Diffraction at the LHeC

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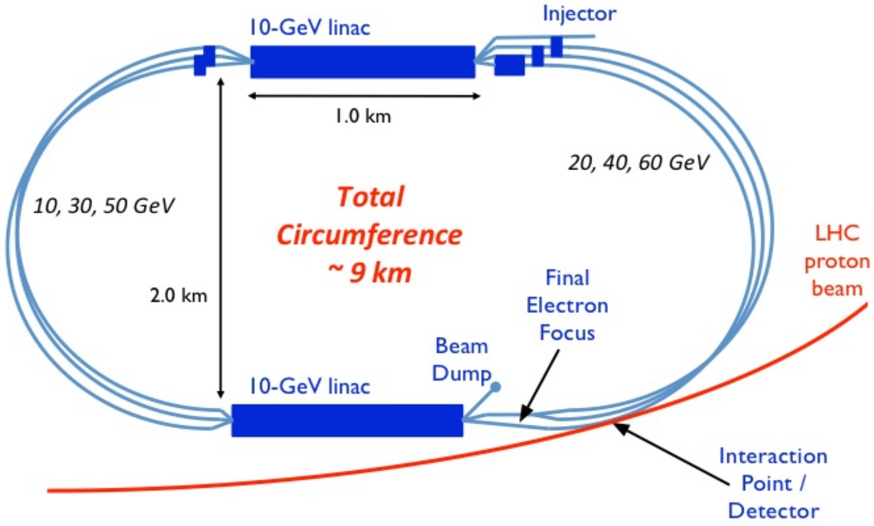
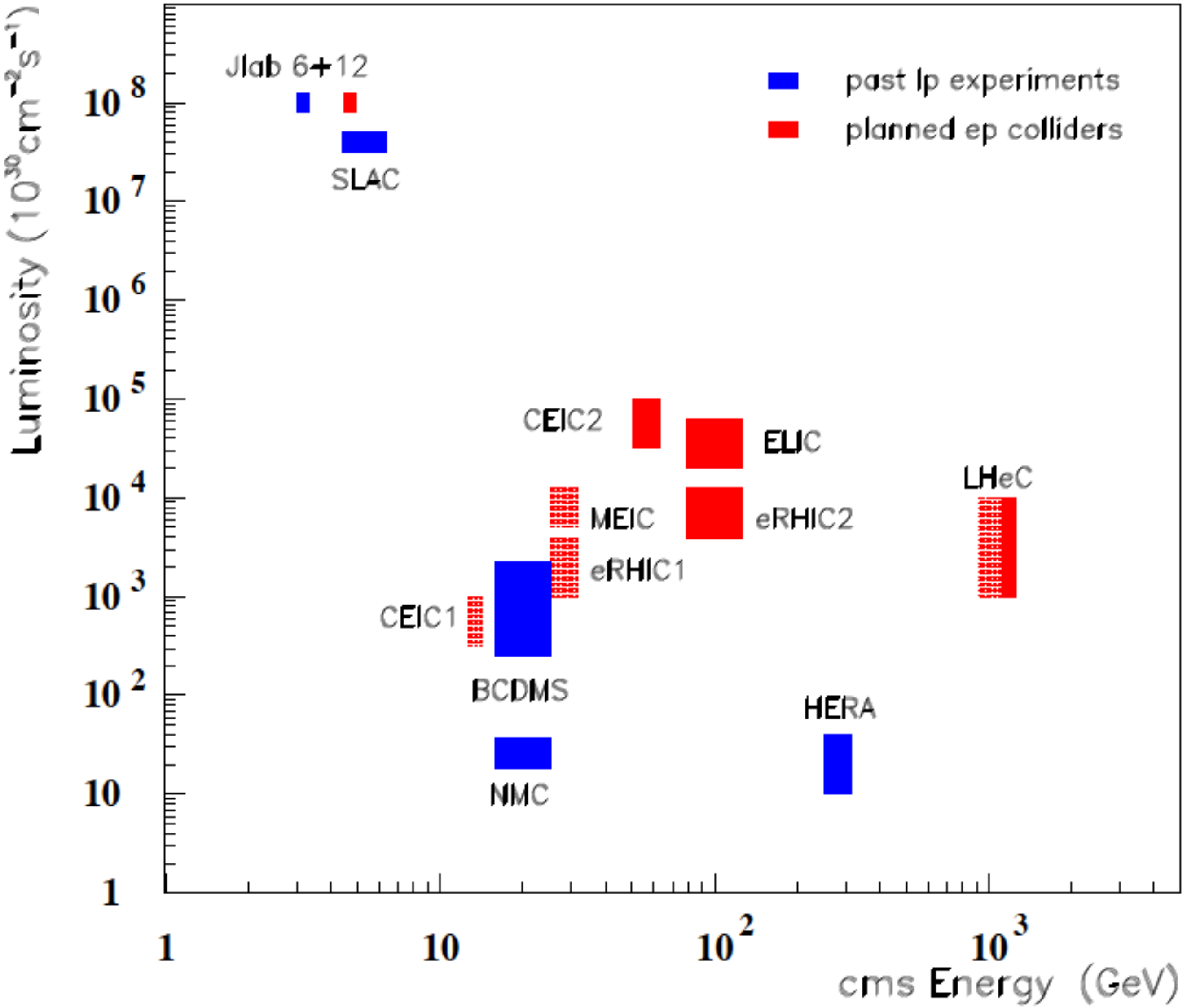
Birmingham University



- *A Lepton-hadron collider for the 2020s / 2030s, based on the high lumi LHC*
- *Adding ep and eA collisions to the LHC pp, AA, pA programme*

Diffraction 2014
Primosten, Croatia
11 September 2014

LHeC Context



- Lepton-hadron scattering at the TeV centre of mass scale (60 GeV electrons x LHC protons & ions)

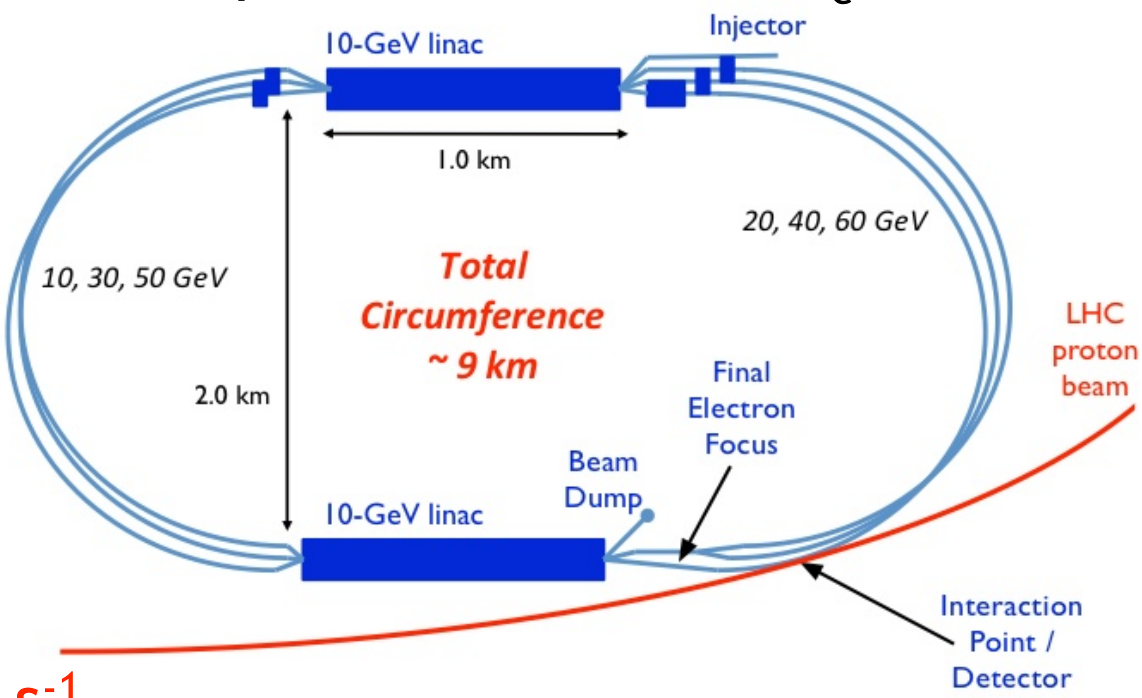
- High luminosity: 10^{33} - 10^{34} cm^{-2} s^{-1}

- Runs simultaneous with ATLAS / CMS in post-LS3 HL-LHC period

Baseline# Design (Electron "Linac")

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

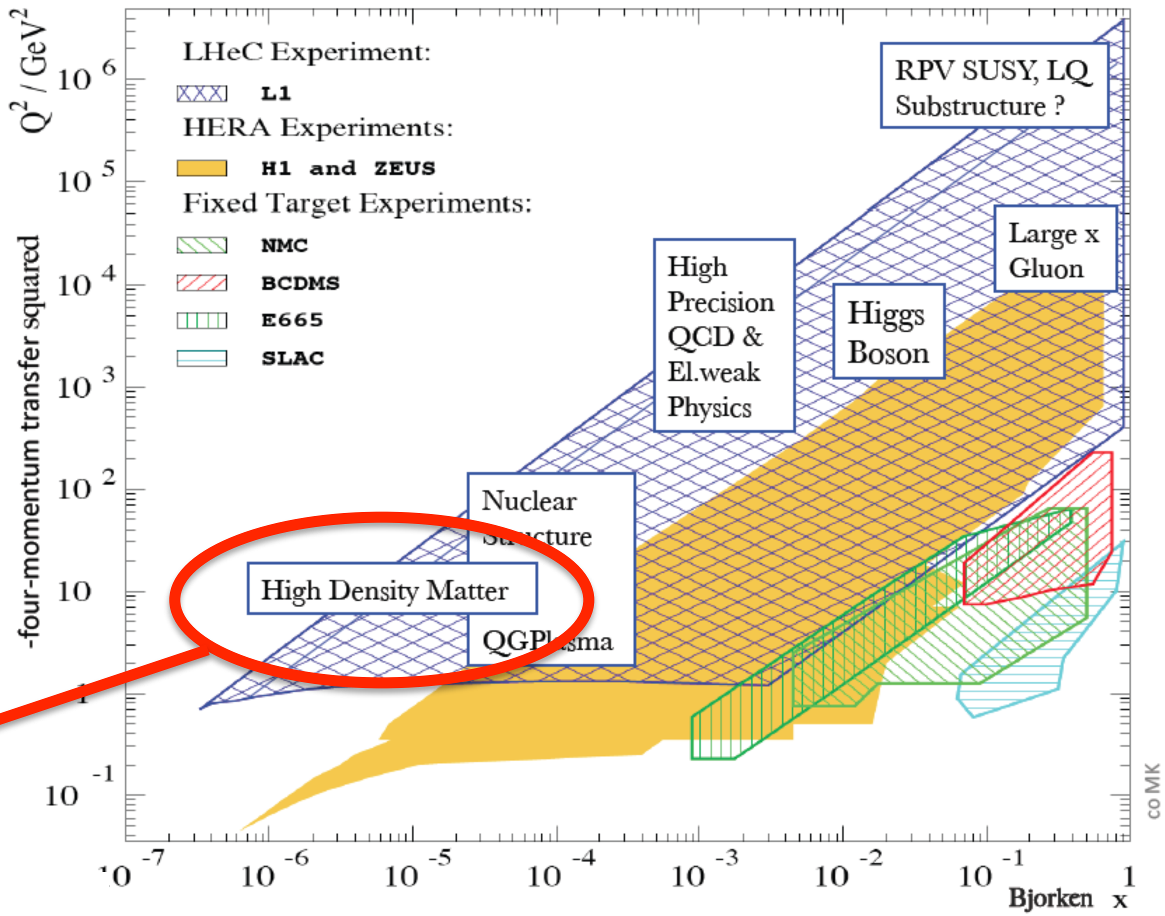
- Two 10 GeV linacs,
- 3 returns, 20 MV/m
- Energy recovery in same structures [CERN plans energy recovery prototype]



- ep Lumi 10^{33} – 10^{34} cm^{-2} s^{-1}
→ 10 - 100 fb^{-1} per year
→ 100 fb^{-1} – 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)**

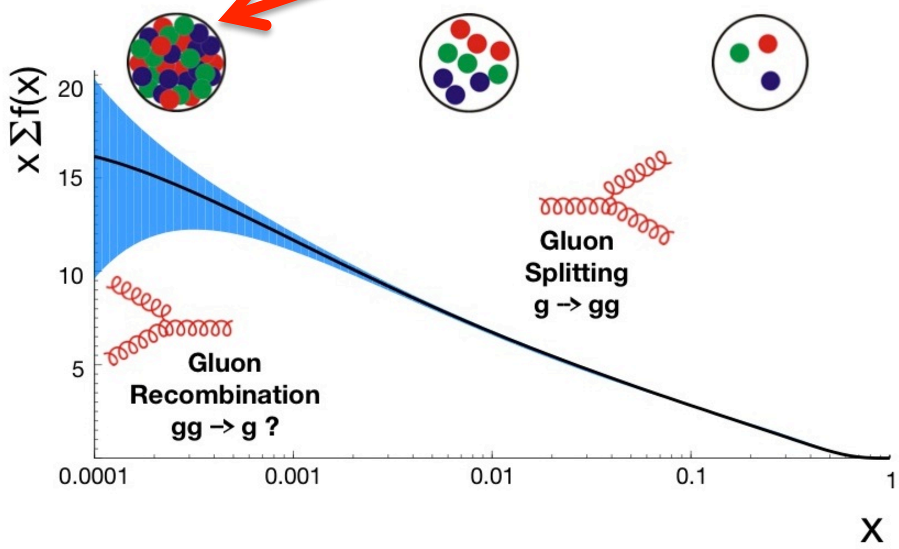
Alternative designs based on electron ring and on higher energy, lower luminosity, linac also exist

Physics Overview



Wide ranging and varied physics goals require precision throughout accessible region.

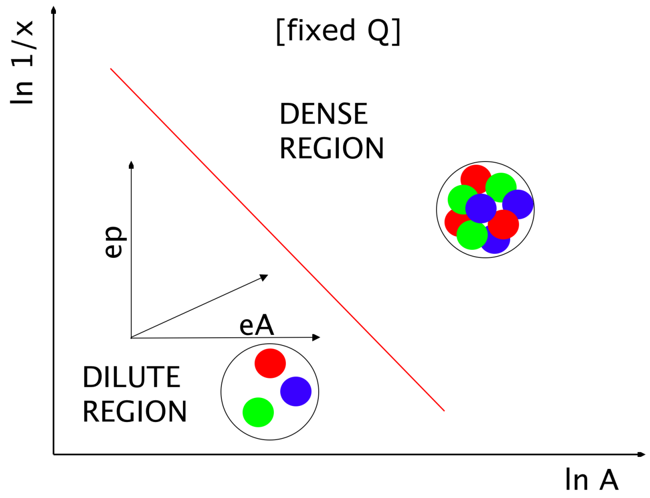
Newly accessed low x region is special.



High density, small coupling partonic regime of non-linear evolution dynamics, dominated by gluons → confinement and hadronic mass generation

LHeC: Accessing saturation region at large Q^2

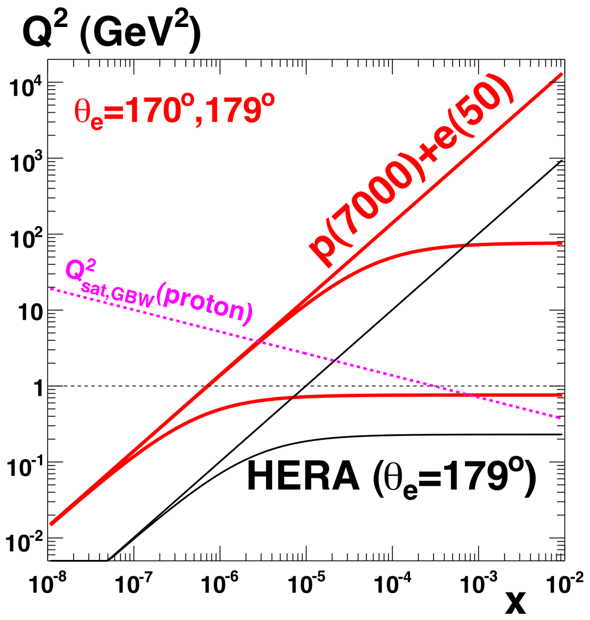
LHeC delivers a 2-pronged approach:

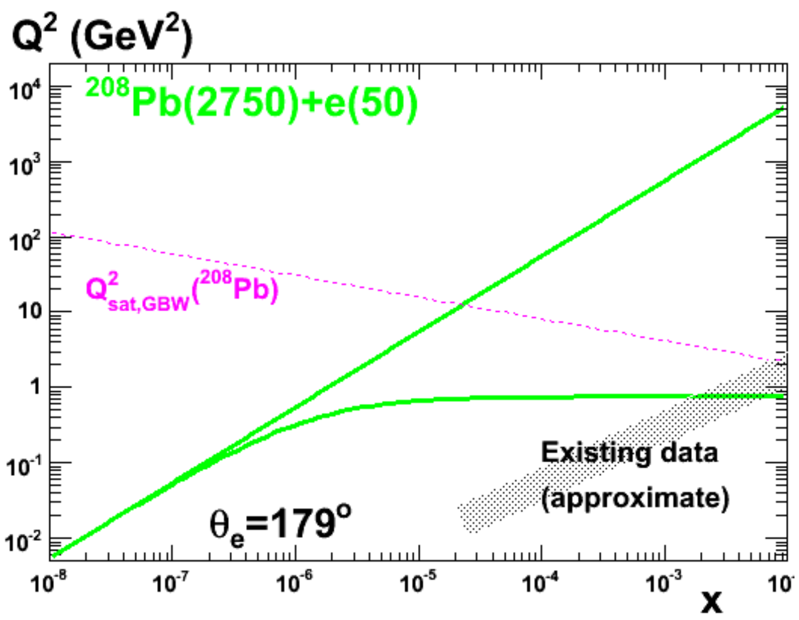


Enhance target `blackness' by:

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]

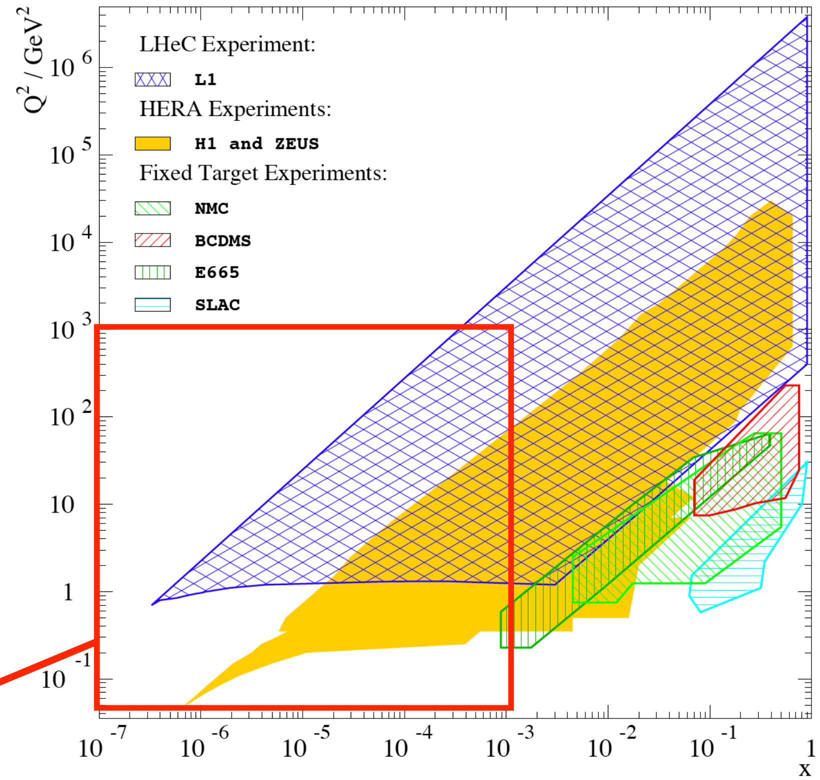


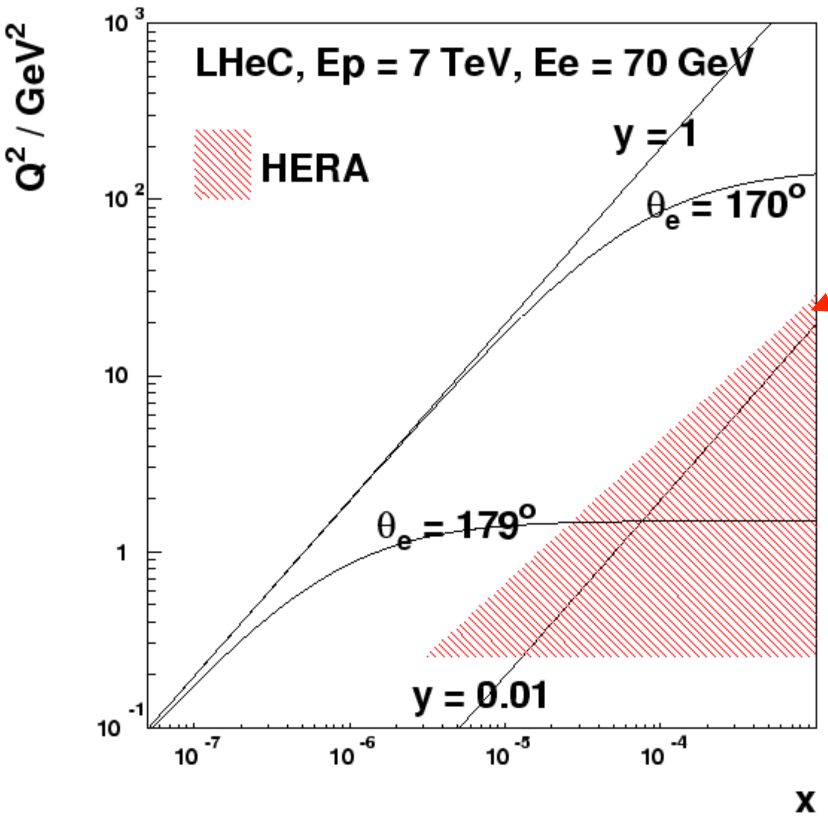


… Reaches saturated region in both ep & eA inclusive data according to models

Low x Acceptance Requirements

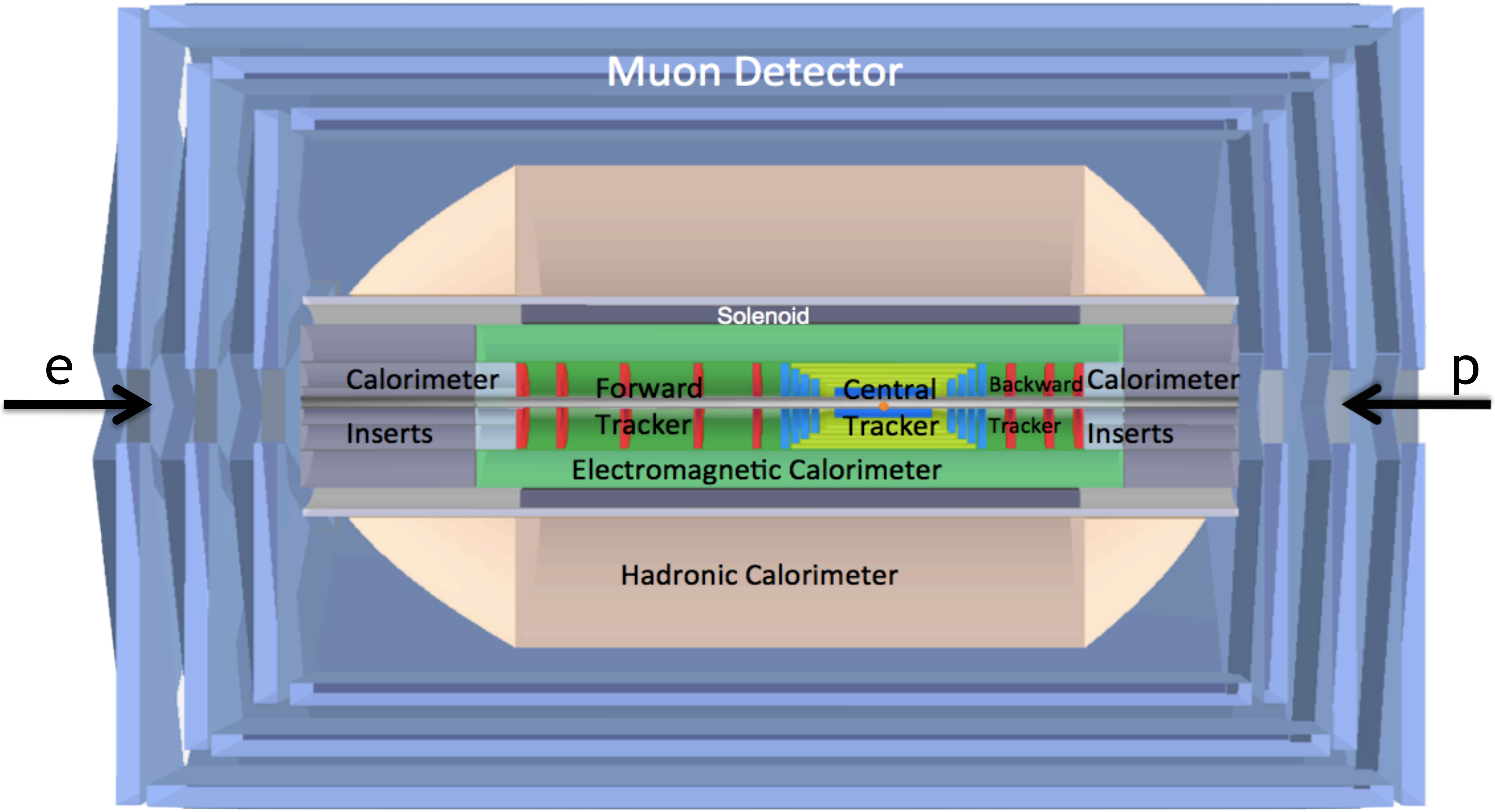
Access to Q^2=1 GeV^2 in ep mode for all x > 5 x 10^{-7} requires scattered electron acceptance to 179°





Small angle forward acceptance similarly important for hadronic final state studies - e.g. forward (Mueller-Navalet) jets.

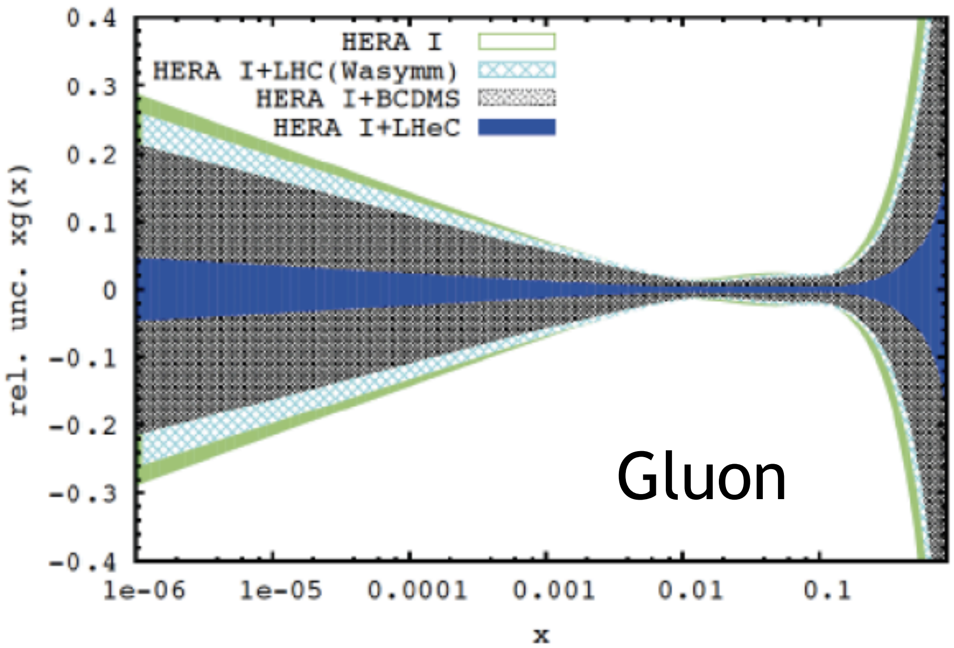
Detector Design Overview

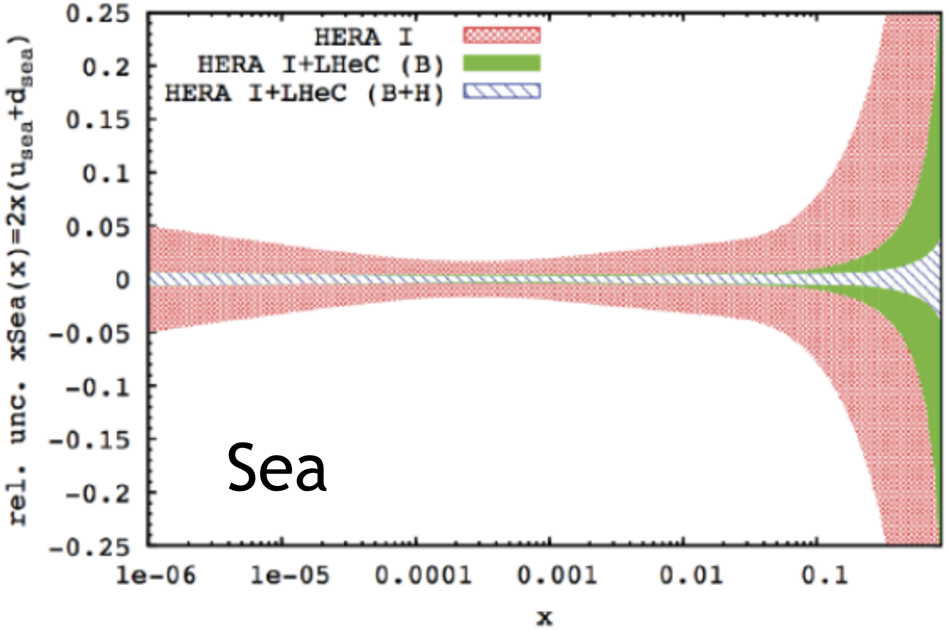


- Forward / backward asymmetry reflecting beam energies
- 1º electron hits two tracker planes
- Present size 14m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)

Low x PDF Constraints

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

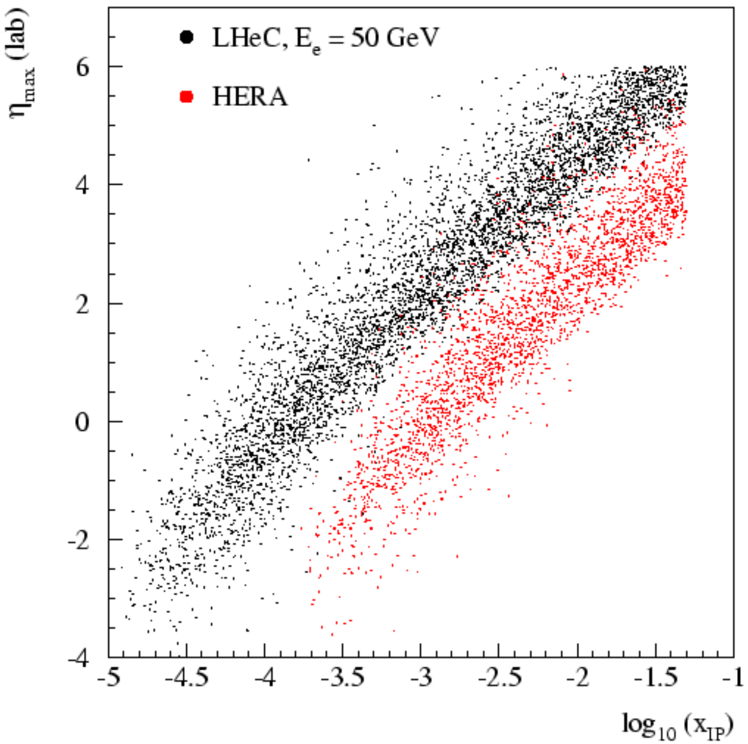


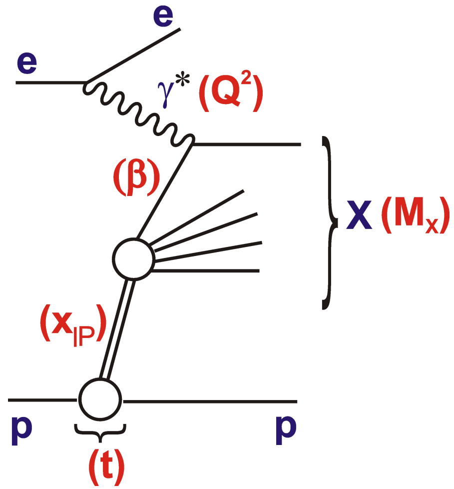


Current gluon knowledge at $x<10^{-4}$ very limited, even with LHC

LHeC offers strong constraints to $x=10^{-6}$,
including full flavour decomposition

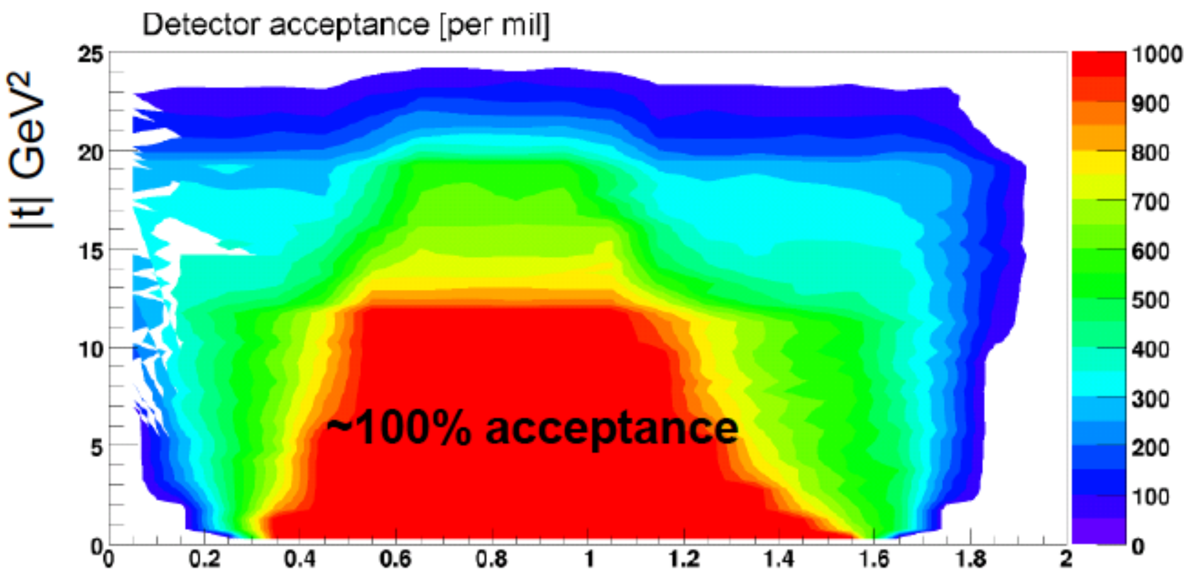
Selecting Diffraction





– η_{max} cut around 3 selects events with x_{IP} <~ 10^{-3}

- \`FP420'-style proton spectrometer approaching beam to 12σ (~250 μm), gives complementary acceptance around x_{IP} ~ 10^{-2}



Good acceptance for 0.002<ξ<0.013

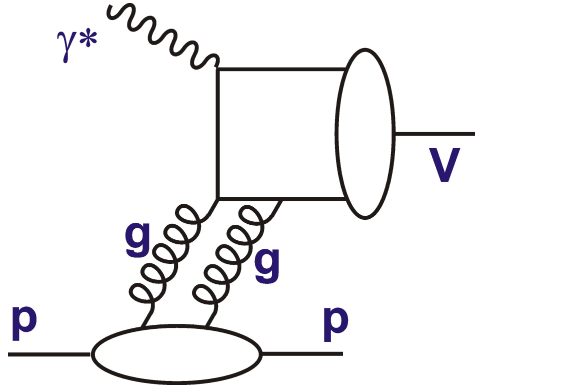
- Leading neutron (ZDC) calorimeter foreseen around 100m from IP

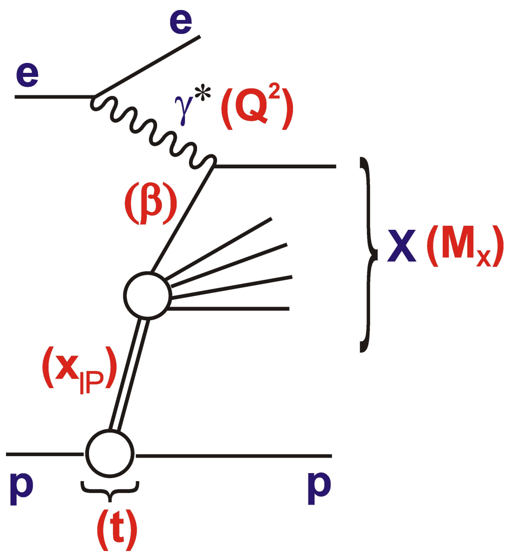
Exclusive / Diffractive Channels and Saturation

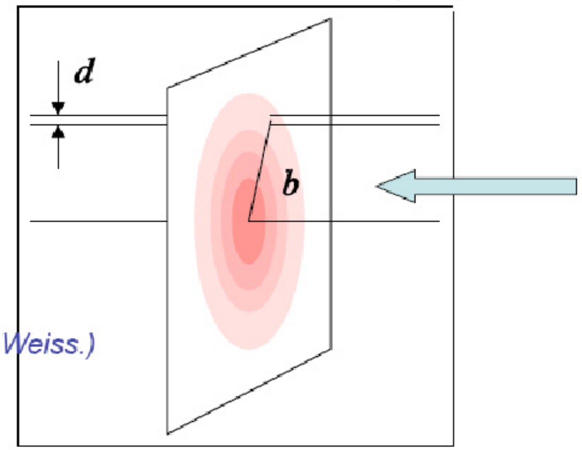
1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon

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

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





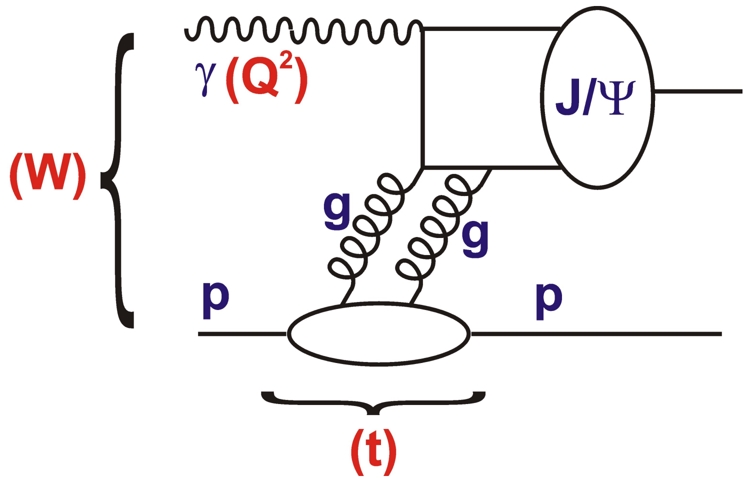


(figure from C. Weiss.)

Central black region growing with decrease of x.

Test Case: Elastic J/Ψ Photoproduction

• `Cleanly' interpreted as hard 2g exchange coupling to qqbar dipole (see HERA/LHC UPC data via MNRT etc)



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

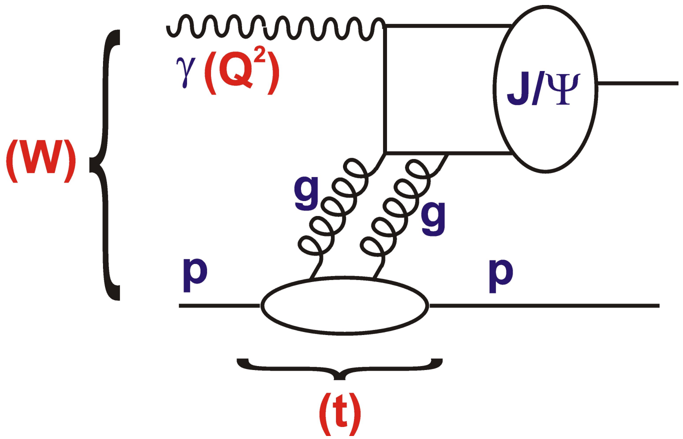
• Clean experimental signature (just 2 leptons)

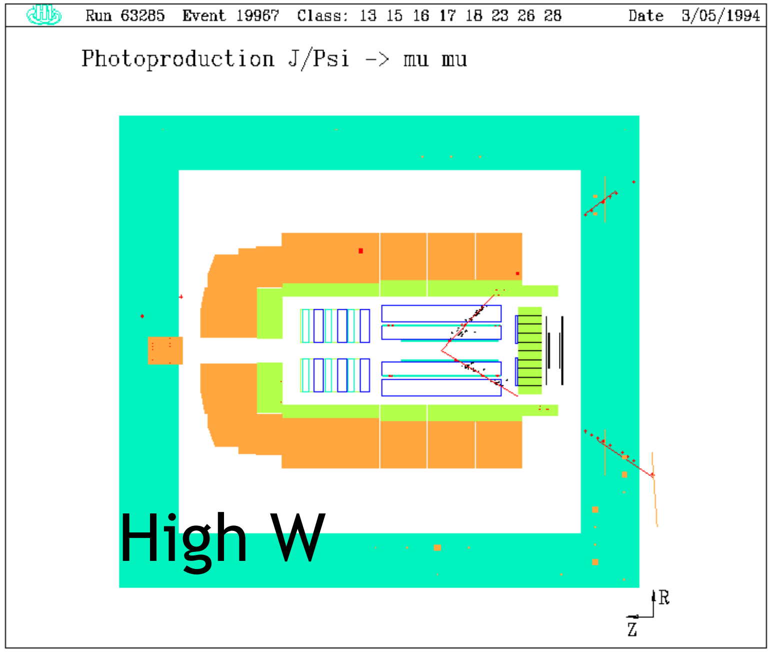
… LHeC reach extends to: $x_g \sim (Q^2 + M_V^2) / (Q^2 + W^2) \sim 5.10^{-6}$

$\overline{Q^2} = (Q^2 + M_V^2) / 4 \sim 3\ \text{GeV}^2$

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

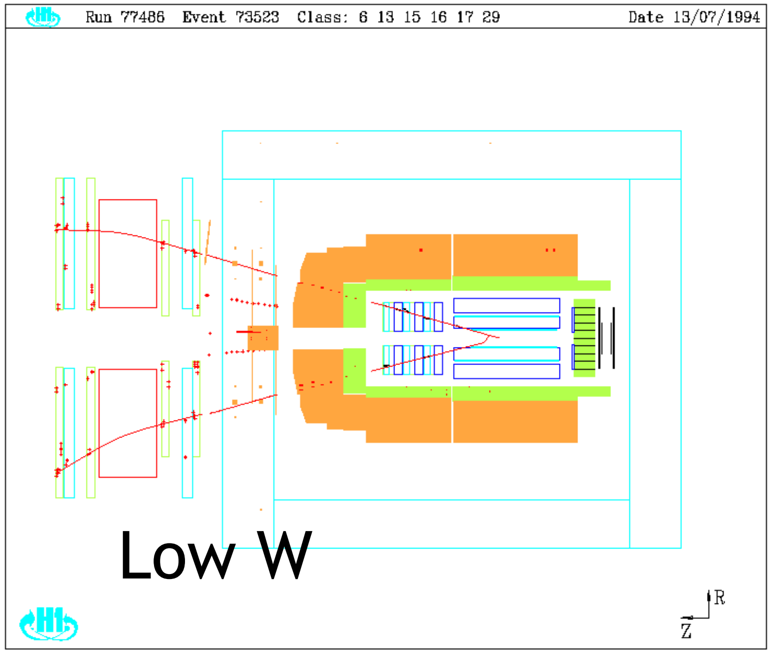
J/Ψ Kinematics





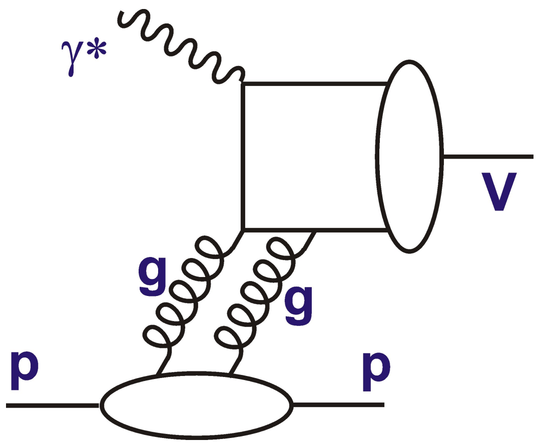
- At fixed $\sqrt{s}$, decay muon direction is determined by $W = \sqrt{s_{\gamma p}}$

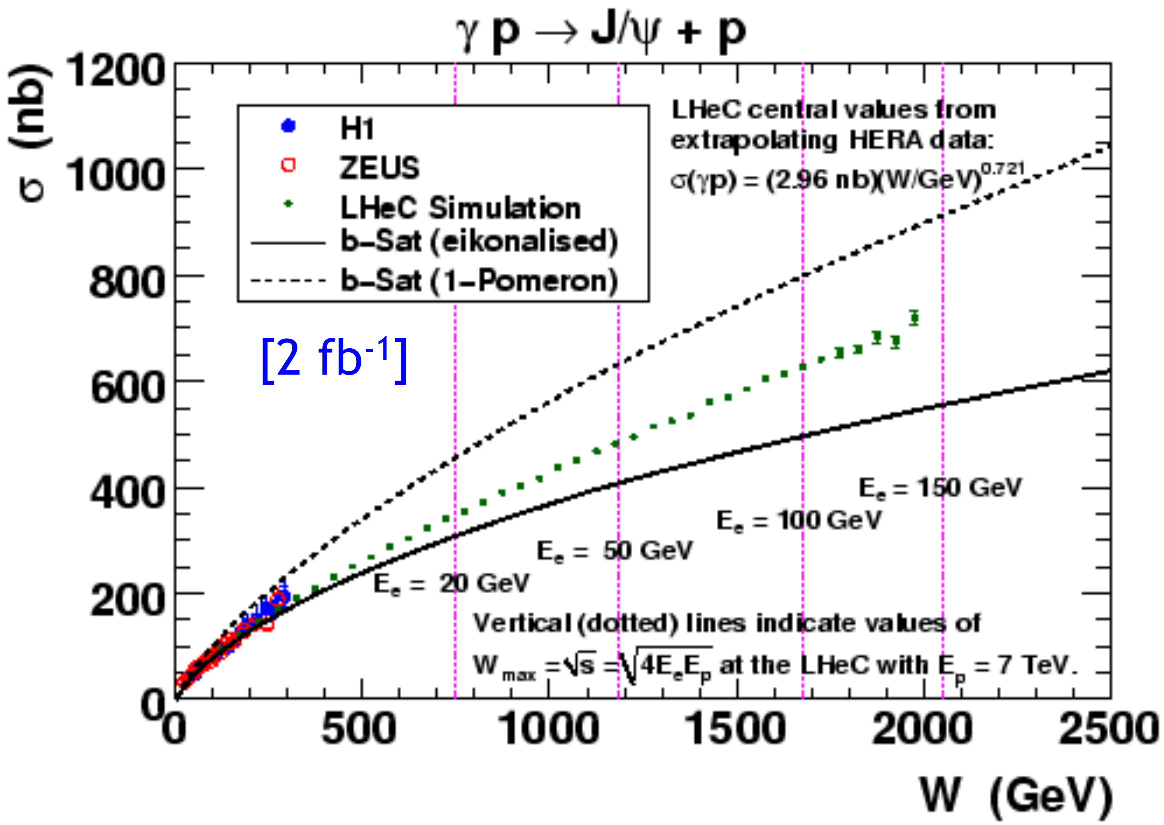
- To access highest W, acceptance in outgoing electron beam direction crucial



Comparison with Dipole model Predictions

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

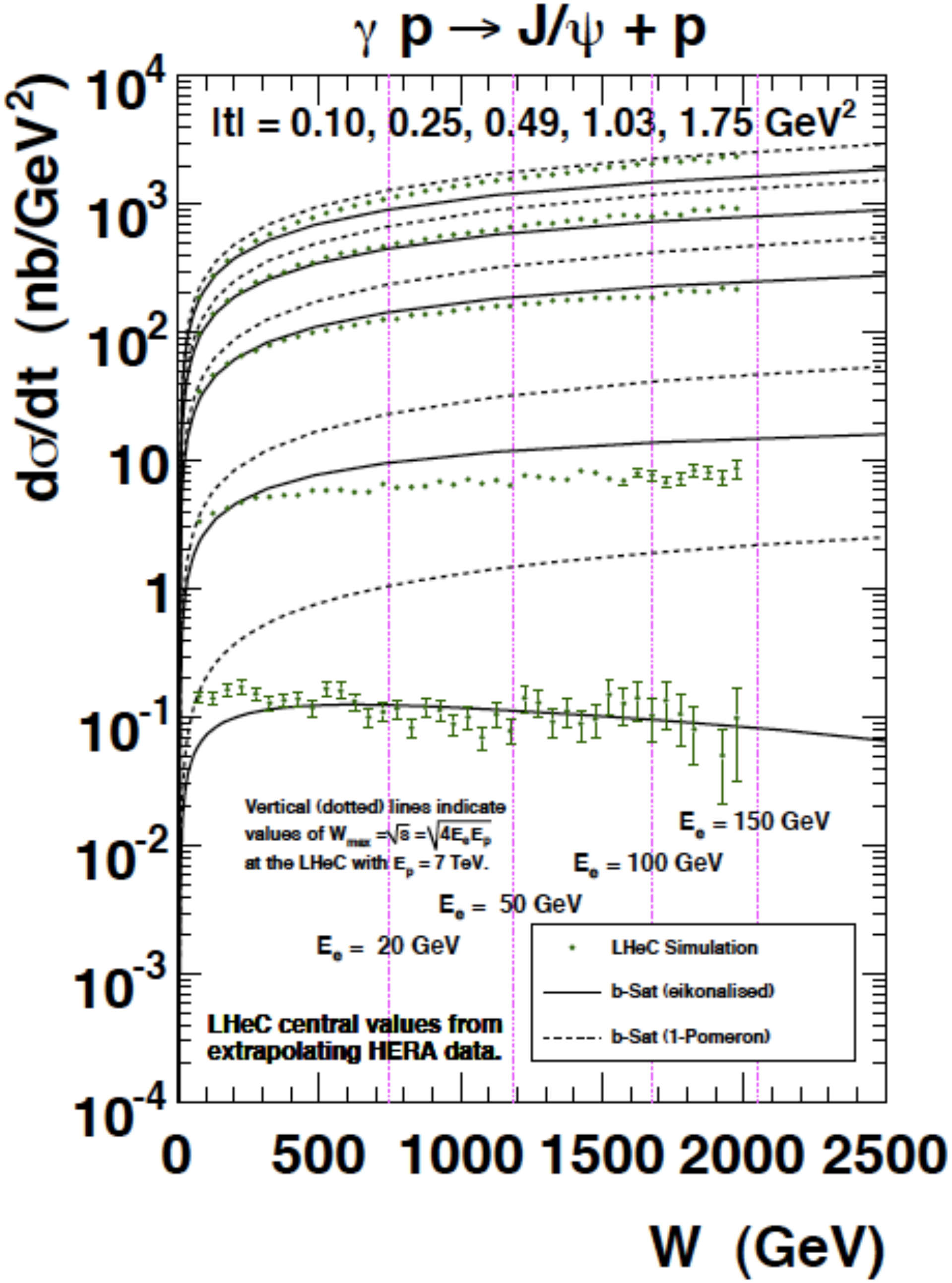




• Significant non-linear effects expected in LHeC kinematic range.

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

t Dependence of Elastic J/ψ Photoproduction



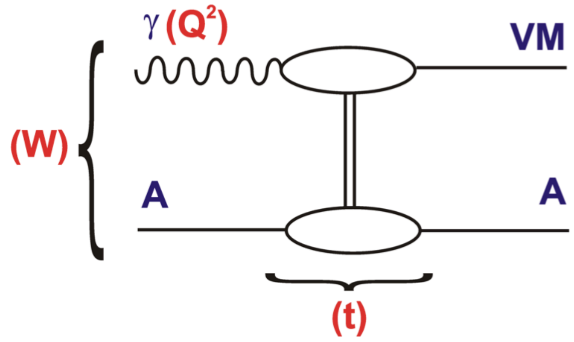
- J/ψ photoproduction double differentially in W and t …

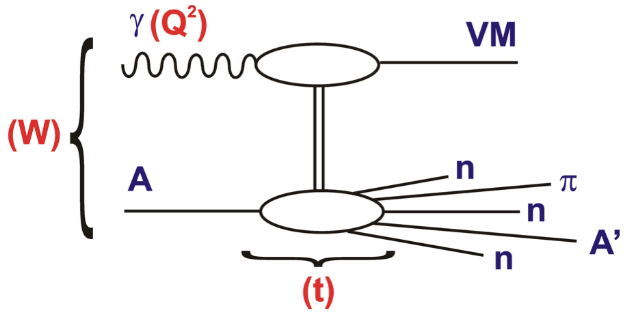
- Precise t measurement from decay μ tracks over wide W range extends to $|t| \sim 2\ GeV^2$ and enhances sensitivity to saturation effects

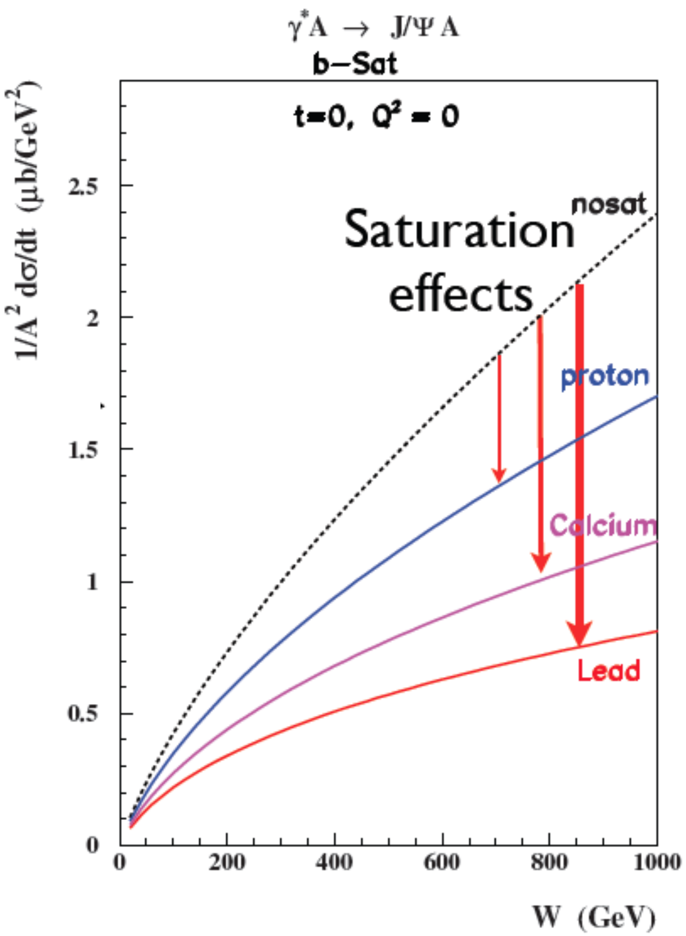
- Measurements also possible in multiple Q^2 bins

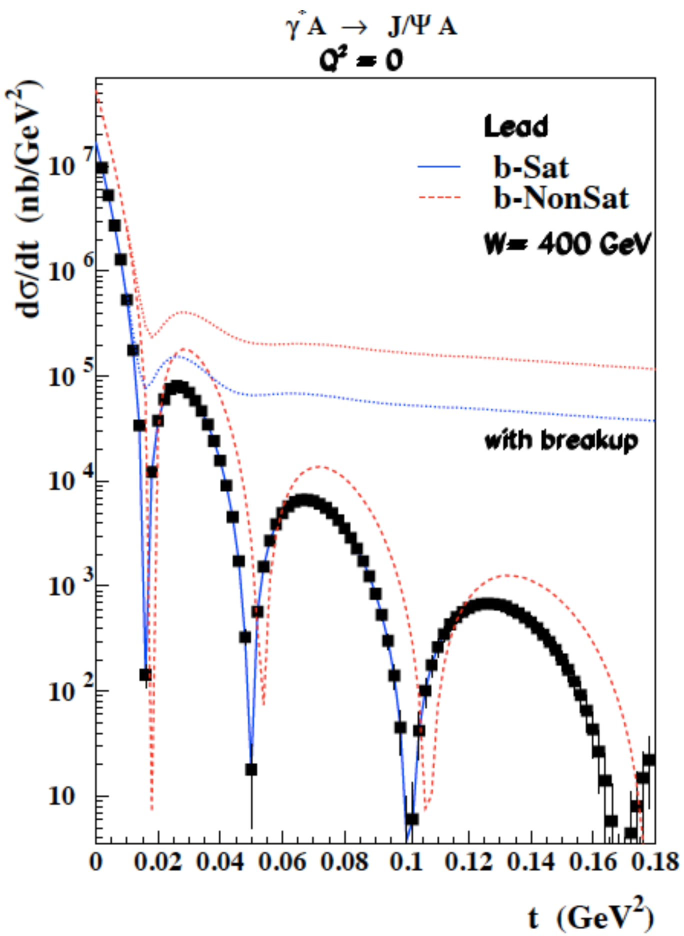
Exclusive Diffraction in eA

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



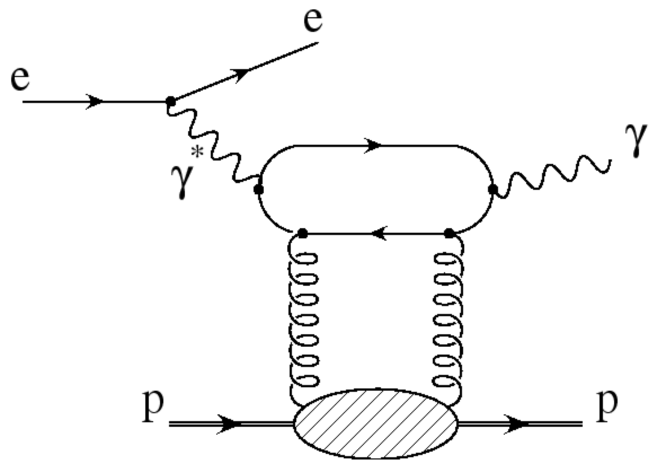






Experimental separation of incoherent diffraction based mainly on ZDC

Deeply Virtual Compton Scattering



• No vector meson wavefunction Complications

• Cross sections suppressed by photon coupling

→ limited precision at HERA

→ would benefit most from high luminosity of LHeC

Simulations based on FFS model in MILOU generator

→ Double differential distributions in (x, Q^2) with

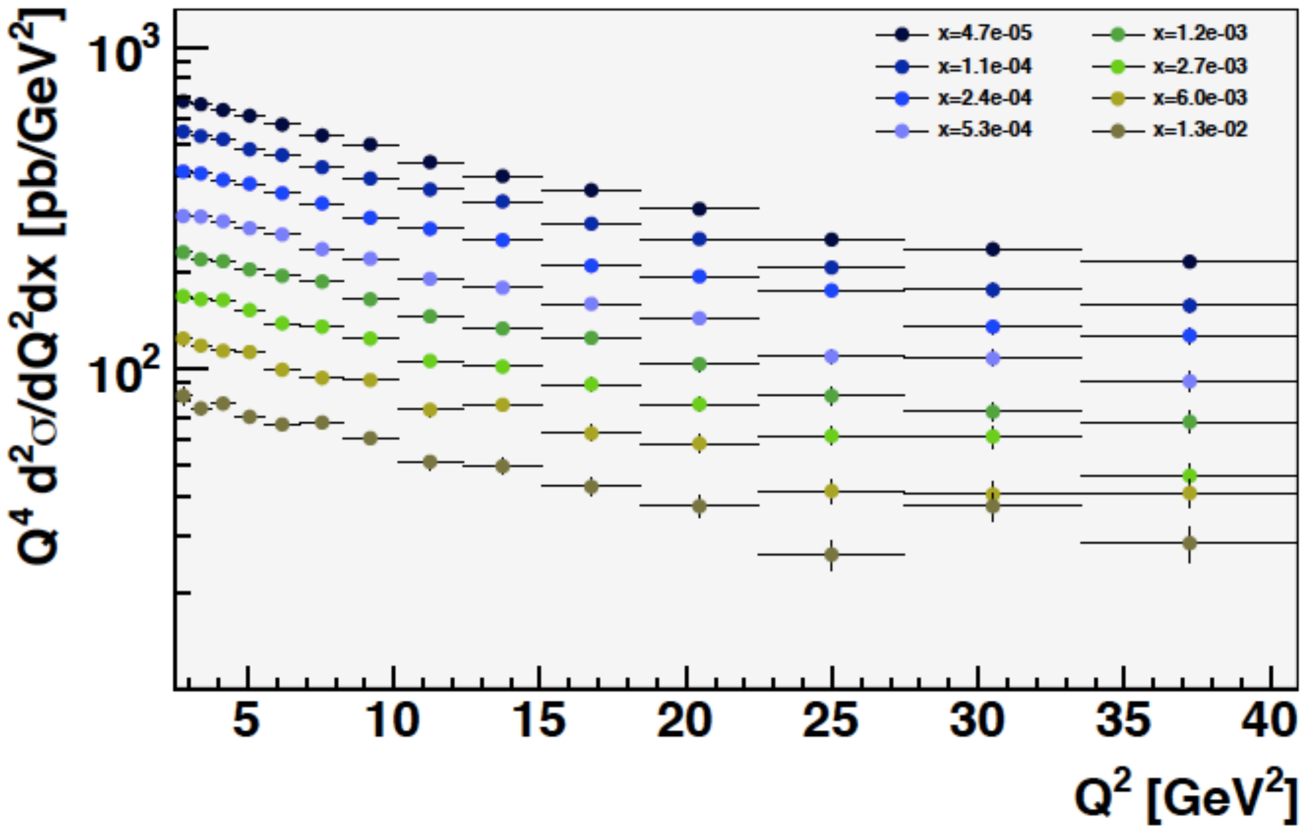
1° and 10° cuts for scattered electron

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

(relies on ECAL performance / linearity at low energies)

DVCS with low luminosity & high acceptance

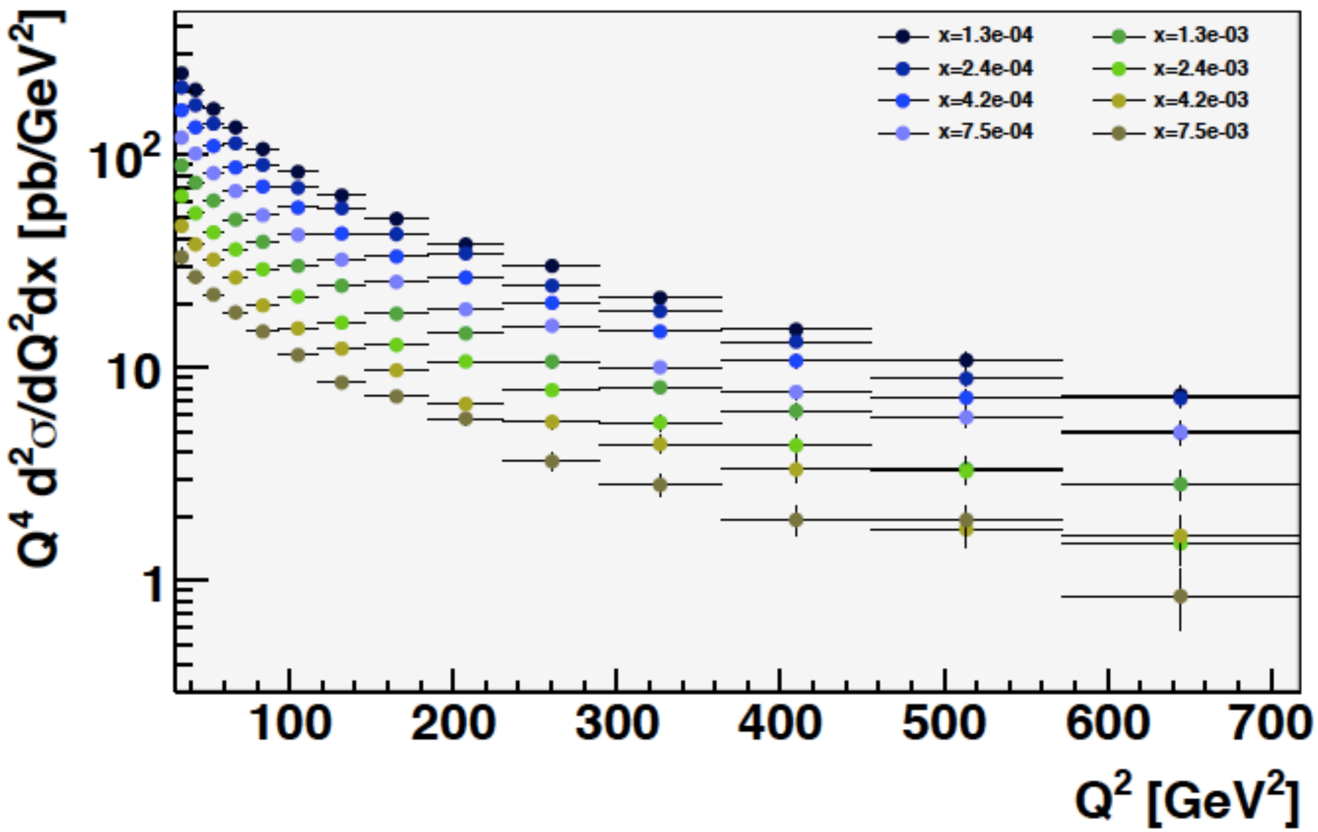
1 fb^{-1}, E_e = 50 GeV, 1° acceptance, p_T^γ > 2 GeV



- Precise double differential data in low Q^2 region
- Statistical precision deteriorates for Q^2 >~ 25 GeV^2
- W acceptance to ~ 1 TeV (five times HERA)

DVCS with high luminosity and low acceptance

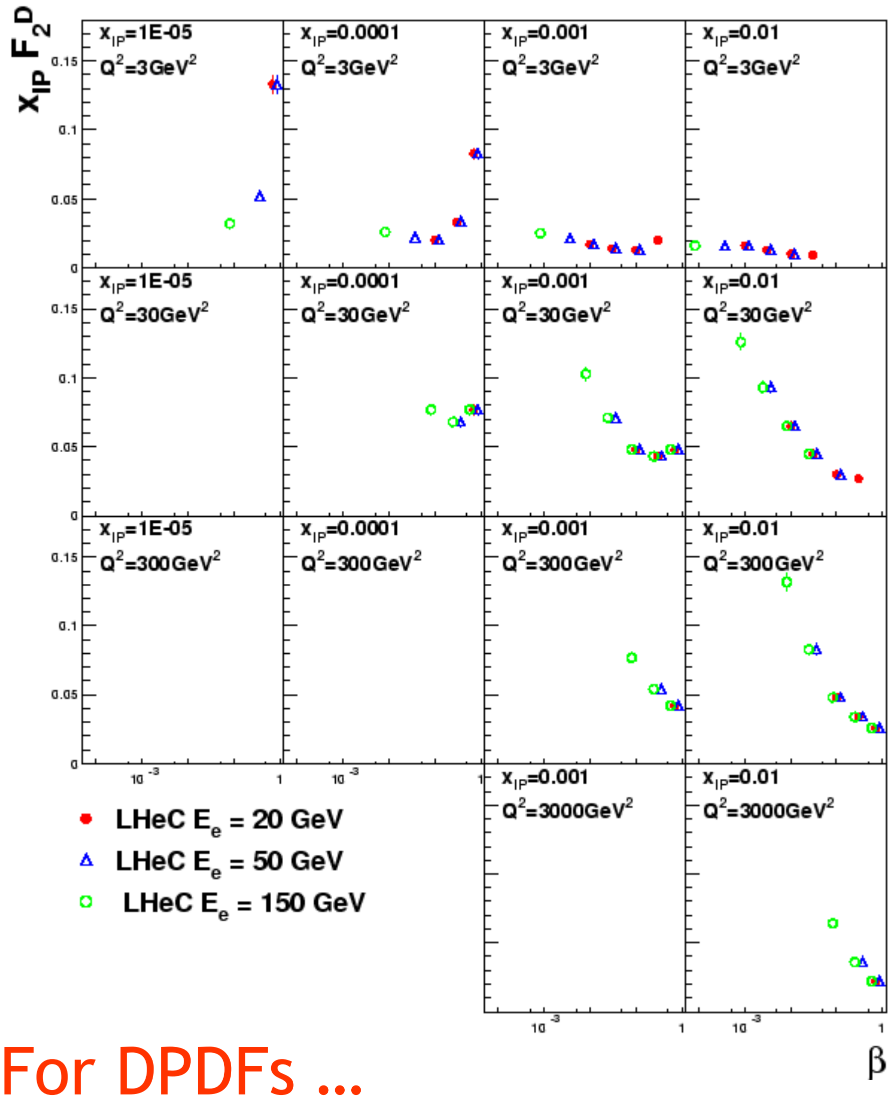
100 fb^{-1}, E_e = 50 GeV, 10° acceptance, p_T^{γ} > 5 GeV

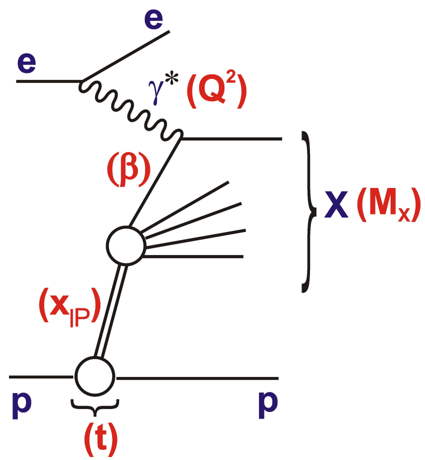


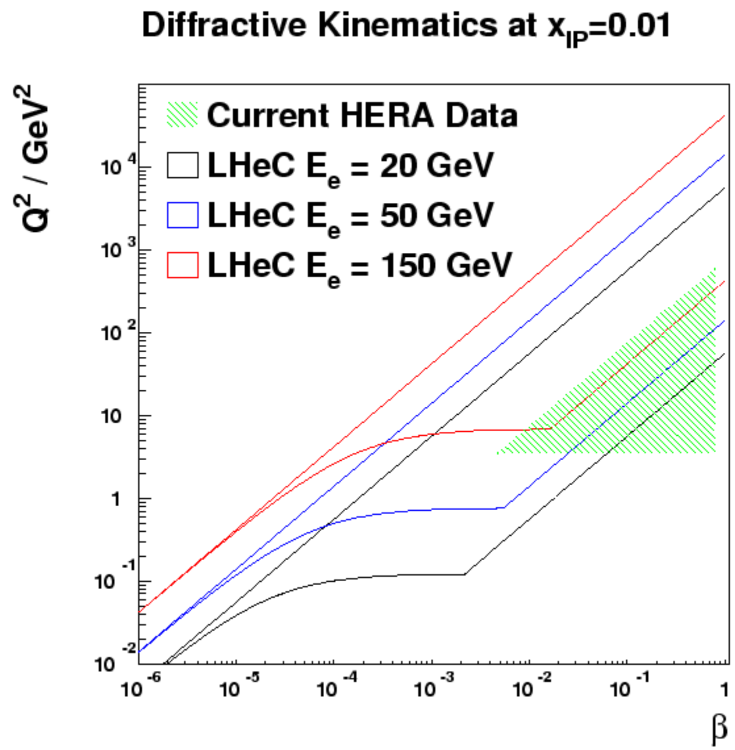
- High lumi gives precision data to Q^2 of several hundred GeV^2

  → Completely unprecedented region for DVCS / GPDs

Inclusive Diffraction / Diffractive PDFs





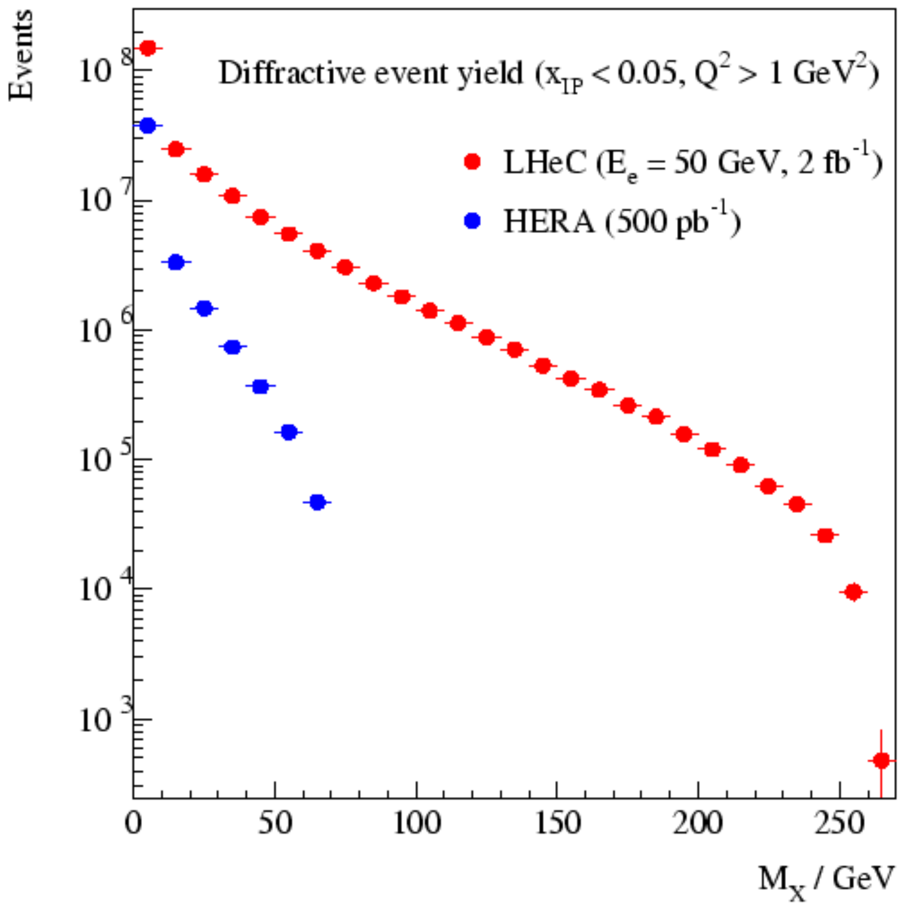


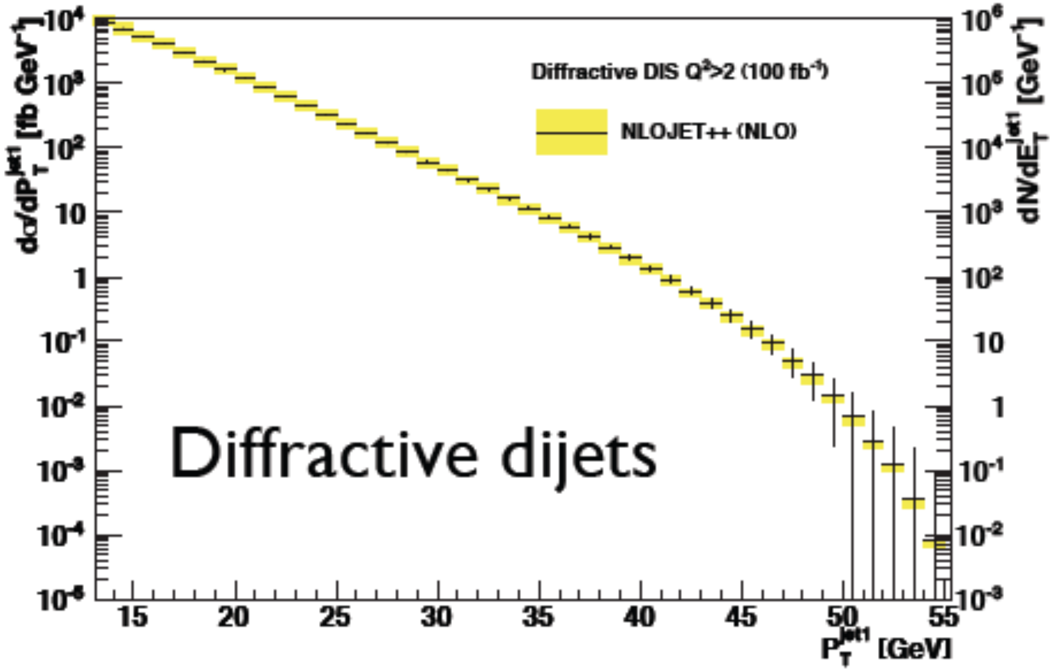
For DPDFs …

- 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

New Region of Large Diffractive Masses

Large x_{IP} region highly correlated with large Mx



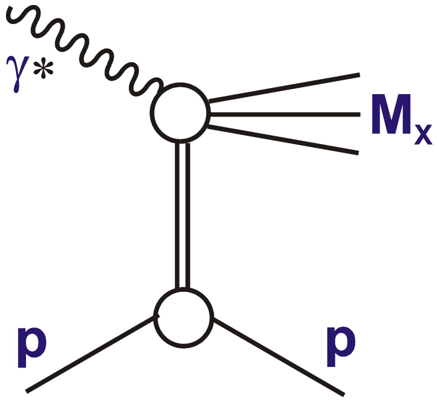


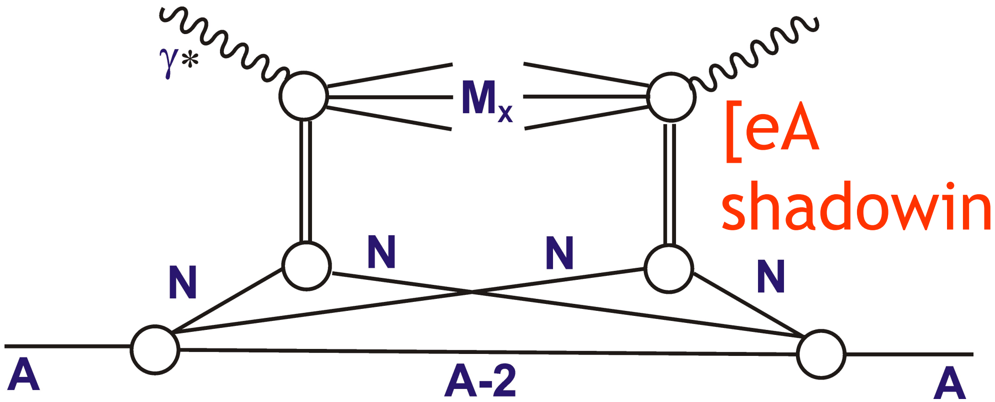
- \`Proper' QCD (e.g. large E_T) with jets and charm accessible
- New diffractive channels … beauty, W / Z bosons
- Unfold quantum numbers / precisely measure new 1^- states

F_2^D and Nuclear Shadowing

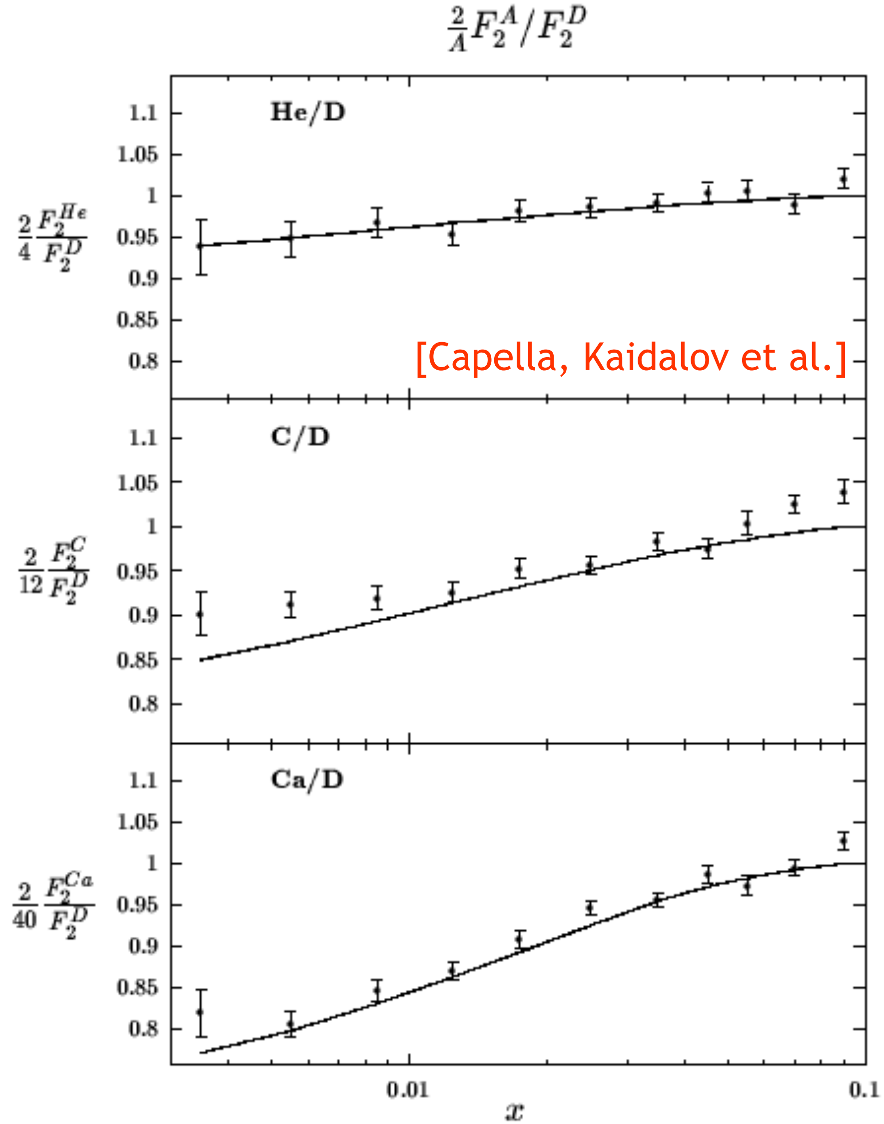
Nuclear shadowing can be described (Gribov-Glauber) as multiple interactions, starting from ep DPDFs

[Diff DIS]





[eA shadowing]

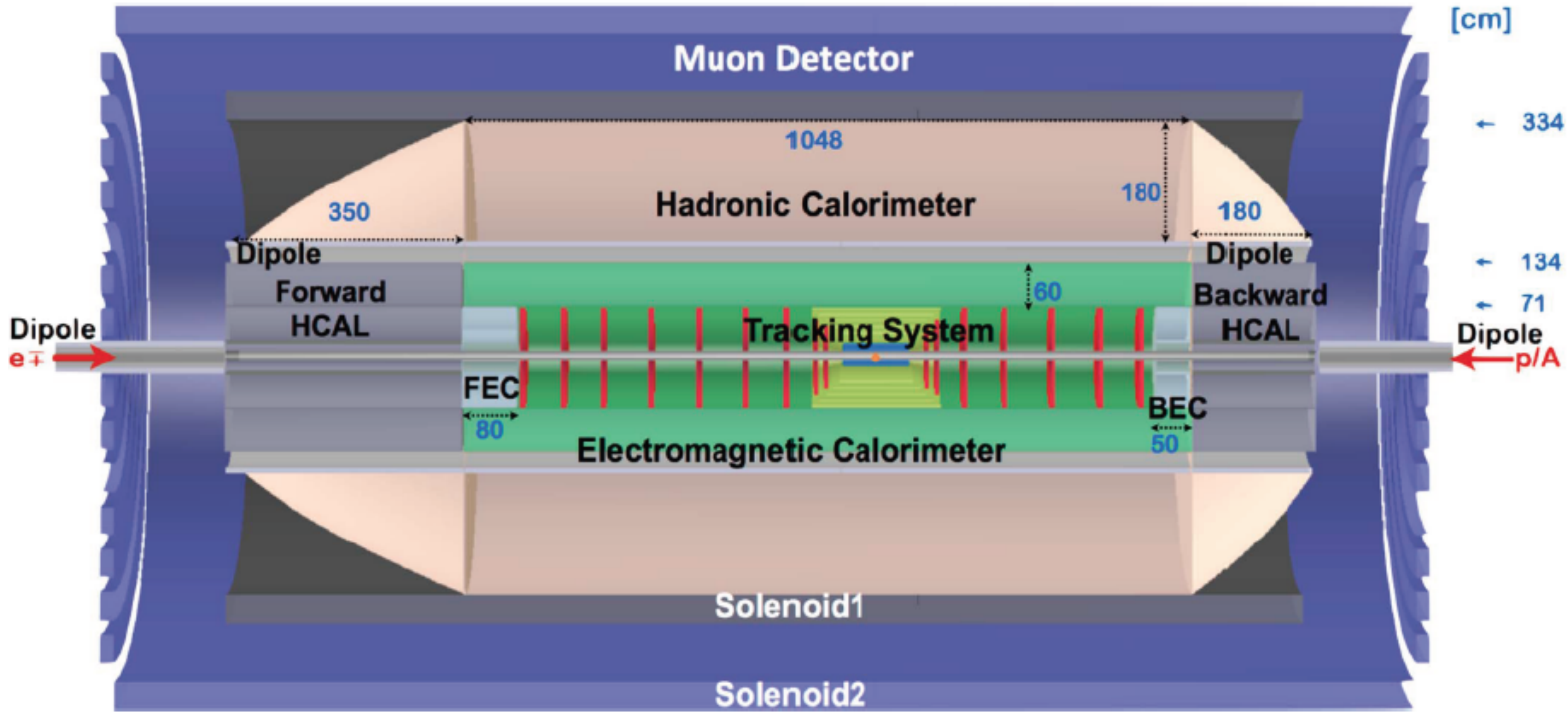


… starting point for extending precision LHeC studies into eA collisions

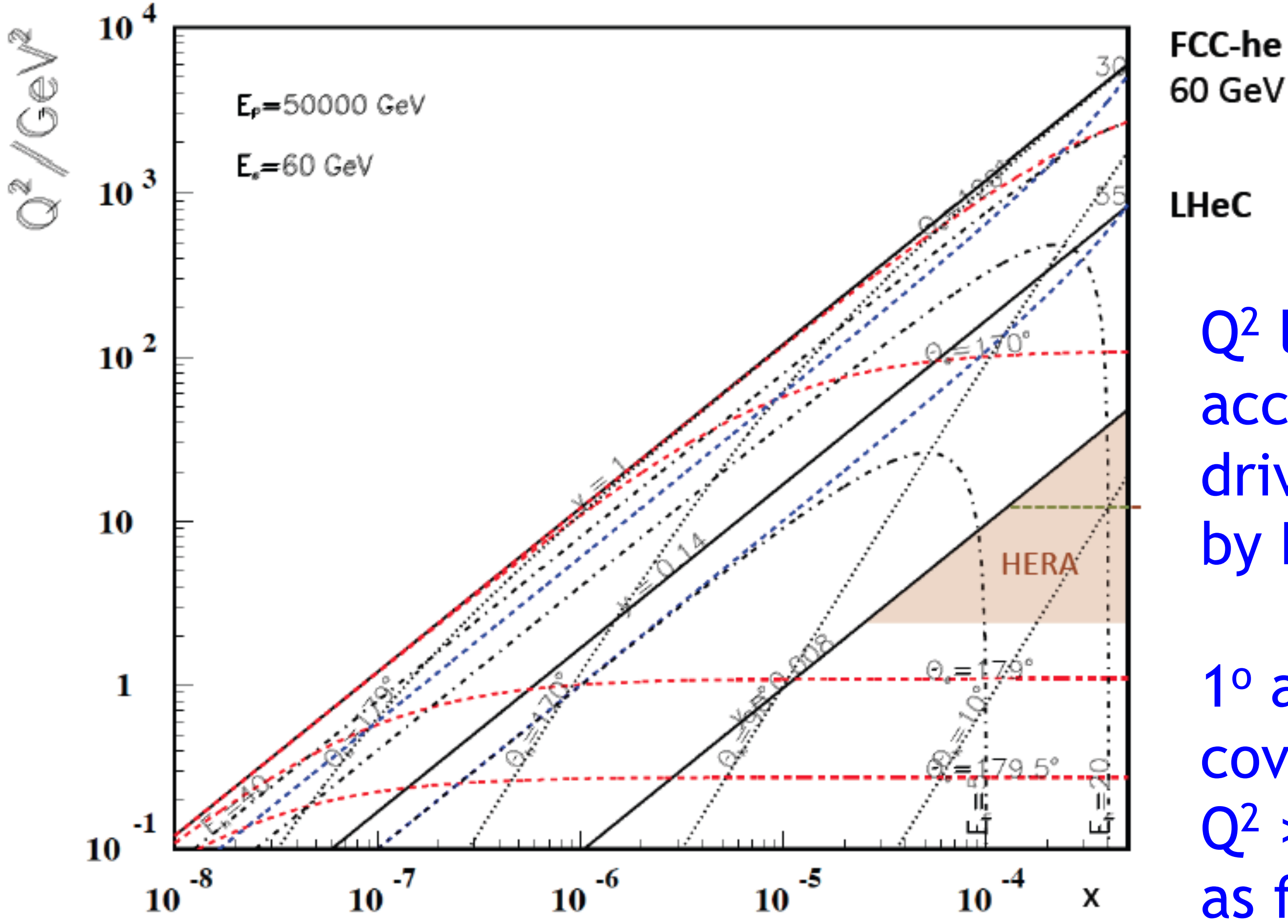
The More Distant Future: ep at a CERN Future Circular Collider

First studies with current electron design, (E_e = 60 GeV) enhanced with crab cavities, and E_p=50 TeV.
Detector, scaled by up to ln(50/7) ~ 2

→ $\sqrt{s_{ep}}$ = 3.5 TeV, Lumi = few.10^{34} $cm^{-2}s^{-1}$



Low x and Diffraction at an ep FCC



Q^2 limit of acceptance driven solely by E_e →

1° acceptance covers all at Q^2 > 1 GeV^2, as for LHeC

Sensitive to gluon density down to x~10^{-7} for Q^2>1 GeV^2
e.g. exclusive J/Ψ photoproduction to W~3 TeV

→ No detailed studies done so far

Status and Plans

- CDR 2012 (630 pages, summarising 5 year workshop. 200 authors from 69 institutes)

- Renewed interest following
  1) Possibility of 10^{34} cm^{-2} s^{-1} luminosity
  2) Higgs discovery → closer look at what limits HL-LHC sensitivity and precision,
  3) Associated technical developments (High gradient cavities, Energy recovery linacs)

- New International Advisory Committee and Coordination Group set up by CERN, with mandate to further develop LHeC, also in context of FCC.

- Low x / eA group (N Armesto, P Newman, A Stasto)
  → Please contact us …

Summary

- Low x physics is Strong Interaction energy frontier: discovery!
  - Dense partonic systems → correlations / interactions
  - Onset of non-linear dynamics → Gribov black-disk limit
    → Confimement, Hadronic mass generation …

- Diffraction plays a pivotal role:
  - Enhances / complements inclusive data in saturation search
  - Parton correlations, impact parameter dependence

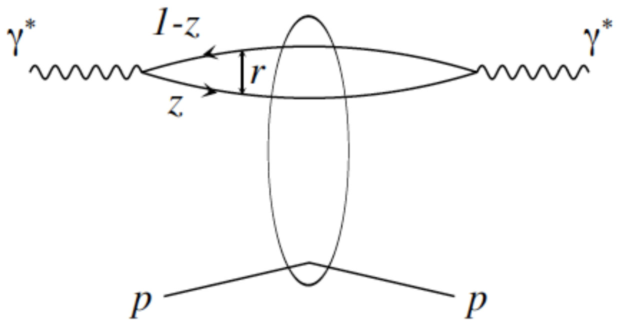
- Lots still to be studied to fully make case for LHeC and FCC-he
  - Better modelling of simulated LHeC measurements
  - Propagation to underlying physics (GPDs, DPDFs)
  - Poorly covered LHeC topics, FCC studies barely began

- More, at LHeC web
http://lhec.web.cern.ch
and …

- LHeC Study Group (CDR), J Phys G39 (2012) 075001
- Klein & Schopper, CERN Courier, June 2014
- Newman & Stasto, Nature Phys 9 (2013) 448
- Bruening & Klein, Mod Phys Lett A28 (2013) 1130011

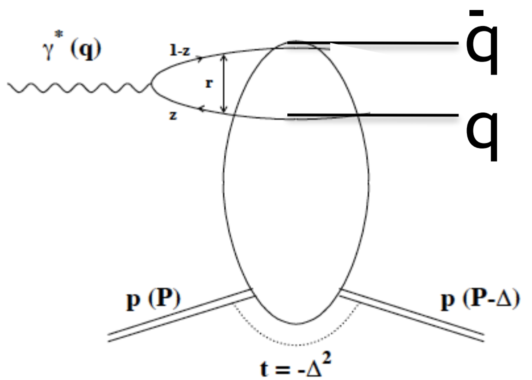
Back-ups

Diffractive DIS, Dipole Models & Saturation



Inclusive Cross Section

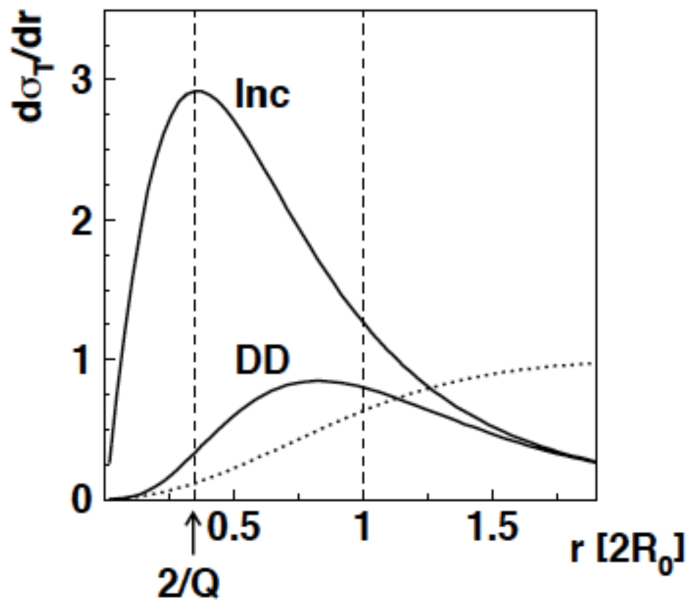
$$\sigma_{T,L}(x,Q^2) = \int d^2\mathbf{r} \int_0^1 d\alpha \, |\Psi_{T,L}(\alpha,\mathbf{r})|^2 \hat{\sigma}(x,r^2)$$



Diffractive DIS

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

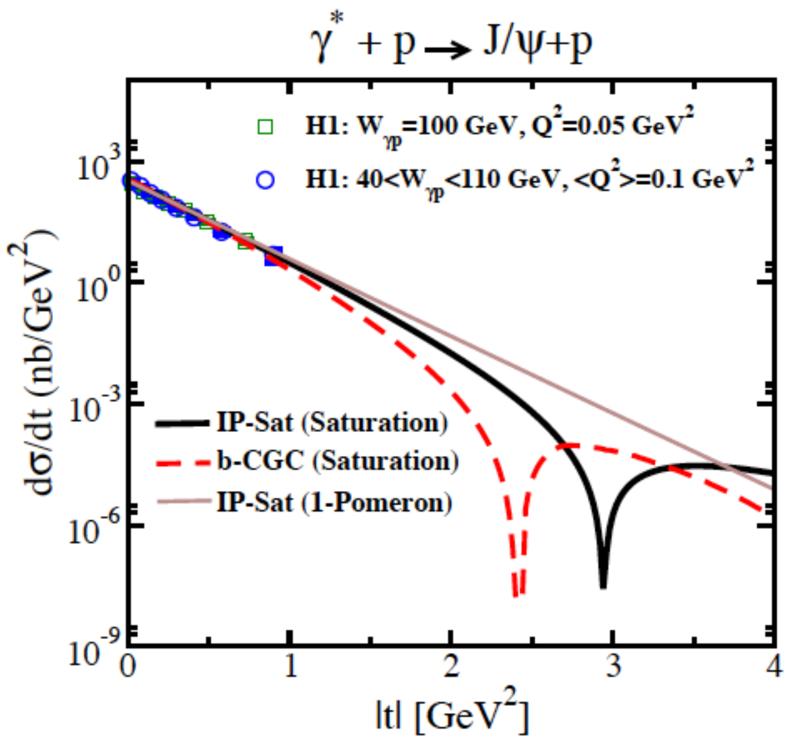
Extra factor of dipole cross section weights DDIS cross section towards larger dipole sizes → enhanced sensitivity to saturation effects.

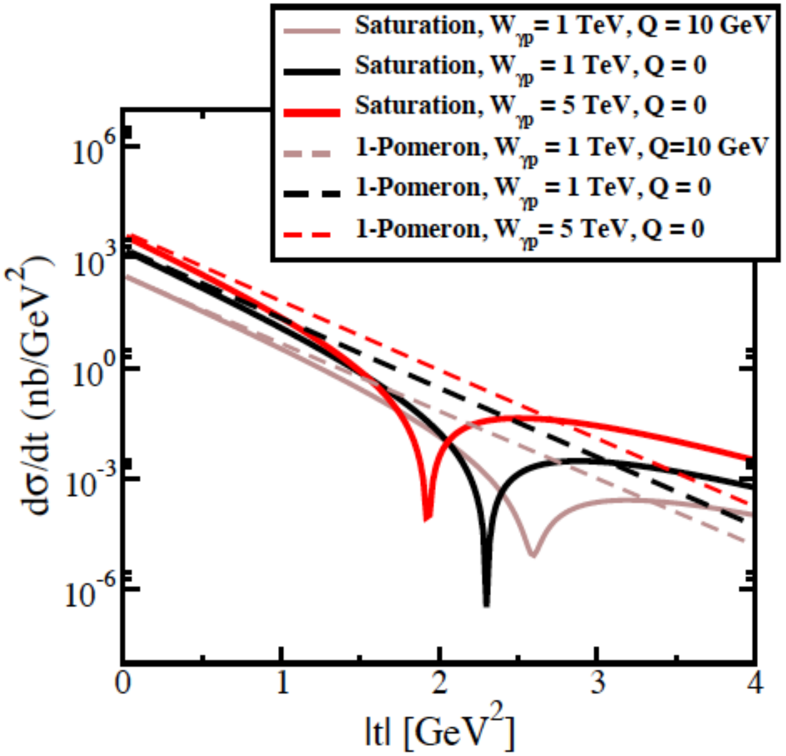


Signals in t Dependences: e.g. J/ψ Photoproduction

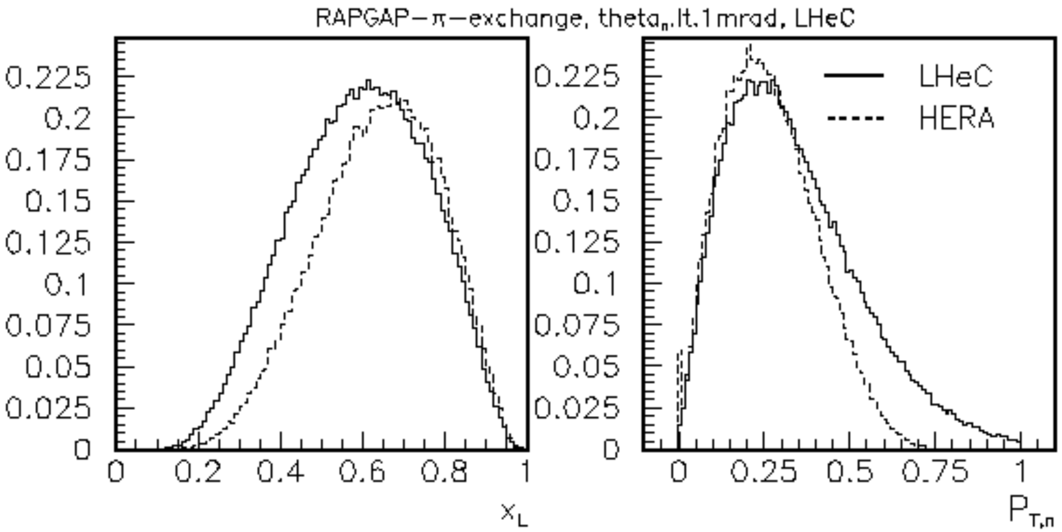
t dependences measure Fourier transform of impact parameter distribution. → Unusual features can arise from deviations from Gaussian matter distribution

e.g. Characteristic dips in model by Rezaeian et al, (just) within LHeC sensitive t range.



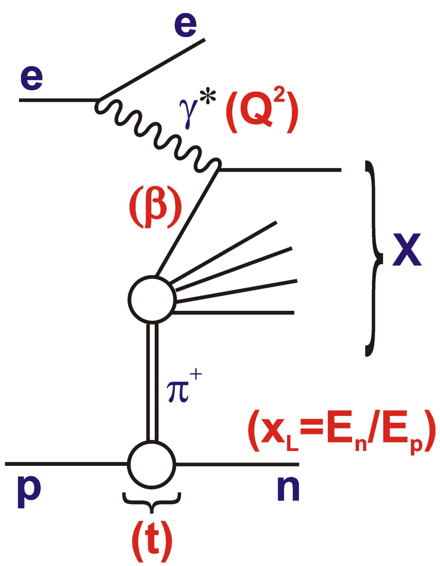


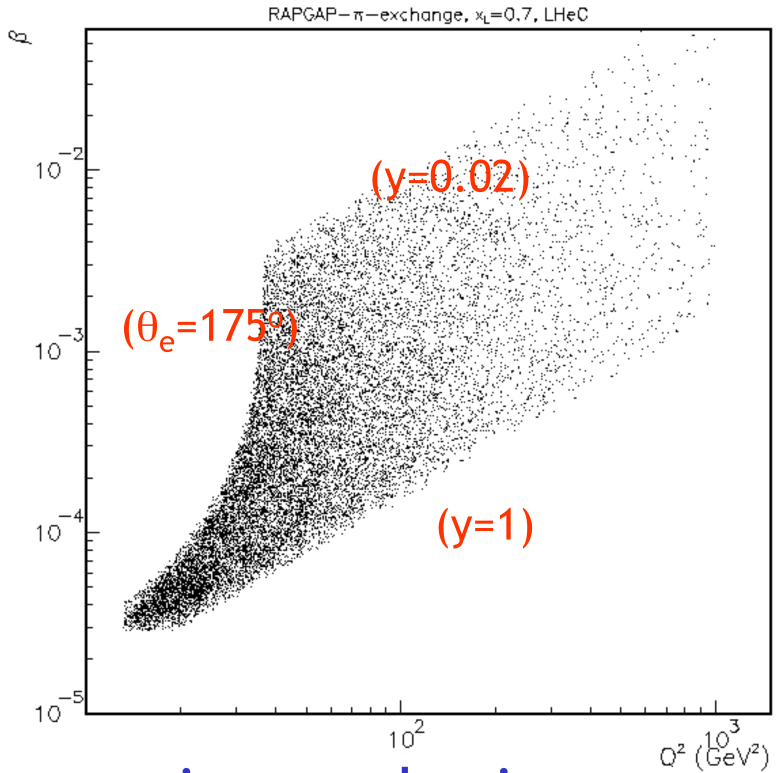
π Structure with Leading Neutrons



[Bunyatyan]

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





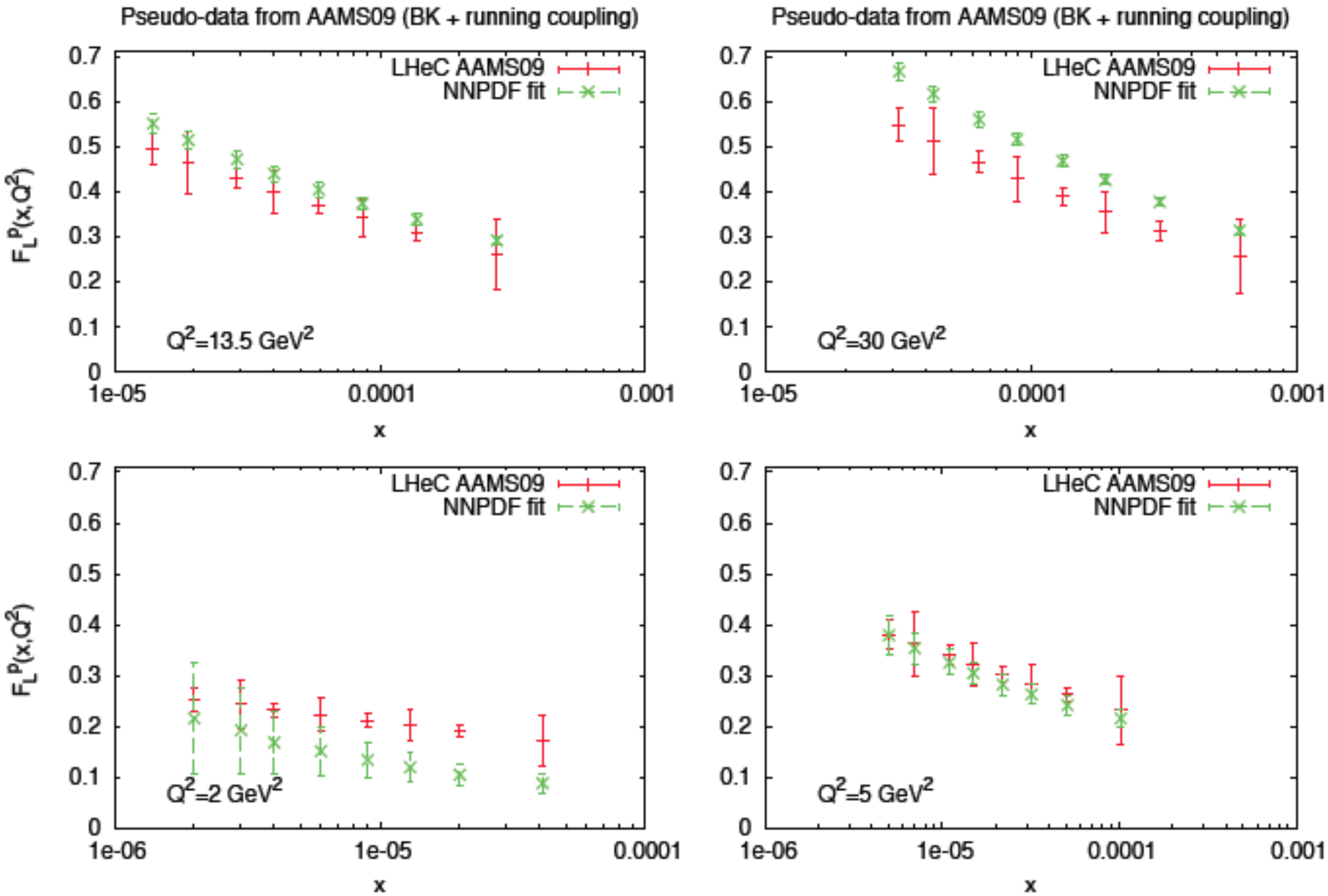
- With θ_n < 1 mrad, similar x_L and p_t ranges to HERA (a bit more p_t lever-arm for π flux).

- 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 …

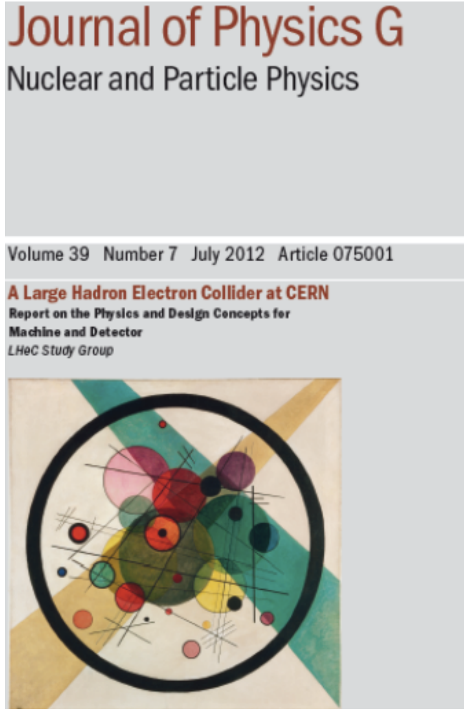
Establishing Saturation in Inclusive Data

(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

Conceptual Design Report (July 2012)



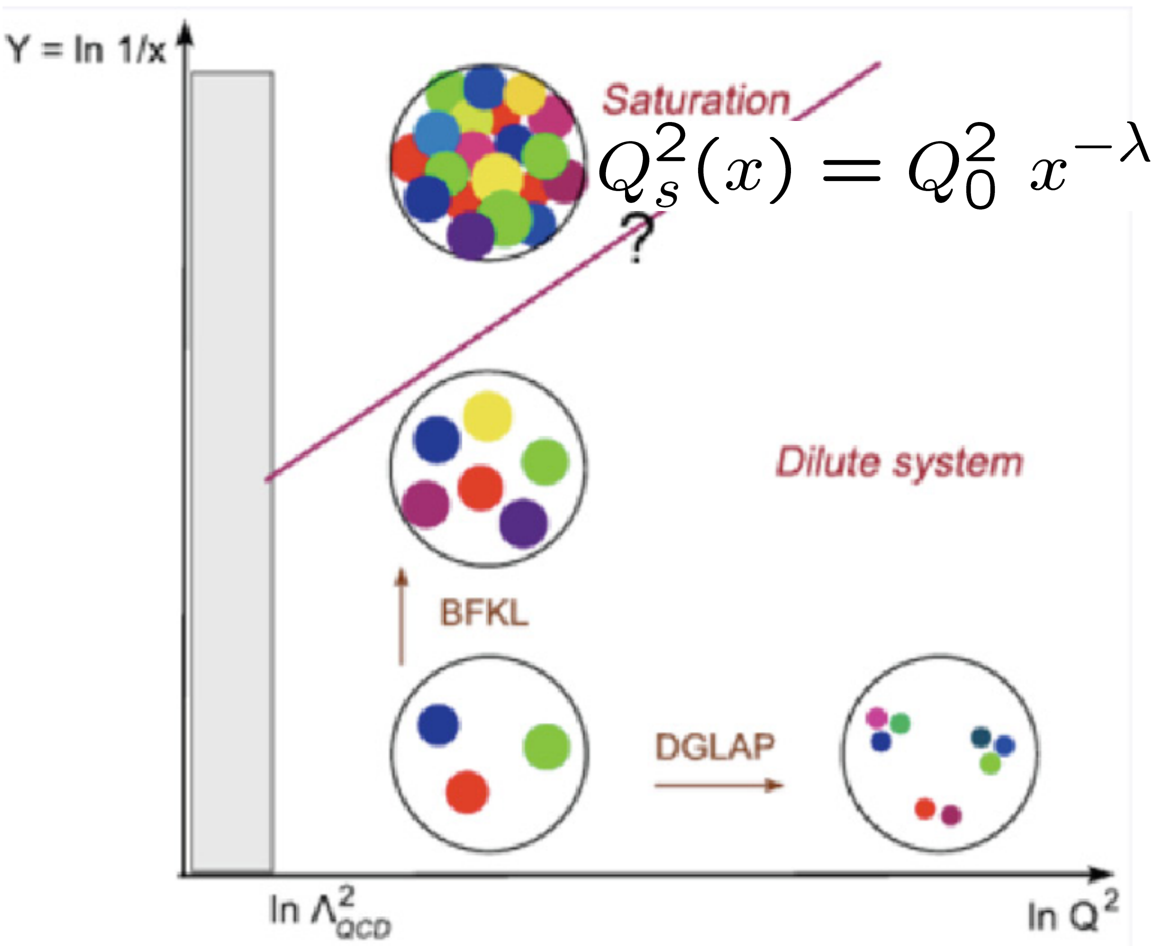
[arXiv:1206.2913]

Substantial low x chapter (81 pages, 34 authors)

See also talks by Nestor and Hannu

Filling up the Proton

Lines of constant ‘blackness’ ~diagonal in kinemaic plane …
Scattering cross section appears constant along them
(`Geometric Scaling’)



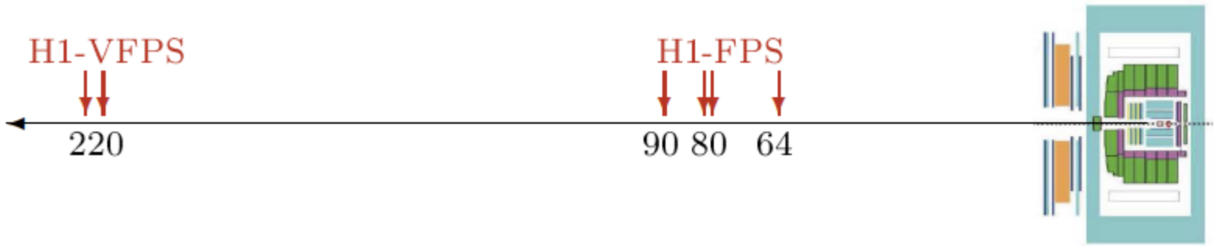
Limited previous evidence in ep and eA restricted to small Q^2 <~ 1 GeV^2.

→ Partonic interpretation precluded

Usual to implement via `dipole models’, with saturation built into dipole-proton x-section.

Signatures and Selection Methods at HERA

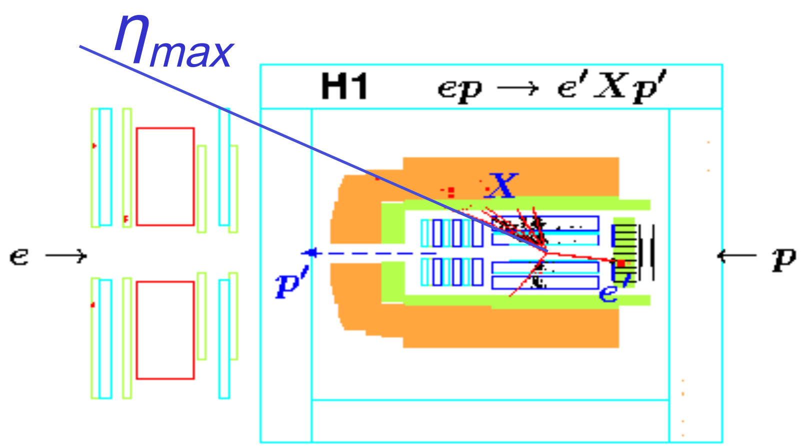
1) Measure scattered Proton in Roman Pots



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

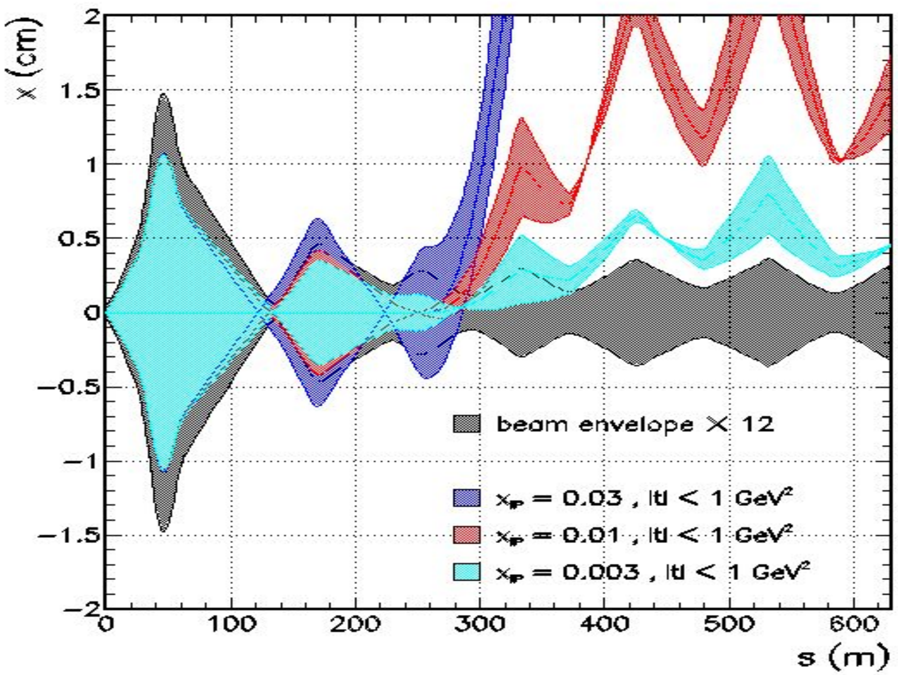
2) Select Large Rapidity Gaps

-Limited by control over proton dissociation contribution



- Methods have very different systematics → complementary
- What is possible at LHeC?…

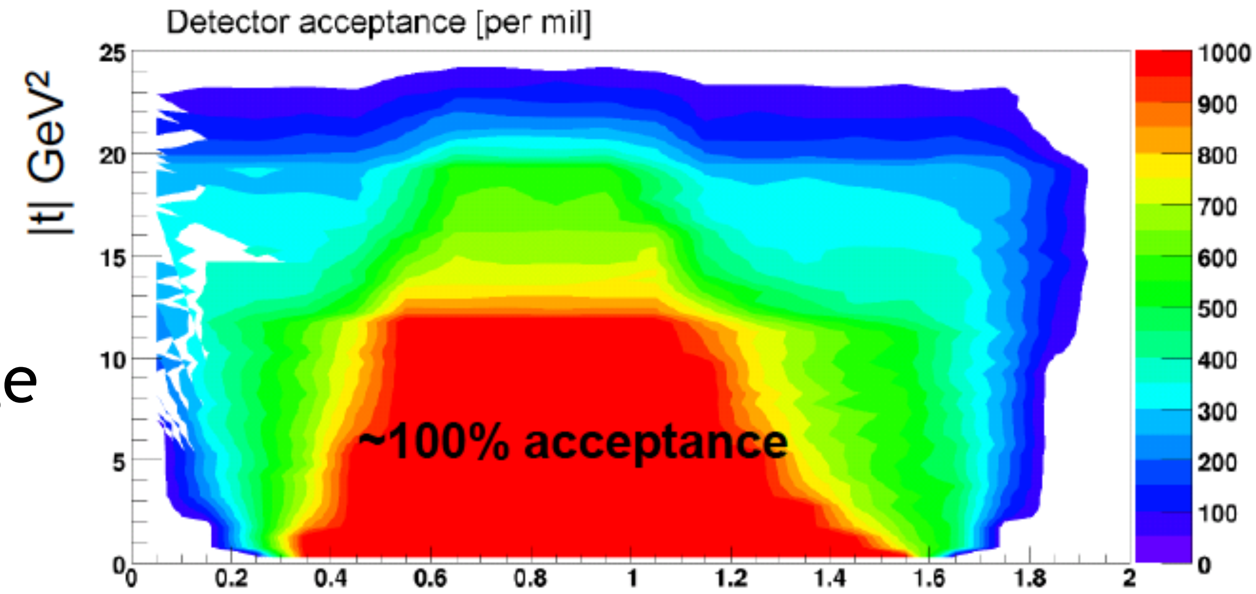
Forward Proton Spectrometer



With `FP420'-style proton spectrometer approaching beam to 12σ (~250 μm), can tag and measure elastically scattered protons with high acceptance over a wide x_{IP}, t range

Complementary acceptance to Large Rapidity Gap method

Together cover full range of interest with some redundancy



Good acceptance for 0.002<ξ<0.013

Leading Neutrons

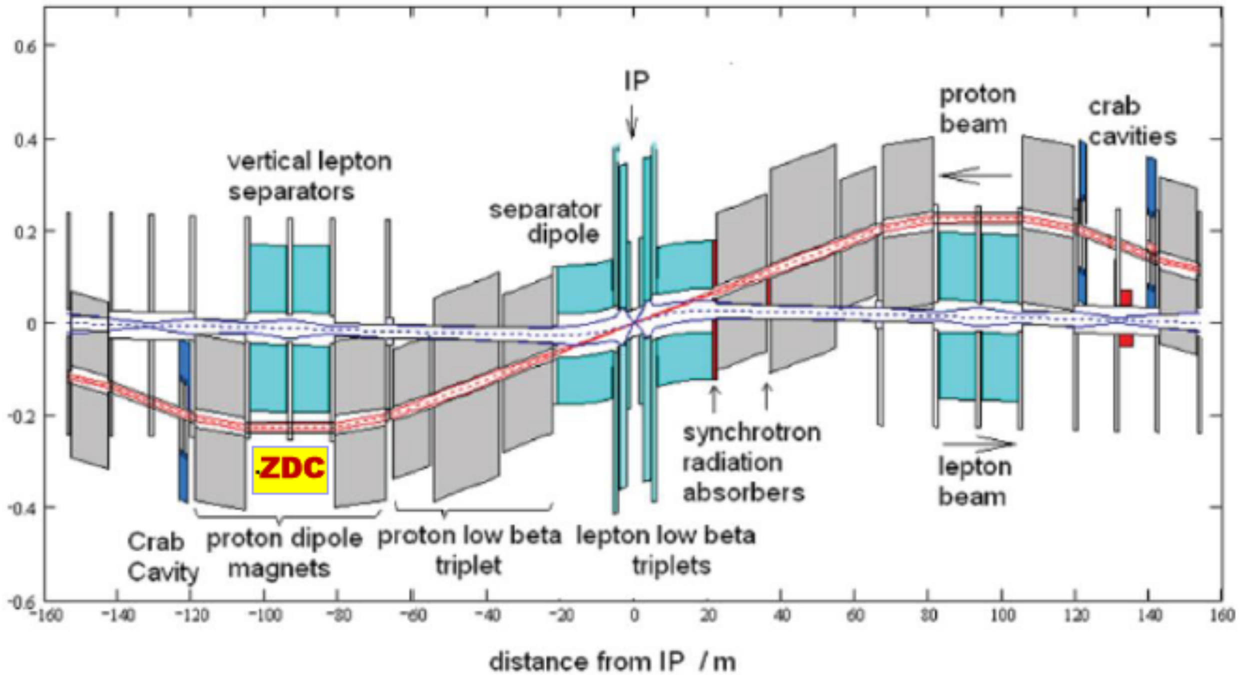
- Crucial in eA, to determine whether nucleus remains intact e.g. to distinguish coherent from incoherent diffraction

- 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

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%

CDR Parameters - LHeC

10^{33} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [$10^{33}cm^{-2}s^{-1}$]	1	1
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	3.75	50
Beta Function $\beta^{*}_{x,y}$ [m]	0.1	0.12
rms Beam size $\sigma^{*}_{x,y}$ [μm]	7	7
rms Beam divergence $\sigma'_{x,y}$ [μrad]	70	58
Beam Current [mA]	430 (860)	6.6
Bunch Spacing [ns]	25 (50)	25 (50)
Bunch Population	$1.7*10^{11}$	$(1*10^{9})$ $2*10^{9}$
Bunch charge [nC]	27	(0.16) 0.32

"Ultimate" proton beam parameters

100 times HERA Luminosity and 4 times cms Energy

Advanced Luminosity Parameters*) - LHeC

10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [$10^{33}cm^{-2}s^{-1}$]	16	16
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20
Beta Function $\beta^*_{x,y}$ [m]	0.05	0.10
rms Beam size $\sigma^*_{x,y}$ [μm]	4	4
rms Beam divergence $\sigma'_{x,y}$ [μrad]	80	40
Beam Current [mA]	1112	25
Bunch Spacing [ns]	25	25
Bunch Population	$2.2*10^{11}$	$4*10^{9}$
Bunch charge [nC]	35	0.64

HL-LHC proton beam parameters

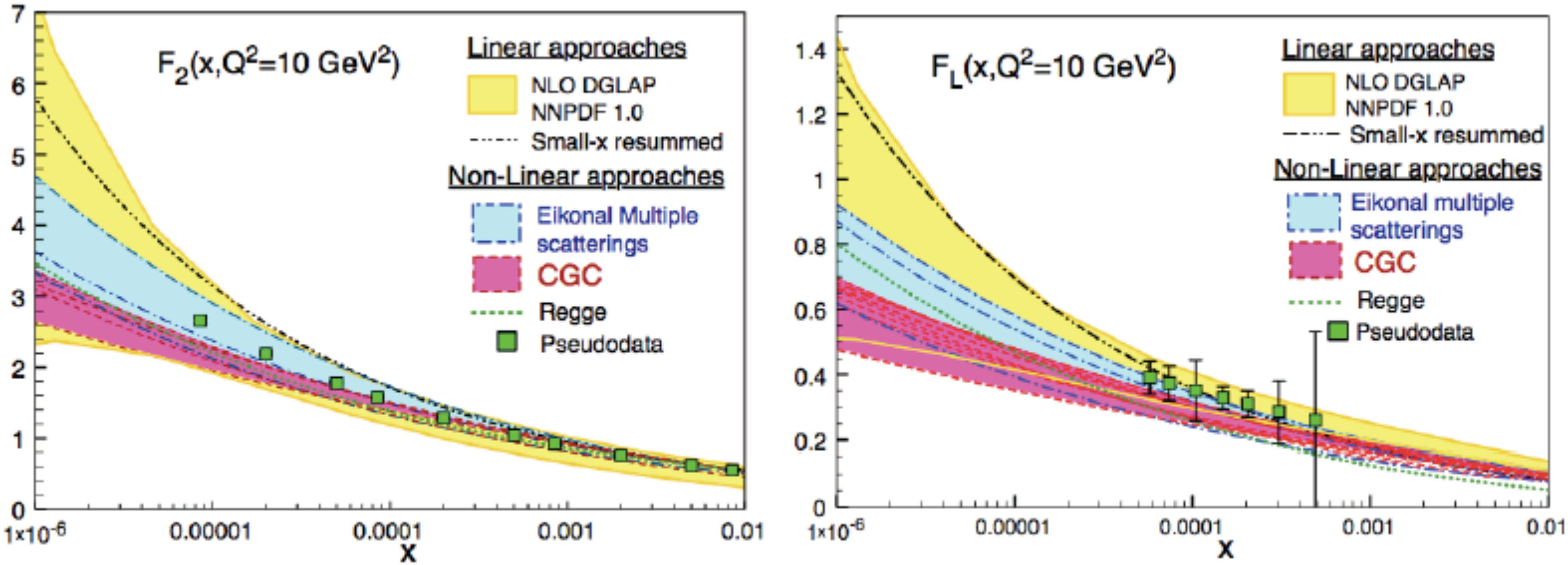
1000 times HERA Luminosity and 4 times cms Energy

*) under study now

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

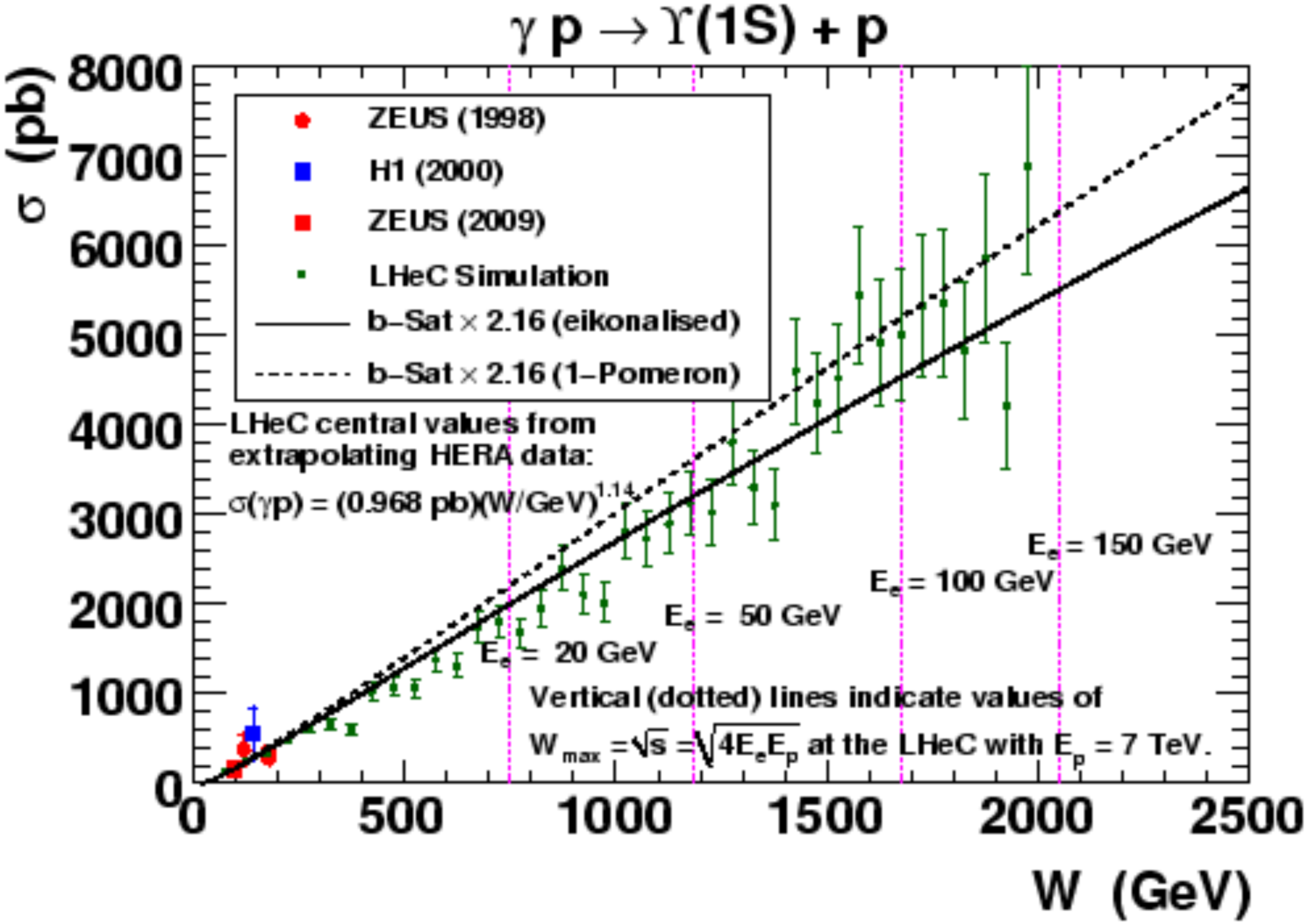
F_2 and F_L pseudodata at Q^2 = 10 GeV^2



• 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?

Similar Study for Upsilon



[b-sat curves scaled to match best fit to HERA data]

- Sat^n effects smaller than J/Ψ (smaller dipole sizes, higher x).
- Cross sections also much smaller than for J/Ψ.

- Huge increase over HERA range → anomalously large HERA cross sections can be tested.