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

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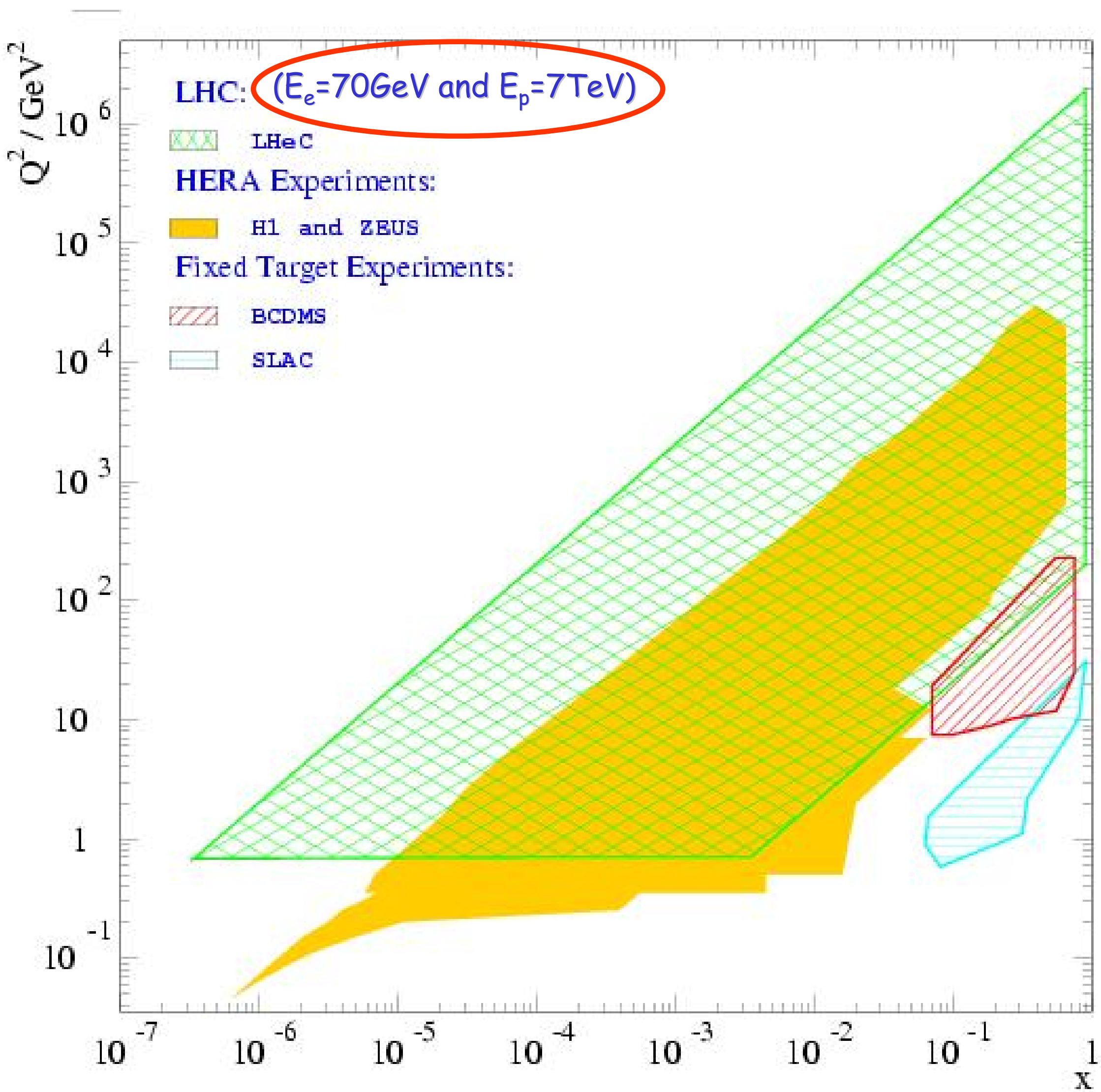
Birmingham Seminar

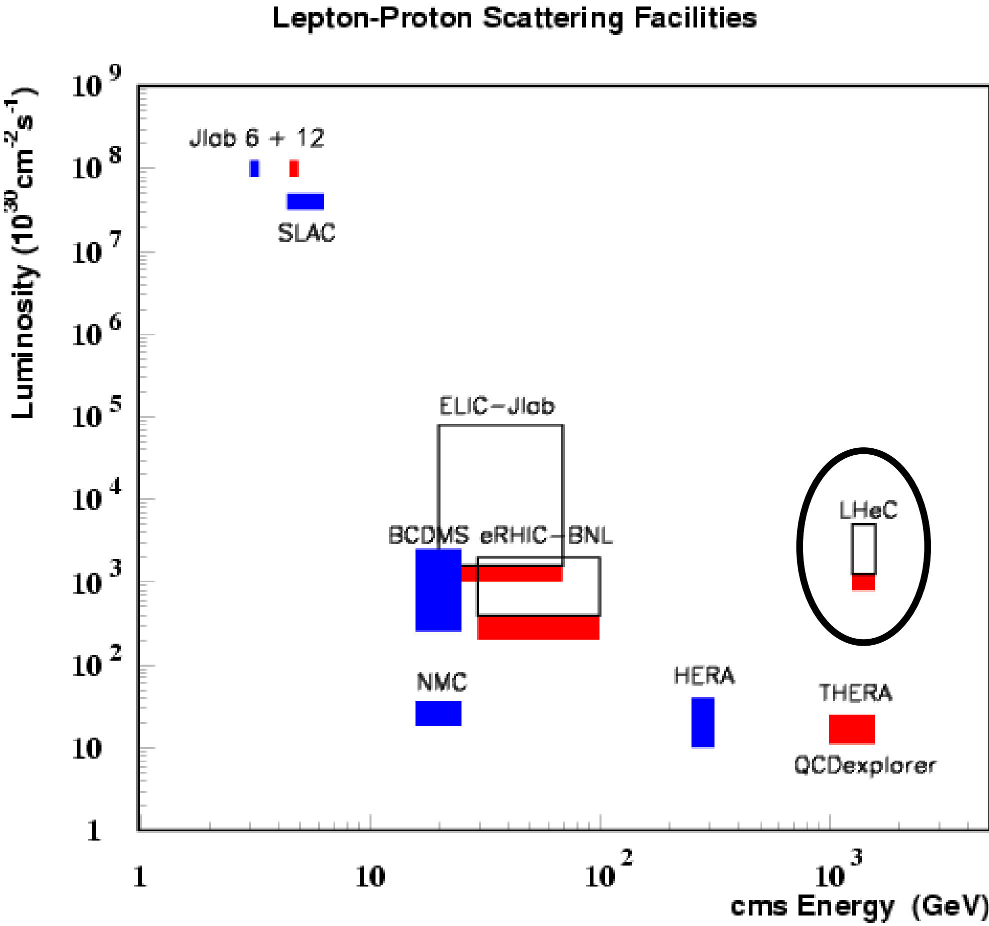
20 February 2008



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

Contents

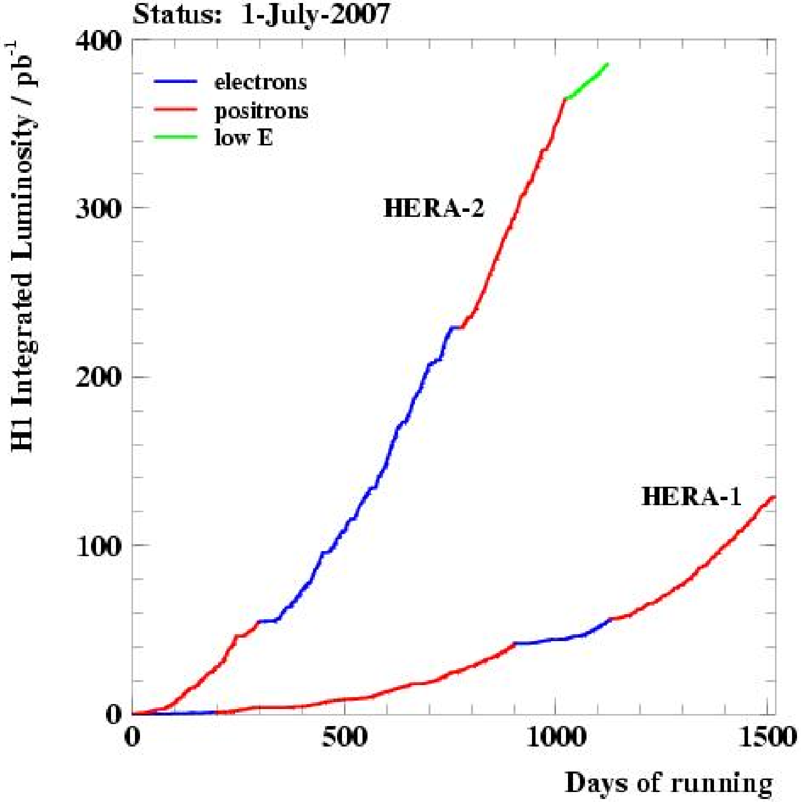
- DIS at the end of HERA and the start of LHC
- The Case for high luminosity TeV Scale DIS
- Some first Physics case studies (a little low x bias)
- LHeC Design Possibilities
- First Detector Considerations
- Organisation and workshop plans



(... a very early perspective - much more detail to follow in 2008/9 workshop)

HERA (1992-2007)

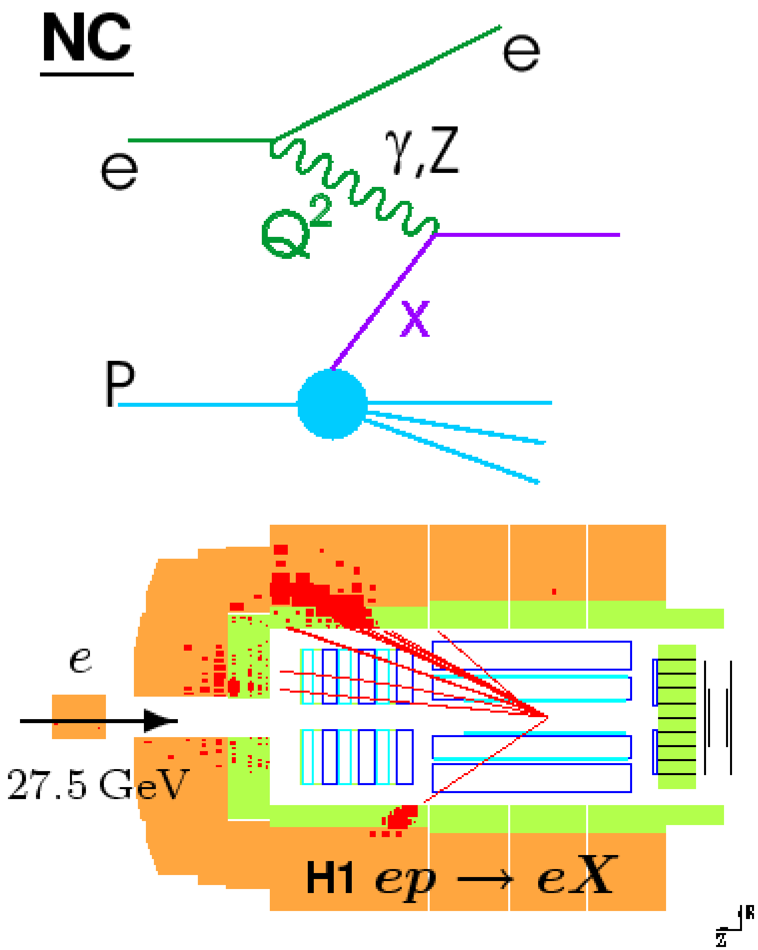
- The only ep collider ever built (equivalent energy to 50 TeV fixed target)

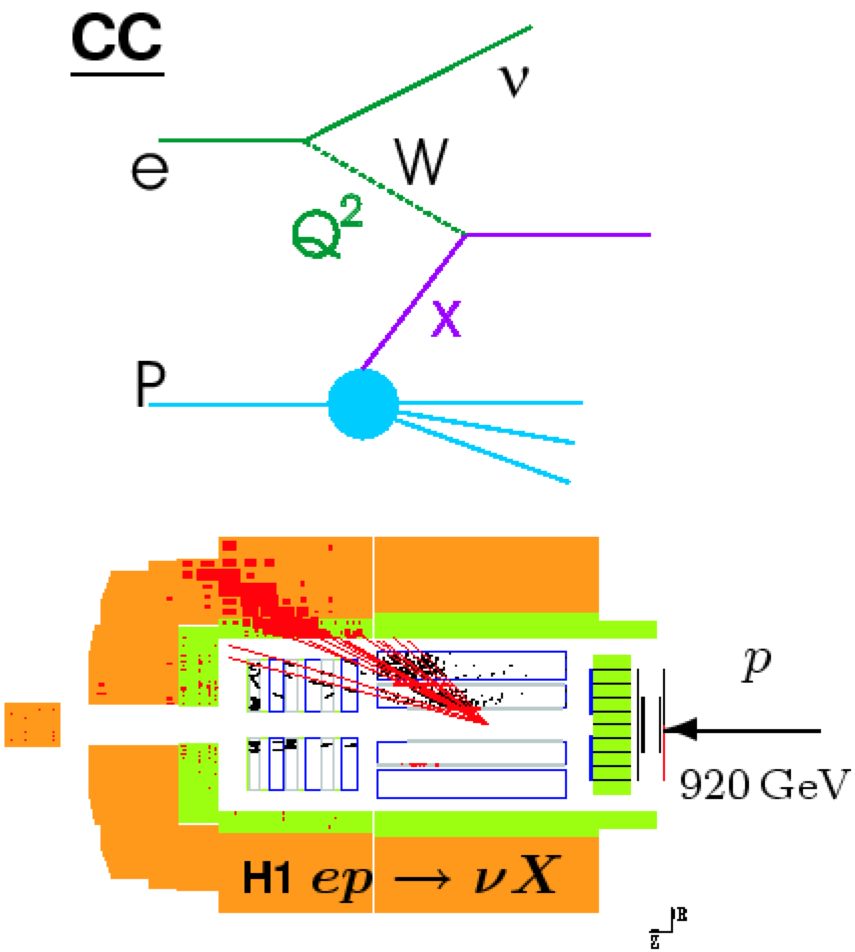


- … "the world's most powerful microscope" using virtual boson to resolve p structure (~7.10^{-19} m)

- Ended '07 with low E_p run (F_L etc)

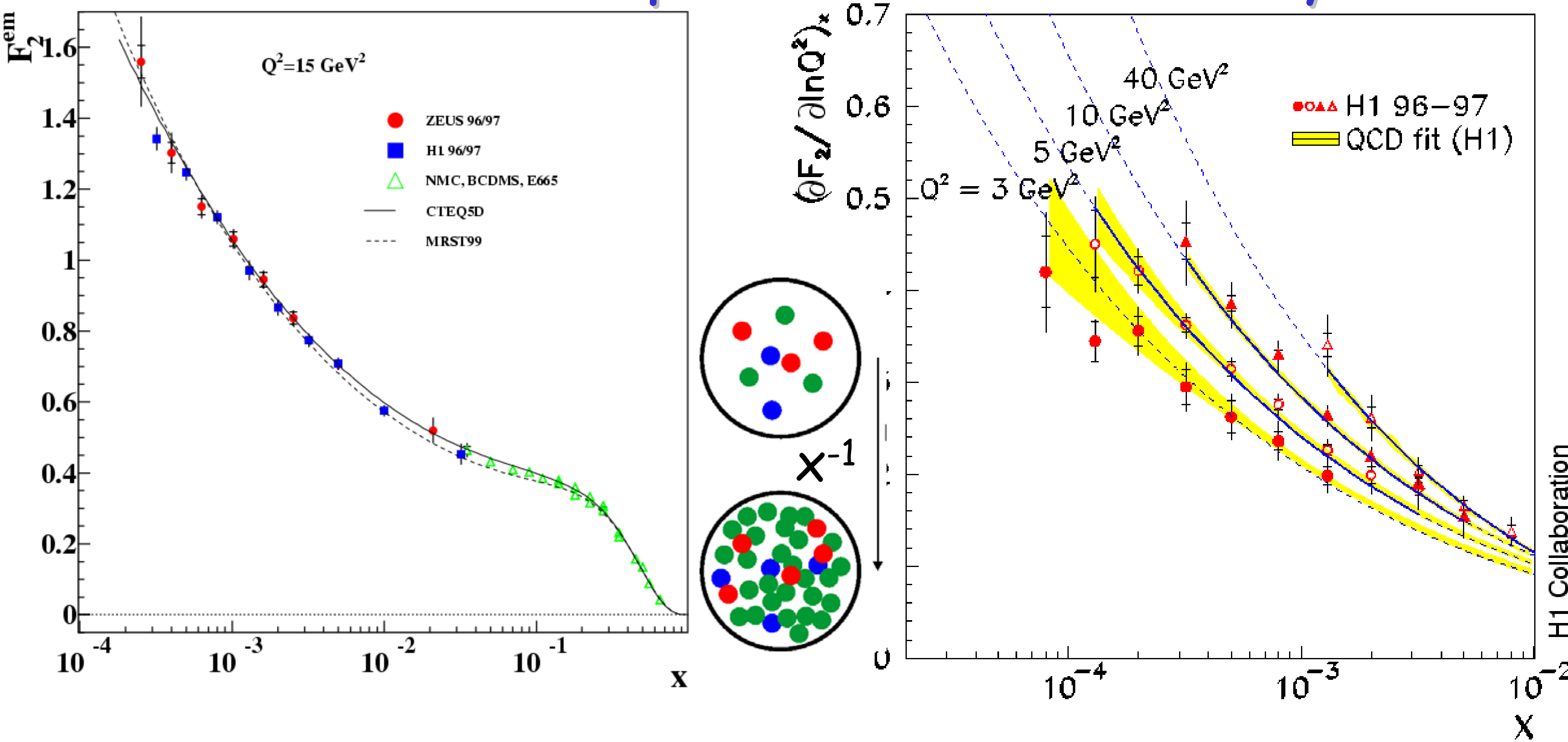
DIS: Classic Pictures of eq Scattering





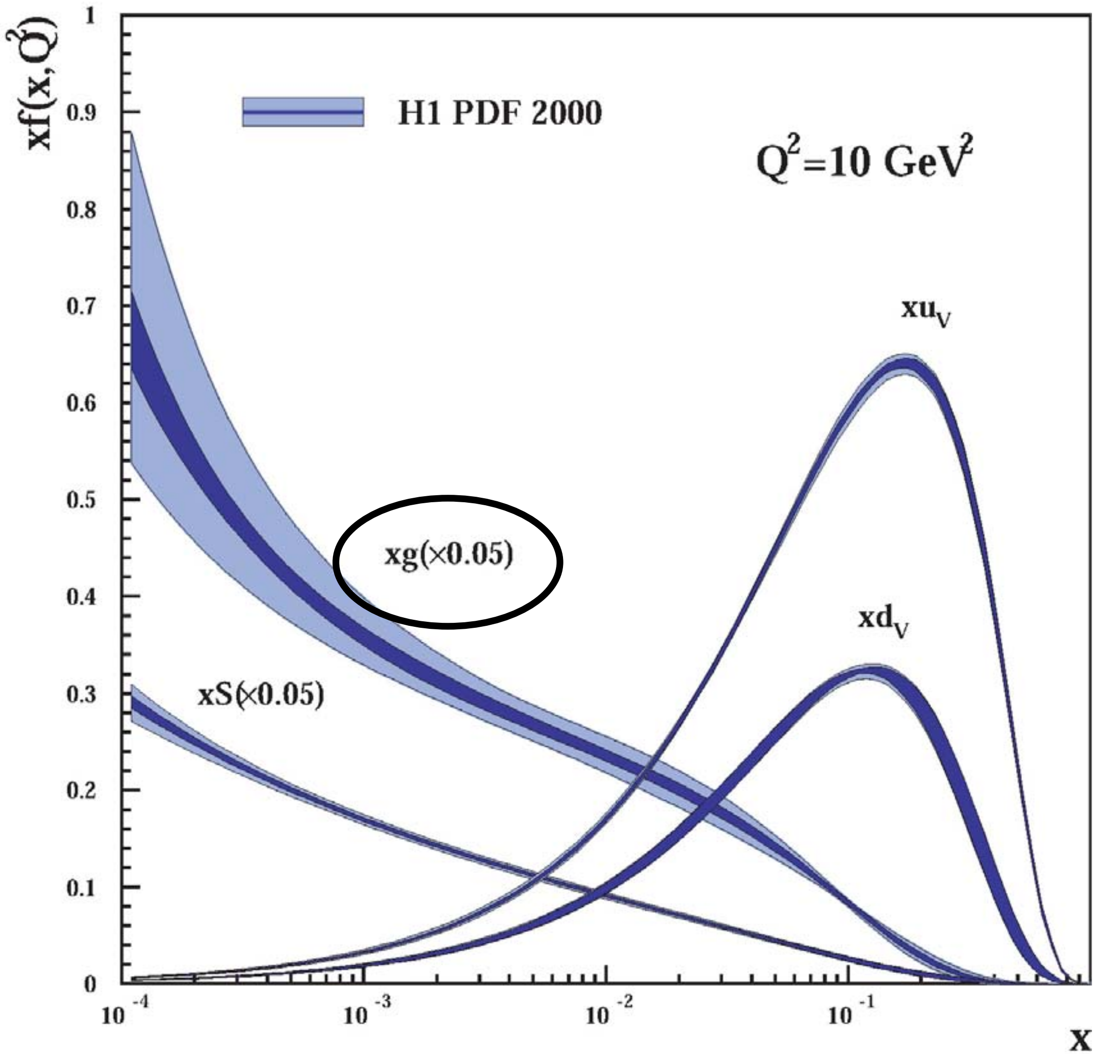
- Precision measurements at low Q^2 dominated by γ^* exchange.
- Lumi limitations at highest Q^2 (searches, high x partons, W, Z exchange → parton flavour decomposition)

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

- Much improvement still to be expected (final H1 + ZEUS)

Limitations / Questions …

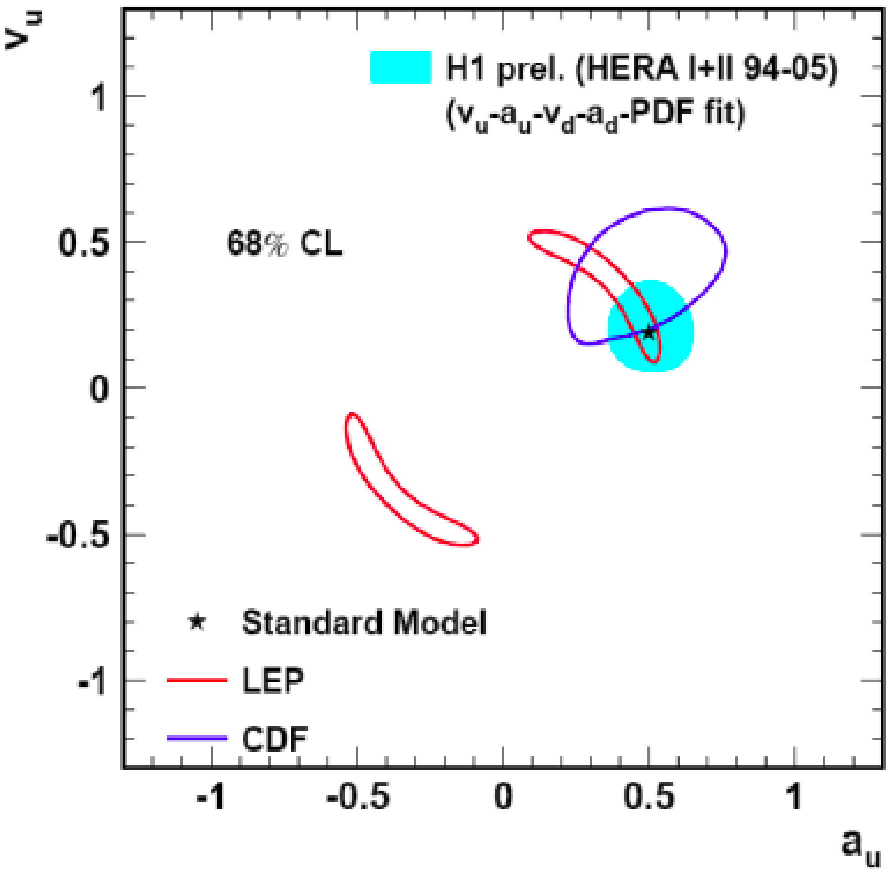
? High x and low x uncertainties? …

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

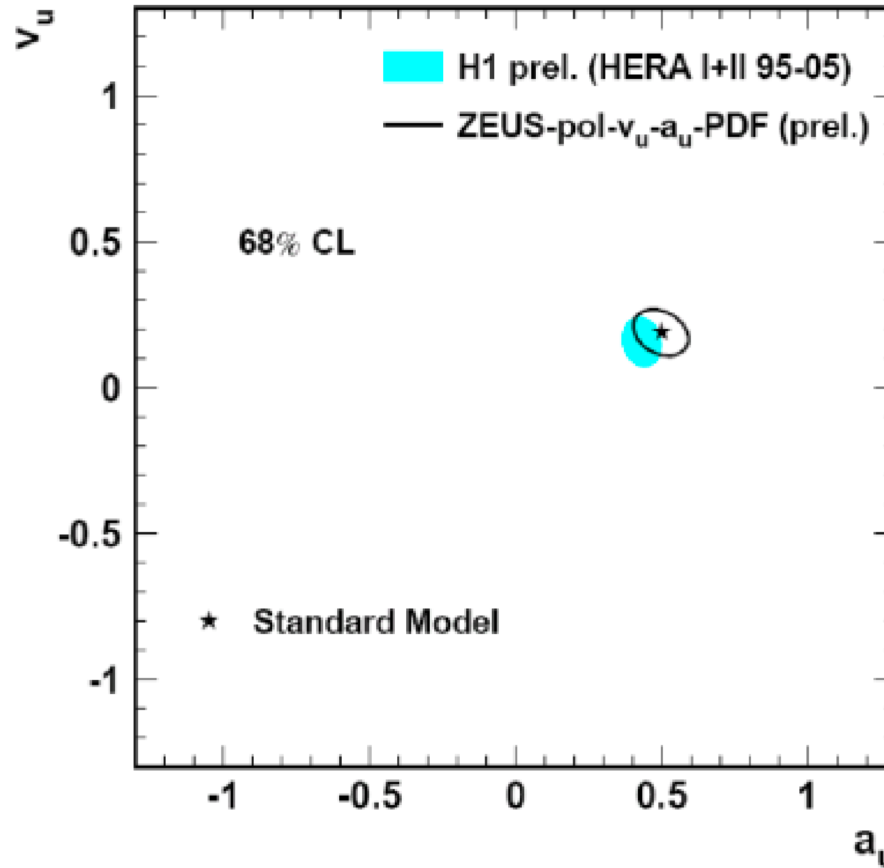
? Can we trust the (NLO DGLAP) theory at all x?

Light Quark Couplings to Z Boson

Fit to PDFs and u,d couplings



Fit to PDFs and u couplings *only*



Combined fits to PDFs and light quark couplings to Z using polarised lepton data

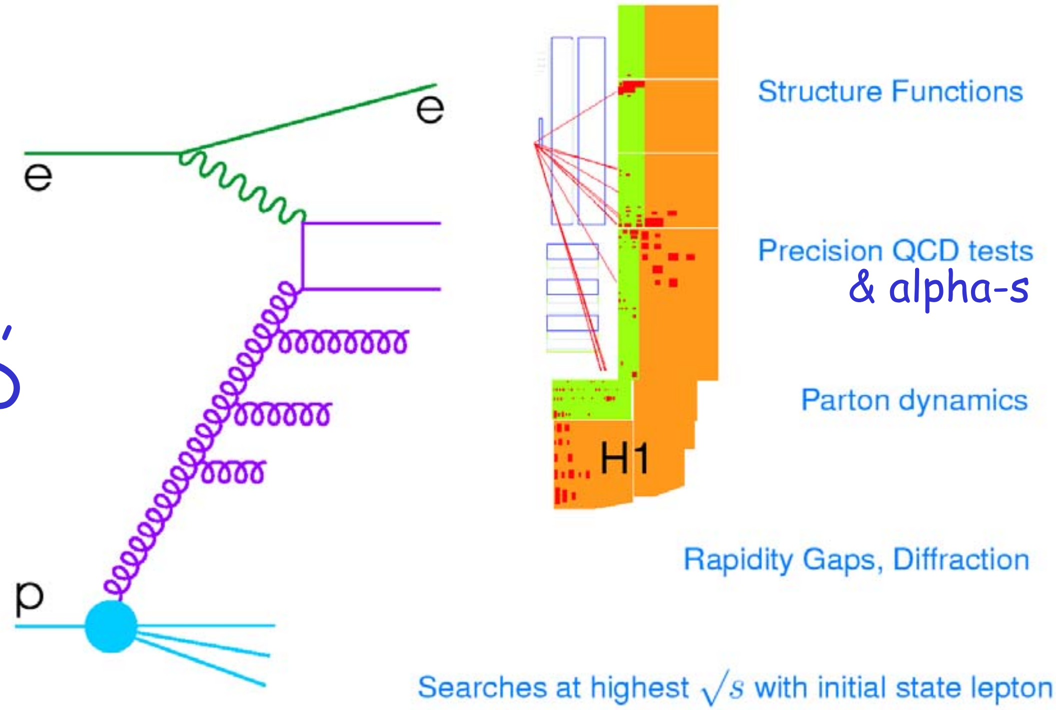
… world leading precision on up quark coupling

… uses high Q2 data → luminosity limited

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



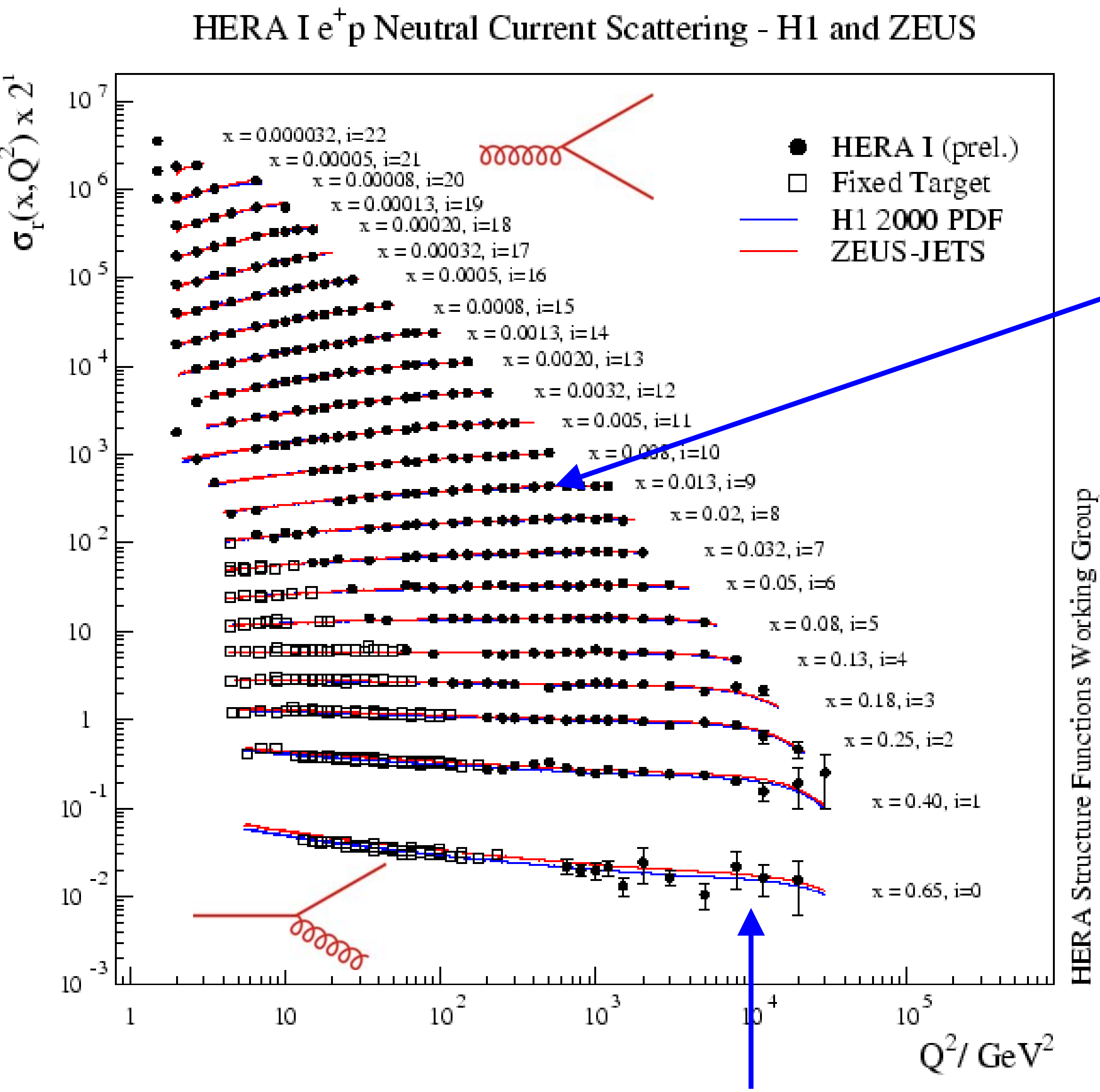
- Forward Jets,
  - Direct tests of assumed parton evolution patterns

  ? Understanding limited by instrumentation near beam-pipe

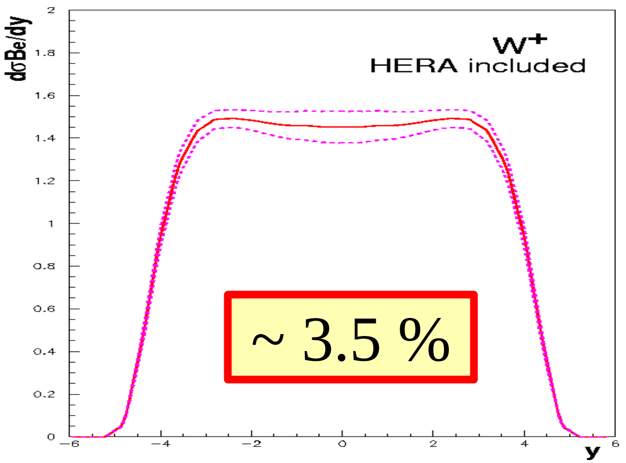
- Diffraction
  - Unique clean probe of gap dynamics and elastic scattering

  ? Understanding limited by (forward) detectors …

Optimising HERA Output

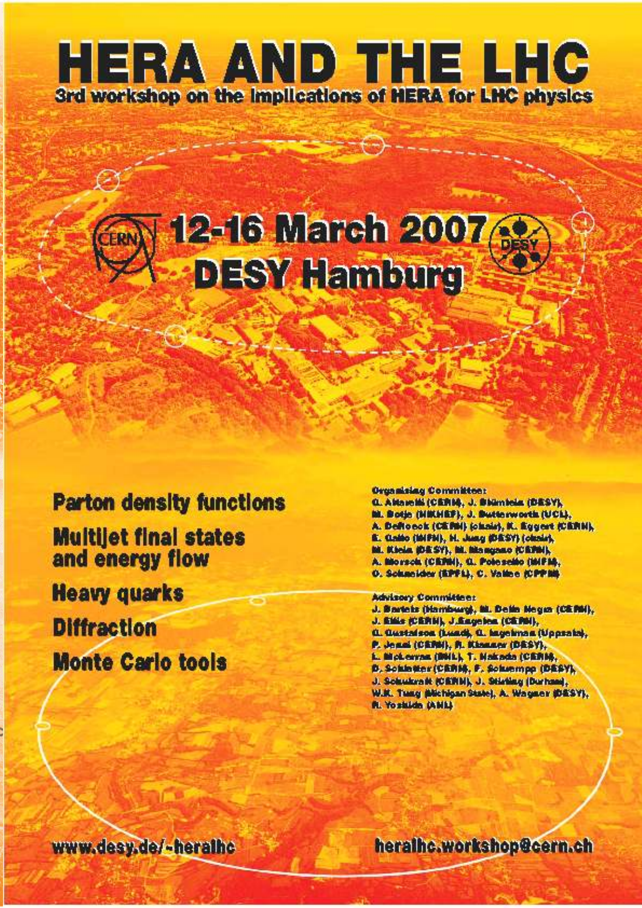


- Combinations of H1 & ZEUS data underway.
- Systematics limited in bulk region … final goal: 1% accuracy → few % precision on M_W^2 scale on LHC rapidity plateau



Luminosity / statistics limit high x / Q^2

HERA-LHC Workshop ...



- how best to use information from HERA at LHC?
- “sharpening LHC tools” using HERA data
- what is still needed from HERA
- next (final?) installment in May 2008

Motivation for TeV Scale DIS

-New Physics of eq Bound States, ν^*, Selectrons …
 leptoquarks, RP violating SUSY, quark compositeness

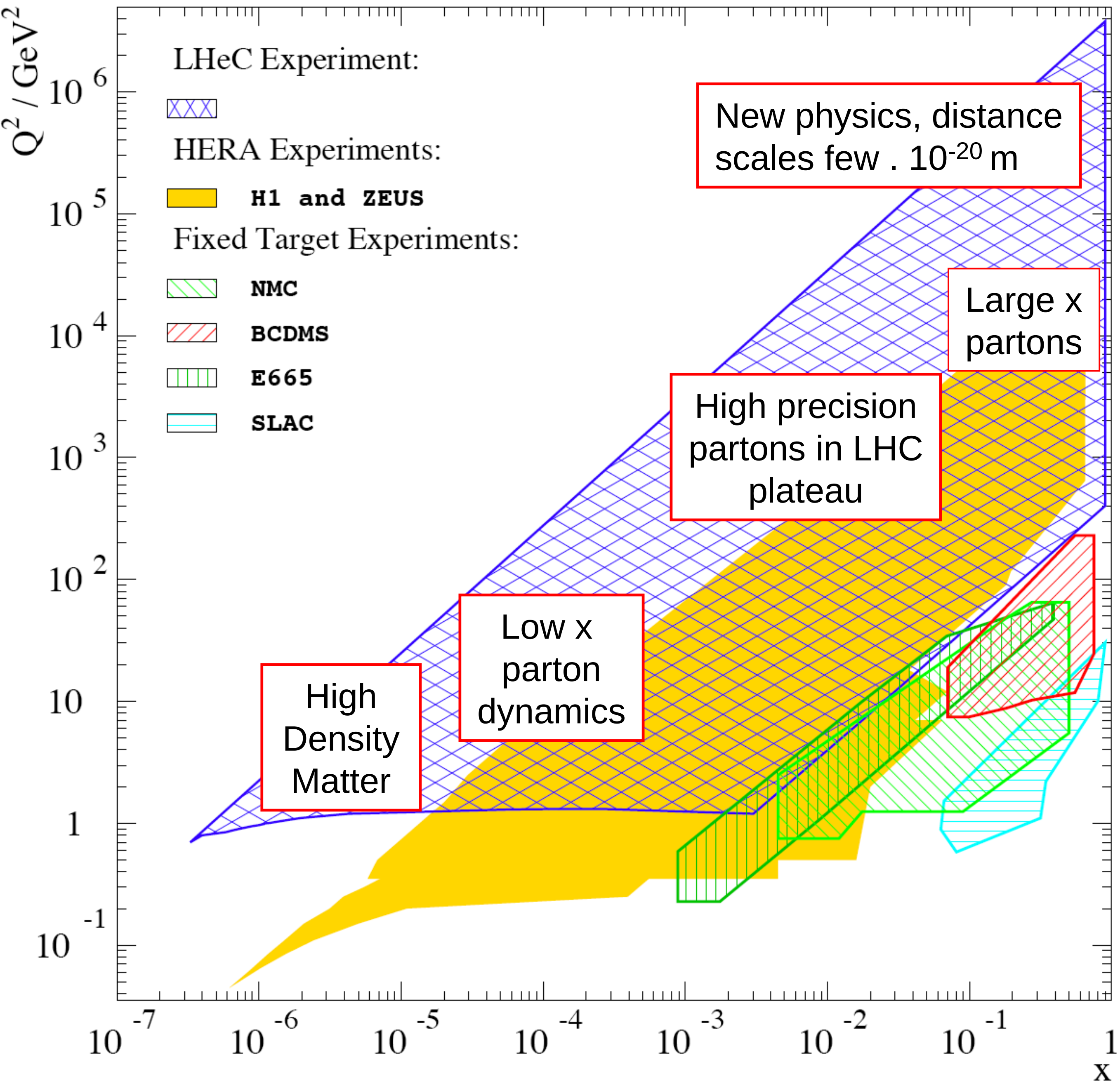
-The Low x Limit of Quantum Chromodynamics
 high parton densities with low coupling
 `saturating; the parton growth, new evolution dynamics
 diffraction and confinement
 quark-gluon dynamics and the origin of mass

-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



$\sqrt{s} = 1.4$ TeV

$W \leq 1.4$ TeV

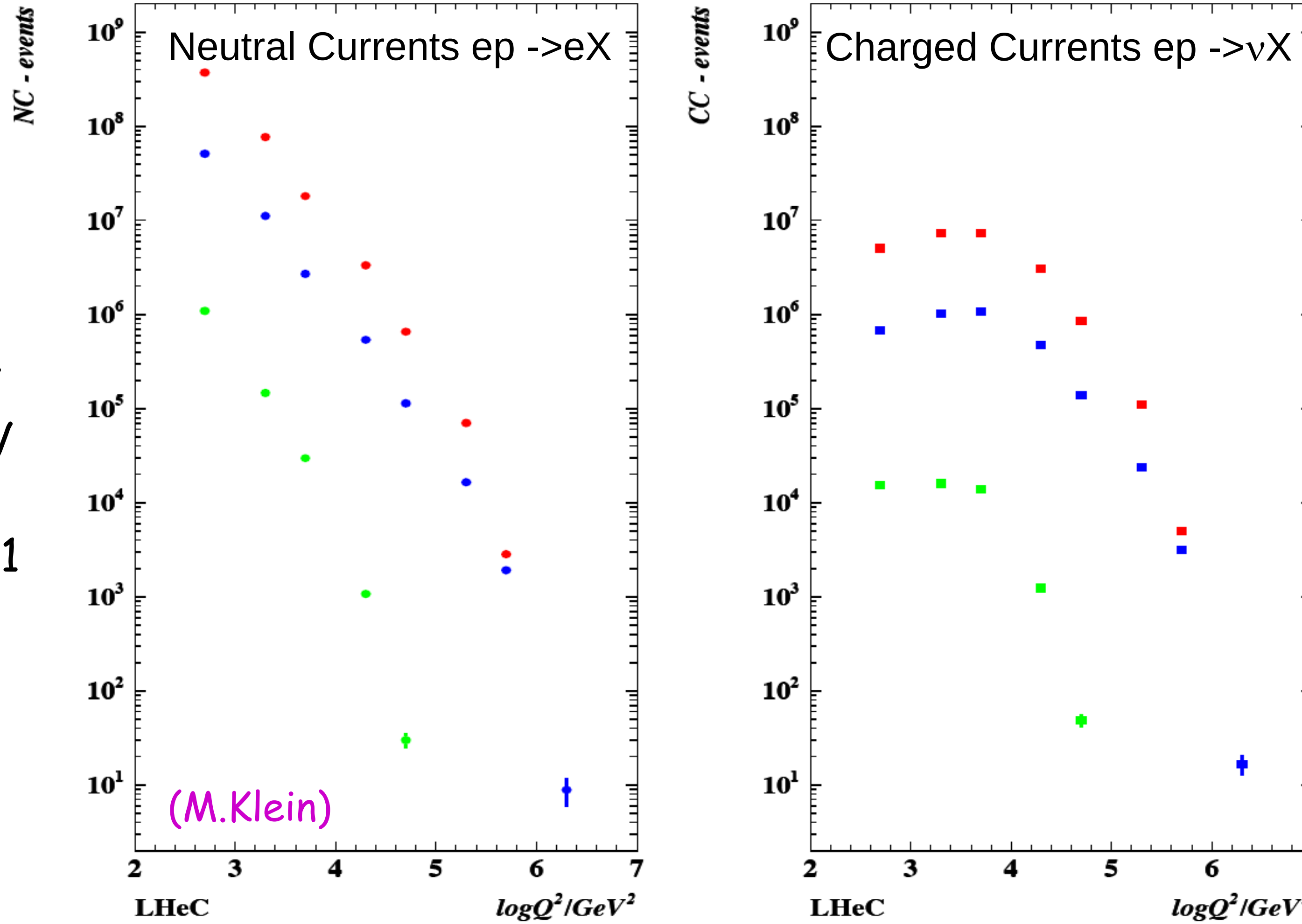
$x \geq 5.10^{-7}$ at $Q^2 \leq 1$ GeV^2

- 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

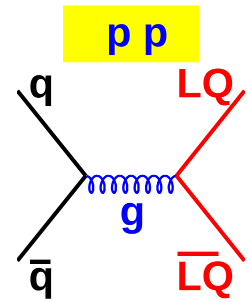
- HERA 1fb-1
  Ep = 920 GeV
  Ee = 27.5 GeV
- LHeC 100 fb-1
  Ep = 7 TeV
  Ee = 70 GeV
- LHeC 10 fb-1
  Ep = 7 TeV
  Ee = 140 GeV

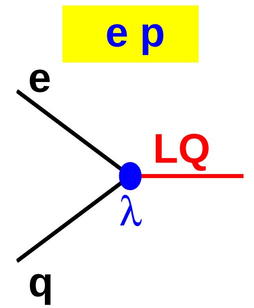


- Reaching highest Q^2 (and x) region requires very high lumi
- Reduced lumi can be compensated by increased energy

Lepton-quark Bound States

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





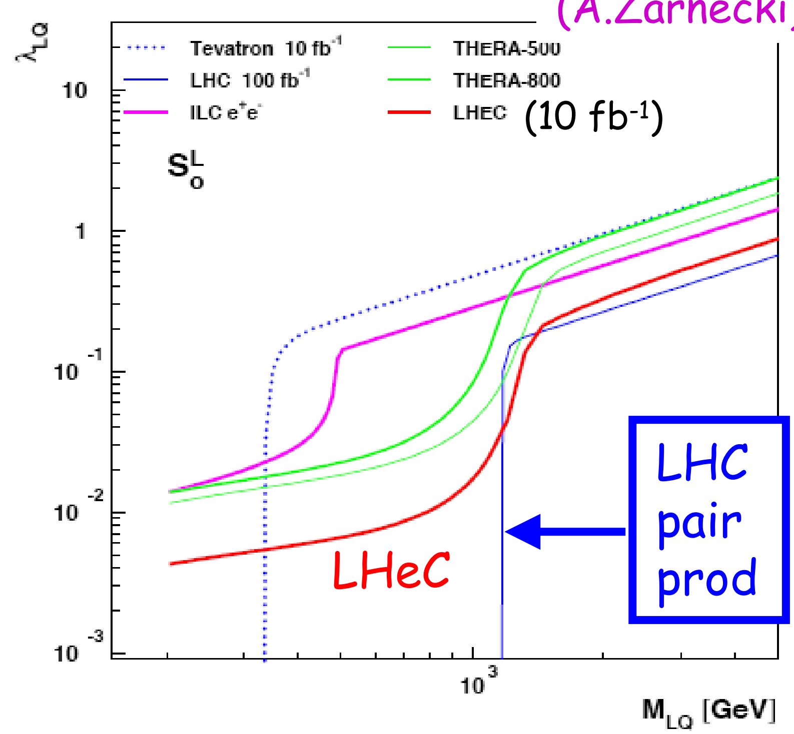
Yukawa coupling, λ

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

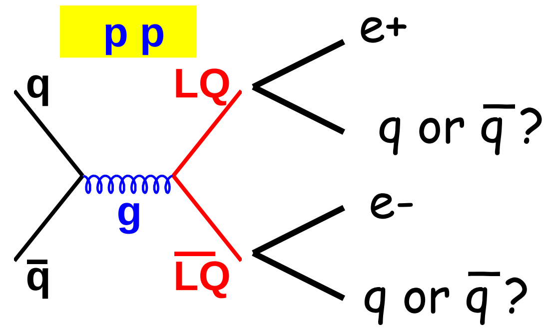
- (Mostly) pair produced in pp, single production in ep.

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

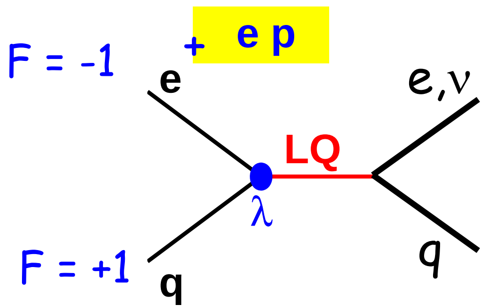
(A.Zarnecki)

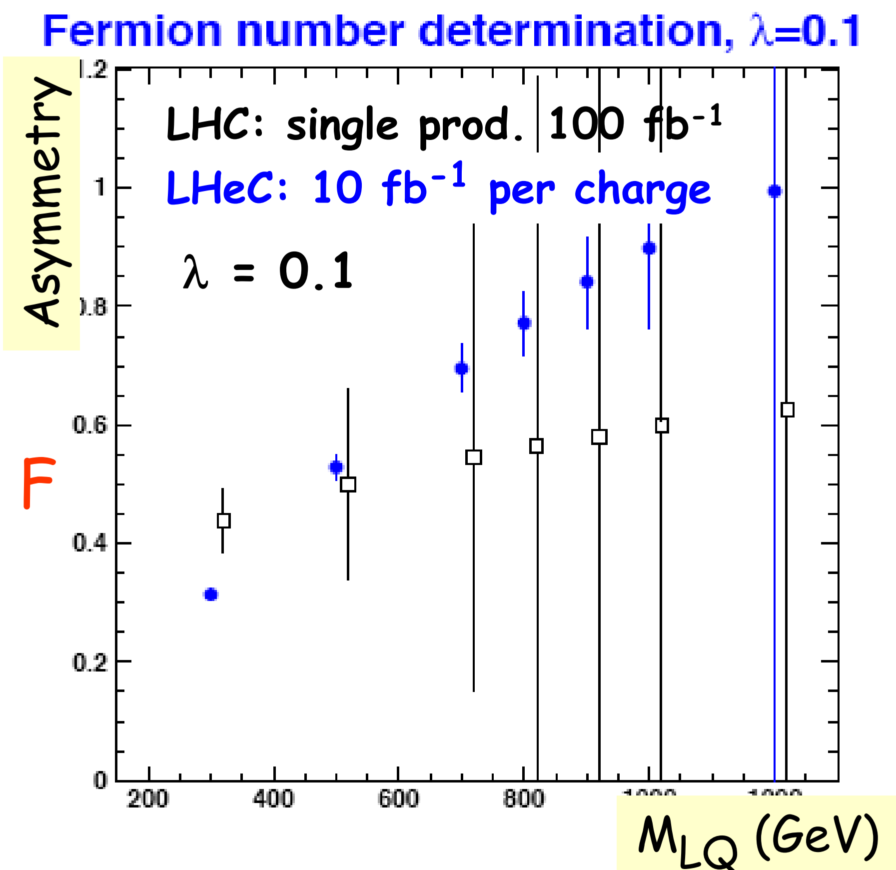


Leptoquark Properties at LHeC



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



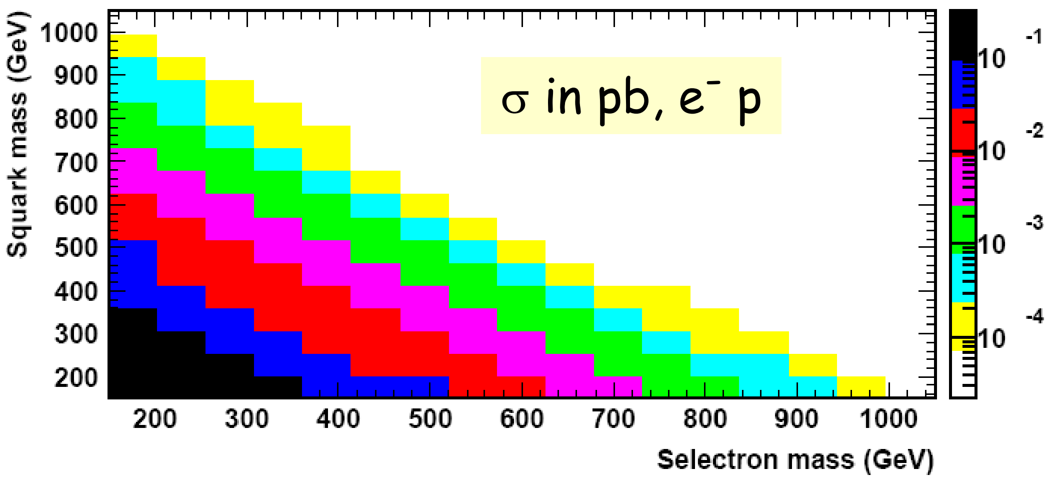


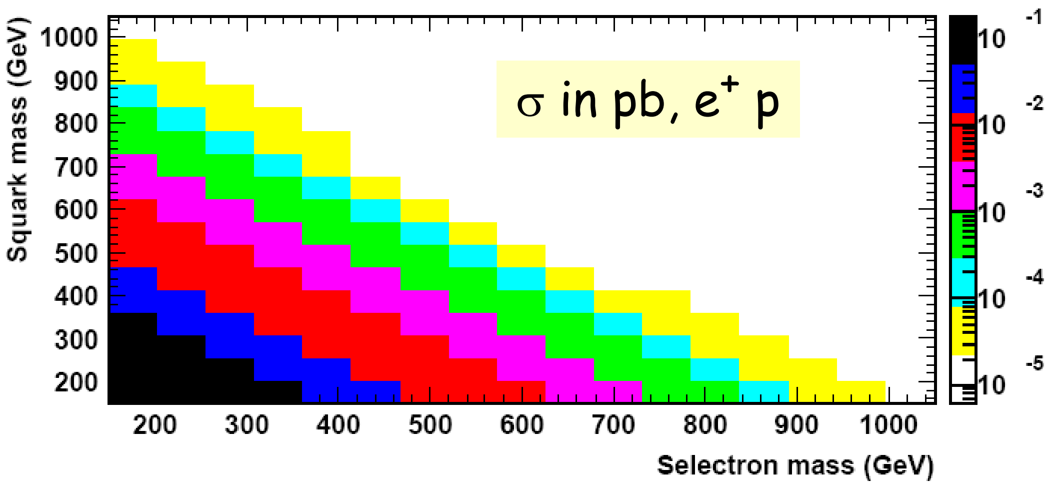
LHeC: - Resonant production at high x implies q rather than qbar. Sign of e^+p / e^-p asymmetry then determines fermion number F

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

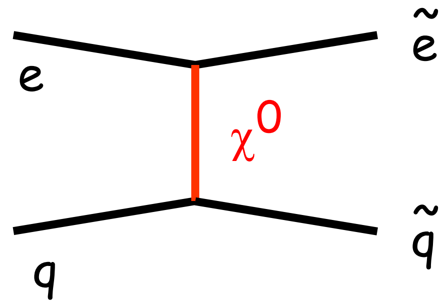
Supersymmetry

tan β = 10, M_2 = 380 GeV, μ = -500 GeV





(E.Perez)



Pair production via t-channel exchange of a neutralino.

Cross-section sizeable for ΣM < 1 TeV

i.e. if squarks are "light", could observe selectrons up to ~ 500 GeV, a little beyond LHC?

Systematic Precision Requirements

e.g. Requirements based on reaching per-mil α_s (c.f. 1-2% now)

The new collider …

- should be 100 times more luminous than HERA …

… achievable using low β focusing quad's (acceptance → 170°)

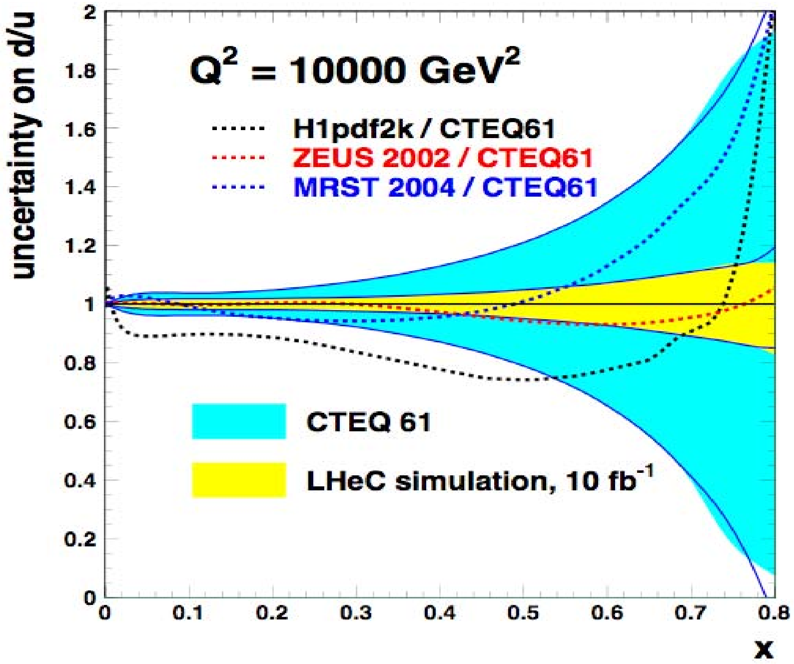
The new detector

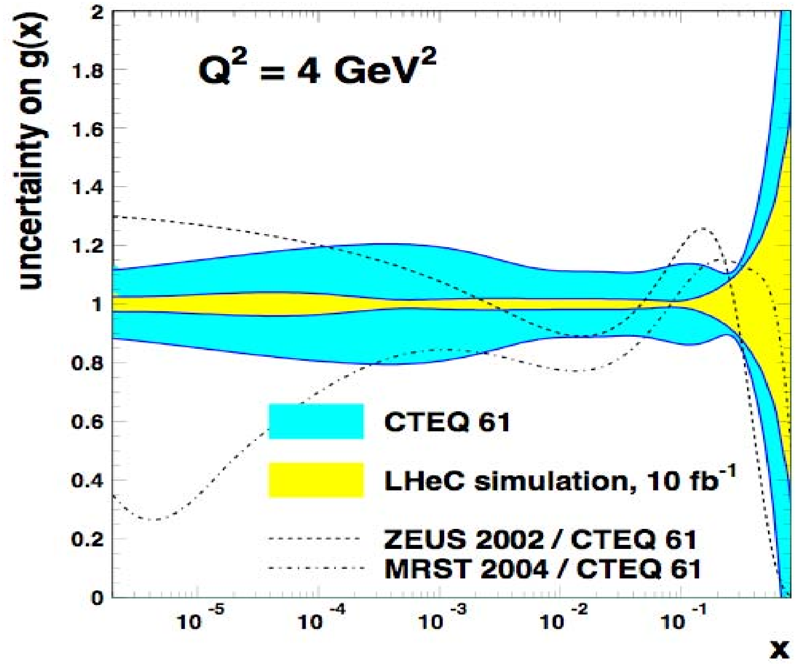
- should be at least 2 times better than H1 / ZEUS

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

Lumi = 10^{33} cm^{-2} s^{-1}	(HERA 1-5 x 10^{31} cm^{-2} s^{-1})
Acceptance 10-170° (→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%)

LHeC Impact on High x Partons and α_s



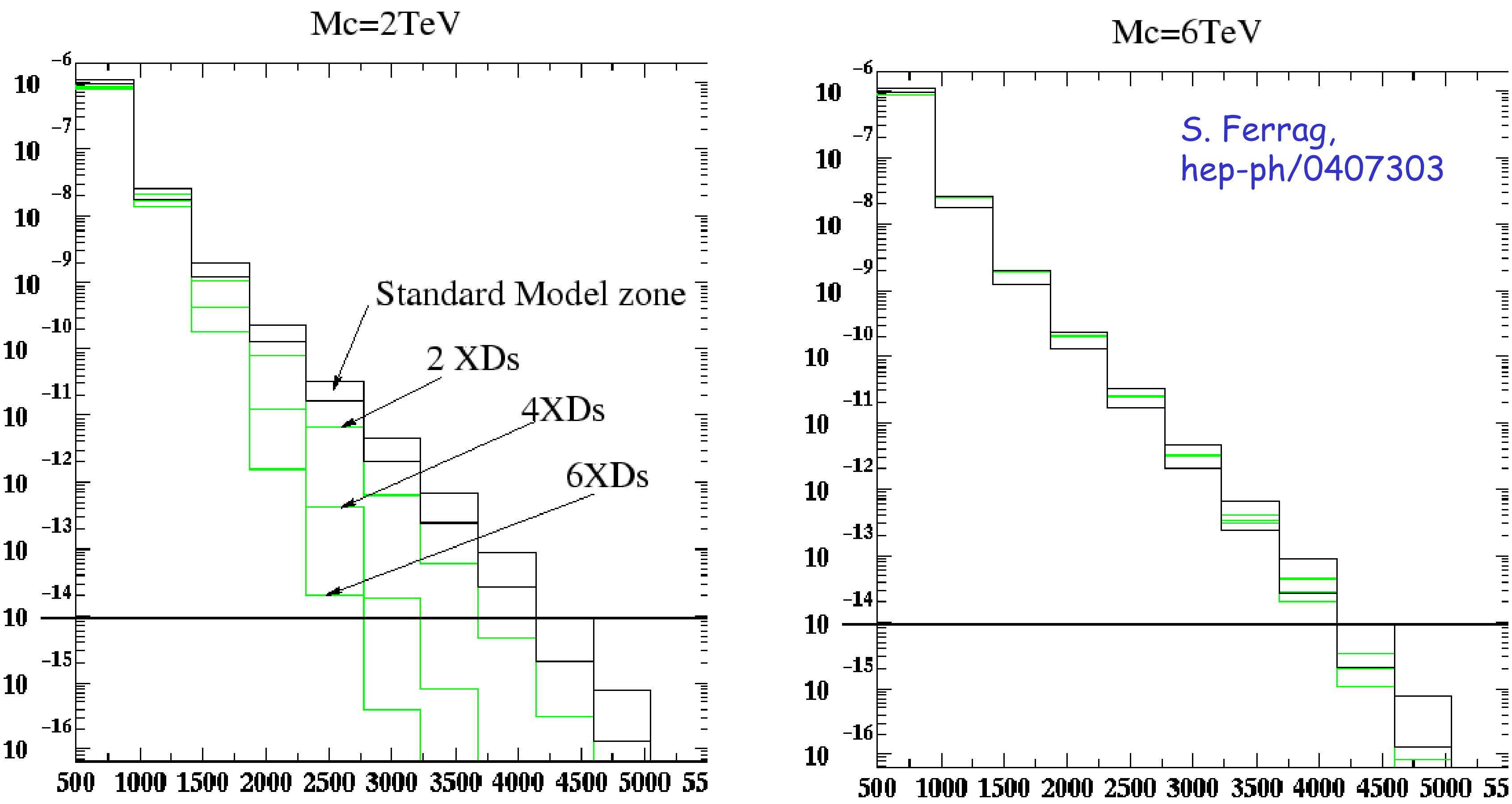


Full NC/CC sim (with systs giving per mil α_s) & NLO DGLAP fit using standard HERA technology…

… high x pdfs → LHC discovery & interpretation of new states?

Partons Limiting Searches for New Physics

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

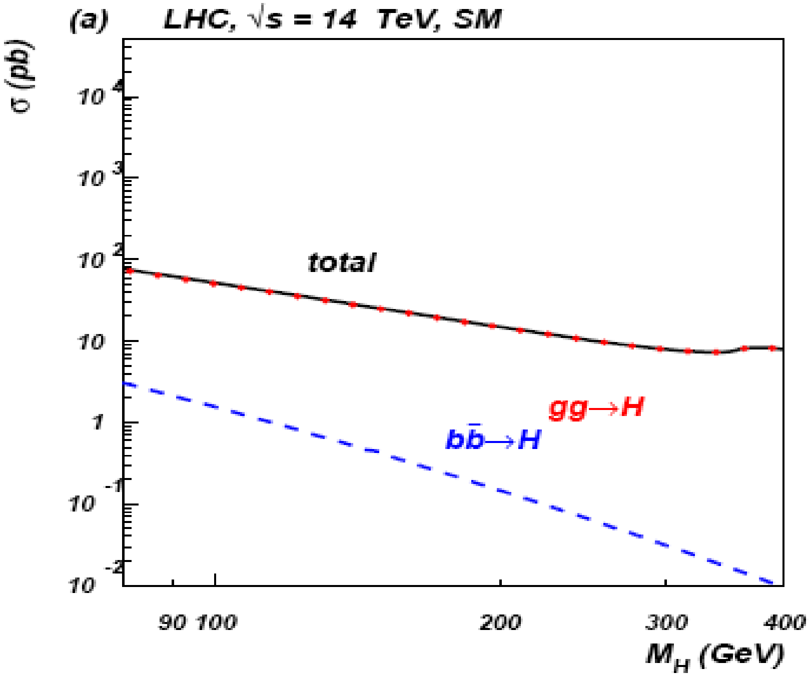


… in this example, high x PDF uncertainties reduce sensitivity to compactification scales from 6 TeV to 2 TeV for 2XDs

Heavy Quarks: HERA → LHC

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

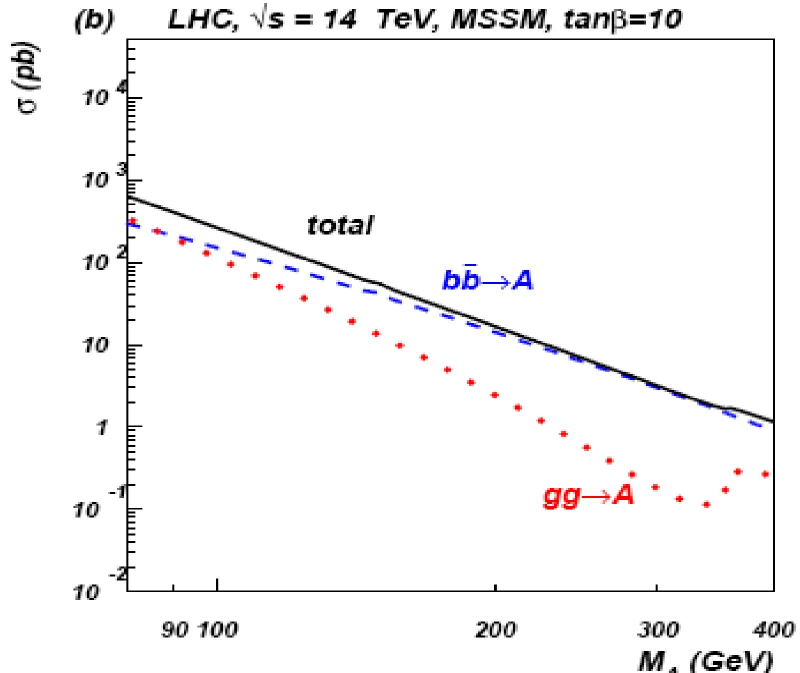
• Crucial for understanding LHC initial state for new processes (e.g. bbbar->H) and backgrounds.



Higgs

<-SM

MSSM->



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

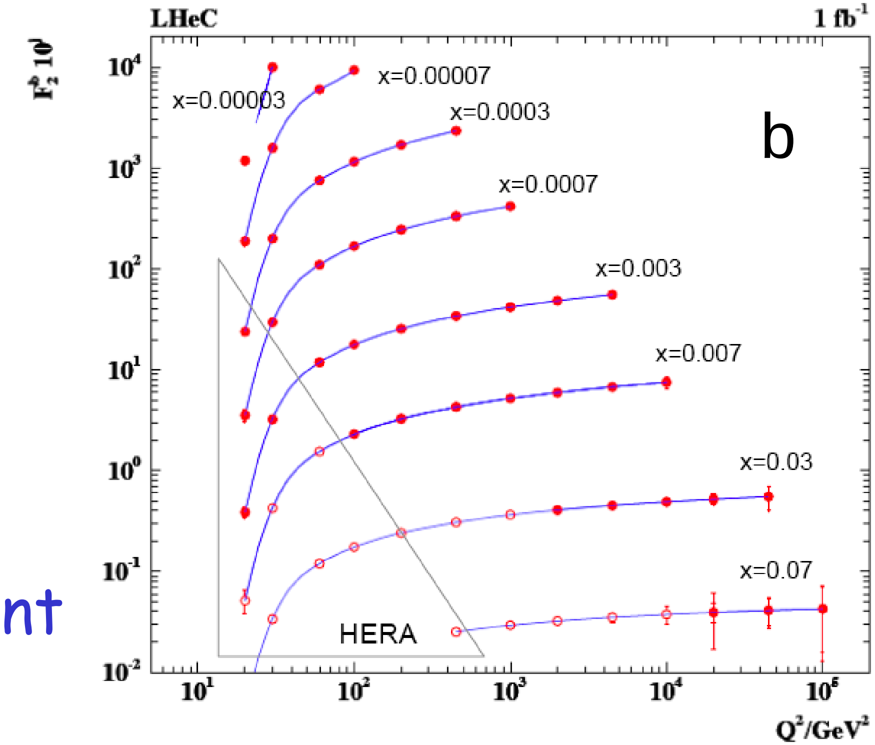
Heavy Quarks: LHeC

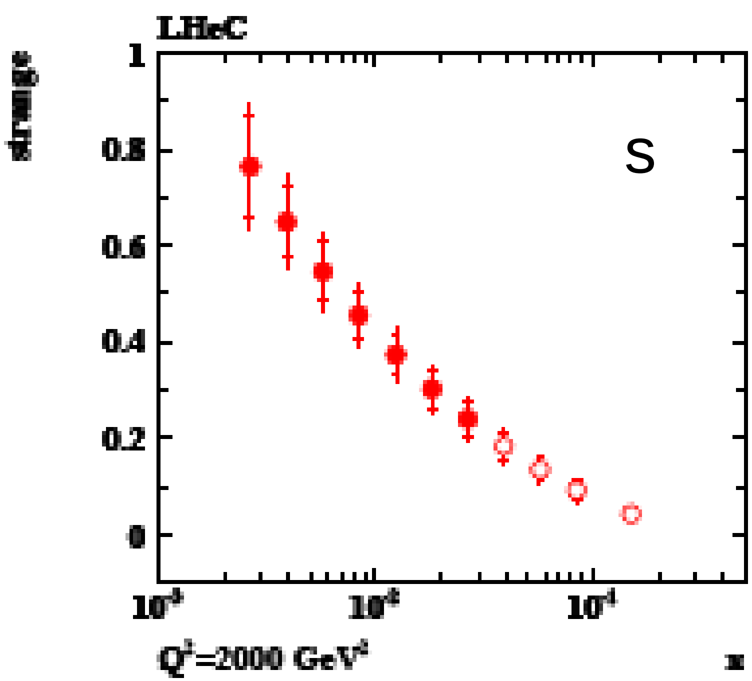
High precision c, b measurements (modern Si trackers, beam spot 15 * 35 μm^2 , increased rates at larger scales).

Systematics at 10% level

→beauty is a low x observable!

→s (& sbar) from charged current

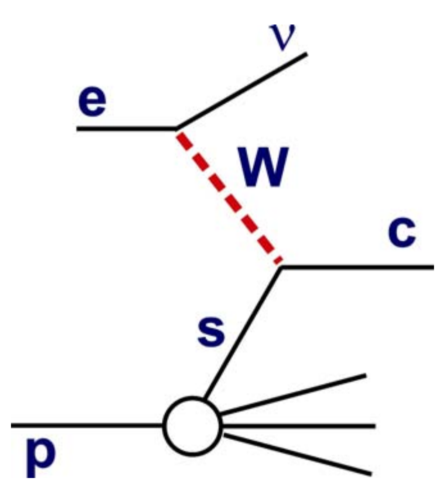




● LHeC 10° acceptance

○ 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

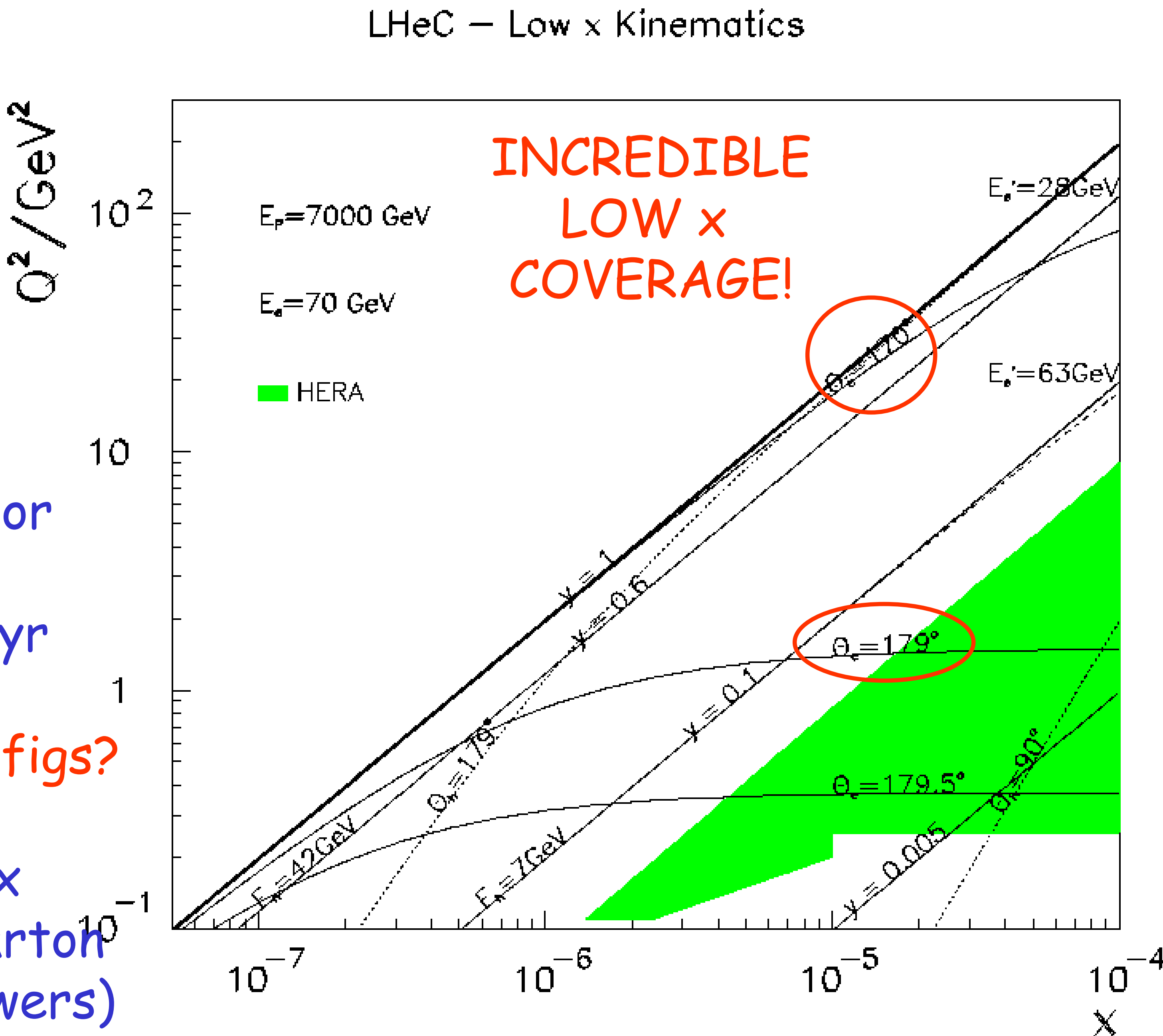
Requires detectors close to beam pipe

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

Lumi ~ 1 fb^{-1} / yr

2 detector configs?

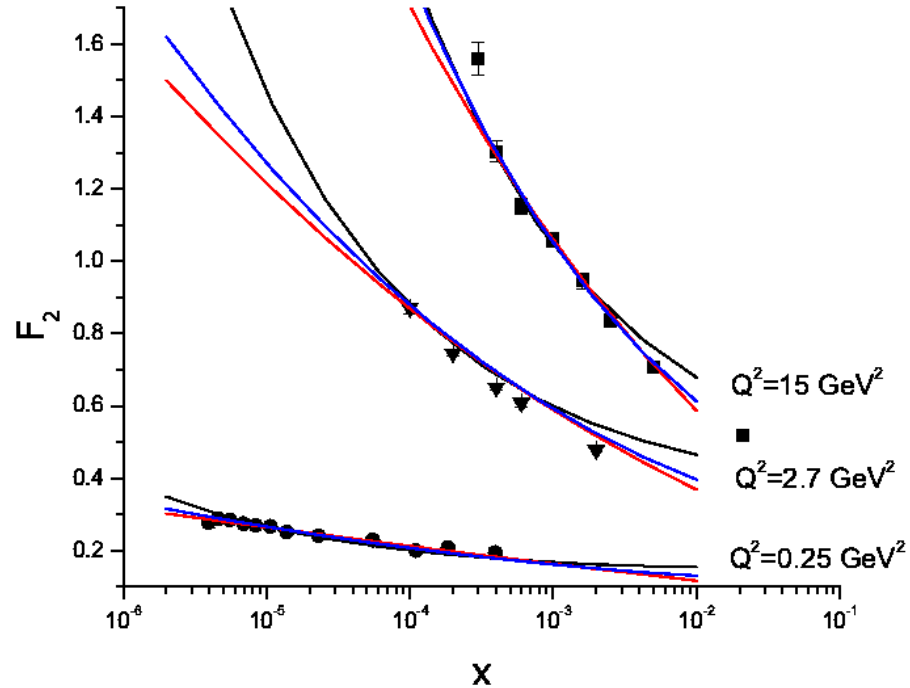
Definitive low x facility (e.g. parton saturation answers)



Example Search for Gluon Saturation at HERA

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

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



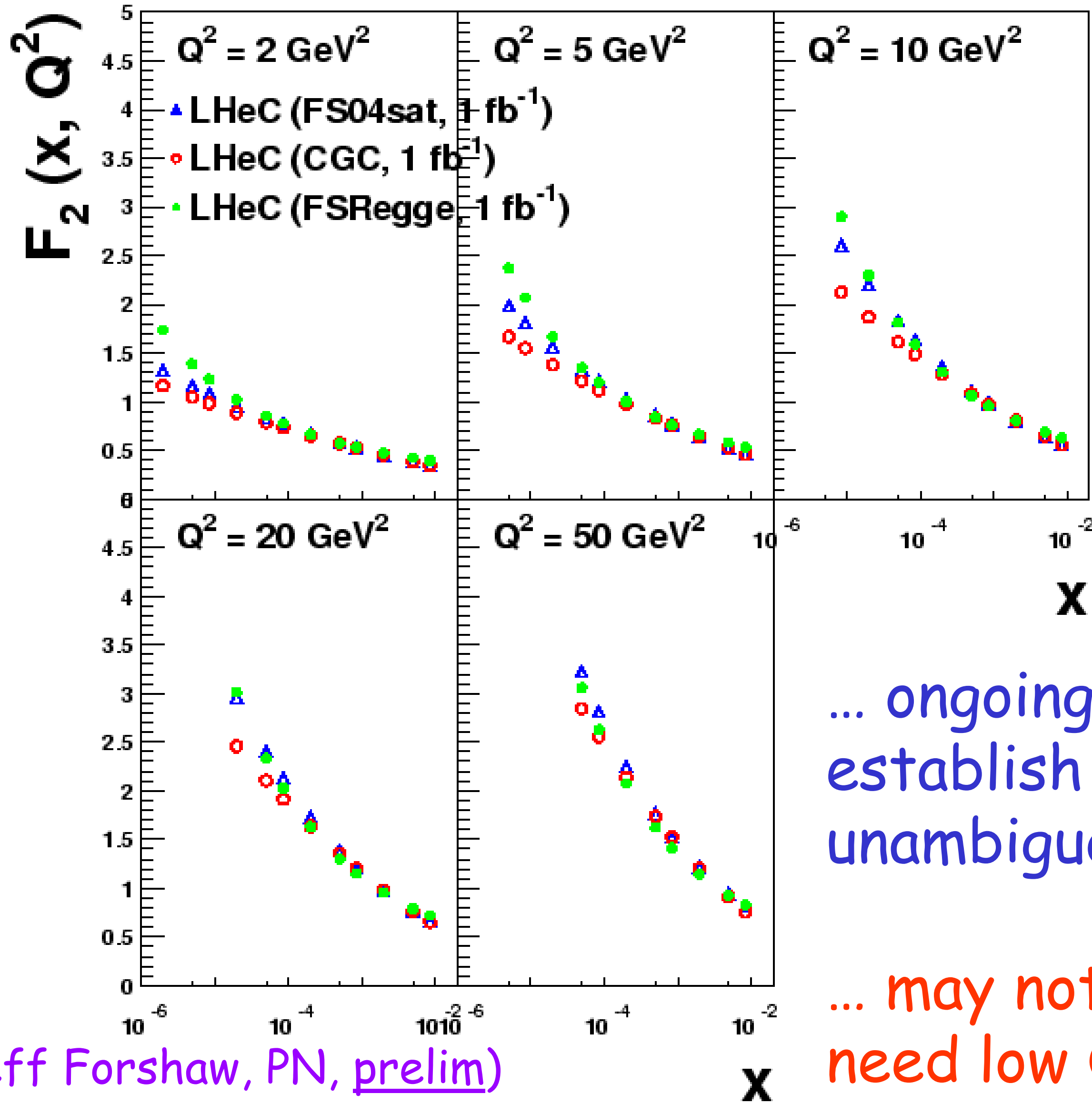
FS04 Regge (~FKS): 2 pomeron model, <u>no saturation</u>
FS04 Satn: <u>Simple implementation of saturation</u>
CGC: <u>Colour Glass Condensate version of saturation</u>

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

… 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)

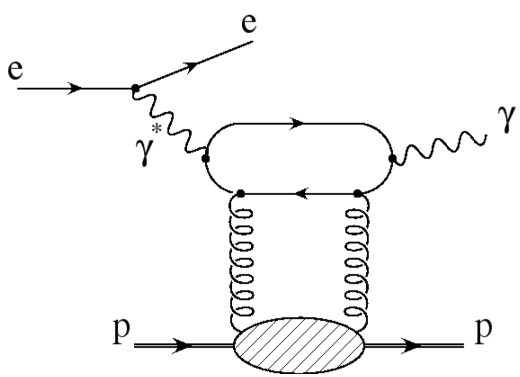
Precise data in LHeC region, $x > \sim 10^{-6}$ (detector → 1°)

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

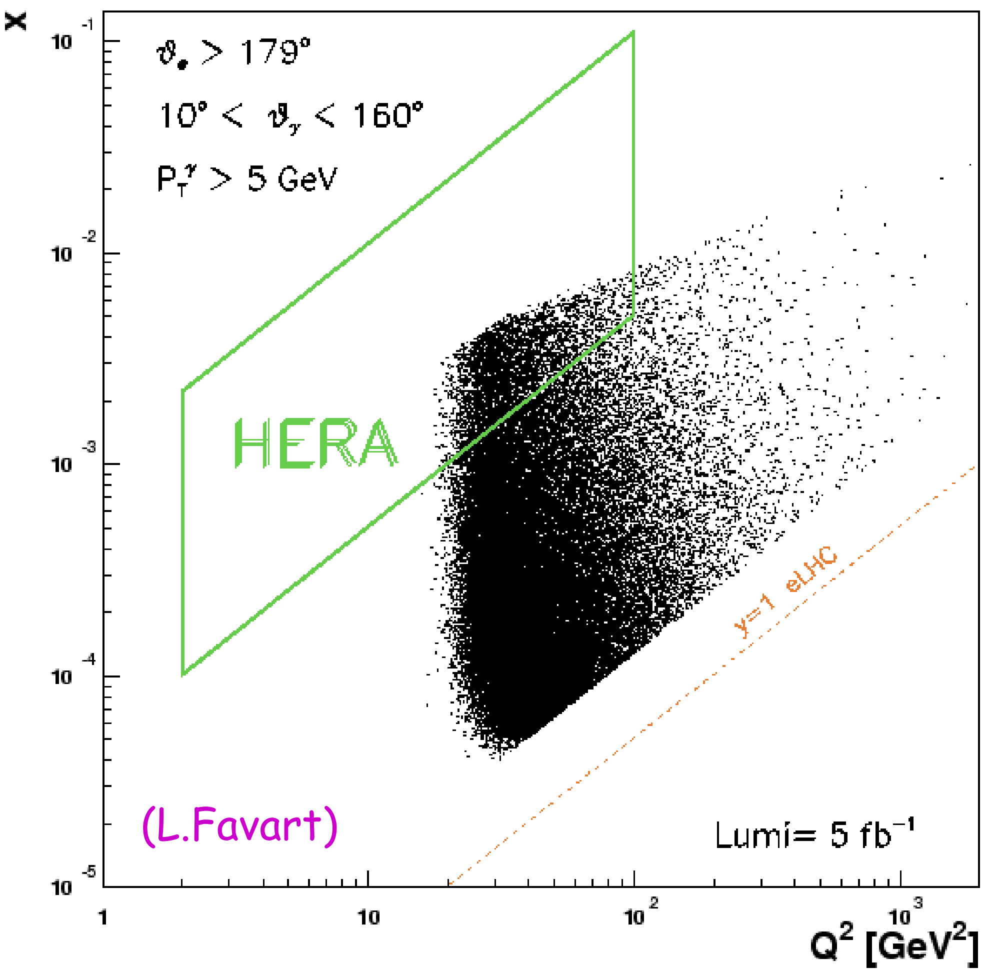
… ongoing work on how to establish saturation partons unambiguously …

… may not be easy and will need low Q^2 (θ → 179°) region

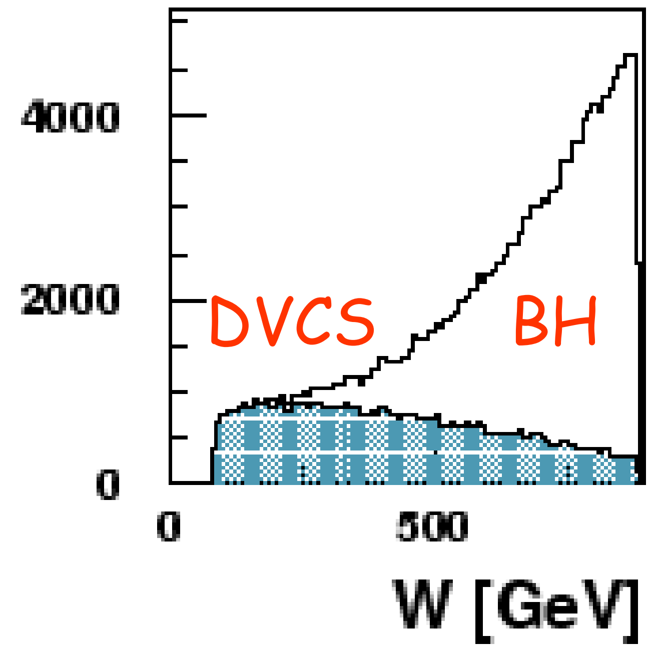
DVCS Measurement



… the classic approach to `generalised parton densities' (GPDs)

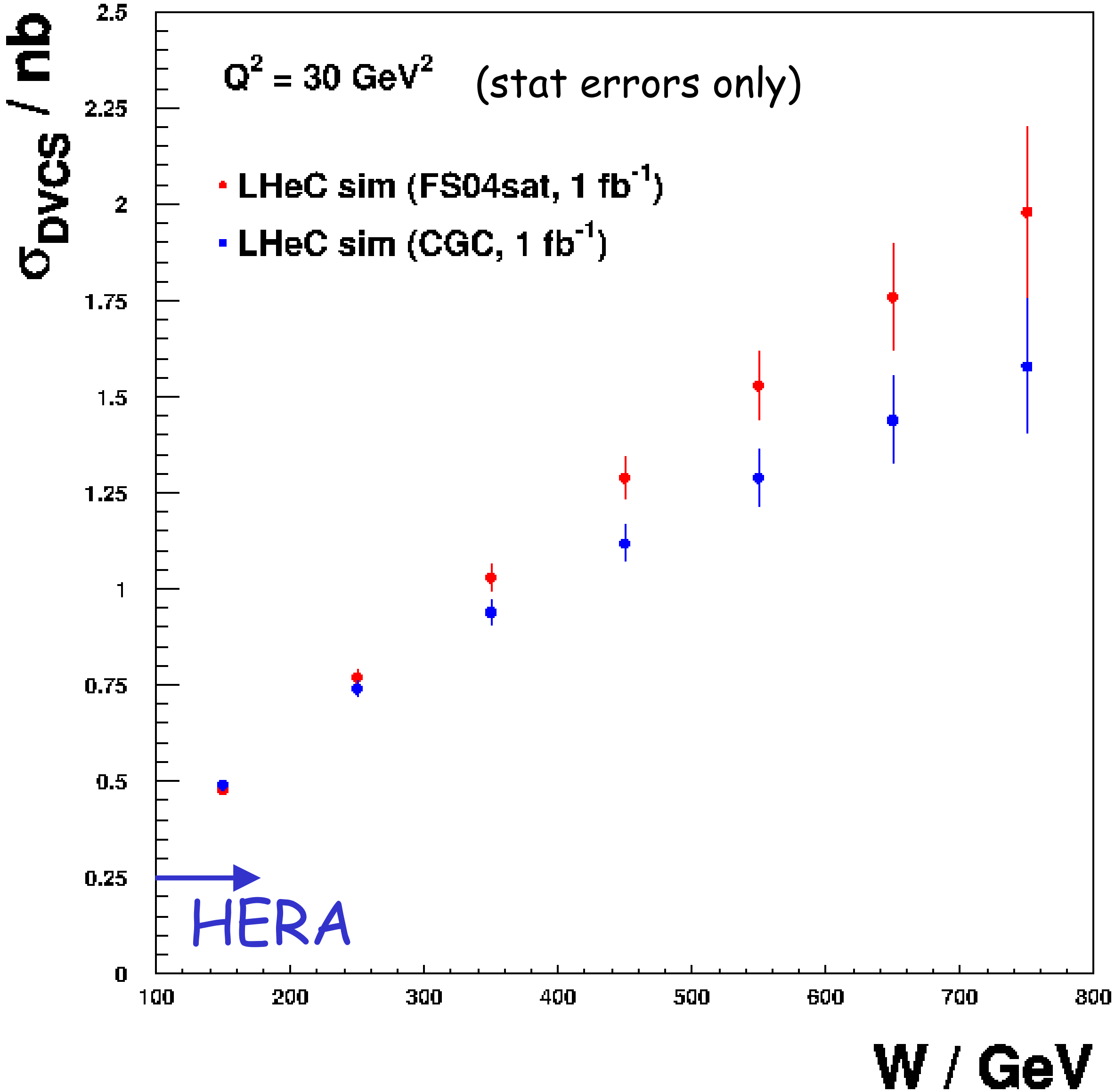


… can be tackled as at HERA through inclusive selection of ep → epγ and statistical subtraction of Bethe-Heitler background



Example of DVCS at LHeC

(1° acceptance)



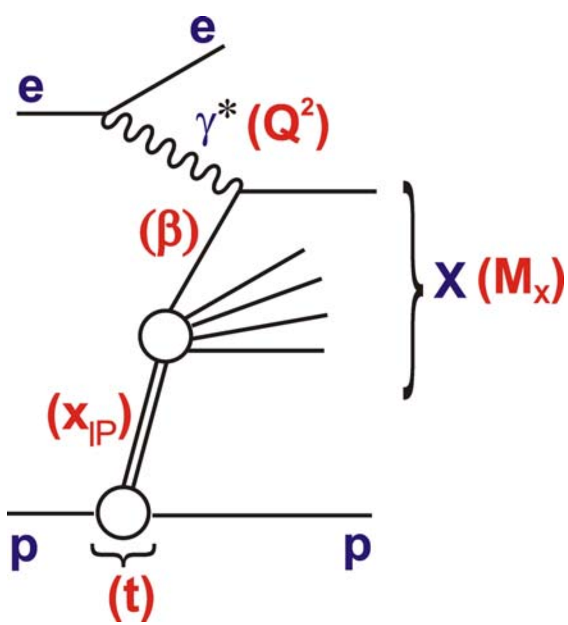
Statistical precision with 1fb^{-1} ~ 2-11%

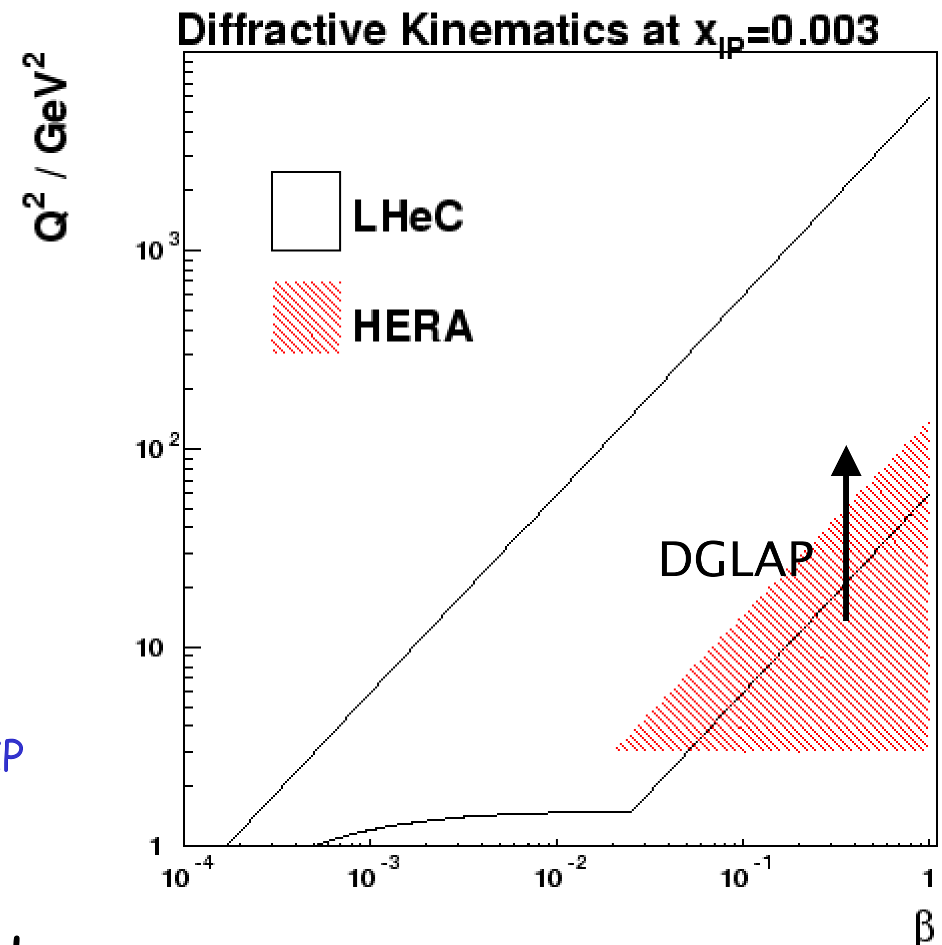
With F_2, F_L, could help establish saturation and distinguish between different models which contain it!

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

VMs similar story

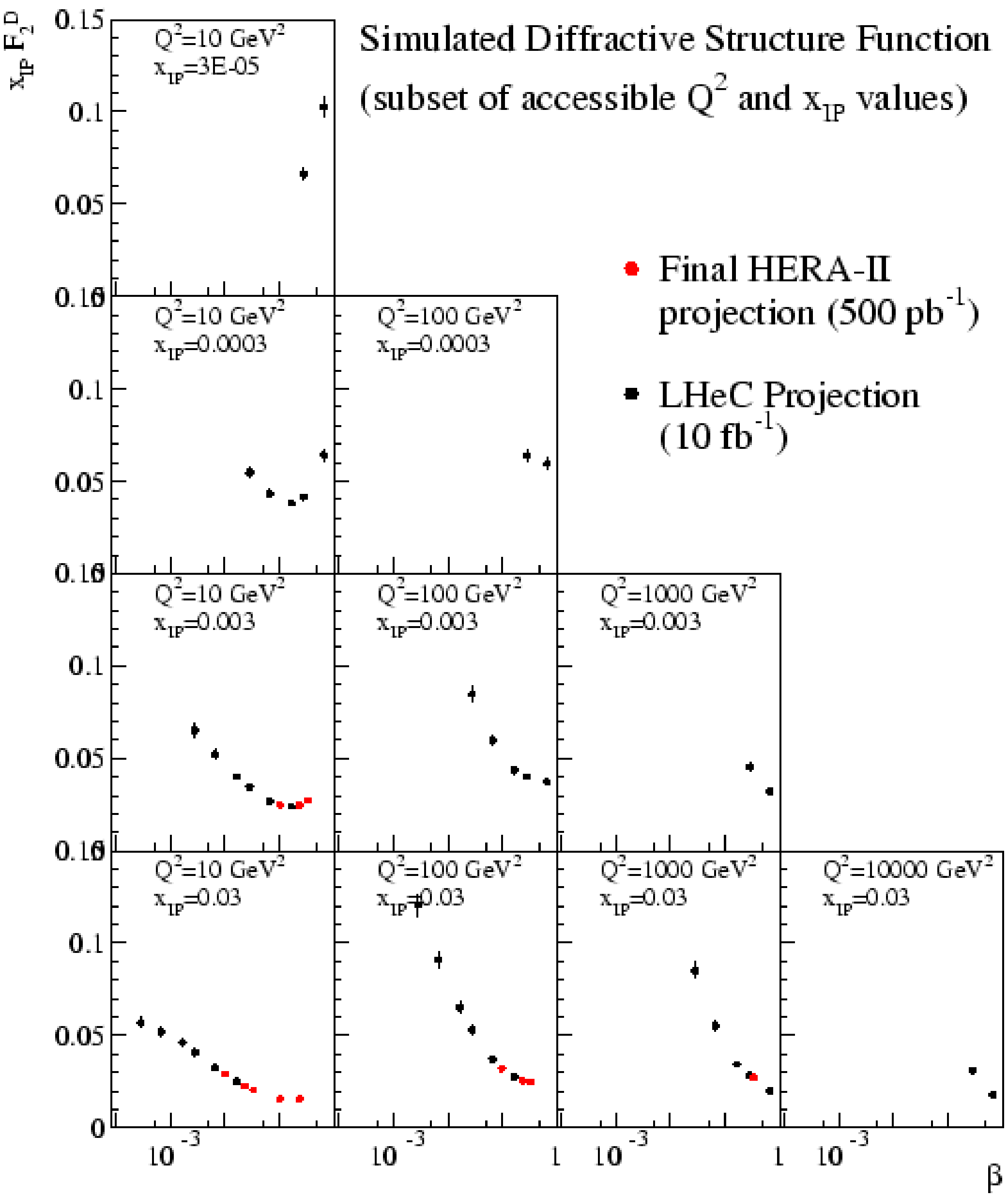
LHeC Diffractive DIS Kinematics





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

LHeC Simulation

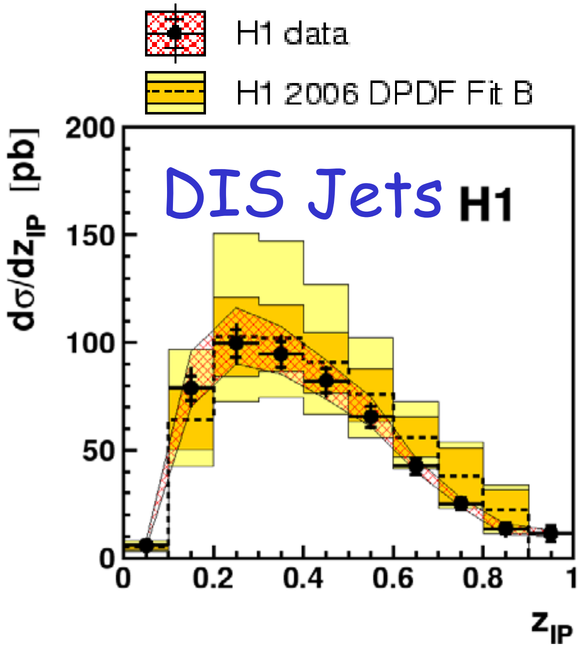


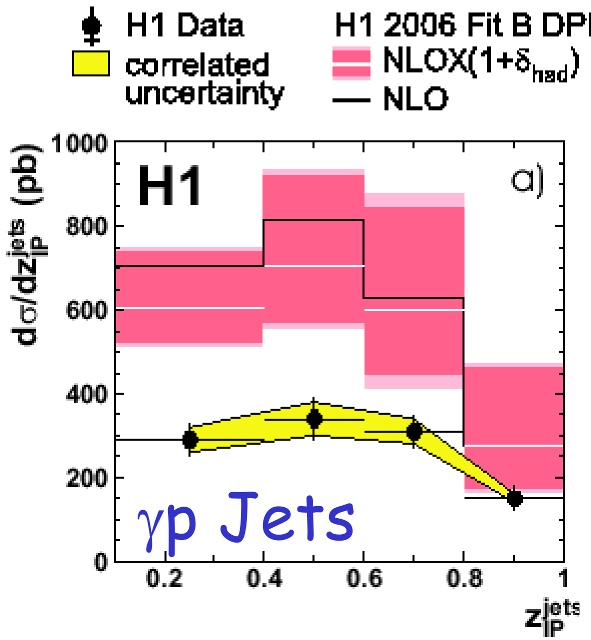
2) Extension to lower x_{IP}
→cleaner separation of diffractive exchange

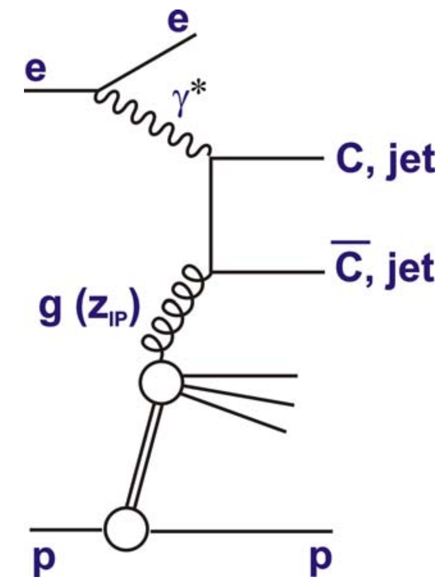
3) Lower β at fixed Q^2, x_{IP}
→parton saturation?
→BFKL type dynamics?
→ Large masses … Z, W, b, exclusive 1^{--} states

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

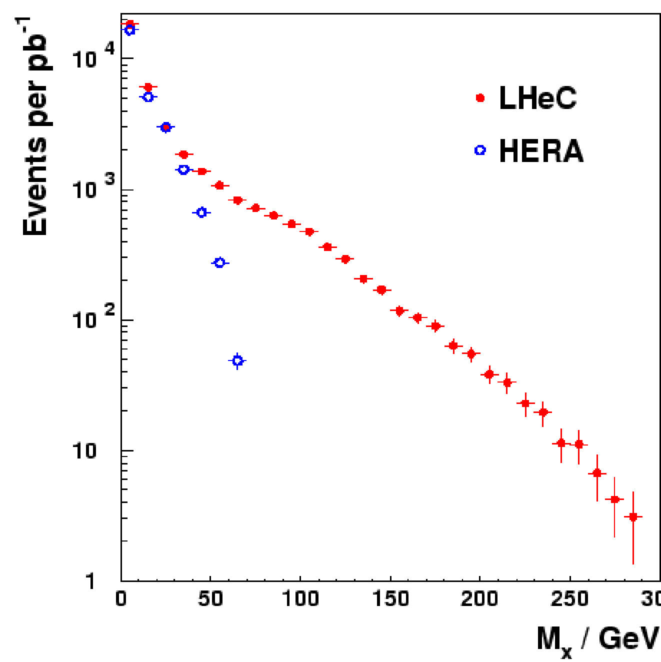
Diffractive Final States at HERA & the LHeC





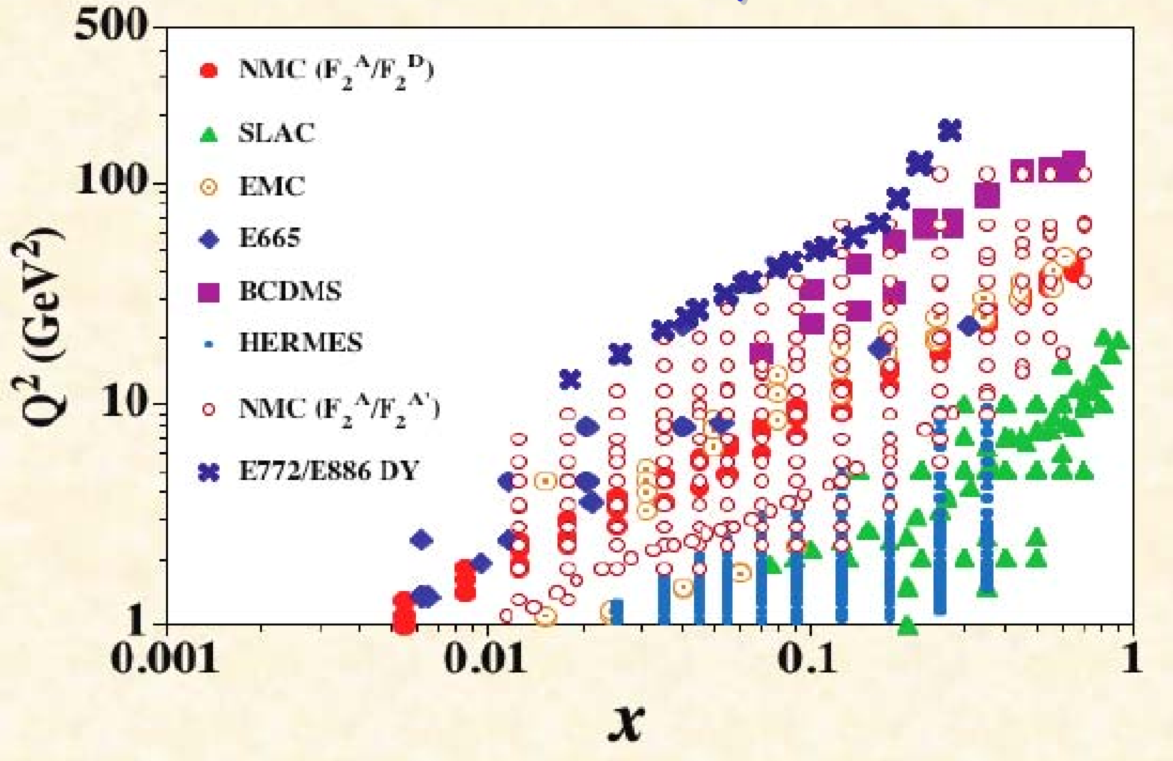


- HERA jet / charm measurements kinematically restricted to high z_{IP}, where F_2^D least sensitive to gluon!
- Also restricted to low $p_T < M_x/2$ where scale uncertainties large.
- γp jets → gap survival → diff H ???



- M_x up to hundreds of GeV at LHeC!

With AA at LHC, LHeC is also an eA Collider



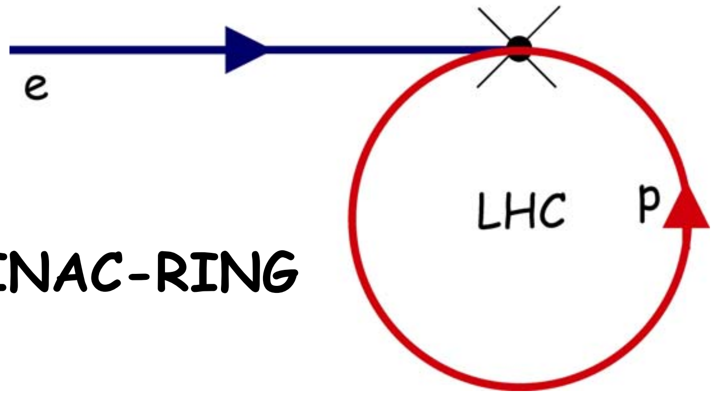
- Very limited x and Q^2 range so far (unknown for x <~ 10^{-2}, gluon poorly constrained)
- LHeC extends kinematic range by 4 orders of magnitude

- 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 ALICE, RHIC … initial state in quark-gluon plasma production is presumably made out of saturated partons

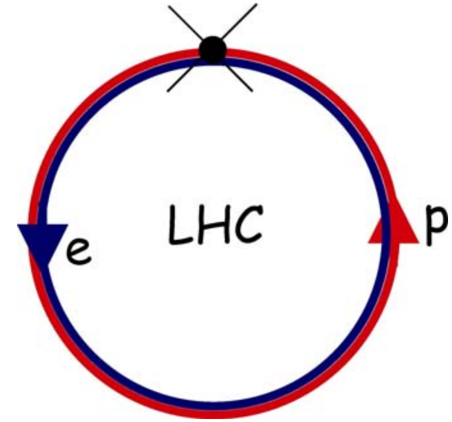
How Could it be Done using LHC?

… 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

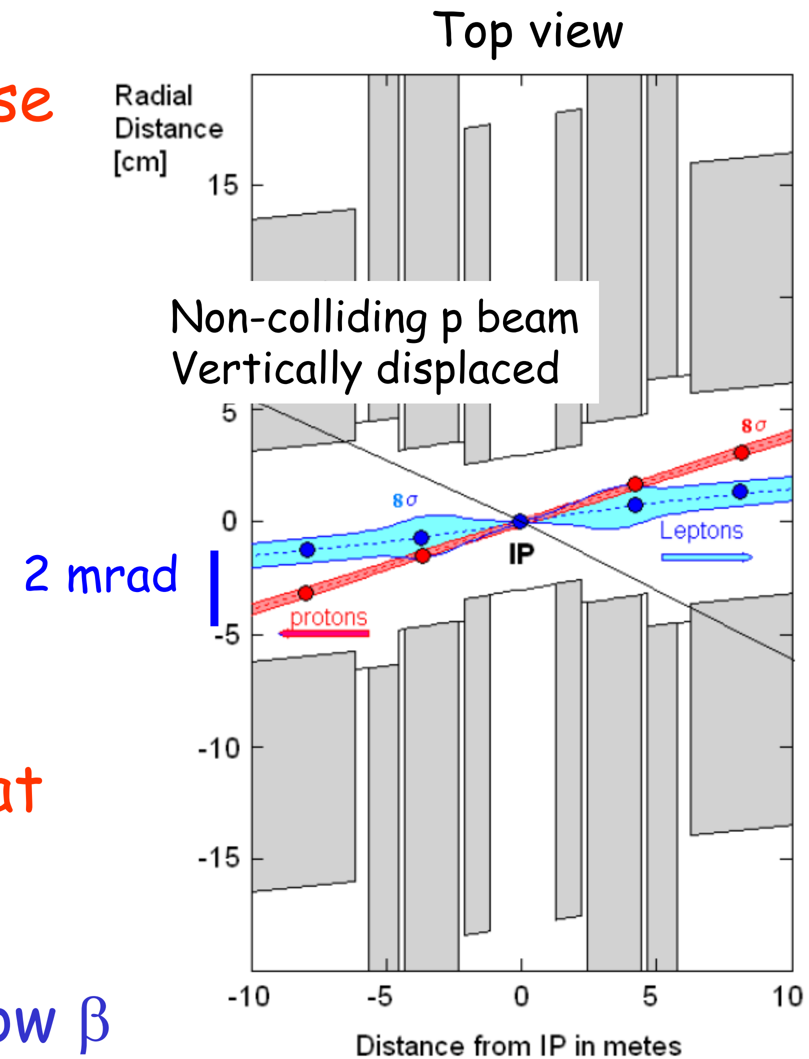
• LHC fixes p beam parameters

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

• Match e & p beam shapes, sizes

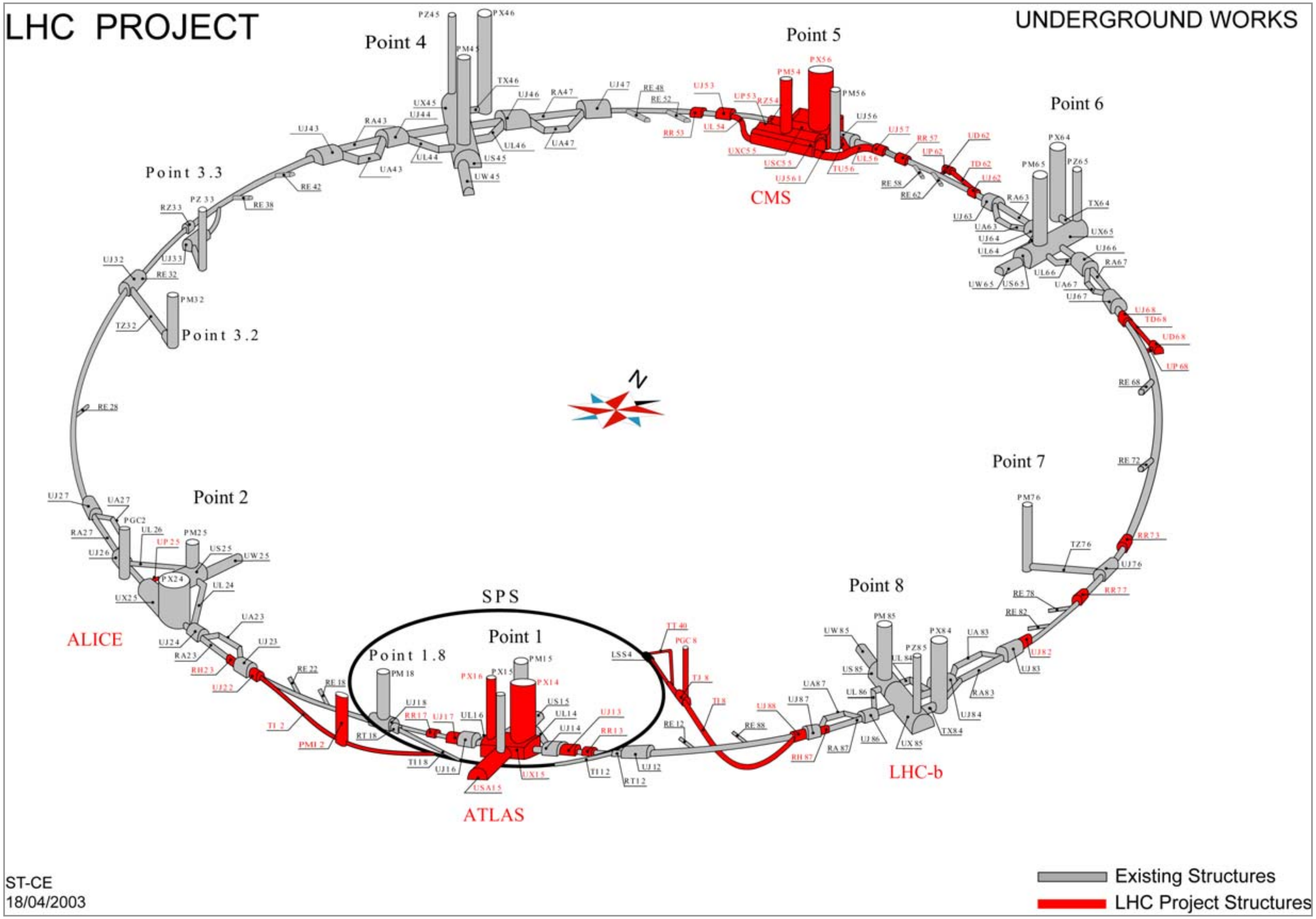
• Fast separation of beams with tolerable synchrotron power requires finite crossing angle

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



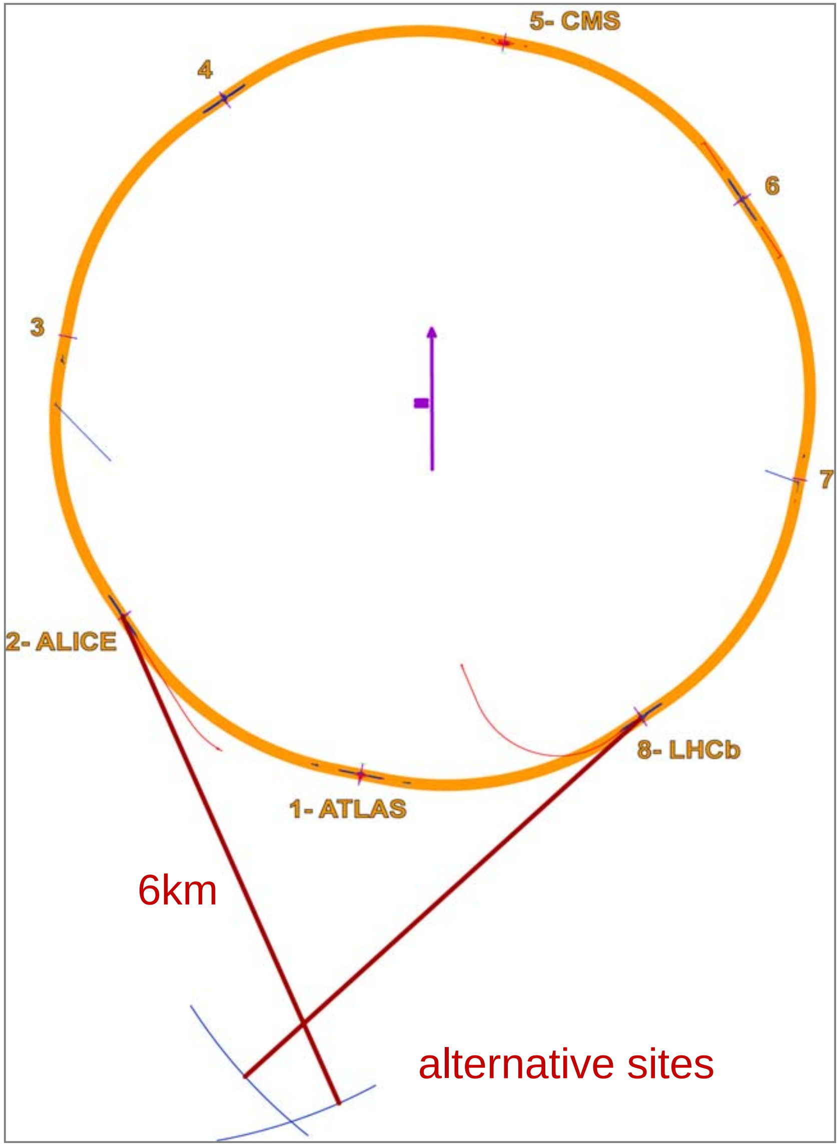
• High luminosity running requires low β focusing quadrupoles close to interaction point (1.2 m) → acceptance limitation to 10° of beampipe

Ring-Ring Design



- Assume ring would have to bypass P1, P5, P3 and P6
- P8 / P2 could be possible ep/eA interaction regions?

Linac-Ring Design



- 140 GeV electron beam at 23 MV/m is 6km + gaps
- CMS energy → 2 TeV!

		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 (2 linacs?) …else prohibitive power usage?

Some First Low x 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.

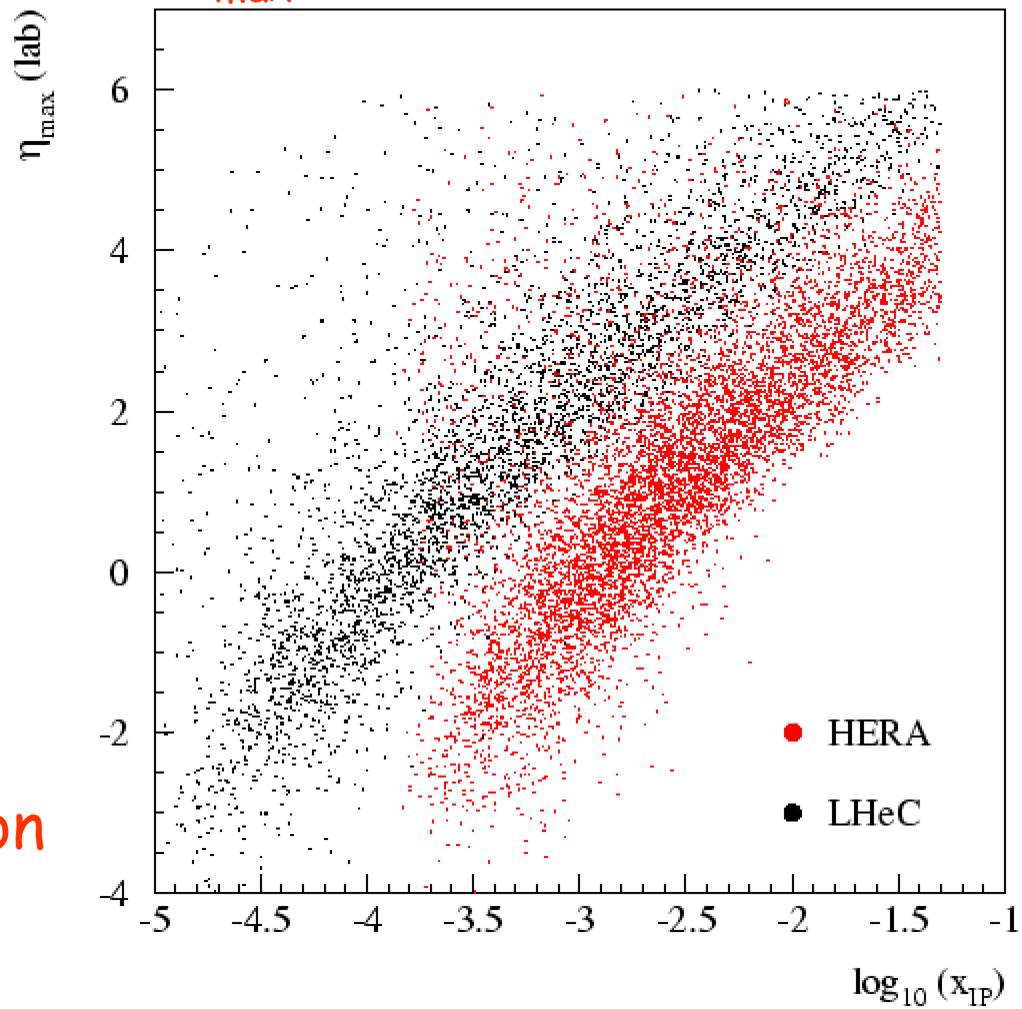
- Study of low x / Q^2 and of range overlapping with HERA, with sensitivity to energy flow in outgoing proton direction requires forward acceptance for hadrons to 1°

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

Forward and Diffractive Detectors

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

η_{max} from LRG selection …



- 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
  - Not new at LHC ☺
  - Being considered integrally with interaction region

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, S. Vigdor, KH. Meier

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 → CERN/ECFA sponsored workshop(s)
2009: → Conceptual Design Report

Planned Working Groups:

- Accelerator Design (ring-ring and linac-ring)
- Interaction region, Forward and Backward 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: 1-3 September, l'Esplanade du Lac, Divonne

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]

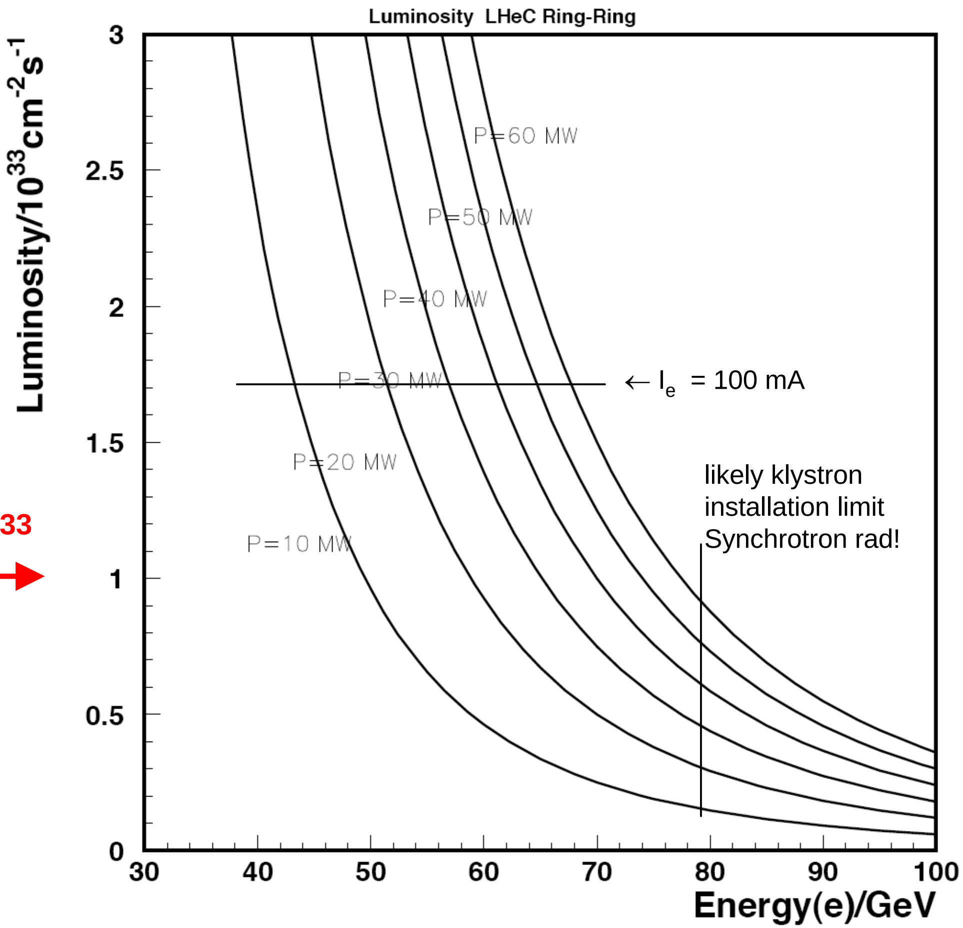
Luminosity: Ring-Ring

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

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn}} \cdot \frac{I_e}{\sqrt{\beta_{px}\beta_{py}}} = 8.310^{32} \cdot \frac{I_e}{50mA} \frac{m}{\sqrt{\beta_{px}\beta_{pn}}} cm^{-2}s^{-1}$$

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

10^{33} →



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

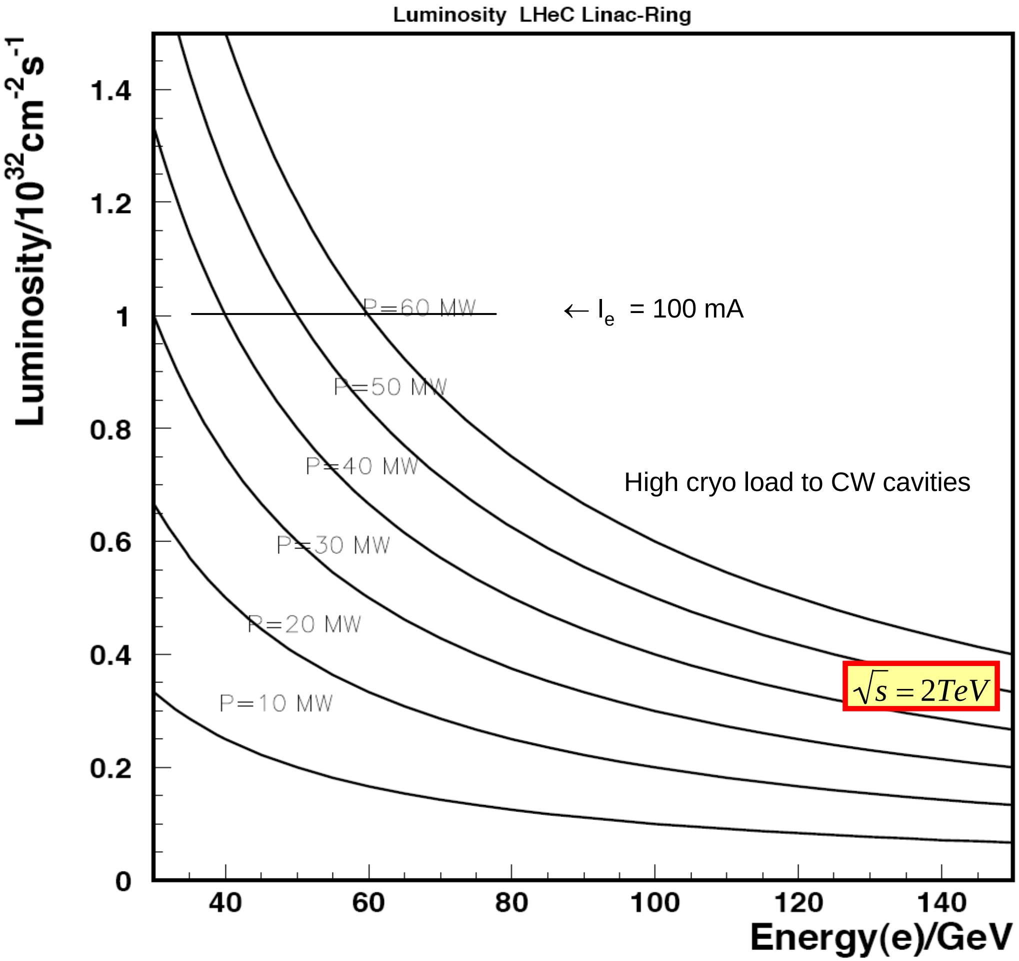
Luminosity: Linac-Ring

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

$\varepsilon_{pn} = 3.8 \mu m$

$N_p = 1.7 \cdot 10^{11}$

$\beta^* = 0.15 m$



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

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

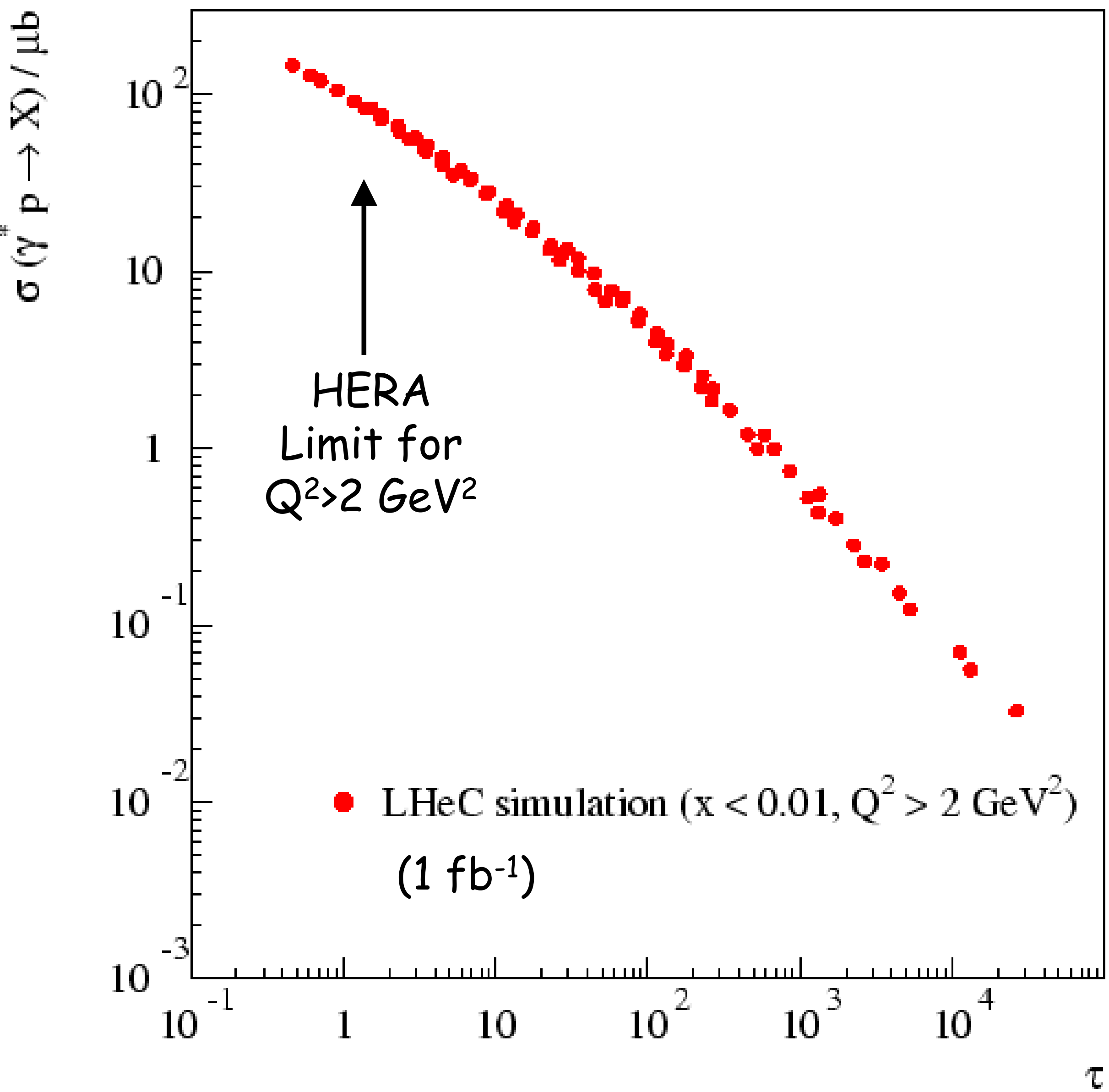
Luminosity horizon: high power: ERL (2 Linacs?)

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



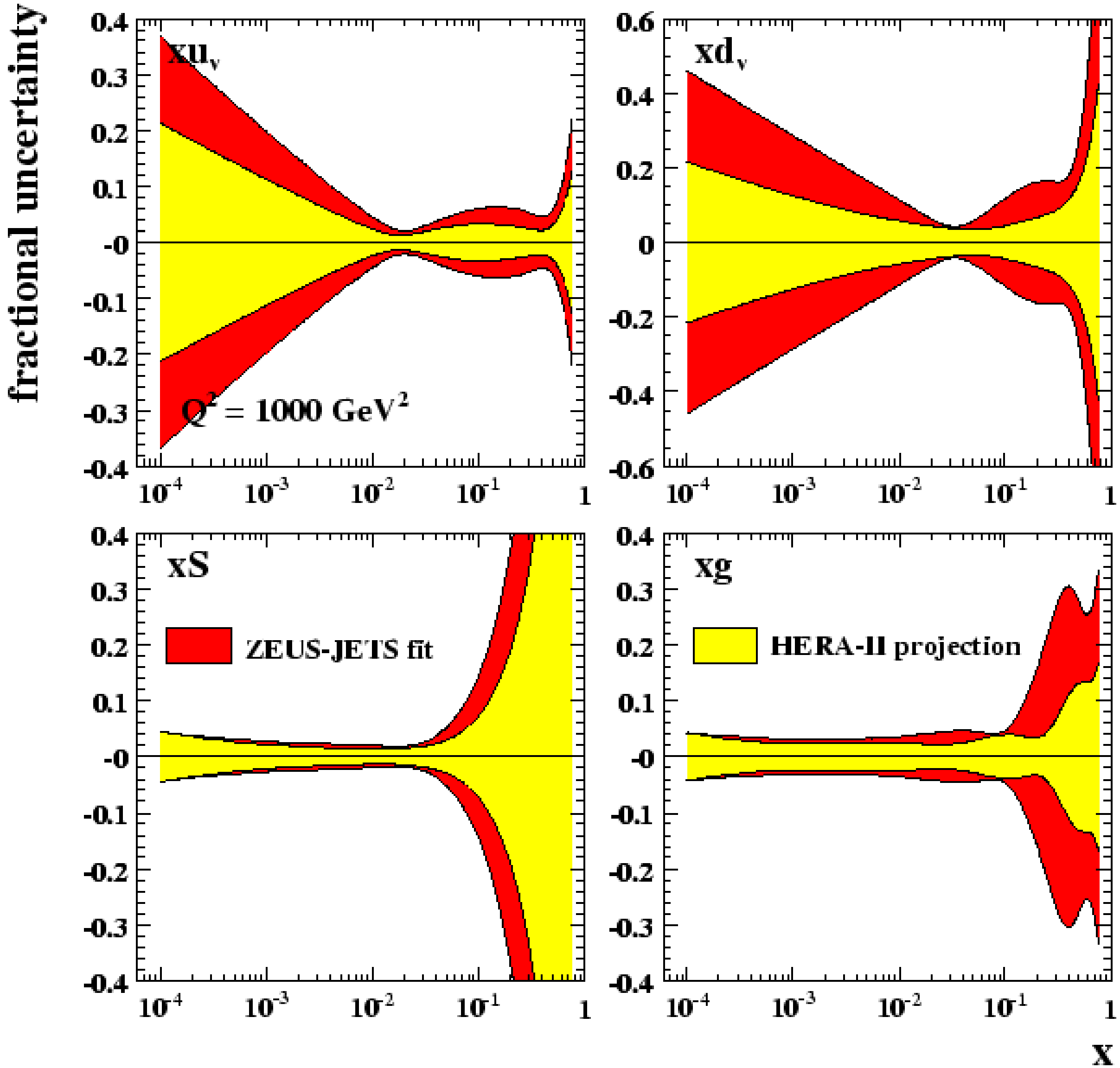
LHeC reaches $\tau \sim 0.15$ for Q^2=1 GeV^2 and $\tau \sim 0.4$ for Q^2=2 GeV^2

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

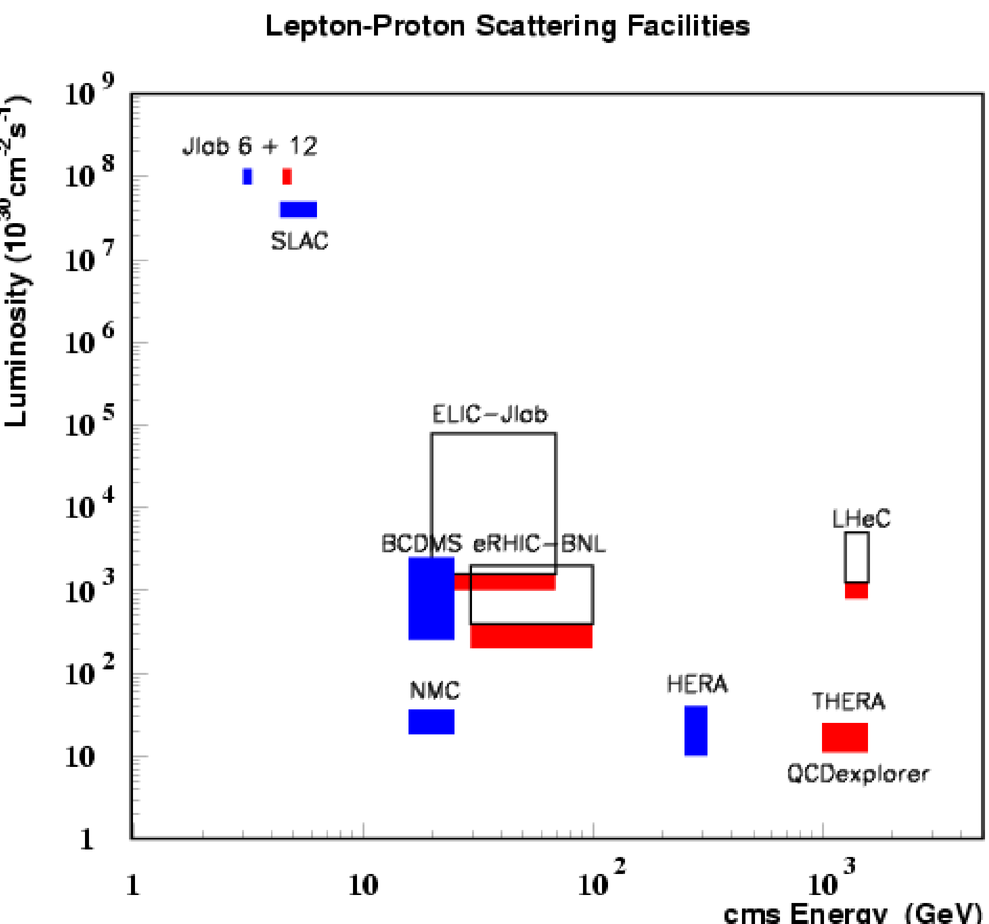
Only statistical
improvements
considered

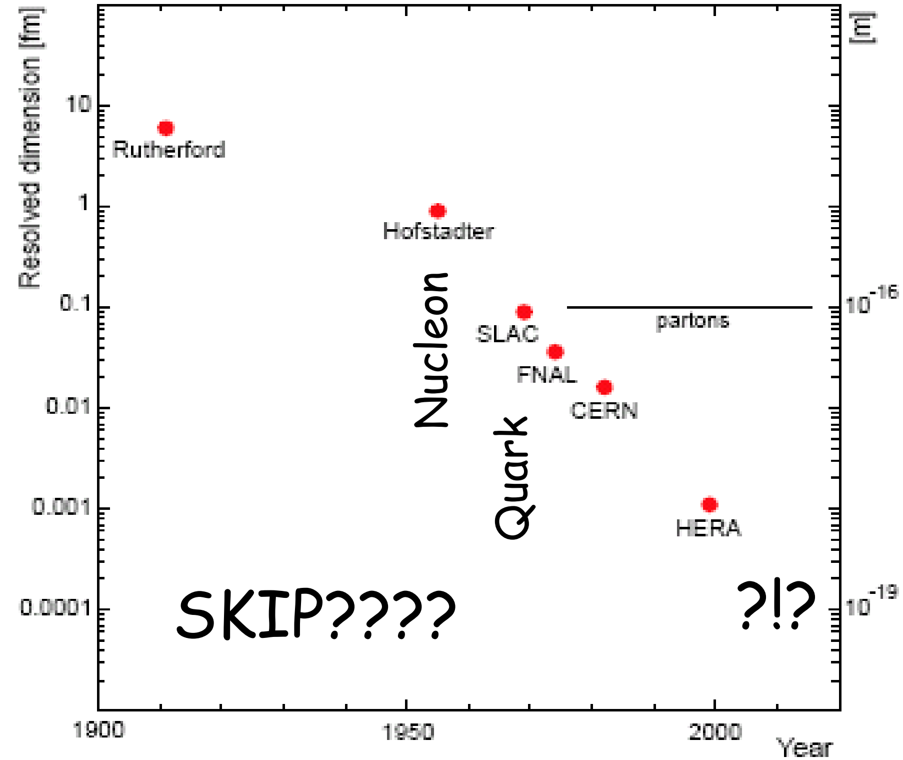
… high x LHC
discovery region
(esp. gluon) still
not well known

(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!

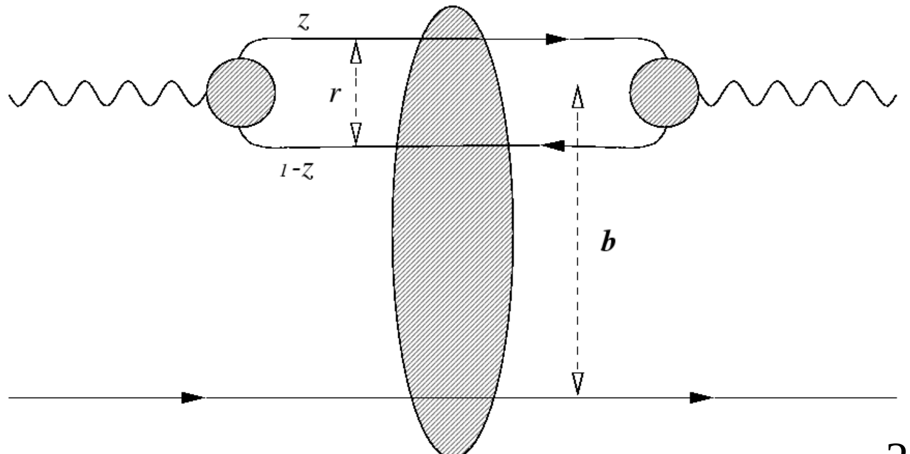




- Combining the LHC protons with an electron beam is natural next step in pushing the frontiers of ep physics: small resolved dimensions, high Q^2 and low x
- Can be done without affecting pp running

Reminder : Dipole models

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



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

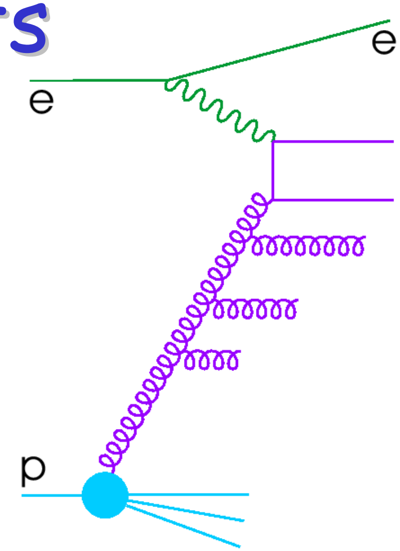
• Simple unified picture of many inclusive and exclusive processes … strong interaction physics in (universal) dipole cross section σ_{dipole}. Process dependence in wavefunction Ψ Factors

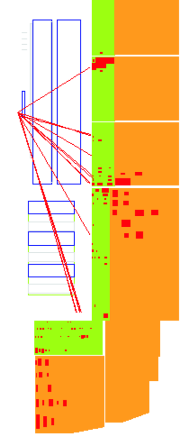
• qqbar-g dipoles also needed to describe inclusive diffraction

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^*…

Forward Jets

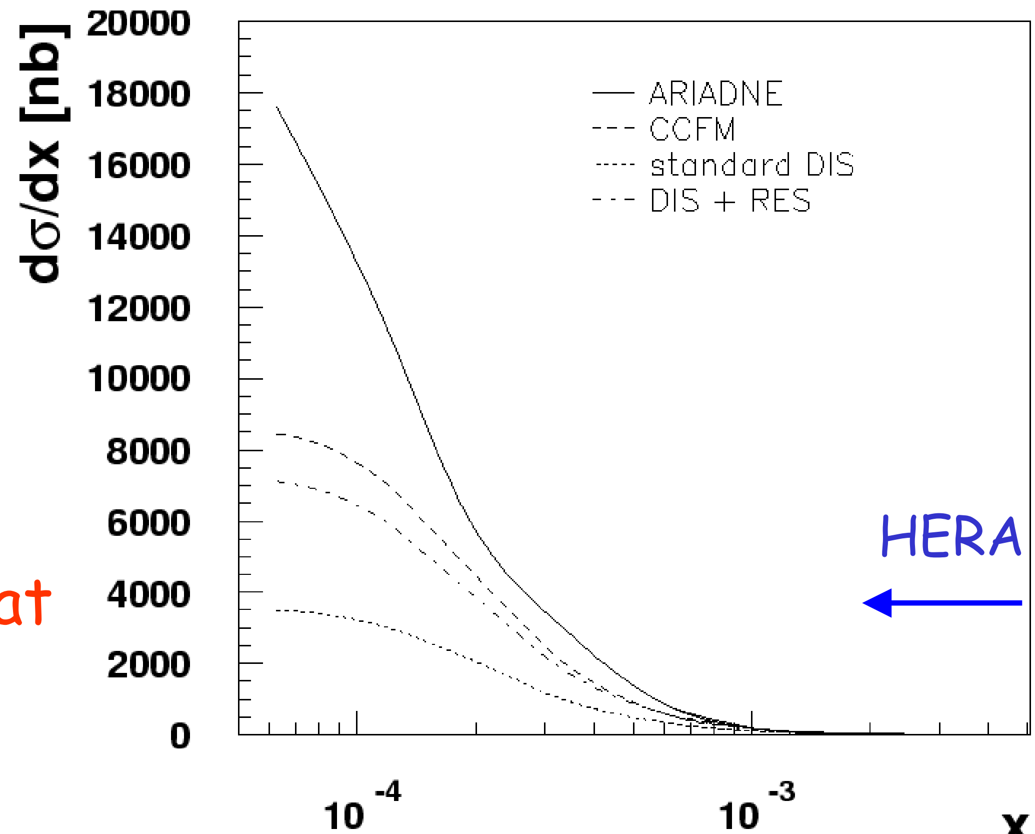
SKIP???





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

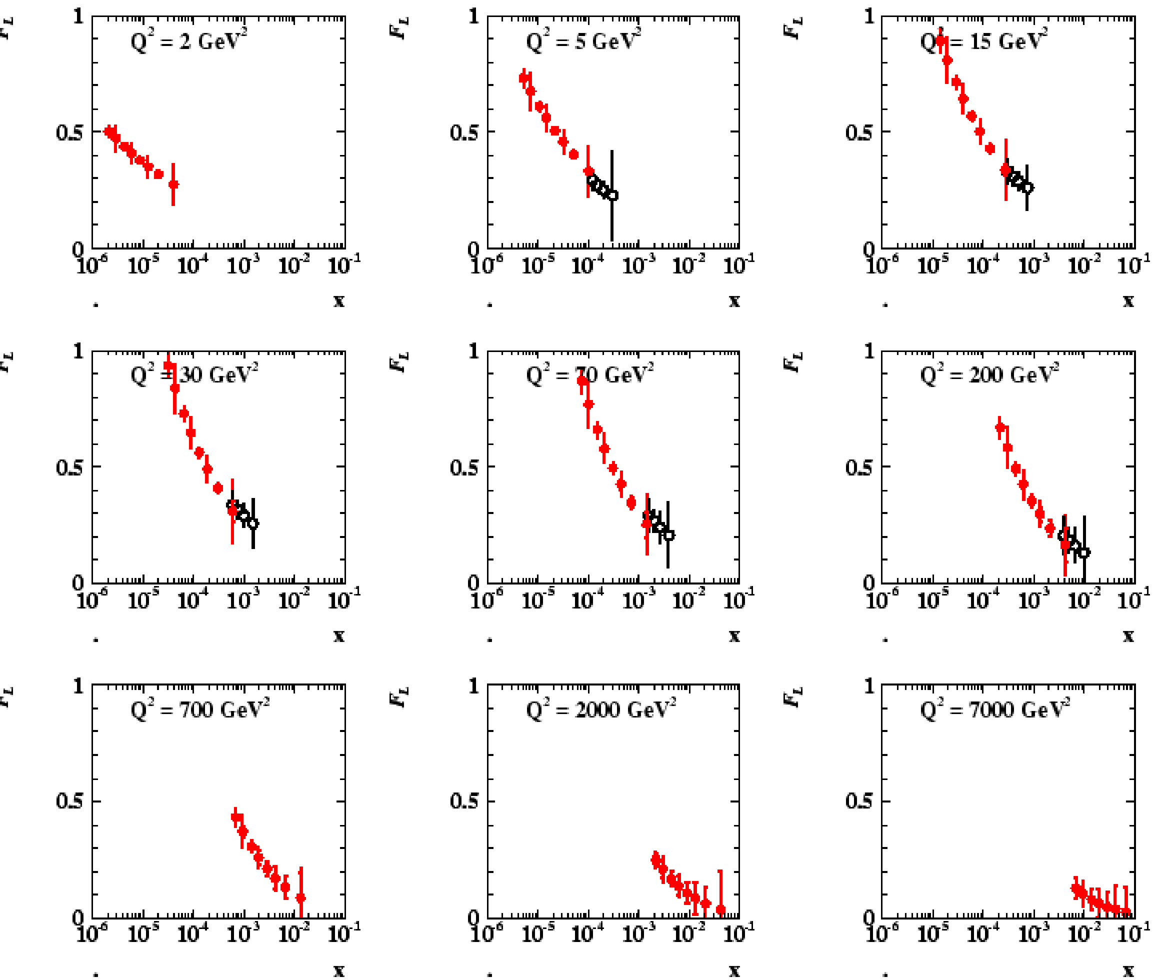
At LHeC … more emissions due to longer ladder & more instrumentation →measure at lower x where predictions really diverge.



The Gluon from F_L?

● LHeC

○ H1 low Ep run (projected)



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

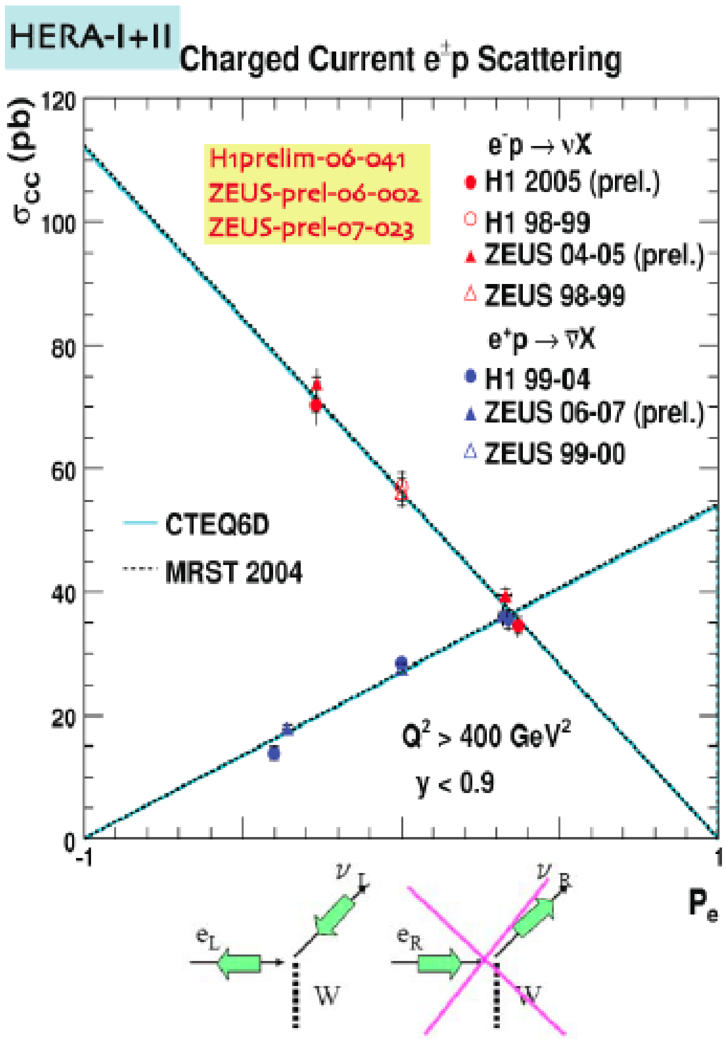
E_p (TeV)	Lumi (fb^{-1})
7	1
4	0.8
2	0.2
1	0.05
[0.45	0.01]

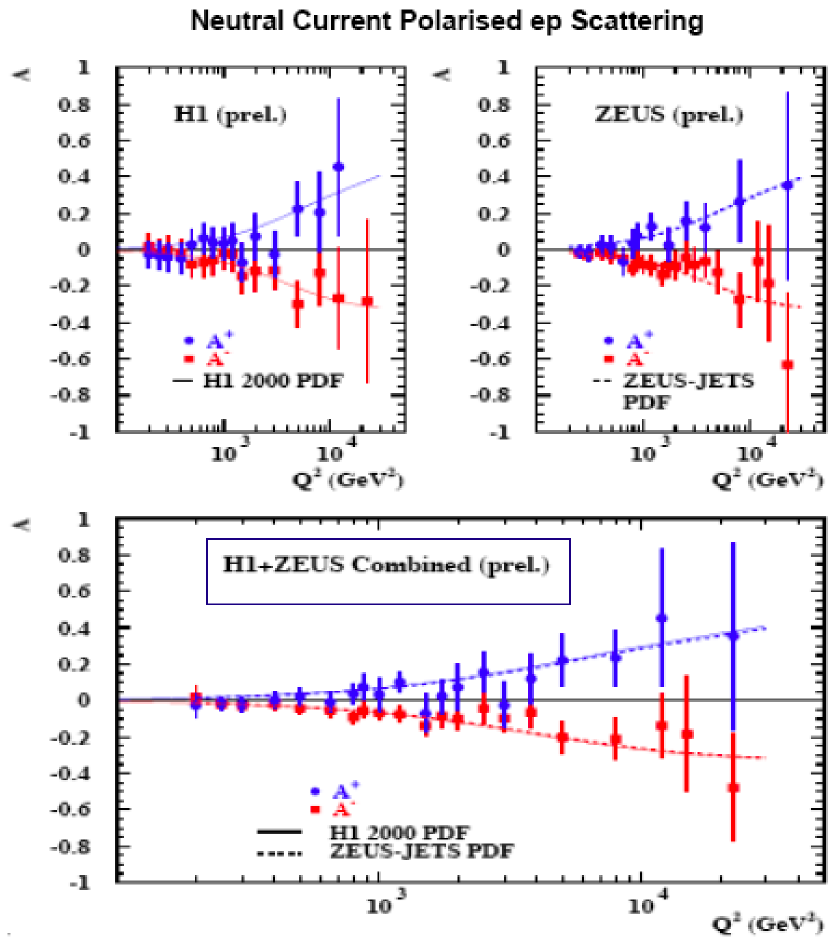
[~ 1 year of running]

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

Electroweak Measurements at HERA





NC: parity violation at ~10^{-18} m