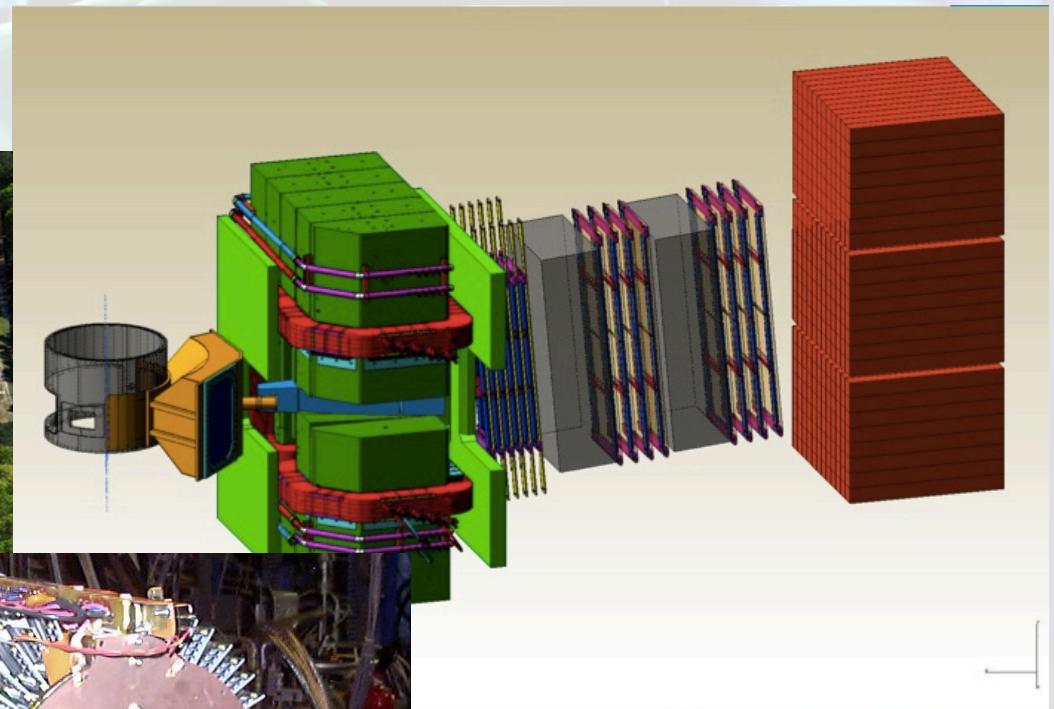
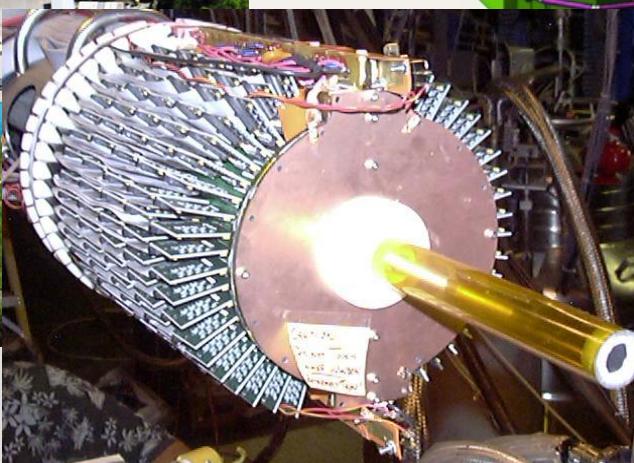
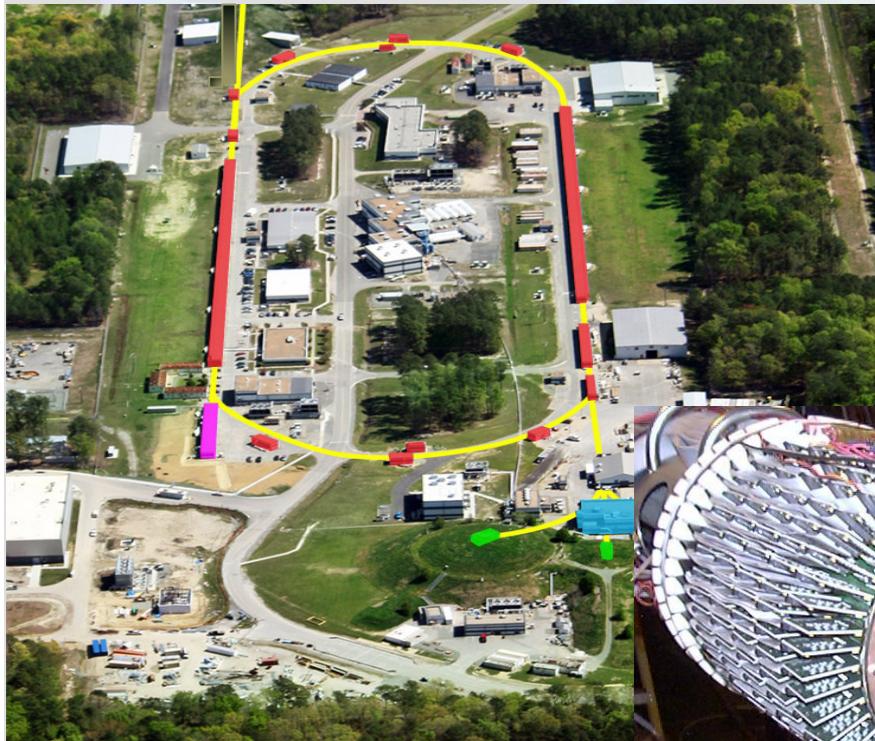




Tagging DIS Processes at 12 GeV at JLab

Thia Keppel



EMMI Workshop on Cold Dense Nuclear Matter
GSI, October 2015

Jefferson Lab
Thomas Jefferson National Accelerator Facility

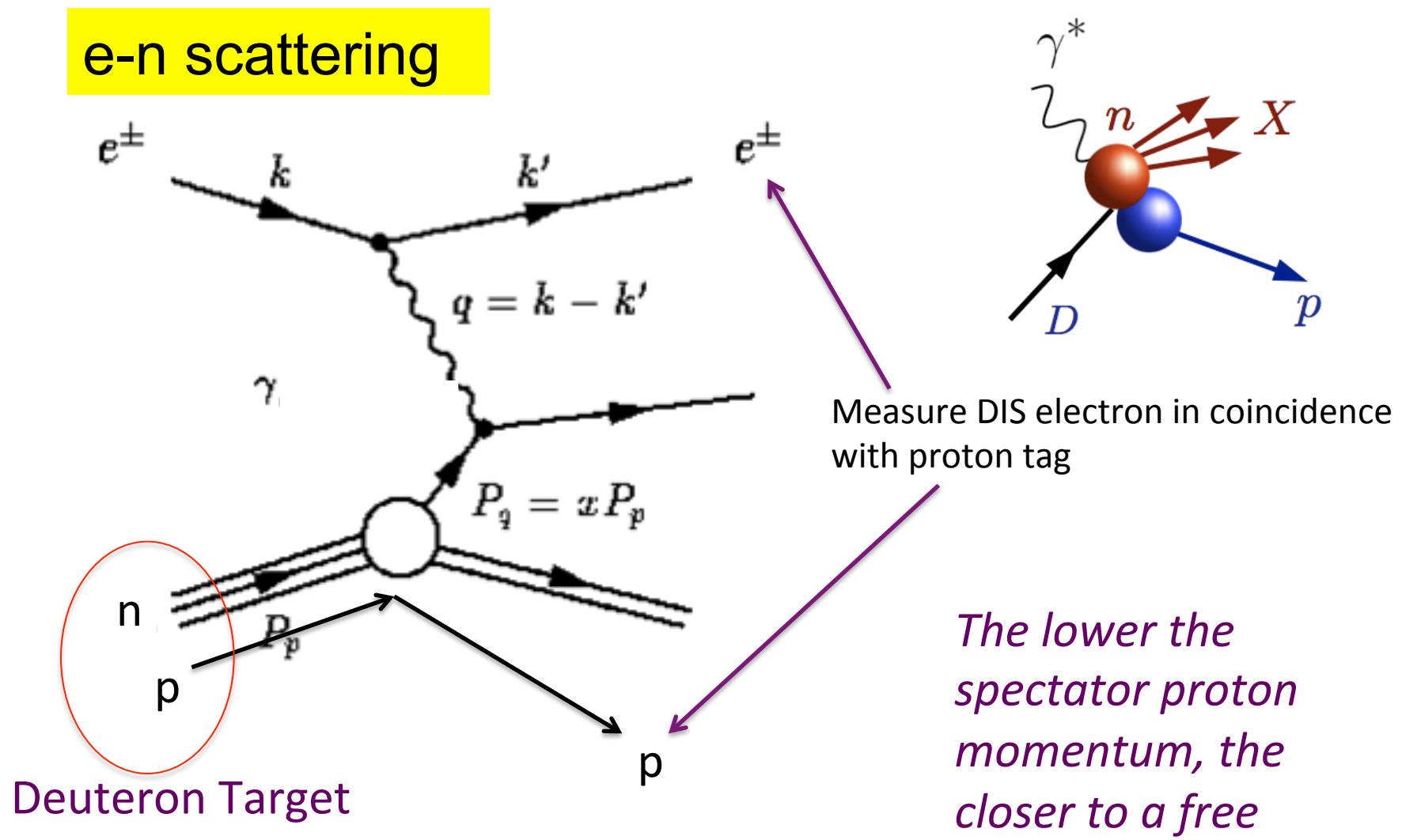


Tagged Deep Inelastic Scattering (TDIS)

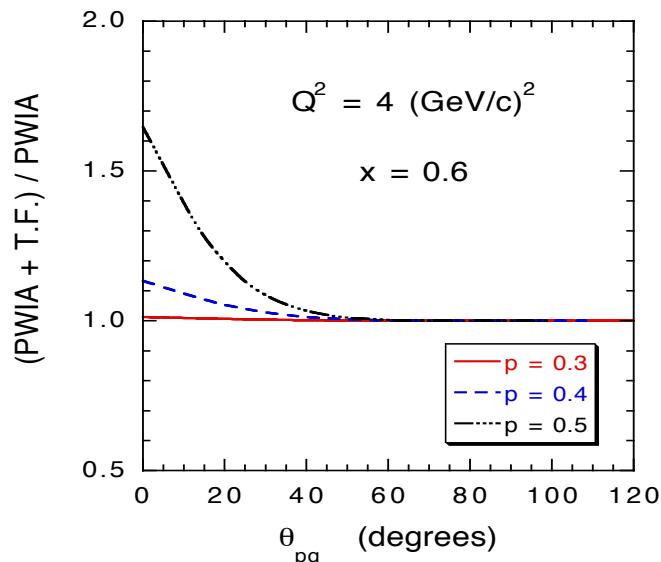
An experimental technique to probe the target regime in semi-inclusive deep inelastic scattering

- Nucleon valence structure at large x
- Probe the meson cloud of the nucleon
- Pion structure function
- EMC effect
- Diffractive scattering, structure of the Pomeron
- Fracture functions
- N-N interactions, short range correlations
- DVCS, remove ~15% background from $(e,e' \Delta)\gamma$, $(e,e' \pi)\gamma, \dots$ – also neutron, pion DVCS!
- Lambda \rightarrow p pi- decay to measure p \rightarrow K+ Lambda kaon cloud of the nucleon

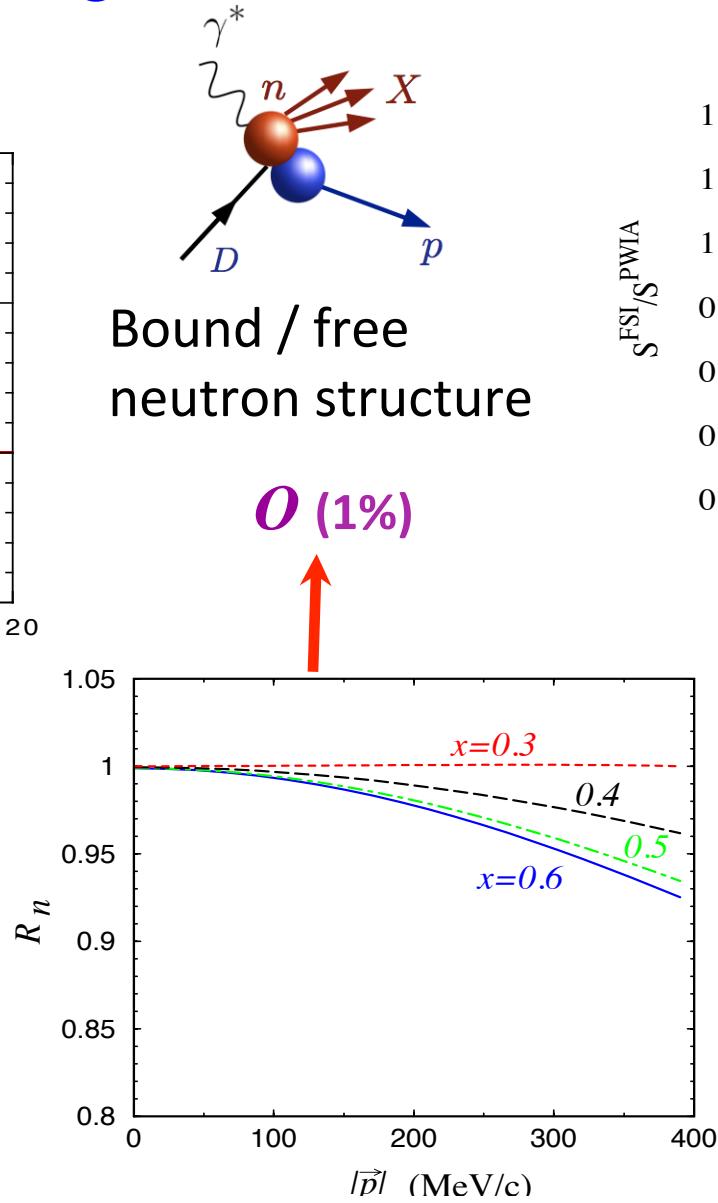
BONUS at JLab – first experiment to use fixed target tagging at JLab to create an effective free neutron target



The BONUS approach: tag spectator proton at (very) low momentum *and* large angle in electron-deuteron scattering



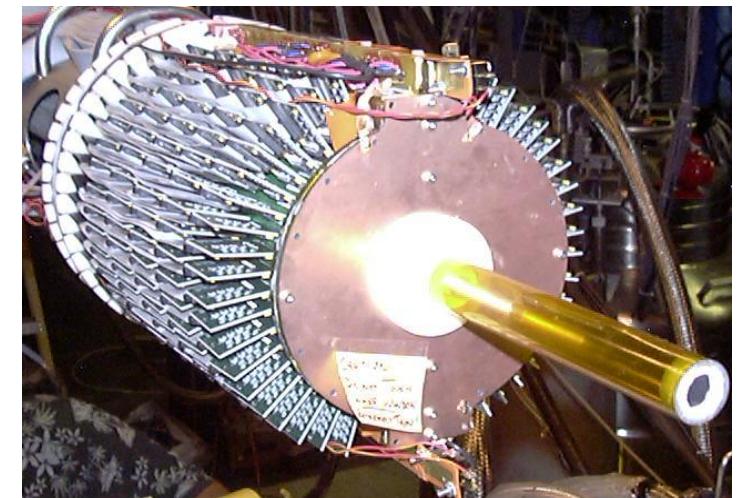
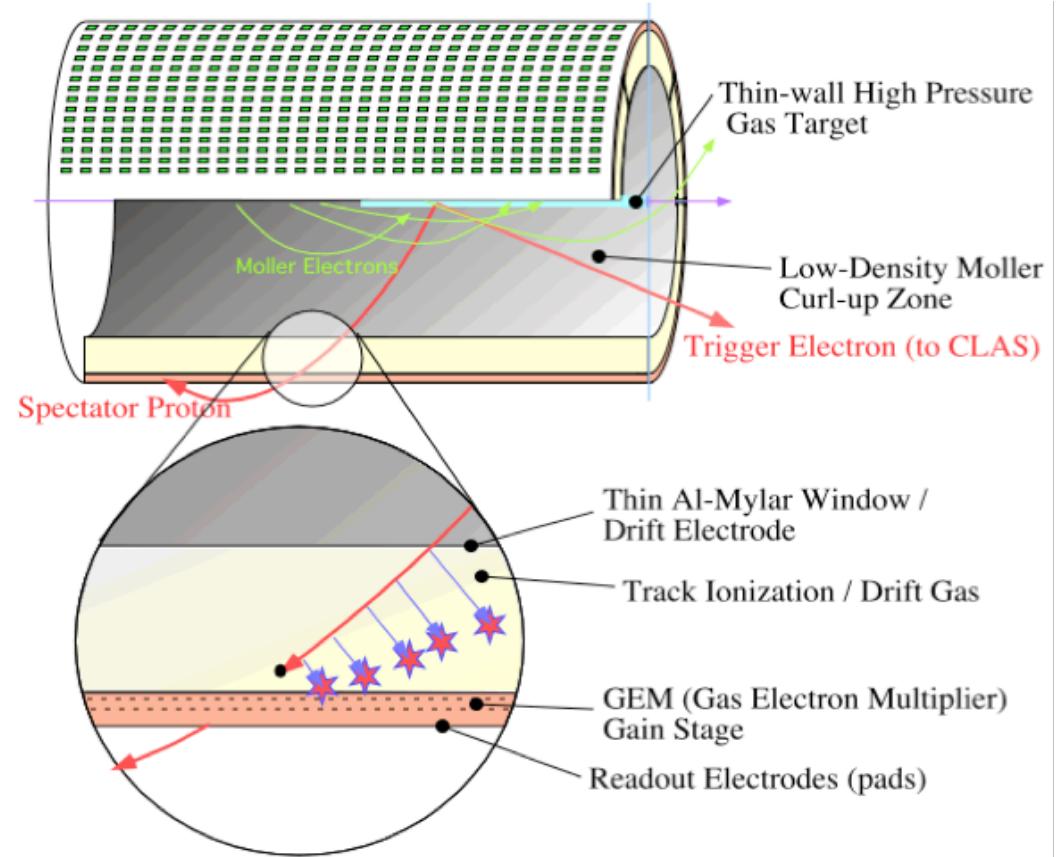
Target fragmentation
negligible



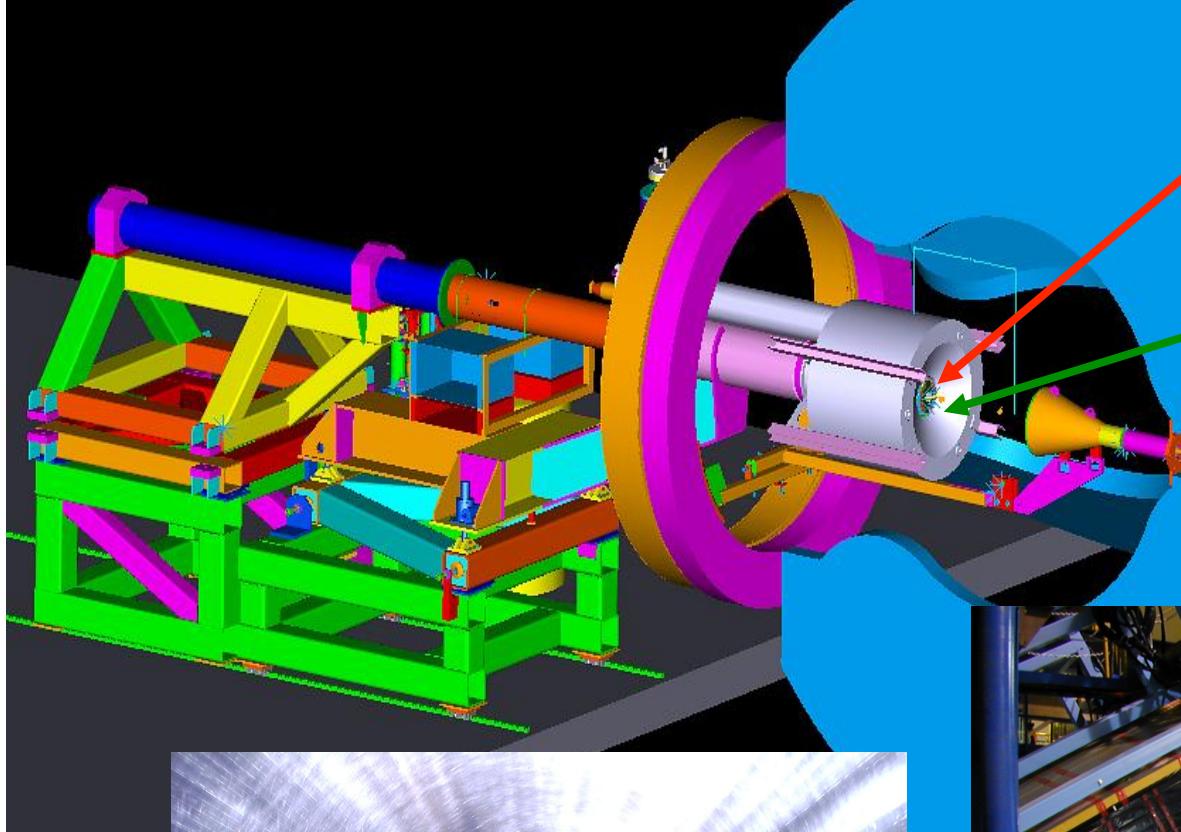
Final state
interactions
 $O(5\%)$

Spectator Proton Tagging

- Low momentum spectator must escape target
 - Thin deuterium gas target
 - Low density detector media
 - Minimal insensitive material
- Large acceptance
 - Backward angles important
 - Symmetric about the target
- Detector sensitive to spectators, insensitive to background
 - Use solenoidal field to contain Moller electrons
- GEM-based radial TPC

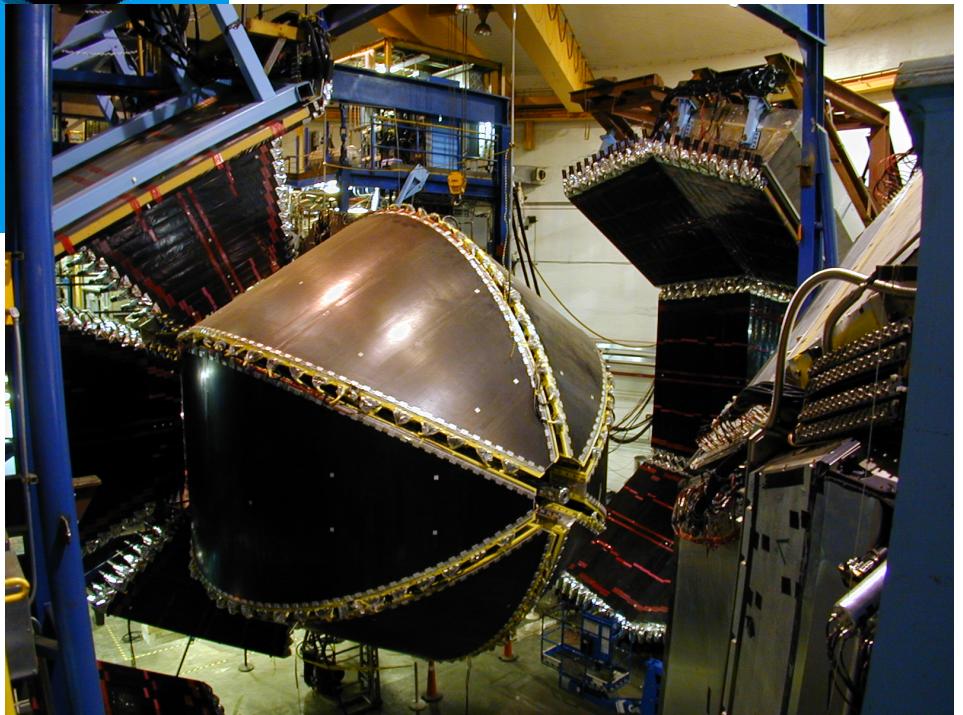
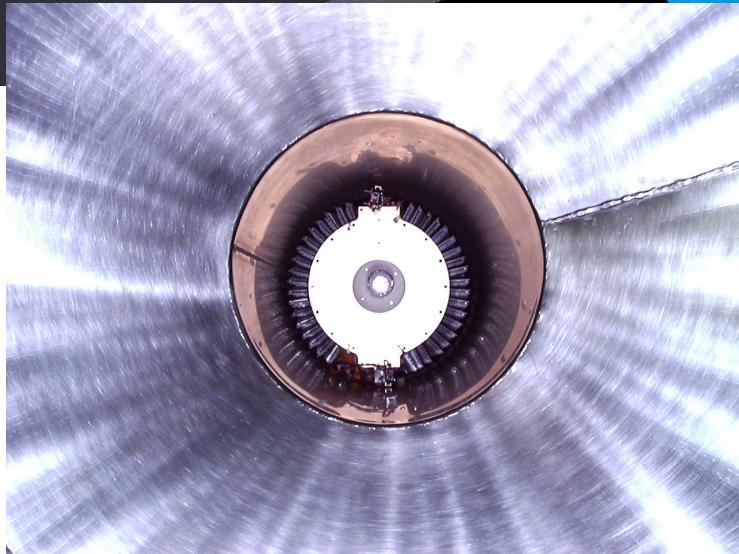


GEM-based radial Time Projection Chamber



BoNuS rTPC
(low momentum p
detector)

Solenoid Magnet
(track curvature in
TPC)

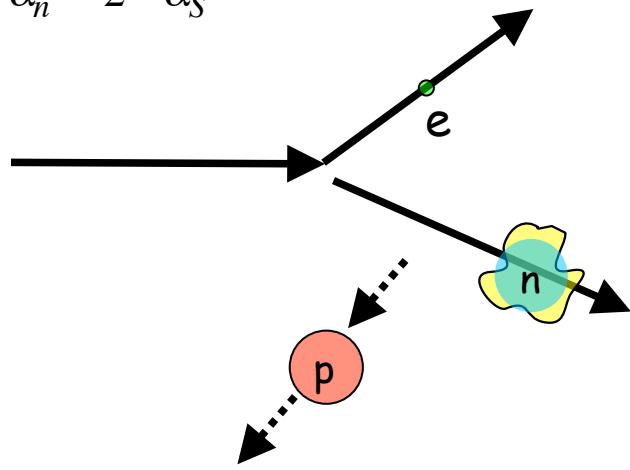


Spectator Tagging – results

visible neutron mass peaks

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

$$\alpha_n = 2 - \alpha_S$$

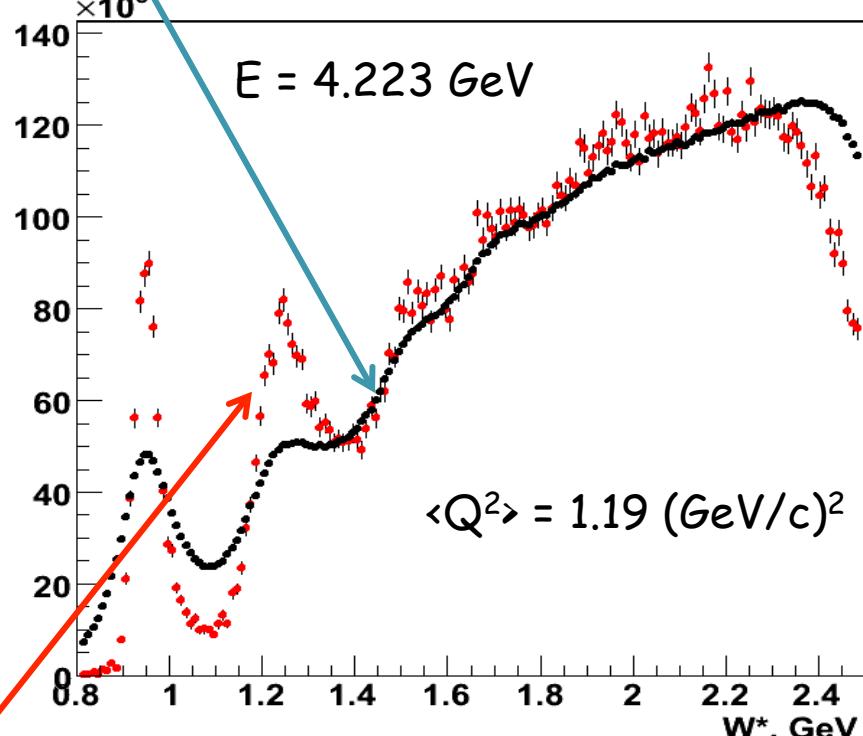


$$p_S = (E_S, \vec{p}_S); \quad \alpha_S = \frac{E_S - \vec{p}_S \cdot \hat{q}}{M_D/2}$$

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

$$W^2 = M^2 + 2M\nu - Q^2$$

Inclusive data



$$W^{*2} = (p_n + q)^2 = p_n^\mu p_\mu + 2((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}) - Q^2$$

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

*

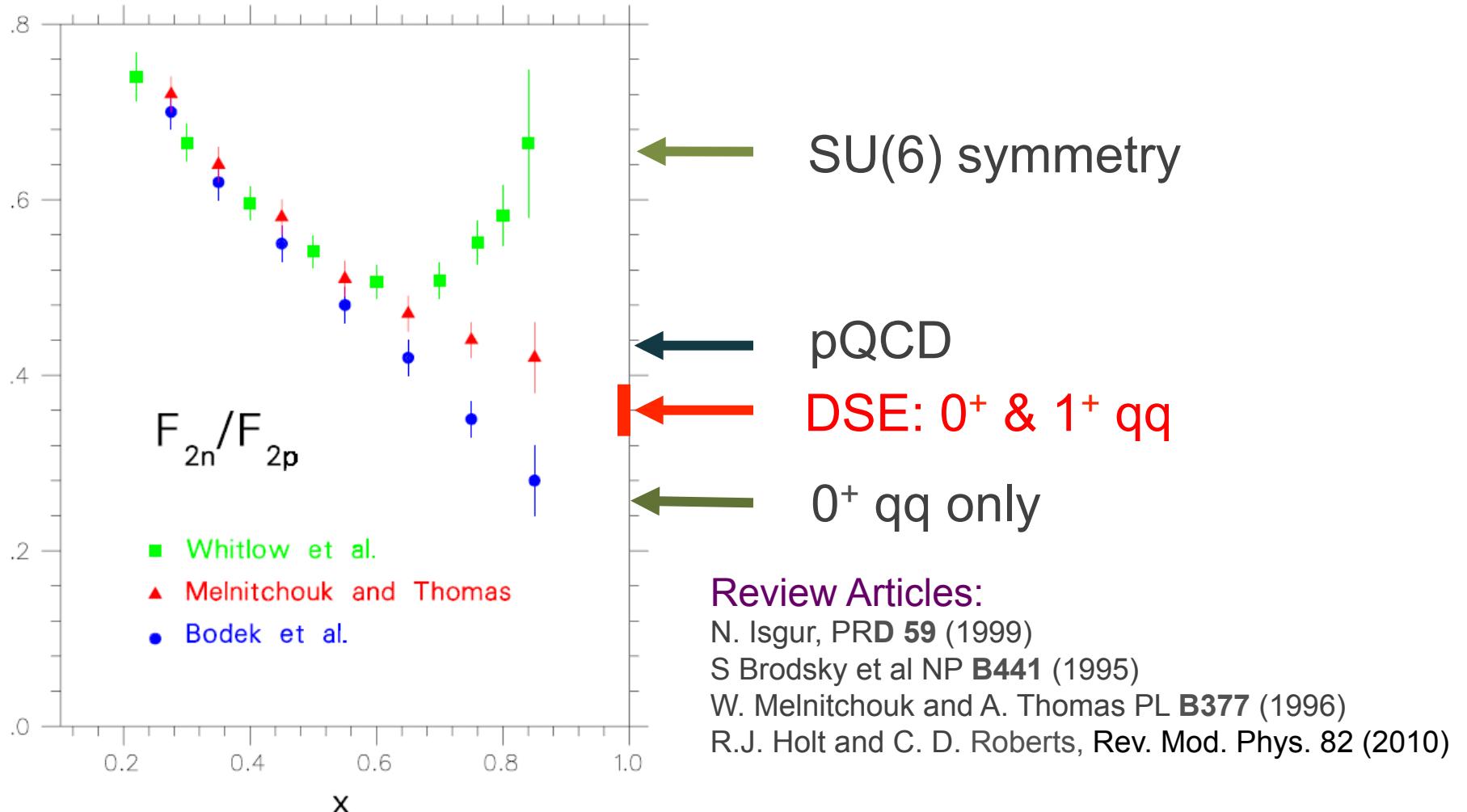
Tagged data

F_2^n/F_2^p (and, hence, d/u) is essentially unknown at large x:

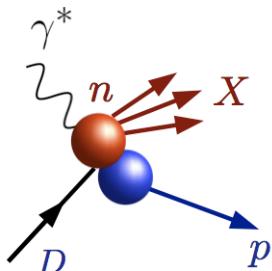
- Conflicting fundamental theory pictures

- F_2^n data inconclusive due to uncertainties in deuterium nuclear corrections

- Translates directly to large uncertainties on d(x), g(x) parton distribution functions



Neutron target via low momentum proton tagging achieved



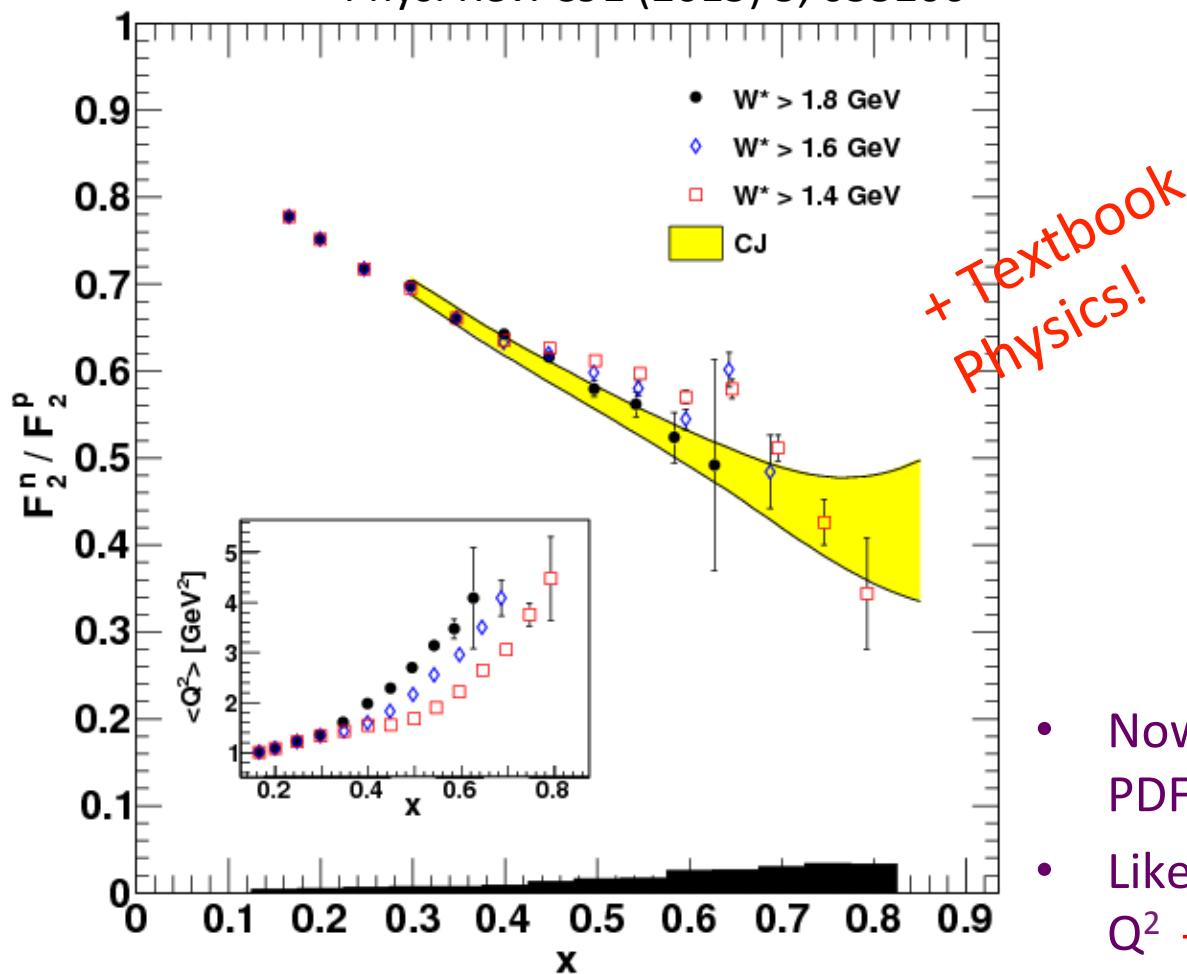
Phys. Rev. Lett. 108 (2012) 199902

Phys. Rev. C89 (2014) 045206 – editor's
suggestion

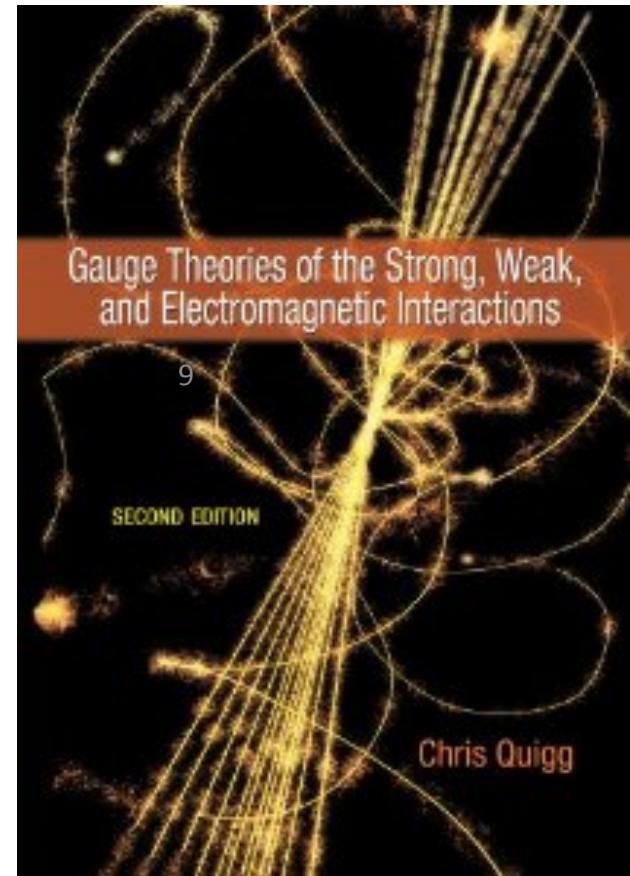
Nucl. Instrum. Meth. A592 (2008) 273-286

Phys. Rev. C92 (2015) 1, 015211

Phys. Rev. C91 (2015) 5, 055206



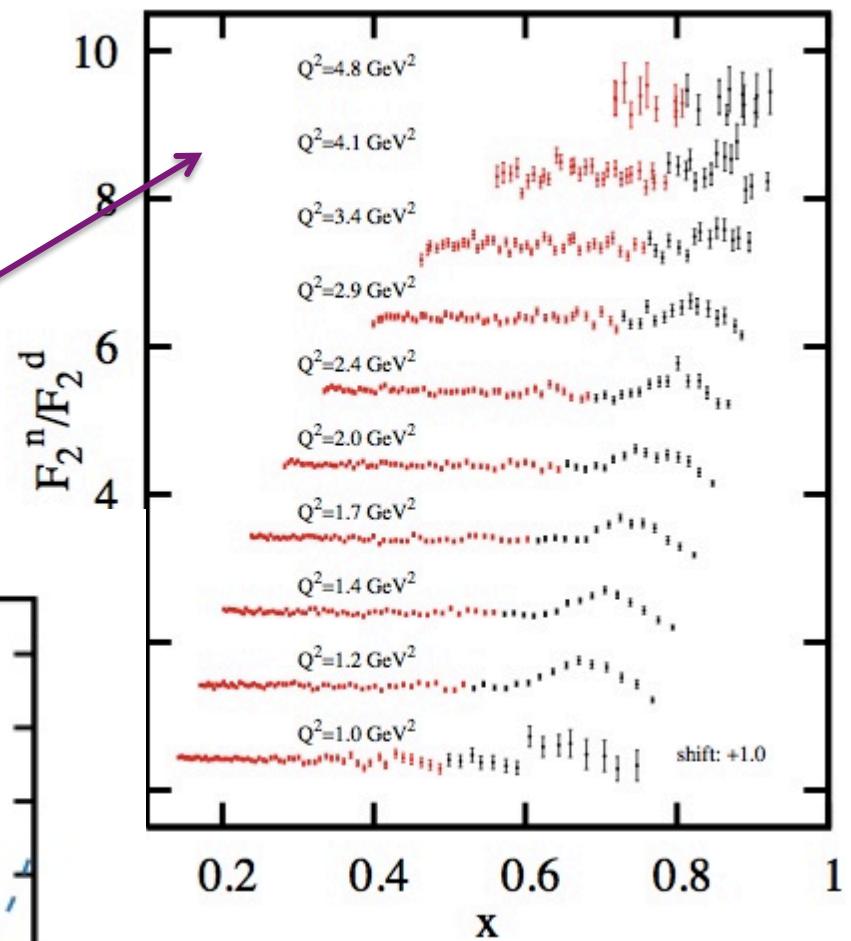
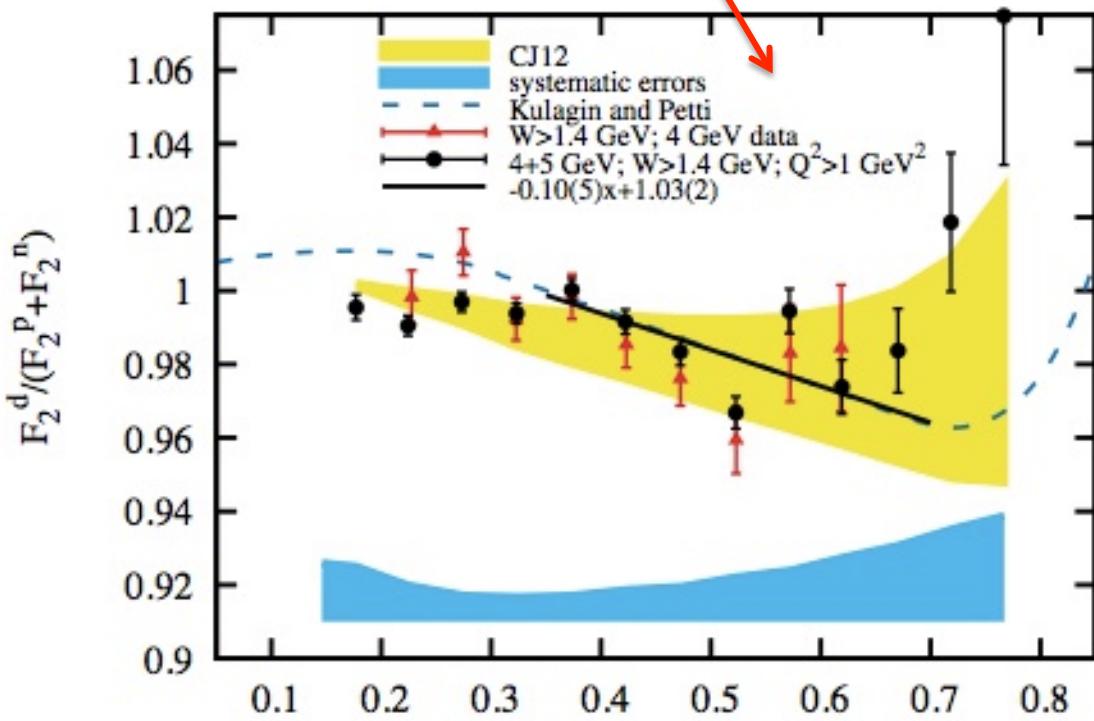
+ Textbook
Physics!



- Now input for (CTEQ-JLab) global PDF fits
- Likely not quite high enough x , W , Q^2 - BONUS at 12 GeV coming!

First Measurement of the EMC Effect in the Deuteron

- BONUS actually measured F_2^n/F_2^D
- F_2^p known
- Extract EMC Ratio $R_{EMC}^D = F_2^D/(F_2^n + F_2^p)$

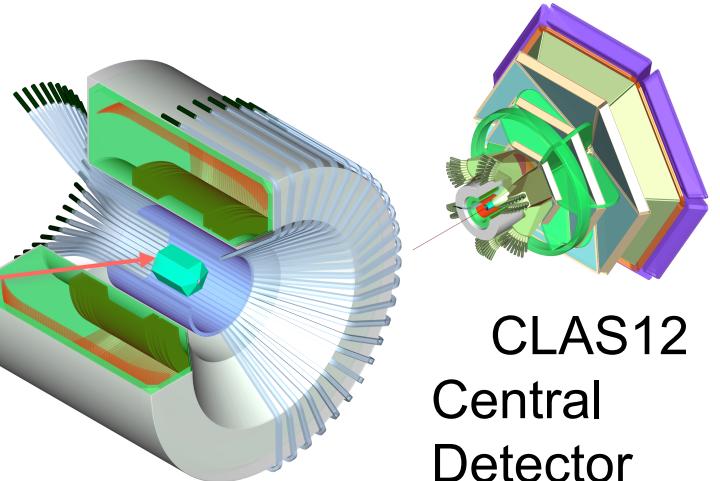
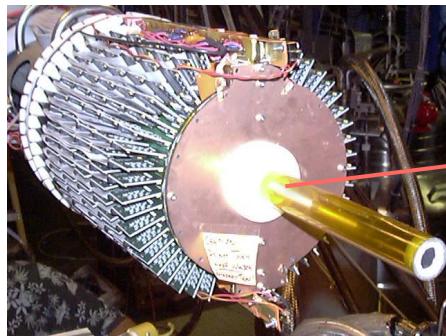


Results consistent with conventional nuclear physics *and* also with short-range correlations

BONUS12, with better precision and larger W , Q^2 , will determine R_{EMC}^D with improved accuracy

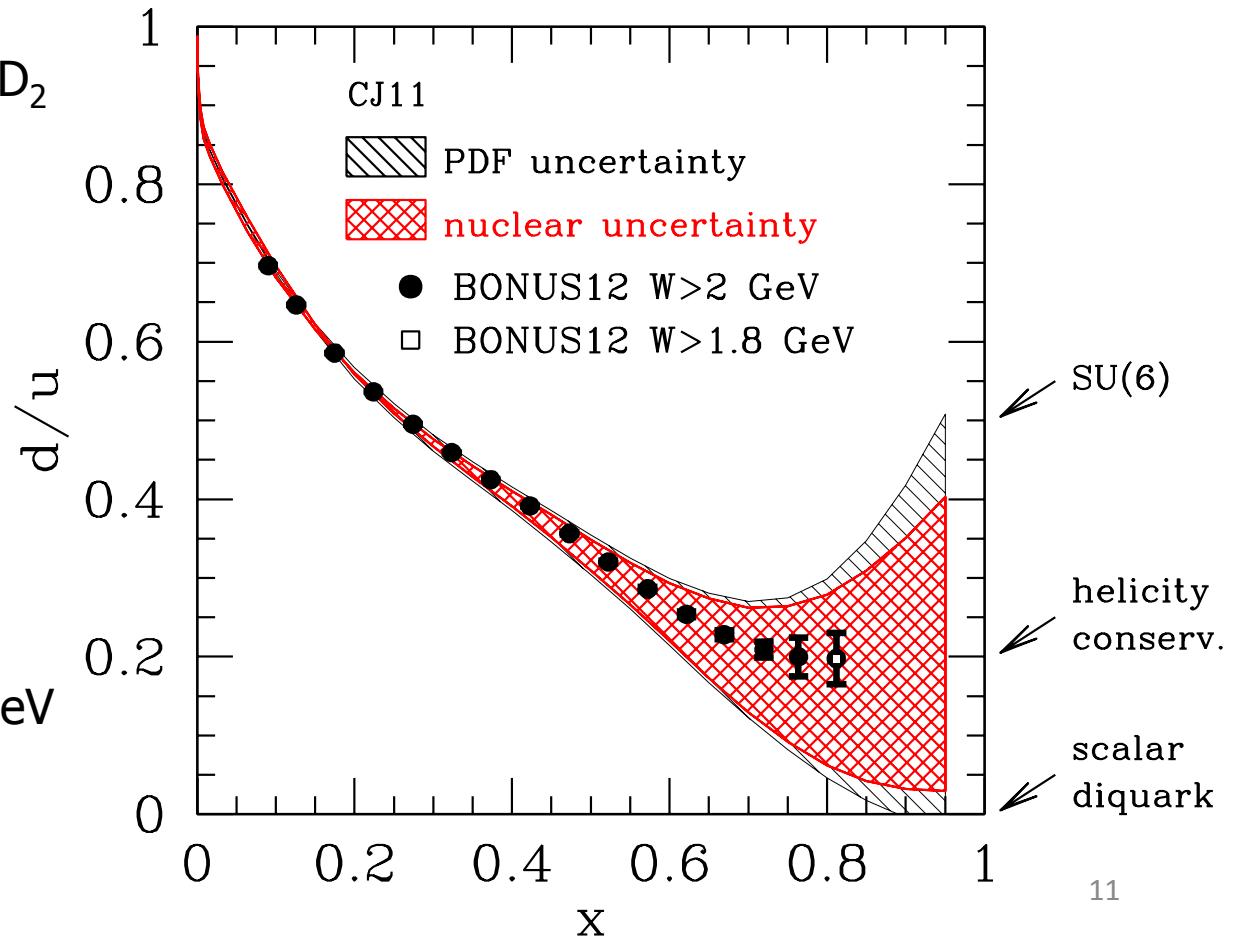
Plans for 12 GeV

E12-06-113
“BONUS12”,
PAC42 high
impact



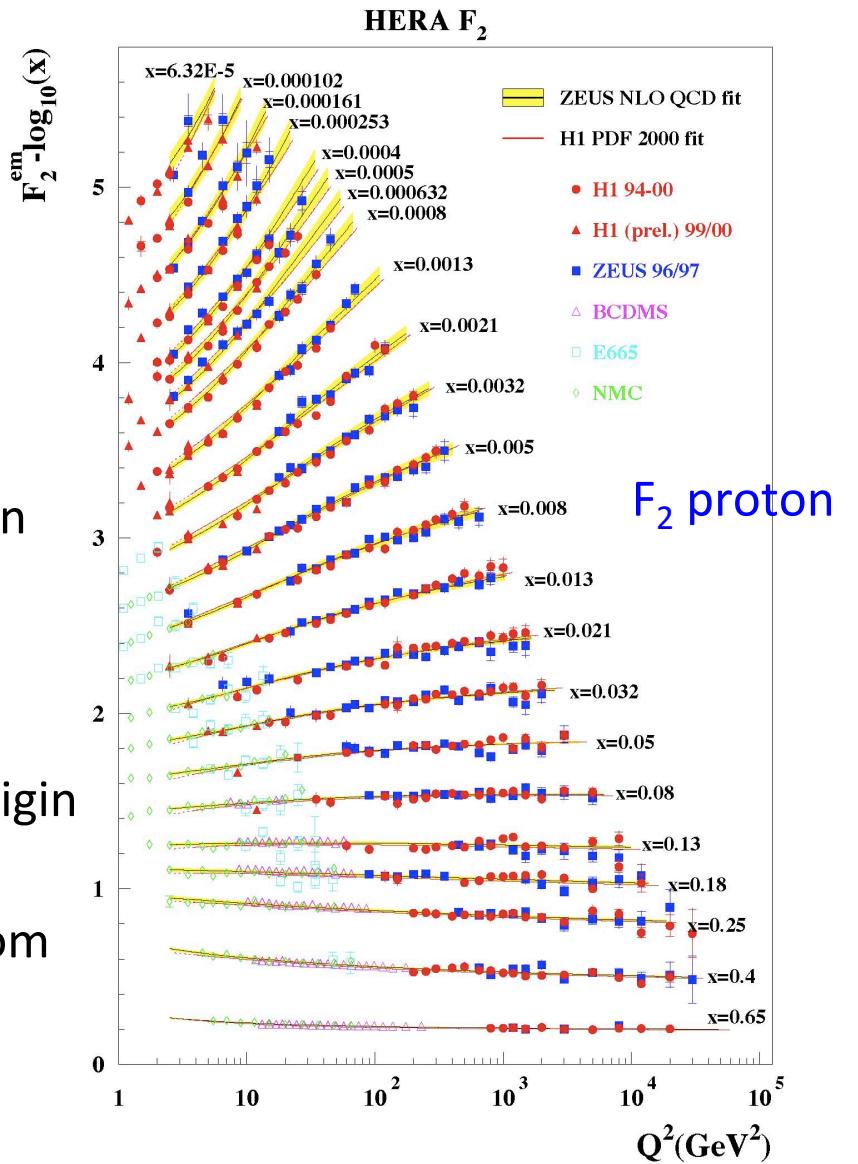
CLAS12
Central
Detector

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



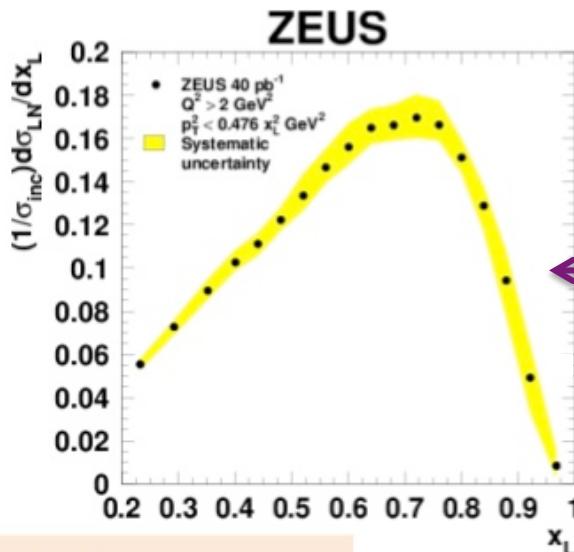
Can we use tagging to create a pion target?

- The pion is fundamental - simplest hadron with only two valence quarks.
- The pion plays a key role in nucleon and nuclear structure
 - QCD's Goldstone boson
 - Explains the long-range nucleon-nucleon interaction
 - A basic part of the standard model of nuclear physics
- Many questions, for instance what is the origin of the $d(\bar{u}) - u(\bar{d})$ flavor asymmetry?
 - asymmetry in anti-quarks generated from pion valence distribution?
- **Pion structure function measurements hindered by lack of pion target**

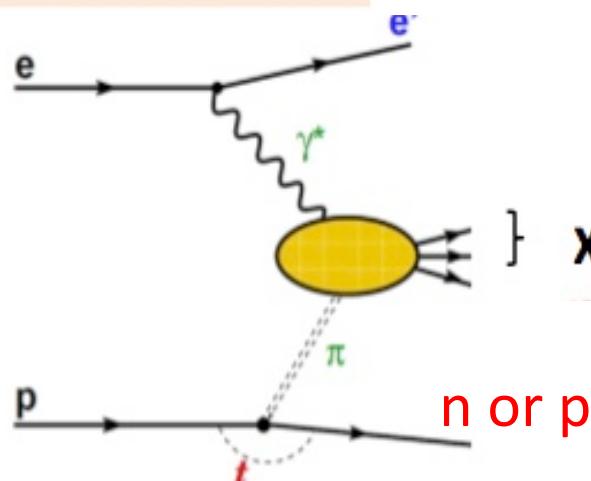


TDIS at HERA – neutron tag for pion scattering

DESY 08-176 JHEP06 (2009) 74



DESY 07-011
Nucl.Phys.B776(2007) 1-37

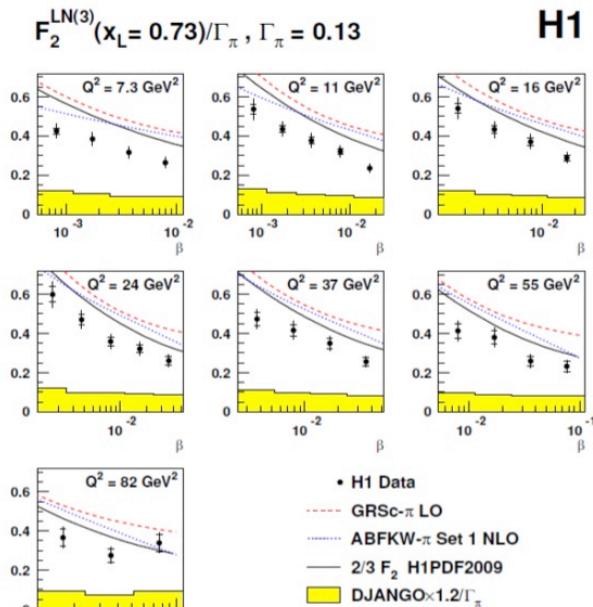
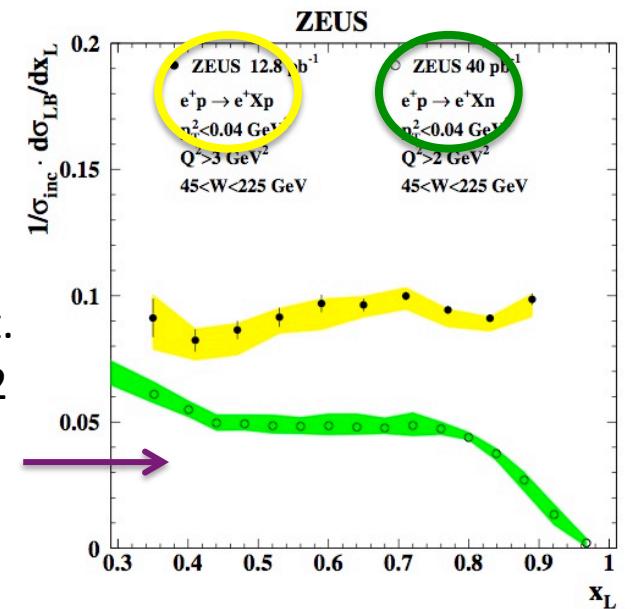


$$x_L = E^N/E^p_{\text{beam}} \sim 1$$

- The leading neutron results are different from the proton.*

- There is no elastic (diffractive) peak present.
- Leading neutron rate ~ 2 times lower than leading proton rate for $x_L < 1$.
- Proton isoscalar events include diffractive Pomeron
- Neutron events isovector only

- One pion exchange is the dominant mechanism.*
- Can extract pion structure function*



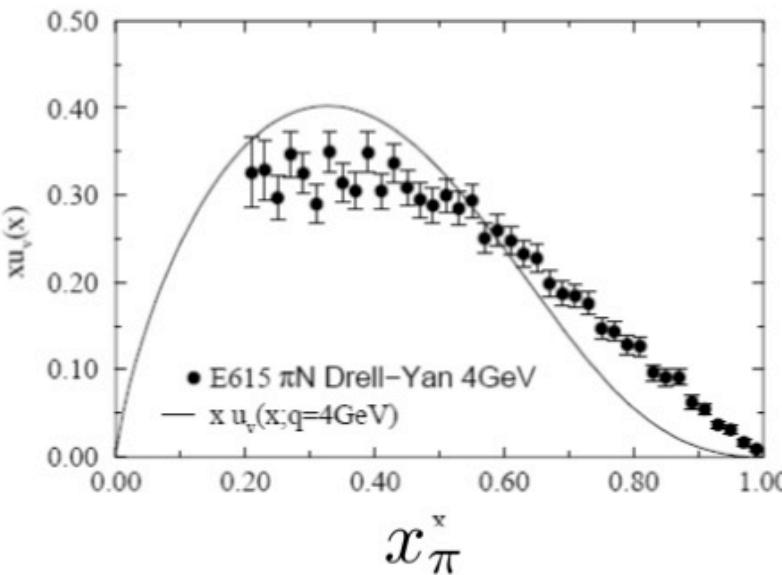
DESY 09-185 Eur. Phys. J. C68 (2010) 381

Pion Structure Function at Large x: Results from Drell-Yan

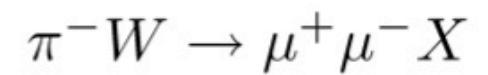
Large x Structure of the Pion

Initial observations:

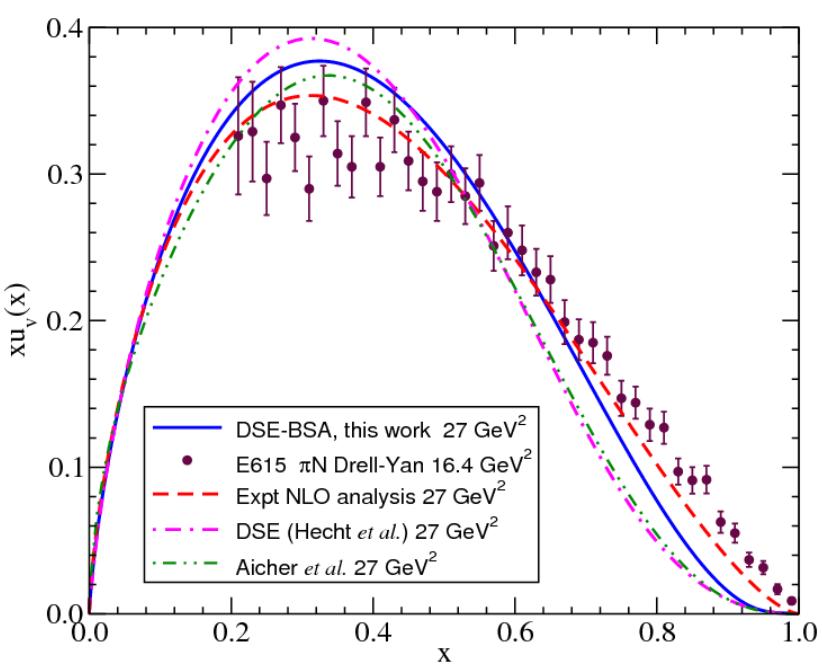
- PDF $\sim (1-x_\pi)$ as $x_\pi \rightarrow 1$
- Agrees with structureless model
- Differs from pQCD prediction of $(1-x_\pi)^2$



FNAL E615, CERN NA3,10



$$\sigma \propto \bar{u}(x_{\pi^-}) u(x_N)$$



- Data do not agree with pQCD, Dyson-Schwinger, Light Front, Instanton,...,numerous models!
- Problem with data analysis?
 - NLO fit
 - Improved proton PDFs
 - Sea quark contribution
 - More flexible extractions of PDFs
- Only soft gluon resummation shows “convex” shape (Aicher, Schäfer, Vogelsang, Phys. Rev. Lett. 105, 252003 (2010))

C.D. Roberts, [arXiv:1203.5341 \[nucl-th\]](https://arxiv.org/abs/1203.5341)

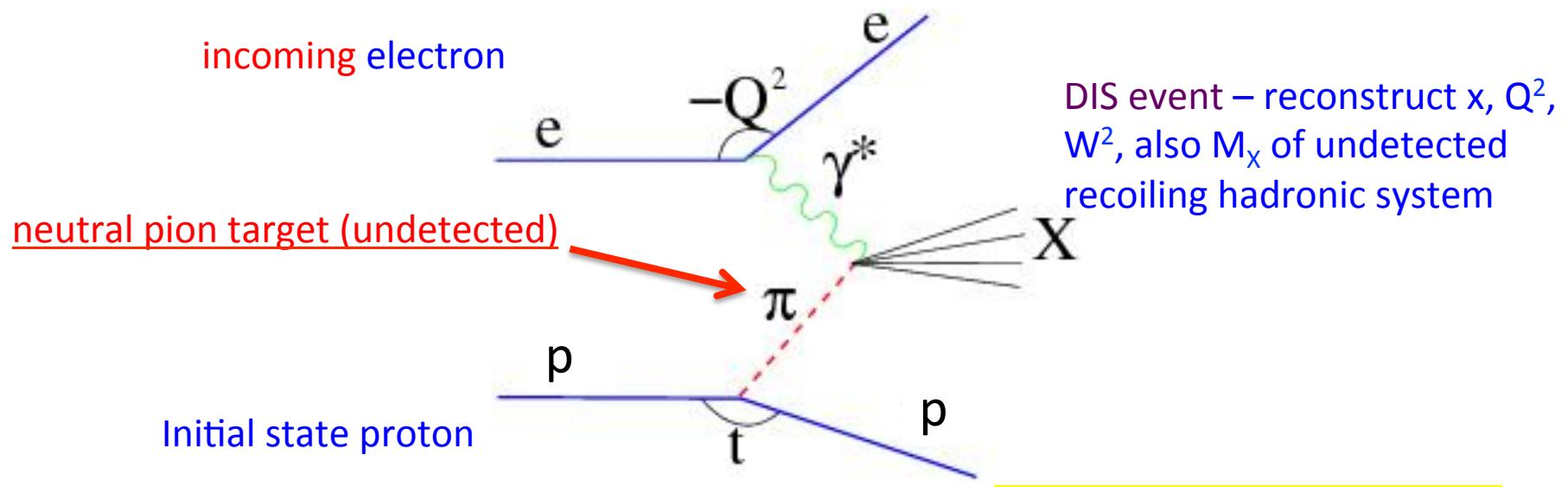
New data set would be important verification! 14

BONUS-type Tagging Facilitates HERA-type Probe of Meson Cloud at JLab

Example: Sullivan process scattering from **proton-pion** fluctuation

Hydrogen Target

detect scattered electron

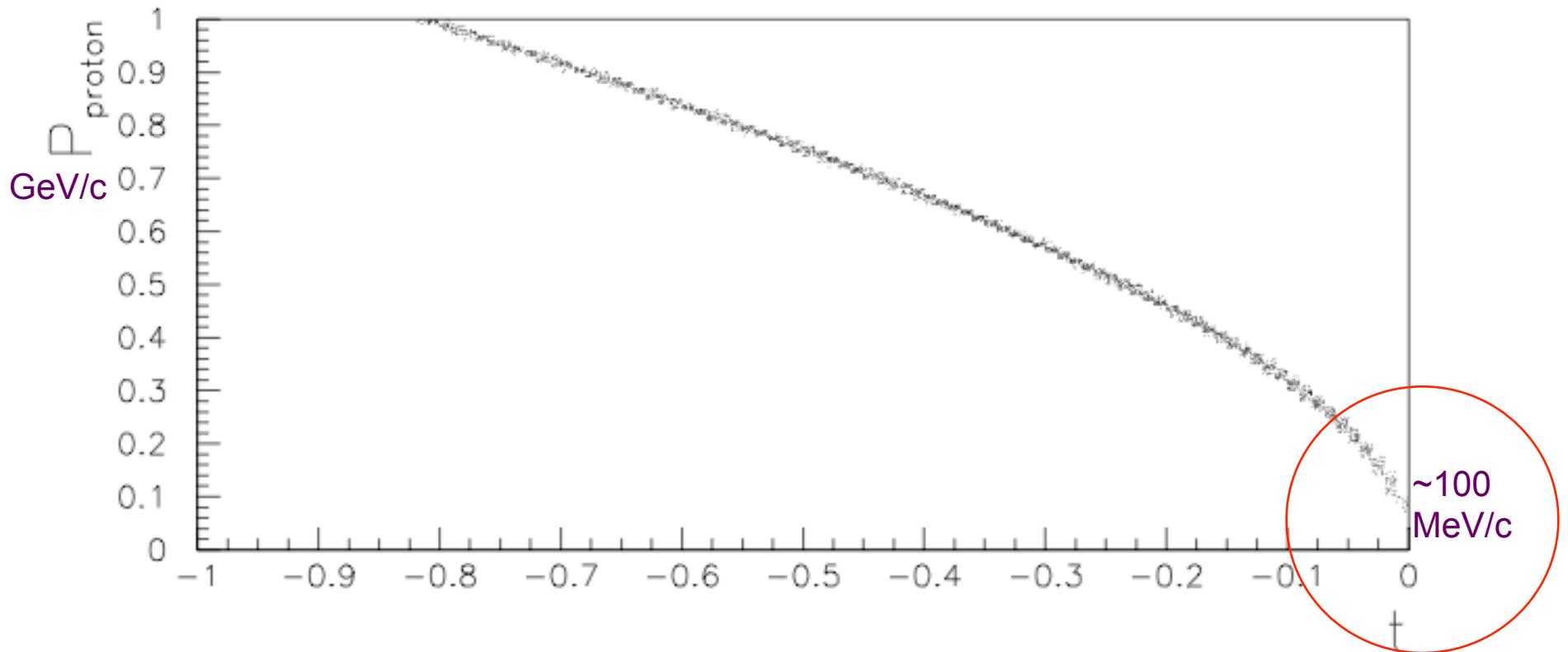


Detected protons need to be low momentum

- Tag target hadron
- Extrapolate to pole

tagged final state spectator proton

Extrapolation to the pole



- Want *low* momentum protons – closer to low t , pion pole
- Measure range in momentum to extrapolate

Roberts estimates ~5% uncertainty at TDIS kinematics, based on framework in C.D. Roberts, S. Qin (2015)

Tagging Facilitates TDIS Probe of Meson Cloud: T²DIS

Example: Sullivan process scattering from **neutron-pion** fluctuation

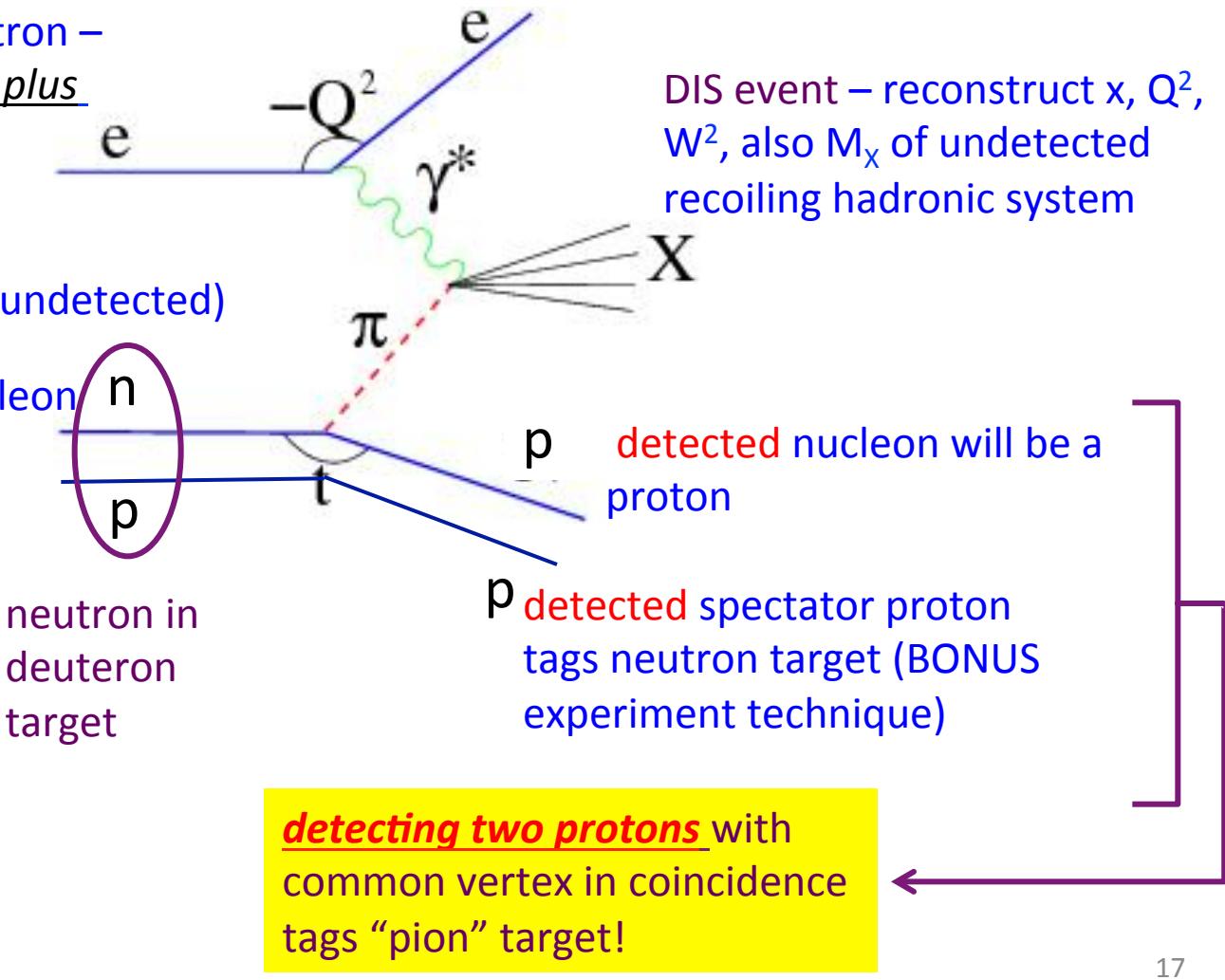
Deuterium Target

Incoming electron –
high current a plus

**detect scattered electron –
large acceptance a plus**

want **charged** pion target (undetected)

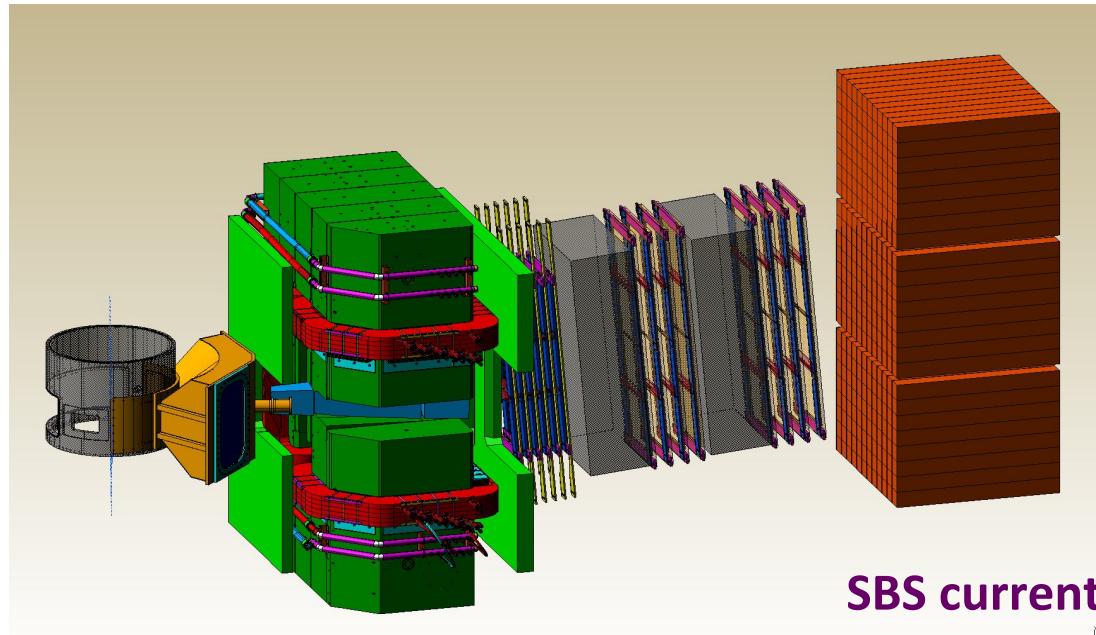
need fluctuating nucleon
to be a neutron.....



Detected protons both need to be low momentum
- Tag target hadron
- Extrapolate to pole
- Barely off-shell neutron

Proposed TDIS Experiment: BONUS-type Detector....and.....

- ✓ High luminosity:
 - $50 \mu\text{Amp}$, $\mathcal{L} = 3 \times 10^{36}/\text{cm}^2 \text{ s}$
 - Hall A
- ✓ Super Bigbite “SBS” ~ 70 msr spectrometer
 - modified for electron detection
 - 40 planes of GEM tracking + PID
- ✓ UVA solenoid for BONUS-type rTPC
- ✓ New rTPC with fine strip readout
- ✓ HCAL calorimeter for RTPC calibration



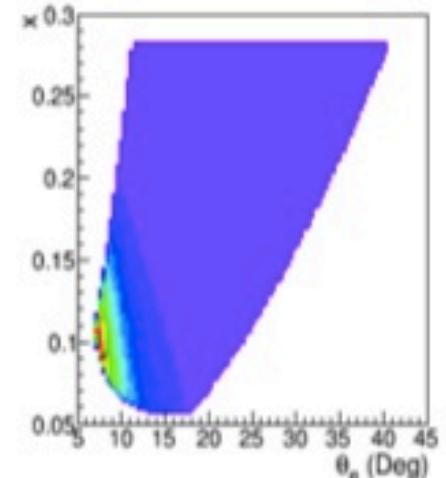
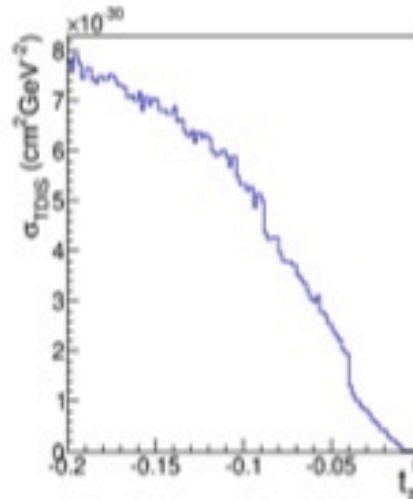
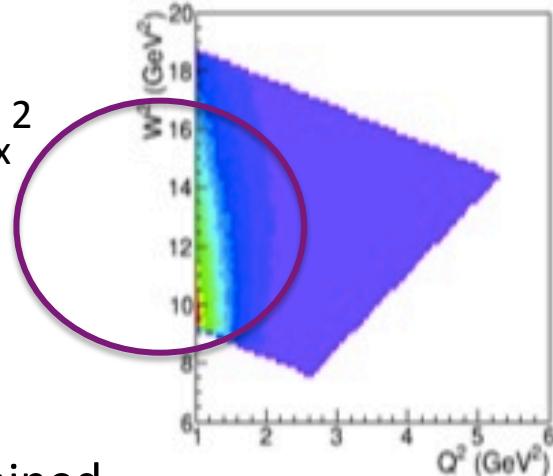
SBS currently under construction



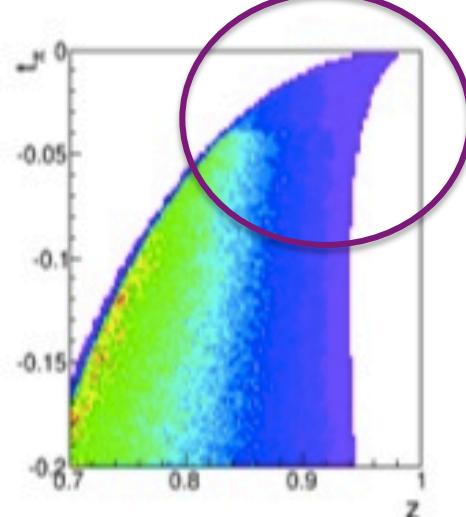
Projected TDIS Kinematics – optimized for meson cloud

High W^2

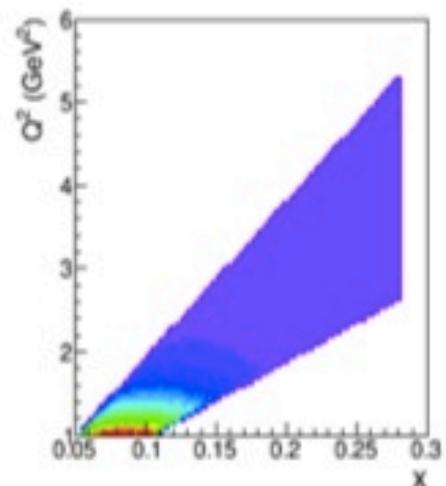
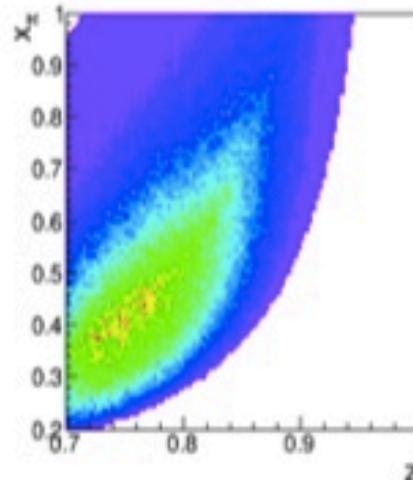
- High M_x^2
- DIS!



All data obtained *simultaneously* at one $E = 11$ GeV setting, only a target change – will run hydrogen and deuterium (neutron)



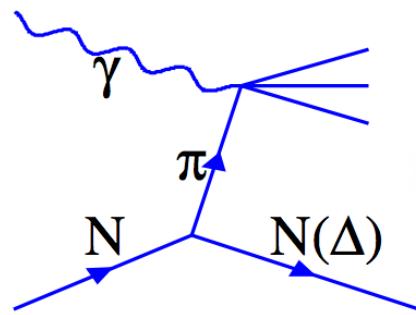
Low t , high z



x range ~ 0.1
 $1 < Q^2 < 2 \text{ GeV}^2$

How to estimate rates?

- Use Sullivan process and pion cloud model

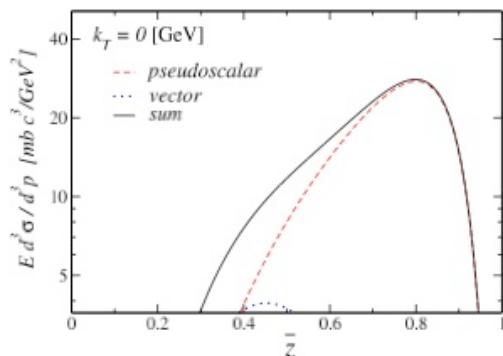


$$F_2^{(\pi N)}(x) = \int_x^1 dz f_{\pi N}(z) F_{2\pi}\left(\frac{x}{z}\right)$$

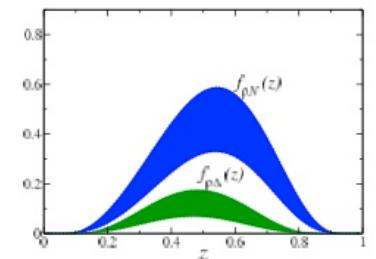
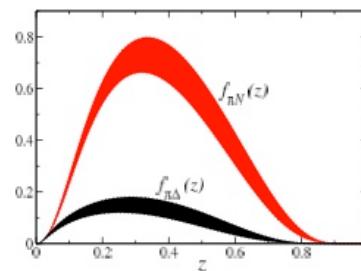
$$f_{\pi N}(z) = c_I \frac{g_{\pi NN}^2}{16\pi^2} \int_0^\infty \frac{dk_\perp^2}{(1-z)z} \frac{G_{\pi N}^2}{(M^2 - s_{\pi N})^2} \left(\frac{k_\perp^2 + z^2 M^2}{1-z} \right) f_{\pi N}(z)$$

$f_{\pi N}(z)$ = light-cone momentum distribution of pions in the nucleon

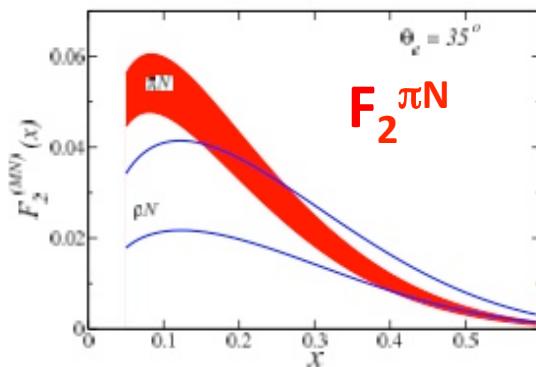
Pion expected to be dominant – also estimated ρ, Δ



Form factor $G_{\pi N}$ constrained by comparing the meson cloud contributions with data on inclusive $pp \rightarrow nX$ scattering



Light-cone momentum distributions, $f_{\pi N}(\rho)$ and $f_{\rho N}(\rho)$, as a function of the meson light-cone momentum fraction



Convolute the light-cone distributions with the structure function of the meson (from GRV)

Important to note – kinematic limits:

- $z \sim |k|/M$, where k is π 3-momentum = $-p'$
- $60 < k < 400$ MeV/c corresponds to $z < \sim 0.2$
- Also, $x < z$!
- Low x , high W at 11 GeV means $Q^2 \sim 2$ GeV²

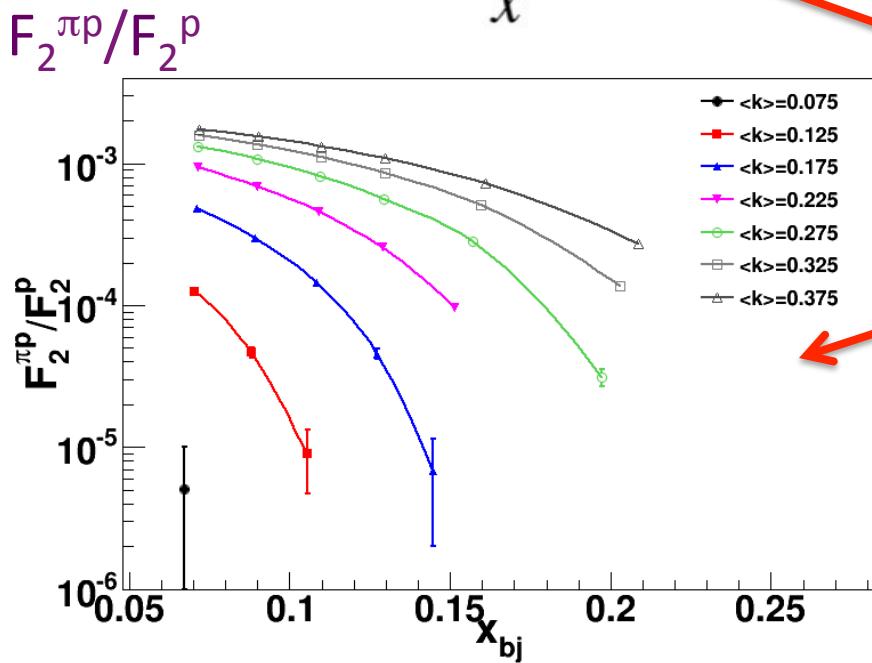
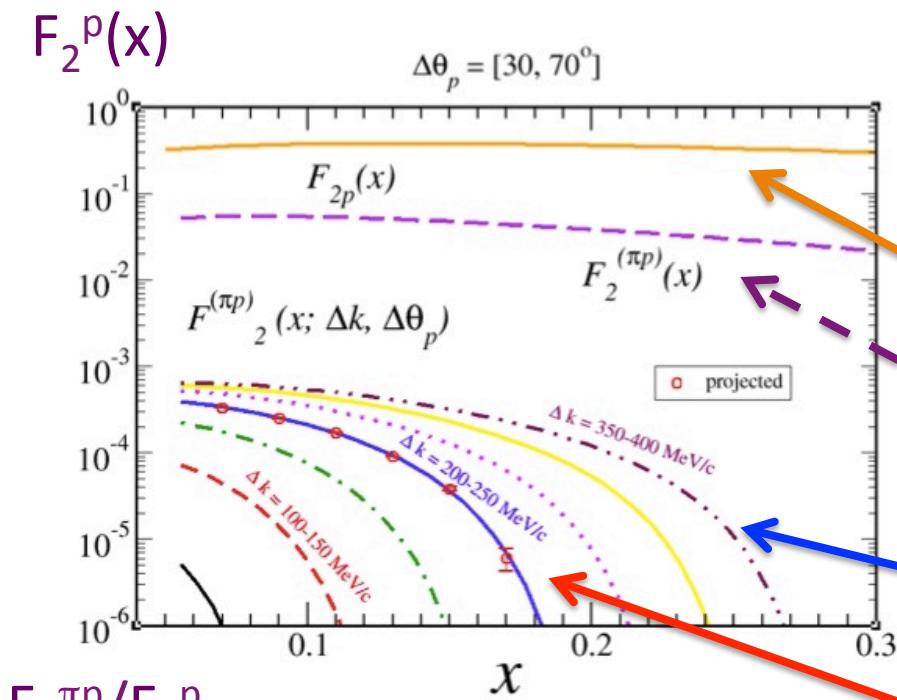
T. J. Hobbs, T. Londergan, W. Melnitchouk, et al. (2014, in preparation)

H. Holtmann, A. Szczurek and J. Speth, Nucl. Phys. A 596, 631 (1996)

W. Melnitchouk and A. W. Thomas, Z. Phys. A 353, 311 (1995)

Projected Results I

- proton



$F_2^p(x)$ is well-known inclusive DIS

$F_2^{(\pi p)}(x)$ is total pion contribution to structure function

Colored lines are pion contribution for different bins in p_{proton}

Data for $200 < p_{\text{proton}} < 250$ MeV/c are representative to show uncertainty

Full data set shown here

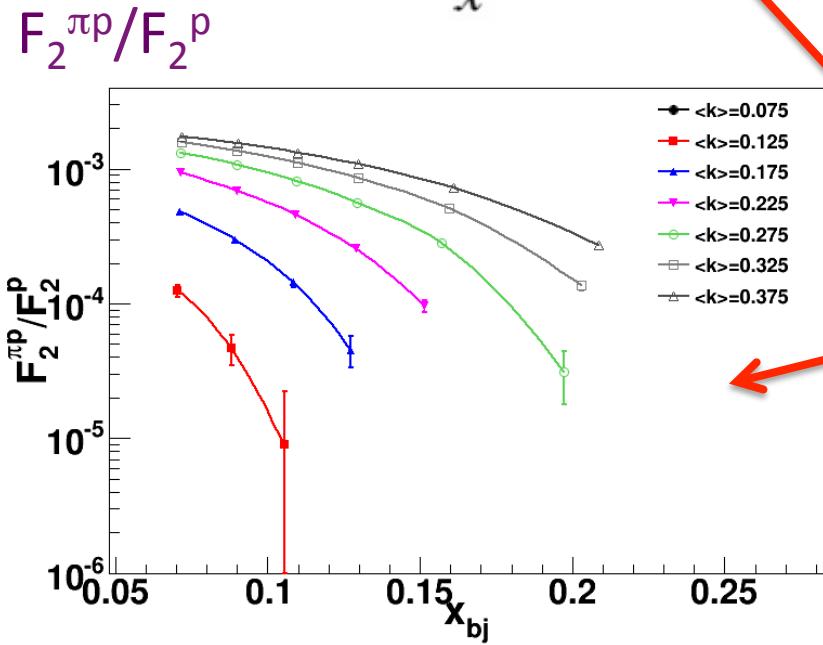
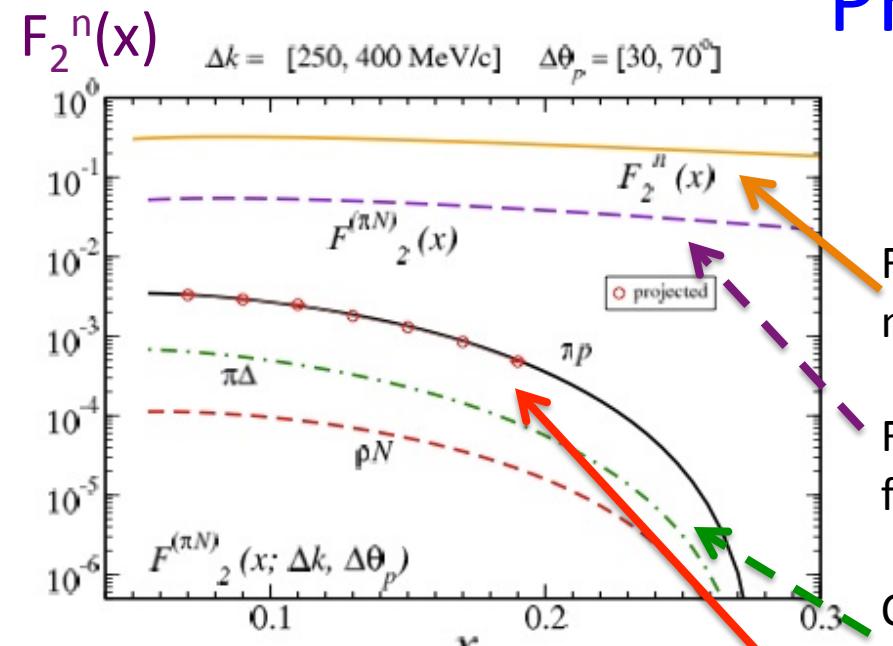
- all momentum bins in MeV/c

Error bars largest at highest x points – less statistics

- at fixed x, these are the lowest t values

Projected Results II

- neutron



$F_2^n(x)$ is inclusive DIS – tagged by additional low momentum, backward angle p as in BONUS

$F_2^{(\pi N)}(x)$ is total *pion* contribution to structure function

Colored lines are expected *total* Delta and rho contribution for $250 < p_{\text{proton}} < 400 \text{ MeV/c}$.

Data for pion contribution are representative to show uncertainty

Full data set shown here

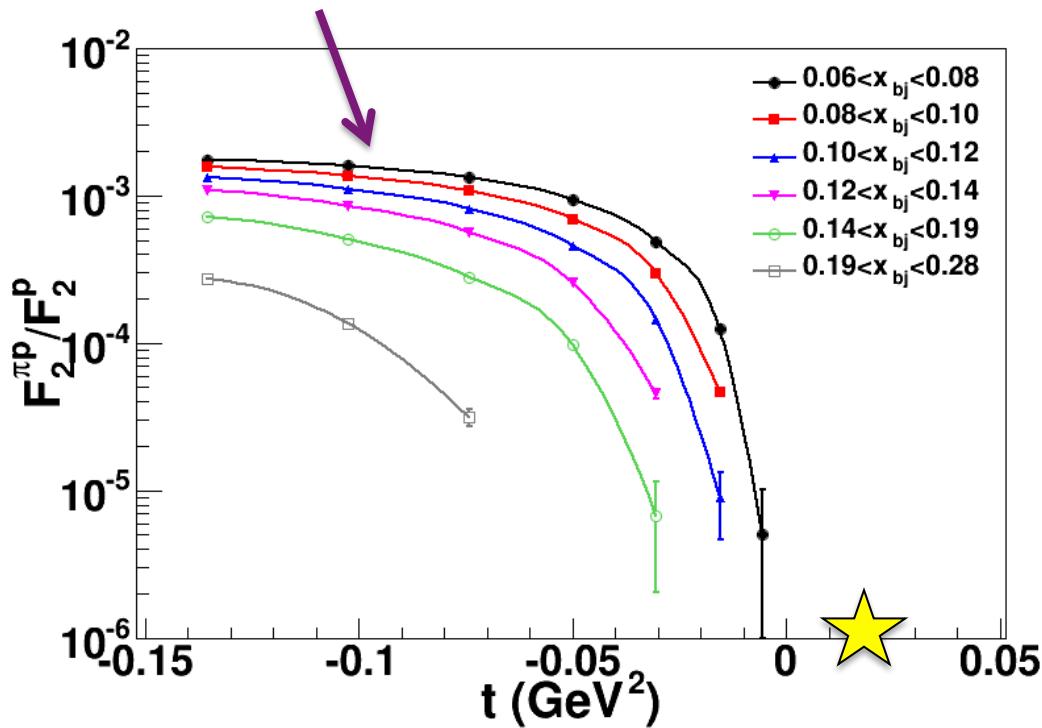
- all momentum bins in MeV/c

Do not show lowest momentum $\langle x \rangle = 0.075$ data
- run lower luminosity due to larger background

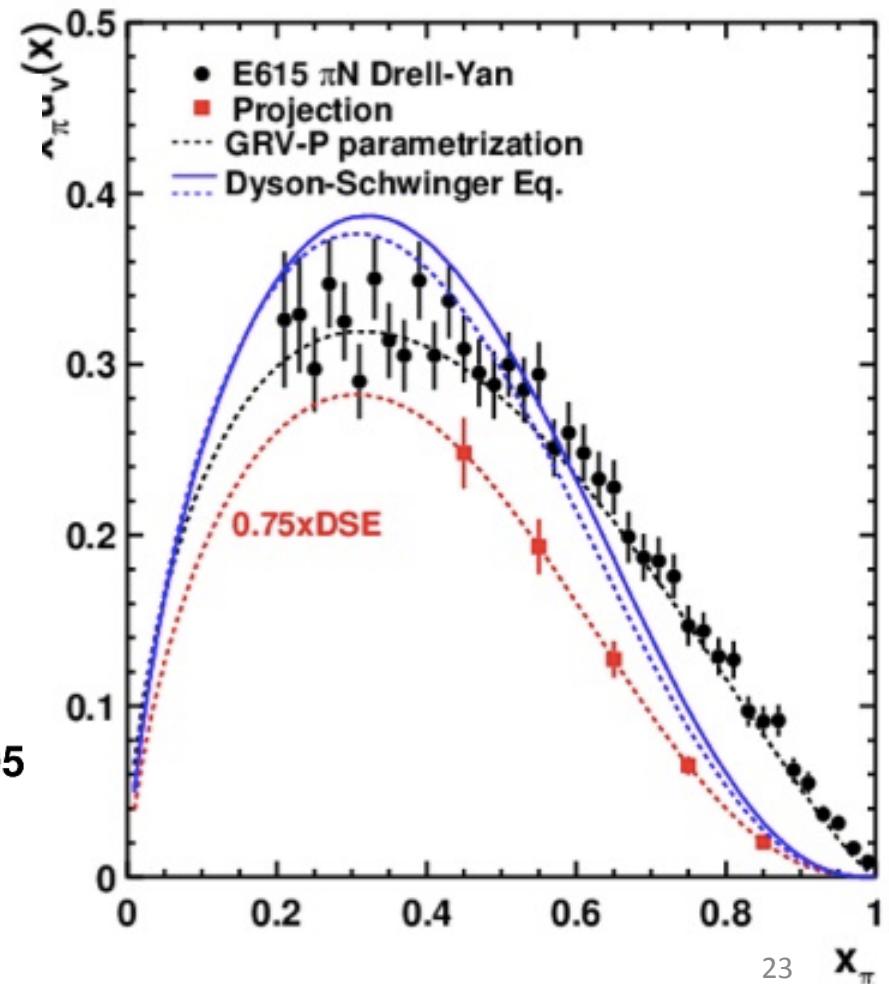
Projected Results – Pion Structure Function from TDIS at JLab

- Large x structure of the pion is of particular recent interest, verify resummed Drell-Yan results
- Q^2 range will check evolution
- Large x , low Q complementary to HERA low x , high Q

- Low t extrapolation to the pion pole

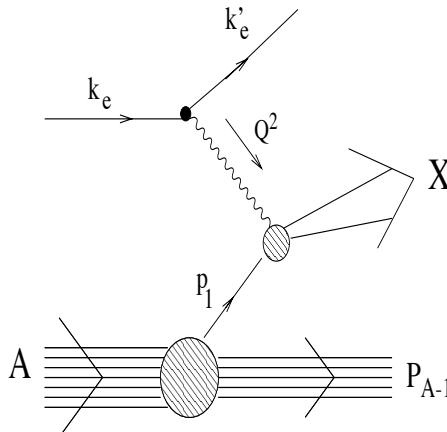


Will also measure n, p (π^- , π^0) difference
- look for isospin dependence



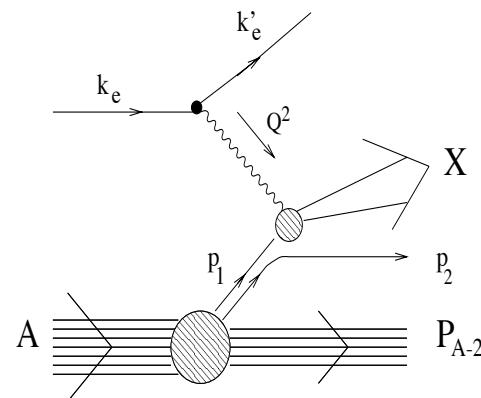
Tagged EMC Effect: Do nucleons with different binding energies contribute differently to the EMC effect?

DIS on weakly bound nucleons $A(e,e'(A-1))X$



- DIS on low momentum nucleon
- Detect scattered electron and low momentum, low excitation energy ($A-1$) nucleus

DIS on deeply bound nucleons $A(e,e'(A-2))X$

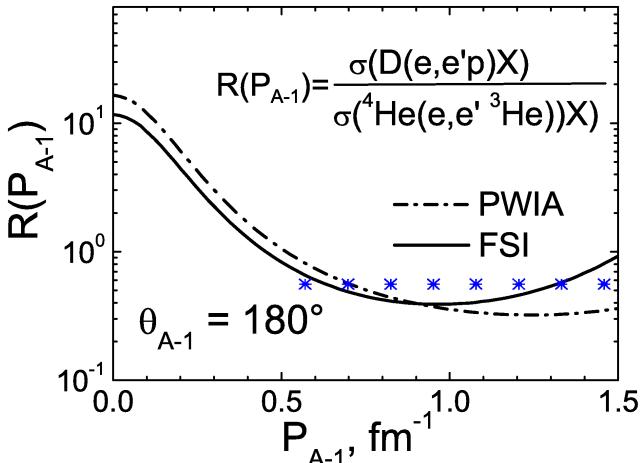


- DIS on high momentum nucleon
- Detect scattered electron, the high momentum nucleon from the pair and low momentum, low excitation energy ($A-2$) nucleus

What can we learn from detecting the scattered electron and the spectator ($A-1$) nucleus in coincidence?

- Test the validity of the spectator model
- Investigate the nature of Final State Interaction (FSI) between the Hadronic jet with surrounding nuclear medium
- Investigate the A -dependence of possible medium induced modifications of DIS structure function
- Origin of the EMC effect including testing the local EMC model
- Flavor dependent nuclear parton distribution

Testing the Spectator Model, FSI effects & the structure functions scaling



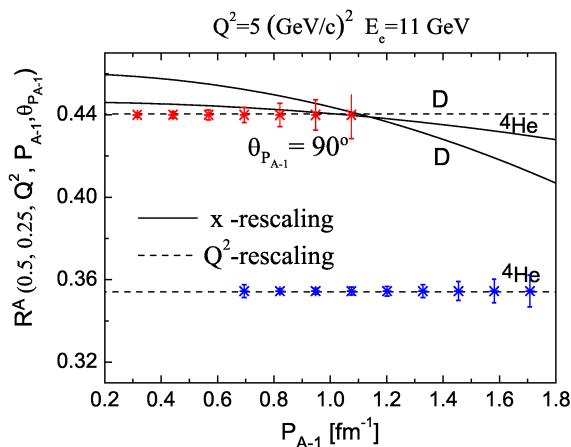
C. Ciofi degli Atti, L.P. Kaptari and S. Scopetta, Eur. Phys. J. A5, 191 (1999)

Measure the cross sections for the same nucleus A and for two different x values at the same spectator momentum

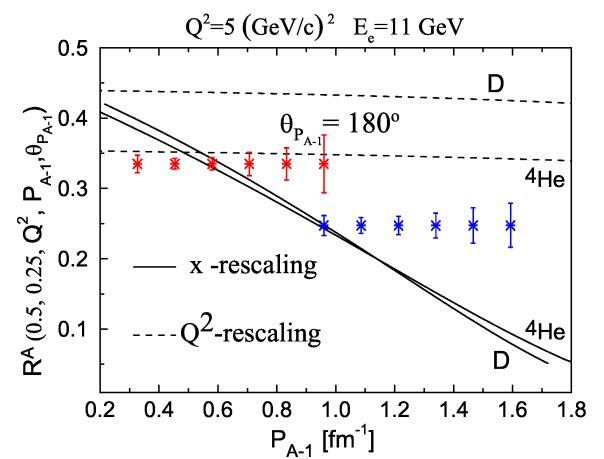
$$R(x, Q^2, |\vec{P}_{A-1}|, ^2H, ^4He) = R(|\vec{P}_{A-1}|) \approx \frac{n_0^D(|\vec{P}_{A-1}|)}{n_0^{^4He}(|\vec{P}_{A-1}|)}$$

- Measure the cross sections for deuterium and 4He at the same value of x, Q^2 and momentum of the recoil ($A-1$) nucleus
- The A dependence of the ratio R is entirely dominated by the A dependence of the nucleon momentum distribution, which is strong at low momenta and fairly well-known
- The experimental observation of the intact spectator with low excitation energy is a good indication that FSI effects are small (especially with deuterium as a recoil)

For x-rescaling, R depends on $P_{(A-1)}$



For Q^2 -rescaling, R independent of $P_{(A-1)}$



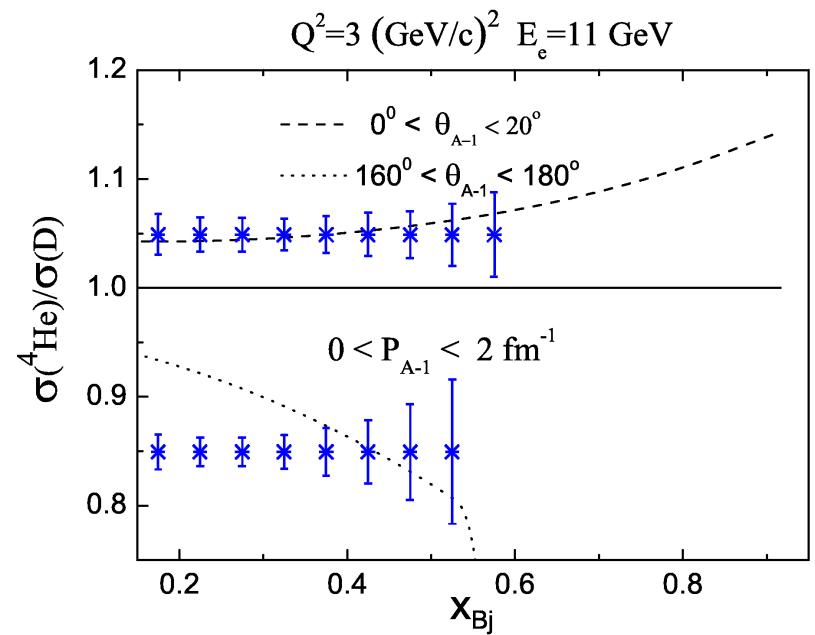
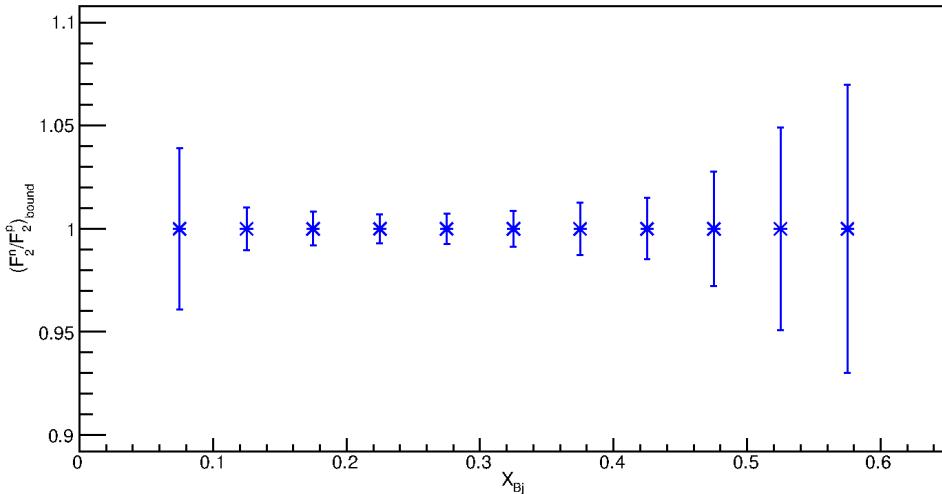
$$R(x, x', z, Q^2) = \frac{x'}{x} \frac{F_2^{N/A}(x/z^A, Q^2)}{F_2^{N/A}(x'/z^A, Q^2)}$$

$$R(x, x', Q^2) = \frac{x'}{x} \frac{F_2^{N/A}(x, \xi_A(Q^2))}{F_2^{N/A}(x', \xi_A(Q^2))}$$

Local EMC Model & Flavor dependent nuclear parton distribution

- In the binding model of the EMC effect, the slope of the ratio of structure functions is generated by the average value of the nucleon removal energy $\langle E \rangle$
- The larger $\langle E \rangle$, the stronger the EMC slope (NN correlations produce high values of $\langle E \rangle$)
- Separate the contribution from weakly bound and deeply bound nucleons

Flavor dependent EMC effect



- (d/u)bound compared to (d/u)free for different nucleon momentum
- Flavor dependence of the EMC effect?

Proposal for CLAS12 and ALERT recoil detector – Prototype being developed

Tagging opens a door to access effective (neutron, pion, kaon..?) targets

- *critical, fundamental hadron structure measurements*
- *neutron and pion structure function*

TDIS opens a door to probe meson cloud of the nucleon

- *direct measurement of nucleon-meson fluctuation component of DIS*
- *measurement of isospin dependence ($p-n$ difference)*

Tagging can provide a new, precision window to the EMC effect

Thank You!!!

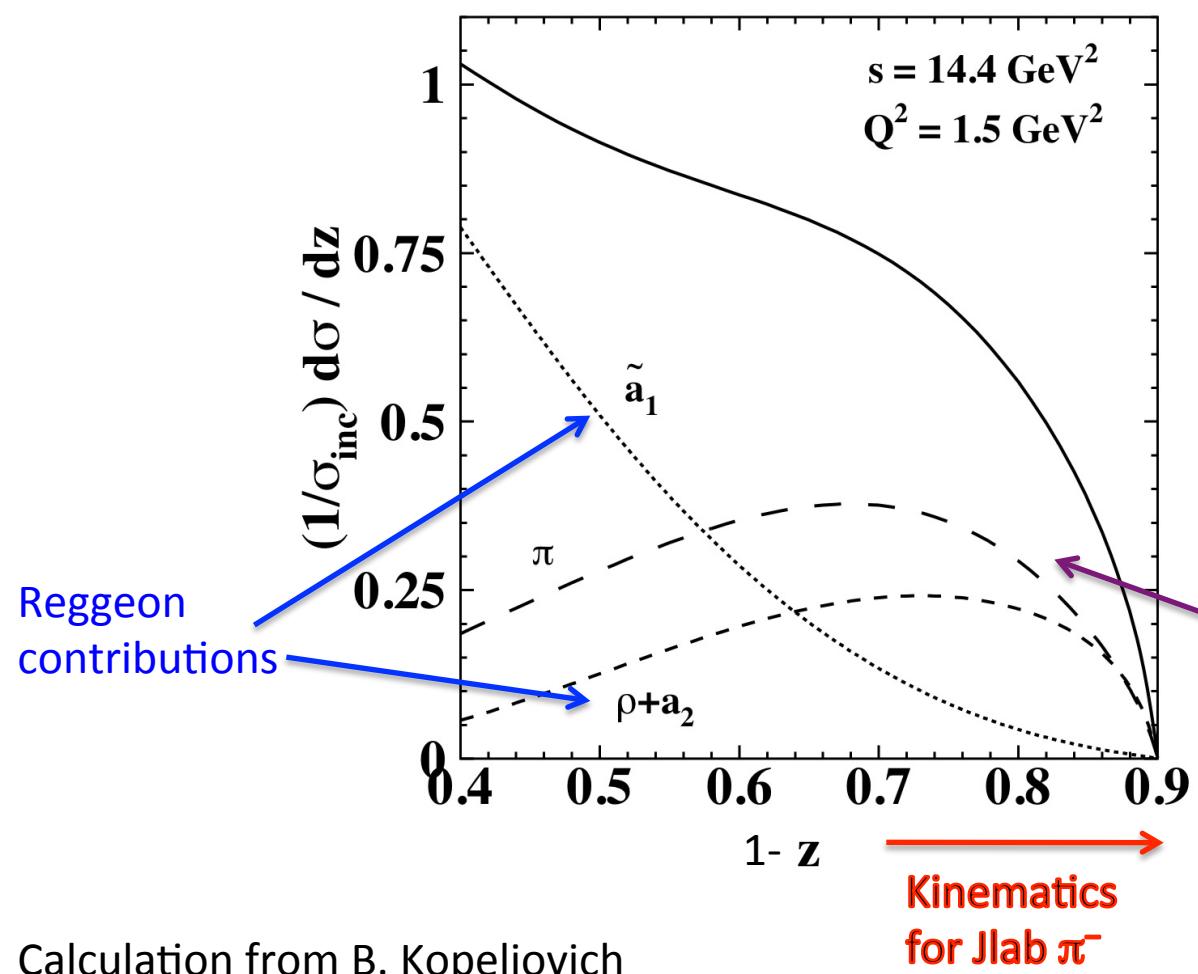


Backups

EMMI Workshop on Cold Dense Nuclear Matter
GSI, October 2015

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Developing the F_2^π case specifically



$1 - z = \text{light-cone momentum fraction of hadron (proton tag)}$
In the target fragmentation region

Pion contribution,
~50% at JLab kinematics

Calculation from B. Kopeliovich
at JLab TDIS kinematics

Approach to data analysis

Measure tagged:untagged (inclusive electron) ratio R^T :

$$R^T = \frac{d^4\sigma(ep \rightarrow e' X p')}{dxdQ^2 dz dt} / \frac{d^2\sigma(ep \rightarrow e' X)}{dxdQ^2} \Delta z \Delta t \sim \frac{F_2^T(x, Q^2, z, t)}{F_2^p(x, Q^2)} \Delta z \Delta t.$$

Proton Structure Function well known, use to obtain:

$$\rightarrow F_2^T(x, Q^2, z, t) = \frac{R^T}{\Delta z \Delta t} F_2^p(x, Q^2).$$

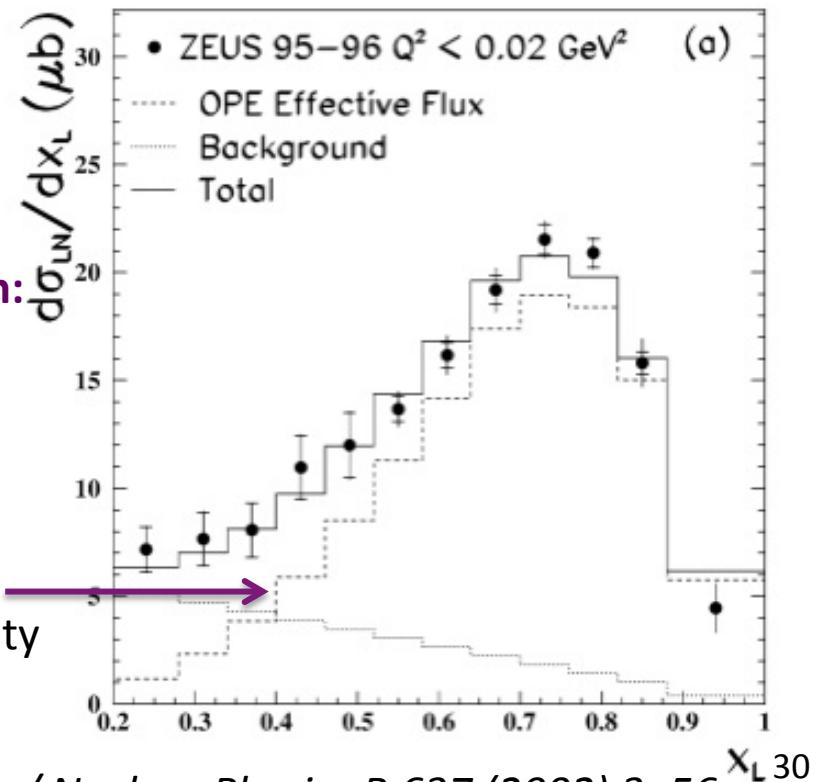
NOTE! This tagged structure function is the unambiguous result!

- Mesonic component of nucleon structure for n
- Pomeron/Reggeon behavior for p?

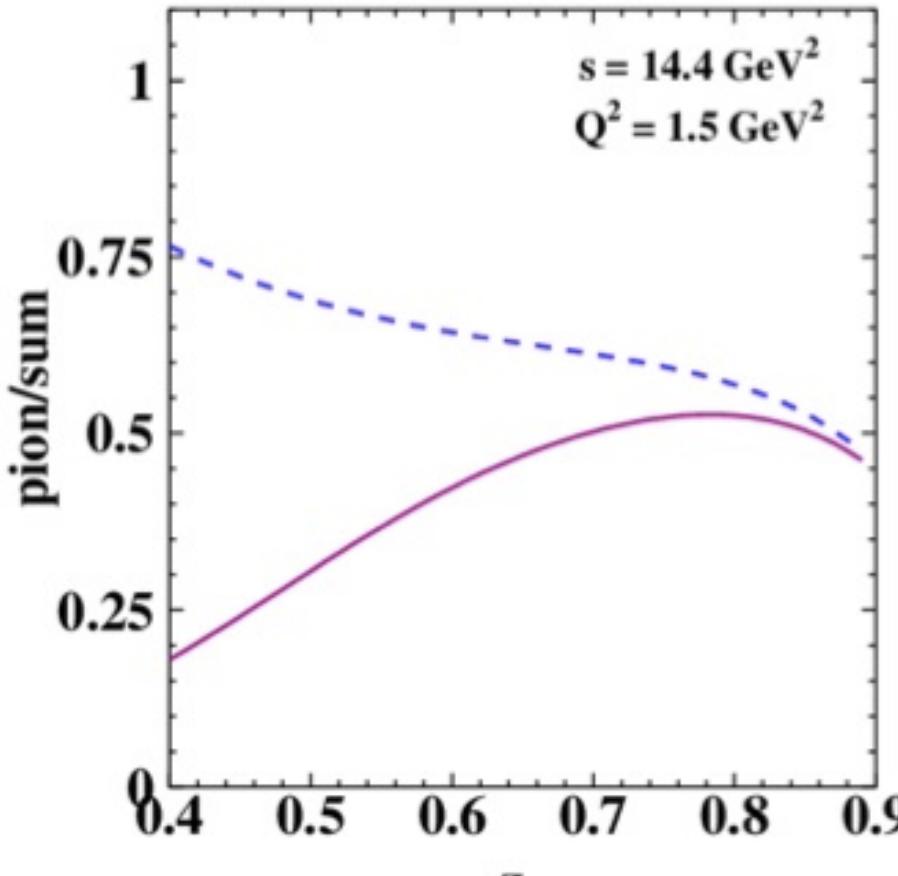
Additional considerations for Pion Structure Function:

$$F_2^{(\pi N)}(x, z, k_\perp) = \underbrace{f_{\pi N}(z, k_\perp)} F_{2\pi}\left(\frac{x}{z}\right)$$

- Pion flux model required
- Adopt HERA approach
 - fit for One Pion Exchange contribution
- Use multiple models, evaluate theory uncertainty
- Can normalize to Drell-Yan

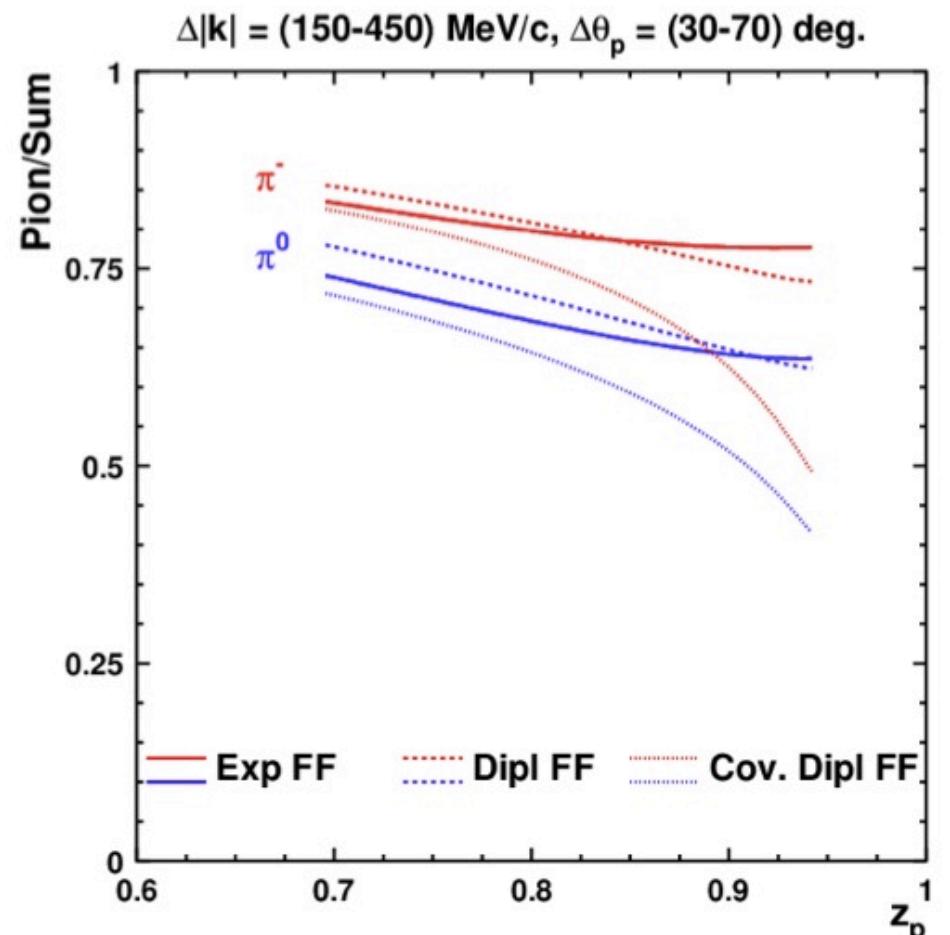


Pion flux is largest uncertainty, \sim 10-20%



B. Kopeliovich, I. Potashnikova (2015)

Rho, Regge



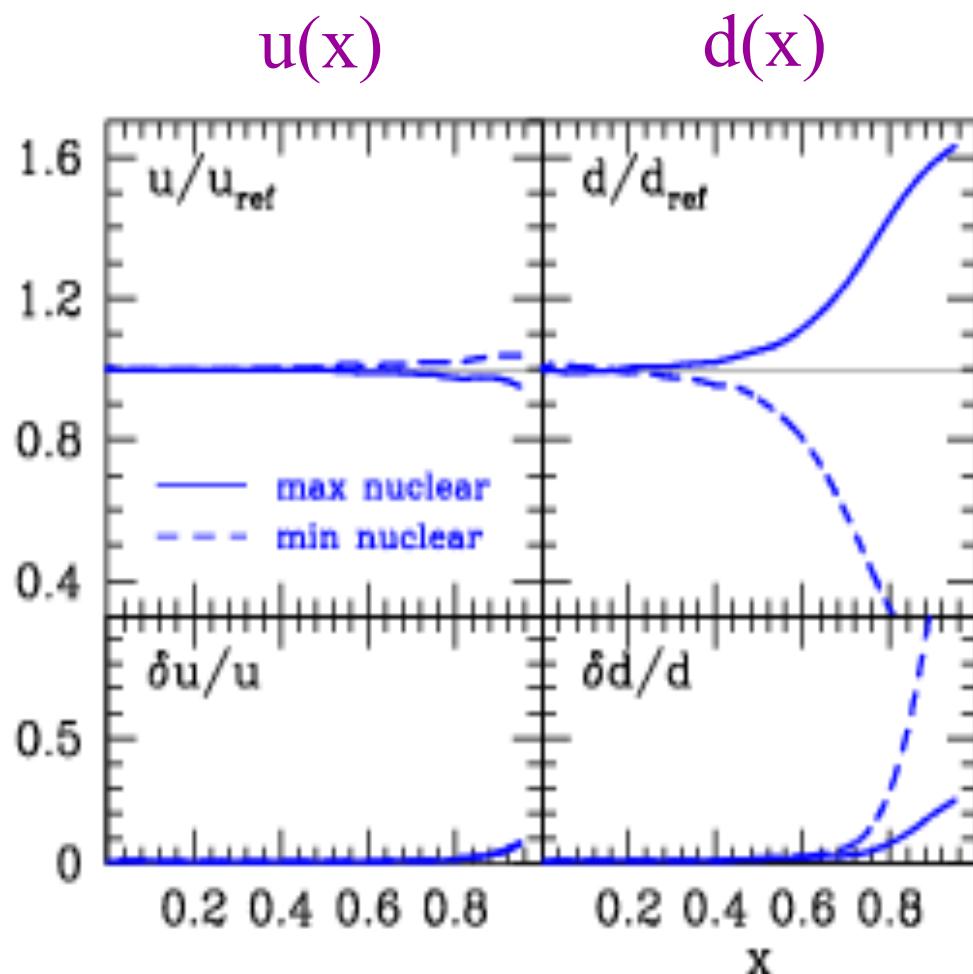
T. Hobbs, W. Melnitchouk, T. Londergan (2014)

Rho, Delta

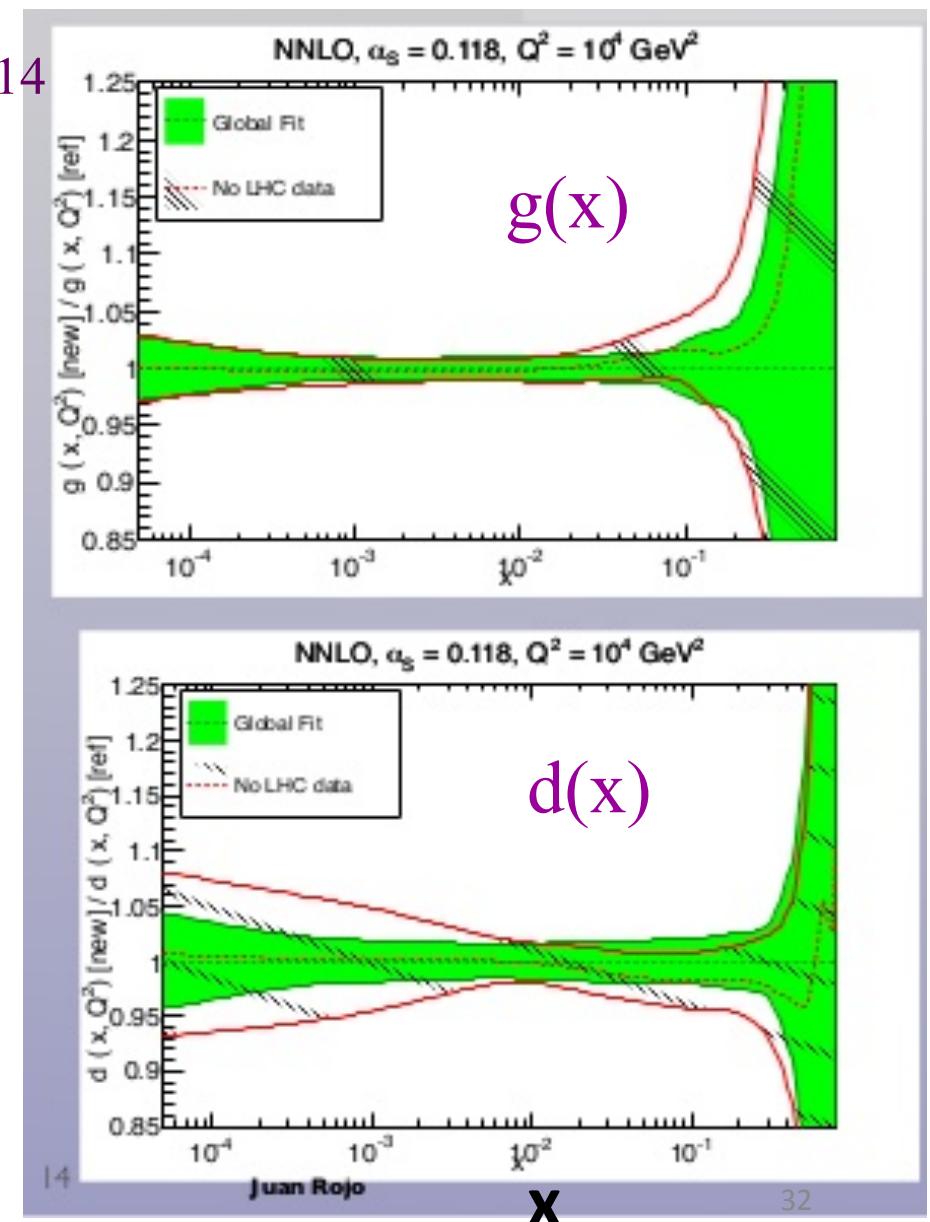
Can also normalize to Drell-Yan (5% uncertainty)....

Translates Directly to Large x Valence d,g pdf Uncertainties

CJ2012



NNPDF 2014



Extrapolation to the pole

Need range of low
momentum protons

The ratio of off-shell to on-
shell pion electromagnetic
form factor

C.D. Roberts, S. Qin (2015)

Pion's valence-quark GPD in
unified DSE framework:
virtuality-independent form
factor entails virtuality-
independent parton
distribution function

Within ~5% at proposed
kinematics

