ZDC overview

EIC Asia Workshop @ RIKEN
17 March 2023
Yuji Yamazaki (Kobe University)

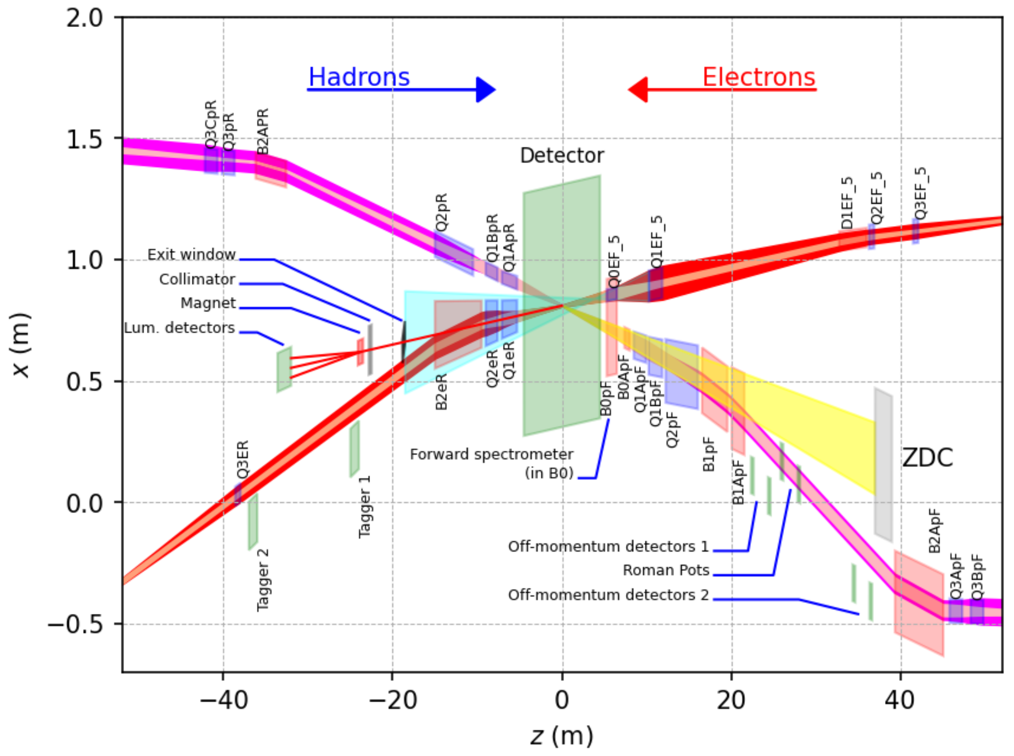
This talk

- EIC and forward-physics detectors

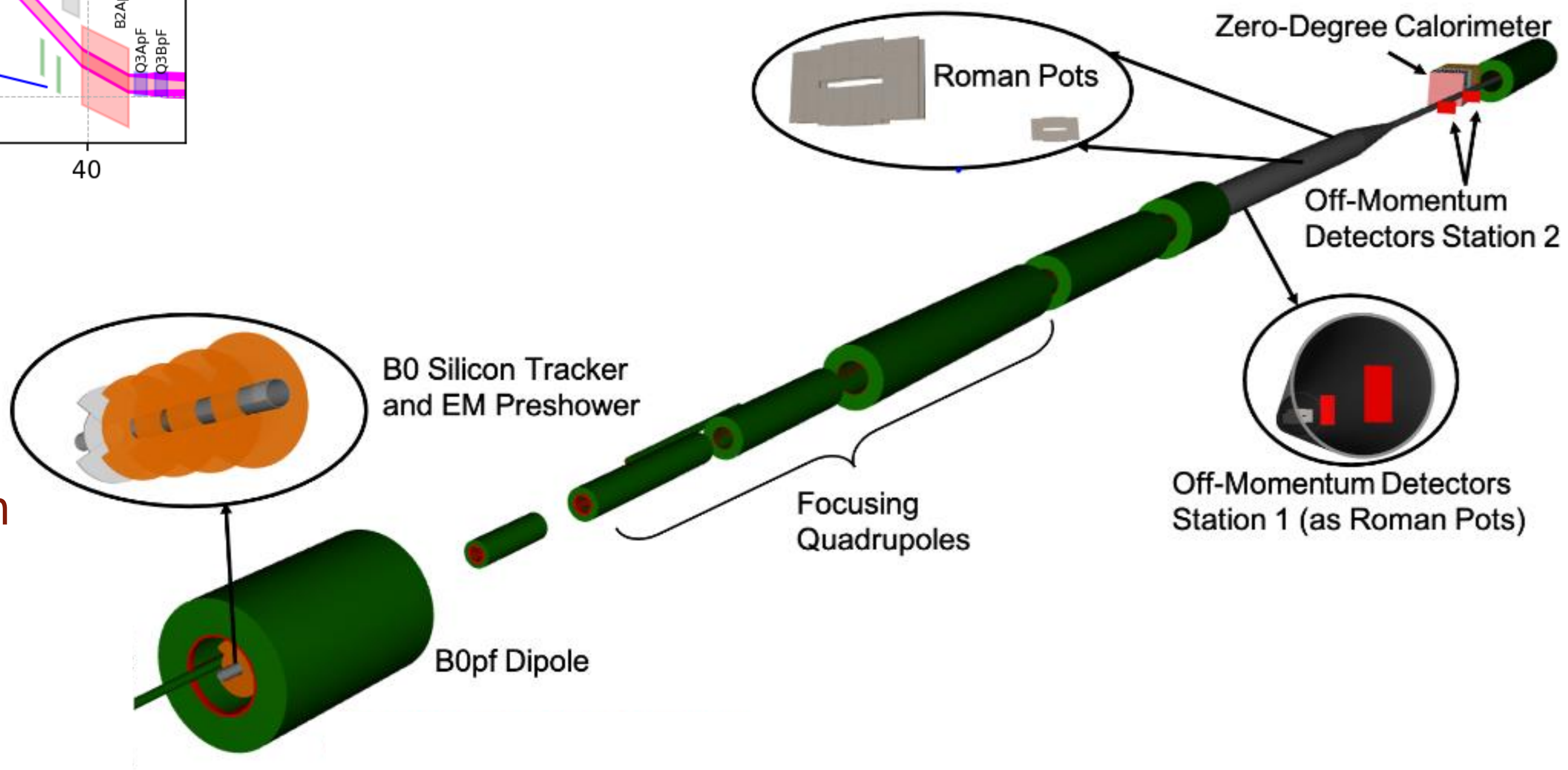
- Physics with forward neutrons
  - photons to detect de-excitation
  - spectator tagging, especially for nuclear effect
  - meson structure functions
  - inclusive measurements

- ZDC requirement and technical challenges
  - design consideration
  - various options

EIC forward detectors



- Charged particles:
  Roman pots, off-momentum detectors,
  B0 tracker/EM preshower
- Neutrals (n, γ, π^0): B0, **ZDC**



ZDC at around z = +35m

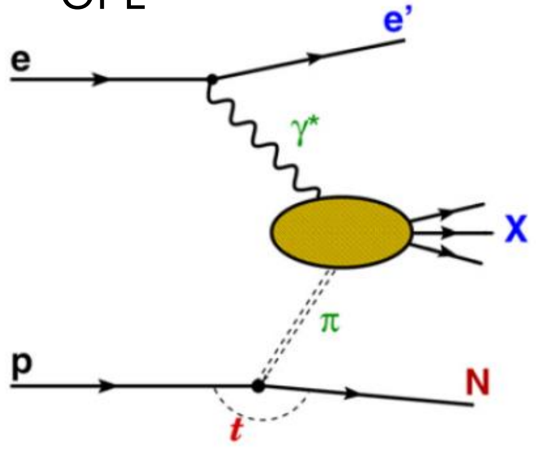
Aperture: ~ 4mrad

Available space: 60 x 60 x 200 cm

ZDC physics motivation

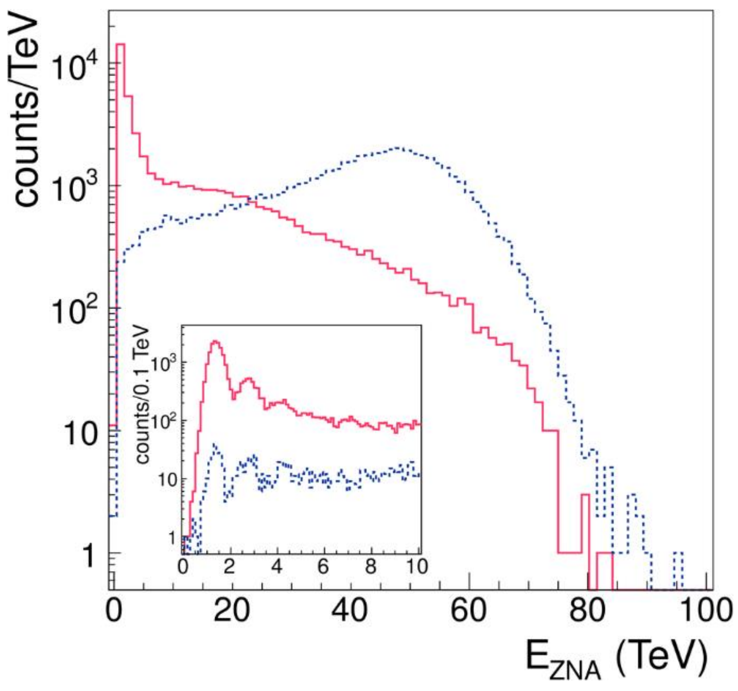
- Spectator tagging for:
  - HI studies
  - nuclear effect in DIS
- Tagging γ from de-excited scattered ion
  - to increase the purity of quasi-elastic eA collisions
- Meson structure function through Sullivan process
  - a.k.a. OPE = One Pion Exchange model for pion exchange
- Production mechanism of nucleon in the ep final state
  - through semi-inclusive measurements

OPE

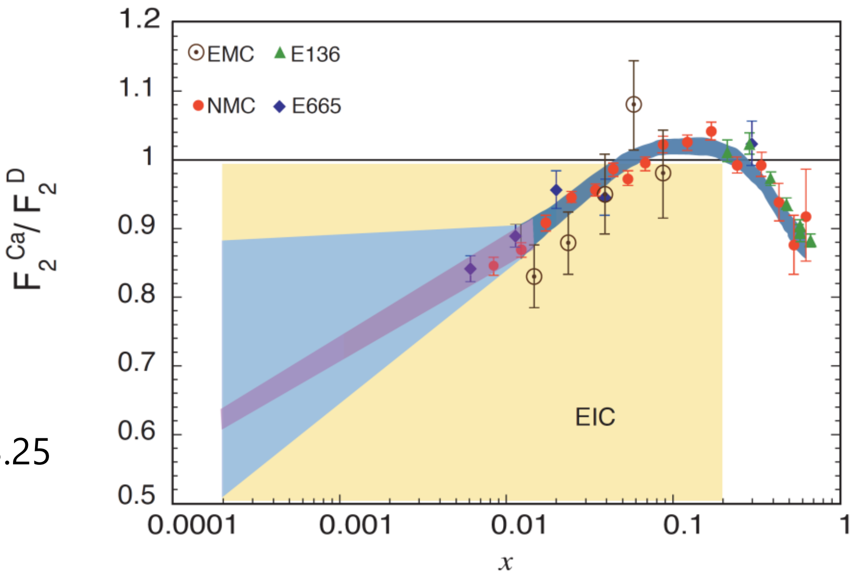


Physics with ZDC + B0: spectator tagging

- Heavy ions: many neutrons from "ion remnant"
  - maybe useful to measure "centralilty"
  - need to measure energy in multi-TeV range
- Light ions (d, ^{3}He ...)
  - precise determination of the nuclear effect
  - The nuclear effect is one of the major source of uncertainties in proton parton densities in high-x



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

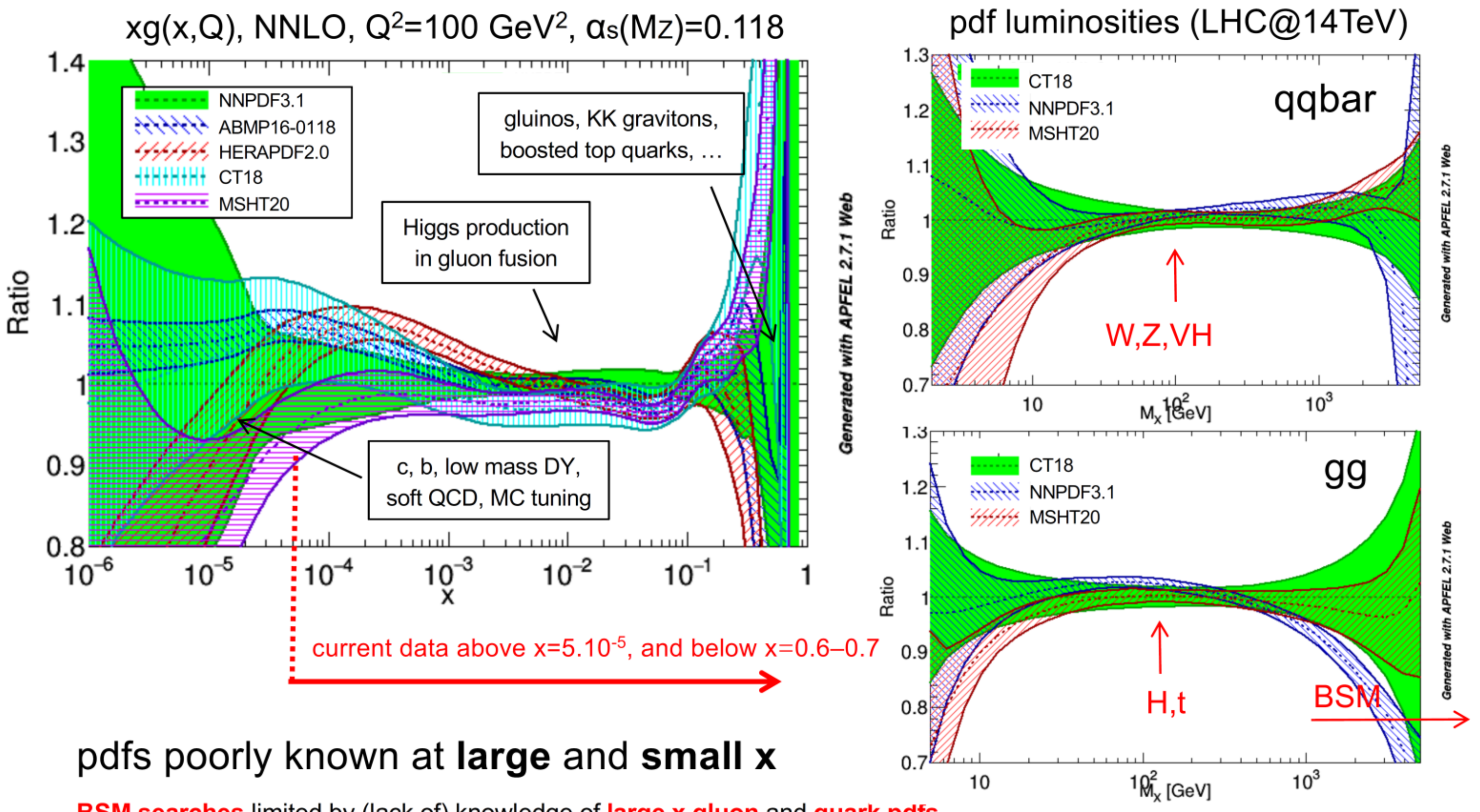


EIC White Paper fig. 3.25

Impact of high-x PDFs at the LHC

- High-x data constrained mainly from fixed-target DIS and DY experiments
- Important uncertainty for new physics searches
- need to pin down before moving to FCC-hh

pdfs: the situation today



pdfs poorly known at **large** and **small x**

BSM searches limited by (lack of) knowledge of **large x gluon** and **quark pdfs**

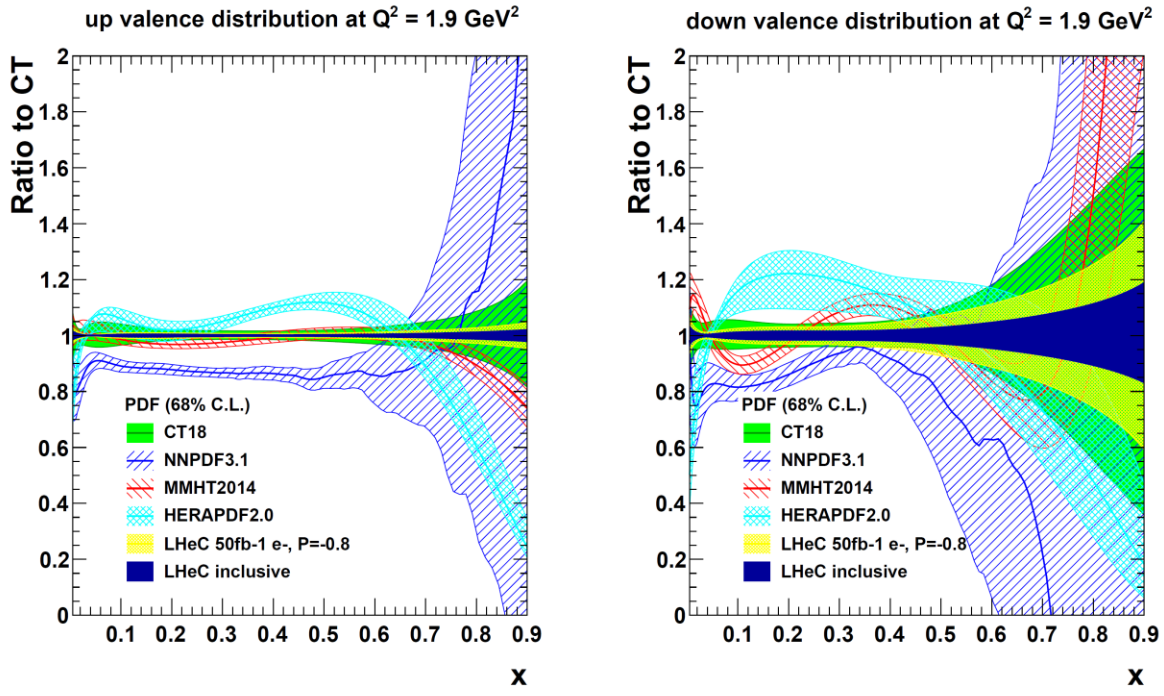
… plus precision **MW**, **$\sin^2\vartheta W$** (where small discrepancies may indicate BSM physics) and **Higgs**, also limited by **pdf uncertainties** at medium x, where we know pdfs best!

crucial also to ensure **BSM deviations not inadvertently absorbed into pdfs**, see EG. arXiv:2104.02723 , 1905.05215 2

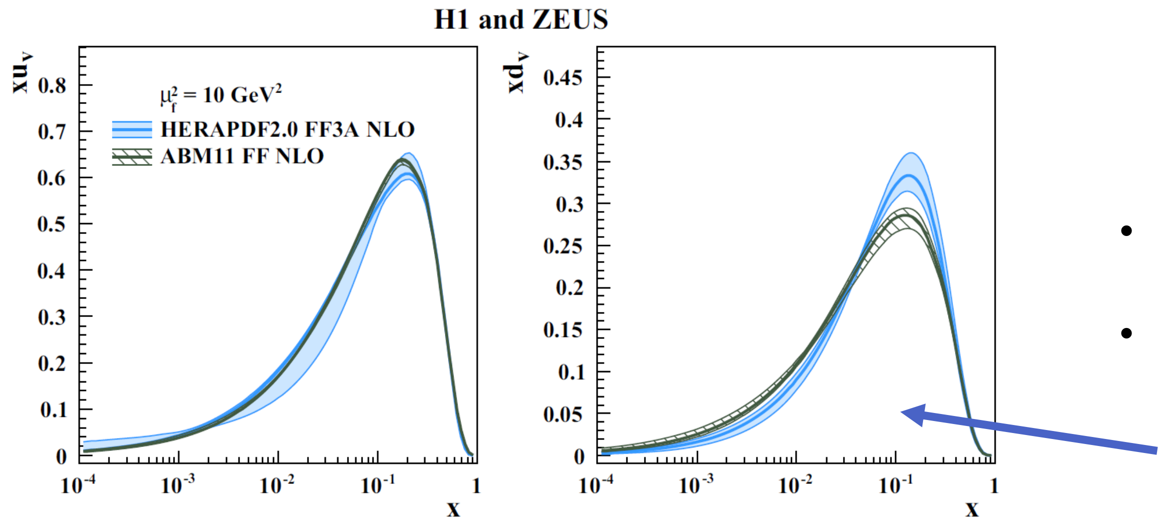
Claire Gwenlan, DIS2021

PDF uncertainty from used datasets

- Quite a bit of difference between PDFs with or without the fixed target data when performing DGLAP fit
  - **u/d ratio** in particular
- Maybe because of our lack of knowledge in nuclear effect?
  - Or just different systematics in different experiments?



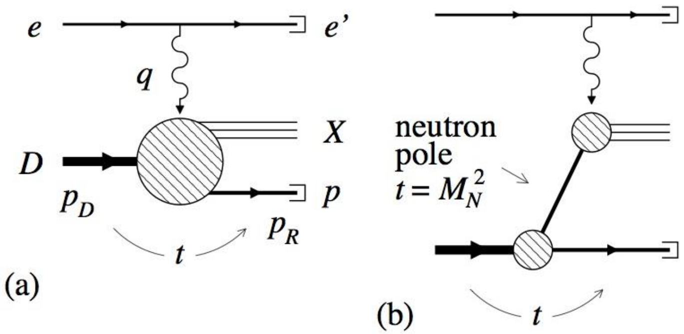
↑ LHeC TDR update arXiv:2007.14491



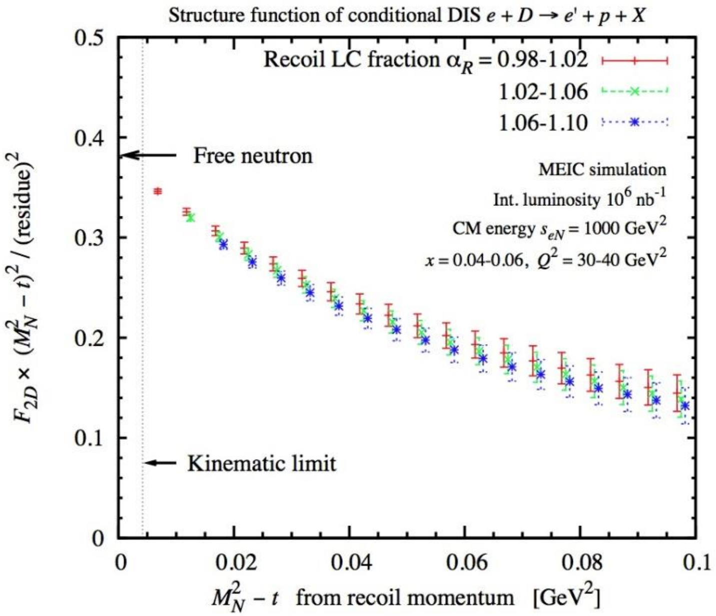
- HERAPDF 2.0: HERA data only
  Eur.Phys.J.C 75 (2015) 12, 580
- ABM11 (PRD 86, 054009): including
  - BCDMS, NMC, SLAC
  - Drell-Yan from FNAL
  - Dimuon from νN

tagged eD/eA DIS for precise determination of the nuclear effect

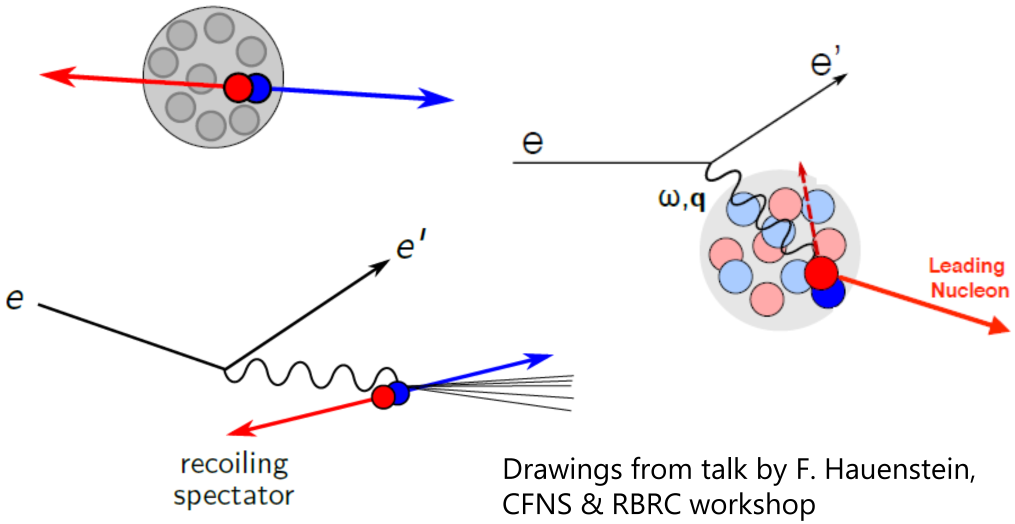
- Proton-tagged $\boldsymbol{eD}$ and $\boldsymbol{eA}$ scattering
  - $e(p+n) \to en + p$ **DIS for neutron!**
  - Way to understand **nuclear (EMC) effect** or short-range correlation **(SRC)** by comparing small and large system
- Neutron-tagged $(ep+n)$: proton structure with t
  - Cross-check with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



Need to interpolate to t = 0

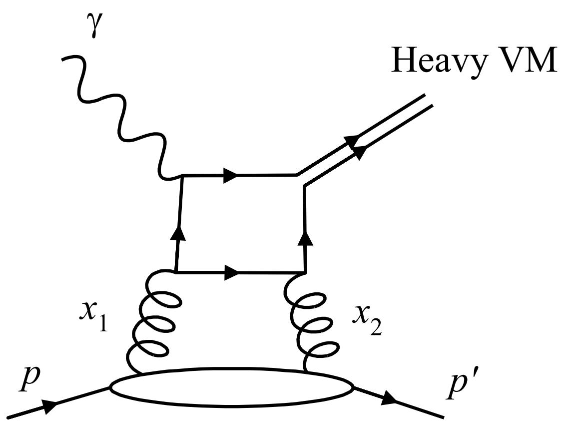


J.Phys.Conf.Ser. 543 (2014) 012007



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

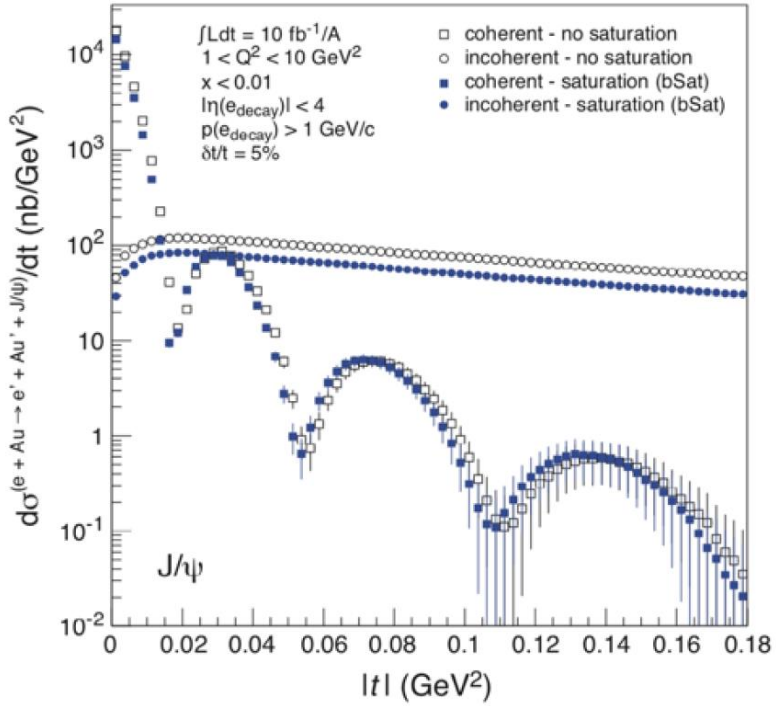
Photons from de-excitation

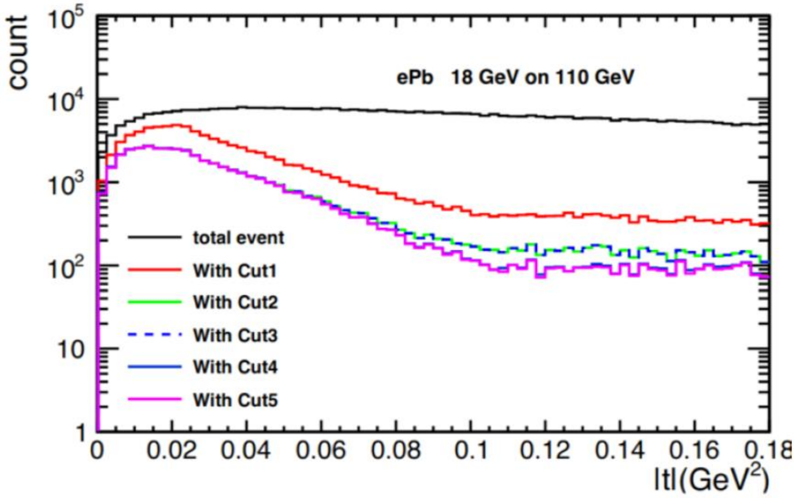


- vetoing nuclear excitation events in heavy eA collisions by tagging **~300 MeV photons** from de-excitation
- sensitivity to saturation effect through quasi-elastic J/ψ production
  - t-distribution of vector meson reveals the transverse parton profile of the ion: central part may not be visible if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

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

e+Au YR Fig. 7.83

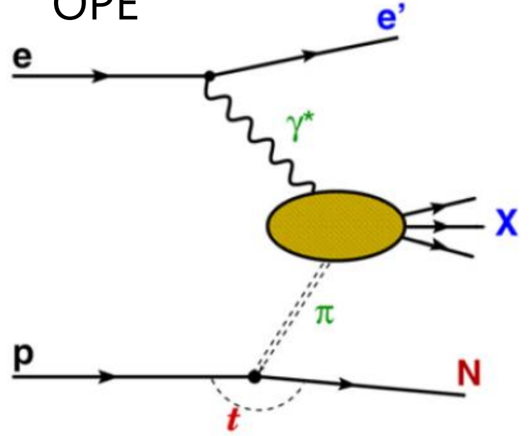




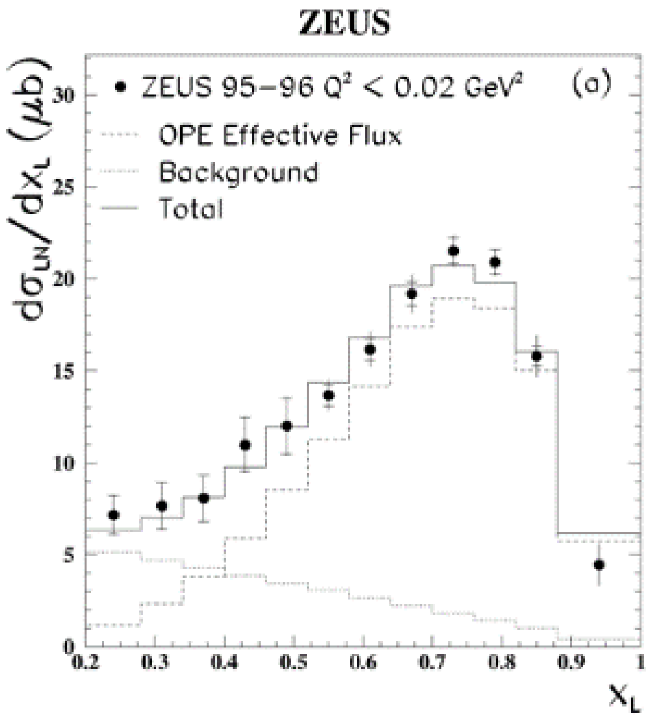
Meson structure function through ZDC

- Through "Sullivan process"
  - one-pion exchange dominated in high x_F regime in neutron production: neutron spectrum agrees well with the OPE model
  - may work for Kaon as well, through Λ/Σ production decay n or π^0 goes to ZDC
- NB: ZDC π^0 acceptance is low below a few tens of GeV
  - most of both photons go within ZDC aperture for > 50 GeV $\pi^{0\prime}s$
  - the B0 detector should serve for it

OPE



Nucl.Phys.B637(2002)3



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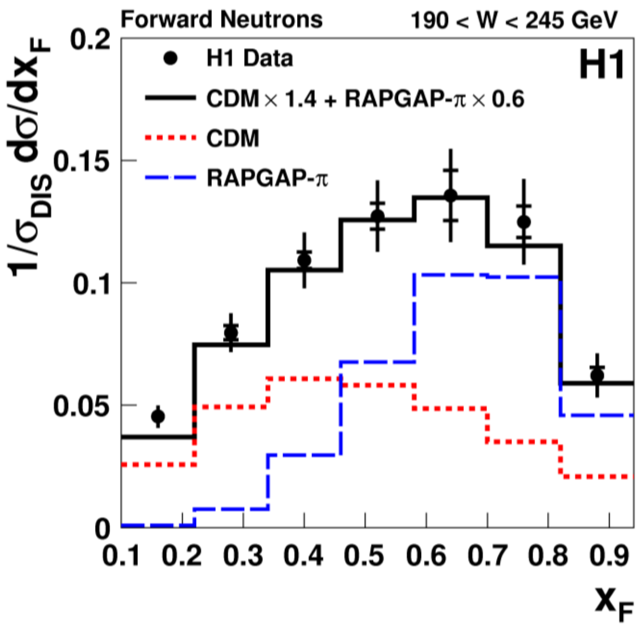
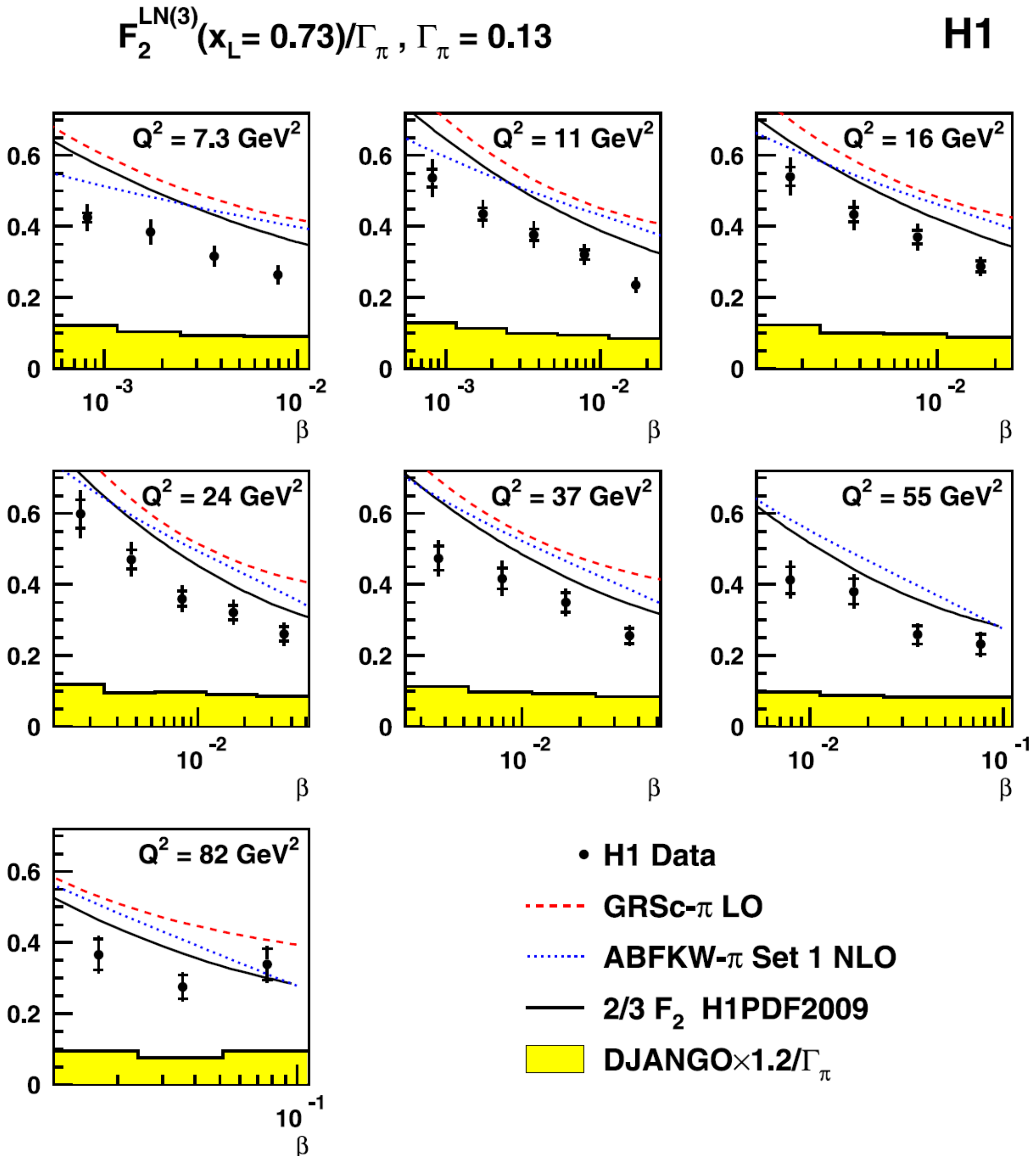


HERA extraction of the pion structure function

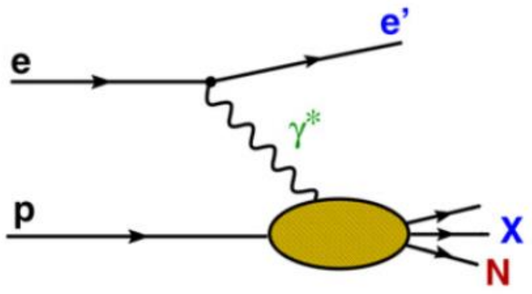
- $x_\pi = x_{Bj}/(1 - x_L)$
  x_L: neutron momentum fraction
  - the shape of the SF for proton and pion are the same if $F_2 \propto x^{-\lambda}$ with constant λ
  - This holds quite well: see 2/3 F2 H1PDF2009, which is the proton structure function!
- The absolute value is smaller
  - ZEUS similar result (almost half of the theoretical prediction)
  - **Neutrons produced less than expected… where did they go?**



Neutrons: production mechanism in ep

- **Baryon number should conserve:**
  there should exist at least either a proton or neutron somewhere in rapidity
- Most basic interpretation: fragmentation
- Fast neutron ($\xi \equiv x_L = E_N/E_p \gg 0.1$):
  meson exchange model
  - similar to Pomeron/Reggeon exchange for diffraction

fragmentation



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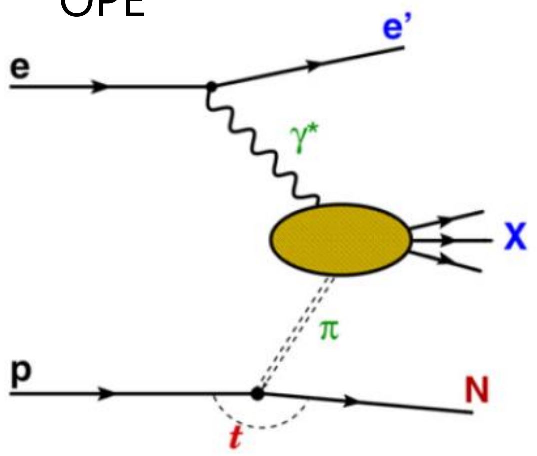
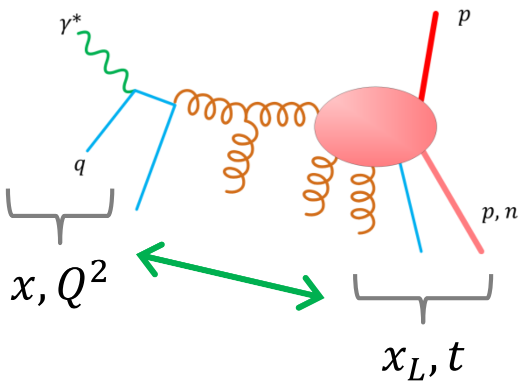


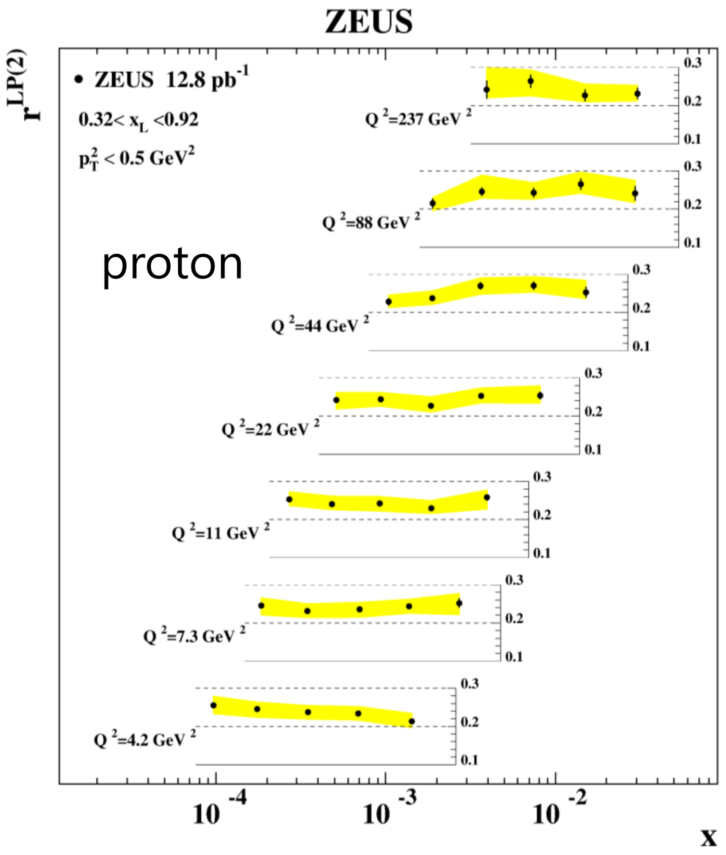
- **For both models, factorization holds** between photon vertex (x, Q^2) and baryon vertex (x_L, t)
- How far can the baryons travel over rapidity?
  - non-forward neutron would also be interesting

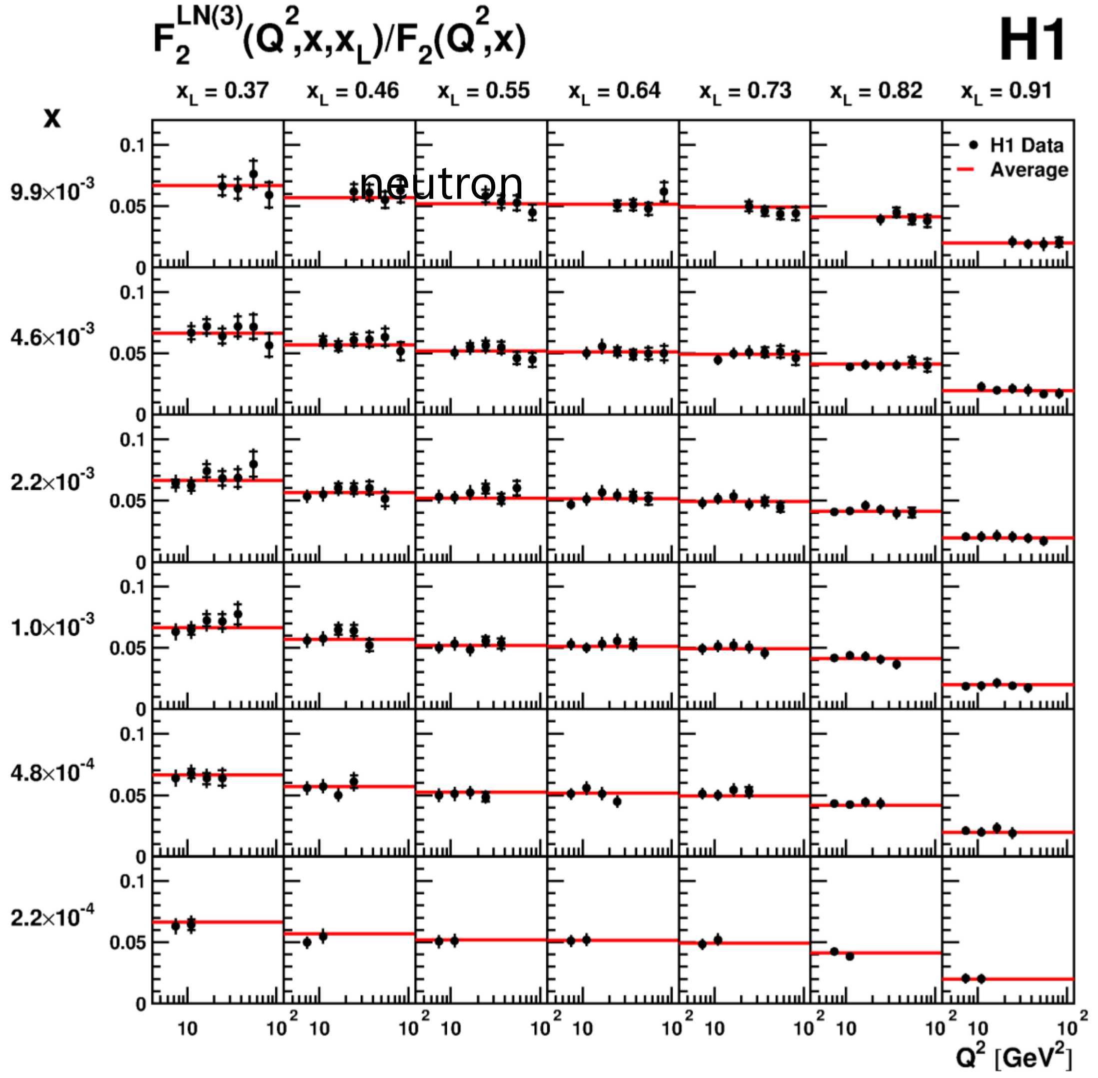
Factorisation properties: does the baryon talk to γ^*?

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



The left and right vertices are way separated

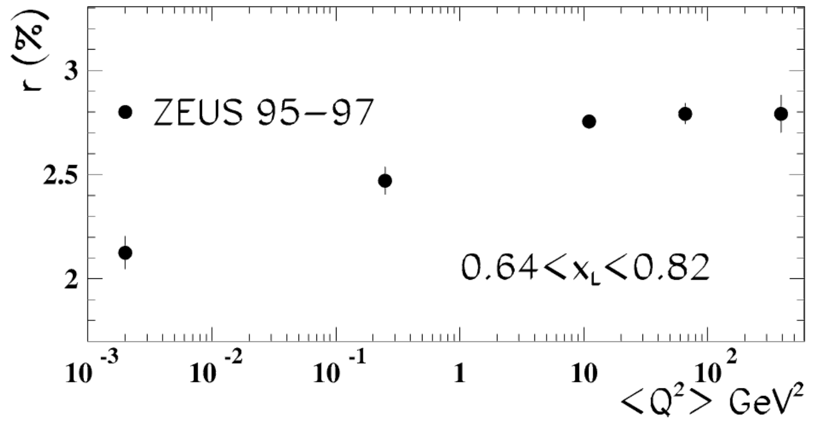


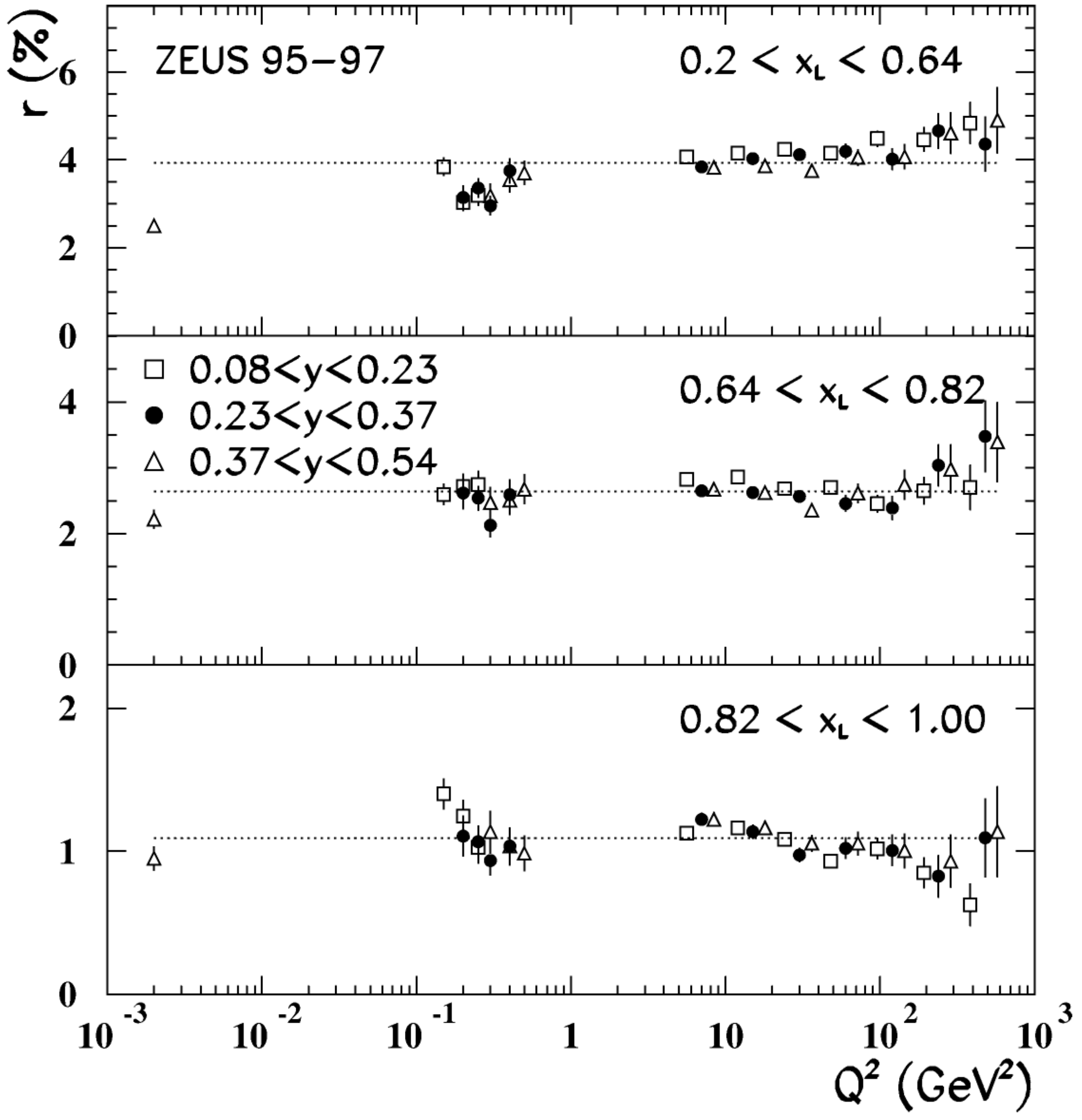


A bit more in detail: Q^2 dependence?

- 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?

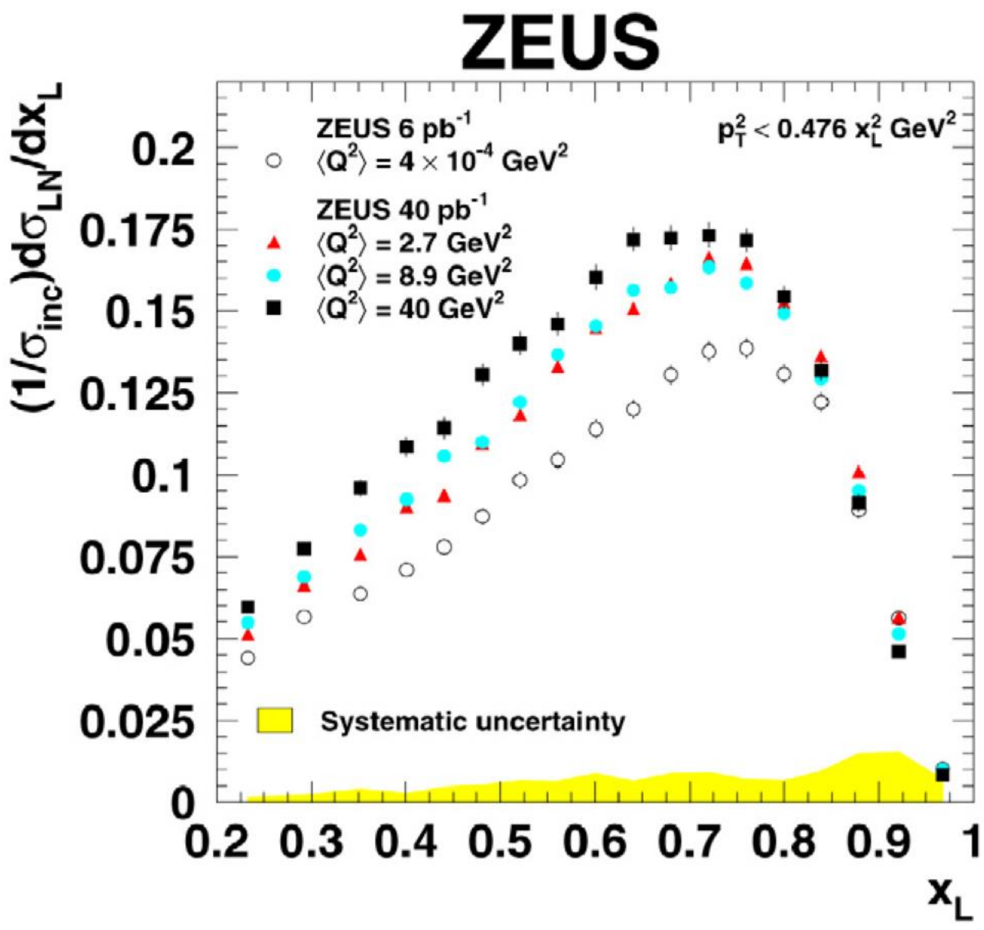
NPB 637(2002) 3-56 (also right figure)

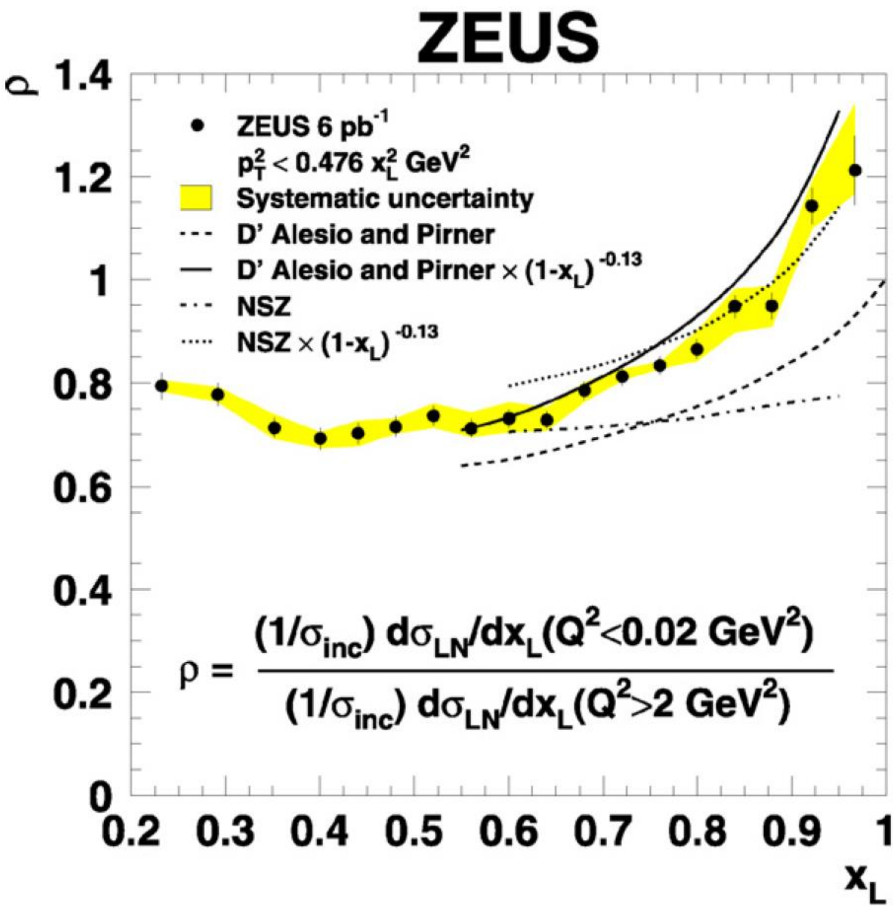




Photoproduction / DIS $Q^2 > 2\ \mathrm{GeV}^2$ vs x_L

- clear x_L dependence on the ratio Photoproduction / DIS
- Photons with small Q^2 behaves like hadrons: re-scattering effect?

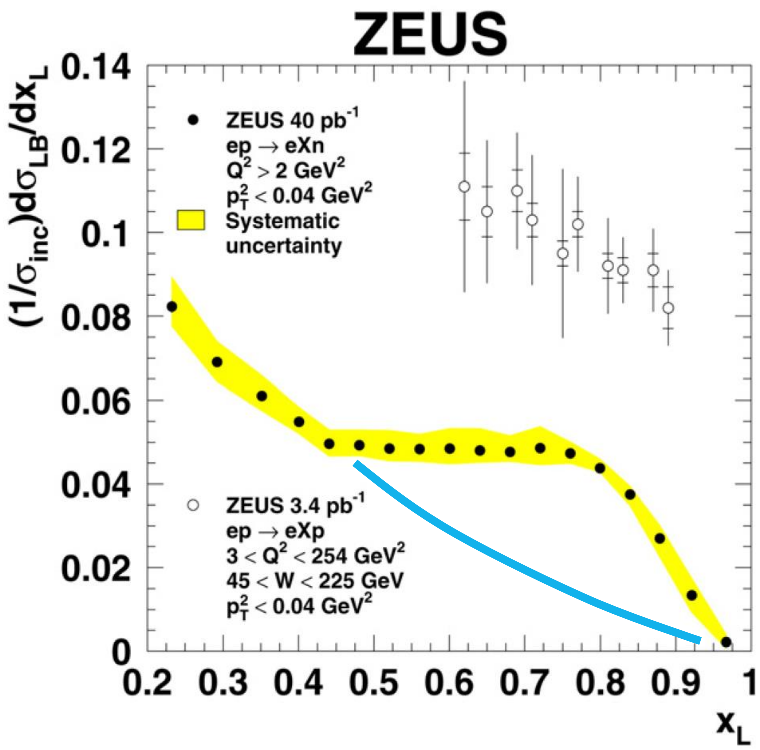


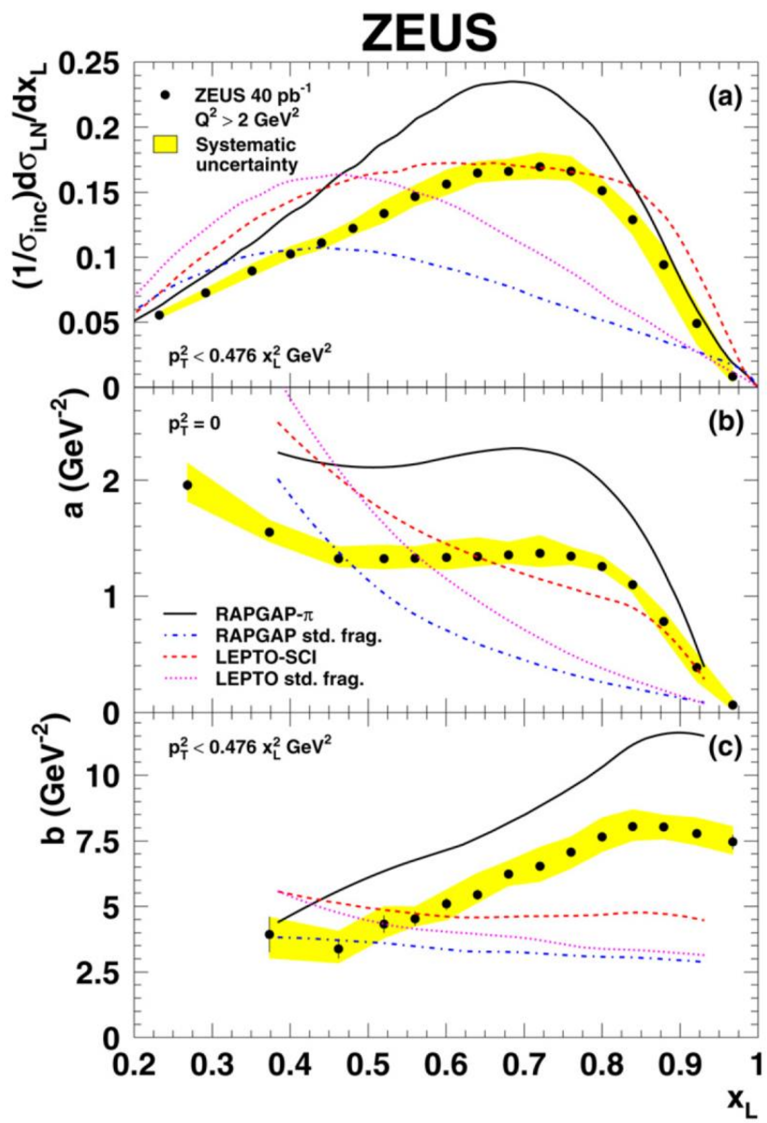


Factorisation studies: summmary

- Factorisation holds approximately
  - hint of mild absorption (20-30%)
  - very little (x, Q^2) dependence on leading baryon production probability

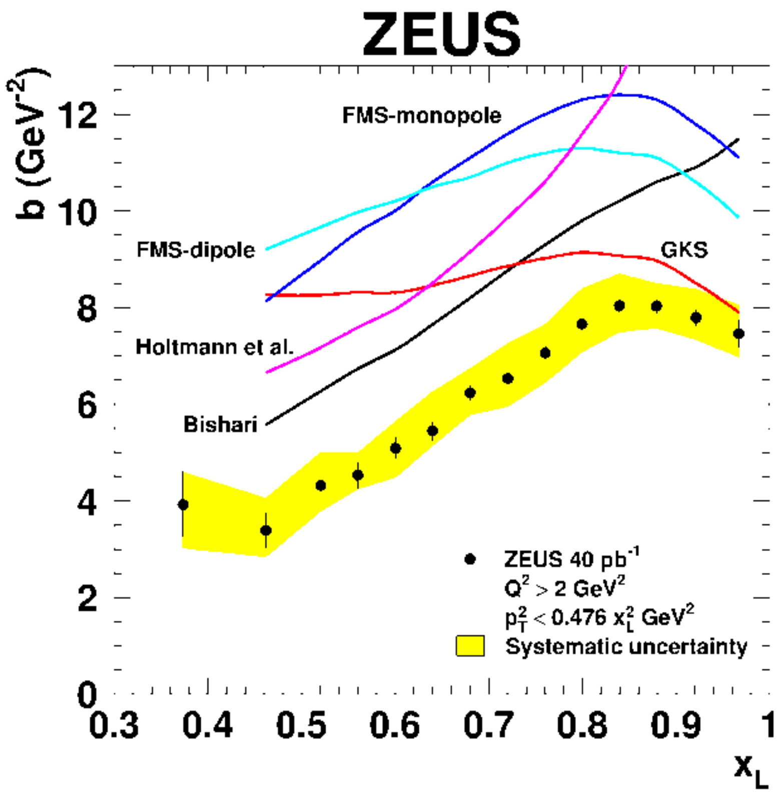
- However, the fragmentation model does not work well: one-pion peak missing
  - OPE seems better

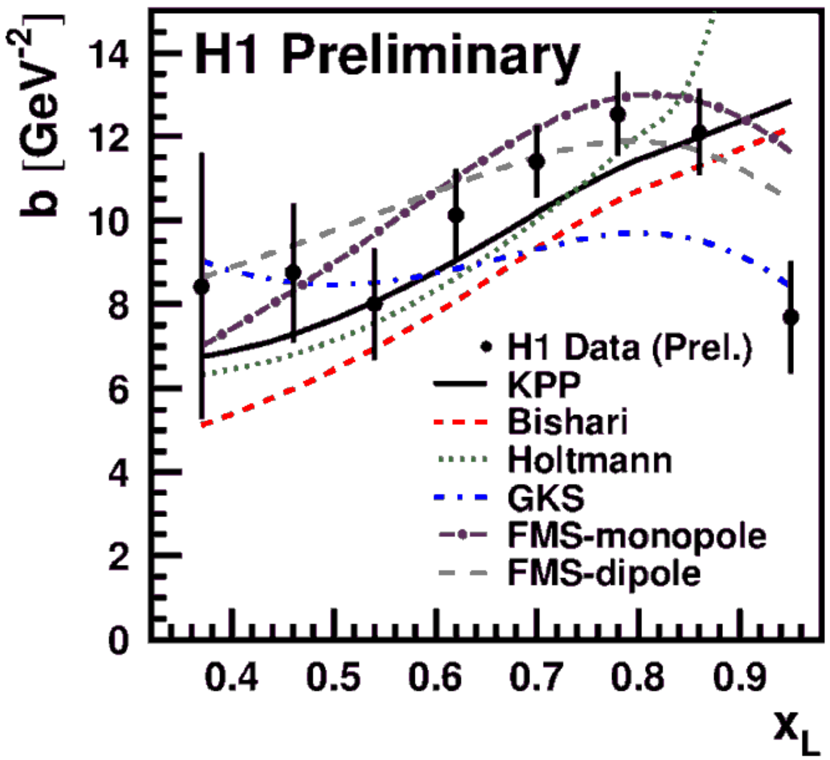




Forward neutron: rich structure in b-slope $\propto e^{bt}$

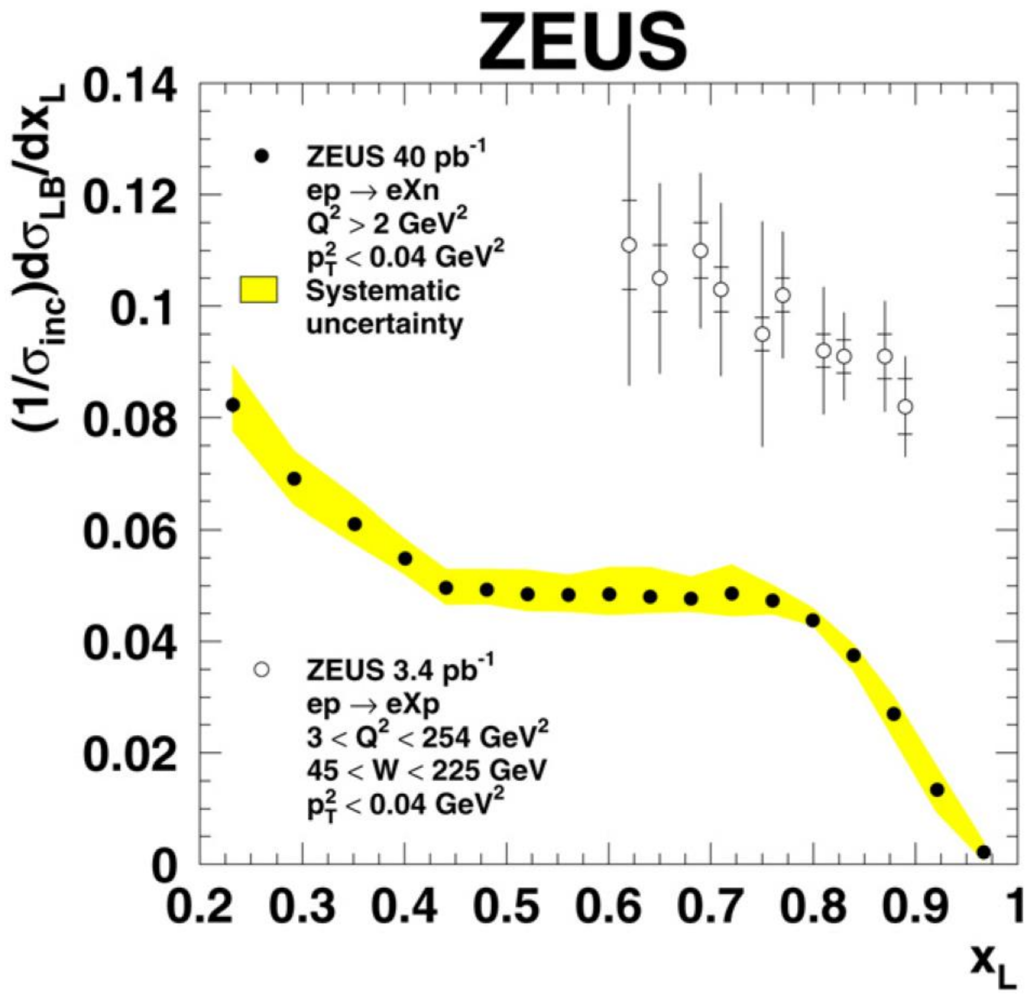
- Compared to various **pion flux** (e.g. $\pi - n$ vertex factor shape) in the OPE model
  - Qualitatively in agreement with various models
  - need to evaluate sub-leading components near $x_L = 1$ and low-x_L for more detailed discussion?





The forward baryon yield

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



ZDC requirement

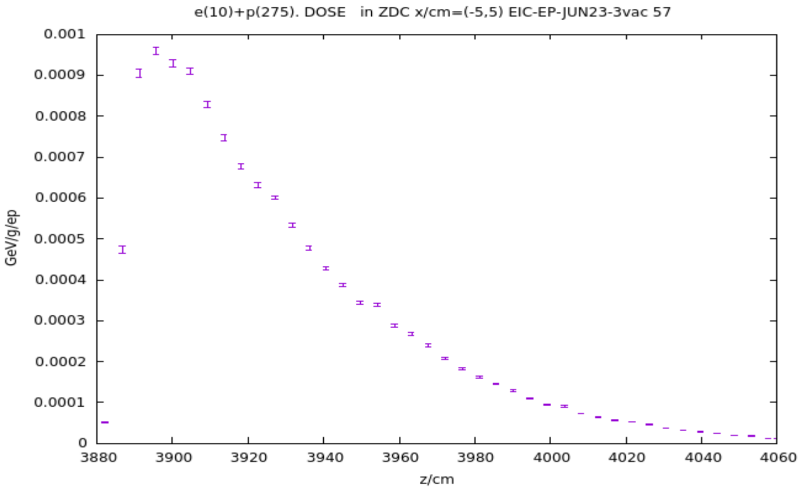
- EM energy resolution: not demanding, but
  - degradation may occur for crystals and/or photon sensors due to radiation
- EM position 0.5mm: fine-pitch layer needed
- Hadron energy resolution: $50\%/\sqrt{E}$
- Neutron position: 3mrad/sqrt(E) or 0.6mm @ 275 GeV
  - better resolution is not necessary since energy resolution also contributes to p_T
  - crucial to determine the zero degree: still good position resolution is useful
- Calibration: kinematic end point (275 GeV)
- Need dynamic range up to multi-TeV

	Energy range	Energy resolution	Position resolution	Others
Neutron	up to the beam energy	$\frac{50\%}{\sqrt{E}} + 5\%$, ideally $\frac{35\%}{\sqrt{E}} + 2\%$	$\frac{3\text{mrad}}{\sqrt{E}}$	Acceptance: 60 cm × 60 cm
		Note: The acceptance is required from meson structure measurement. Pion structure measurement may require a position resoultion of 1 mm.		
Photon	0.1 – 1 GeV	20 – 30%		Efficiency: 90 – 99%
		Note: Used as a veto in e+Pb exclusive J/ψ production		
	20 – 40 GeV	$\frac{35\%}{\sqrt{E}}$	0.5–1 mm	
		Note: u-channel exclusive electromagnetic π^0 production has a milder requirement of $\frac{45\%}{\sqrt{E}} + 7\%$ and 2 cm, respectively. Events will have two photons, but a single-photon tagging is also useful. Kaon structure measurement requires to tag a neutron and 2 or 3 photons, as decay products of Λ or Σ.		

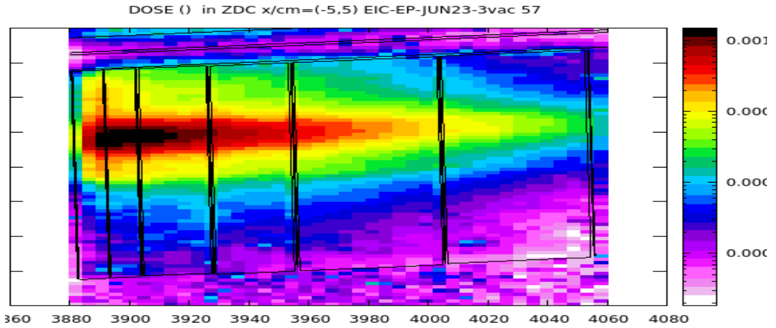
Table 2: Physics requirement for ZDC

ZDC boundary condition (1): radiation

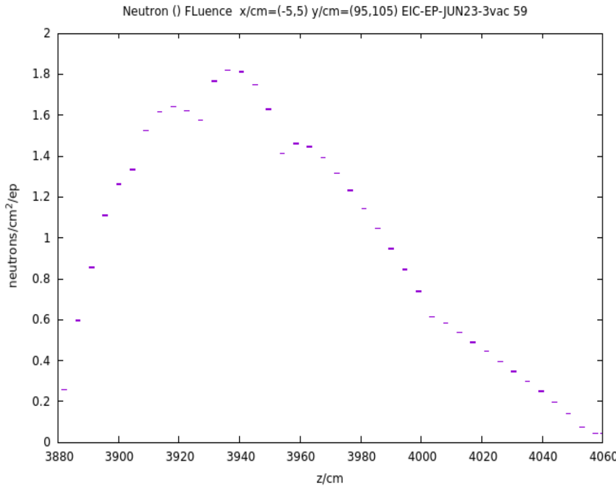
- Study by Vitali Baturin in 2021
- total ionization dose:
  $10^3\ \mathrm{GeV/g/s} = 1.6 \times 10^{-4}$ Gy/s
  or 1.5 kGy/yr
  - Plastic scintillator would survive for ~ 0.2 kGy/yr according to CMS study
- total number of neutrons:
  $2 \times 10^6\ \mathrm{neut./cm^2/s}$
  $= 2 \times 10^{13}\ \mathrm{neut./cm^2/yr}$
  - four year to reach 10^{14}
  - OK for silicon pads, not quite for SiPM (except for that for CMS HGCAL?)



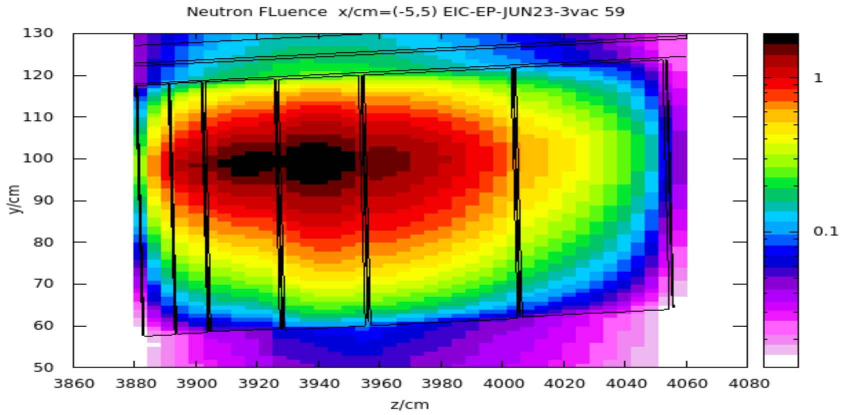
dose in very small transverse area



dE/dt =1.E-3[GeV/g/ep]*1.E+6[ep/s]=**1. E+3 [GeV/g/s]**



even the neutron flux is rather concentrated

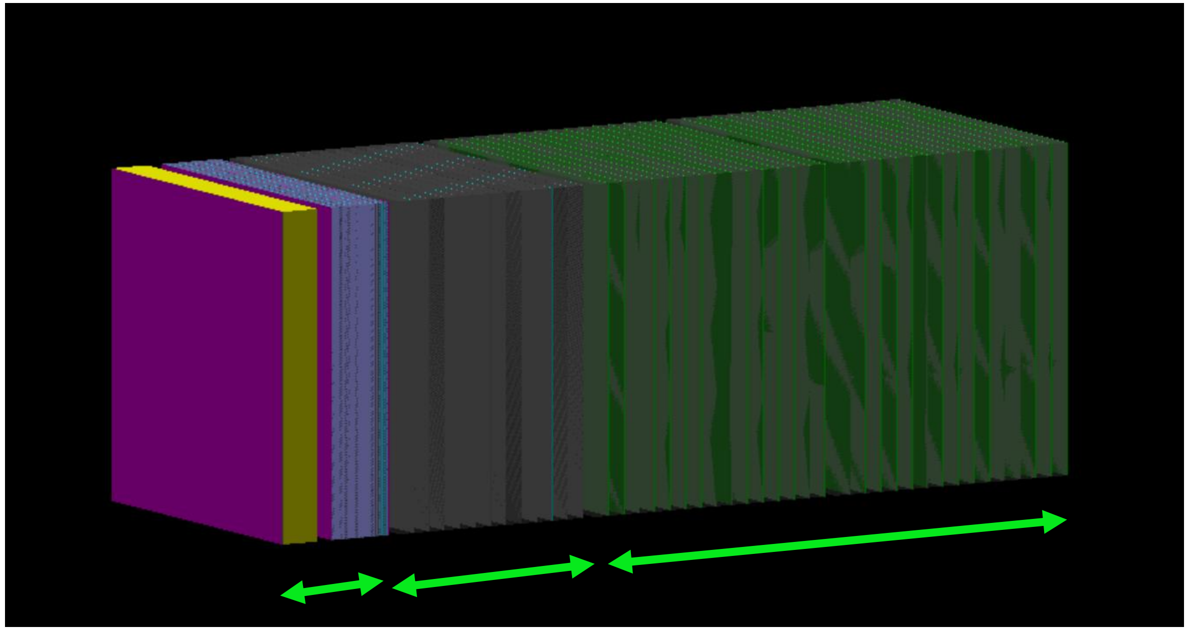


dn/dt =2.E+0[neut/cm^2/ep]*1.E+6[ep/s]=**2. E+6 [neut/cm^2/s]**

ZDC for ePIC (2022 proposal)

ZDC in Fun4All
S. Shimizu (RIKEN -> KEK) et al.

- 60 x 60 x ~200cm
  - small shower leak for hadron resolution
- Planning to measure γ from de-excitation
  - First layer: crystal, fully active
- Radiation environment is hard
  - > 10kGy, $\sim 10^{14}$ 1MeV n_{eq}
  - Crystal: PbWO4 (at least – or even e.g. LYSO)
  - SiW for the second EM section
    SiPb for the first Hadcal section
    - Plastic sandwich etc. for cost and resolution (e/h) for outside the shower core (~ 10cm in radius)
- Need compact photon sensors that stands for 10^{14} neutrons
  - MCP-PMT or most recent SiPM?



EMC (Crystal 3x3x7cm LYSO?/ W+Si 1cm pad + 3 layer pixel)

HadCal 1 (Pb + Si 3x3cm?)

HadCal 2 (Pb + Sci 10x10cm?)

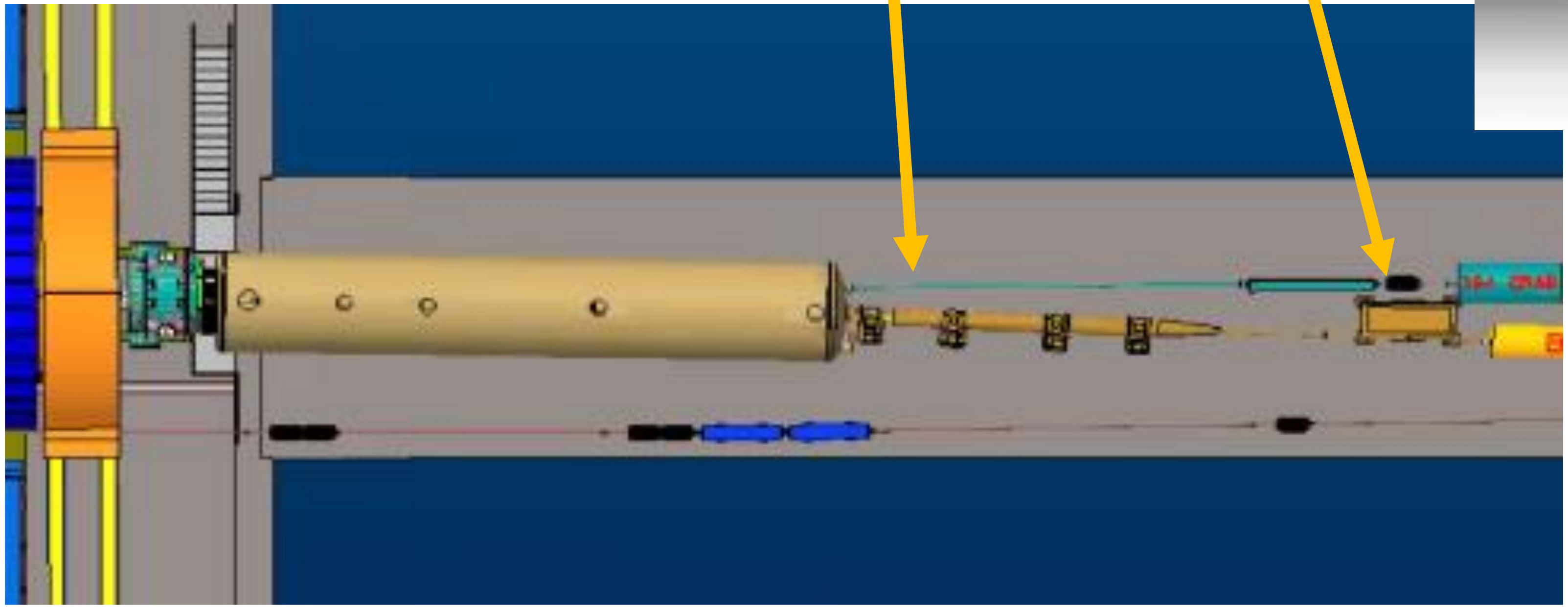
Required energy resolution: $\frac{\sigma(E)}{E} < 50\%/\sqrt{E}$ E in GeV
position: < 1 mm for neutrons (!)

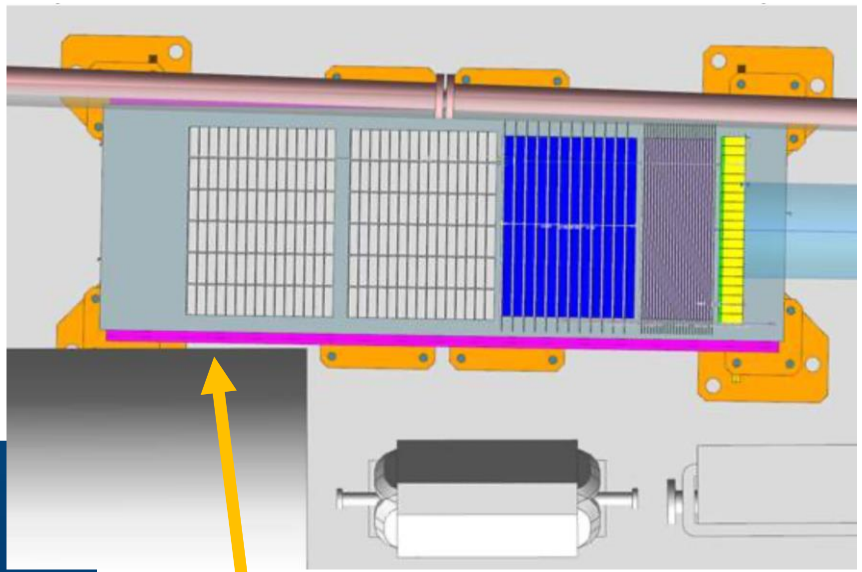
ZDC boundary condition (2): obstacles

- Tight available space around ZDC
- No exit window for photons
  - beam pipe wall > $2X_0$ (?) along the zero-degree line
    no way that converted electron arrives ZDC

ZDC

Drawings from Y. Furletova





collision with electron beamline:
plan to move closer to IP by 1m

ZDC: "baseline" detector ideas

- To reduce costs and R&D time, to be in time for 2025 to start

1. staging the crystal layer
   - need rad-hard photon sensor (e.g. SiPM) and/or bright crystals
   - need to design the beam-pipe exit window for photons
   - still keeping the central part of the ZDC EM (ca. 40x40cm) like FoCal EM with reduced layers

2. staging or switching the hadronic section
   from partially-Si-based sandwich to e.g. dual readout
   - silicon pads are certainly rad-hard but expensive
   - fused silica for EM readout would stand for dose in the dual-readout design
     even though scintillator fibers may be degraded after some time

Summary

- ZDC, Roman pots and spectator detectors are vital "ancillary" detectors for EIC physics
  - accelerator was made to keep the forward aperture open!
  - forward particle tagging is a must for tomography
  - some HEP interest: precise determination of neutron PDF and nuclear effect

- ZDC is located in hostile environment
  - need to balance the performance and cost
  - need your ideas, expertise and person-power

BACKUP

Scintillator dose rate and maximum dose

from CMS HGCAL TDR

- Dose constant: the dose with 1/e light yield
  - strongly depending on dose rate per unit time
  - slow dose gives more damage
- EIC ZDC:
  - 0.18 Gy / hr = 0.018 krad / hr
  - 5 kGy for 10 years
- The radiation rate is quite optimum
  - we should accept 1/e light yield after 10 years

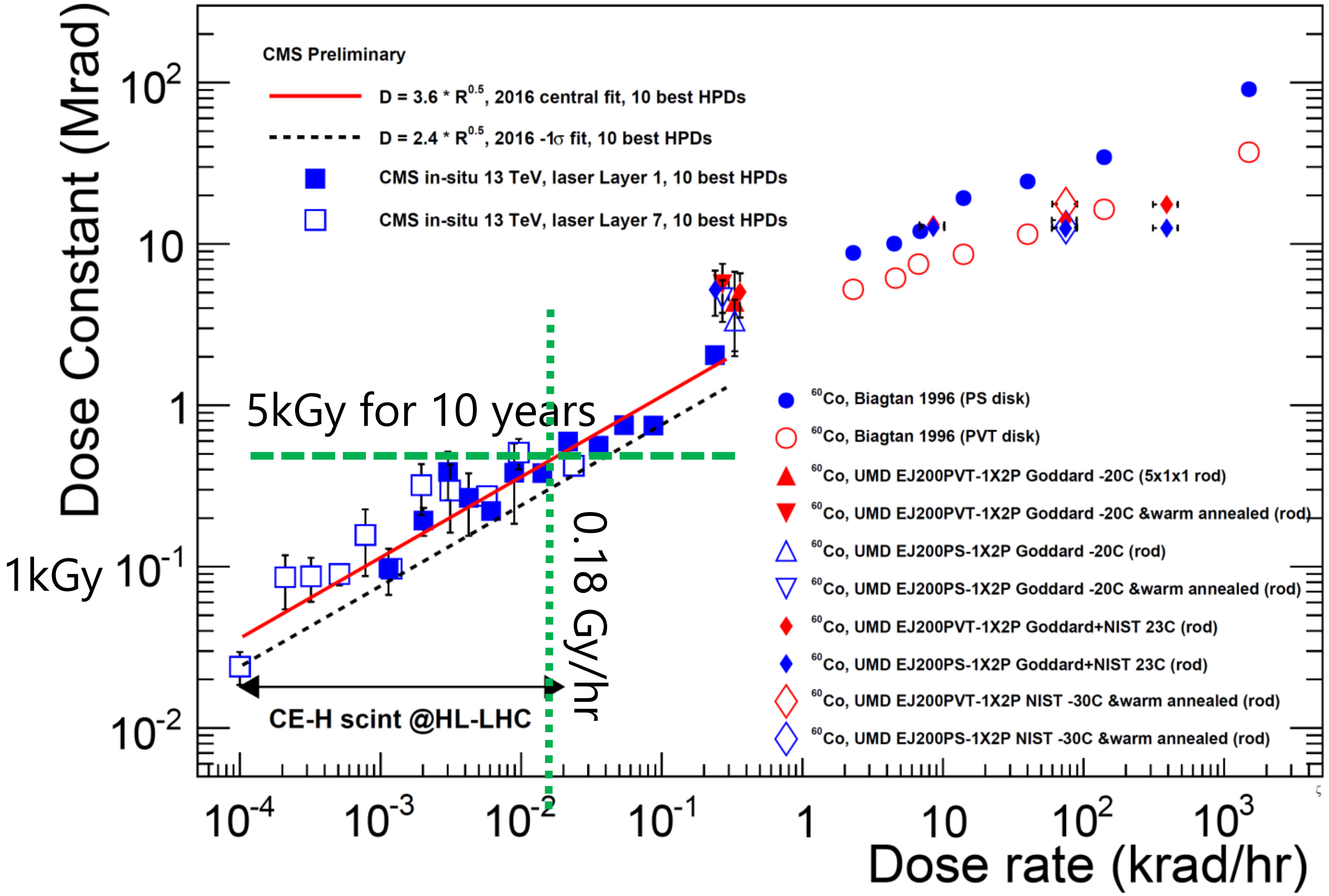


Figure 2.10: Dose constant, D_c, versus dose rate, R, for both in situ measurements from CMS (boxes) and dedicated studies. Lines corresponding to $D_c = 3.6 \times R^{0.5}$, and $D_c = 2.4 \times R^{0.5}$ are shown. The in situ measurements refer to SCSN81, a PS based scintillator used in the endcaps of the present detector.

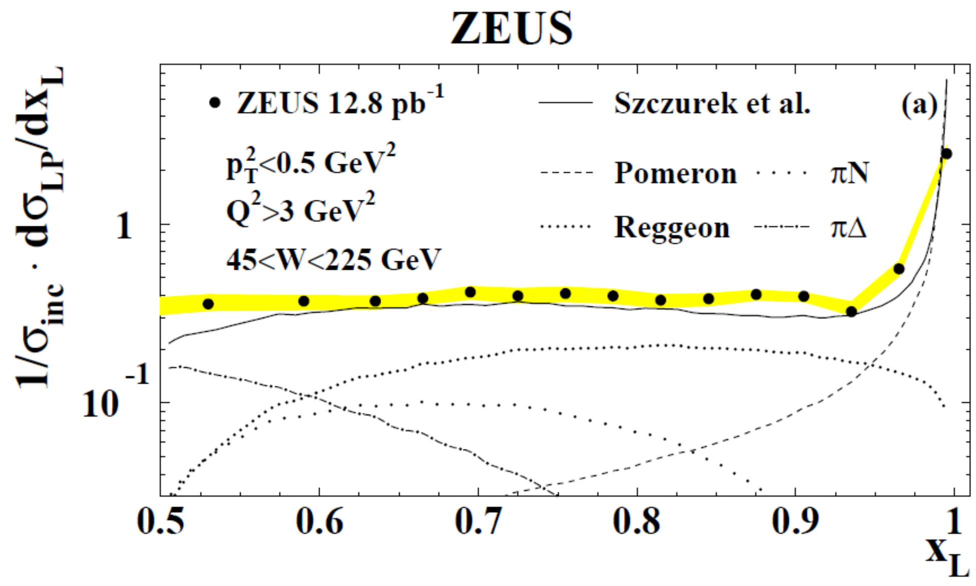
Consideration for 300MeV photons

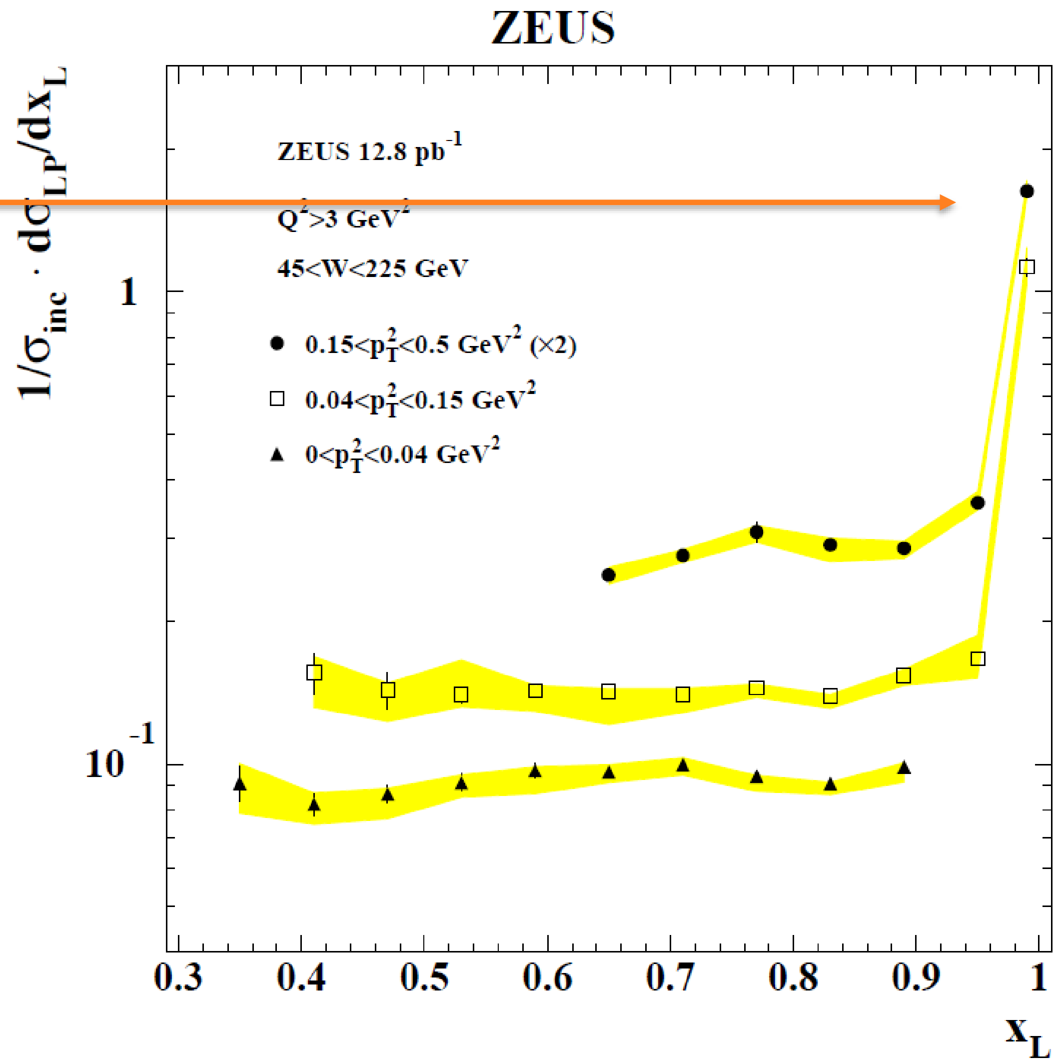
- Any initial state radiation from heavy ions?
  - maybe serious for Au, Pb etc.
    This is irreducible
- Pile-up of stray particles in the ZDC area?
  - charged pions/kaons
  - fast neutrons of O(1GeV)
- May need charged particle veto (tracking) in front of ZDC
- May need timing to remove most of the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

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)

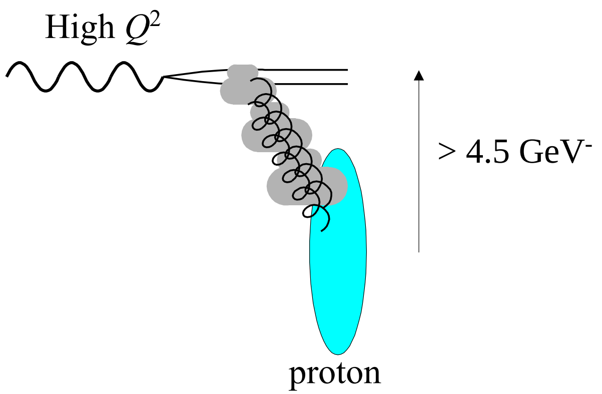


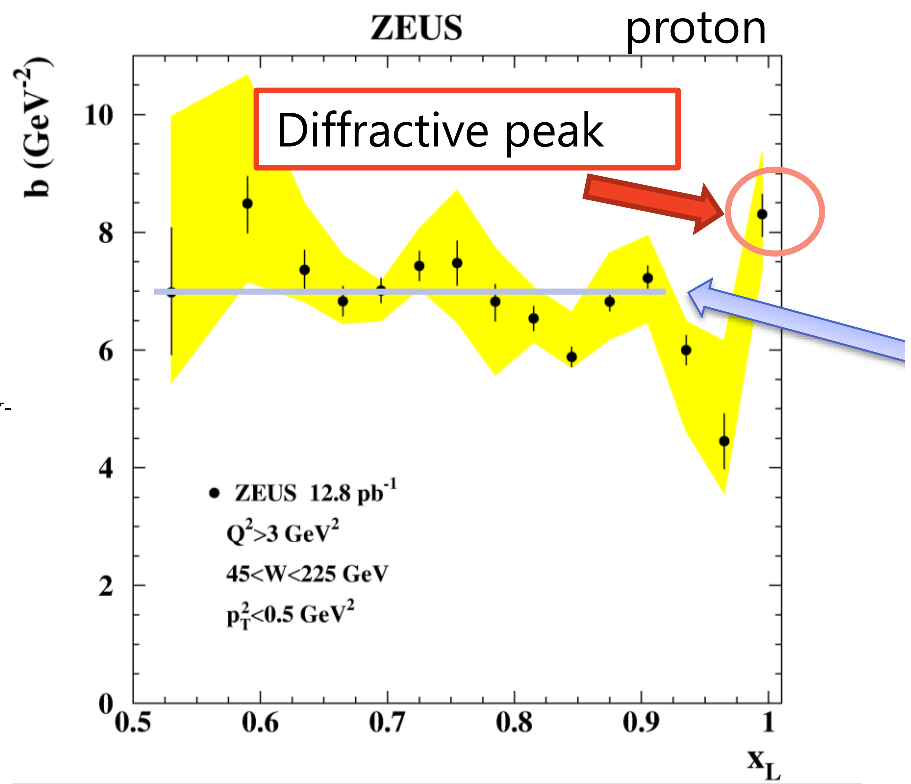


EIC should be able to study much more precisely

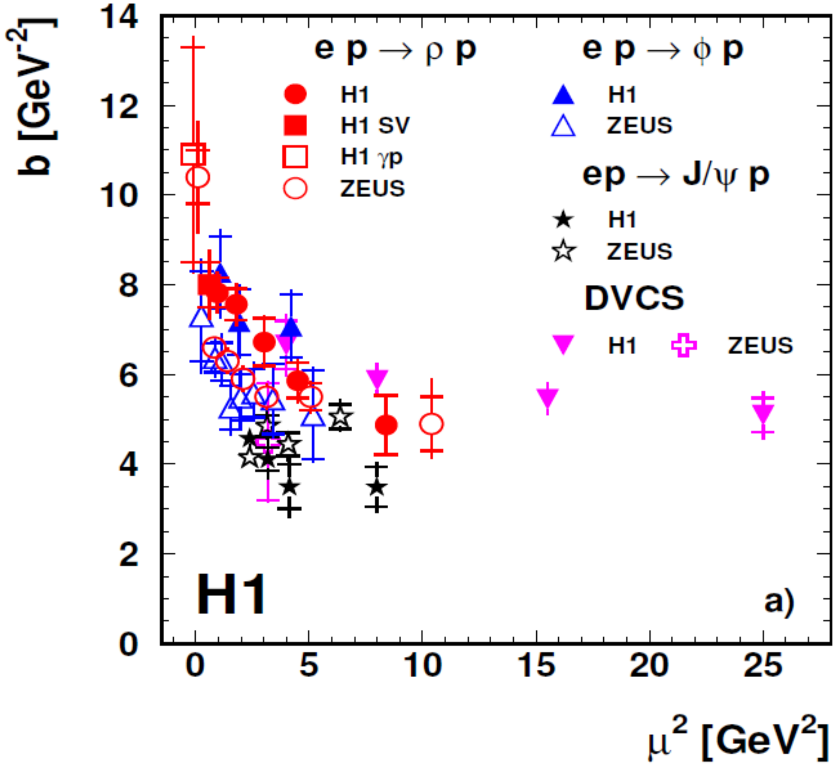
p_T dependence for forward protons

- 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

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

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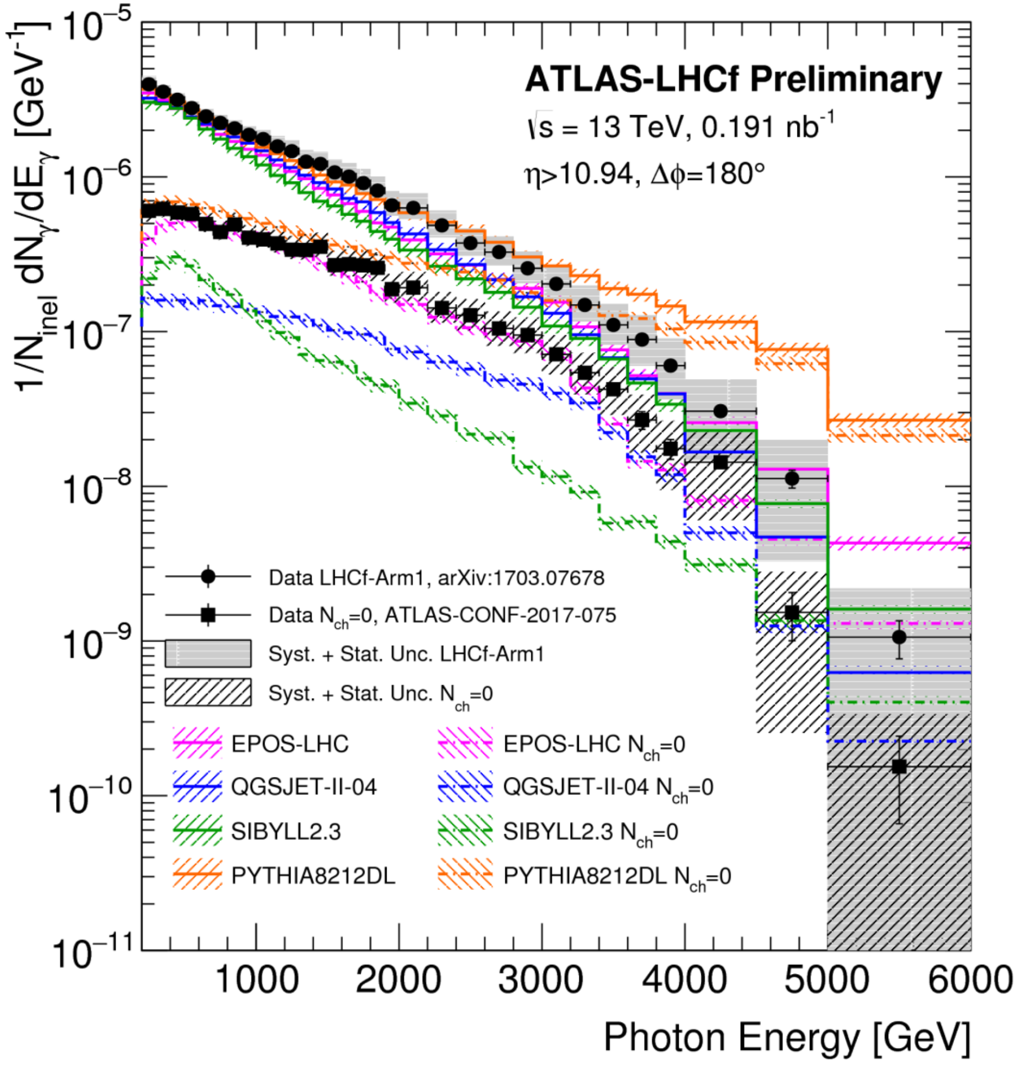
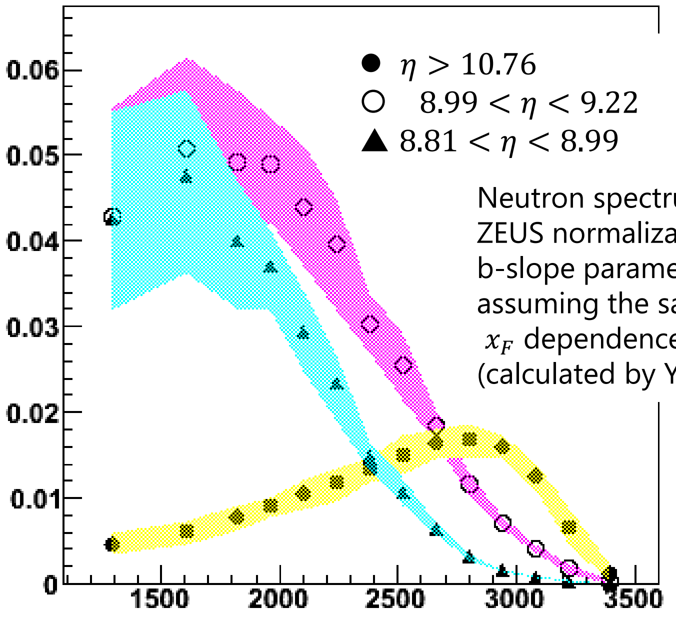


Neutron puzzle (2): pp vs ep

- 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