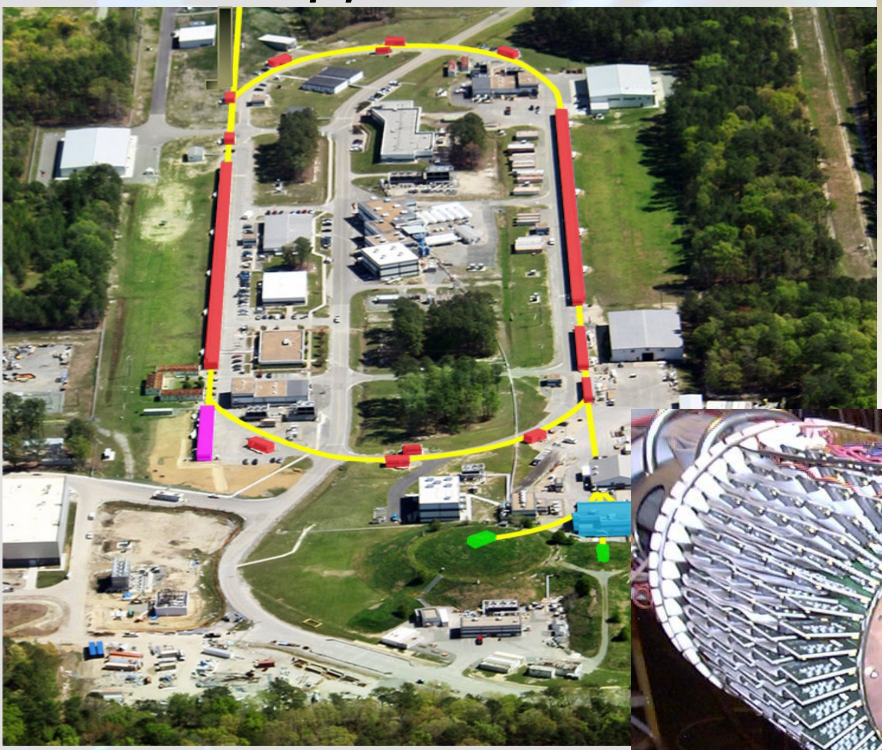
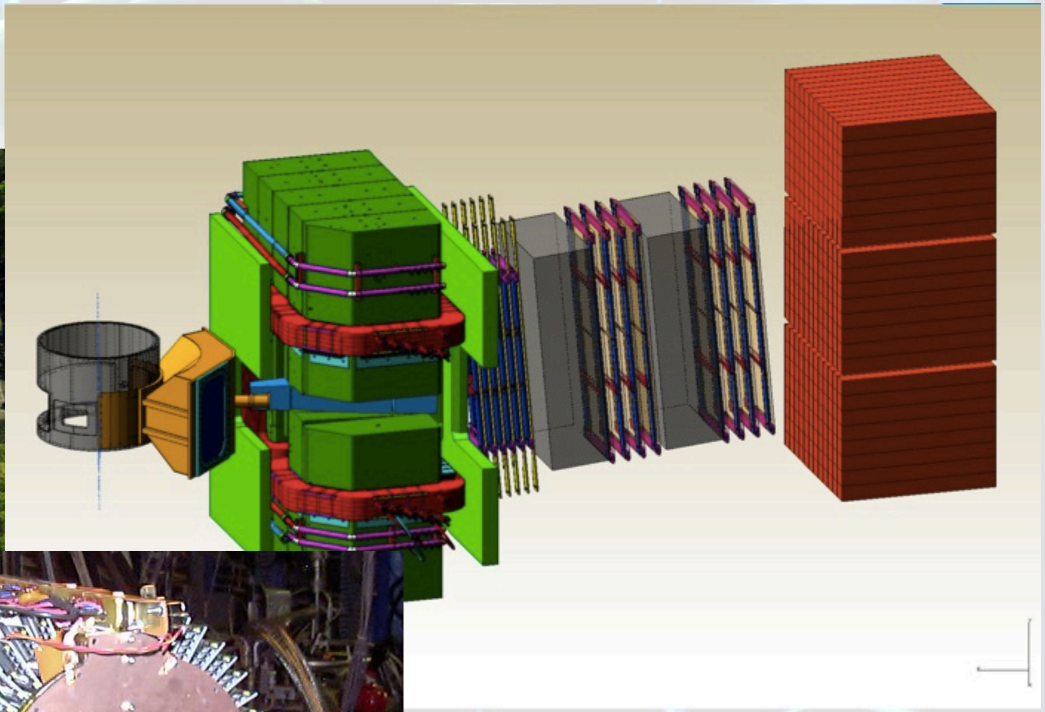
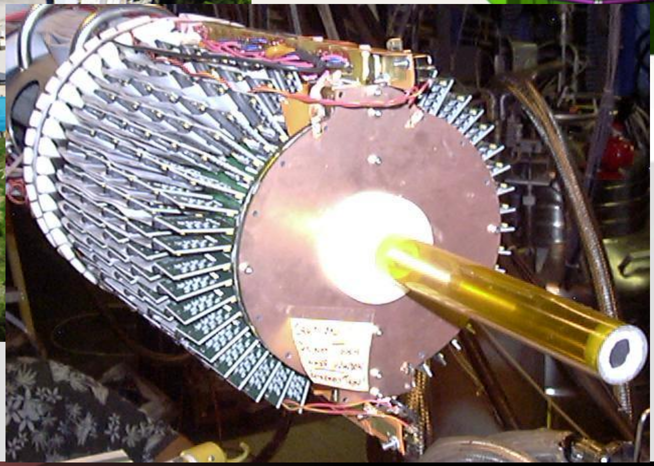
Exploring Pion and Nucleon Structure with Tagged Structure Functions

Thia Keppel







International Nuclear Physics Conference
Adelaide, September 2016

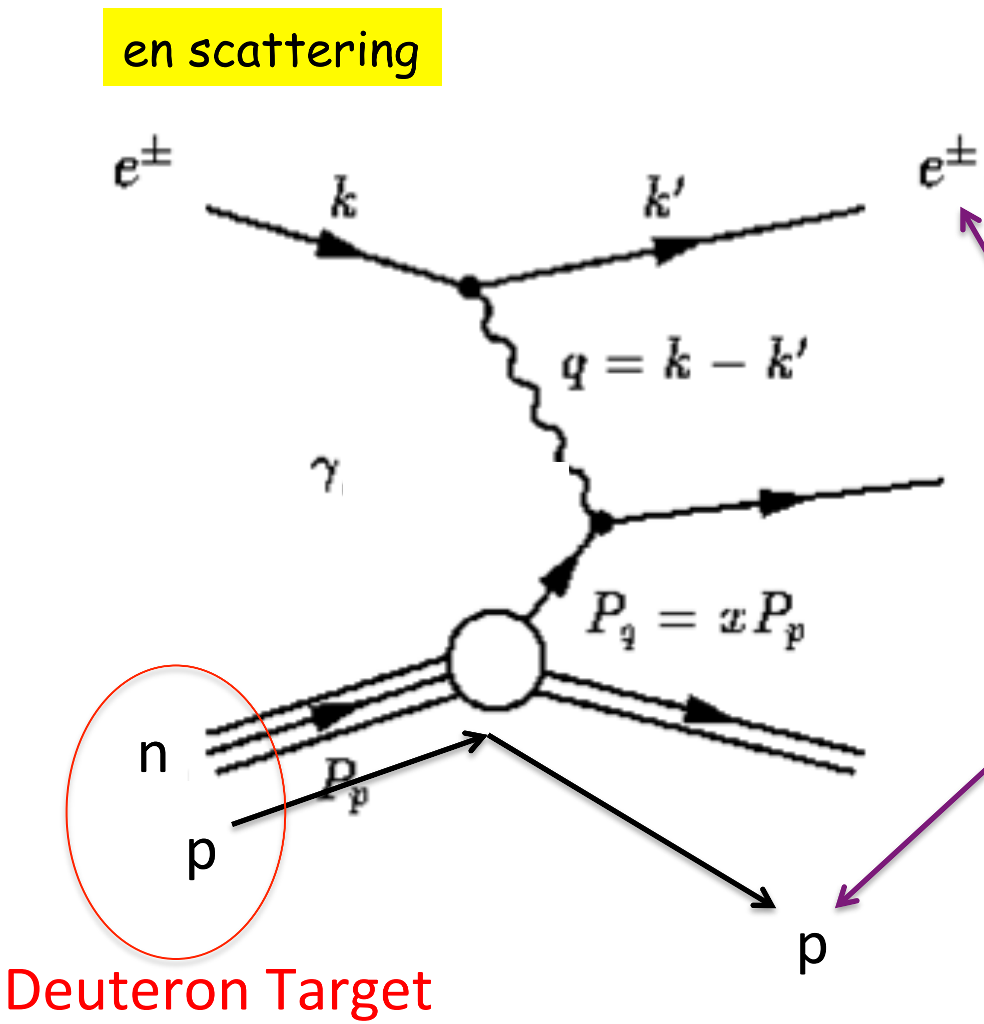
Tagged Deep Inelastic Scattering (TDIS)

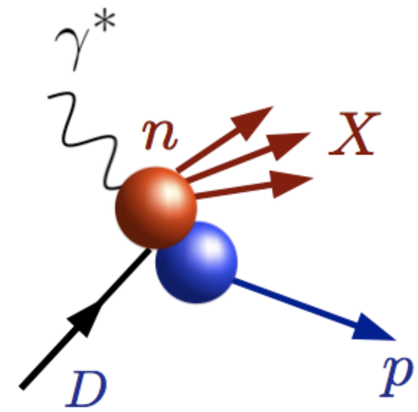
An experimental technique to probe the *target* regime in semi-inclusive deep inelastic scattering

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

Understand nucleon structure at a deeper level

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



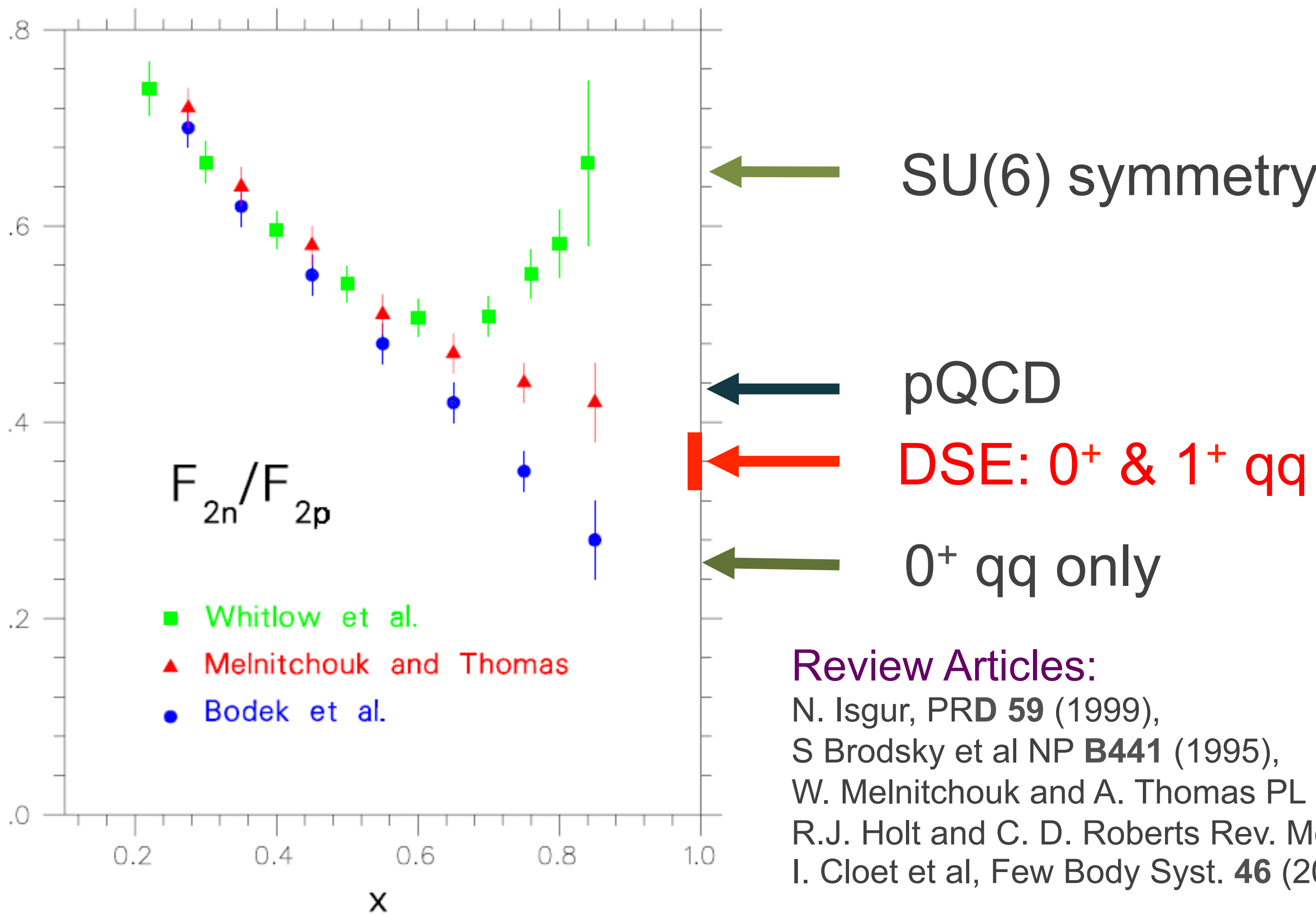


Measure DIS electron in coincidence with proton tag

Why measure from a neutron target?....

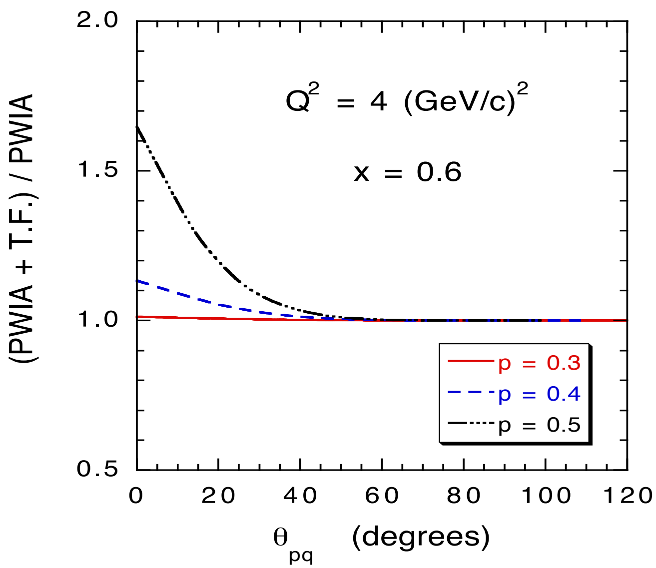
F_2^n/F_2^p (and, hence, d/u) is essentially unknown at large x:

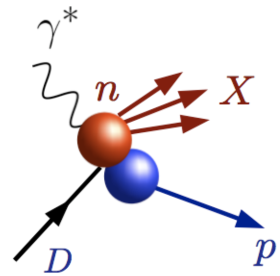
- Conflicting fundamental theory pictures
- Data inconclusive due to uncertainties in deuterium nuclear corrections
- Translates directly to large uncertainties on d(x), g(x) parton distribution functions



Review Articles:
N. Isgur, PRD **59** (1999),
S Brodsky et al NP **B441** (1995),
W. Melnitchouk and A. Thomas PL **B377** (1996),
R.J. Holt and C. D. Roberts Rev. Mod. Phys. **82** (2010),
I. Cloet et al, Few Body Syst. **46** (2009) 1.

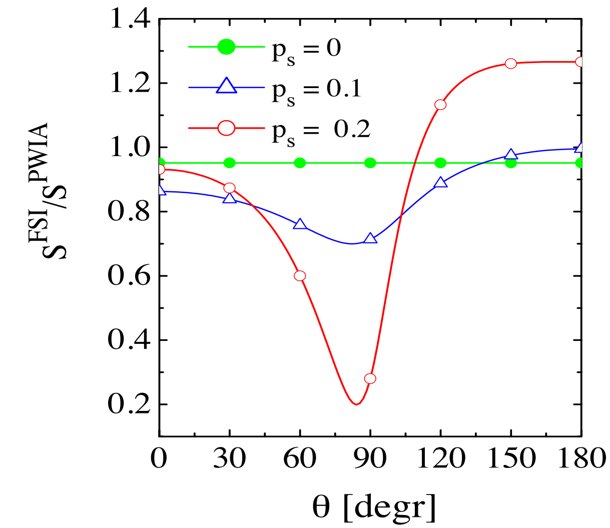
The BONUS approach: tag spectator proton at (very) low momentum and large angle in electron-deuteron scattering

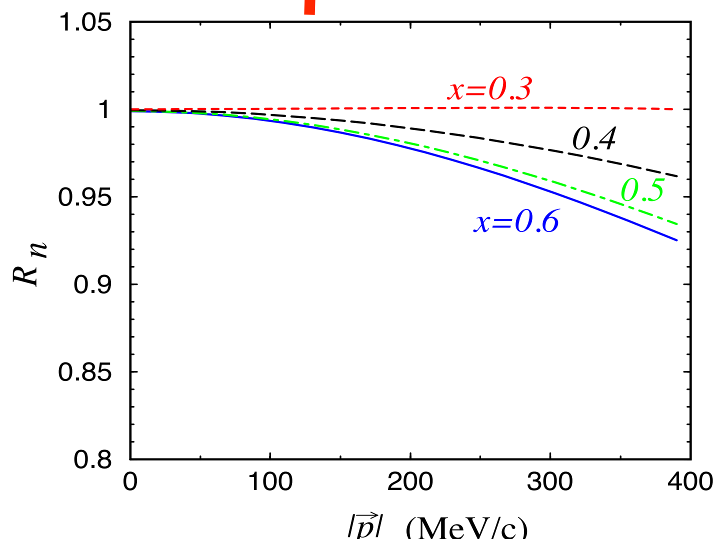




Bound / free neutron structure

O **(1%)**





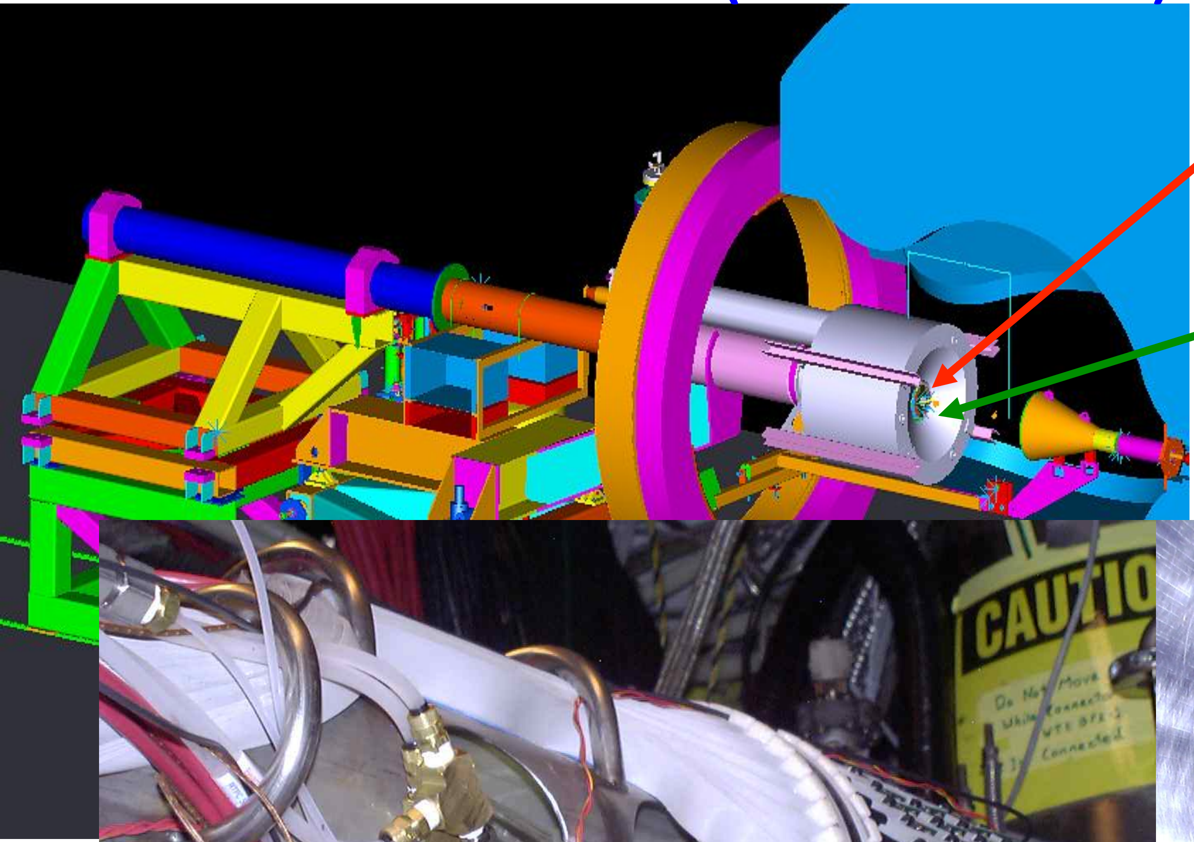
Target fragmentation

negligible

Final state interactions

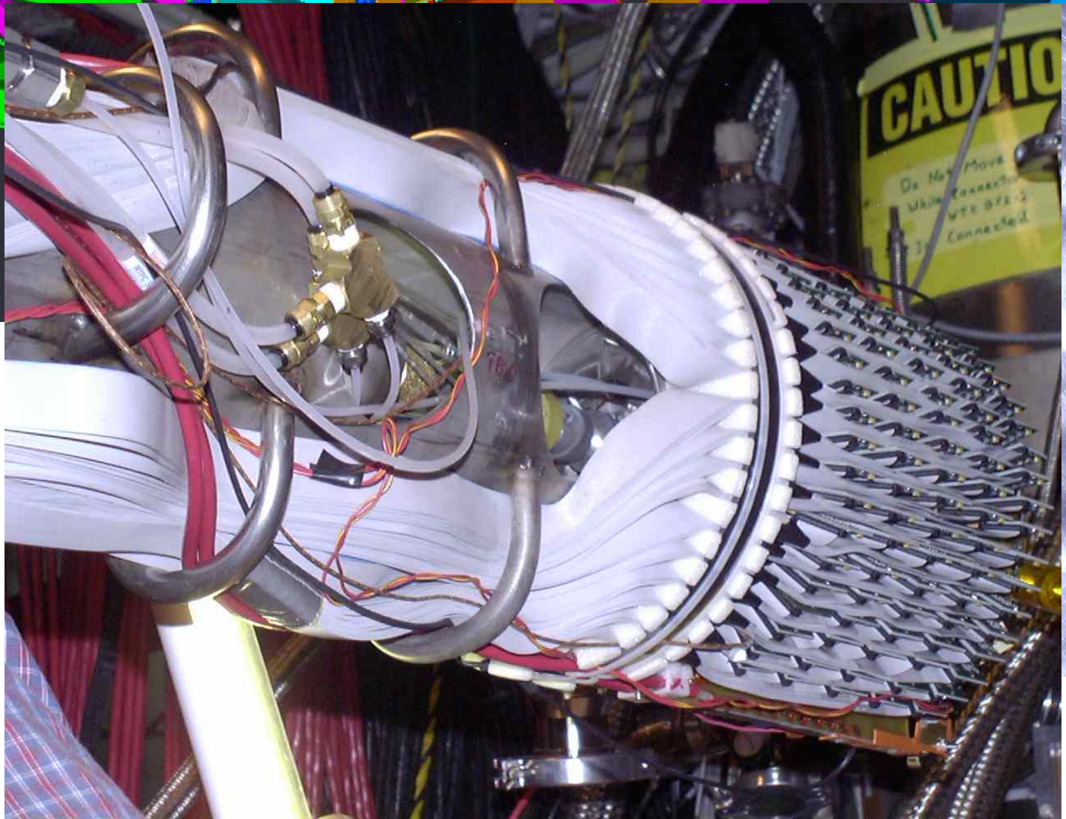
O **(5%)**

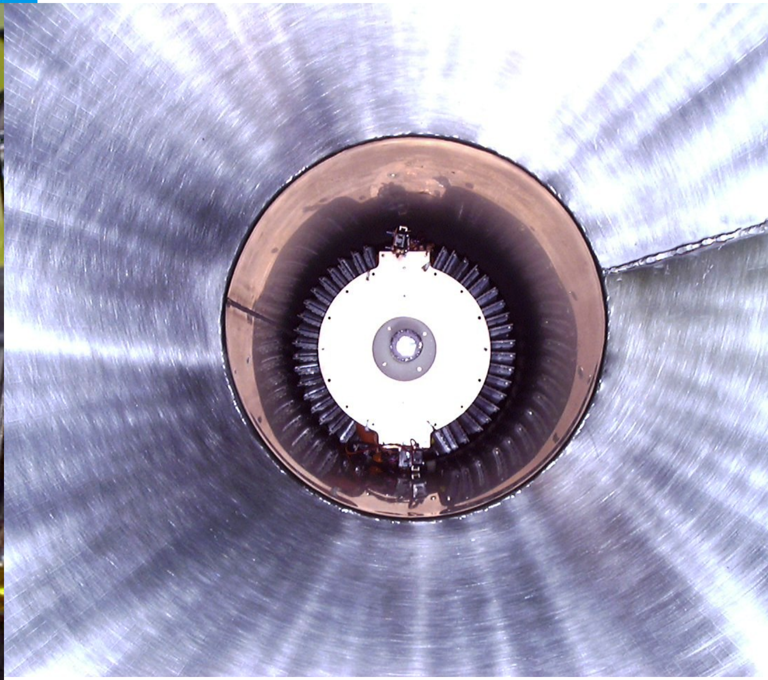
BONUS in CLAS6 (e detector)



BoNuS GEM-based rTPC (low momentum p detector)

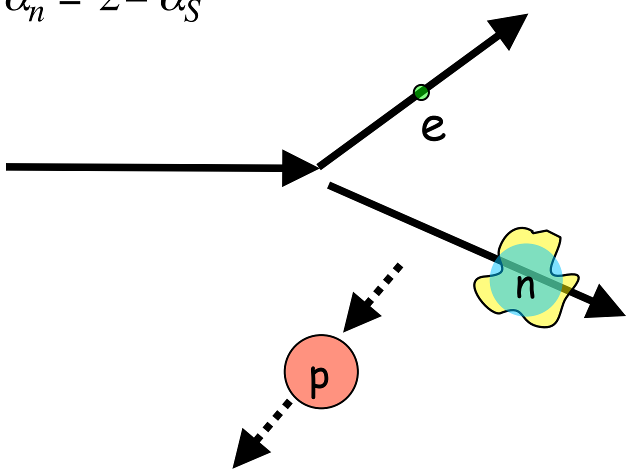
Solenoid Magnet (track curvature in TPC)





Spectator Tagging - results

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

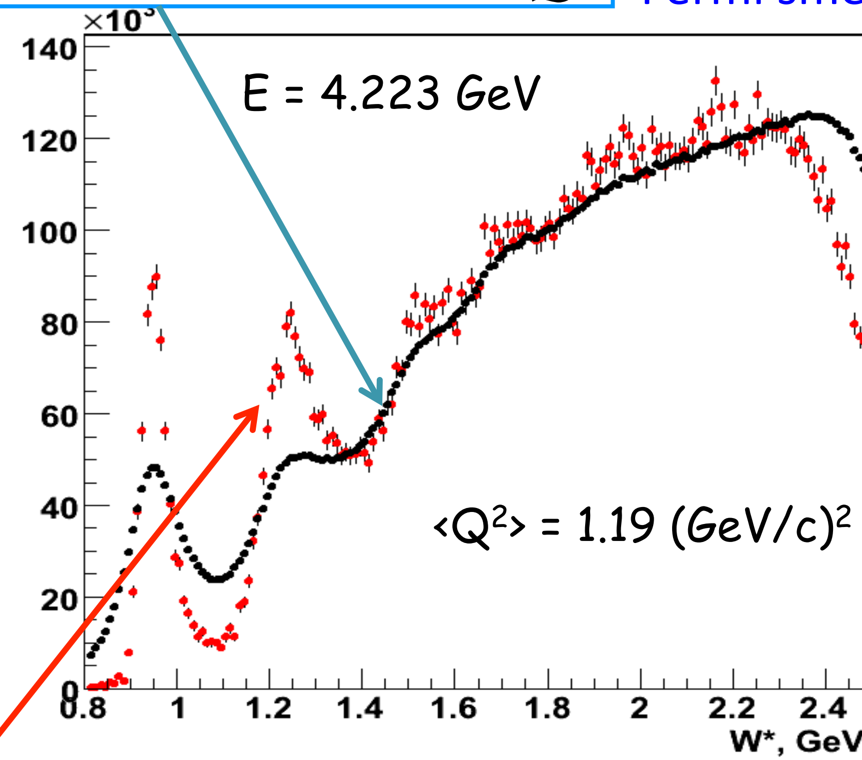


$$p_S = \left(E_S, \vec{p}_S\right); \quad \alpha_S = \frac{E_S - \vec{p}_S \cdot \hat{q}}{M_D/2}$$

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

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

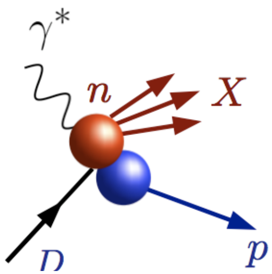
Inclusive data – Fermi smearing



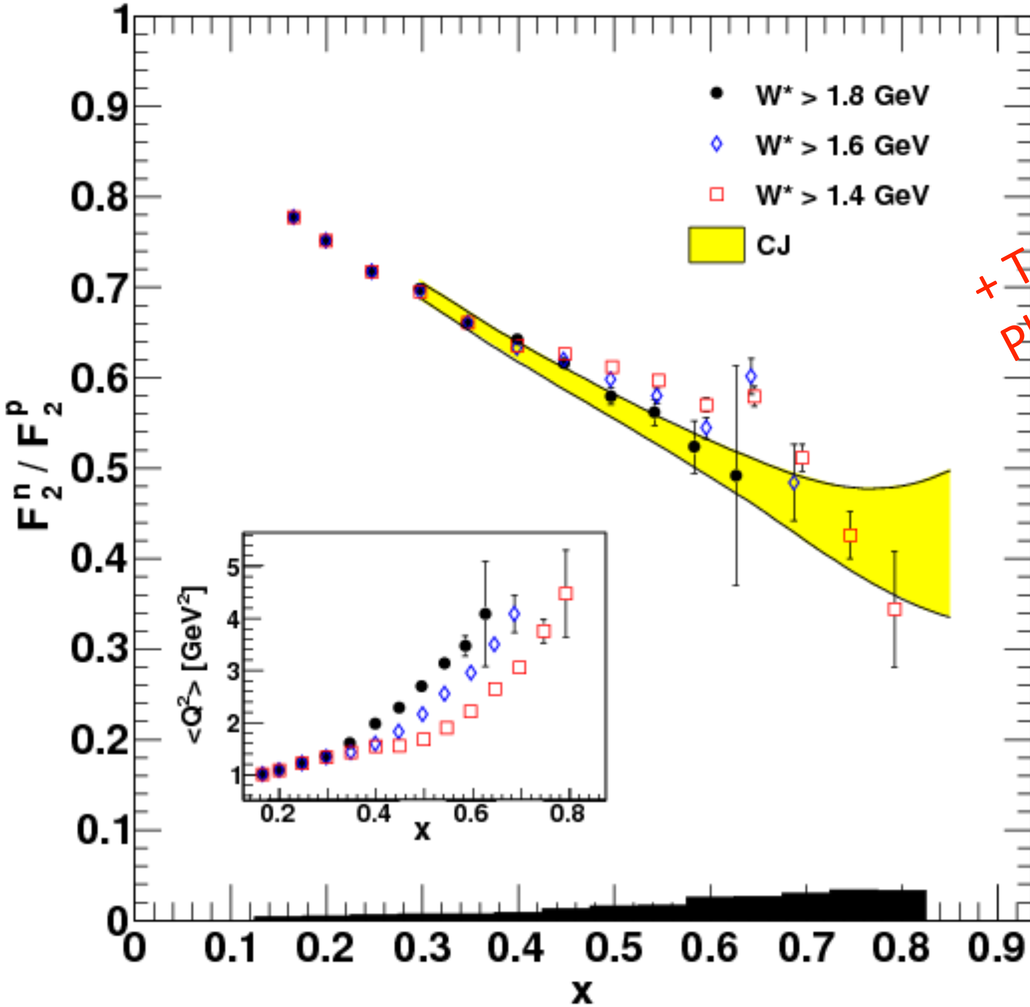
$$\boxed{\begin{aligned} W^{*2} &= \left(p_n + q\right)^2 = p_n^{\mu} p_{\mu} + 2\left((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}\right) - Q^2 \\ &\approx M^{*2} + 2M\nu(2-\alpha_S) - Q^2 \end{aligned}}$$

* Tagged data – know nucleon momentum

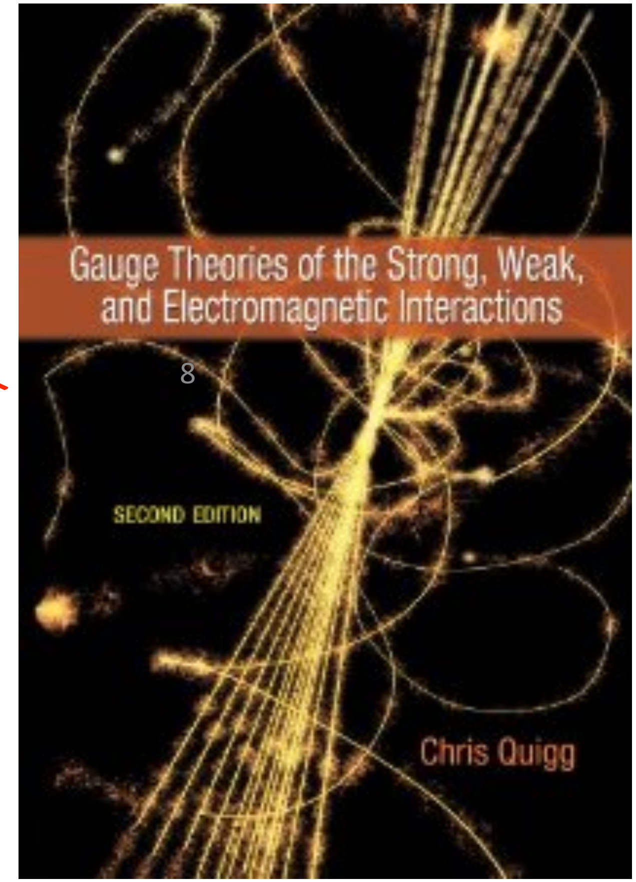
Low momentum proton tagging *achieved*



Phys. Rev. Lett. 108 (2012) 199902
Phys. Rev. C89 (2014) 045206
– editor's suggestion
Nucl. Instrum. Meth. A592 (2008) 273-286
Phys.Rev. C91 (2015) 055206



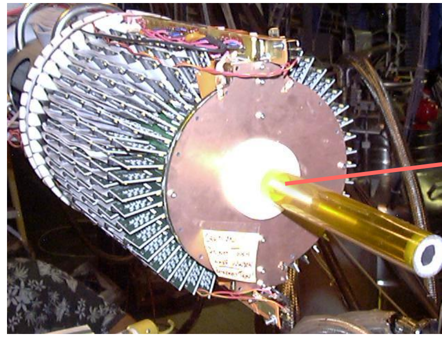
+ Textbook Physics!

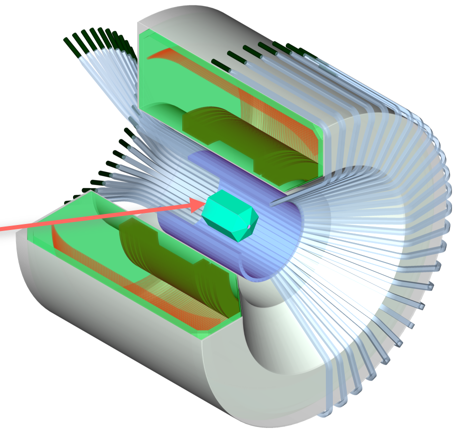


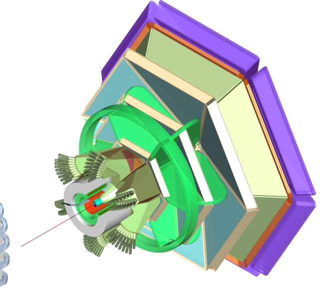
- Now input for (CJ) global PDF fits
- Likely not quite high enough x, Q^2

Plans for 12 GeV

E12-06-113
"BONUS12"
approved

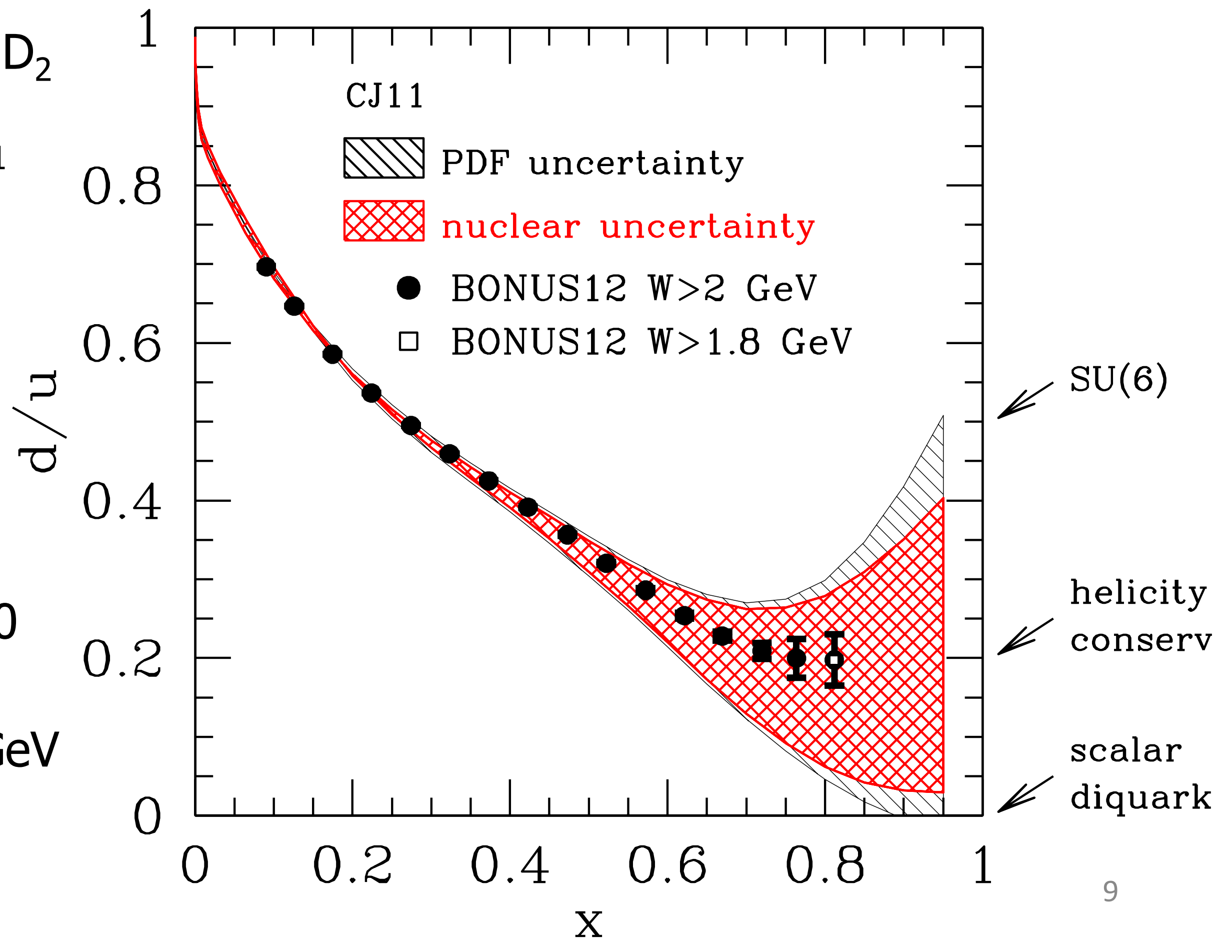






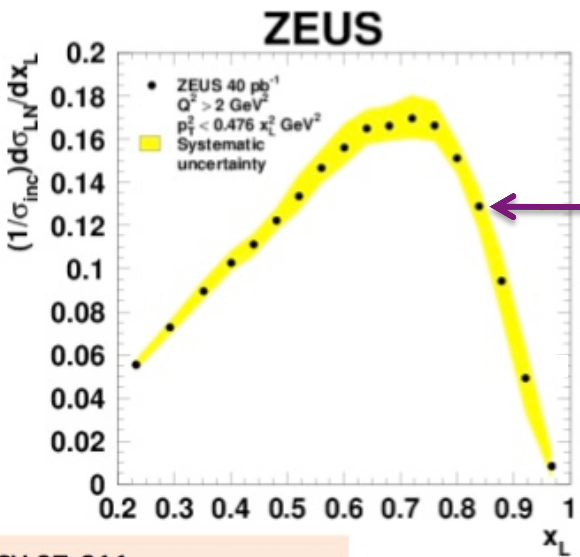
CLAS12
Central
Detector

- Data taking of 35 days on D_2 and 5 days on H_2 with $\mathrm{L} = 2 \cdot 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$
- **Planning for 2018 run**
- DIS region with
  - $Q^2 > 1\ \mathrm{GeV}^2/c^2$
  - $W^* > 2$ GeV
  - $p_s < 100$ MeV/c
  - $\theta_{pq} > 110°$
- Largest value for $x^* = 0.80$ (bin centered $x^* = 0.76$)
- Relaxed cut of $W^* > 1.8$ GeV gives max. $x^* = 0.83$



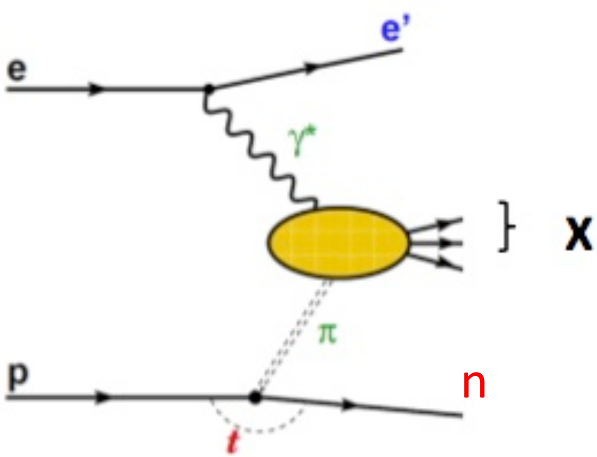
TDIS at HERA – proton and *neutron* tag

DESY 08-176 JHEP06 (2009) 74



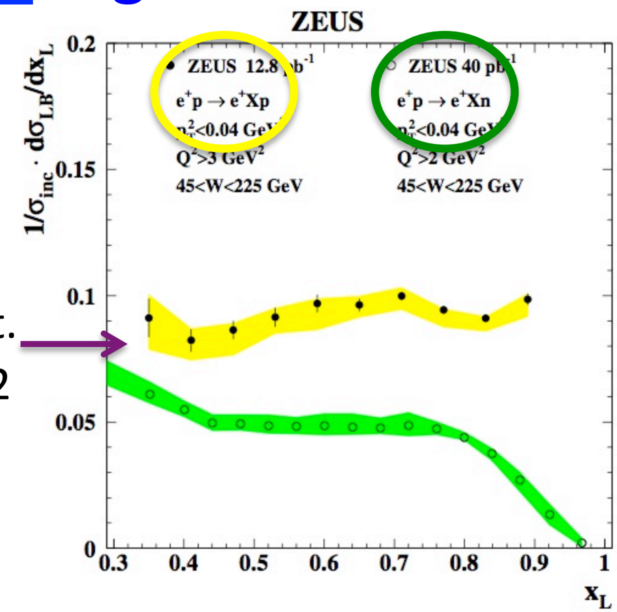
DESY 07-011
Nucl.Phys.B776(2007) 1-37

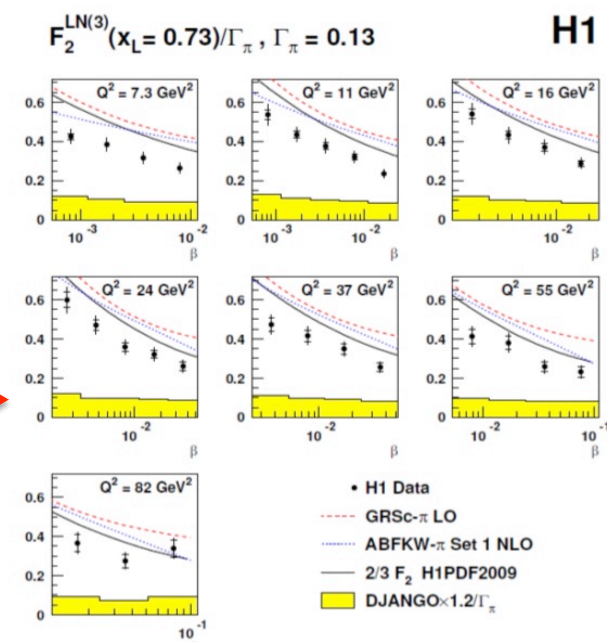
$x_L = E^p/E^p_{beam} \sim 1$



- *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
- Pion ~$(1-x_L)$

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

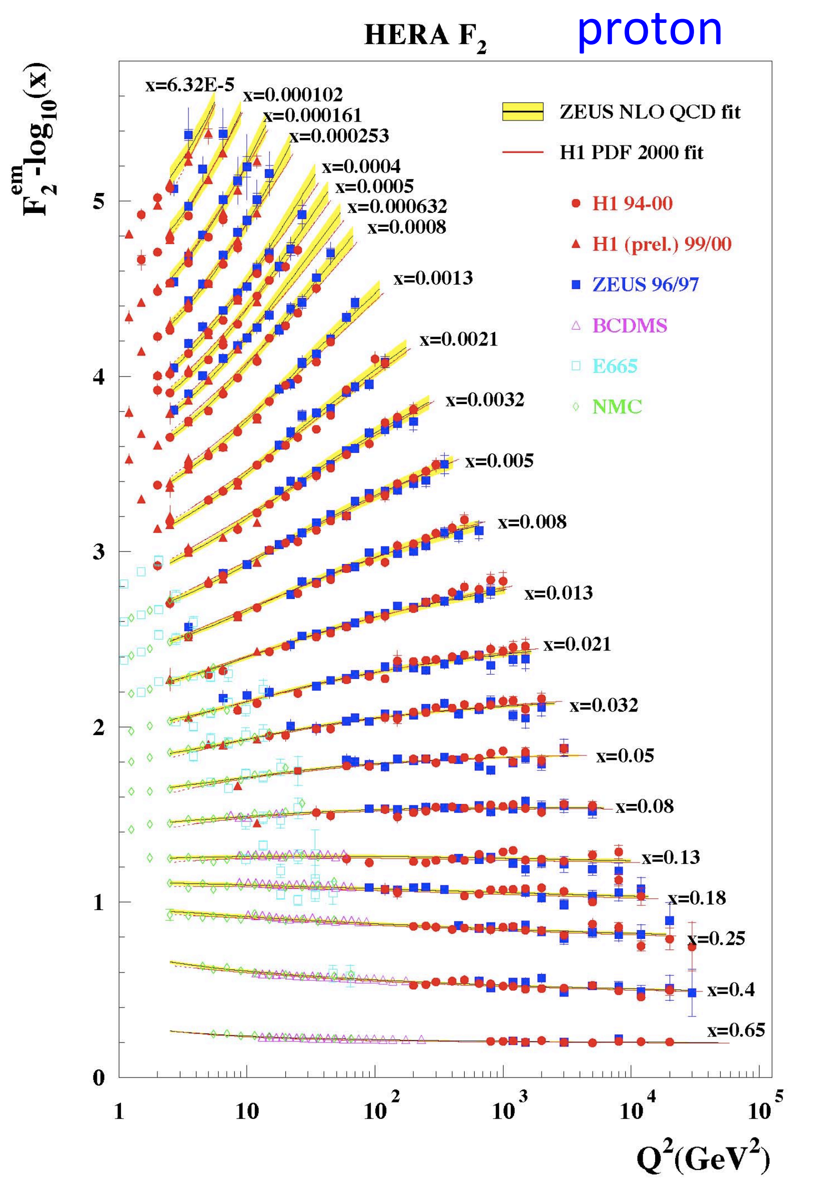




DESY 09-185 Eur. Phys. J. C68 (2010) 381

Pion structure function measurements hindered by lack of pion target

- Only have the rather scant data from HERA and pion Drell-Yan experiments
- 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(bar) flavor asymmetry?
  - asymmetry in anti-quarks generated from pion valence distribution?



BONUS-type Tagging Facilitates HERA-type Probe of Meson Cloud at Jefferson Lab

Example: Sullivan process scattering from proton-pion fluctuation

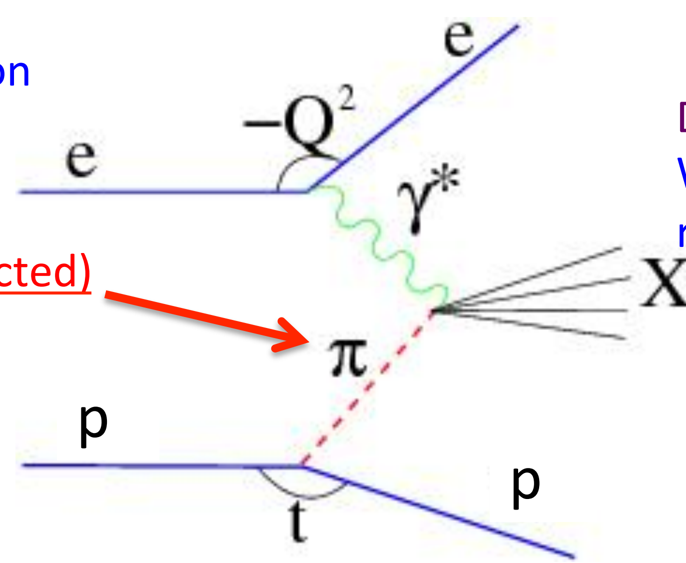
Hydrogen Target

detect scattered electron

incoming electron

DIS event – reconstruct x, Q^2, W^2, also M_X of undetected recoiling hadronic system

neutral pion target (undetected)



Initial state proton

tagged final state spectator proton

Detected protons need to be *low* momentum
- Tag target hadron
- Extrapolate to pole

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

<u>C1 Approval for JLab Hall A:</u>

✓High luminosity,

50 μAmp, $\mathcal{L} = 3 \times 10^{36}/cm^2\ s$

✓Large acceptance

Super Bigbite ~70 msr, hadron spectrometer

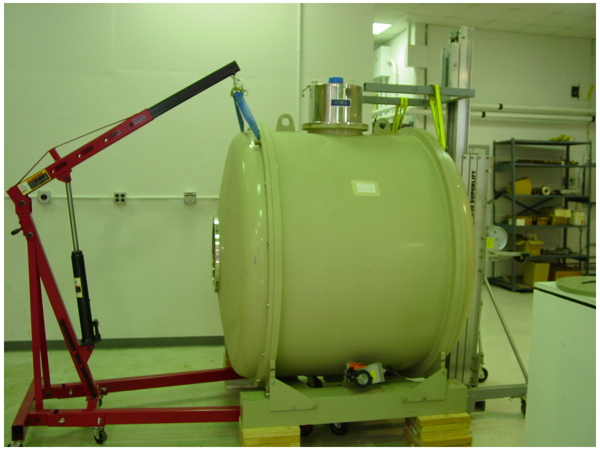
✓HCAL will be used in RTPC calibration

Need to…

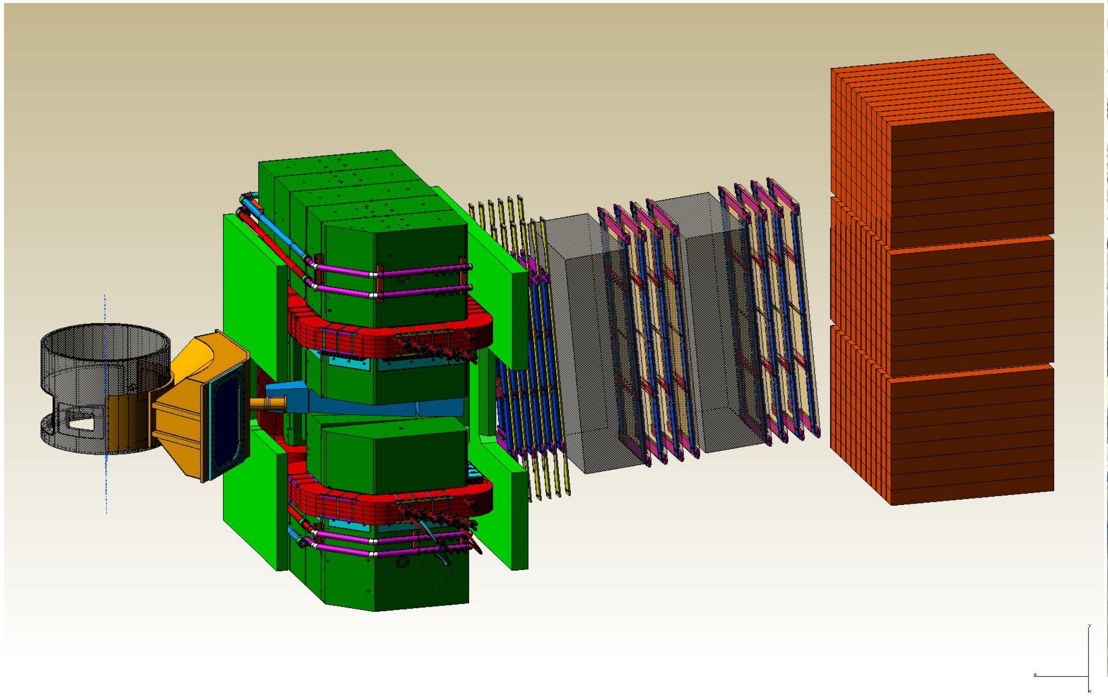
Add BONUS-type RTPC, requires solenoidal field

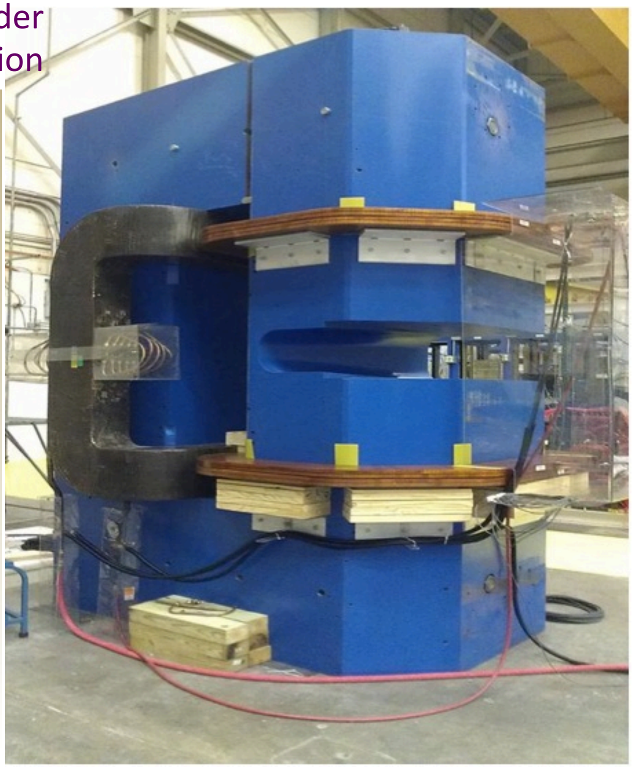
Modify SBS for electron detection

superconducting solenoid



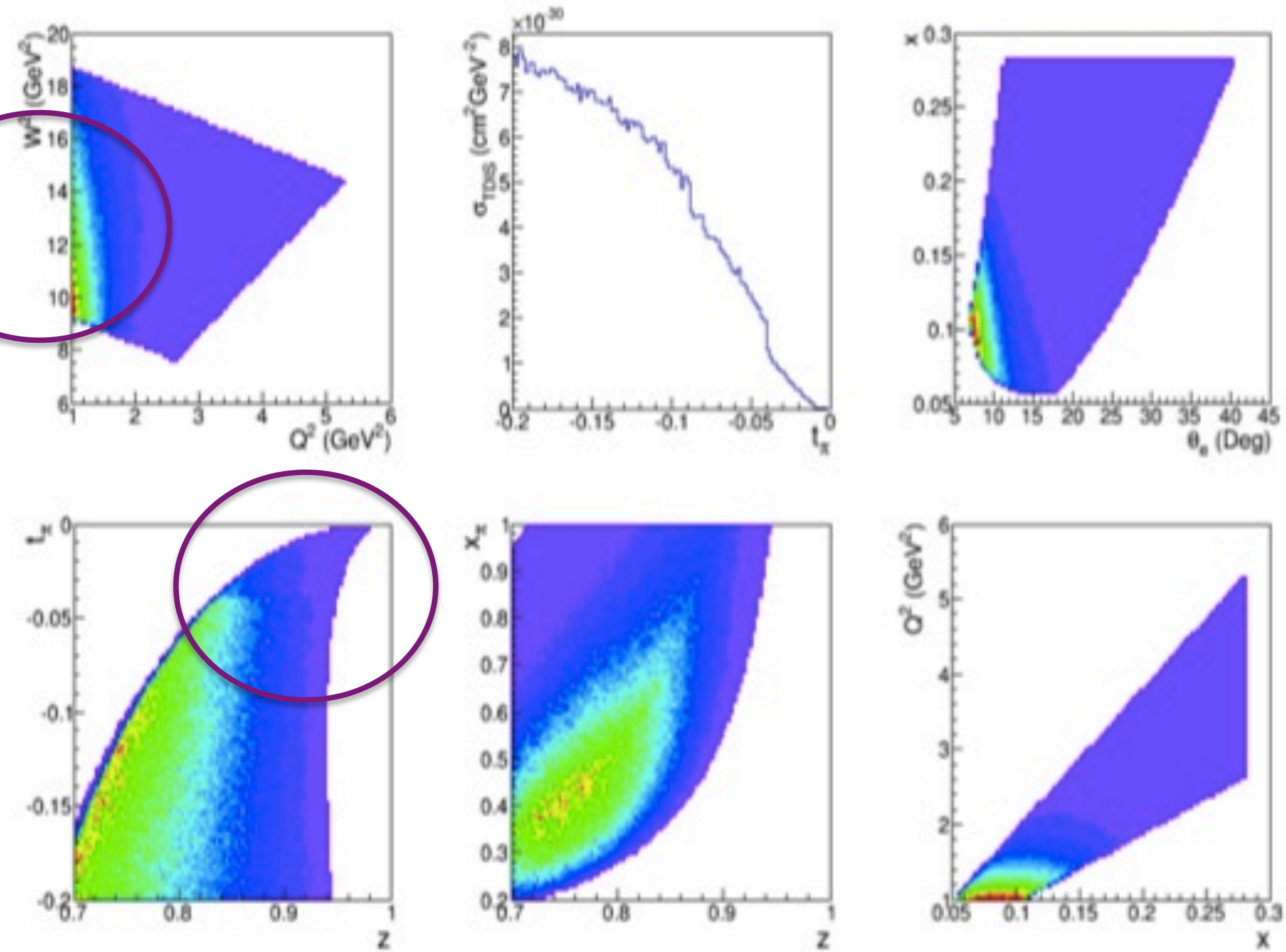
SBS under construction





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)

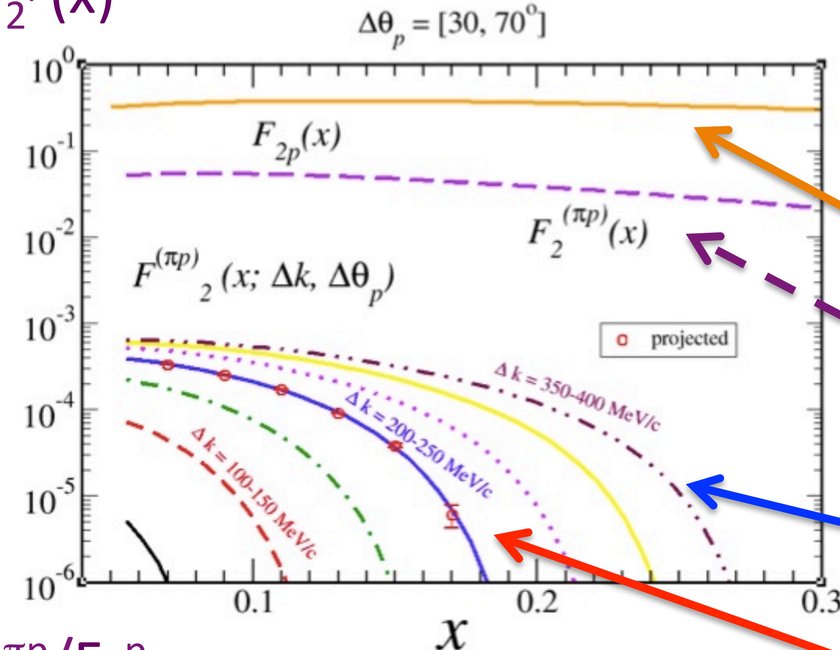
Low t, high z

x range ~ 0.1

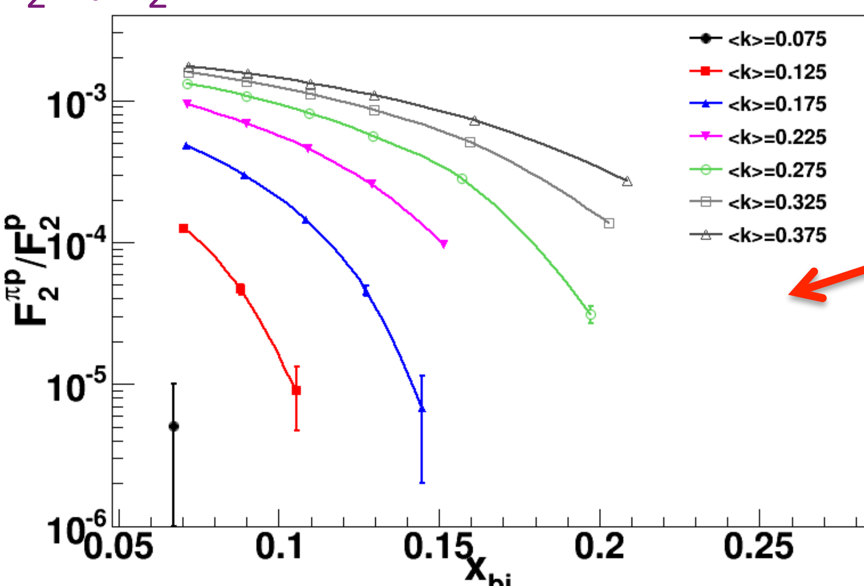
$1 < Q^2 < 2$ GeV^2

Projected Results I - proton

$F_2^p(x)$



$F_2^{\pi p}/F_2^p$



$F_2^p(x)$ 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}

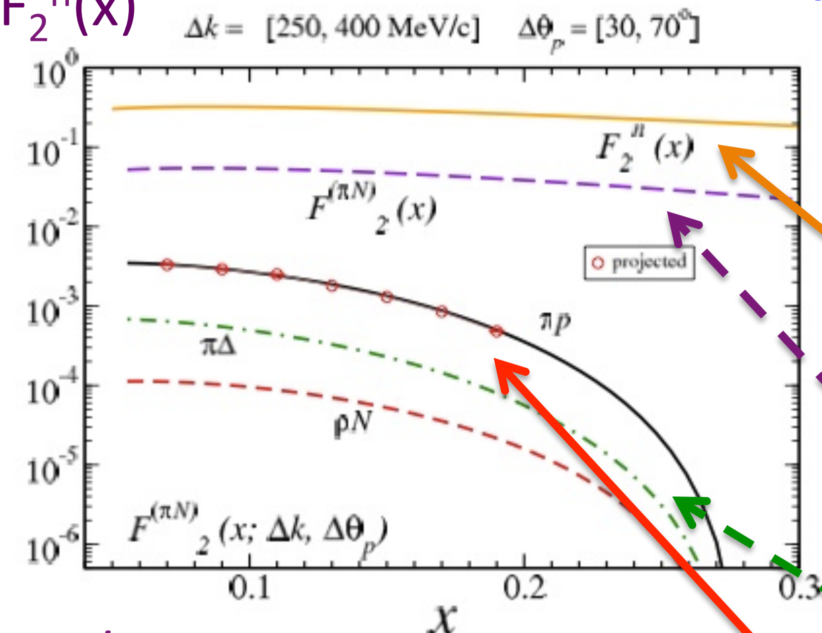
Data for 200 < p_{proton} <250 MeV/c are representative to show uncertainty

Full data set shown here
- all momentum bins in MeV/c

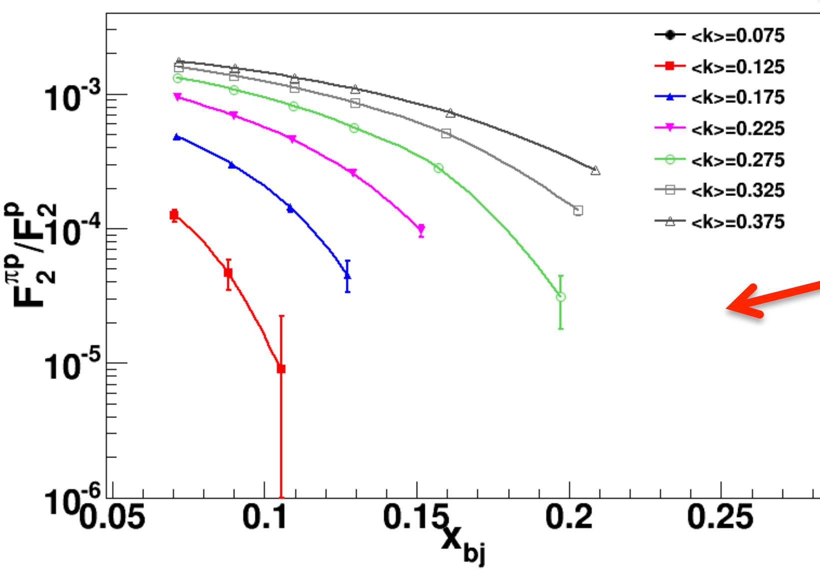
Error bars largest at highest x points – less statistics
- at fixed x, these are the lowest t values

Projected Results II - neutron

$F_2^n(x)$



$F_2^{\pi p}/F_2^p$



$F_2^n(x)$ 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_{proton} < 400 MeV/c.

Data for pion contribution are representative to show uncertainty

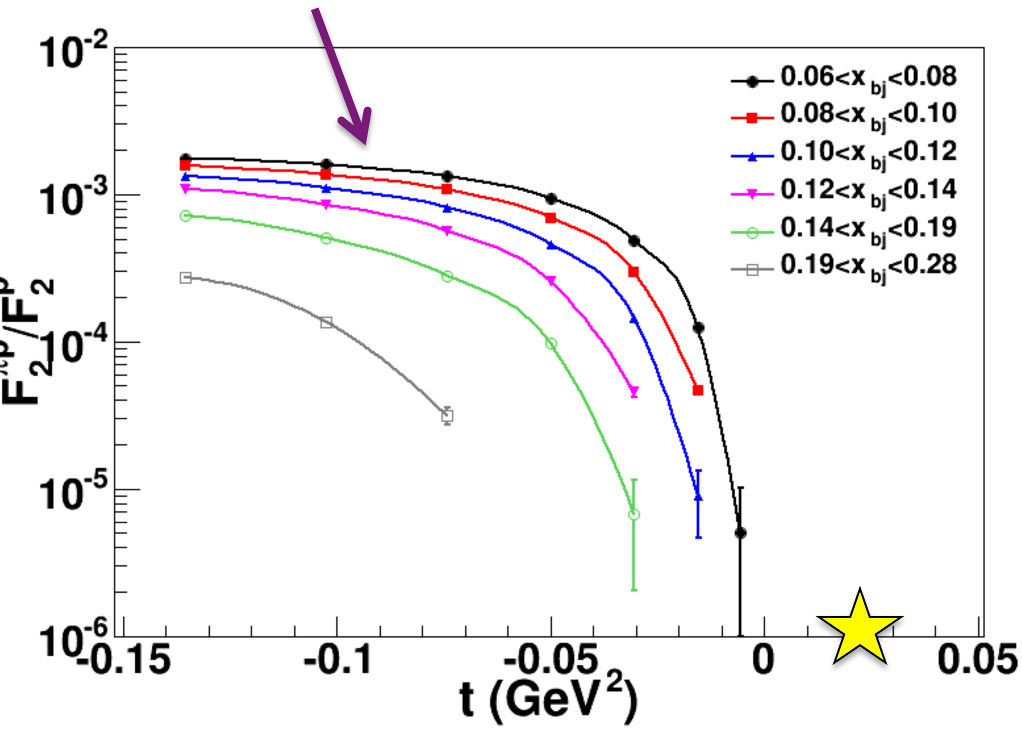
Full data set shown here
- all momentum bins in MeV/c

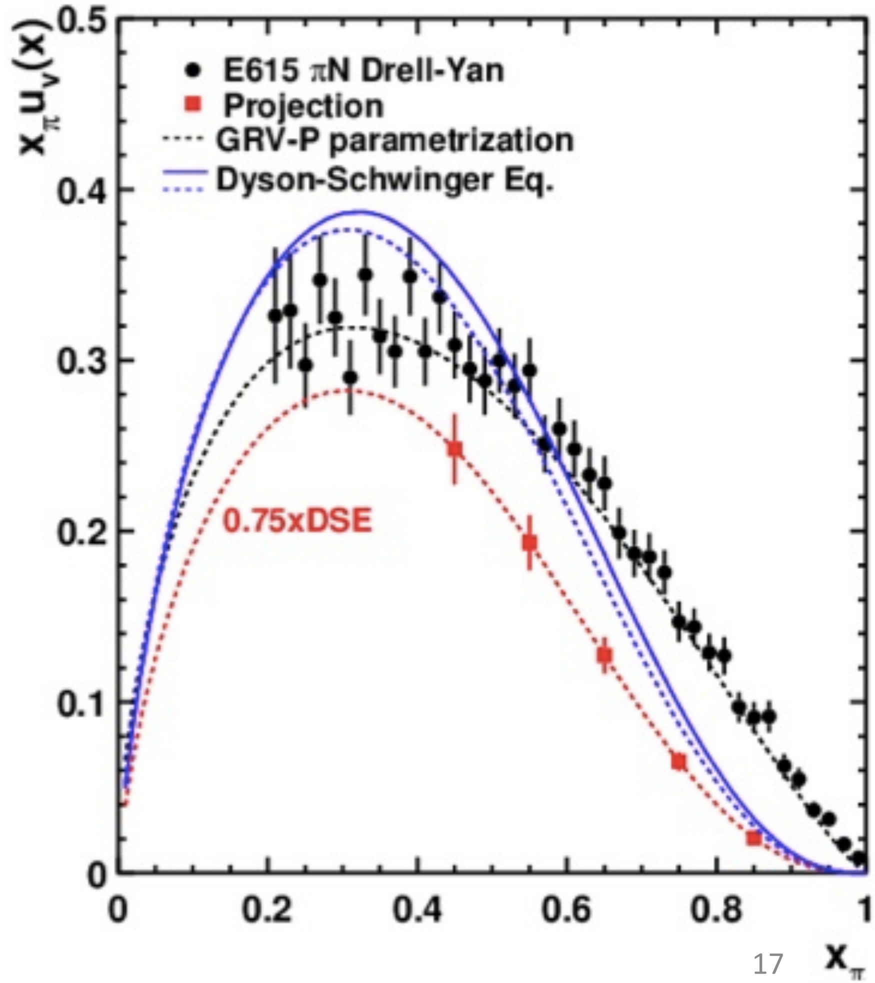
Do not show lowest momentum <x> = 0.075 data
- run lower luminosity due to larger background

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

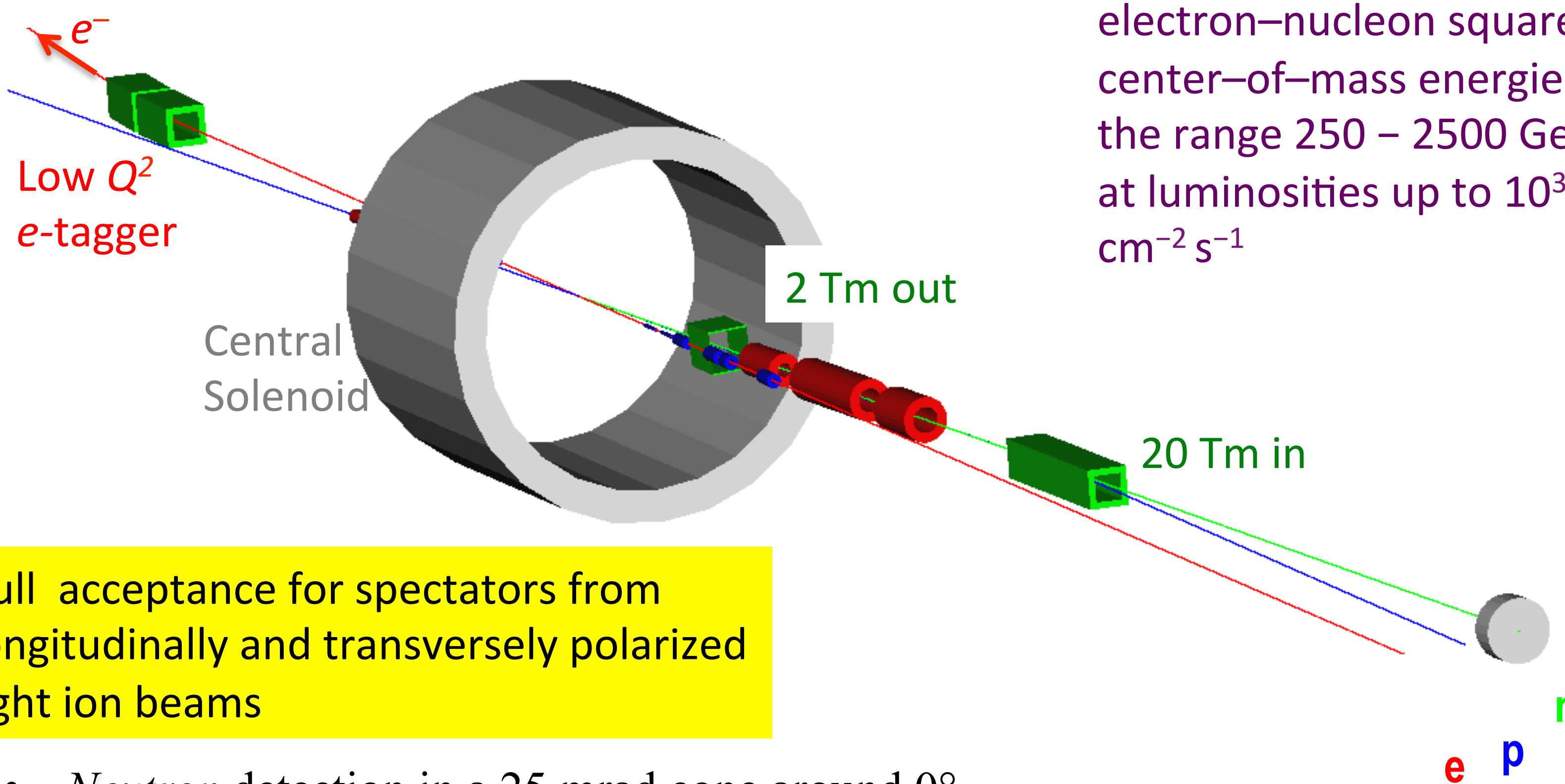




Will also measure n, p (π^-, π^0) difference
- look for isospin dependence

Tagged DIS at the EIC

The technique is uniquely suited to colliders: there is no target material absorbing low-momentum nucleons



The mEIC designs provide electron–nucleon squared center–of–mass energies in the range 250 – 2500 GeV^2 at luminosities up to 10^{34} cm^{-2} s^{-1}

- Full acceptance for spectators from longitudinally and transversely polarized light ion beams

- *Neutron* detection in a 25 mrad cone around 0°
- Secondary high dispersive ion focus ~40 m downstream of IP

Summary

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

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

TDIS opens a door to probe meson cloud of the nucleon

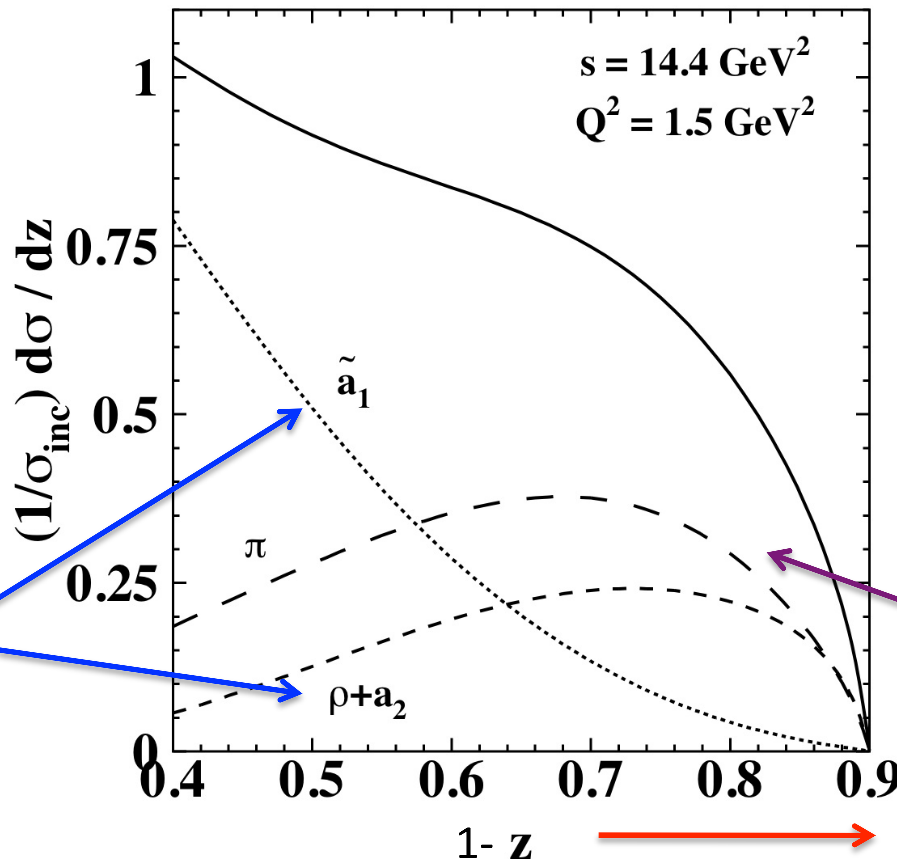
- *direct measurement of nucleon-meson fluctuation component of DIS*
- very few experiments to date
- fundamental QCD
- measurement of isospin dependence (p–n difference)

Understand nucleon structure at a deeper level

Thank You!!!

Backups

Developing the F_2^{π} case specifically



1-z = light-cone momentum fraction of hadron (proton tag)
In the target fragmentation region

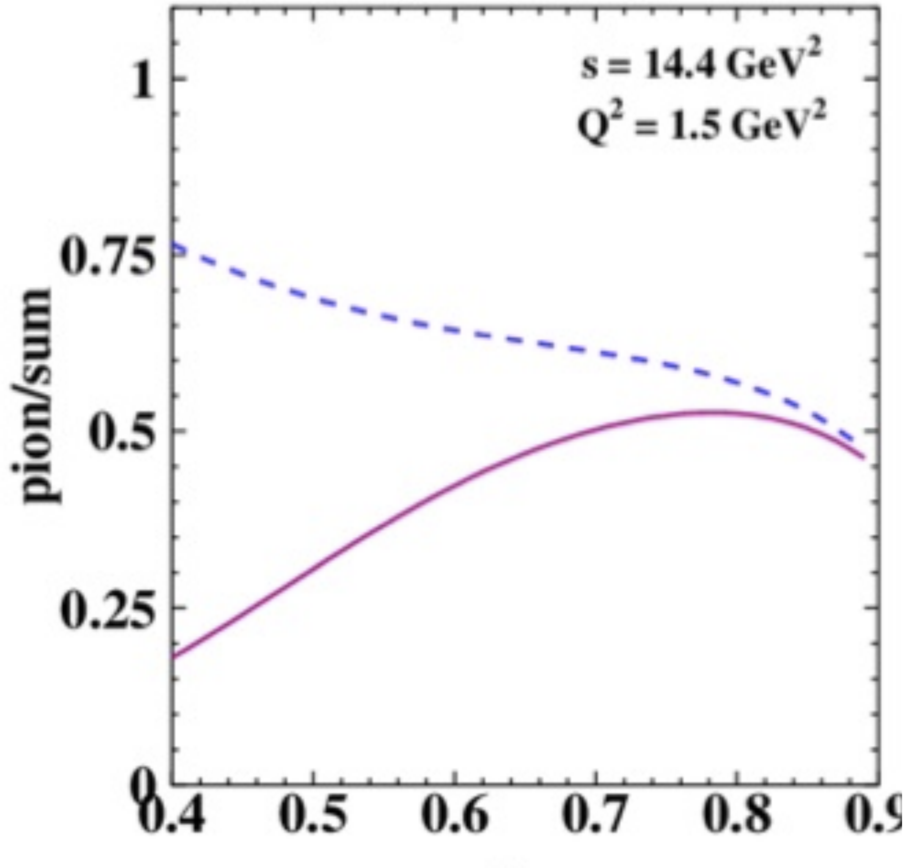
Reggeon contributions

Pion contribution, ~50% at JLab kinematics

Kinematics for Jlab π^-

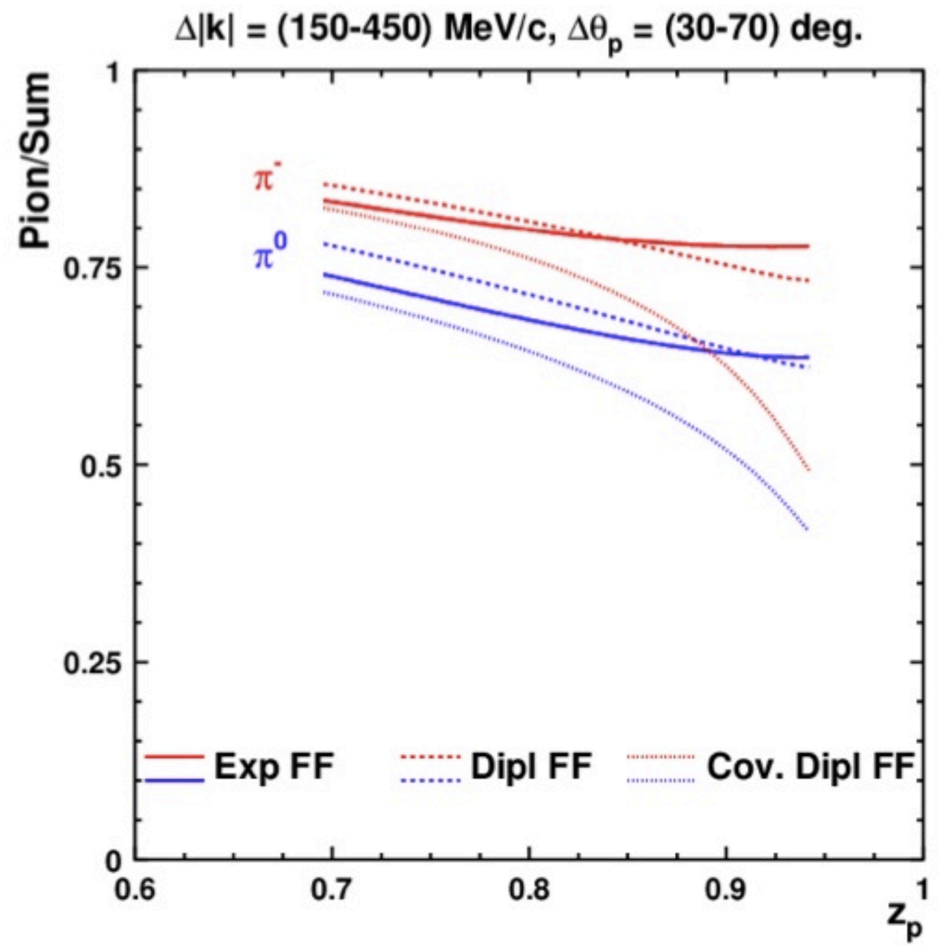
Calculation from B. Kopeliovich
at JLab TDIS kinematics

Pion flux is largest uncertainty, ~10-20%



B. Kopeliovich, I. Potashnikova (2015)

Rho, Regge

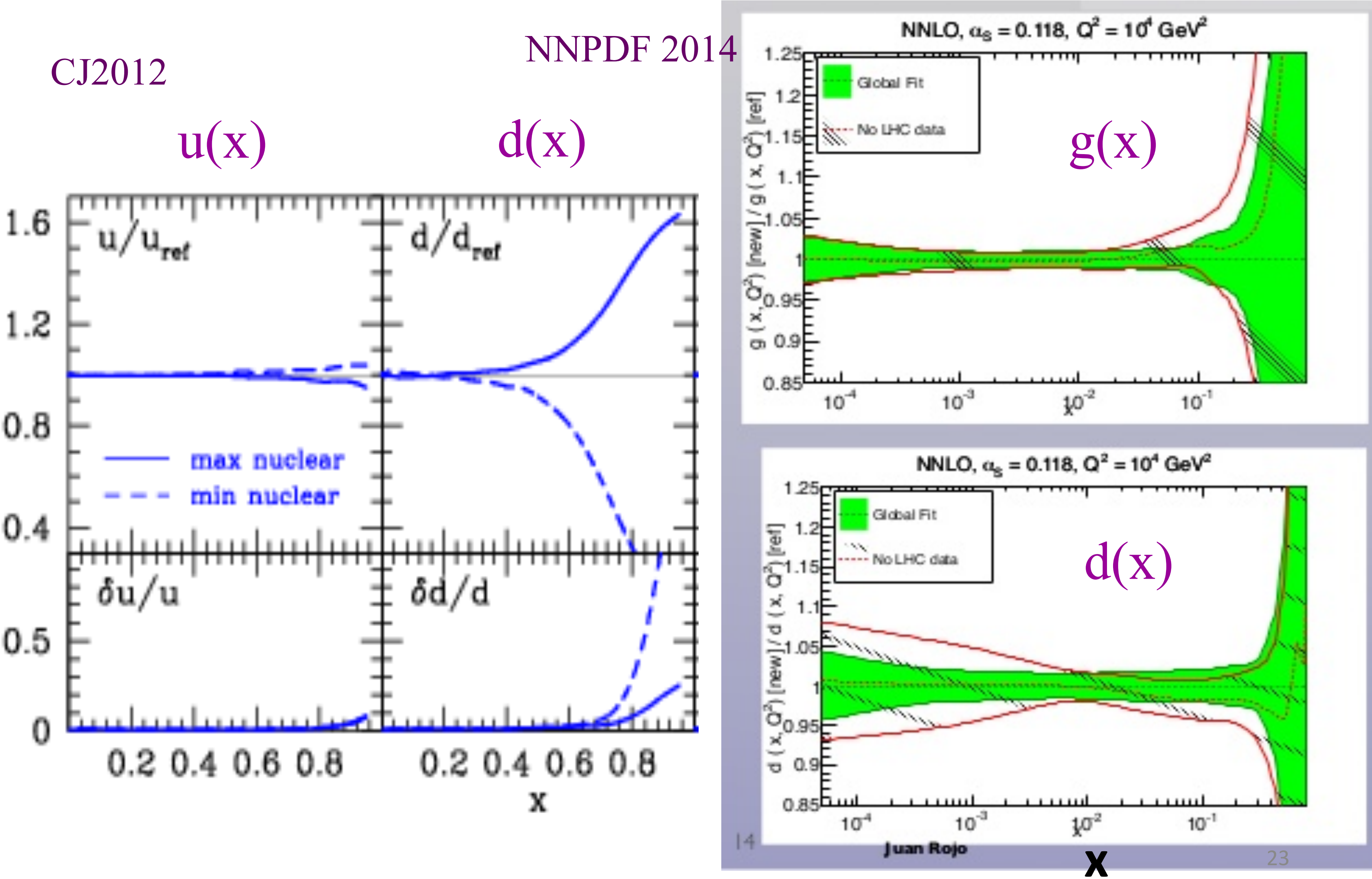


T. Hobbs, W. Melnitchouk, T. Londergan (2014)

Rho, Delta

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

Translates Directly to Large x Valence d,g pdf Uncertainties



Tagging Facilitates TDIS Probe of Meson Cloud: T^2DIS

Example: Sullivan process scattering from neutron-pion fluctuation

Deuterium Target

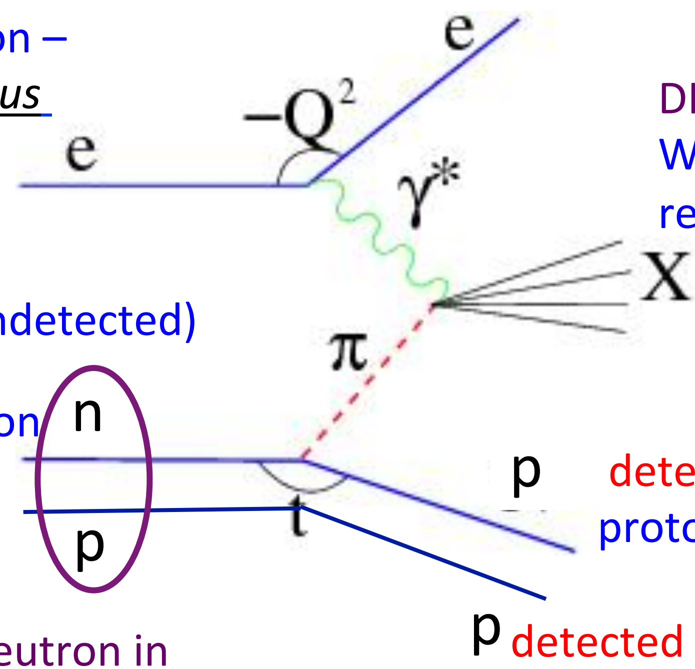
detect scattered electron –
large acceptance a plus

Incoming electron –
high current a plus

DIS event – reconstruct x, Q^2, W^2, also M_X of undetected recoiling hadronic system

want *charged* pion target (undetected)

need fluctuating nucleon to be a neutron…….



detected nucleon will be a proton

detected spectator proton tags neutron target (BONUS experiment technique)

neutron in deuteron target

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

detecting two protons with common vertex in coincidence tags "pion" target!

Extrapolation to the pole

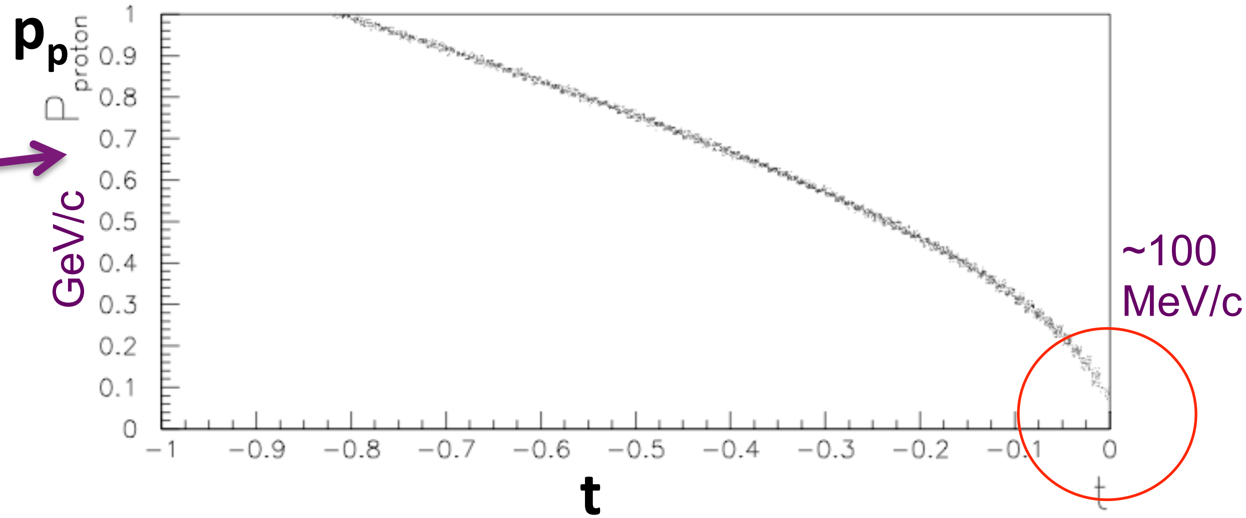
Need range of low momentum protons

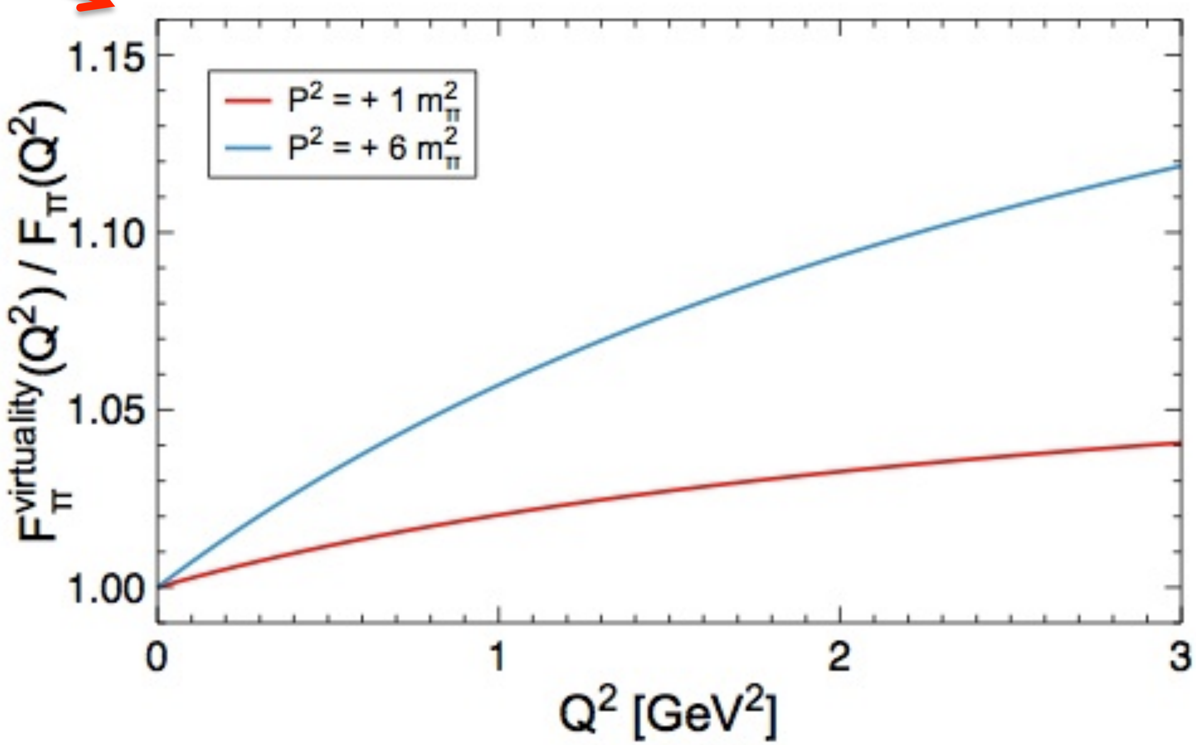
The ratio of off-shell to on-shell pion electromagnetic form factor

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

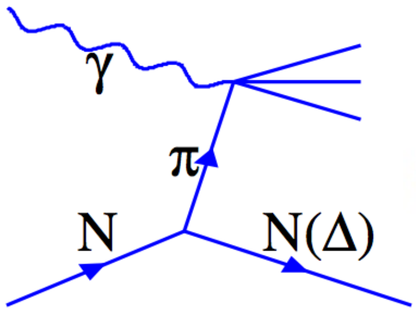
Within ~5% at proposed kinematics





How to estimate rates?

- Use Sullivan process and pion cloud model



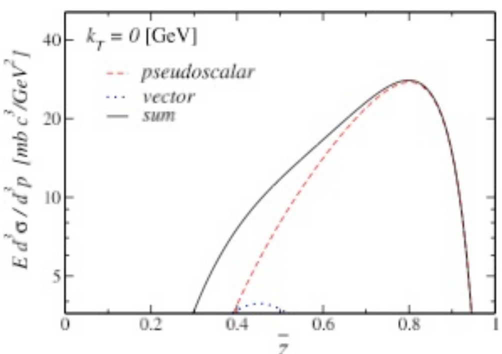
$$F_2^{(\pi N)}(x) = \int_x^1 dz\, f_{\pi N}(z)\, F_{2\pi}\left(\frac{x}{z}\right)$$

$F_2^{(\pi N)}$ = contribution to inclusive F_2 from scattering off of the virtual pion, *use for estimate*

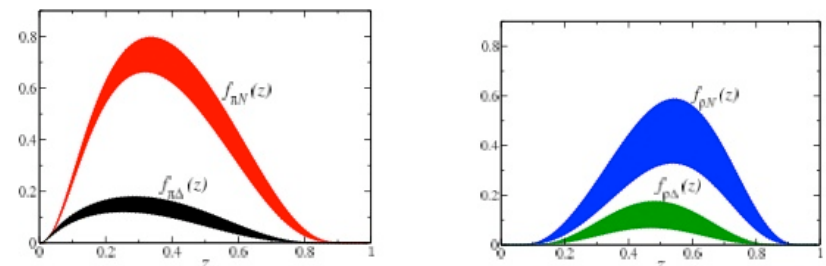
$$f_{\pi N}(z) = c_I \frac{g_{\pi NN}^2}{16\pi^2} \int_0^\infty \frac{dk_\perp^2}{(1-z)\,z} \frac{G_{\pi N}^2}{(M^2 - s_{\pi N})^2} \left(\frac{k_\perp^2 + z^2 M^2}{1-z}\right)$$

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

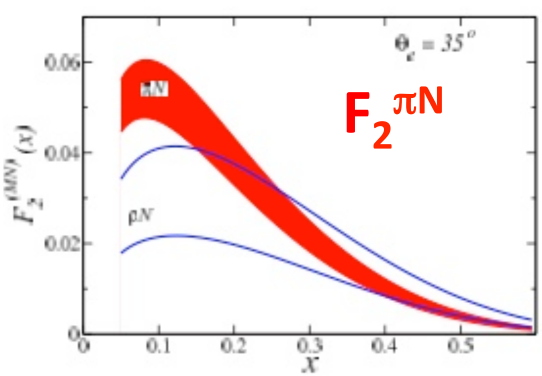
Pion expected to be dominant – also estimated ρ, Δ



Form factor GπN constrained by comparing the meson cloud contributions with data on inclusive pp → nX scattering



Light-cone momentum distributions, fπ(ρ)N and fπ(ρ)Δ, 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 ~< |**k**|/M, where **k** is π 3-momentum = **-p'**
- 60 < **k** < 400 MeV/c corresponds to z < ~0.2
- Also, x < z!
- Low x, high W at 11 GeV means Q^2 ~2 GeV^2

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)

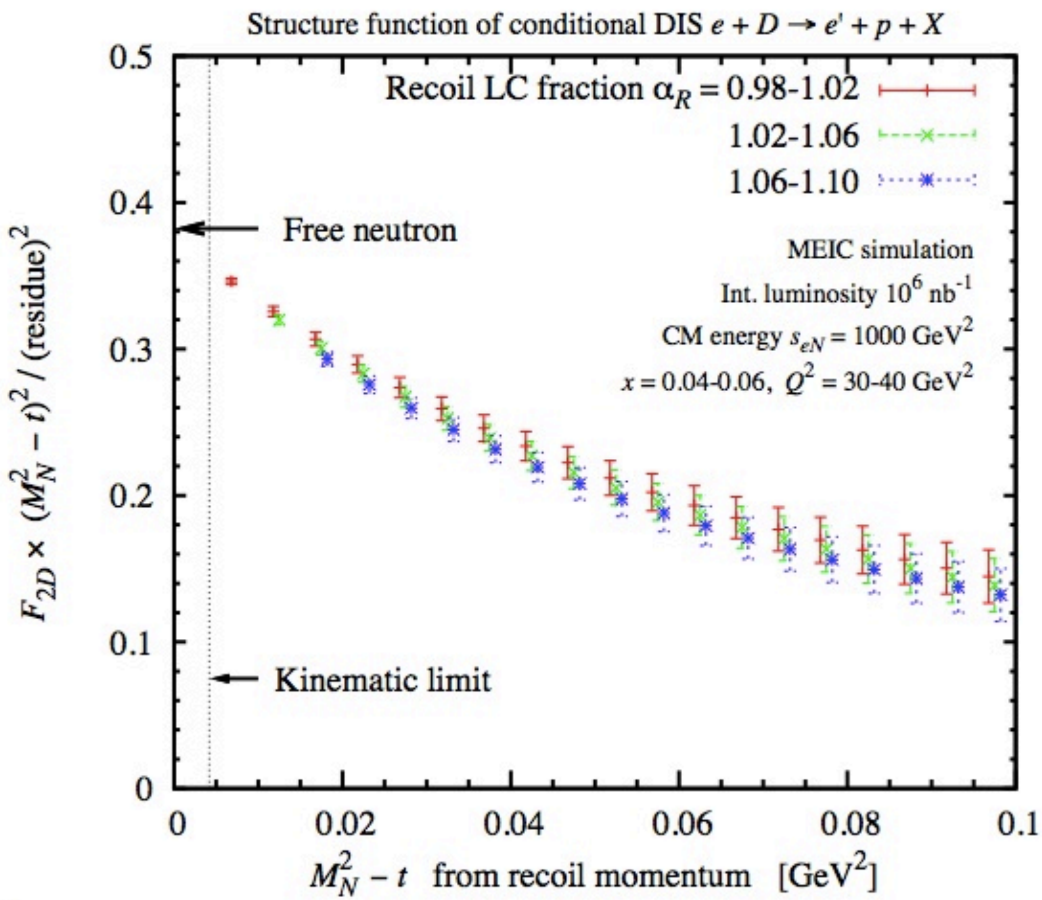
W. Melnitchouk and A. W. Thomas, Z. Phys. A 353, 311 (1995)

Projected Data Example: Neutron Structure at the (m)EIC

$e + D \rightarrow e' + p + X$ a la BONUS

$\alpha_R \equiv 2(E_R + p^z_R)/(E_D + p^z_D)$

residue = free neutron



Isovector $F_2^p - F_2^n$ studies of small–x dynamics in the non-singlet sector, largely unexplored (QCD structure of Reggeon exchange, non-singlet diffraction, etc.).

TDIS measurements require coverage for [protons] with low momenta relative to beam momentum (pT < 200 MeV, pT/p(beam) ~ 0.8 – 1.2), and good momentum resolution (ΔpT ~ 20 MeV).

TDIS also requires that the intrinsic momentum spread in the ion beam be small to allow for accurate reconstruction.

MEIC being designed for this purpose