Forward baryon production and meson structure in *ep* collisions

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EIC-Asia Workshop on QCD and Hadron Structure

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- High-energy DIS and forward baryon production: reviewing HERA results
- Interpretation with meson exchange model
  - One-Pion Exchange (OPE) models and non-OPE contribution
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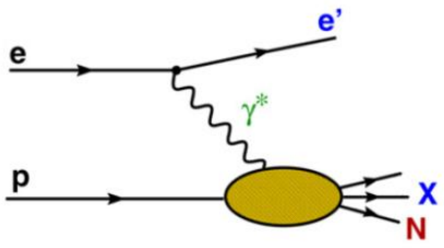
  - Yield of forward protons and neutrons
- Factorisation breaking in baryon production
  - Baryon yield for photoproduction and DIS
  - t dependence of the baryon in inclusive processes
  - cf: exclusive processes (diffraction, vector meson production, DVCS …)
- 1st year measurement at the EIC: what to measure first

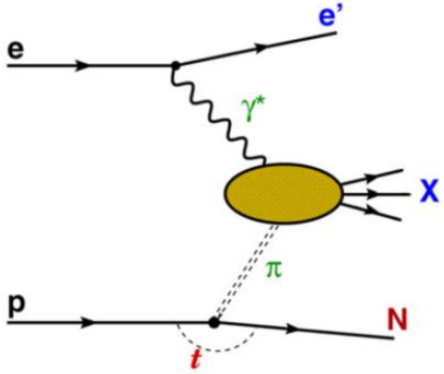
Forward baryon production and DIS

- Baryon number should conserve: there should exist either a proton or neutron
- A popular view: t-channel **particle (meson) exchange**
  - Diffractive production (Pomeron) exists!
- More generic: **fragmentation**
  - **Limiting fragmentation,** in particular: the fragmentation occurs independent of the upper vertex i.e. (x, Q^2)

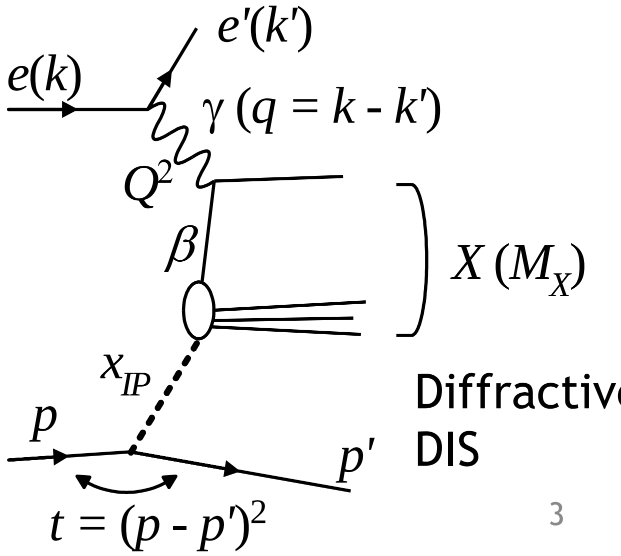
fragmentation



Meson exchange model



$N(z,t)$ or $N(z,p_T)$



Diffractive DIS

Kinematical variables for leading baryons (LNs):

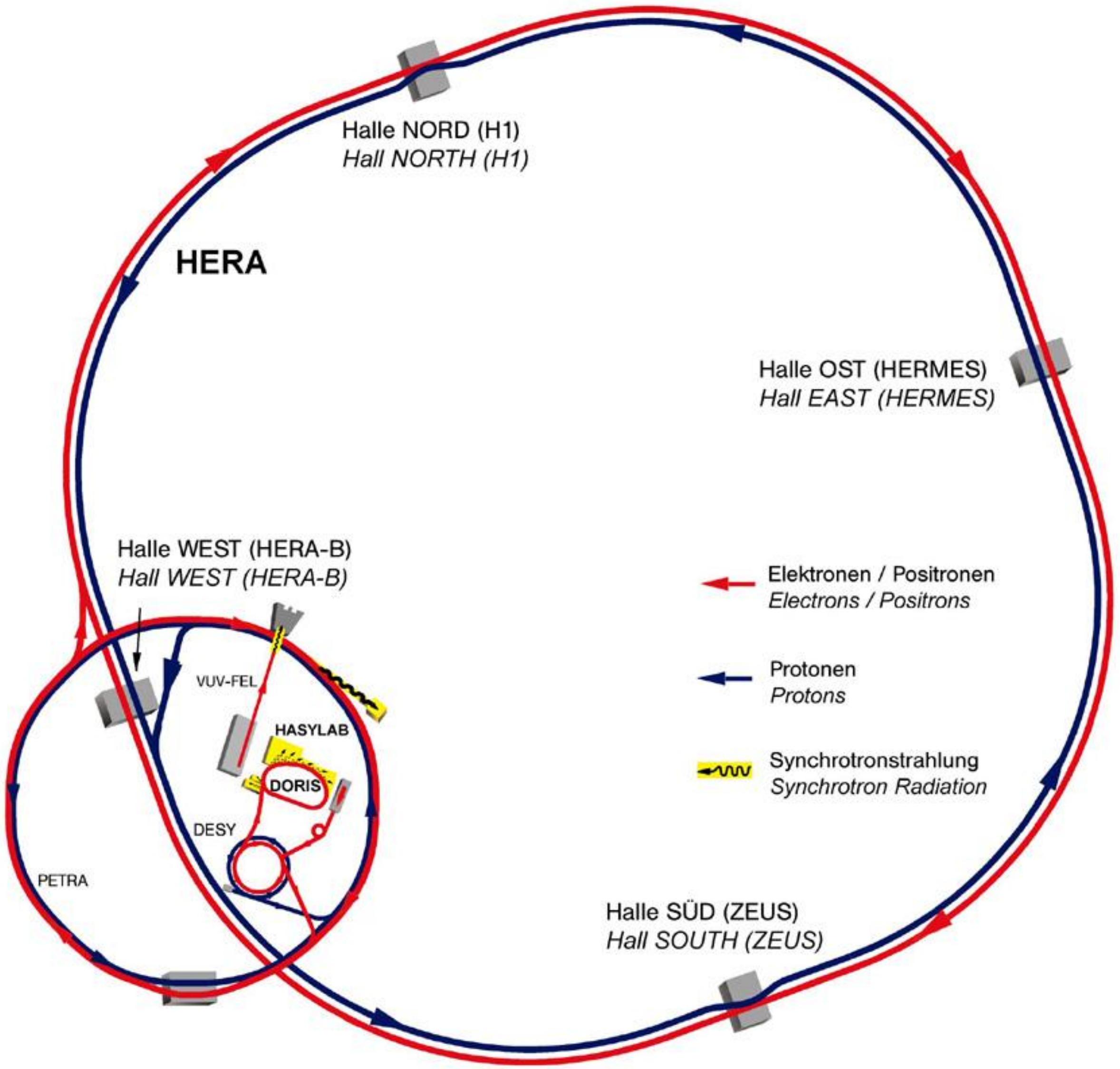
$z = p'_L/p = x_L$: fraction of the longitudinal mom. carried by LN

$p_T(LN) = zp\sin\theta_{LN}$: transverse momentum of the LN

$t = (p - p')^2 \simeq -p_T^2/z = -zp\sin^2\theta_{LN}$

: momentum transfer via the exchange

HERA: the only electron-proton collider (so far)



- Circumference: 6.3 km (similar size to the Tevatron at Fermilab)
- Proton beam: 920 GeV
- Electron/positron beam: 27.5 GeV

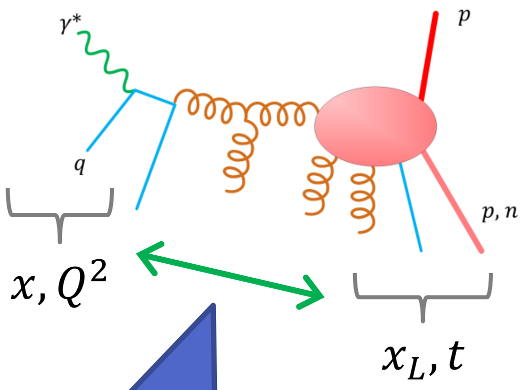
→ centre-of-mass energy $\sqrt{s} = 318\,\mathrm{GeV}$
Resolve structure down to 10^{-18} m

- 220 bunch operation (96ns bunch spacing)
- Operated in 1992-2007

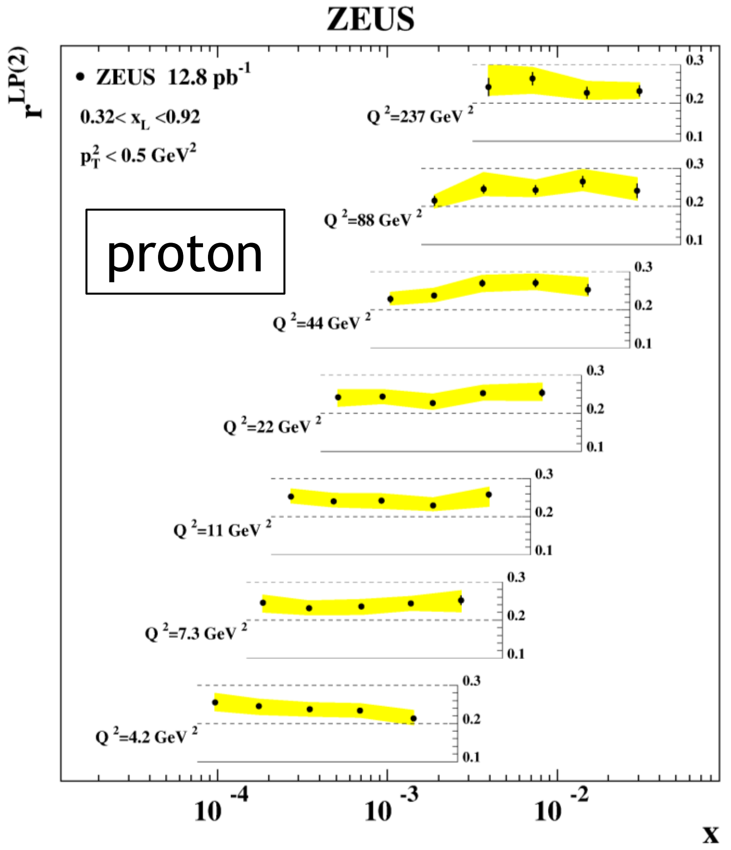
Does the baryon talk to the virtual photon?

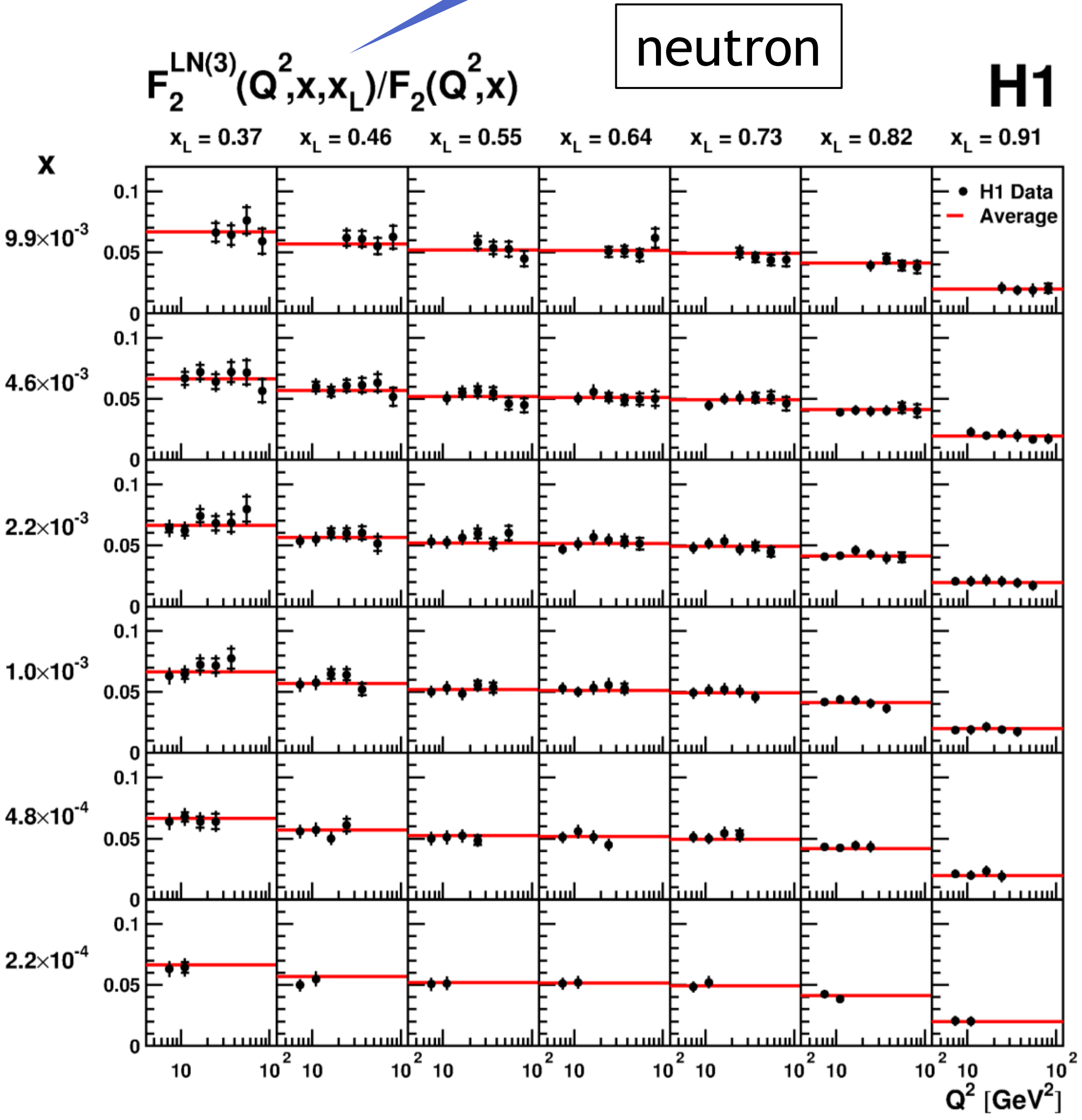
$x_L \equiv z$

- The answer is basically no!
  - No strong yield dependence on $x,\ Q^2$ "limiting fragmentation"



The photon and LN vertices are way separated in rapidity



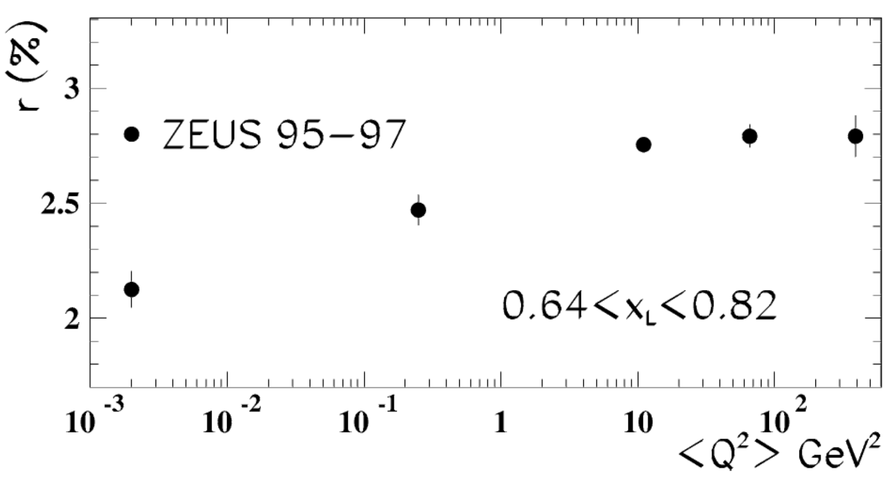


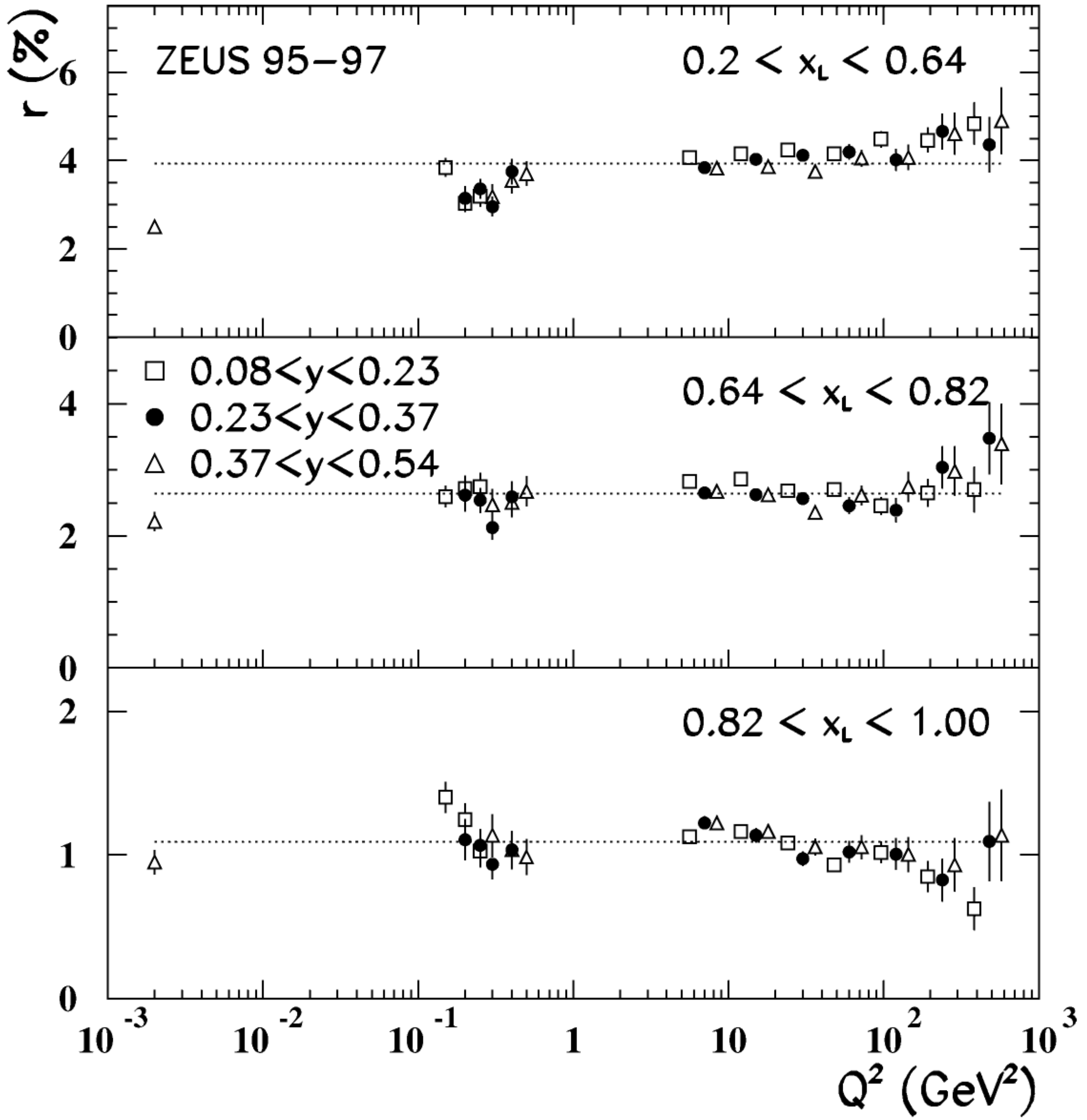
fraction of events with proton is flat in x

… and flat in Q^2 for given (x, z) bins

A bit more in detail: Q^2 dependence?

NPB 637(2002) 3-56 (also right figure)





- slight dependence in Q^2
  - re-scattering (absorption) for photoproduction events? (photon = hadron)
- different dependence for x_L
  - low-x_L : stronger dependence
  - what is the mechanism?

Longitudinal spectrum of the forward neutron

- Limit by aperture, not corrected
  - yield at high z is enhanced
- Still **a peak**, corresponding to **pion exchange**

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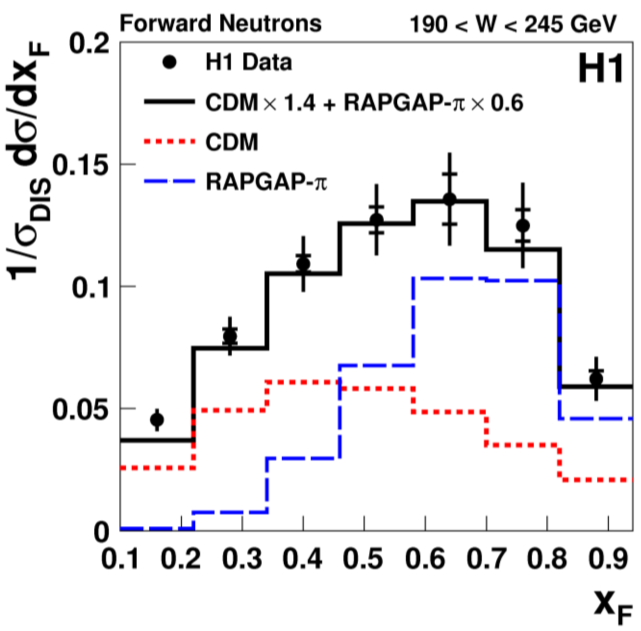

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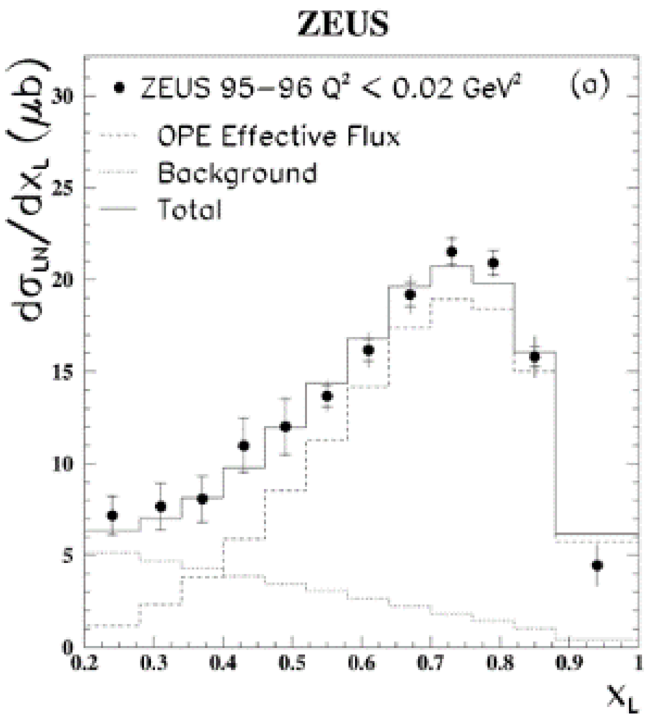
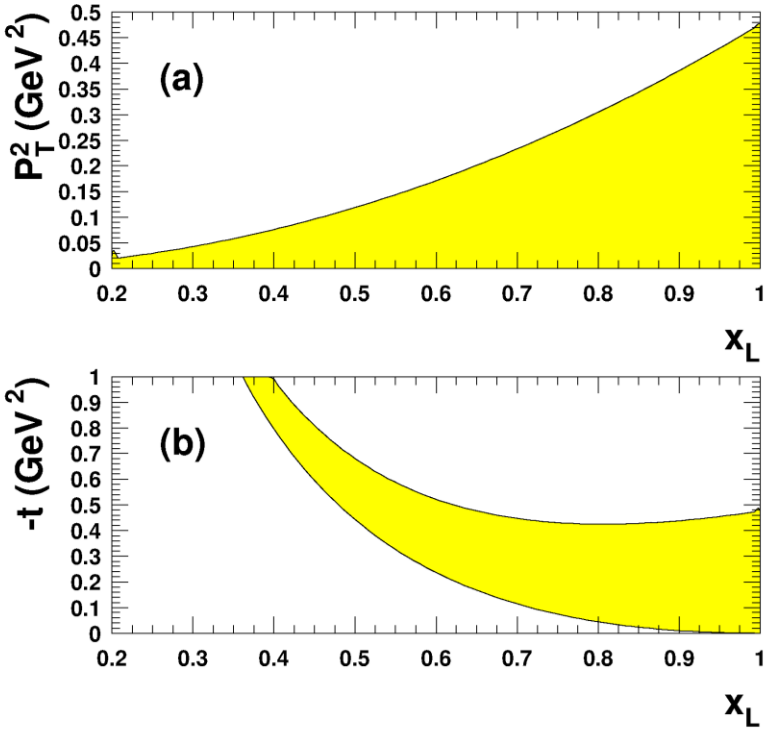
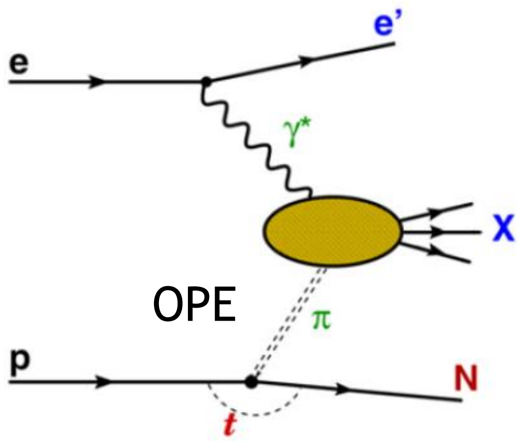
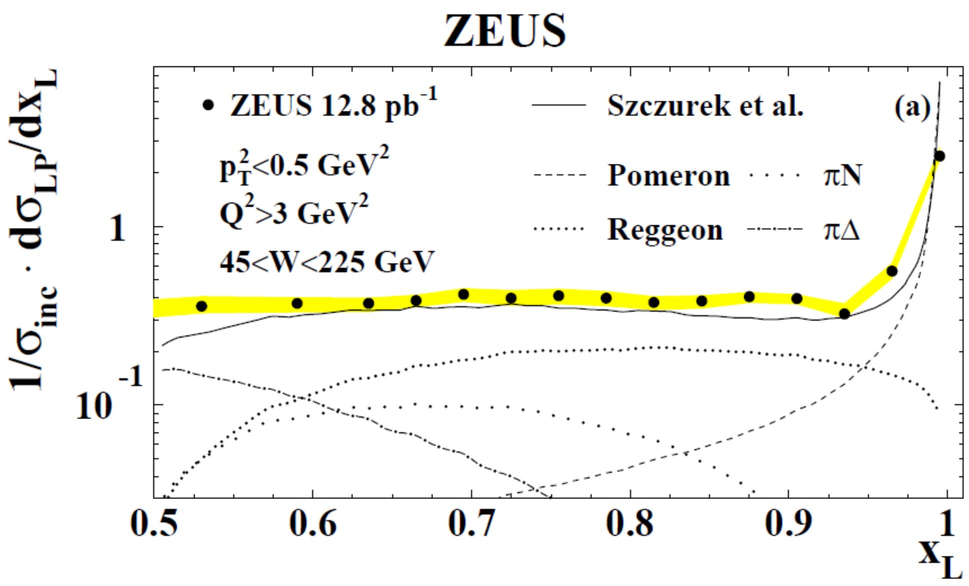


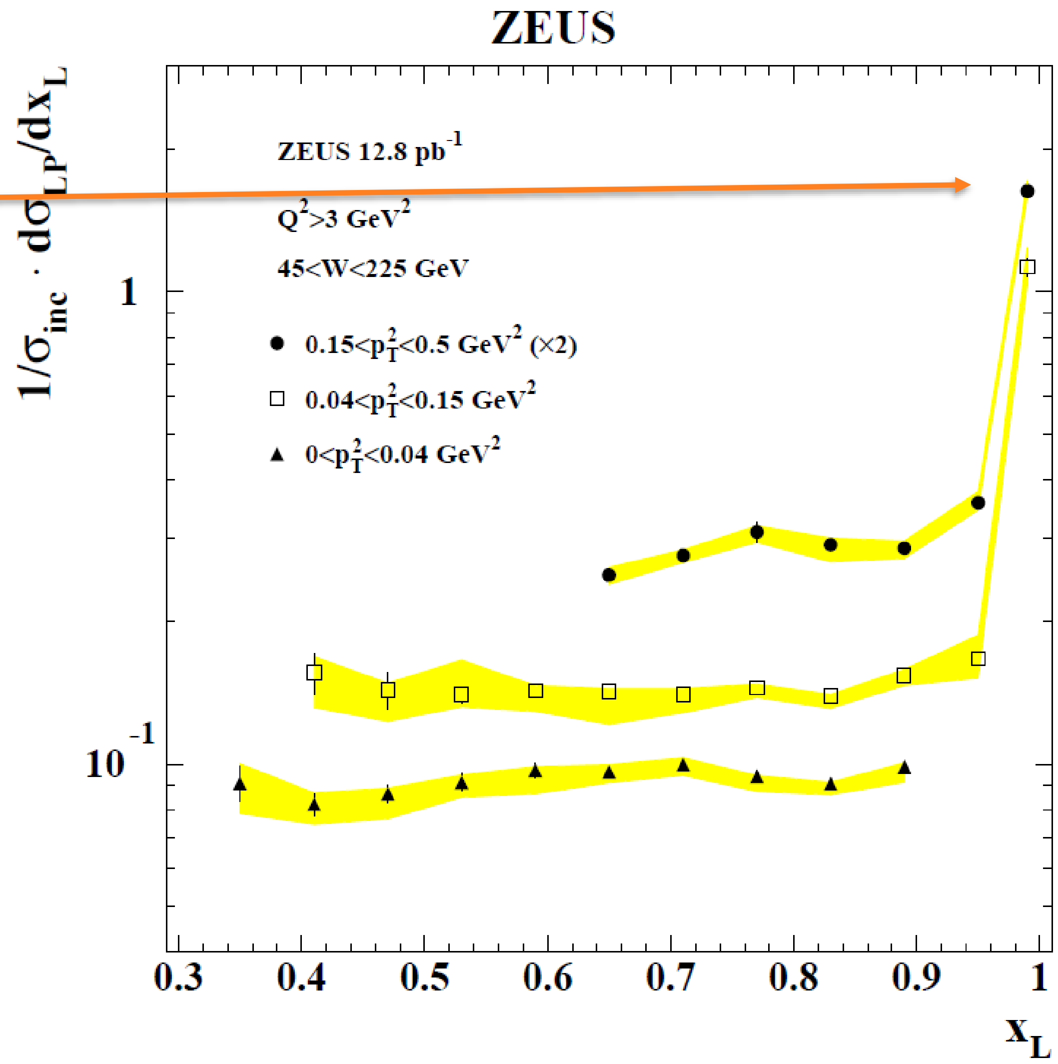




Longitudinal spectrum of forward proton

- $x_L = p_Z^{LB}/p_{beam}$
- Very flat
  (except for diffractive peak)
- Explained by:
  - Limited fragmentation, or
  - pariticle exchange model
    (many Regge poles superimposed)

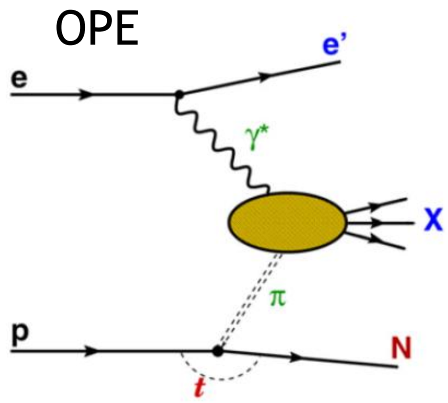




EIC should be able to study much more precisely

Meson exchange model and pion structure

The formalism of pion exchange



- The cross section = $\sigma(\gamma^*\pi) \times$ (pion flux): **Regge factorisation**

$$\frac{d^2\sigma(W^2, Q^2, z, t)}{dzdt} = f_{\pi/p}(z,t)\sigma_{\gamma^*\pi}\left((1-z)W^2, Q^2\right)$$

- The $f_{\pi/p}(z,t)$ takes the following form in most of the models:

$$f_{\pi/p}(z,t) \propto -\frac{t}{(t-m_\pi^2)^2}(1-z)^{\alpha(t)}F^2(z,t)$$

$\alpha(t)$: pion trajectory

$F(z,t)$: introducing cutoff at the low-t end

$F = 1$ (Bishari)

$F = \exp\frac{t-m_\pi^2}{\Lambda^2}$ (Holtman and others: generalized form of monopole $F = \left(\frac{\Lambda^2-m_\pi^2}{\Lambda^2-t}\right)$)

p_T spectrum of neutrons

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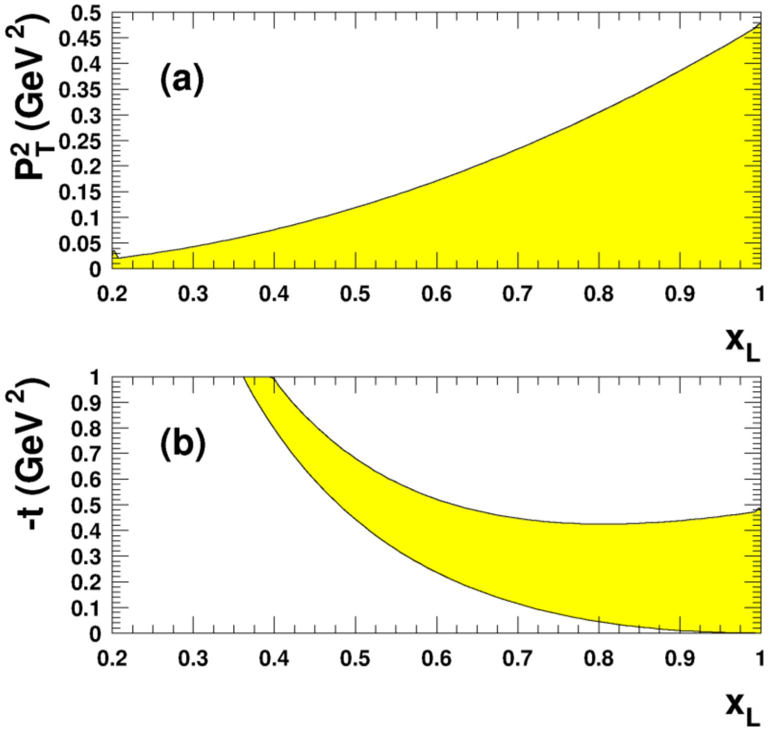
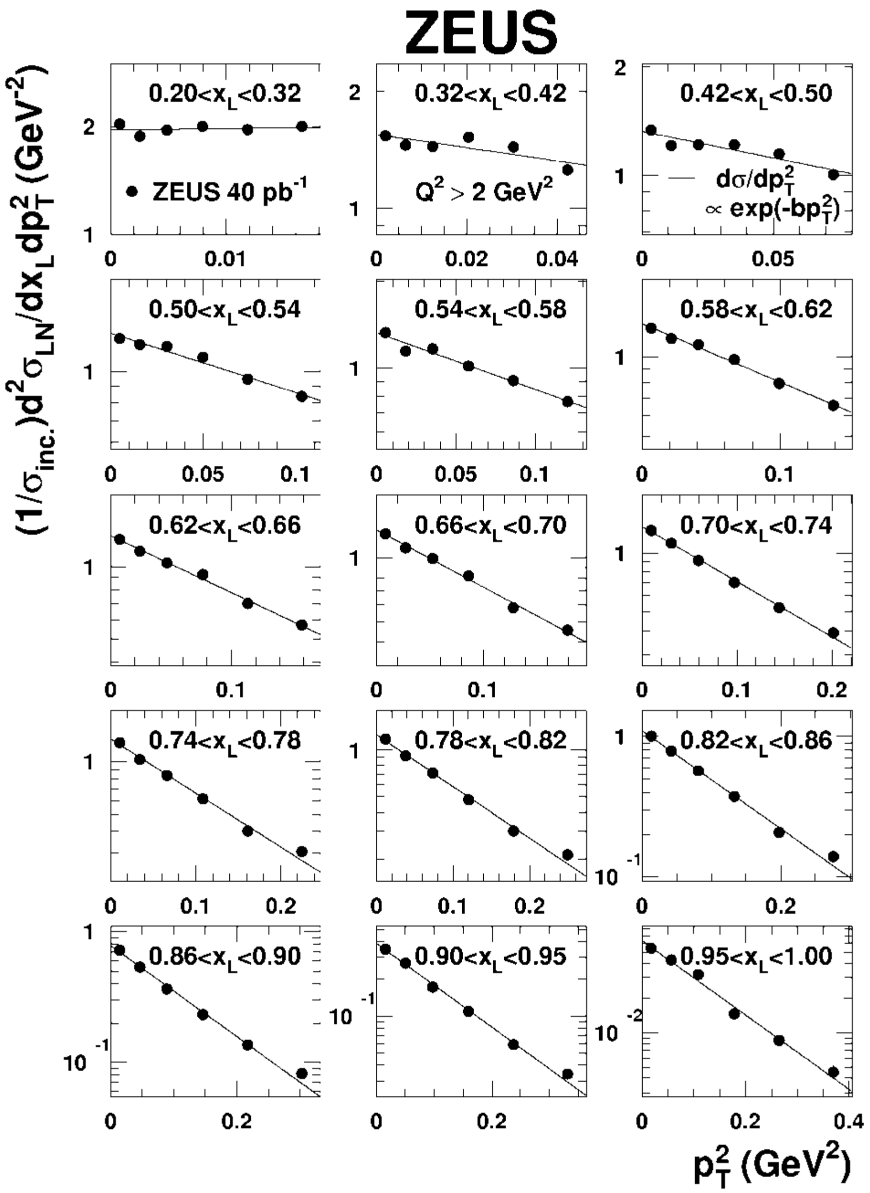
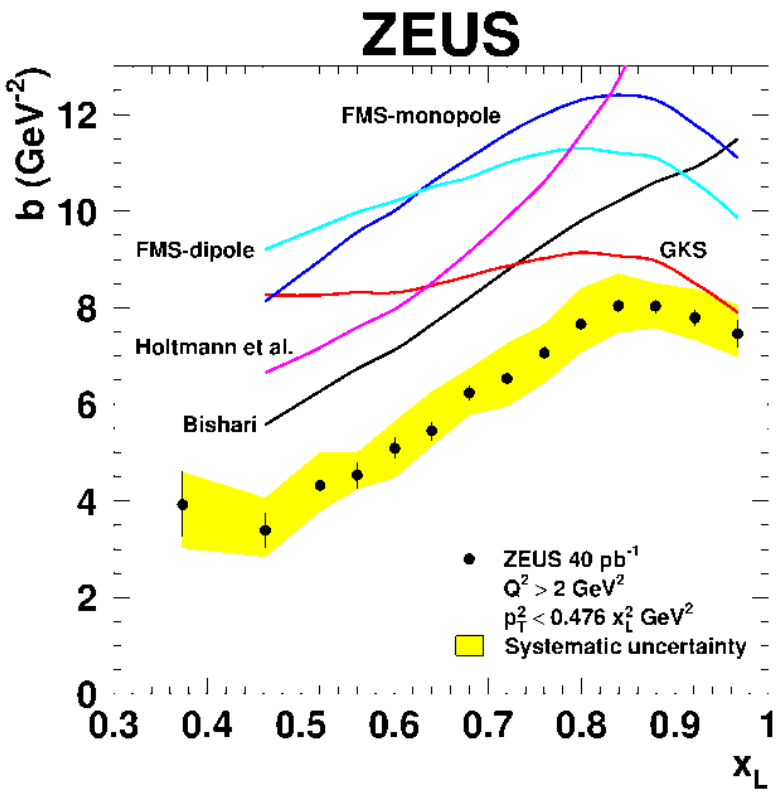
- Exponential behaviour in low-t regions
  - Seems to have rapid change in slope as a function of $x_L = z$
  - … even through it is visually enhanced by the acceptance change vs x_L

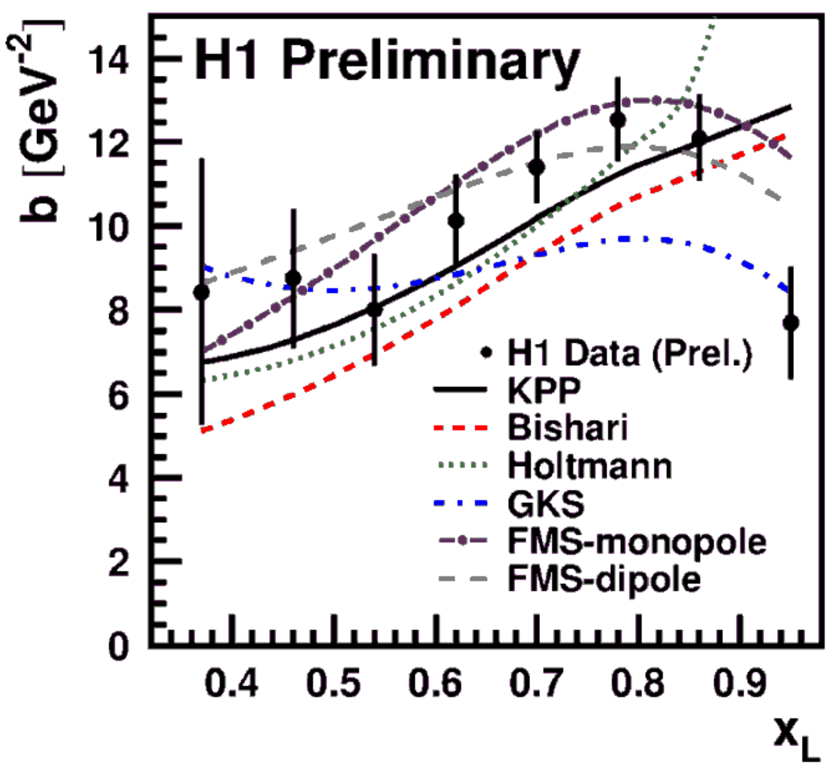




Forward neutron: rich structure in b-slope

- Compared to various pion flux (e.g. $\pi - n$ vertex factor shape)
  - Qualitatively in agreement with various models
  - Need to evaluate sub-leading components near $z = 1$ and **low-z**
    - sub-leading meson exchange and/or non-diffraction (standard fragmentation)



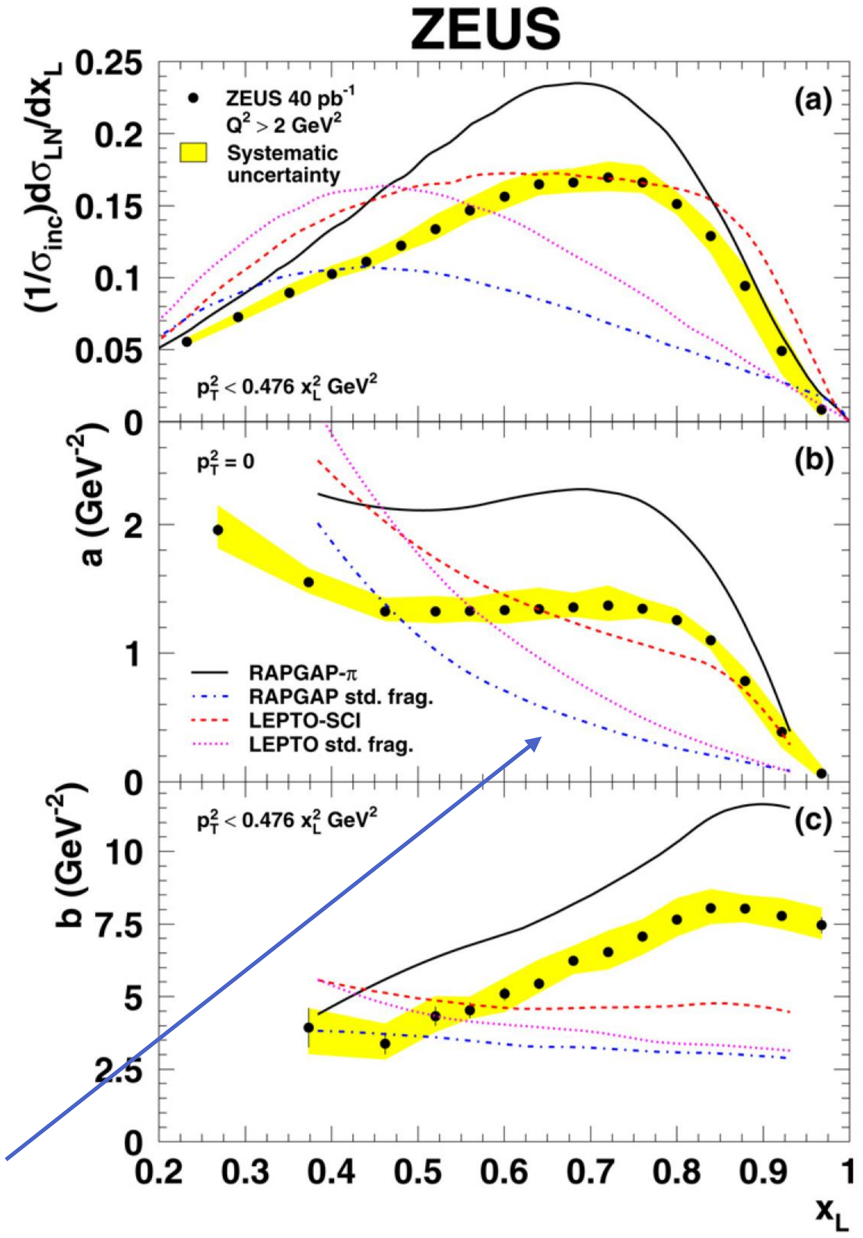


Need precise (p_T, z) spectrum at the EIC for measuring the pion flux

Comparison with non-pion-exchange models

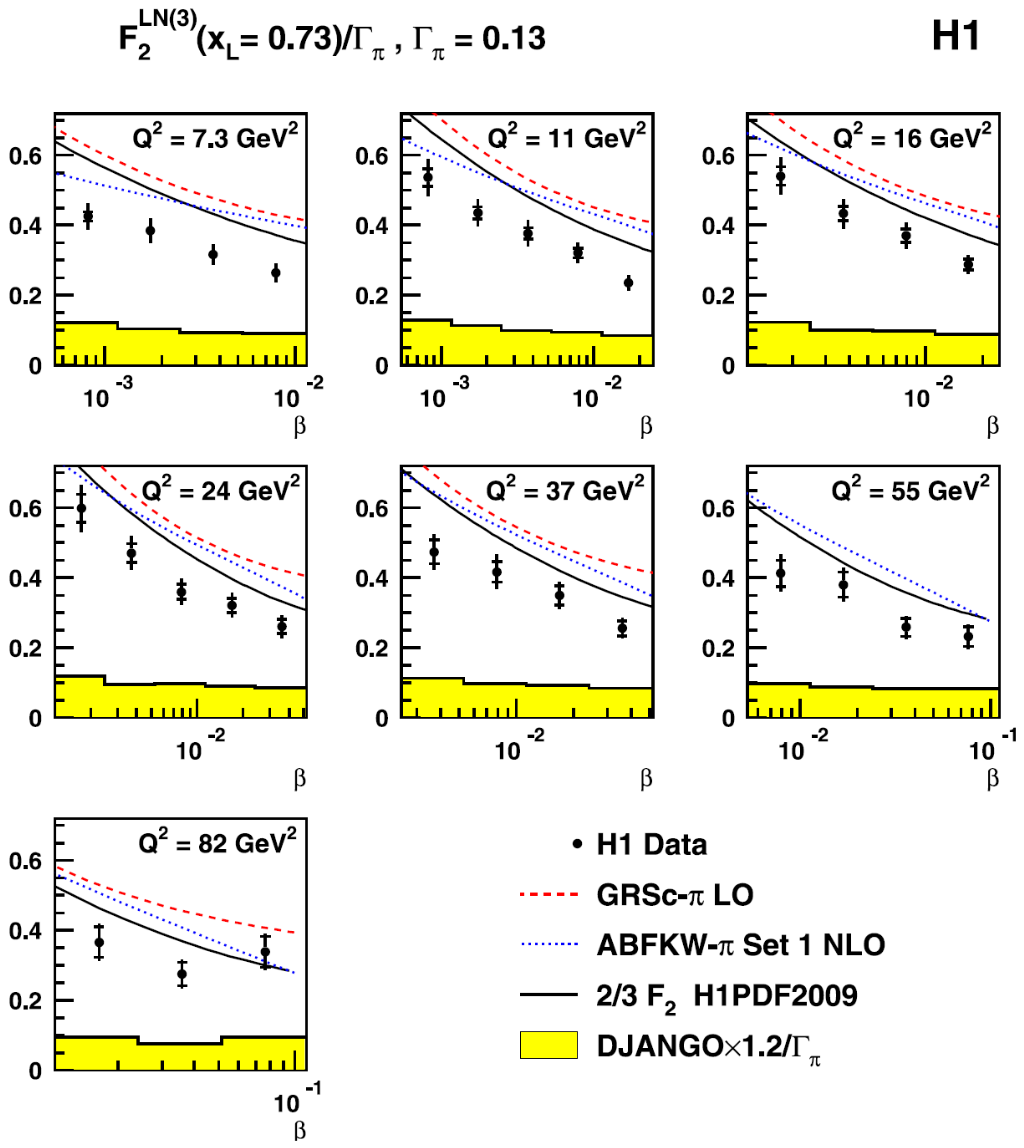
- SCI model: soft-colour interaction, i.e. generic t-channel exchange of soft partons
  - unified model for fragmentation + particle exchange (no double counting)
  - can explain the observed, peak somewhat
  - p_T spectrum too broad
- Models based on fragmentation only
  - "pion" peak missing
- How do we bridge the pion exchange model and the standard fragmentation at middle/low z?

Non-diffractive process may be background to OPE
Need to go to high-z to avoid that



HERA extraction of the pion structure function

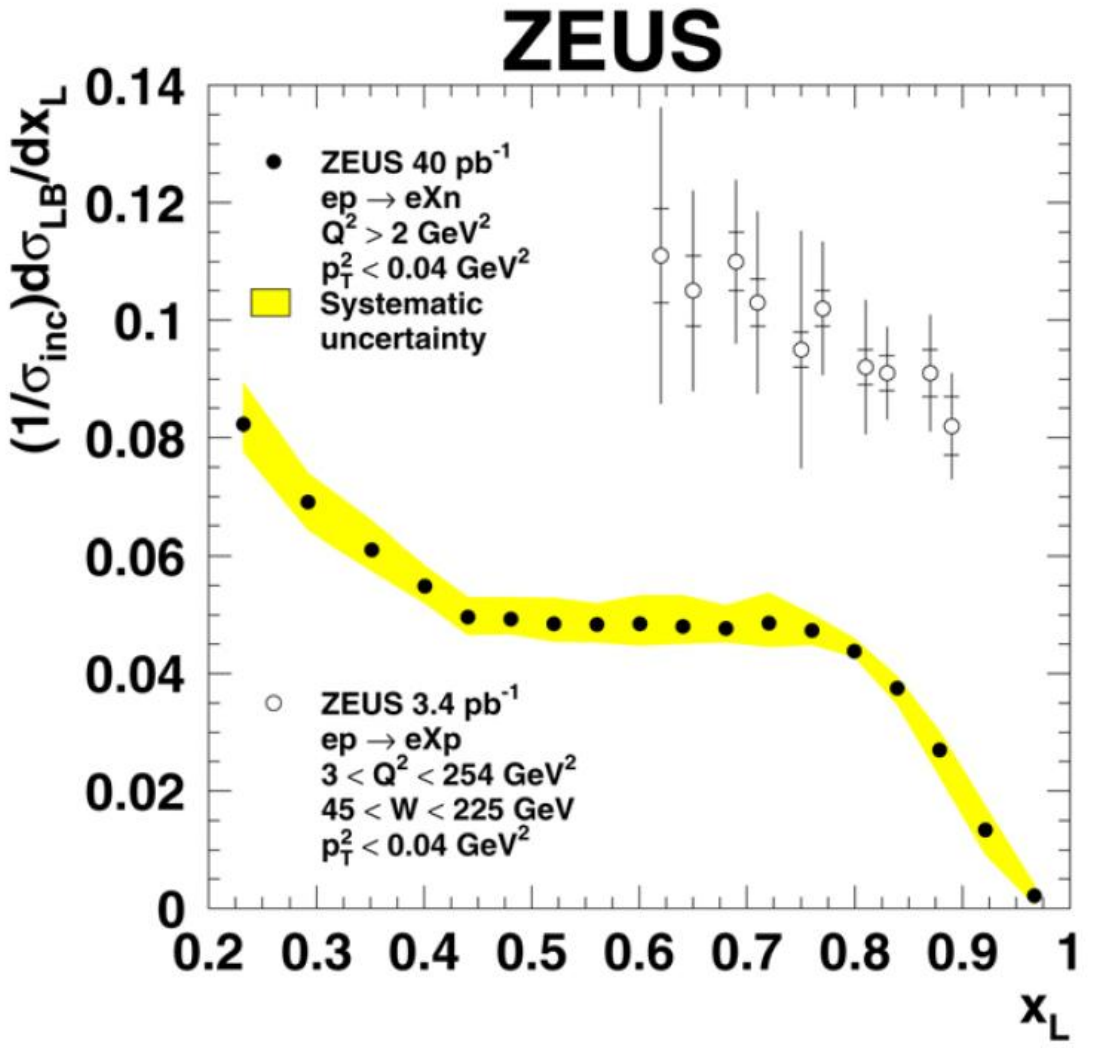
- $x_\pi = \beta \equiv x_{Bj}/(1-x_L)$
  $x_L \equiv z$: neutron momentum fraction
  - the shape of the SF for proton and pion should be the same if $F_2^p \propto x^{-\lambda}$ with constant λ ($1-z$ just rescales x for x_π)
  - This holds quite well: see 2/3 F2 H1PDF2009, which is the proton structure function!
- The absolute value of **the SF is smaller**
  - ZEUS similar (even smaller)
  - **What is the reason?**
- EIC: high-x_π SF possible with high statistics



Why are the pion SFs too small?

- Naïve isovector exchange: neutrons are more than proton in the final state of hadron-hadron collisions
- This was not the case at HERA! More protons there for very forward range $p_T^2 < 0.04\ \mathrm{GeV}^2$
- Where are these neutrons?
  - or are there more protons than expected?

This must be the first thing to check!



To be away from the flux uncertainty …

- The F-term of the **pion flux is unity near $t = t_{min}$** (e.g. $F = \exp\frac{t-m_\pi^2}{\Lambda^2}$)
  - Smaller uncertainty in the flux
  - Also the exchanged pion is on-shell-like there
- **Need measure near the t threshold = very low p_T**
- For that, we need:
  - neutron position resolution
  - very precise determination of zero degree
  - low beam spread

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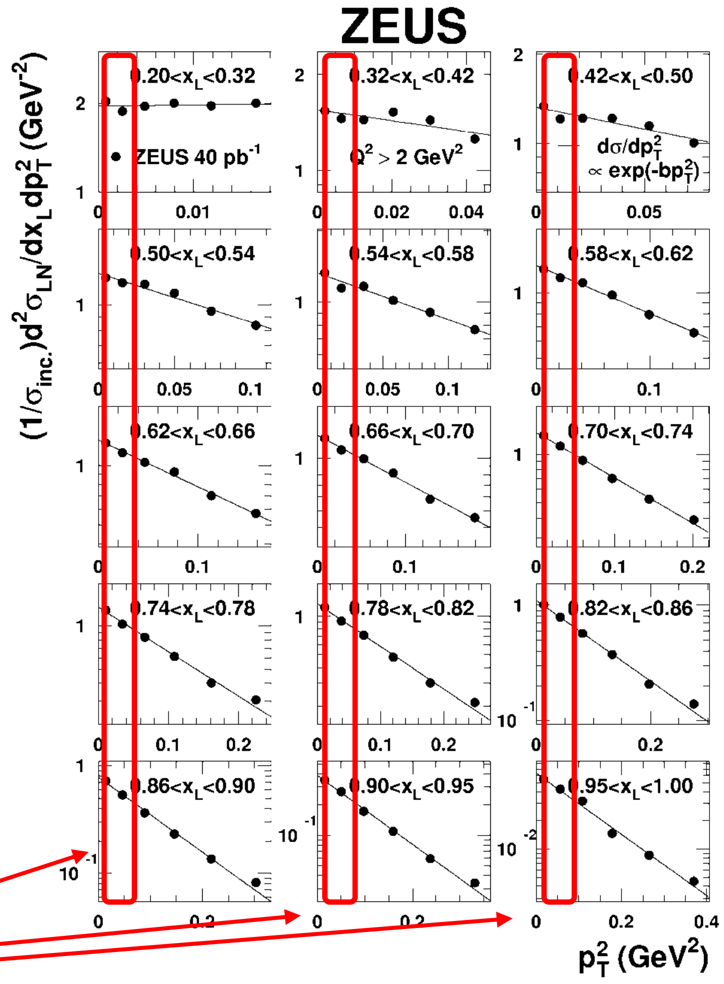
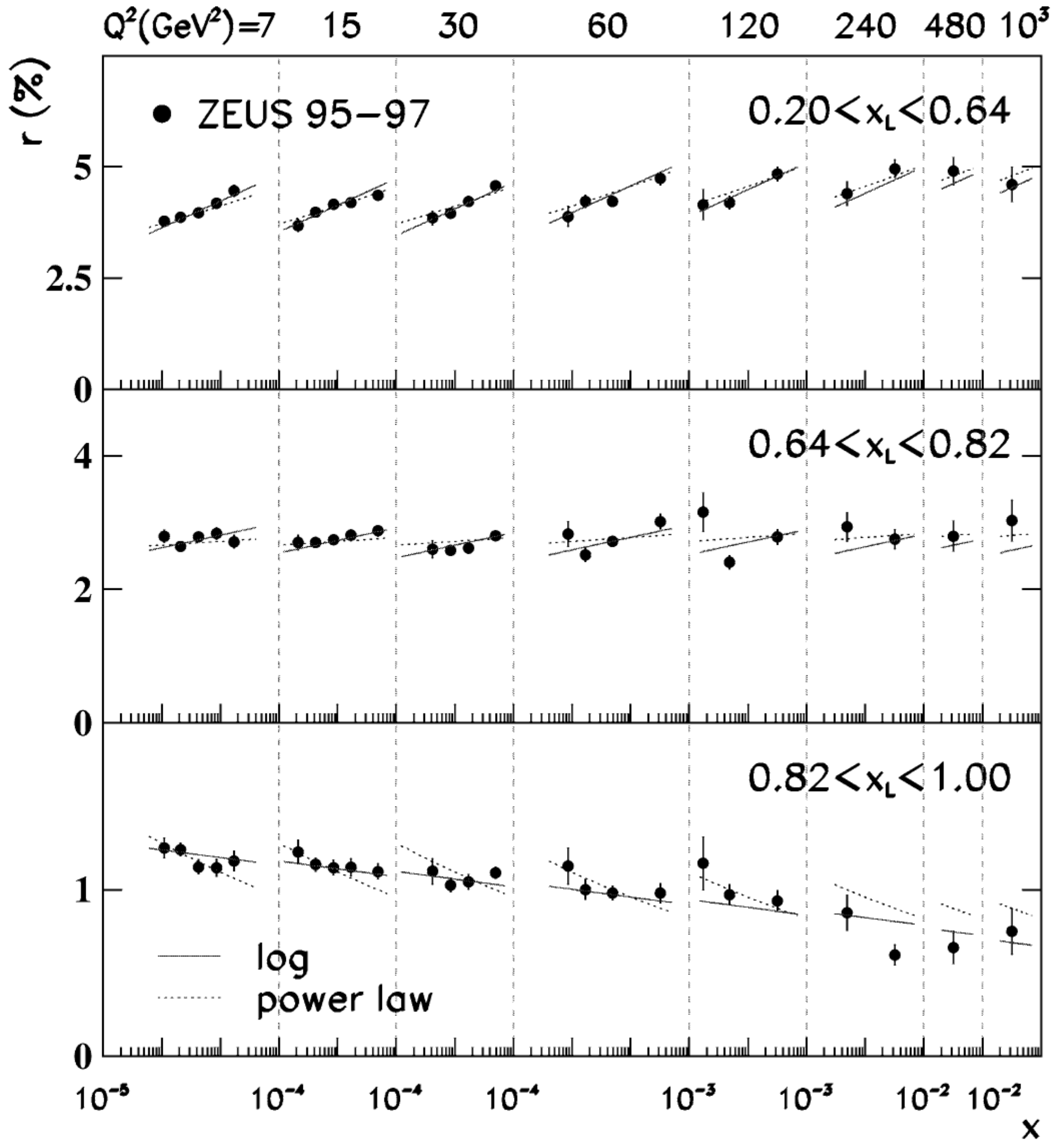


Focusing on these points!

Possible factorisation breaking in baryon production

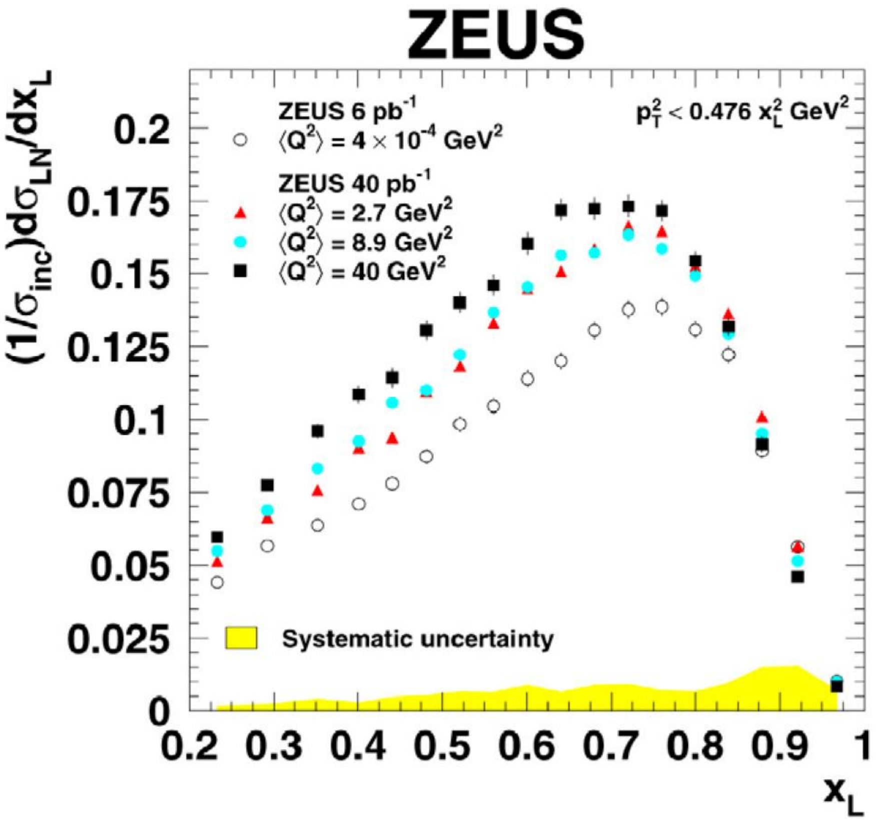
Fraction of events with forward neutrons: x-dependence?

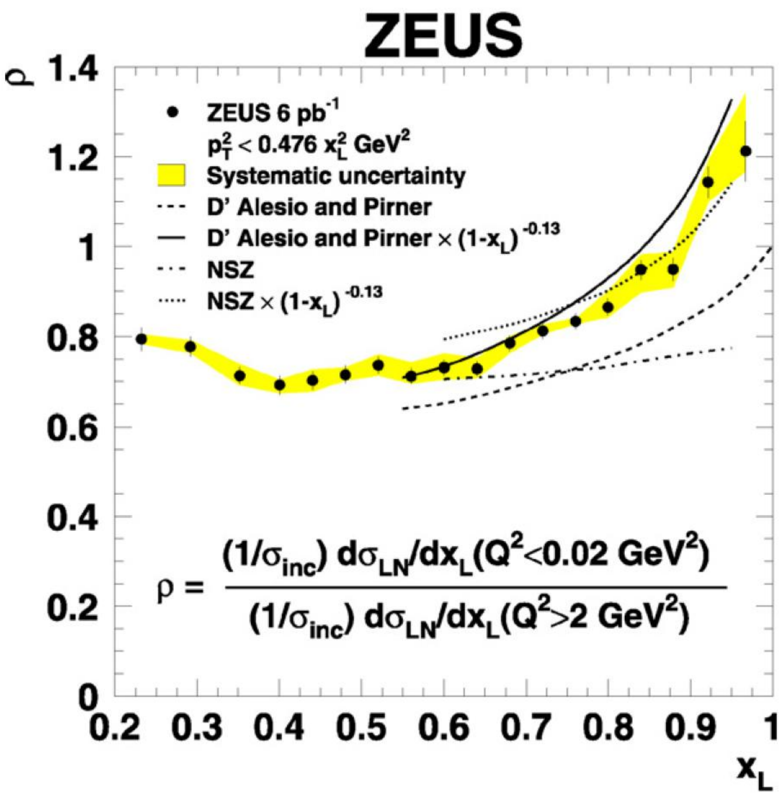
- Leading neutron events have very high statistics (> 10% of DIS)
  - very detailed kinematic dependence can be studied
  - factorization or not?
    it seems we have logarithmic factorization breaking
    It was not conclusive within DIS

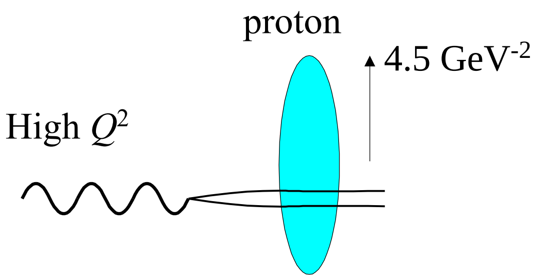


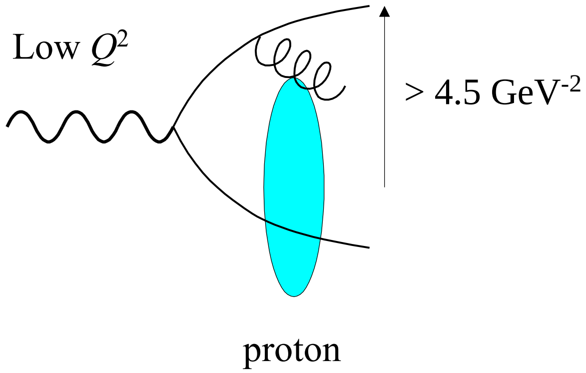
In Q^2: (photoproduction) / (DIS $Q^2 > 2\ \mathrm{GeV}^2$)

- Mild suppression in photoproduction = large photon
  - implying 20-30% absorption **(re-scattering)**
- clear $x_L = z$ dependence on the ratio photoproduction / DIS



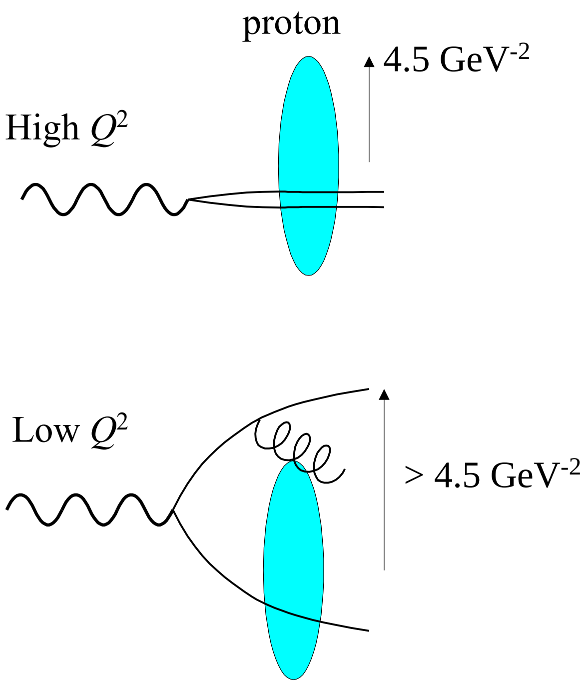


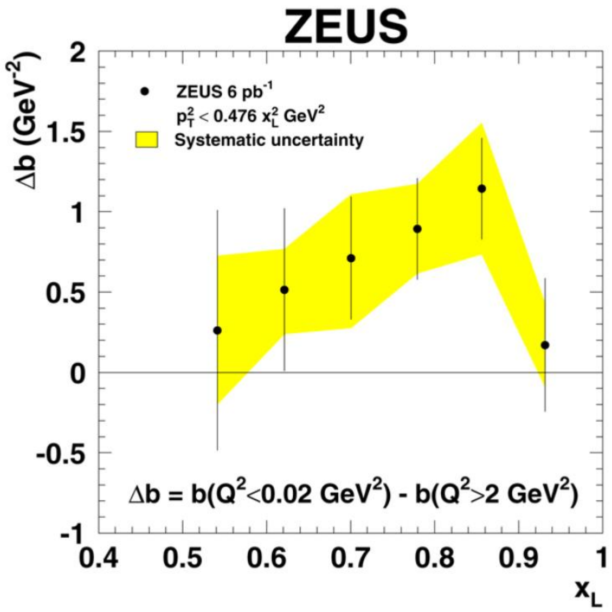


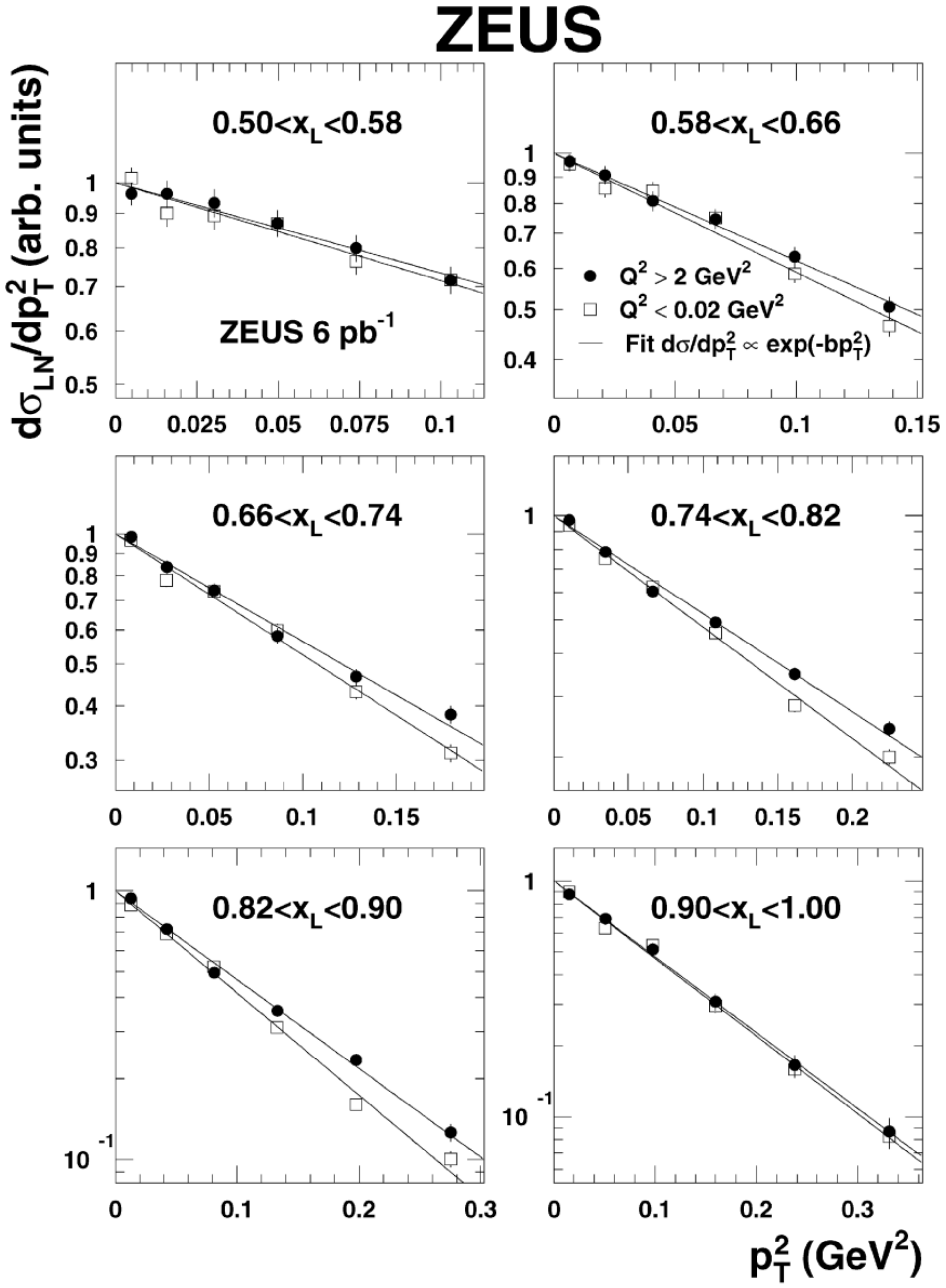


Slope $Q^2 \simeq 0$ vs $Q^2 > 2$ GeV

- We see factorisation breaking in the slope too
  - Absorption or rescattering of "small configuration" = large overlap

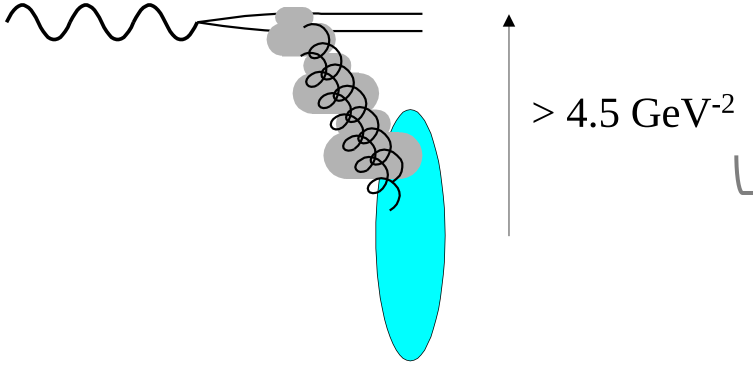


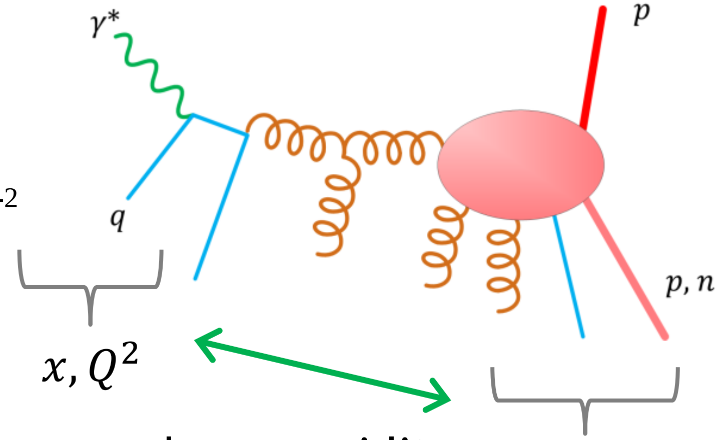


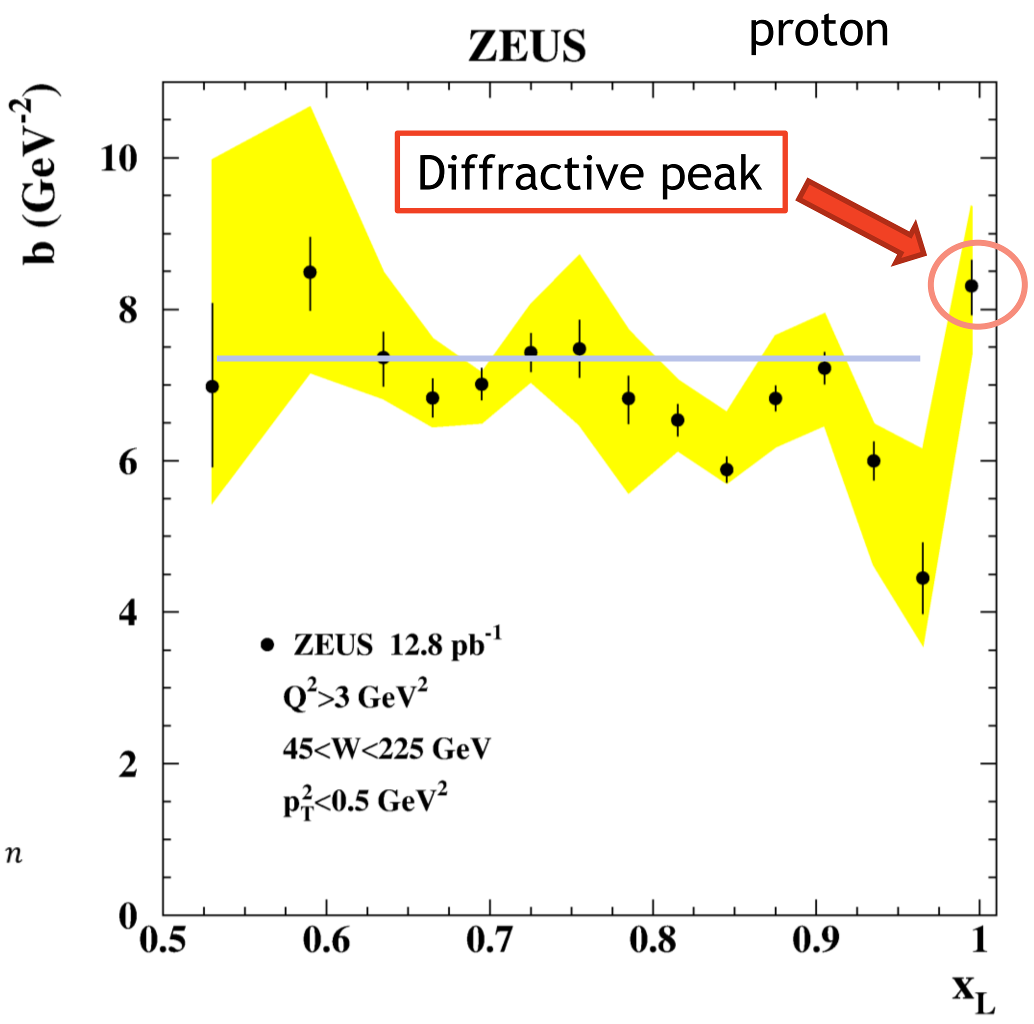


B-slope of leading baryons at HERA

- Proton: flat at $b \sim 7\ \mathrm{GeV}^{-2}$ ($\sigma \propto e^{-bp_T^2}$)
  - Larger than the proton size
  - The vertex is somewhat soft = peripheral but not too soft either (unlike elastic pp)
  - Large rapidity separation between the dipole and the forward system at high energies may smear the transverse size

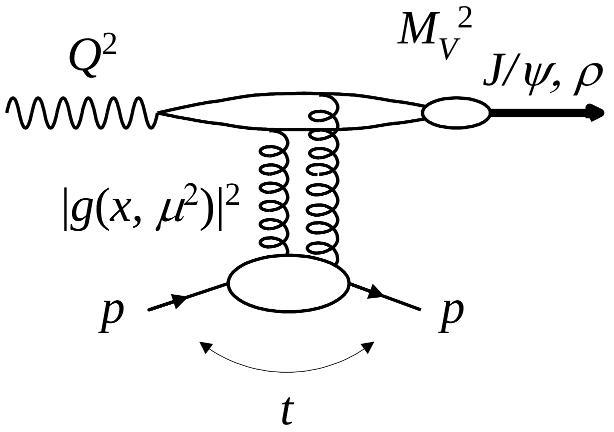


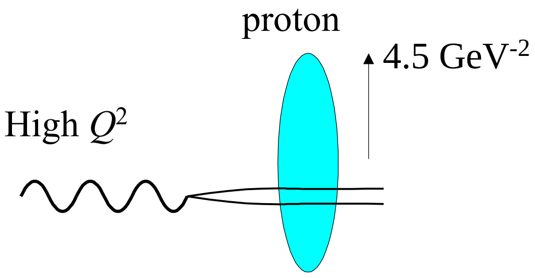




cf. b-slope for vector meson electroproduction

- Where does the dipole size become negligible?
  - Seems to have universal behaviour as a function of $Q^2 + M_V^2$
    M_V: vector meson mass
- Asymptotically approaches to $b \simeq 5\ \mathrm{GeV}^{-2}$ around $Q^2 + M_V^2 \simeq 10\ \mathrm{GeV}^2$
  - Slightly smaller than the forward baryon b-slope ($7\ \mathrm{GeV}^{-2}$)





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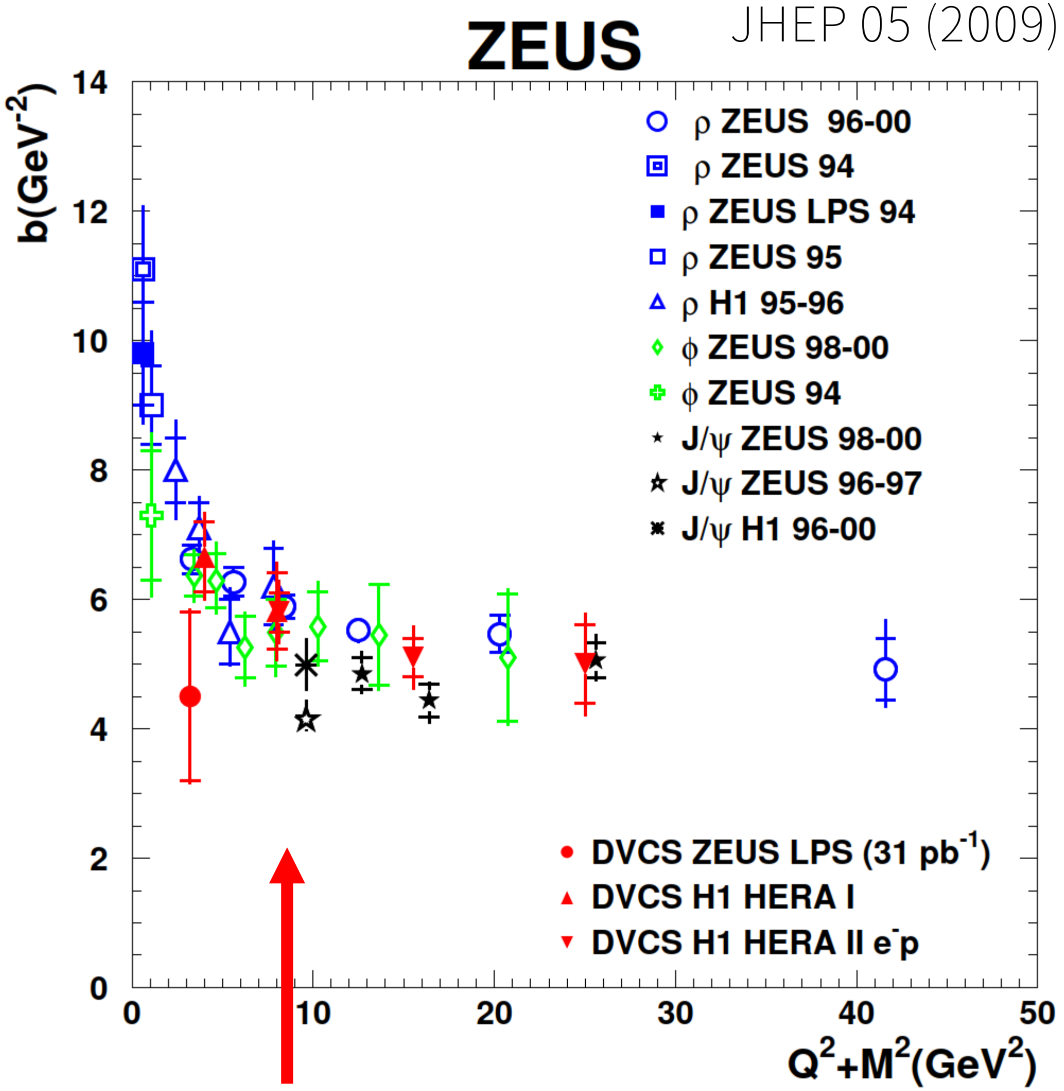
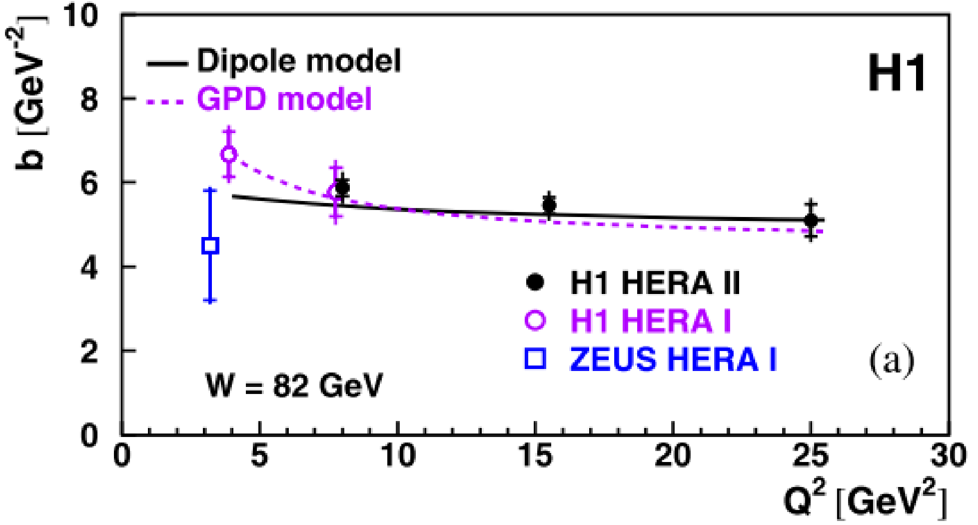
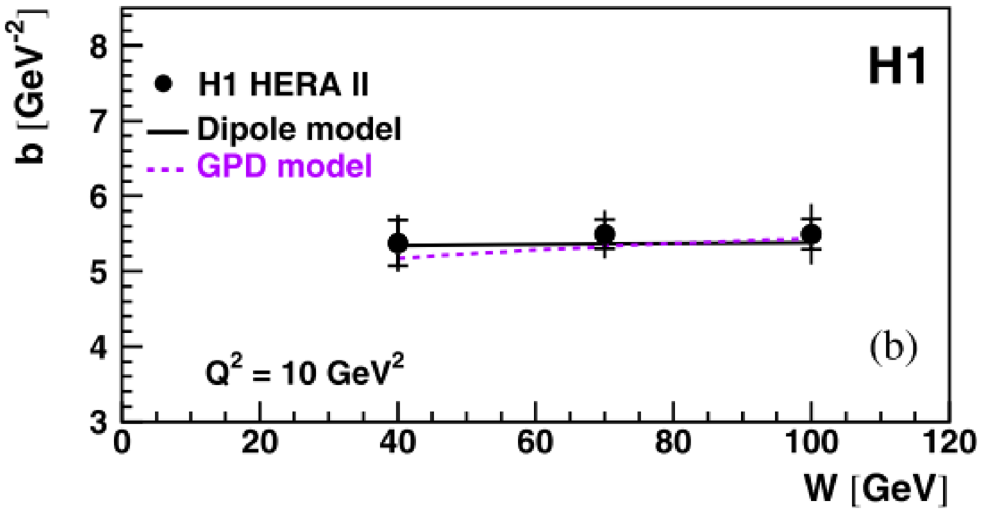


Somewhere around here

DVCS b-slope

- GPD model seems to have been describing the increase in b when the hard scale is absent





JLab t-slope for exclusive J/ψ production

- Exclusive photoproduction $\gamma p \rightarrow J/\psi\ p$ from J/ψ-007 and GlueX experiments
  - Compilation in arXiv:2512.15064, by M. Boer et al.
  - Interpreted as energy-momentum tensor, then Fourier-transformed to extract the shape in radius

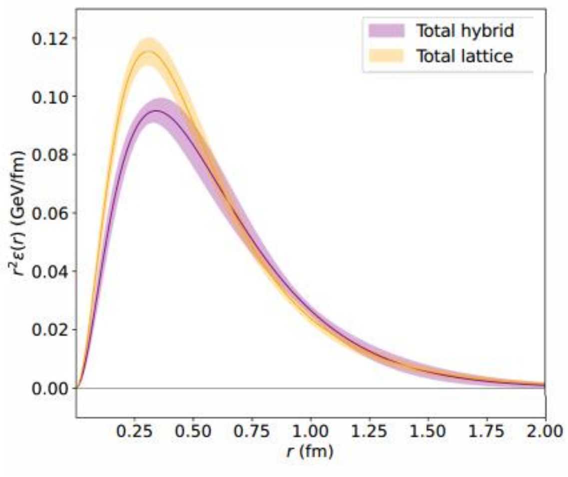
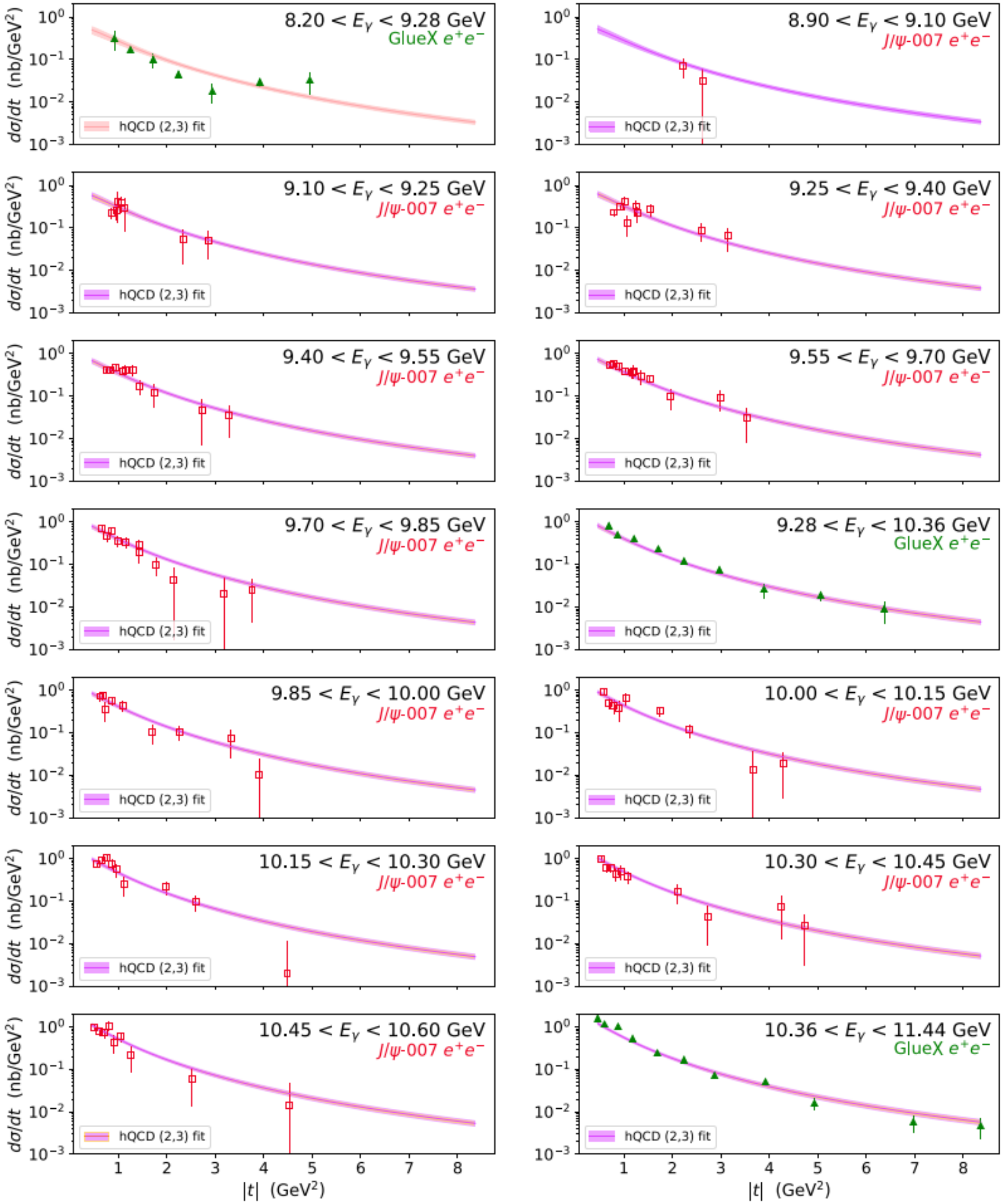


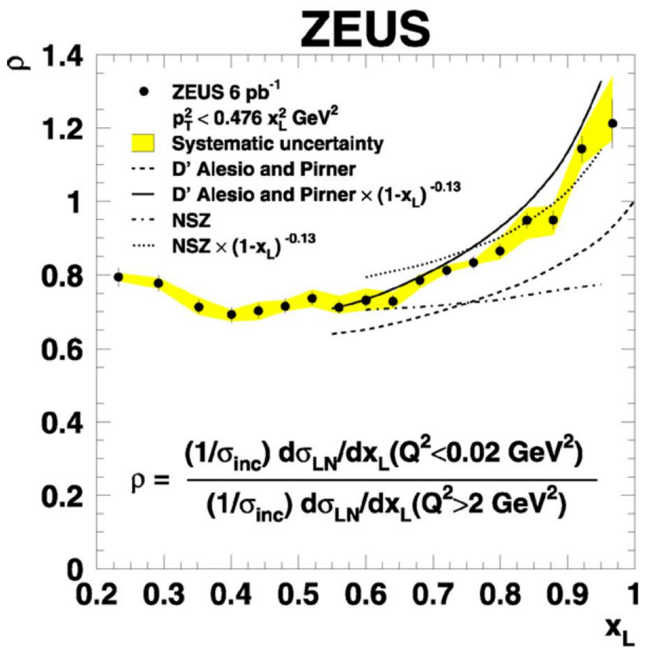
Fig. 12 The total mass density where we combined the gluon extraction FFs from Fig. 11 and the quark FFs evaluated in lattice [219].



Towards pion structure:
day-1 measurements at the EIC

The day-1 measurement we need to do for neutrons

- p_T spectrum vs z is absolutely important
  - Very good p_T (position) resolution detector for neutrons
  - "beam spot" = zero-degree determination
  - need for runs with small beam spread in p_X, p_Y: **large $\boldsymbol{\beta}^*$ = low lumi runs**
- Need to measure (z, p_T) spectrum in sufficiently narrow (x, Q^2) bins
  - **to first test the Regge factorisation Ansatz:**
    $$\frac{d\sigma(W^2,Q^2,z,t)}{dzdt} = f_{\pi/p}(z,t)\sigma_{\gamma^*\pi}\left((1-z)W^2, Q^2\right)$$
  - At HERA (was $40\ \mathrm{pb}^{-1}$ data): only $Q^2 \simeq 0$ vs $Q^2 > 1\ \mathrm{GeV}^2$, or fine bins in Q^2 but not in (z,t)
    - Need $\gg 100\ \mathrm{pb}^{-1}$ to map (x, Q^2, z, t) but may not need $\gg 1\ \mathrm{fb}^{-1}$
  - Need photoproduction data: may need ZDC coincidence for saving photoproduction data if it is not saved by default in the current streaming scheme



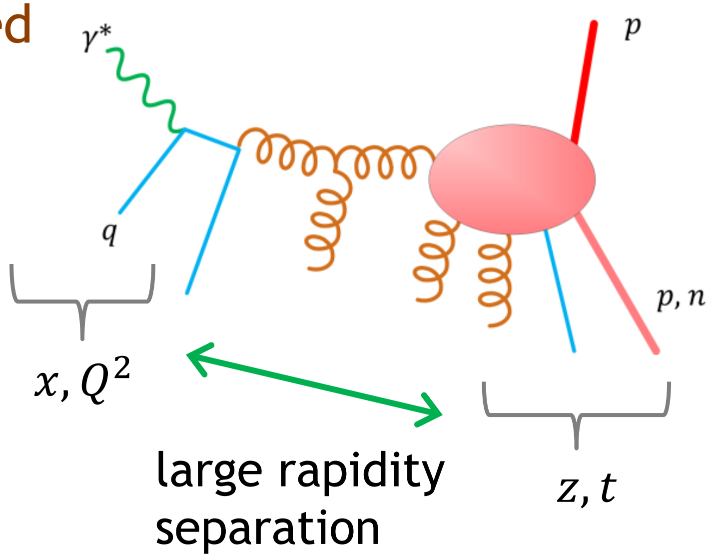
Limiting fragmentation and "Regge" factorization

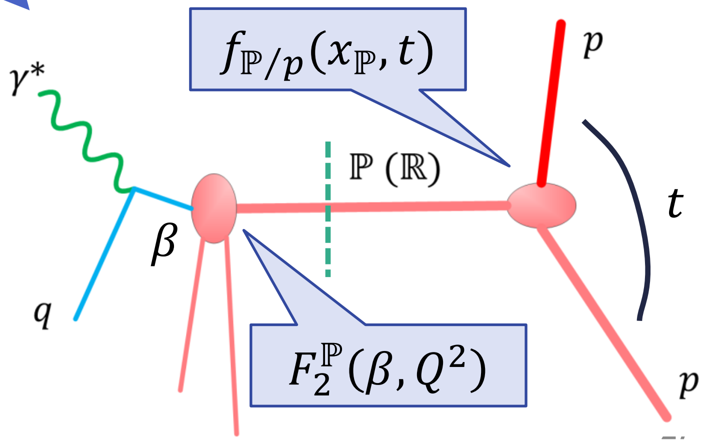
- **Limiting fragmentation:** the LN variables (z, t) are independent of (x, Q^2)
  - large rapidity separation, (almost) no information propagated
- **Regge factorisation:** the cross section is the product of the (particle flux) $\times$ $\sigma(\gamma$-particle)

$$\frac{d\sigma(W^2, Q^2, z, t)}{dzdt} = f_{\pi/p}(z,t)\sigma_{\gamma^*\pi}((1-z)W^2, Q^2)$$

- **For both models, factorisation holds** between photon vertex (x, Q^2) and baryon vertex (x_L, t)
  - The independence does not distinguish the two models
  - Proof of the Regge factorization:

    $\sigma_{\gamma^*\pi}$ is independent of the soft vertex variables z and t
    - E.g. pion structure function should be independent of x_L values: we could measure in a few bins in x_L

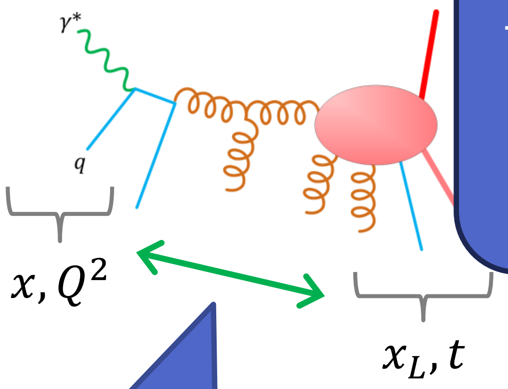




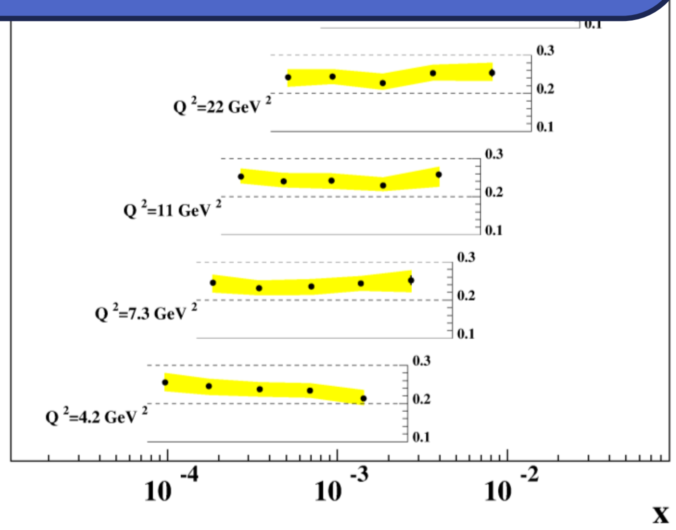
Does the baryon talk to the virtual photon?

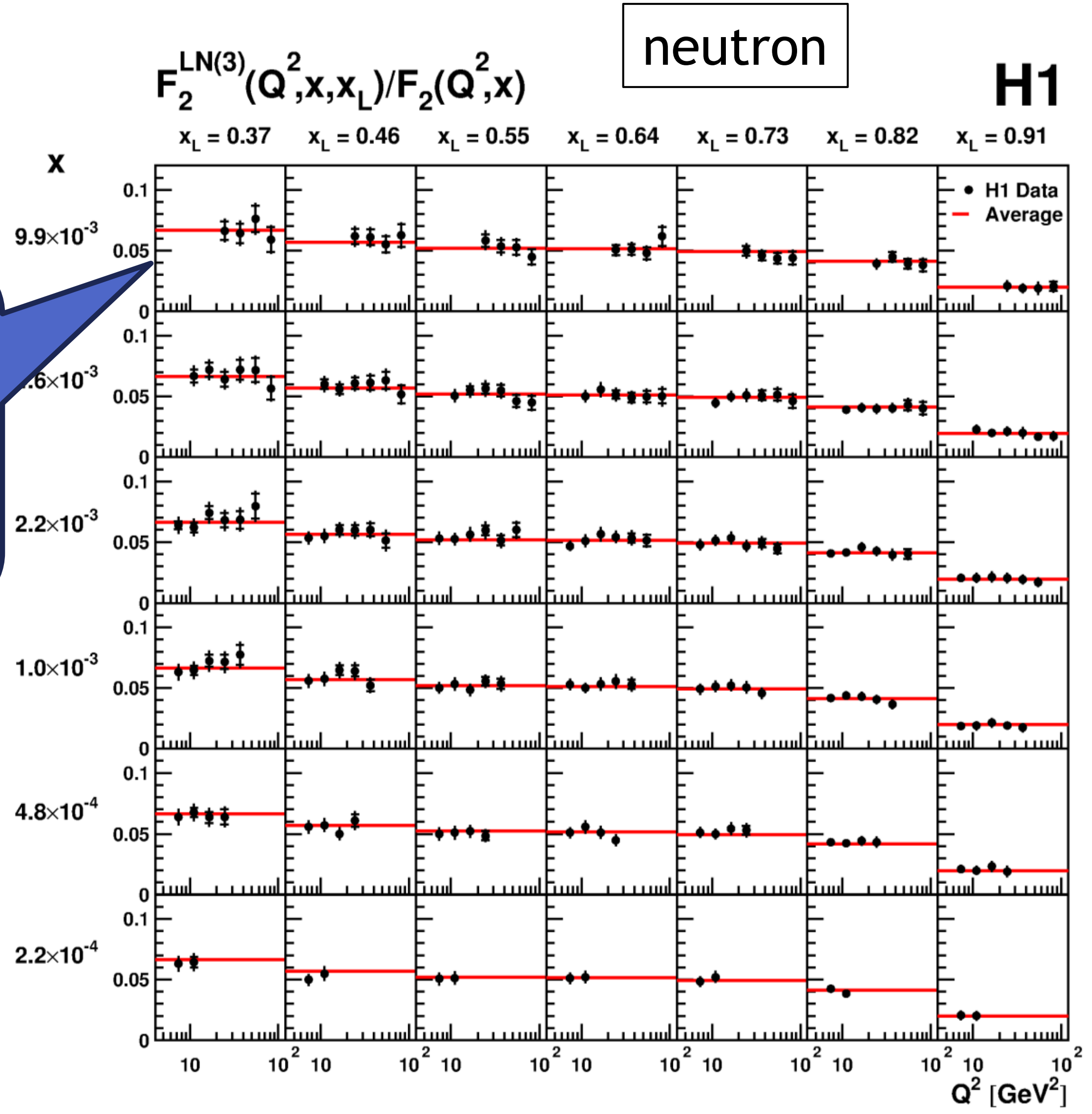
- The answer is basically no!
  - No strong yield dependence on $x,\ Q^2$ "limiting fragmentation"

The trend of the "height of the red lines" vs x_L (horizontal boxes) should be independent of x (vertical boxes) and Q^2 (x axis within the box)



The photon and LN vertices are way separated in rapidity





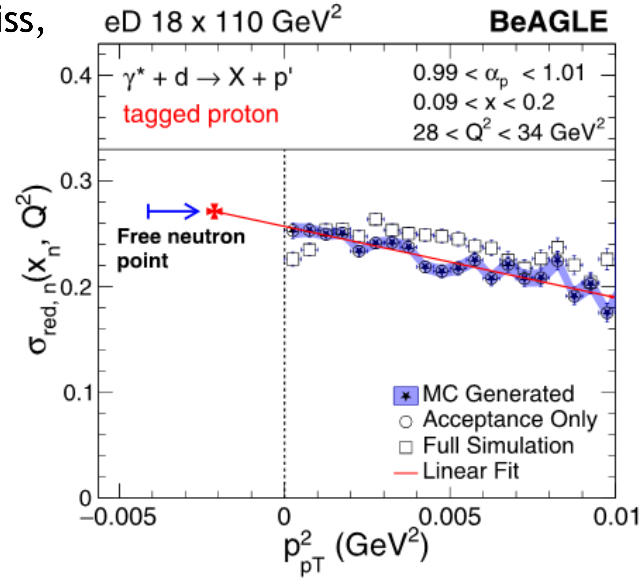
fraction of events with proton is flat in x

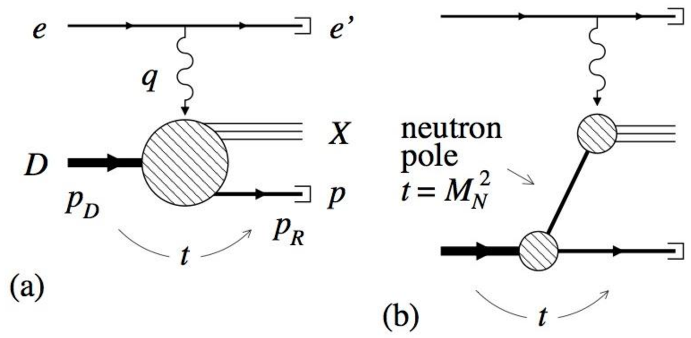
... and flat in Q^2 for given (x, z) bins

Example of t reconstruction: eD scattering

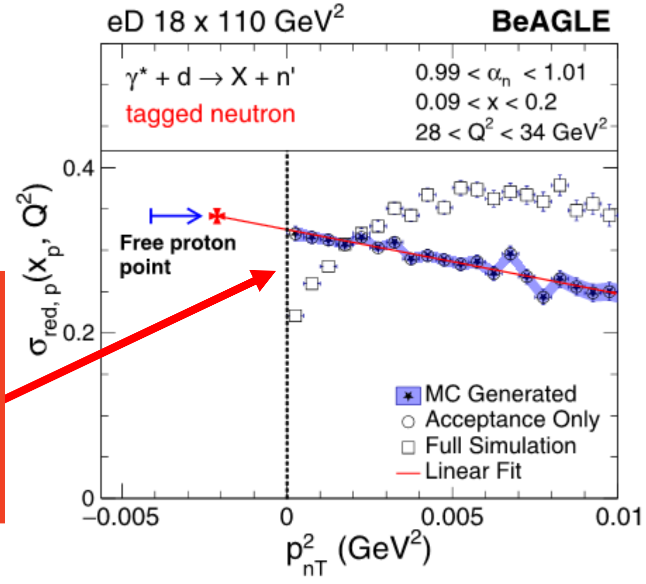
- Proton-tagged eD scattering
  - $e(p+n) \to en + p$ **DIS for neutron**
- Neutron-tagged eD scattering
  - $e(p+n) \to en + p$ **DIS for proton,** which can be compared to ep scattering to understand the t effect
- Way to understand **nuclear (EMC) effect**
  - Or short-range correlation **(SRC),** by comparing $(ep + en)$ with untagged eD DIS

A. Jentsch, Z. Tu, C. Weiss, PRC 104, 065205 (2021)





large smearing in mearsuring the recoil t due to finite resolution: severer for n than p



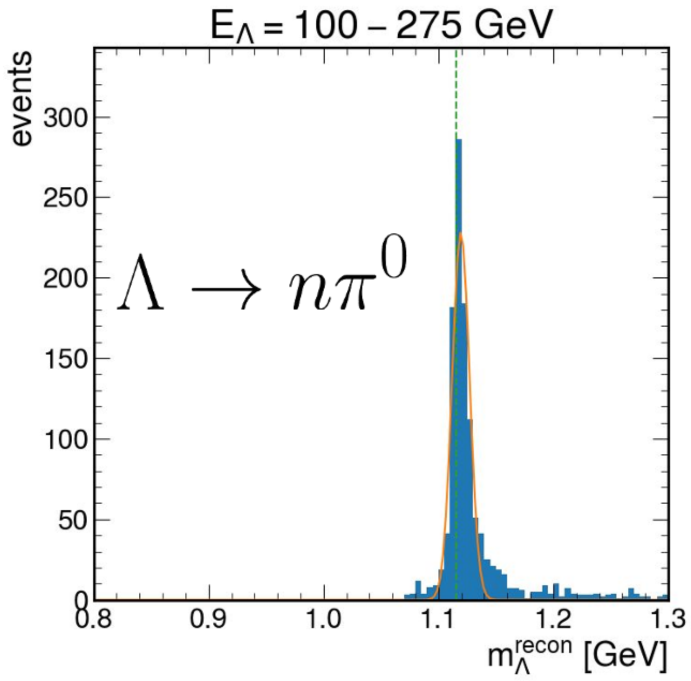
Summary

- Old experimental results for forward baryon production are reviewed
- The neutron production at HERA supports the presence of the Sullivan process, allowing us to extract the meson structure
- A few remarks, however:
  - We need good transverse momentum resolution
    if we like to evade the meson flux uncertainty
  - We seem to have had suppression in forward neutron production
    We may have some mechanism to "absorb" the forward baryon
    even for high-Q^2 DIS
- ZDC position and incident angle resolutions are important
  - Also for reconstructing the Λ decay vertex through γ direction:
    we also need photon angular resolution

Backup: kaon and pion structure

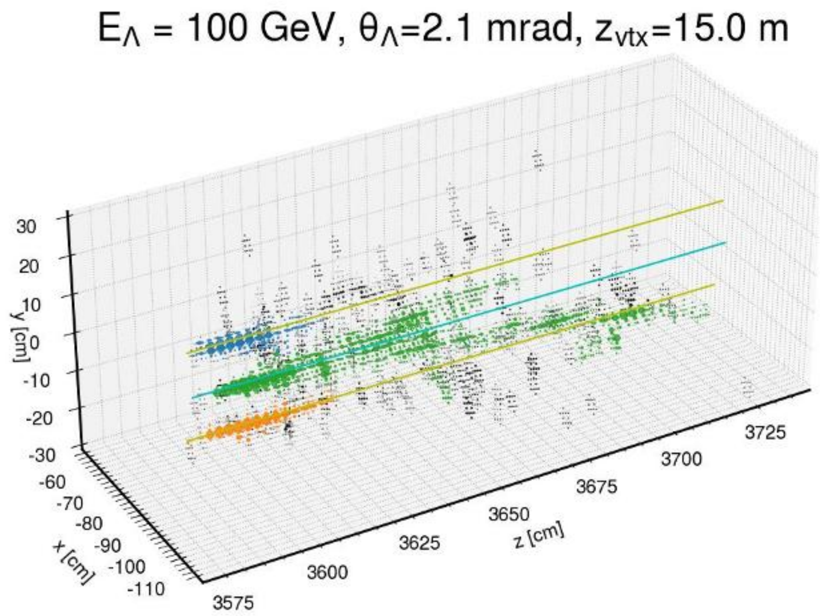
Kaon structure: measurement

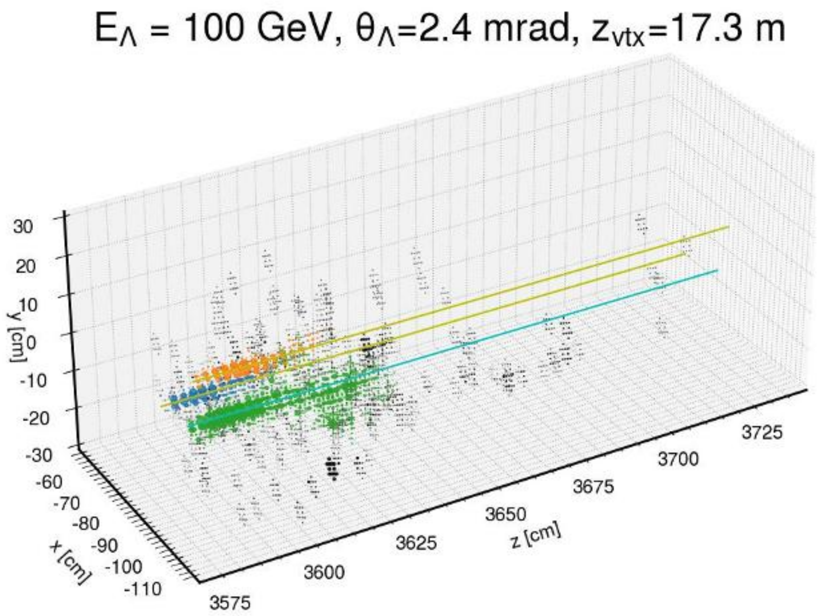
- using $\gamma^* p \to (\gamma^* K^+) + \Lambda^0$, $\Lambda^0 \to n\pi^0$ (35.9%)
  - all decay products go to ZDC if: π^0 is energetic ($\gtrsim$ 10 GeV) or decay close to ZDC
  - precise determination of the **direction of 2 γ's** from π^0 allows to reconstruct Λ vertex, hence **more precise m_Λ** to reject background



Credit: Sebouh Paul

M. Arratia
ePIC meeting, July 2024

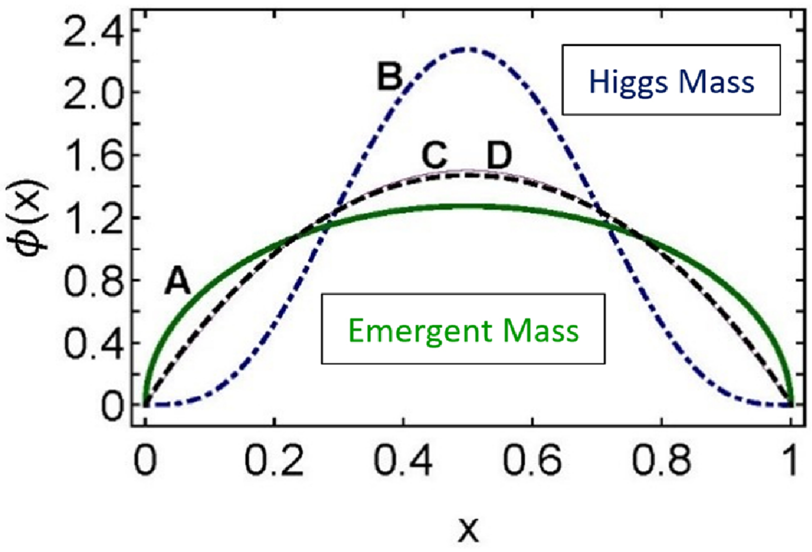




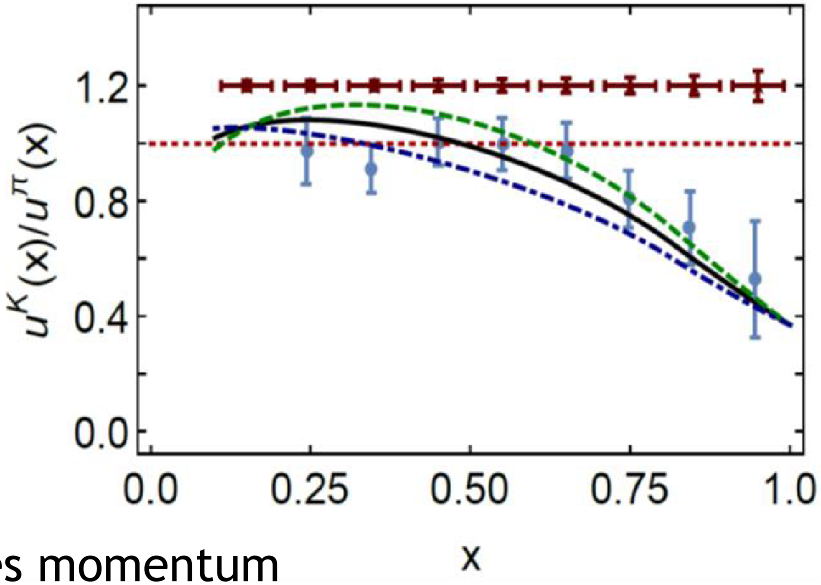
Eur. Phys. J. A (2019) **55**: 190

Why Kaon structure?

- Kaon mass is more dominated by the Higgs mass of strange quarks than that for pions
  - Fraction of mass from kinetic energy of partons is small
- The Fermi motion may be smaller
  - the valence quark momentum is less spread
- Important ingredient of the origin of the mass
- The difference from pion is large at $x_{\pi/K} \to 1$



Parton distribution amplitude, A: pion, B: η_c, D: "heavy pion": $m_{u,d}$ replaced by m_s

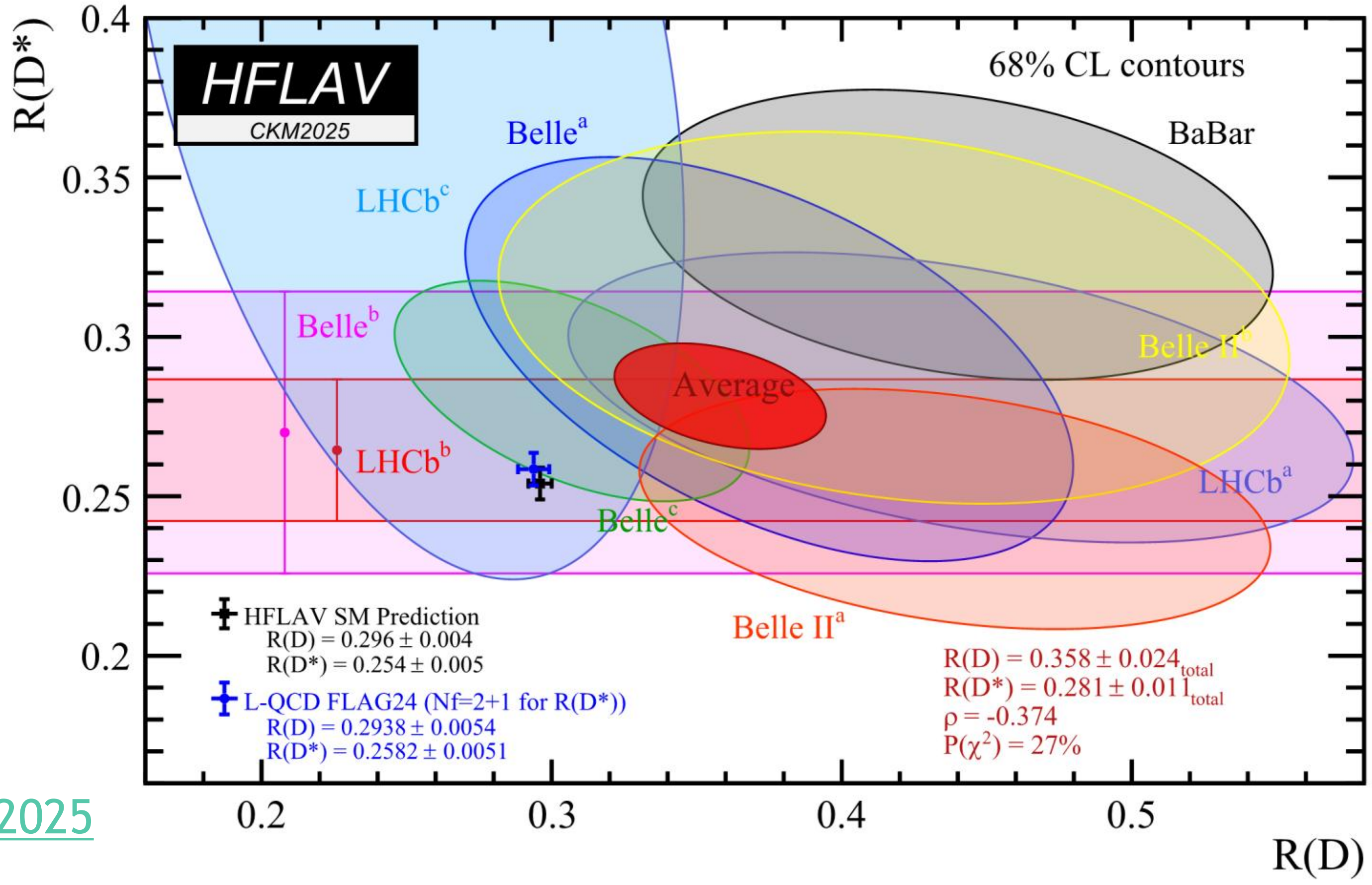


Ratio of parton densities K/π slightly enhanced at middle x, but less pronounced if glue takes momentum

Meson structure and HEP

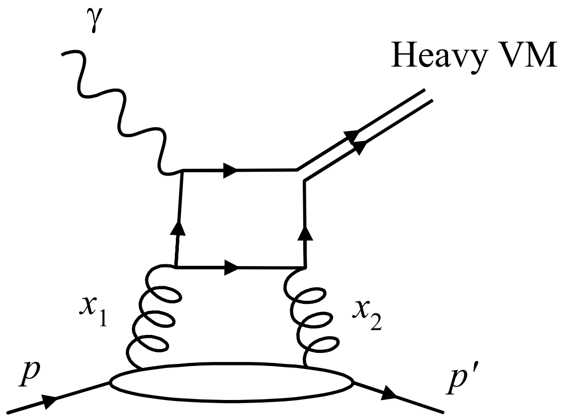
- Heavy quark meson structure needs to be known better
  - there may be hidden uncertainty in the flavor anomaly
- HEP theorists are counting for lattice QCD
  - experimental data on hadron structure with different quark mass may give insight

$R(D^*)=BF(B\to D^*\tau\nu_\tau)/BF(B\to D^*\, l\, \nu_l)$ etc.

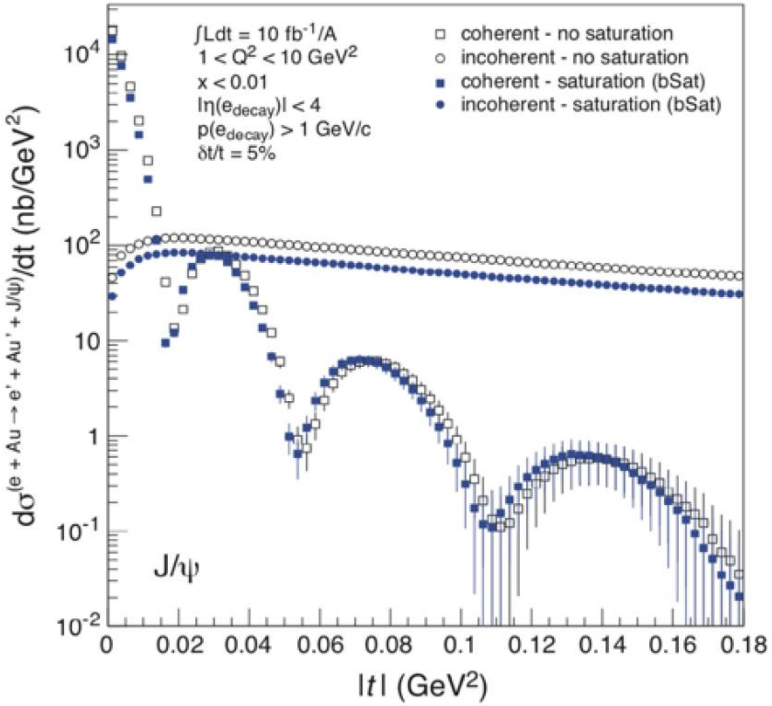


From HFAG for CKM2025

Photons from de-excitation

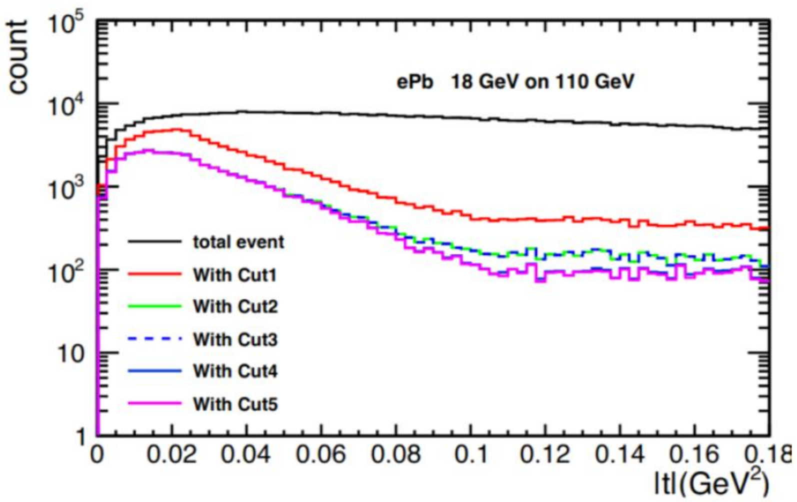


- vetoing nuclear excitation events in heavy eA collisions by tagging ~**300 MeV photons** from de-excitation
- sensitivity to saturation effect through quasi-elastic J/ψ production
  - t-distribution of vector meson reveals the transverse parton profile of the ion: central part may not be visible if it is saturated
    → t distribution becomes narrower



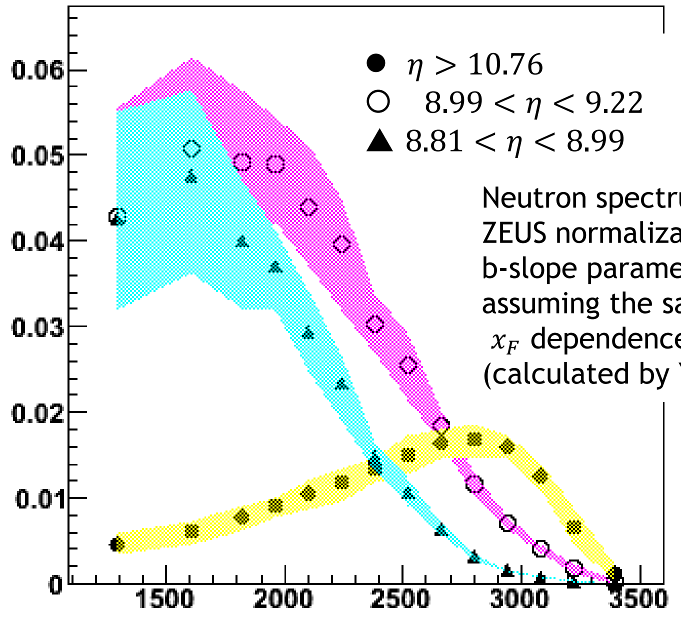
e+Au YR Fig. 7.83

reduction of the incoherent contribution through
no spectator neutron (red),
no additional photon (green)
and no proton (purple) requirements



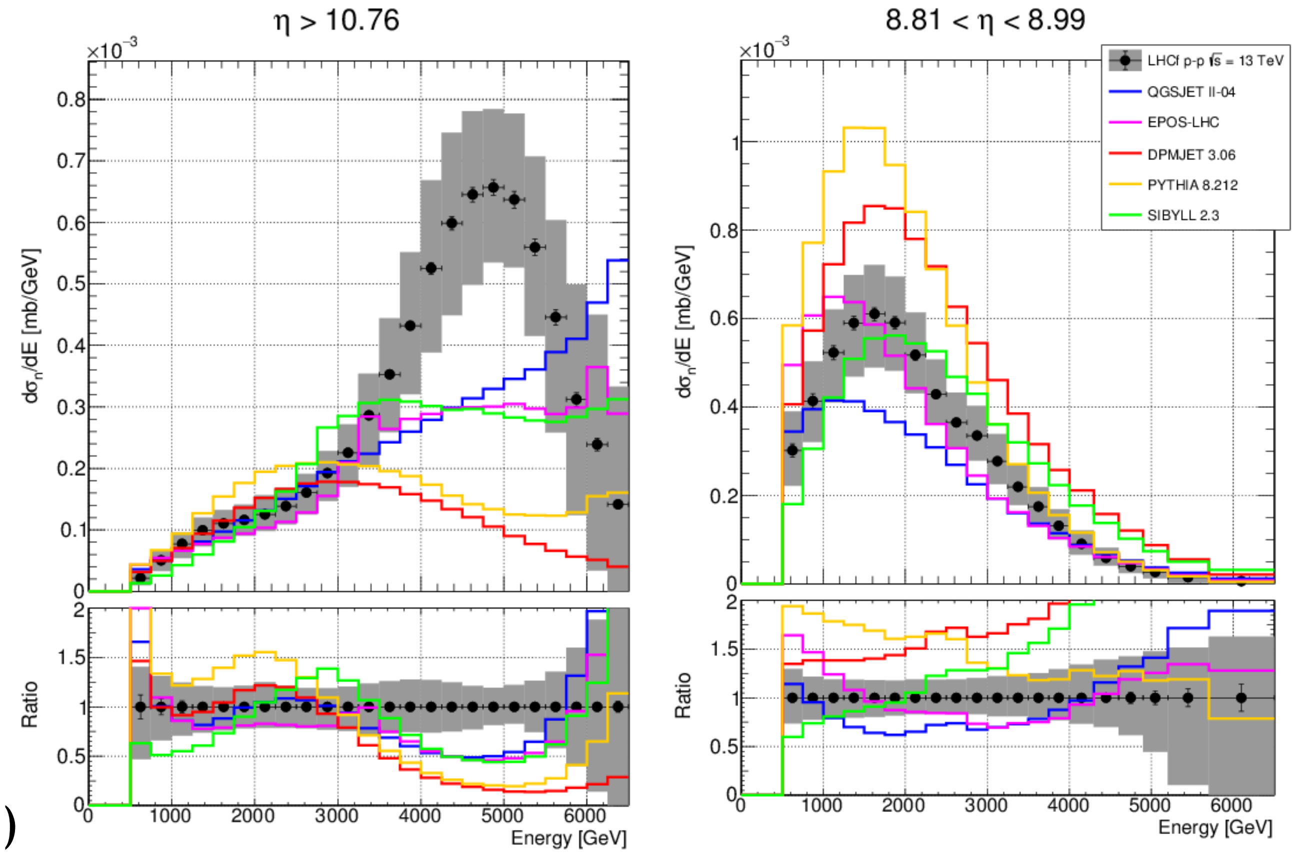
Neutron puzzle (2): pp vs ep

- Limited fragmentation ⇒ the same spectra
- LHCf data similar to ep, but models suggest harder spectrum at $x_F \sim 1$
  - due to projectile fragmentation? $pp \rightarrow N^* + Y,\ N^* \rightarrow n + (\text{hadrons})$
  - Corresponding to proton dissociation for ep DIS: $\gamma^* p \rightarrow X N^*$ LRG-tagged neutron?



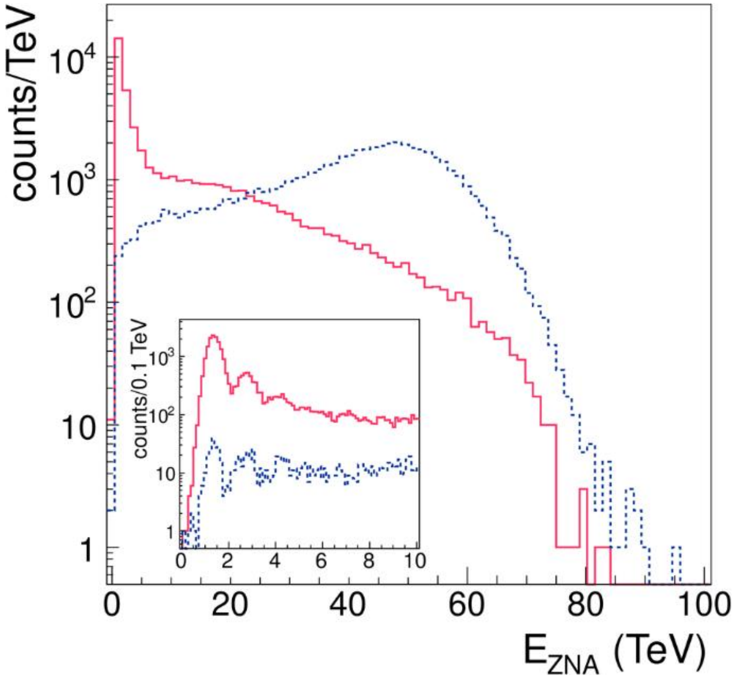
E_n (7 TeV beam)

LHCf data

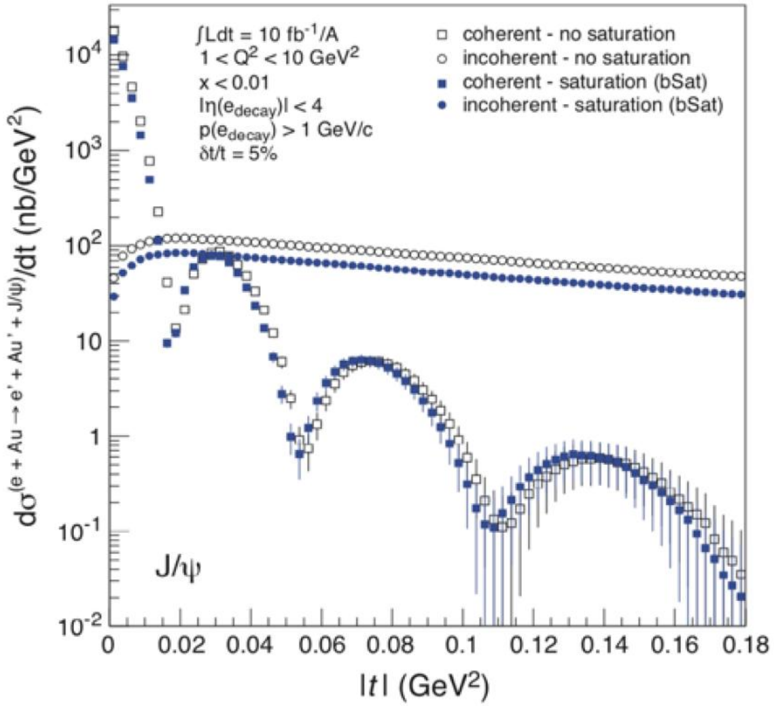


EIC Yellow Report physics using ZDC +B0 (1)

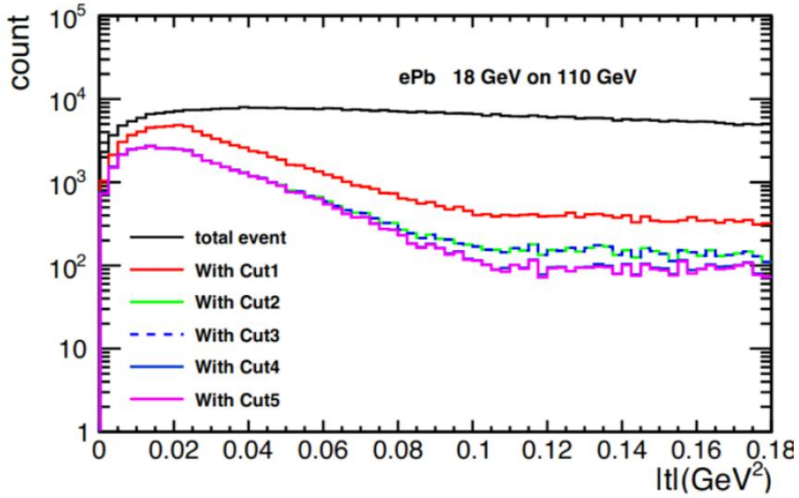
- Spectator tagging
  - for inelastic eA collisions:
    heavy ions, eD / e[3]He : $n \times E_{beam}$ energy in ZDC
  - vetoing nuclear excitation events
    by tagging **~300 MeV photons** from de-excitation



ALICE ZDC (A-side)
with and without
activities in plug area
2.76 TeV run

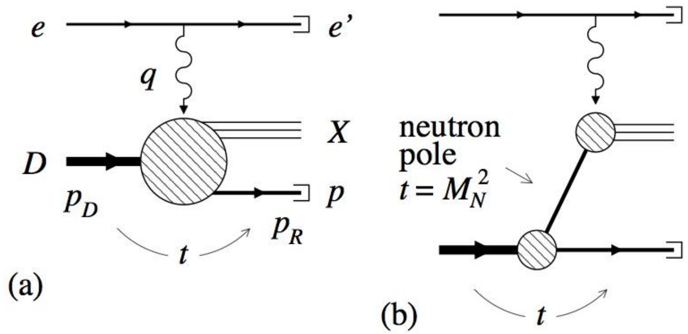


e+Au YR Fig. 7.83

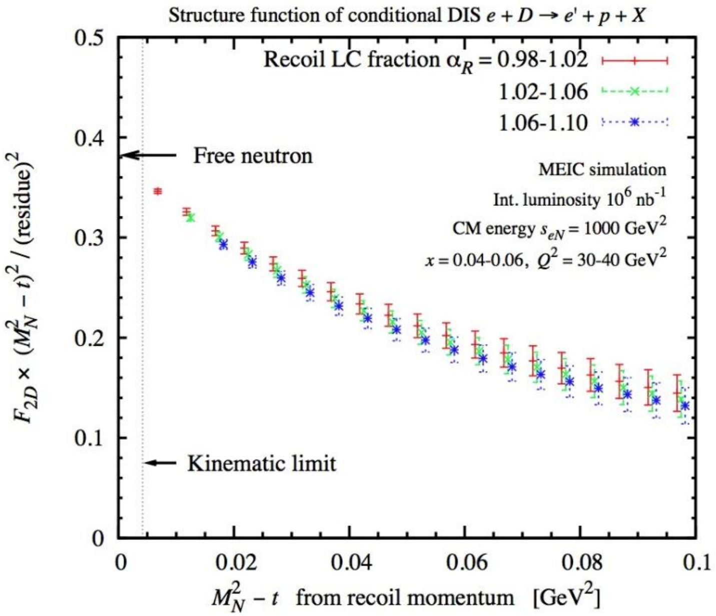


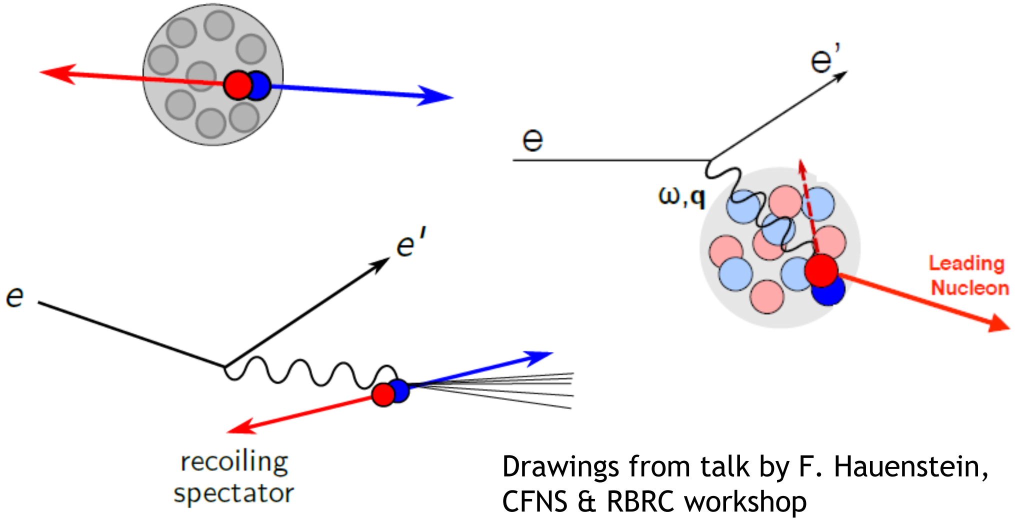
Proton/neutron tagged eD/eA DIS

- Proton-tagged eD and eA scattering
  - $e(p+n) \to en + p$ **DIS for neutron!**
  - Way to understand
    nuclear (EMC) effect
    or short-range correlation **(SRC)**
    by comparing small and large system
- Neutron-tagged $(ep+n)$: proton structure with t
  - Cross-check with ep runs: $t = 0$ **reference given!**



Need to interporate to t = 0



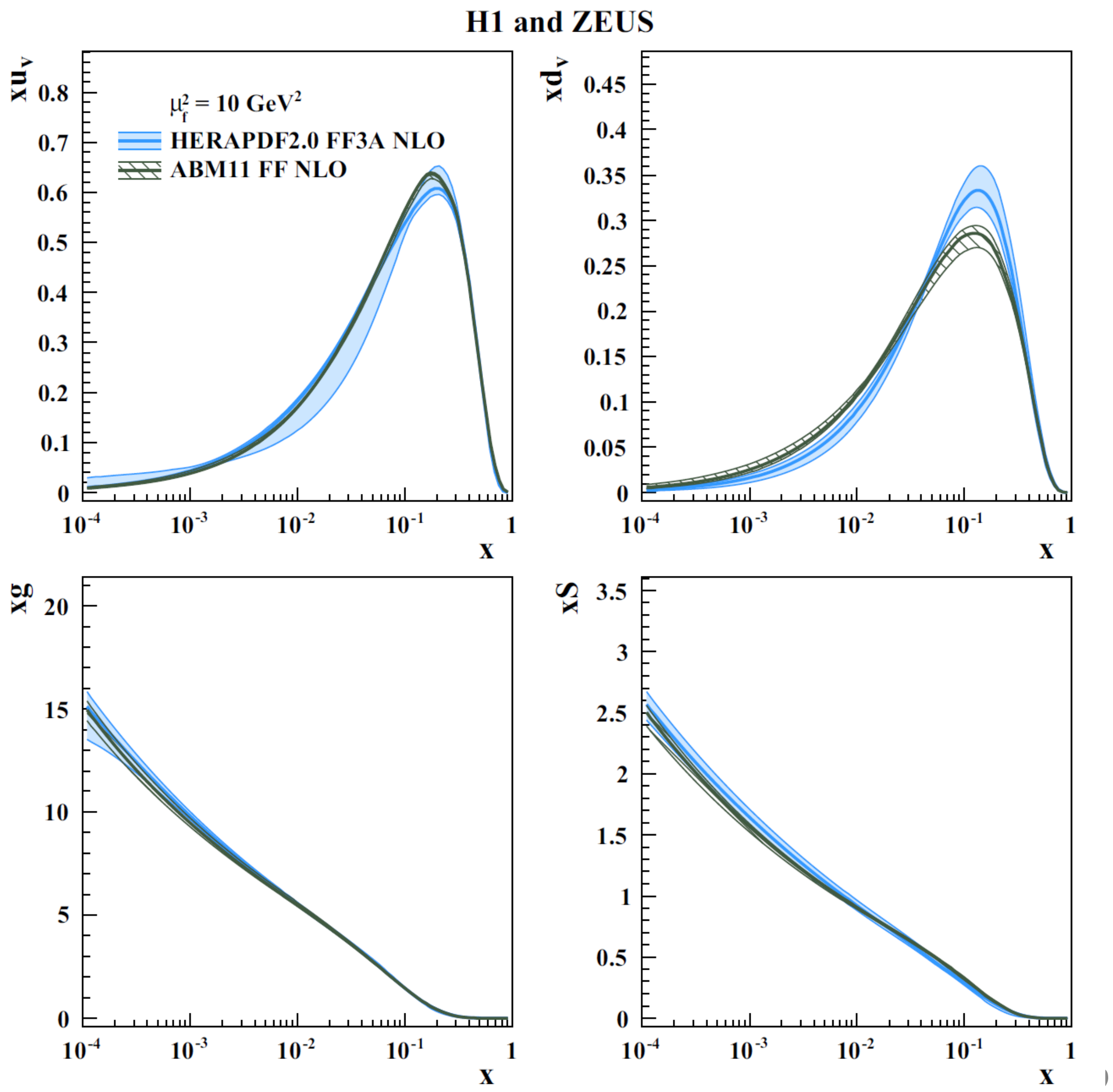


Drawings from talk by F. Hauenstein, CFNS & RBRC workshop https://indico.bnl.gov/event/6568/

J.Phys.Conf.Ser. 543 (2014) 012007

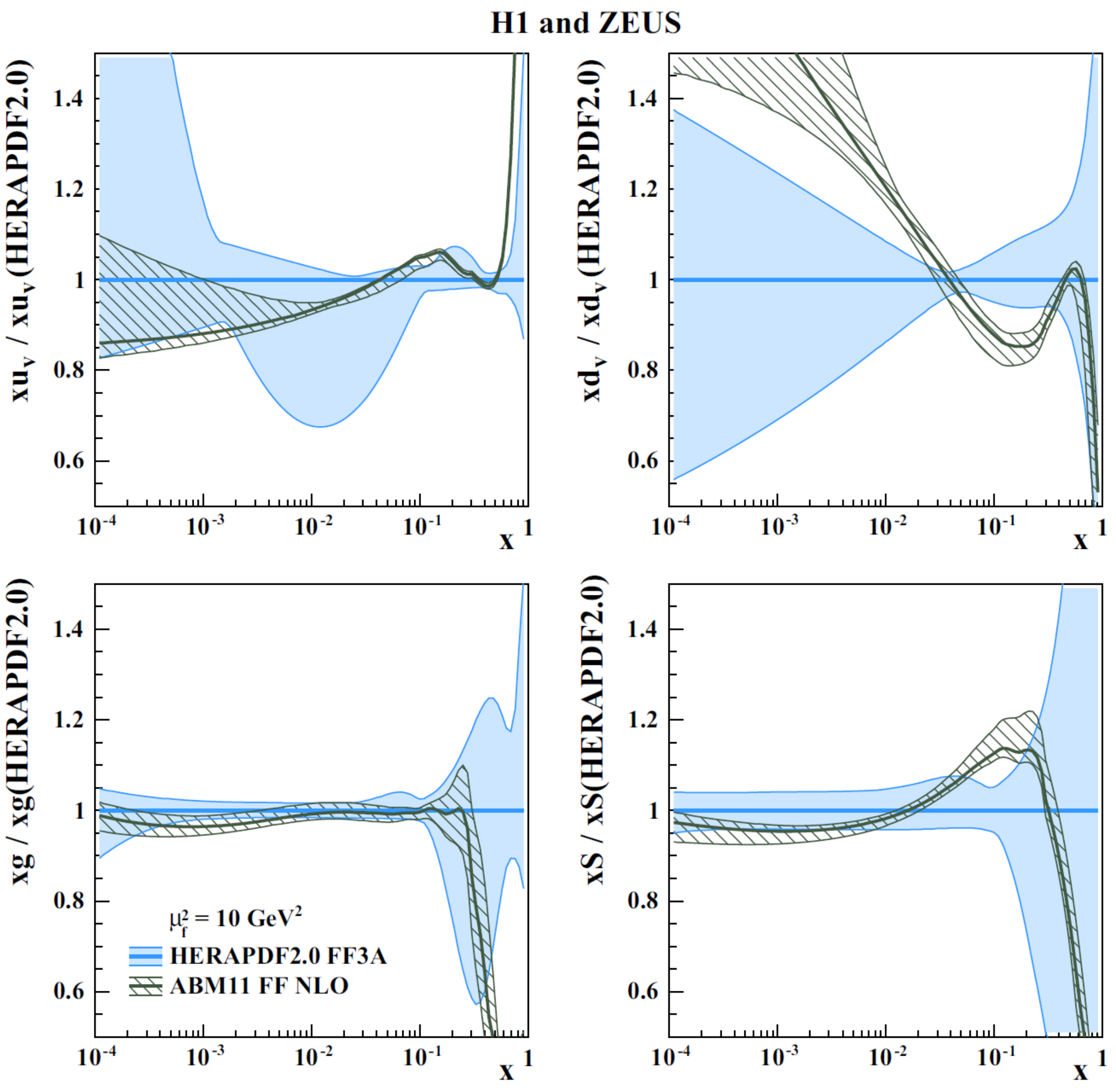
Understanding EMC effect for HEP

- PDF fits show some mild tension between HERA and fixed-target data
- Example: HERAPDF 2.0 vs ABM11
  - HERAPDF 2.0: HERA data only
  - ABM11 (PRD 86, 054009): including
    - BCDMS, NMC, SLAC
    - Drell-Yan from FNAL
    - Dimuon from νN
- PDF at high-x will be one of the major systematics for high-mass BSM state search (M > 1 TeV) at the LHC



PDF comparison: HERA-only and with fixed target data

- This might simply be systemati of DIS experiments
  - Repeating the measurement with much better detector and environment at the EIC
- Or a real nuclear effect?
  - eD and e^3He data should help

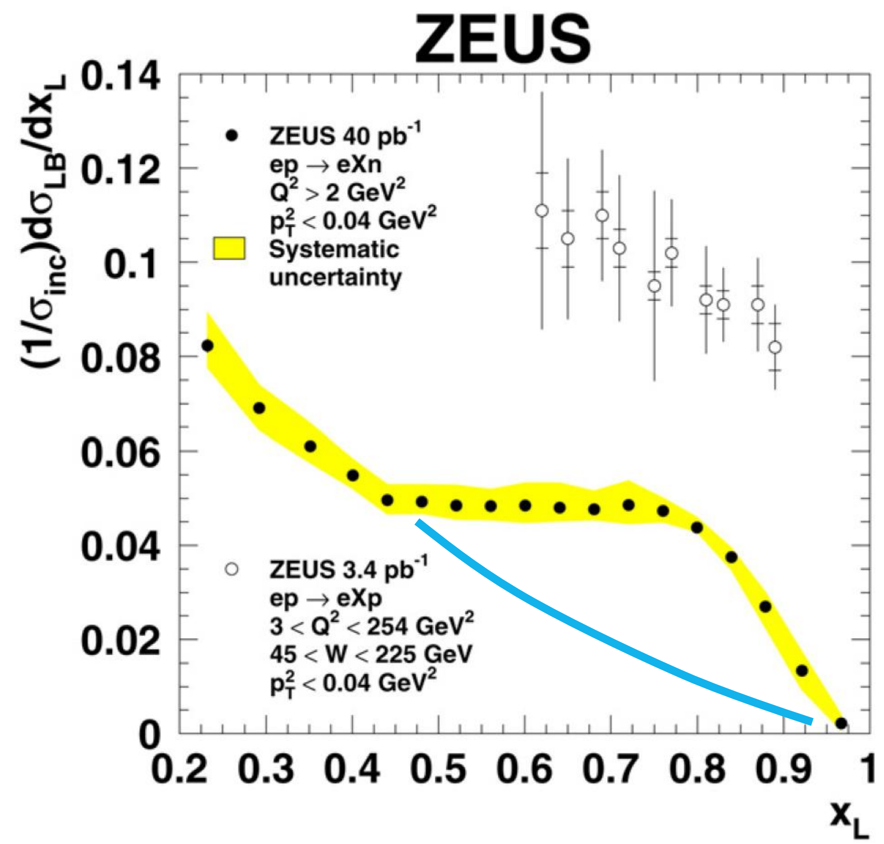


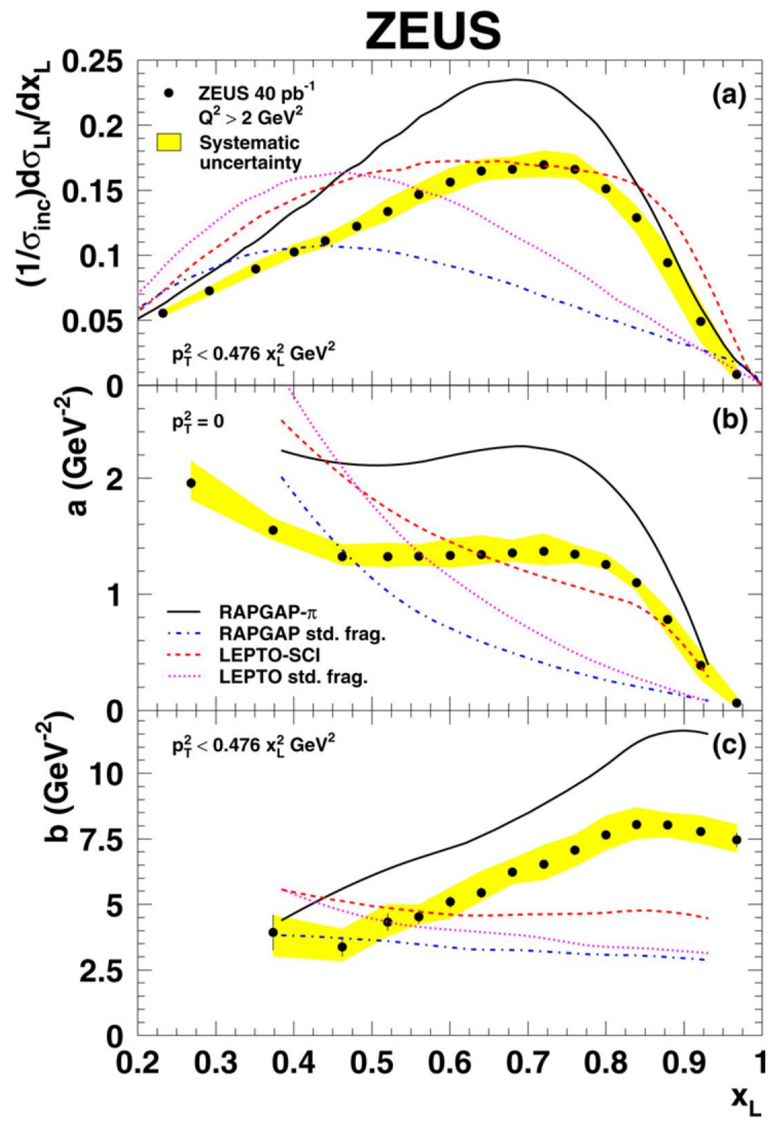
Consideration for 300MeV photons

- Any initial state radiation from heavy ion?
  - maybe serious for Au, Pb etc.
    This is irreducible
- Pile-up of stray particles in the ZDC area?
  - charged pions/kaons
  - fast neutrons of O(1GeV)
- Need charged particle veto (tracking) in front of ZDC
- May need timing to remove most of the background, especially neutrons
  - better to use fast crystals for EM ZDC

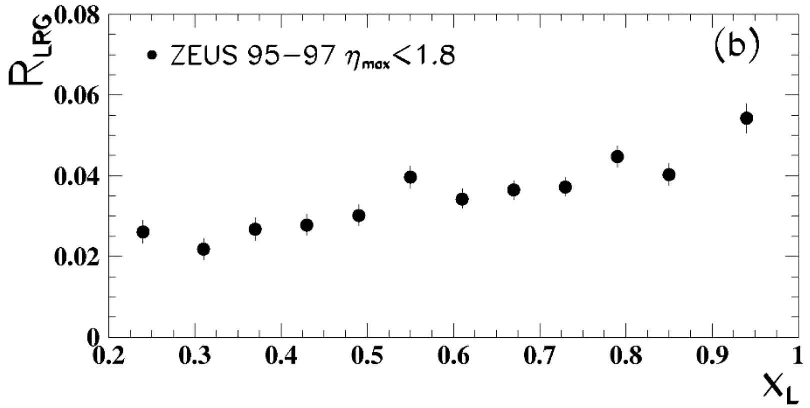
Vertex factorization: summary

- Factorisation holds approximately
  - hint of mild absorption (20-30%)
  - very little (x, Q^2) dependence on leading baryon production probability
- Fragmentation model: one-pion (+sub-leading) peak missing
  - no clear sign of meson poles in the proton spect however

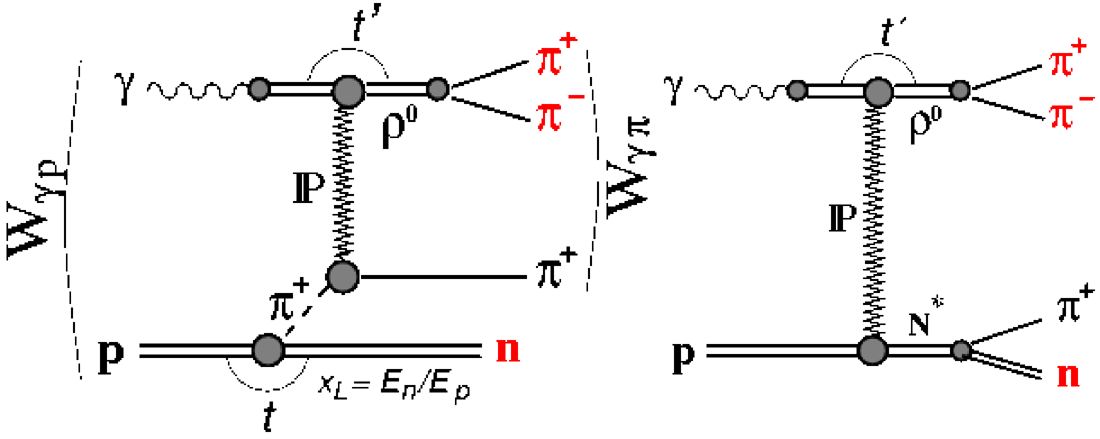




Events with a neutron at HERA and rapidity gap



inclusive DIS (7%)

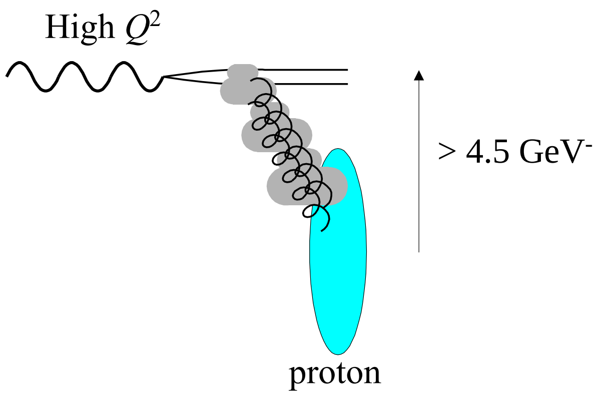


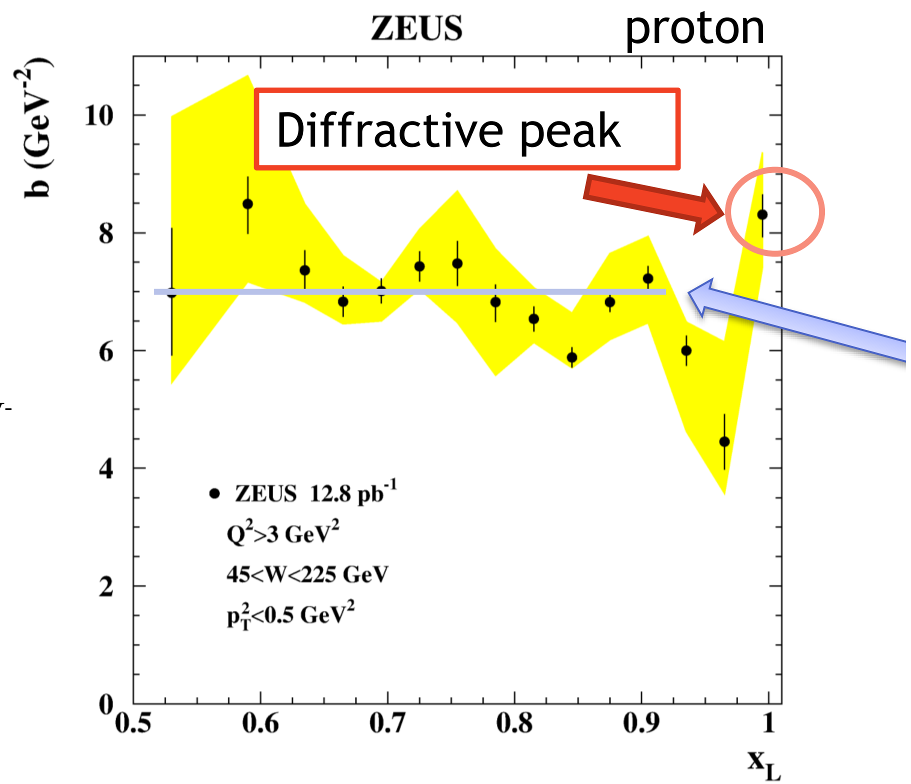
- Fraction of LRG (Large Rapidity Gap) events in neutron-tagged events: 40 – 70% of inclusive DIS
- proton elastic/diffraction: no neutron, hence decrease the above ratio
- Neutrons may come from:
  - $\gamma^*\pi$ diffractive scattering: LRG + neutron
  - proton diffractive dissociation: may yield LRG + **neutron through N^*, Δ etc**
  - fraction of LRG increses with z : possible sign of above two processes

Possible background source to OPE

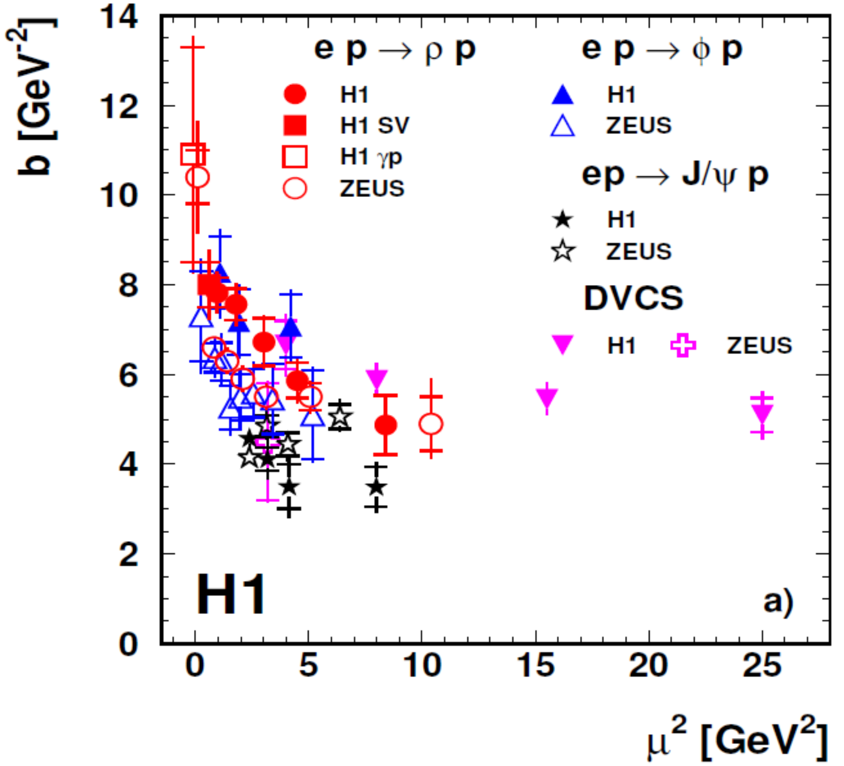
p_T dependence for forward protons

- p_T dependence: again almost flat for proton
  - $b \sim 7\ \mathrm{GeV}^{-2}$ ($\sigma \propto e^{-bp_T^2}$) , constant
  - Slightly larger than proton size
    - Somewhat peripheral? Semi-soft, not directly probing proton





$\mu^2 = (Q^2 + M_V^2)/4$



cf. quasi-elastic vector-meson production
Strong Q^2 and M_{VM} dependence

Limiting fragmentation and "Regge" factorization

- **Limiting fragmentation**: the LN variables (z, t) are independent of (x, Q^2)
  - large rapidity separation, (almost) no information propagated
- **Regge factorisation**: the cross section is the product of the (particle flux) $\times$ $\sigma(\gamma\text{-particle})$

$$\frac{d\sigma(W^2, Q^2, z, t)}{dzdt} = f_{\pi/p}(z,t)\sigma_{\gamma^*\pi}\left((1-z)W^2, Q^2\right)$$

- **For both models, factorisation holds** between photon vertex (x, Q^2) and baryon vertex (x_L, t)
  - The independence does not distinguish the two models
  - Proof of the Regge factorization: $\sigma_{\gamma^*\pi}$ is independent of the soft vertex variables z and t
- The factorization may be broken if **a perturbative partonic state is exchanged** between two vertices
  - Precise measurement at EIC may be able to