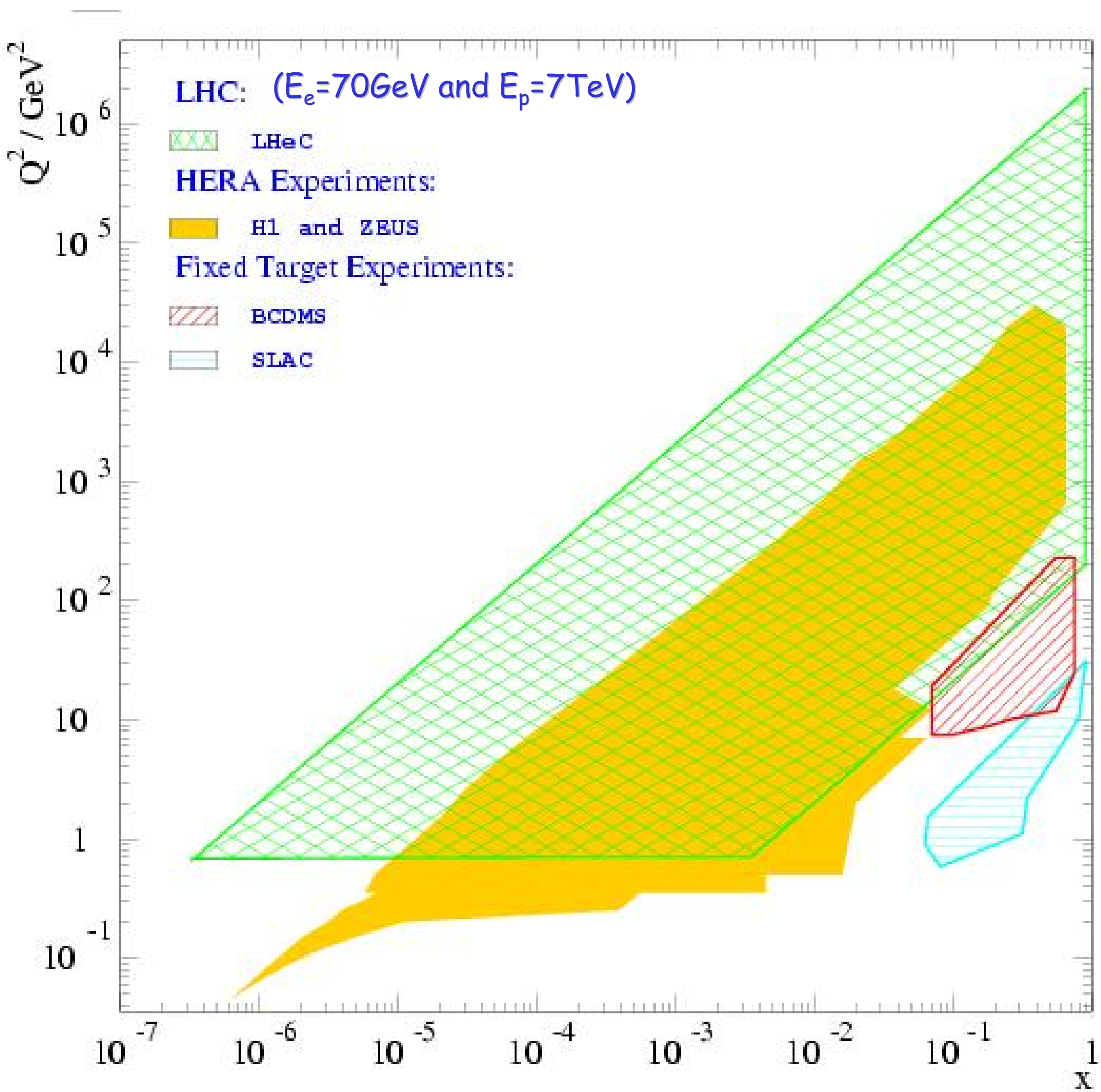
Deep-Inelastic Scattering at the TeV Energy Scale and the LHeC

P Newman, Birmingham

Antwerpen Meeting on Diffraction and Forward Physics at HERA and the LHC

26 October 2007



hep-ex/0603016
JINST 1 (2006) P10001.

Recent info (eg fromDIS07) at
http://epweb2.ph.bham.ac.uk/user/newman/lhec/lhec.html

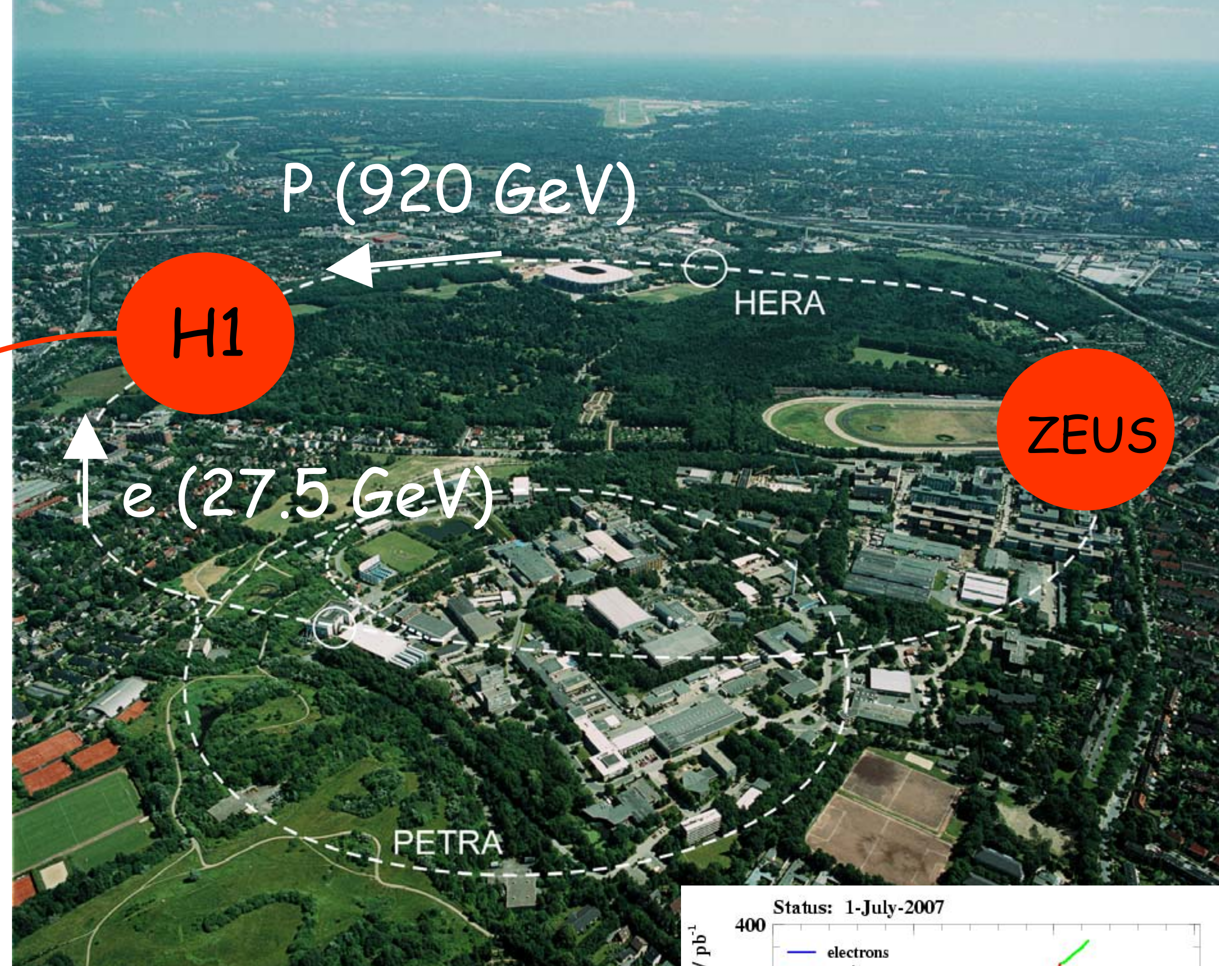
Contents

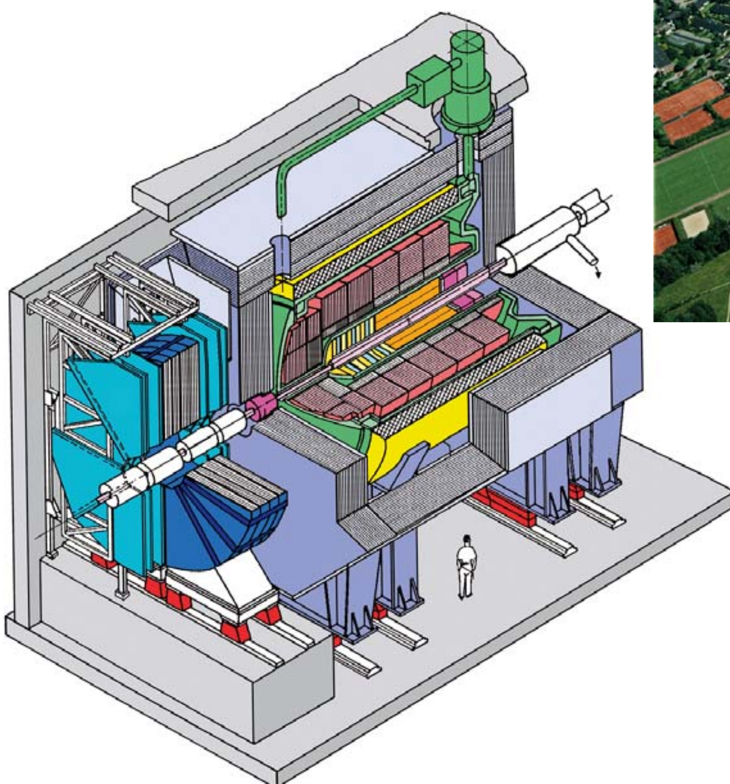
- DIS at the end of HERA
- Partons, discoveries and the LHC
- The Case for TeV Scale DIS
- LHeC Design Possibilities
- LHeC First Detector Considerations
- Some first Physics case studies (emphasis on low x)
- Timelines and Organisation

Caveat: LHeC is in its infancy! - So far, this is just a sketch
- Many many gaps!

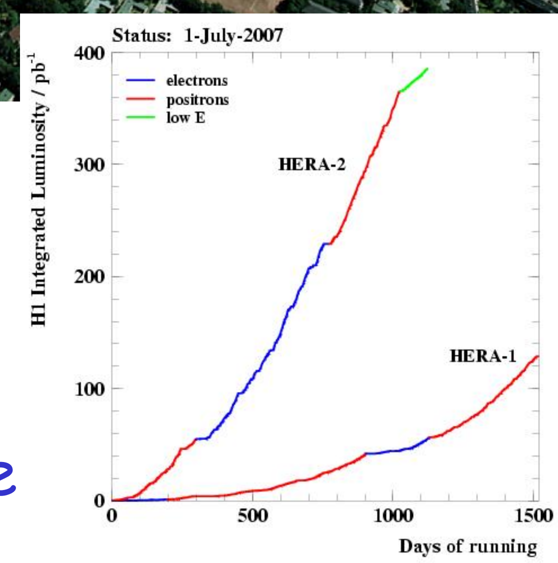
HERA (1992-2007)

- The world's only ever ep collider (Equivalent energy to 50 TeV fixed target)

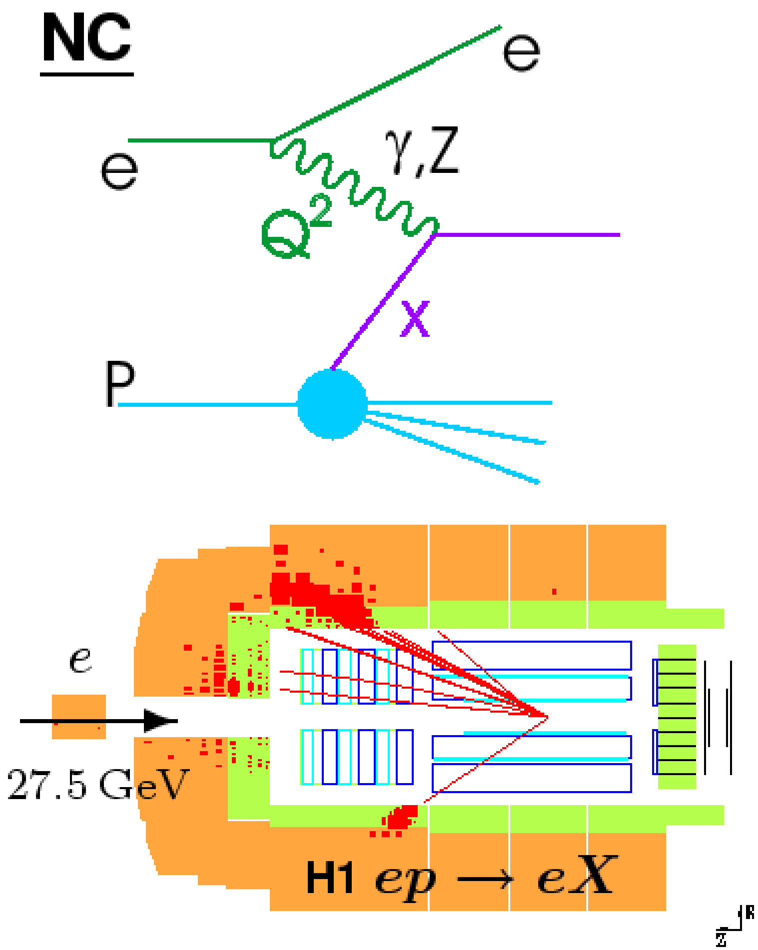


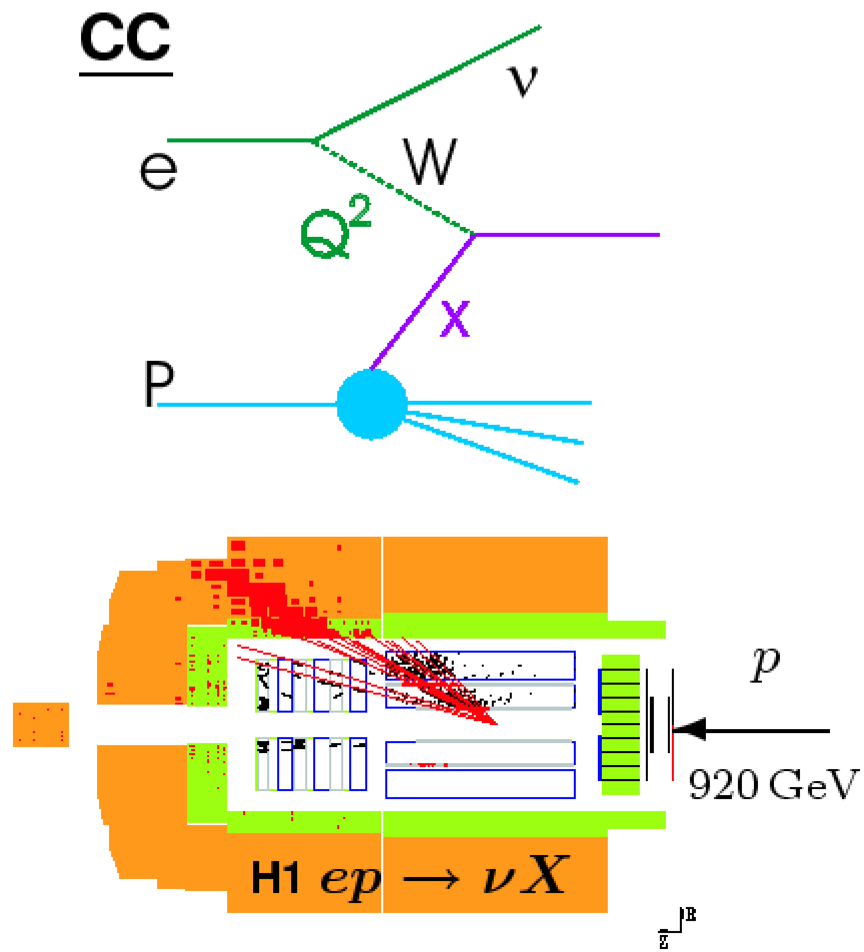


- … "the world's most powerful microscope" using virtual boson to resolve p structure



Sensitivity to Partons

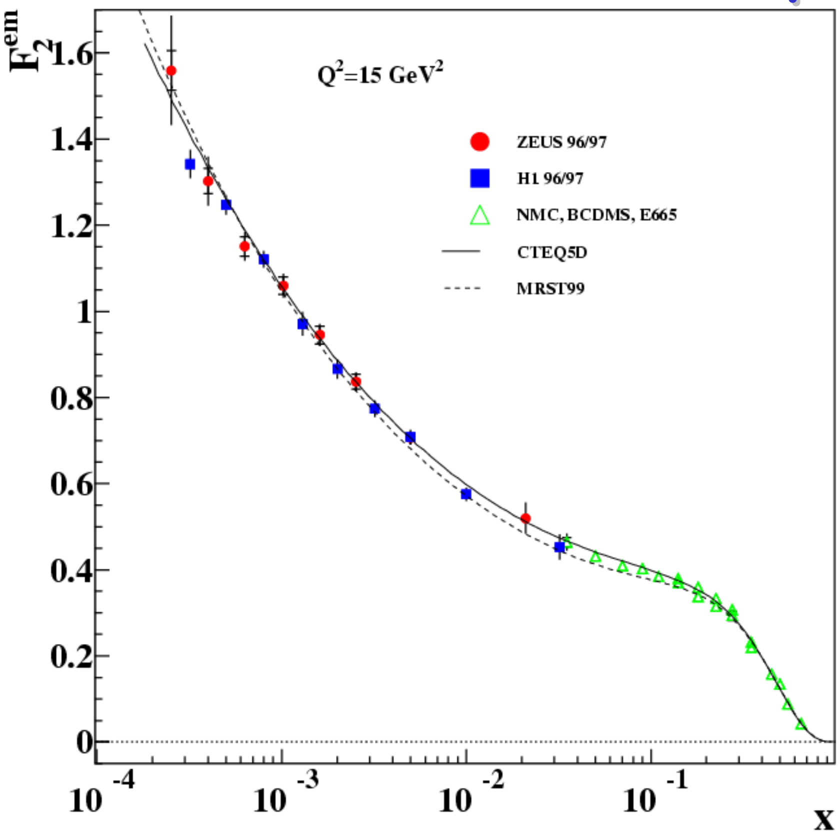


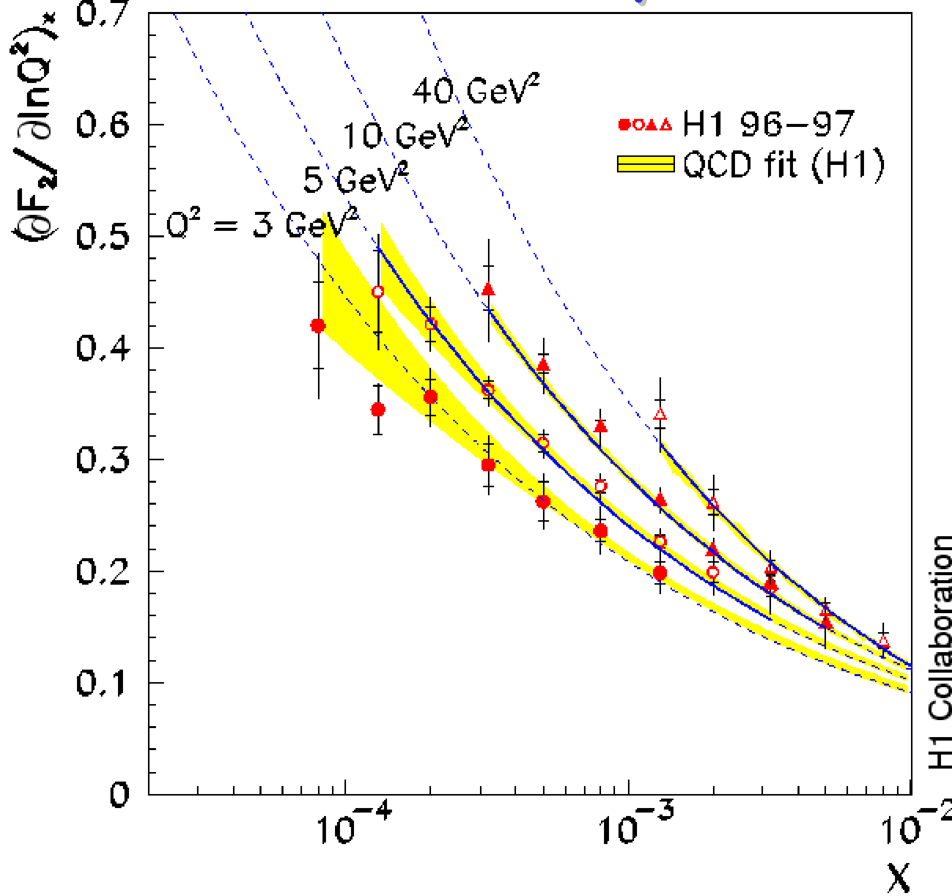


Cross section dominated by γ^* exchange (measures e_q^2 weighted quark distribution).

W, Z exchange at high Q^2 sensitive to flavour decomposition

The Birth of Experimental Low x Physics

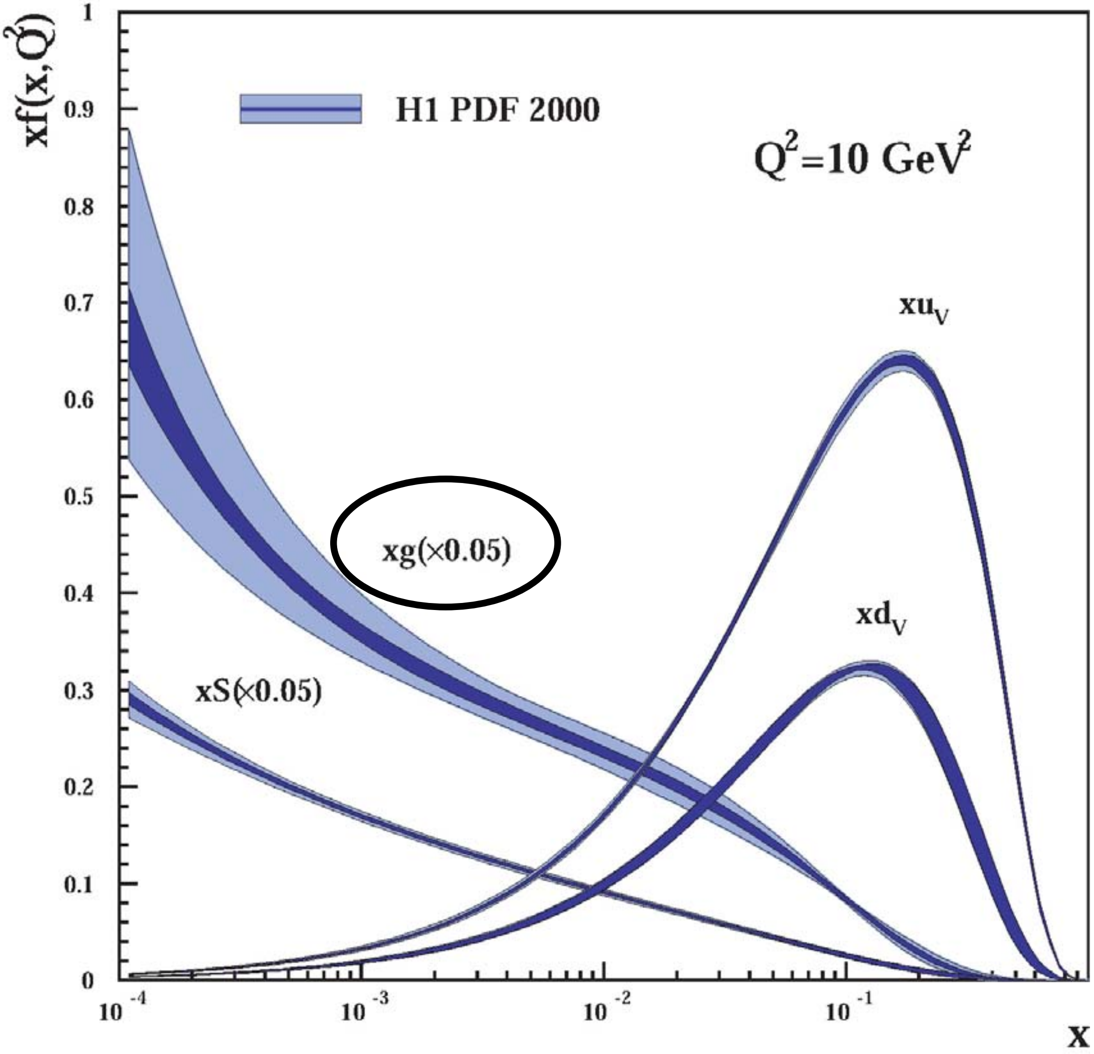




- Biggest HERA discovery: strong increase of quark density (F_2) and gluon density ($d F_2 / d \ln Q^2$) with decreasing x in newly explored regime.

- Low x, `large' Q^2 is high density, low coupling limit of QCD …

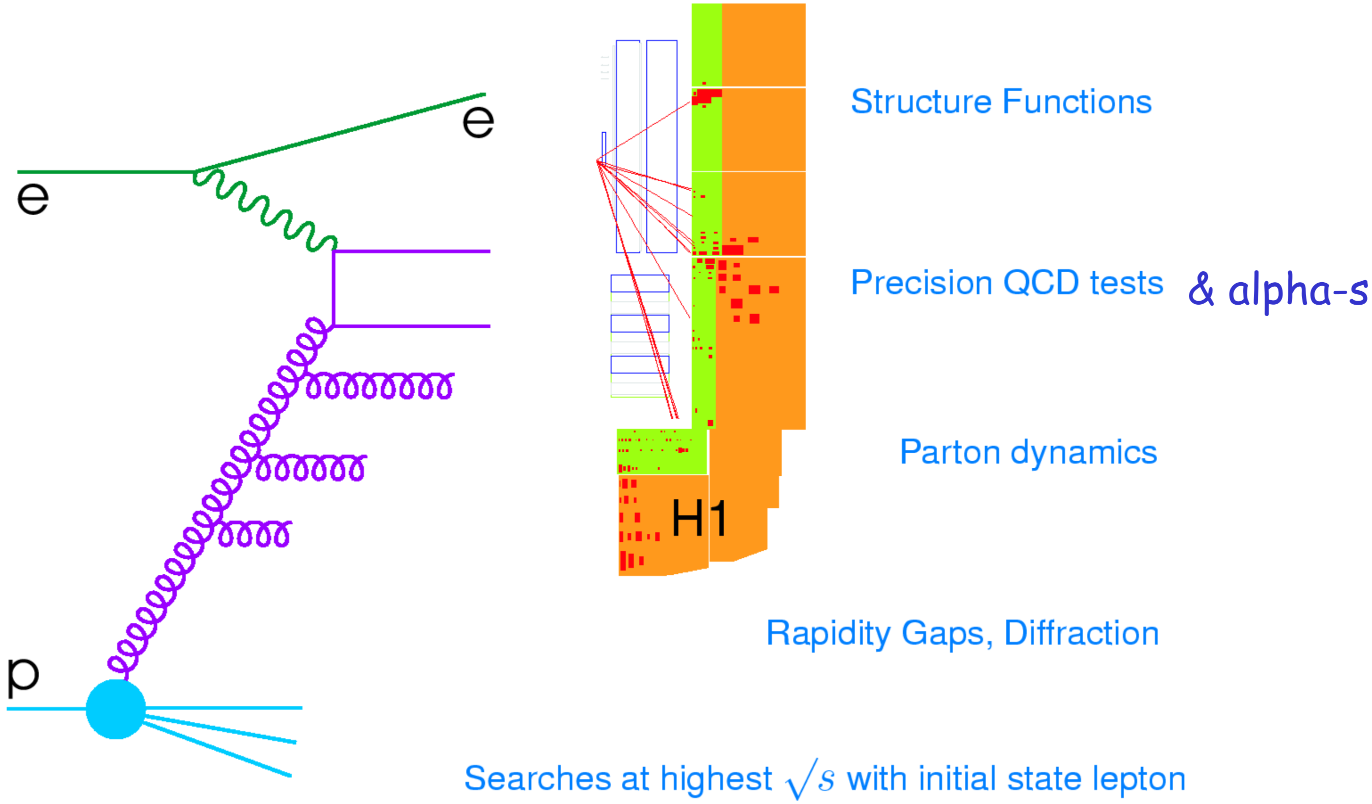
What *is* a Proton?



- DGLAP fits to NC and CC data, up to order α_s^2 in QCD used to obtain valence, sea quarks and gluon.
- Can be done using H1 data alone.
- `Global' fits by MRST, CTEQ also use input from Pp and elsewhere.

- How is enormous gluon density at low x tamed?
- Can we trust the (NLO DGLAP) theory at all x?
- Limited precision at high x (see later)

Beyond Inclusive Measurements

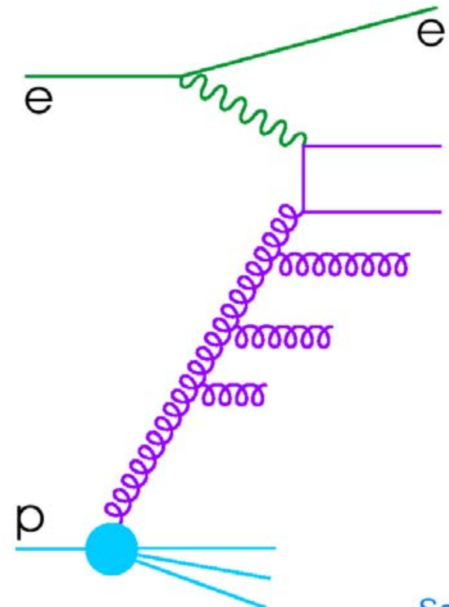


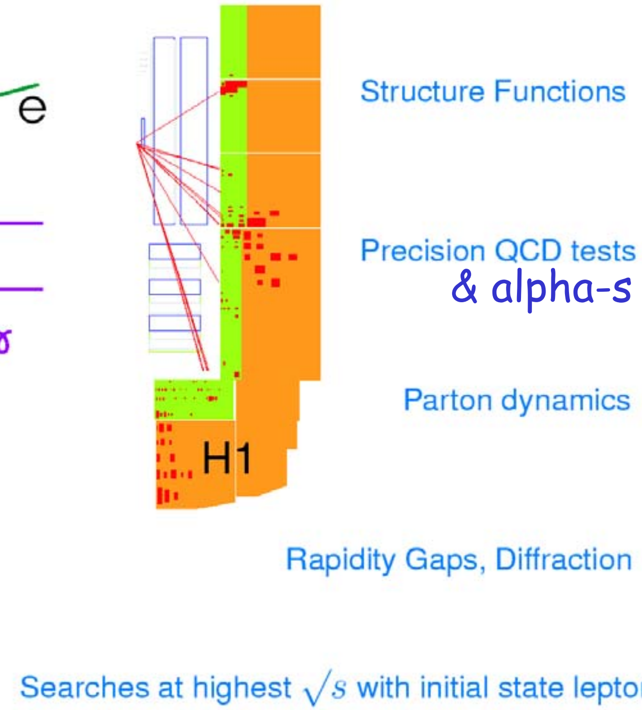
- Precision QCD tests → pdf info, gluon sensitivity
  - Understanding often limited by theory (scale) uncertainties, largely due to relatively low p_t region accessed.
- 'Forward jets', diffraction → direct tests of assumed parton evolution patterns, novel or poorly understood QCD effects
  - Understanding limited by forward instrumentation

Beyond Inclusive Measurements

- Hadronic Final States:
  - Jets, heavy flavours give complementary pdf info, direct sensitivity to gluon

  ? Usefulness of HERA data often limited by theory (scale uncties) … better at LHeC



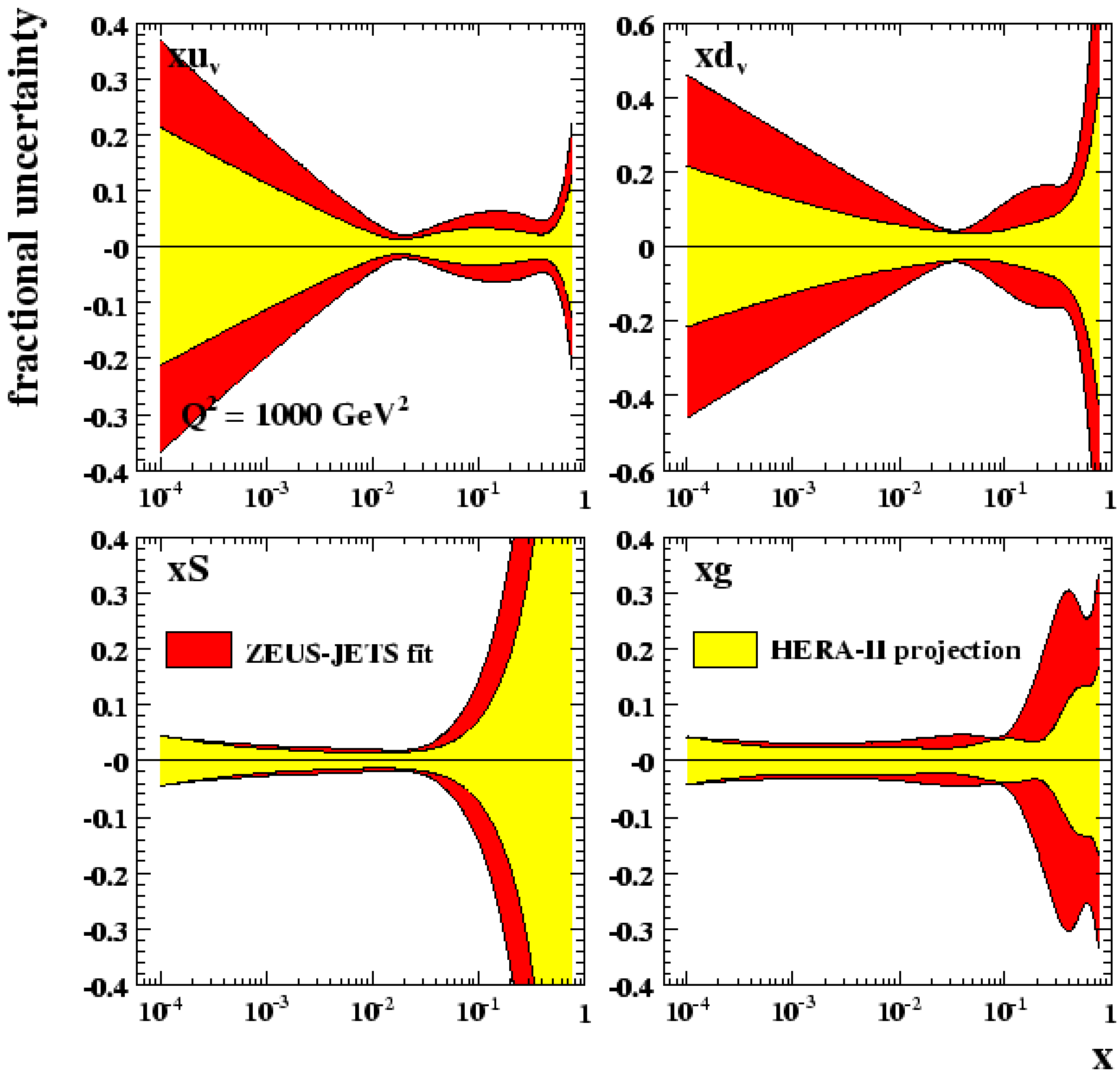


  - Additional studies … 3g, 4g vertices, instantons?

- Forward Jets, Diffraction
  - Direct tests of assumed parton evolution patterns
  - Novel / poorly understood QCD effects (diffraction …)

  ? Understanding limited by (forward) detectors …

How well could we know the Partons at HERA?

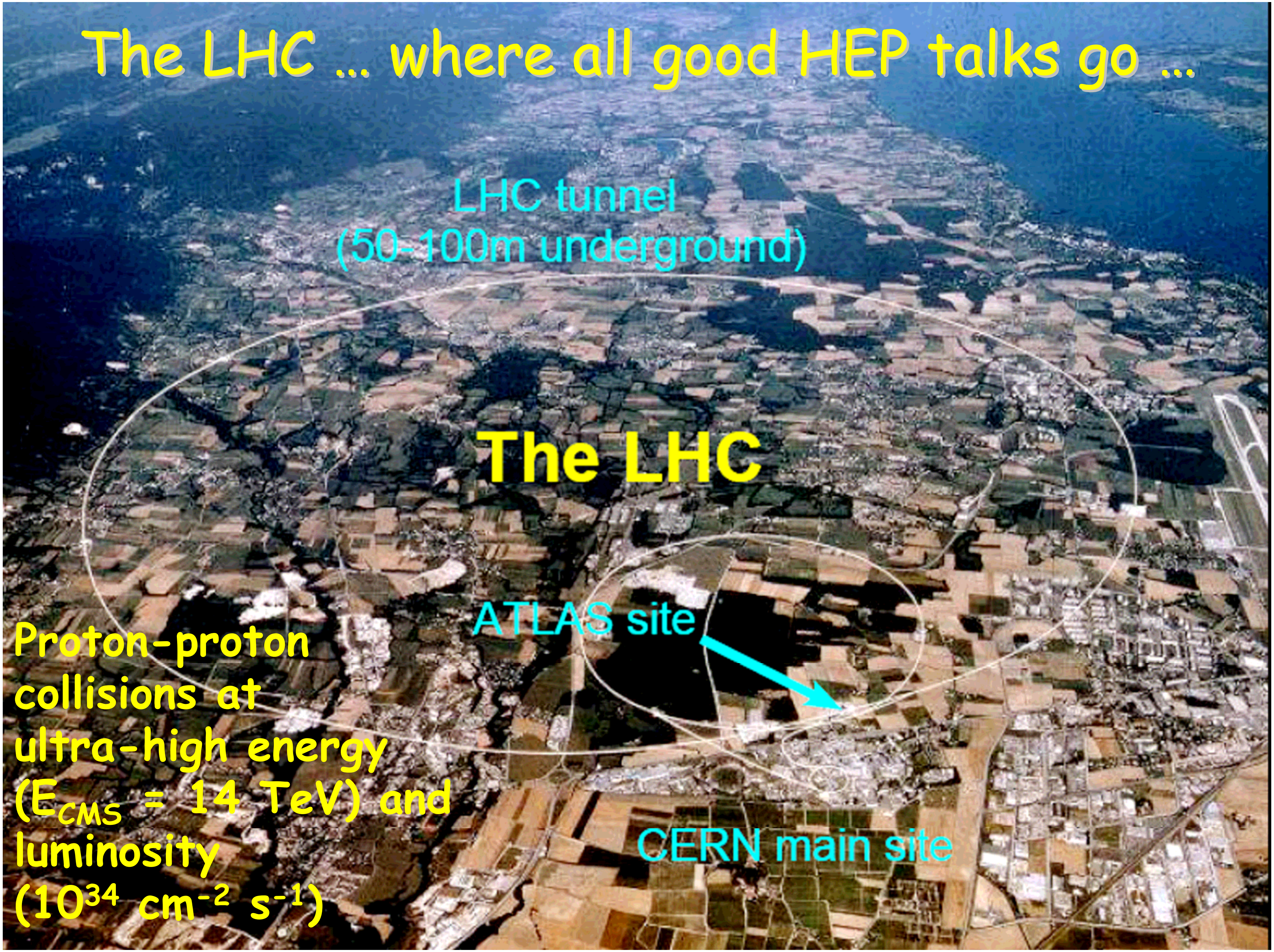


700 pb-1
H1 + ZEUS
combined

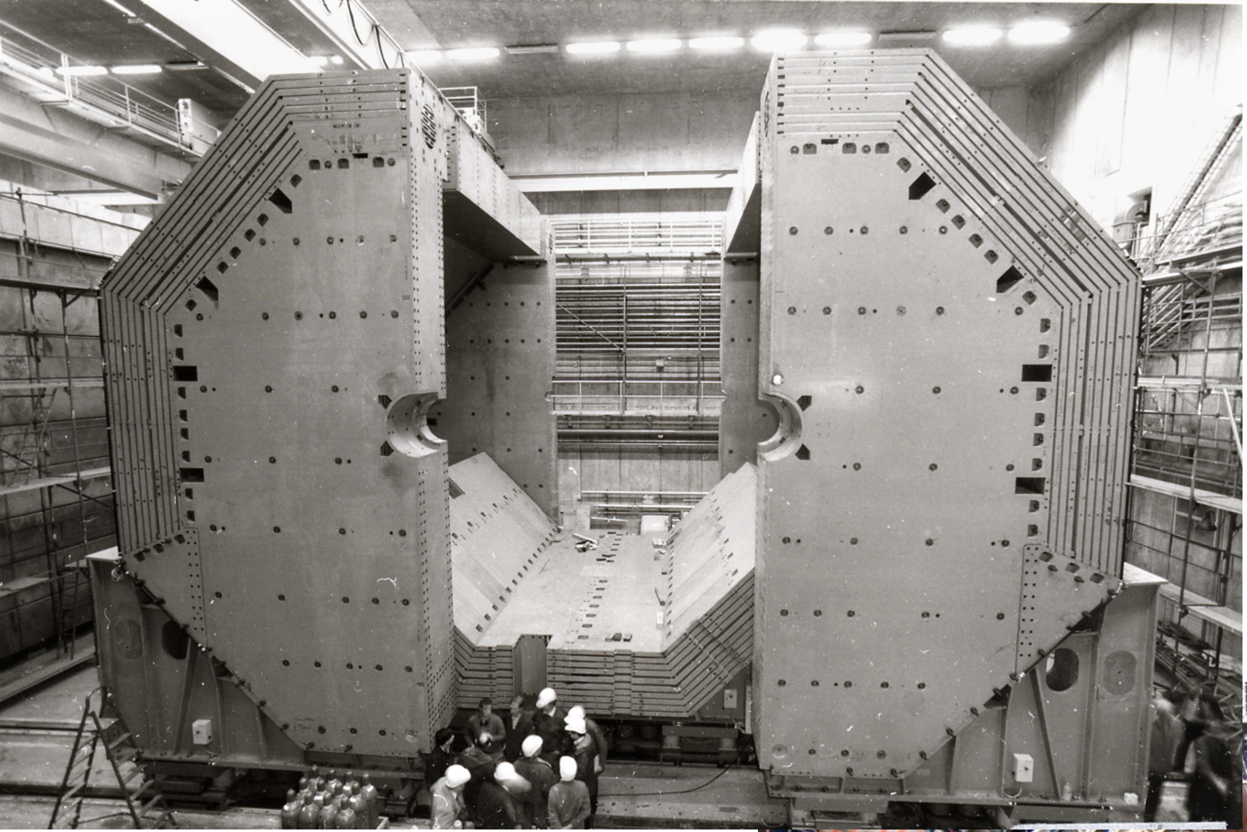
Only statistical improvements considered

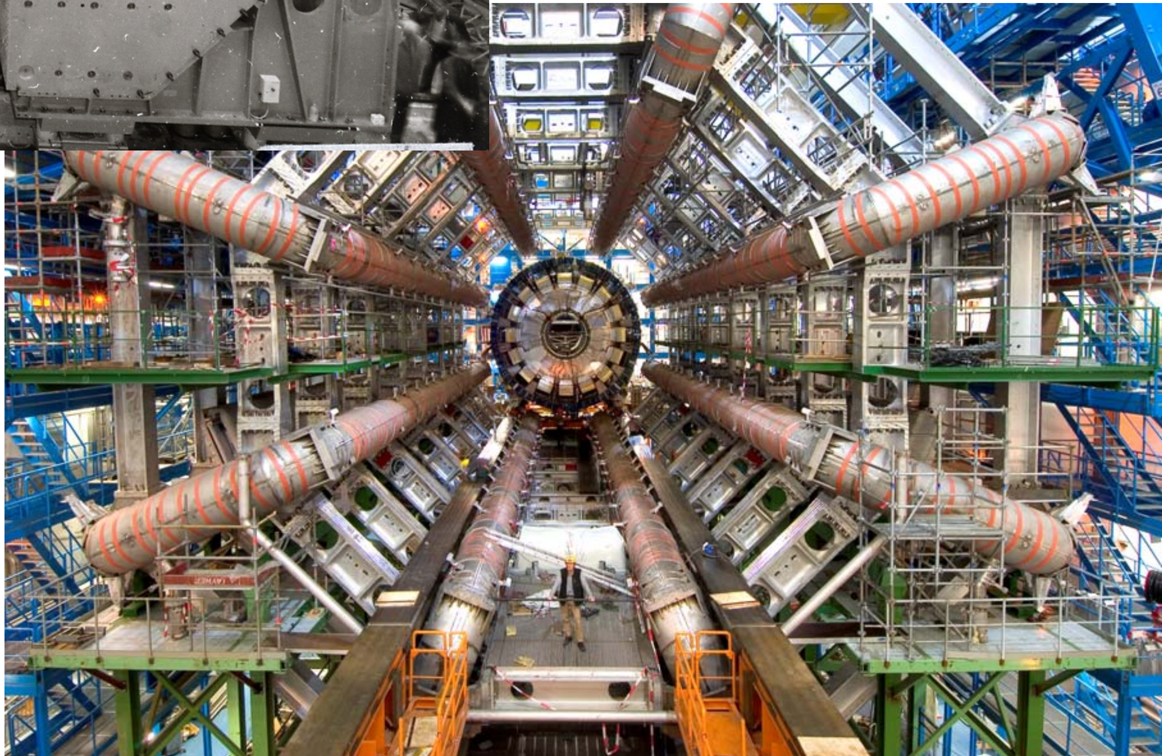
… high x LHC discovery region (esp. gluon) still not well known

(Gwenlan et al., HERA-LHC Workshop)

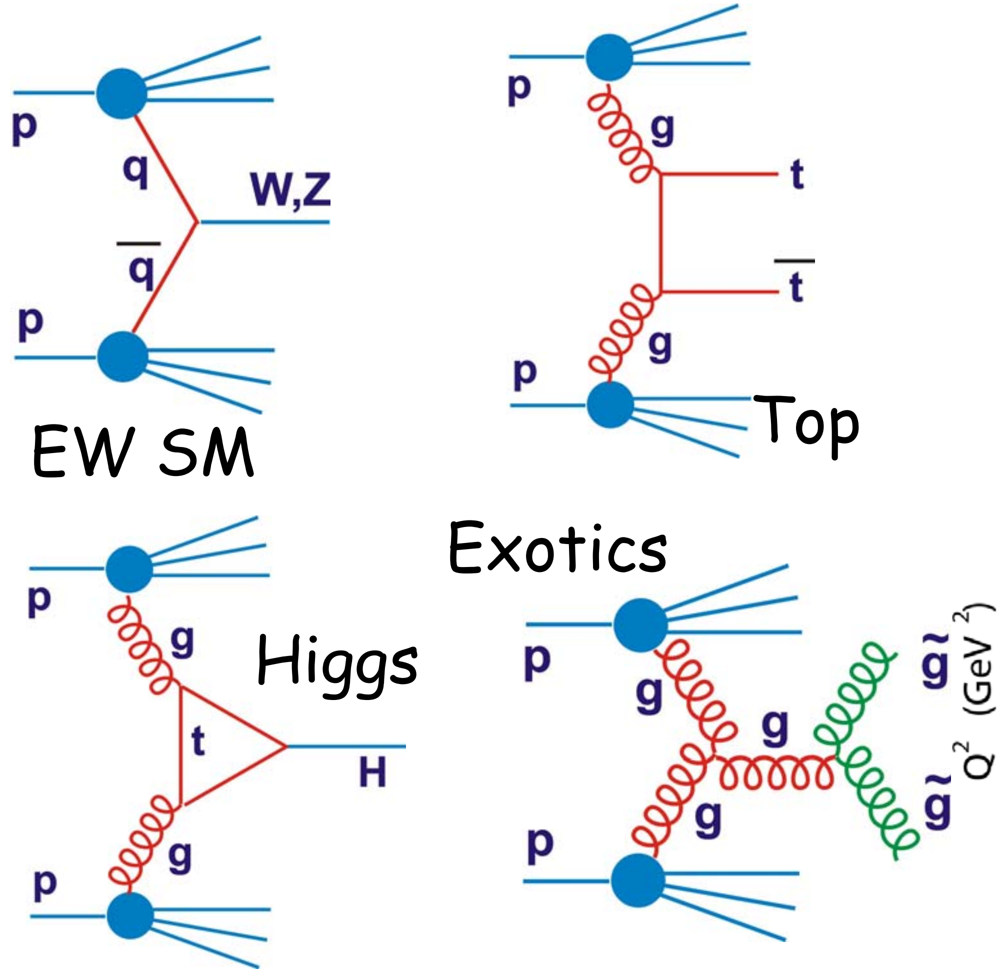

The LHC … where all good HEP talks go …
LHC tunnel
(50-100m underground)
The LHC
ATLAS site
CERN main site
Proton-proton collisions at ultra-high energy (E_{CMS} = 14 TeV) and luminosity (10^{34} cm^{-2} s^{-1})

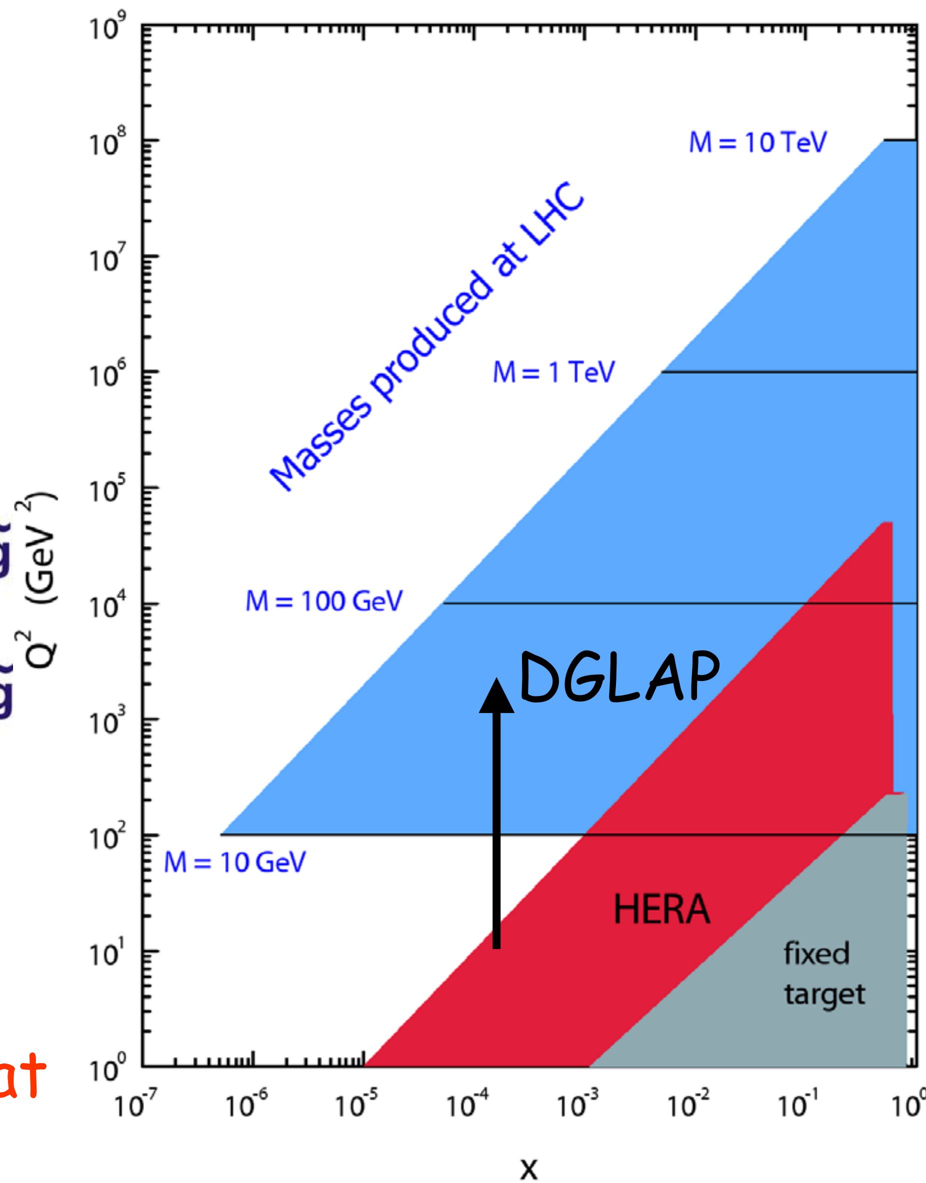
Scale: H1 v ATLAS





Partons @ LHC

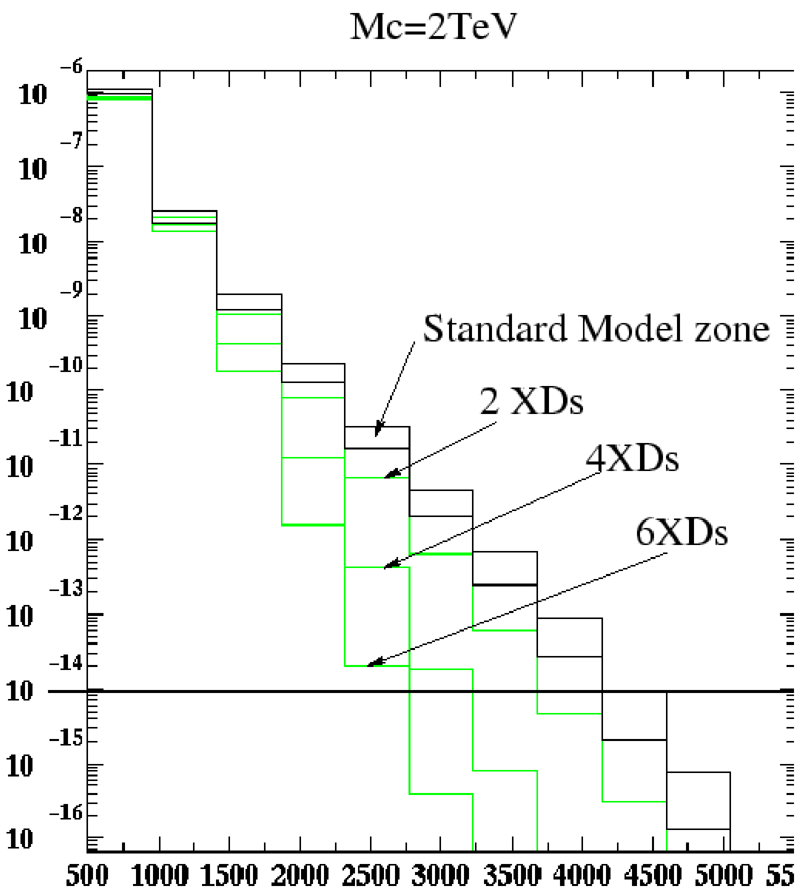


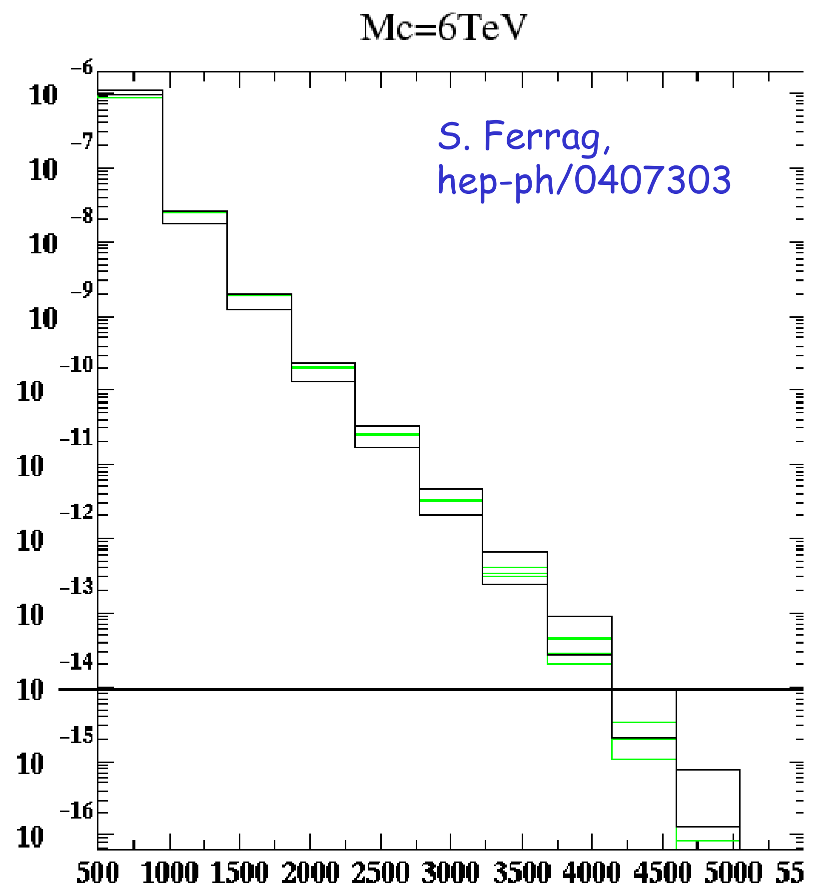


- LHC rapidity plateau requires PDFs over similar x range to that probed at HERA!
- … if we can trust the standard (DGLAP) evolution equations

Partons Limiting Searches for New Physics

Some BSM models give deviations in high mass dijet spectra, even reducing them!... e.g. a model of extra dimensions ...





... in this example, high x PDF uncertainties reduce sensitivity to compactification scales from 6 to 2 TeV for 2 new dim's

Some Physics Motivation for TeV Scale DIS

-New Physics in the eq Sector
  leptoquarks, RP violating SUSY, quark compositeness

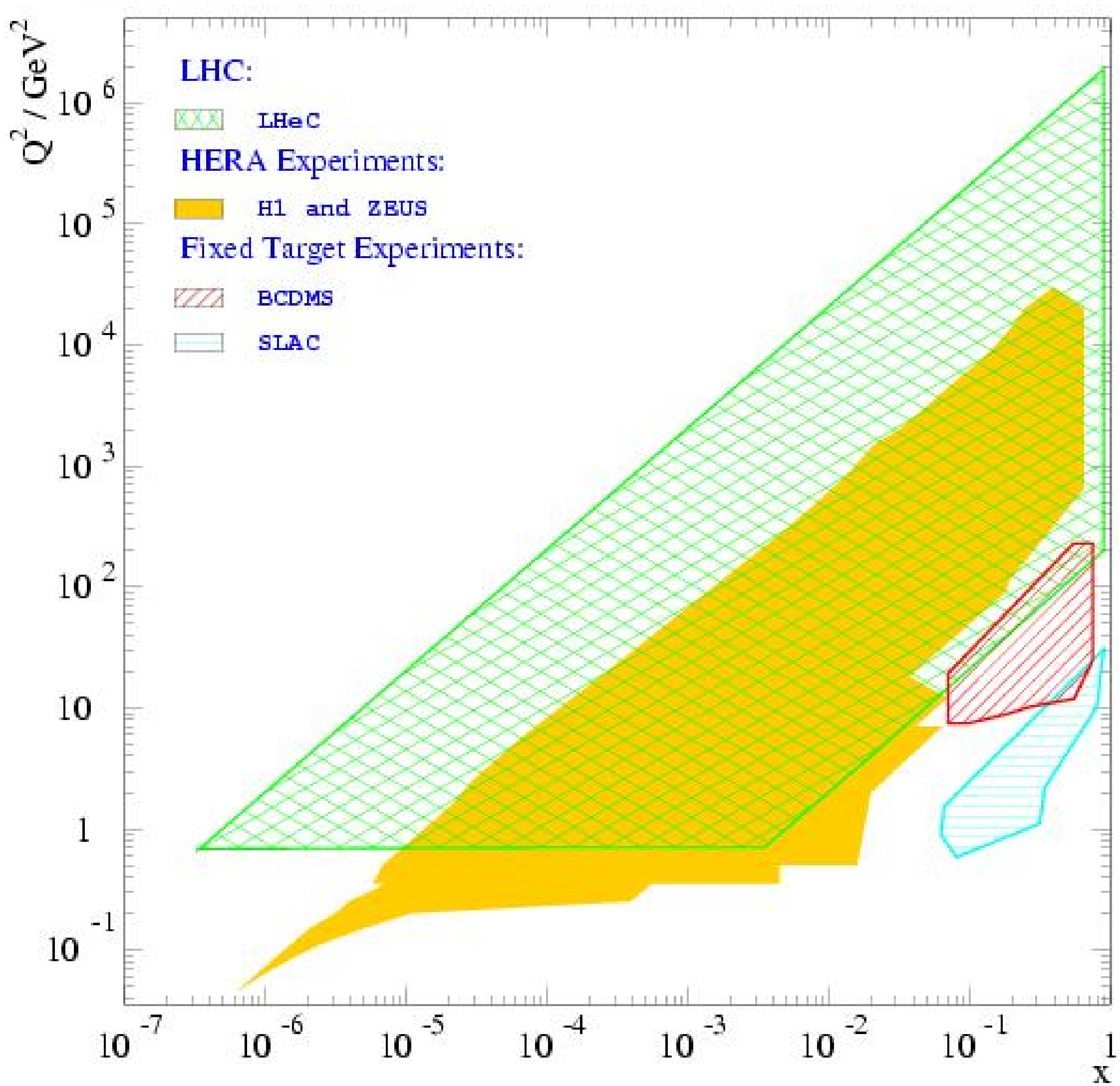
-The Low x Limit of Quantum Chromodynamics
  high parton densities with low coupling
  parton saturation, new evolution dynamics

-Quark-Gluon Dynamics and the Origin of Mass
  confinement and diffraction

-Precision Proton Structure for the LHC
  essential to know the initial state precisely!
  including heavy flavour (b), gluon

-Nuclear Parton Densities
  eA with AA -> partons in nuclei, Quark Gluon Plasma

LHeC Inclusive Kinematics



$$E_e = 70 \text{ GeV}$$
$$E_p = 7 \text{ TeV}$$
$$\sqrt{s} = 1.4 \text{ TeV}$$

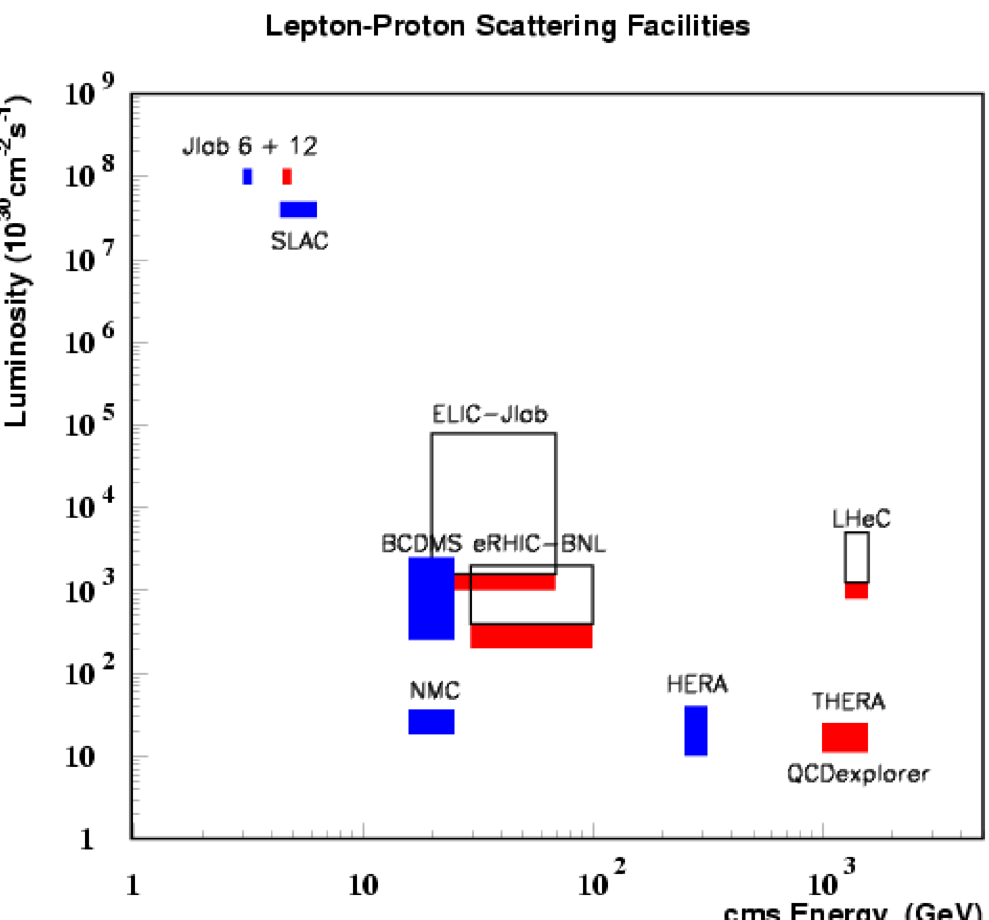
- Extension of high Mass (Q2) frontier
- Extension in Q^2 lever-arm in x range Covered by HERA
- Extension of low x (high W) frontier

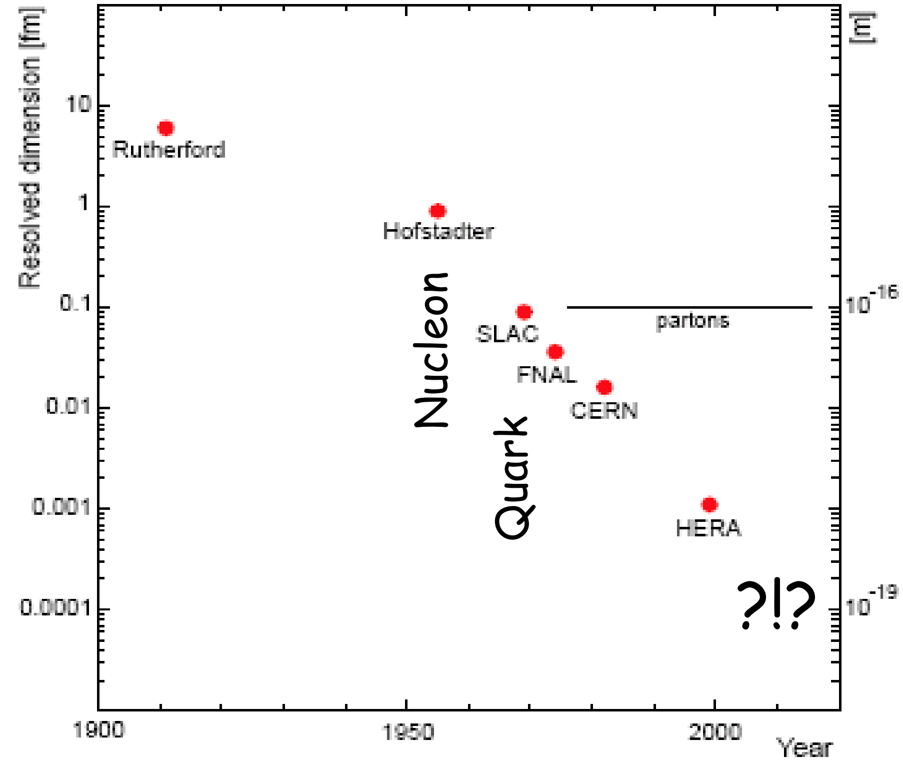
$$W \leq 1.4 \text{ TeV}$$
$$x \geq 5.10^{-7} \text{ at } Q^2 \leq 1 \text{ GeV}^2$$

- Unprecedented ep lumi > 10^{33} cm^{-2} s^{-1} !
- eA mode possible using LHC ion beam

LHeC Context

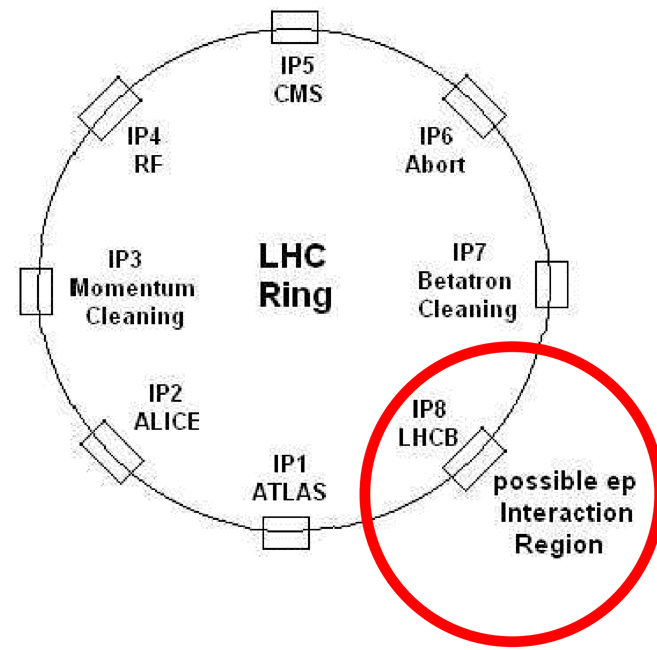
Latest of several proposals to take ep physics into the TeV energy range …
… but with unprecedented lumi!



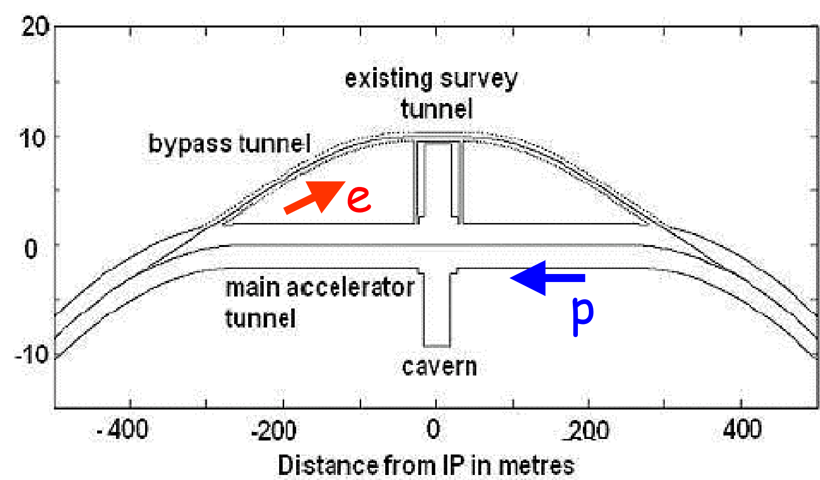


- Combining the LHC protons with an electron beam is natural next step in pushing the frontiers of ep physics: small resolved dimensions, high Q^2 and low x
- Can be done without affecting pp running

A Possible Design



- On timescale of LHC upgrades?...
- ep in parallel with standard pp operation
- Proton beam parameters fixed by LHC
- 70 GeV electron beam, compromising between energy and synchrotron (0.7 GeV loss per turn)
- Superconducting RF cavities then consume 50MW for Ie=70mA
- Electron beam by-passes existing experiments via existing survey tunnels



Interaction Region

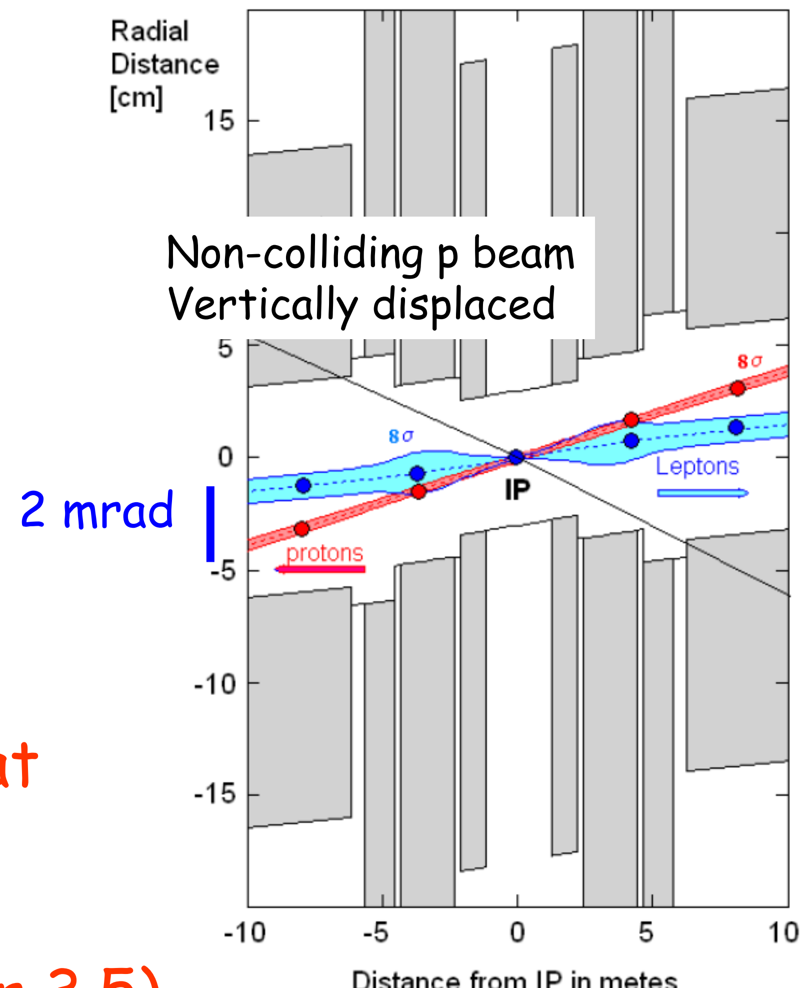
- Matching electron and proton beam shapes and sizes determines β^* x emittance for electron beam

- High luminosity requires low β quadrupoles close to interaction point (1.2 m)

- Fast separation of beams with tolerable synchrotron power requires finite crossing angle

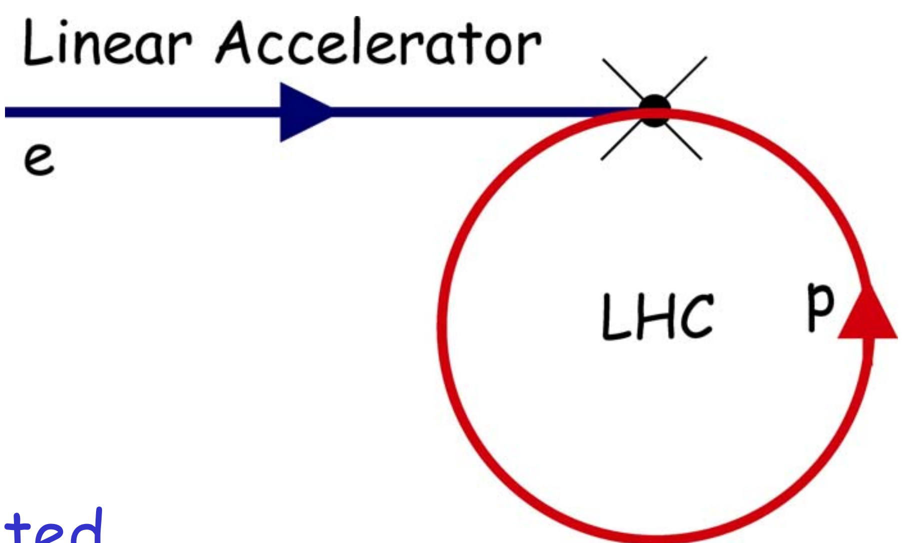
- 2 mrad angle gives 8σ separation at first parasitic crossing

Top view



- Resulting loss of luminosity (factor 3.5) partially compensated by "crab cavities" … -> 10^{33} cm^{-2} s^{-1}

Another Possible Design?



• Recent investigation (Chatopadhay & Zimmermann) of linac solution to electron beam, using CW cavities.

• Full details eagerly anticipated

• Similar in spirit to previous ideas (QCD-explorer, THERA), but luminosity of a few x 10^{33} achievable?

Less interference with existing LHC set-up

Direct relation to linear collider R&D

Some First Detector Considerations

HERA E_e=30GeV → ← E_p=920GeV

LHeC E_e=70GeV → ← E_p=7000GeV

- Considerably more asymmetric beam energies than HERA!
  - Hadronic final state at newly accessed lowest x values goes central or backward in the detector ☺
  - At x values typical of HERA (but larger Q^2), hadronic final state is boosted more in the forward direction.

- Full study of low x / Q^2 and of range overlapping with HERA, with sensitivity to energy flow in outgoing proton direction requires forward acceptance for hadrons to 1^o

Systematic Precision etc

Possible requirements based on how to reach per-mil α_s value

The new collider …
- should be 100 times more luminous than HERA

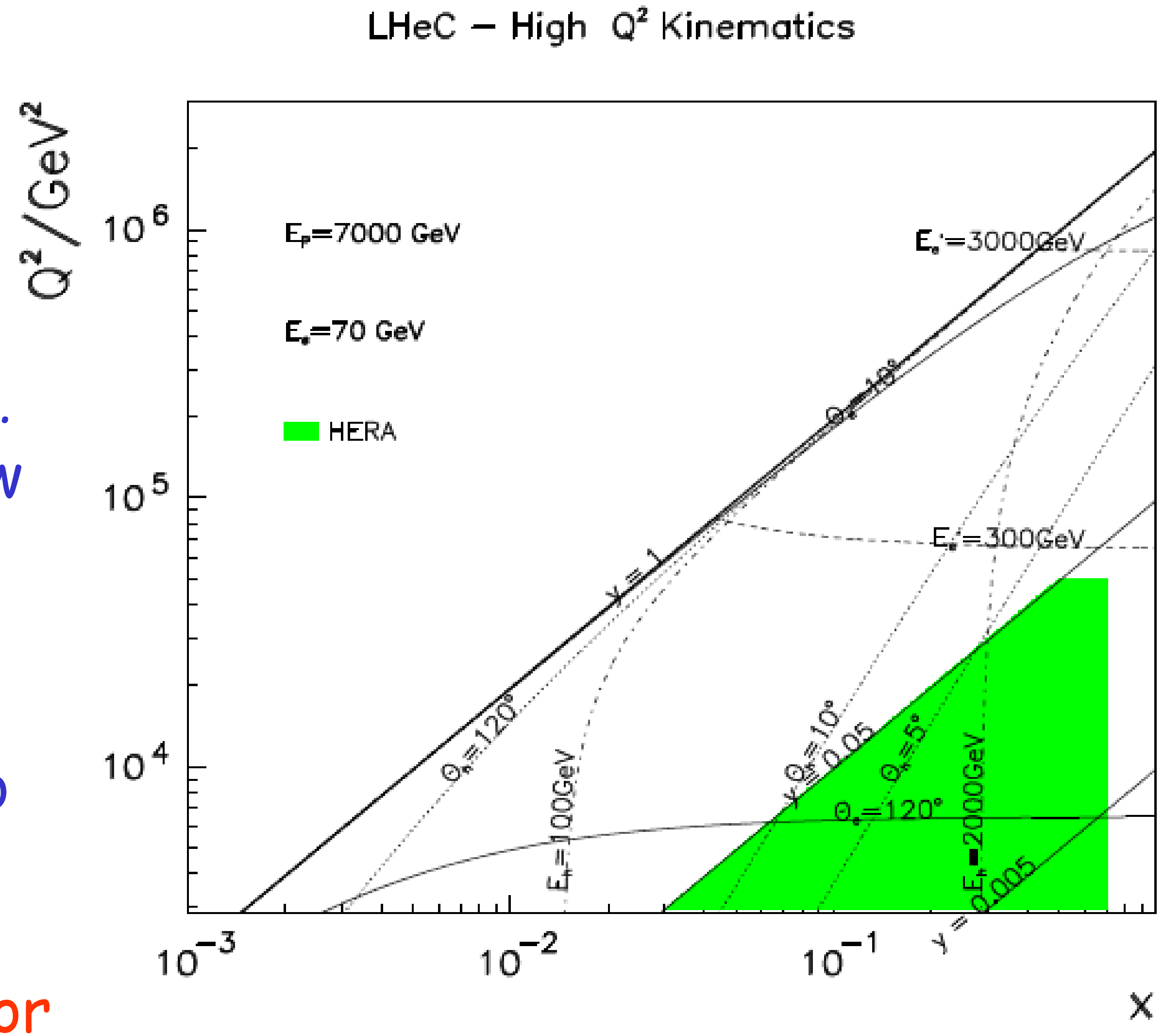
The new detector
- should be at least 2 times better than H1 / ZEUS

Redundant determination of kinematics from e and X
is a huge help in calibration etc!

Lumi = $10^{33} - 10^{34}$ cm^{-2} s^{-1}	(HERA 1-5 x 10^{31} cm^{-2} s^{-1})
Acceptance 1-179^{o}	(HERA 7-177^{o})
Tracking to 0.1 mrad	(HERA 0.2 – 1 mrad)
EM Calorimetry to 0.1%	(HERA 0.2-0.5%)
Had calorimtry to 0.5%	(HERA 1%)
Luminosity to 0.5%	(HERA 1%)

The LHeC for High Q^2 Investigations

2 modes considered:

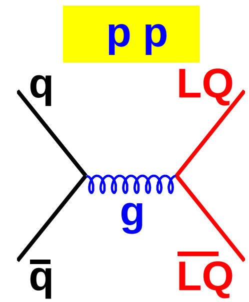


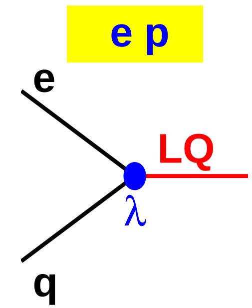
1) Focusing magnet to optimise lumi … detector acceptance restricted to θ < 170° … Little acceptance below Q^2=100 GeV^2

2) No focusing … lower lumi, but acceptance to 179° → (see later)

… 2 versions of detector to use at different times?
… low x studies at 10^{32} cm^{-2}s^{-1}, high Q^2 at 10^{33} cm^{-2}s^{-1}

Lepton-quark Bound States





- Leptoquarks appear in many extensions to SM... explain apparent symmetry between lepton and quark sectors.

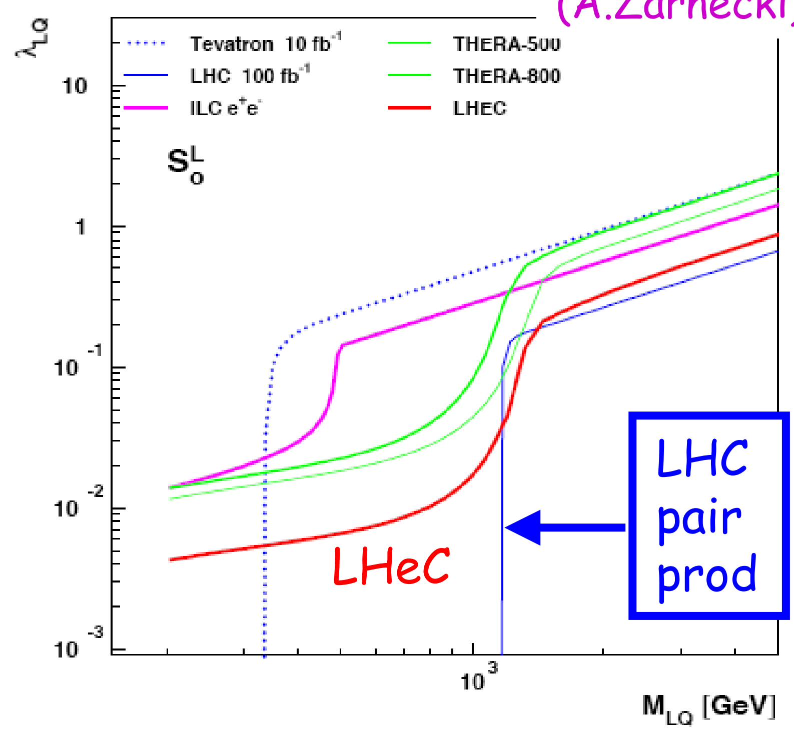
Yukawa coupling, λ

- Scalar or Vector color triplet bosons carrying L, B and fractional Q, complex spectroscopy likely!

- (Mostly) pair produced in pp, single production in ep.

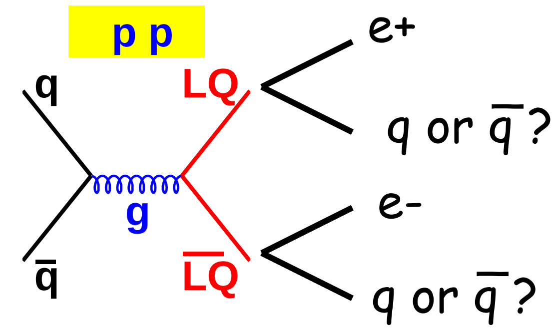
- LHC sensitivity (to ~1.5 TeV) extends beyond LHeC, but difficult to determine quantum numbers / spectroscopy!

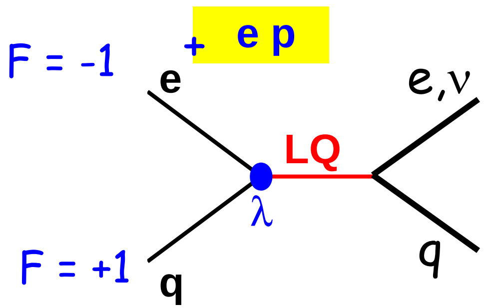
(A.Zarnecki)



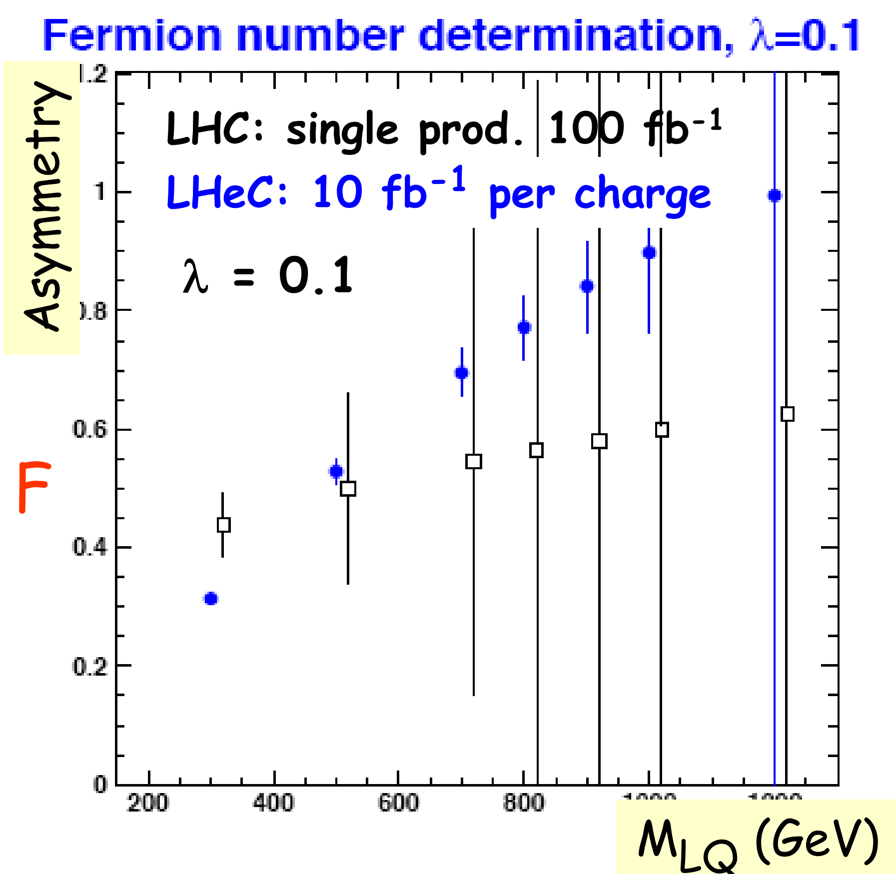
Leptoquark Properties at LHeC

LHC: - Hard to determine quantum numbers from pair production.
- Single production cross sections tiny.

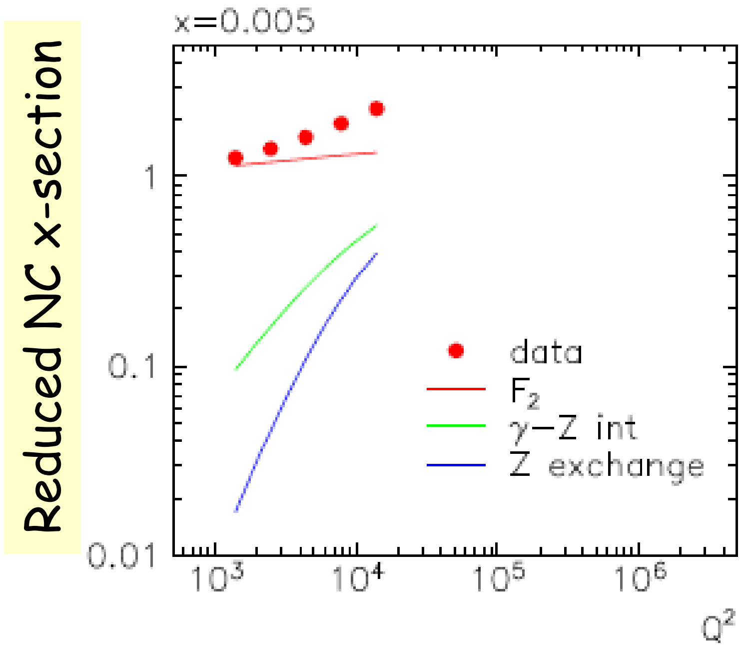


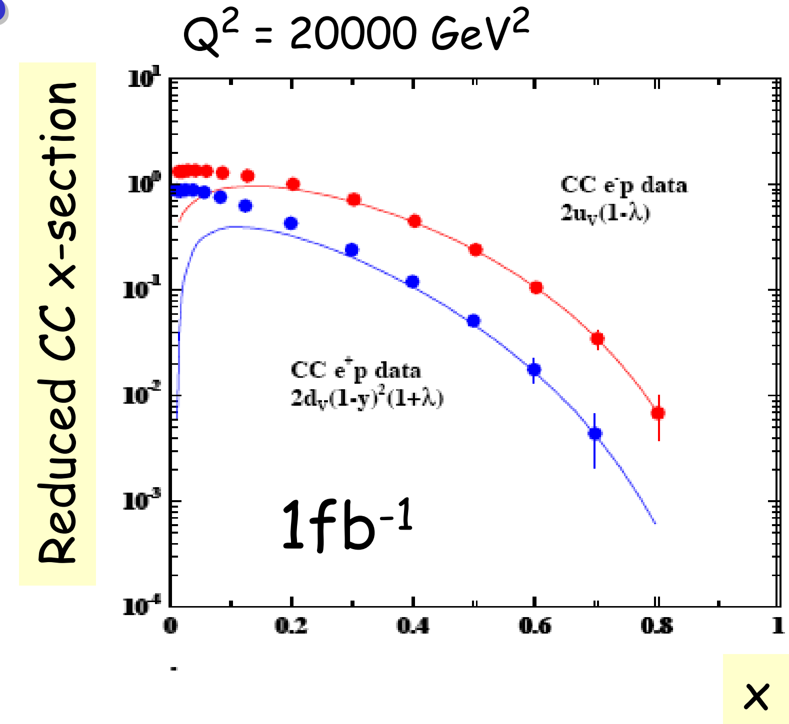


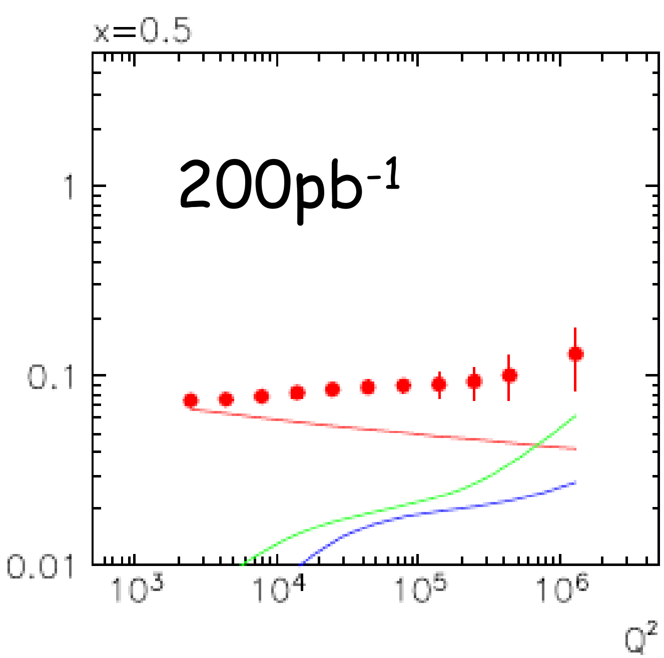
LHeC: - Resonant production at high x implies q rather than qbar. Sign of e^+p / e^-p asymmetry thus determines fermion number F
- Disentangle scalar / vector from angular distributions.
- Disentangle chiral couplings by varying beam polarisation



Inclusive Cross Sections



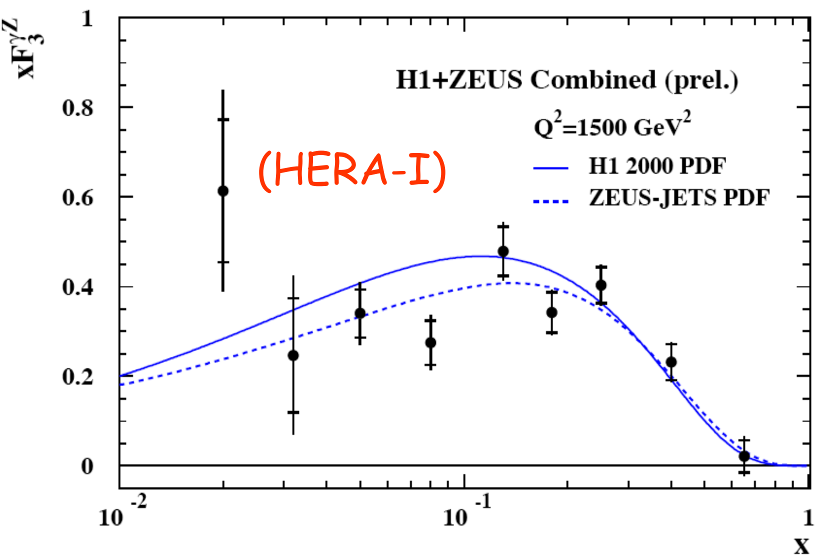




- LHeC is a genuine electroweak collider … exploit helicity and W exchange for quark flavour and q / qbar decomposition.

- It provides high NC and CC rates up to large values of x, for e.g. d/u determination

Example Proton Structure Constraint: xF_3

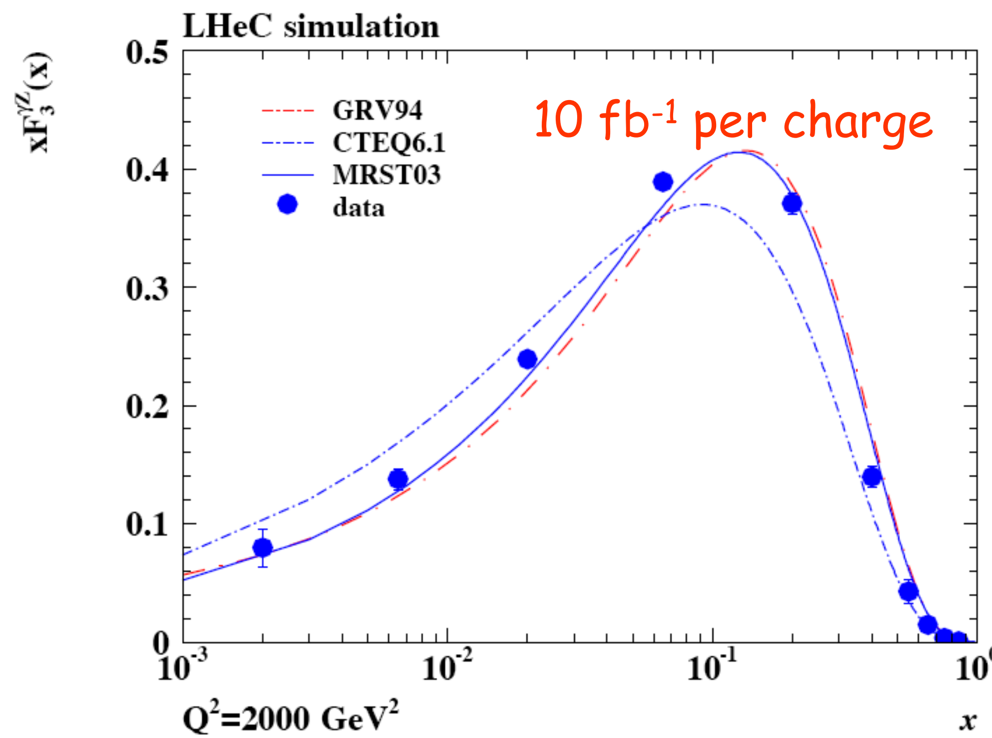


$$xF_3^{\gamma Z} \sim a_u e_u (u - \overline{u}) + a_d e_d (d - \overline{d})$$

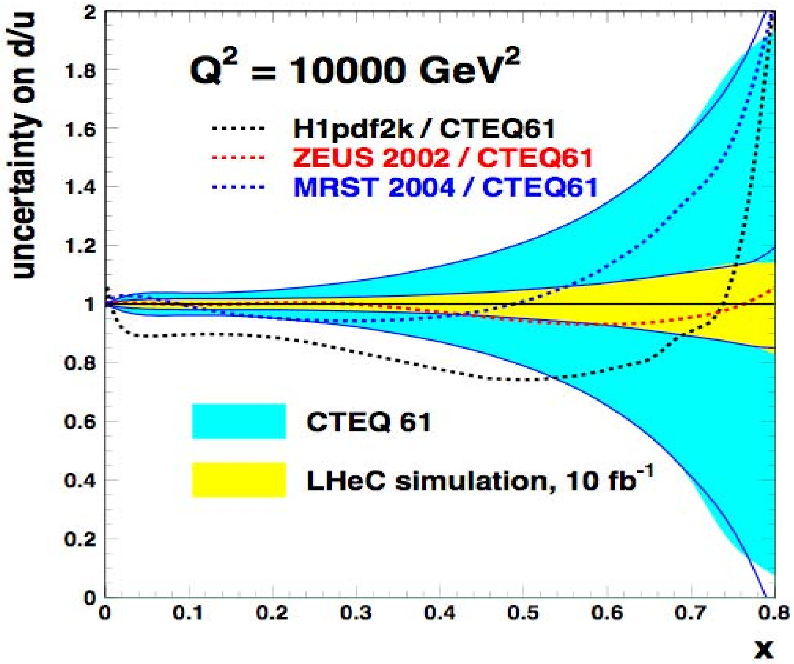
Valence quark density extracted from e^+p / e^-p NC cross section asymmetry …
(also from W^+ v W^- at LHC)

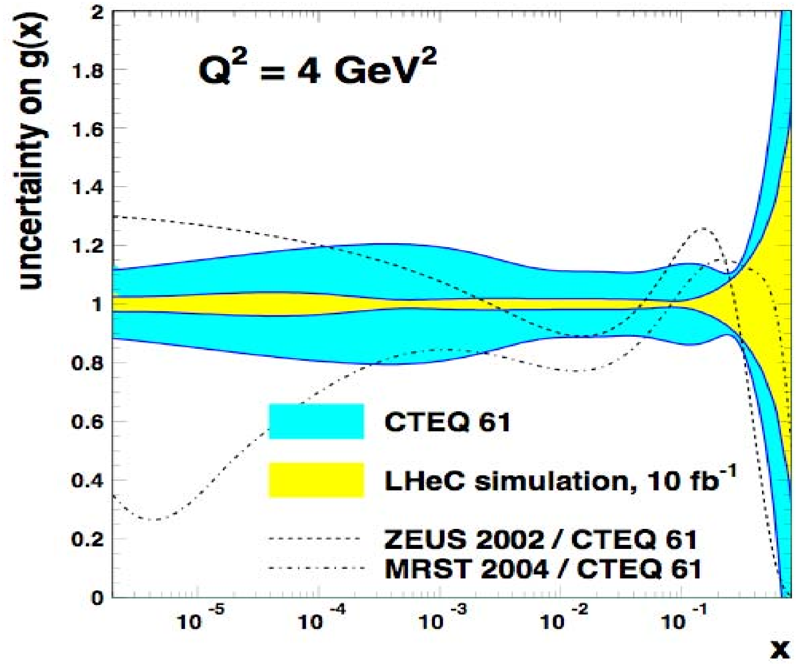
Improved precision and extension to lower x at LHeC

Tests symmetry of q and qbar in sea and / or measures valence density at very low x



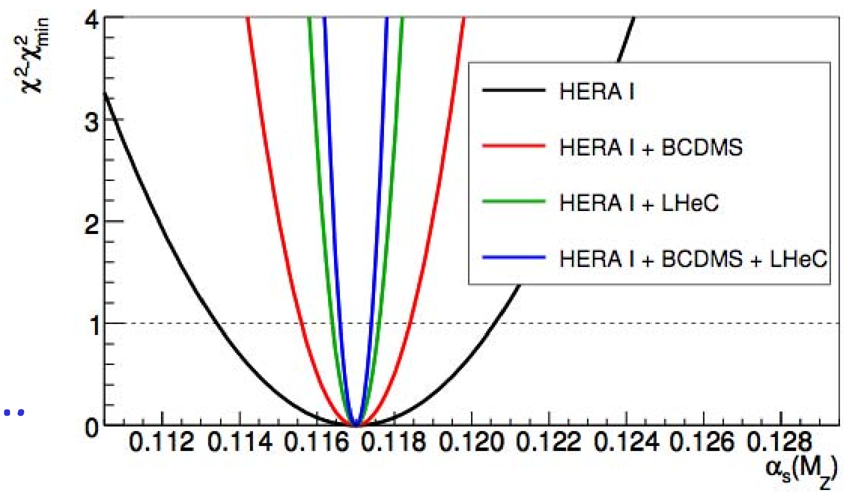
LHeC Impact on High x Partons and α_s





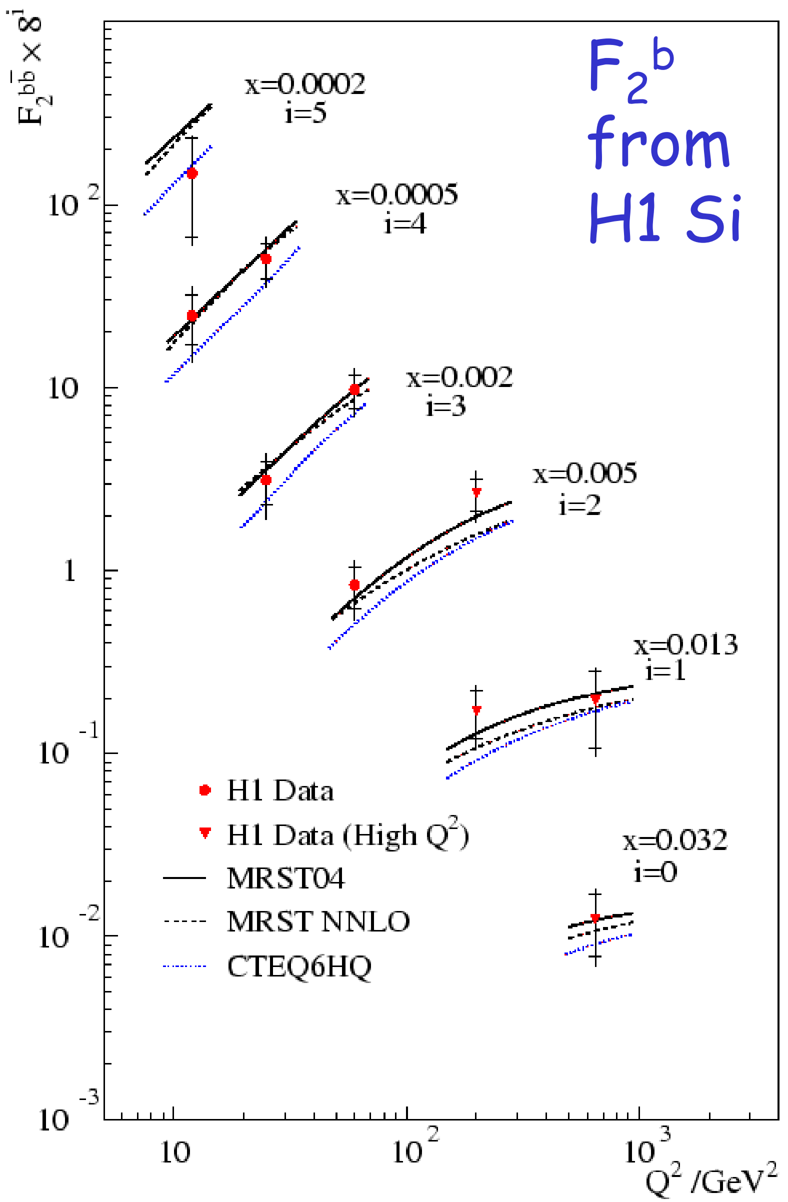
… crucial to LHC discovery
& interpretation of new states?

Projected LHeC α_s precision few/mil (c.f. 1-2% now) … full NC/CC sim (with systs) + NLO fit …



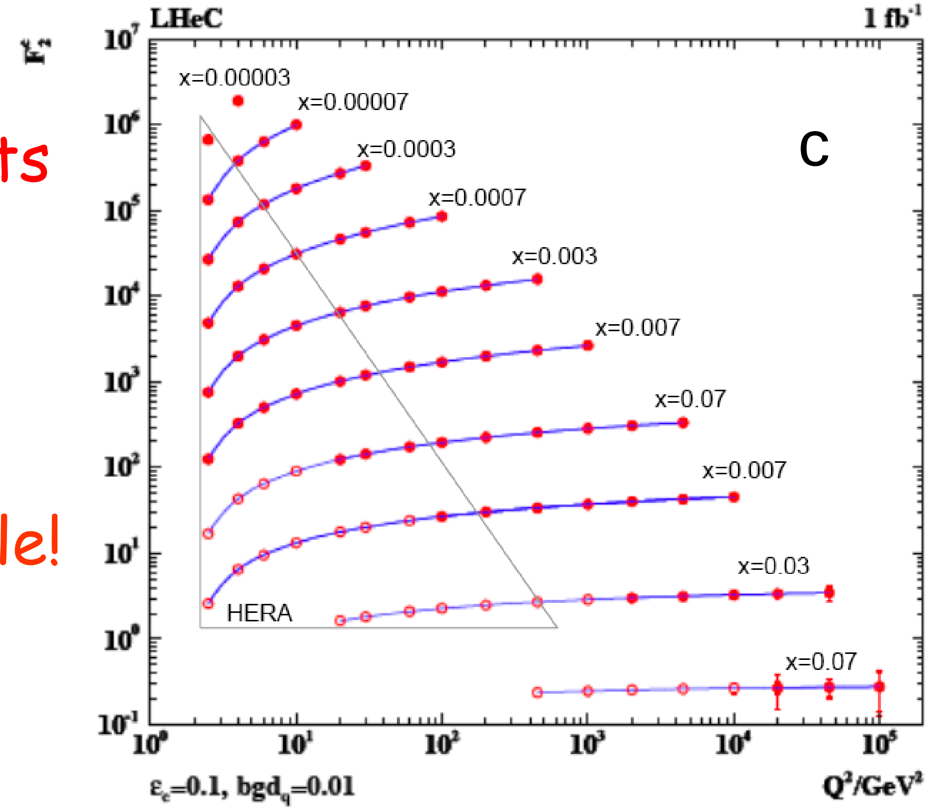
Heavy Quarks: HERA → LHC

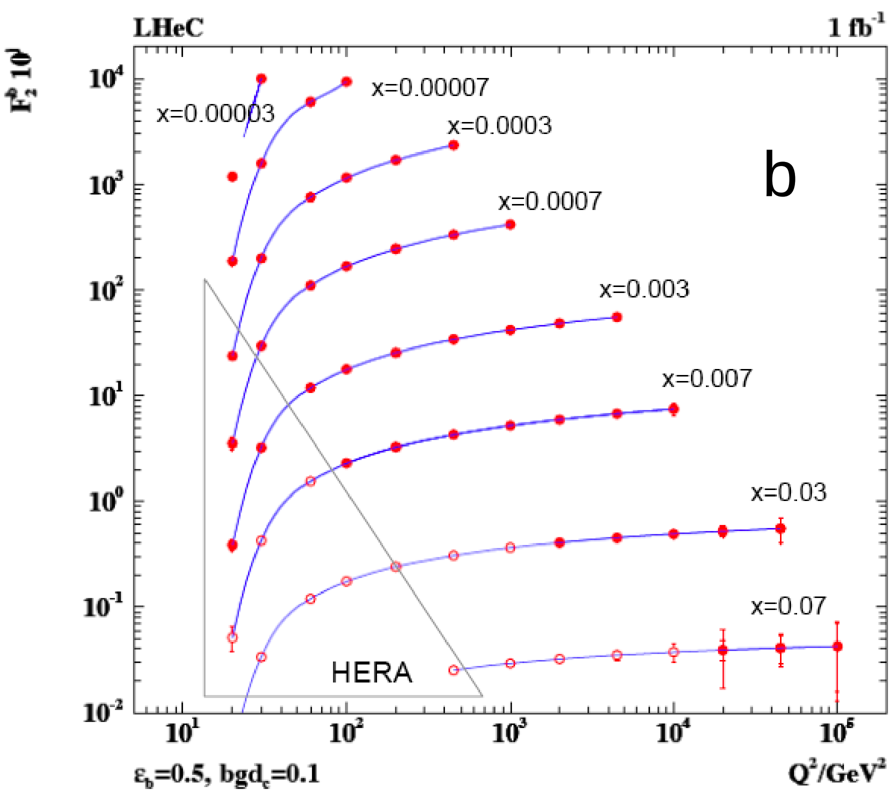
- HERA HF information limited by kinematic range and luminosity. (reasonable charm, pioneering beauty, almost no strange)
- Crucial for understanding LHC initial state for new processes (e.g. bbbar->H) and backgrounds.
- LHC predictions rely strongly on extrapolations and pQCD (e.g. CTEQ6: 7% effect on W,Z rates by varying HF treatment).



Heavy Quarks: LHeC

High precision c, b measurements
(modern Si trackers, beam spot 15 * 35 μm^2, increased rates at larger scales).
Systematics at 10% level
Even beauty is a low x observable!





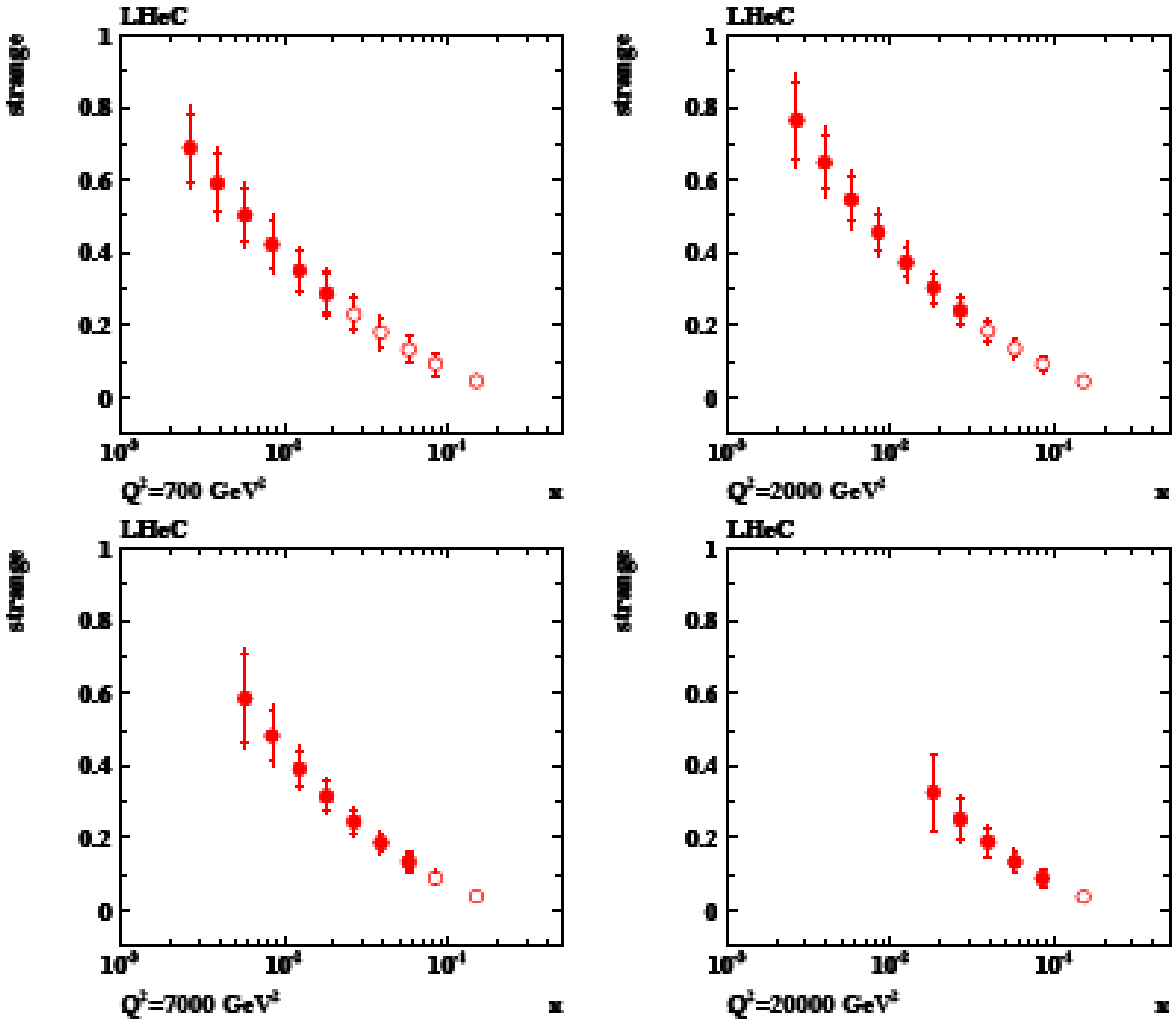
● LHeC 10° acceptance

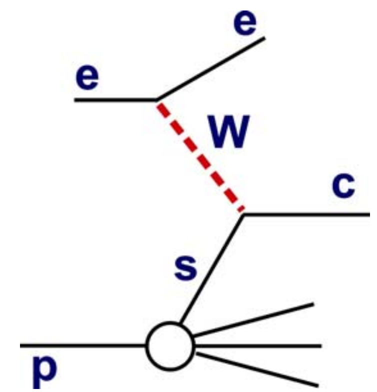
○ LHEC 1° acceptance

Assumes …
- 50% b, 10% charm efficiency
- 1% light → c mistag prob.
- 10% c → b mistag prob.
- 1 fb^{-1}

Strange quark distribution

- s and sbar from charm in charged current (Ws → c)





● LHeC 10° acceptance

○ LHEC 1° acceptance

Assumes …
- 10% c efficiency
- 1% uds → c mistag

- 1 fb^{-1}

The LHeC for Low x Investigations

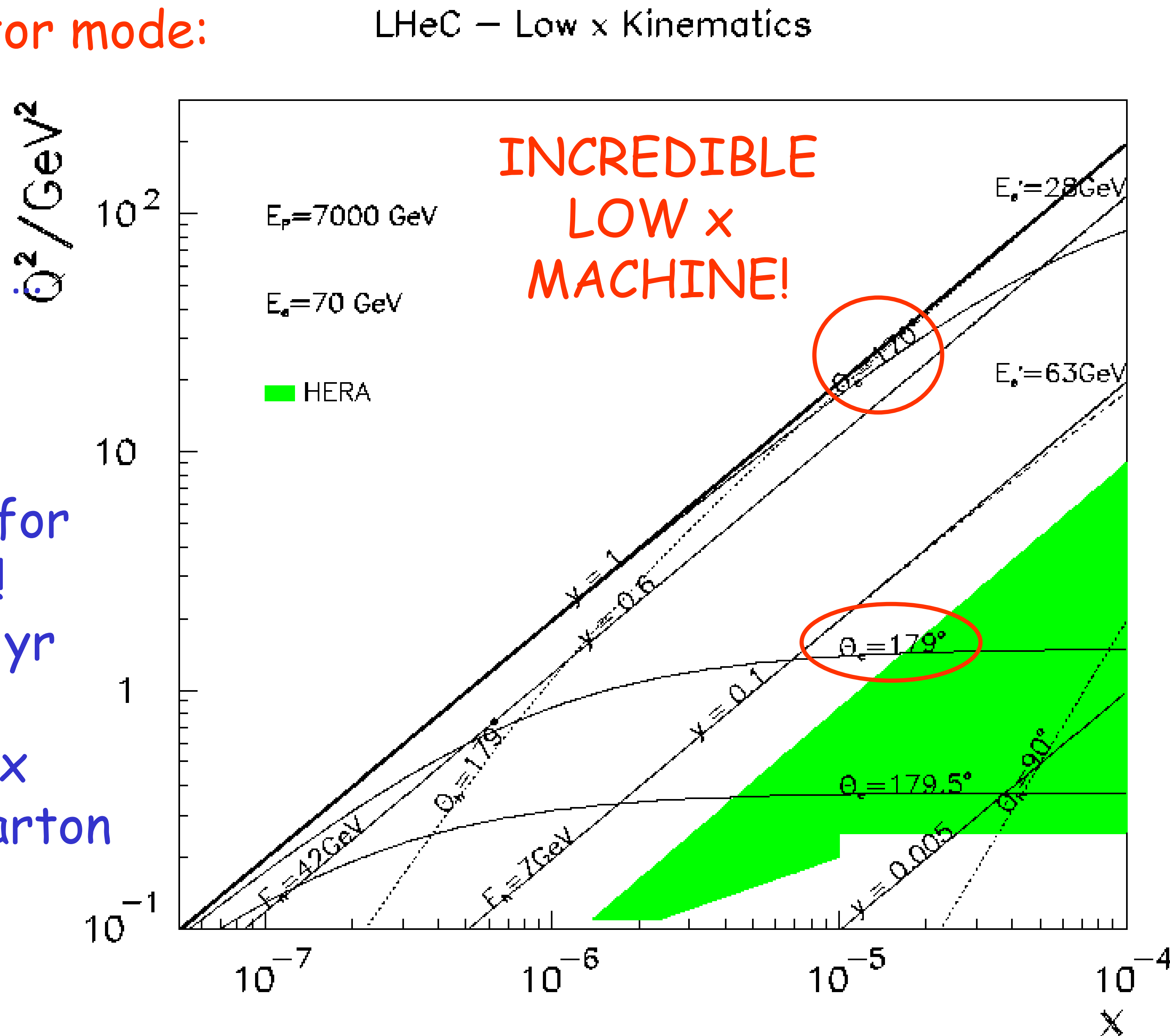
Second detector mode:

No focusing magnet for optimised lumi ..

Acceptance to 179° → access to Q^2=1 GeV2 for all x > 5 x 10^{-7} !

Lumi ~ 1 fb^{-1} / yr

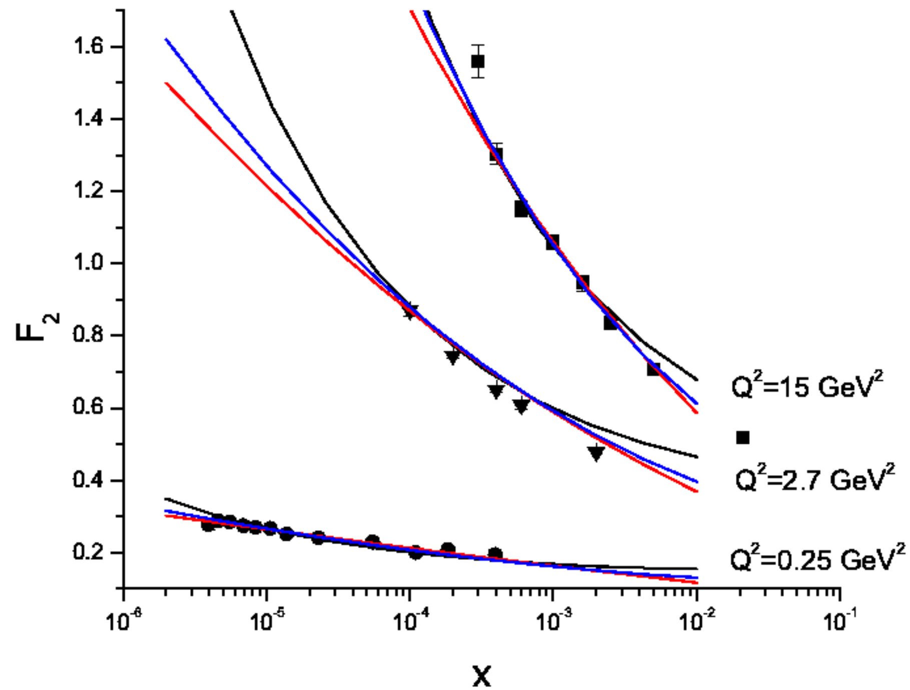
Definitive low x facility (e.g. parton saturation answers)



An Example Dipole Approach to HERA Data

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

Fit inclusive HERA data with dipole models containing varying assumptions for σ_{dipole}.



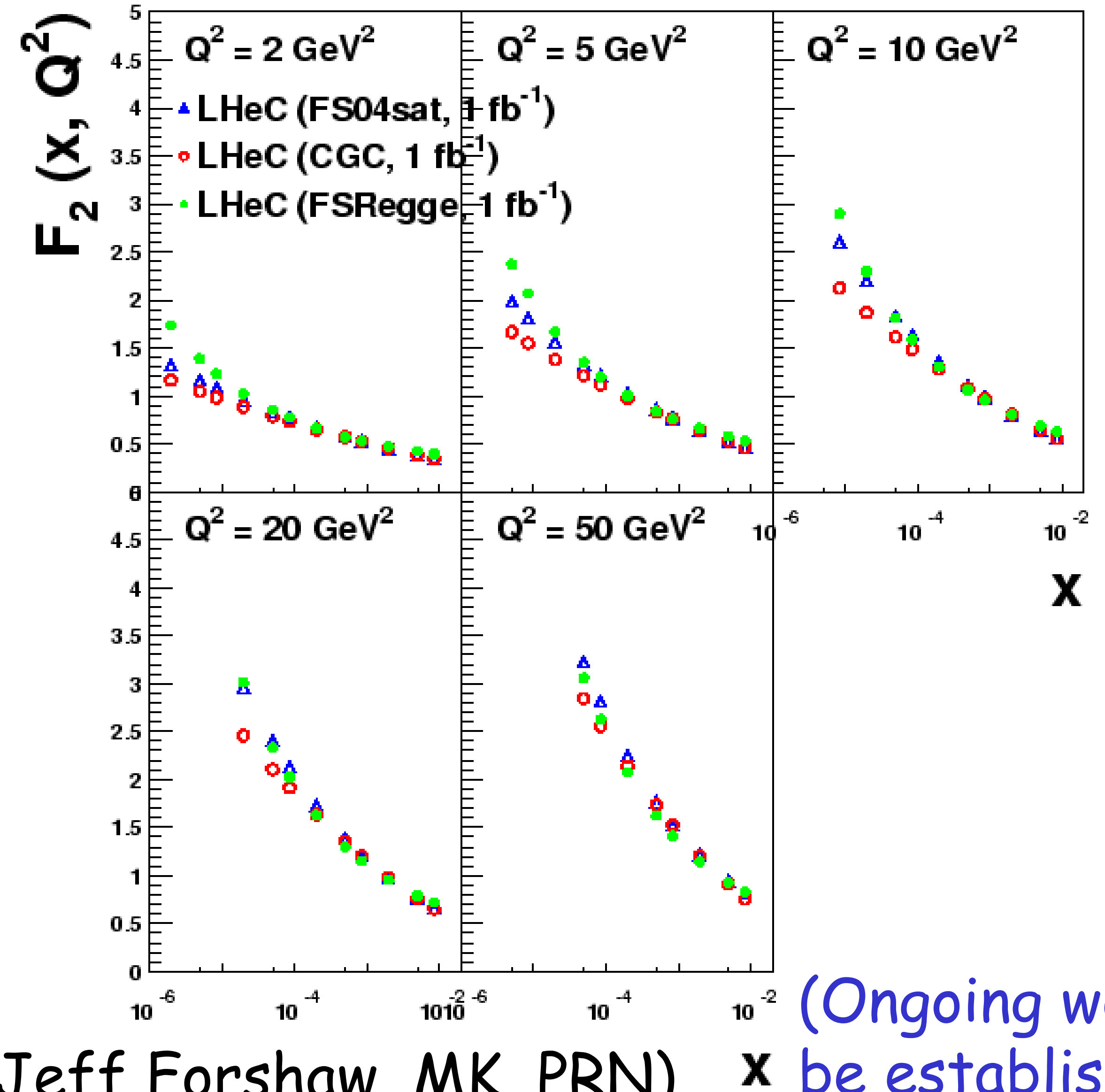
FS04 Regge (~FKS): 2 pomeron model, no saturation
FS04 Satn: Simple implementation of saturation
CGC: Colour Glass Condensate version of saturation

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

… partonic interpretation (e.g. $gg \rightarrow g$) not possible ☹

Example low x F_2 with LHeC Data

Statistical precision < 0.1%, systs 1-3%



(Jeff Forshaw, MK, PRN)

Precise data in LHeC region, x>~10^{-6} (detector → 1°)

- FS04, CGC models incorporating saturation suppressed at low x, Q^2 … possible to understand in terms of partons?

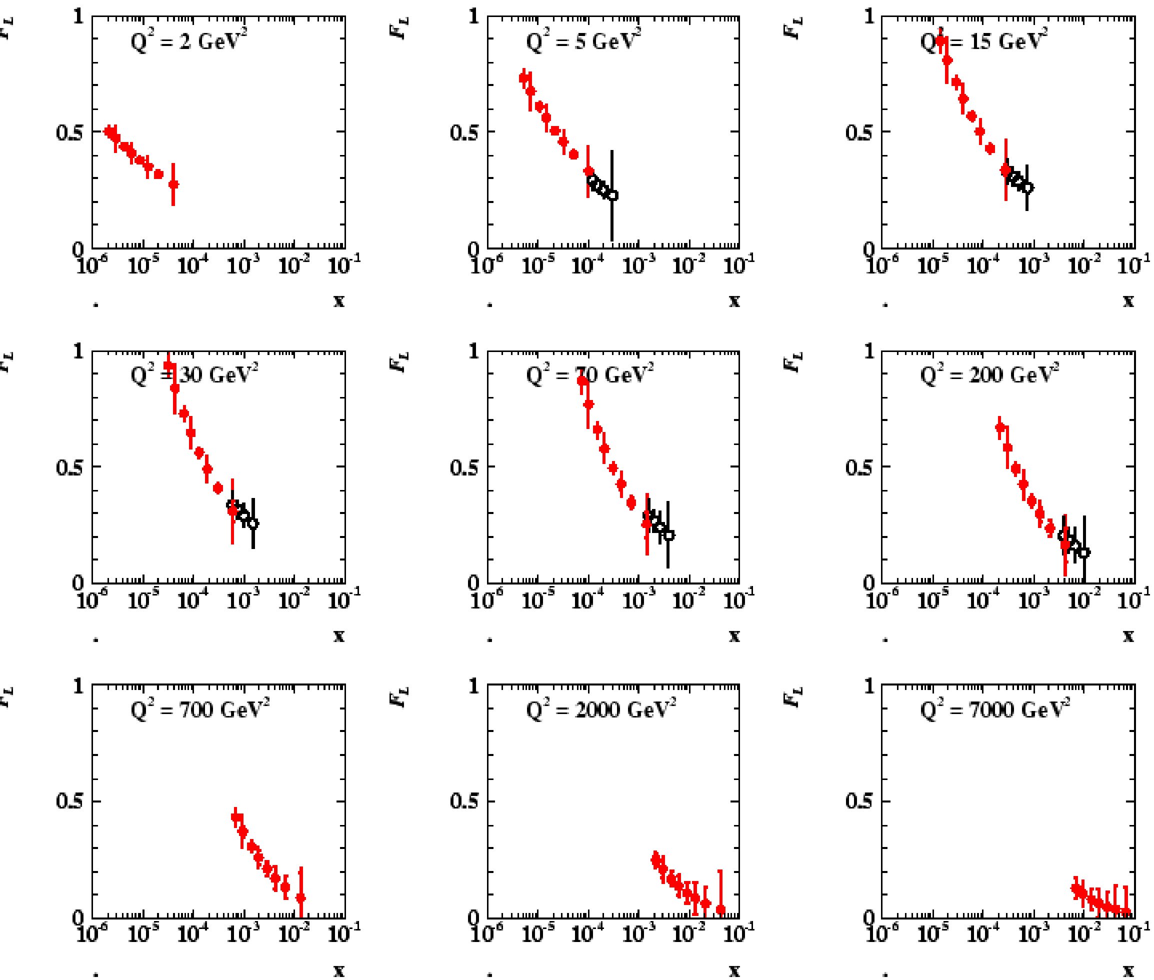
- Low Q^2 (θ > 170°) region essential!

(Ongoing work on how effect may be established unambiguously)

What about F_L?

● LHeC

○ H1 low Ep run (projected)



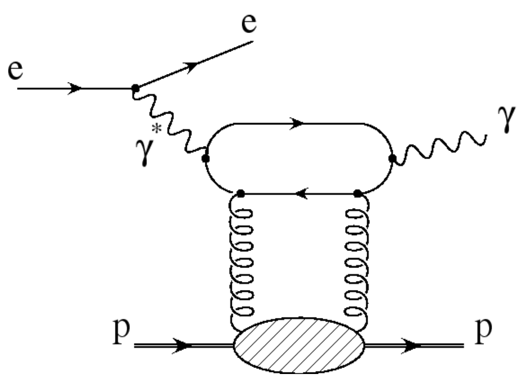
Vary proton beam energy as recently done at HERA …

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

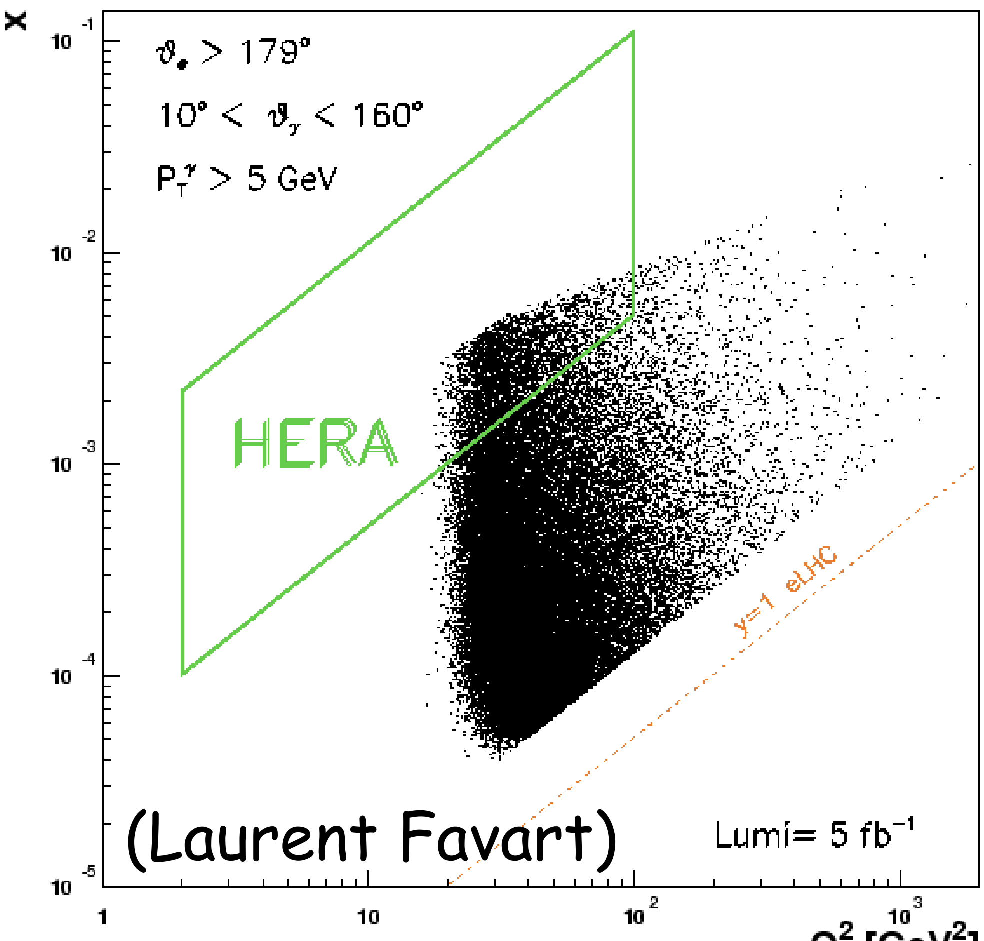
… precision typically 5%, stats limited for $Q^2 > 1000$ GeV^2
… a fantastic gluon constraint!

Typically lose 1-2 points at high x if E_p = 0.45 TeV not possible

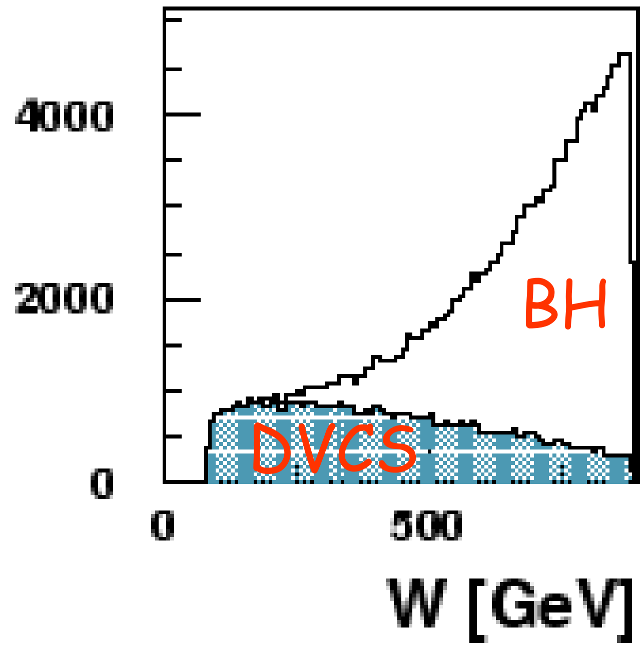
DVCS Measurement



... can be tackled as at HERA through inclusive selection of ep → epγ and statistical subtraction of Bethe-Heitler background

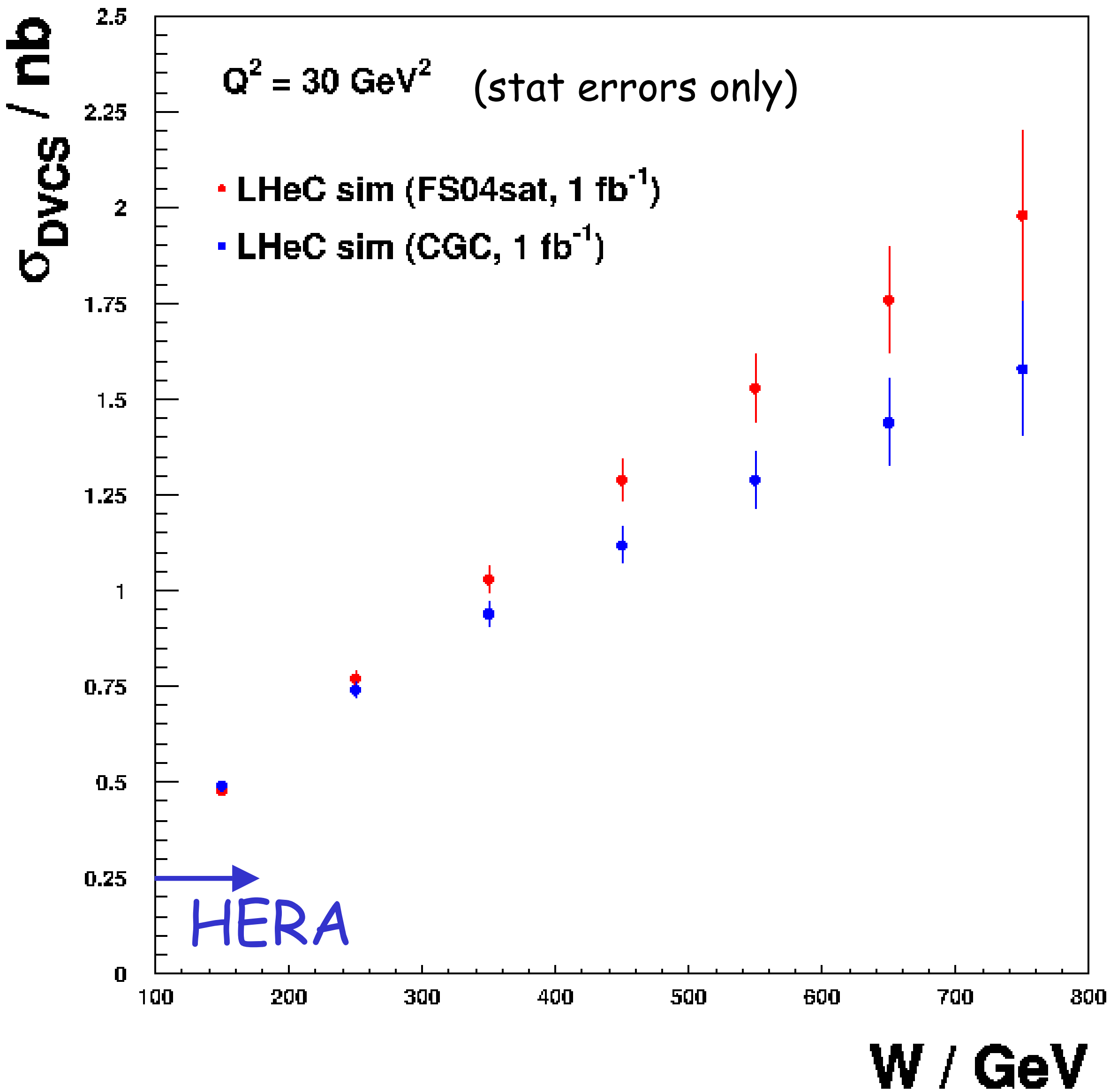


(Laurent Favart)



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

Example of DVCS at LHeC



(1^o acceptance)

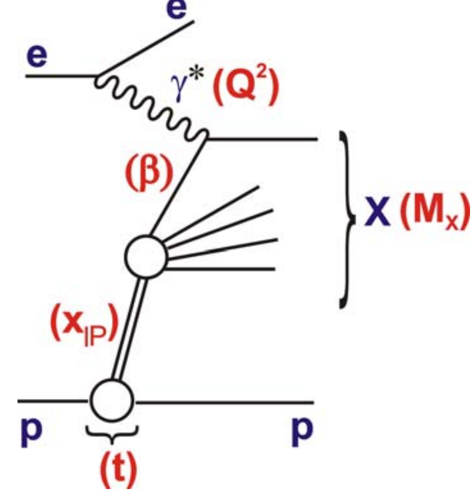
Statistical precision with $1fb^{-1}$ ~ 2-11%

With F2, FL, could help establish saturation and distinguish between different models which contain it!

VMs similar story

Diffractive DIS at HERA

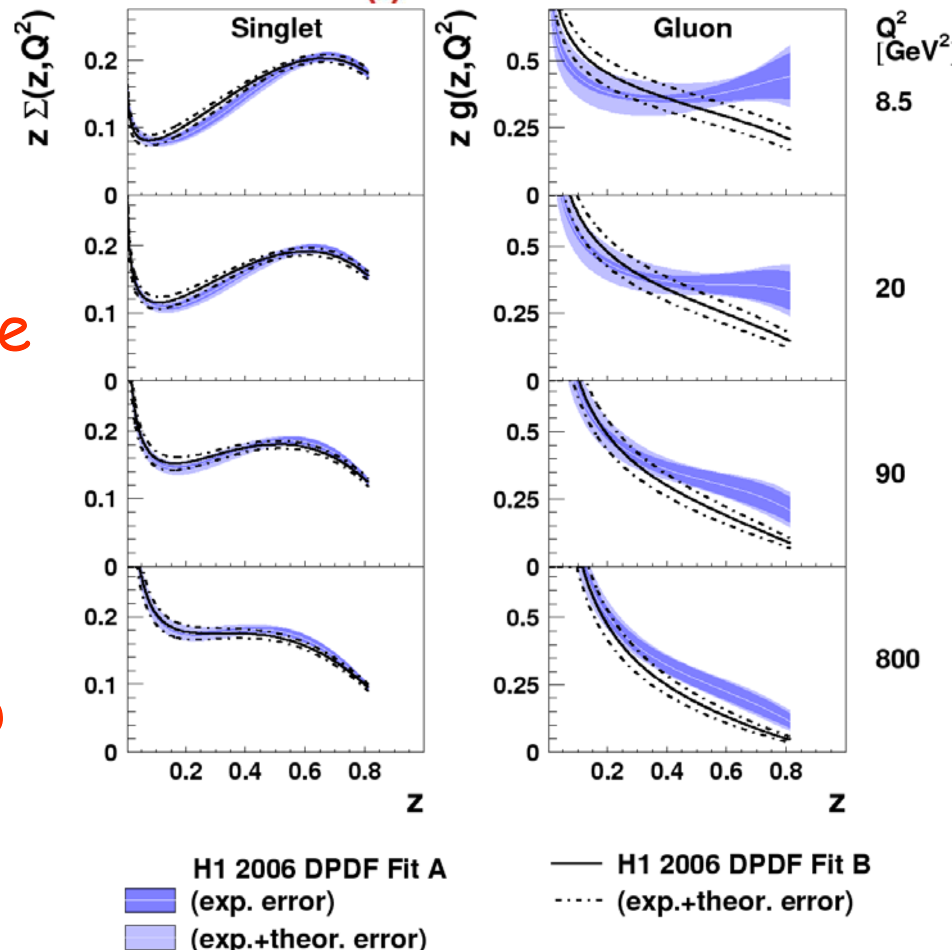
`Discovery' at HERA (~10% of low x events are of type ep -> eXp)



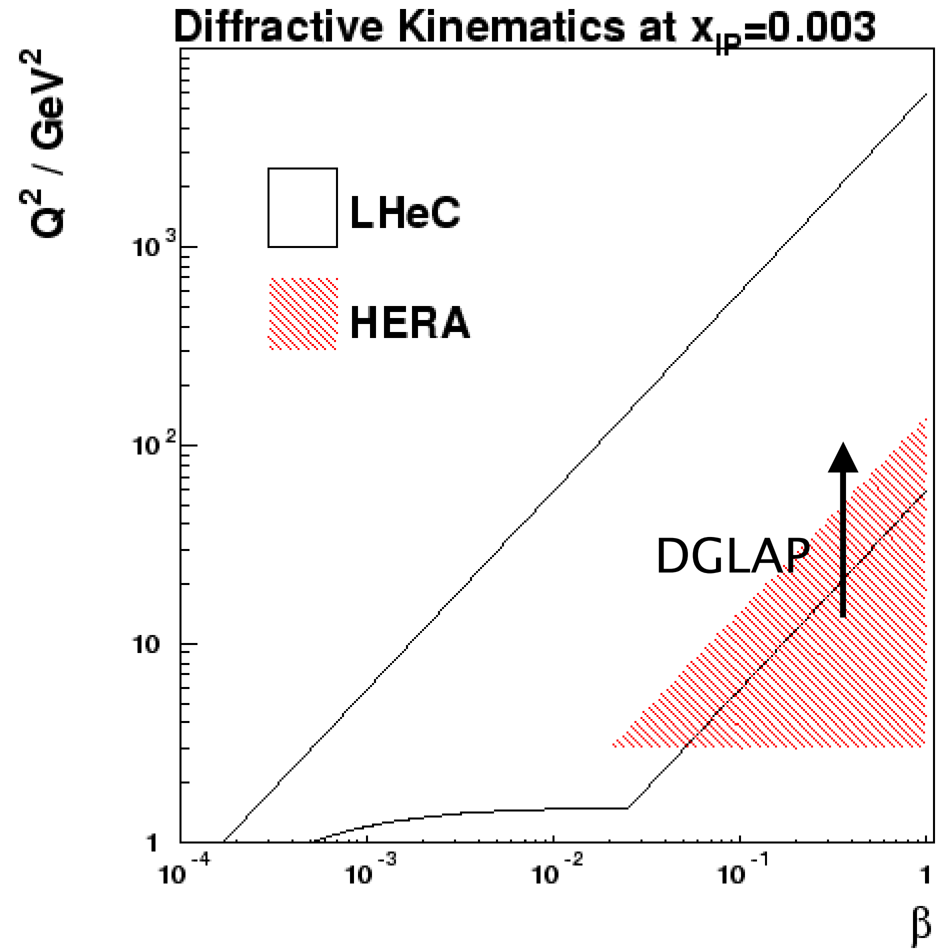
- Parton-level mechanism, relations to diffractive pp scattering, inclusive DIS, confinement still not settled.

- QCD Factorisation: Diffractive parton densities (DPDFs) universal to diffractive DIS (apply to both HERA and LHeC)

… can also be used to predict pp with additional `gap survival' factors



LHeC Diffractive Kinematics

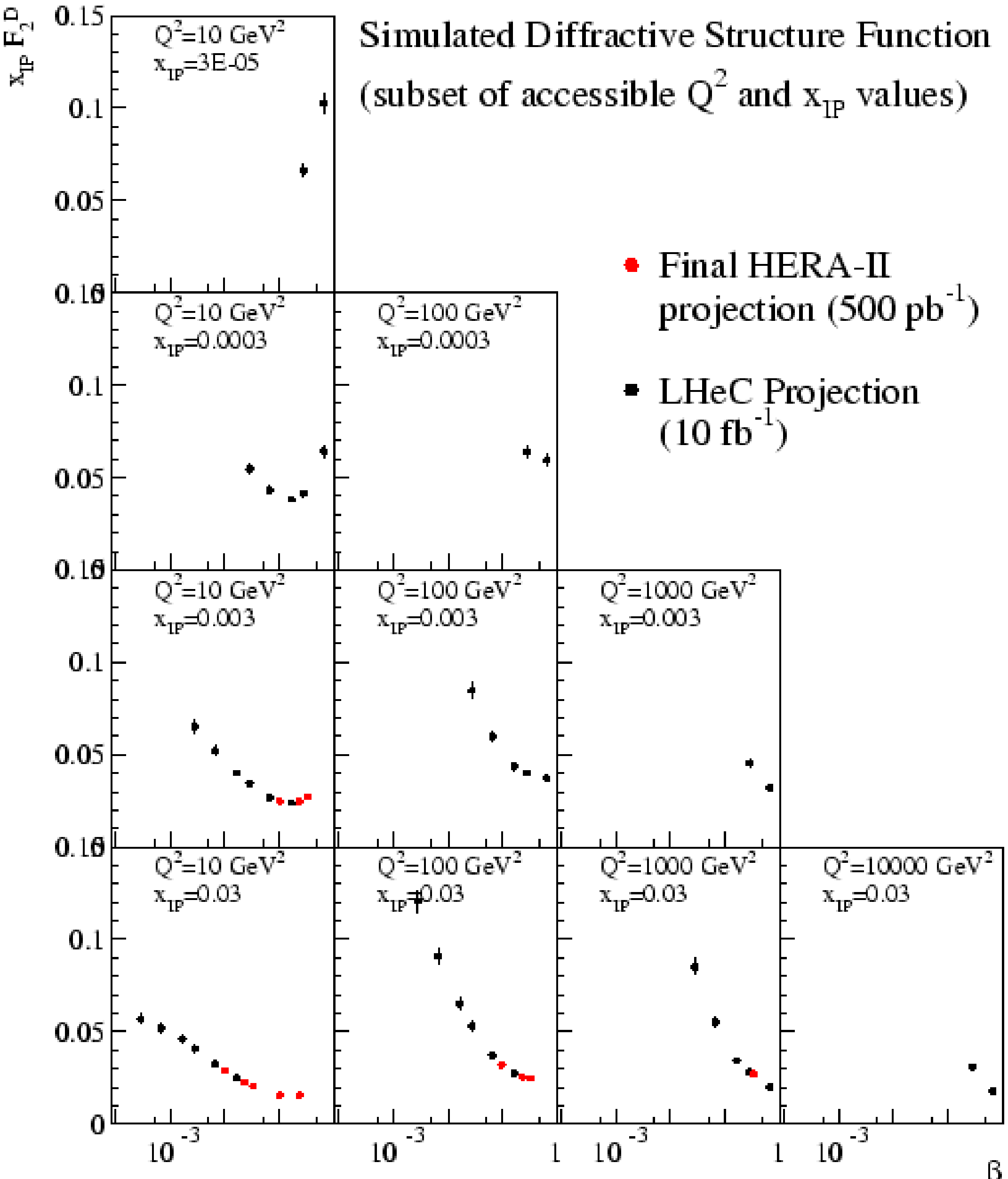


• Tests of factorisation and evolution dynamics: DPDFs extracted at HERA predict LHeC cross section at moderate /large β, higher Q^2 using DGLAP.

• New dynamics: LHeC opens new low β region – parton saturation, BFKL etc showing up first in diffraction?

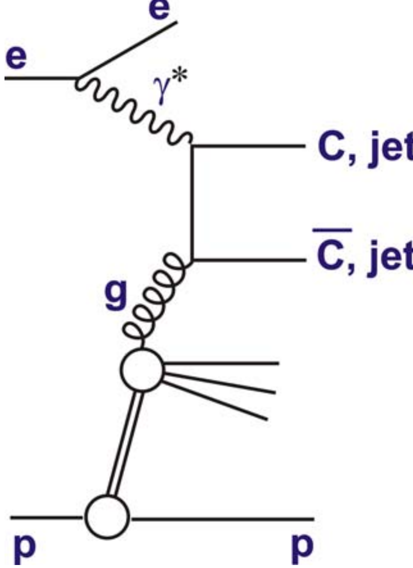
•Large Diff. Masses: Z, W, b production, studies of new 1^{--} states

LHeC Simulation

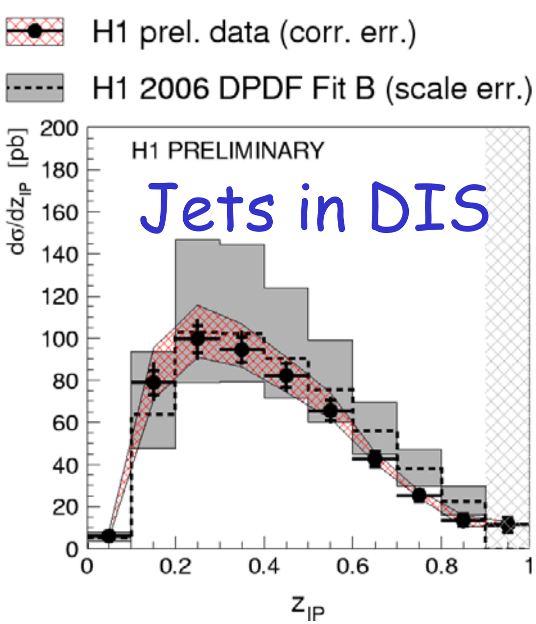


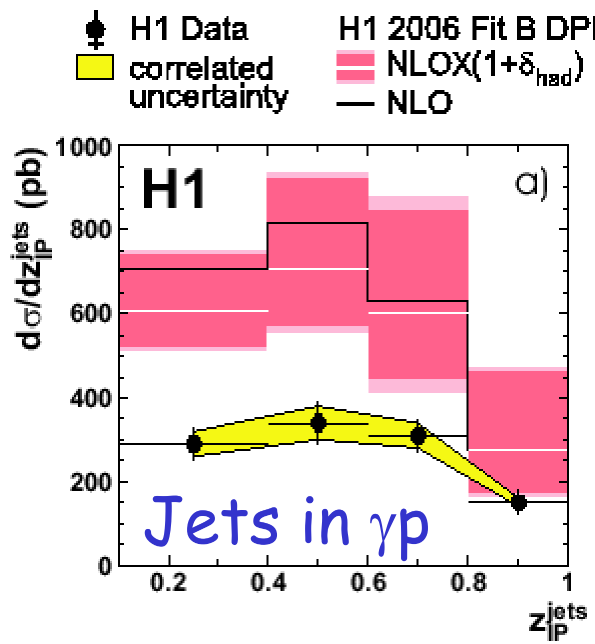
- Statistical precision ~1%, systs 5-10% depending strongly on forward detector design
- Big extension to lower x_{IP} … cleaner separation of diffractive exchange
- Higher Q^2 at fixed β & x_{IP} → CC (and Z in NC) → DPDF flavour decompositions
- Lower β at fixed Q^2, x_{IP}

Final States in Diffraction

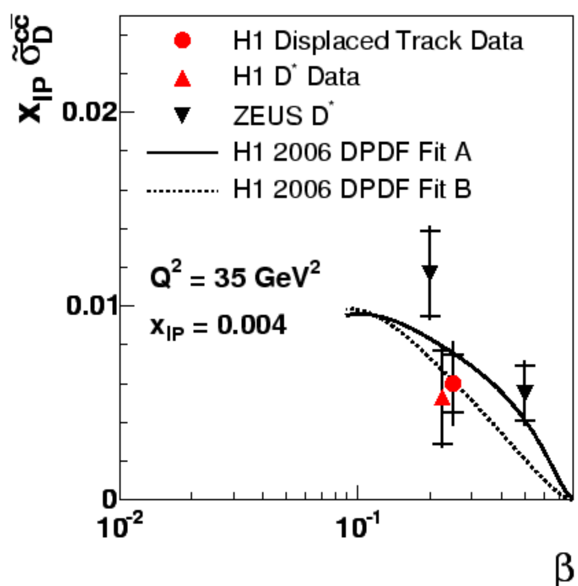


- Factorisation tests done at HERA with gluon initiated jet / charm processes… BUT …
- Kinematically restricted to high β region where F_2^D is least sensitive to the gluon!
- Kinematically restricted to low $p_T < M_X/2$ where scale uncertainties are large.
- γp surprises → understanding gap survival?… Diff H @ LHC?





Charm in DIS



Final States in Diffraction at the LHeC

- At LHeC, diffractive masses M_x up to hundreds of GeV can be produced with low x_{IP}

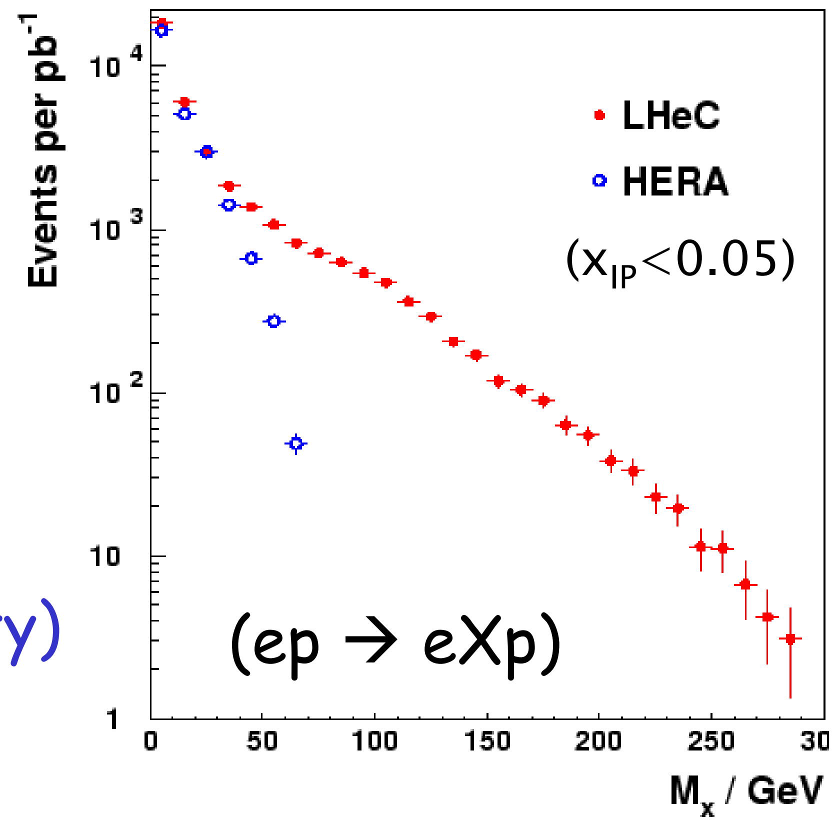
- Low β, low x_{IP} region for jets and charm accessible

- Final state jets etc at higher pt … much more precise factorisation tests and DPDF studies (scale uncty)

- New diffractive channels … beauty, W / Z bosons

- Unfold quantum numbers / precisely measure exclusively produced new / exotic 1^- states

(RAPGAP simulation)



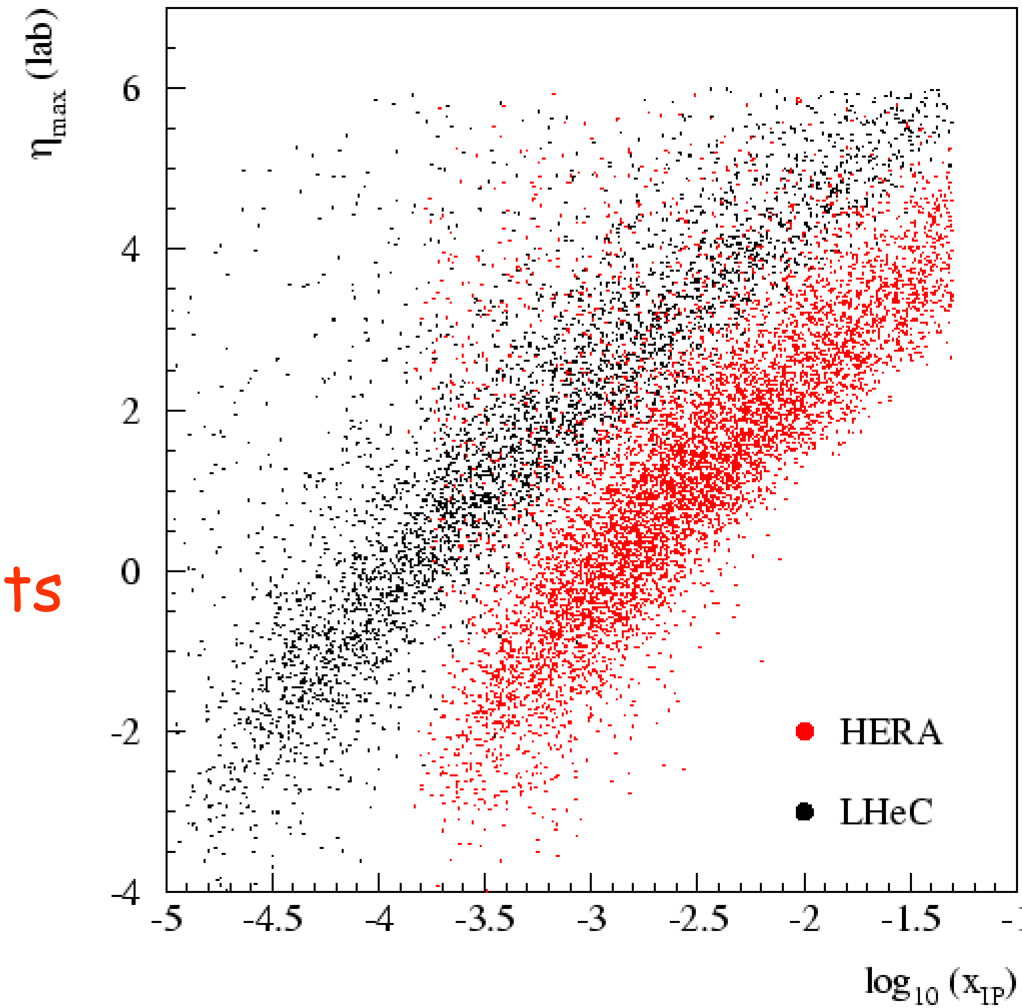
Diffractive Detector Considerations

- Accessing x_{IP} = 0.01 with rapidity gap method requires η_{max} cut around 5 …forward instrumentation essential!

- Roman pots, FNC should clearly be an integral part

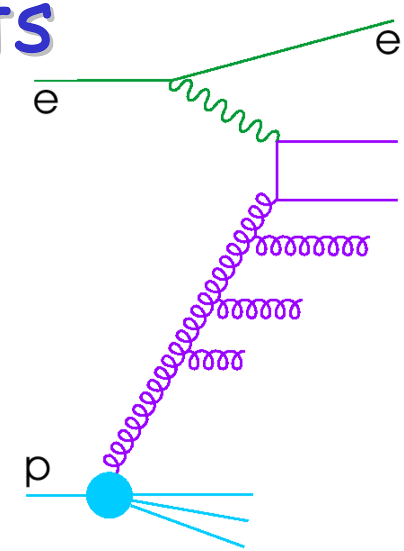
- Not new at LHC! Roman pots already integrated into CDF, Atlas via Totem, FP420, FP220)

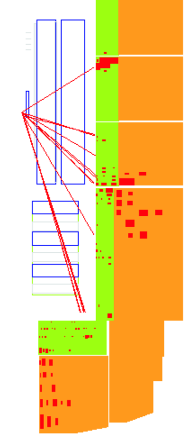
η_{max} and LRG selection …



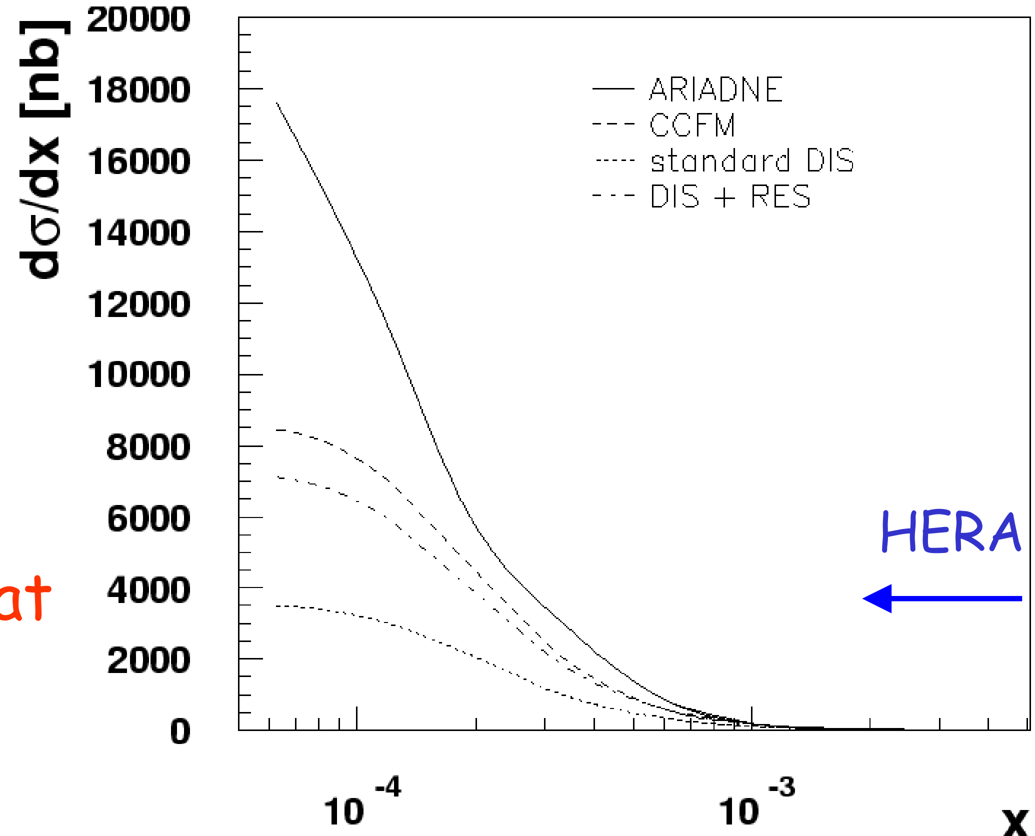
Forward Jets

Long HERA program to understand parton cascade emissions by direct observation of jet pattern in the forward direction. … DGLAP v BFKL v CCFM v resolved γ^*…



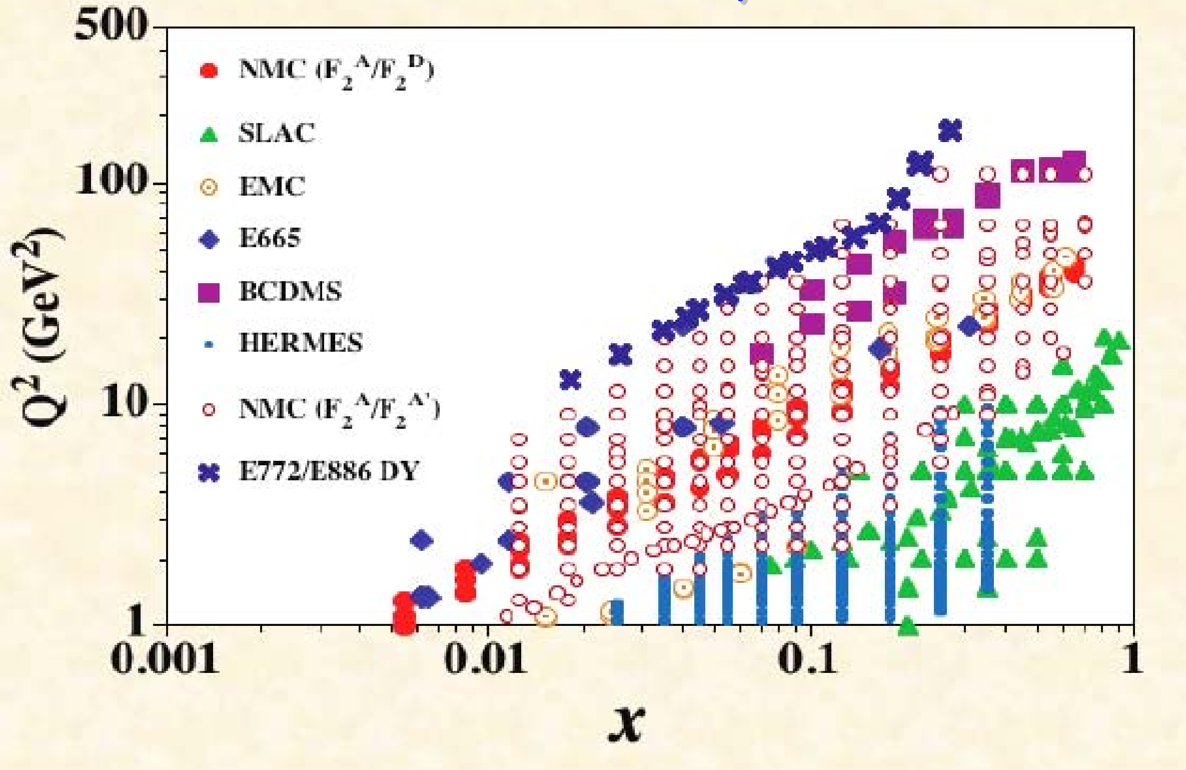


Conclusions limited by kinematic restriction to high x (>~ 2.10^{-3}) and detector acceptance.



At LHeC … more emissions due to longer ladder & more instrumentation → measure at lower x where predictions really diverge.

With AA at LHC, LHeC is also an eA Collider



- Very limited x and Q^2 range so far (unknown for x <~ 10^{-2}, gluon poorly constrained)

- LHeC extends kinematic range by 4 orders of magnitude

- With wide range of x, Q^2, A, opportunity to extract and understand nuclear parton densities in detail

- e.g. enhanced sensitivity to low x gluon saturation

- Symbiosis with ALICE, RHIC … disentangling quark gluon plasma from shadowing or parton saturation effects

Organisation and Possible Timeline

Scientific Advisory Committee (A. Caldwell, J. Dainton, J. Feltesse, A.Skrinsky R. Horisberger, R. Milner, A. Levy, G. Altarelli, S. Brodsky, J. Ellis, L. Lipatov, F. Wilczek, S. Chattopadhyay, R. Garoby, S. Myers, F. Willeke, J. Engelen, R. Heuer, YK. Kim, P. Bond,)

Steering Group (O. Bruning, S. Forte, M. Klein, P. Newman, E. Perez, D. Pitzl, W. Smith, B. Surrow, K. Tokushuku, U. Wiedemann) … final list to be confirmed … meeting today to plan workshop!

Nov 2007:	Presentation to plenary ECFA
2008:	First workshop
2009:	Second workshop → Conceptual Design Report
2011:	Technical Design Report?

Much more to be done to fully evaluate physics potential, determine optimum running scenario and design detector

… your involvement very welcome (in parallel with HERA, LHC)!

Summary

LHC is a totally new world of energy and luminosity! LHeC proposal aims to exploit this for lepton-hadron scattering

New discoveries expected at LHC … interpretation may require ep, eA in comparable energy range

LHeC naturally extends low x and high Q^2 frontiers of ep physics … new precision in our understanding of QCD

First conceptual design exists … no show-stopper so far
some encouraging first physics studies / idle speculations

… time for a workshop!

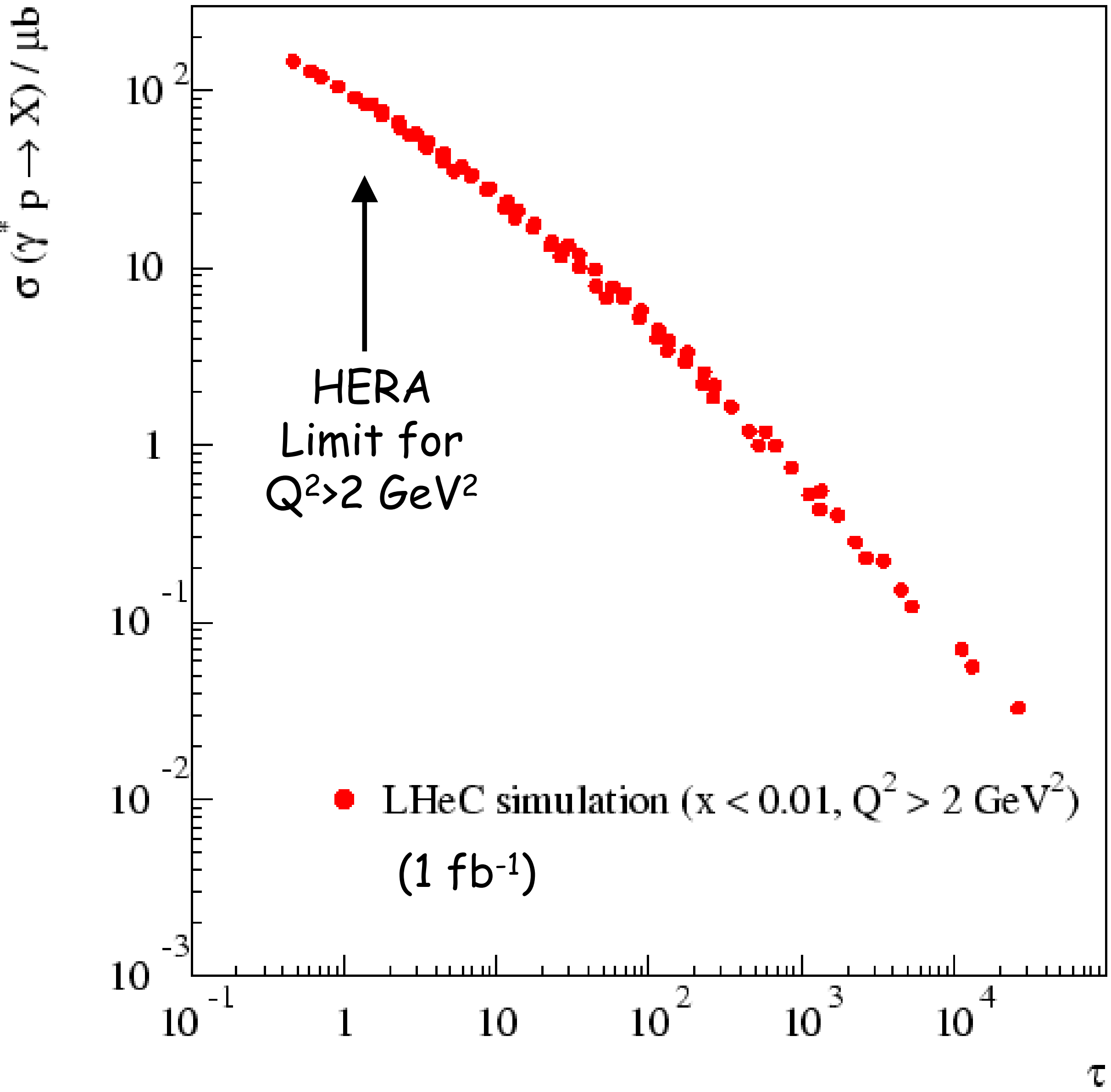
[Thanks in particular to J Dainton, L Favart, J Forshaw, M Klein, A Mehta, E Perez, F Willeke]

Overview of LHeC Parameters

Table 3: *Main Parameters of the Lepton-Proton Collider*

Property	Unit	Leptons	Protons
Beam Energies	GeV	70	7000
Total Beam Current	mA	74	544
Number of Particles / bunch	10^{10}	1.04	17.0
Horizontal Beam Emittance	nm	7.6	0.501
Vertical Beam Emittance	nm	3.8	0.501
Horizontal β-functions at IP	cm	12.7	180
Vertical β-function at the IP	cm	7.1	50
Energy loss per turn	GeV	0.707	$6 \cdot 10^{-6}$
Radiated Energy	MW	50	0.003
Bunch frequency / bunch spacing	MHz / ns	40 / 25	
Center of Mass Energy	GeV	1400	
Luminosity	$10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.1	

Geometric Scaling at the LHeC



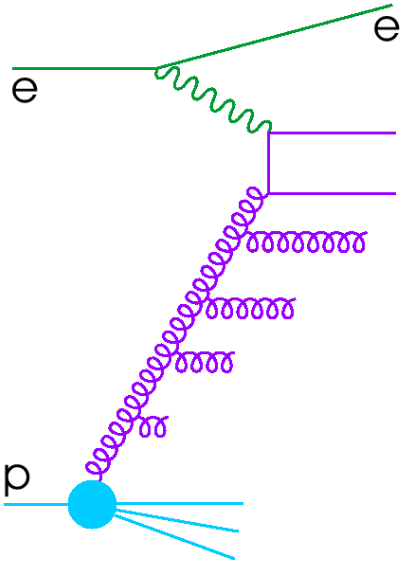
LHeC reaches $\tau \sim 0.15$ for Q^2=1 GeV^2 and $\tau \sim 0.4$ for Q^2=2 GeV^2

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?

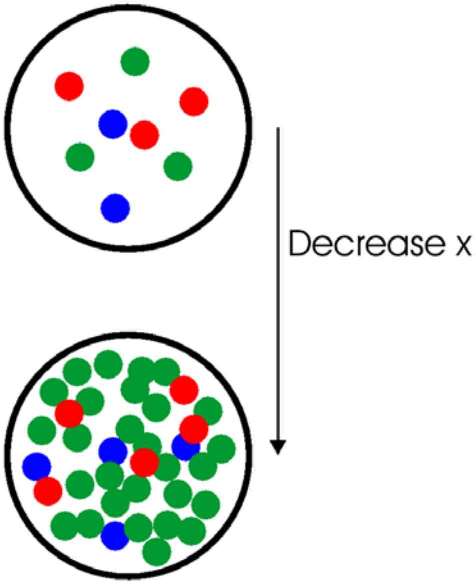
Current Status of Low x Physics



RHIC, Tevatron and HERA have taught us a lot,
… but many questions are not fully answered…

• Are non-DGLAP parton evolution dynamics visible in the initial state parton cascade?

• How and where is the parton growth with decreasing x tamed (unitarity) … barely separated from confinement region?

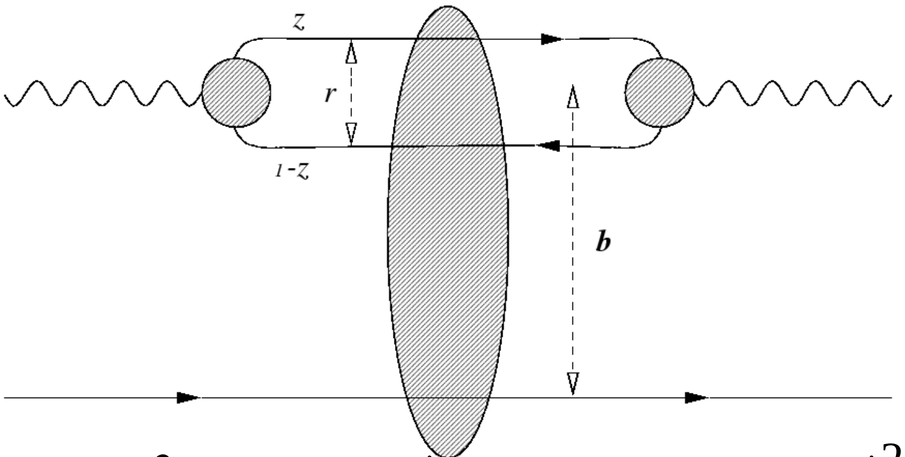


• Large (~ constant?) fraction of diffraction?

Problem is that low x kinematically correlated to low Q^2, which brings problems with partonic interpretation

Reminder : Dipole models

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



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

• 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