# Small x physics at the LHeC and FCC-he

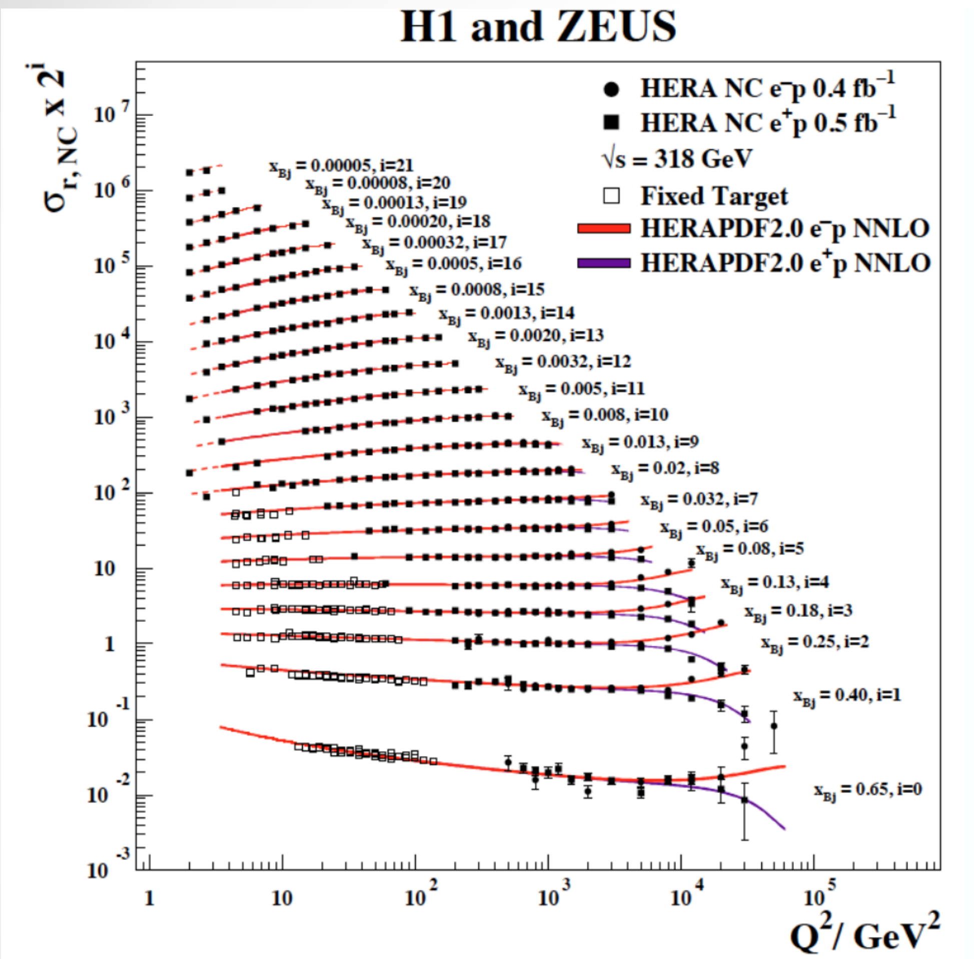
**Claire Gwenlan**, Oxford

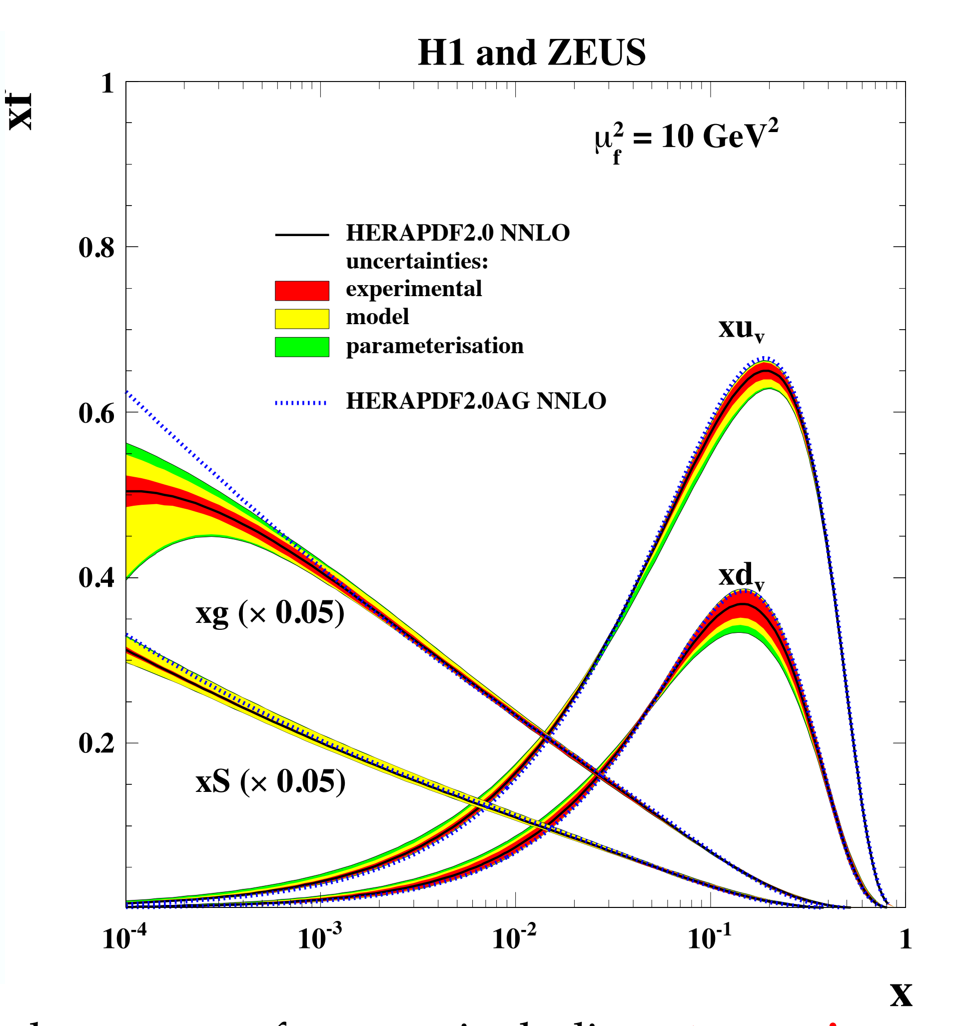
for the LHeC study group, http://cern.ch/lhec

with special thanks to: Nestor Armesto, Max Klein, Anna Stasto and Graeme Watt

DIS16, DESY, Hamburg, Germany

# HERA legacy

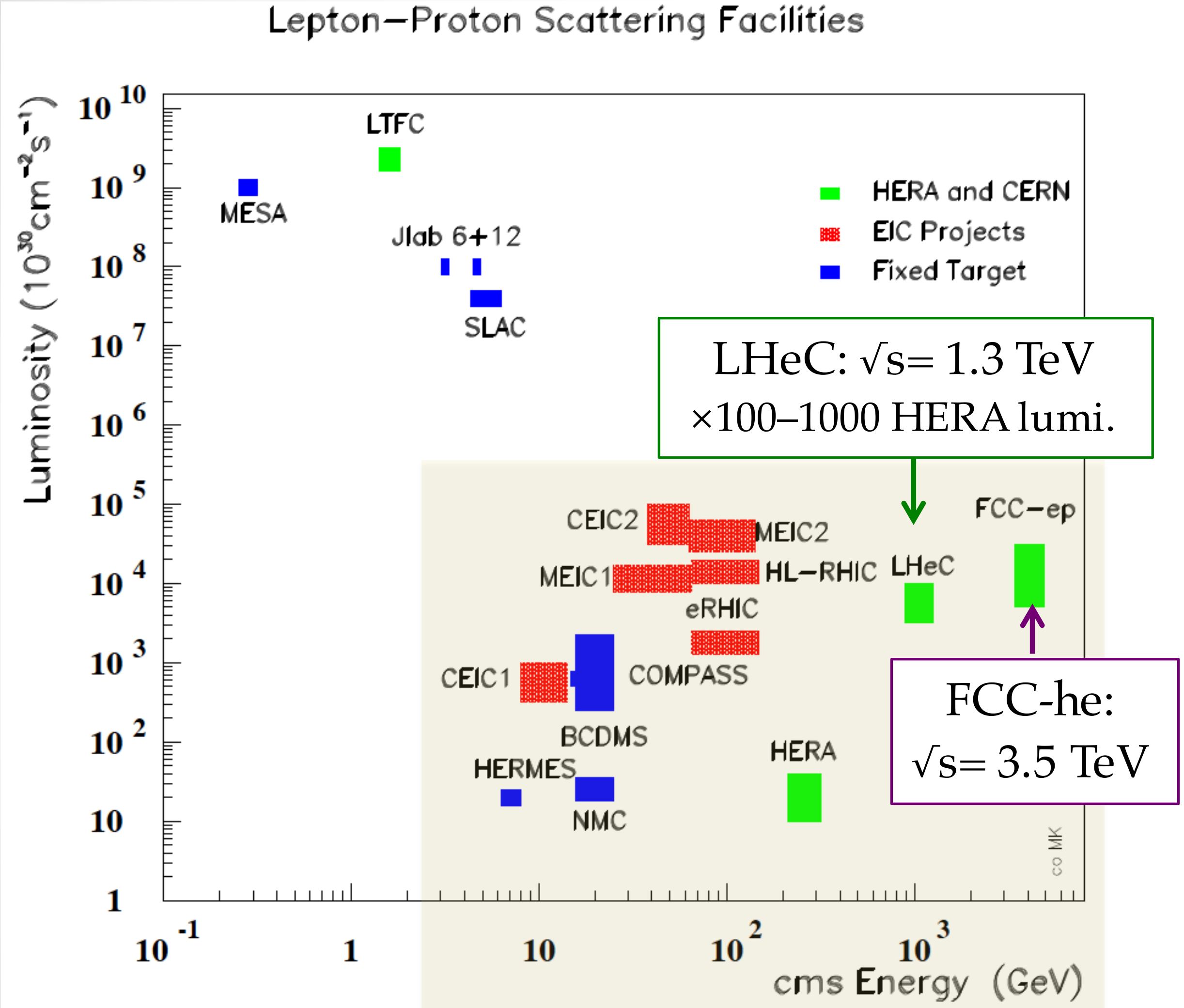



- **HERA, a success story:** established detailed structure of proton, including **strong rise of gluon at small x**; large contribution from **diffraction** (10% of DIS events);
  and much more (jets, **α**s, **γ** structure c, b, BSM limits … )

**BUT:** no eA/eD, limited lumi at high x/for searches, limited kinematic reach at low x, …

# DIS: past, present and future




**LHeC** and **FCC-he**:

high energy: $\sqrt{s} \simeq 1 - 5$ TeV

high luminosity: $10^{34}$ cm$^{-2}$s$^{-1}$

(high luminosity benefits high x,$Q^2$ studies – linked to small x via DGLAP evolution)

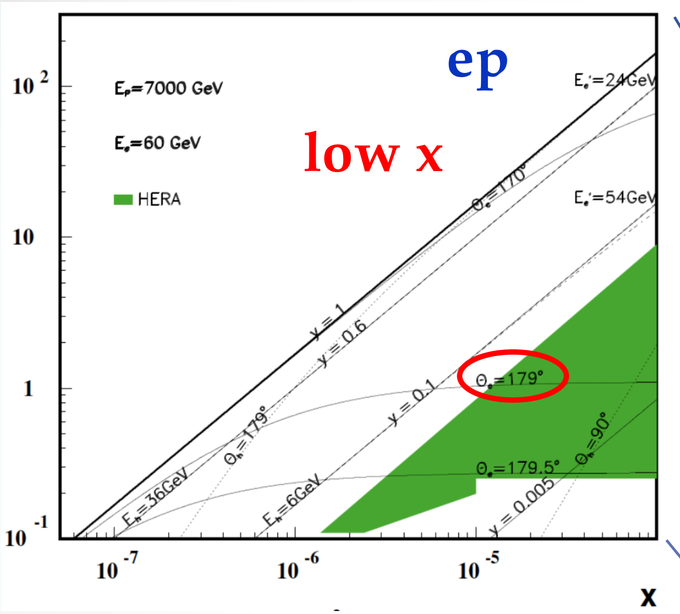
this talk: **small x physics**

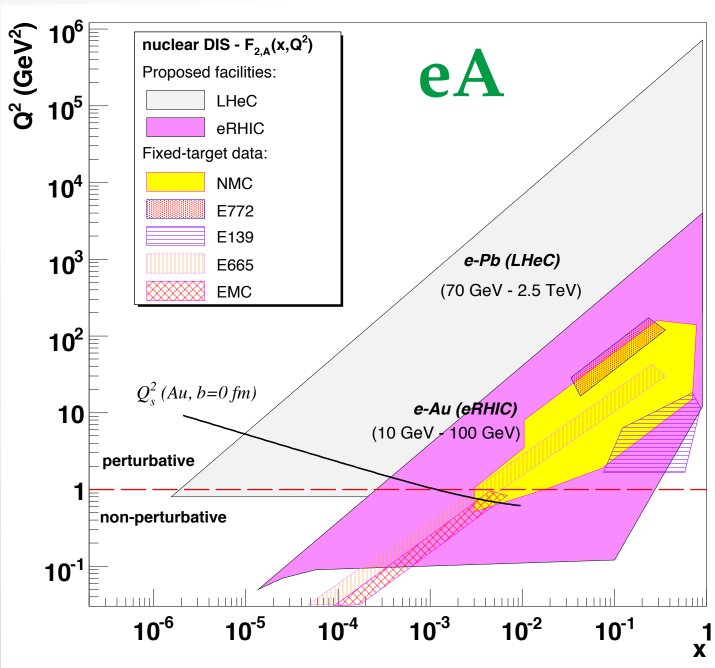
- low x gluon constraints
- inclusive diffraction
- exclusive diffraction
- jet observables

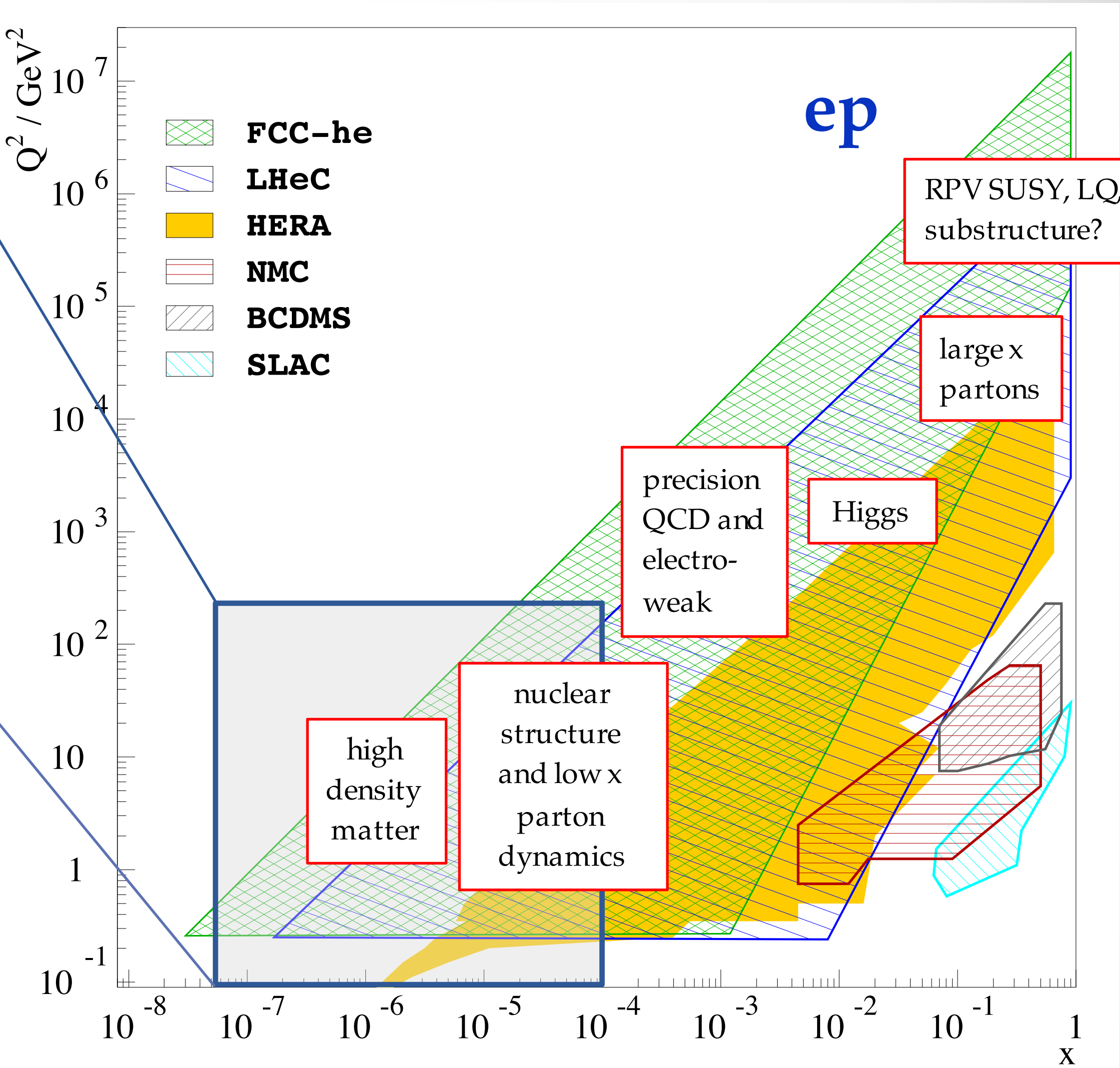
**many other physics goals, see also other LHeC talks in this workshop:**

P. Newman (LHeC project and detector); A. Cooper-Sarkar (PDFs); I. Helenius (eA); O. Behnke (Higgs)

# LHeC kinematics



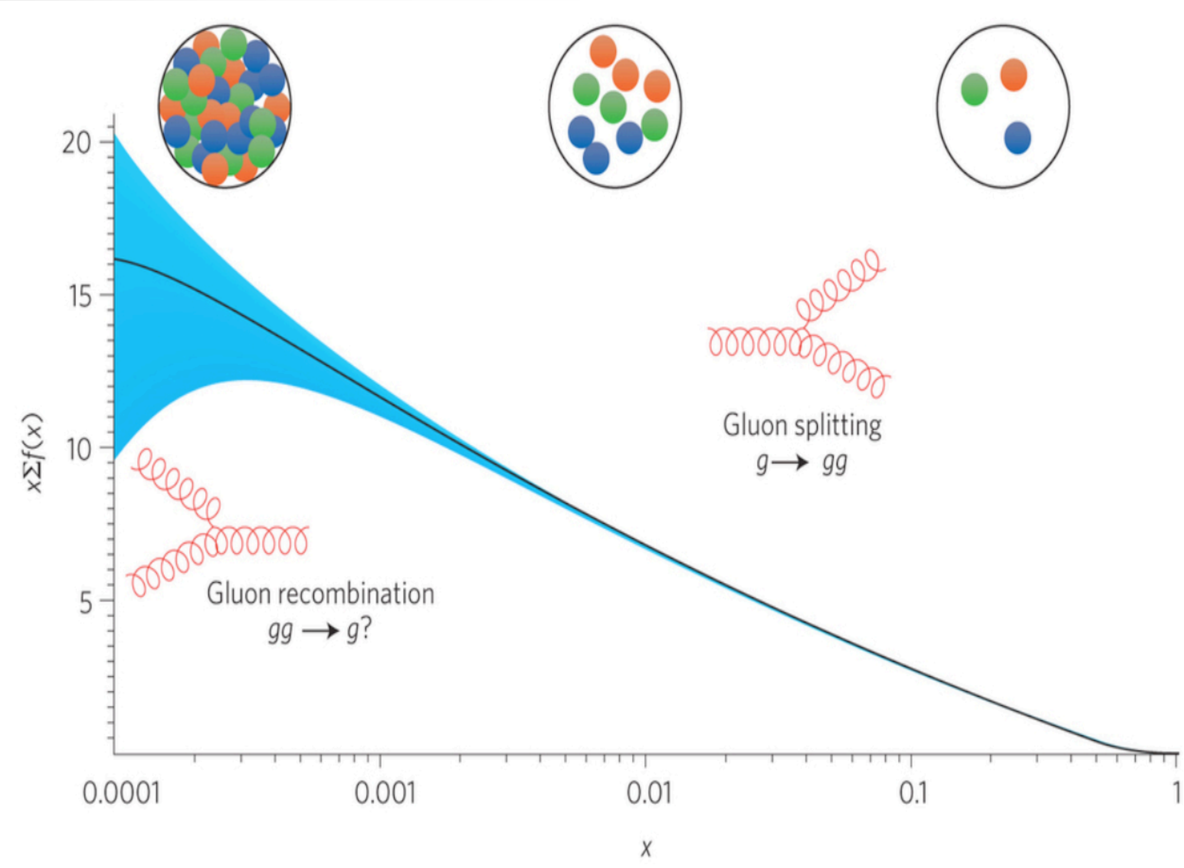




**access to low x requires 1◦ acceptance (1– 179◦)**

higher electron energy reduces small x region unless acceptance larger

obvious extension of kinematic reach for FCC-he

# why is small x interesting?




**HERA**: observation of strong rise of proton structure functions towards small x

**driven by growth of gluon density**

QCD rad. of partons, linear evolution (DGLAP)

- at small x, potentially large logs in 1/x; evolution must be modified (EG. BFKL)
- and surely gluon density cannot rise forever!? **unitarity** of scattering amplitude

– gluon recombination; saturation; non-linear effects in evolution?

LHeC can unambiguously access this novel regime

**with unique access to dense regime at fixed, semi-hard $Q^2$ while decreasing x**

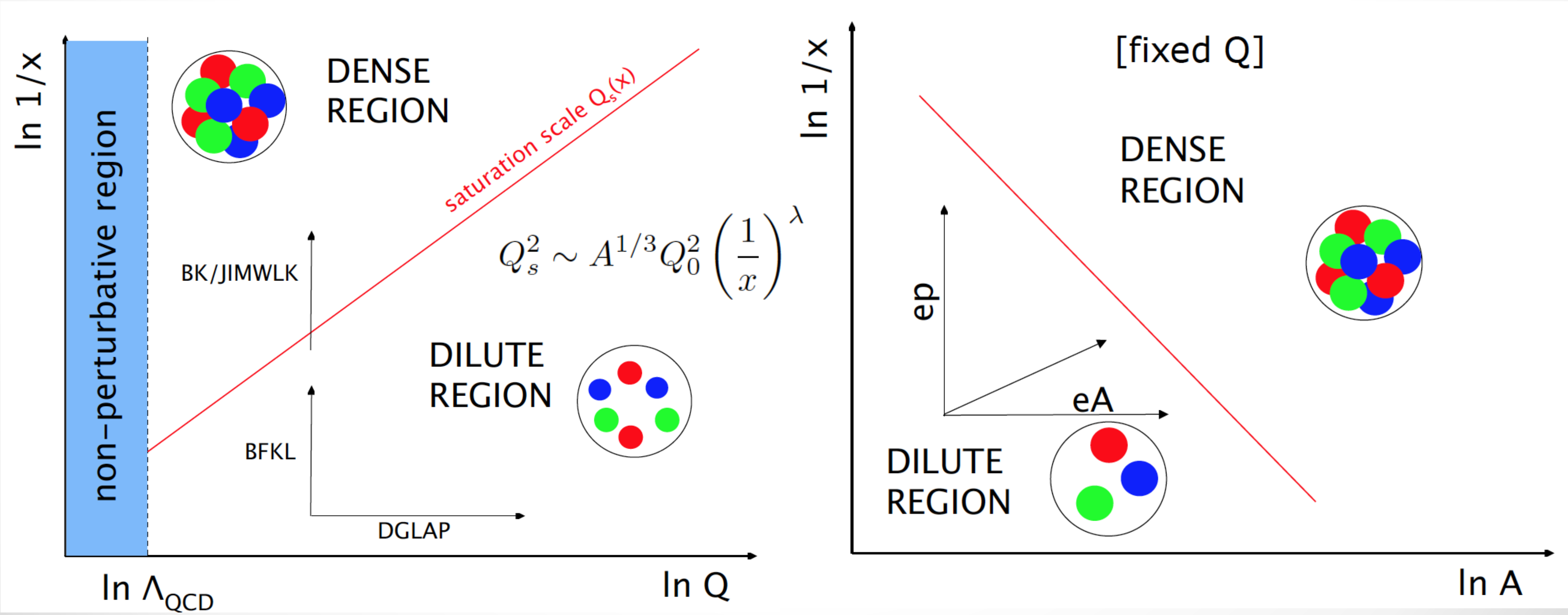
"I firmly believe that the small x problem … is the most interesting problem in QCD"
A.H. Mueller, 1990

# status of small x

- **three pQCD-based alternatives to describe small x ep and eA data**
  differences at moderate $Q^2$ ($> \Lambda^2_{QCD}$) and small x
  - DGLAP (fixed order perturbation theory)
  - resummation schemes (BFKL, CCFM, ABF, CCSS, …)
  - saturation (EG. in context of dipole models)

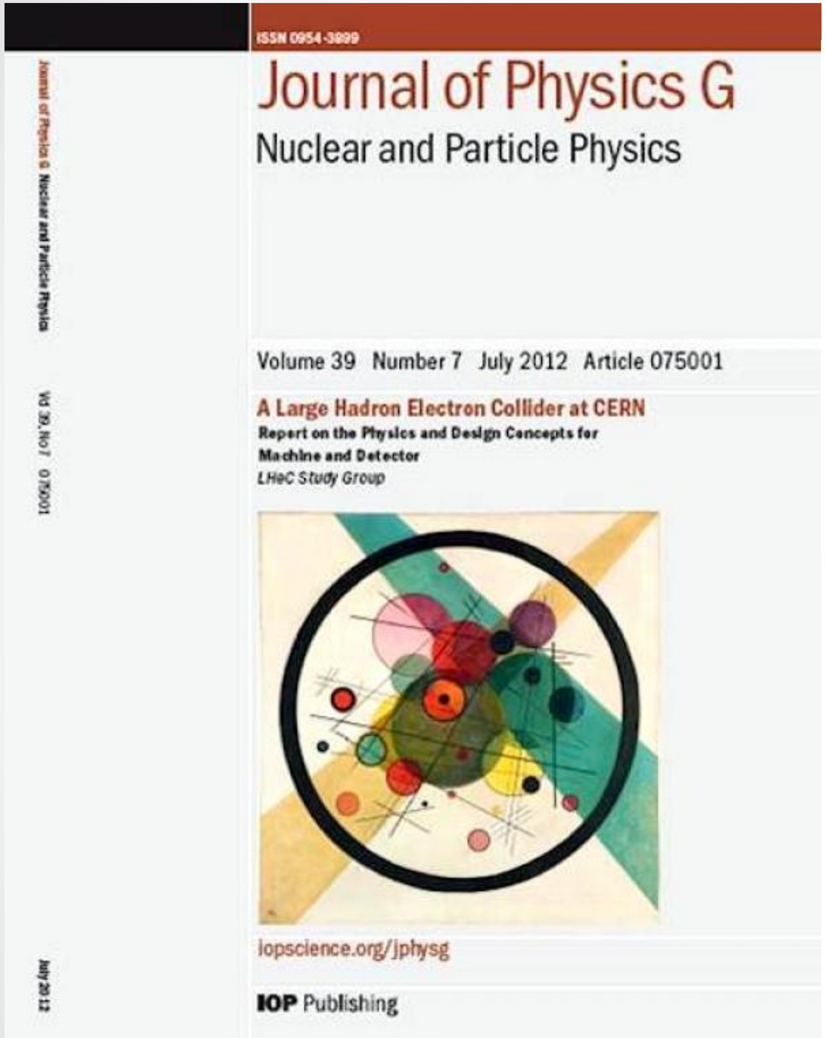
(see eA talk, I. Helenius)

- **non-linear effects are density effects:**
- **two-pronged approach at LHeC: decrease x / increase A** ↗



# small x physics at the LHeC

http://cern.ch/lhec






CDR: arXiv:1206.2913

193 experimentalists and theorists from 76 institutes

supported by CERN, ECFA, NuPECC

*further publications:*

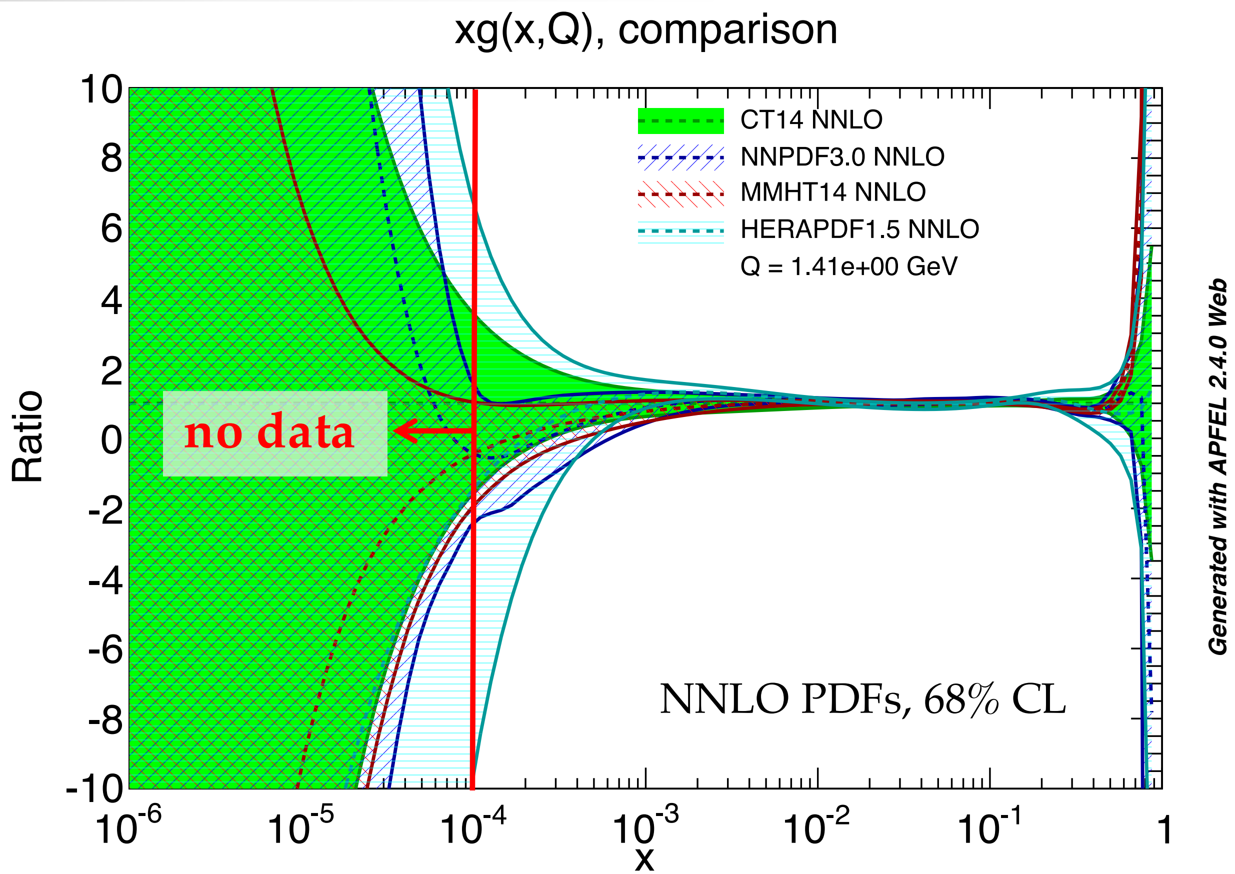
**O. Bruening, M. Klein**
Mod. Phys. Lett. A28 (2013) 16, 133001

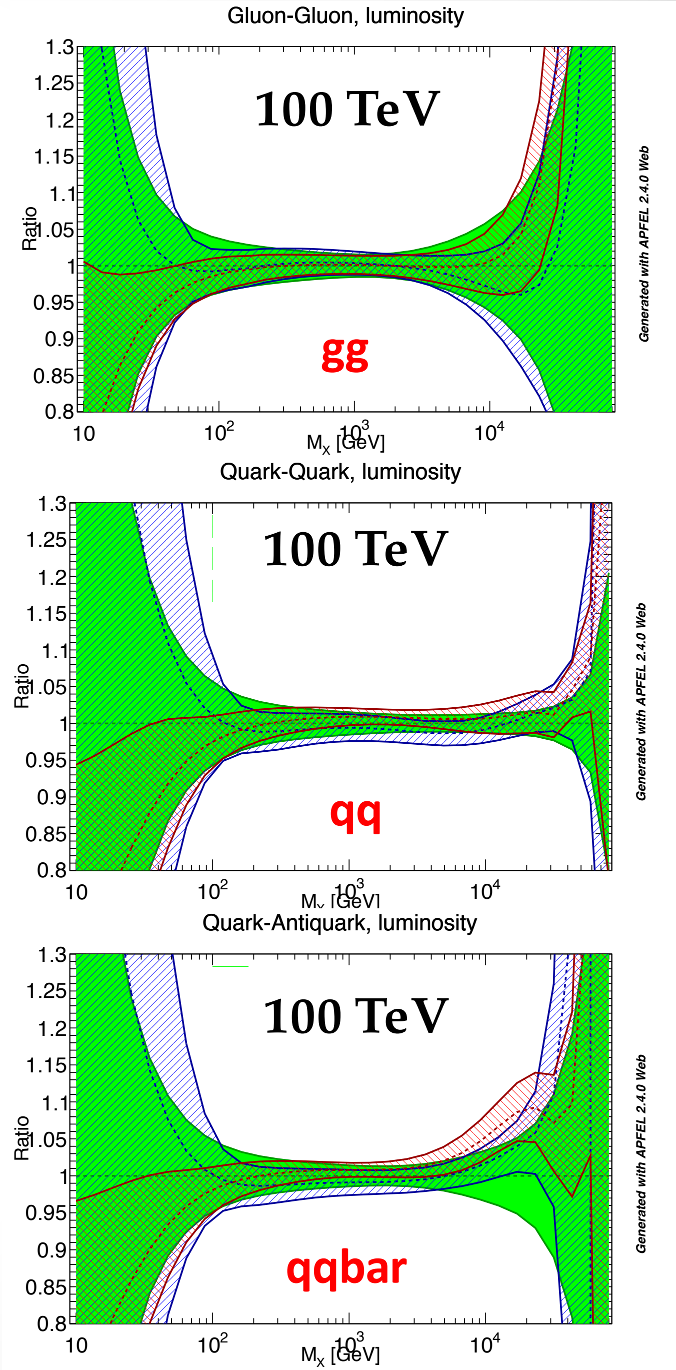
**LHeC study group**
arXiv:1211.5102

**LHeC study group**
arXiv:1211.4831

# Parton Distribution Functions

PDF luminosities



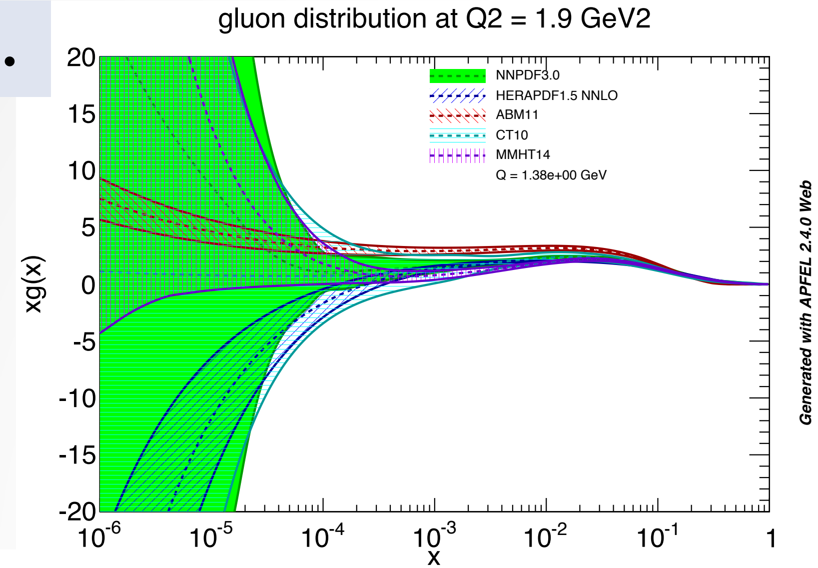




**low-x**: no current data to constrain $x \lesssim 10^{-4}$;
**rely purely on extrapolation**

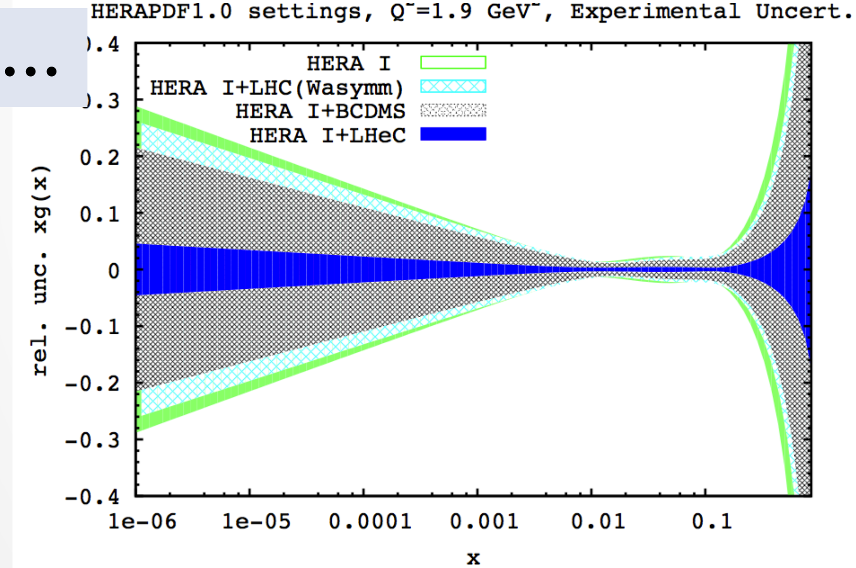
(see talk by A. Cooper-Sarkar for more on PDFs with the LHeC)

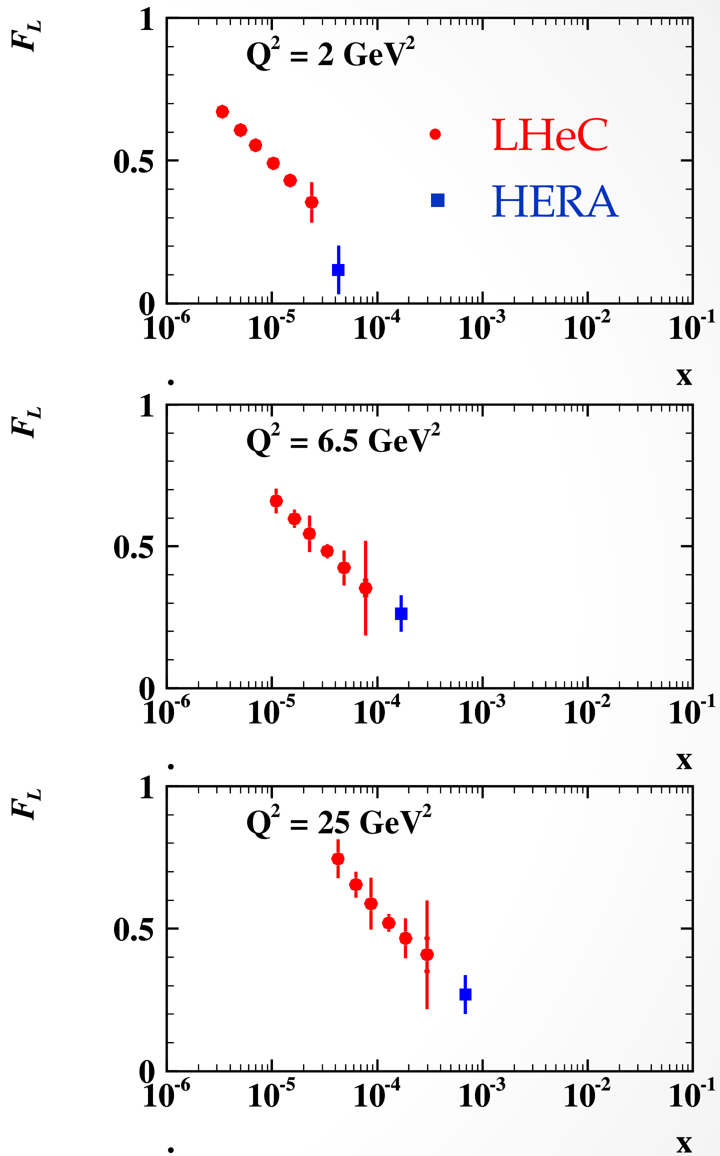
# constraints on gluon at low x

now…




then…



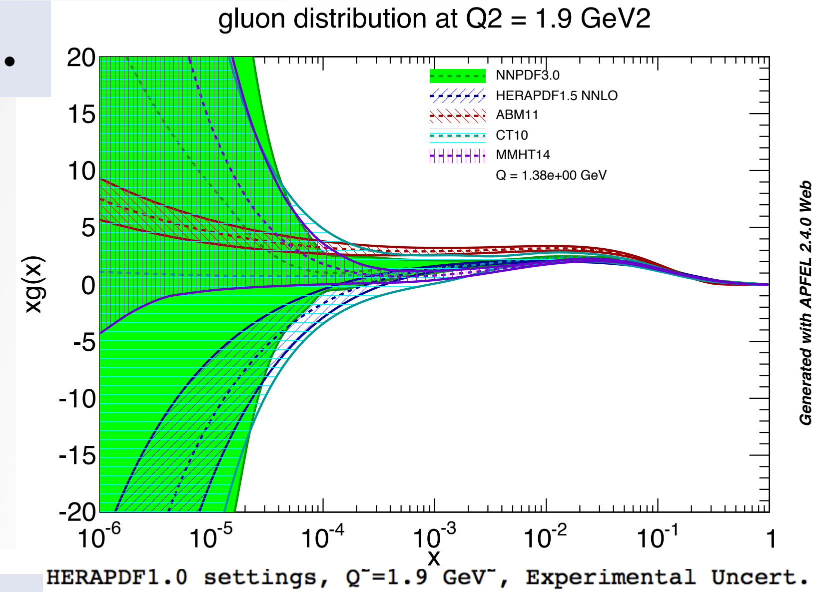

**HERA** sensitivity stops at x≃0.0005

**LHeC:** gluon measurement down to below $x=10^{-5}$

additional measurement of longitudinal structure function would further improve

# constraints on gluon at low x

now…

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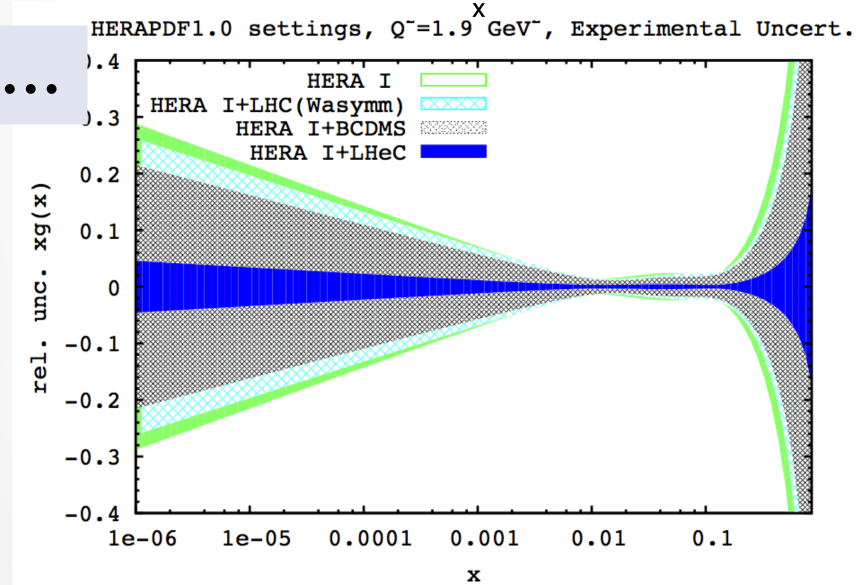


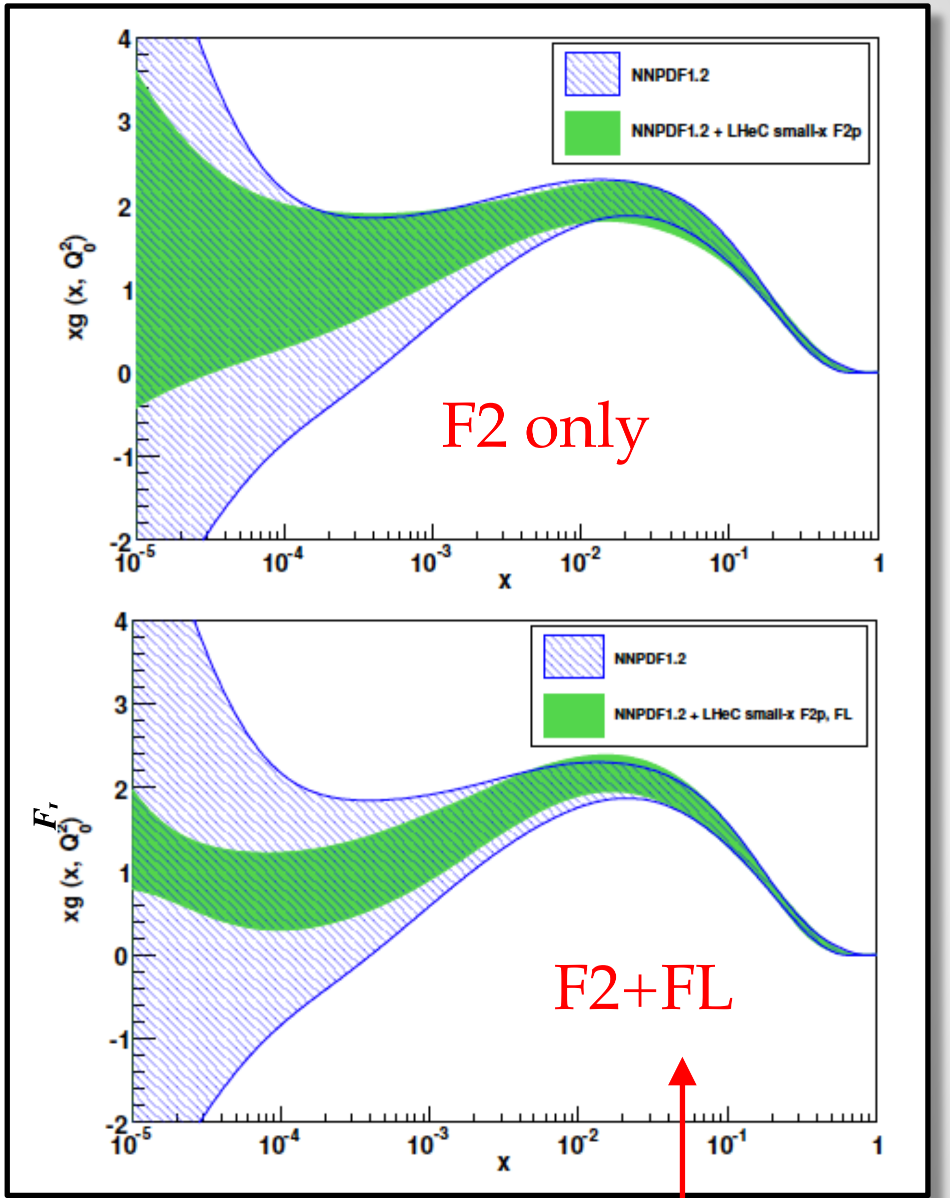


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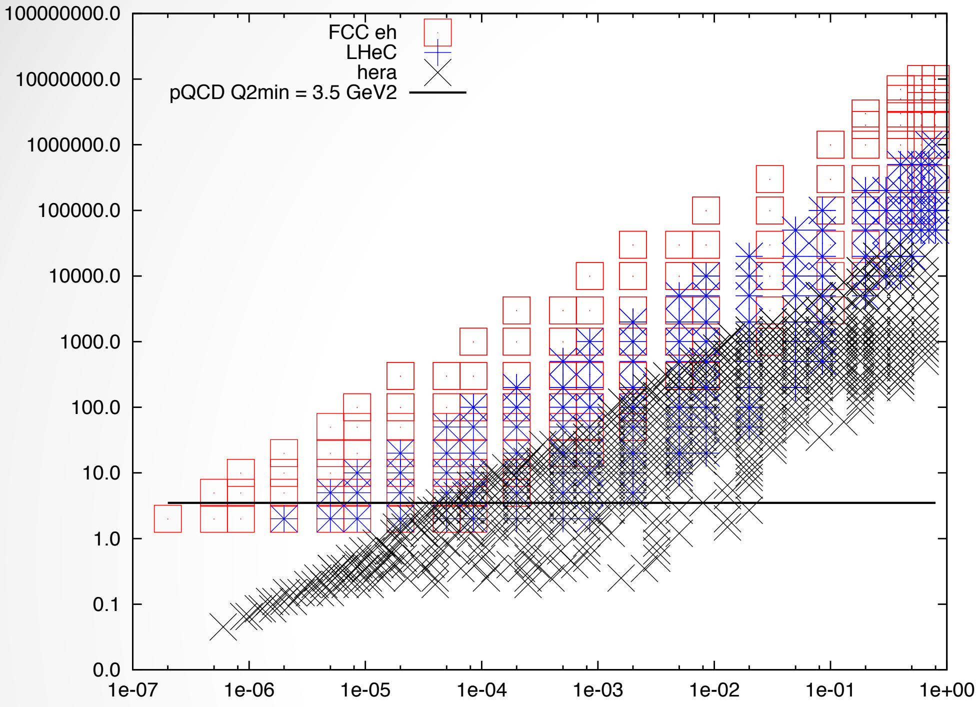
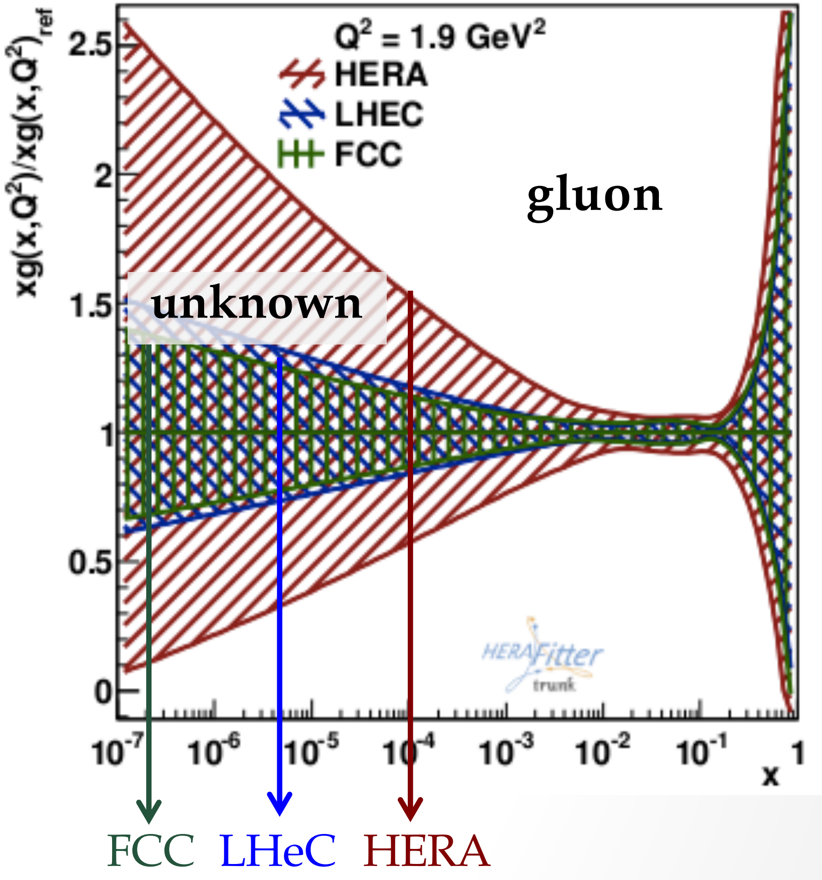
# FCC–he vs LHeC vs HERA




*Voica Radescu*




**FCC-eh**: Ep=50 TeV, Ee=100 GeV

NC and CC: e-p, P=80%, 1000 $fb^{-1}$

stat: 0.1 – 30%, uncor 0.7%, syst 1 – 5%

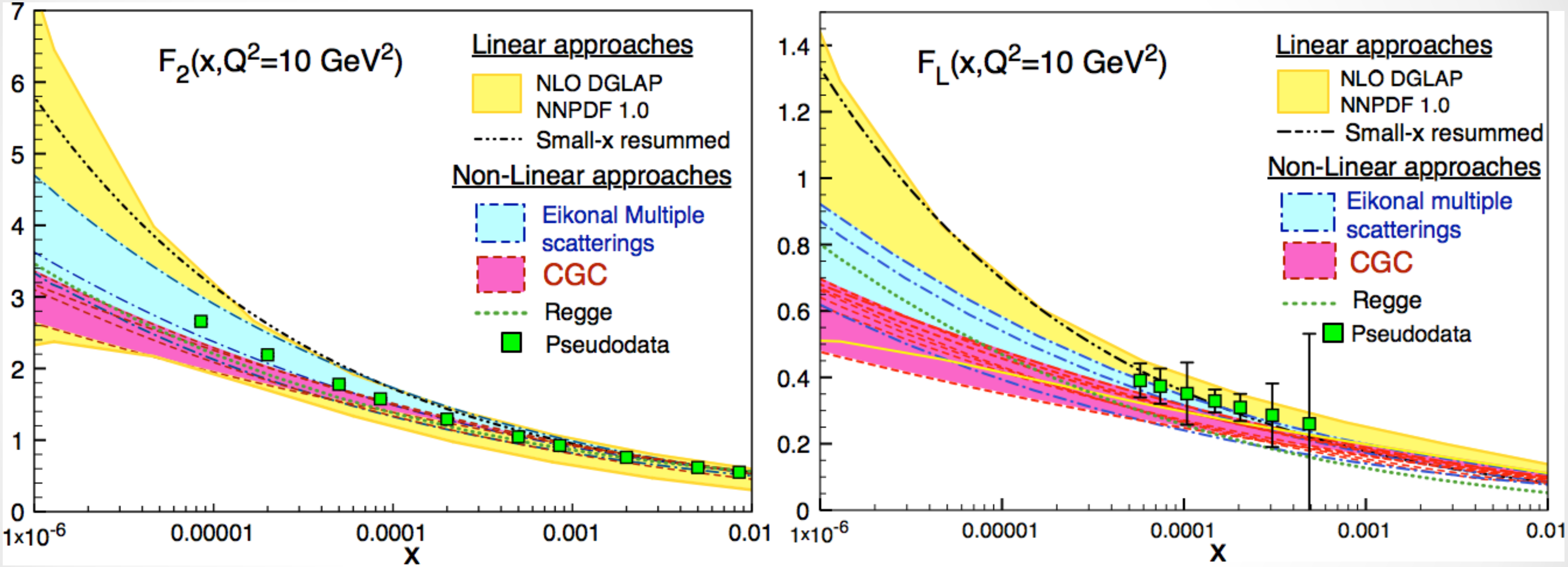
coverage down to $x=2\times10^{-7}$, up to $Q^2 = 10^7$ GeV$^2$

need FCC to constrain much below $x=10^{-5}$

FCC-eh can further improve, and explore low-x phenomenology

# sensitivity to effects beyond DGLAP

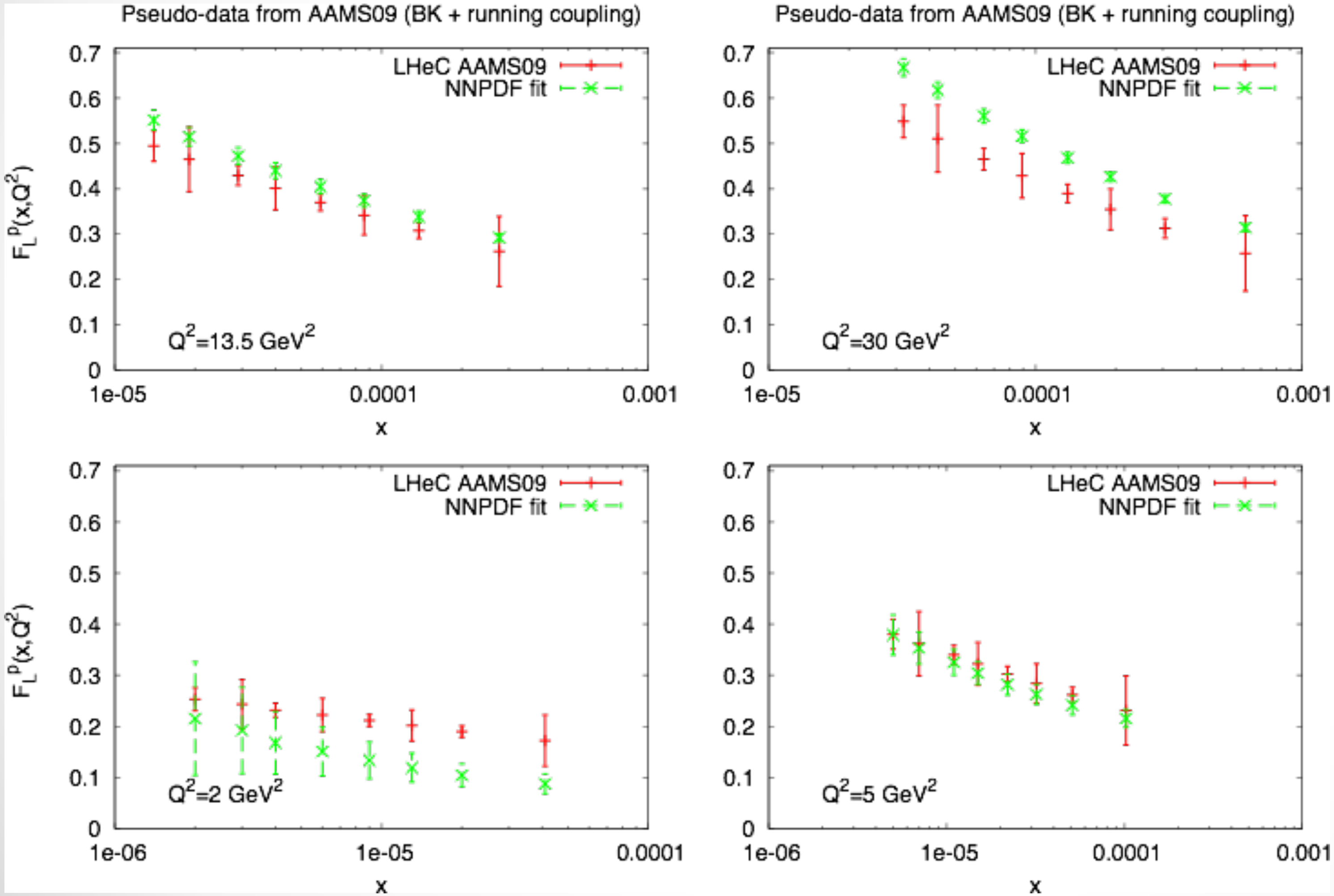
- measurements of $F_2$ and $F_L$, sensitive probe of novel small x QCD dynamics




**LHeC $F_2$ and $F_L$ data will have discriminatory power on models**

# sensitivity to effects beyond DGLAP

- measurements of $F_2$ **and** $F_L$, sensitive probe of novel small x QCD dynamics

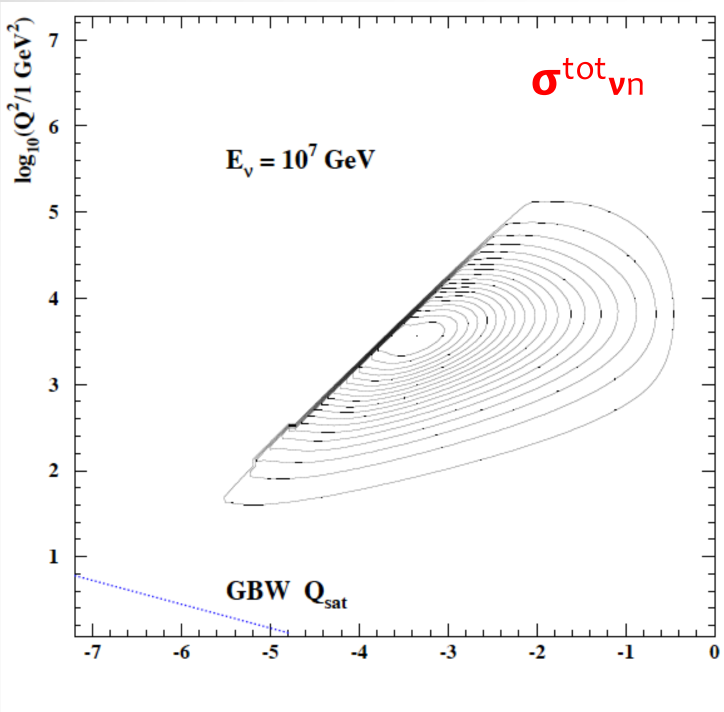



DGLAP fits cannot **simultaneously** accommodate precise LHeC $F_2$ and $F_L$ if saturation effects included

($F_2$ and $F_{2c}$ could also work as an alternative)

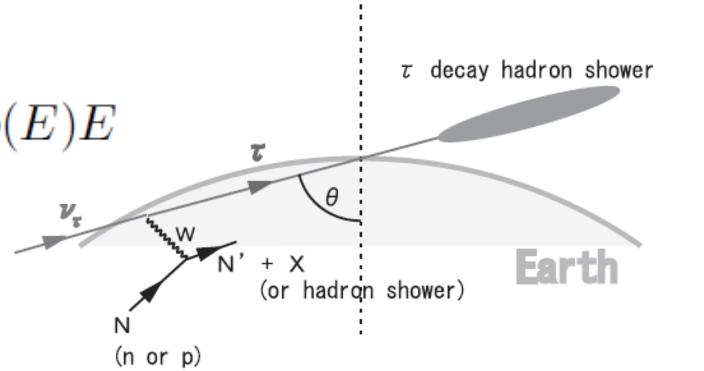
simulated LHeC data include saturation effects at low x

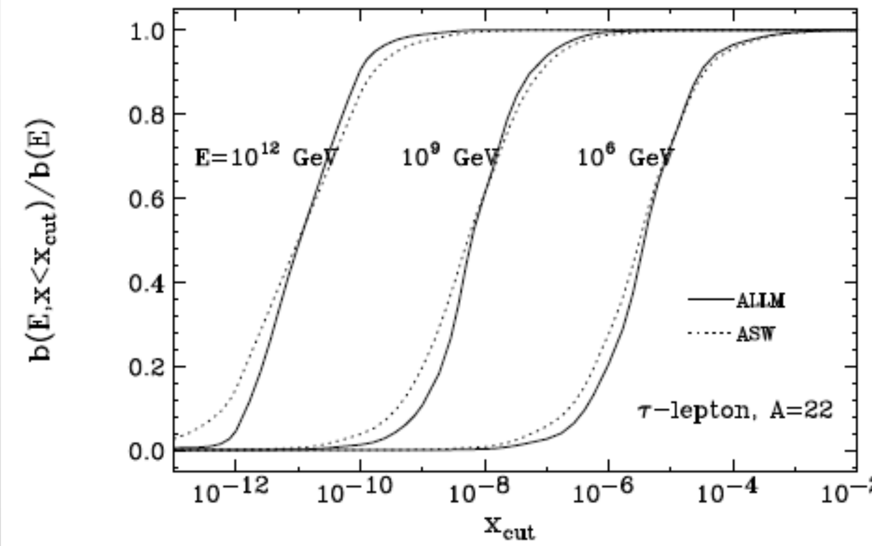
# implications for UHEνs

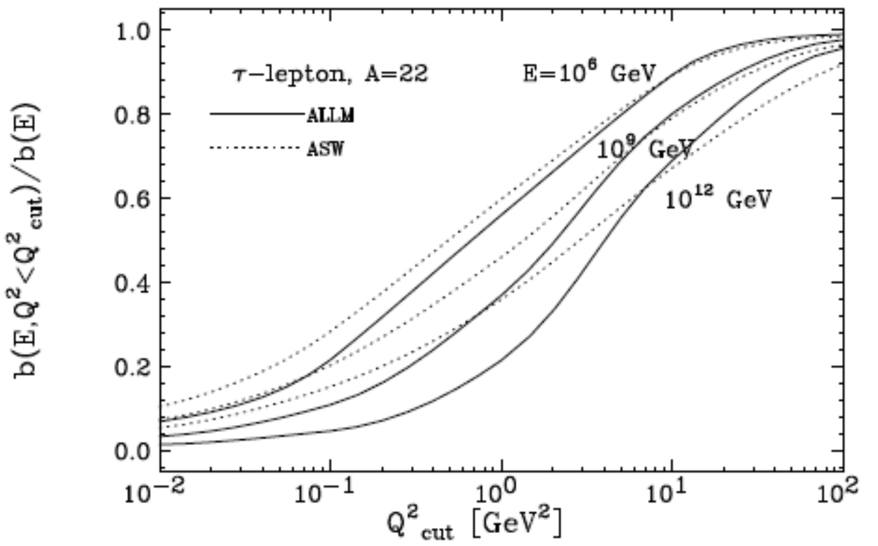



- ν-n/A cross section (τ energy loss) dominated by DIS structure functions/(n)PDFs at small-x and large (small) $Q^2$
- key ingredient for estimating fluxes

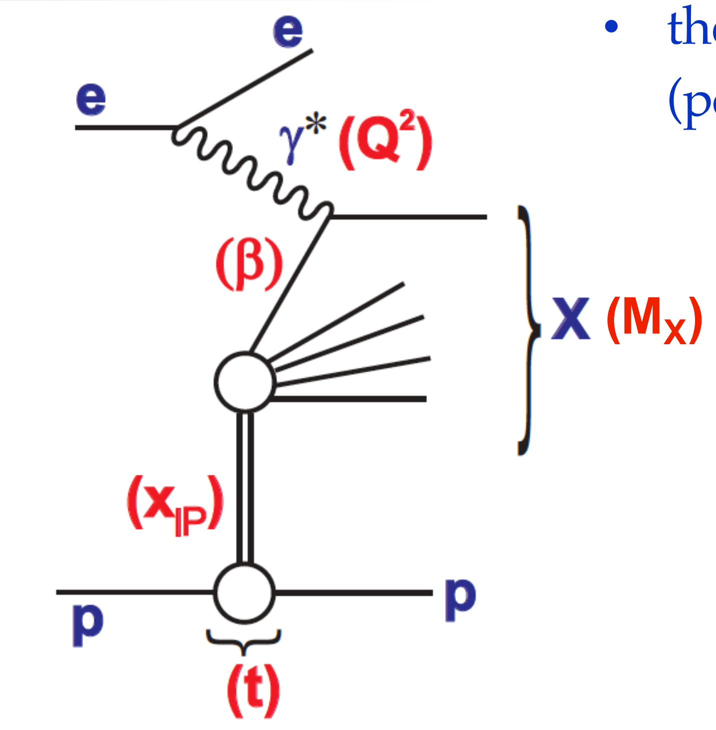
$$-\left\langle \frac{dE}{dX} \right\rangle = a(E) + b(E)E$$



# diffraction




- theoretical description in terms of colourless exchange (pomeron, IP)

momentum fractions:

$$x_{IP} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2}$$ pomeron w.r.t proton

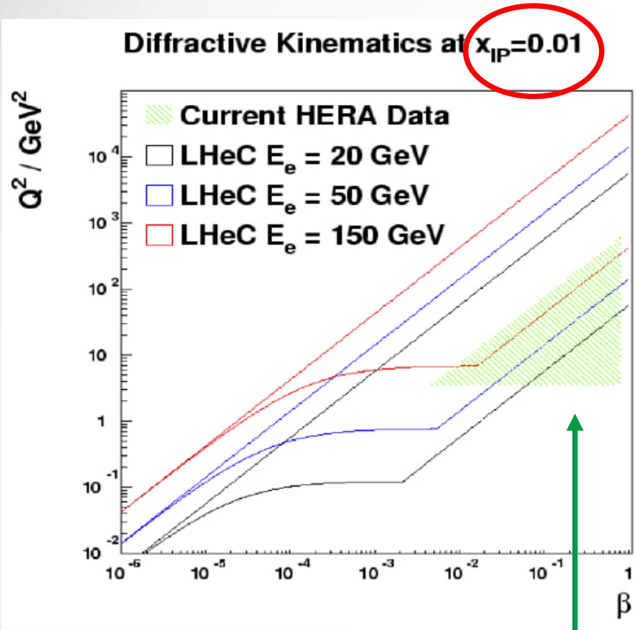
$$\beta = \frac{Q^2}{Q^2 + M_X^2 - t}$$ parton w.r.t pomeron

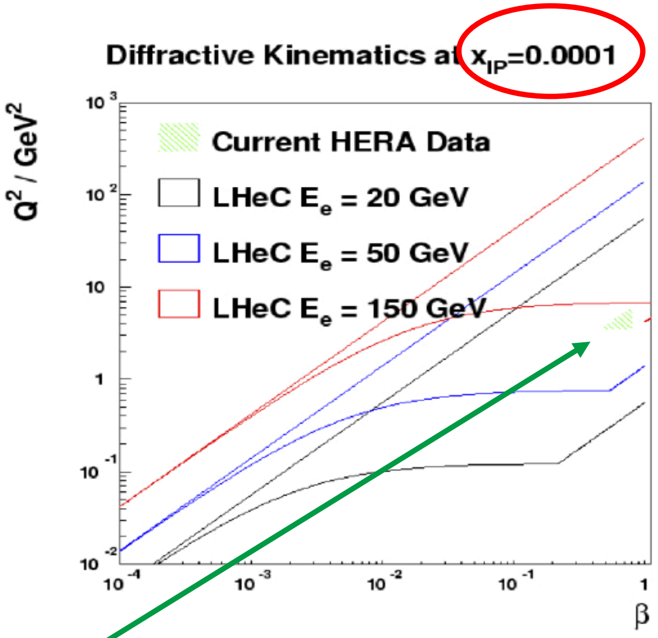
$$x = x_{IP}\beta$$ Bjorken-x

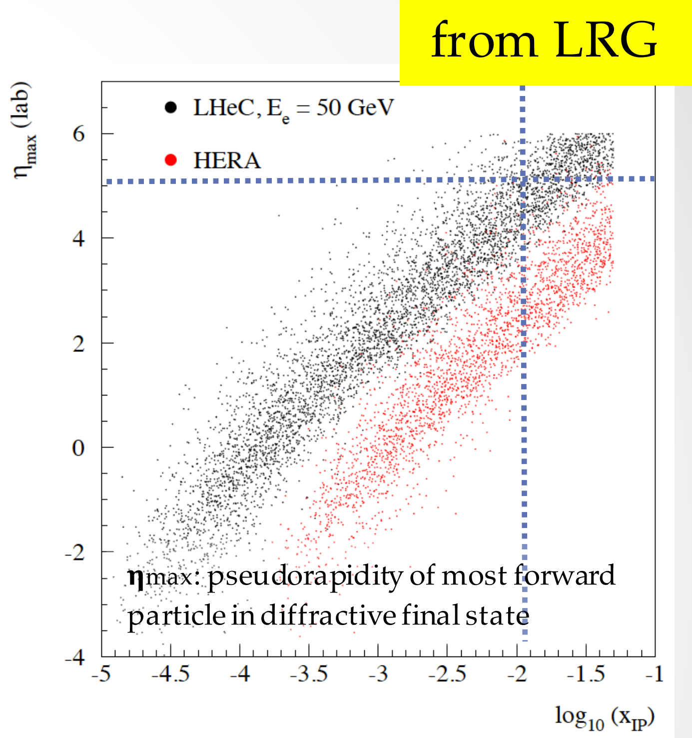
**with the LHeC:**

- tests of **factorisation** in extended kinematic range (ep and eA), and constraints on **diffractive PDFs** (DPDFs)
  (factorisation proven at high scales; diffractive structure functions are convolutions of DPDFs and coefficient functions)
- new domain for **diffractive masses**
- sensitivity to **non-linear** or **saturation** phenomena
- study relation between **diffraction** in ep and **shadowing** in eA

# diffractive kinematics and selection




- significant extension of diffractive kinematic region c.f. HERA

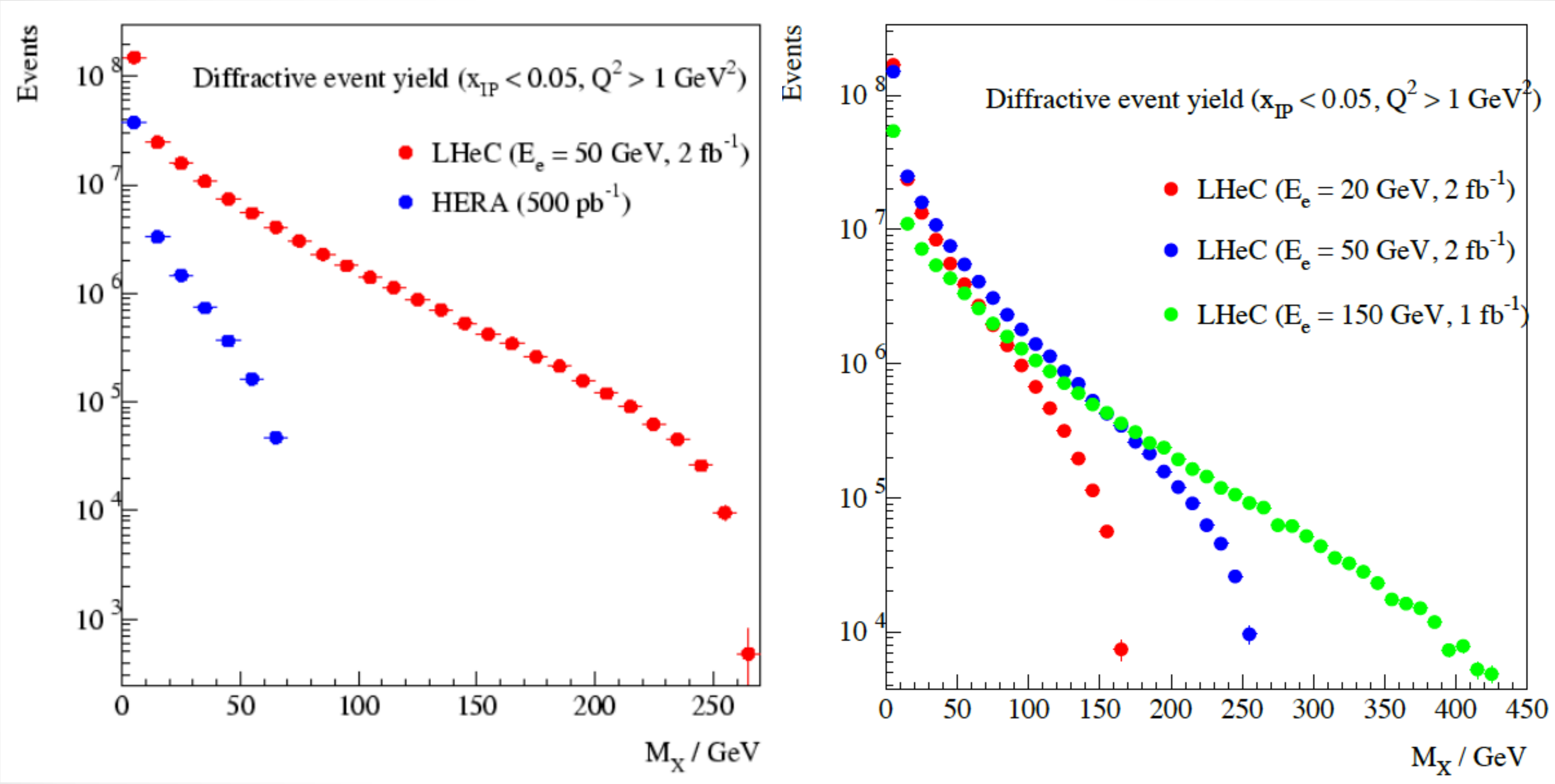
- **methods for selecting diffractive events**:

1. large rapidity gap selection (LRG)
   access to small $x_{IP}$ (up to 0.01 for $\eta_{max}$< 5)
2. leading proton tagging, could be used for larger $x_{IP}$

two methods complementary, with some overlap in acceptance

# diffractive mass distribution

RAPGAP simulation

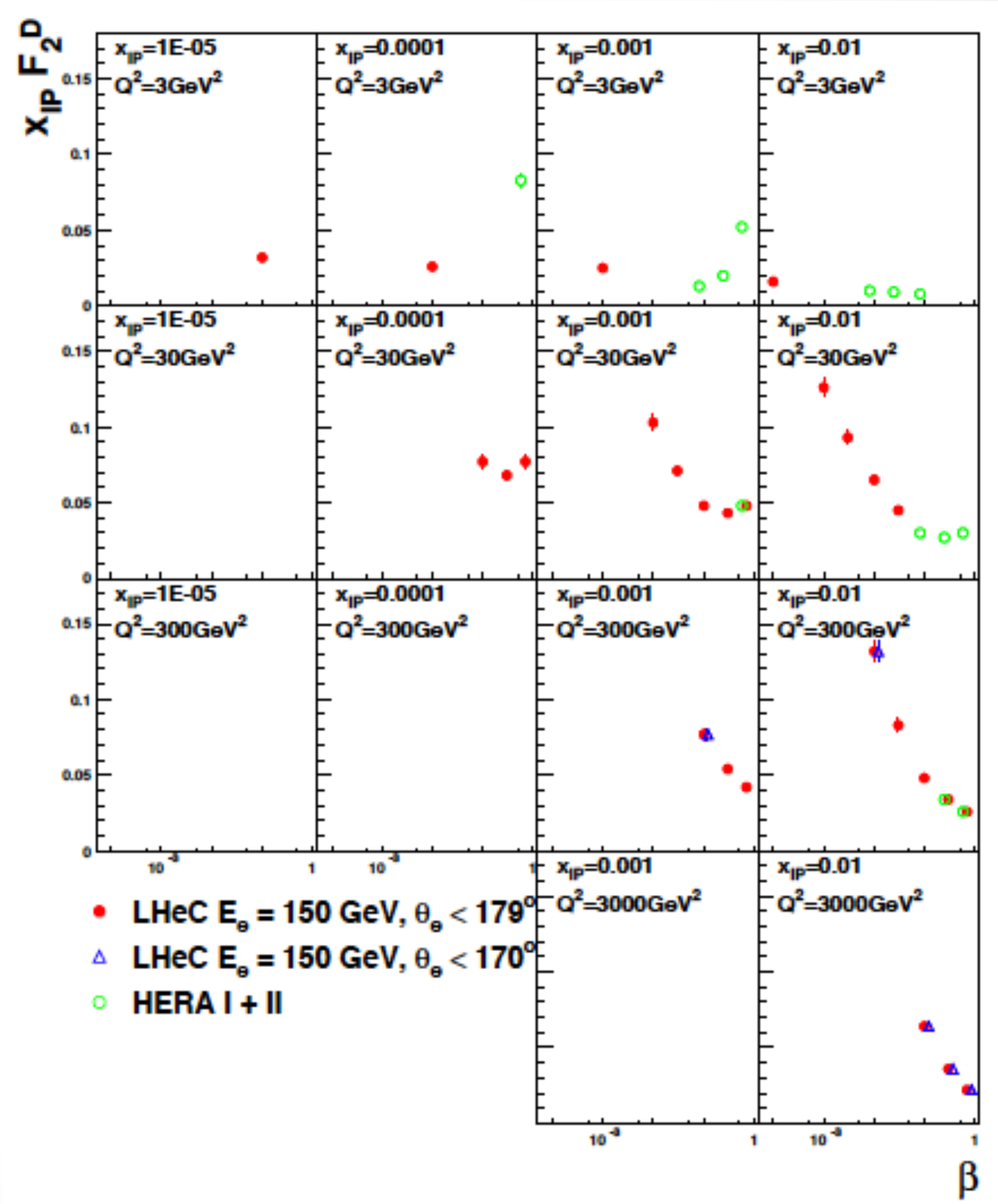



- compared with HERA, huge extension in Mx reach (low values of β)
- **new domain of diffractive masses**
- Mx can include – beauty, W, Z, new and exotic states EG. 1-- odderon

# diffractive structure functions

- LHeC pseudodata; simulated using large rapidity gap and leading proton methods ($E_e$=150 GeV, L=2fb$^{-1}$)
- stat. uncerts. < 1%
- acceptance of detector matters

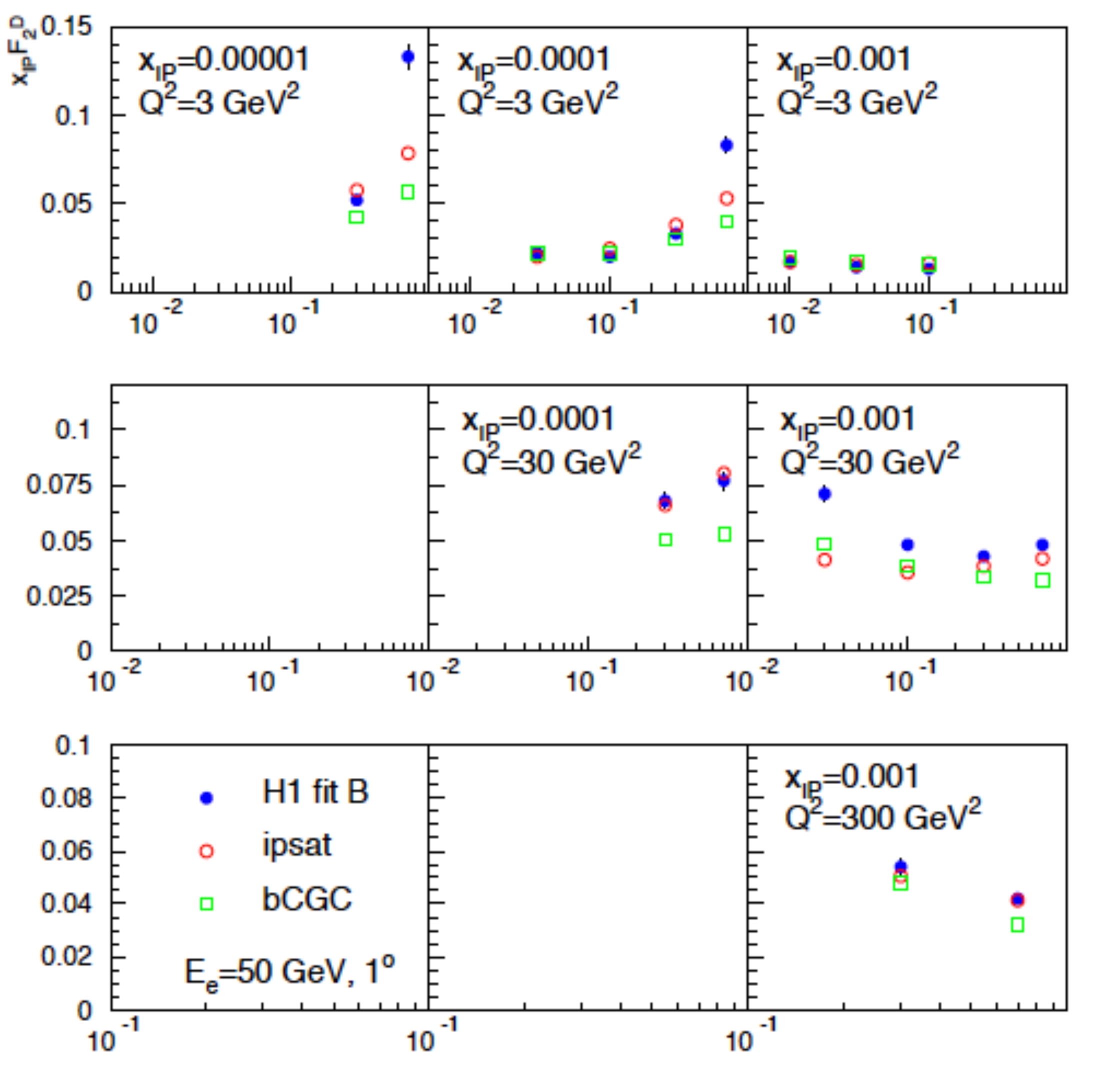
large extension in kinematic reach compared to HERA



# diffractive SFs and non-linear dynamics

- **LHeC** could discriminate between range of models **with** and **without** saturation effects

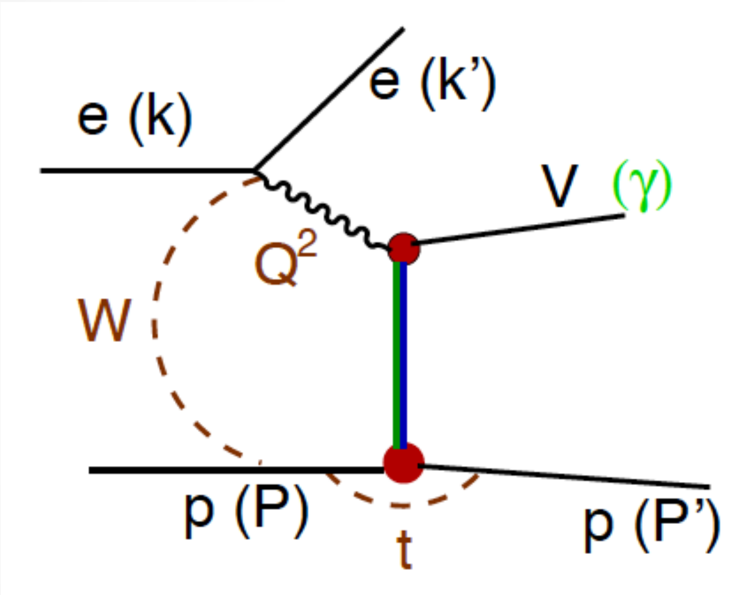
possibility to study **saturation** and its **realisation**



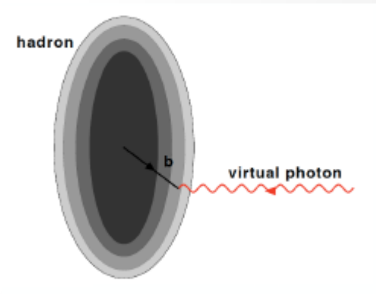

ipsat, bCGC: dipole models incl. saturation effects
H1 fit B: linear extrapolation from HERA DPDFs

# exclusive diffraction

**exclusive diffractive processes**, such as exclusive vector meson producton and deeply virtual compton scattering (DVCS) provide information on **proton structure** and **small x dynamics**, complementary to that from inclusive measurements




- **access to Generalised Parton Distributions (GPDs)**
  (encoding 3d structure of nucleon)
- **t-dependence** gives information about impact parameter profile (spatial distribution)

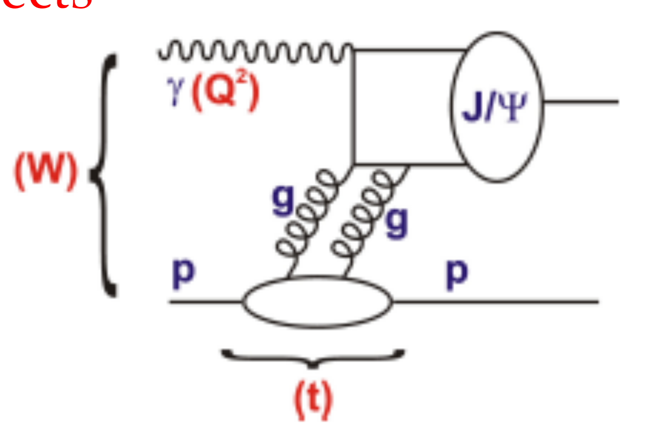


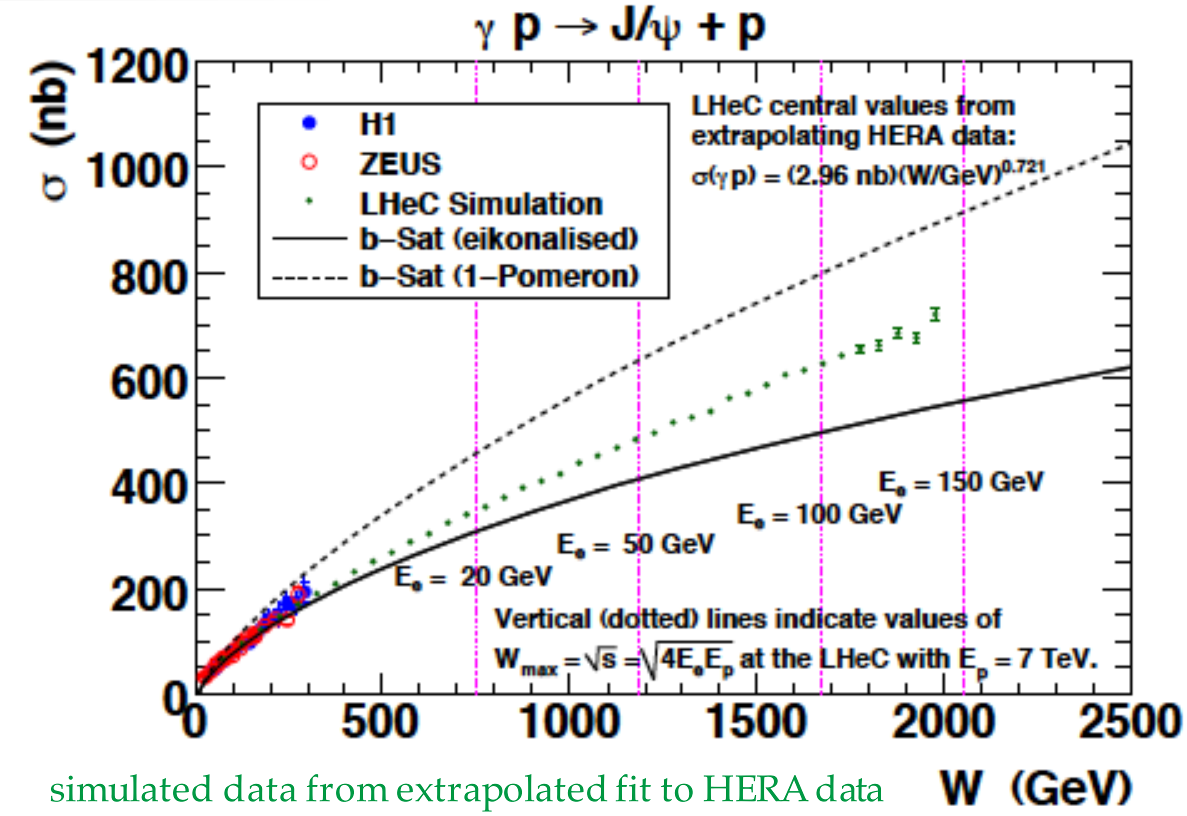

- **sensitivity to non-linear evolution and saturation effects**

# elastic vector meson production

- elastic J/psi production sensitive to saturation effects
- **b-Sat dipole model** (Golec-Biernat, Wuesthoff, Bartels, Motyka, Kowalski, Watt)

- eikonlised: with saturation
- 1-Pomeron: no saturarion




simulated data from extrapolated fit to HERA data

- large effects, even for t-integrated observables
- different behaviour as a function of ϒp centre-of-mass energy, W, depending on whether **saturation included** or not

**LHeC** can distinguish these different scenarios

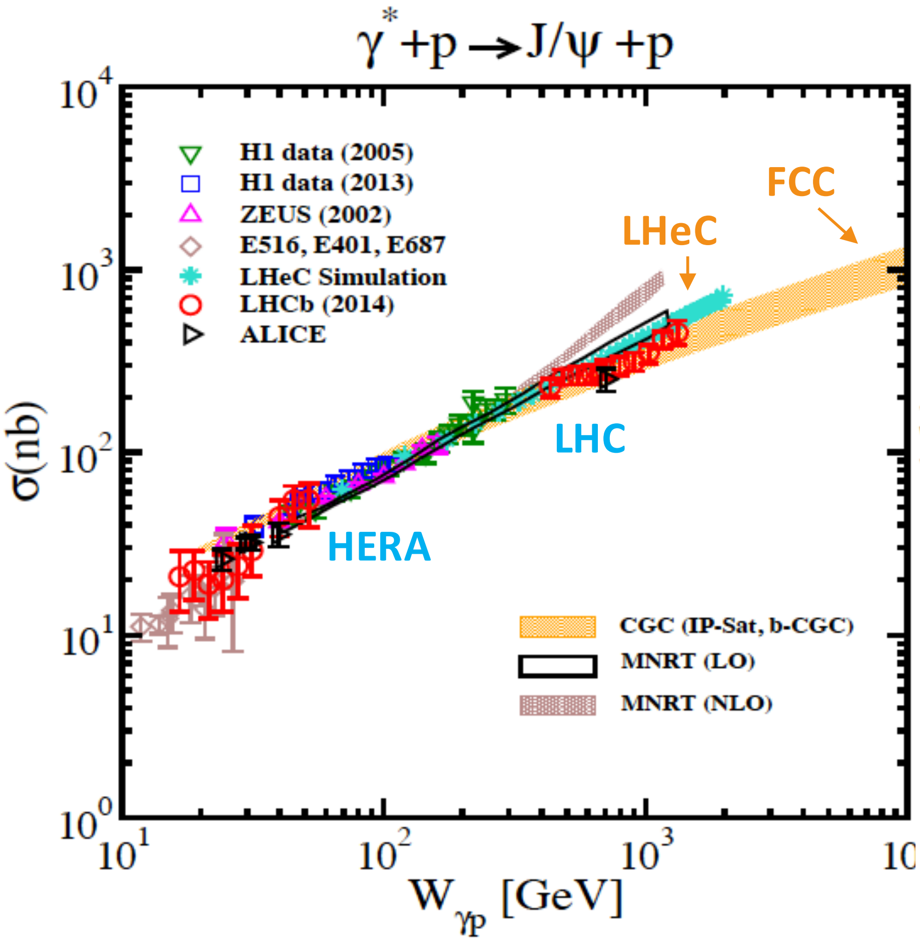
# elastic vector meson production

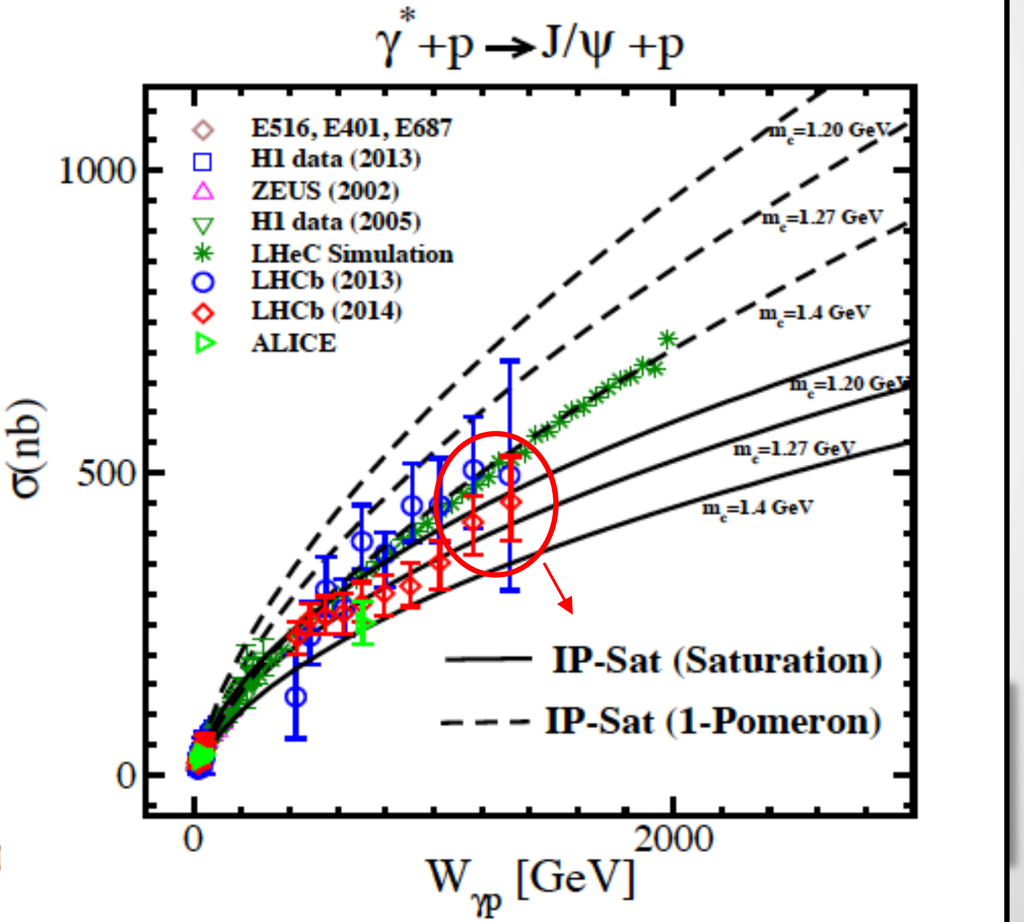
- elastic J/psi production sensitive to saturation effects

**with ALICE and LHCb data**

Armesto and Rezaeian (arXiv:1402.4831)

- ultra-peripherial collisions at the LHC and beyond are a (less precise) alternative



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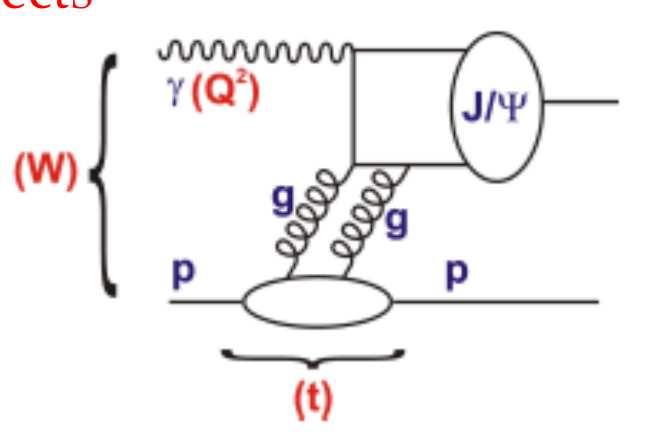


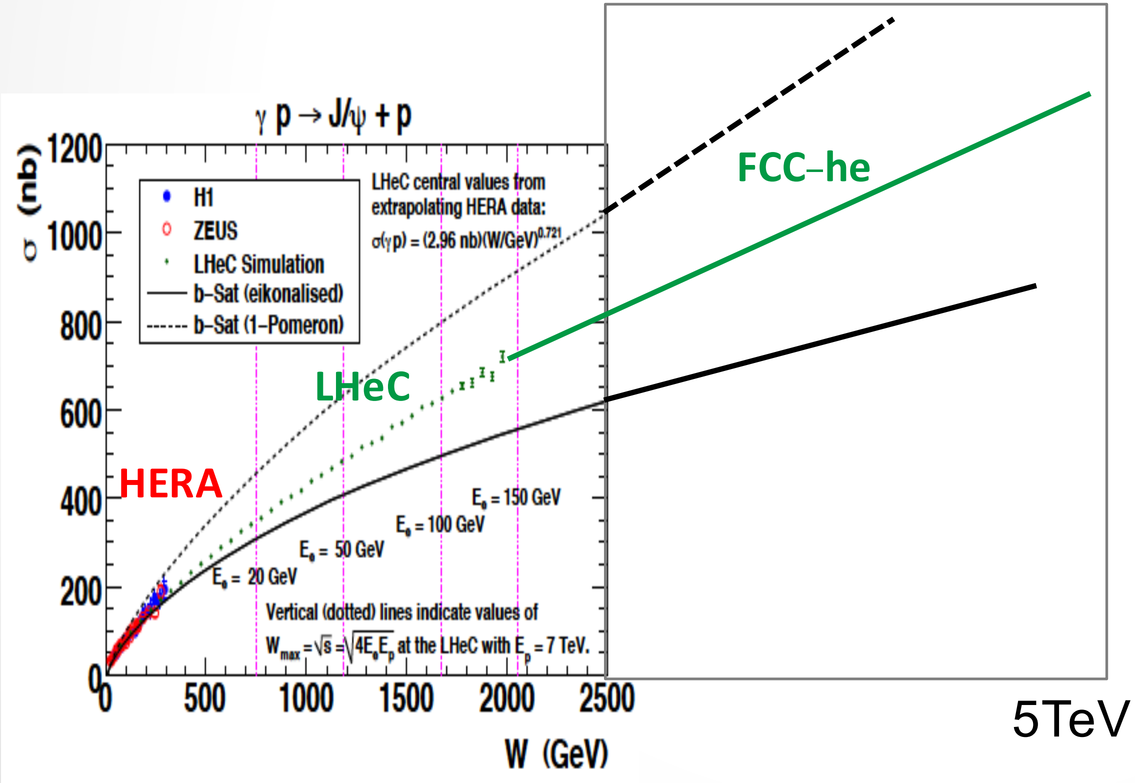


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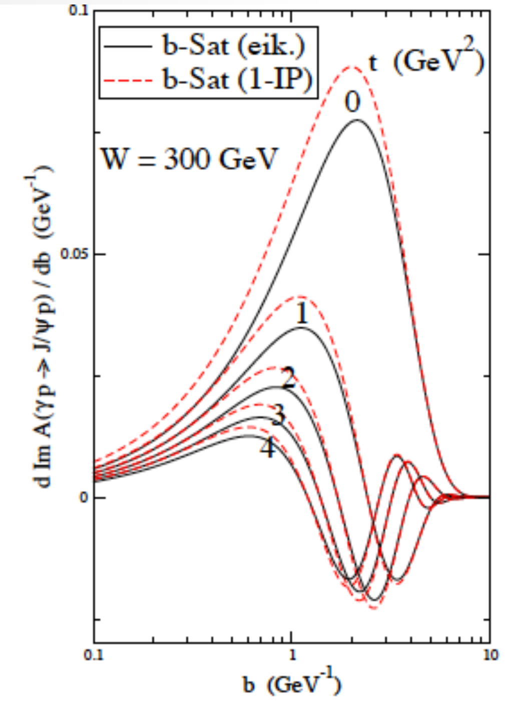
**LHeC** can distinguish these different scenarios

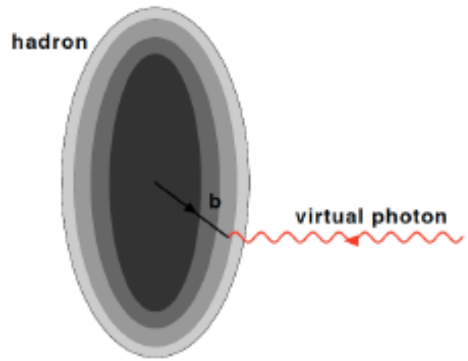
# elastic VM production – t dependence

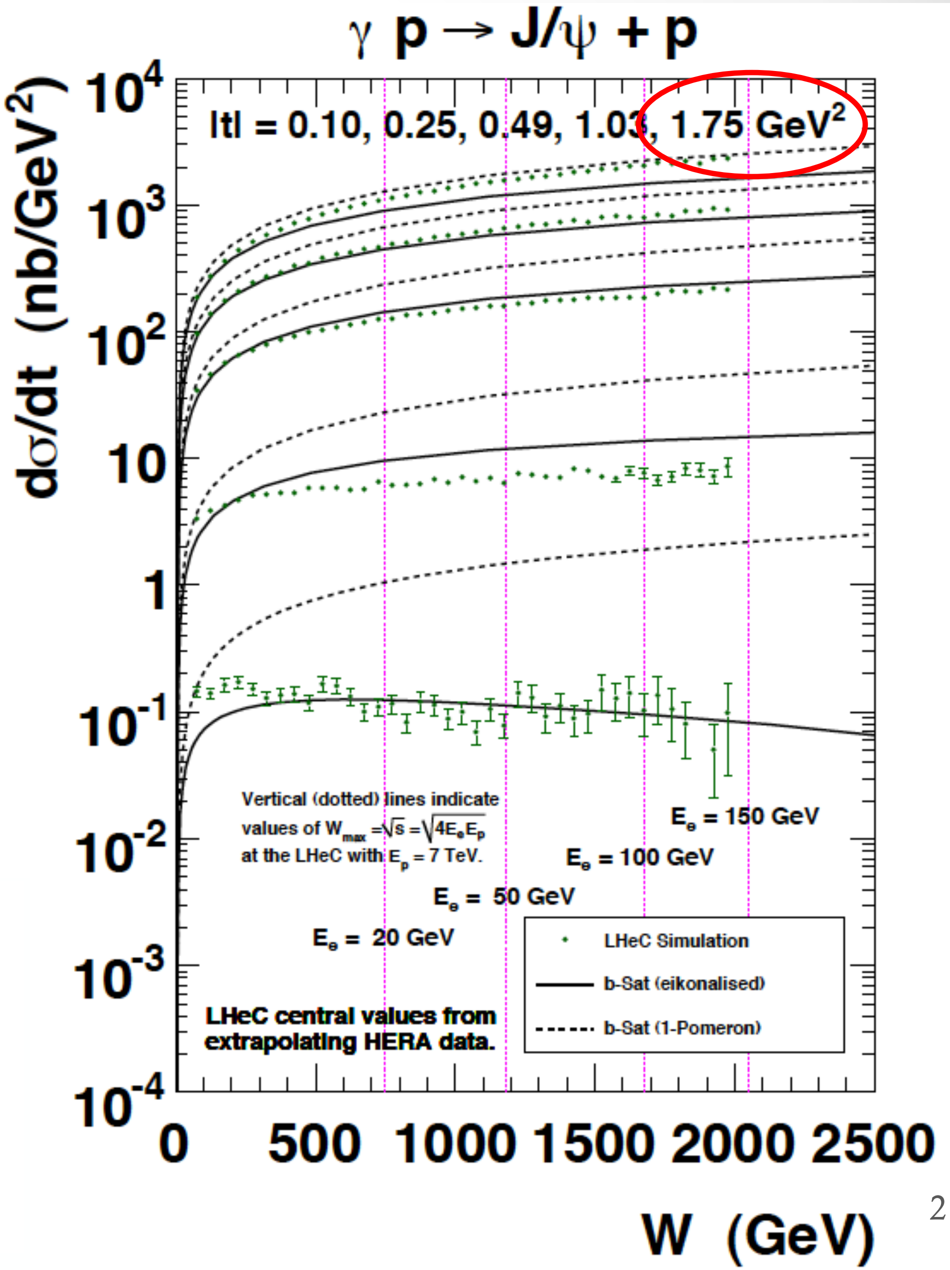
- measurements **differential in t** give gluon transverse mapping of hadron/nucleus

- **cross section in bins of W and t**
- even for small t values and smallest energies, significant differences between models (effect increases with increasing W and t)
- LHeC can discriminate



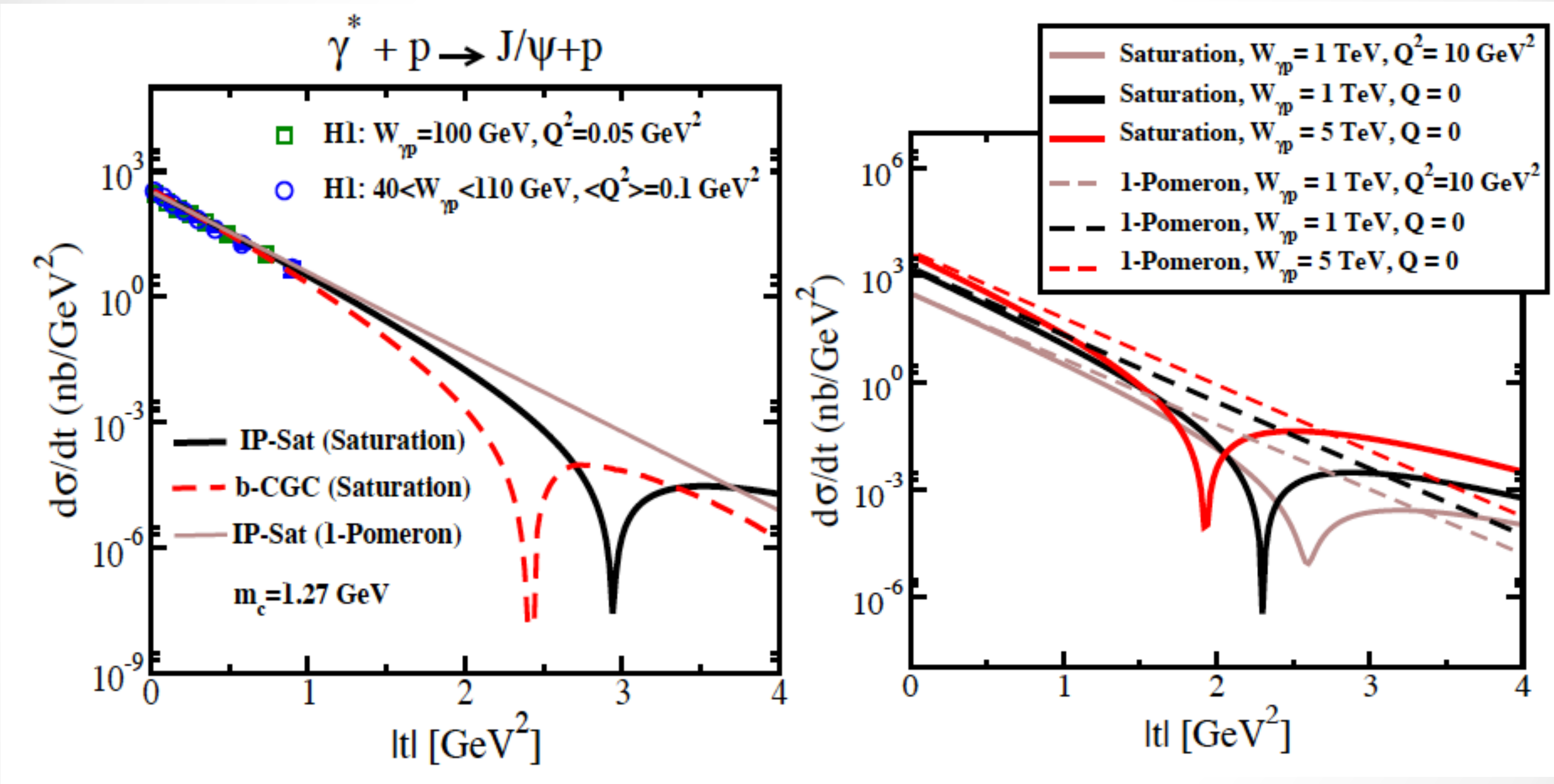

**larger t**: increased sensitivity to small impact parameters where density of interacting region highest



# elastic VM production – dips in t profile

- measurements **differential in t** give gluon transverse mapping of hadron/nucleus

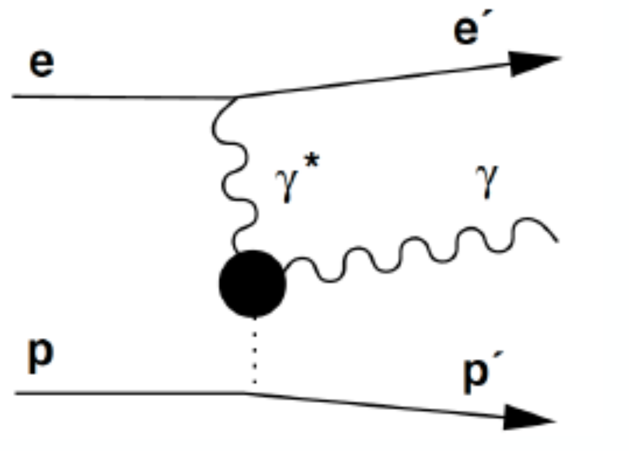



- **t-dependence is a Fourier Transform of the impact parameter profile**
- characteristic dips a feature of saturation models
- positions of dips depend on energy and scale
- within LHeC-sensitive range

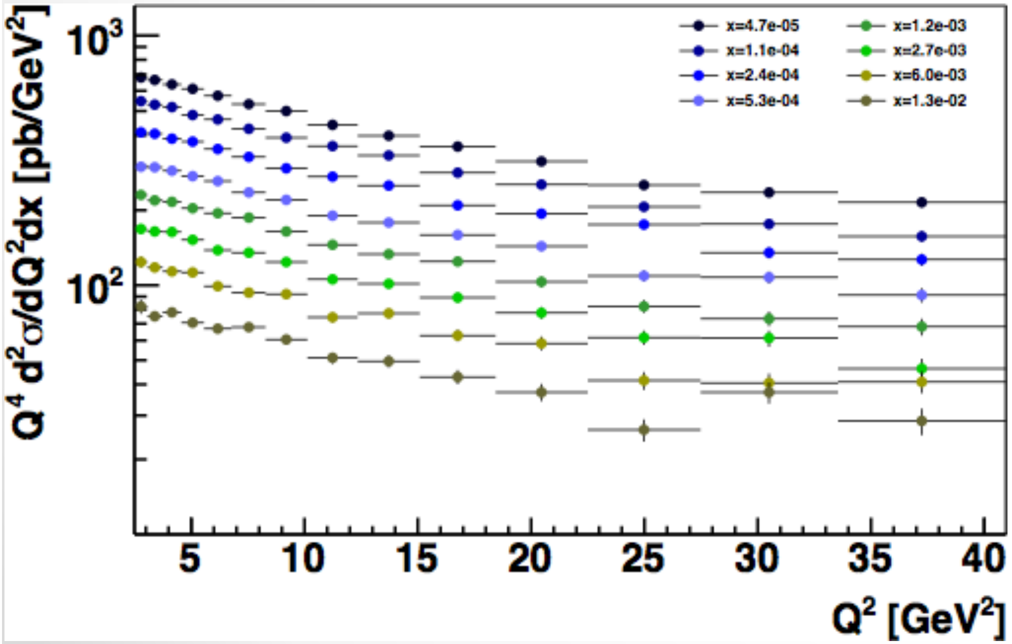
arXiv:1402.4831

# deeply virtual compton scattering

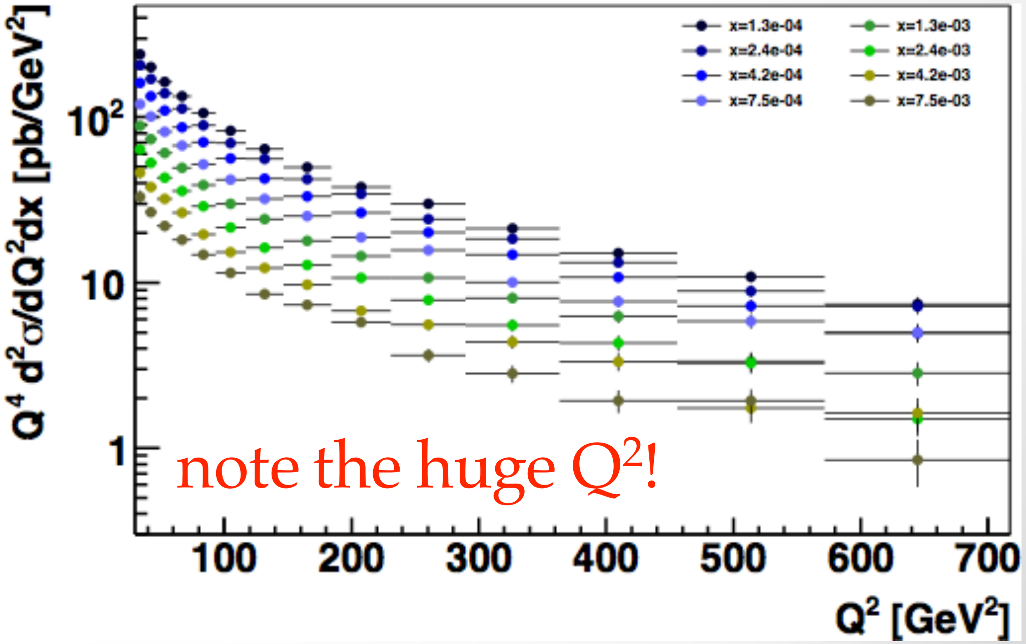
- DVCS: ‘golden channel’ for accessing **GPDs**
  - clean; no vector meson wave-function uncerts.
- sensitive to **singlet quark** as well as **gluon**
- Fourier Transform of GPDs gives transverse scan of hadron
- sensitive to dynamics EG. non-linear effects




**L**=1 **fb**–1; **E**e=50 **GeV, θ**=1°, **pt**$^{\gamma}$ > 2 **GeV**



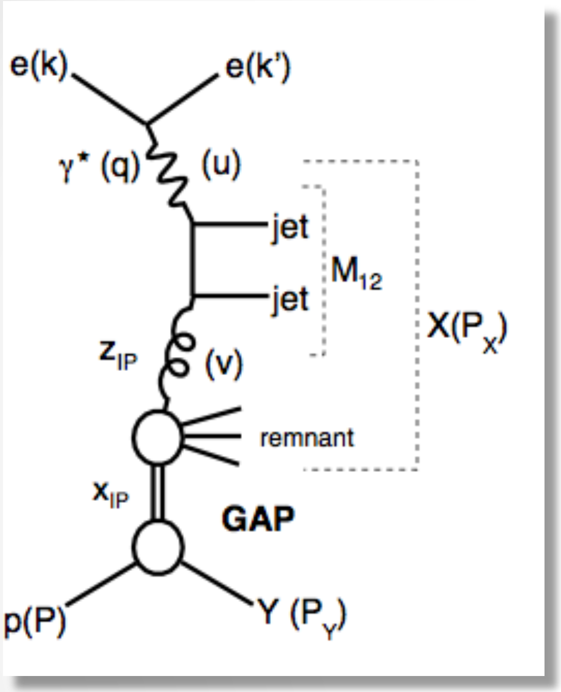

**L**=100 **fb**–1; **E**e=50 **GeV, θ**=10°, **pt**$^{\gamma}$ > 5 **GeV**

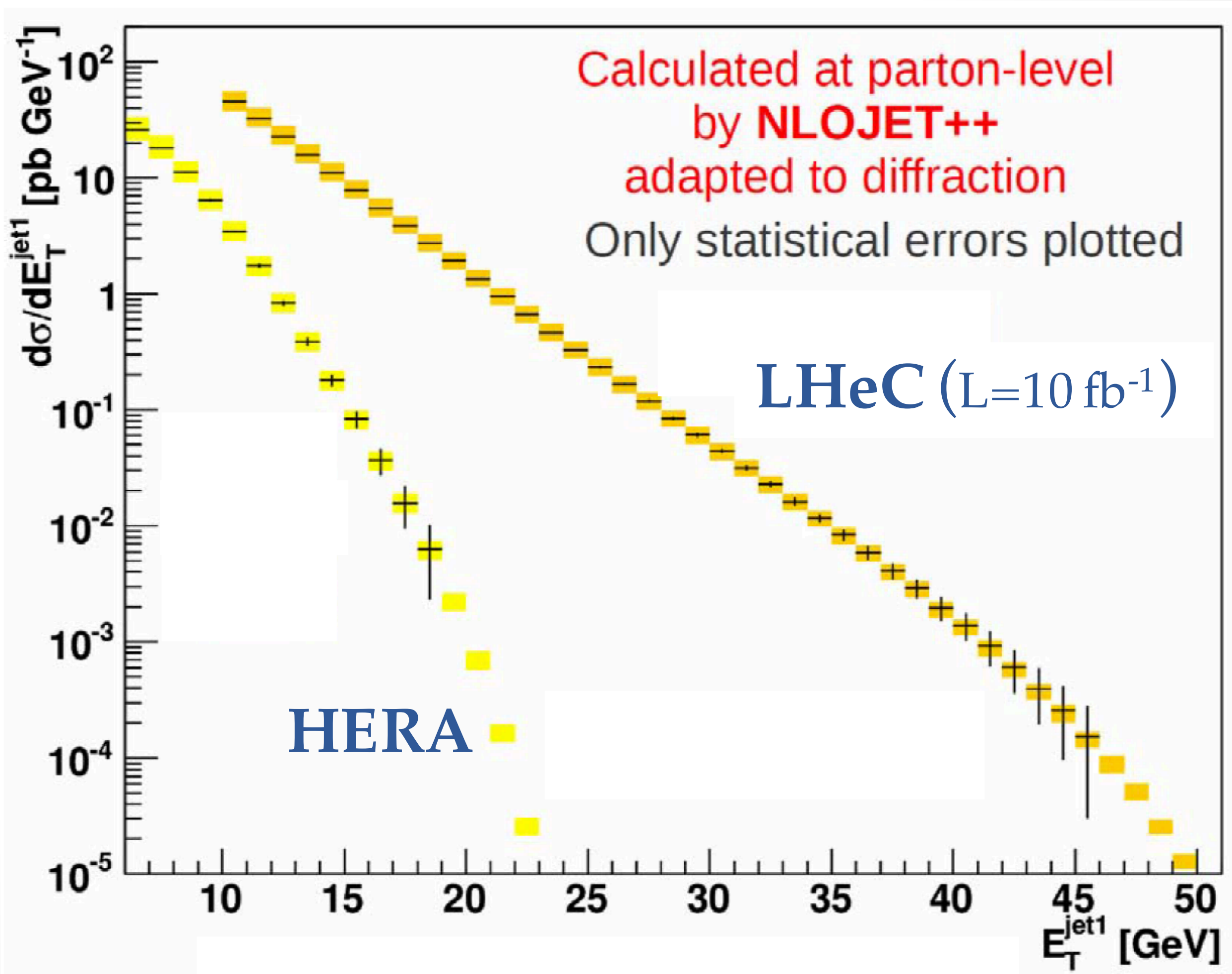


# diffractive dijet production in DIS

- diffractive dijet and open heavy flavour production offer possibilities for:
  - checking **factorisation** in hard diffraction
  - constraining **diffractive PDFs**

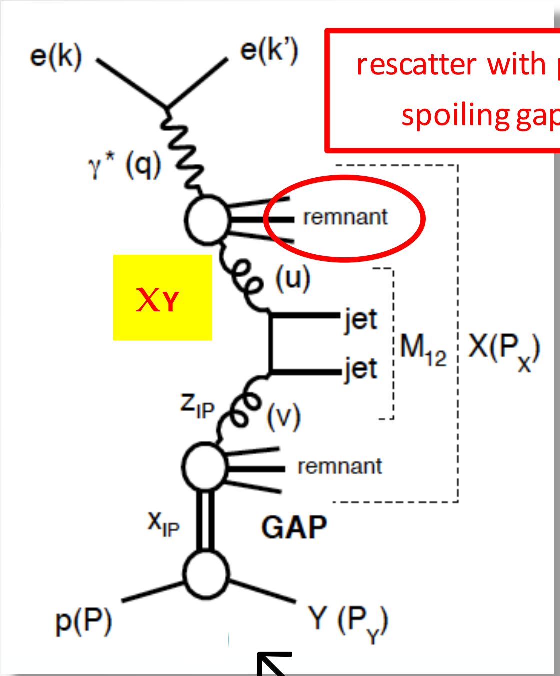
  (sensitive to gluon; complementary information c.f. inclusive diffraction)

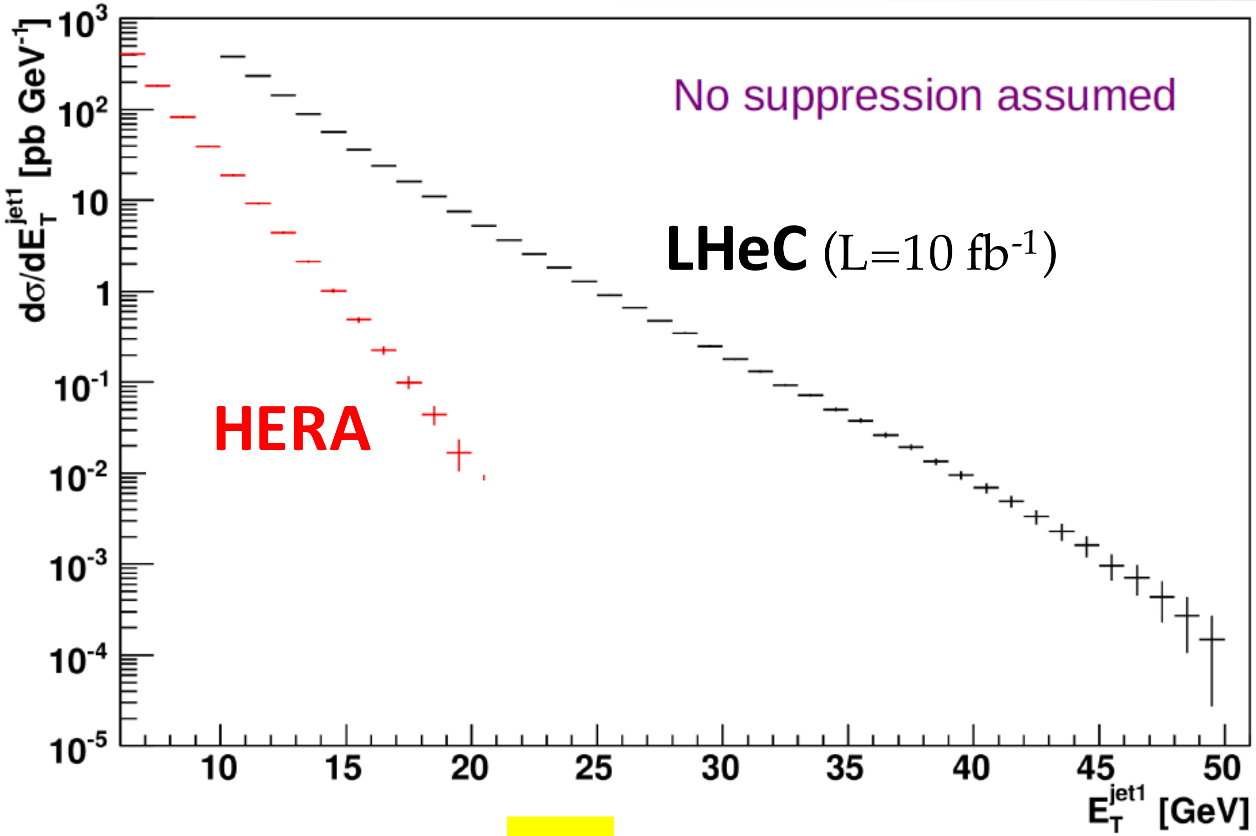



**LHeC**: large yields up to high jet pt

# diffractive dijets in photoproduction



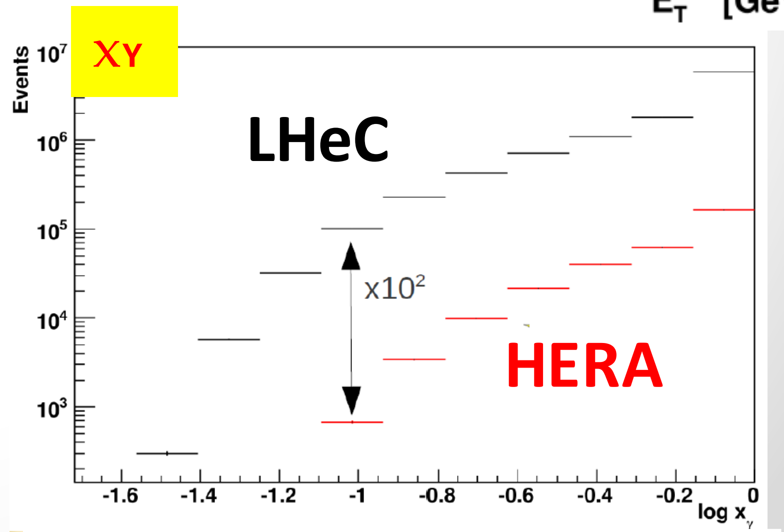




direct and **resolved** photons

$x_\gamma$ = photon momentum fraction

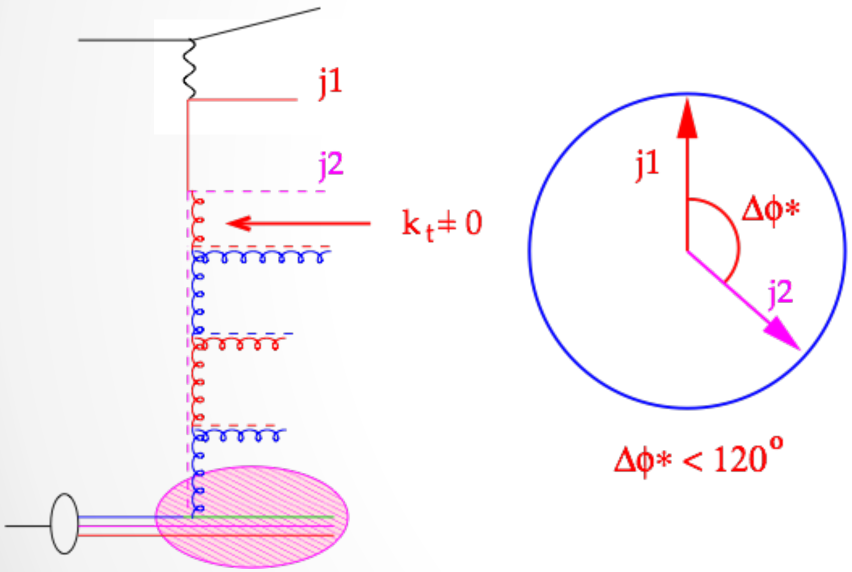
if additional interactions, suppression expected at low $x_\gamma$ (factorisation breaking), **but picture from HERA unclear**

**LHeC**: tests of factorisation possible in much larger kinematic range with larger statistics

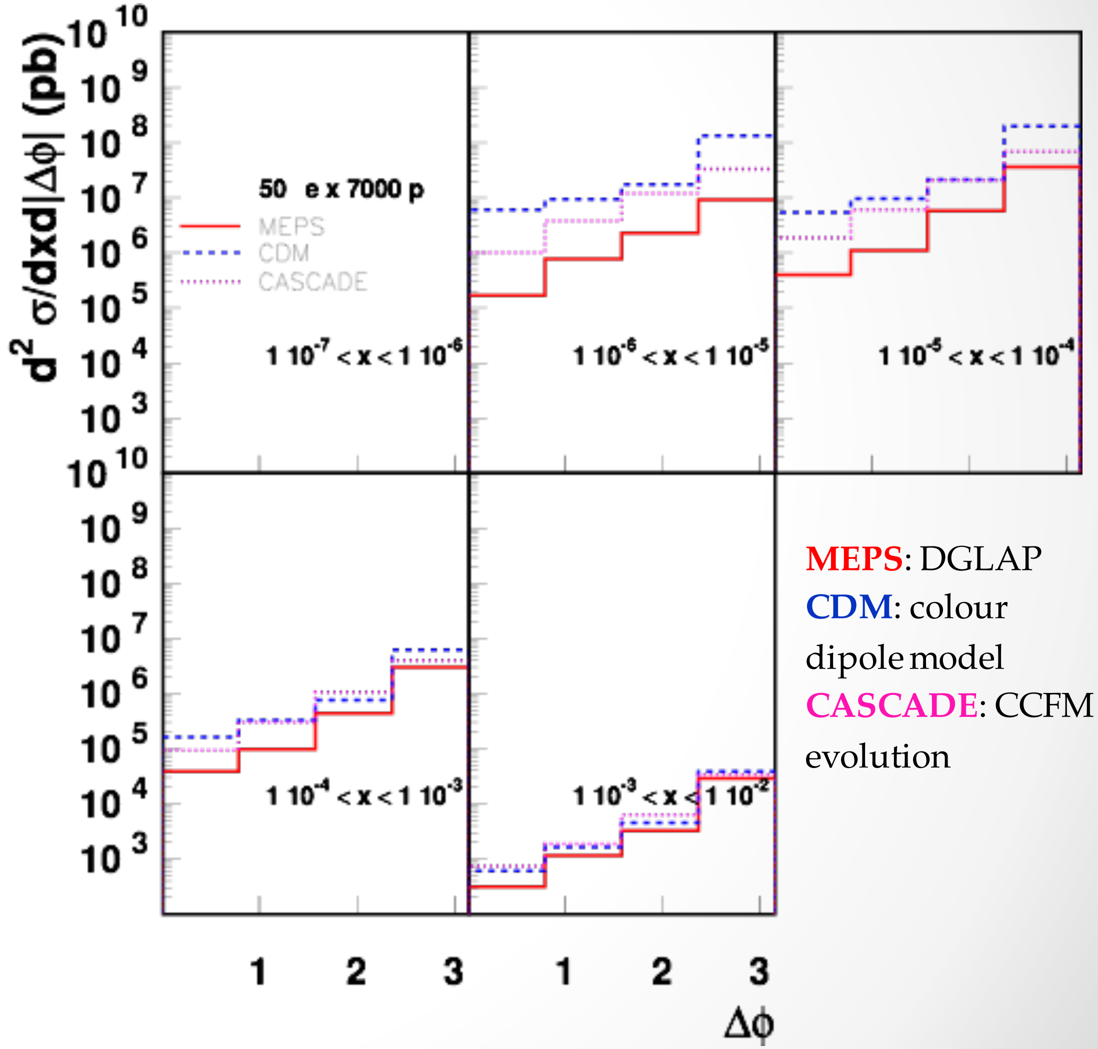


# jet observables:

- **dijet azimuthal decorrelations** and **forward jets** (Q~pt) can shed light on mechanism of QCD radiation
  - kt ordered (DGLAP)
  - kt unordered (BFKL)
  - saturation?




(if incoming gluon has sizeable kt, jets no longer back-to-back; must balance kt of incoming virtual gluon)




**MEPS**: DGLAP
**CDM**: colour dipole model
**CASCADE**: CCFM evolution

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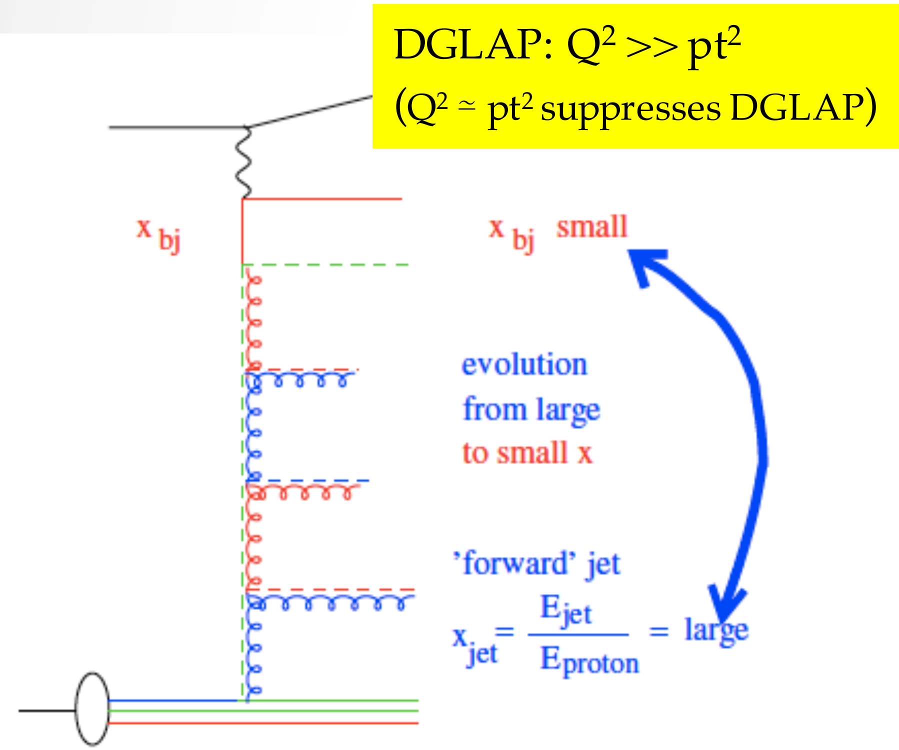
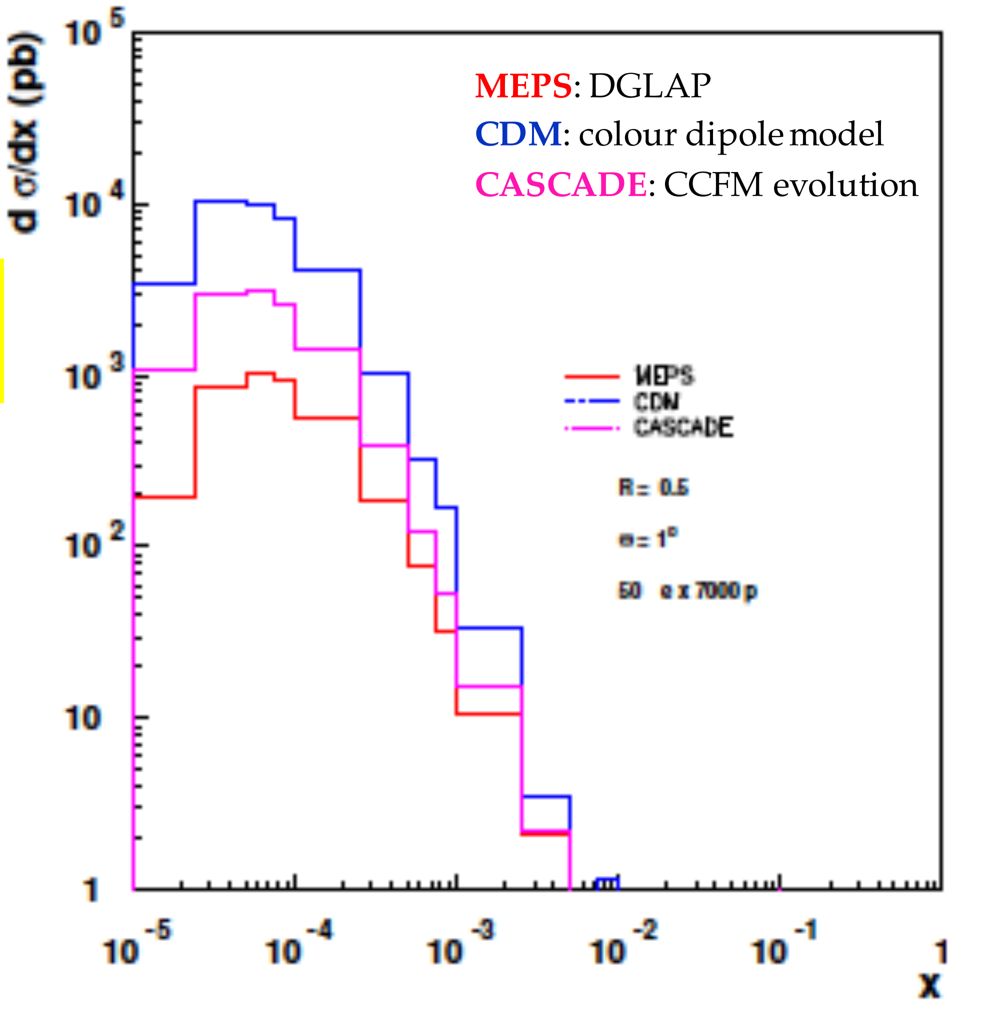



- LHeC could perform measurements with large rapidity separations and different
- (Q,pt) combinations to systematically test parton dynamics

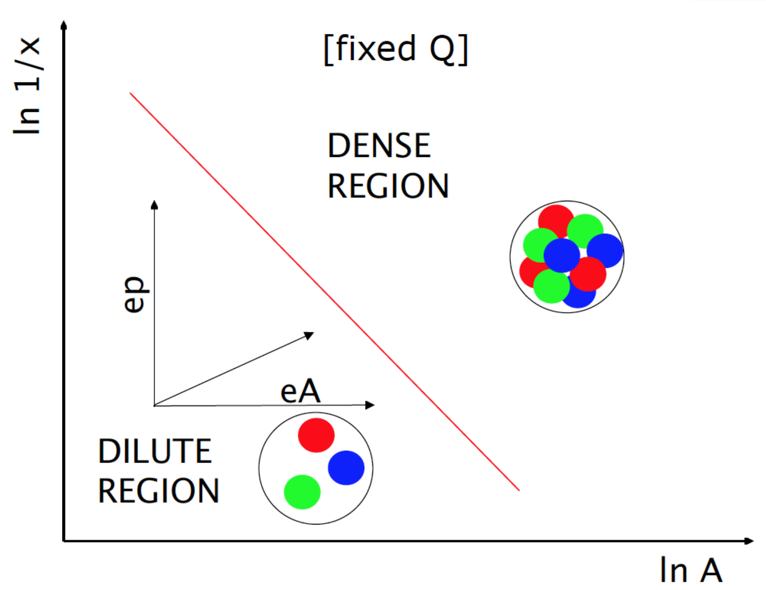
# summary

- **with an LHeC (and FCC-he) at CERN:**
- unprecedented access to small x in ep and eA
- high precision tests of collinear factorisation and determination of PDFs
- novel sensitivity to physics beyond standard pQCD
- stringent tests of QCD radiation
- access to 3d structure of hadrons / nucleus at small x

**with ep <u>and</u> eA** (see also talk by I. Helenius)**, LHeC can answer the question of saturation/ non-linear dynamics**

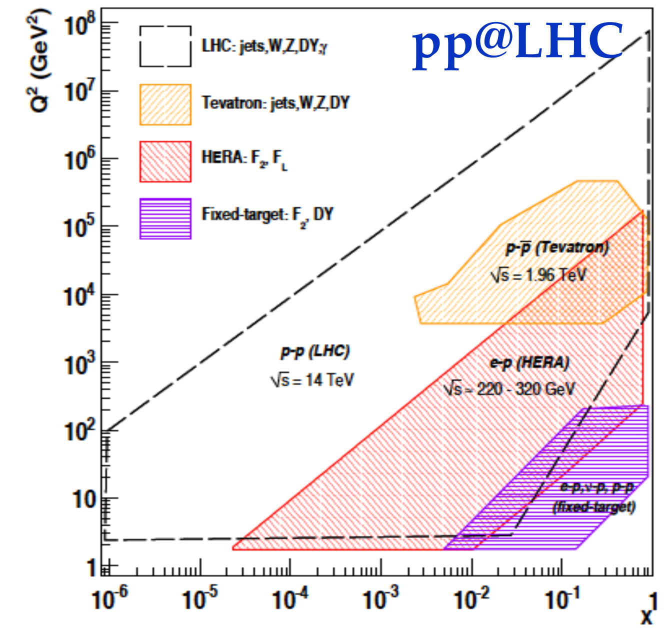
**future plans** – following CERN mandate, towards a TDR**:**

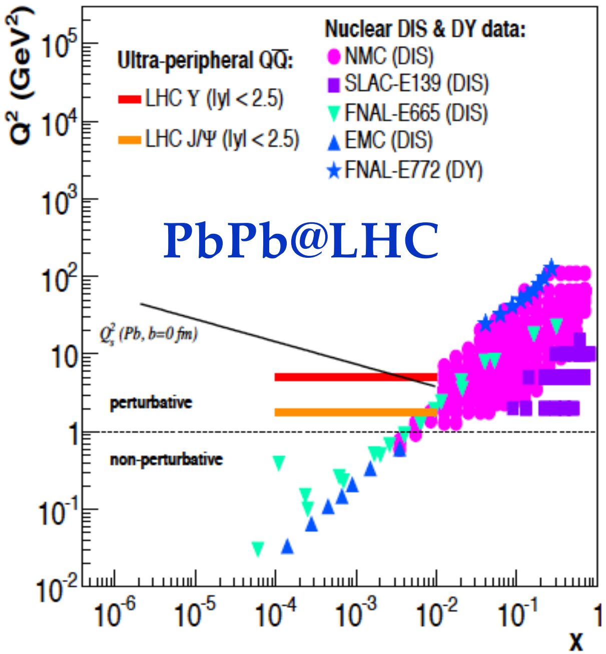
- further studies on **DPDFs** (and nDPDFs)
- **GPDs** using vector meson production and DVCS, and study complementarity
- **complementarity** with LHC

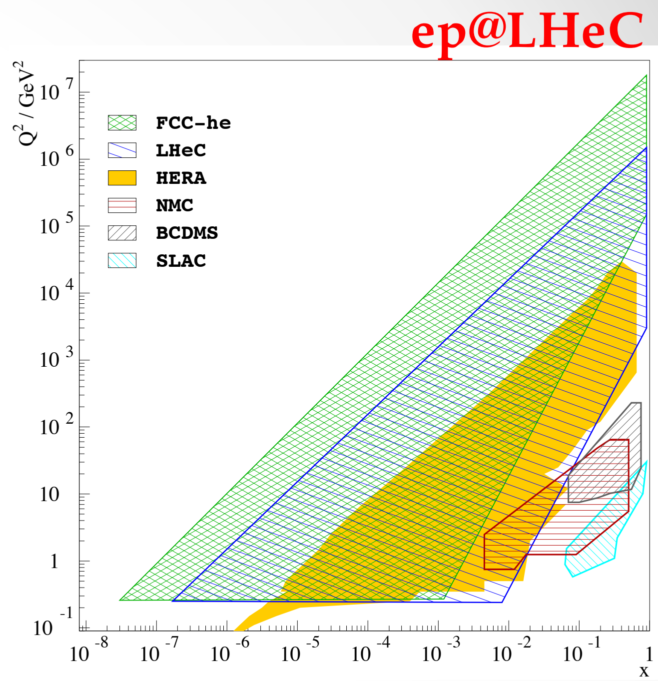


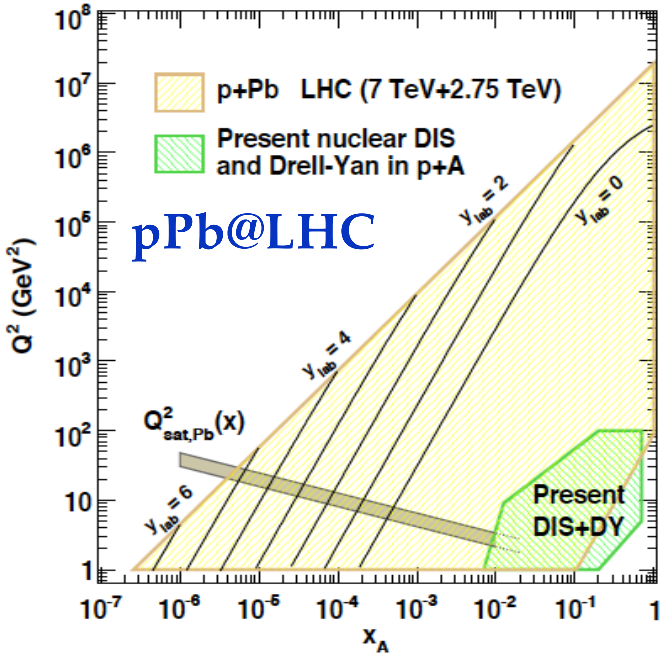
# extras

# LHeC vs LHC kinematics

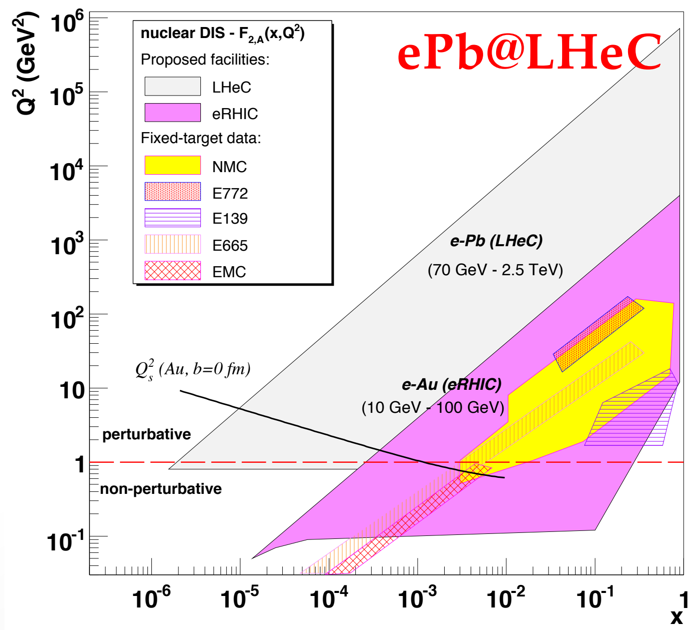


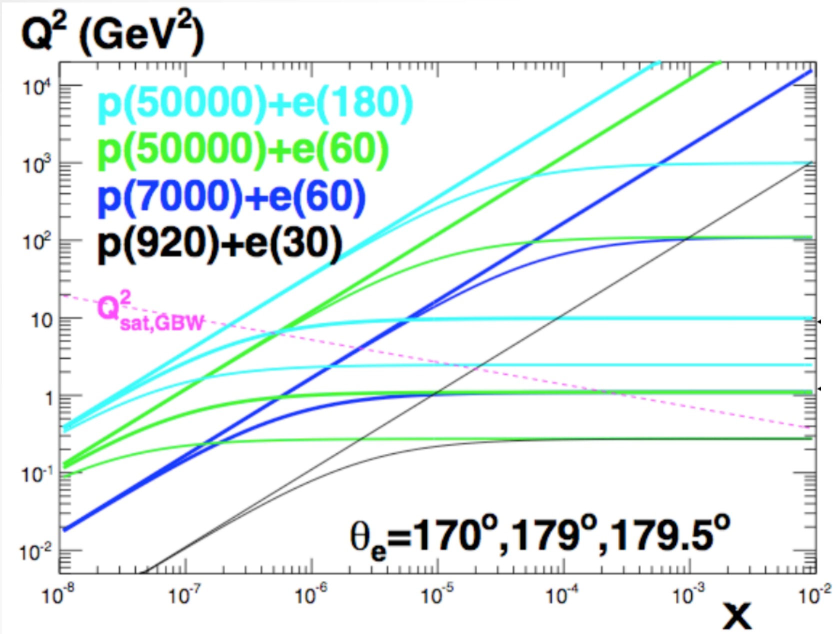




- LHeC will explore region overlapping with LHC:
- in a cleaner experimental set up
- on firmer theoretical grounds

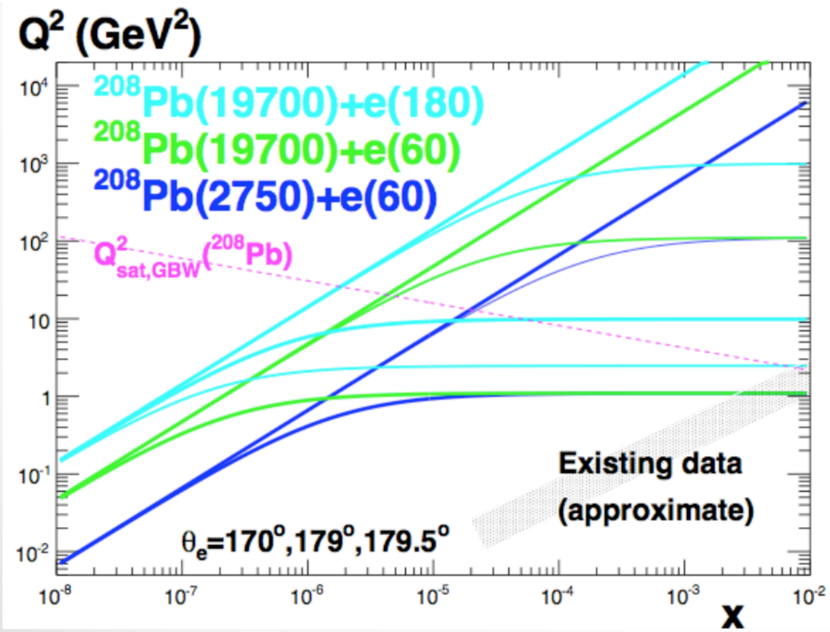


# FCC–eh kinematics

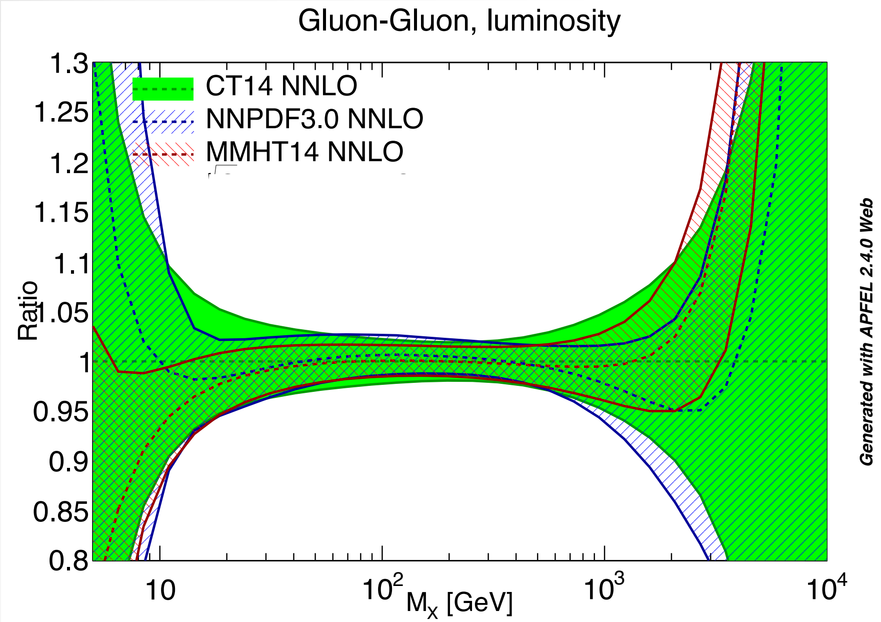


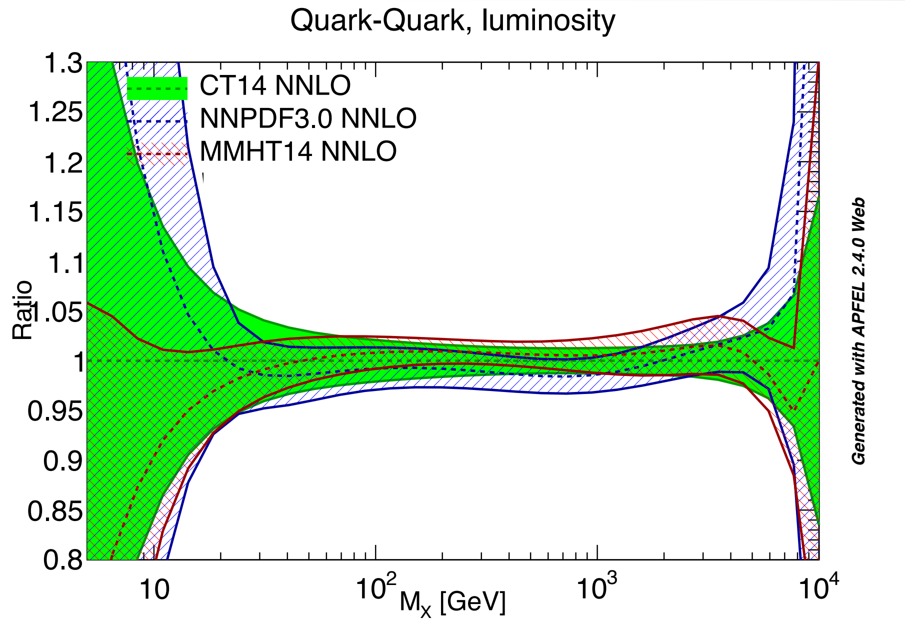

← 180 GeV

← 60 GeV

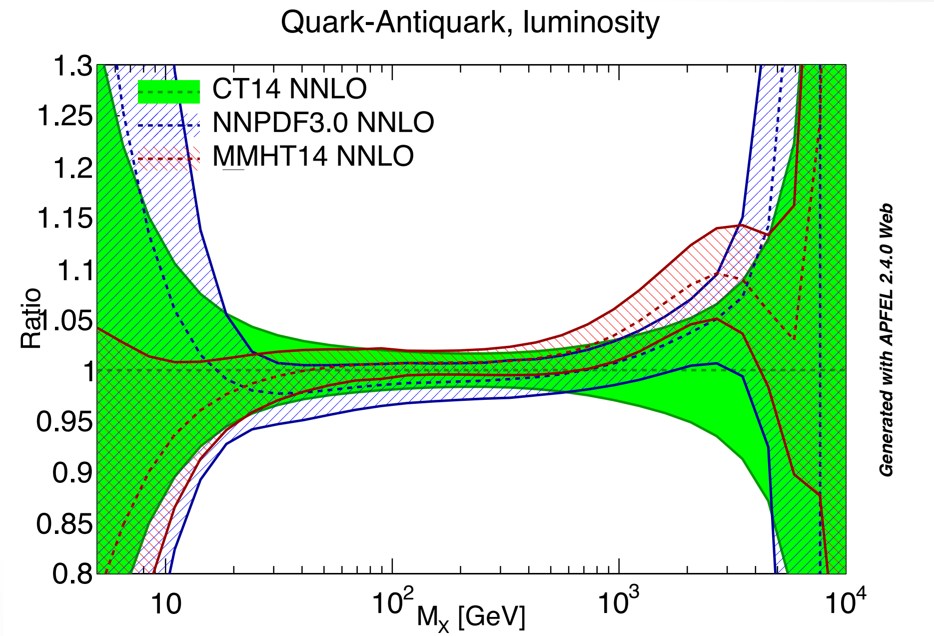


# parton distribution functions

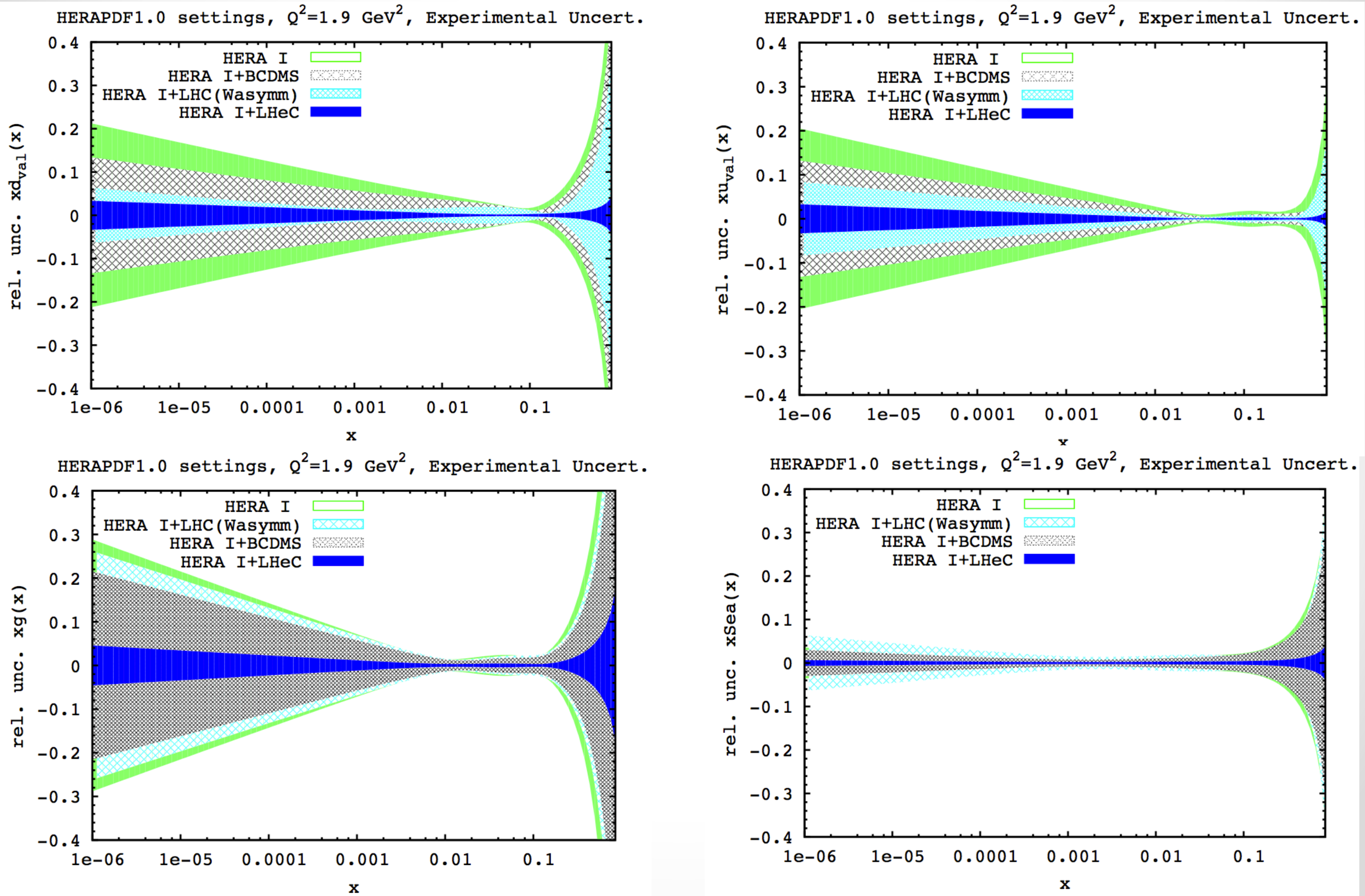



- **parton-parton luminosities @ 13 TeV**



# PDFs at low x



HERAPDF1.0 settings, Q^2=1.9 GeV^2, Experimental Uncert.
HERA I
HERA I+BCDMS
HERA I+LHC(Wasymm)
HERA I+LHeC
rel. unc. xd_val(x)
x
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HERA I
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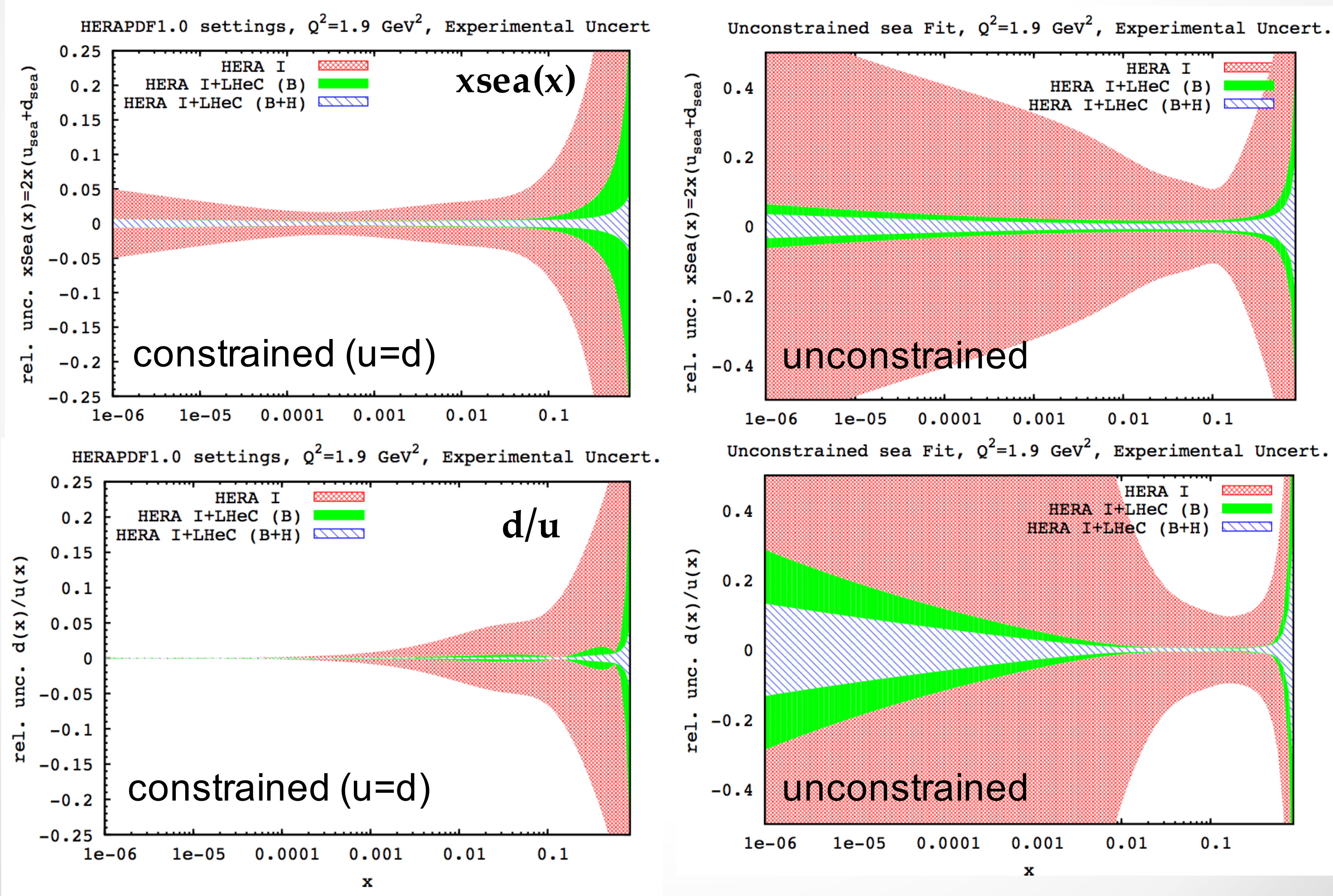
HERA I+BCDMS
HERA I+LHeC
rel. unc. xSea(x)
x

# LHeC PDFs with released assumptions

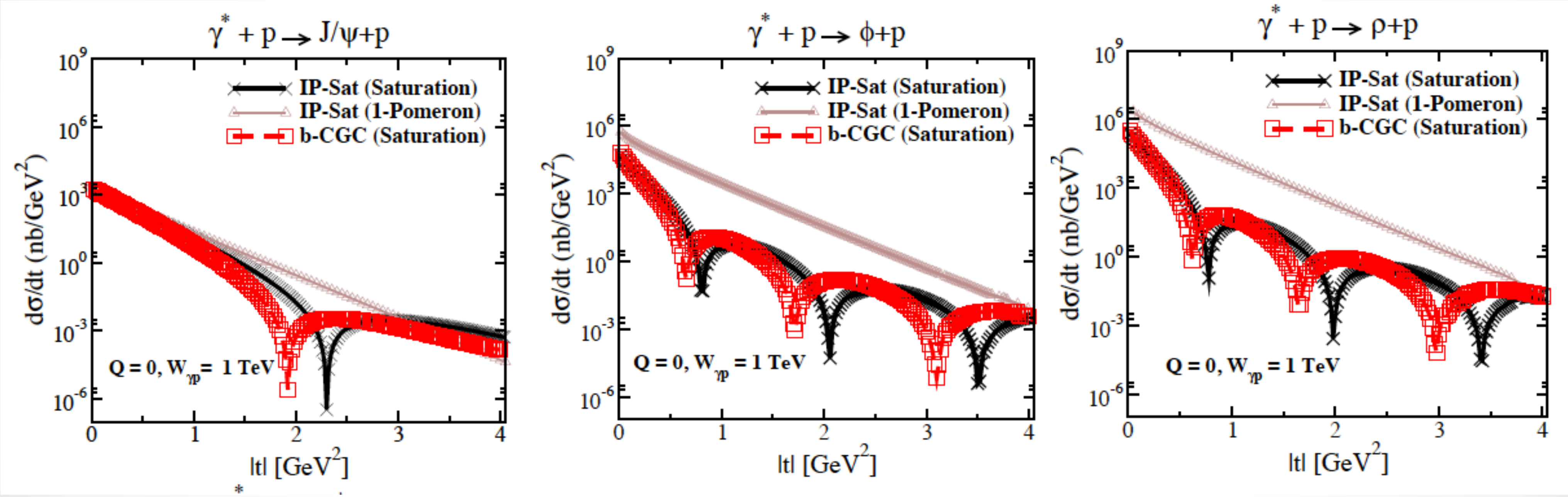
- LHeC does not need to rely on 'usual' constraint that u=d at low x, which **may not be valid**



# elastic VM production – dips in t profile

**$J/\psi$, $\phi$, $\rho$:**

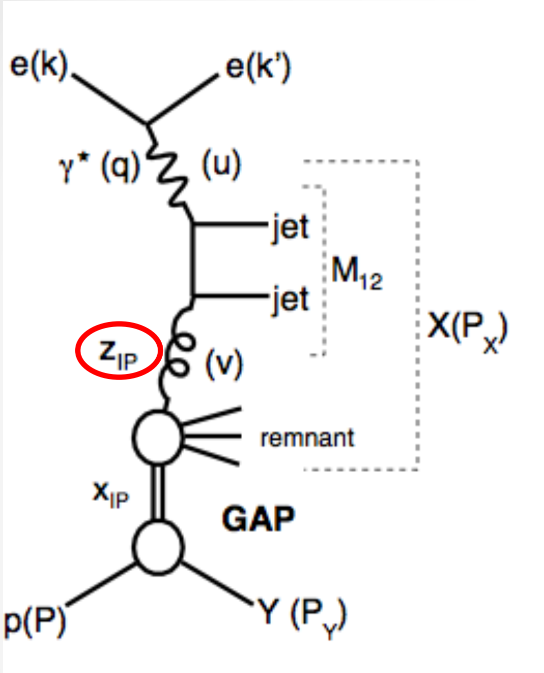
Armesto and Rezaeian (arXiv:1402.4831)




- **dips in t move to lower values for lighter vector mesons**
- possibility to test in ultra-peripheral collisions at the LHC?

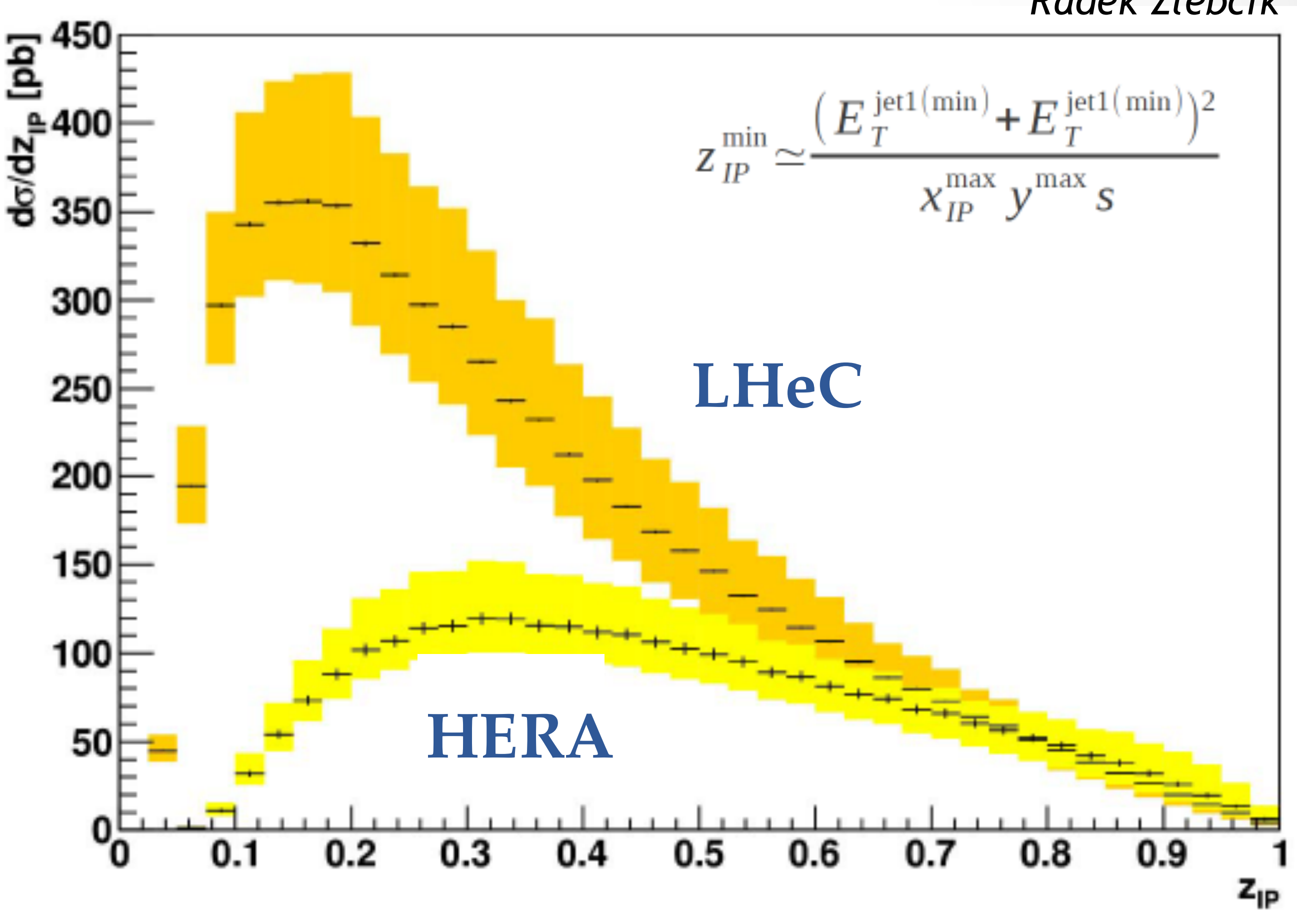
# diffractive dijet production in DIS

- diffractive dijet and open heavy flavour production offer possibilities for:
  - checking factorisation in hard diffraction
  - constraining diffractive PDFs (DPDFs)




**LHeC**: access to smaller $z_{IP}$; sensitive to gluon part of diffractive PDF (only weakly constrained with inclusive data)

Radek Zlebcik




$$z_{IP}^{min} \simeq \frac{\left(E_T^{jet1(min)} + E_T^{jet1(min)}\right)^2}{x_{IP}^{max}\, y^{max}\, s}$$

(HERA: $z_{IP}$ ~ 0.07; LHeC: $z_{IP}$ ~ 0.02)

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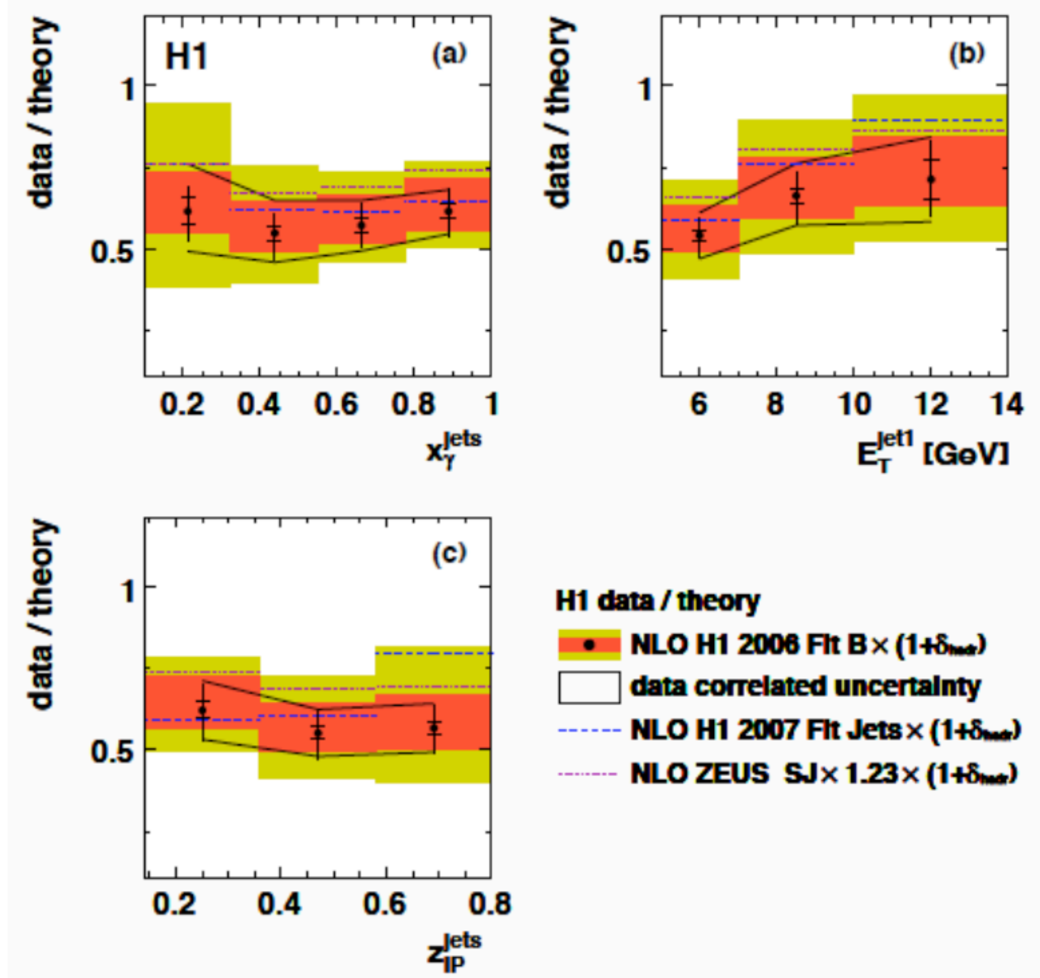
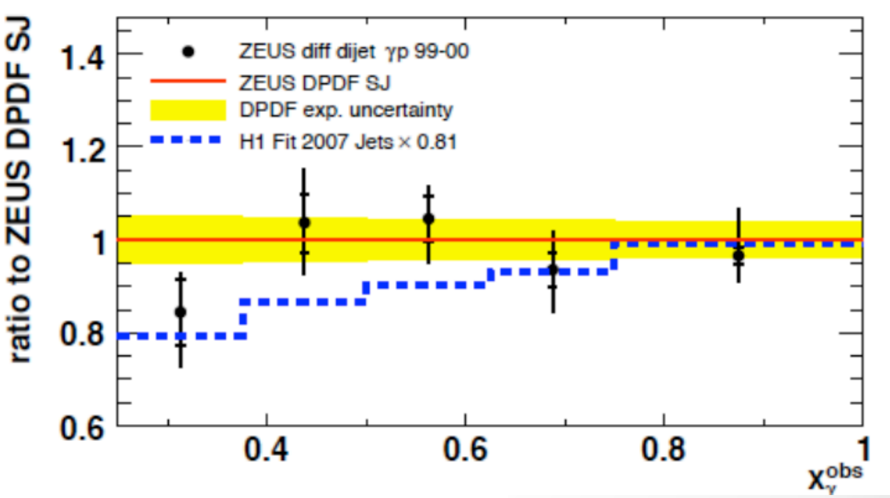



HERA measurements

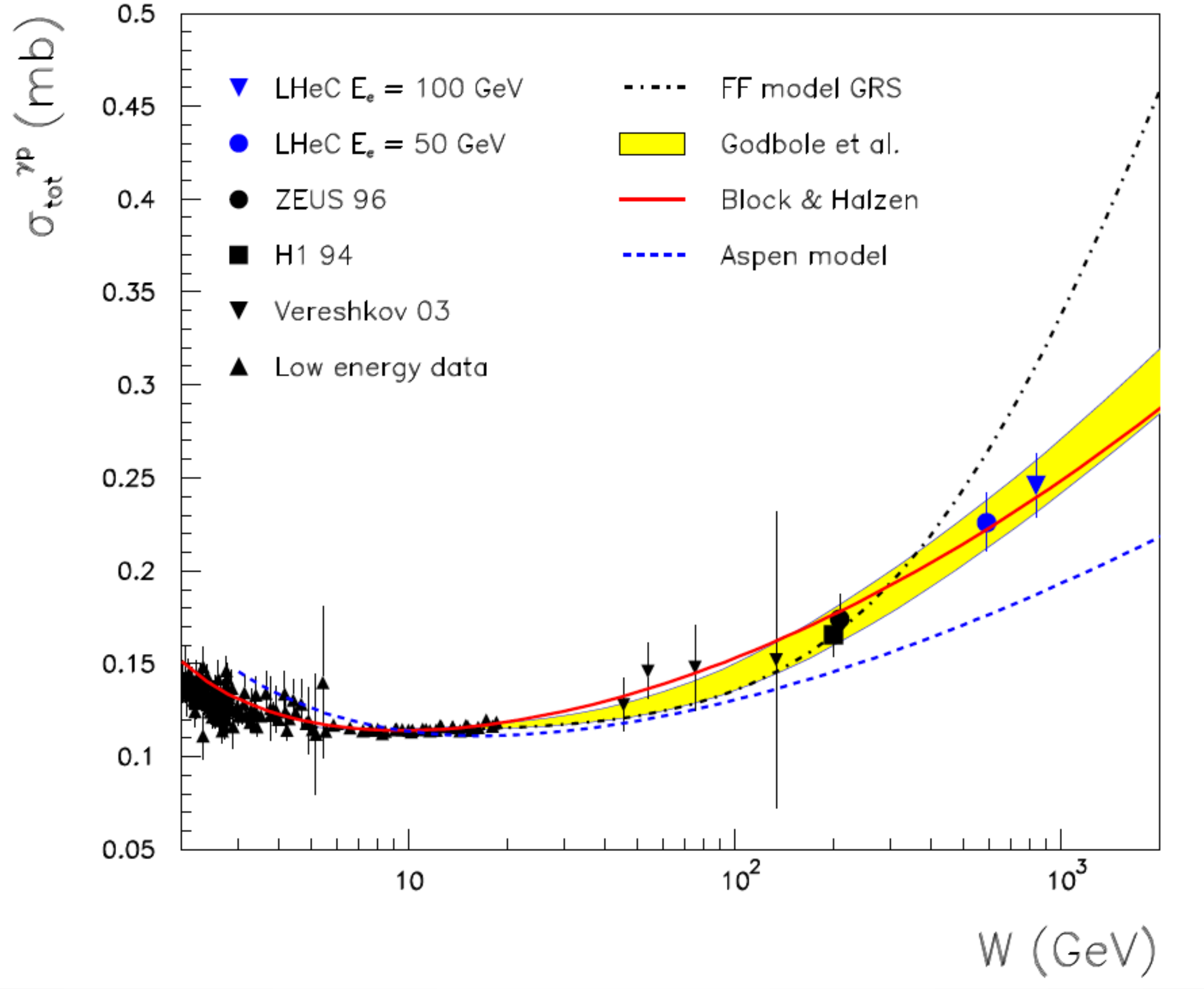



- **H1**: observes suppression, but independent of x**Y**
- **ZEUS**: consistent with no suppression (except in lowest x**Y** bin)

(measurements are in slightly different phase space)

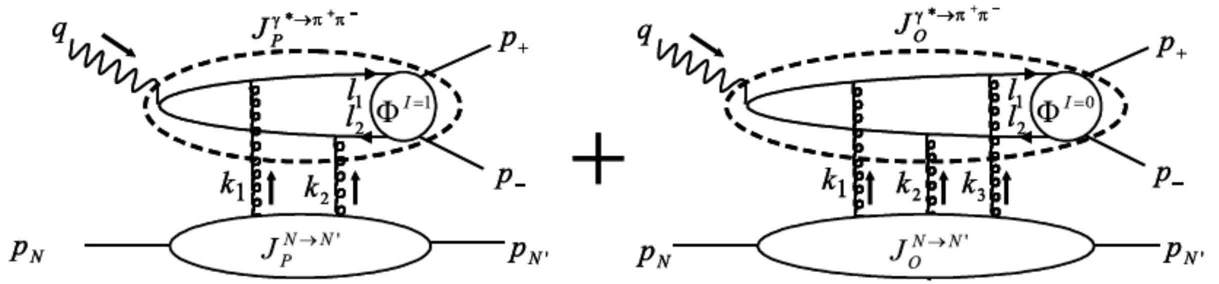
# photoproduction cross section

- small angle electron detector 62m from the interaction point: $Q^2 < 0.01$ GeV, $y \sim 0.3 \Rightarrow W \sim 0.5 \sqrt{s}$
- substantial enlargement of lever arm in W



# odderon

- **odderon**: C-odd exchange contributing to particle-antiparticle difference in cross section, searched for in: $\gamma^{(\star)}p \to Cp$, where $C = \pi^0, \eta, \eta', \eta_c \ldots$ or through odderon-pomeron interference



$$A(Q^2,t,m_{2\pi}^2) = \frac{\int \cos\theta \, d\sigma(W^2,Q^2,t,m_{2\pi}^2,\theta)}{\int d\sigma(W^2,Q^2,t,m_{2\pi}^2,\theta)} = \frac{\int_{-1}^{1} \cos\theta \, d\cos\theta \, 2\,\mathrm{Re}\left[\mathcal{M}_P^{\gamma_L^*}(\mathcal{M}_O^{\gamma_L^*})^*\right]}{\int_{-1}^{1} d\cos\theta \left[|\mathcal{M}_P^{\gamma_L^*}|^2 + |\mathcal{M}_O^{\gamma_L^*}|^2\right]}$$

expect sizeable charge asymmetry