EIC far-forward physics
(… from a HEP physicist's view)

6th Korea-Japan PHENIX/sPHENIX/RHICf/EIC Collaboration Meeting
15 July 2021

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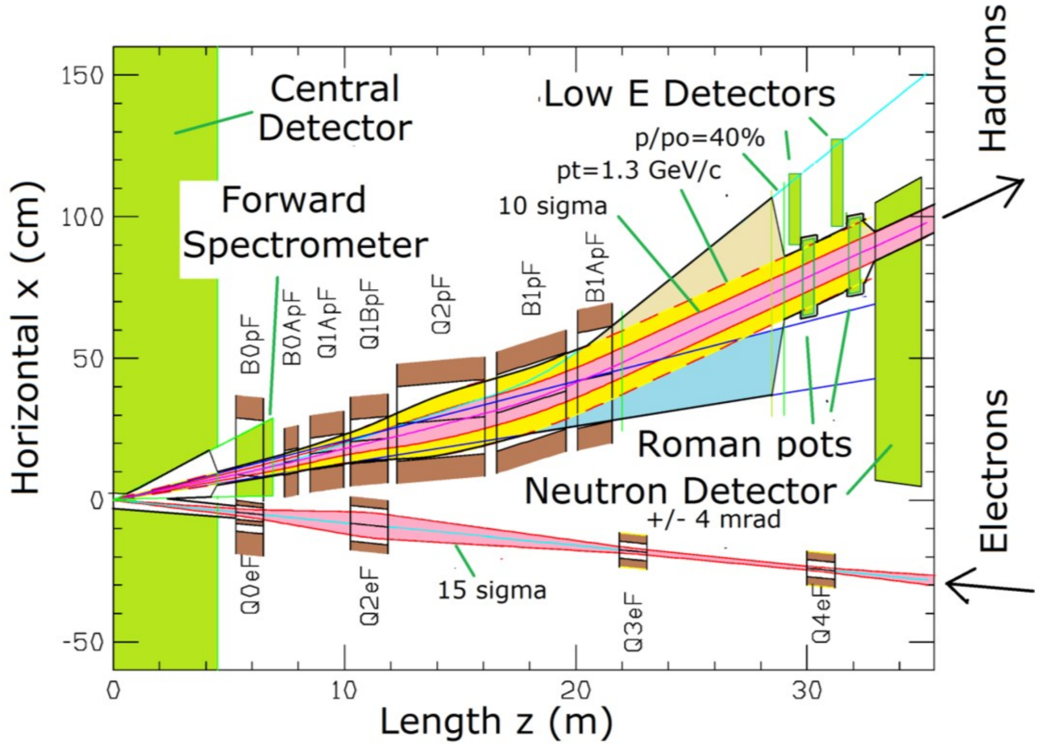
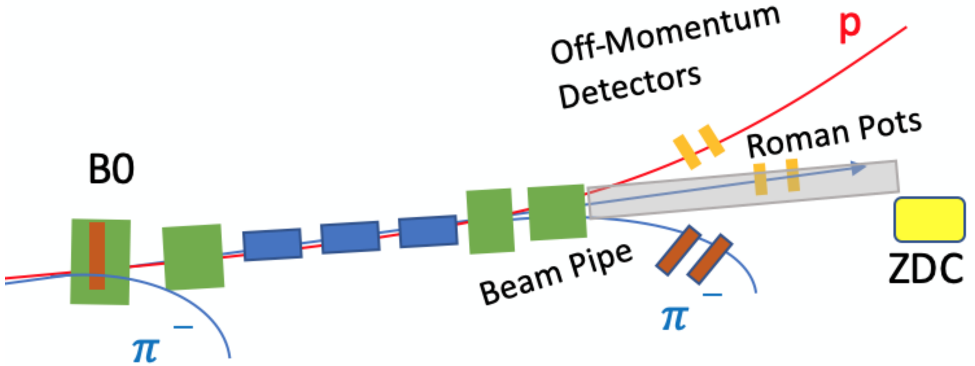
EIC forward detectors

- Roman pots
  - kinematical acceptance?
- ZDC
  - 4-6mrad acceptance
  - 50% / $\sqrt{\mathrm{E}}$ for hadrons
  - should measure 300 MeV γ
- B0
  - charged particle tracker
  - considering also to put EM calorimetry

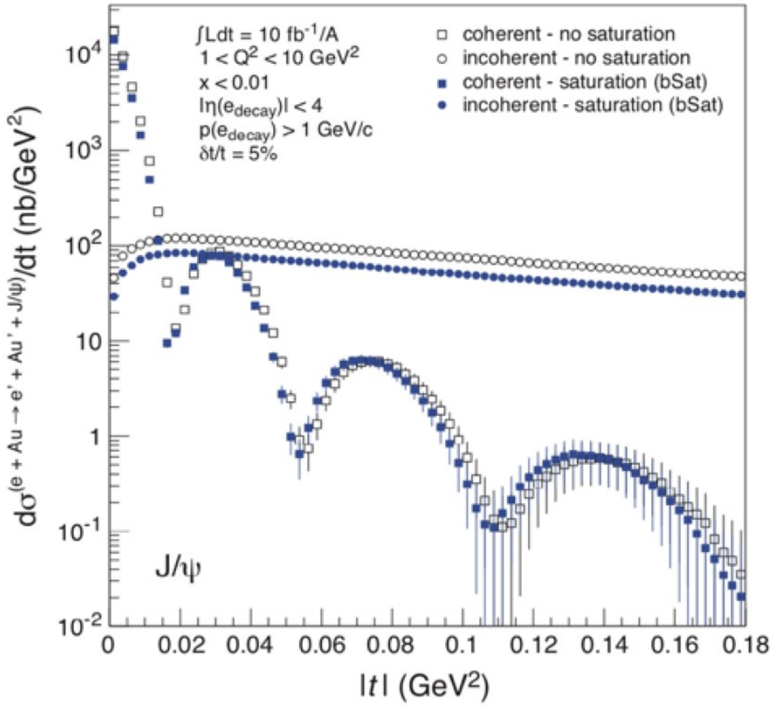


- Today I concentrate on neutrals – ZDC and B0

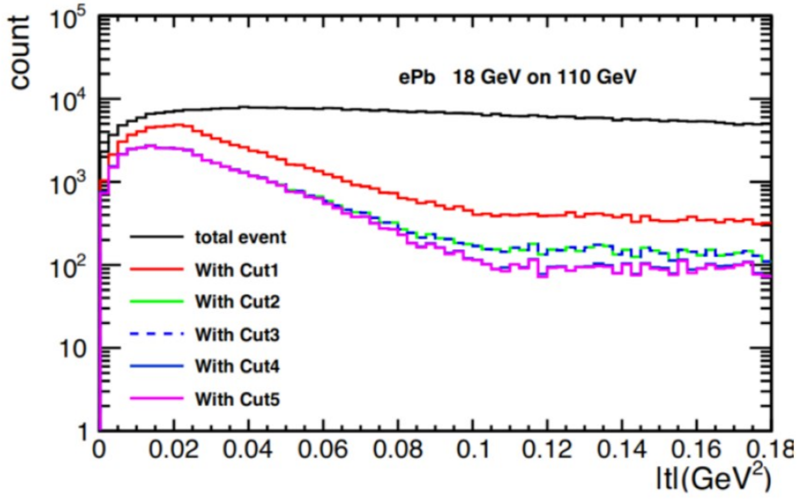


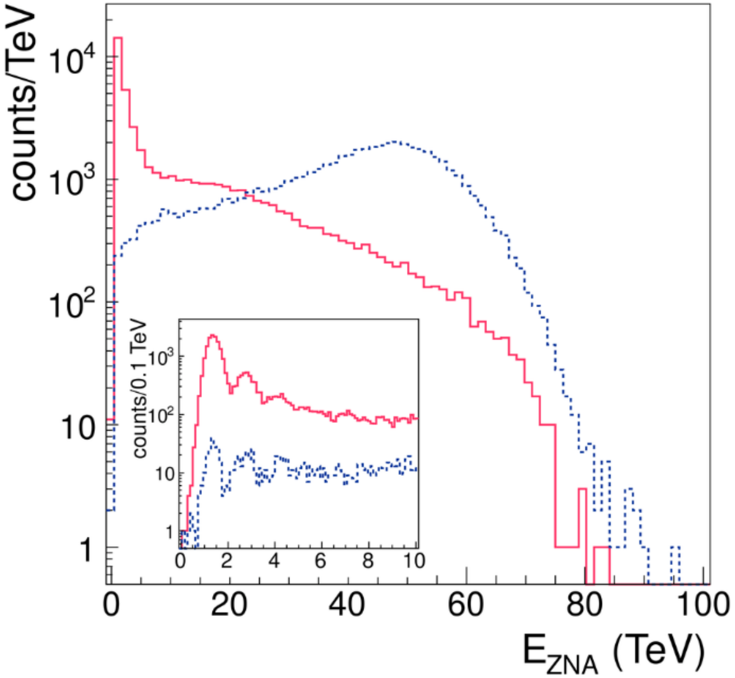
EIC Yellow Report physics using ZDC +B0 (1)

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



e+Au YR Fig. 7.83

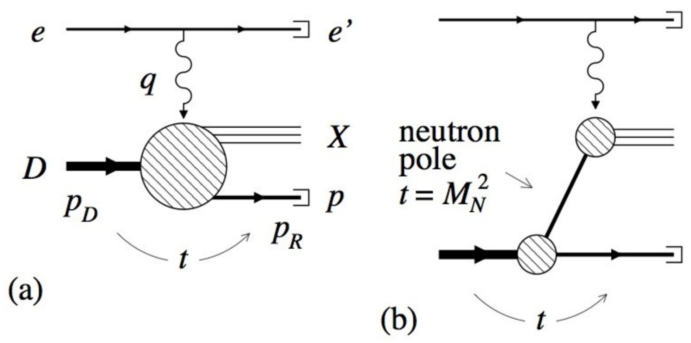




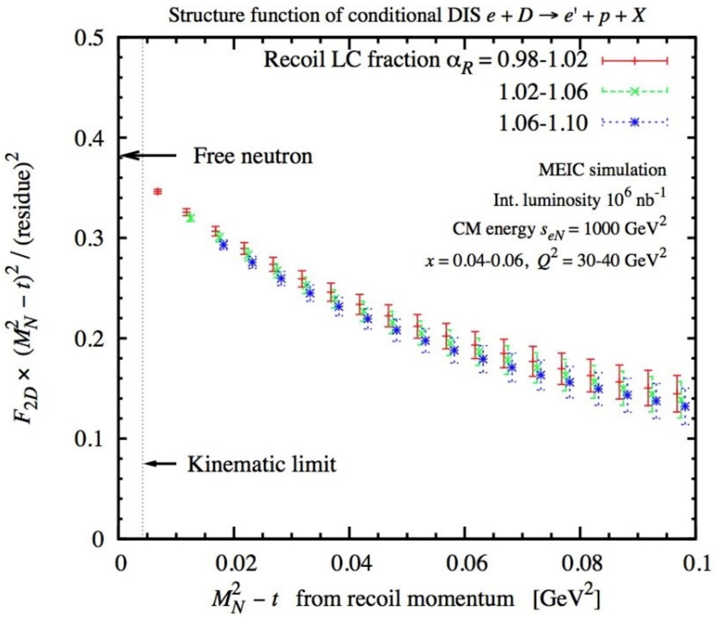
ALICE ZDC (A-side)
with and without
activities in plug area
2.76 TeV run

Proton/neutron tagged eD/eA DIS

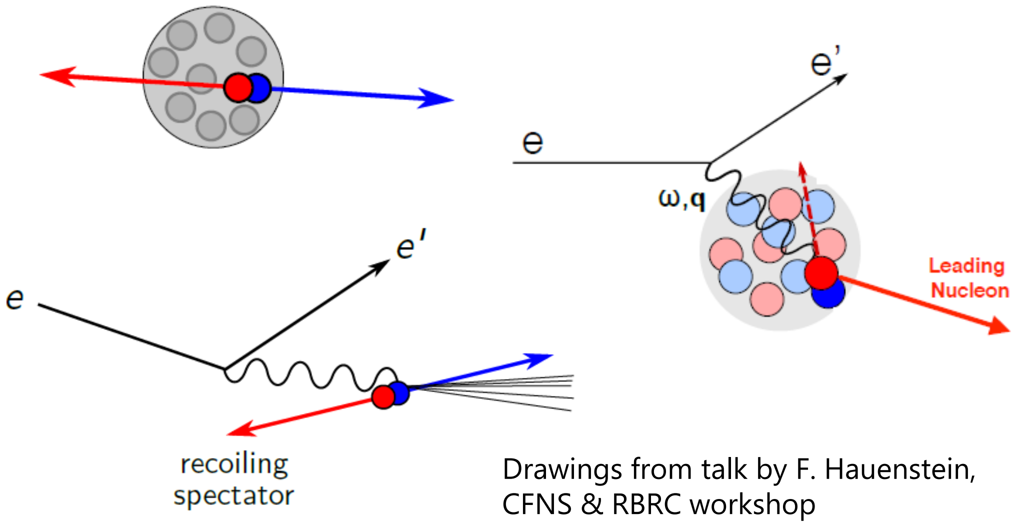
- Proton-tagged $\boldsymbol{eD}$ and $\boldsymbol{eA}$ scattering
  - $e(p+n) \rightarrow en + p$ **DIS for neutron!**
  - Way to understand
    nuclear (EMC) effect
    or short-range correlation **(SRC)**
    by comparing small and large system
- Neutron-tagged $(ep+n)$: proton structure with t
 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



Need to interporate to t = 0



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

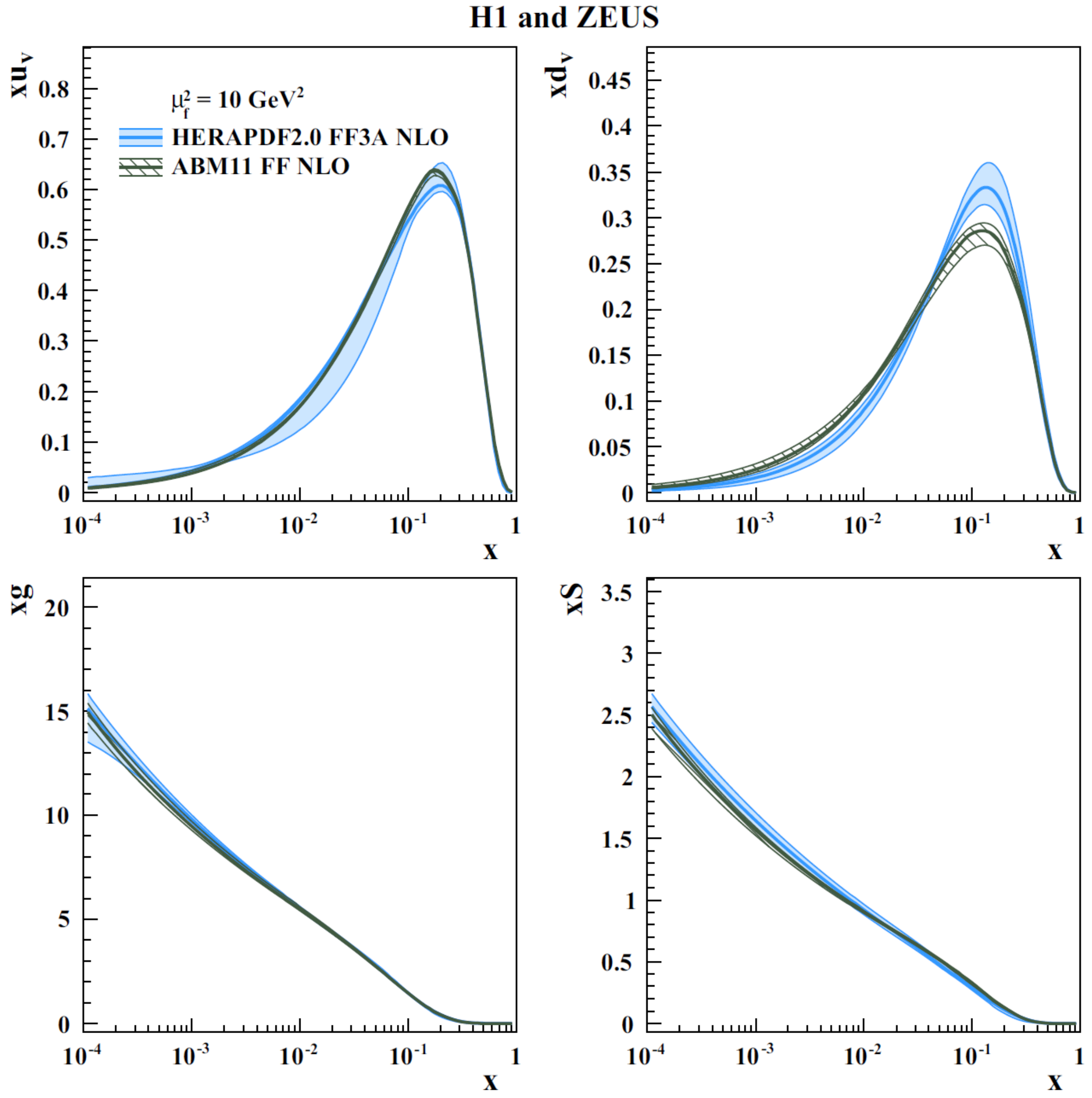


Drawings from talk by F. Hauenstein,
CFNS & RBRC workshop
https://indico.bnl.gov/event/6568/

Understanding EMC effect for HEP

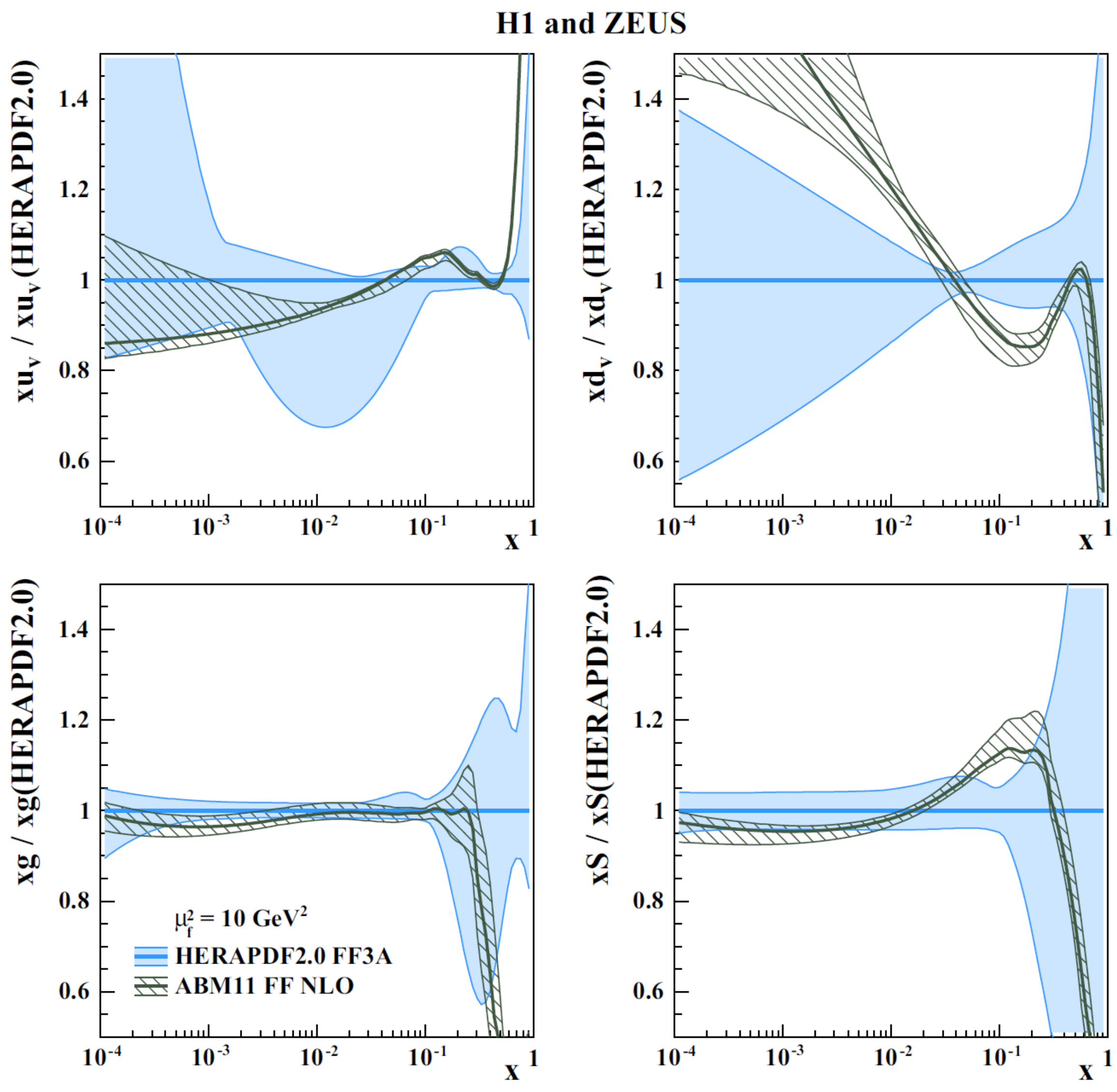
- PDF fits show some mild tension between HERA and fixed-target data
- Example: HERAPDF 2.0 vs ABM11
  - HERAPDF 2.0: HERA data only
  - ABM11 (PRD 86, 054009): including
    - BCDMS, NMC, SLAC
    - Drell-Yan from FNAL
    - Dimuon from νN

- 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 systematics 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



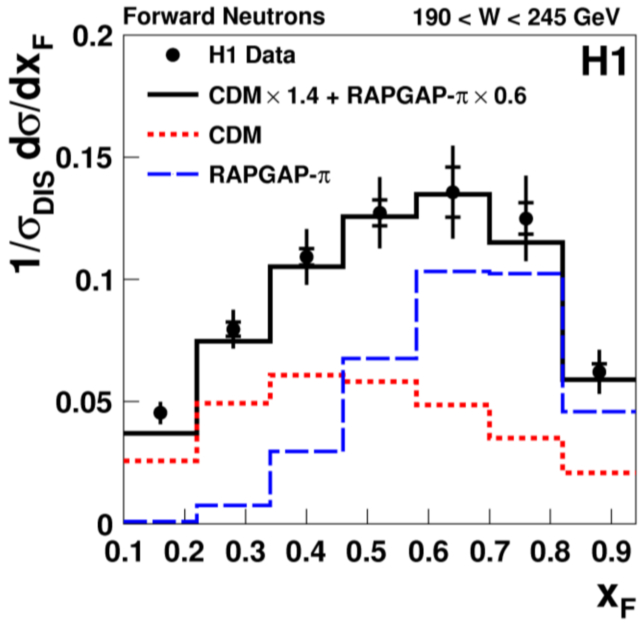
Consideration for 300MeV photons

- 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

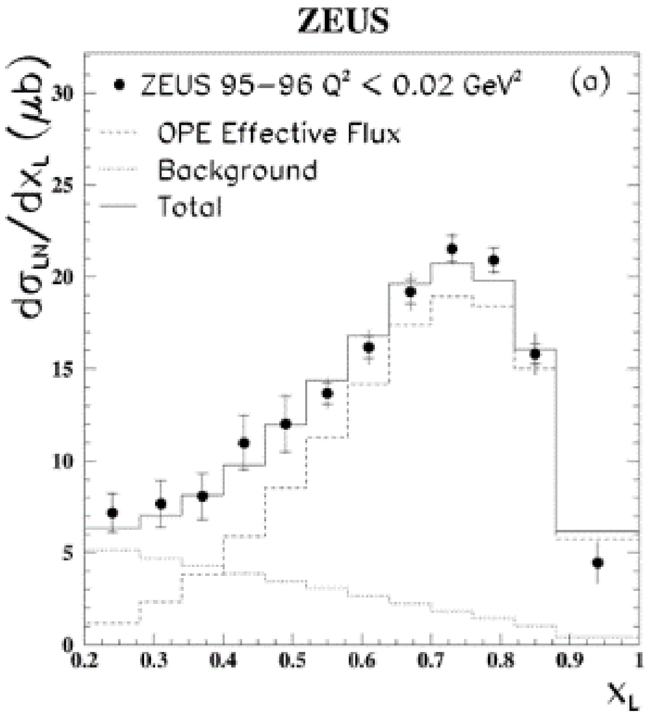
EIC Yellow Report physics using ZDC +B0 (2)

- Meson structure through "Sullivan process"
  - one-pion dominance in high x_F regime

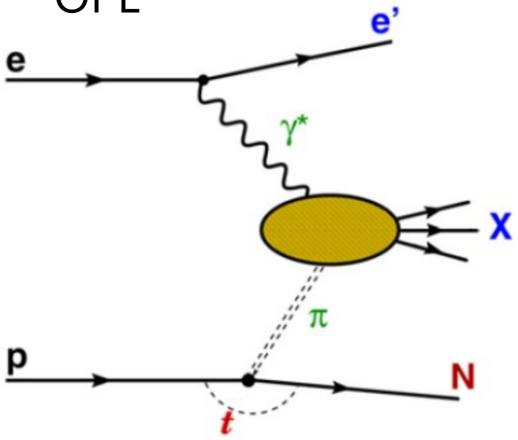
DESY-14-035



Nucl.Phys.B637(2002)3

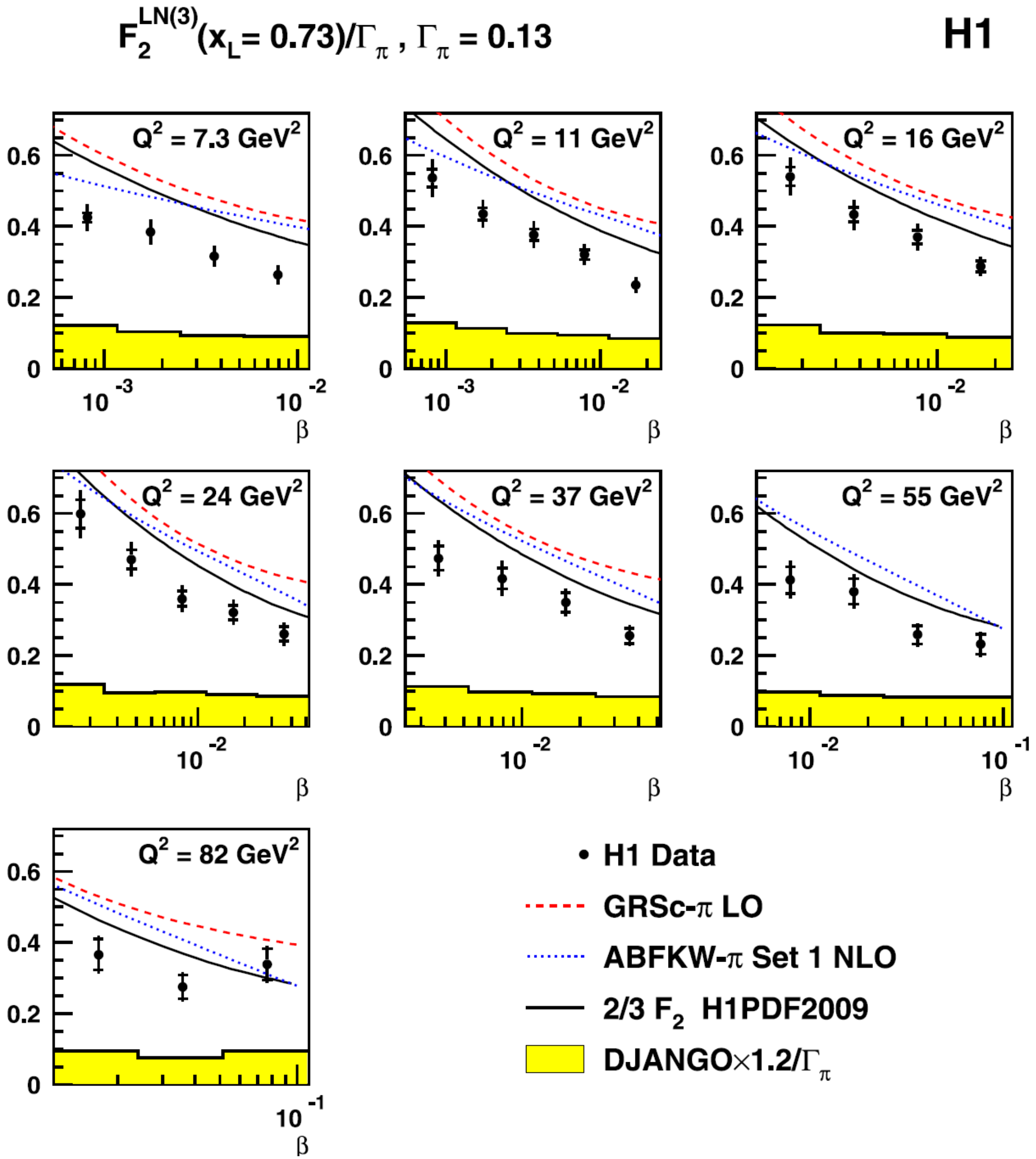


OPE



HERA extraction of the pion structure function

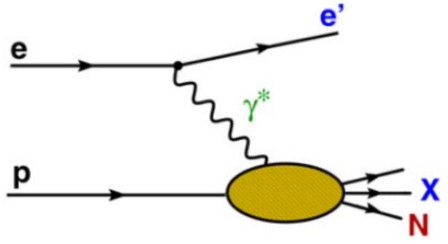
- $x_\pi = x_{Bj}/(1 - x_L)$
  x_L: neutron momentum fraction
  - the shape of the SF for proton and pion are the same if $F_2 \propto x^{-\lambda}$ with constant λ
  - This holds quite well: see 2/3 F2 H1PDF2009, which is the proton structure function!
- The absolute value is smaller
  - ZEUS similar result (almost half of the theoretical prediction)
- High-x_π measurement at EIC should be interesting



One step back: Question at HERA was more fundamental

- What is the production mechanism of forward baryons?
  - Baryon number should conserve: so there should exist either a proton or neutron, which should be there without **meson exchange**
  - Another view: **fragmentation**
    - **For both models, factorization holds** between photon vertex (x, Q^2) and baryon vertex (x_L, t)
  - How far can the baryons travel over rapidity?
    - non-forward neutron would also be interesting

fragmentation



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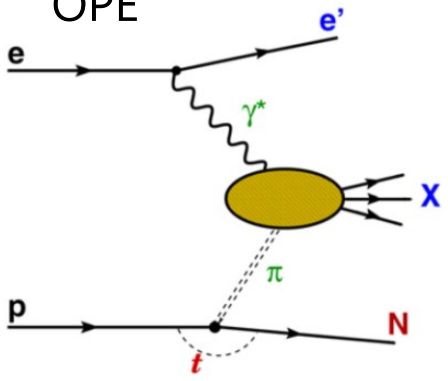
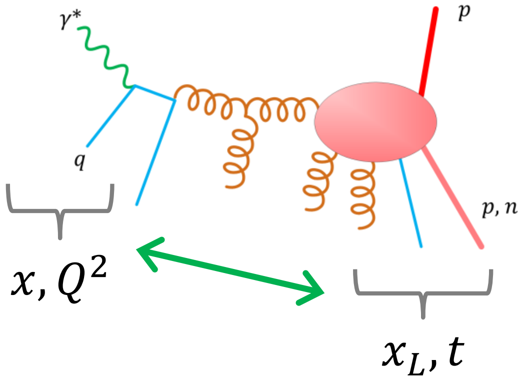
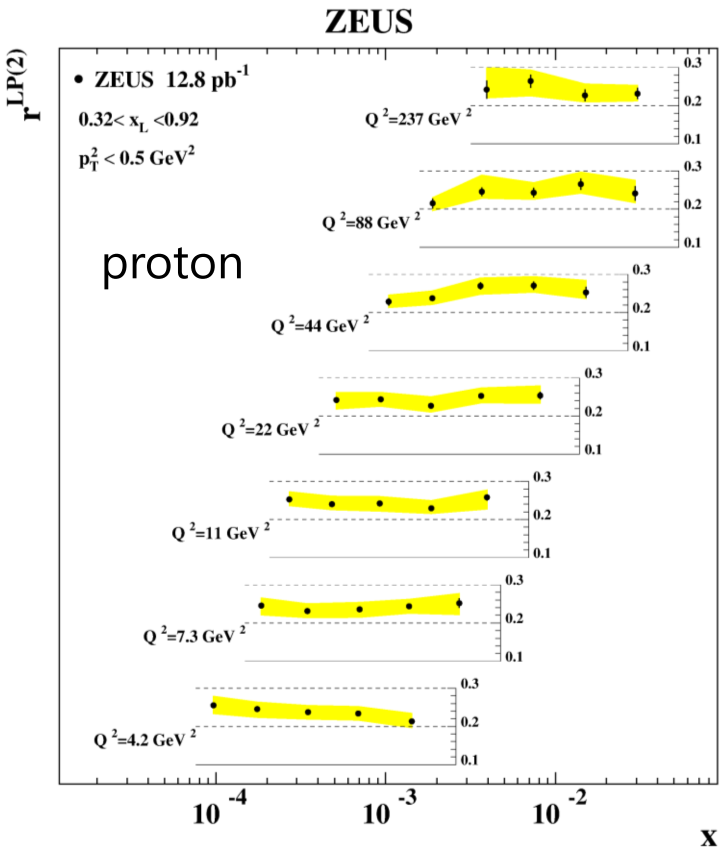


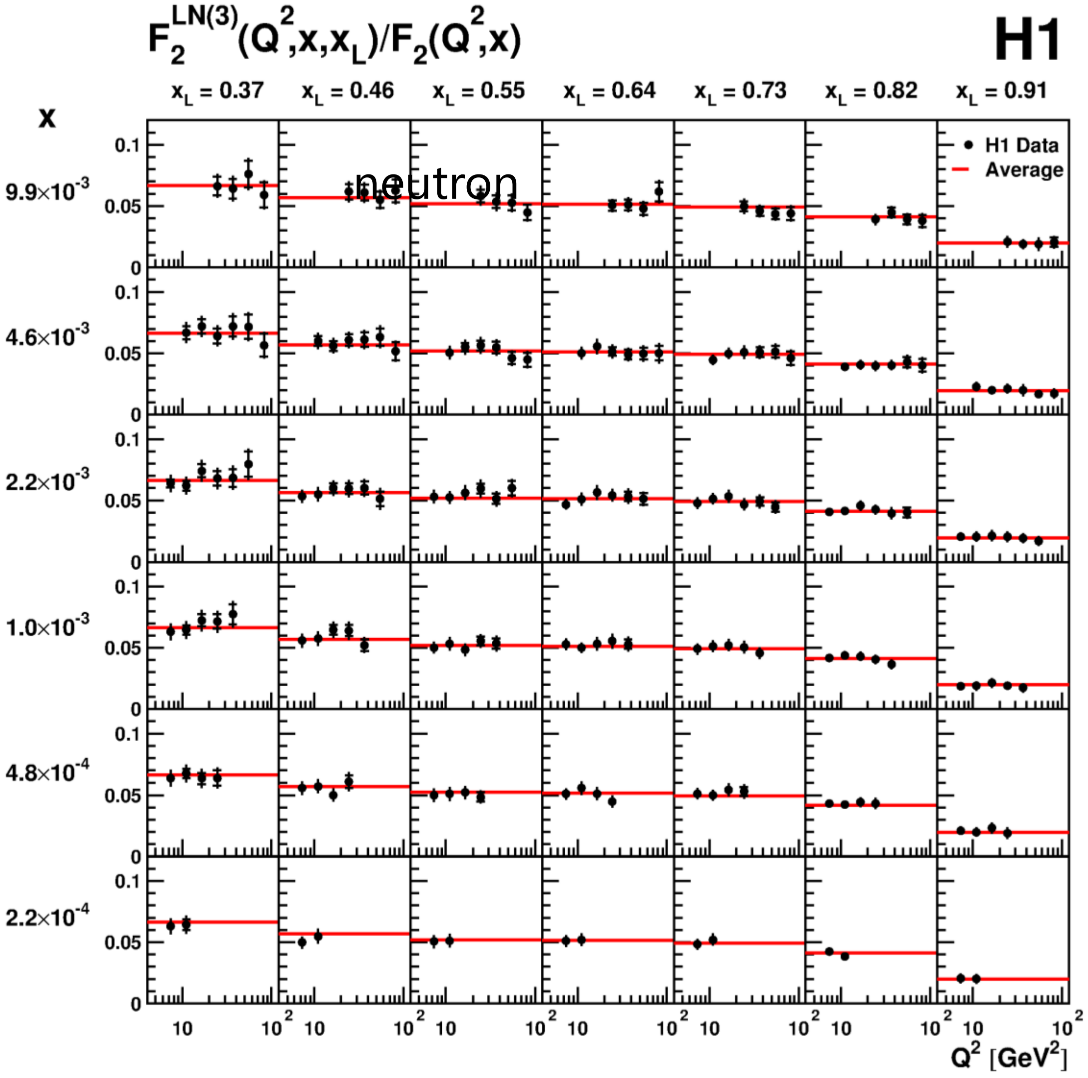
Does the baryon talk to the virtual photon?

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



The left and right vertices are way separated

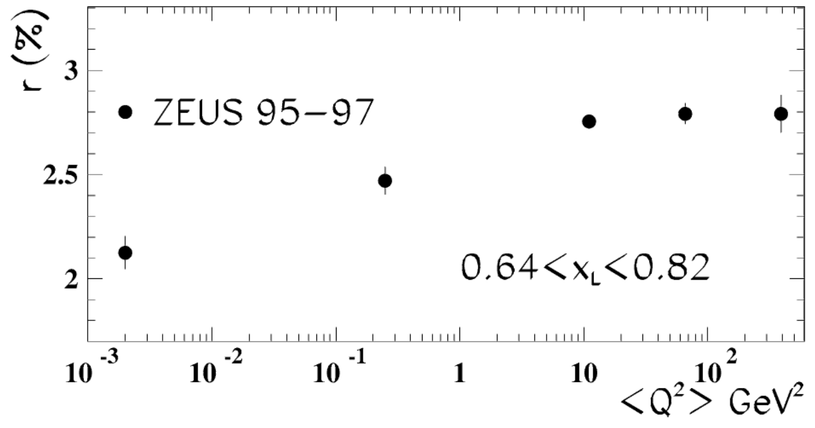


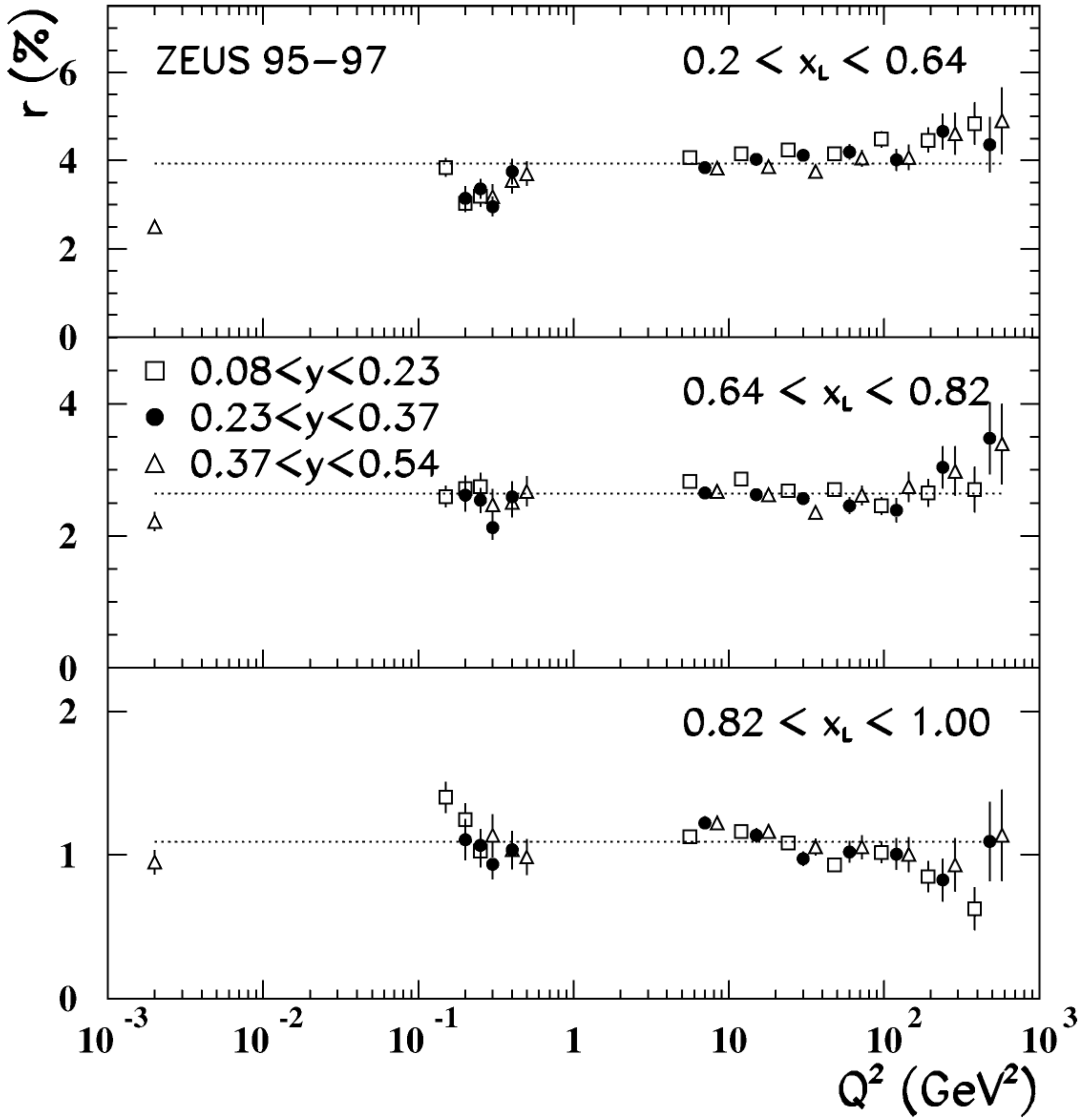


A bit more in detail: Q^2 dependence?

- 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?

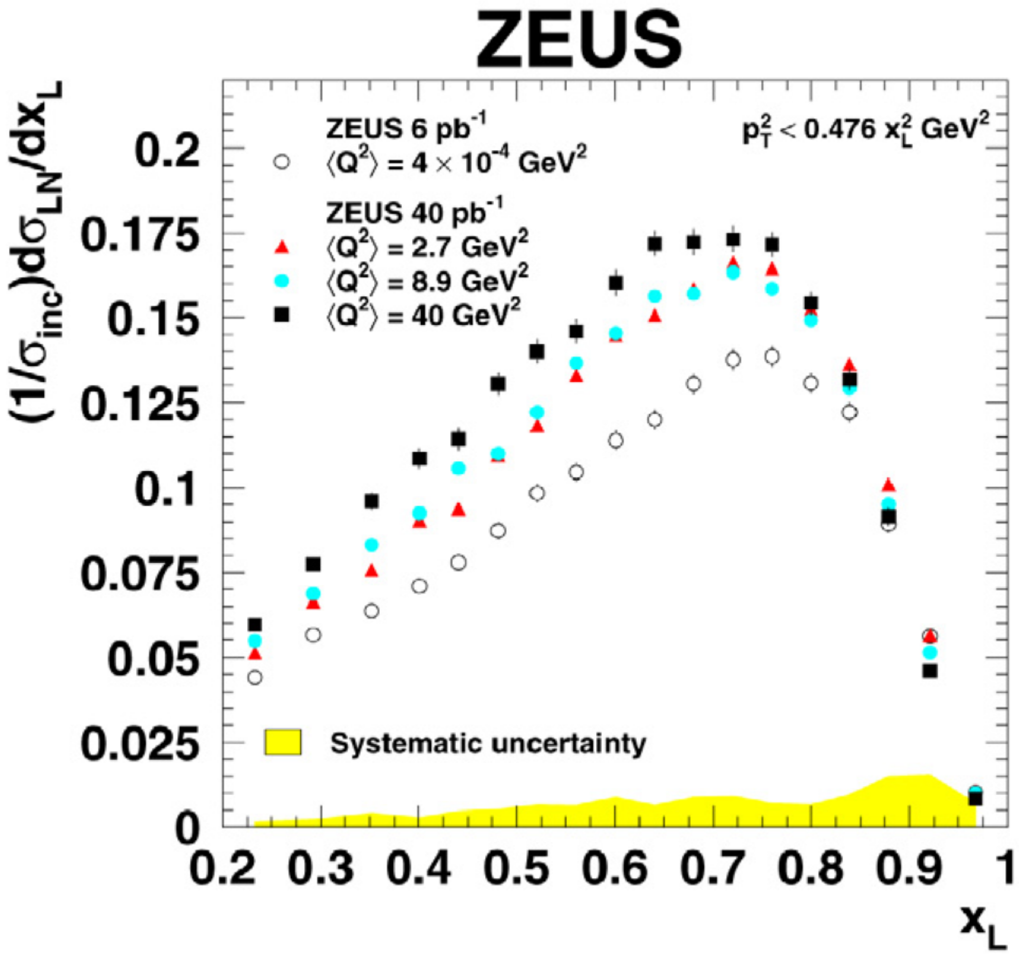
NPB 637(2002) 3-56 (also right figure)

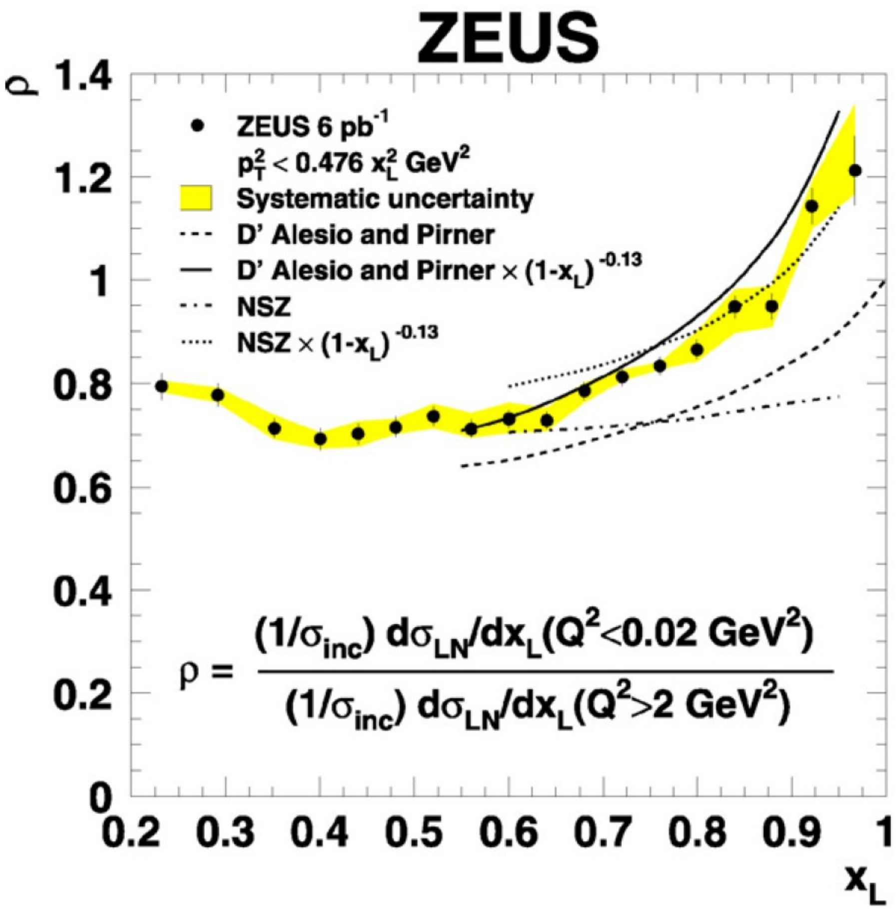




Photoproduction / DIS $Q^2 > 2\ \mathrm{GeV}^2$ vs x_L

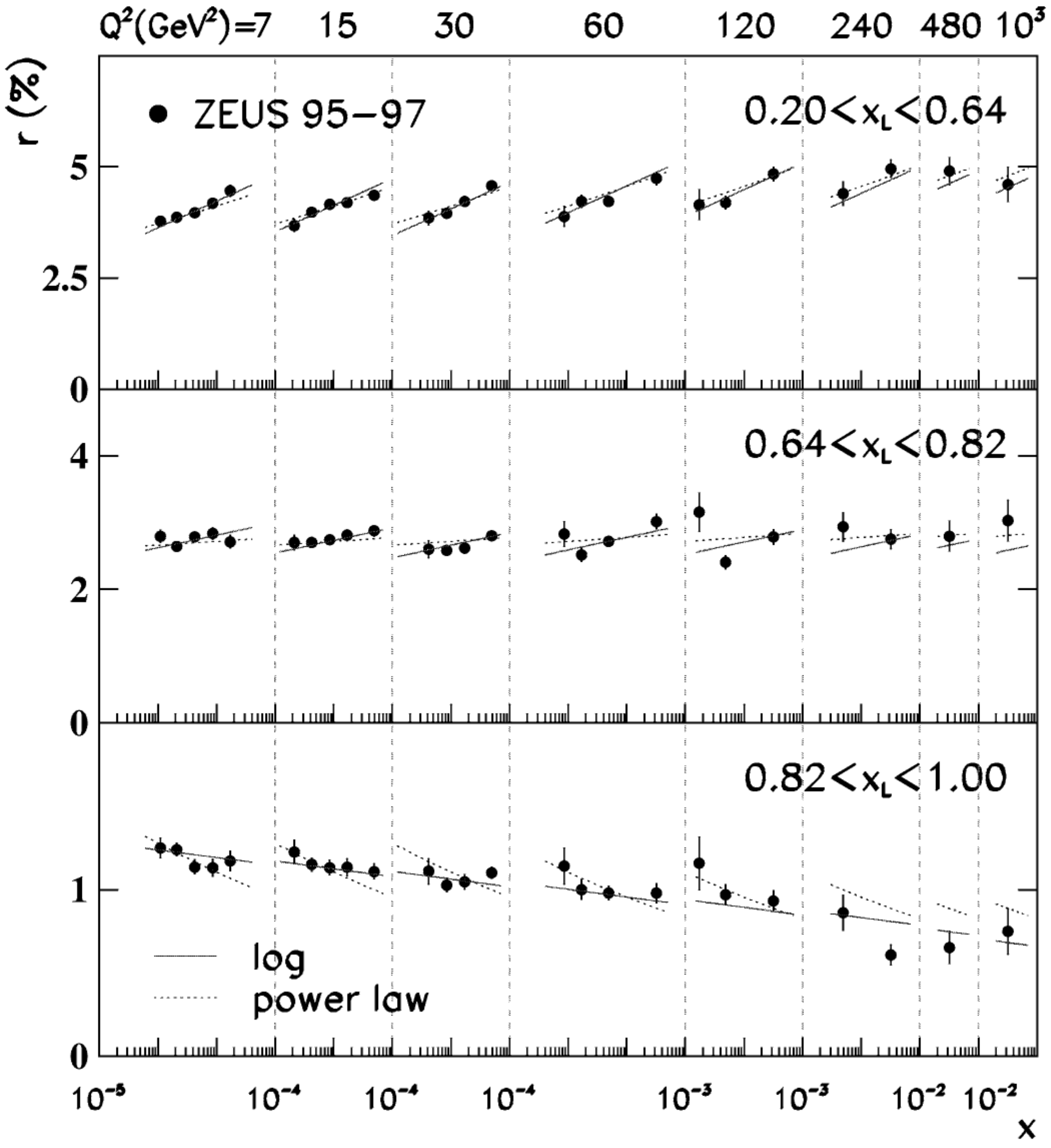
- clear x_L dependence on the ratio Photoproduction / DIS





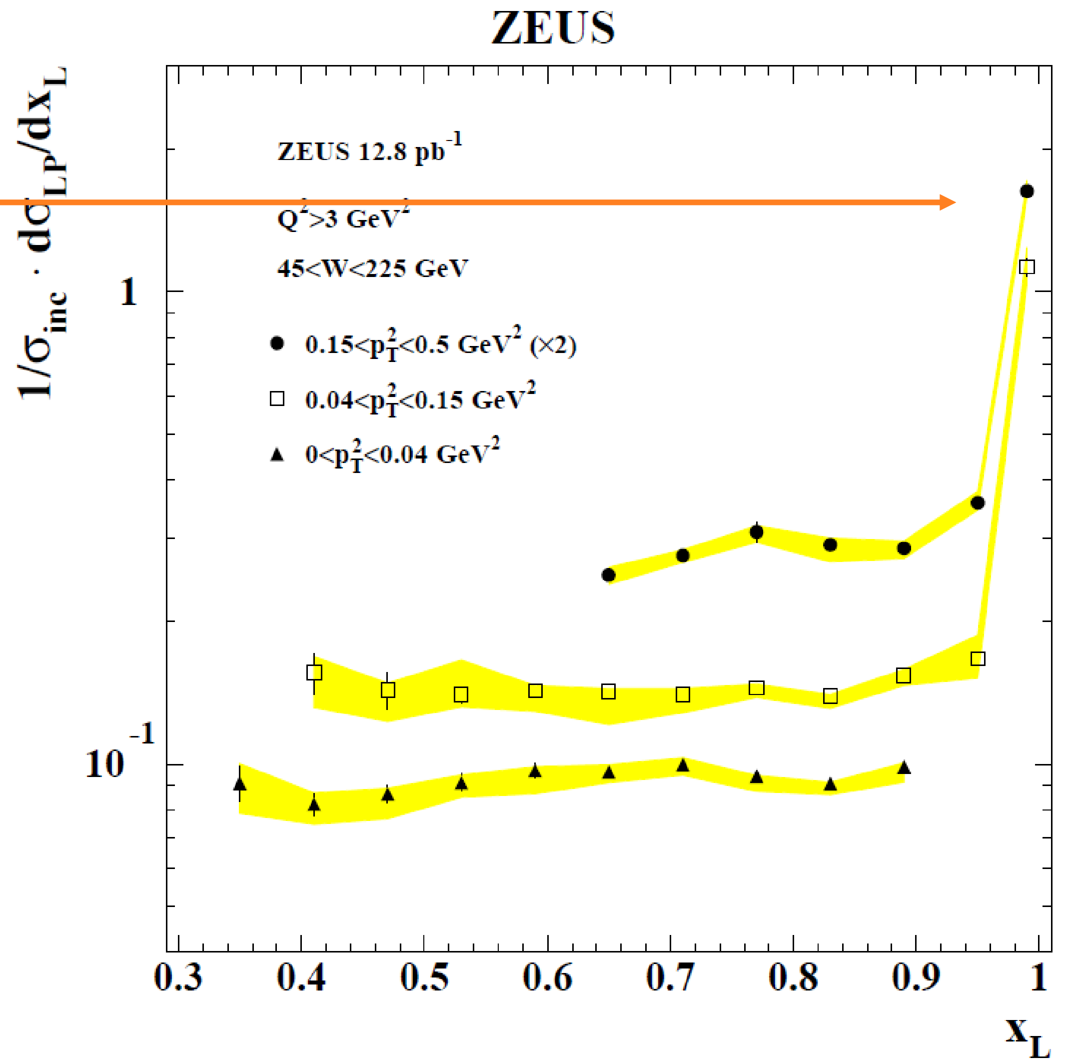
a bit more in detail: x-dependence?

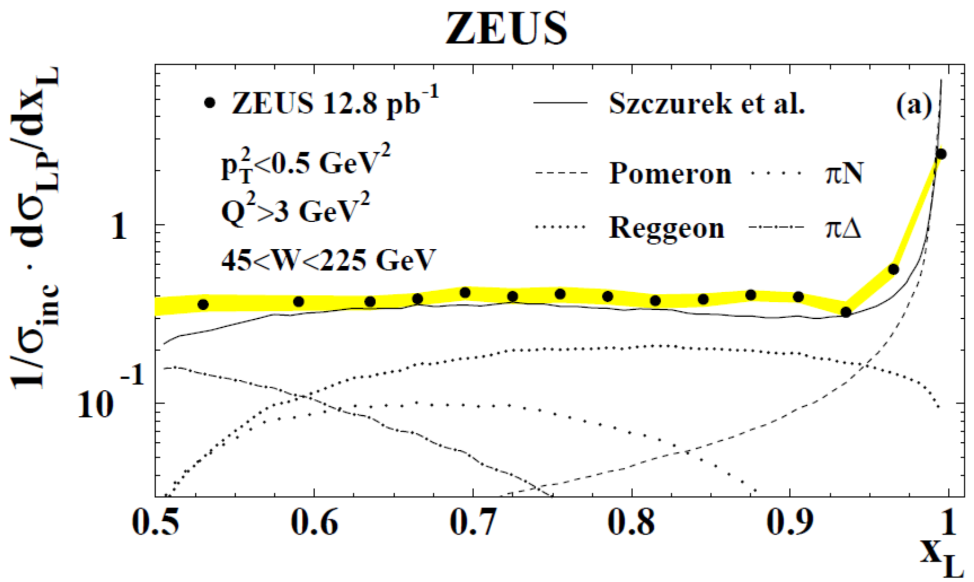
- Leading neutron events have very high statistics (> 10% of DIS)
  - very detailed kinematic dependence can be studied
  - factorization or not?
    Pion structure effect?



Longitudinal spectrum of forward proton

- $x_L = p_Z^{LB} / p_{beam}$
- Very flat
  (except for diffractive peak)
  - Limited fragmentation, or
  - pariticle exchange model (Regge poles superimposed)
- Strong contrast to neutron (with the pion peak)

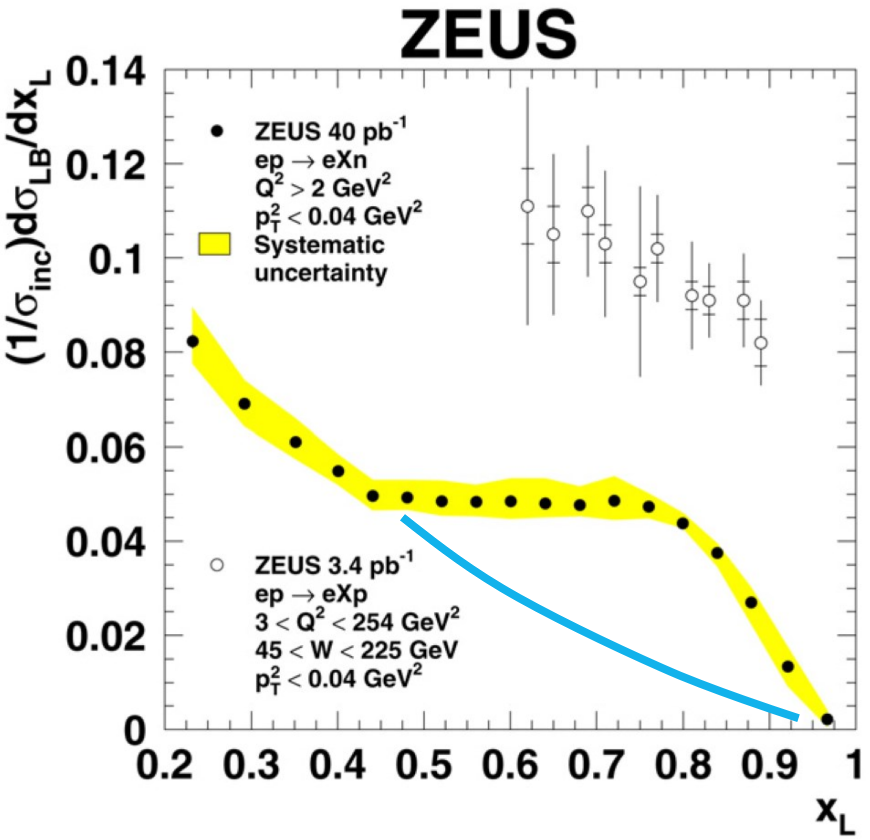


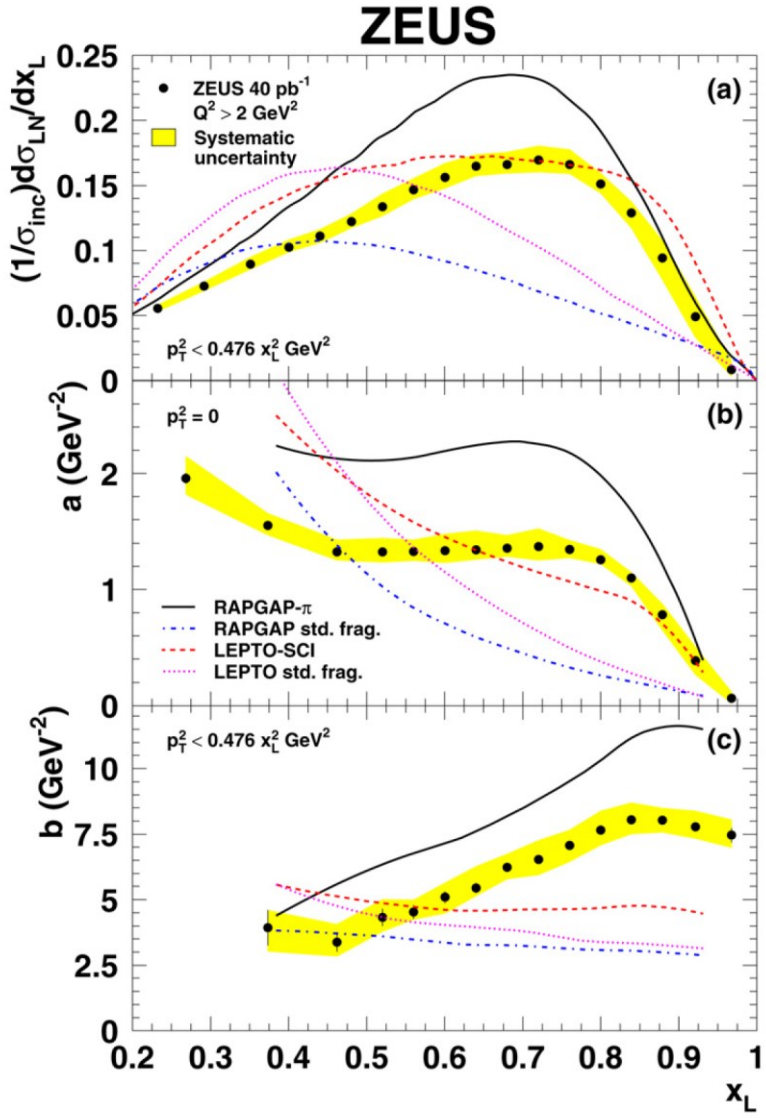


EIC should be able to study much more precisely

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 spectra, however

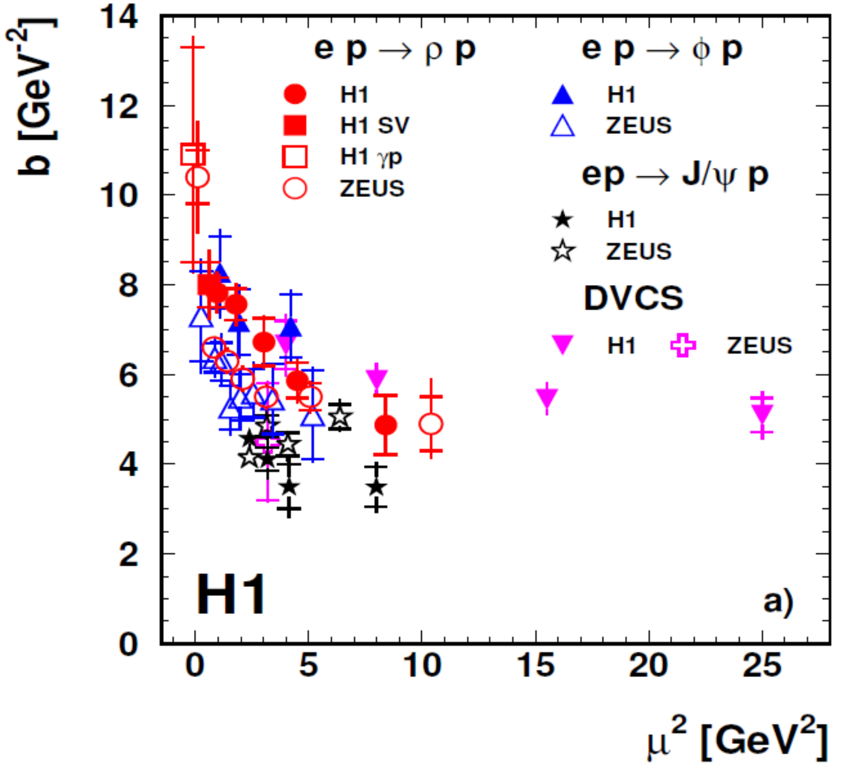


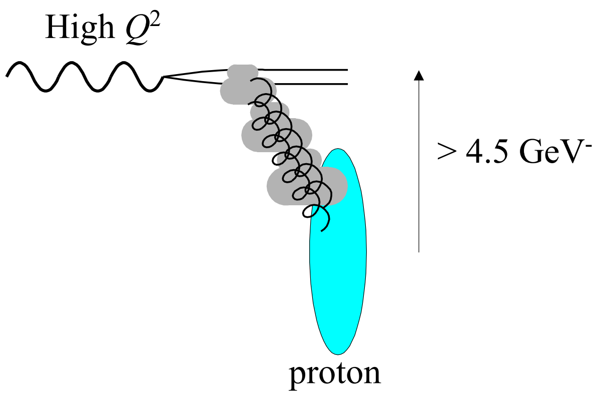


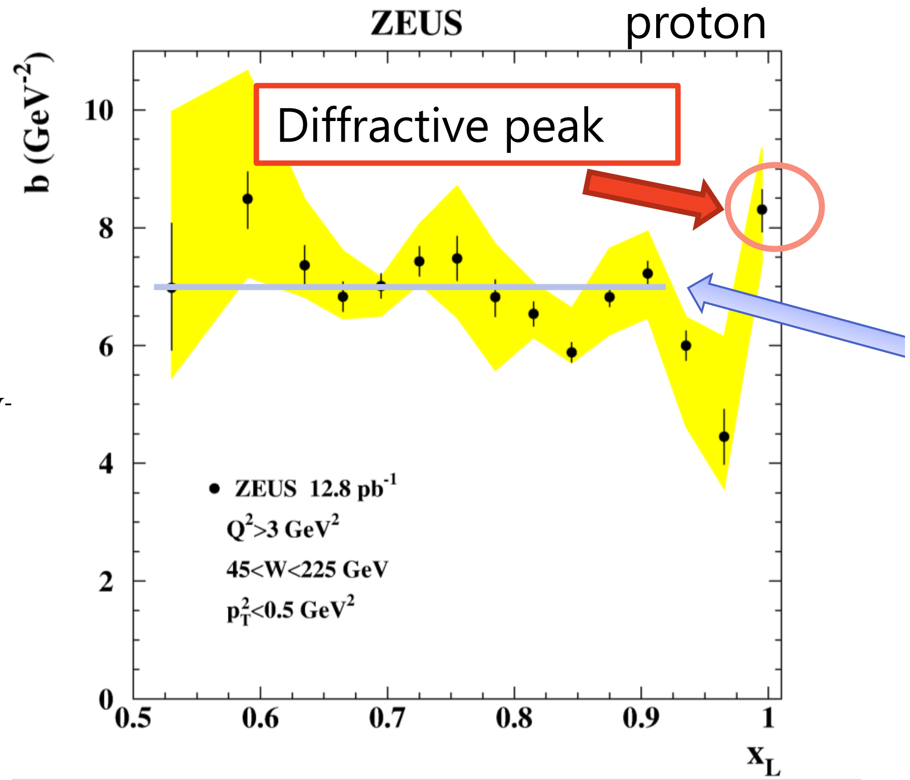
p_T dependence for forward protons

- 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

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



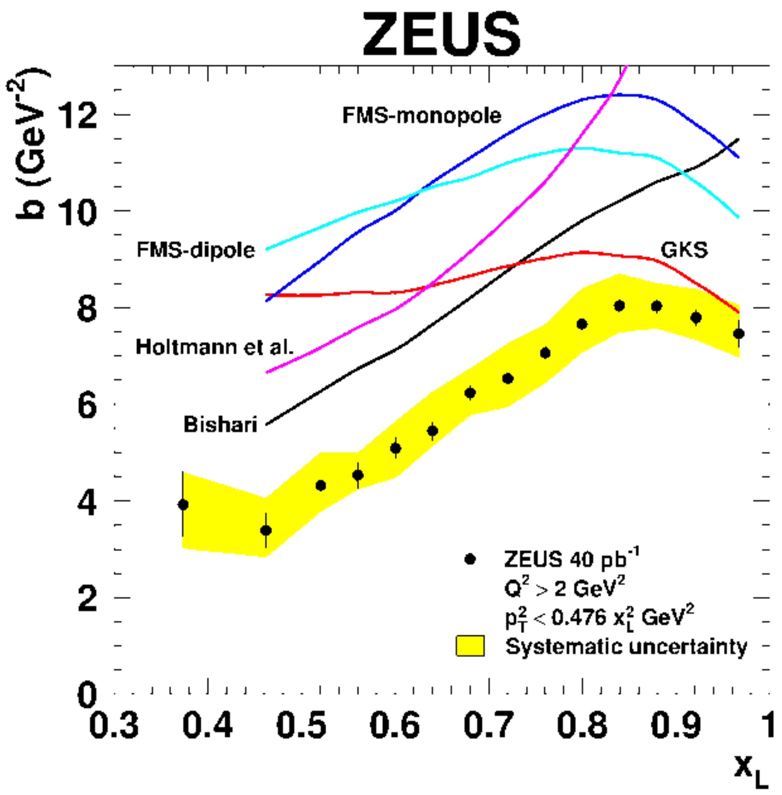


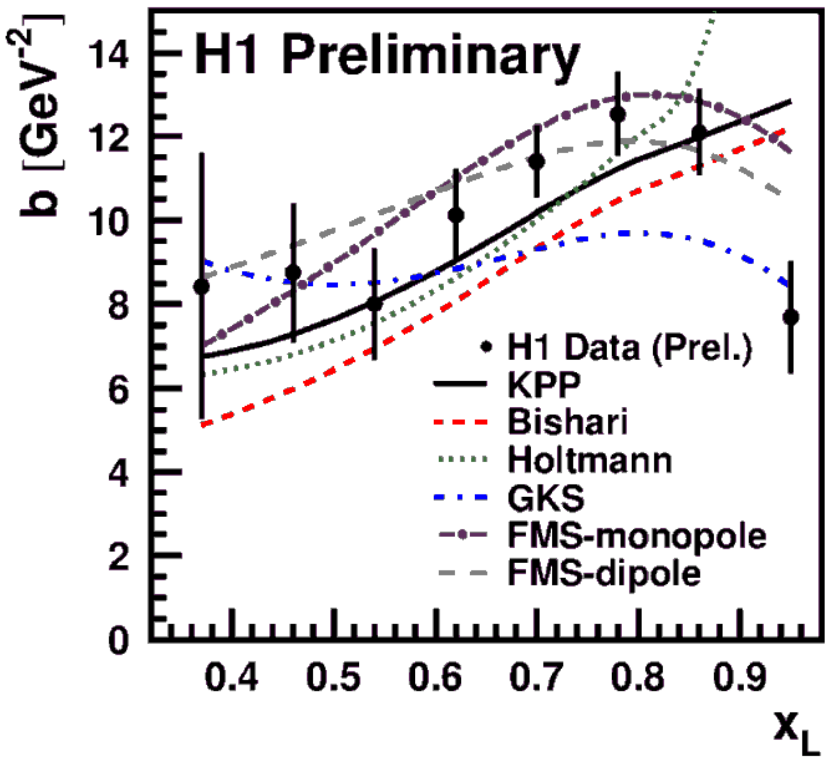


cf. quasi-elastic vector-meson production
Strong Q^2 and M_{VM} dependence

Forward neutron: rich structure in b-slope

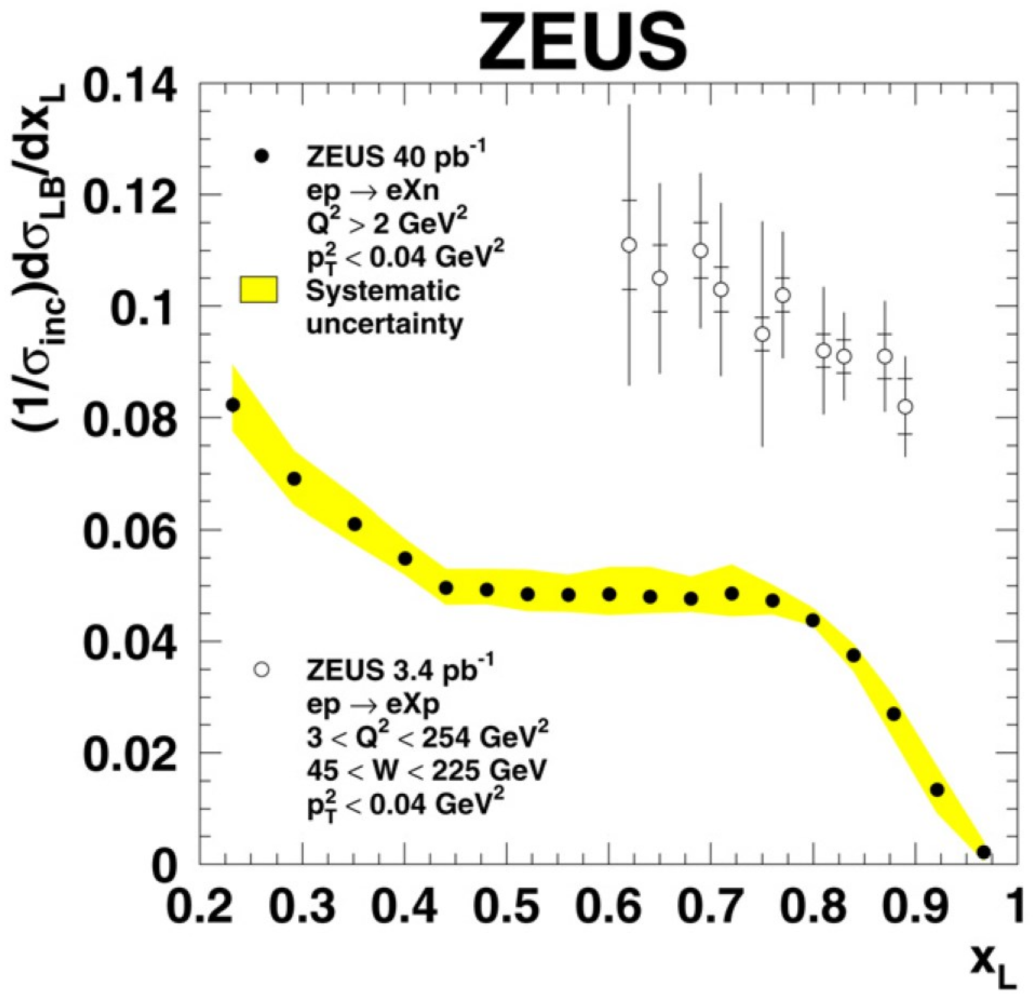
- Compared to various pion flux (e.g. $\pi - n$ vertex factor shape)
  - Qualitatively in agreement with various models
  - need to evaluate sub-leading components near $x_L = 1$ and low-x_L for more detailed discussion?





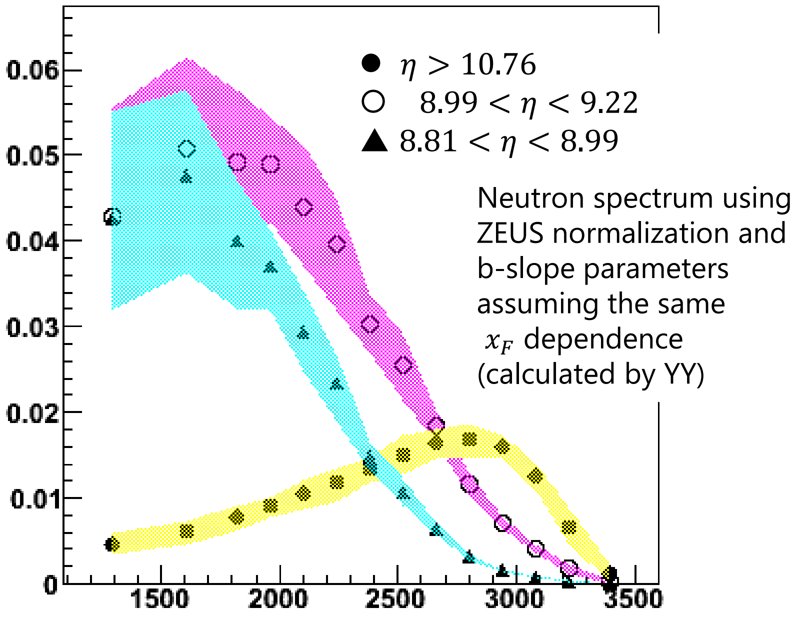
The forward baryon yield

- 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?



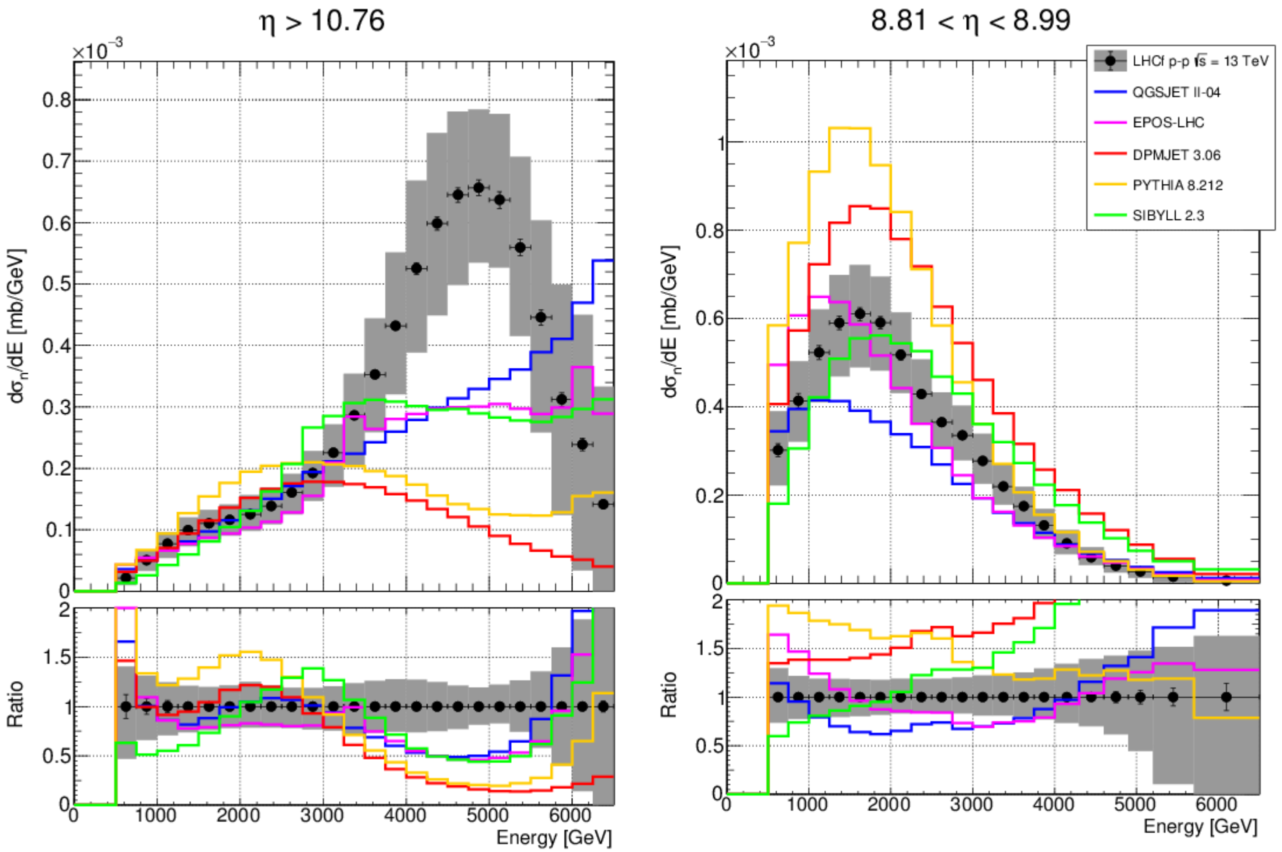
Neutron puzzle (2): pp vs ep

- 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: $\gamma^* p \rightarrow XN^*$ LRG-tagged neutron?

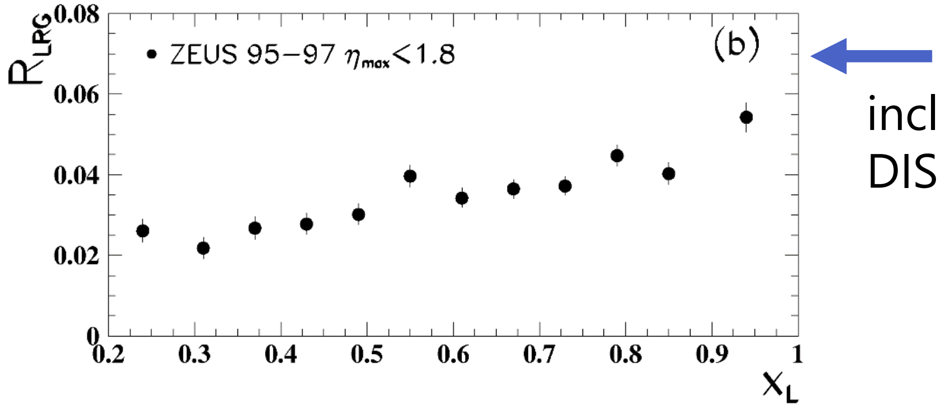


E_n (7 TeV beam)

LHCf data



Events with a neutron at HERA and rapidity gap



inclusive DIS (7%)

- Fraction of LRG (Large Rapidity Gap) events: 2/3 ~ ½ of inclusive DIS
- Among LRG evnets
  - proton elastic/diffraction: no neutron
  - proton diffractive dissociation could yield neutrons through fragmentation or decay of excitation → could be fewer than inclusive DIS
  - fraction of LRG increses with x_F : possible sign of neutron production through diffractive process
  - However, this is not the main machanism to produce neutrons
- More diffraction in LHC pp collisions? (we usually think it is fewer)

Summary

- YR focuses much on spectator tagging and exclusive process for ep collisions
- I believe inclusive measurements are also interesting
  - applicability of the one-pion exchange
  - the neutron yield
  - absorption effect
- Neutron structure: real measurement, finally at the EIC!
  - Also very useful for HEP to disentangle isospin structure at high-x
- I did not discuss about the neutral pion production
  - one of the decay photon from π^0's miss the ZDC for E < 30 GeV, unlike LHCf
  - B0 detector may do it well

BACKUP

Boundary condition for ZDC in EIC

dipole

Big aperture

4mrad = 12cm

Beam ~ 100 GeV

Size: ± 80 cm $\times$ 2m

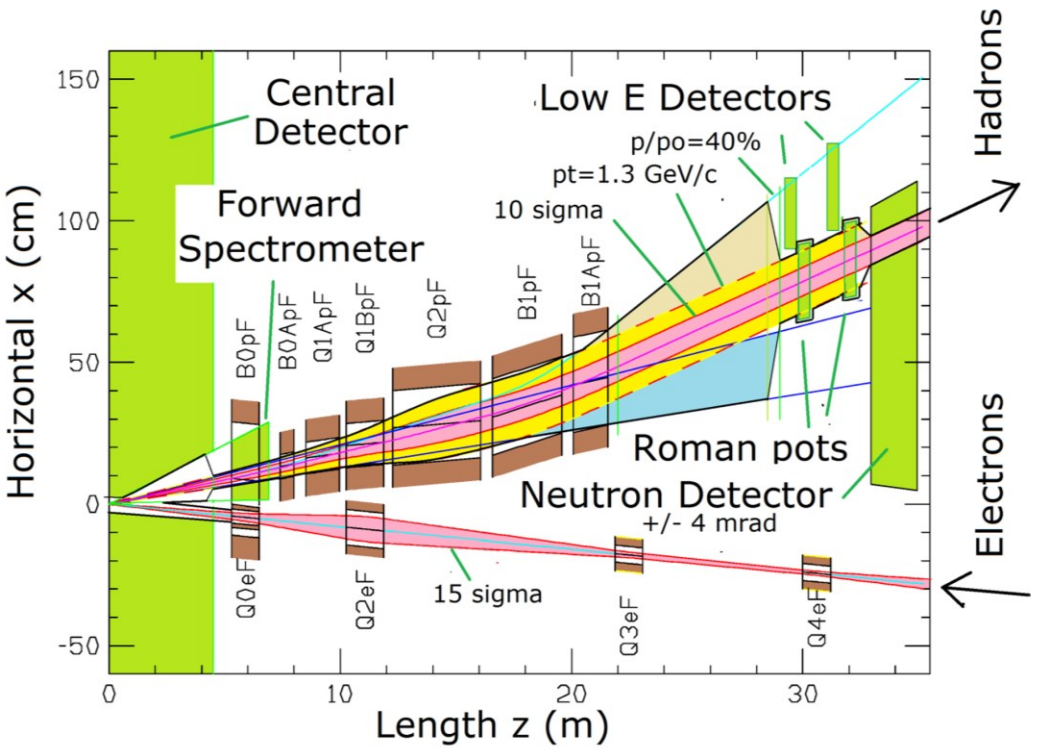
Big enough

Dose for ep

– for 300 fb^{-1} ?

Dose for eA

– How much int. lumi?



Energy or position resolution?

1mm / 33m = 0.03mrad = 3 MeV @ 100 GeV: 0.03%

Hadrons: $50\%/\sqrt{E}$ @ 10 GeV = 17%, @100 GeV = 5%

Photons: $4\%/\sqrt{E}$ @ 10 GeV = 1.3%, @100 MeV = 12%

Energy resolution is much more important

Position resolution: 1cm is enough

For HadCal:

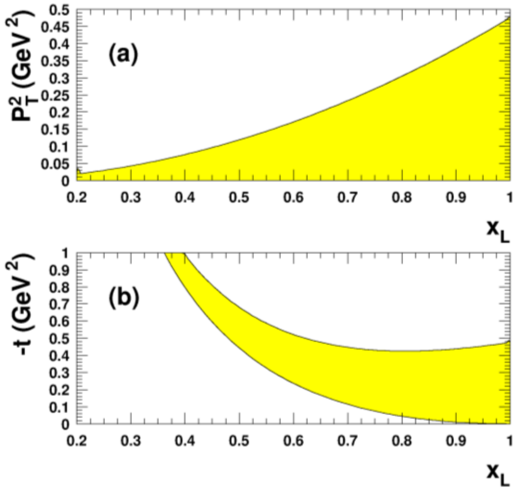
1. compensation by hardware or software
2. Small leakage of shower: need big calorimeter

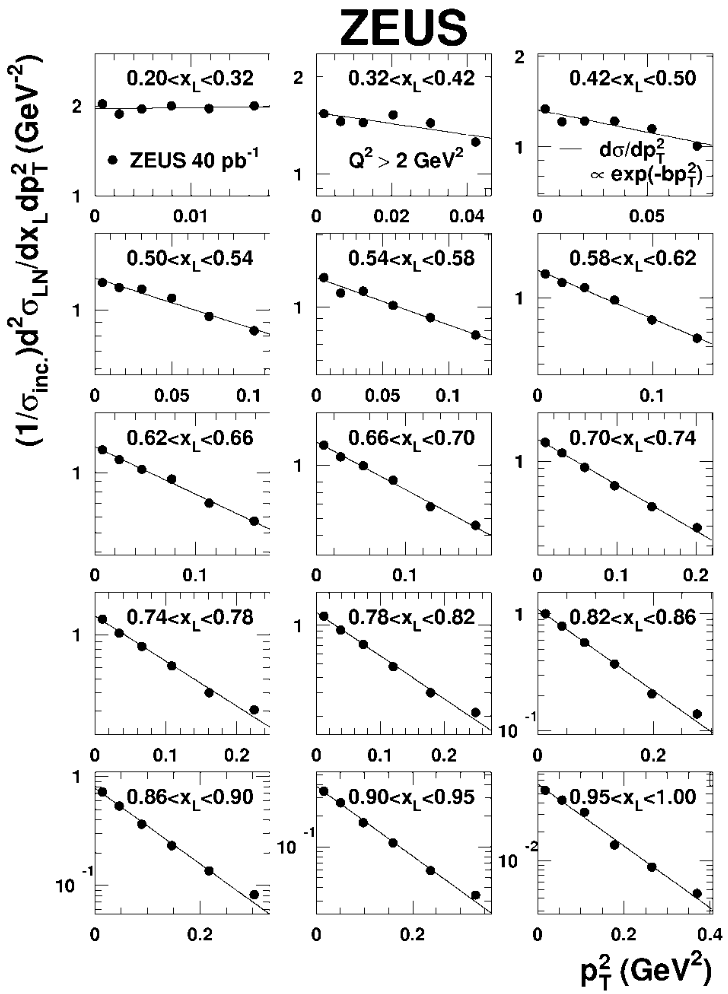
For EMCal: need non-sampling calorimetry

We should aim for $4\%/\sqrt{E}$

Aperture enough?

- eRHIC: 4mrad × 100 GeV = 400 MeV
  - $|t| < 0.2\ \mathrm{GeV}^2$: not much ….
  - OK for break-up neutrons
- JLEIC: 10mrad, 1 GeV
  - $|t| < 1\ \mathrm{GeV}^2$: much better….
- HERA: 0.5mrad = 0.5 GeV
- LHeC: 0.35 mrad = 2.5 GeV



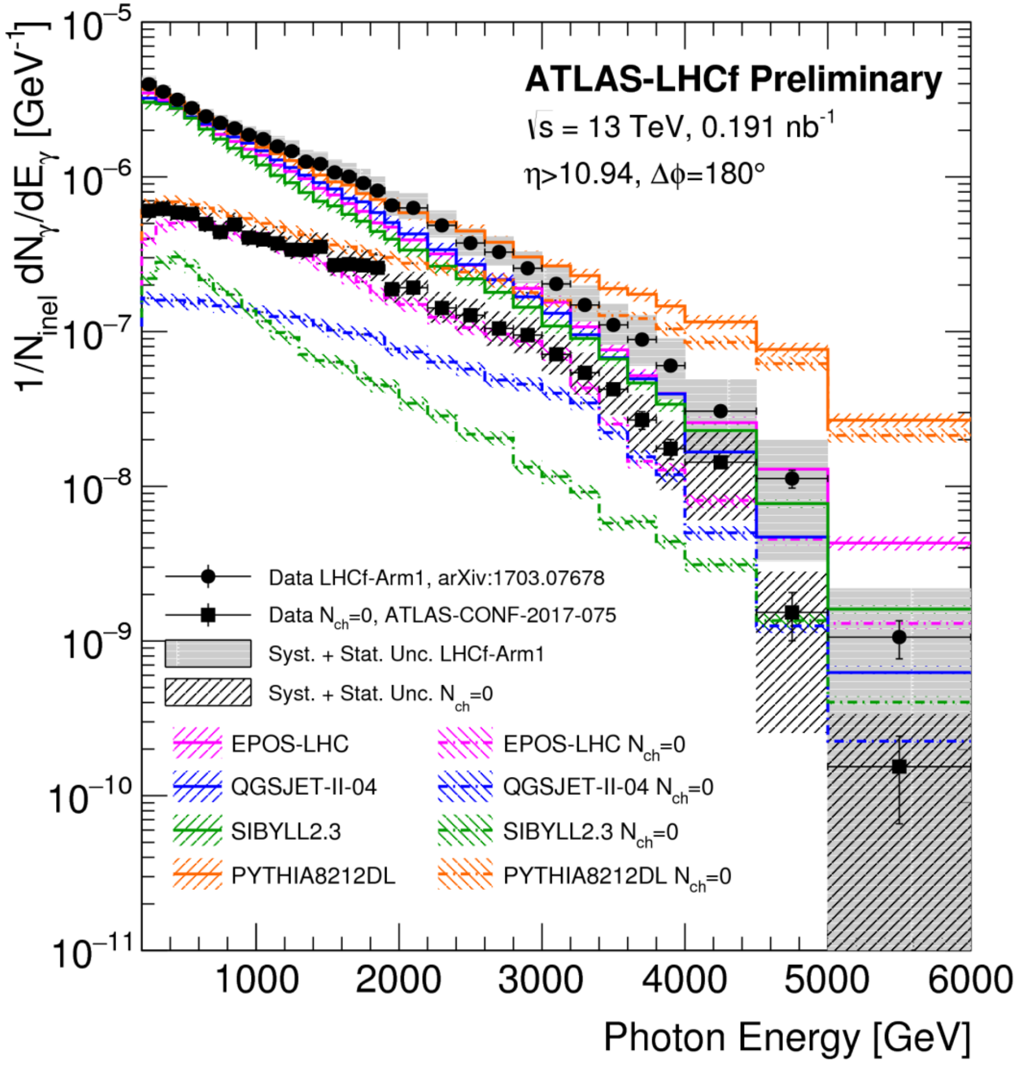


π^0 production by LHCf and ATLAS

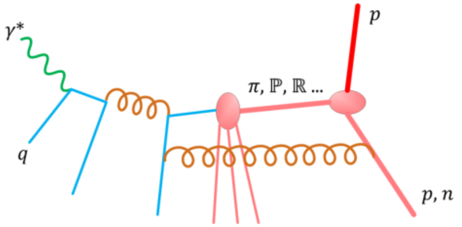
- Impact to cosmic ray simulation
- π^0 tagging thanks to excellent position resolution of the LHCf calorimeter (200 μm for 100 GeV e^-)
- Diffractive events tagged by LRG in ATLAS

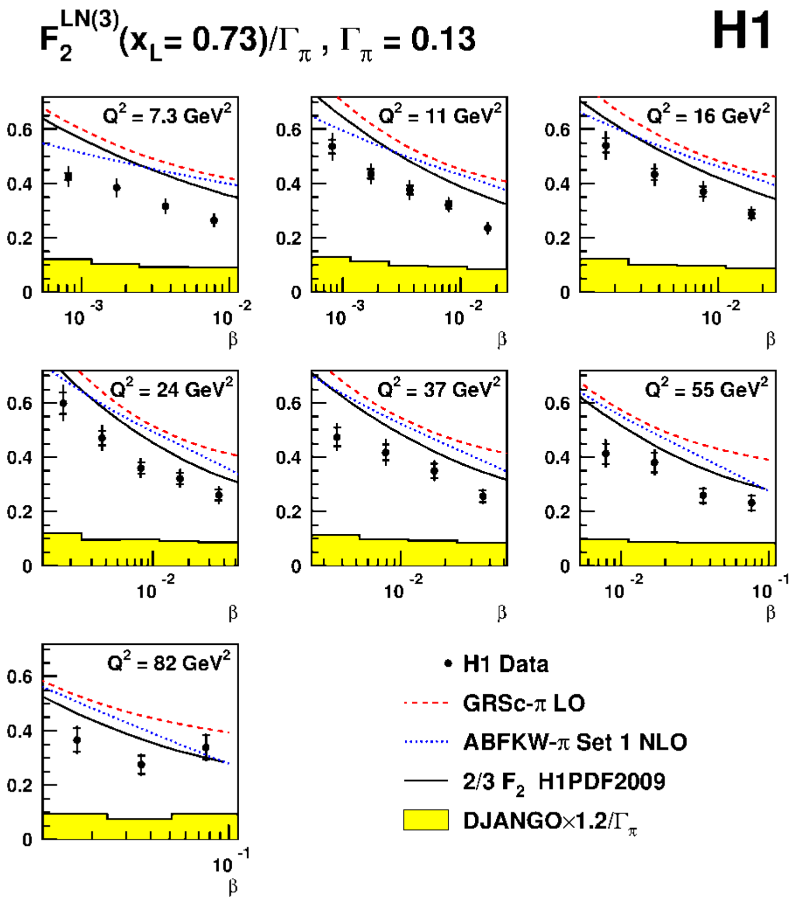
Need EM section with excellent position resolution

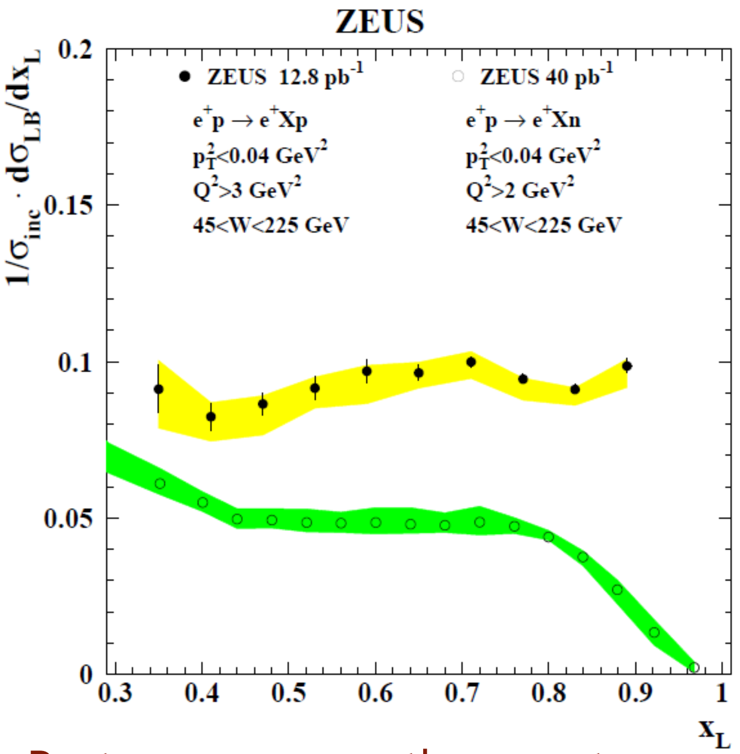
ATLAS-CONF-2017-075



Neutron puzzle (1) suppression?







- Neutron yield is 20-30% fewer than naïve prediction of $p : n = 1 : 2$ expected from isovector exchange
- Absorbtion? Rescattering?

- Protons are more than neutron
  - Again no consistent with isovector exch.

Where did neutron disappear?