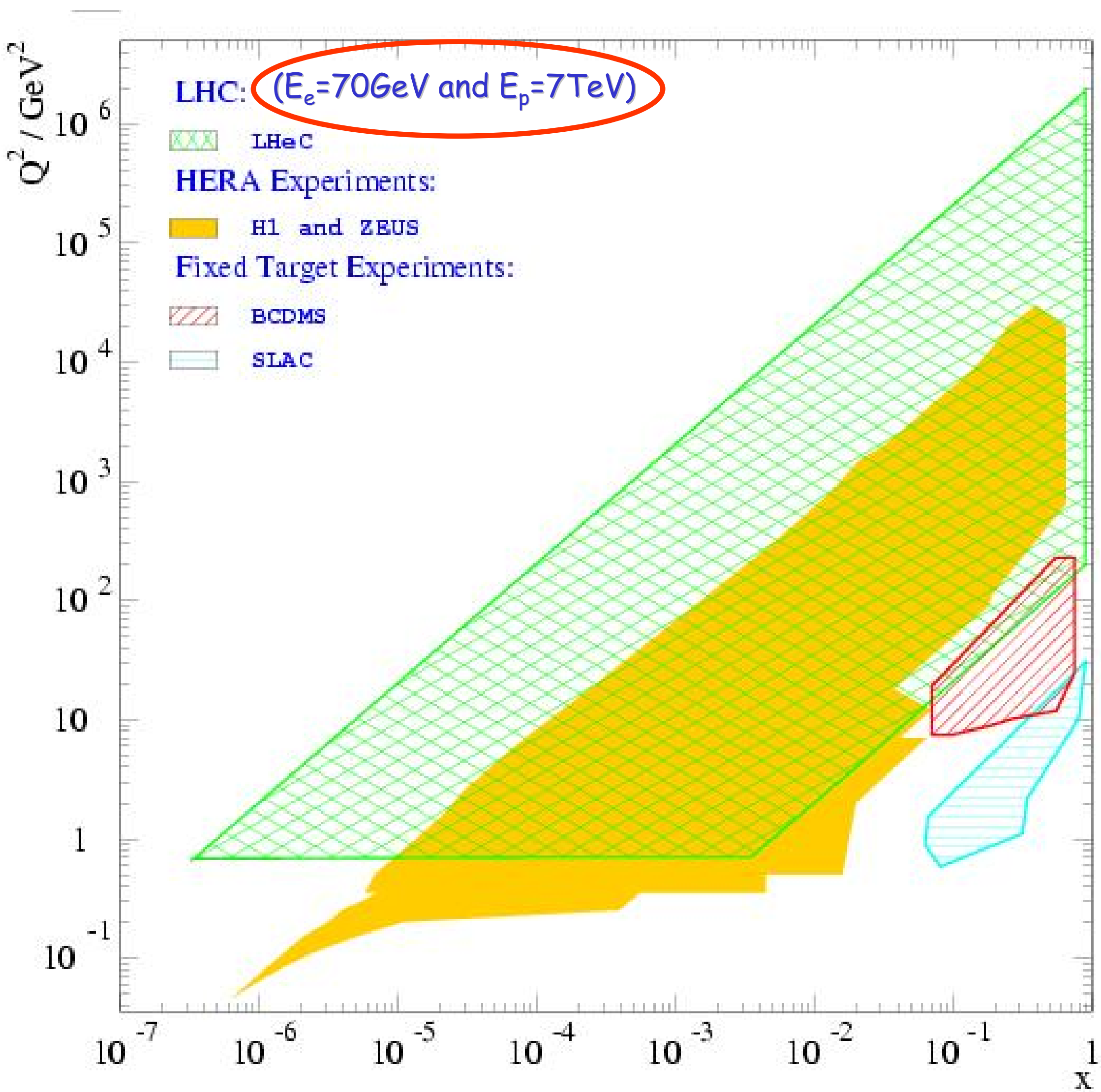
Deep-Inelastic Scattering at the TeV Energy Scale and the LHeC

P Newman,
University of Birmingham

Manchester Meeting on Forward Physics at The LHC

9 December 2007



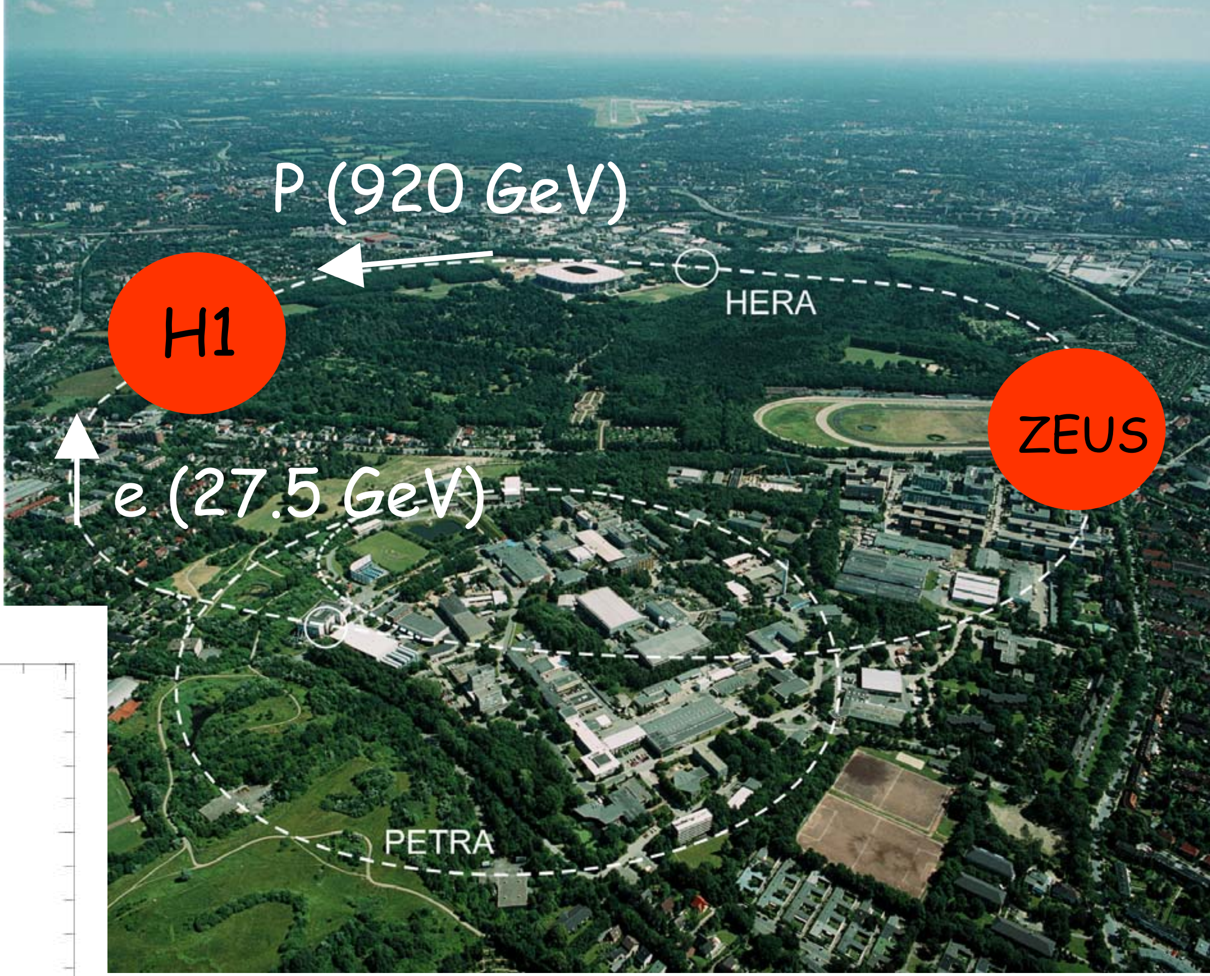
- JINST 1 (2006) P10001 [hep-ex/0603016]
- Recent info (eg ECFA, DIS07) from http://www.lhec.org.uk

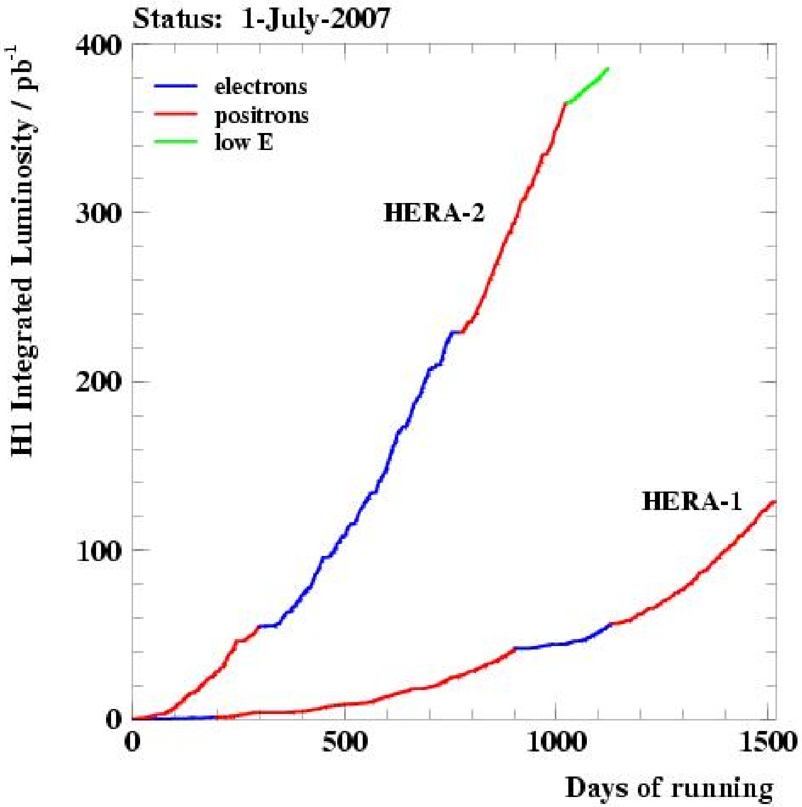
Contents

- DIS at the end of HERA
- The Case for TeV Scale DIS
- Some first Physics case studies (emphasis on fwd / low x)
- LHeC Design Possibilities
- First Detector Considerations
- Organisation and workshop plans

HERA (1992-2007)

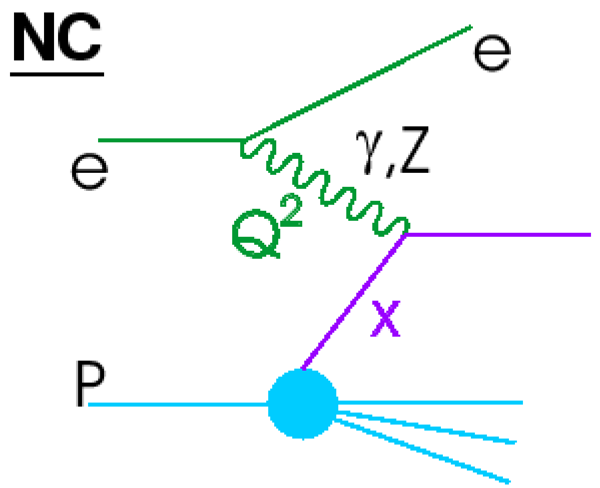
• The only ep collider ever built (equivalent energy to 50 TeV fixed target)

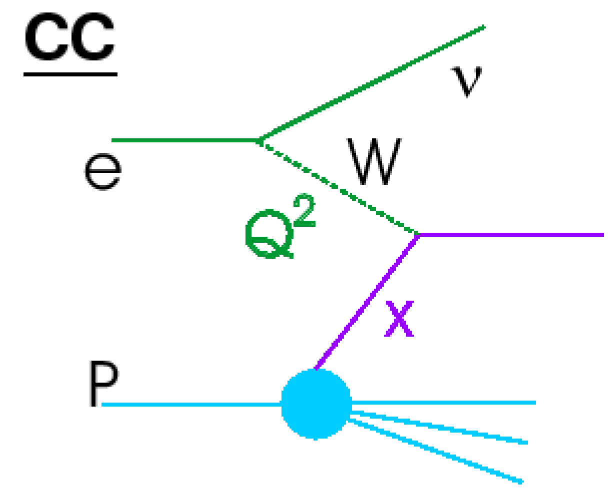


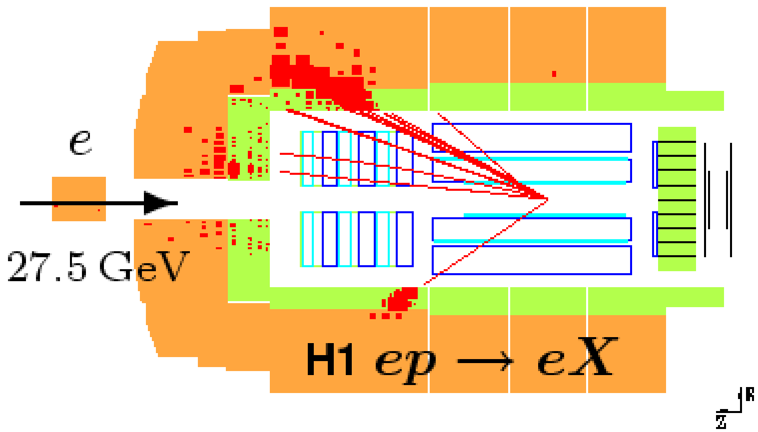


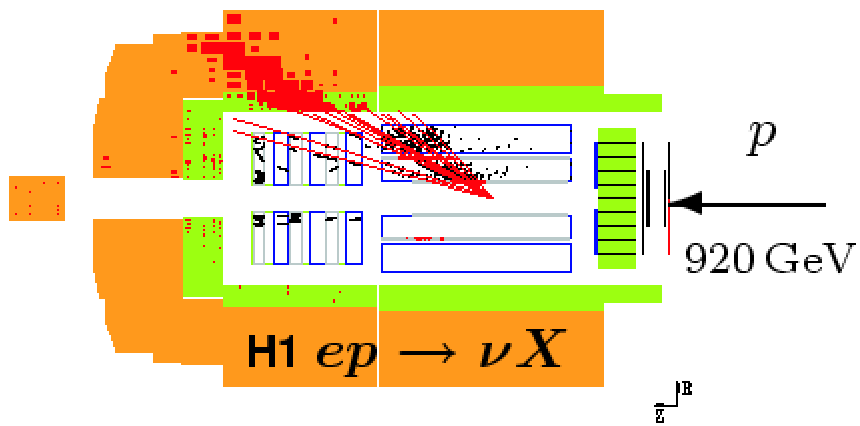
•… "the world's most powerful microscope" using virtual boson to resolve p structure

DIS: Classic Pictures of eq Scattering



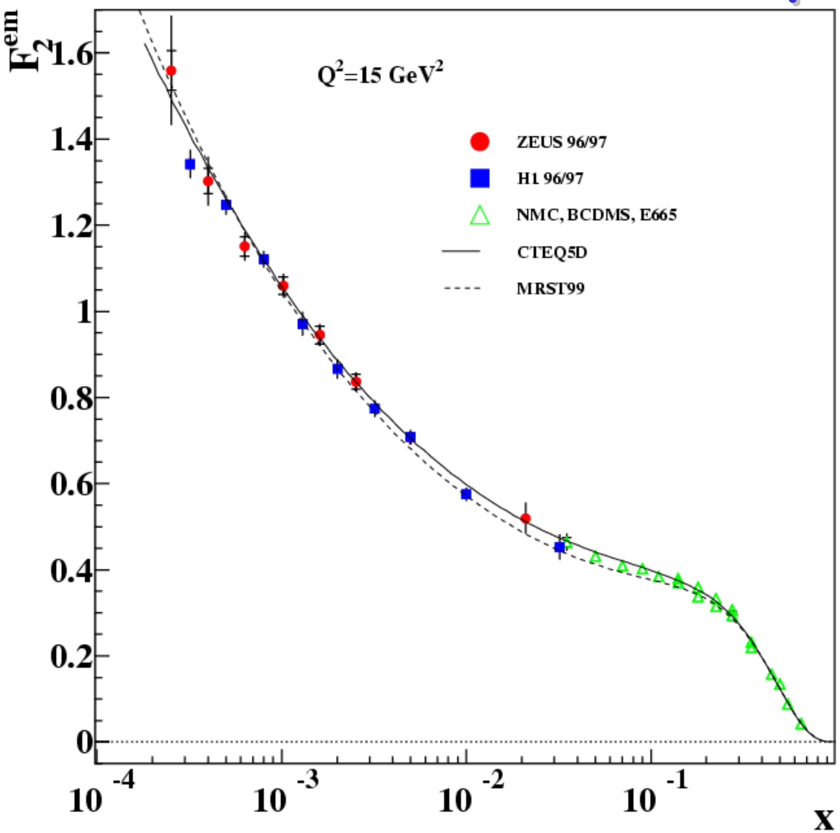


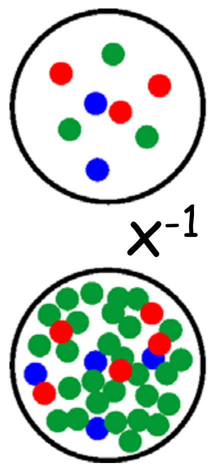


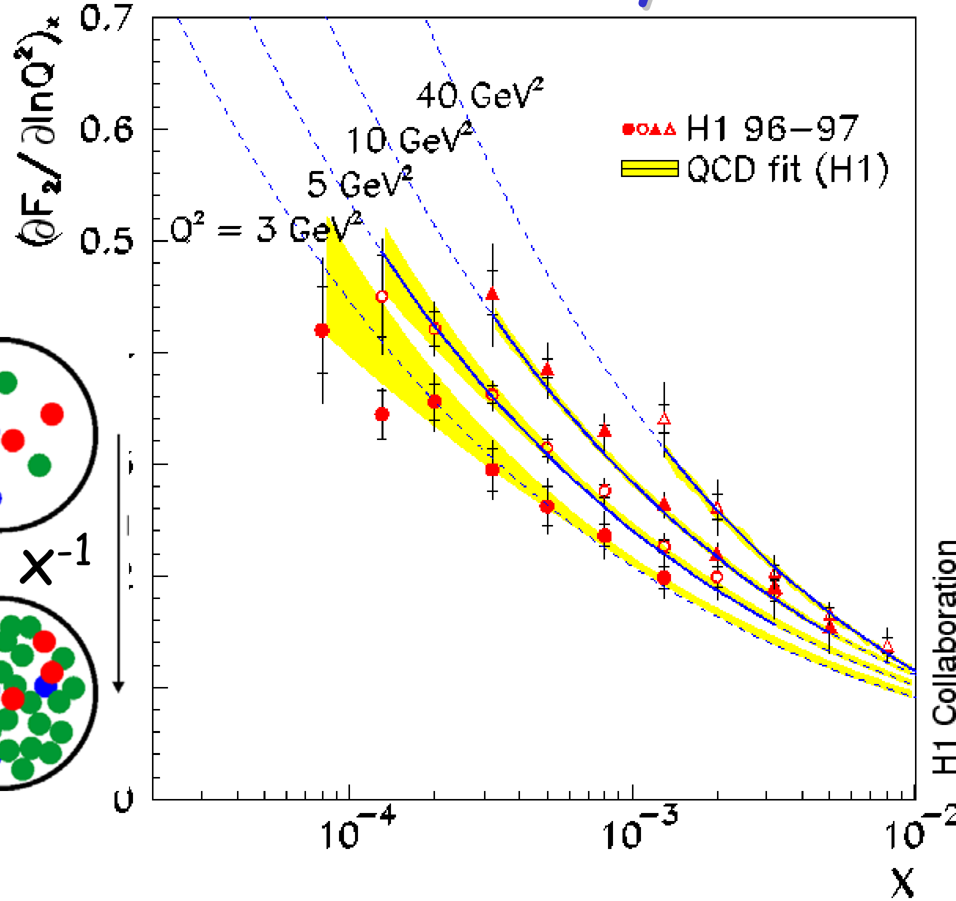


- Precision measurements at low Q^2 dominated by γ^* exchange.
- Lumi limitations at highest Q^2 (searches, high x partons, W, Z exchange → parton flavour decomposition)

The Birth of Experimental Low x Physics

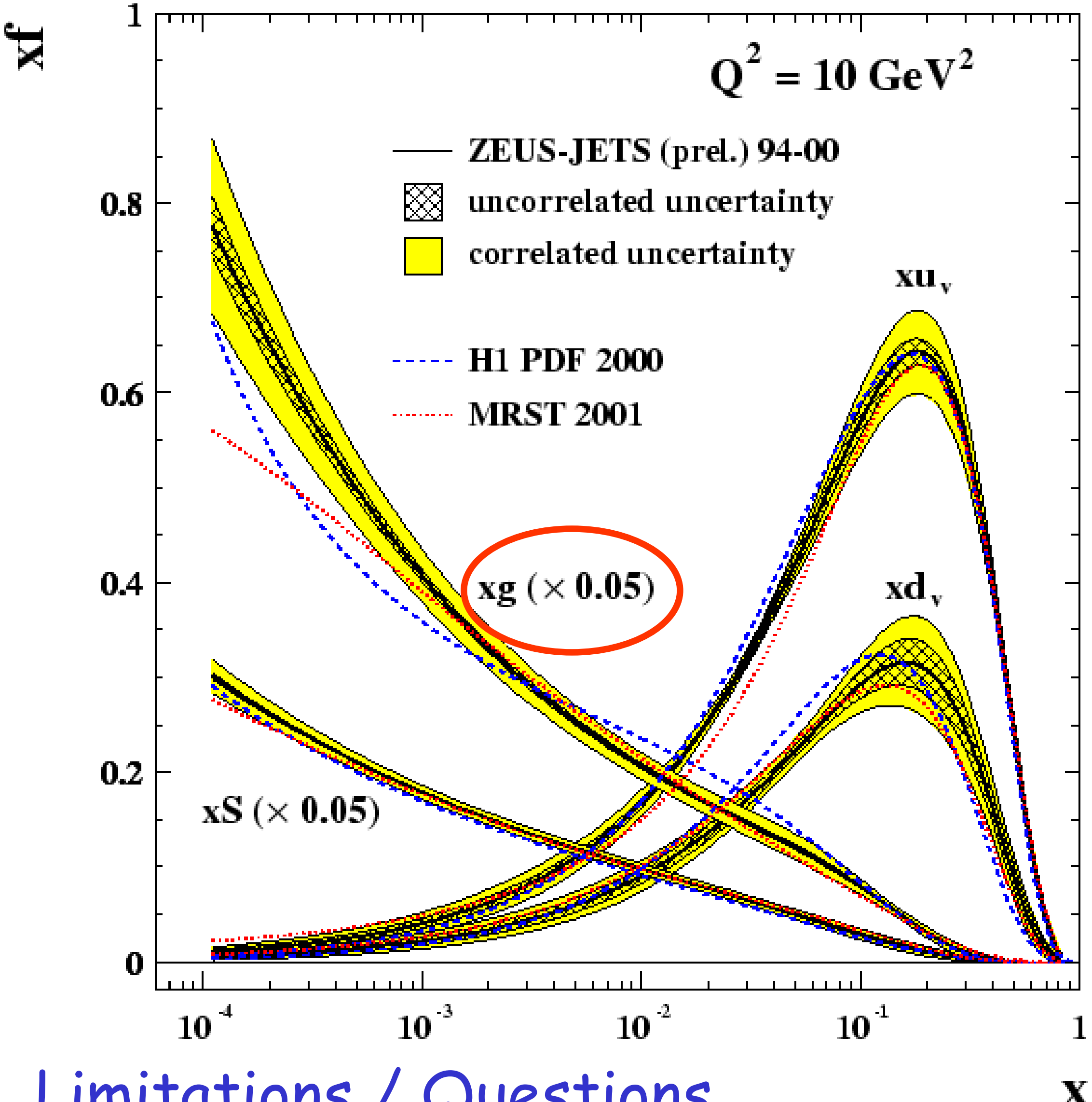






- Biggest HERA discovery: strong increase of quark density (F_2) and gluon density ($d F_2 / d \ln Q^2$) with decreasing x.
- Low x, `large' Q^2 region is a new high density, low coupling limit of QCD …
- Understanding limited by low x /low Q^2 kinematic correlation

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 HERA data alone … result well matched to LHC rapidity plateau
- Some improvement still expected (final H1 + ZEUS)

Limitations / Questions …

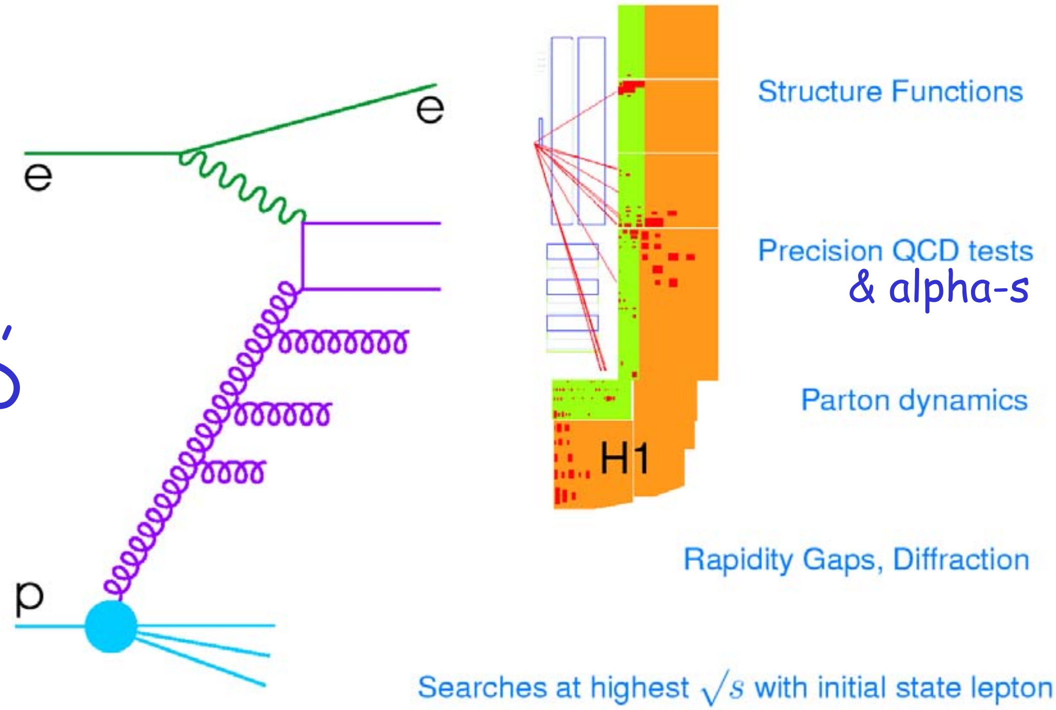
? High x and low x uncertainties? …

? How is enormous gluon density at low x tamed (gg→g?)

? Can we trust the (NLO DGLAP) theory at all x?

Beyond Inclusive Measurements

- Hadronic Final States:
  - Jets, heavy flavours → complementary pdf info, gluon directly, how to treat HF in QCD
  - ? Usefulness of HERA data often limited by scale uncties in theory



- Forward Jets,
  - Direct tests of assumed parton evolution patterns
  - ? Understanding limited by instrumentation near beam-pipe

- Diffraction
  - Unique clean probe of gap dynamics and elastic scattering
  - ? Understanding limited by (forward) detectors …

Motivation for TeV Scale DIS

-New Physics of eq Bound States

leptoquarks, RP violating SUSY, quark compositeness

-The Low x Limit of Quantum Chromodynamics

high parton densities with low coupling

parton saturation, new evolution dynamics

diffraction and confinement

quark-gluon dynamics and the origin of mass

-Precision Proton Structure for the LHC and elsewhere

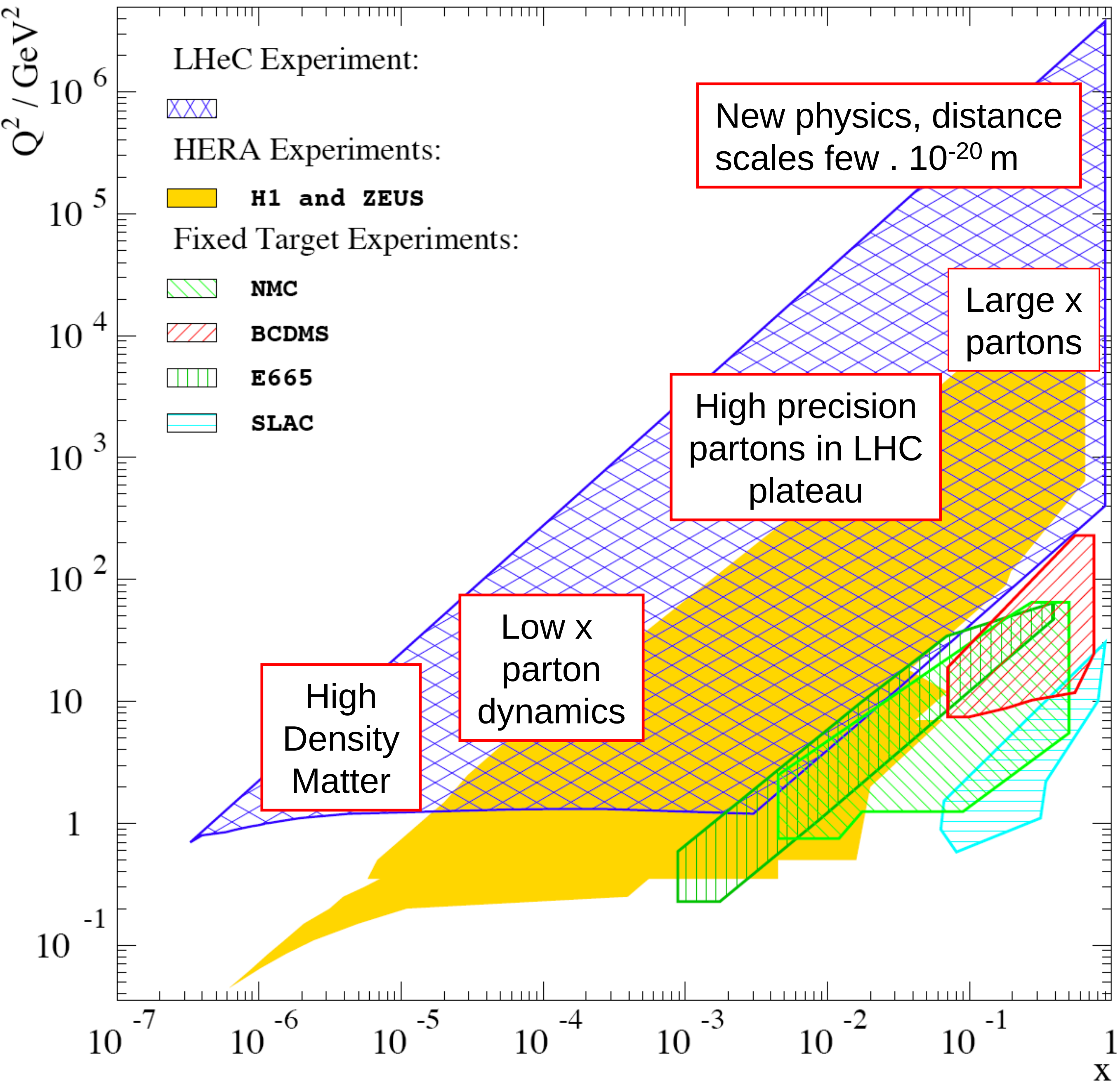
essential to know the initial state precisely (b, g …)

-Nuclear Parton Densities

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

… some considerations follow with E_e = 70 GeV, E_p = 7 TeV, lumi ~ 10^{33} cm^{-2} s^{-1} (~ 10 fb^{-1} $year^{-1}$)…

Inclusive Kinematics for 70 GeV x 7 TeV



$$\sqrt{s} = 1.4 \text{ TeV}$$

$$W \leq 1.4 \text{ TeV}$$

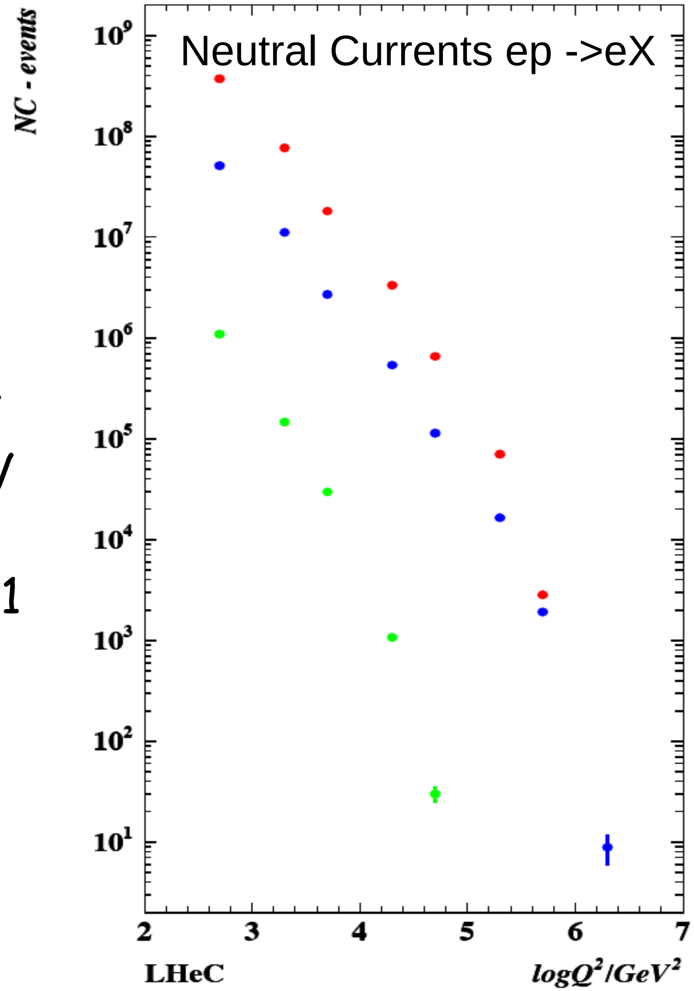
$$x \geq 5.10^{-7} \text{ at } Q^2 \leq 1 \text{ GeV}^2$$

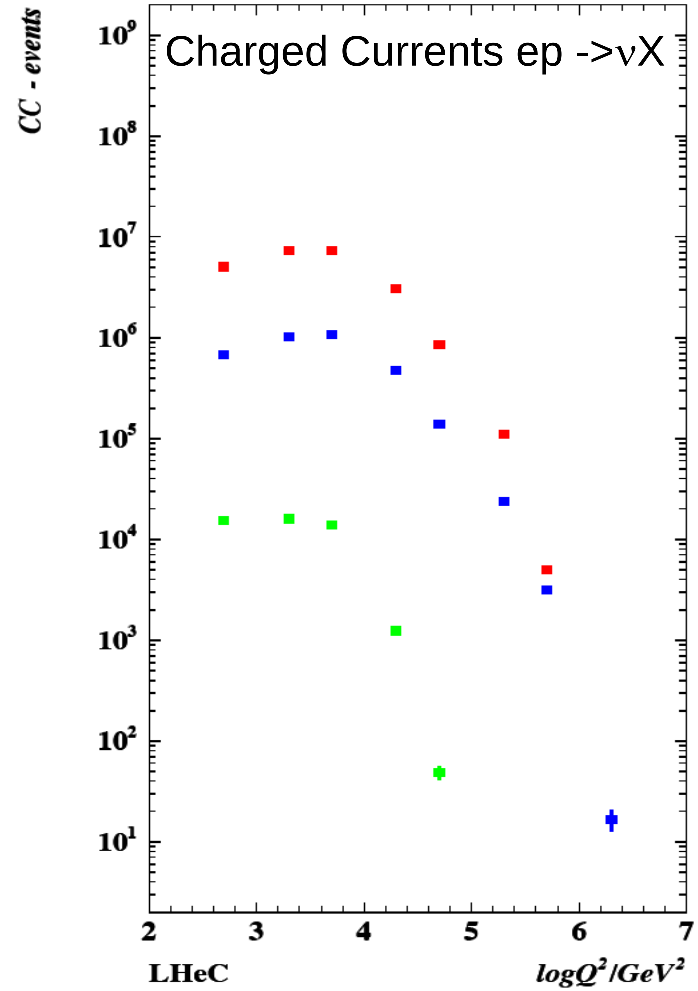
- High mass (Q^2) frontier
- Q^2 lever-arm at moderate x
- Low x (high W) frontier

The LHeC for High Q^2 Investigations

Inclusive event yields

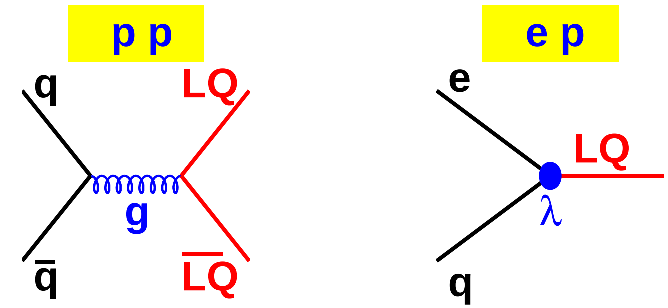
- HERA 1fb-1 (green): Ep = 920 GeV, Ee = 27.5 GeV
- LHeC 100 fb-1 (red): Ep = 7 TeV, Ee = 70 GeV
- LHeC 10 fb-1 (blue): Ep = 7 TeV, Ee = 140 GeV





- Reaching highest Q^2 (and x) region requires very high lumi
- Reduced lumi can be compensated by increased energy

Lepton-quark Bound States



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

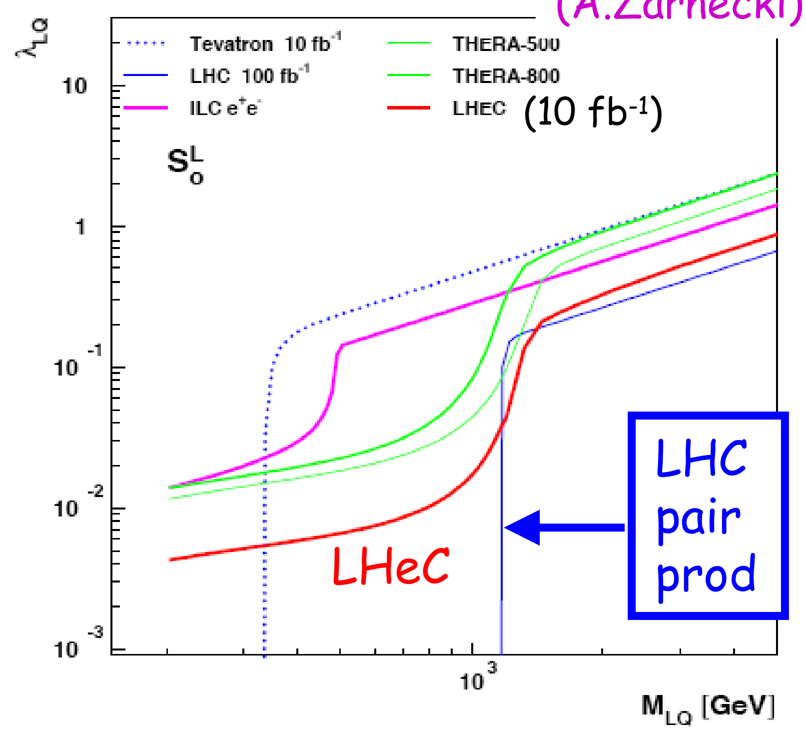
Yukawa coupling, λ

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

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

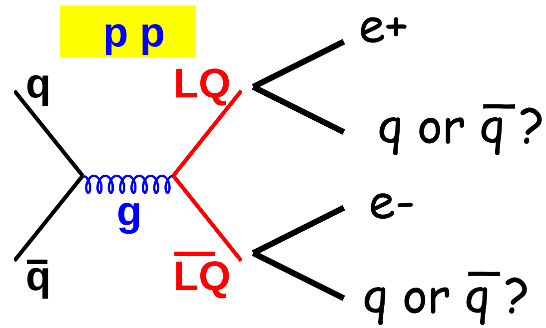
- LHC sensitivity (to ~1.5 TeV) similar to LHeC, but difficult to determine quantum numbers / spectroscopy!

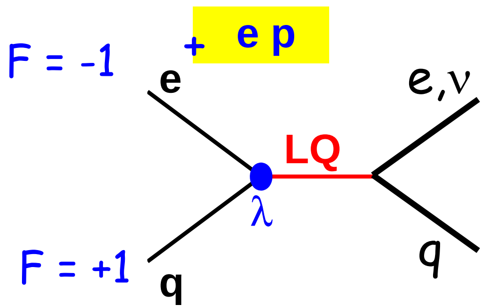
(A.Zarnecki)



Leptoquark Properties at LHeC

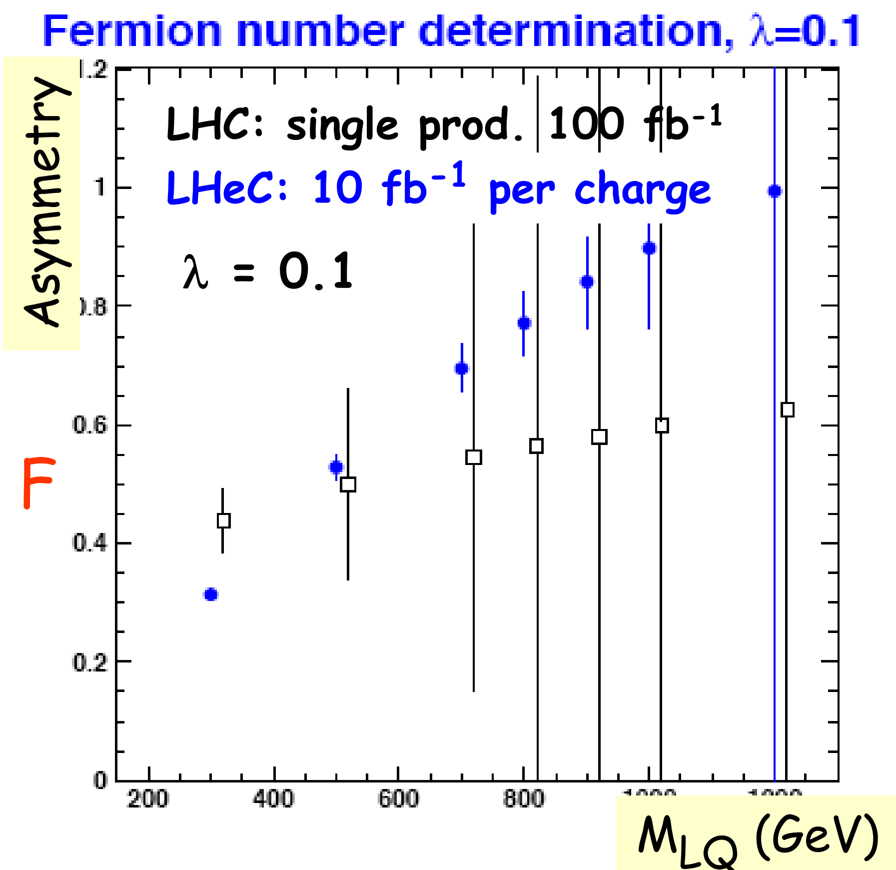
LHC: - Hard to determine quantum numbers from pair production.



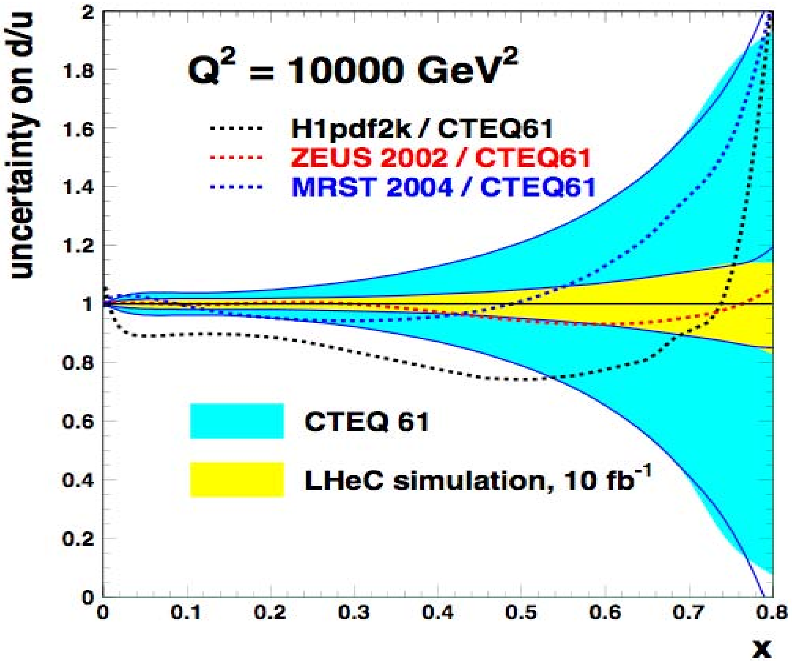


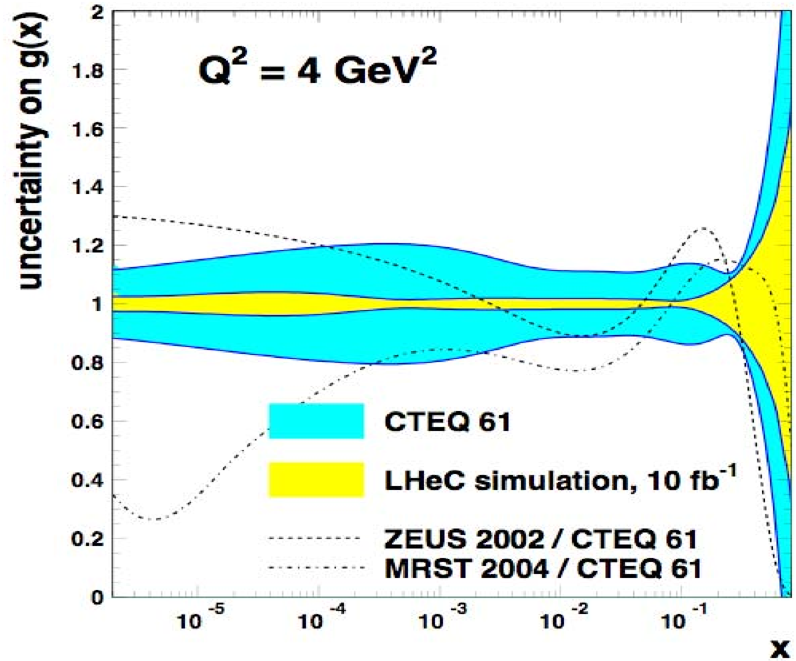
LHeC: - Resonant production at high x implies q rather than qbar. Sign of e^+p / e^-p asymmetry then determines fermion number F

- Disentangle scalar / vector from angular distributions.
- Disentangle chiral couplings by varying beam polarisation



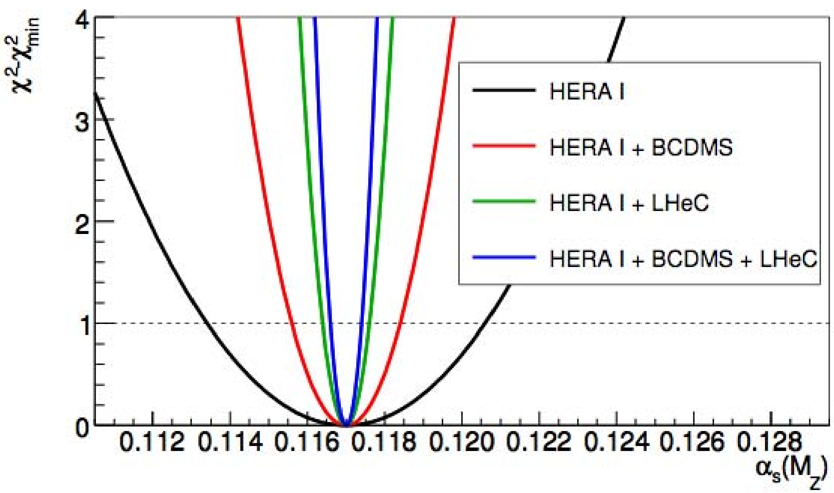
LHeC Impact on High x Partons and α_s





Full NC/CC sim (with systs)
& NLO DGLAP fit …

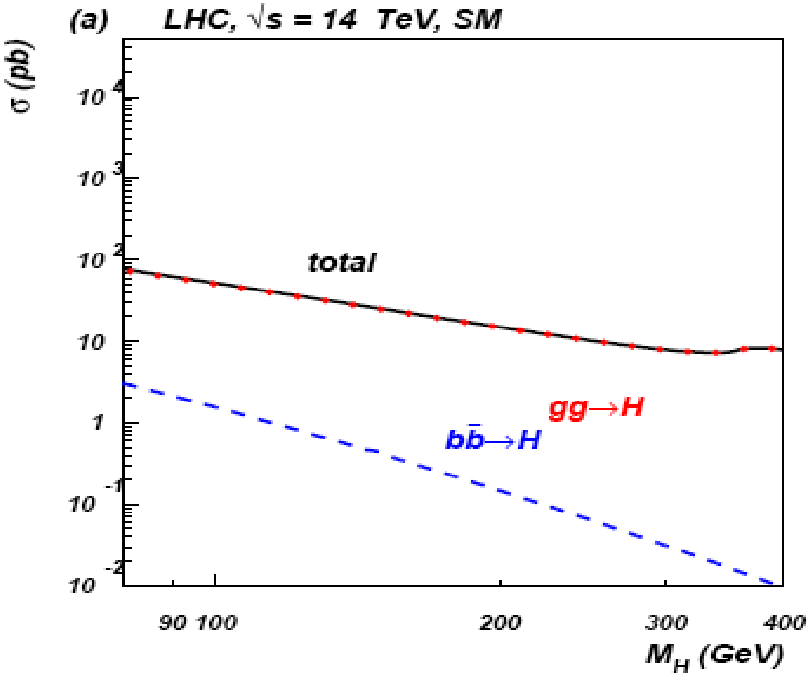
… high x pdfs → LHC discovery
& interpretation of new states?
… projected α_s precision few/mil
(c.f. 1-2% now)



Heavy Quarks: HERA → LHC

- HERA HF information limited by kinematic range and lumi (reasonable charm, some beauty, almost no strange)

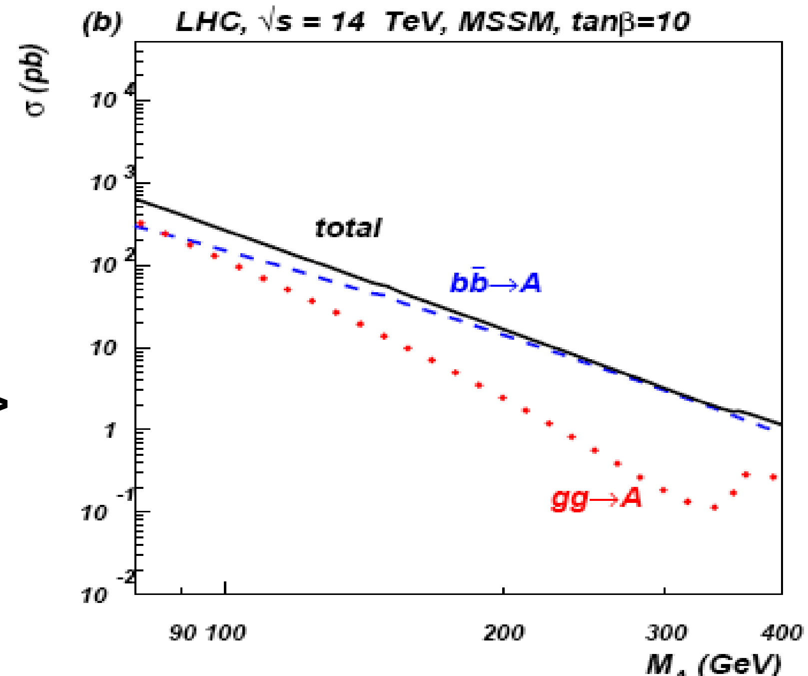
- Crucial for understanding LHC initial state for new processes (e.g. bbbar->H) and backgrounds.



Higgs

<-SM

MSSM->



- LHC predictions rely strongly on extrapolations and pQCD (e.g. CTEQ: 7% effect on W,Z rates varying HF treatment).

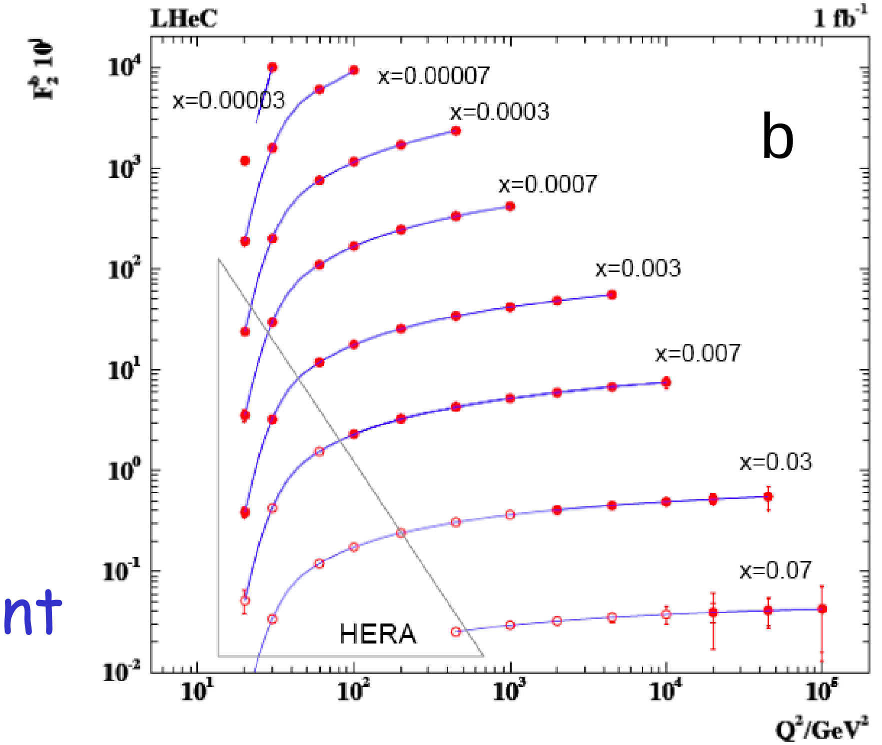
Heavy Quarks: LHeC

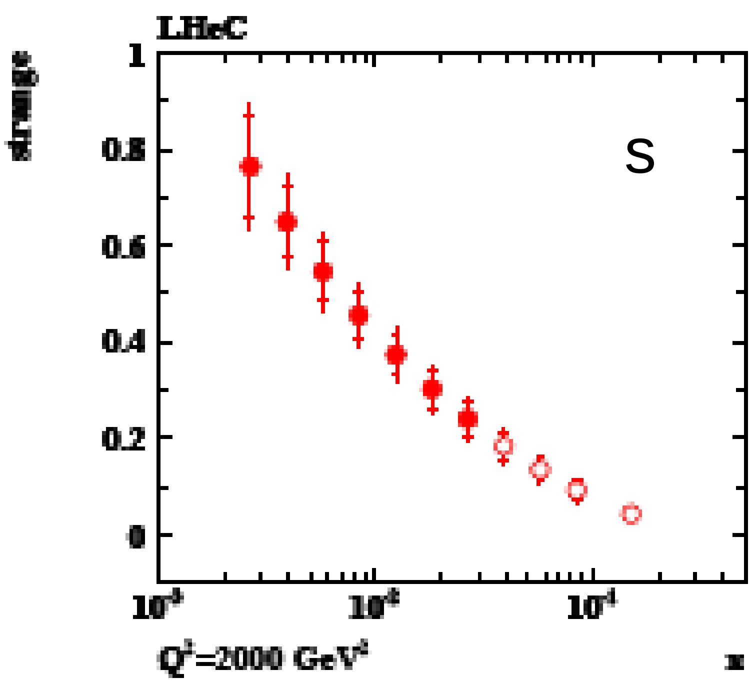
High precision c, b measurements
(modern Si trackers, beam spot 15 * 35 μm^2 , increased rates at larger scales).

Systematics at 10% level

→beauty is a low x observable!

→s (& sbar) from charged current

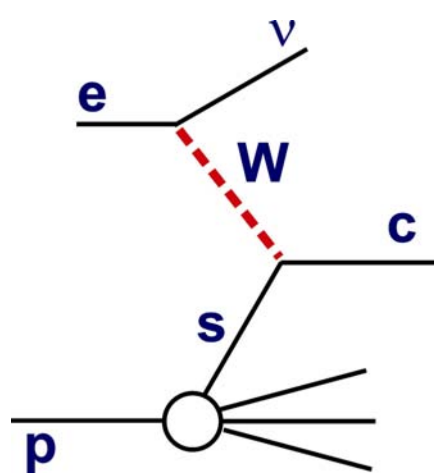




● LHeC 10° acceptance

○ LHEC 1° acceptance

(A. Mehta, M. Klein)



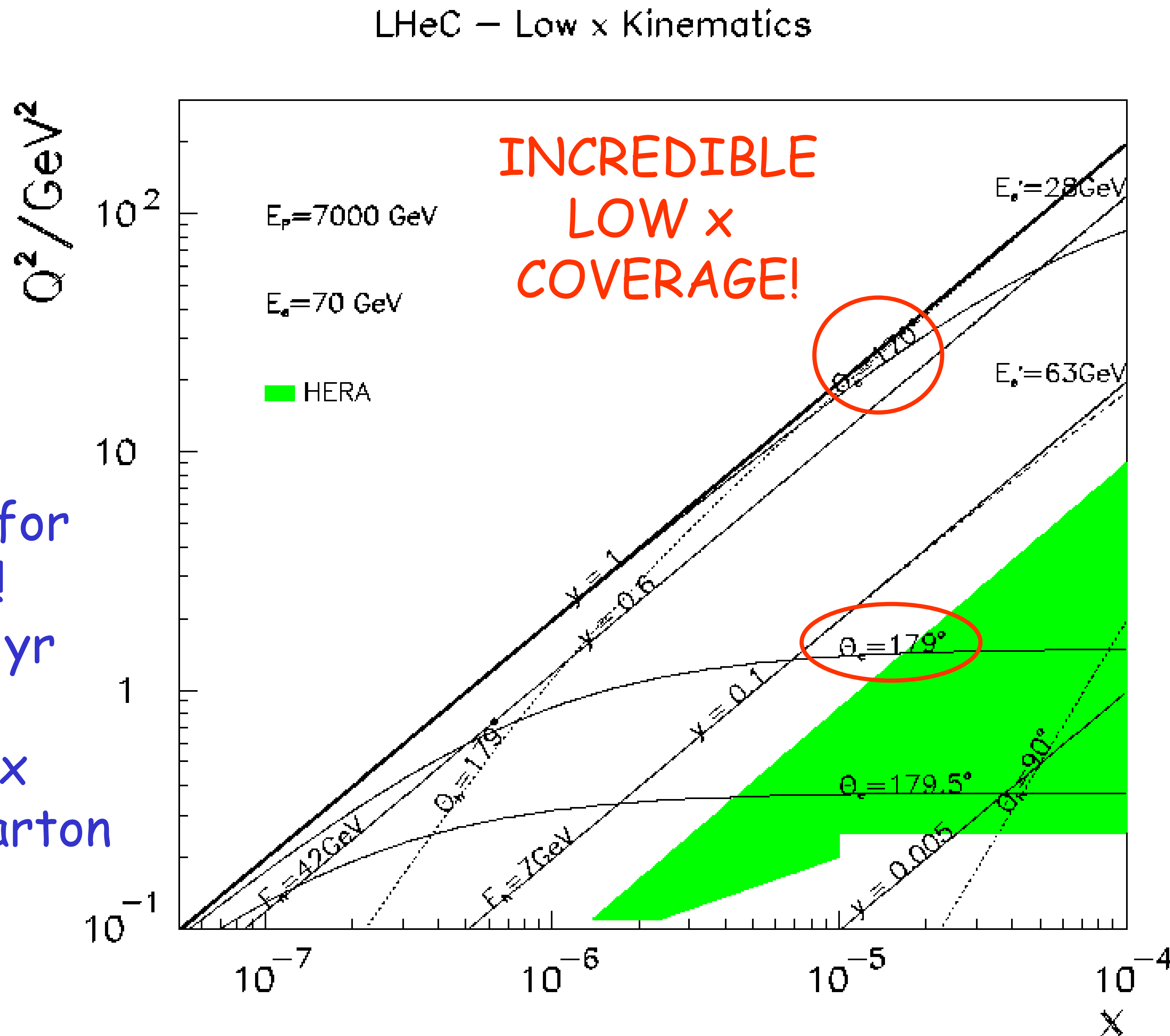
(Assumes 1 fb^{-1} and
- 50% beauty, 10% charm efficiency
- 1% uds → c mistag probability.
- 10% c → b mistag)

The LHeC for Low x Investigations

Requires detectors close to beam pipe

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

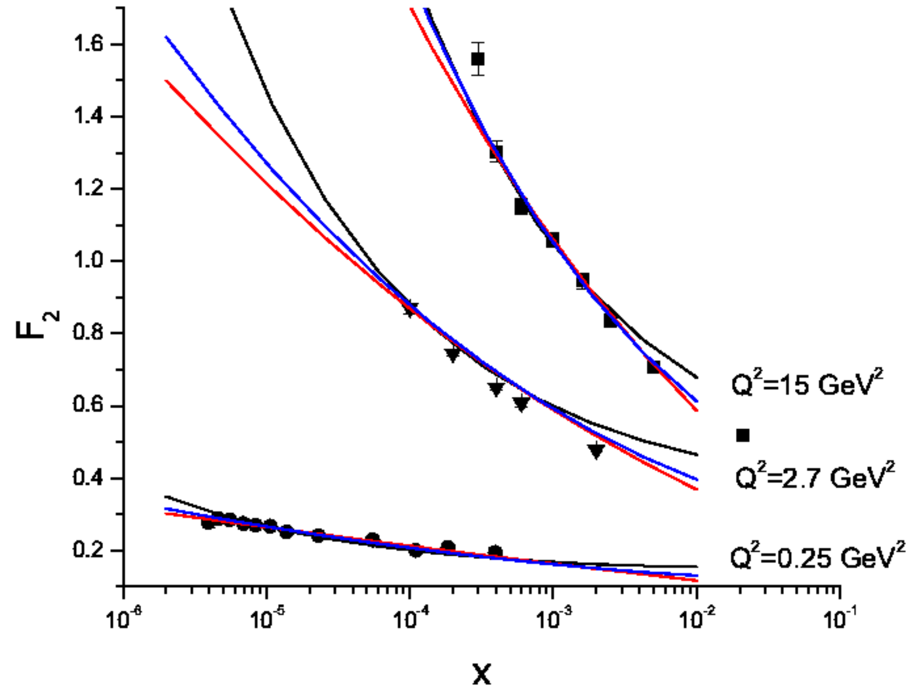
Definitive low x facility (e.g. parton saturation answers)



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}.



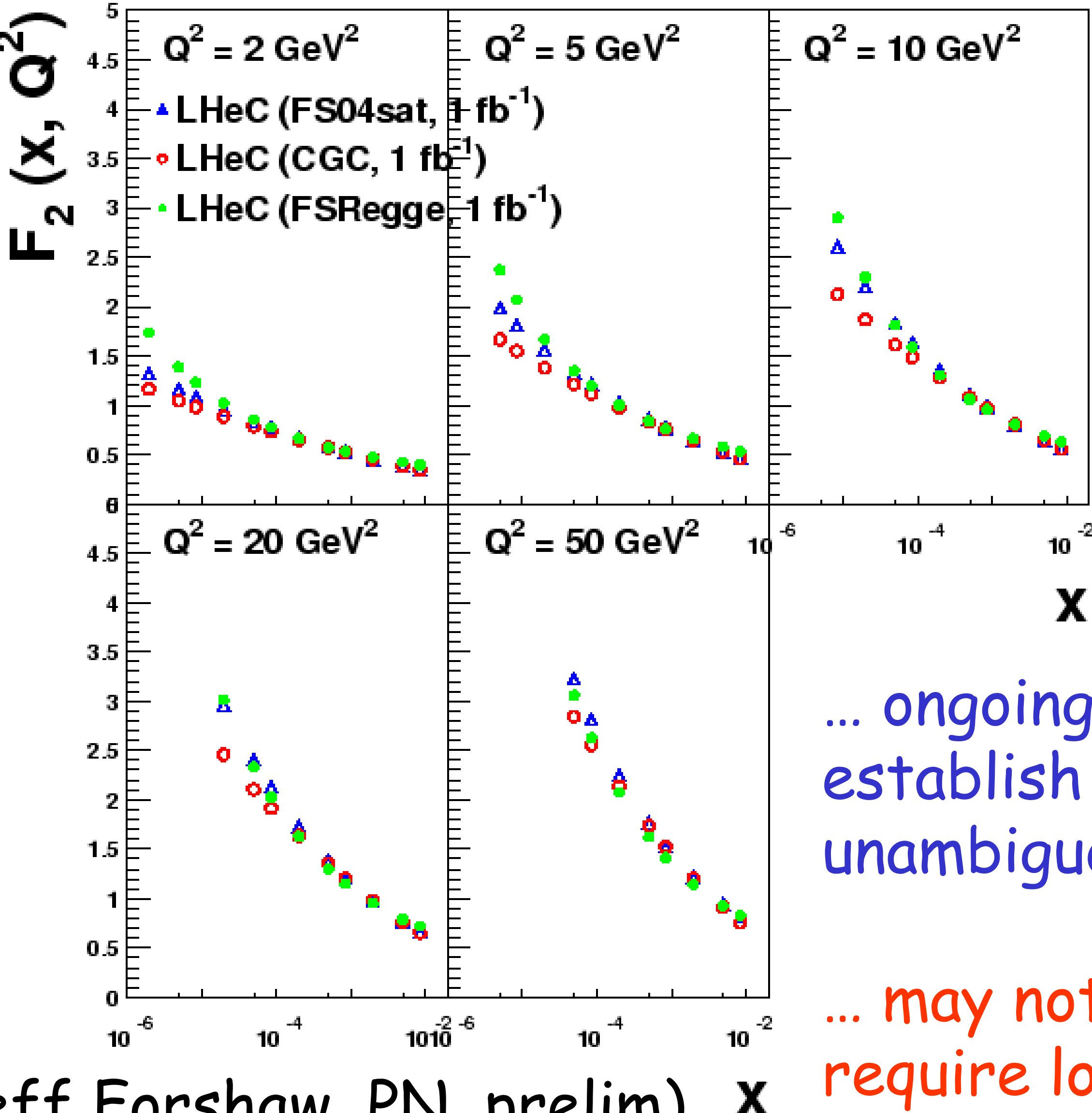
FS04 Regge (~FKS): 2 pomeron model, no saturation
FS04 Satn: Simple implementation of saturation
CGC: Colour Glass Condensate version of saturation

- 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

… any saturation at HERA not easily interpreted partonically

Example low x F_2 with LHeC Data

Stat. precision < 0.1%, syst, 1-3%



(Jeff Forshaw, PN, prelim)

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

- Extrapolated FS04, CGC models including sat'n suppressed at low x, Q^2

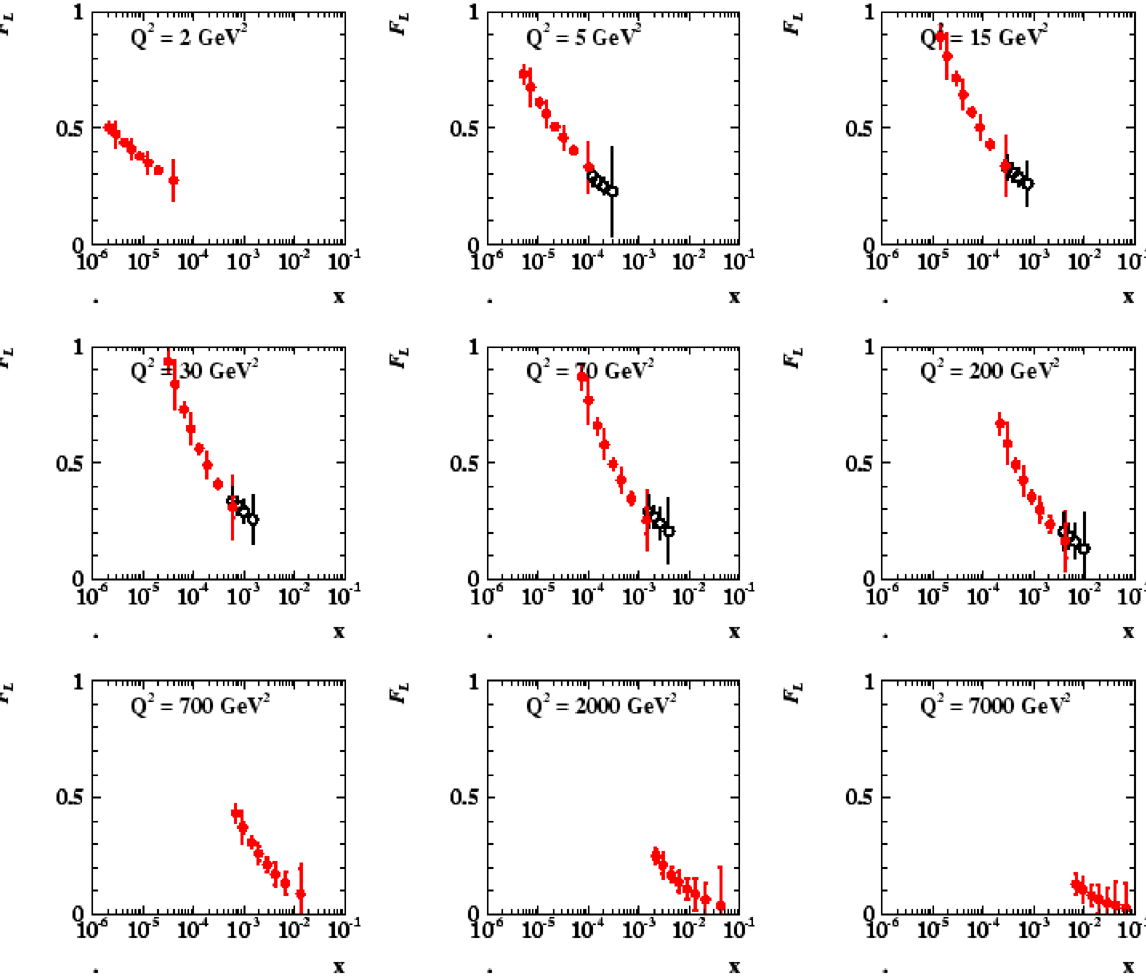
… ongoing work on how to establish saturation partons unambiguously …

… may not be easy and will require low Q^2 (θ > 170°) region

The Gluon from F_L?

● LHeC

○ H1 low Ep run (projected)



Vary proton beam energy as recently done at HERA ?...

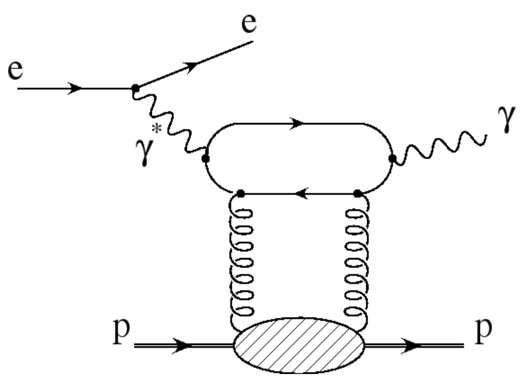
E_p (TeV)	Lumi (fb^{-1})
7	1
4	0.8
2	0.2
1	0.05
[0.45	0.01]

[~ 1 year of running]

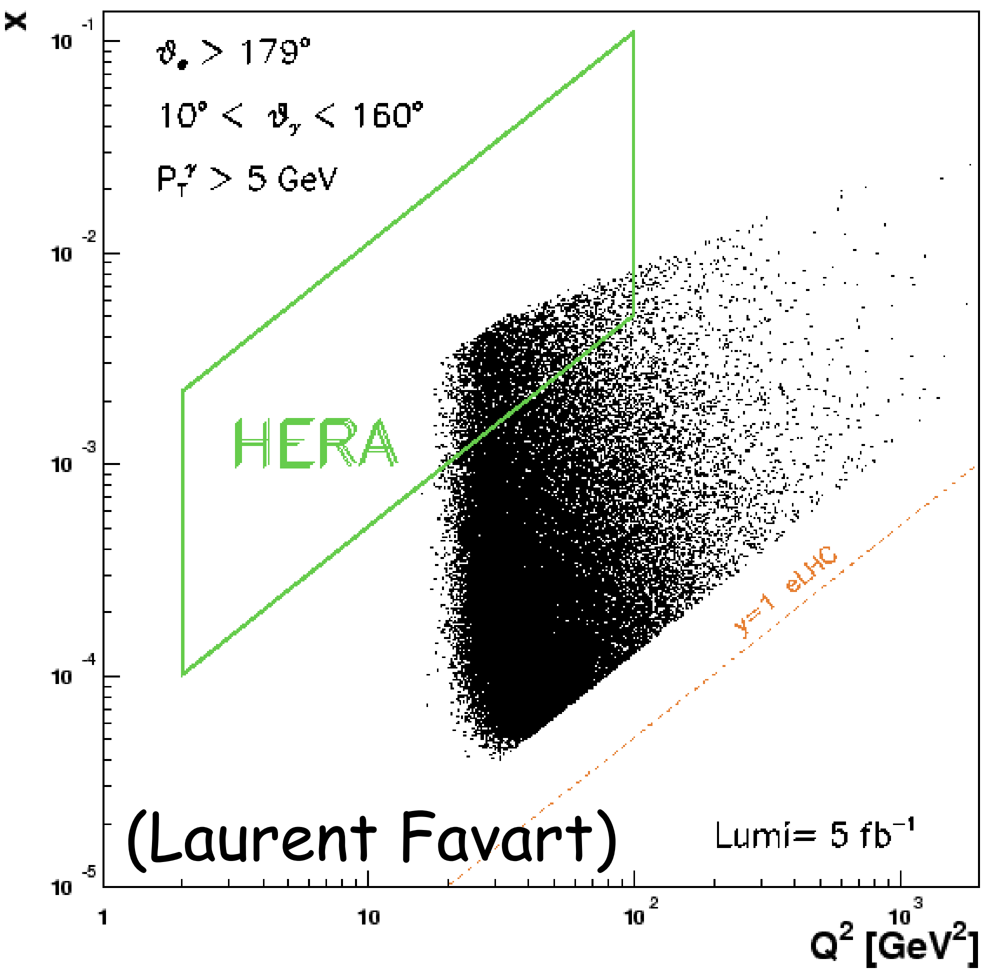
Typically lose 1-2 points at high x if E_p = 0.45 TeV not possible

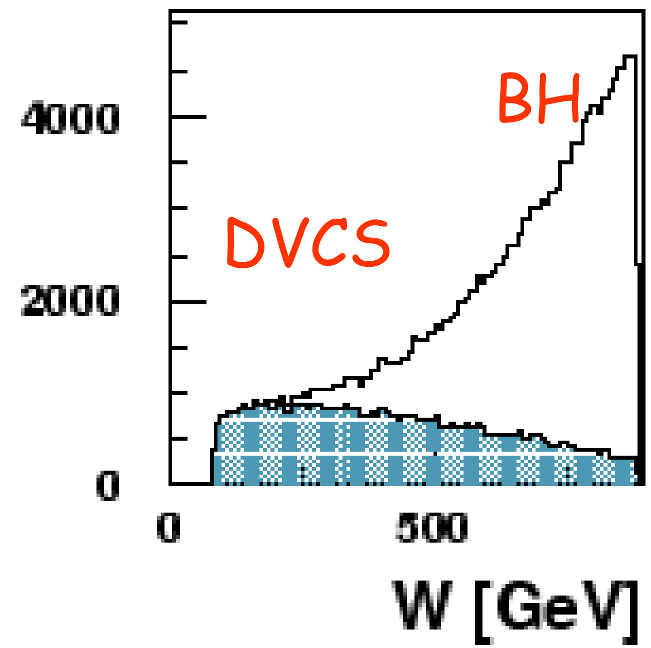
... precision typically 5%, stats limited for Q^2 > 1000 GeV^2

DVCS Measurement



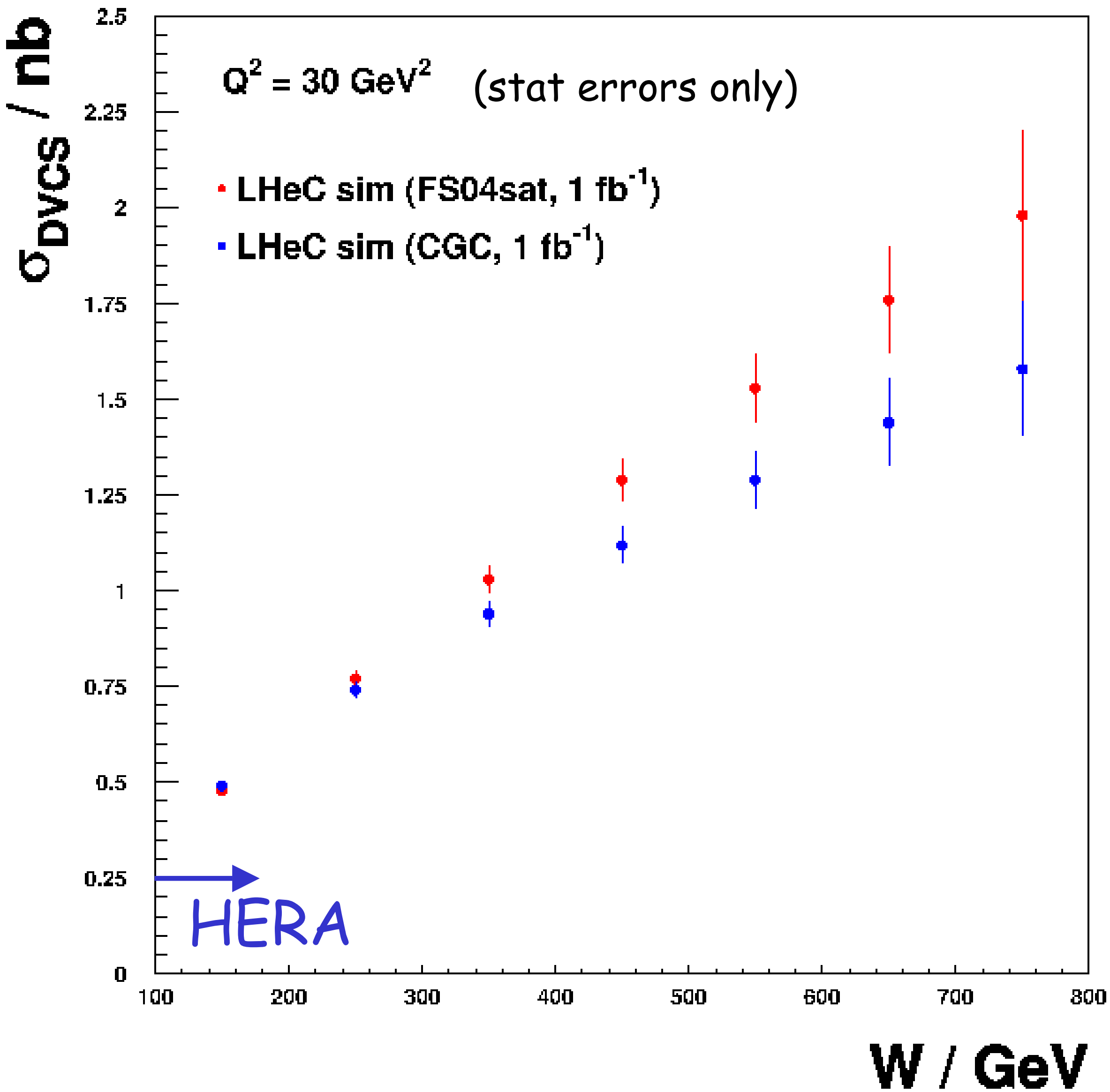
... can be tackled as at HERA through inclusive selection of $ep \rightarrow ep\gamma$ and statistical subtraction of Bethe-Heitler background





Example of DVCS at LHeC

(1° acceptance)



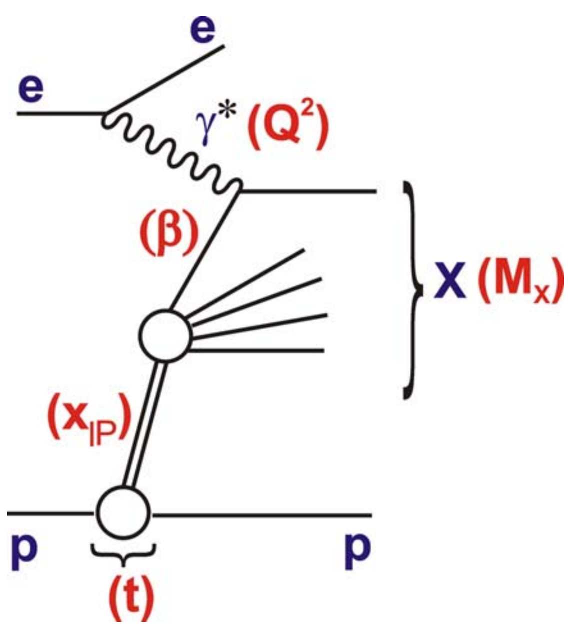
Statistical precision with 1fb^{-1} ~ 2-11%

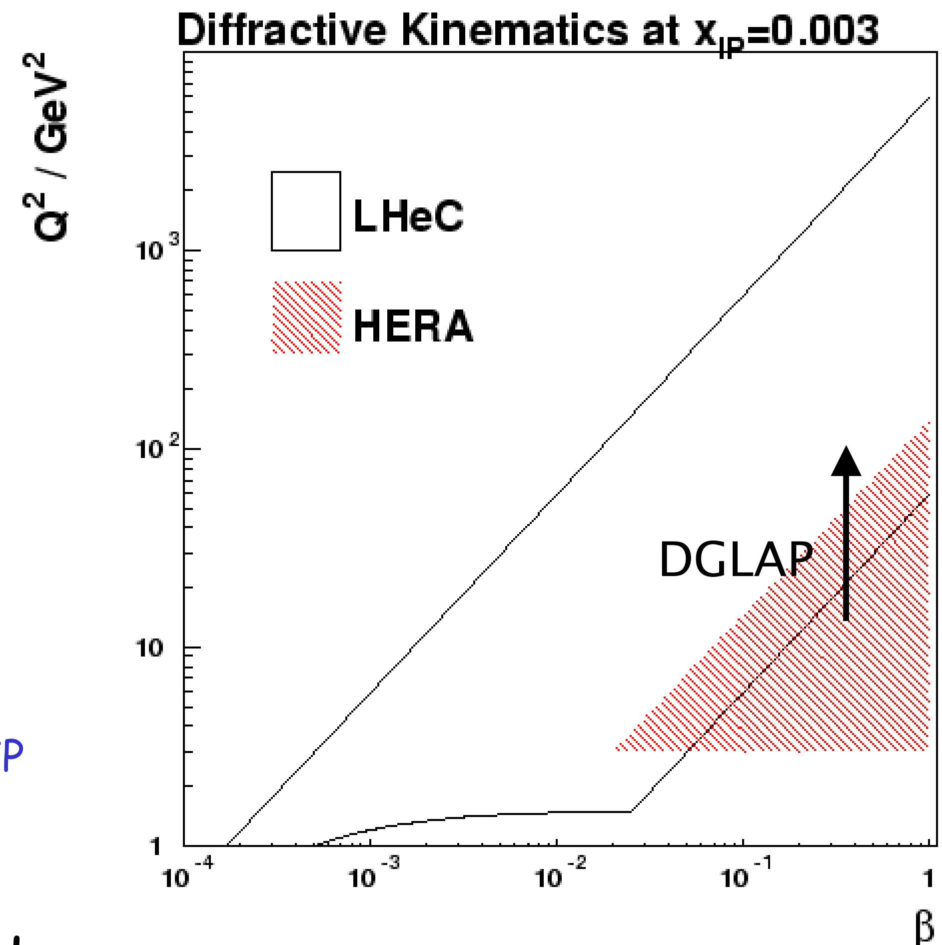
With F_2, F_L, could help establish saturation and distinguish between different models which contain it!

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

VMs similar story

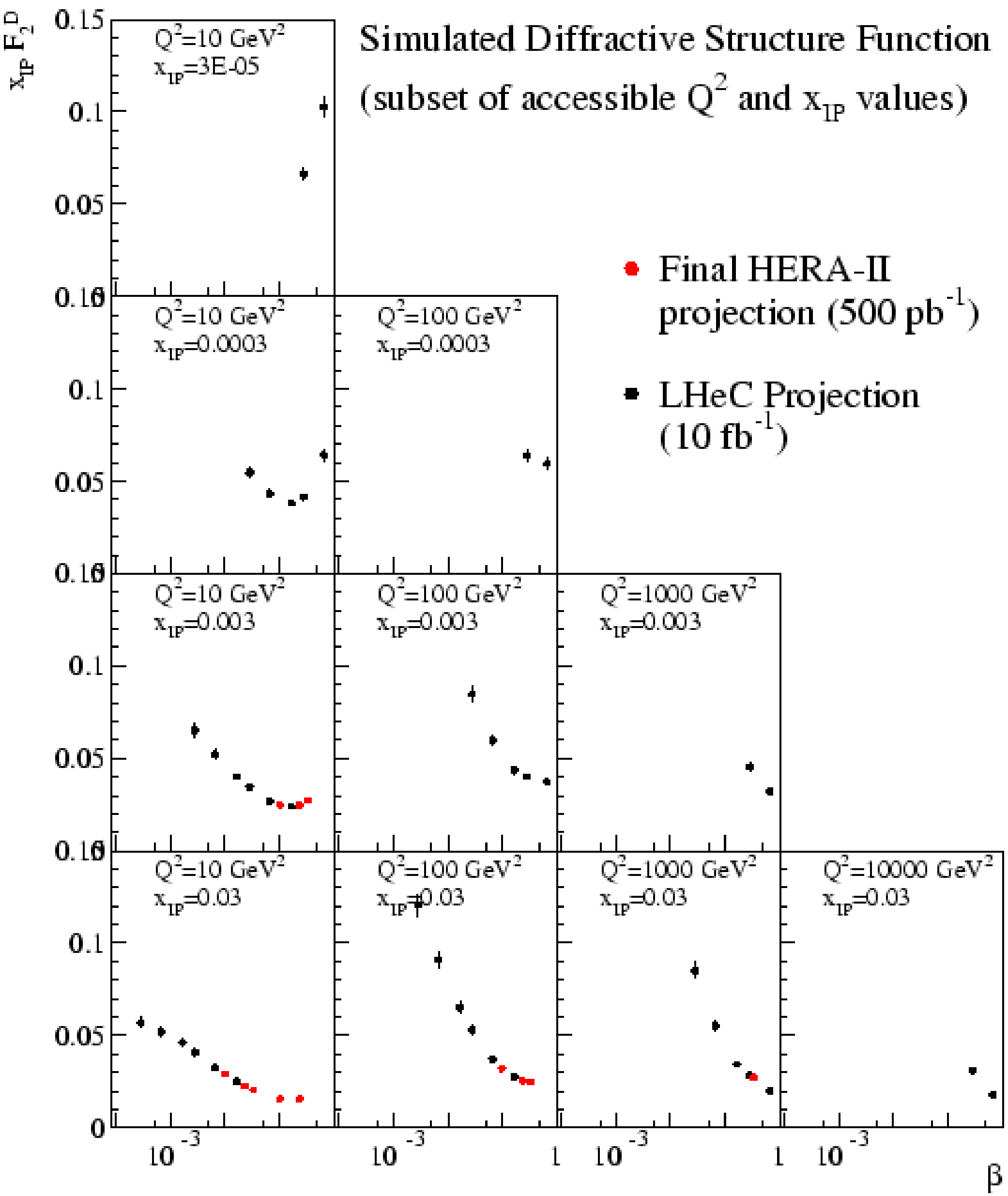
LHeC Diffractive DIS Kinematics





1) Higher Q^2 at fixed β, x_{IP}
   → gluon from DGLAP
   → quark flavour decomposition (CC and Z effects in NC)

LHeC Simulation

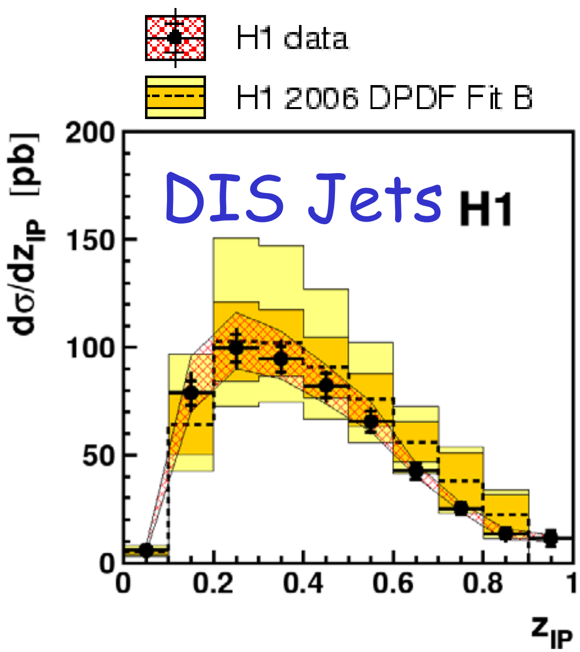


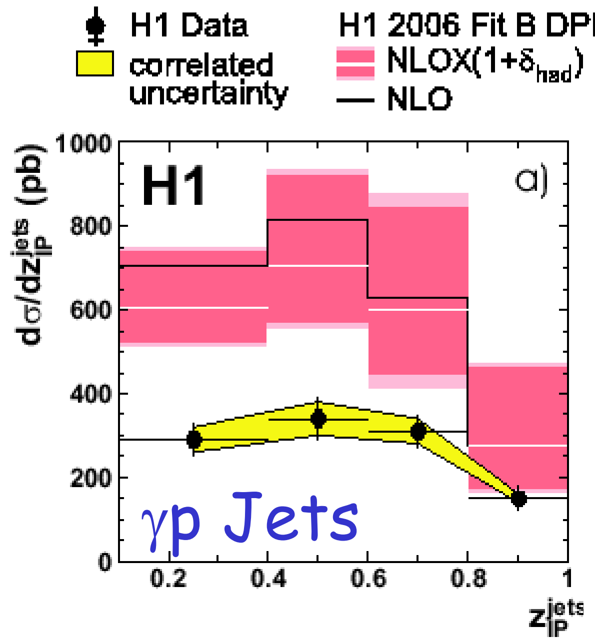
2) Extension to lower x_{IP}
→cleaner separation of diffractive exchange

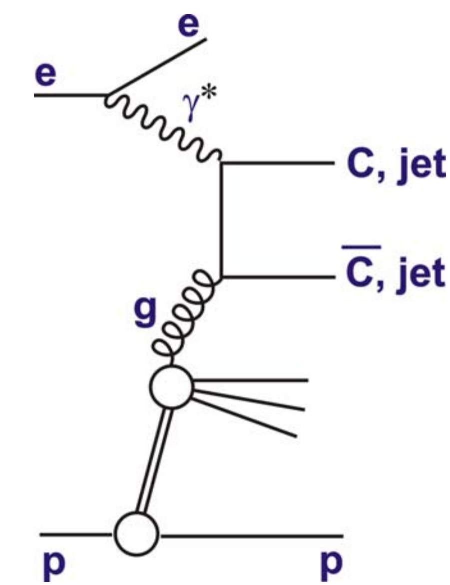
3) Lower β at fixed Q^2, x_{IP}
→parton saturation?
→BFKL type dynamics?
→ Large masses … Z, W, b, exclusive 1^{--} states

… **Statistical precision ~1%, systs 5-10%** depending strongly on forward detector design

Diffractive Final States at HERA & the LHeC



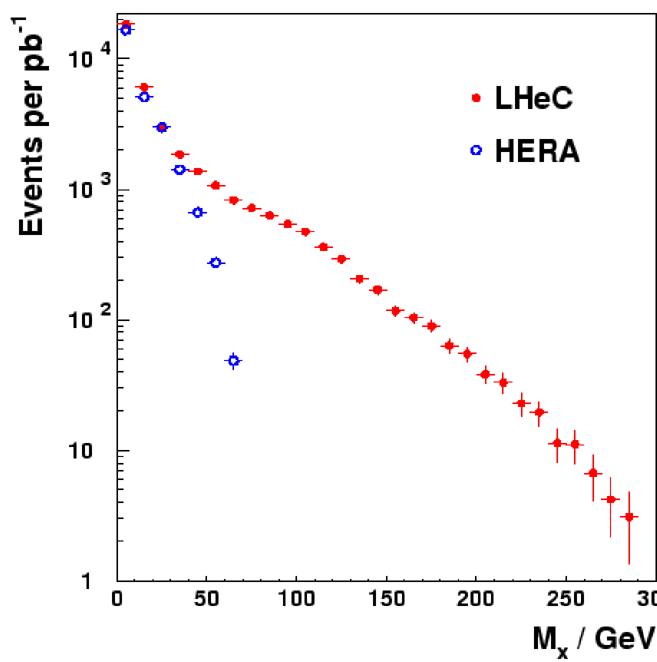




• HERA jet / charm measurements kinematically restricted to high β, where F_2^D least sensitive to gluon!

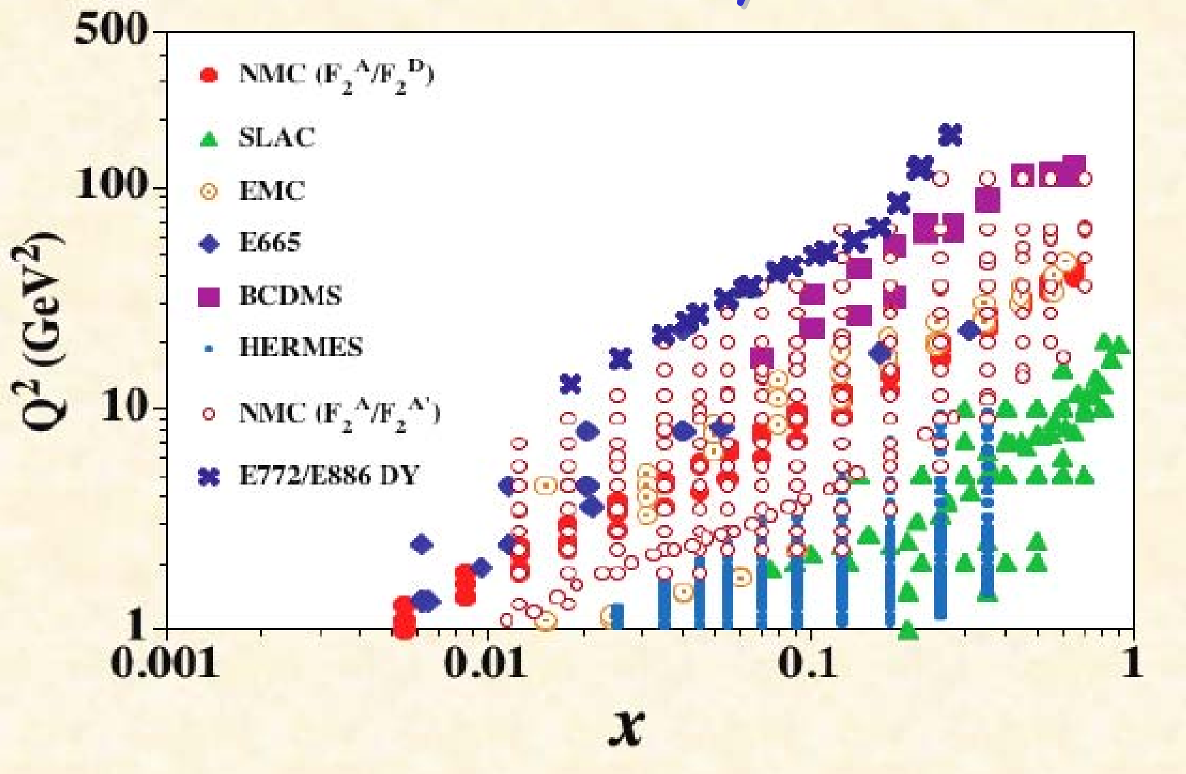
• Also restricted to low $p_T < M_x/2$ where scale uncertainties large.

• γp jets → gap survival → diff H ???



• M_x up to hundreds of GeV at LHeC!

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

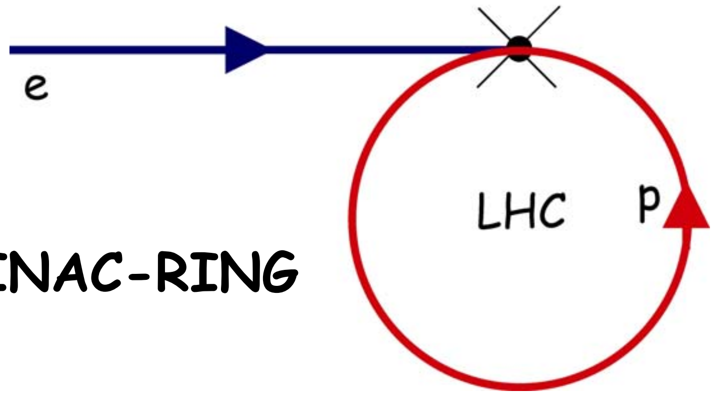
- e.g. enhanced sensitivity to low x gluon saturation

- c.f. ions at LHC, RHIC … initial state in quark gluon plasma production is presumably made out of saturated partons

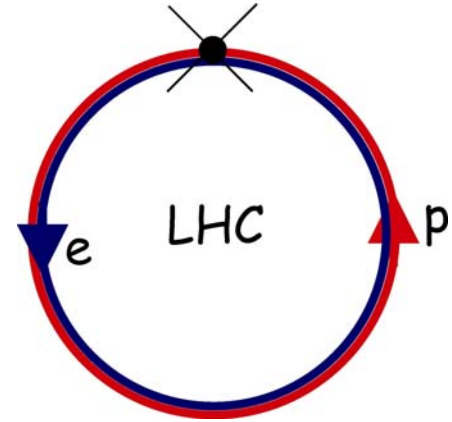
How Could it be Done using LHC?

… essential to allow simultaneous ep and pp running …

LINAC-RING



RING-RING



- Previously considered as `QCD explorer' (also THERA)
- Reconsideration (Chattopadhyay & Zimmermann) with CW cavities began
- Main advantages: low interference with LHC, $E_e \rightarrow$ 140 GeV, LC relation
- Main difficulty: peak luminosity only ~$0.5.10^{32}$ cm^{-2} s^{-1} at reasonable power

- First considered (as LEPxLHC) in 1984 ECFA workshop
- Recent detailed re-evaluation with new e ring (Willeke)
- Main advantage: high peak lumi obtainable (10^{33} cm^{-2} s^{-1})
- Main difficulties: building it around existing LHC, e beam life

Ring-Ring Parameters

• LHC fixes p beam parameters

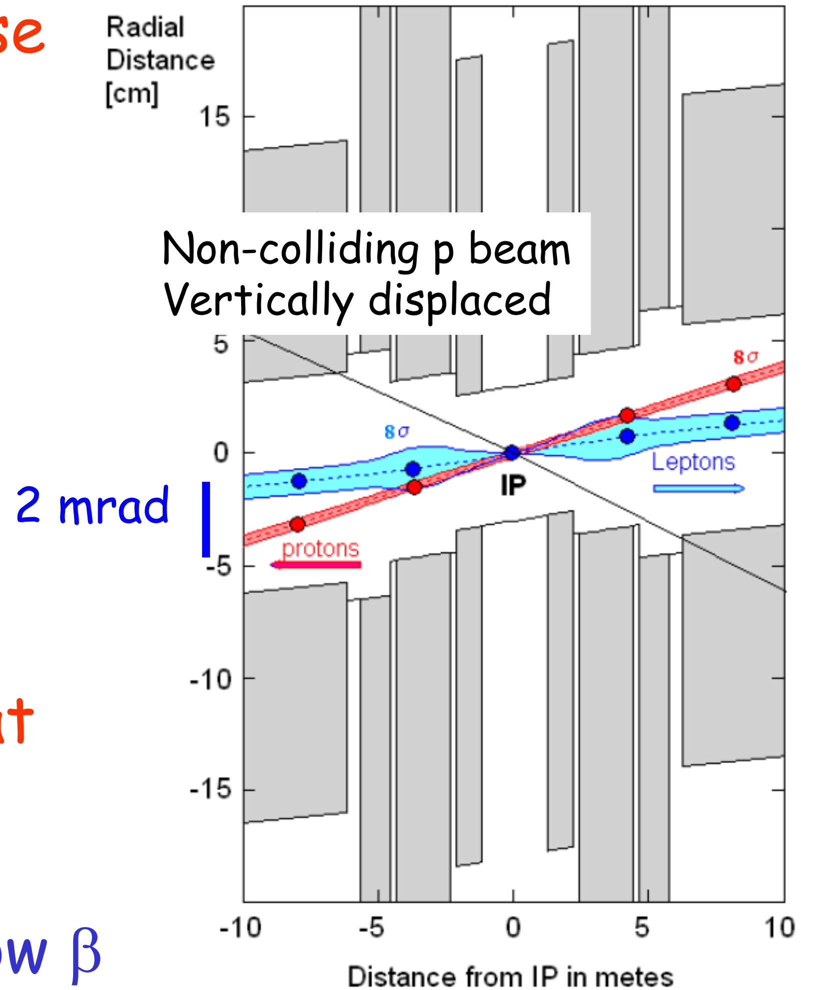
• 70 GeV electron beam, (compromise energy v synchrotron → 50 MW)

• Match e & p beam shapes, sizes

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

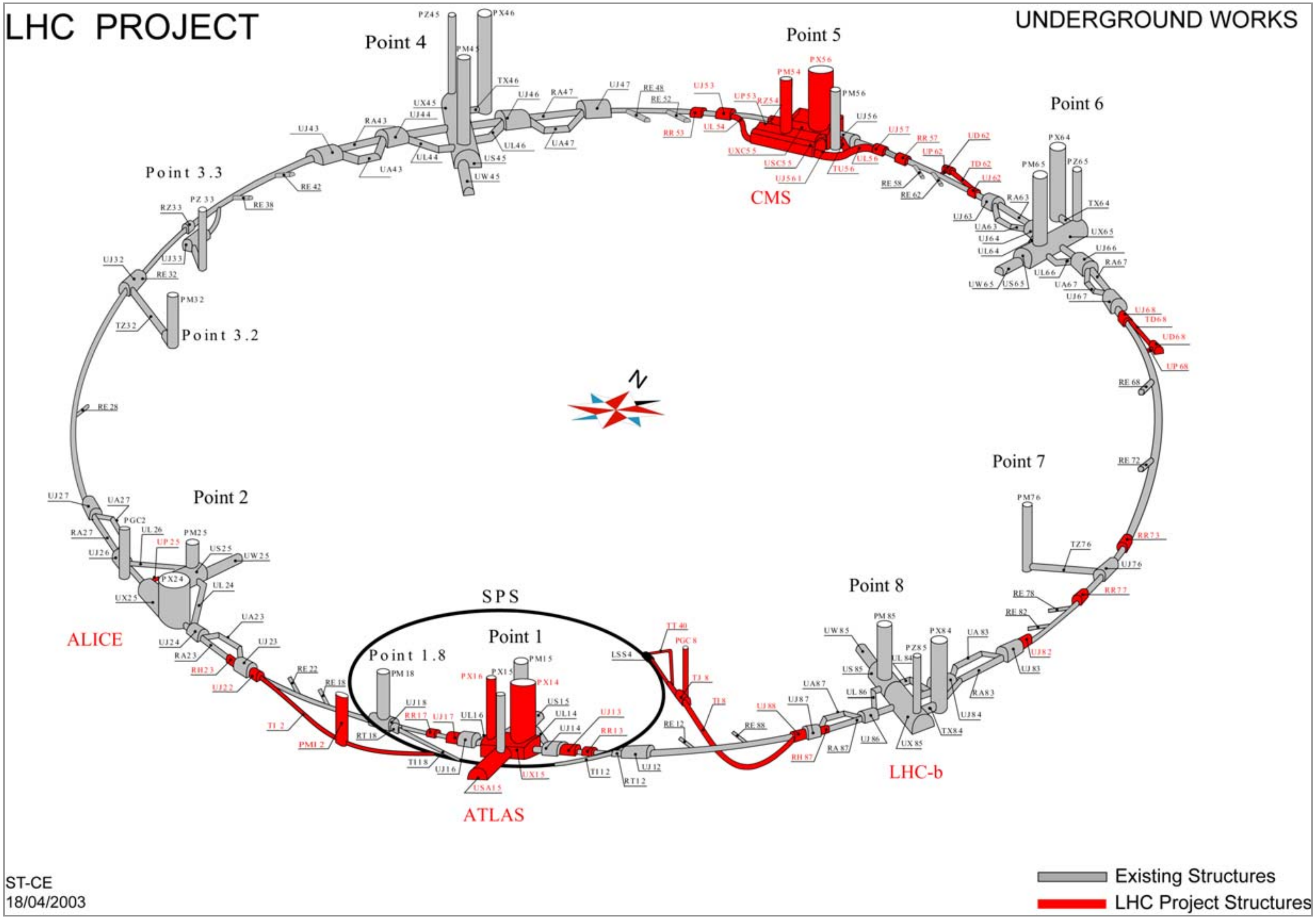
• 2 mrad angle gives 8σ separation at first parasitic crossing

Top view



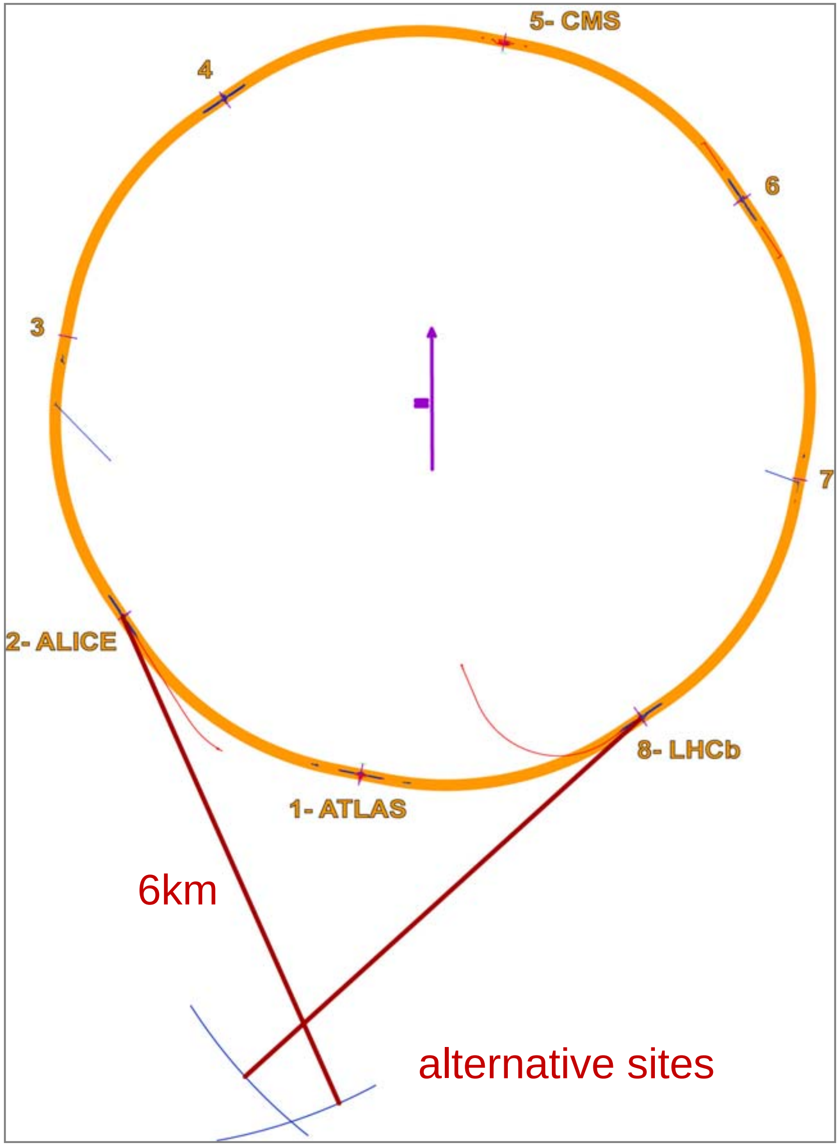
• High luminosity running requires low β focusing quadrupoles close to interaction point (1.2 m) → acceptance limitation to 10° of beampipe

Ring-Ring Design



- e ring would have to bypass experiments and P3 and 6
- ep/eA interaction region could be in P2 or P8.

Linac-Ring Design



(70 GeV electron beam at 23 MV/m is 3km + gaps)

		ring-linac pulsed		ring-linac, cw , ~99% energy recovery	
	units	e-	p	e-	p
energy	GeV	70	7000	70	7000
punch population	10^{10}	2	17	2	17
σ_z	cm	0.03	7.55	0.03	7.55
beam current (pulsed)	mA	101	858	101	858
emittance $\varepsilon_{x,y}$	nm	0.5, 0.5			
$\beta^*_{x,y}$	cm	15, 15			
spacing	ns	25			
e-linac/ring length	km	3.5		7 (2 linacs)	
e- pulse length		1 ms		cw	
repetition rate		5 Hz		continuous	
e- beam power	MW	35		7000	
peak luminosity	10^{32} $cm^{-2}s^{-1}$	**0.6**		**2x110**	

S. Chattopadhyay (Cockcroft), F.Zimmermann (CERN), et al.

Relatively low peak lumi, but good average lumi
Energy recovery in CW mode (else prohibitive power usage)

Some First Detector Considerations

- Low x studies require electron acceptance to 1° to beampipe

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.

- 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°

… dedicated low x ring-ring set-up (no focusing magnets?)

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} cm^{-2} s^{-1} (ring-ring)	(HERA 1-5 x 10^{31} cm^{-2} s^{-1})
Acceptance 1-179°	(HERA 7-177°)
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%)

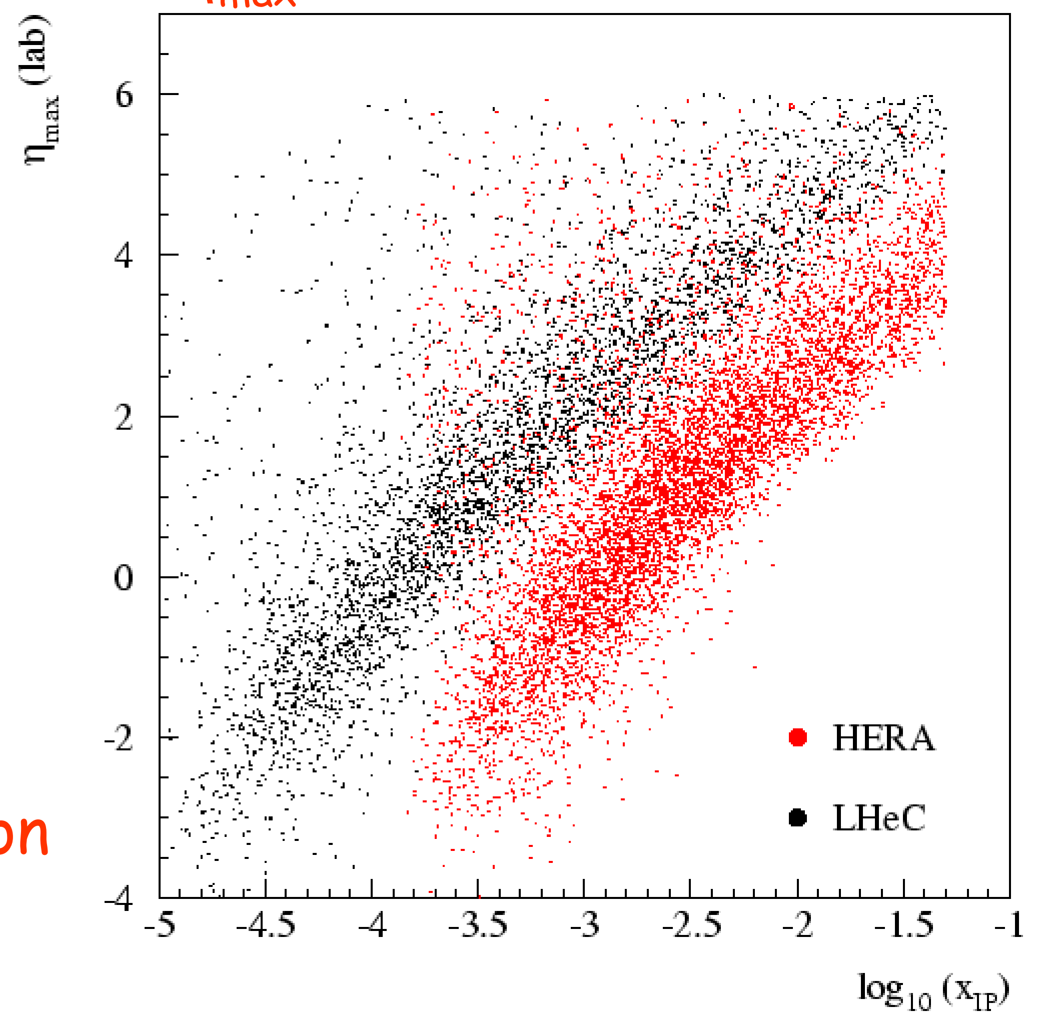
Forward and Diffractive Detectors

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

- 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 ☺
  - Being considered integrally with interaction region

η_{max} from LRG selection …



Organisation and Plans

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

Steering Group: O. Bruning, J. Dainton, A. de Roeck, S. Forte, M. Klein (chair), P. Newman, E. Perez, W. Smith, B. Surrow, K. Tokushuku, U. Wiedemann

Nov 2007:	Presentation made to ECFA
2008-9	→ ECFA sponsored workshop(s)
2009:	→ Conceptual Design Report

Planned Working Groups:

- Accelerator Design (ring-ring and linac-ring)
- Interaction region and Forward Detectors
- Infrastructure
- Detector Design
- New Physics at Large Scales
- Precision QCD and Electroweak Interactions
- Physics at High Parton Densities (low x, eA)

Summary

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

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

LHeC extends low x and high Q^2 frontiers of ep physics

First ring-ring and linac ring accelerator considerations and early physics studies very encouraging

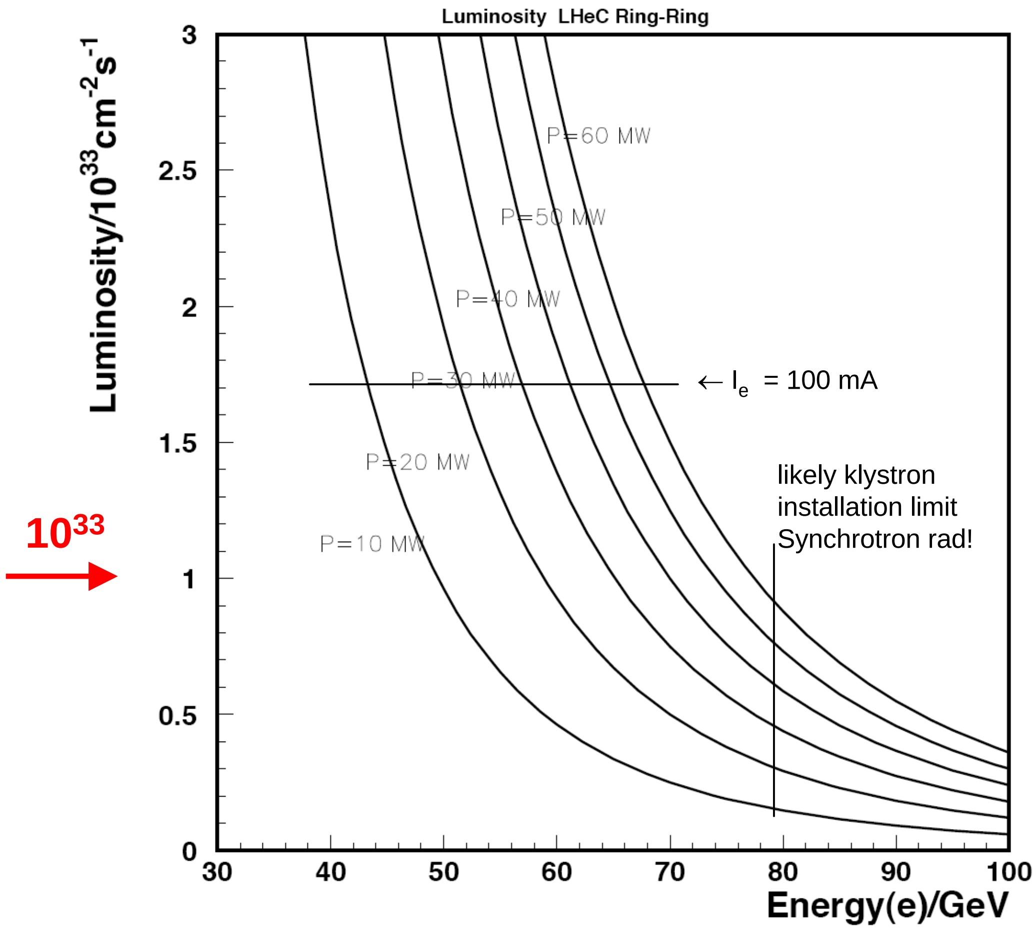
2008 workshop: Much to be done to fully evaluate physics potential, running scenarios and design detector

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

Luminosity: Ring-Ring

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn}} \cdot \frac{I_e}{\sqrt{\beta_{px}\beta_{py}}} = 8.3\,10^{32} \cdot \frac{I_e}{50mA} \frac{m}{\sqrt{\beta_{px}\beta_{pn}}} cm^{-2}s^{-1}$$

$$\varepsilon_{pn} = 3.8\mu m$$
$$N_p = 1.7 \cdot 10^{11}$$
$$\sigma_{p(x,y)} = \sigma_{e(x,y)}$$
$$\beta_{px} = 1.8m$$
$$\beta_{py} = 0.5m$$



$$I_e = 0.35mA \cdot \frac{P}{MW} \cdot \left(\frac{100GeV}{E_e}\right)^4$$

10^{33} can be reached in RR
E_e = 40-80 GeV & P = 5-60 MW.

HERA was 1-4 10^{31} cm^{-2} s^{-1}
huge gain with SLHC p beam

F.Willeke in hep-ex/0603016:
Design of interaction region
for 10^{33} : 50 MW, 70 GeV

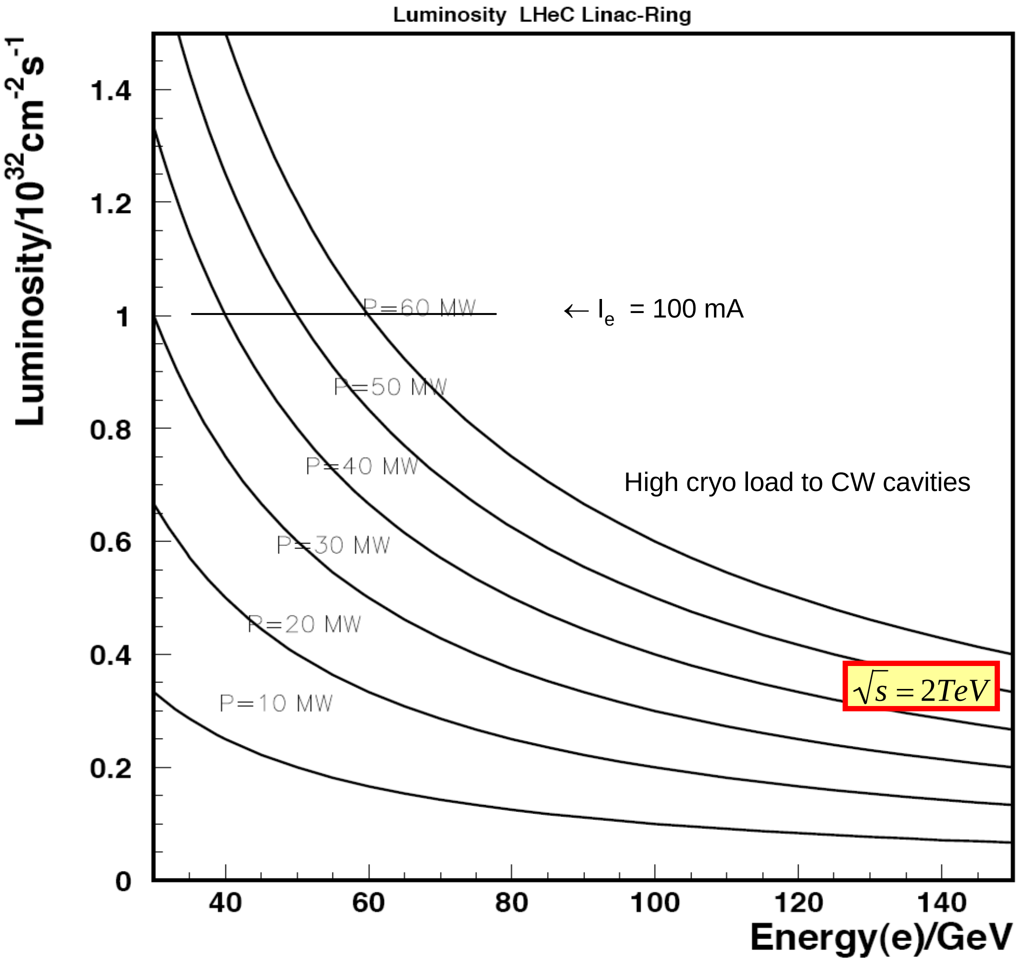
May reach 10^{34} with ERL in bypasses, or/and reduce power.
R&D performed at BNL/eRHIC

cf also A.Verdier 1990, E.Keil 1986

Luminosity: Linac-Ring

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn} \beta^*} \cdot \frac{P}{E_e} = 1 \cdot 10^{32} \cdot \frac{P/MW}{E_e/GeV} cm^{-2} s^{-1}$$

$$\varepsilon_{pn} = 3.8 \mu m$$
$$N_p = 1.7 \cdot 10^{11}$$
$$\beta^* = 0.15 m$$



$$I_e = 100 mA \cdot \frac{P}{MW} \cdot \frac{GeV}{E_e}$$

LHeC as Linac-Ring version
can be as luminous as HERA II:

4 10^{31} can be reached with LR:
E_e = 40-140 GeV & P=20-60 MW
LR: average lumi close to peak

140 GeV at 23 MV/m is 6km +gaps

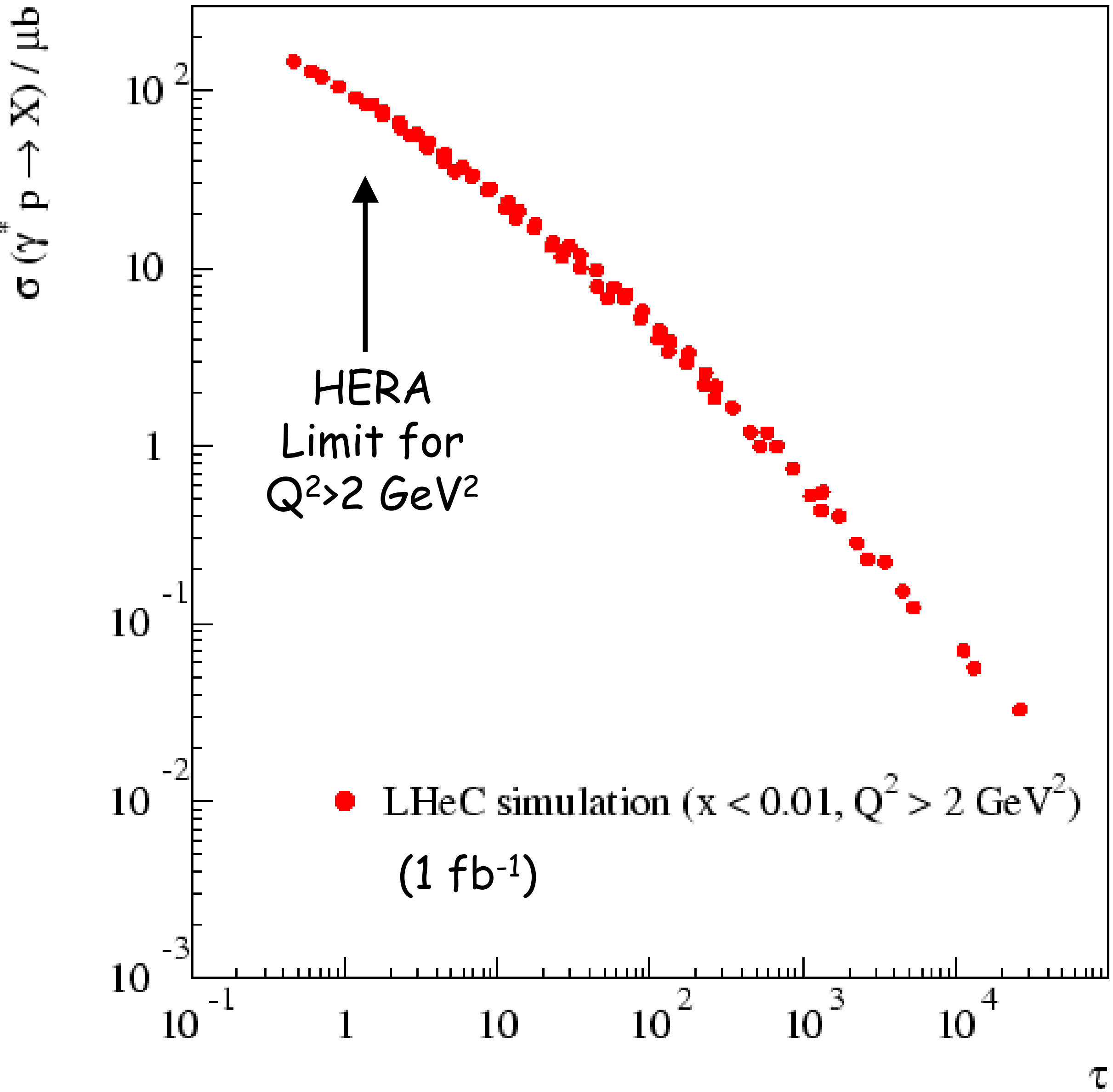
Luminosity horizon: high power:
ERL (2 Linacs?)

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



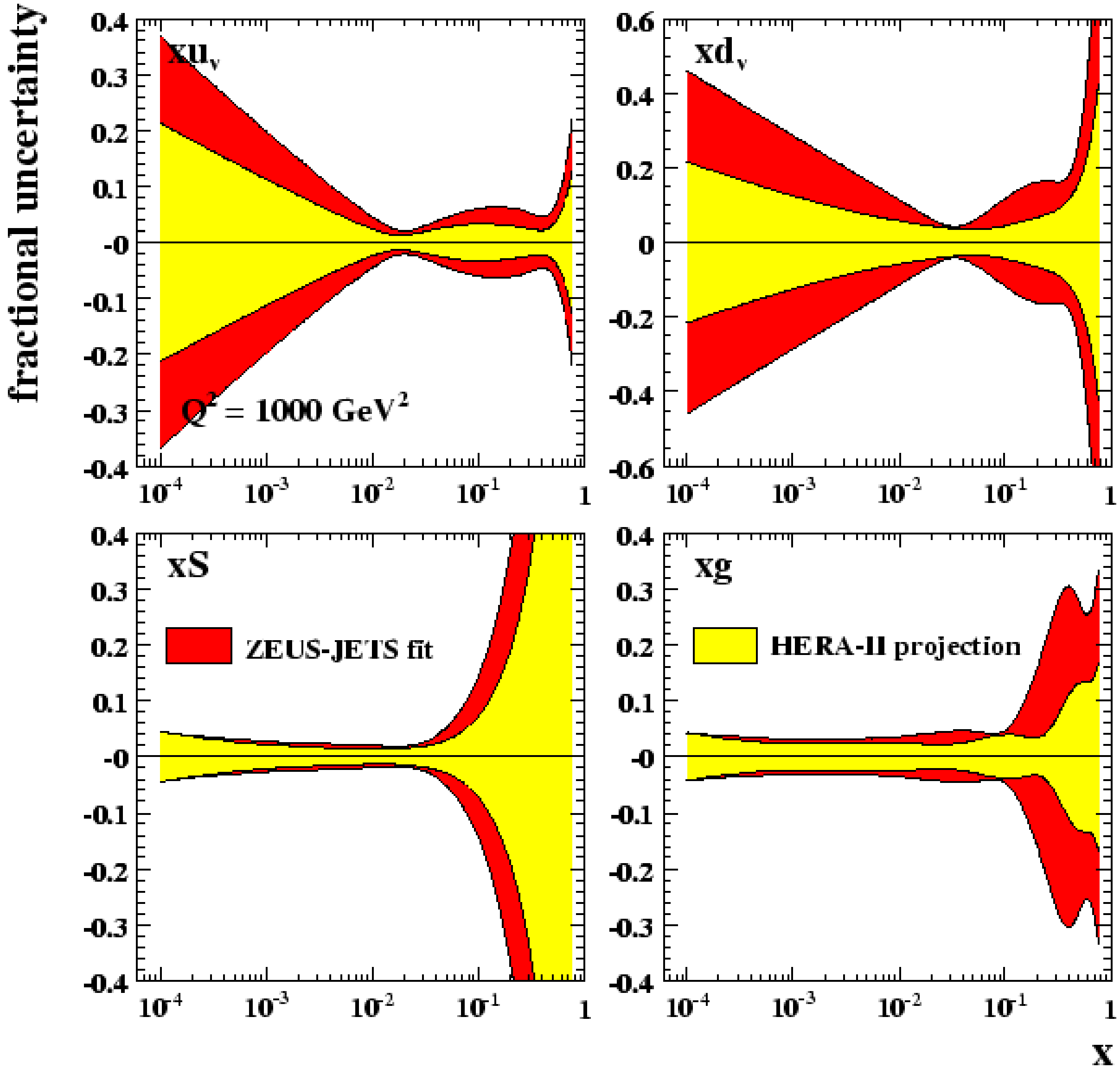
LHeC reaches $\tau \sim 0.15$ for Q^2=1 GeV^2 and $\tau \sim 0.4$ for Q^2=2 GeV^2

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?

How well could we know the Partons at HERA?



700 pb-1
H1 + ZEUS
combined

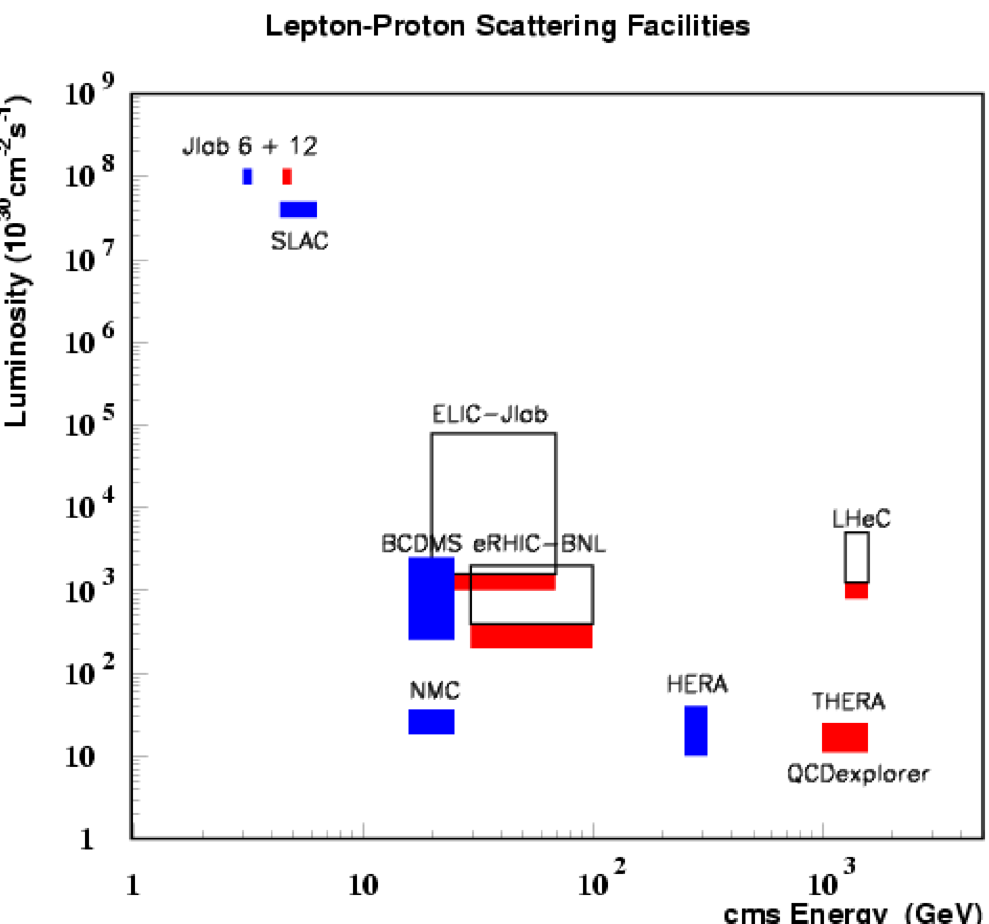
Only statistical improvements considered

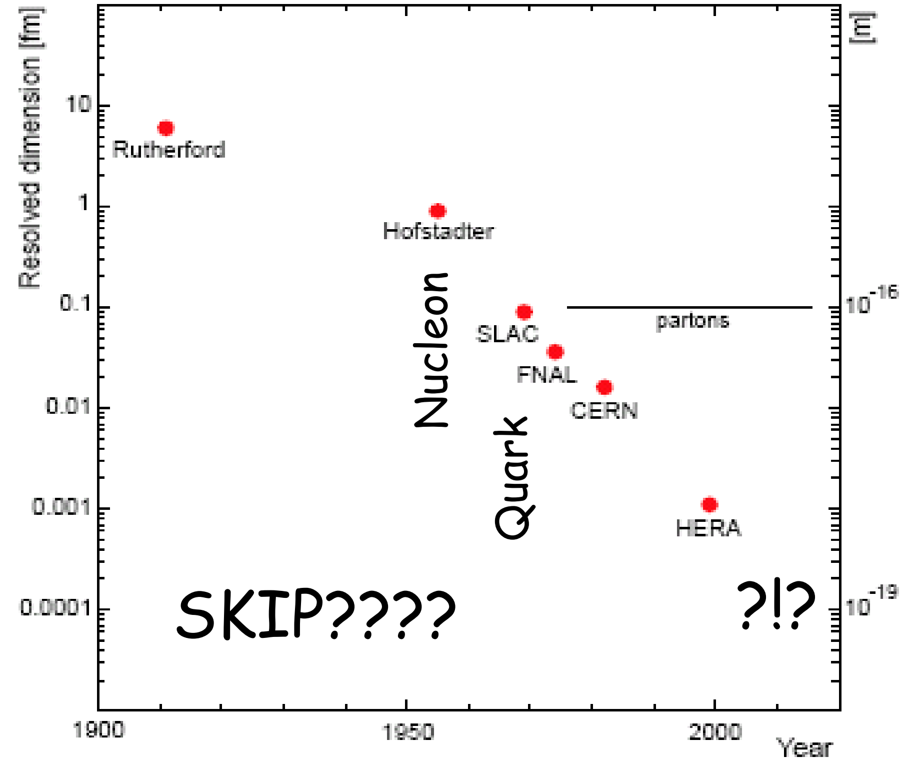
… high x LHC discovery region (esp. gluon) still not well known

(Gwenlan et al., HERA-LHC Workshop)

LHeC Context

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

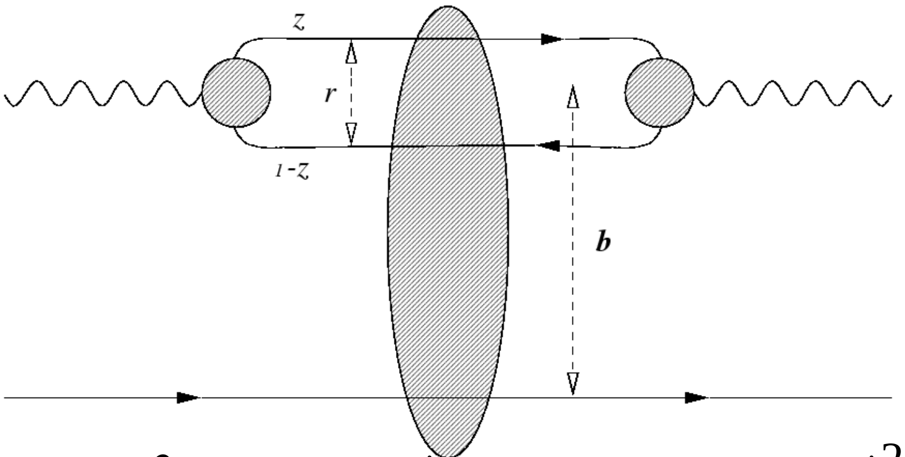




- Combining the LHC protons with an electron beam is natural next step in pushing the frontiers of ep physics: small resolved dimensions, high Q^2 and low x
- Can be done without affecting pp running

Reminder : Dipole models

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



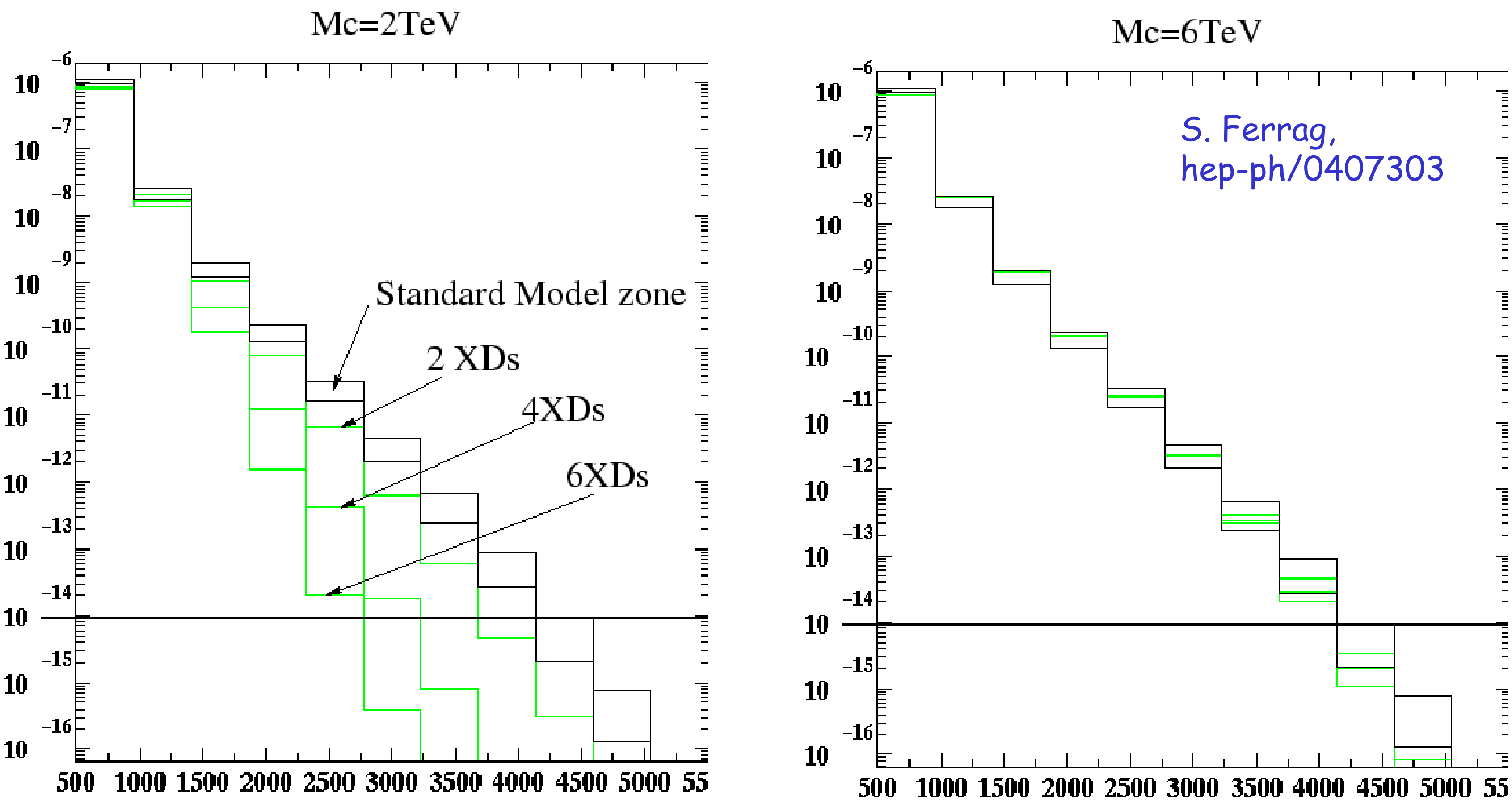
$$\sigma_{\gamma^* p}^{T,L}(x,Q^2) \sim \int dz\, d^2r \left|\psi_{\gamma^*}^{T,L}(z,r,Q^2)\right|^2 \sigma_{dipole}(x,r,z)$$

• 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

Partons Limiting Searches for New Physics

Some BSM models give deviations in high mass dijet spectra
… e.g. a model of extra dimensions …

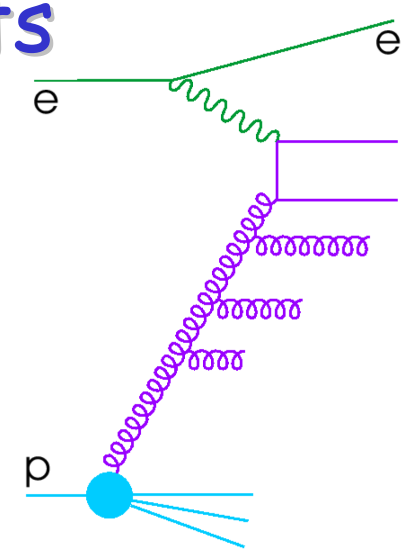


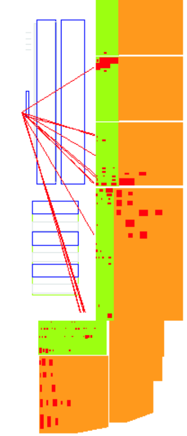
… in this example, high x PDF uncertainties reduce sensitivity to compactification scales from 6 TeV to 2 TeV

Forward Jets

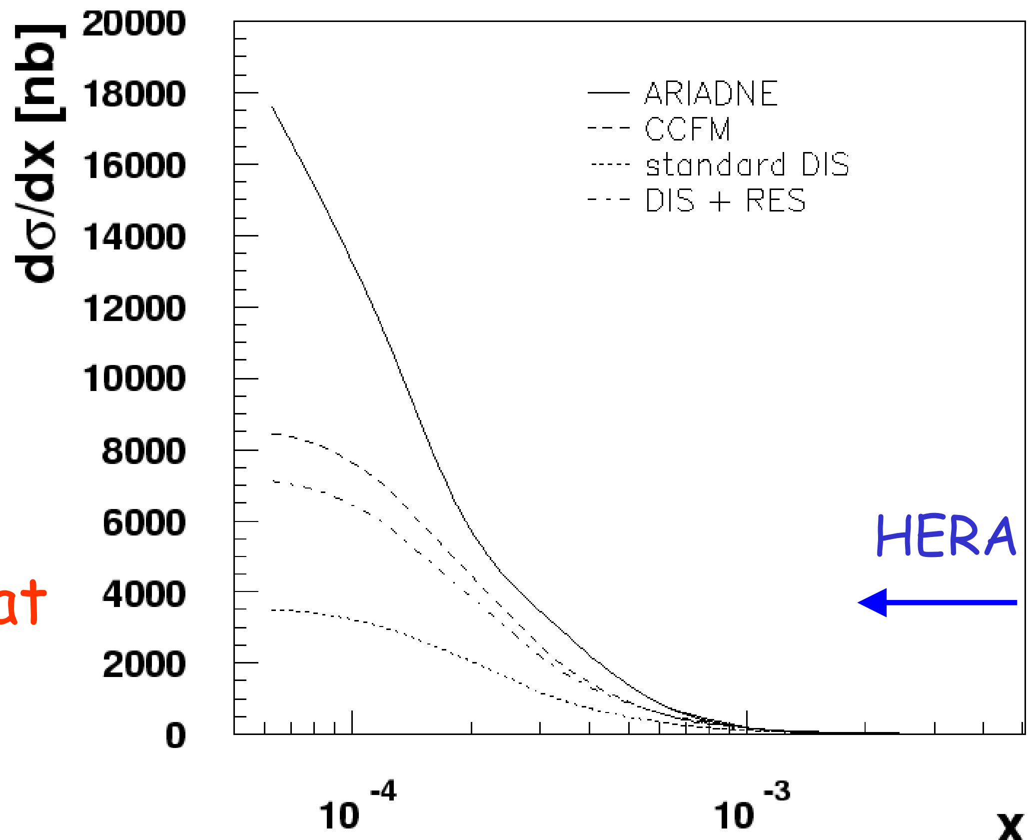
Long HERA program to understand parton cascade emissions by direct observation of jet pattern in the forward direction.
… DGLAP v BFKL v CCFM v resolved γ^*…

SKIP???





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.