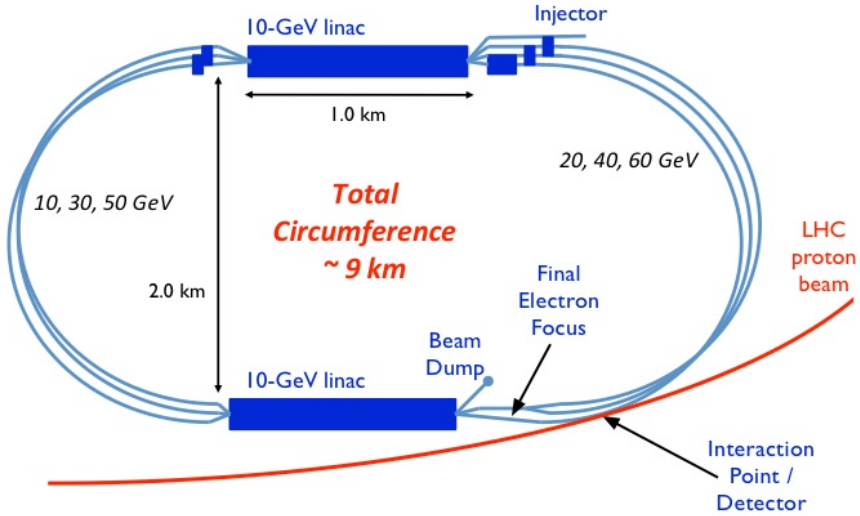
Low x Physics and Saturation: From HERA to Future DIS and the LHeC

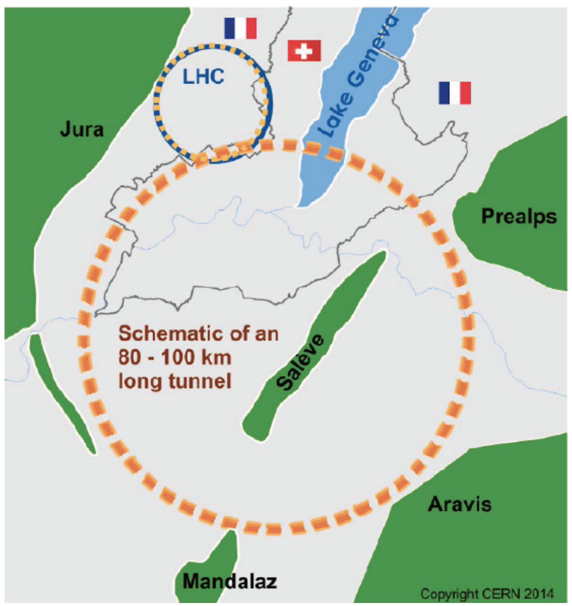
Paul Newman
Birmingham University



LHeC FCC hh ee he

Saturation: Recent Developments, New Ideas and Measurements

RIKEN BNL Research Center Workshop
April 26-28, 2017 at Brookhaven National Laboratory



Low x Physics at HERA: the "Pathological" Gluon

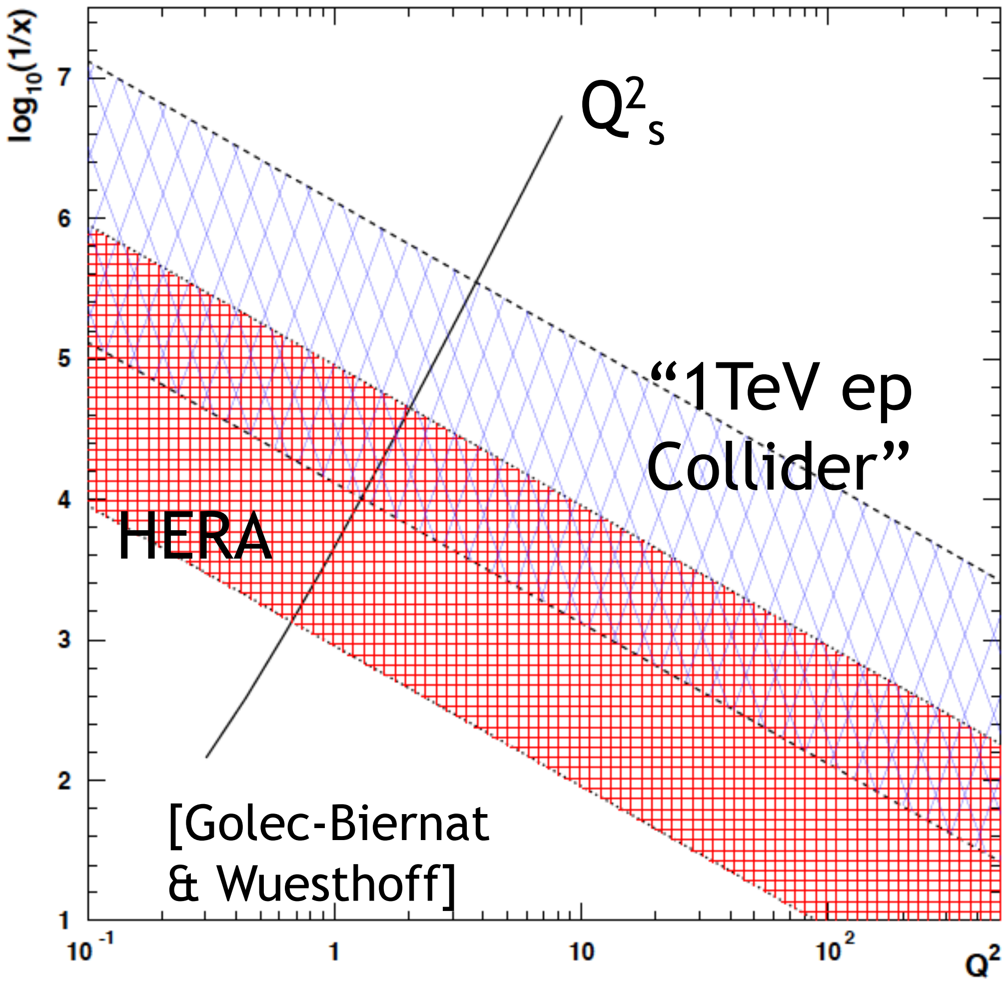
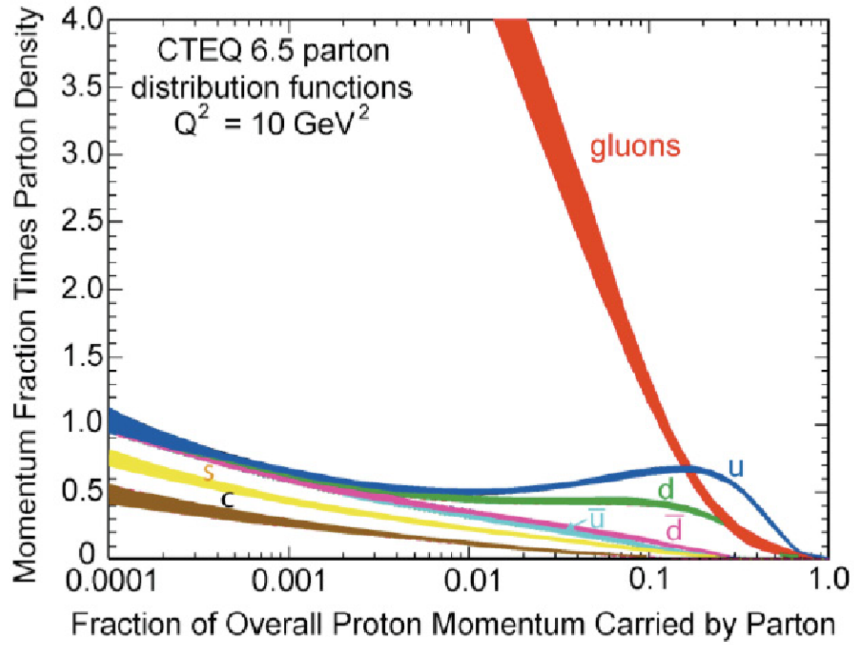


Figure 5: The position of the critical line in the (x, Q^2)-plane. The narrow hatched area corresponds to the acceptance region of HERA. The wide hatched region indicates the range for a future 1 TeV ep-collider. The boundaries are lines of constant y.

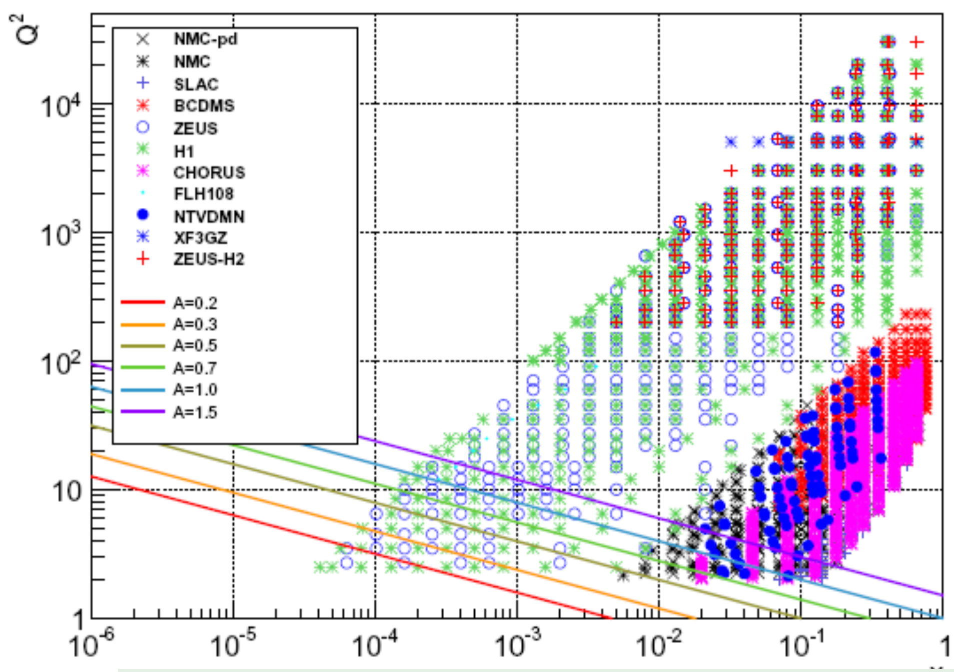


1998: Low x HERA data are well fitted in (dipole) models that include saturation effects
- x dependent "saturation scale", $Q^2_s(x)$

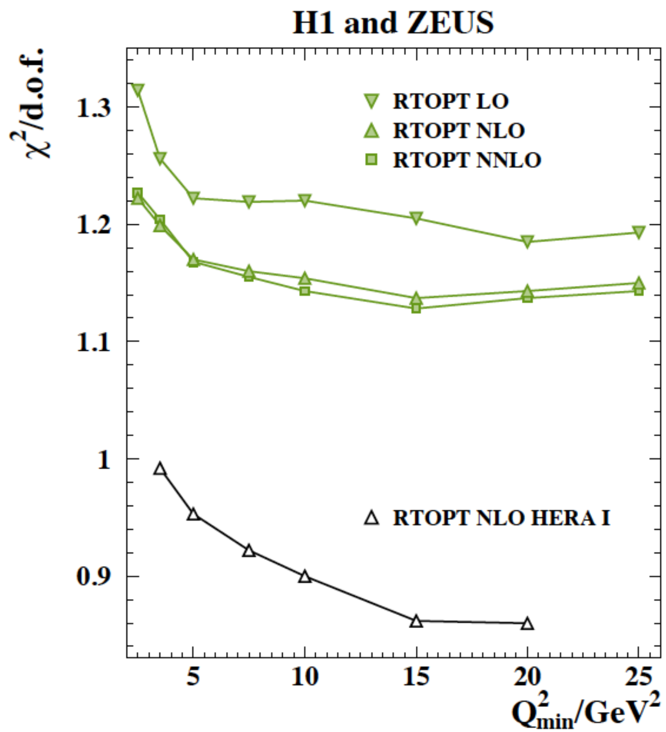
$$\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{\sim -0.3}$$

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



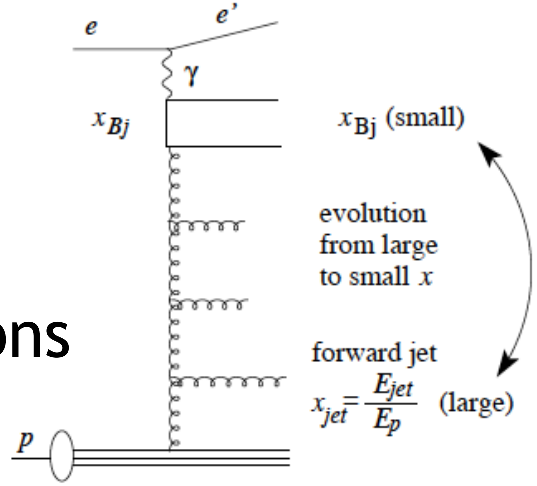
Final HERA-2 Combined PDF Paper:
"some tension in fit between low & medium Q^2 data… not attributable to particular x region" (though kinematic correlation)

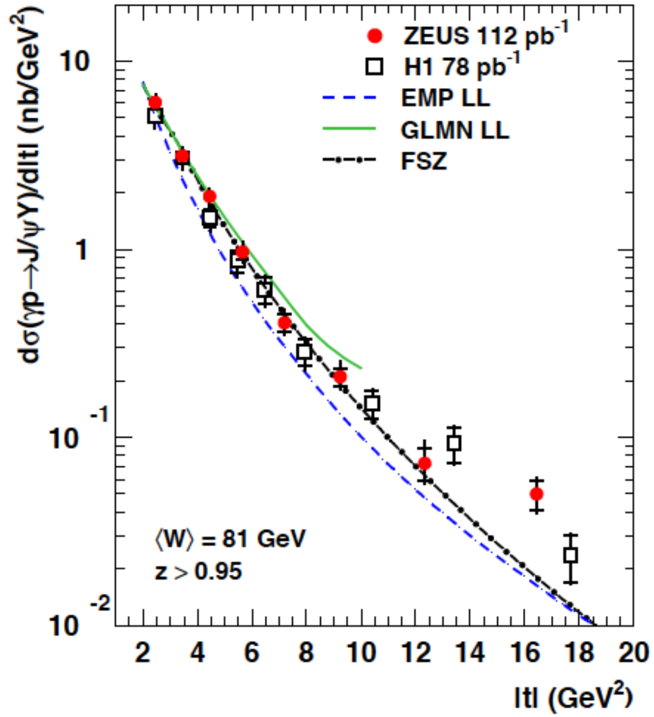
… something happens, but interpretation?

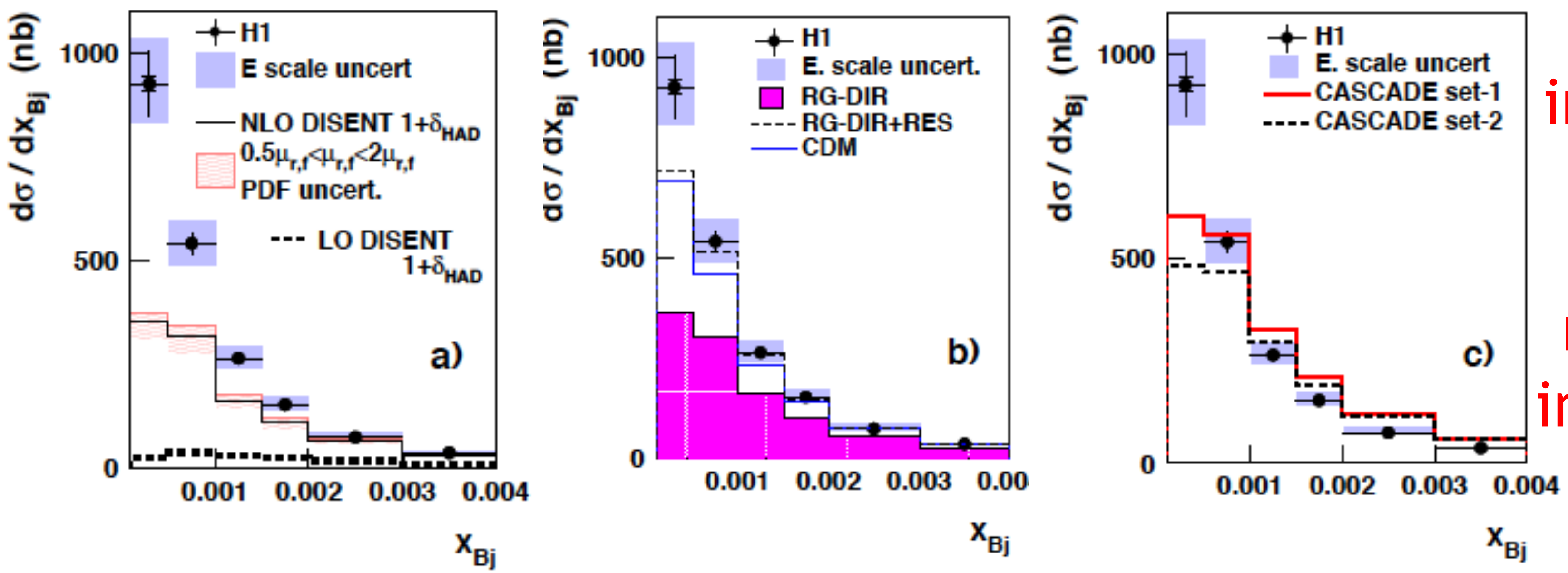
Hadronic Final State Observables

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

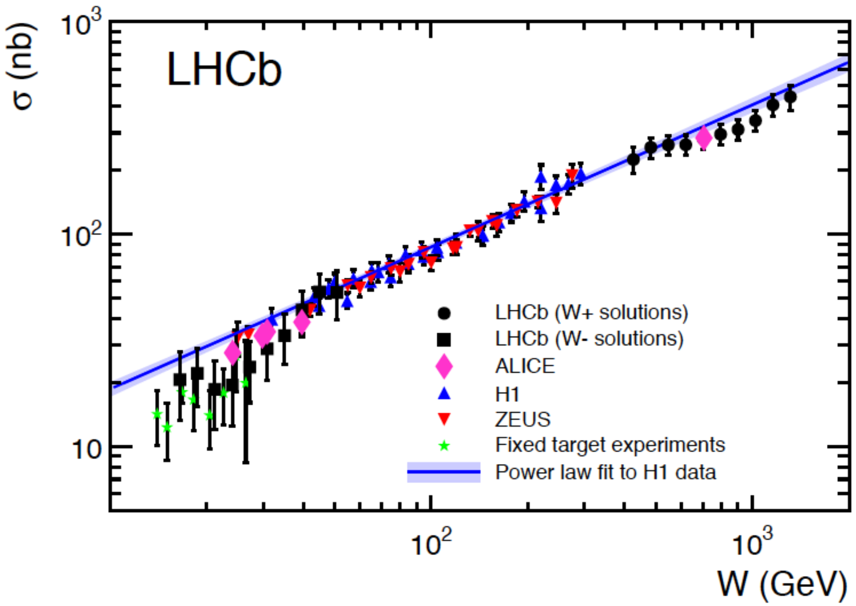
- Forward jets
- Azimuthal decorrelations
- High |t| p-diss J/Ψ…



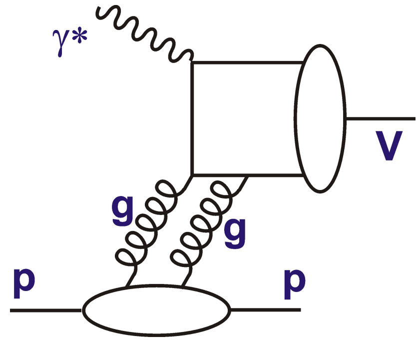




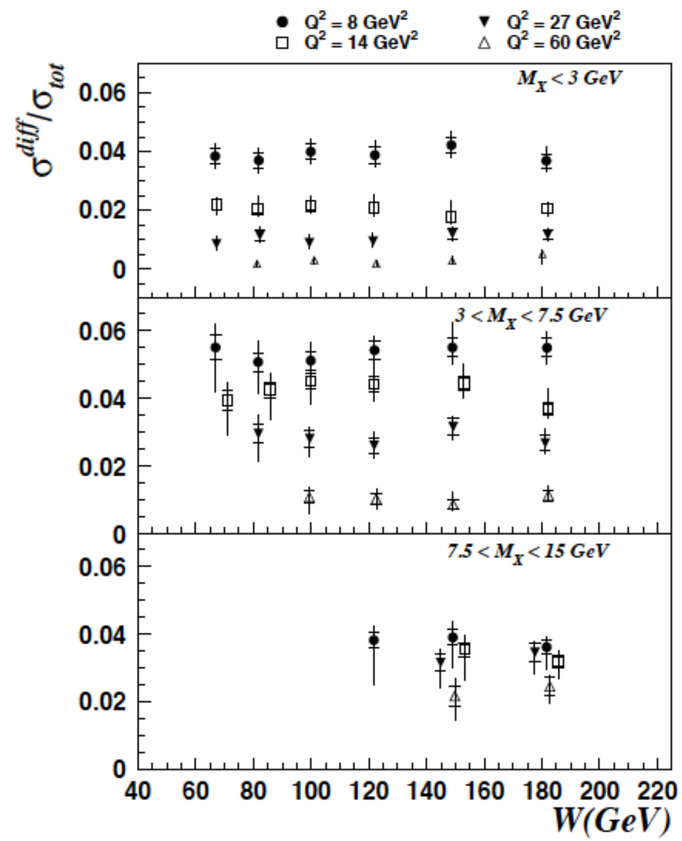
Some interesting effects … not easily interpreted



Low x Saturation in Diffractive Data?



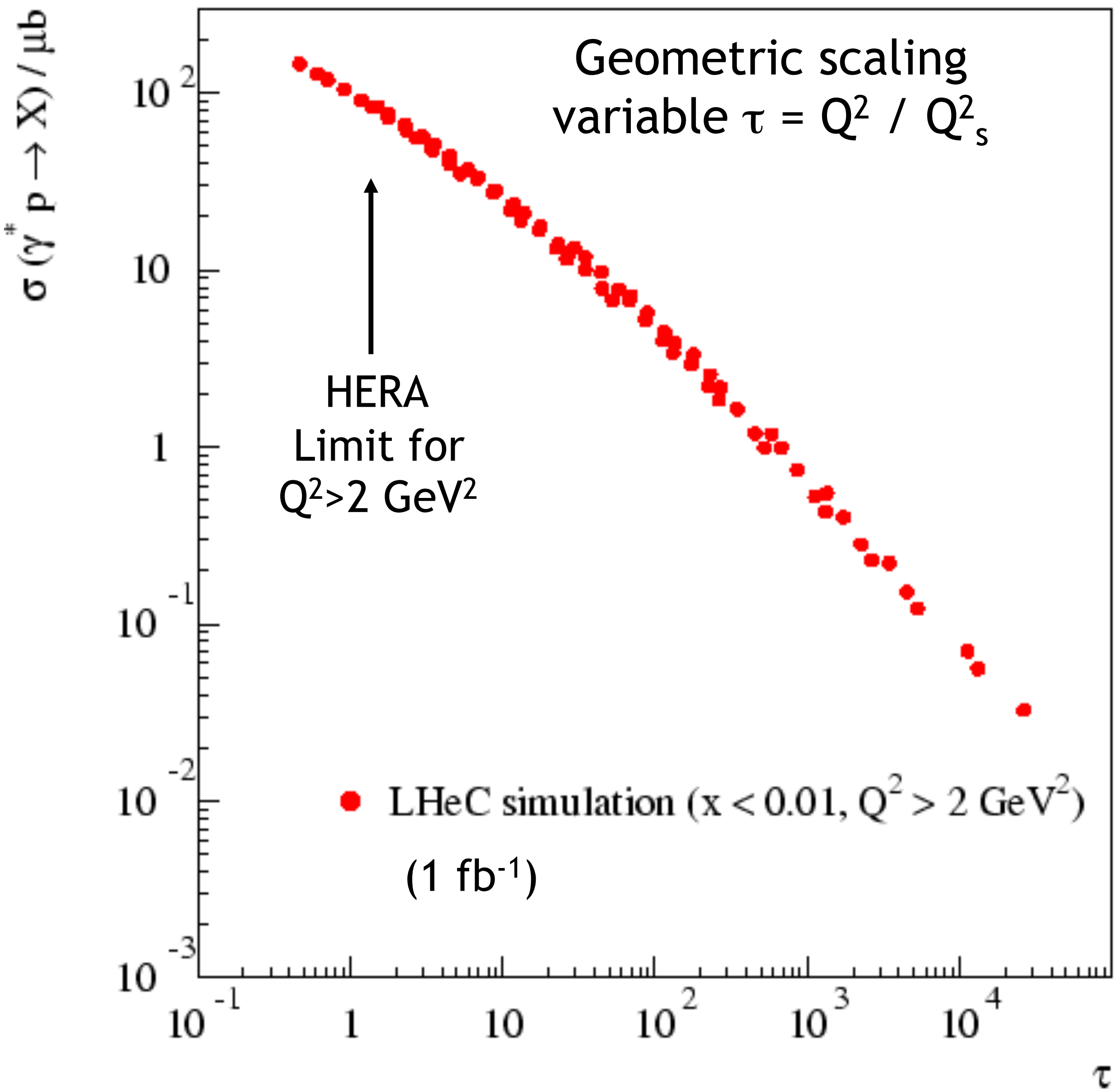
- **Elastic J/Ψ in γp …**
- No evidence for change in shape at high W (i.e. low x), even at LHC (t dependence yet to be exploited)



- **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



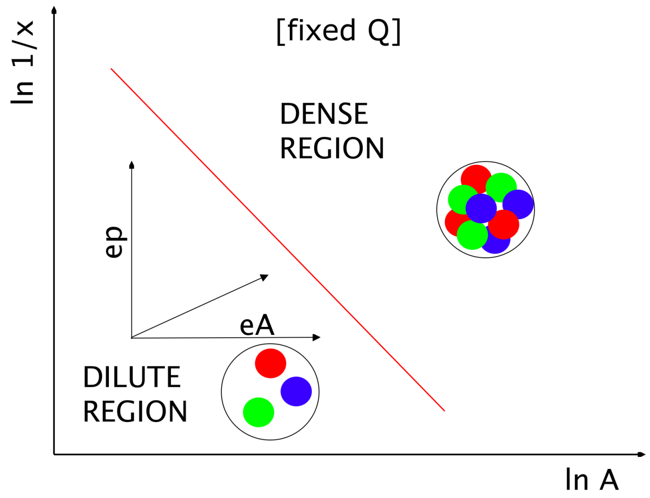
… HERA had very limited aceptance for $\tau<1$ … **saturation effects depend mainly on data with $0.045 < Q^2 < 1$ GeV^2**

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

Can also be enhanced with nuclei.

Accessing saturation region at large Q^2

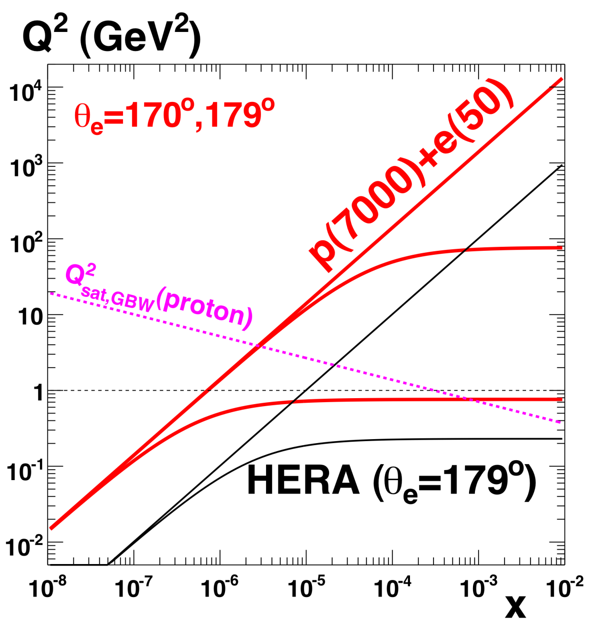
2-pronged approach: EIC and LHeC

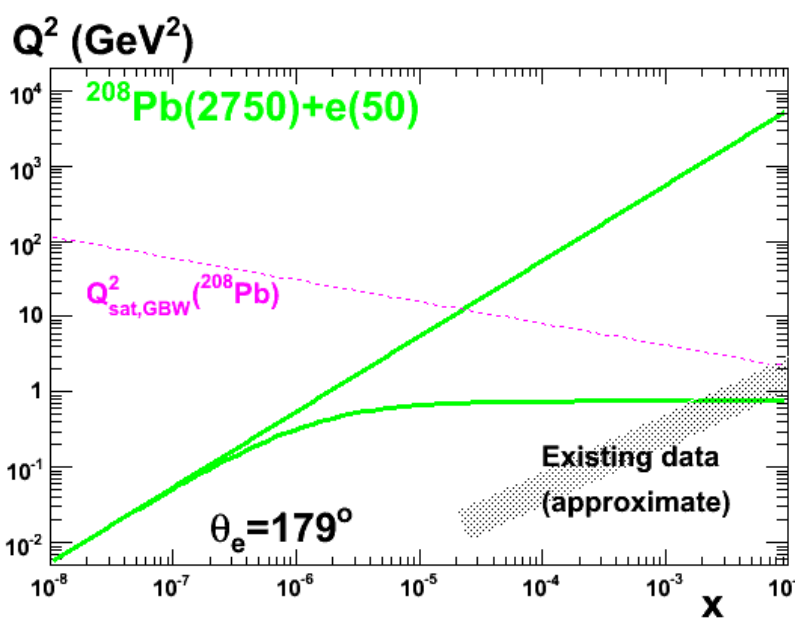


Enhance target `blackness' by:

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

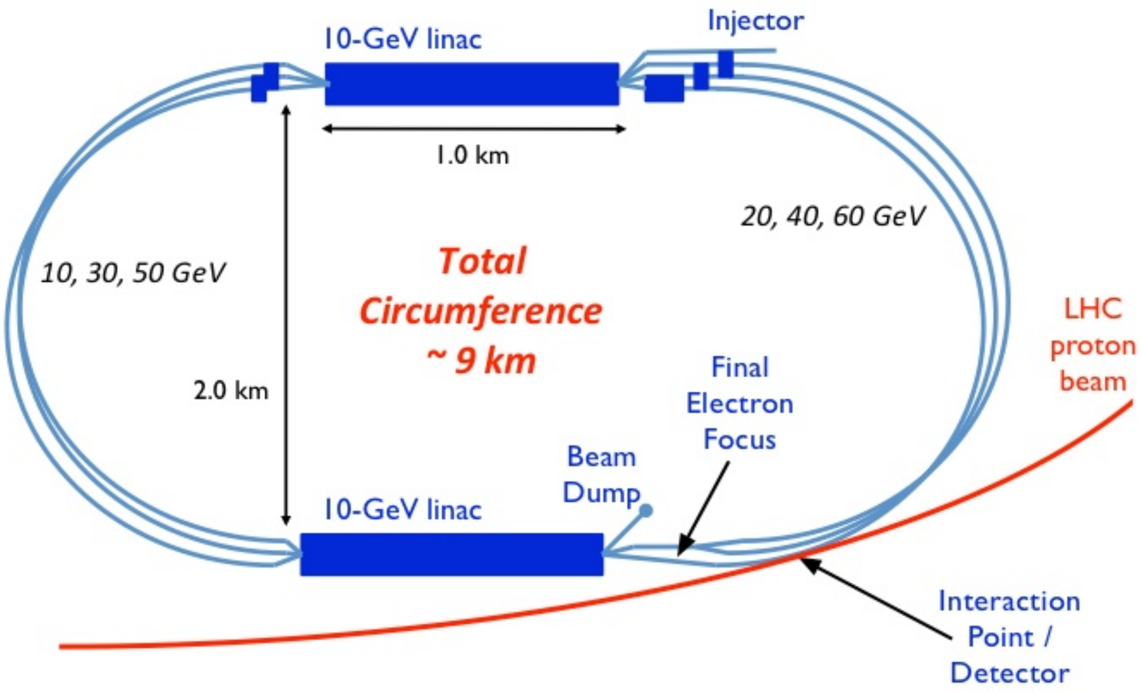
Baseline Design (Electron "Linac")

- 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]

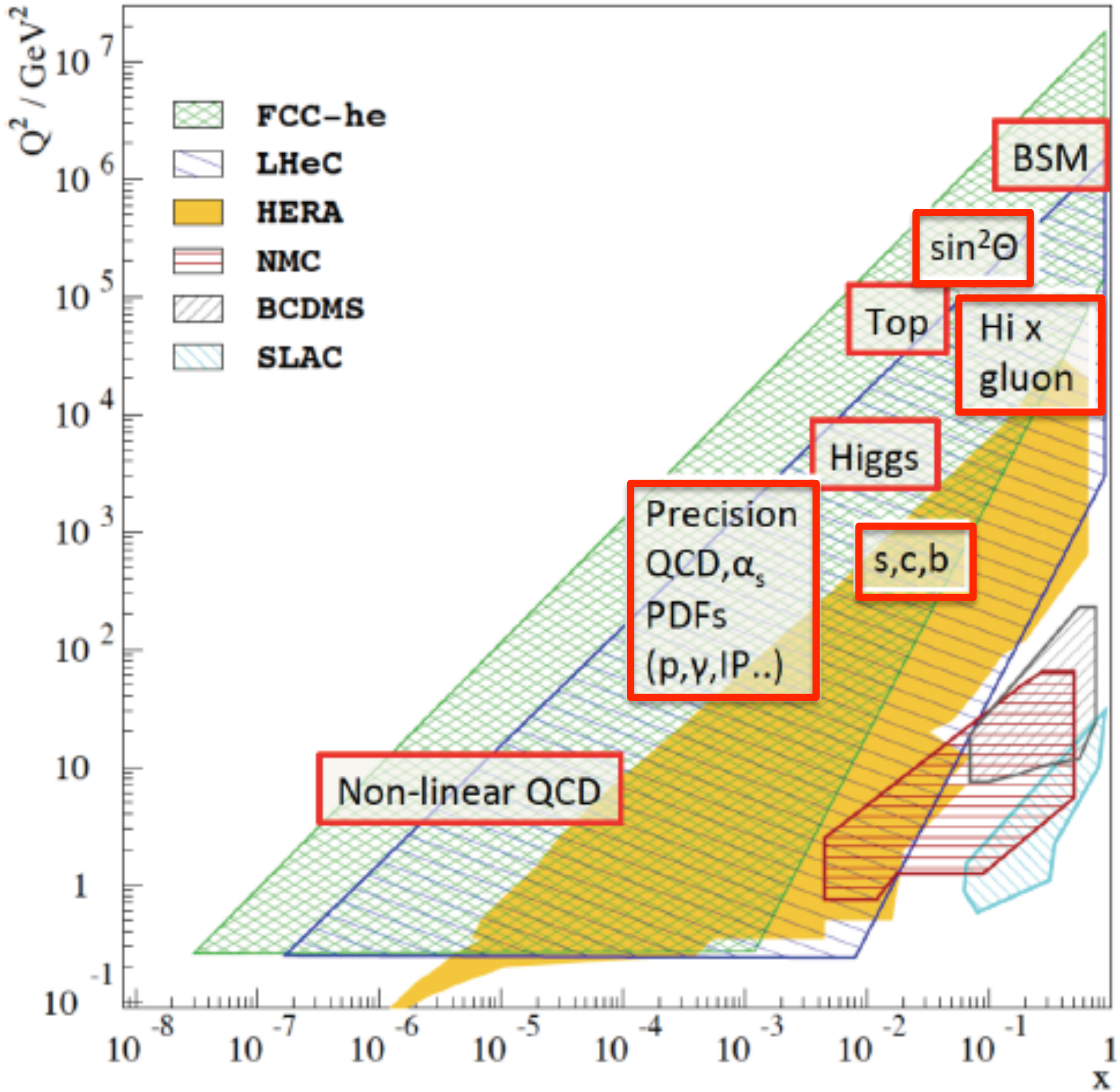


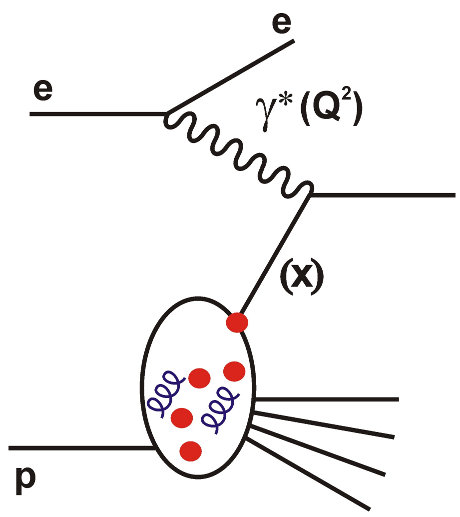
- ep lumi → 10^{34} cm^{-2} s^{-1}

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

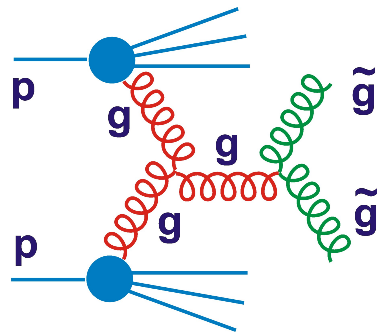
- **eD and eA collisions have always been integral to programme**
- **e-nucleon Lumi estimates ~ 10^{31} (10^{32}) cm^{-2} s^{-1} for eD (ePb)**

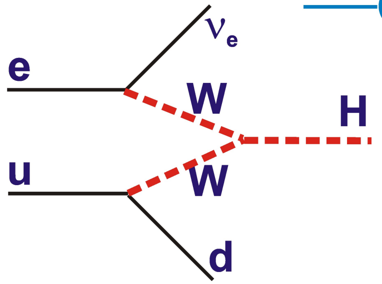
LHeC Physics at 10^{34} $cm^{-2}s^{-1}$





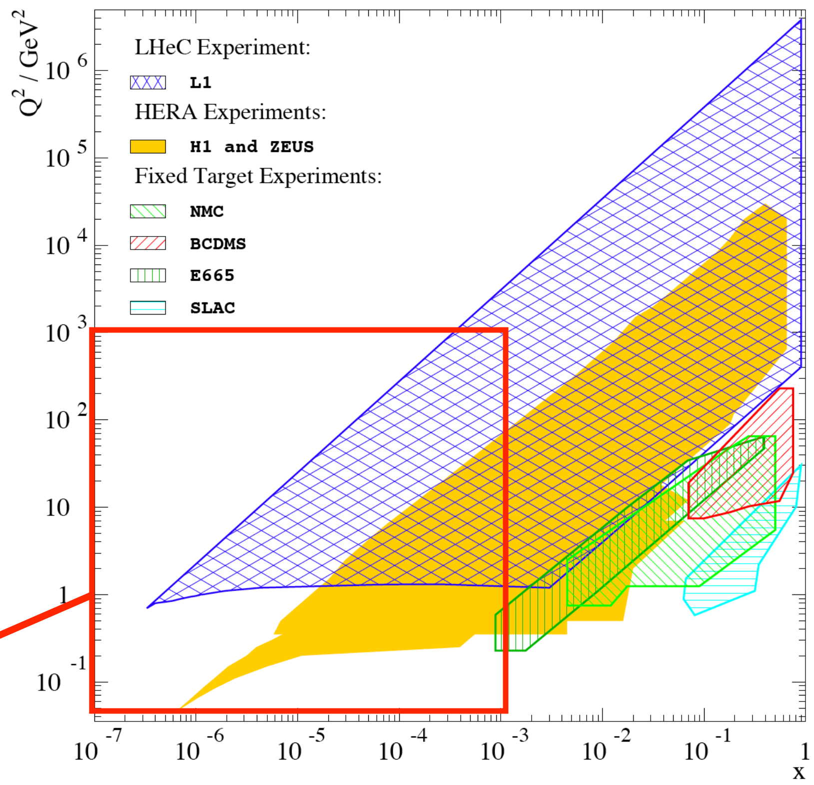
Diverse physics goals require precision throughout wide accessible kinematic region.

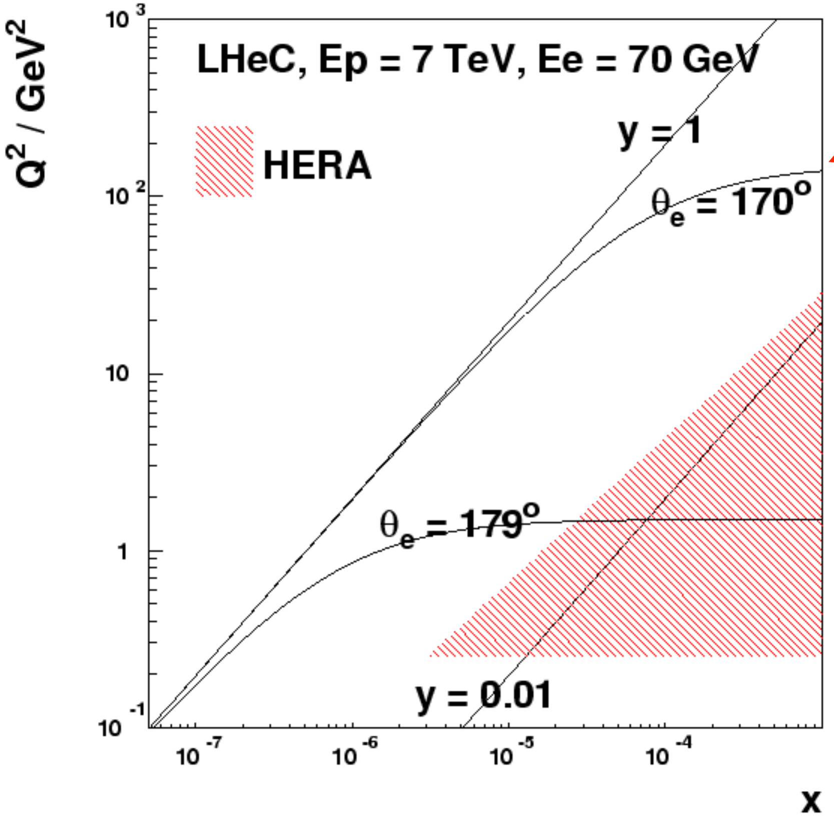




LHeC Kinematic Detector Requirements

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



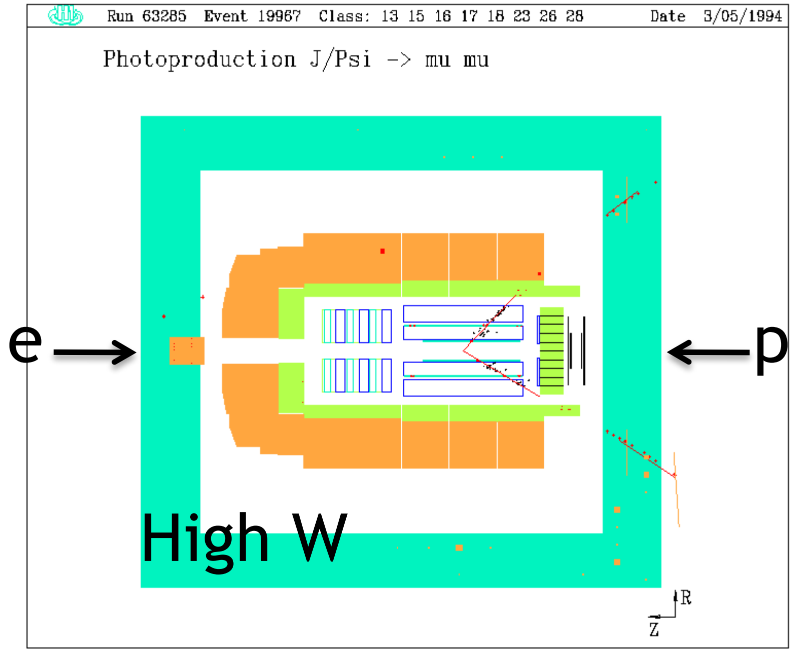


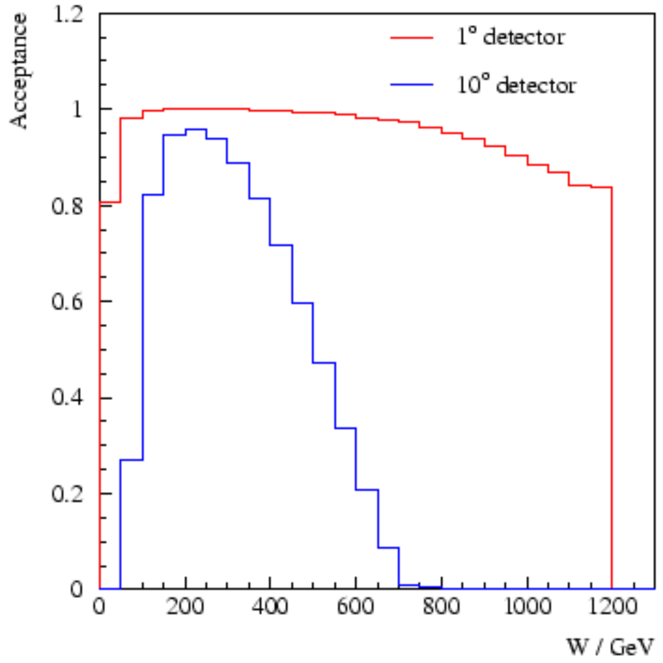
Also need 1° acceptance in proton direction to contain hadrons for kinematic reconstruction, Mueller-Navelet jets, maximise acceptance for new massive particles …

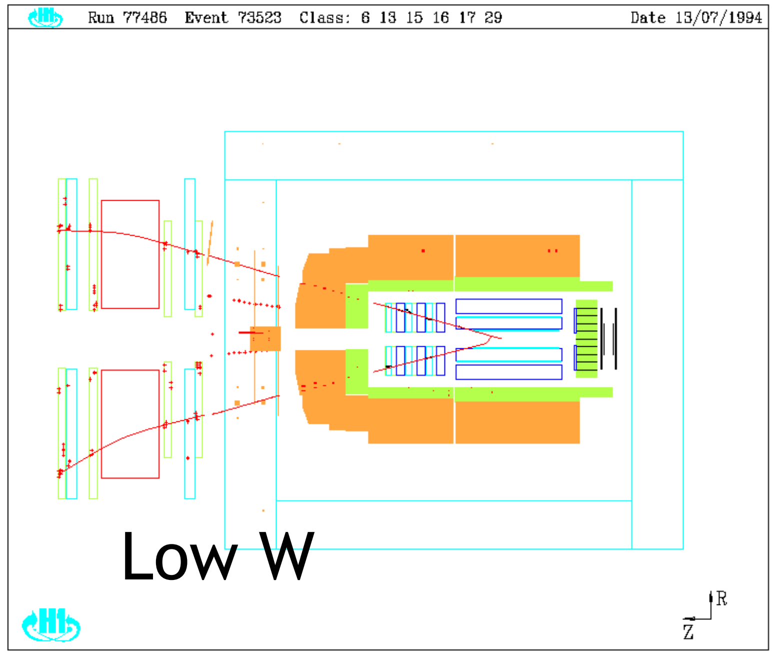
Elastic J/Ψ Kinematics

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

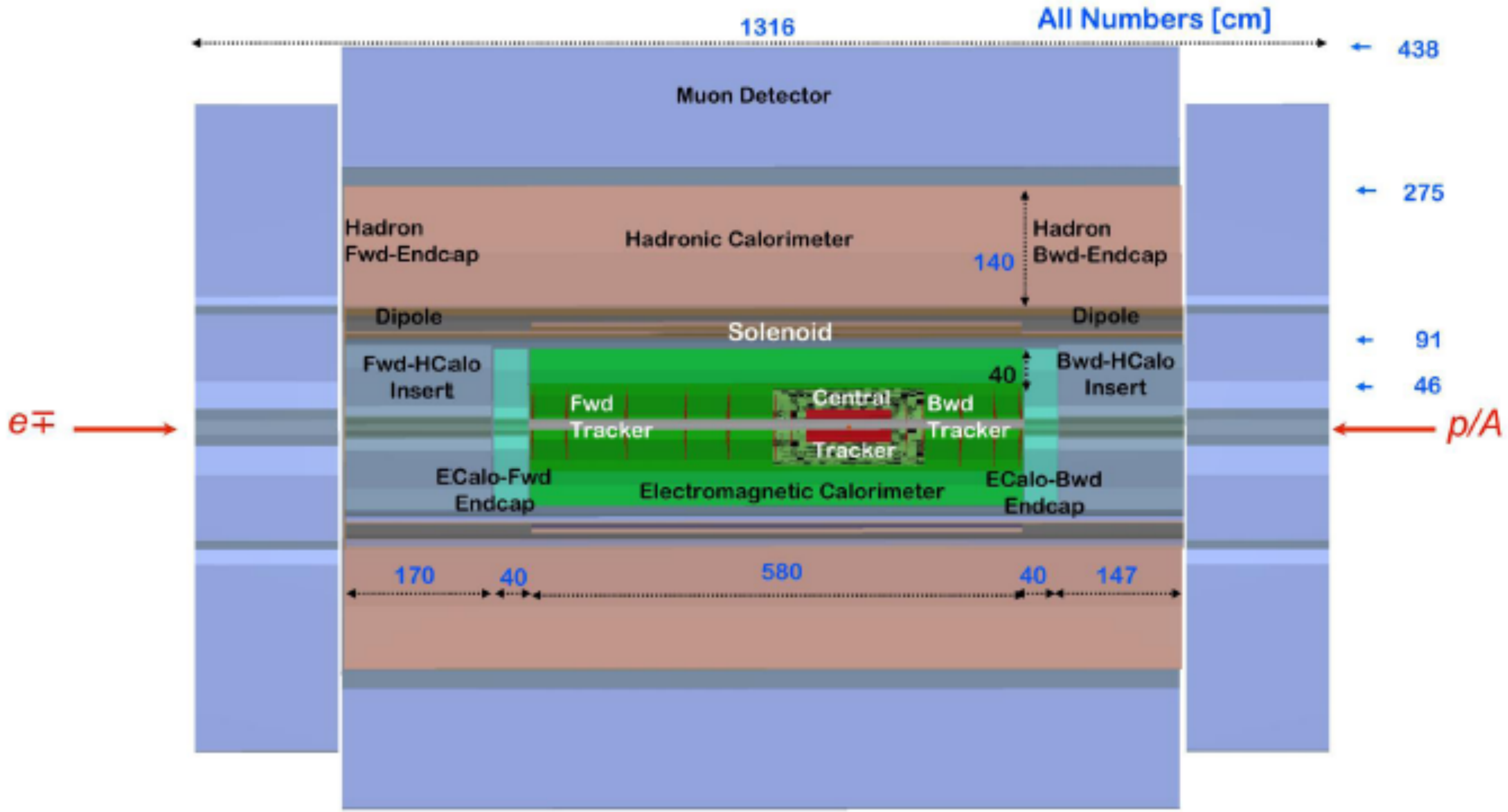
- To access highest W, acceptance in outgoing electron beam direction crucial





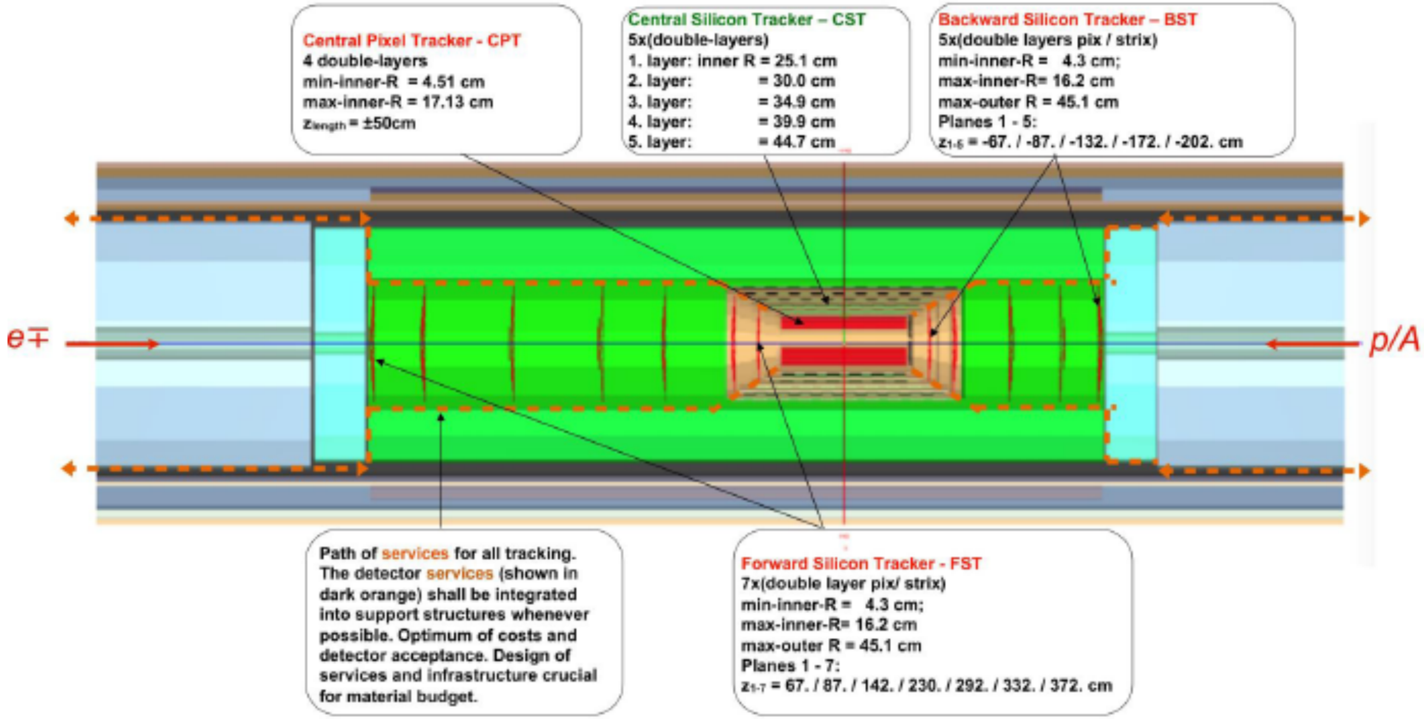


LHeC Detector Design Overview



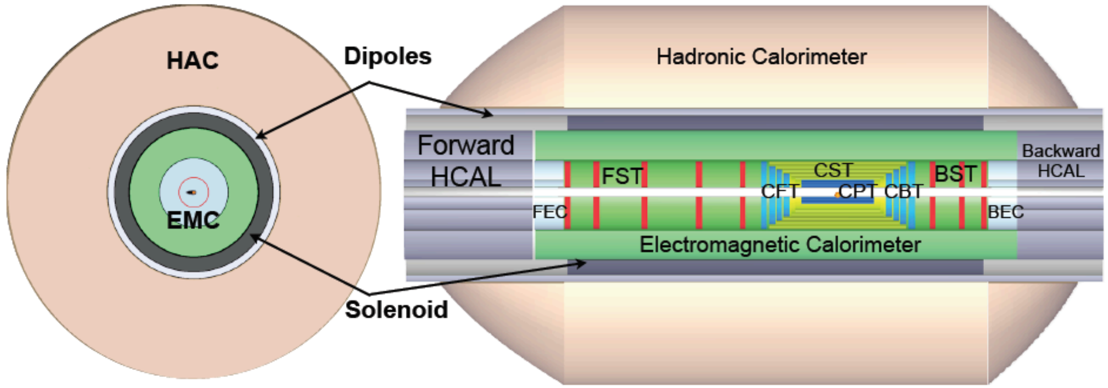
- Present size 13m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)
- Forward / backward asymmetry reflecting beam energies
- Demanding tracking → high fraction of pixels, wide acceptance

Detector Details



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

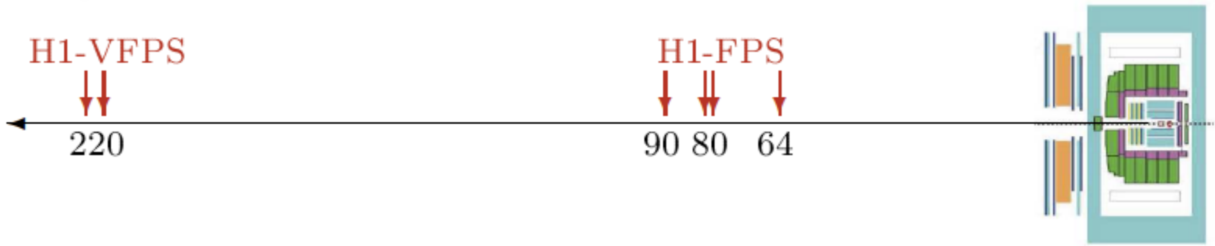
- Lar / Tile calorimeter leaning heavily on LHC experience



- Beamline insrumentation considered from outset.

Intact Proton Selection Methods beyond HERA

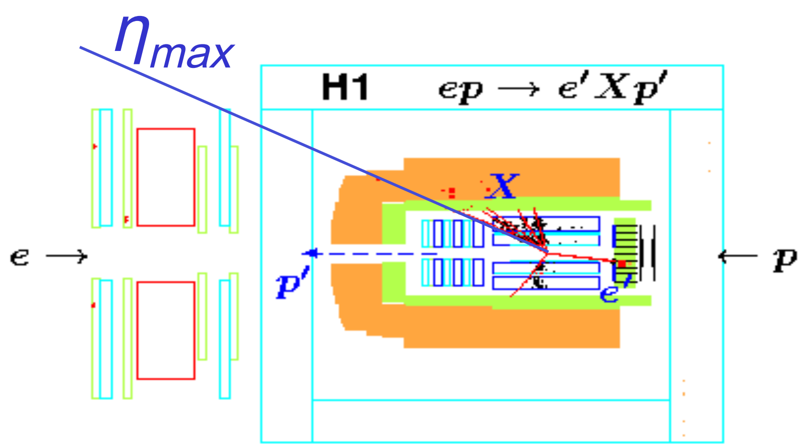
1) Measure scattered Proton in Roman Pots



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

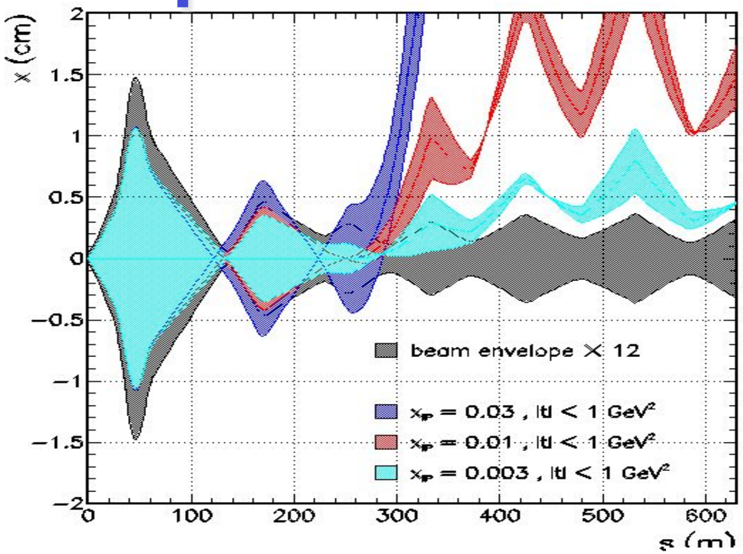
2) Select Large Rapidity Gaps

-Limited by control over proton dissociation contribution



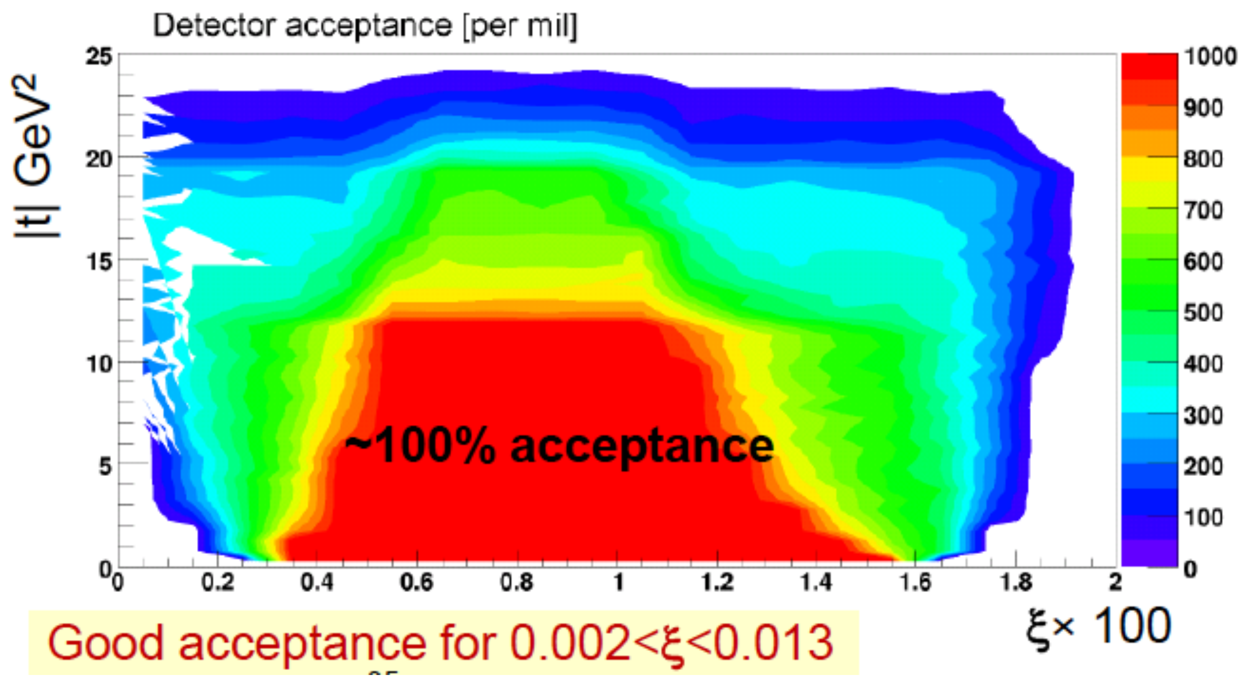
- Methods have very different systematics → complementary
- In practice, method 2 yielded lasting HERA results, because of statistical and kinematic range limitations of Roman pots
- Roman pots mainly contsrained t distributions
- **LHeC & EIC different → higher lumi + pot design from outset**

Forward Proton Spectrometer



- Proton spectrometer uses outcomes of FP420 project (proposal for low ξ Roman pots at ATLAS / CMS – not yet adopted)
-
- Approaching beam to 12σ (~250 μm) 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



(NEW) DGLAP PDF Fits to LHeC Pseudo-Data

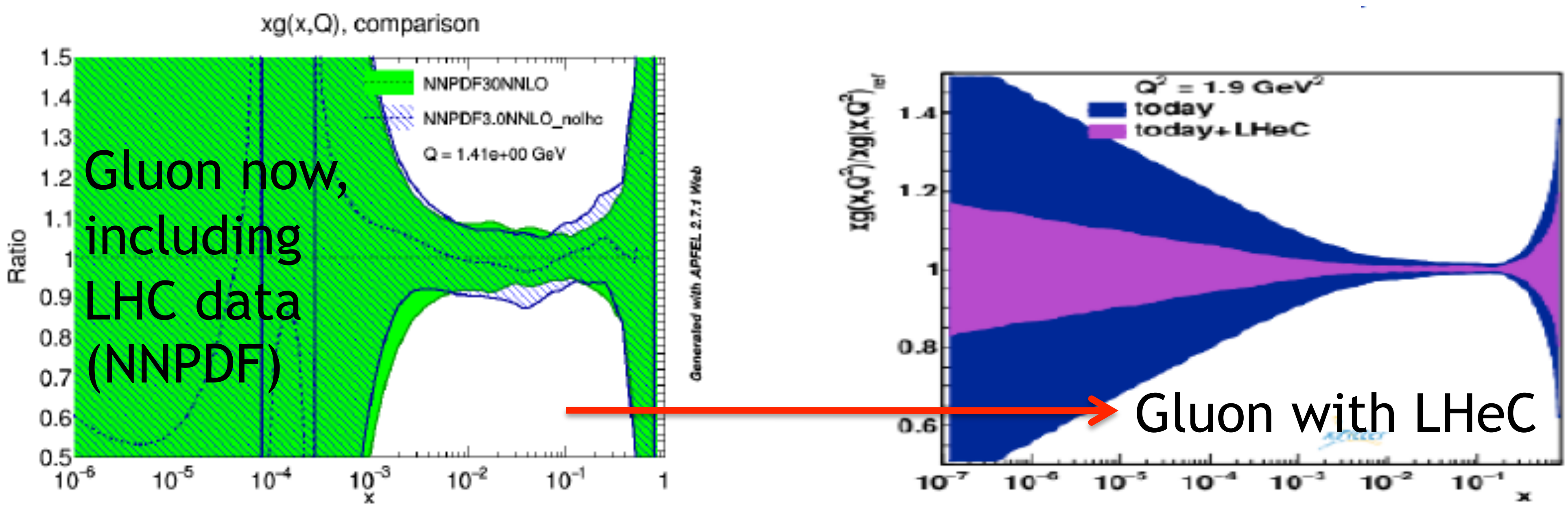
-Simulated NC, CC `pseudo-data' with reasonable assumptions on systematics (typically 2x better than H1 and ZEUS at HERA).

- 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

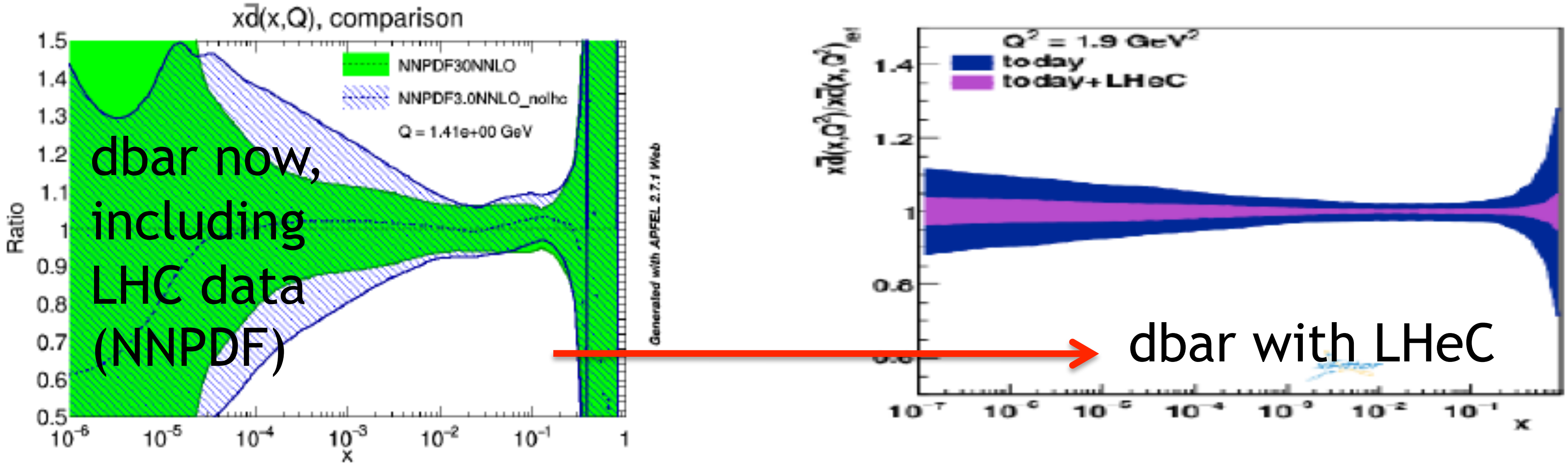
Low x Gluon with LHC, with and without LHeC



<u>**Standard LHC channels do not help much:**</u>

- 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



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
CC	60 (60)	50 (7)	−0.8	−1	1000
NC	60 (60)	50 (7)	+0.8	−1	300
CC	60 (60)	50 (7)	+0.8	−1	300
NC	60 (60)	50 (7)	0	+1	100
CC	60 (60)	50 (7)	0	+1	100
NC	20 (60)	7 (1)	0	−1	100
CC	20 (60)	7 (1)	0	−1	100

e−, neg. pol.

e−, pos. pol.

e+, unpol.

low energy

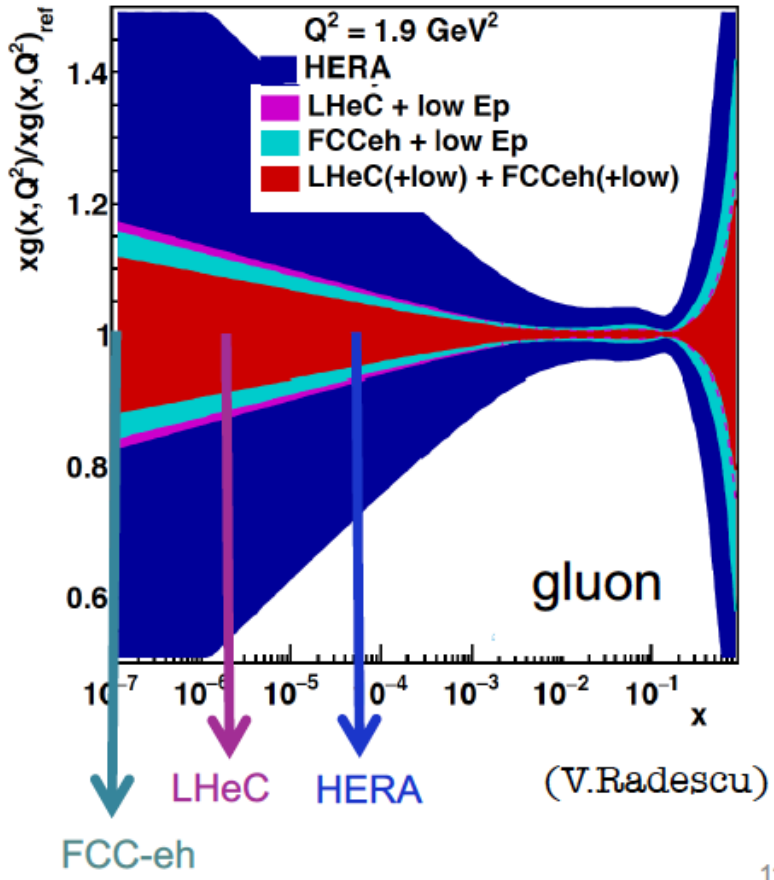
* second and third columns show FCC-eh (LHeC)

(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%

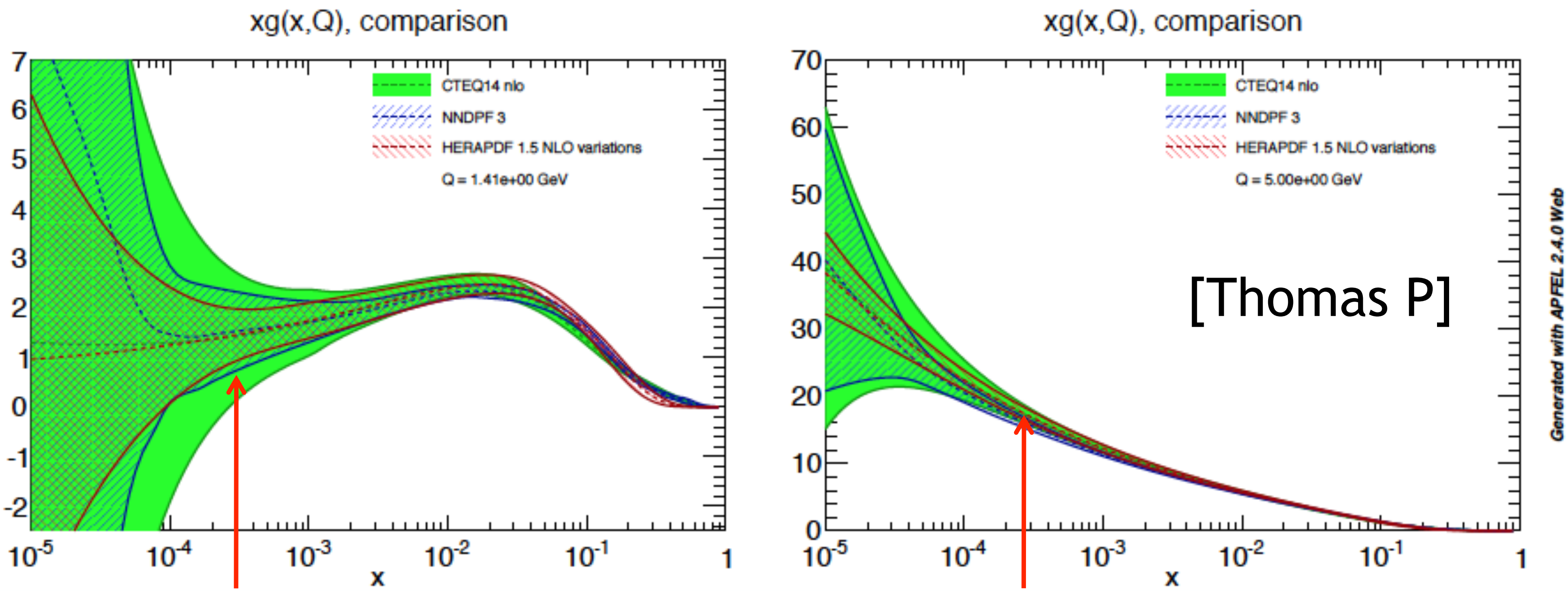
Some improvement in precision

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



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

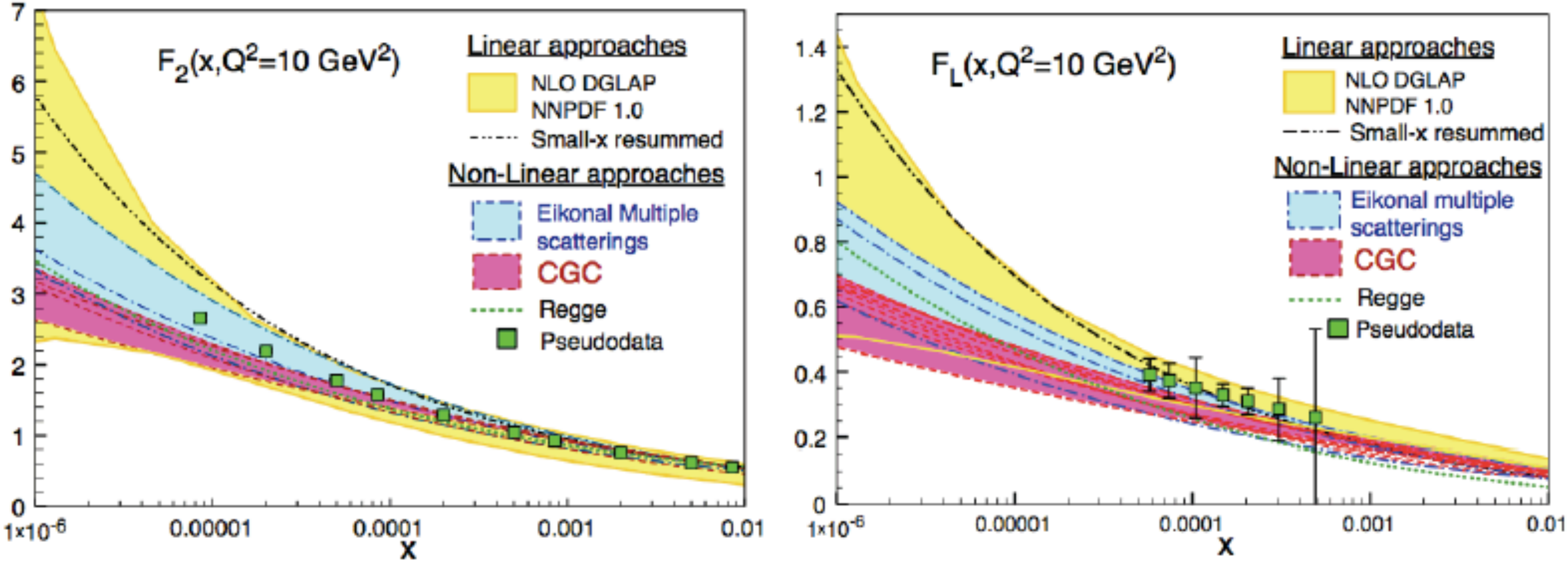
Unconstrained by data

- 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



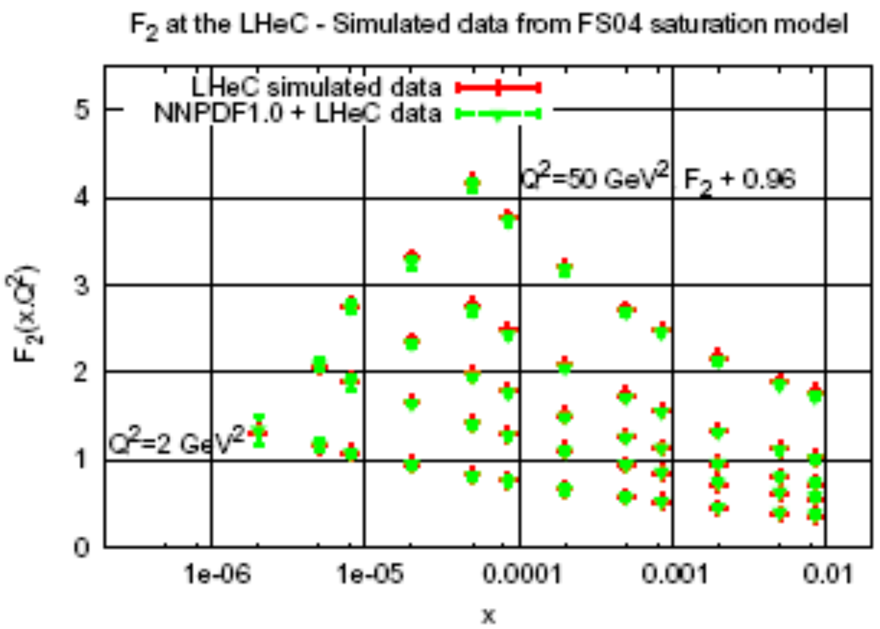
• LHeC can distinguish between different QCD-based models for the onset of non-linear dynamics

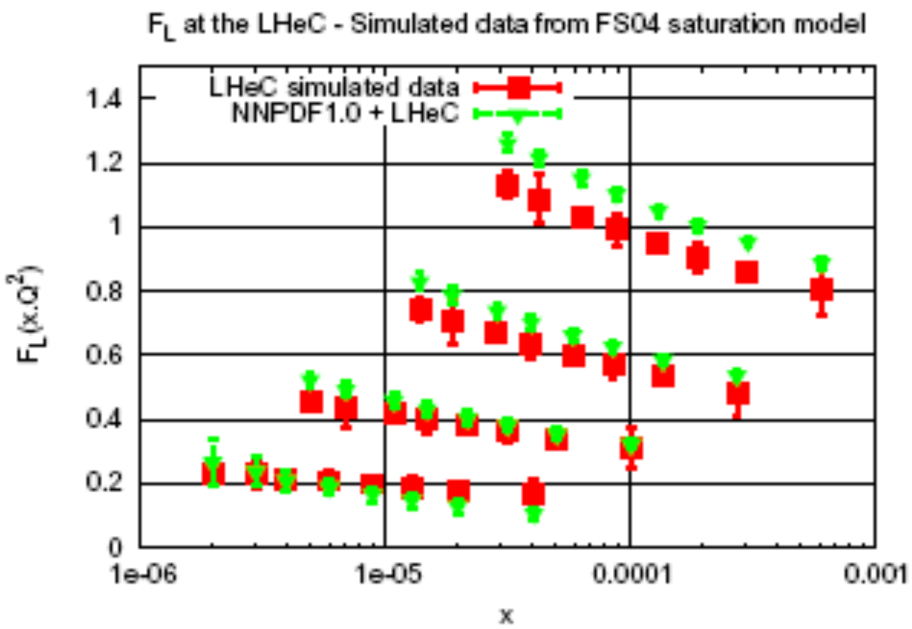
… but can sat^n effects hide in standard fit parameterisations?

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





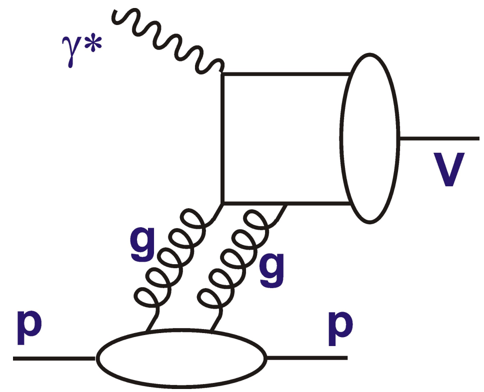
• Unambiguous observation of saturation will be based on tension between different observables e.g. F_2 v F_L in ep or F_2 in ep v eA

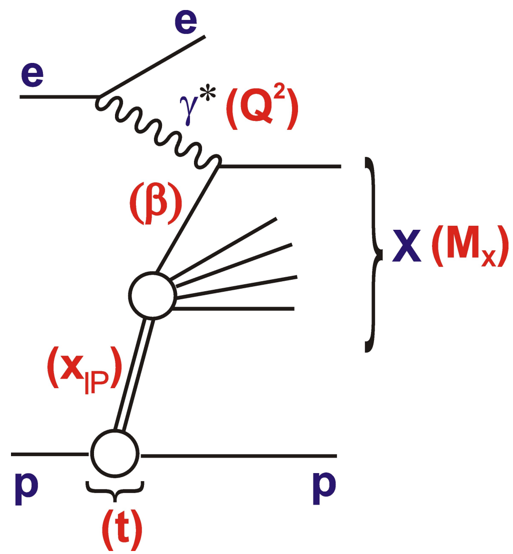
Exclusive / Diffractive Channels and Saturation

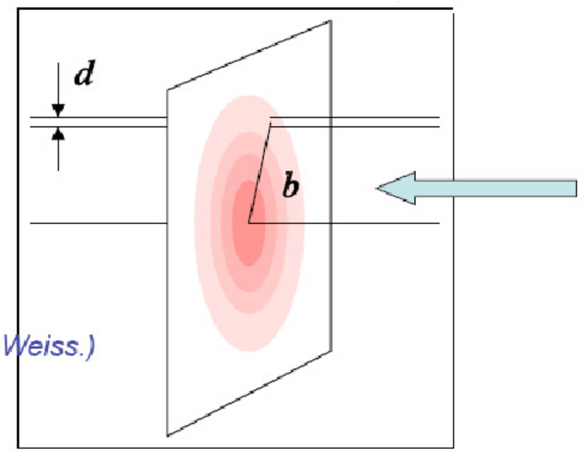
1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon

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

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



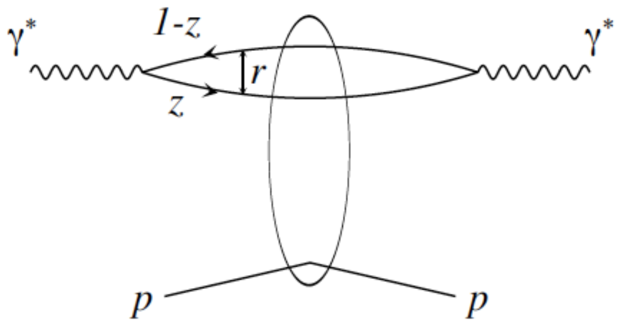




Central black region growing with decrease of x.

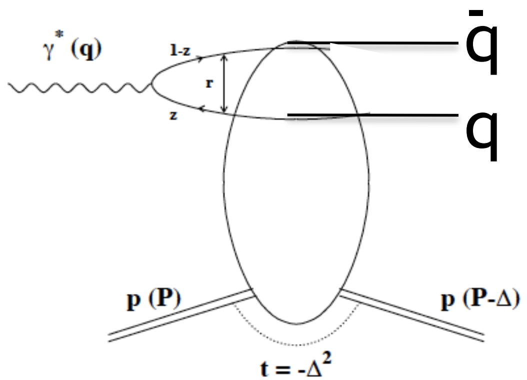
(figure from C. Weiss.)

Advantage of Diffractive DIS: Dipole Language



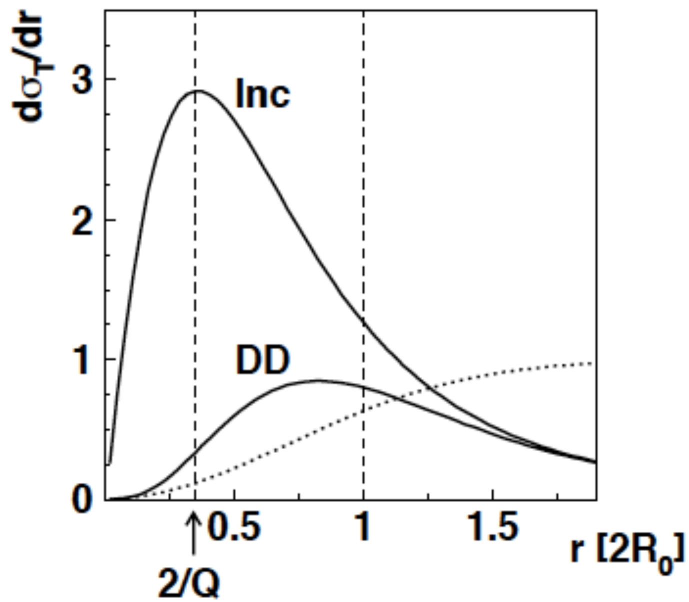
Inclusive Cross Section

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



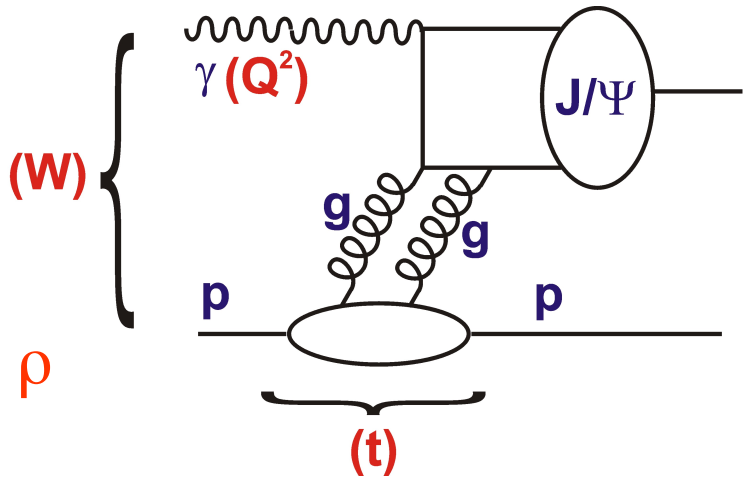
Diffractive DIS

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



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)

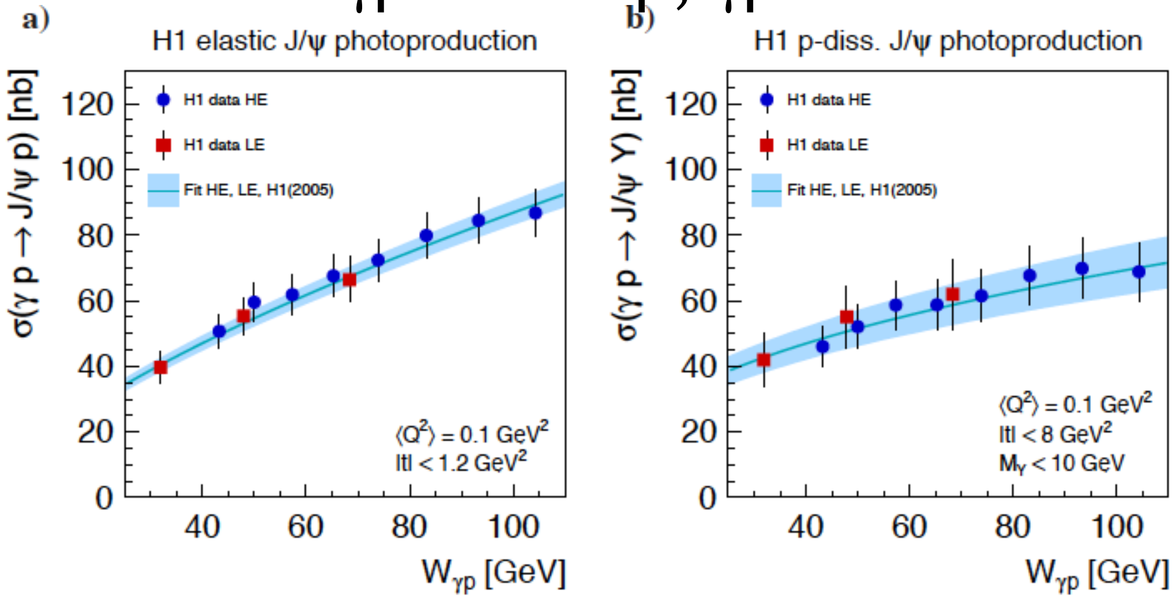
- Scale $\overline{Q^2} \sim (Q^2 + M_V^2) / 4 \;>\sim 3\ \text{GeV}^2$ ideally suited to reaching Lowest possible x whilst remaining in perturbative regime

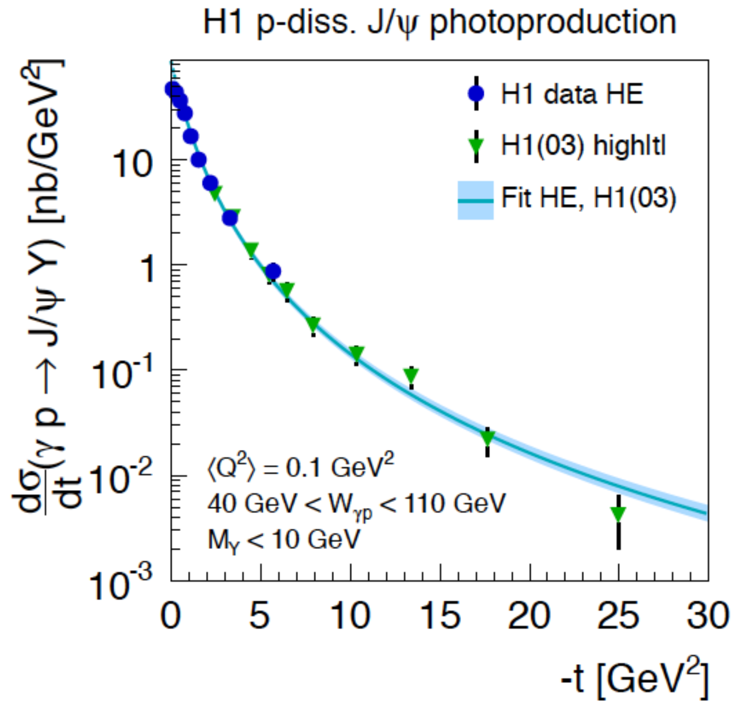
… eg LHeC reach extends to: $x_g \sim (Q^2 + M_V^2) / (Q^2 + W^2) \sim 5.10^{-6}$

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

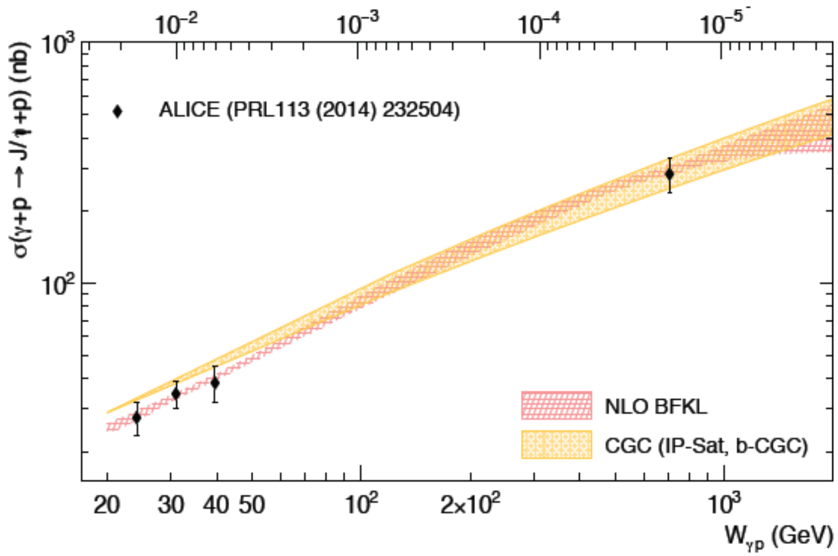
Existing Diffractive J/Ψ Photoproduction Data

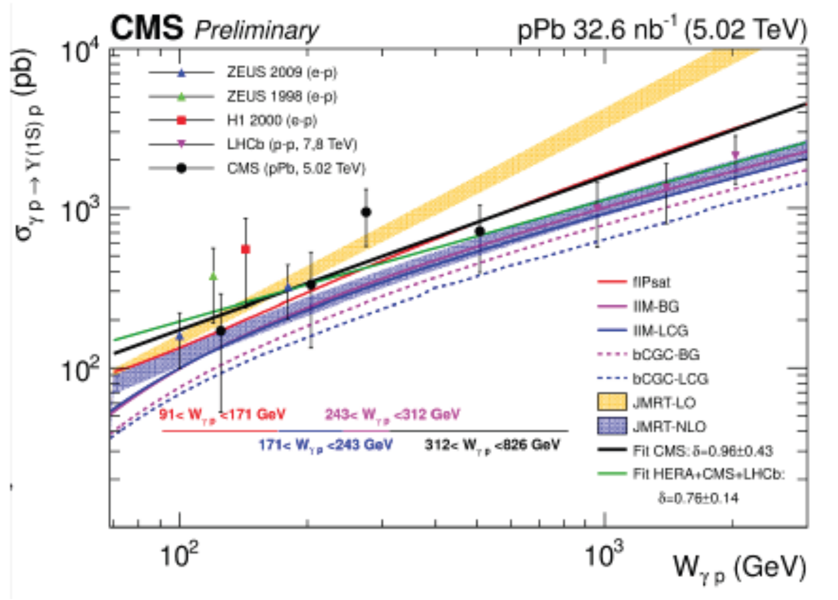
HERA: $\gamma p \rightarrow J/\Psi p$, $\gamma p \rightarrow J/\Psi\ Y$





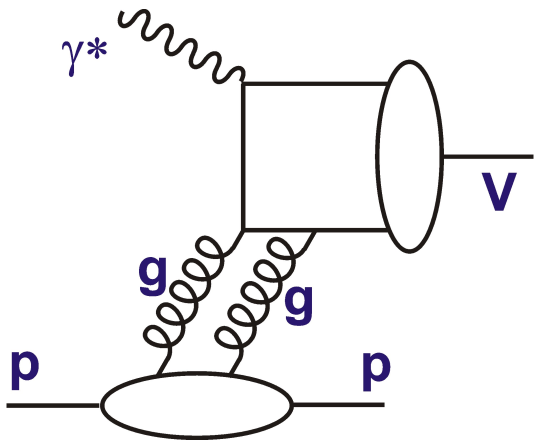
UPC at LHC: $\gamma p \rightarrow J/\Psi p$

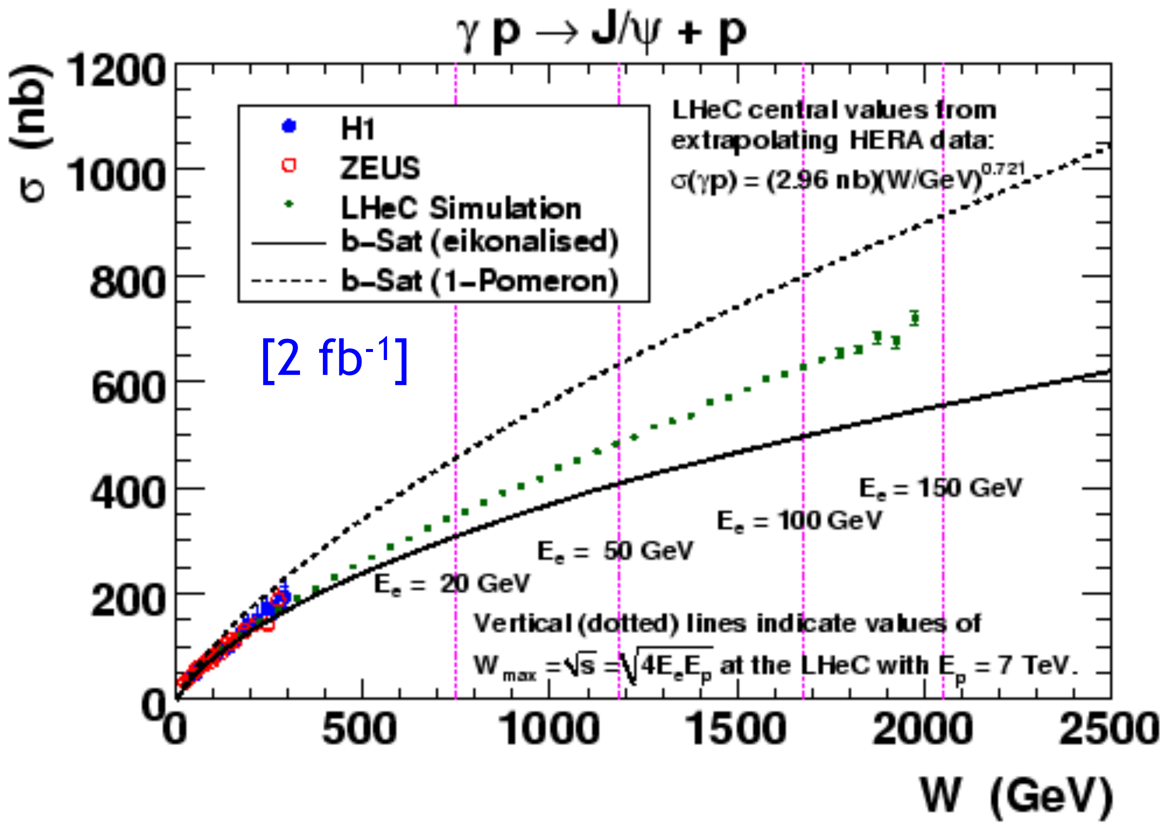




Comparison with Dipole model Predictions

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

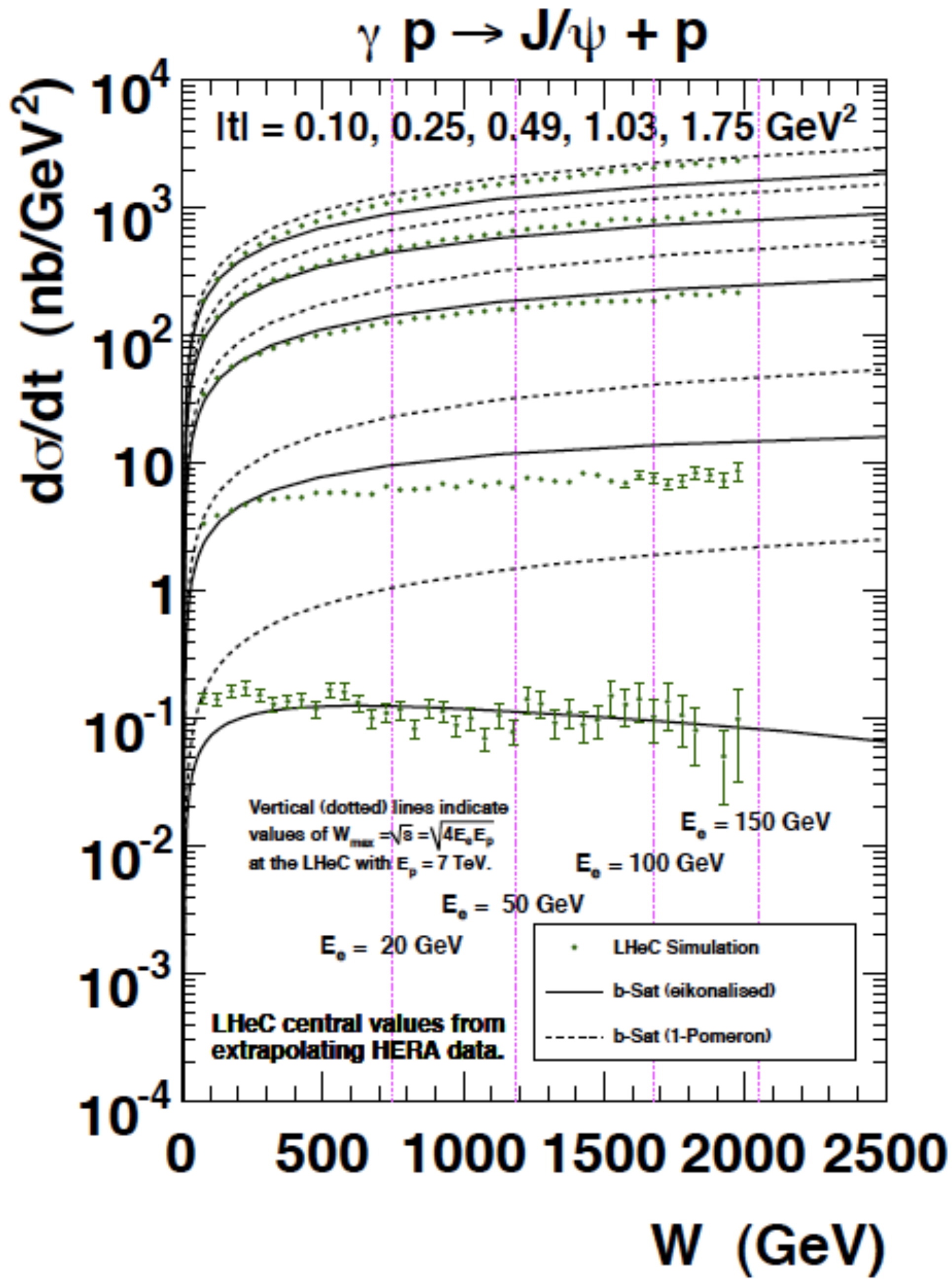




• Significant non-linear effects expected in LHeC kinematic range.

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

t Dependence of Elastic J/ψ Photoproduction



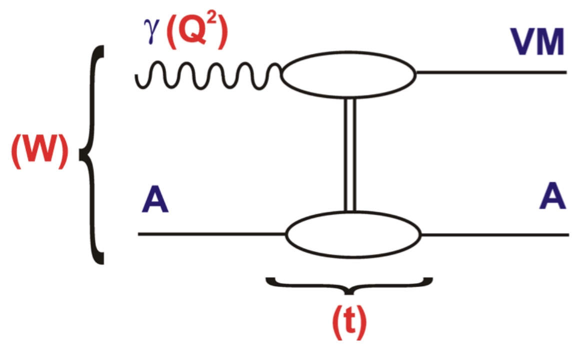
- Precise t measurement from decay μ tracks over wide W range extends to |t| ~ 2 GeV^2 and enhances sensitivity to saturation effects

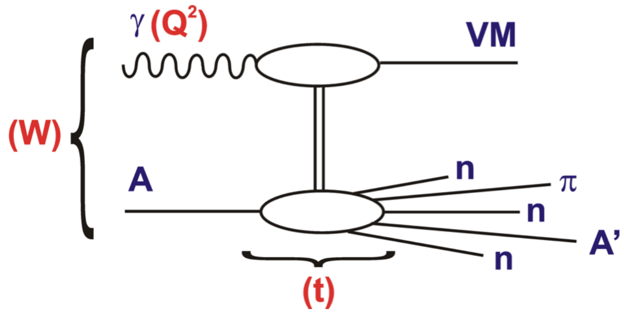
- Measurements also possible in multiple Q^2 bins

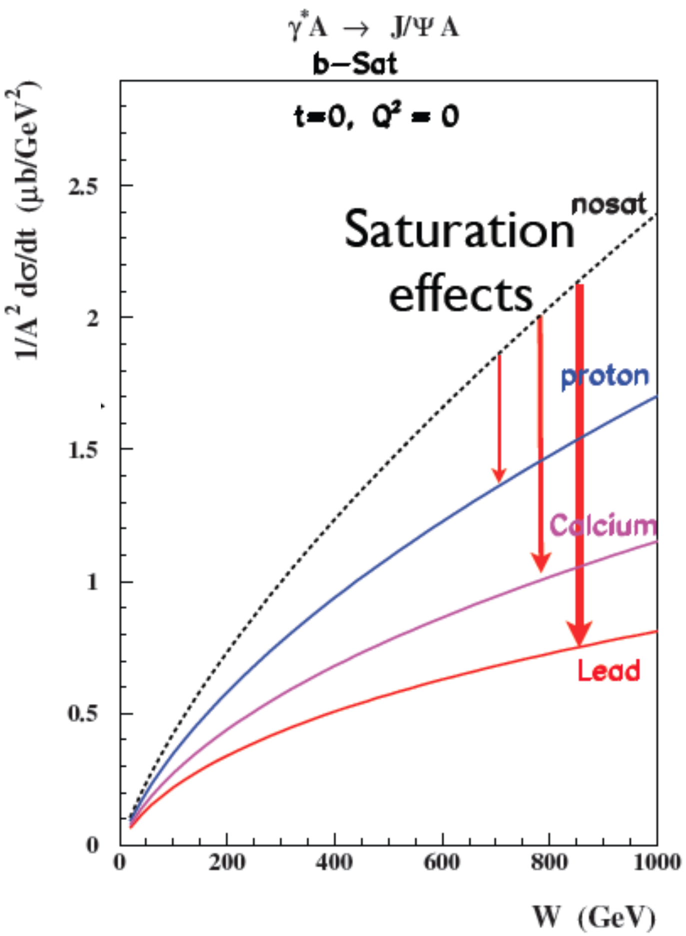
- Level of precision from ep and eA unlikely to be matched in UPC
- Incoherent ep diffraction still needs to be studied

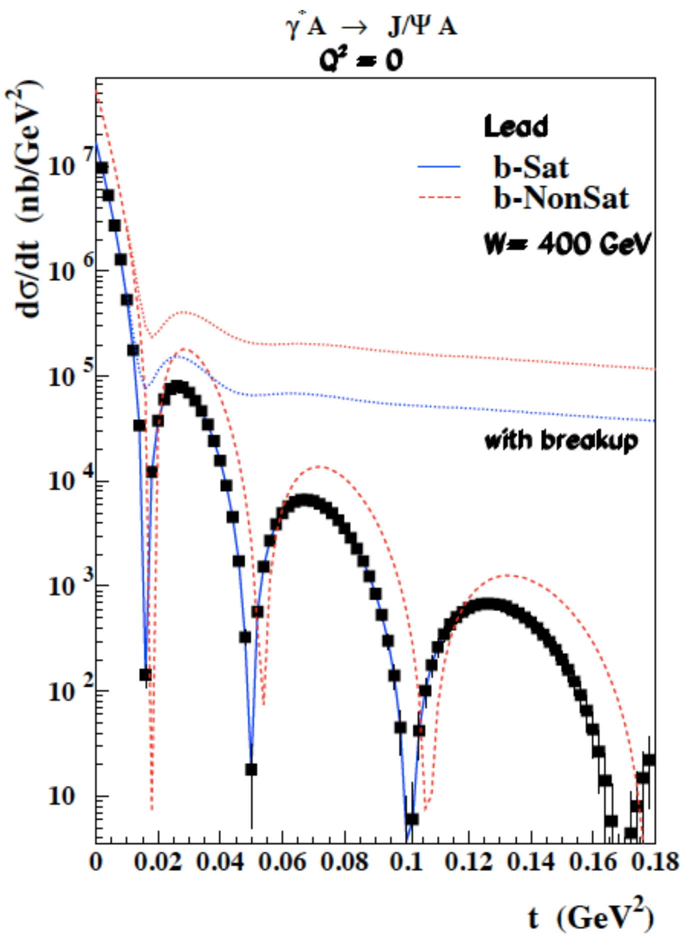
Exclusive Diffraction in eA

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



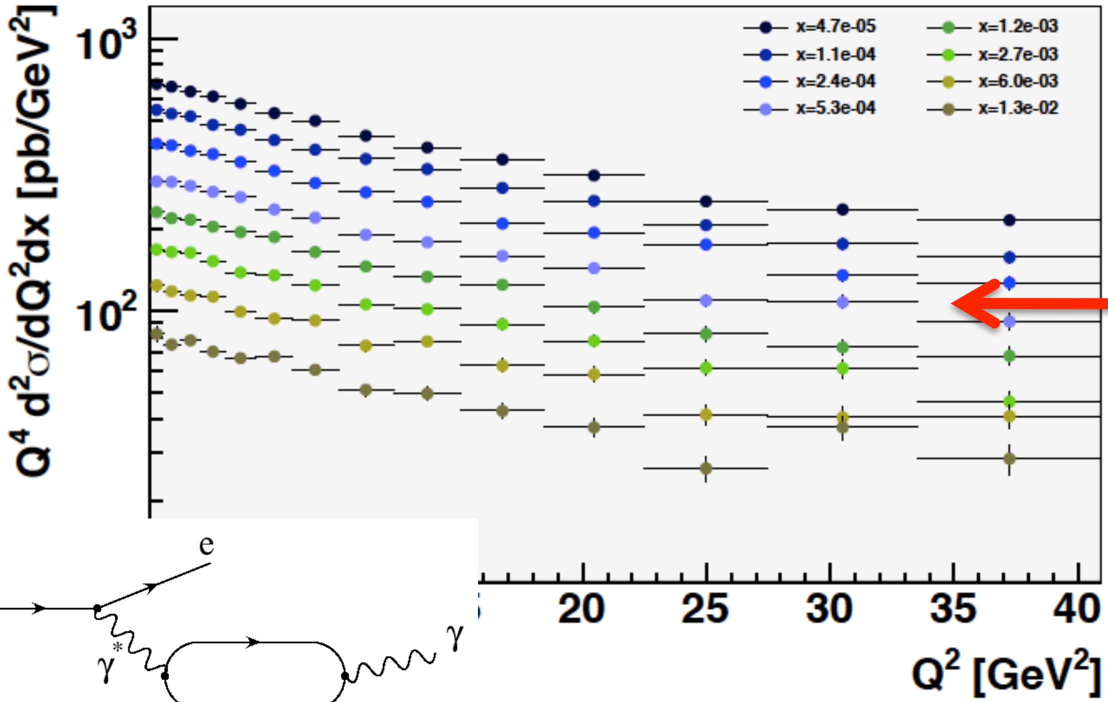




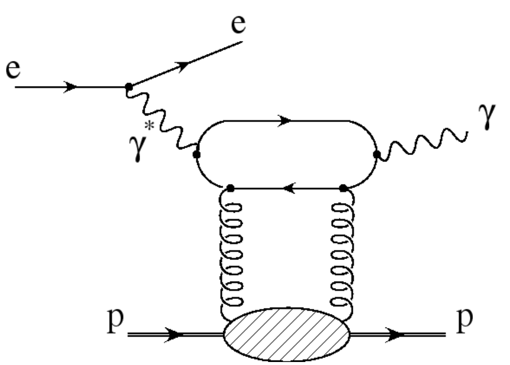


Experimental separation of incoherent diffraction based mainly on ZDC

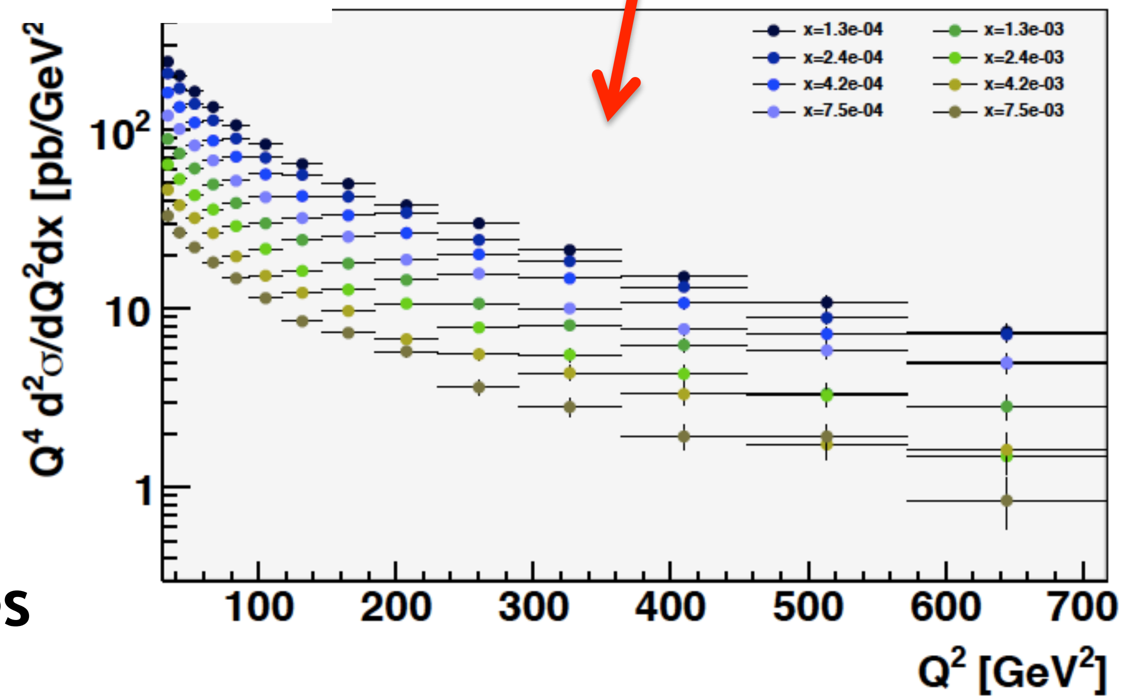
DVCS
(MILOU simulation)



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



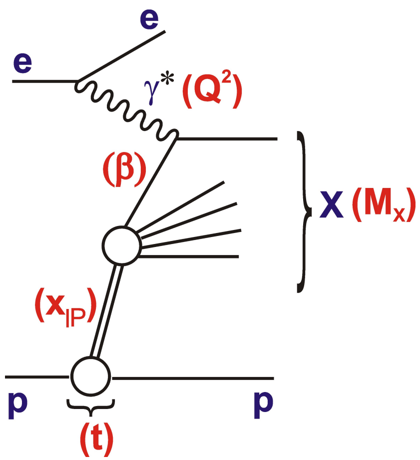
100 fb^{-1}, E_e = 50 GeV,
10° acc'nce, p_T^{γ} > 5 GeV

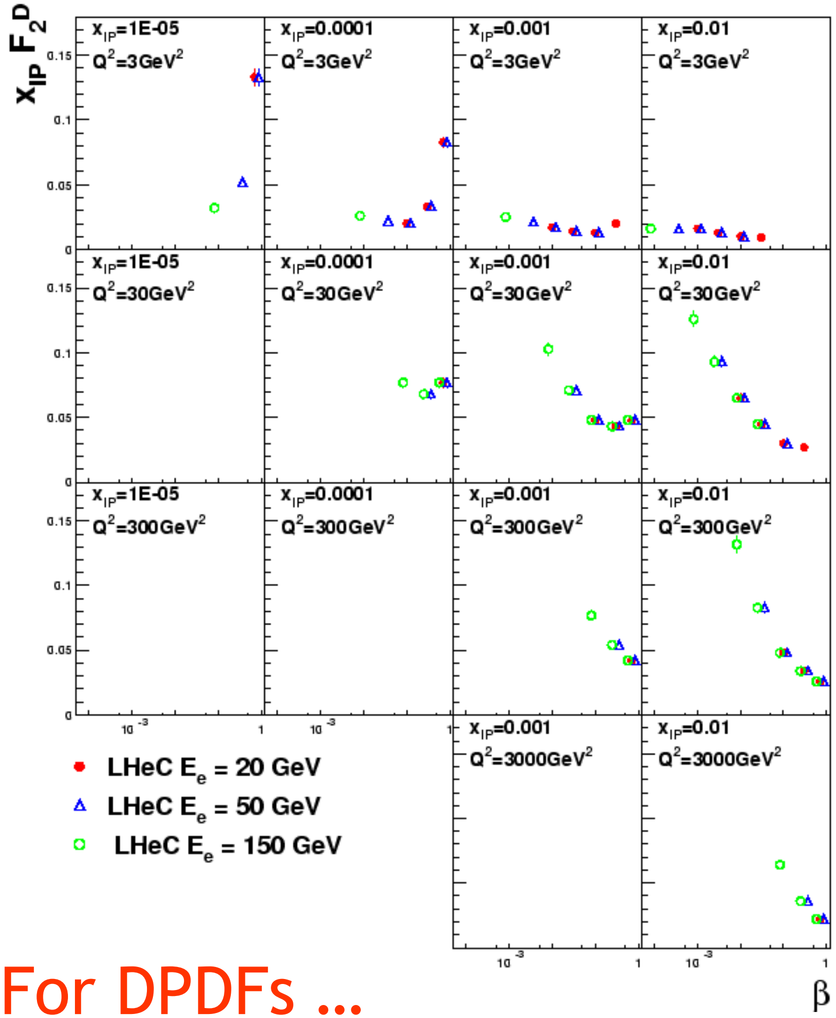


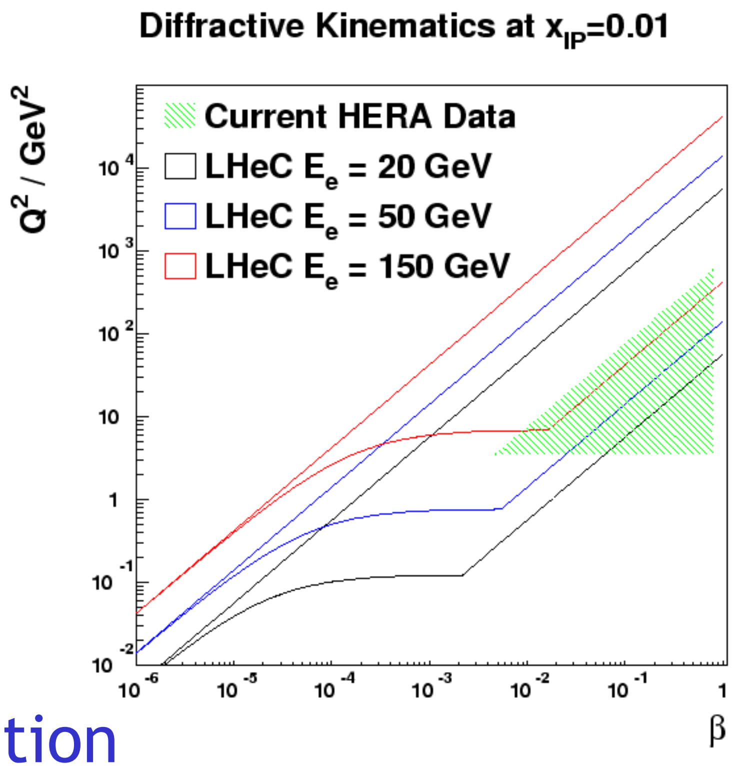
Precise data with
W → 1 TeV, Q^2 → 700 GeV^2,
x → 5.10^{-5}

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

Inclusive Diffraction / Diffractive PDFs at LHeC







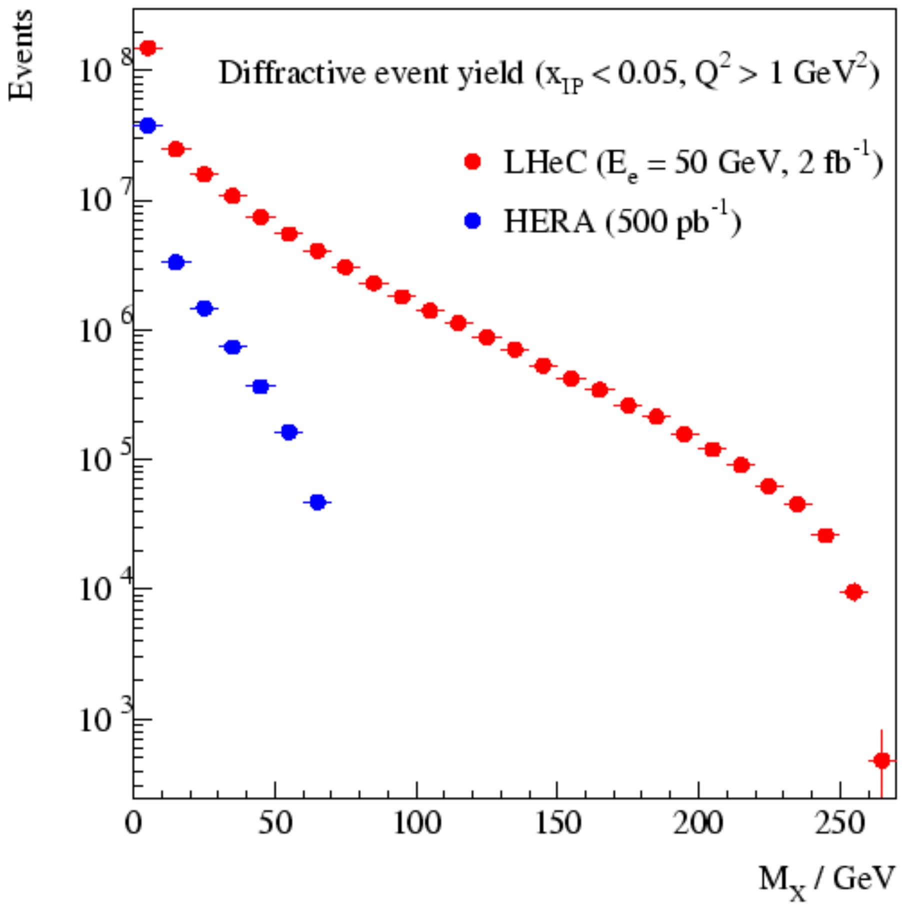
For DPDFs …

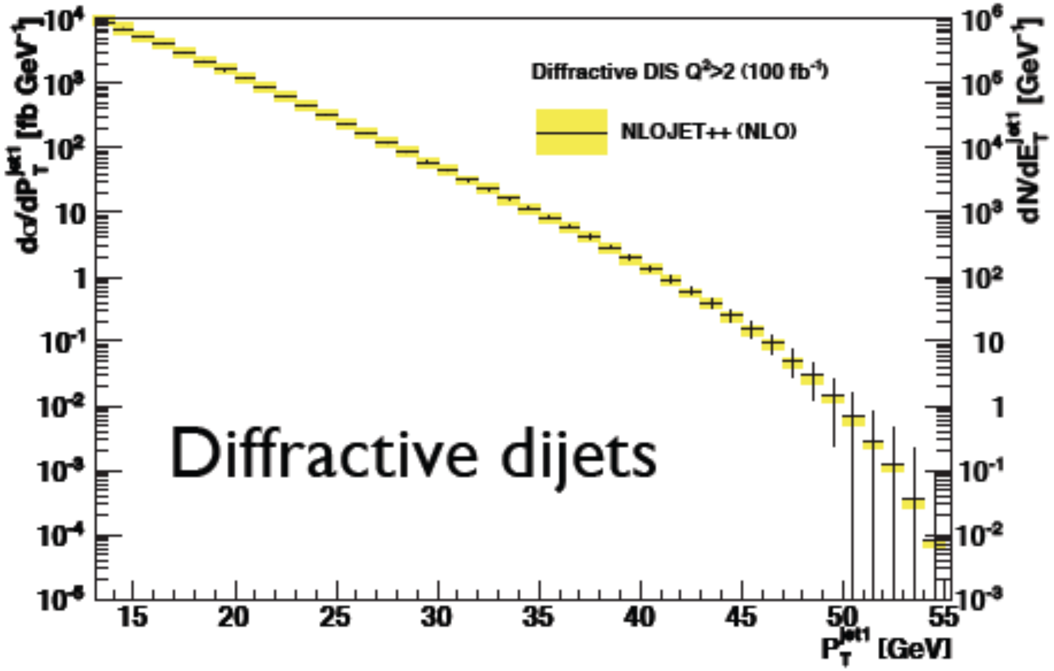
- Low x_{IP} → cleanly separate diffraction
- Low β → Novel low x DPDF effects /non-linear dynamics?
- High Q^2 → Lever-arm for gluon, Flavour separation via EW

Still to do: detailed DPDF sensitivity study

New Region of Large Diffractive Masses

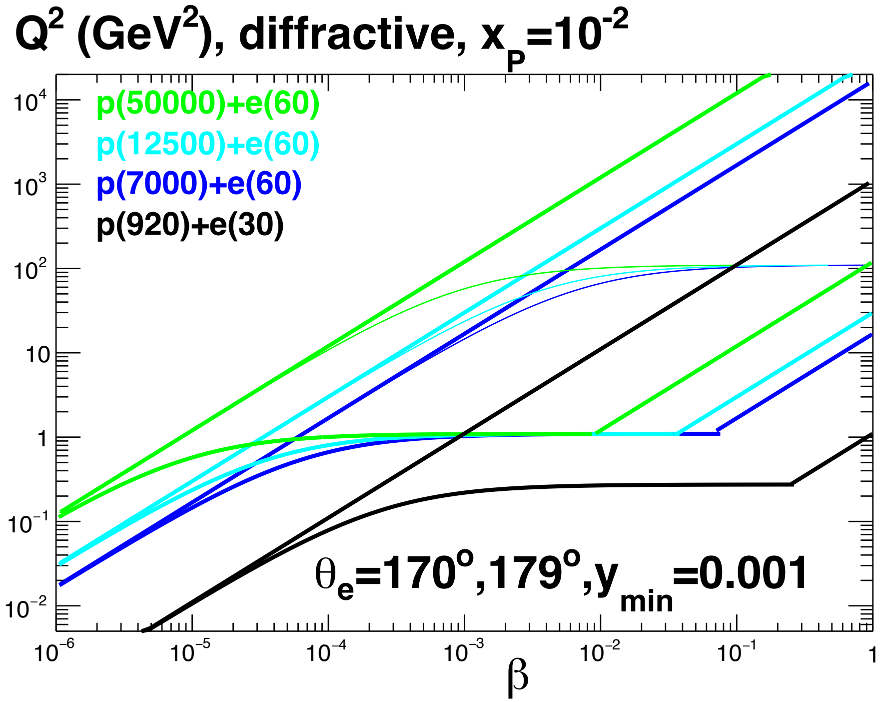
Large x_{IP} region highly correlated with large Mx



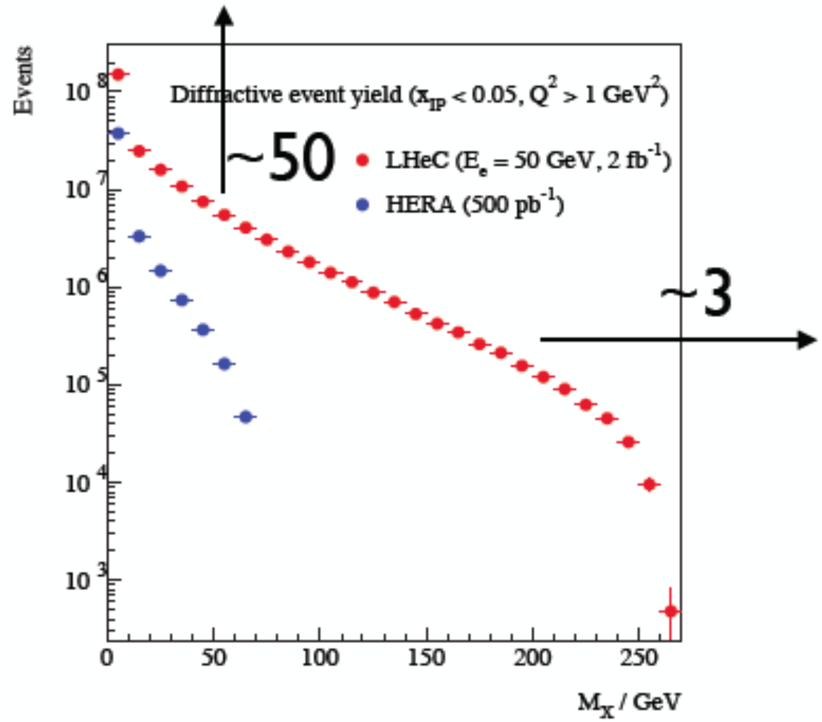


- \`Proper' QCD (e.g. large E_T) with jets and charm accessible
- New diffractive channels … beauty, W / Z bosons
- Unfold quantum numbers / precisely measure new 1^- states

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



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



-Similarly for masses and transverse momenta of jets.

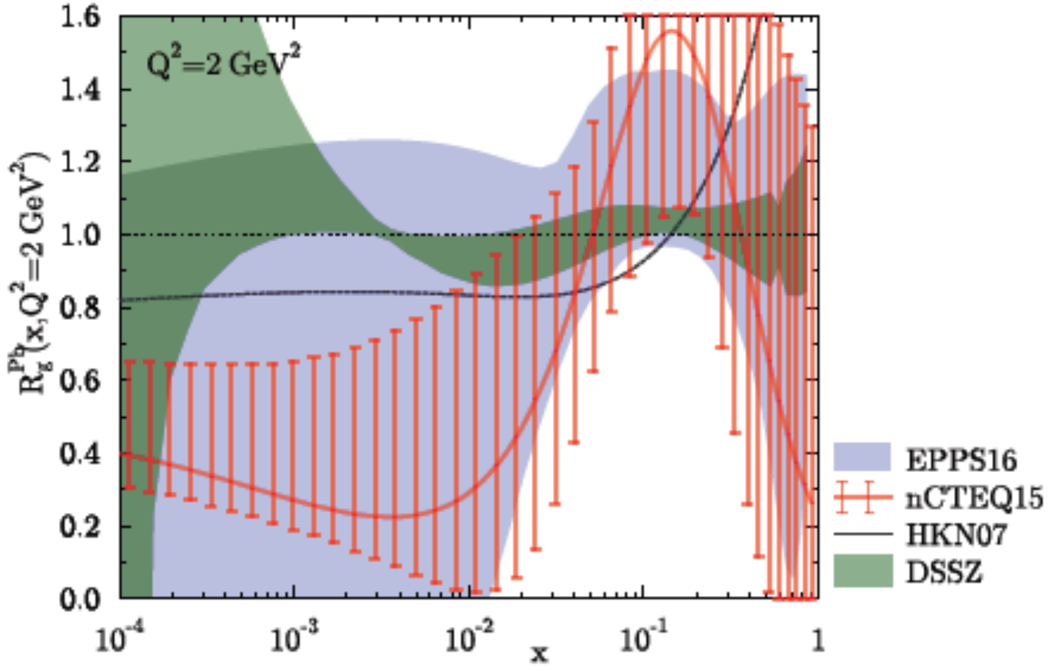
- W range for VMs → multi-TeV

Current Status of Nuclear Parton Densities

- Significant uncertainties in the nuclear PDFs (nPDFs)

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

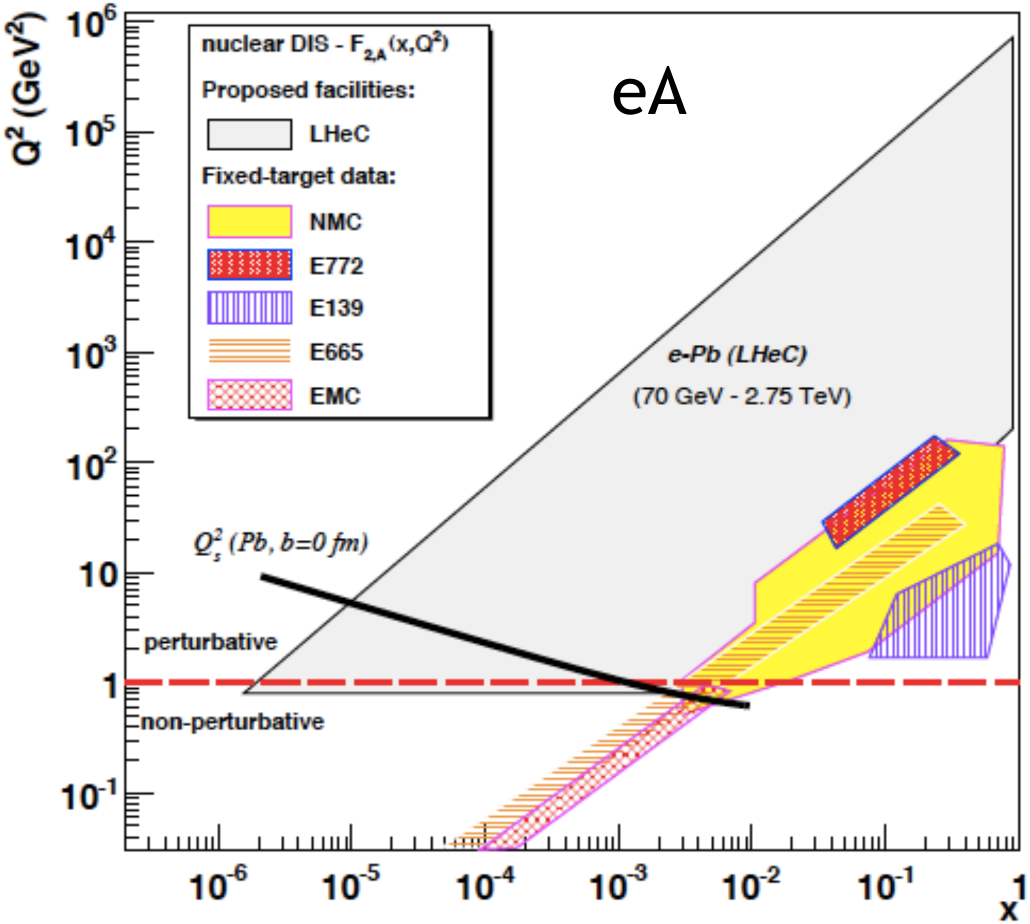
[Slide from Hannu Paukkunen]

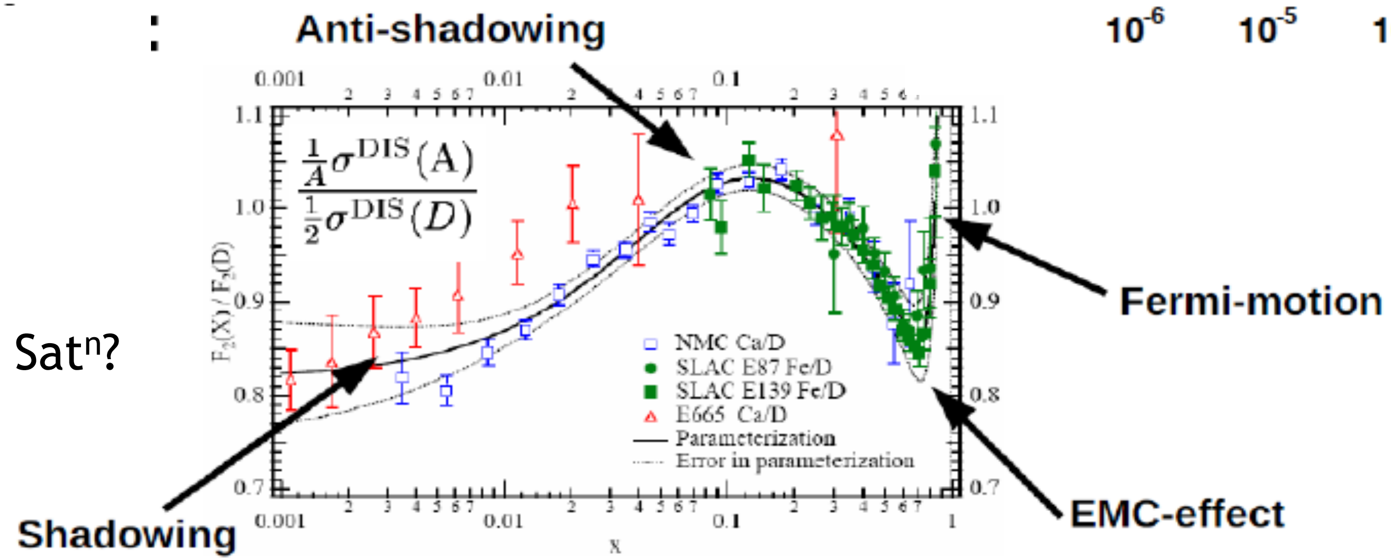


- Especially the small-x (here, $x \lesssim 10^{-2}$) behaviour of nPDFs at smallish Q^2 are largely unknown — may become a bottleneck e.g. in
  - distinguishing effects of non-linear evolution
  - precision studies of phenomena in heavy-ion collisions
  - calculations of cosmic-ray interactions in the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

EPPS Input Data

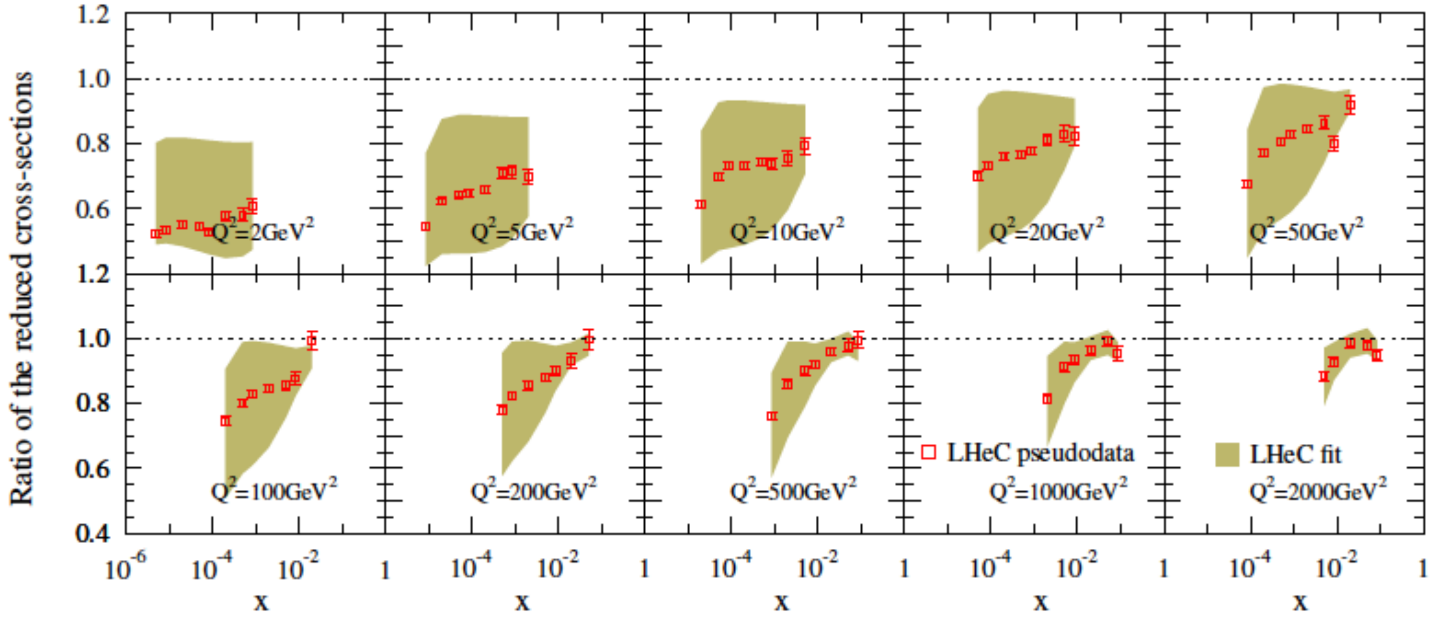
- Exciting phenomenology not matched by DIS data
- EPPS16 also uses various Drell-Yan, semi-inclusive π^0 in PHENIX dAu, W,Z, dijets in ATLAS and CMS
- Direct γ, B, D mesons at LHC promising if theoretical understanding sufficient





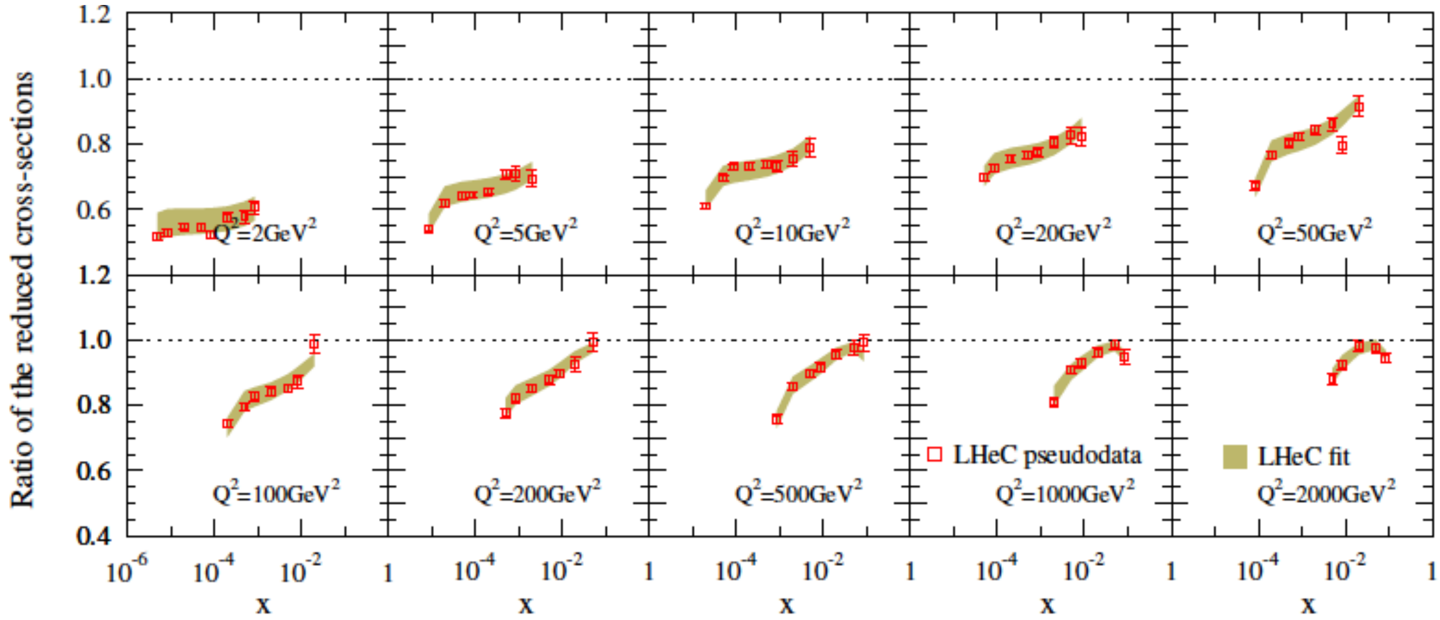
LHeC: Four orders of magnitude Increase in kinematic range over previous DIS experiments.

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

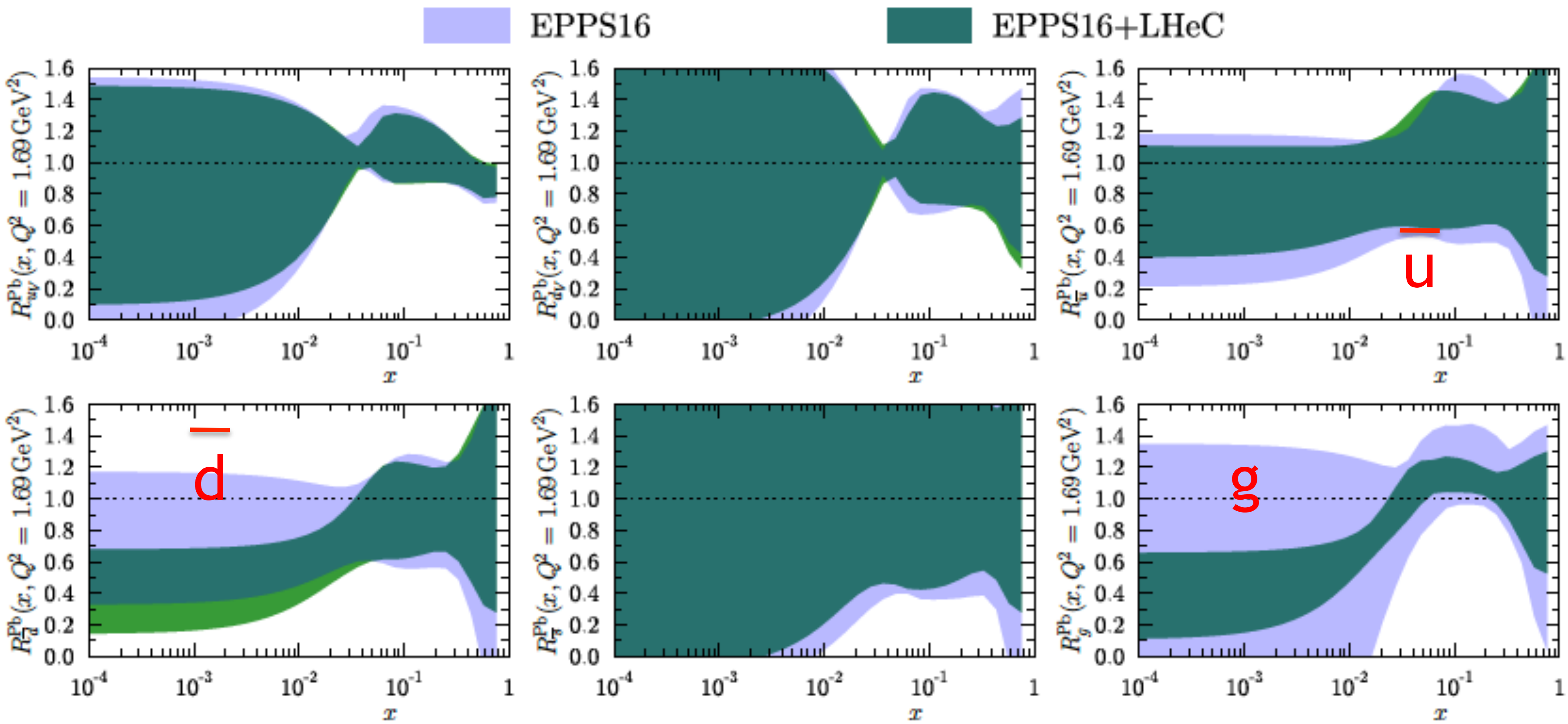


LHeC NC pseudodata before inclusion in EPPS16

EPPS16 after including LHeC pseudodata

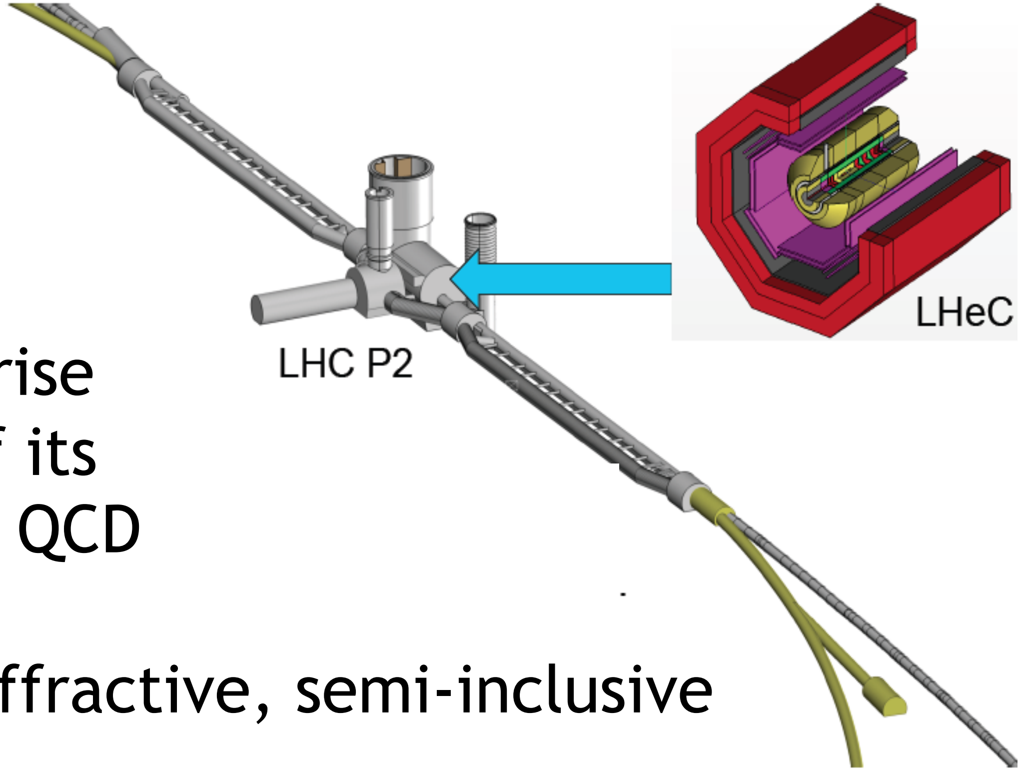


Improvement in EPPS16 nPDFs



[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

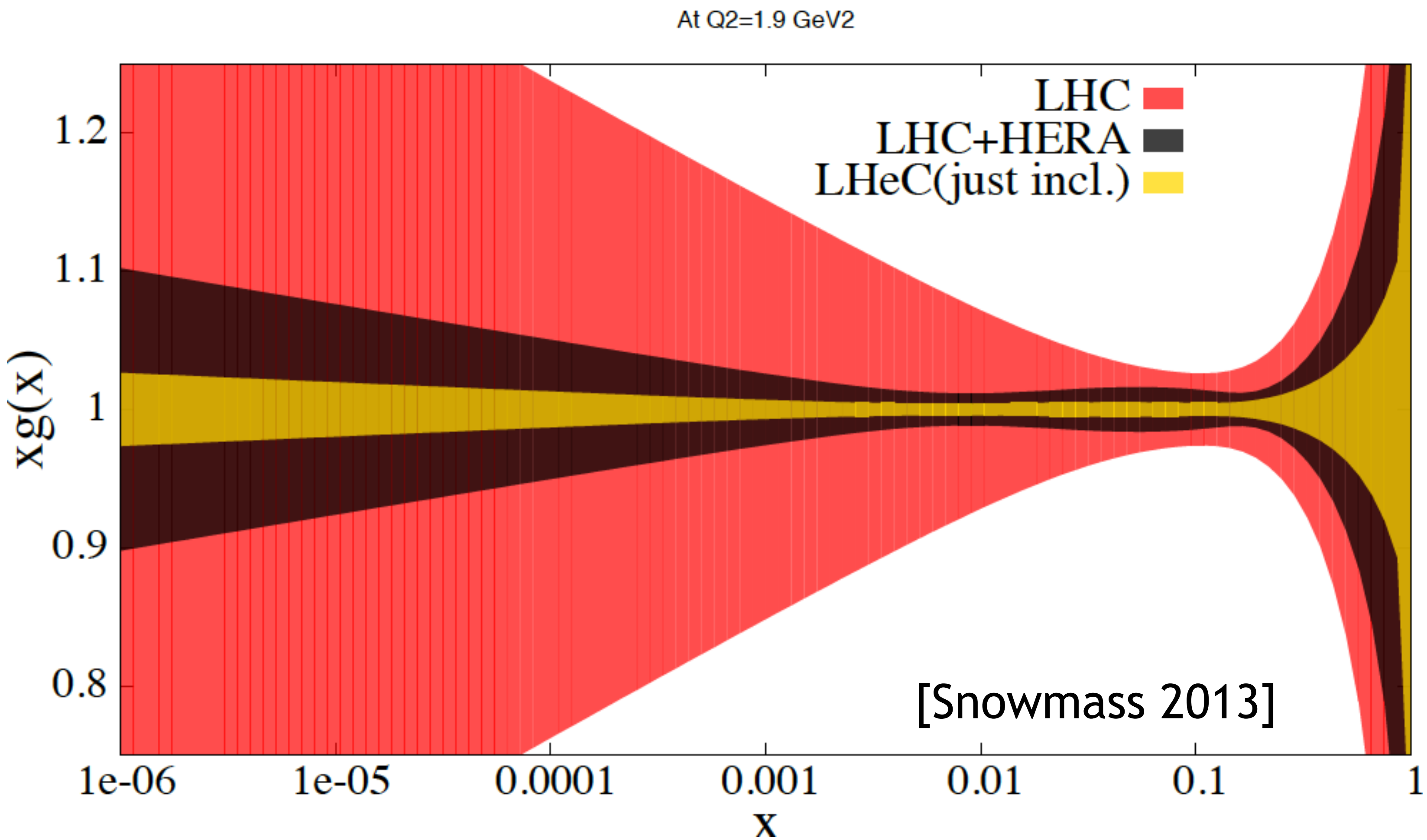
• Needs ep and eA inclusive, diffractive, semi-inclusive over a range of energies

• 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!

Back-Ups Follow

What can be done with LHC alone?

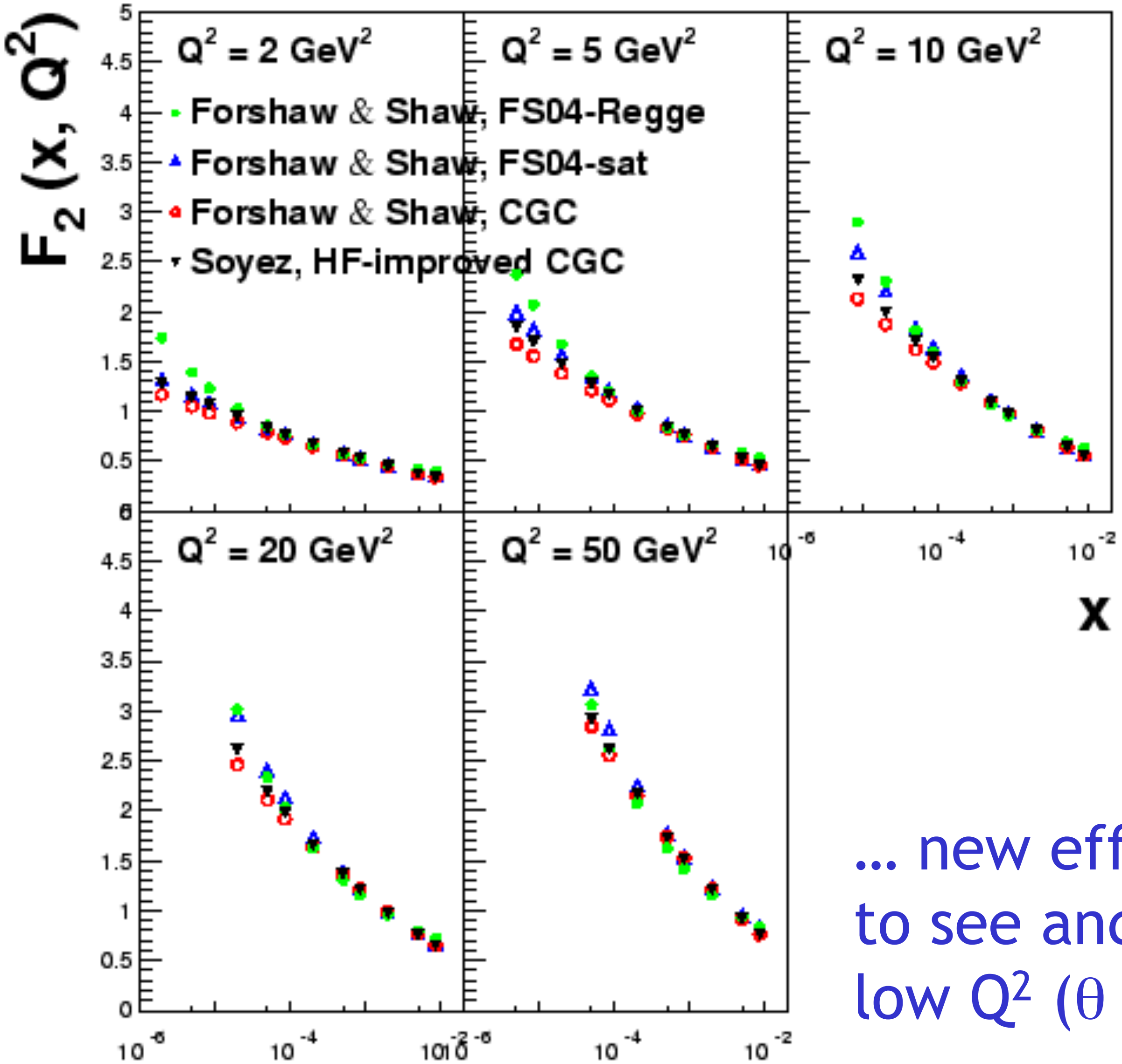


- LHC = current LHC W, Z and jet data
- Remarkable what can be achieved with LHC data alone
- Can we improve substantially? – Often already systs limited

Some models of low x F_2 with LHeC Data

With 1 fb^{-1} (1 year at 10^{33} cm^{-2} s^{-1}), 1^o 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 ($\theta \rightarrow 179^o$) region …

F_L Simulation

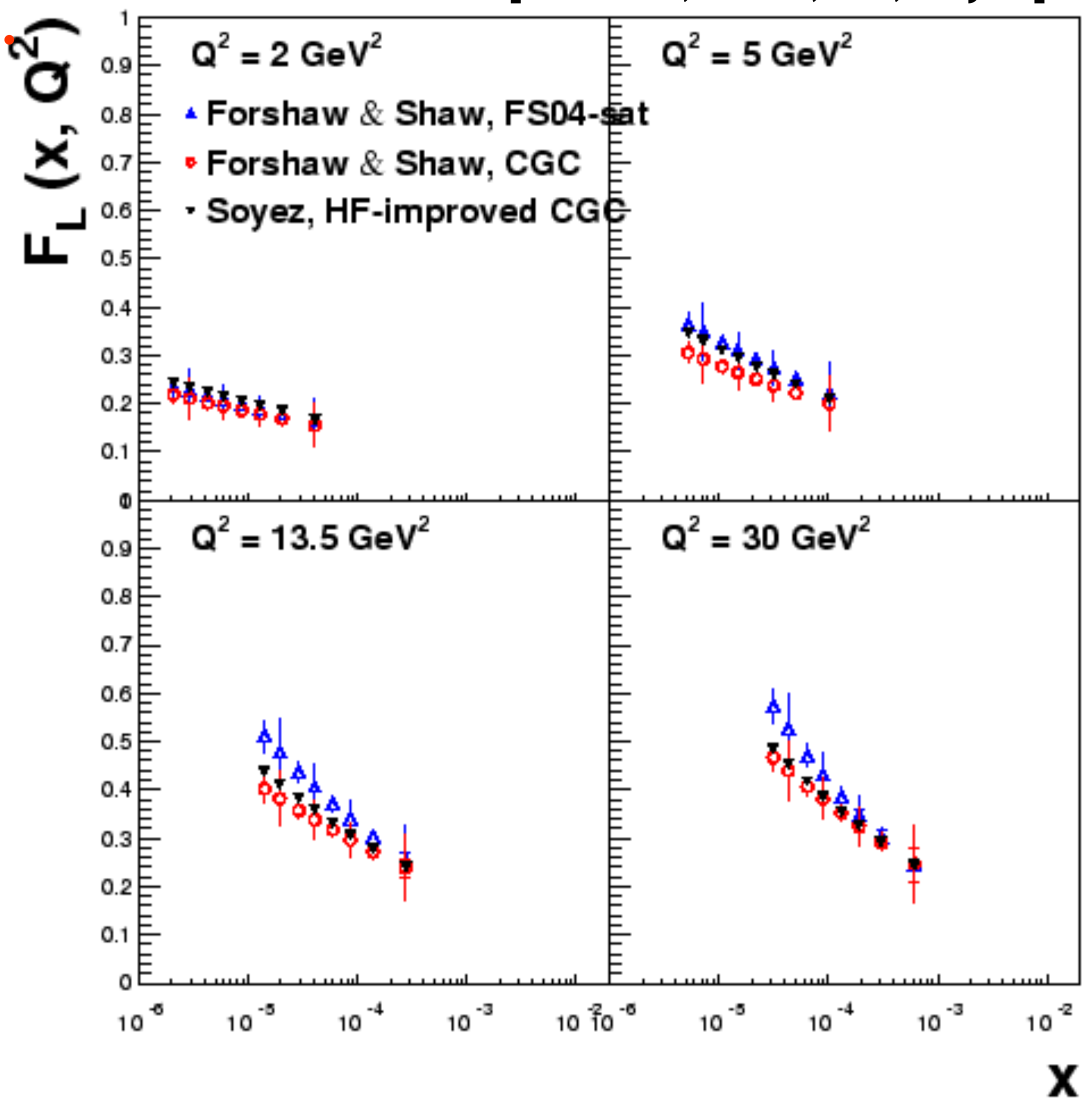
Vary proton beam energy
as recently done at HERA ?…
'direct' gluon measurement …

E_p (TeV)	Lumi (fb^{-1})
7	1
4	0.8
2	0.2
1	0.05
[0.45	0.01]

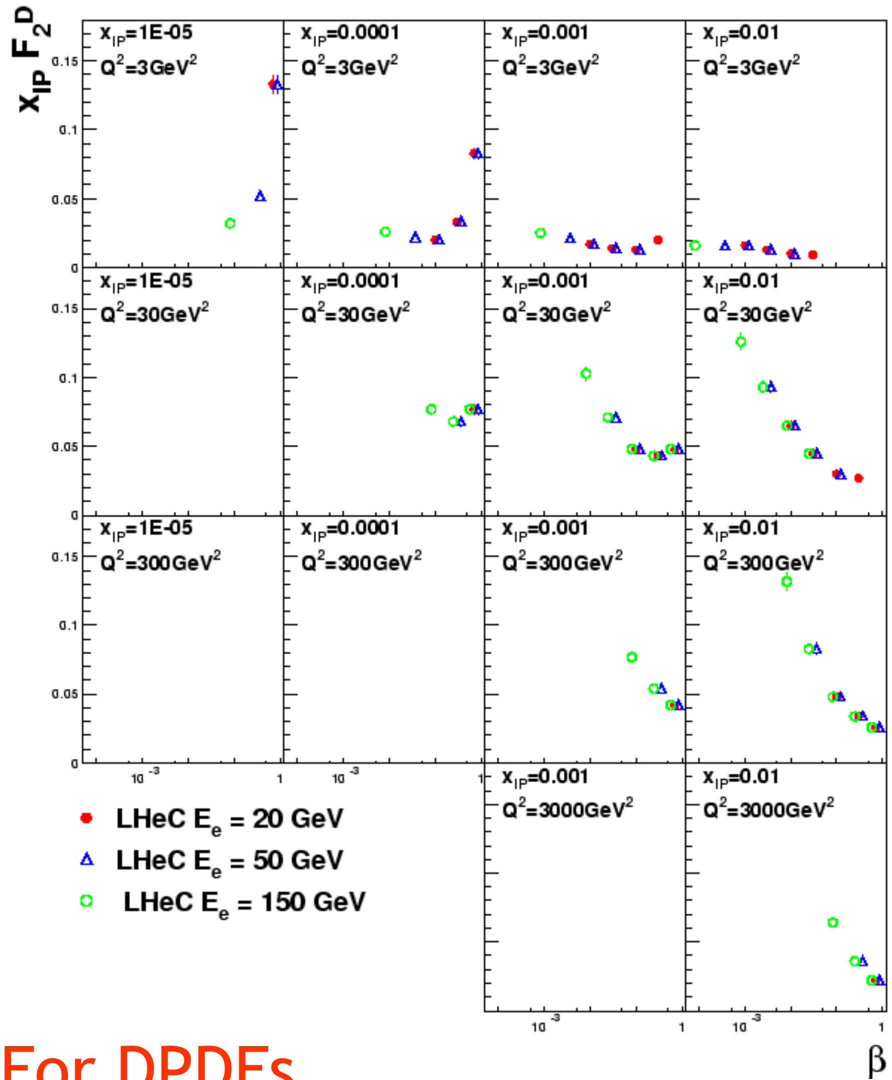
… precision typically 5%
… stats limited for
$Q^2 > 1000$ GeV^2
… could also vary E_e …

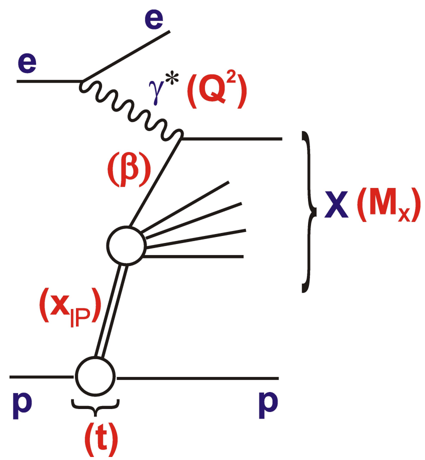
… selected lowest x data
compared with 3 dipole
models including saturation …

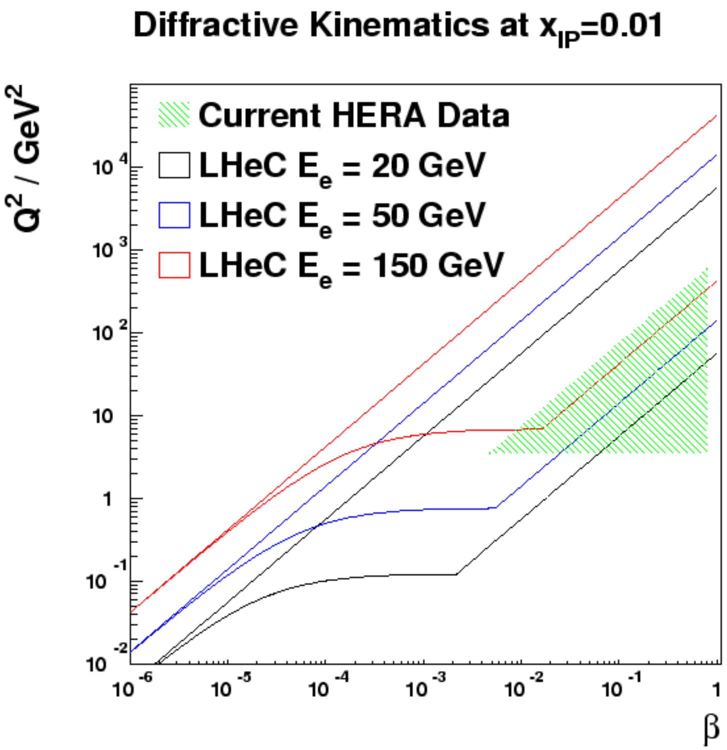
[Forshaw, Klein, PN, Soyez]



Inclusive Diffraction / Diffractive PDFs





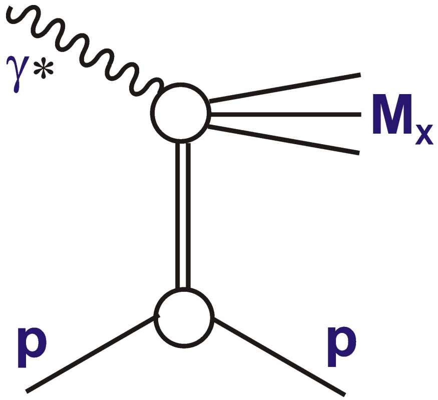


For DPDFs …

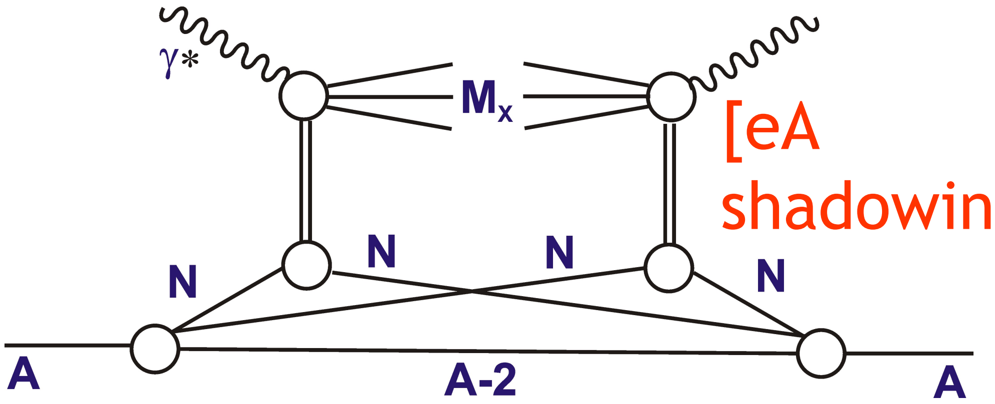
- Low x_{IP} → cleanly separate diffraction
- Low β → Novel low x DPDF effects /non-linear dynamics?
- High Q^2 → Lever-arm for gluon, Flavour separation via EW

F_2^D and Nuclear Shadowing

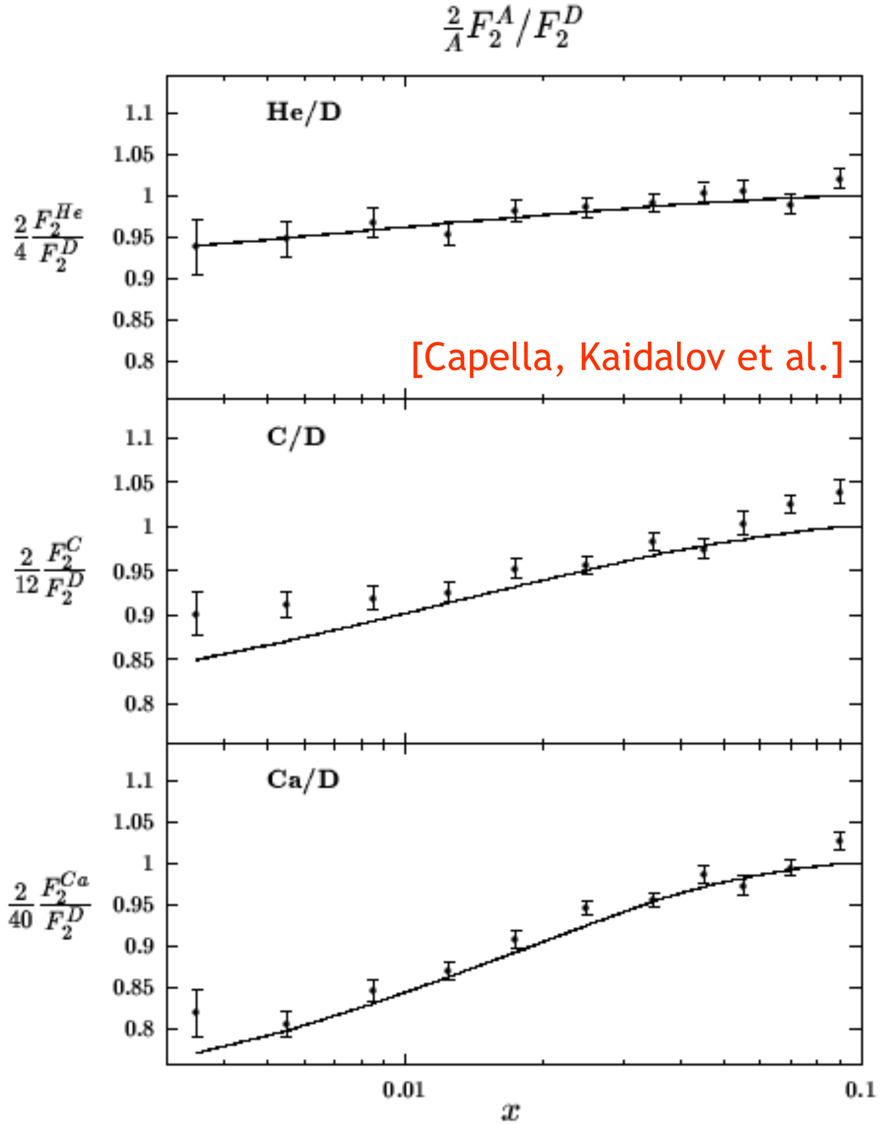
Nuclear shadowing can be described (Gribov-Glauber) as multiple interactions, starting from ep DPDFs



[Diff DIS]

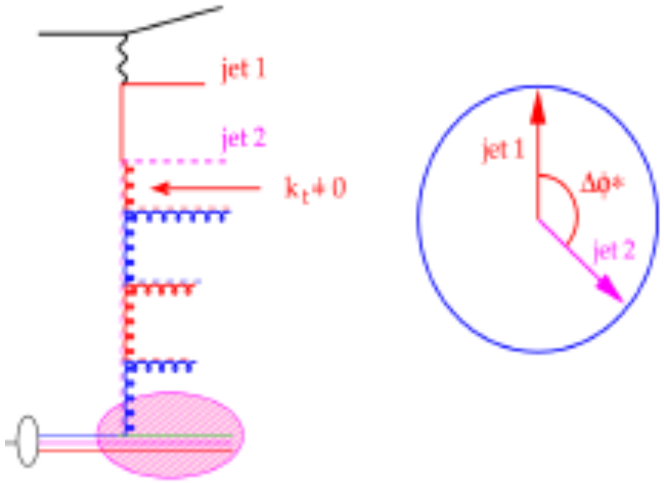


[eA shadowing]



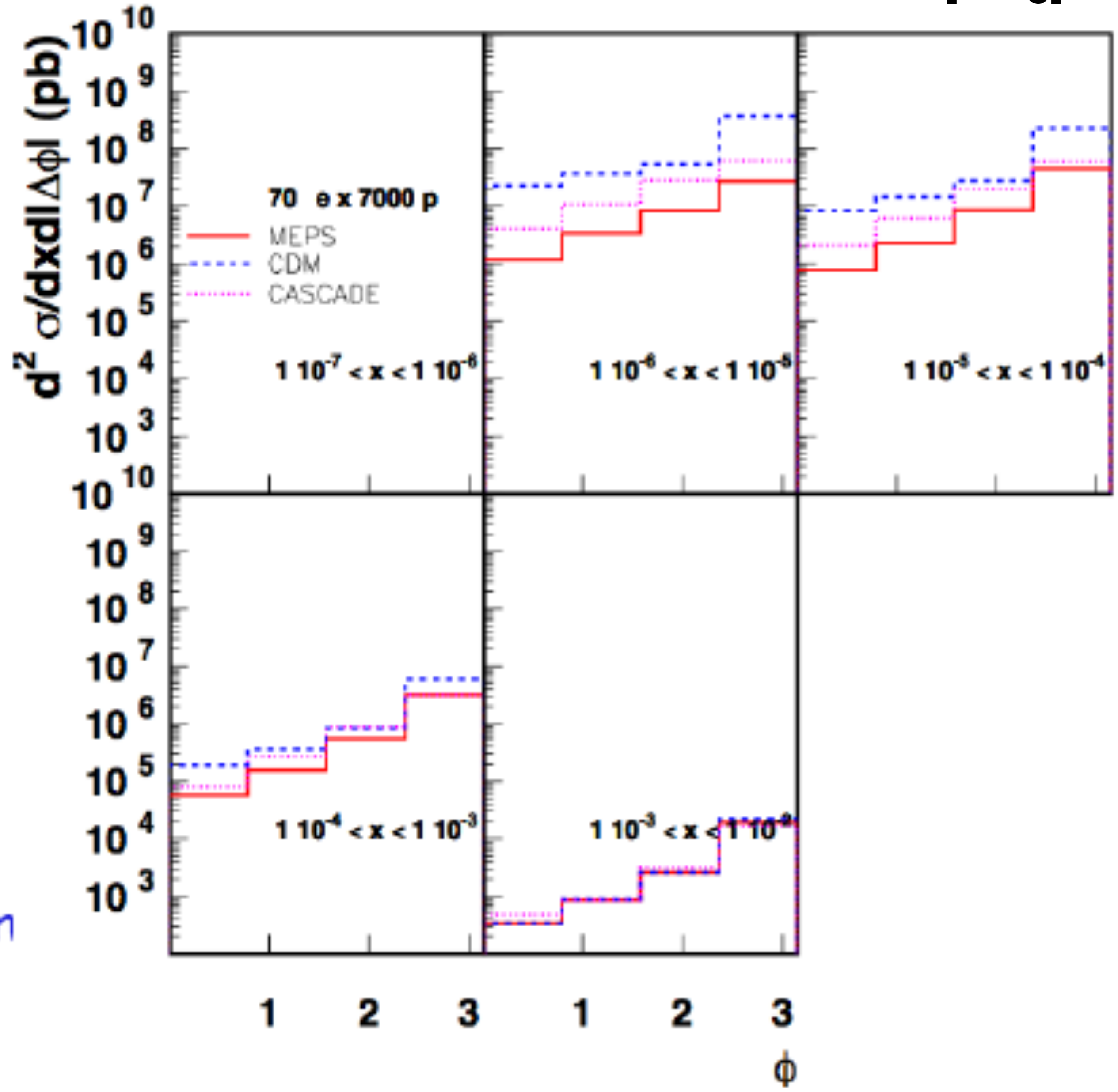
… starting point for extending precision LHeC studies into eA collisions

Azimuthal (de)correlations between Jets



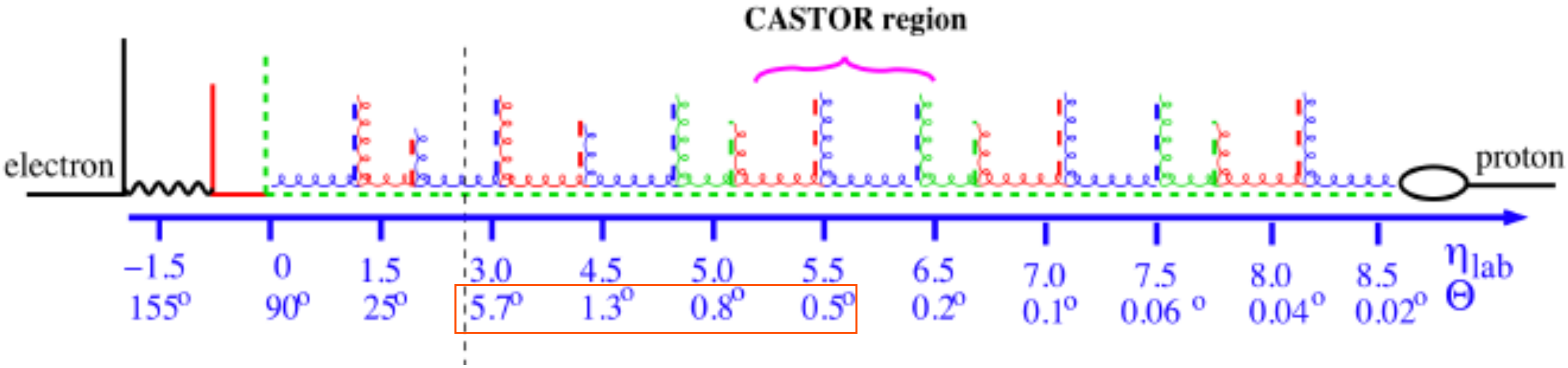
- $5 < Q^2 < 100 \text{ GeV}^2$
  $-1 < \eta < 2.5$
  $E_T > 5 \text{ GeV}$
- small $k_t \rightarrow \Delta\phi \sim 180$
- large k_t from evolution

[Jung]



Forward Instrumentation and Jets

[Jung]



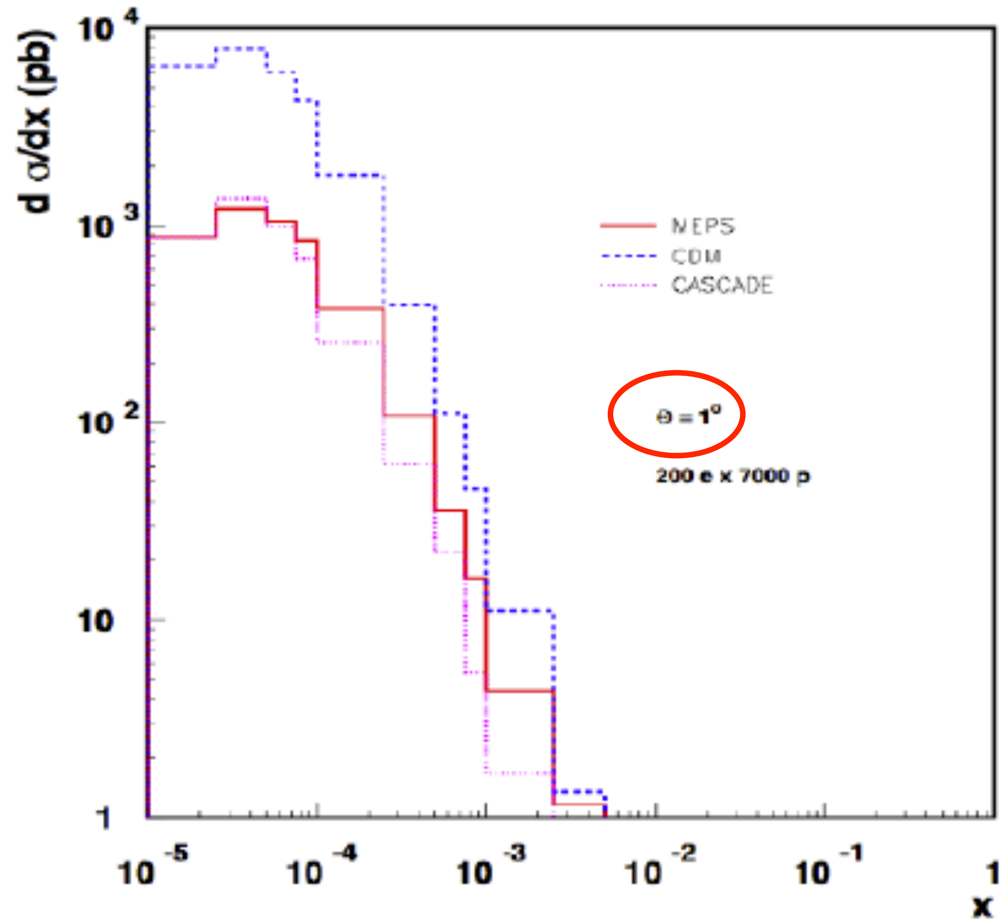
- DIS and forward jet:

$$x_{jet} > 0.03$$

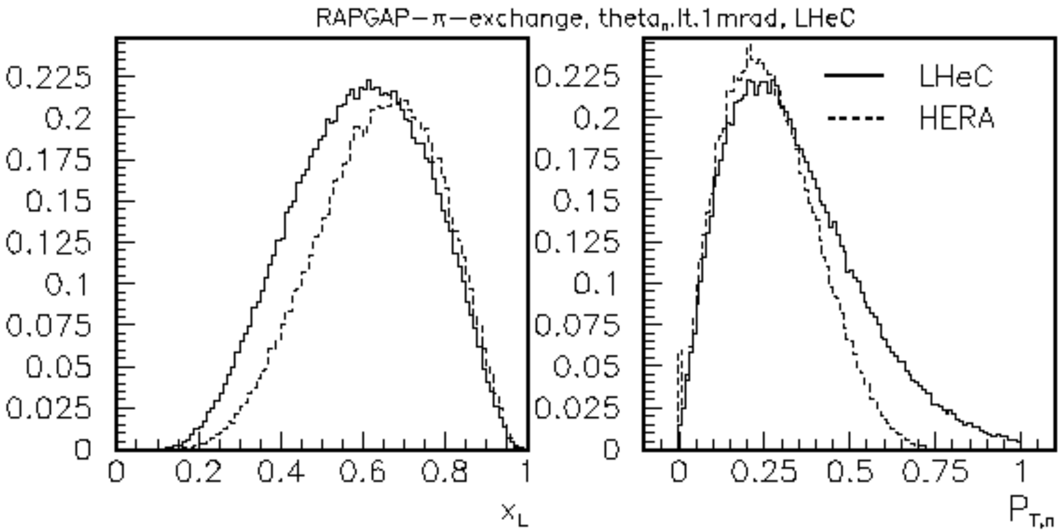
$$0.5 < \frac{p_{t\ jet}^2}{Q^2} < 2$$

x range (and sensitivity to novel QCD effects) strongly depend on θ cut

Similar conclusions for Δϕ decorrelations between jets

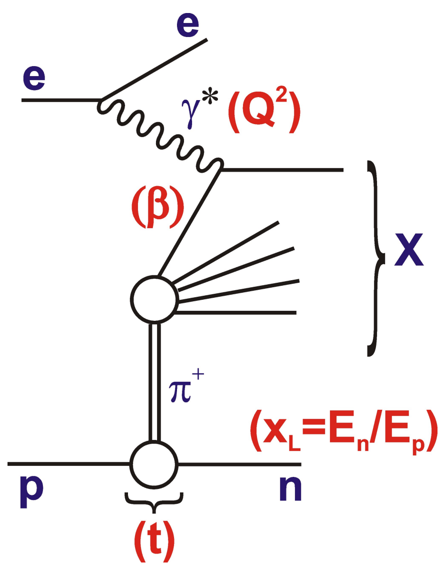


π Structure with Leading Neutrons



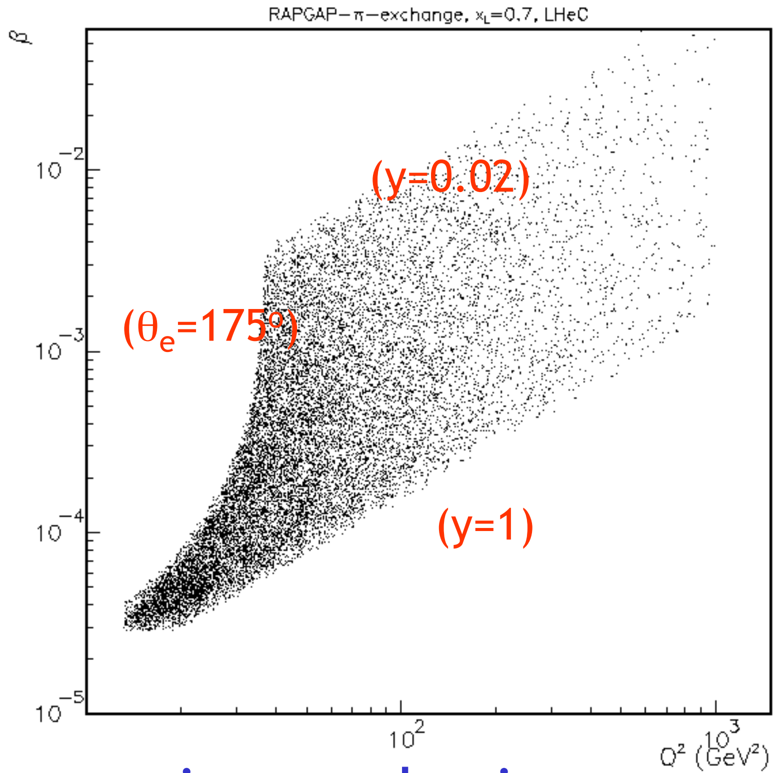
[Bunyatyan]

(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).

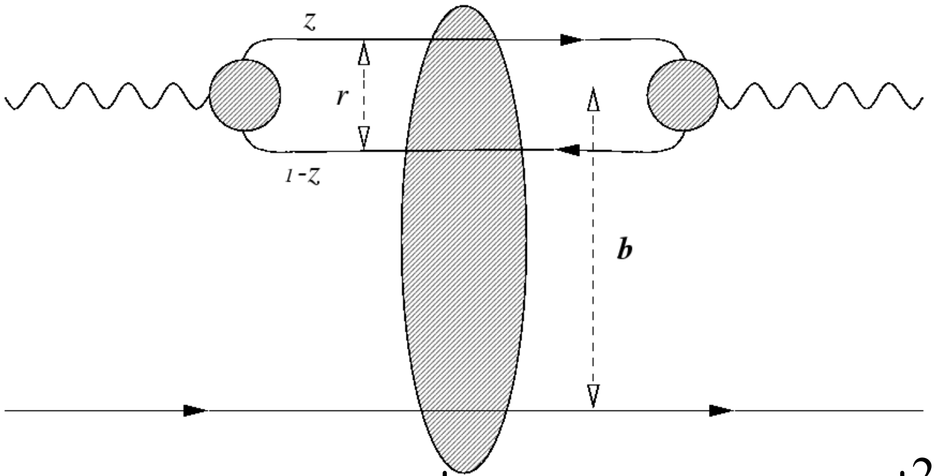
- Extentions to lower β and higher Q^2 as in leading proton case. → F_2^π At $\beta<5.10^{-5}$ (cf HERA reaches $\beta\sim10^{-3}$)



Also relevant to absorptive corrections, cosmic ray physics …

Reminder : Dipole models

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

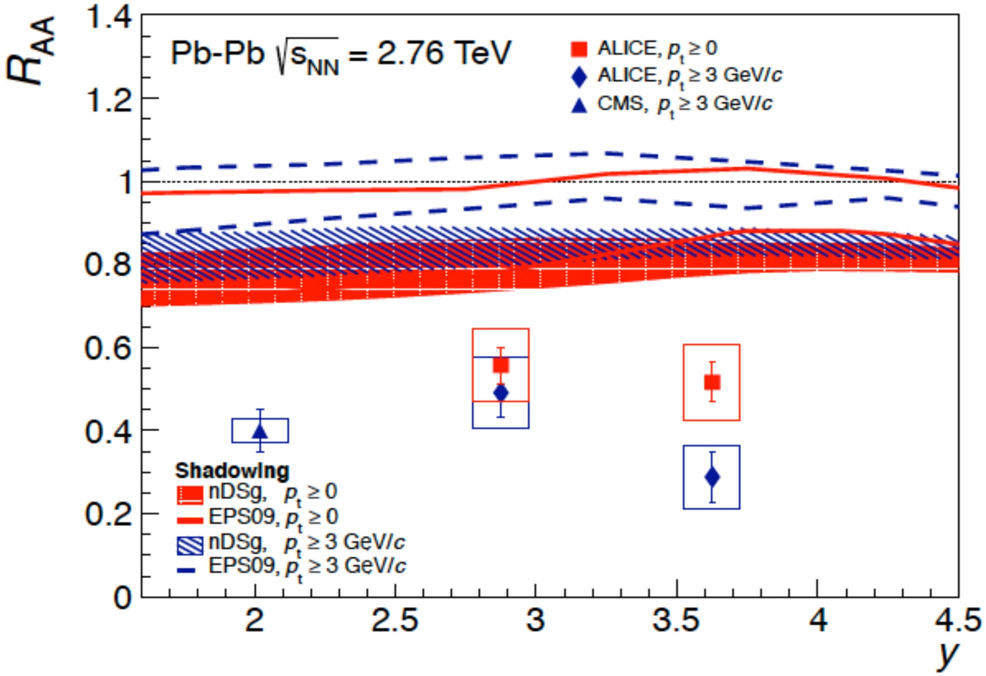


$$\sigma_{\gamma^* p}^{T,L}(x,Q^2) \sim \int \mathrm{dz}\ \mathrm{d}^2 r\ \left|\psi_{\gamma^*}^{T,L}(z,r,Q^2)\right|^2 \sigma_{dipole}(x,r,z)$$

- 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

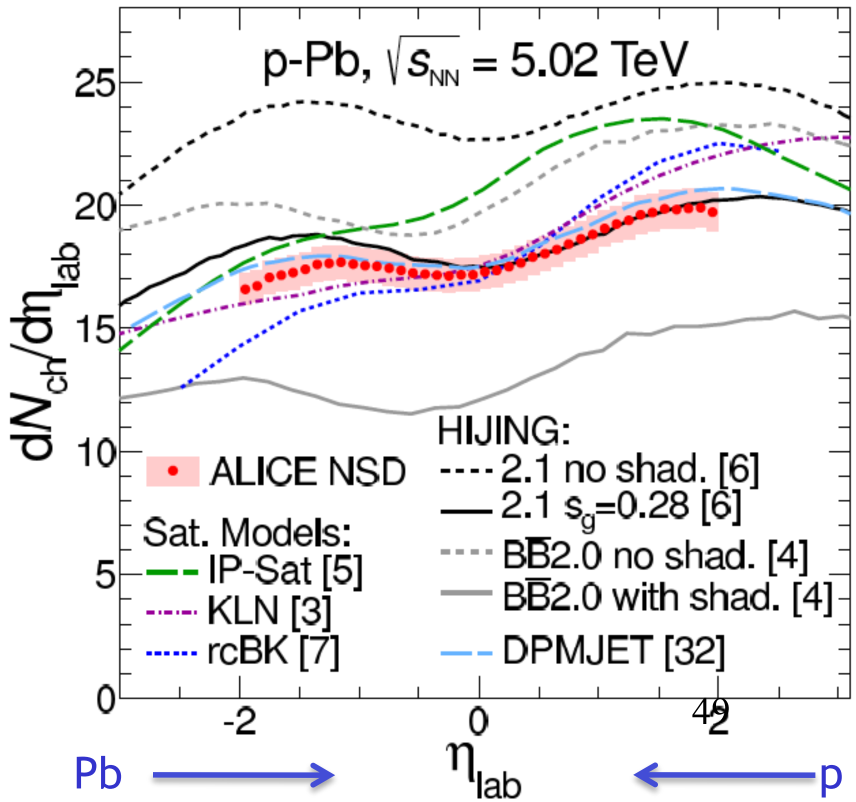
Current Low x Understanding in LHC Ion Data

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

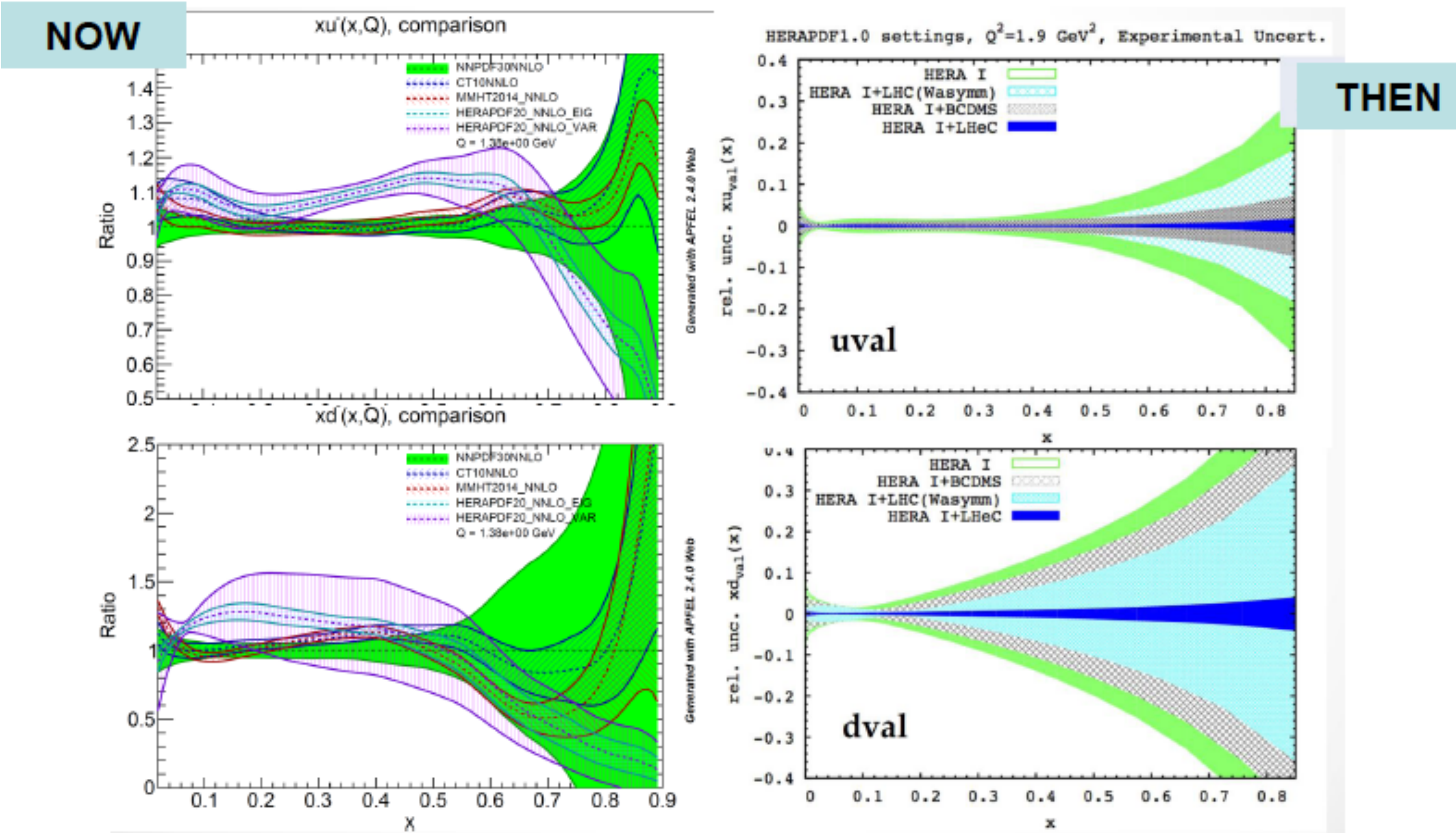


η dependence of pPb charged particle spectra best described by shadowing-only models (saturation models too steep?)

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

Valence Quarks at LHeC

Disentangle sea and valence through CC, xF_3 etc

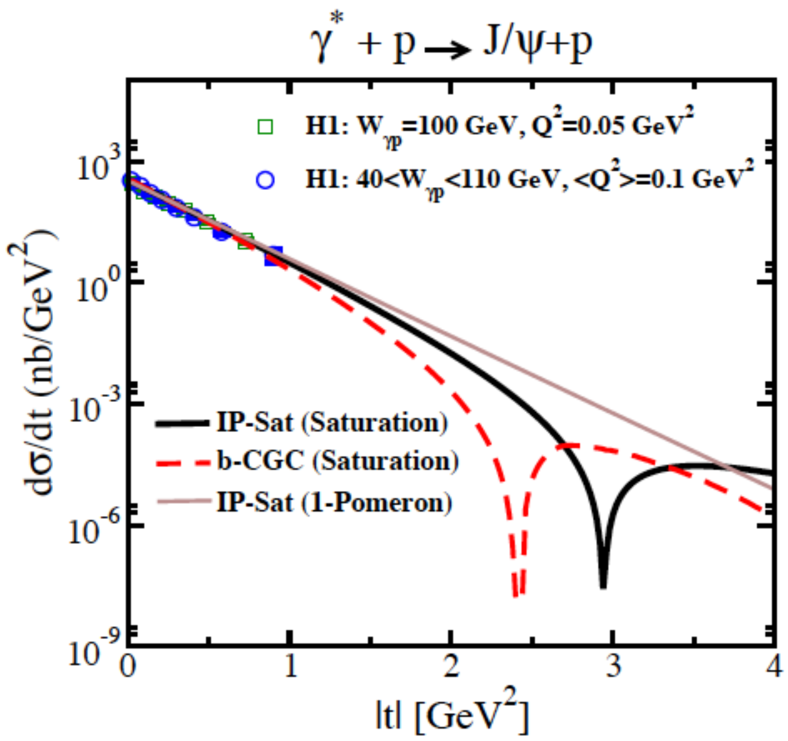


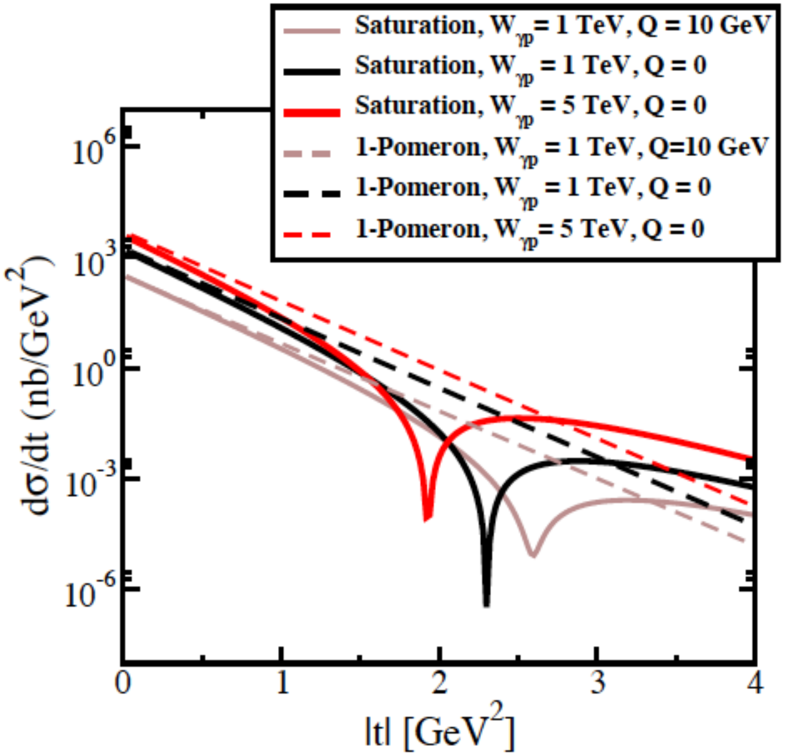
- Also, precision light quark axial / vector couplings, weak mixing angle, α_s and full flavour decomposition …

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

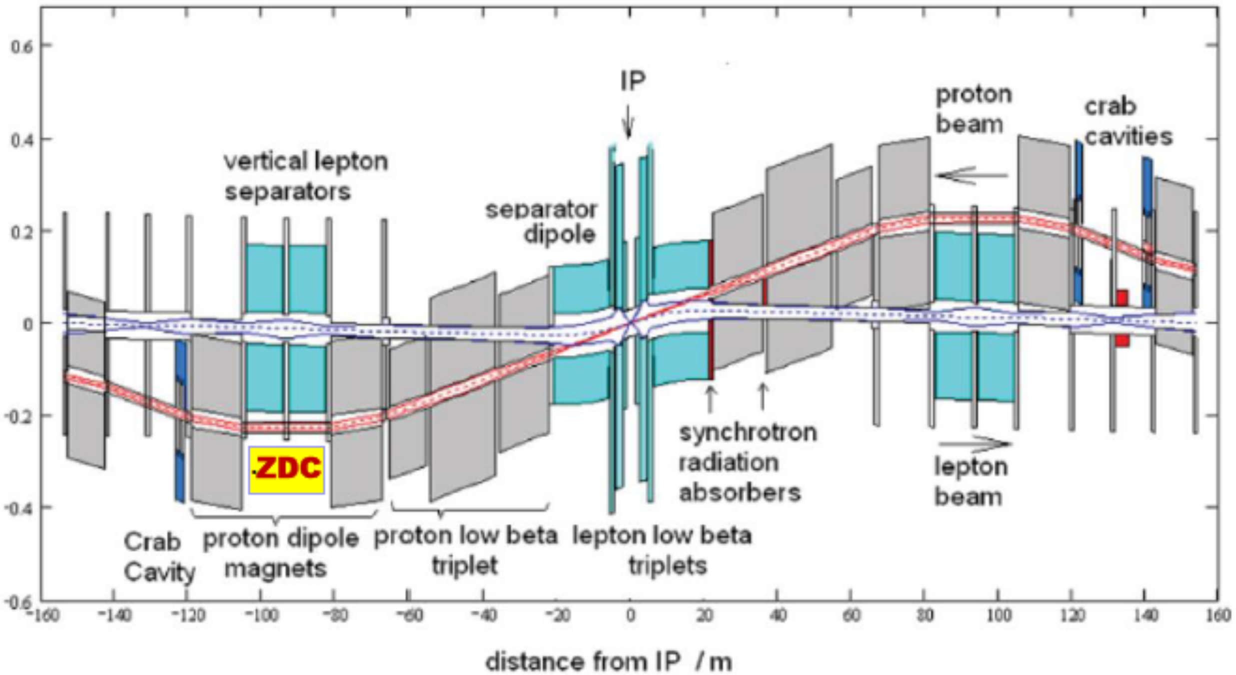
- Crucial in eA, to determine whether nucleus remains intact e.g. to distinguish coherent from incoherent diffraction

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

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

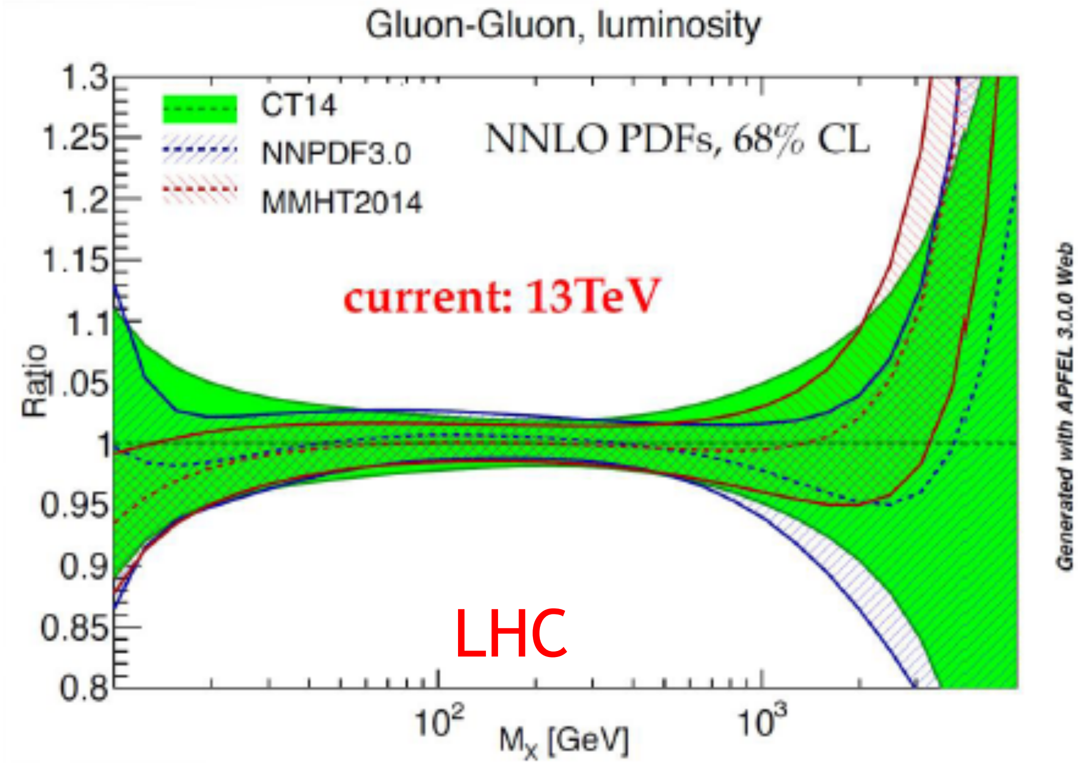
- Has previously been used in ep to study π structure function

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

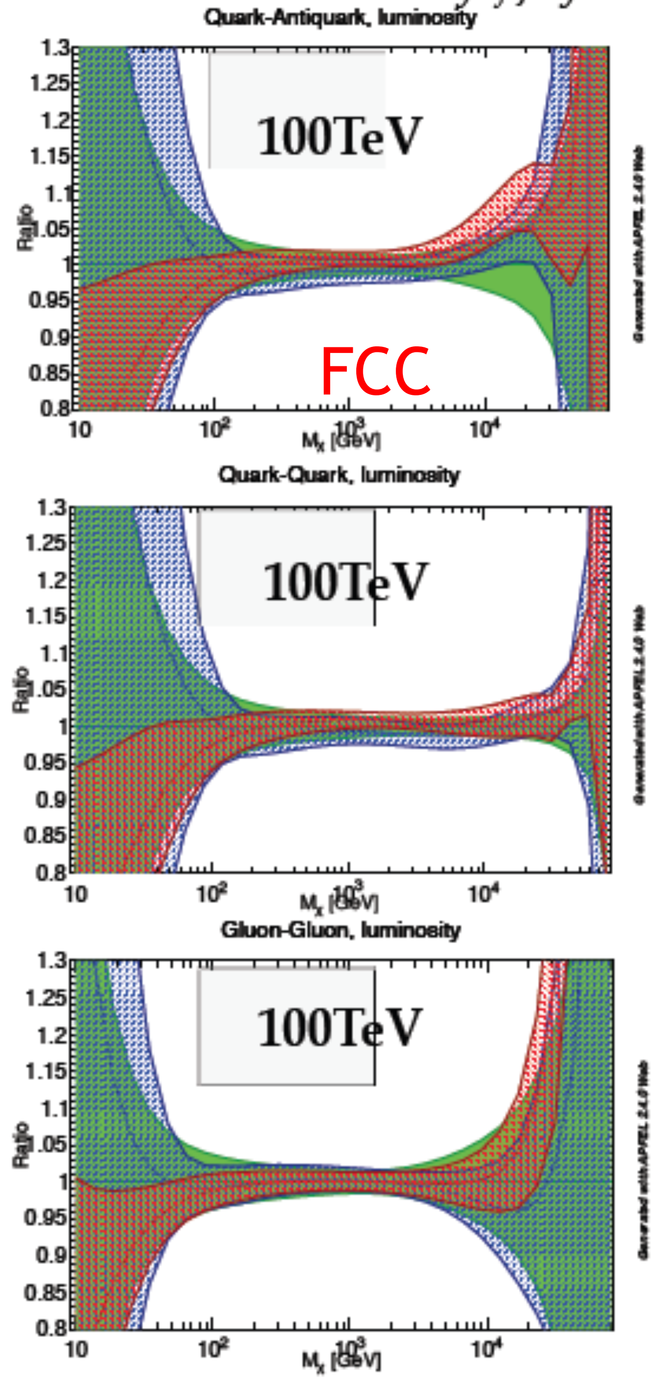


… to be further investigated

Current PDF Uncertainties



Courtesy of Joey Huston



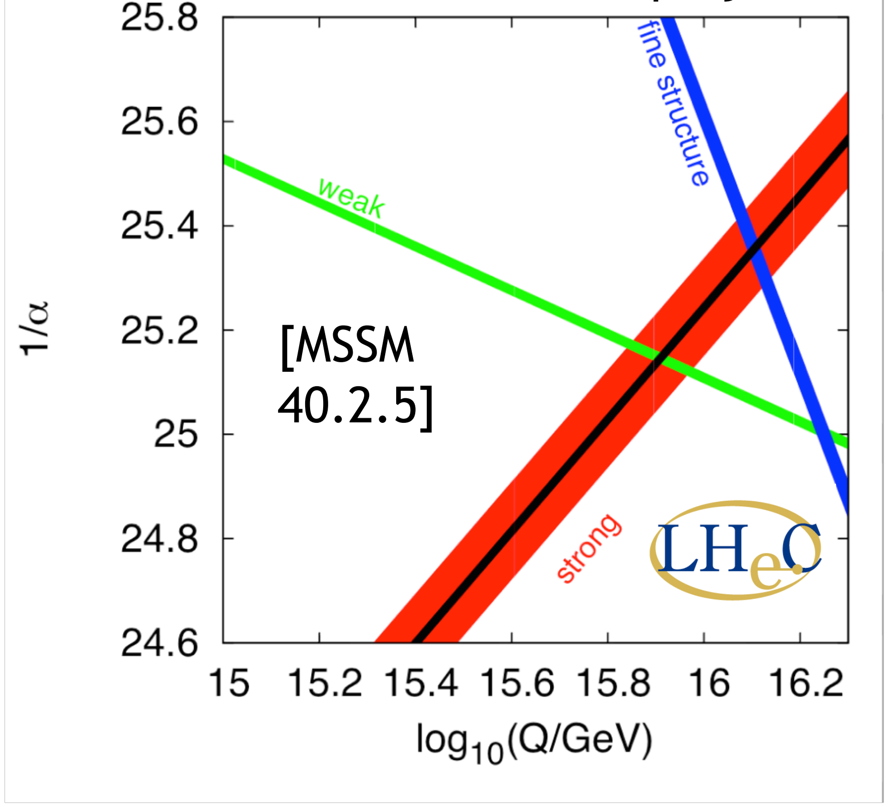
Low x / M_x → novel QCD / unitarity

Medium x / M_x → precision H and EW

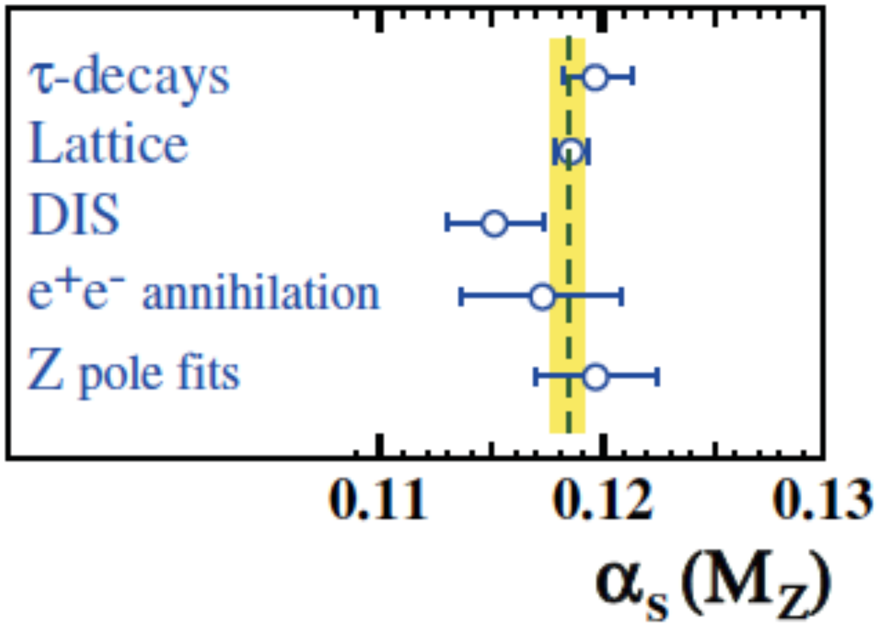
High x / M_x → new particle mass frontier

Precision α_s

Red = current world average
Black = LHeC projected



- Least constrained fundamental coupling by far (known to ~1%)
- Do coupling constants unify (with a little help from SUSY)?
- (Why) is DIS result historically low?



- Simulated LHeC precision from fitting inclusive data
→ per-mille (experimental)
→ also requires improved theory

Context of Precision α_s

Snowmass13 report – arXiv:1310.5189

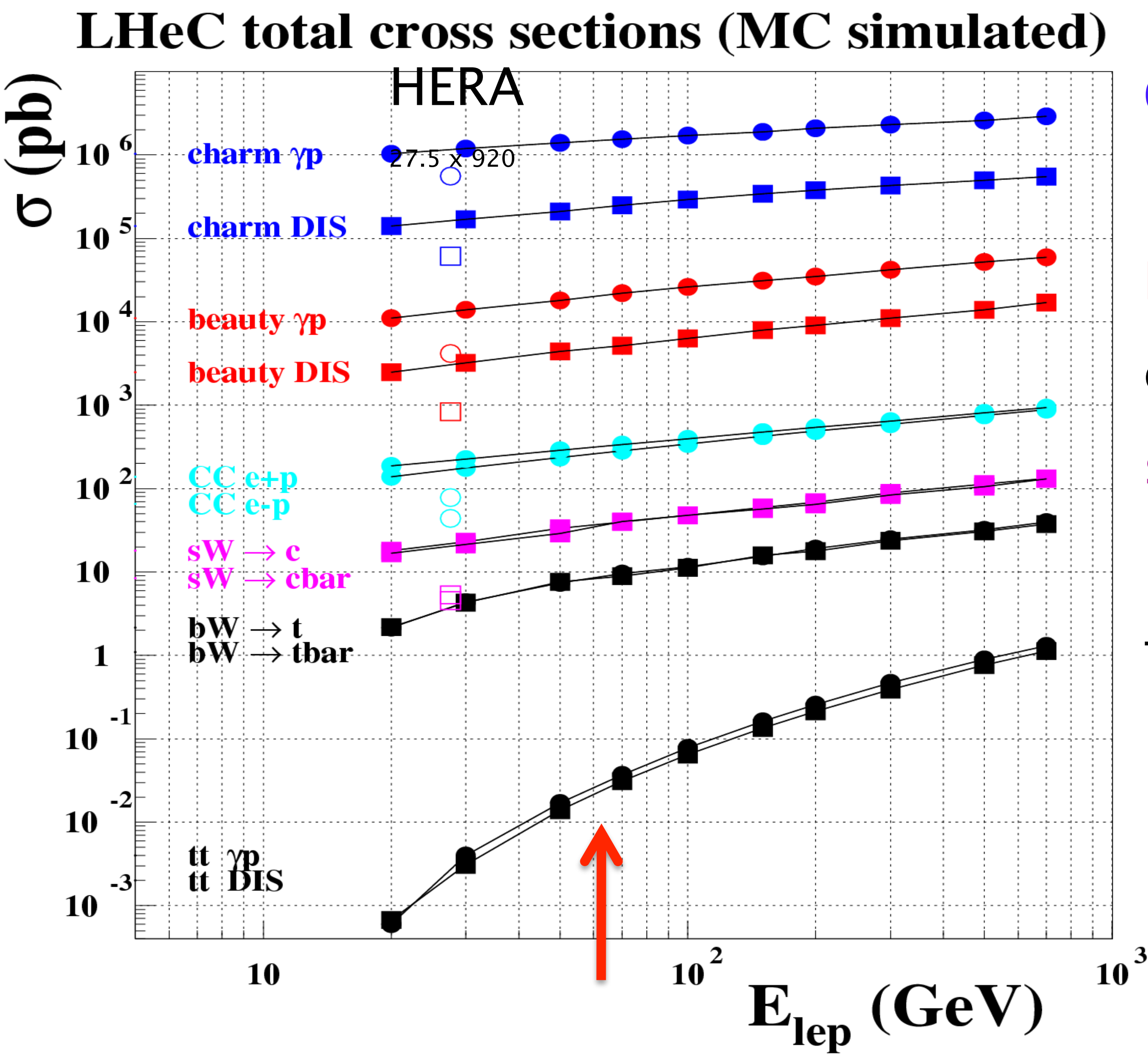
Method	Current relative precision	Future relative precision
e^+e^- evt shapes	expt $\sim 1\%$ (LEP) thry ~ 1–3% (NNLO+up to N^{3}LL, n.p. signif.) [27]	$< 1\%$ possible (ILC/TLEP) $\sim 1\%$ (control n.p. via Q^2-dep.)
e^+e^- jet rates	expt $\sim 2\%$ (LEP) thry $\sim 1\%$ (NNLO, n.p. moderate) [28]	$< 1\%$ possible (ILC/TLEP) $\sim 0.5\%$ (NLL missing)
precision EW	expt $\sim 3\%$ (R_Z, LEP) thry $\sim 0.5\%$ (N^{3}LO, n.p. small) [9,29]	0.1% (TLEP [10]), 0.5% (ILC [11]) $\sim 0.3\%$ (N^{4}LO feasible, ~ 10 yrs)
τ decays	expt $\sim 0.5\%$ (LEP, B-factories) thry $\sim 2\%$ (N^{3}LO, n.p. small) [8]	$< 0.2\%$ possible (ILC/TLEP) $\sim 1\%$ (N^{4}LO feasible, ~ 10 yrs)
ep colliders	~ 1–2% (pdf fit dependent) [30,31], (mostly theory, NNLO) [32,33]	0.1% (LHeC + HERA [23]) $\sim 0.5\%$ (at least N^{3}LO required)
hadron colliders	$\sim 4\%$ (Tev. jets), $\sim 3\%$ (LHC $t\bar{t}$) (NLO jets, NNLO $t\bar{t}$, gluon uncert.) [17,21,34]	$< 1\%$ challenging (NNLO jets imminent [22])
lattice	$\sim 0.5\%$ (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]	$\sim 0.3\%$ (~ 5 yrs [38])

per mille (precision EW)

per mille (ep colliders)

… tensions between lattice and DIS α_s results as a sensitive probe of new physics?...

Cross Sections and Rates for Heavy Flavours



Charm [10^{10} / 10 fb^{-1}]

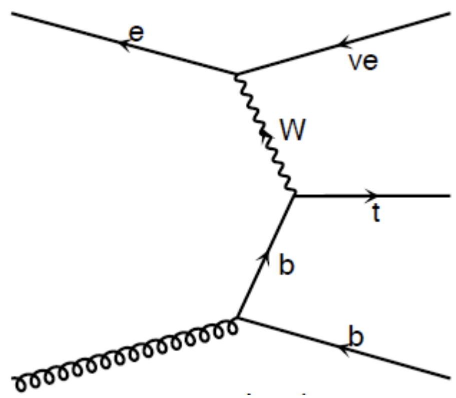
Beauty [10^{8} / 10 fb^{-1}]

cc

sW → c [4.10^{5} / 10 fb^{-1}]

bW → t [10^{5} / 10 fb^{-1}]

ttbar [10^{3} / 10 fb^{-1}]



c.f. luminosity of ~10-100 fb^{-1} per year

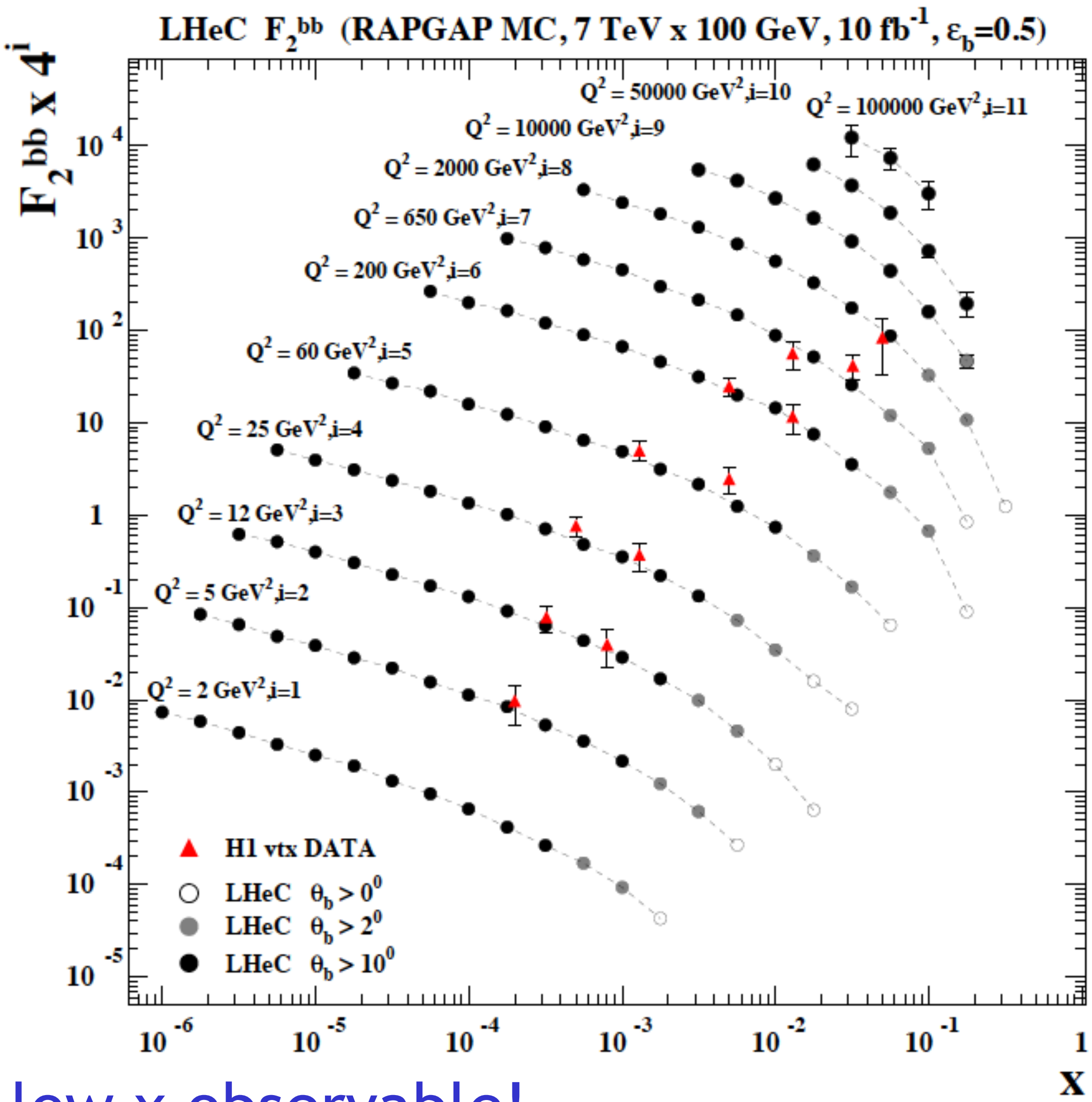
...

e.g. Beauty Production

Precise c, b measurements from impact parameter distributions (modern Si trackers, beam spot 15 * 35 μm^2 , increased HF rates at higher scales).

(Assumes 10 fb^{-1} and
- 50% beauty, 10% charm efficiency
- 1% uds → c mistag probability.
- 10% c → b mistag)

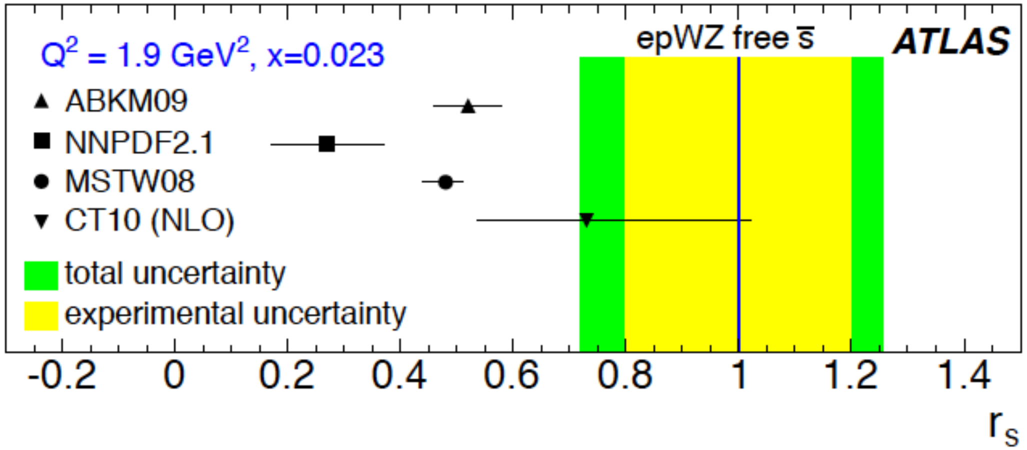
Systematics at 10% level

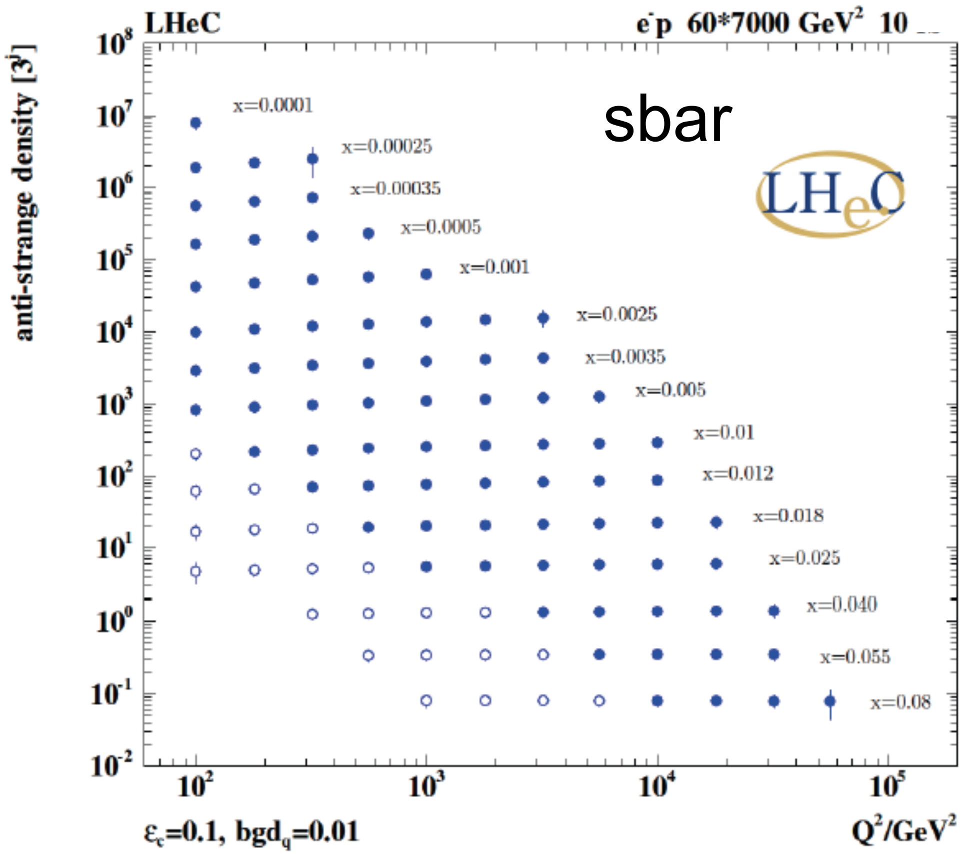


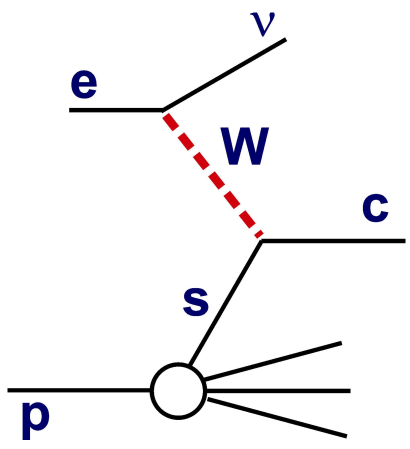
→beauty as a low x observable!

e.g. Strange and Anti-strange Quarks

Evidence from LHC that strange density is larger than thought: SU(3) symmetric sea?...



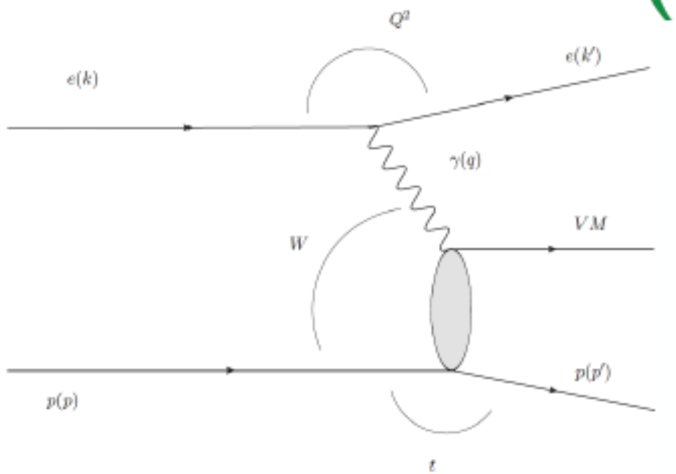


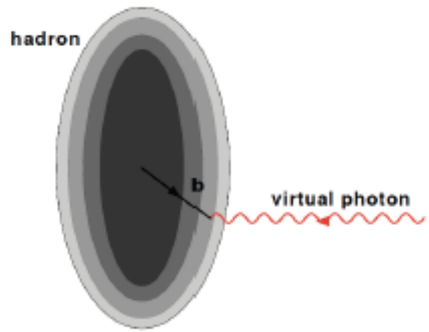


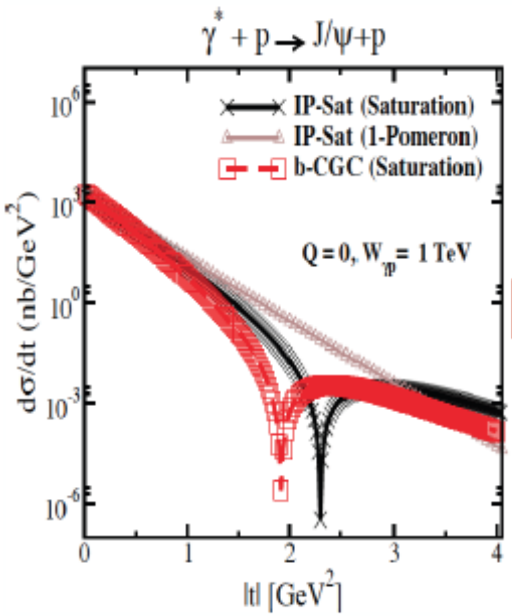
Assuming 10% charm tagging efficiency, 1% light quark background

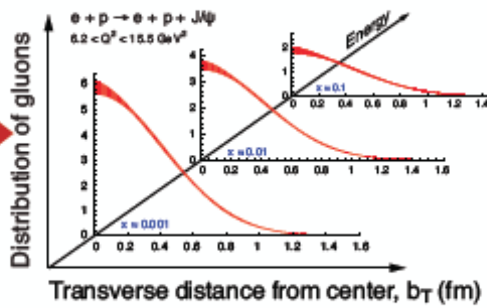
Transverse structure (I):

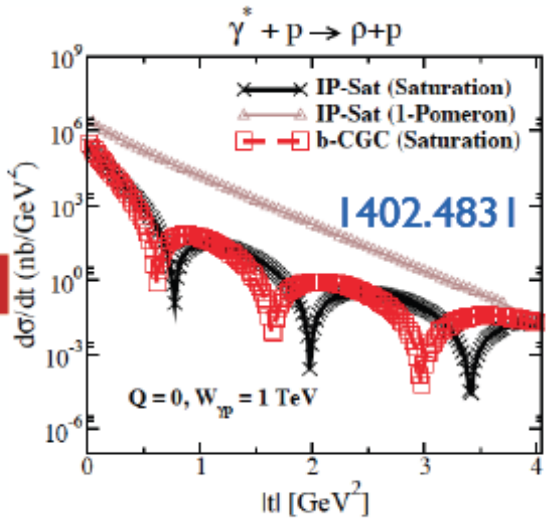
- Exclusive VM meson production/DVCS provides a transverse scan of the partonic structure of the hadron, may also be sensitive to dynamics:









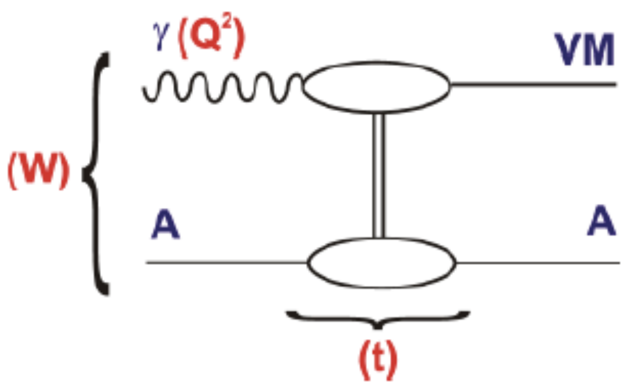


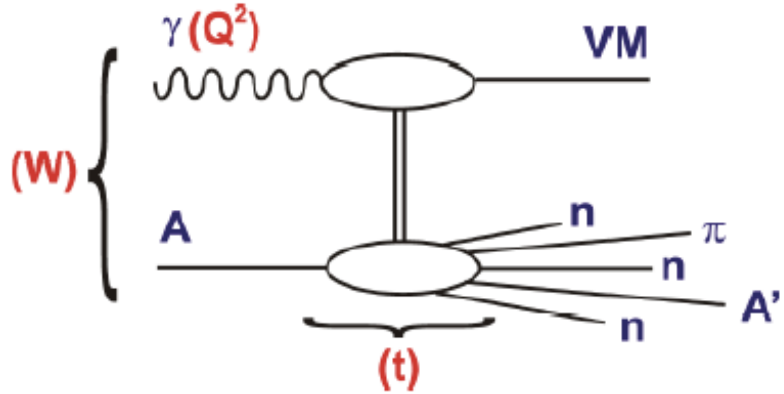
1402.4831

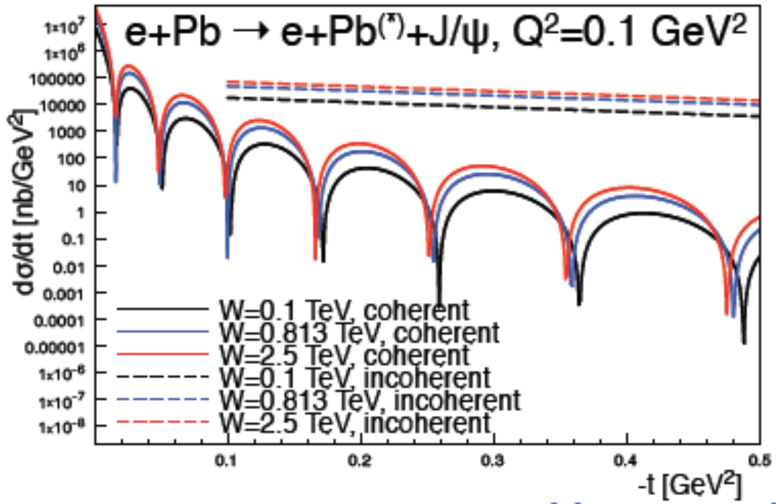
Rezaeian

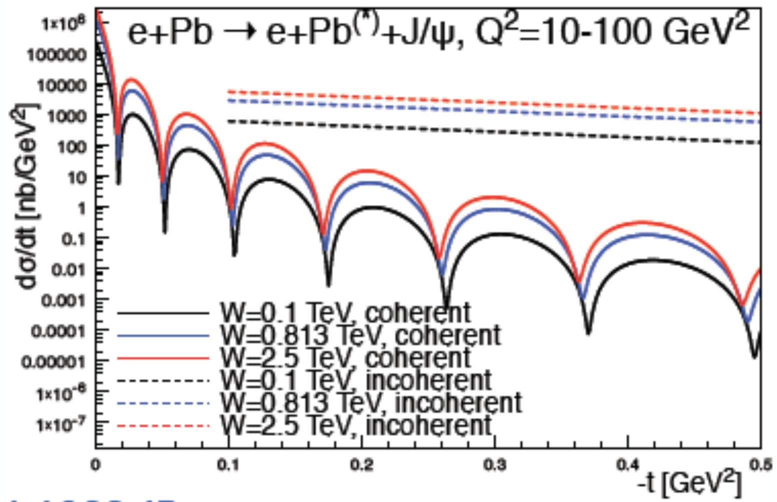
Transverse structure (II):

- Coherent versus incoherent diffraction may help to solve the issue of the existence/number of hot spots in p and A, relevant for fluctuations, azimuthal asymmetries, definition of MPIs,…









Mantysaari, 1011.1988, IPsat

The LHeC pseudodata

- Assume $\mathcal{L}_{\mathrm{ep}} = 10\,\mathrm{fb}$, $\mathcal{L}_{\mathrm{ePb}} = 1\,\mathrm{fb}$ (per nucleon)
- Considered energy configs: $\sqrt{s_{\mathrm{p}}} = 7\,\mathrm{TeV}$, $\sqrt{s_{\mathrm{Pb}}} = 2.75\,\mathrm{TeV}$ (per nucleon) on $E_e = 60\,\mathrm{GeV}$ electrons.
- The pseudodata are here obtained from ratios of reduced cross sections σ^i_{ePb}, σ^i_{ep} and relative point-to-point ($\delta^i_{\mathrm{uncor.}}$) and normalization ($\delta^i_{\mathrm{uncor.}}$) uncertainties as

$$R_i = R_i(EPS09) \times \left[1 + \delta^i_{\mathrm{uncor.}} r^i + \delta_{\mathrm{norm.}} r^{\mathrm{norm.}}\right]$$

where

$$R_i(EPS09) = \frac{\sigma^i_{\mathrm{ePb}}(CTEQ6.6 + EPS09)}{\sigma^i_{\mathrm{ep}}(CTEQ6.6)},$$

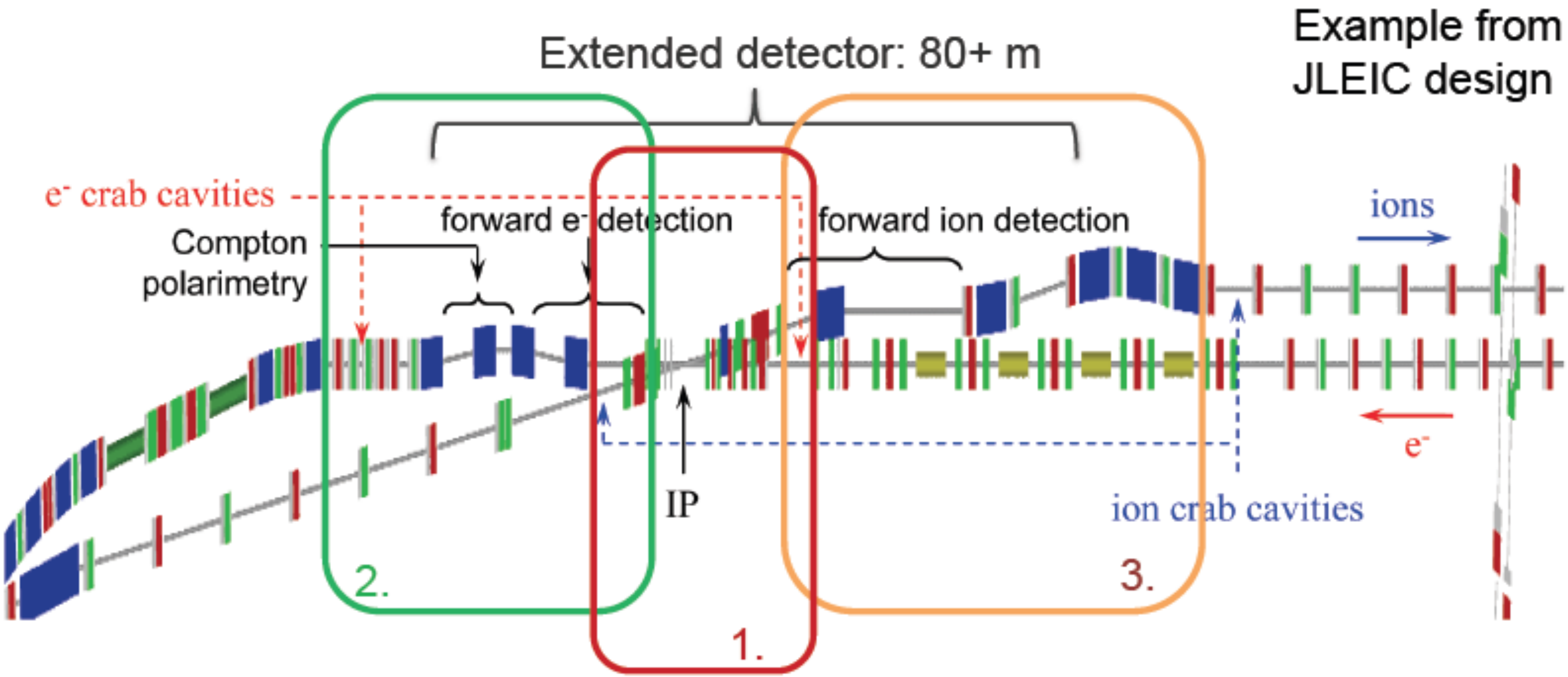
and r^i and $r^{\mathrm{norm.}}$ are Gaussian random numbers.

- In EPS09 $R_{u_V} \approx R_{d_V}$, $R_{\overline{u}} \approx R_{\overline{d}} \approx R_{\overline{s}}$ (free in EPPS16, but would not expect large deviations from this)
- EPS09 and CTEQ6.6 used only in generating the pseudodata.

EIC Forward Proton Spectrometer

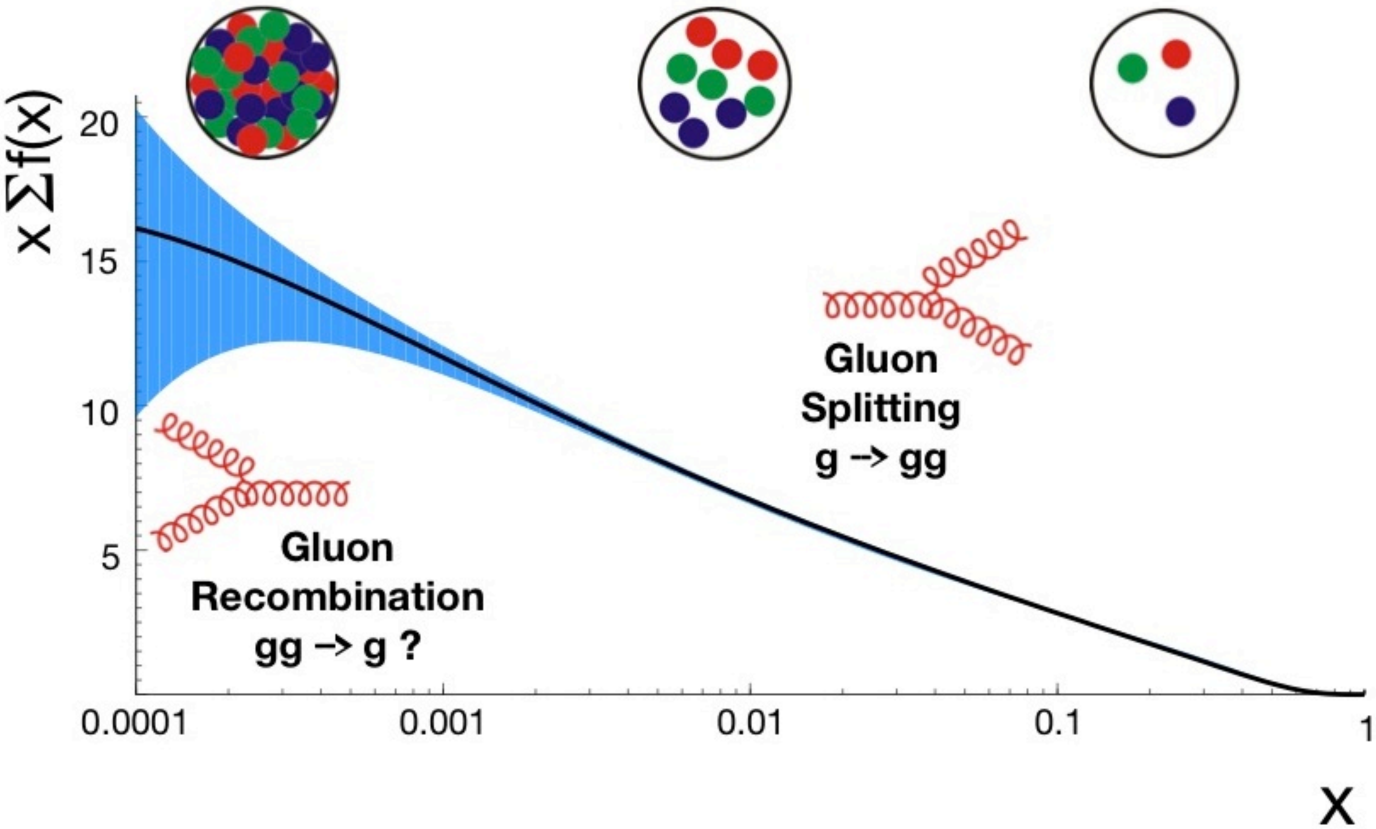
- Beamline instrumentation intrinsic to design from outset
- Many possible access points:

4m , 18m, 38m at eRHIC
12m – 45m at JLEIC



Low-x Physics and Parton Saturation

• Somewhere & somehow, the low x growth of cross sections must be tamed to satisfy unitarity …
non-linear effects

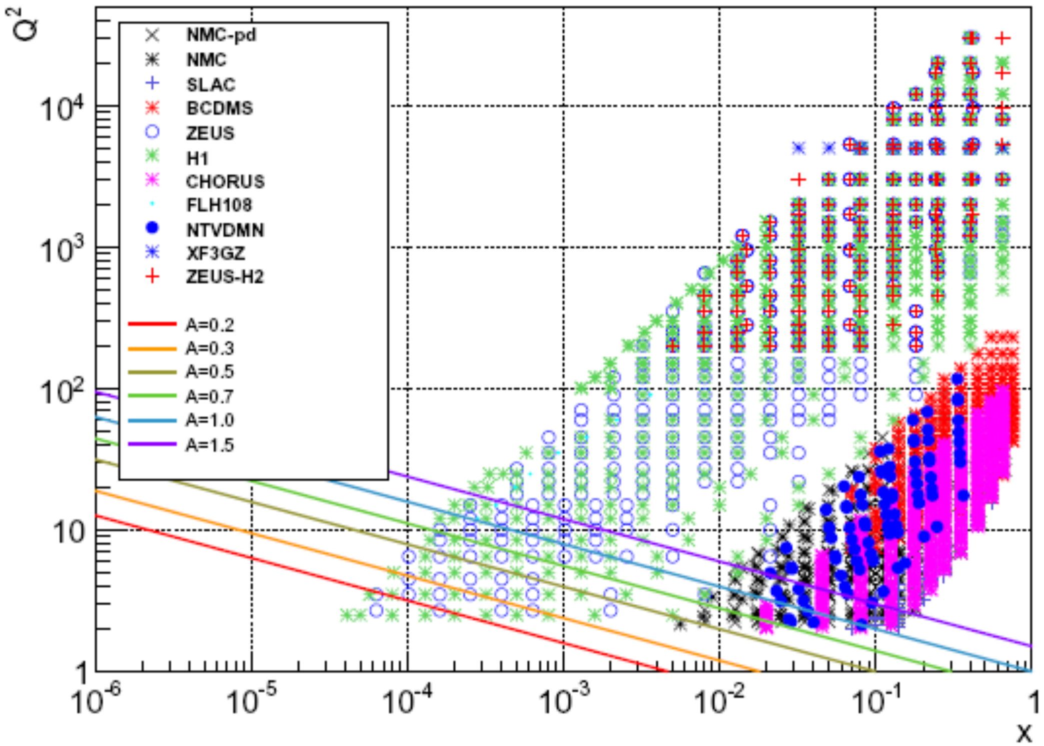


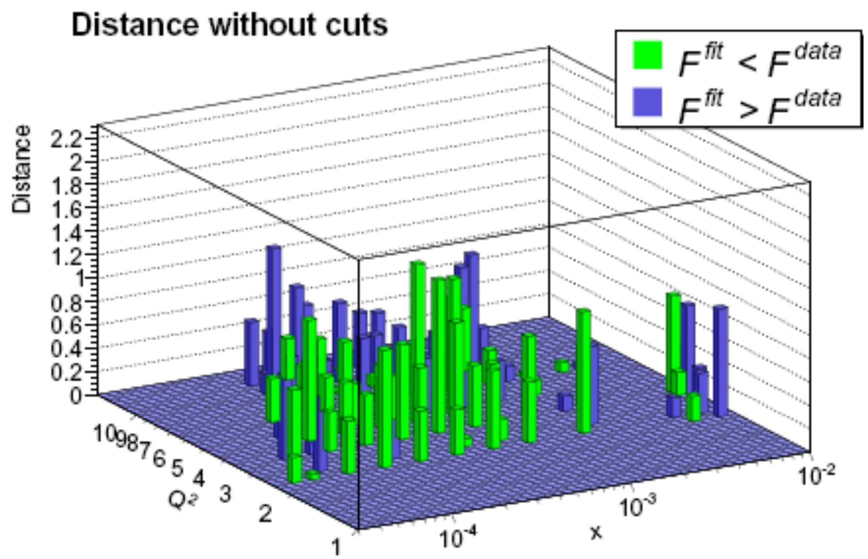
→new high density, small coupling parton regime of non-linear parton evolution dynamics

• x dependent "saturation scale", $Q^2_s(x)$ and dynamics of onset not well known theoretically:

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

e.g. NNPDF study of low Q^2 NLO DGLAP



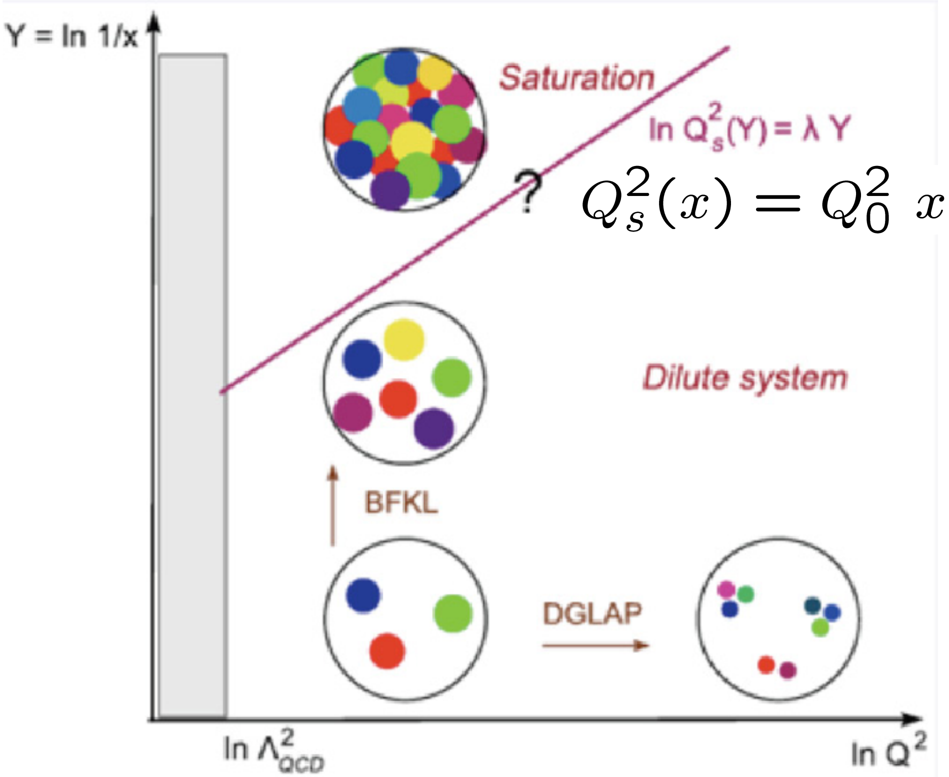


- Fit HERA data in limited regions above lines of $Q^2 > Ax^{-0.3}$
  → backwards evolve to lower scales and compare χ^2
- Signed pulls show backward evolution consistently above data

… something happens, but not easily interpreted …

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

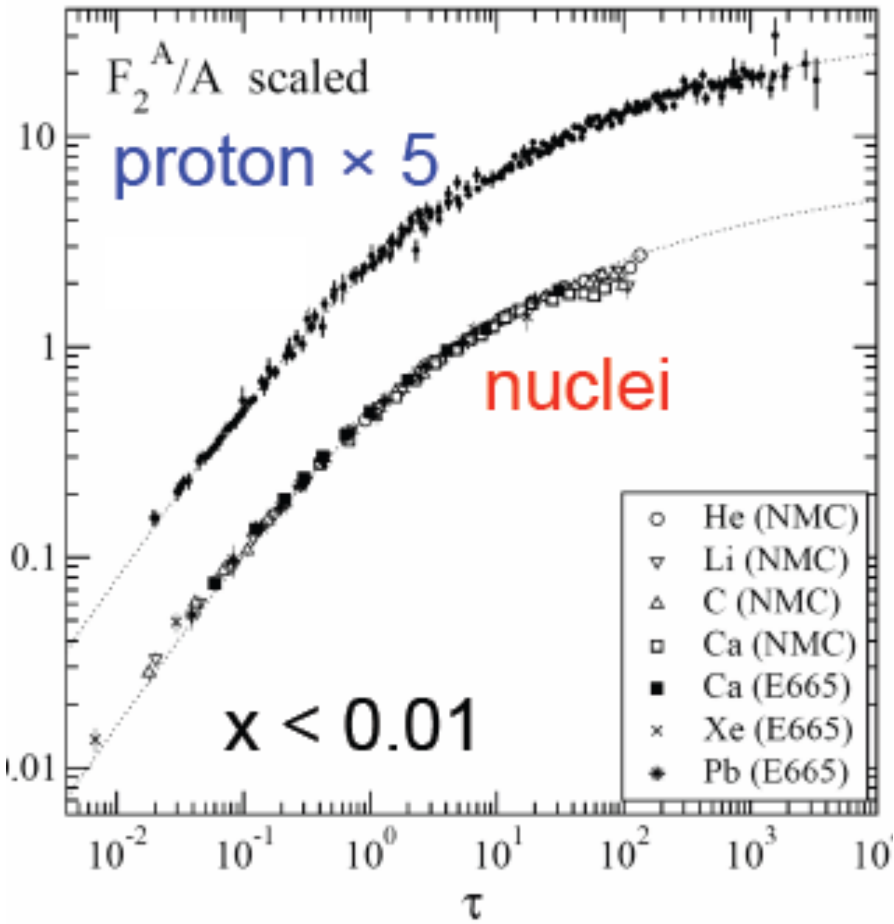
Non-linear effects in HERA and eA Data?



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

Lines of constant ‘blackness’ diagonal … scattering cross section appears constant along them … “Geometric Scaling”

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



Something appears to happen around $\tau = Q^2/Q^2_s = 1$ (confirmed in many analyses)

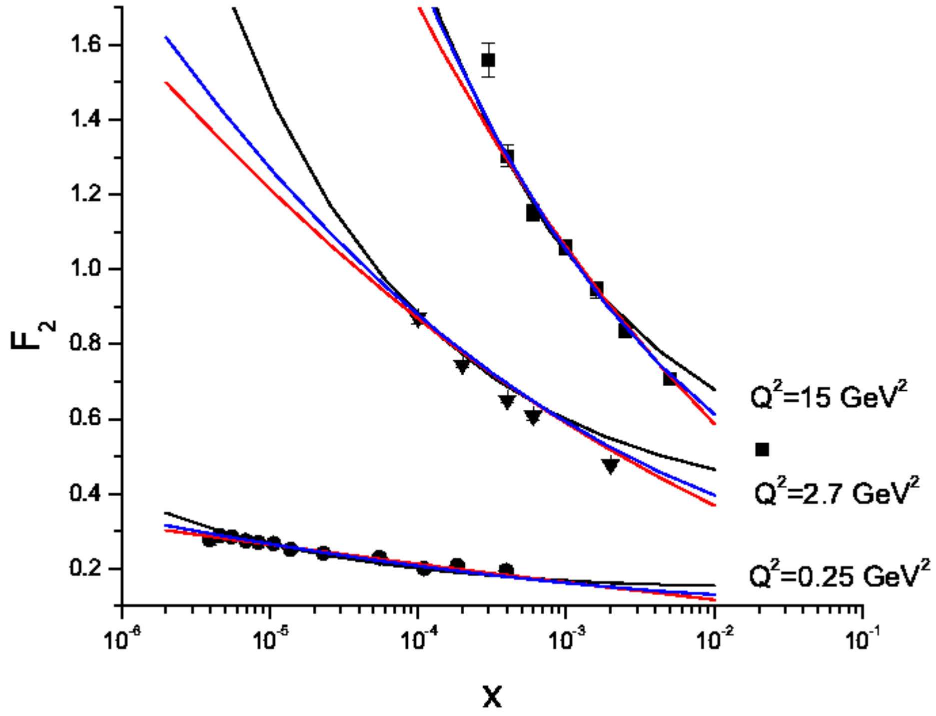
BUT … Q^2 small for τ <~ 1

… not easily interpreted in QCD

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

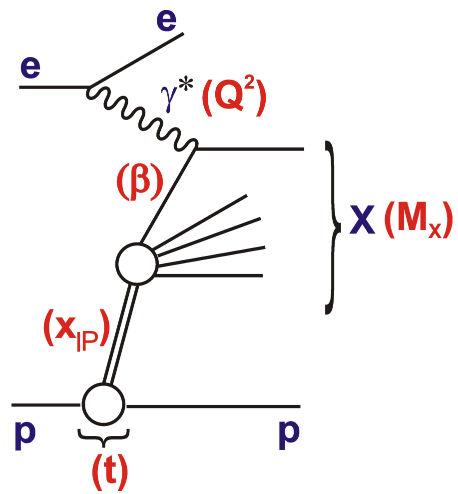


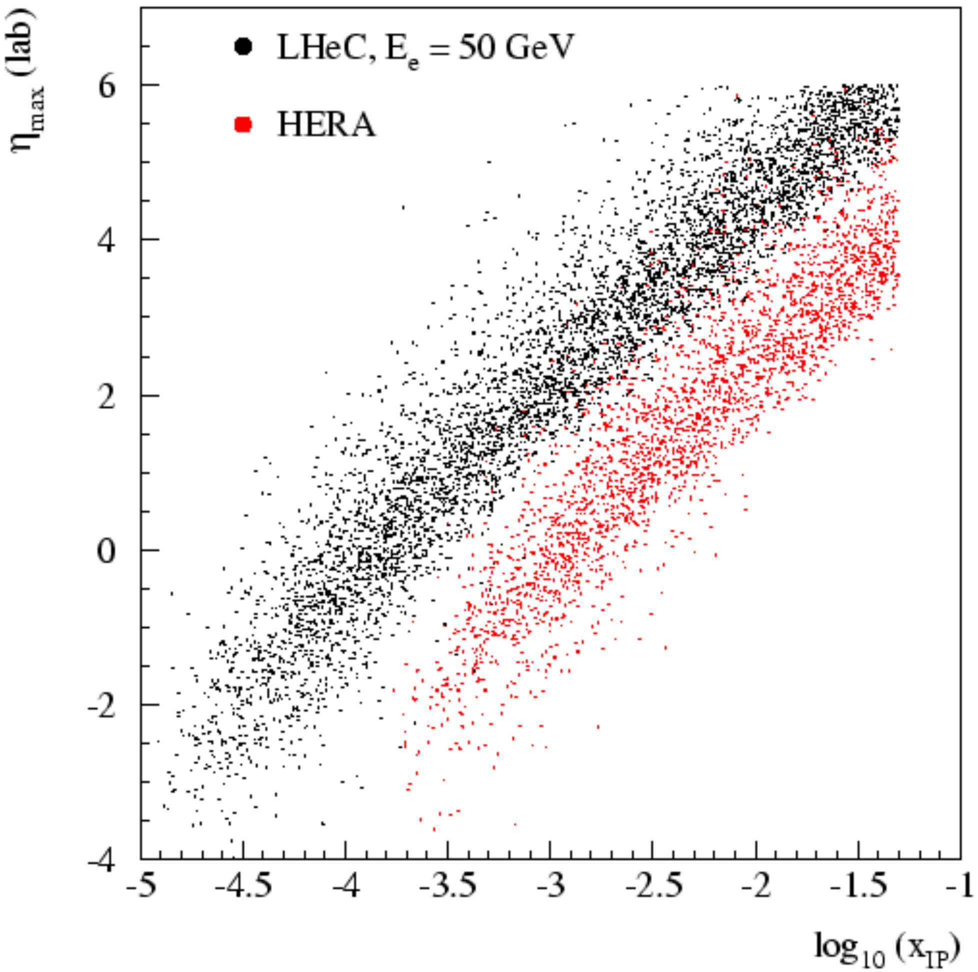
FS04 Regge (~FKS): 2 pomeron model, <u>no saturation</u>
FS04 Satn: <u>Simple implementation of saturation</u>
CGC: <u>Colour Glass Condensate version of saturation</u>

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

<u>… any saturation at HERA not easily interpreted partonically</u>

Rapidity Gap Selection

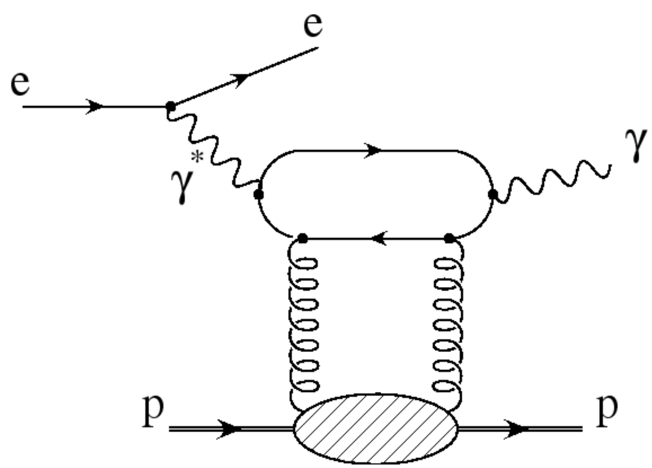




– η_{max} v ξ correlation entirely determined by proton beam energy

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

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

1º and 10º cuts for scattered electron

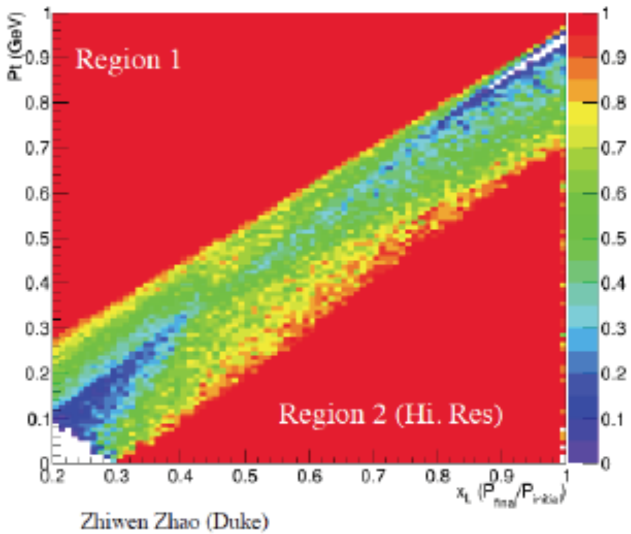
→Kinematic range determined largely by cut on p_T^{γ}

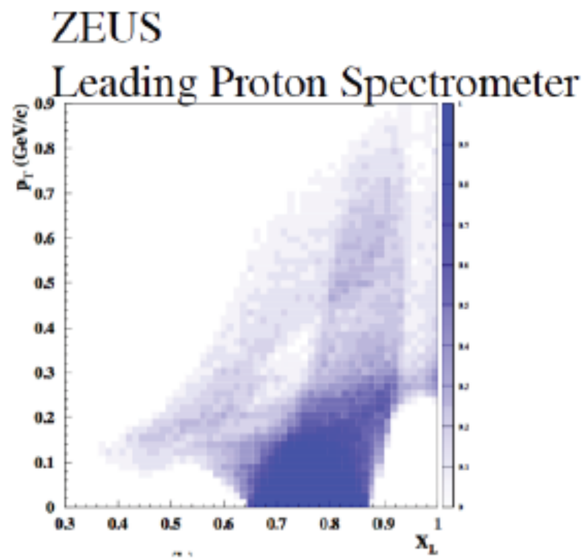
(relies on ECAL performance / linearity at low energies)

EIC Forward Proton Spectrometer

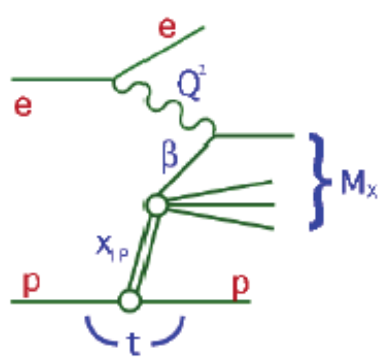
Full Acceptance for Forward Physics!

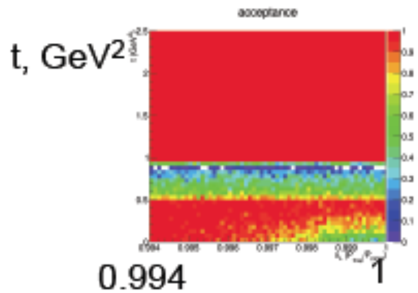
Example: acceptance for p’ in e + p → e’ + p’ + X





Diffraction





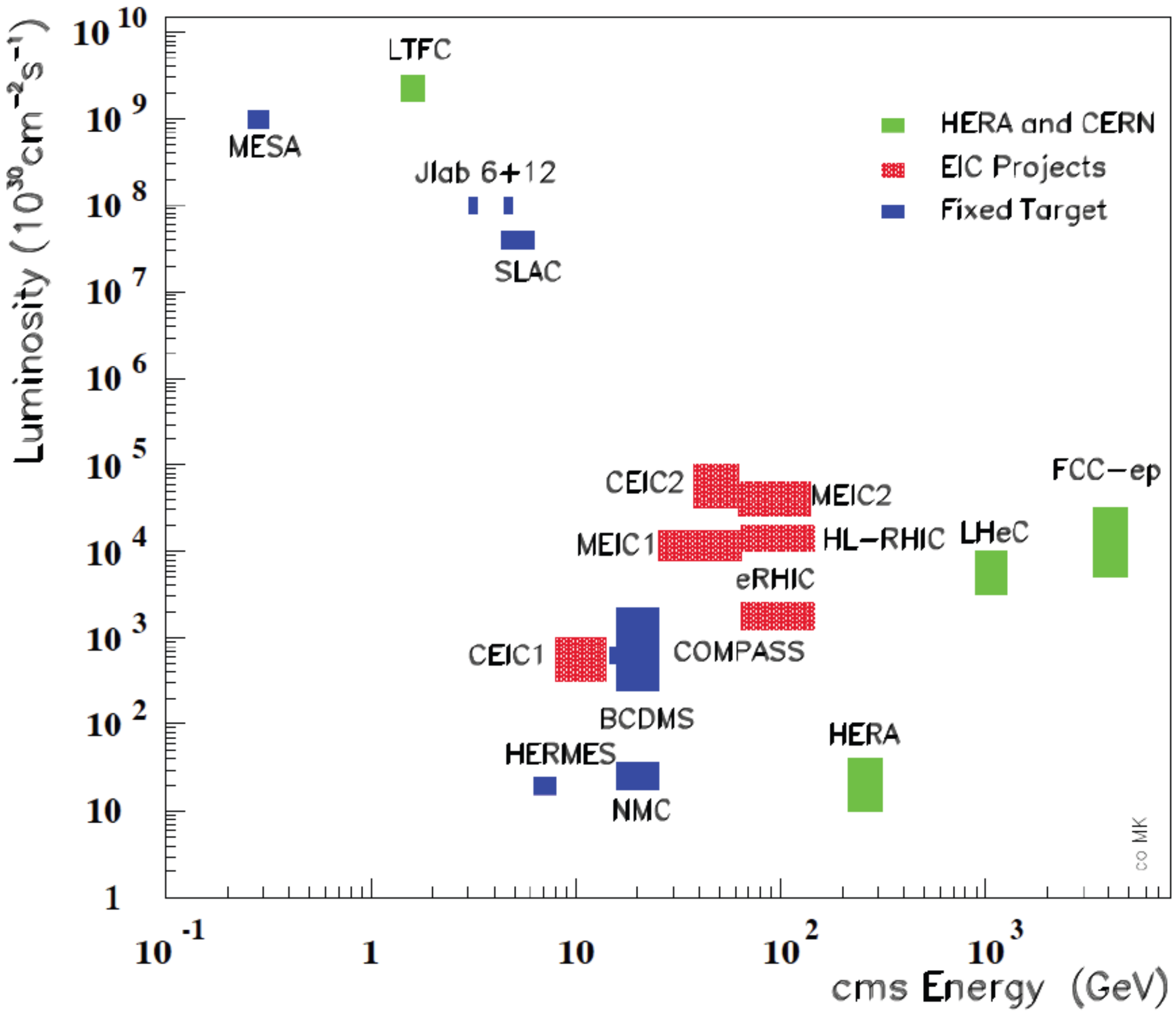
Acceptance in diffractive peak (X_L>~.98)

ZEUS: ~2%

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

These detectors came of age at LHC: we should be ambitious

LHeC / FCC-he Context



Main weakness: No polarised hadrons

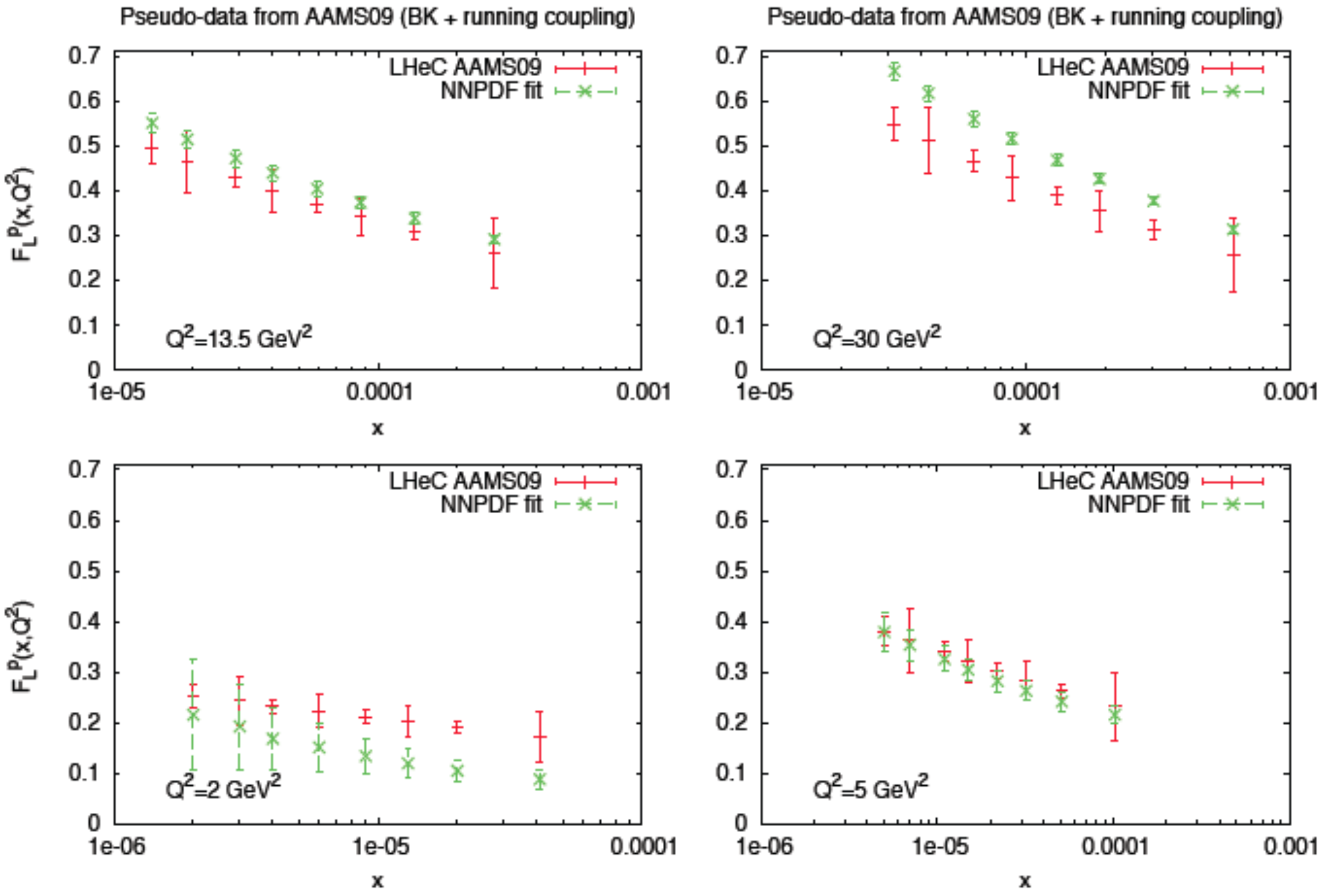
Lepton-hadron scattering at the TeV scale …

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

Establishing Saturation in Inclusive Data

(Lack of) quality of NNPDF fit to F_2 and F_L pseudodata with saturation effects included …



• 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