Accessing Large-x PDFs at Jefferson Lab and EIC

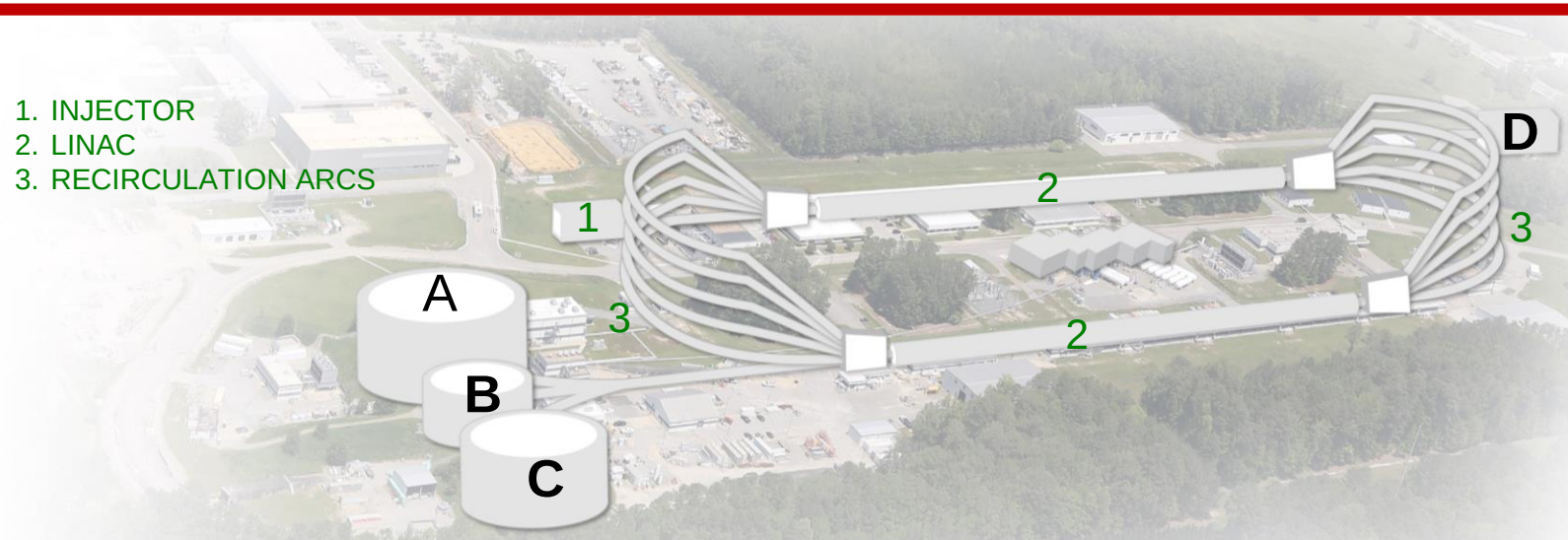
Rolf Ent

CTEQ Fall Meeting and Pre-Workshop

Parton Distributions as a Bridge from Low to High Energies

November 8-10, 2018, Jefferson Lab

CEBAF at Jefferson Lab



- CEBAF Upgrade completed in September 2017
  - CW electron beam
  - E_{max} = 12 GeV
  - I_{max} = 90 μA
  - Pol_{max} = 90%
- Commissioning:
  - April 2014: hall A
  - October 2014: hall D
  - February/March 2017: halls C & B

CEBAF World-leading Capabilities

- Nuclear experiments at ultra-high luminosities, up to 10^{39} electrons-nucleons /cm^2/ s
- World-record polarized electron beams
- Highest intensity tagged photon beam at 9 GeV
- Ability to deliver a range of beam energies and currents to multiple experimental halls simultaneously
- Unprecedented stability and control of beam properties under helicity reversal

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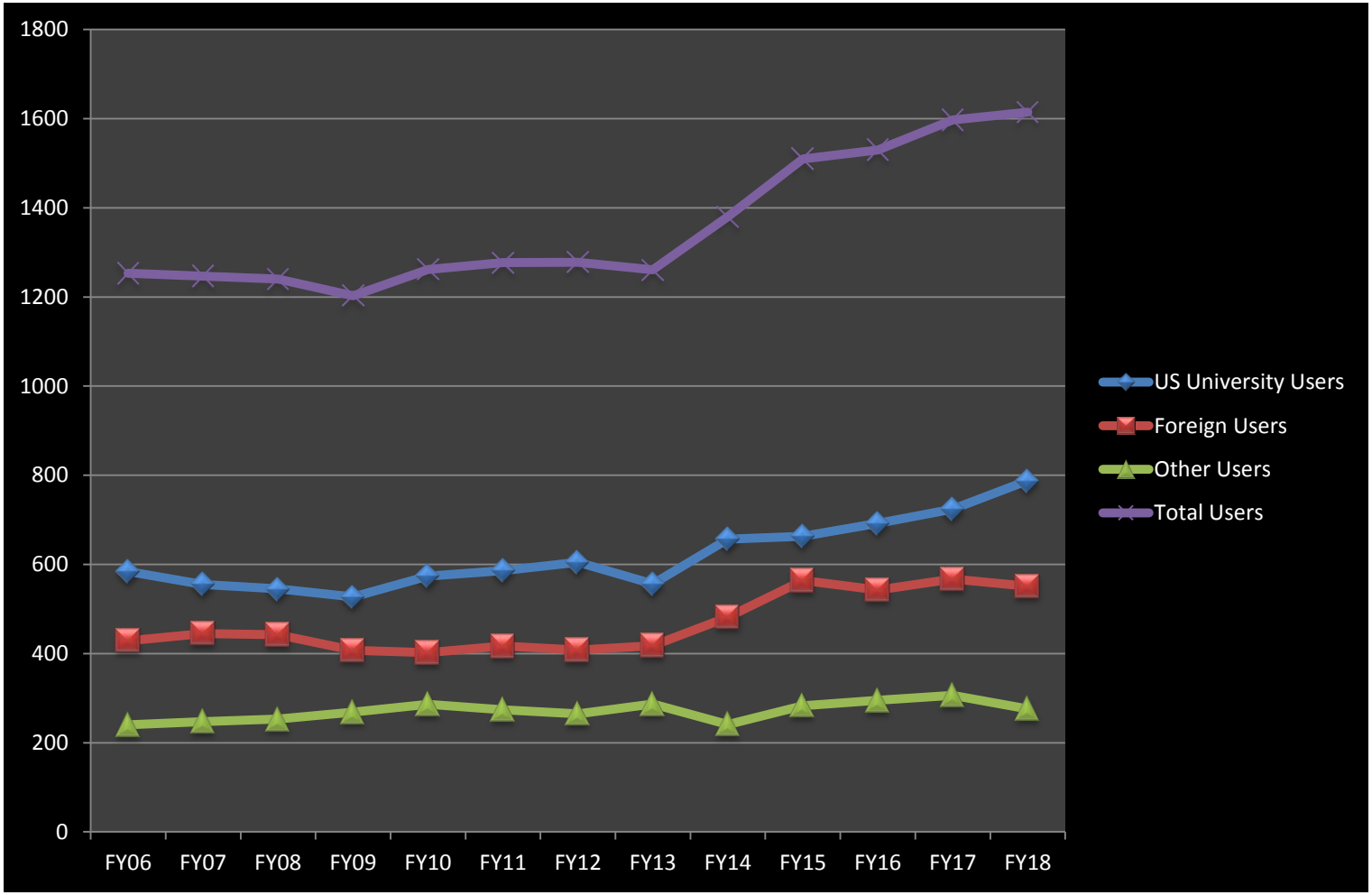
JEFFERSON LAB USER GROWTH



"Other Users" include US National Labs and Industry

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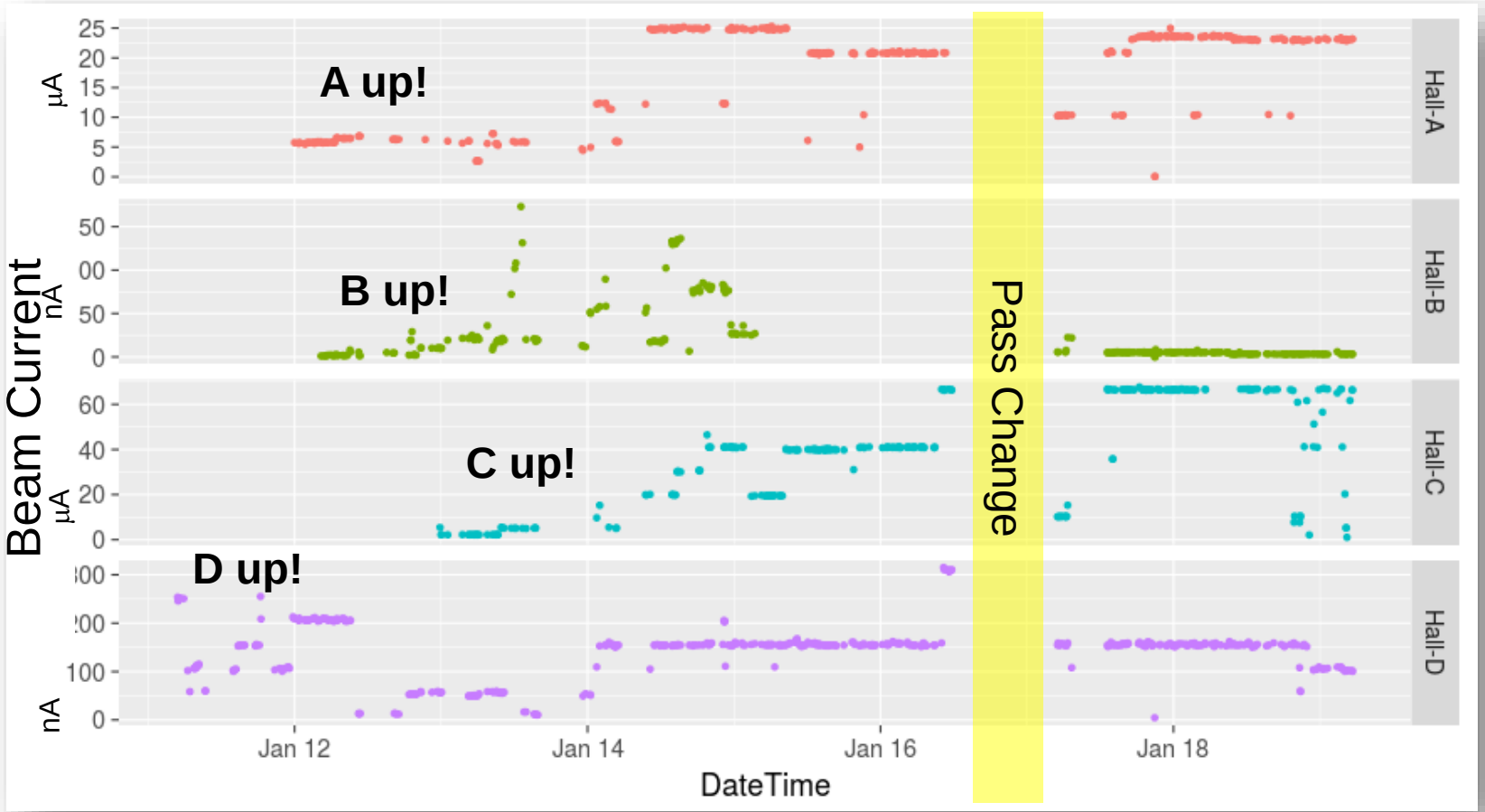
INITIATED FOUR HALL OPERATION



Simultaneous 4-Hall Beam Delivery since Jan 18, 2018

Now operating total 900 kW CW beam power to 4 Halls

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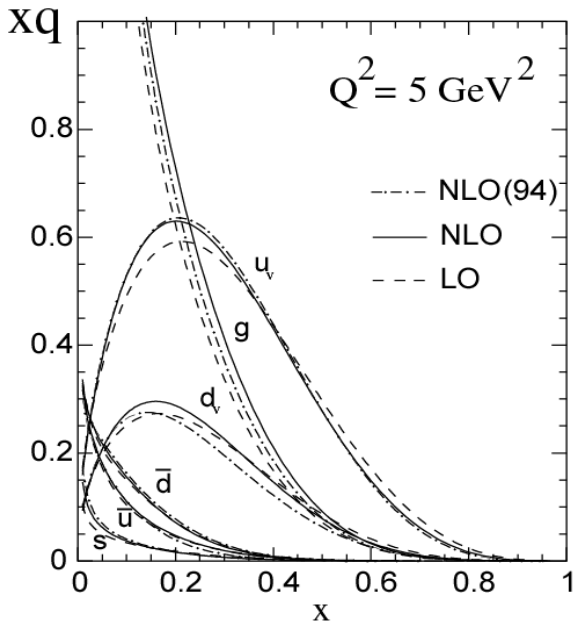
MEASURING HIGH-X STRUCTURE FUNCTIONS

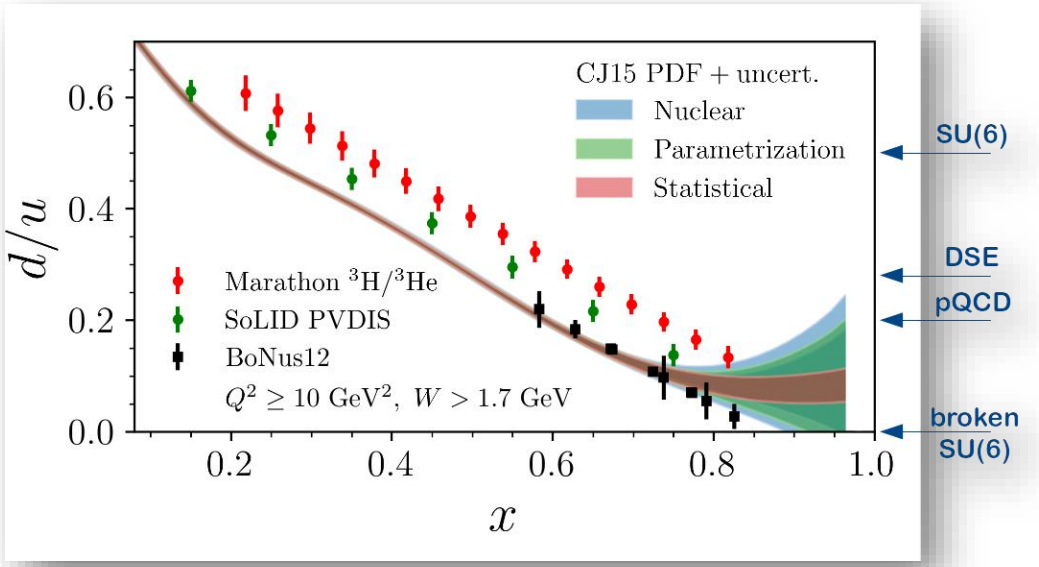
REQUIRES:

- High beam polarization
- High electron current
- High target polarization
- Large solid angle spectrometers



12 GeV will access the regime (x > 0.3), where valence quarks dominate

Projected JLab 12 GeV *d/u* Extraction



x →1 predictions	F_2^n/F_2^p	d/u	A_1^n	A_1^p
SU(6)	2/3	1/2	0	5/9
Diquark Model/Feynman	1/4	0	1	1
Quark Model/Isgur	1/4	0	1	1
Perturbative QCD	3/7	1/5	1	1
QCD Counting Rules	3/7	1/5	1	1

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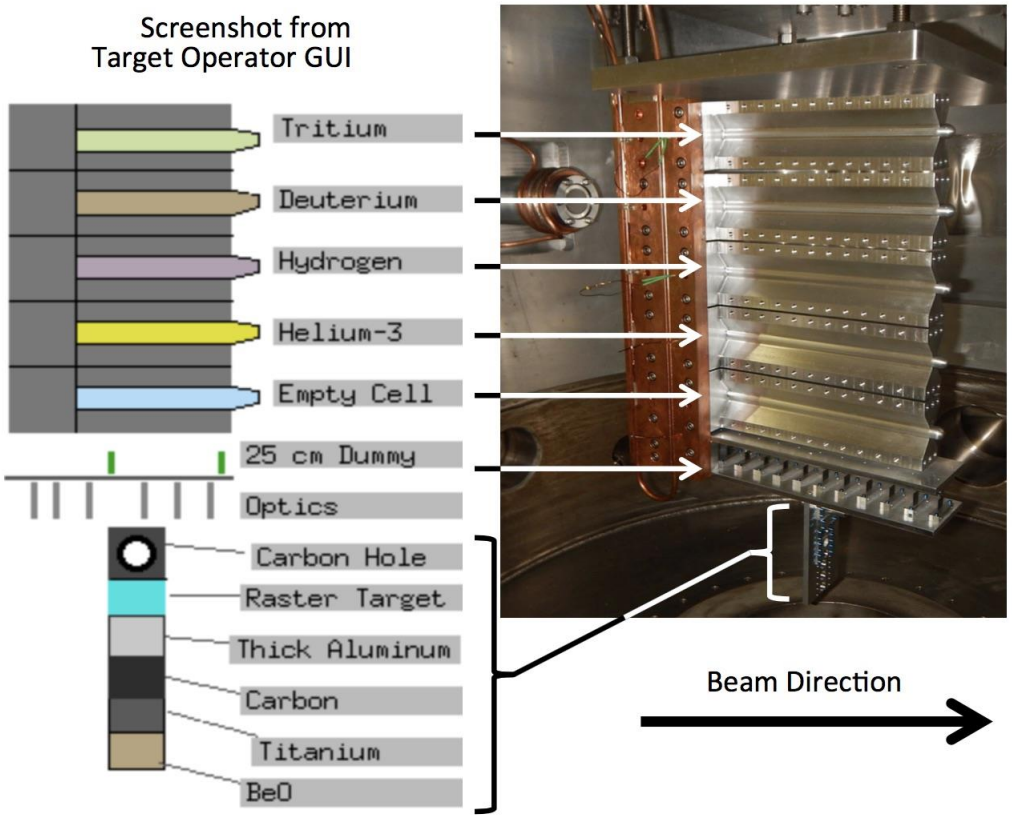
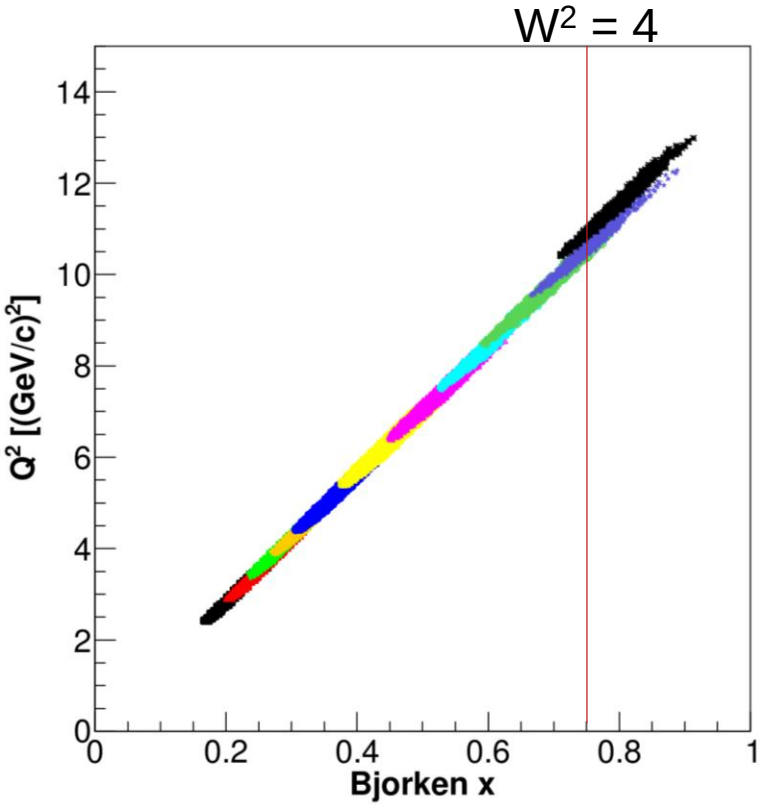
HALL A – FIRST USE OF 3H TARGETS AT ELECTRON LAB SINCE 3 DECADES





- Running tritium family of experiments in 2017/2018 – 3 completed including MARATHON 3H/3He, 4th ongoing
- Expect first results to be from direct nuclear ratios: D/p, 3H/3He

HALL A – FIRST USE OF 3H TARGETS AT ELECTRON LAB SINCE 3 DECADES

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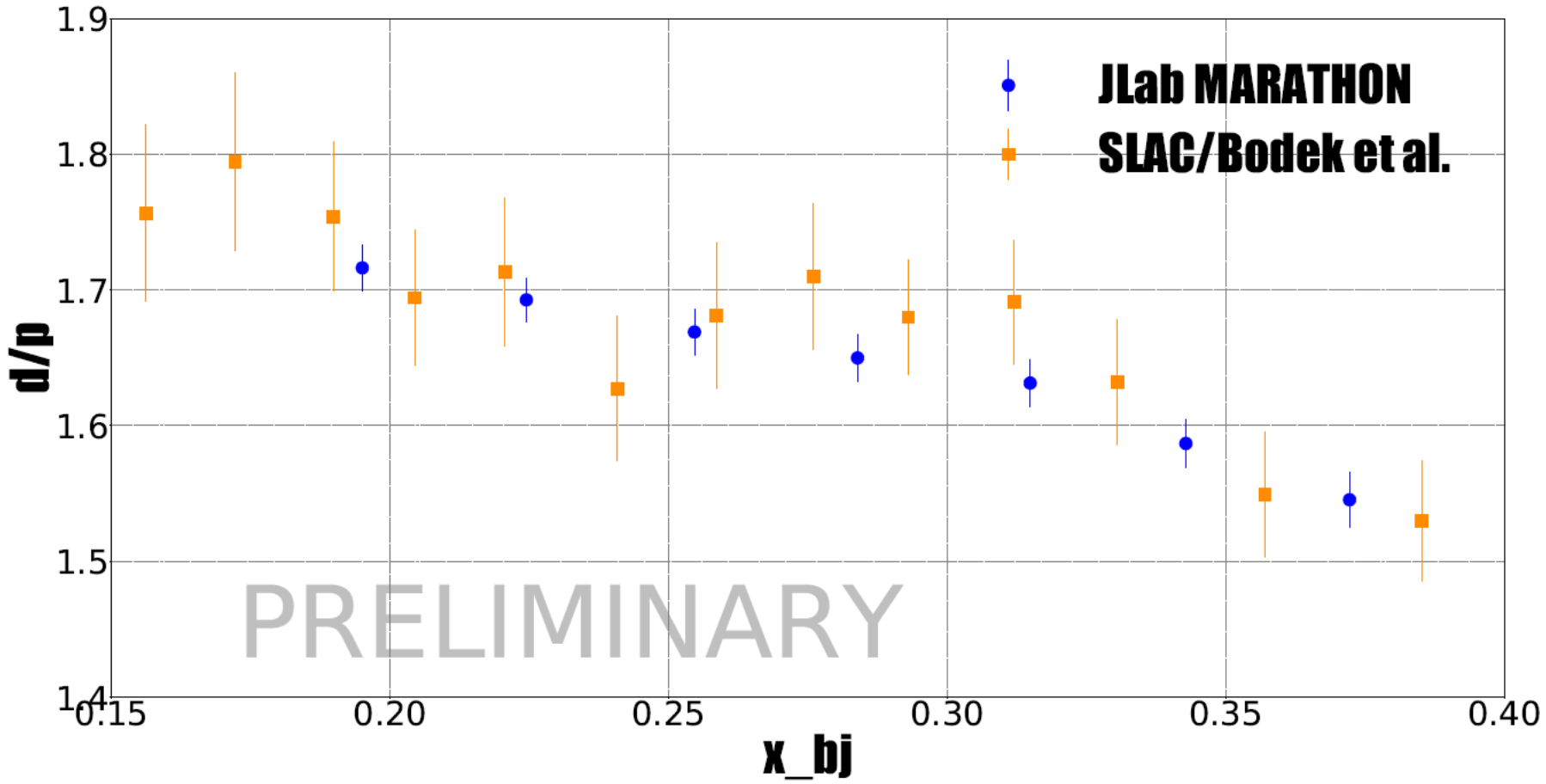

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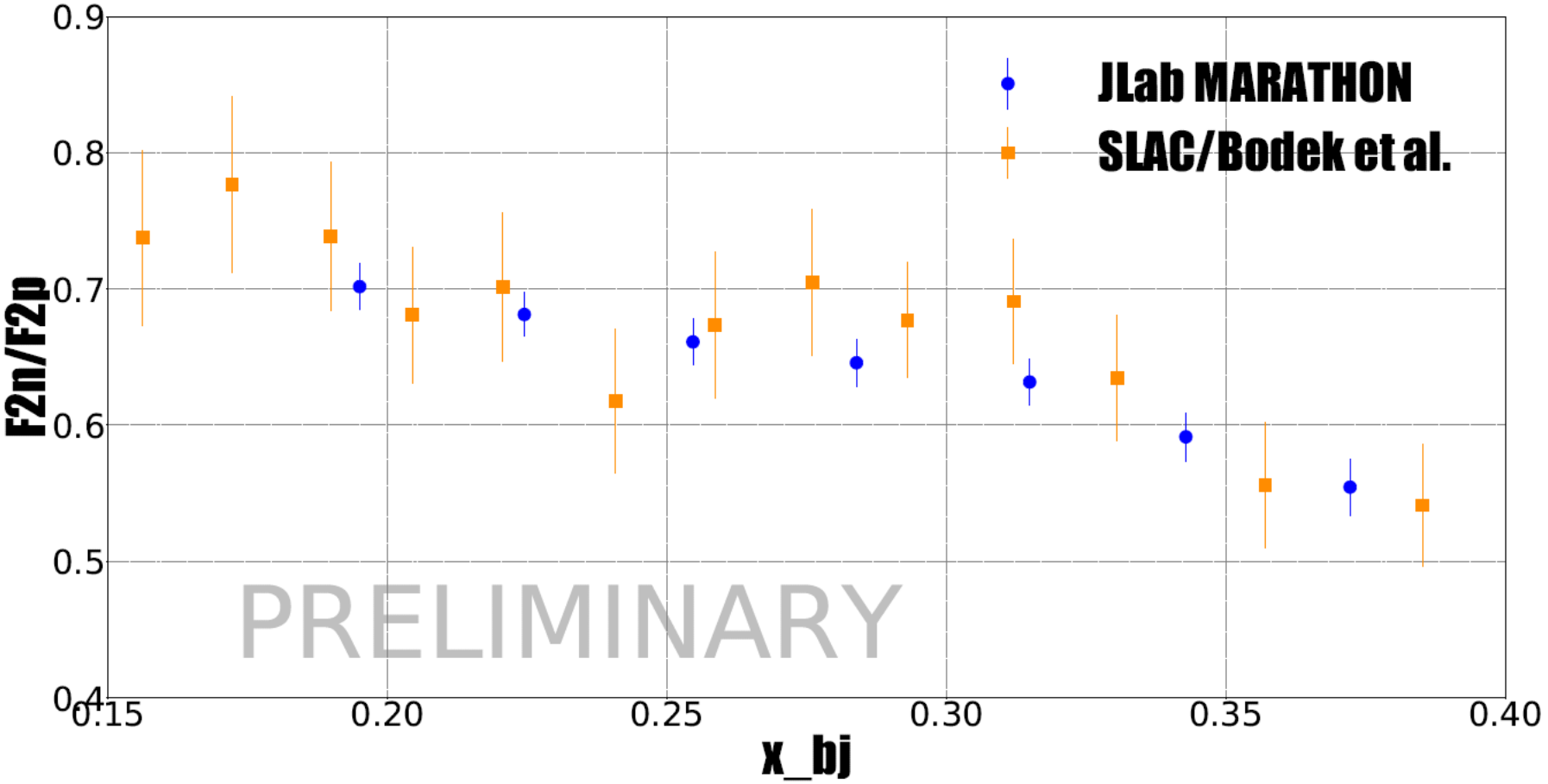
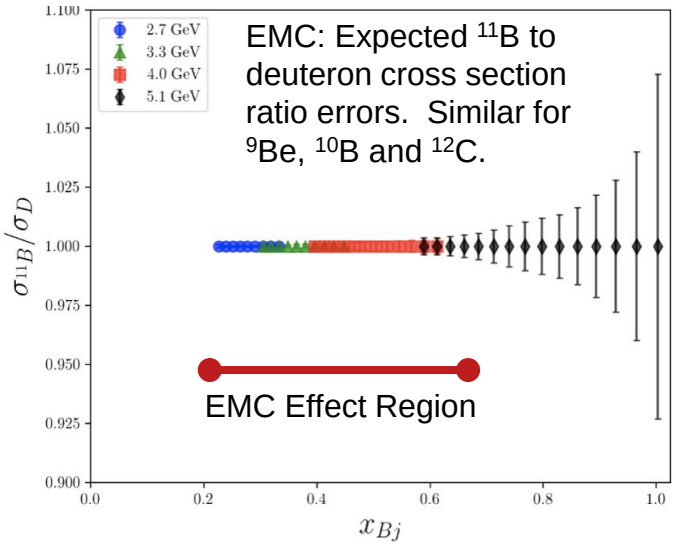
HALL A – FIRST USE OF 3H TARGETS AT ELECTRON LAB SINCE 3 DECADES

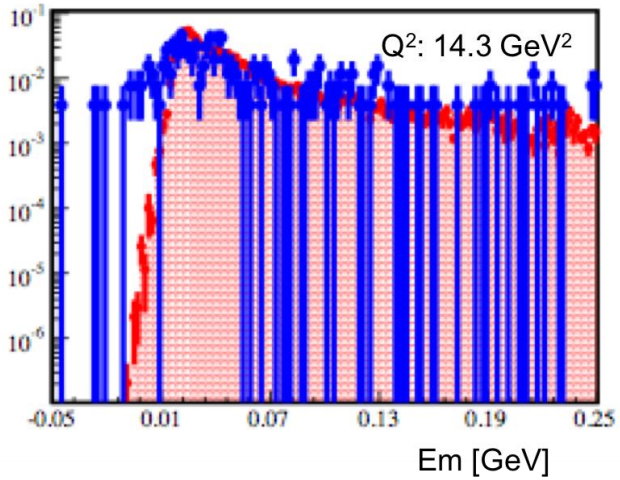
- Expect first results to be from direct nuclear ratios: D/p, 3H/3He
- PRELIM ratio of low-x calibration data, error bars only include random errors
- F2n/F2p extracted using F2d/(F2p+F2n) of Kulagin and Petti (near 1)



HALL C – COMMISIONING EXPERIMENTS COMPLETE; SERIES OF TMD STUDIES AND KAON L/T ONGOING

- SHMS calibration initial physics data acquired
  - $F_2^{H,D}$ structure functions, EMC effect
  - D(e,e'p) at high missing momentum
  - Color Transparency (CT) – ^{12}C(e,e'p)
    - Data for 3 Q^2 points acquired.
    - Highest Q^2 is where BNL A(p,2p) saw rise in transparency
  - TMD studies (SIDIS) and Kaon electroproduction scaling measurement underway
- Analyses of CT, F_2, D(e,e'p), and EMC effect measurements moving along
  - Preliminary results for F_2 and CT shown at DNP





CT: Good agreement between data and simulation even at the highest Q^2. Will improve as SHMS optics model is optimized.

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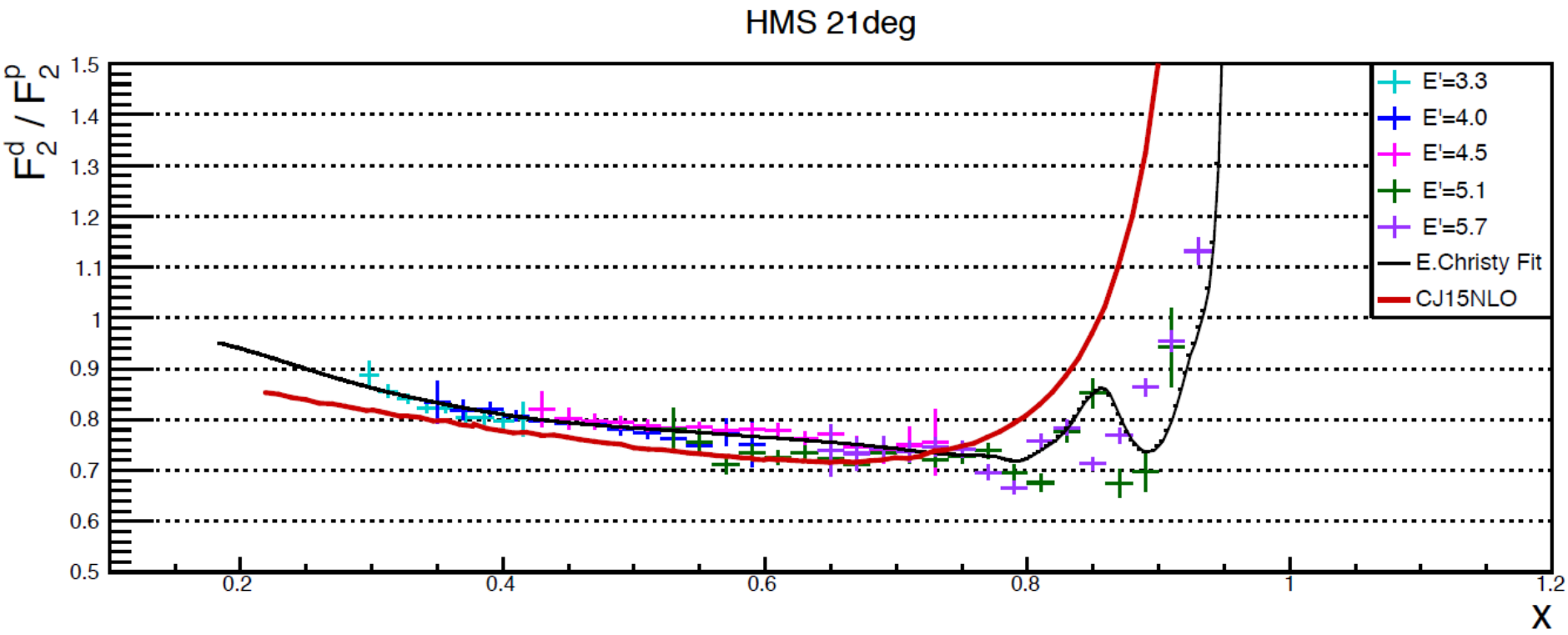
HALL C – $F_2^{H,D}$ COMMISIONING EXPERIMENT COMPLETE

- Data and Christy fit: $W^2 > 1.2$ GeV^2
- CJ: $W^2 > 3.5$ GeV^2



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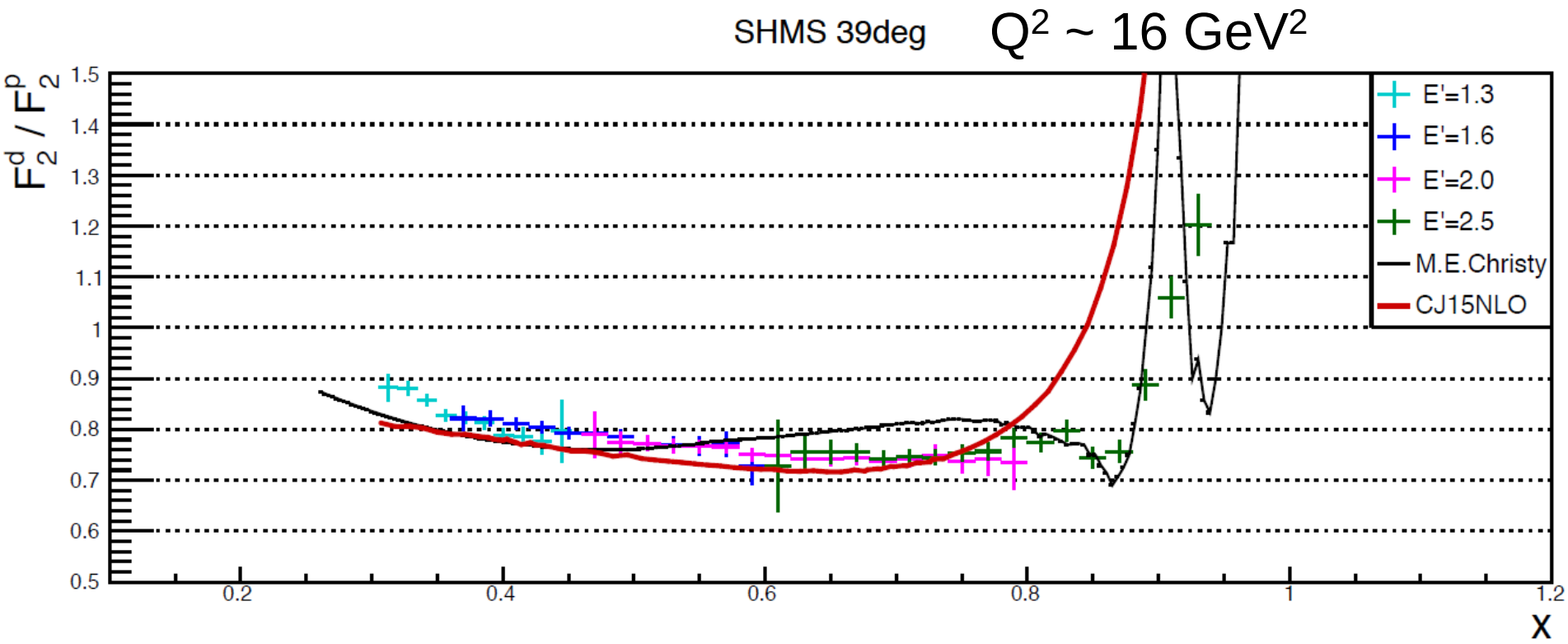

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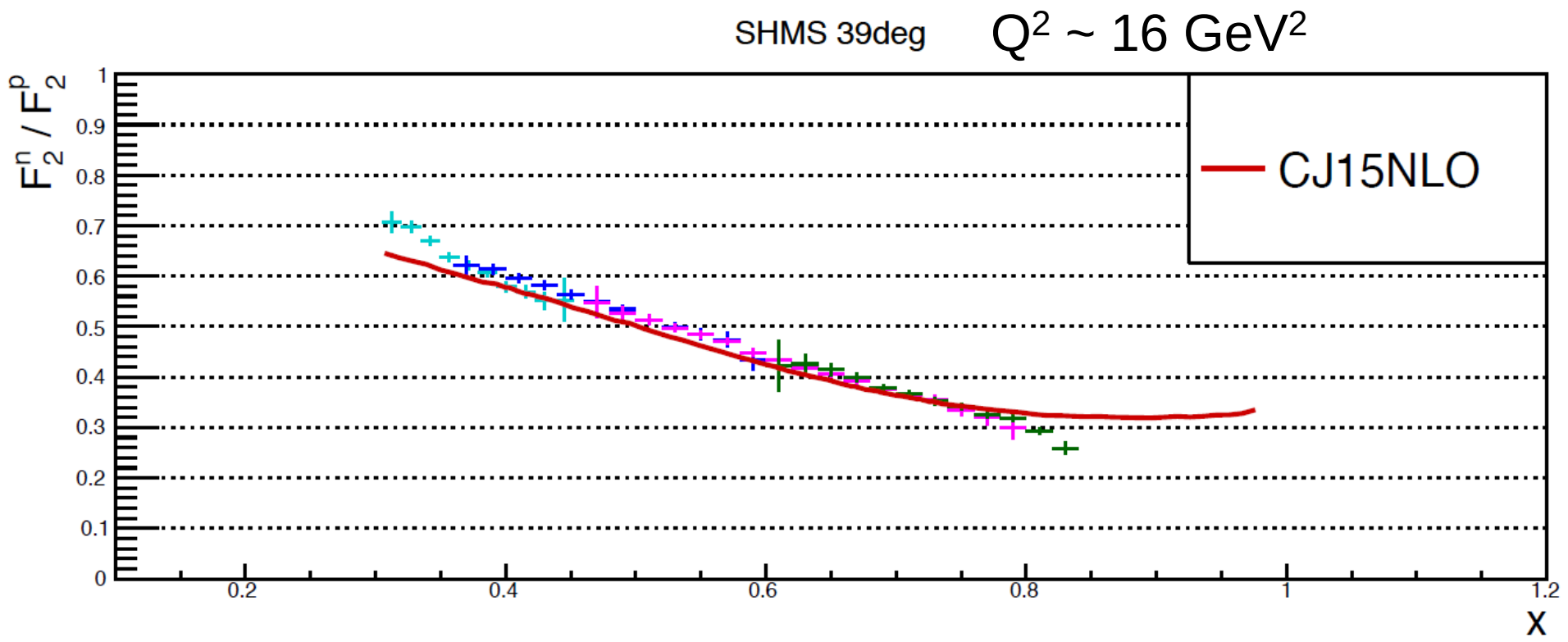
HALL C – $F_2^{H,D}$ COMMISIONING EXPERIMENT COMPLETE

- Extracted by multiplying (F2n/F2p)/(F2d/F2p) from CJ
- (large!!) theory uncertainty not included yet
- Data and CJ: $W^2 > 3.5$ GeV^2



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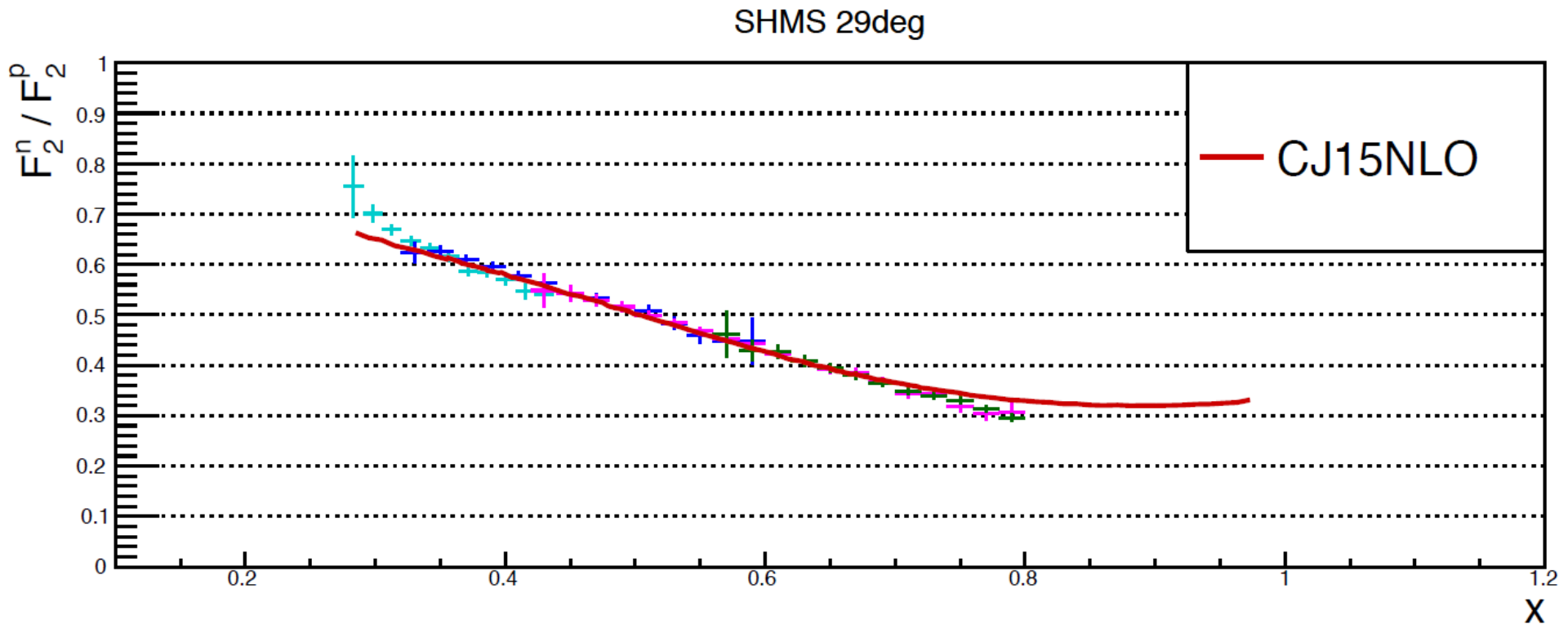

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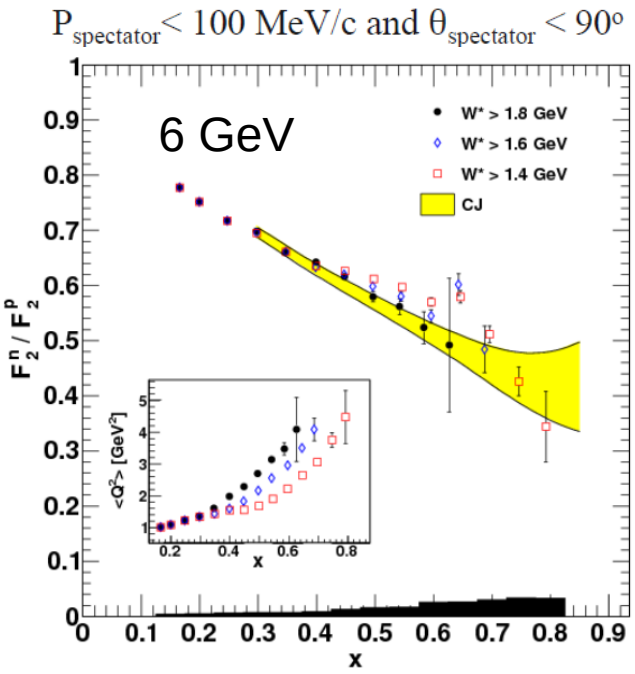
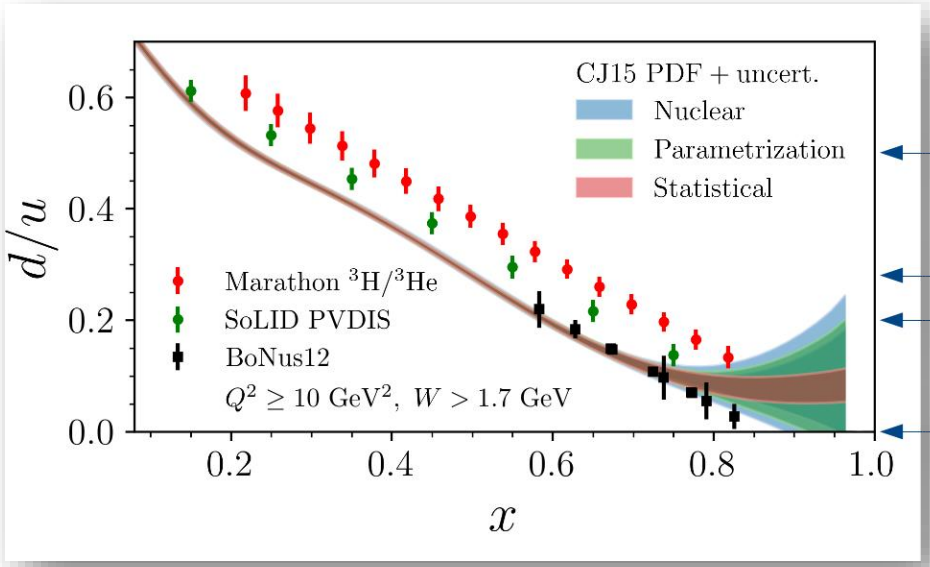
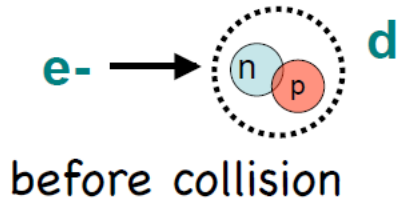
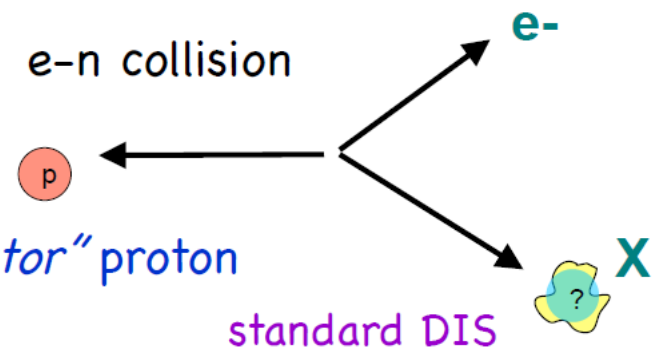
HALL B – BONUS12 EXPERIMENT EXPECTED IN 2020



Projected JLab 12 GeV *d/u* Extraction







Measure e D -> e p_S X

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Exploring the 3D Nucleon Structure

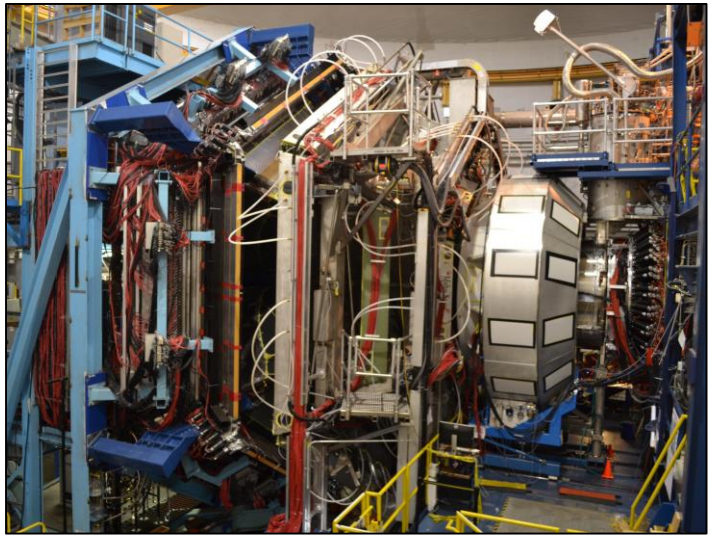
- After decades of study of the partonic structure of the nucleon we finally have the experimental and theoretical tools to systematically move beyond a 1D momentum fraction (x_{Bj}) picture of the nucleon.
    - High luminosity, large acceptance experiments with polarized beams and targets.
    - Theoretical description of the nucleon in terms of a 5D Wigner distribution that can be used to encode both 3D momentum and transverse spatial distributions.

- **Deep Exclusive Scattering (DES)** cross sections give sensitivity to electron-quark scattering off quarks with longitudinal momentum fraction (Bjorken) x at a transverse location b.

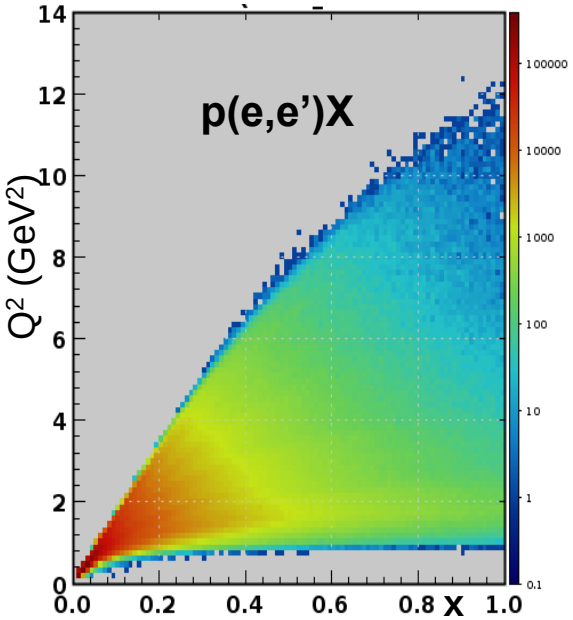
- **Semi-Inclusive Deep Inelastic Scattering (SIDIS)** cross sections depend on transverse momentum of hadron, $P_{h\perp}$, but this arises from both intrinsic transverse momentum (k_T) of a parton and transverse momentum (p_T) created during the [parton → hadron] fragmentation process.

Nuclear Femtography

HALL B – CLAS12: TOWARD HIGH IMPACT SCIENCE

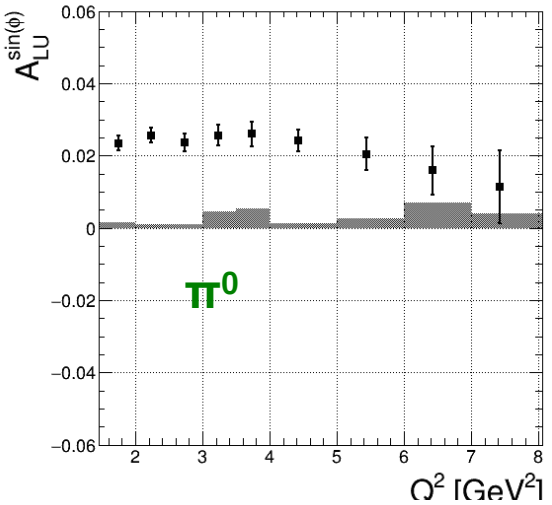


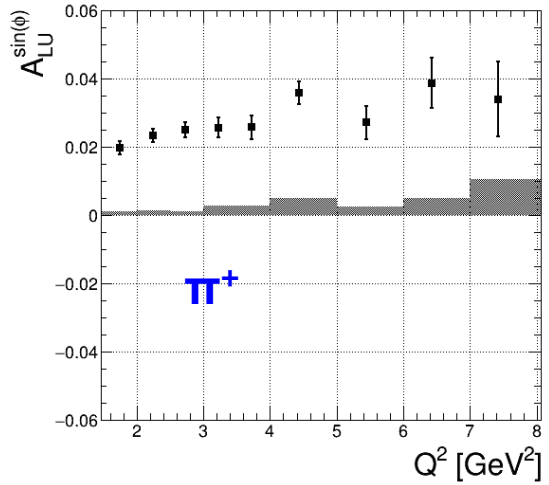
Kinematic reach at 10.6 GeV



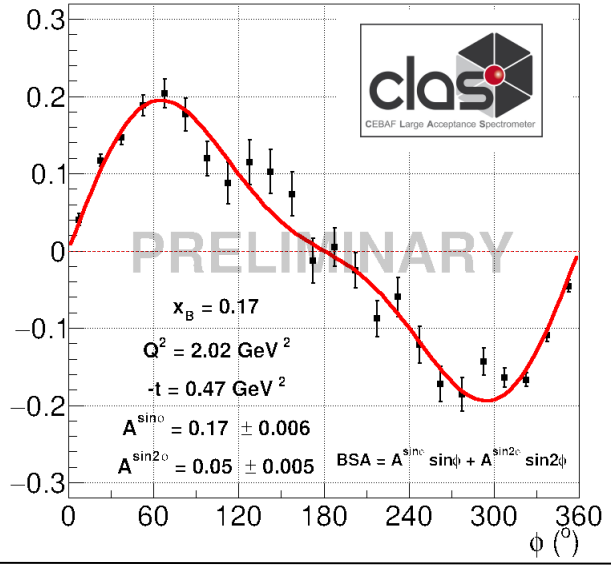
p(e,e'π)X

Beam-spin asymmetry

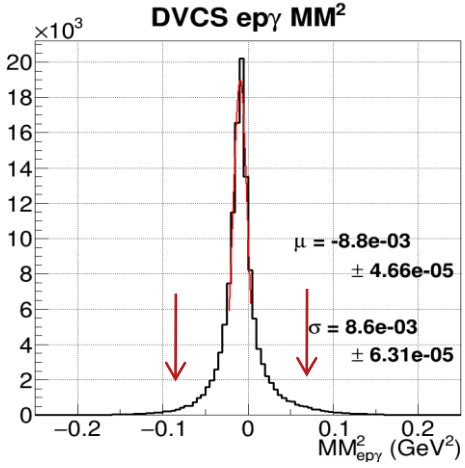




DVCS raw BSA



DVCS epγ MM^2



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OVERALL GOAL OF JEFFERSON LAB SIDIS PROGRAM

validate basic reaction mechanism of SIDIS at JLab energies

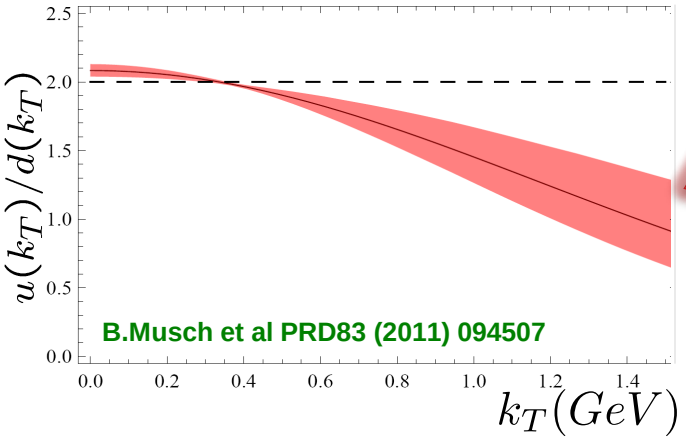
and then

spin and flavor dependence of quark transverse momentum distributions

There are indications from both theory (lattice, chiral constituent quark model) and experimental data of different k_T dependences of quark flavor distributions

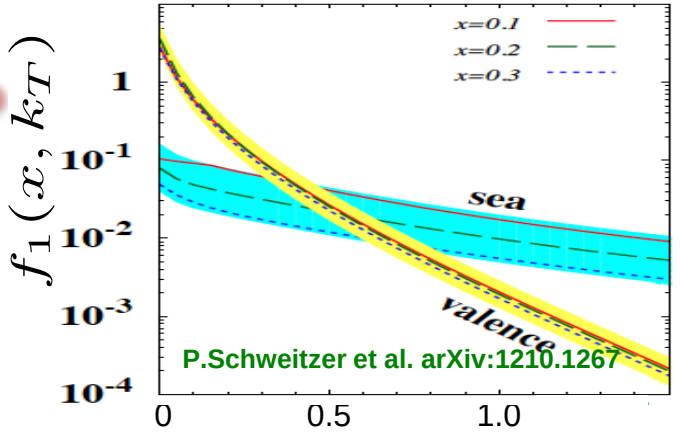
Hall C SIDIS program concentrates on the validation and the transverse momentum dependence of unpolarized SIDIS cross sections

PROBING THE FLAVOR-DEPENDENCE OF K_T-DISTRIBUTIONS



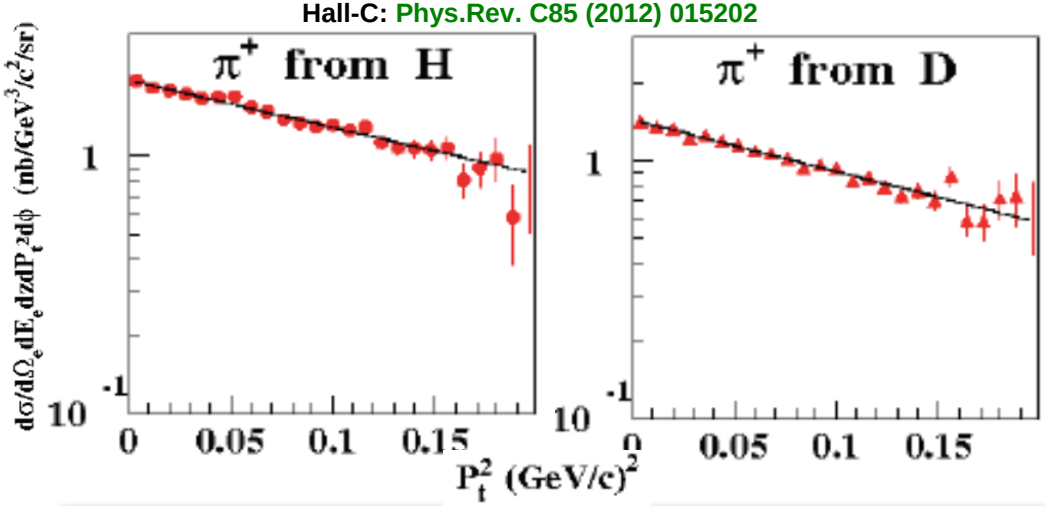
Higher probability to find more sea & d-quarks at **large k_T**

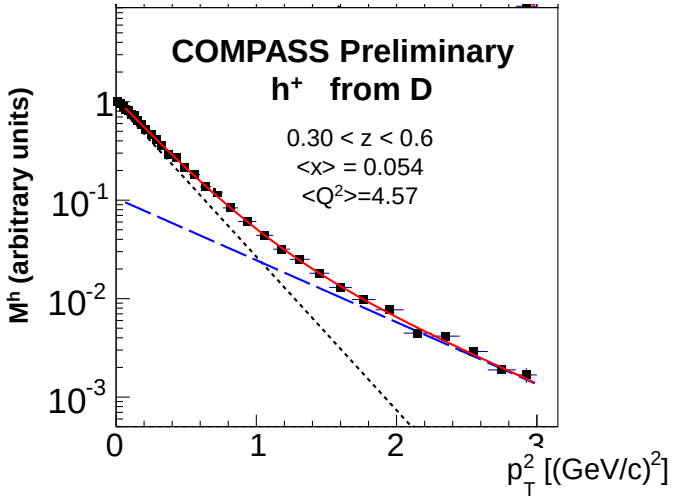
Measurements of hadronic multiplicities provide a crucial input for studies of **k_T** dependence of spin independent distributions



HERMES, PRD 87 (2013) 074029
COMPASS, EPJC 73 (2013) 2531

Hall-C: Phys.Rev. C85 (2012) 015202





There are indications from both theory (lattice, chiral constituent quark model) and experimental data of the k_T dependence of quark flavor distribution.

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Hall C SIDIS Program – basic (e,e'π) cross sections
(and (e,e'K))

Why need for (e,e'π) cross sections?

PAC37 Report: "the **cross sections** are **such basic tests of the understanding of SIDIS** at 11 GeV kinematics that they will play a **critical role** in establishing the entire SIDIS program of studying the partonic structure of the nucleon. In particular they complement the CLAS12 measurements in areas where the precision of spectrometer experiments is essential, being able to separate P_T and ϕ-dependence for small P_T."

$$\sigma = \sum_q e_q^2 f(x) \otimes D(z)$$

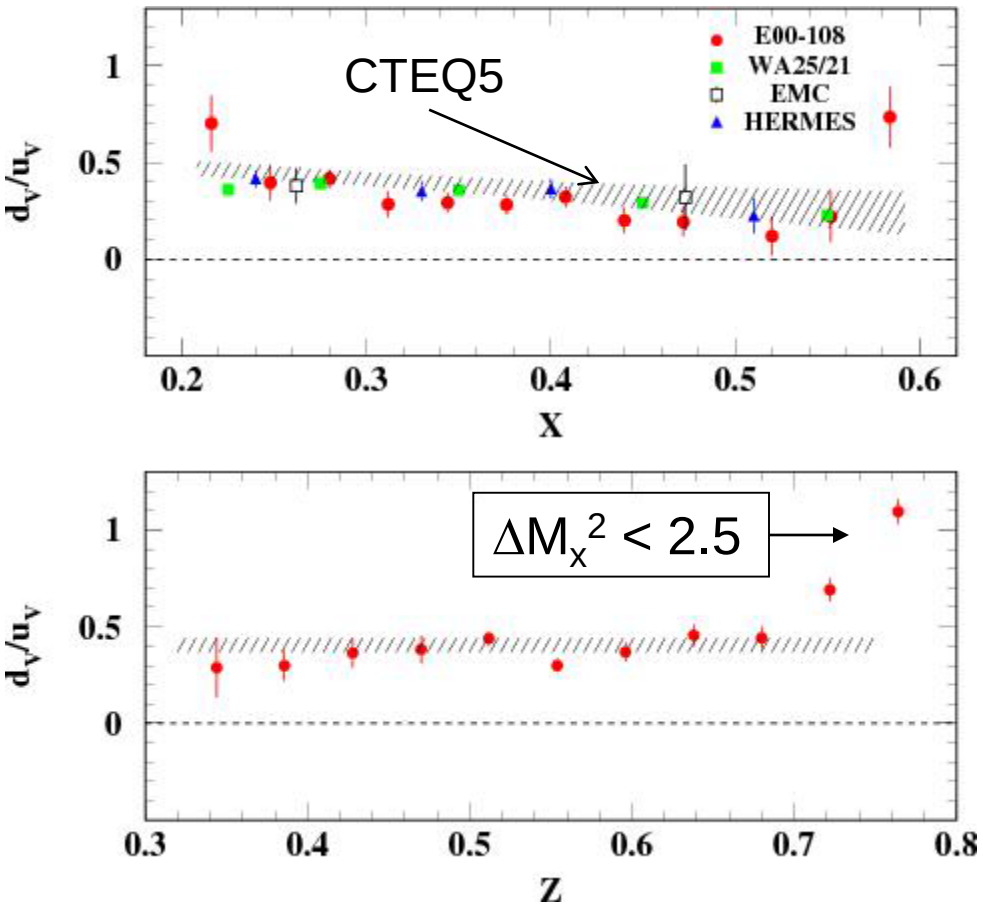
Basic precision cross section measurements:

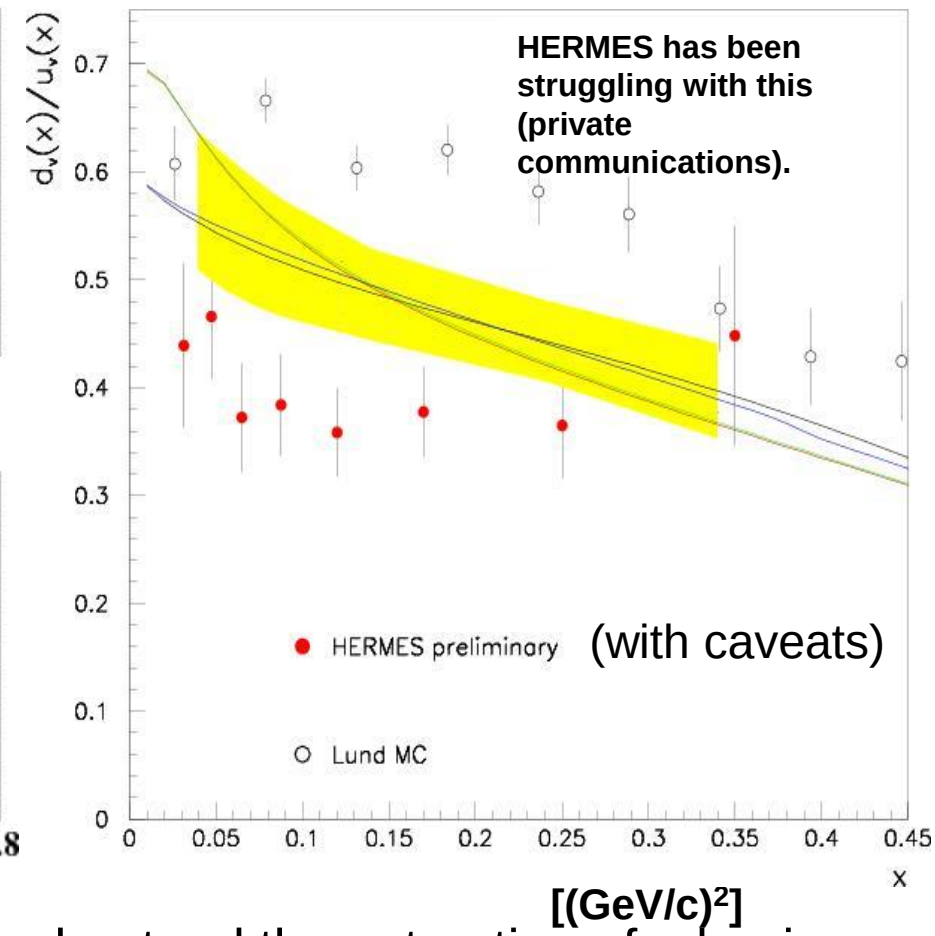
- Crucial information to validate theoretical understanding
  - Convolution framework requires validation for most future SIDIS experiments and their interpretation
  - Can constrain Q^2 dependence & TMD evolution
  - Questions on target-mass corrections and ln(1-z) re-summations require precision large-z data

Goal: Measure the basic SIDIS cross sections of **π^+, π^-, π^0 (and K^+)** production off the proton (and deuteron), including a map of the P_T dependence ($P_T \sim \Lambda < 0.5$ GeV), to validate(*) a flavor decomposition and the k_T dependence of (unpolarized) up and down quarks

(*) Can only be done using spectrometer setup capable of %-type measurements (an essential ingredient of the global SIDIS program!)

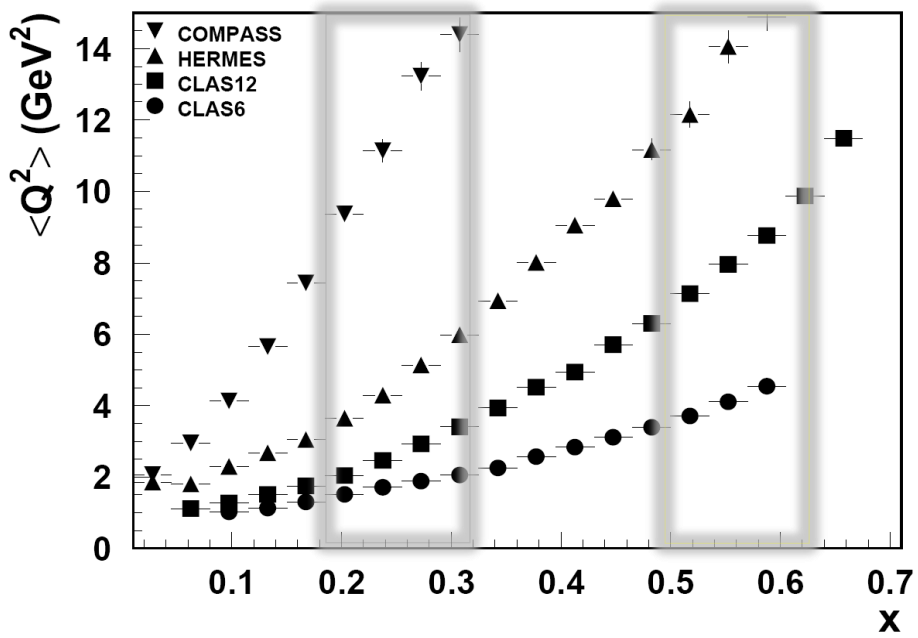
Example - The Problem Child: d_v/u_v

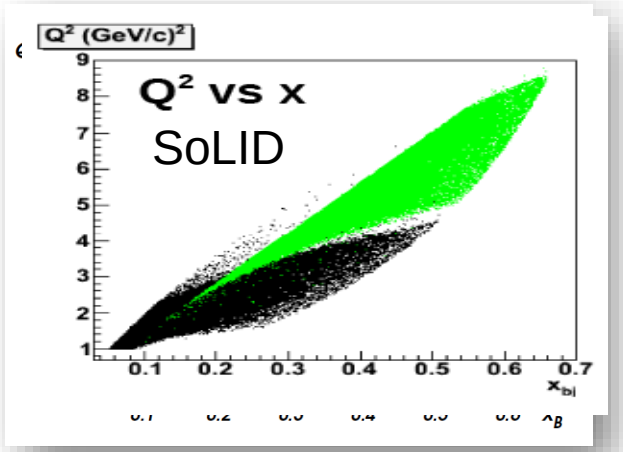




As long as we do not quantitatively understand the extraction of a basic and known quantity like d_v/u_v (at intermediate x) from SIDIS data, we should question the SIDIS analysis, and leave no stone unturned to reach final quantitative understanding.

Need precision over range in Q^2 @ fixed x

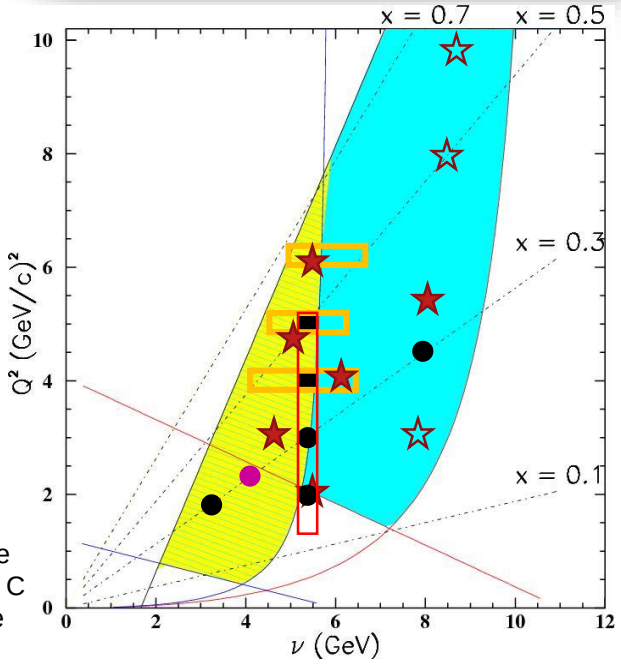




$$\frac{d\sigma(ep \to e' hX)}{dxdy\ dzdP_{h\perp}} \propto \sum_q e_q^2 C\left[q(x,k_T) D_q^h(z,p_T)\right]$$

Still many complications:

- Description valid? At what energies?
- TMD evolution
- Target-Mass effects
- ln(1-z) resummation



Symbols and rectangles indicate the kinematics of approved Hall C experiments within the available phase space

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Hall C SIDIS Program (typ. x/Q^2 ~ constant)

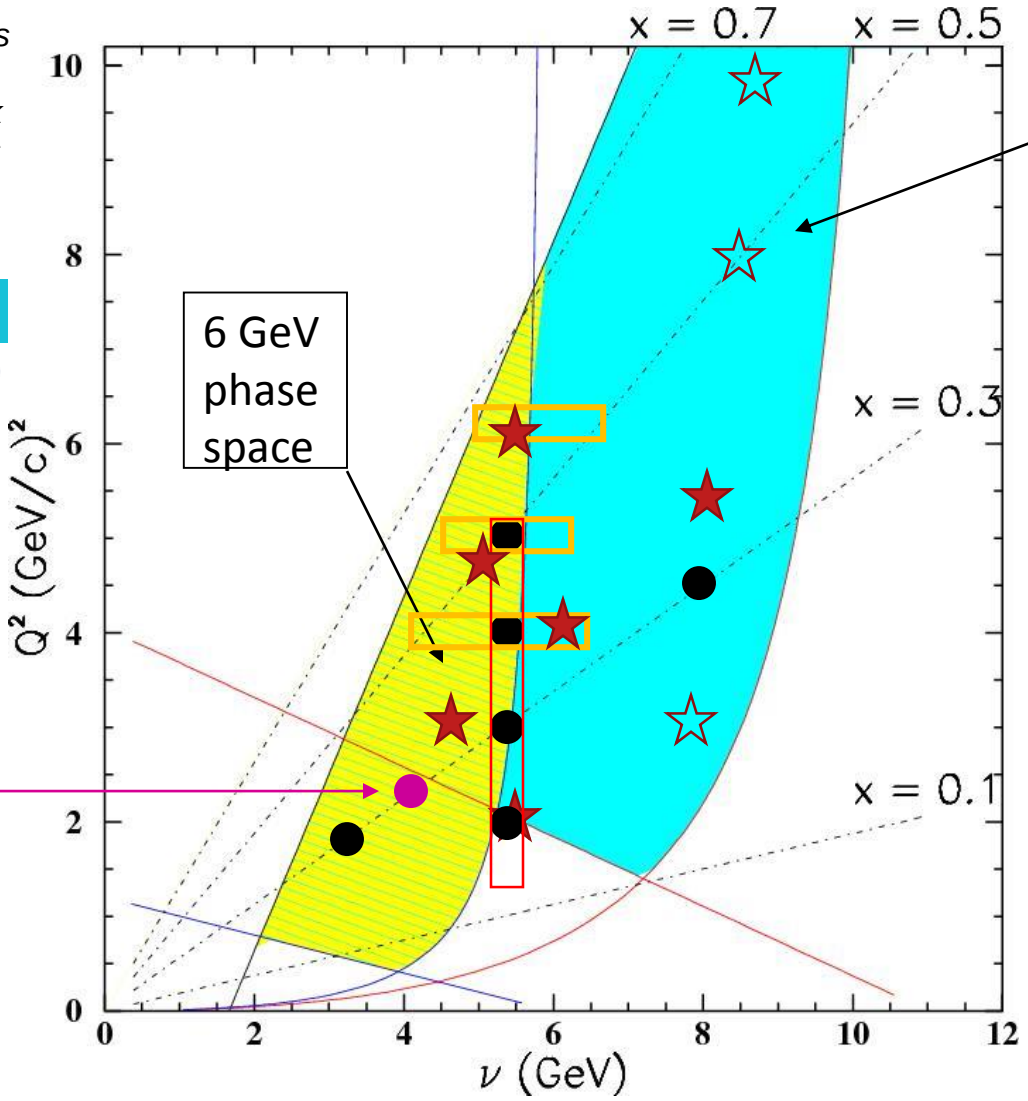
HMS + SHMS (or NPS) Accessible Phase Space for SIDIS; w. typical z range 0.3-0.65

Accurate cross sections for validation of SIDIS factorization framework and for L/T separations

E12-13-007
Neutral pions:
Scan in (x,z,P_T)
Overlap with E12-09-017 & E12-09-002

Parasitic with E12-13-010

E00-108 (6 GeV)



Charged pions:

E12-06-104
L/T scan in (z,P_T)
No scan in Q^2 at fixed x: $R_{DIS}(Q^2)$ known

E12-09-017
Scan in (x,z,P_T)
+ scan in Q^2 at fixed x

E12-09-002
+ scans in z

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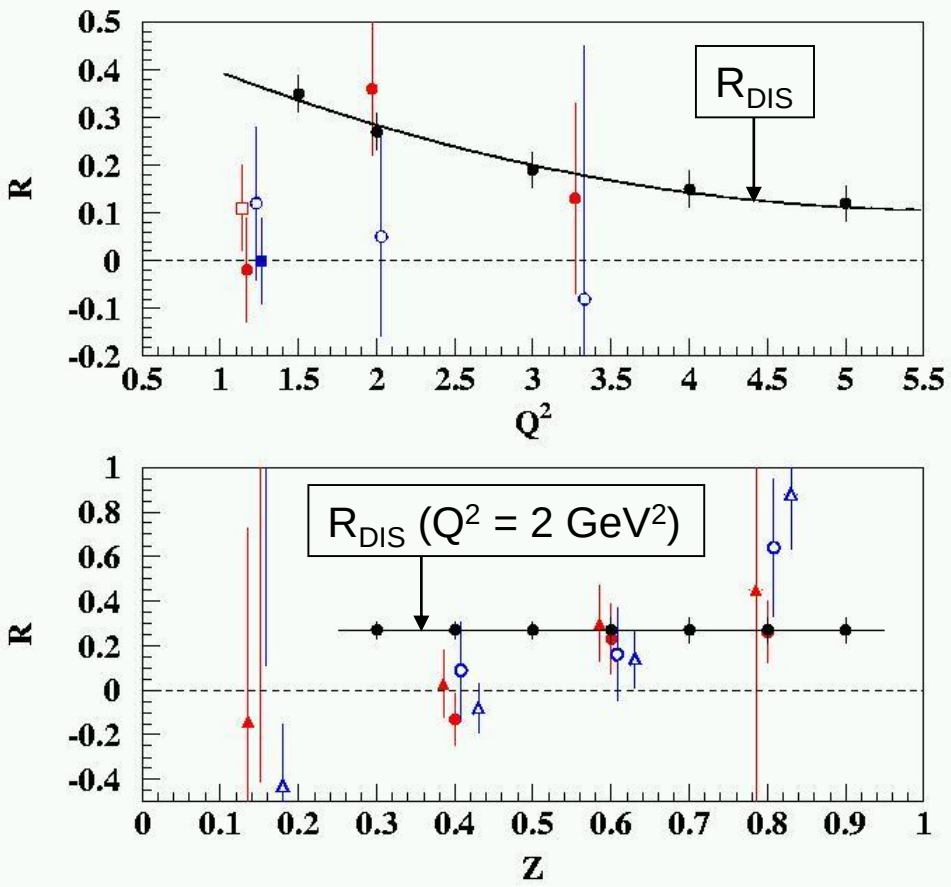
LONGITUDINAL CROSS SECTION: $R = \sigma_L/\sigma_T$ IN SIDIS

- R_{DIS} is in the naïve parton model related to the parton's transverse momentum:
  $R = 4(M^2x^2 + \langle k_T^2 \rangle)/(Q^2 + 2\langle k_T^2 \rangle)$.
- $R_{DIS} \rightarrow 0$ at $Q^2 \rightarrow \infty$ is a consequence of scattering from free spin-½ constituents



Cornell 70's existing (H and D, π^+ and π^-)
JLab 12-GeV projected (H and D, π^+ and π^-)

- Knowledge on R_{SIDIS} is non-existing
- R_{SIDIS} may (will!) vary with z, and with p_T
  (JLab E12-06-104 will scan versus p_T too)
- Knowledge on R_{SIDIS} needed for any TMD-related asymmetry
- Even if one can relate R_{SIDIS} to a flavor-dependent average transverse momentum in a naïve parton model, R_{SIDIS} can not easily be integrated in a global TMD analysis as it is sensitive to gluon and HT effects.

Features of 3D Distributions/TMDs

$$f^a(x, k_T^2; Q^2)$$

Ex. TMD PDF for a given combination of parton and nucleon spins

$$\sigma = \sum_q e_q^2 f(x) \otimes D(z)$$

$$f^a(x, k_T^2; Q^2)$$

nucleon polarization \ quark polarization	U	L	T
U	f_1		$h_1^\perp$ Boer-Mulders
L		g_1 helicity	$h_{1L}^\perp$ worm-gear
T	$f_{1T}^\perp$ Sivers	g_{1T} worm-gear	h_1 transversity, $h_{1T}^\perp$ pretzelosity

- transverse position and momentum of partons are correlated with the spin orientations of the parent hadron and the spin of the parton itself
- transverse position and momentum of partons depend on their flavor
- transverse position and momentum of partons are correlated with their longitudinal momentum
- spin and momentum of struck quarks are correlated with remnant
- quark-gluon interaction play a crucial role in kinematical distributions of final state hadrons, both in semi-inclusive and exclusive processes

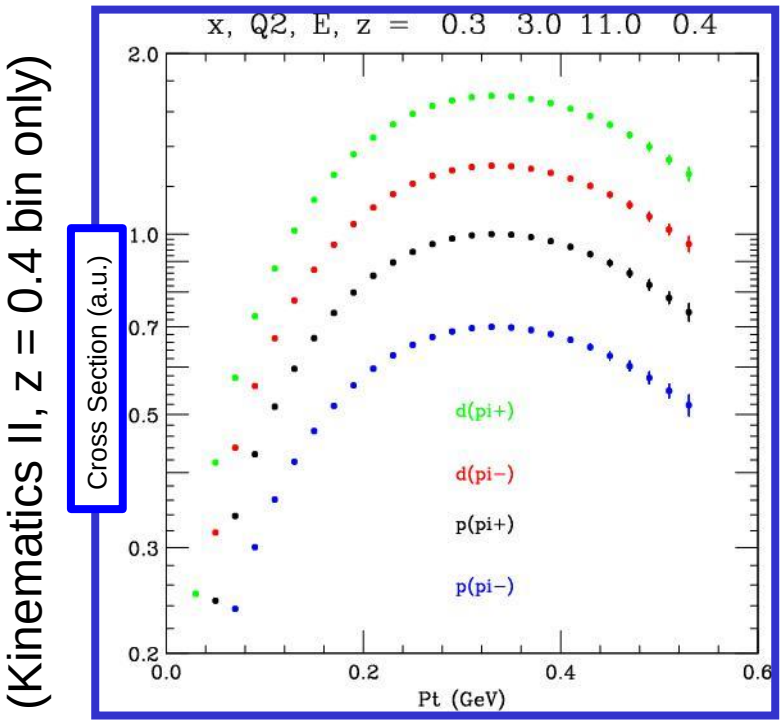
Hall C SIDIS Program – basic (e,e'π) cross sections

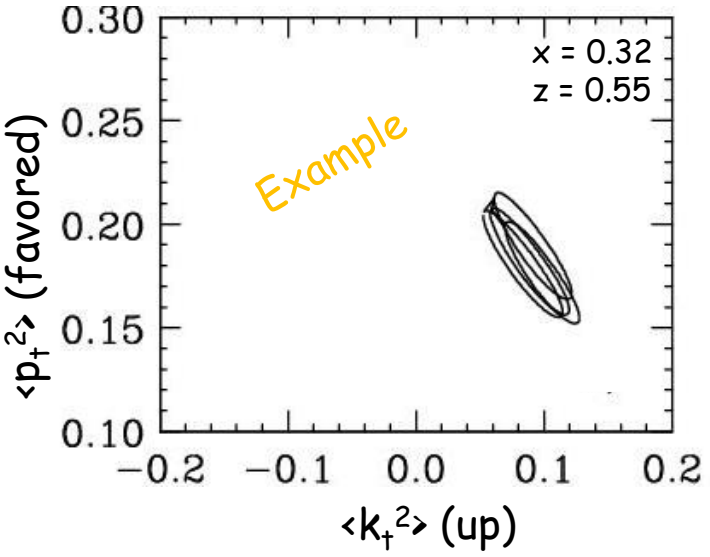
Goal: Measure the basic SIDIS cross sections of π^+, π^-, π^0 **(and K^+)** production off the proton (and deuteron), including a map of the P_T dependence ($P_T \sim \Lambda < 0.5$ GeV), to validate(*) a flavor decomposition and the k_T dependence of (unpolarized) up and down quarks

$$\sigma = \sum_q e_q^2 f(x) \otimes D(z)$$

(*) Can only be done using spectrometer setup capable of %-type measurements (an essential ingredient of the global SIDIS program!)

$\pi^{+/-}$





Basic precision cross section measurements:

- Crucial information to validate theoretical understanding
  - Convolution framework requires validation for most future SIDIS experiments and their interpretation
  - Can constrain Q^2 dependence & TMD evolution
  - Questions on target-mass corrections and ln(1-z) re-summations require precision large-z data

π^0 with Neutral-Particle Spectrometer (NPS)

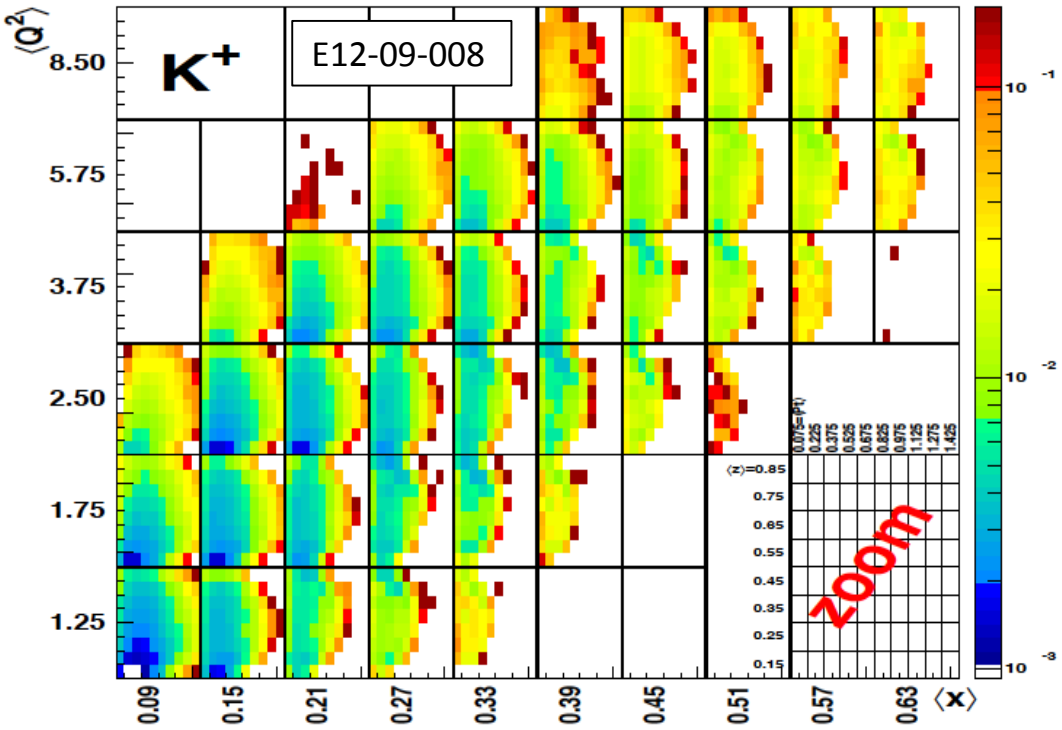
SIDIS π/K on unpolarized protons/deuterons

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

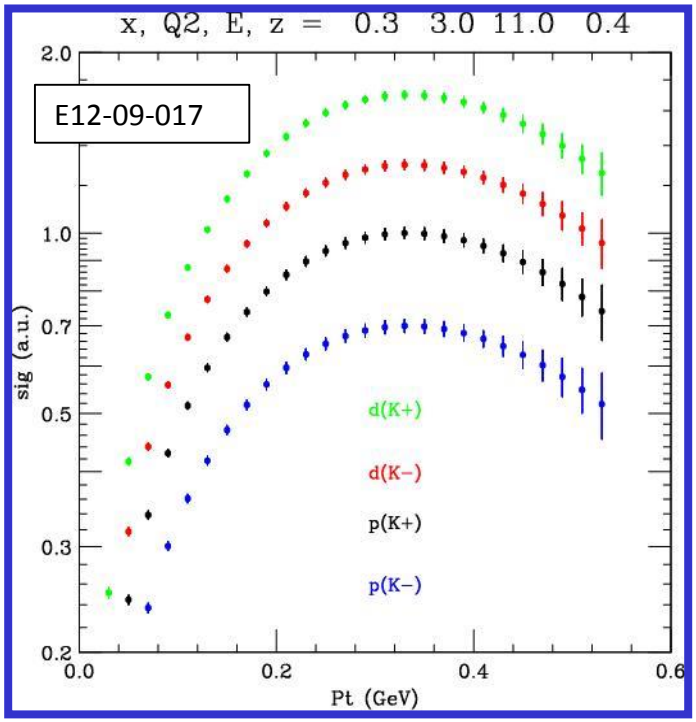
E12-06-112

$$\frac{d\sigma}{dx_B\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\left\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}\right\},$$

Kaons



(CLAS12)



(Hall C, Kinematics II, z = 0.4 bin only)

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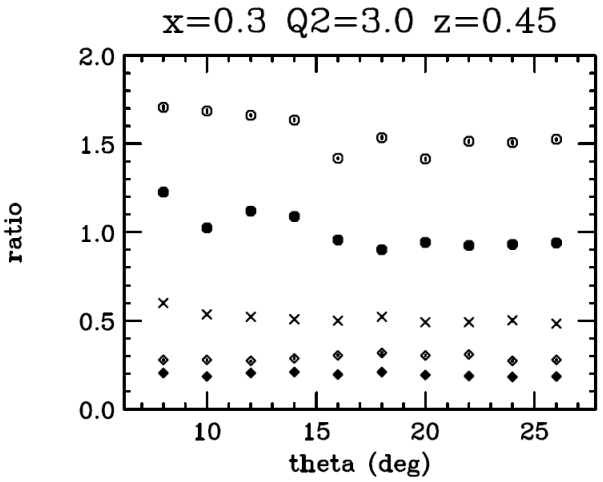
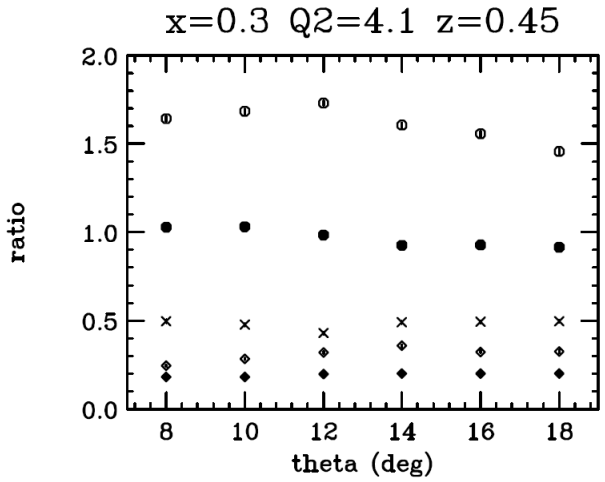
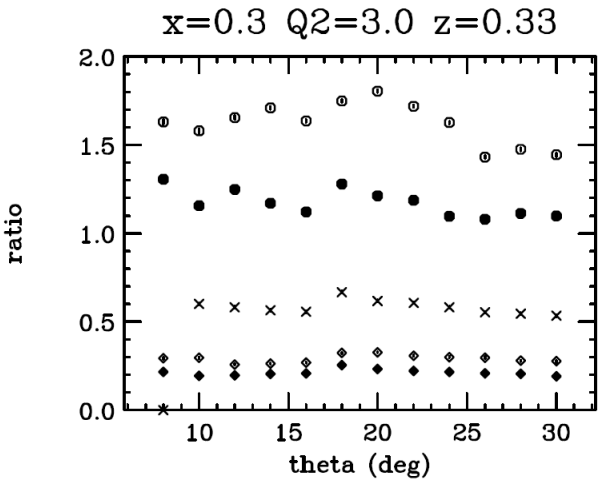
E12-09-017 Quasi-Online Results – Pions

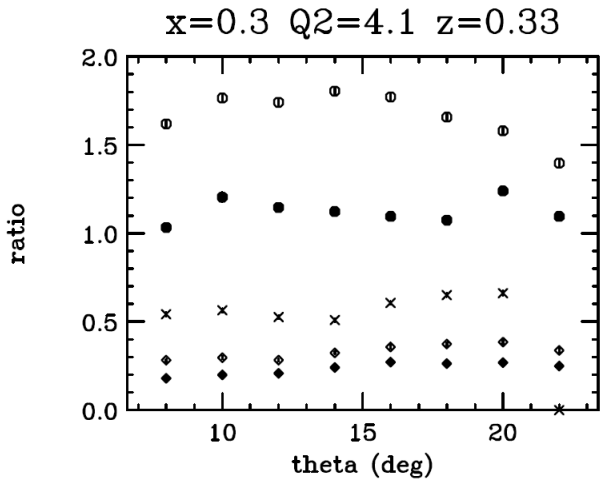
not normalized by target density: just ratios of counts/mC corrected for computer dead time.





Ratio to pi+ from LH2 of
pi+ from LD2 (open circles)
pi+ from Al (open diamonds)
pi- from LH2 (crosses)
pi- from LD2 (filled circles)
pi- from Al (filled diamonds)





Anashe Bandari
& Peter Bosted

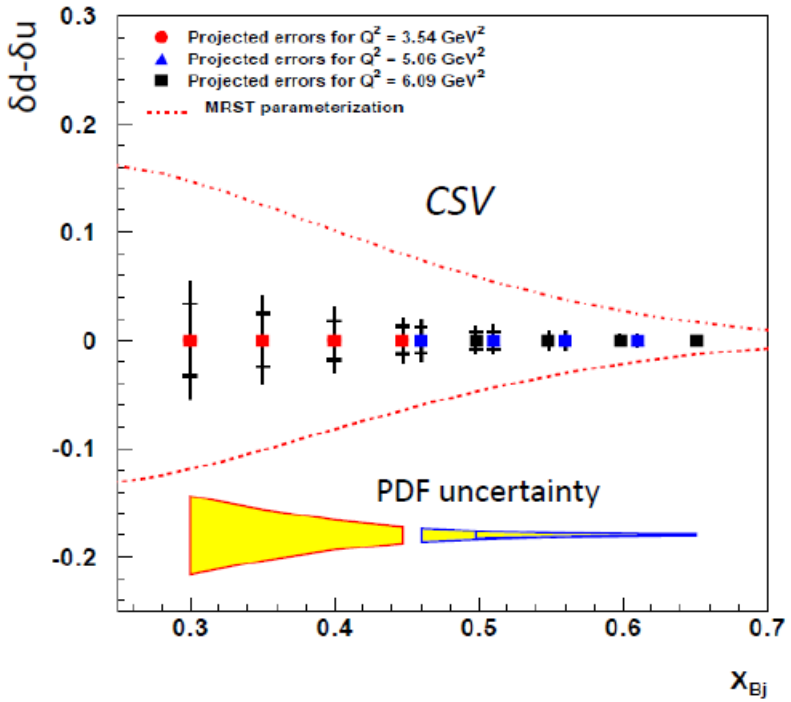
Jefferson Lab

HALL C E12-09-002: THE HUNT FOR CSV

- Charge symmetry (CS) is an approximate symmetry in the nuclear world, respected to better than 1%: $M_p \approx M_n$, energy levels in mirror nuclei (after Coulomb corrections), …
- At the quark level CS implies $u^p(x,Q^2) = d^n(x,Q^2)$, $d^p(x,Q^2) = u^n(x,Q^2)$. *This is widely assumed but never thoroughly checked by experiment!*
- In QCD charge symmetry violation (CSV) originates from EM interactions (small at high energies) and $\delta m = m_d - m_u$.
- Naively, CSV ~ $(m_d - m_u)/\langle M \rangle$, where $\langle M \rangle$ ~ 0.5 – 1 GeV from the strong Hamiltonian → one expects an ~1% effect

$$R^D_{meas} = \frac{4Y^{D\pi-}(x,z) - Y^{D\pi+}(x,z)}{Y^{D\pi+}(x,z) - Y^{D\pi-}(x,z)}$$

Experiment aims, assuming a thorough understanding of the SIDIS reaction mechanism is validated, to extract CSV info from the charged-pion yield ratio on a D target.



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Hall C SIDIS Program – basic (e,e'π) cross sections

(Hall C's basic SIDIS cross section data at a 6-GeV JLab showed agreement with partonic expectations laying the foundation for a vigorous 12-GeV SIDIS program. PRL 98 (2007) 022001; PL B665 (2008) 20; PRC 85 (2012) 015202. At a 12-GeV JLab, Hall C's role will be again to provide basis SIDIS cross sections, furthering our understanding.)

Low-energy (x,z) factorization, or possible ca… *quark distribution and fragmentation f…* must be well validated to subst… output.
Many questions remain… .2-1) and low-intermediate Q^2 (…

Neutral Particle Spectrometer (NPS) under construction with NSF/MRI grant support and DOE capital equipment (CUA, ODU, Ohio, Orsay, Glasgow, Yerevan, JLab, …)

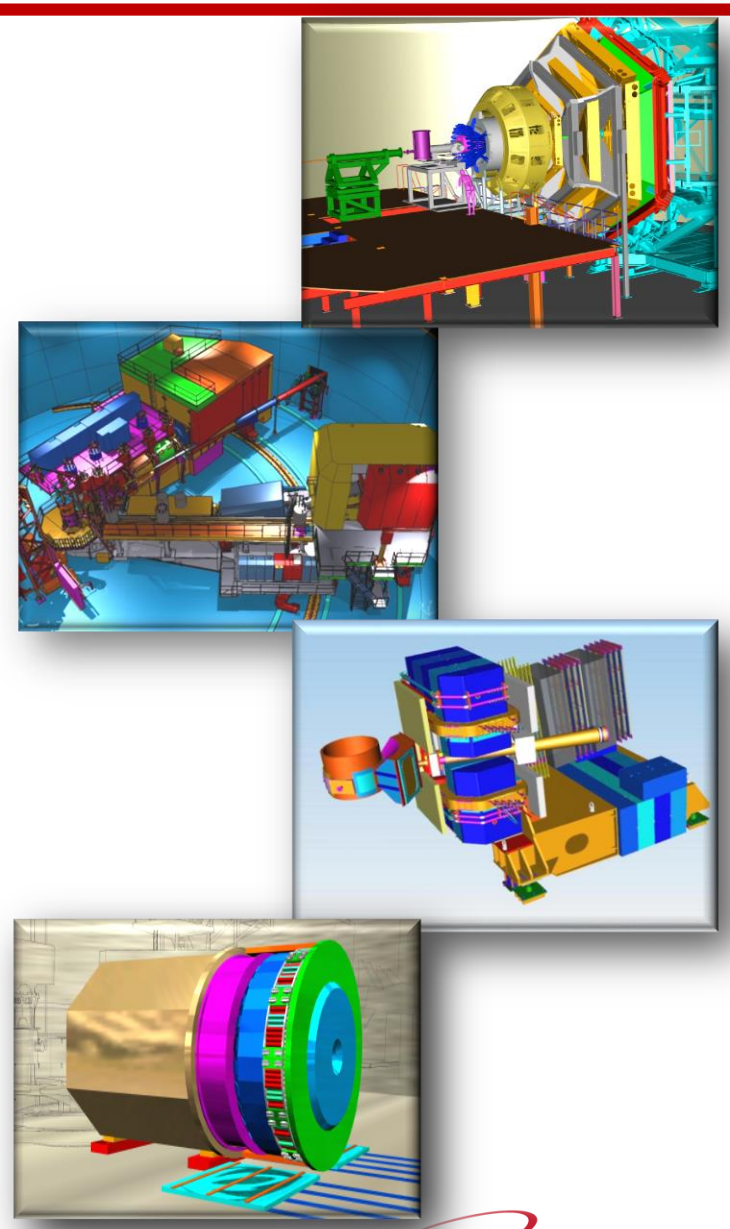
W… π^0) beyond (e,e'$\pi^{+/-}$)?

(e… …ntal advantages:
- ☺ …active ρ contributions
- ☺ no exclusive pole contributions
- ☺ reduced resonance contributions
- ☺ proportional to average D

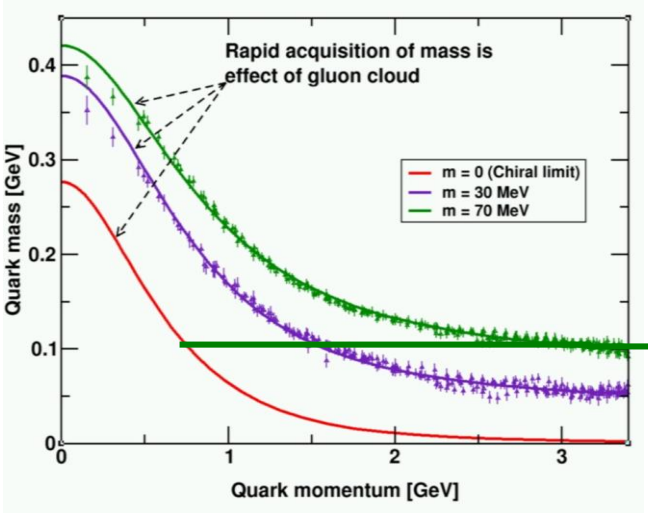
Further advantages:
- Can verify: $\sigma^{\pi^0}(x,z) = \frac{1}{2}(\sigma^{\pi^+}(x,z) + \sigma^{\pi^-}(x,z))$
- Confirms understanding of flavor decomposition & of k_T dependence

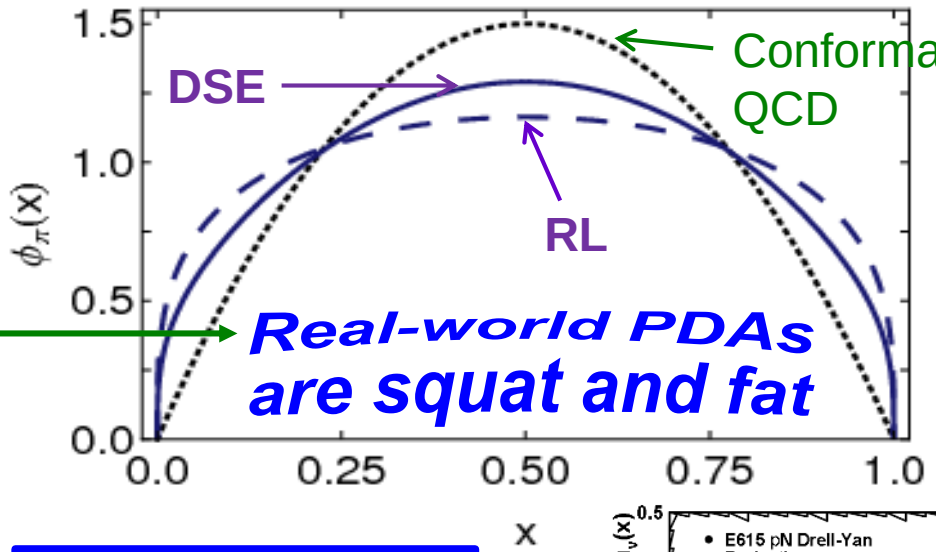
Together Stronger: SIDIS/TMD with 12 GeV

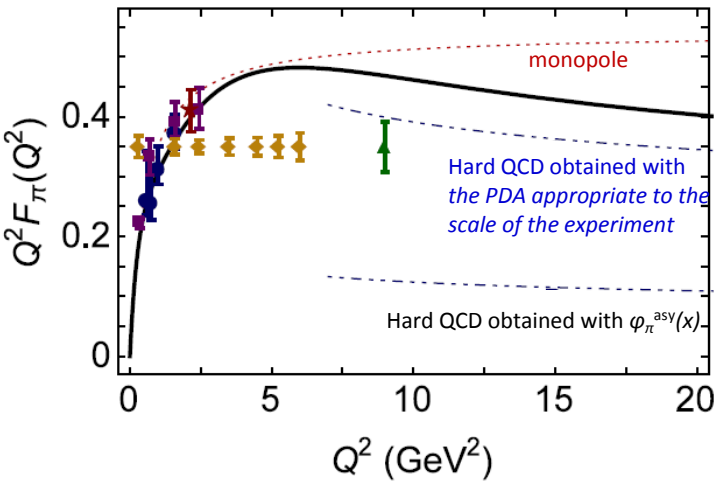
- CEBAF Large Acceptance Spectrometer (CLAS12) in Hall B: general survey experiments, large acceptance and medium luminosity
- SHMS, High Momentum Spectrometer (HMS) and Neutral-Particle Spectrometer (NPS) in Hall C: precision cross sections for L-T studies and ratios, small acceptance and high luminosity
- Super Bigbite Spectrometer (SBS) in Hall A : dedicated large-x TMD study, medium acceptance and high luminosity
- Future: Solenoidal Large Intensity Device (SoLID) in Hall A: multi-dimensional mapping, large acceptance and high luminosity



PION FORM FACTOR AND STRUCTURE FUNCTION @ 12 GEV





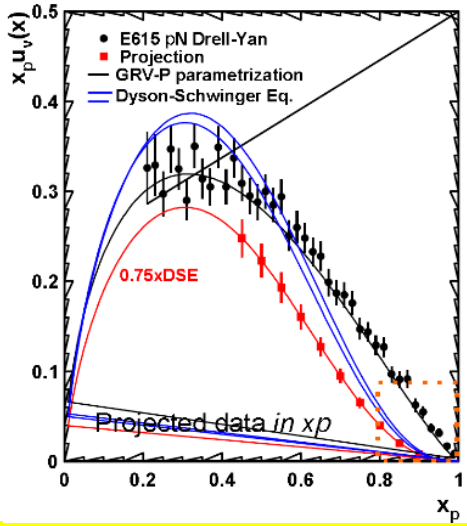


Pion FF – first quantitative access to hard scattering scaling regime?

Implications if so: two longstanding puzzles could be solved

1. Magnitude of pion form factor in hard scaling regime
2. Power of pion parton behavior at large x

Also implications for nucleon and N form factor interpretation (not shown here).*



Pion SF – $(1-x)^1$ or $(1-x)^2$ dependence at large x?

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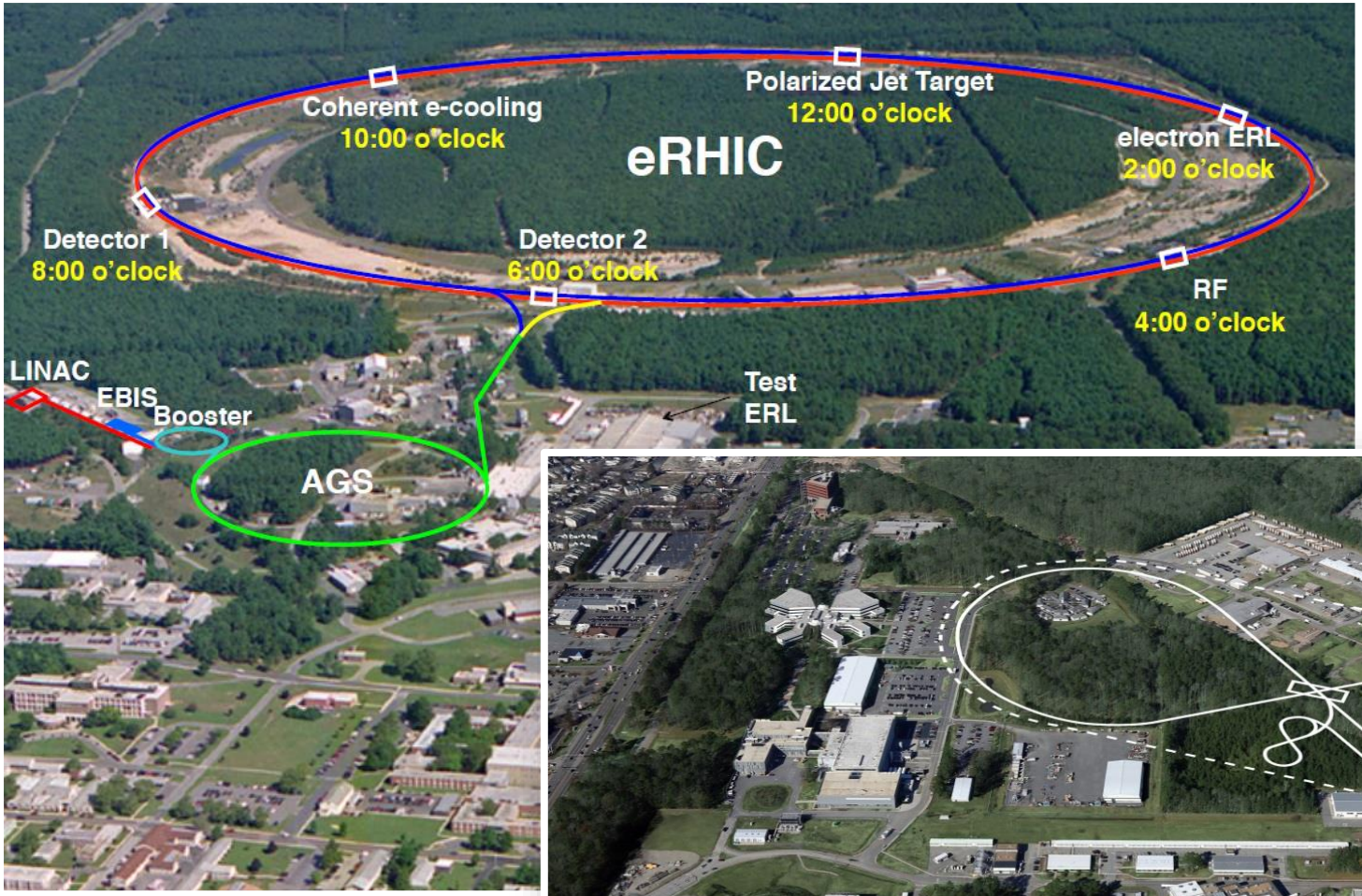
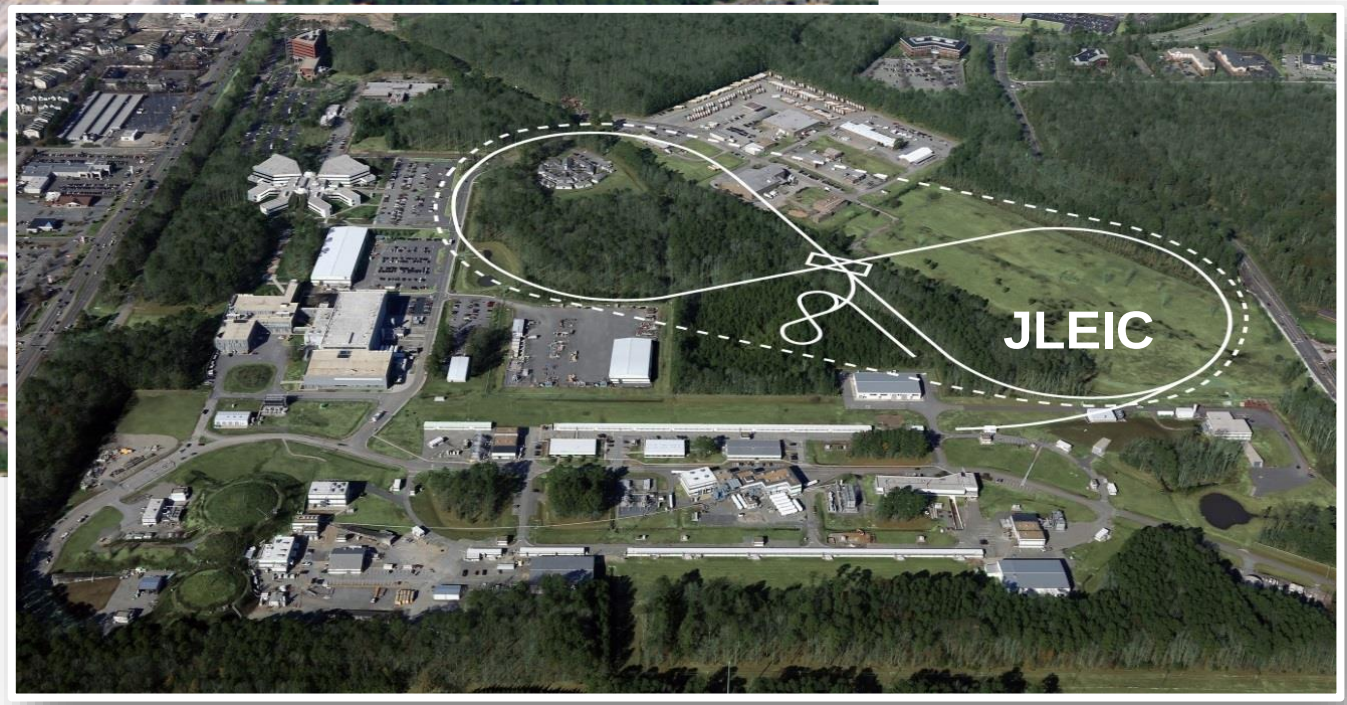
US-BASED EIC PROPOSALS

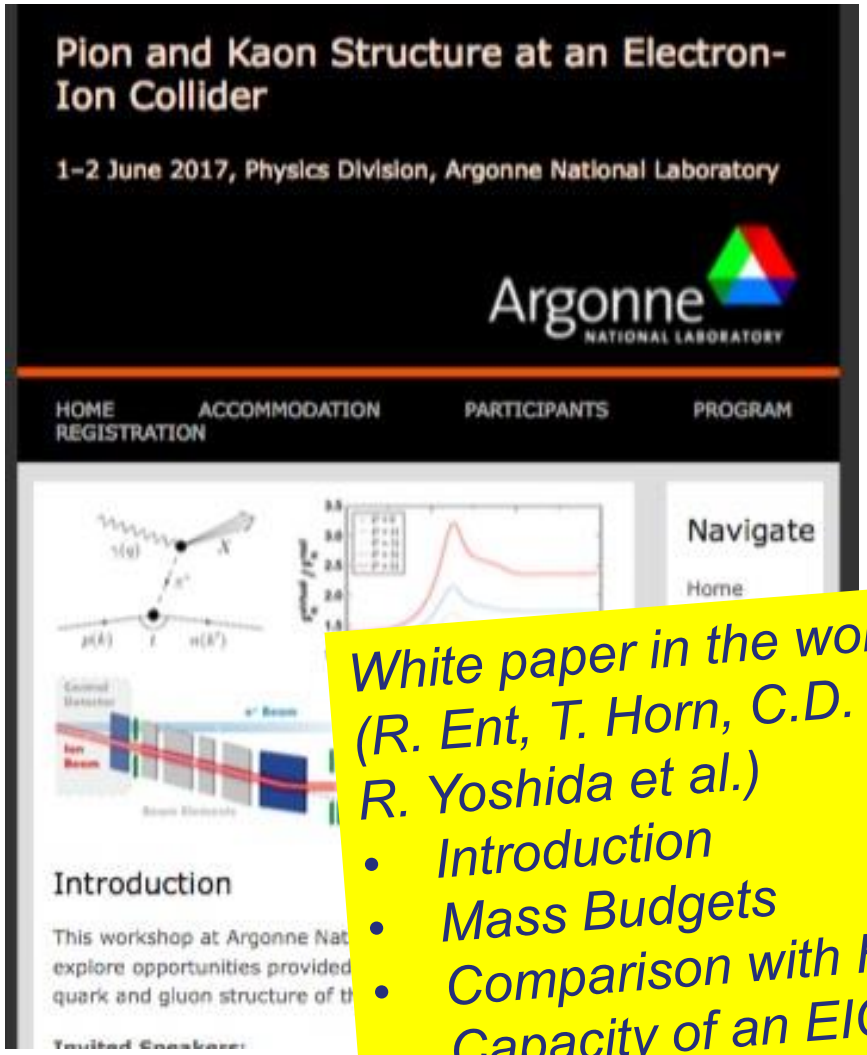


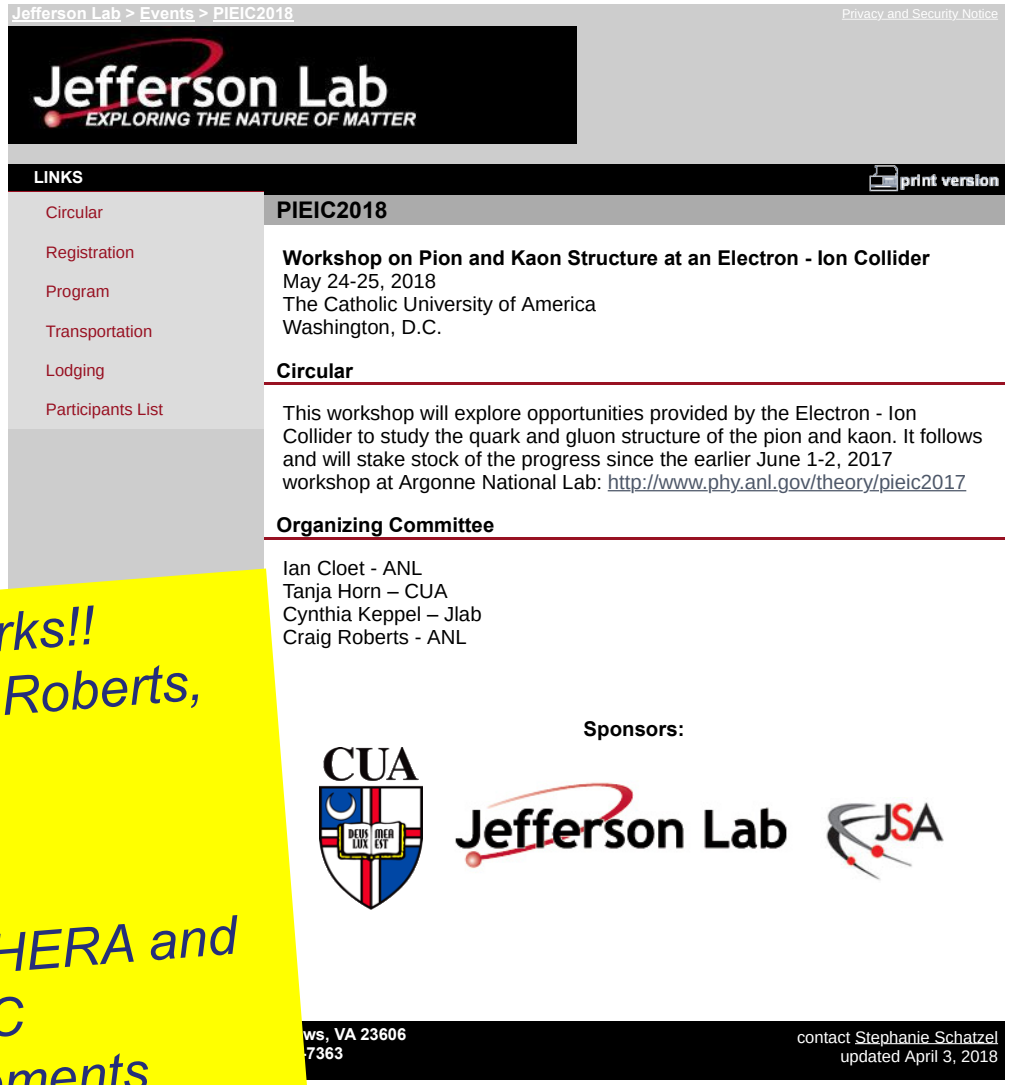
Brookhaven Lab
Long Island, NY



Jefferson Lab
Newport News, VA

PION AND KAON STRUCTURE AT AN EIC - WHITE PAPER IN PRODUCTION





White paper in the works!!
(R. Ent, T. Horn, C.D. Roberts, R. Yoshida et al.)

- *Introduction*
- *Mass Budgets*
- *Comparison with HERA and Capacity of an EIC*
- *Key EIC Measurements*

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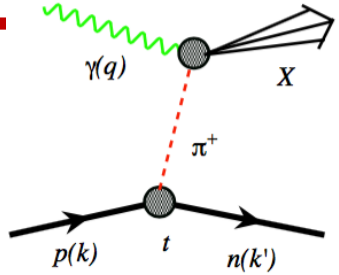
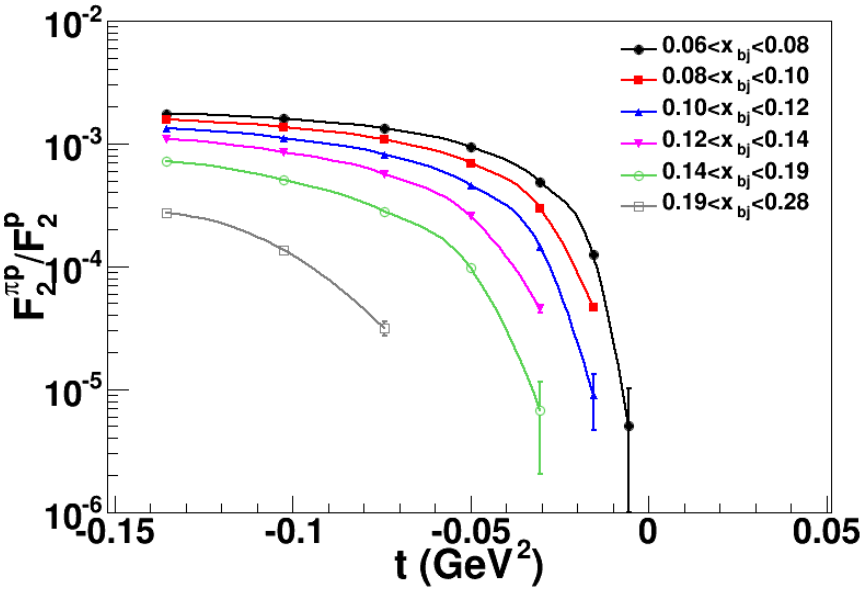
EIC – VERSATILITY AND LUMINOSITY IS KEY

Why would pion and kaon structure functions, and even measurements of pion structure beyond (pion GPDs and TMDs) be feasible at an EIC?



- $L_{EIC} = 10^{34} = 1000 \times L_{HERA}$
- Detection fraction @ EIC in general much higher than at HERA
- Fraction of proton wave function related to pion Sullivan process is roughly 10^{-3} for a small –t bin (0.02).
- Hence, pion data @ EIC should be comparable or better than the proton data @ HERA, or the 3D nucleon structure data @ COMPASS
- If we can convince ourselves we can map pion (kaon) structure for –t < 0.6 (0.9) GeV2, we gain at least a decade as compared to HERA/COMPASS.



Ratio of the F_2 structure function related to the pion Sullivan process as compared to the proton F_2 structure function in the low-t vicinity of the pion pole, as a function of Bjorken-x (for JLab kinematics)

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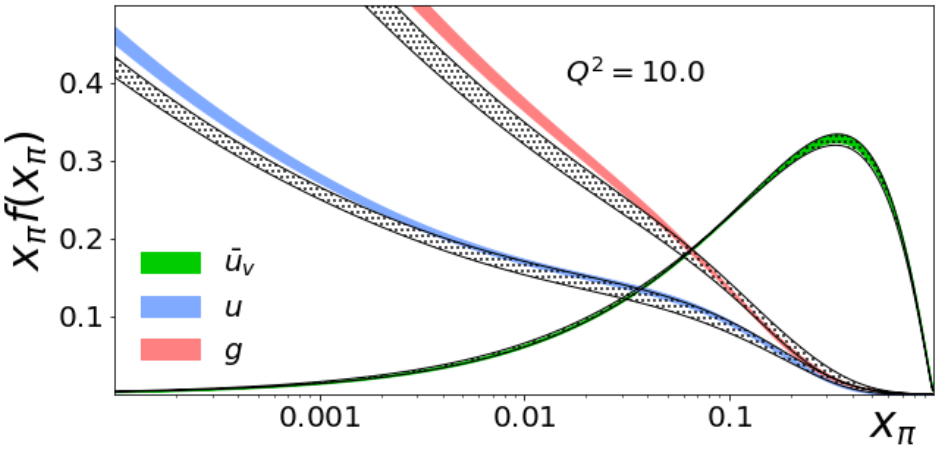
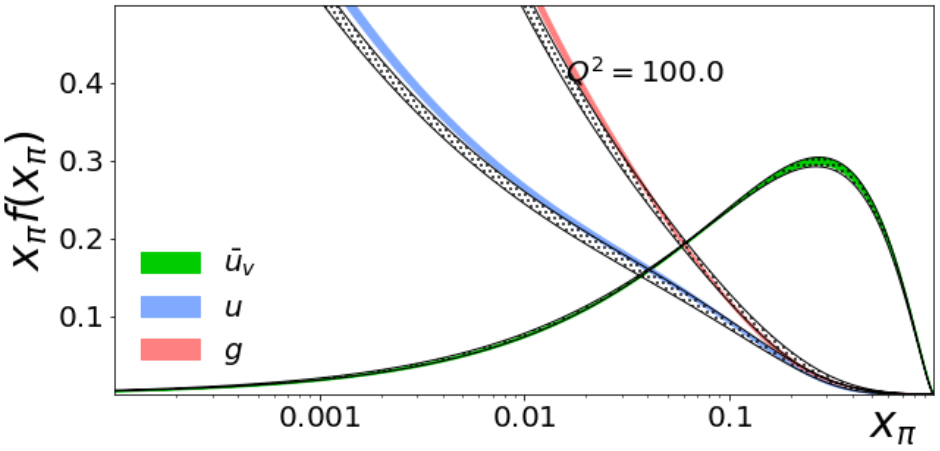
GLOBAL PION PDF FIT WITH EIC PSEUDODATA

- 5 GeV (e-) on 50 GeV (p)
- 0.1 < y < 0.8
- EIC pseudodata fitted existing data using self-serve pion PDF (N. Sato, based on work in PRL 121 (2018) 152001)
- Work ongoing:
  - Why did the curves shift?
  - The pion D-Y data, even if not many, already do constrain the curves surprisingly well – due to symmetries and sum rules?
  - Curves to improve with the EIC projections, especially for kaon as will have similar-quality data.

Precision gluon constraints of pion and kaon pdfs are possible.





T. Horn, N. Sato, R. Trotta

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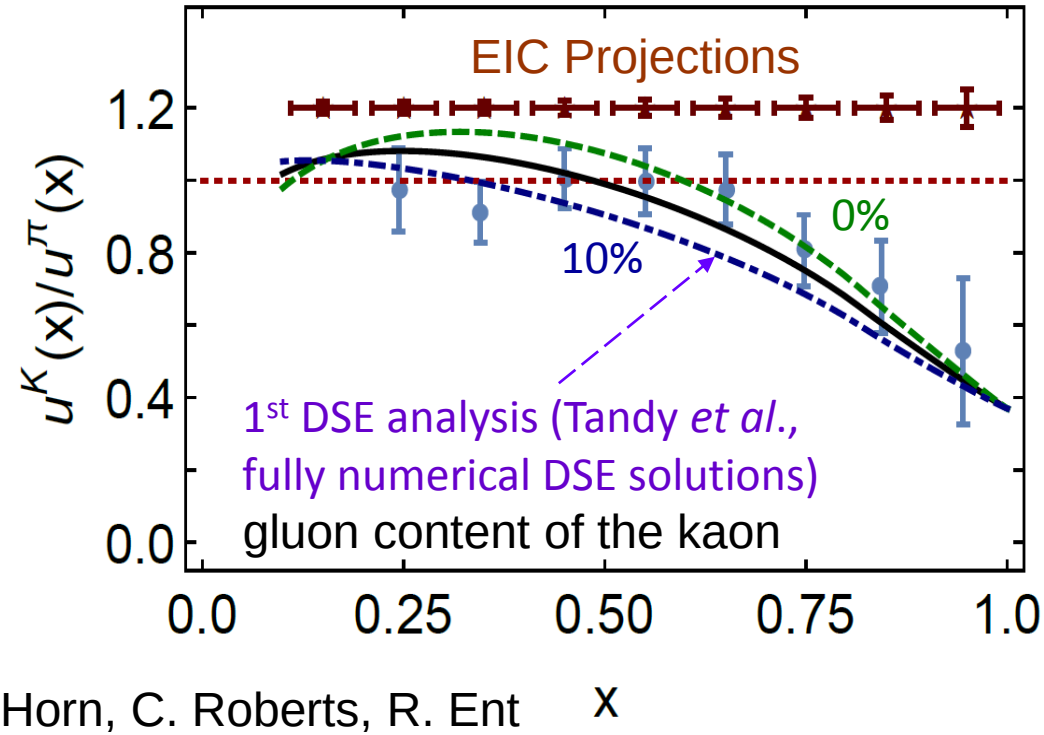
KAON STRUCTURE FUNCTIONS – GLUON PDFS

Based on Lattice QCD calculations and DSE calculations:

- Valence quarks carry some 52% of the pion's momentum at the light front, at the scale used for Lattice QCD calculations, or ~65% at the perturbative hadronic scale
- At the same scale, valence-quarks carry ⅔ of the kaon's light-front momentum, or roughly 95% at the perturbative hadronic scale



T. Horn, C. Roberts, R. Ent

Thus, at a given scale, there is far **less glue in the kaon than in the pion**:

- ❑ heavier quarks radiate less readily than lighter quarks
- ❑ heavier quarks radiate softer gluons than do lighter quarks
- ❑ Landau-Pomeranchuk effect: softer gluons have longer wavelength and multiple scatterings are suppressed by interference.
- ❑ Momentum conservation communicates these effects to the kaon's u-quark.

DETERMINING LARGE-X PARTON DISTRIBUTIONS WITH EIC

Procedure: use projected EIC data in CTEQ-Jefferson Lab "CJ" PDF Fits

So far, have used JLEIC 10x100 GeV^2 projections in bins $0.1 < x < 0.9$ for:

- ✓ F_2^p
- ✓ F_2^n from deuterium with tagged proton spectator
- • F_2^d

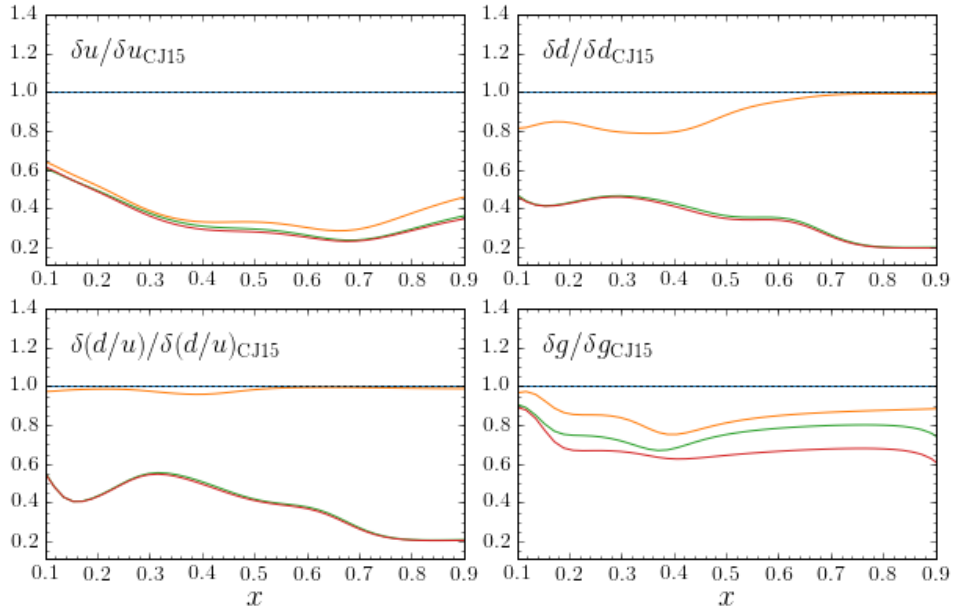
Measurements ranging to high (up to a few 1000 GeV2) will enable studies of target mass, higher twist, pert/nonpert. studies)

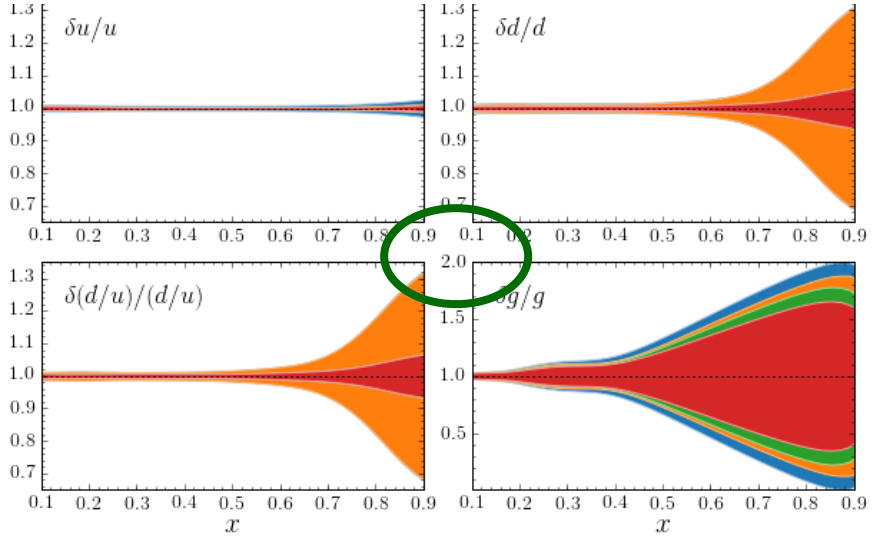
Can check on-shell extrapolation by measuring F_2^p from deuterium with tagged neutron spectator, comparing to proton target data

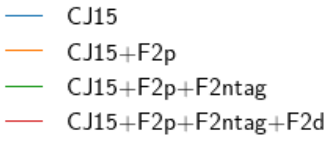
Can check nuclear corrections to F_2^d against $F_2^{n\ (tagged)}$

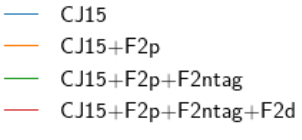
A. Accardi (Hampton), R. Ent, J. Furletova, C. Keppel, K. Park, R. Yoshida (JLab), M. Wing (UC London)

EIC E-D (WITH N_{TAG}) PROJECTION WITH 100/FB LUMINOSITY









- *d quark precision will become comparable to current u!! (becomes ~5% at x = 0.9)*
- similar improvement in g(x)
- The u quark uncertainty becomes less than ~1%; may be important for large mass BSM new particles.
- With d quark nailed by F_2^n, fitting F_2^d data will explore details of nuclear effects

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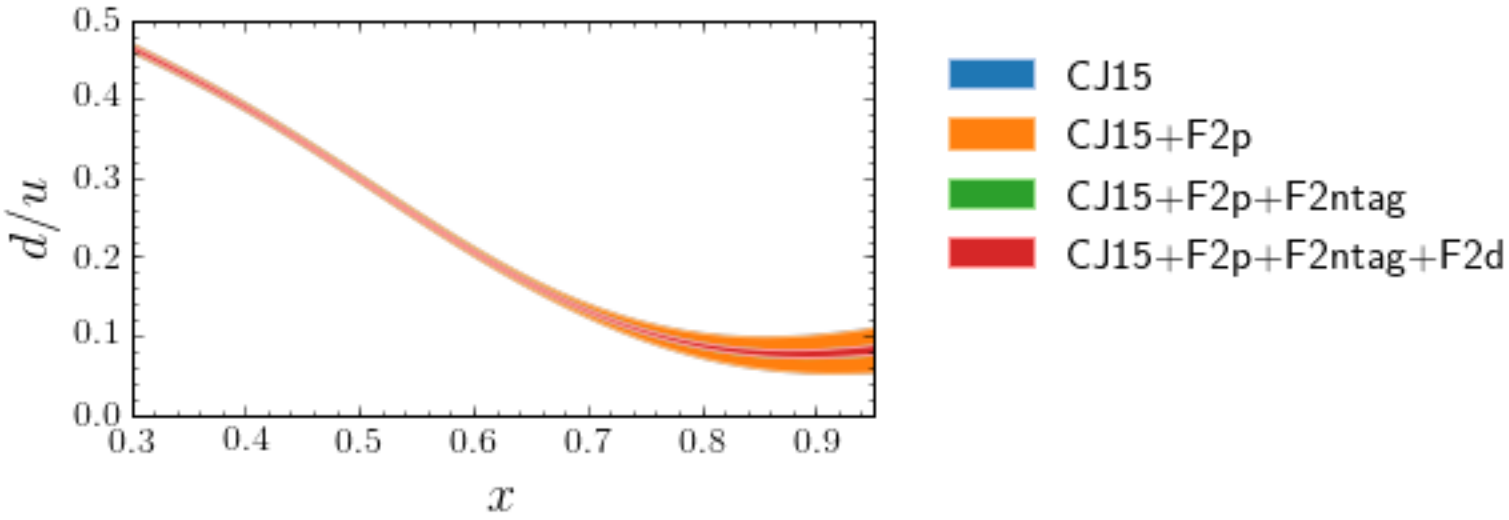
IMPROVED D(X) PRECISION OF EIC IS GOOD NEWS



- The d-quark goes from a few 10% to ~few% percent level
- Resolve long-standing mystery of d/u at large x, bell-weather for fundamental models of nucleon structure
- D/(p+n) in one experiment for the first time – unprecedented handle on nuclear medium modifications
- Facilitate accurate neutron excess/isoscalar corrections
  - Important also for neutrino physics and nuclear PDFs

NEW EMPHASIS ON STUDIES WITH PDFSENSE

Data Sets

● LHeC CC e^-p
▲ LHeC NC e^+p
□ EIC NC e^+p
■ LHeC CC e^+p
▼ EIC NC e^-p
◇ EIC CC e^+p
◆ LHeC NC e^-p
○ EIC CC e^-p

EIC run is for 10 GeV leptons on 250 GeV protons

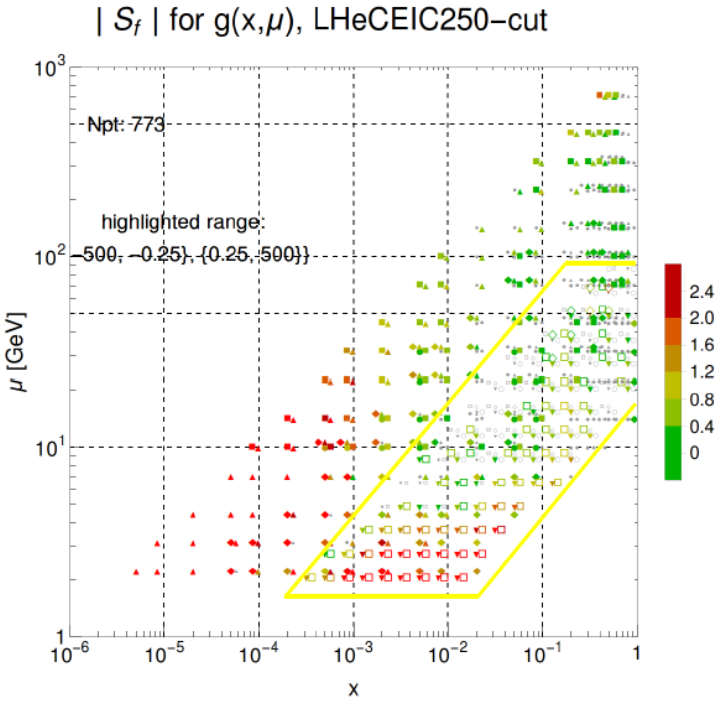
→ EIC points roughly outlined by the golden trapezoid at right

→ there is some overlap in kinematical coverage with LHeC pseudo-data

→ EIC measurements are a sensitive probe in the few GeV quark-hadron transition region for

$$x \gtrsim 5 \times 10^{-4}$$

→ this region is comparatively less explored by LHeC, which is sensitive to lower x



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NEW EMPHASIS ON STUDIES WITH PDFSENSE

Data Sets

- ● LHeC CC e^-p
- ■ LHeC CC e^+p
- ◆ LHeC NC e^-p
- ▲ LHeC NC e^+p
- ▼ EIC NC e^-p
- ○ EIC CC e^-p
- □ EIC NC e^+p
- ◇ EIC CC e^+p

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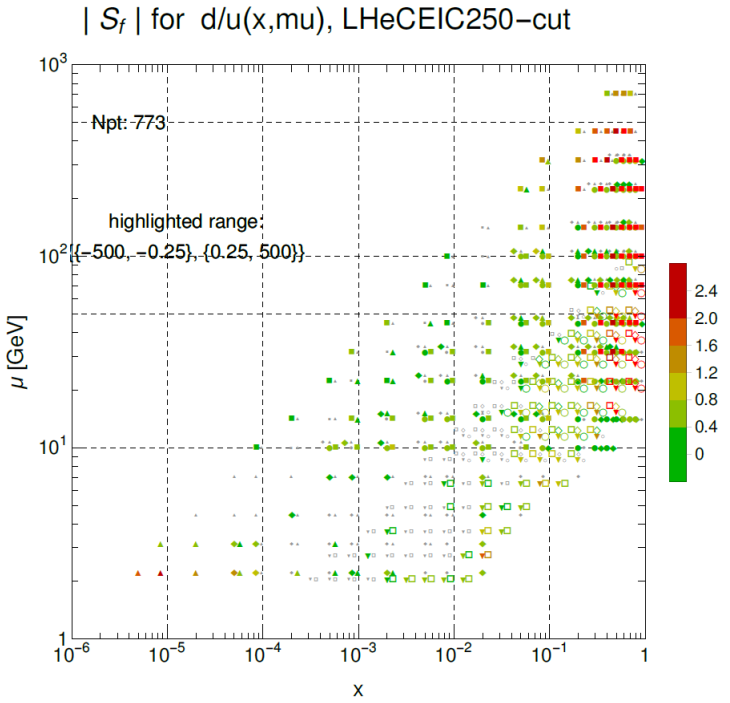

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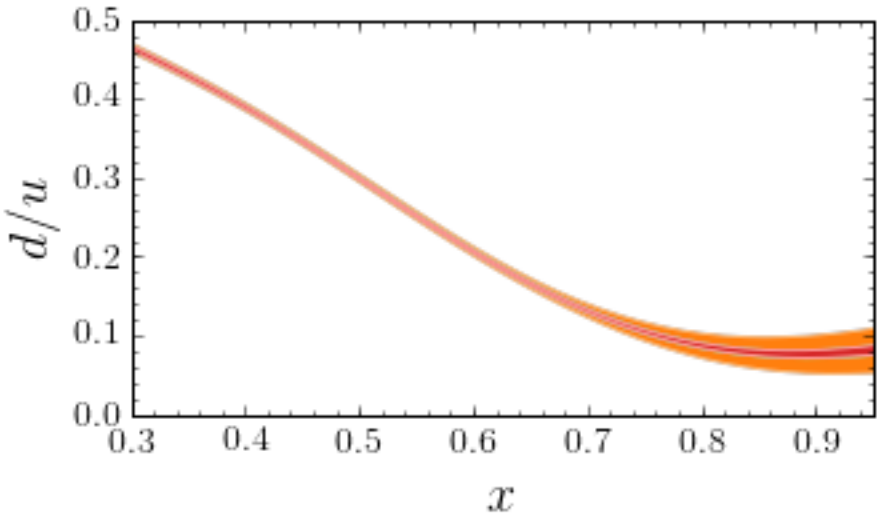
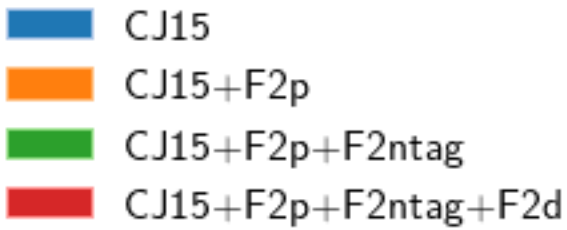
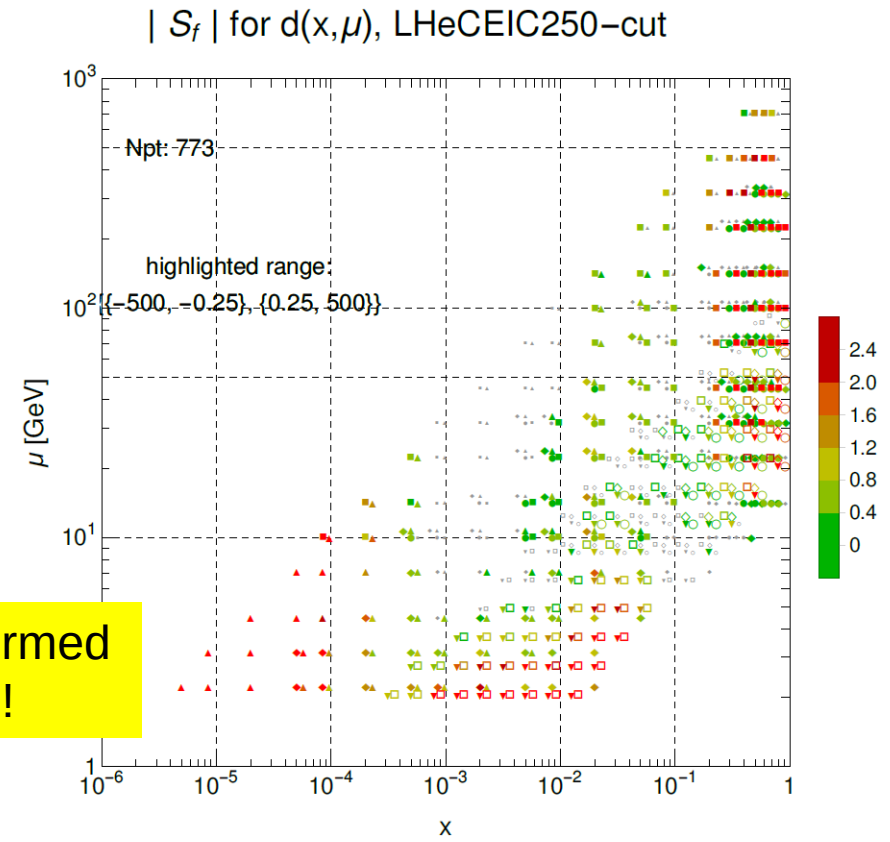
IMPROVED D(X) PRECISION OF EIC IS GOOD NEWS





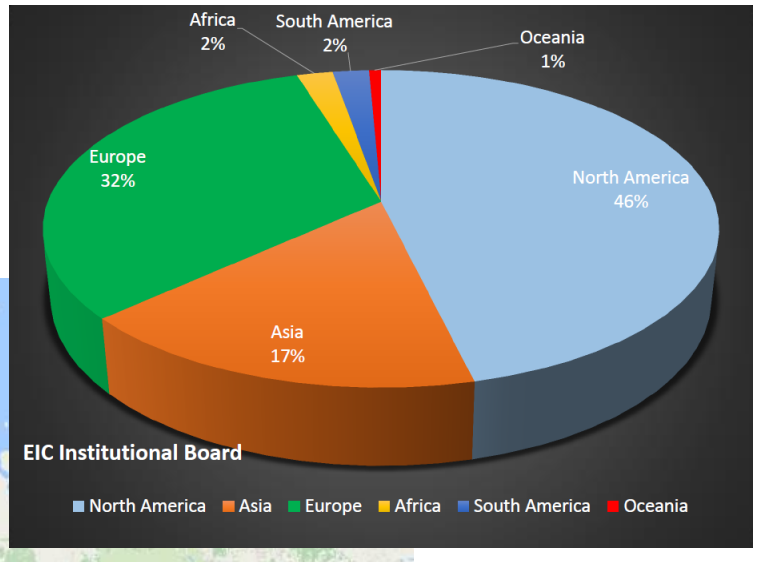


- The d-quark goes from a few 10% to ~few% percent level
- Resolve long-standing mystery of d/u at large x, bell-weather for fundamental models of nucleon structure

Sensitivity confirmed with PDFSense!

Worldwide Interest in EIC Physics

The EIC Users Group: EICUG.ORG



Formed 2016 – now 833 collaborators, 30 countries, 177 institutions... (Nov. 4, 2018)

Annual EICUG meeting
2016 Argonne, IL
2017 Trieste, Italy
2018 Washington, DC
2019 Paris, France

Eagerly awaiting CD-0 after very positive National Academy of Science report on EIC

SUMMARY

Not much of a summary, but …

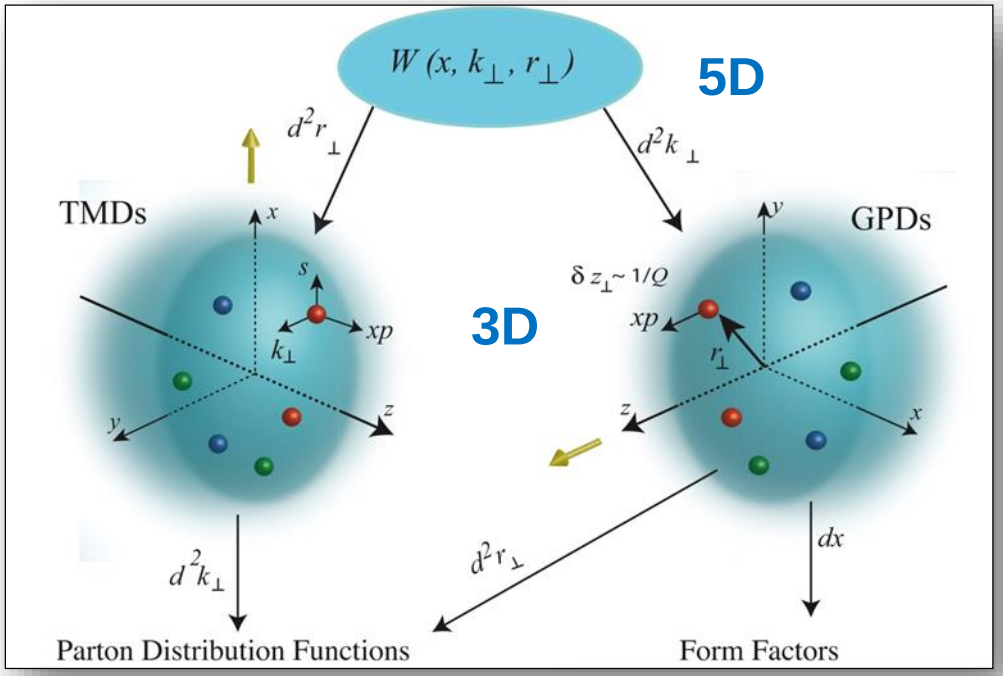
… the future is bright

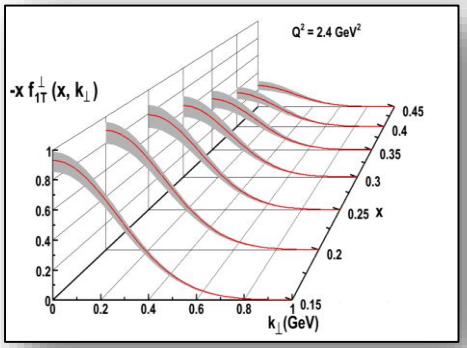
All four Halls operational, and much large-x data relevant for *"Parton Distributions as a Bridge from Low to High Energies"* upcoming.

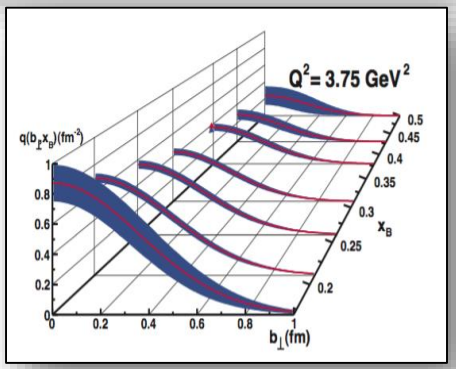
- $^{3}H/^{3}He$ (d/u) ratios, $F_2^{H,D}$, SIDIS validation data complete
- Global unpolarized SIDIS/TMD, CSV hunt data ongoing
- BoNuS12 (and A_1^n/polarized PDFs) anticipated in 2020

- Multiple dedicated studies ongoing to investigate impact of EIC on PDFs – large x, PDFSense, π/K structure
- EIC CD-0 on the horizon?

NEW PARADIGM FOR NUCLEON STRUCTURE







- TMDs
  - Confined motion in a nucleon (semi-inclusive DIS)
- GPDs
  - Spatial imaging (exclusive DIS)
- Requires
  - High luminosity
  - Polarized beams and targets
  - Sophisticated detector systems

Major new capability with JLab12

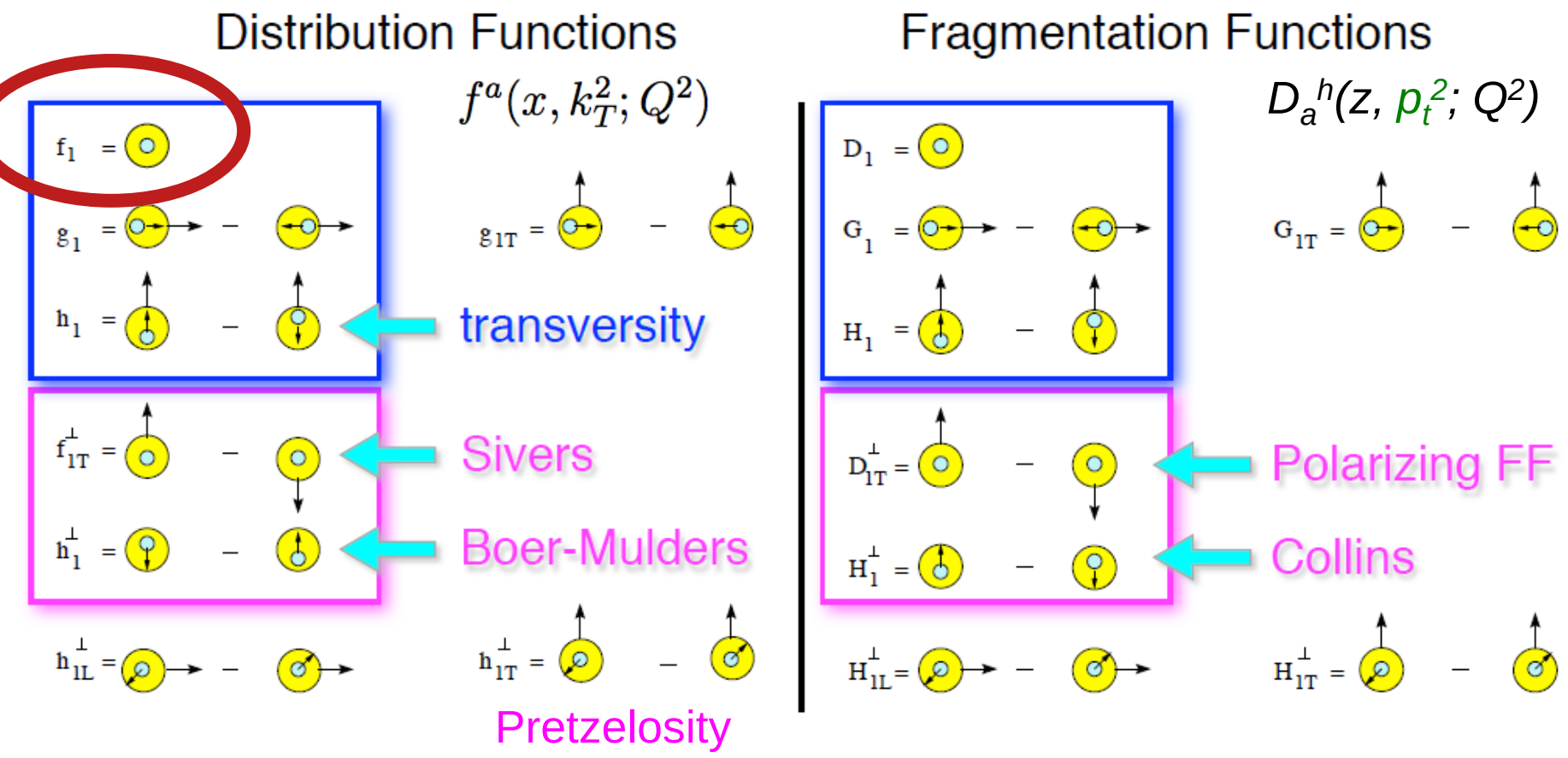
Jefferson Lab

TMDs and 3D FFs

Functions surviving on integration over Transverse Momentum

The **others** are sensitive to ***intrinsic k_T*** in the nucleon & in the fragmentation process

Mulders & Tangerman, NPB 461 (1996) 197

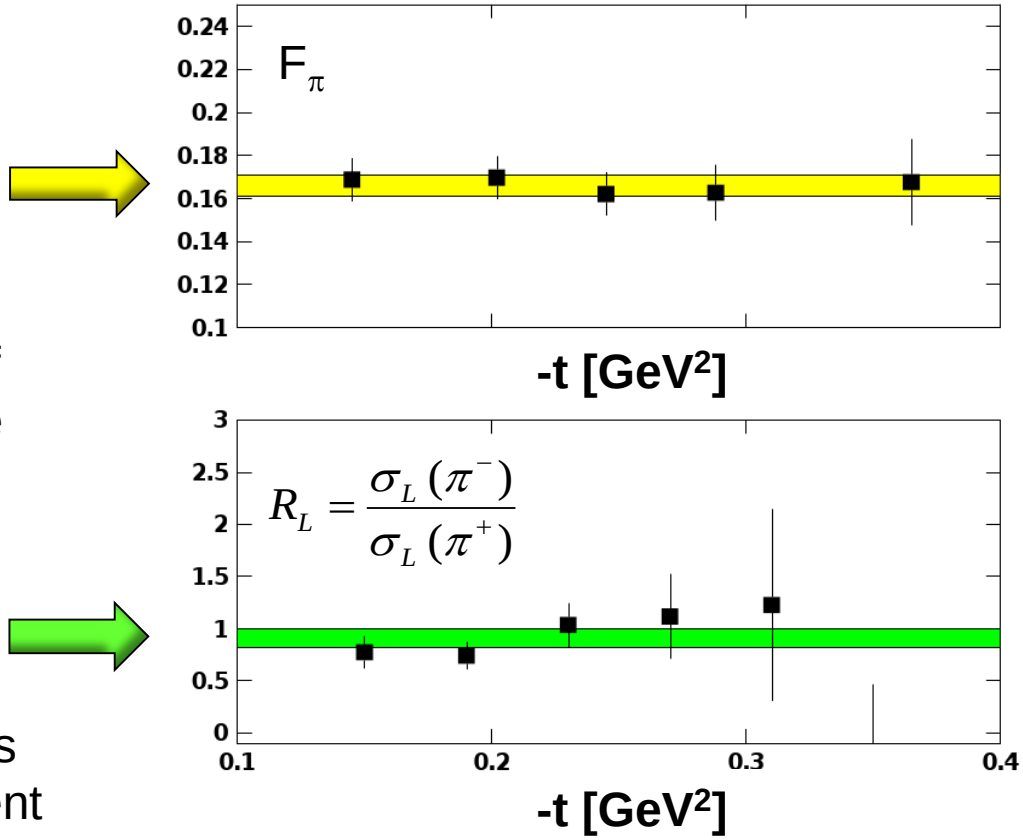


EXPERIMENTAL VALIDATION (PION FORM FACTOR EXAMPLE)

Experimental studies over the last decade have given *confidence* in the electroproduction method yielding the physical pion form factor

Experimental studies include:

- Take data covering a range in –t and compare with theoretical expectation
  - F_π values do not depend on -t – confidence in applicability of model to the kinematic regime of the data
- Verify that the pion pole diagram is the dominant contribution in the reaction mechanism
  - R_L (= $\sigma_L(\pi^-)/\sigma_L(\pi^+)$) approaches the pion charge ratio, consistent with pion pole dominance



*[G. Huber et al, PRL**112** (**2014**)182501]*

*[T. Horn, C.D. Roberts, J. Phys. G**43** (**2016**) no.7, 073001]*

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