# Low-x Physics at Electron-Proton and Proton-Proton Colliders

## WE-Heraeus Seminar on Forward Physics at the LHC and EIC
## Physikzentrum Bad Honnef
## 24 October 2024


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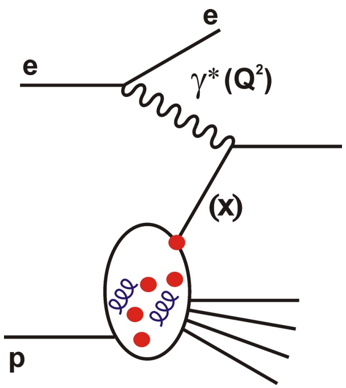
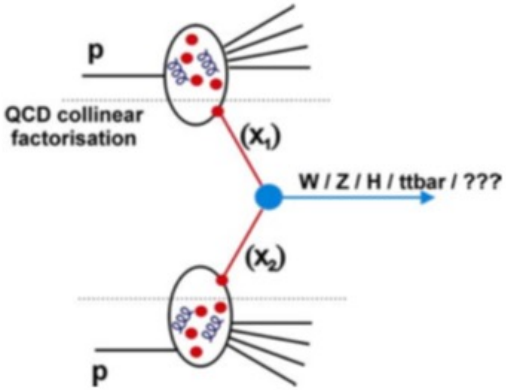
(University of Birmingham)


1) Where HERA leaves us
2) What can the LHC do?
3) Future DIS facilities



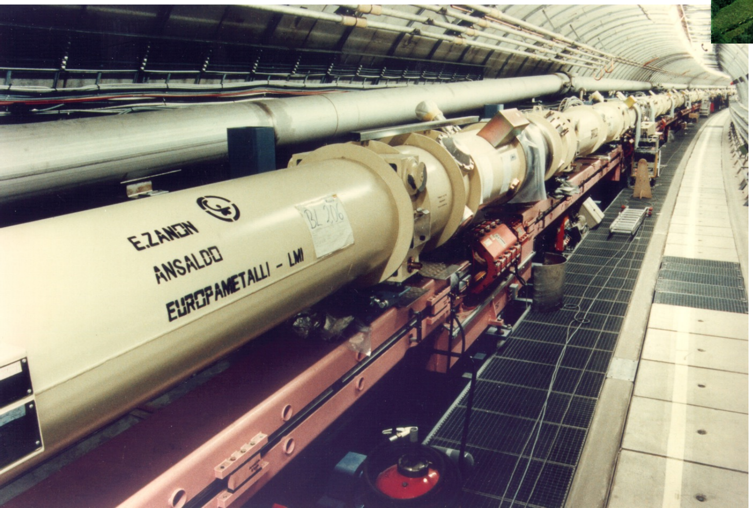

Focus on collinear proton PDFs
(Diffractive channels, Heavy ion targets covered in other talks)

# HERA, DESY, Hamburg

So far still the only collider of electron and proton beams ever

$\sqrt{s_{ep}} \sim 300$ GeV … equivalent to a 50 TeV beam on a fixed target

'Birth' of experimental low-x physics

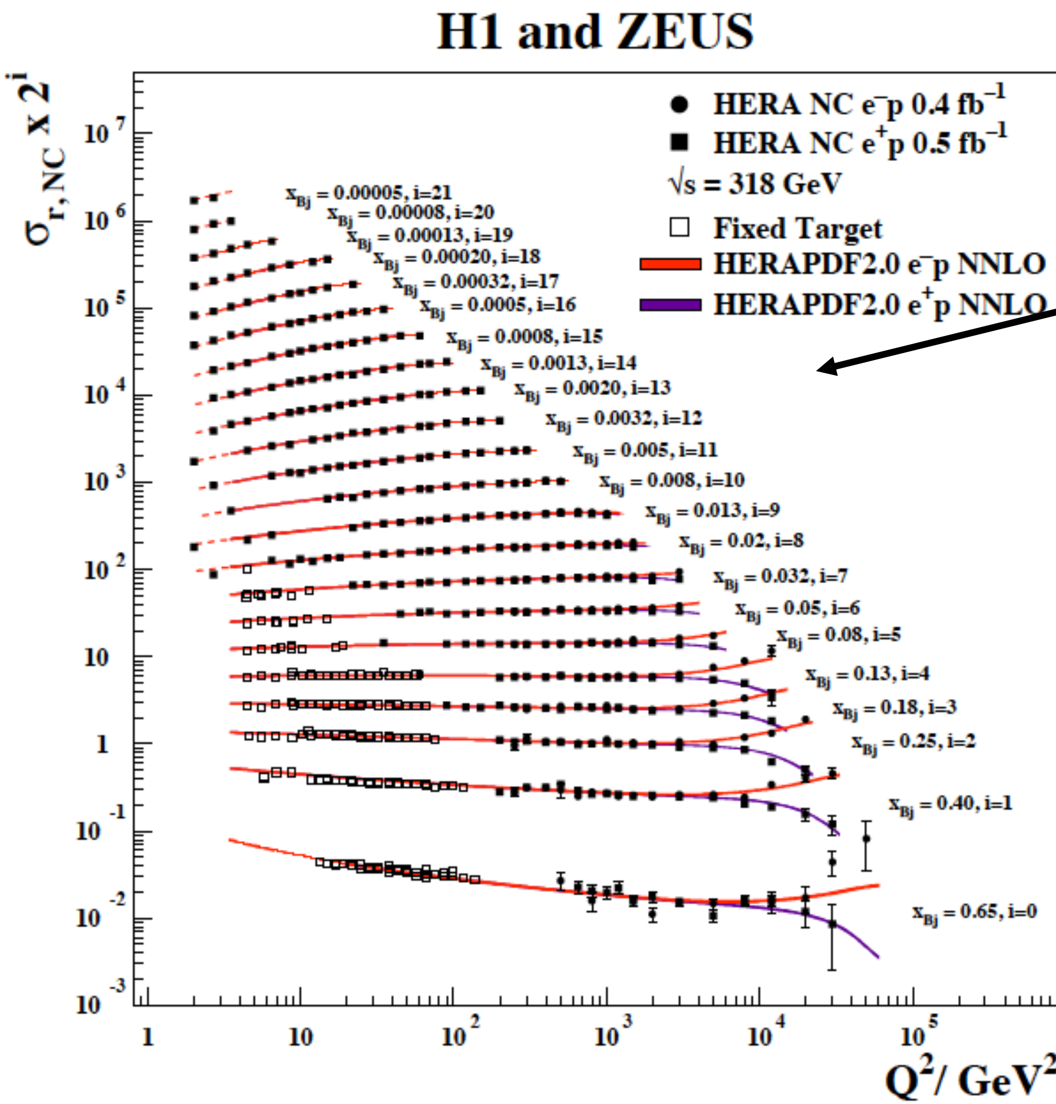




→ Taught us much of what we know about proton structure

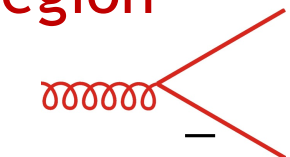
→ Only ~0.5 $fb^{-1}$ per experiment
→ No deuteron or nuclear targets

# Low x Physics is Driven by the Gluon

… knowledge comes mainly from inclusive NC HERA data




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

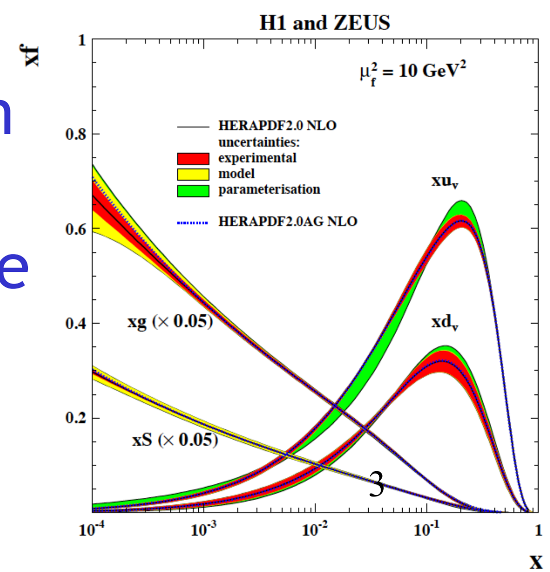


$$g \to q\bar{q}$$

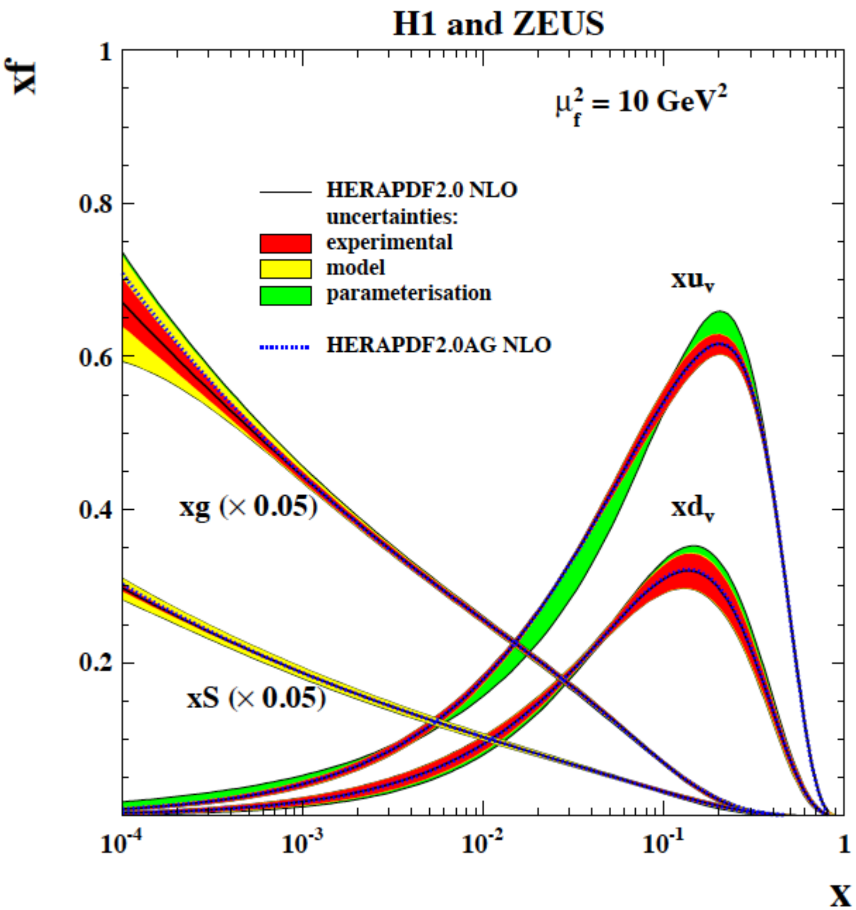
- e.g. Prytz approx:

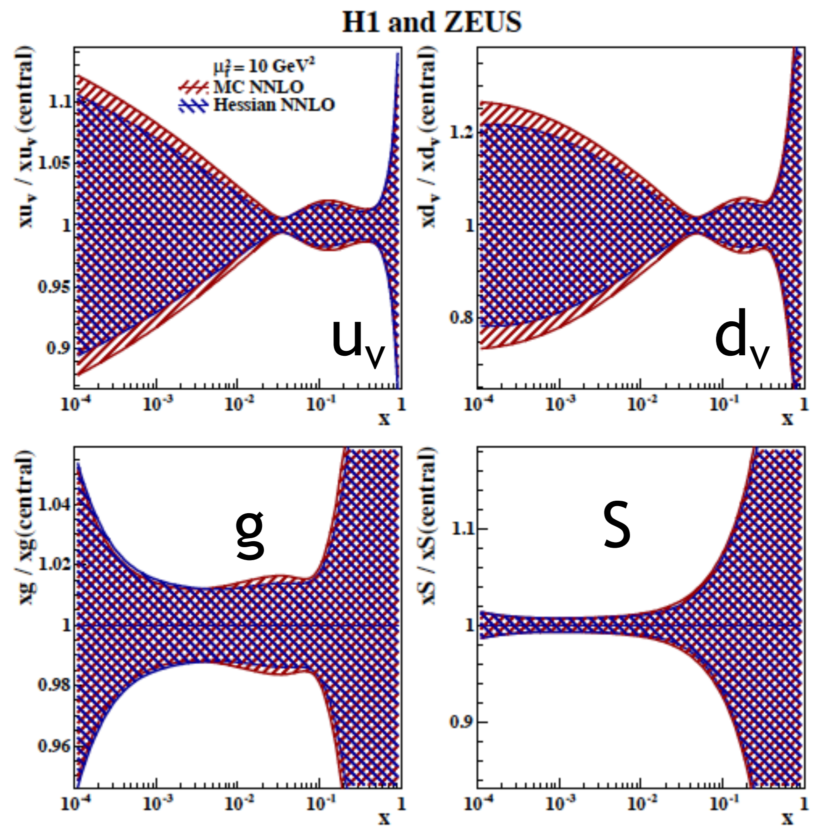
$$\frac{dF_2(x,Q^2)}{d\ln Q^2} \sim G(2x)$$

- needs lever-arm in $Q^2$ … reasonable precision only to $x \sim 10^{-3}$.



# Final HERA Picture of Proton (HERAPDF2.0)

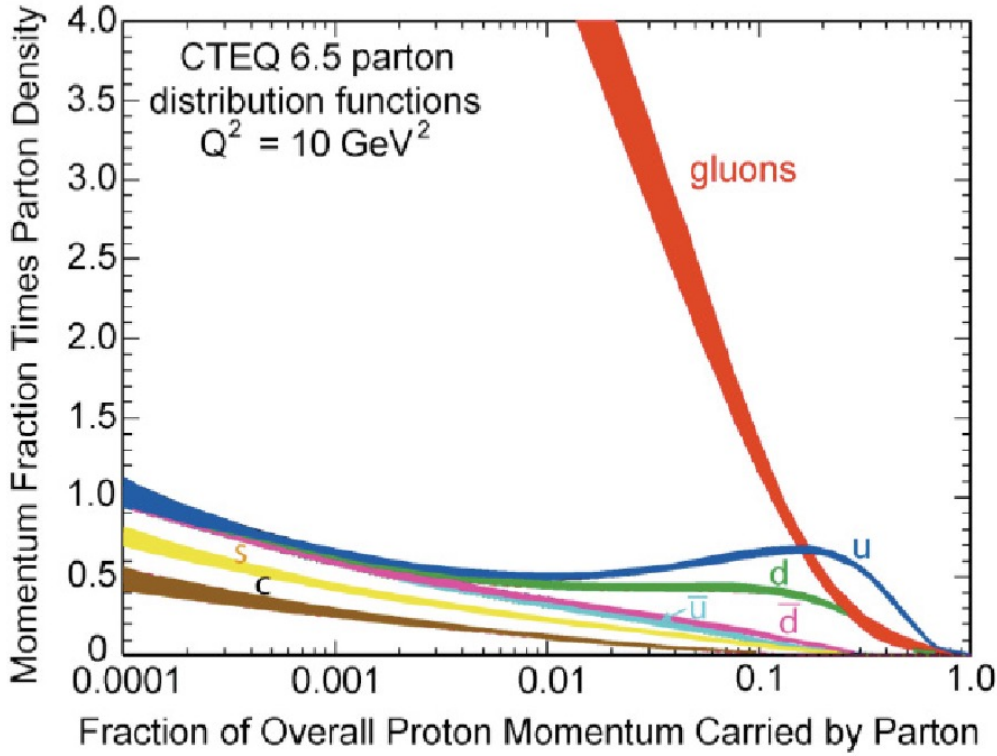


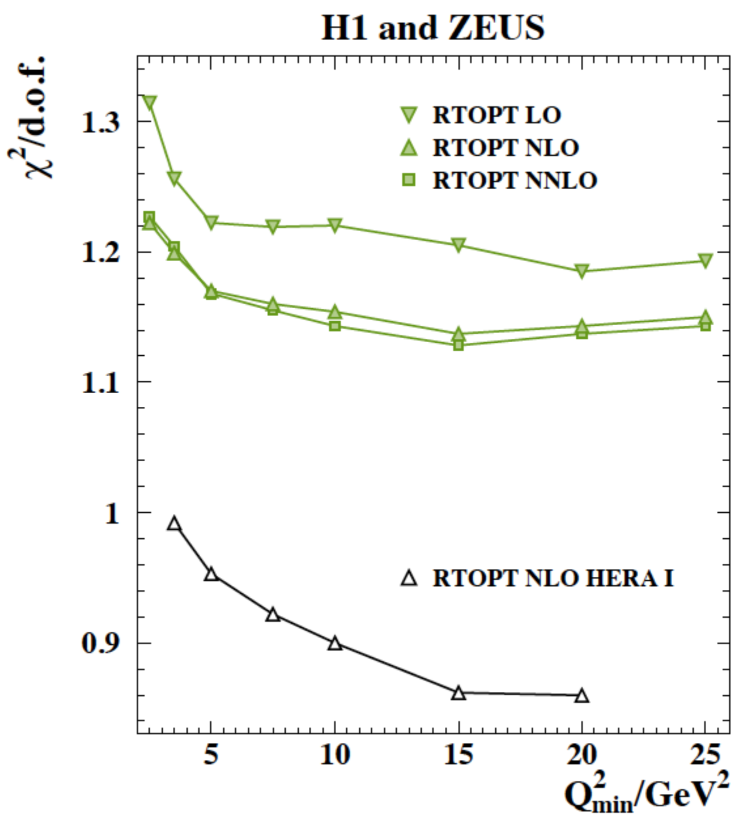




- Sea quarks well known down to $x=10^{-4}$
- ~2% precision on gluon for $10^{-3} < x < 10^{-1}$
- Gluon uncertainty explodes between $x=10^{-3}$ and $x=10^{-4}$
- Gluon itself is rising in a seemingly non-sustainable way …

# The "Pathological" Gluon

- Fast growth of low x gluon appears unsustainable → new low x gluon-driven dynamics?

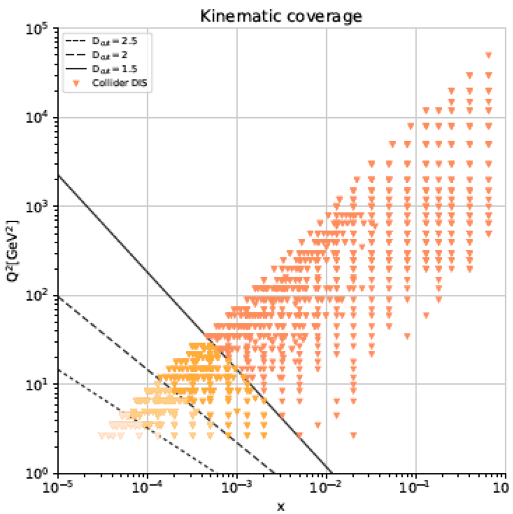


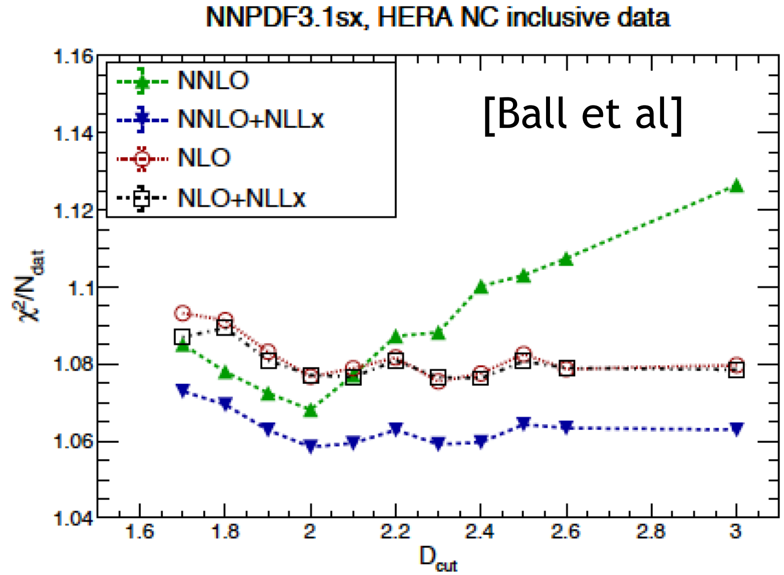




**Some evidence for deviations from (NNLO) DGLAP at lowest $Q^2$ in Final HERA-2 Combined PDF Paper:**

"some tension in fit between low & medium $Q^2$ data… not attributable to particular x region (though there is a kinematic correlation)"

# New Low x effects at HERA?



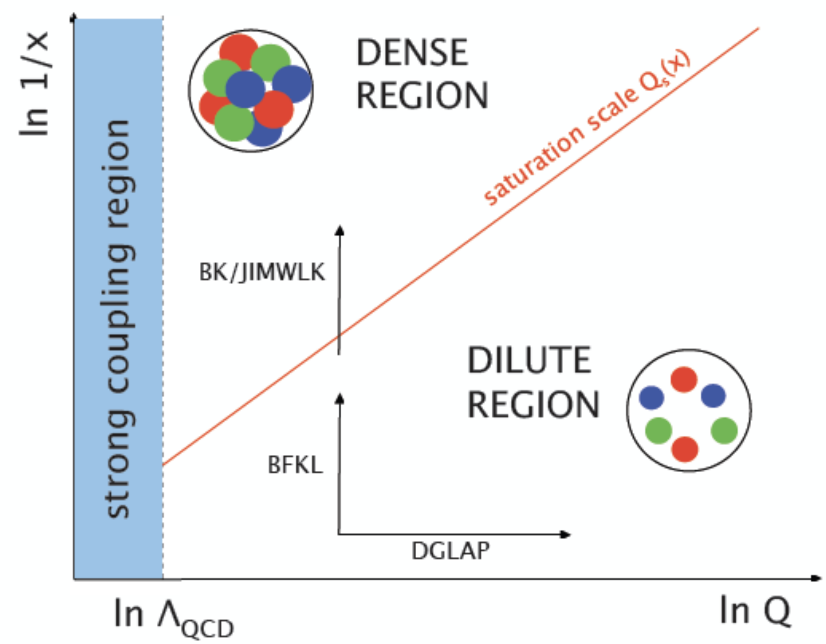

## Energy effects?

Including NLL ln(1/x) (BFKL) resummation in fits improves $\chi^2$ and describes difficult low x, low $Q^2$ region (also improves $F_L$)

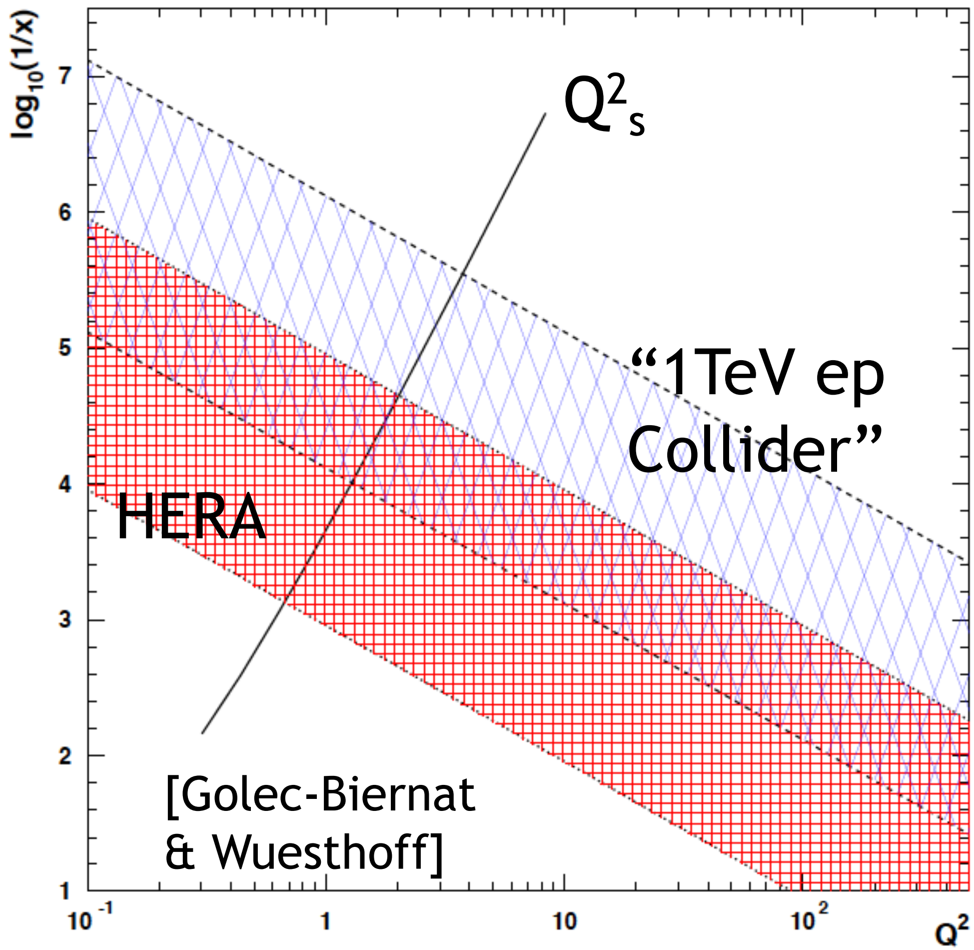
## Density effects?

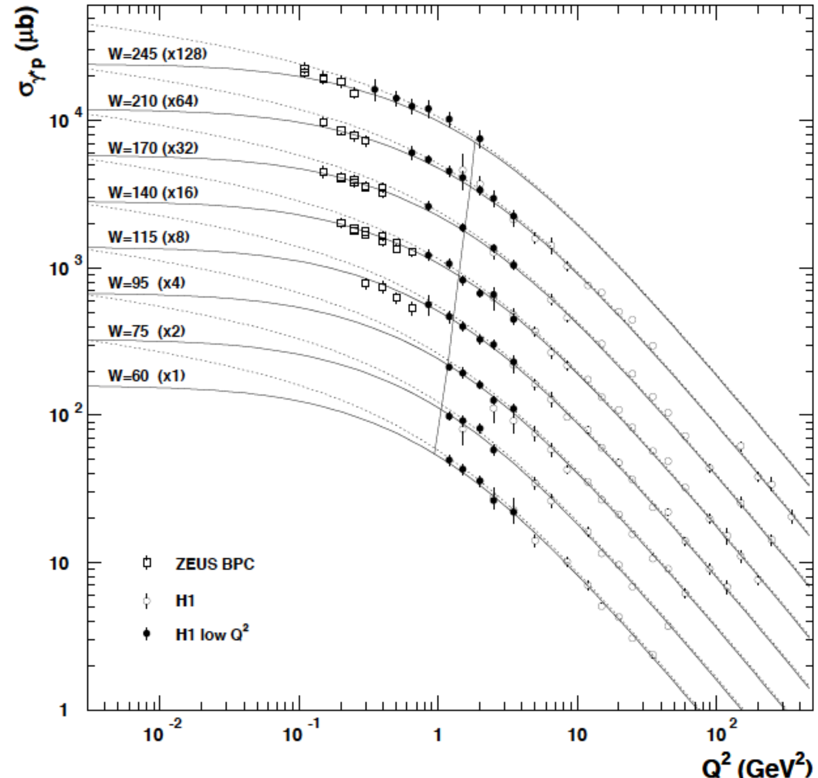
→ Non-linear gluon recombination (gg→g)?

… `Saturation' models successful in describing HERA data down to lowest x and $Q^2$ values



# $Q^2$ < 1 GeV$^2$ data → Best description with Dipole Model, including saturation



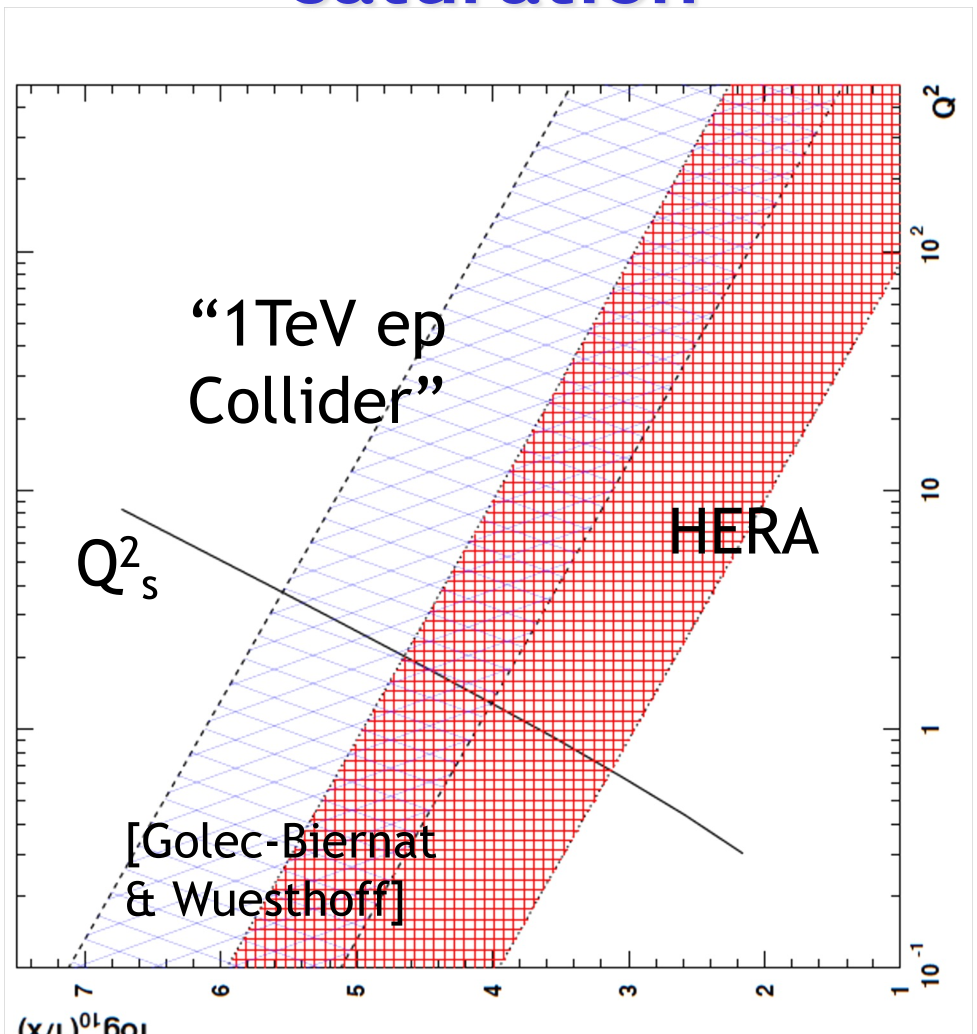



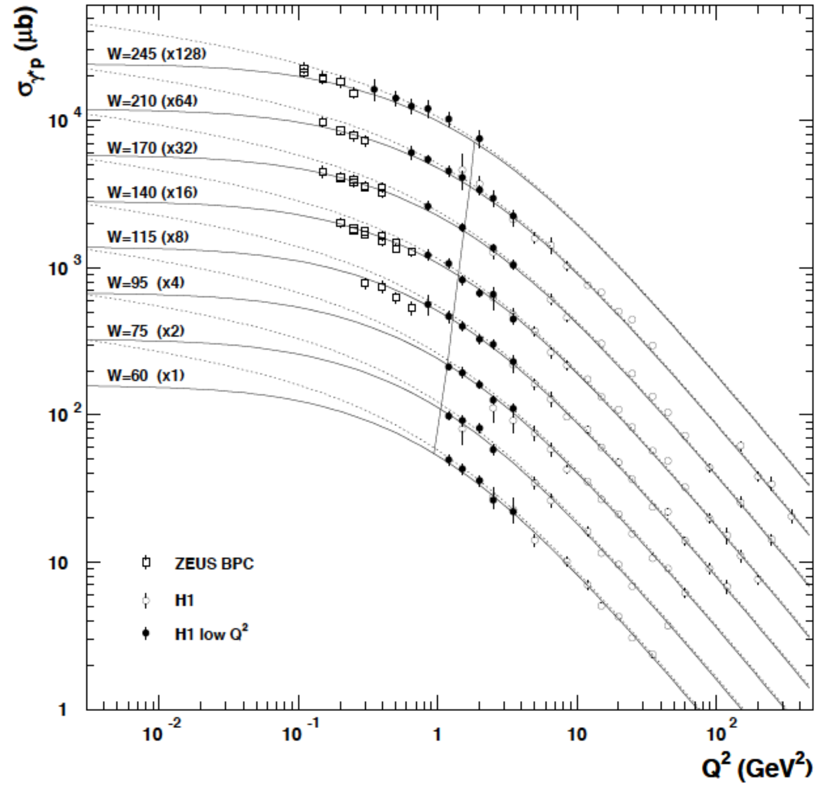

All data ($Q^2$ >~ 0.05 GeV$^2$) are well fitted in (dipole) models that include saturation effects

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

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

# $Q^2$ < 1 GeV$^2$ data → Best description with Dipole Model, including saturation

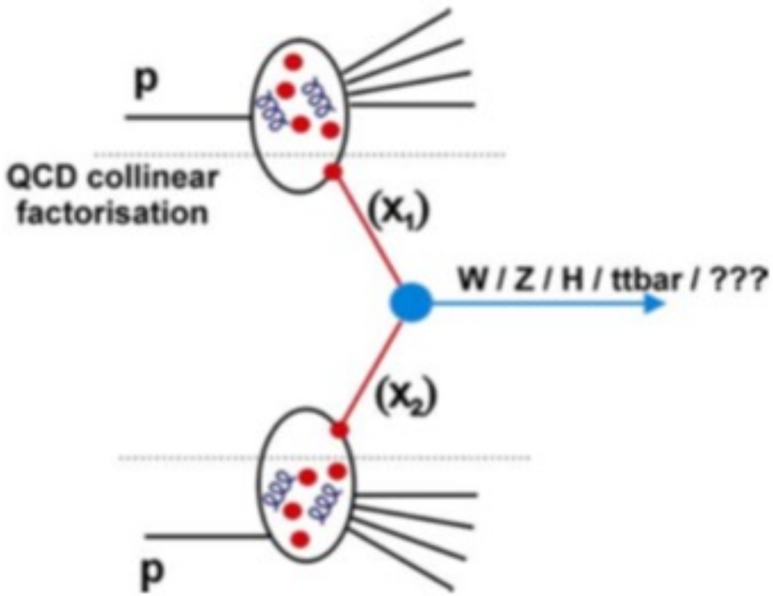


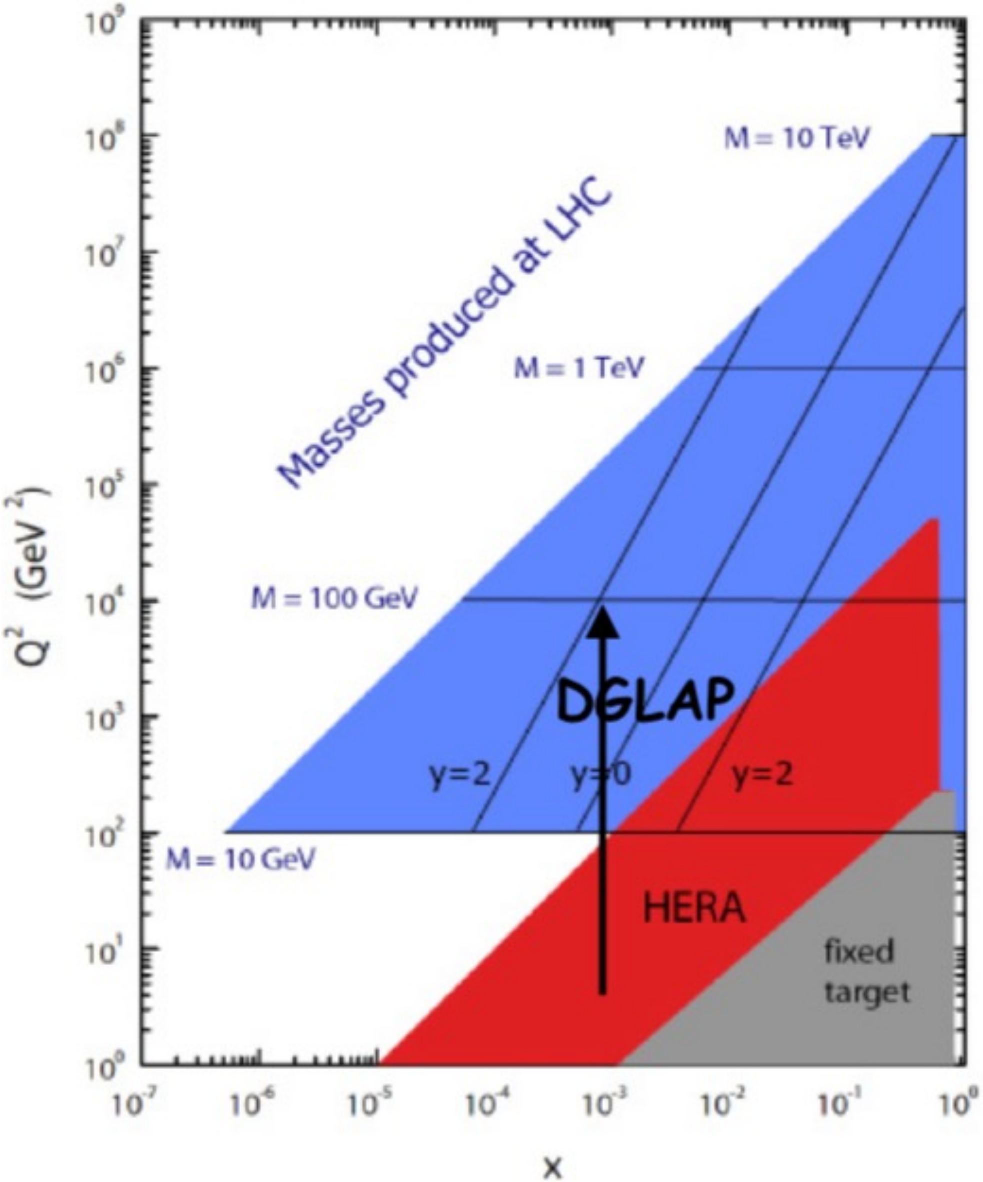




$Q^2_s$ ~ 1 GeV$^2$ at HERA
→ Most of the relevant data are at non-perturbative $Q^2$ values
→ quarks and gluons unreliable degrees of freedom

# From HERA to LHC

→ LHC in principle extends low x region even beyond HERA

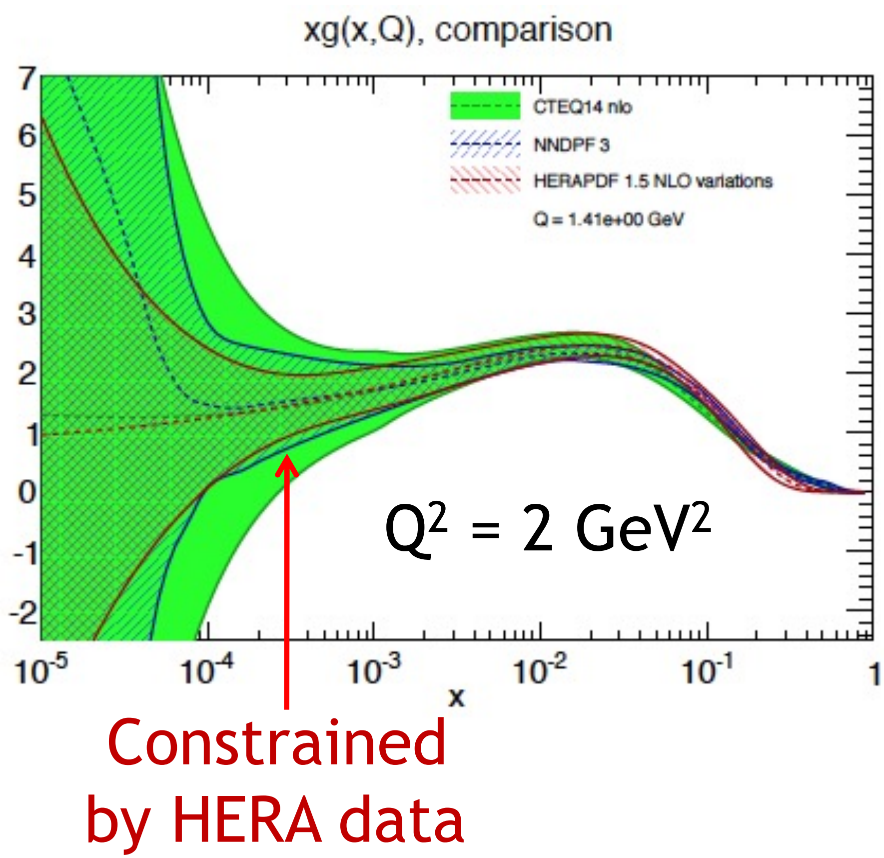


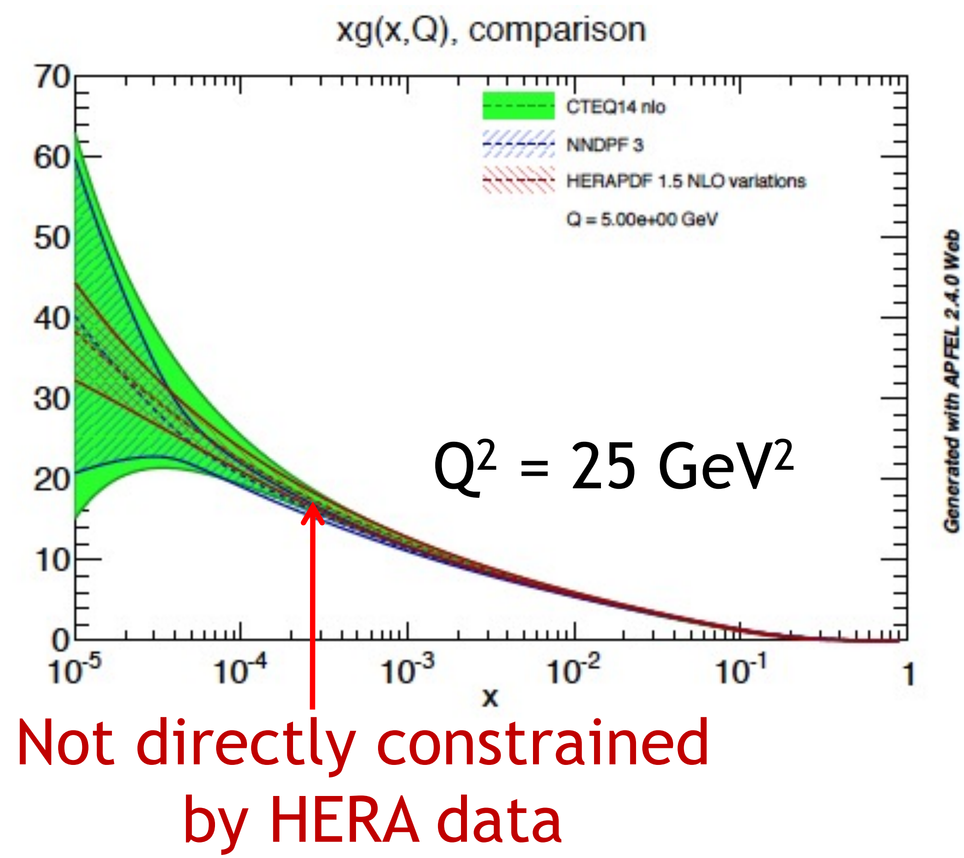




Assuming collinear factorisation and a full understanding of low x dynamics …

# LHC v HERA at low x

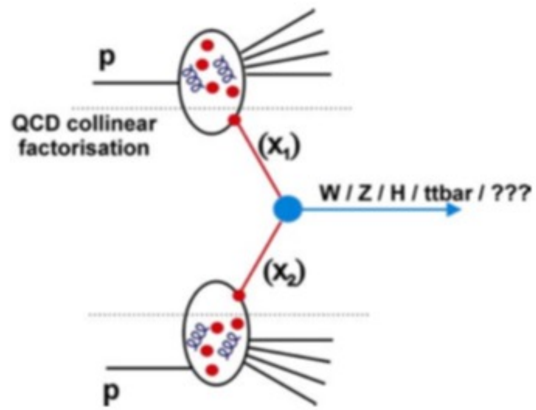
- LHC comparisons with PDFs based purely on DGLAP $Q^2$ evolution from HERA may reveal novel low x effects

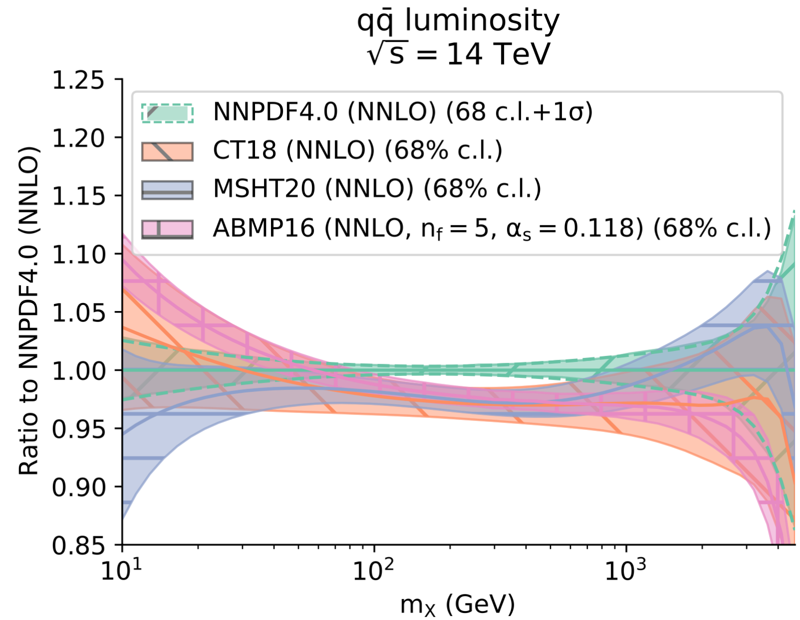


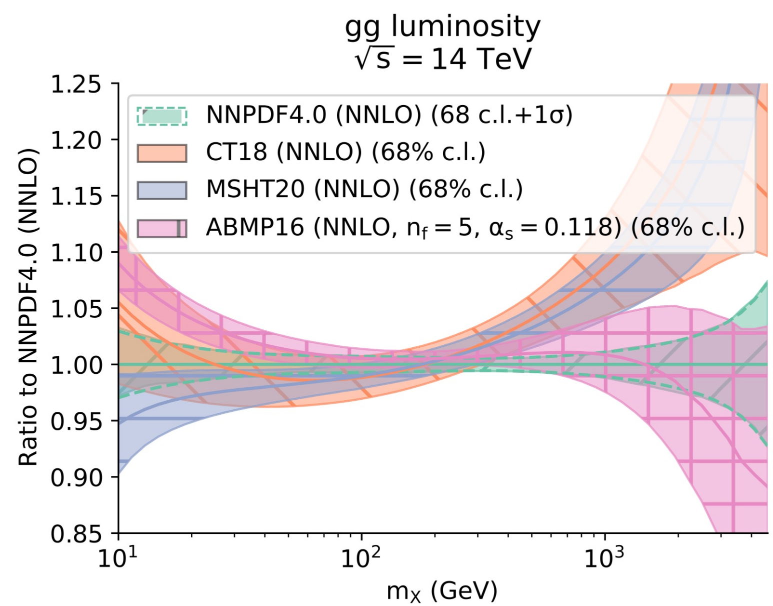

- Converging solutions after DGLAP evolution maybe misleading
- Motivation to measure LHC low x processes and compare with theory based on DGLAP (as well as including in DGLAP fits)

# Low x Kinematics at the LHC




[NNPDF4.0 , arXiv:2109.02653]




- LHC masses produced by low x partons are very small …

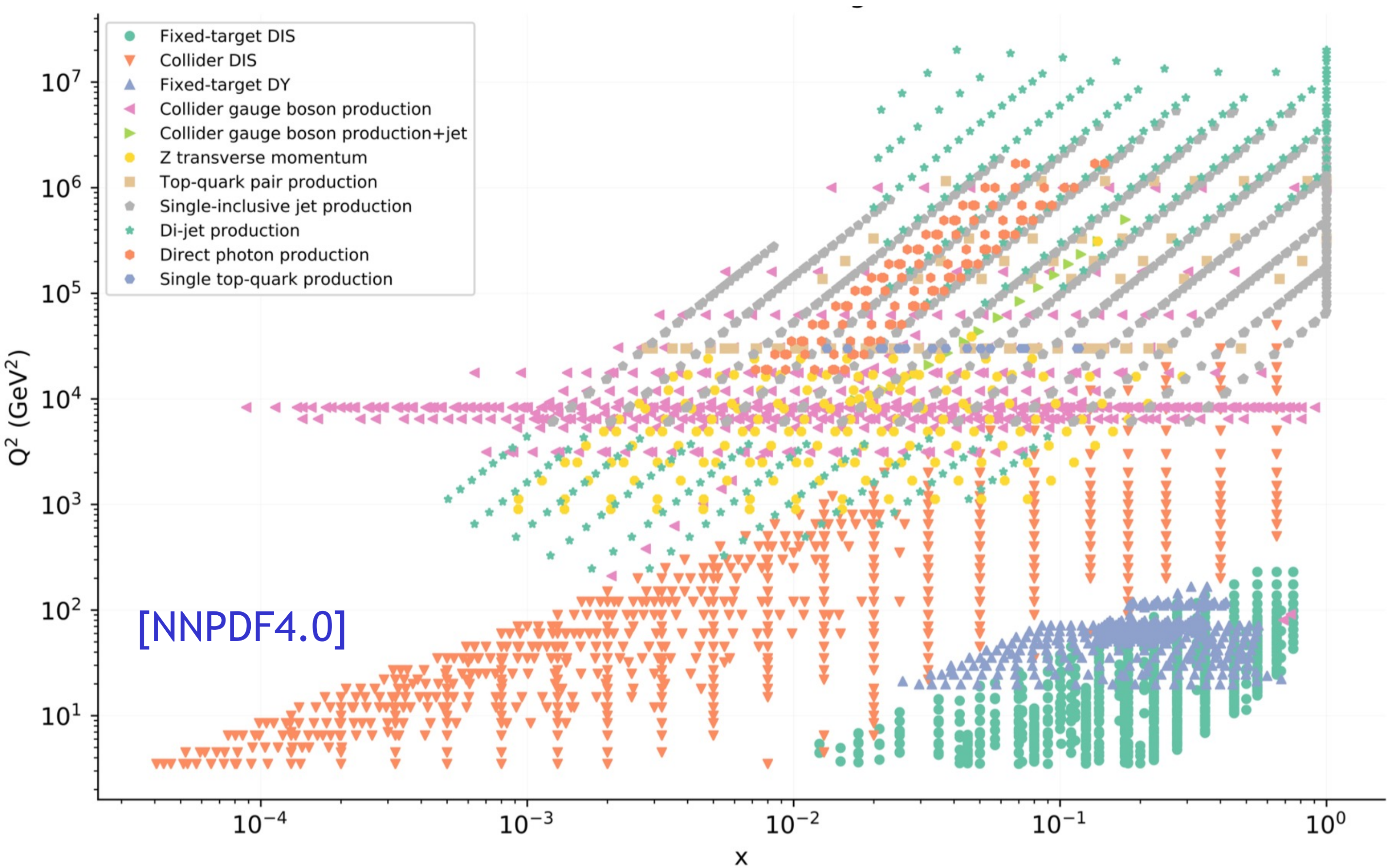
- At mid-rapidity:

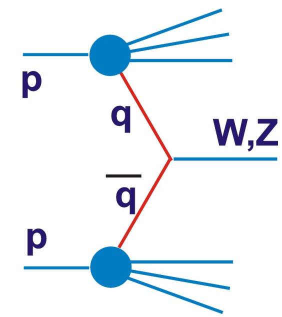
$$M_X = 2xE_p$$

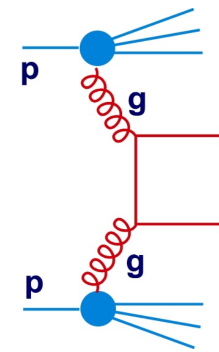
… e.g. two x=$10^{-4}$ partons produce $M_X$ = 1.4GeV at mid-rapidity
→ Not even triggered
→ Not even on parton lumi plots

- Asymmetric configurations are essential → forward physics

# Constraining Low x PDFs with LHC Data



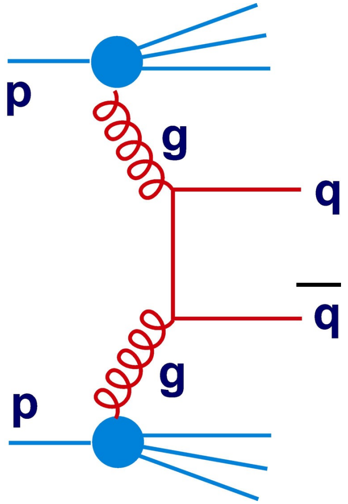



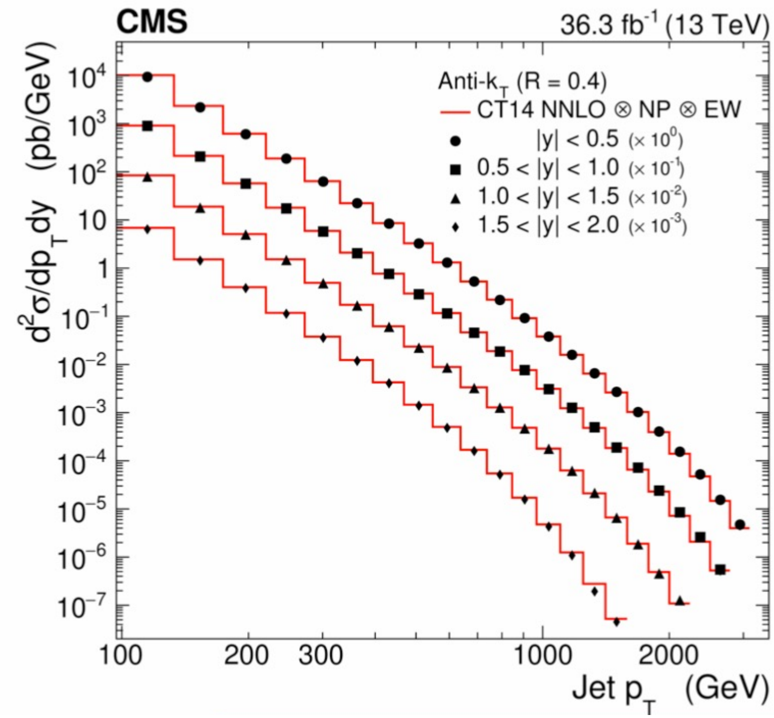

Observables included in global fits that constrain low x …

- Electroweak gauge bosons (and Drell Yan) → quarks
- Jet production → gluons

… the more forward, the better!

# LHC Gluons: Jet Production



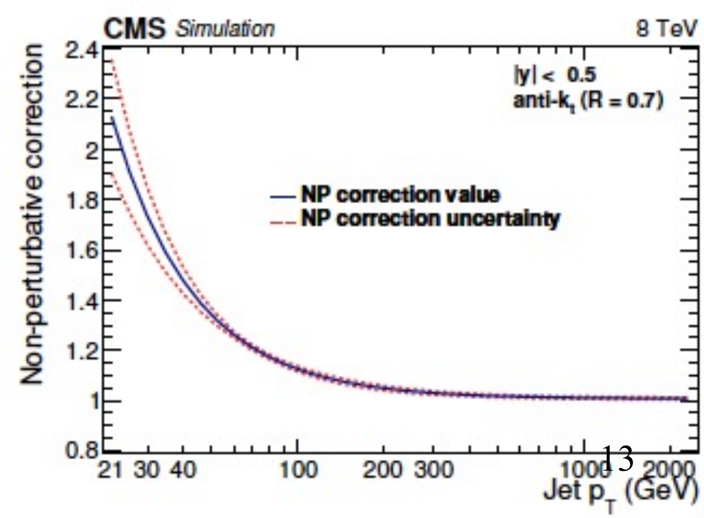




Gluon-sensitive, though even at low(ish) $p_T$, qg → qg is larger than gg → gg

- Recent availability of NNLO calculations increases interest

- Remarkable kinematic range, but high $p_T$ → not really a low x observable

- Low $p_T$ region limited experimentally by jet energy scale uncertainty and non-perturbative corrections to the jets

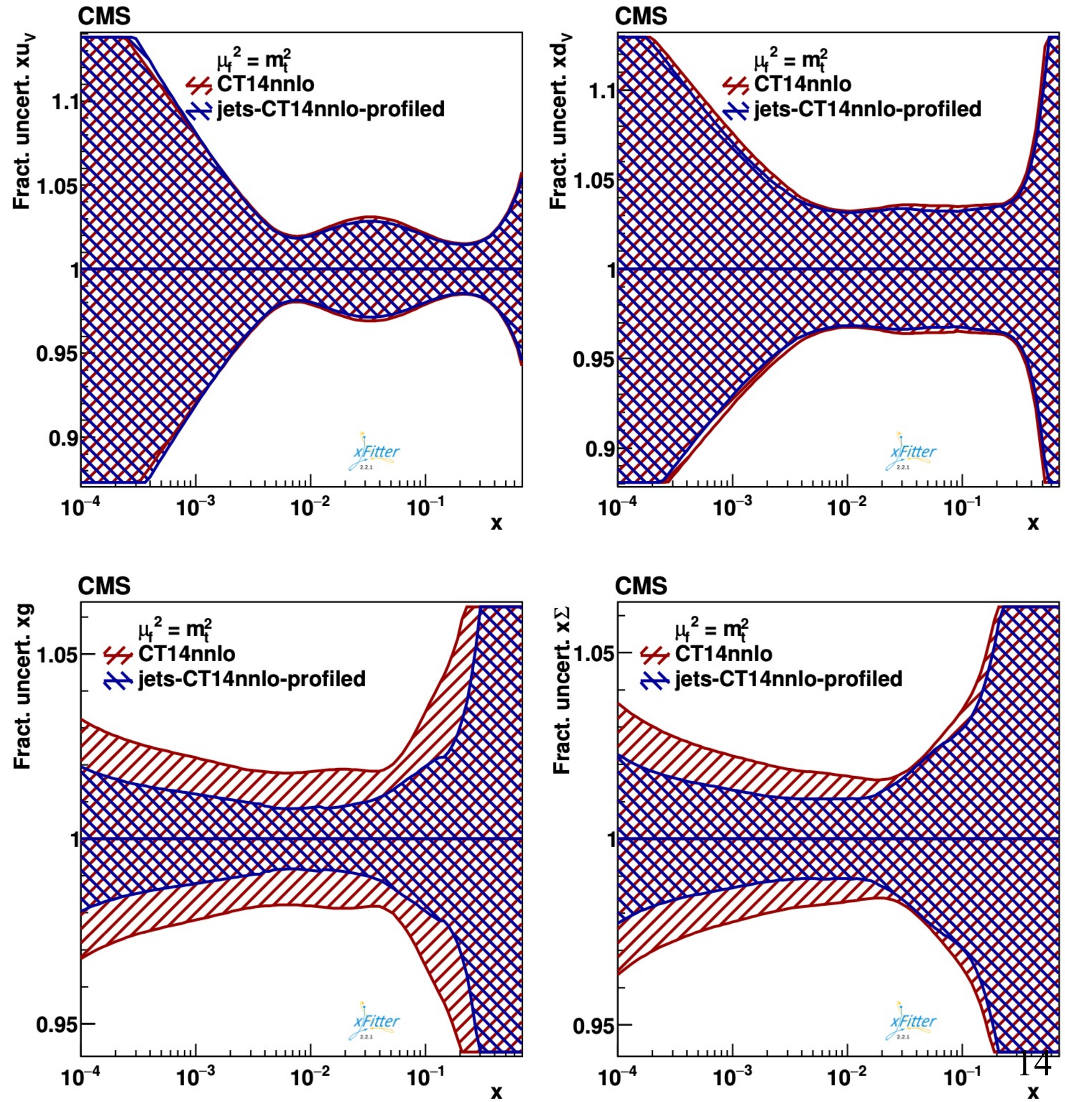


# PDF Constraints from CMS QCD ANALYSIS

- CMS 13 TeV Double-differential inclusive jets
- NC and CC cross sections from HERA

Inclusive jets have substantial (sometimes surprising) impact on gluon precision at all x relative to CT14 PDFs (which already used previous LHC data).

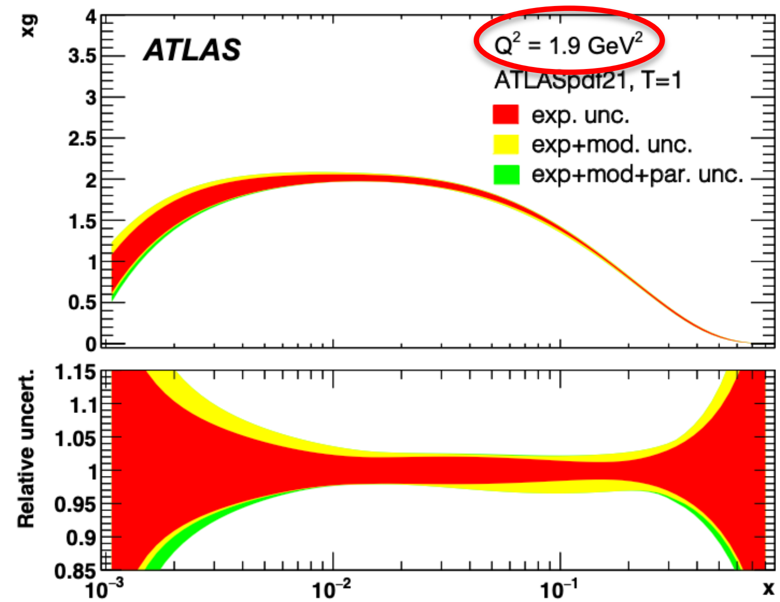
Singlet quark precision also improves



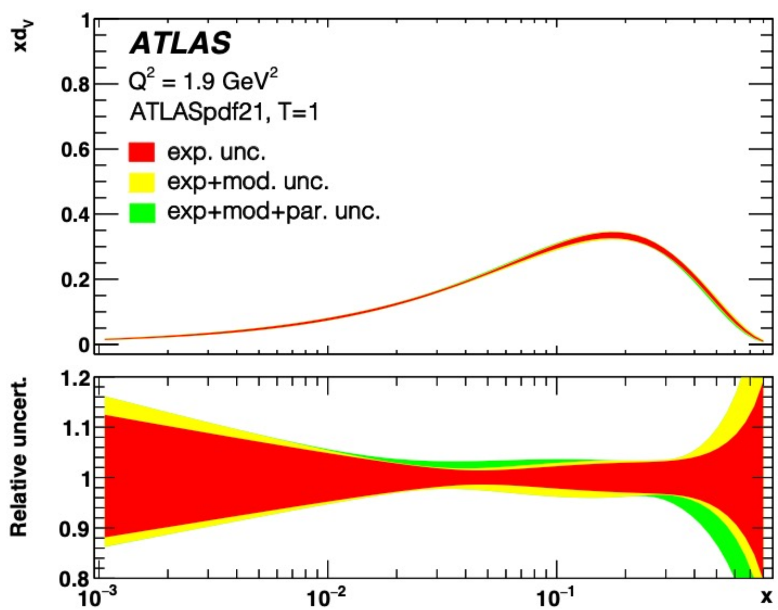
# ATLAS ‘Global’ Fit (ATLASpdf21)

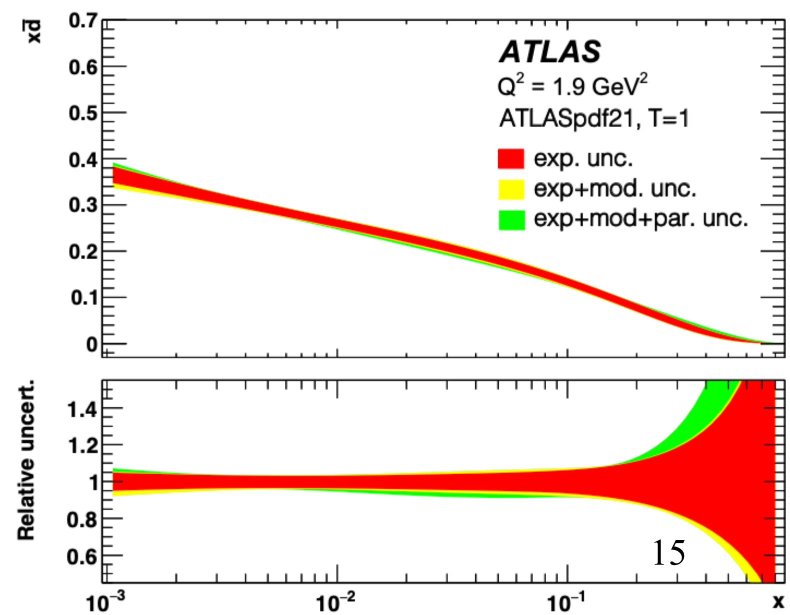
[EPJ C82 (2022) 438]

| Data set | $\sqrt{s}$ [TeV] | Luminosity [fb$^{-1}$] |
|---|---|---|
| Inclusive $W, Z/\gamma^*$ [9] | 7 | 4.6 |
| Inclusive $Z/\gamma^*$ [13] | 8 | 20.2 |
| Inclusive $W$ [12] | 8 | 20.2 |
| $W^\pm$ + jets [23] | 8 | 20.2 |
| $Z$ + jets [24] | 8 | 20.2 |
| $t\bar{t}$ [25, 26] | 8 | 20.2 |
| $t\bar{t}$ [15] | 13 | 36 |
| Inclusive isolated $\gamma$ [14] | 8, 13 | 20.2, 3.2 |
| Inclusive jets [16–18] | 7, 8, 13 | 4.5, 20.2, 3.2 |

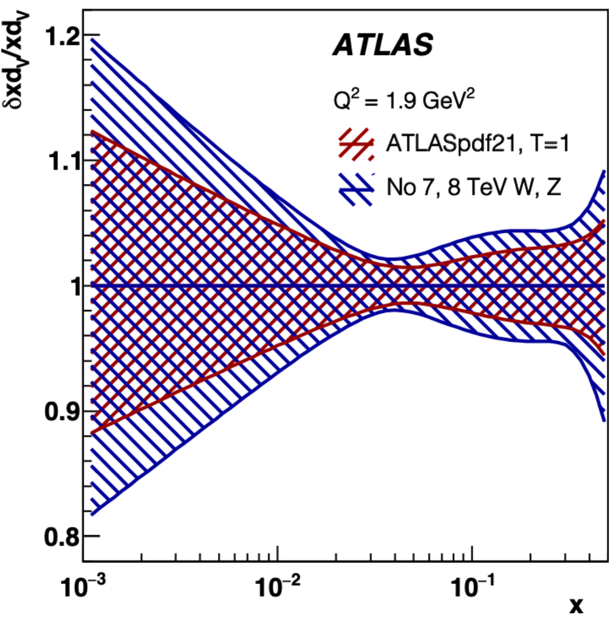



Including quark and gluon-sensitive observables and the correlations between them



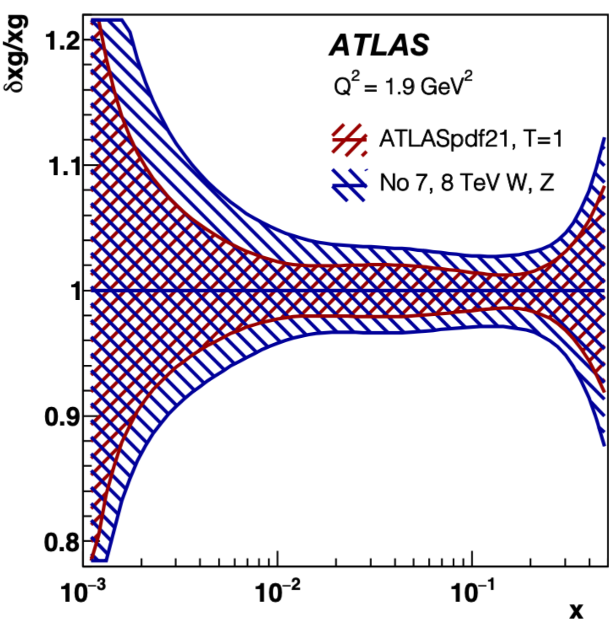



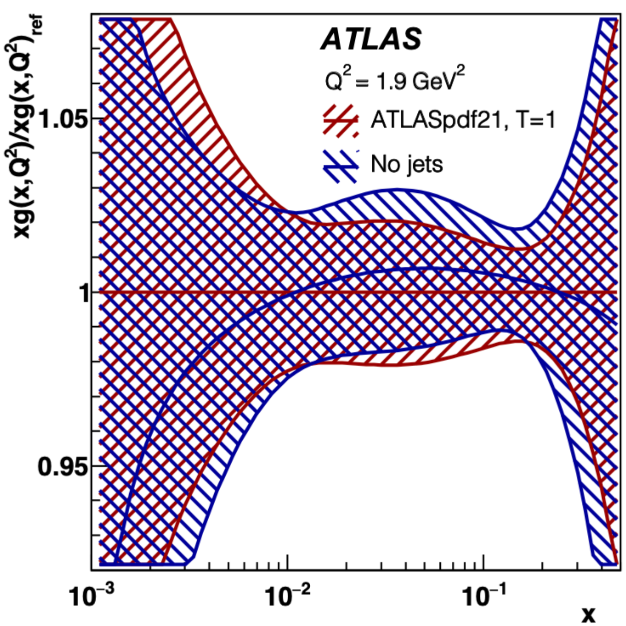
# Impact of Different ATLAS Data Sets

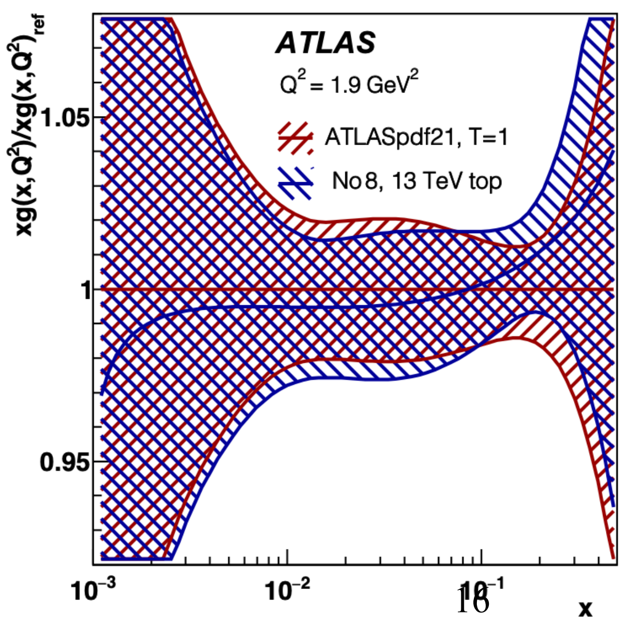



- W and Z data strongly constrain quark densities
- Also some (indirect) impact on the gluon, including low x

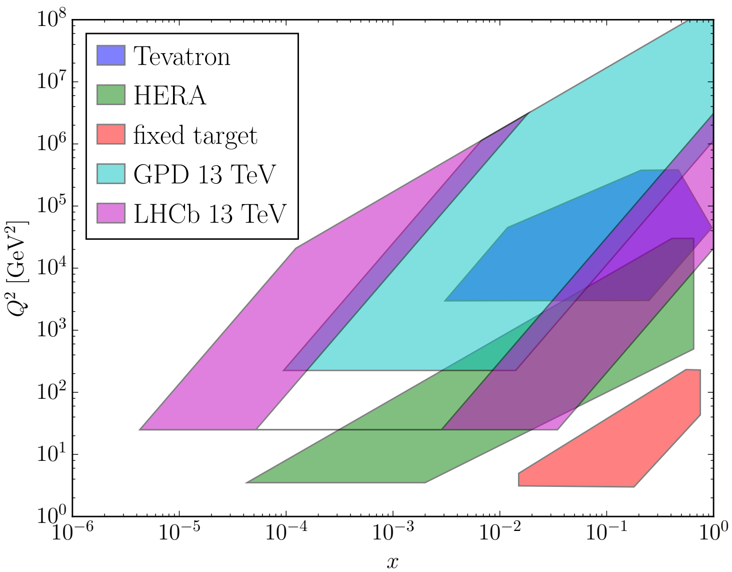
- Jet and top data primarily reduce gluon uncertainty at large x



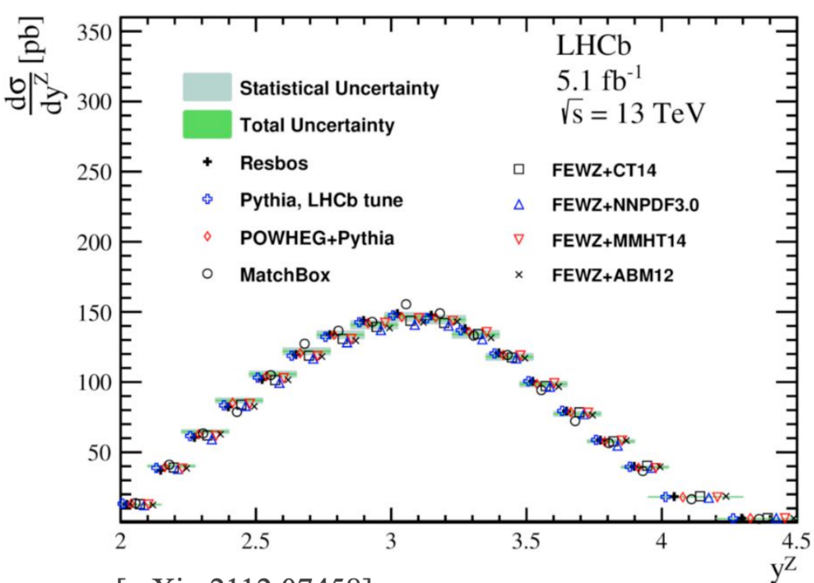



# Favourable LHCb Kinematics for Low x Physics

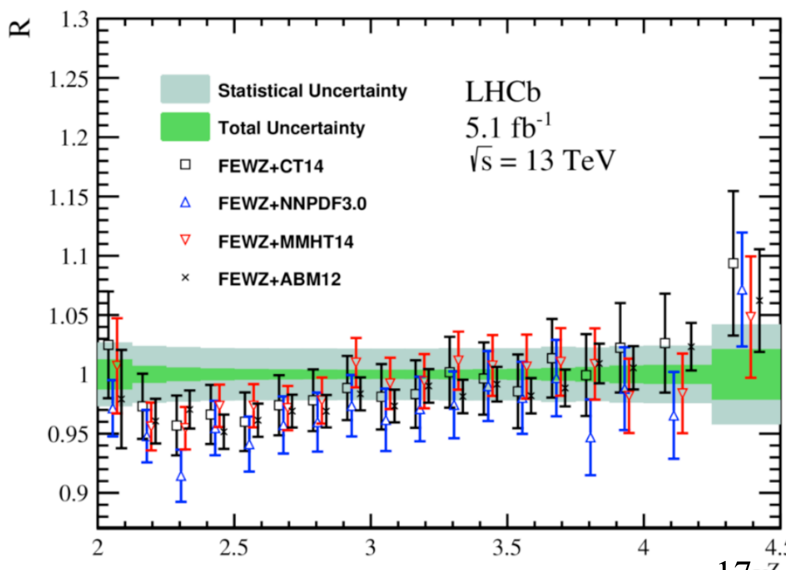



- "Fixed target-like" forward instrumentation ($2 < \eta < 4.5$) → probes asymmetric x values
  … to $x\sim10^{-5}$ in perturbative domain
  … also genuine fixed target (SMOG)

- e.g. inclusive Z production challenging theory (shape of NLO FEWZ)
- Also W, top, Drell Yan …



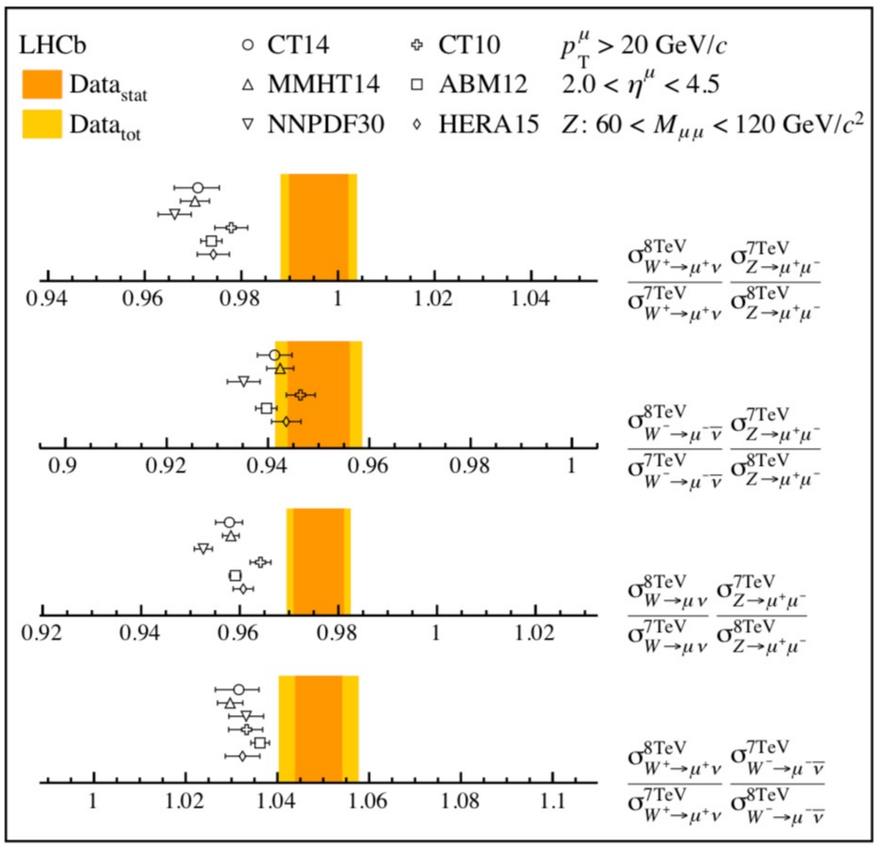

[arXiv:2112.07458]

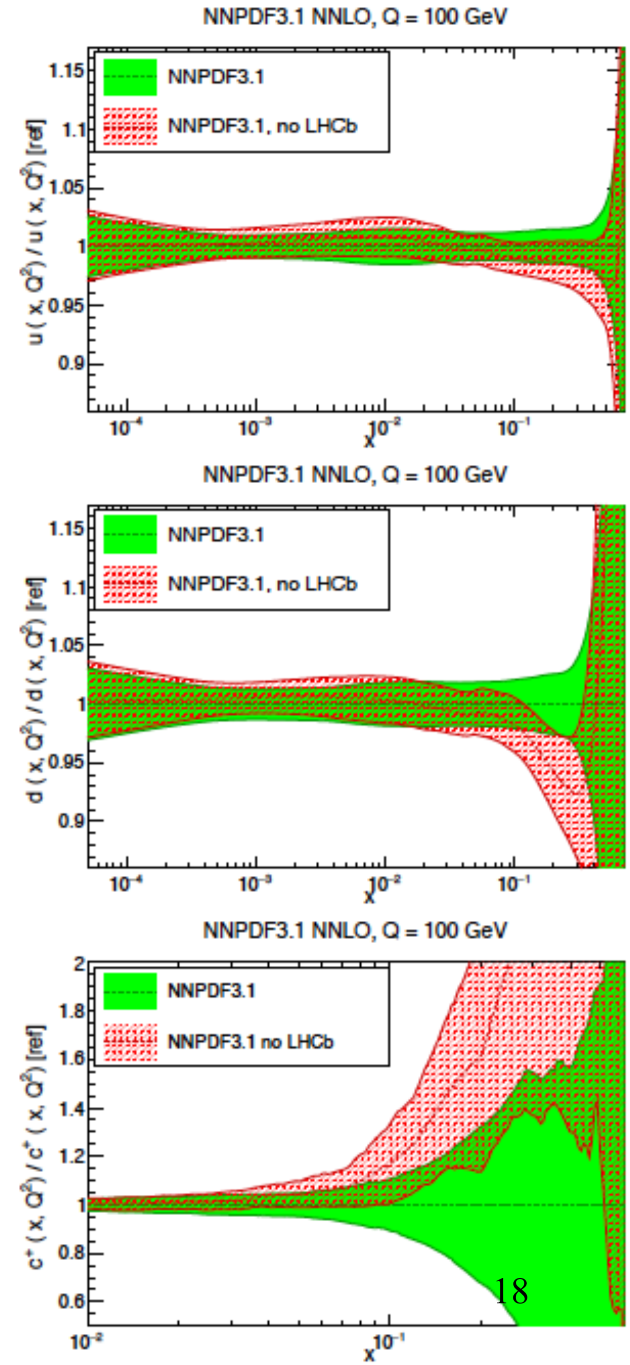



[arXiv:2112.07458]

# More LHCb Data: Double Ratios: W, Z, 7-8 TeV

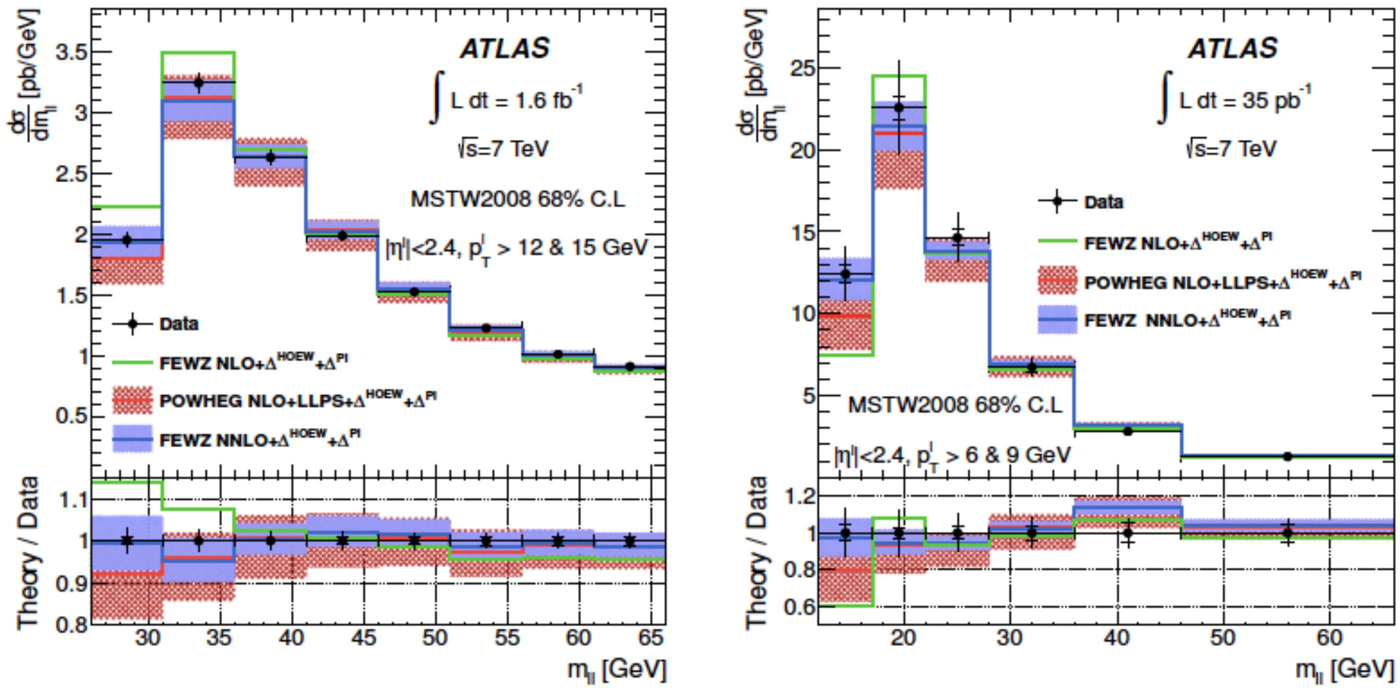
- Data have an impact (shifts in central values, reductions in uncertainties)




... BUT mostly at large x

# Drell-Yan Below Z Pole: ATLAS

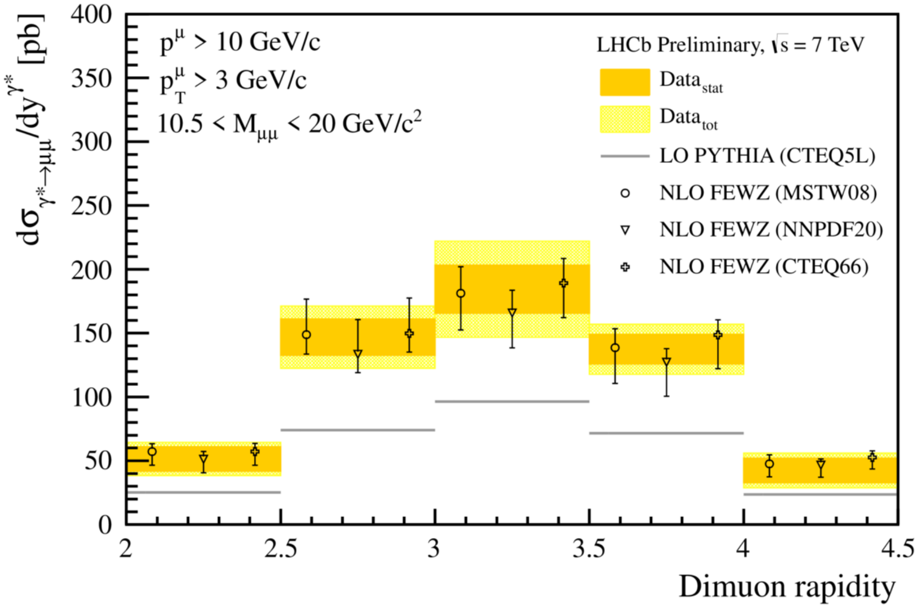


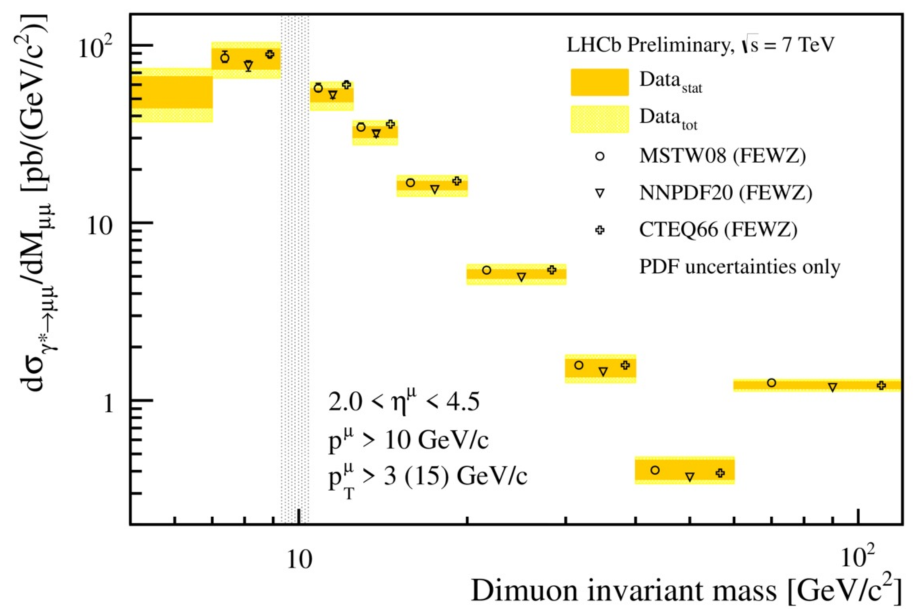

- Lowest x direct constraints come from DY ($q\bar{q} \rightarrow l^+l^-$) at low $m_{ll}$ → eg ATLAS dedicated sample down to $m_{ll}$ = 12 GeV

- Significant improvement in data description when NLO → NNLO

- MSTW2008 PDFs adequate to describe

# Drell Yan at very low masses: LHCb



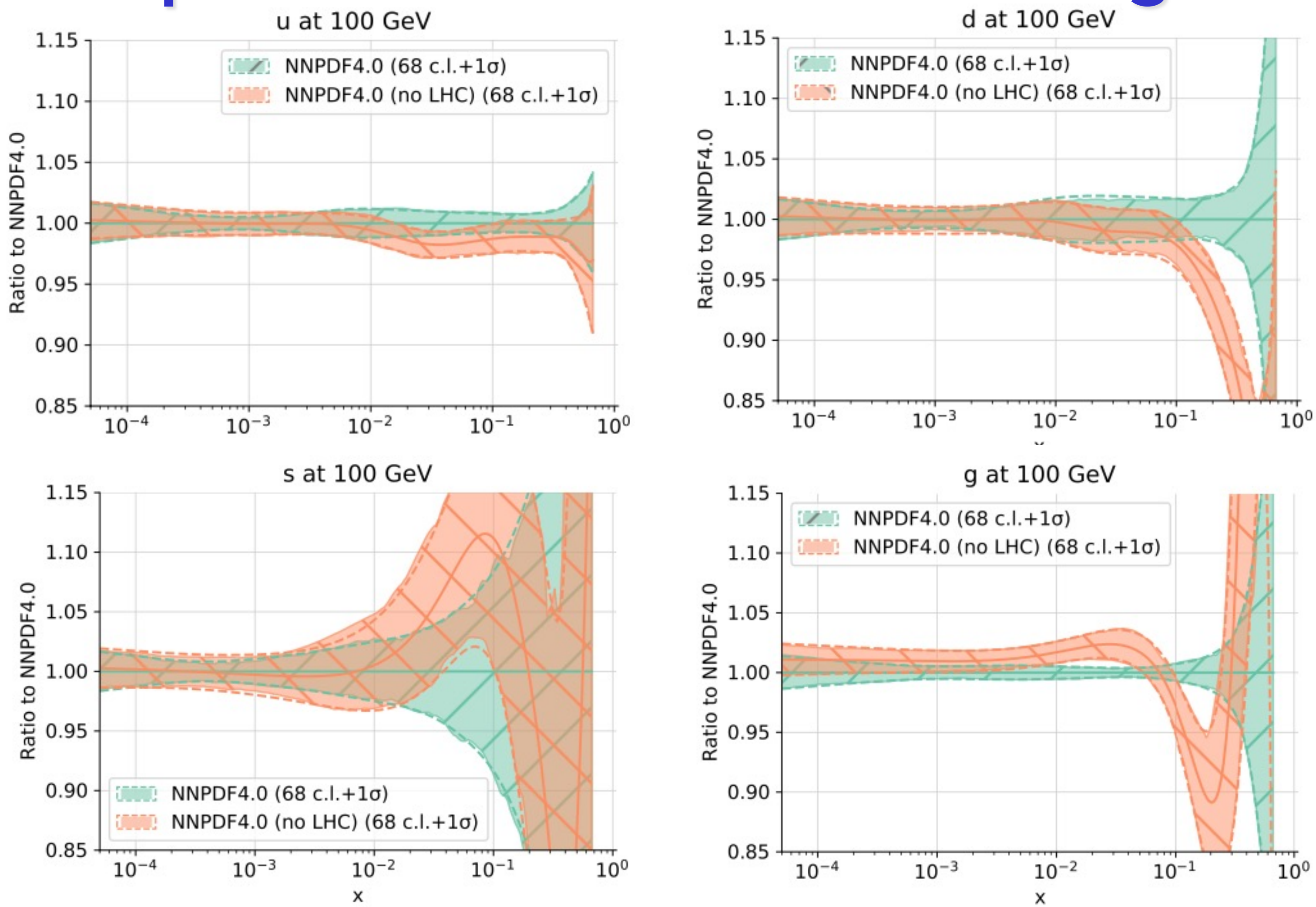




- Data extend to $m_{ll}$ = 5 GeV at forward rapidities!

- Preliminary data look compatible with previous generations of PDF sets (NLO comparisons)

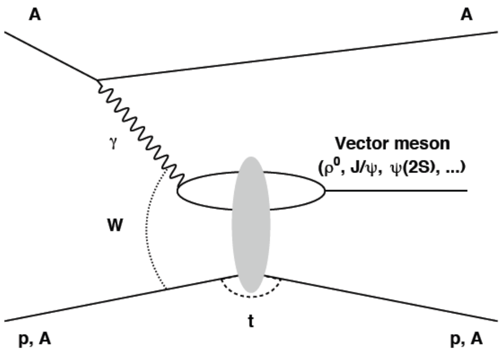
[CONF note 2012]

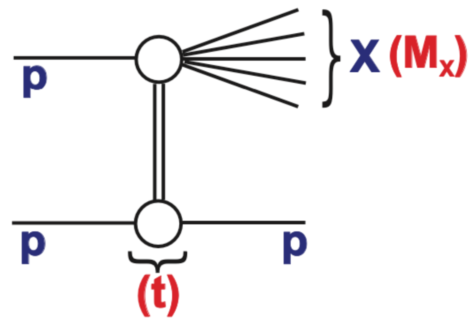
# LHC Impact on Global Fits according to NNPDF

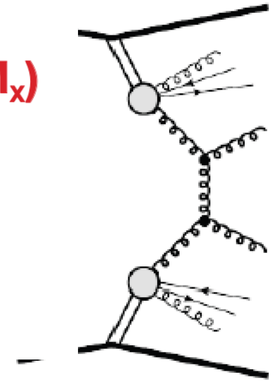


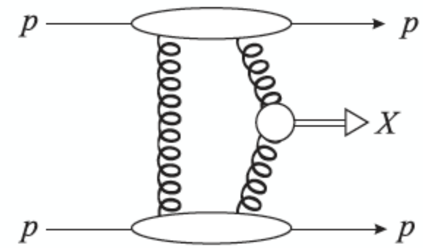

- LHC has contributed at all x, but the most significant impact is at large x
- Discrepancies between low x gluon in different global fits
- Available data not expected to change fundamentally in the future
- Very different from nuclear PDFs → LHC pA transformational

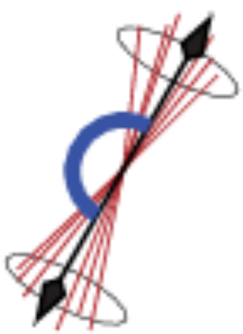
# Dedicated low-x observables in LHC Physics



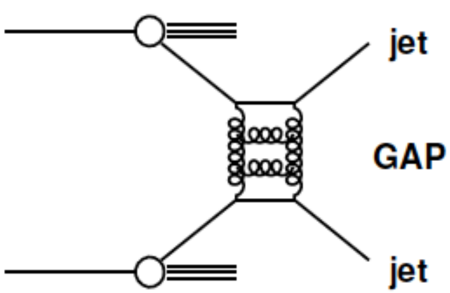





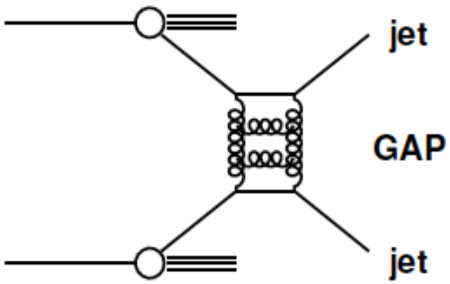
Strongly interacting colour-singlet exchanges discussed in diffractive sessions tomorrow:

- Ultra-peripheral collisions
- Diffractive dissociation
- Central inclusive production
- Central exclusive production

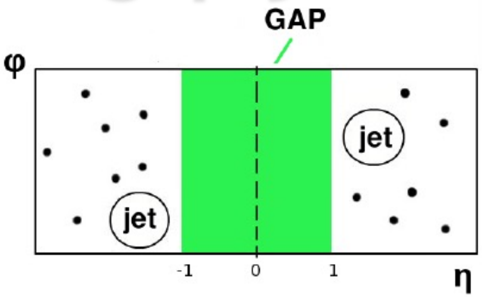



Other topics

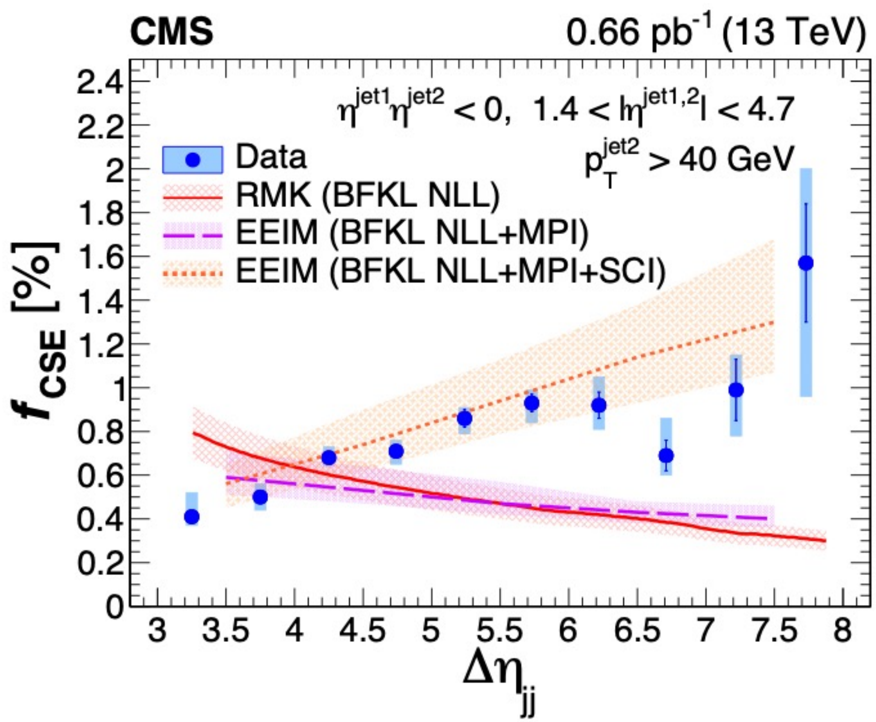
- Azimuth decorrelations between jets
- Gaps between jets
- ...

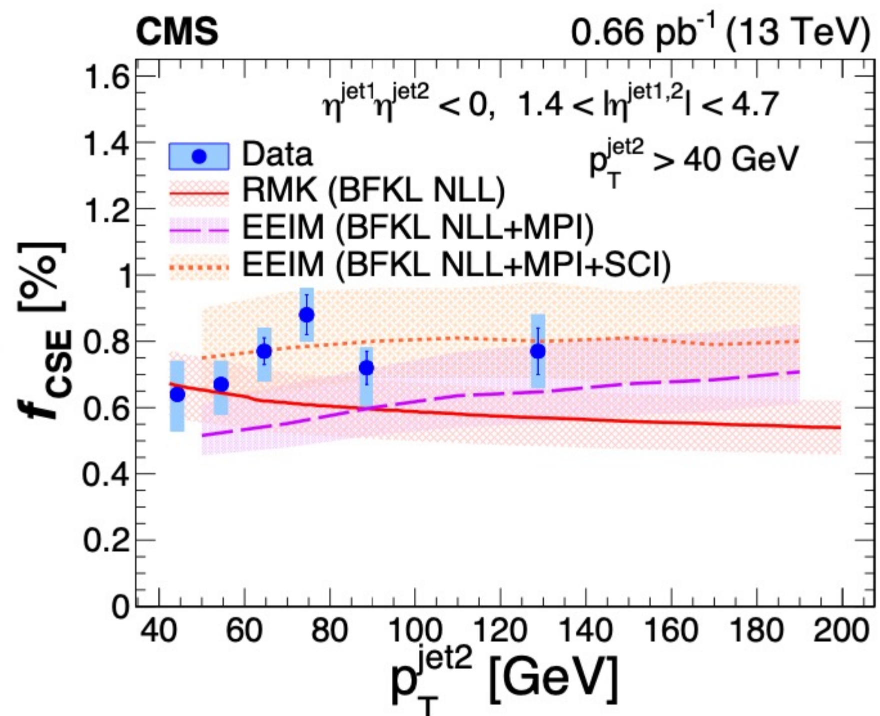



# LHC Searches for BFKL Dynamics: Jet-gap-jet events




- Gaps between jets are a classic signature for BFKL dynamics
- Complicated by rapidity gap survival probability and pile-up

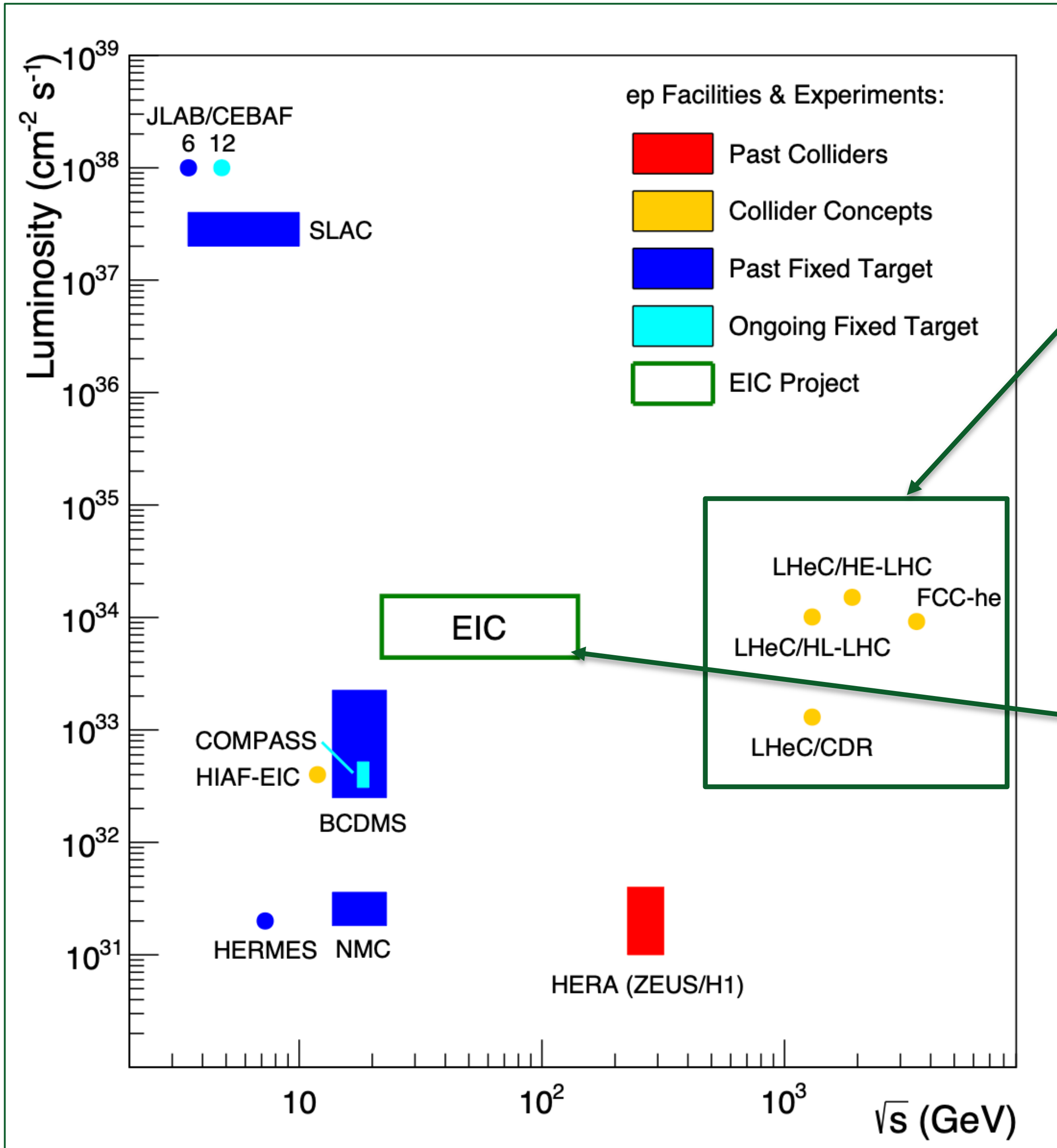


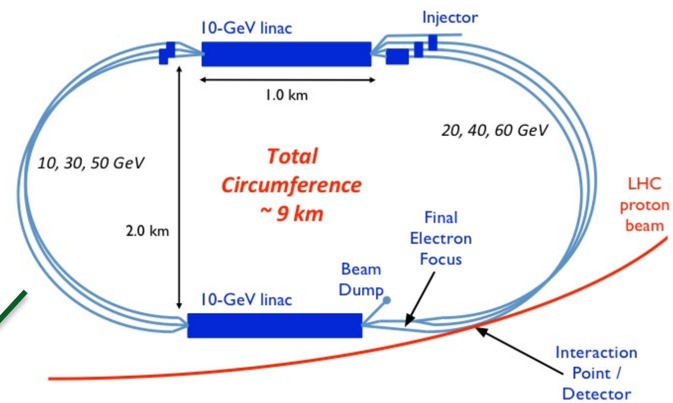



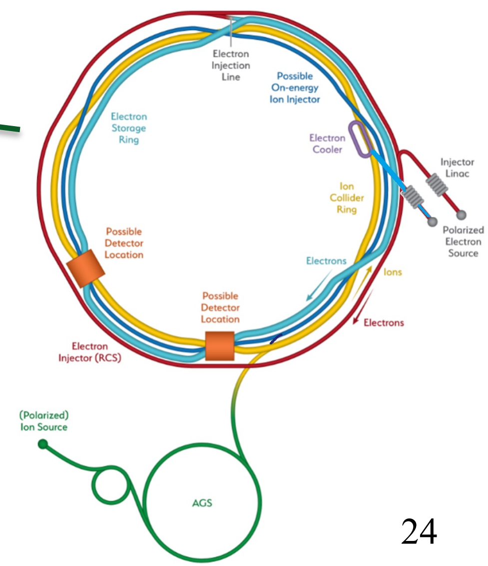



- Broad agreement with BFKL models

# Low x Prospects at Future ep Colliders



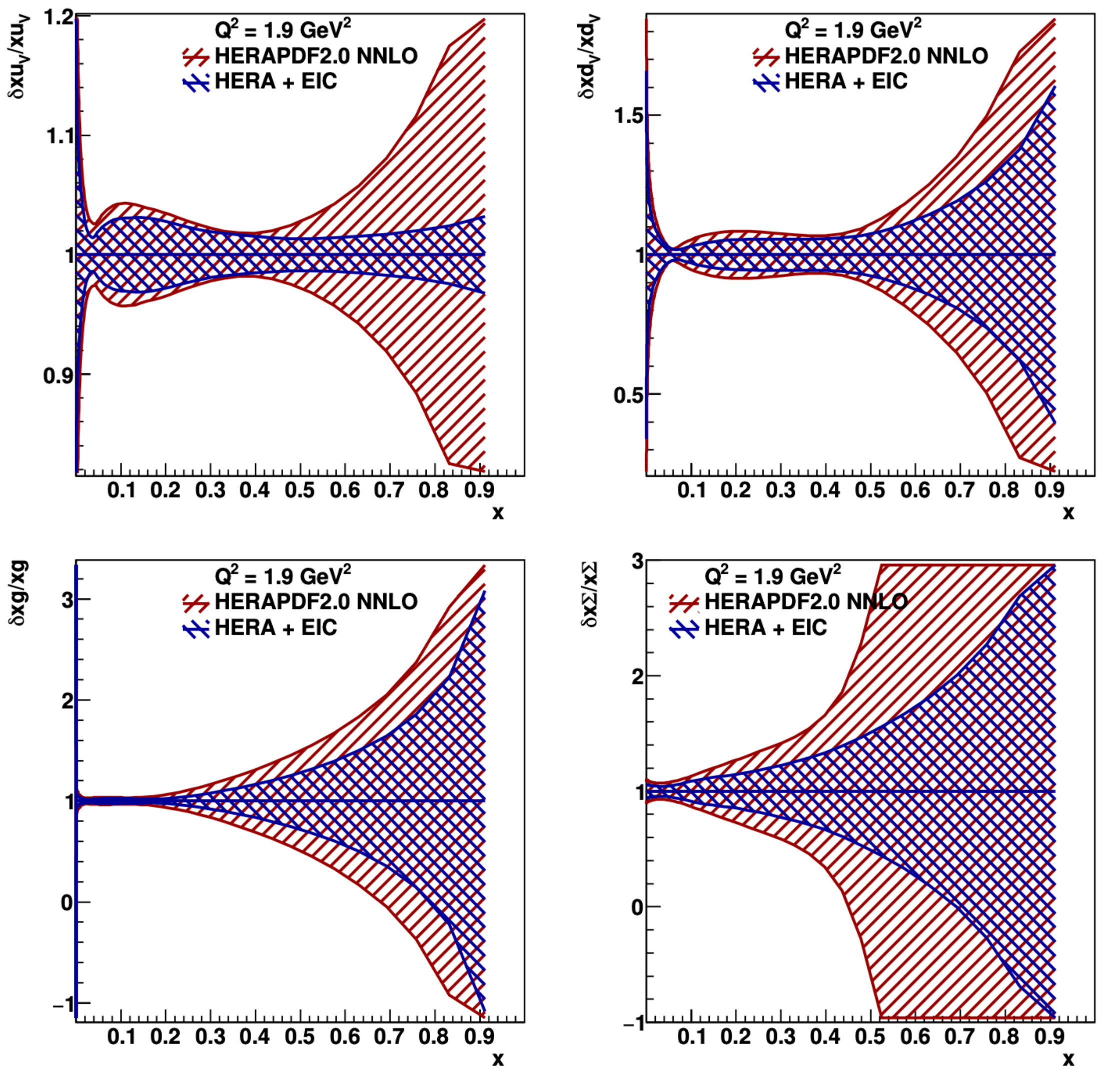



# PDFs in ep at the Electron-Ion Collider

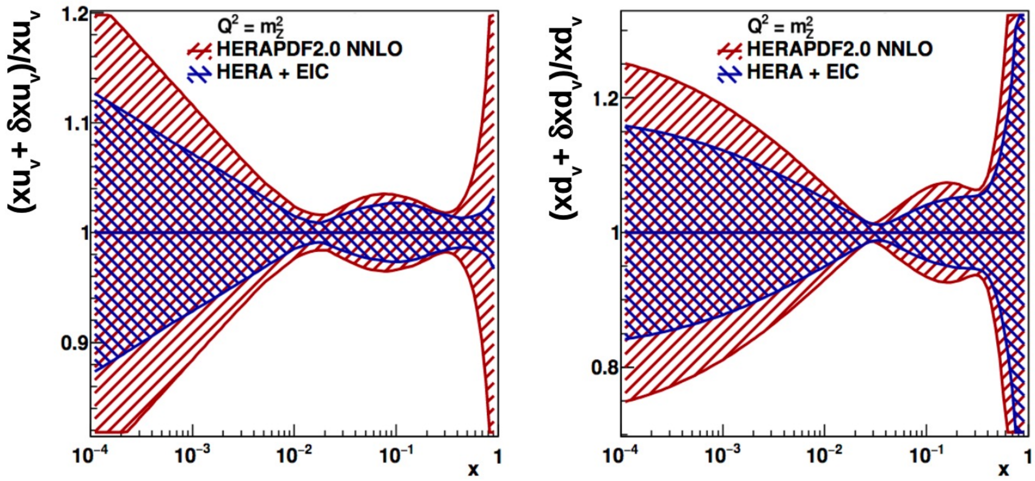
Due to lower $\sqrt{s}$, EIC doesn't extend beyond HERA x range for direct constraints in ep

Improved precision and constraints at high x / intermediate $Q^2$ lead to new level of precision at high x for 'DIS-only' fits

Biggest impact is on up quarks

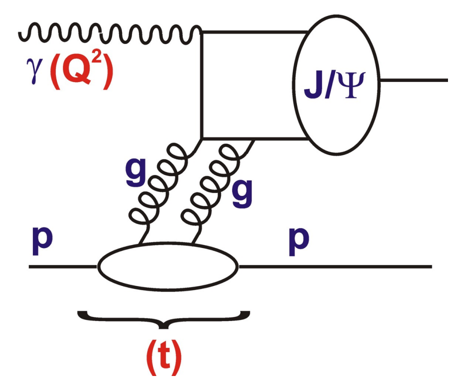


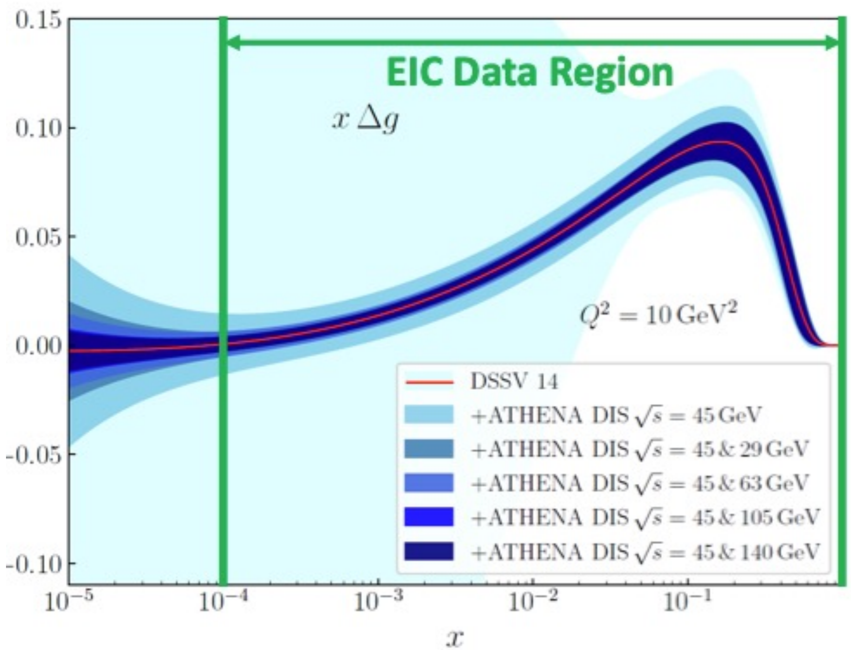
# Low x in ep at the Electron-Ion Collider




Indirect low x constraints via sum rules … eg valence quarks at low x (where they are small)

Sensitivity through diffractive channels (~ gluon squared)




Revolutionary impact on spin / helicity distributions at low x, especially gluon.

# Low x Physics in eA at EIC

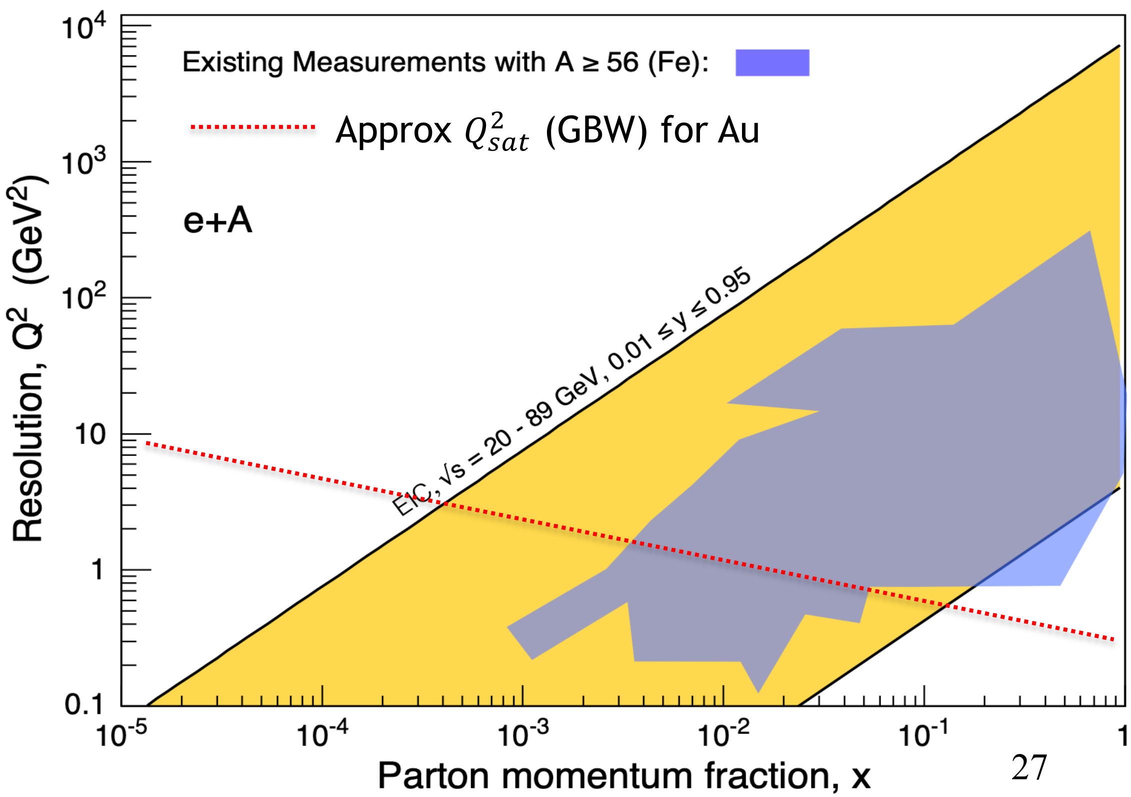
**Understanding dense systems of gluons is one of the three pillars of EIC science**

- Nuclei enhance the density of partons (" $A^{1/3}$ " factor) → low-x effects become visible at larger x values than in the proton case

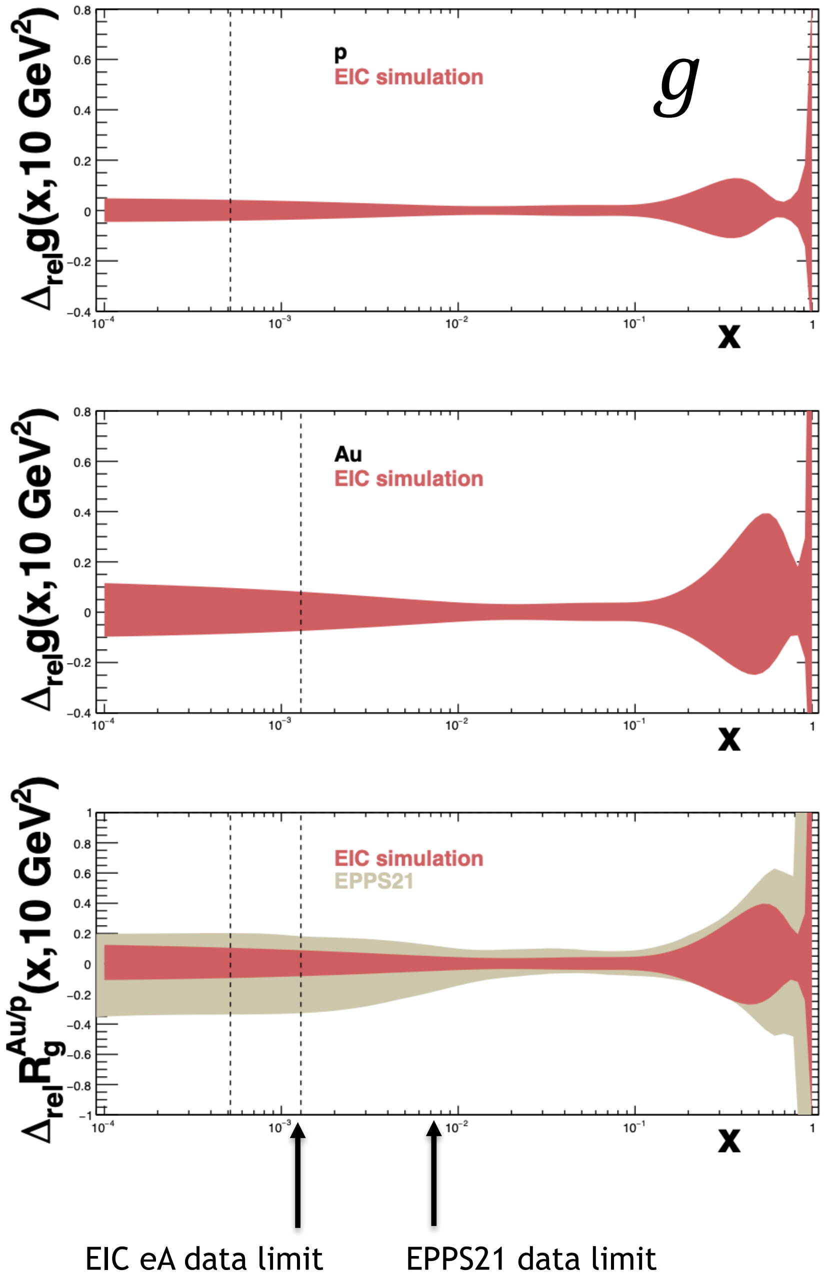
- No previous eA collider data → PDFs currently poorly constrained in DIS below x~$10^{-2}$

- Picture changed by pA At LHC, but with theory complications

- EIC will have very large impact on eA phase space, potentially extending into region of saturation in perturbative domain



# Impact on Nuclear PDFs: Gluon




Studies in xFitter framework to assess sensitivity of EIC relative to EPPS21 (which includes LHC data)

Projected uncertainty on gluon density of proton from EIC-only fit

Projected uncertainty on gluon density of (gold) nucleus from EIC-only fit → ~10%

Projected uncertainty on nuclear modification ratio, EIC-only compared with EPPS'16

→ Factor ~ 2 improvement at x~0.1

→ Substantial improvement in low x region

# Future ep Options at CERN

## LHeC

50 GeV electrons on LHC p, A beams

## FCC-eh

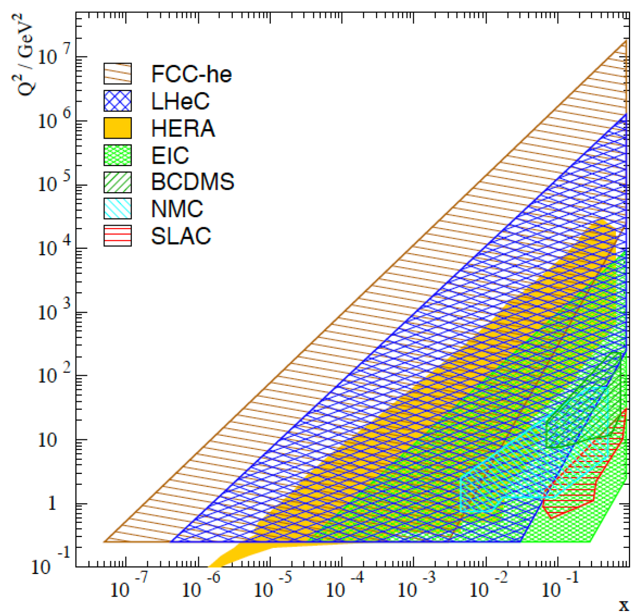
50 GeV(+) electrons on FCC hadrons

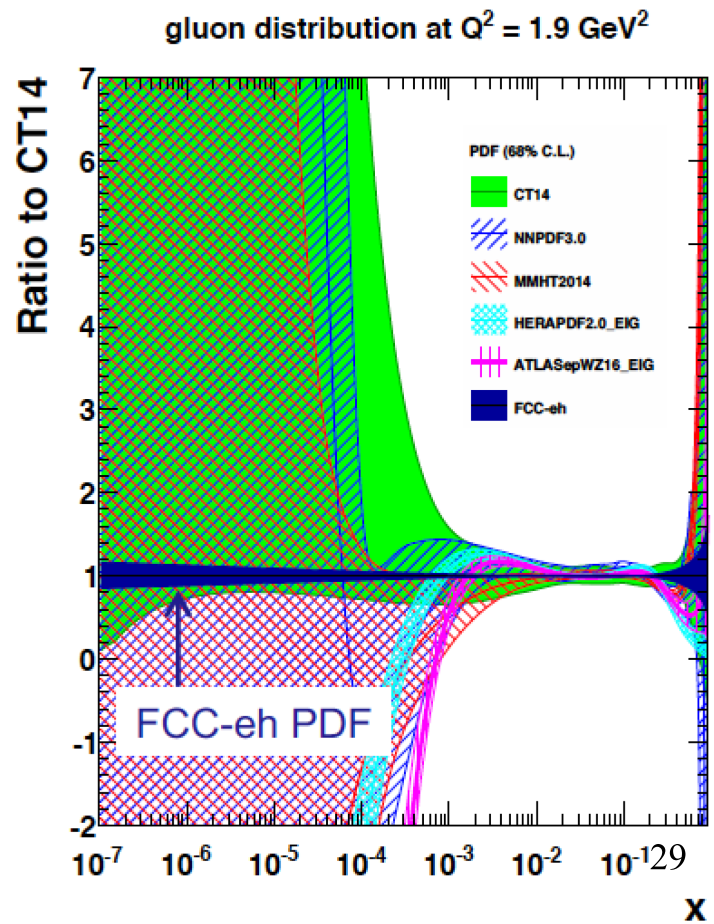
Renewed mandate, working group structure and coordination (J d'Honft) → Open `Kick-off' meeting October 31

## Extending energy frontier …

→ >2 orders of magnitude extension to lower x at for ep at FCC-eh

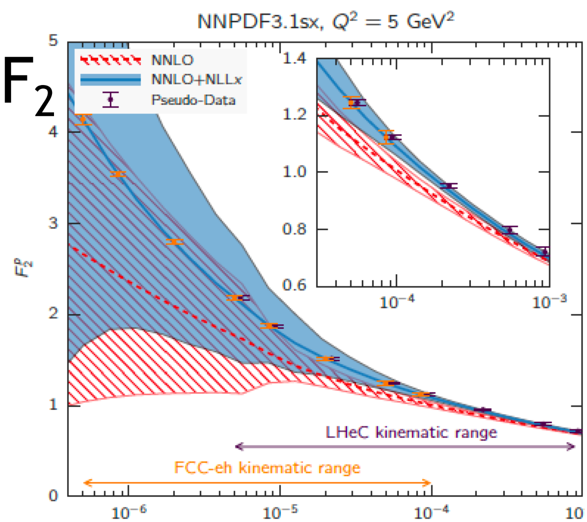
→ Revolutionary impact on low x PDFs

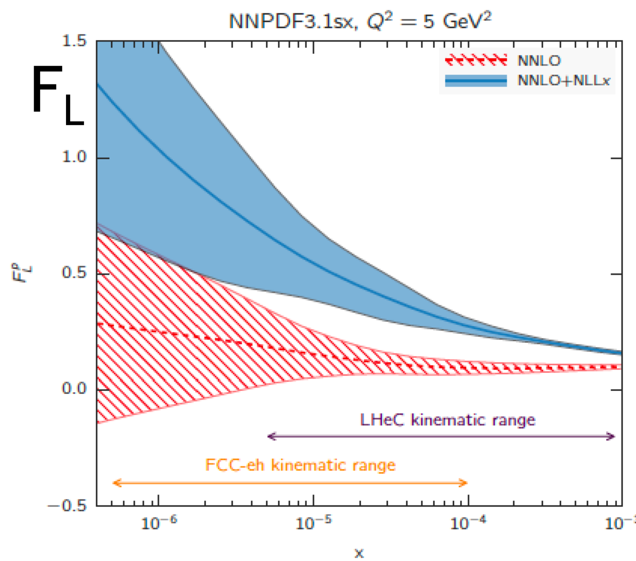


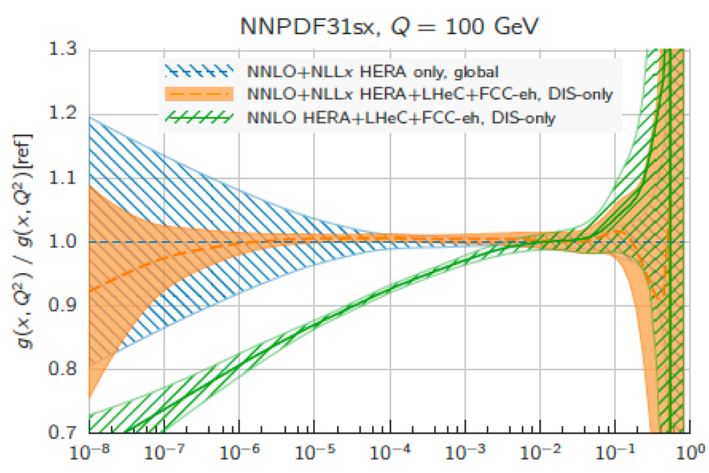
# Potential of LHeC & FCC-eh to establish BFKL

- Extrapolated $F_2$ and $F_L$ predictions in LHeC and FCC-eh regime based on NNPDF fits to HERA data with and without NLL 1/x resummation




- Huge error bands due to lack of current constraints at $x < 10^{-4}$
- Data precision will distinguish and reveal new dynamics



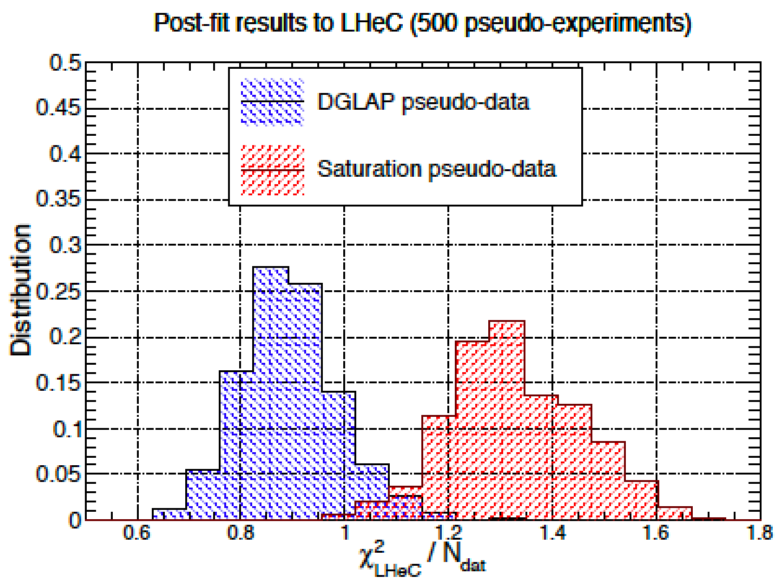

- Extracted PDFs including LHeC and FCC-eh pseudodata highly sensitive to inclusion of NLL 1/x resummation in simulated data

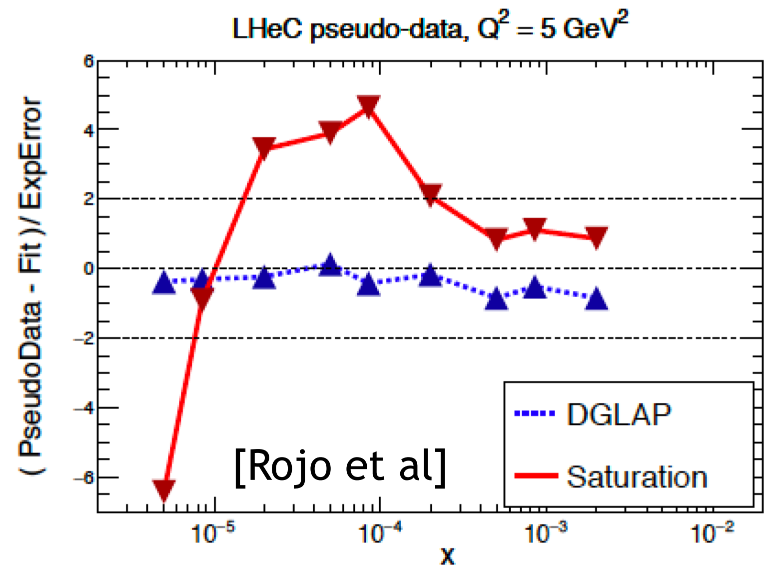
# Can Parton Saturation be Established in ep @ LHeC?

→ Create LHeC pseudodata including saturation by extrapolating (DGLAP-improved) GBW model based on fit to HERA data:

→ try to fit using pure NNLO DGLAP machinery

... Cannot absorb the non-linear effects into the initial conditions




If this is not a smoking gun: unambiguous observation of saturation will be based on tension between observables: e.g. $F_2$ v $F_L$ in ep, $F_2$ in ep v eA, diffractive channels

# Summary

- HERA leaves many questions about low x physics
  - Implications of fast-rising gluon?
  - Novel dynamics?... Resummation?... Saturation?...

- Some progress at the LHC
  - Mainstream LHC ep data have much more impact on high x than low x
  - Some promising low x channels maybe under-exploited?

- Future electron-proton (& ion) colliders promise transformation
  - EIC in nuclear mode will probe saturation region
  - Ultra-low x physics could be opened at LHeC / FCC-eh