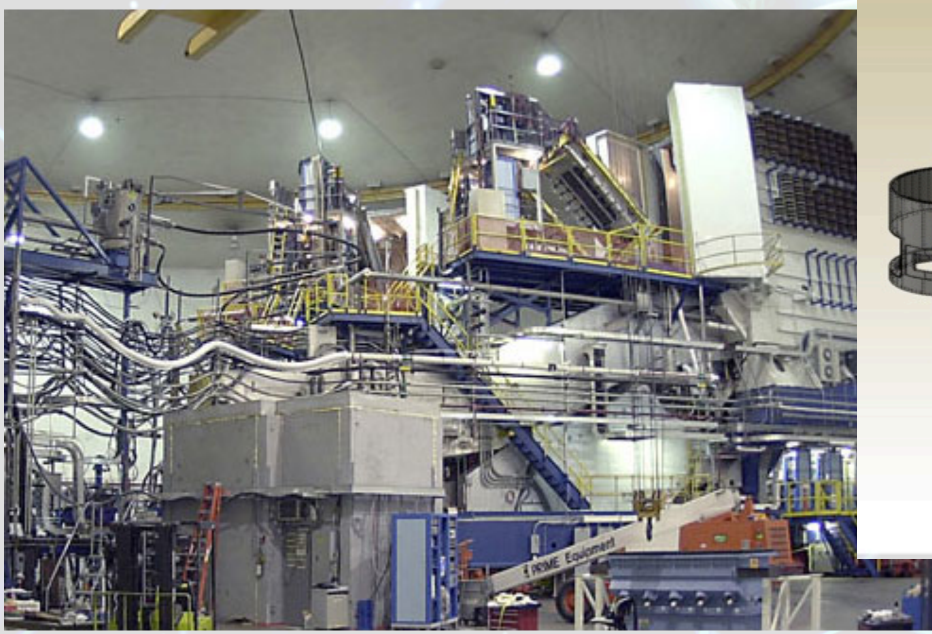
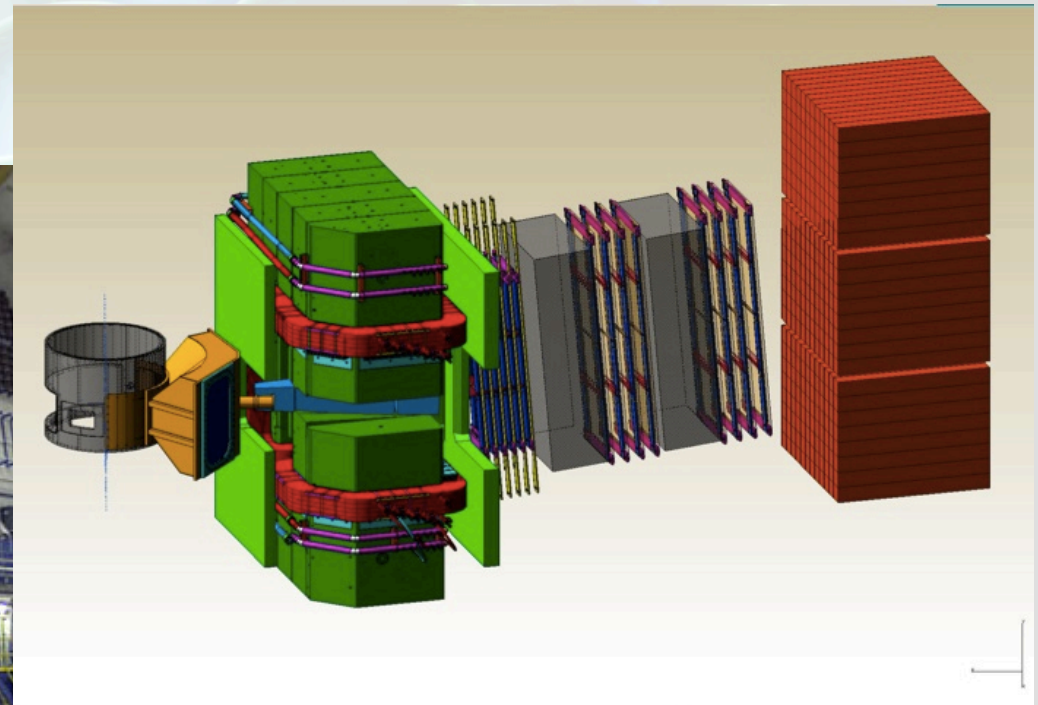
Nucleon Fragmentation with 12 GeV: Tagged Deep Inelastic Scattering (TDIS)

Thia Keppel





High Energy Nuclear Physics with Spectator Tagging
Old Dominion University, March 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
- Spectator Tagging opens a door to probe nucleon fragmentation
- TDIS opens a door to access effective (neutron, pion, kaon..?) targets
    - fundamental hadron structure measurements
    - pion structure function
- Directly probe the partonic components of the meson cloud of the nucleon
    - very few experiments to date
    - fundamental QCD
    - help understand flavor asymmetry of the nucleon sea
    - measurement isospin dependence (p–n difference)

Understand nucleon structure at a deeper level

Abundant Evidence for *Some* Mesonic Content of the Nucleon

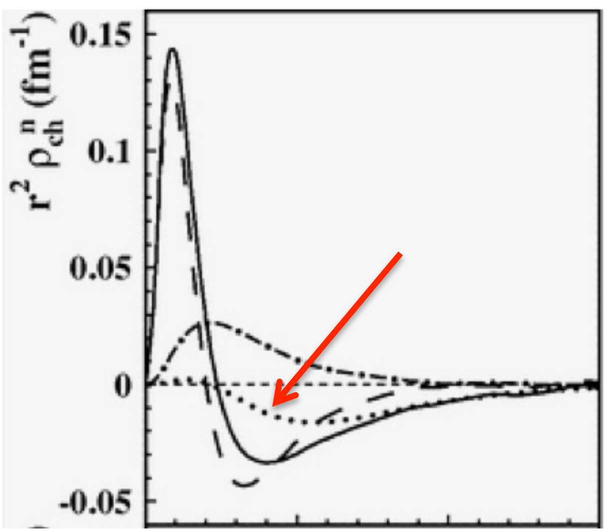
PHYSICAL REVIEW VOLUME 72, NUMBER 12 DECEMBER 15, 1947

On the Interaction Between Neutrons and Electrons*

E. FERMI AND L. MARSHALL
Argonne National Laboratory and Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received September 2, 1947)

ment equal to $e\hbar/2\mu c$, we are led to the estimate that the average number of mesotrons near a neutron is 0.2. Therefore, in calculating the nu-

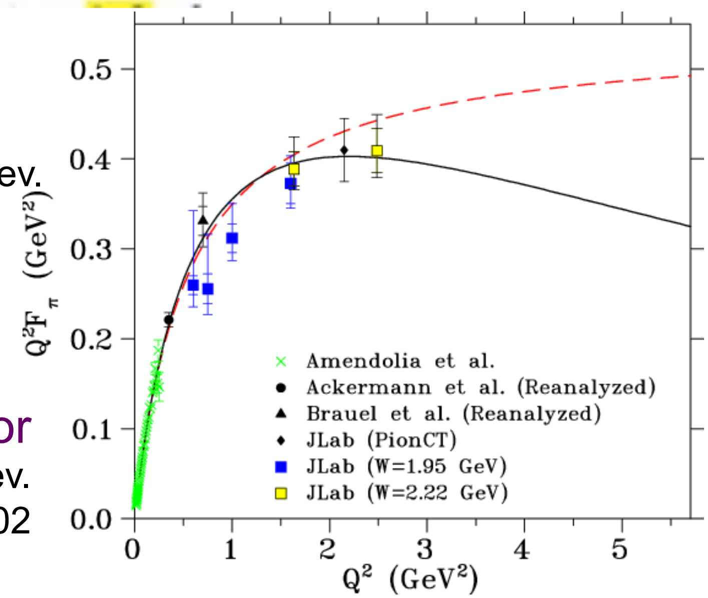


Neutron Charge Density

Pasquini and Boffi, Phys. Rev. D 76, 074011 (2007) Kelly, Phys. Rev. C 66, 065203 (2002)

Pion Form Factor

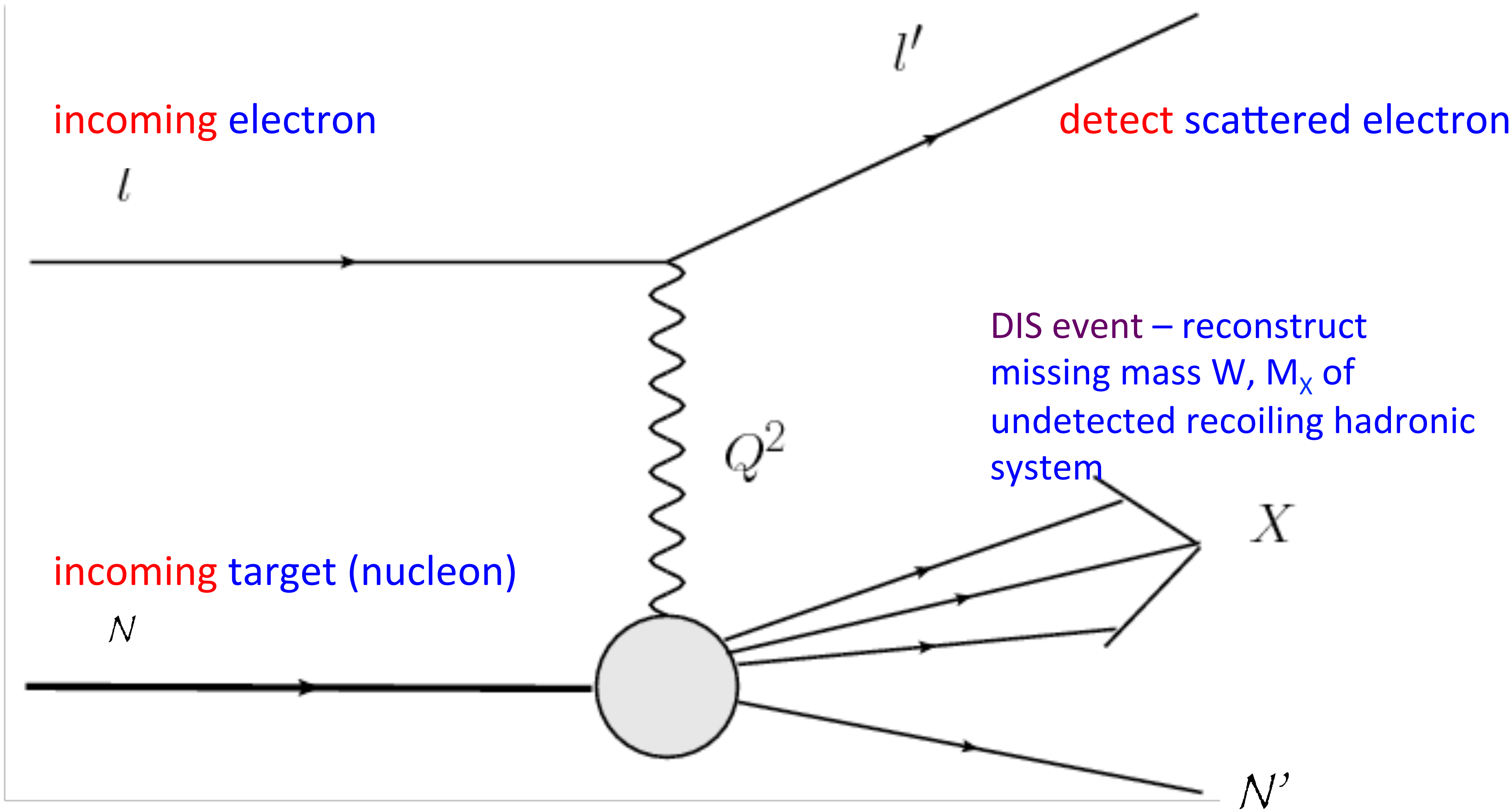
Blok et al., Phys.Rev. C78 (2008) 045202



- Partially conserved axial current, chiral quark models, vector meson dominance models - substantial, successful theory development
- In contrast, scant experimental data – do not know magnitude of mesonic content
- How does mesonic content affect structure functions, parton distributions?

Tagged Deep Inelastic Scattering:

The Basic Experimental Approach



Describe with standard DIS variables x_{Bj}, Q^2, W^2, *plus:*

detect outgoing target nucleon

M_x = mass of system X

t = four-momentum transfer squared at the nucleon vertex

Tagging Facilitates TDIS Nucleon Fragmentation Experiments at JLab

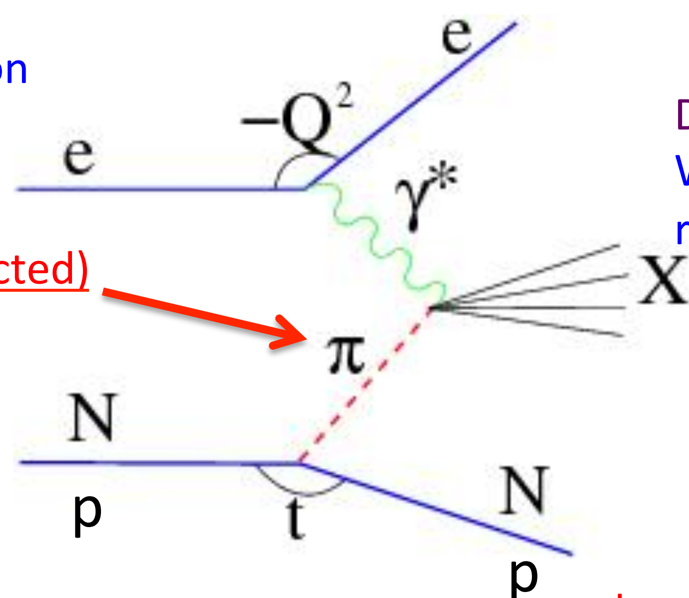
Example: Sullivan process scattering from proton-pion fluctuation

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

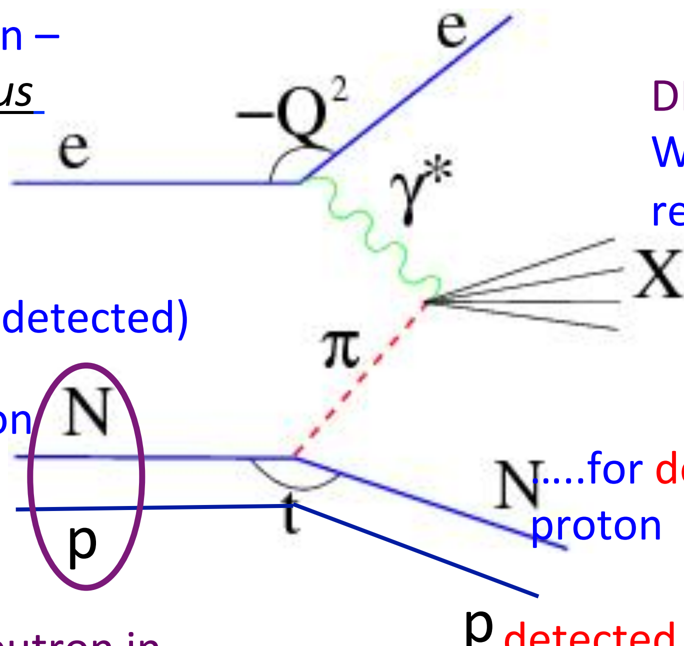
tagged final state spectator proton

Tagging Facilitates TDIS Nucleon Fragmentation Experiments at JLab

Example: Sullivan process scattering from neutron-pion fluctuation

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…….

….for detected nucleon to be a proton

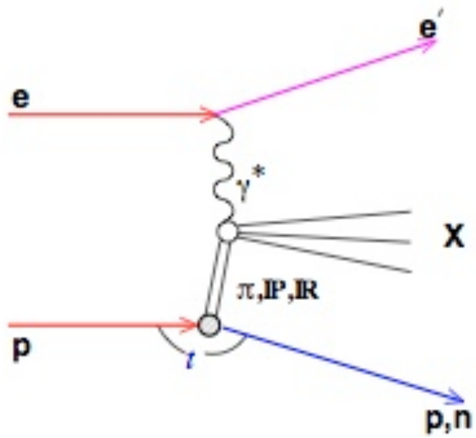
neutron in deuteron target

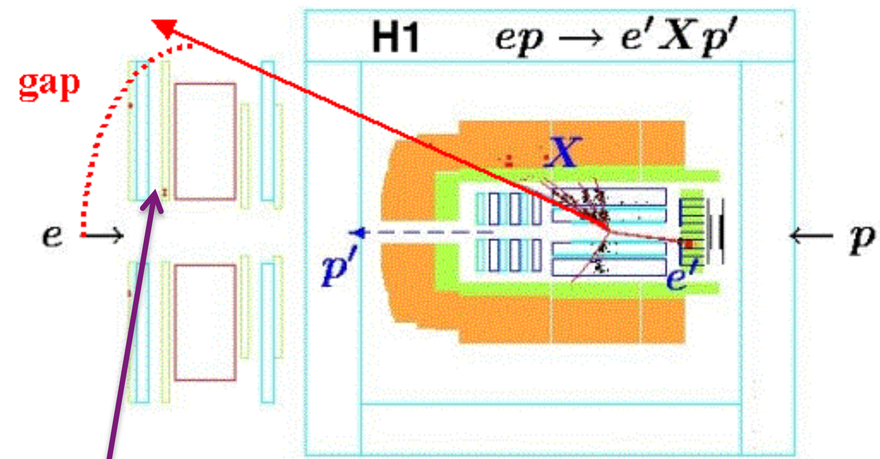
detected spectator proton tags neutron target (BONUS experiment technique)

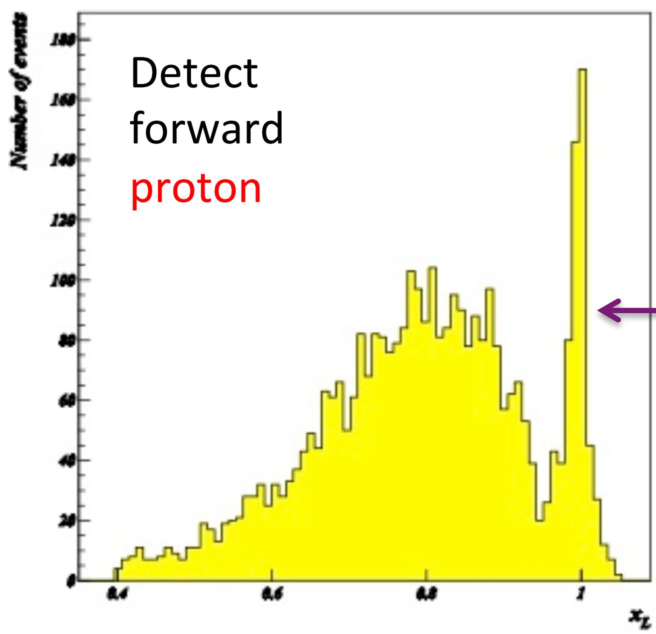
detecting two protons with common vertex in coincidence tags "pion" target!

TDIS at HERA – *proton* tag

- *Tag leading baryon production*
- *ep → eXN via color singlet exchange*







x_L

DESY 10-095 Eur.Phys.J. C71 (2011) 1578

Diffractive Scattering:

Large rapidity gap

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

Proton tagged data is well described by Regge theory inspired fits.

Gluons >> quarks in Pomeron?

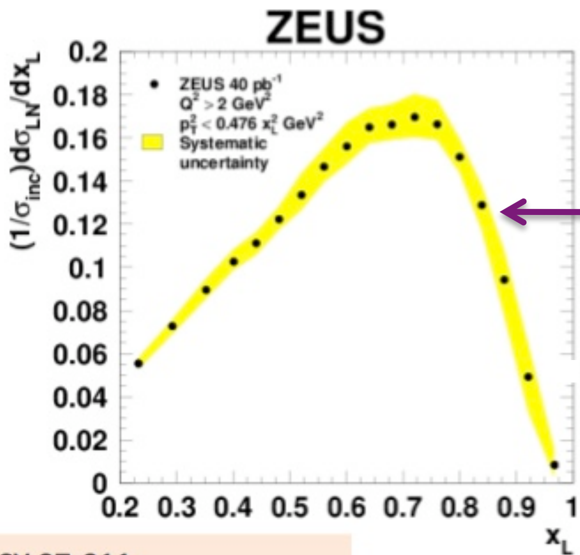
$$F_2^{D(4)} = f_{I\!P}(x_{I\!P},t)F_{I\!P}(\beta,Q^2) + n_{I\!R}\cdot f_{I\!R}(x_{I\!P},t)F_{I\!R}(\beta,Q^2)$$

Pomeron contribution   Reggeon contribution

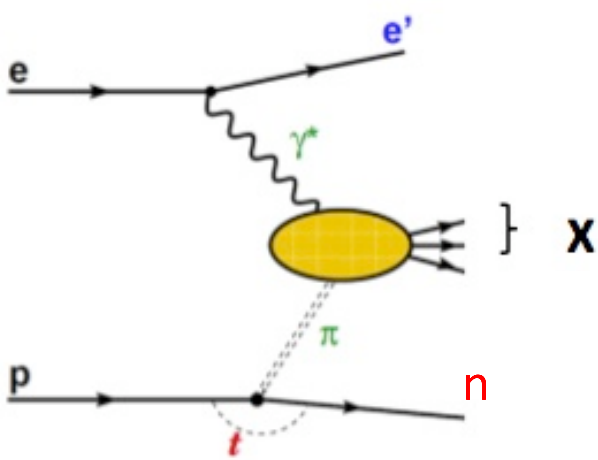
The Pomeron diverges as $1/(1-x_L)$, the f-Reggeon is flat.

TDIS at HERA – *neutron* tag

DESY 08-176 JHEP06 (2009) 74

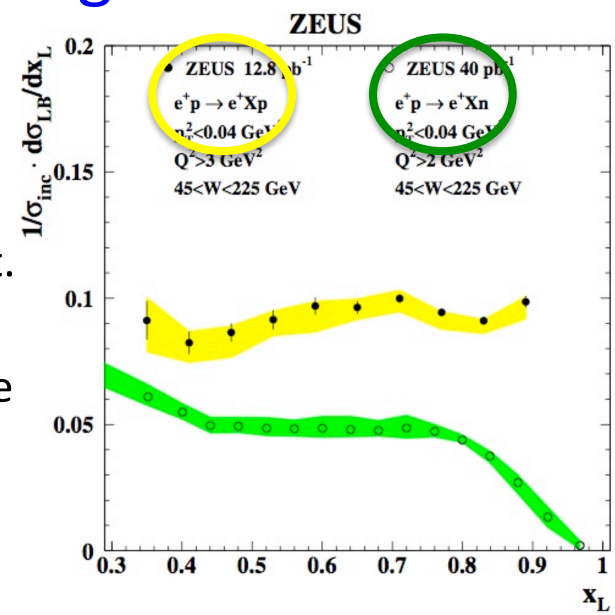


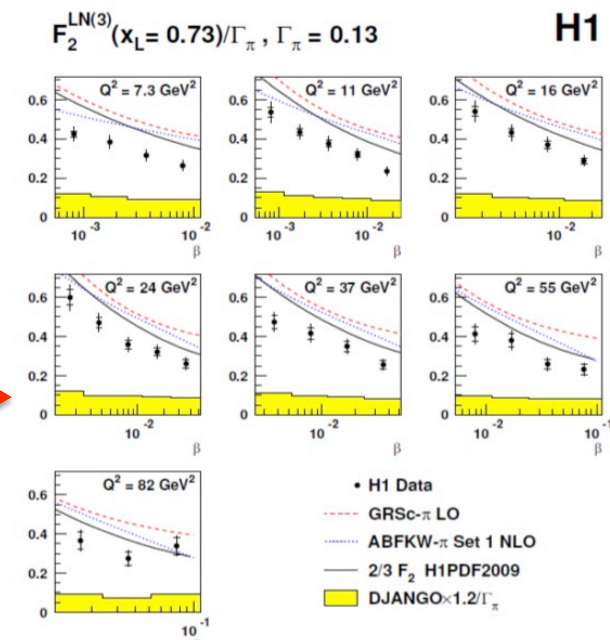
DESY 07-011
Nucl.Phys.B776(2007) 1-37



- *The leading neutron results are different.*
- There is no elastic (diffractive) peak present.
- Pion ~$(1-x_L)$
- The leading neutron rate is roughly a factor of two lower than the 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*





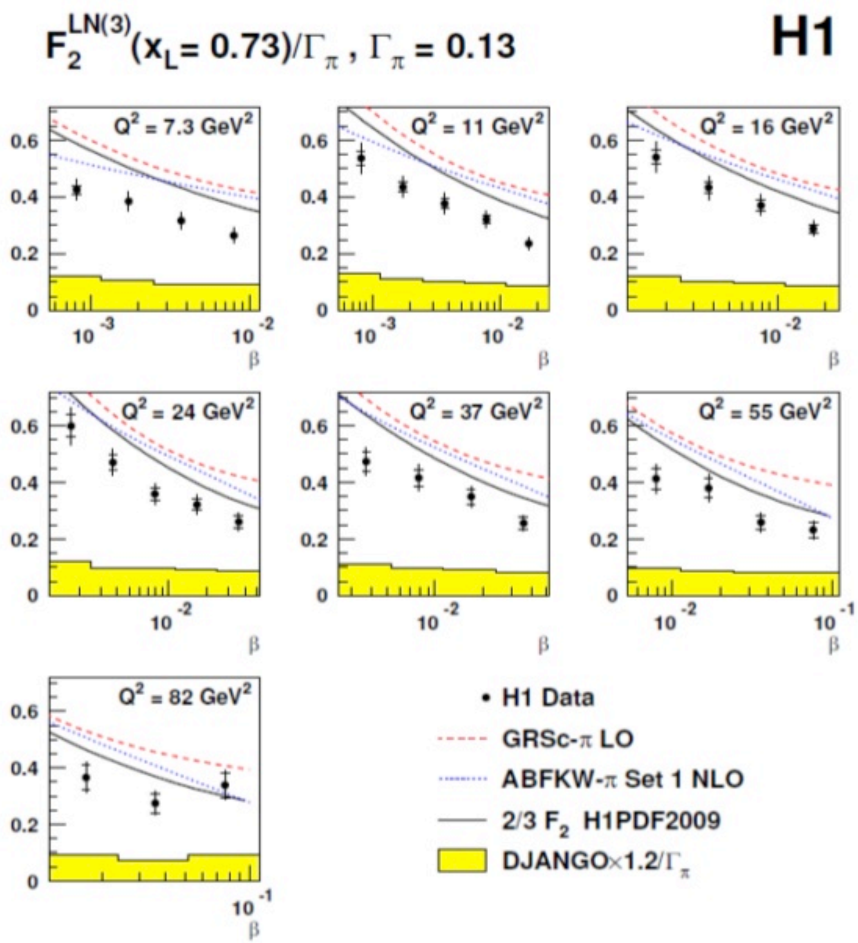
DESY 09-185 Eur. Phys. J. C68 (2010) 381

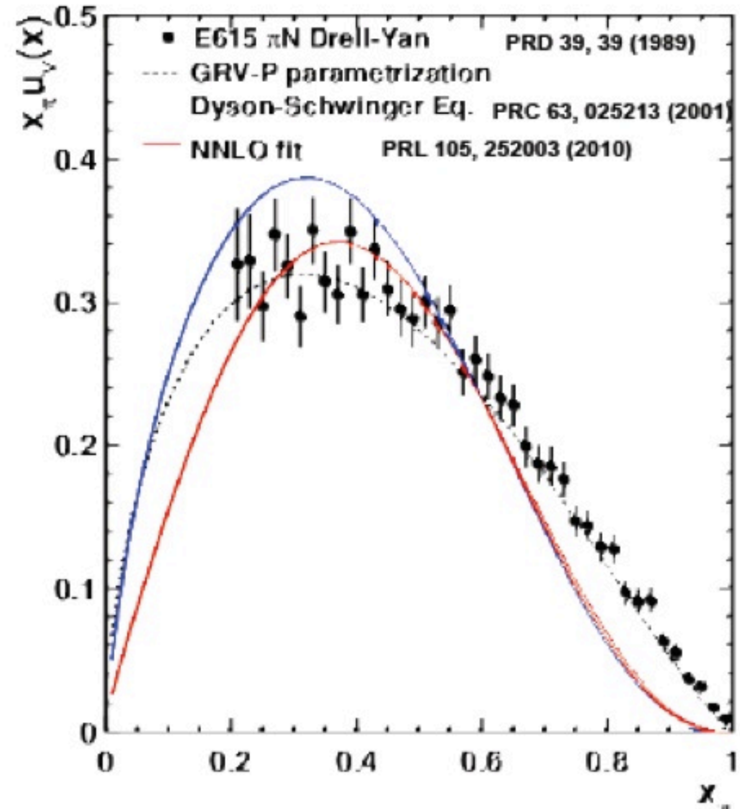
Why are we interested in the pion?

- The pion is fundamental.
- The pion is the 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
- "….any veracious description of the pion must properly account for its dual role as a quark-antiquark bound-state and the Nambu-Goldstone boson associated with dynamic chiral symmetry breaking. It is this dichotomy and its consequences that makes an experimental and theoretical elucidation of pion properties so essential to understanding the strong interaction."
  Holt and Roberts, Rev. Mod. Phys. **82**, 2991 – Published 28 October 2010
- 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?

Pion Structure Function Measurements

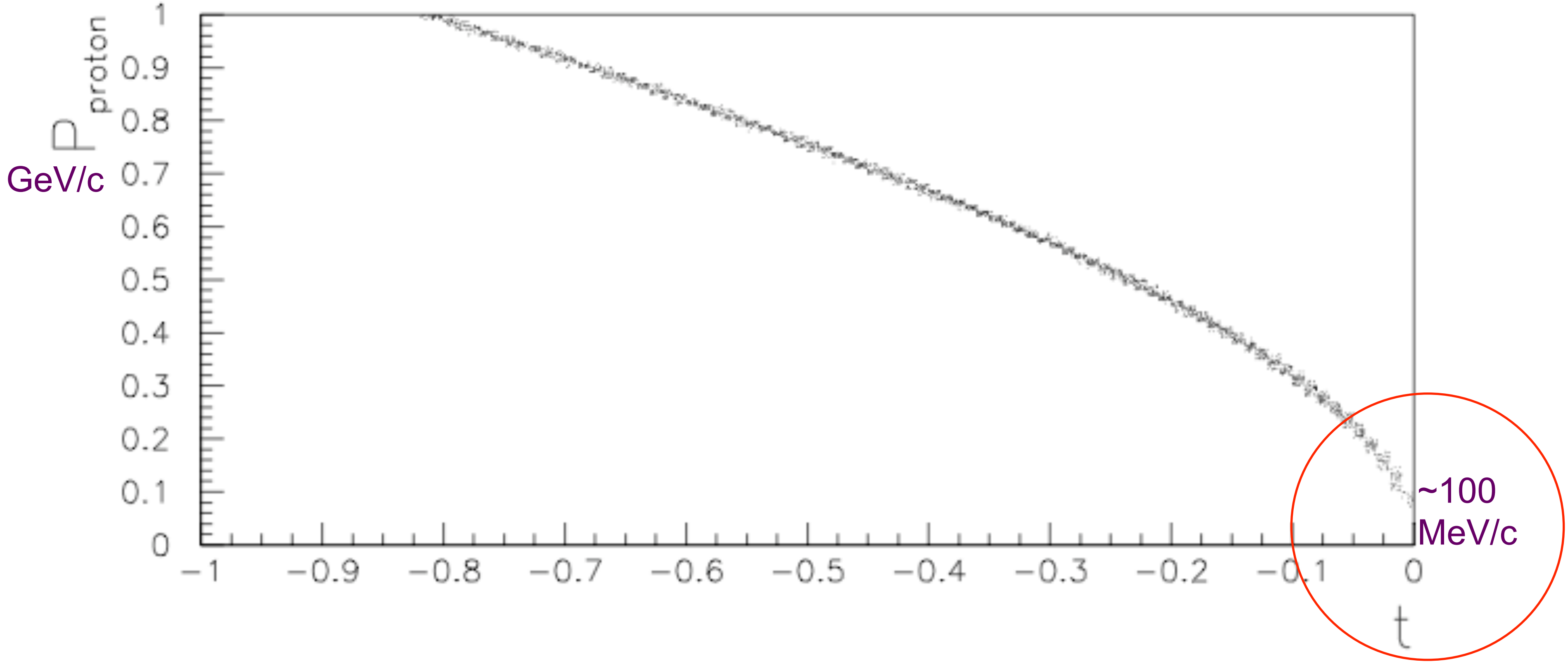
- Knowledge of the pion structure function is *very limited* due to the lack of a pion target.
  - Pionic Drell-Yan from nucleons in nuclei
  - HERA TDIS data at low x





- Theoretical calculations in the valence region tend to disagree with each other – and with the data
- Recent NNLO refit of D-Y data, including resummation of soft gluon contributions, agree with DSE

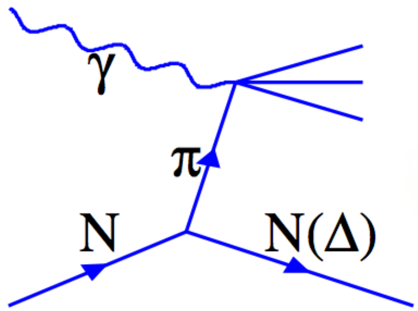
Back to the experiment…how to identify fluctuating nucleon?



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

How to estimate rates?

- Use Sullivan process and pion cloud model



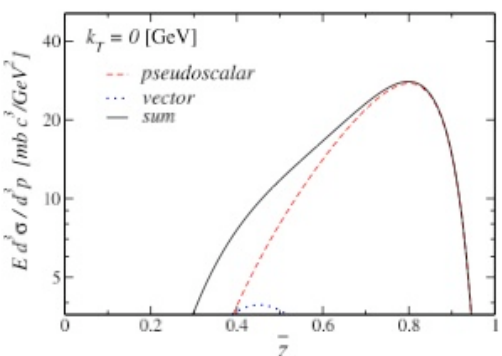
$$F_2^{(\pi N)}(x) = \int_x^1 dz\, f_{\pi N}(z)\, F_{2\pi}\left(\frac{x}{z}\right)$$

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

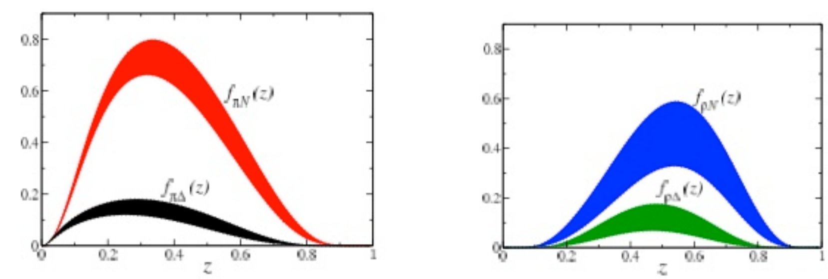
$$f_{\pi N}(z) = c_I \frac{g_{\pi NN}^2}{16\pi^2} \int_0^\infty \frac{dk_\perp^2}{(1-z)}\frac{G_{\pi N}^2}{z\,(M^2 - s_{\pi N})^2}\left(\frac{k_\perp^2 + z^2 M^2}{1-z}\right)$$

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

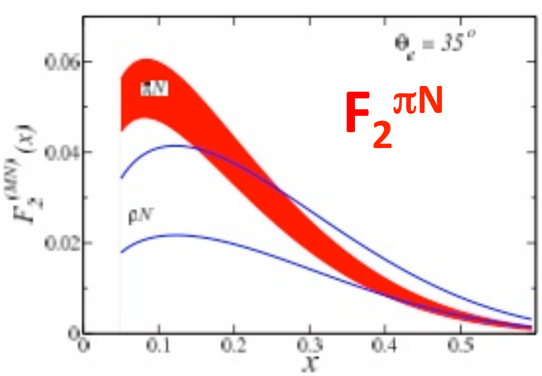
Pion expected to be dominant – also estimated ρ, Δ



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:

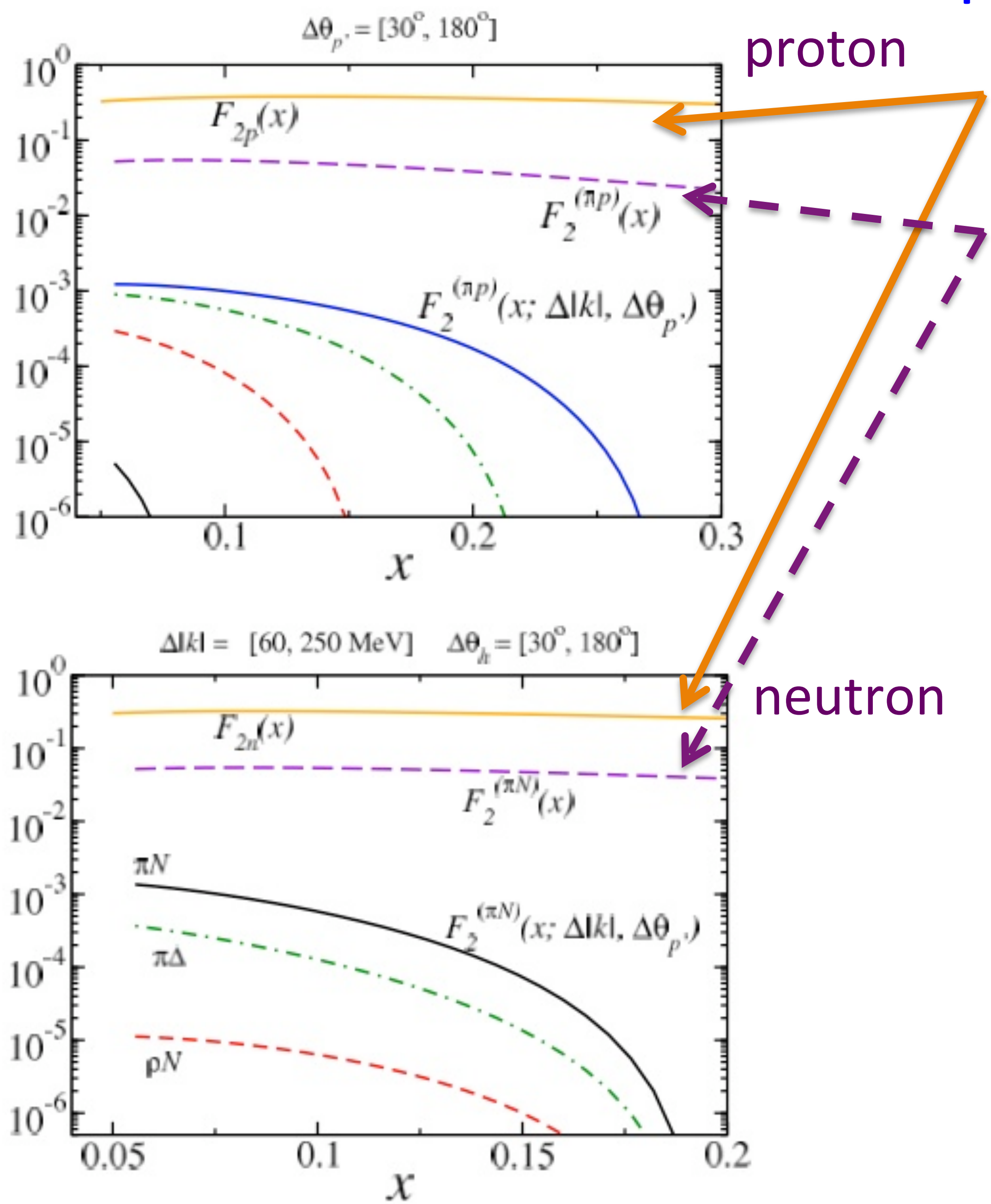
- z ~< |**k**|/M, where **k** is π 3-momentum = **-p'**
- 60 < **k** < 400 MeV/c corresponds to z < ~0.2
- Also, x < z!
- Low x, high W at 11 GeV means Q^2 ~2 GeV^2

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)

Basis for rate estimations of physics signal



Inclusive structure function $F_2(x)$

Contribution to F_2 from pions via Sullivan process

top:

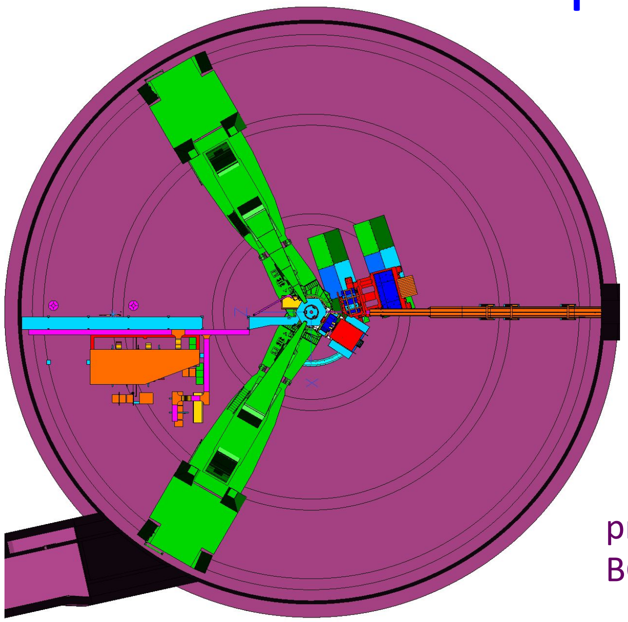
- For different tagged p momenta ranges Δ**k:** 60-100, 100-200, 200-300, 300-400 MeV
- Neutron will be similar

bottom:

- Neutron plot shows contributions from ρ, Δ
- Proton will be similar

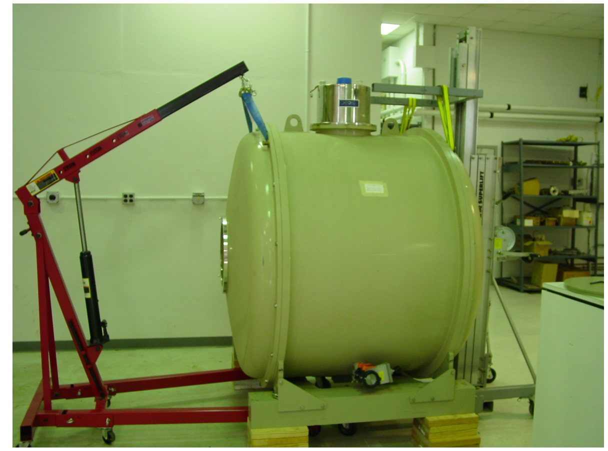
Signal is orders of magnitude smaller than inclusive DIS – ***need high luminosity***

Proposed TDIS Experiment



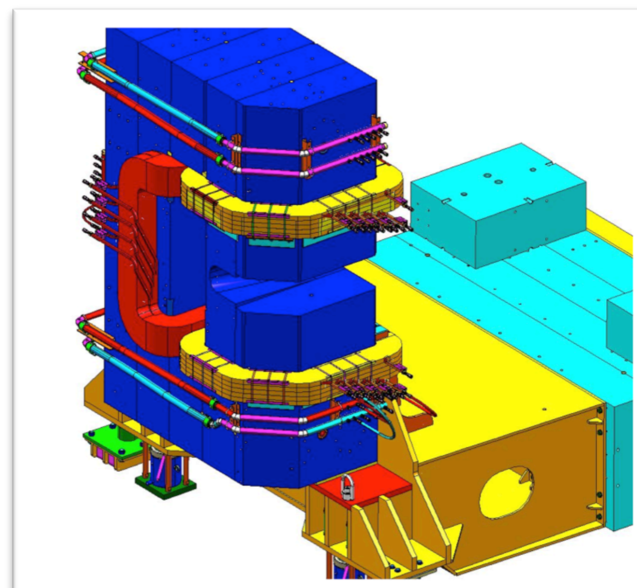
e- beam

proton tag detection in
BONUS-type RTPC at pivot



Superconducting solenoid

scattered electron detection in Super
Bigbite Spectrometer (SBS)



Propose for Hall A:

✓High luminosity,

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

✓Large acceptance

Super Bigbite ~70 msr, hadron spectrometer

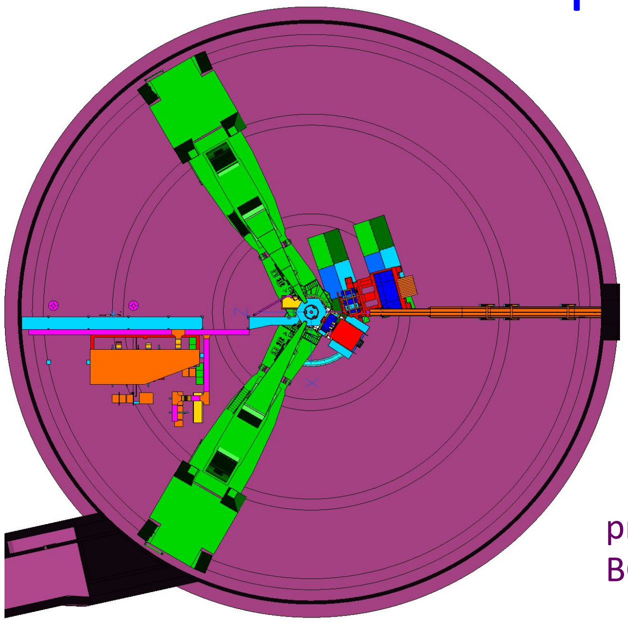
✓HCAL will be used in RTPC calibration

Need to…

Add BONUS-type RTPC, requires solenoidal field

Modify SBS for electron detection

Proposed TDIS Experiment



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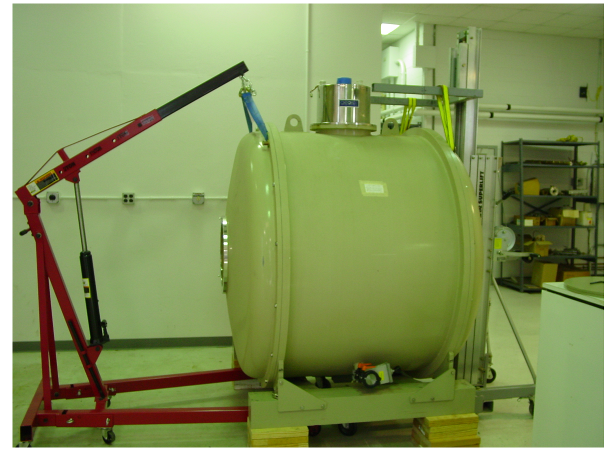

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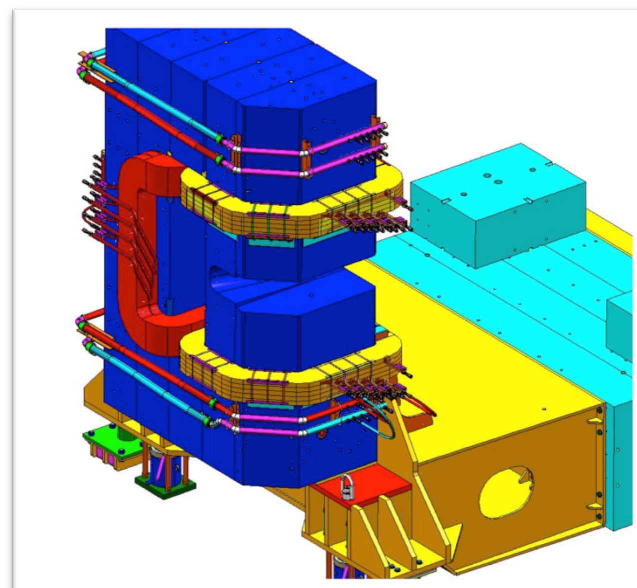

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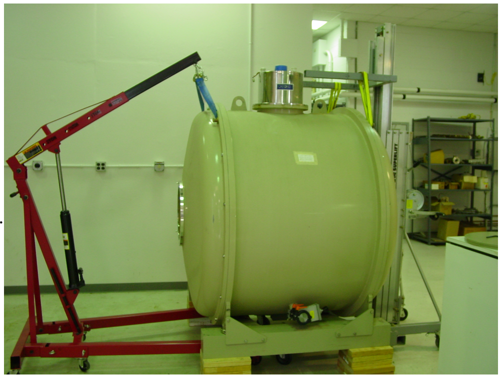
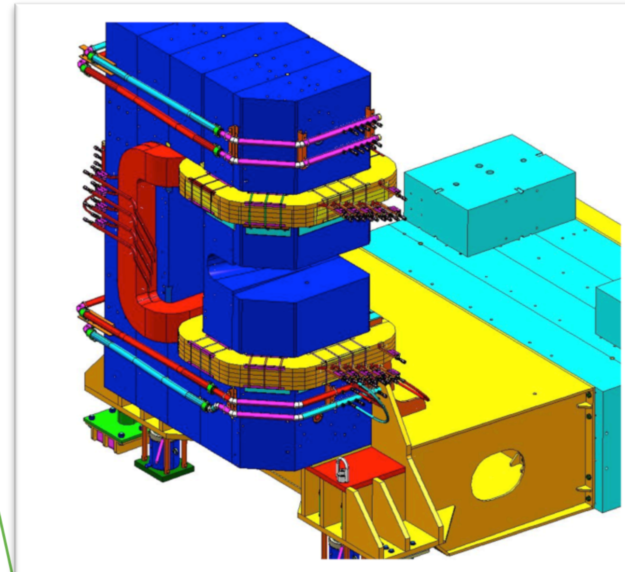
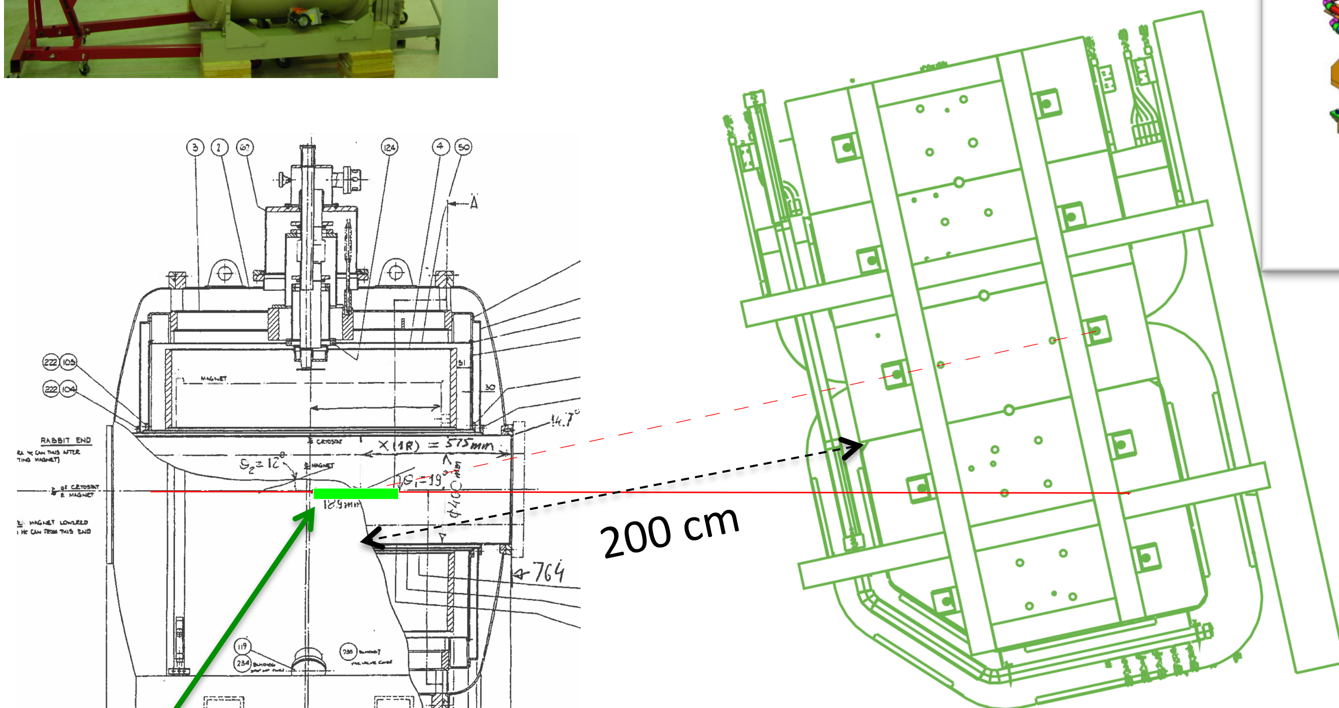
Need to…
  Add BONUS-type RTPC, requires solenoidal field
  Modify SBS for electron detection

Magnets and Acceptance



SBS central angle of 12 degrees
SBS to target distance 200 cm
SBS solid angle of 50 msr
Solenoid 40 cm diameter bore
Solenoid 4.7 Tesla max field
Solenoid 153 cm long





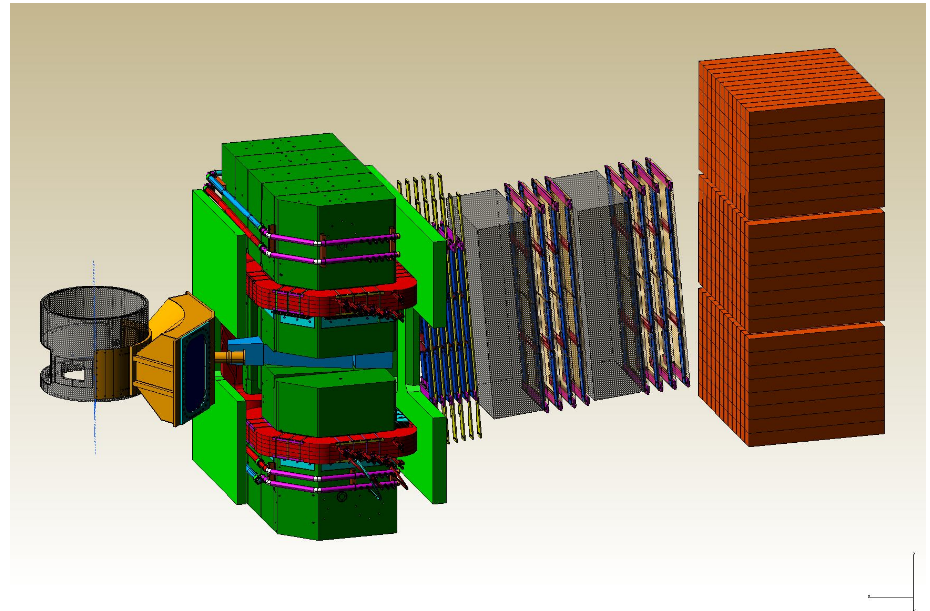
RTPC tagging target

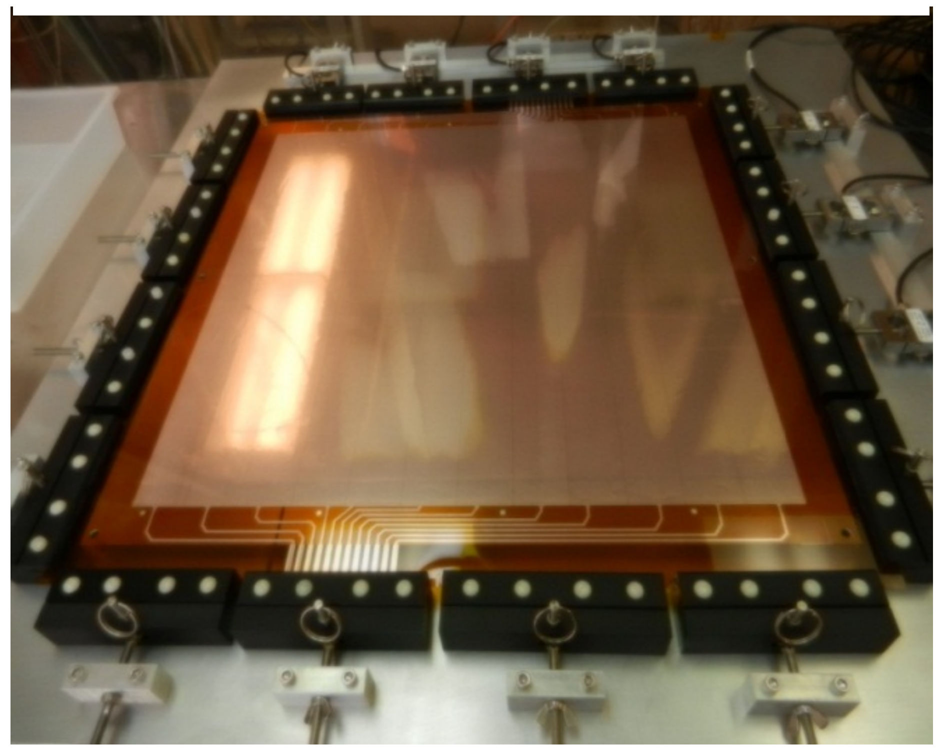
Solenoid

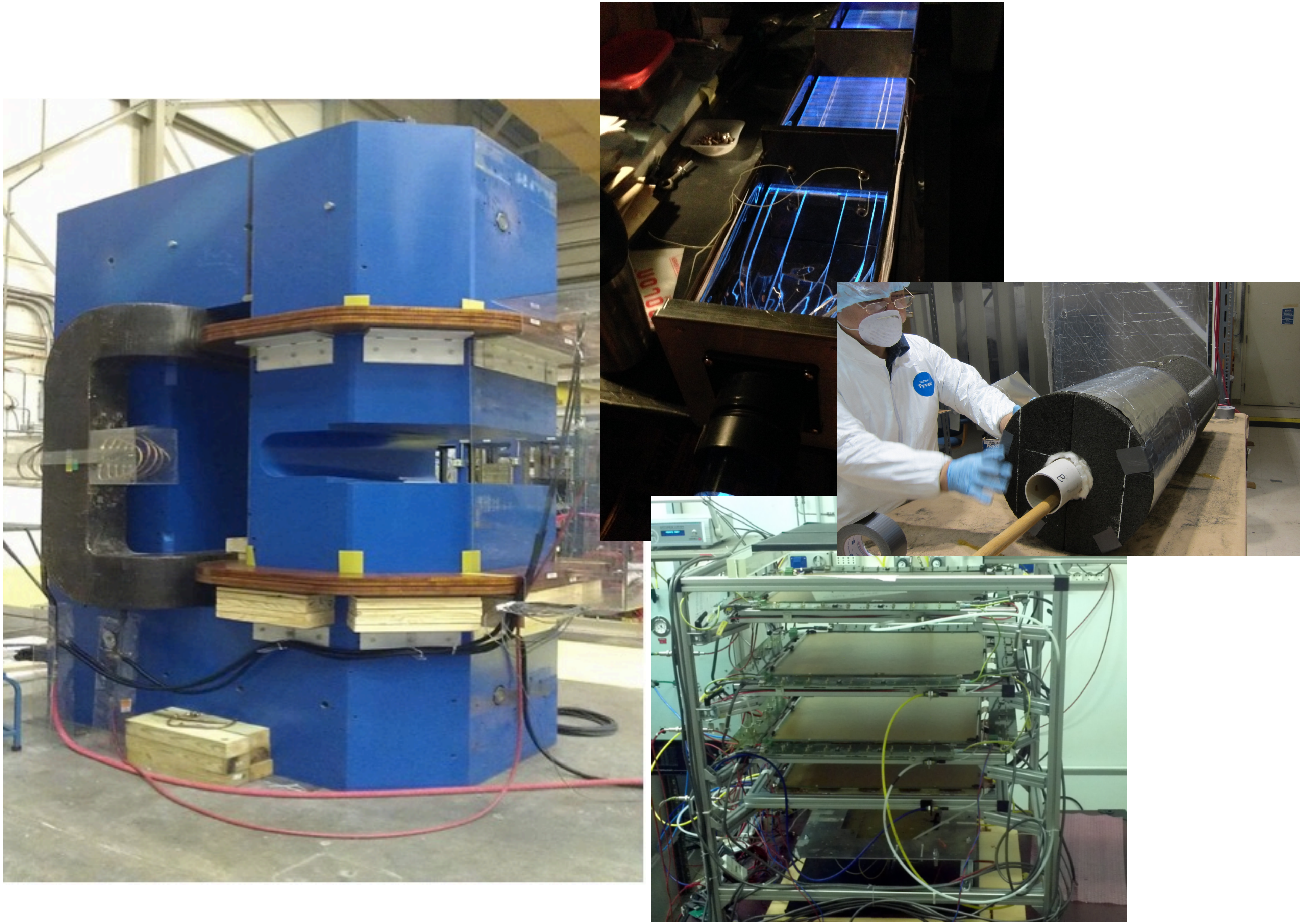
Super Bigbite

SBS Project

- Project started October 2013
  - **P**assed second annual review November 2014
  - Some recommendations, but *overall very positive, project on track*
- Spectrometer, ECAL work at JLab
  - Power Supply in hall
  - 48D48 magnet modified, assembled, in test lab
  - Support structure to arrive next week
  - Working vacuum, beamline
  - Thermal annealing of ECAL
- GEM construction at UVA, INFN
- Coordinate detector at Idaho State
- HCAL Hadron calorimeter at CMU



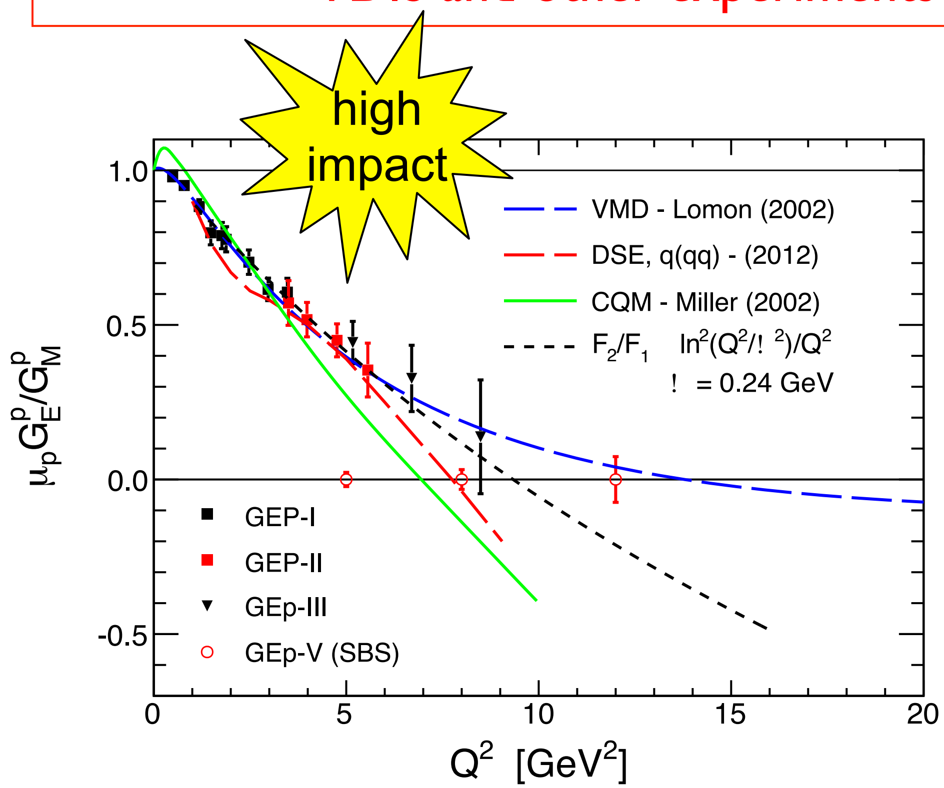


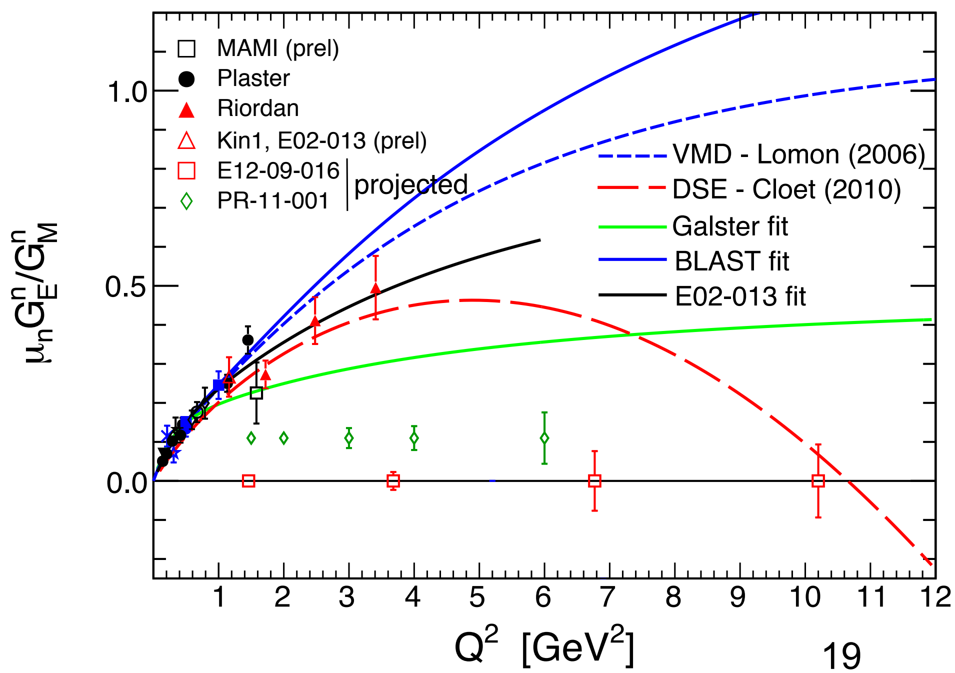


SBS Program: Nucleon Form Factors at Large Q^2

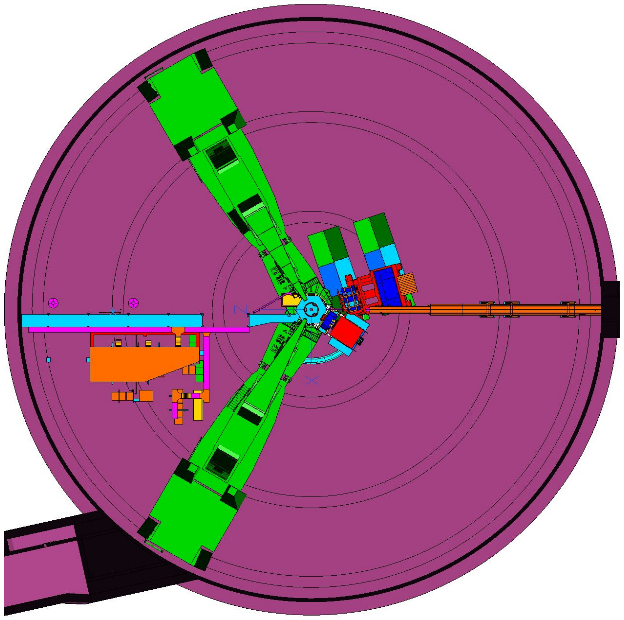
- Determination of the charge form factors GEn and Gep up to 10 - 12 GeV^2
- Precision measurements of the magnetic form factors GMn and GMp up to 15 GeV^2

- Beam planned for SBS in 2018
- Program Expanding
  - Semi-inclusive experiment approved 2011
  - TDIS and other experiments proposing





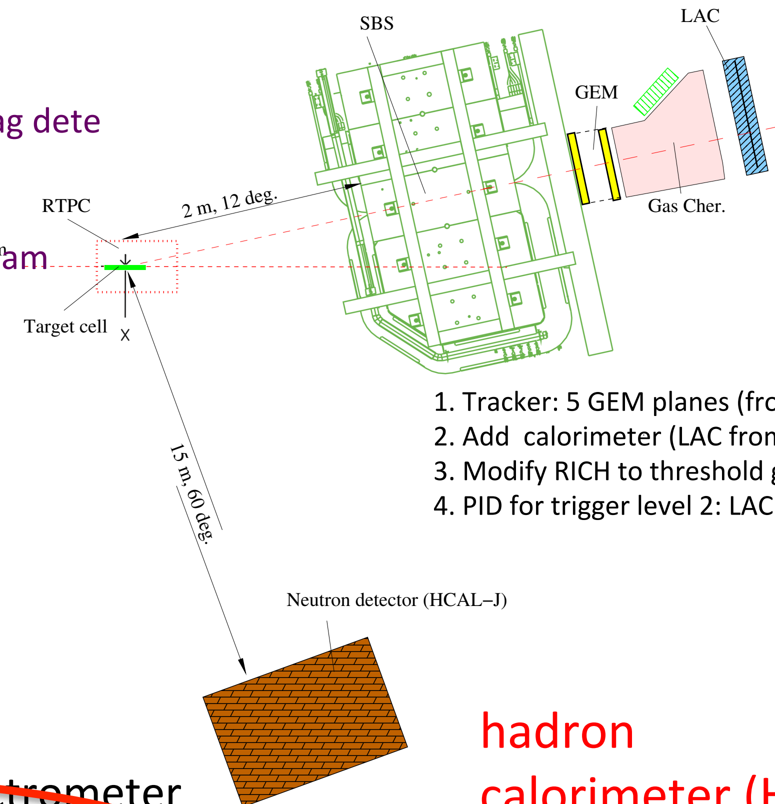
Calibrate Tagging Acceptance and Efficiency



proton tag dete

scattered electron detection in Super Bigbite Spectrometer (SBS)

e- beam



1. Tracker: 5 GEM planes (from G_E^P polarimeter)
2. Add calorimeter (LAC from CLAS6)
3. Modify RICH to threshold gas Cherenkov
4. PID for trigger level 2: LAC + Cherenkov

Propose for Hall A:

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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

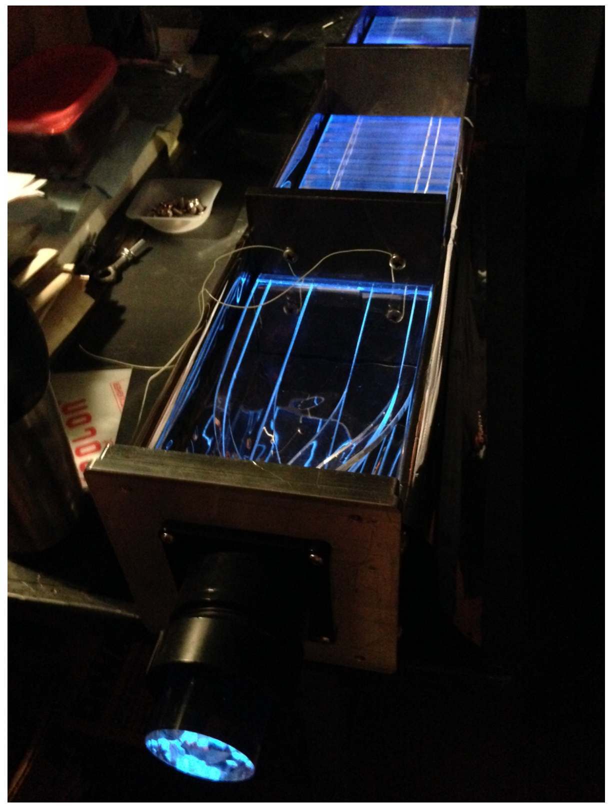
Modify SBS for electron detection

hadron calorimeter (HCAL) for quasi-elastic neutron calibration

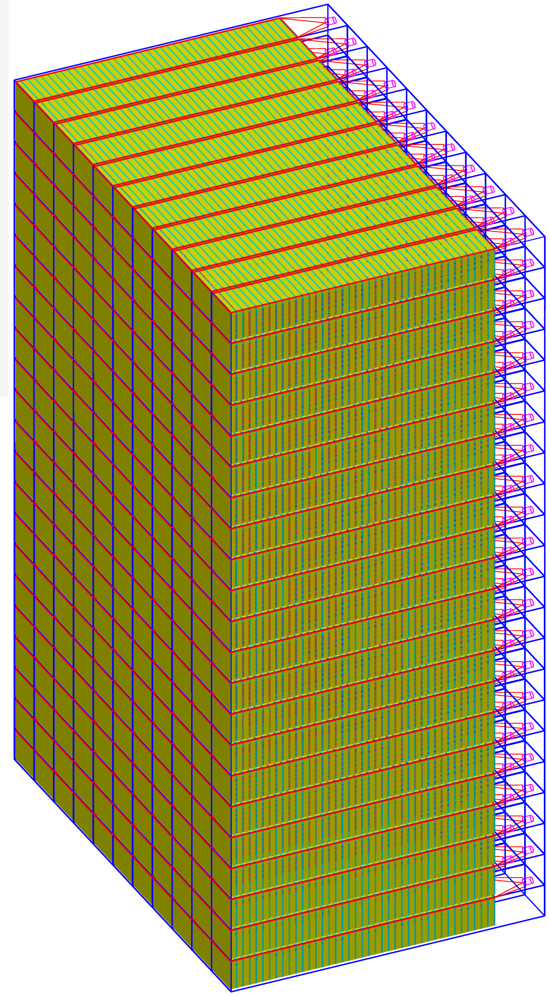
Hadron Calorimeter

- Mechanical prototype completed Fall 2013
- Scintillator delivered to CMU Jan. 2014
- Working Prototype completed May 2014
- Timing Test Results June 2014
- Construction underway

Prototype
50% loaded



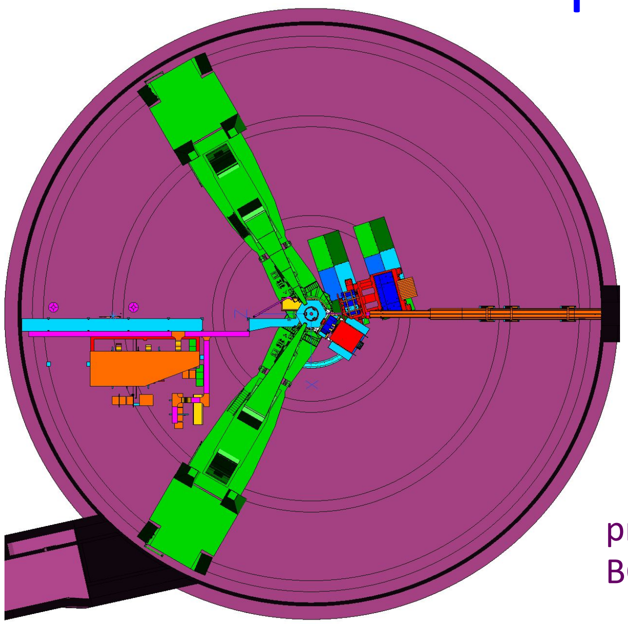
Prototype
Lit with UV LED



Modular Design:

- 15 cm x 15 cm x 1m modules
- 40 layers scintillator and iron per module
- 288 Modules (39 tons)

Proposed TDIS Experiment



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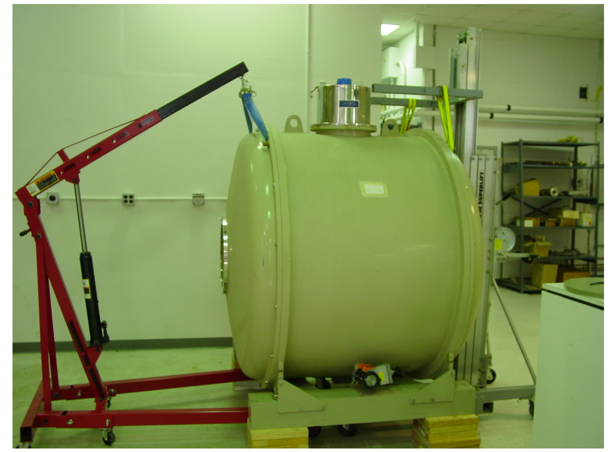

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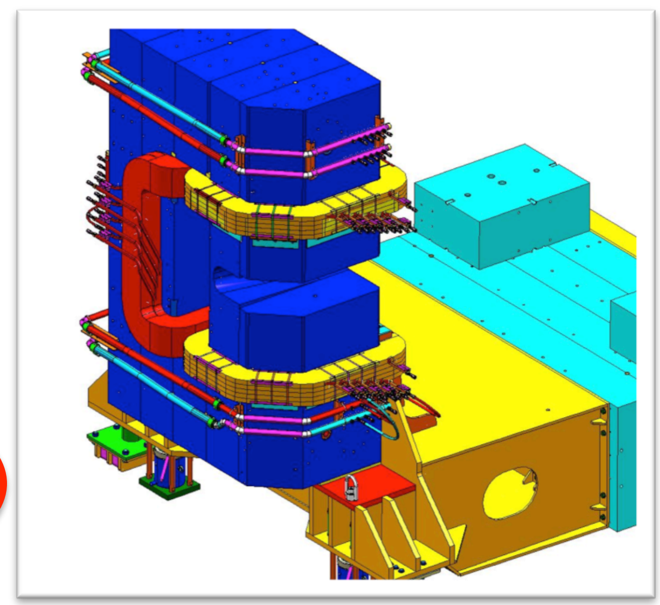

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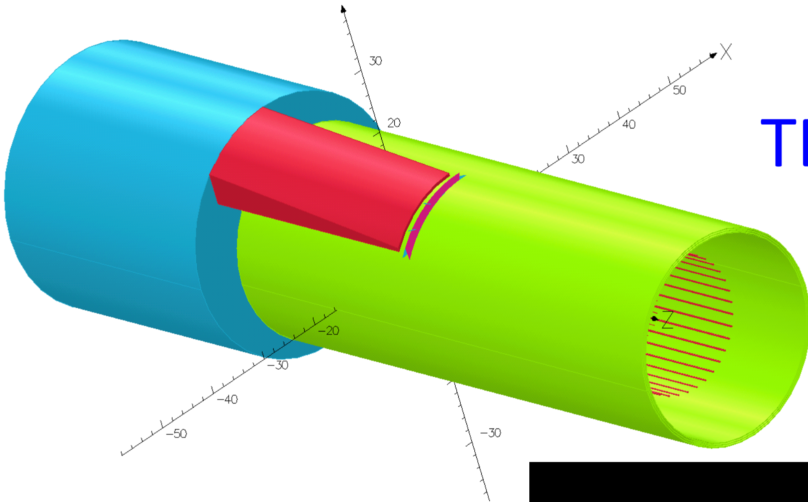
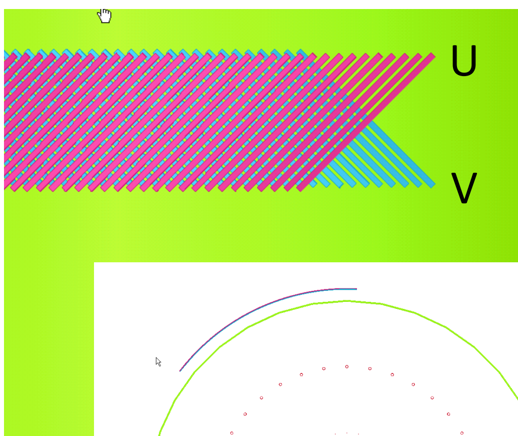
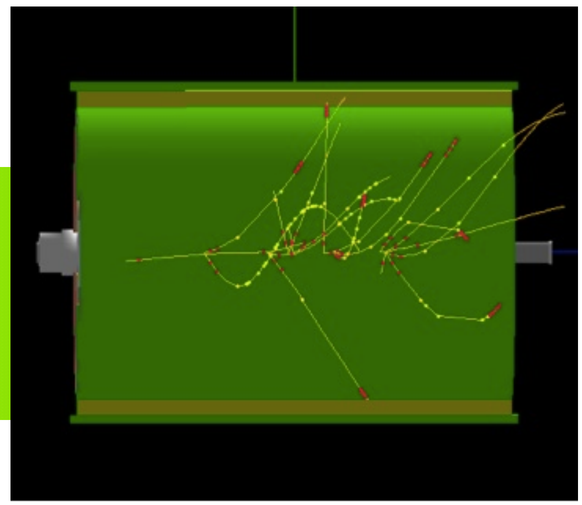
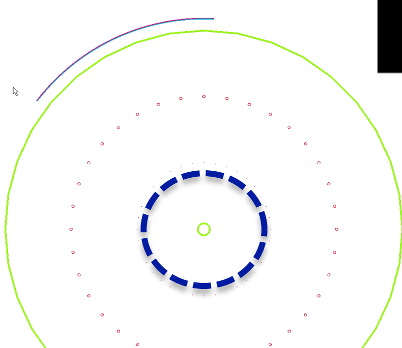


TDIS RTPC





- Luminosity of 3 x 10^{36} Hz/cm^2
  - *Higher current means Al target straw*
- Need to preserve *low p* tagging
  - *40 cm long target cell (1 atm H_2 at 77 K)*
- Larger bore, higher field
  - *Increased drift region (40 cm bore)*
  - *Improved momentum resolution (<10%)*
  - *4.7 T*
  - *Momentum up to 400 MeV/c*
- Coordinate resolution of 1 mm
  - *1 mm x 21 mm in each U&V*
  - *Angular resolution of 0.2 degrees*
  - *24,000 readout pads*
- Sensitive volume
  - *He-CH_4 (10%) – 0.15 atm & 77K*
  - *Inner radius (track) of 5 cm*
  - *Outer radius (track) of 15 cm*
- *Benefit from decade of active GEM development, for instance:*



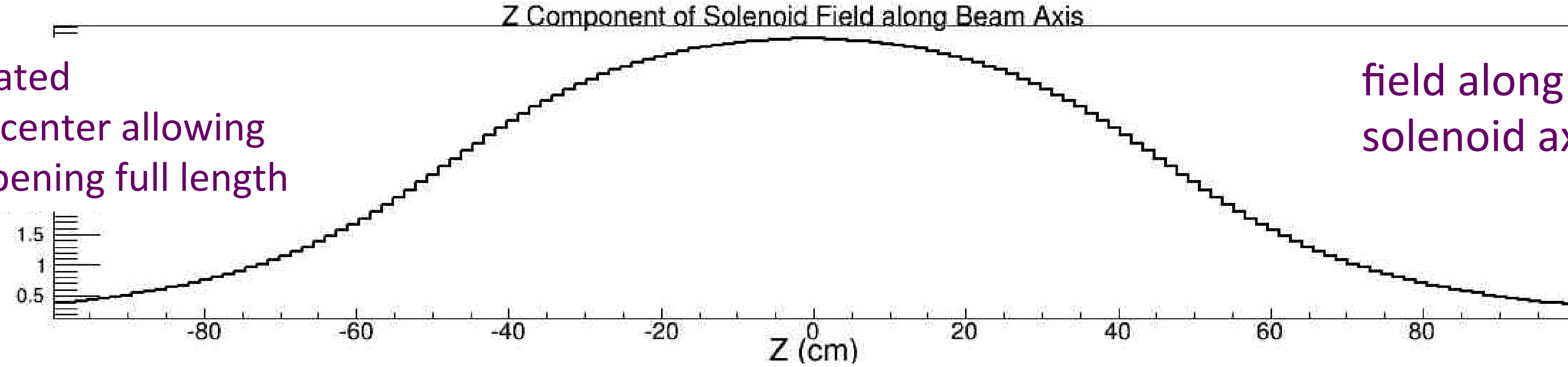
5 cm radius of inner electrical wire grid
10 cm radius of middle electrical wire grid
15 cm radius of GEM foil
15.6 cm radius of U&V readout strips

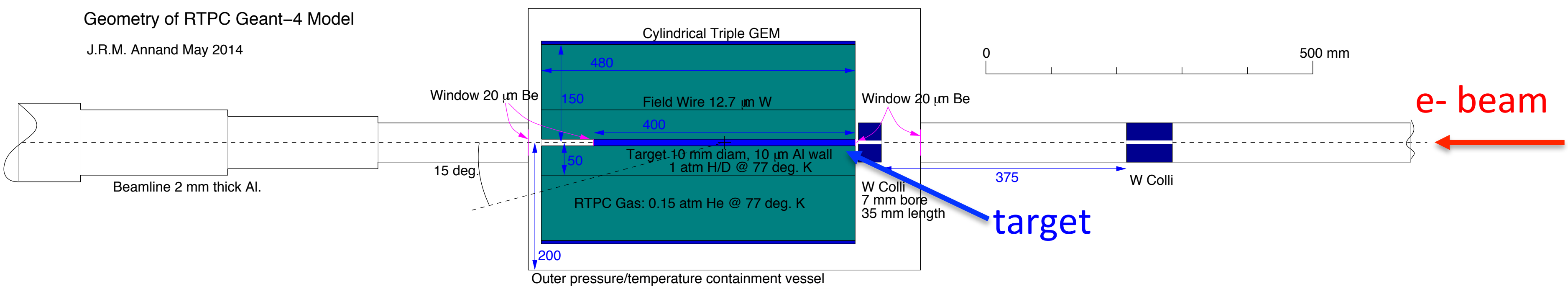
Das et al, Gas-gain study of standard CERN GEM and thick GEM in low-pressure He/CO_2 mixed gas
NIM A 625 (2011) 39
Buzulutskov A. etal, GEM operation in helium and neon at low temperatures
NIM A548 (2005) 487
"Advances in Cryogenic Avalanche Detectors" (review), JINST 7:C02025,2012
Adamova et al, The CERES/NA45 radial drift Time Projection Chamber, 0.34/0.64 mm resolution
NIM A 593 (2008) 203
Lener et al, Performance of a GEM-based Time Projection Chamber prototype for the AMADEUS experiment, 0.25 mm resolution
arXiv:1302.3054

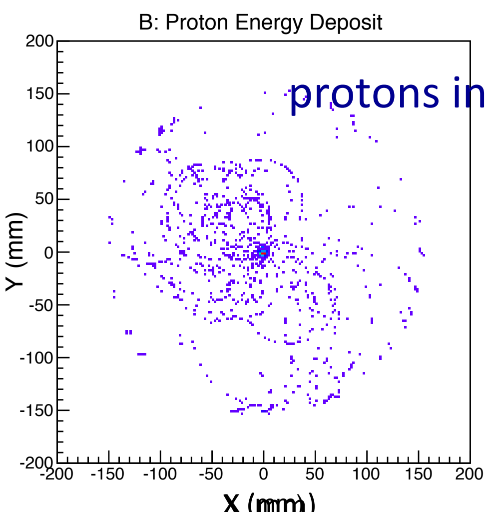
Radial TPC in Field for Monte Carlo Simulations

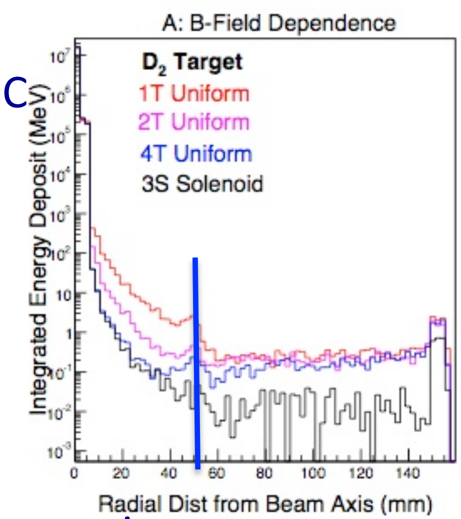
target located
20 cm off center allowing
15 deg. opening full length

field along the
solenoid axis









Moller containment

Monte Carlo simulates electromagnetic interactions

Moller scattering, secondaries ~10 MHz

photoproduction ~20 MHz

Includes deuteron photodisintegration

~20 MHz

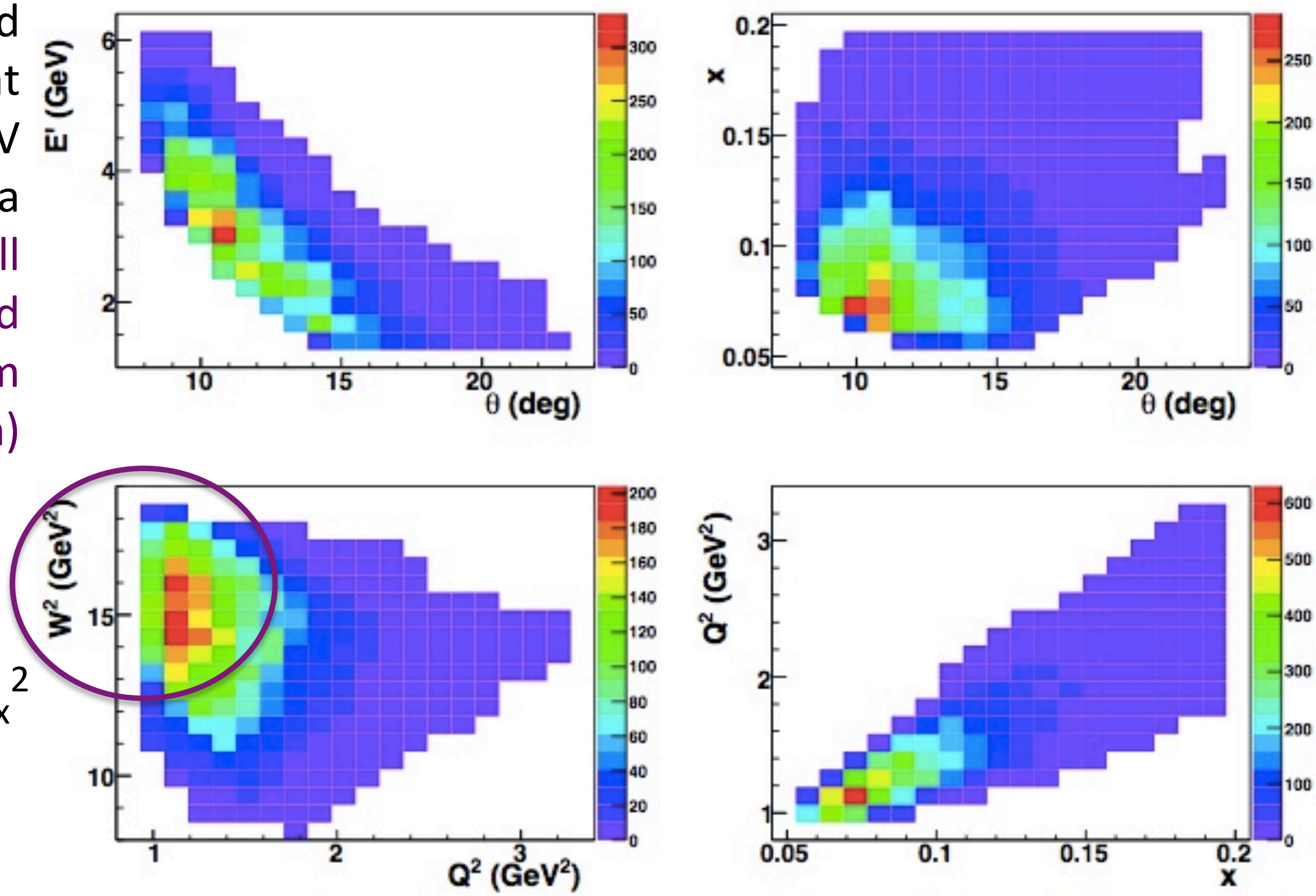
Elastic scattering by far largest

direct calculation 170 MHz

5 MHz/cm^2 s - OK for GEMs

Projected Kinematics – electron arm

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

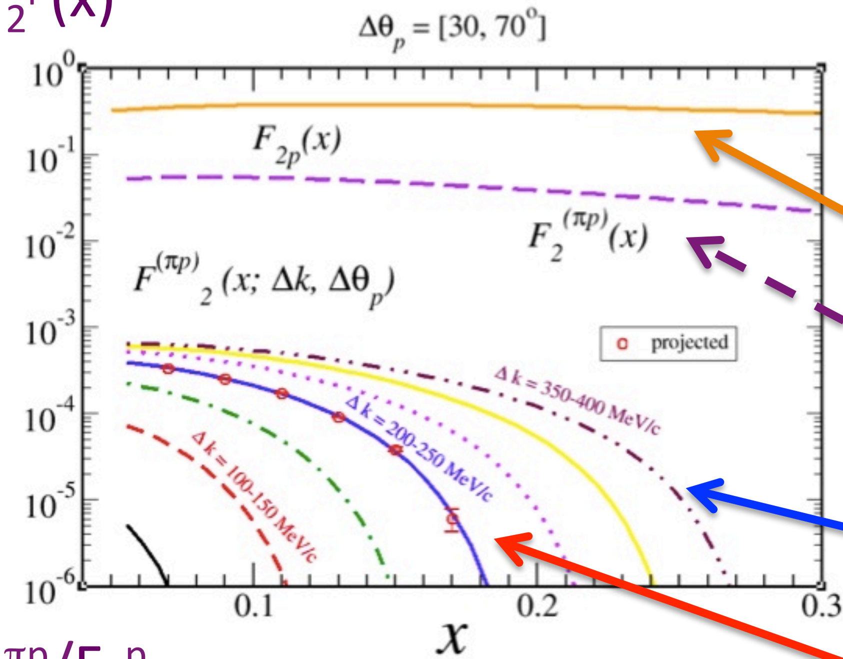


High W^2
- High M_x^2
- DIS!

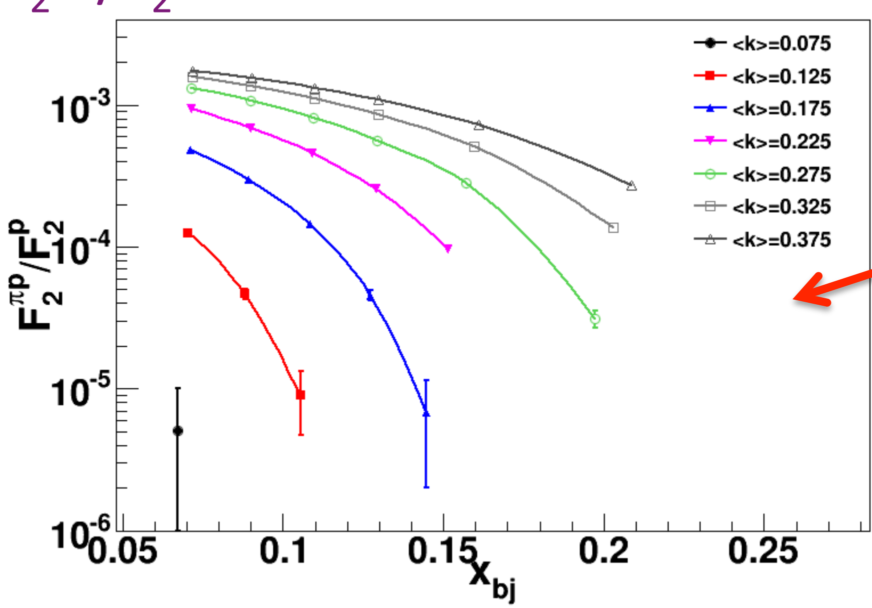
x range ~ 0.1
$1 < Q^2 < 2$ GeV^2

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}

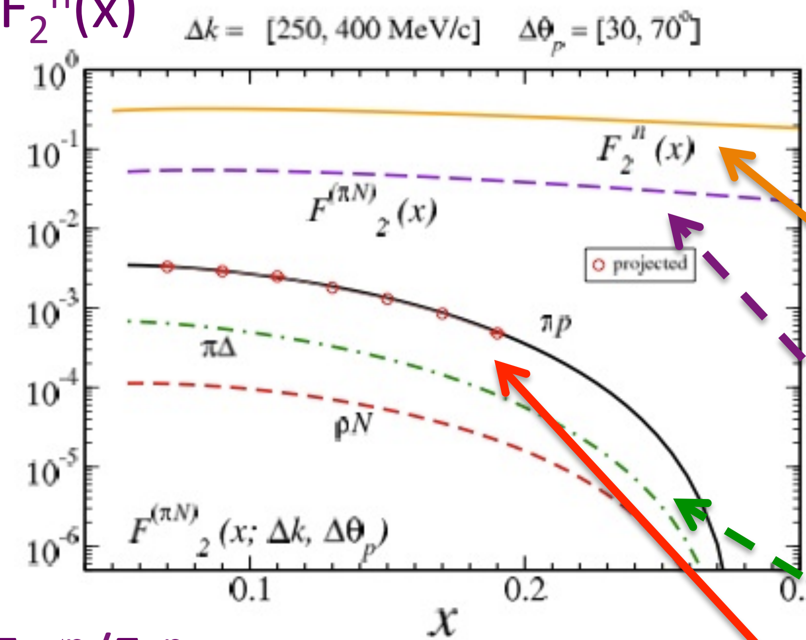
Data for 200 < p_{proton} <250 MeV/c are representative to show uncertainty

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

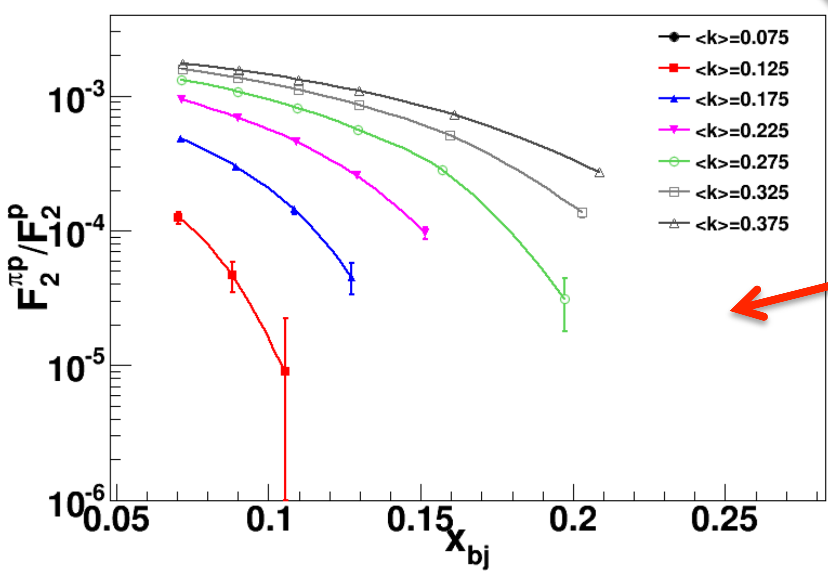
Error bars largest at highest x points – less statistics
- at fixed x, these are the lowest t values

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

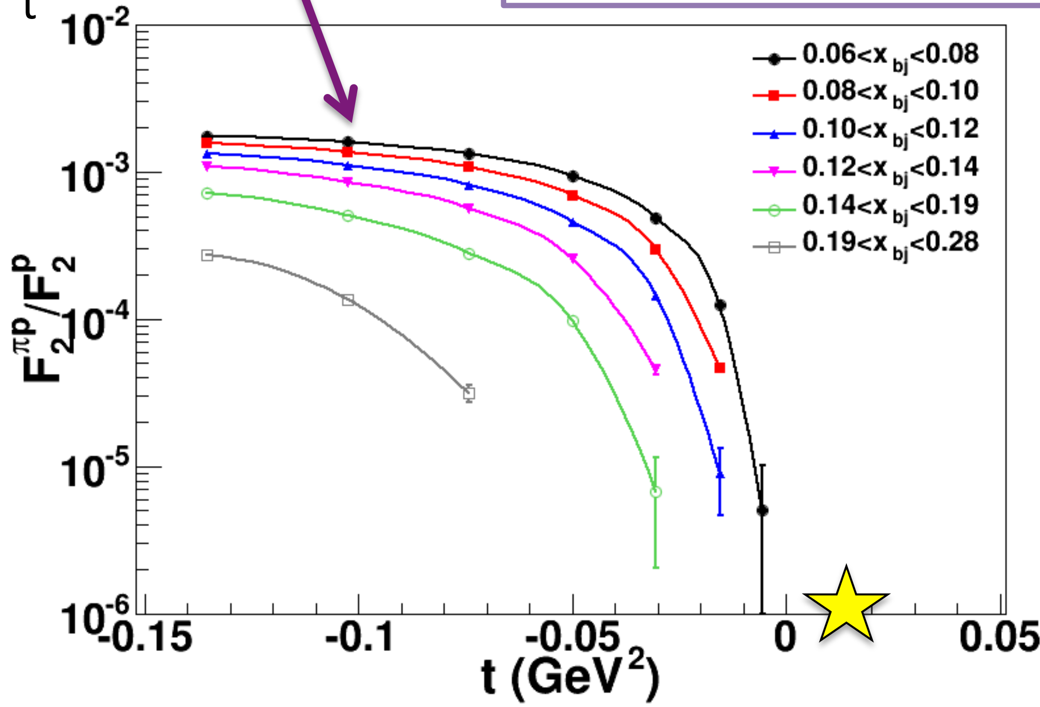
Full data set shown here
- all momentum bins in MeV/c

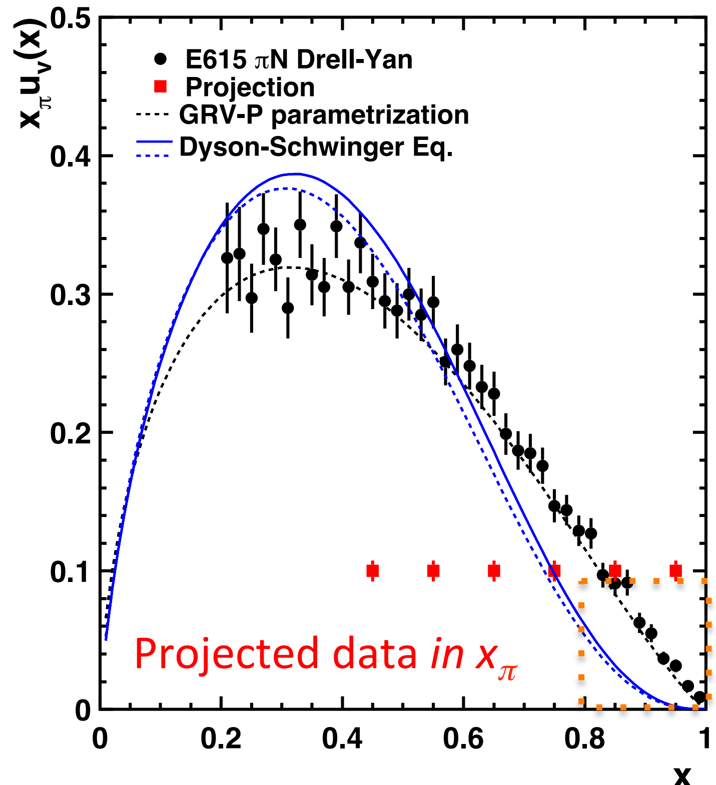
Do not show lowest momentum <x> = 0.075 data
- run lower luminosity due to larger background

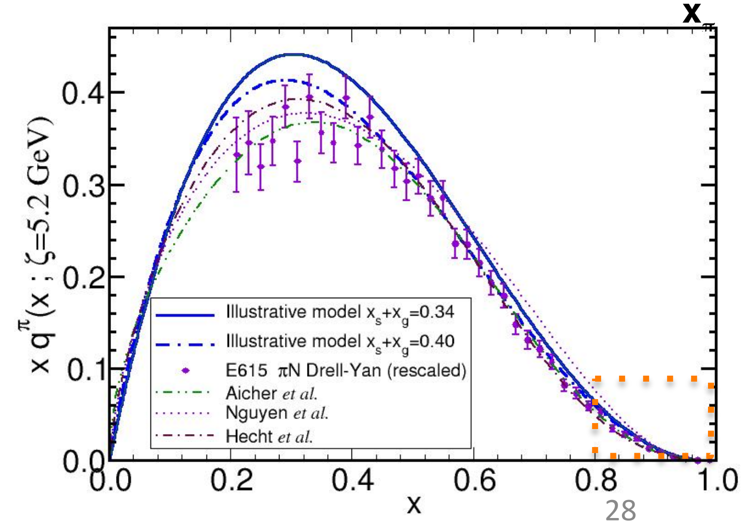
Projected Results – Pion Structure Function from TDIS at JLab

- 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

- Low t extrapolation to the pion pole
- Proton p determines t







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

Summary

Spectator Tagging opens a door to probe nucleon fragmentation
TDIS opens a door to access effective (neutron, pion, kaon..?) targets

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

Directly probe the partonic components of the meson cloud of the nucleon

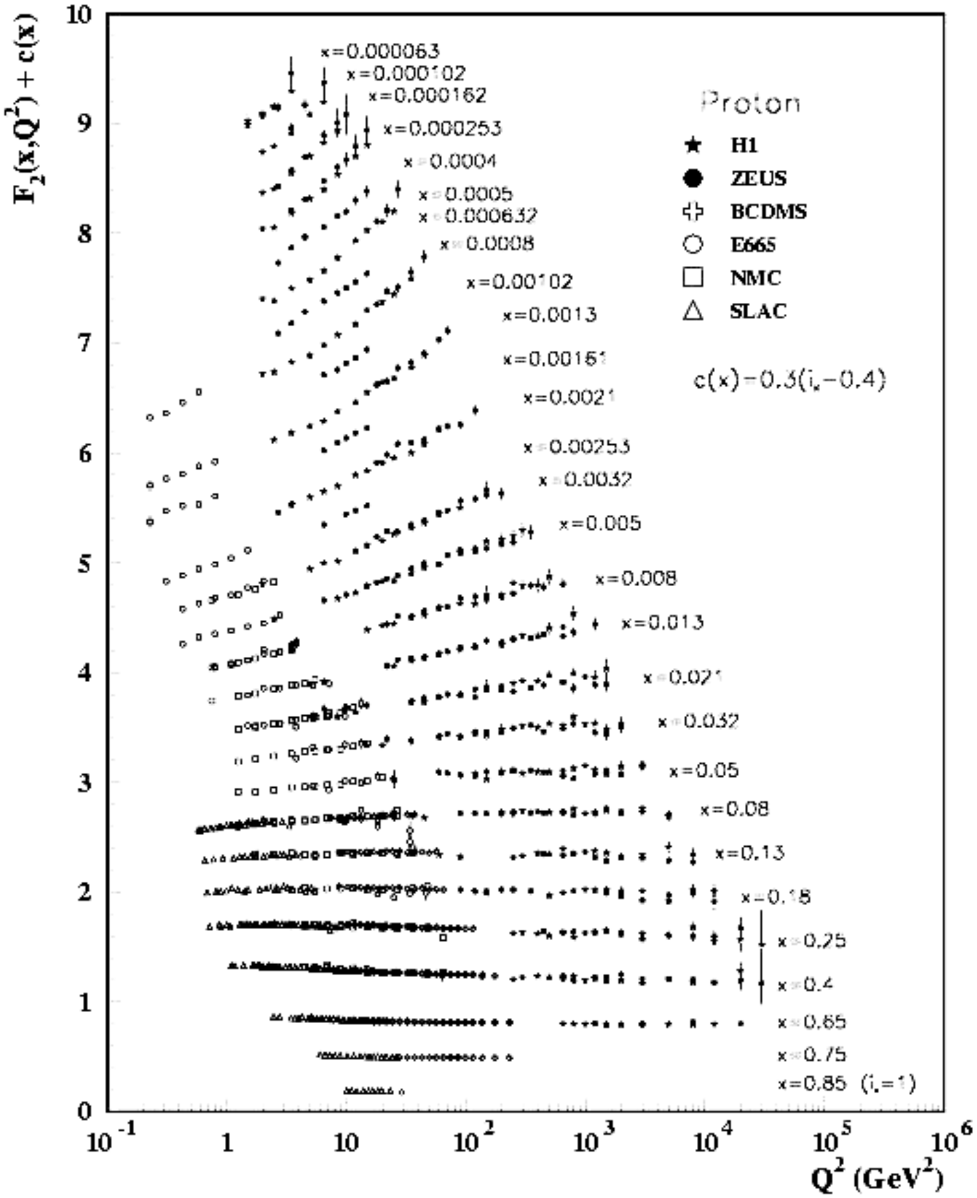
very few experiments to date
fundamental QCD
help understand flavor asymmetry of the nucleon sea
measurement isospin dependence (p–n difference)

Understand nucleon structure at a deeper level

Thank You!!!

Backups

Structure Function Measurements



Proton –

- Well understood
- F_2^p measured over 5 orders of magnitude in x, Q^2
- F_2^p measured by dozens of experiments at numerous laboratories and for decades
- F_L measurements also exist
- Well described by DGLAP, global pdf fits

Neutron –

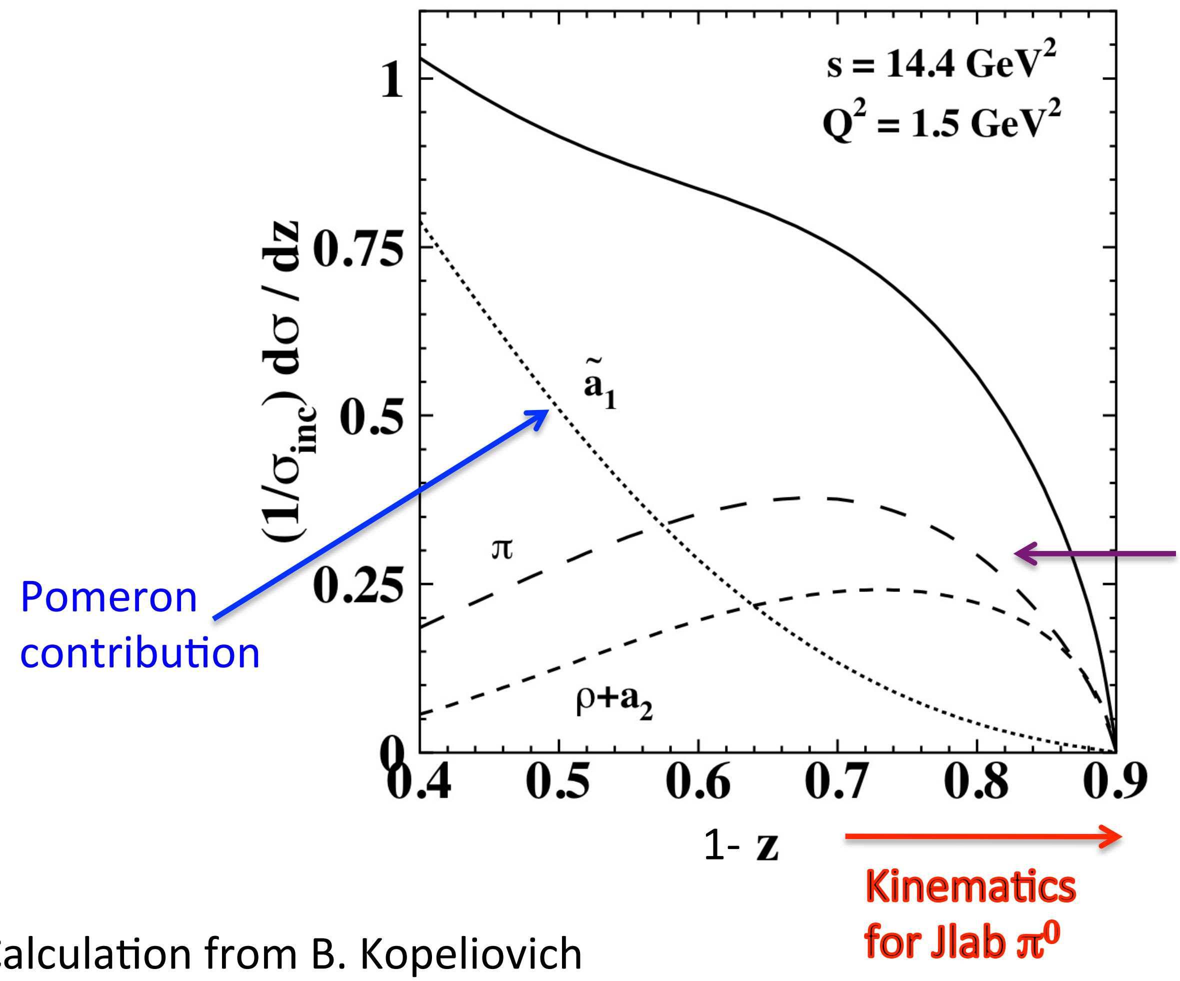
- One experiment
- Limited kinematics (low Q, high x)
- No F_L data
- Deuteron Available

Pion –

- Two experiments
- Limited kinematics (low x, moderate x, scant Q^2 reach at same x)
- No F_L data

Developing the F_2^π case

hydrogen target, worst theoretical backgrounds



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

Calculation from B. Kopeliovich
at JLab TDIS kinematics

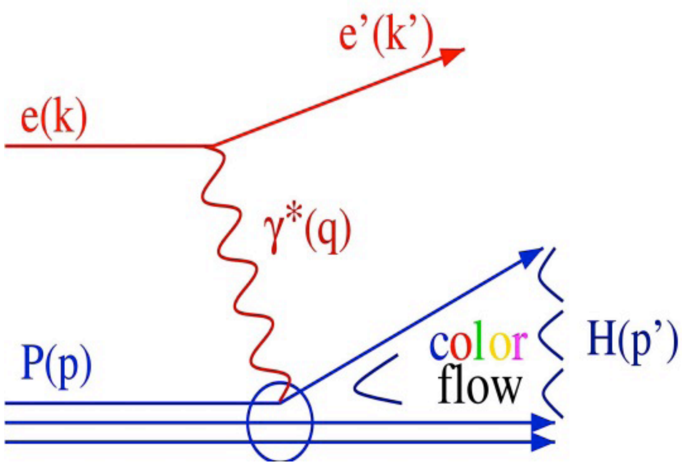
Dominant Sources of Systematic Uncertainty

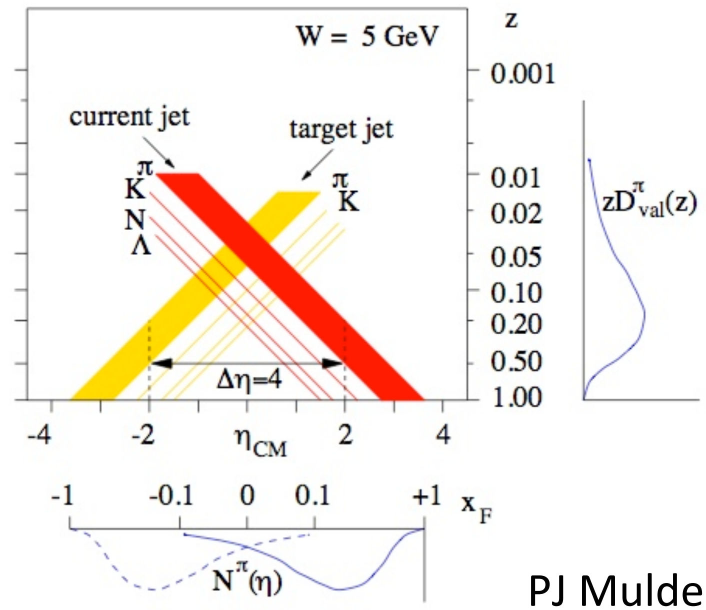
- Accidental background subtraction 5%
  - Requested beam time to run 5 days at reduced luminosity to evaluate
- (Untagged) DIS electron cross section 3%
  - Target density, beam charge, spectrometer acceptance, detector and trigger efficiency, ….
  - SBS and RTPC stay at same kinematics, entire detector system serves as a luminosity monitor
  - Will correct inclusive electron to very well-known cross sections
- RTPC absolute efficiency 2%
  - Propose to run with HCAL quasi-elastic neutrons to calibrate at p<200 MeV/c
  - Stability of RTPC will be monitored with accidental elastic protons
- RTPC deadtime uncertainty ~ 1%
  - Requested beam time to run at lower luminosity, also during calibration
- RTPC momentum resolution (<)1%
  - Large momentum bins proposed
- RTPC angular acceptance ~ 1%
  - Survey and simulation, calibration via D(e,e'n)p,
- Beam position (<)1%
  - Precision BPMs, calibration of the position dependence

- **TOTAL ESTIMATE** 6.5%

Understanding Target Region Important for Semi-inclusive Physics at JLab

- Significant component of JLab 12 GeV program
  - Flavor decomposition, transverse momentum dependent pdfs, single spin asymmetries
  - Focus on current fragmentation region





PJ Mulders

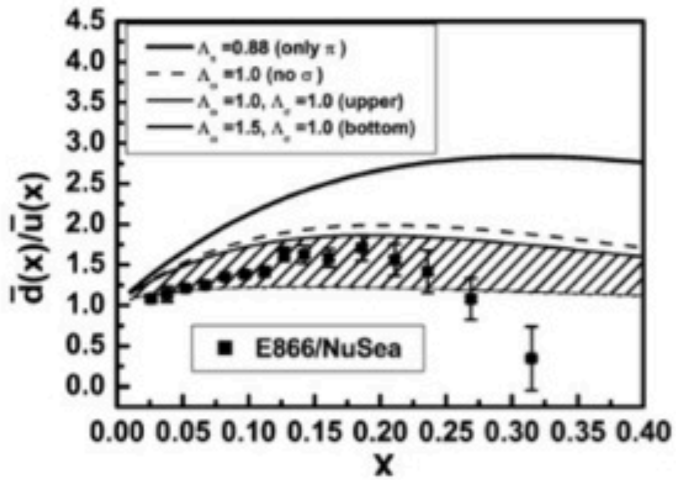
At JLab energies the current and target fragmentation regions are <u>*not*</u> widely separated, *hence a quantitative understanding of target fragmentation will be a prerequisite for the analysis of semi-inclusive DIS in the current fragmentation region.*

Sign change of $\bar{d}(x) - \bar{u}(x)$ at $x \sim 0.25$?

(or $\bar{d}(x)/\bar{u}(x) < 1$ at $x \sim 0.25$?)

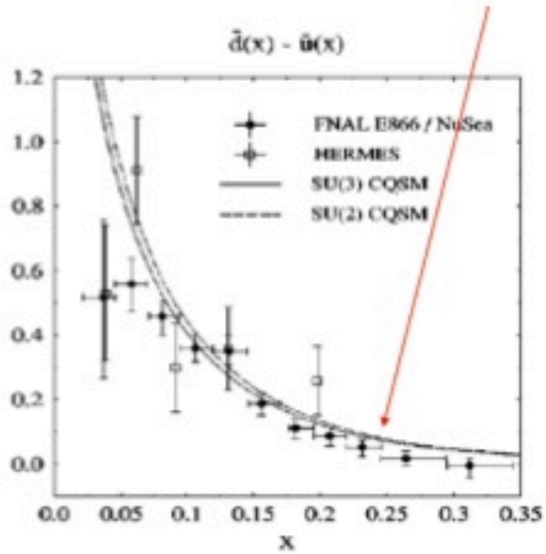
Why is it interesting? (no models can explain it yet!)

Meson cloud model



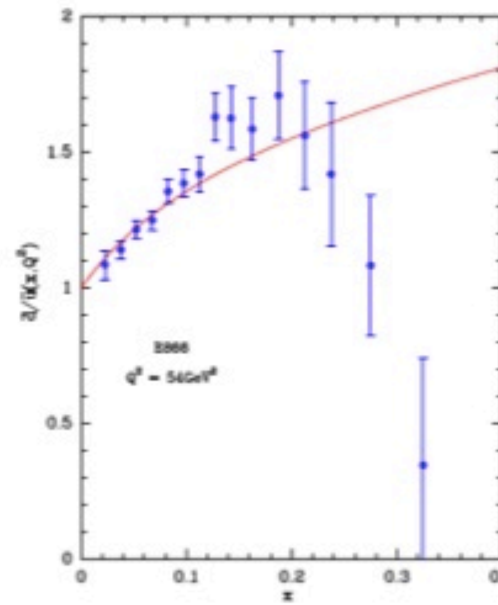
From Alberg's talk

Chiral-quark soliton model



From Wakamatsu's talk

Statistical model



From Soffer's talk

J-C Peng, Trento 2013 workshop

Think about both hydrogen and deuterium

p(e,e' p)X   n(e,e' p)X

- Charged pion exchange has less background from Pomeron and Reggeon processes, ρ^0 production.
- The π^+N cloud doubles π^0N cloud in the proton.

$$
\begin{aligned}
|p> &\rightarrow \sqrt{1-a-b}|p_0> \\
&+ \sqrt{a}\left(-\sqrt{\frac{1}{3}}|p_0\pi^0> + \sqrt{\frac{2}{3}}|n_0\pi^+>\right) \\
&+ \sqrt{b}\left(-\sqrt{\frac{1}{2}}|\Delta_0^{++}\pi^-> - \sqrt{\frac{1}{3}}|\Delta_0^{+}\pi^0> + \sqrt{\frac{1}{6}}|\Delta_0^{0}\pi^+>\right)
\end{aligned}
$$

Regge approach: a=0.105, b=0.015
Nikolaev et al.,PRD60(1999)014004

Chiral approach: a=0.24,b=0.12
Thomas, Melnitchouk & Steffens,PRL85(2000)2892