Further Prospects for Pion Structure Measurements at the EIC

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June 2020

Workshop on Pion and Kaon Structure Functions at the EIC

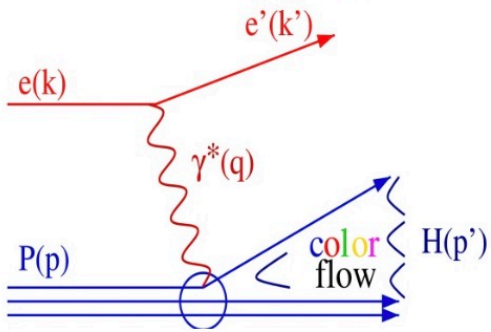
Jefferson Lab

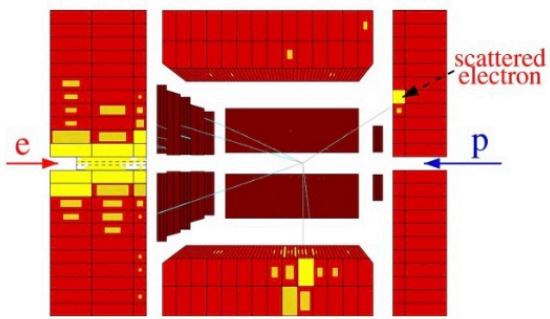
U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

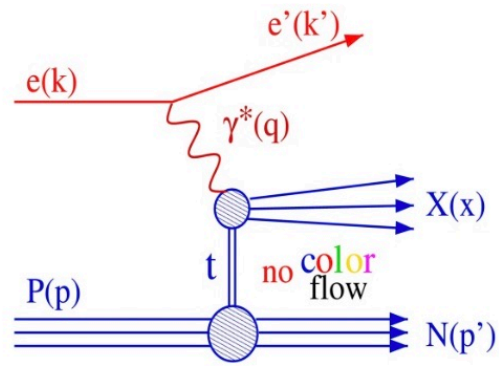
Kinematics of DIS Events

Inclusive nondiffractive deep inelastic scattering (DIS) events

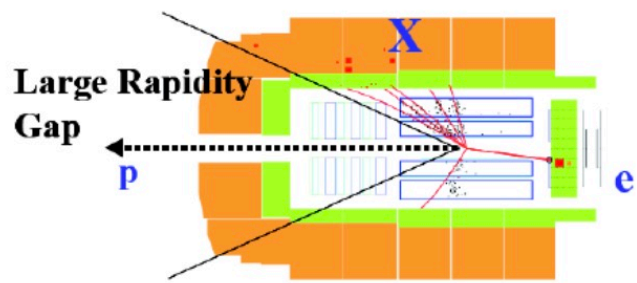




Diffractive DIS events



Proton or dissociative system, measured in FPS/LPS



$s = (k+p)^2$ center of mass energy squared

$W^2 = (q+p)^2$ photon-proton center of mass sqared

$Q^2 = -q^2 = -(k-k')^2$ virtuality, size of the probe

$x = \frac{Q^2}{2p\cdot q}$ x: fraction of the proton momentum carried by the struck parton

$y = \frac{p\cdot q}{p\cdot k}$ Y: inelasticity, fraction of the electron momentum carried by the virtual photon

For diffractive events in addition:

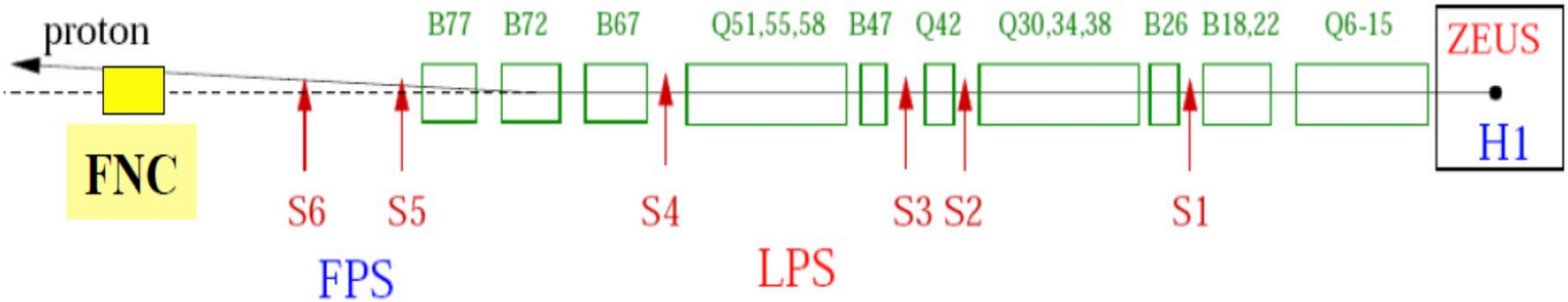
M_x mass of the diffractive system x

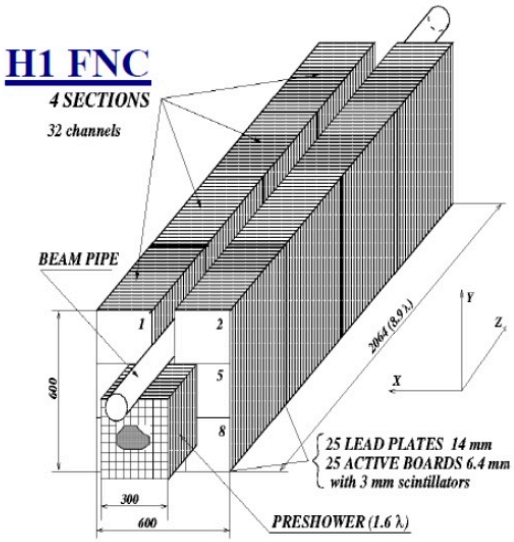
$t = (p-p')^2$ four-momentum transfer squared at the proton vertex

$x_{IP} = \frac{(p-p')\cdot q}{p\cdot q} = \frac{M_x^2+Q^2}{W^2+Q^2}$ momentum fraction of the proton carried by the Pomeron

$\beta = \frac{Q^2}{2(p-p')\cdot q} = \frac{x}{x_{IP}} = \frac{Q^2}{M_x^2+Q^2}$ fraction of the Pomeron momentum which enters the hard scattering

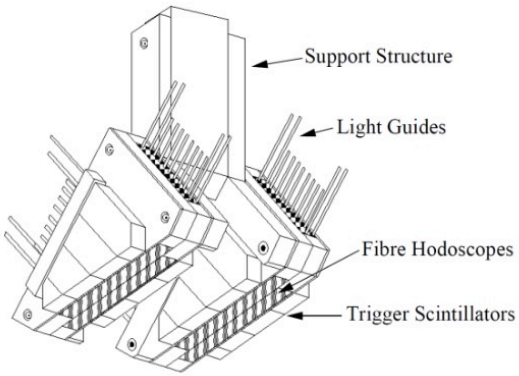
Forward Nucleon Tagged DIS (TDIS) at HERA





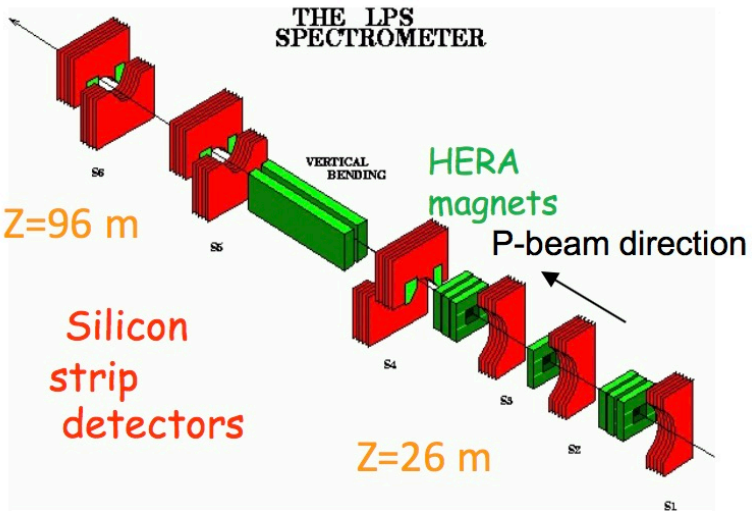
$\sigma_E/E \approx 0.63/\sqrt{E} \oplus 2\%$

Position resolution 2-3 mm



H1 FPS module

Scintillating fibers



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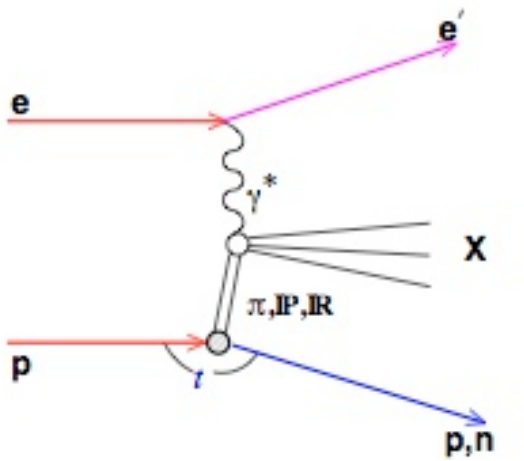
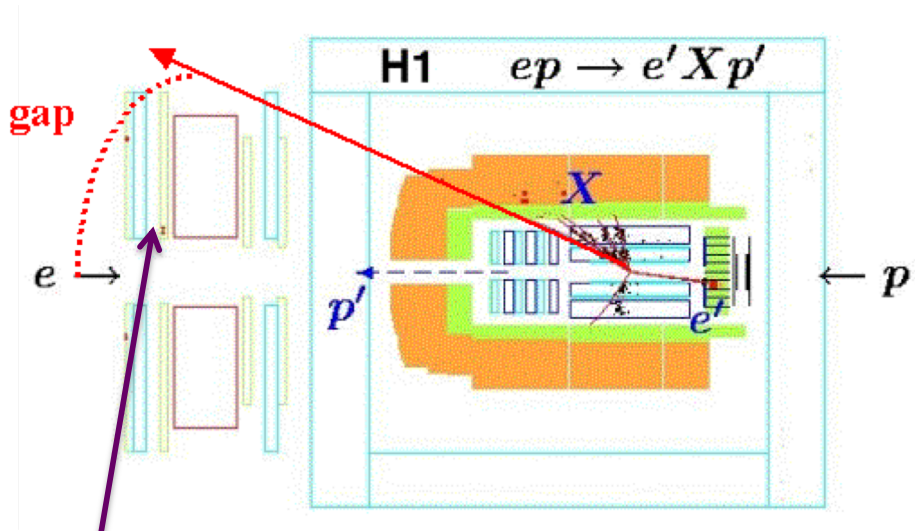
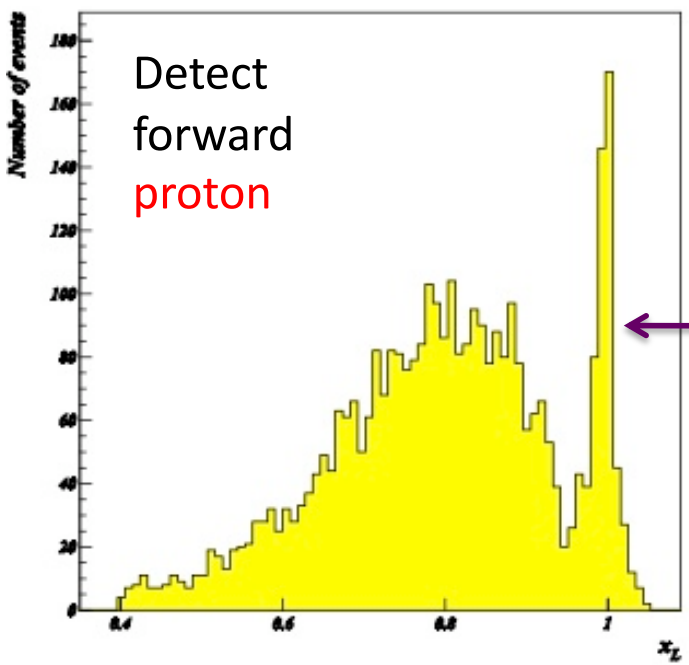
TDIS at HERA – *proton* tag

- *Tag leading baryon production*
- *ep → eXp*





Diffractive Scattering:



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

X_L

Large rapidity gap

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

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

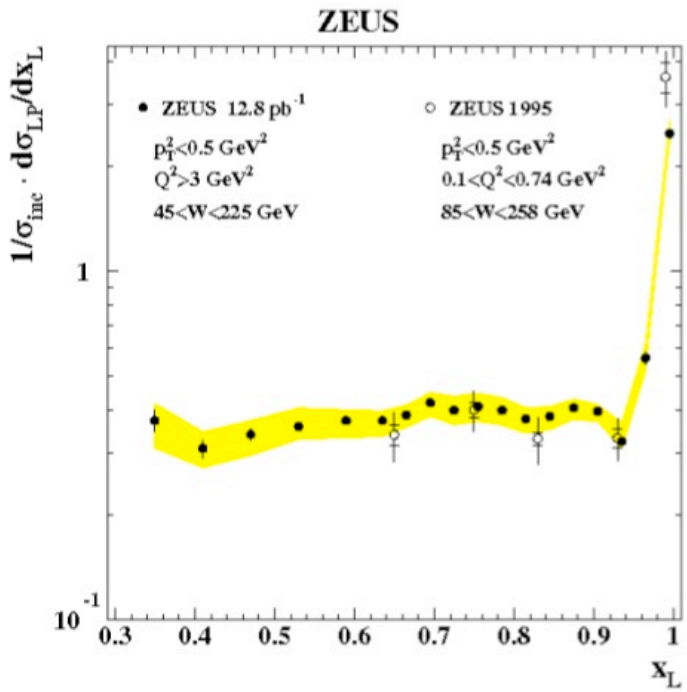
Gluons >> quarks in Pomeron?

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

Pomeron contribution Reggeon contribution

TDIS Measurements at HERA

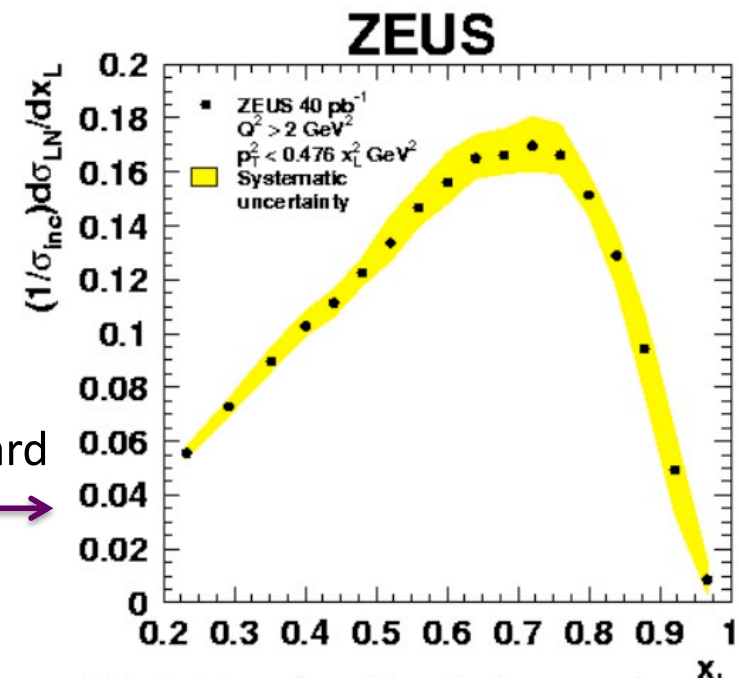
- *Tag leading baryon production*
- *ep → eXN*



Detect forward proton

$x_L = E^N/E^p_{beam}$

Detect forward neutron



Tagged proton:

- Dramatic increase as $x_L \rightarrow 1$
  - Diffractive peak, large rapidity gap
- Yield flat below x ≈0.95

Dramatic difference!

Tagged neutron:

- Yield → 0 at limit $x_L \rightarrow 1$
- Yield drops below x ≈0.75
- *Isovector* contributions → 0 at limit $x_L \rightarrow 1$

Consider the proton a superposition of states…

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

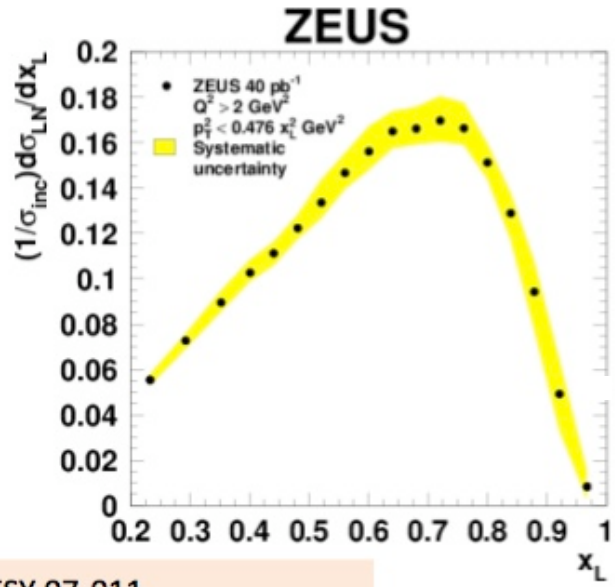
Chiral approach: *a=0.24, b=0.12*
Thomas, Melnitchouk & Steffens, PRL85 (2000) 2892

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

- The π^+N cloud doubles π^0N cloud in the proton.

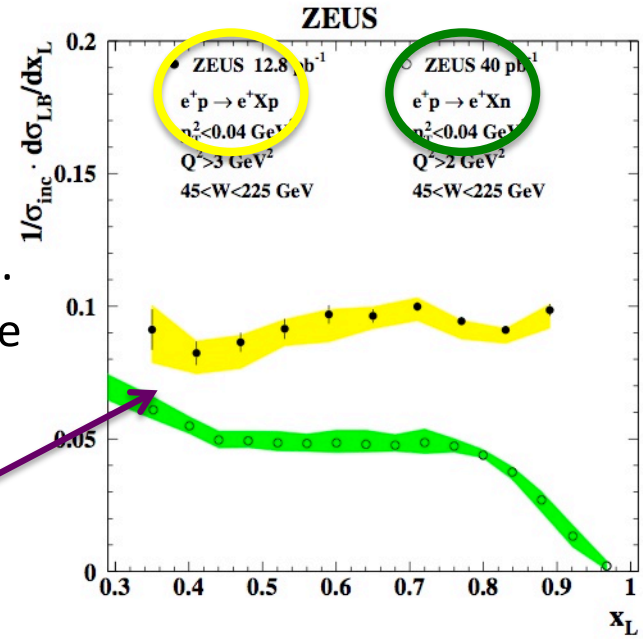
TDIS at HERA – *neutron* tag

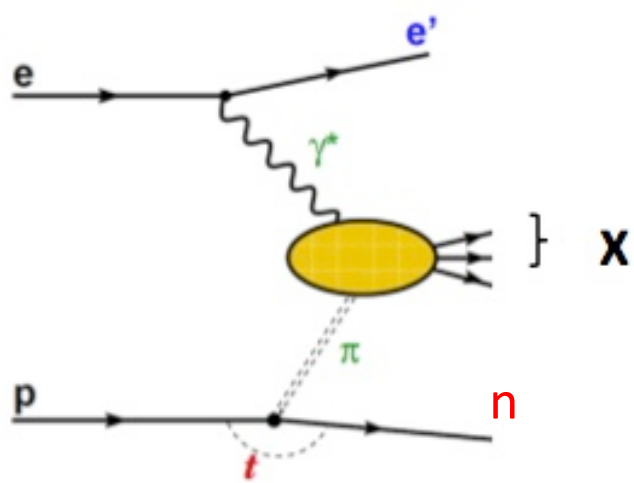
DESY 08-176 JHEP06 (2009) 74



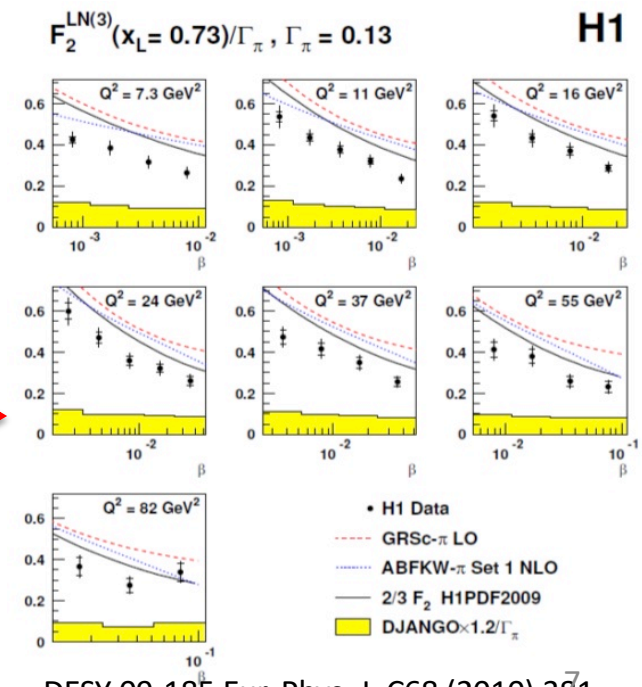
DESY 07-011
Nucl.Phys.B776(2007) 1-37

- *The leading neutron results are different.*
- There is no elastic (diffractive) peak present.
- 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





- *Model one pion exchange as the dominant mechanism.*
- *Can extract pion structure function*



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

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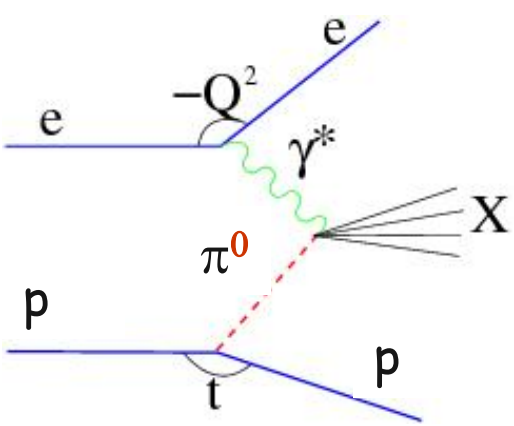
\end{aligned}
$$

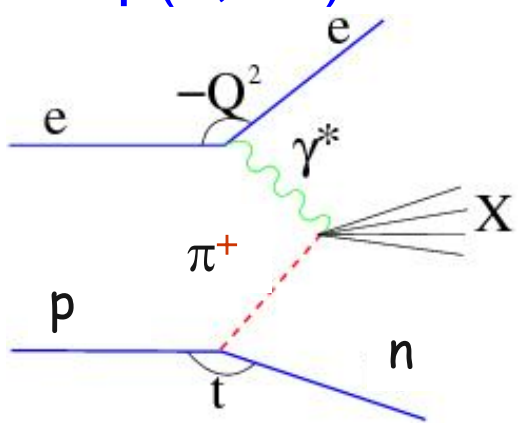
- The π^+N cloud doubles π^0N cloud in the proton.
- Important to measure tagged p *and* n *and* d!

Also Λ+k!

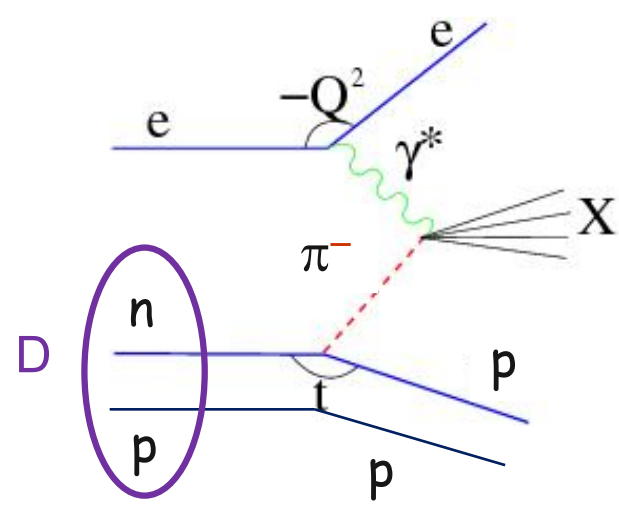
p(e,e'p)X



p(e,e'n)X



n(e,e'p)X



Backgrounds for different "tags" will be different

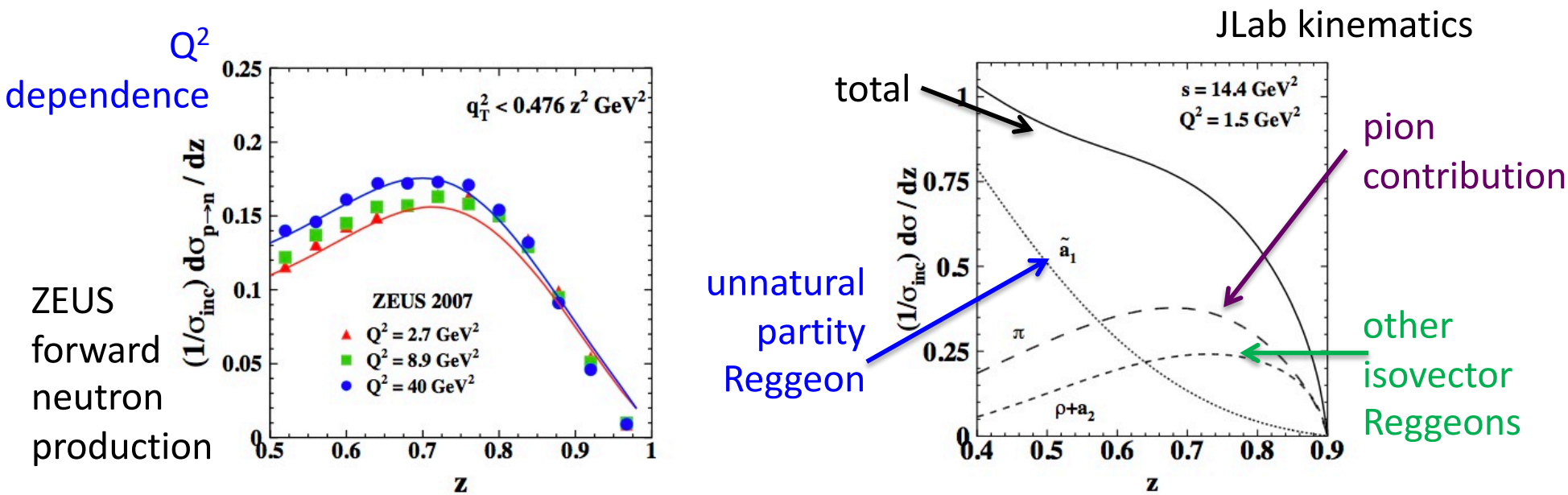


Fig. 2. *Left:* comparison of the calculated Q^2-dependence of the fractional cross section of neutron production with data from [2]. *Right:* the tractional cross section calculated at $Q^2 = 1.5\,\mathrm{GeV}^2$ and $\nu = 8\,\mathrm{GeV}$.

B. Kopeliovich et al., 16th EDS Blois (2015), arXiv:1510.08868 [hep-ph]

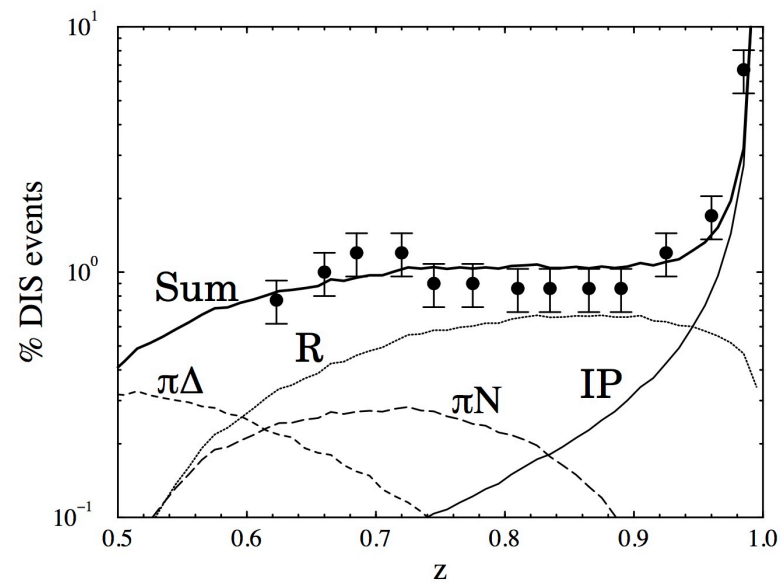
- *Charged* pion exchange has less background from Pomeron and Reggeon processes
- Measuring isospin dependence (p–n difference) will assist identification of Sullivan process
- Contribution from pion pole larger at smaller x
  - Study pole dependence to emphasize meson contribution

A lot of fascinating questions remain!

- Understand diffractive difference
- Identify/subtract diffractive component (from all targets)
- Identify/subtract/learn about theoretical "backgrounds"
  - Deploy neutron and proton (and other?) beams
  - Deploy multiple tags – p,n,.., study isospin expectations
  - Expand kinematic range – in x,Q,t,z,..
- Will need close experiment-theory collaboration, large and disparate data set to disentangle
- COMPASS data will help

The EIC will enable all of this ☺

Analysis of preliminary ZEUS (leading proton tag) data by Szczurek, Nikolaev and Speth, Phys. Lett. B428 (1998) 383-390



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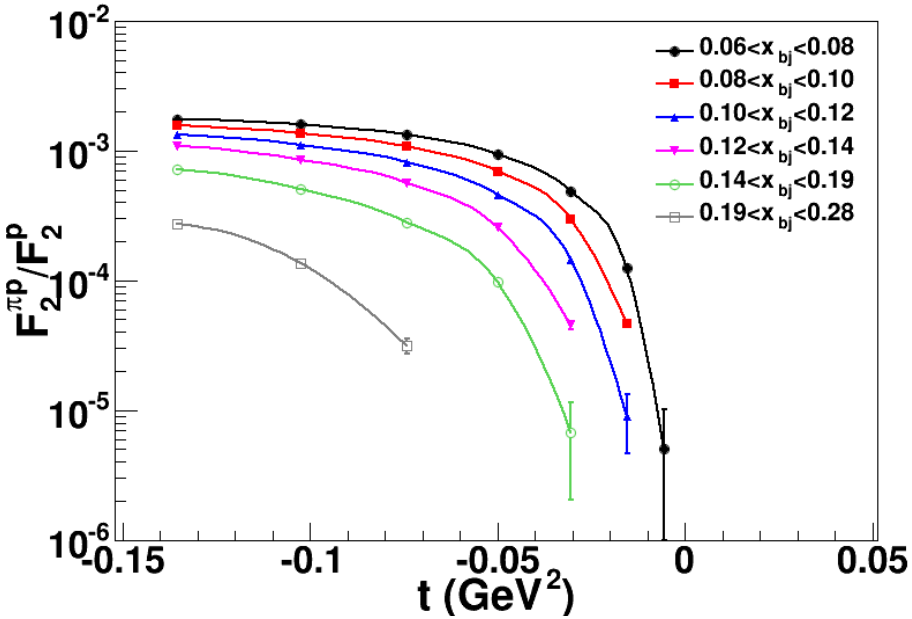
Suppose we DO manage to cleanly select Sullivan process targets….

- Create effective pion (and kaon) beams!
- What can we do with these at the EIC…?...

EIC – Versatility *and Luminosity* are Key

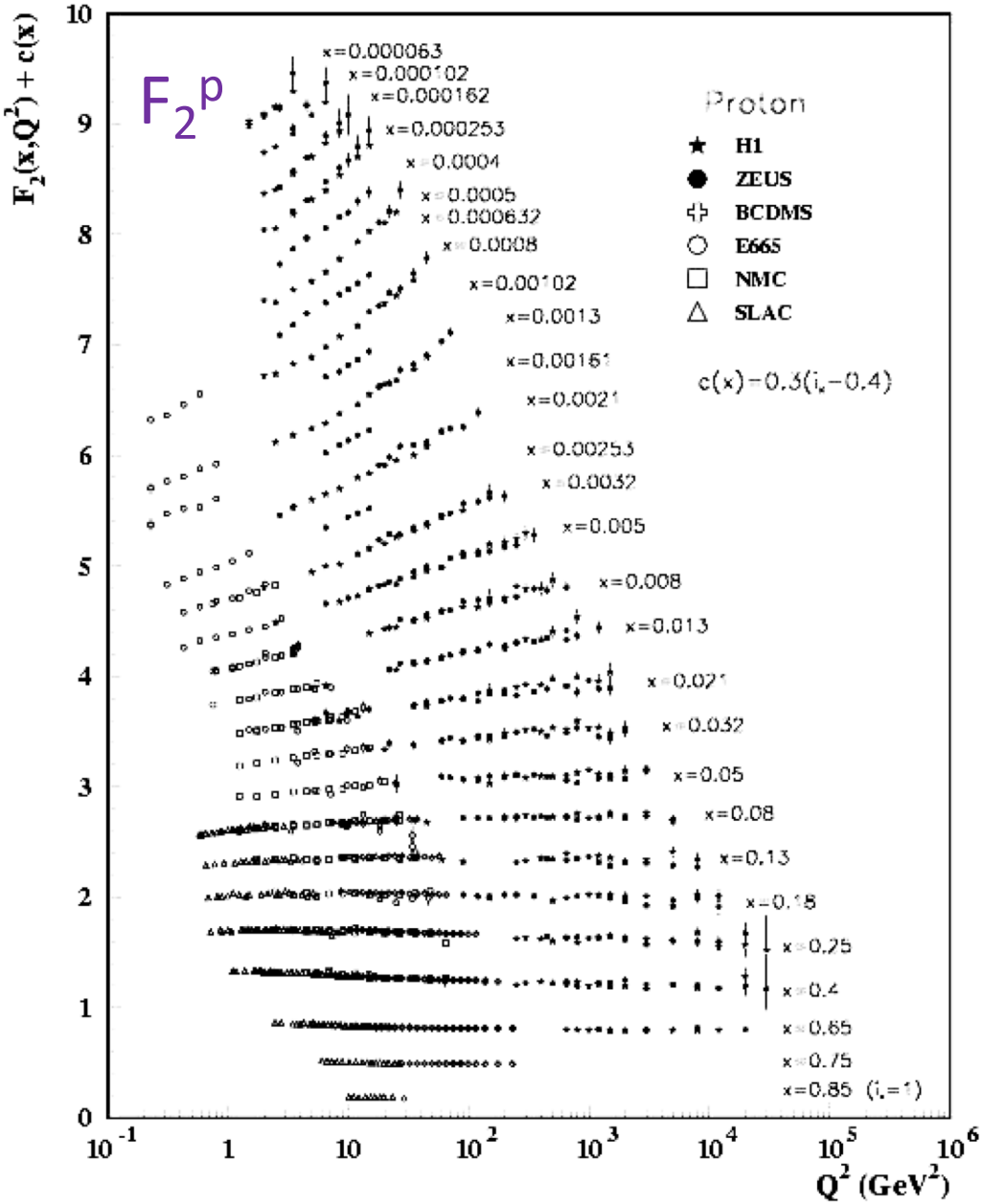
Why would measurements with (Sullivan) pion and kaon targets be feasible at an EIC?

- $L_{EIC} = 10^{34} = 1000 \times L_{HERA}$
- 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 < 0.06 (0.9) GeV^2, 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 TDIS experiment)

Inclusive Structure Function Measurements



e,e'p

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
  - Backbone of global pdf fits

e,e'π

Pion –

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

- EIC will facilitate mapping out pion (and kaon) SFs and pdfs over a broad kinematic range! (see numerous talks at this meeting)
- What is the pionic contribution to the *proton* SFs and pdfs?

Leading Neutron Cross-sections and Structure Functions

$$\frac{d^3\sigma(ep \to enX)}{dx\, dQ^2\, dx_L} = \frac{4\pi\alpha^2}{x\,Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{LN(3)}(Q^2, x, x_L)$$

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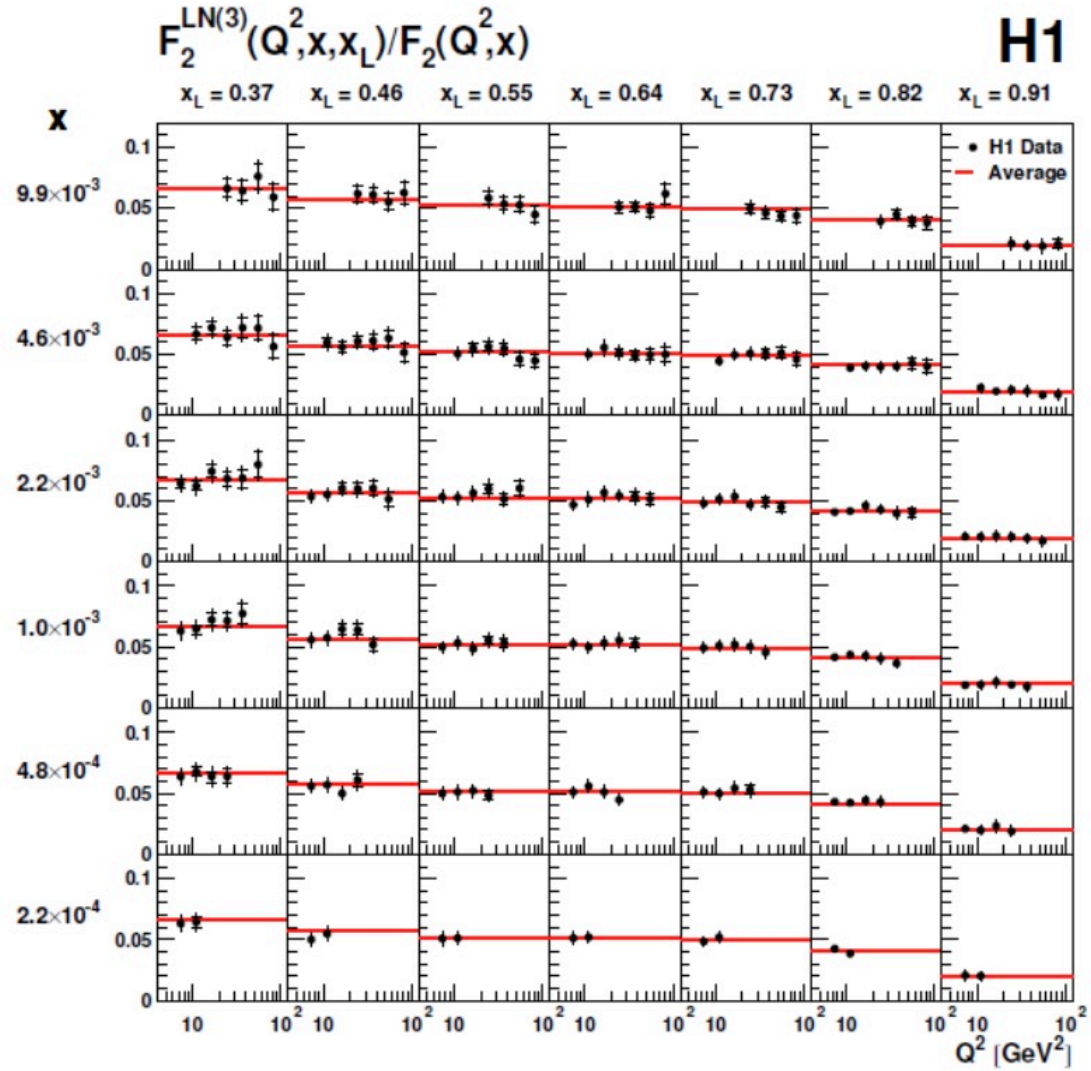
- Pion parton distributions play a role in ***nucleon and nuclear*** parton distributions
- The neutron tagged structure function seems to have the same Q^2 dependence as the inclusive structure function
  - Need to verify!
  - What about proton tagged?
- **EIC should be able to measure with better precision, with wider range in kinematics**
  - Isolating backgrounds



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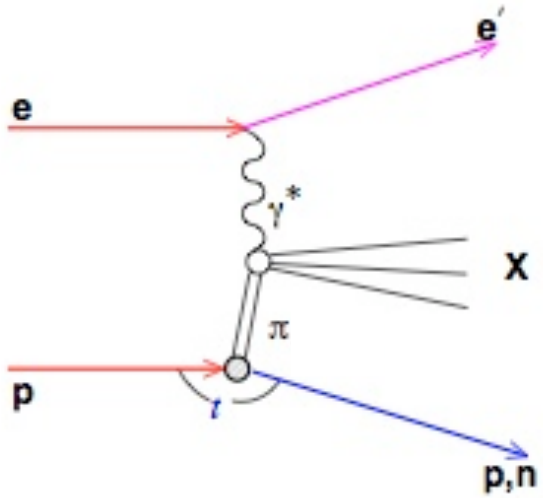
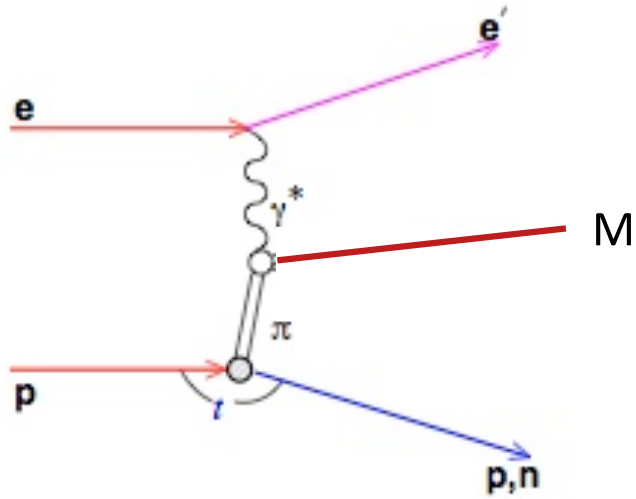
Or…. Exclusive Studies

Effective Pion Target





TDIS:

X = reconstructed mass of recoiling hadronic state -(p,n)

TDES!:

Detect *all* final state particles – select exclusive states

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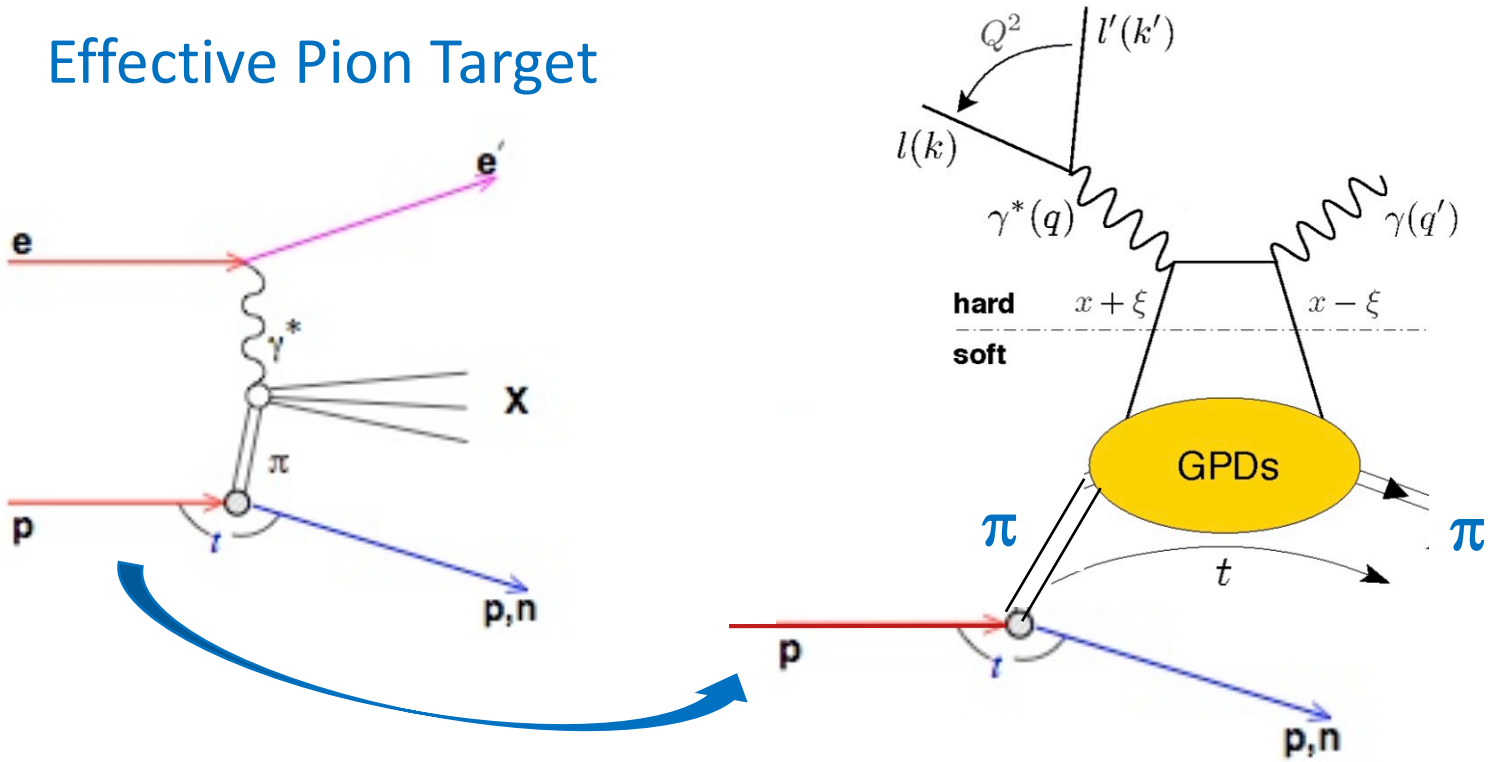
Example: Pion GPD studies… T-DVCS, DV-TCS?

Effective Pion Target



Deeply Virtual Compton Scattering *from a pion*

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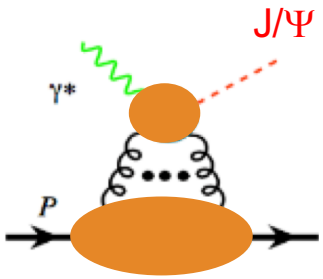
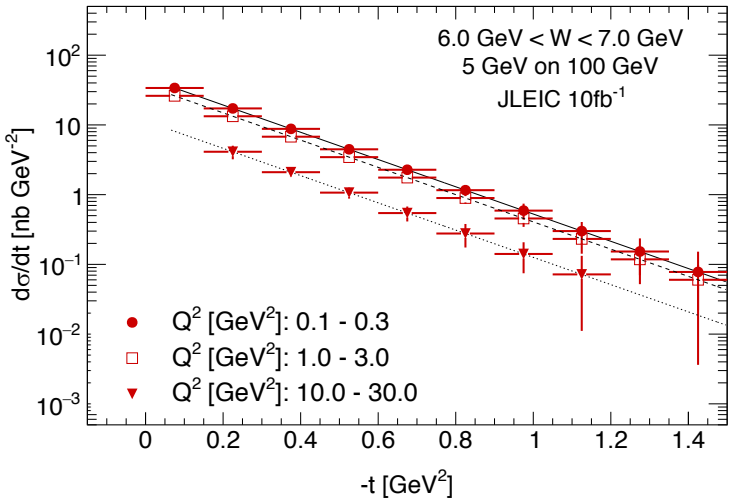
Elastic J/Ψ production near threshold at an EIC

At an EIC a study of the Q^2 dependence in the threshold region is possible

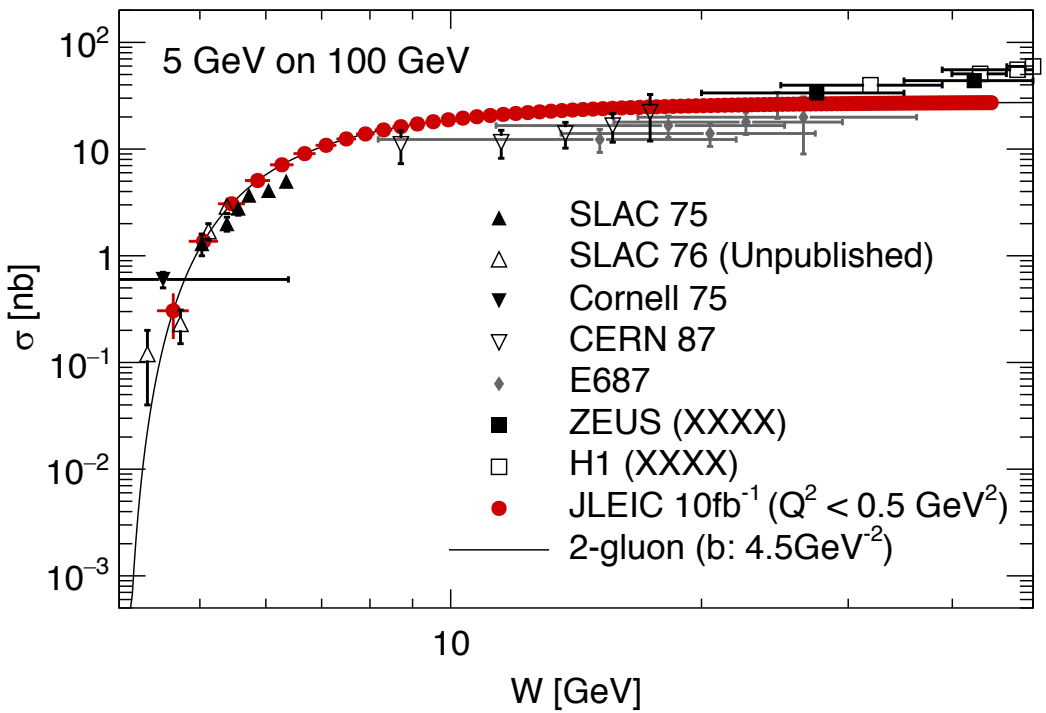


S. Joosten, Z-E. Meziani (via R. Ent)

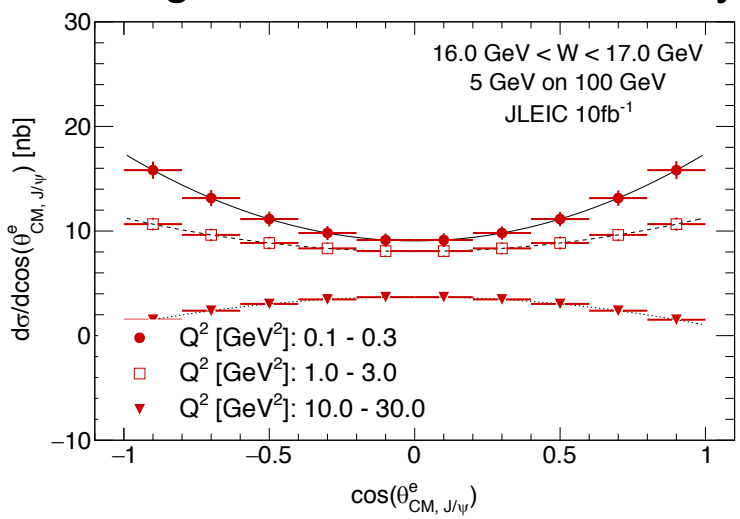
t distribution



Total electroproduction cross section

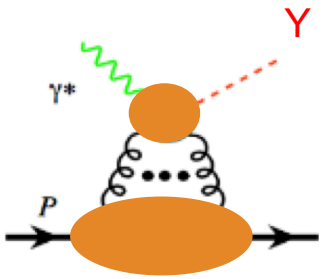


angular distribution of decay



Elastic Y production near threshold at an EIC

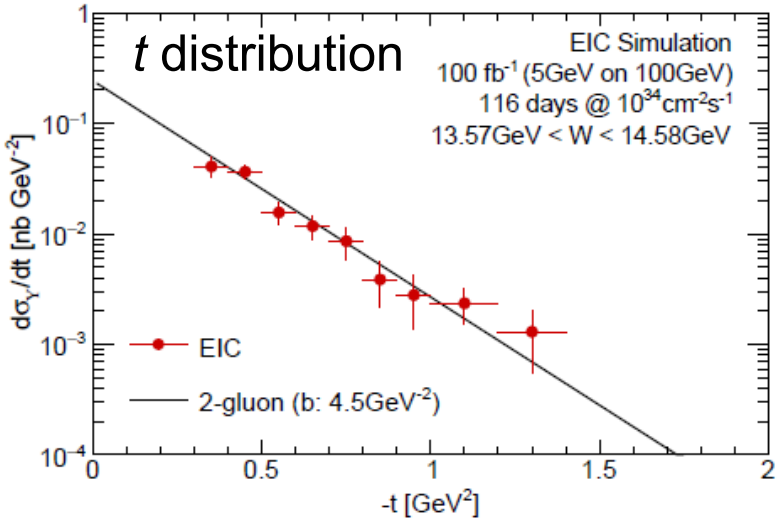
At an EIC a study of the Q^2 dependence in the threshold region is possible

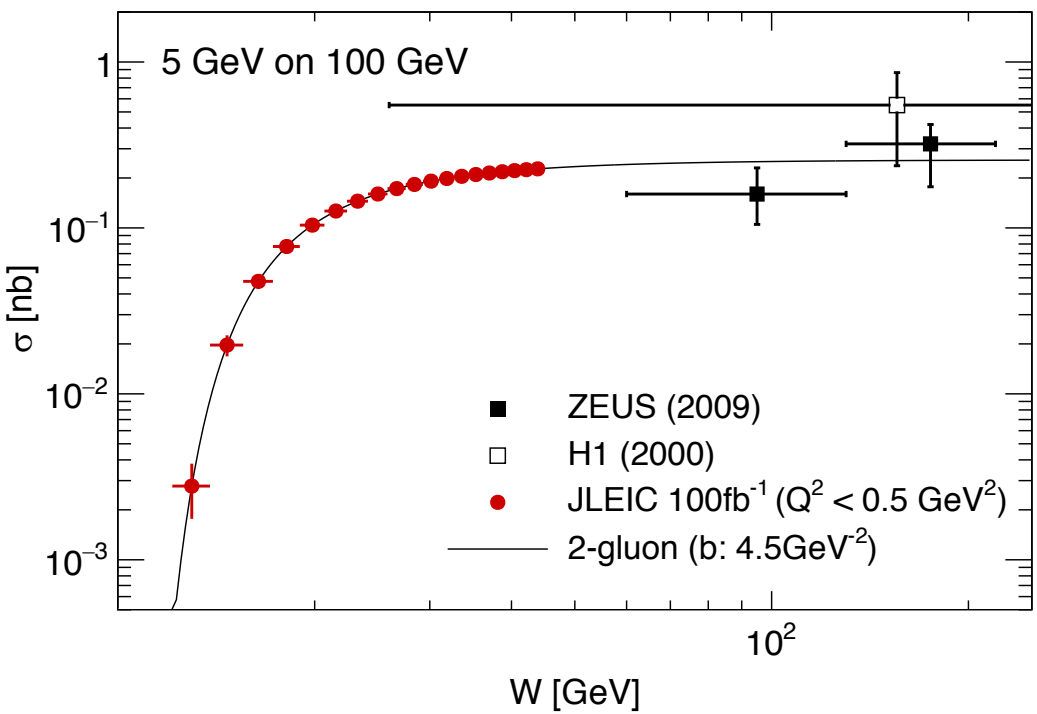


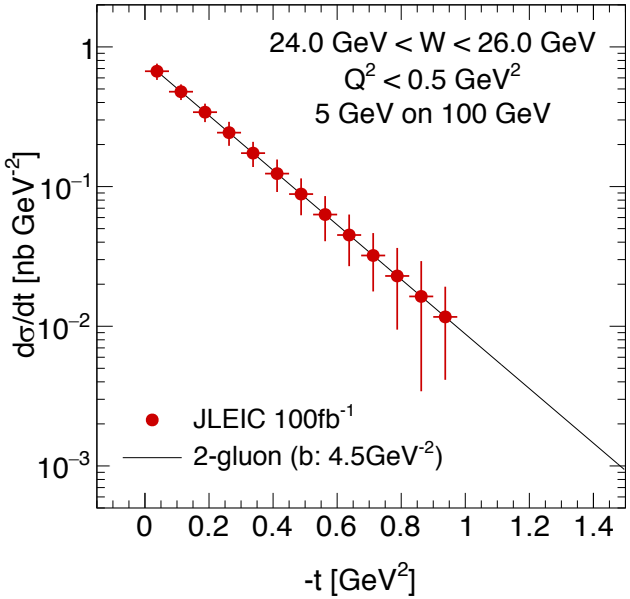
S. Joosten, Z-E. Meziani

Low W → trace anomaly
Large W → Gluon GPDs

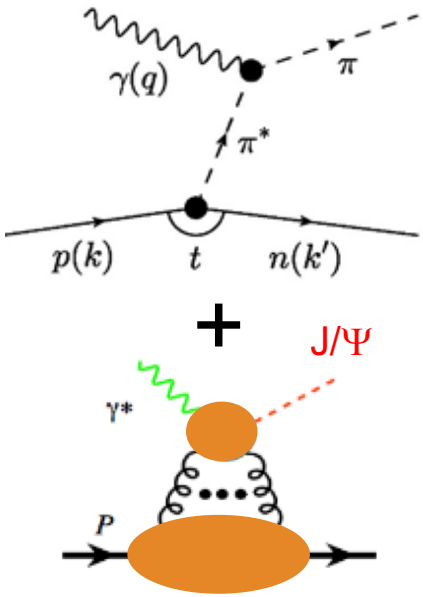
(see arXiv:1802.02616)

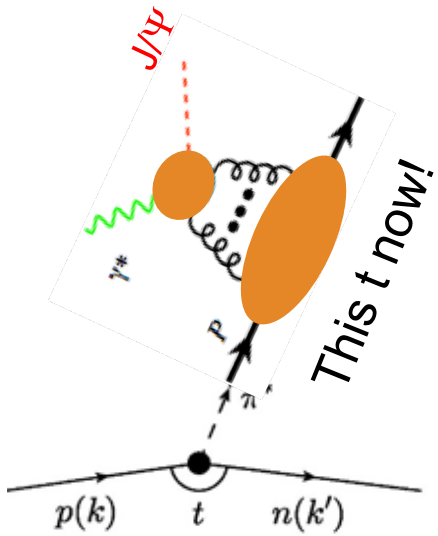


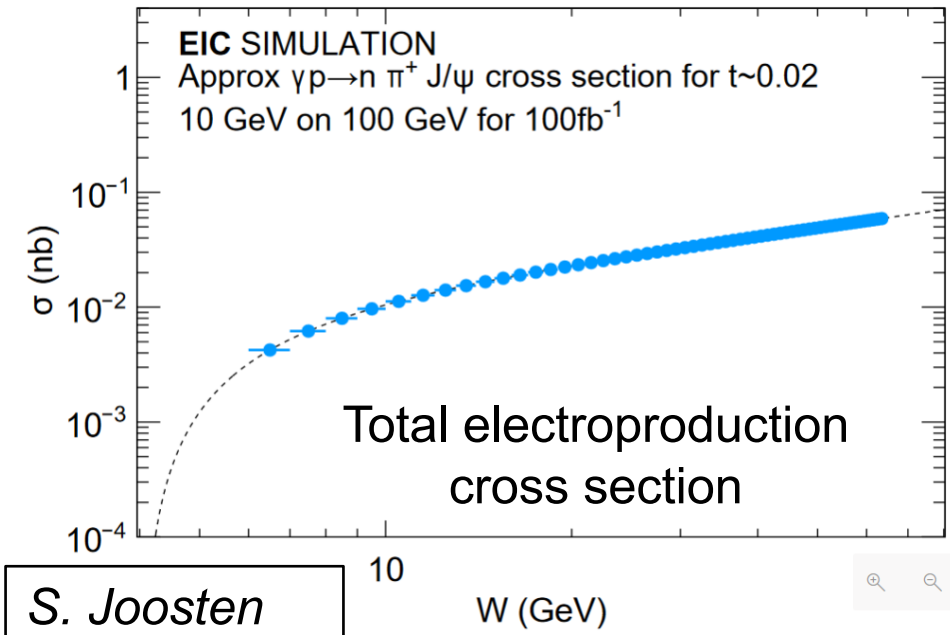




Elastic J/Ψ production *off the pion* at an EIC

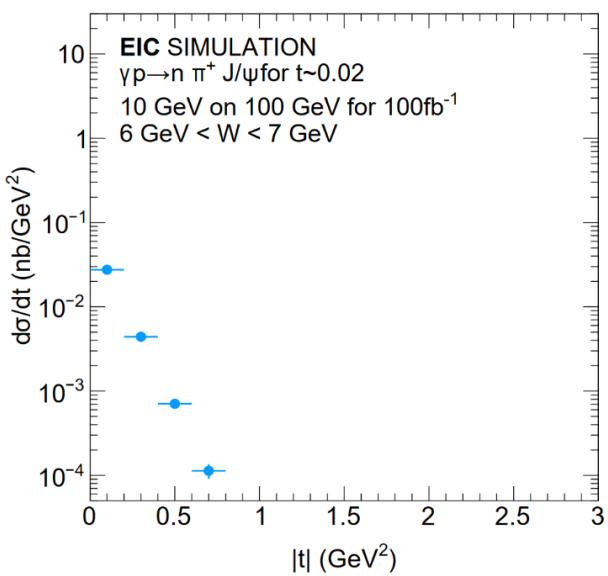


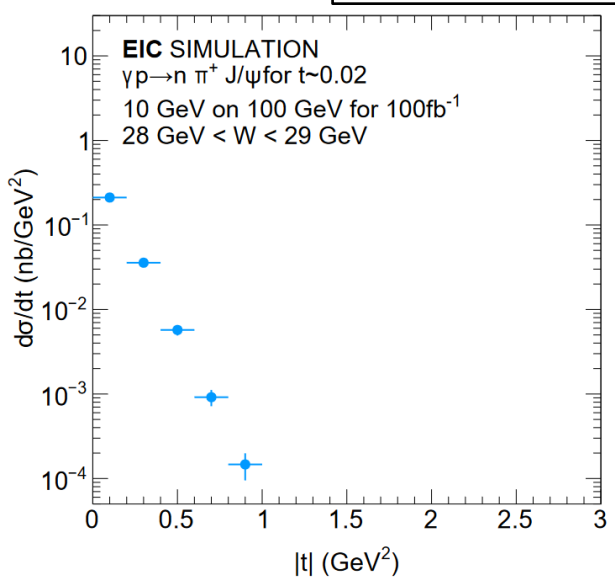


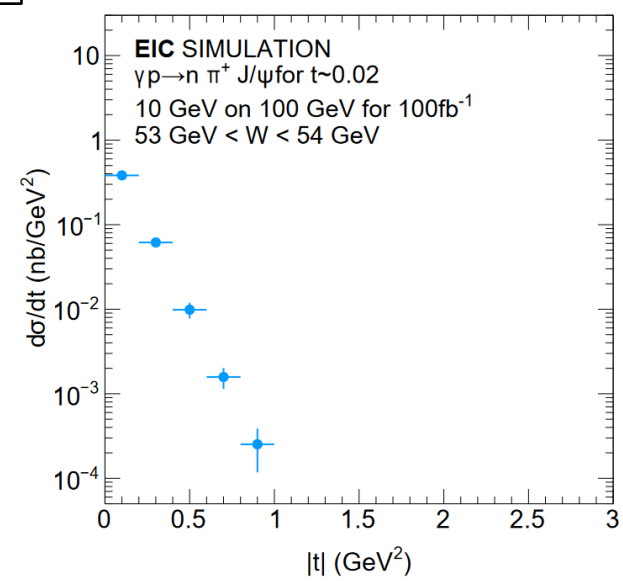


t distributions

S. Joosten







Pion TMD studies? T-SIDIS S-TDIS?

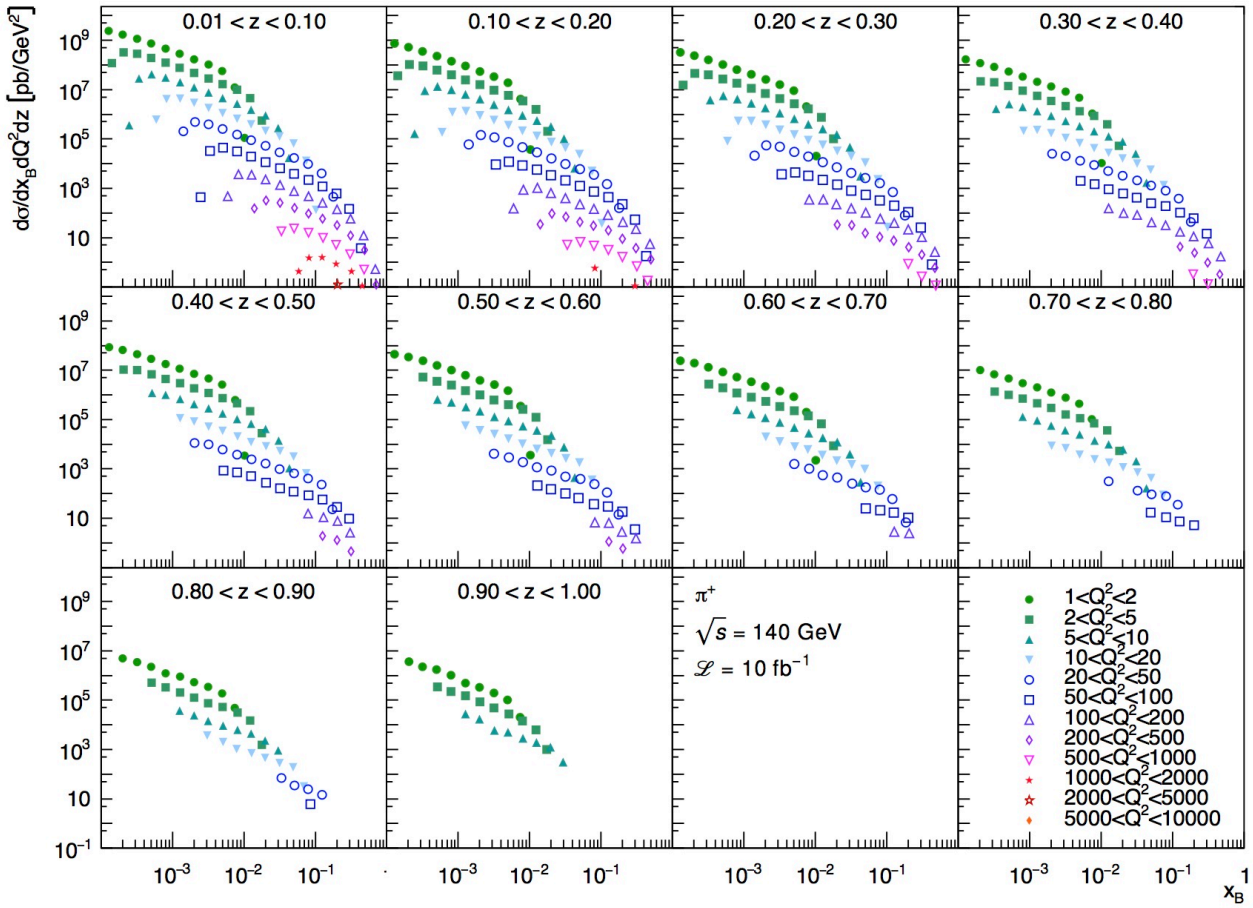


FIG. 7: Differential cross section for pion production at $\sqrt{s} = 140$ GeV as a function of x_B for bins in Q^2 and z measurable at an EIC.

Aschenauer, Borsa, Sassot, Van Hulse, Phys. Rev. D 99, 094004 (2019)

SIDIS multiplicities will be measured (here pictured for pion production)

High precision, good statistics and multiplicites

Can think about *pion* TMDs from tagging at same time

Cross section down ~10^3 – need luminosity, but maybe possible

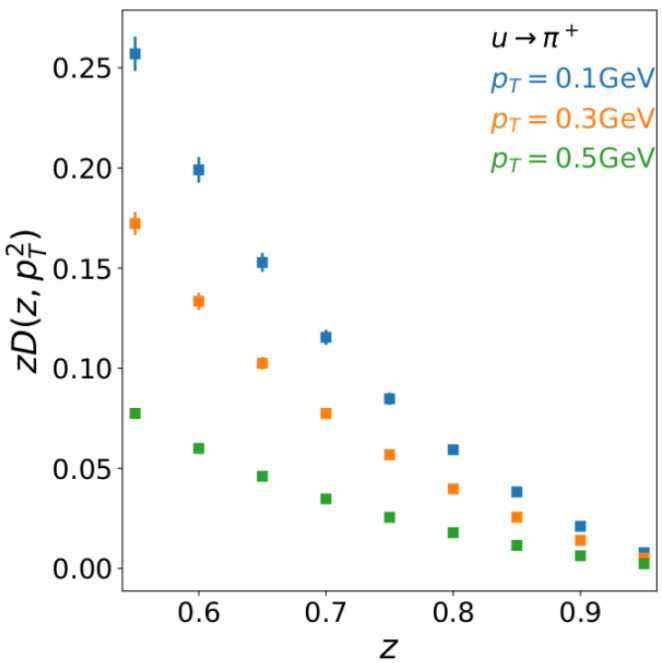
Jefferson Lab

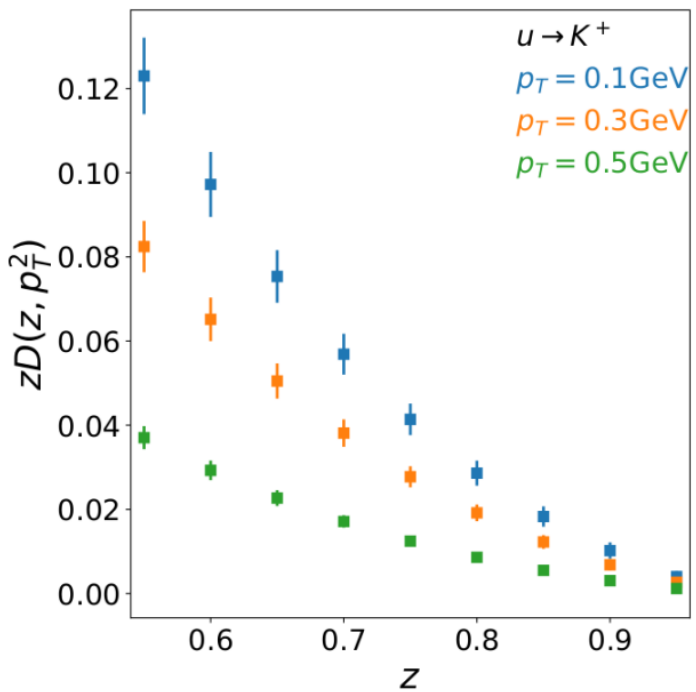
Quark Fragmentation into Pions and Kaons

- Timelike analog of mass acquisition measure fragmentation of quarks into pions and kaons

M. Diefenthaler
(R. Ent)

- (Proton) projections for integrated luminosity = 10 fb^{-1}
  - High statistics… pion fragmentation possible





- EIC can provide precision data at large x (z>0.5) and transverse momentum (as picked up on the fragmentation process) of k_T=0.1, 0.3, 0.5

Summary: rich – and novel – physics to explore

- Solve mysteries left by HERA
  - Interplay of diffractive component
  - Pomeron, Reggeon, mesonic content of the nucleon
- Create effective pion (kaon) targets
  - Multiple targets created by robust, varied tagging capability
- Facilitates **new** measurements
  - Meson pdfs
  - Mesonic component of nucleon pdfs
    - Separate, study off-shell, Q, dependencies
  - 3D structure of the Pion (TMDs, GPDs)
  - J/Psi production from the pion
  - Fragmentation studies

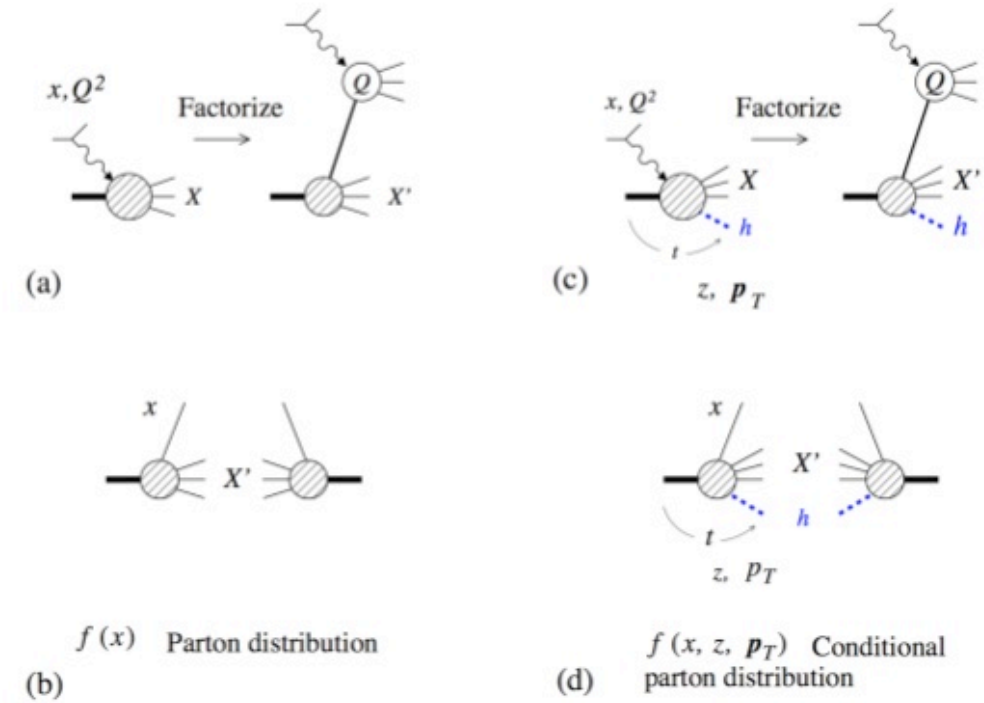
  - *What would you study with a pion target/beam?*

Thanks!

Backups

Fracture Functions Allow for Rigorous Description of TDIS

(conditional pdfs, ~diffractive pdfs)



- Particular, conditional case of DIS
- Defined through factorization theorem, universal
- Factorization for FF in SIDIS has been proven at collinear and soft level
- Hard cross section same as inclusive
- DGLAP evolution same as PDFs
- *Can be extracted from data*

(a) Inclusive DIS e N → e' + X

(b) Parton distribution f(x) *describes the probability distribution of quarks with respect to their light-cone momentum fraction x in the target*

(c) Conditional cross section with an identified hadron in the target fragmentation region eN → e' + h(target) + X

(d) Fracture function, or conditional parton distribution *describes the probability to find a hadron h in the target fragmentation region, with light-cone momentum fraction 1 − z and transverse momentum p_T, after removing a quark with light-cone momentum fraction x.*

L. Trentadue and G. Veneziano, Phys. Lett. B 323 (1994) 201

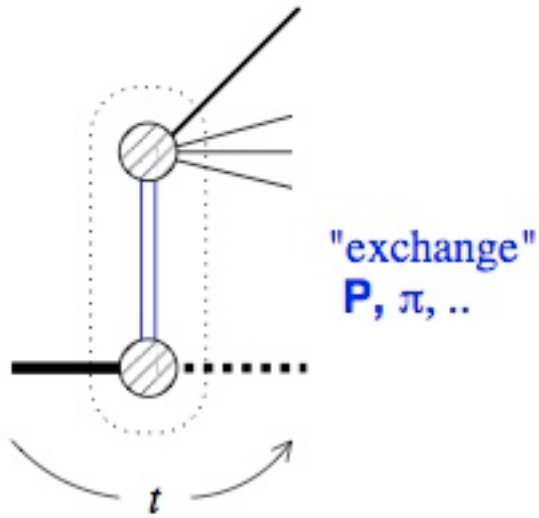
D. Graudenz, Nucl. Phys. B432, (1994) 351

A. Berera and D.E. Soper, Phys. Rev. D53 (1996) 6162

D. De Florian and R. Sassot, Phys. Rev. D56 (1997) 426

J.C. Collins, Phys. Rev. D57 (1998) 3051

Fracture Functions – nucleon structure and dynamics
different physical interpretations in different regions of x

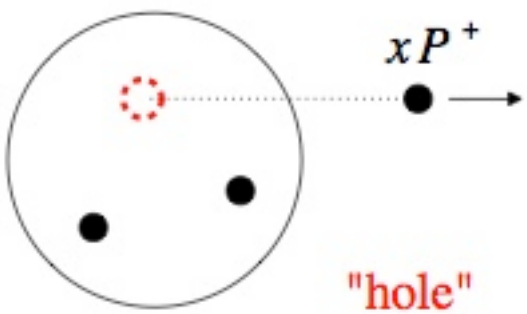


p → p x << 1

Pomeron exchange

p → n or n → p x~0.1

charged pion exchange



x > 0.3

hadronization of nucleon with "hole" in light cone wavefunction

Non-perturbative interactions: χSB fields in QCD vacuum, color confinement

Measuring Fracture Functions

Definition

$f(x,z,p_T)$ =

probability to find hadron in target fragmentation region….

(“tag” the recoil proton)

……after removing a quark with light cone momentum fraction x

(standard DIS $F_2(x)$)

Measure

tagged DIS/untagged (inclusive) DIS

Approach to data analysis

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

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

Proton Structure Function well known, use to obtain:

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

NOTE! This tagged structure function is the unambiguous result!

- Mesonic contribution to nucleon structure function
- Pomeron?
- Look for impact on sea asymmetry

Additional considerations for pion flux:

- Pole extrapolation
- t,z dependence
- p, n difference
- Theory models