Low x Inclusive and Diffractive DIS: From HERA to Future Facilities

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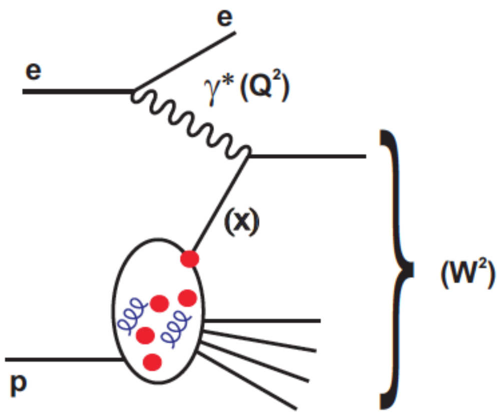
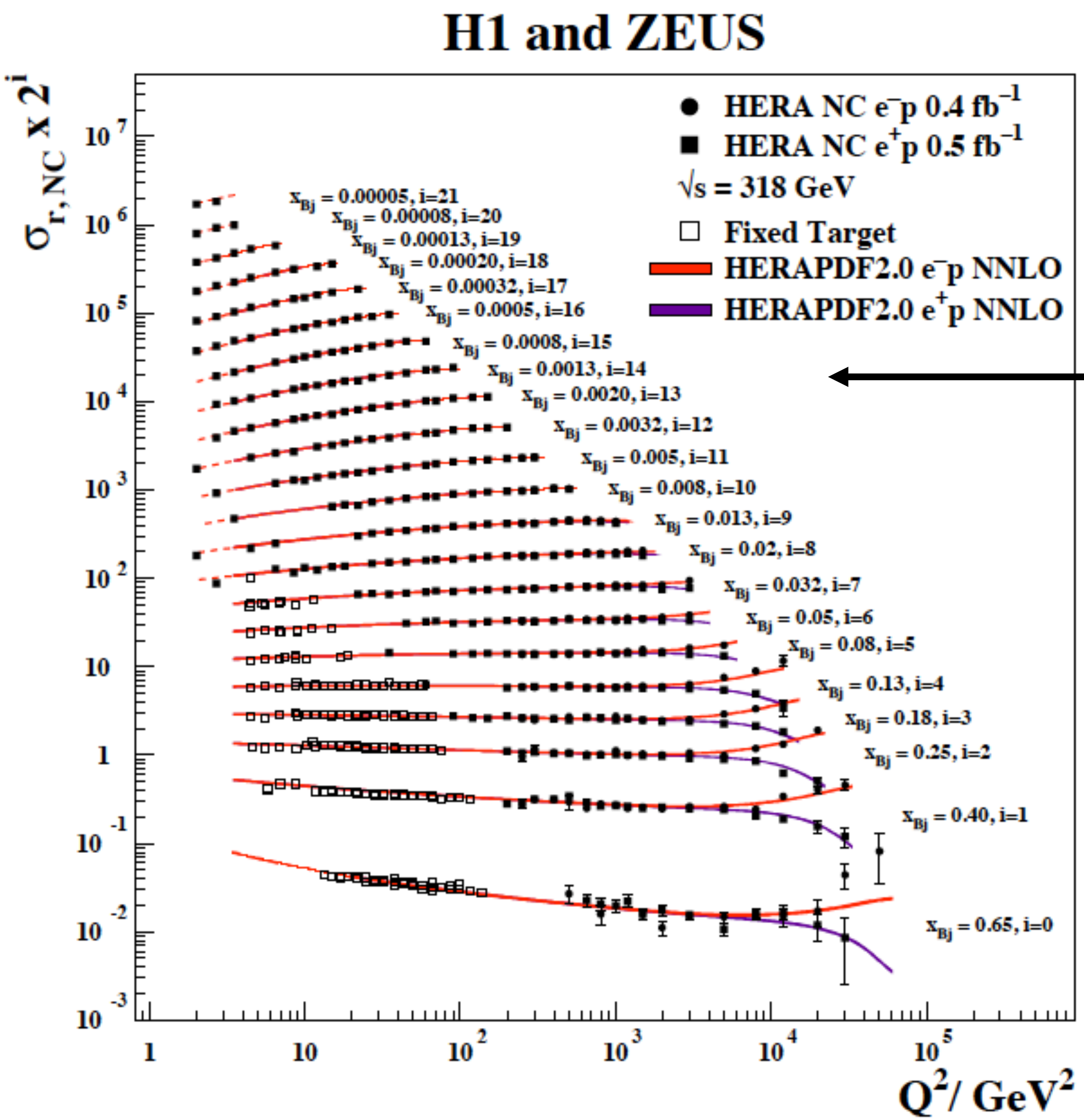


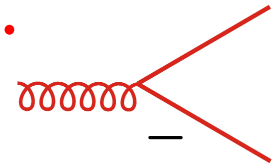
See also plenaries by Raju, Eugenio & Tuomas

Where knowledge of Low x Gluon Comes From

… entirely from inclusive Neutral Current HERA data …



- NC Q^2 dependence in perturbative region driven by …

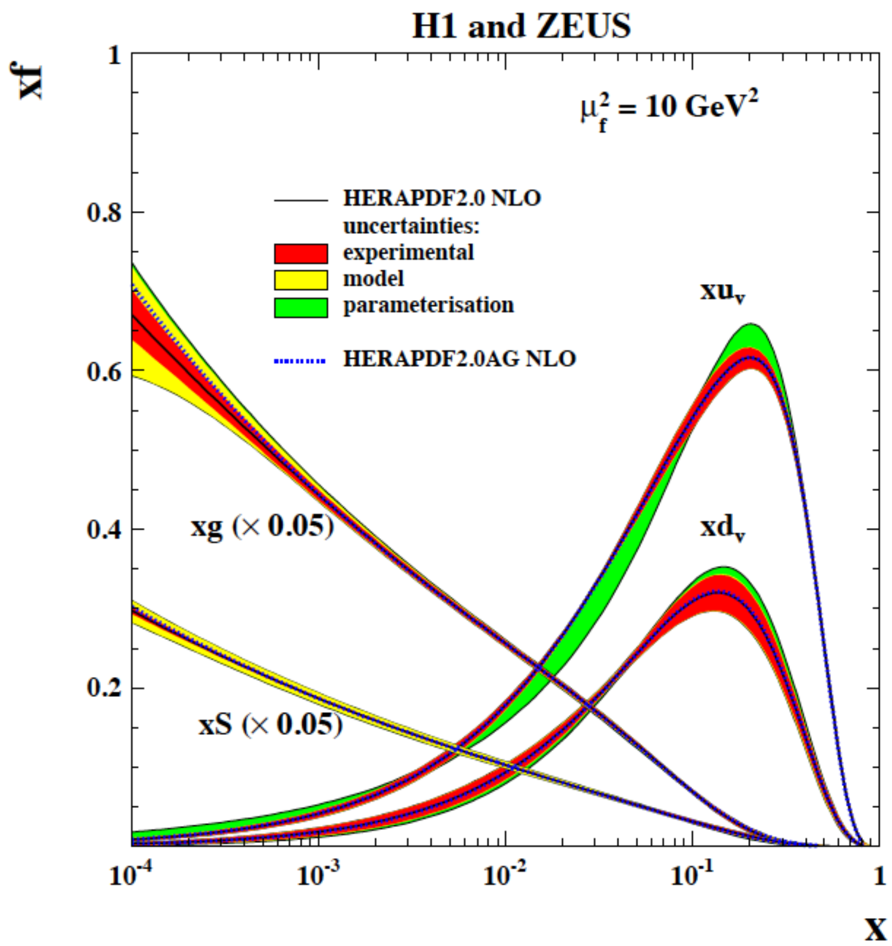


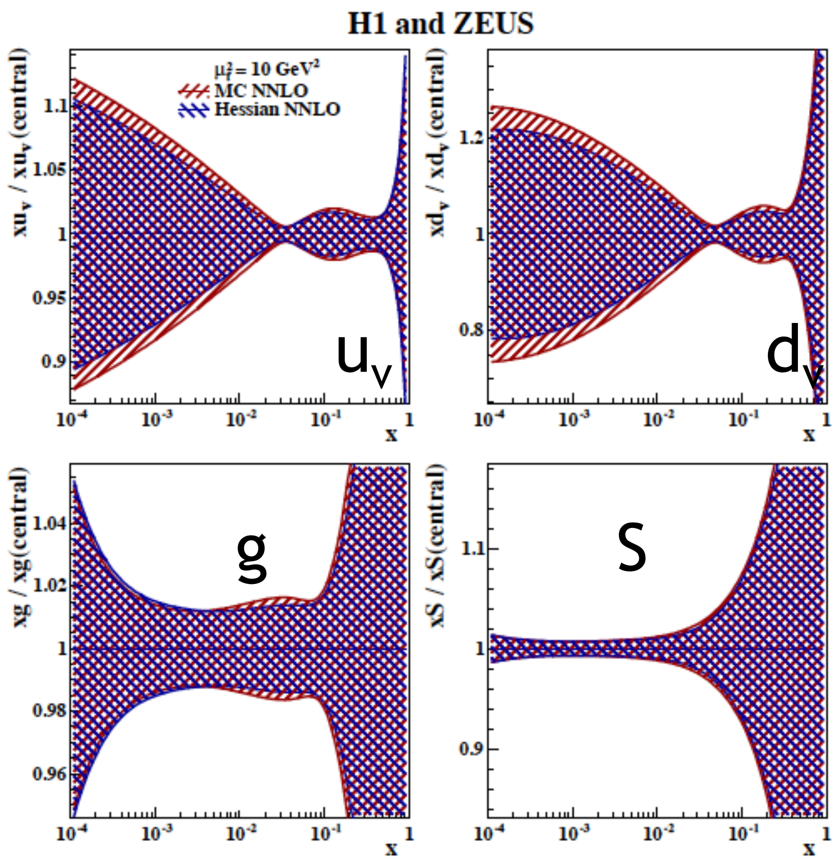
$g \to q\bar{q}$

- e.g. Prytz approx: $\frac{dF_2(x,Q^2)}{d\ln Q^2} \sim G(2x)$

- Gluon from scaling violations needs lever-arm in Q^2 … reasonable precision at HERA only to $x \sim 10^{-3}$ / 10^{-4}.

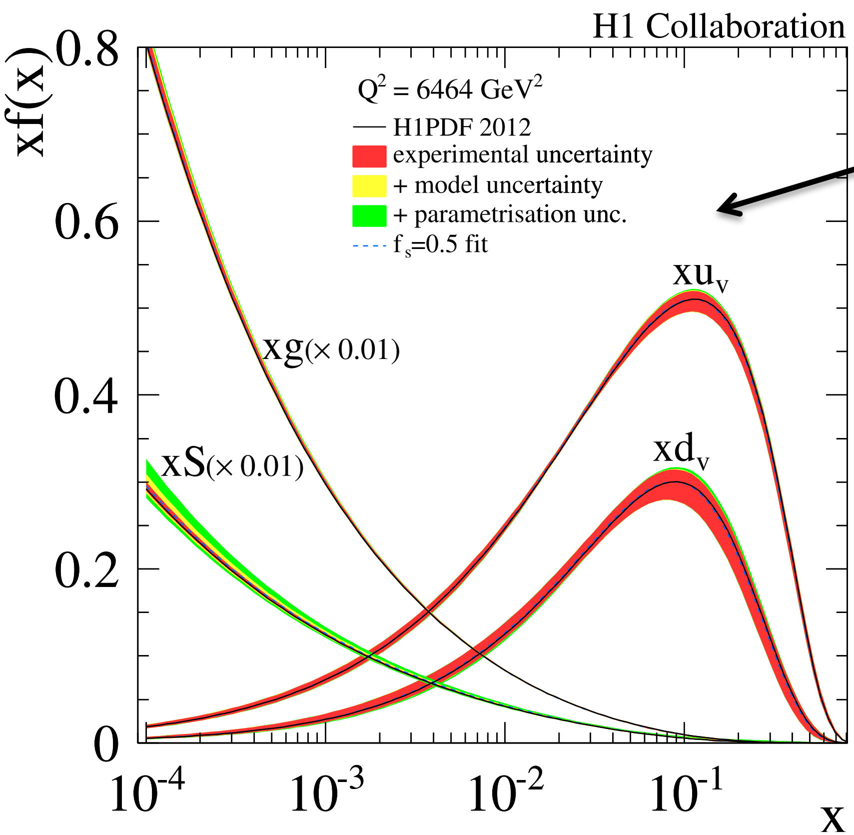
Final HERA Picture of Proton (HERAPDF2.0)





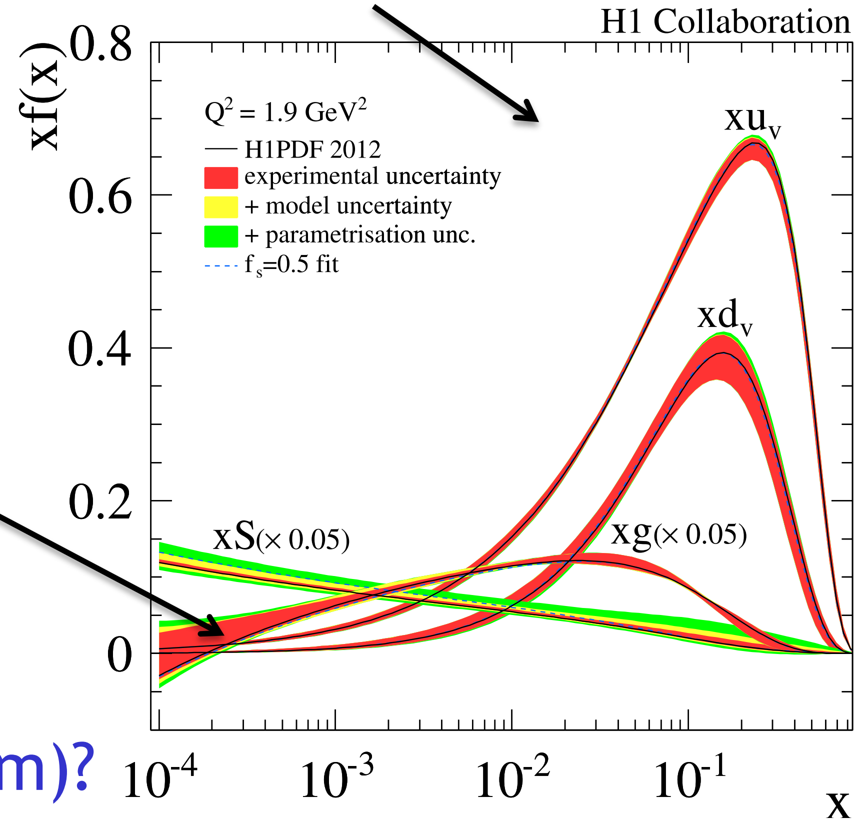
- ~2% precision on gluon over a wide range of x
- Uncertainty explodes towards $x=10^{-4}$
- Gluon itself is rising in a non-sustainable way …
- Note the 'Standard' presentation is at $Q^2 = 10$ GeV^2

The Gluon Density at Other Scales



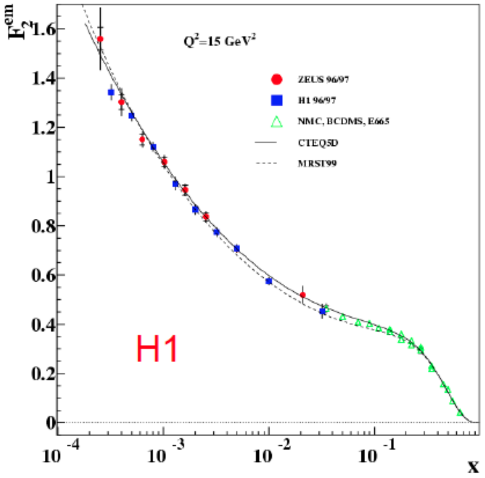
- Electroweak scale ~ M_Z^2 (as relevant to precision LHC physics) … gluon rise gets sharper …

- Starting scale ~ 1.9 GeV^2 (as relevant to future sat'n studies

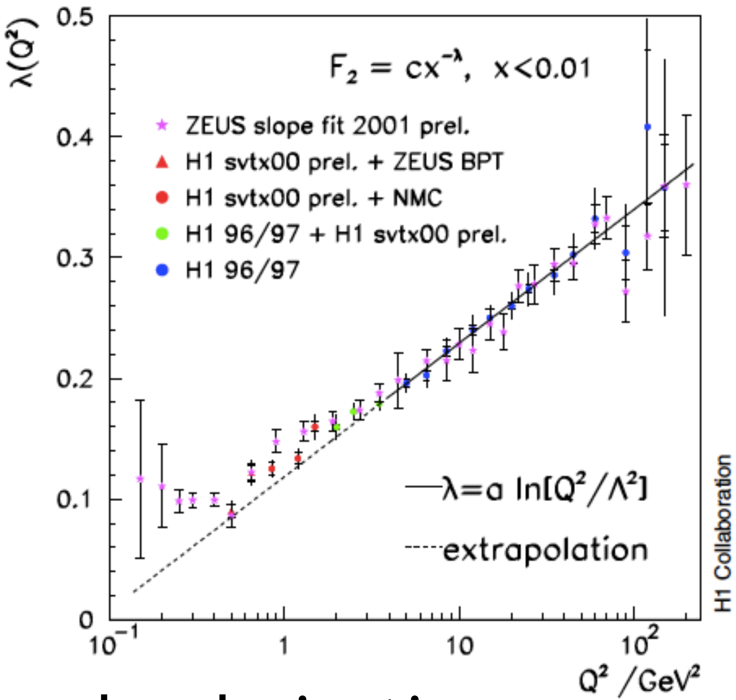


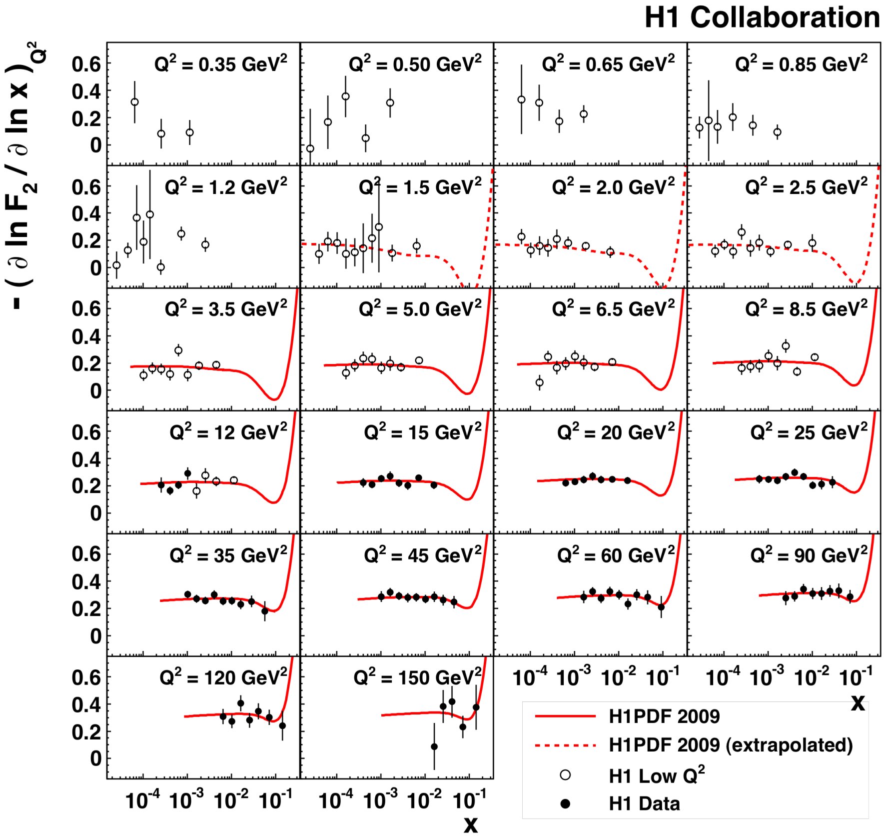
- Gluon close to zero in pure DGLAP approach (and coupling not so weak).
  - Saturating hadrons with a small number of ("large") gluons?
  - Alternative language (dipole models, gluons not degrees of freedom)?

Looking for Saturation in the HERA Data



HERA-I inclusive data well described by $F_2 = Ax^{-\lambda(Q2)}$ with fixed A~0.2 for all Q^2 >~ 1 GeV^2





From 2D local x-derivatives:

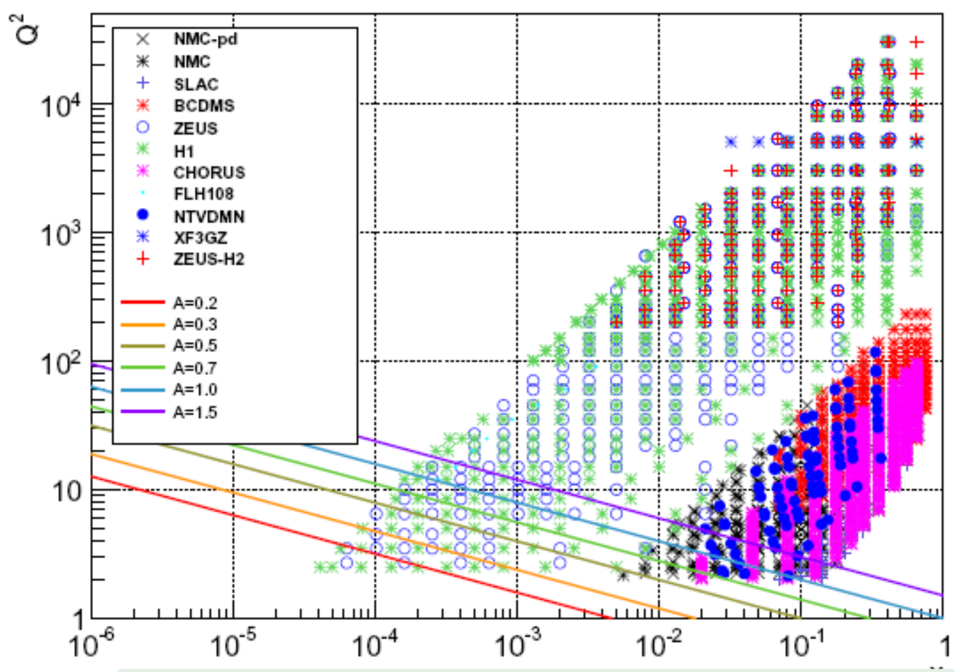
no evidence here for deviation from monatonic rise of structure functions towards low x in perturbative region.

… but this does not include:

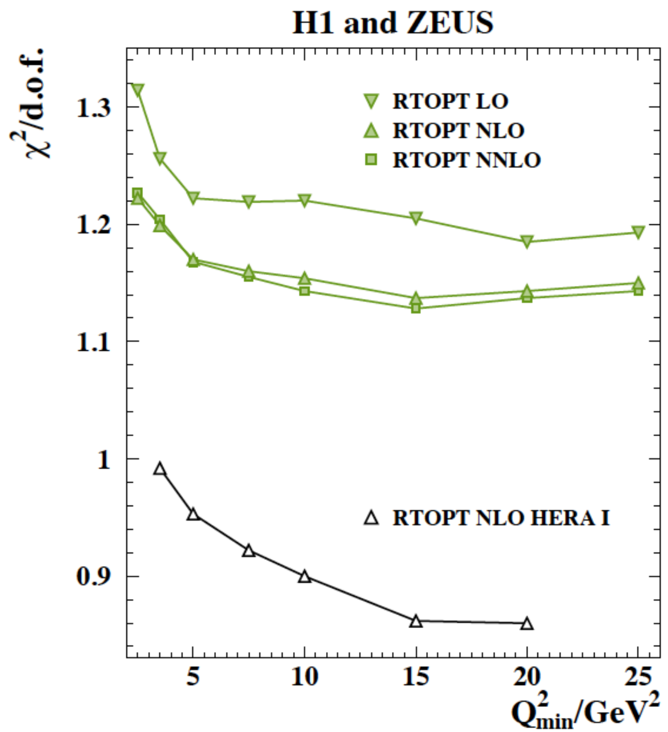
- More precise HERA-II data
- Very low Q^2 data

Different Approaches and improved data in Perturbative region

e.g. NNPDF: NLO DGLAP description deteriorates when adding data in lines $Q^2 > Ax^{-0.3}$ parallel to 'saturation' curve in x/Q^2.



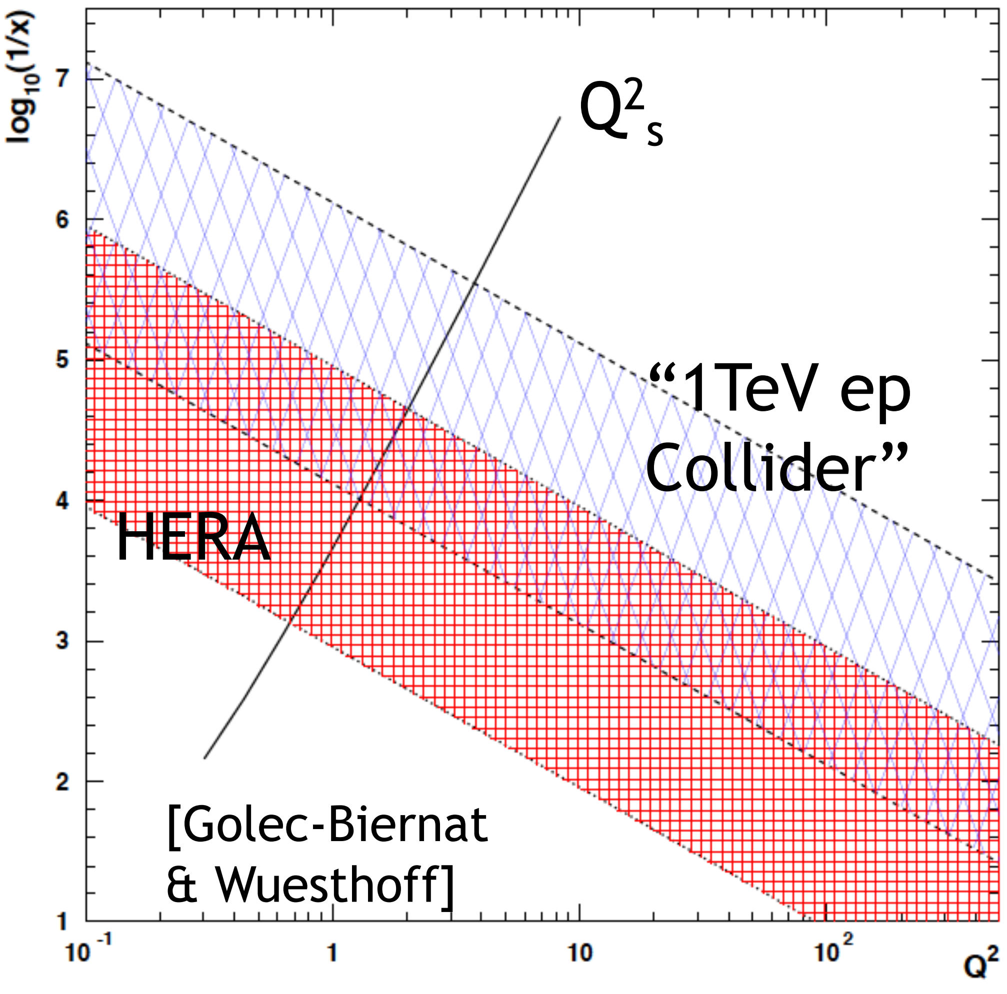
A	$\chi^2_{\text{without cuts}}/d.o.f.$	$\chi^2_{\text{cut}}/d.o.f$
0.5	$19.68/25 = 0.79$	$106.22/25 = 4.25$
1.0	$54.41/44 = 1.24$	$138.24/44 = 3.14$
1.5	$62.31/59 = 1.06$	$860.65/59 = 14.6$

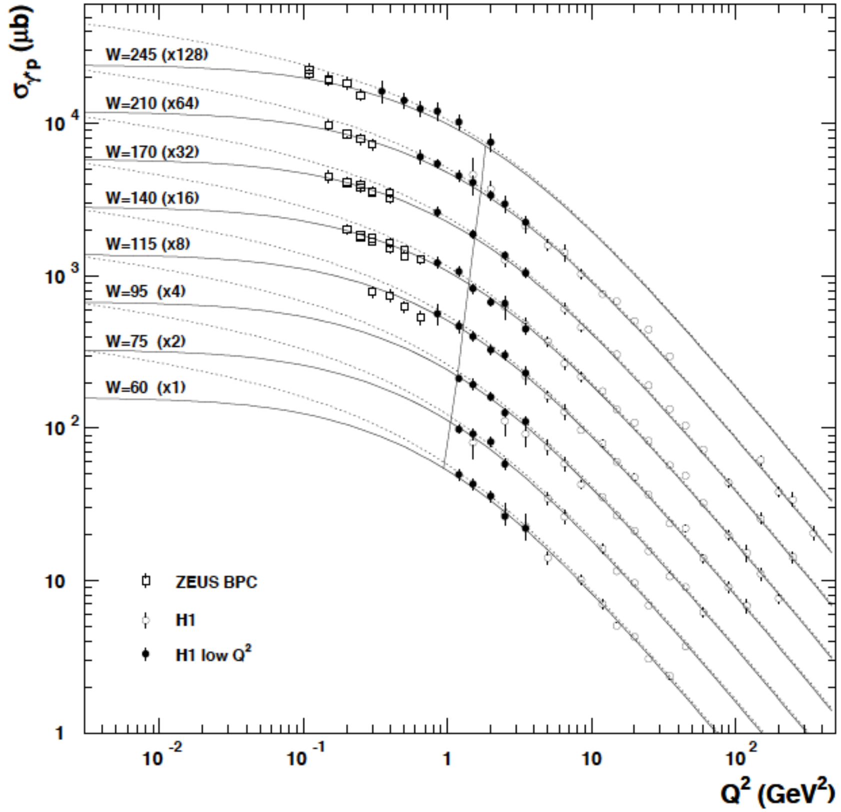


Final HERA-2 Combined PDF Paper:
"some tension in fit between low & medium Q^2 data… not attributable to particular x region" (though kinematic correlation)

… something happens … interpretation?

Introducing Q^2 < 1 GeV^2 data … and a Dipole Model with Saturation



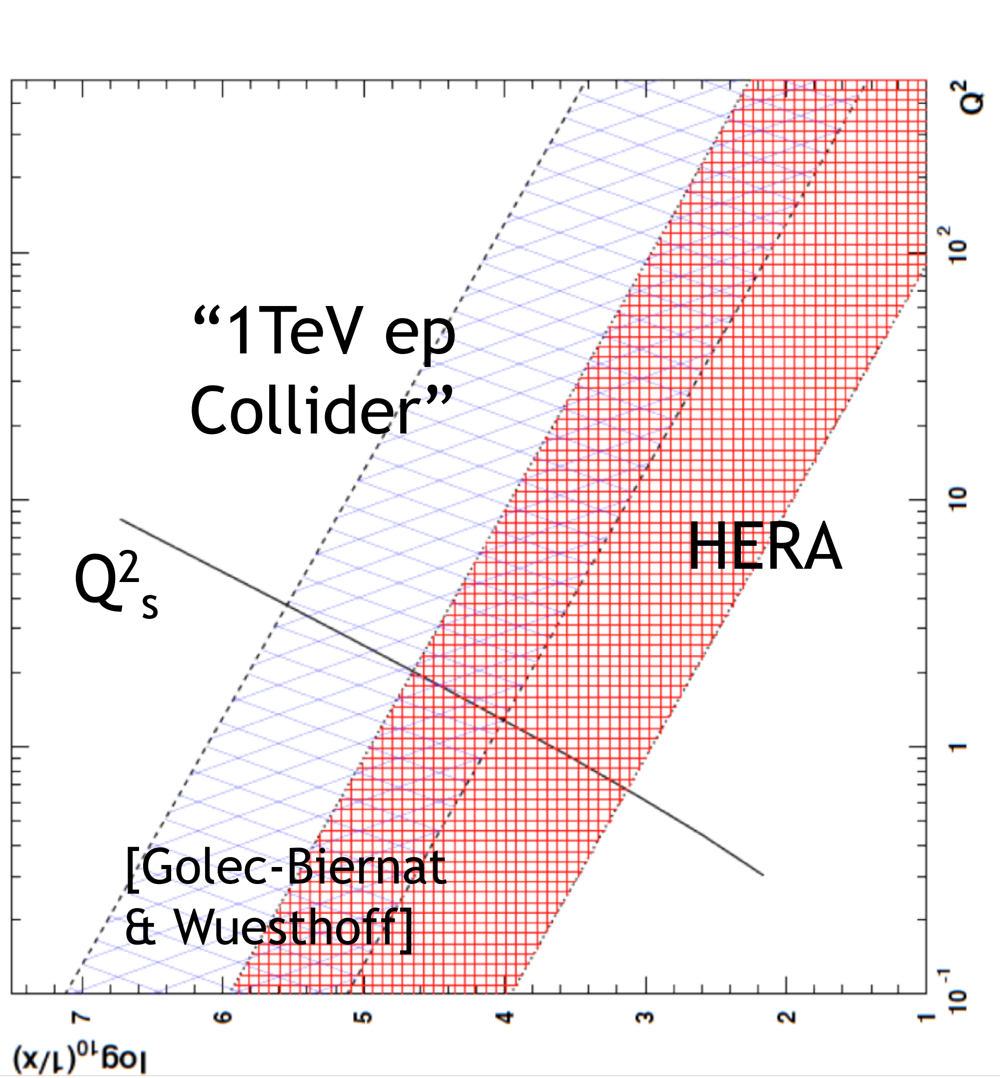


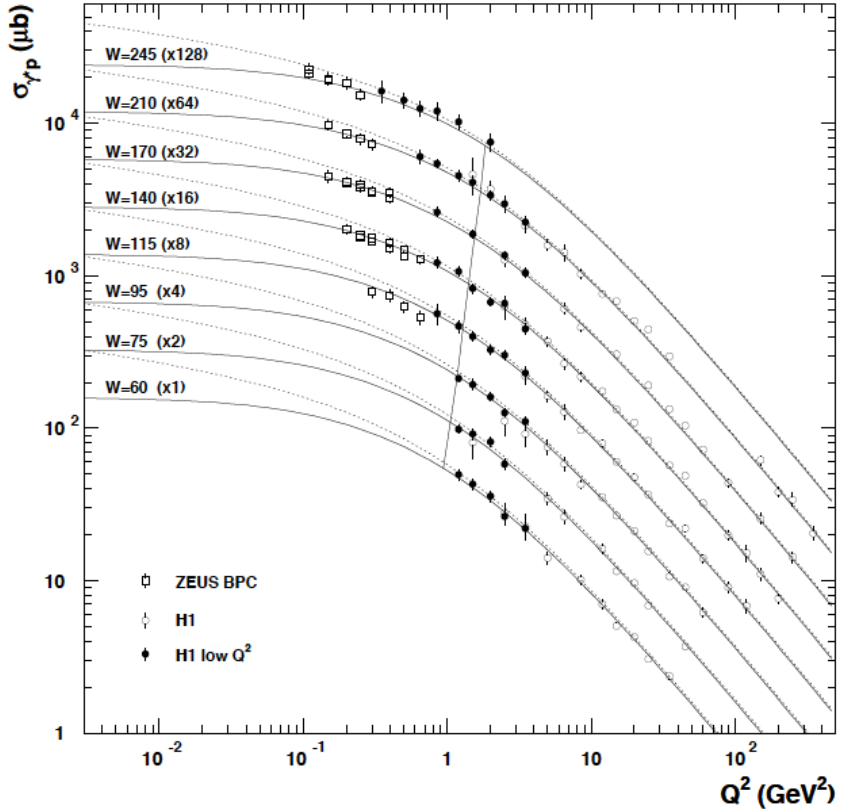
All data (Q^2 >~ 0.05 GeV^2) are well fitted in (dipole) models that include saturation effects

- x dependent "saturation scale", $Q^2_s(x)$

$$\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{\sim -0.3}$$

Introducing $Q^2 < 1$ GeV^2 data … and a Dipole Model with Saturation



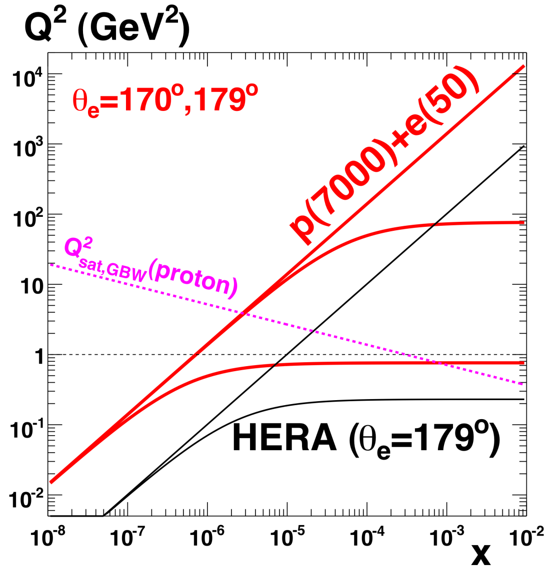


… at HERA, Q^2_s doesn't get above about 0.5 GeV^2

→Saturation may have been observed at HERA … well described by CGC+dipoles

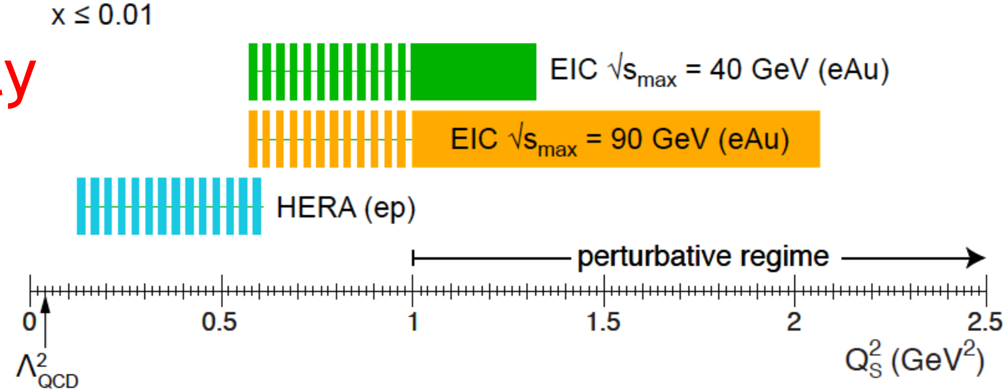
→***Gluon*** sat^n not observed? (and may not be in inclusive ep in foreseeable future)

How to Access Saturation at Future Lepton-Hadron Facilities



1) Increase √s - Probing lower x at fixed Q^2 in ep [clean evolution of single source → LHeC gets Q^2_s ~ few GeV^2]

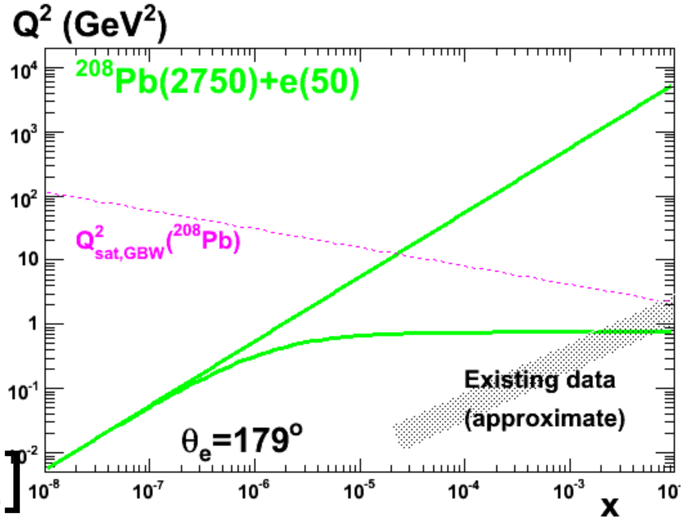
2) Use nuclear target - Overlap many sources to enhance density ~ $A^{1/3}$ ~ 6 for Au … [EIC gets to Q^2_s ~ 2 GeV^2, challenge is to disentangle nuclear effects]



3) Non-inclusive observables (diffraction)

At least two of these at once is needed for a convincing picture … →

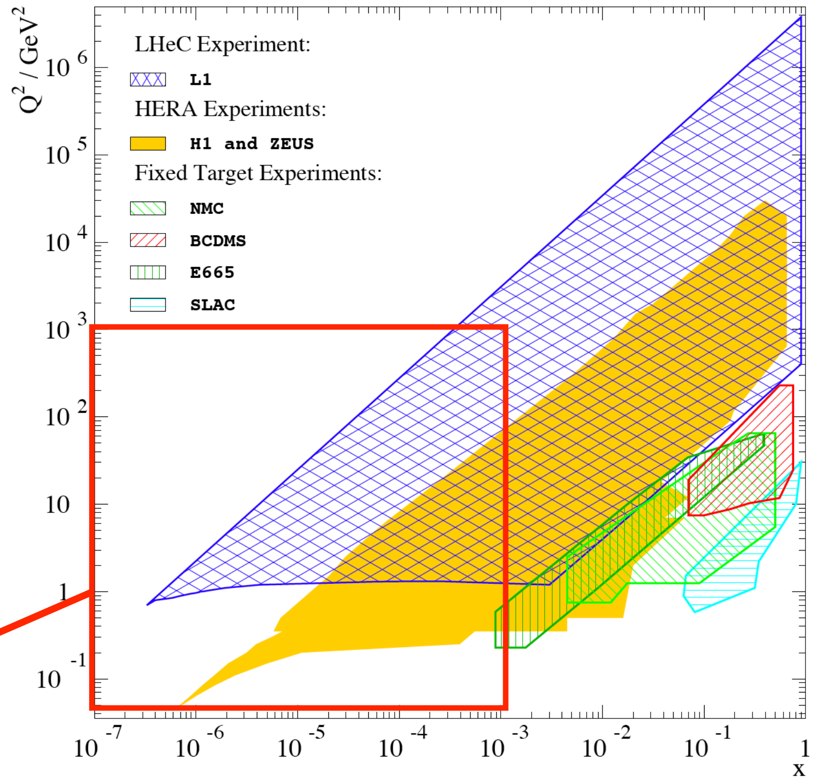
4) Go to LHC [Lacks detailed understanding]

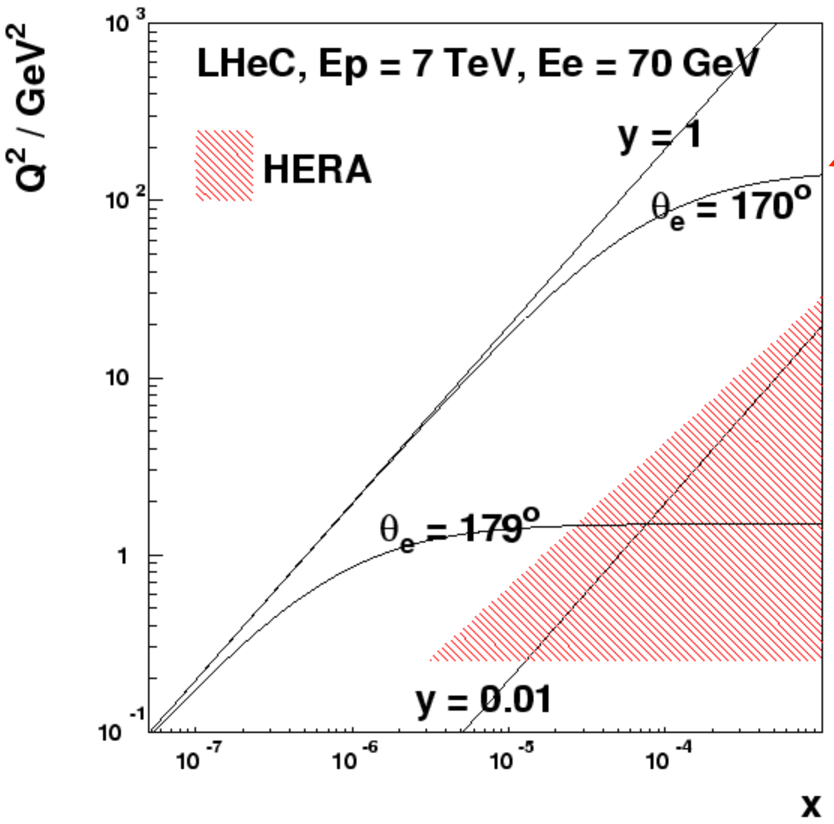


Maximal Detector Acceptance is Vital

eg from LHeC …

Access to Q^2=1 GeV^2 in ep mode for all x > 5 x 10^{-7} requires scattered electron acceptance to 179°



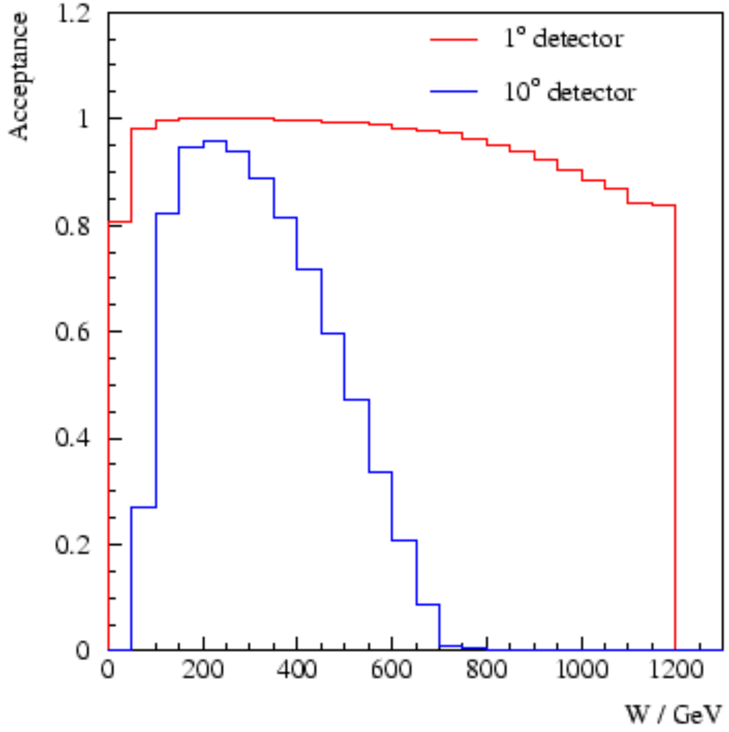


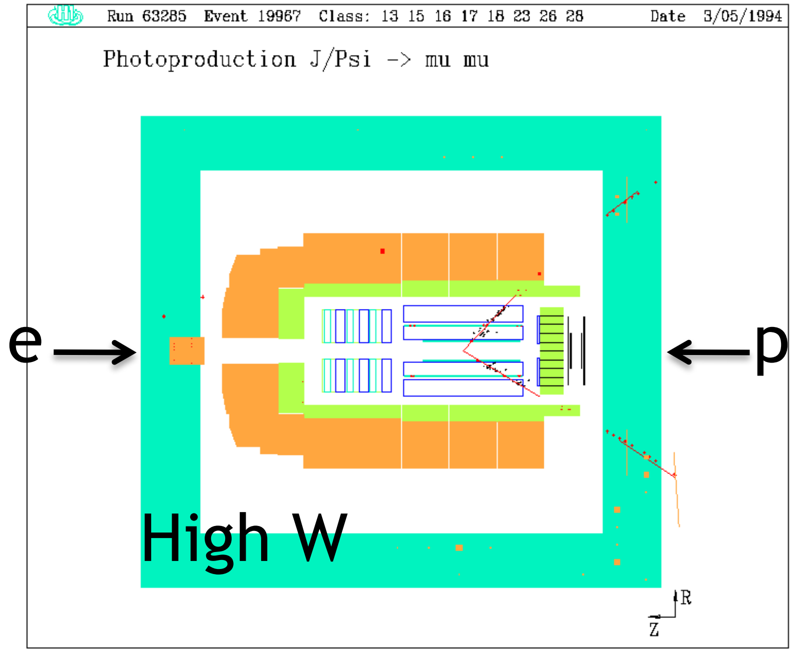
Also need 1° acceptance in proton direction to contain hadrons for kinematic reconstruction, Mueller-Navelet jets, maximise acceptance for new massive particles …

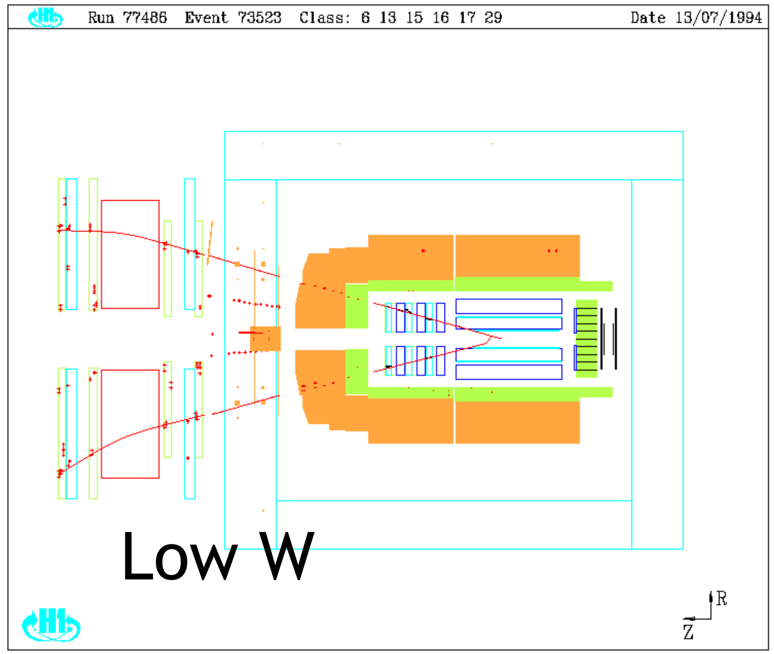
Elastic J/Ψ Kinematics (example from LHeC)

- At fixed $\sqrt{s}$, decay muon direction is determined by $W = \sqrt{s_{\gamma p}}$

- To access highest W, acceptance in outgoing electron beam direction crucial



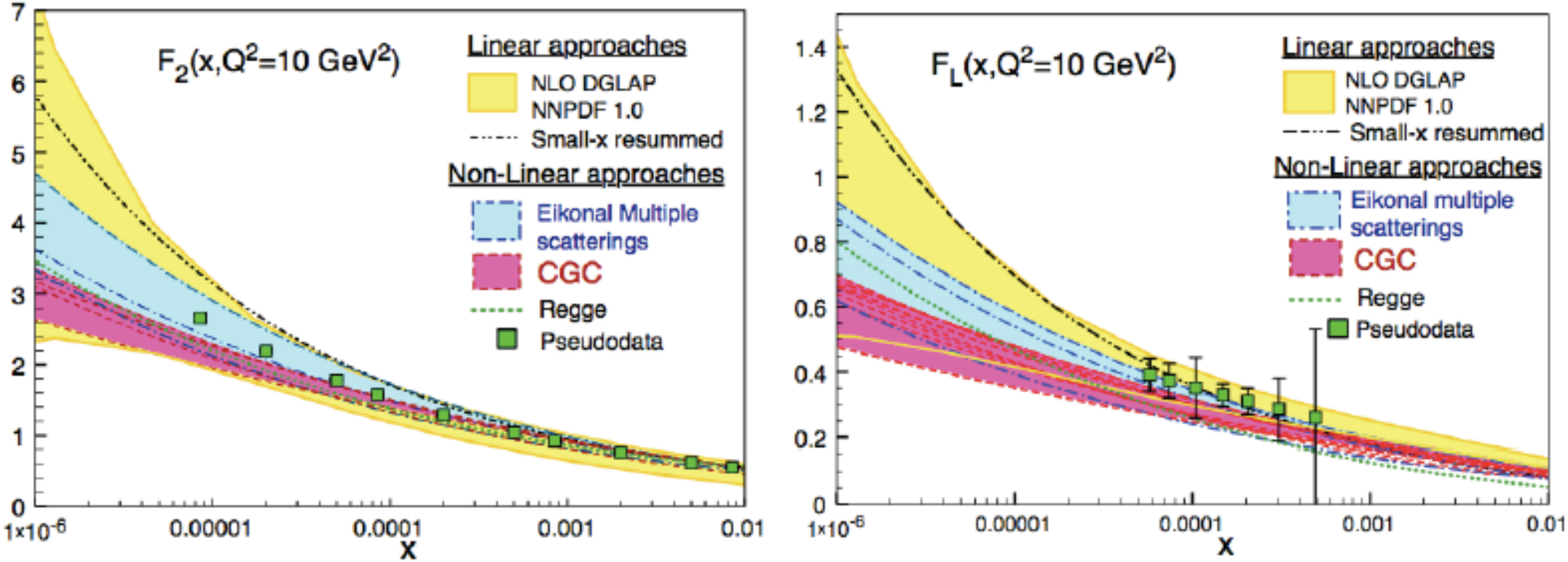




Inclusive DIS in ep at LHeC ep and Saturation

With 1 fb^{-1} (1 month at 10^{33} cm^{-2} s^{-1}), F_2 stat. < 0.1%, syst, 1-3%
F_L measurement to 8% with 1 year of varying E_e or E_p

F_2 and F_L pseudodata at Q^2 = 10 GeV^2



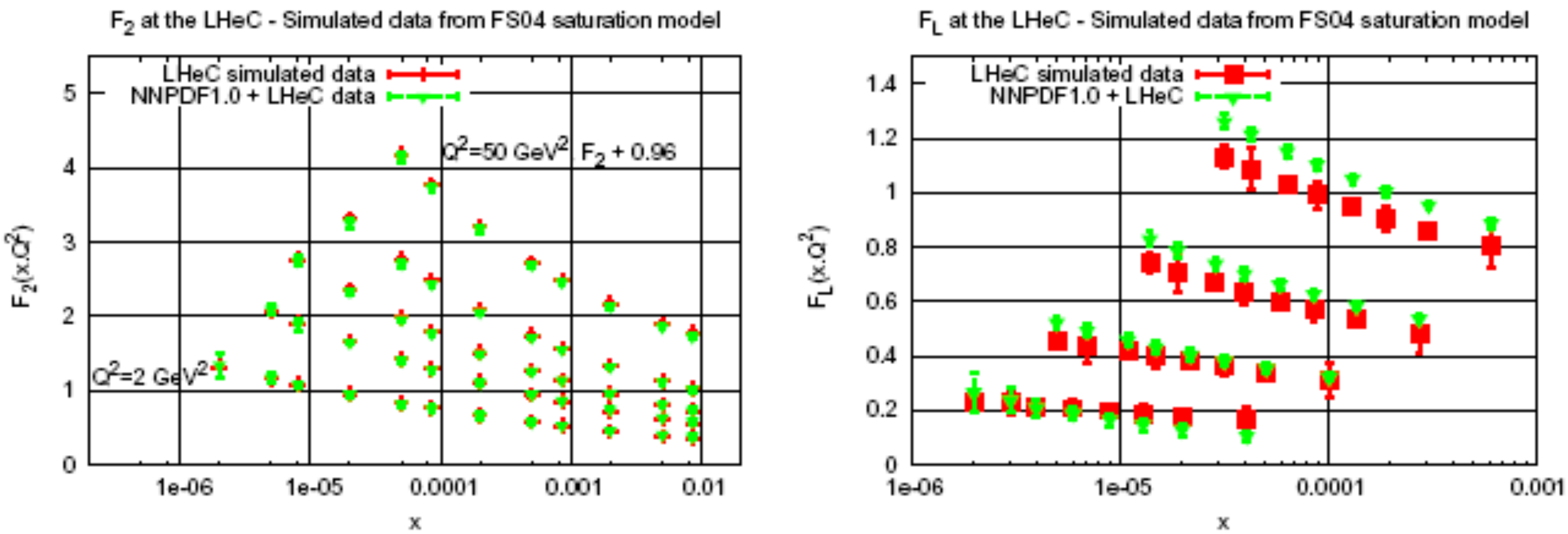
- LHeC can distinguish between different QCD-based models for the onset of non-linear dynamics

… but can sat^n effects hide in standard fit parameterisations?

Can Saturation be Established in ep @ LHeC?

Simulated LHeC F_2 and F_L data based on an (old) dipole model containing low x saturation (FS04-sat)… Try to fit in NLO DGLAP

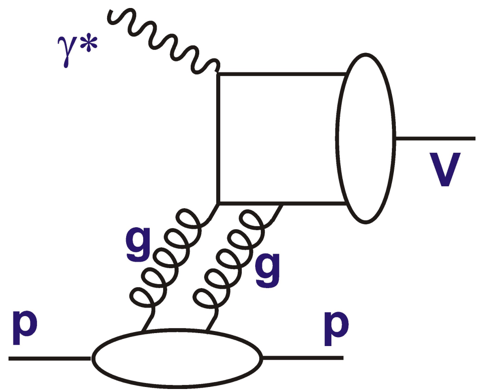
… NNPDF (also HERA framework) DGLAP QCD fits work OK if only F_2 is fitted, but cannot accommodate saturation effects if F_2 and F_L both fitted



• Unambiguous observation of saturation will be based on tension between different observables e.g. F_2 v F_L in ep or F_2 in ep v eA

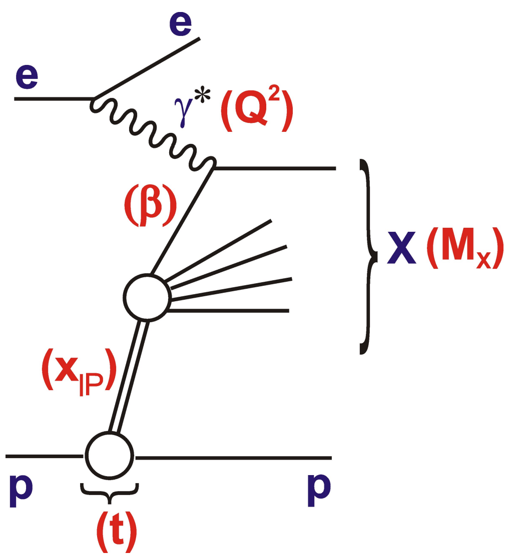
Exclusive / Diffractive Channels and Saturation

1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon (at least for exclusives)

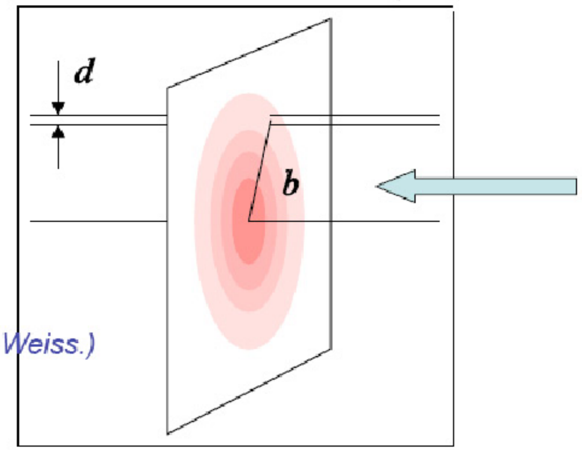


2) Additional variable t gives access to impact parameter (b) dependent amplitudes

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

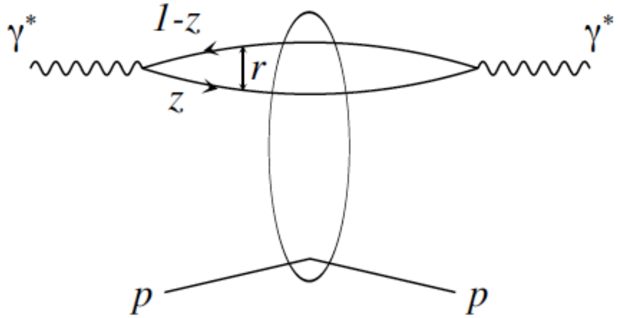


(figure from C. Weiss.)



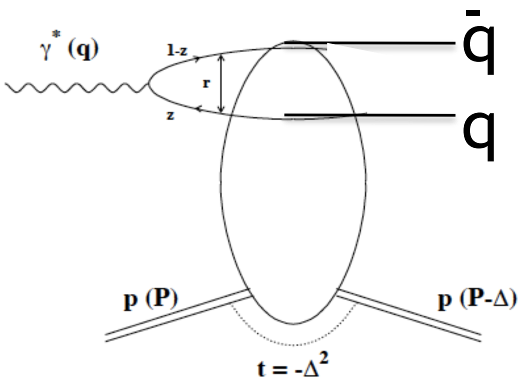
Central black region growing with decrease of x.

Advantage of Diffractive DIS: Dipole Language



Inclusive Cross Section

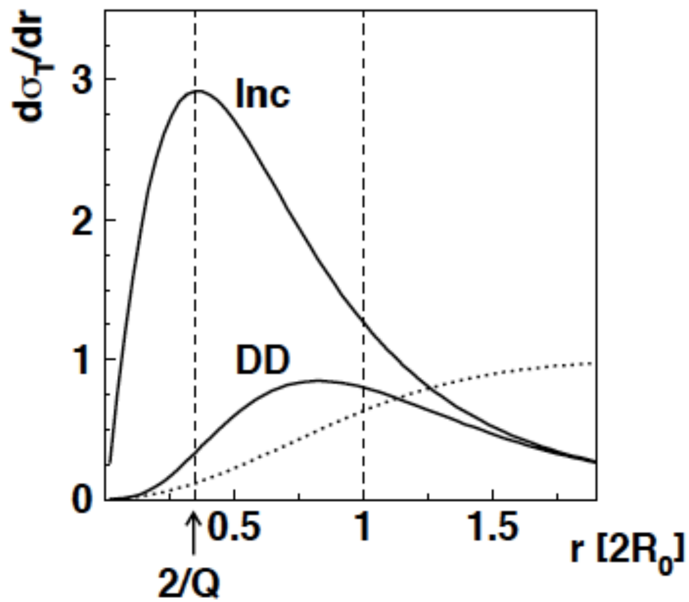
$$\sigma_{T,L}(x,Q^2) \;=\; \int d^2\mathbf{r} \int_0^1 d\alpha \,|\Psi_{T,L}(\alpha,\mathbf{r})|^2 \hat{\sigma}\,(x,r^2)$$



Diffractive DIS

$$\left.\frac{d\sigma^D_{T,L}}{dt}\right|_{t=0} \;=\; \frac{1}{16\pi} \int d^2\mathbf{r} \int_0^1 d\alpha \,|\Psi_{T,L}(\alpha,\mathbf{r})|^2 \hat{\sigma}^2\,(x,r^2)$$

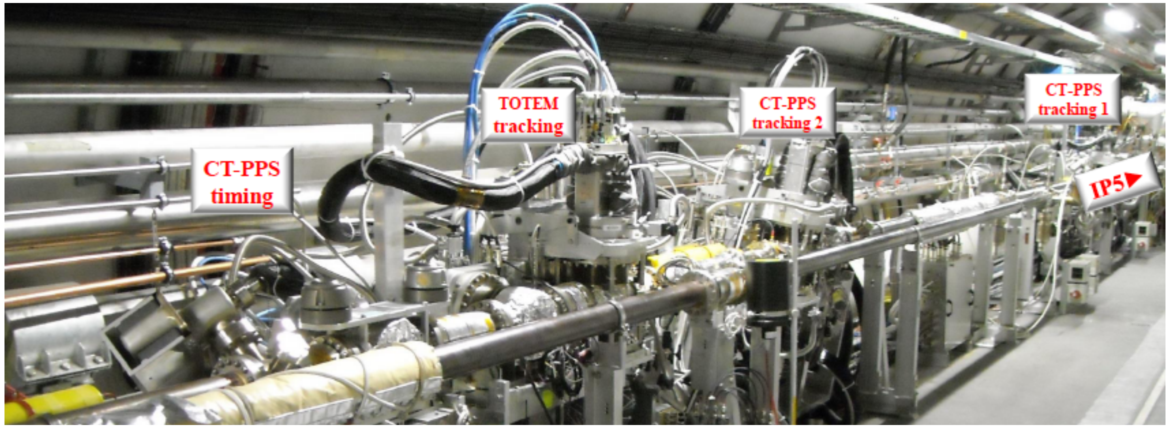
3) Extra factor of dipole cross section weights DDIS cross section towards larger dipole sizes → enhanced sensitivity to saturation effects.

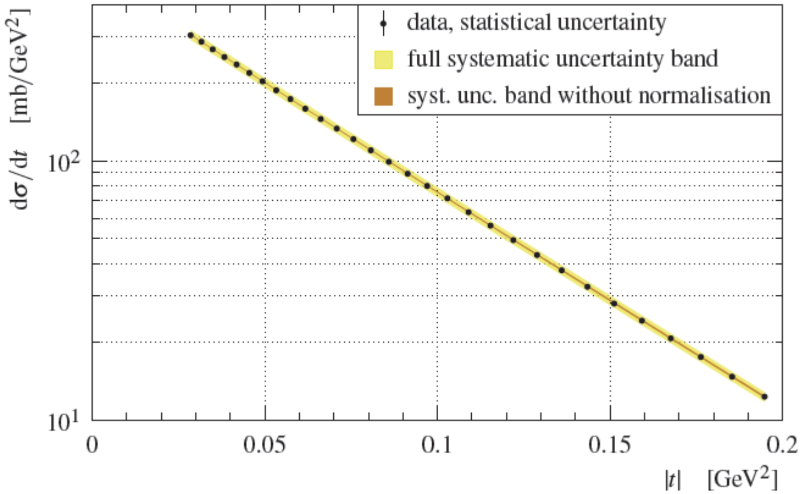


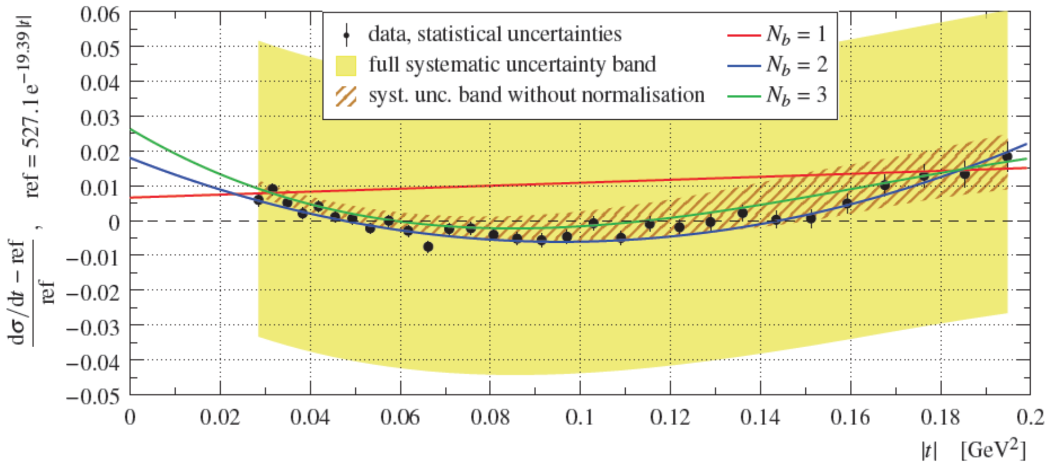
Proton Spectrometers Come of Age

LHC experiments (TOTEM, ALFA@ATLAS) have shown that it's possible to make precision measurements and cover wide kinematic range with Roman pots.

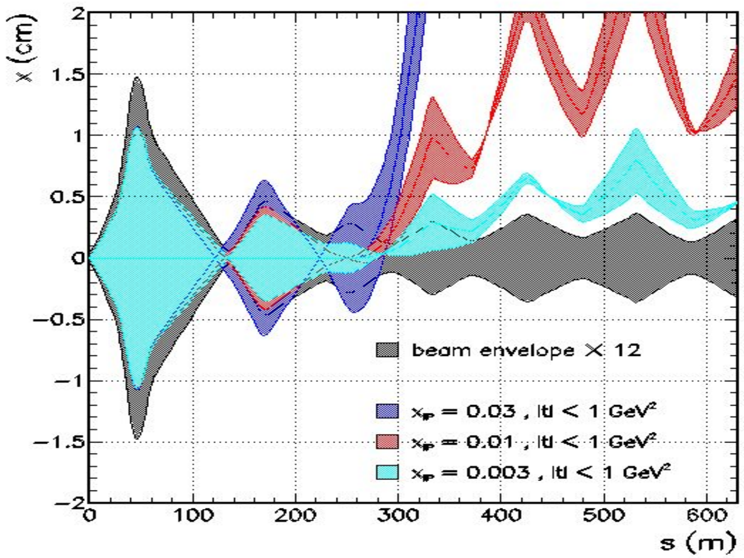
e.g. TOTEM operates 14(?) pots in 2017, with several at full LHC lumi (~50ps timing and precision tracking detectors) → Sensitivity to subtle new effects eg non-exponential term in elastic t dependence …





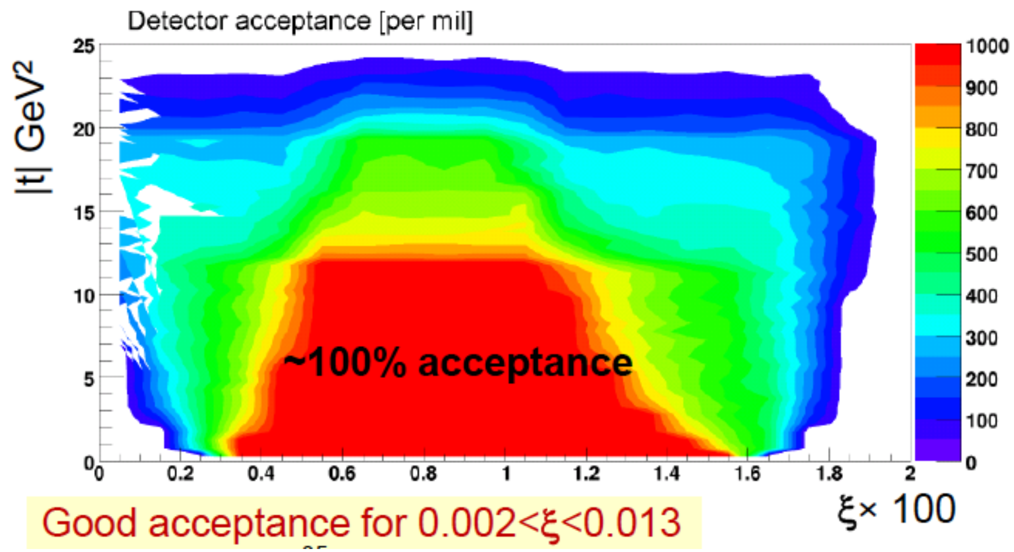


Future DIS Forward Proton Spectrometers



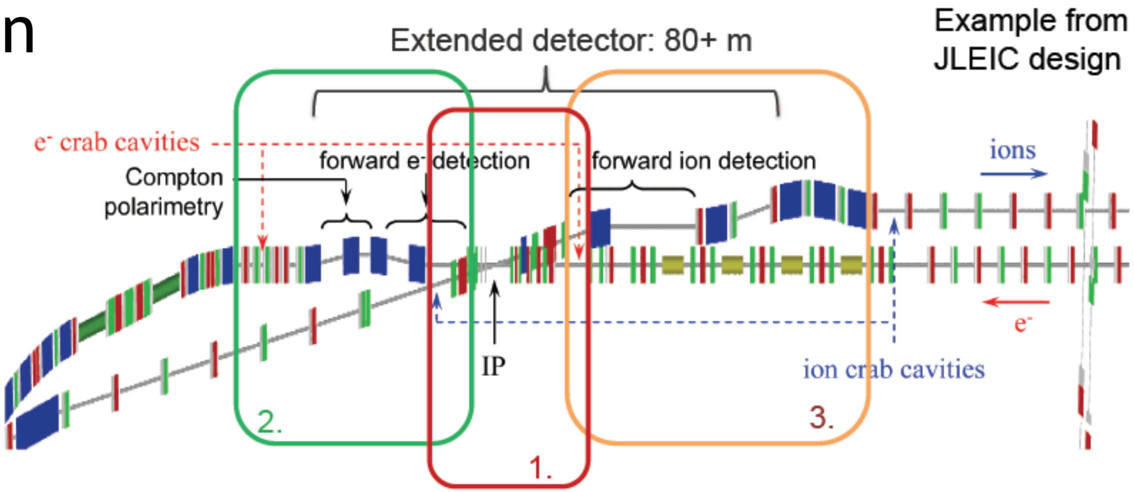
We should ensure full acceptance Roman pot forward detector systems are integrated into our future facility designs from outset

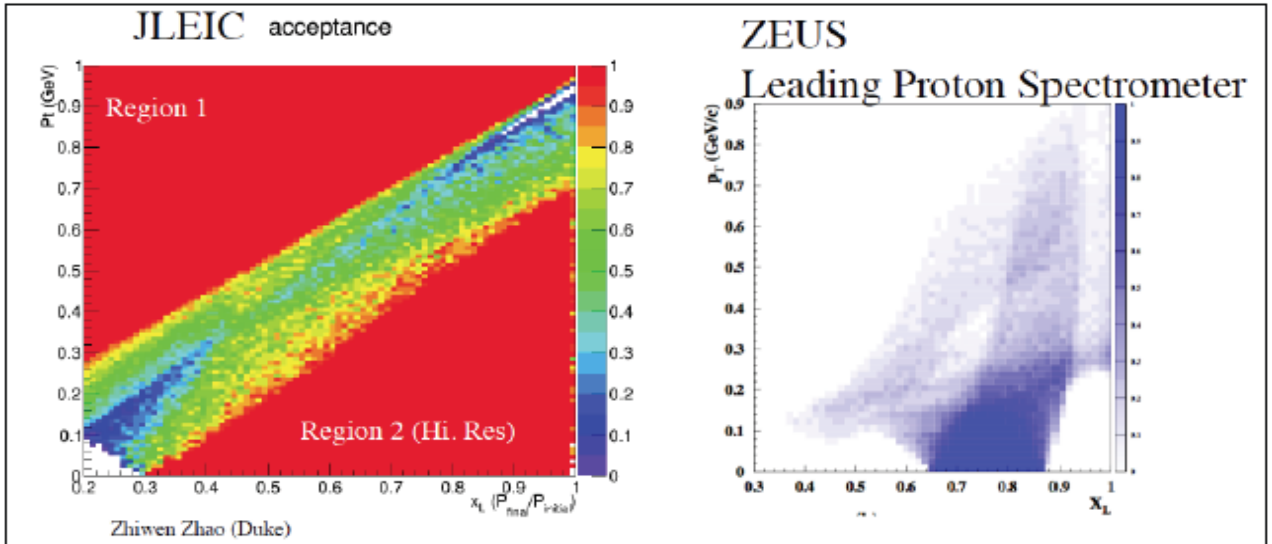
- eg LHeC Proton spectrometer uses outcomes of FP420 project (proposal for low ξ Roman pots at ATLAS / CMS – not yet adopted)
- Tags elastically scattered protons with high acceptance over a wide



EIC Forward Proton Spectrometer

- Beamline instrumentation intrinsic to e-RHIC and JLEIC designs from outset
- e.g JLEIC version with access points at 12m – 45m from IP…



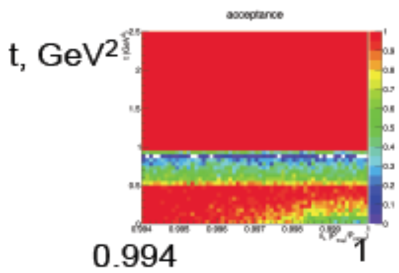


Acceptance in diffractive peak (X_L>~.98)

ZEUS: ~2%

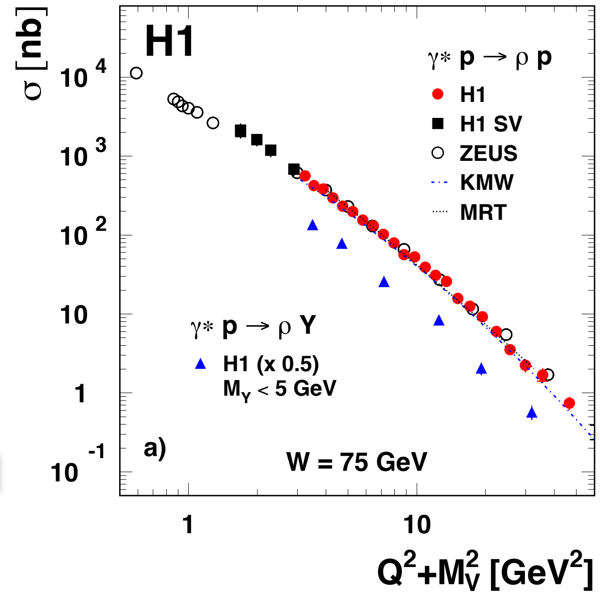
JLEIC: ~100% (also covers much higher X_L than ZEUS)

[Rik Yoshida]



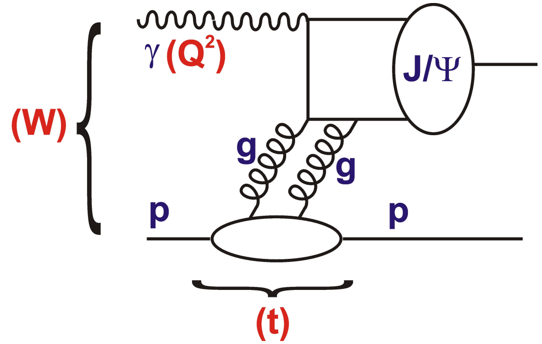
Exclusive Vector Mesons

• Huge database of measurements from HERA, Ψ, J/Ψ, ϕ, ρ, ρ', DVCS … mapping soft-hard transition, unfolding σ_T, σ_L …



Test Case: J/Ψ Photoproduction

• `Cleanly' interpreted as hard 2g exchange coupling to qqbar dipole



• c and c-bar share energy equally, simplifying VM wavefunction relative to ρ

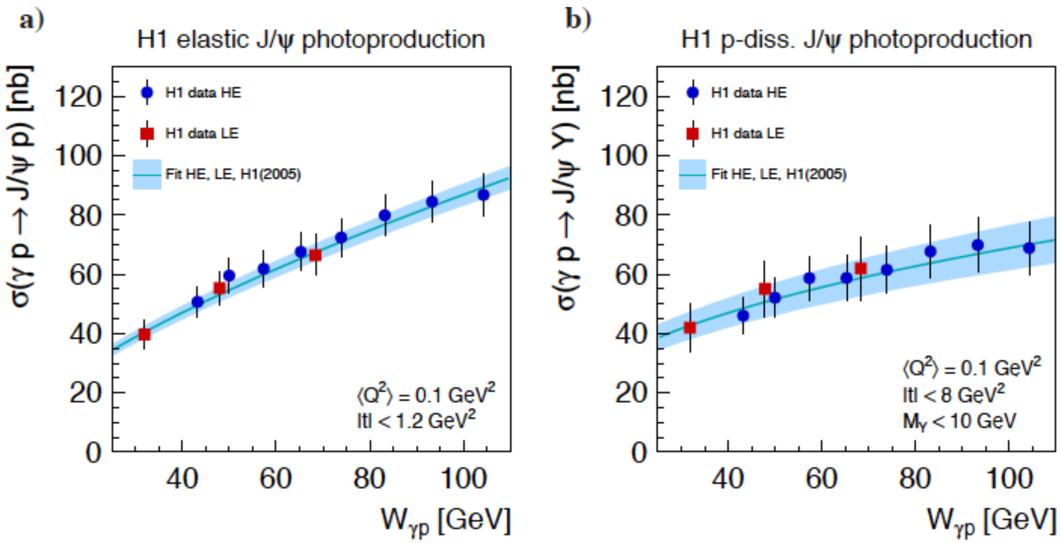
• Clean experimental signature (just 2 leptons)

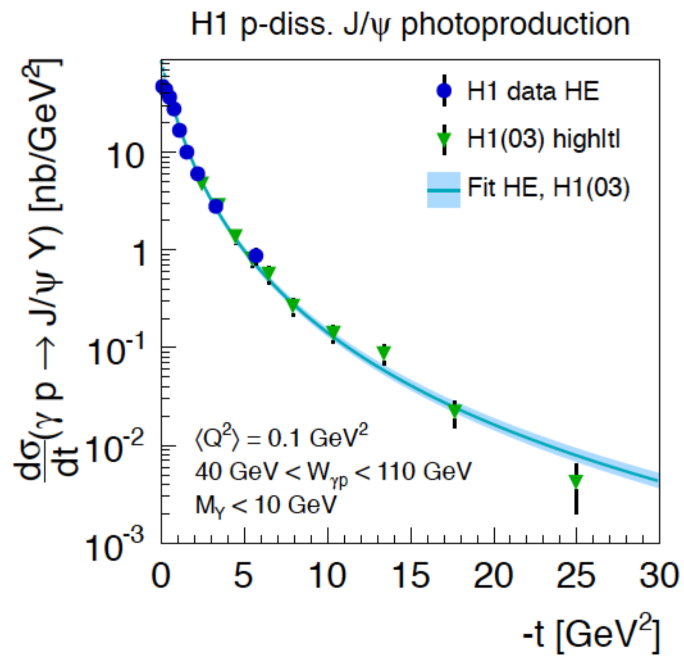
• Scale $\overline{Q}^2 \sim (Q^2 + M_V^2) / 4 \;>\!\sim 3\ \text{GeV}^2$ ideally suited to reaching Lowest possible x whilst remaining in perturbative regime

… eg LHeC reach extends to: $x_g \sim (Q^2 + M_V^2) / (Q^2 + W^2) \sim 5.10^{-6}$

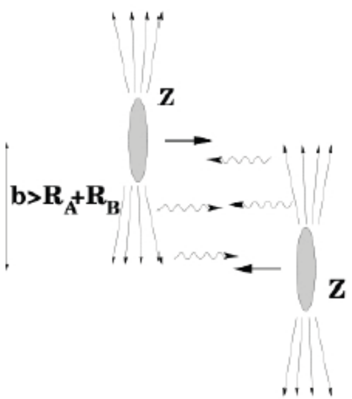
Existing Diffractive J/Ψ Photoproduction Data

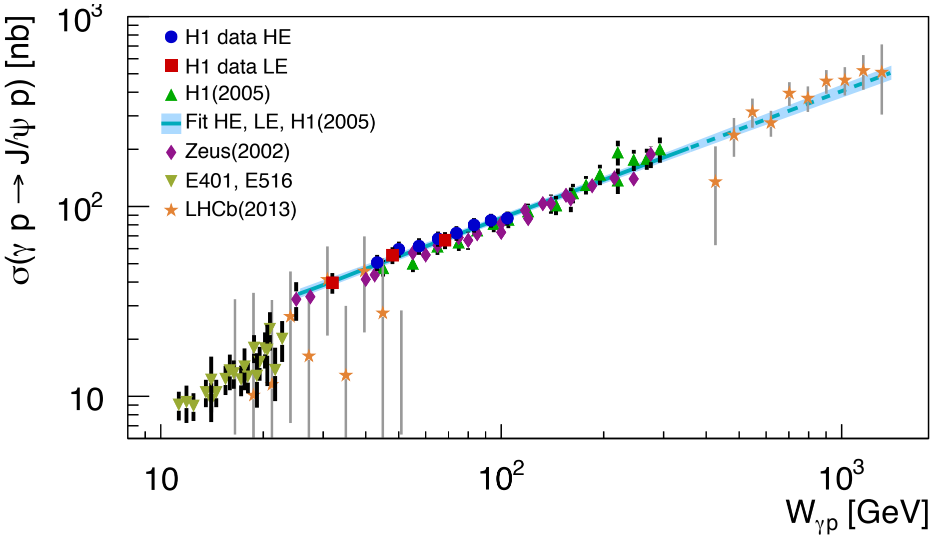
… HERA: $\gamma p \rightarrow J/\Psi p$, $\gamma p \rightarrow J/\Psi\, Y$:





… Adding Ultraperipheral Collisions at LHC:

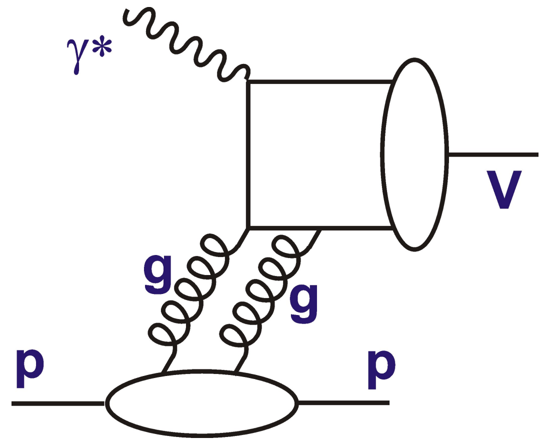


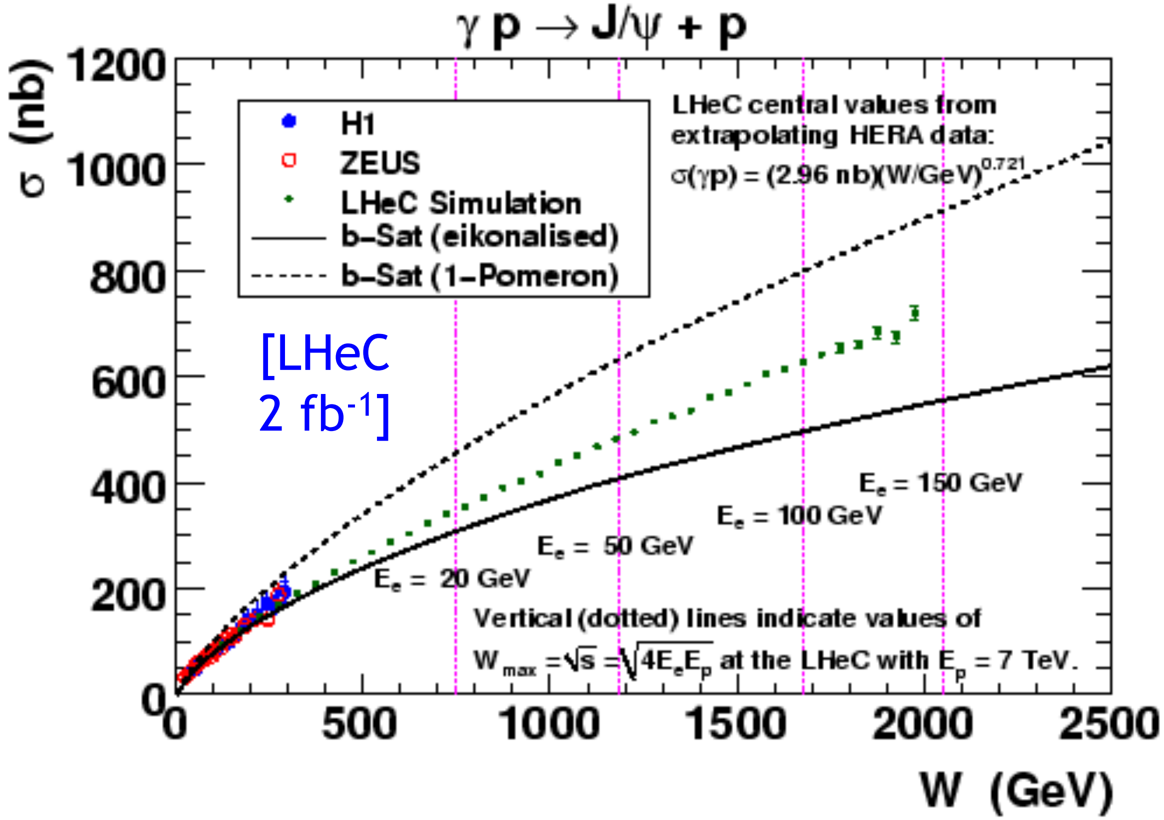


- No evidence for deviation from monatomic rise with increasing W (decreasing x).
- See also pPb, PbPb results

J/Ψ from future ep v Dipole model Predictions

e.g. "b-Sat" Dipole model
- "eikonalised": with impact-parameter dependent saturation
- "1 Pomeron": non-saturating

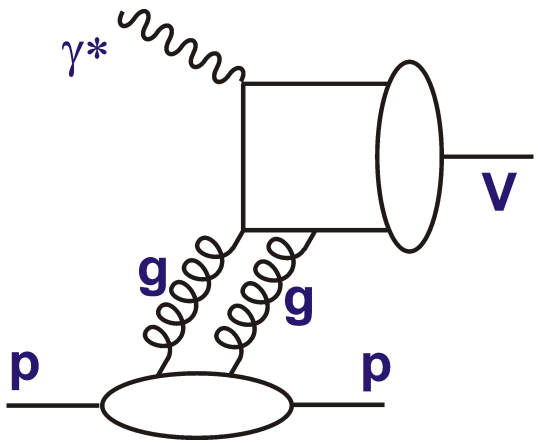




- Significant non-linear effects expected in LHeC kinematic range

"beware unrealistic non-sat Straw men" [T. Lappi]

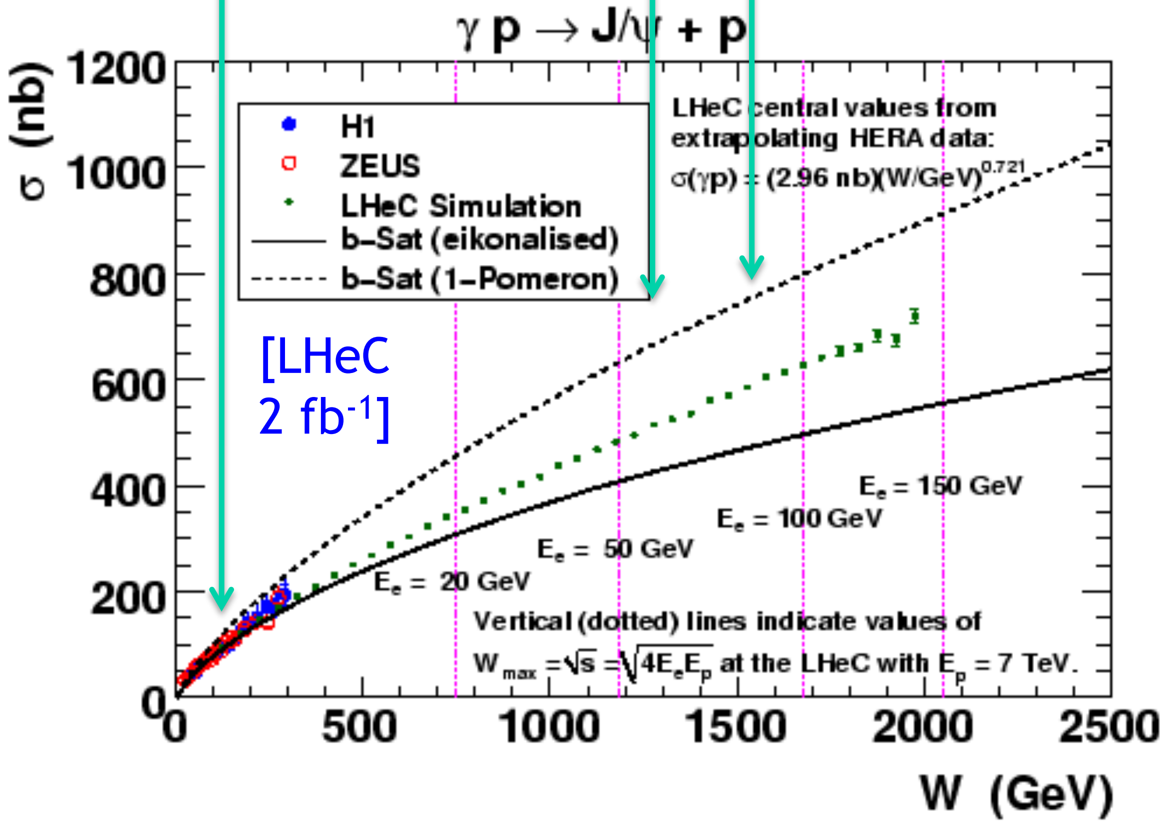
J/Ψ from future ep v Dipole model Predictions



Current EIC design

Current LHeC design

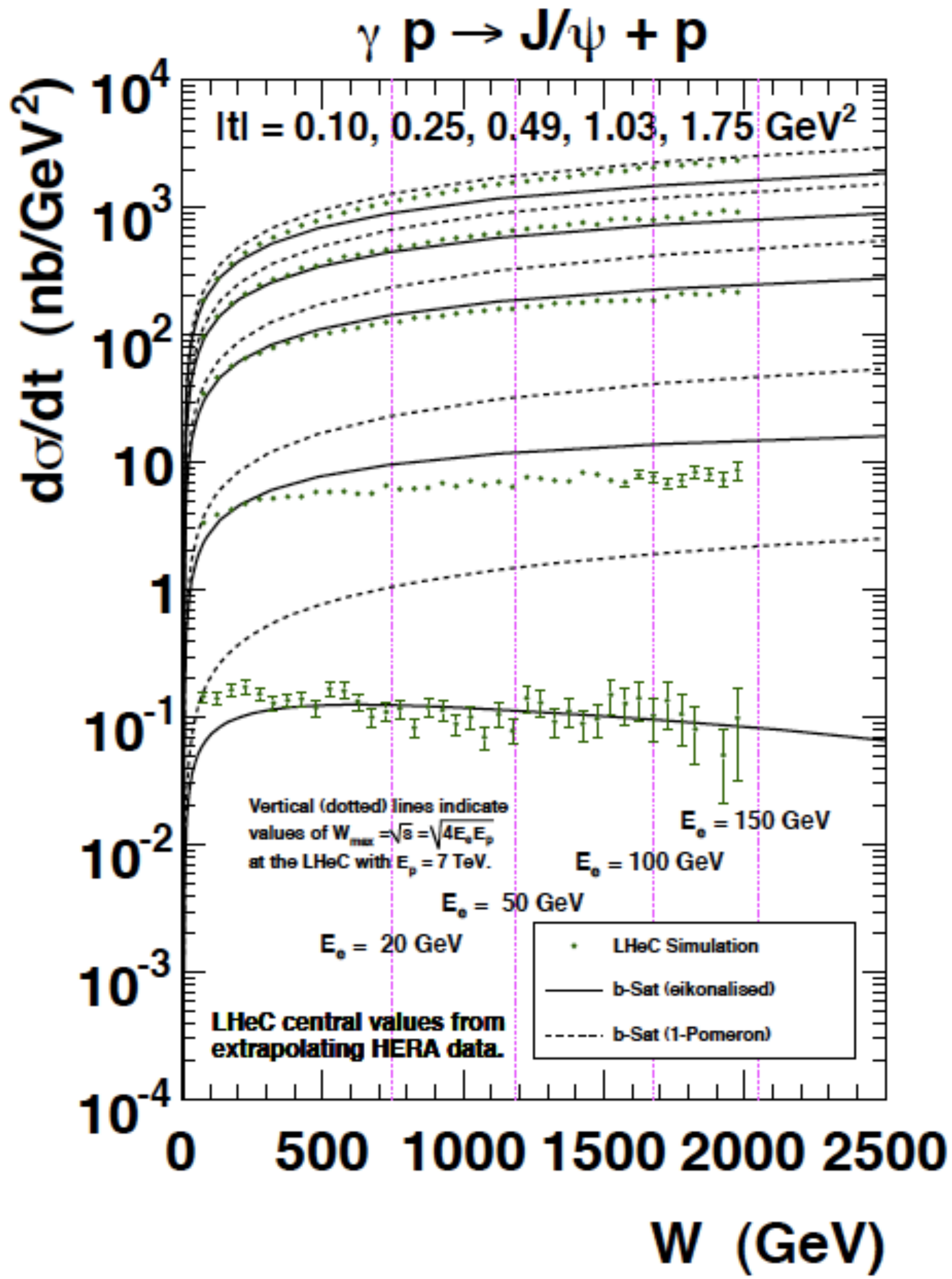
Current LHCb limit



- Lack of sat^n signal at LHC to date suggests increasing energy alone Is not the answer

- Need detailed mapping in ep and eA and scanning of t (& maybe also of Q^2).

t Dependence of Elastic J/ψ at LHeC

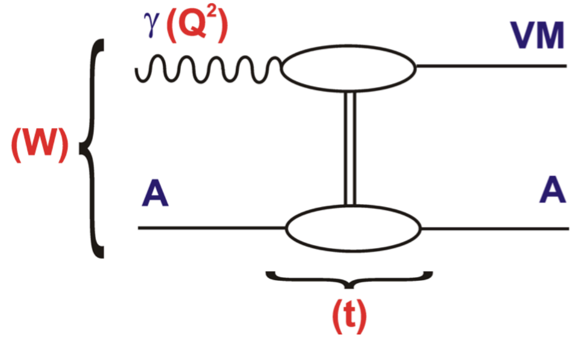


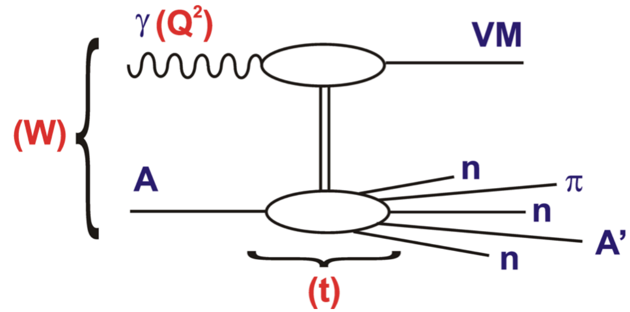
- Precise t measurement from decay μ tracks over wide W range extends to |t| ~ 2 GeV² and enhances sensitivity to saturation effects

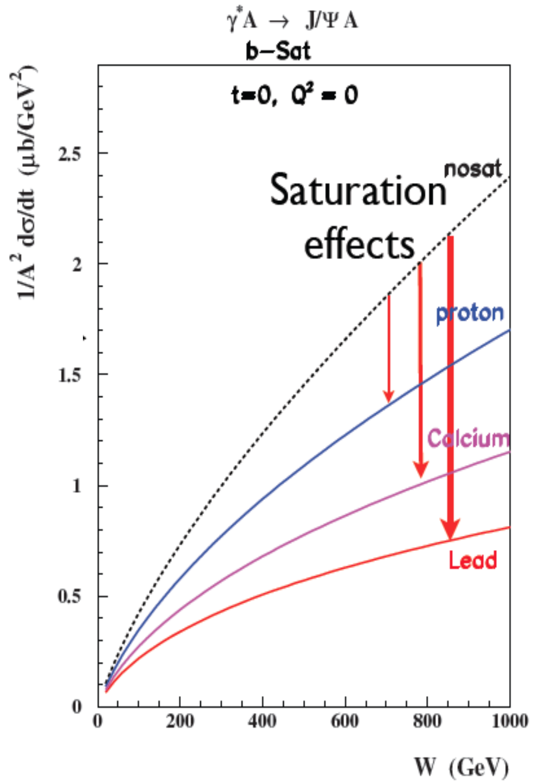
- Measurements also possible in multiple Q² bins

Exclusive Diffraction in eA

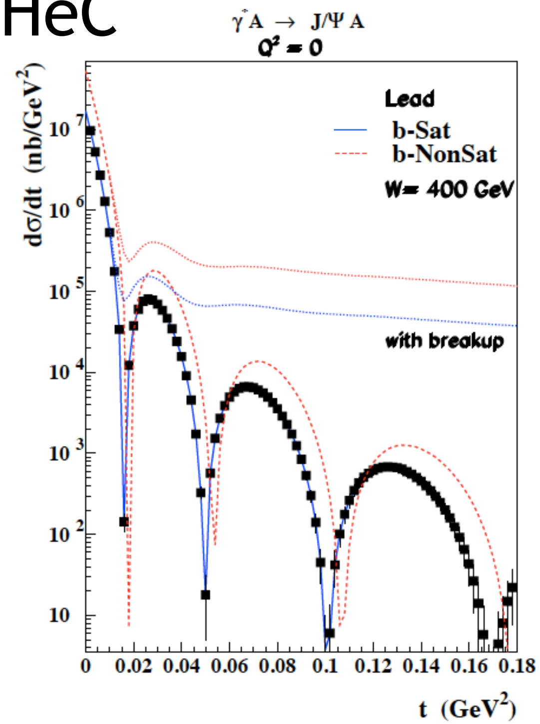
- Separation of coherent / incoherent can be done based on ZDC
- Large saturation effects predicted at LHeC in coherent case (eA → eVA)
- Smaller saturation effects at EIC → cleaner opportunity to image structure via conjugate variables b

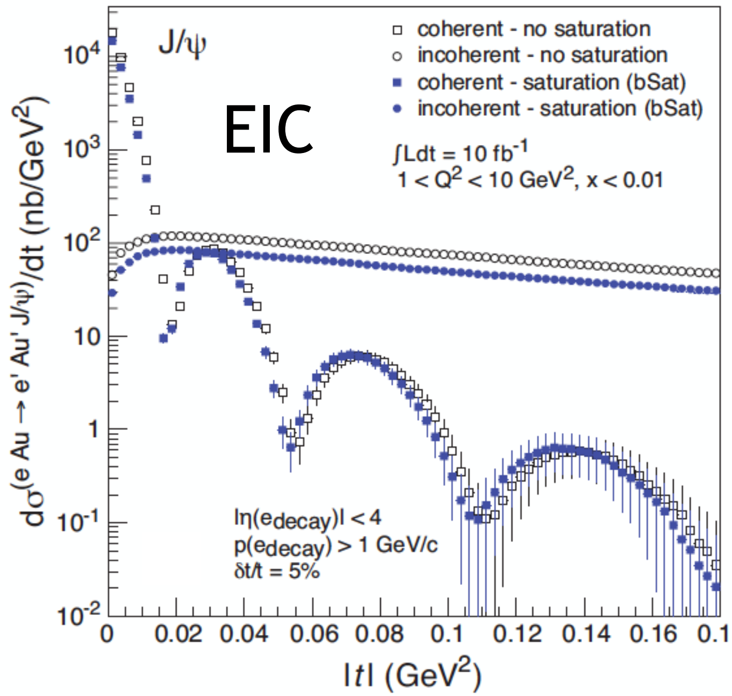




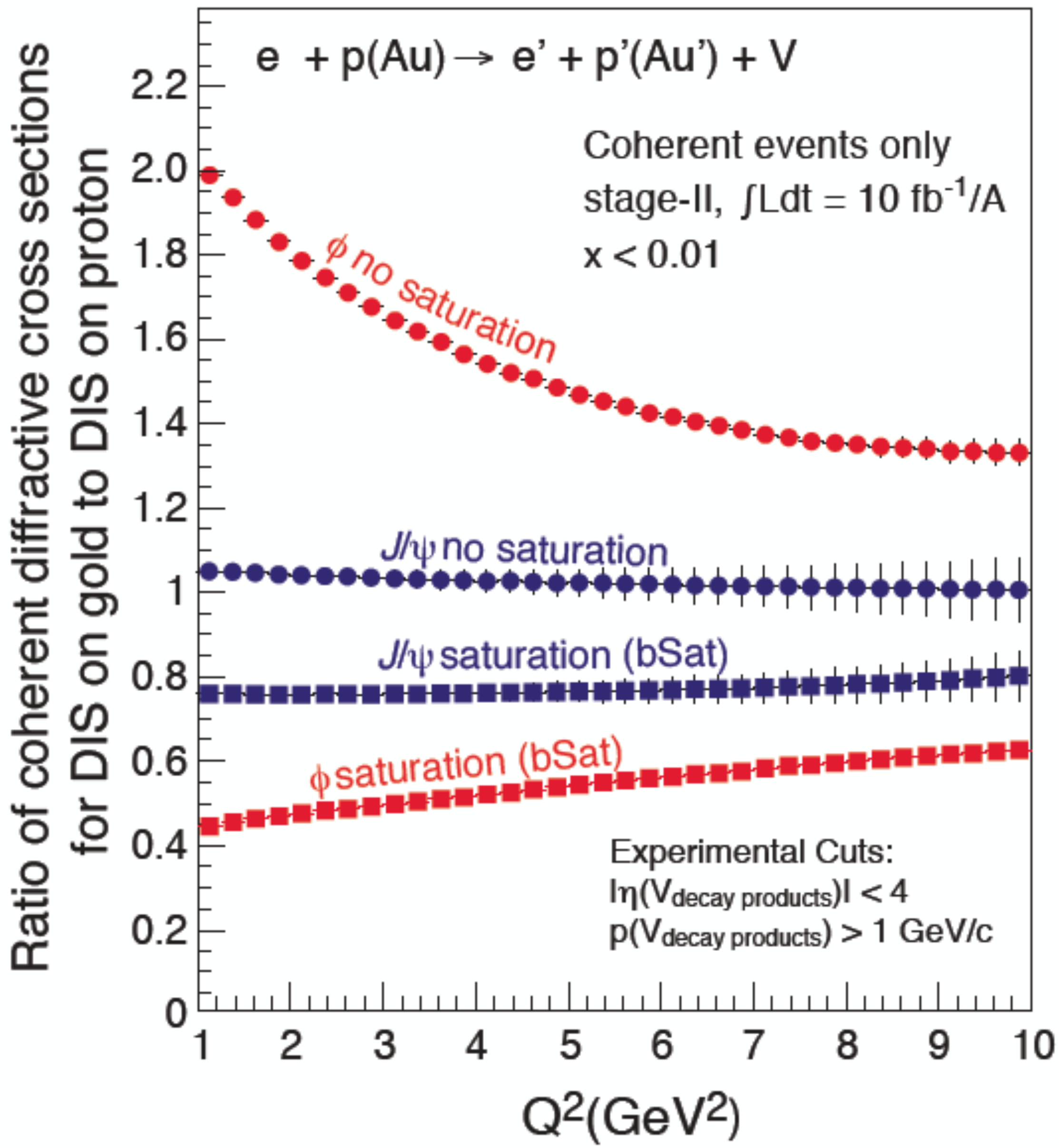


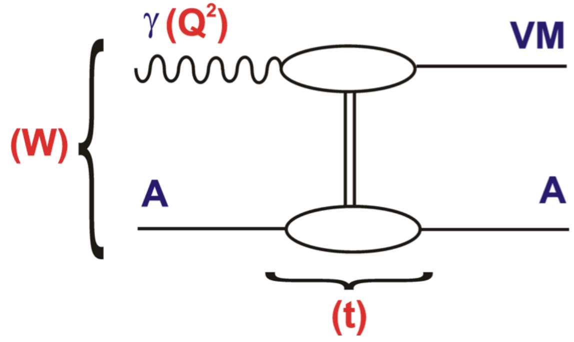
LHeC





Light Vector Mesons in eA / ep at EIC

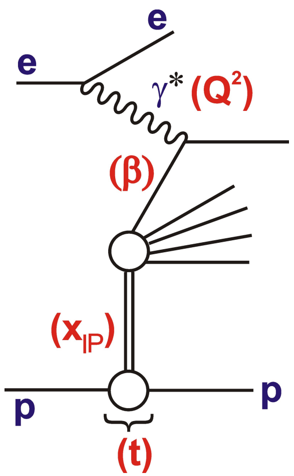




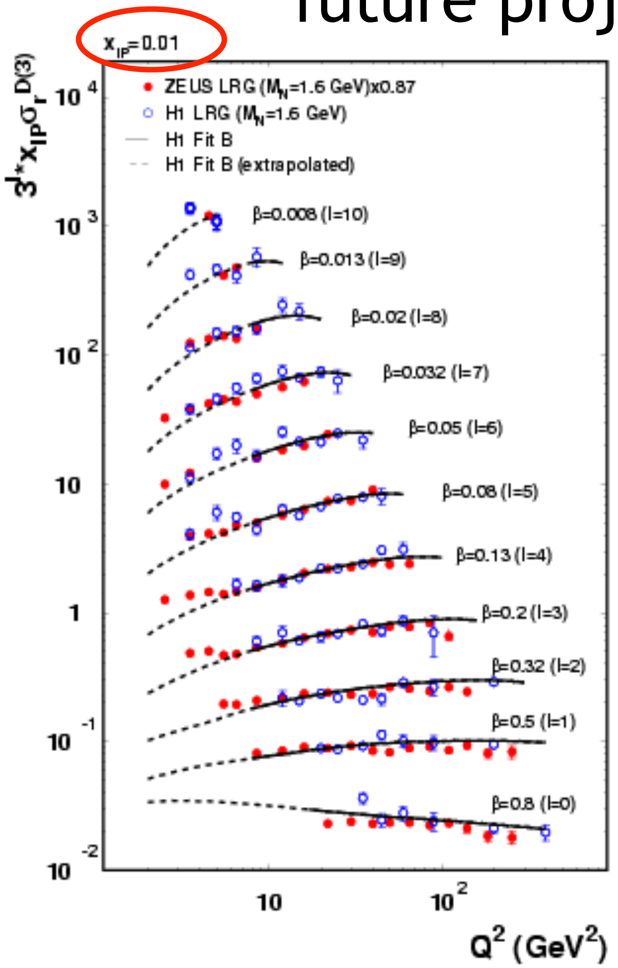
- bSat saturation model predicts big saturation effects from comparisons of eA with ep for elastic ρ, φ.

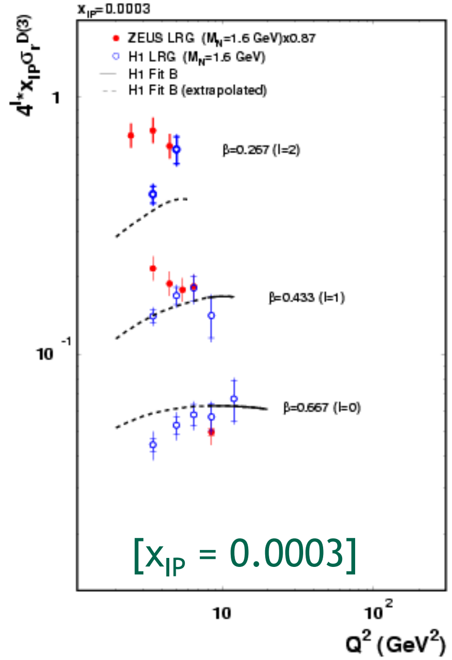
- Effects for φ larger than for J/Ψ due to lower scale.

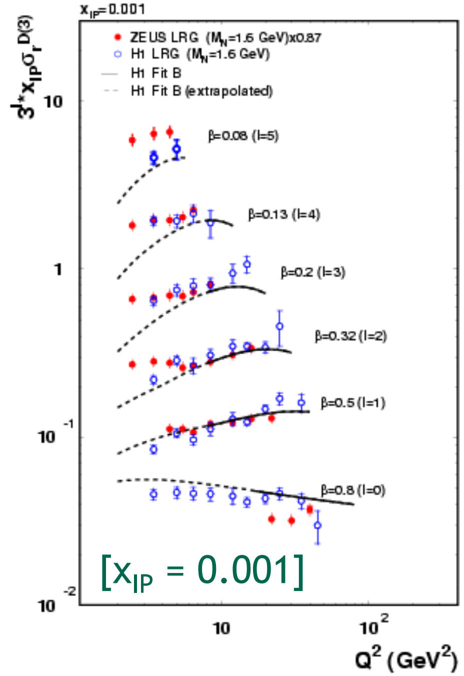
Inclusive Diffraction at HERA

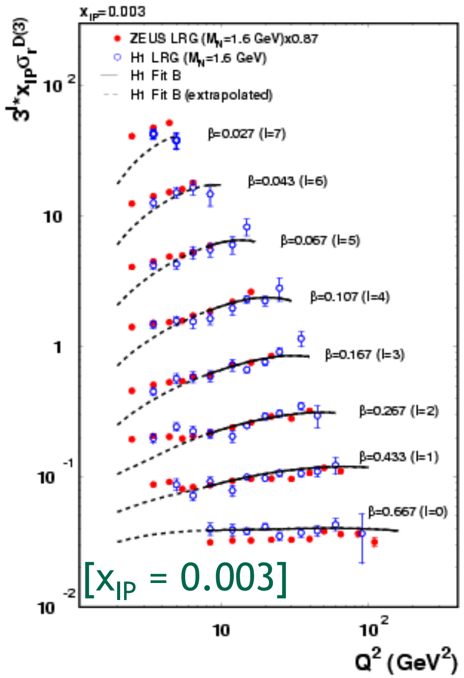


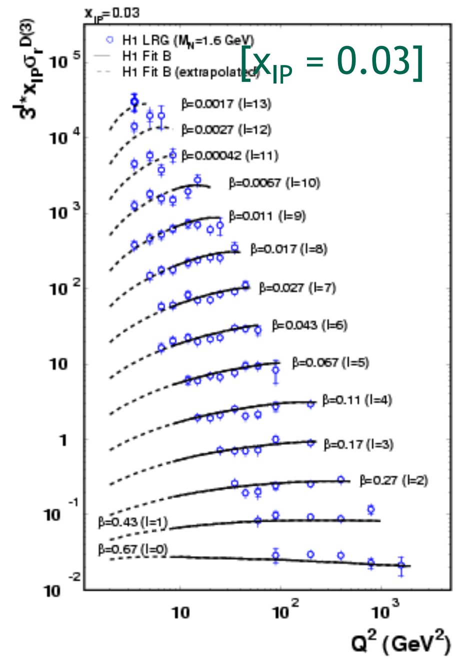
-Huge topic with rich outputs
- Not yet fully explored for future projects



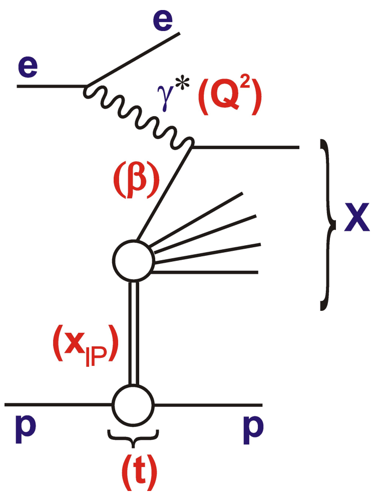


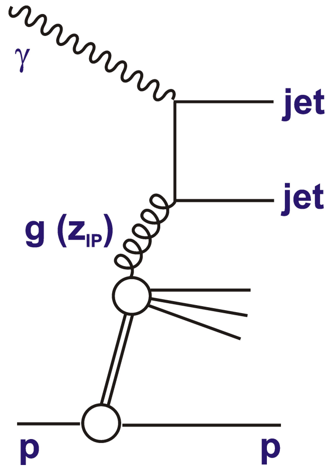


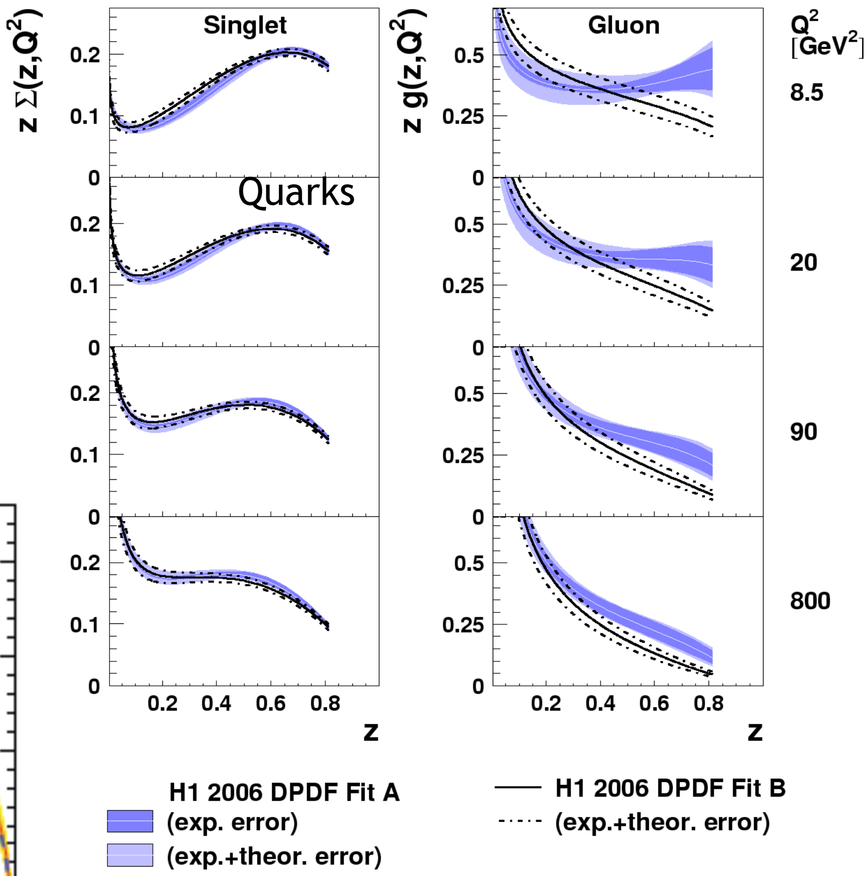


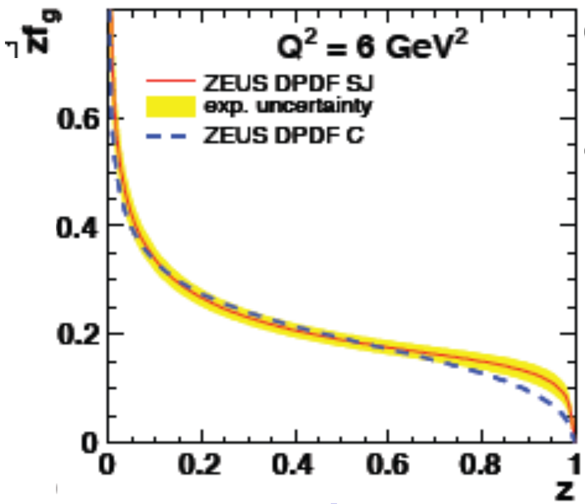


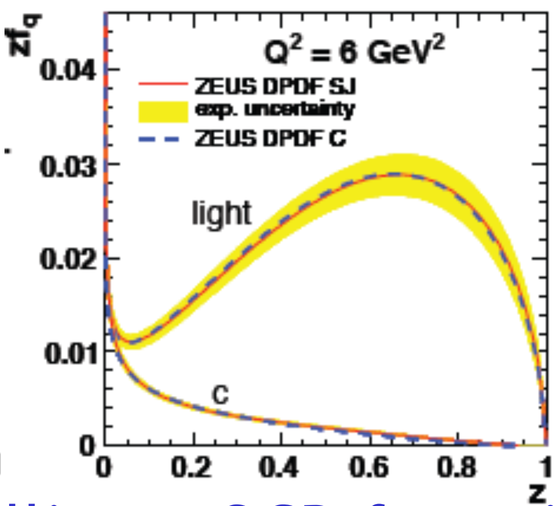
Diffractive Parton Densities (DPDFs)











… semi-inclusive collinear QCD factorisation works!

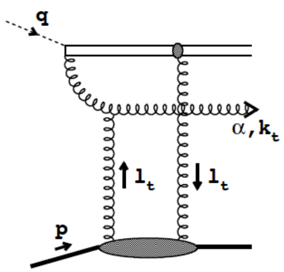
… DPDFs from F_2^D lead to impressive description of all HERA 'hard' diffractive data (not shown here)

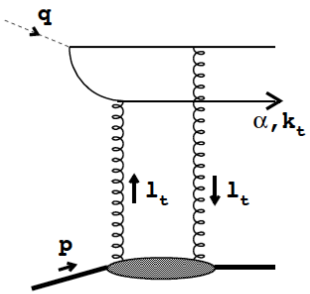
… Failure of diffractive PDF fits to data at lowest Q^2 …

Diffractive DIS & Dipole Models

– χ^2 / ndf increases systematically in H1 DPDF fits when data of $Q^2 < 8.5$ GeV^2 are included (slightly lower in ZEUS)
… low Q^2 breakdown of pure Leading Twist DGLAP approach

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

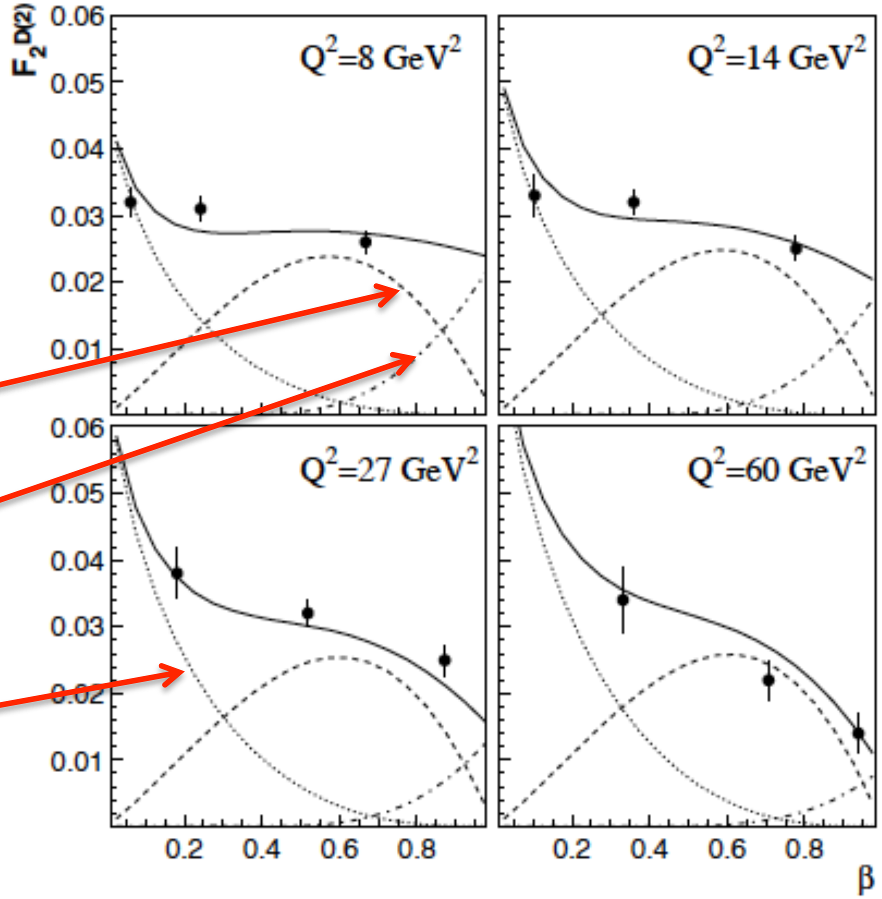




qq_T (Leading Twist)

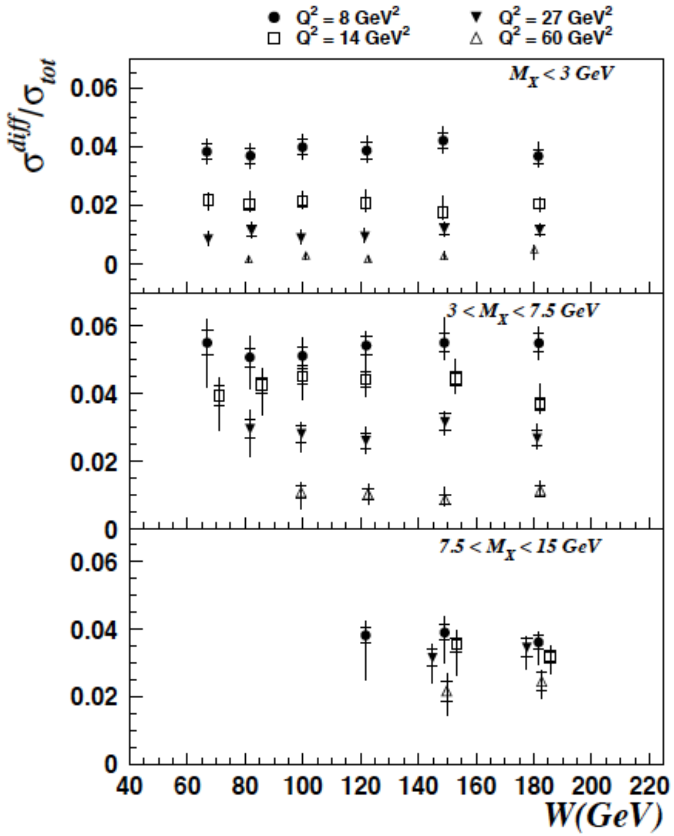
qq_L (Higher Twist)

qqg_T (Leading Twist)

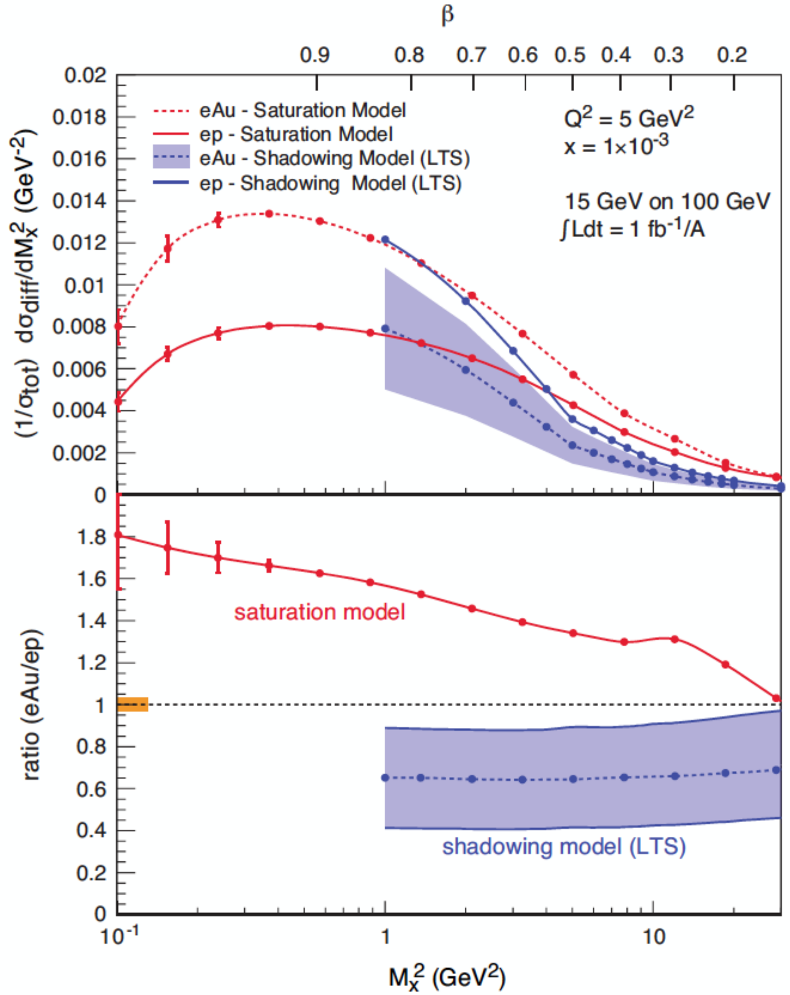


- Not yet describing fine detail
- Unravelling this rich phenomonology can yield big rewards!

Diffractive : Inclusive Ratio



- Famous HERA plot … Rather flat diffractive/inclusive ratio v x at fixed Q2, taken as evidence for saturation

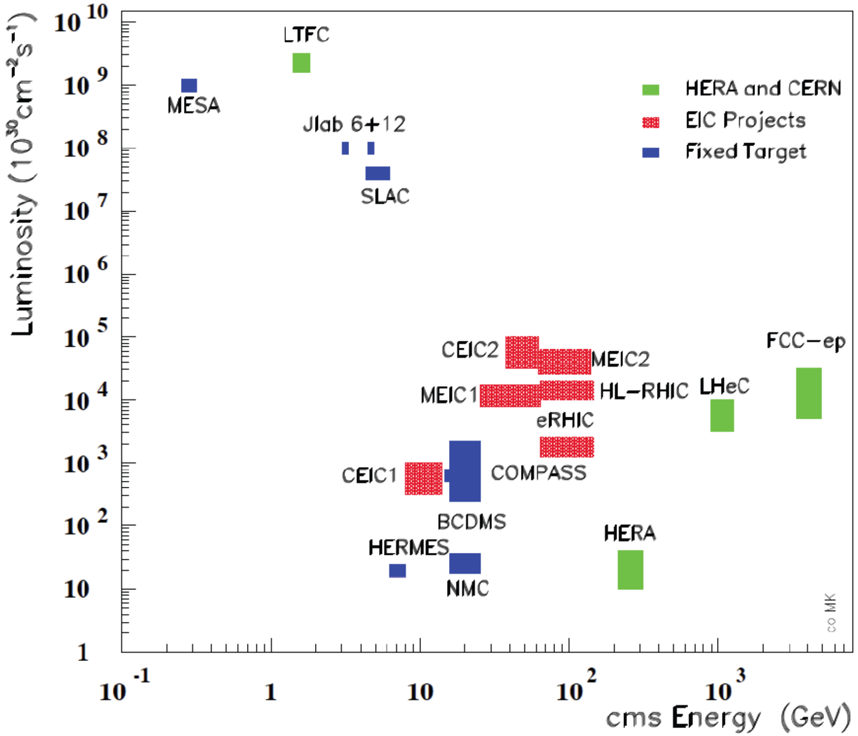


- EIC 'Day 1' simulations confirm the importance of this sort of observable to disentangle saturation and shadowing …

… increasing diff/incl ratio with A in saturation case …

Summary

• HERA showed that the closer you look at low x physics, the more surprising it gets and the more it teaches you … and that was with only 0.5fb-1 per experiment (eg DVCS came late and with limited precision)

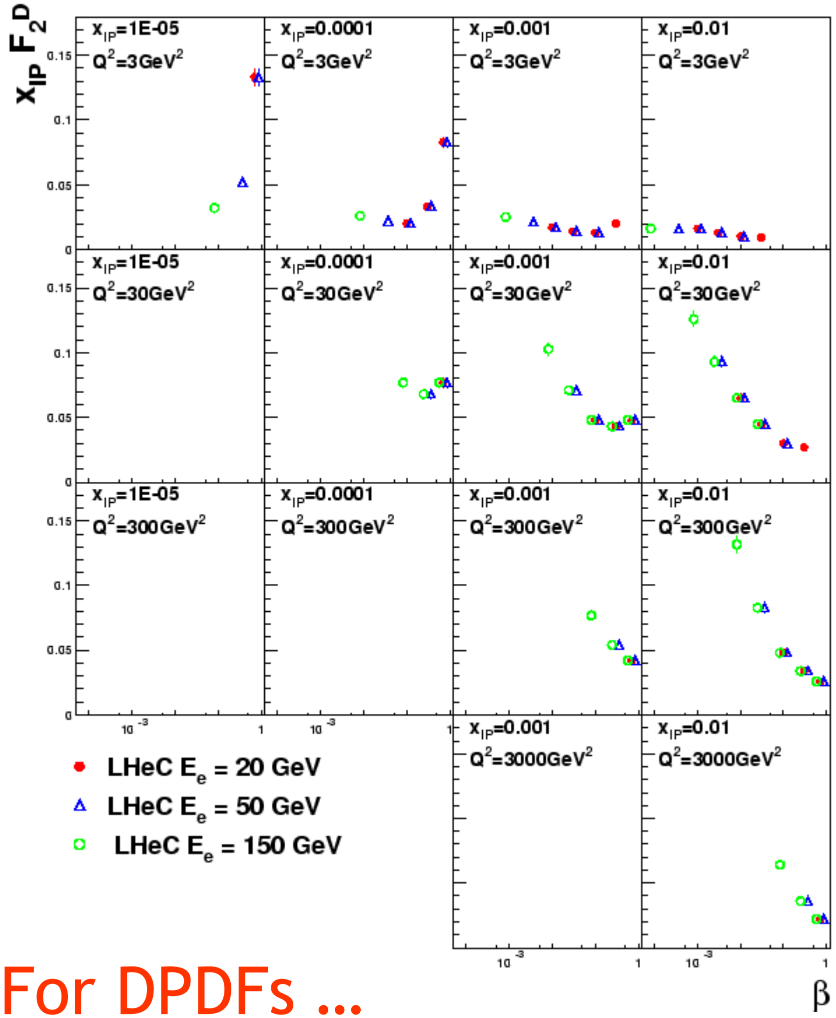


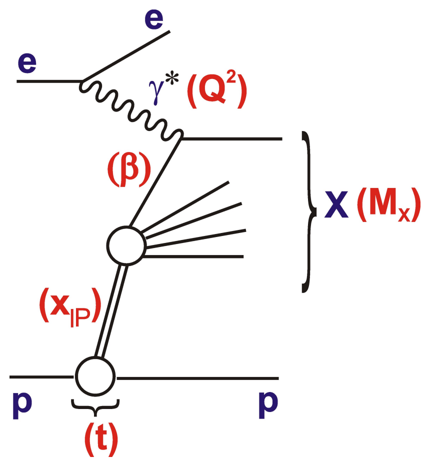
• Future DIS facilities are vital to fully establish and characterise the dynamics of saturation and precisely map its onset

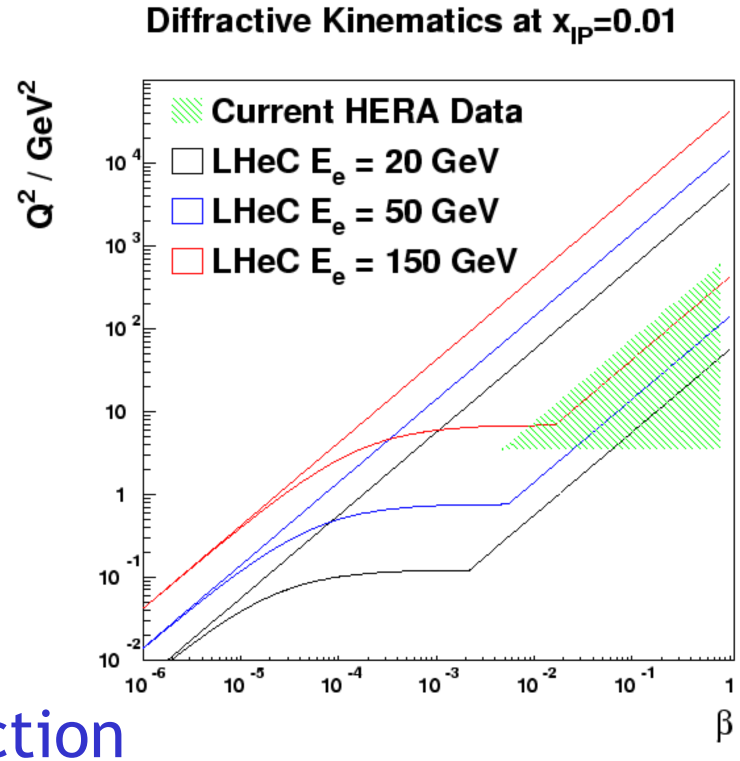
• Extrapolating and interpolating from HERA and including LHC suggests studies at future DIS facilities will need to include non-perturbative region and a multi-observable approach … ep and eA inclusive, diffractive, semi-inclusive over a range of energies

Back-Ups Follow

Inclusive Diffraction / Diffractive PDFs at LHeC







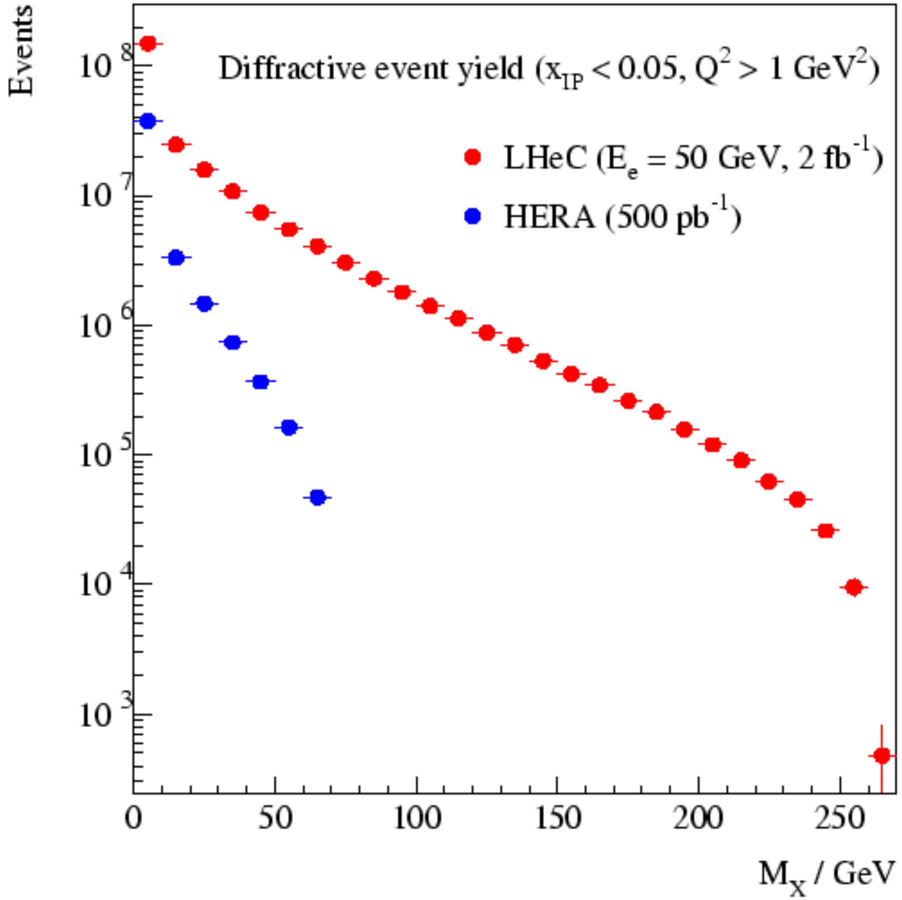
For DPDFs …

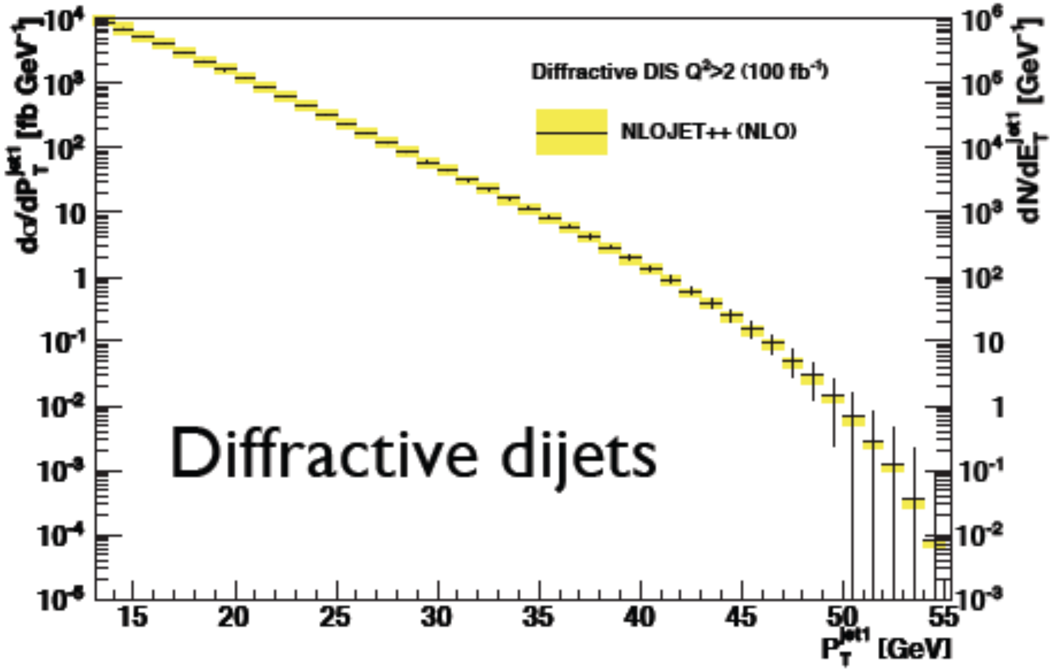
- Low x_{IP} → cleanly separate diffraction
- Low β → Novel low x DPDF effects /non-linear dynamics?
- High Q^2 → Lever-arm for gluon, Flavour separation via EW

Still to do: detailed DPDF sensitivity study

New Region of Large Diffractive Masses

Large x_{IP} region highly correlated with large Mx

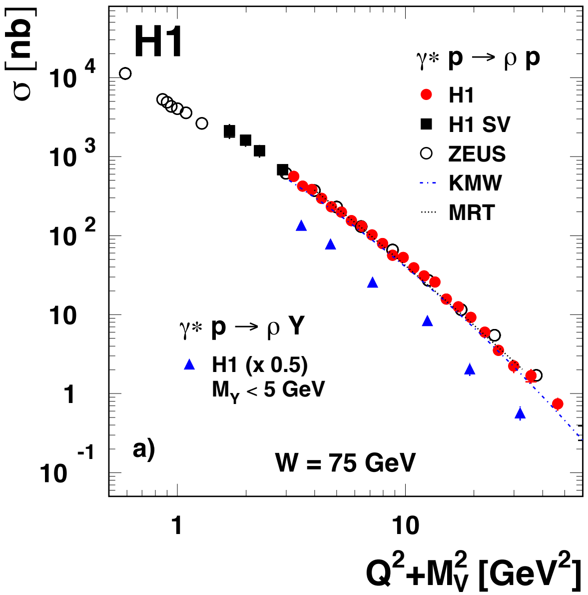


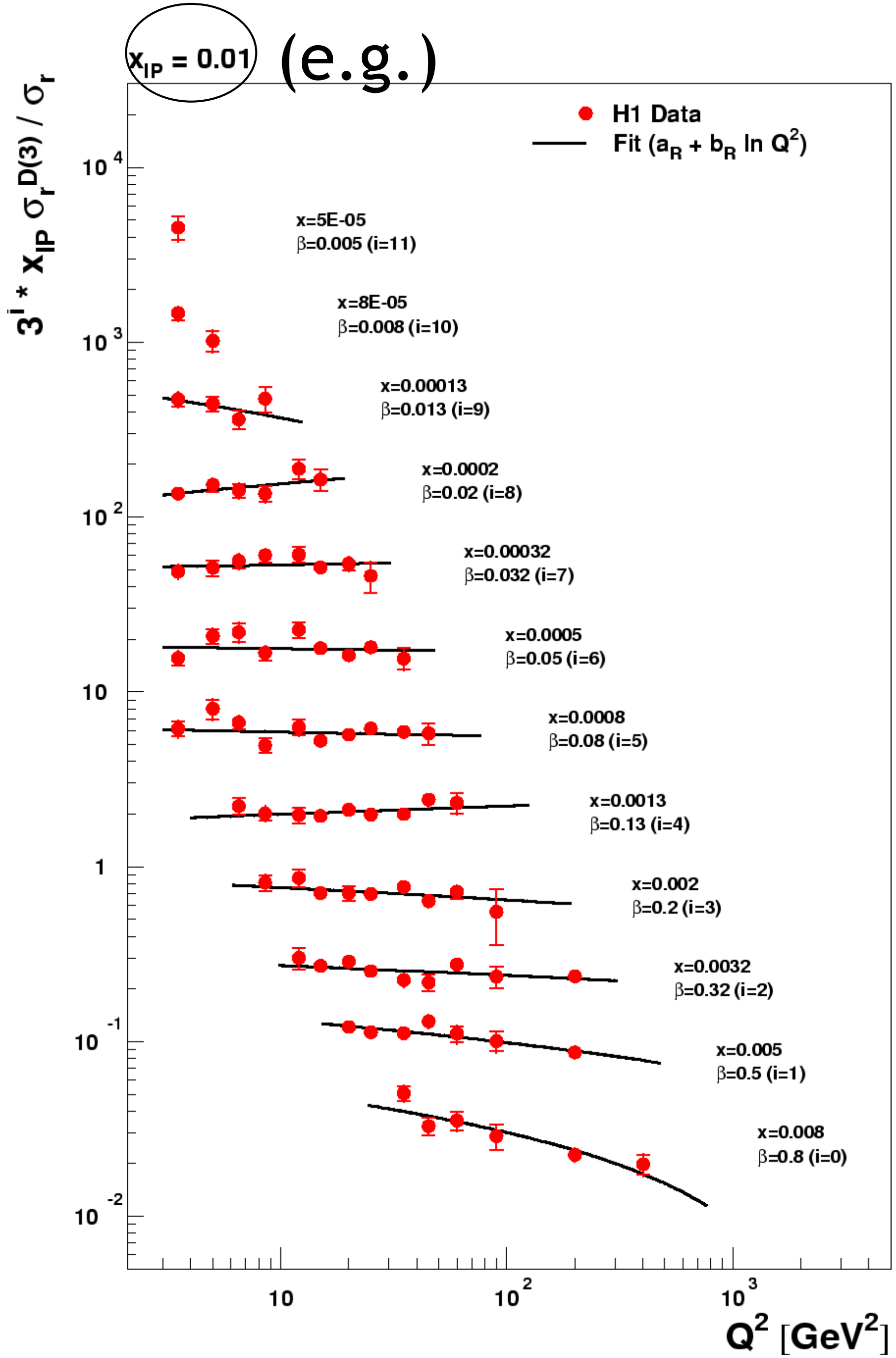


- \`Proper' QCD (e.g. large E_T) with jets and charm accessible
- New diffractive channels … beauty, W / Z bosons
- Unfold quantum numbers / precisely measure new 1^- states

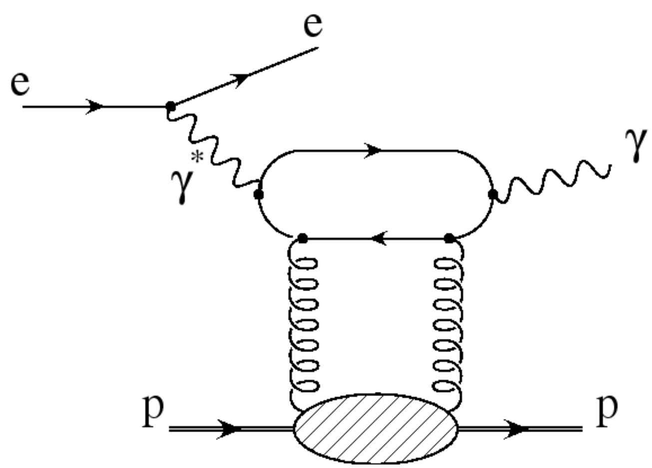
Similarity of diffractive & inclusive Data

- Q^2 evolution of inclusive and diffractive cross sections compatible at low β…
- …Ratio σ_r^D/σ_r ~ independent of Q^2 at fixed x_{IP} and x (`universal structure of QCD vacuum?')
- Contrasts with Q2-suppressed Vector Mesons





Deeply Virtual Compton Scattering



• No vector meson wavefunction complications

• Cross sections suppressed by photon coupling

→ limited precision at HERA

→ would benefit most from high lumi of LHeC and EIC

LHeC Simulations based on FFS model in MILOU generator

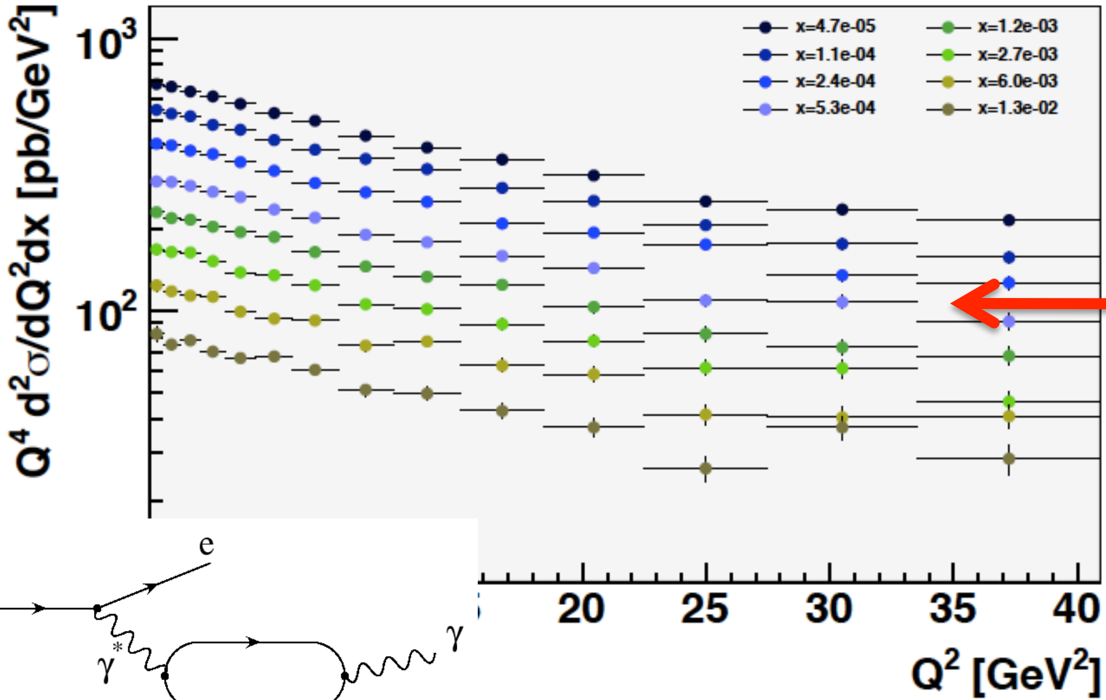
→ Double differential distributions in (x, Q^2) with

1^o and 10^o cuts for scattered electron

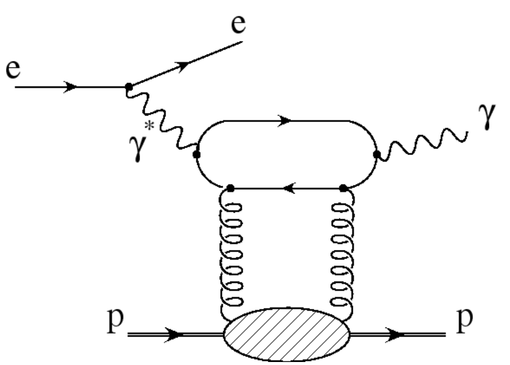
→Kinematic range determined largely by cut on p_T^γ

(relies on ECAL performance / linearity at low energies)

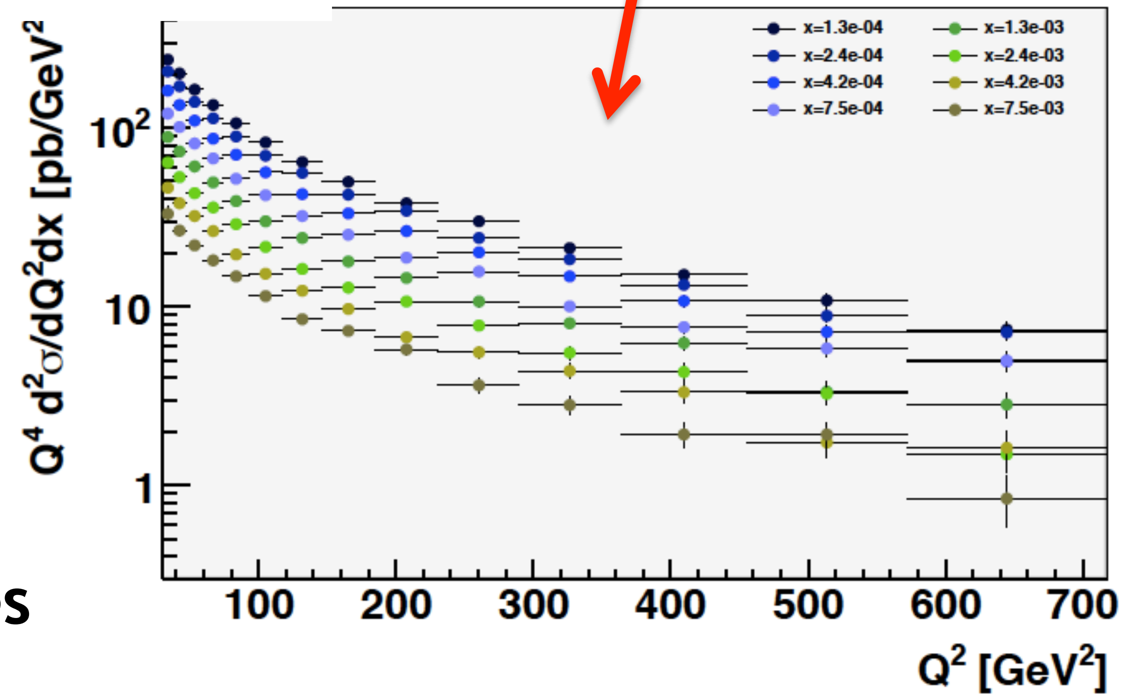
DVCS
(MILOU simulation)



1 fb^{-1}, E_e = 50 GeV,
1° acc'nce, p_T^γ > 2 GeV



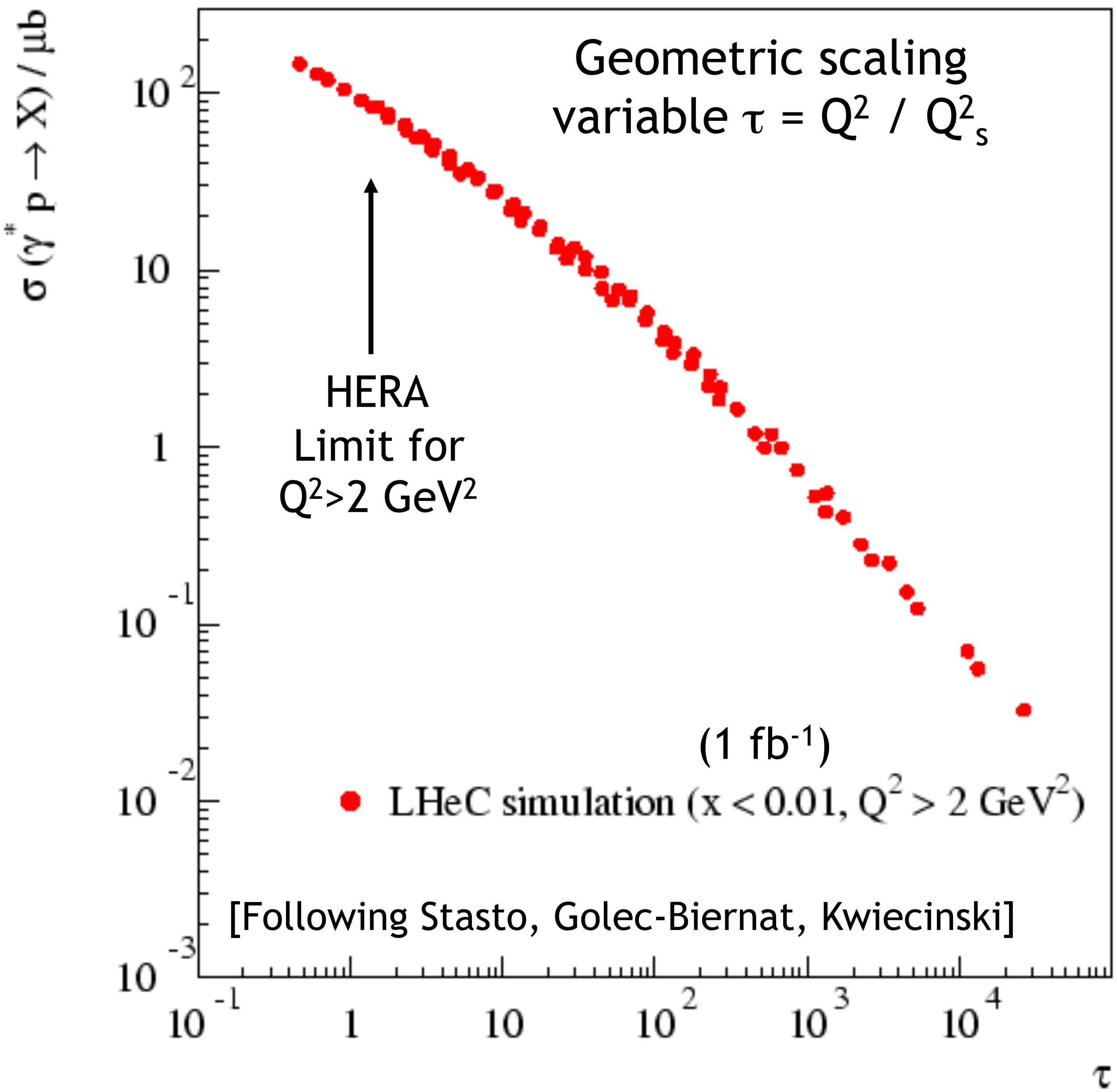
100 fb^{-1}, E_e = 50 GeV,
10° acc'nce, p_T^γ > 5 GeV



Precise data with
W → 1 TeV, Q^2 → 700 GeV^2,
x → 5.10^{-5}

Still to do:
- Beam charge asymmrtries
- Sensitivity to GPDs

Problem of Inclusive Data in a 1D nutshell: `Geometric Scaling'

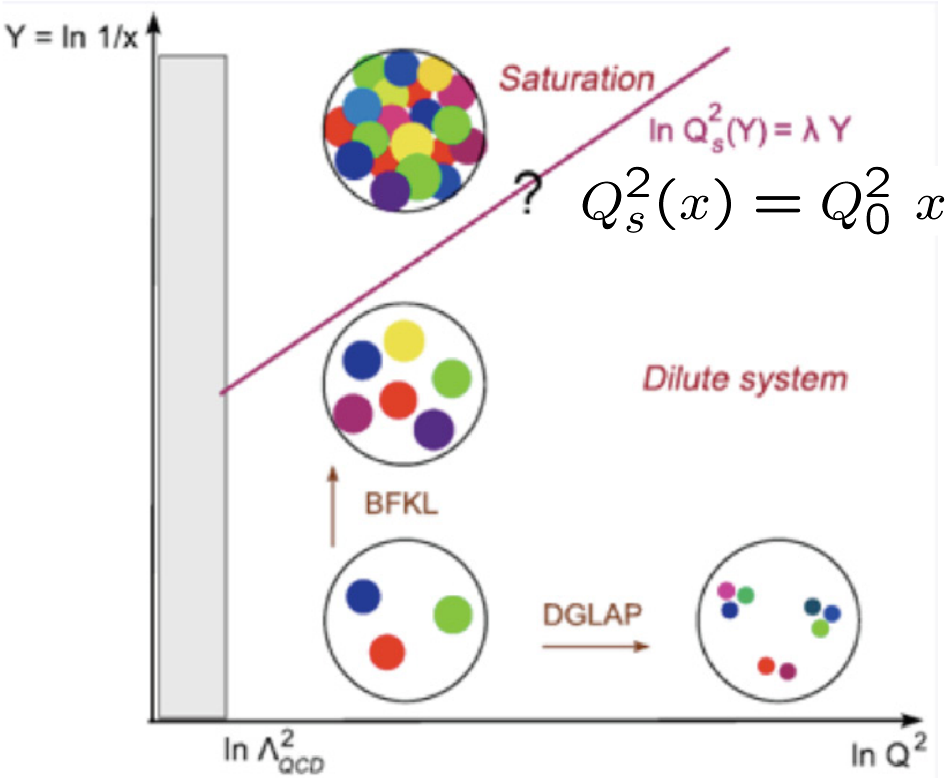


... HERA had very limited aceptance for $\tau<1$ ... **saturation effects depend mainly on data with $0.045 < Q^2 < 1$ GeV^2**

e.g. LHeC reaches $\tau \sim 0.15$ for $Q^2=1$ GeV^2 and $\tau \sim 0.4$ for $Q^2=2$ GeV^2

Can also be enhanced with nuclei.

Non-linear effects in HERA and eA Data?

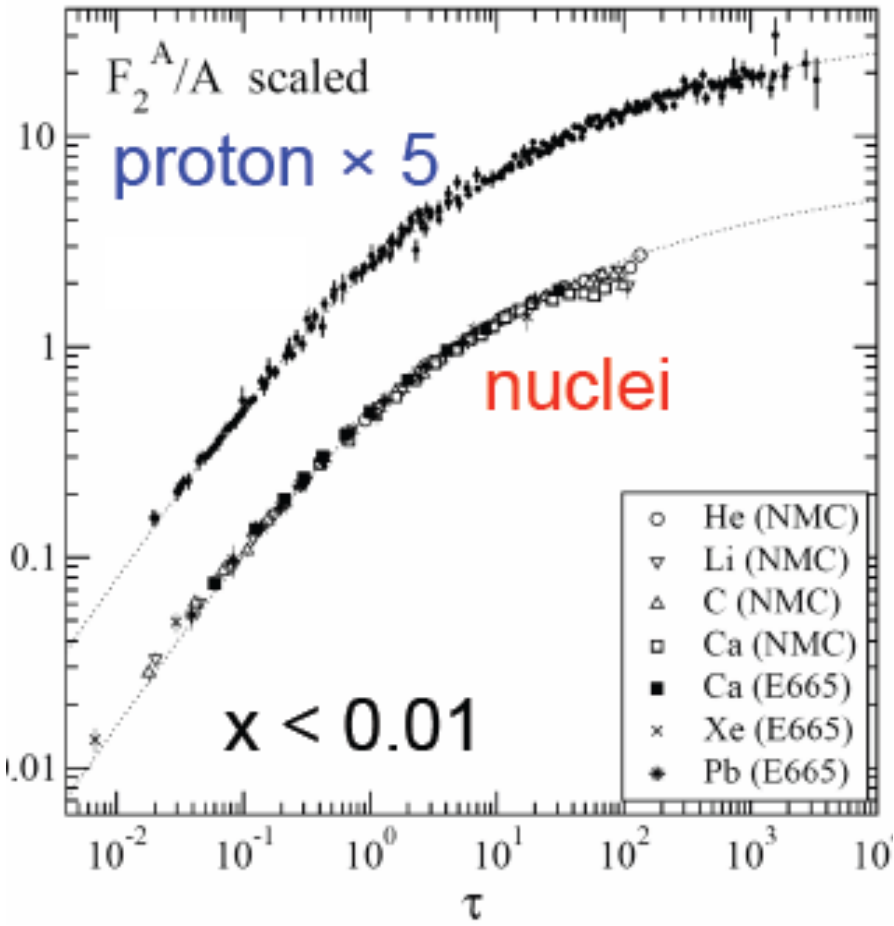


$$Q_s^2(x) = Q_0^2 \; x^{-\lambda}$$

Something appears to happen around $\tau = Q^2/Q^2_s = 1$ (confirmed in many analyses)
BUT … Q^2 small for τ <~ 1
… not easily interpreted in QCD

Lines of constant 'blackness' diagonal … scattering cross section appears constant along them … "Geometric Scaling"

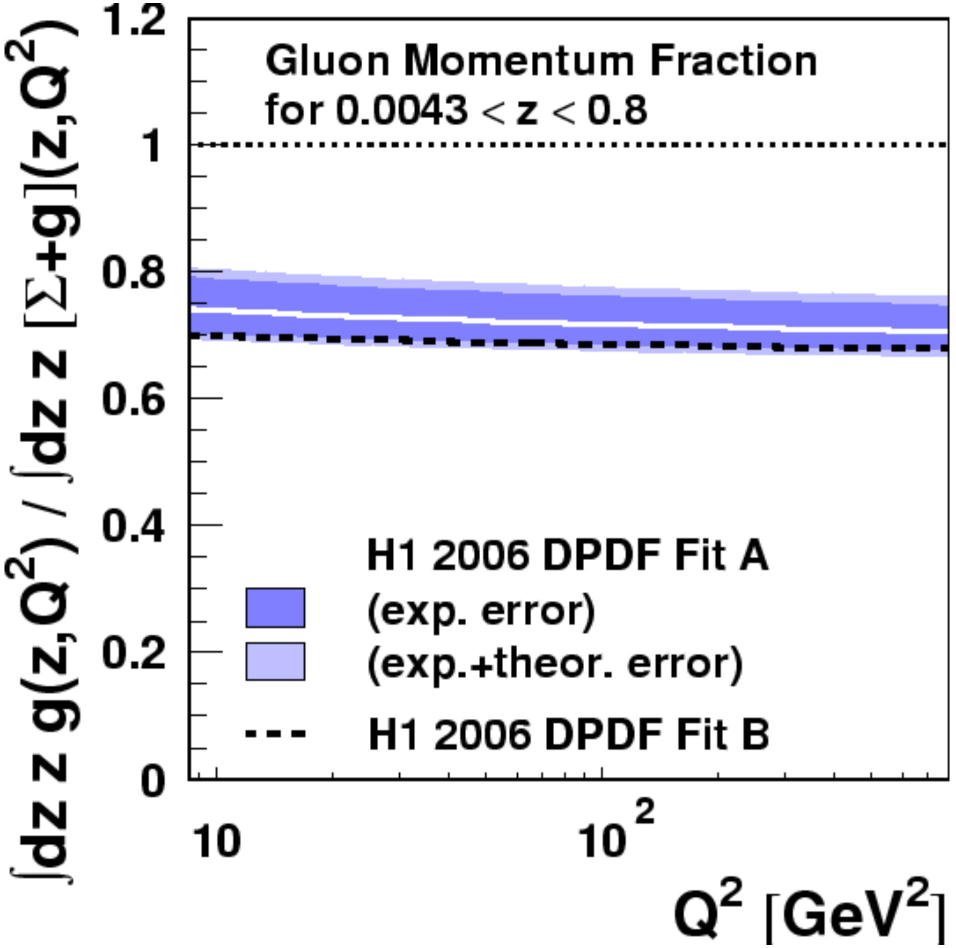
$$\sigma_{tot}^{\gamma^* h \to X}(x, Q^2) = \sigma_{tot}^{\gamma^* h \to X}(Q^2/Q_s^2(x))$$



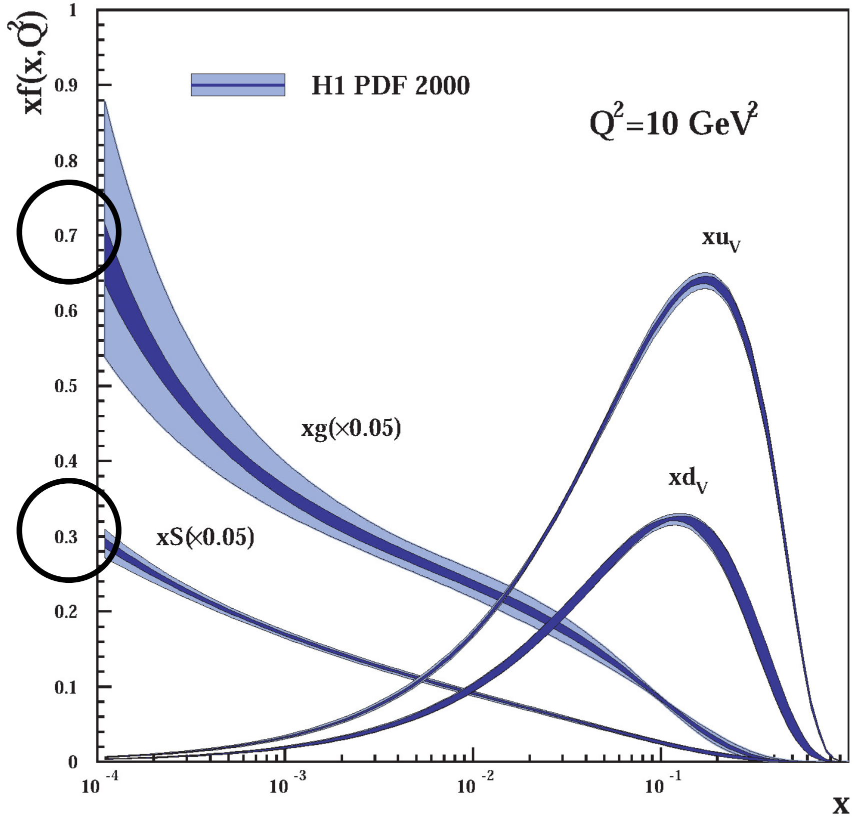
… but what do the DPDFs actually *mean*?

… what about **low z** … ratio of quarks to gluons is about 70:30 for both diffractive PDFs and (low x) inclusive PDFs …

Diffractive PDFs



Inclusive PDFs



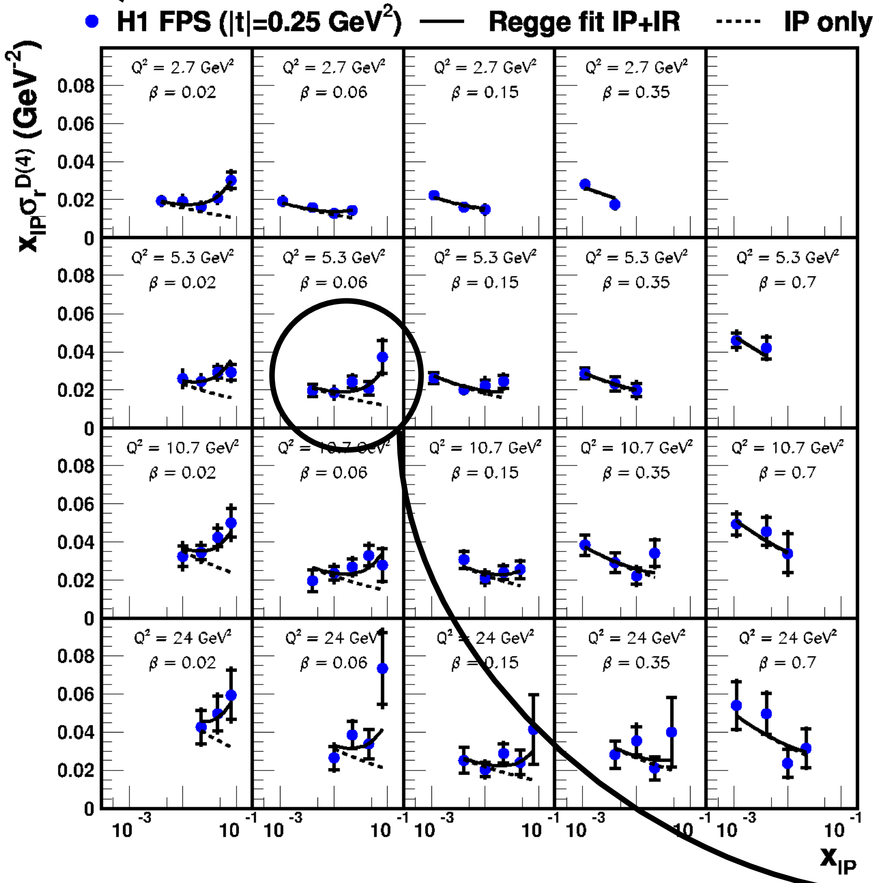
ep → eXY Data

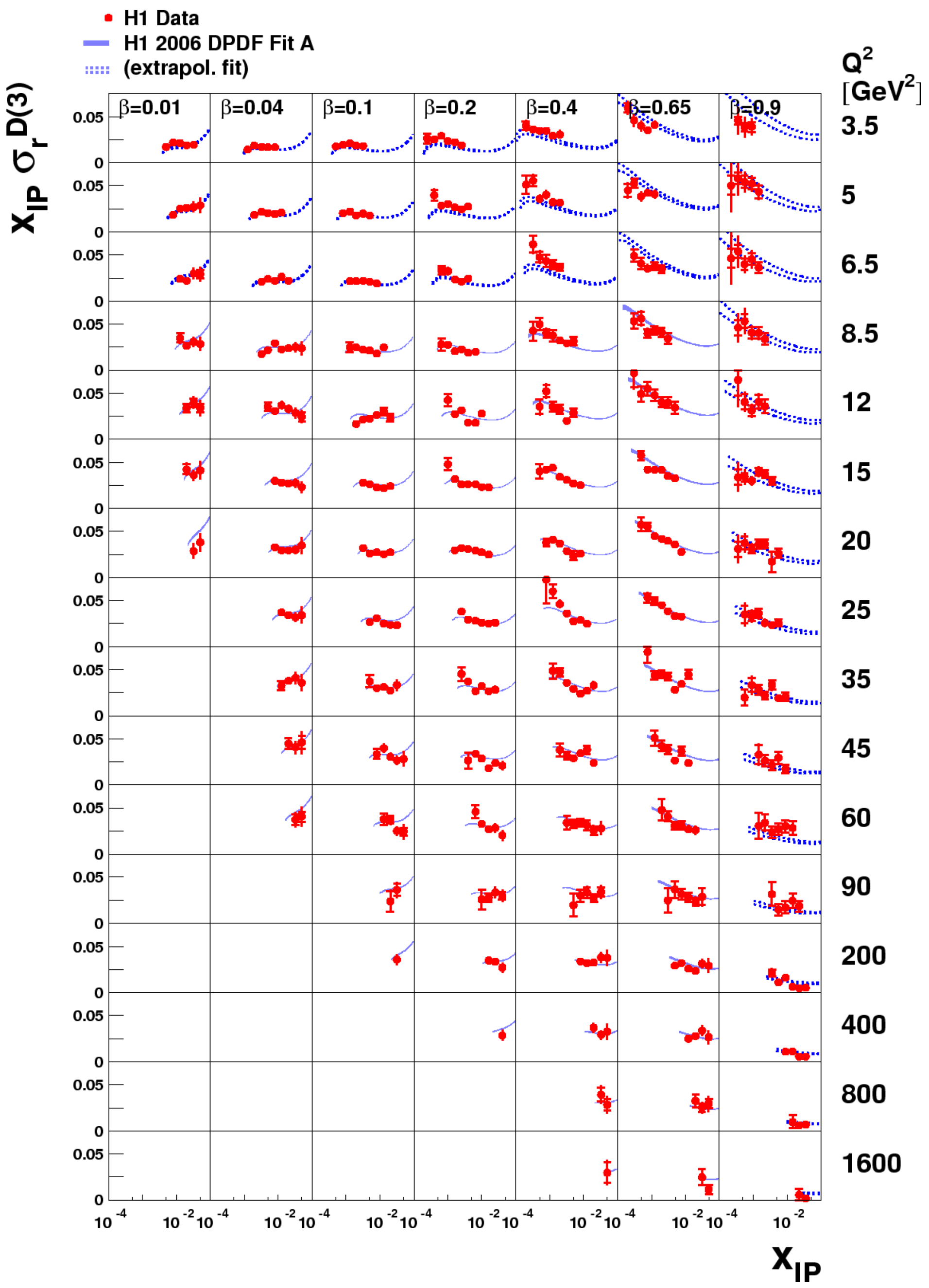
LRG: M_Y < 1.6 GeV

$$3.5 \leq Q^2 \leq 1600\ \mathrm{GeV}^2$$

FPS: Y=p

$$2.7 \leq Q^2 \leq 24\ \mathrm{GeV}^2$$



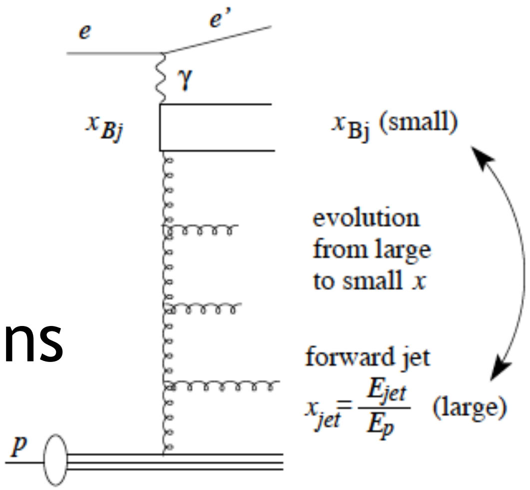


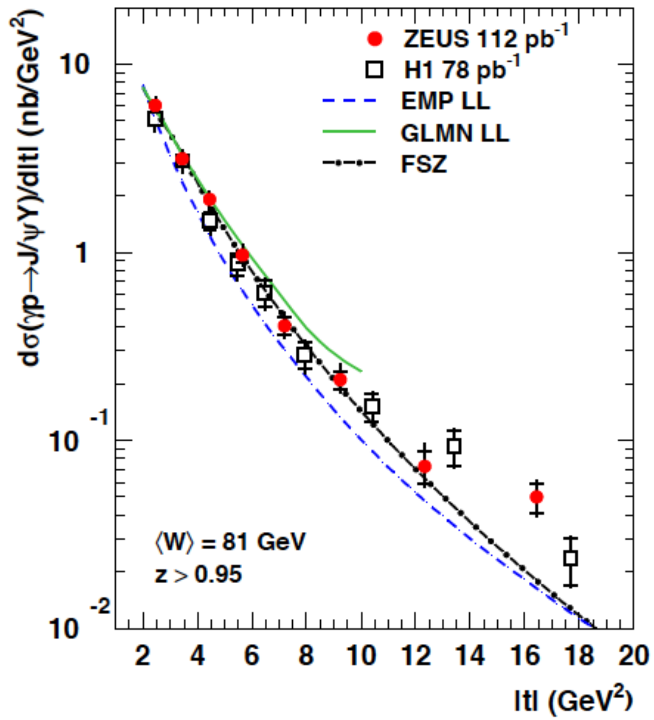
x_{IP} dependence shows clear IP+IR structure

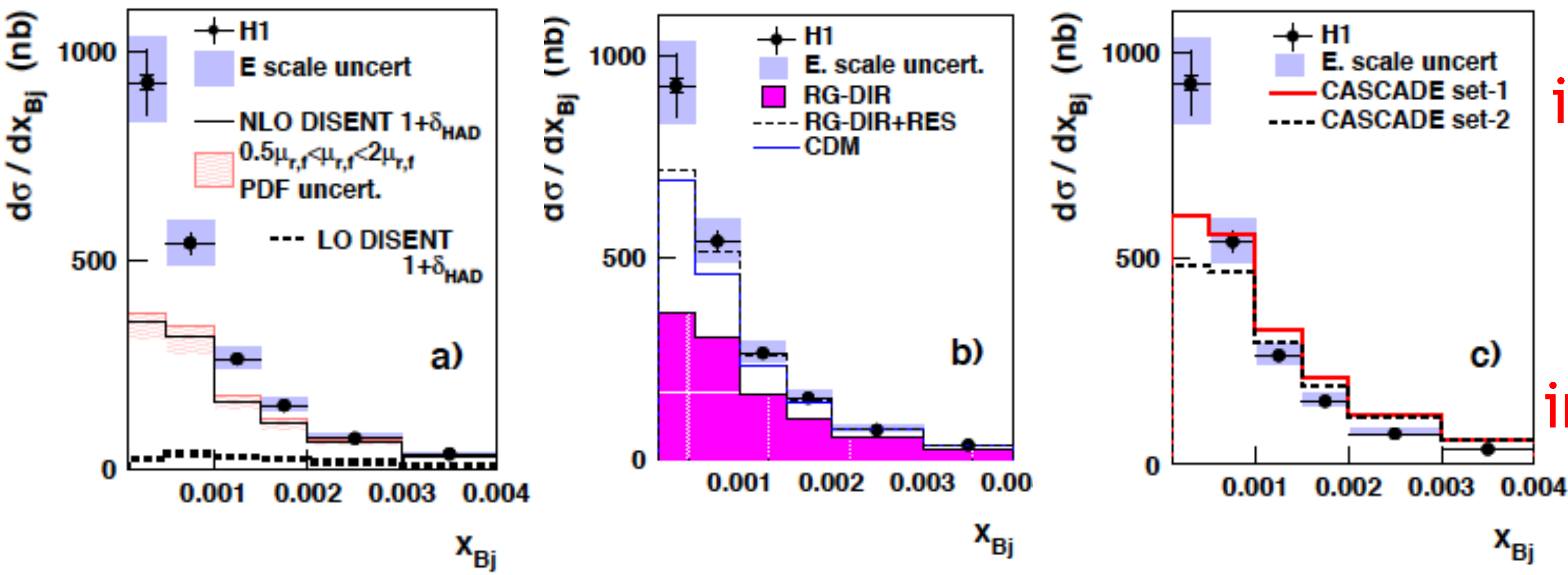
Moving to Hadronic Final State Observables: HERA

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

- Forward jets
- Azimuthal decorrelations
- High |t| p-diss J/Ψ…





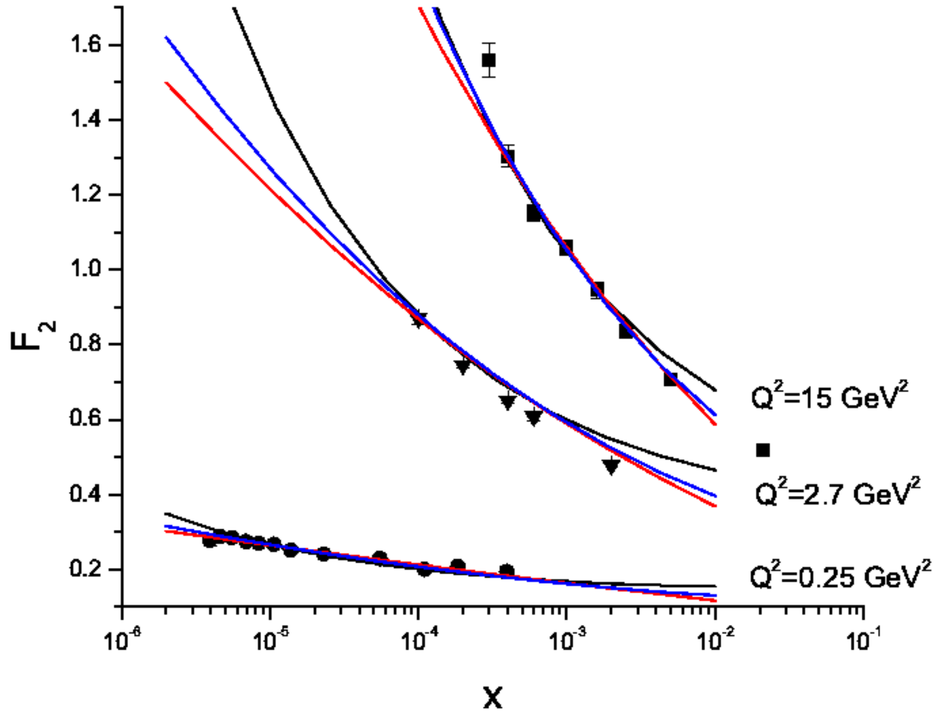


Some interesting effects … not easily interpreted

Parton Saturation after HERA?

e.g. Forshaw, Sandapen, Shaw
hep-ph/0411337,0608161
... used for illustrations here

Fit inclusive HERA data
using dipole models
with and without parton
saturation effects



FS04 Regge (~FKS): 2 pomeron model, no saturation
FS04 Satn: Simple implementation of saturation
CGC: Colour Glass Condensate version of saturation

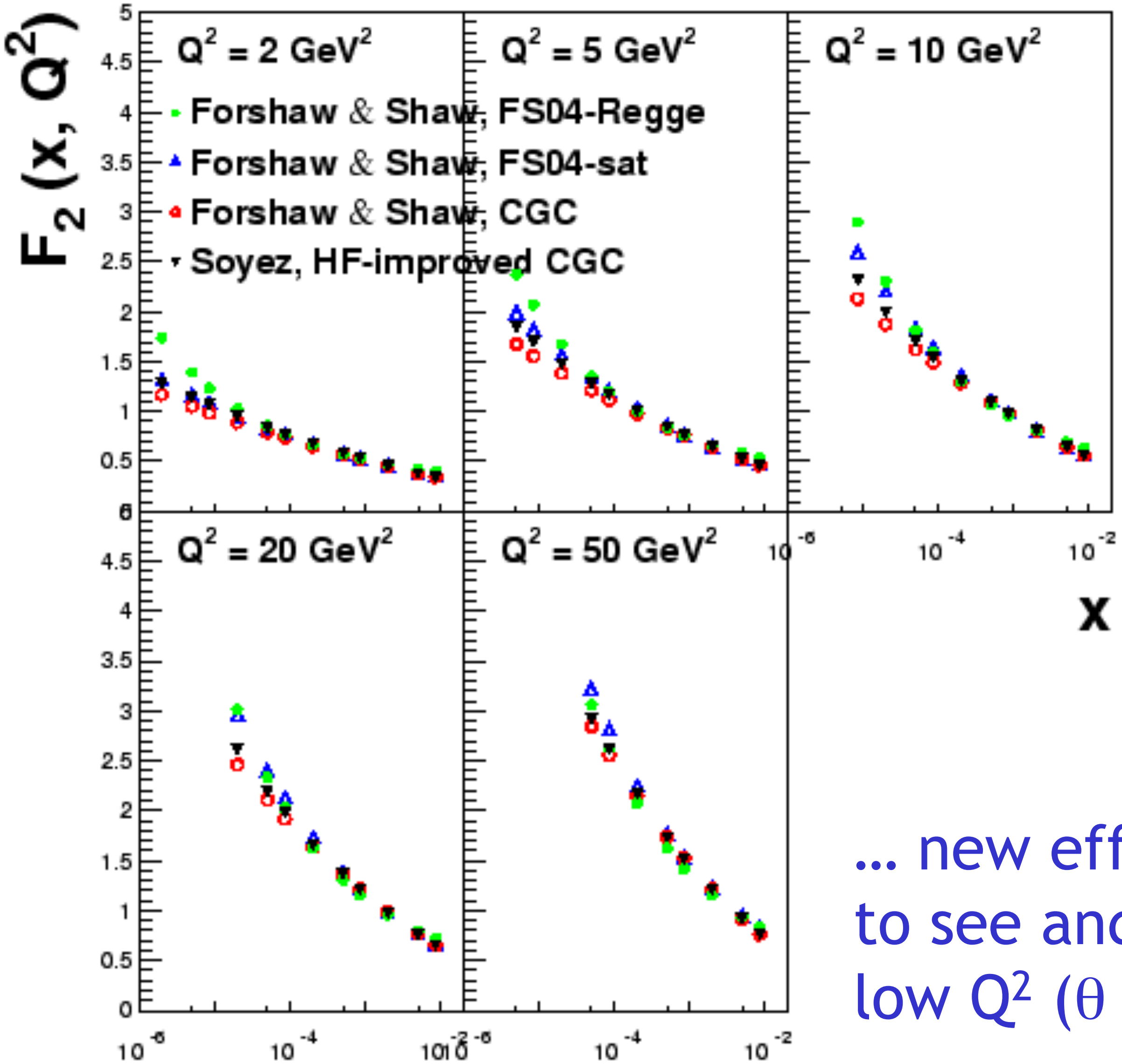
- All three models can describe data with $Q^2 > 1\mathrm{GeV}^2$, $x < 0.01$
- Only versions with saturation work for $0.045 < Q^2 < 1\ \mathrm{GeV}^2$

... any saturation at HERA not easily interpreted partonically

Some models of low x F_2 with LHeC Data

With 1 fb^{-1} (1 year at 10^{33} cm^{-2} s^{-1}), 1° detector:
stat. precision < 0.1%, syst, 1-3%

[Forshaw, Klein, PN, Soyez]



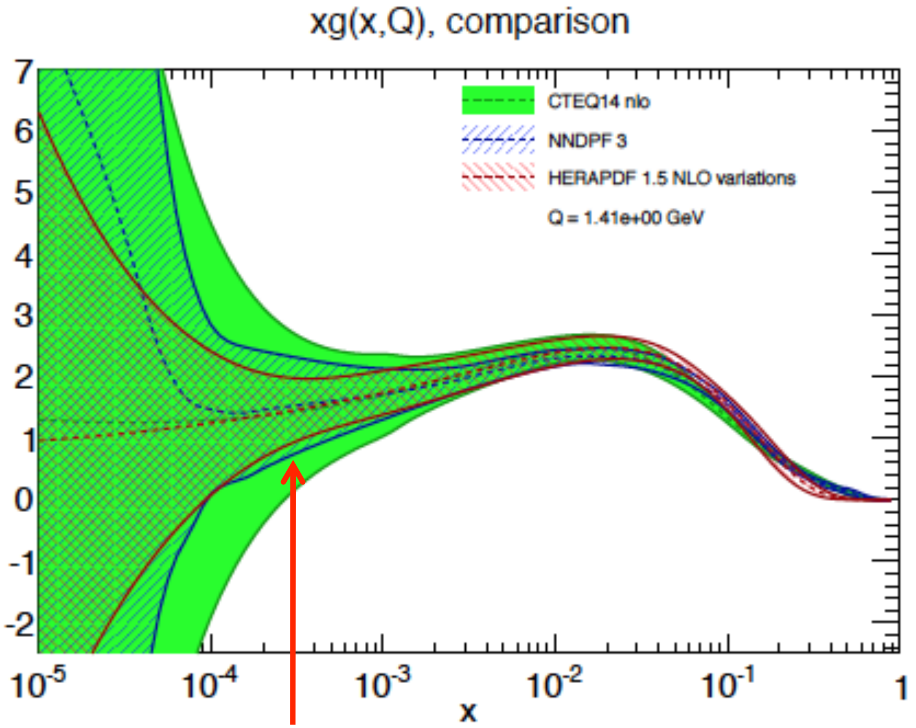
Precise data in LHeC region, x > ~10^{-6}

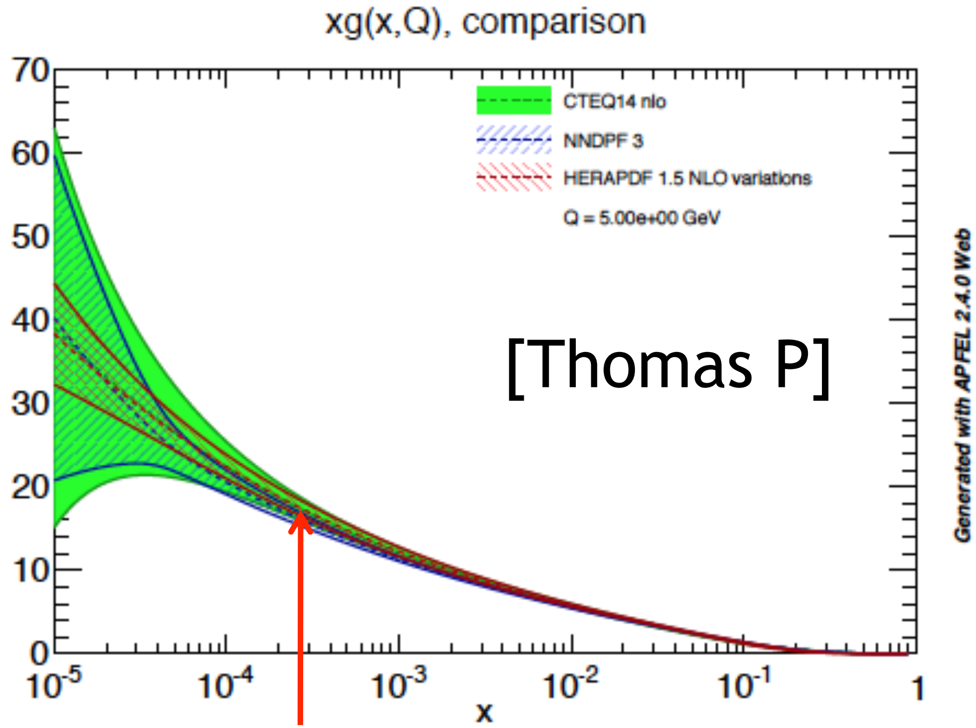
- Extrapolated HERA dipole models …
- FS04, CGC models including saturation suppressed at low x & Q^2 relative to non-sat FS04-Regge

… new effects may not be easy to see and will certainly need low Q^2 ($\theta \rightarrow 179°$) region …

How to persuade those who don't care …
…Why this is already dangerous at the LHC

- Use of PDFs based purely on DGLAP Q^2 evolution at low(ish) x, high Q^2 at the LHC will give incorrect results if there are saturation effects in the low x, low Q^2 data …



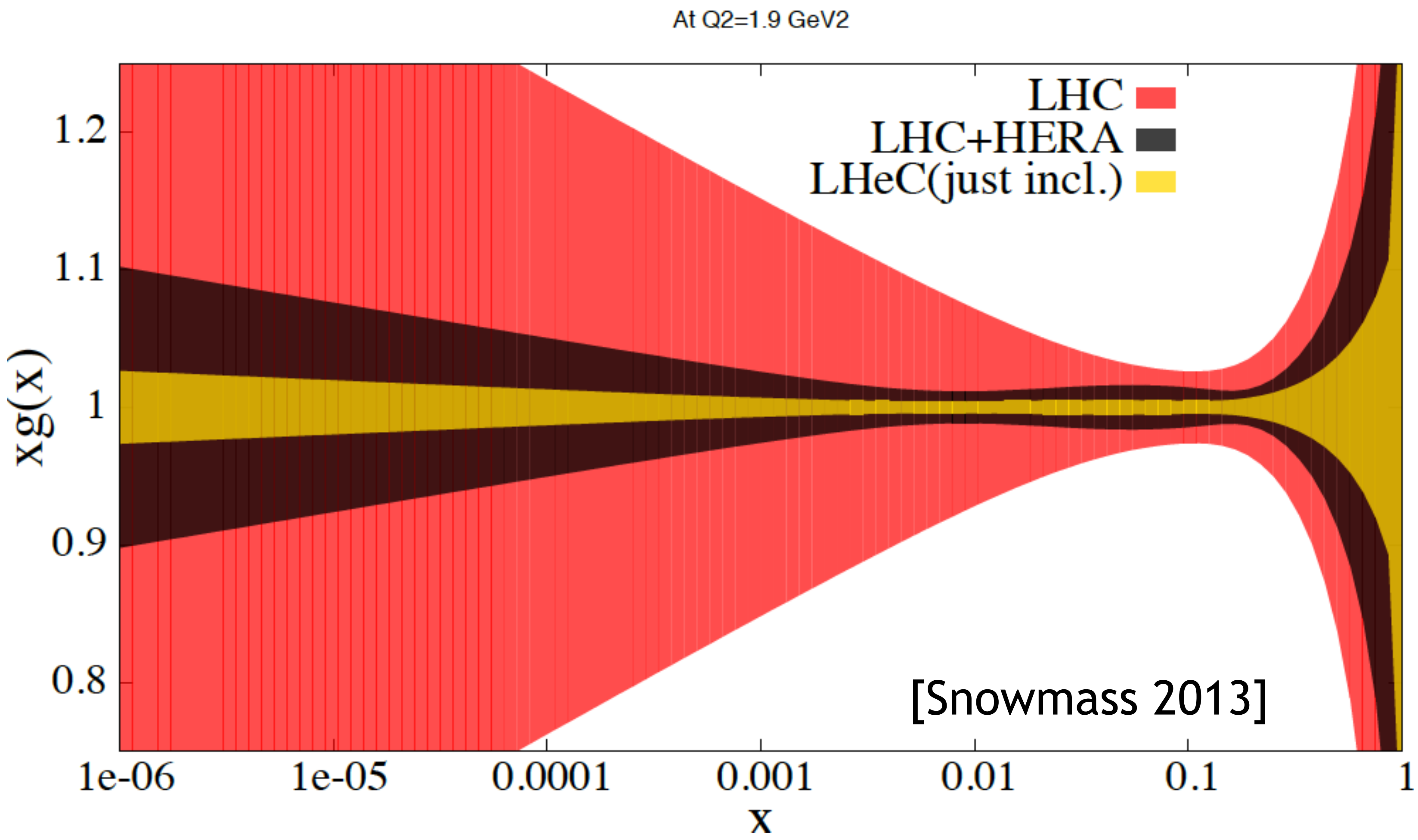


Constrained by data

Unconstrained by data

- Convergent solutions after DGLAP evolution can already be misleading at the LHC … worse at lower x → LHeC, FCC-eh …

What can be done with LHC alone?

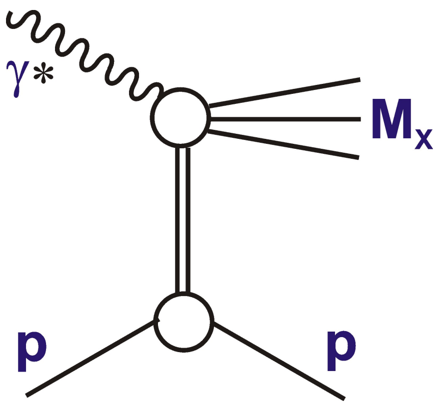


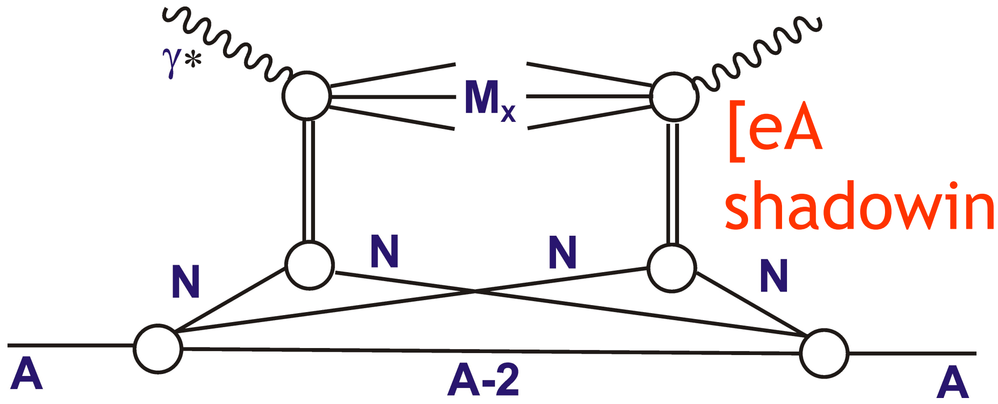
- LHC = current LHC W, Z and jet data
- Remarkable what can be achieved with LHC data alone
- Can we improve substantially? – Often already systs limited

F_2^D and Nuclear Shadowing

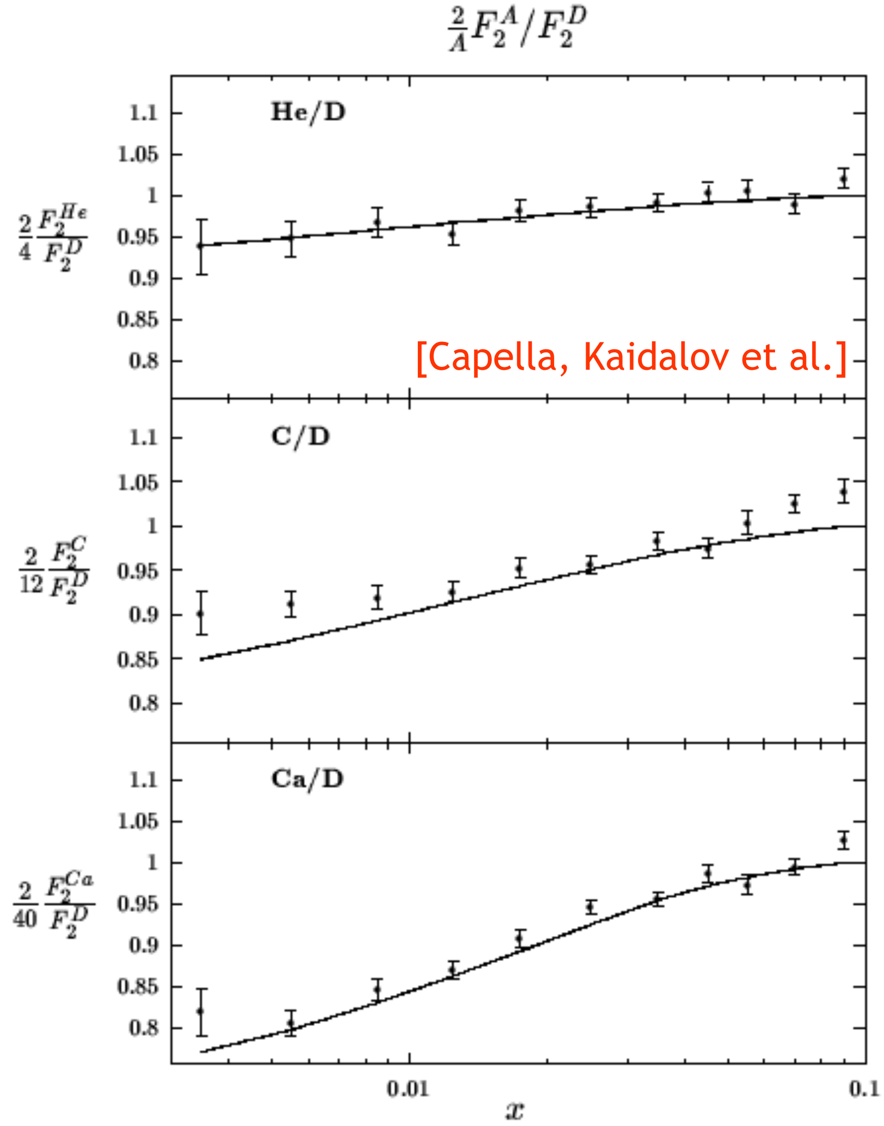
Nuclear shadowing can be described (Gribov-Glauber) as multiple interactions, starting from ep DPDFs

[Diff DIS]





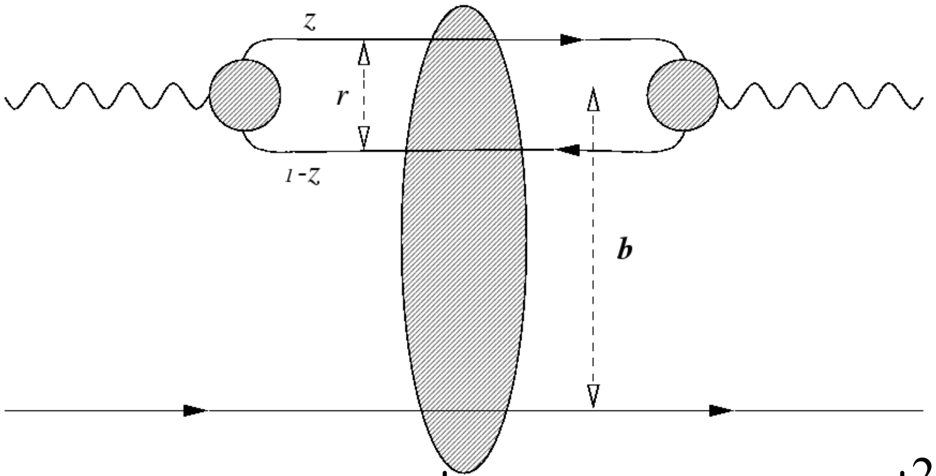
[eA shadowing]



… starting point for extending precision LHeC studies into eA collisions

Reminder : Dipole models

• Unified description of low x region, including region where Q^2 small and partons not appropriate degrees of freedom …



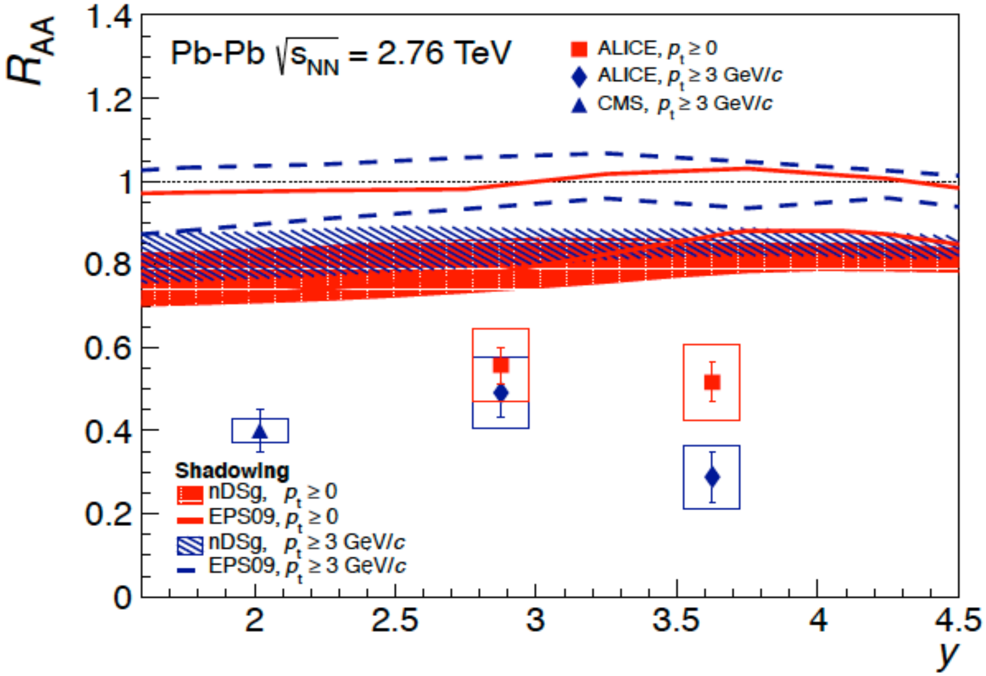
$$\sigma^{T,L}_{\gamma^* p}(x,Q^2) \sim \int dz\, d^2r\, \left|\psi^{T,L}_{\gamma^*}(z,r,Q^2)\right|^2 \sigma_{dipole}(x,r,z)$$

• Simple unified picture of many inclusive and exclusive processes … strong interaction physics in (universal) dipole cross section σ_{dipole}. Process dependence in wavefunction Ψ Factors

• qqbar-g dipoles also needed to describe inclusive diffraction

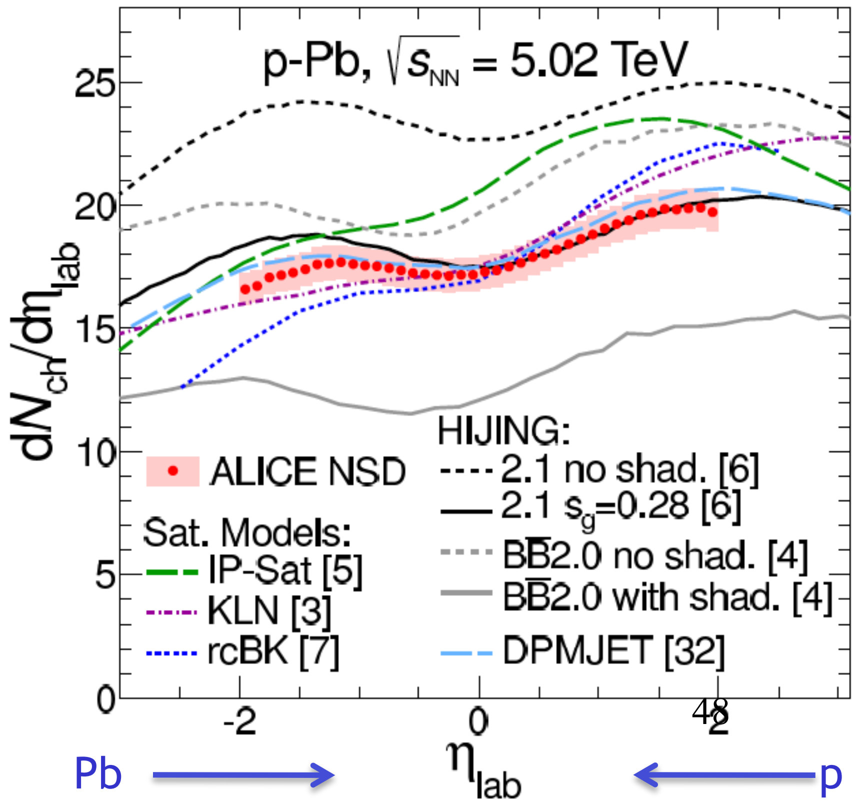
Current Low x Understanding in LHC Ion Data

Inclusive J/Ψ AA data



Uncertainties in low-x nuclear PDFs preclude precision statements on medium produced in AA (e.g. extent of screening of c-cbar potential)

Minimum Bias pA data



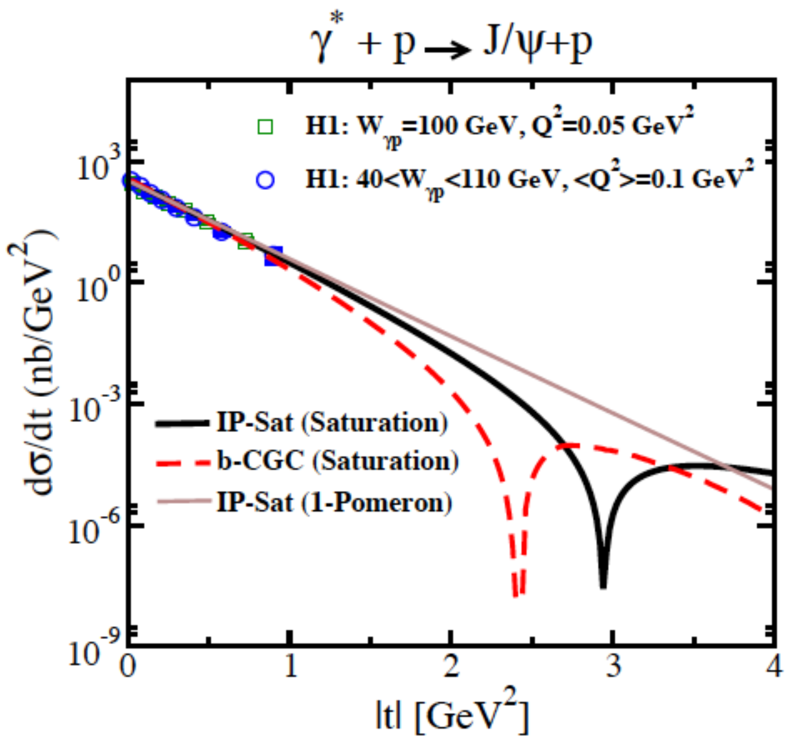
η dependence of pPb charged particle spectra best described by shadowing-only models (saturation models too steep?)

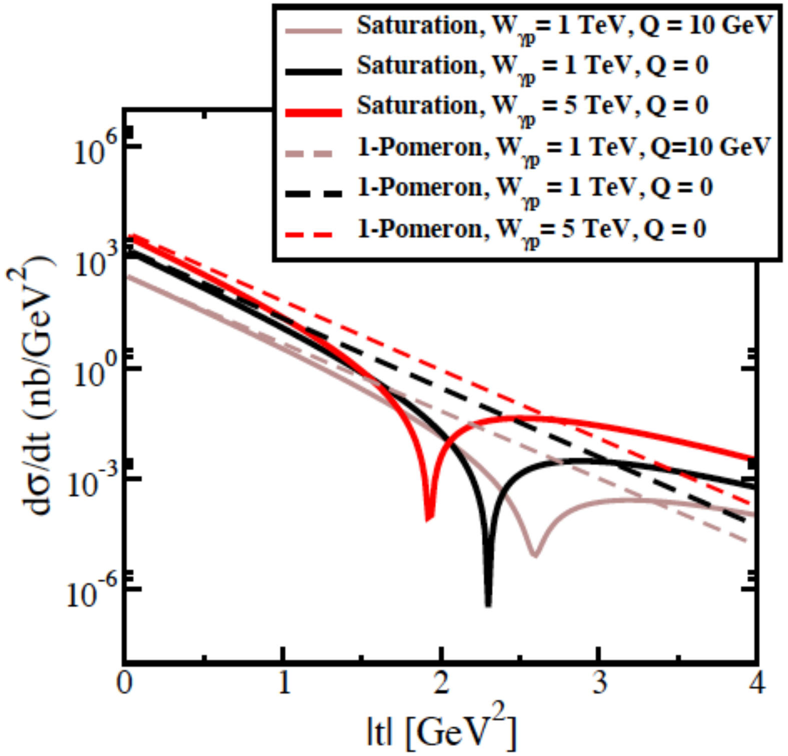
… progress with pPb, but uncertainties still large, detailed situation far from clear

Signals in t Dependences: e.g. J/ψ Photoproduction

t dependences measure Fourier transform of impact parameter distribution. → Unusual features can arise from deviations from Gaussian matter distribution

e.g. Characteristic dips in model by Rezaeian et al, (just) within LHeC sensitive t range.





Leading Neutrons

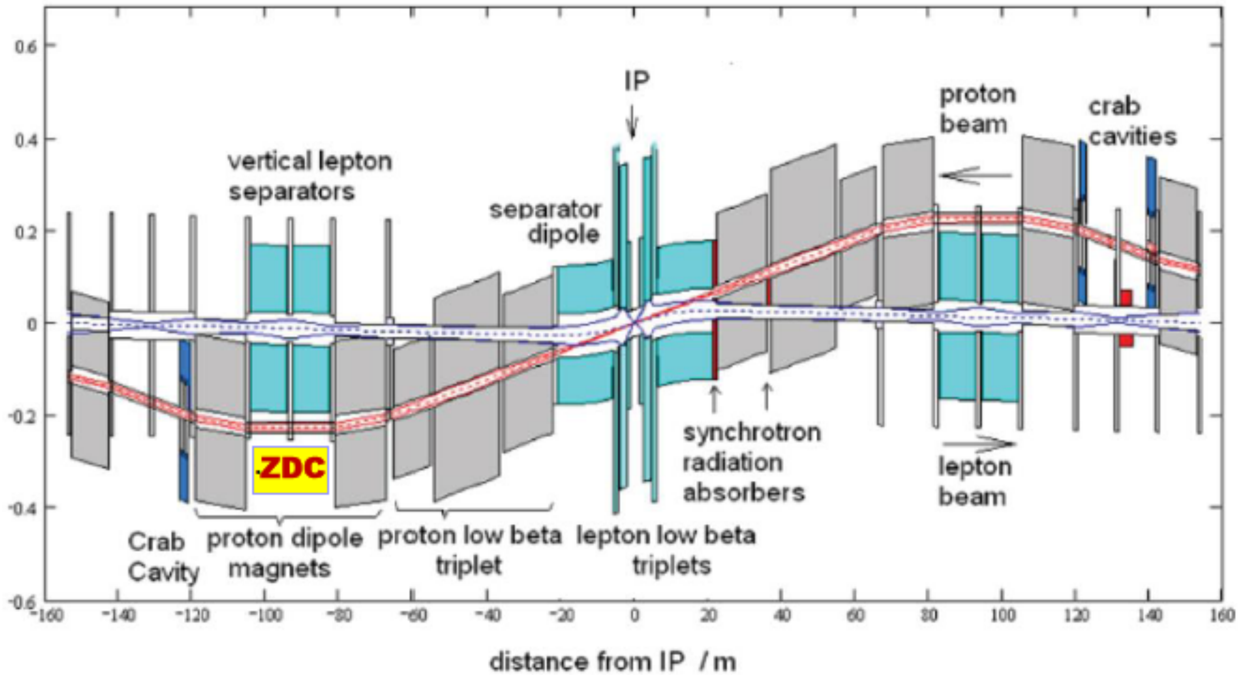
- Crucial in eA, to determine whether nucleus remains intact e.g. to distinguish coherent from incoherent diffraction

- Crucial in ed, to distinguish scattering from p or n

- Forward γ and n cross sections relevant to cosmic ray physics

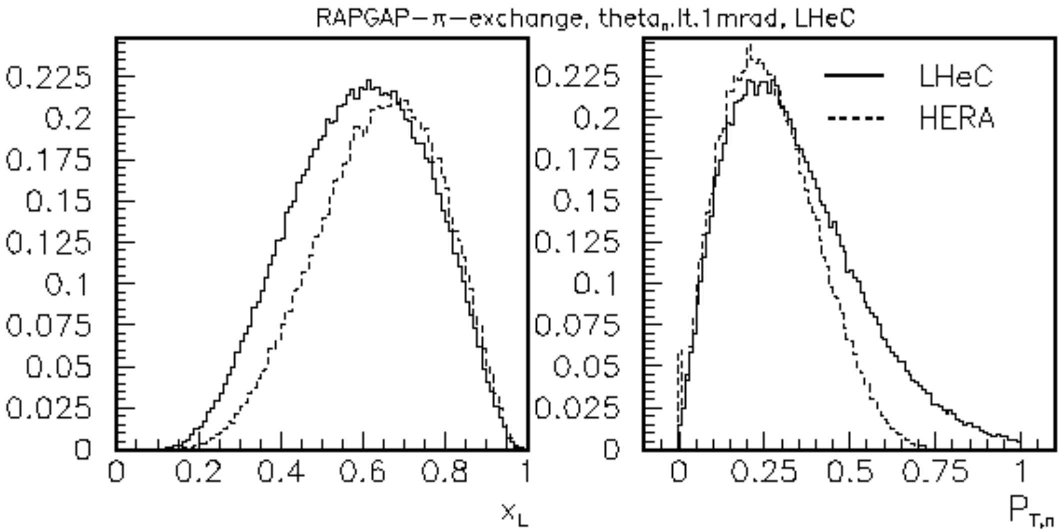
- Has previously been used in ep to study π structure function

Possible space at z ~ 100m (also possibly for proton calorimeter)



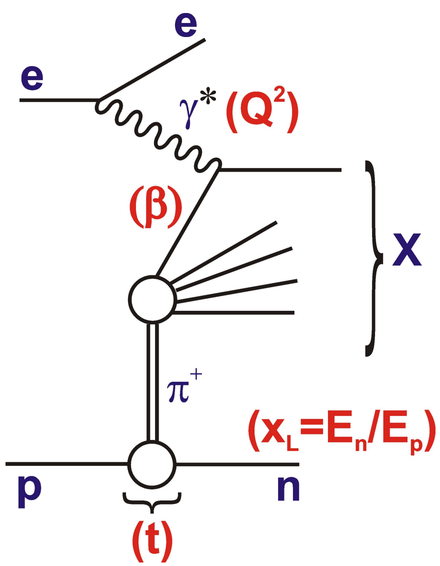
... to be further investigated

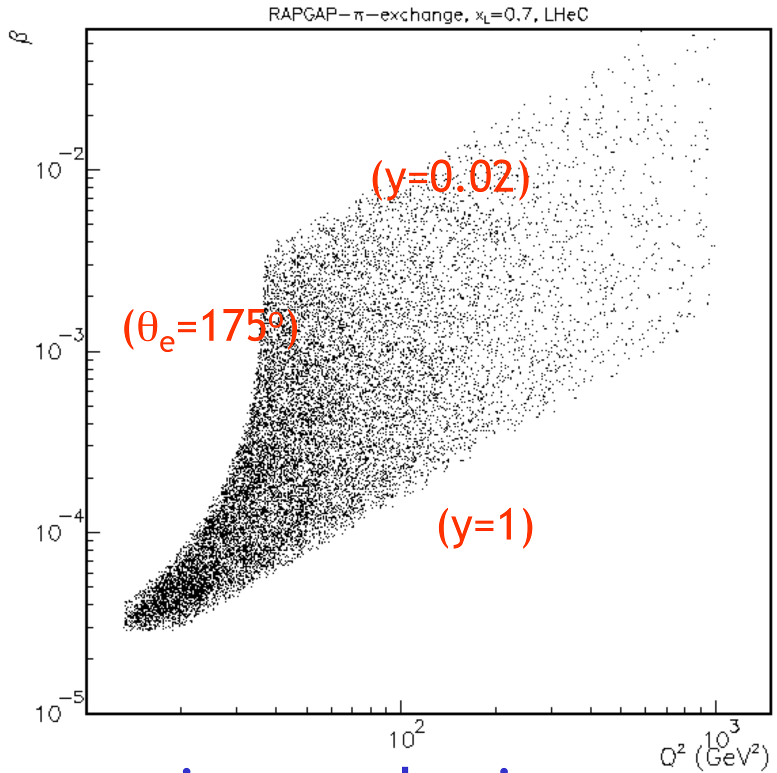
π Structure with Leading Neutrons



[Bunyatyan]

(RAPGAP MC model, E_p=7TeV, E_e=70GeV)



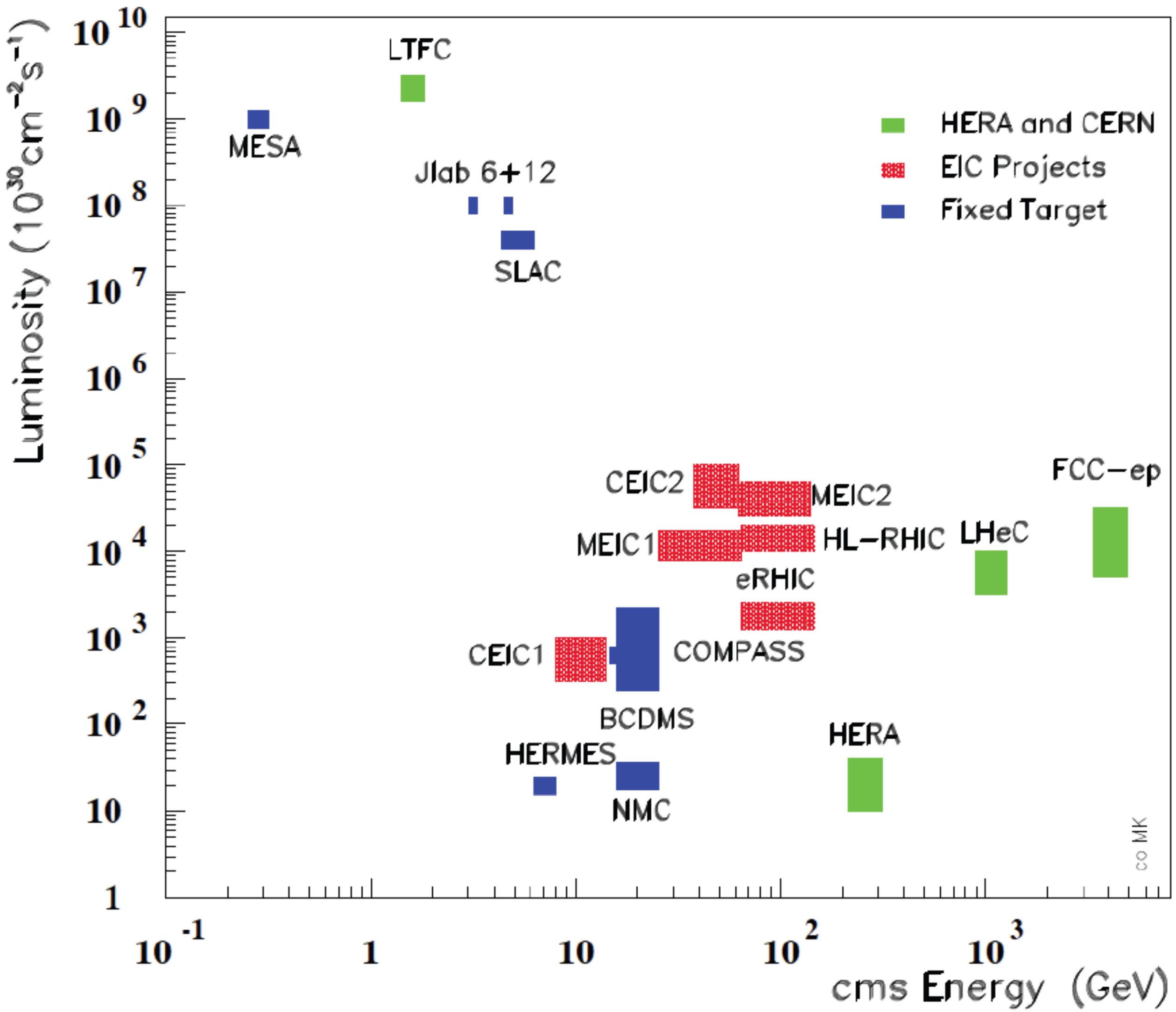


- With θ_n < 1 mrad, similar x_L and p_t ranges to HERA (a bit more p_t lever-arm for π flux).

- Extentions to lower β and higher Q^2 as in leading proton case. → F_2^π At $\beta<5.10^{-5}$ (cf HERA reaches $\beta\sim10^{-3}$)

Also relevant to absorptive corrections, cosmic ray physics …

LHeC / FCC-he Context



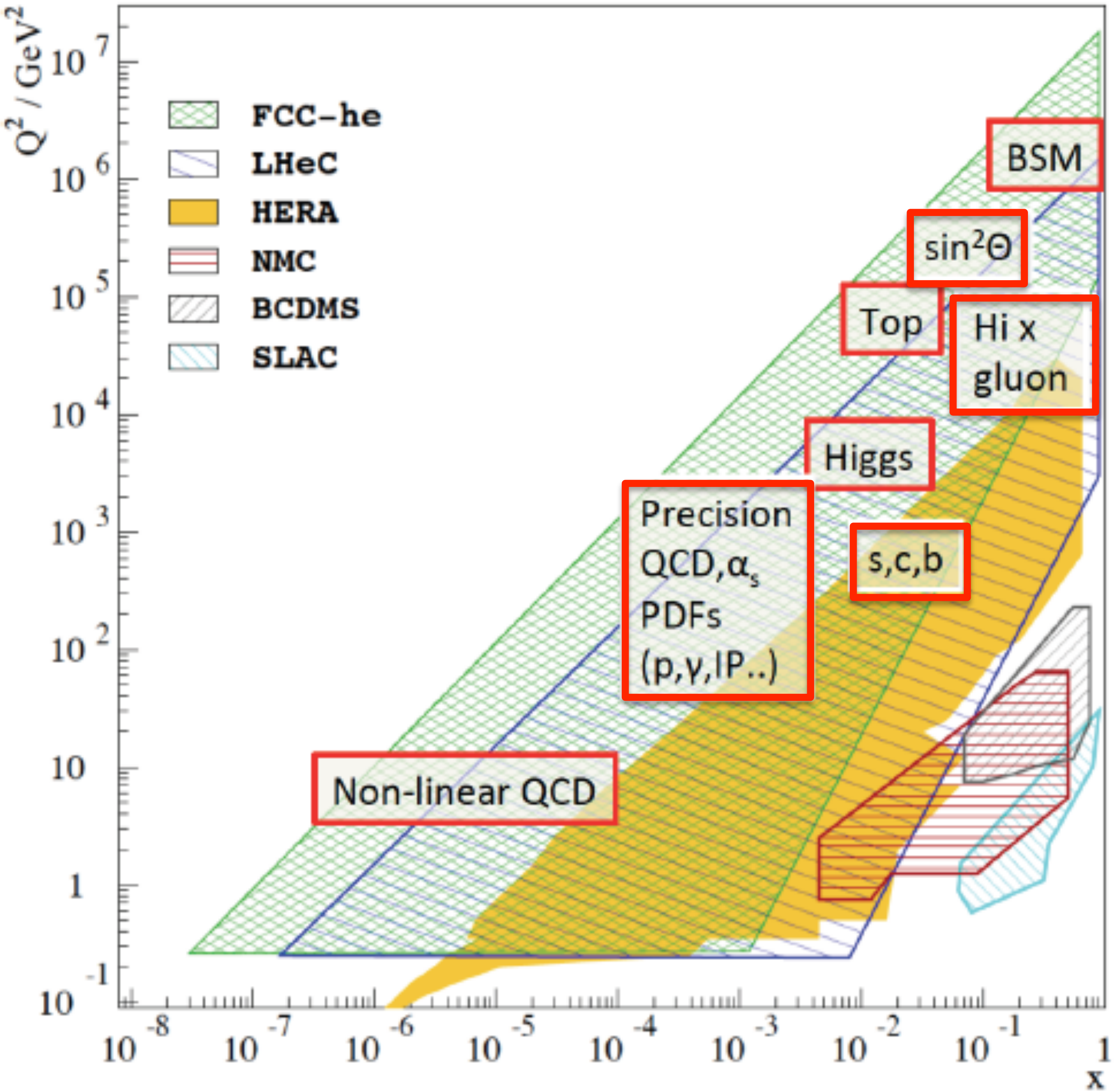
Main weakness: No polarised hadrons

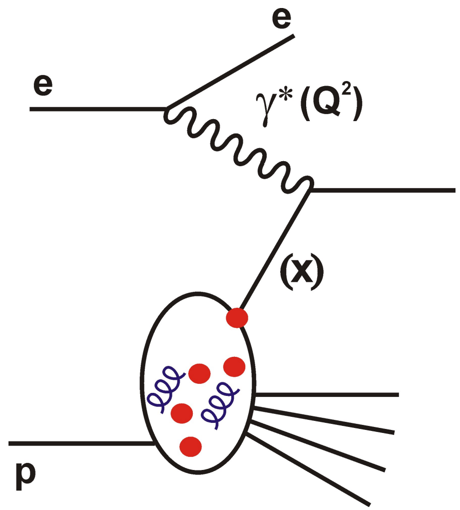
Lepton-hadron scattering at the TeV scale …

LHeC: 60 GeV electrons x LHC protons & ions
→ 10^{34} cm^{-2} s^{-1}
→ Simultaneous running with ATLAS / CMS sometime in HL-LHC period

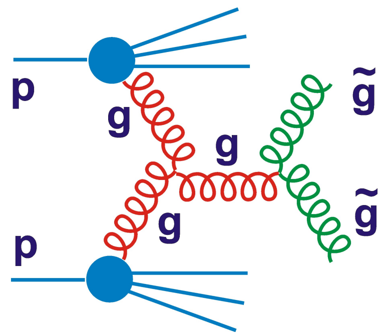
FCC-he: 60 GeV electrons x 50 TeV protons (and corresponding ions) from FCC

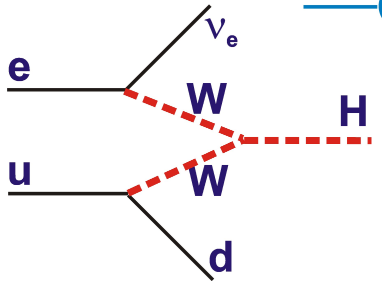
LHeC Physics at 10^{34} cm^{-2}s^{-1}





Diverse physics goals require precision throughout wide accessible kinematic region.





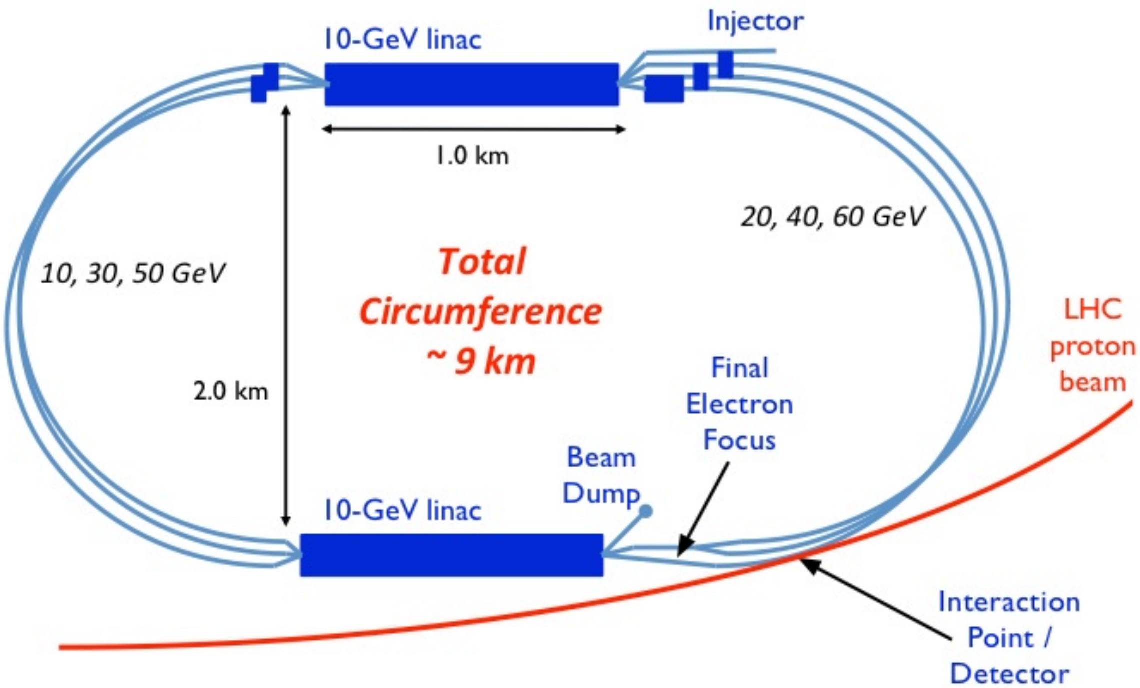
Baseline Design (Electron "Linac")

- Design constraint: power consumption < 100 MW → E_e = 60 GeV

- Colliding with E_p = 7 TeV from LHC (or even 50 TeV from FCC) and equivalent ion beams

- Two 10 GeV linacs,
- 3 returns, 20 MV/m
- Energy recovery in same structures

[Energy recovery Linac prototype planned @ Orsay]

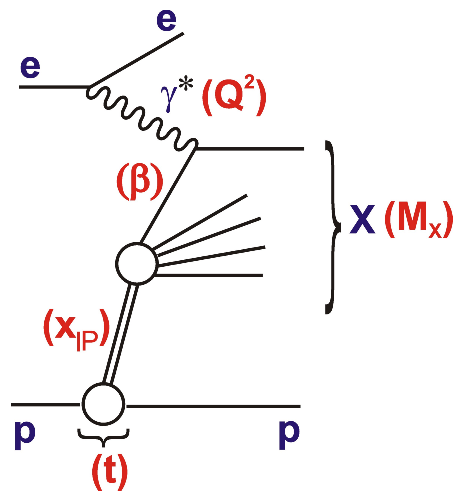


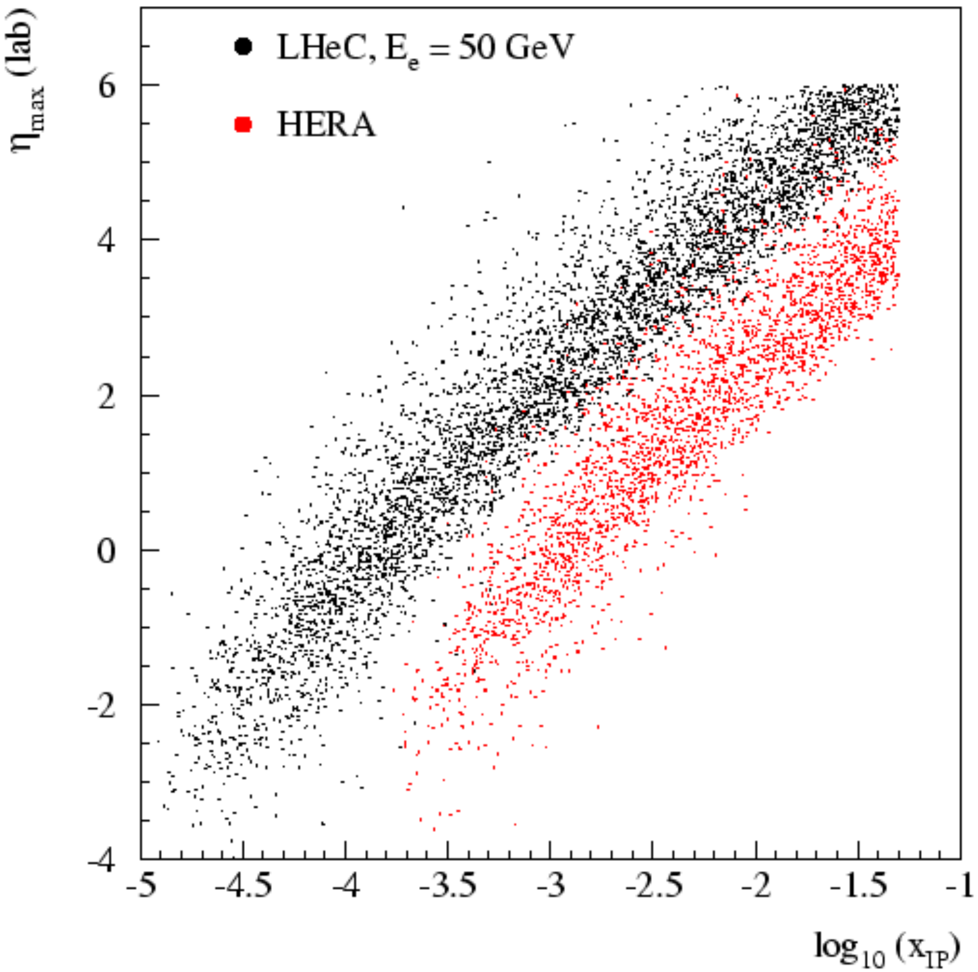
- ep lumi → 10^{34} cm^{-2} s^{-1}

→ ~100 fb^{-1} per year →~1 ab^{-1} total

- **eD and eA collisions have always been integral to programme**
- **e-nucleon Lumi estimates ~ 10^{31} (10^{32}) cm^{-2} s^{-1} for eD (ePb)**

Rapidity Gap Selection



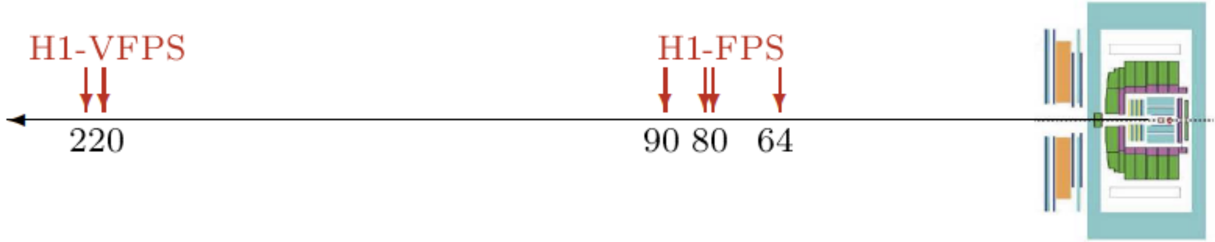


– η_{max} v ξ correlation entirely determined by proton beam energy

- Cut around η_{max} ~ 3 selects events with x_{IP} <~ 10^{-3} at LHeC (cf x_{IP} <~ 10^{-2} at HERA

Intact Proton Selection Methods beyond HERA

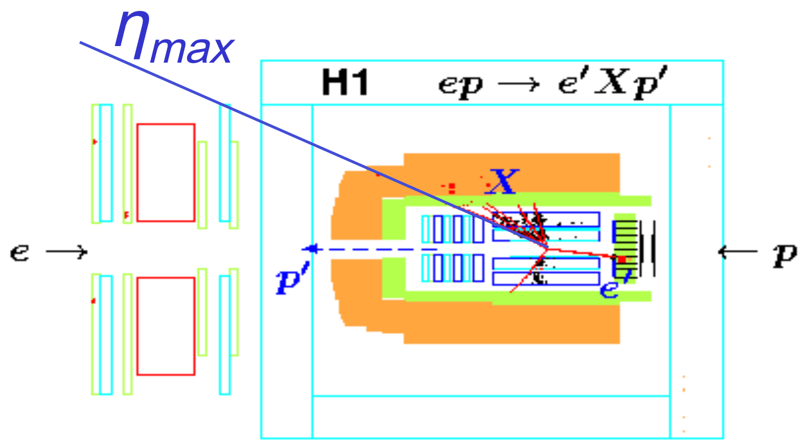
1) Measure scattered Proton in Roman Pots



- Allows t measurement, but limited by stats, p- tagging systs

2) Select Large Rapidity Gaps

-Limited by control over proton dissociation contribution



- Methods have very different systematics → complementary
- In practice, method 2 yielded lasting HERA results, because of statistical and kinematic range limitations of Roman pots
- Roman pots mainly contsrained t distributions
- **LHeC & EIC different → higher lumi + pot design from outset**

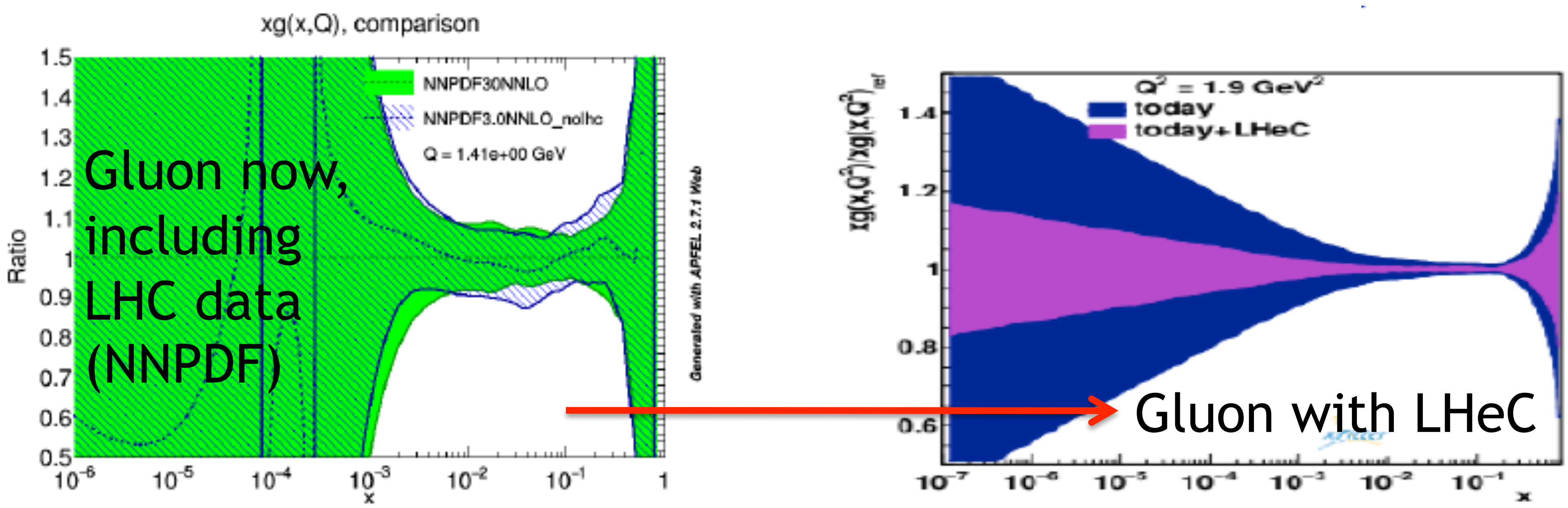
(NEW) DGLAP PDF Fits to LHeC Pseudo-Data

-Simulated NC, CC `pseudo-data' with reasonable assumptions on systematics (typically 2x better than H1 and ZEUS at HERA).
- NEW: Luminosity increased since CDR → up to 1ab^{-1}
- NEW: Fitting framework → as for HERAPDF 2.0 at NLO

source of uncertainty	error on the source or cross section
scattered electron energy scale $\Delta E_e'/E_e'$	0.1 %
scattered electron polar angle	0.1 mrad
hadronic energy scale $\Delta E_h/E_h$	0.5 %
calorimeter noise (only $y < 0.01$)	1-3 %
radiative corrections	0.3%
photoproduction background (only $y > 0.5$)	1 %
global efficiency error	0.7 %

- NLO DGLAP fit using HERAPDF2.0, including:
  - LHeC NC and CC e^+p and e^-p cross sections
  - NEW: HERA-1 and HERA-2 final combined H1+ZEUS data
  - Fixed target BCDMS data with W>15 GeV
  - NEW: HERA jet and various Tevatron / LHC data

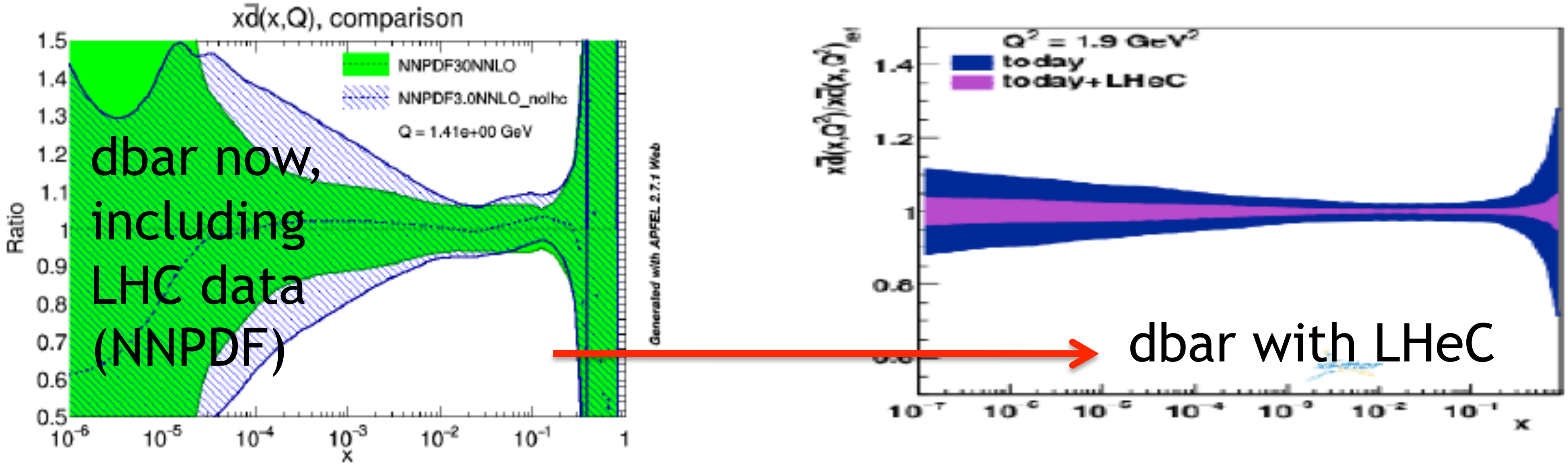
Low x Gluon with LHC, with and without LHeC



Standard LHC channels do not help much:

- ATLAS and CMS constraints as currently included in PDF fits (jets, top) don’t extend below $x \sim 10^{-3}$.
- Other channels may help if theoretical issues can be overcome (LHCb c,b, maybe even exclusive J/Ψ)
- Current knowledge basically comes from HERA: stops at $x \sim 5.10^{-4}$
- LHeC gives constraints to $x \sim 10^{-6}$ from scaling violations and F_L

Low x Sea with LHC, with and without LHeC

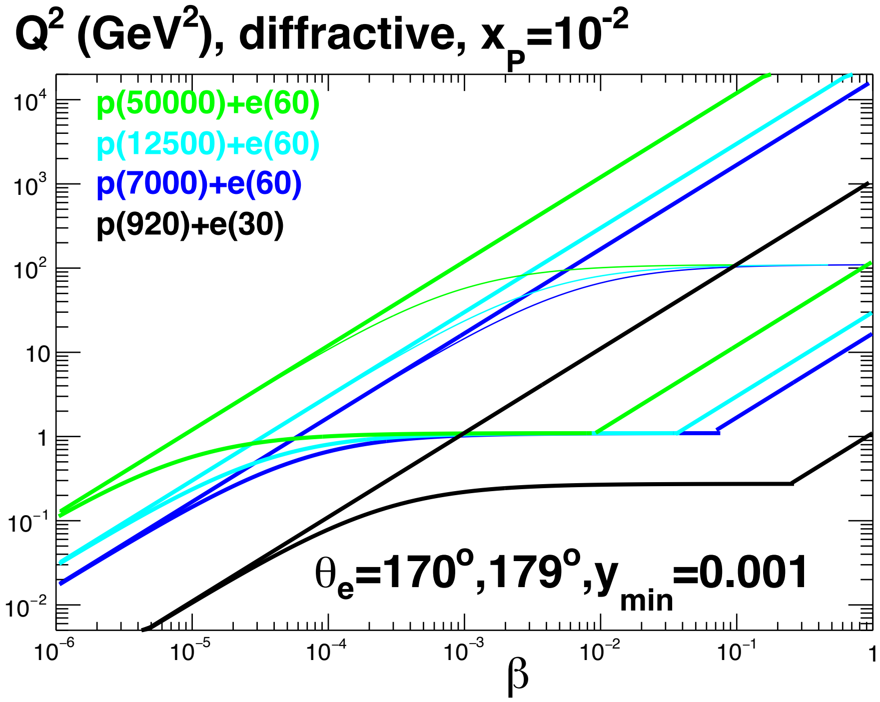


<u>**LHC channels help, but not on same level as LHeC:**</u>

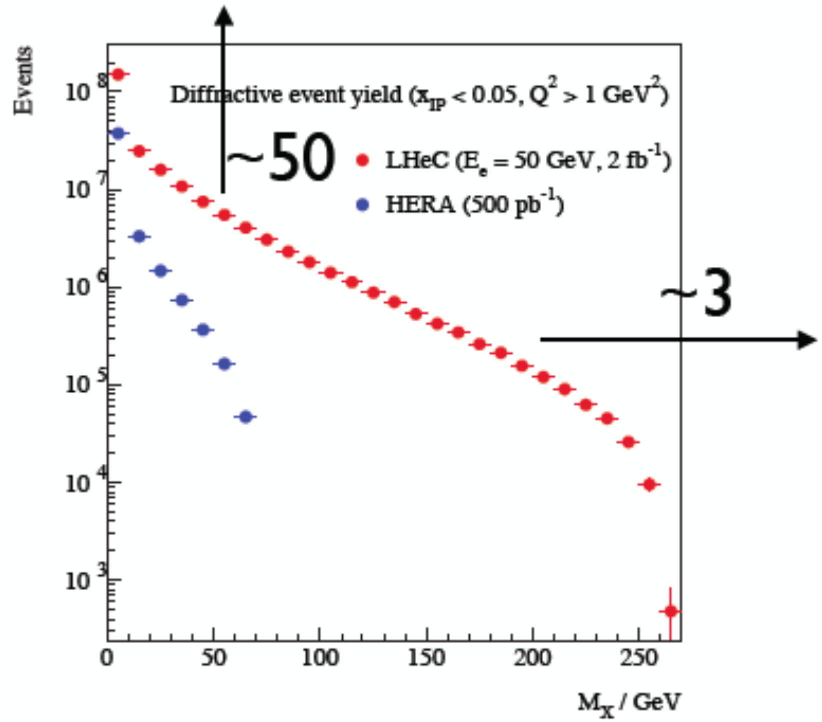
- ATLAS and CMS low mass Drell-Yan data have an impact
- Also potentially LHCb Drell-Yan
- Other channels may help (see eg ALICE direct photon / FOCAL)
- LHeC goes to $x \sim 10^{-6}$, directly from F_2

… this is what DIS does best …

The More Distant Future: ep at a CERN Future Circular Collider



FCC-eh kinematics sensitive to diffractive structure in larger (β,Q^2) range than (x,Q^2) range sampled for the proton @ HERA!



-Similarly for masses and transverse momenta of jets.

- W range for VMs → multi-TeV