A future DIS experiment at the LHC ?

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Deep Inelastic Electron-Nucleon Scattering at the LHC*

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Abstract

The physics, and a design, of a Large Hadron Electron Collider (LHeC) are sketched. With high luminosity, $10^{33}\text{cm}^{-2}\text{s}^{-1}$, and high energy, $\sqrt{s} =$ 1.4 TeV, such a collider can be built in which a 70 GeV electron (positron) beam in the LHC tunnel is in collision with one of the LHC hadron beams and which operates simultaneously with the LHC. The LHeC makes possible deep-inelastic lepton-hadron (ep, eD and eA) scattering for momentum transfers Q^2 beyond $10^6\,\text{GeV}^2$ and for Bjorken x down to the 10^{-6}. New sensitivity to the existence of new states of matter, primarily in the lepton-quark sector and in dense partonic systems, is achieved. The precision possible with an electron-hadron experiment brings in addition crucial accuracy in the determination of hadron structure, as described in Quantum Chromodynamics, and of parton dynamics at the TeV energy scale. The LHeC thus complements the proton-proton and ion programmes, adds substantial new discovery potential to them, and is important for a full understanding of physics in the LHC energy range.

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Emmanuelle Perez
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with J.B. Dainton, M. Klein, P. Newman, F. Willeke

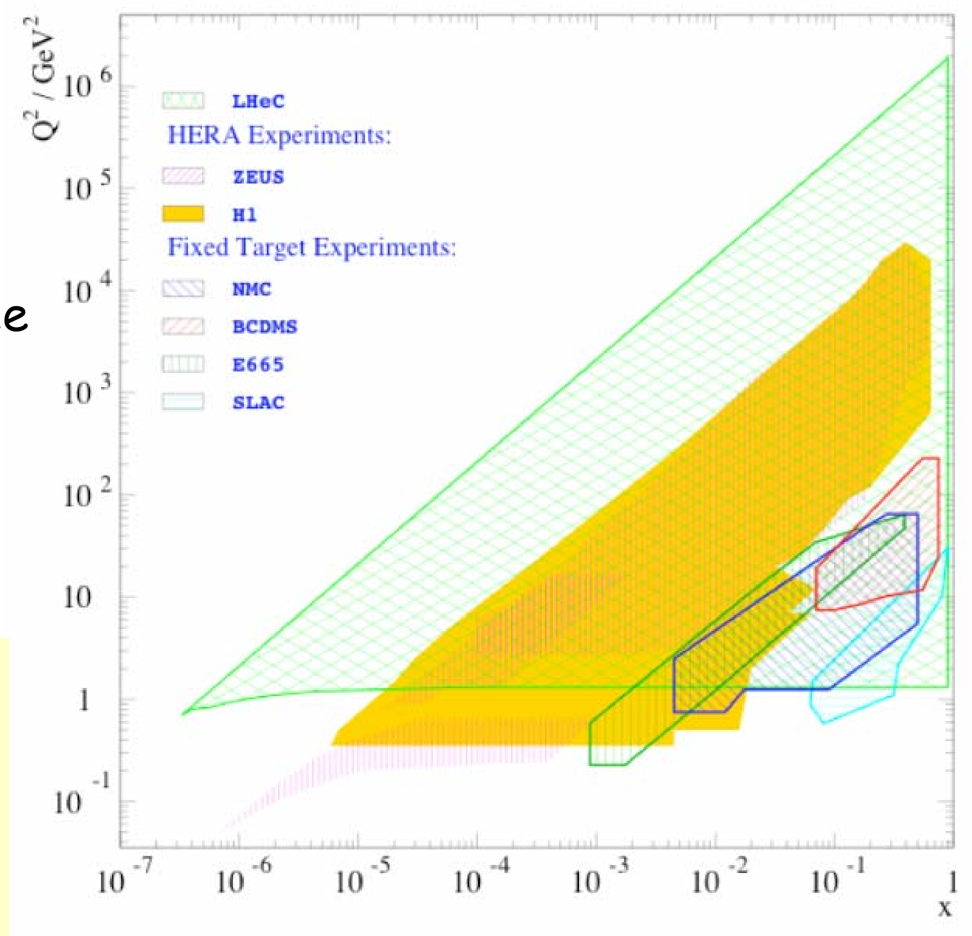
- Examples of motivations for DIS at the TeV scale in view of the LHC results
- Feasibility study : LHeC

Introduction

DIS experiments :

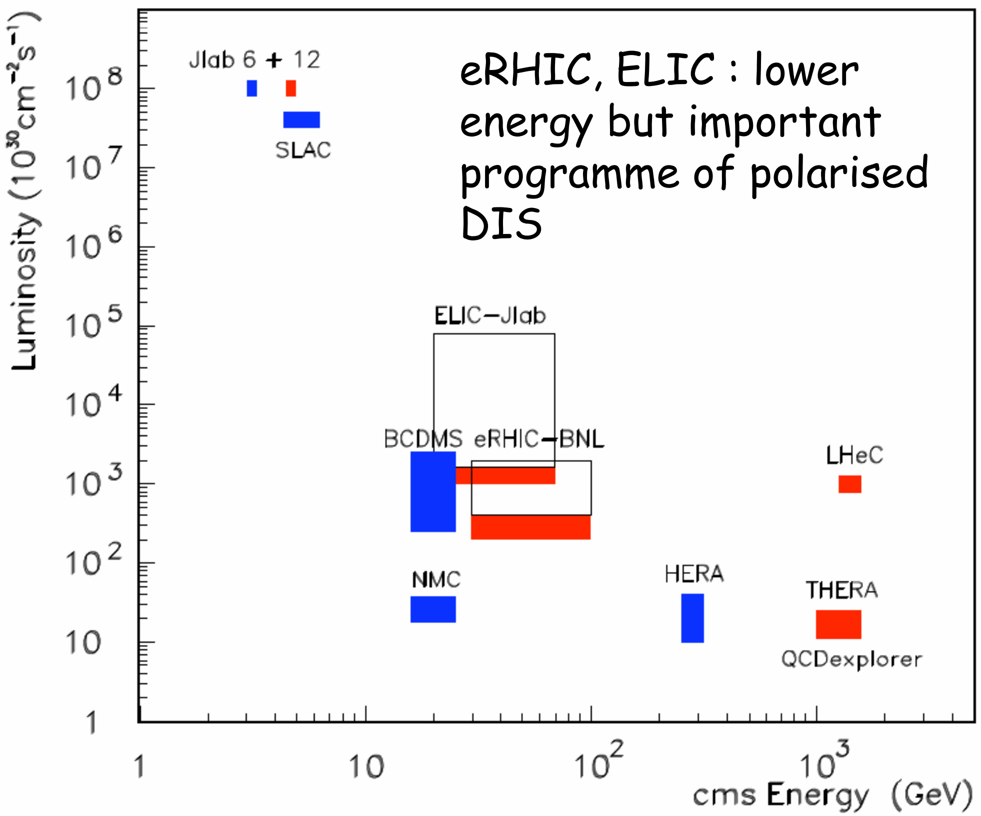
- Provide key data to understand the proton structure
- and more generally for our understanding of QCD
- No agreed future DIS programme once HERA stops taking data in mid-07
- But still many unanswered questions (low x, diffraction, precise pdfs in a larger kinematic domain,…)

→ Consider the feasibility of pursuing the DIS programme using the 7 TeV LHC proton (A) beam and bringing it in collision with a 70 GeV electron beam in the LHC tunnel: LHeC.



$\sqrt{s}$ = 1.4 TeV : covers much higher Q^2 and lower x than HERA.

Introduction



LEP-LHC

A. Verdier LHC Workshop Aachen 90, p.820
E. Keil LHC Project Report 93 (1997)

R. Brinkmann, F. Willeke THERA book and Proceedings Snowmass 2001

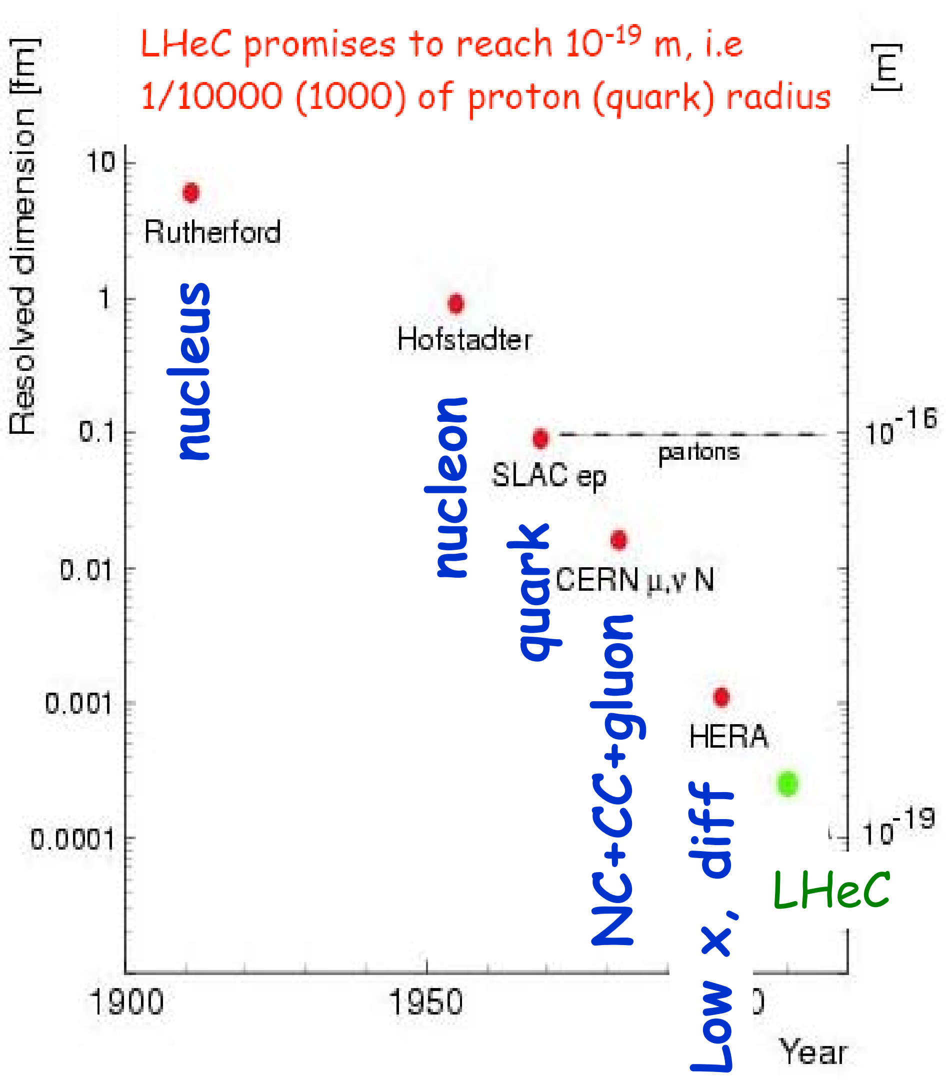
QCD explorer (CLIC-LHC')

D. Schulte, F. Zimmermann CLIC 608

Compared with linac-ring: LHeC provides both a high $\sqrt{s}$ and a very high luminosity (of about 10^{33} cm^{-2} s^{-1}, i.e. integrated luminosities of about 10 fb^{-1} per year can be considered).

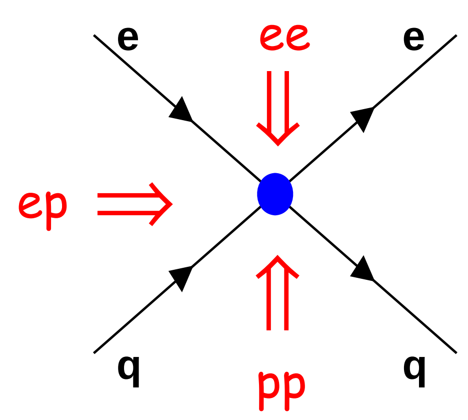
DIS at the high energy frontier

Going higher in Q^2 : towards quark substructure ?



Quark substructure can be seen at the LHC in dijet spectra or angular distributions.
But other New Physics processes could fake this signature.

Complementarity between pp, ee and ep could help in underpinning the nature of NP.



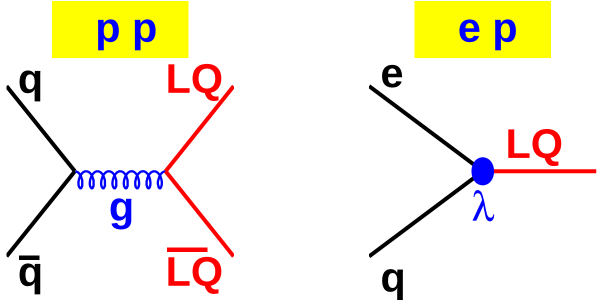
Leptoquarks

Apparent symmetry between the lepton & quark sectors ?
Exact cancellation of QED triangular anomaly ?

- LQs appear in many extensions of SM
- Scalar or Vector color triplet bosons
- Carry both L and B, frac. em. charge

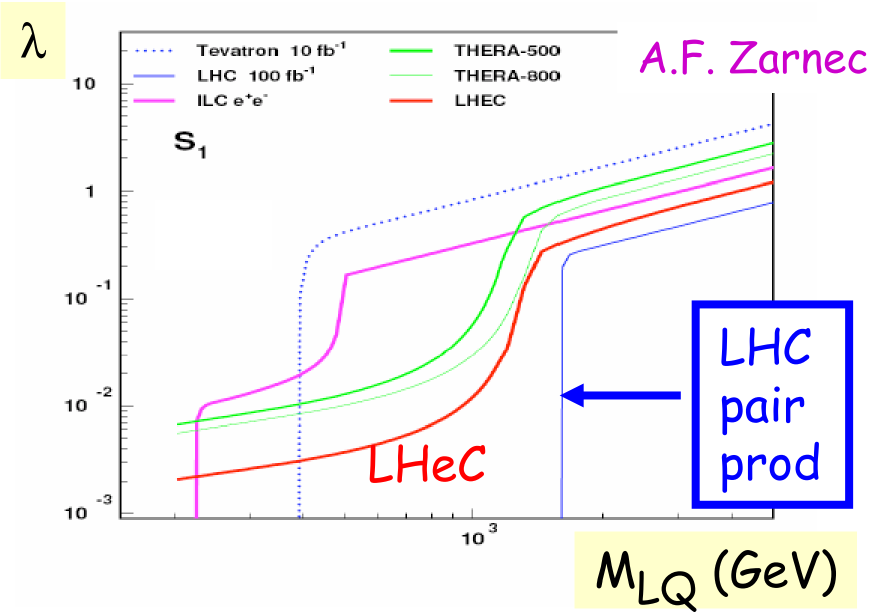
LQ decays into (lq) or (νq) :

ep		pp		
eq	νq	llqq	lνqq	ννqq
NC DIS	CC DIS	Z/DY + jj QCD	W + jj	W/Z + jj QCD



λ (unknown) Yukawa coupling l-q-LQ

- ep : resonant peak, ang. distr.
- pp : high E_T lljj events



A.F. Zarnecki

LHC could discover eq resonances with a mass of up to 1.5 – 2 TeV via pair production.

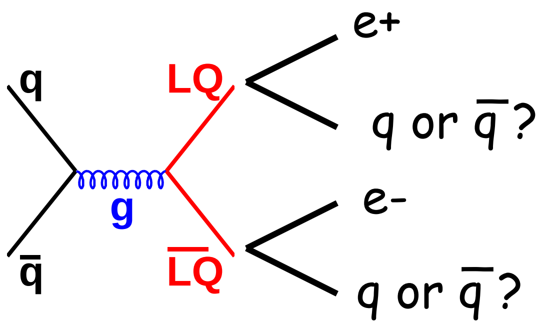
Quantum numbers ? Might be difficult to determine in this mode.

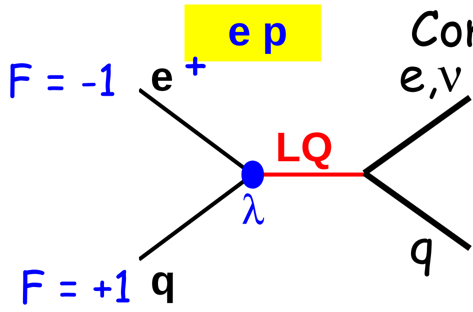
Determination of LQ properties

pp, pair production

ep, resonant production

- Fermion number



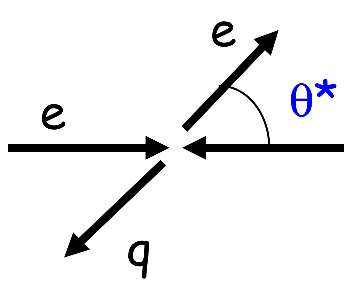


Compare σ with e+ and e- :

F=0 LQs : $\sigma(e^+)$ higher
F=2 LQs : $\sigma(e^-)$ higher

- Scalar or Vector

$q\bar{q} \rightarrow g \rightarrow LQ\ \overline{LQ}$:
angular distributions depend on the structure of g-LQ-LQ. If coupling similar to γWW, vector LQs would be produced unpolarised…



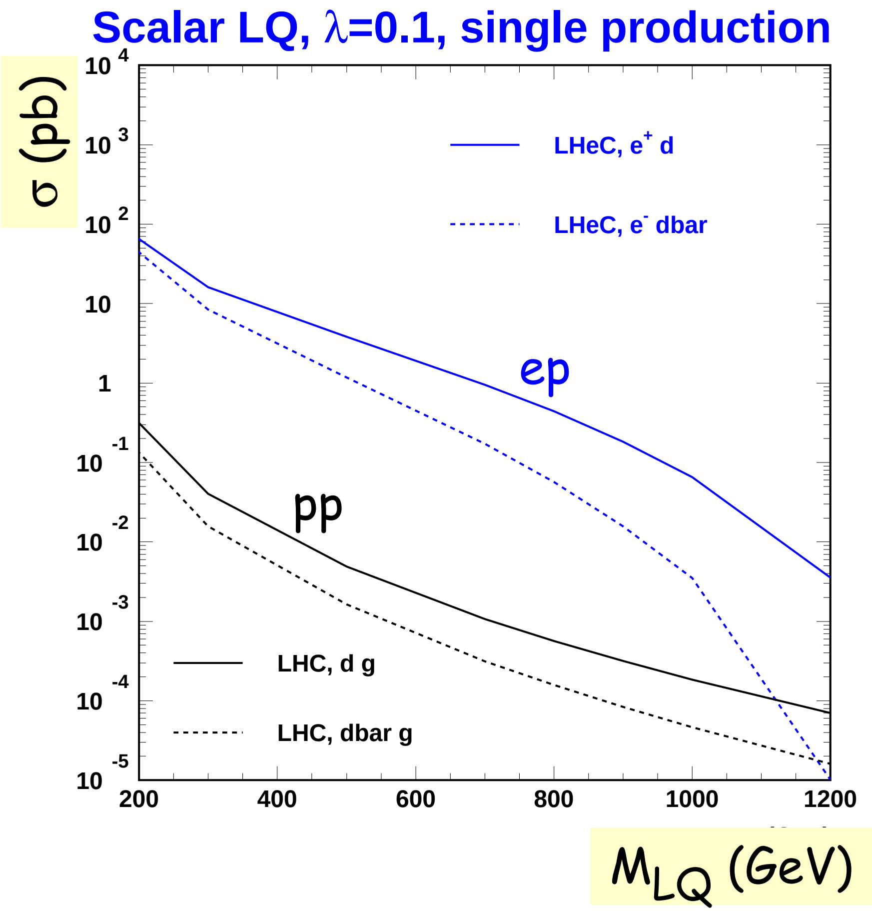
cos(θ*) distribution gives the LQ spin.

- Chiral couplings

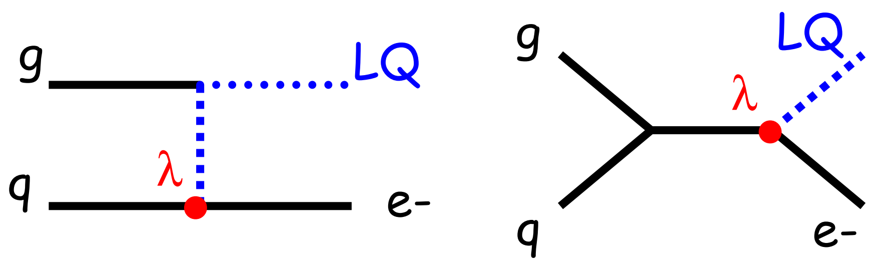
?

Play with lepton beam polarisation.

Single LQ production at LHC



Single LQ production also possible at the LHC.



$\gamma \to$ ee followed by eq -> LQ not considered yet. Not expected to change much the results shown here (Tevatron).

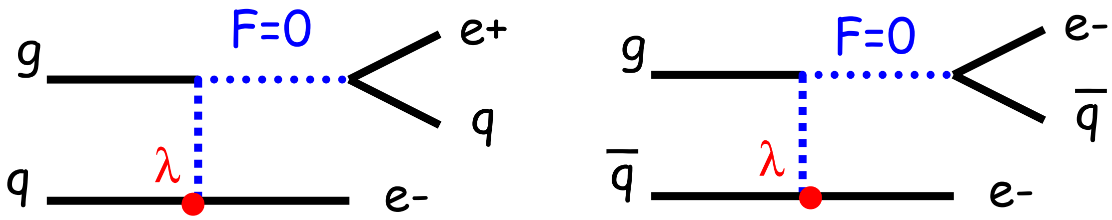
Smaller x-section than at LHeC.
And large background from Z + 1 jet.

Can be used in principle to determine the LQ properties.

Single LQ production at LHC

Single LQ production at LHC to determine the LQ properties ?
Example : Fermion number :

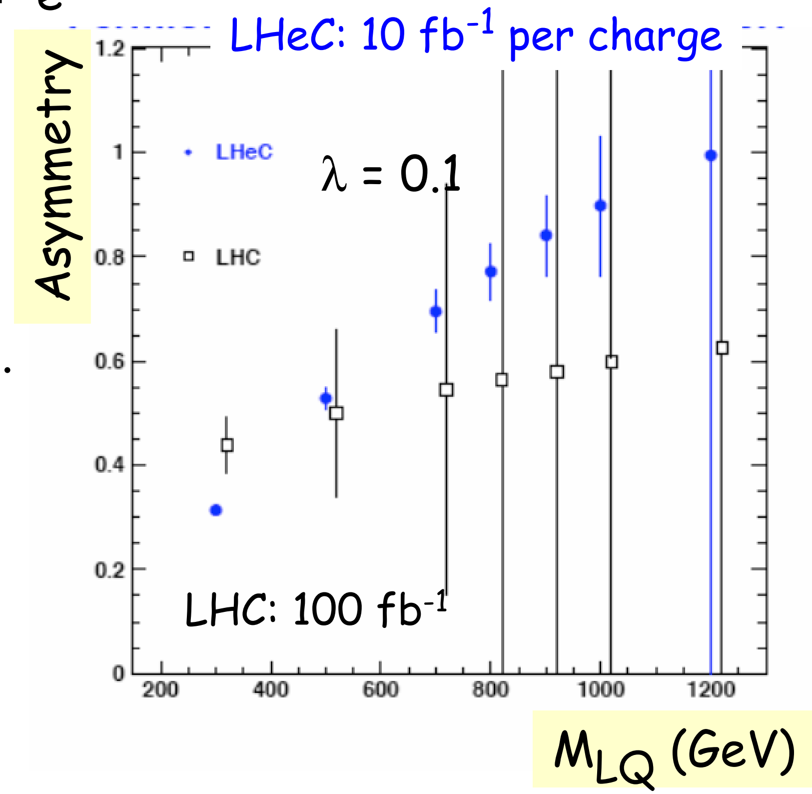
Look at signal separately when resonance is formed by (e+ + jet) and (e- + jet) :



$\sigma(e+) > \sigma(e-)$

Sign of the asymmetry gives F, but could be statistically limited at LHC. Easier in ep !

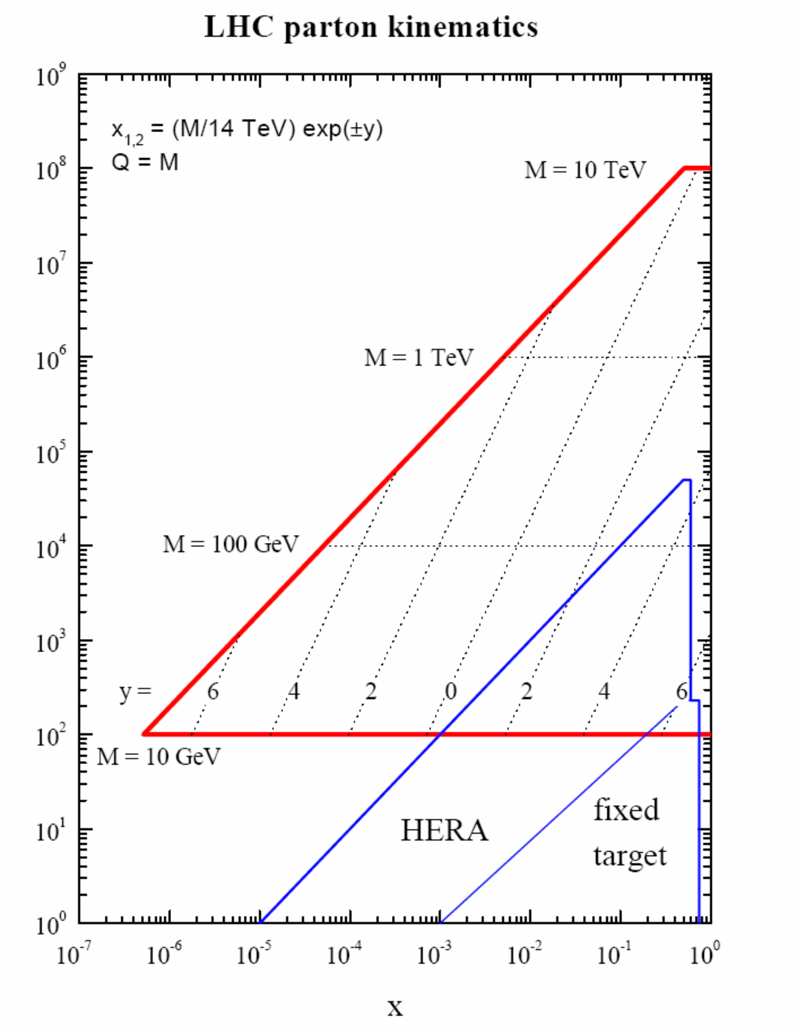
Idem for the simultaneous determination of coupling λ at e-q-LQ and the quark flavor q.



If LHC observes a LQ-like resonance, M < 1 TeV, with indications (single prod) that λ not too small, LHeC would solve the possibly remaining ambiguities.

p structure & interpretation of LHC discoveries

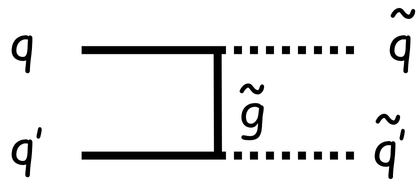
(ATLAS & CMS)



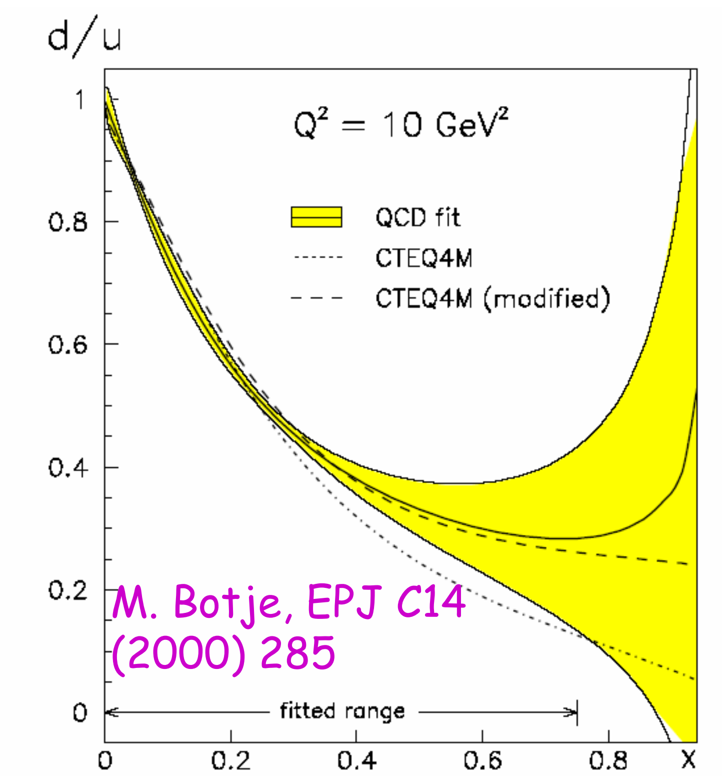
- Highest masses → mainly quarks @ high x
  Constraints on d(x) at high x still limited
- Medium masses involve lower x partons
  Better constraints on $\bar{d}-\bar{u}$ at $x < 10^{-2}$ might be needed…
- Knowledge of b pdf important
- QCD evolution at low x could also be relevant for the interpretation of LHC discoveries

Quark densities at high x

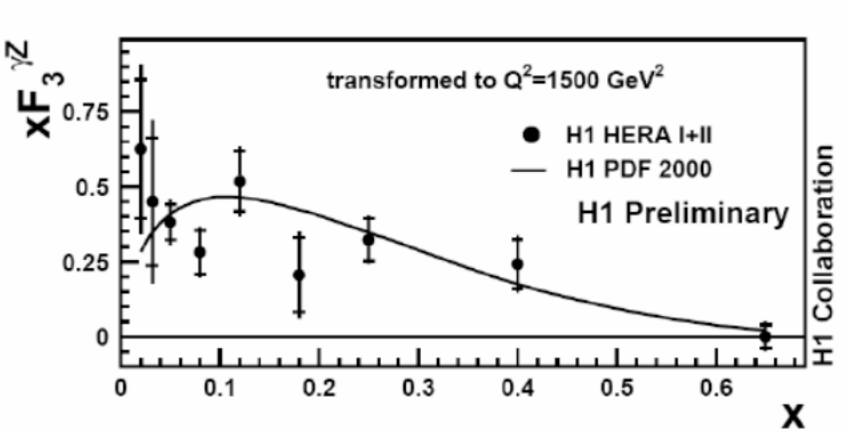
Toy example : heavy squarks



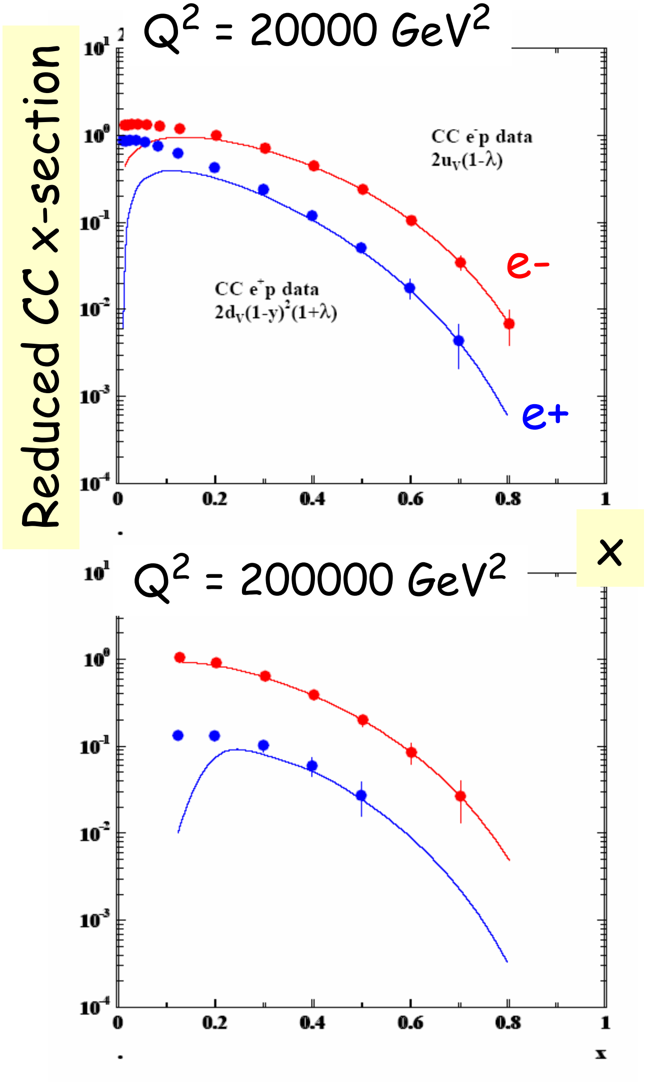
Measure σ and $M(\tilde{q})$. Would like to know :
- gluino mass
- which squarks are observed, i.e. have the mass $M(\tilde{q})$
  (e.g. are $\tilde{u}$ and $\tilde{d}$ degenerate – more generally, relate new colored particles to flavor)



Disentangling u and d come from (so far) :
- F_2^p (4u + d) and F_2^n (d + u) : uncertainties at high x due to nuclear effects in deuteron
- CC DIS data in e^+p and in e^-p (stat. limited so far for high x)
- xF_3 in NC DIS data (~ $2u_v + d_v$) – also stat. limited so far

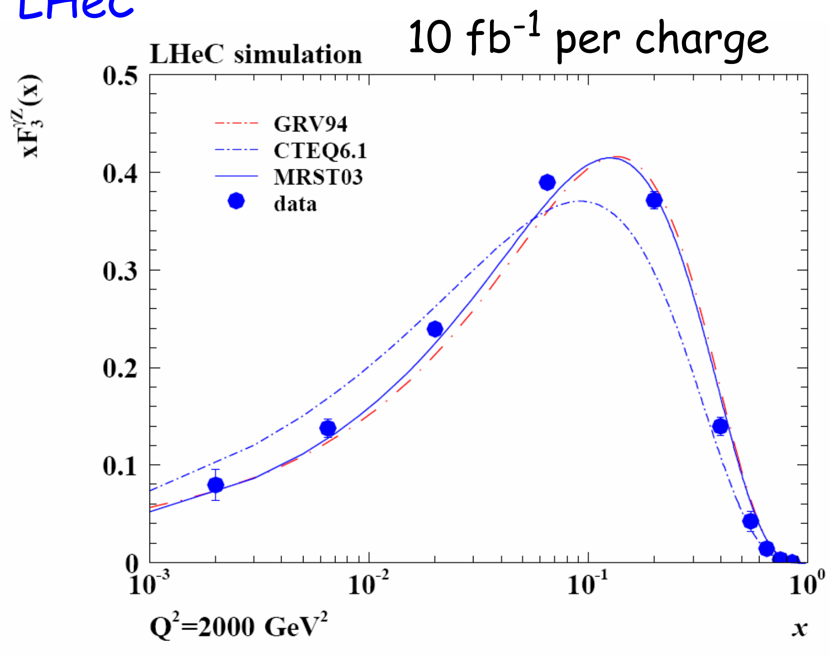


Better constraints on d(x) at high x



- CC DIS at LHeC: simulation for 1 fb^{-1}
  High CC rates up to high x : would allow an accurate determination of d/u at high x.

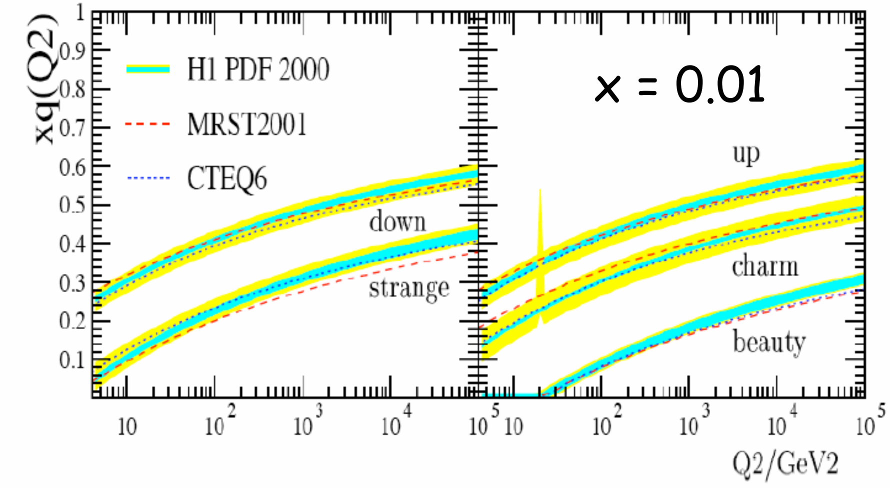
- xF3 at LHeC



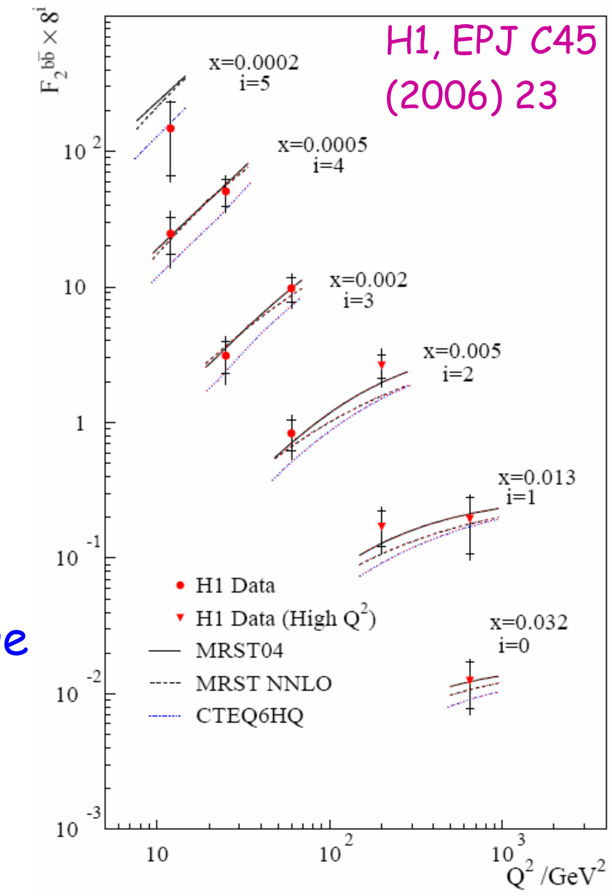
- e-deuteron data at LHeC in addition to ep could help (tagging and reco. of the spectator proton → free of nuclear corrections)

- high rate of ν and $\bar{\nu}$ CC DIS on H target… NuMi beam at FNAL ?

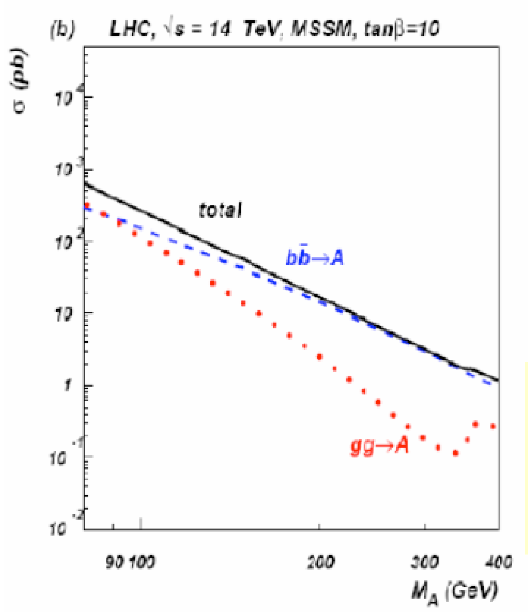
Charm and Beauty pdf's



At $Q^2 = Q^2_{LHC}$, large contribution from charm ! Beauty significant as well.



Intrinsic c and b at high x ? E.g. for heavy s-charm and sbottom…



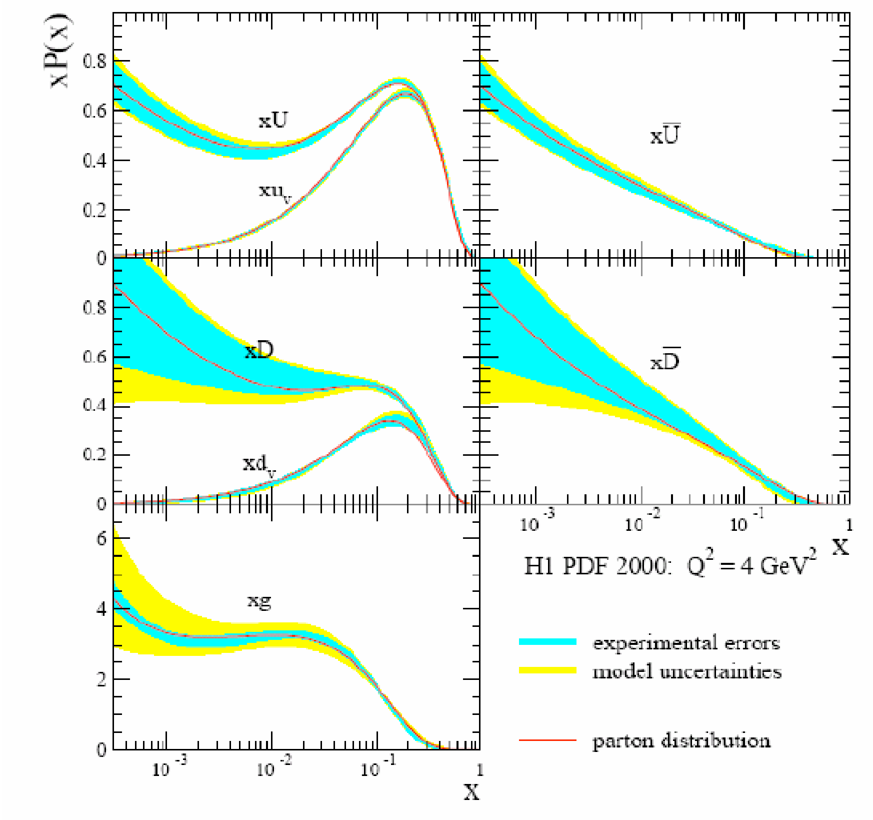
Generally, precise knowledge of esp. b(x) important since b involved in the initial state of many new physics processes.
e.g. determination of tan(β) from $b\bar{b}$ -> h/A.

LHeC: high lumi, large b fraction, small beam spot → would extend the range of b & c measurements and bring them to a new level of precision (~ %, compared to 10% at HERA)

Quark densities at medium x

$$xP = A_p x^{B_p} (1-x)^{C_p} f_p(x)$$

M. Klein & B. Reisert



Fit to H1 + BCDMS data, release $B_U = B_D$ and $A_U = A_{\bar{U}}$, $A_D = A_{\bar{D}}$, i.e. do not impose that :

$q = \bar{q}$ at low x
$\bar{u} = \bar{d}$ at low x

$\bar{D} = \bar{d} + \bar{s}$ becomes poorly constrained already at x below 10^{-2}

Further constraints would come from

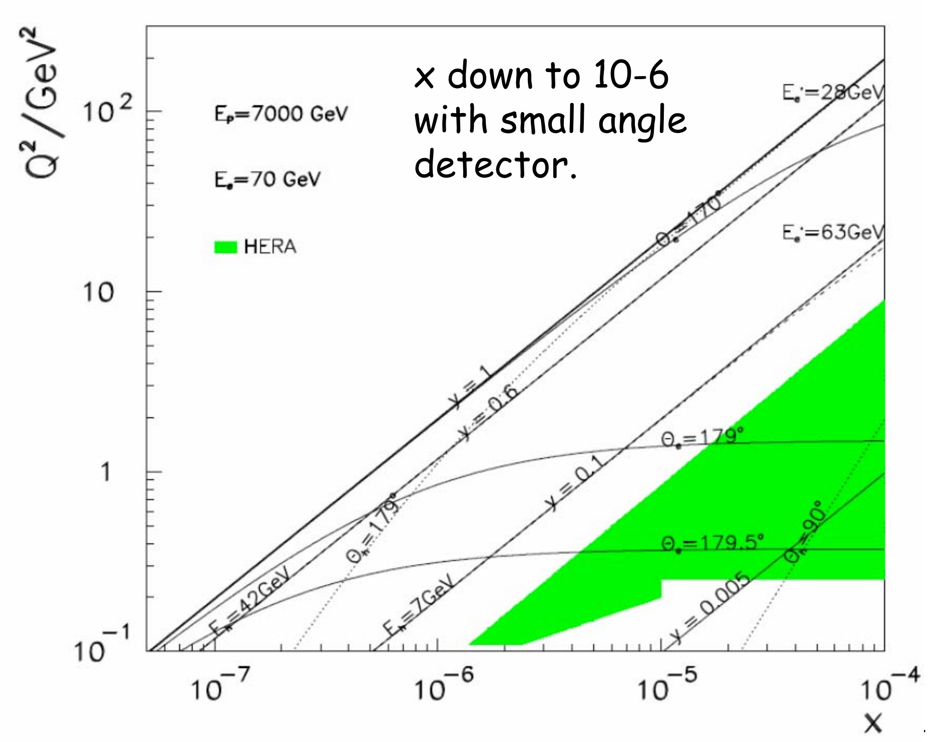
- xF_3 at LHeC, at low-medium x
- e-deuteron data at LHeC ("free" of shadowing corrections via Glauber's relation of shadowing to diffraction)
- W production at the LHC

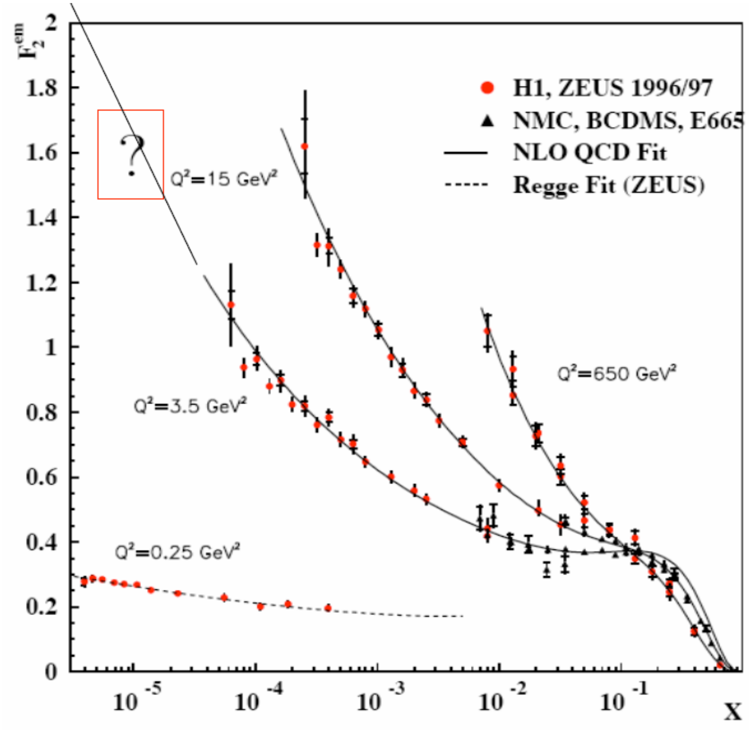
A precise decomposition of the proton structure amongst the various flavours is likely to be important if SUSY-like new physics is observed.

QCD at low x

Many questions yet unanswered…

-Saturation of parton densities ?
- evolution dynamics ? (DGLAP, updfs, BFKL,..)
- origin of high density phase ? Color Glass Condensate ?
- Understanding of diffraction ?
  $\rightarrow$ see talk by P. Newman



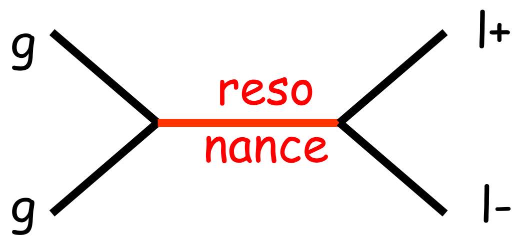


LHeC would provide a dramatic extension of the low x kinematic range.

Important for LHC (pp, pA and AA) and for ultra-high-energy neutrino cross-sections.

Low x evolution and New Physics at LHC ?

Example: "light" (< 1 TeV) Randall-Sundrum graviton, missed at the Tevatron because of low coupling / not large enough luminosities

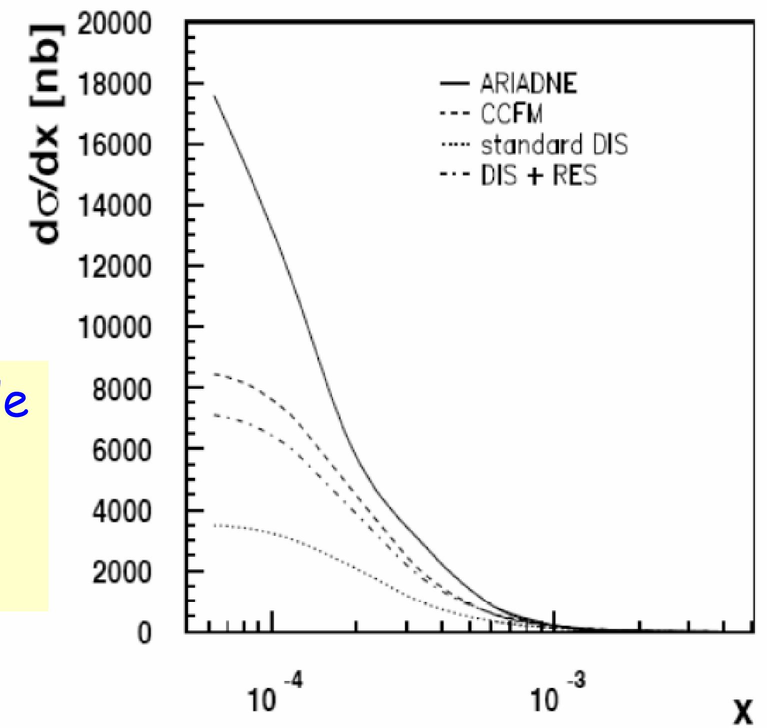


Spin 2 graviton or spin 1 Z' boson ?

In collinear factorisation : angular distributions disentangle between spin 1 & spin 2.

kT factorisation: virtual gluons i.e. not only transverse. Polarisation tensor $\varepsilon^\mu \varepsilon^\nu \sim k_T^\mu \, k_T^\nu$, would affect the angular distributions... Large effect ?
Work in progress...

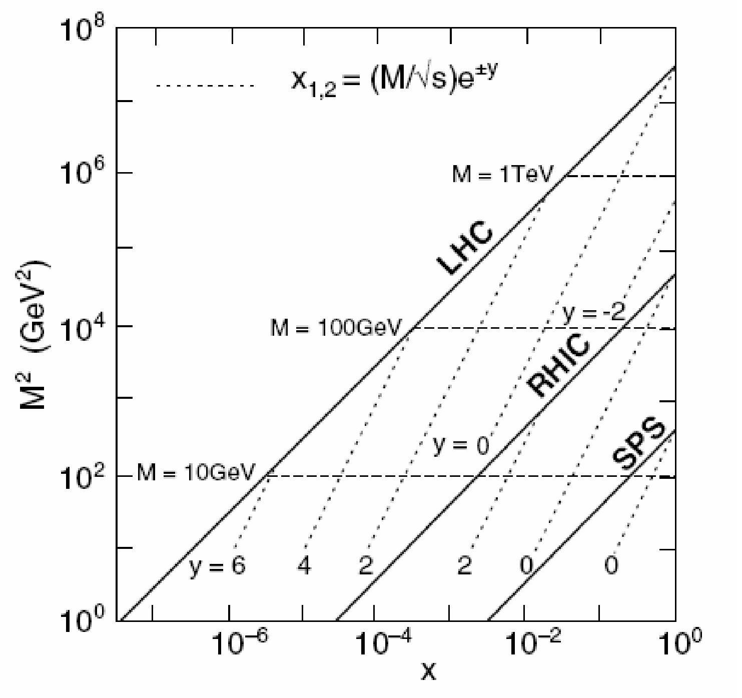
Studies of forward jets at LHeC would provide further constraints on the unintegrated gluon density – and more generally on the evolution pattern at low x.



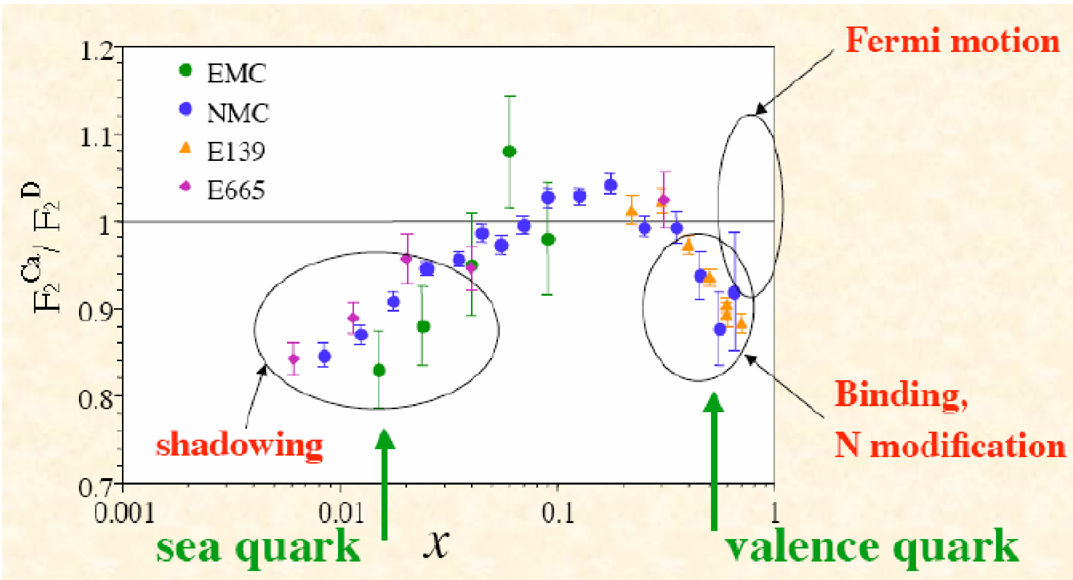
Low x partons in heavy ions

Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.5 TeV (x 30 larger than $\sqrt{s}$ at RHIC)

Goal is to establish and understand the Quark-Gluon Plasma by investigating medium effects on produced partons (jet quenching, quarkonia suppression).

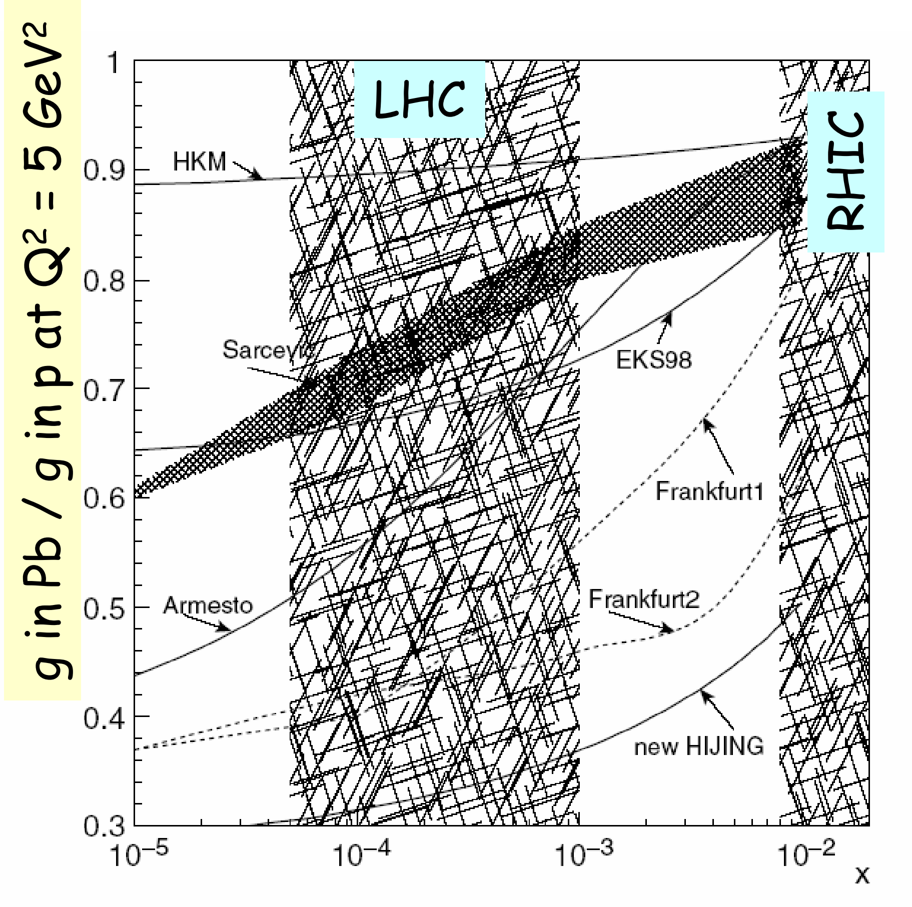


Very low x partons involved. Need to disentangle medium effects from initial state effects, esp. shadowing & probably saturation of g density.



So far, no experimental data in the very low x domain.

Low x gluon in heavy ions



Low x g in Pb very poorly known.
Variation by a factor of 3 between different predictions (i.e. one order of magnitude for gg induced x-sections)

Further constraints from heavy flavor production in pA collisions at LHC ?

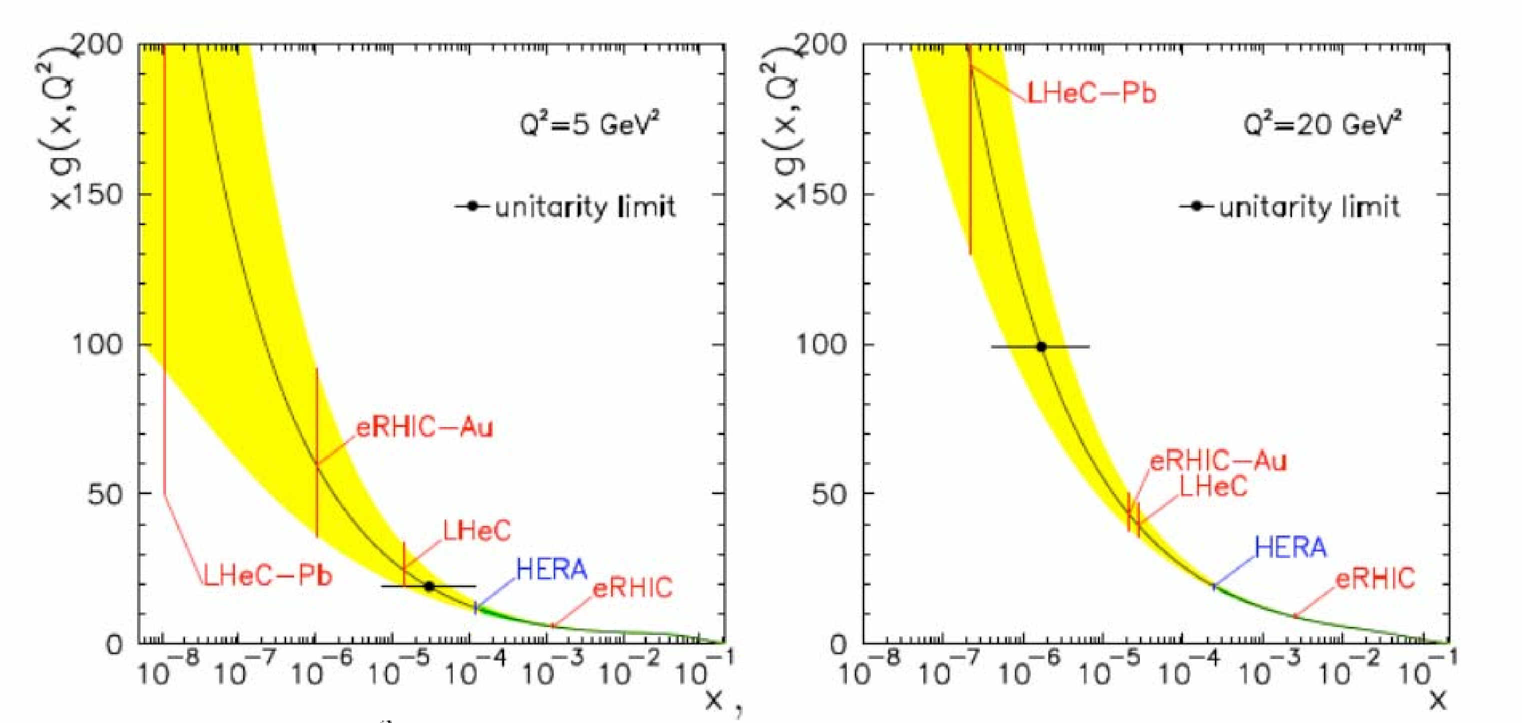
- scale uncertainties
- uncertainties from m_c etc…

→ constraints would come from comparing x-sections in pA and in pp ?
Need precise knowledge on low x gluon in proton… Evolution, updfs ?

- Universality of shadowing ? eA data would test it.
- High parton densities regime → important diffractive component, under control ?

A determination of g in Pb from inclusive e-Pb DIS scattering would be of primary value, given the complexity and the importance of QGP.

High parton densities regime



High density $\frac{g_A / \pi r_A^2}{g_p / \pi r_p^2} = A^{1/3} \frac{g_A}{A g_p}$

Unitarity $$xg(x,Q^2) \leq \frac{1}{\pi N_c \alpha_s(Q^2)} Q^2 R^2 \simeq \frac{Q^2}{\alpha_s}$$

Striking effects predicted:
bj -> black disc limit $F_2 \rightarrow Q^2 \ln(1/x)$
~50% diffraction
colour opacity, change of $J/\Psi(A)$

Measurements of eA and ep at high densities: relationship (Gribov-Glauber) of nuclear shadowing to diffraction; huge impact on the understanding of partonic matter in nuclei.

LHeC : general parameters

Additional e ring in the LHC tunnel. Maintain the existing facility for pp collisions

- Proton beam parameters = those of standard pp LHC operation
- Electron beam : Ee as high as possible – but can not be too high because of synchrotron radiation.
  E.g. Ee = 70 GeV, then $E_{loss,\ SR} \sim 0.7$ GeV per turn in the LHC tunnel.
  Intensity is then limited by the available power for the accelerating RF cavities.
  Ee = 70 GeV, P = 50 MW $\rightarrow$ Ie $\approx$ 70 mA.

- Optics at the Interaction Region :
  - match the beam x-sections, i.e. ($\beta^* \times$ emittance) is the same for e and p.
  - take $\beta_{xp}\, \beta_{yp} = 1\ m^2$ for reasonable p-beam x-section
  - this, with Ie and Ip, leads to a luminosity of $\sim 10^{33}\ cm^{-2}\ s^{-1}$
  - Feasible ? β^*_e limited from :
    - chromaticity $\sim 1/\beta^*$: if β^* too small, parts of the beam on resonances
    - beam-beam effects : shift ($\sim \beta^*$) the betatron tune of the lepton beam;
    - beam-beam separation (bunch spacing 25 ns) requires a small enough lepton beam emittance (hence a larger beam-beam tune shift than HERA)

$\rightarrow$ limited window for β^* of the lepton beam, but feasible e.g. with a LEP-like structure of FODO cells (376 cells).

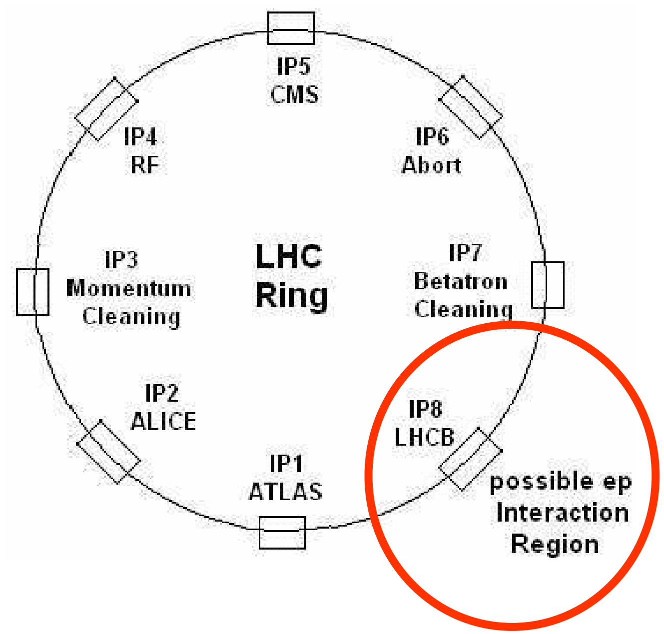
Main parameters

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	

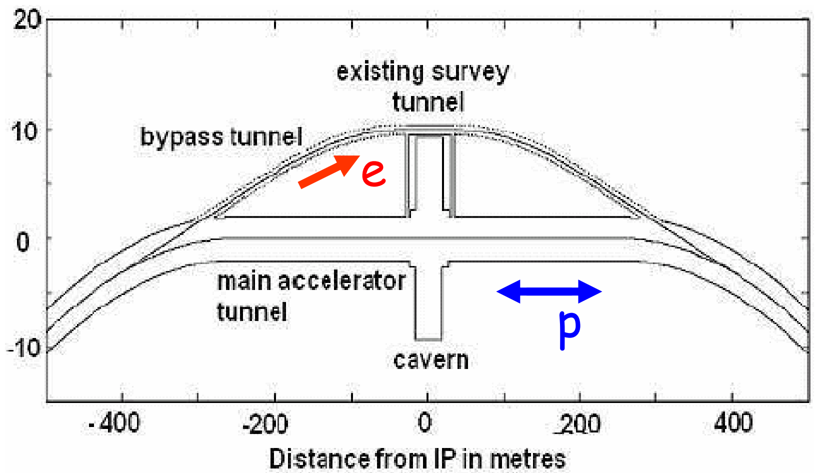
Lepton Ring

- LEP-like FODO cells in the 8 arcs
- in straight sections : superconducting RF cavities, 1 GHz, gradient of 12 MV/m, need ~ 800 cells.



- After completion of the b-physics programme at the LHC $\rightarrow$ could use IP8 ?

- In parallel with pp, pA and AA data taking, i.e. need a bypass around IP1, IP5, and possibly IP2 :



Need to drill two connection tunnels, about 250 m long, up to 2 m in diameter.

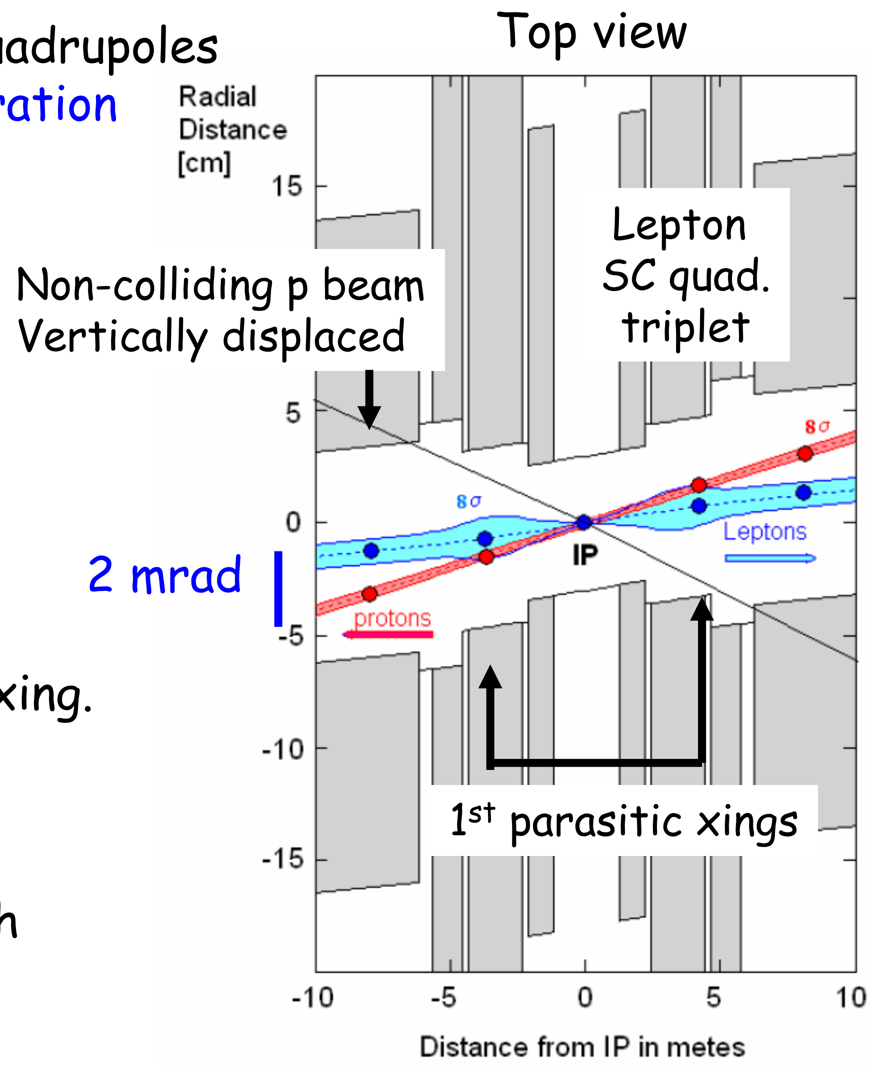
Interaction Region (high lumi)

Low β^* for high lumi requires that the quadrupoles be close from the IR. Need a quick separation of the beams, avoiding too strong fields.

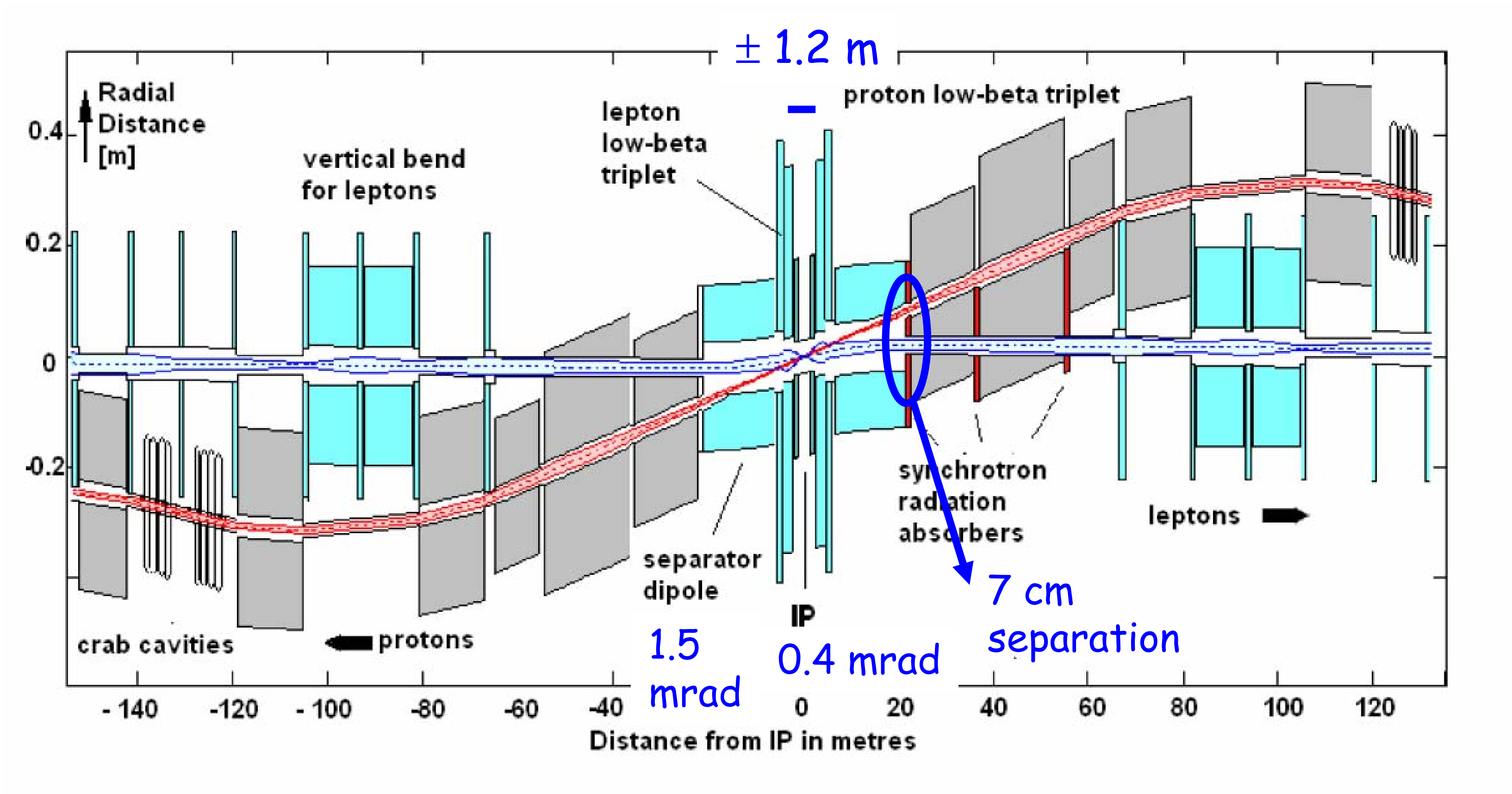
→ For a bunch spacing of 25 ns, need a horizontal x-ing angle of 2 mrad

Ensures that the beams are separated by > 8 σ at the 1st parasitic xing.

Lumi reduction due to θ_c (factor 3.5) compensated by “crab-cavities”, which rotate the p bunches.



Interaction region



Magnet free space is ± 1.2 m -> detector acceptance of 10 degrees.

For low x, need to go down to 1 degree. But luminosity is less an issue, so can have lepton quads. further away (3m) and a larger x-ing angle.

Conclusions

- Within the next 2 years, the LHC will enter a completely new domain of high energy physics :
  - very high $\sqrt{s}$
  - very low x, high parton densities

- For both, capital discoveries are expected. The understanding and interpretation of these data will be complex, and might require ep & eA data in the same energy range.

- A continuation of the DIS programme at the TeV scale would bring to a new level of precision measurements & tests of QCD (e.g. improved alphas determination)

- First conceptual design : this programme could take place using the LHC proton beam. No show-stopper found so far. Luminosity of 10^{33} cm^{-2} s^{-1} seems possible (x 20 HERA)

- How to best optimise the IR ? Two phases (low x, highest luminosity) ? How to prioritize between LHeC and LHC lumi/energy upgrades ?

Expect that the LHC data will tell. Meanwhile, we should be open-minded and think about it !