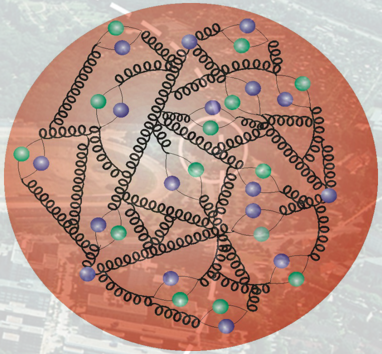
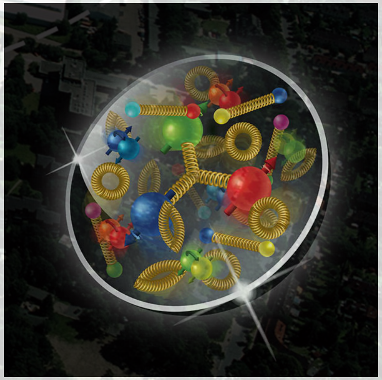
The Hadronic Final State at HERA and its Connection to the EIC

Paul Newman
Birmingham University





HERA-4-EIC Workshop
Friday 10 June 2022

A personal perspective, covering:

- Precision final state obsevables
- Observables for novel final state effects
- Diffraction (exclusive and inclusive)

The Hadronic Final State in ep Colliders

Much of HERA physics in this talk based on RMP review … inevitably incomplete and outdated (apologies!)

The Hadronic Final State at HERA

Paul R. Newman*
School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, UK

Matthew Wing†
Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK; DESY, Notkestrasse 85, 22607 Hamburg, Germany

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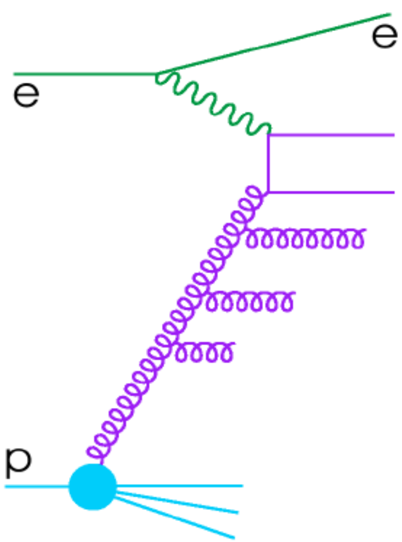
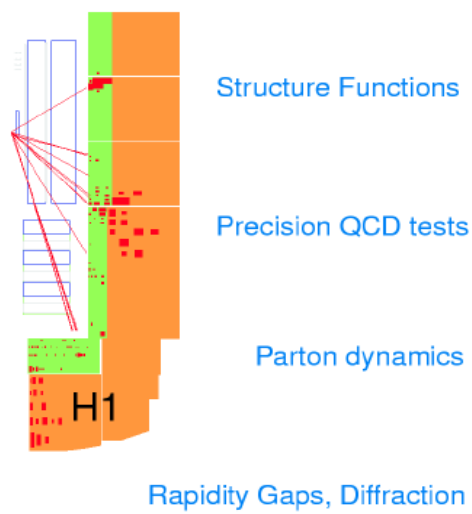
[Rev.Mod.Phys. 86 (2014), 1037]

Many overlaps between HERA & EIC, but also many obvious differences
HERA can guide some of our thinking, but should not constrain us!

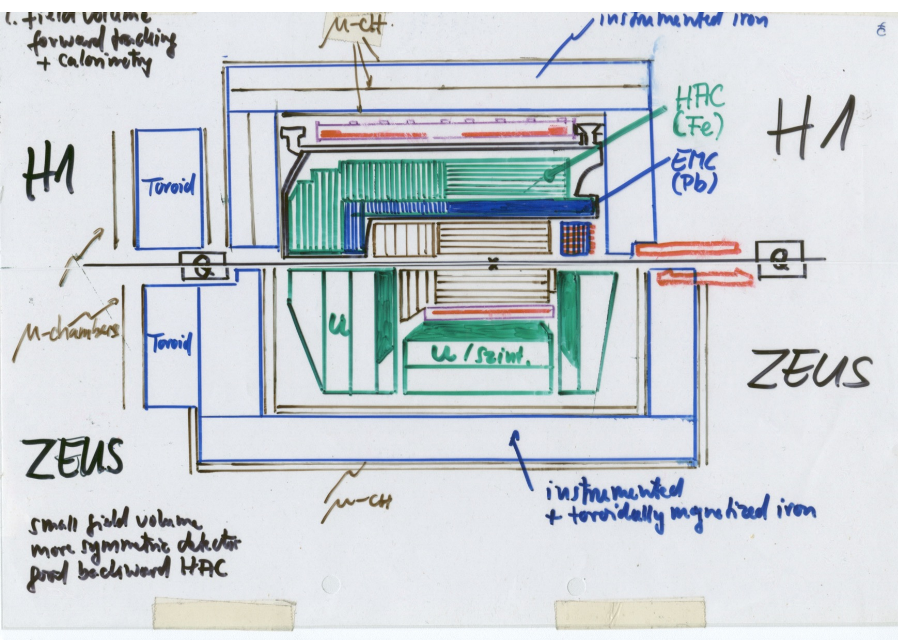




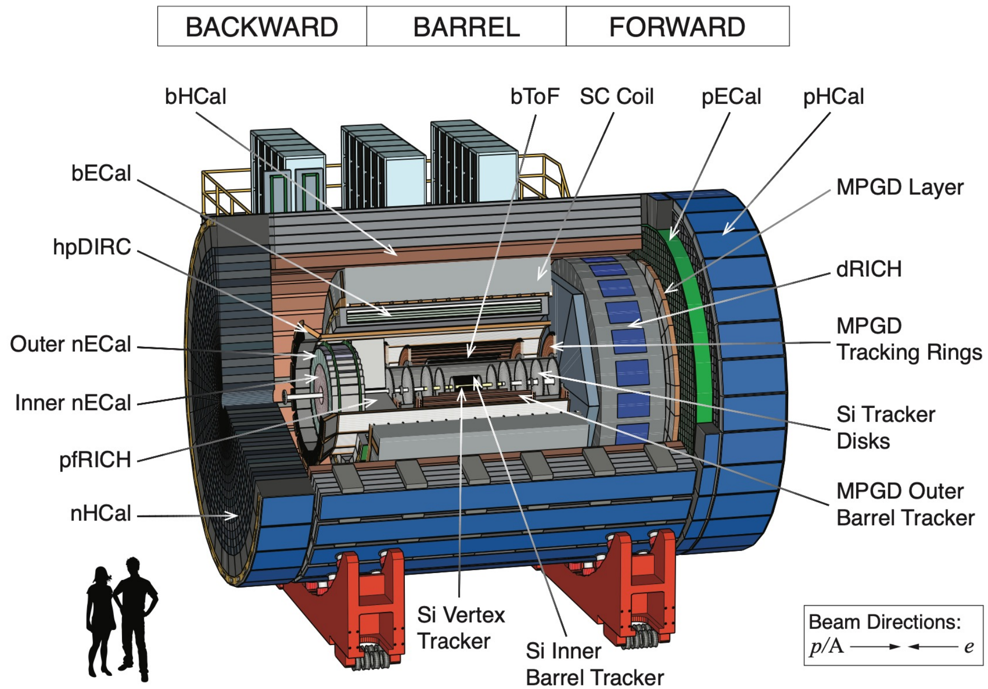
ep Collisions are an ideal laboratory for precision testing of QCD and searching for novel dynamics at low x

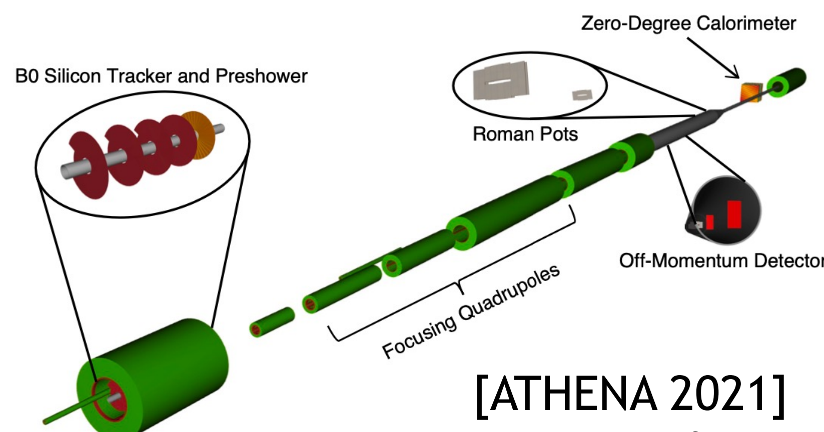
Obvious HERA - EIC Differences

- Centre of mass energy
- Polarisation of targets
- Nuclear targets
- Detector Technologies
- Forward region emphasis



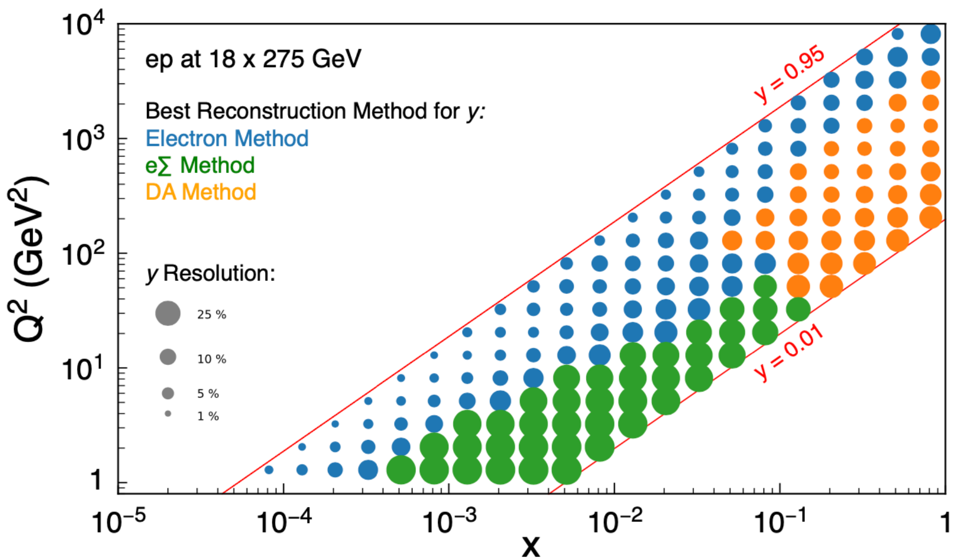
[F Eisele, ~ 1986]





[ATHENA 2021]

Kinematic Reconstruction and Detector Calibration from HERA→EIC



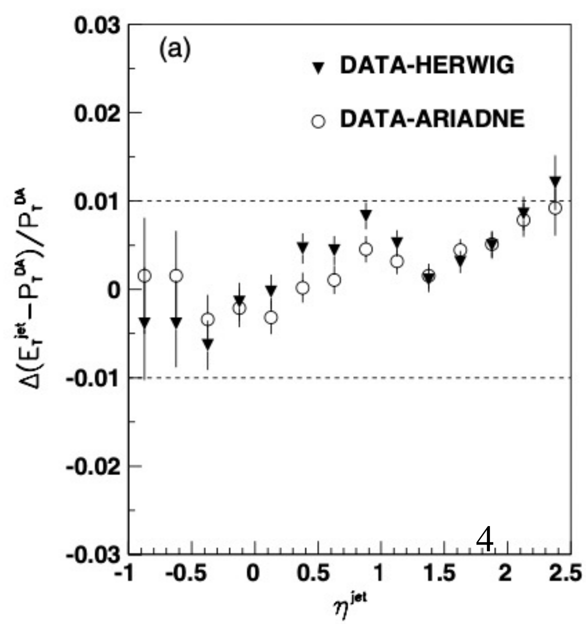
- The many methods of kinematic variable reconstruction involving the HFS developed at HERA are already being applied at EIC.

- They lead into more modern techniques involving kinematic fitting / machine learning

- This redundancy is also crucial in determining hadronic energy scale

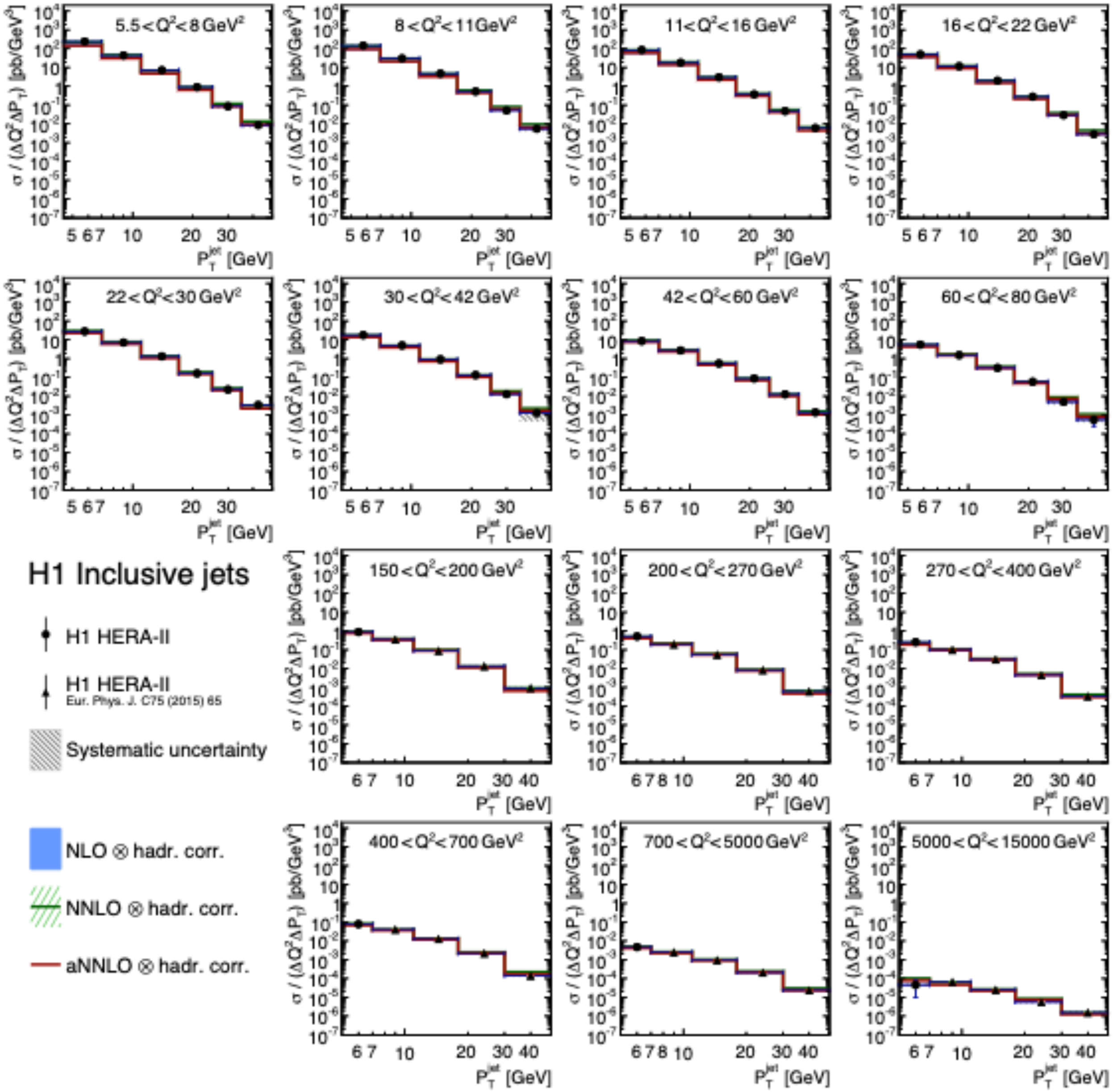
- <1% achieved at HERA!

- EIC needs to invent even more clever Hadronic Final State calibration techniques, particularly at low p_T.



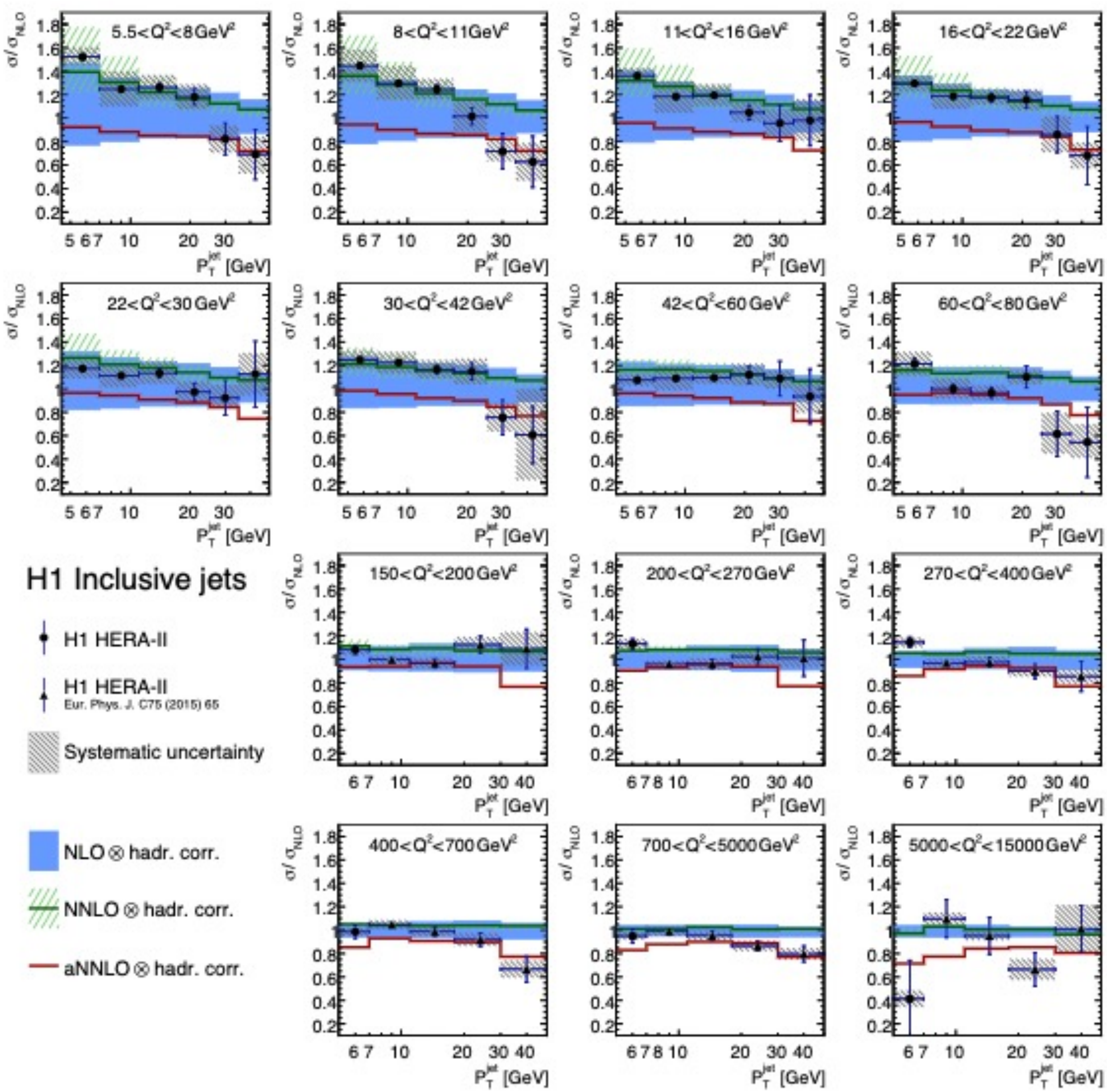
(Non-Diffractive) Hadronic Final States

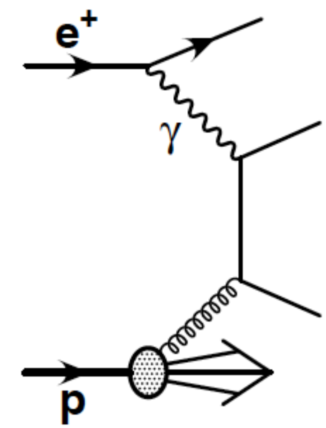
High Precision Jet Data in DIS at HERA



- Excellent agreement with QCD over wide kinematic range

High Precision Jet Data in DIS at HERA



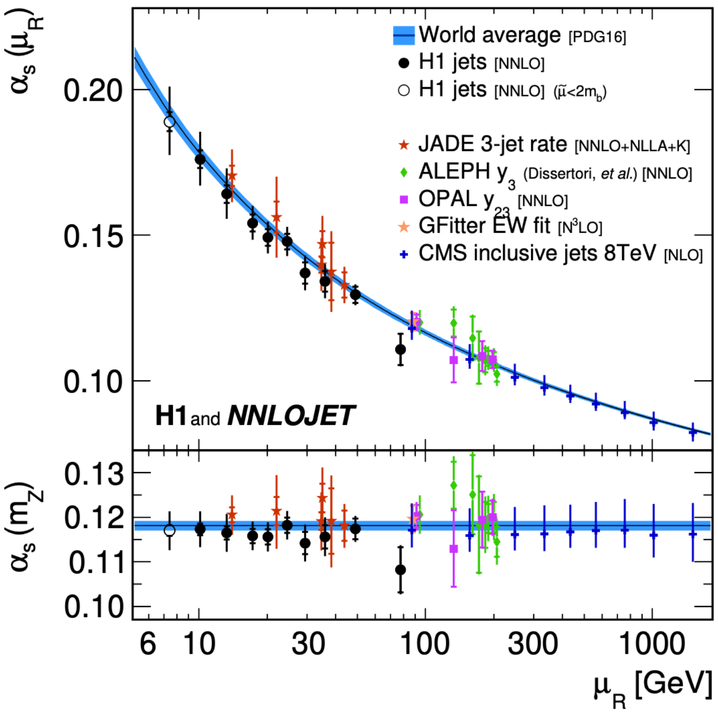


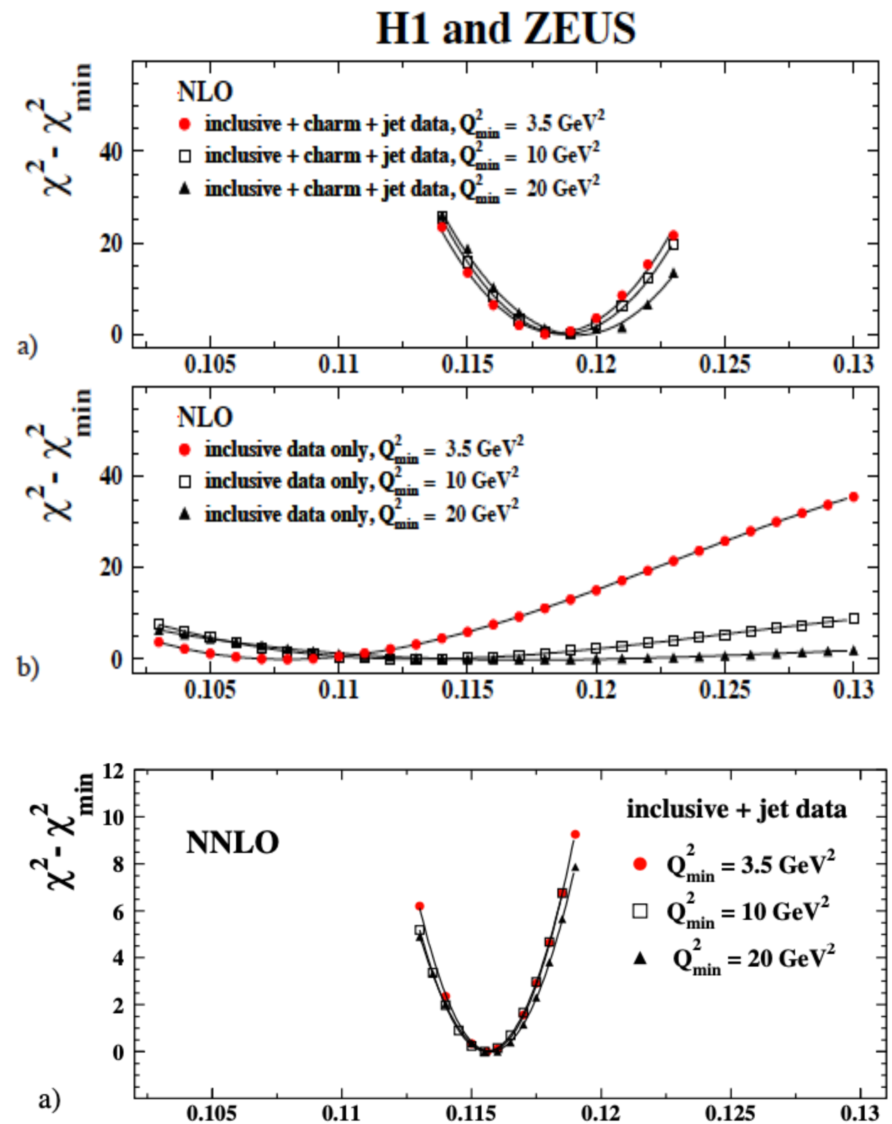
- Excellent agreement with QCD over wide kinematic range (???)

- Role in benchmarking jet algorithms

- Sensitive to gluon density already at lowest order
→ constraints on PDFs and α_s.

Jets and α_s



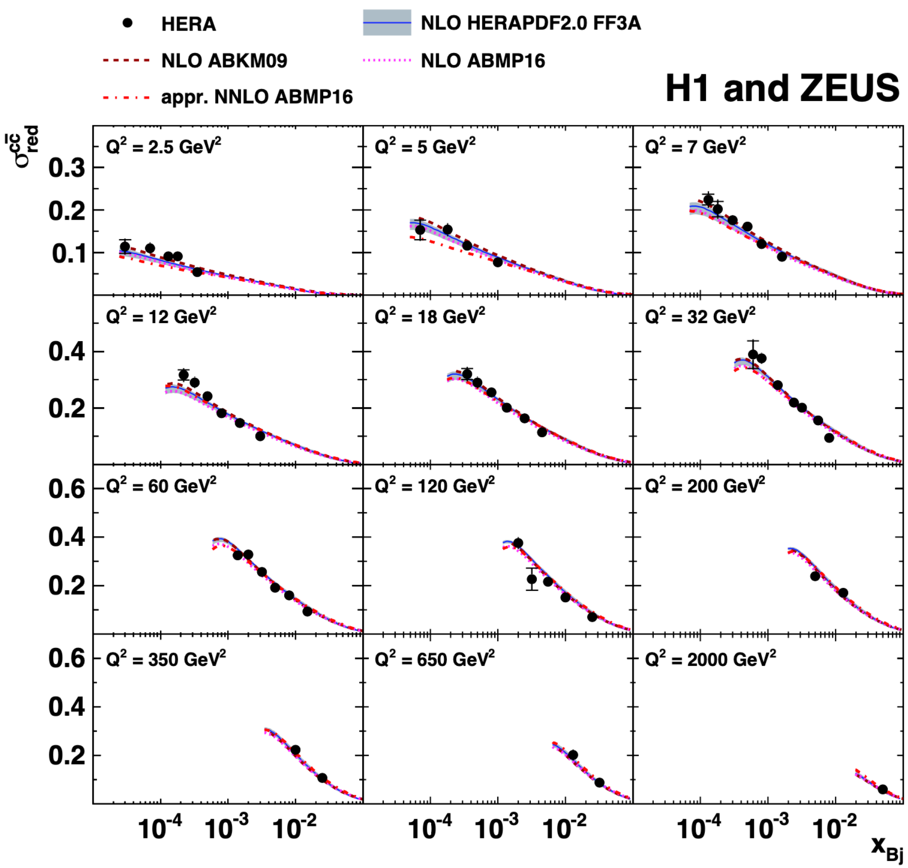


- Jets alone constrain as and beautifully illustrate it's running with scale.

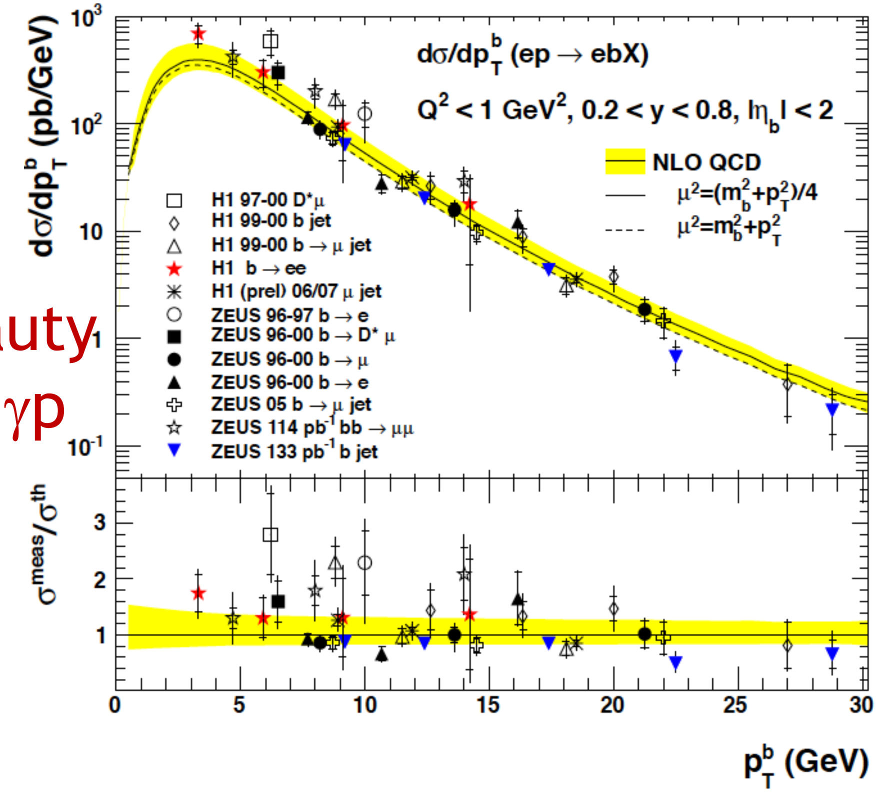
- Including jet and charm data in HERA-II fits allows simultaneous α_s extraction without significant impact on PDFs
- Recent extensions to NNLO … Competitive with world-best

High Precision HERA Heavy Flavour Data

Charm in DIS



Beauty in γp

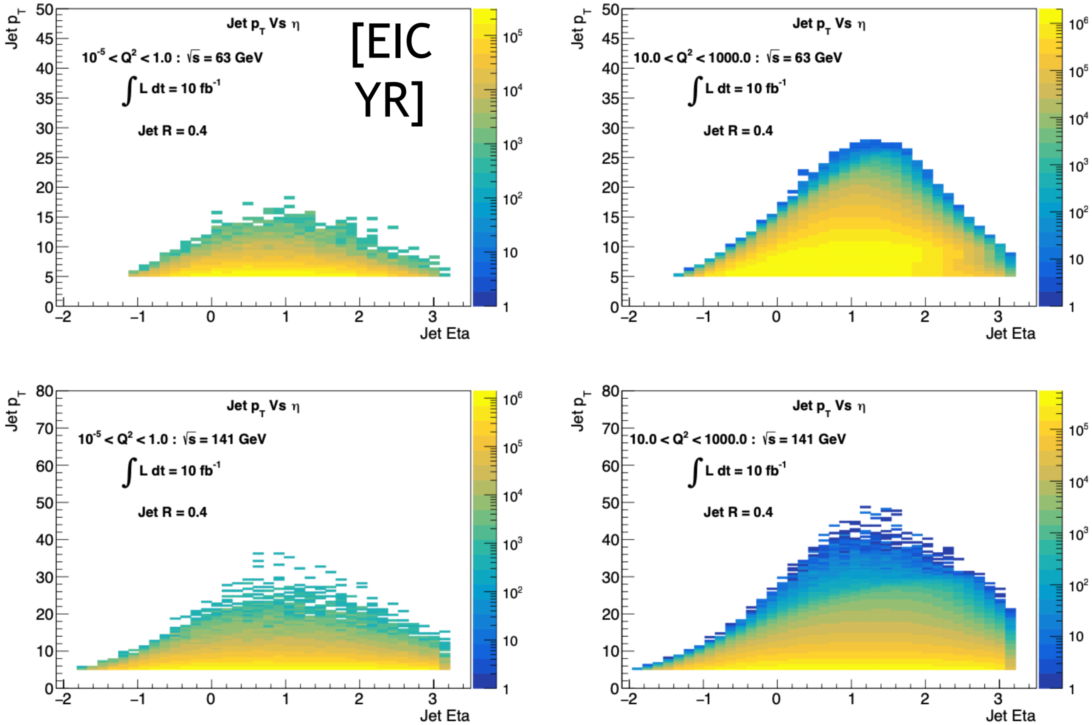


- Stunning consistency with inclusive data via PDFs and (N)NLO QCD

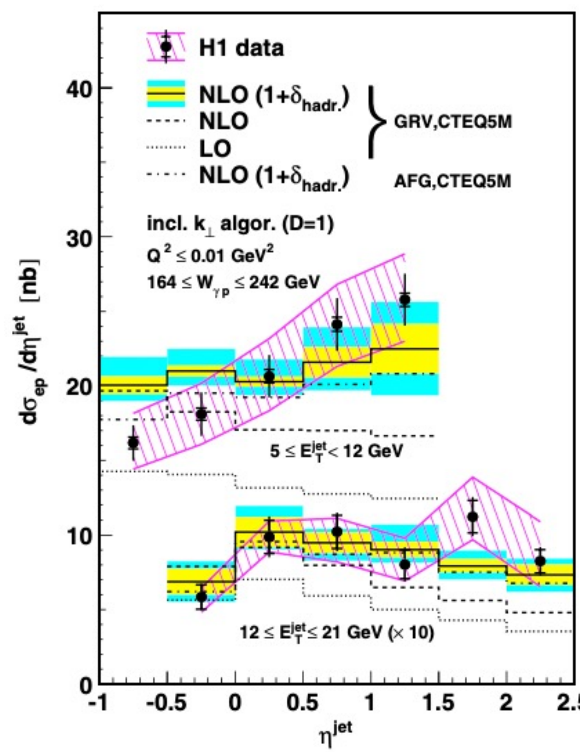
- Clear presentation of charm and beauty contribution to DIS via σ(NC)

- Testing ground for development of heavy flavour schemes in QCD

Different Challenges with Jets at EIC



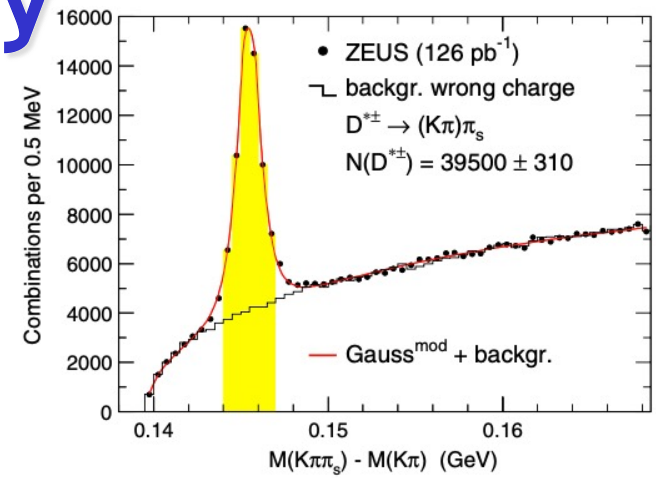
- Due to the lower centre of mass energy, typical jet transverse momenta are much lower at EIC than HERA

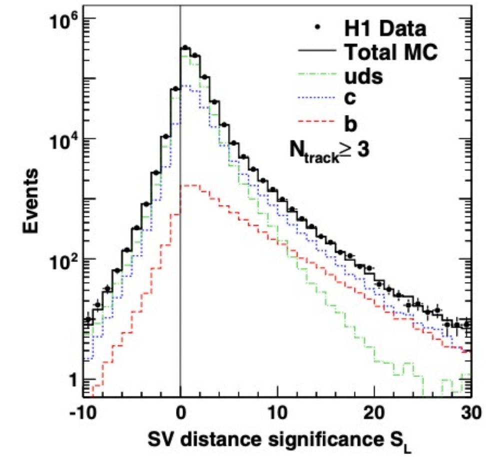


- HERA showed that it is possible to control jets down to E_T~5GeV or slightly lower, but …
  - … Large hadronisation uncertainties
  - … Large scale dependences / HO corrections

- At EIC jets likely to be a tool for studying novel QCD effects (especially in eA) rather than for precision observable

Evolving Heavy Flavour Observables

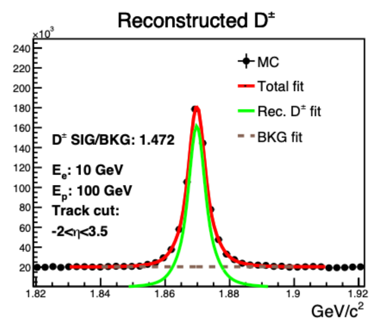


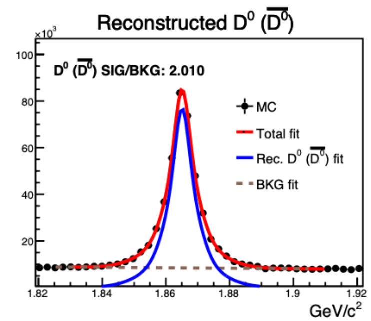


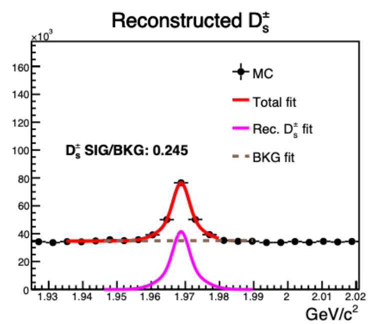
- HERA relied heavily on D*and secondary vertex significance observables … Most studies restricted to the central region

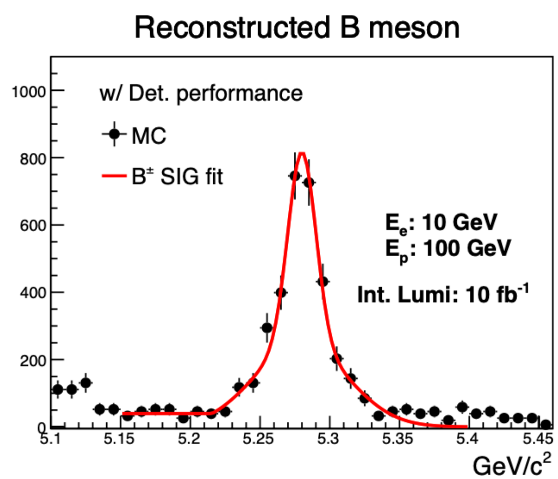
- EIC will have outstanding tracking / vertexing and particle ID over wide range, extending to forward pseudorapidity

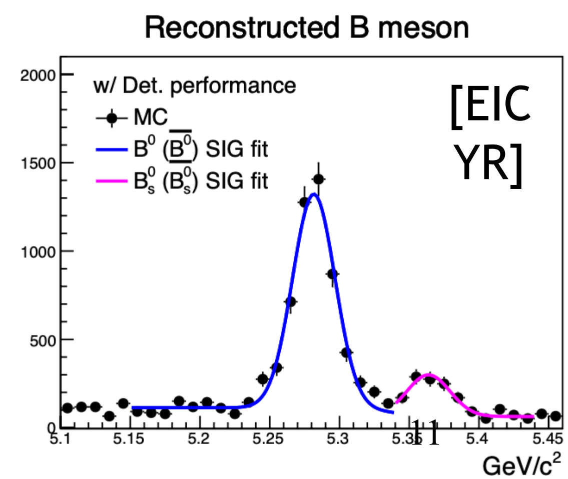
- HF as precision tool … less sensitive to CMS energy than jets?









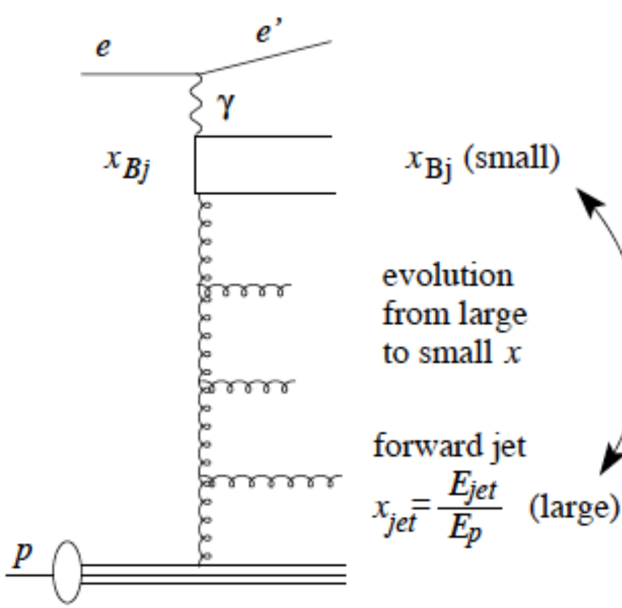


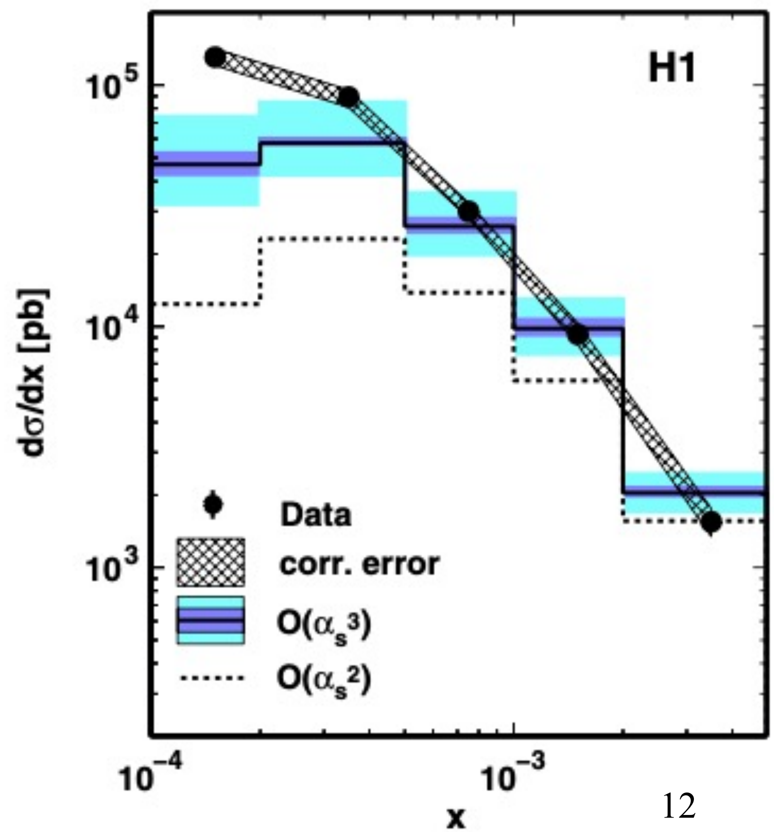
Jets and Novel QCD Dynamics

… at HERA → search for low x BFKL effects
… at EIC → applicable particularly in search for high density effects ('saturation') in eA mode

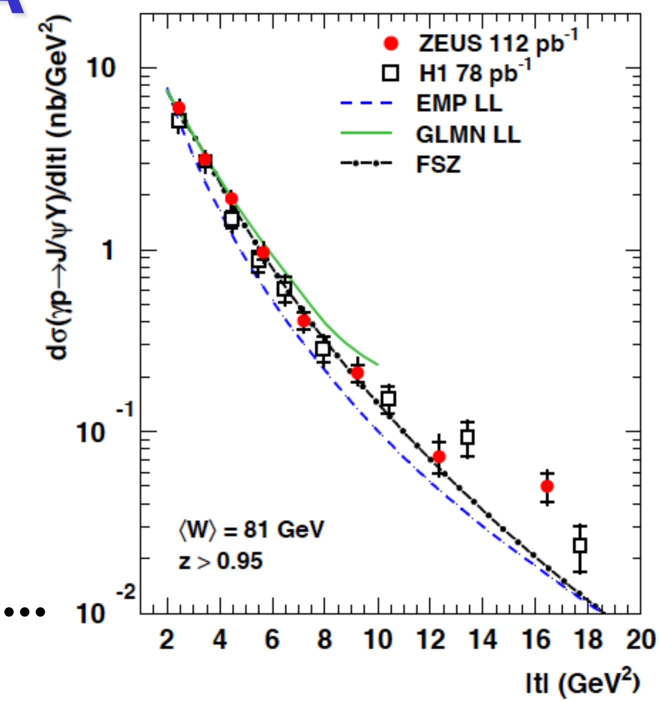
Large $\Delta\eta$ (`forward') jets, implying lack of (DGLAP) evolution in transverse momentum of emissions along the parton cascade

[2 fwd + 1 central jets]



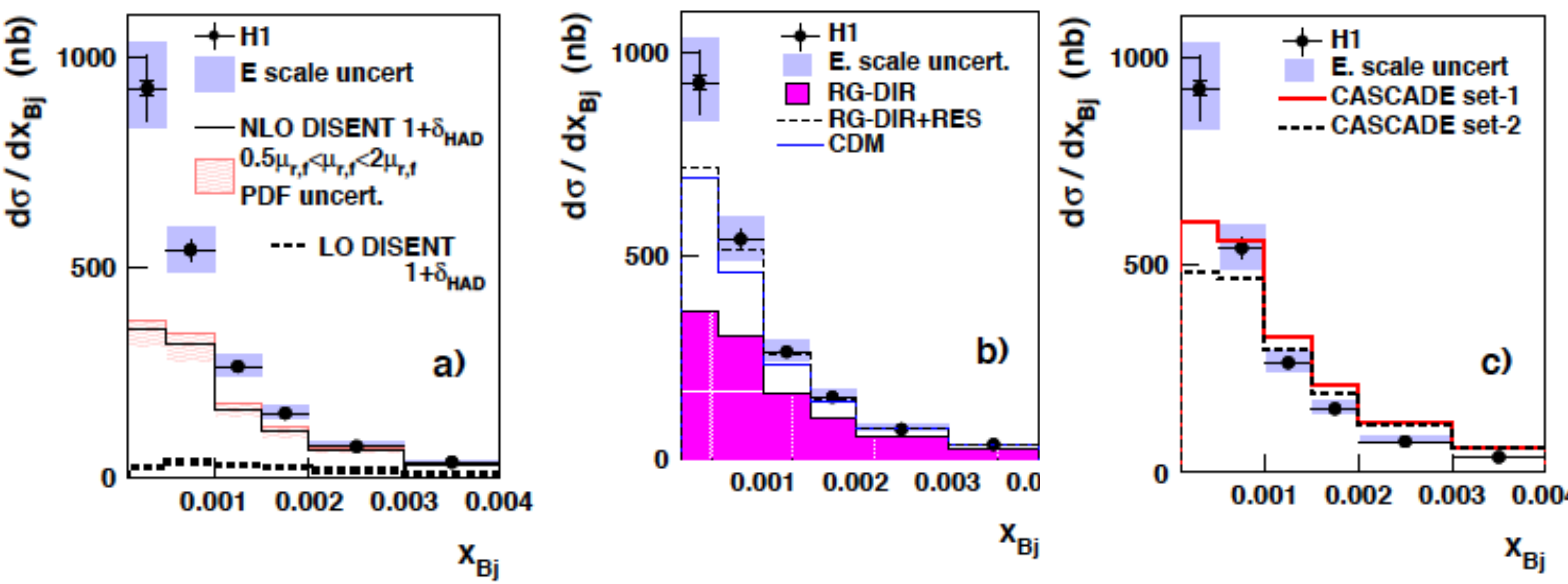


“BFKL” Dynamics in the HERA Low x Hadronic Final State?



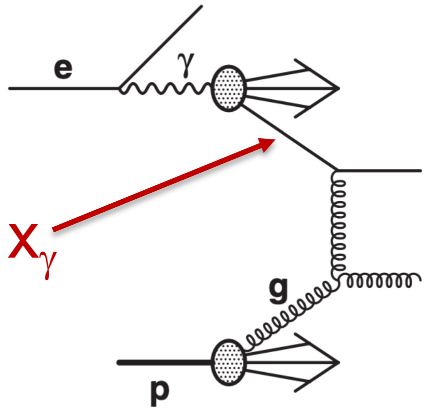
Inventive new observables to search for deviations from p_T ordering in the parton cascade …

- Forward jets, π^0 …
- Azimuthal decorrelations
- High |t| (p-dissociative) diffractive J/Ψ…

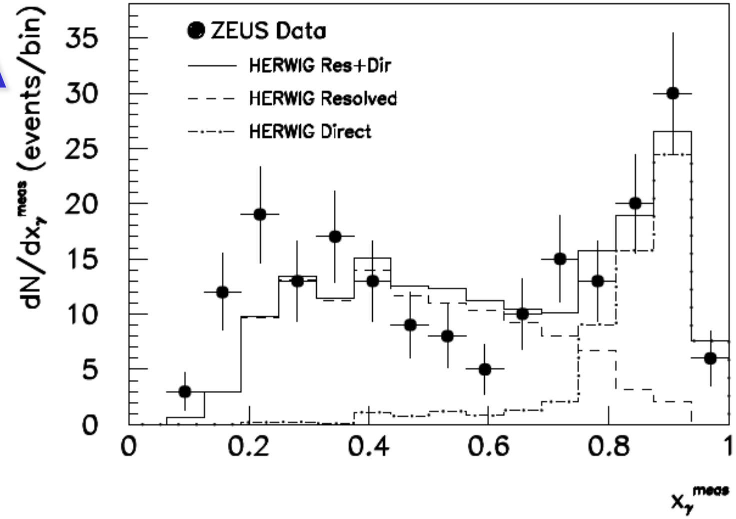


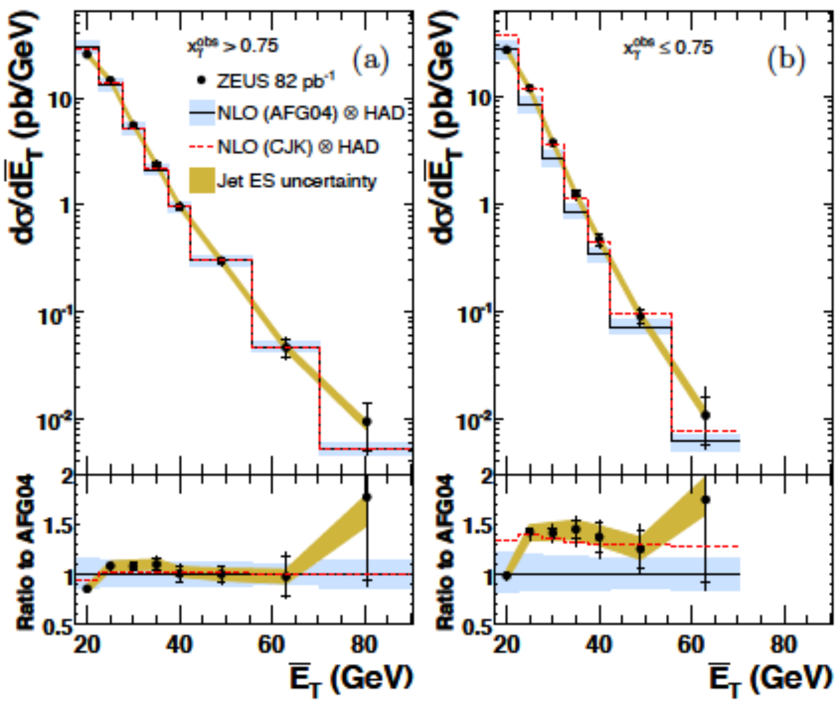
Some interesting effects … though not 100% convincing

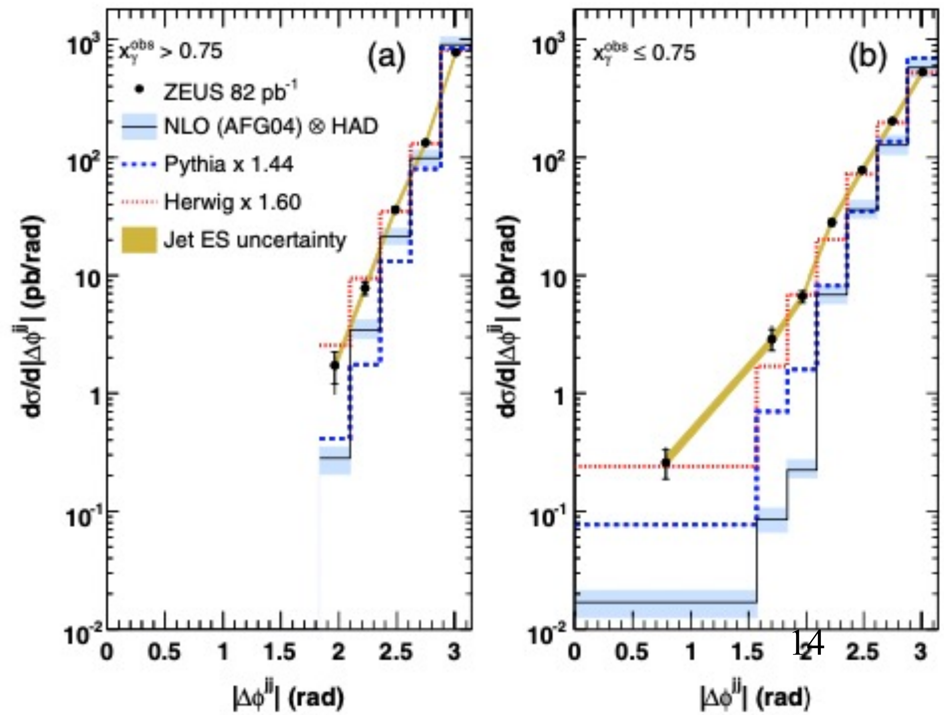
Photon Structure at HERA



HERA discovered hard scattering in photoproduction and used it to constrain the photon PDFs





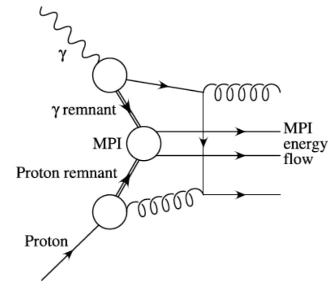


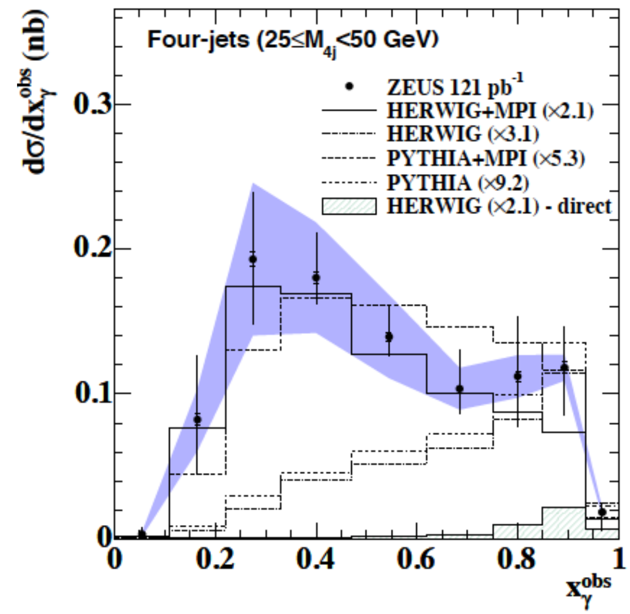
More HERA HFS Pioneering topics (many now taken up at LHC)

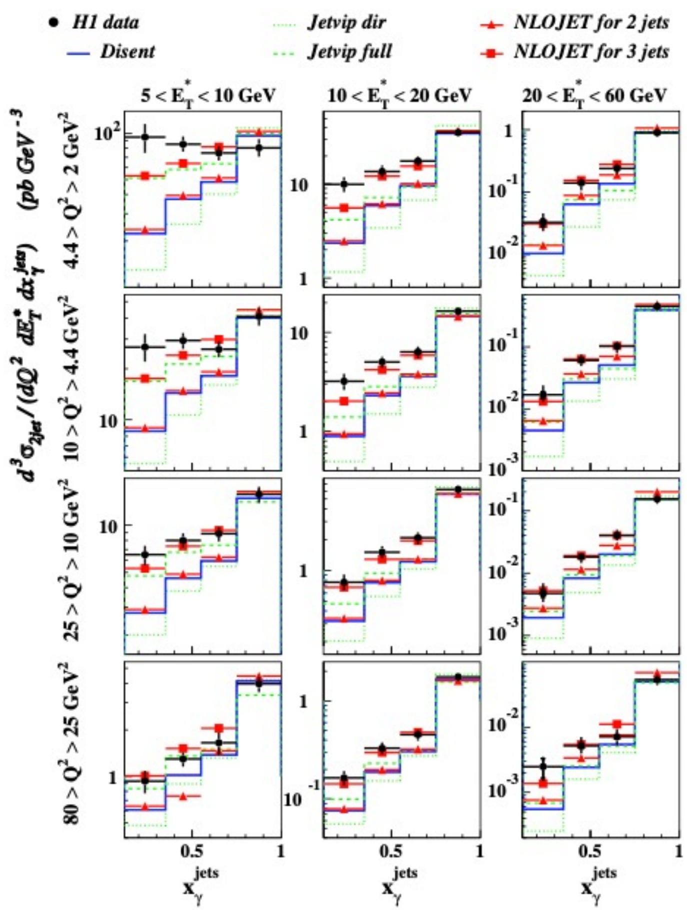
- Explicit searches for Multi-Parton Interactions

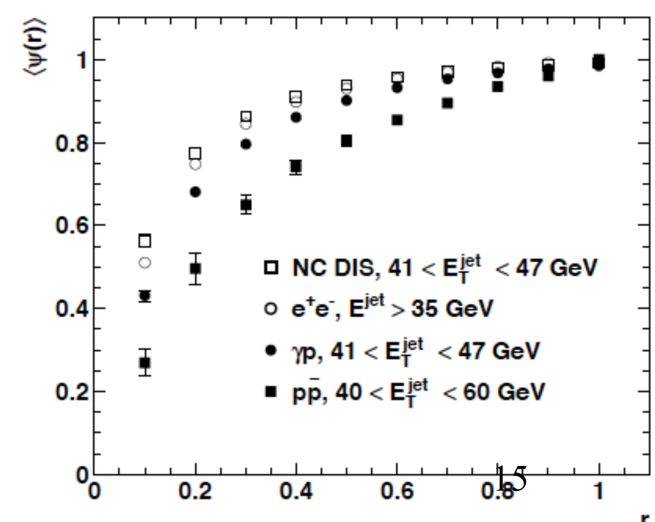
- Virtual photon 'structure'

- Jet substructure



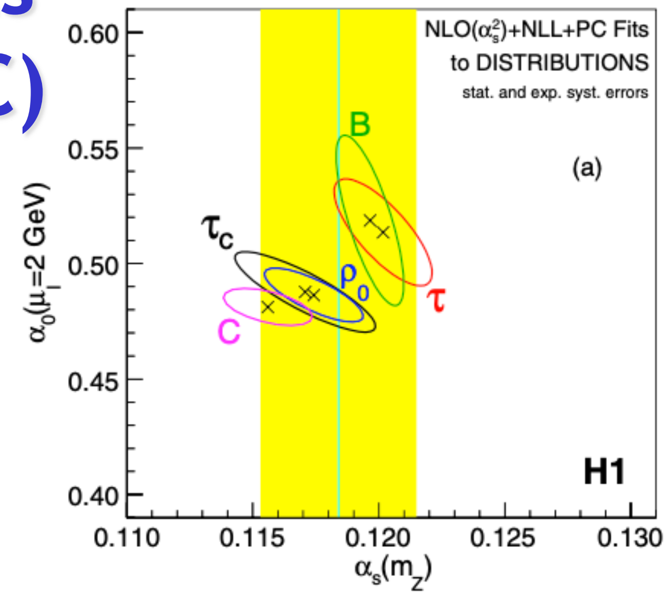




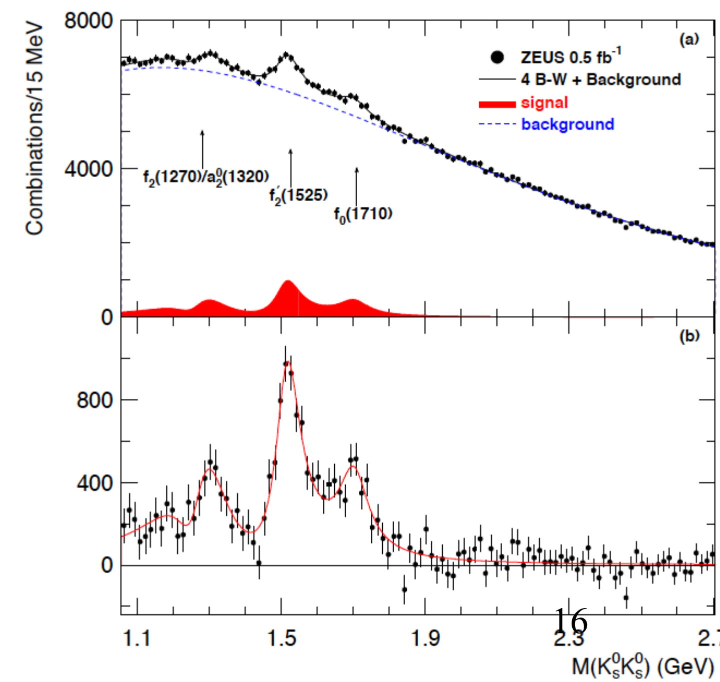


More HERA HFS Achievements (more directly relevant to EIC)

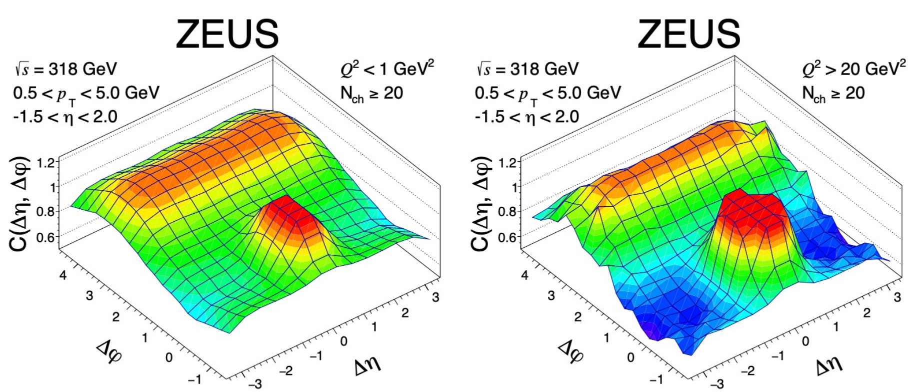
- Event shapes



- Evidence for new hadronic states (~~Pentaquarks~~? Glueballs?)



- Collective Flow from charged particle correlations?



(a) *Photoproduction.* (b) *NC DIS with $Q^2 > 20$ GeV^2.*

- Testing ground for machine learning in unfolding and elsewhere

DIFFRACTIVE CHANNELS

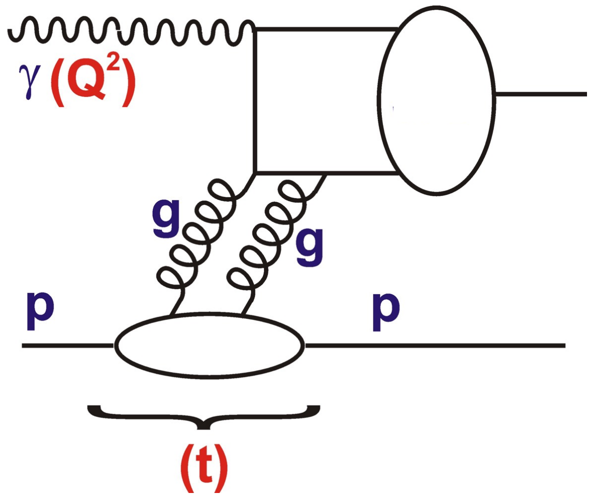
Diffraction: A Central Theme at HERA & EIC

Microscopic interpretation as 2 gluon (or other parton) exchange:

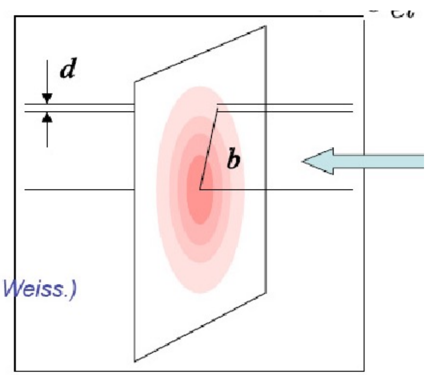
1) Sensitivity to correlations between partons and transverse structure

2) Additional variable t gives access to impact parameter (b) dependent amplitudes

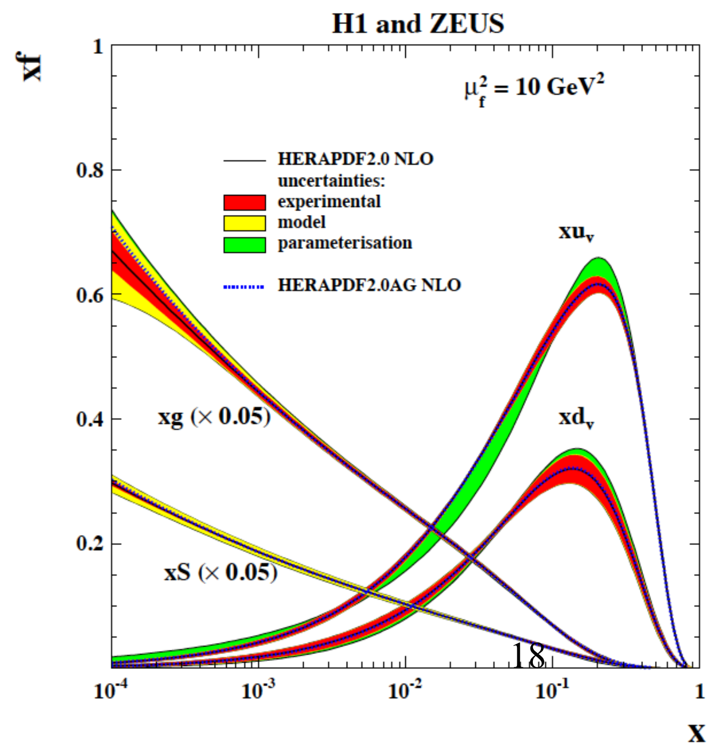
3) In eA, sensitivity to (pathologically rising?) low x gluon → non-linear / saturation?



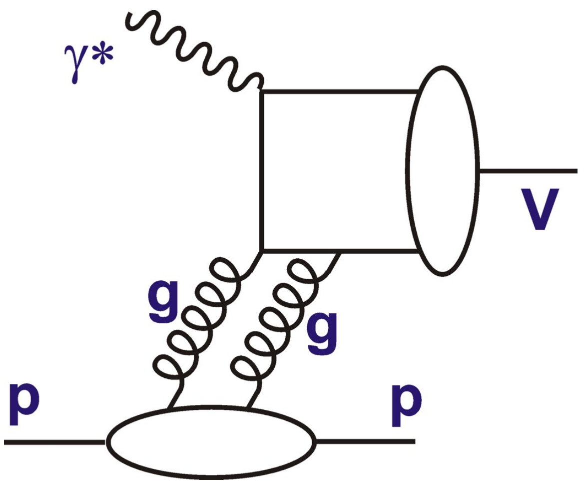
→ Large t (small b) probes densest packed part of proton?..



(figure from C. Weiss.)



Exclusive Vector Meson Production

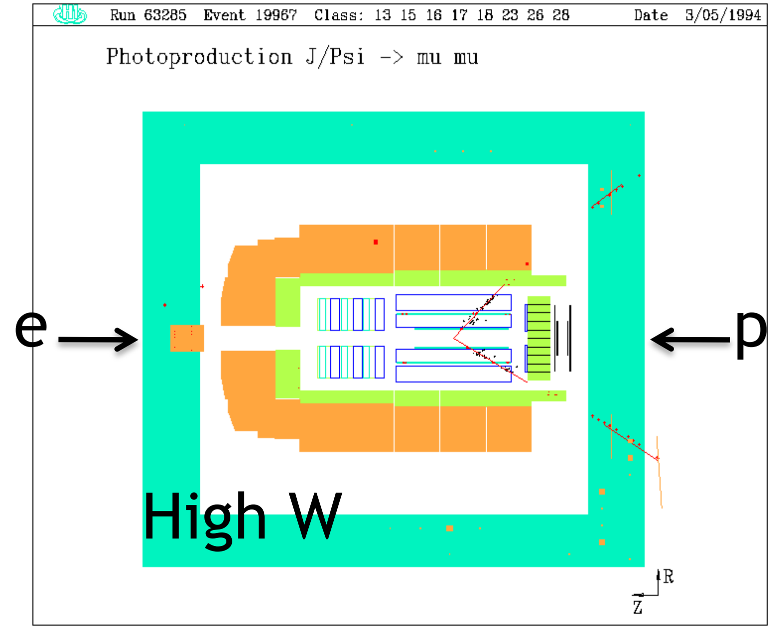


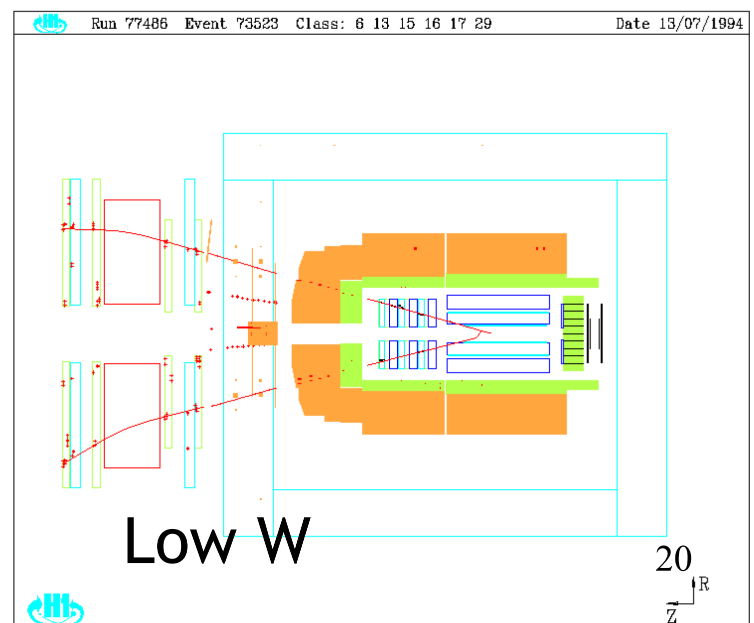
Experimental Selection (examples from H1 - Elastic J/Ψ → μμ)

2-prong decays give beautifully clean events.

→ Select by requiring otherwise empty detector

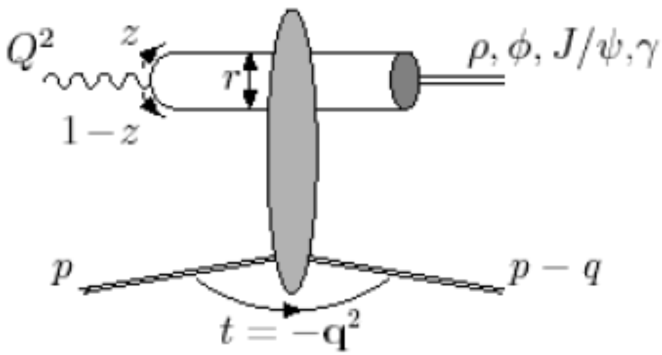
→ Decay muon direction is determined by $W = \sqrt{s_{\gamma p}}$





Describing Vector Mesons in terms of Partons

Factorisation theorem



Dipole Models

step 1. γ fluctuation into $q\bar{q}$ dipole

step 2. dipole – proton interaction $A = \int dr^2\, dz\, \Psi_\gamma\, \sigma(dip-p)\, \Psi_V$

step 3. pair recombination into VM

1. γ wave function

well known : $\Psi(z, k_t)$

however : large $|t|$ studies -> chiral odd contributions

- Basically known

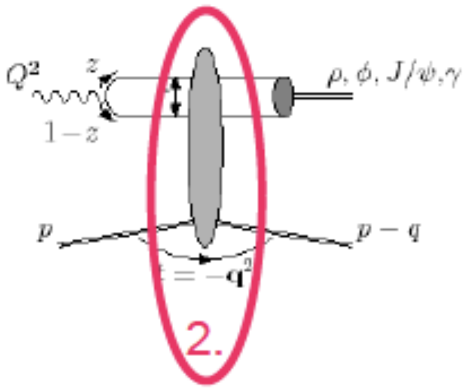
3. pair recombination into VM

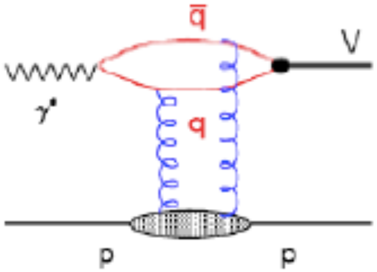
- VM wave function description ?
- role on σ_L / σ_T and helicity amplitudes

- Limits theoretical precision

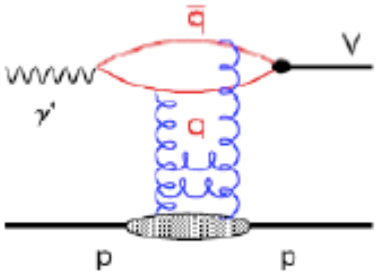
The Dipole-Proton Interaction

2. dipole – proton interaction - The interesting physics





LO 2 gluons



LL1/x ladder

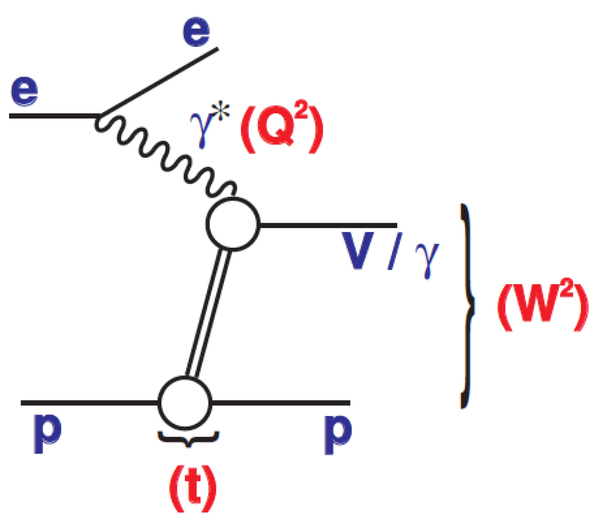
VM production is a promising candidate to learn about the gluon distribution in hadrons and the correlations among gluons

Many models on the details of $\sigma(r)$

What is the relevant scale?... r depends on Q^2 and M_V^2

$$Q^2_{eff} = z\,(1-z)\,(Q^2+M_V^2) \sim (Q^2+M_V^2)\;/\;4 \qquad \text{[MRT...]}$$

Vector Mesons & the Soft → Hard Transition



Behaviour usually parameterised in Regge-theory motivated form

$$\frac{d\sigma_{el}}{dt} \sim \left(\frac{W^2}{W_0^2}\right)^{2\alpha(t)-2} e^{bt}$$

– $\alpha(t)=\alpha(0)+\alpha' t$ is the 'effective pomeron trajectory'
'Universal' description of soft physics: $\alpha(t) \sim 1.08 + 0.25t$

- e^{bt} empirically motivated – Fourier transform of spatial distribution of interaction
$b = b_{dipole} + b_{proton} \rightarrow b_{proton}$ as dipole size → 0

- Signatures for 'hard' behaviour include increase in $\alpha(0)$
and decrease in b

Photoproduction of Light v Heavy VM

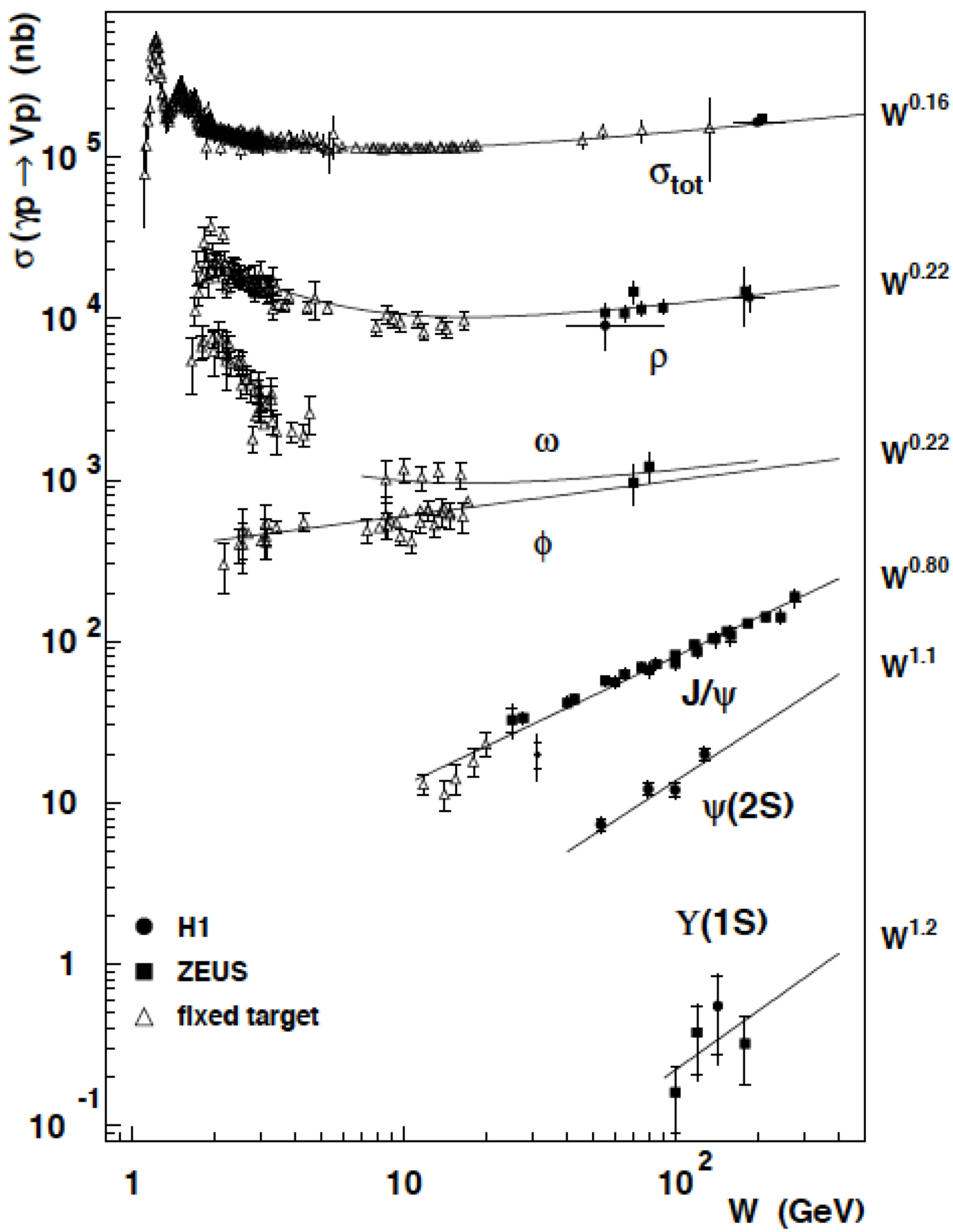
Increasing M_V leads to harder energy dependences

$\sigma \propto W^{\delta}$ with $\delta = 4\alpha(<t>) - 4$

- Consistent with soft pomeron for light vector mesons

- For J/Ψ, effective
  $\alpha(t) \sim 1.20 + 0.13t$

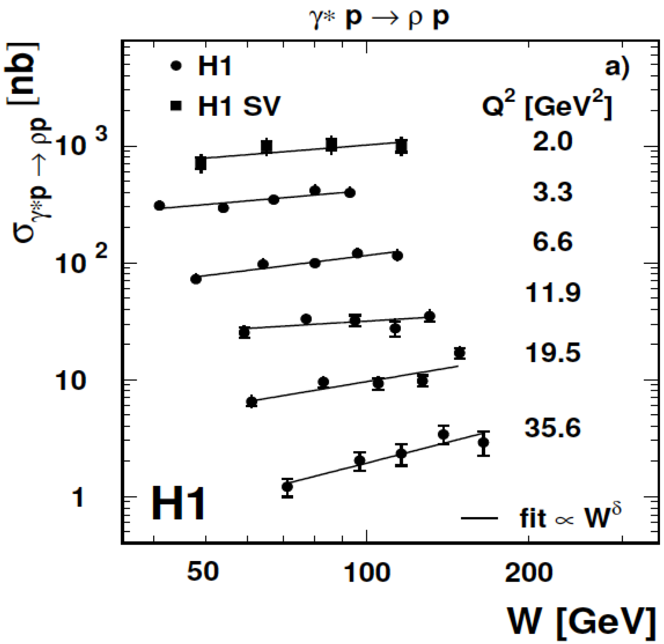
… c, b mass implies pQCD already valid for J/Ψ, Υ at $Q^2 = 0$

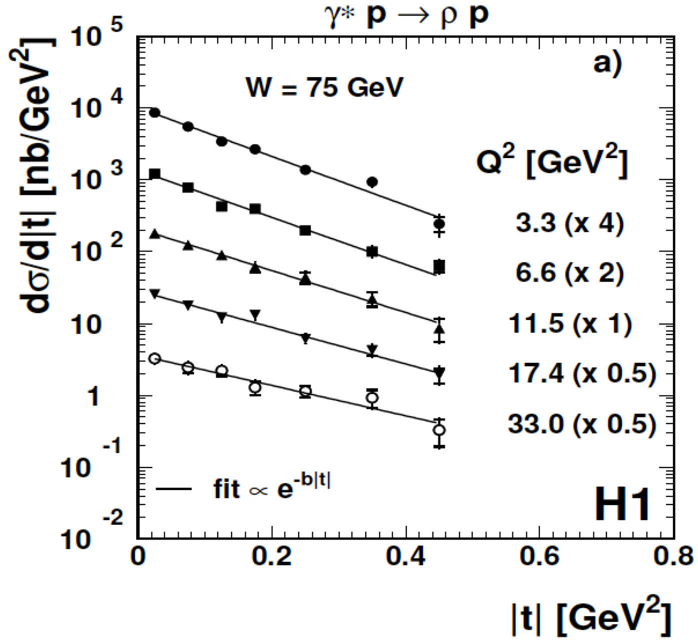


Turning the Q^2 Handle

-J/Ψ: W & t dependences ~ unchanged - already hard @ $Q^2=0$

- Light vector meson behaviour evolves from soft to hard (eg ρ^0)





- Vector mesons produced from longitudinal and transverse polarised photons behave slightly differently
- Fast reduction in cross section with Q^2 illustrates higher twist nature of process: $\sigma_L \sim 1/(Q^2+M_V^2)^{2.1}$, $\sigma_T \sim 1/(Q^2+M_V^2)^{2.9}$

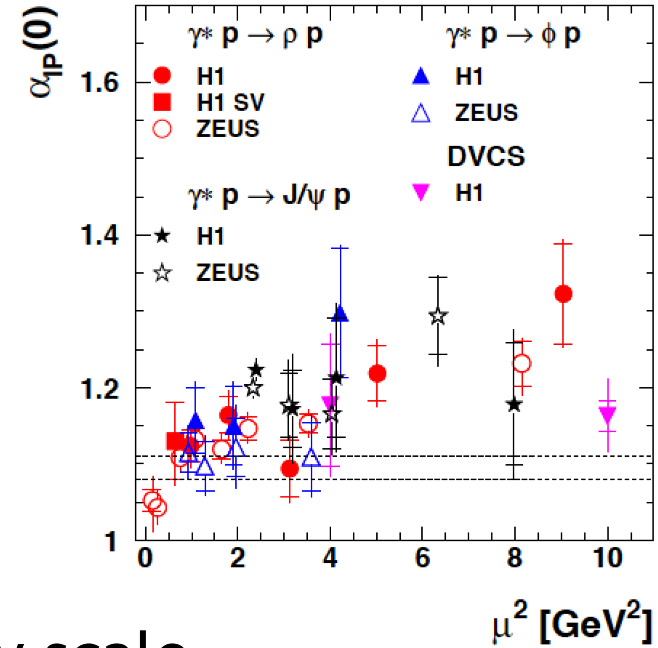
… reasonably well described by dipole (2 gluon) models

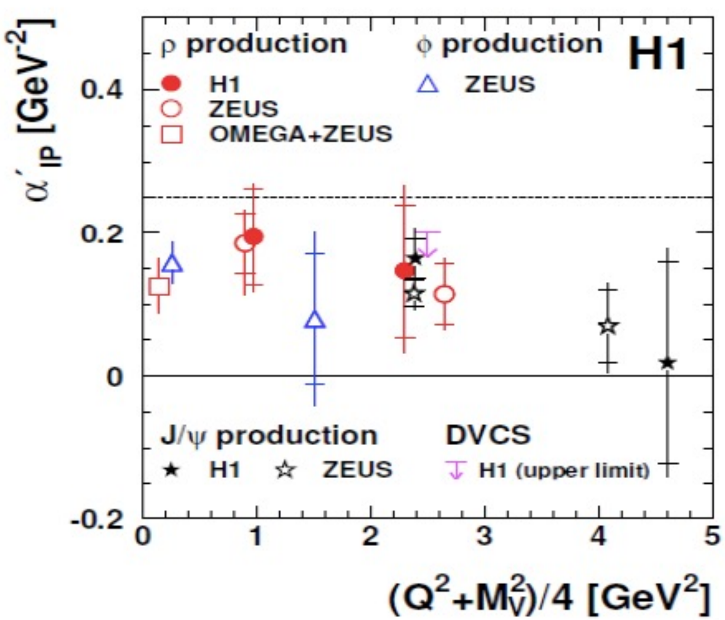
VM Overall Characterisation Summary

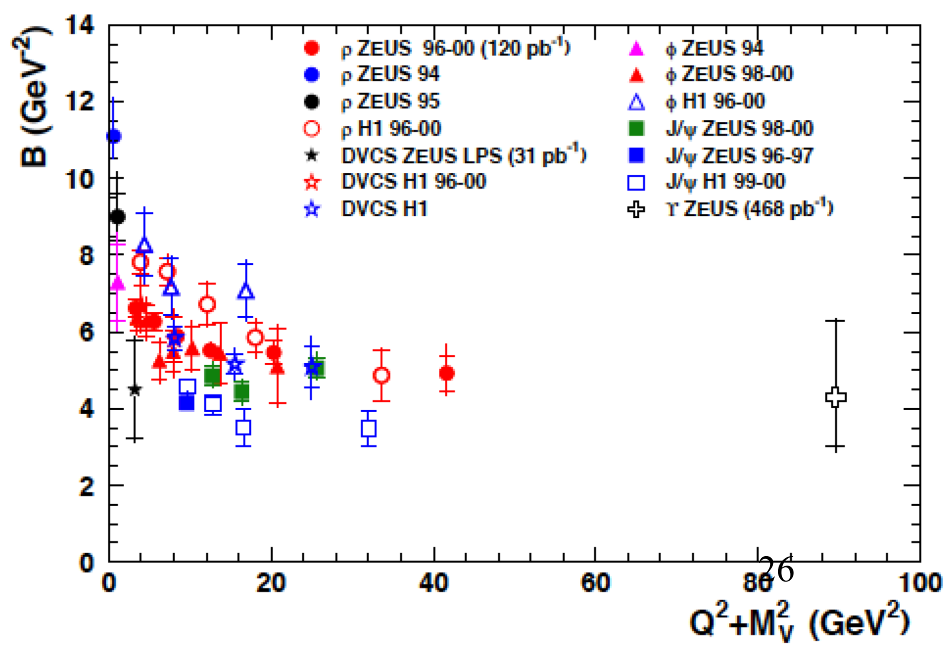
- Approximate scaling between different meson species in $(Q^2 + M_V^2)/4$

-t-slope approaches B~ 4-5 GeV^{-2} ~ 0.6fm
… slightly smaller than EM size of proton?

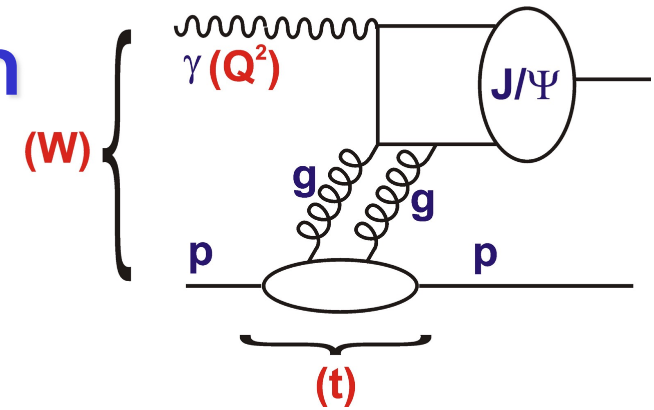
– α' shows no significant variation with any scale.







Exclusive J/Ψ Photoproduction



Maybe the ideal place to look for gluon saturation in ep, eA …

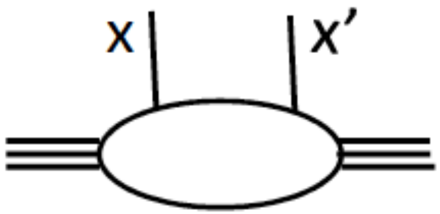
Advantages

- Clean 2 lepton experimental signature
- Scale $\bar{Q}^2 \sim (Q^2 + M_V^2)/4 \gtrsim 3\ \mathrm{GeV}^2$ ideally suited to reaching lowest possible x whilst in perturbative regime

Possible clear saturation signature: energy (W) dependence flattening in a manner dependent on t or in eA as A grows?

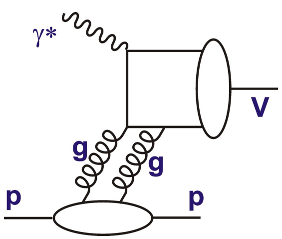
Complications

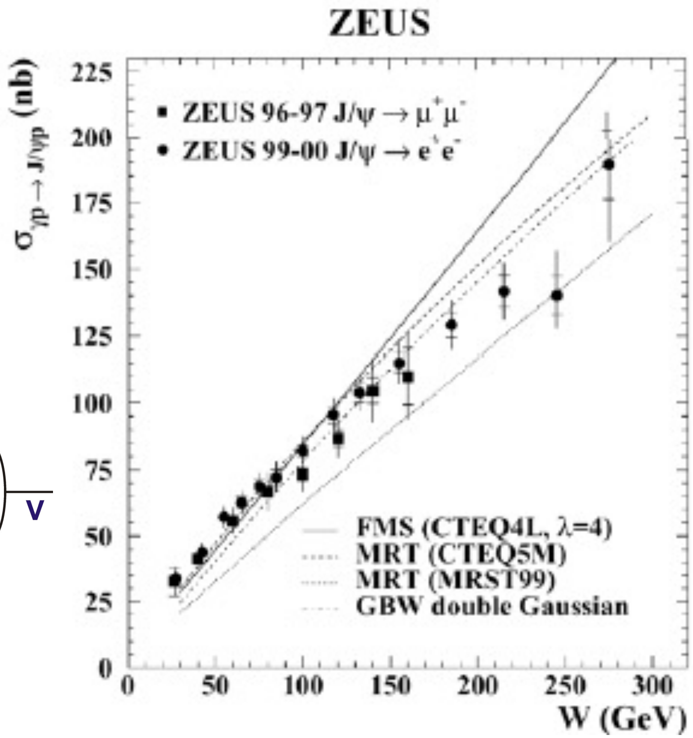
- Vector meson wavefunction

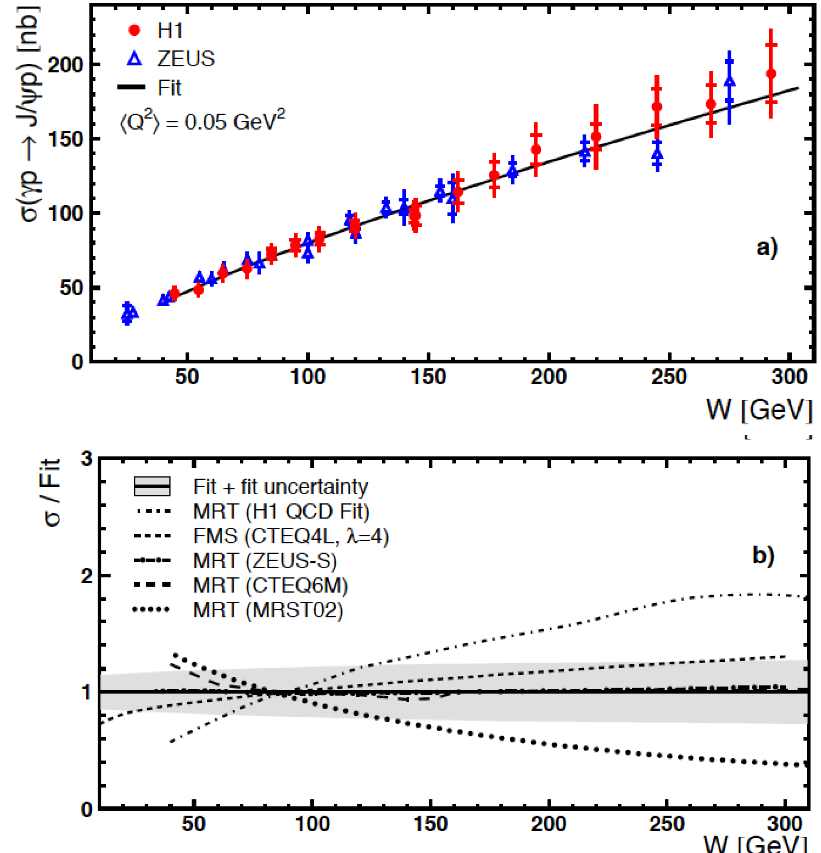


- Difficulties in collinear factorization theory → large scale uncertainties (NLO v LO convergence)

HERA Photoproduction of J/Ψ and the Gluon







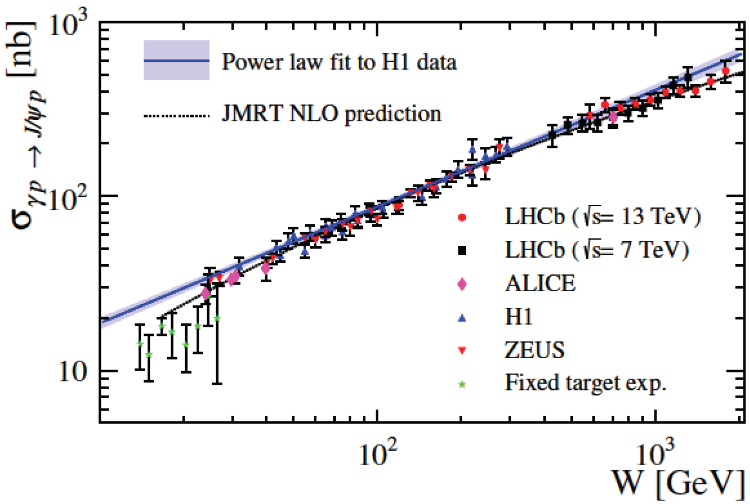
- QCD models based on 2-gluon exchange describe HERA data well & suggest power to discriminate between PDFs

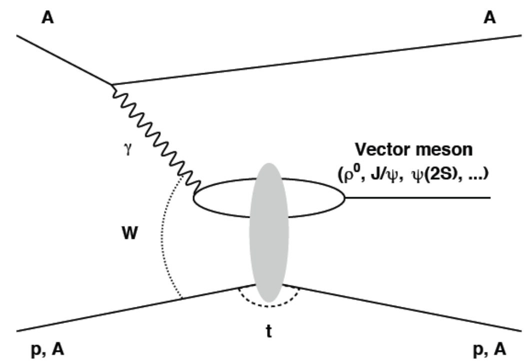
- Sensitivity limited by theory uncertainties

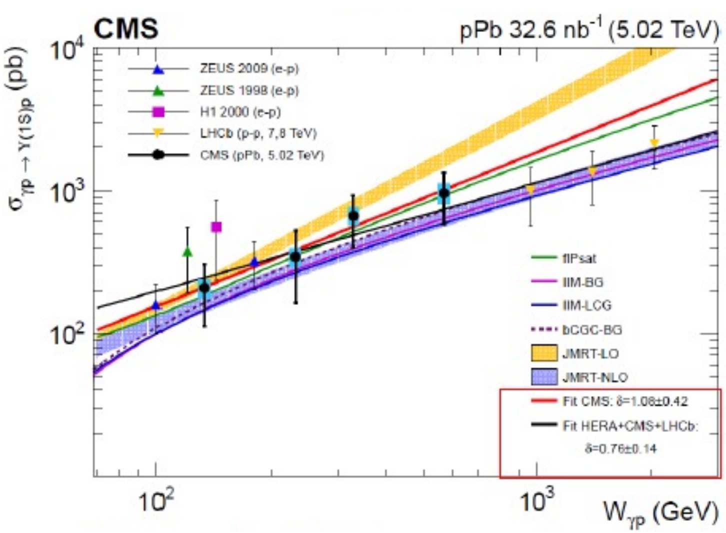
- No evidence for saturation phenomena in HERA J/Ψ data

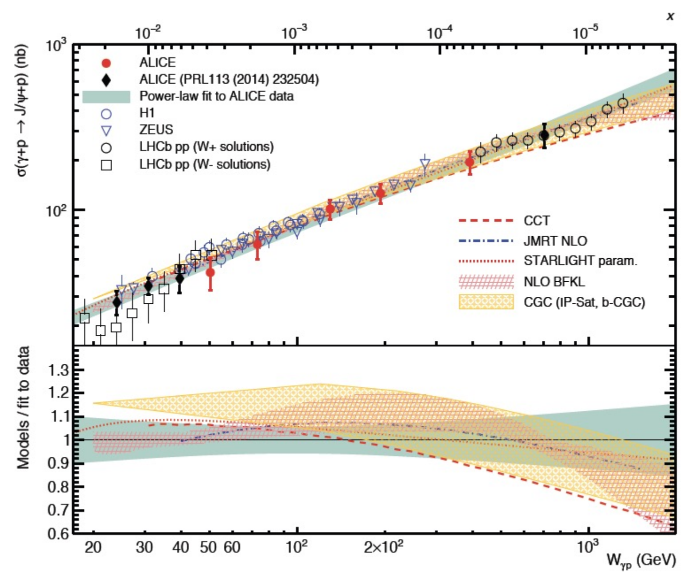
Exclusive J/Ψ Data from the LHC

J/Ψ Photoproduction also studied (at higher energy) in Ultraperipheral Collisions at LHC





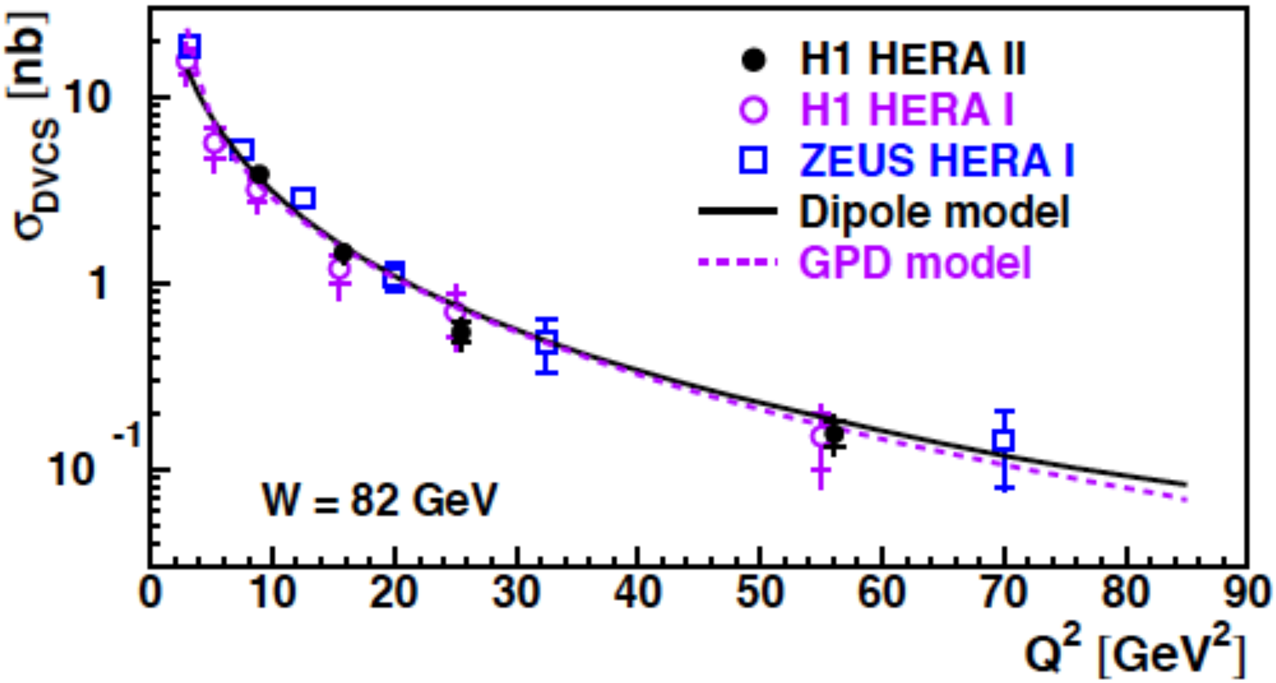


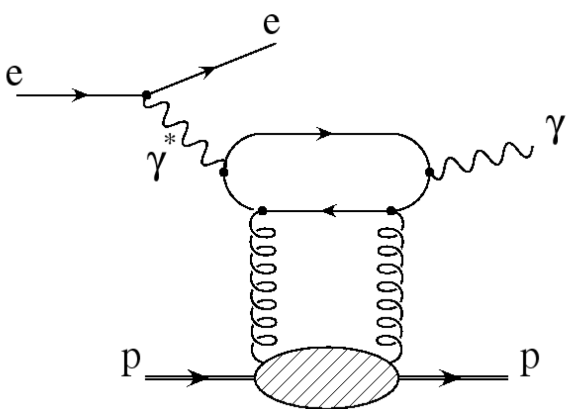


- No sign of deviation from simple power law behaviour (yet)
- More subtle signatures in t dependences and eA/ep? → EIC …

Deeply Virtual Compton Scattering (ep → eγp)

- HERA measurements were luminosity-limited (lower cross sections than VM due to γ coupling)
- HERA did not have polarised proton beams



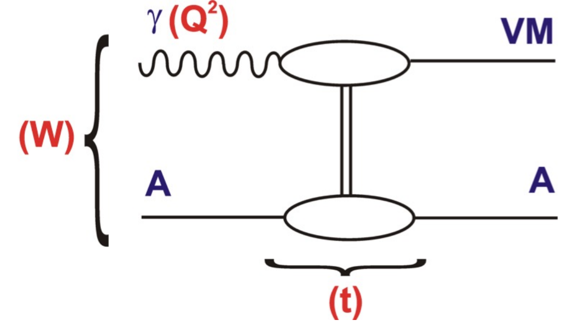


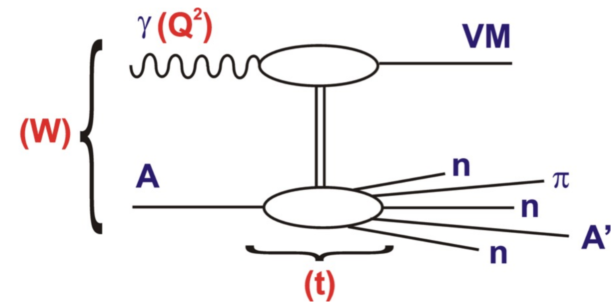
MUCH BIGGER TOPIC AT EIC!

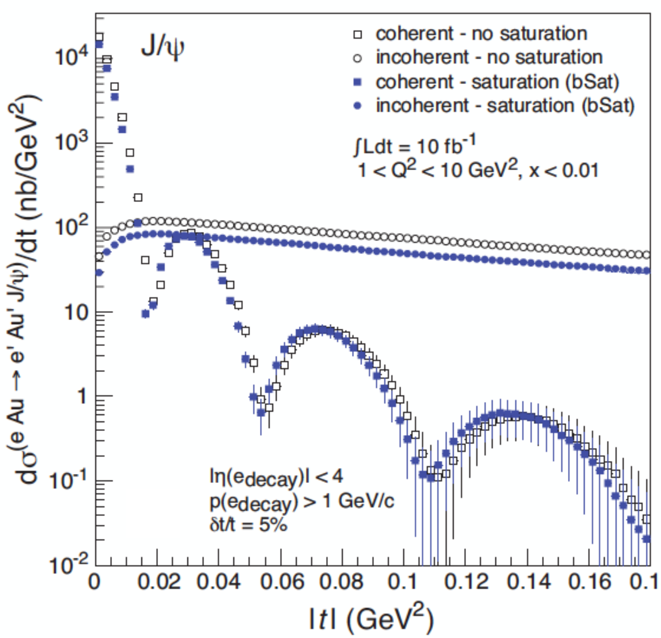
… large range of exclusive (and semi-inclusive) measurements addressing EIC ‘understanding spin’ theme that go beyond HERA programme

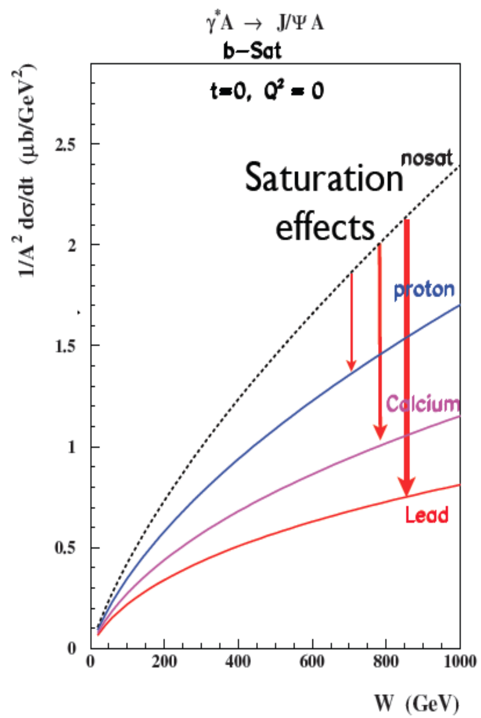
EIC Exclusive Diffraction in eA

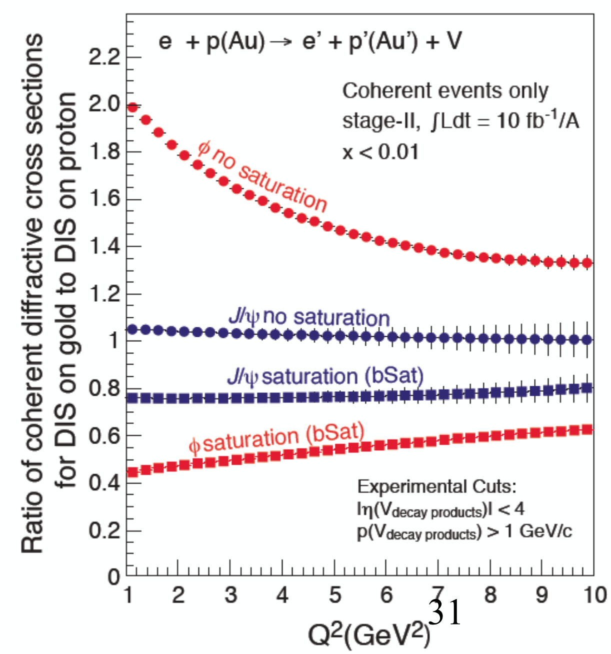
- Separation of coherent / incoherent can be done based on ZDC
- Opportunity to image structure
- Significant saturation effects predicted in coherent case (eA → eVA), visible in total cross sections, A and t dependences
- ϕ mesons may be most sensitive



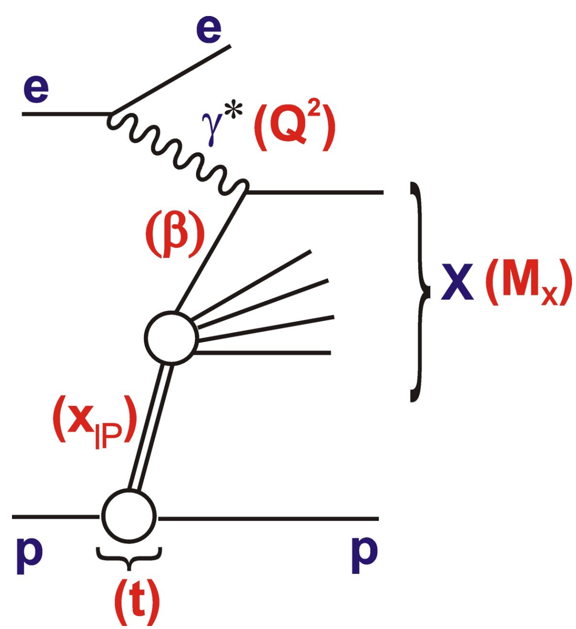








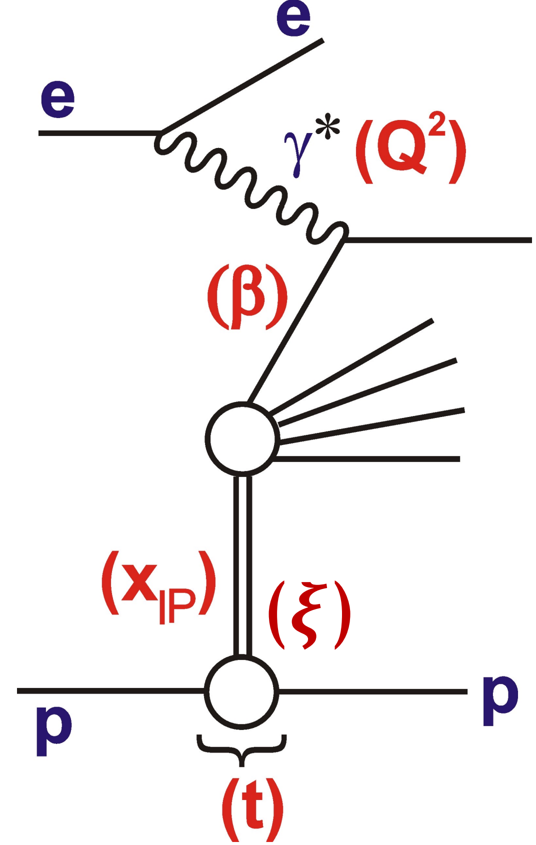
Inclusive Diffraction in DIS

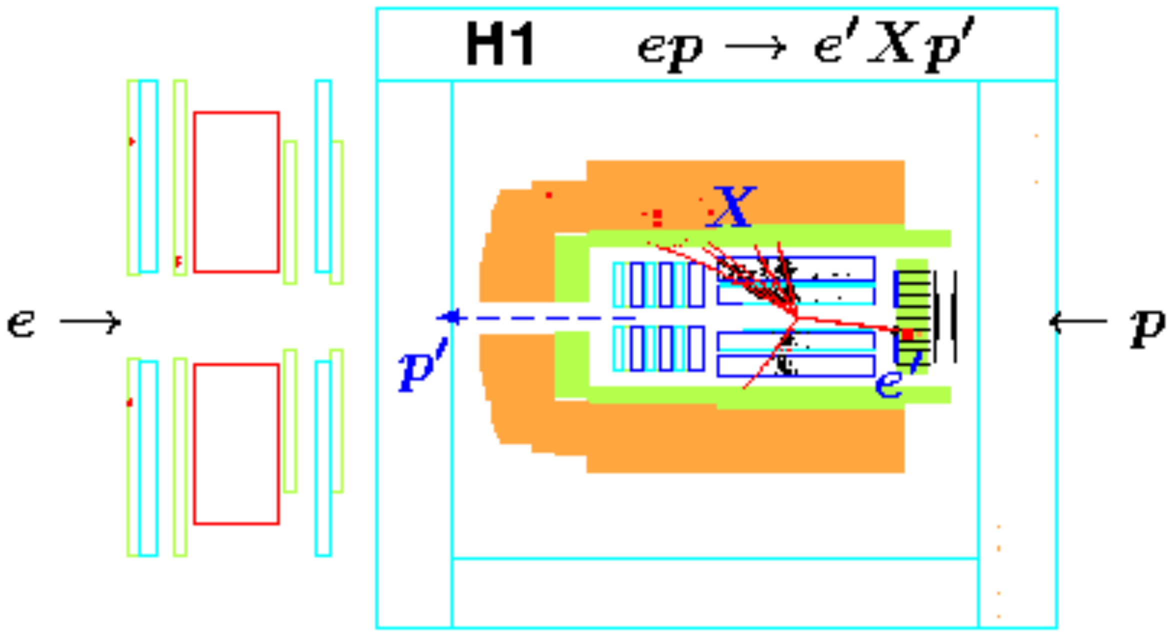


Diffractive DIS

Vector meson production is a ‘higher twist’ (Q^2 suppressed) process

There are ‘leading twist’ diffractive processes with same Q^2 dependence as the bulk DIS cross section …

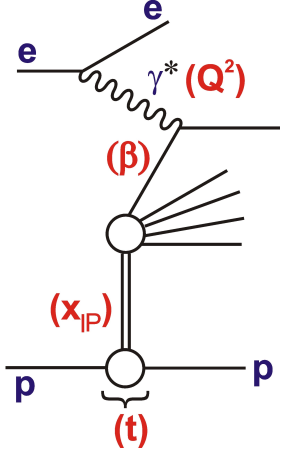




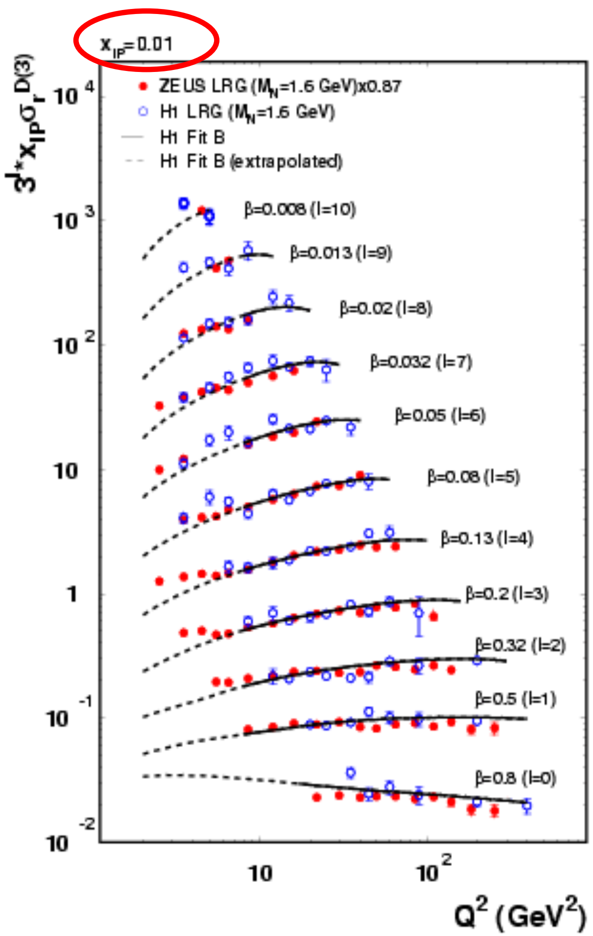
<u>HERA conclusion:</u>

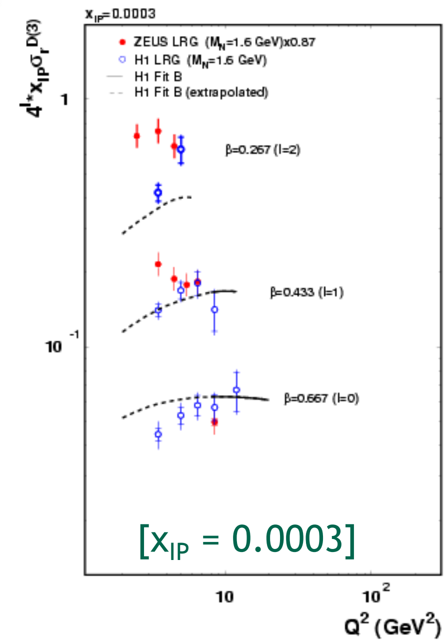
(Mostly) DIS from a universal(ish) soft colourless target … sometimes referred to as a `pomeron’

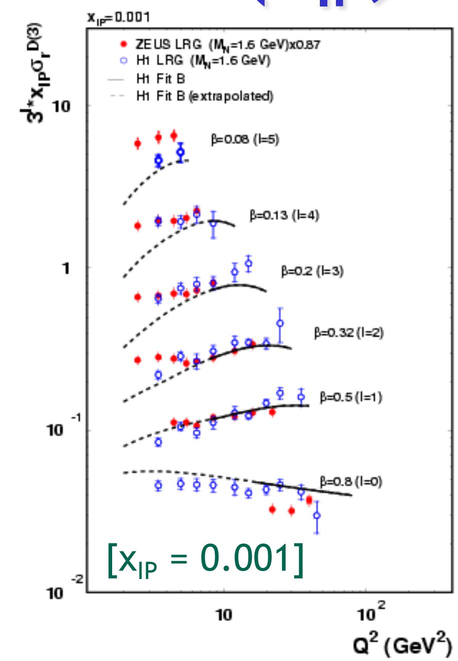
(β, Q^2) Dependences at fixed (x_{IP}, t)

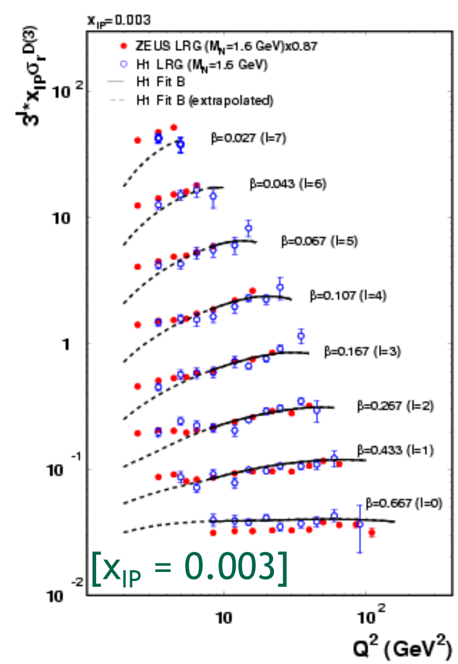


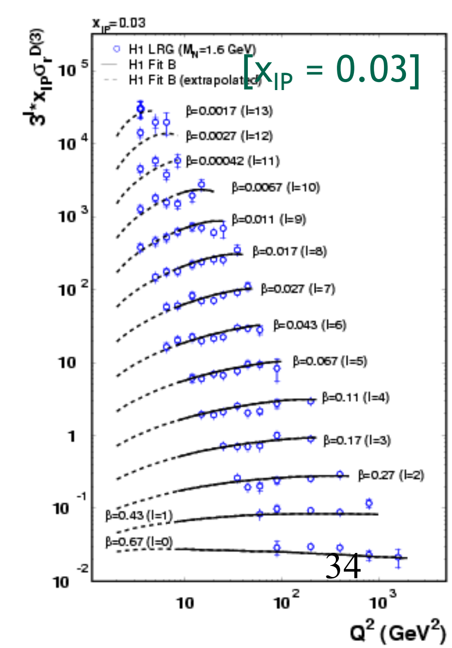
Leading twist and ~10% of total x-sec

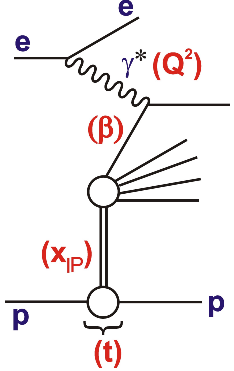






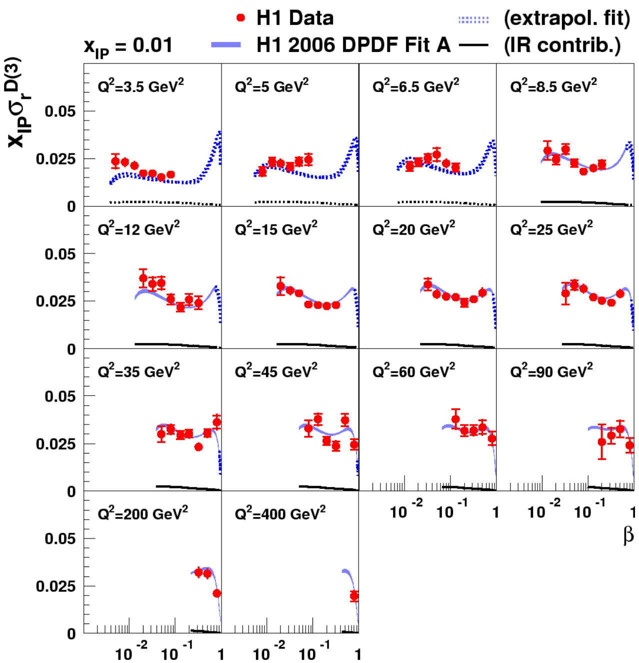


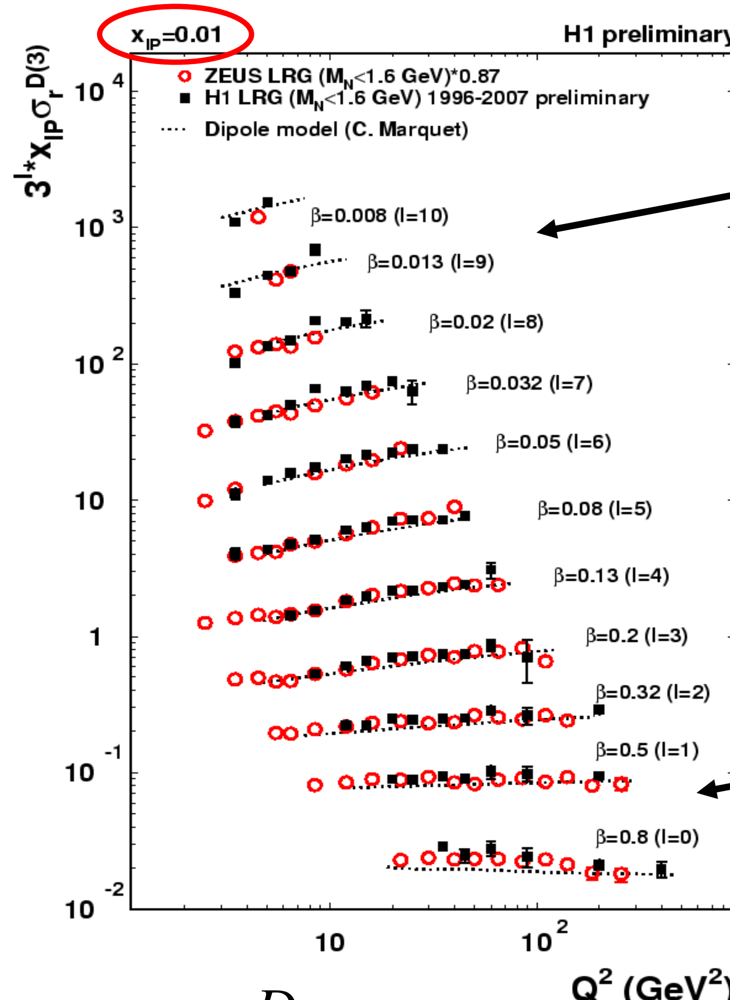


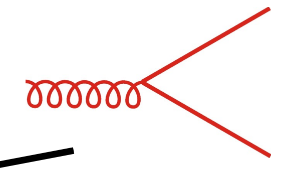


Sensitivity to Diffractive Quarks & Gluons

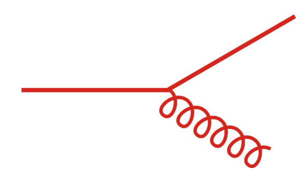
Similarly to
Inclusive DIS ...







Q^2 dependence tells us gluon density via DGLAP eqns

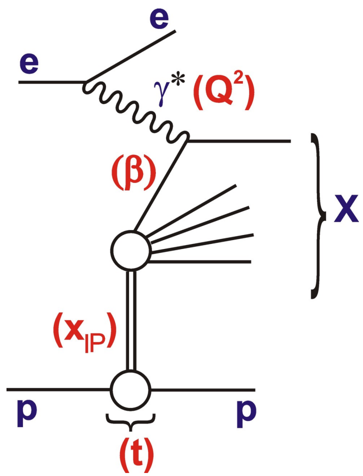


Diffractive cross section measures quark density

$$F_2^D = \sum_q e_q^2 \, \beta \, (q + \bar{q})$$

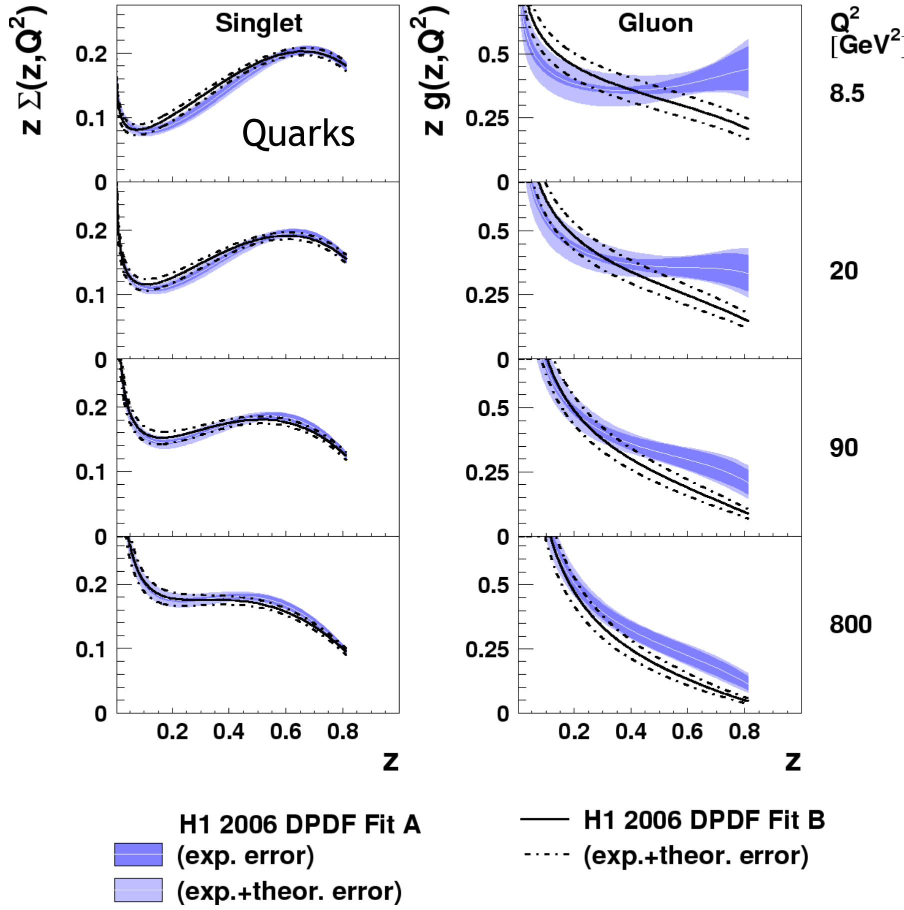
$$\frac{d\sigma_r^D}{d\ln Q^2} \sim \frac{\alpha_s}{2\pi}\left[P_{qg} \otimes g + P_{qq} \otimes q \right]$$

Diffractive Parton Densities (DPDFs)



DPDFs extracted through fits to inclusive (& jet) data, assuming NLO/NNLO DGLAP evolution, similarly to inclusive DIS

e.g. H1

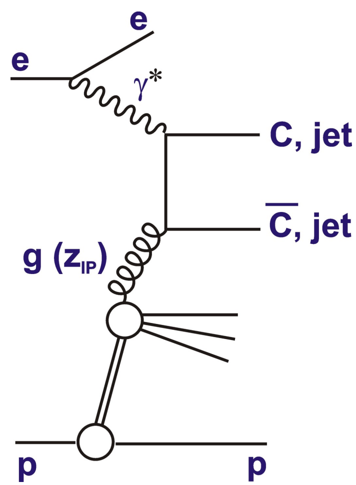


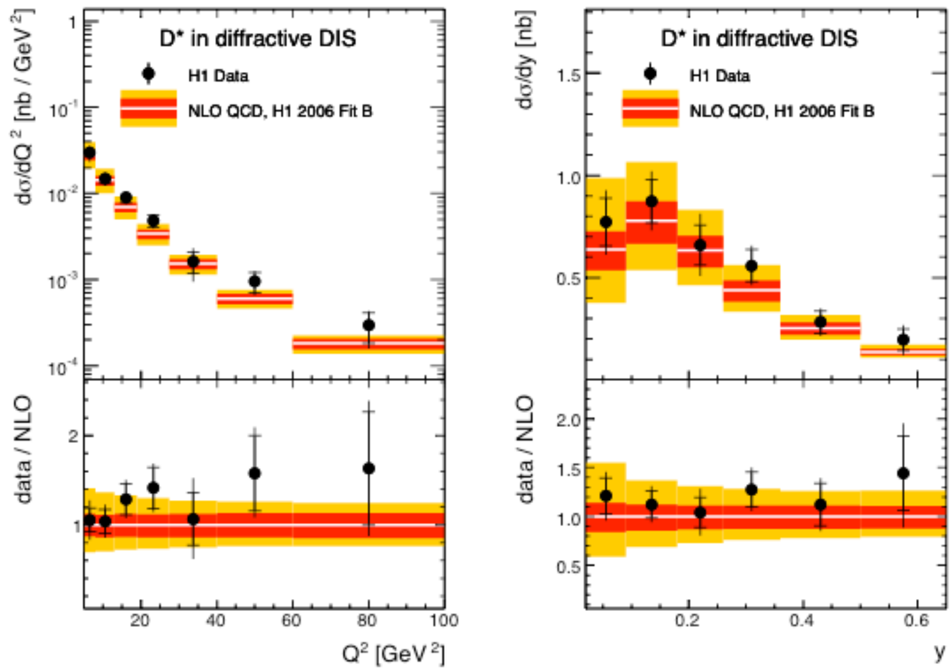
… dominated by gluon density extending to large momentum fractions, z

- NLO DGLAP QCD fits describe data over most of phase space
- Failure of diffractive PDF fits to describe data at lowest Q^2 …

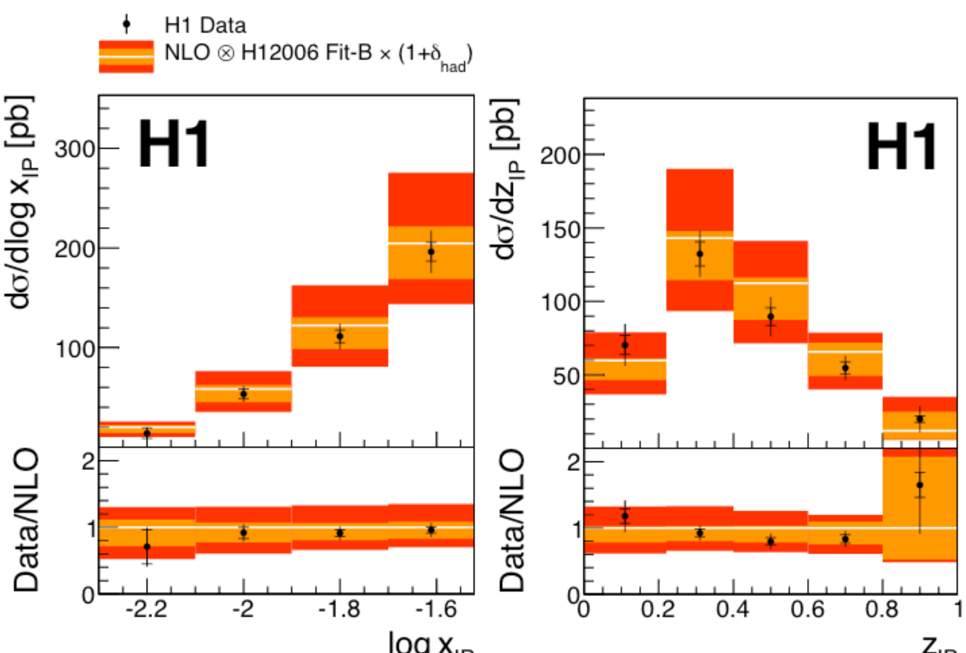
Testing Factorisation; eg HERA Jets & Charm

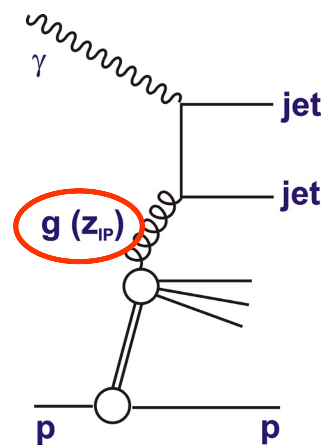
Remarkably good description of all variables in Diffractive DIS over a wide kinematic range





Charm in DIS





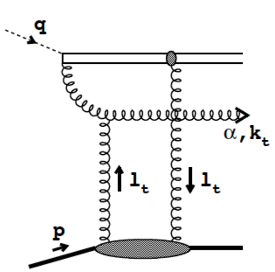
Dijets in DIS

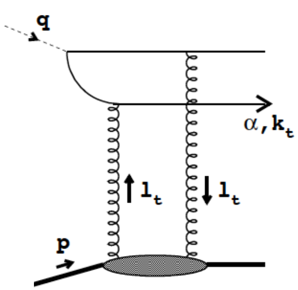
[Diffractive photoproduction addresses `Rapidity Gap Survival Probabilities']

Diffractive DIS & Dipole Models

- Quality of H1 & ZEUS DPDF fits degrades at low Q^2 <~ 5 GeV^2
  … low Q^2 breakdown of pure Leading Twist DGLAP approach

- Dipole models also applied, but need qqbar-g terms (and perhaps higher Fock states)

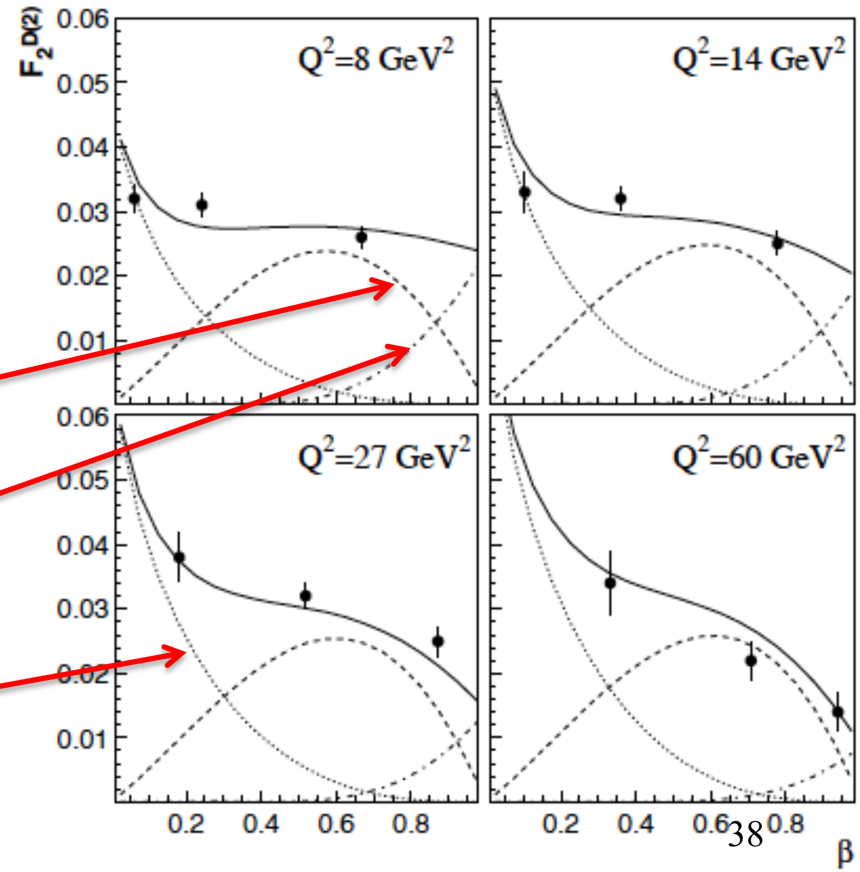




qq_T (Leading Twist)

qq_L (Higher Twist)

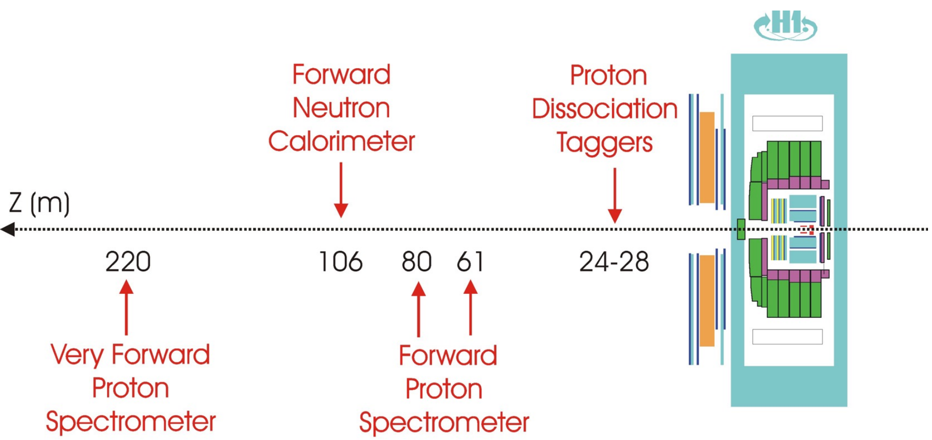
qqg_T (Leading Twist)



- Higher twist contribution at large β interesting @ EIC

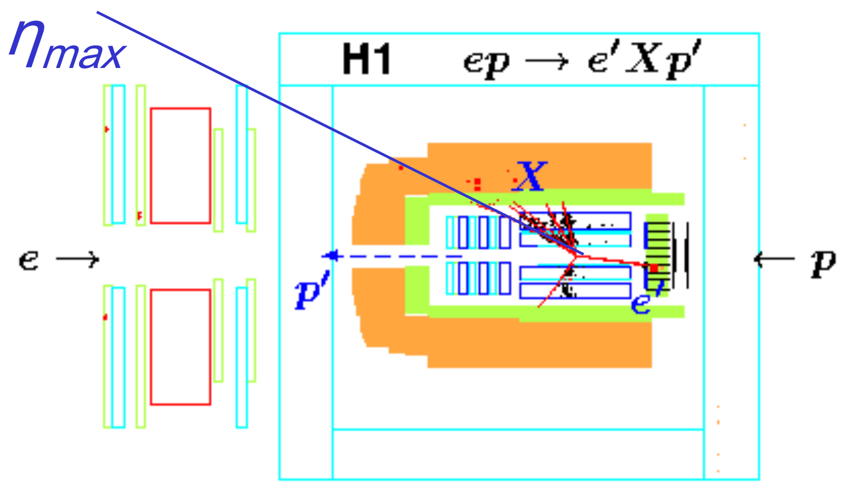
Signatures and Selection Methods at HERA

Scattered proton in Leading Proton Spectrometers **(LPS)**



Limited by statistics and p-tagging systematics

`Large Rapidity Gap' **(LRG)** adjacent to outgoing (untagged) proton

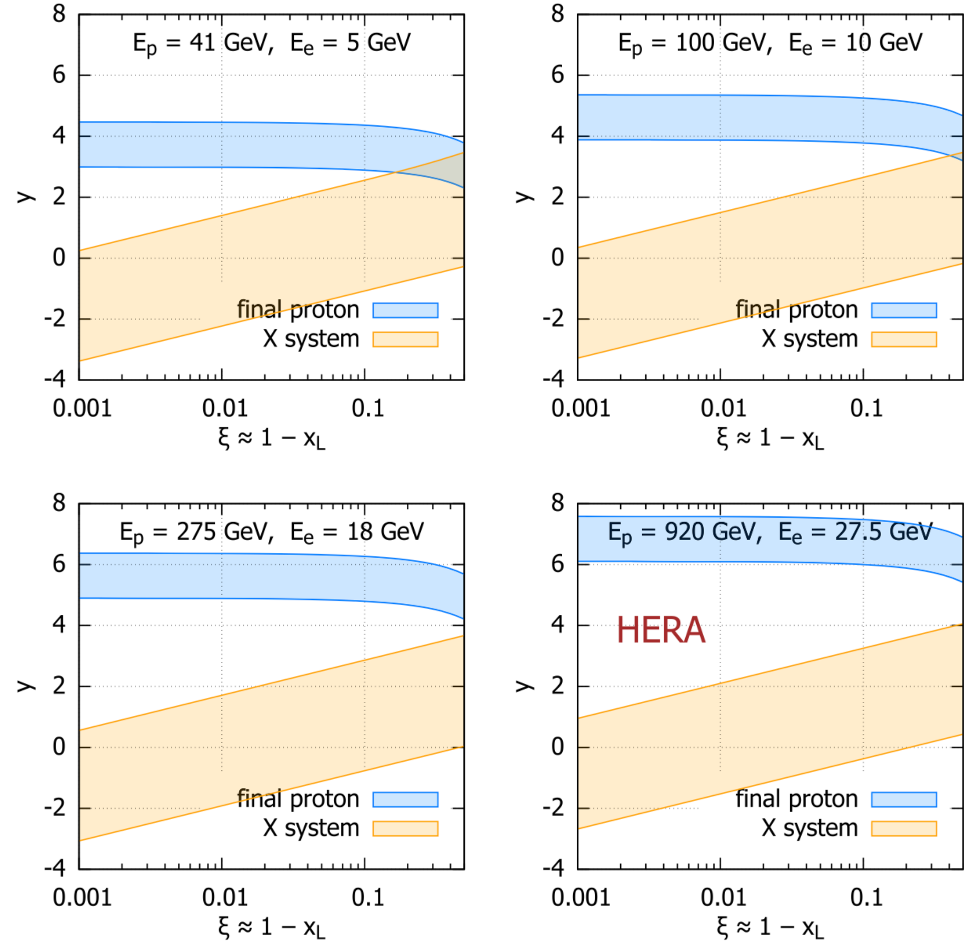


Limited by p-diss systematics

- The 2 methods have very different systematics
- LRG was the main method used at HERA
- At EIC it will be LPS (technologies improved, gaps are smaller!)

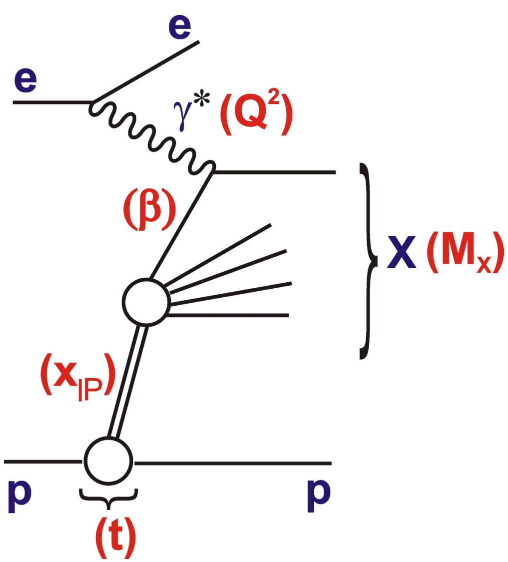
Rapidity Gap Kinematics at EIC

Rapidity gaps in inclusive diffraction at EIC are only large at the highest $\sqrt{s}$ and the smallest ξ



… c.f. Random hadronisation fluctuations in non-diffractive processes are exponentially suppressed, but can easily reach ~2-3 units.

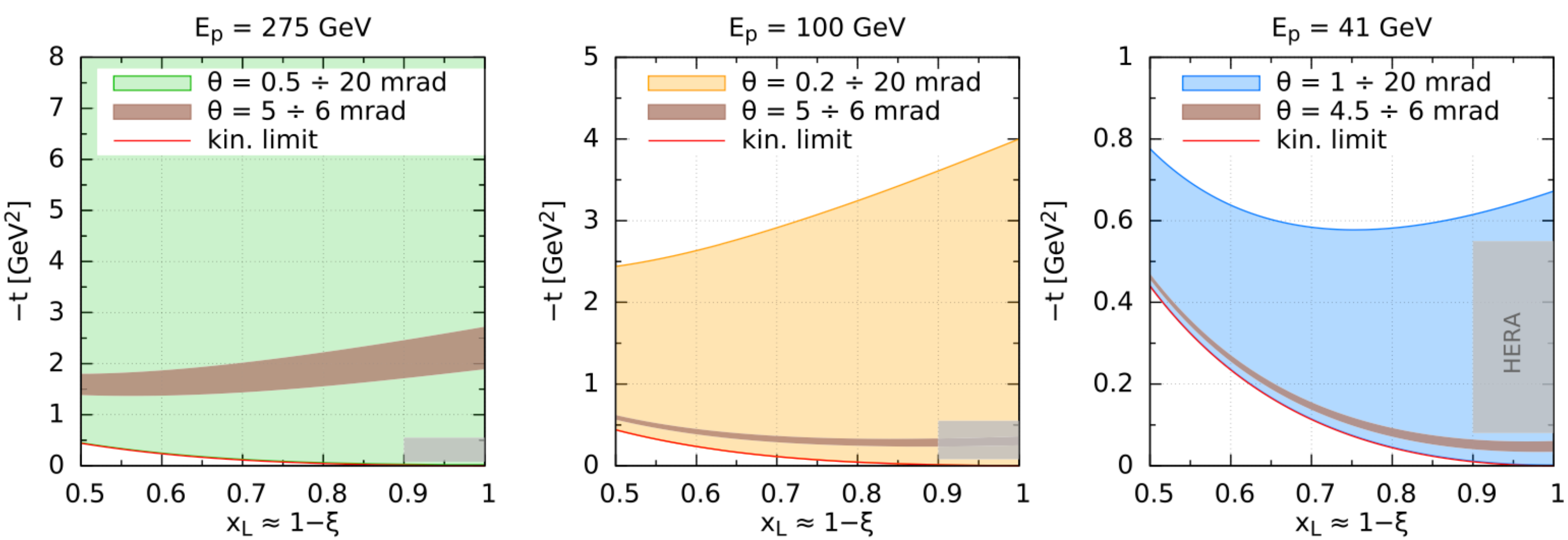
Inclusive Diffraction in ep at EIC: Scattered proton kinematics



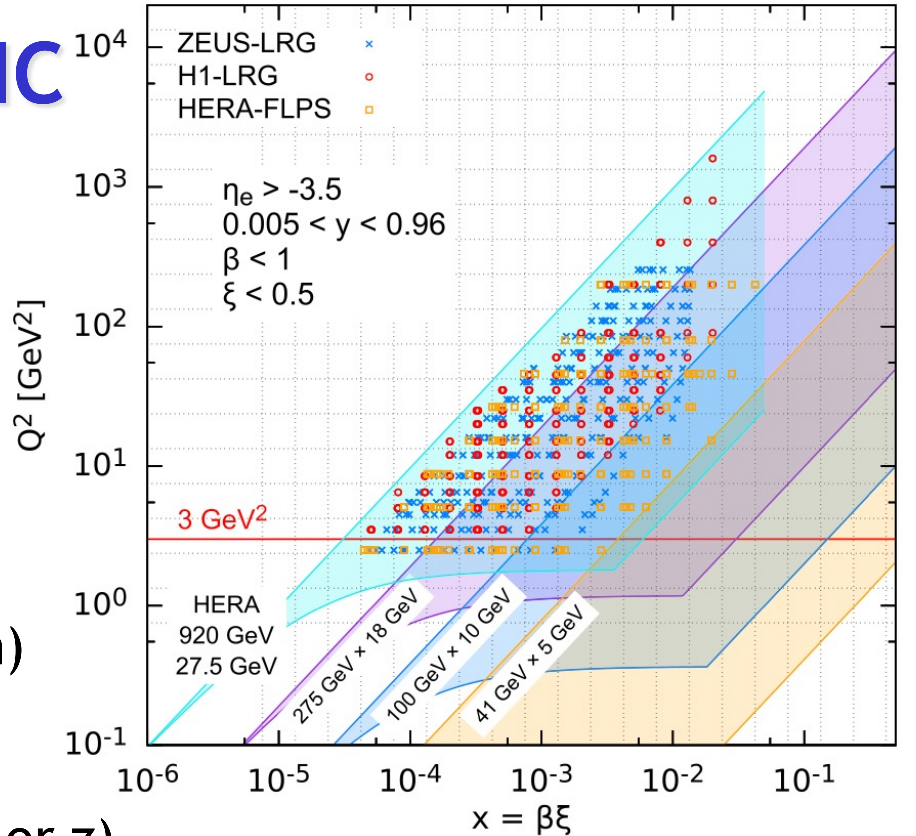
$$t \approx -p_T^2 \qquad x_L = {E'_p}/{E_p} = 1 - x_{\mathrm{IP}}$$

Planned EIC Roman pots provide:

- Good coverage in most interesting low ξ (large x_L), low |t|, region for all $\sqrt{s}$
- Interesting coverage at larger ξ at large $\sqrt{s}$ (sub-leading `Reggeon' exchanges)



Inclusive Diffraction @ EIC



Lower CMS energy than HERA, but …

- Inclusive diffraction never been studied with nuclear or polarised targets

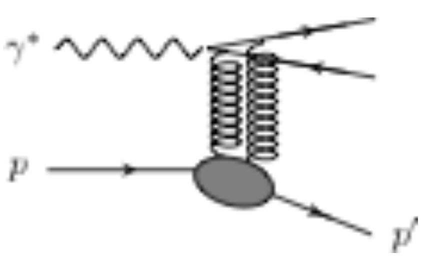
- Fills gap in kinematic plane at large x, low Q^2 (there are no fixed target data)

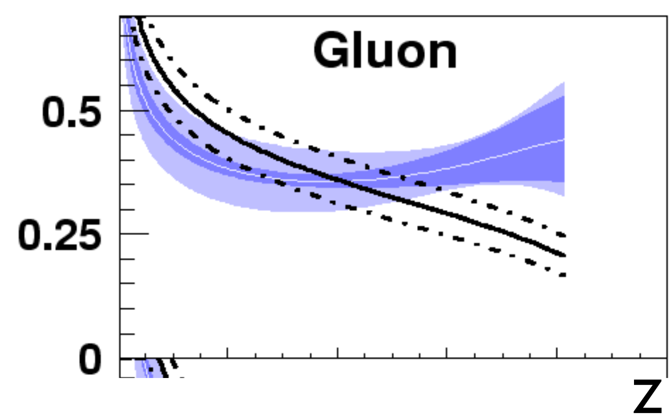
→ Sensitive to sub-leading (non-pomeron) exchanges at large ξ

→ Sensitivity to poorly constrained structure at large momentum fraction (β or z) …

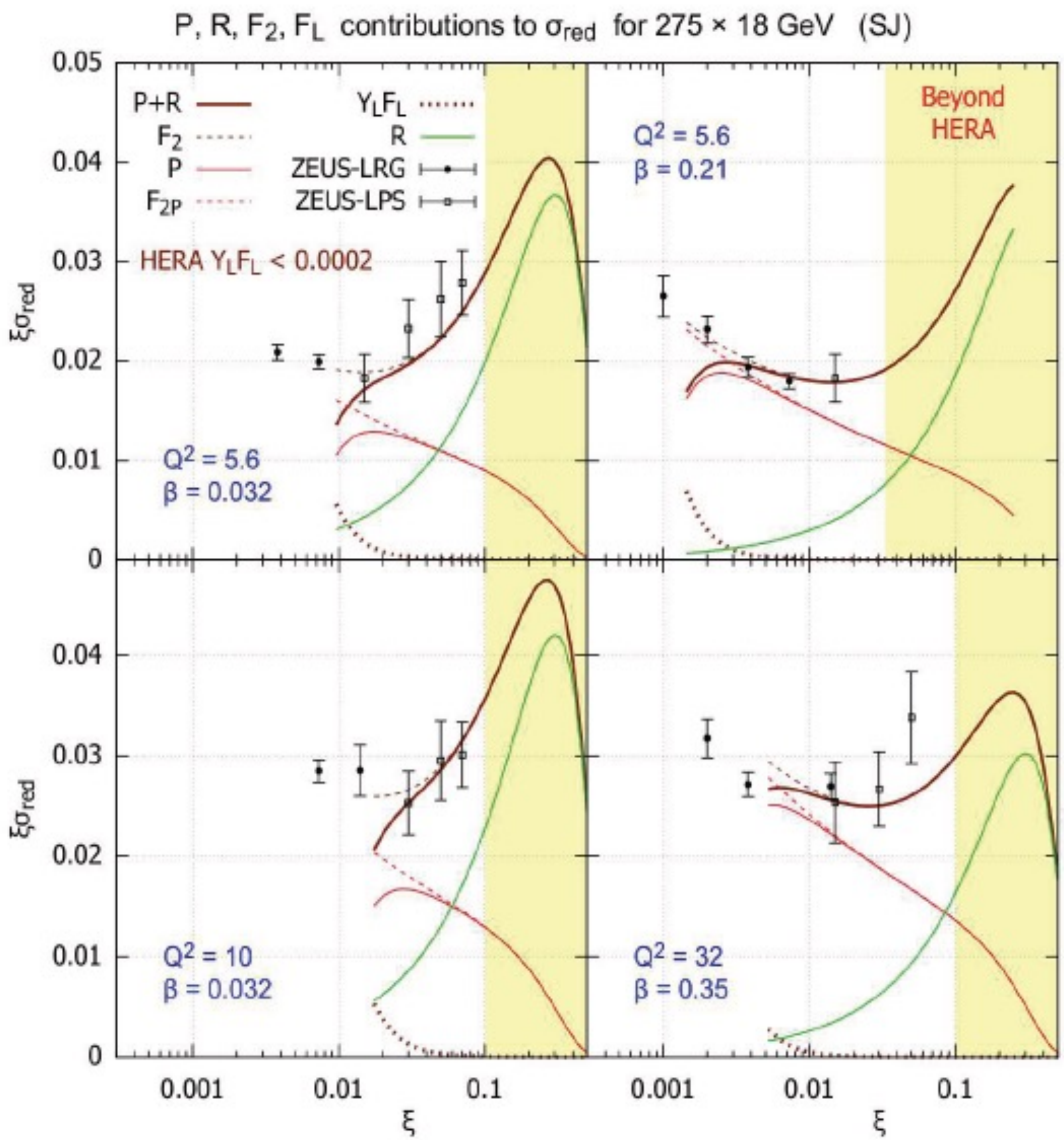
… longitudinal photon exchanges (F_L^D) dominate

… perturbative 2 gluon exchange processes (e.g. exclusive dijet production) should be present [barely touched at HERA]



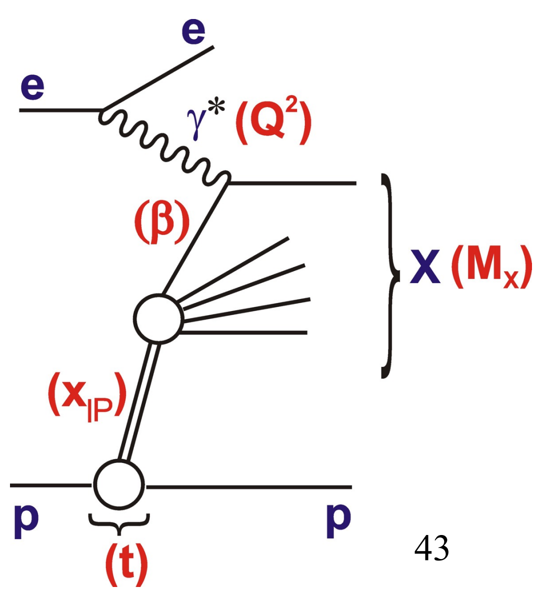


Inclusive Diffraction in ep at EIC: Sensitivity to sub-leading (non-pomeron) exchange



→ Access to previously unexplored high ξ phase space

→ Opportunity to understand sub-leading Reggeon (meson) exchanges and measure their structure



Inclusive Diffraction in ep at EIC: Sensitivity to diffractive longitudinal structure function

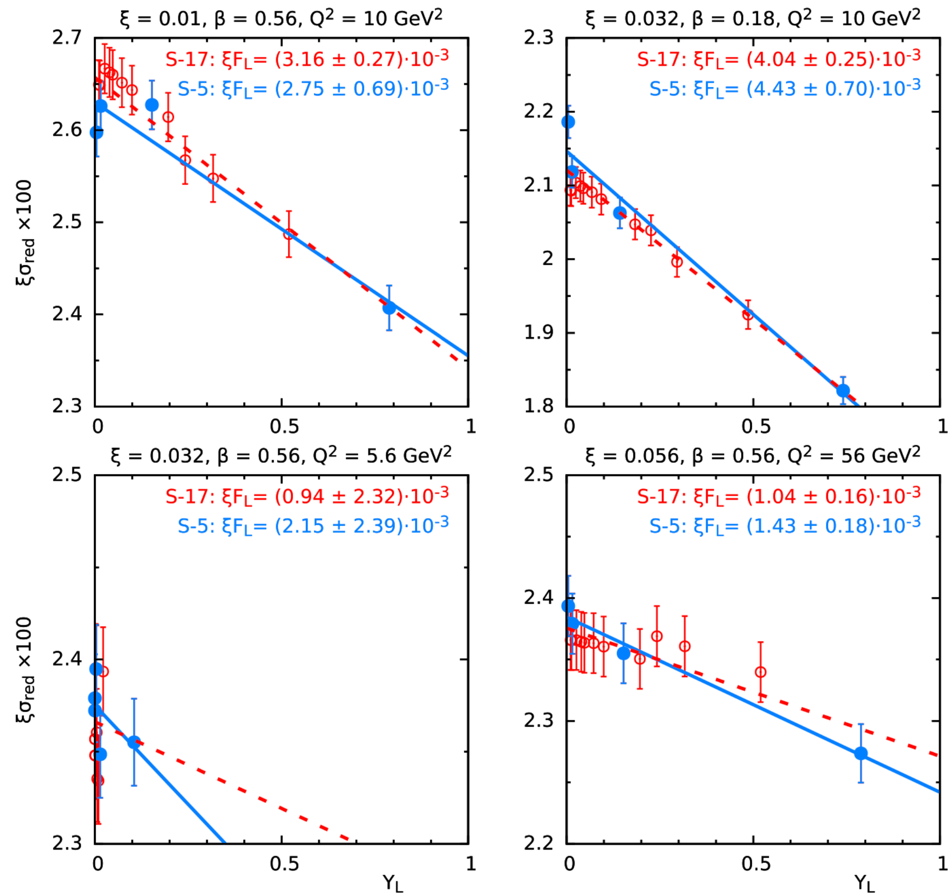
- Longitudinal structure function is proportional to gluon density at lowest order.

- Measurement at same (ξ,t,β,Q^2) and varying $\sqrt{s}$ (hence y) gives sensitivity to F_L^D (Rosenbluth plots)

$$\sigma_{\rm red}^D = F_2^D - \frac{y^2}{1+(1-y)^2} F_L^D$$

Y_L

- Precision strongly dependent on correlations between systematics at different $\sqrt{s}$

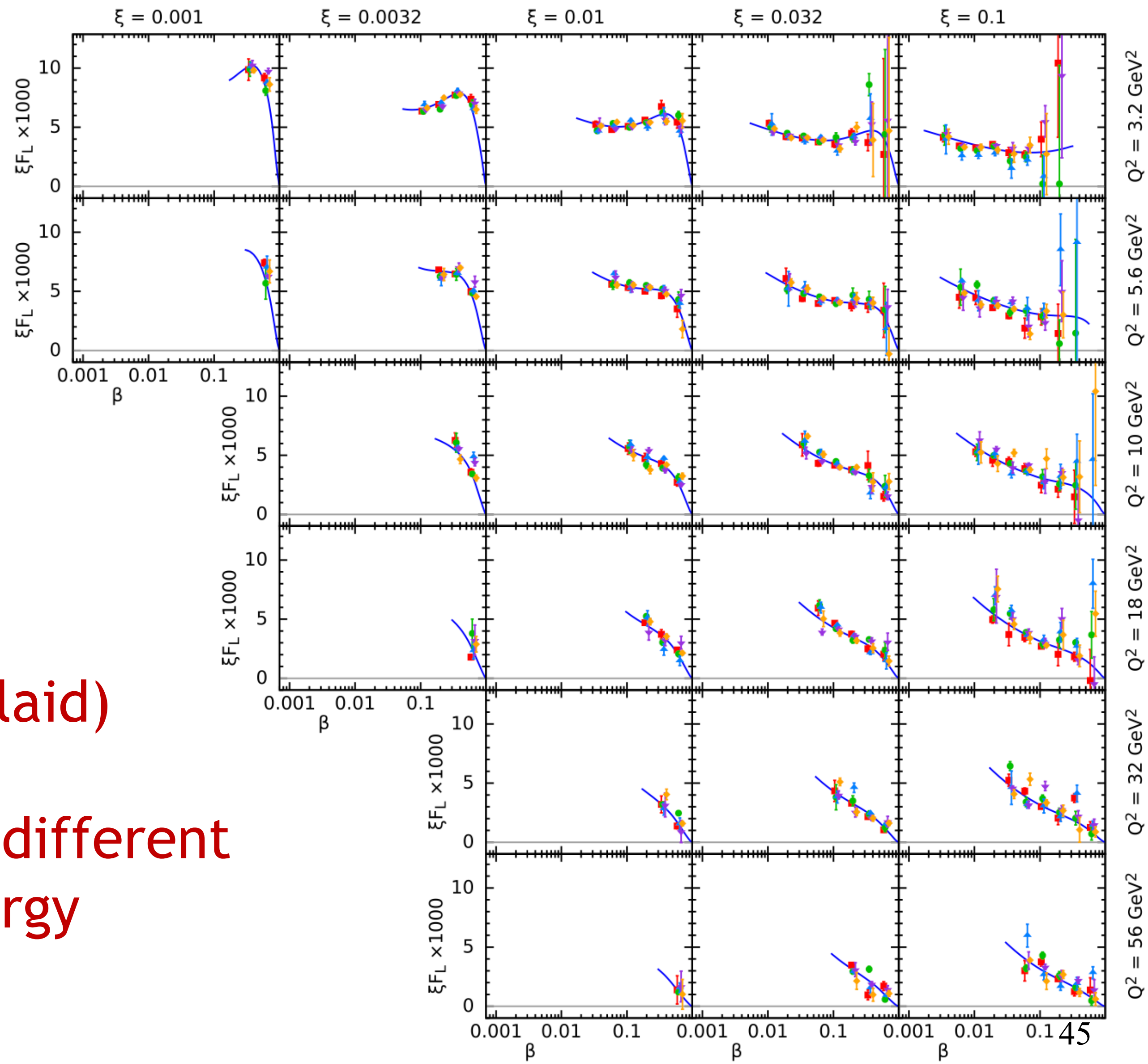


[Rosenbluth plots with 5 or 17 beam energy Combinations]

Simulations of EIC measurements of F_L^D

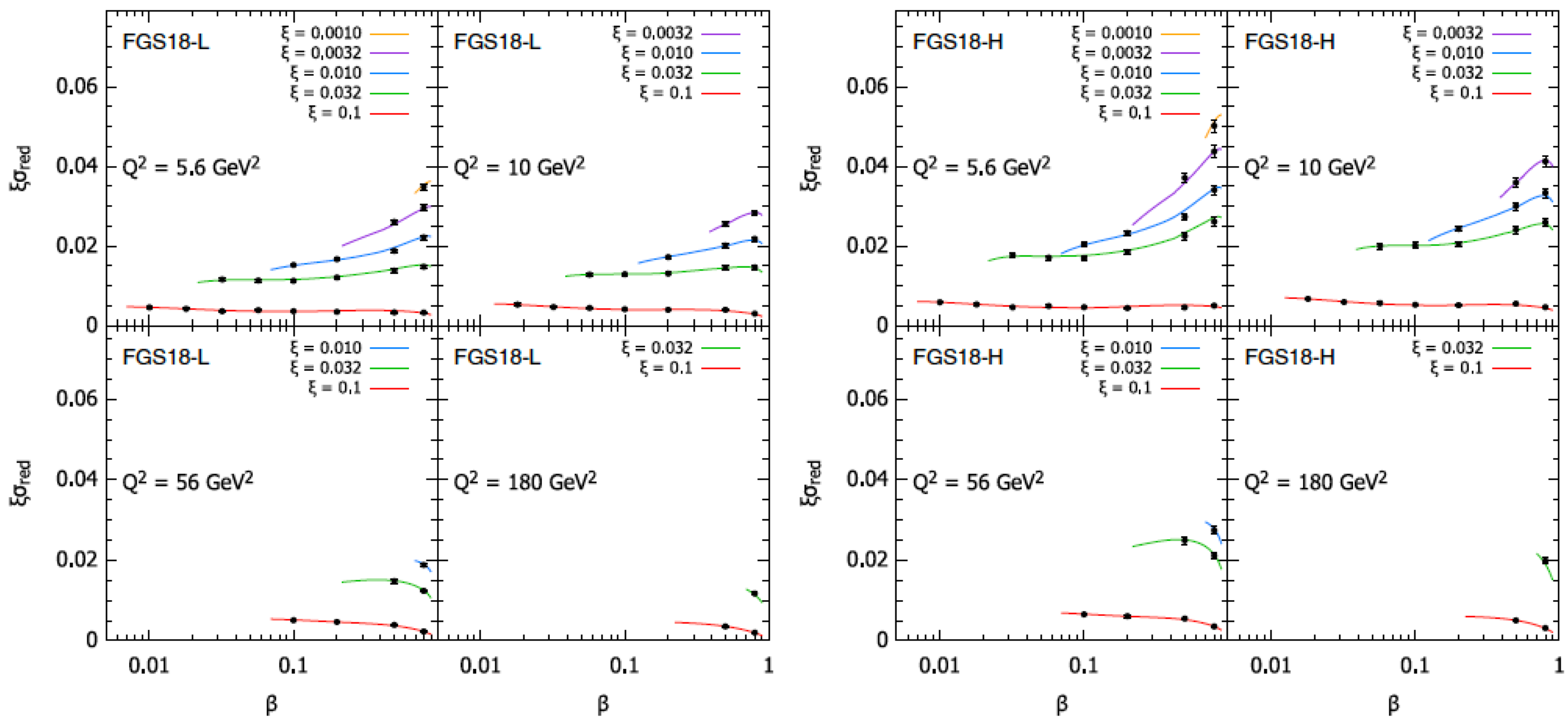
- Assuming 1% uncorrelated systematic uncertainties and 17 beam energy combinations (5 different Simulations overlaid)

- Not drastically different with 5 beam energy combinations



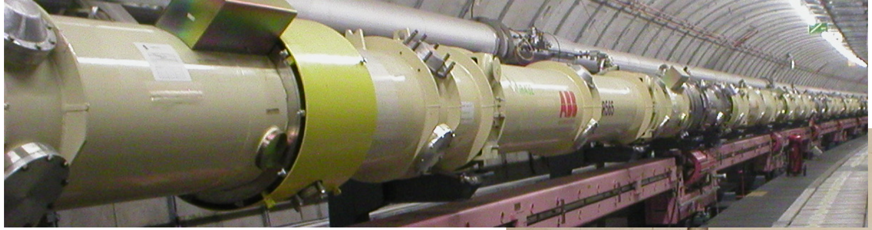
Inclusive Diffraction from Nuclei at EIC: Selected Simulated Data for e Au → e X Au

- Inclusive diffraction from nuclei never previously studied
- Comparing eA / ep may reveal non-linear (satur'n) dynamics



Simulations based on different versions of FGS model →
- illustrates accessible kinematic range and ability to distinguish between (widely varying) models

Final Words



Researching this talk was fascinating, but required weeks rather than hours!

EIC physics programme remains a fast developing topic

Exciting times ahead as we refine it and prepare for data

We should not be constrained by the past!

For hadronic final states (and elsewhere), HERA can be a helpful guide

Thanks to the Organisers!