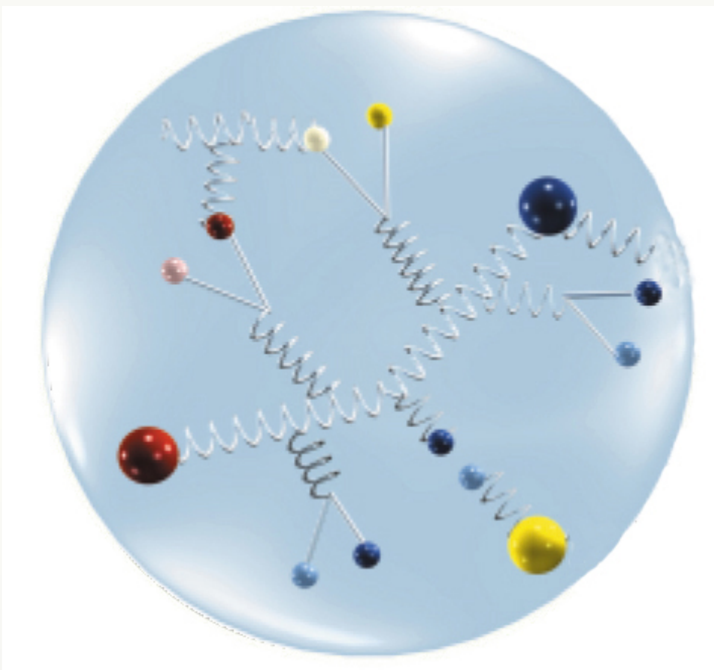
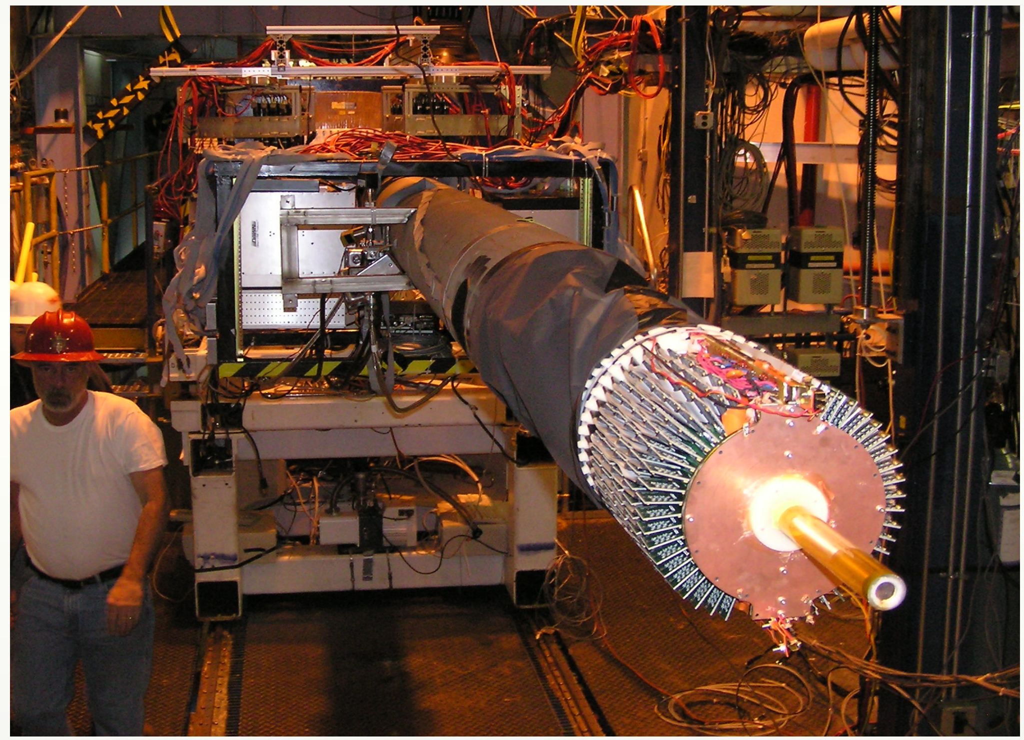
Structure of (Free) Neutrons: The BONuS & BONuS12 Experiments

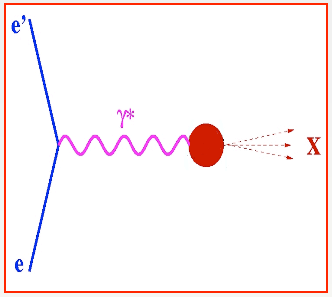




Sebastian Kuhn

Old Dominion University

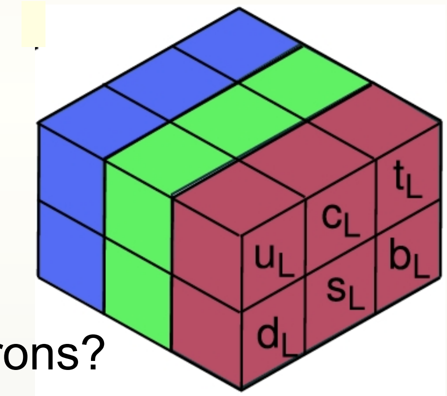
Overview



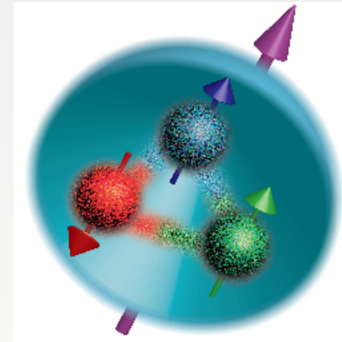
- Neutron Structure Functions (esp. at large x) - Why?
- The Neutron - No Free ~~Lunch~~ Target
  (Nucleon structure modifications in Nuclei)
- Spectator Tagging
  (Principle and Experimental Realization - the RTPC)
- The “BoNuS” experiment
- New ideas for recoil detectors
- The (11 GeV) Future of “BoNuS”
  (Conclusion and Outlook)

Fundamental Problem of Nuclear and Hadronic Physics

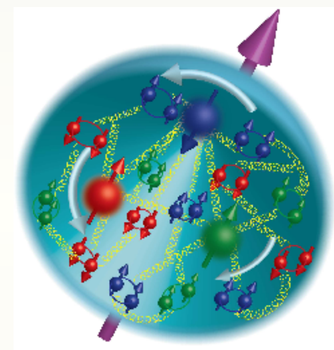
- Nearly all well-known ("visible") mass in the universe is due to hadronic matter
- Fundamental theory of hadronic matter exists since the 1960's: Quantum Chromo Dynamics
  - "Colored" quarks (u,d,c,s,t,b) and gluons; Lagrangian
- BUT: knowing the ingredients doesn't mean we know how to build hadrons and nuclei from them!
  - akin to the question: "Given bricks and mortar, how do you build a house?"
- Four related puzzles:
  - What is the "quark-gluon wave function" of known hadrons?
  - How are hadrons (nucleons) bound into nuclei? Does their quark-gluon wave function change inside a nucleus?
  - How do fast quarks and gluons propagate inside hadronic matter?
  - How do fast quarks and gluons turn back into observable hadrons?

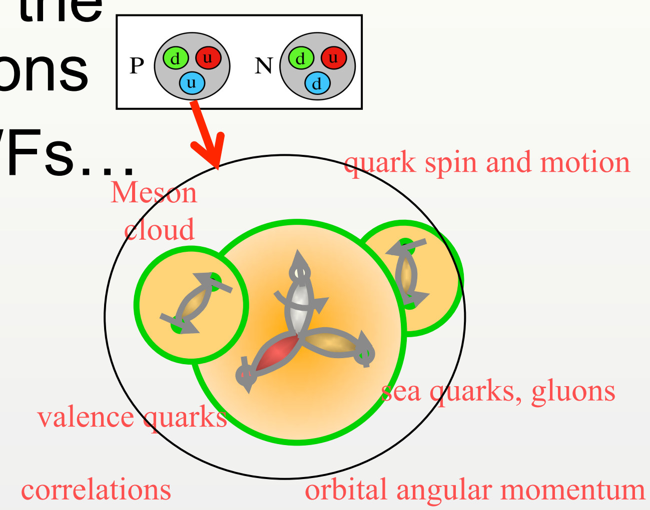


What are Nucleons?



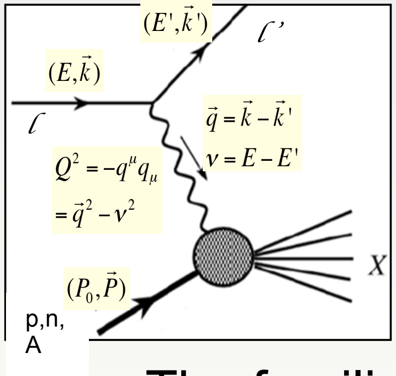
- Stationary solutions of the QCD Lagrangian with $A = 1$, $I = ½$; $S = B = C = T = 0$ and $s = ½$
- Bound systems of 3 light valence quarks (*uud* or *udd*) and a large number of sea quarks ($q\bar{q}$) and gluons
- Bound states of effective "constituent quarks"
- Describable as a superposition of Fock states, including bare *qqq*, and excitations of the chiral condensate ("pion cloud"); solitons
- Characterized by SFs, FFs, GPDs, WFs…
- …your definition here…
- Classical Nuclear Physics: "Structure-less" hard objects



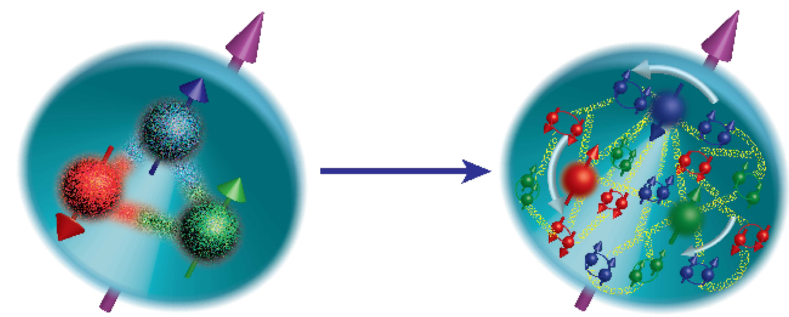


How Do We Study Hadron/Nuclear Structure?

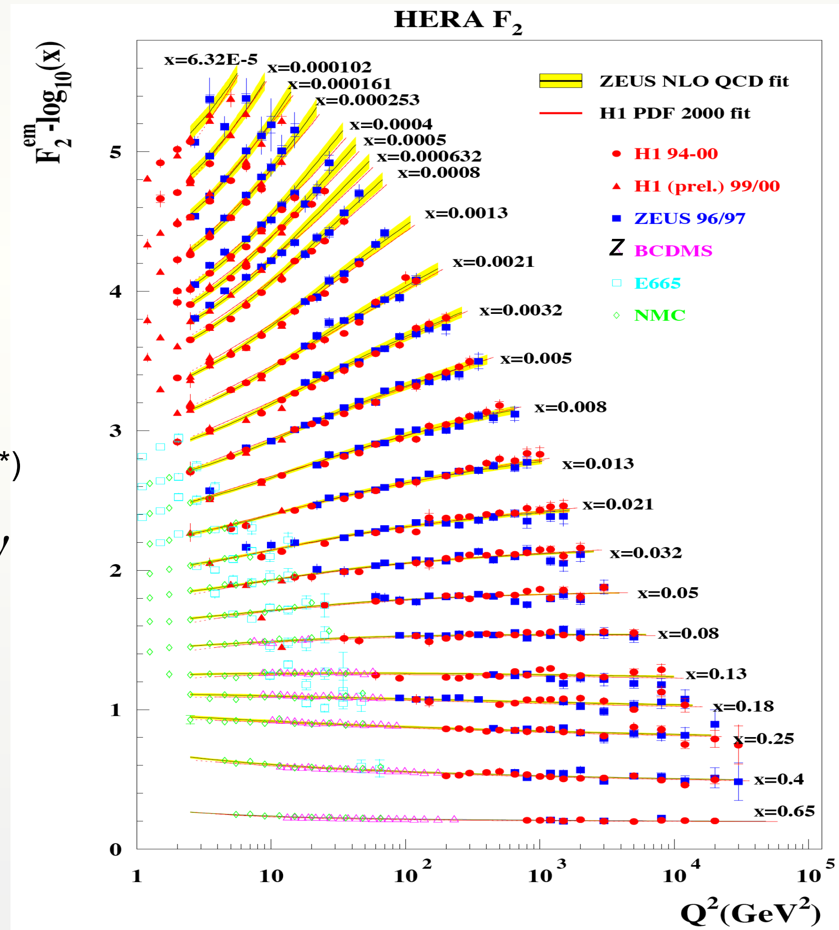
- Energy levels: Nuclear and particle (baryon, meson) masses, excitation spectra, excited state decays -> Spectroscopy *(What exists?)*
- Elastic and inelastic scattering, particle production
  Reactions (*Relationships?*)
- Probing the internal structure directly
  Imaging (*Shape and Content?*)
- Particular way to encode this: Structure Functions
  - *"Parton wave function"?*
    5(6)-dim. Wigner distribution ➔ …



Introduction

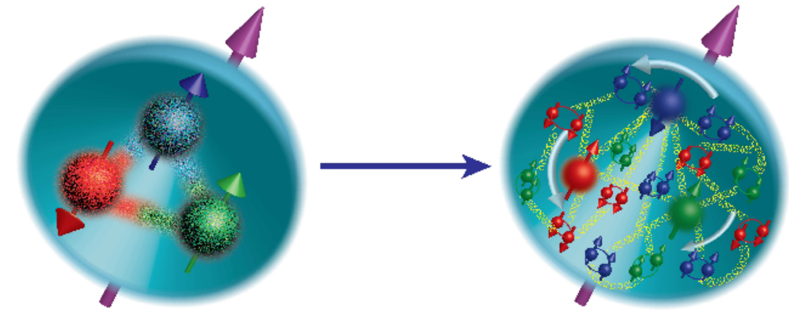


- The familiar (?) 1D world of Nucleon longitudinal structure:
  - Take a nucleon
  - Move it real fast along z
    $\Rightarrow$ light cone momentum
    $P_+ = P_0 + P_z$ (>>M)
  - Hit a "parton" (q, g,…) inside
  - Measure **its** l.c. momentum
    $p_+ = p_0 + p_z$ (m≈0)
  - $\Rightarrow$ Momentum Fraction $\xi = p_+ / P_+$ *)
  - In DIS: $\xi = (q_z - \nu)/M \approx x_{Bj} = Q^2/2M\nu$
  - Probability: $F_1(x) = \frac{1}{2}\sum_i e_i^2 q_i(x)$
  - Because of spin-1/2: 2nd SF F_2(x)

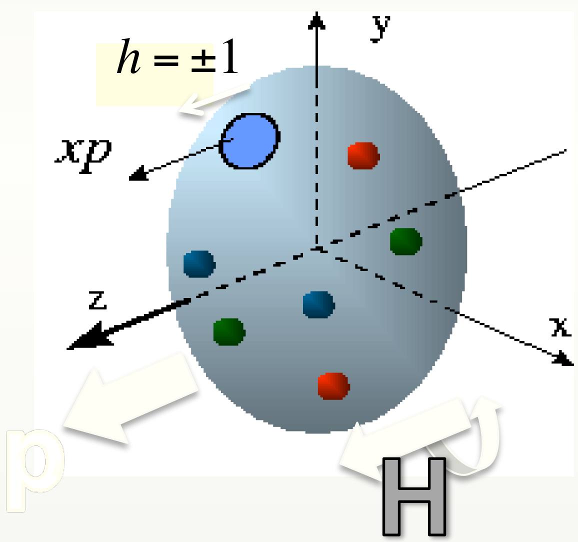


*) Advantage: Boost-independent

Introduction



- So there we are:



$$q(x;Q^2), \langle h \cdot H \rangle q(x;Q^2)$$

Traditional “1-D” Parton Distributions (PDFs) (inclusive, integrated over many variables)

Parton model: DIS can access

$$F_1(x) = \tfrac{1}{2} \sum_i e_i^2 q_i(x) \; \left(\text{and } F_2(x) \approx 2xF_1(x)\right)$$

Complications: pQCD evolution and radiation (logarithmic dependence on Q^2)

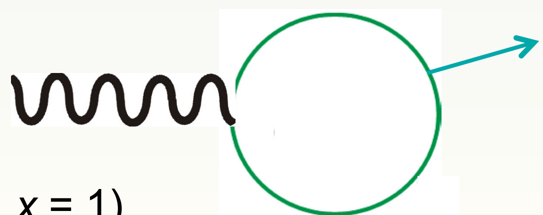
SIDIS: allows flavor tagging ⇒ separated q_i

Complications: Higher Twist and resonances:

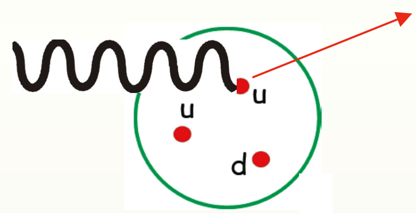
- Non-zero $R = F_L/2xF_1$
- Further Q^2-dependence (power series in $\frac{1}{Q^n}$)

⇒ Our 1D View of the Nucleon

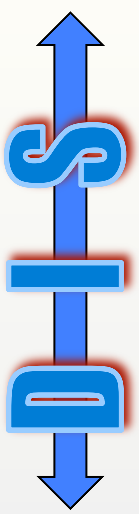
(also depends on the resolution of the virtual photon ~ $1/Q^2$)



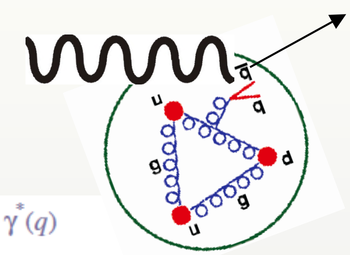
- Elastic scattering
  (Whole system recoils, x = 1)



- Resonances
  ($x < 1$, $W < 2$ GeV)

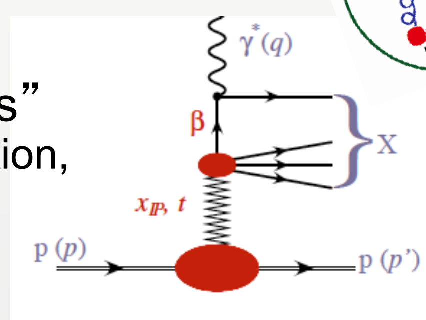


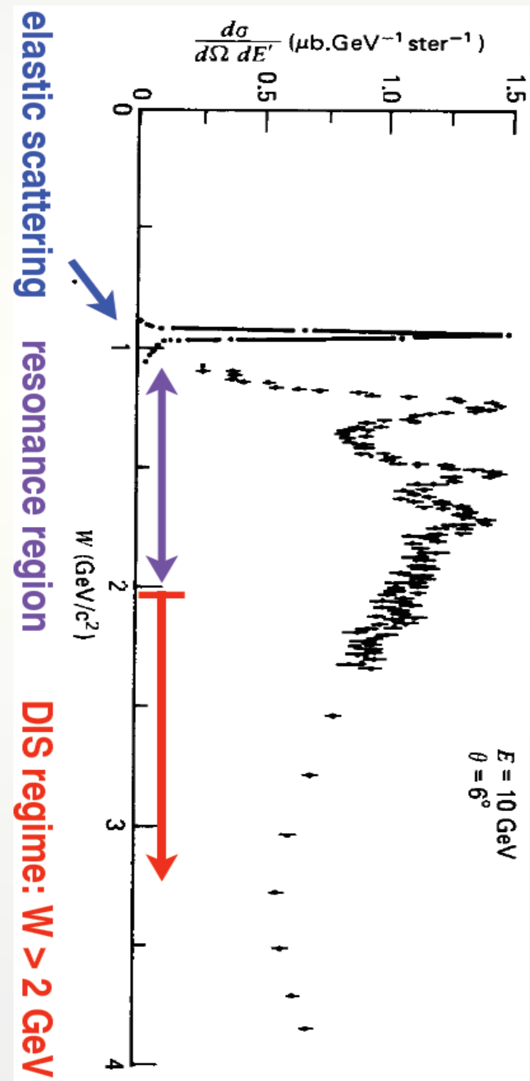
- Valence quarks
  ($x \approx 0.3 - 0.9$, $W > 2$ GeV)

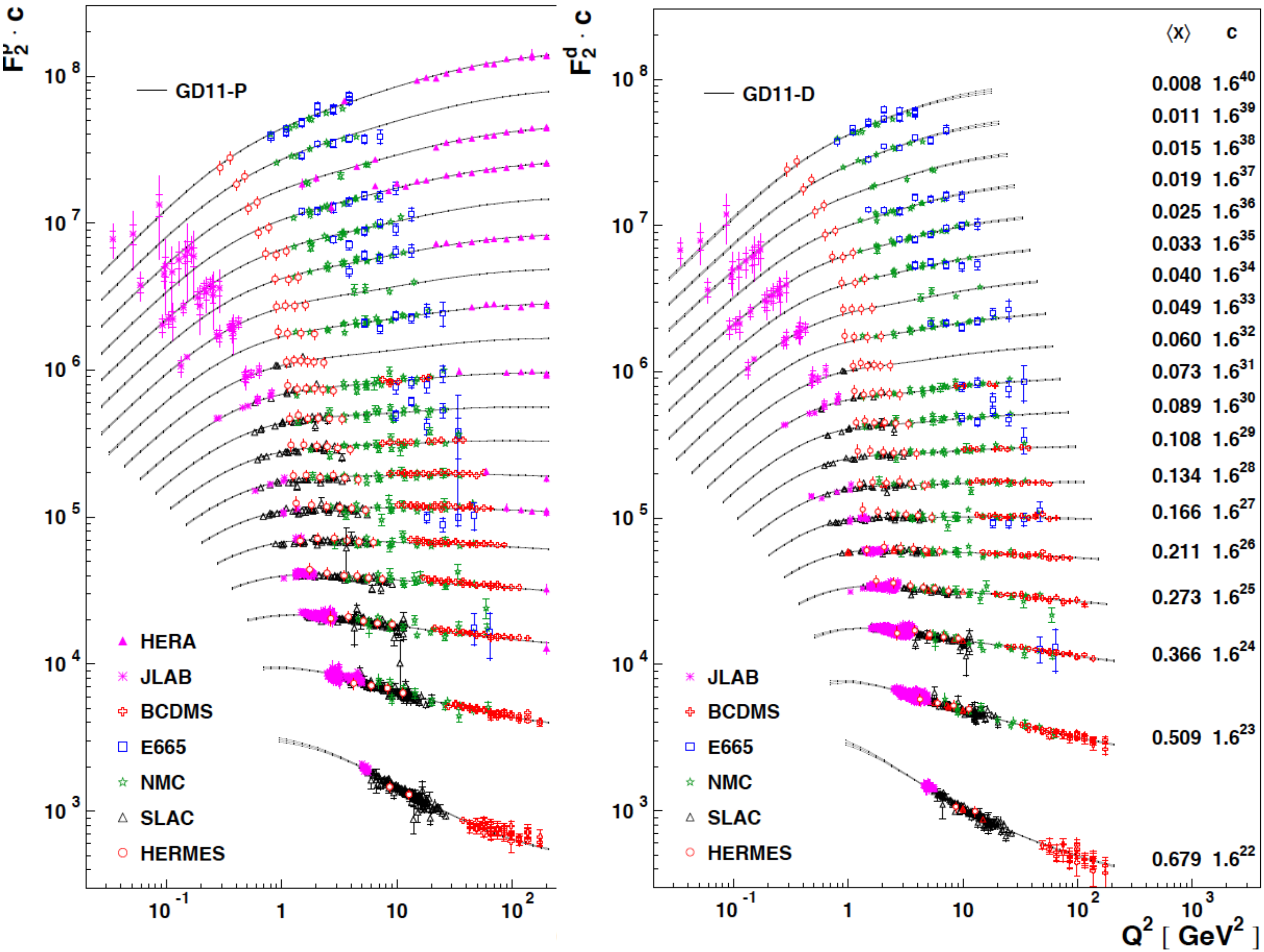


- Sea quarks, gluons
  ($x < 0.3$)

- "Wee Partons"
  ($x \rightarrow 0$, Diffraction, Pomerons)

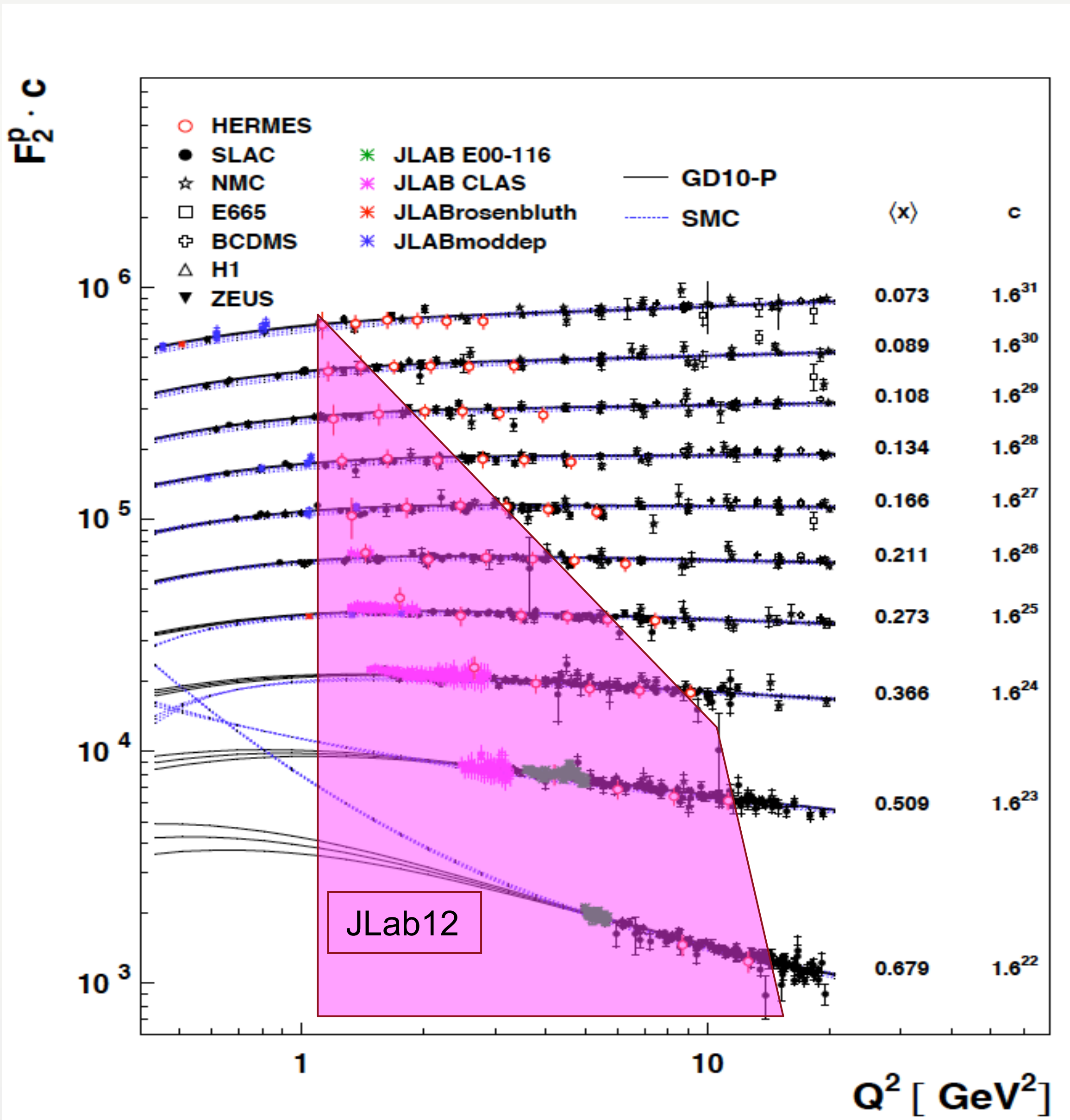


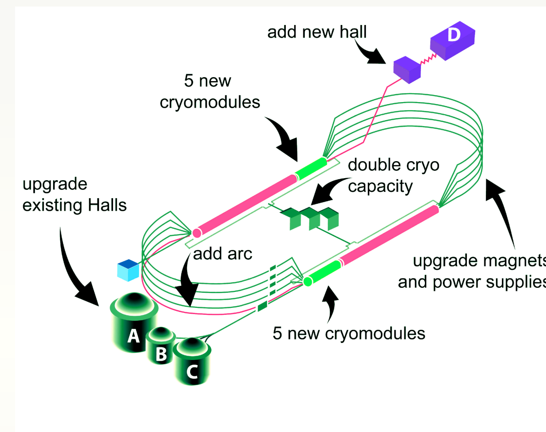




$F_2^p \cdot c$
GD11-P
HERA
JLAB
BCDMS
E665
NMC
SLAC
HERMES
$F_2^d \cdot c$
GD11-D
JLAB
BCDMS
E665
NMC
SLAC
HERMES
⟨x⟩ c
0.008 1.6^{40}
0.011 1.6^{39}
0.015 1.6^{38}
0.019 1.6^{37}
0.025 1.6^{36}
0.033 1.6^{35}
0.040 1.6^{34}
0.049 1.6^{33}
0.060 1.6^{32}
0.073 1.6^{31}
0.089 1.6^{30}
0.108 1.6^{29}
0.134 1.6^{28}
0.166 1.6^{27}
0.211 1.6^{26}
0.273 1.6^{25}
0.366 1.6^{24}
0.509 1.6^{23}
0.679 1.6^{22}
Q^2 [GeV^2]

Jefferson Lab in Context





JLab DIS

Future: 12 GeV

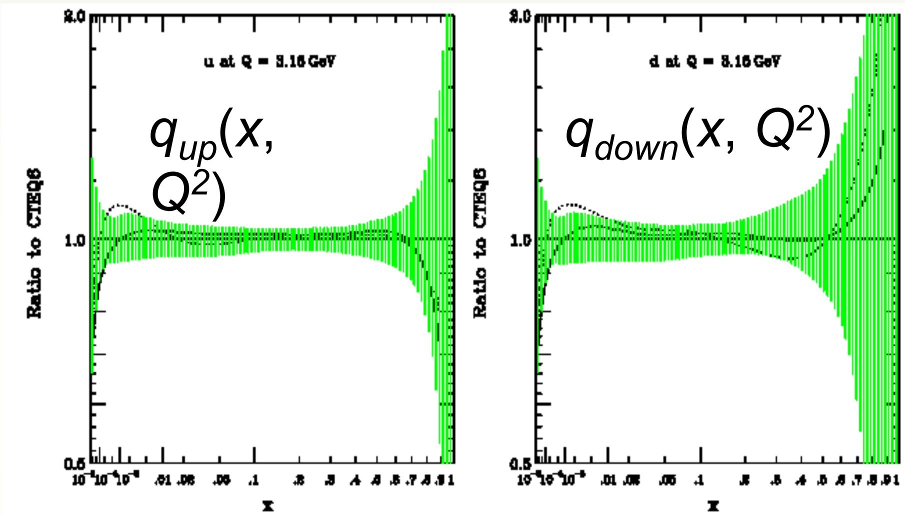
Q^2 = 1…13 GeV^2

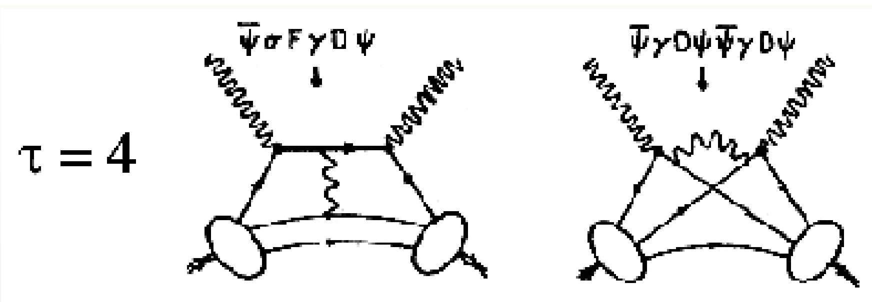
x = 0.06…0.8

W = 0.94…4 GeV

Structure Functions and Moments: Why large x? Why neutron?

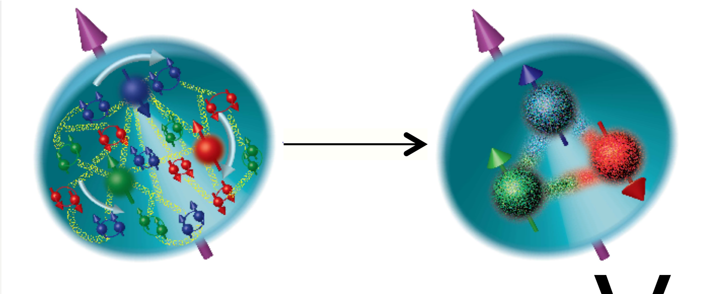
$$\frac{d\sigma}{d\Omega dE'} = \sigma_{Mott}\left(\frac{F_2(x)}{\nu} + 2\tan^2\frac{\theta_e}{2}\frac{F_1(x)}{M}\right); \quad F_2(x,Q^2) = x \sum_{f=up,down,\ldots} z_f^2\left(q_f(x,Q^2) + \bar{q}_f(x,Q^2)\right)$$



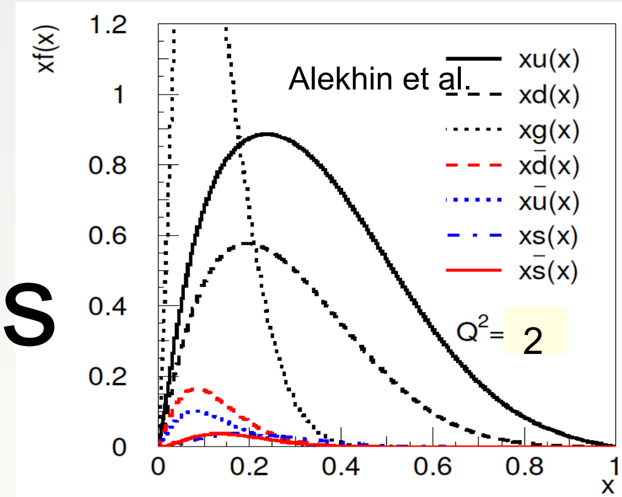


- $q_{down}/q_{up}(x\rightarrow1)$ is a crucial test of valence quark models
  - SU(6) breaking, pQCD,…
- Precise PDFs at large *x* needed as input for LHC, ν experiments etc.
  - Large *x*, medium Q^2 evolves to medium *x*, large Q^2
  - Also: NUCLEAR structure functions
- Moments can be directly compared with OPE (twist expansion), Lattice QCD and Sum Rules
  - All higher moments are weighted towards large *x*
- Quark-Hadron Duality

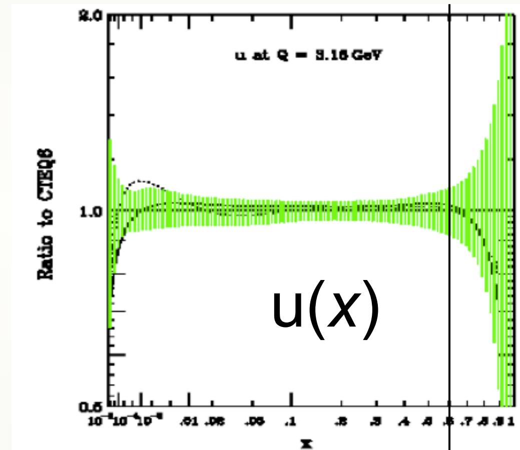
$$M_n^{CN}(Q^2) = \int_0^\infty dx\underline{x^{(n-2)}}F_2(x,Q^2) = \sum_{\tau=2k}^{\infty} E_{n\tau}(\mu,Q^2)O_{n\tau}(\mu)\left(\frac{\mu^2}{Q^2}\right)^{\frac{1}{2}(\tau-2)}$$ + TM corr.

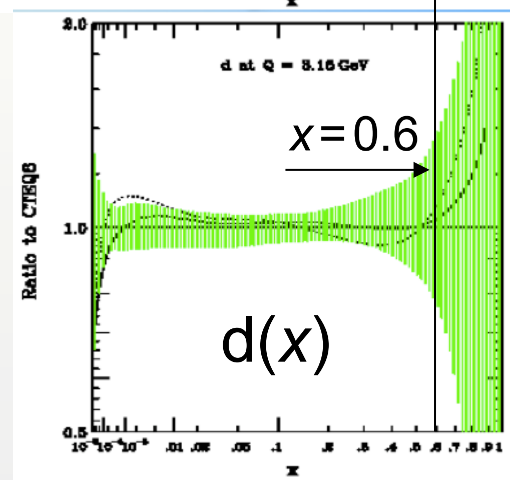


Valence PDFs

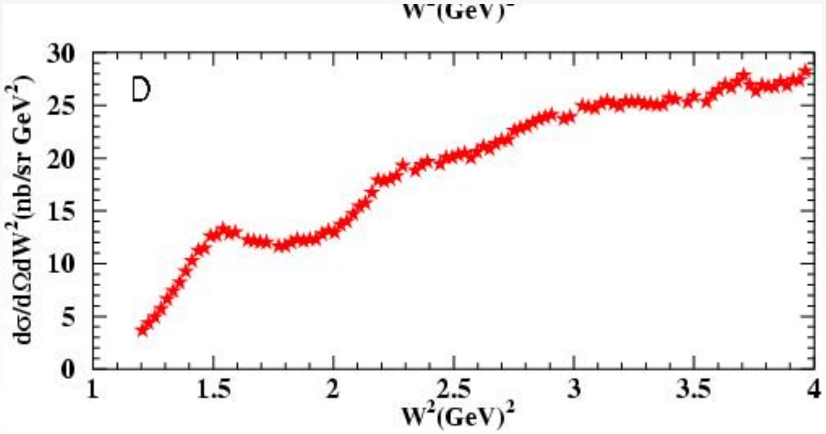


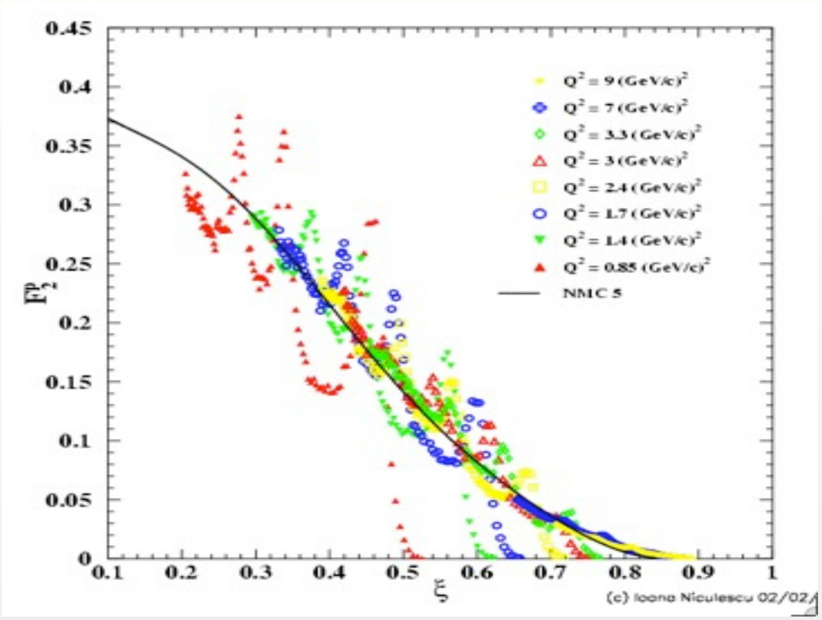
- Behavior of PDFs still unknown for $x \to 1$
  - SU(6): d/u = 1/2, Δu/u = 2/3, Δd/d = -1/3 for all x
  - Relativistic Quark model: Δu, Δd reduced
  - Hyperfine effect (1-gluon-exchange): Spectator spin 1 suppressed, d/u = 0, Δu/u = 1, Δd/d = -1/3
  - Helicity conservation: d/u = 1/5, Δu/u = 1, Δd/d = 1
  - Orbital angular momentum: can explain slower convergence to Δd/d = 1
- Plenty of data on proton → mostly constraints on u and Δu
- Knowledge on d limited by lack of free neutron target (nuclear binding effects in d, ^{3}He)
- Large x requires very high luminosity and resolution; binding effects become dominant uncertainty for the neutron





Structure Functions and Resonances





- Precise structure functions in Resonance Region constrain nucleon models
  [Separate resonant from non-resonant background; isospin decomposition]
- Needed as input for spin structure function data, radiative corrections,…
- Compare with DIS structure functions to test duality

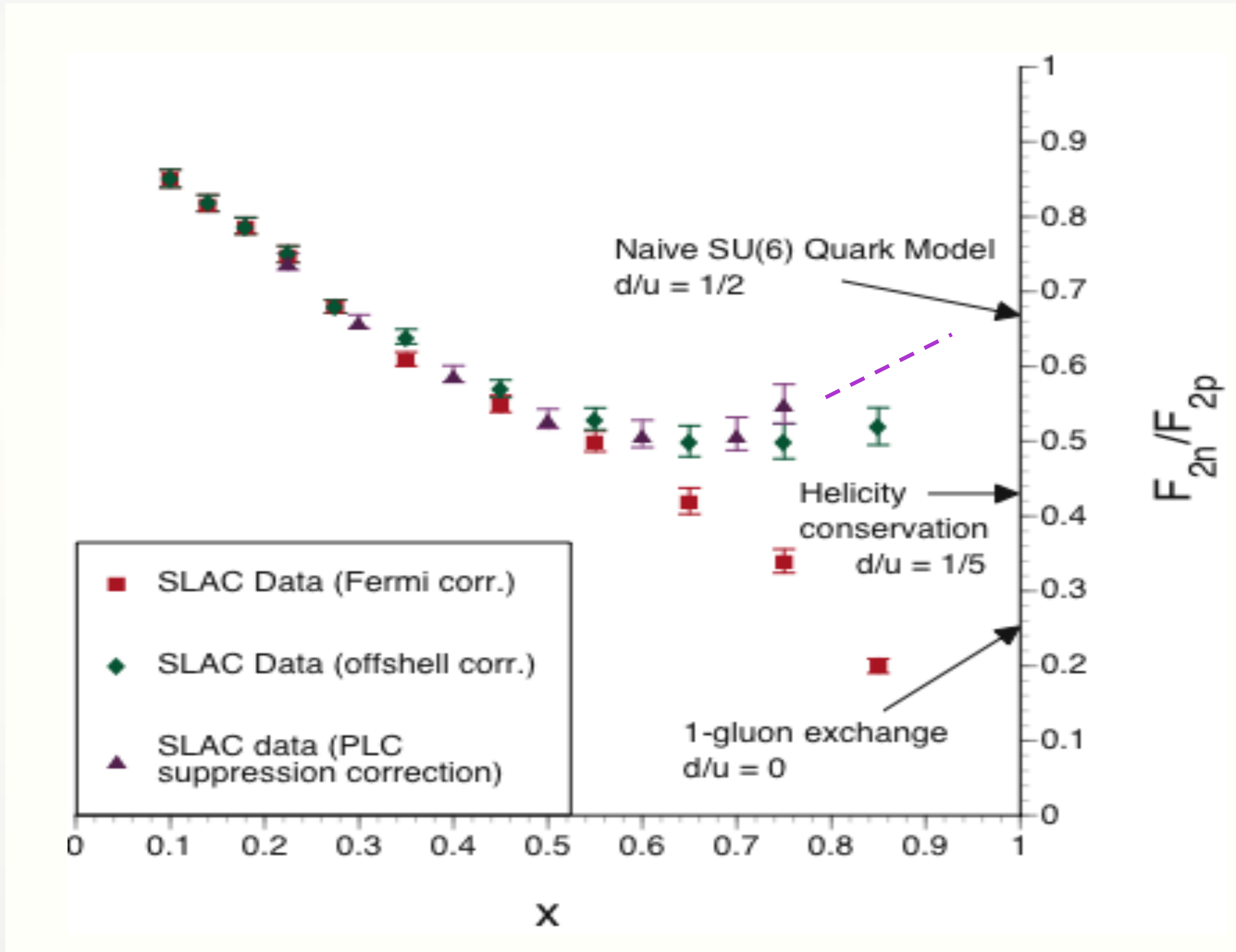
Present Knowledge of d/u (x → 1)

$$\frac{F_{2n}}{F_{2p}} \approx \frac{1+4d/u}{4+d/u} \Rightarrow$$

$$\frac{d}{u} \approx \frac{4F_{2n}/F_{2p}-1}{4-F_{2n}/F_{2p}}$$

$F_{2n}/F_{2p} = F_{2d}/F_{2p} - 1$

???

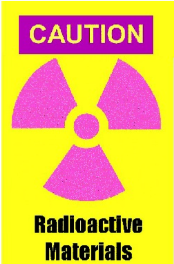


- Limited by “Nuclear Binding Uncertainties”

Neutron Data Are Important…
…but hard to get

- Free neutrons decay in 15 minutes.

- Radioactivity!

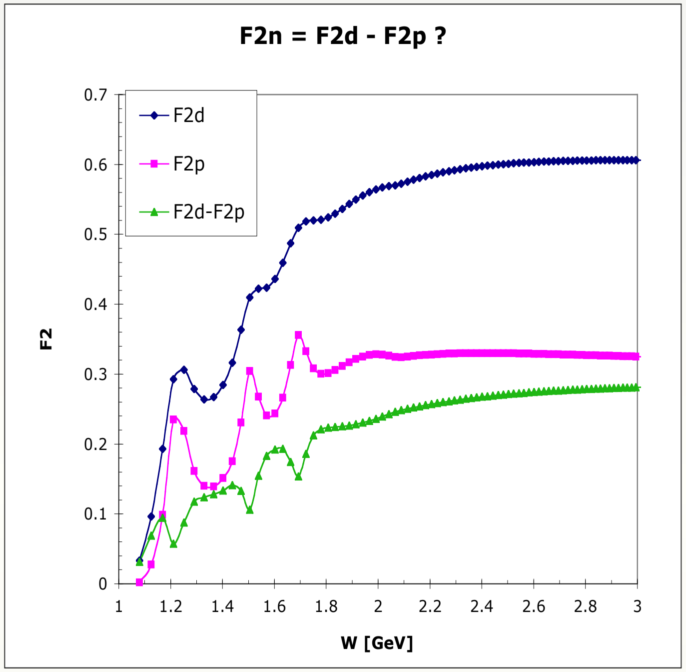


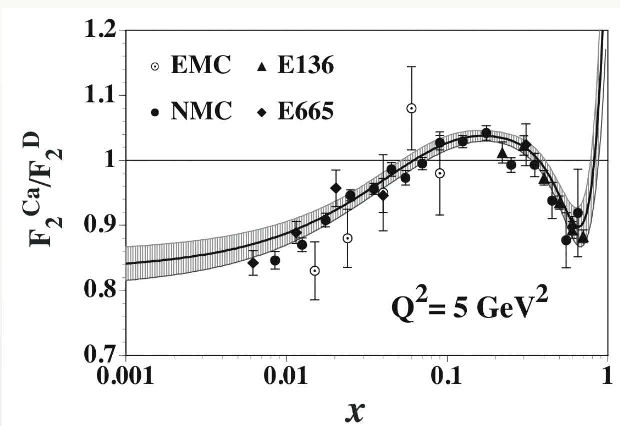
- Zero charge makes it difficult to create a dense target

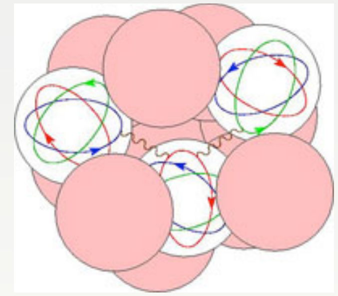
Magnetic bottle: 10^3 - 10^4 n/cm^2 [TU München]
Typical proton target: $4{\cdot}10^{23}$ p/cm^2 [10 cm LH] – 10^{14} p/cm^2 [HERMES]

=> Alternative Solution: Deuterons, Tritons and Helium-3…
BUT: Nuclear Model Uncertainties:
Fermi motion, off-shell effects (binding), structure modifications (EMC effect), extra pions/Deltas, coherent effects, 6-quark bags…

Nuclear Effects

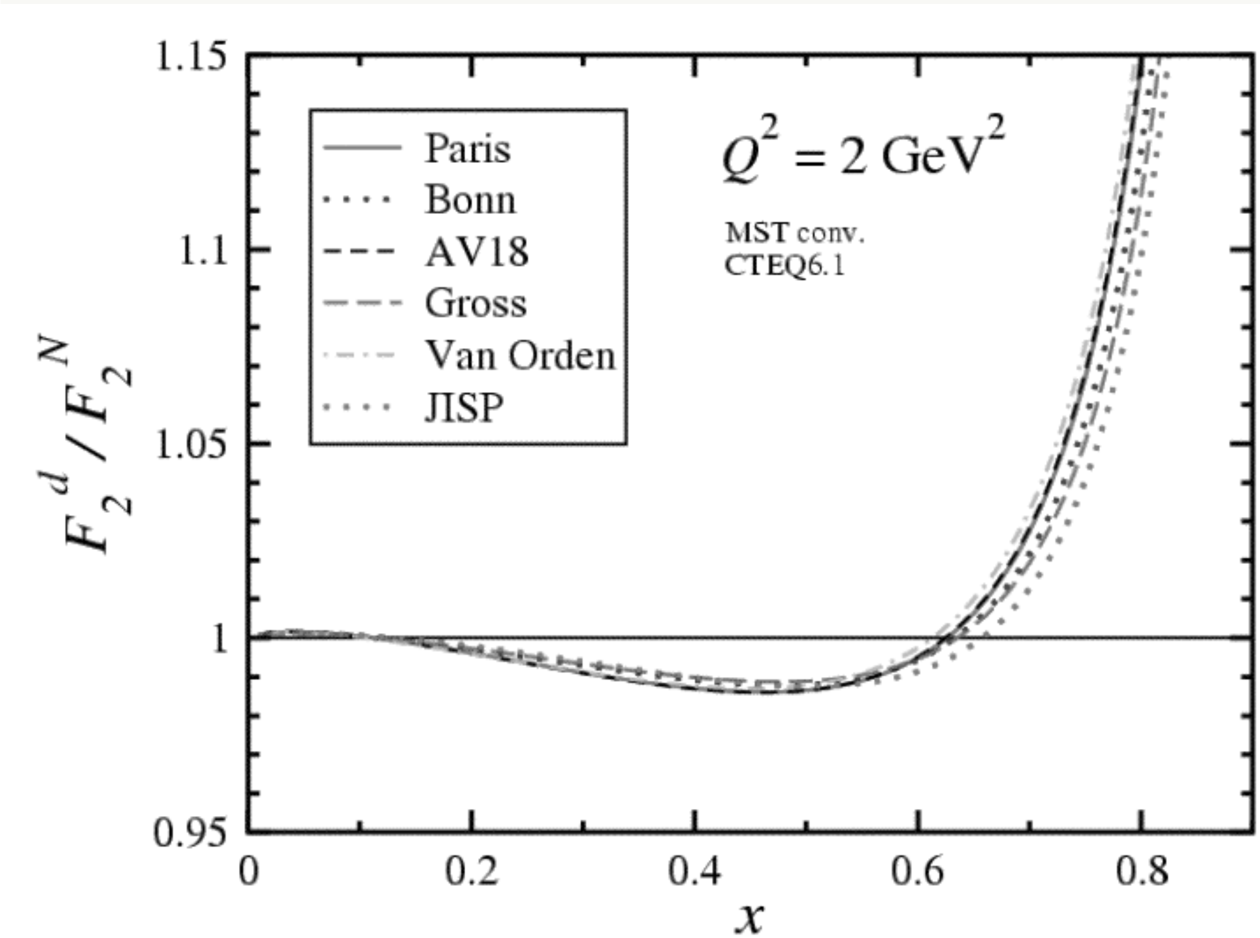






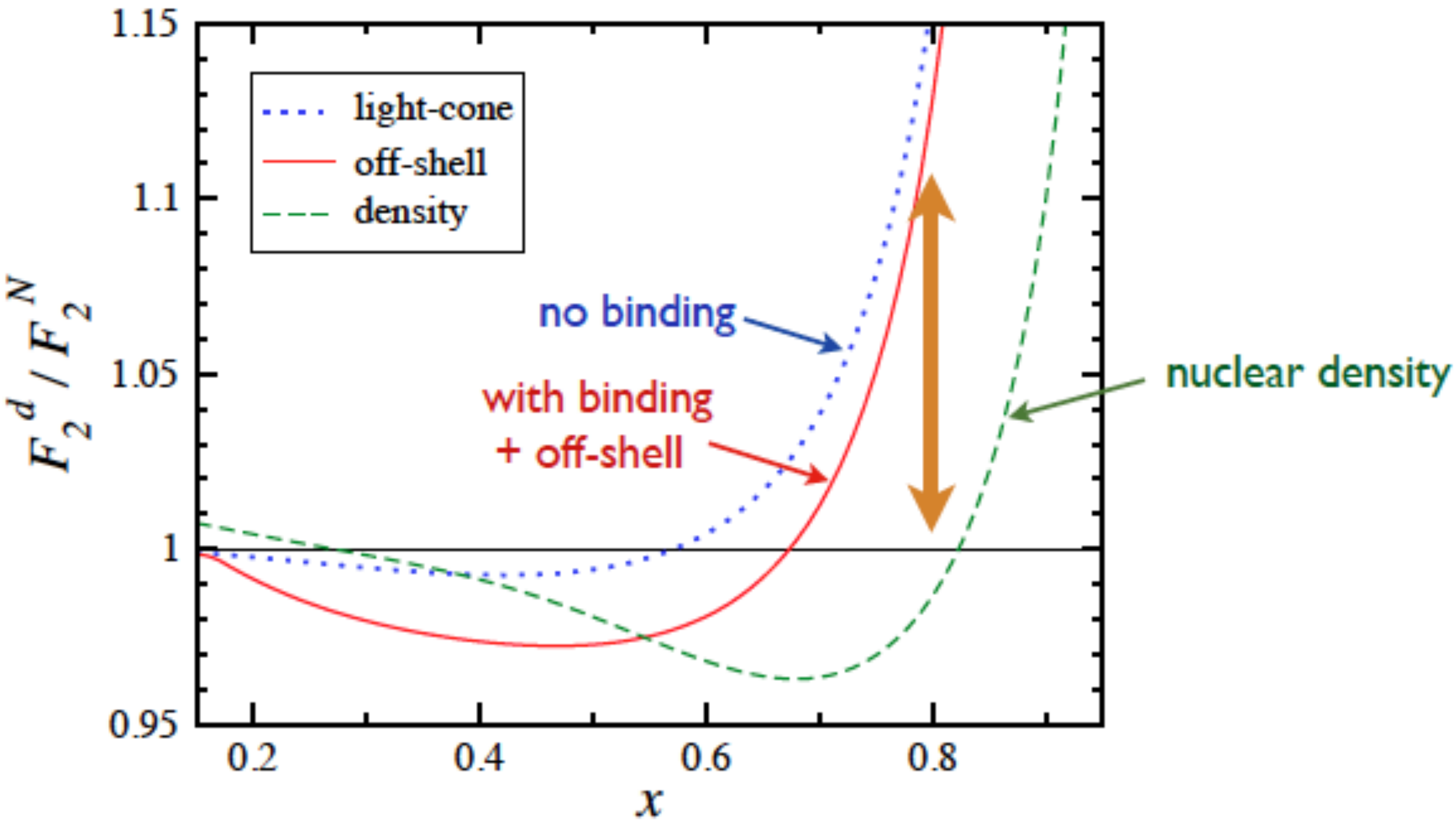
	Deuteron↑	**^{3}He↑ (^{3}H)**
0^{th} order approximation	p↑n↑	p↑p↓n↑
D-state and other configurations (S', P, …)	$\mu_D = \mu_p + \mu_n -$ 0.022	$\mu_{He} = \mu_n -$ 0.214
Tensor polarization	$P_{zz} \approx 0.1$	Not applicable
Kinematic "smearing"	p_{RMS} = 130 MeV/c	p_{RMS} = 170 MeV/c
Binding and "off-shell"-effect	E_{bound}-$E_{free} \approx$ -10 MeV	E_{bound}-$E_{free} \approx$ -20 MeV
EMC-effect, final state interaction, coherent processes	A = 2, $\rho \approx 0.063$ N/fm^3	A=3, $\rho \approx 0.094$ N/fm^3
Extra pions?	2% ?	5% ?
Contributions from Delta resonances?	$P_{\Delta\Delta} < 0.5\%$	$P_{NN\Delta} \approx 2\%$?
Other exotic components?	6-quark bags?	6- and 9-quark bags?

Large *x* - Large Nuclear Effects



- Even simple "Fermi Smearing" leads to significant dependence on D wave function
- Different models for off-shell and "EMC" effects lead to large additional variations
- Contributions from MEC, $\Delta(1232)$ and "exotic" degrees of freedom unknown
- FSI?

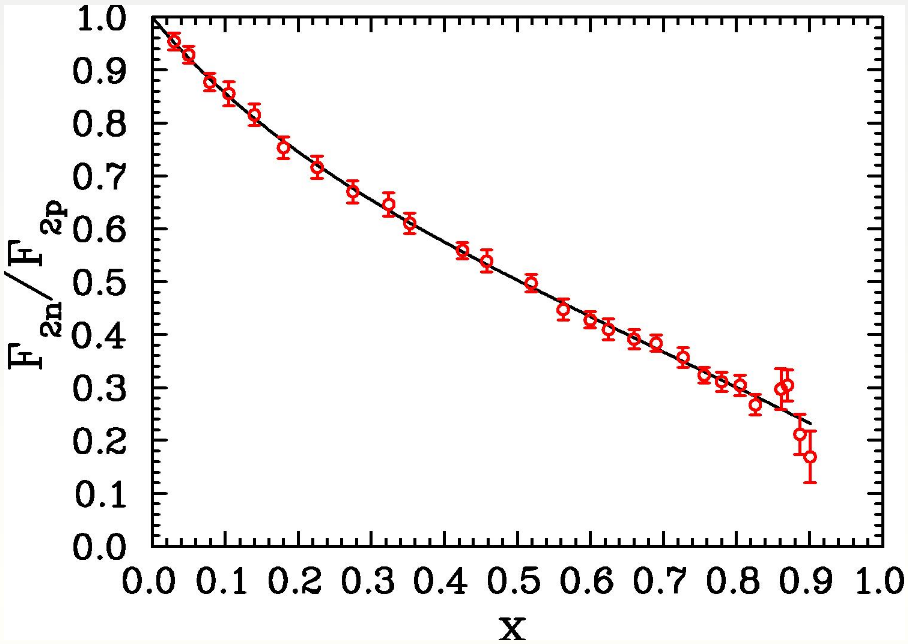
EMC effect in deuteron

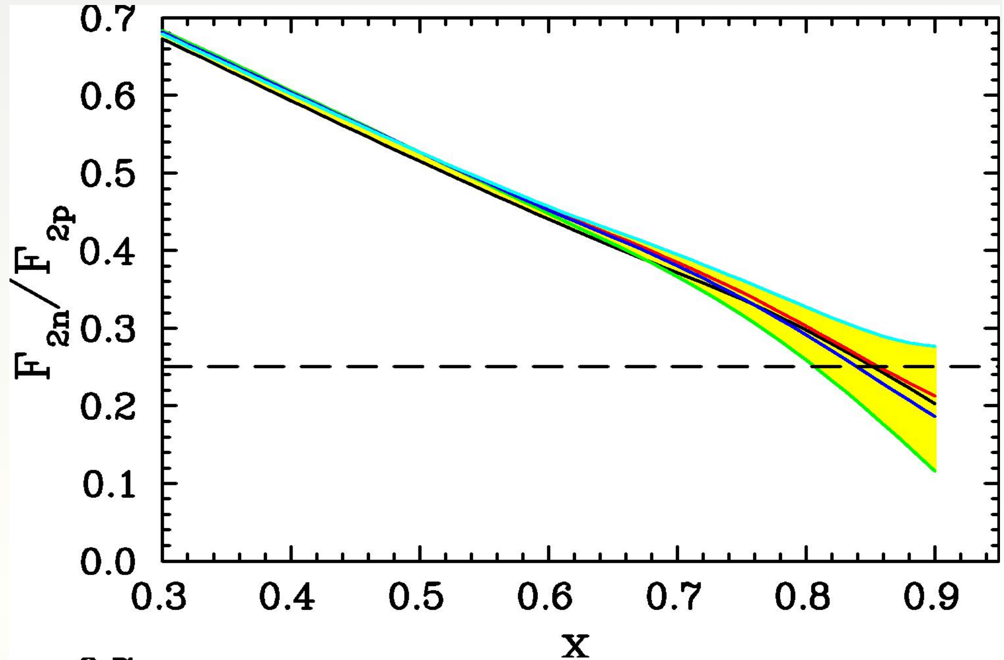


→ using off-shell model, will get *larger* neutron *cf. light-cone* model

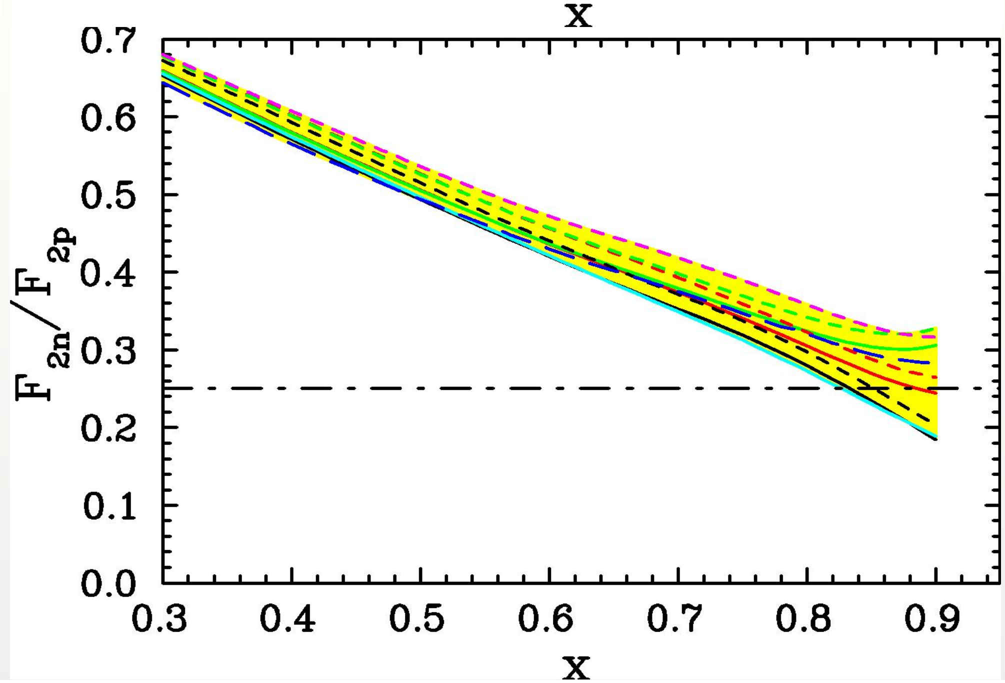
→ but will get *smaller* neutron *cf. no nuclear effects* or *density* model

Specific Model: Relativistic on-shell smearing model of Deuterium (Arrington et al.)



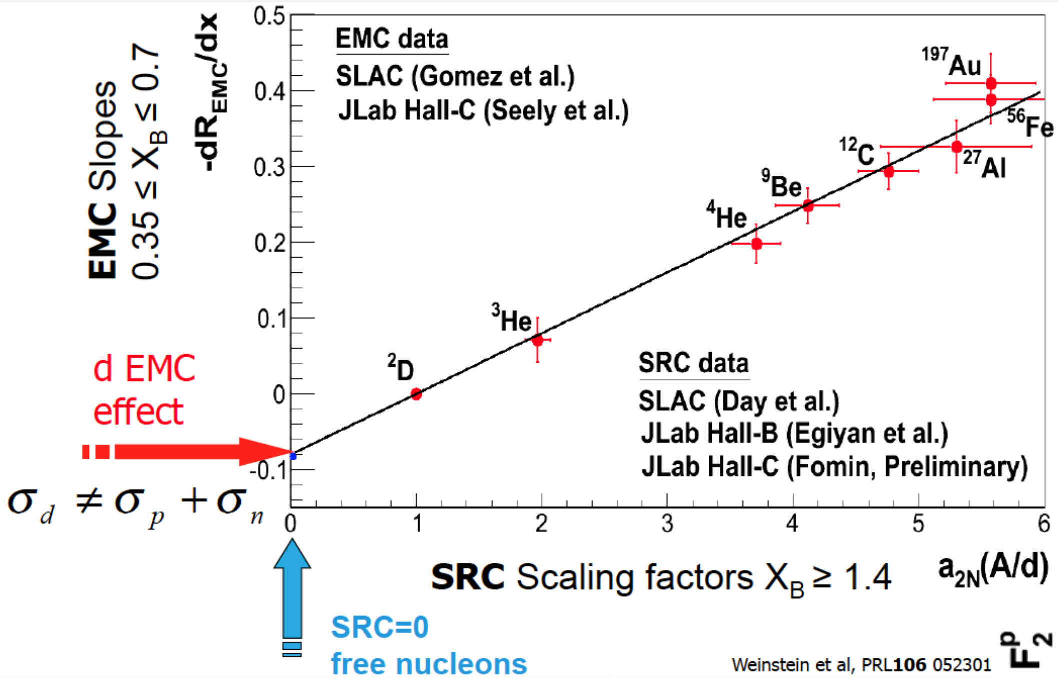


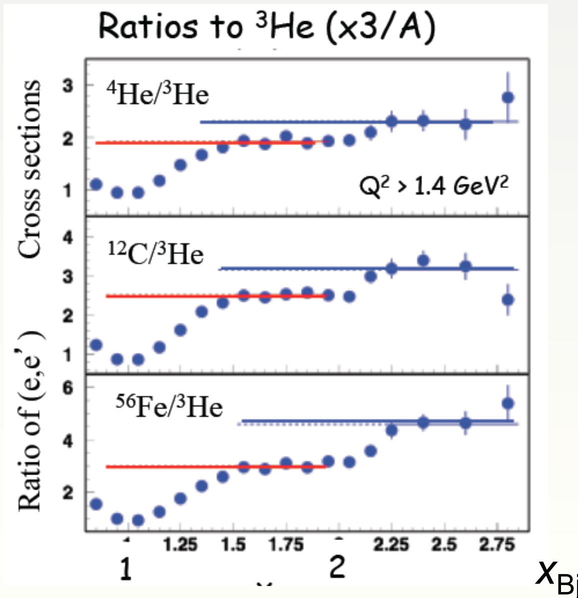
- Use same data, same extraction procedure, but vary N-N potential (top) and nuclear model (bottom)
- Calculate S_p, S_n, using same input F_{2p},F_{2n} and same N-N potential (CD-Bonn)



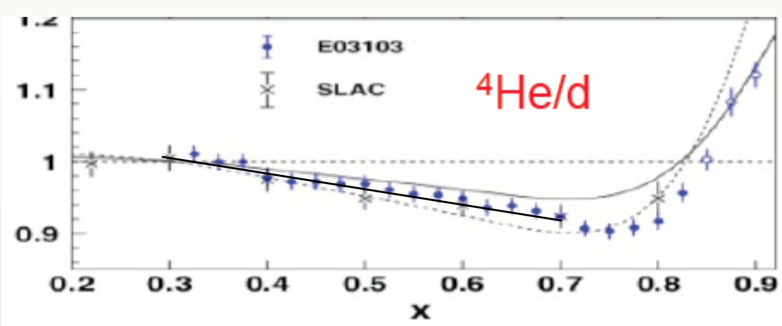
Estimating the EMC effect in Deuterium

L. Weinstein, E.I. Piasetzky, D. Higinbotham, J. Gomez, O. Hen and R. Shneor, PRL106 052301 (2011)

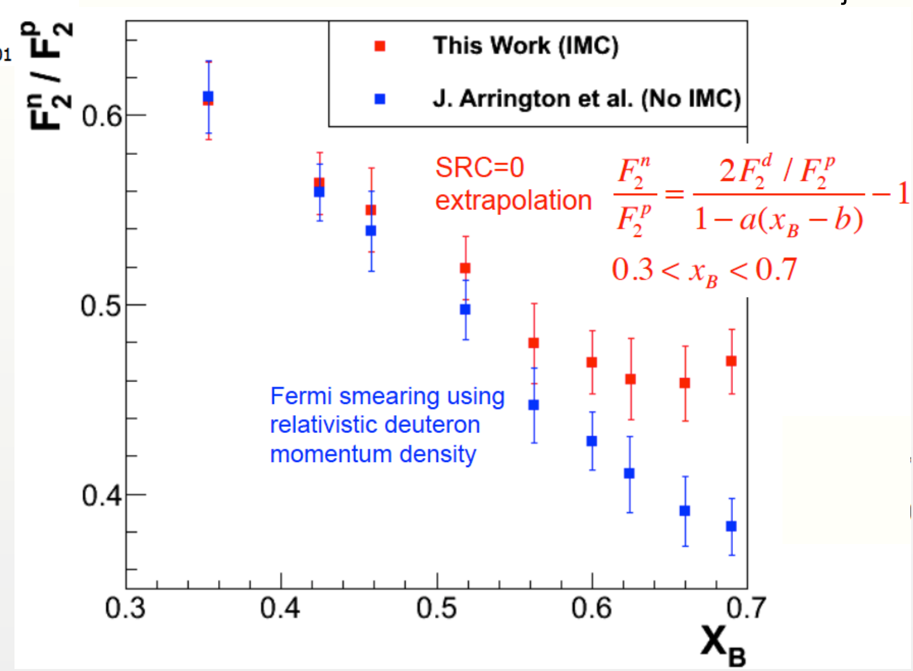




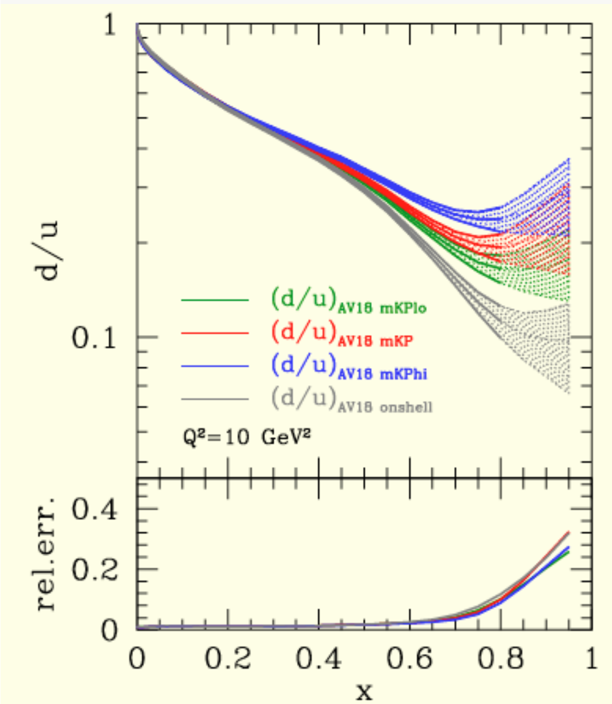
Probability of a nucleon inside the nucleus to be in a "short-range" (tensor) correlation (dominated by pn correlations 10:1)



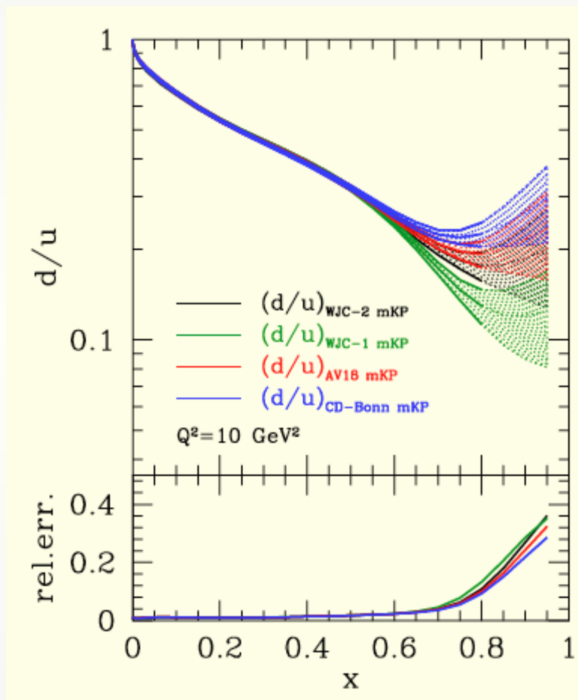
J. Seely, PRL 103, 202301 (2009)



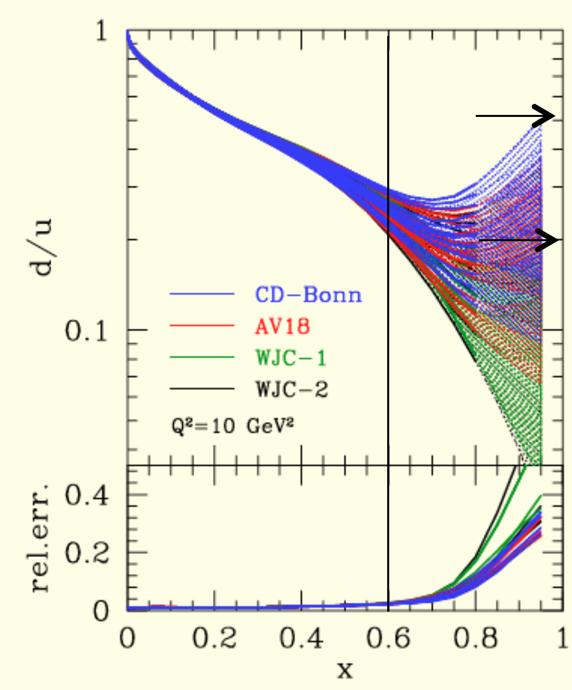
CTEQ6x (CJ) Fit of world data with relaxed cuts, TMC, HT, and various deuteron models



Dependence on off-shell prescription



Dependence on WF



Total (worst case) uncertainty

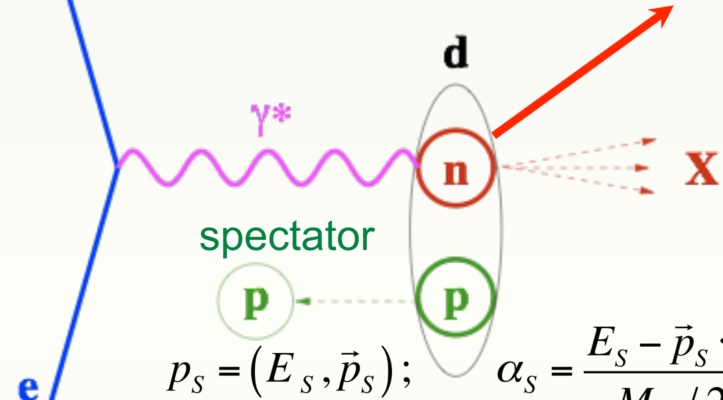
Bound Neutron Structure Functions - 2 Questions:

1) How can we explore the structure of the neutron if all we have are neutrons bound in nuclei?
   - In many cases, a neutron bound in deuterium can be considered “nearly free”.
   - BUT: For certain kinematics (large $x > 0.5$, resonance region $W < 2$) the high-momentum (short-distance tail) of the deuteron wave function plays a large role and might distort the result.

2) Can we learn something about what happens to a nucleon if it is part of a short-distance pair?
   - Many ideas: Off-shell modifications of on-shell structure functions, color delocalization, suppression of point-like components, $\Delta\Delta$ components, extra mesons or 6-quark bags
   - Fundamental question about QCD in bound hadron systems that we haven’t understood yet. Relevant for QCD phase diagram (high baryon density, neutron stars, color superconductivity?)

Spectator Tagging

d(e,e'p$_s$)X

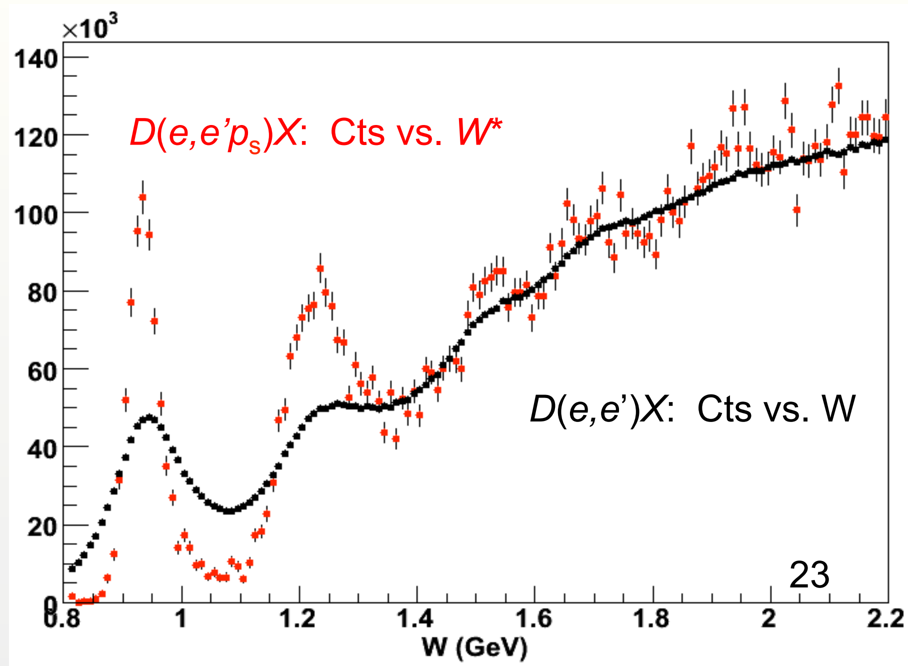


$$p_S = \left(E_S, \vec{p}_S\right); \qquad \alpha_S = \frac{E_S - \vec{p}_S \cdot \hat{q}}{M_D / 2}$$

$$p_n = \left(M_D - E_S, -\vec{p}_S\right); \alpha_n = 2 - \alpha_S \qquad M^{*2} = p_n^{\mu} p_{n\mu}$$

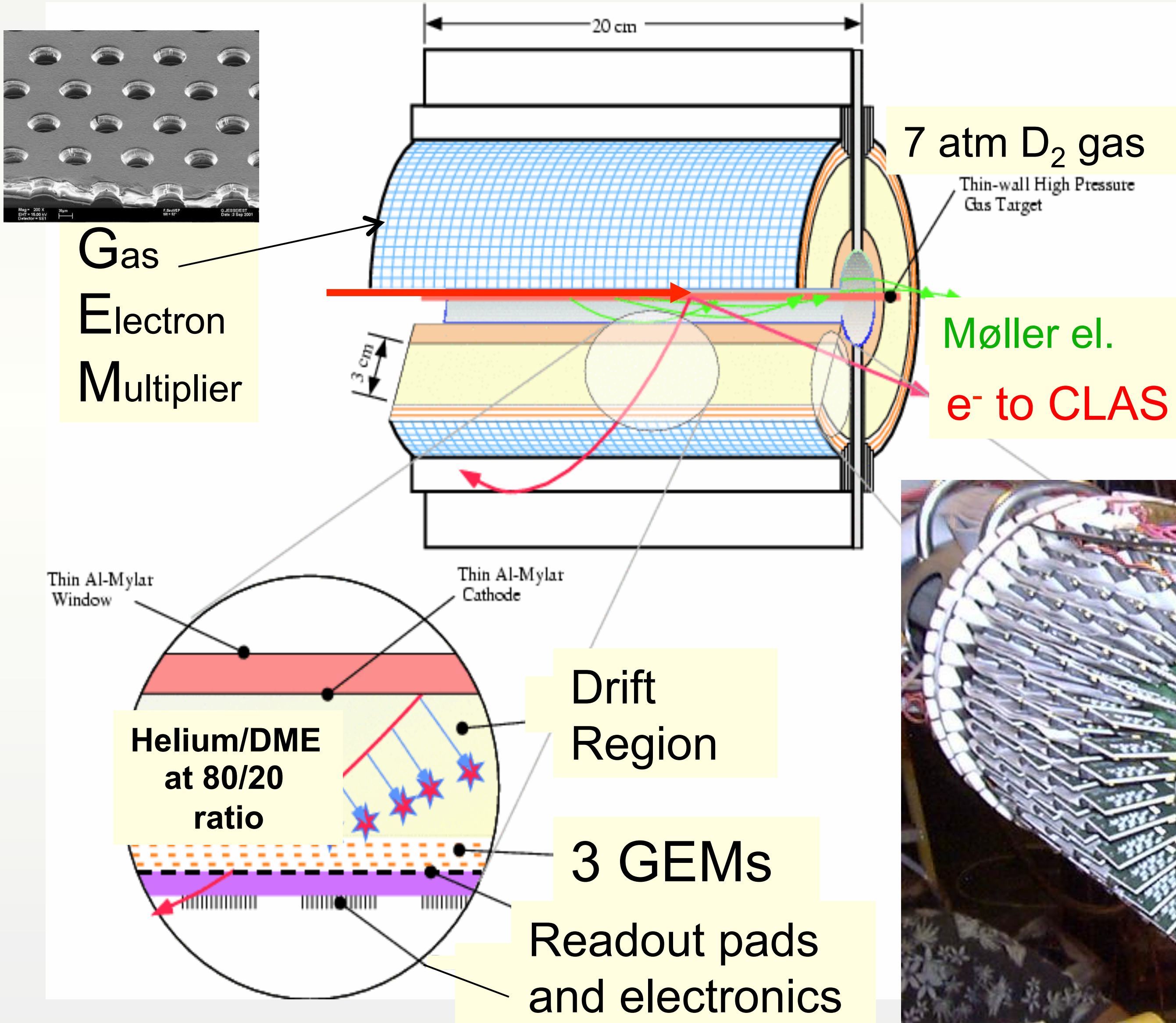
$$\boxed{x = \frac{Q^2}{2 p_n{}^{\mu} q_{\mu}} \approx \frac{Q^2}{2M\nu(2-\alpha_S)}}$$

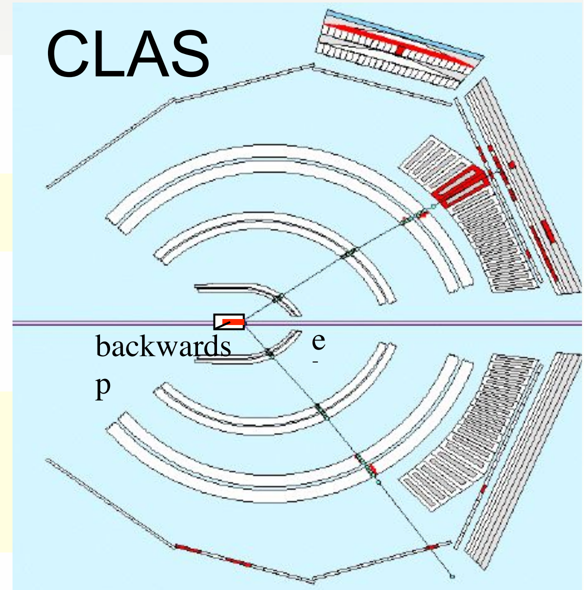
$$\boxed{\begin{aligned} W^{*2} &= \left(p_n + q\right)^2 = M^{*2} + 2\left((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}\right) - Q^2 \\ &\approx M^{*2} + 2M\nu(2-\alpha_s) - Q^2 \end{aligned}}$$

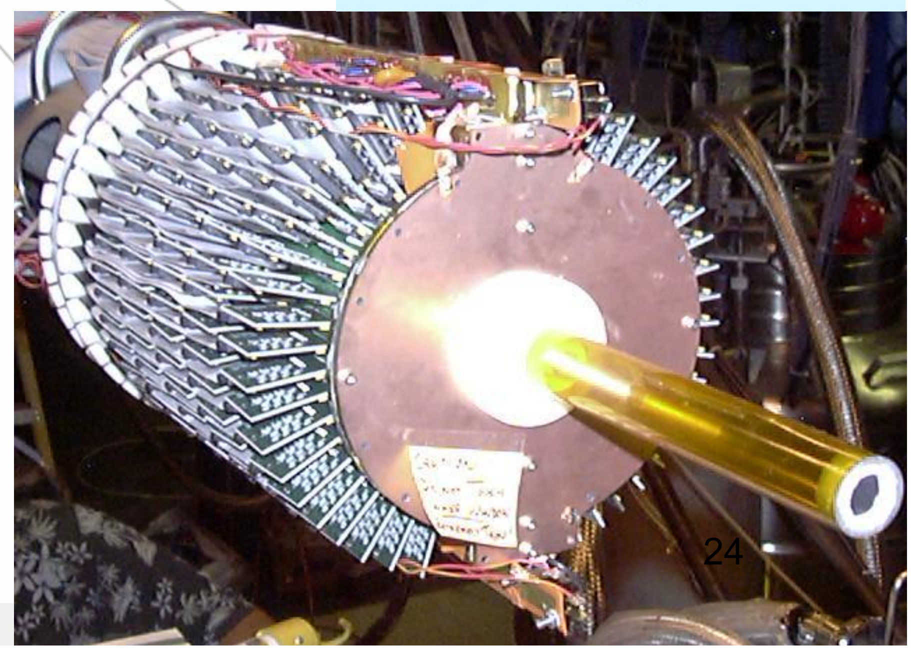


Spectator Tagging

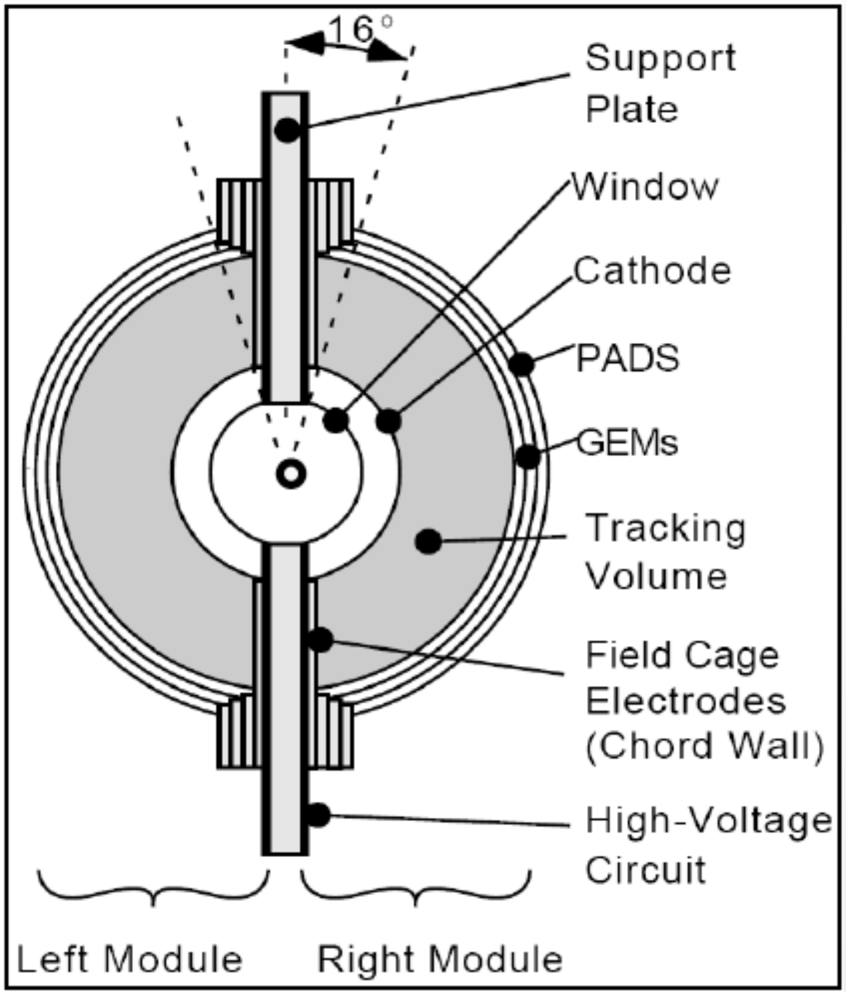
Example: BoNuS

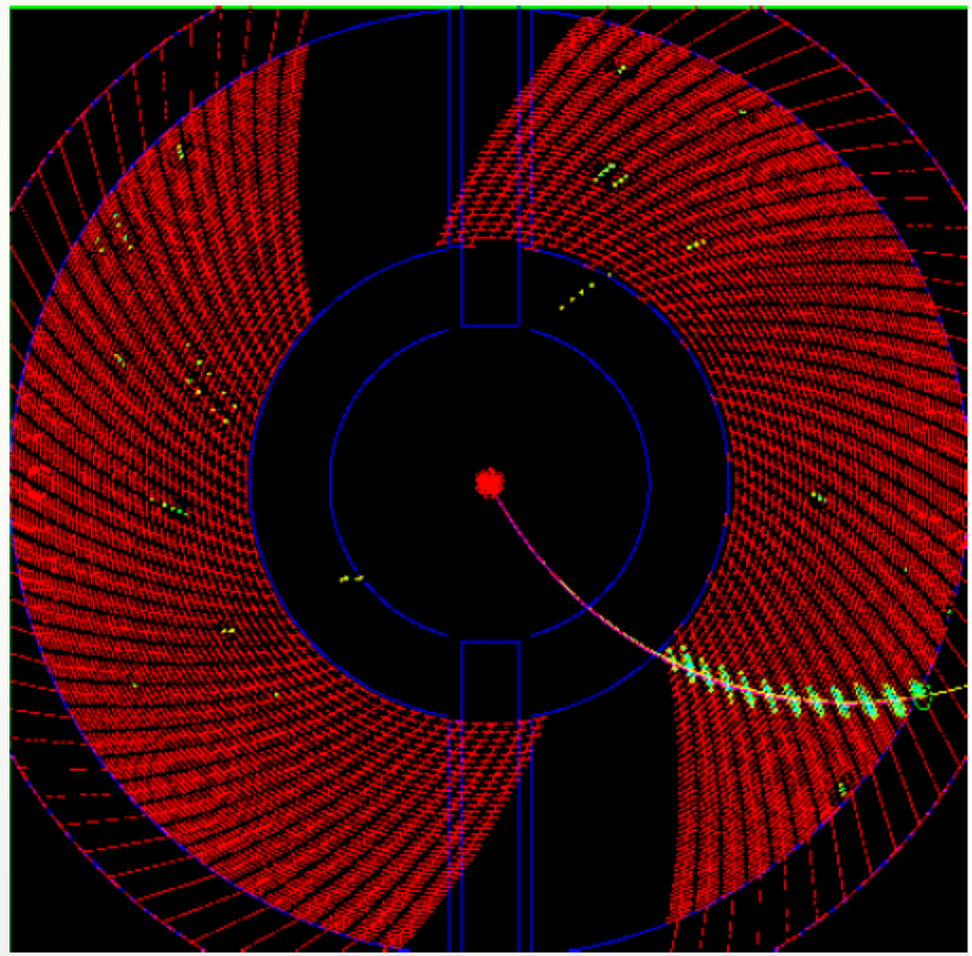




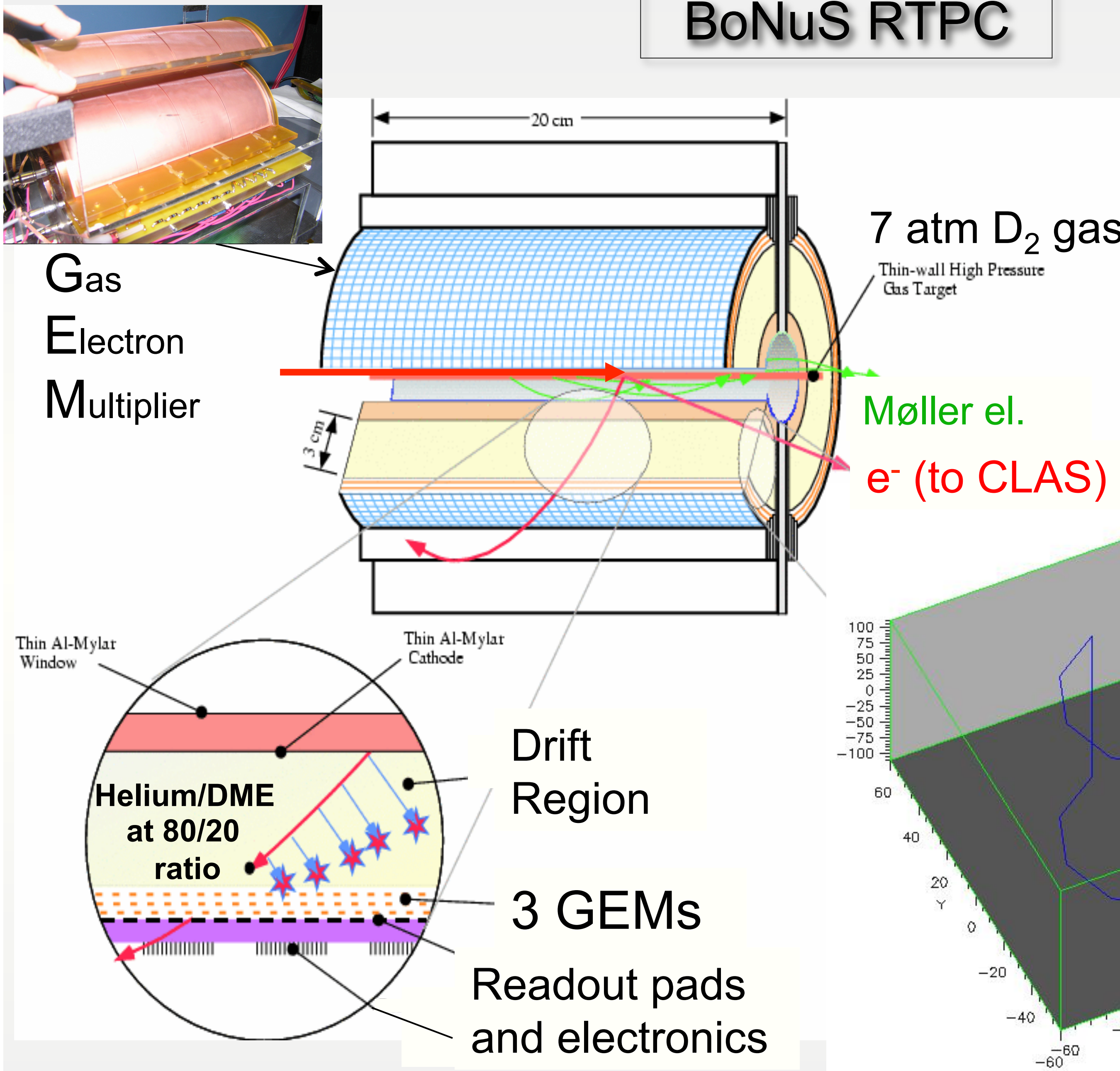


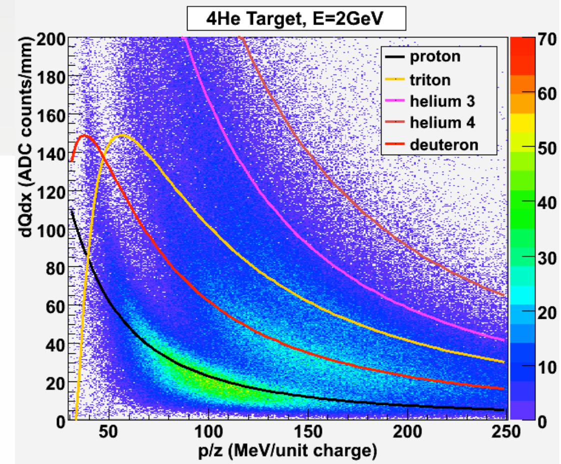
RTPC Cross Section



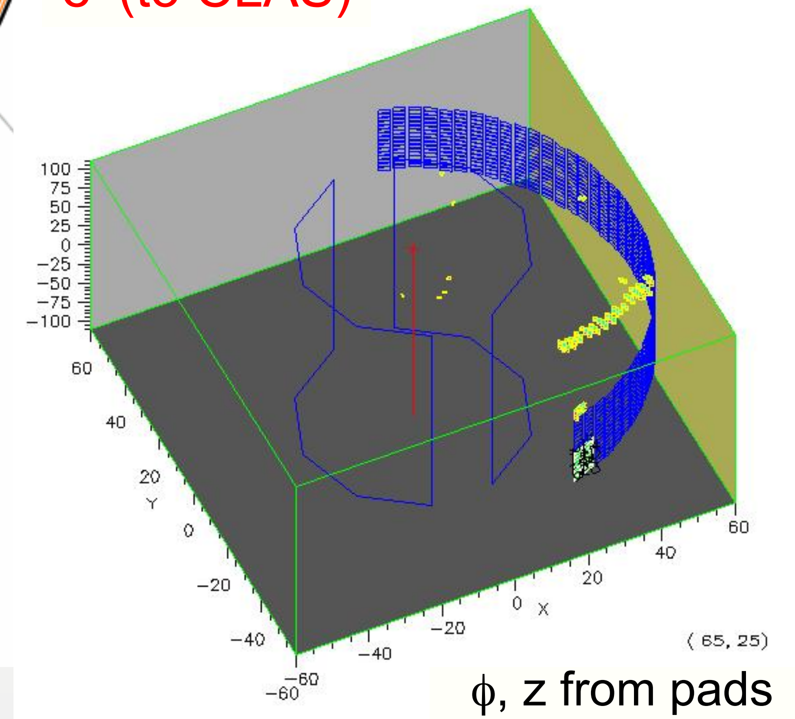


BoNuS RTPC



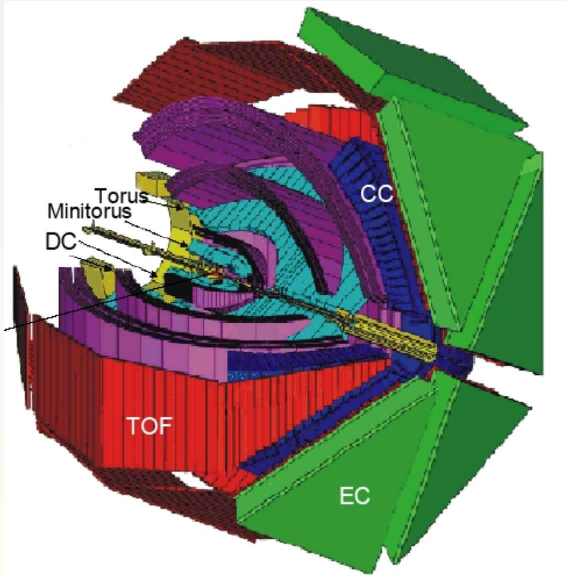


dE/dx from charge along track (particle ID)

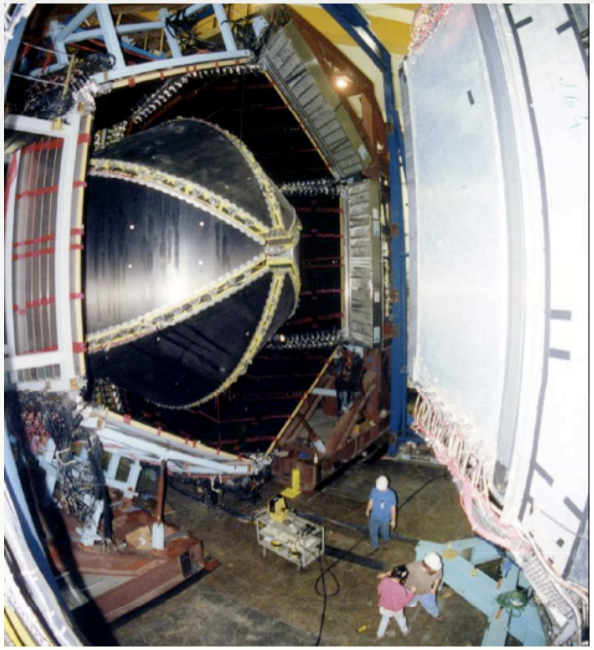


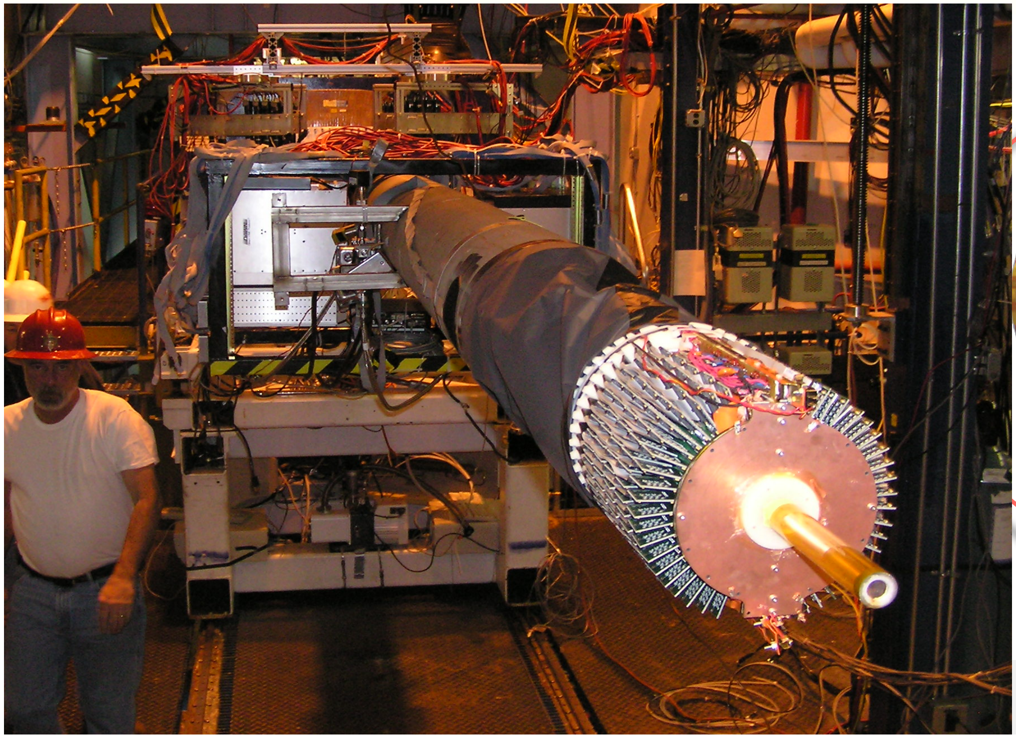
ϕ, z from pads
r from time

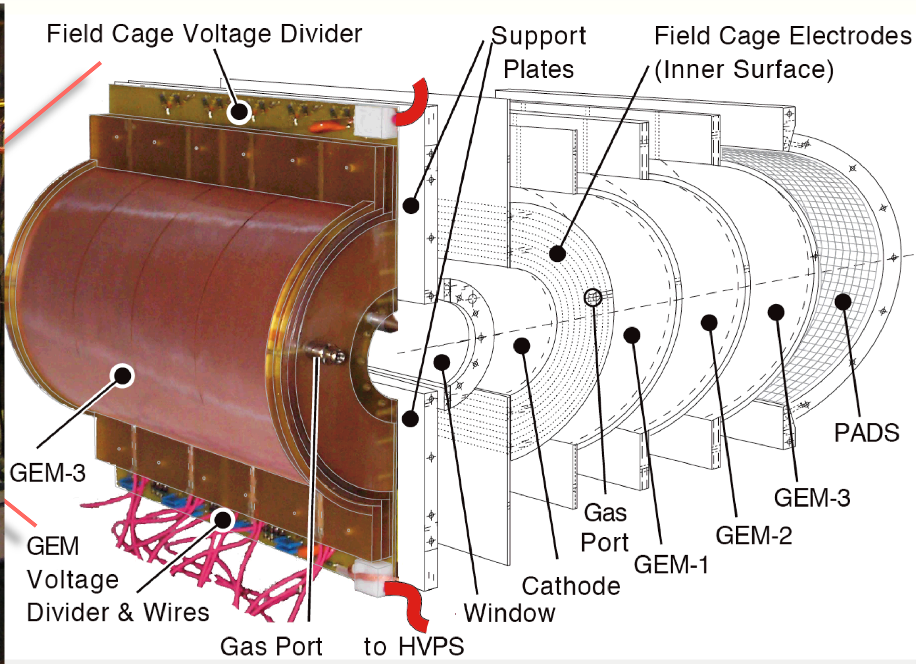
Nucl. Instr. Meth. **A592**, 273 (2008)



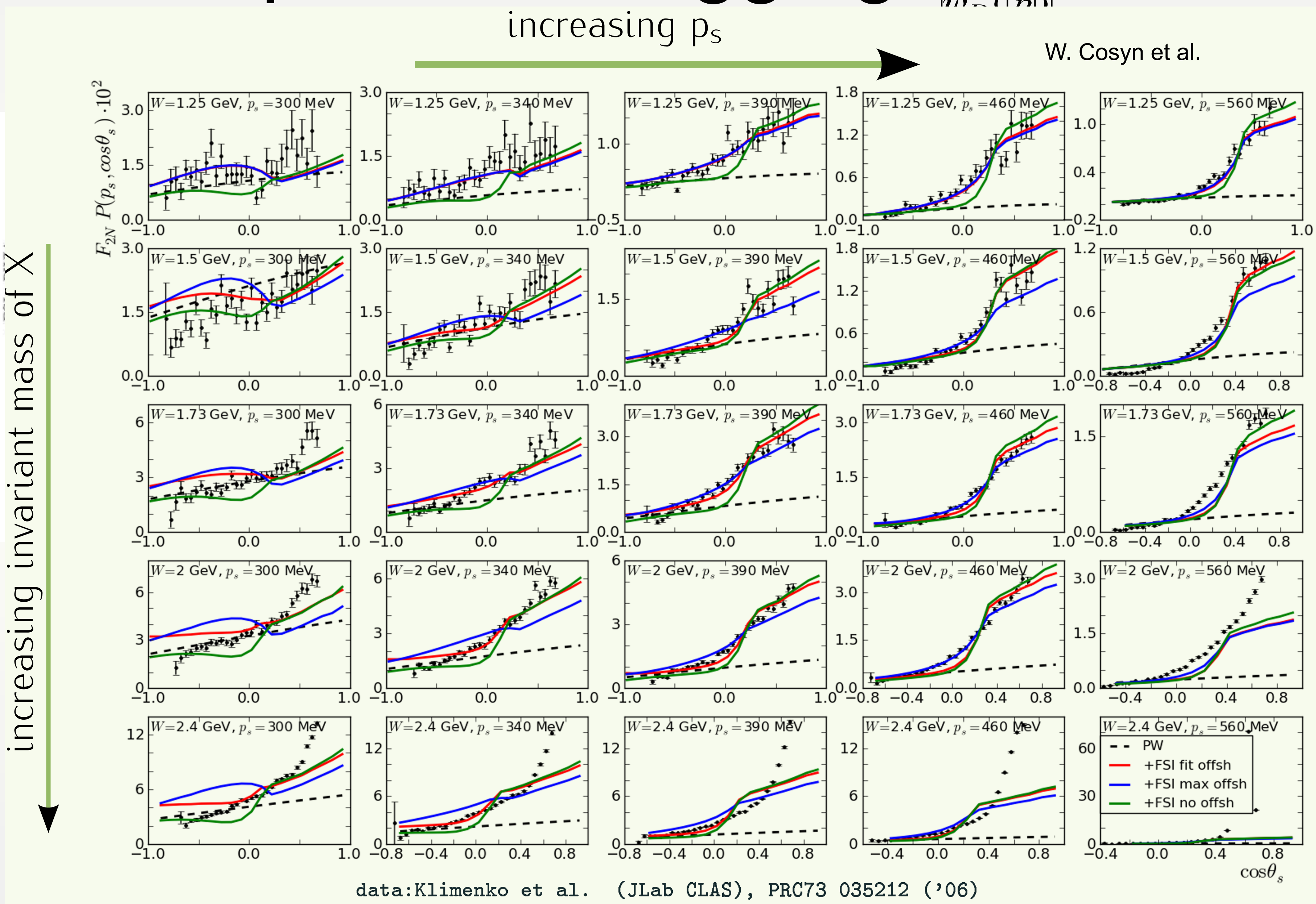
BoNuS in CLAS





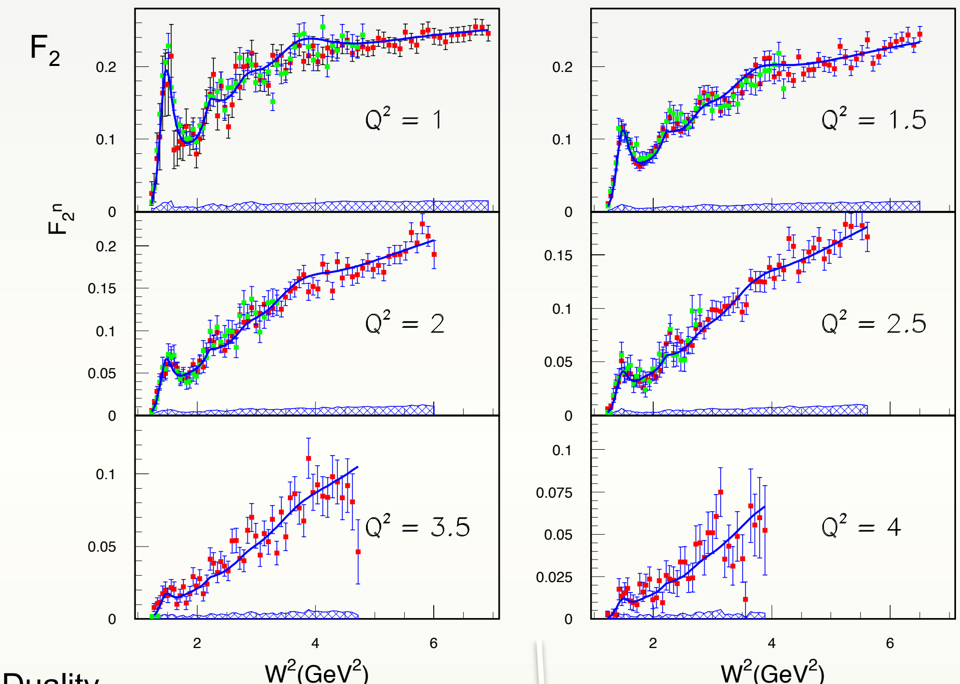


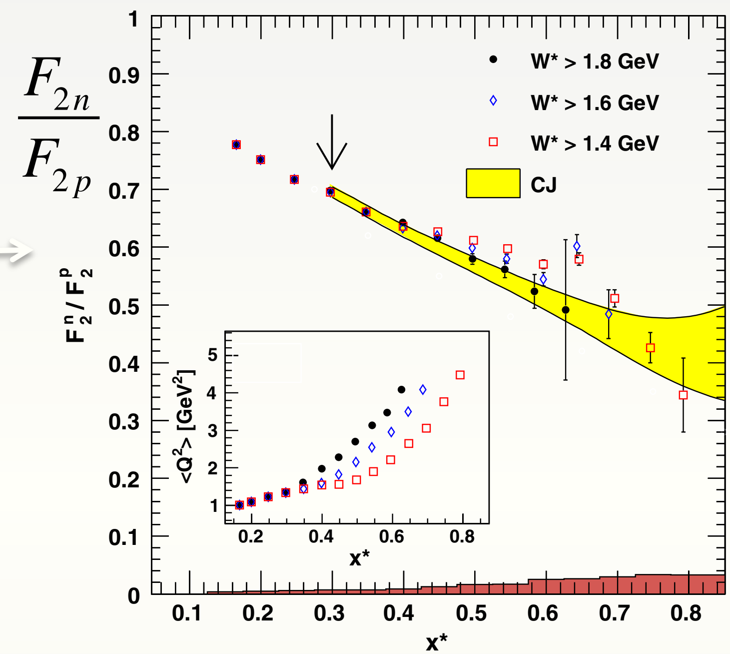
Spectator Tagging



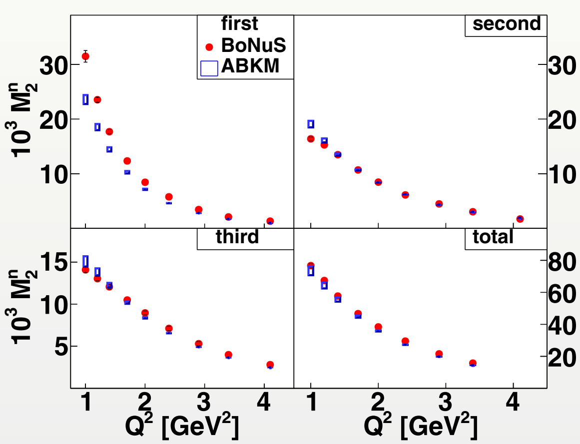
Spectator Tagging

Example: BoNuS - Results

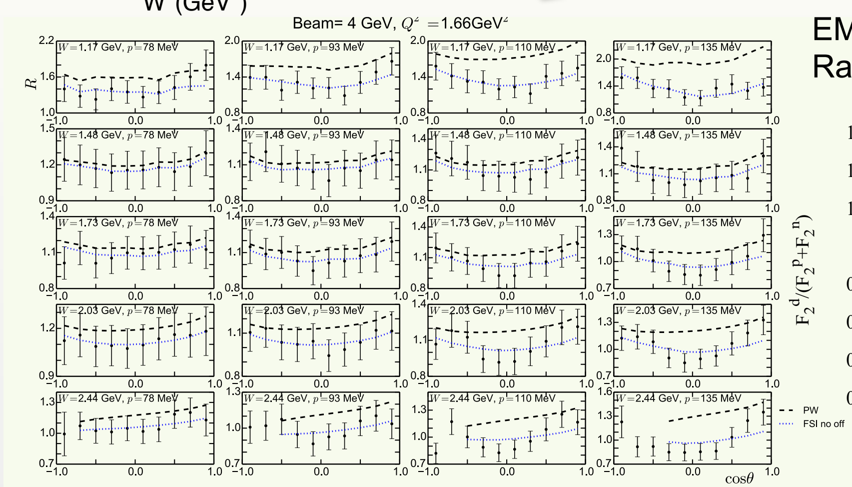




Duality

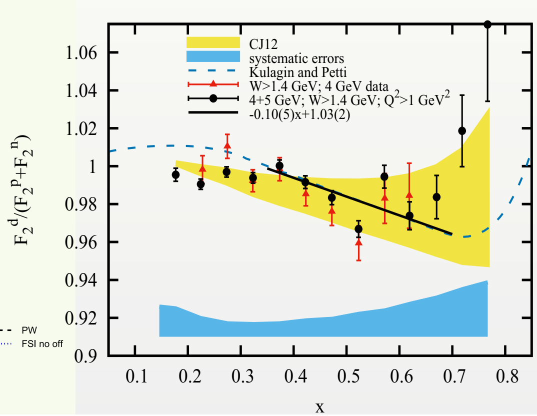


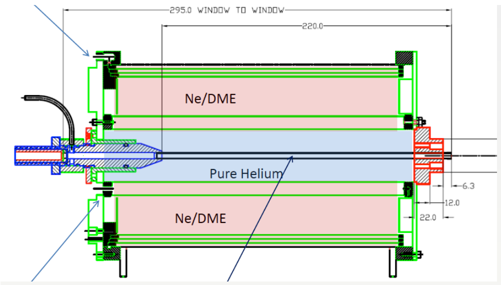
FSI: Cosyn et al.



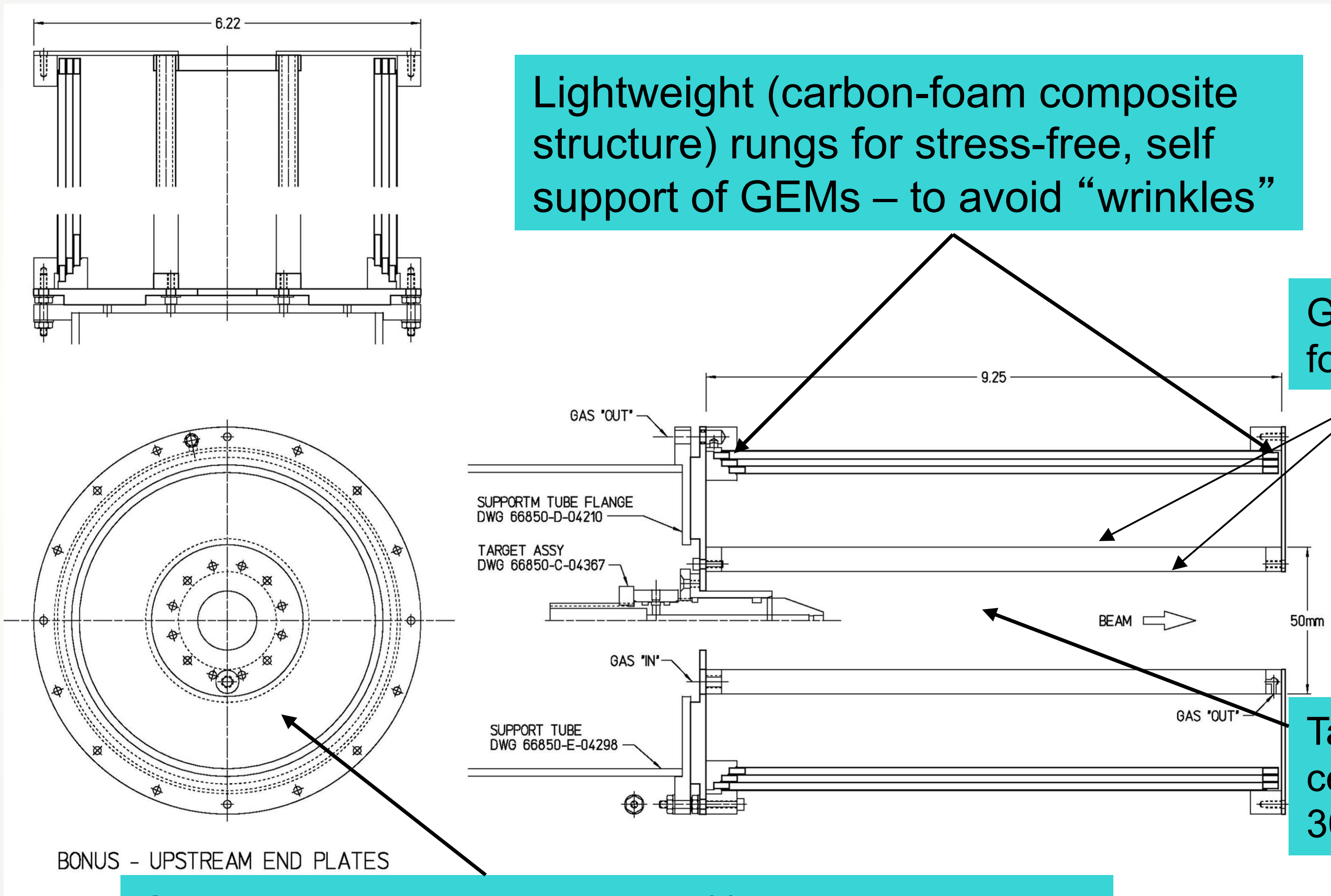
EMC Ratio

PHYSICAL REVIEW C **92**, 015211 (2015)





The 2nd RTPC (EG6)

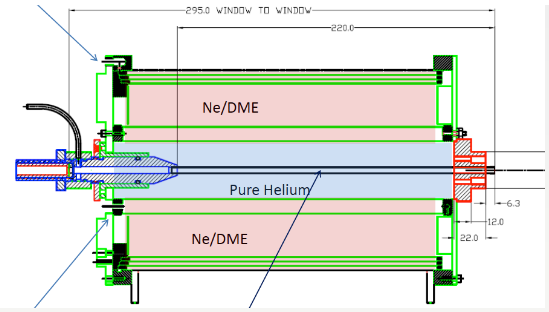


Lightweight (carbon-foam composite structure) rungs for stress-free, self support of GEMs – to avoid "wrinkles"

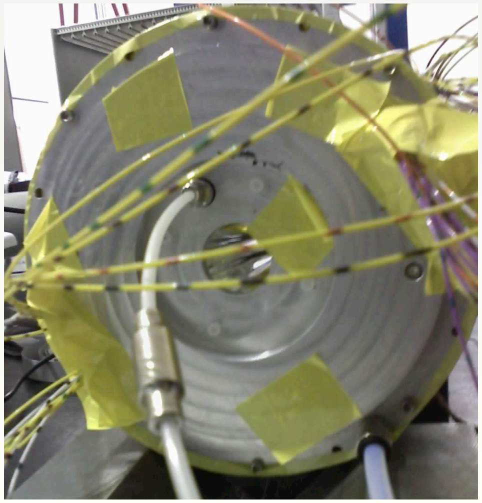
Ground and cathode foils, each 6μm thick

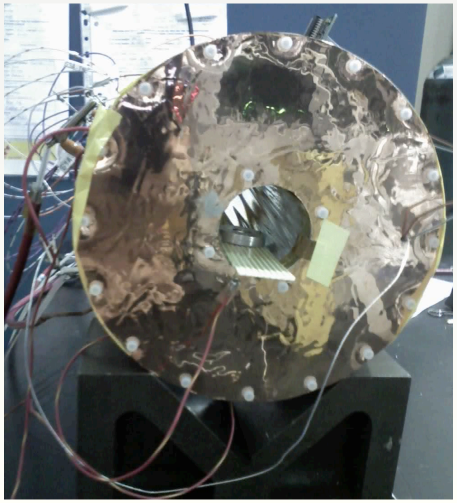
Target region - new cell – ID 4mm, 30μm thick wall

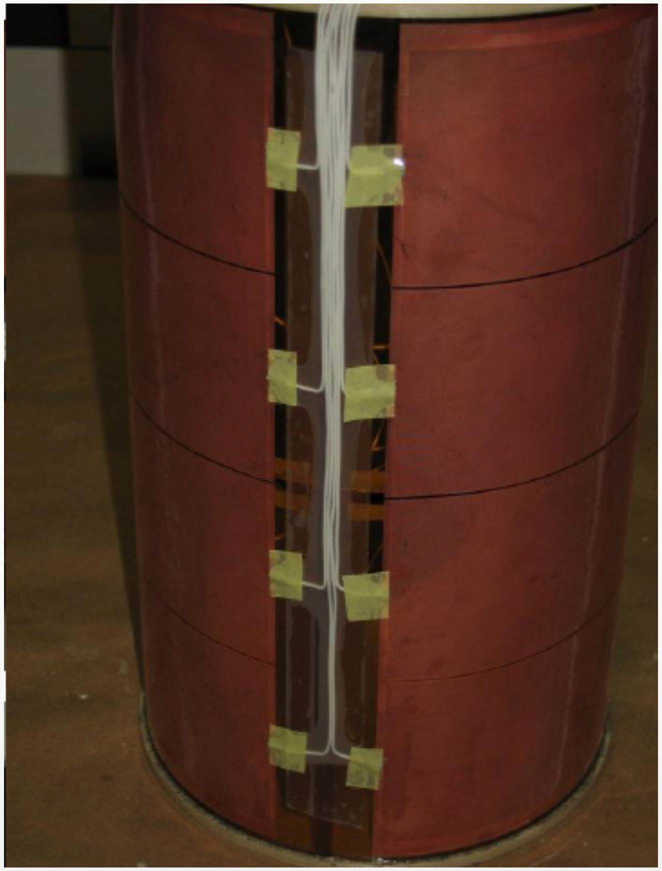
Open, 2π geometry – only 80% were accessible due to the GEM and readout pad sizes

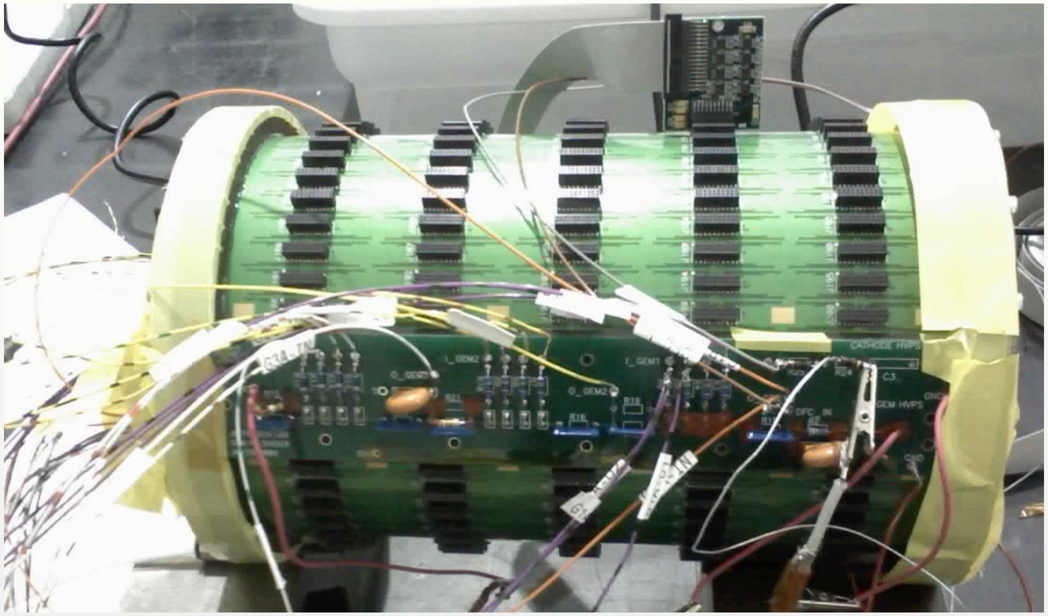


The New RTPC (ii)

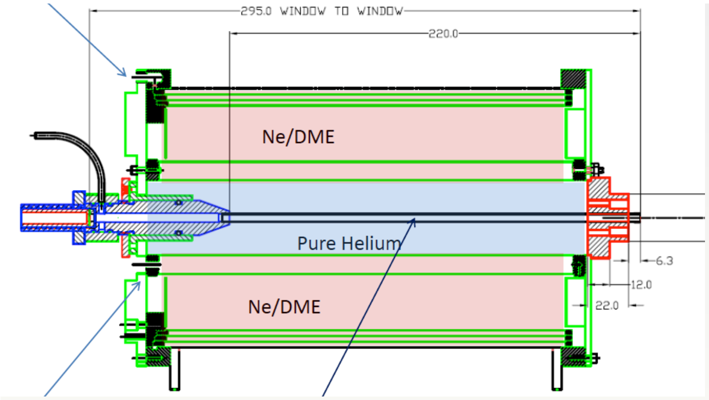




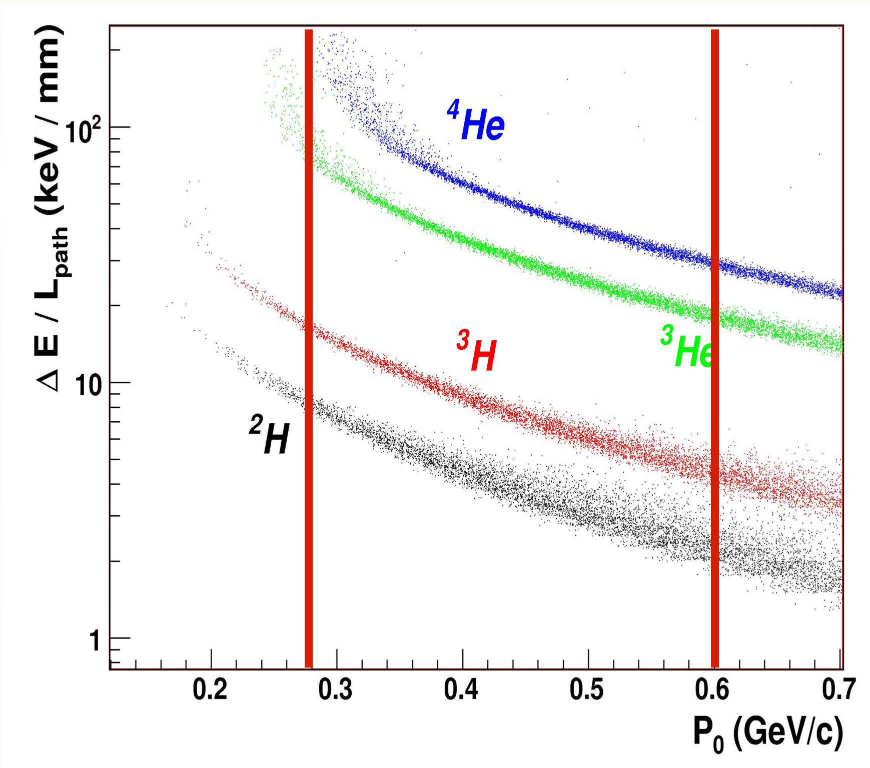




The New RTPC (iii)



Expected PID with fully calibrated RTPC



Better gain uniformity – better PID:

- new GEM foils
- stress free support
- calibration system (α-source and elastic scattering)

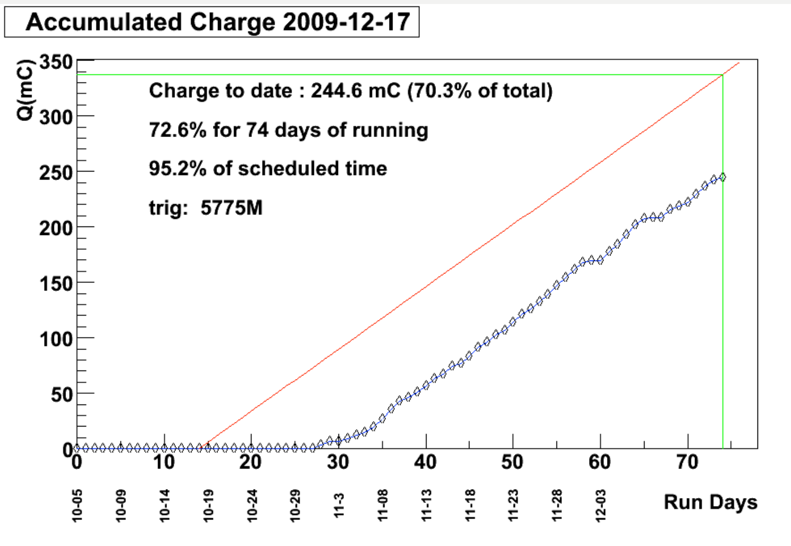
Lower momentum threshold (250 MeV for α's)

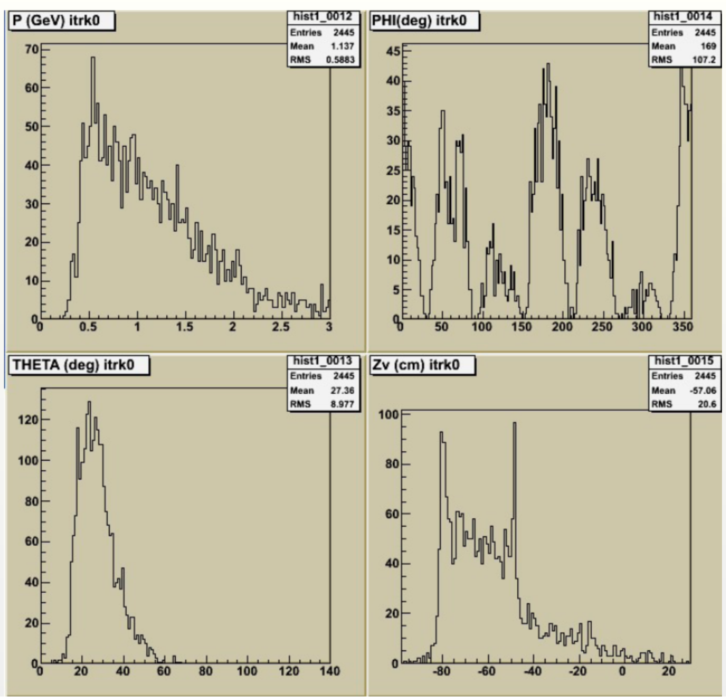
- thinner target walls

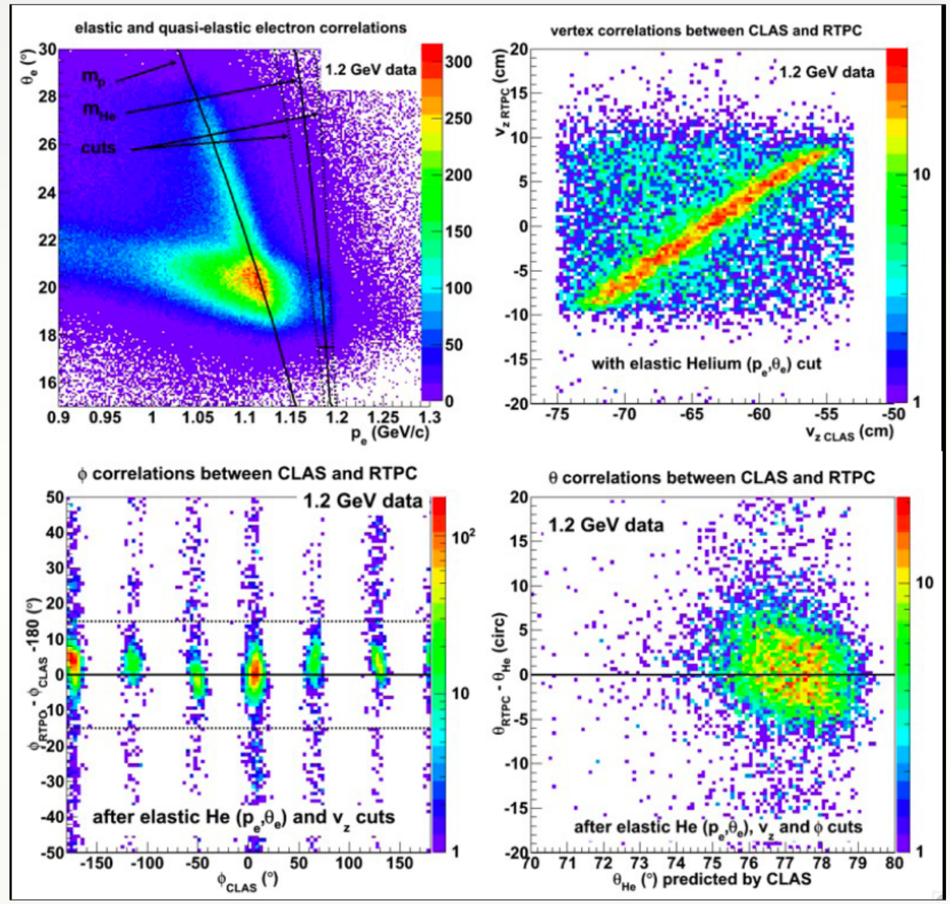
New Drift Gas NE-TME

- higher density, but similar speed
- larger signal

2nd RTPC Experiment - EG6







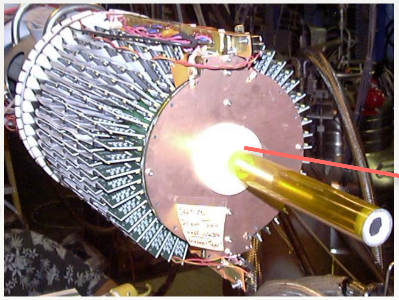
Detector calibration, 1st step analysis under way

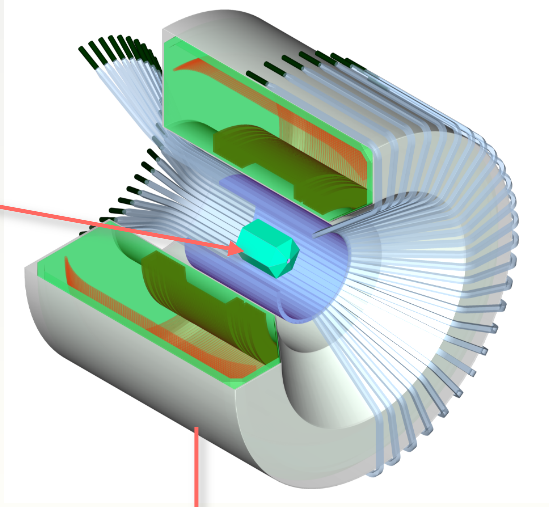
1st results maybe in 1 year

Plans for 12 (really: 11) GeV

BoNuS12

E12-06-113

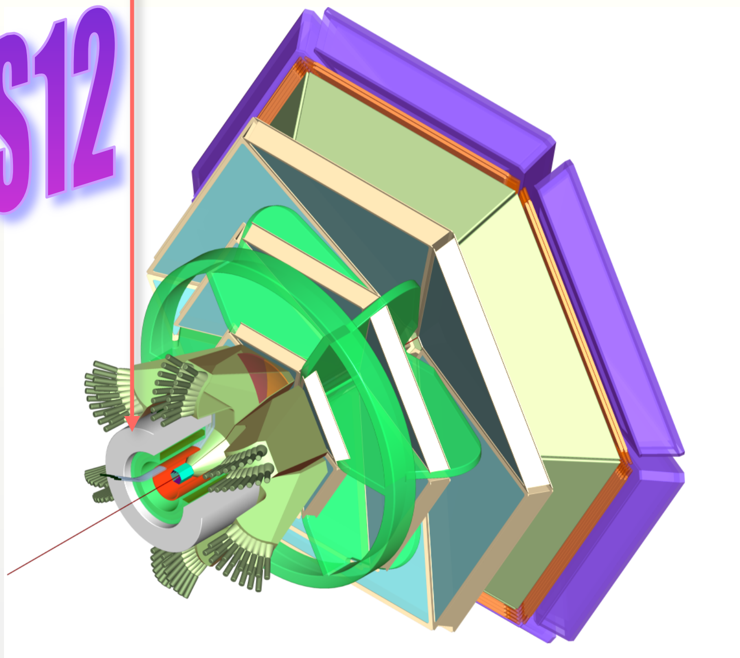




Central Detector

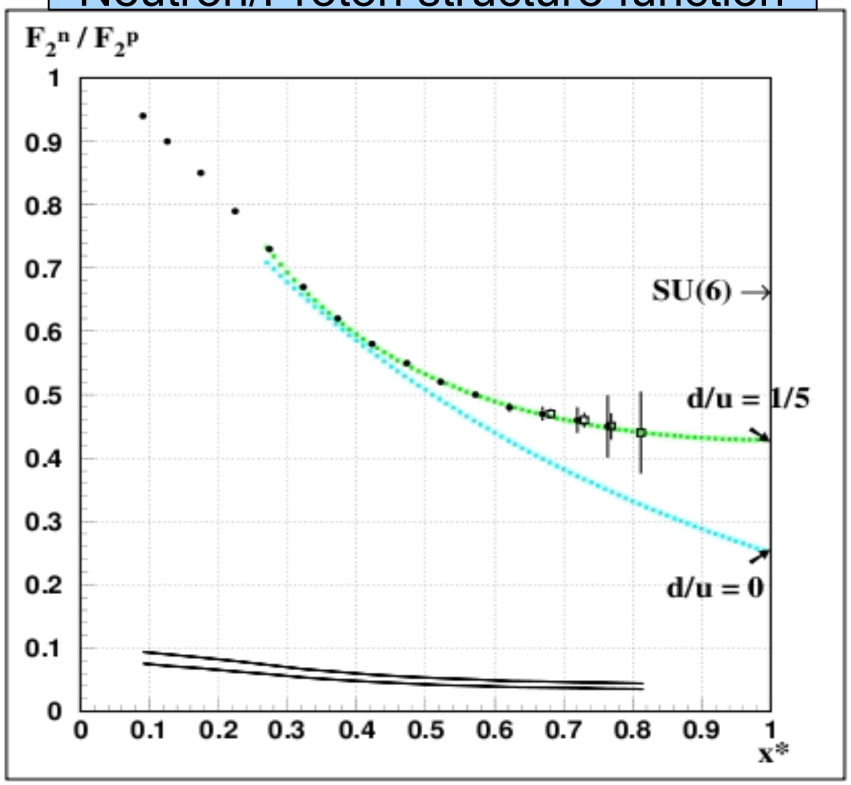
- Data taking of 35 days on D_2 and 5 days on H_2 with $\mathcal{L} = 2 \cdot 10^{34}$ cm^{-2} sec^{-1}
- **Planned** BoNuS detector DAQ and trigger **upgrade**
- DIS region with
  - $Q^2 > 1$ GeV$^2/c^2$
  - $W^* > 2$ GeV
  - $p_s > 70$ MeV/c
  - $10° < \theta_{pq} < 170°$
- Extend to higher momenta using central detector alone

CLAS12

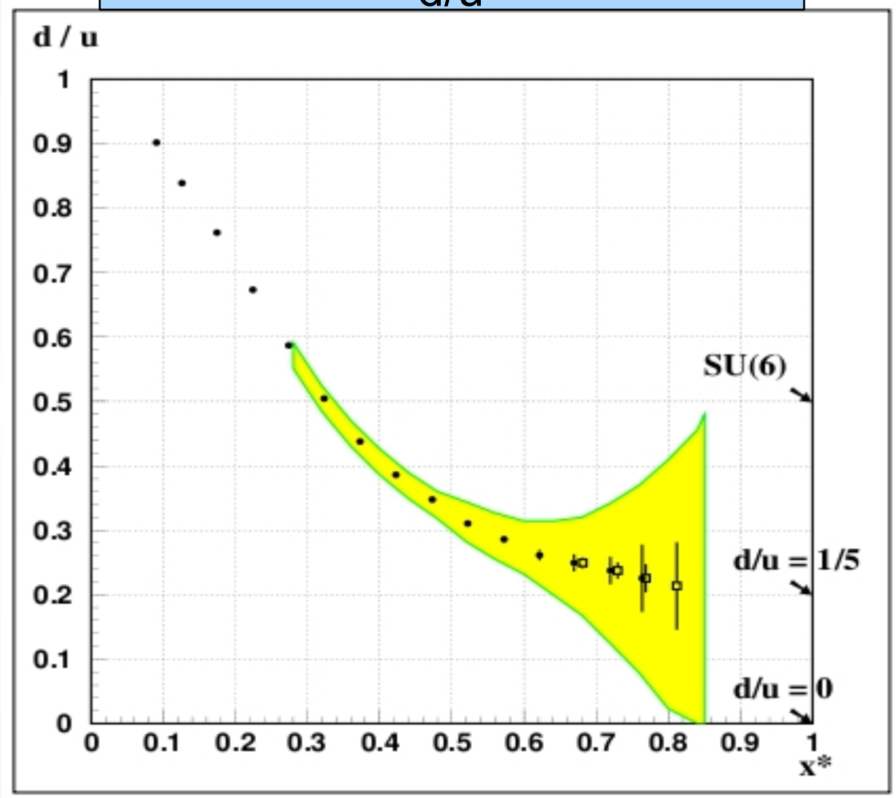


Expected Results

Neutron/Proton structure function



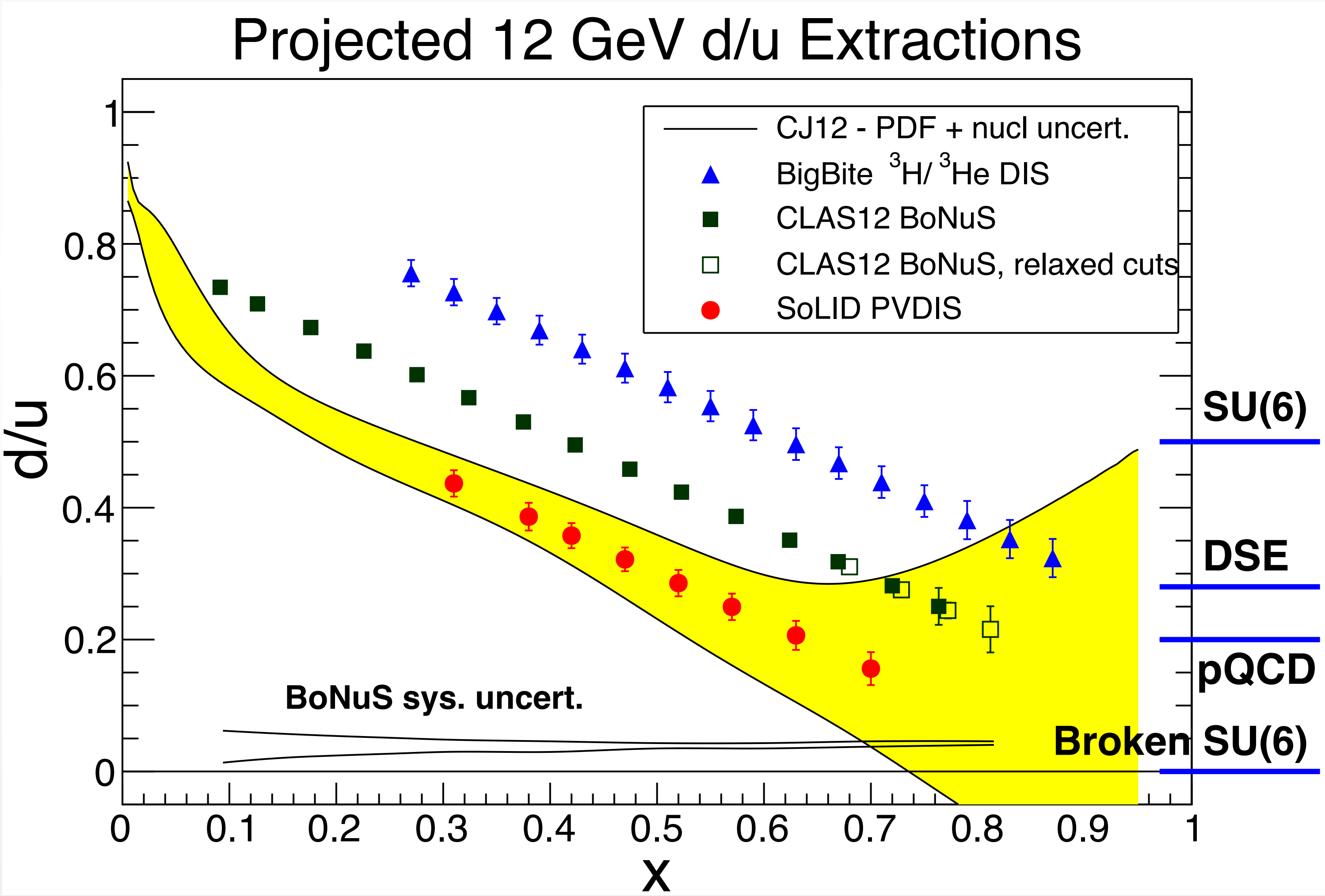
d/u



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)

The future: JLab at 11 GeV



Backup Slides

Simple (Constituent) Quark Model

Flavor	Isospin I	I_3	Strangeness S	Charge Q	Baryon Number B
U	$1/2$	$+1/2$	0	$+2/3$	$1/3$
D	$1/2$	$-1/2$	0	$-1/3$	$1/3$
S	0	0	-1	$-1/3$	$1/3$

$$|\Delta^{++}\uparrow\rangle = |U\uparrow U\uparrow U\uparrow\rangle$$

$$|\Delta^{+}\uparrow\rangle = 1/\sqrt{3}\,(|U\uparrow U\uparrow D\uparrow\rangle + |U\uparrow D\uparrow U\uparrow\rangle + |D\uparrow U\uparrow U\uparrow\rangle)$$

The case of the proton is a bit more complicated, since the wave function cannot be symmetric in spin and flavor separately. The most intuitive way to derive the proton wave function is by observing that 2 of the 3 quarks are equal (U), and therefore their relative spin wave function should be symmetric also. This leads to the conclusion that the two U–quarks couple their spins to a total spin of one. Let's denote the case where this spin has a z-projection of $+1$ as $(UU\Uparrow) := |U\uparrow U\uparrow\rangle$, while the projection with $S_z = 0$ will be indicated by $(UU\Rightarrow) := 1/\sqrt{2}\,(|U\uparrow U\downarrow\rangle + |U\downarrow U\uparrow\rangle)$. We can now combine the spin $1/2$ of the remaining D quark with the spin 1 of the UU pair in two ways to get total spin and projection $1/2$; the proper way follows simply from insertion of the correct Clebsch-Gordon coefficients:

$$|P\uparrow\rangle = 1/\sqrt{3}\left(\sqrt{2}|(UU\Uparrow)D\downarrow\rangle - |(UU\Rightarrow)D\uparrow\rangle\right). \tag{2}$$

Quark Model:

- SU(6)-symmetric wave function of the proton in the quark model:

$$\left| p\uparrow \right\rangle = \frac{1}{\sqrt{18}}\left(3u\uparrow\left[ud\right]_{S=0} + u\uparrow\left[ud\right]_{S=1} - \sqrt{2}u\downarrow\left[ud\right]_{S=1} - \sqrt{2}d\uparrow\left[uu\right]_{S=1} - 2d\downarrow\left[uu\right]_{S=1}\right)$$

- In this model: d/u = 1/2, Δu/u = 2/3, Δd/d = -1/3 for all x
  => A_{1p} = 5/9, A_{1n} = 0, A_{1D} = 1/3 *)

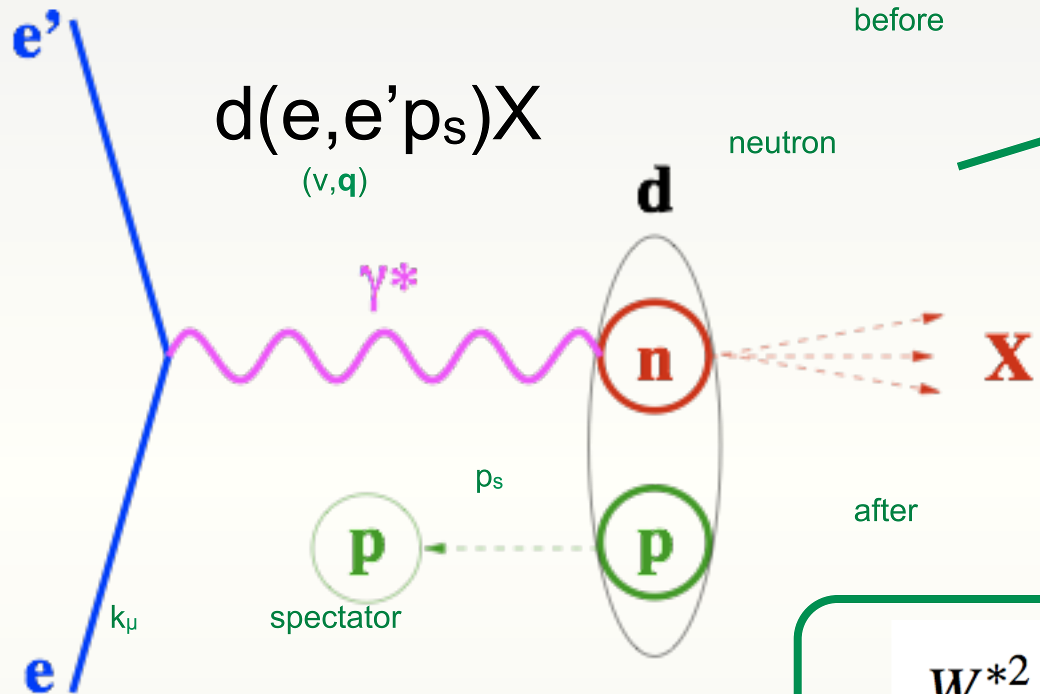
- Hyperfine structure effect: S=1 suppressed => d/u = 0, Δu/u = 1, Δd/d = -1/3
  for x -> 1 => A_{1p} = 1, A_{1n} = 1, A_{1D} = 1

- pQCD: helicity conservation (q↑↑p) => d/u =2/(9+1) = 1/5, Δu/u = 1, Δd/d = 1
  for x -> 1

- Wave function of the neutron via isospin rotation:
  replace u -> d and d -> u => using experiments with protons and neutrons one can extract information on u, d, Δu and Δd in the valence quark region.

*) $$A_{1p} = \frac{4/9 \cdot u \cdot \Delta u/u + 1/9 \cdot d \cdot \Delta d/d}{4/9 \cdot u + 1/9 \cdot d} = \frac{4 \cdot \Delta u/u + \left(d/u\right) \cdot \Delta d/d}{4 + \left(d/u\right)}$$

$d(e,e'p_s)X$



$$p_N^\mu = (M_d - E_s, -\vec{p}_s)$$

$$E_p + E_n = M_d$$

$$E^* = M_d - \sqrt{M_s^2 + p_s^2}$$

$$M^{*2} = (M_d - E_s)^2 - \vec{p}_s^{\,2}$$

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

$$\alpha_s = \frac{E_s - p_{s_{||}}}{M_s}$$

$$x^* = \frac{Q^2}{2p_N^\mu q^\mu} \approx \frac{Q^2}{2M\nu(2-\alpha_s)} = \frac{x}{2-\alpha_s}$$

- plane-wave impulse approximation
- backward-emitted p is spectator
- struck neutron is off-shell
- momenta are equal and opposite
- Lorentz invariants are corrected for initial neutron 4-momentum

PWIA Spectator Formalism

Cross Section

$$\frac{d\sigma}{dx^* dQ^2} = \frac{4\pi\alpha_{\mathrm{EM}}^2}{x^* Q^4}\left[\frac{y^{2}}{2(1+R)} + (1-y) + \frac{M^{*2}x^{*2}y^{2}}{Q^2}\frac{1-R}{1+R}\right] F_2(x^*, \alpha_s, p_T, Q^2) \times S(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s} d^2 p_T ,$$

Off-Shell F_2

$R=\sigma_L/\sigma_T$

Light Cone

Spectral Function

Nonrelativistic w.f.

$$P(\vec{p}_s) = J\,|\psi_{\mathrm{NR}}(p_s)|^2$$

$$J = 1 + \frac{p_{s_{||}}}{E_n^*} = \frac{(2-\alpha_s)M_d}{2(M_d - E_s)}$$

$$S(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s} d^2 p_T = P(\vec{p}_s) d^3 p_s$$

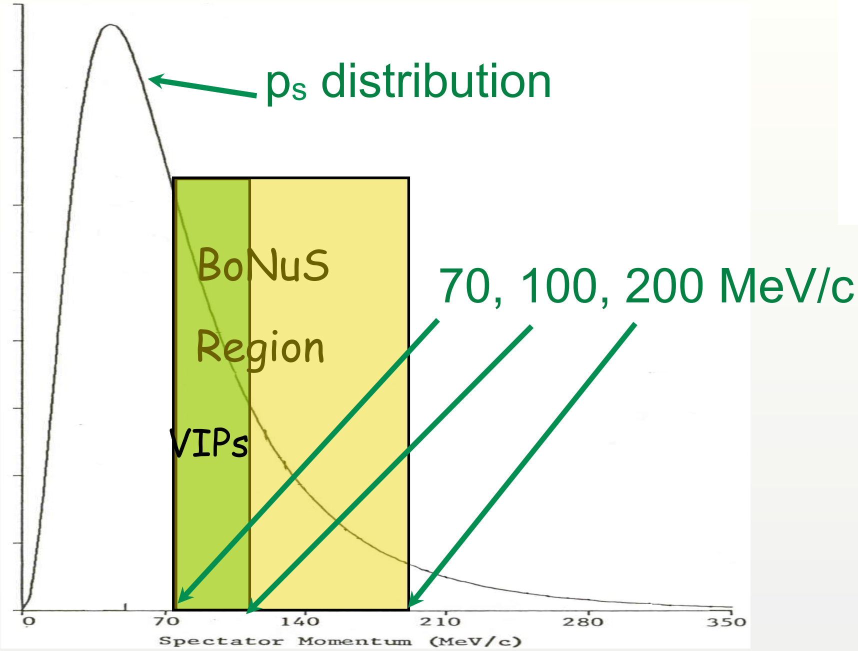
$$S^{\mathrm{LC}}(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s} d^2 p_T = |\psi_{\mathrm{NR}}(|\vec{k}|^2)|^2 d^3 k$$

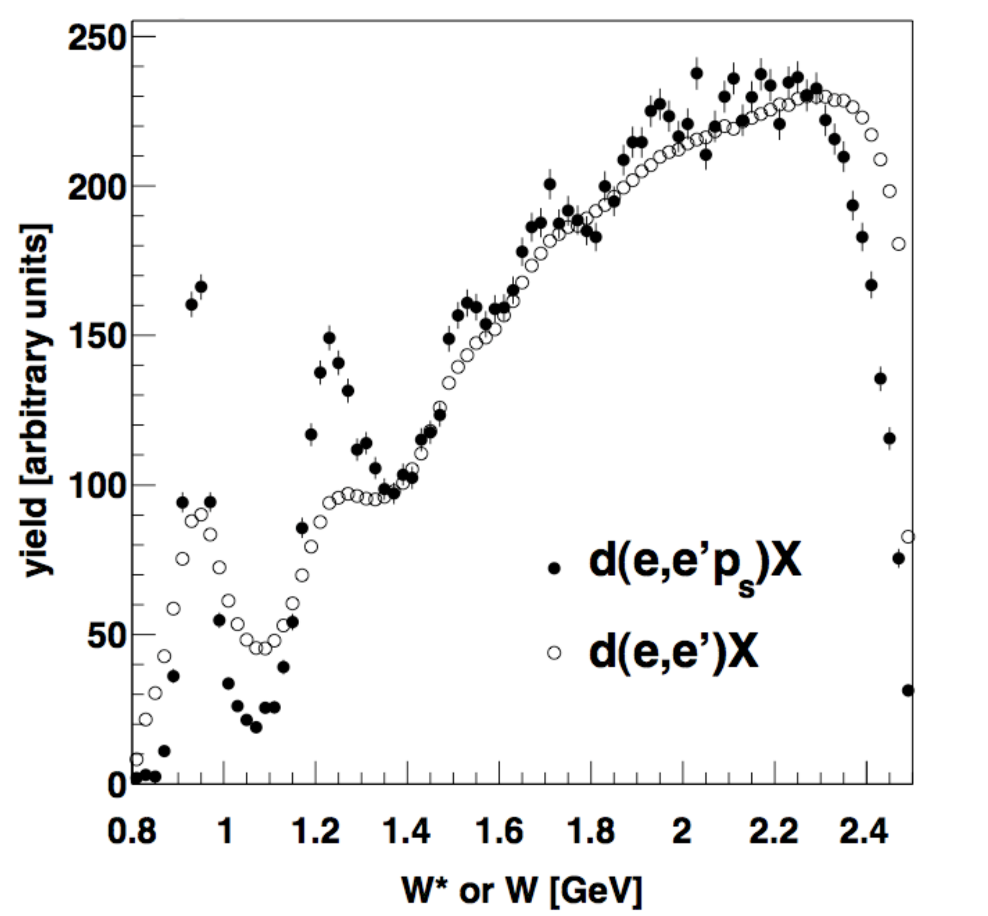
$$|\vec{k}| = \sqrt{\frac{M^2 + p_T^2}{\alpha_s(2-\alpha_s)} - M^2} \qquad \alpha_s = 1 - \frac{k_{||}}{\sqrt{M^2 + \vec{k}^2}}$$

$$k_0 = \sqrt{M^2 + \vec{k}^2} \qquad \vec{p}_T = \vec{k}_T$$

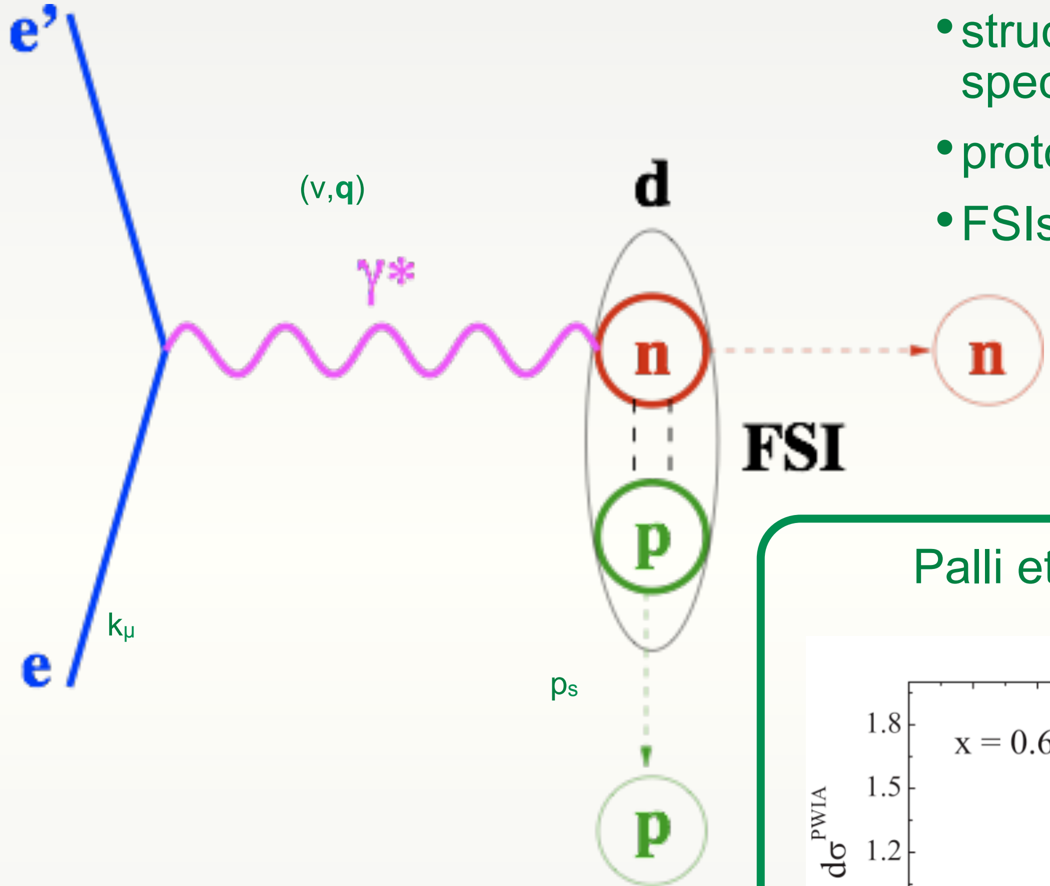
$$\int\int\int S^{\mathrm{LC}}(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s} d^2 p_T = 1$$

- Very Important Protons $70 < p_s < 100$ MeV/c
- Corrections make resonances stand out
- F_2^n/F_2^p can be measured at high x*



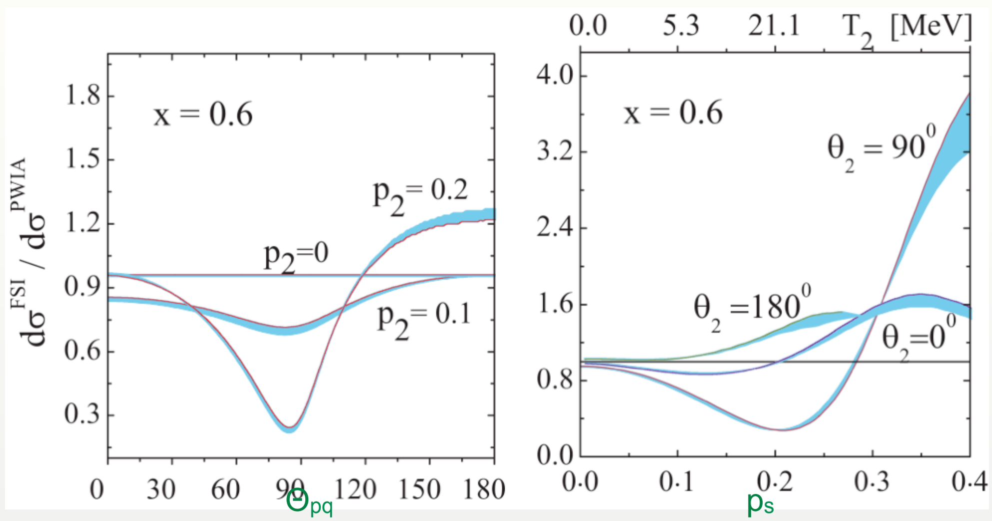


Final State Interactions



- struck neutron can interact with the spectator proton
- proton momentum is enhanced
- FSIs are small at low p_s and large Θ_{pq}

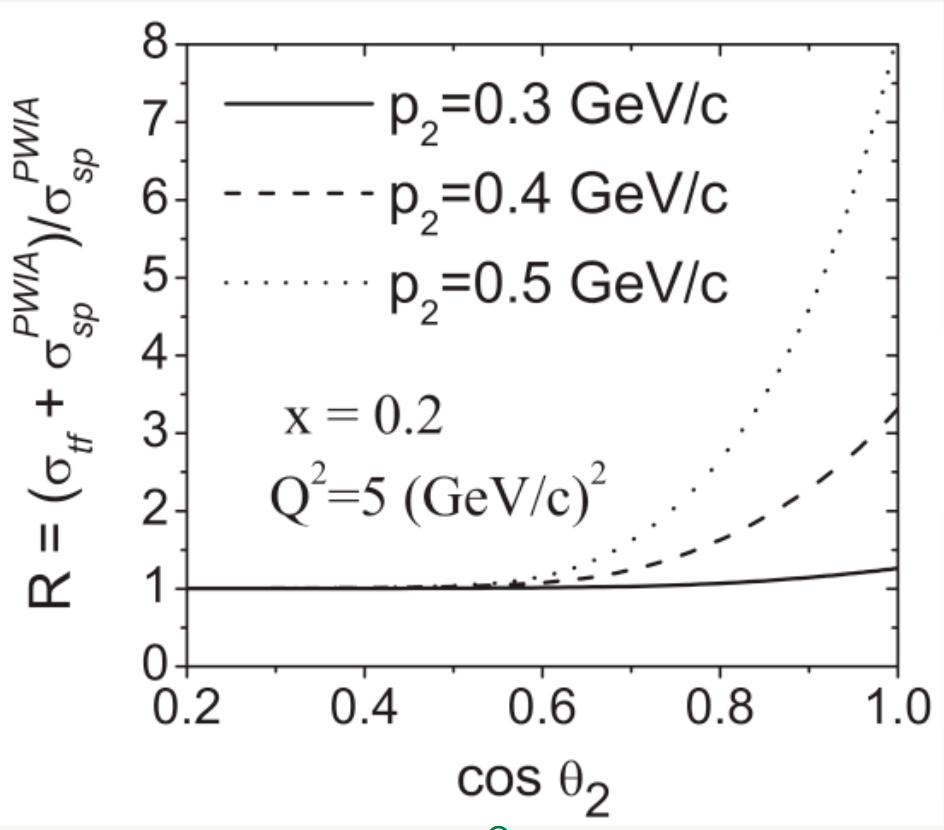
Palli et al, PRC80(09)054610



- several groups have calculated FSIs
- $\Theta_{pq} > 110^o$ minimizes FSIs

Target Fragmentation

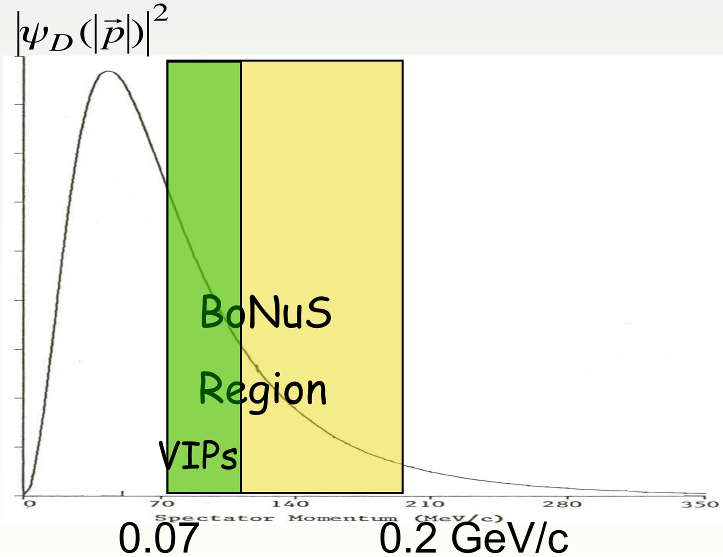
Palli et al, PRC80(09)054610

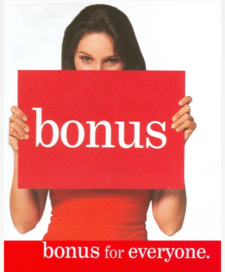


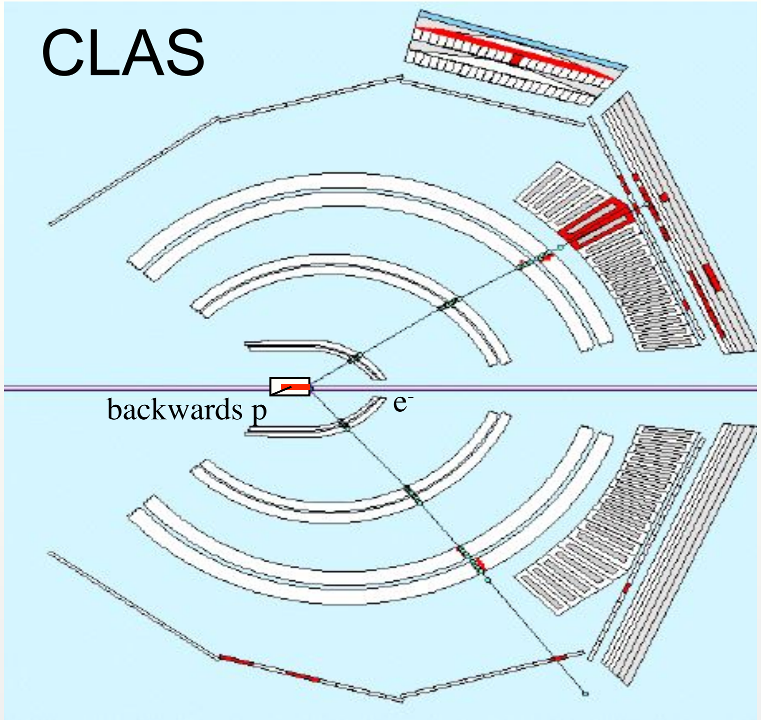
cos Θ_{pq}

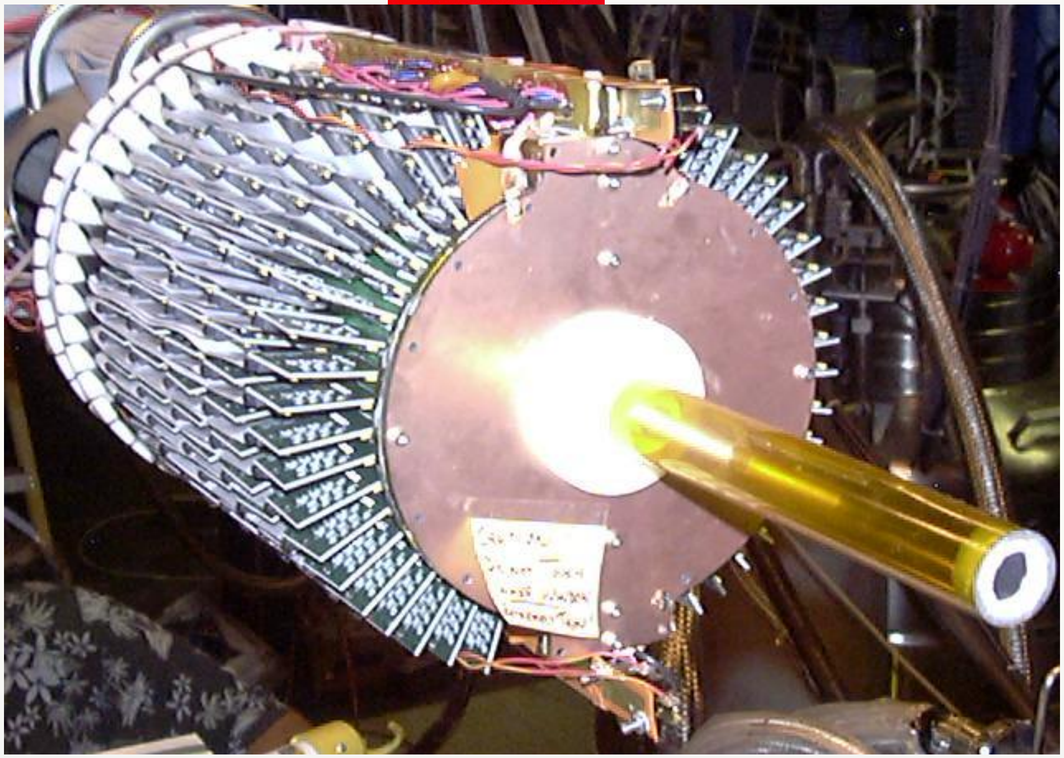
- target fragmentation enhances the proton yield only at forward angles (cos Θ_{pq} >0.6)
- this can be ignored

Low Spectator Momenta - Nearly Free Neutrons ?



The  Experiment

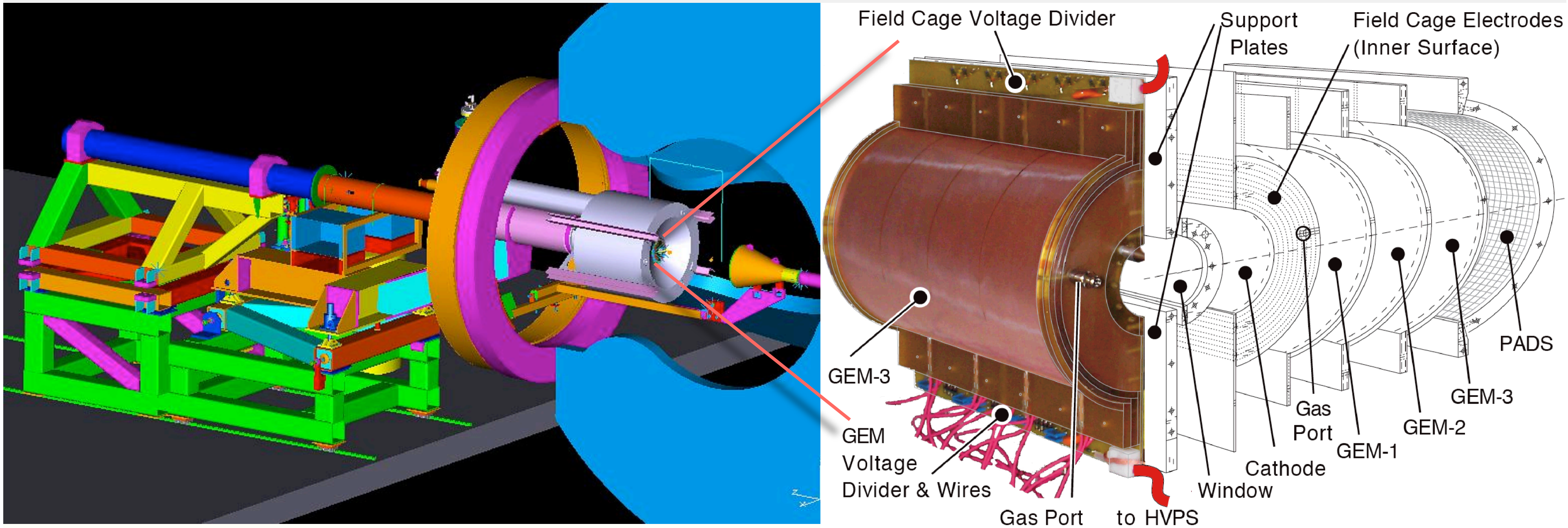


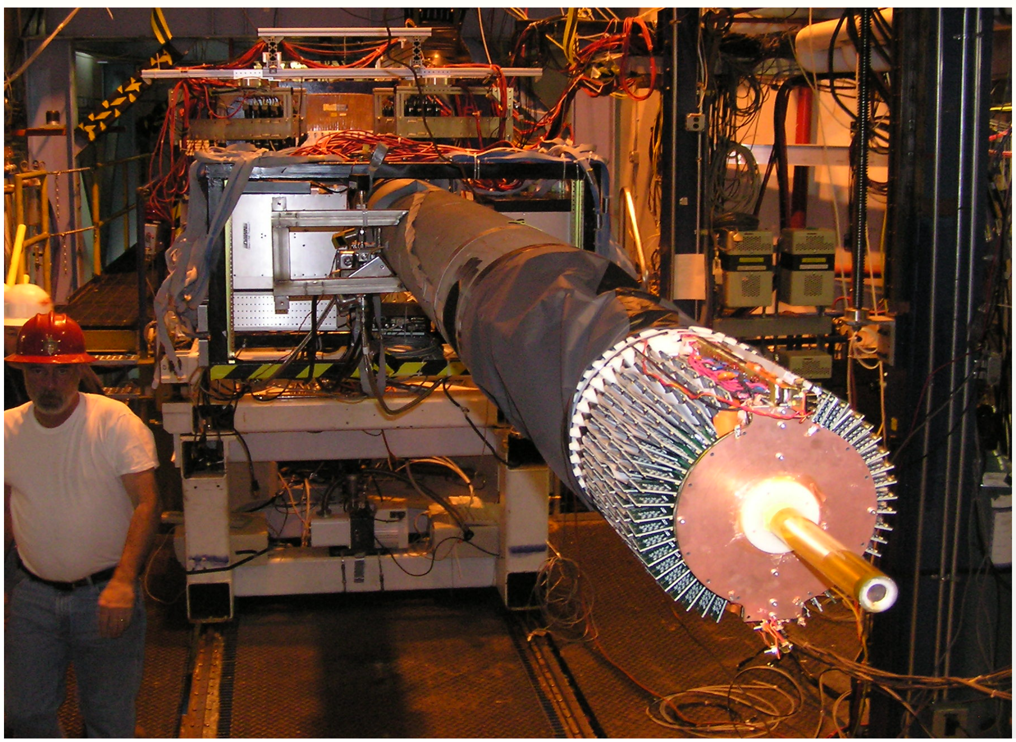


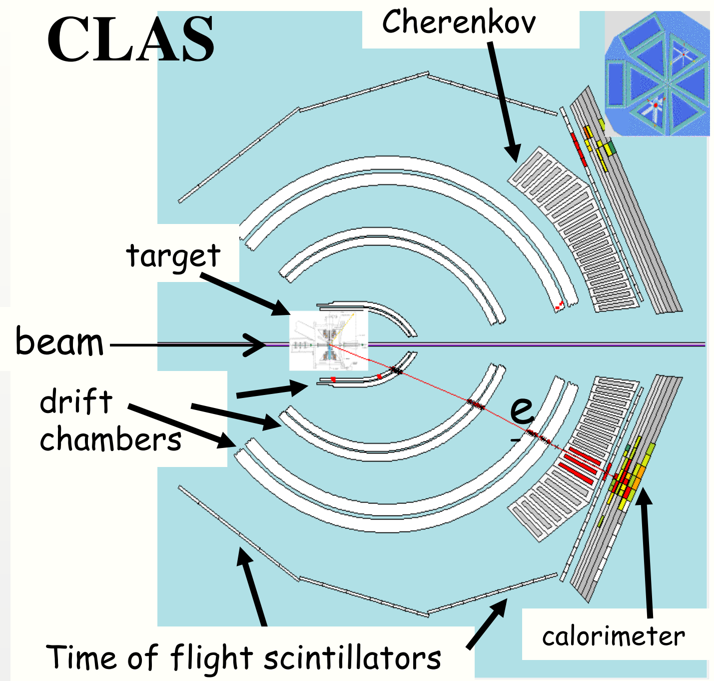
Radial TPC (view from downstream)

*BoNuS = **B**arely **o**ff-shell **Nu**cleon **S**cattering

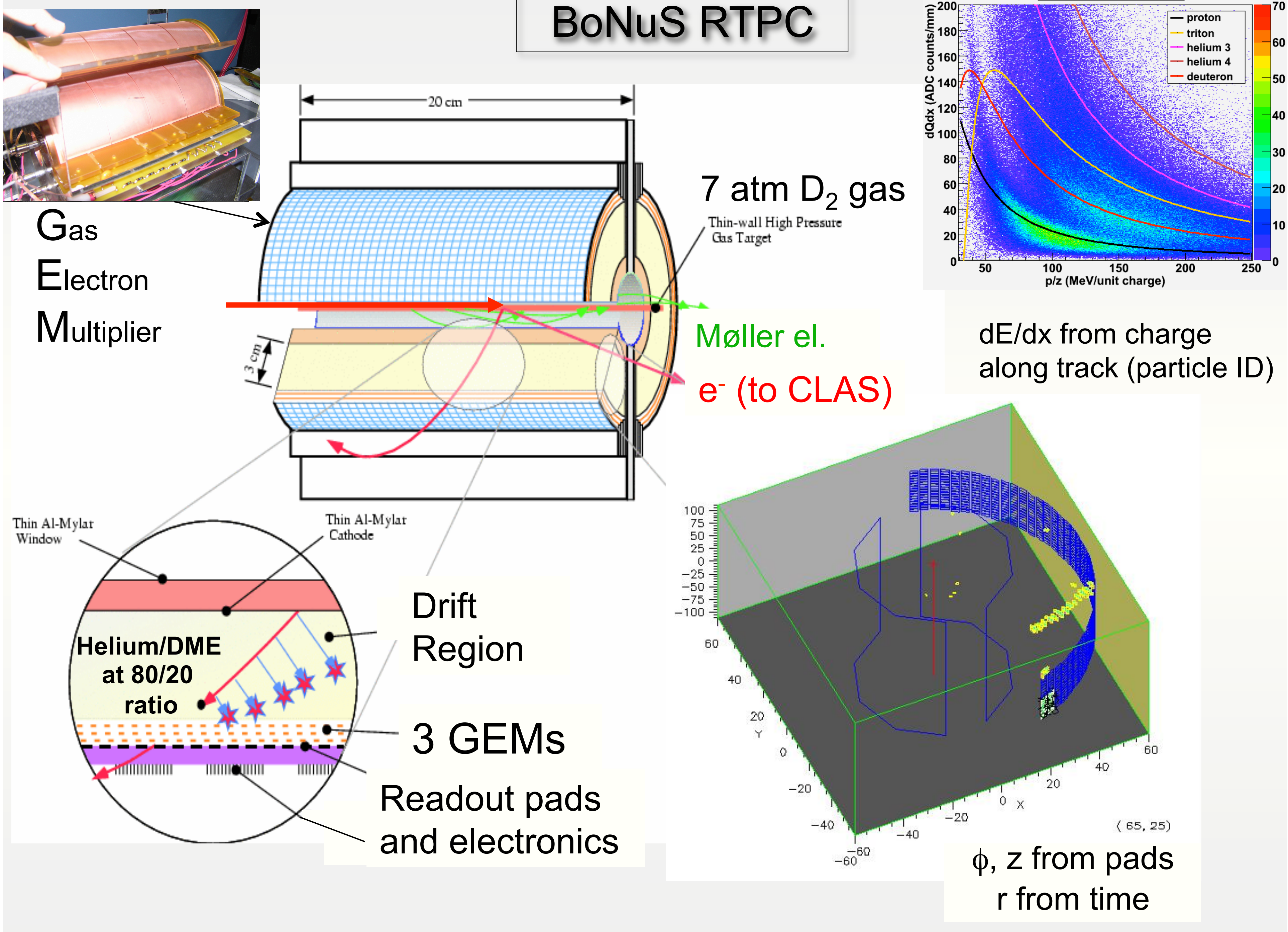
**RTPC = Radial Time Projection Chamber


Field Cage Voltage Divider
Support Plates
Field Cage Electrodes (Inner Surface)
GEM-3
GEM Voltage Divider & Wires
Gas Port
to HVPS
Window
Cathode
Gas Port
GEM-1
GEM-2
GEM-3
PADS



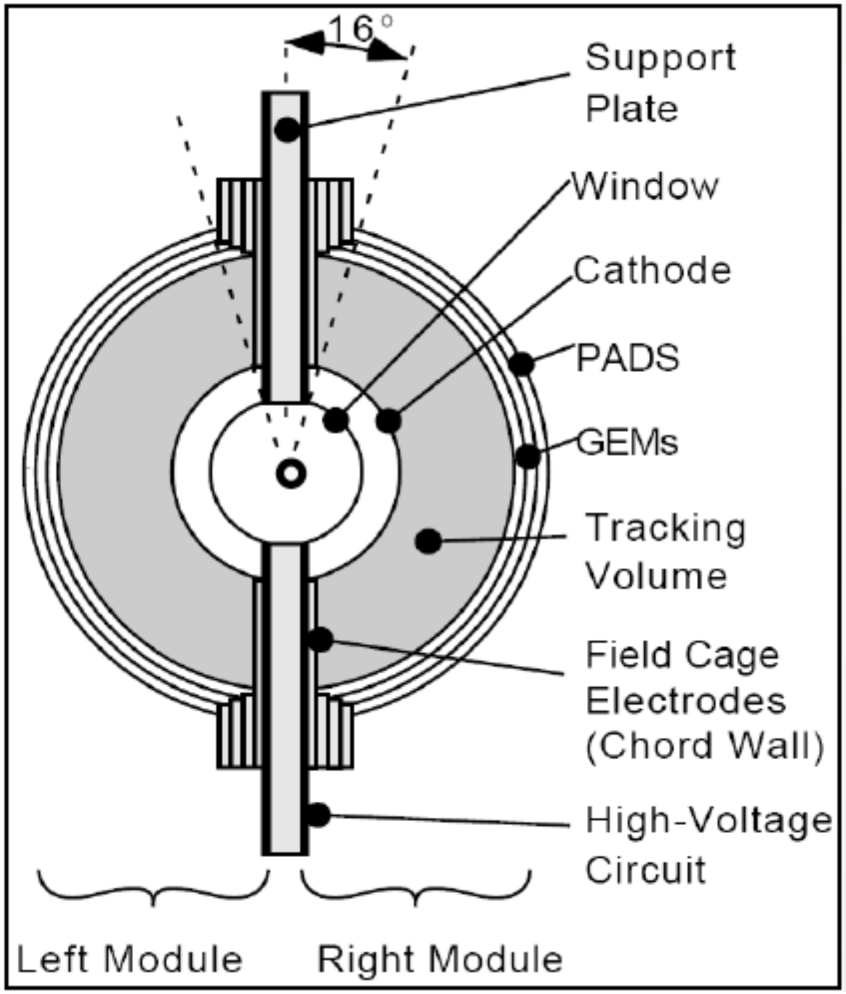

CLAS
Cherenkov
target
beam
drift chambers
e
Time of flight scintillators
calorimeter

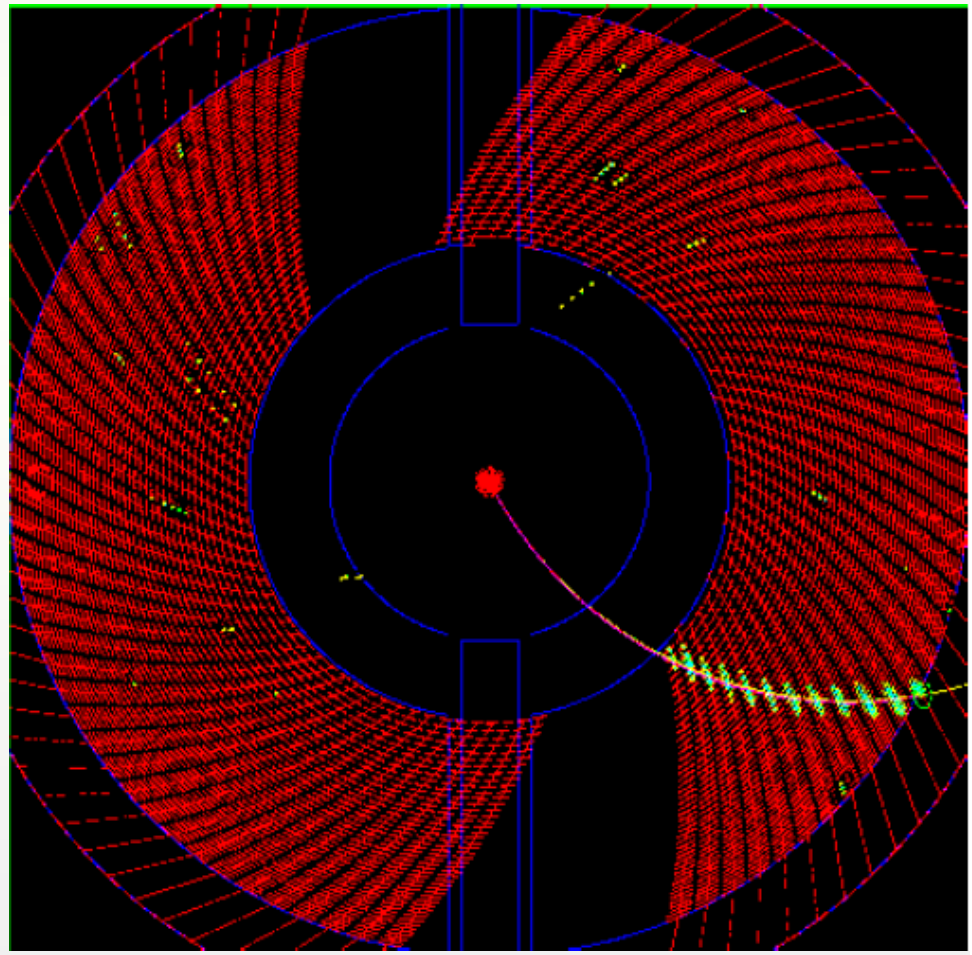
BoNuS RTPC



Gas
Electron
Multiplier
20 cm
3 cm
7 atm D_2 gas
Thin-wall High Pressure Gas Target
Møller el.
e⁻ (to CLAS)
4He Target, E=2GeV
dQdx (ADC counts/mm)
p/z (MeV/unit charge)
proton
triton
helium 3
helium 4
deuteron
dE/dx from charge along track (particle ID)
Thin Al-Mylar Window
Thin Al-Mylar Cathode
Helium/DME at 80/20 ratio
Drift Region
3 GEMs
Readout pads and electronics
(65, 25)
ϕ, z from pads
r from time

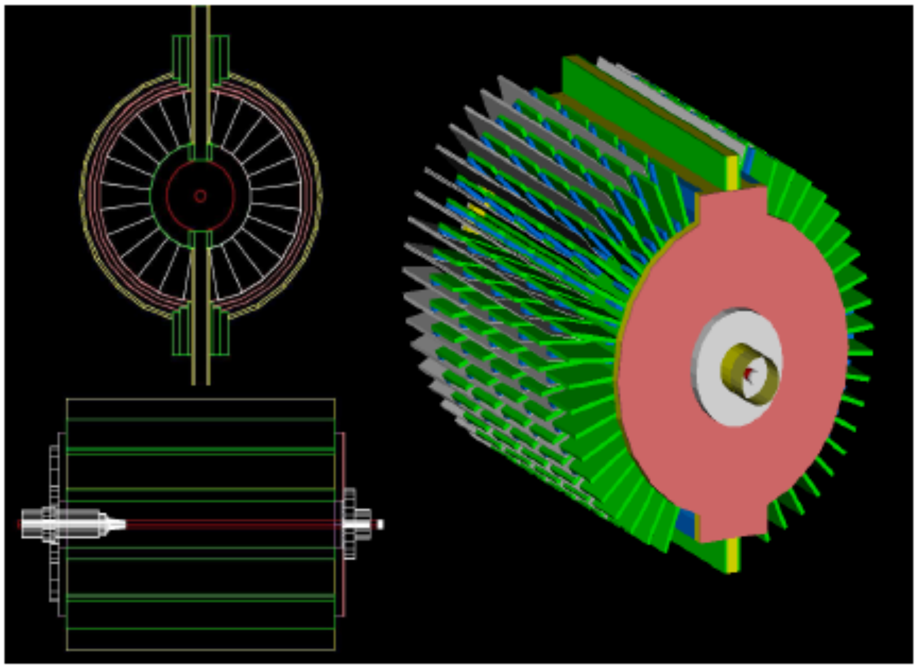
RTPC Cross Section



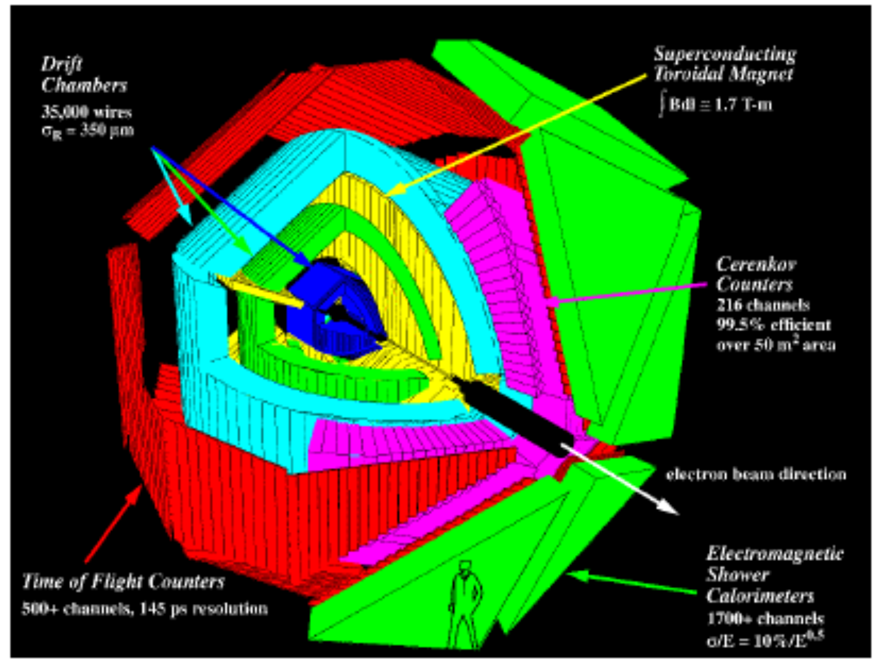


Simulation Overview

Evgen (fsgen or other event generators) → RTPC (BONUS) CLAS(gsim) → Gsim Post Processing (gpp) → Reconstruction (user_ana) → Skim → Higher Level Simulation Ntuple



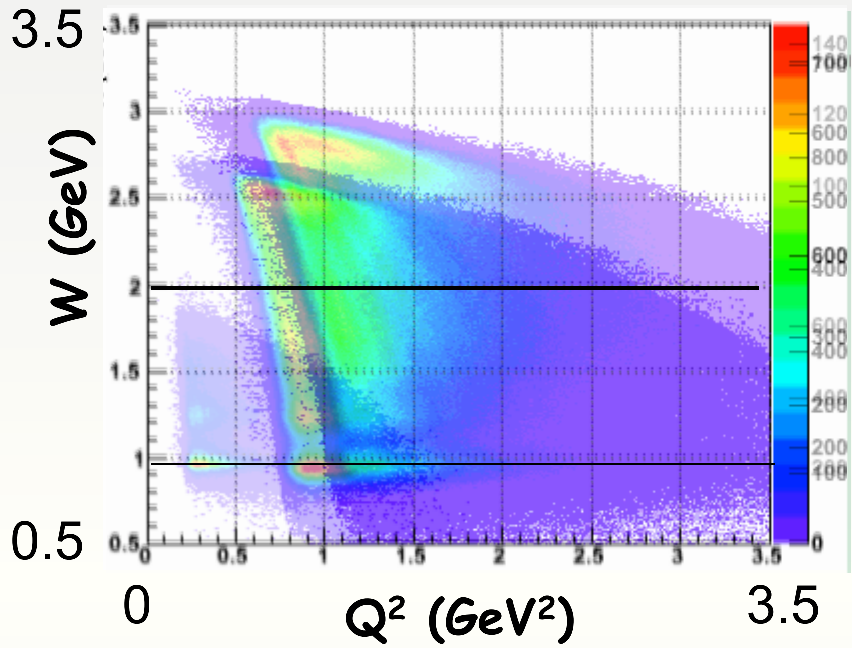
+

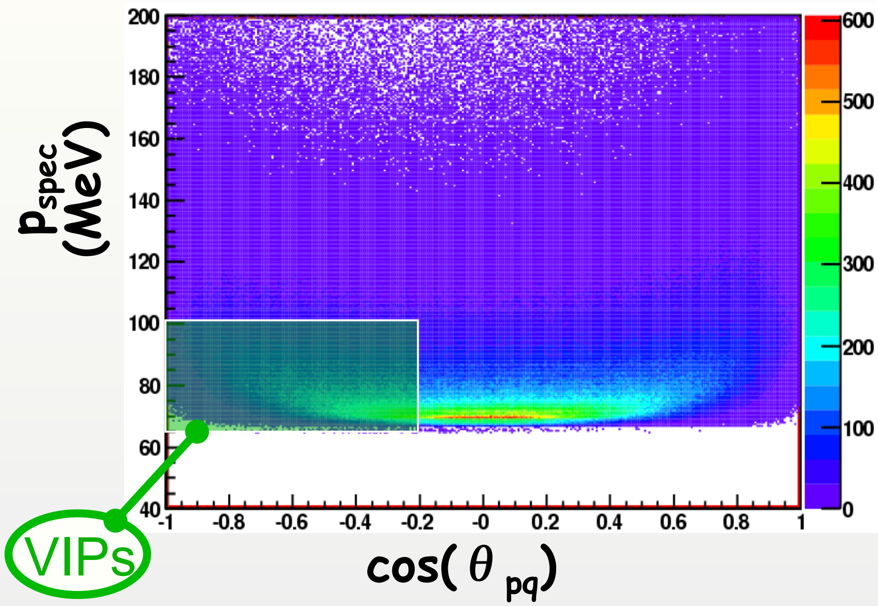


What can be done with simulation?

- Help to design the detector and choose the best configurations of HV and Drift Gas
- Debug/optimize reconstruction code of RTPC
- Generate energy loss correction tables, radiation length tables
- Detector's acceptance and efficiency study

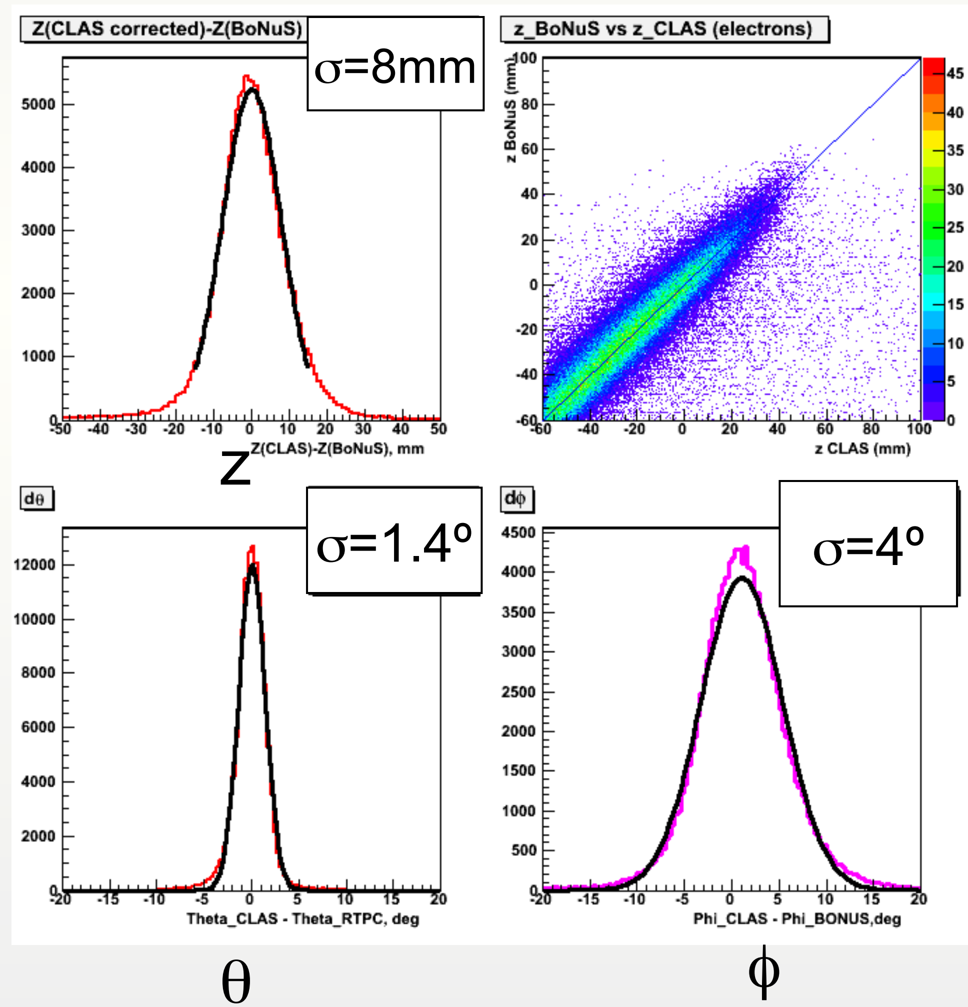
Kinematic Coverage - 2.1, 4.2 & 5.3 GeV



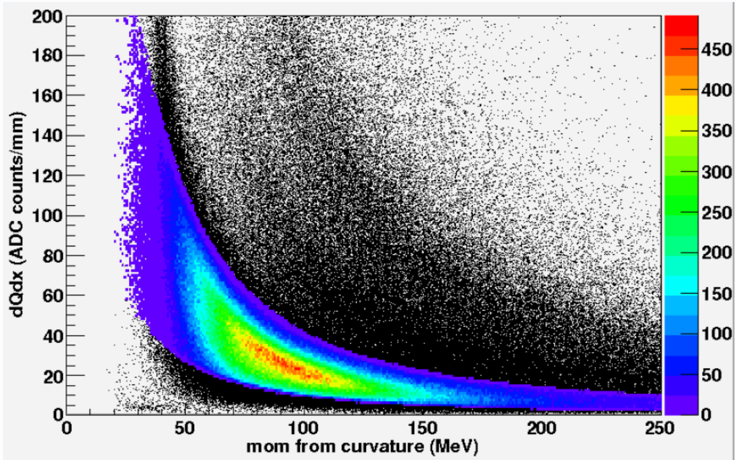


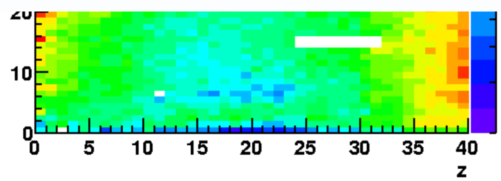
RTPC Performance

e^- reconstructed in CLAS & RTPC



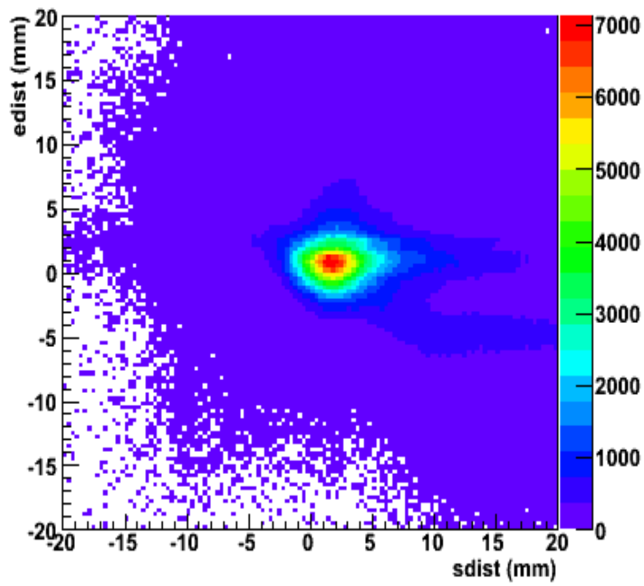
Particle ID (after gain calibration of each channel)



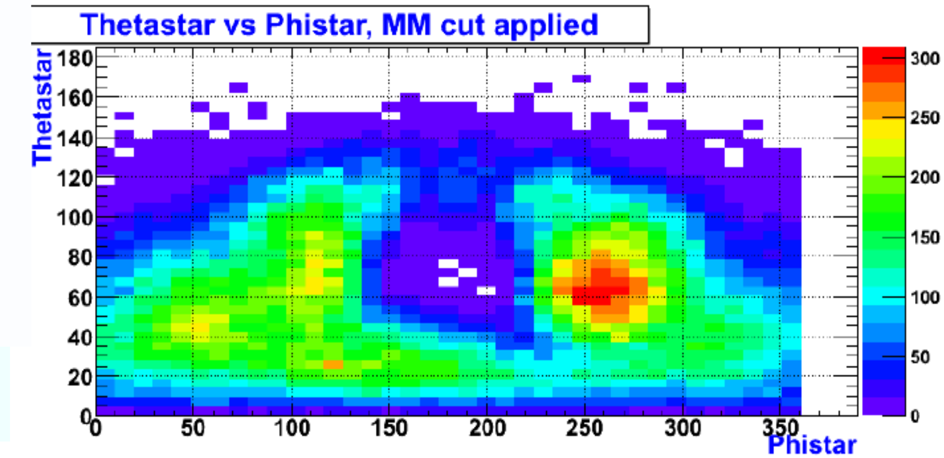


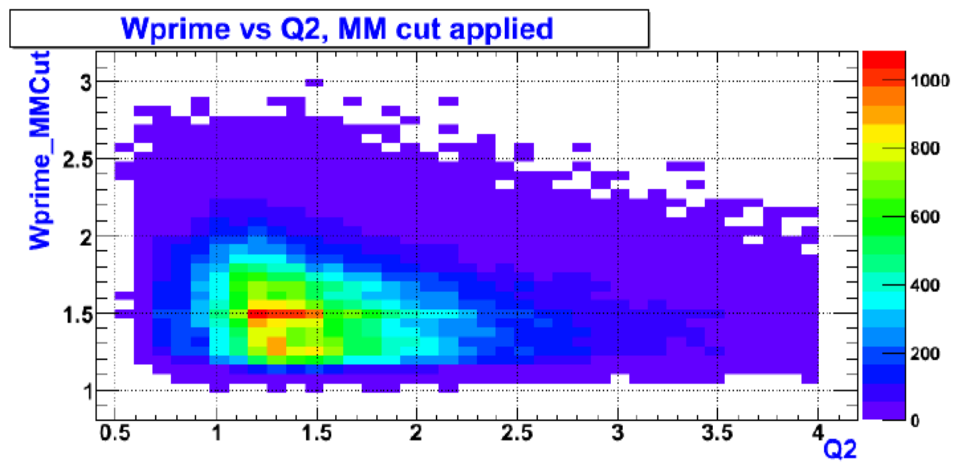
"hotter" ("colder")
than average pads

Out-of-time track suppression



inematics coverage, $D(e,e'\pi^{-}p)p$, E = 5.3 GeV



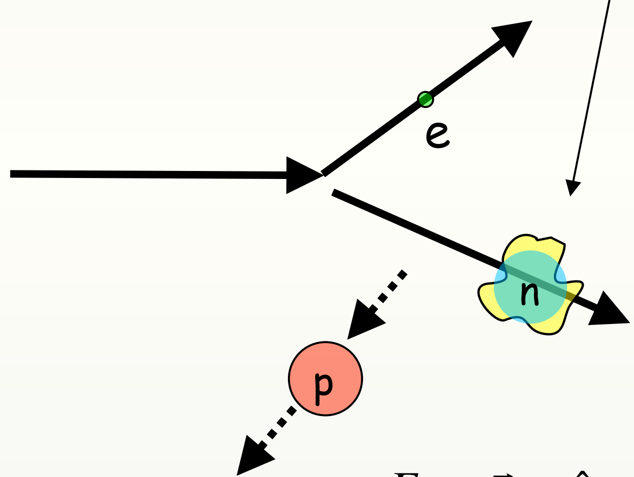


Minimizing Nuclear Uncertainties: "Spectator Tagging"

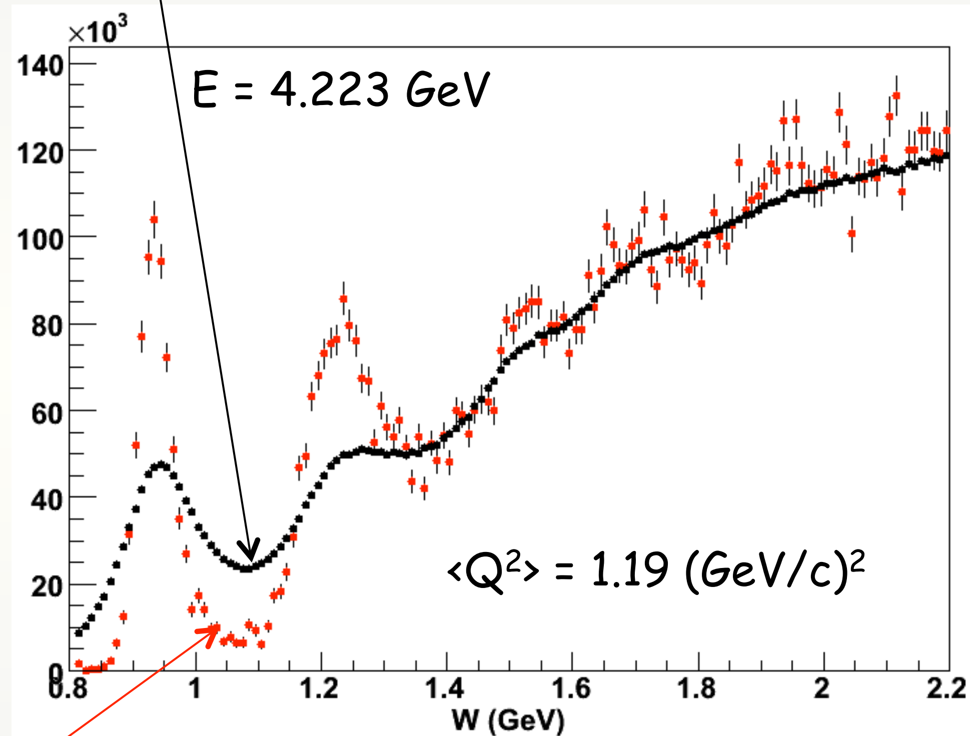
$$\boxed{W^2 = M^2 + 2M\nu - Q^2}$$

$$p_n = \left(M_D - E_S, -\vec{p}_S\right);$$

$$\alpha_n = 2 - \alpha_S$$



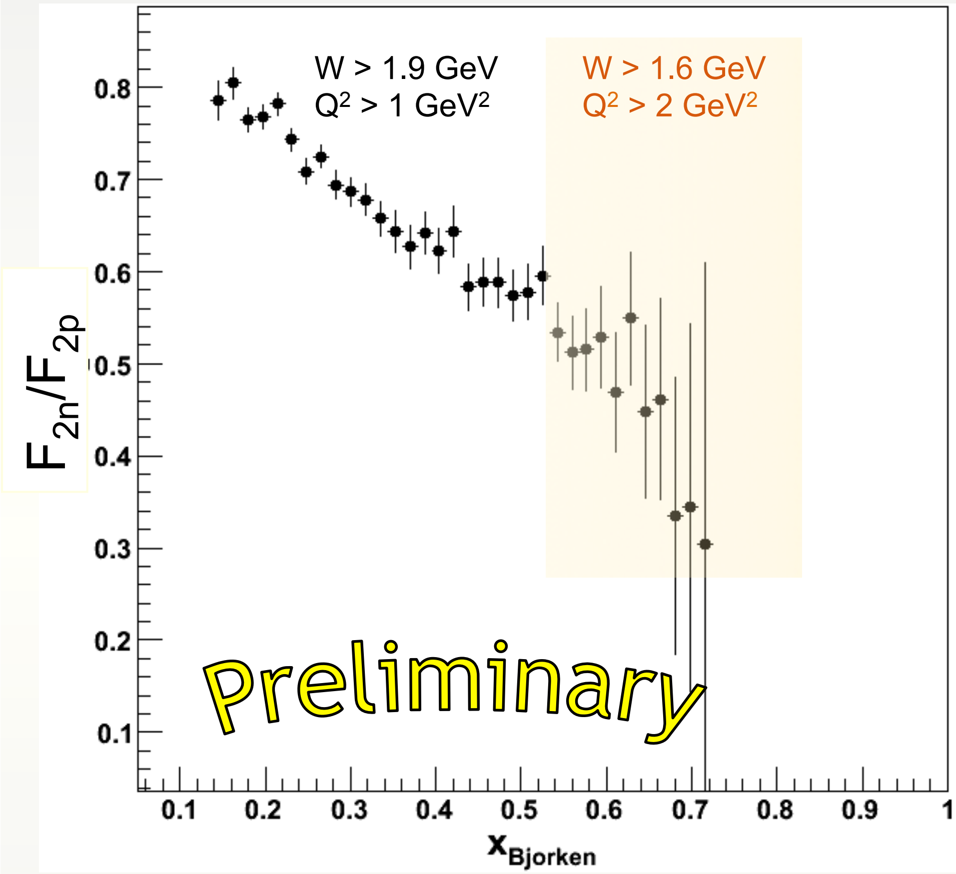
$$p_S = \left(E_S, \vec{p}_S\right); \quad \alpha_S = \frac{E_S - \vec{p}_S \cdot \hat{q}}{M_D/2}$$



$$\boxed{\begin{aligned} W^{*2} &= \left(p_n + q\right)^2 = p_n^{\mu} p_{n\mu} + 2\left((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}\right) - Q^2 \\ &\approx M^{*2} + 2M\nu(2 - \alpha_S) - Q^2 \end{aligned}}$$

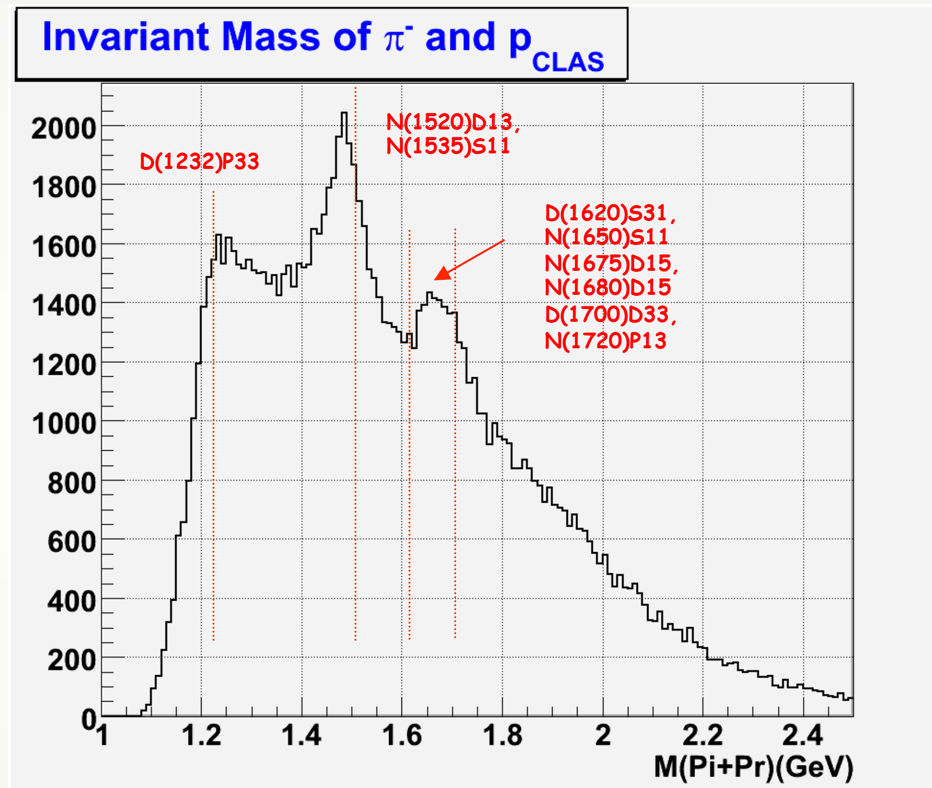
$$x^* = \frac{Q^2}{2 p_n^{\mu} q_{\mu}} \approx \frac{Q^2}{2M\nu(2 - \alpha_S)}$$

Preliminary Results from BoNuS



Baryonic Resonances, D(e,e′π-p)p

E = 5.26 GeV, Accepance and momentum not corrected yet

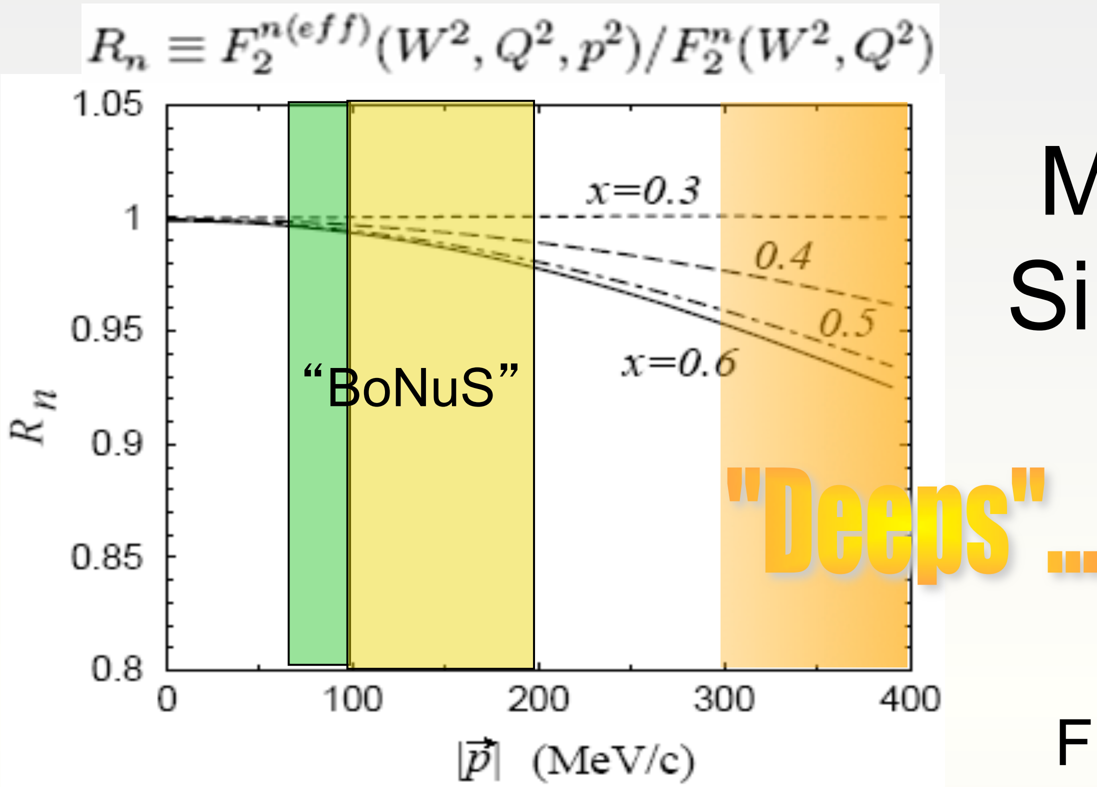


- Measured tagged n / inclusive d
- Multiplied with F_{2d}/F_{2p}
- Normalized at small *x*
- Acceptance corrections underway

$D(e, e' \pi^- p_{CLAS})p_s$ +

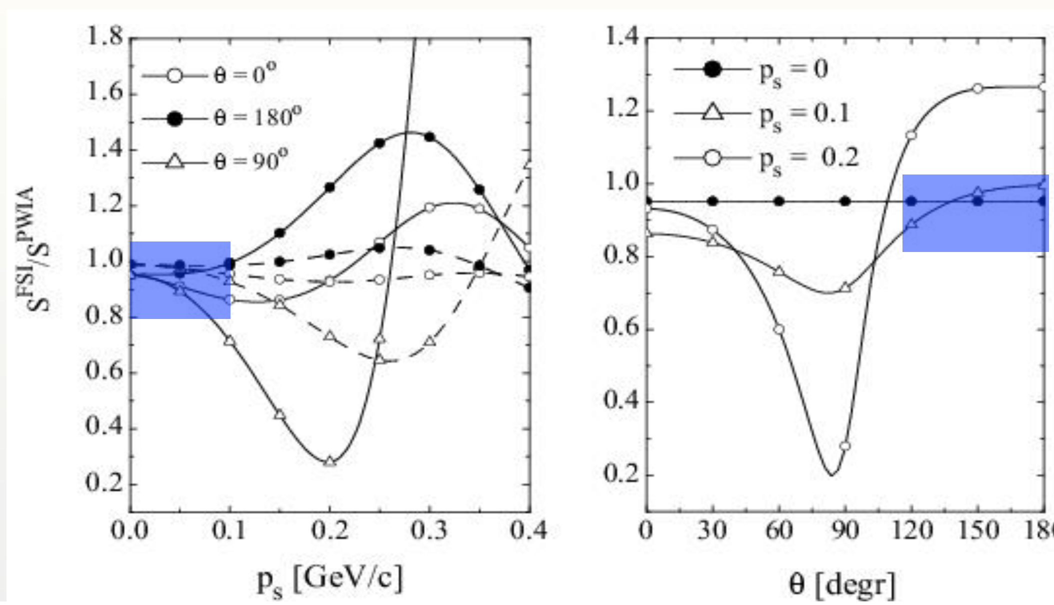
$D(e, e' \pi^- p_{RTPC})p_{decay}$

Modifications to Simple Spectator Picture



Binding Effects ↑

Final State Interactions ↓

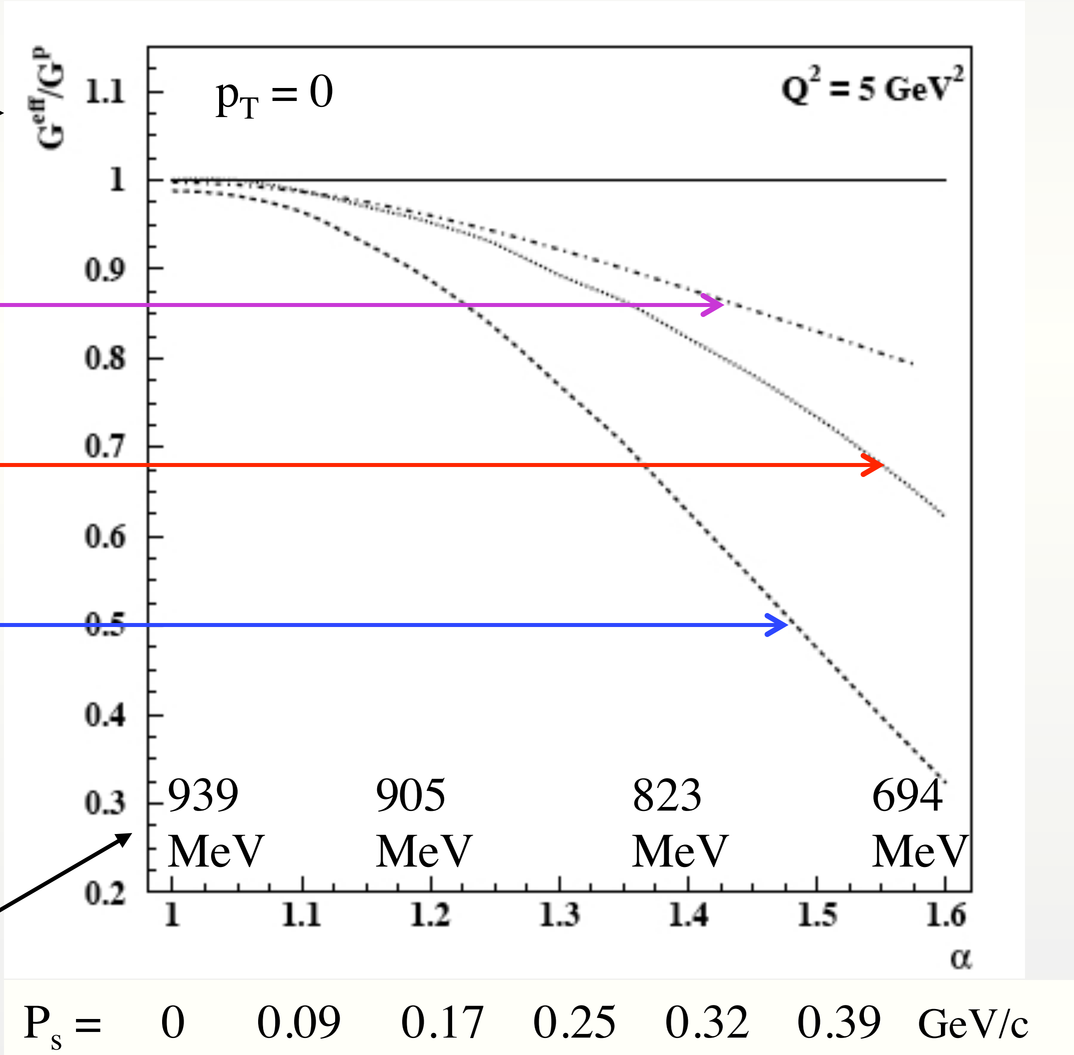


Ciofi degli Atti and Kopeliovich, Eur. Phys. J. A17(2003)133

Deviations from free structure function:

Off-shell Effects [should depend on α (p_s), x, Q^2]

$$\frac{F_{2N}^{eff}(x=0.6,Q^2,\alpha)}{F_{2N}^{eff}(x=0.2,Q^2,\alpha)}$$



Modification of the off-shell scattering amplitude (Thomas, Melnitchouk et al.)

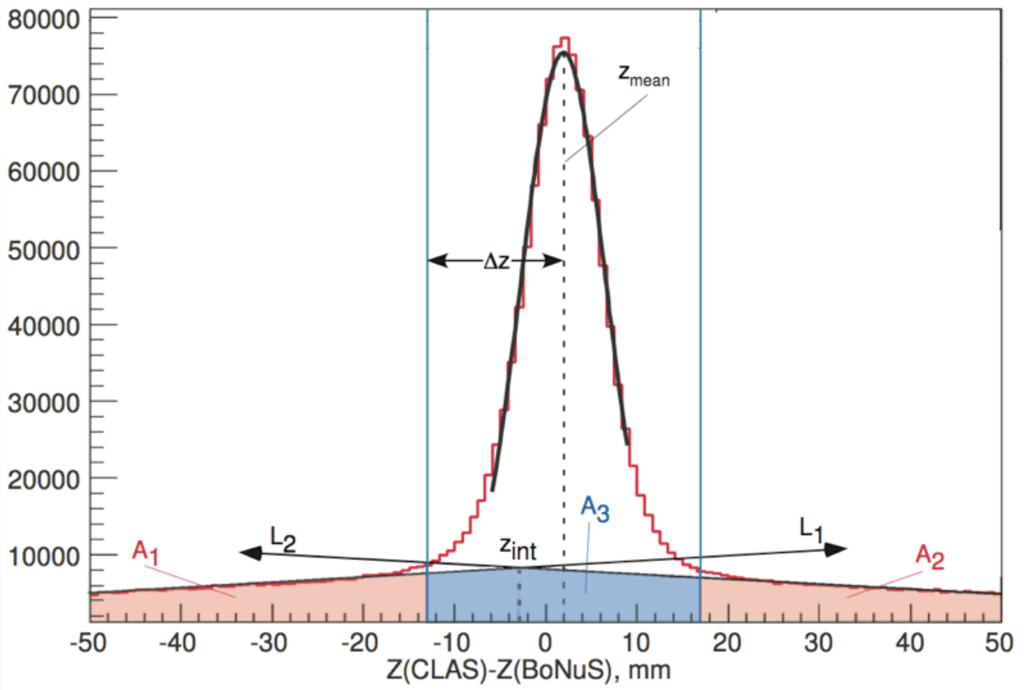
Color delocalization
Close et al.

Suppression of "point-like configurations"
Frankfurt, Strikman et al.

… plus 6-quark bags, ΔΔ, MEC…

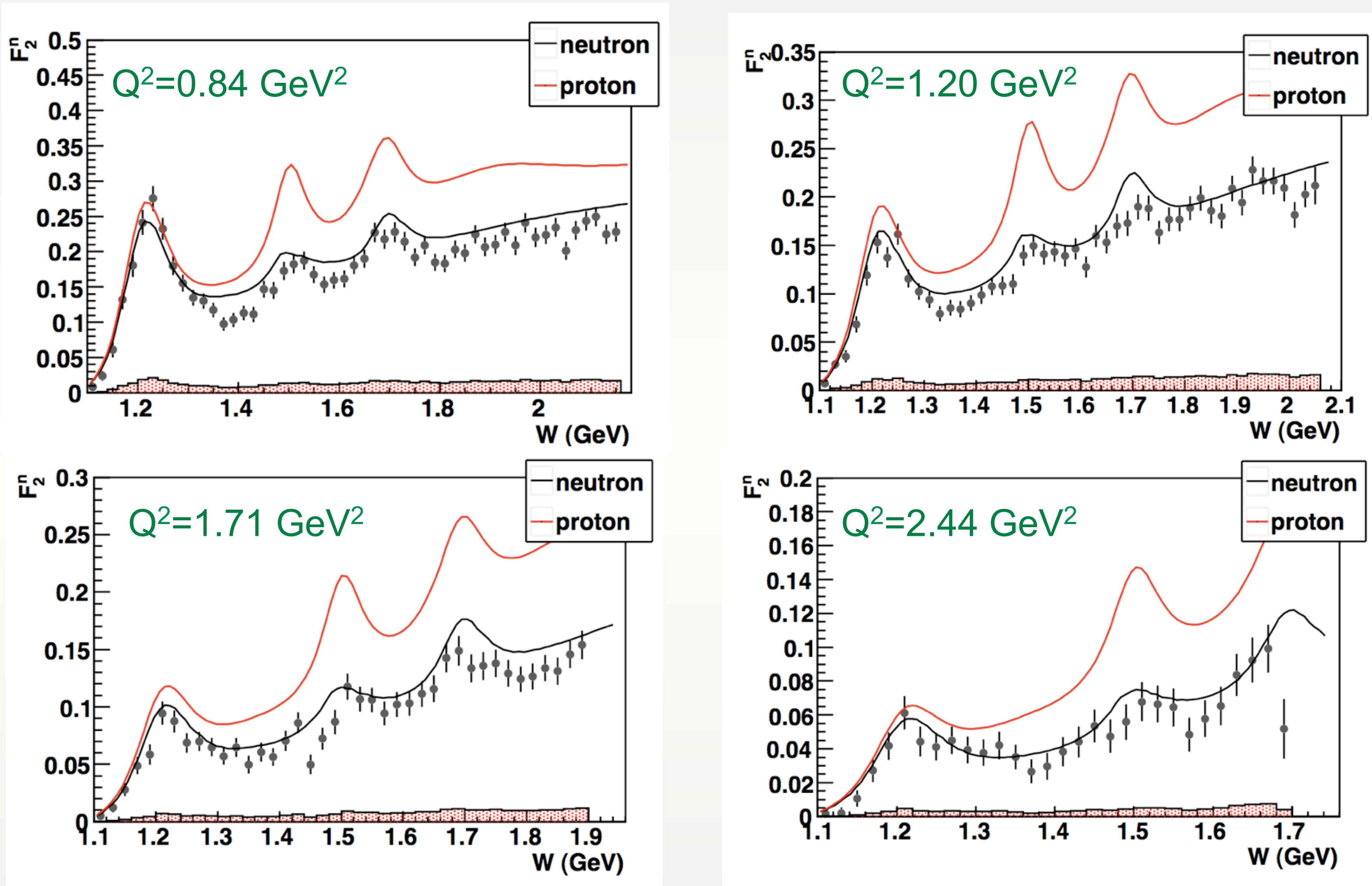
"Off-shell" mass of the nucleon M^*

- The Ratio Method
  - ⋆ measure tagged counts divided by inclusive counts
  - ⋆ correct this ratio for backgrounds
  - ⋆ one scale factor gives F_2^n/F_2^d
- The Monte Carlo Method
  - ⋆ measure tagged counts
  - ⋆ divide by spectator model Monte Carlo results
  - ⋆ multiply by F_2^n used in the model
- The two methods have different systematic errors, but give very similar results.



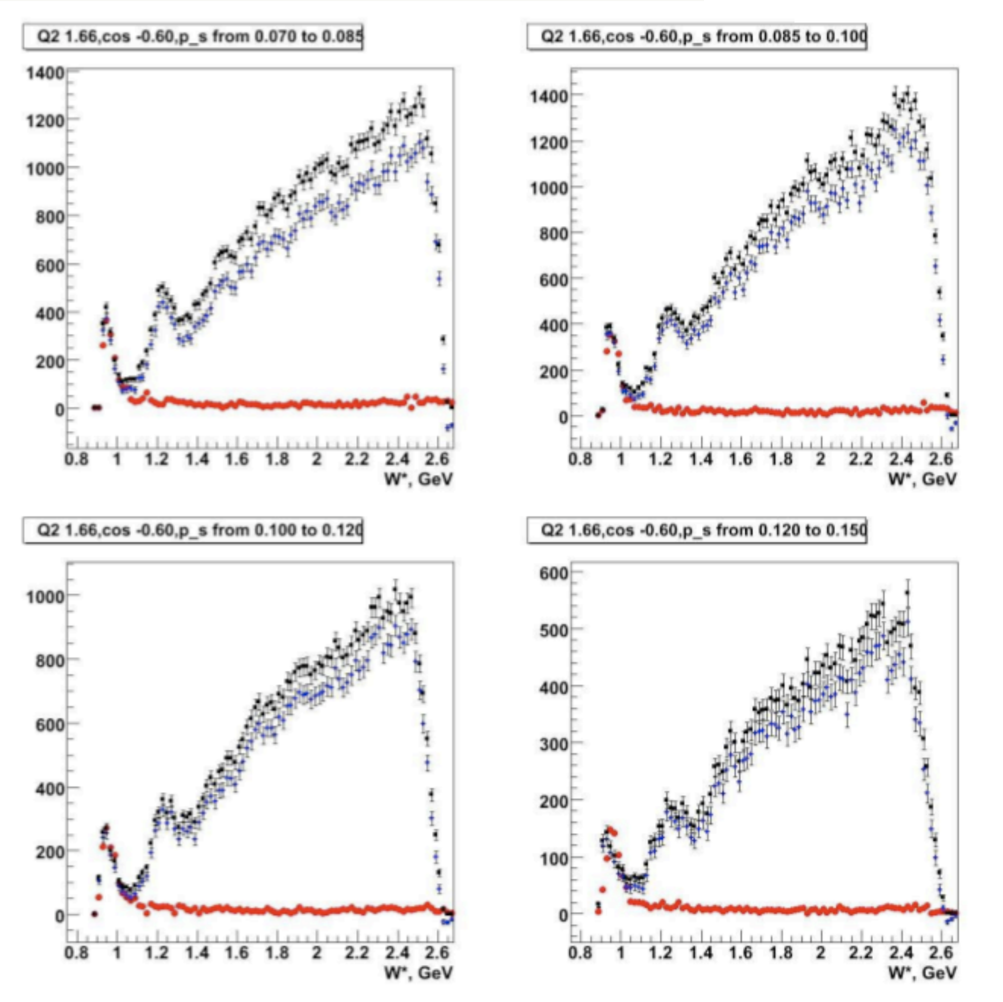
- Z is the position along the beam direction
- Tracking of the electron gives Z(CLAS)
- Tracking of the spectator proton gives Z(BoNuS)
- ΔZ=Z(CLAS)-Z(BoNuS) shows a coincidence peak and a triangular background
- Fits to the triangular background allows us to measure backgrounds underneath the peak
- Blue area = R_{bg} x Pink area
- R_{bg} is independent of kinematics

BoNuS F_2^n



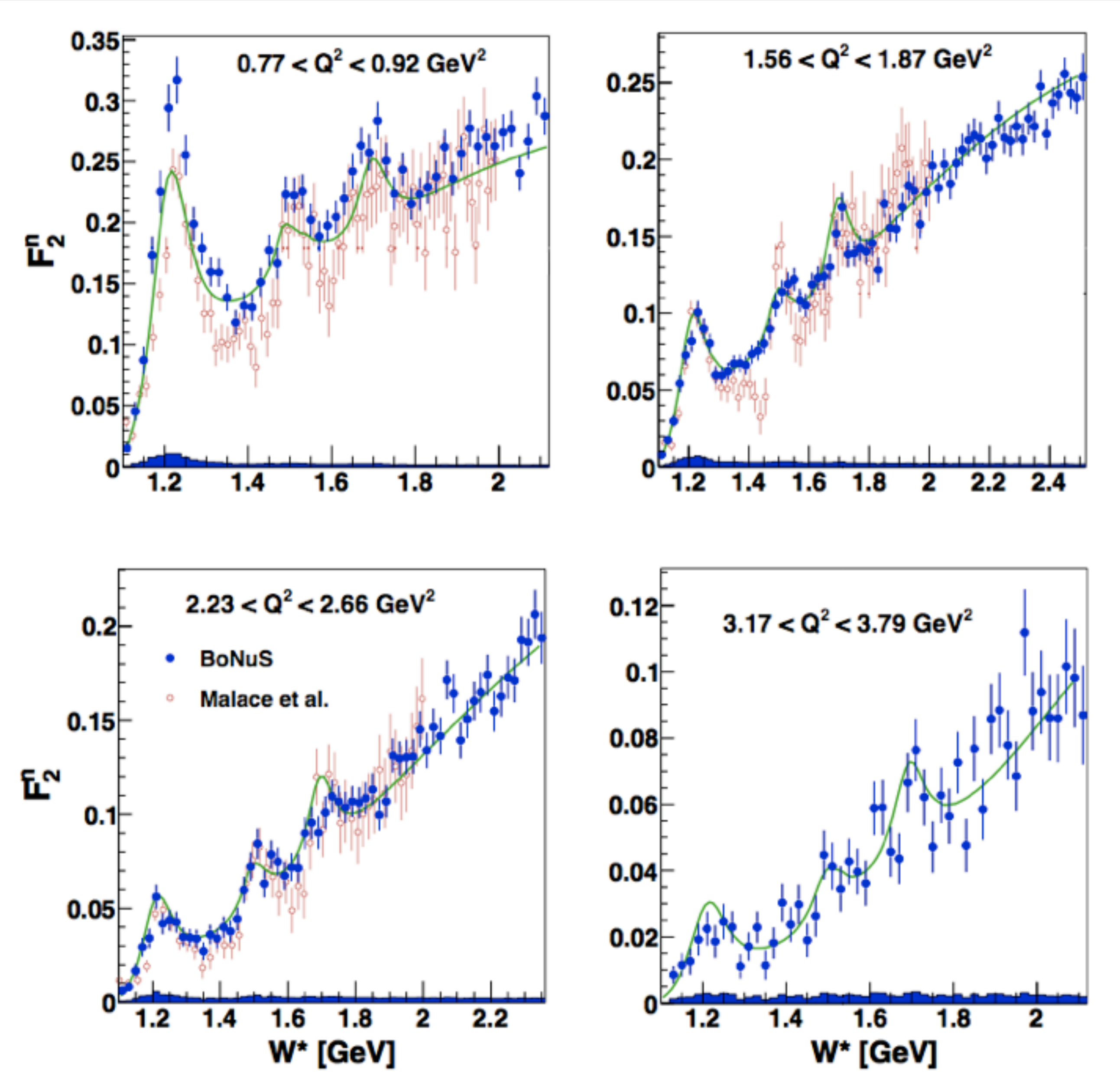
4 of 16 spectra: $0.8 < Q^2 < 4.5$; $E_{beam} = 4.2$ & 5.3 GeV; Bosted/Christy world fits

$$R(data/MC) = \frac{F_{2n}^{eff}(W^*, Q^2, \vec{p_s})}{F_{2n}^{model}(W, Q^2)}$$



Left: Black=raw tagged data; blue=accidental subtracted data; red=elastic and radiative tail

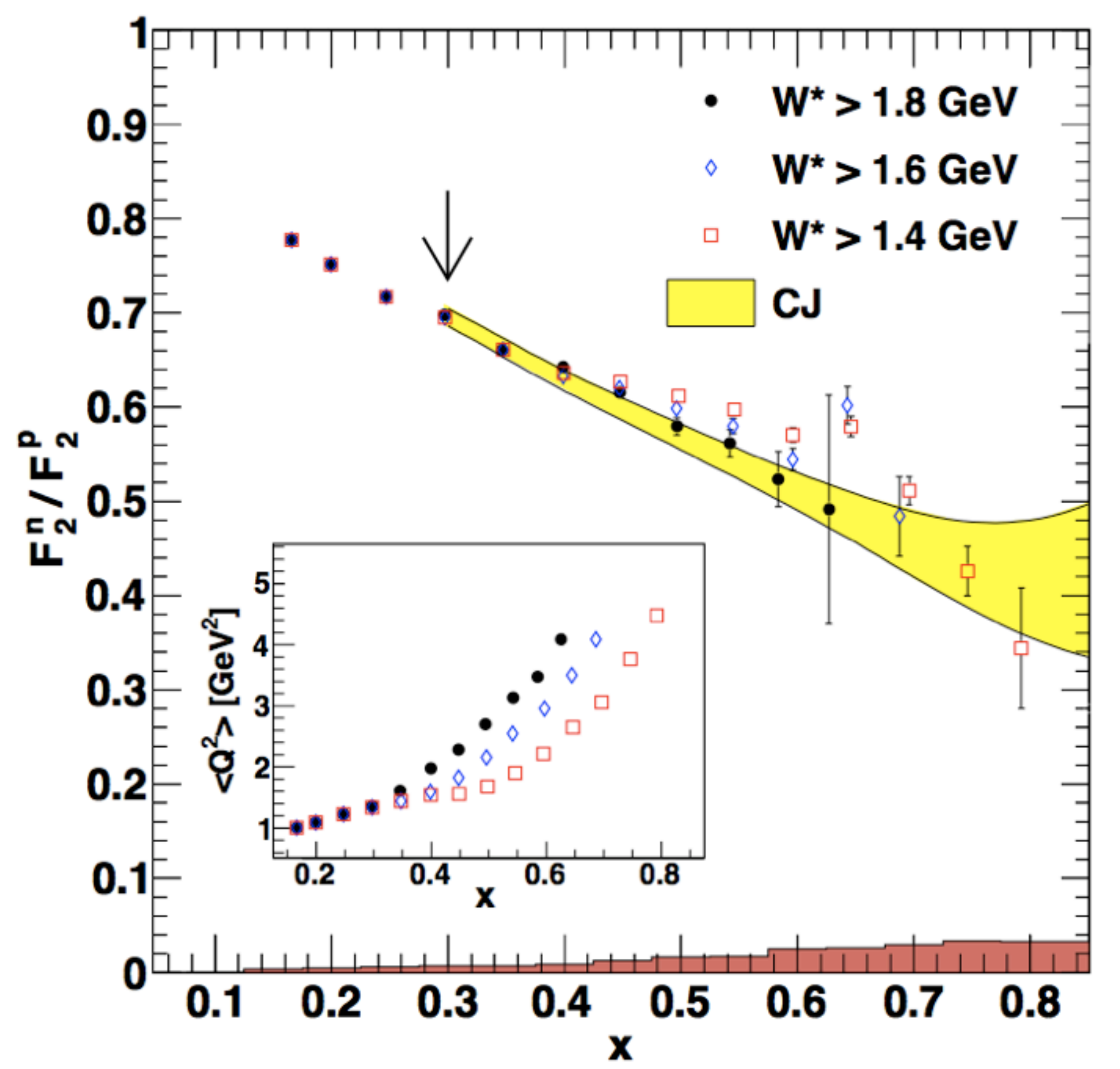
Final 4 GeV Data F_{2n}



BoNuS data compared to a state of the art nuclear physics extraction of neutron structure functions from deuterium (red points, Malace, et al.)

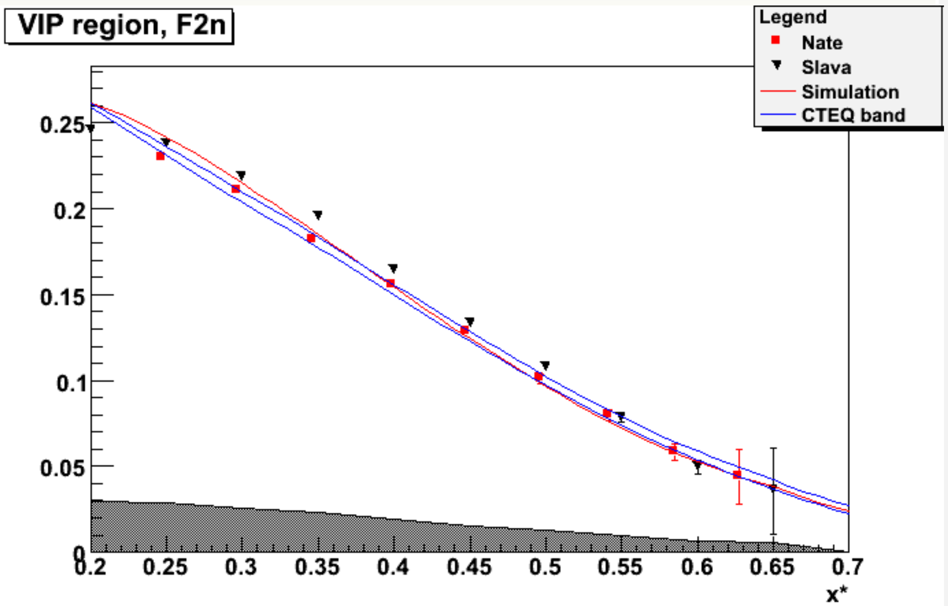
and a model (green line by Christy et al.)

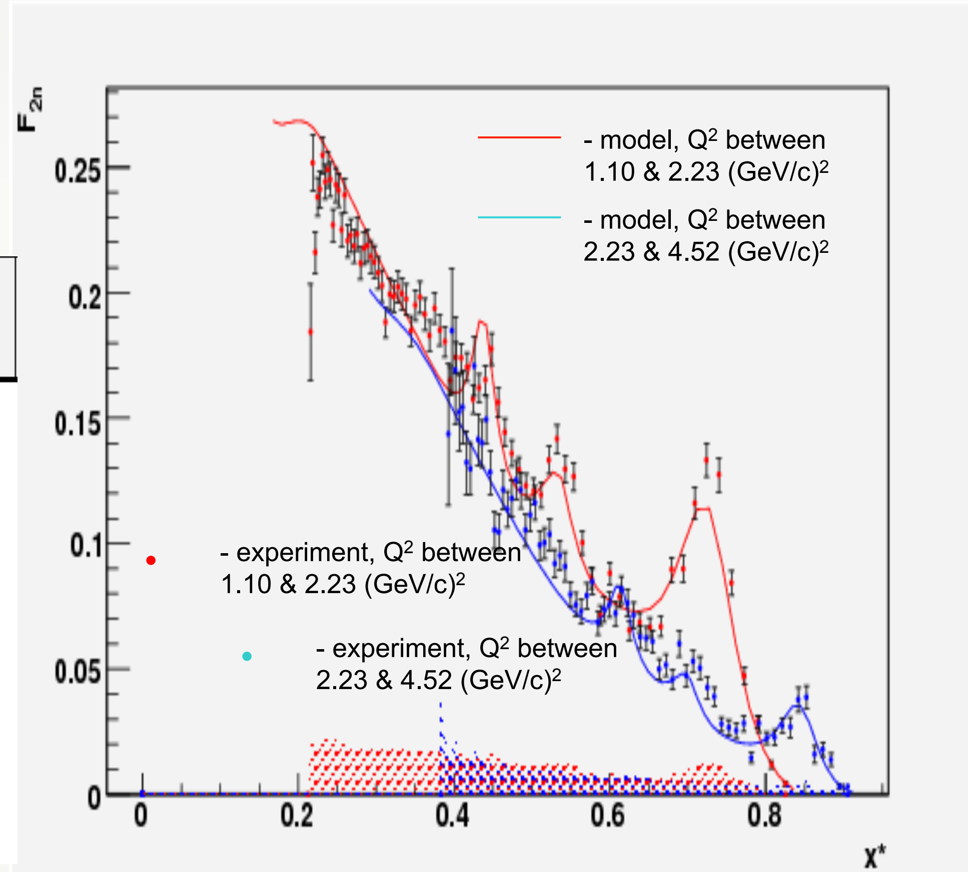
BoNuS F_2^n/F_2^p



- F_2^n/F_2^n vs. x
- Curves are CETQ error bands
- CETQ cuts off at low x because Q^2 is too low
- Lower cuts in W* imply higher x but the inclusion of resonance contributions.
- Results are consistent with CETQ trends at high x.

Results from BoNuS (iii)

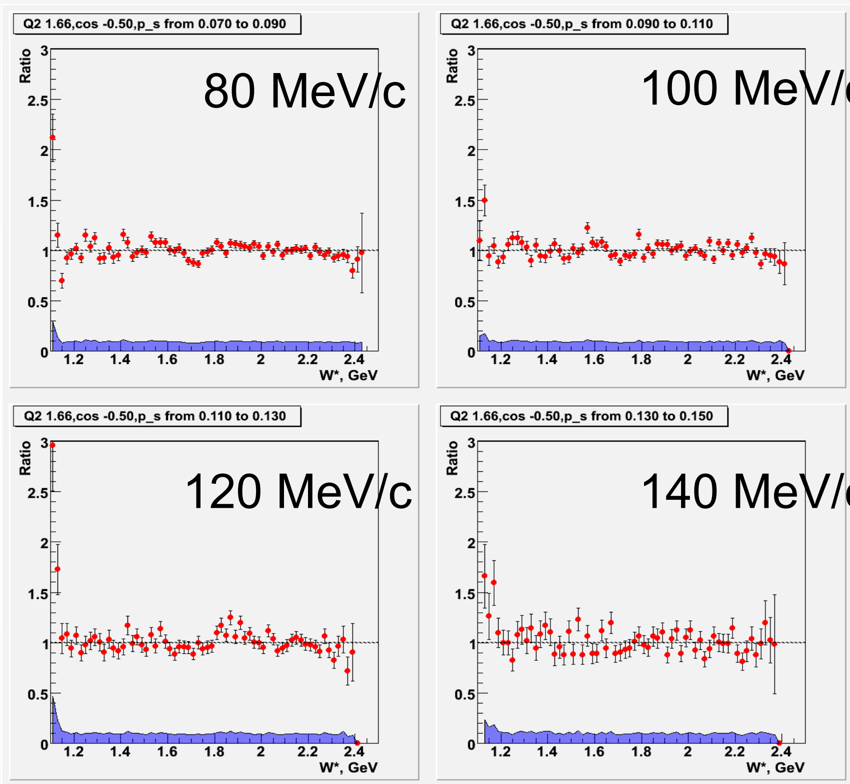




5 GeV Data

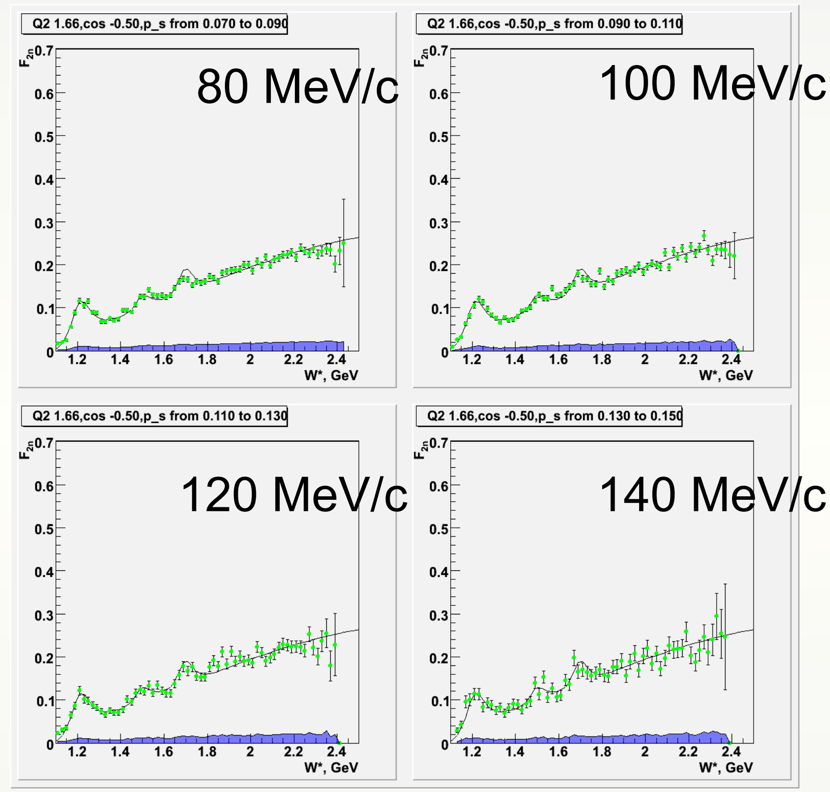
Results from BoNuS (iv)

Testing the Spectator Assumption - dependence on p_s



W* [GeV]

Ratio Data/Model



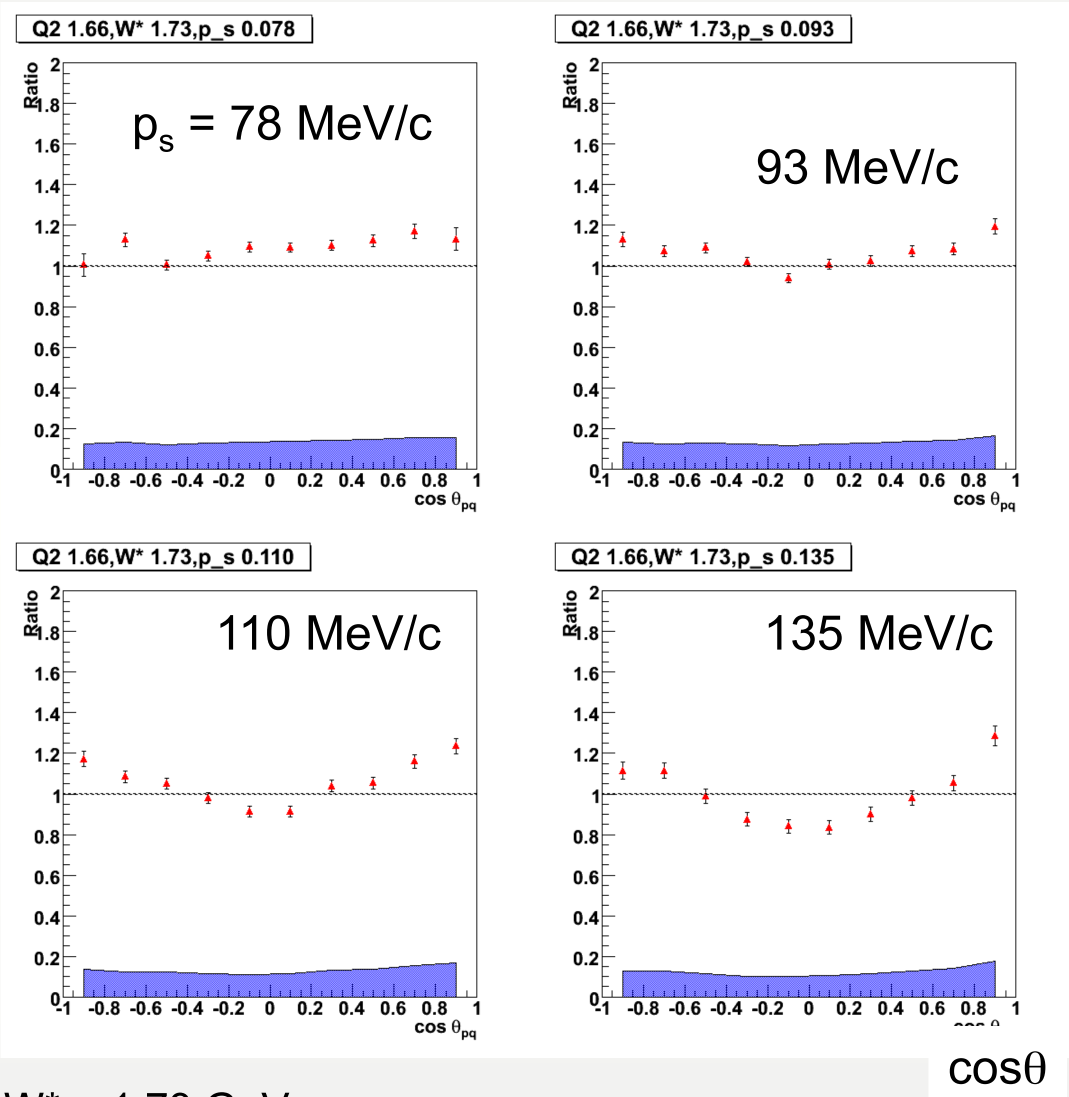
W* [GeV]

Extracted "effective structure function" F_{2n}

- Data have radiative elastic tail subtracted
- Simulation uses simple spectator model, radiative effects, full model of RTPC and CLAS

Results from BoNuS (v)

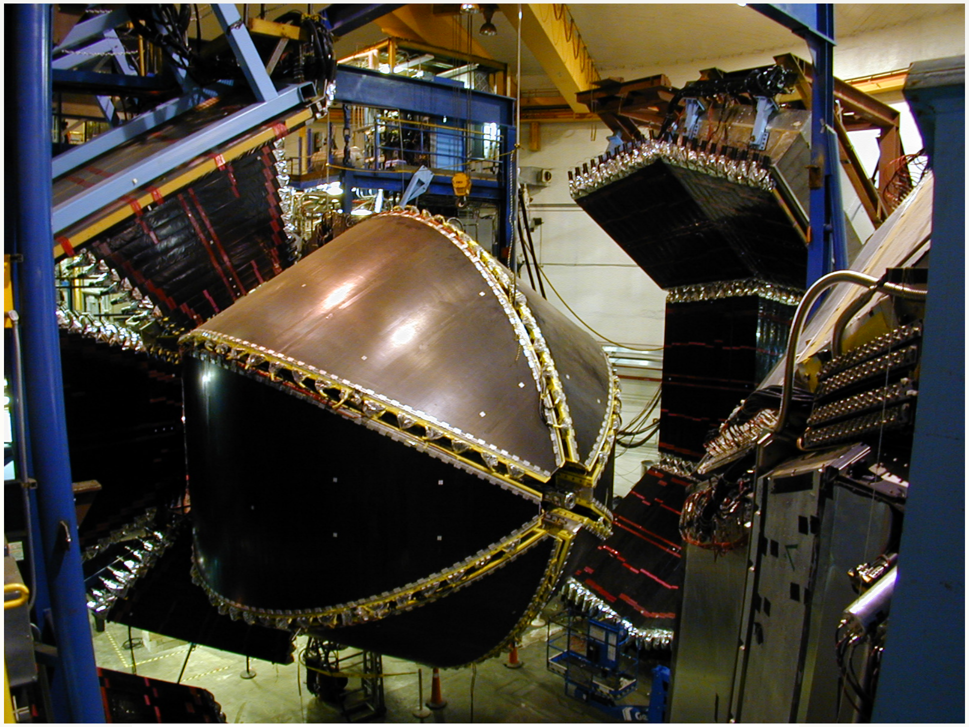
Testing the Spectator Assumption - dependence on θ_{pq}



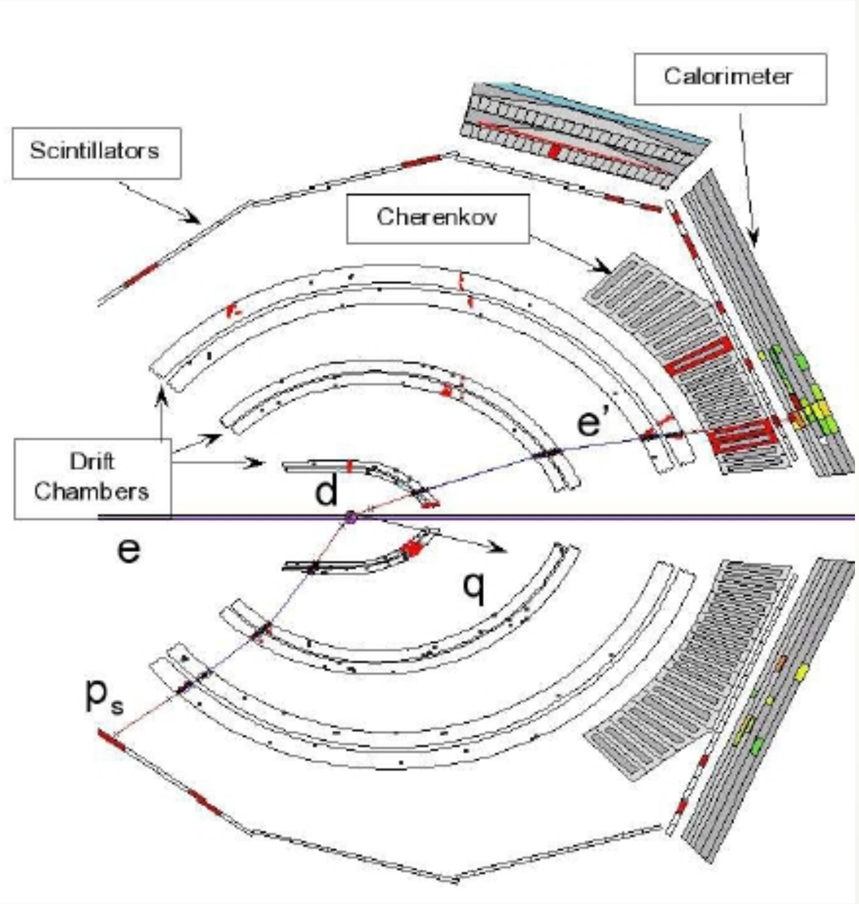
W* = 1.73 GeV
Q^2 = 1.66 $(GeV/c)^2$

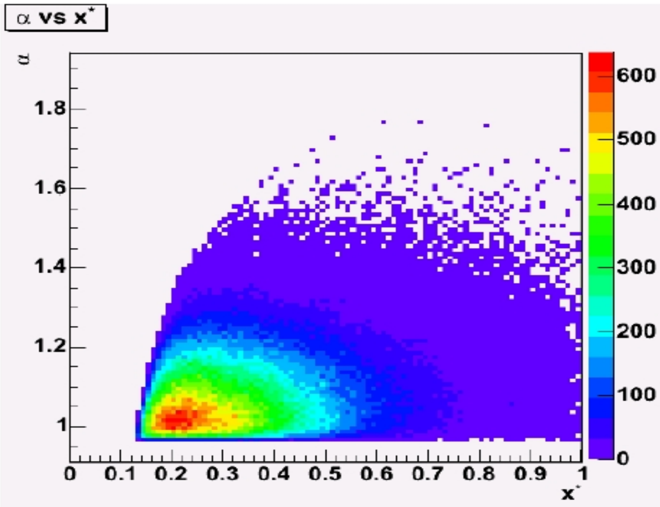
- So far, no strong deviations from naïve PWIA spectator picture at lower spectator momenta
- Possible indication of θ-dependence at higher p_s
- Have systematics for a wide range in Q^2, W* and beam energies

High spectator momenta (0.25 - 0.7 GeV/c): “Deeps”

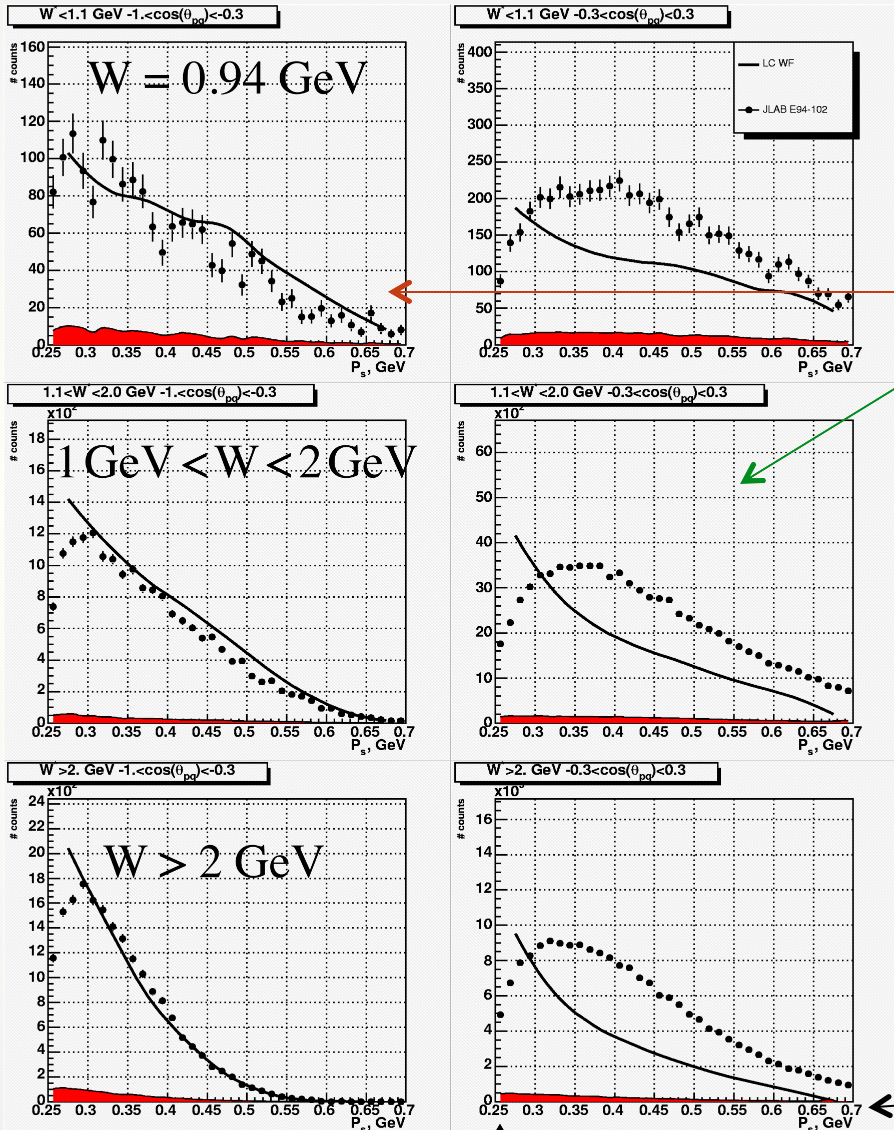


CLAS





Results from "Deeps": Momentum Distribution



Vertical axis: Number of events

Horizontal axis: Proton momenta from 250 to 700 MeV/c

Left: Angular range > 107.5^{O}
Right: Angular range 72.5^{O} - 107.5^{O}

3 different ranges in the final state mass W of the unobserved struck neutrons

PWIA model with "light cone"-wave function for deuterium

700 MeV/c

P_s

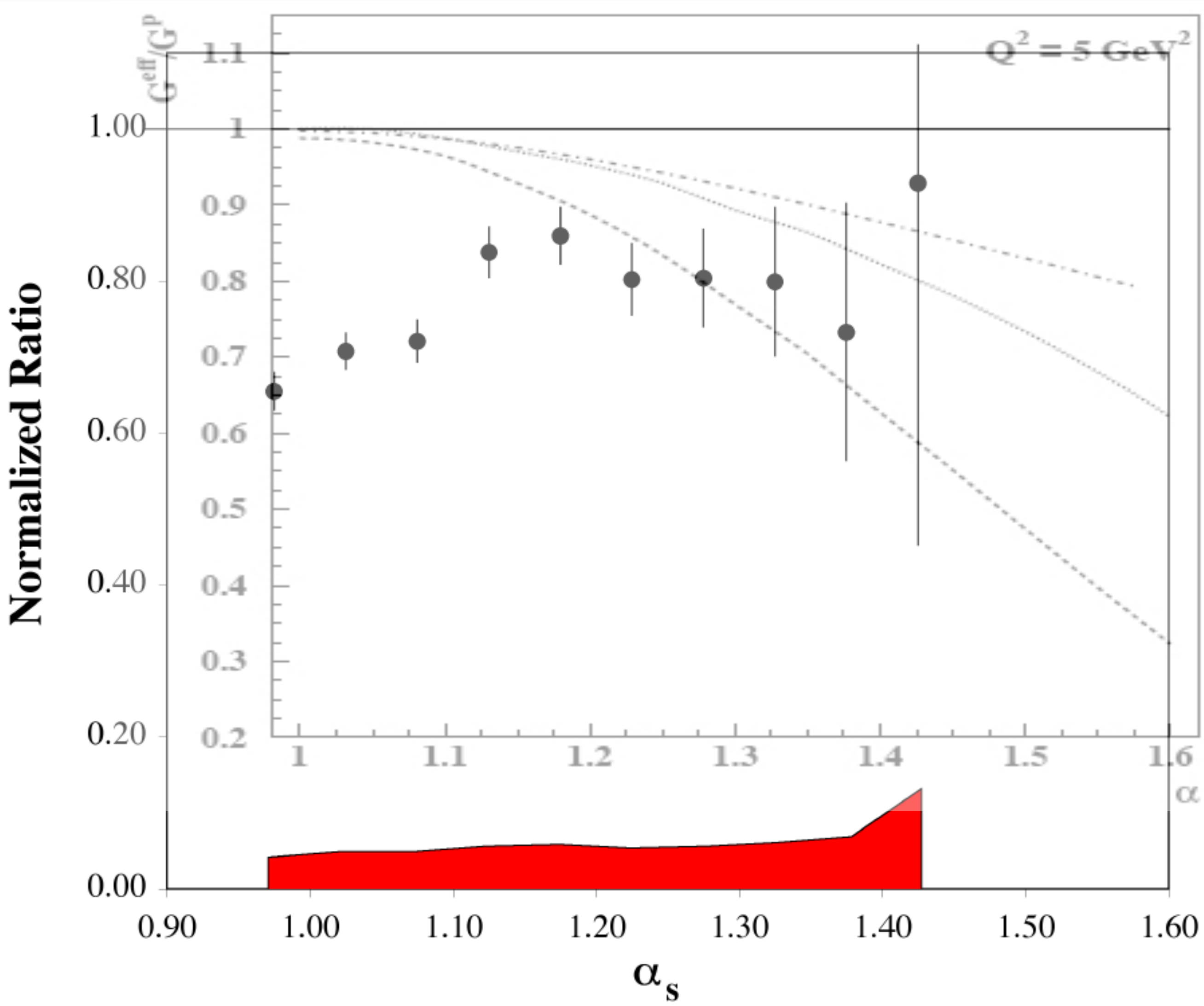
250 MeV/c

Results from "Deeps": Ratio Method

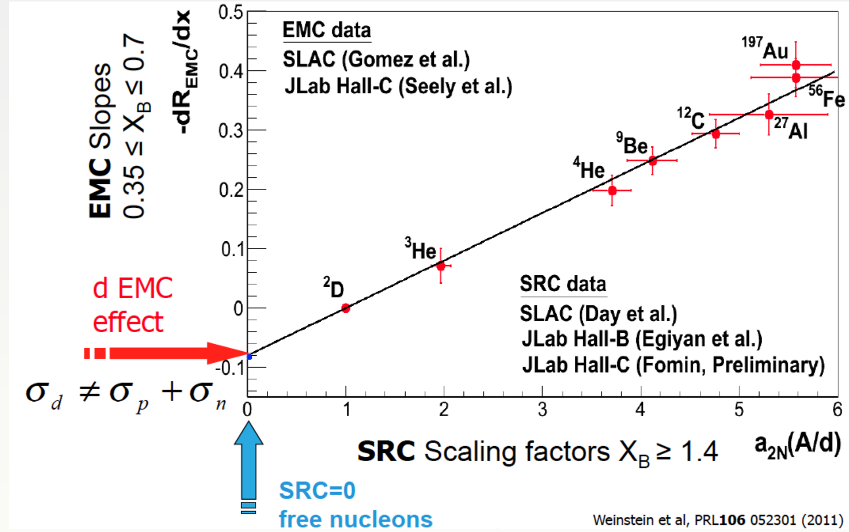
Ratio =

$$\frac{\dfrac{\sigma(x^*=0.55,\alpha_s)}{\sigma(x^*=0.25,\alpha_s)}(\text{bound n})}{\dfrac{\sigma(x=0.55)}{\sigma(x=0.25)}(\text{free n})}$$

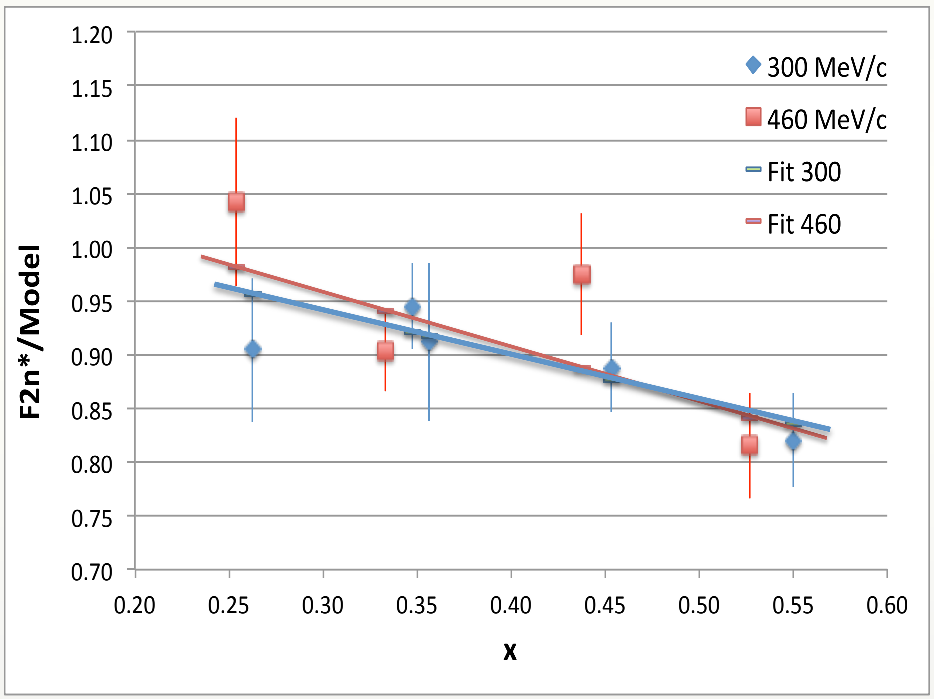
- Independent of deuteron WF, acceptance, kinematic factors
- Should be sensitive to off-shell effects at large x, but also influenced by FSI and target fragmentation
- Fixed p_T = 0.3 GeV/c - TOO LARGE!

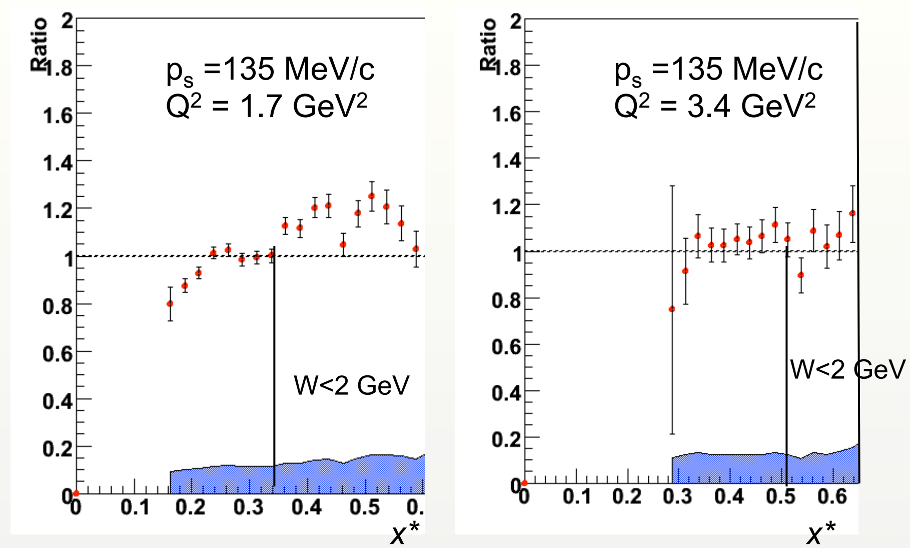


What can we say about the EMC effect in Deuterium?



Slope for most tightly bound nuclei (20% SRC) about -0.4!





Deeps backward angles > 110^o
Slope approx. -0.4 – -0.5 nearly independent of p_s

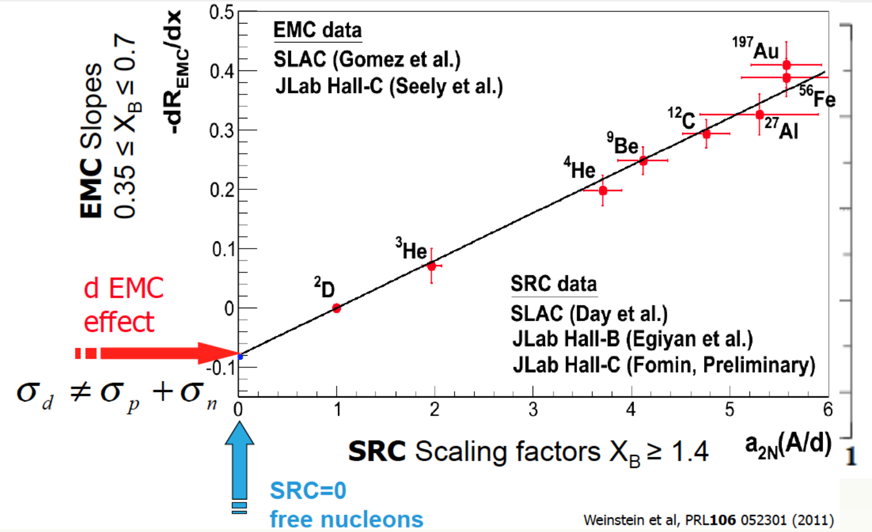
BoNuS results for low p_s indicate little dependence on x^*

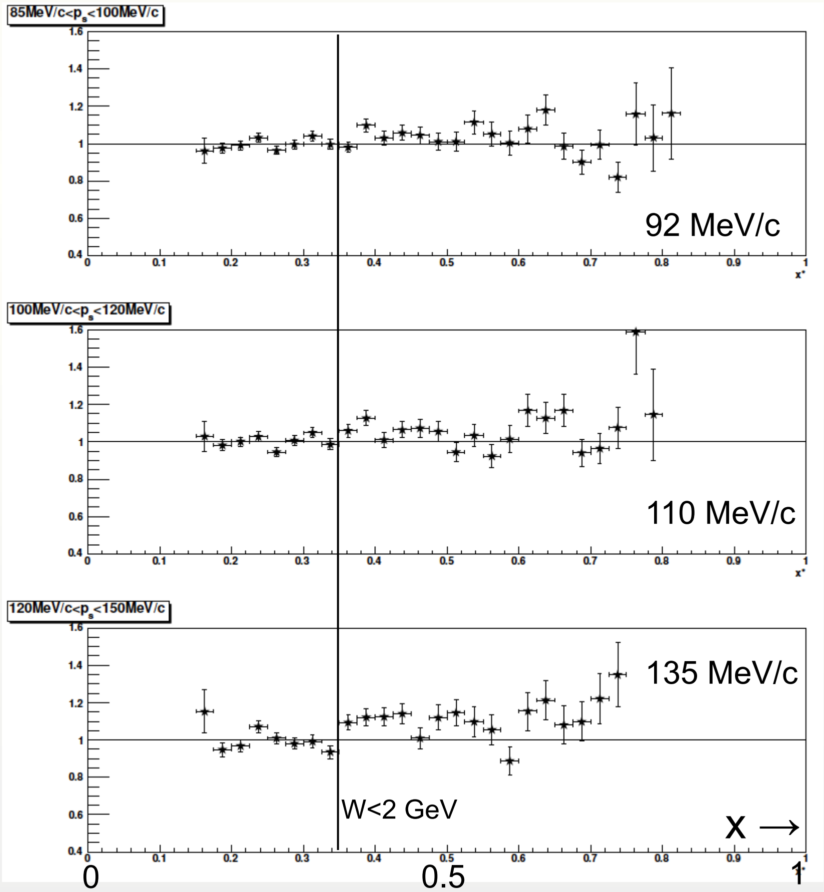
What can we say about the EMC effect in Deuterium?

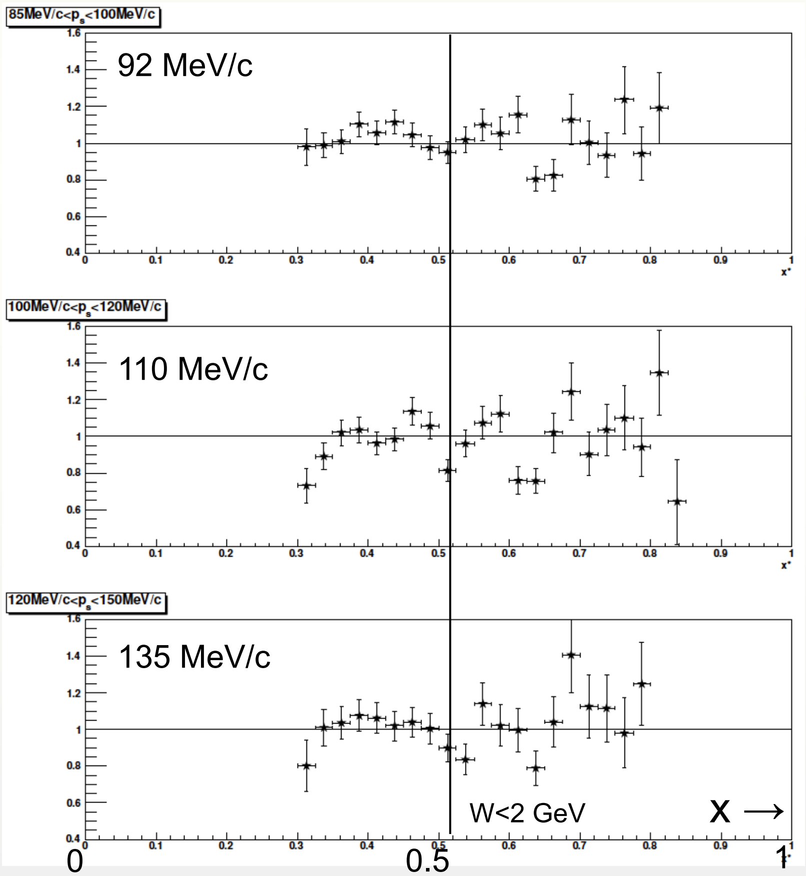
see talk by L. Weinstein

Ratio $F_{2n}(x, p_s)/F_{2n}(x,p_s=78\ \text{MeV/c})$

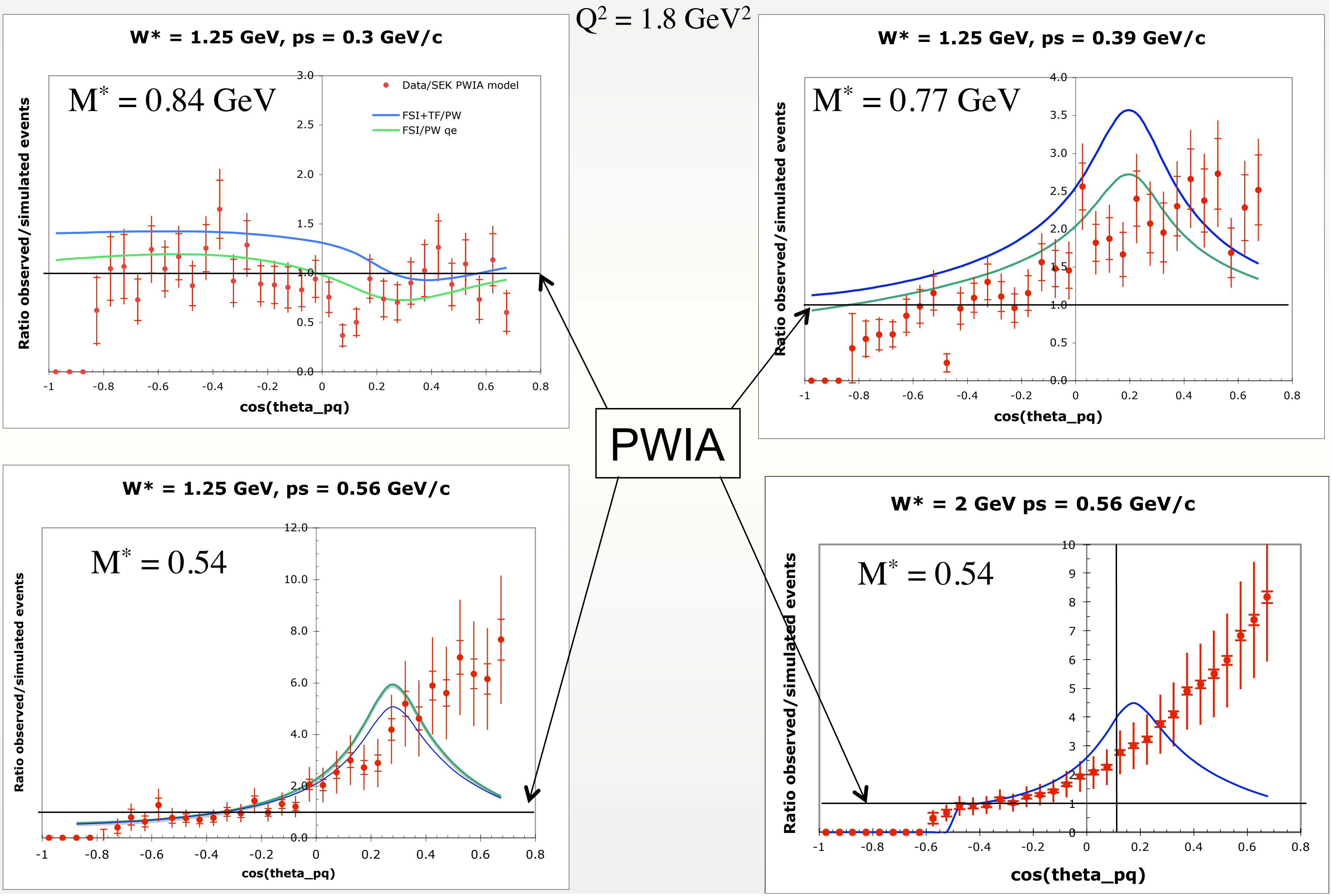
as function of spectator momentum p_s



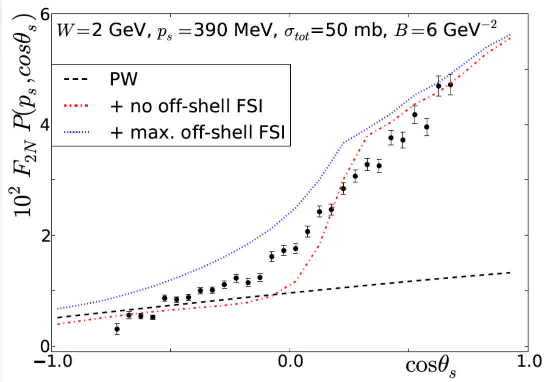




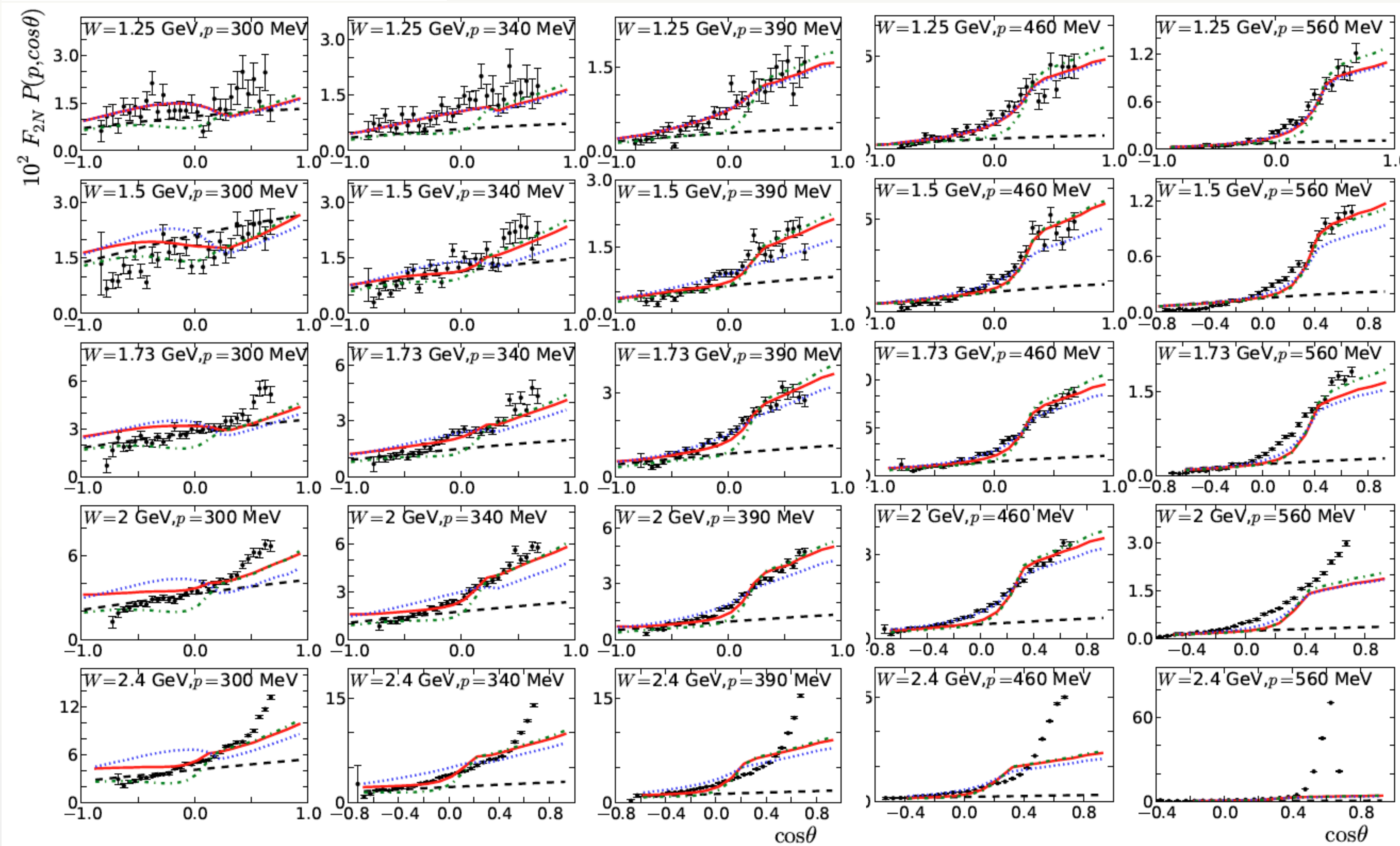
Results from “Deeps”: Comparison w/ FSI model (CdA et al.)



Further Study of FSI

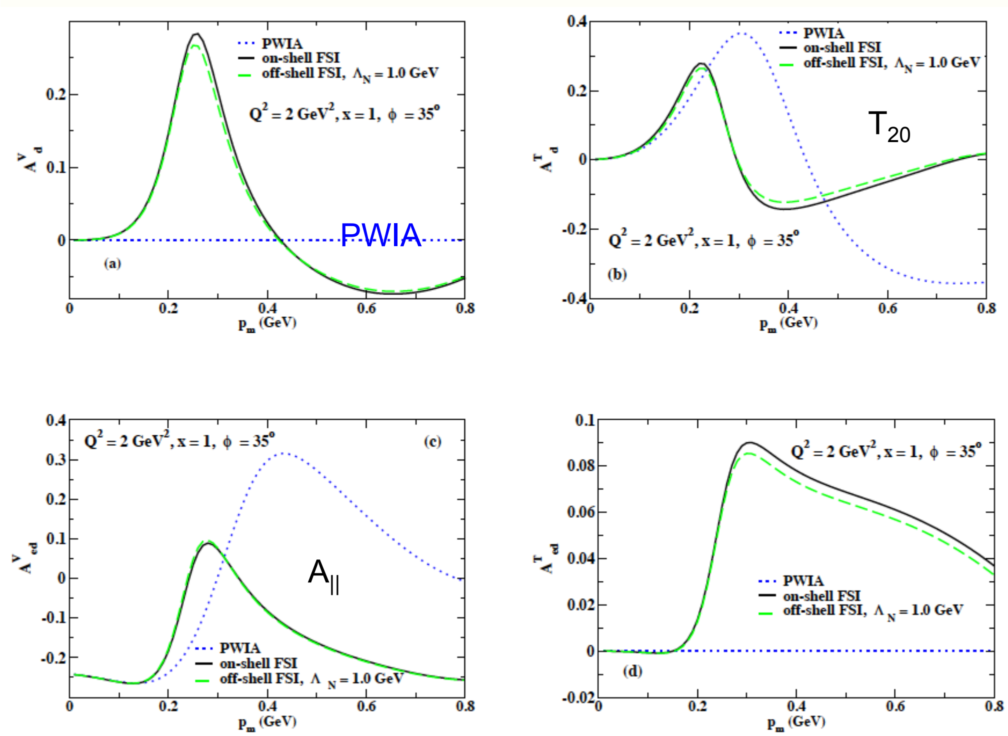


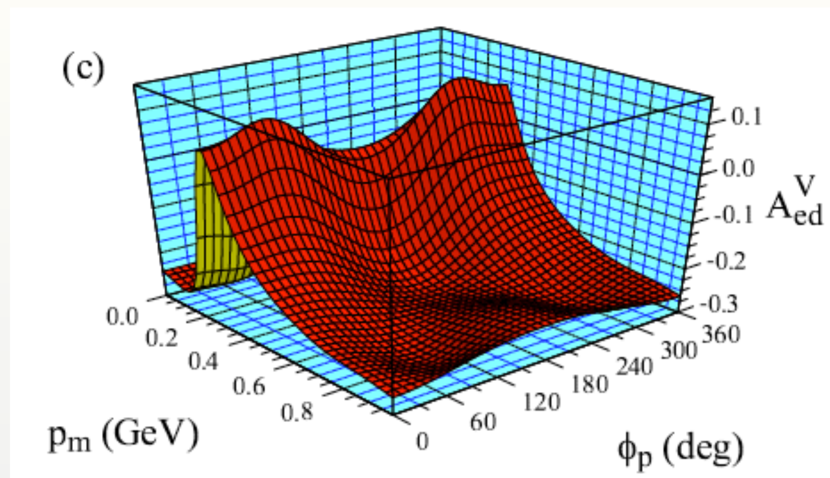
W. Cosyn and M. Sargsian

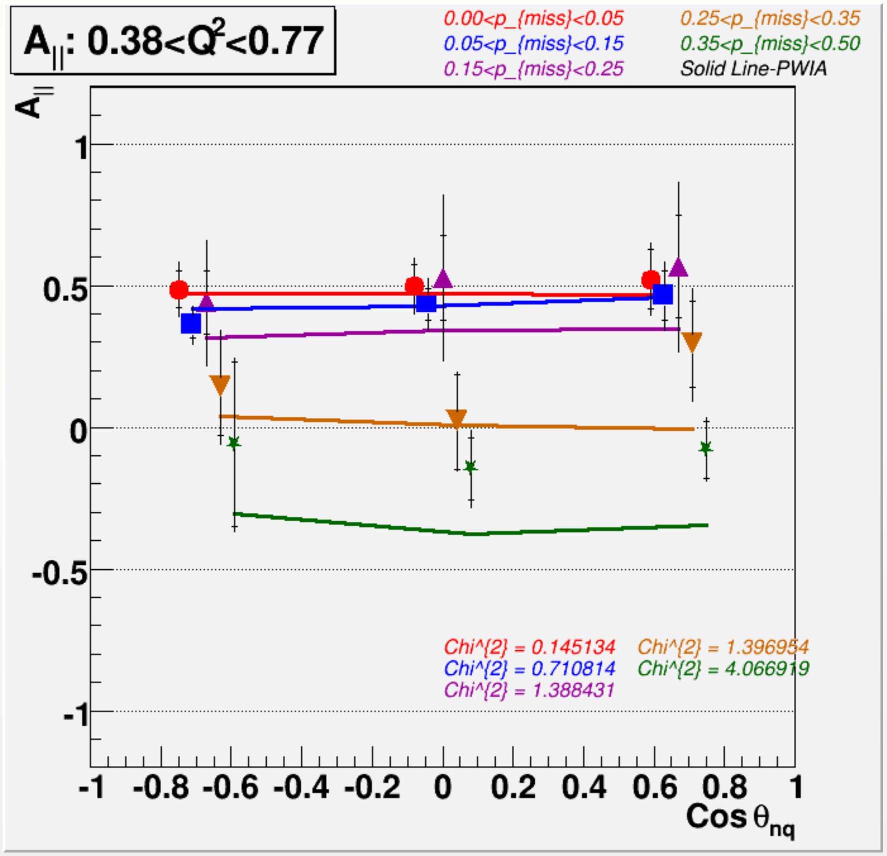


Testing FSI Models in the quasi-elastic channel

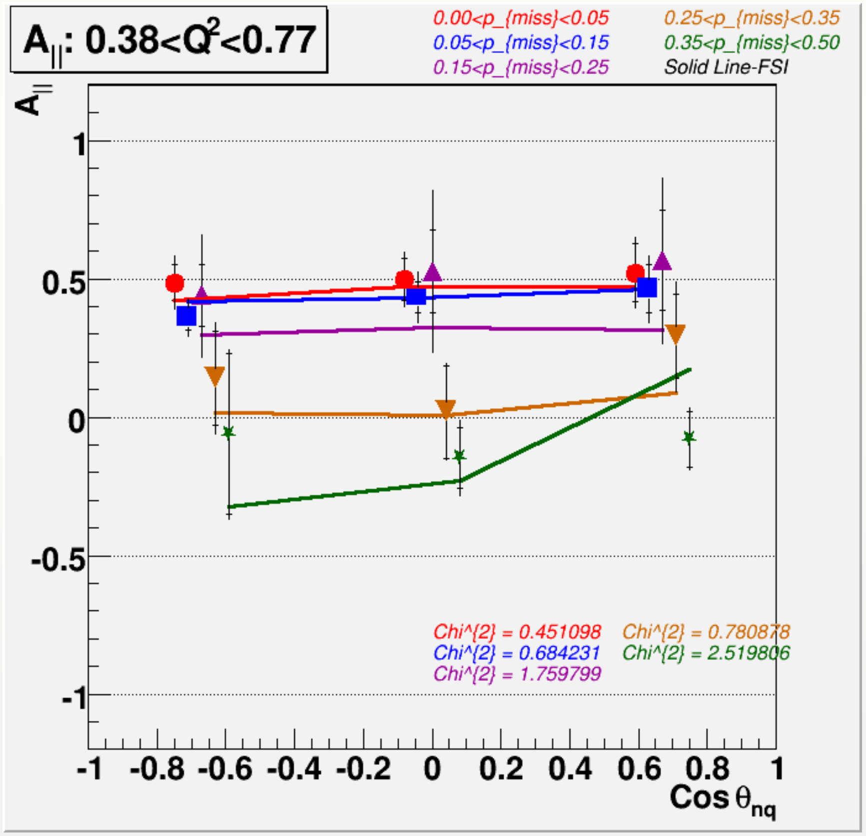
- W. Van Orden and S. Jeschonnek have developed a fully relativistic description of cross sections, vector and tensor asymmetries for D(e,e'p)n, including (spin-dependent) FSI (based on known phase shifts)



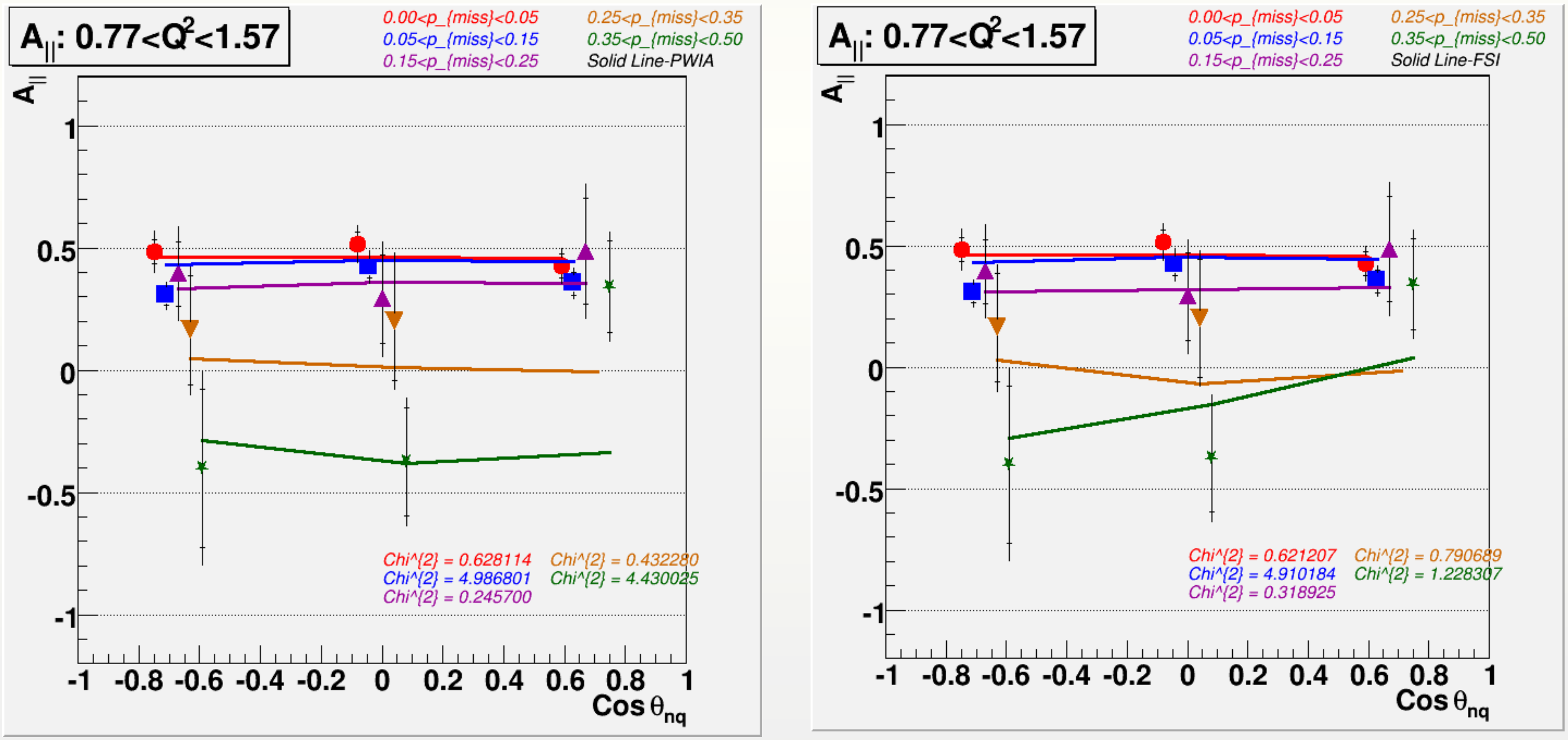




A||: 0.38<Q2<0.77
0.00<p_{miss}<0.05
0.05<p_{miss}<0.15
0.15<p_{miss}<0.25
0.25<p_{miss}<0.35
0.35<p_{miss}<0.50
Solid Line-PWIA
A||
Chi^{2} = 0.145134
Chi^{2} = 0.710814
Chi^{2} = 1.388431
Chi^{2} = 1.396954
Chi^{2} = 4.066919
Cos θnq



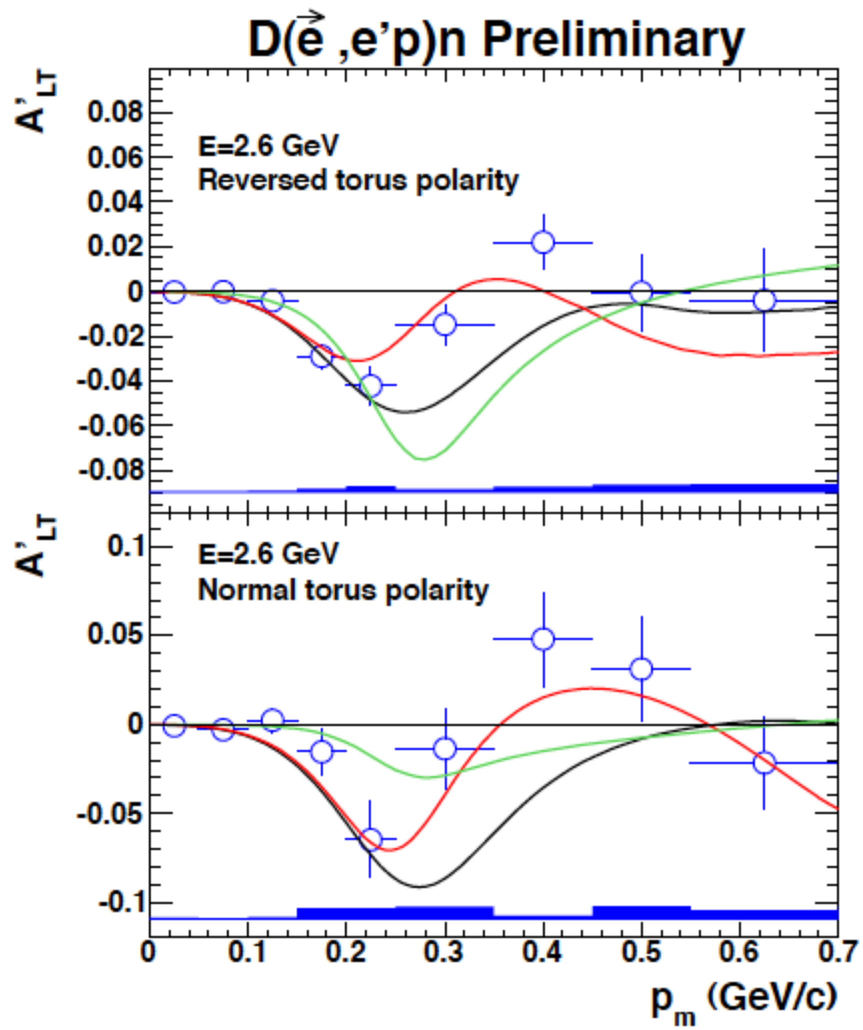
A||: 0.38<Q2<0.77
0.00<p_{miss}<0.05
0.05<p_{miss}<0.15
0.15<p_{miss}<0.25
0.25<p_{miss}<0.35
0.35<p_{miss}<0.50
Solid Line-FSI
A||
Chi^{2} = 0.451098
Chi^{2} = 0.684231
Chi^{2} = 1.759799
Chi^{2} = 0.780878
Chi^{2} = 2.519806
Cos θnq



A||: 0.77<Q2<1.57
0.00<p_{miss}<0.05
0.05<p_{miss}<0.15
0.15<p_{miss}<0.25
0.25<p_{miss}<0.35
0.35<p_{miss}<0.50
Solid Line-PWIA
Chi^{2} = 0.628114
Chi^{2} = 4.986801
Chi^{2} = 0.245700
Chi^{2} = 0.432280
Chi^{2} = 4.430025
Cos θnq
A||: 0.77<Q2<1.57
0.00<p_{miss}<0.05
0.05<p_{miss}<0.15
0.15<p_{miss}<0.25
0.25<p_{miss}<0.35
0.35<p_{miss}<0.50
Solid Line-FSI
Chi^{2} = 0.621207
Chi^{2} = 4.910184
Chi^{2} = 0.318925
Chi^{2} = 0.790689
Chi^{2} = 1.228307
Cos θnq

5^{th} structure Function in d(e,e'p) – J. Gilfoyle

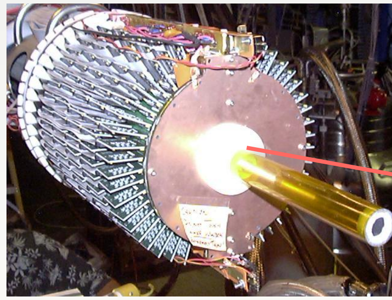
1. Arenhövel (black) - Non-relativistic Schrödinger Equation with RC, MEC, IC, and FSI. Averaged over the CLAS acceptance.
2. Laget (green) - Diagrammatic approach for $Q^2 = 1.1\ \mathrm{GeV}^2$ (lower panel) and $Q^2 = 0.7\ \mathrm{GeV}^2$ (upper panel).
3. Jeschonnek and Van Orden (JVO in red) - Relativistic calculation in IA, Gross equation for the deuteron ground state, SAID parameterization of the NN scattering amplitude for FSI . Off-shell form factor cutoff set to $\Lambda_N = 1.0\ \mathrm{GeV}$ (PRc, 81, 014008, 2010). Averaged over the CLAS acceptance.

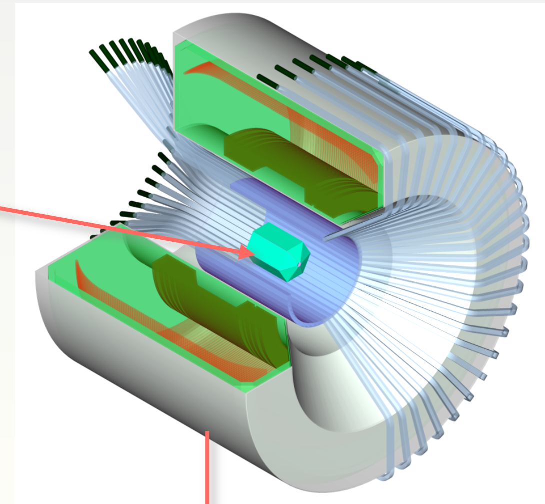


CLAS data mining

- Joint effort of a large group of people (many of them here) to re-analyze existing nuclear target data from CLAS
- Proposal to DOE for funding (mostly for a dedicated postdoc) - presently “in limbo”
- Relevant for spectator physics:
  – E6 data, $d(e,e'p_s)X$: extend Q^2 range, lower p momentum threshold
  – E6 data: Look for $d(e,e'\Delta_s)\Delta$ and other “exotic” final states
  – EG1/EG4/EG1-DVCS: study $\vec{d}(\vec{e},e'p)n$ *vs*. missing momentum to learn more about spin effects and FSI
- Discussion Friday afternoon

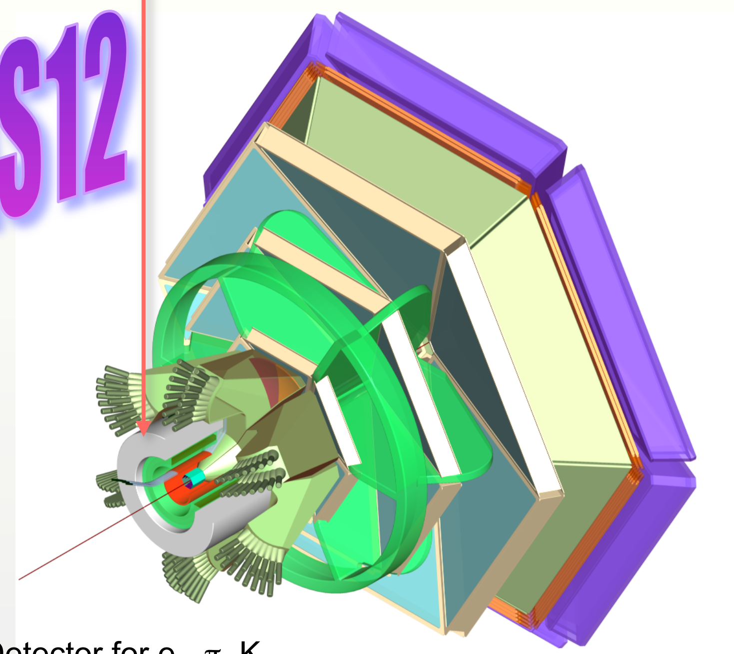
Plans for Jefferson Lab at 11-12 GeV





Central Detector

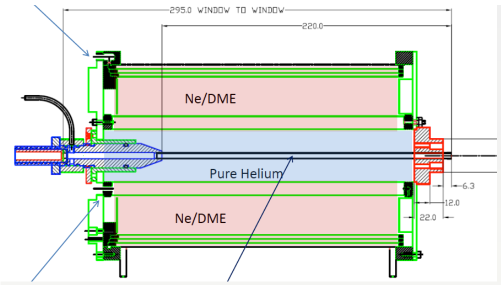
CLAS12

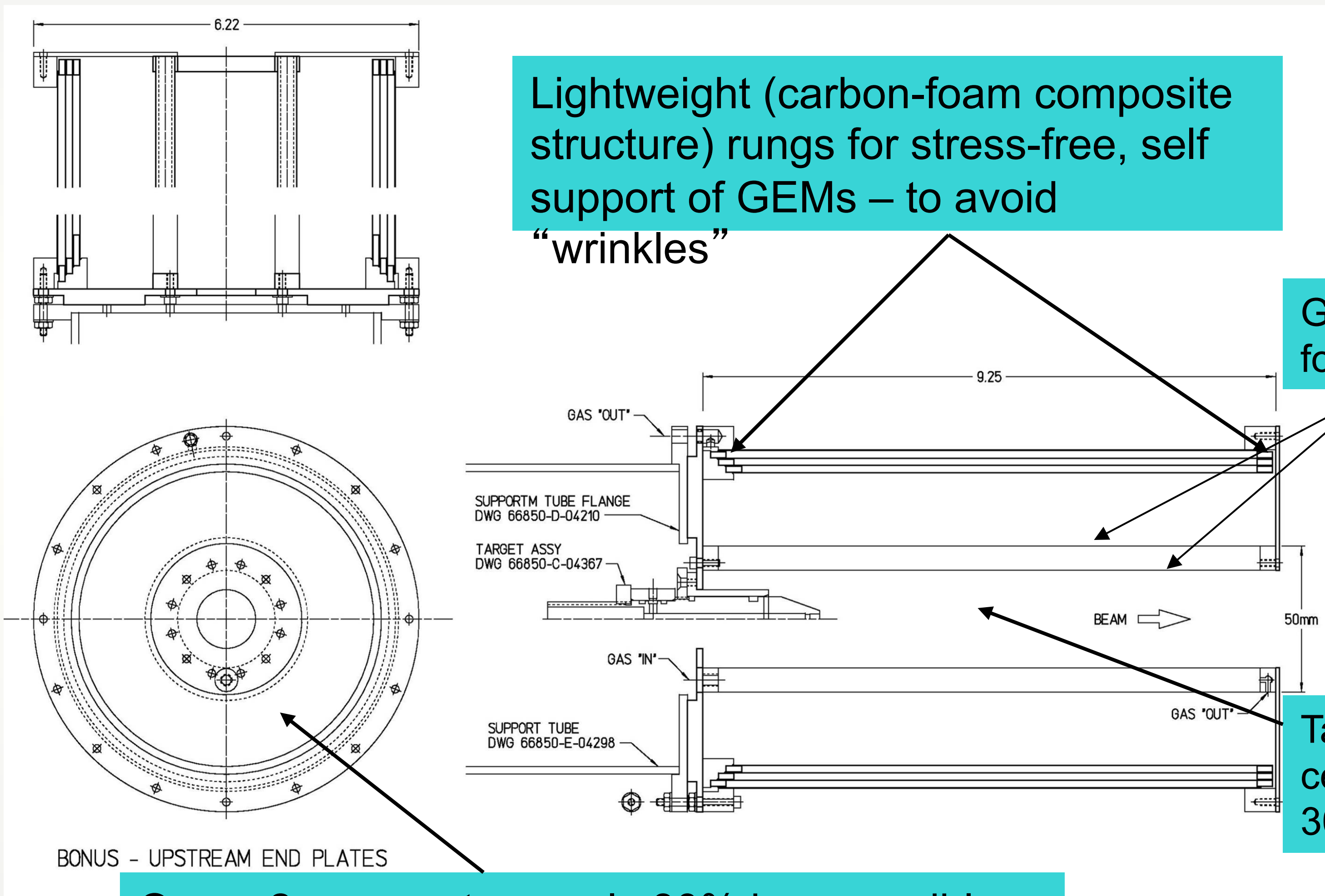


Forward Detector for e-, π, K,…

- CLAS12 will have central detector for medium-low momentum large angle particles
- Can be replaced by “BoNuS” type RTPC for much lower spectator momenta
- Can insert polarized target inside Central Detector - study tagged pol. SFs? (Polarized EMC effect LOI [Brooks] approved by PAC35)

The New RTPC



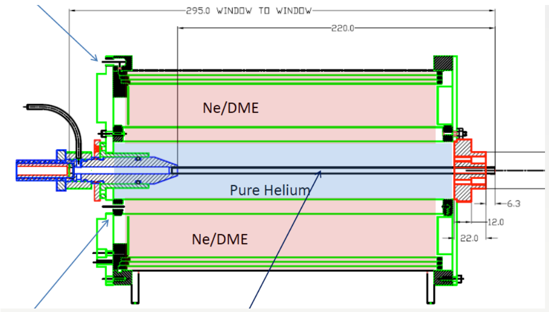


Lightweight (carbon-foam composite structure) rungs for stress-free, self support of GEMs – to avoid "wrinkles"

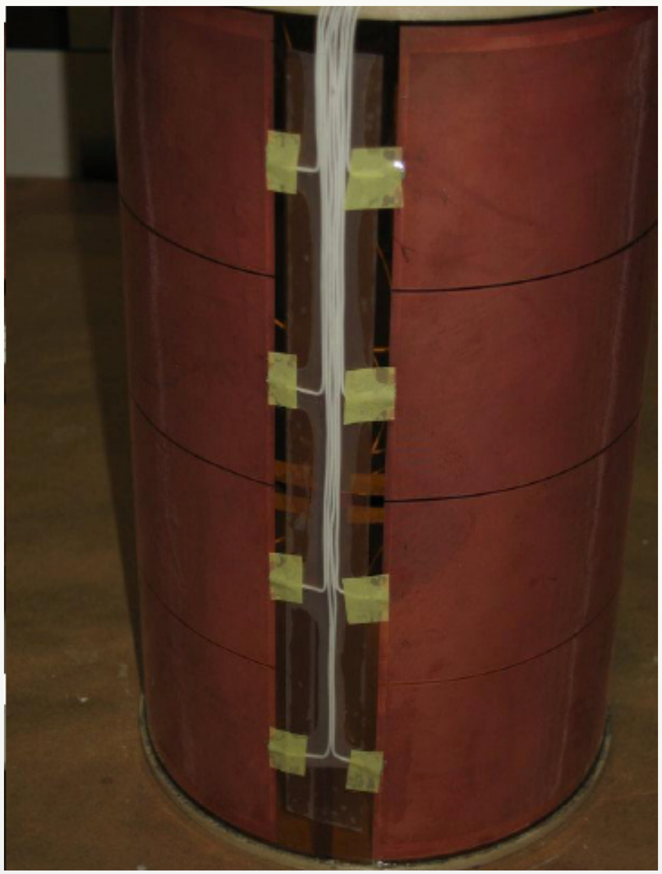
Ground and cathode foils, each 6μm thick

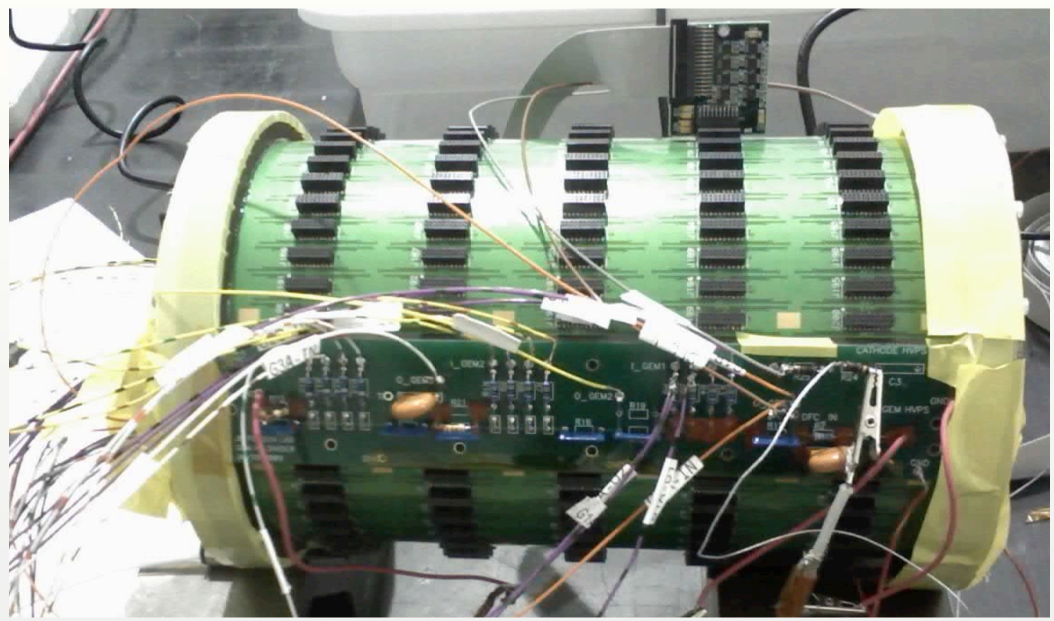
Target region - new cell – ID 4mm, 30μm thick wall

Open, 2π geometry – only 80% is accessible due to the GEM and readout pad sizes



The New RTPC (ii)

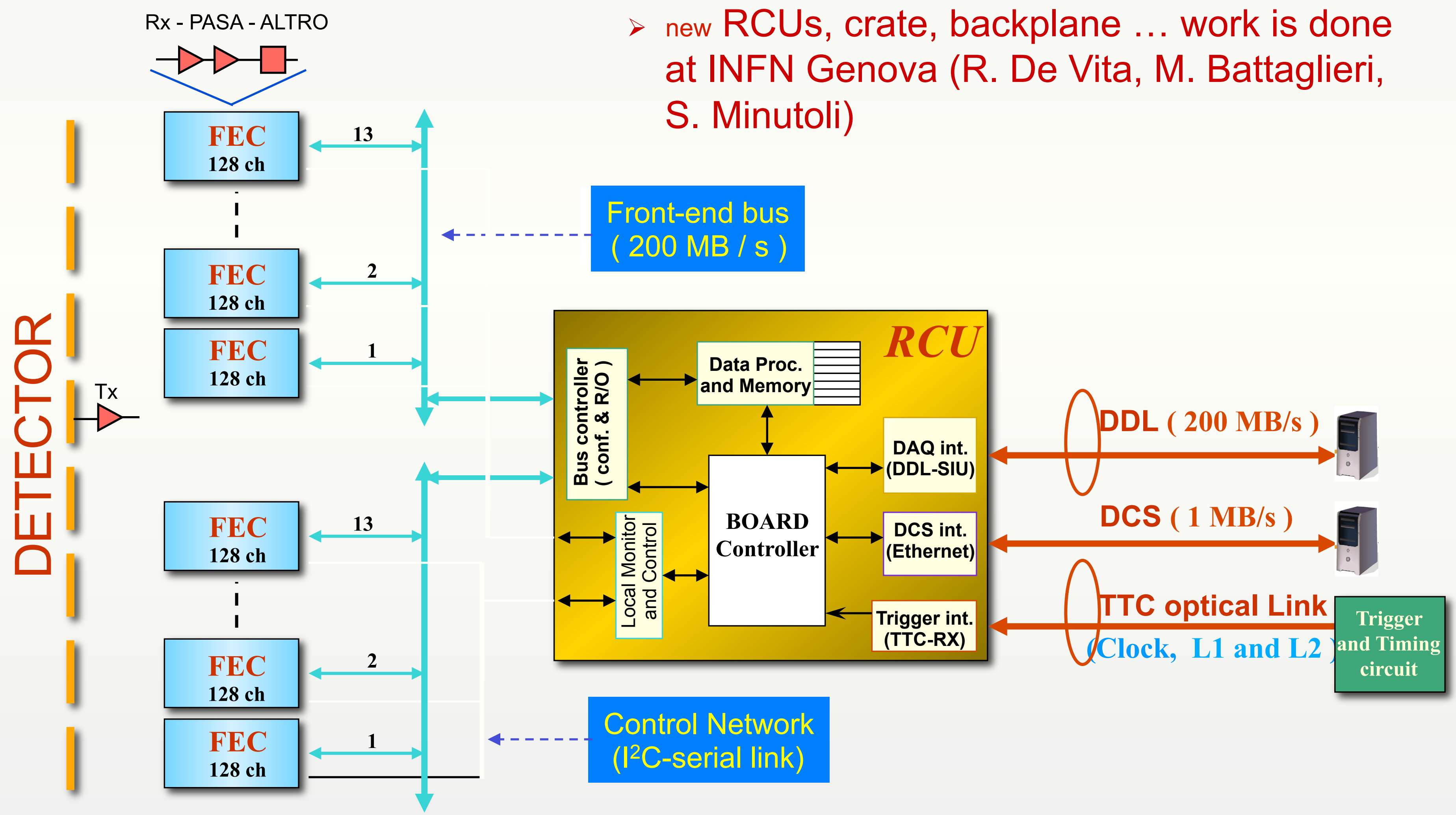




DAQ with new Readout Control Unit board

Increased DAQ rate - 0.5 kHz to 5 kHz

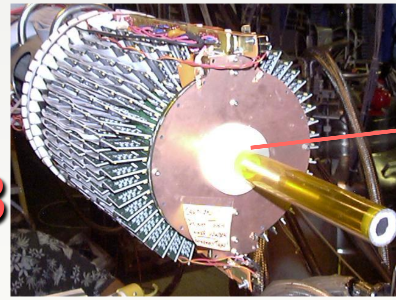
- new RCUs, crate, backplane … work is done at INFN Genova (R. De Vita, M. Battaglieri, S. Minutoli)

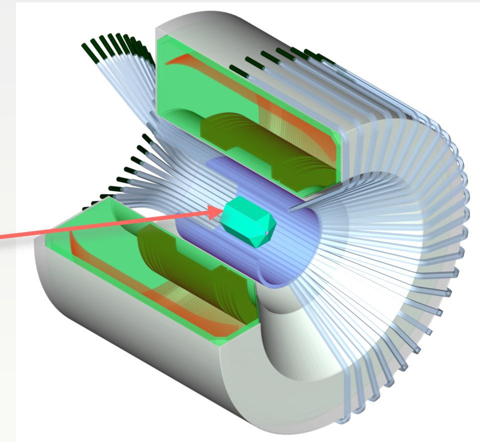


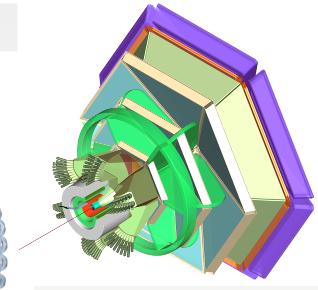
Plans for 12 GeV

BoNuS

E12-06-113

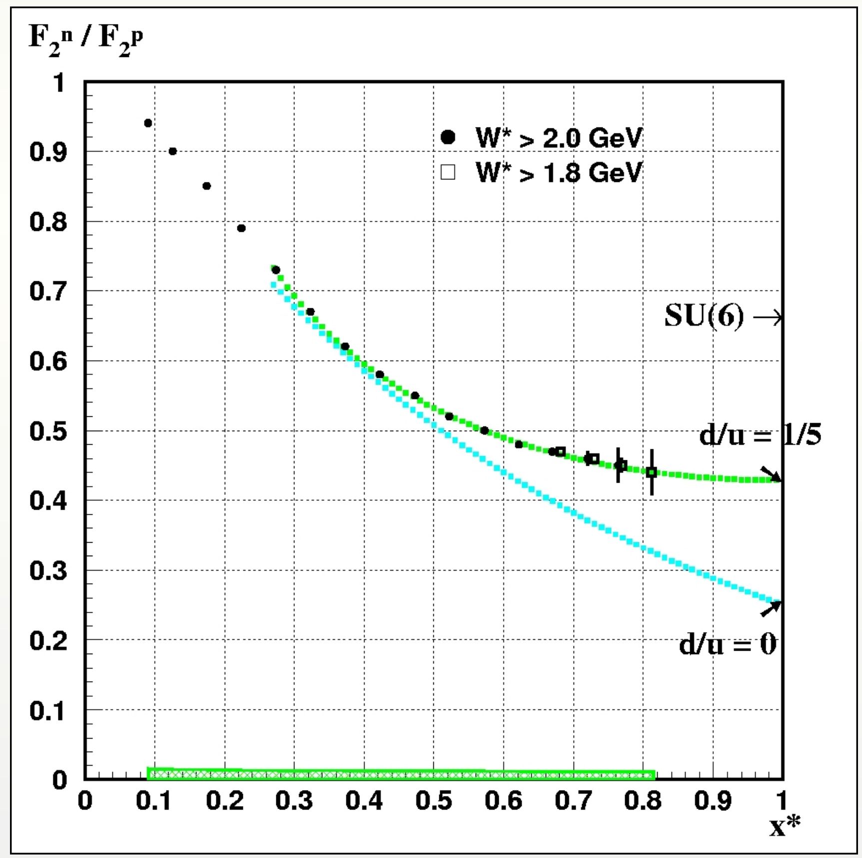






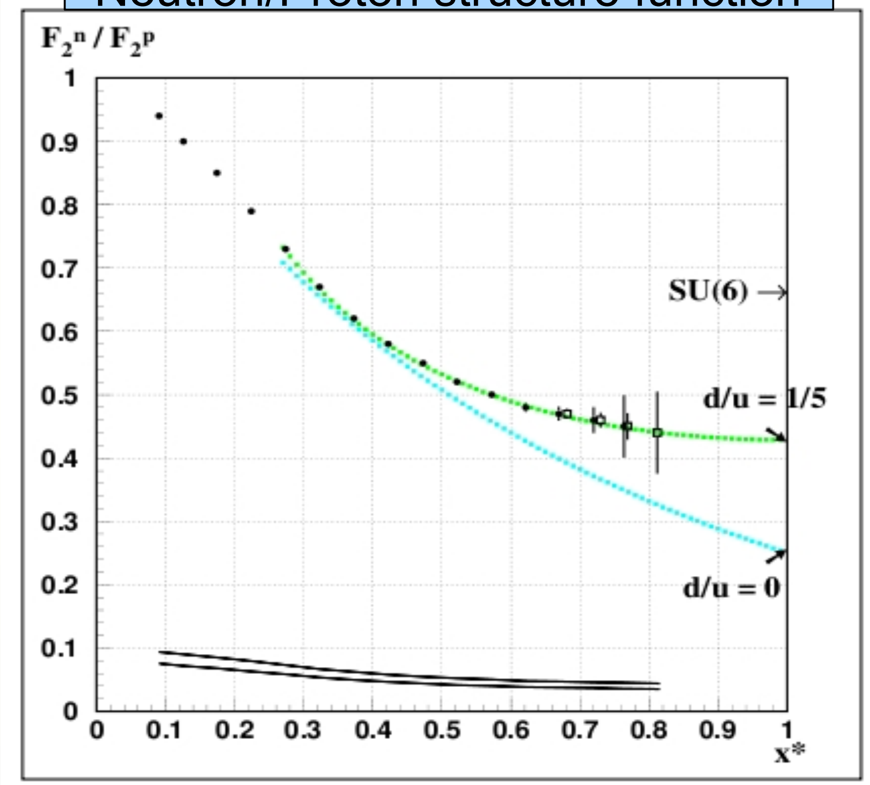
CLAS12
Central
Detector

- Data taking of 35 days on D_2 and 5 days on H_2 with $\mathcal{L} = 2 \cdot 10^{34}\ \text{cm}^{-2}\ \text{sec}^{-1}$
- **Planned** BoNuS detector DAQ and trigger **upgrade**
- DIS region with
  - $Q^2 > 1\ \text{GeV}^2/c^2$
  - $W^* > 2$ GeV
  - $p_s > 70$ MeV/c
  - $10° < \theta_{pq} < 170°$
- Largest value for $x^* = 0.80$ (bin centered $x^* = 0.76$)
- Extend to higher momenta using central detector alone

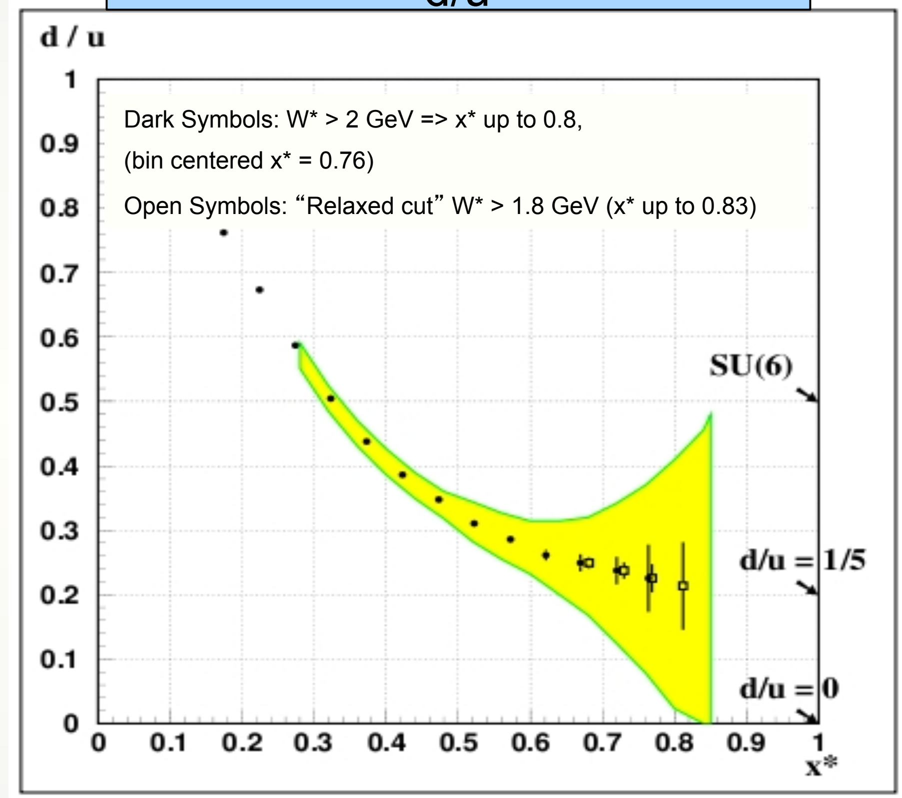


Expected Results - BoNuS12 E12-06-113

Neutron/Proton structure function



d/u



Data taking of 35 days on D_2 and 5 days on H_2 with $\mathcal{L} = 2 \cdot 10^{34}$ cm^{-2} sec^{-1}

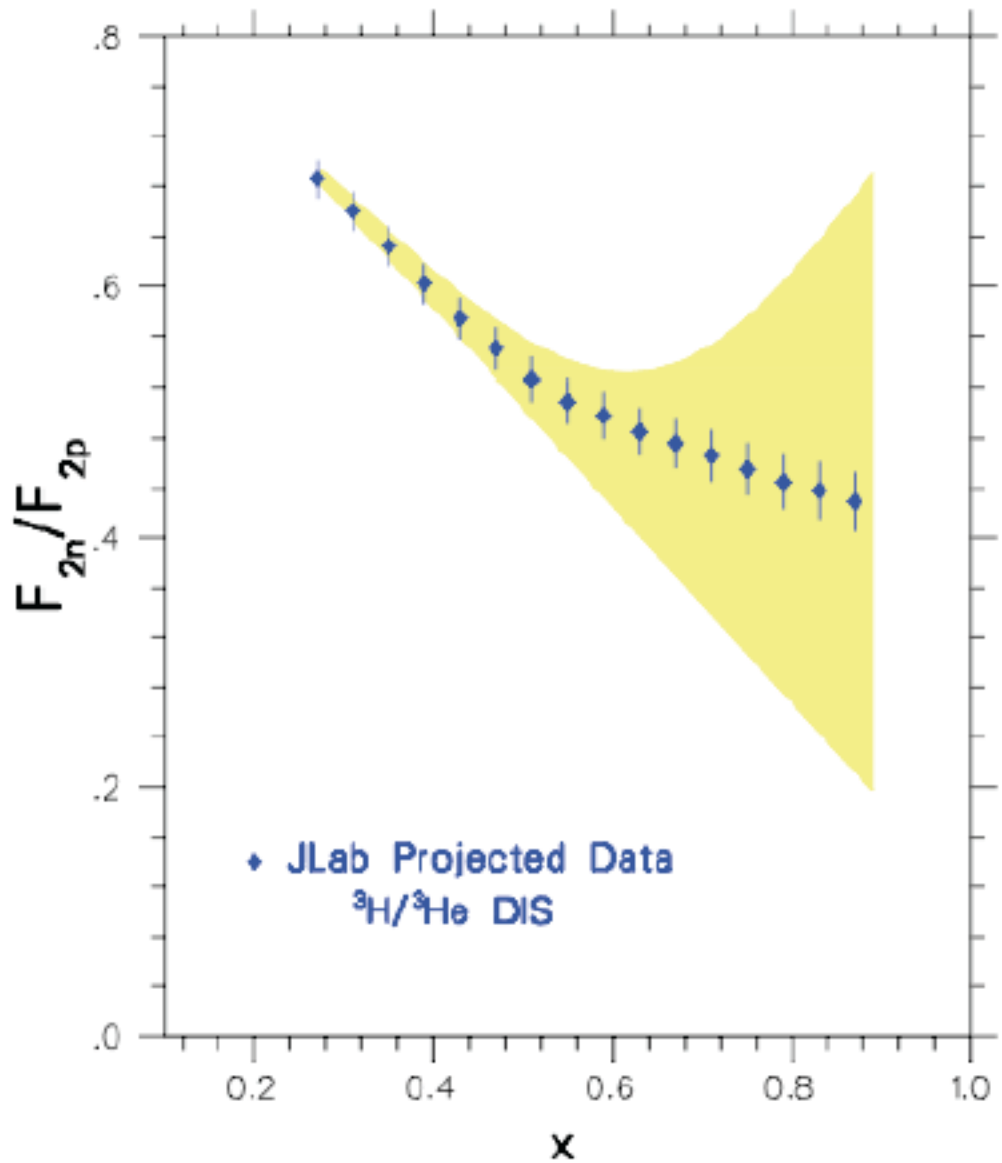
- DIS region with
  - $Q^2 > 1$ GeV$^2/c^2$
  - $W^* > 2$ GeV
  - $p_s > 70$ MeV/c
  - $-10° < \theta_{pq} < 170°$

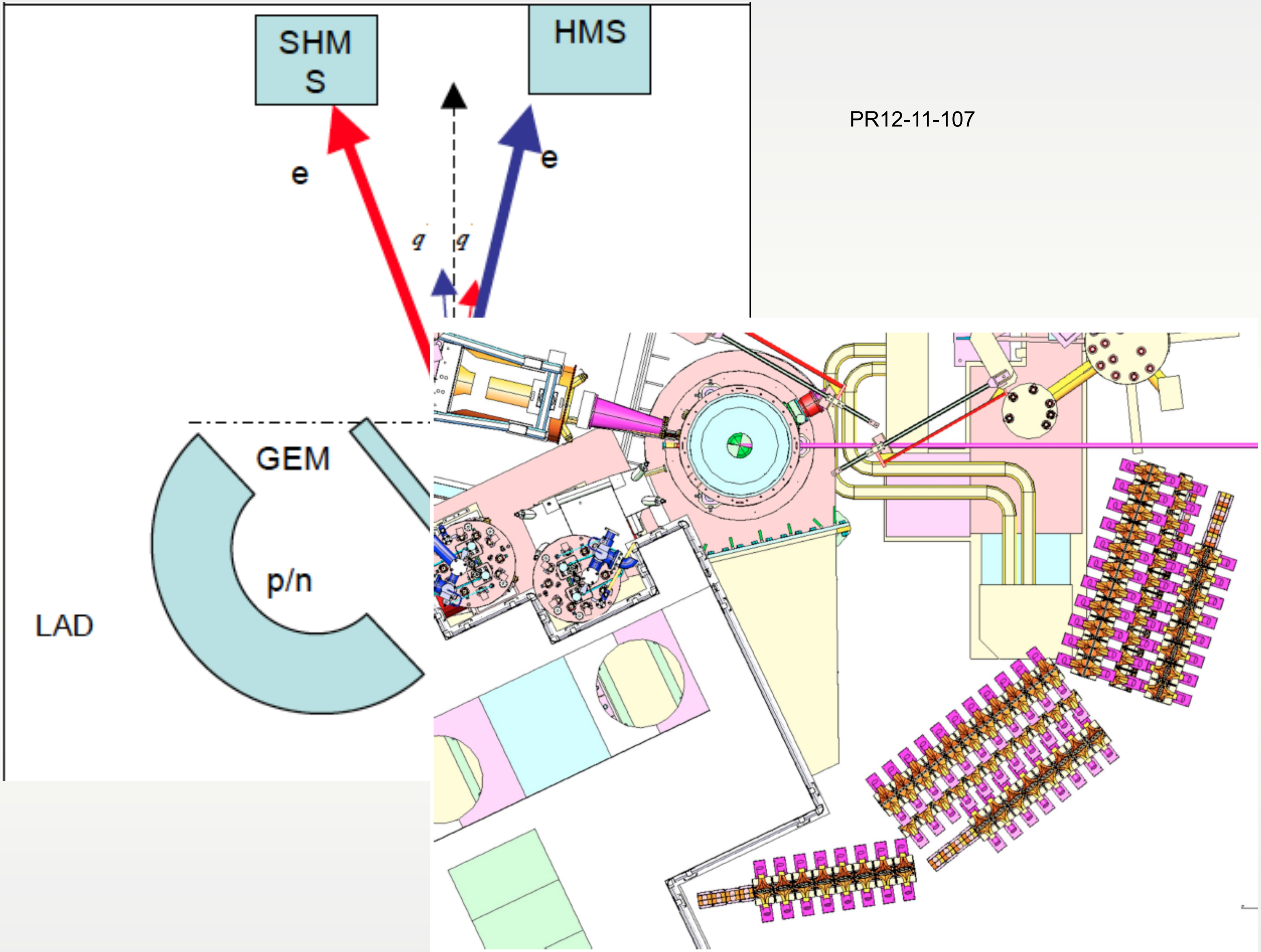
New methods – DIS from A=3 ("MARATHON")

- extract n/p ratio from ratio of A=3 structure functions

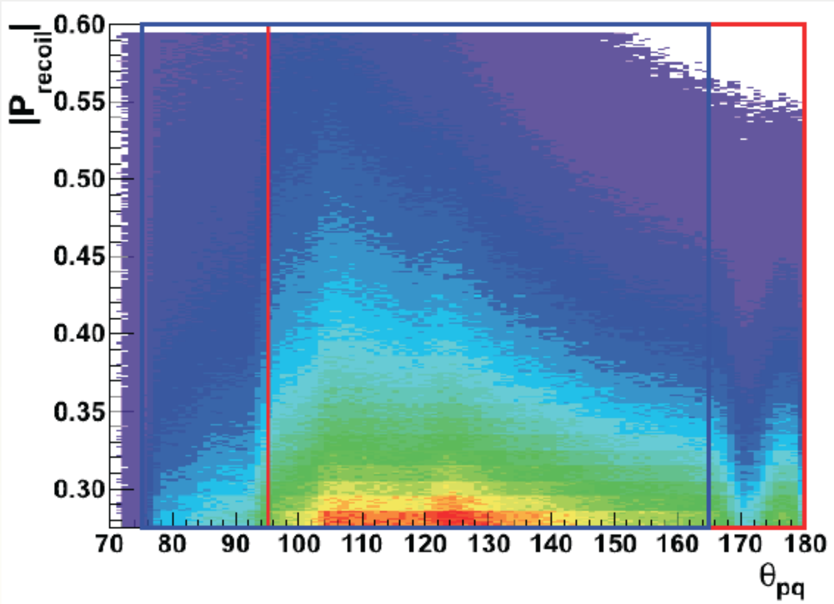
$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}}{2F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}} - \mathcal{R}}$$

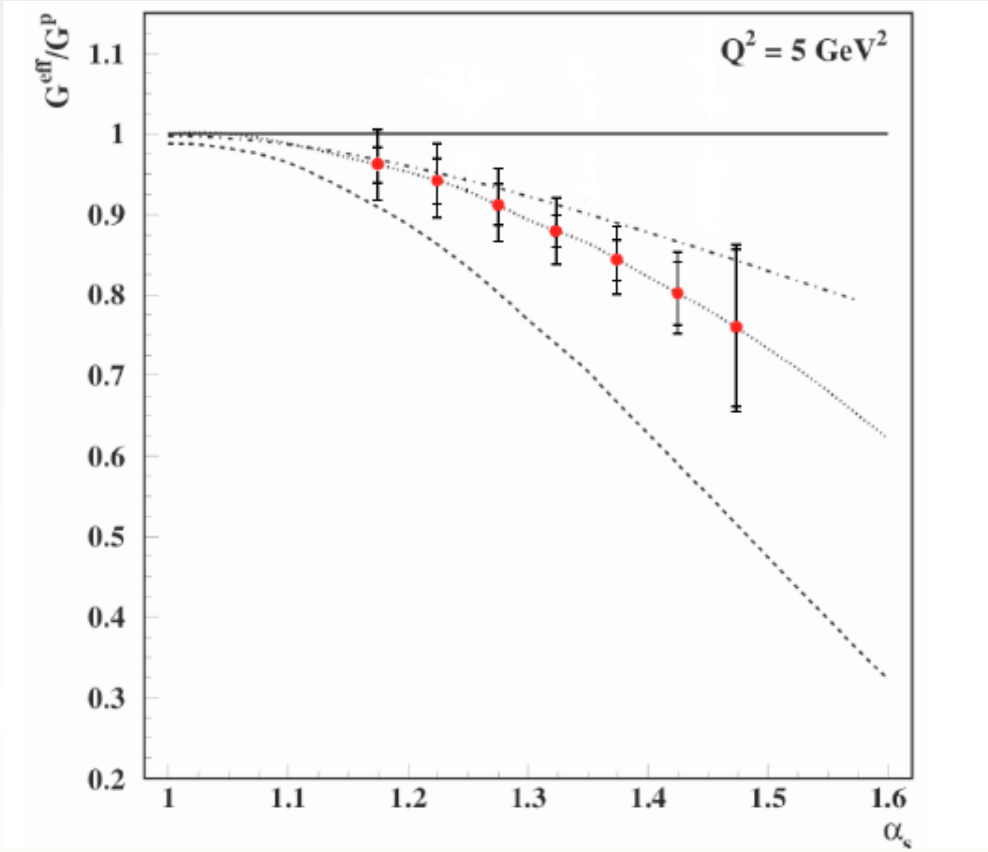
→ ratio of ^{3}He to ^{3}H EMC ratios cancels to ~1% for $x < 0.85$





PR12-11-107


|P_recoil|
0.60
0.55
0.50
0.45
0.40
0.35
0.30
70 80 90 100 110 120 130 140 150 160 170 180
θ_pq


G^eff/G^p
Q^2 = 5 GeV^2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1 1.1 1.2 1.3 1.4 1.5 1.6
α_s

PR12-11-107

Conclusion

- Few-body nuclei (D and ^{3}He) continue to be “neutron targets of choice”
- Interpretation of results complicated by off-shell effects, possible structure modifications and final state interaction…
- …but we can also learn a lot about NN interaction and few-body nuclear structure by studying these effects
- New, more precise theoretical calculations are becoming available and can be tested experimentally
- New experimental techniques allow us to minimize binding effects or study them in detail
- Started new initiative to “mine” CLAS data for more insight into the interplay between Nuclear and Quark d.o.f.
- Lots more data at 12 GeV!

Conclusion - Status of Spectator Experiments

- Lots of data with coincident spectator detection already exist, many have been (partially) analyzed
  - FSI seems very important in perpendicular and forward kinematics
  - simple spectator picture with LC wave functions seems to work reasonably in some kinematic regions
  - Possible modifications of internal nucleon structure (dependent on spectator momentum) still an open question
- New data from EG6 will extend this study to ^{4}He target
- Data mining initiative will unlock much more information from all nuclear data taken with CLAS
- Lots more exciting experiments after JLab energy upgrade!
- Requires theory-experiment interaction: Agree on definition of "reduced cross section"; need predictions of this cross section including FSI over large kinematic range (not only for p_T = 0 ;-)
- ULTIMATE GOAL: EIC - can smoothly map out $p_{spect.}$ from 0 to 1 GeV/c

Announcement

- Satellite Meeting of the Jefferson Lab Users Group TODAY at 12:30 in the Santa Fe Hilton, Mesa A room
- Lunch (sandwiches) will be served
- Find out what's going on at JLab and what the Users Group Board of Directors is up to