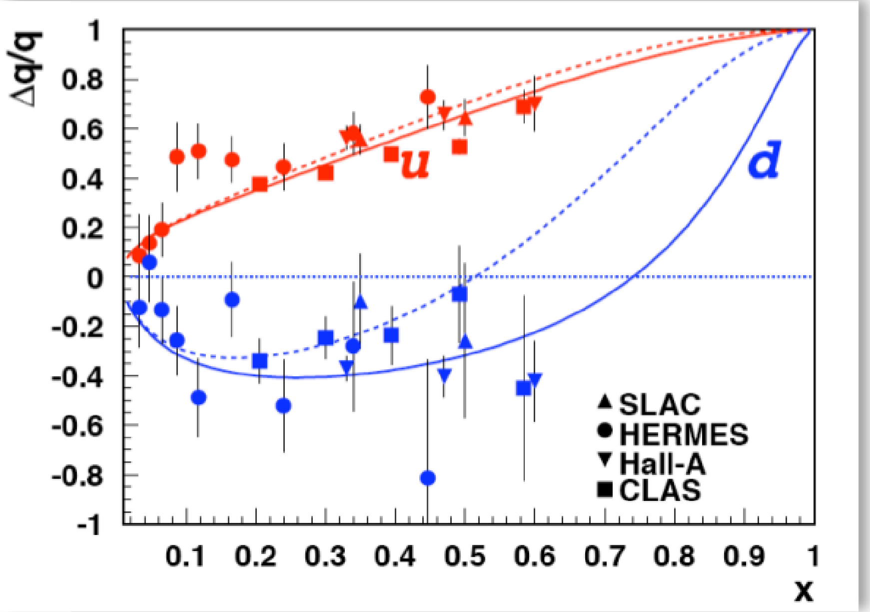
$$F_1(x) = \frac{1}{2}\Sigma_i e_i^2 [q_i(x)]$$

$$g_1(x) = \frac{1}{2}\Sigma_i e_i^2 [\Delta q_i(x)]$$

At high $Q^2$, $A_1 = g_1/F_1$ and:

$$\frac{g_1^n}{F_1^n} = \frac{\Delta u + 4\Delta d}{u + 4d}$$

$$\frac{g_1^p}{F_1^p} = \frac{4\Delta u + \Delta d}{4u + d}$$

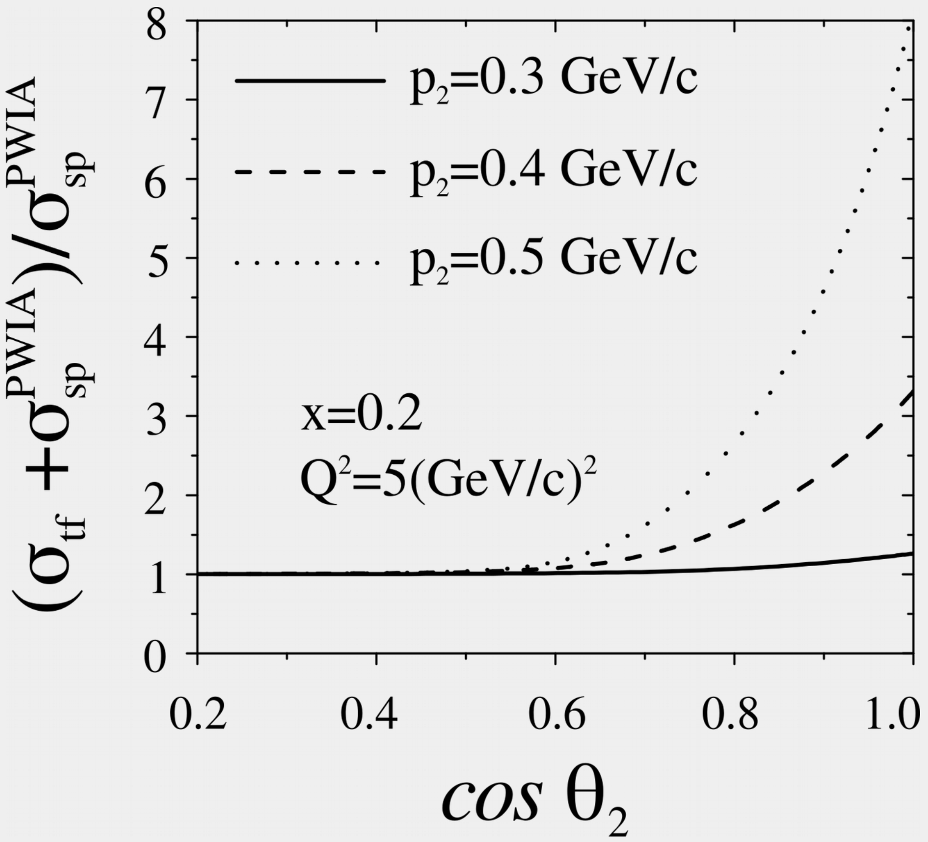



$$\frac{\Delta u}{u} = \frac{4}{15}\frac{g_1^p}{F_1^p}\left(4 + \frac{d}{u}\right) - \frac{1}{15}\frac{g_1^n}{F_1^n}\left(1 + 4\frac{d}{u}\right)$$

$$\frac{\Delta d}{d} = \frac{4}{15}\frac{g_1^n}{F_1^n}\left(4 + 1/\frac{d}{u}\right) - \frac{1}{15}\frac{g_1^p}{F_1^p}\left(1 + 4/\frac{d}{u}\right)$$

# Target Fragmentation

V. Palli et al, Phys. Rev. C 80(2009) 054610



# RTPC construction (now!)