# Low x Physics and Saturation: From HERA to Future DIS and the LHeC

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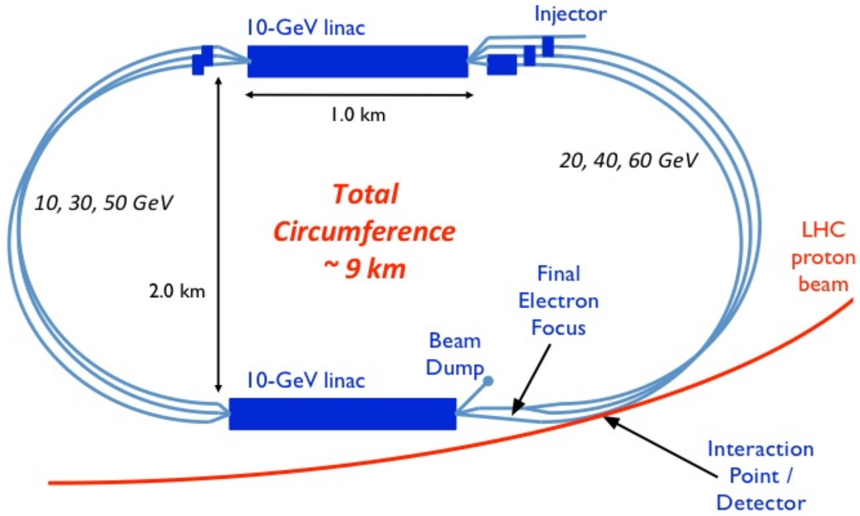
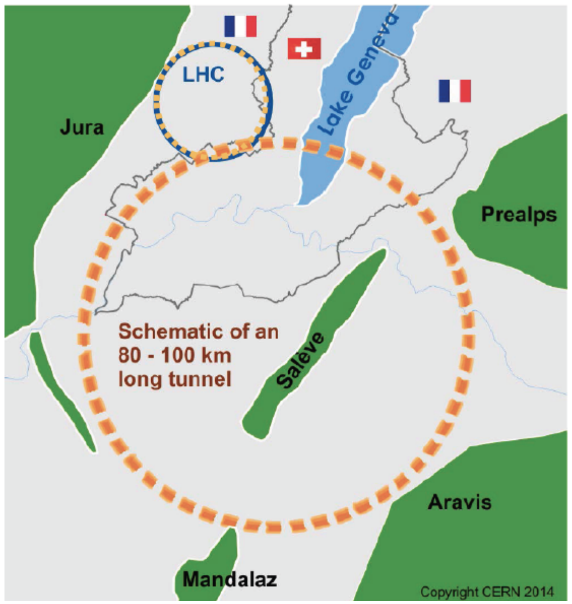






# Low x Physics at HERA: the "Pathological" Gluon

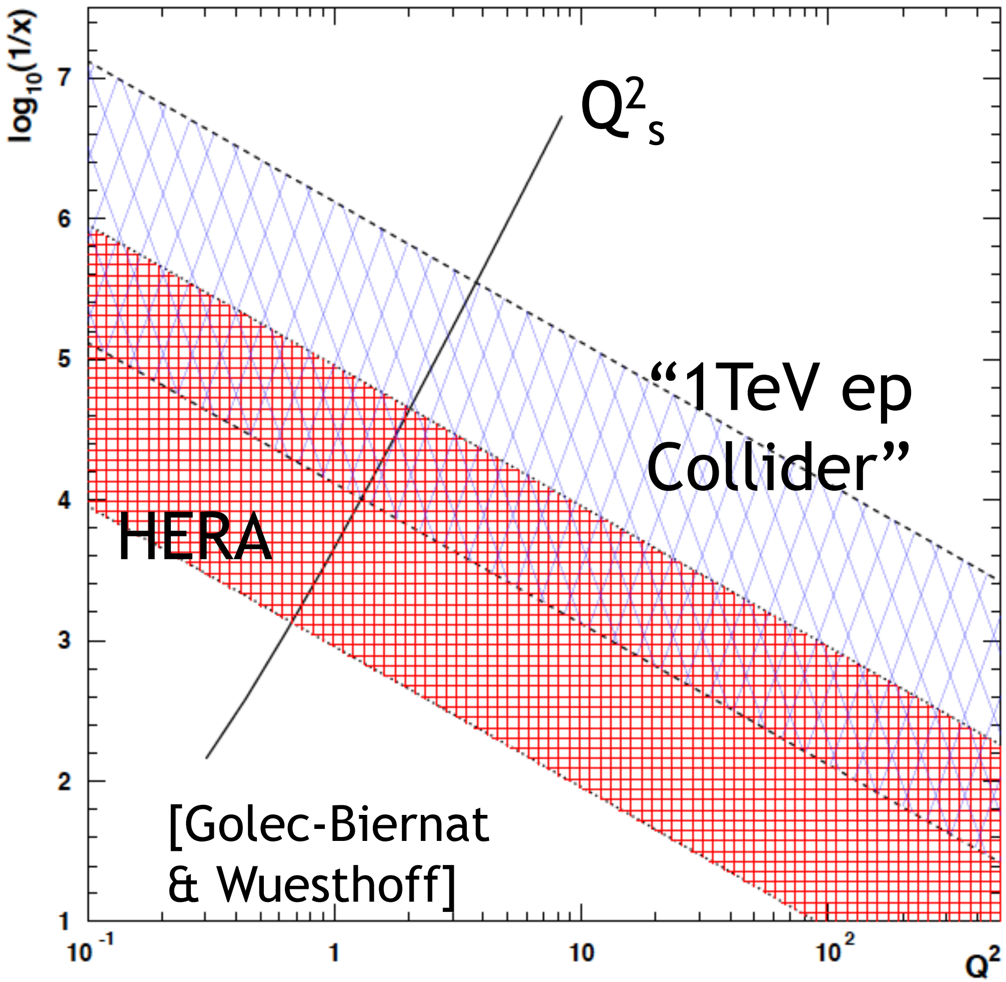
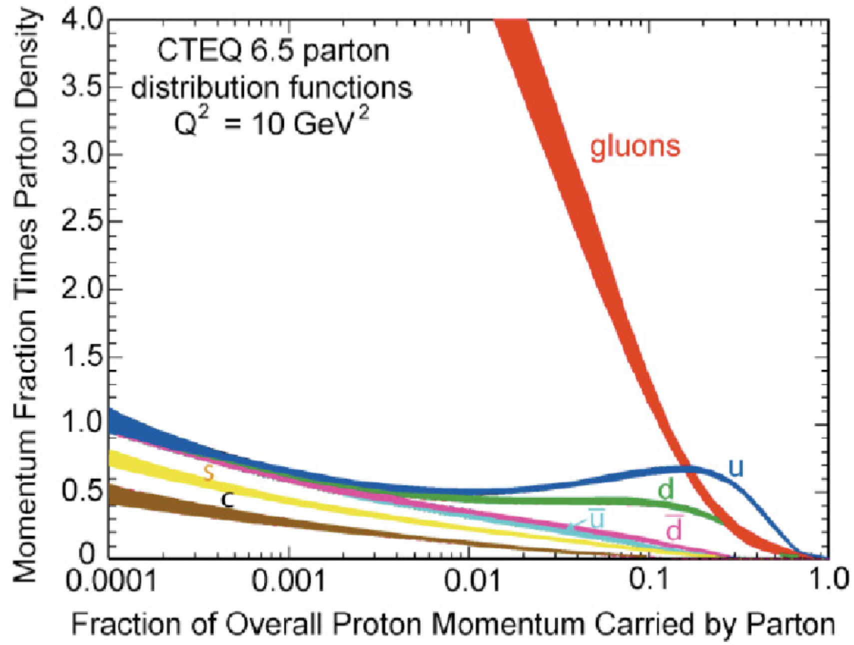



Figure 5: The position of the critical line in the $(x, Q^2)$-plane. The narrow hatched area corresponds to the acceptance region of HERA. The wide hatched region indicates the range for a future 1 $TeV$ $ep$-collider. The boundaries are lines of constant $y$.

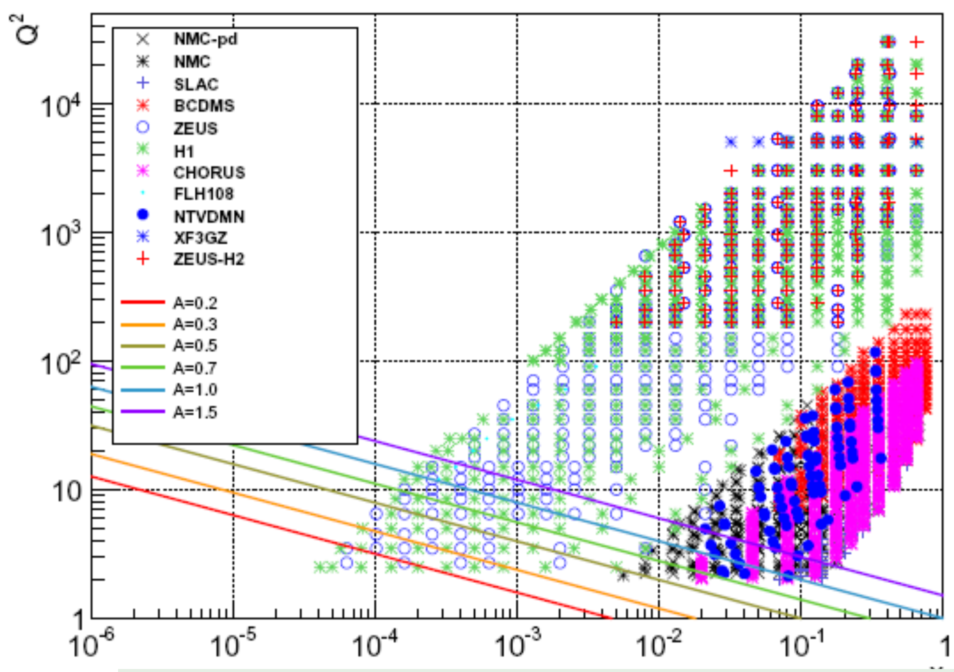



**1998:** Low x HERA data are well fitted in (dipole) models that include saturation effects
- x dependent "saturation scale", $Q^2_s(x)$

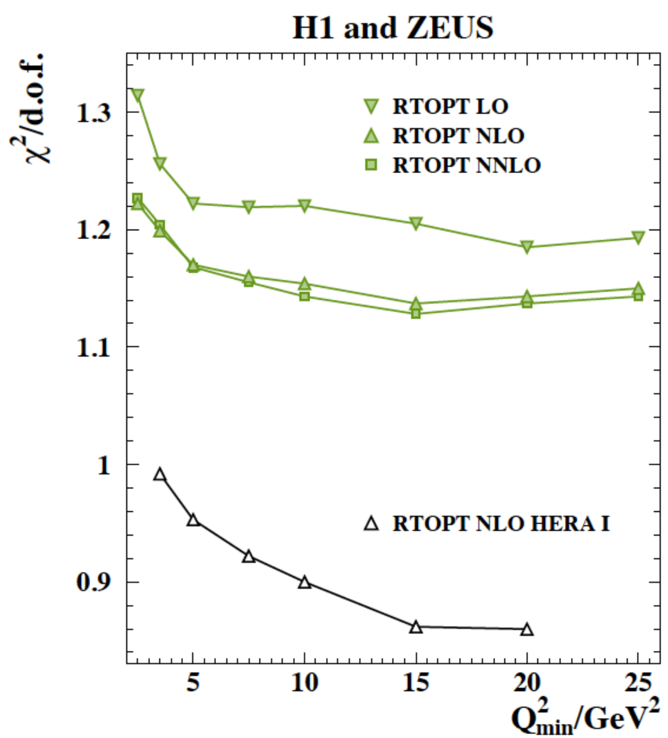
$$\frac{xG_A(x, Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{\sim -0.3}$$

# Saturation and DGLAP PDF fits

**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 | $62.31/59 = 1.06$ | $860.65/59 = 14.6$ |

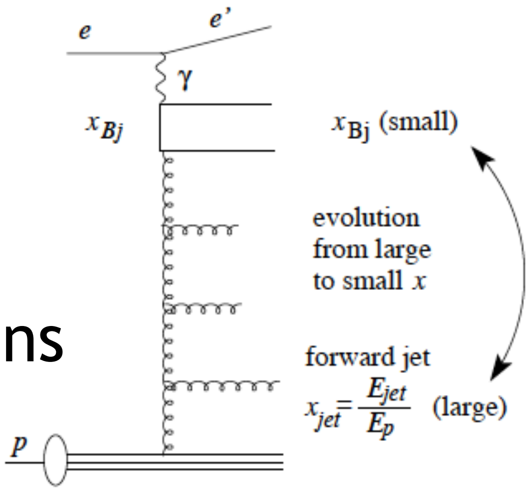


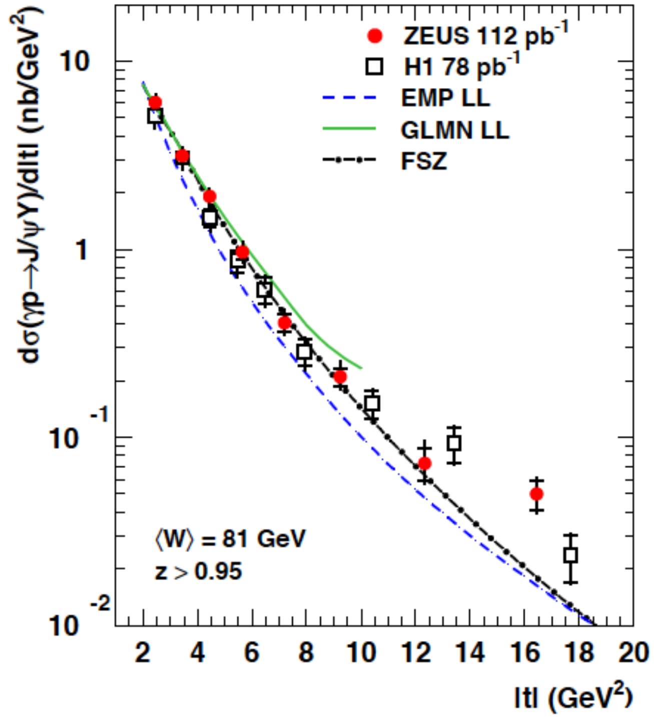

**Final HERA-2 Combined PDF Paper:**
"some tension in fit between low & medium $Q^2$ data… not attributable to particular x region" (though kinematic correlation)
… something happens, but interpretation?

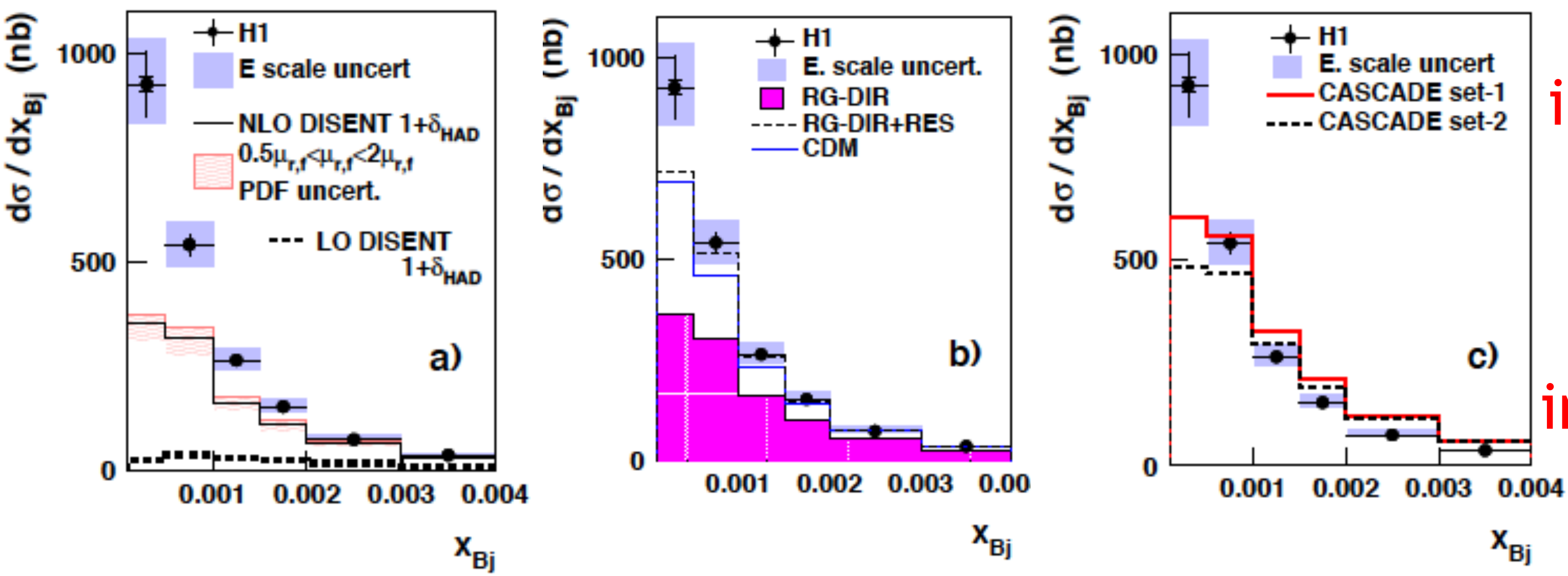
# Hadronic Final State Observables

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…

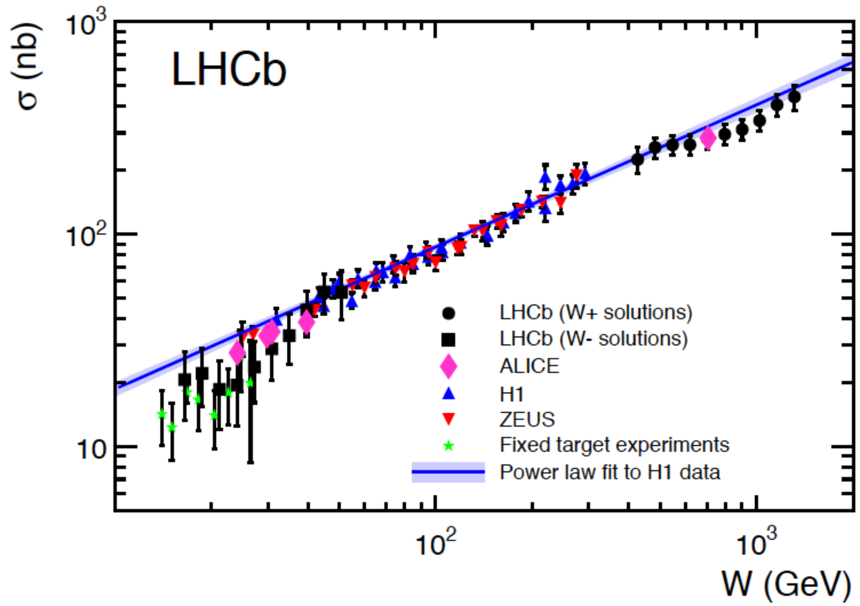


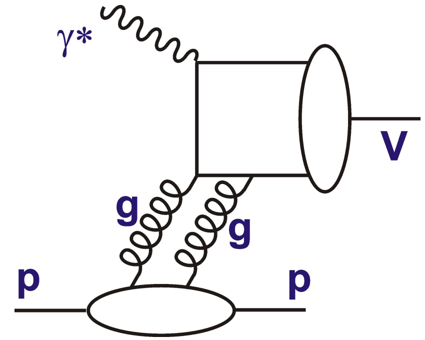



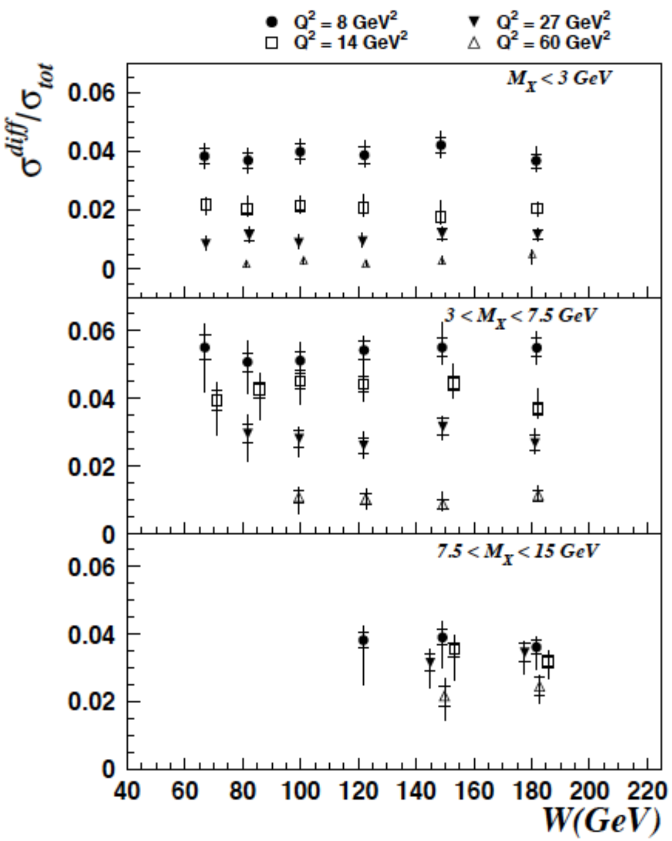

Some interesting effects … not easily interpreted

# Low x Saturation in Diffractive Data?



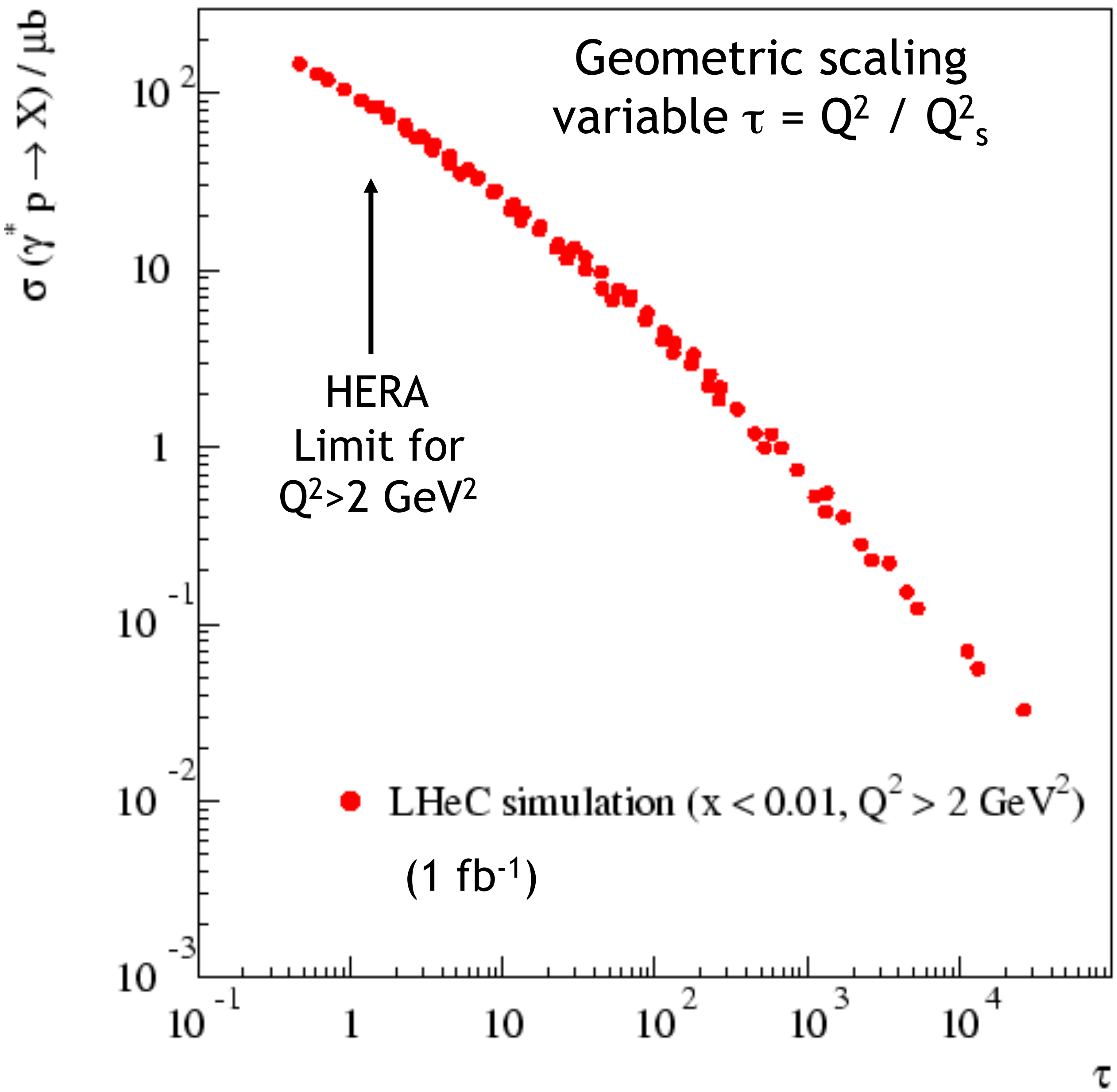

- Elastic J/Ψ in γp …
- No evidence for change in shape at high W (i.e. low x), even at LHC (t dependence yet to be exploited)




- Rather flat diffractive/inclusive ratio and failure of diffractive PDF fits to data below $Q^2$ ~ 5 $GeV^2$ best described by dipole models incorporating saturation …

BOTTOM LINE … HERA not conclusive on location or dynamics of onset and LHC has not given greater clarity

# Problem of Inclusive Data in 1 Dimension




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

LHeC reaches $\tau$ ~ 0.15 for $Q^2$=1 GeV$^2$ and $\tau$ ~ 0.4 for $Q^2$=2 GeV$^2$

Can also be enhanced with nuclei.

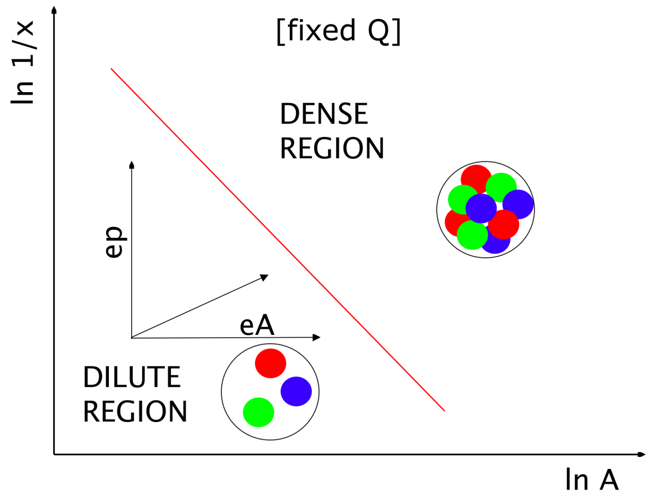
# Accessing saturation region at large $Q^2$

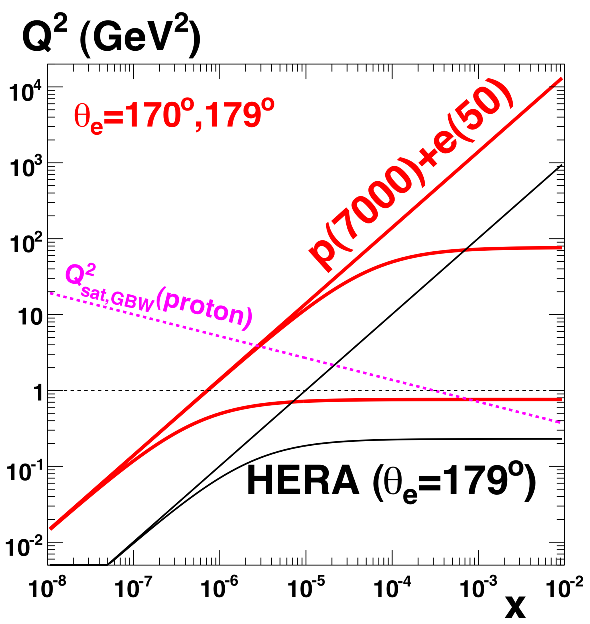
2-pronged approach: EIC and LHeC

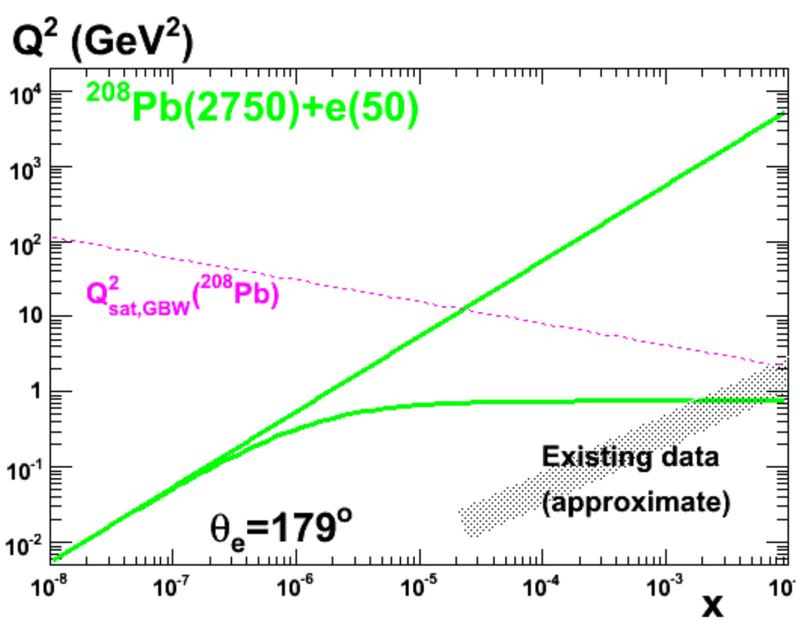
Enhance target `blackness' by:

1) Probing lower x at fixed $Q^2$ in ep
   [evolution of a single source]

2) Increasing target matter in eA
   [overlapping many sources at fixed kinematics …
   Density ~ $A^{1/3}$ ~ 6 for Pb … worth 2 orders of magnitude in x]



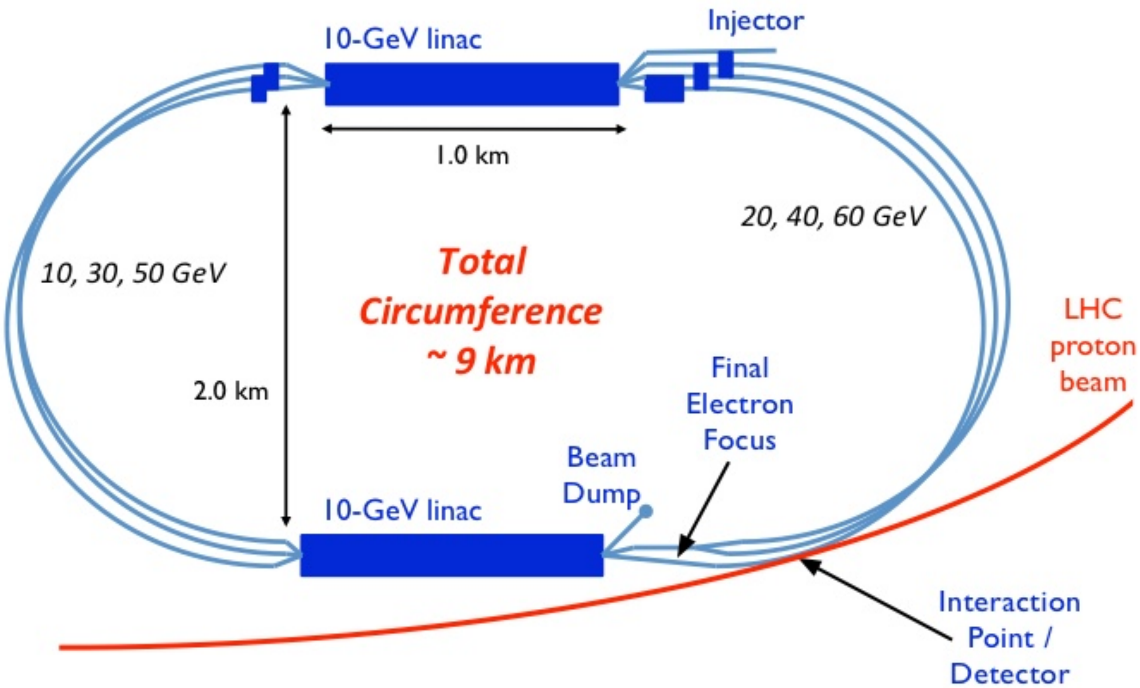

… e.g. LHeC reaches saturated region in both ep & eA inclusive data according to models

# Baseline Design (Electron "Linac")

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

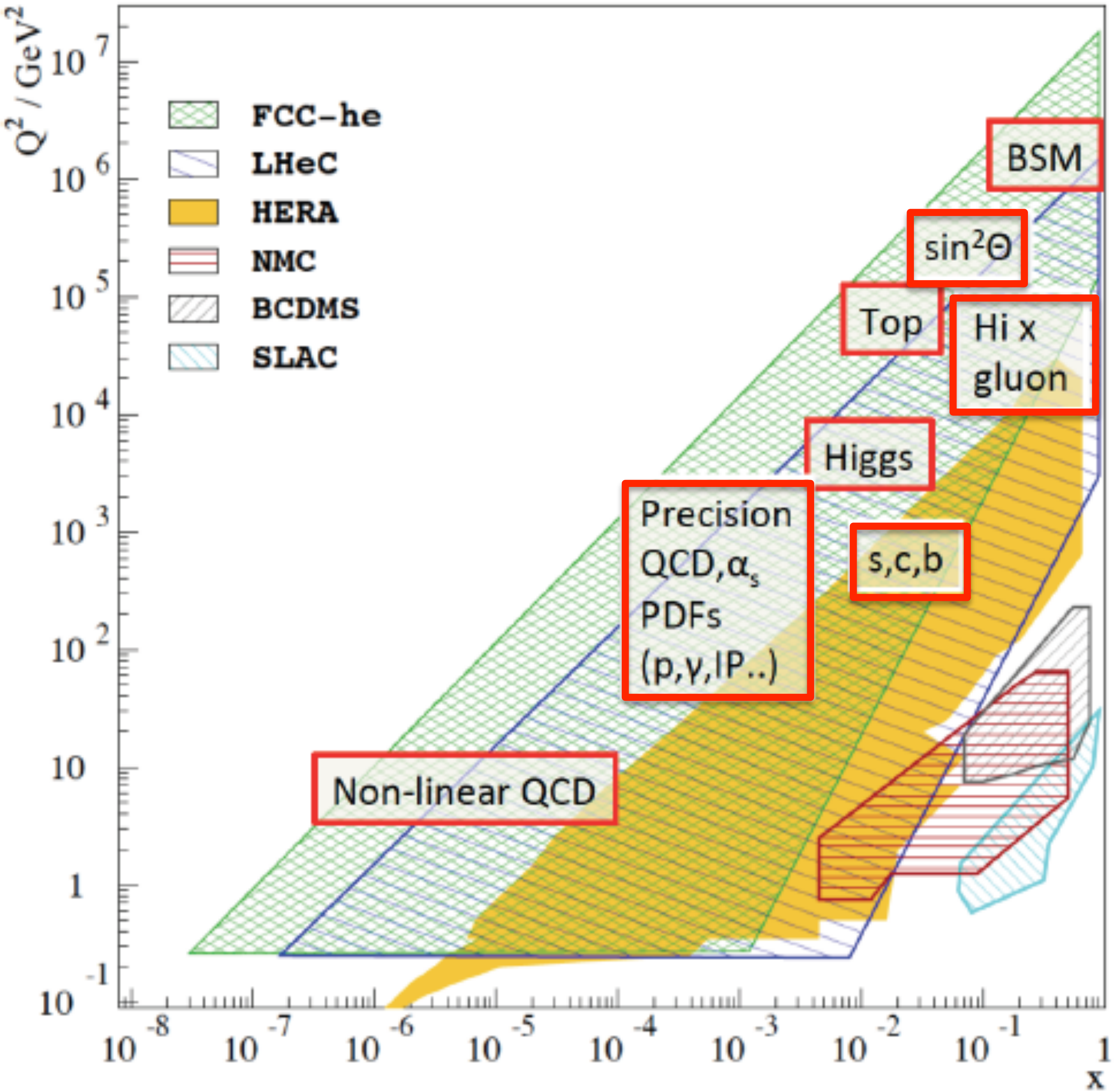
- Colliding with $E_p$ = 7 TeV from LHC (or even 50 TeV from FCC) and equivalent ion beams

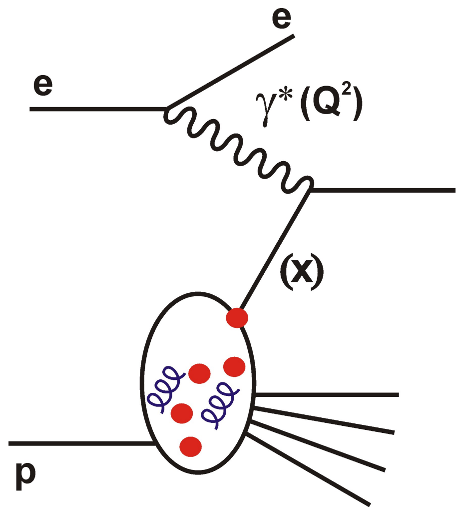
• Two 10 GeV linacs,
• 3 returns, 20 MV/m
• Energy recovery in same structures
[Energy recovery Linac prototype planned @ Orsay]



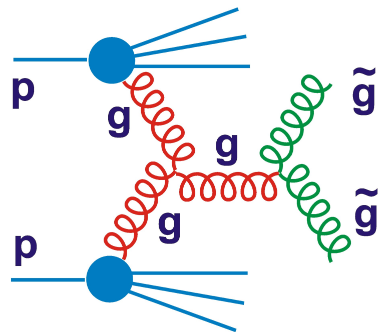

• ep lumi → $10^{34}$ cm$^{-2}$ s$^{-1}$
→ ~100 fb$^{-1}$ per year →~1 ab$^{-1}$ total
• **eD and eA collisions have always been integral to programme**
• **e-nucleon Lumi estimates ~ $10^{31}$ ($10^{32}$) cm$^{-2}$ s$^{-1}$ for eD (ePb)**

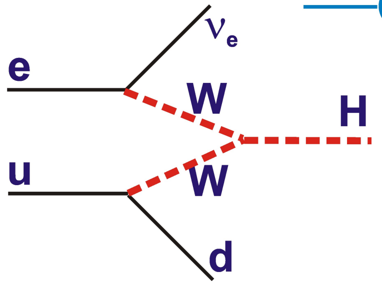
# LHeC Physics at $10^{34}$ cm$^{-2}$s$^{-1}$



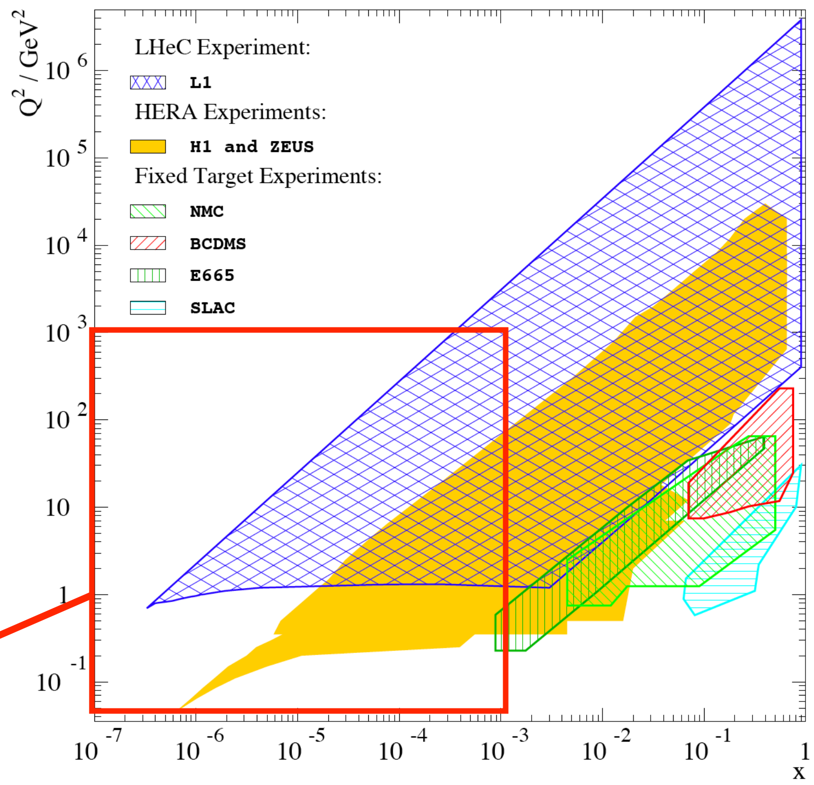

Diverse physics goals require precision throughout wide accessible kinematic region.

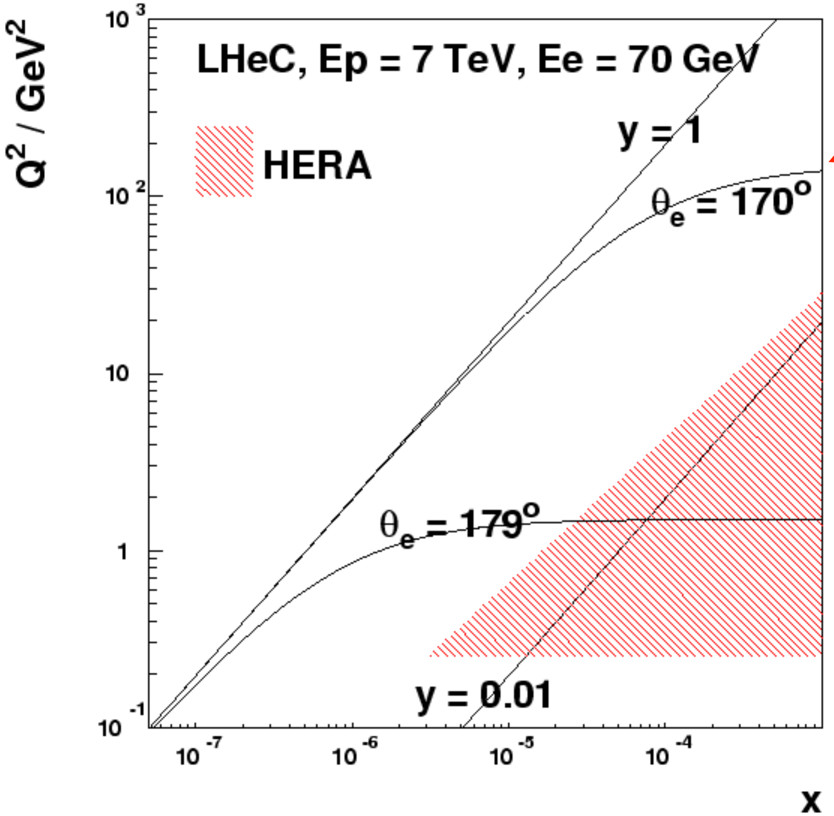


# LHeC Kinematic Detector Requirements

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



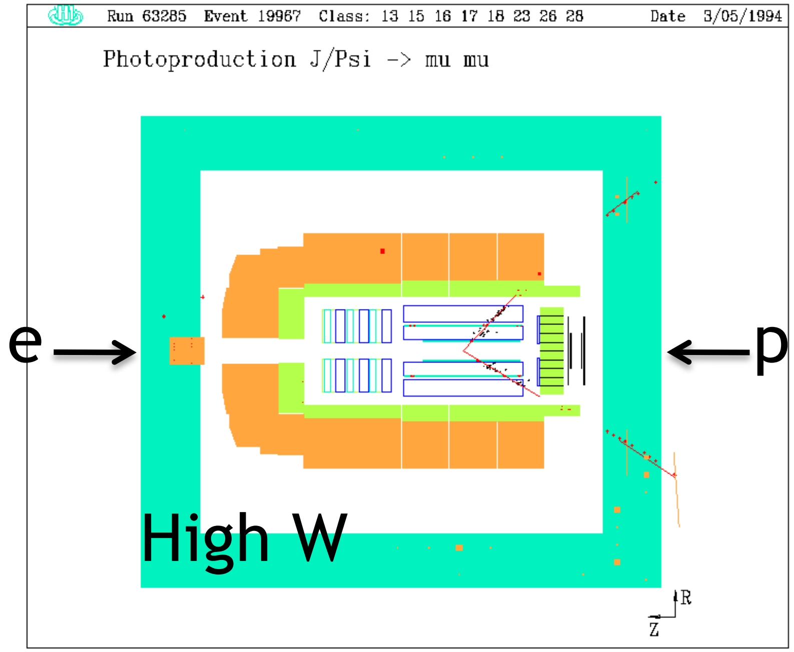



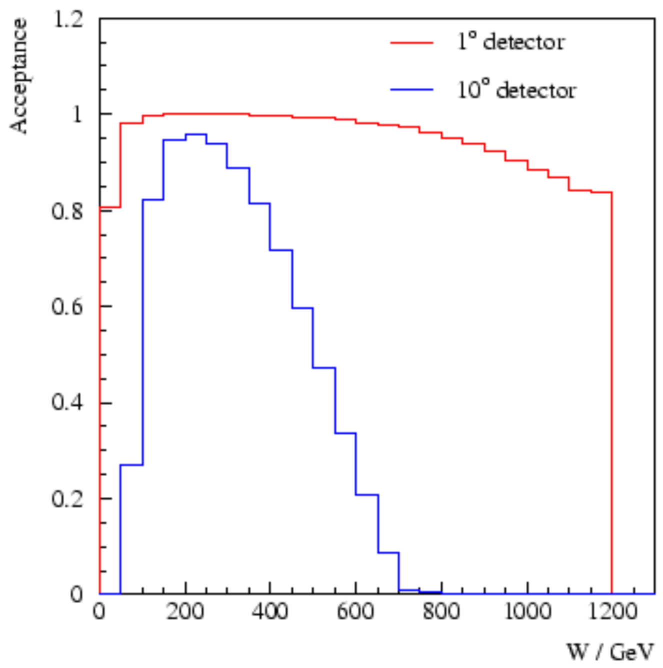

Also need 1° acceptance in proton direction to contain hadrons for kinematic reconstruction, Mueller-Navelet jets, maximise acceptance for new massive particles …

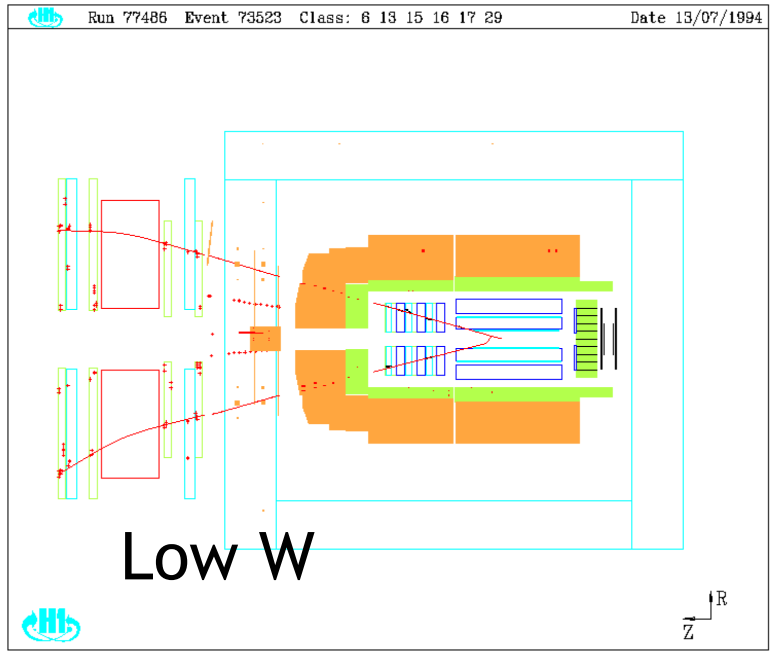
# Elastic J/Ψ Kinematics

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

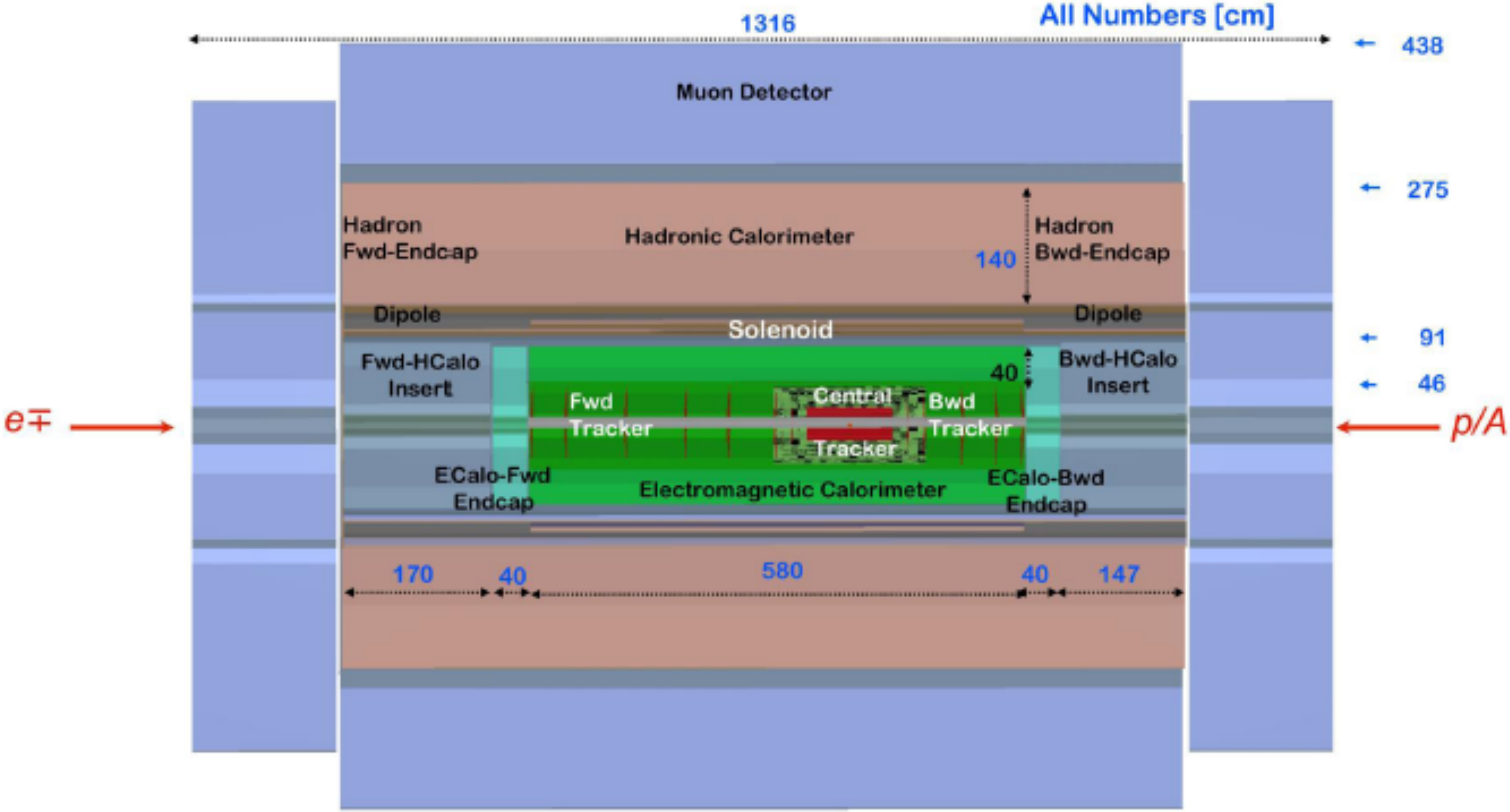
- To access highest W, acceptance in outgoing electron beam direction crucial



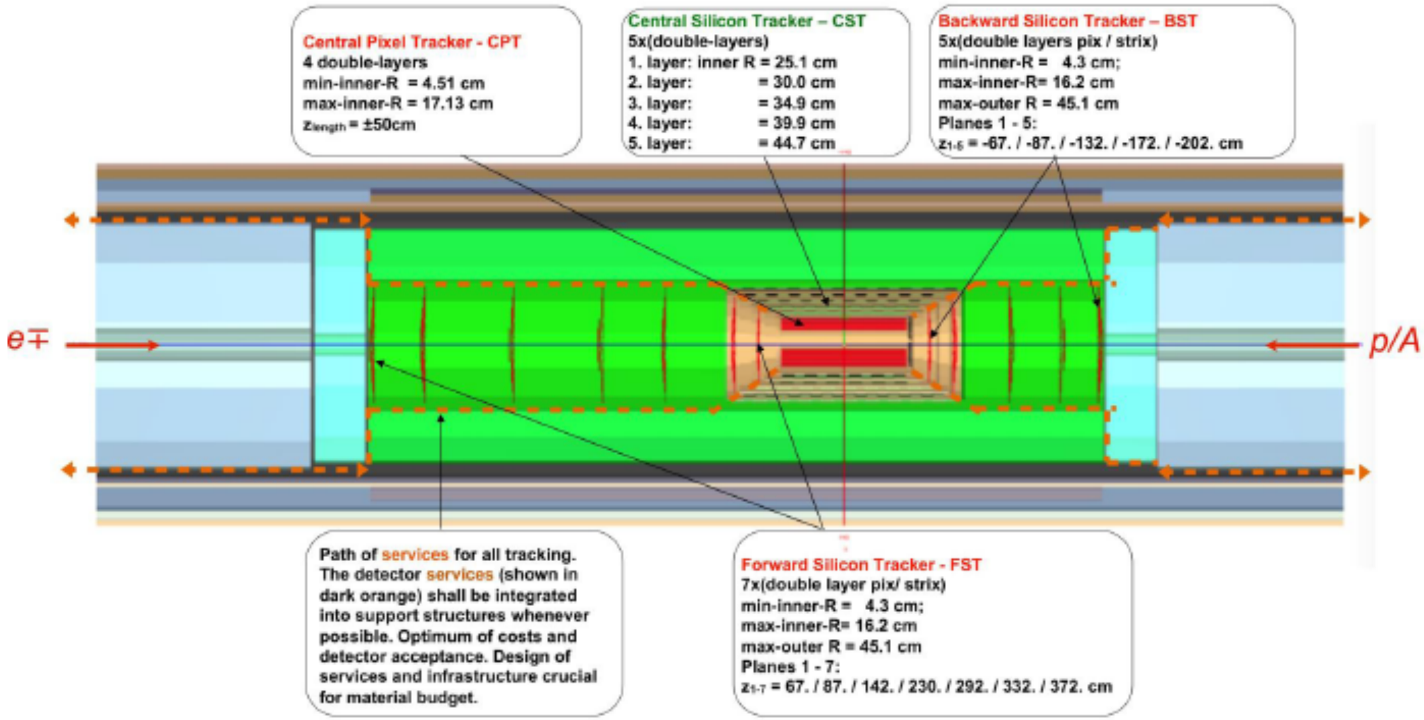



# LHeC Detector Design Overview



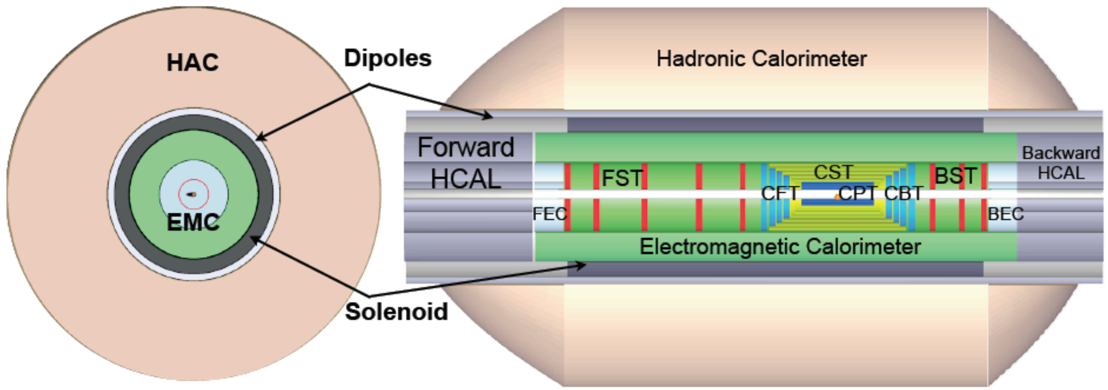

- Present size 13m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)
- Forward / backward asymmetry reflecting beam energies
- Demanding tracking → high fraction of pixels, wide acceptance

# Detector Details




- Long tracking region (pixels + strips) → 1° electron hits 2 tracker planes

- Lar / Tile calorimeter leaning heavily on LHC experience

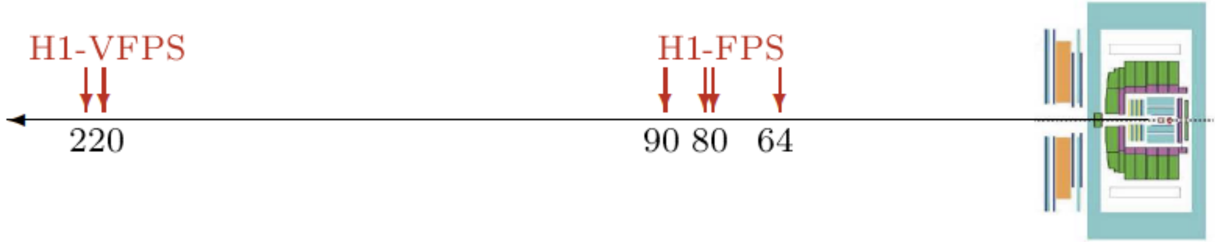




- Beamline insrumentation considered from outset.

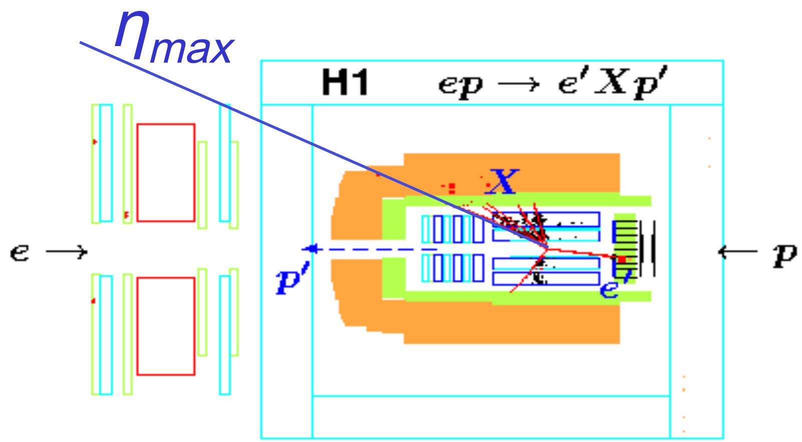
# Intact Proton Selection Methods beyond HERA

1) Measure scattered Proton in Roman Pots




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

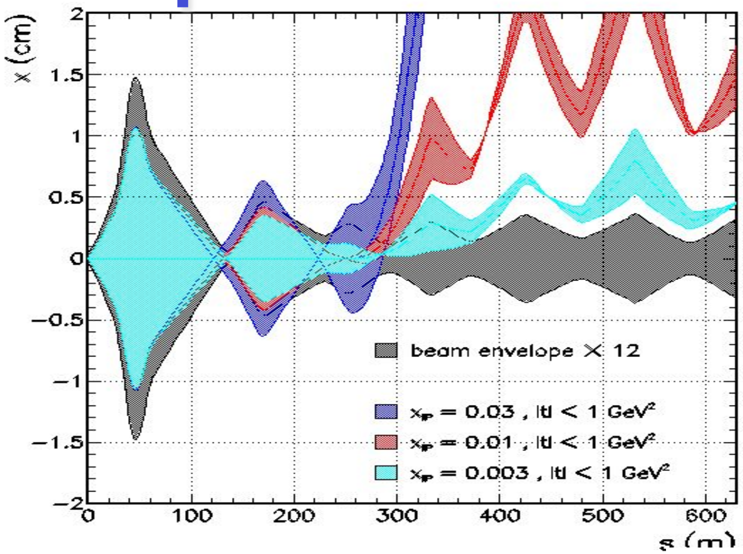
2) Select Large Rapidity Gaps




-Limited by control over proton dissociation contribution

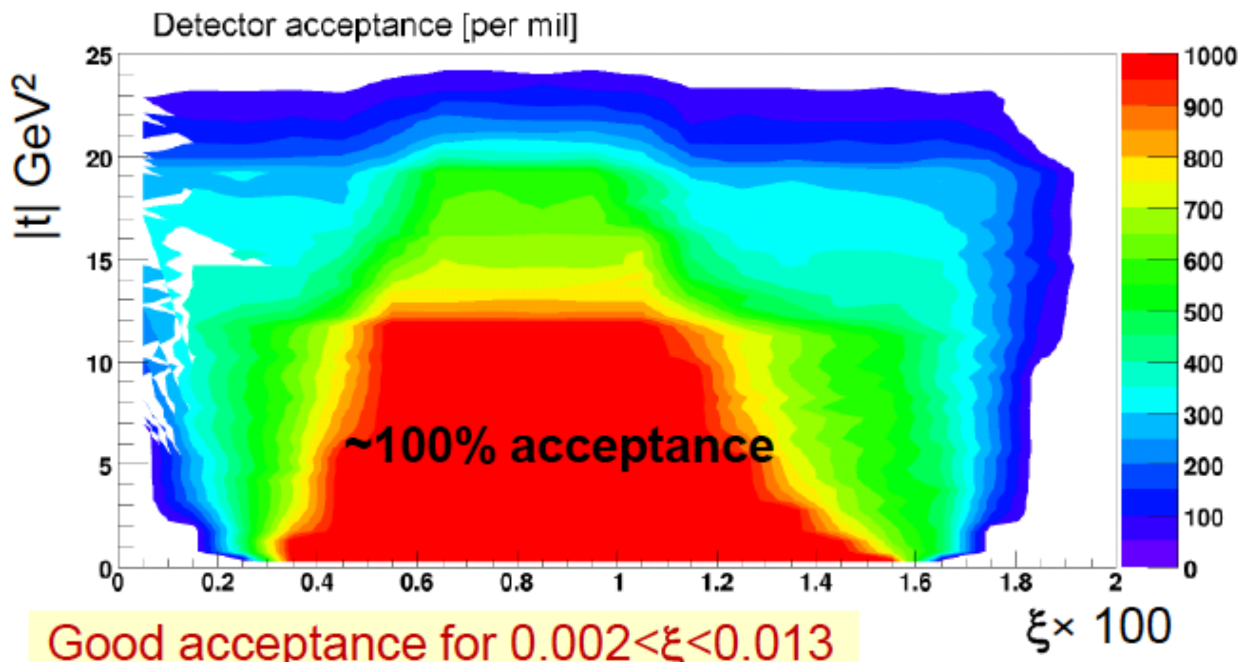
- Methods have very different systematics → complementary
- In practice, method 2 yielded lasting HERA results, because of statistical and kinematic range limitations of Roman pots
- Roman pots mainly contsrained t distributions
- **LHeC & EIC different → higher lumi + pot design from outset**

# Forward Proton Spectrometer




- Proton spectrometer uses outcomes of FP420 project (proposal for low $\xi$ Roman pots at ATLAS / CMS – not yet adopted)
-
- Approaching beam to $12\sigma$ (~250 $\mu$m) tags elastically scattered protons with high acceptance over a wide $x_{IP}$, t range

-These detectors came of age at LHC (TOTEM, AFP) …
- We should build full acceptance forward detector systems with them




Good acceptance for $0.002<\xi<0.013$

# (NEW) DGLAP PDF Fits to LHeC Pseudo-Data

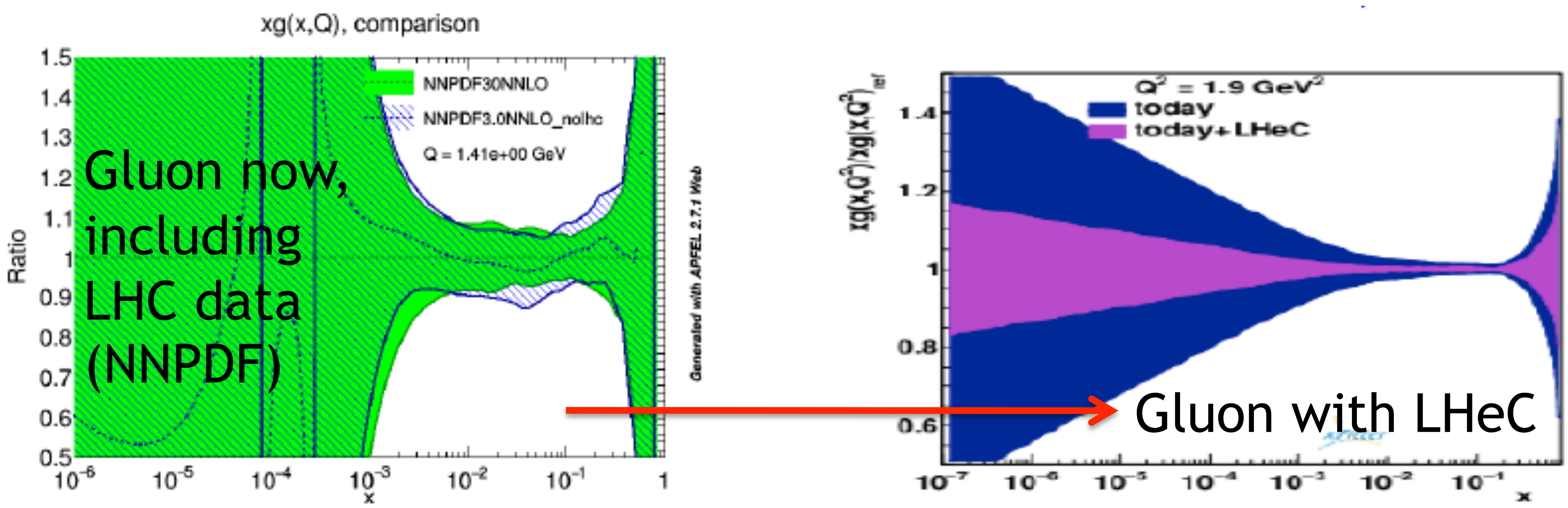
-Simulated NC, CC `pseudo-data' with reasonable assumptions on systematics (typically 2x better than H1 and ZEUS at HERA).

- 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

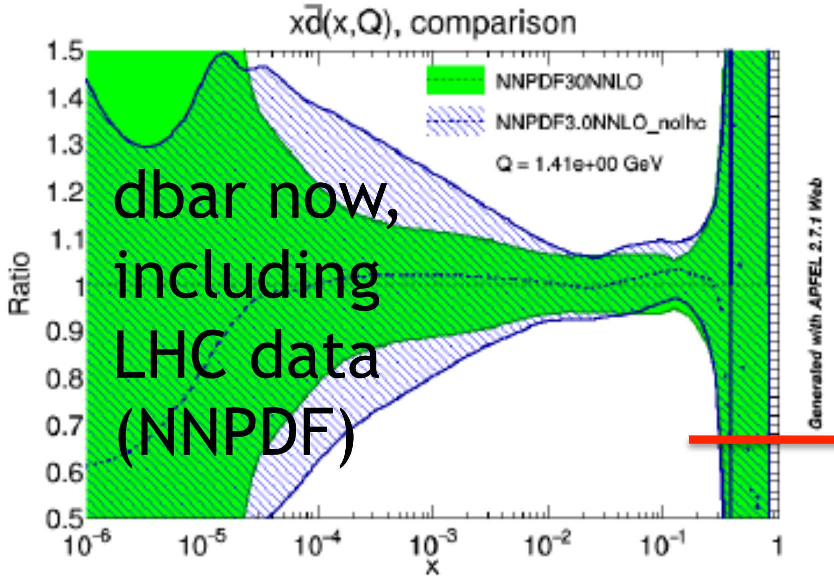
# Low x Gluon with LHC, with and without LHeC

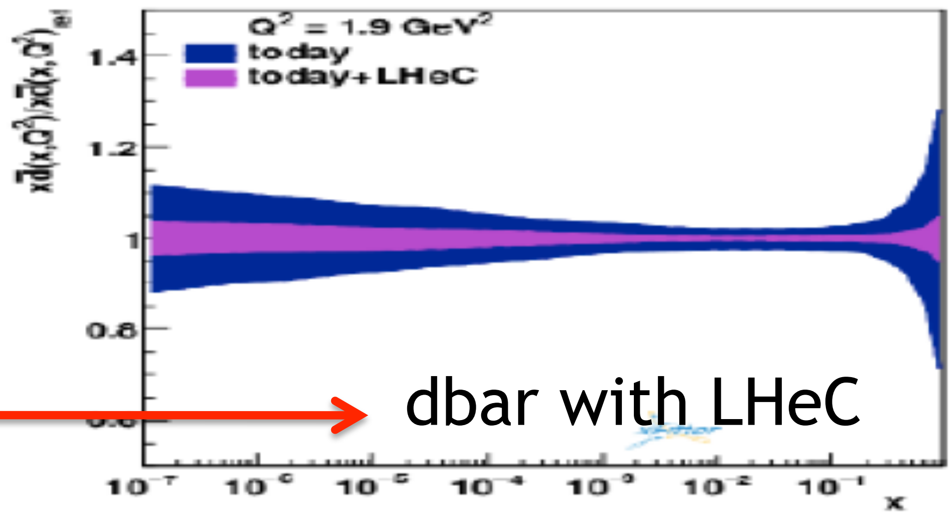



**Standard LHC channels do not help much:**

- 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 $J/\Psi$)
- 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




**LHC channels help, but not on same level as LHeC:**
- 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 …

# FCC-eh Data have also been included

| NC/CC | $E_e$ [GeV] | $E_p$ [TeV] | P(e) | charge | lumi. [$fb^{-1}$] | |
|---|---|---|---|---|---|---|
| NC | 60 (60) | 50 (7) | −0.8 | −1 | 1000 | e−, neg. pol. |
| CC | 60 (60) | 50 (7) | −0.8 | −1 | 1000 | |
| NC | 60 (60) | 50 (7) | +0.8 | −1 | 300 | e−, pos. pol. |
| CC | 60 (60) | 50 (7) | +0.8 | −1 | 300 | |
| NC | 60 (60) | 50 (7) | 0 | +1 | 100 | e+, unpol. |
| CC | 60 (60) | 50 (7) | 0 | +1 | 100 | |
| NC | 20 (60) | 7 (1) | 0 | −1 | 100 | low energy |
| CC | 20 (60) | 7 (1) | 0 | −1 | 100 | |

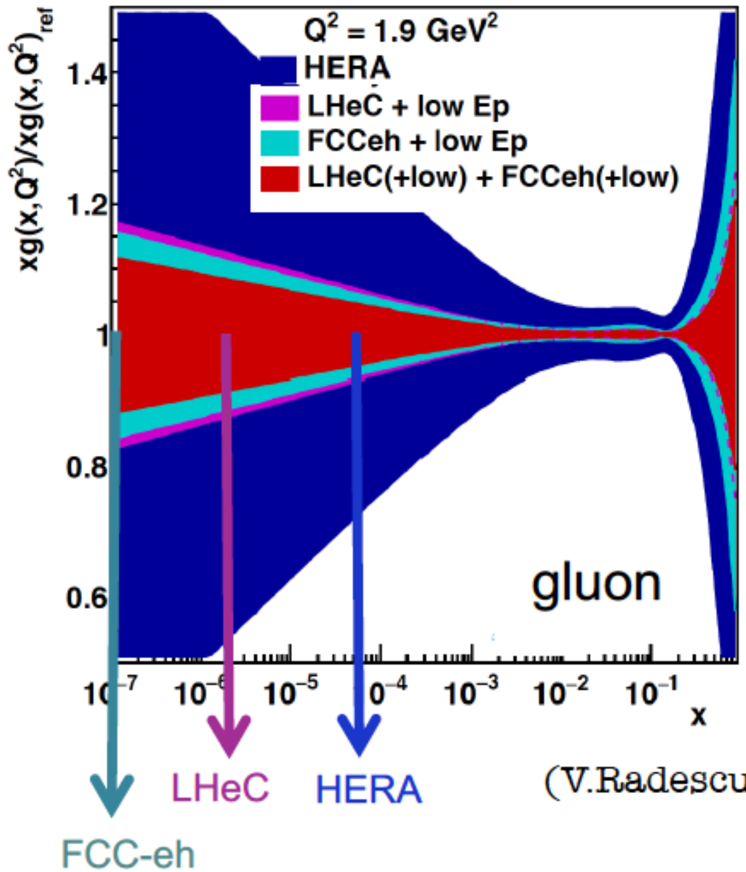
* second and third columns show FCC-eh (LHeC)

(M.Klein)

**error assumptions:**
elec. scale: 0.1%; hadr. scale 0.5%
radcor: 0.3%; γp at high y: 1%
uncorrelated extra eff. 0.5%

Some improvement in precision

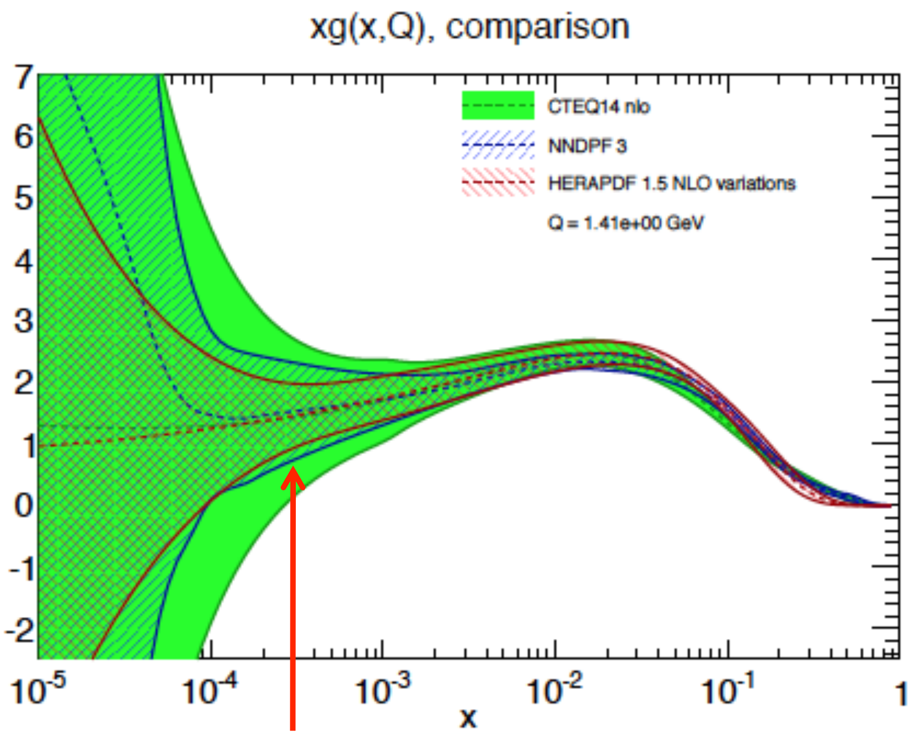
Main impact is direct coverage with data down to $x=10^{-7}$.



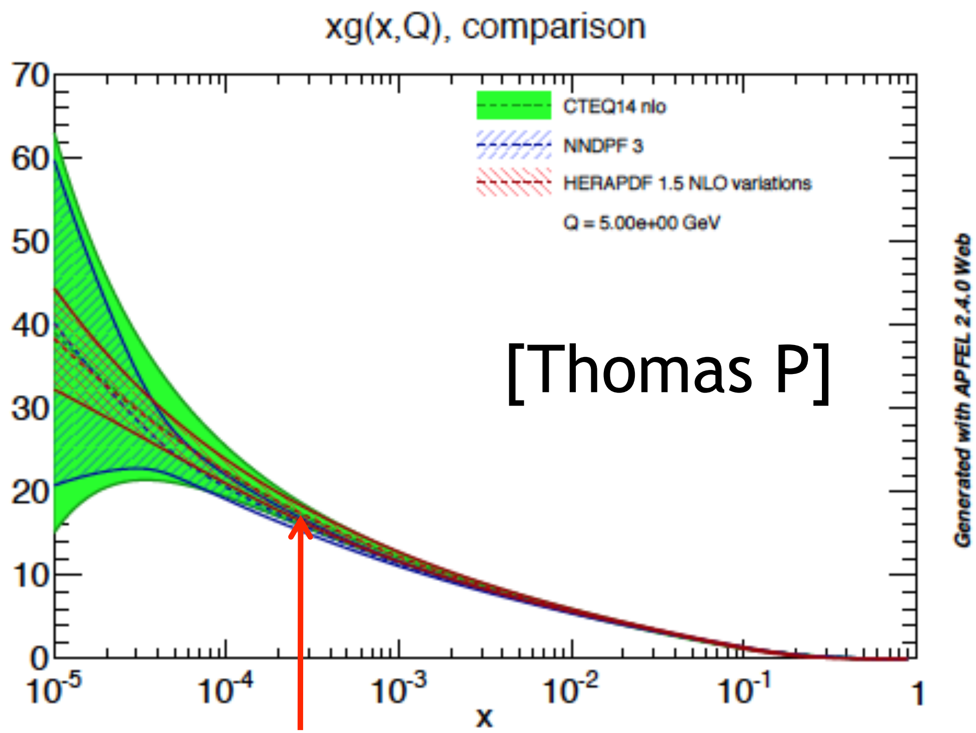

(V.Radescu)

# 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 Q2 data …




Constrained by data



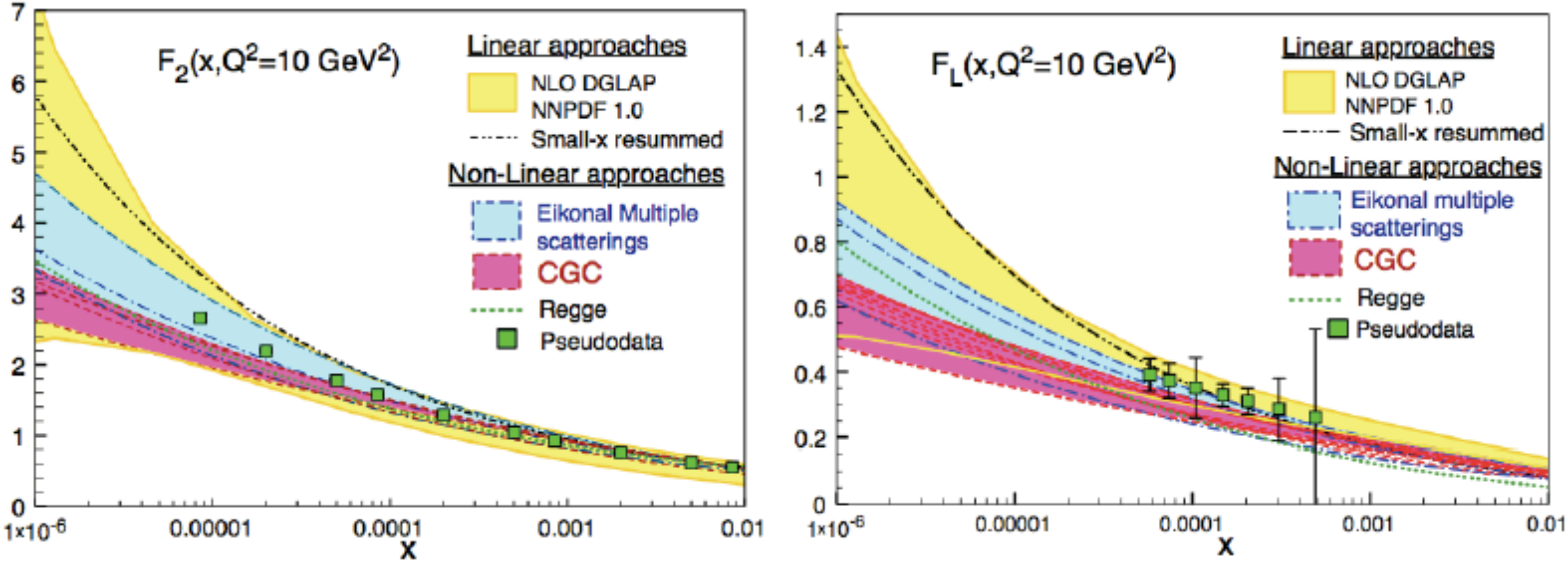

Unconstrained by data

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

# LHeC Sensitivity to Different Saturation Models

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 $GeV^2$



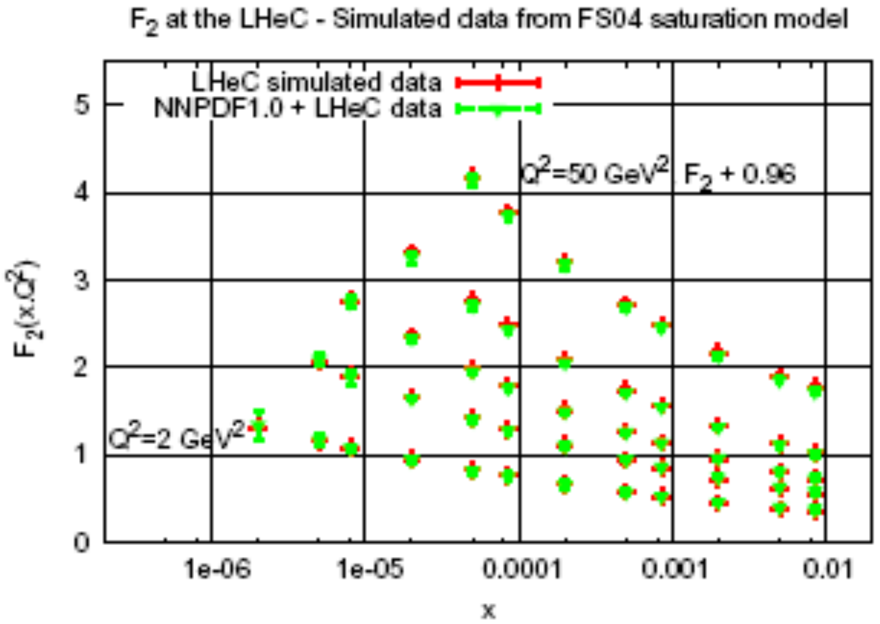

- LHeC can distinguish between different QCD-based models for the onset of non-linear dynamics

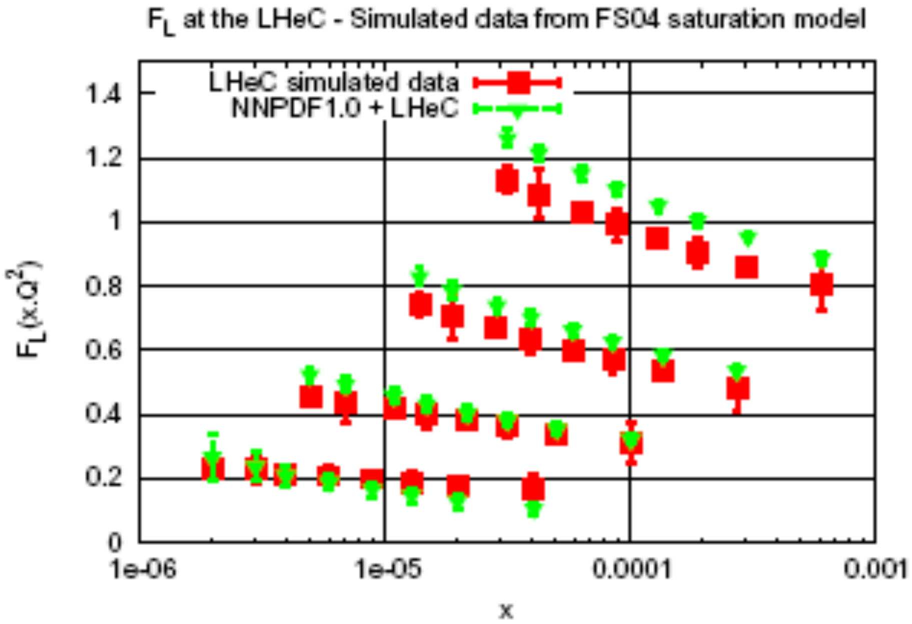
… but can $sat^n$ effects hide in standard fit parameterisations?

# Can Parton 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

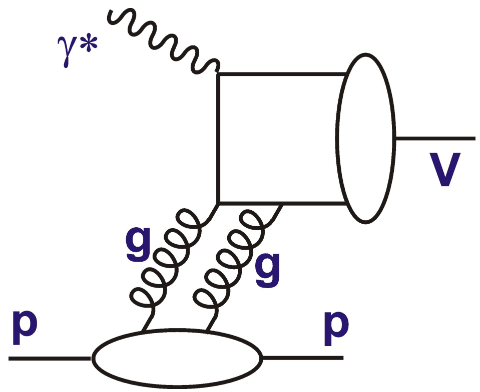



- Unambiguous observation of saturation will be based on tension between different observables e.g. $F_2$ v $F_L$ in ep or $F_2$ in ep v eA

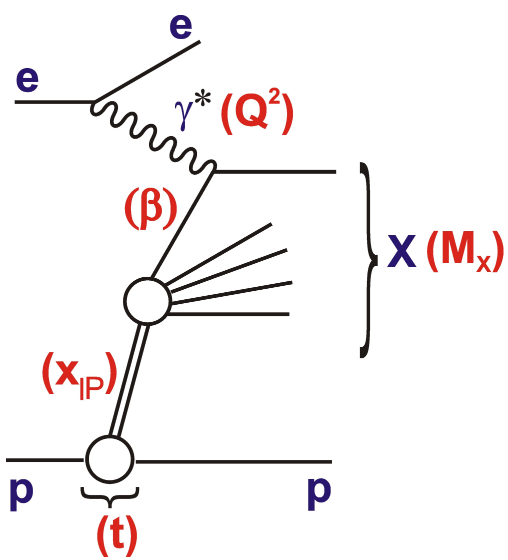
# Exclusive / Diffractive Channels and Saturation

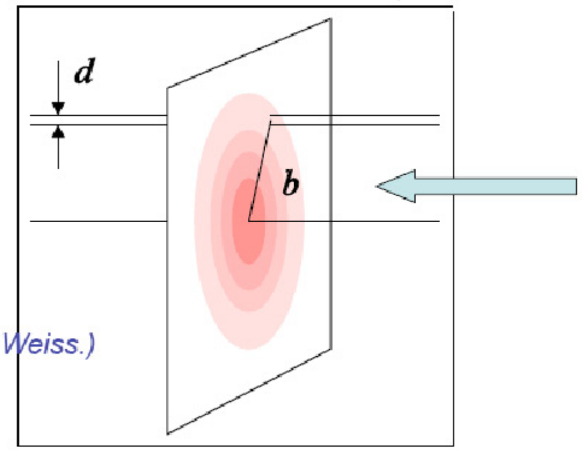
1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon




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

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

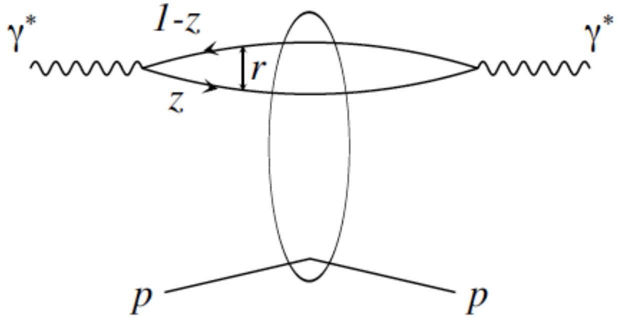



(figure from C. Weiss.)

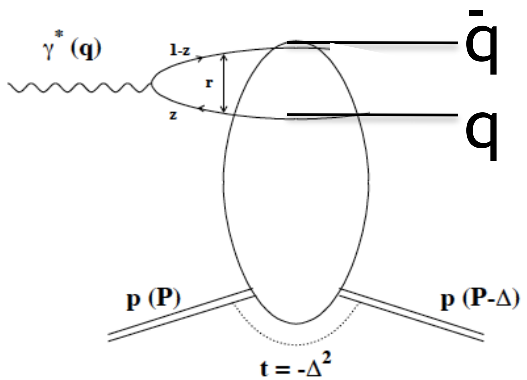
Central black region growing with decrease of x.

# Advantage of Diffractive DIS: Dipole Language




## Inclusive Cross Section

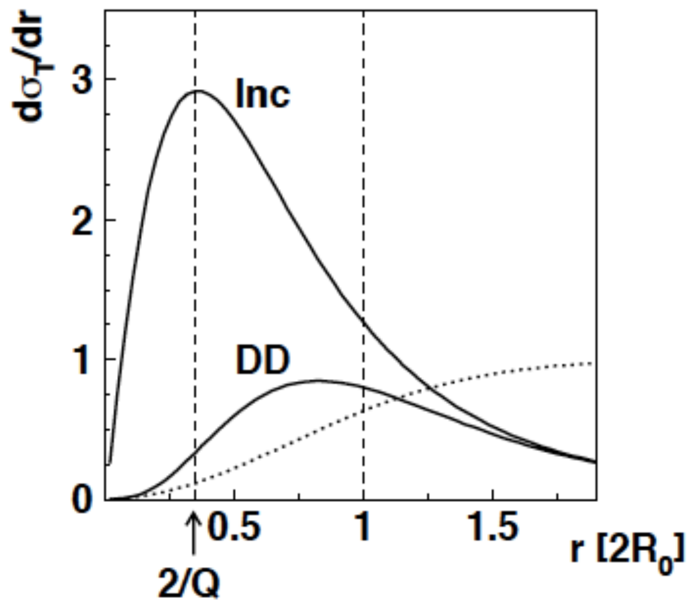
$$\sigma_{T,L}(x,Q^2) = \int d^2\mathbf{r} \int_0^1 d\alpha \, |\Psi_{T,L}(\alpha,\mathbf{r})|^2 \hat{\sigma}(x,r^2)$$



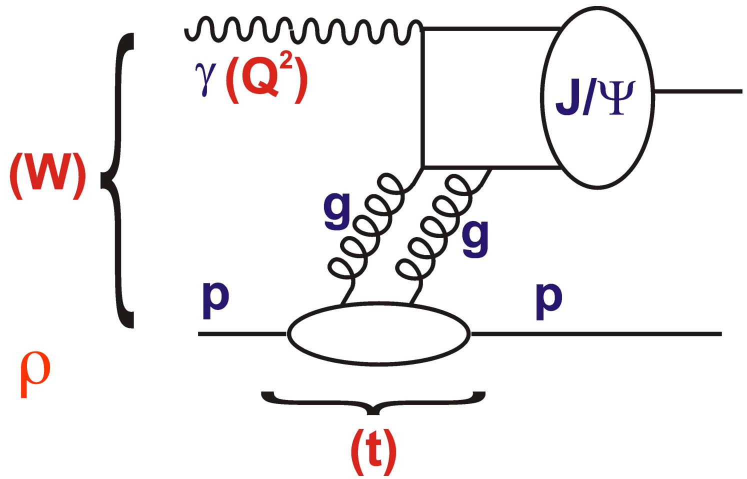

## Diffractive DIS

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

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



# Test Case: Elastic 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)

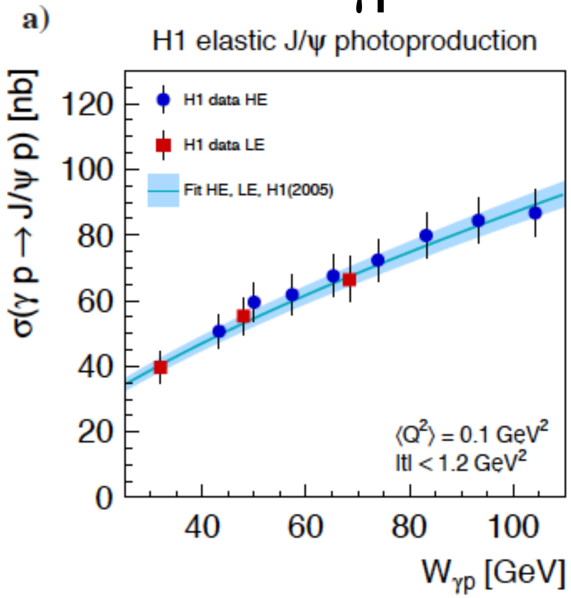
- Scale $\overline{Q^2} \sim (Q^2 + M_V^2) / 4 >\sim 3$ GeV$^2$ ideally suited to reaching Lowest possible x whilst remaining in perturbative regime

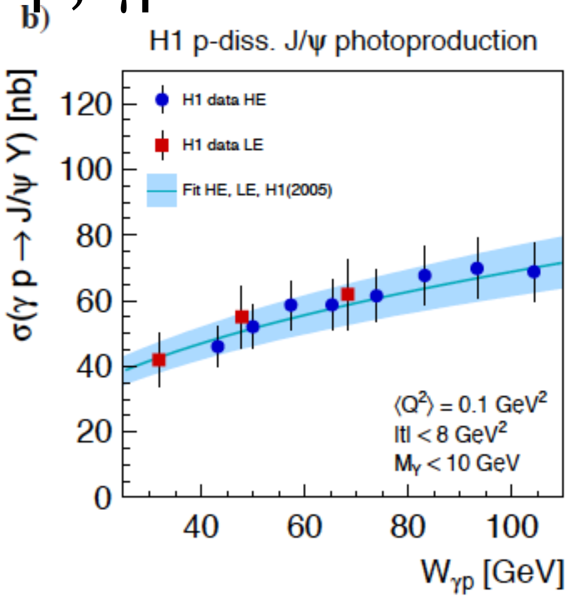
… eg LHeC reach extends to: $x_g \sim (Q^2 + M_V^2) / (Q^2 + W^2) \sim 5.10^{-6}$

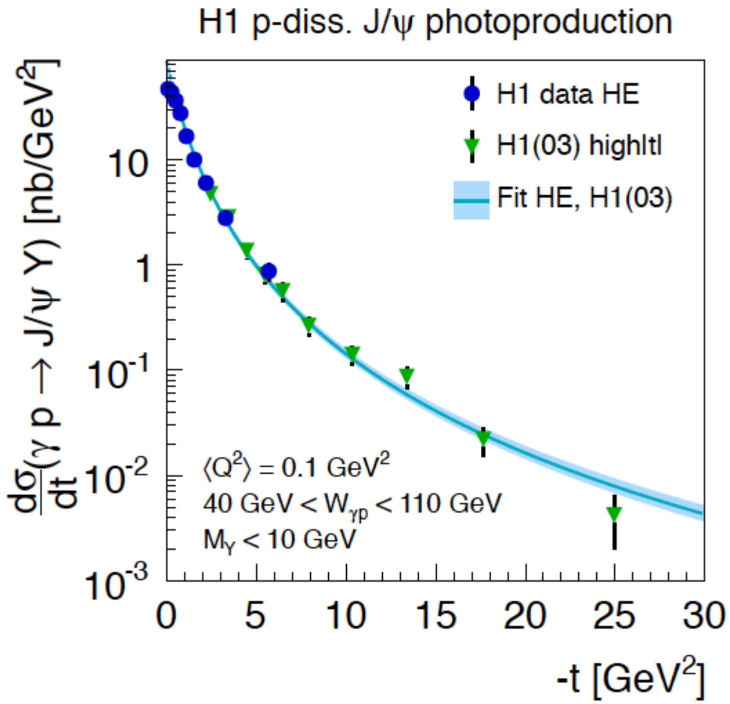
- Simulations (DIFFVM) of elastic J/Ψ → μμ photoproduction
→ scattered electron untagged, 1° acceptance for muons
(similar method to H1 and ZEUS)

# Existing Diffractive J/Ψ Photoproduction Data

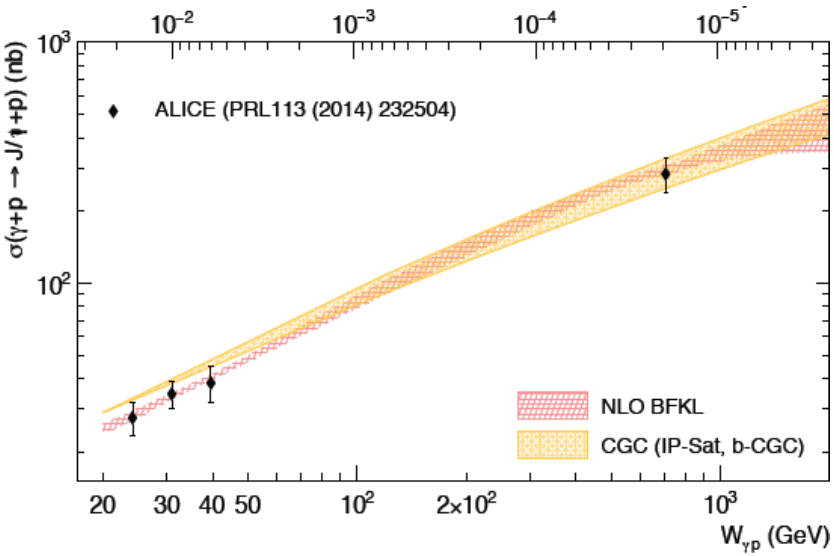
## HERA: $\gamma p \rightarrow J/\Psi p$, $\gamma p \rightarrow J/\Psi\ Y$

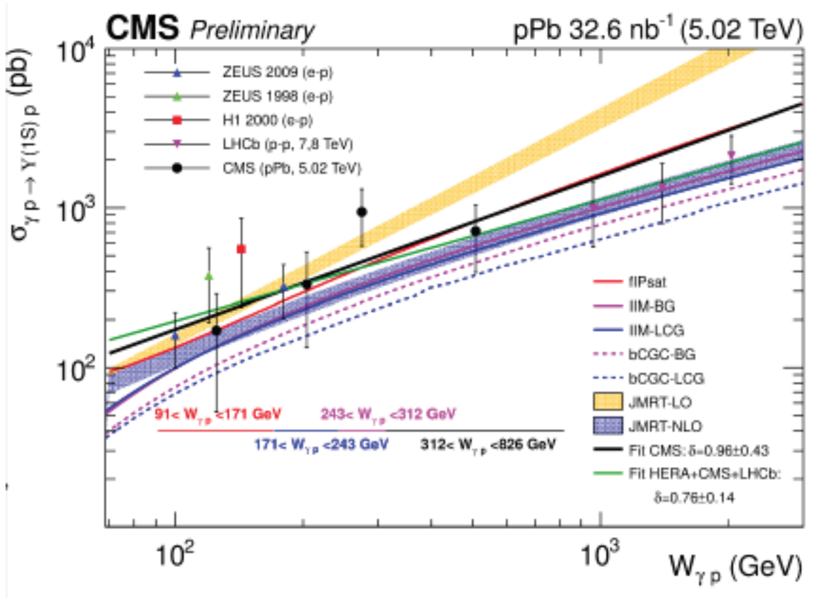


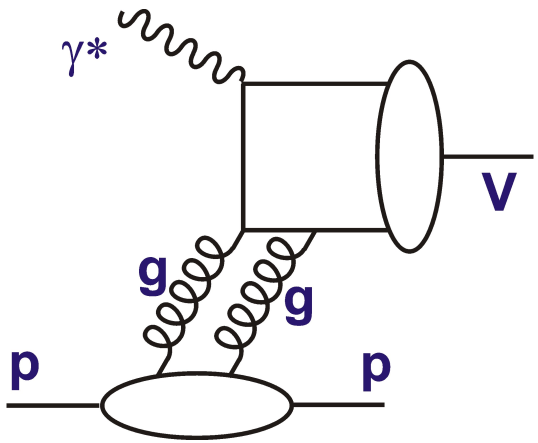

## UPC at LHC: $\gamma p \rightarrow J/\Psi p$

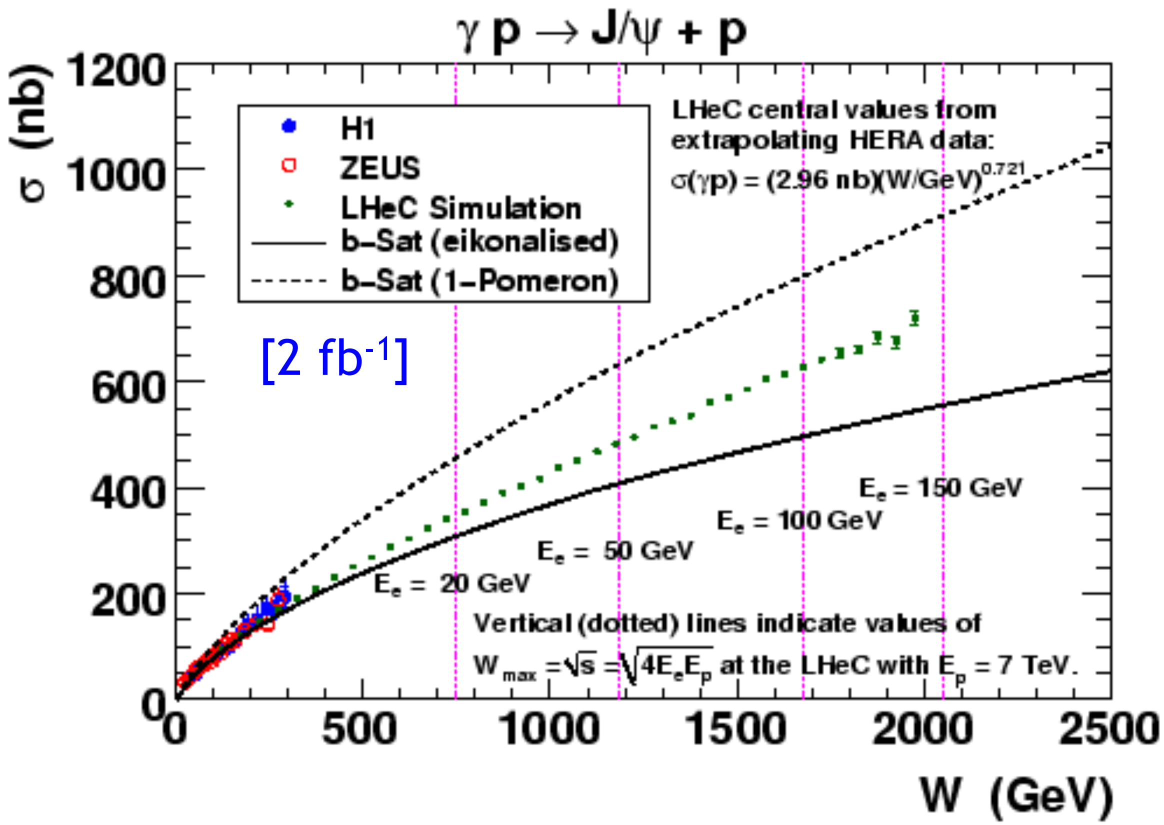


# Comparison with Dipole model Predictions

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

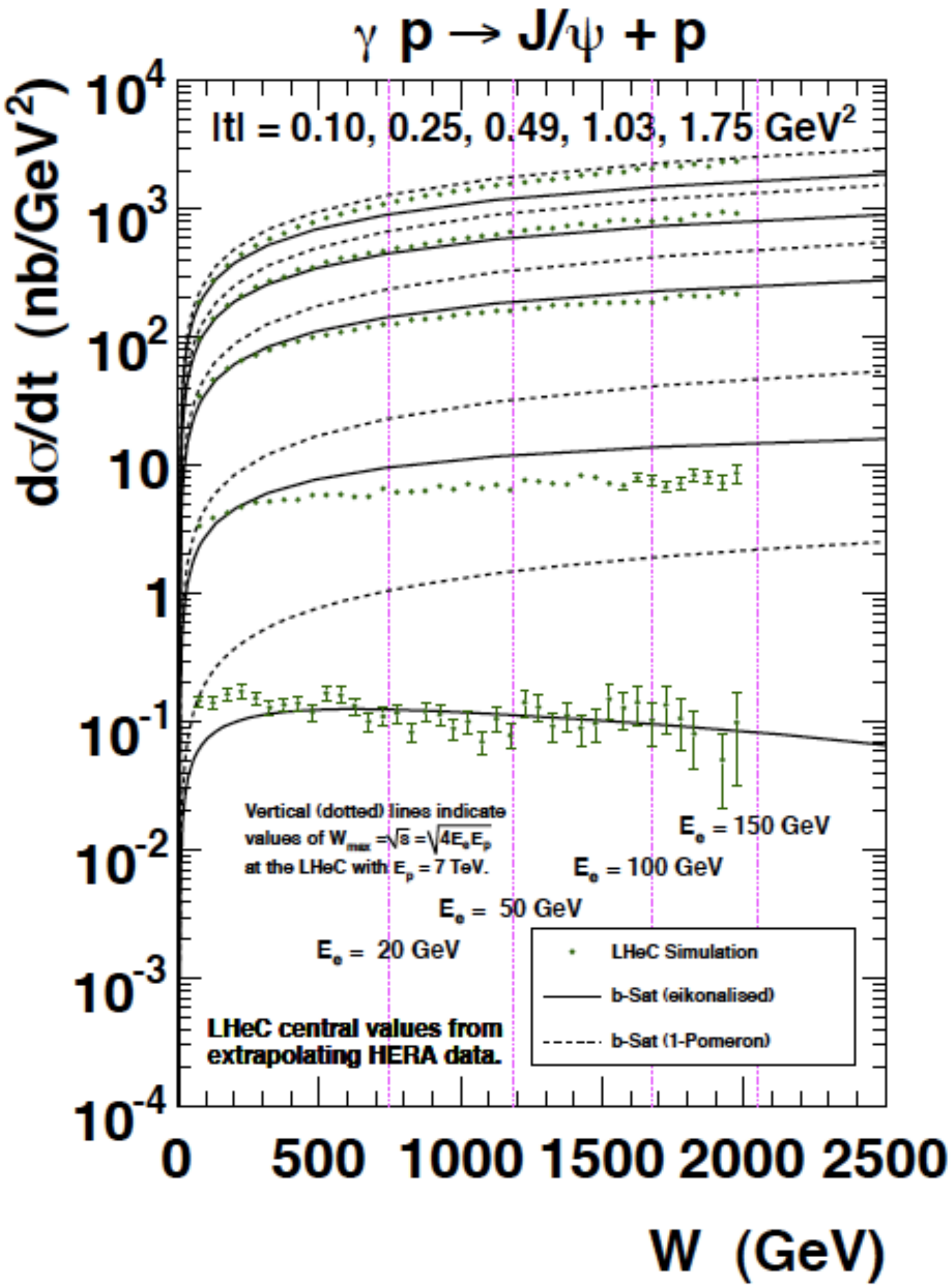



- Significant non-linear effects expected in LHeC kinematic range.

With detailed exploration of ep and eA, including t dependences, this becomes a powerful probe!...

# t Dependence of Elastic J/ψ Photoproduction



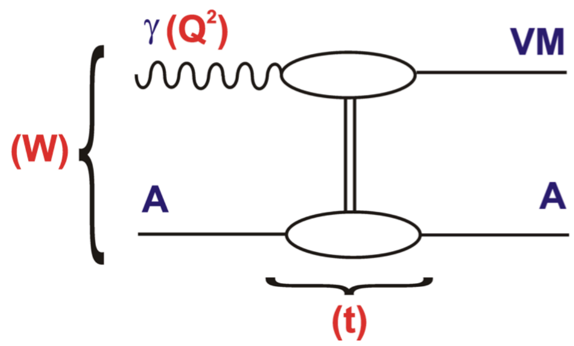

- Precise t measurement from decay μ tracks over wide W range extends to |t| ~ 2 GeV² and enhances sensitivity to saturation effects

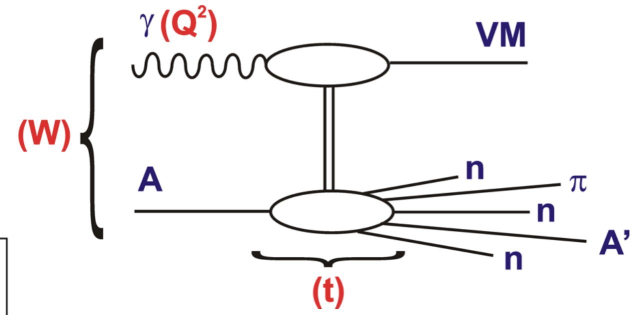
- Measurements also possible in multiple $Q^2$ bins

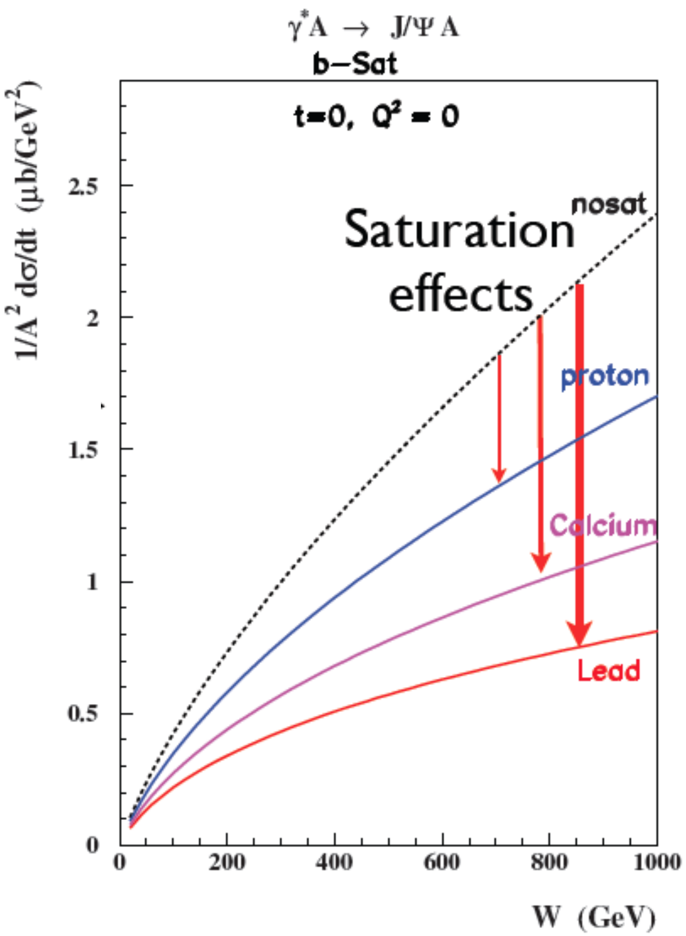
**- Level of precision from ep and eA unlikely to be matched in UPC**
**- Incoherent ep diffraction still needs to be studied**

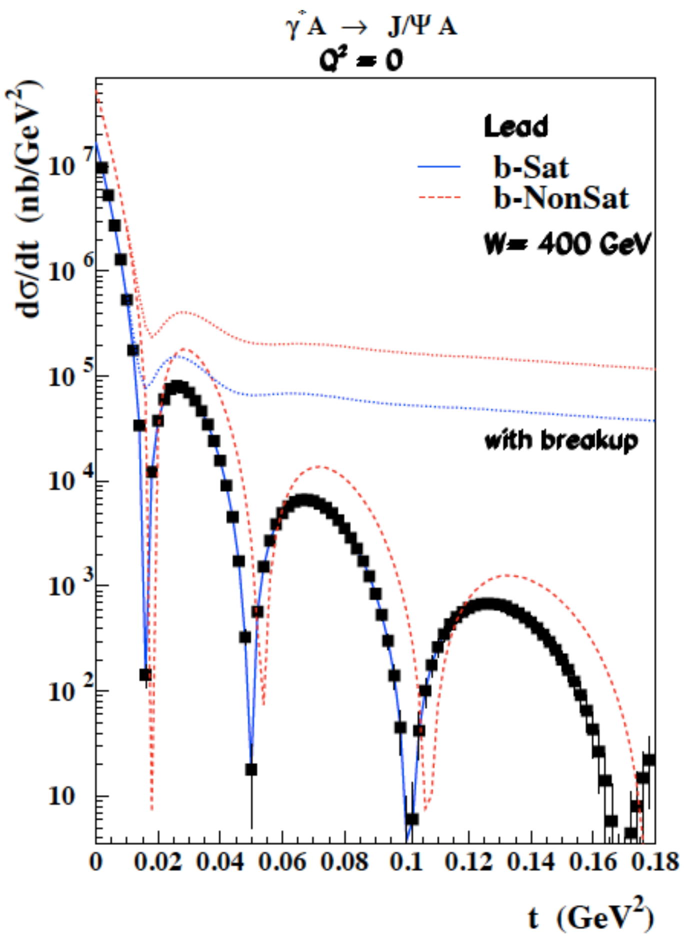
# Exclusive Diffraction in eA

Experimentally clear signatures and theoretically cleanly calculable saturation effects in coherent diffraction case (eA → eVA)



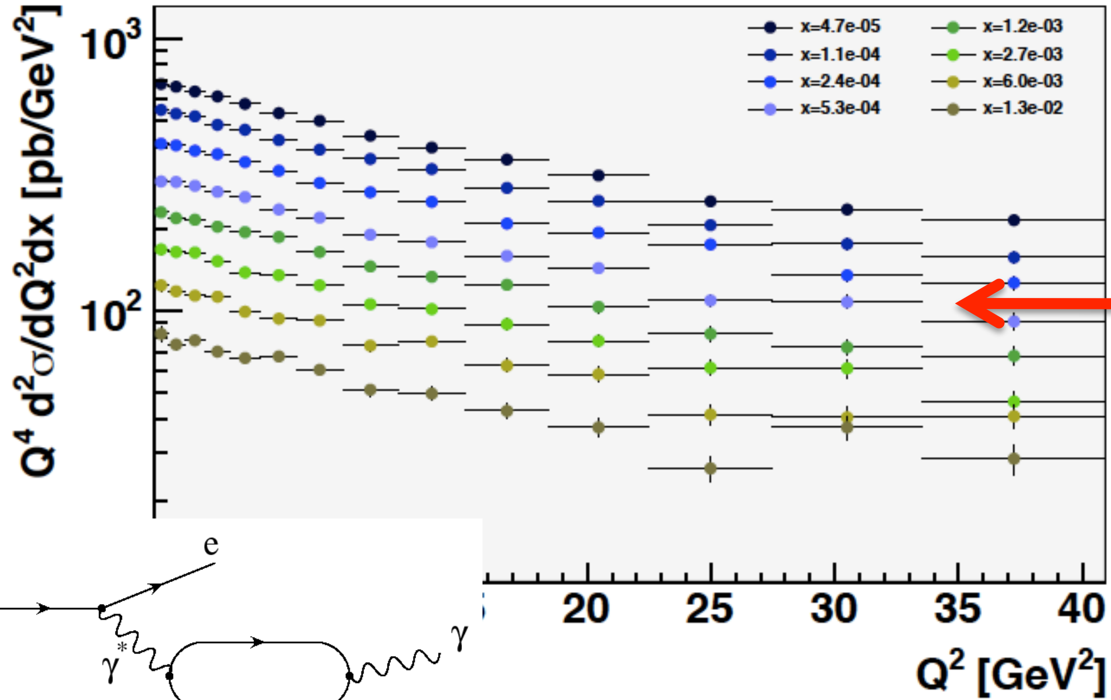



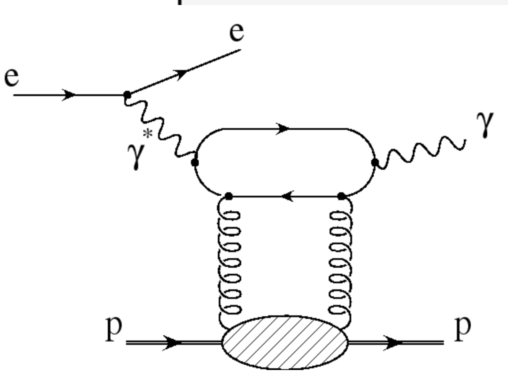




Experimental separation of incoherent diffraction based mainly on ZDC

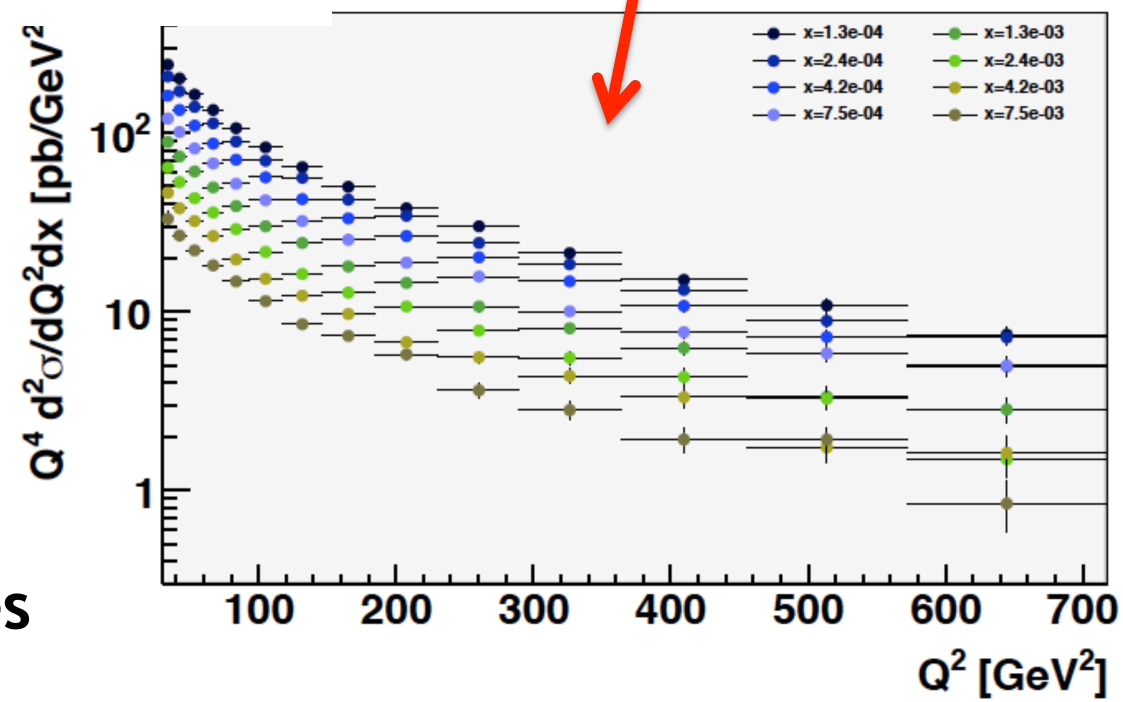
# DVCS
# (MILOU simulation)




$1\ \mathrm{fb}^{-1}$, $E_e = 50$ GeV,
$1^o$ acc'nce, $p_T^\gamma > 2$ GeV



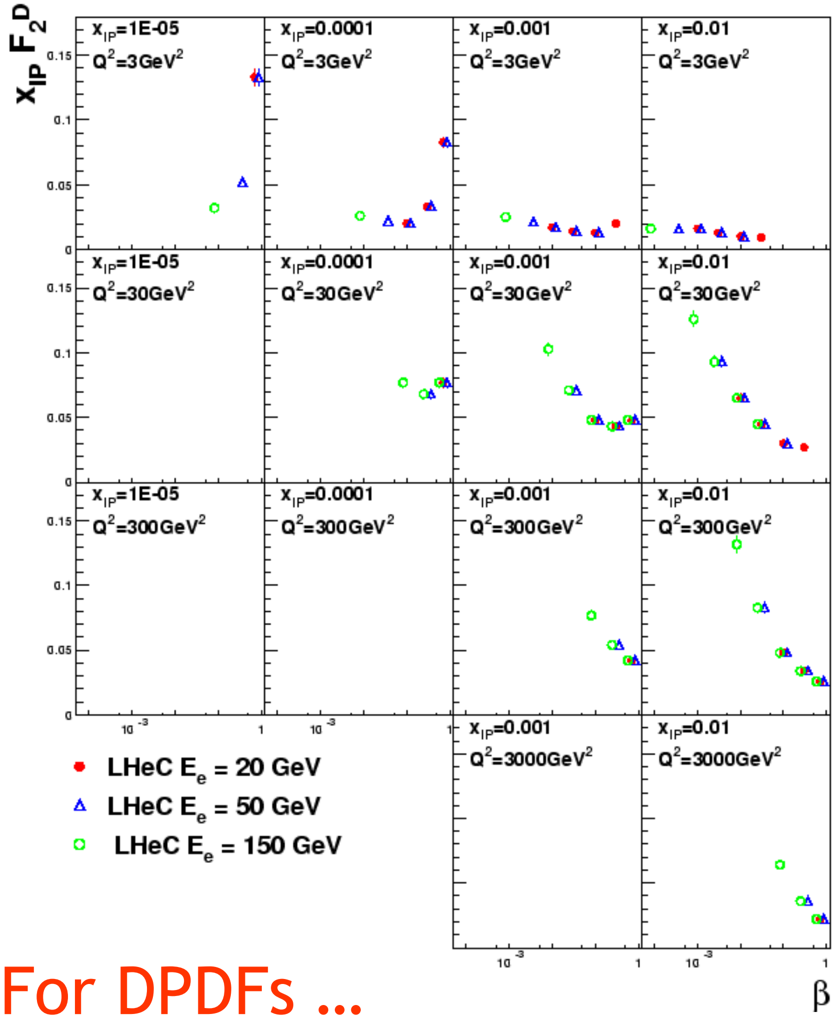

$100\ \mathrm{fb}^{-1}$, $E_e = 50$ GeV,
$10^o$ acc'nce, $p_T^\gamma > 5$ GeV

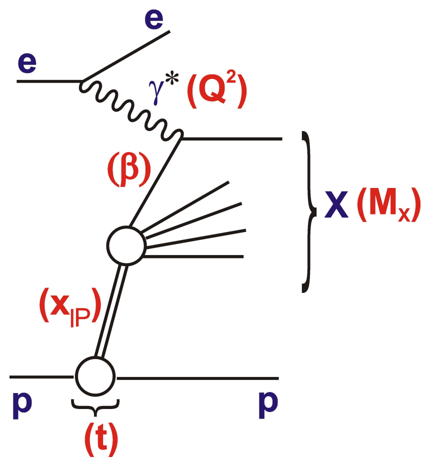


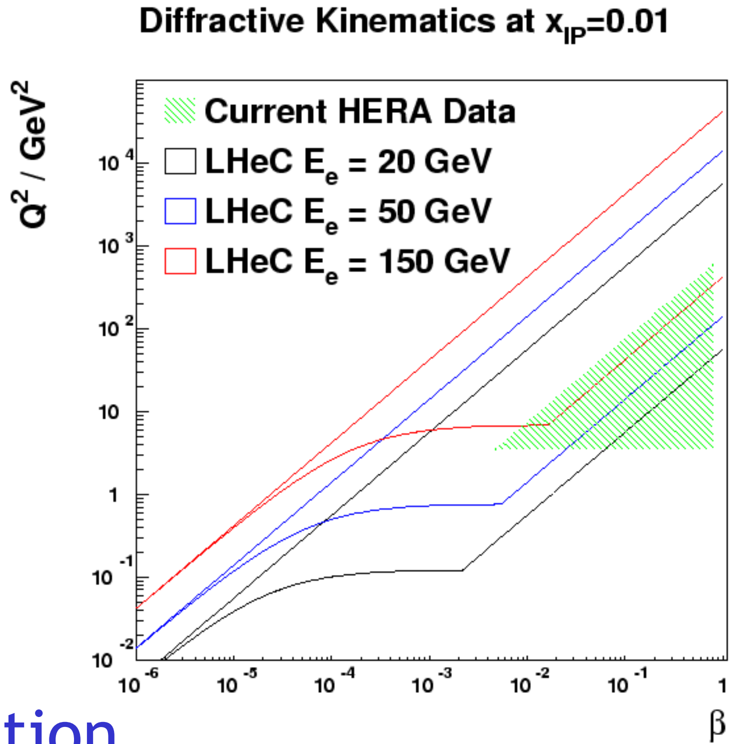

Precise data with
$W \rightarrow 1$ TeV, $Q^2 \rightarrow 700$ GeV$^2$,
$x \rightarrow 5.10^{-5}$

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

# Inclusive Diffraction / Diffractive PDFs at LHeC



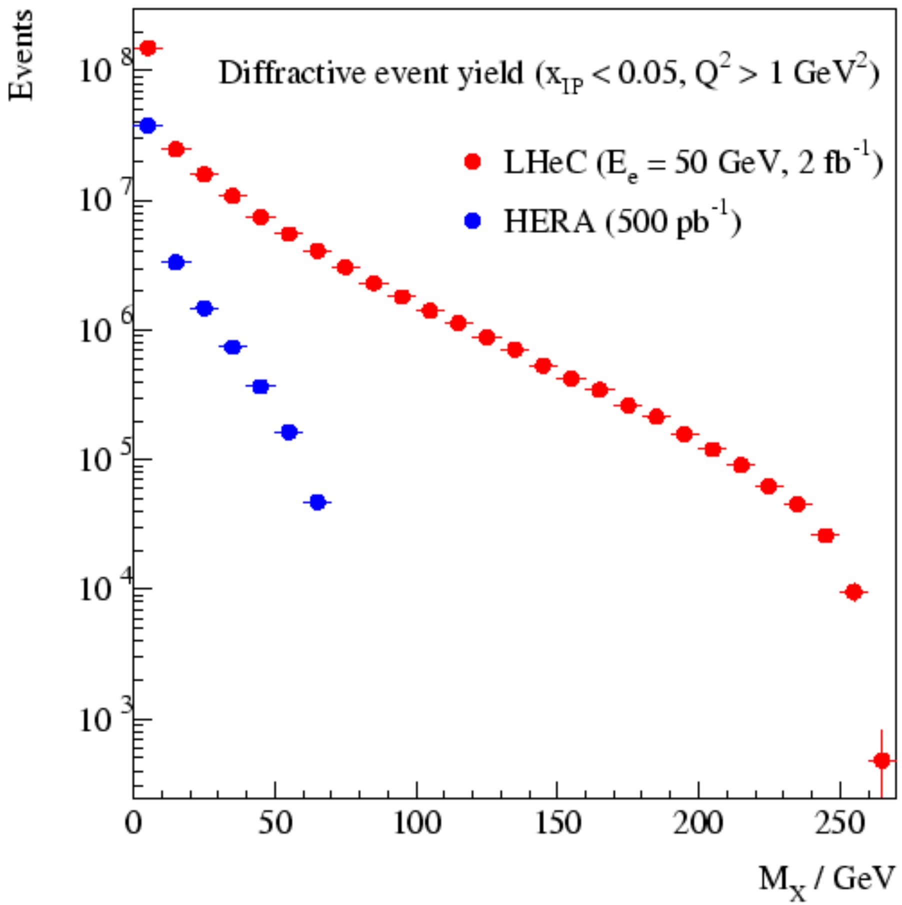

For DPDFs …

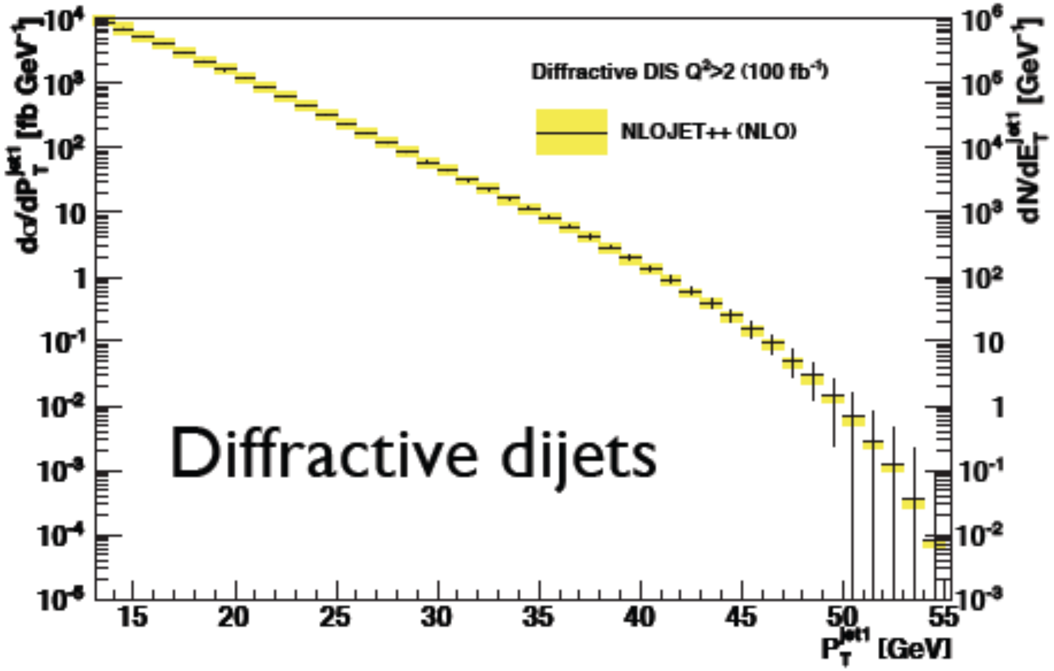
- Low $x_{IP}$ → cleanly separate diffraction
- Low β → Novel low x DPDF effects / non-linear dynamics?
- High $Q^2$ → Lever-arm for gluon, Flavour separation via EW

**Still to do: detailed DPDF sensitivity study**

# New Region of Large Diffractive Masses

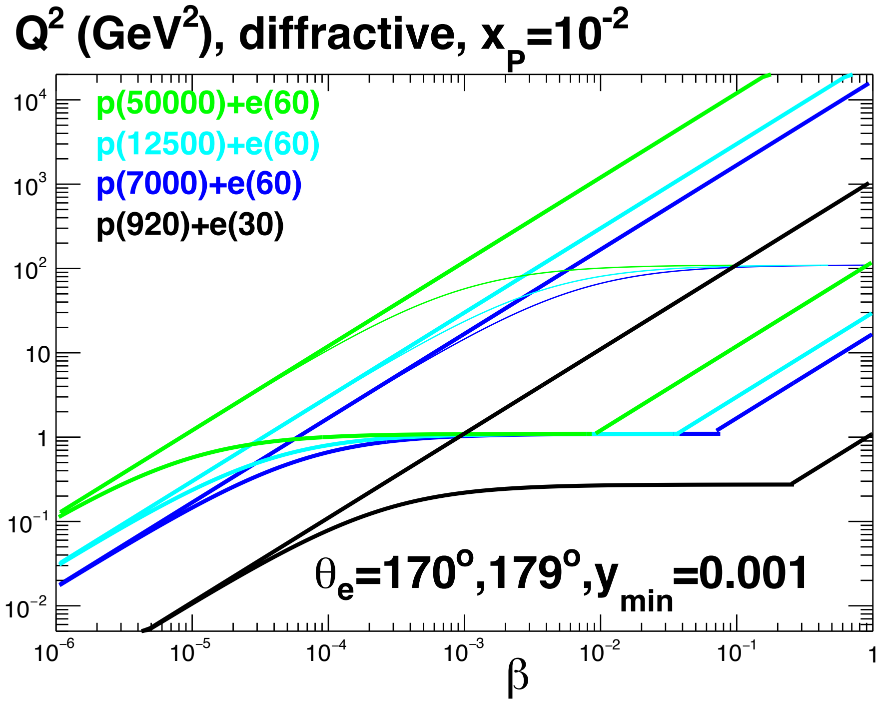
Large $x_{IP}$ region highly correlated with large Mx



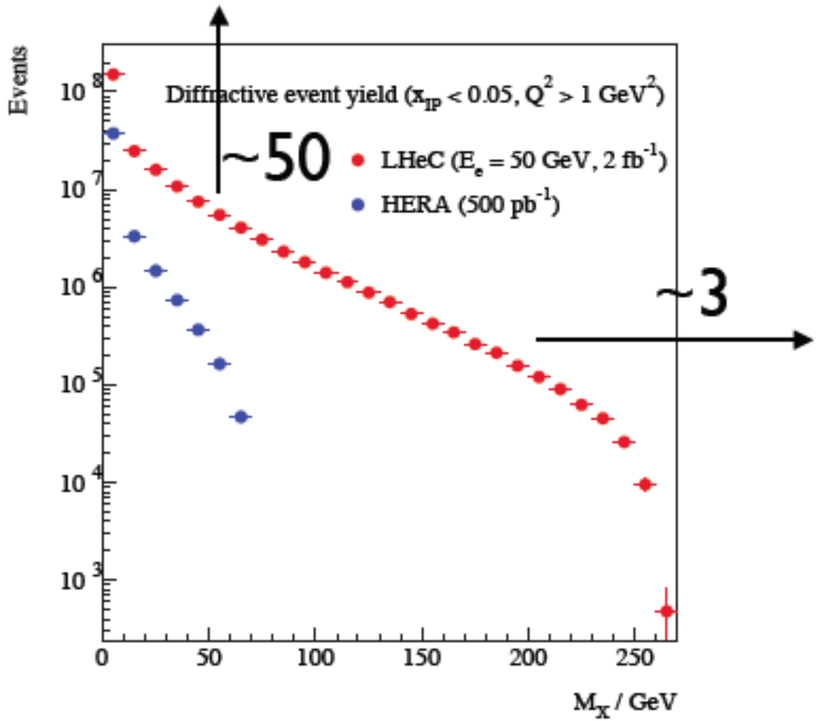




- `Proper' QCD (e.g. large $E_T$) with jets and charm accessible
- New diffractive channels … beauty, W / Z bosons
- Unfold quantum numbers / precisely measure new $1^-$ states

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




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




-Similarly for masses and transverse momenta of jets.

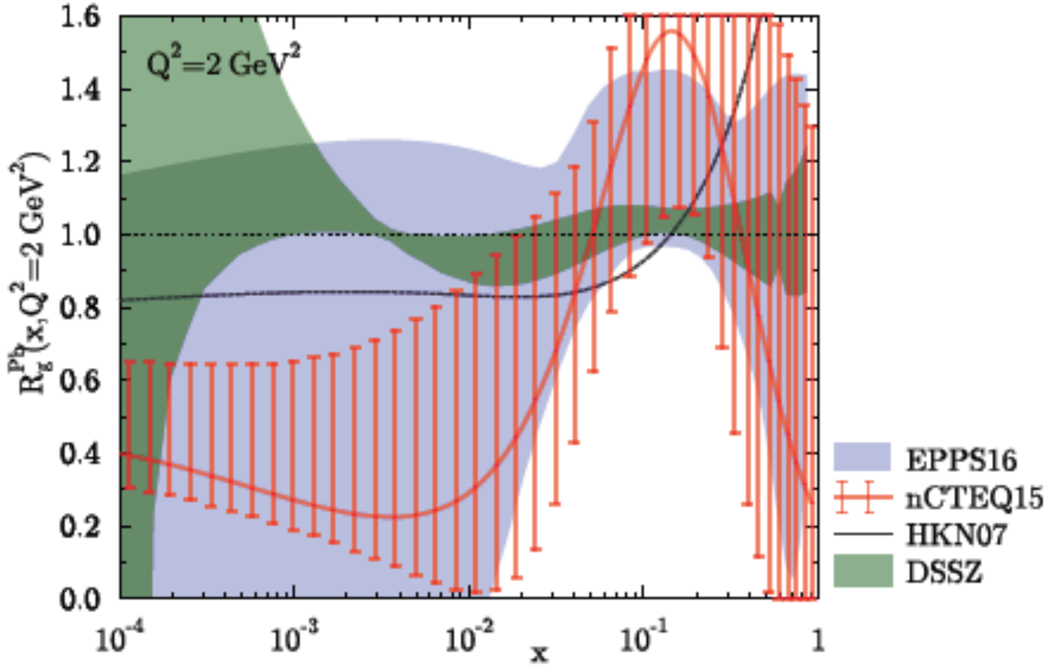
- W range for VMs → multi-TeV

# Current Status of Nuclear Parton Densities

- Significant uncertainties in the nuclear PDFs (nPDFs)

$$R_g^A(x, Q^2) = f_g^{\mathrm{P},A}(x, Q^2)/f_g^{\mathrm{P}}(x, Q^2),$$

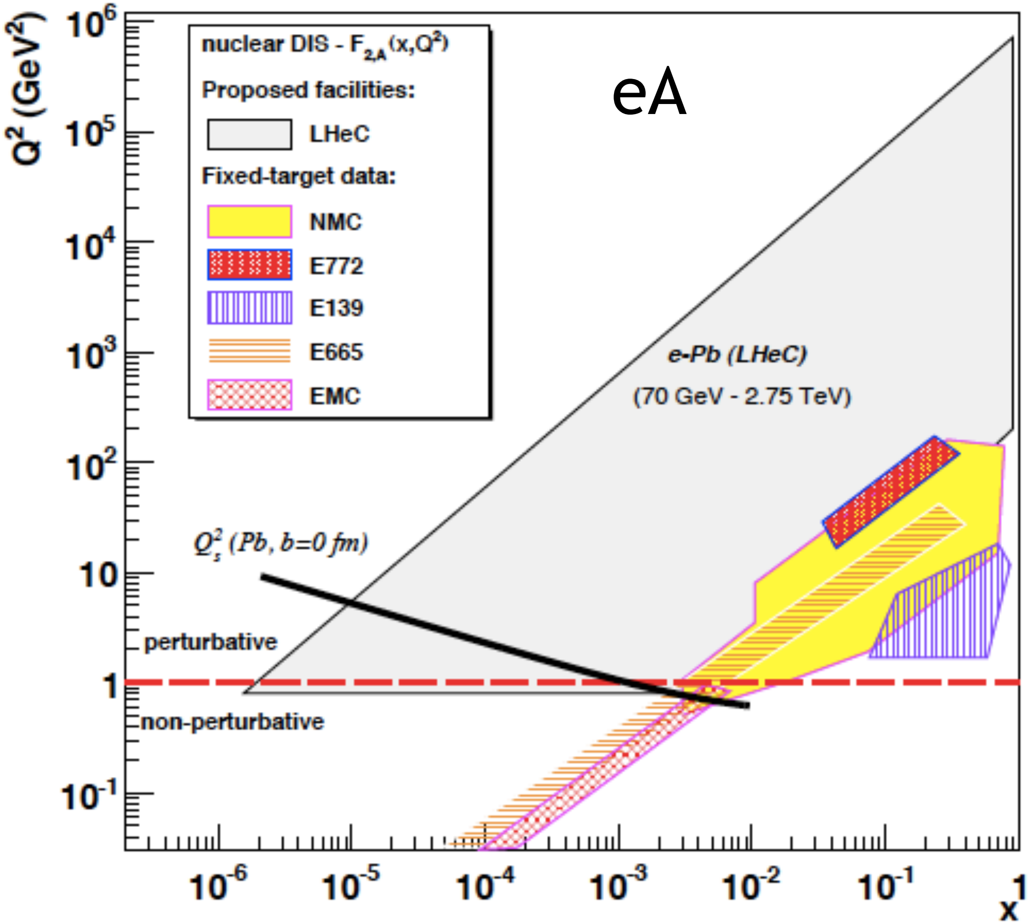
[Slide from Hannu Paukkunen]

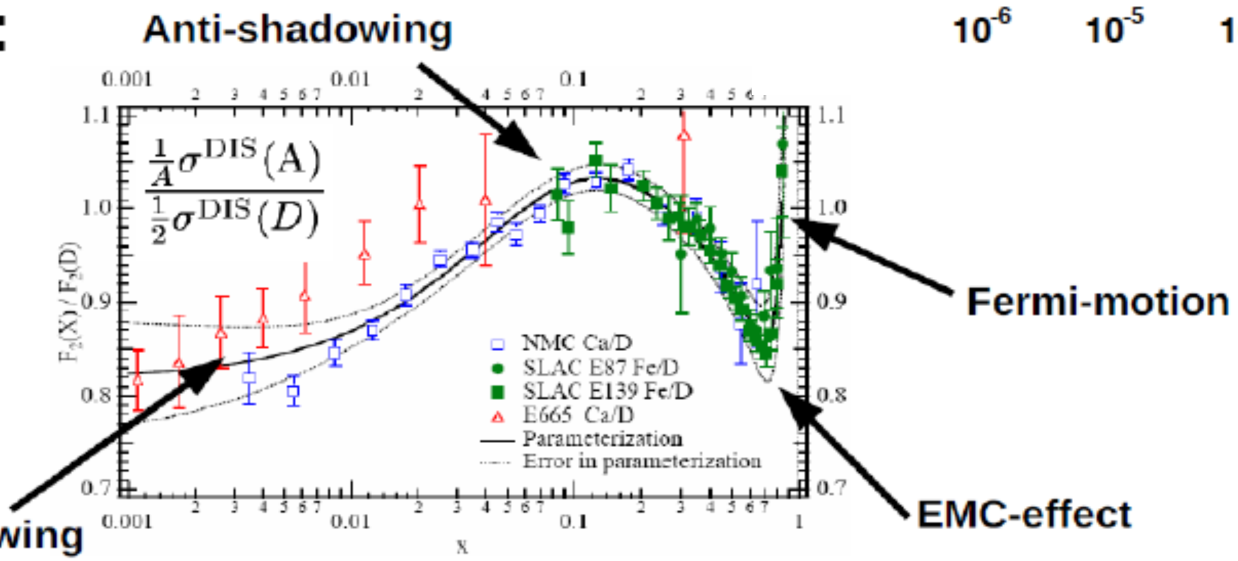



- Especially the small-$x$ (here, $x \lesssim 10^{-2}$) behaviour of nPDFs at smallish $Q^2$ are largely unknown — may become a bottleneck e.g. in
  - distinguishing effects of non-linear evolution
  - precision studies of phenomena in heavy-ion collisions
  - calculations of cosmic-ray interactions in the air

# EPPS Input Data

- Exciting phenomenology not matched by DIS data
- EPPS16 also uses various Drell-Yan, semi-inclusive $\pi^0$ in PHENIX dAu, W,Z, dijets in ATLAS and CMS
- Direct $\gamma$, B, D mesons at LHC promising if theoretical understanding sufficient

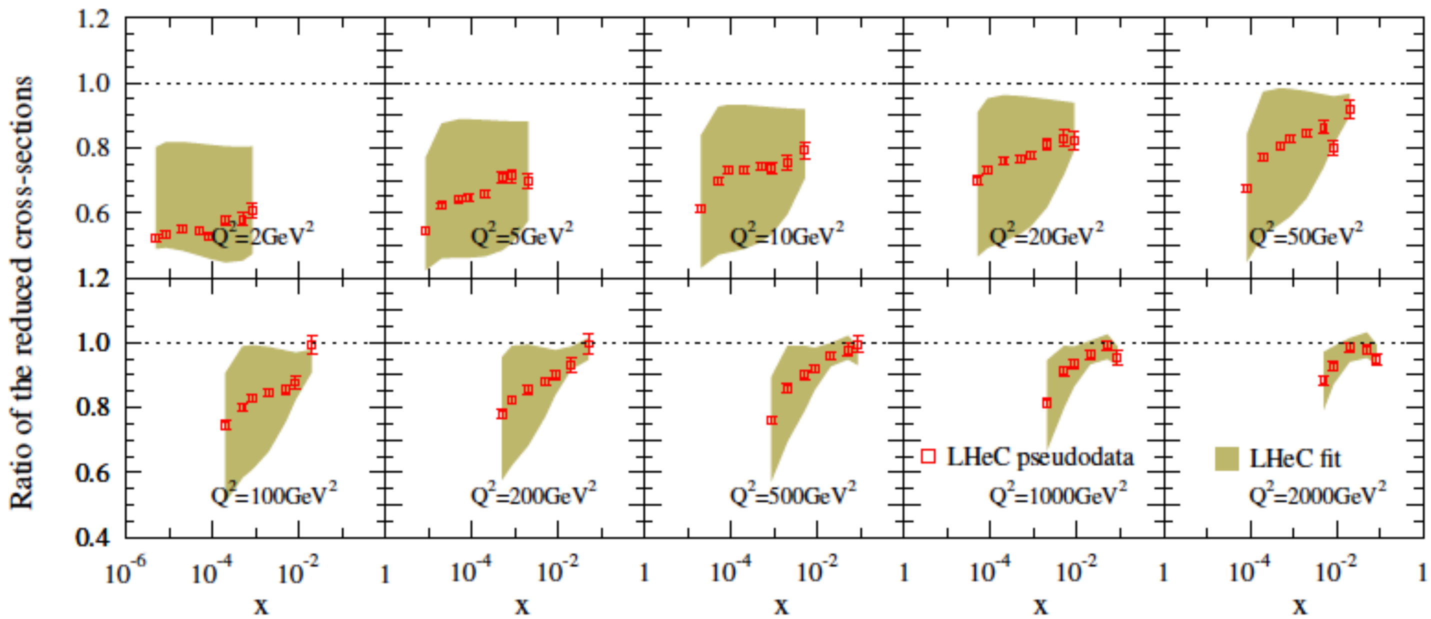



Sat$^n$?

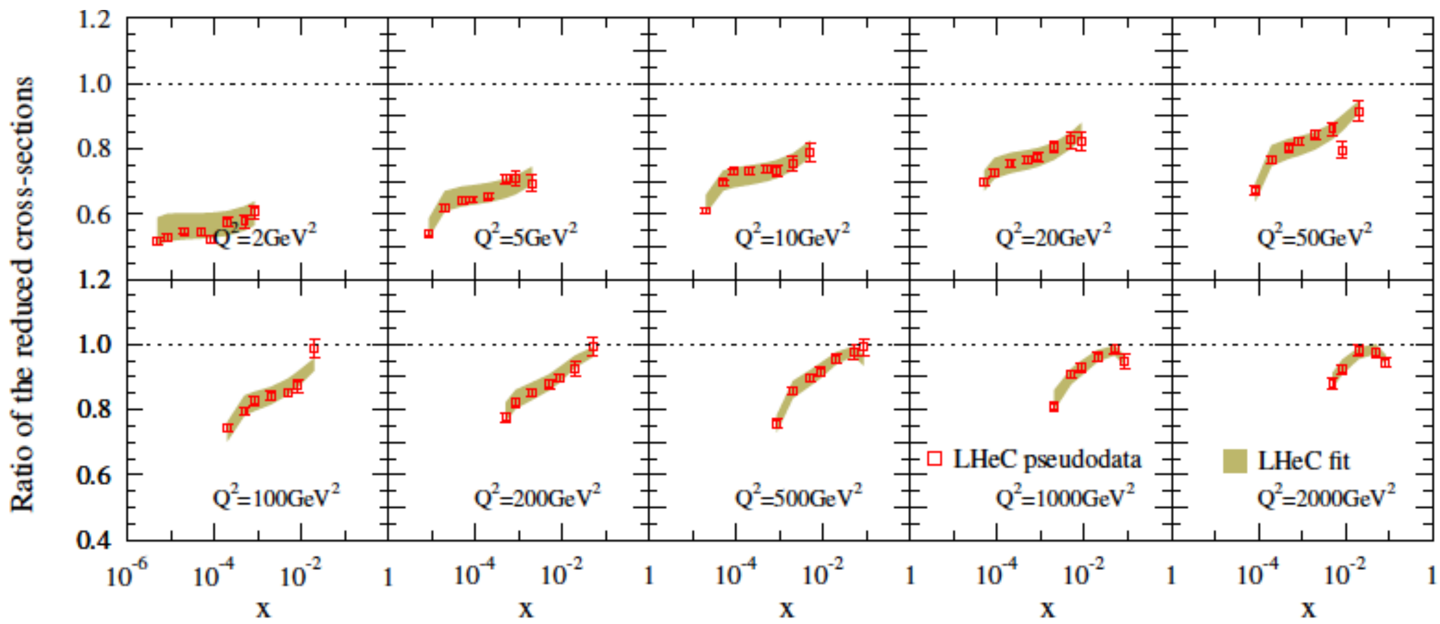
LHeC: Four orders of magnitude Increase in kinematic range over previous DIS experiments.

# Influence of 1fb$^{-1}$ A$^{-1}$ LHeC ePb data on EPPS16

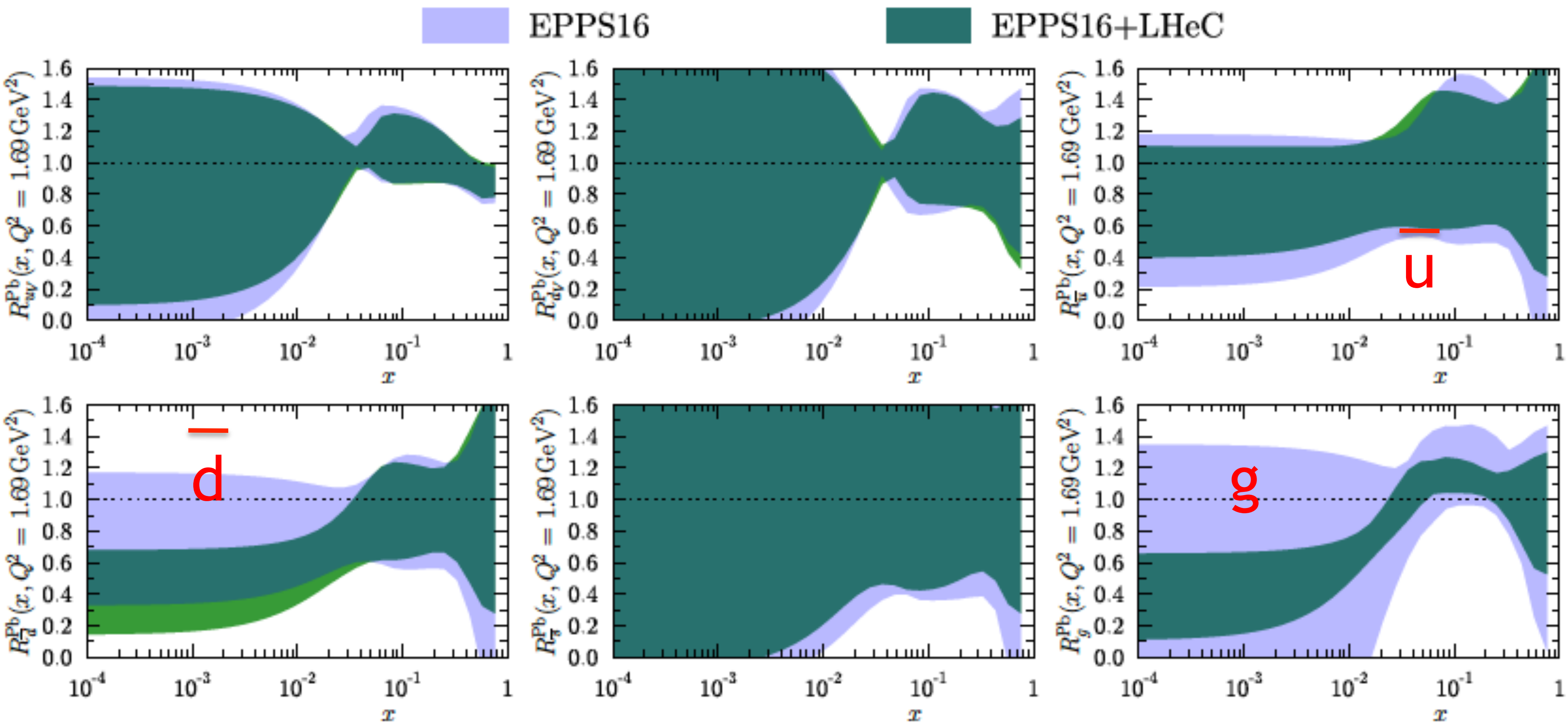



LHeC NC pseudodata before inclusion in EPPS16

EPPS16 after including LHeC pseudodata

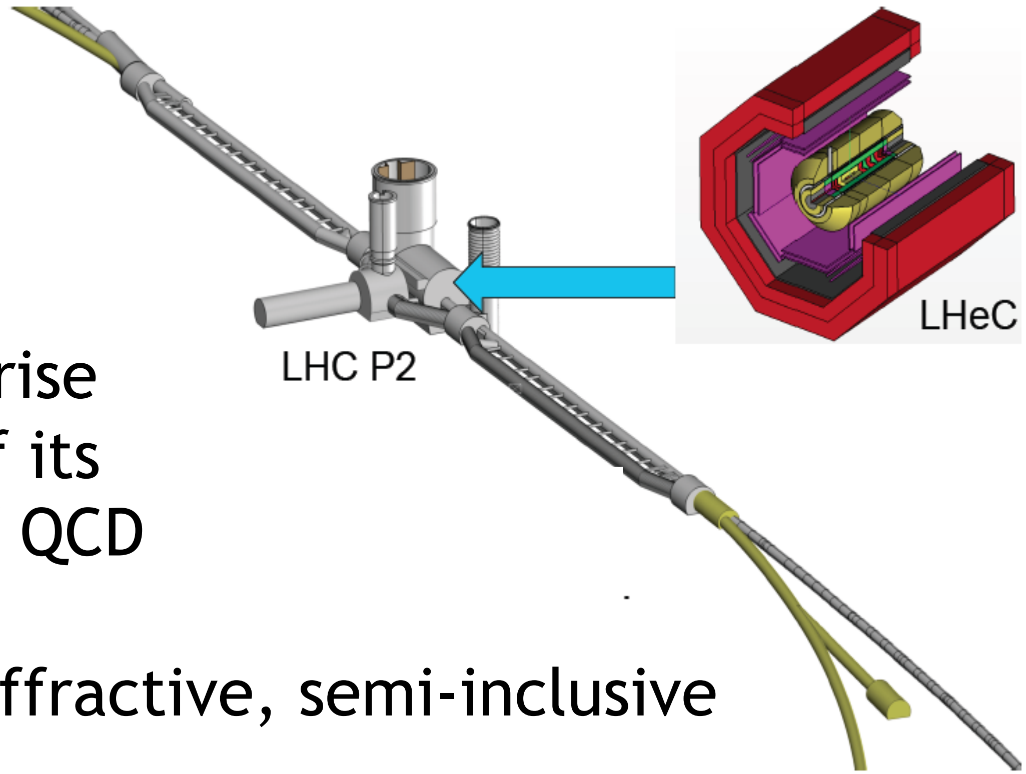


# Improvement in EPPS16 nPDFs




[Probably understates full impact – still some Parameterisation bias in EPPS16 without future eA]

# Summary




• Future DIS facilities are vital to fully establish and characterise saturation and the dynamics of its onset → the energy frontier of QCD

• Needs ep and eA inclusive, diffractive, semi-inclusive over a range of energies

• Complementarity beween EIC and LHeC

• LHeC working towards next CERN Council European Strategy exercise (2020) with a view to running in later stages of LHC (post-LS4, from ~2031) … lots to do!