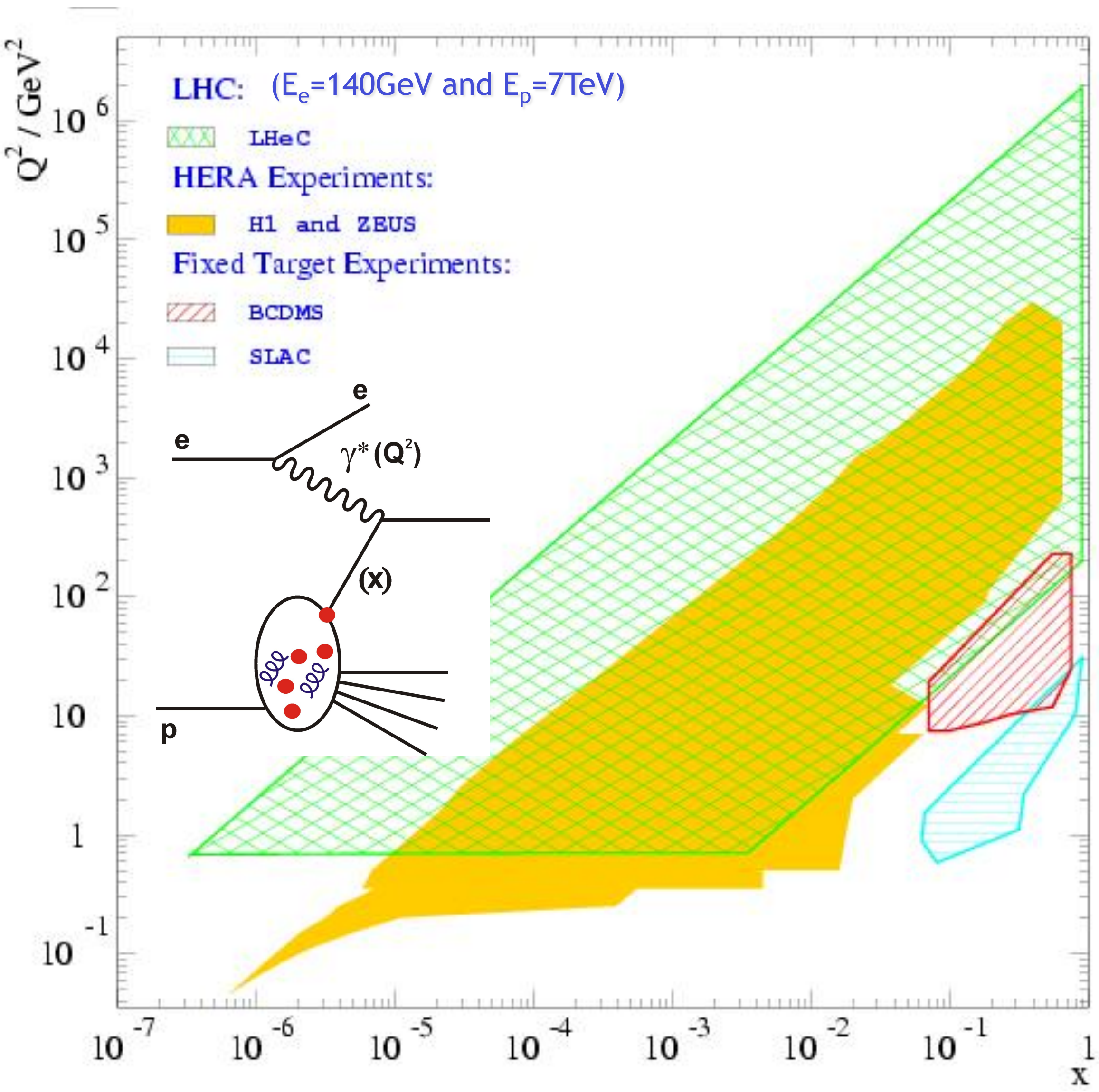
Overview of ep Physics at LHeC

Paul Newman
Birmingham University,



LHeC-UK @Liverpool
8 May 2012

A second generation lepton-hadron collider in the 2020s, based on the high luminosity phase of the LHC

http://cern.ch/lhec

Mostly Material from Conceptual Design Report

arXiv:1206.2913 [physics.acc-ph]

J. Phys. G39 (2012) 075001

Further work published in two documents Submitted to European Strategy Exercise

Summary of Project in general:
arXiv:1211.4831 [hep-ex]

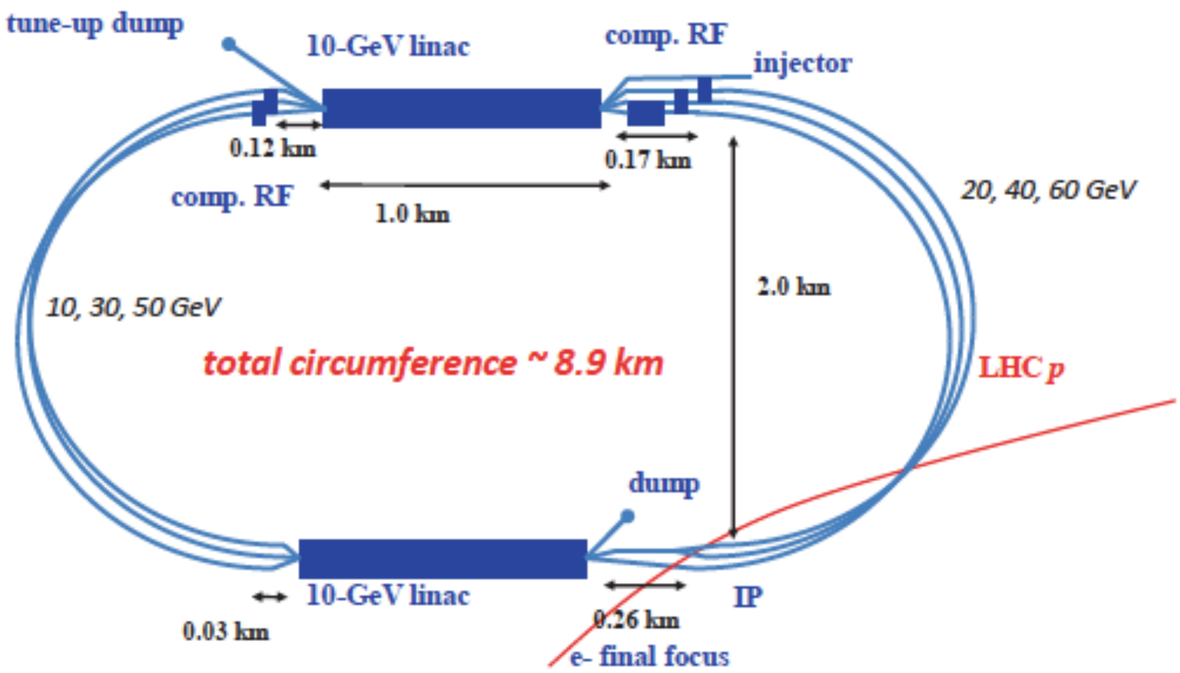
Relationship between LHC & LHeC
arXiv:1211.5102 [hep-ex]

Baseline CDR Design (Electron "Linac")

Design constraint: power<100MW → **E_e = 60 GeV @ 10^{33} cm^{-2} s^{-1}**

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

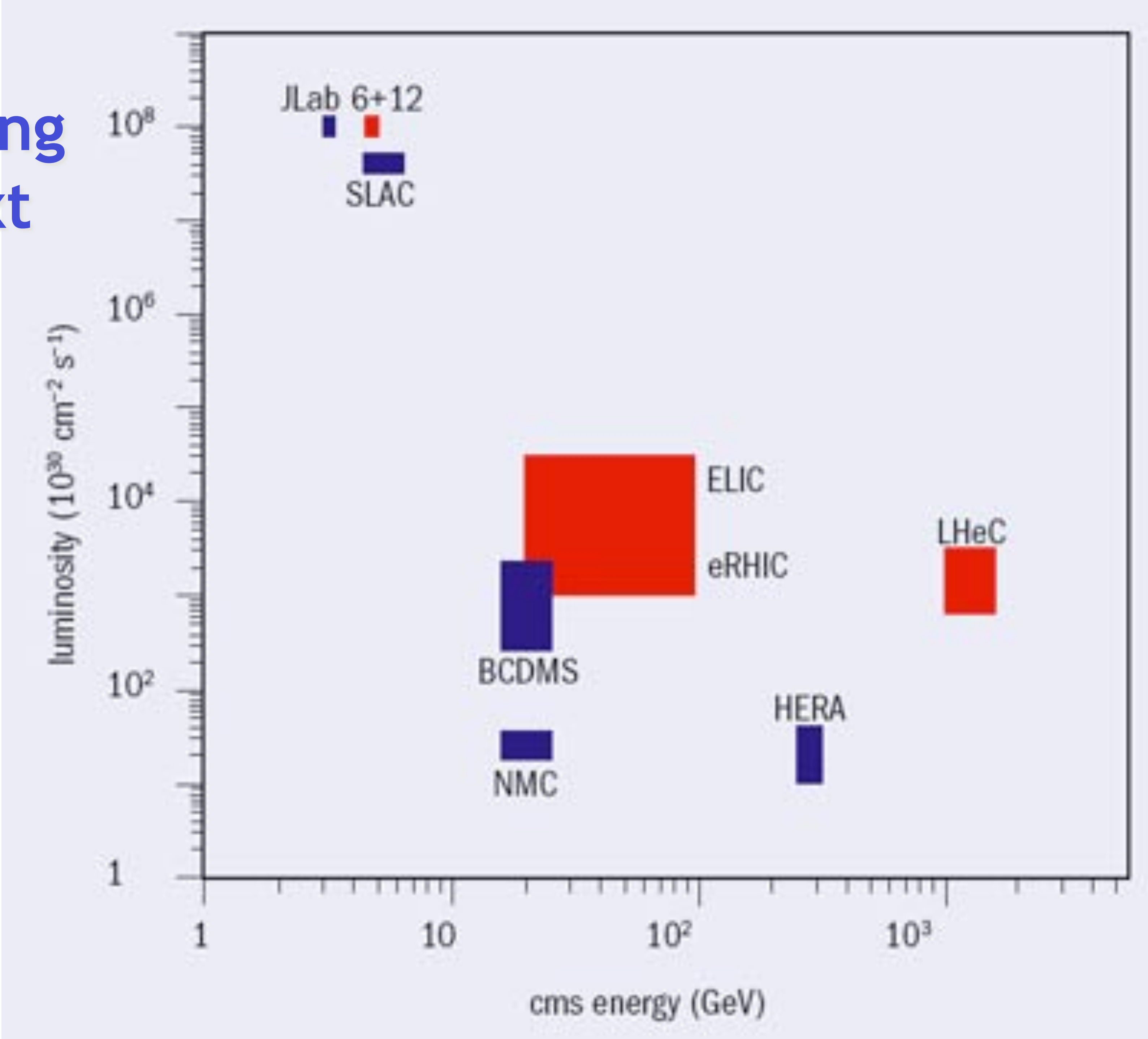
[CERN plans energy recovery prototype]



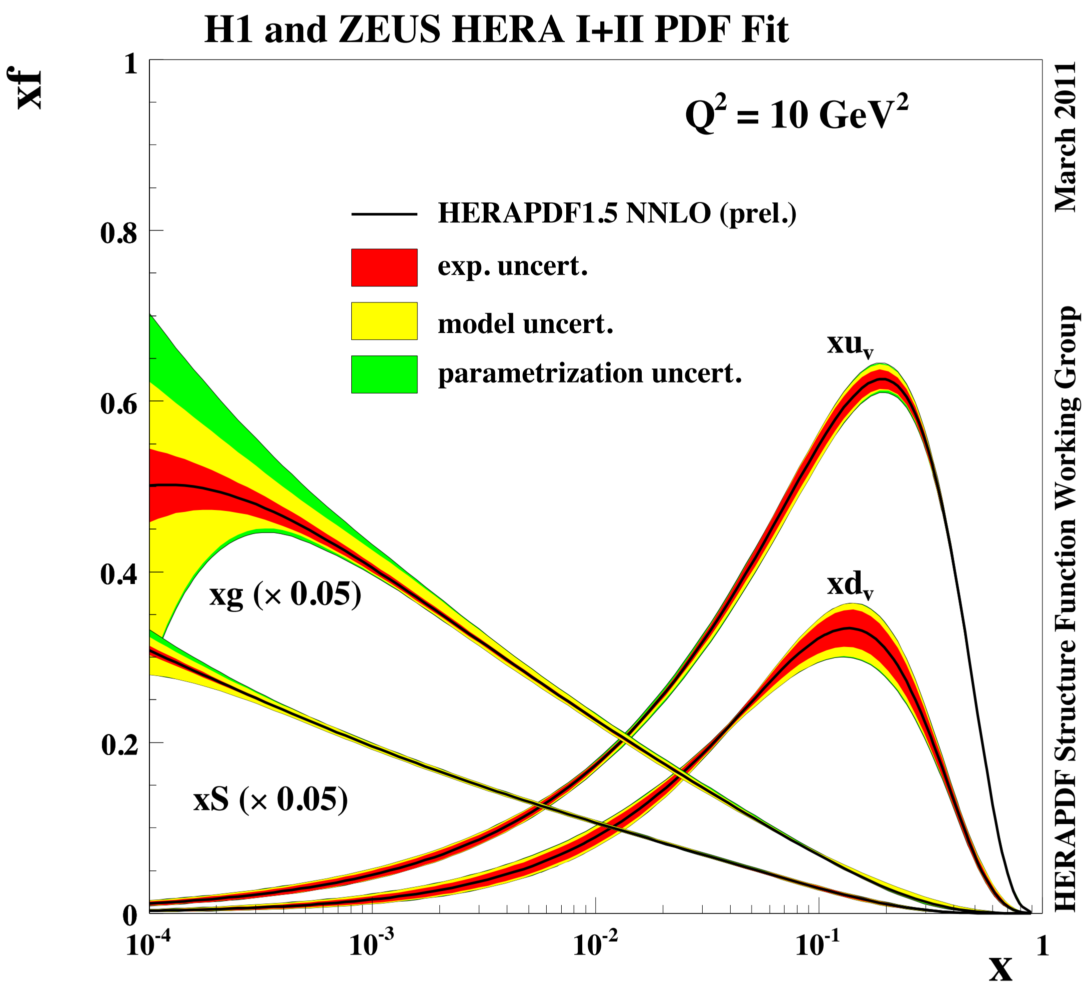
- ep Lumi ~ 10^{33} cm^{-2} s^{-1} corresponds to ~10 fb^{-1} per year (~ 100 fb^{-1} total)
- eD and eA collisions have always been integral to programme
- e-nucleon Lumi estimates ~ 10^{31} (10^{32}) cm^{-2} s^{-1} for eD (ePb)

- Since CDR: ep lumi of 10^{34} cm^{-2} s^{-1} appears possible.

ep Scattering Context



HERA's greatest legacy



- Further progress requires higher energy and luminosity …

Proton parton densities in x range well matched to LHC rapidity plateau

Some limitations:

- Insufficient lumi for high x precision

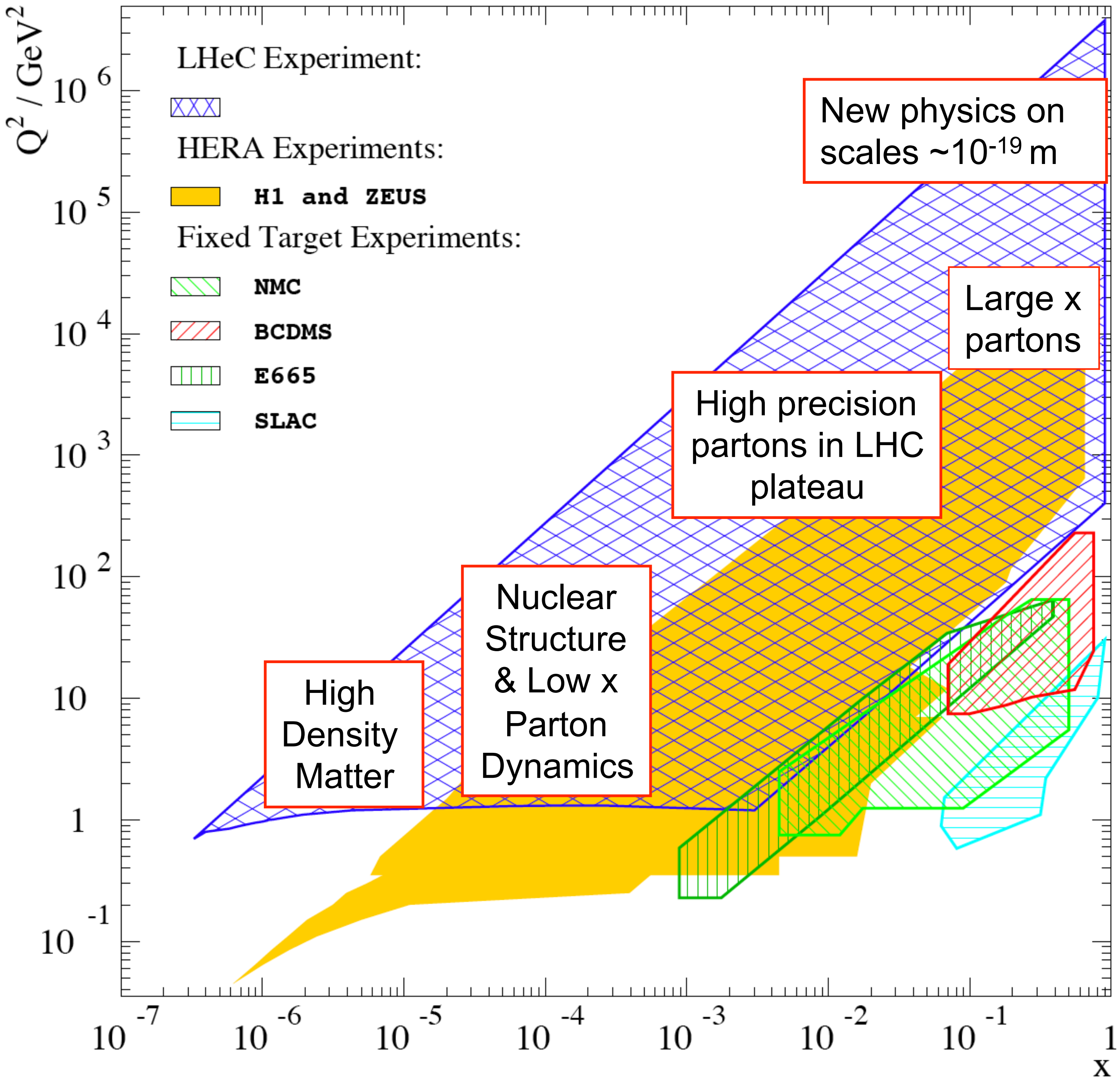
- Lack of Q^2 lever-arm for low x gluon

- Assumptions on quark flavour decomposition

- No deuterons … u and d not separated

- No heavy ions

LHeC Kinematics & Motivation

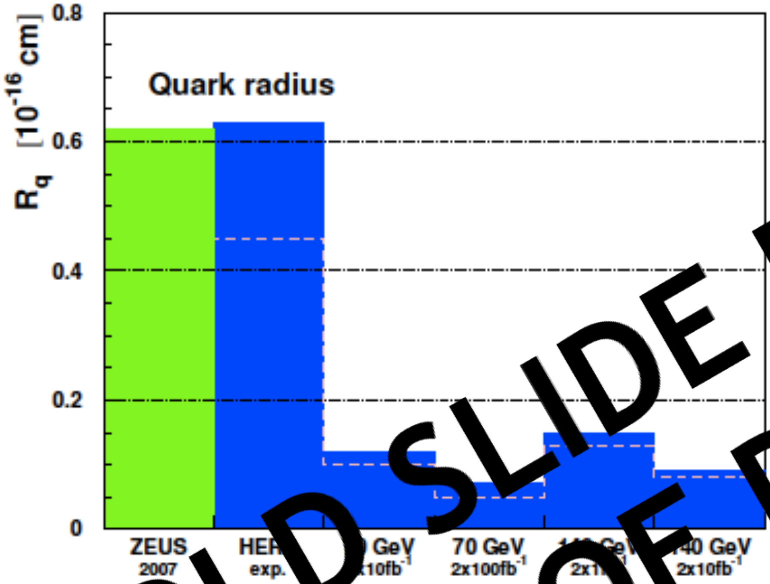


Direct Sensitivity to New Physics

Direct Sensitivity to New Physics

OLD SLIDE FROM DARK DAYS OF PRE 10^{34} LUMI

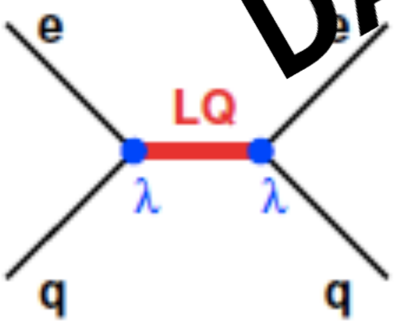
- The (pp) LHC has much better discovery potential than LHeC (unless E_e increases to ~500 GeV and Lumi to 10^{34} cm^{-2} s^{-1})

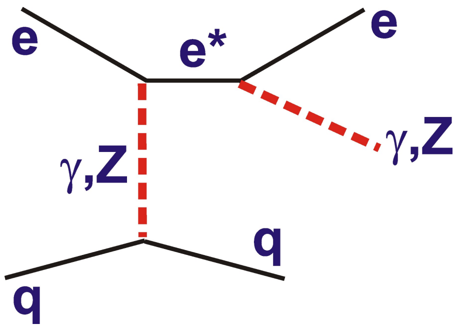


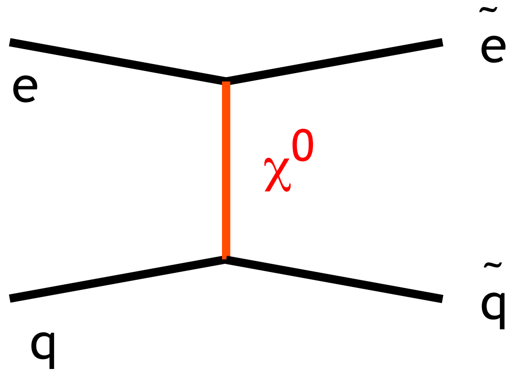
e.g. Expected quark compositeness limits below 10^{-19} m at LHeC

… big improvement on HERA, but already beaten by LHC

- LHeC *is* competitive with LHC in cases where initial state lepton is an advantage and offers cleaner final states







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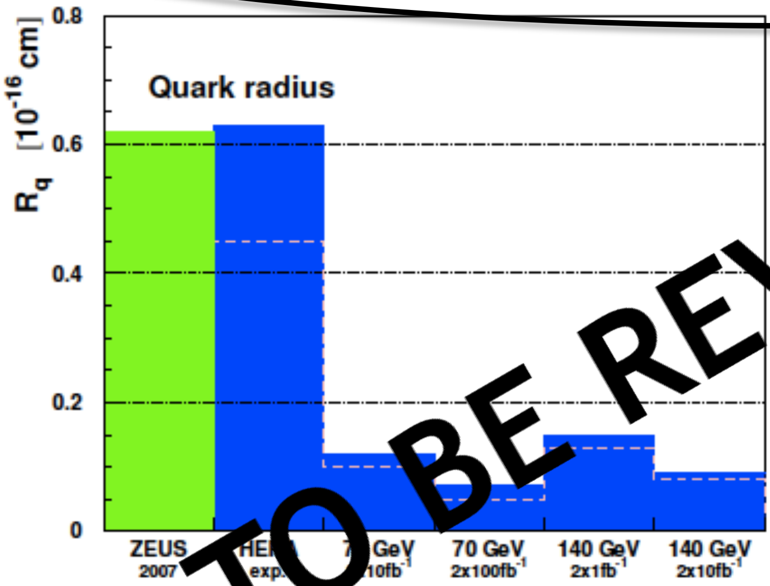
TO BE REVISITED…



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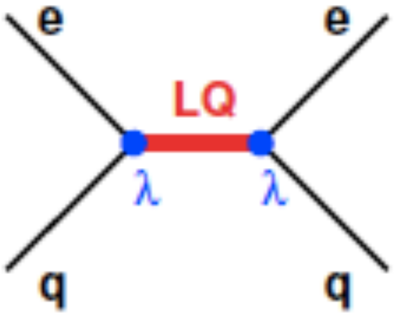
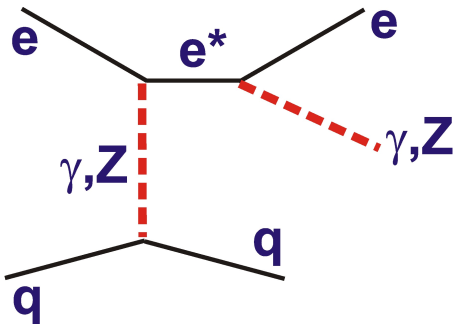
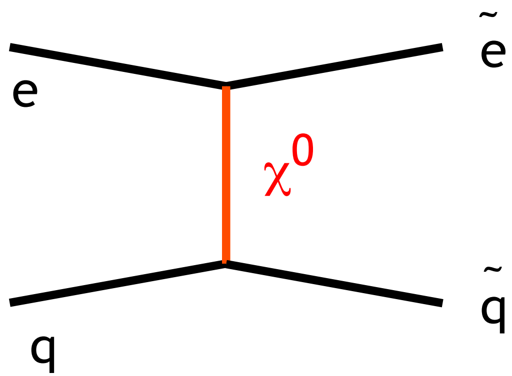
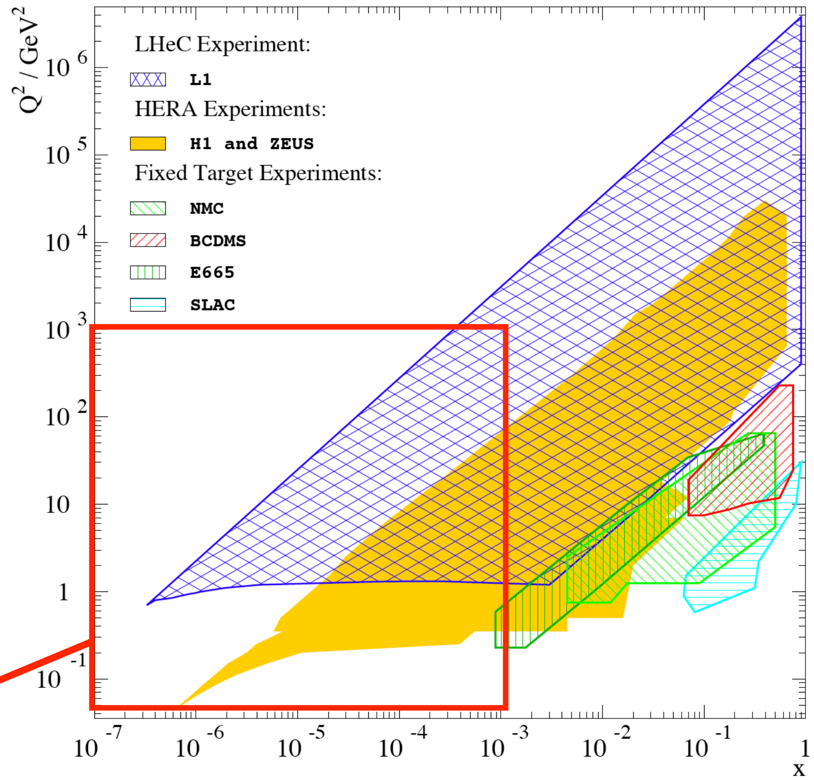


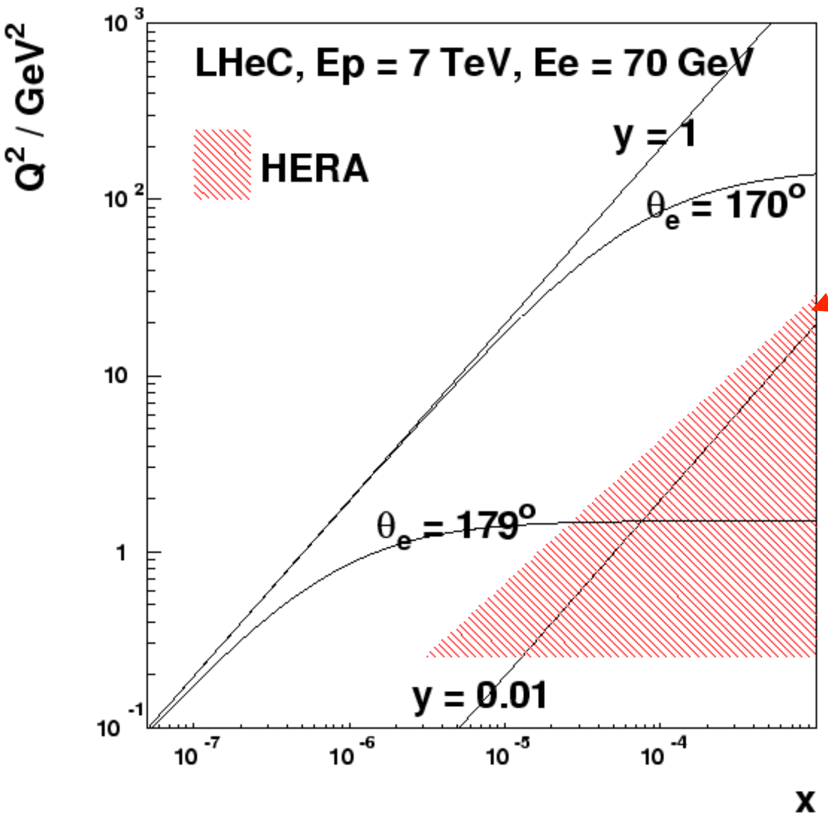




Detector Acceptance Requirements



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



Similarly, need 1° acceptance in outgoing proton direction to contain hadrons at high x (essential for good kinematic reconstruction)

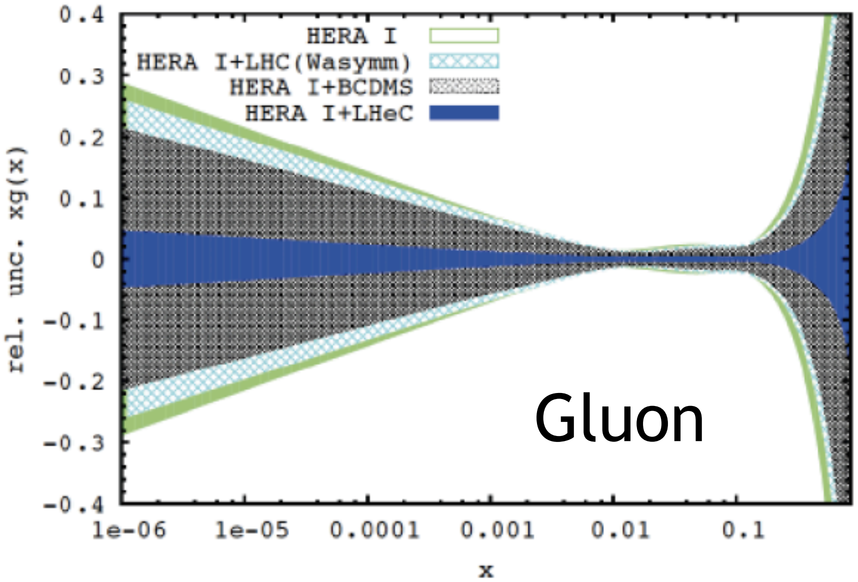
Assumed Systematic Precision

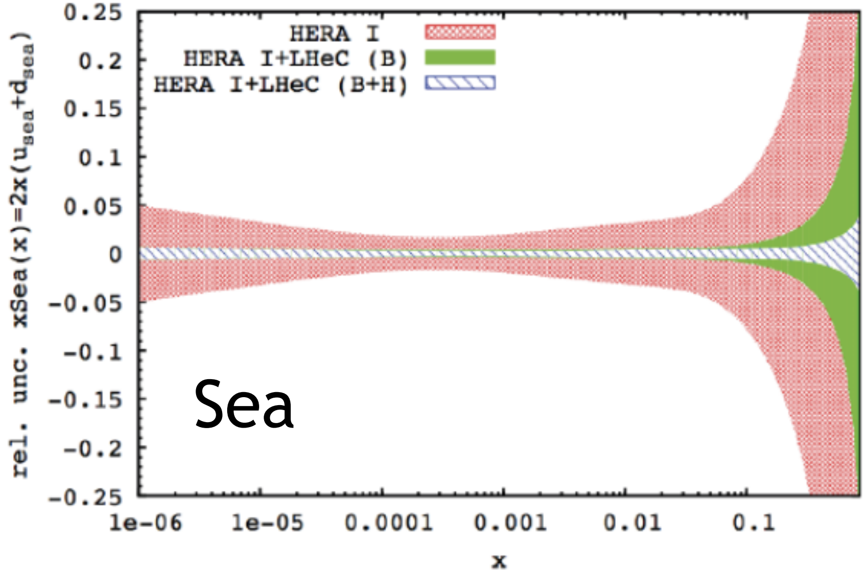
In the absence of a detailed simulation set-up, simulated \`pseudo-data' produced with reasonable assumptions on systematics (typically 2x better than H1 and ZEUS at HERA).

	LHeC	HERA
Lumi [$cm^{-2}s^{-1}$]	10^{33}	$1\text{-}5*10^{31}$
Acceptance [°]	1-179	7-177
Tracking to	0.1 mrad	0.2-1 mrad
EM calorimetry to	0.1%	0.2-0.5%
Hadronic calorimetry	0.5%	1-2%
Luminosity	0.5%	1%

PDF Constraints at LHeC

Full simulation of inclusive NC and CC DIS data, including systematics → NLO DGLAP fit using HERA technology…

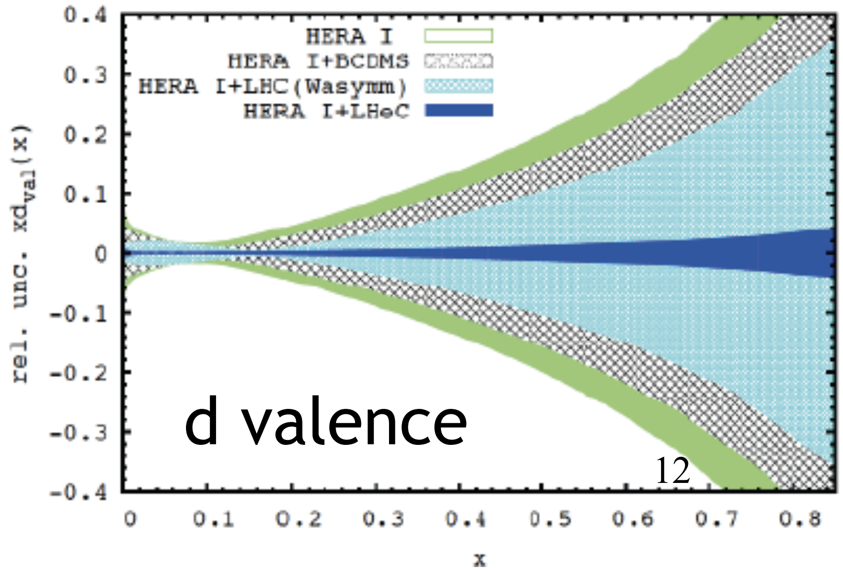




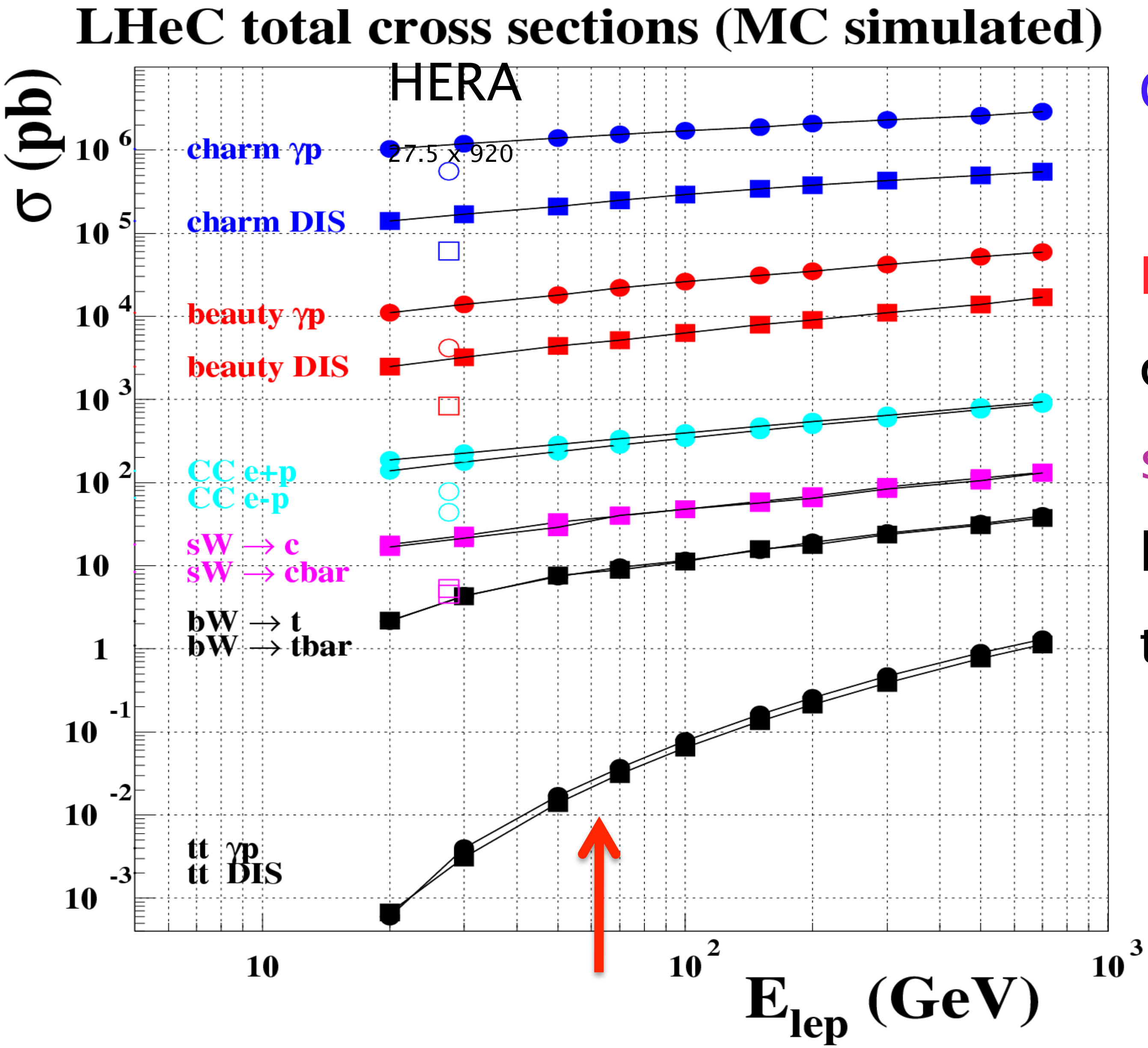
… impact at low x (kinematic range) and high x (luminosity)

… precise light quark vector, axial couplings, weak mixing angle

… full flavour decomposition



Cross Sections and Rates for Heavy Flavours



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

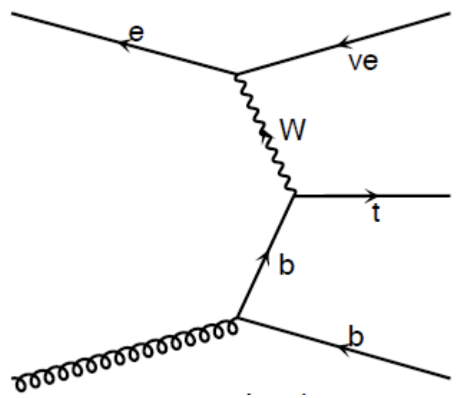
Beauty [10^{8} / 10 fb^{-1}]

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 fb^{-1} per year …

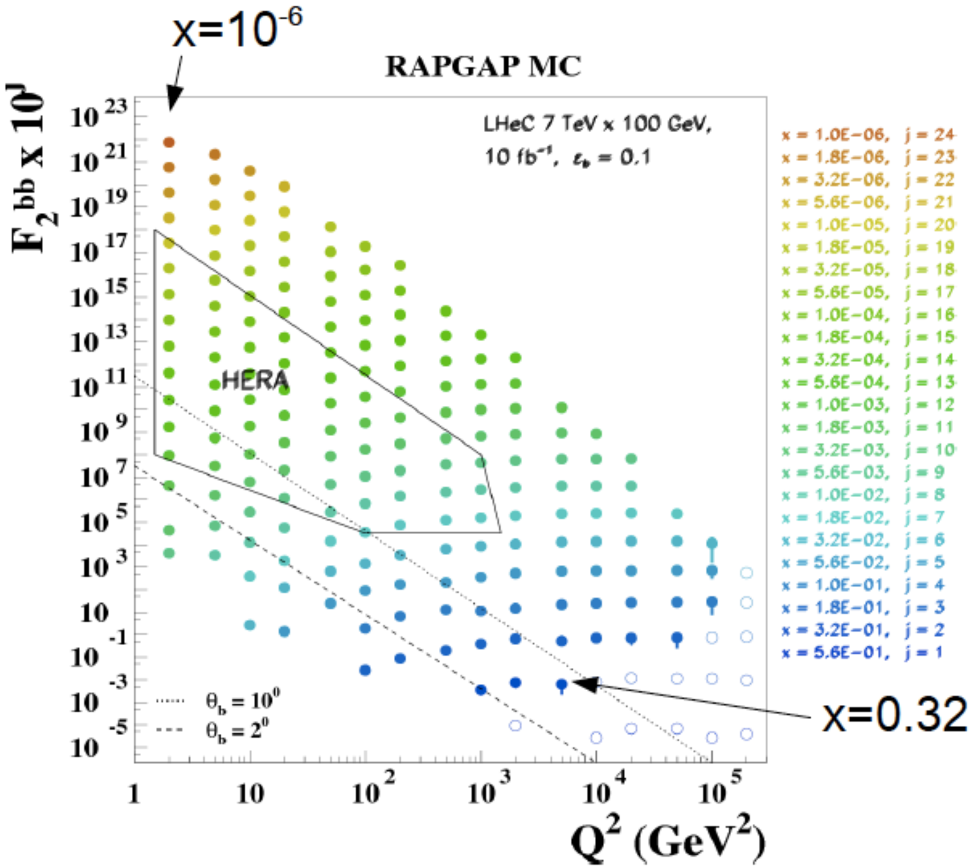
Flavour Decomposition

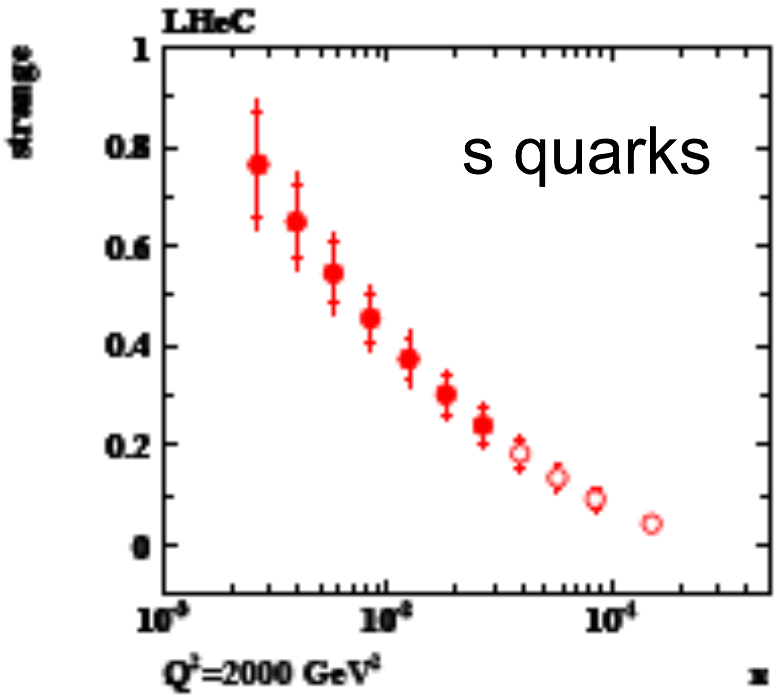
Precision c, b measurements (modern Si trackers, beam spot 15 * 35 μm^2 , increased HF rates at higher scales).

Systematics at 10% level

→beauty is a low x observable!

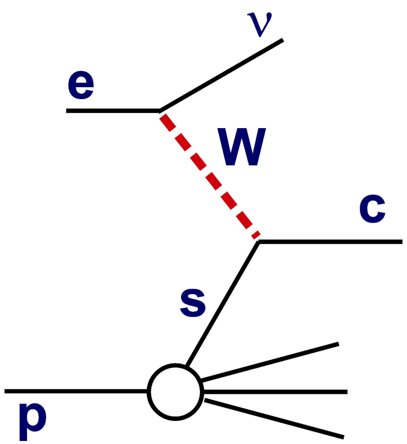
→s, sbar from charged current





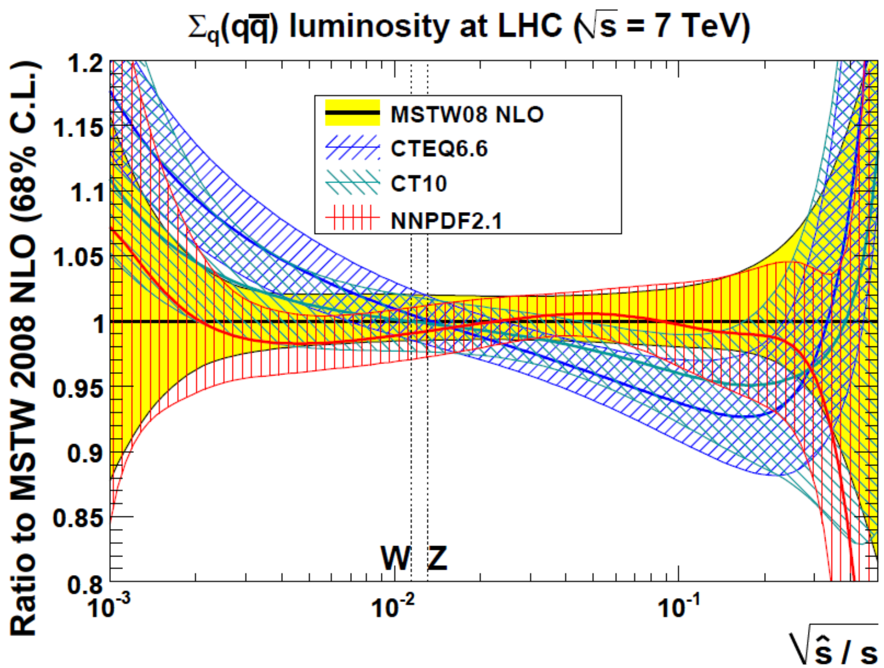
LHeC 10° acceptance

LHEC 1° acceptance



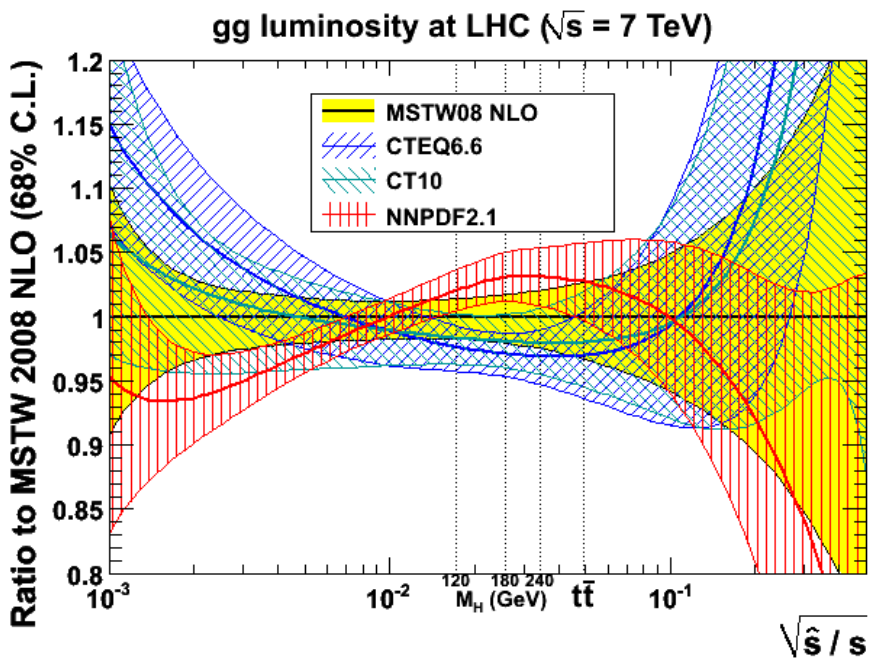
(Assumes 1 fb^{-1} and
- 50% beauty, 10% charm efficiency
- 1% uds → c mistag probability.
- 10% c → b mistag)

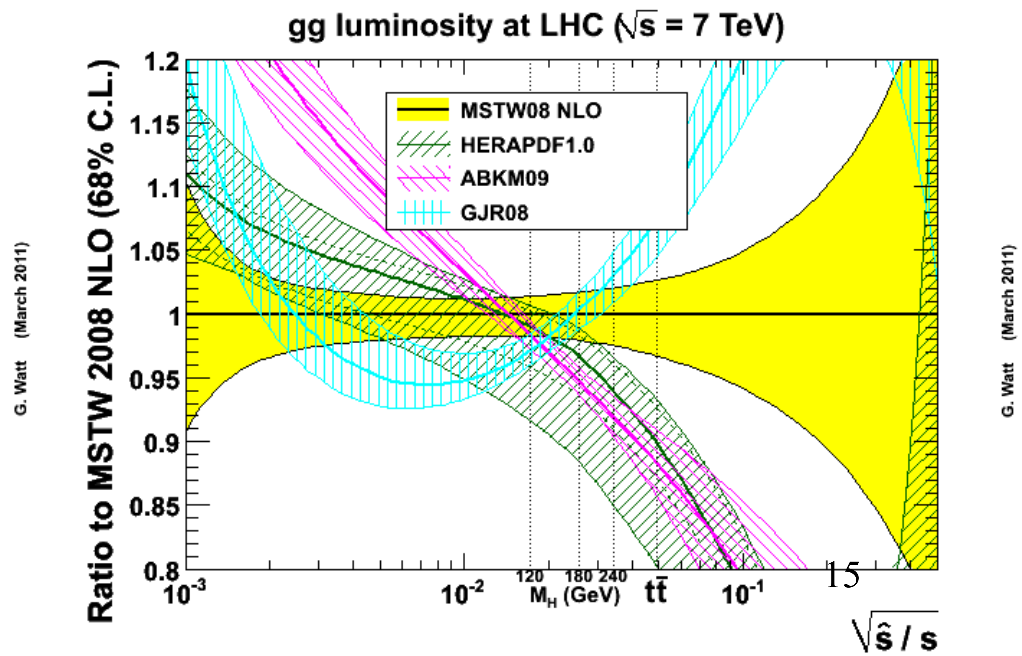
PDFs and LHC



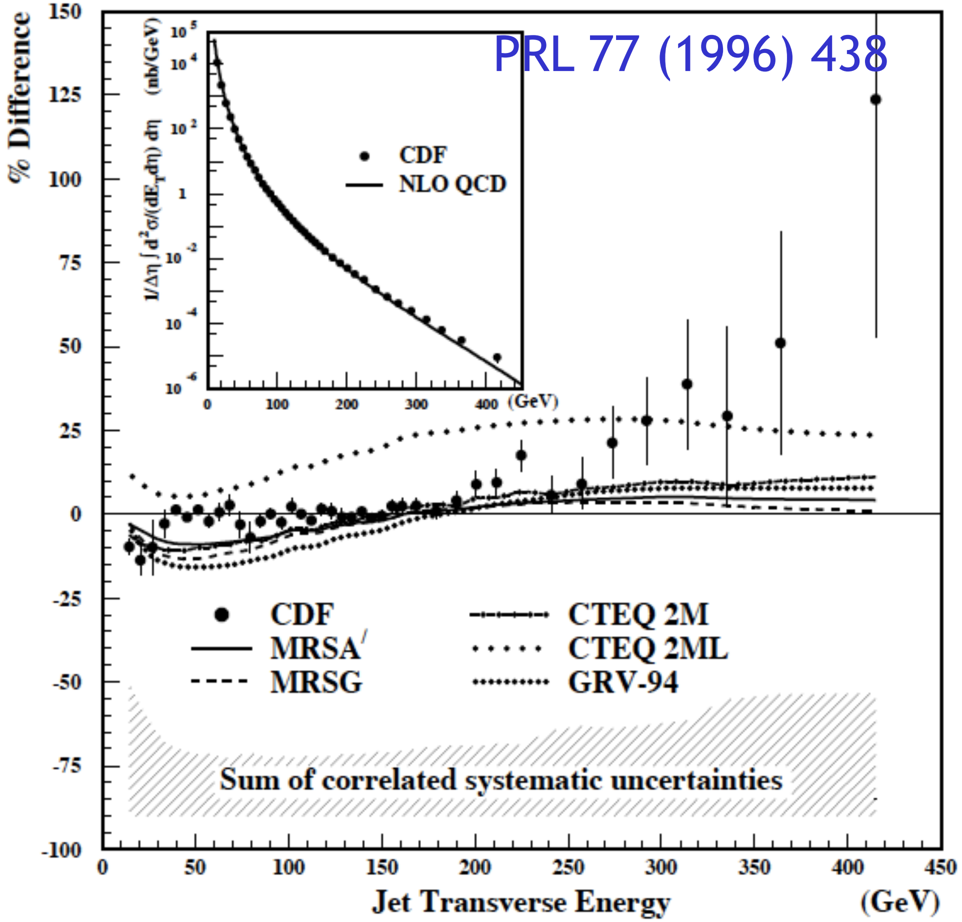
Current uncertainties due to PDFs for particles on LHC rapidity plateau (NLO):

- Most precise for quark initiated processes around EW scale
- Gluon initiated processes less well known
- All uncertainties explode for largest masses





Do we need to Care about High x?



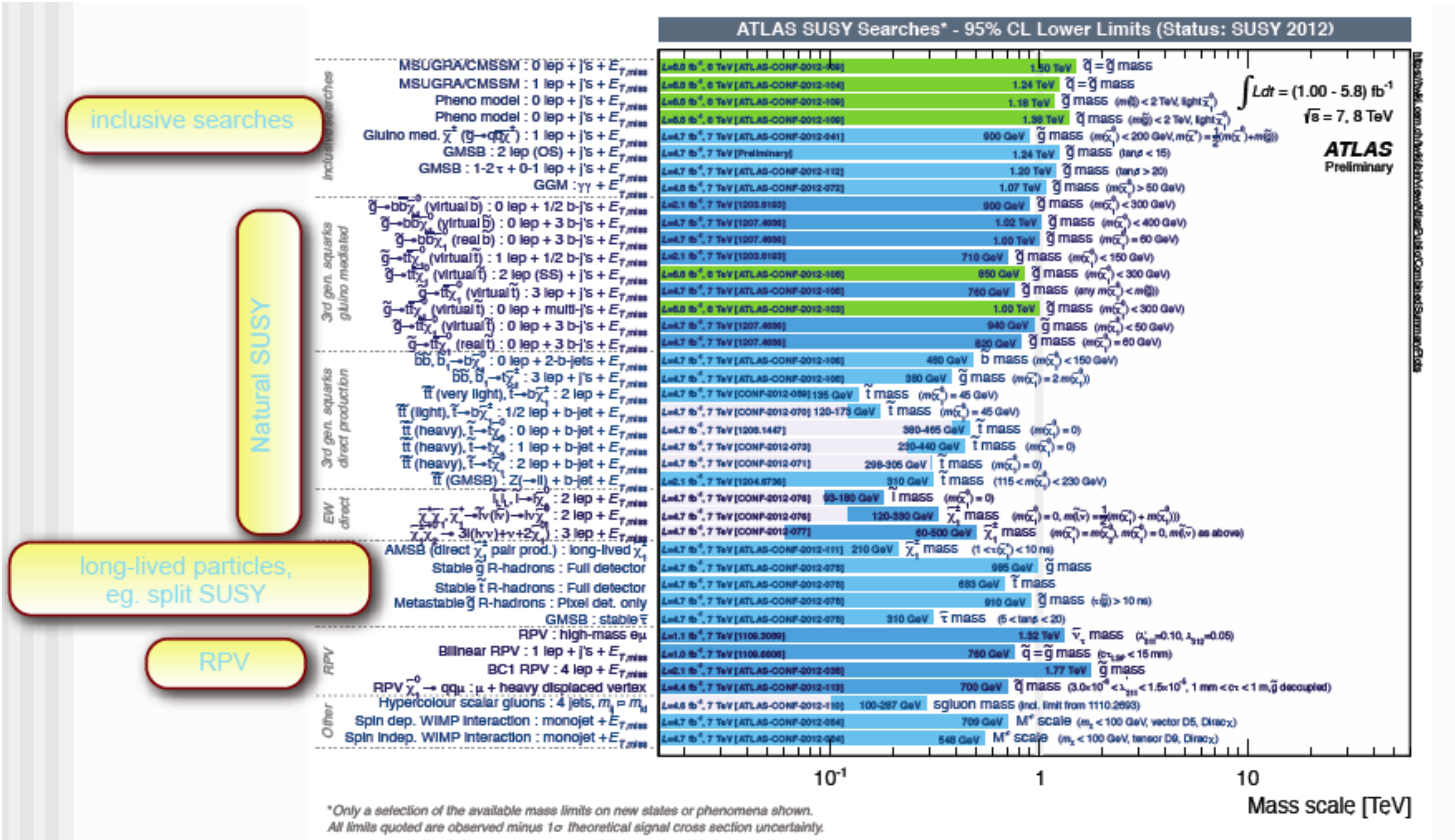
Ancient history (HERA, Tevatron)

- Apparent excess in large E_T jets at Tevatron turned out to be explained by too low high x gluon density in PDF sets

- Confirmation of (non-resonant) new physics near LHC kinematic limit relies on breakdown of factorisation between ep and pp

Searches near LHC kinematic boundary may ultimately be limited by knowledge of PDFs (especially gluon as x → 1)

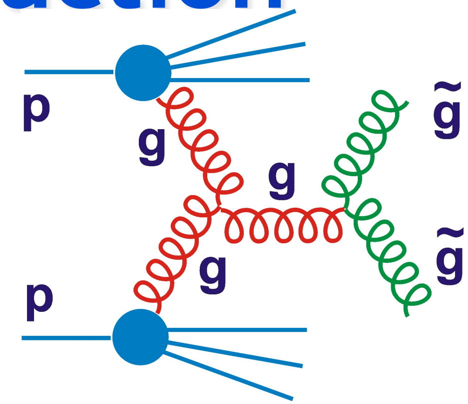
Current Status of LHC Searches



Executive summary: nothing on scale of 1 TeV … need to push sensitivity to higher masses

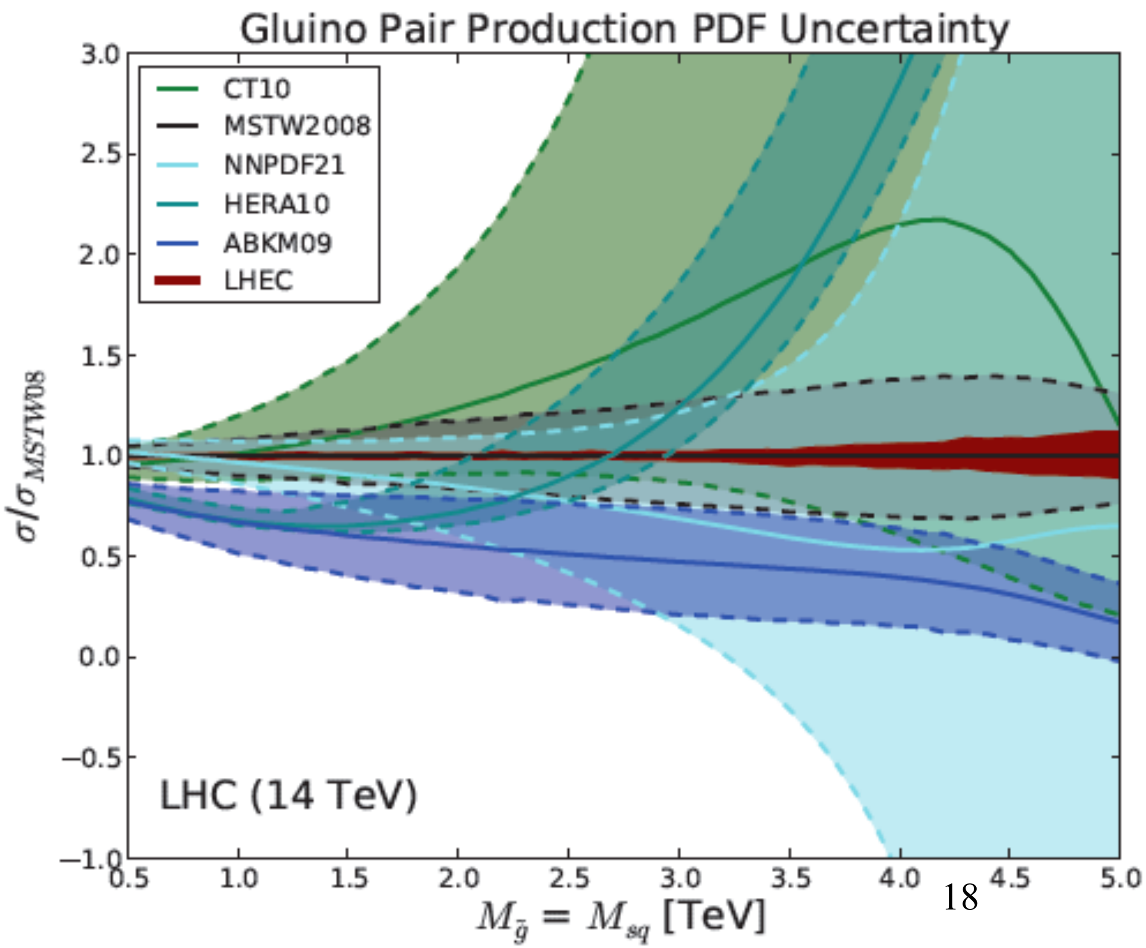
e.g. High Mass Gluino Production

- Signature is excess @ large invariant mass
- Expected SM background (e.g. gg → gg) poorly known for s-hat > 1 TeV.

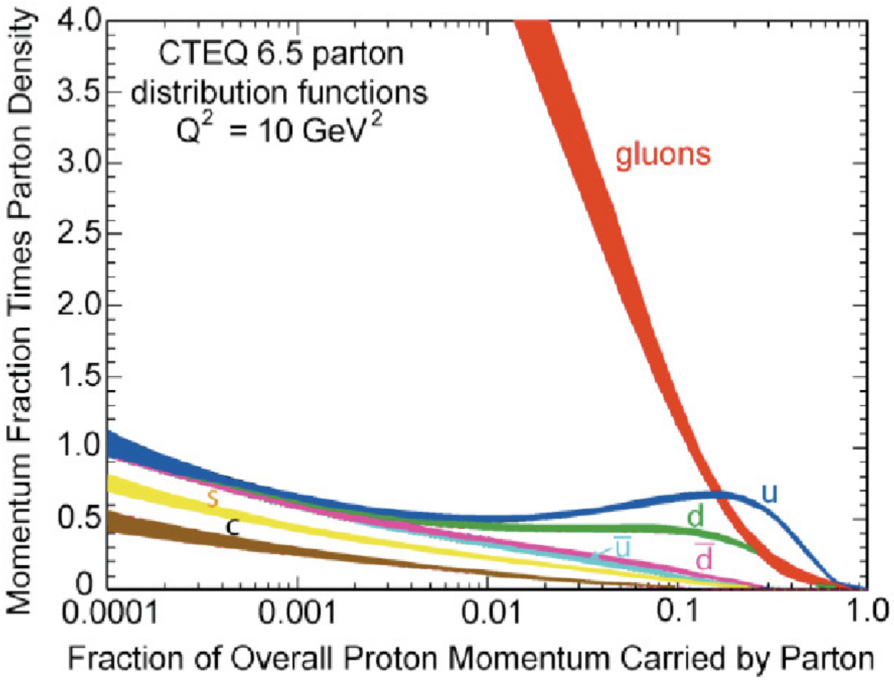


- Both signal & background uncertainties driven by error on gluon density … Essentially unknown for masses much beyond 2 TeV

- Similar conclusions for other non-resonant LHC signals involving high x partons (e.g. contact interactions signal in Drell-Yan)



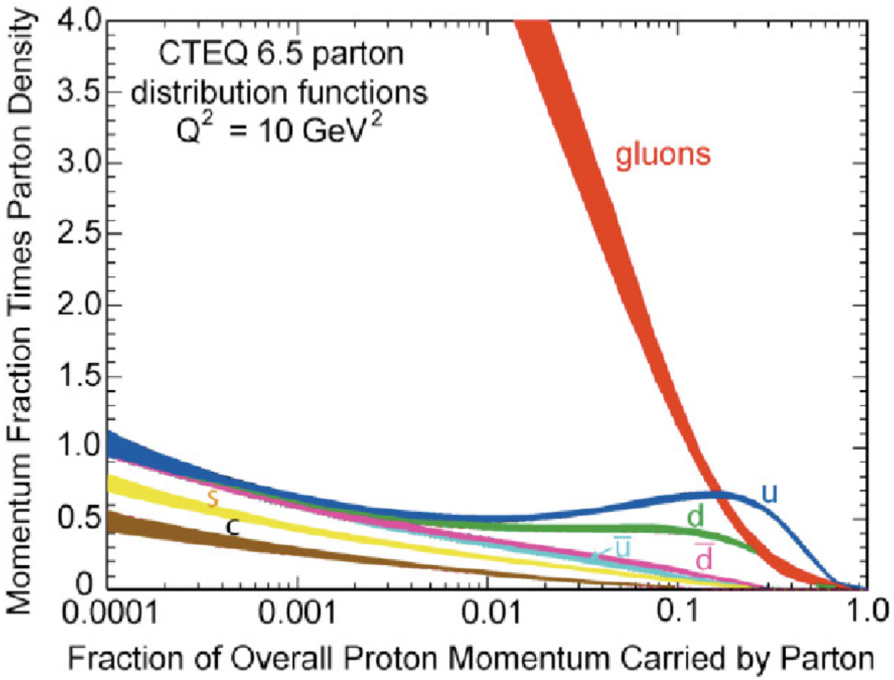
Low-x Physics and Parton Saturation

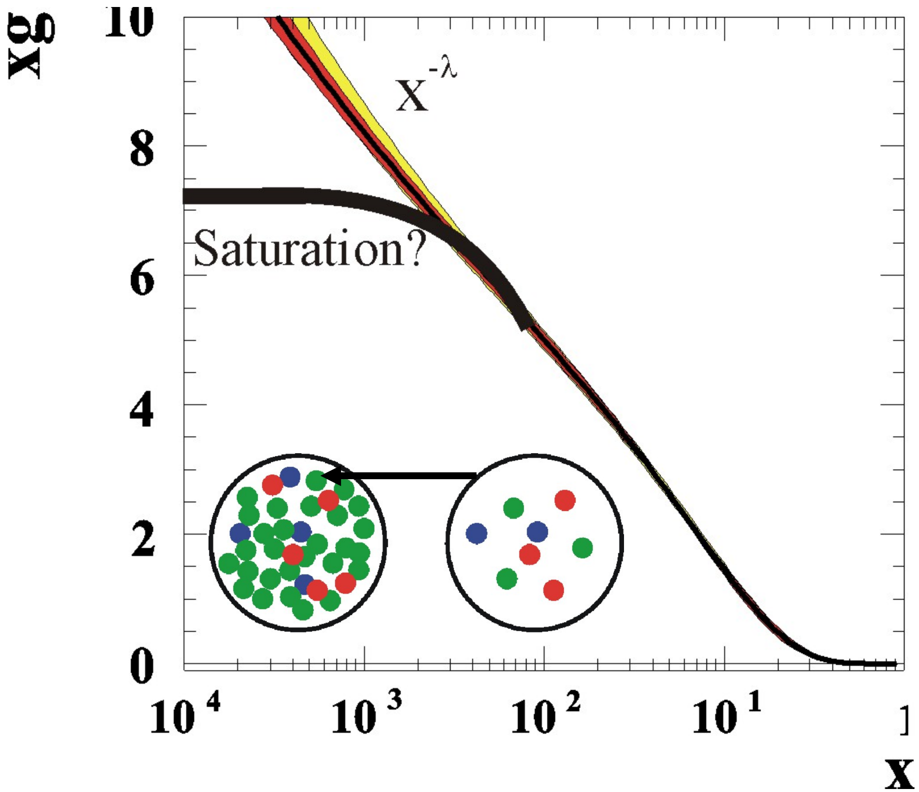


A fundamental QCD problem is looming … rise of low x parton densities cannot continue

… High energy unitarity issues reminiscent of longitudinal WW scattering in electroweak physics:

Low-x Physics and Parton Saturation

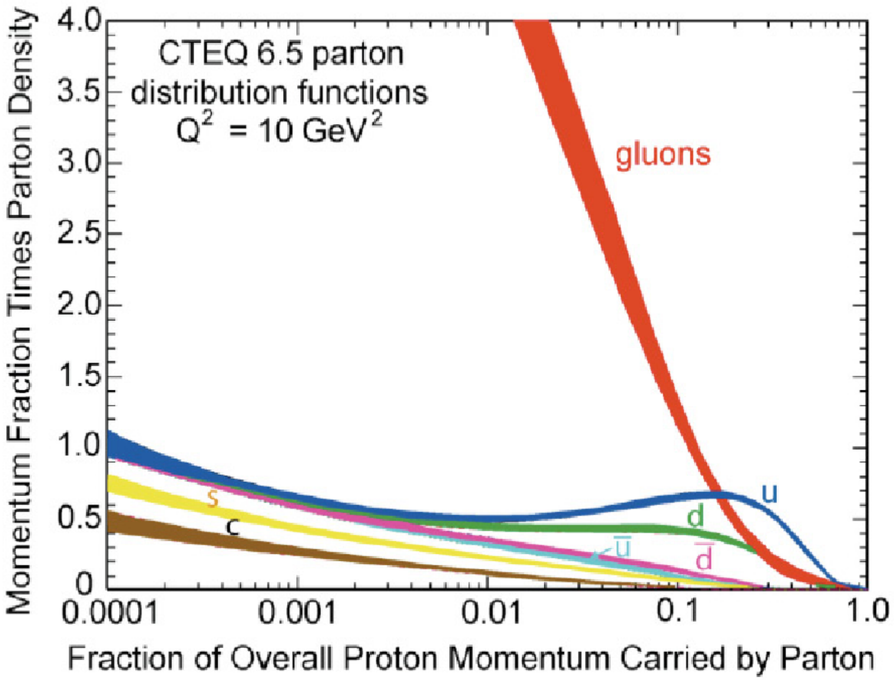


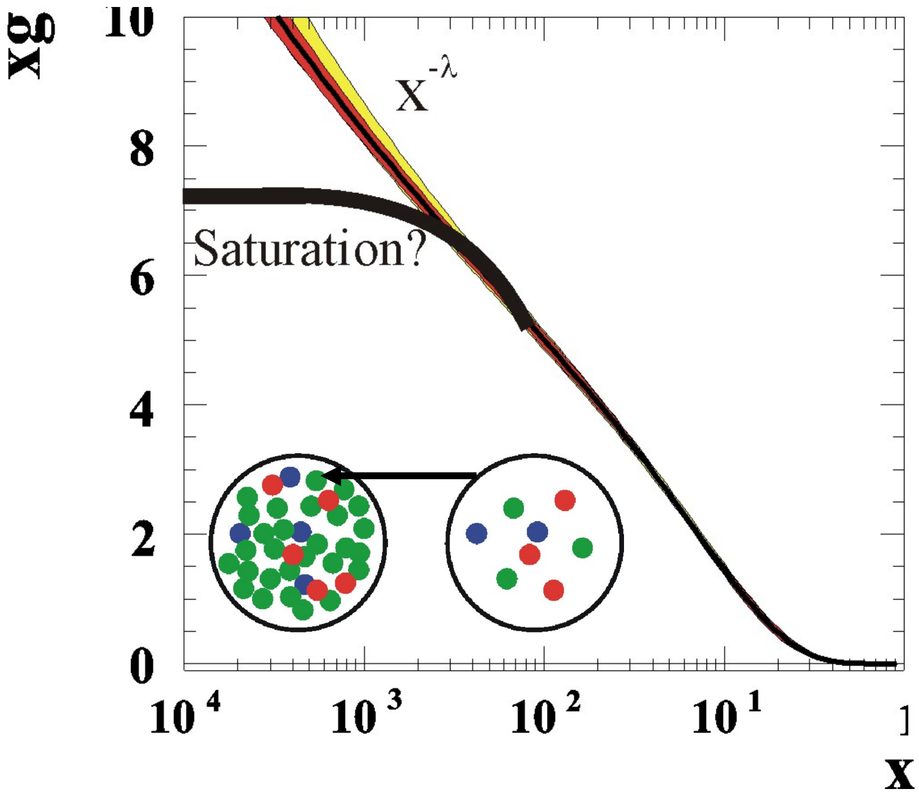


• Somewhere & somehow, the low x growth of cross sections must be tamed to satisfy unitarity … non-linear effects

• Parton level language → **recombination gg → g?**

Low-x Physics and Parton Saturation





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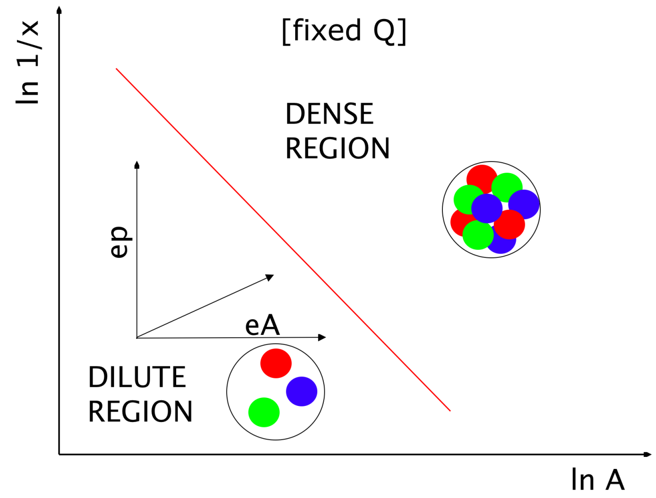
… new high density, small coupling parton regime of non-linear parton evolution dynamics (e.g. Colour Glass Condensate)? …
… gluon dynamics → confinement and hadronic mass generation

Strategy for making the target blacker

LHeC delivers a 2-pronged approach:



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]

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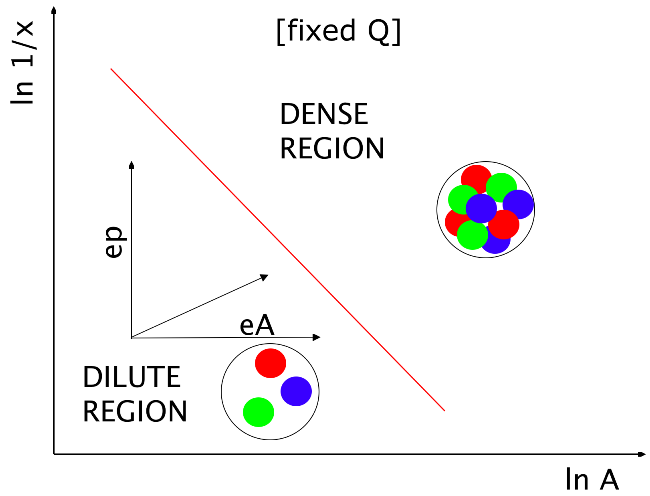
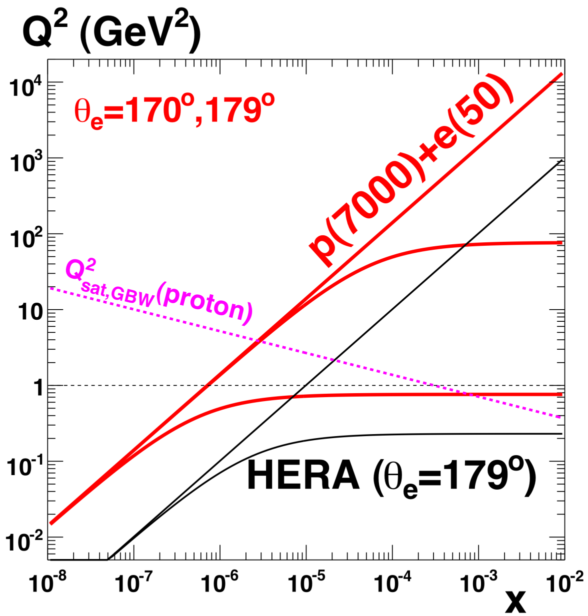
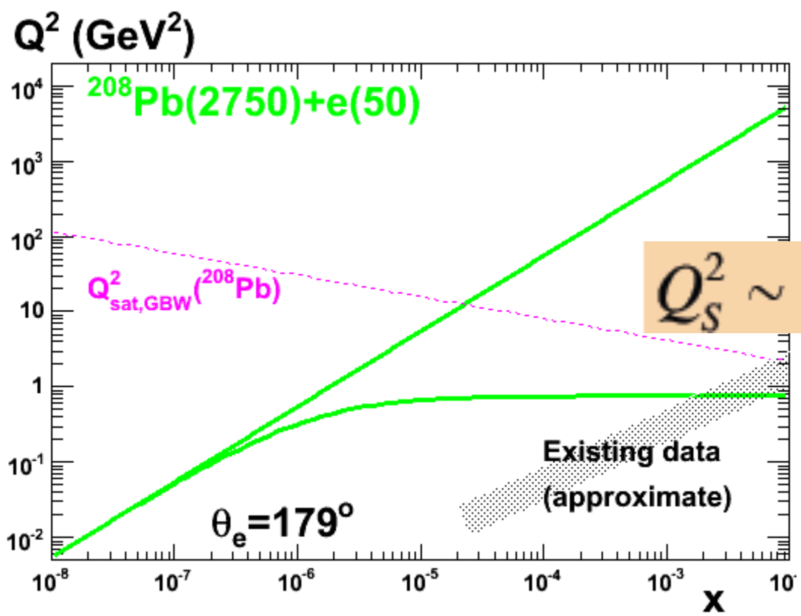


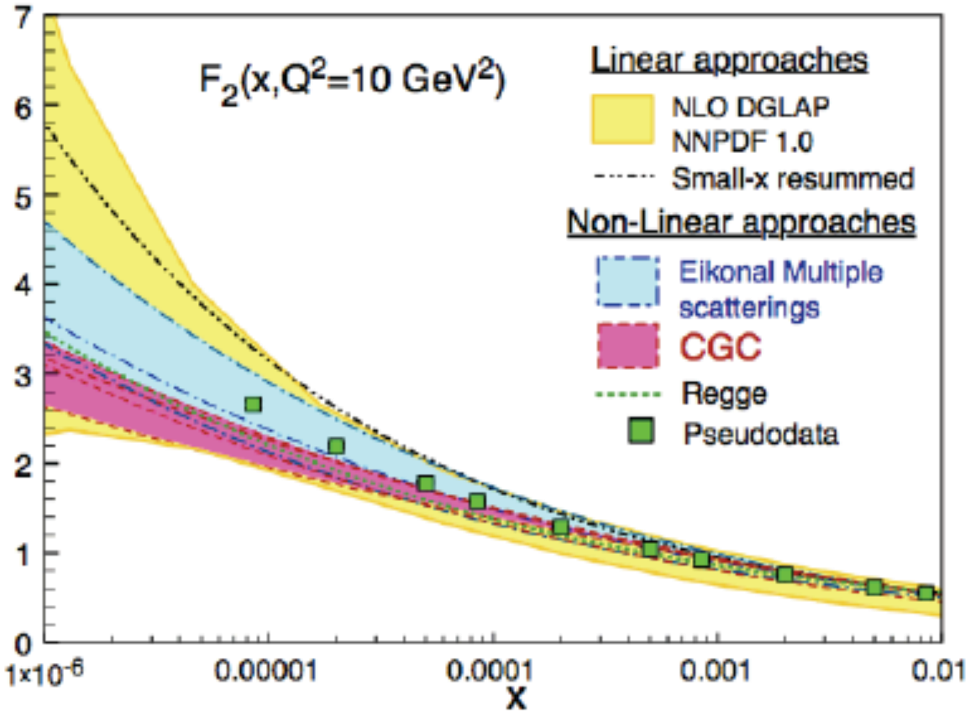


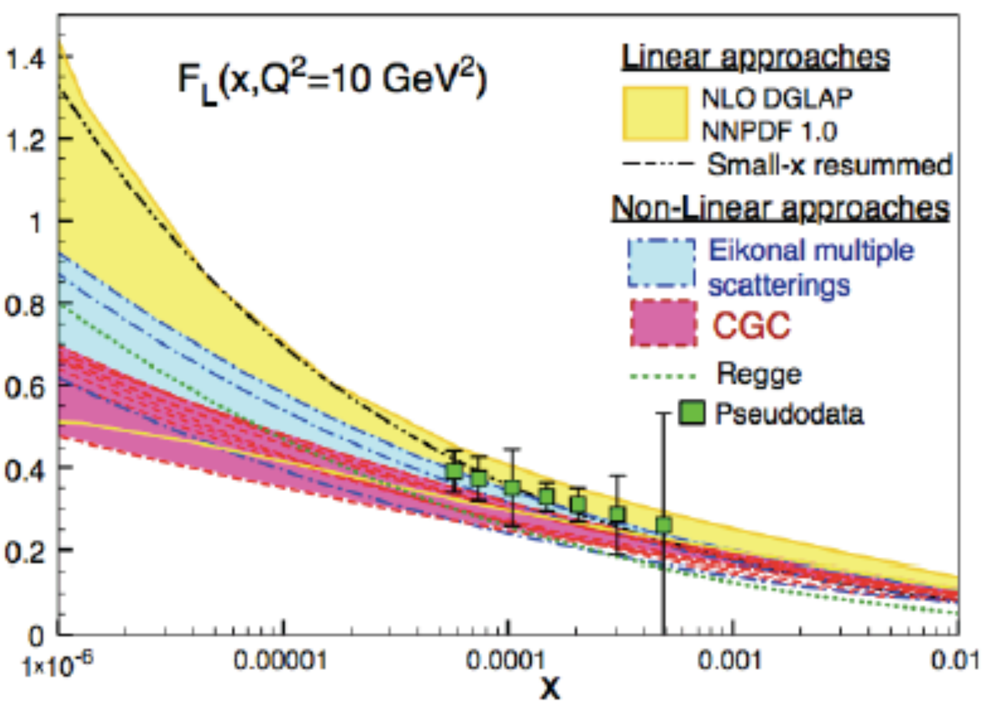


$$Q_S^2 \sim xg(x)\alpha_S \sim cx^{-\lambda}A^{1/3}$$

Establishing and Characterising Saturation

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





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

Can Parton Saturation be Established in ep @ LHeC?

Simulated LHeC data based on a dipole model containing low x saturation (FS04-sat)… Fit with standard (NNPDF) NLO DGLAP

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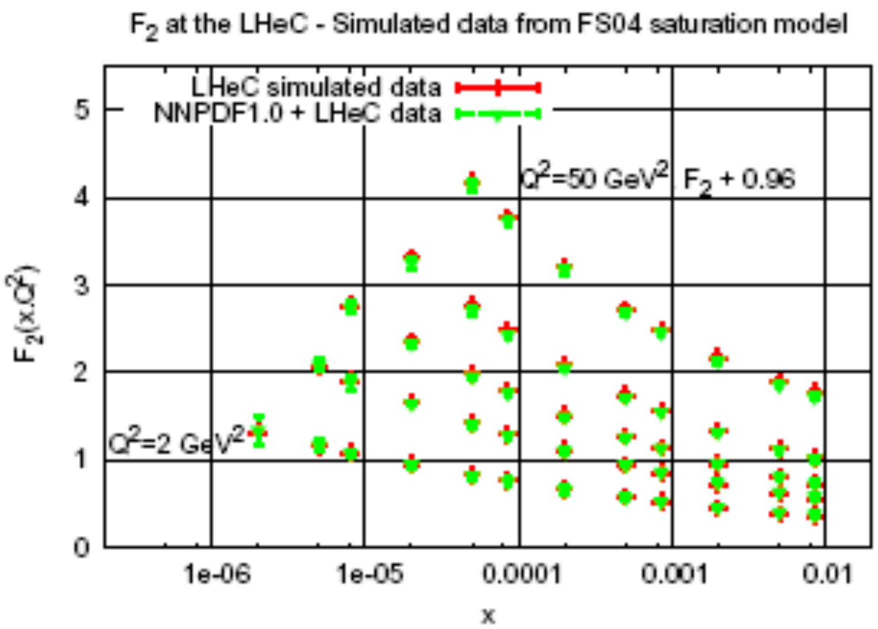
Fitting F_2 only



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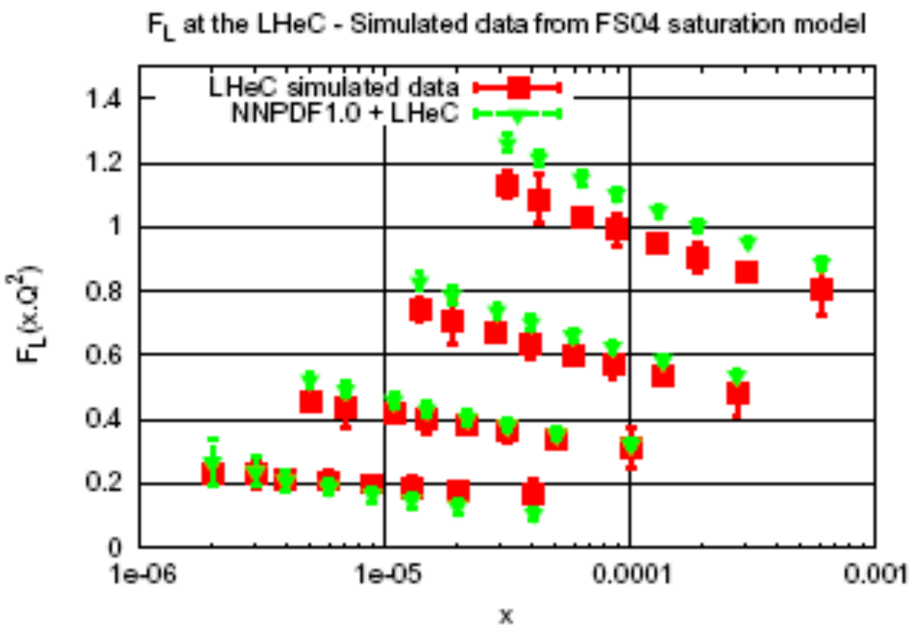
Simulated LHeC F_2 and F_L data based on a dipole model containing low x saturation (FS04-sat)…

Fitting F_2 and F_L



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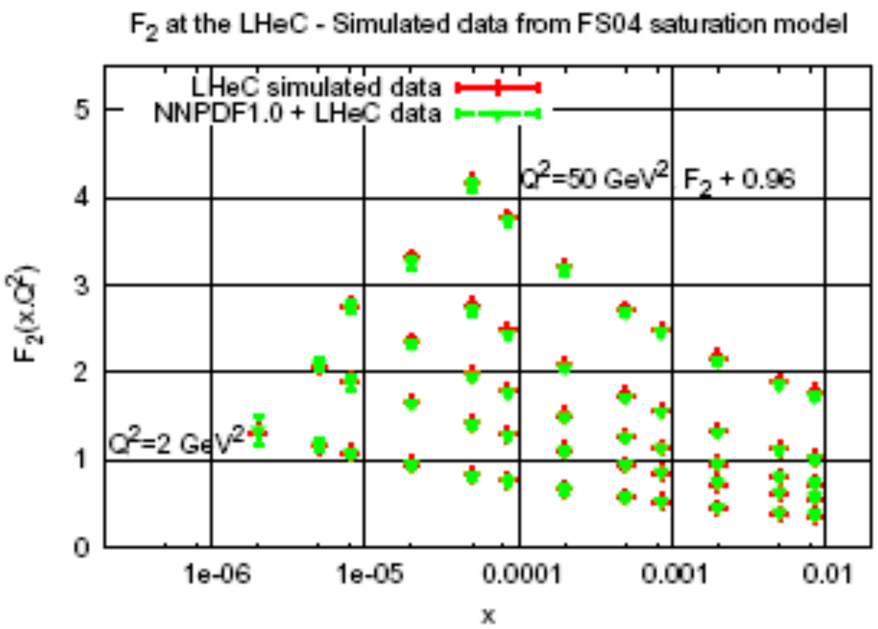
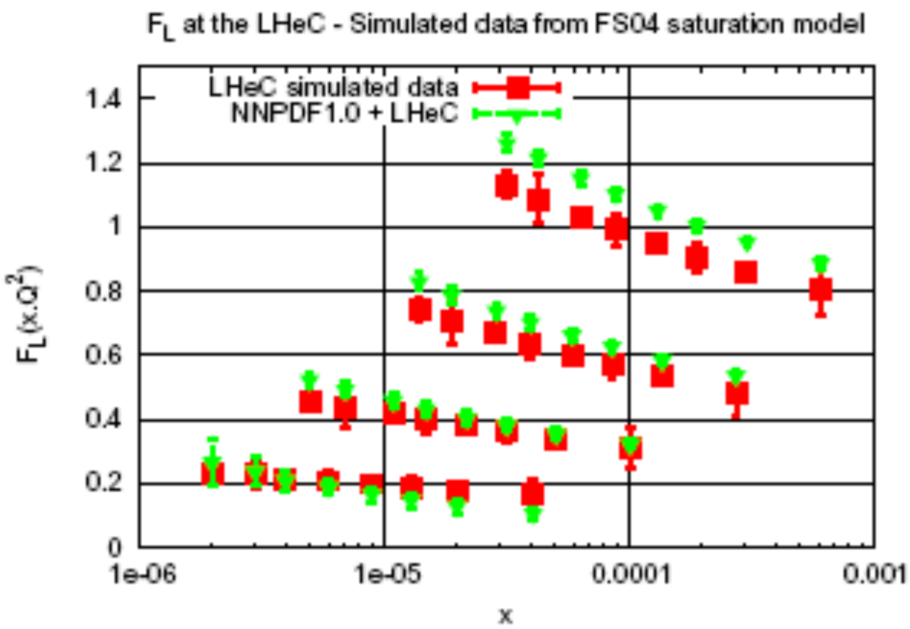
… NNPDF (also HERA framework) DGLAP QCD fits cannot accommodate saturation effects if F_2 and F_L both fitted





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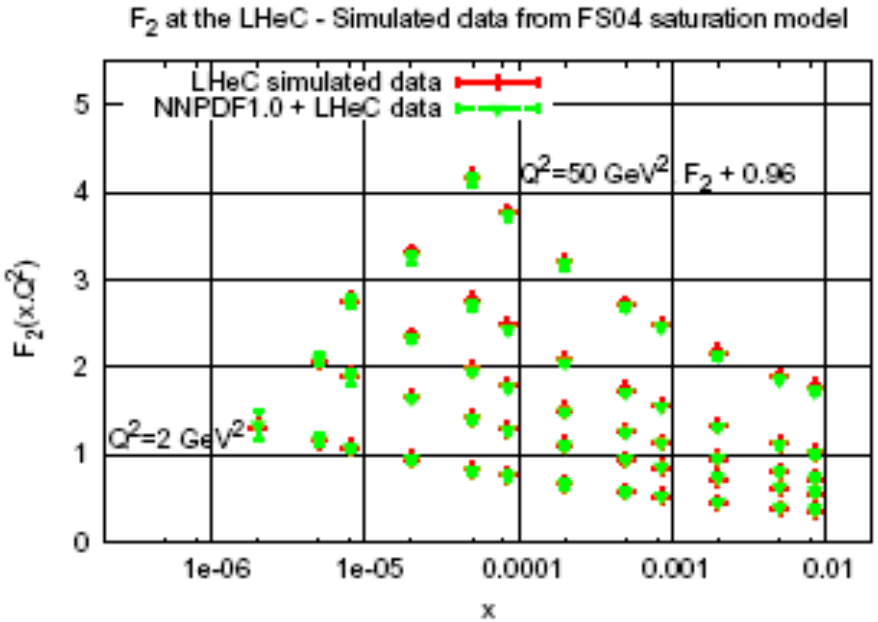
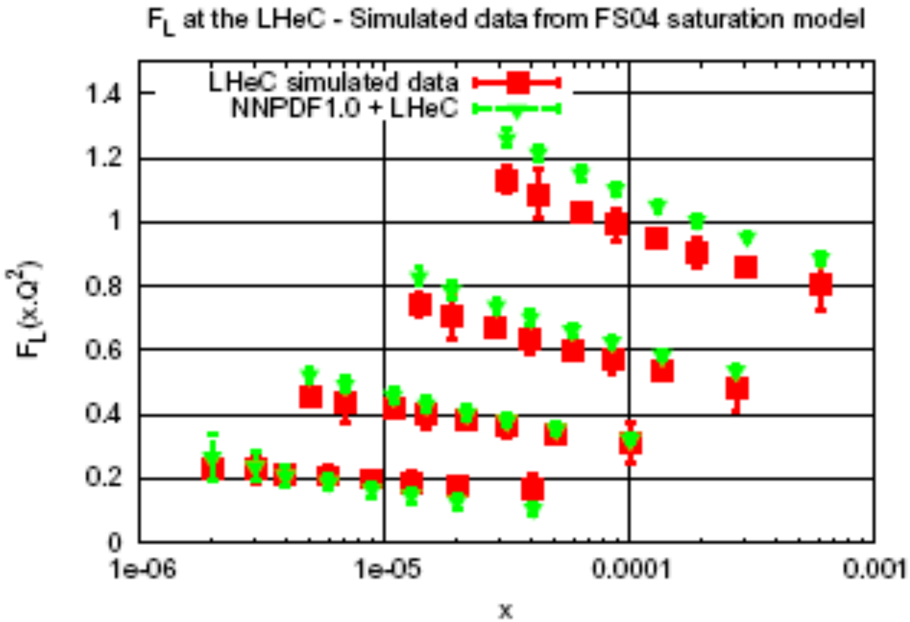




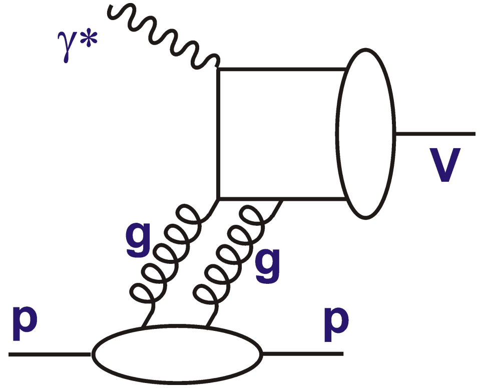
Conclusion: clearly establishing non-linear effects needs a minimum of 2 observables … <u>(F_2^c may work in place of F_L)</u>…

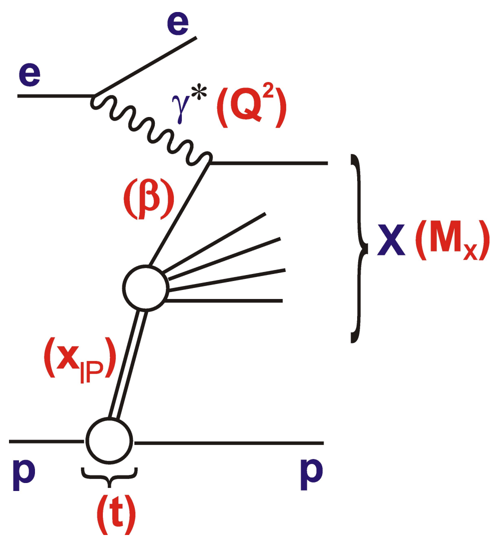
Exclusive / Diffractive Channels and Saturation

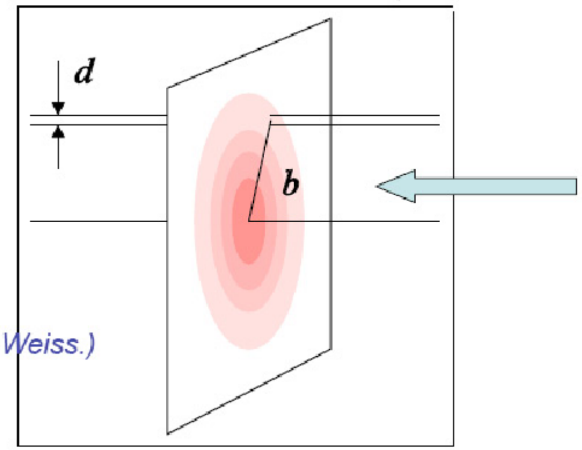
1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon

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

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





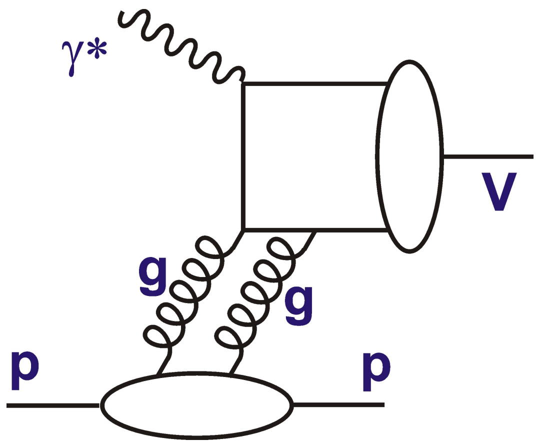


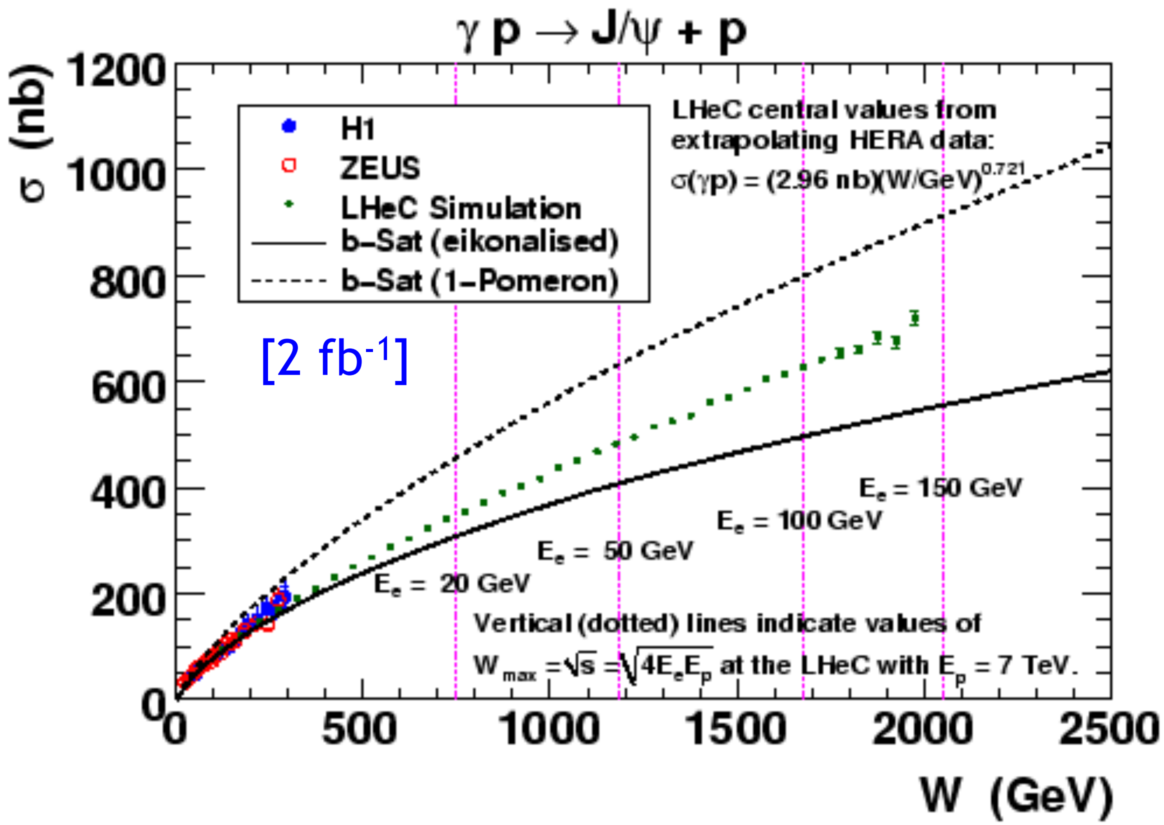
(figure from C. Weiss.)

Central black region growing with decrease of x.

e.g. J/ψ Photoproduction

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



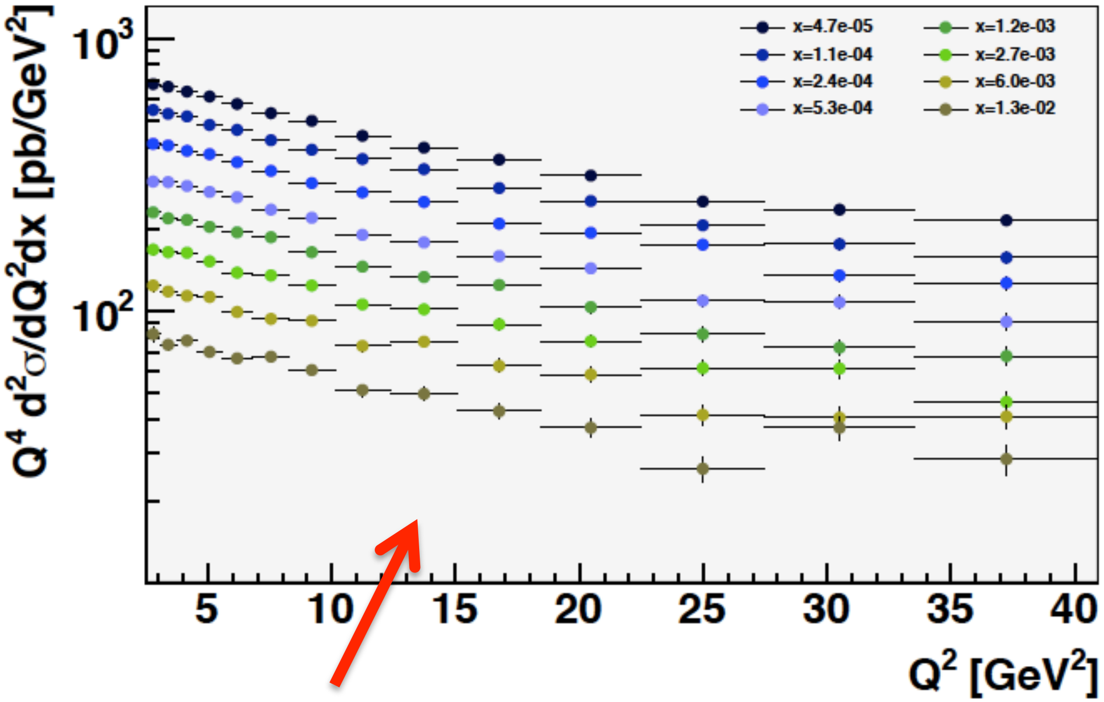


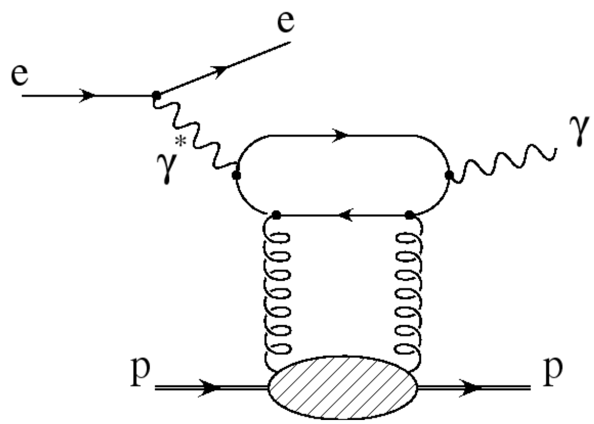
- Significant non-linear effects expected in LHeC kinematic range.

- Data shown are extrapolations of HERA power law fit for E_e = 150 GeV…

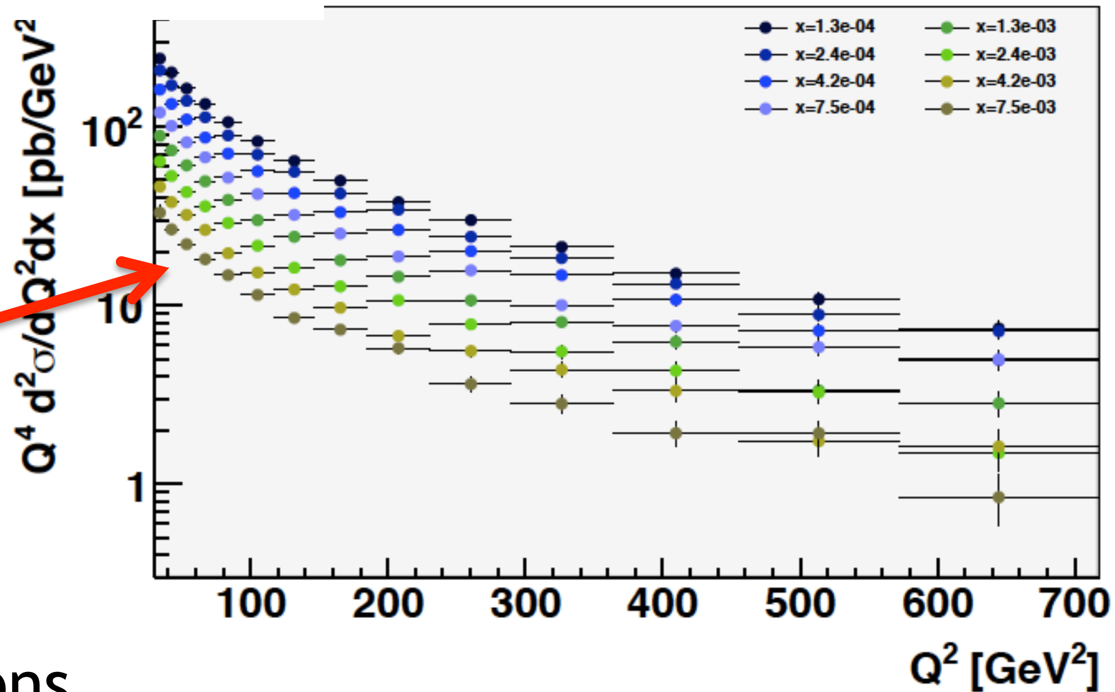
  → Sat^n smoking gun?

e.g. DVCS (MILOU simulation)





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



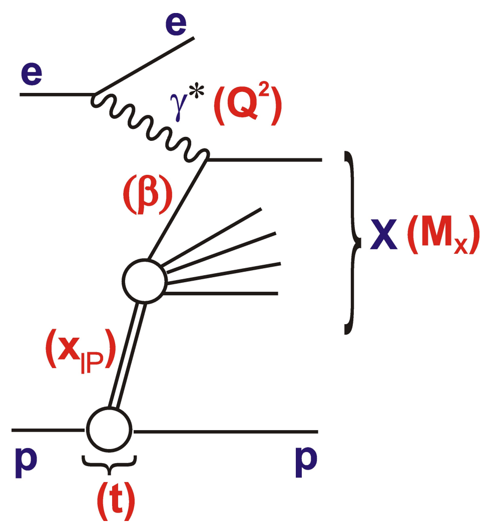
$100\ fb^{-1}$, E_e = 50 GeV,
10° acc'nce, p_T^γ > 5 GeV

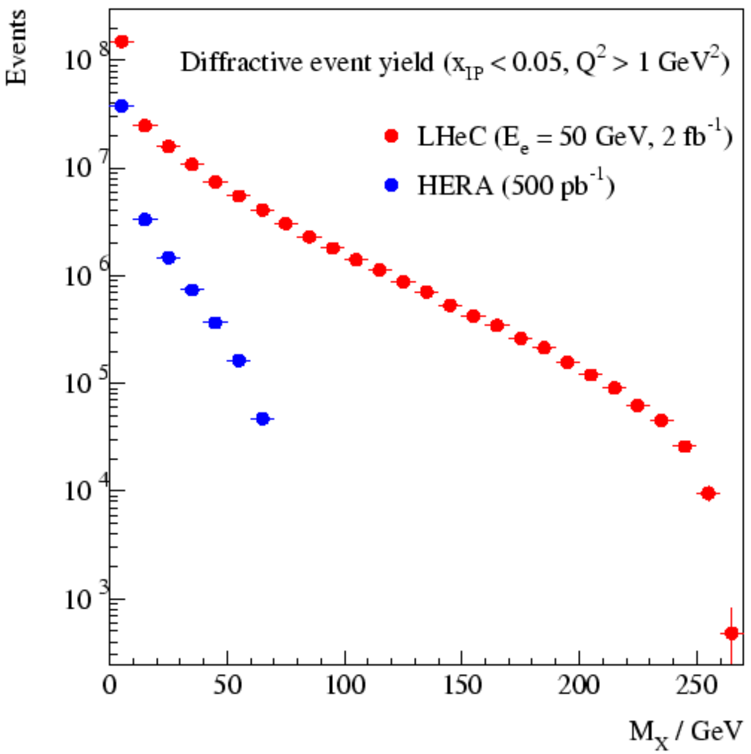
Precise data in completely unexplored high W, Q^2 regions

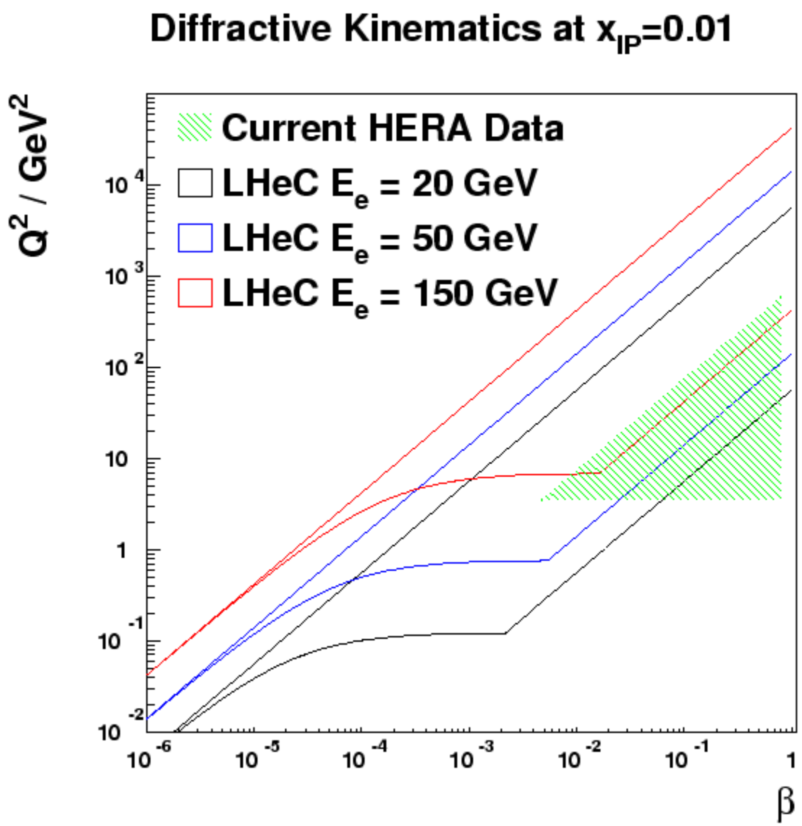
e.g. Inclusive Diffraction (RAPGAP)

- 5-10% data, depending on detector
- DPDFs / fac'n in much bigger range
- Enhanced parton satn sensitivity?
- Exclusive production of any 1^- state with Mx up to ~ 250 GeV

  → X including W, Z, b, exotics?
- Relation to Nuclear Shadowing







Summary

• This contained a few highly selected examples of physics of high energy ep scattering, as might be possible with LHeC.

• Notable omissions include …

- per mille experimental determination of α_s
- mainstream QCD: jet cross sections, forward jets, azimuthal decorrelations between jets …
- tagged forward protons and neutrons
- diffraction in ep and relation to nuclear shadowing
- electroweak coupling determinations
- Higgs (Uta)
- eA (Roy)
- … and lots more I forgot

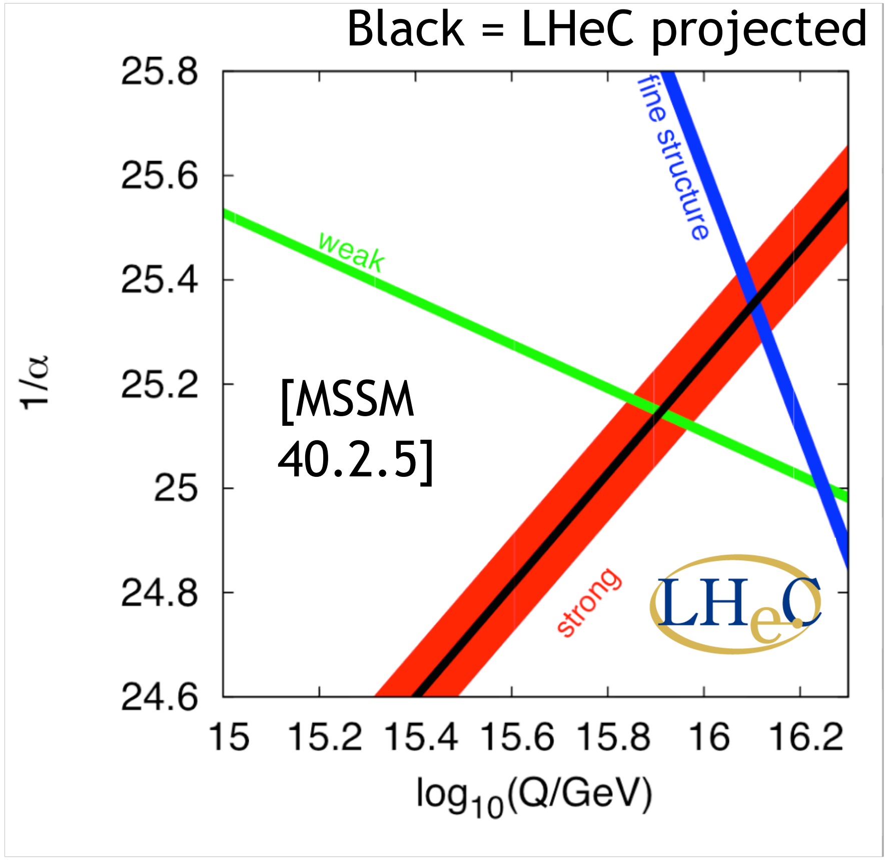
• Discuss … ☺

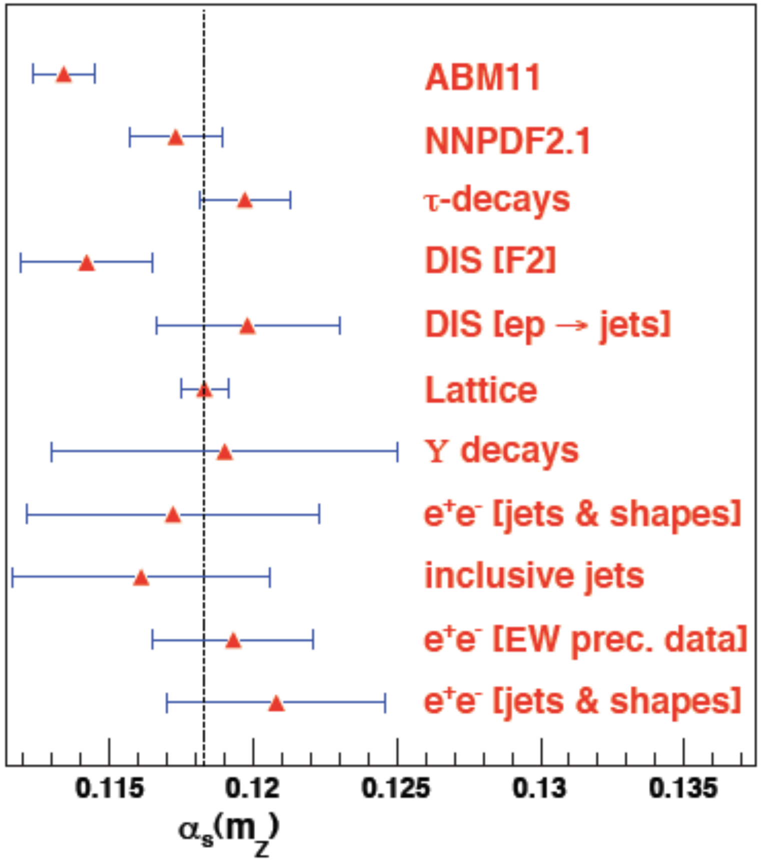
Back-Ups Follow

Precision α_s

- 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?

Red = current world average
Black = LHeC projected

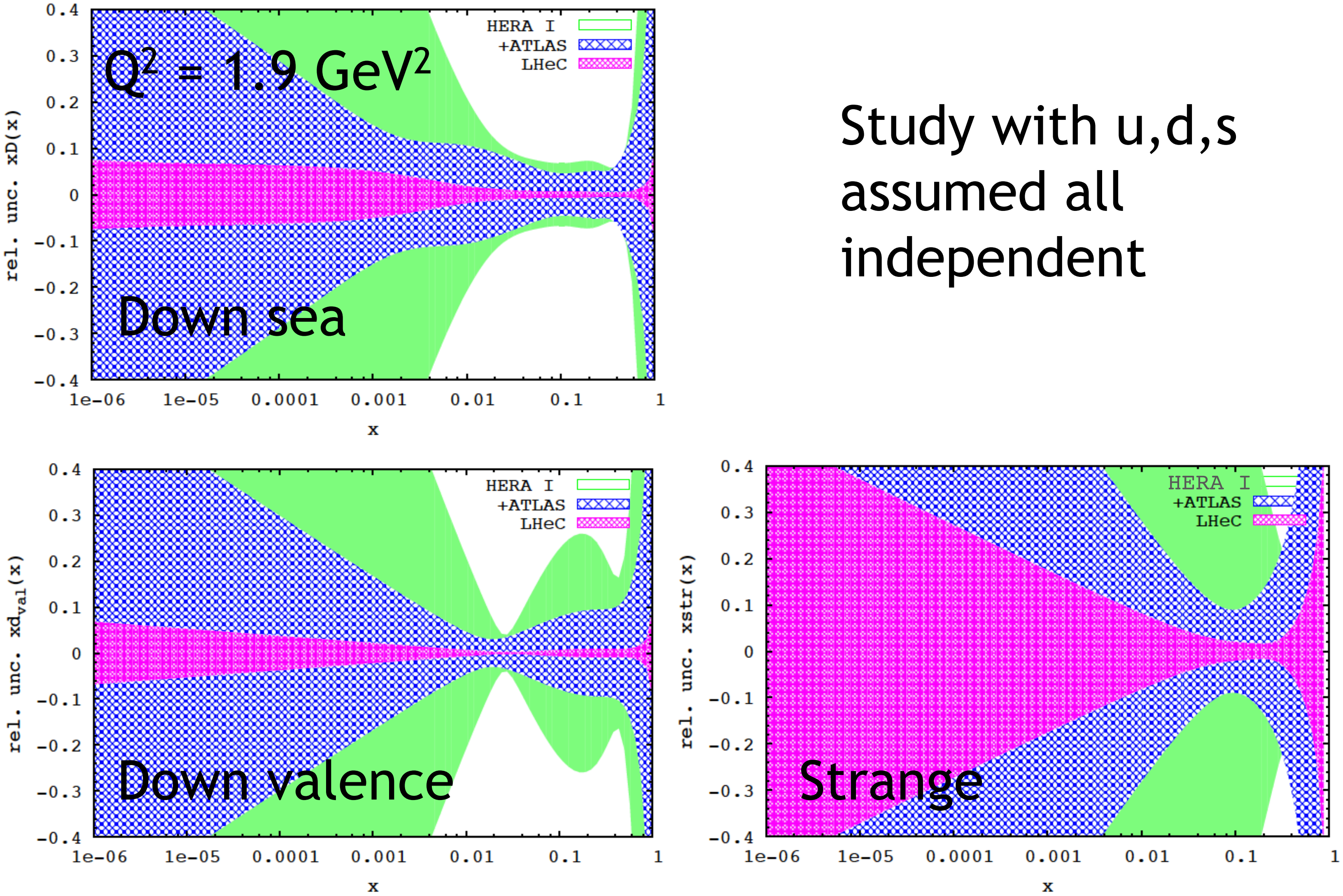




- Simulated LHeC precision from fitting inclusive data

→ per-mille (experimental)
→ also requires improved theory

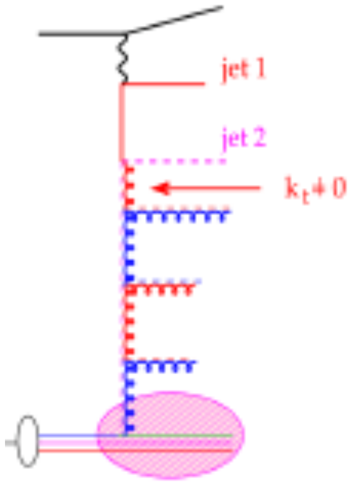
Can all this be done by ATLAS and CMS?

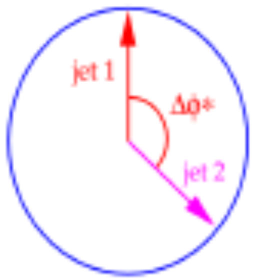


Study with u,d,s assumed all independent

LHC has good sensitivity in narrow range from W,Z, accesses ubar, dbar ~ directly and has already contributed to strange.
→ complementary, but does not compete with LHeC

Azimuthal (de)correlations between Jets



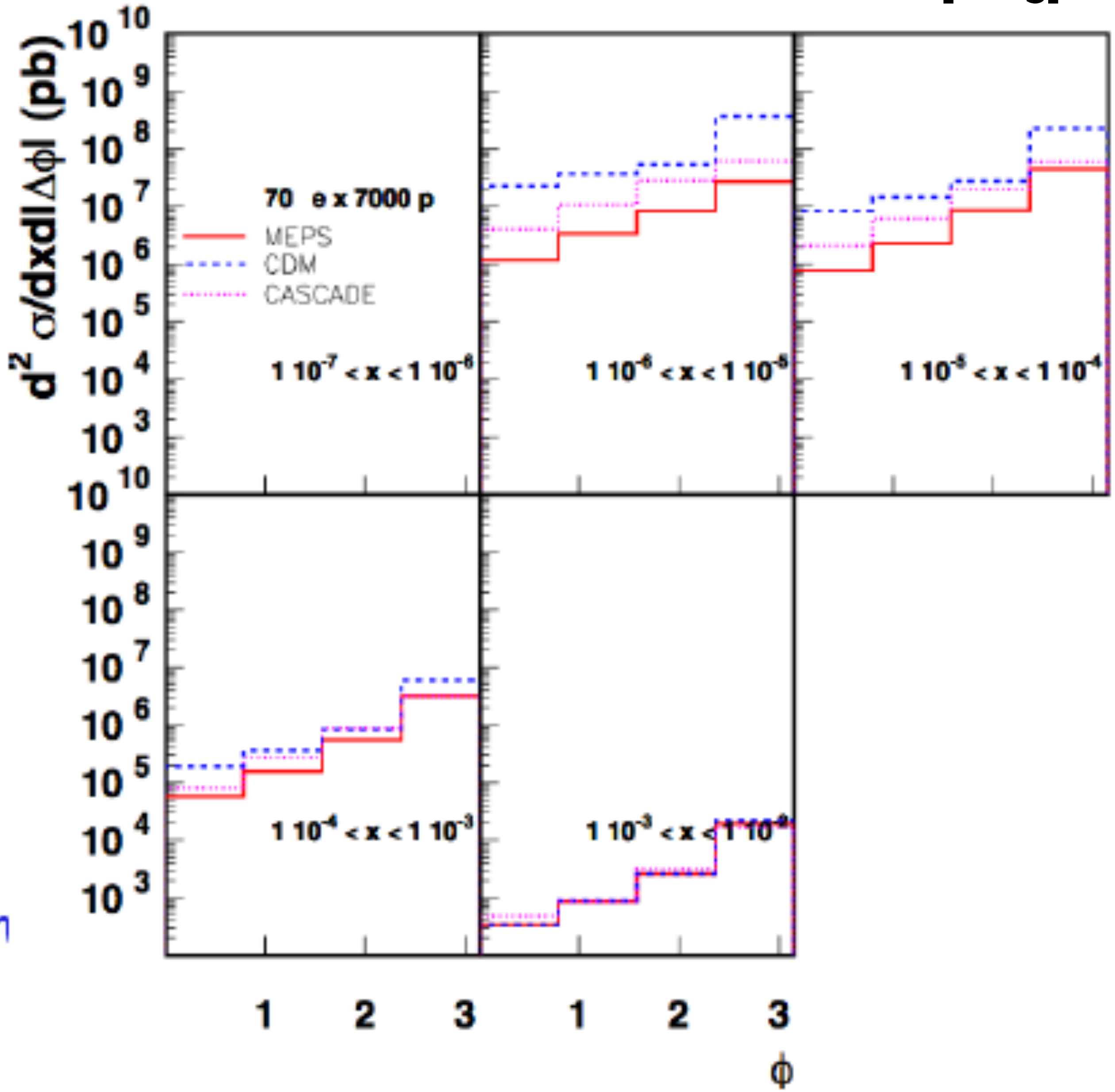


- $5 < Q^2 < 100 \text{ GeV}^2$
  $-1 < \eta < 2.5$
  $E_T > 5 \text{ GeV}$

- small $k_t \rightarrow \Delta\phi \sim 180$

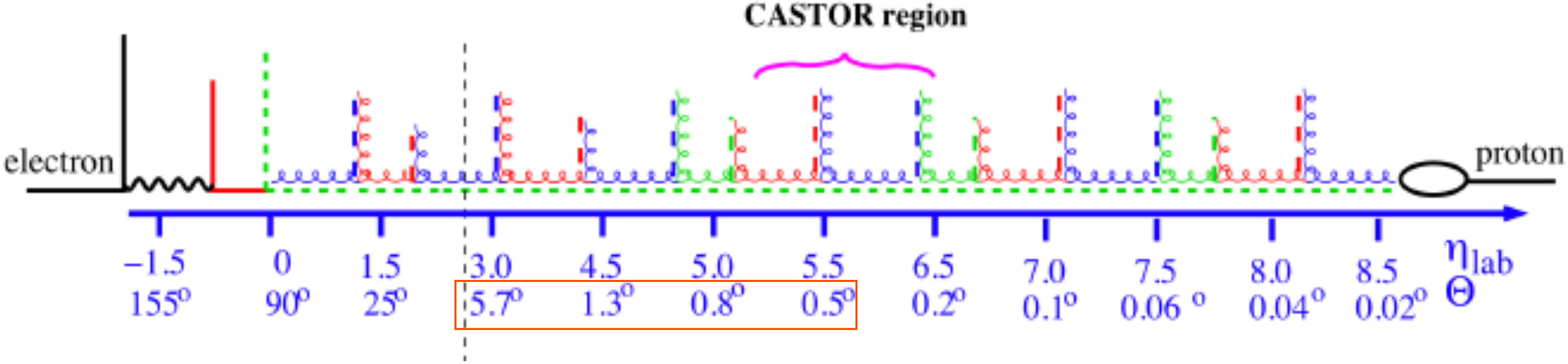
- large k_t from evolution

[Jung]



Forward Instrumentation and Jets

[Jung]



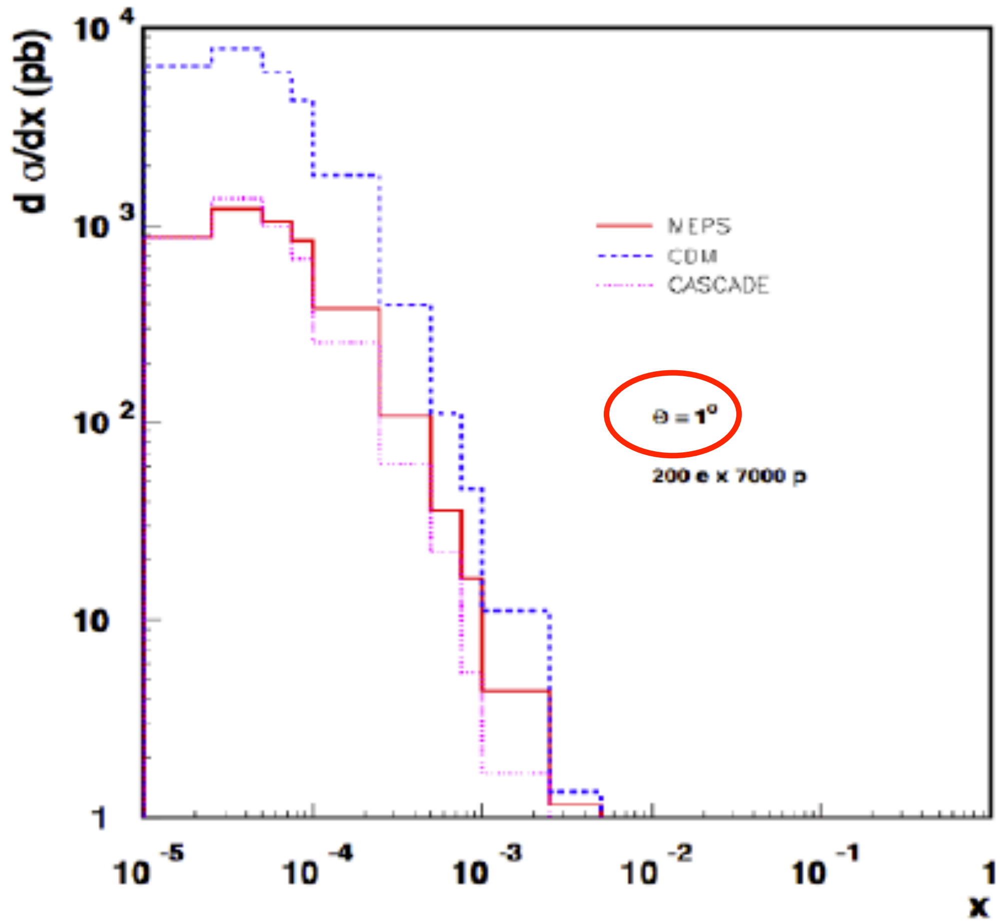
- DIS and forward jet:

$x_{jet} > 0.03$

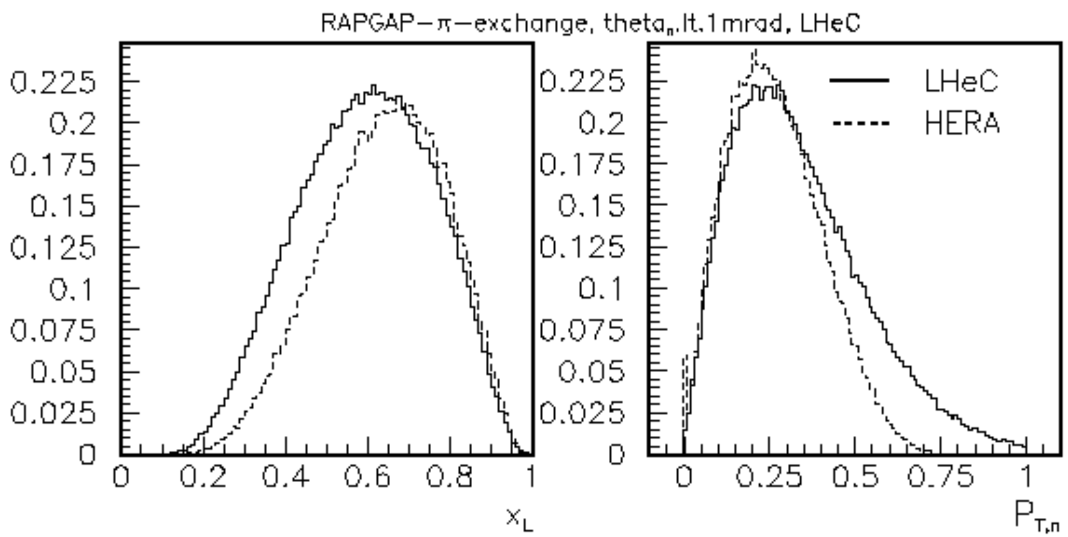
$0.5 < \frac{p_{t\,jet}^2}{Q^2} < 2$

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

Similar conclusions for Δϕ decorrelations between jets

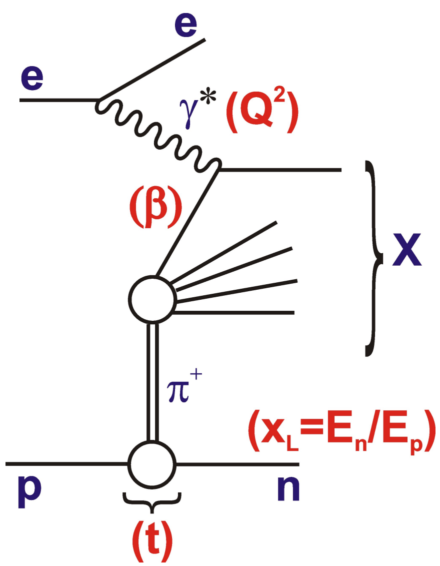


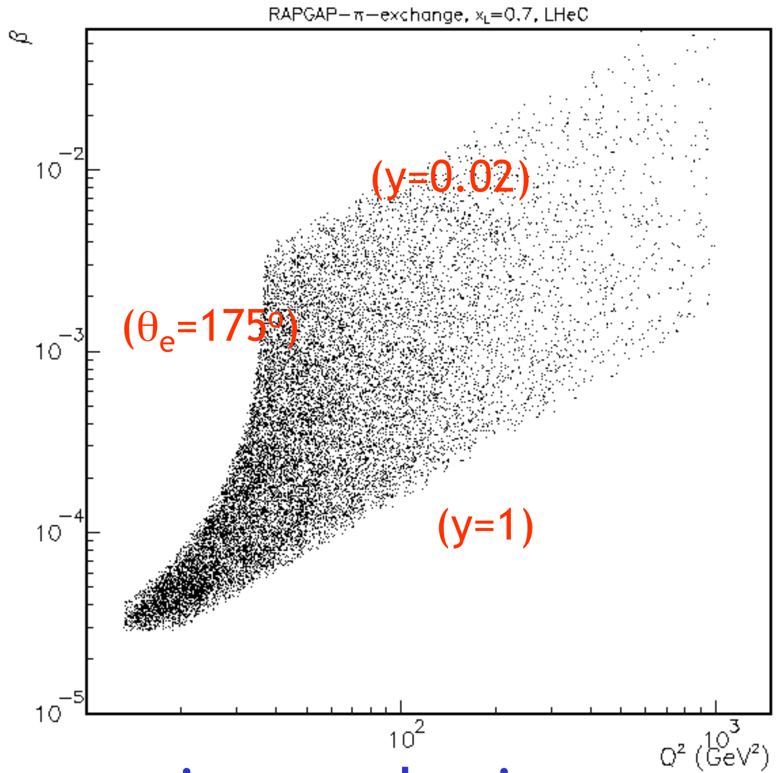
π Structure with Leading Neutrons



[Bunyatyan]

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



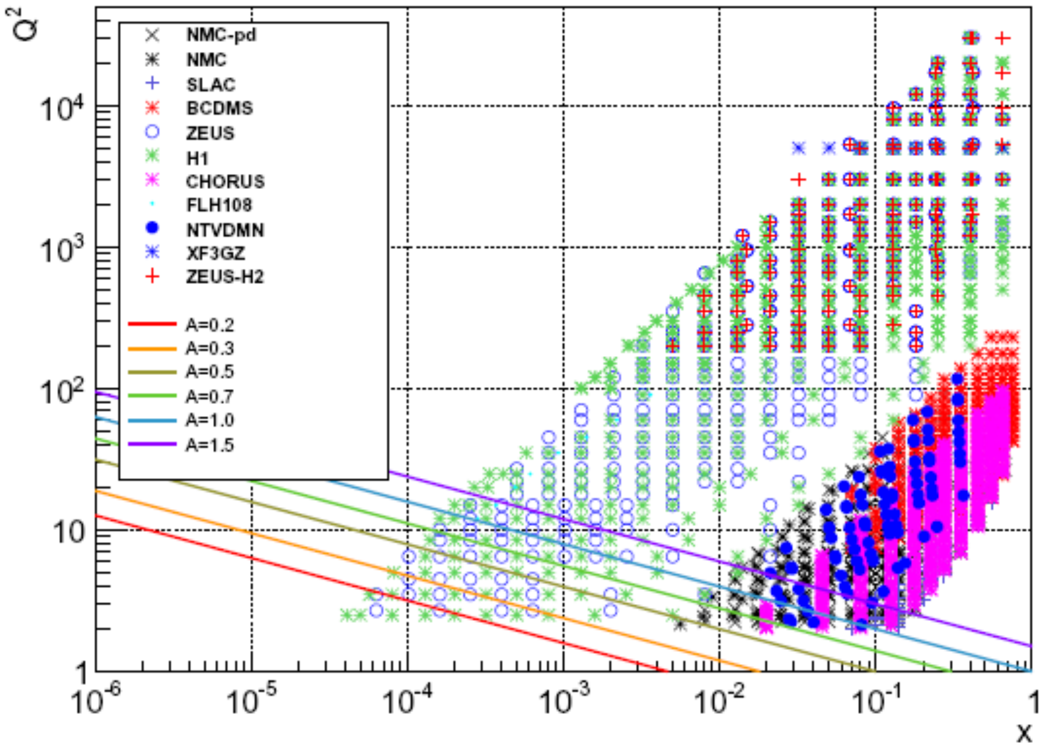


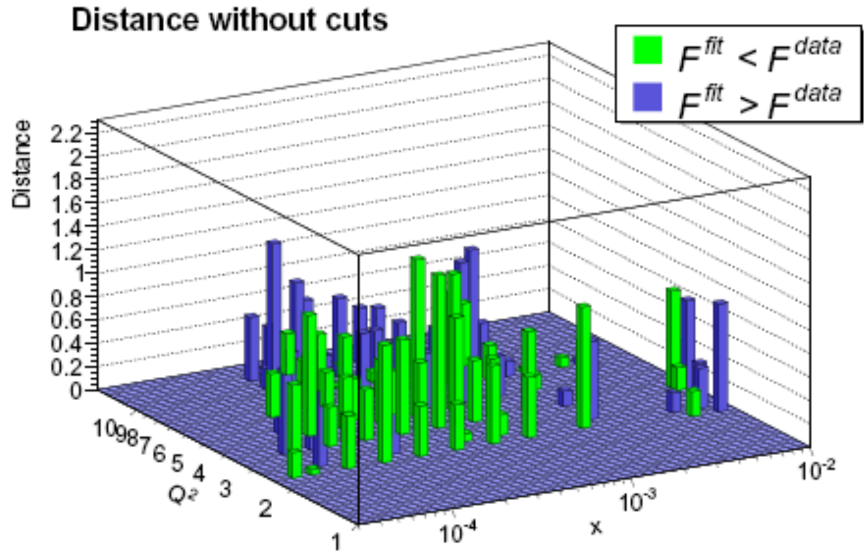
- With θ_n < 1 mrad, similar x_L and p_t ranges to HERA (a bit more p_t lever-arm for π flux).

- Extentions to lower β and higher Q^2 as in leading proton case. → F_2^π At β<5.10^{-5} (cf HERA reaches β~10^{-3})

Also relevant to absorptive corrections, cosmic ray physics …

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

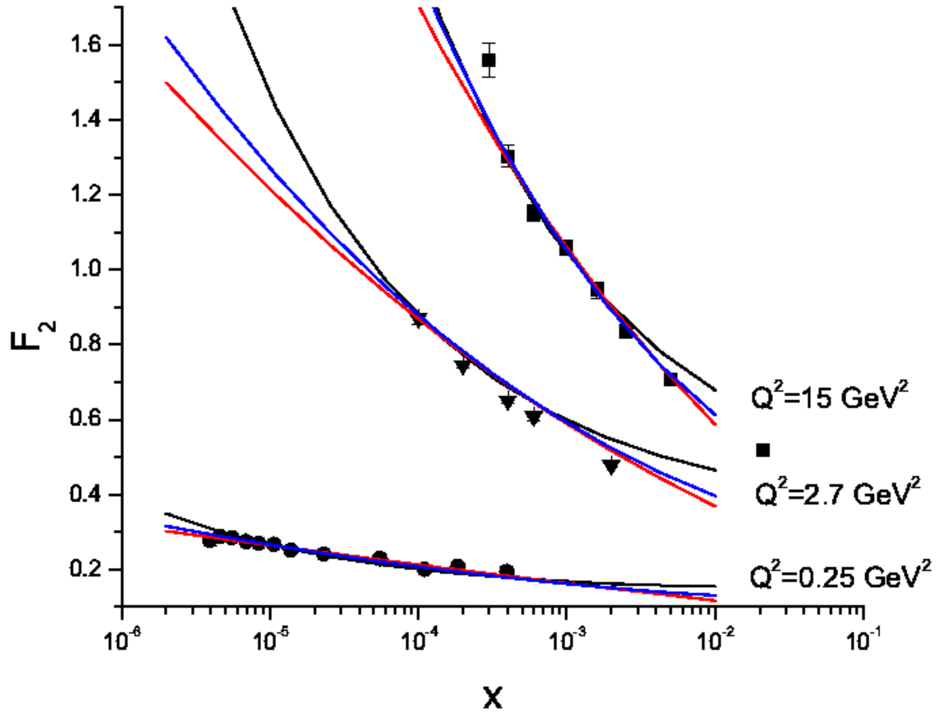
… something happens, but not easily interpreted …

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

Parton Saturation after HERA?

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

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



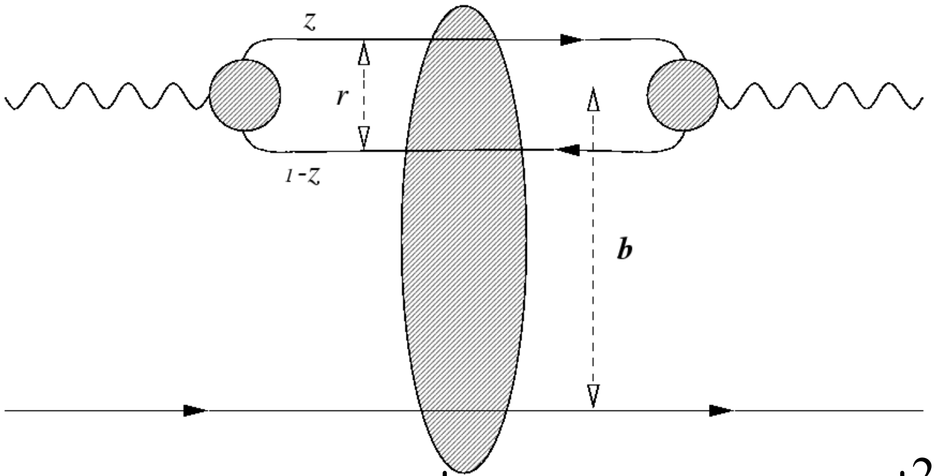
FS04 Regge (~FKS): 2 pomeron model, no saturation
FS04 Satn: Simple implementation of saturation
CGC: Colour Glass Condensate version of saturation

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

… any saturation at HERA not easily interpreted partonically

Reminder : Dipole models

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



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

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

• qqbar-g dipoles also needed to describe inclusive diffraction

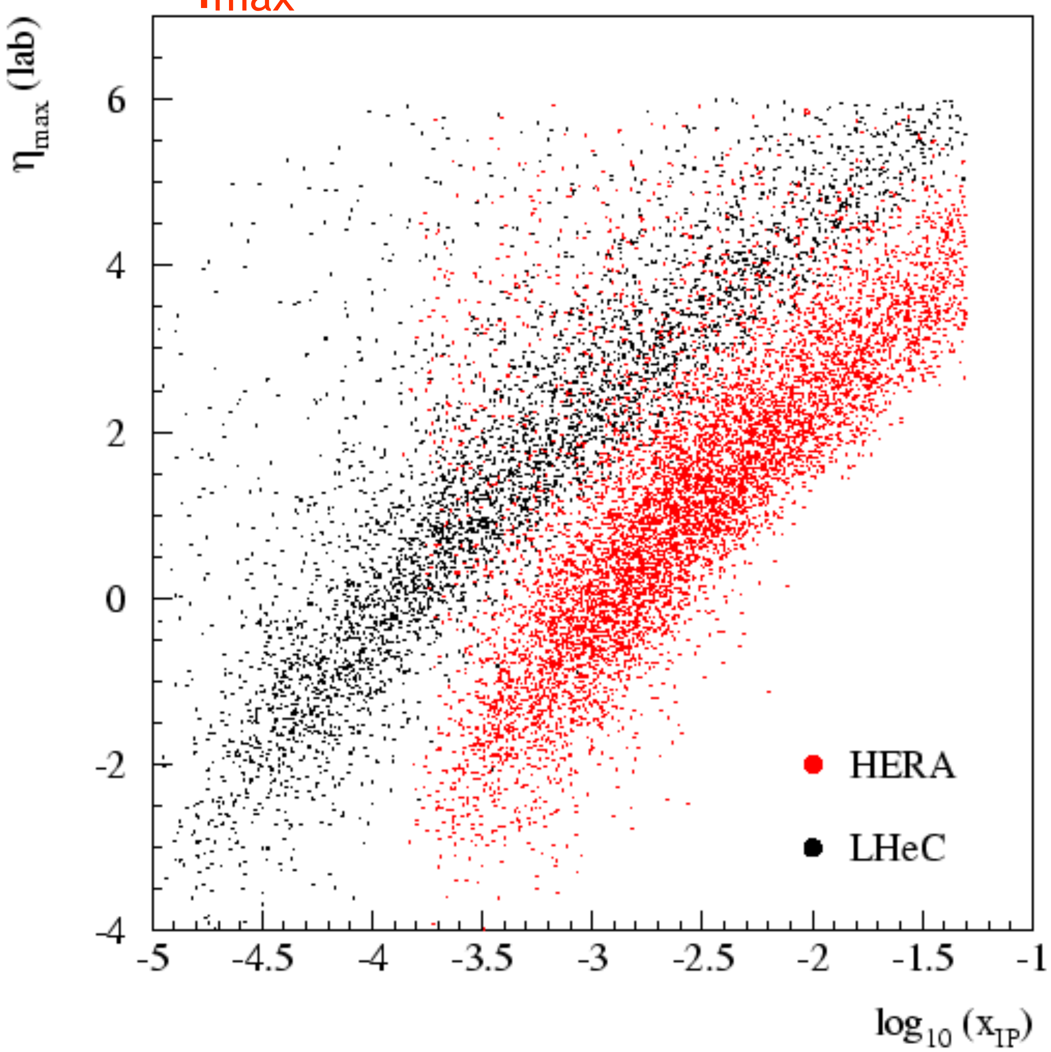
Forward and Diffractive Detectors

- Very forward tracking / calorimetry with good resolution …
- Proton and neutron spectrometers …

- Reaching $x_{IP} = 1 - E_p'/E_p = 0.01$ in diffraction with rapidity gap method requires η_{max} cut around 5 …forward instrumentation essential!

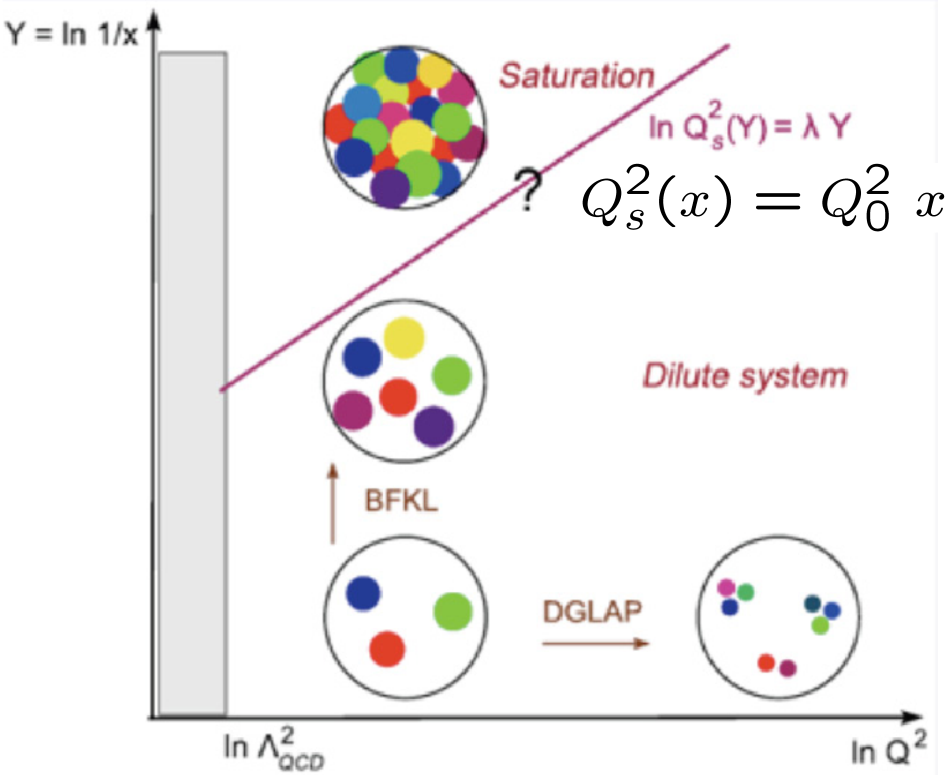
- Roman pots, FNC should clearly be an integral part.
  - Also for t measurements
  - Not new at LHC ☺
  - Being considered integrally with interaction region

η_{max} from LRG selection …



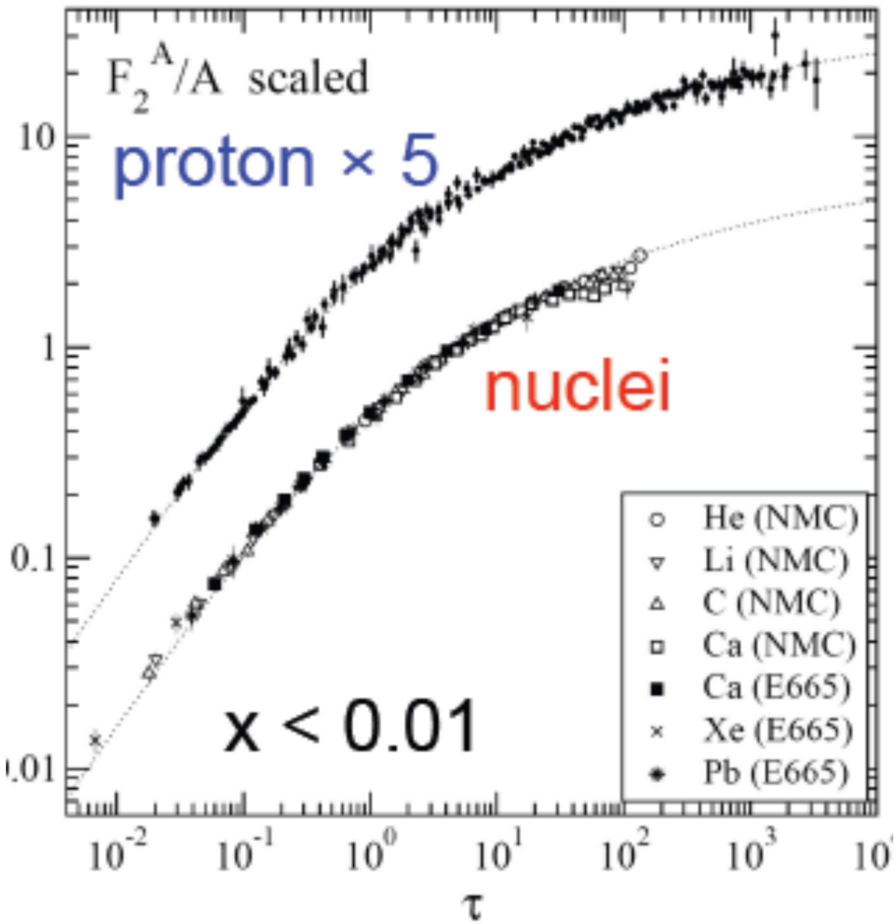
Non-linear effects in HERA and eA Data?

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



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

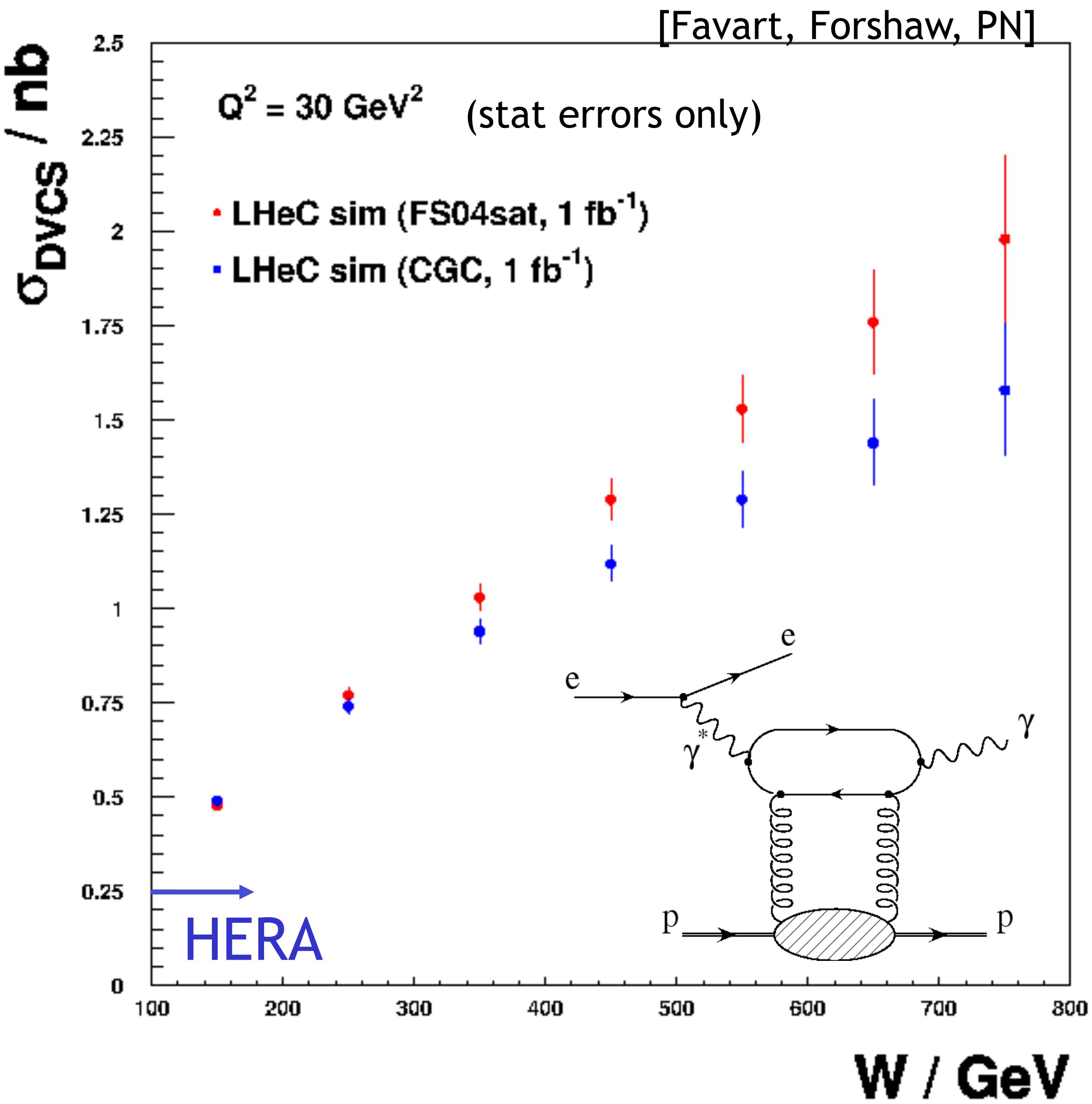
$$\sigma_{tot}^{\gamma^* h \to X}(x, Q^2) = \sigma_{tot}^{\gamma^* h \to X}(Q^2/Q_s^2(x))$$



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

BUT … Q^2 small for τ <~ 1 GeV^2 … not easily interpreted in QCD

DVCS at LHeC



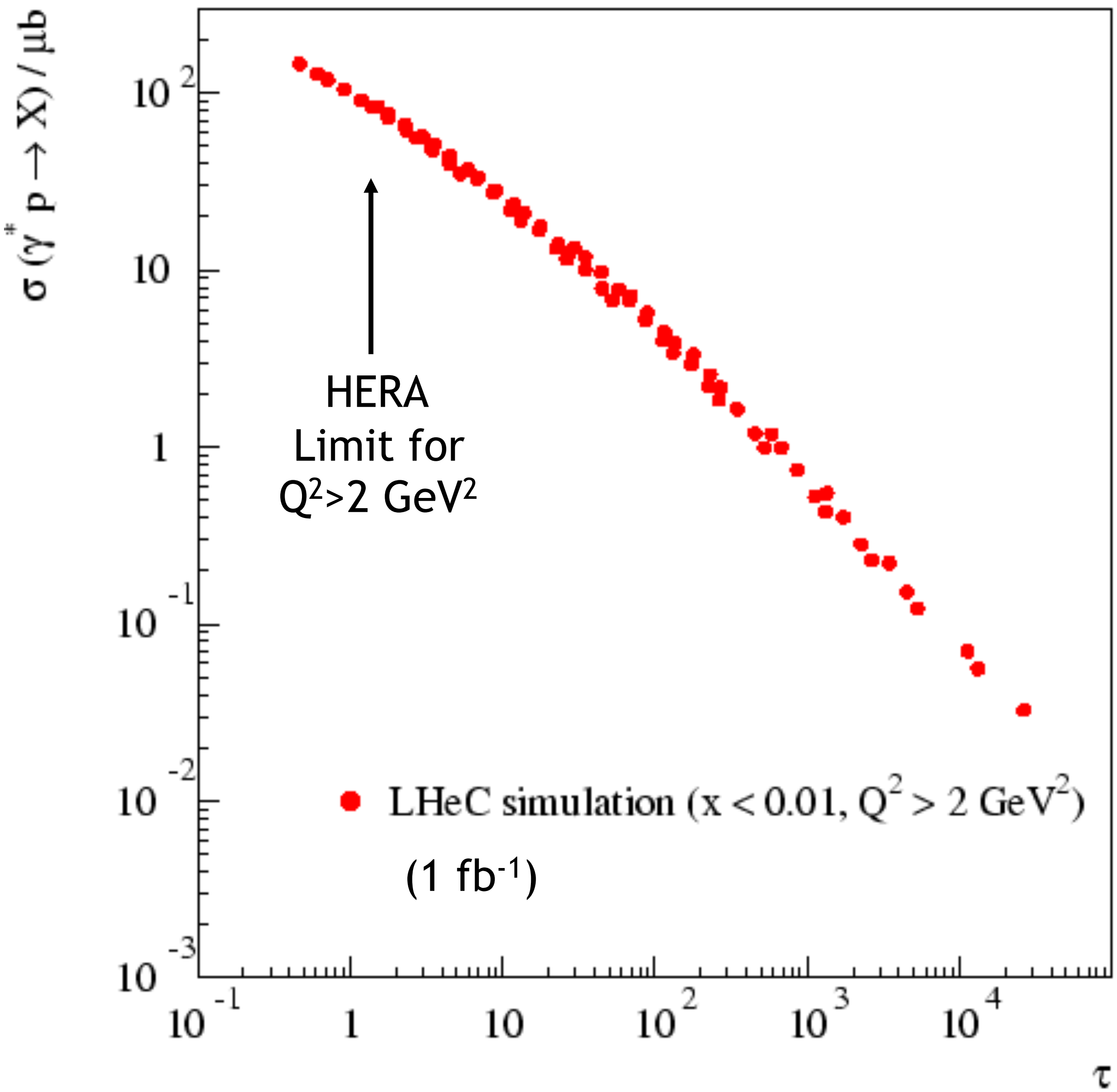
(1^o acceptance)

Statistical precision with 1fb^{-1} ~ 2-11%

With F_2, F_L, DVCS could help establish saturation and distinguish between different models which contain it?

Cleaner interpretation in terms of GPDs at larger LHeC Q^2 values

Geometric Scaling at the LHeC



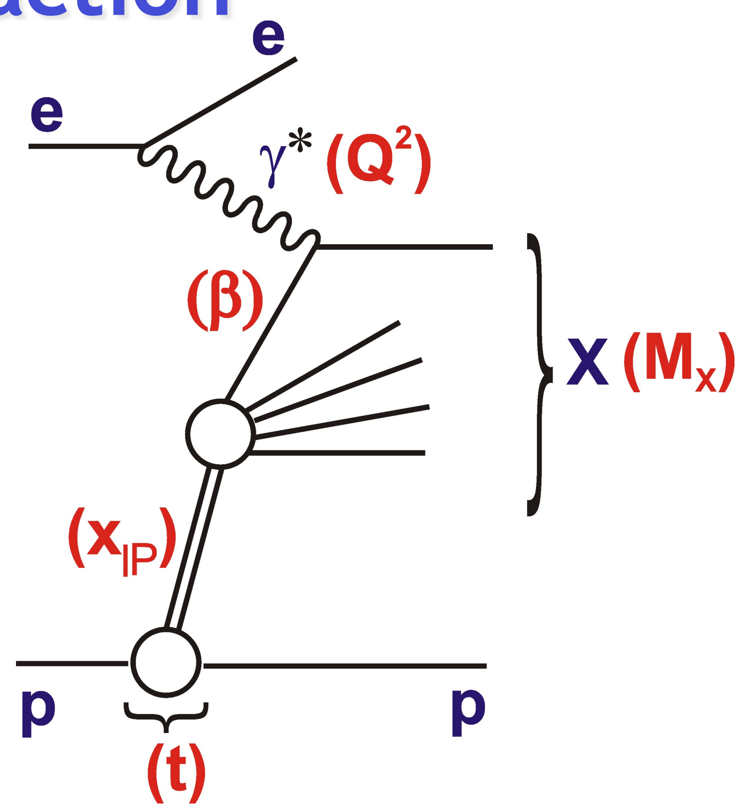
LHeC reaches τ ~ 0.15 for Q^2=1 GeV^2 and τ ~ 0.4 for Q^2=2 GeV^2

Some (though limited) acceptance for $Q^2 < Q^2_s$ with Q^2 "perturbative"

Could be enhanced with nuclei.

Q^2 < 1 GeV^2 accessible in special runs?

Inclusive Diffraction



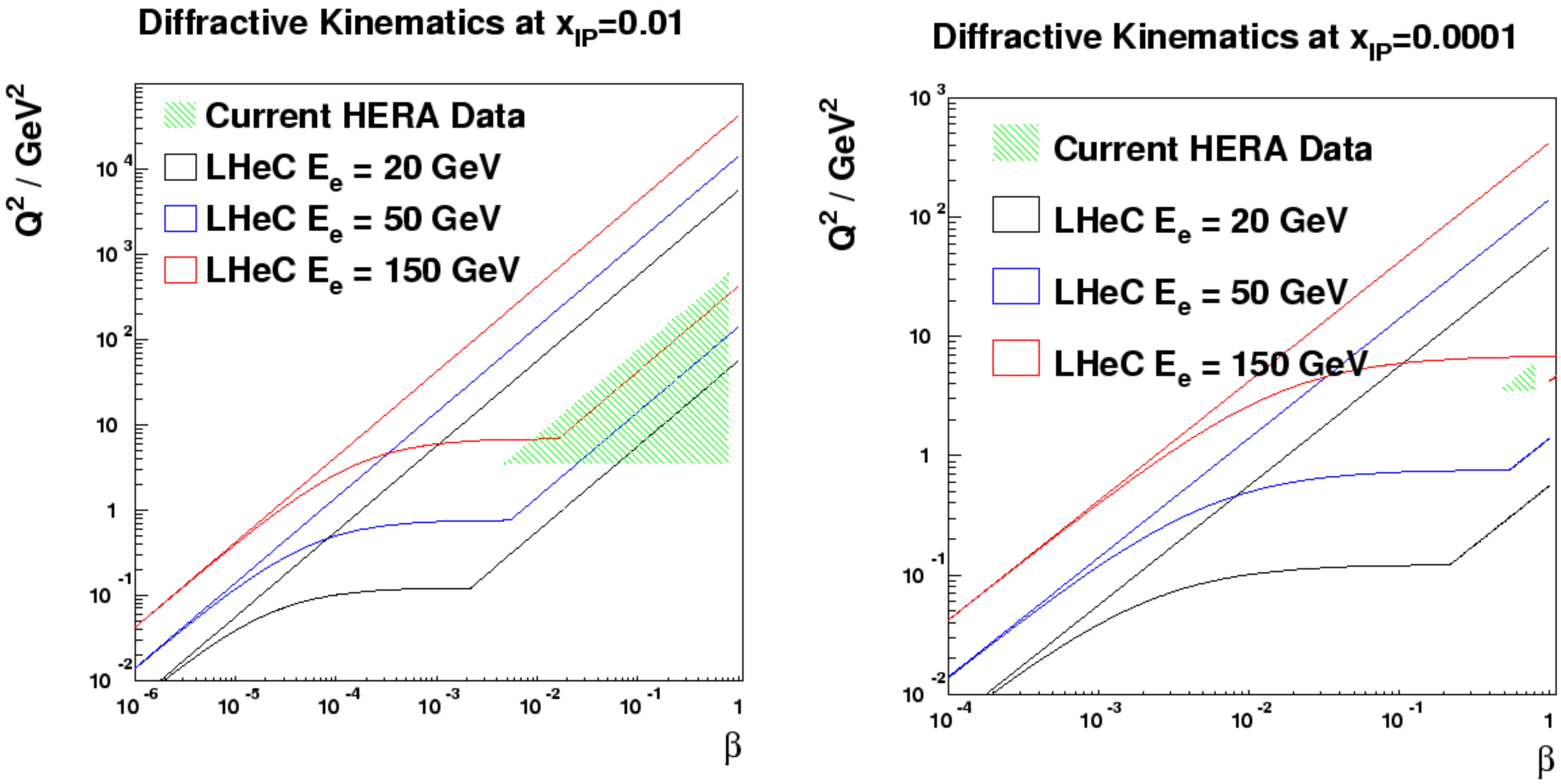
Additional variables ...

x_{IP} = fractional momentum loss of proton (momentum fraction IP/p)

$\beta = x / x_{IP}$ (momentum fraction q / IP)

→ Further sensitivity to saturation phenomena
→ Diffractive parton densities in much increased range
→ Sensitivity to rapidity gap survival issues
→ Can relate ep diffraction to eA shadowing
... Control for interpretation of inclusive eA data

Diffractive Kinematic Plane at LHeC



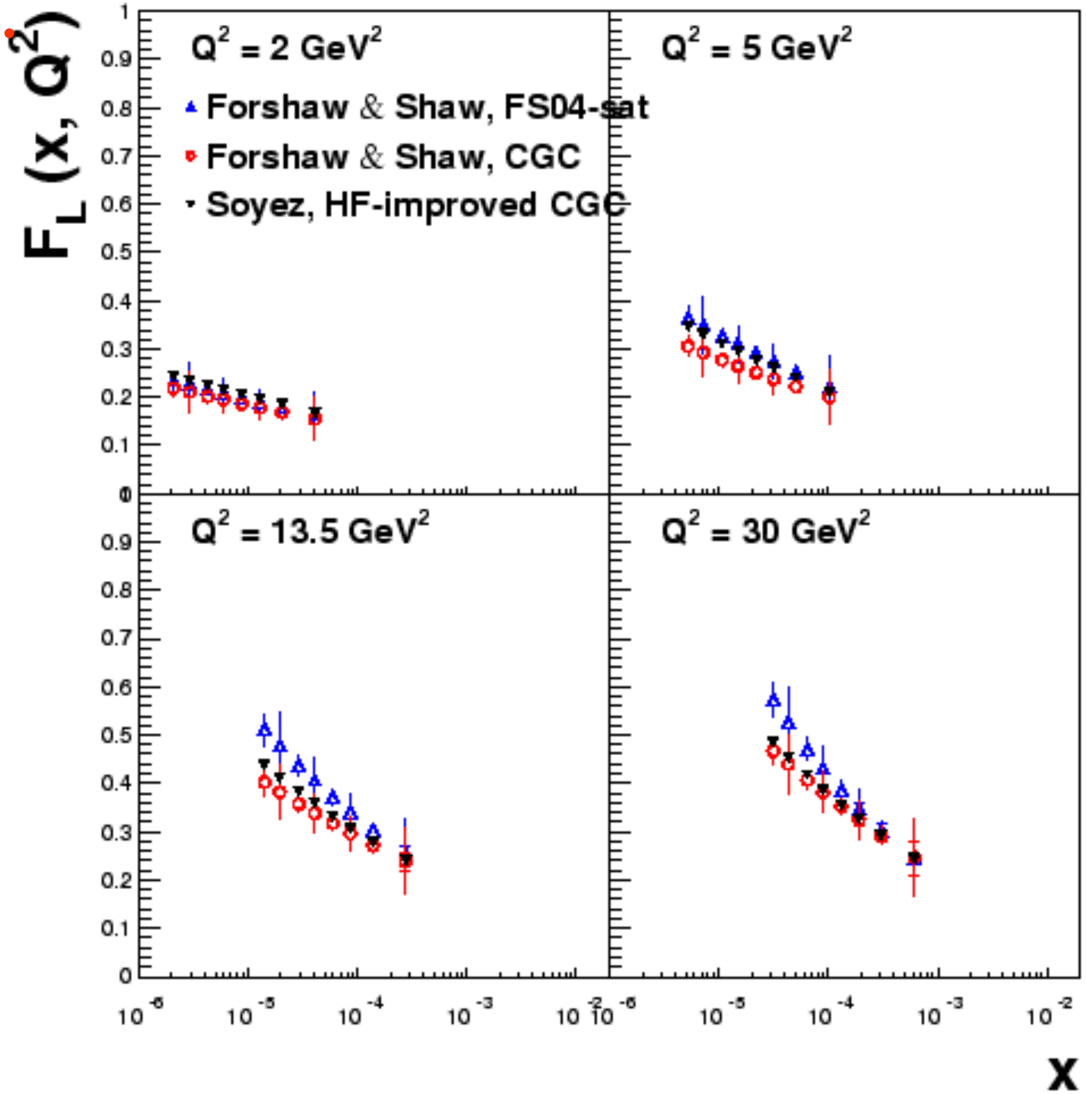
- Higher E_e yields acceptance at higher Q^2 (pQCD), lower x_{IP} (clean diffraction) and β (low x effects)
- Similar to inclusive case, 170° acceptance kills most of plane

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]

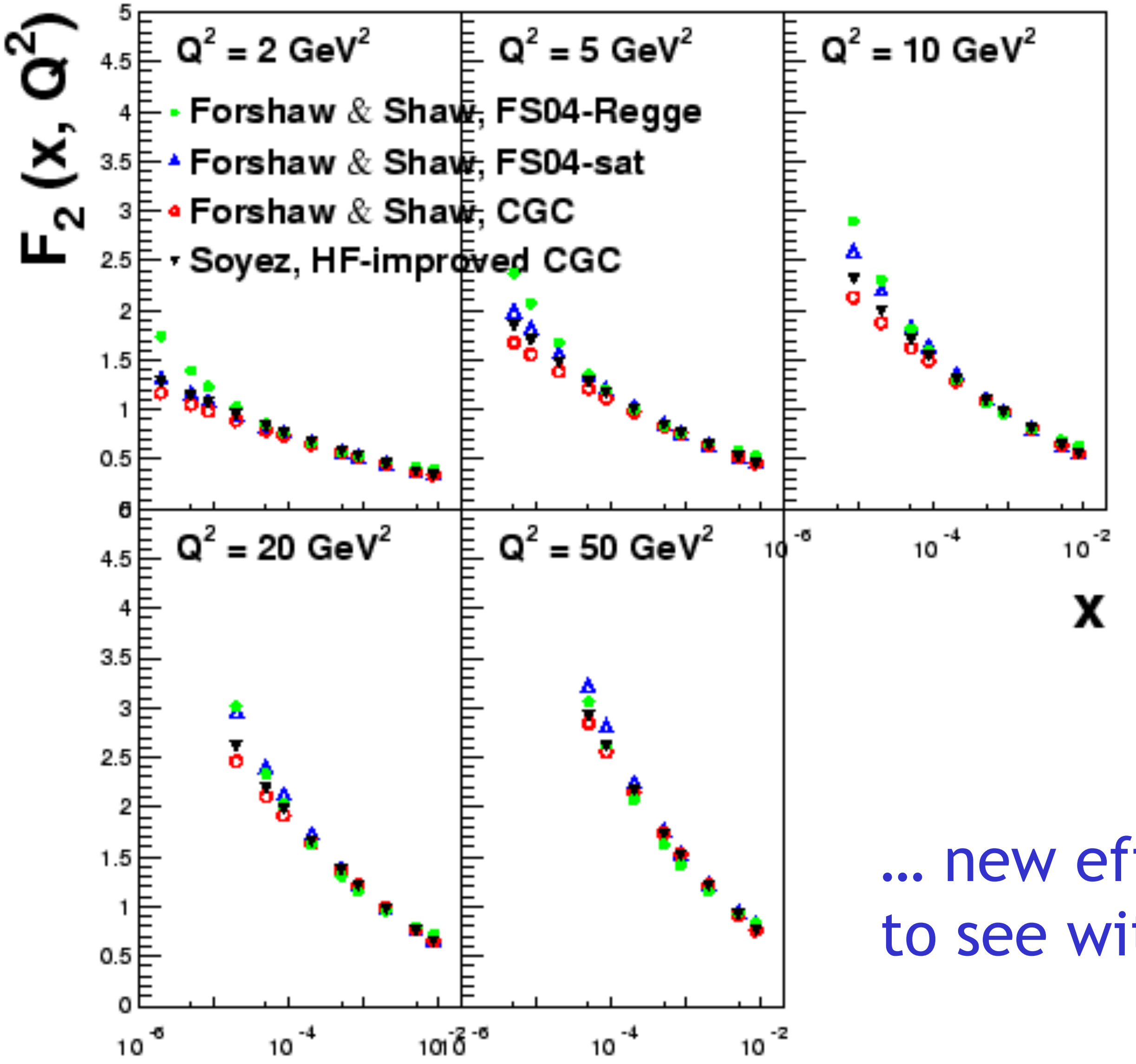
... selected lowest x data
compared with 3 dipole
models including saturation ...



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

Some models of low x F_2 with LHeC Data

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



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

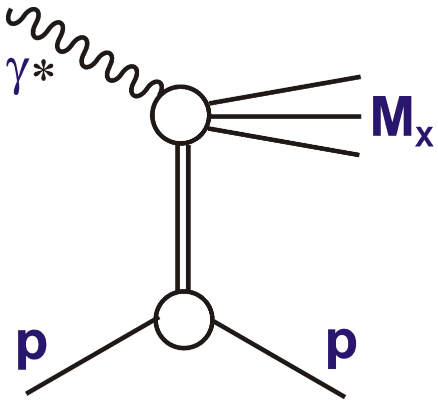
- Extrapolated HERA models …
- FS04, CGC models including saturation suppressed at low x & Q^2 relative to non-sat FS04-Regge

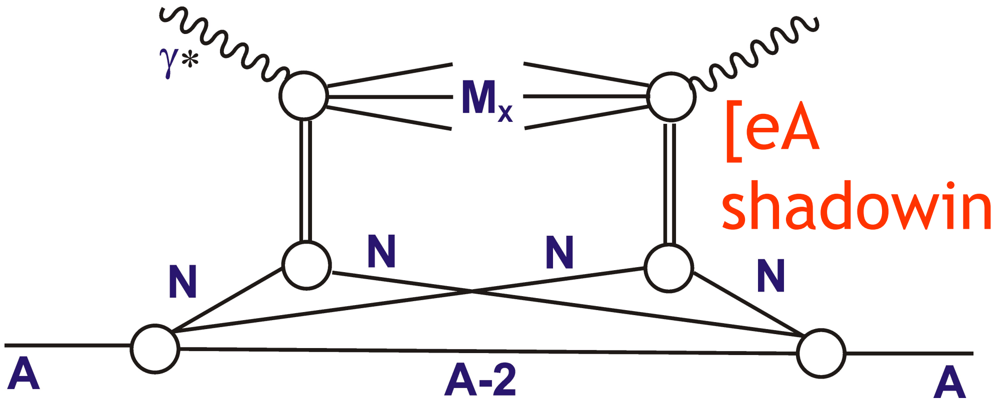
… new effects may not be easy to see with a single observable

F_2^D and Nuclear Shadowing

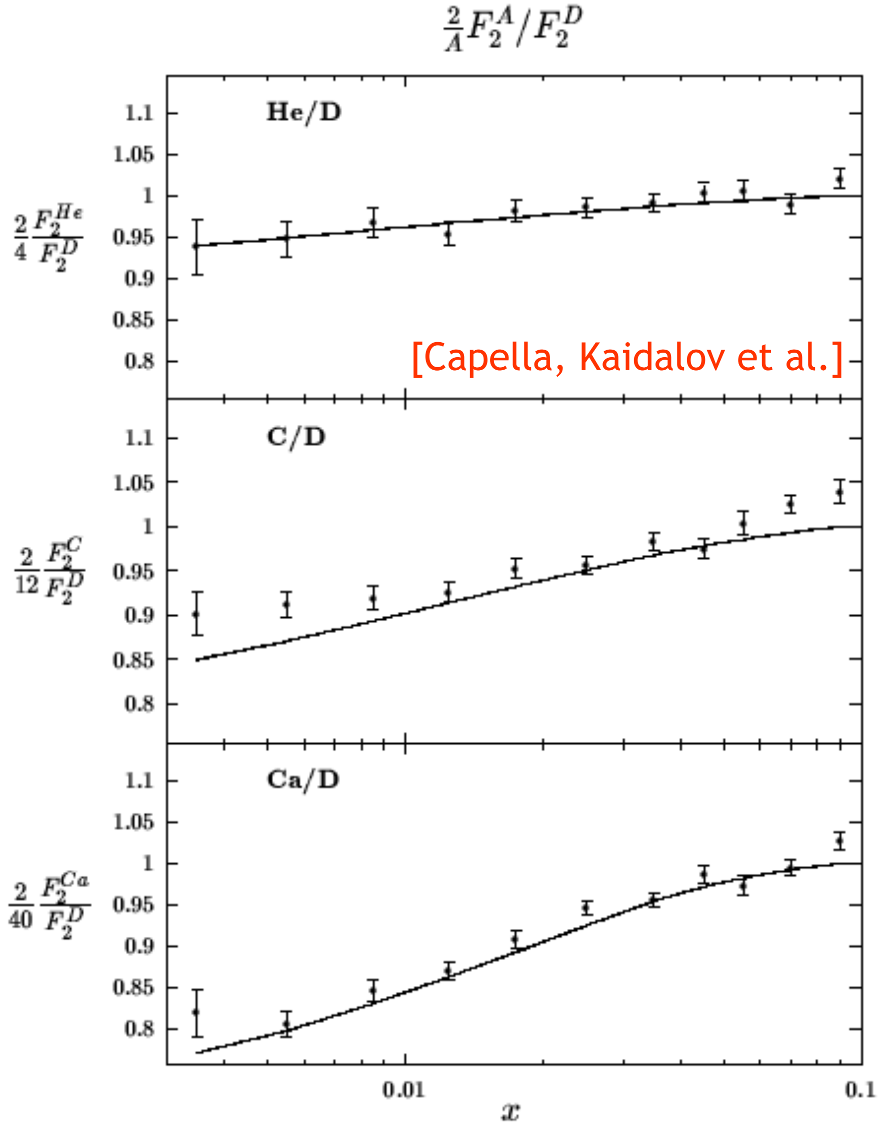
Nuclear shadowing can be described (Gribov-Glauber) as multiple interactions, starting from ep DPDFs

[Diff DIS]



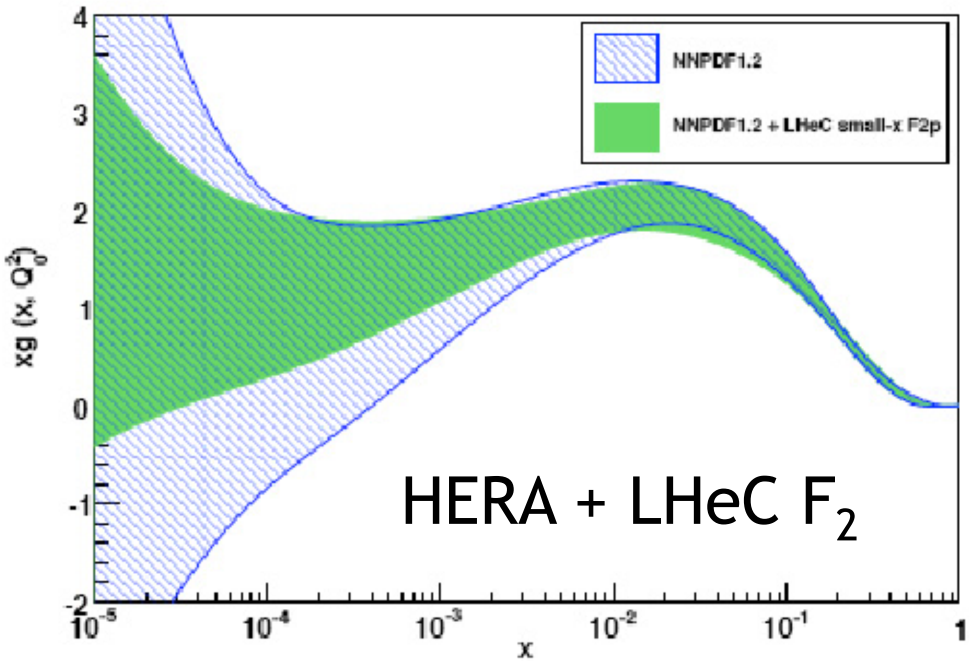


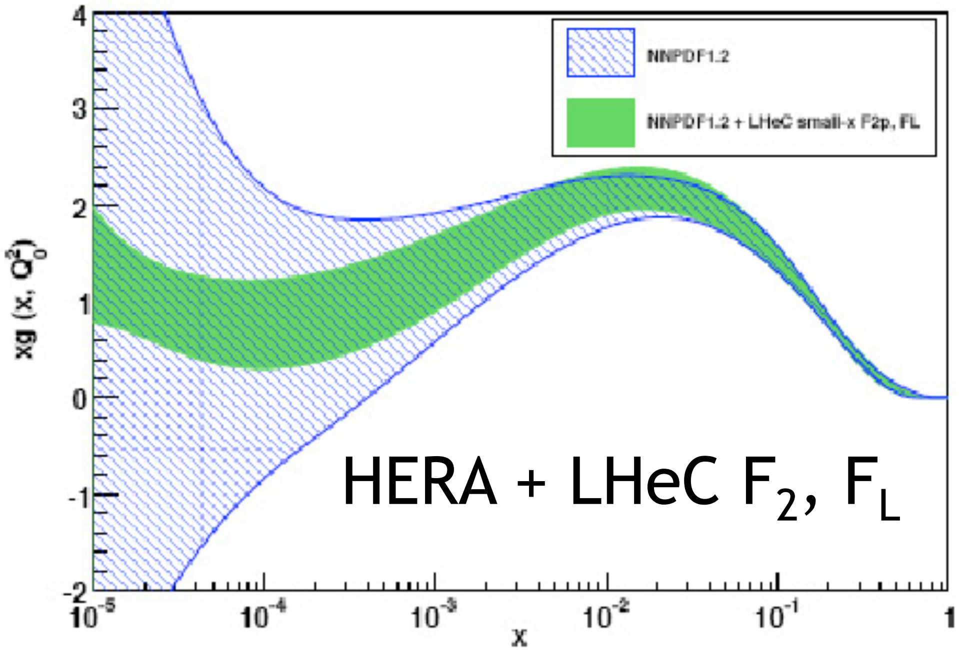
[eA shadowing]



… starting point for extending precision LHeC studies into eA collisions

Fitting for the Gluon with LHeC F_2 and F_L





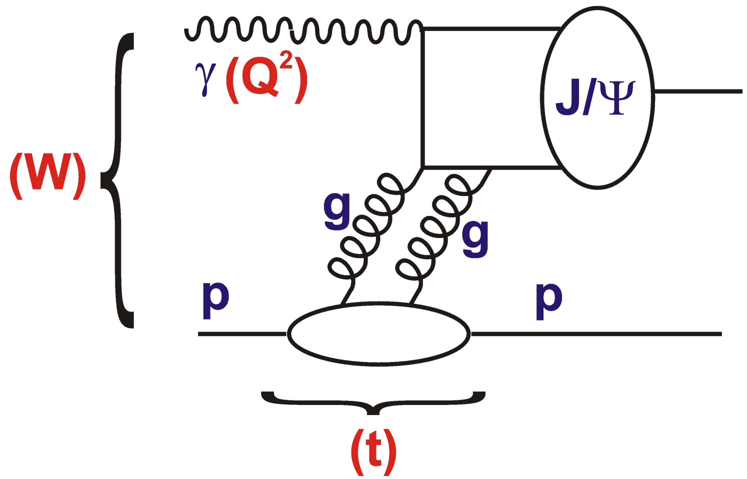
(Q^2 = 2 GeV^2)

Including LHeC data in NNPDF DGLAP fit approach …

… sizeable improvement in error on low x gluon when both LHeC F_2 & F_L data are included.

… but would DGLAP fits fail if non-linear effects present?

Elastic J/Ψ Photoproduction: Golden Channel?



- \`Cleanly' interpreted as hard 2g exchange coupling to qqbar dipole … enhanced sensitivity to low x gluon

- c and c-bar share energy equally, simplifying VM wavefunction

- Clean experimental signature (just 2 leptons)

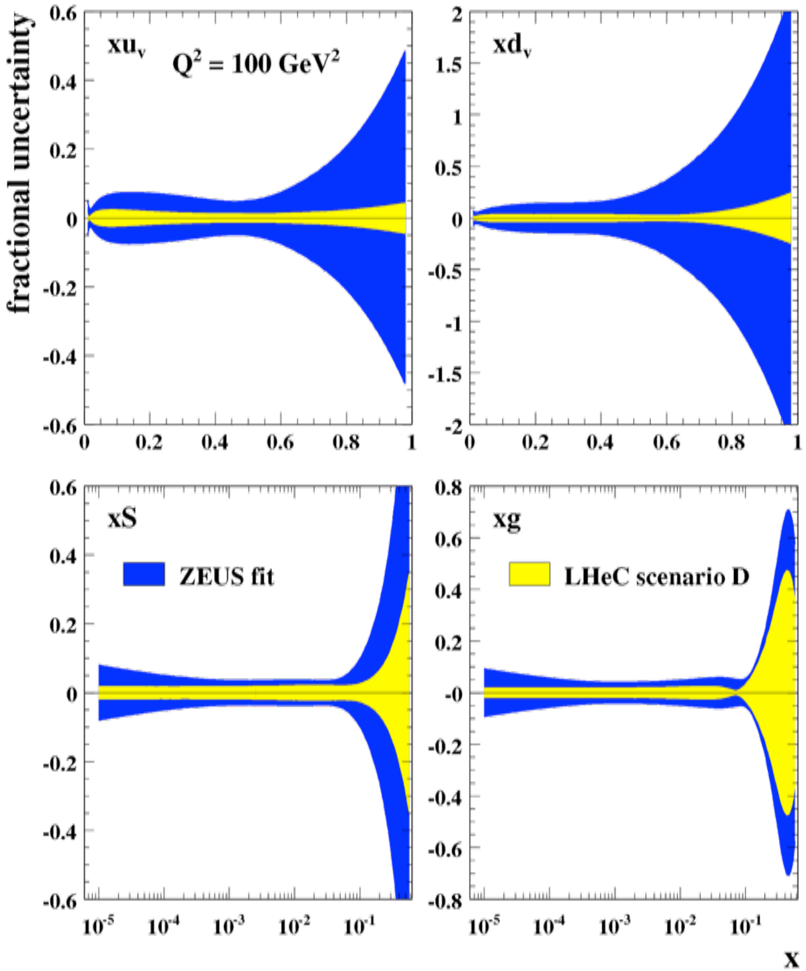
… LHeC reach extends to $x_g \sim 6.10^{-6}$ at $\overline{Q^2} \sim 3$ GeV^2

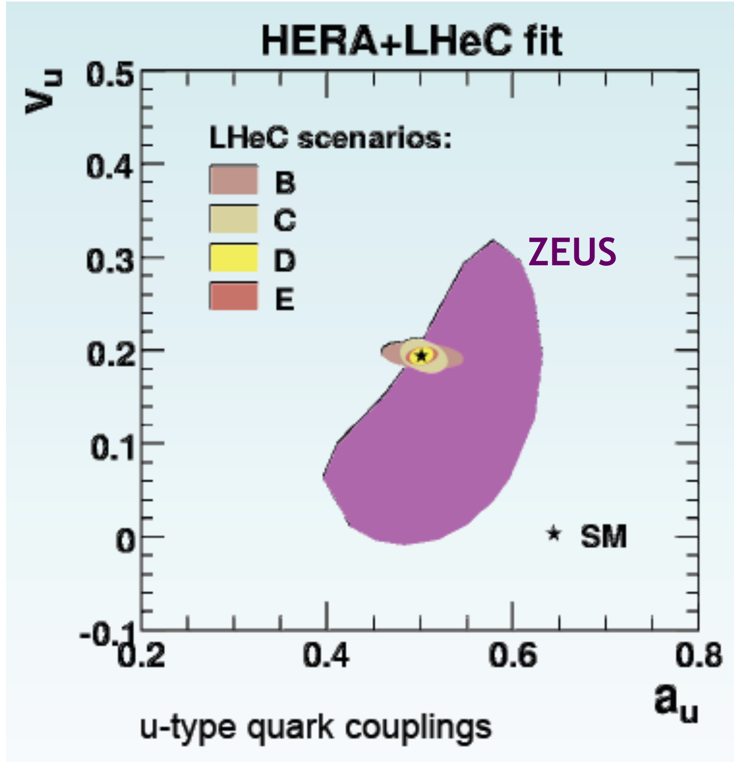
(MNRT etc) $X_g \sim (Q^2 + M_V{}^2) \;/\; (Q^2 + W^2)$ $\qquad \overline{Q^2} = (Q^2 + M_V{}^2) \;/\; 4$

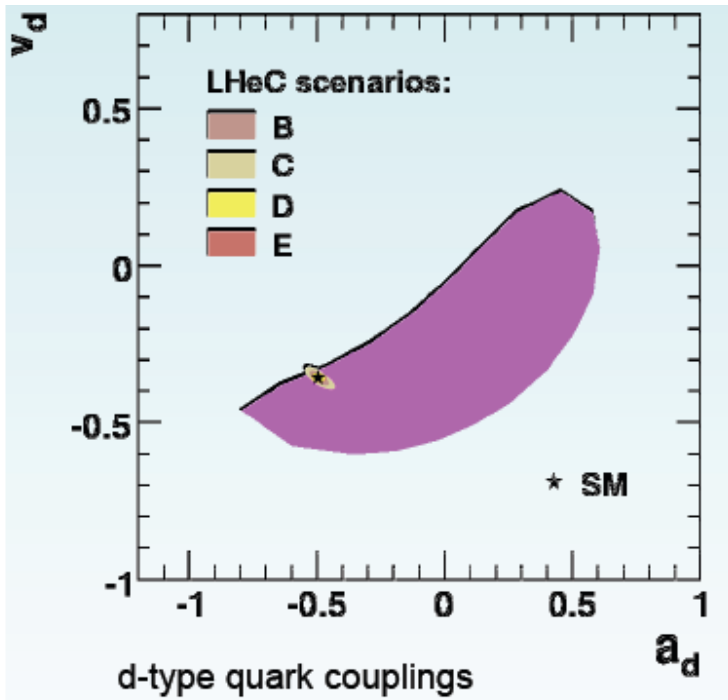
- Simulations of elastic J/Ψ → μμ photoproduction

→ scattered electron untagged, 1° acceptance for muons (similar method to H1 and ZEUS)

PDFs & EW Couplings





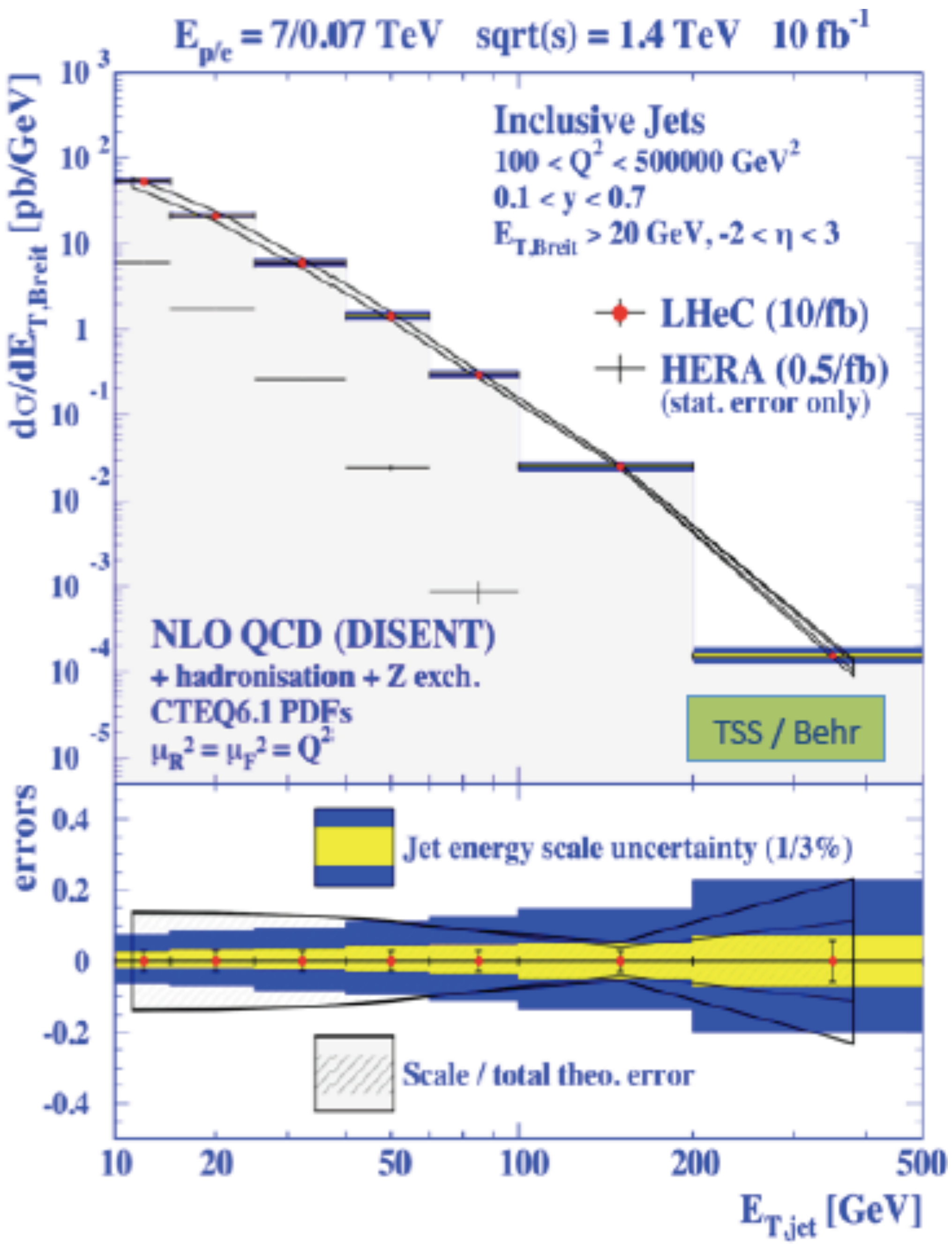


Using ZEUS fitting code, HERA + LHeC data … EW couplings free

E_e = 100 GeV, L = 10+5 fb^{-1}, P = +/- 0.9

Also: Weak mixing angle at TeV scales

Inclusive Jets & QCD Dynamics

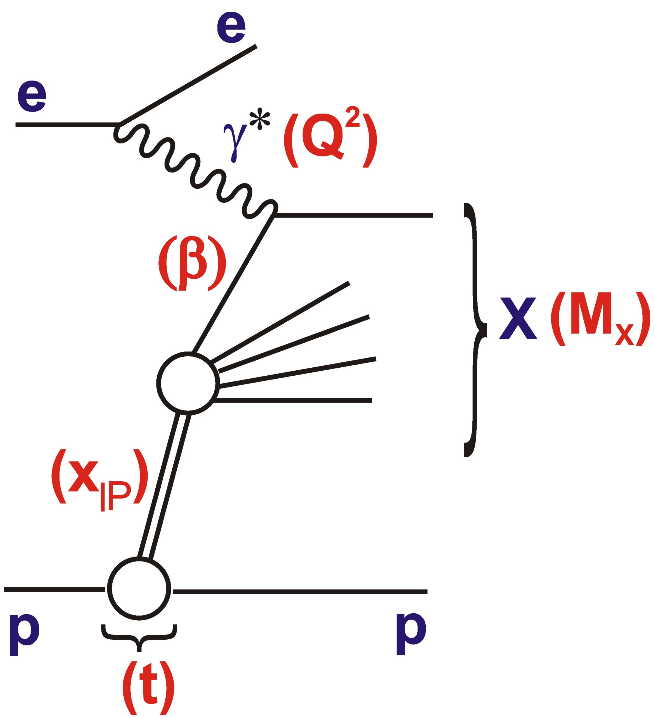


Also differential in Q^2 with high precision to beyond $Q^2 = 10^5$ GeV^2

α_s up to scale ~ 400 GeV

Detailed studies of QCD dynamics, including novel low x effects in regions not probed at HERA and (probably) not at LHC

Inclusive Diffractive Dissociation

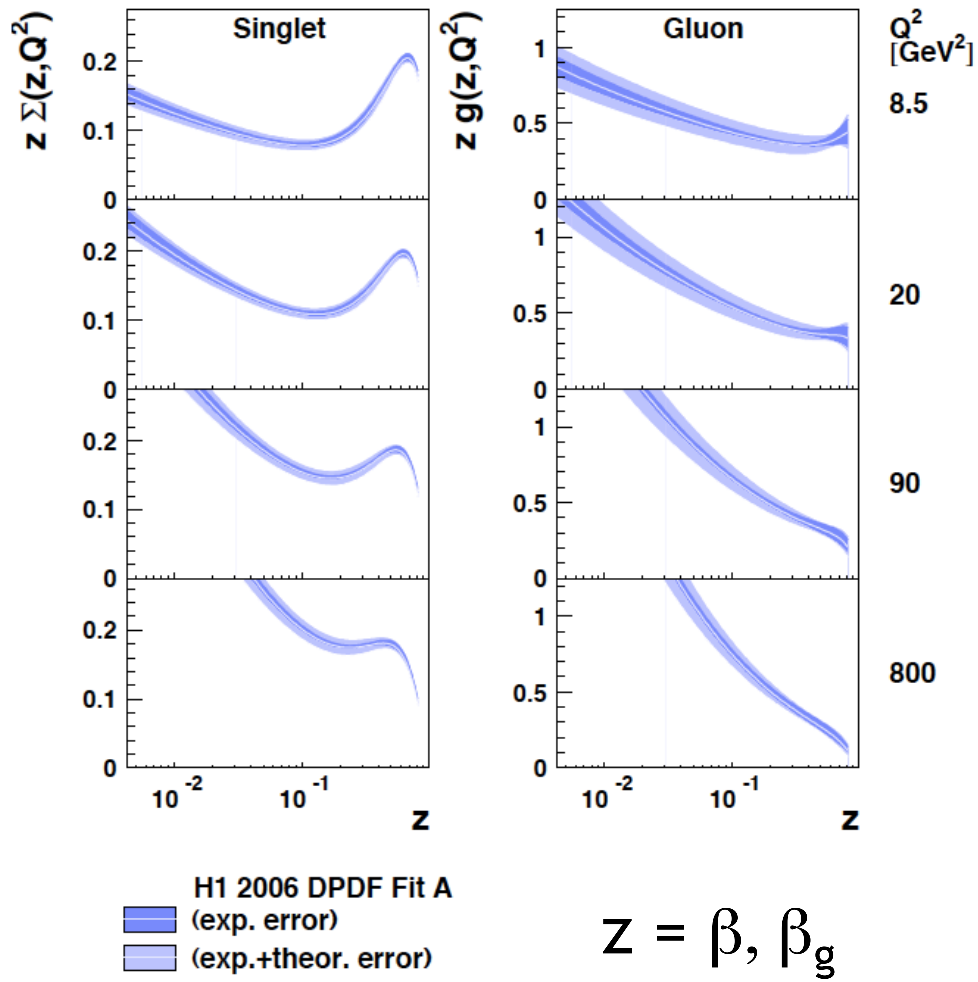


Additional variables …

x_{IP} = fractional momentum loss of proton (fraction IP/p)

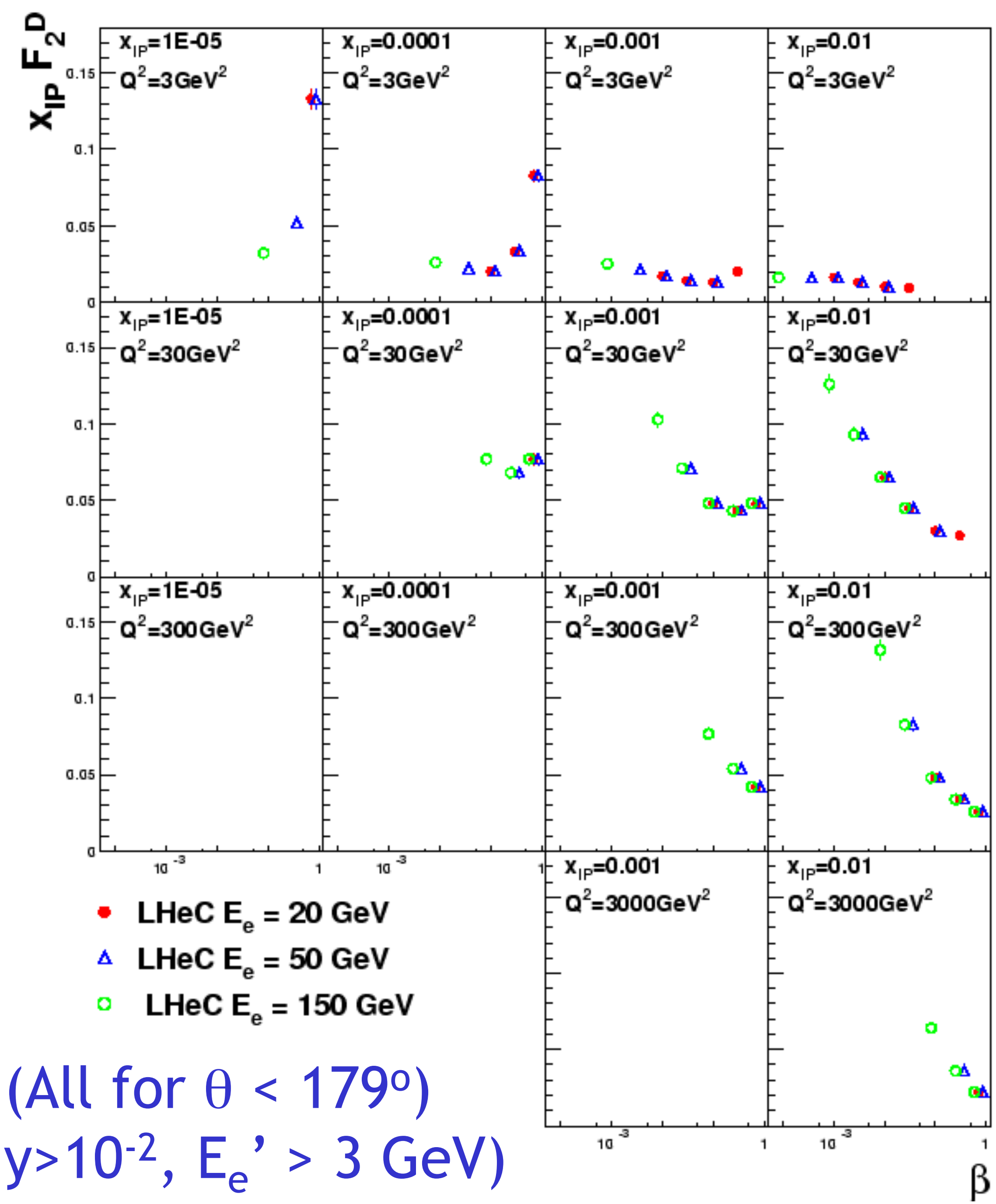
$\beta = x \,/\, x_{IP}$ (fraction q/IP)

… used at HERA to extract diffractive parton densities



$z = \beta, \beta_g$

Simulated Data



(All for θ < 179°)
$y>10^{-2}$, E_e' > 3 GeV)

- Simulated data combining rapidity gap & proton tagging methods
- Small subset of possible bins, emphasising β dependence in 4 wide x_{IP} , Q^2 bins
- Statistical precision not an issue … phase space runs out before data