DIFF07
DESY Hamburg
May 2007

LHeC
an unprecedented probe of hadronic dynamics

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Daresbury Science and Innovation Campus, GB

with M Klein (Univ Liverpool)
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E Perez (CERN)
F Willeke (DESY Hamburg and BNL)

1 Why?
2 How?
3 When?
4 Summary

and more and more …… !

hep-ex/0603016, JINST 1 (2006) P10001, and DIS06 Proceedings

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1. Why?

Why: Leptons ↔ Quarks ?

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- how are leptons and quarks related ?

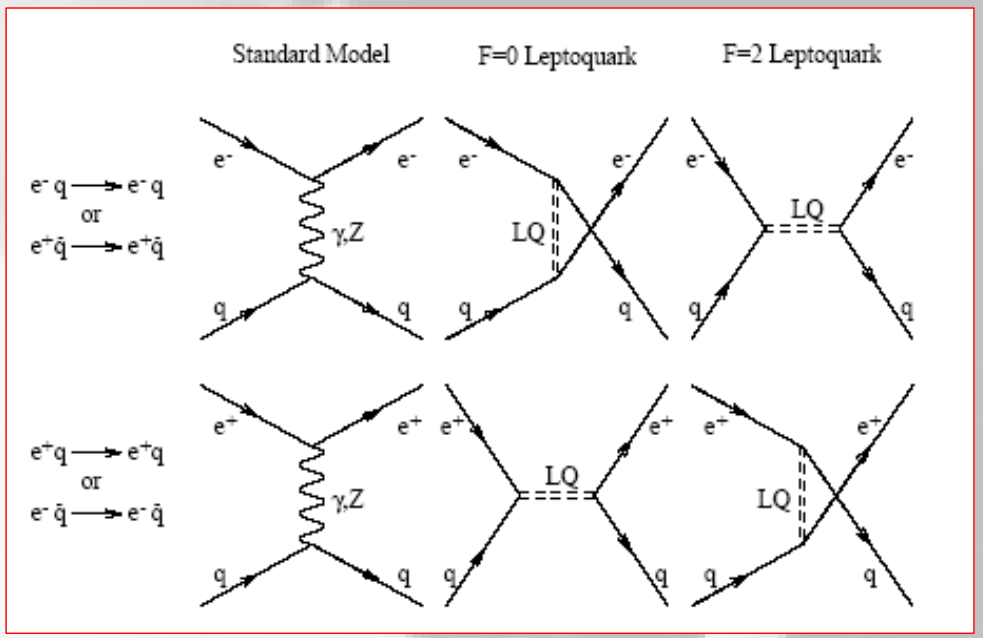
THE UNCONFINED QUARKS AND GLUONS

Abdus Salam

International Centre for Theoretical Physics, Trieste, Italy and Imperical College, London, England

1. Introduction

Leptons and hadrons share equally three of the basic forces of nature: electromagnetic, weak and gravitational. The only force which is supposed to distinguish between them is strong. Could it be that leptons share with hadrons this force also, and that there is just one form of matter, not two?



ICHEP86 Berkeley

- put them together at the highest energy at finest detail

TeV *eq* Kinematic Reach

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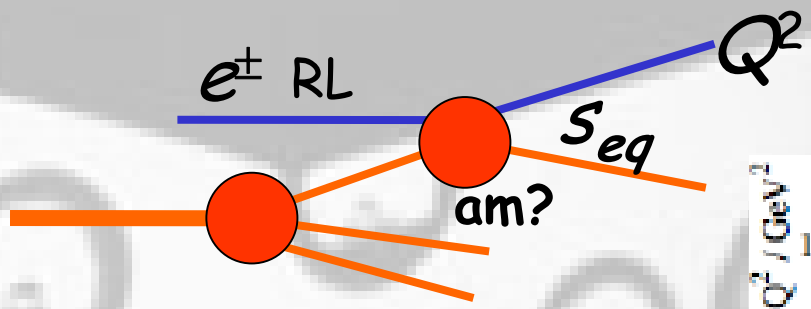
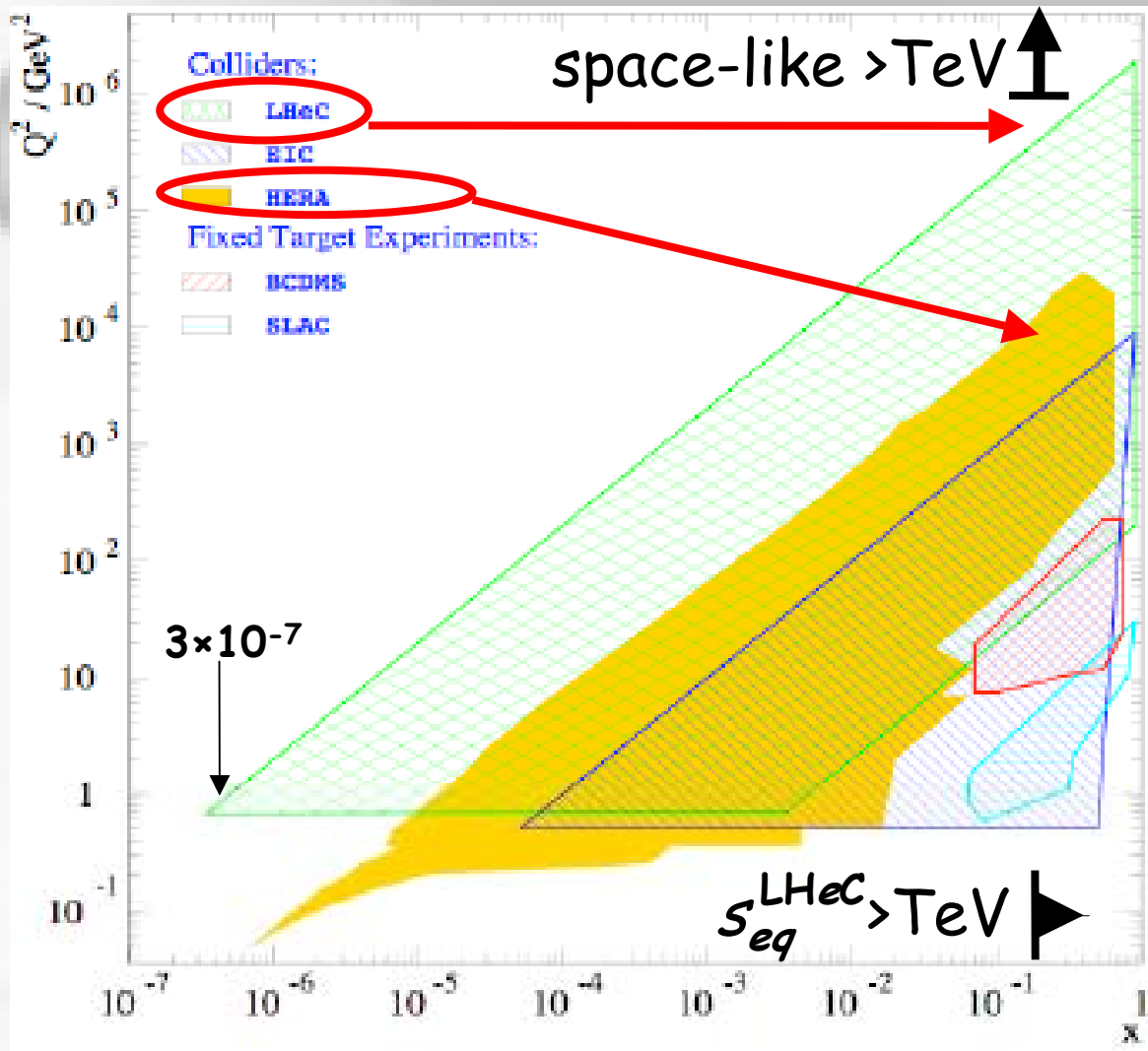


- 2007: HERA
  - $Q^2 \leq 30{,}000\ GeV^2$
  - $s_{eq} \leq (300\ GeV)^2$
    in ~ 0.7 am
- ≥2016?: LHeC
  - $Q^2 \leq 2{\times}10^6\ GeV^2$
  - $s_{eq} \leq (2000\ GeV)^2$
    in ~ 0.1 am !



Lepton+quark @ TeV

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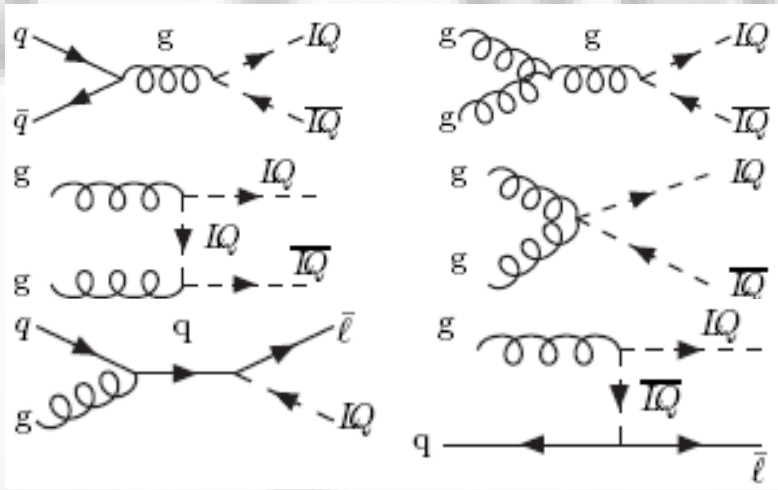
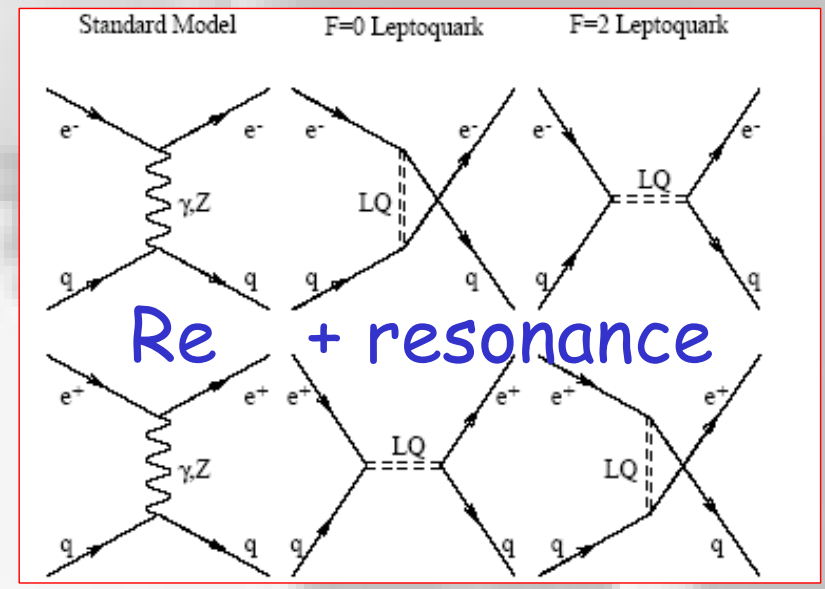
- leptoquark systems – new physics + SM

LHC



LHeC



SM (hadronic) + signal

Lq & *LqLq* production

σ ~ few × 0.1 fb (Λ=0.1)

SM (electroweak) + signal

Lq formation

σ ~ 100 fb (Λ=0.1)

Lepton+quark @ TeV

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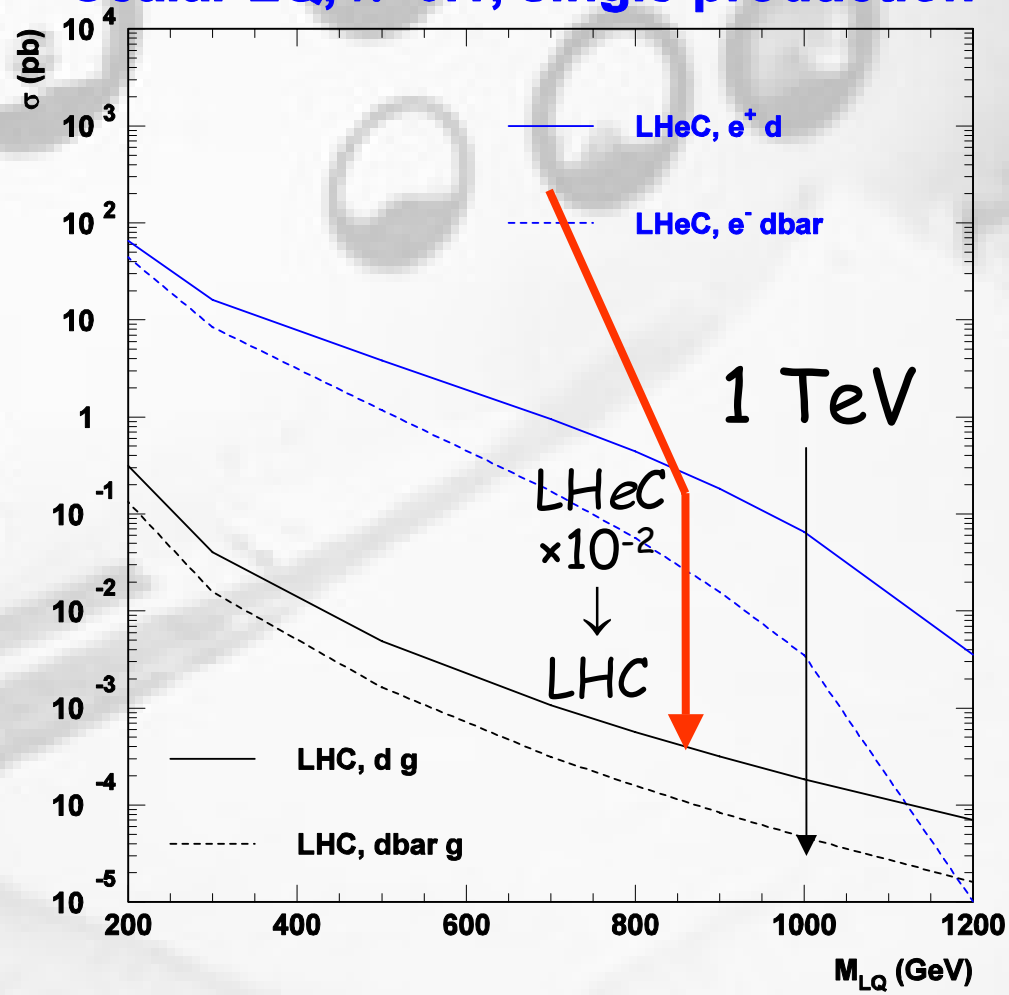
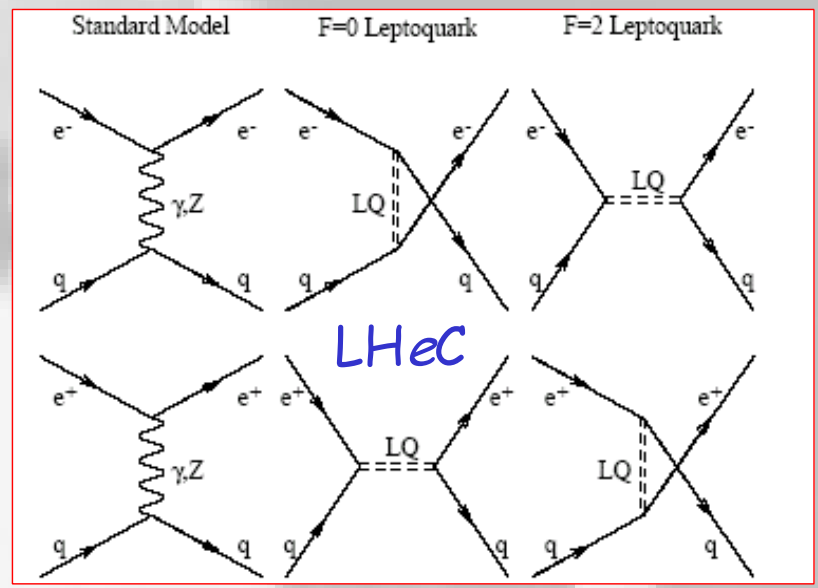
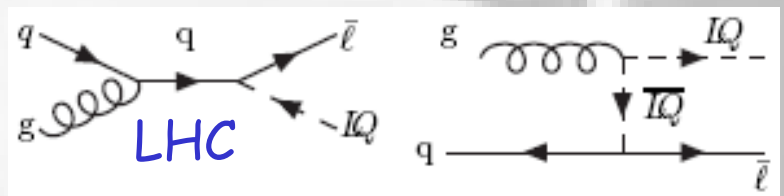
- leptoquark systems – new physics +SM

Scalar LQ, λ=0.1, single production







Lepton+quark @ TeV

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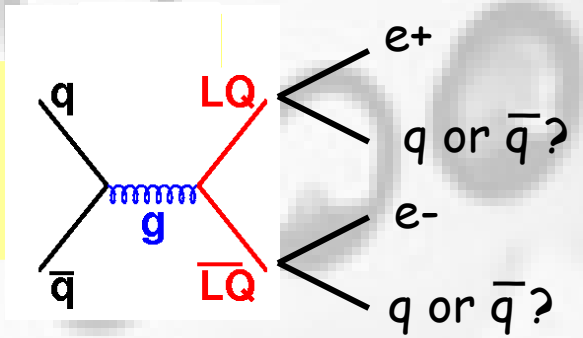
LHC *Lq* pairs+decay

fermion number



spin parity and chirality

$\bar{q}q \rightarrow g \rightarrow \bar{L}q\, Lq$

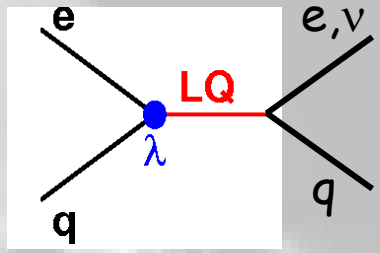
production mechanism ?

disentangle mass spectrum ?

experim! signature

jets + leptons

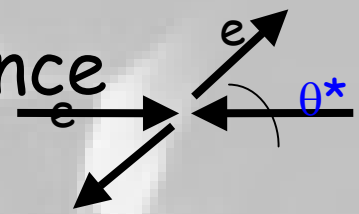
LHeC *Lq* formation+decay



e+ F=0
e- F=2

defined formation (e_{LR})
→ precision BRs (NC CC)

inclusive coherence



unique PWA

SM + signal + interference

jet+lepton+p_T balance
jet +p_T imbalance

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Lepton+quark @ TeV

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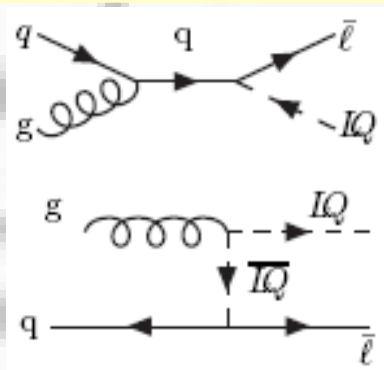
LHC *Lq* +decay



fermion number

$gq \rightarrow Lq\,\bar{l}$

spin parity and chirality

production mechanism ?

disentangle mass spectrum ?

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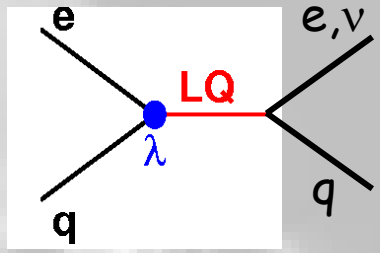
jet + leptons

LHeC *Lq* formation+decay



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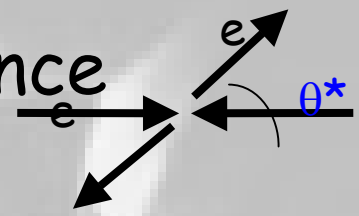

unique PWA

SM + signal + interference

jet+lepton+p_T balance
jet +p_T imbalance

Why: Structure of Matter @TeV

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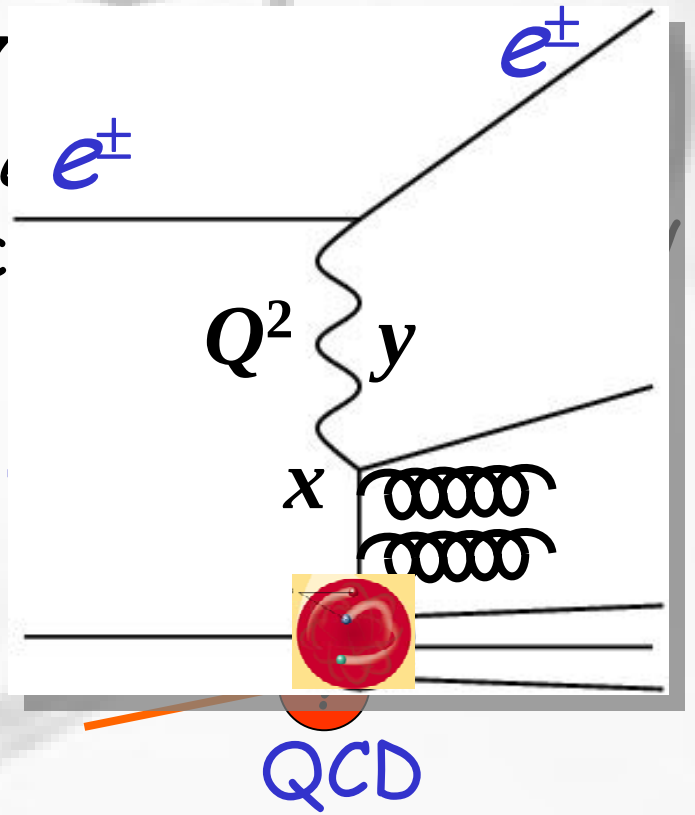
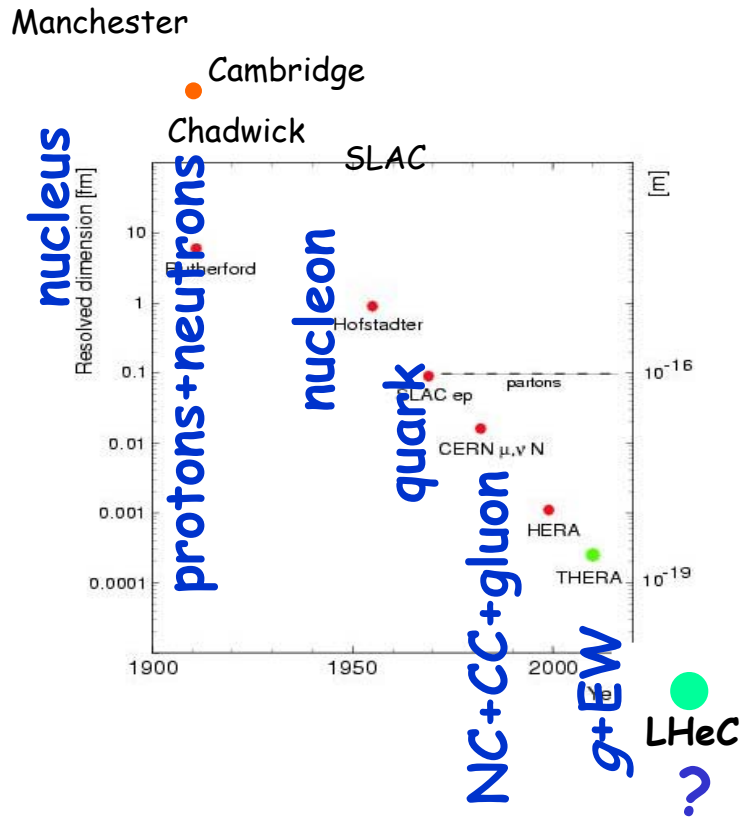
- unique chiral probe @ 0.0001 fm ?
- 7





SM + *q* structure
@ ~ 0.0001 fm ?

Unification ?

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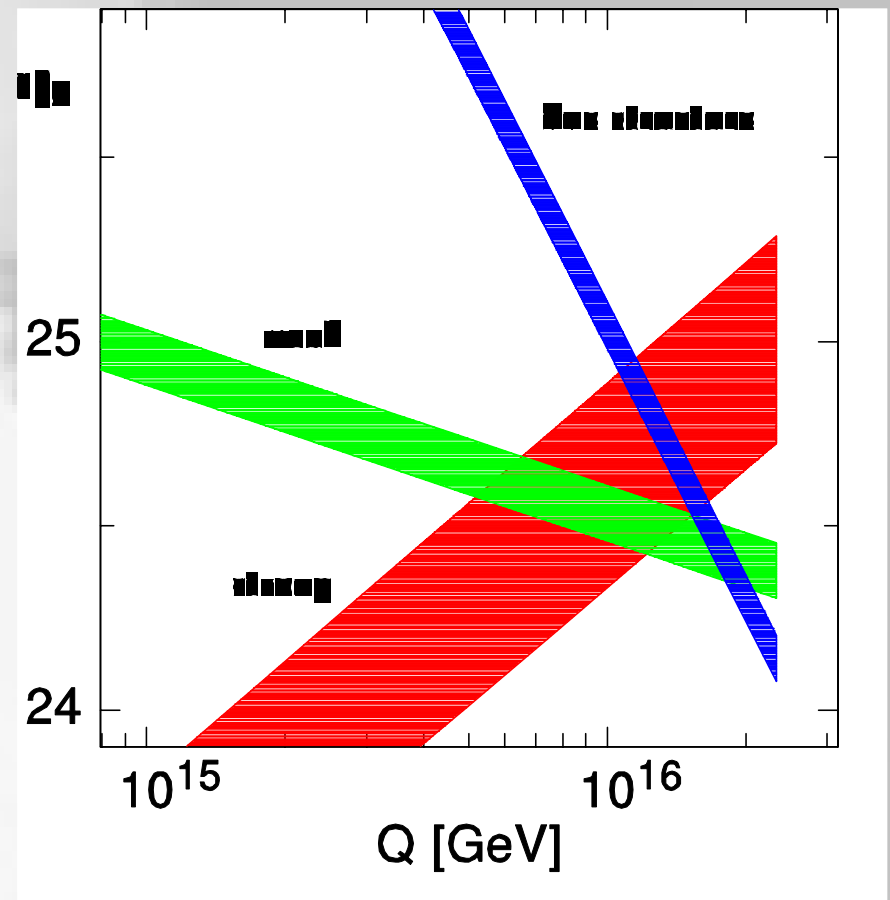
- precision → QCD at highest energy
- short distance structure of SM+
  - 2007 α @ 10^{-3} ppm
  - 2007 G_F @ 10 ppm
  - 2007 G @ 0.1%
  - 2007 α_s @ 1-2%
  - LHeC + detector
    → α_s @ few ‰



precision → extrapolation → discovery
probe new chromodynamic physics – beyond SM ?

Heavy Flavour in Hadron Chromodynamics

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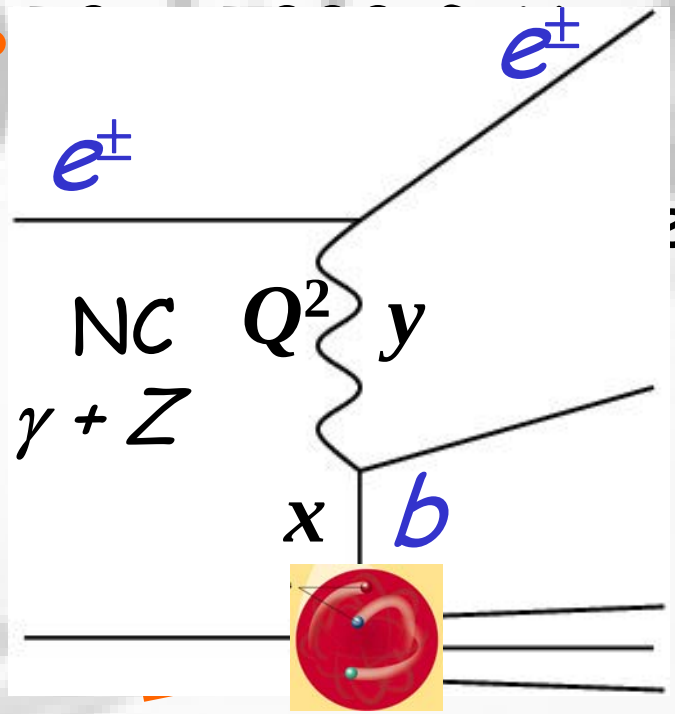
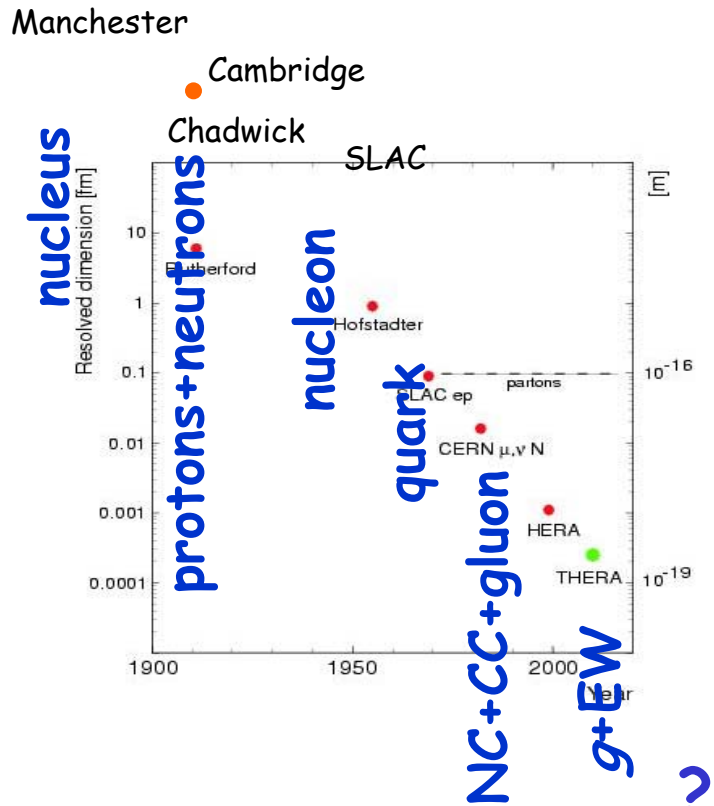
- unique chiral probe @ 0.0001 fm ? = 0.1 am





SM + q structure @ ~ 0.0001 fm ?

Heavy Flavour in Hadron Chromodynamics ……

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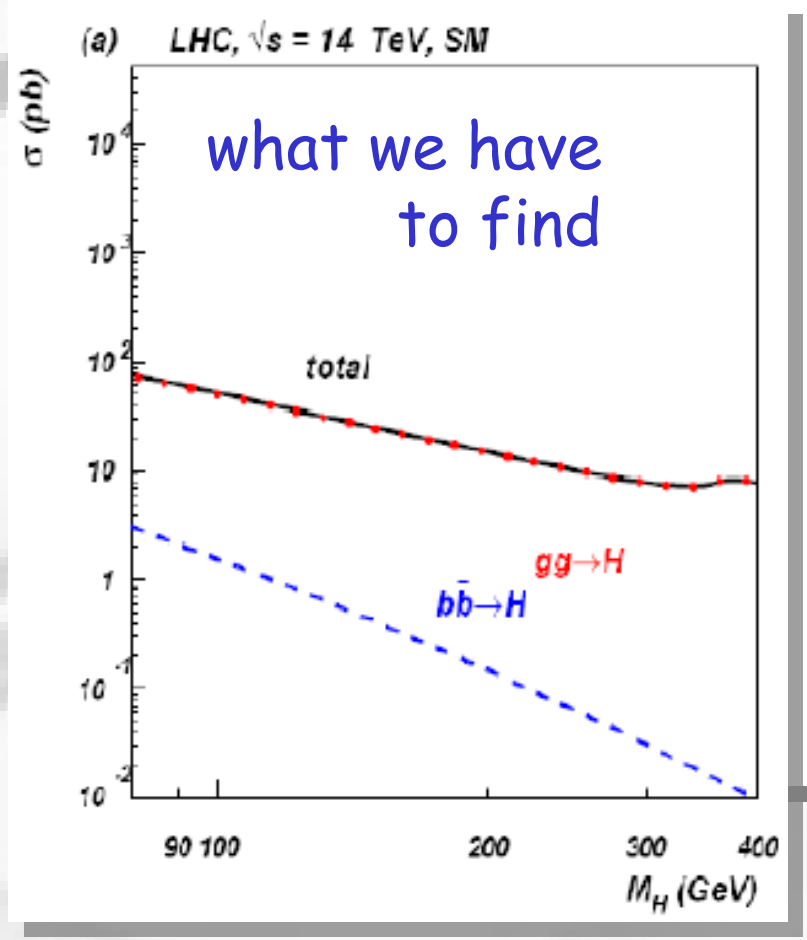
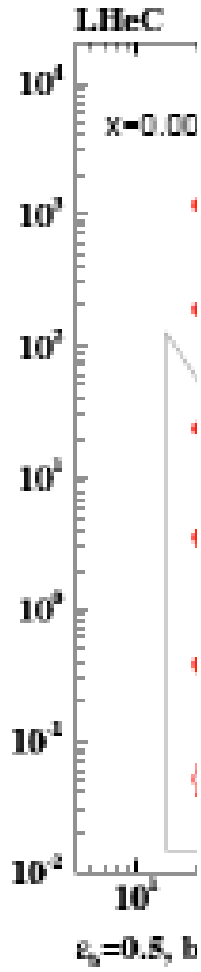
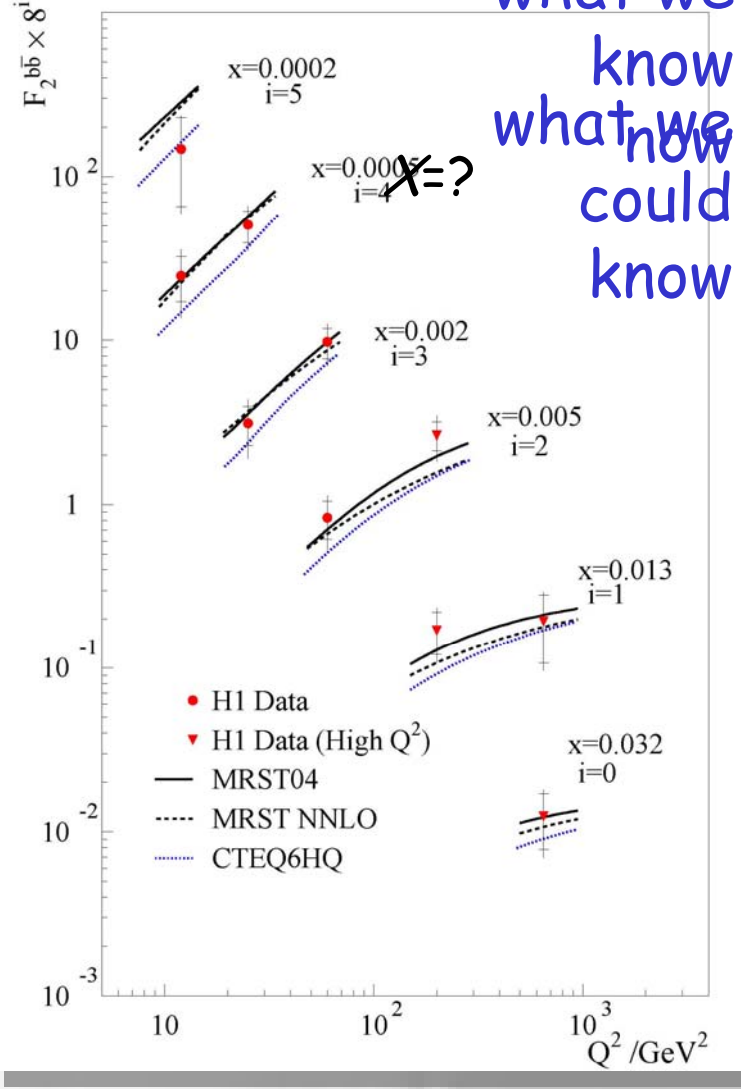
- Higgs at LHC



what we have to find





what we know

what we ~~know~~ X=?

how could know

Why: Dense Colour ?

Most of the mass of ordinary matter is concentrated in protons and neutrons. It arises from [a] profound and beautiful source.

Numerical simulation of QCD shows that if we built protons and neutrons in an imaginary world with no Higgs mechanism - purely out of quarks and gluons with zero mass - their masses would not be very different from what they actually are. Their mass arises from pure energy, associated with the dynamics of confinement in QCD, according to the relation $m = E/c^2$. This profound account of the origin of mass is a crown jewel in our Theory of Matter.

Frank Wilcek CERN October 11, 2000

- probe hadronic matter at highest parton density

QCD is headline stuff !

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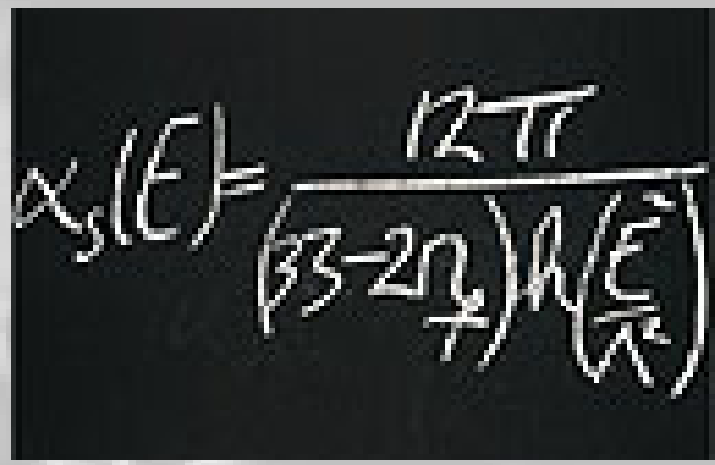
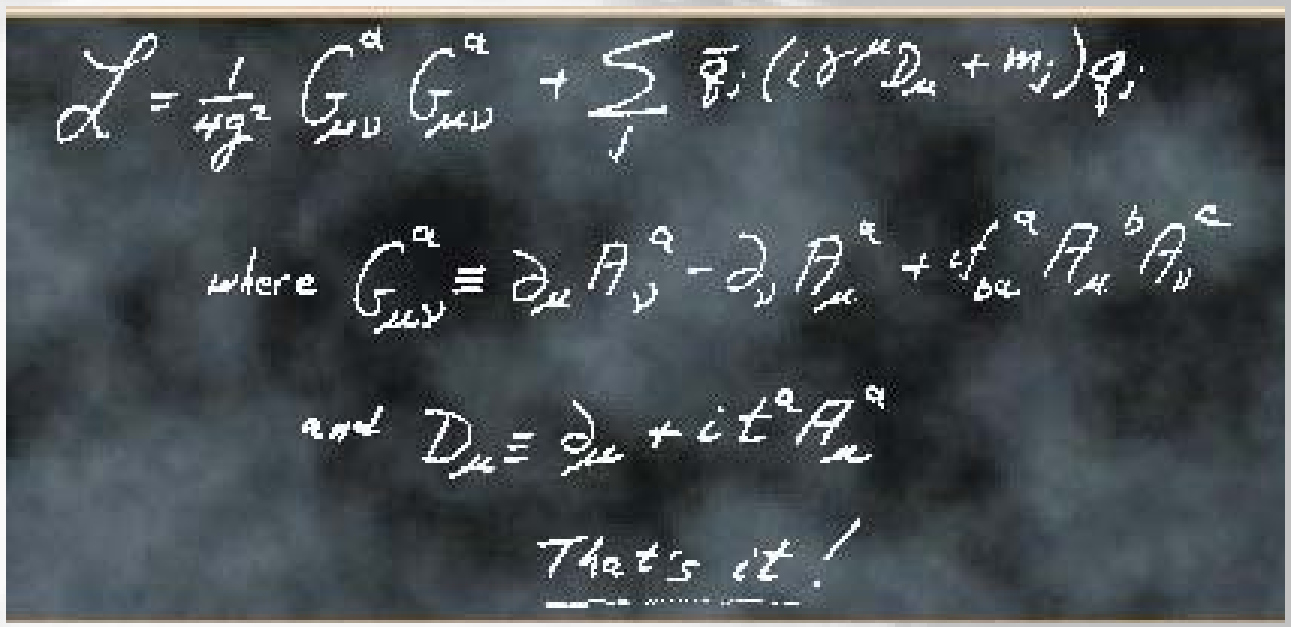
- found on a Guardian web page



- found on Frank Wilcek's blackboard



Growing Field Energy Density

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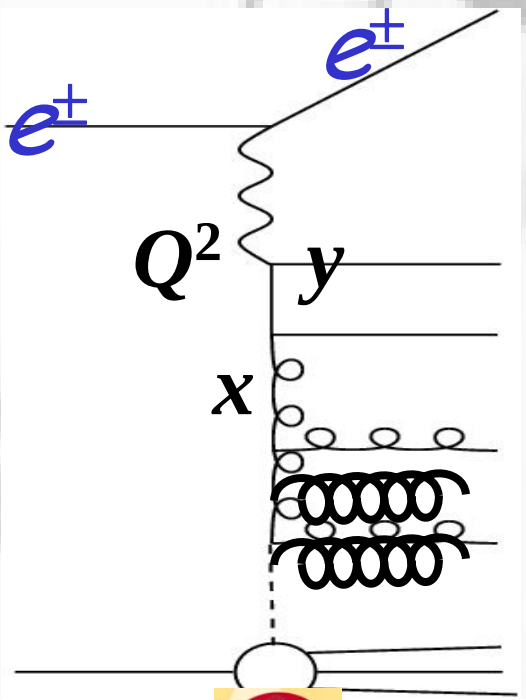
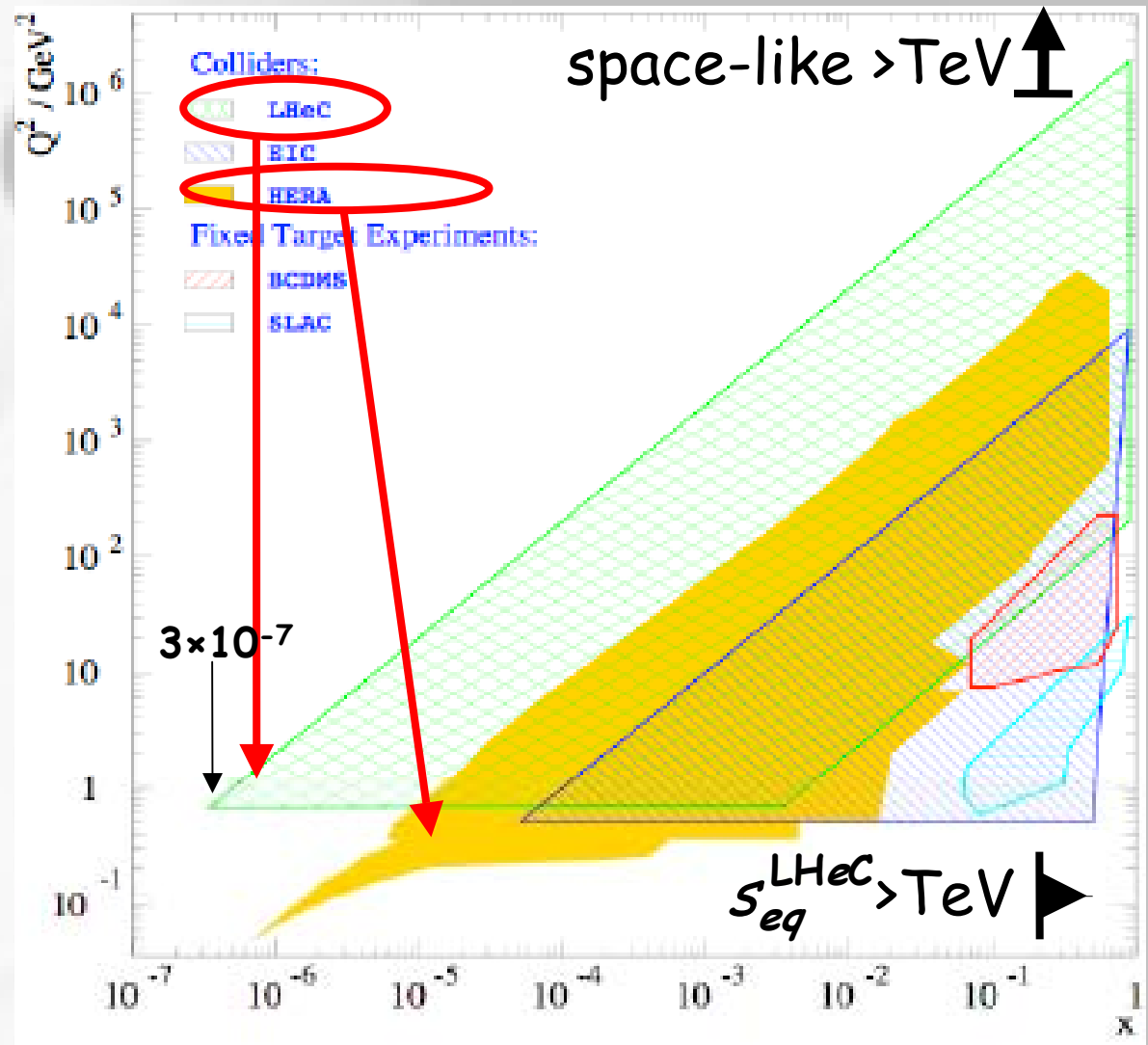
- 2001?: HERA
  - $Q^2 \geq 1\ \mathrm{GeV}^2$
  - $x_{Bj} \geq 5\times10^{-5}$





Gluon recombination

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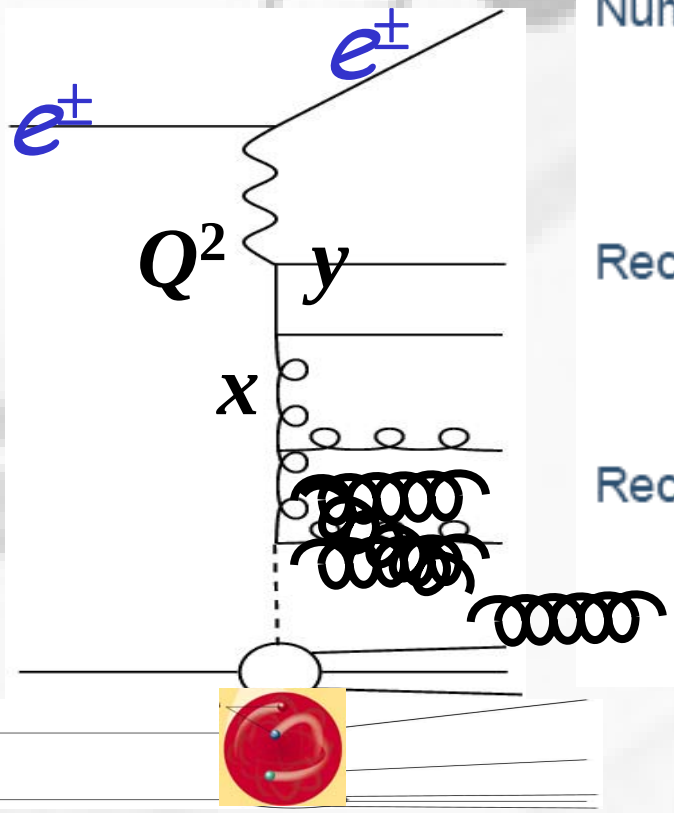
- ≥2016?: LHeC
  - $Q^2 \geq 1\ GeV^2$
  - $x_{Bj} \geq 5\times10^{-7}$

- $Q^2 \rightarrow$ size of gluons
- $x_{Bj} \rightarrow$ phase space for gluons



Number of gluons per unit area: *p* and *A*

$$\rho \sim \frac{xG_A(x,Q^2)}{\pi R_A^2}$$

Recombination cross-section:

$$\sigma_{gg\to g} \sim \frac{\alpha_s}{Q^2}$$

Recombination happens if $\rho\sigma_{gg\to g} \gtrsim 1$, i.e. $Q^2 \lesssim Q_s^2$, with:

$$Q_s^2 \sim \frac{\alpha_s xG_A(x,Q_s^2)}{\pi R_A^2} \sim A^{1/3}\frac{1}{x^{0.3}}$$

low x large nuclei

Gluon recombination @ HERA

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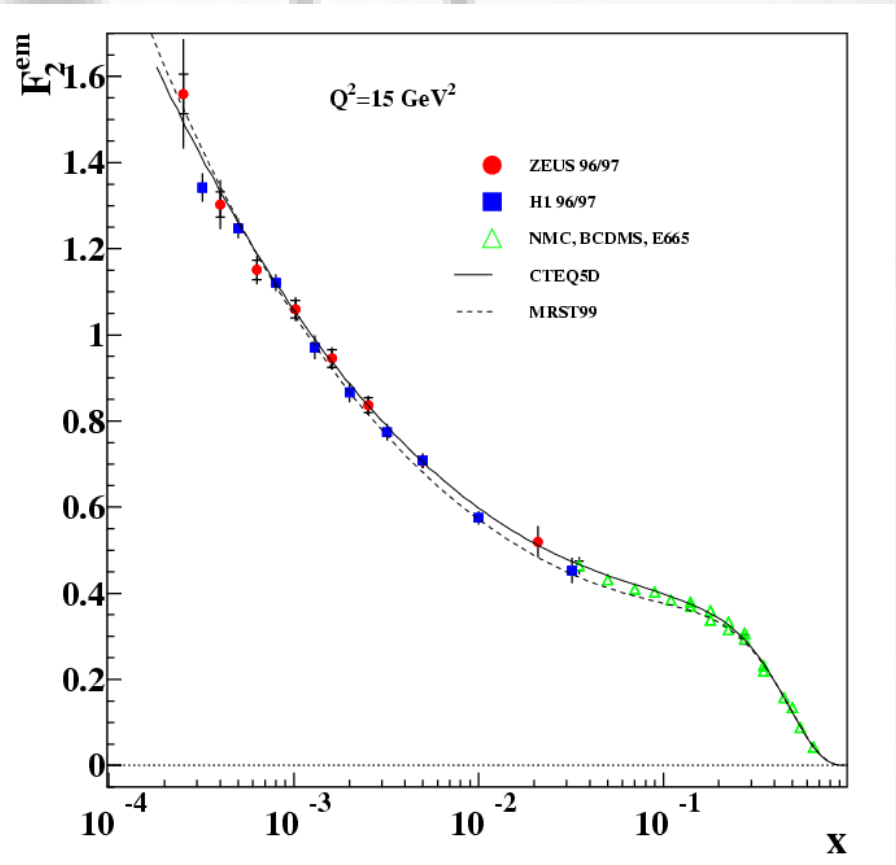
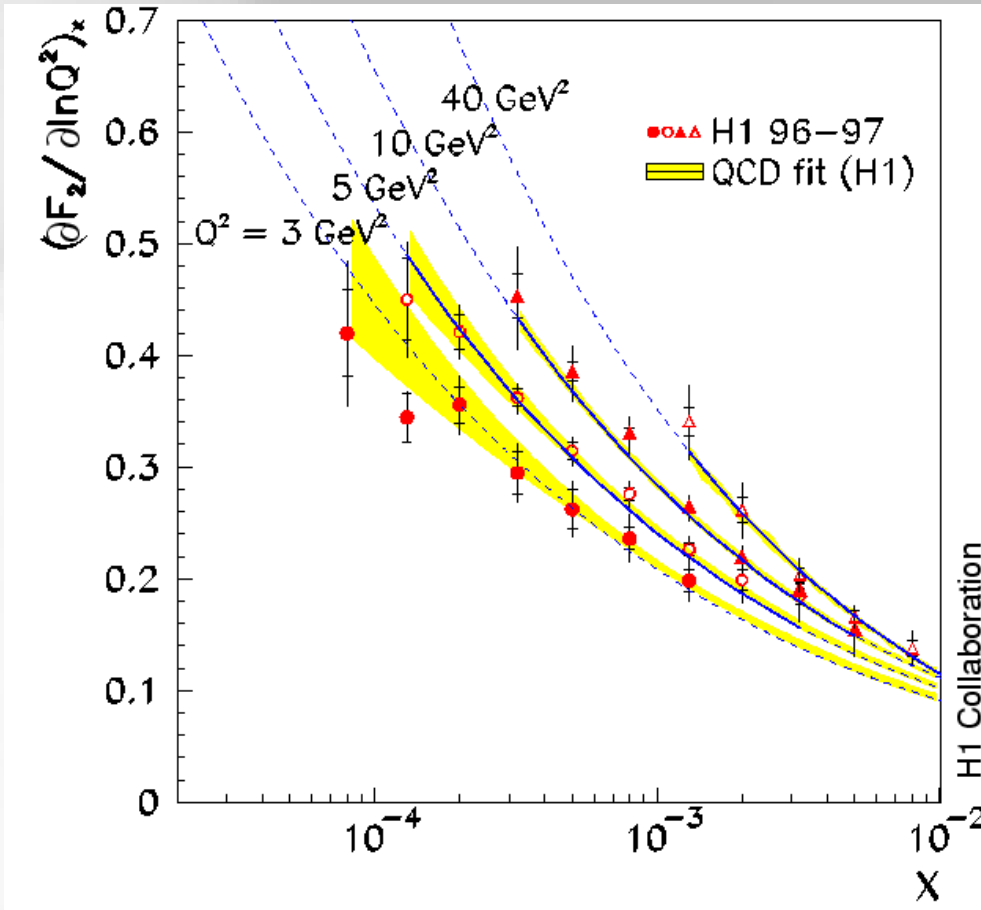
- low-x rise of F_2
  - HERA: precision @ $x > 10^{-4}$ @ $Q^2 = 10$ GeV^2





- relentless rise of quark (F_2) and gluon $\partial F_2/\partial \ln Q^2$

Gluon recombination @ LHeC

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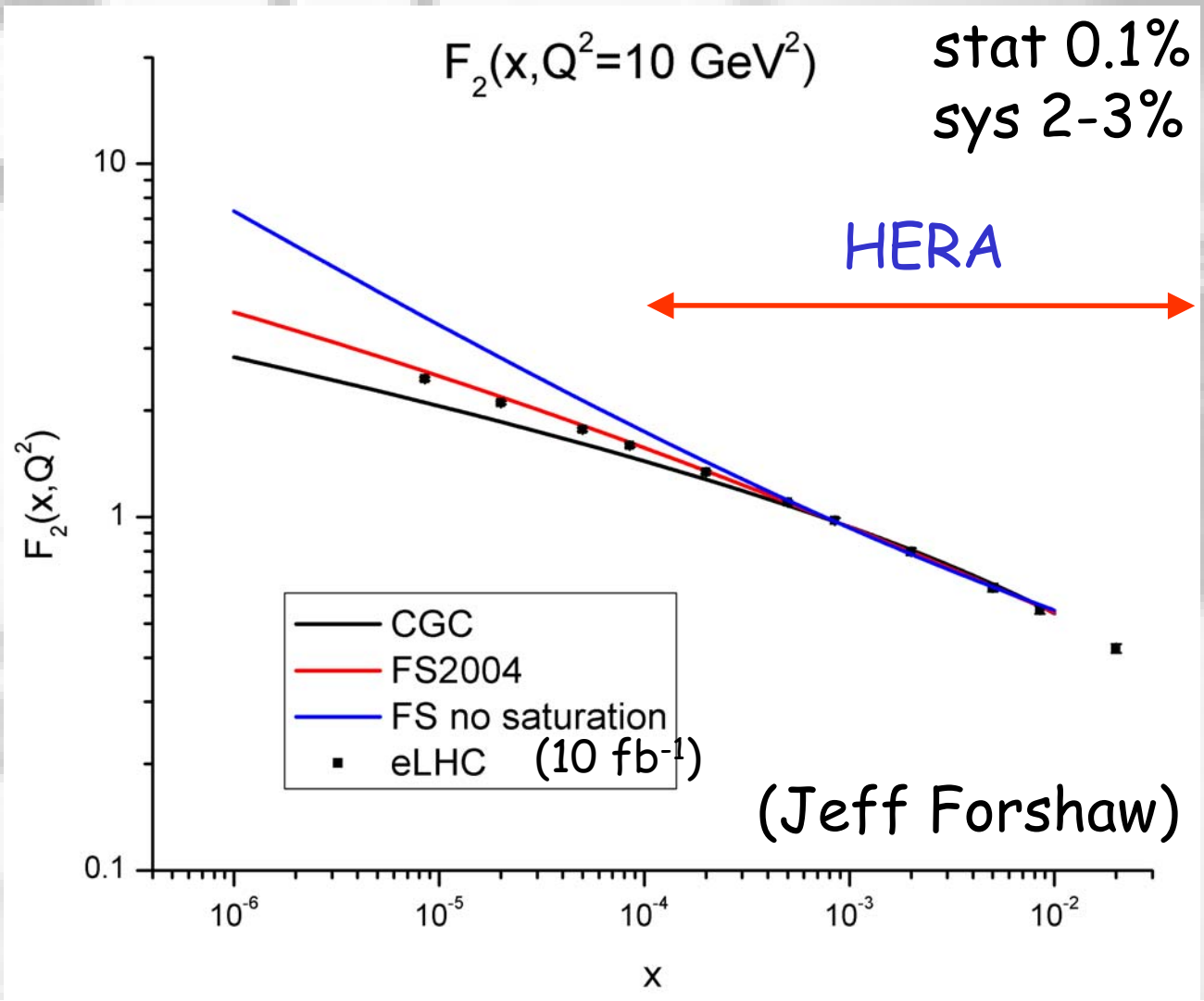
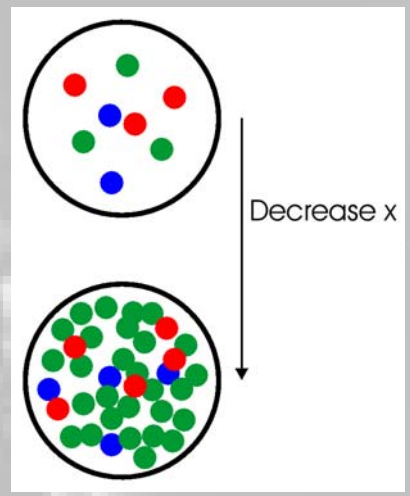
- low-x rise of F_2
  - LHeC: precision @ $x > 10^{-4}$ @ $Q^2 = 250\ GeV^2$





- LHeC "nails" saturation

Gluon recombination @ LHeC

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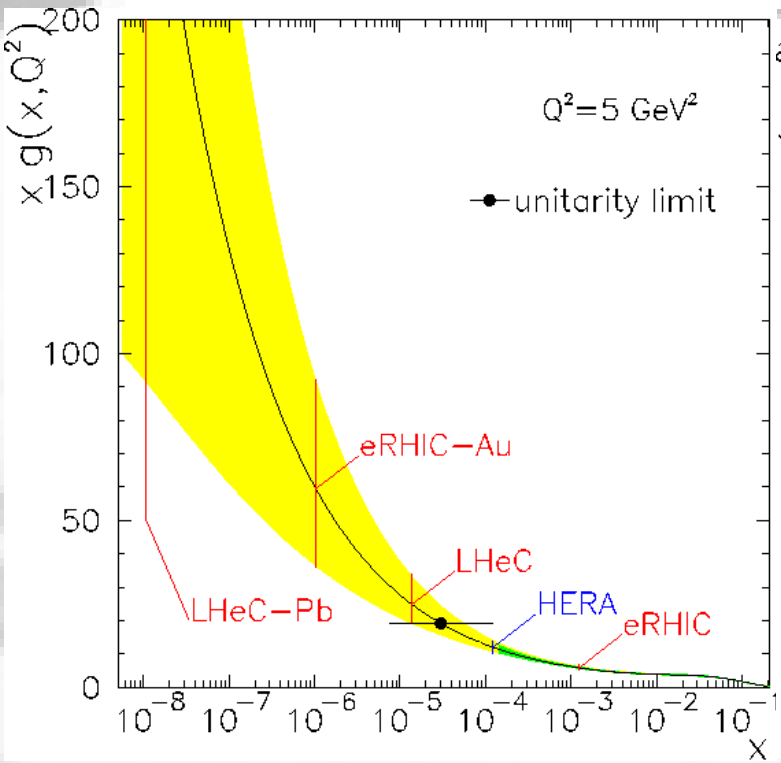
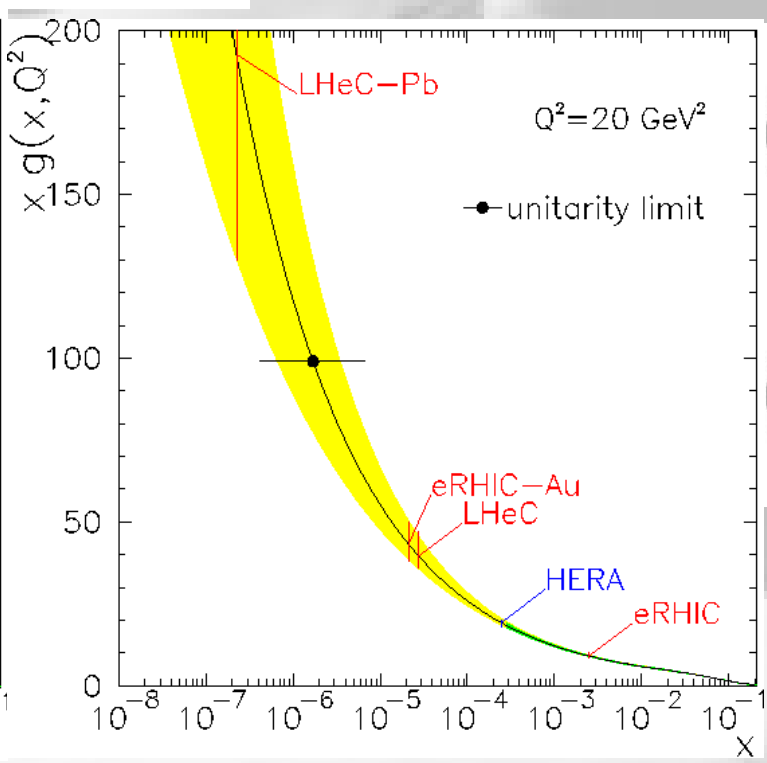
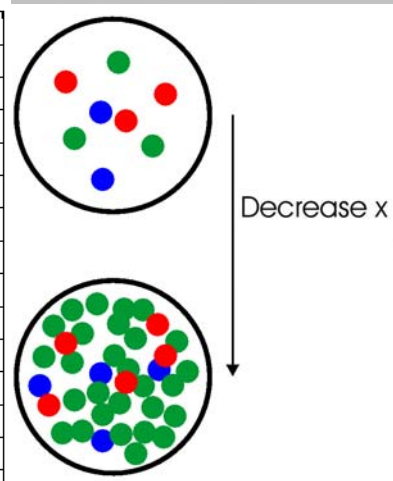
- *ep* saturation $Q^2 \leq 5$ GeV^2

  eA saturation $Q^2 \leq 20$ GeV^2

$$Q_s^2 \sim \frac{\alpha_s x G_A(x, Q_s^2)}{\pi R_A^2} \sim A^{1/3} \frac{1}{x^{0.3}}$$







- LHeC "nails" saturation

Partons in Nuclear Matter

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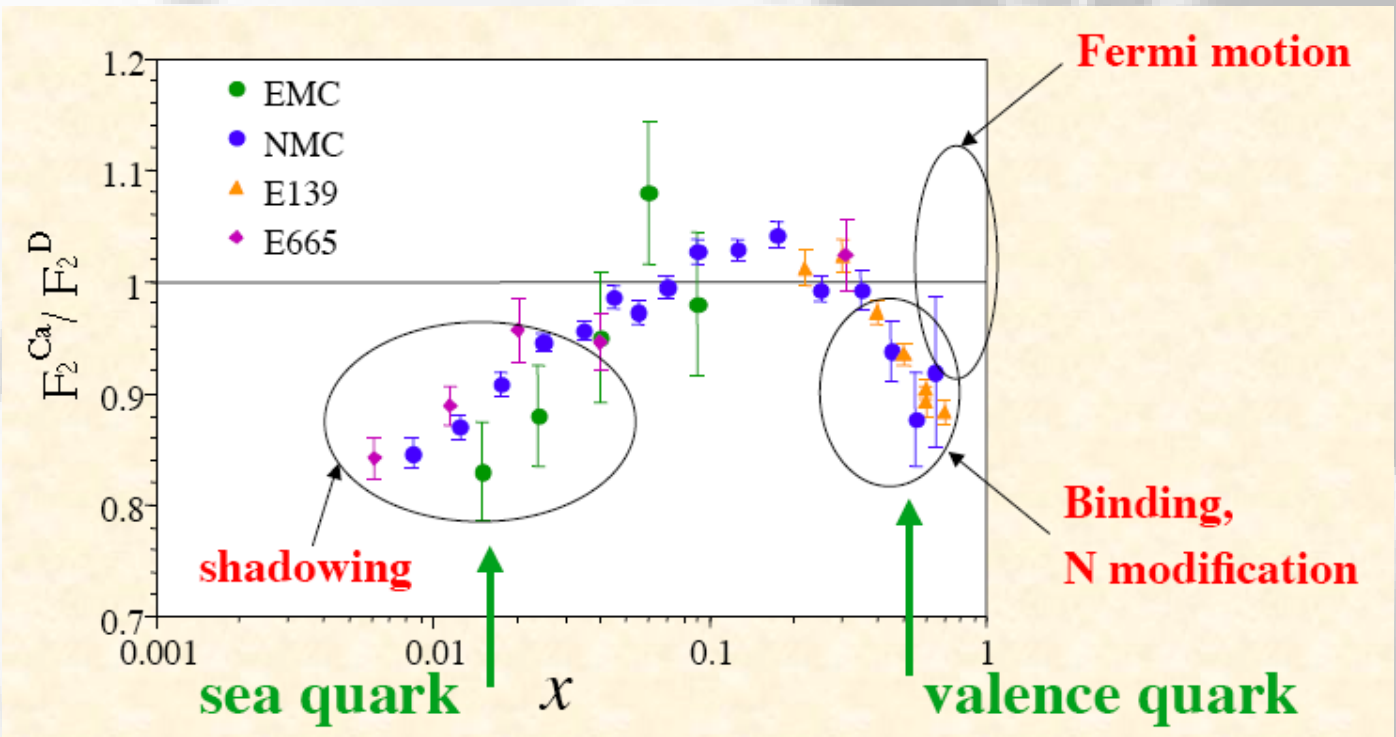
- fundamental to origin of mass in Universe
  - from nucleon valence to QCD-field dominated (x)
  - increasing number of valence partons (A)
- very limited but tantalising old data
  - $Q^2 < 1\ GeV^2 \quad x > 0.01$



1_c dynamics in p and A

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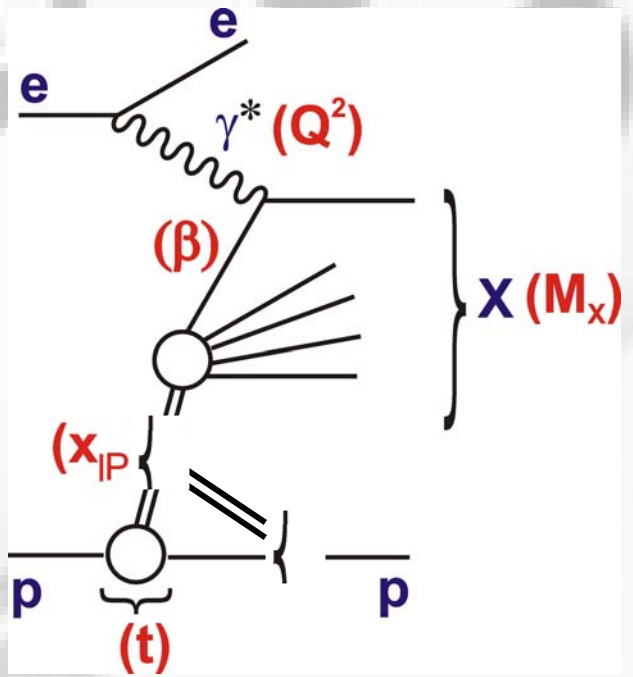
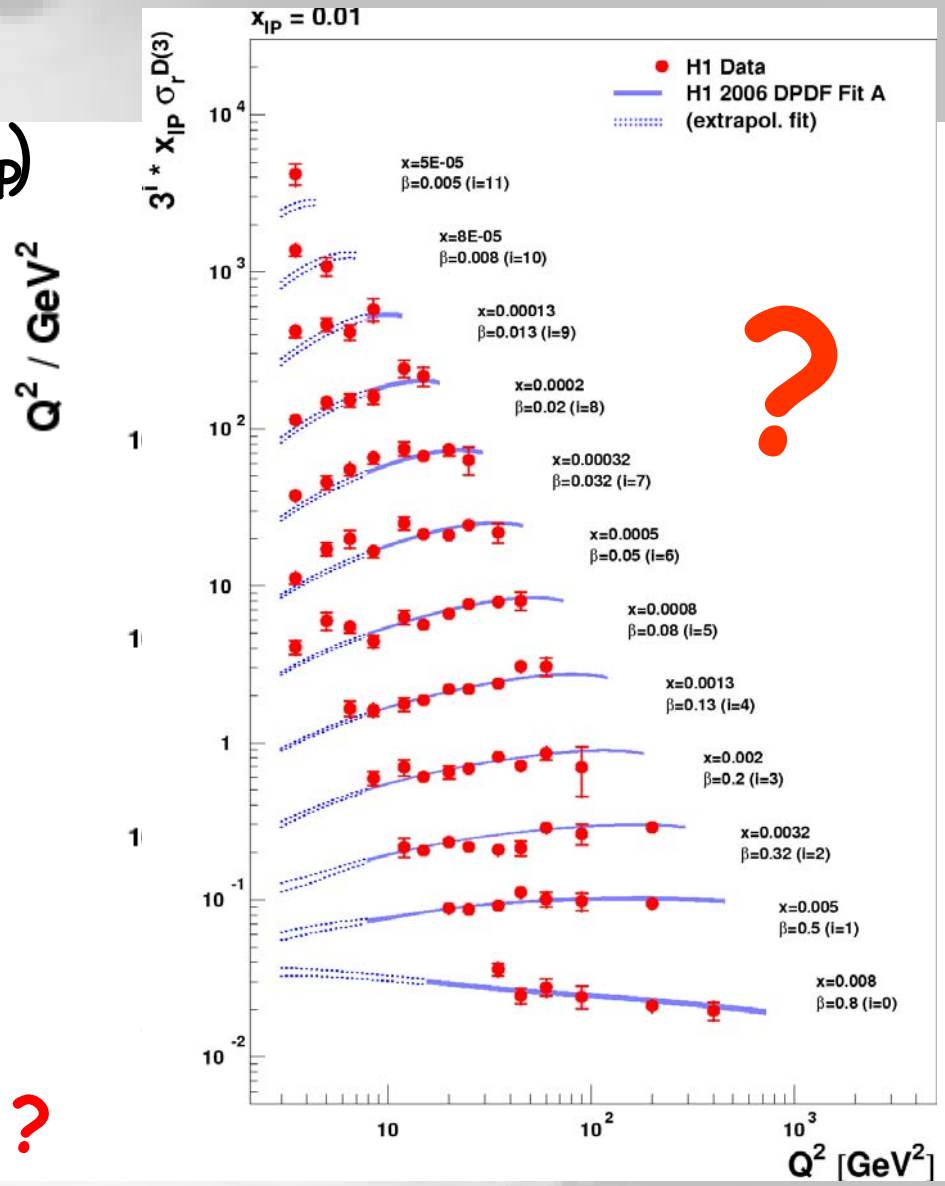
- low-x reach at LHeC
  precision @ $x > 10^{-4}$
  @ Q^2=250 GeV^2 ($x = \beta x_{I\!P}$)



- low x physics of $I\!P$
  $I\!P$ in $I\!P$: triple $I\!R$
  QCD ↔ reggeon calculus ?



1_c dynamics in p and A

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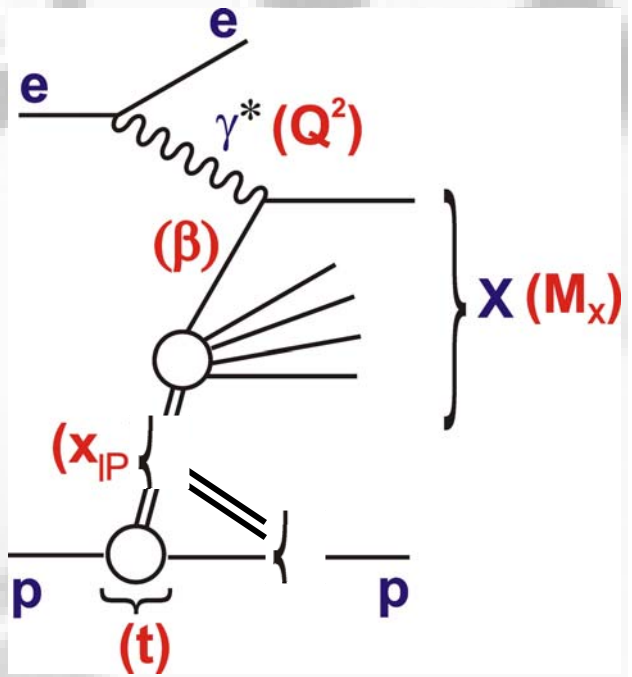
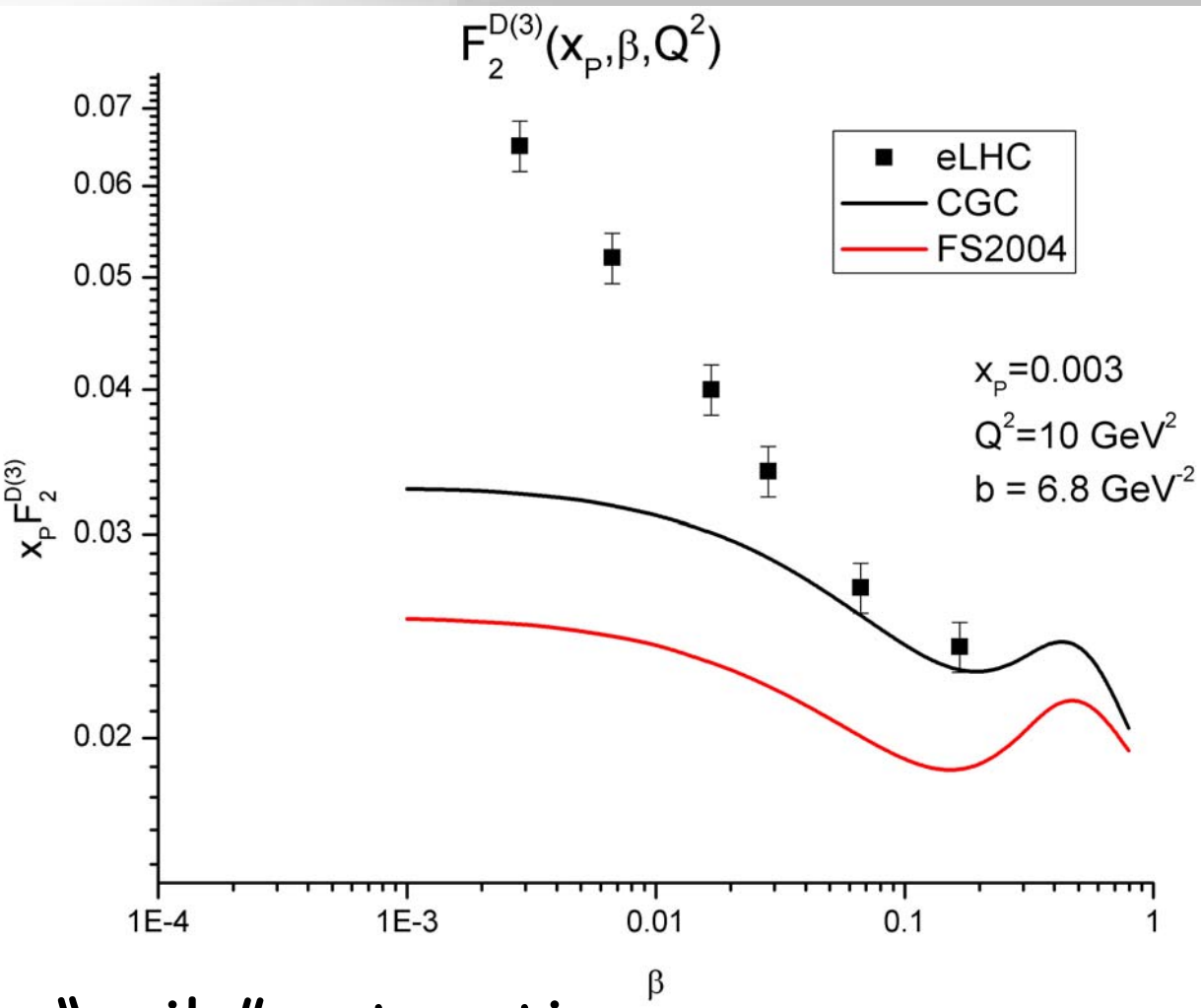
- low-x $\mathbb{P}$ physics at LHeC





- LHeC diffraction "nails" saturation

1_c dynamics in p and A

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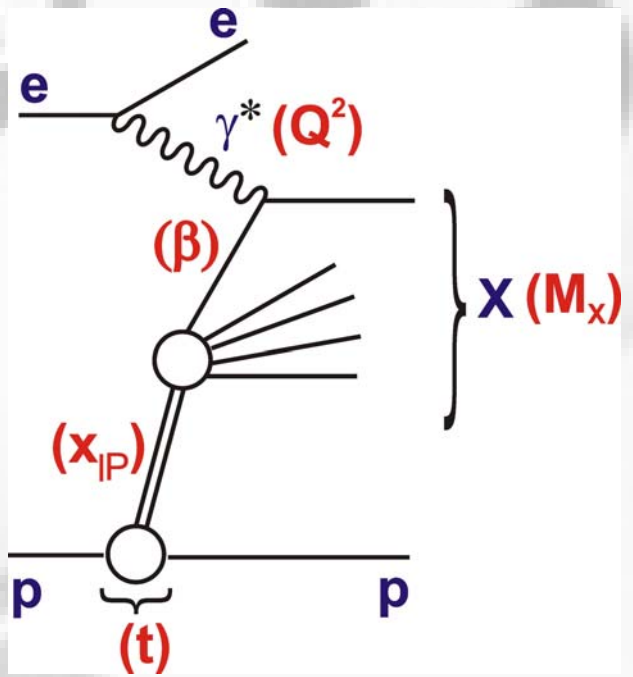
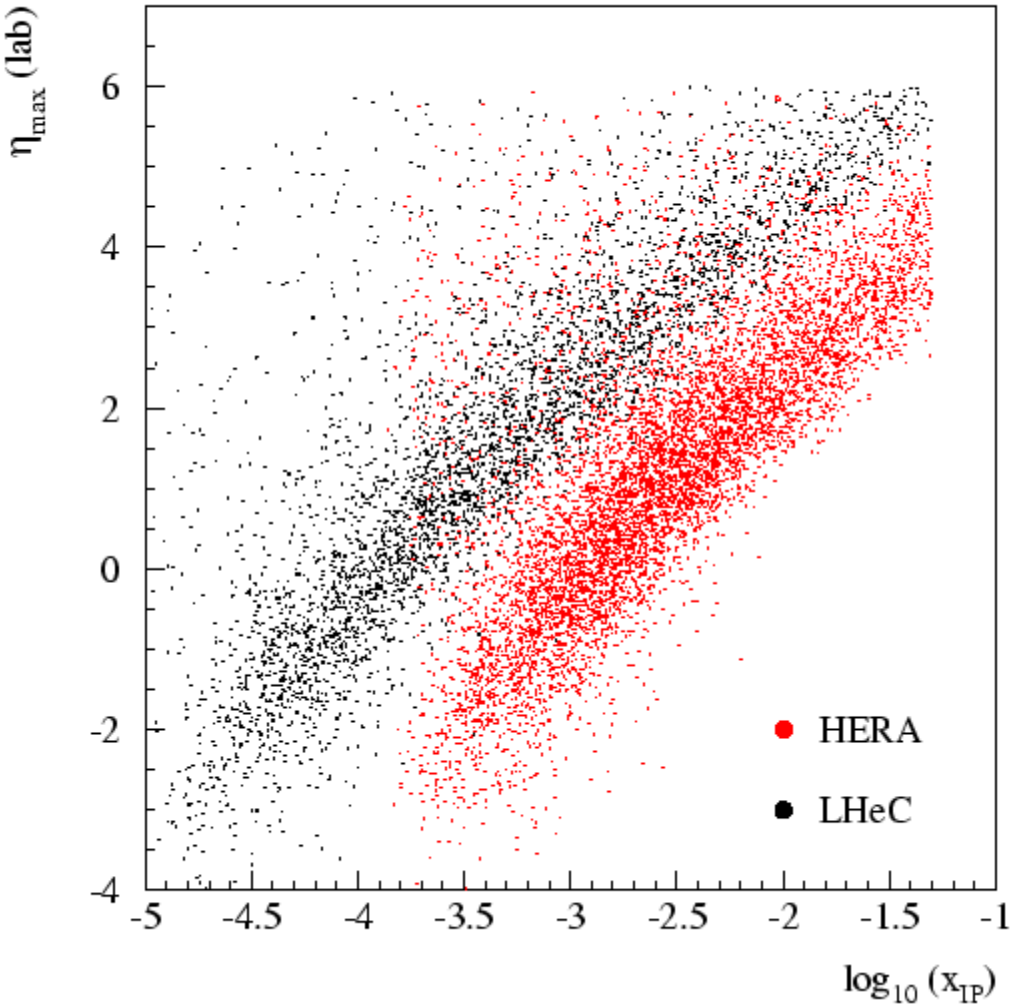
- $\mathbb{P}$ physics at LHeC





- $\gamma^*\mathbb{P}$ physics @ 1 TeV: leptopomerons ?

2.How?

Proton beam

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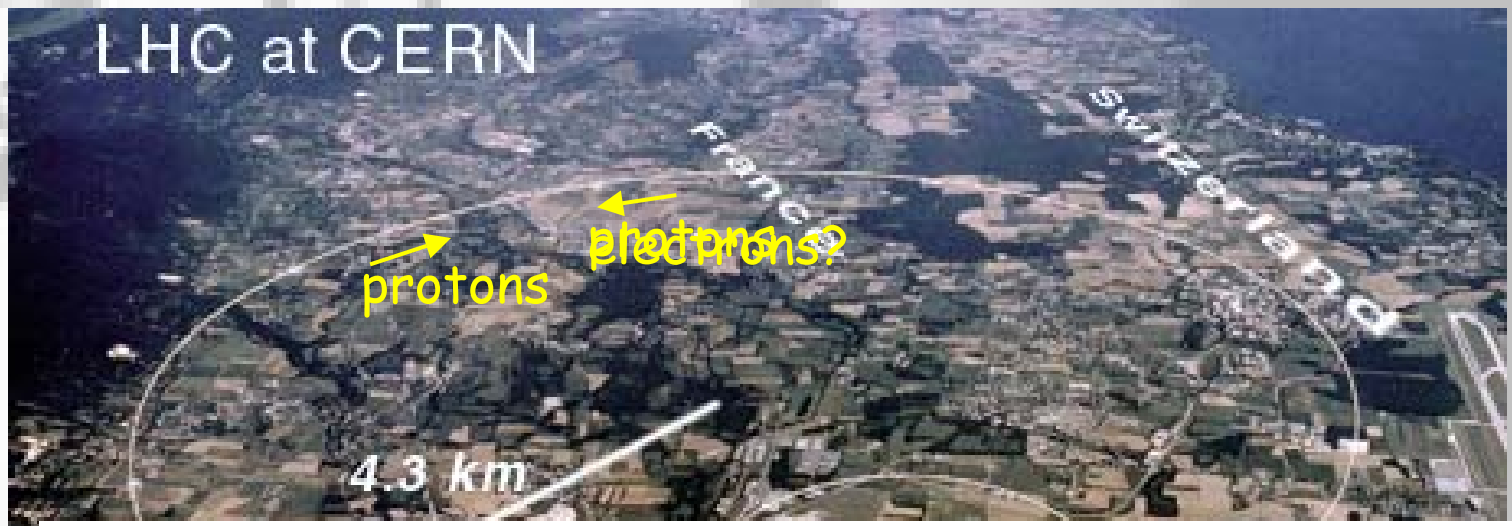
- "standard" LHC protons … with electrons?



Proton Beam Energy	TeV	7	
Circumference	m	26658.883	
Number of Protons per bunch	10^{11}	1.67	N_p
Normalized transverse emittance	μm	3.75	ε_{pN}
Bunch length	cm	7.55	
Bunch spacing	ns	25	

ep Luminosity

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- few 10s GeV electrons (LEP = 70 GeV!)
- RF power = 50 MW = 0.86 LEP = 28% CERN site
- RF power = synchrotron radiation $\propto$ I_e = 74 mA

luminosity $$L = \frac{I_e \cdot N_p \cdot \gamma_p}{4 \cdot \pi \cdot e \cdot \epsilon_{pN} \sqrt{\beta_{xp}\beta_{yp}}}$$

"perfect" bunch x-ing

$$= \frac{74\times10^{-3}\times1.67\times10^{11}\times7000/.938}{4\pi\times1.6\times10^{-19}\times3.75\times10^{-6}\times\sqrt{\beta_{xp}\beta_{yp}}}$$

$$L = 1.15\times10^{33}/\sqrt{\beta_{xp}\beta_{yp}(\mathrm{m}^2)}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

$L \sim 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ for reasonable p-beam $\beta \sim 1$ m

$e^{\pm}p$ Luminosity

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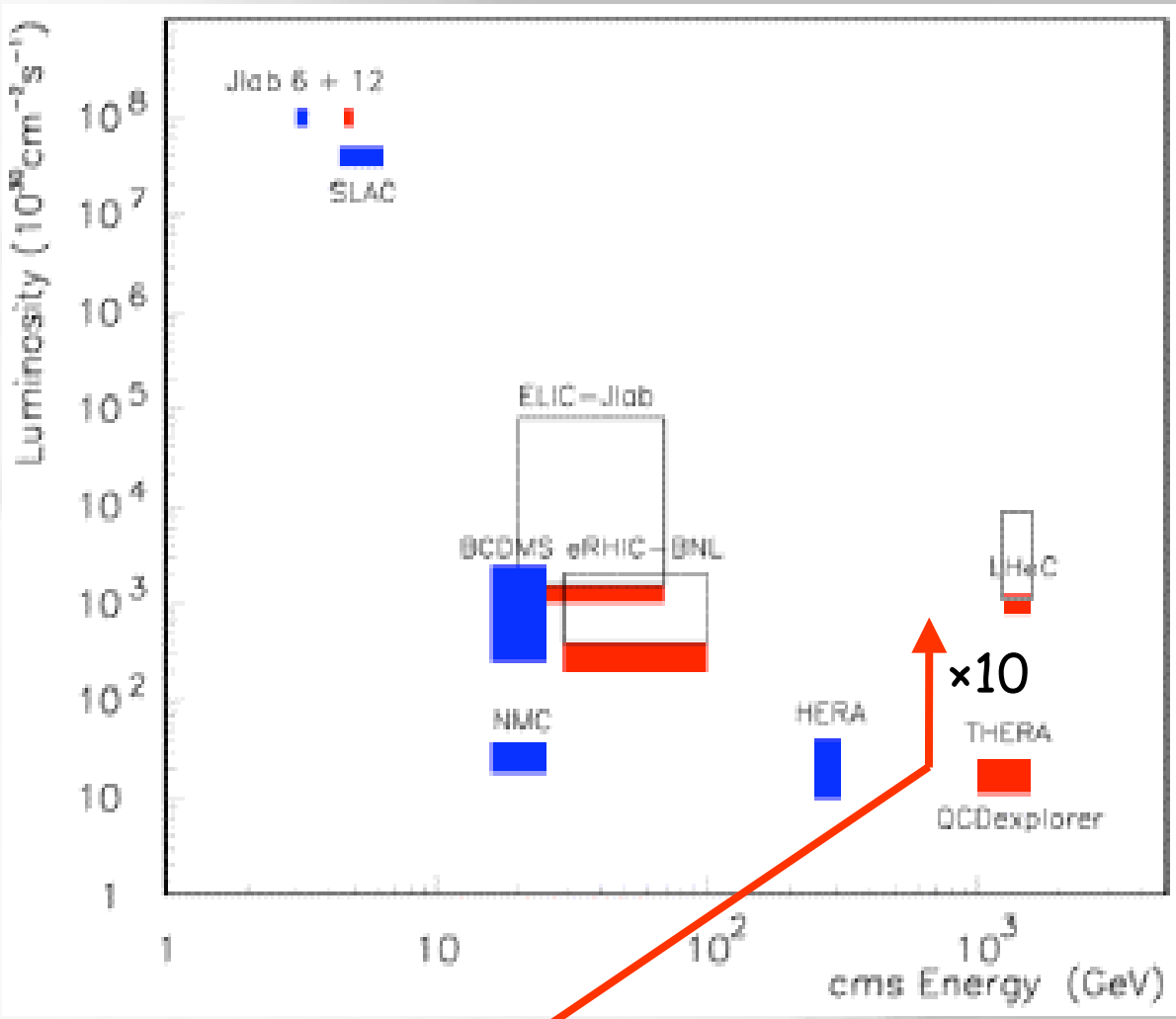
- astounding !
- $\times 10^2$ L_{NMC} μp @ 0.01 fm
- L_{eRHIC} $e_{pol}p_{pol}$ eA @ 0.007 fm
- $\times 10^2$ L_{HERA} $e_{pol}p$ @ 0.001 fm
- L_{LHeC} $e^{\pm}p$ eA @ 0.00014 fm



indisputably a next step … is it feasible ?

Lepton Ring

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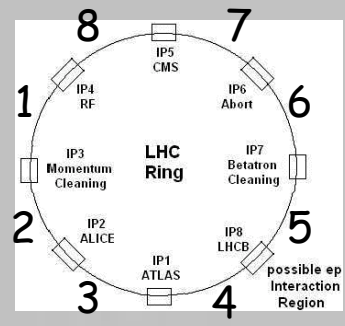
- in LEP tunnel … so like LEP
  - FODO in eight arcs
    β-tron phase advance φ_H=108° φ_V=90°
  - bending radius 3133.3 m
  - $(\delta E/E_{beam})_{rms}$ = 1.1×10^{-3}
  - SR 26 W/cm (E_c=254 KeV)
  - scRF @ 1GHz resonators @ 12 MV/m
    100 m structure = 670 cells
    → sync. phase 31°
    → bucket takes 10× $(\delta E/E_{beam})_{rms}$
  - unlikely *e*-beam instability
    single bunch current modest
    impedance << LEP



LEP=9 W/cm
HERA=13.5 W/cm

scRF proven
@ > 6 MV/m

ep Collisions

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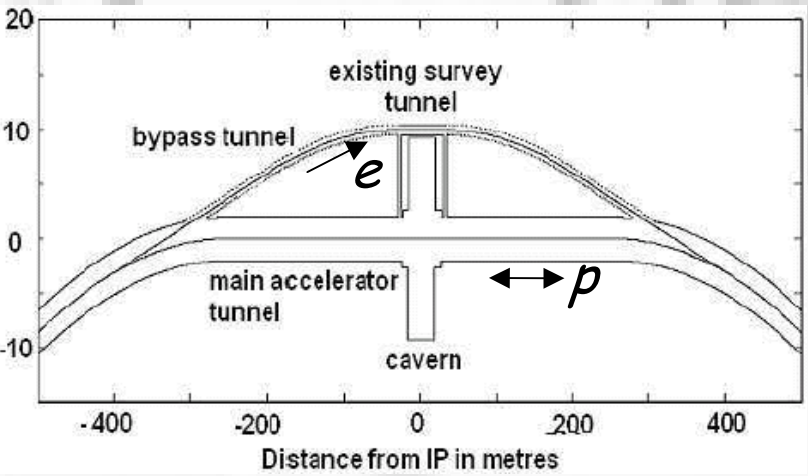
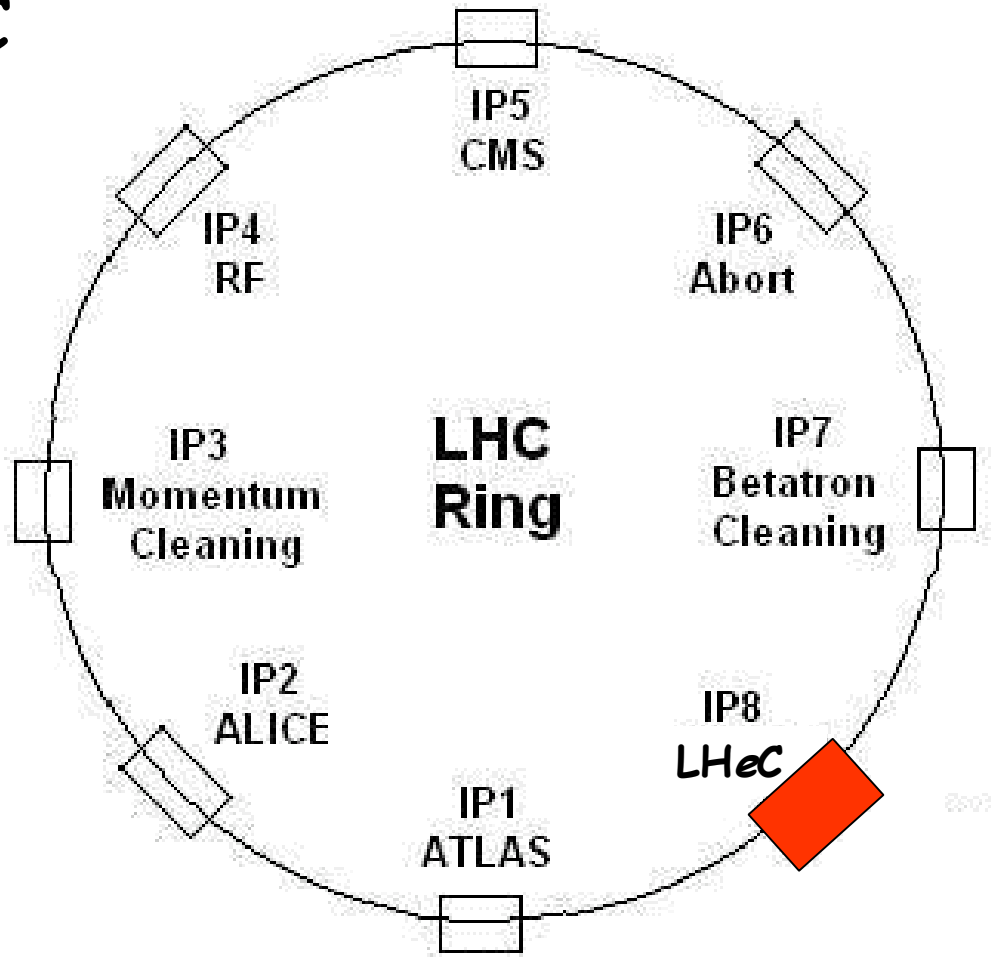
- after *B* physics @ LHC





civil engineering
tunnel 2×250m×2m Ø @IP

ep alongside *pp* data-taking @ LHC

Interaction Region

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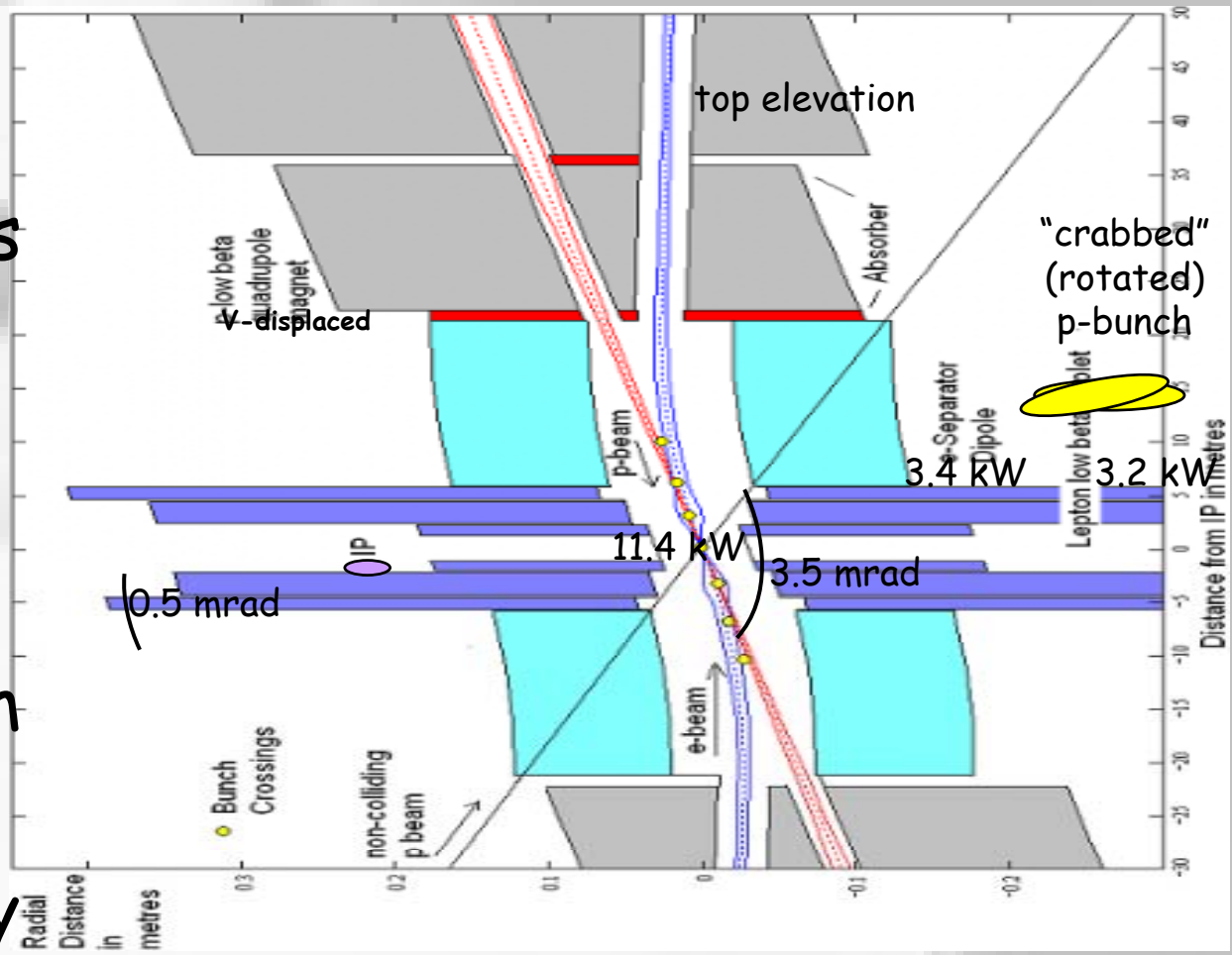
- highest lumi
  - low β_e
    - close sc quads
  - low X-ing angle
    - "hard" bend
      8σ beam sepⁿ
      - SR fan
        → sc *p*-beam
        « HERA
  - "crab" RF cavity
    p-bunch rotation



- 1º beam access = low-lumi/low-*x* option (cf HERA)

Operational Luminosity

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- beam-beam
  - "hour-glass"
  - dynamic β: < HERA
  - long range beam-beam (parasitic interactions): marginal

↳ operational luminosity

$$I_e = 74\text{mA},\ N_p = 1.68\ 10^{11},\ \gamma_i = 7460,\ \epsilon_p = 0.5\ \text{nm}$$
$$\epsilon_{xe} = 25\ \text{nm},\ \epsilon_{ye} = 5\ \text{nm and}\ R = 0.89$$

$$L = \frac{I_e \cdot N_p \cdot \gamma_p \cdot R}{4 \cdot \pi \cdot e \cdot \sqrt{\epsilon_p \beta_{xp} + \epsilon_{ye} \beta_{ye}} \cdot \sqrt{\epsilon_p \beta_{yp} + \epsilon_{ye} \beta_{ye}}} = 1.04 \cdot 10^{33} cm^{-2} s^{-1}$$

LHeC

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- tunnel exists (LEP, LHC)
- injection once existed (LEP) ?
- operating *p*-beam (from 2008)
- operating *A*-beam (from 2008)
- *ep eA* operating alongside *pp pA AA*
- *the* TeV *ep* collider !
- "minimal" mods to LHC !

- LHC upgrade
- cost ?

IR and Experiment

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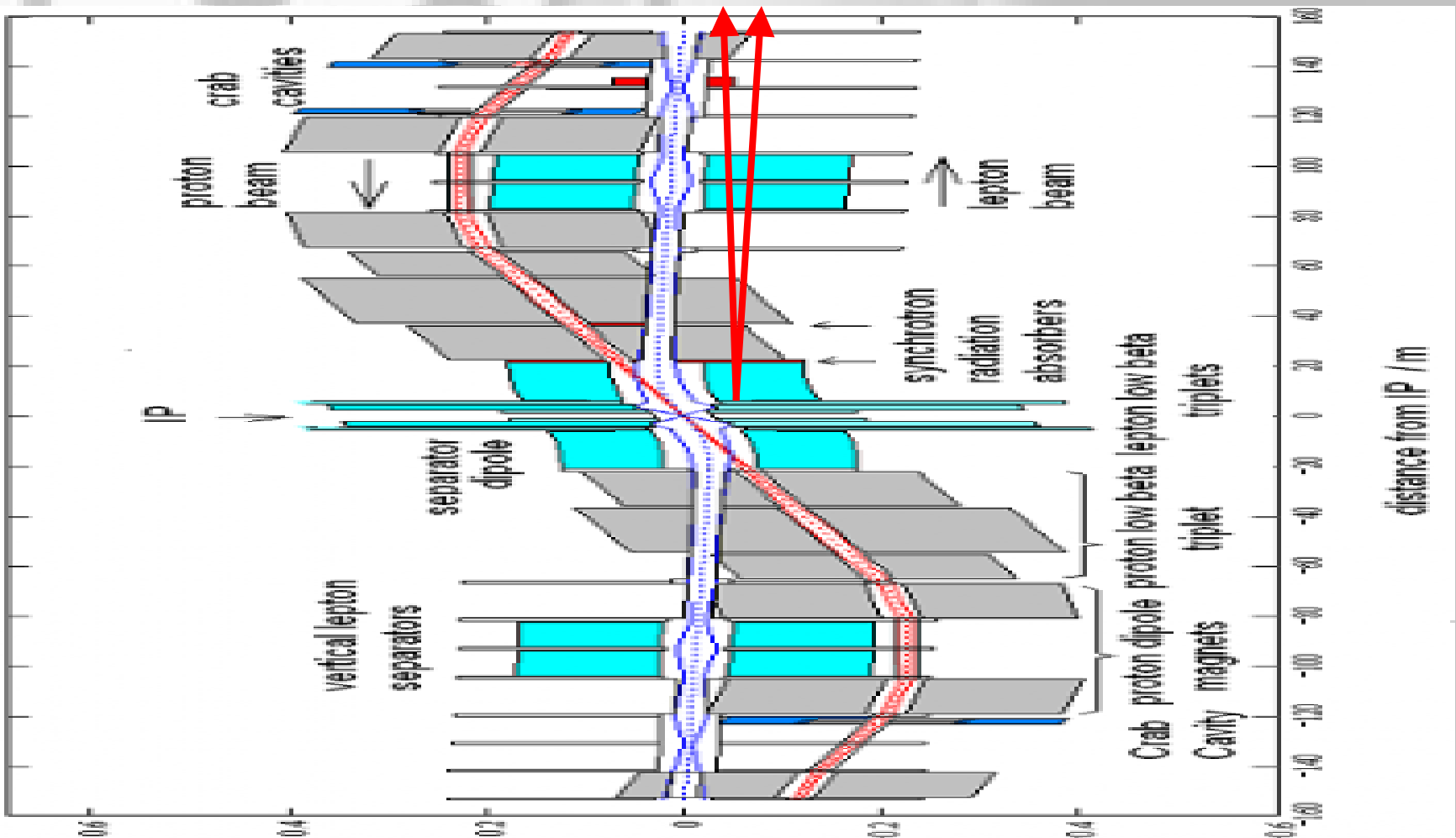
- IR ±many m
- IR ≥9.4° around beam



Asymmetric Collider

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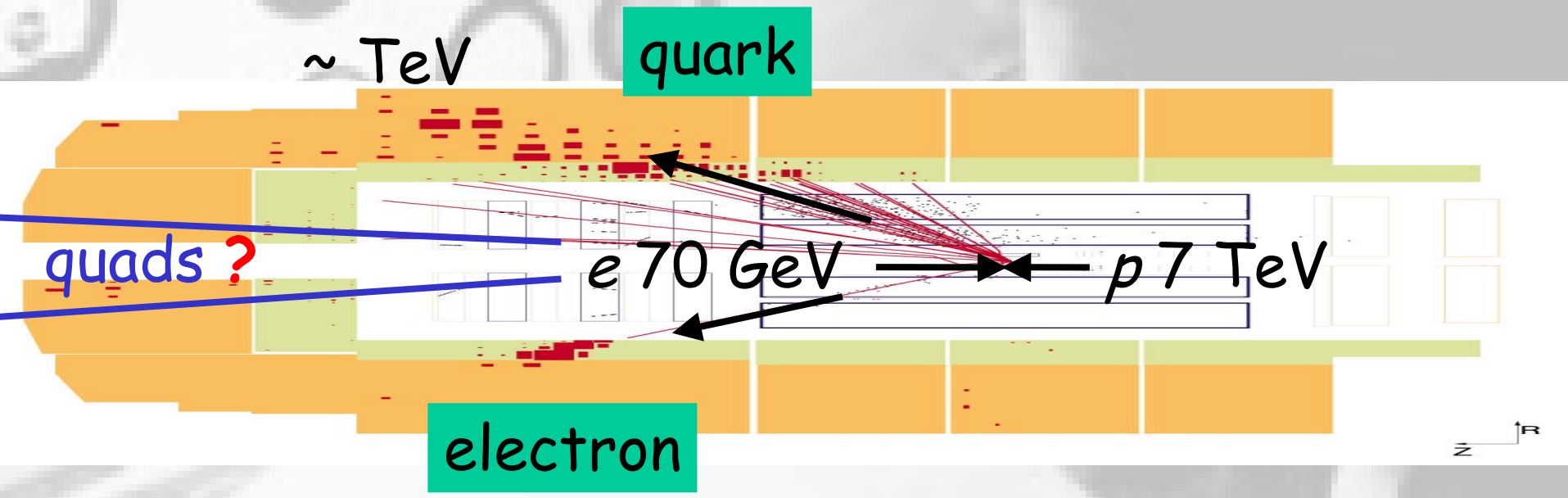
- asymmetric beam momenta: LHeC



- "forward" hemisphere detection to multiTeV
  topological challenge
  precision challenge

3. When?

Timeline

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- 2007: form working groups + steering committee
  initial meeting of conveners + committee
  SAC overview
- 2008: workshop I
- 2009: workshop II

  LHeC Design Study [LHCC]
- 2011: TDR
  - construction 8 years
  - installation *e*-ring above LHC ~1 year
  - LHeC part of LHC upgrade
  - be aware of CLIC progress

Working Group Structure

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- accelerator (injector, ring)
- interaction region
- detector
- the new physics
- high precision QCD
- low x physics
- eA

to be discussed

tbc (SAC)

LHeC Scientific Advisory Committee

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Experimentalists
Joel Feltesse (Saclay/DESY)
Aharon Levy (Tel Aviv)
Allen Caldwell (MPI München)
Roland Horisberger (PSI)
Richard Milner (MIT)
John Dainton (Univ Liverpool)

Accelerator
Stephen Myers (CERN)
Swapan Chattopadhyay (Cockcroft Inst)
Roland Garoby (CERN)
Ferdy Willeke (DESY/BNL)

Theory
Guido Altarelli (Roma)
Lev Lipatov (Petersburg)
Frank Wilczek (MIT)
Stan Brodsky (SLAC)
John Ellis (CERN)

Labs
Jos Engelen (CERN)
Young-Kee Kim (Fermilab)
Rolf Heuer (DESY)
Peter Bond (BNL)

4. Summary

Now

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- LHeC $70_e \otimes 7000_p$ GeV
  - can be built
  - has startlingly good luminosity $\geq 10^{33}$ cm^{-2}s^{-1} grows with LHC *pp* luminosity
  - adds substantially, uniquely, and with synergy to LHC_{TeV} discovery physics
  - probes chromodynamics
    @ new density frontier
    in uniquely comprehensive manner *ep eA*
    with unchallengable precision
    synergetically with LHC *pp pA AA*

Lepton + quark @ TeV

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- energy for
  eq discovery
  extreme chromodynamics

  LHeC and LHC
- precision for
  eq discovery
  eq understanding
  extreme chromodynamics

  LHeC and ILC
- luminosity for
  eq discovery

  LHeC and LHC

In case you were wondering … ?

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Sir John Cockcroft …

doing accelerator physics ca 1950 …

… with 1950 DAQ – pencil and paper!

… with 1950 graphics – ammeter!
voltmeter!

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Extras

Lepton-Parton and Parton-Parton ?

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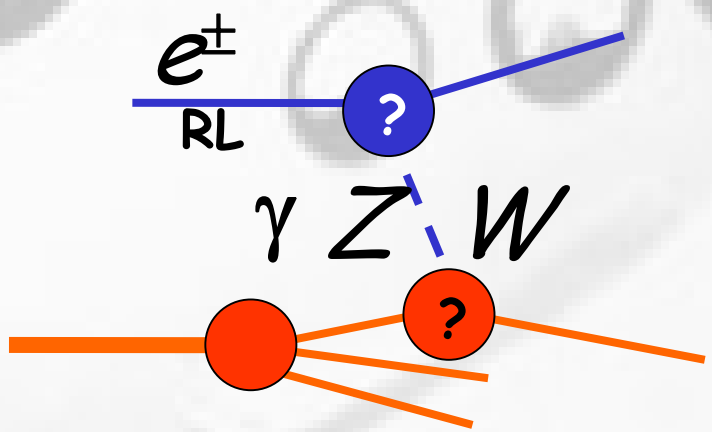
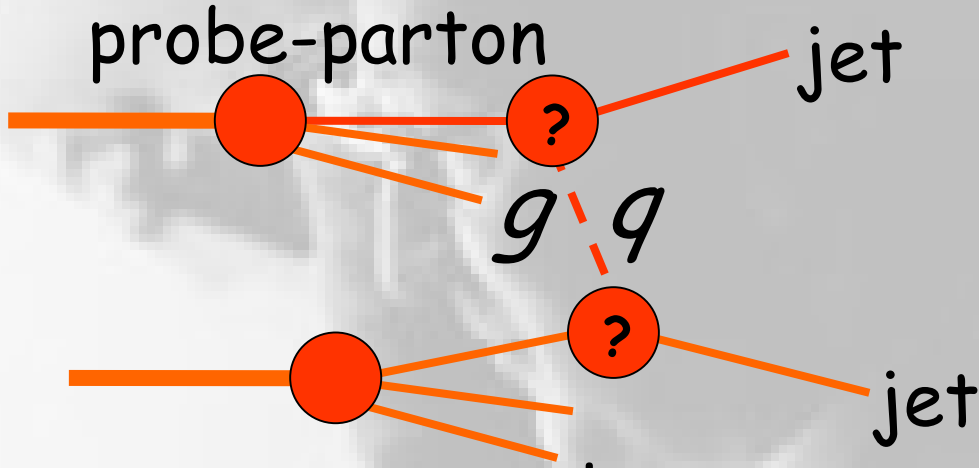
- $ep \rightarrow eX$



- LHeC energy scale:
  70⊗7000 GeV

- $pp \rightarrow$ (jet+jet)X



- pp energy scale:
  7000⊗7000 GeV

probe+p at LHeC scale

$x_{probe/p} = 0.01$

LHC probe parton

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- probe-parton @ $x \leq 0.01$
  - $xq = xU + xD + x\bar{U} + x\bar{D}$

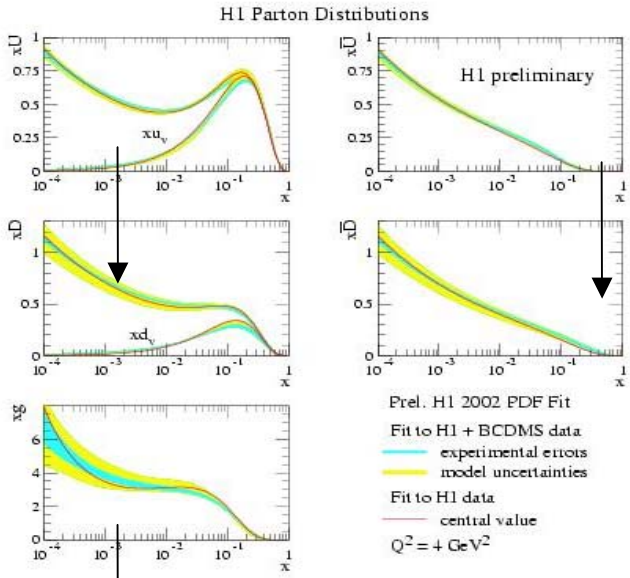
$g:q \sim 2:1$

- probe-parton @ $x \gg 0.01$

$g:q \to 0$

↳ "mixed" LHC probe @ LHeC energy

q LHC probe @ LHC top energy



Lepton-Parton and Parton-Parton

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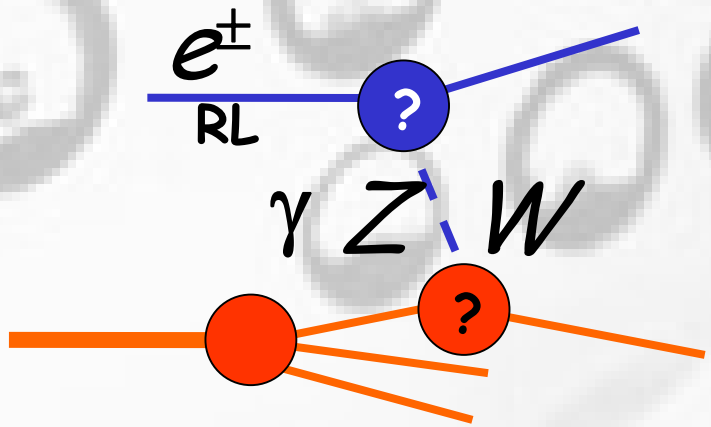
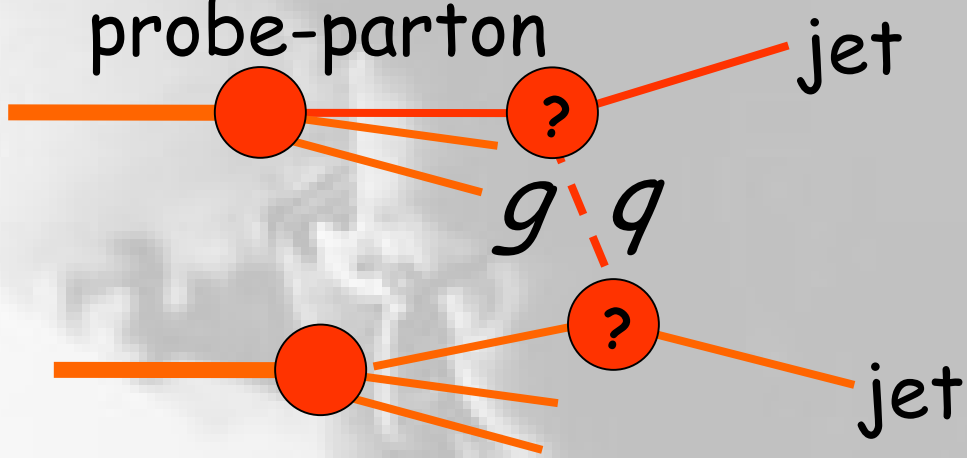
- $ep \rightarrow eX$



- precise probe e
- precise kinematics
- smaller kinematic reach

  but
  - $eq \rightarrow eq$ "formation" $\rightarrow$ TeV
  - precision at lower $x_{Bj} \geq 10^{-7}$

- $pp \rightarrow$ (jet+jet)X



- probe g and q
- kinematics ?
- larger kinematic reach

  x larger $\rightarrow$ probe q

  $q/gq/g \rightarrow eqeq$

  pair production

Polarisation @ LHeC

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Recall experience at LEP above 46 GeV — it is very difficult and the reasons are well understood.

Barber

Self polarization / depolarization.

- Electrons in storage rings can become spin POLARIZED due to emission of synchrotron radiation: Sokolov–Ternov effect (1964).
- The polarization is perpendicular to the machine plane.
- The maximum value is $P_{st} = 92.4\%$.
- Sync. radn. also excites orbit motion. This leads to DEPOLARIZATION!
- The attainable polarization results from a balance between polarization and depolarization.

$$P_\infty \approx P_{st} \frac{1}{1 + (\frac{\tau_{dep}}{\tau_{st}})^{-1}}$$

- Depolarization is worst at RESONANCES:

$$\nu_s = k_0 + k_1 Q_1 + k_2 Q_2 + k_3 Q_3$$

At high energy the synchrotron sideband resonances take control:

$$\text{Strength scale :} \qquad \xi = (\frac{a\gamma\ \sigma_\delta}{Q_s})^2$$

- Overall, roughly at each energy:

$$\tau_{dep}^{-1} \ \propto \ (\text{a polynomial in } \gamma^{2N}) \times \tau_{st}^{-1}$$

- For longitudinal polarization the polarization vector must be rotated into the longitudinal direction before an IP and back to the vertical afterwards ===> spin rotators.
- Depolarization can be strongly enhanced by misalignments, regions where the polarization vector is horizontal between spin rotators etc, etc.....

What's been achieved

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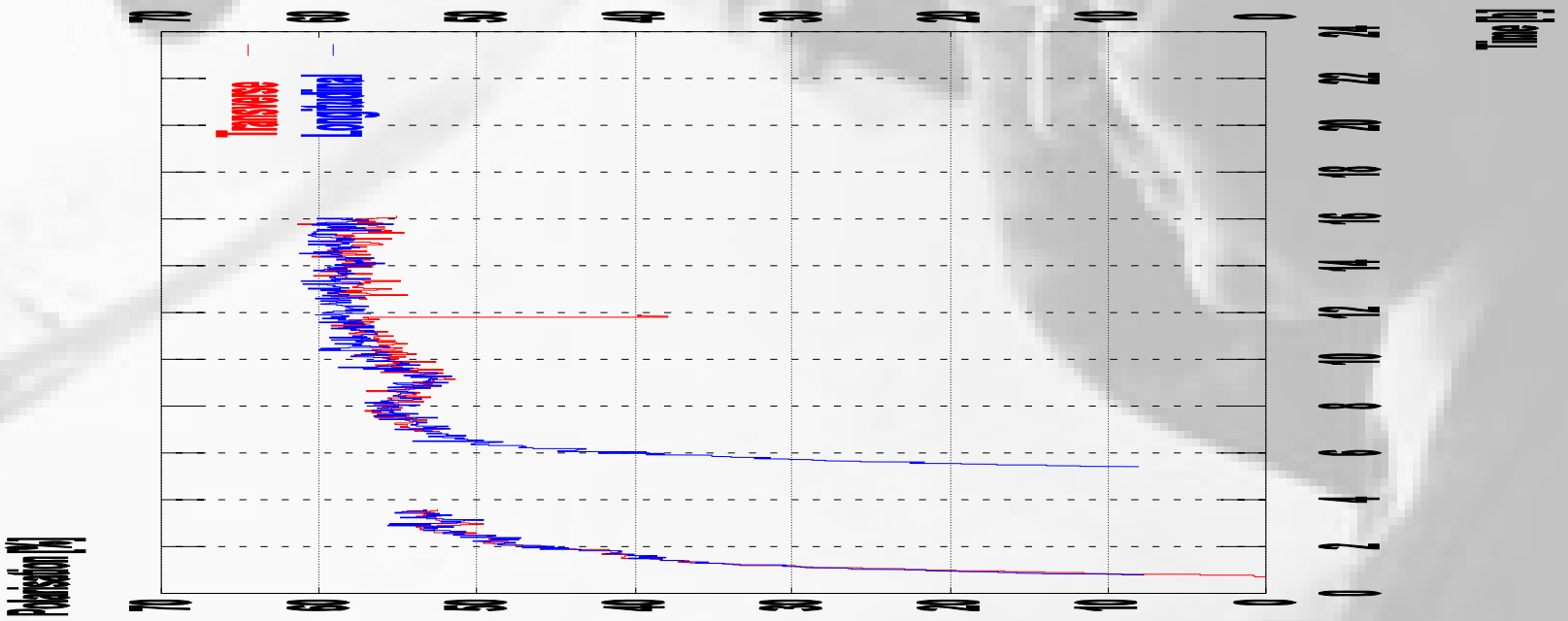
- Sokolov-Ternov + spin-rotators @ HERA



What's been achieved

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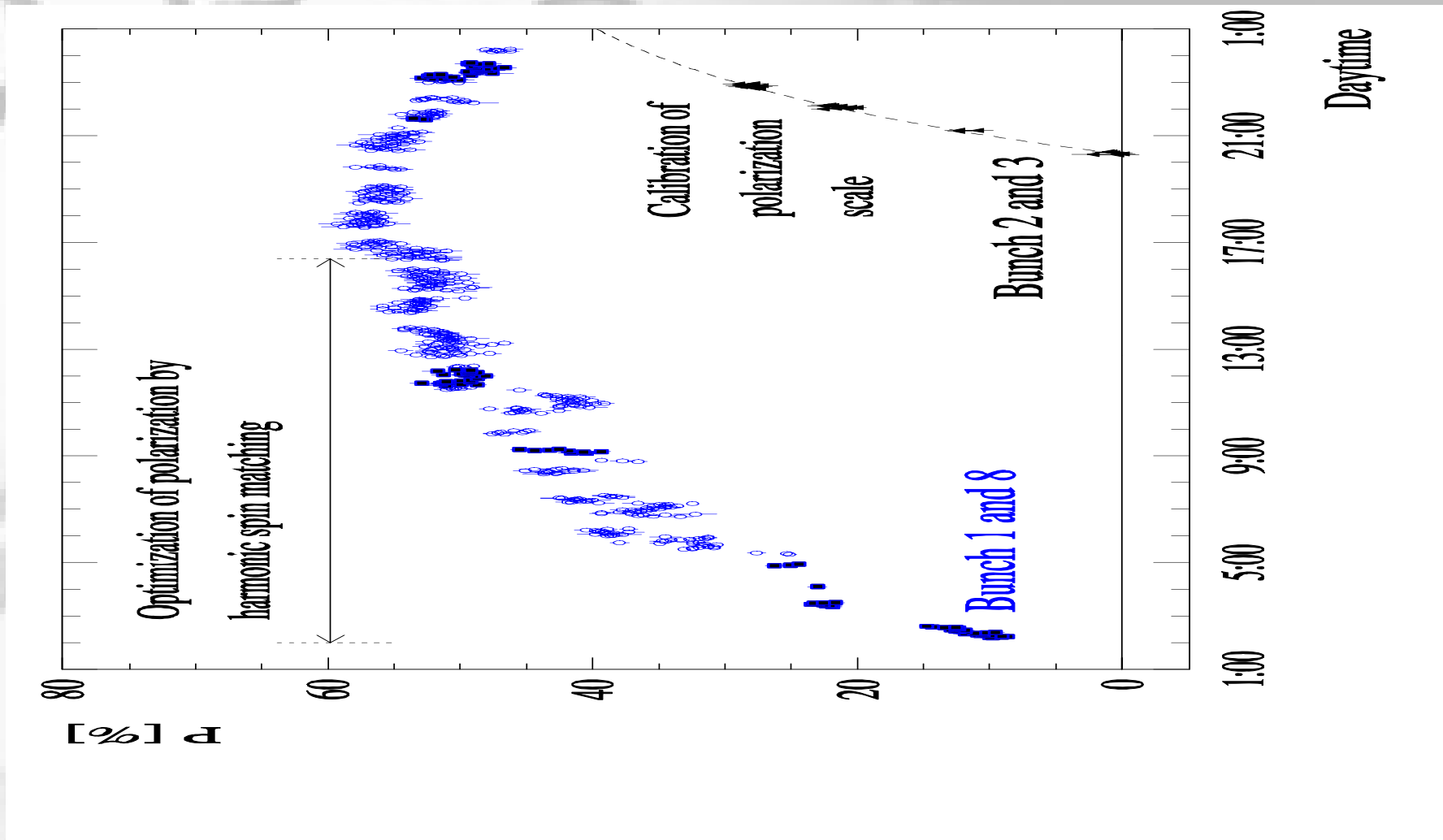
- Sokolov-Ternov @ $LEP_{70\ GeV}$



Diffraction and Rapgap

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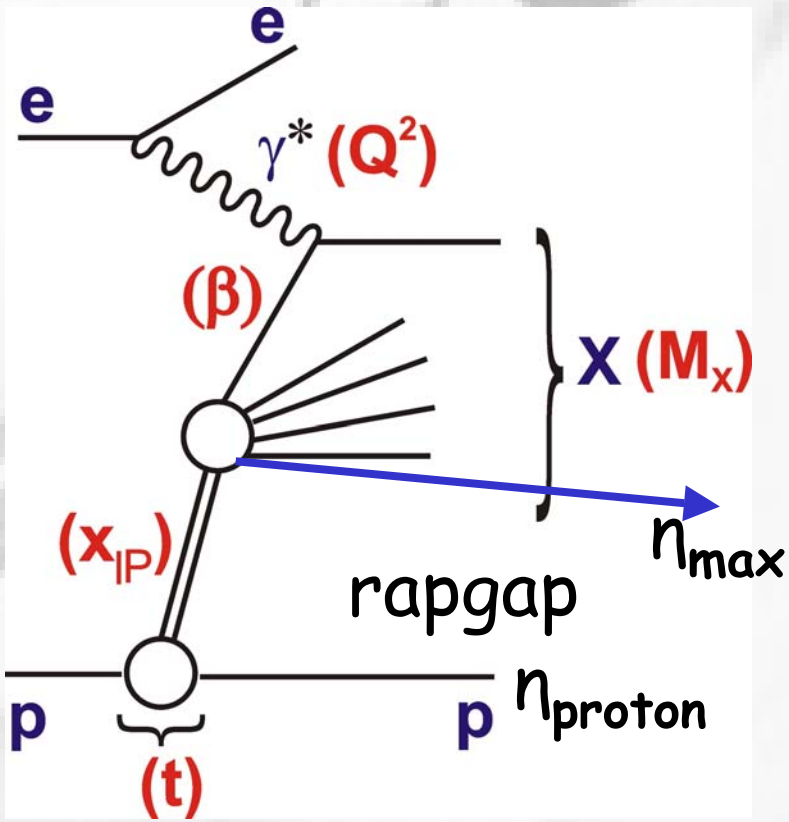
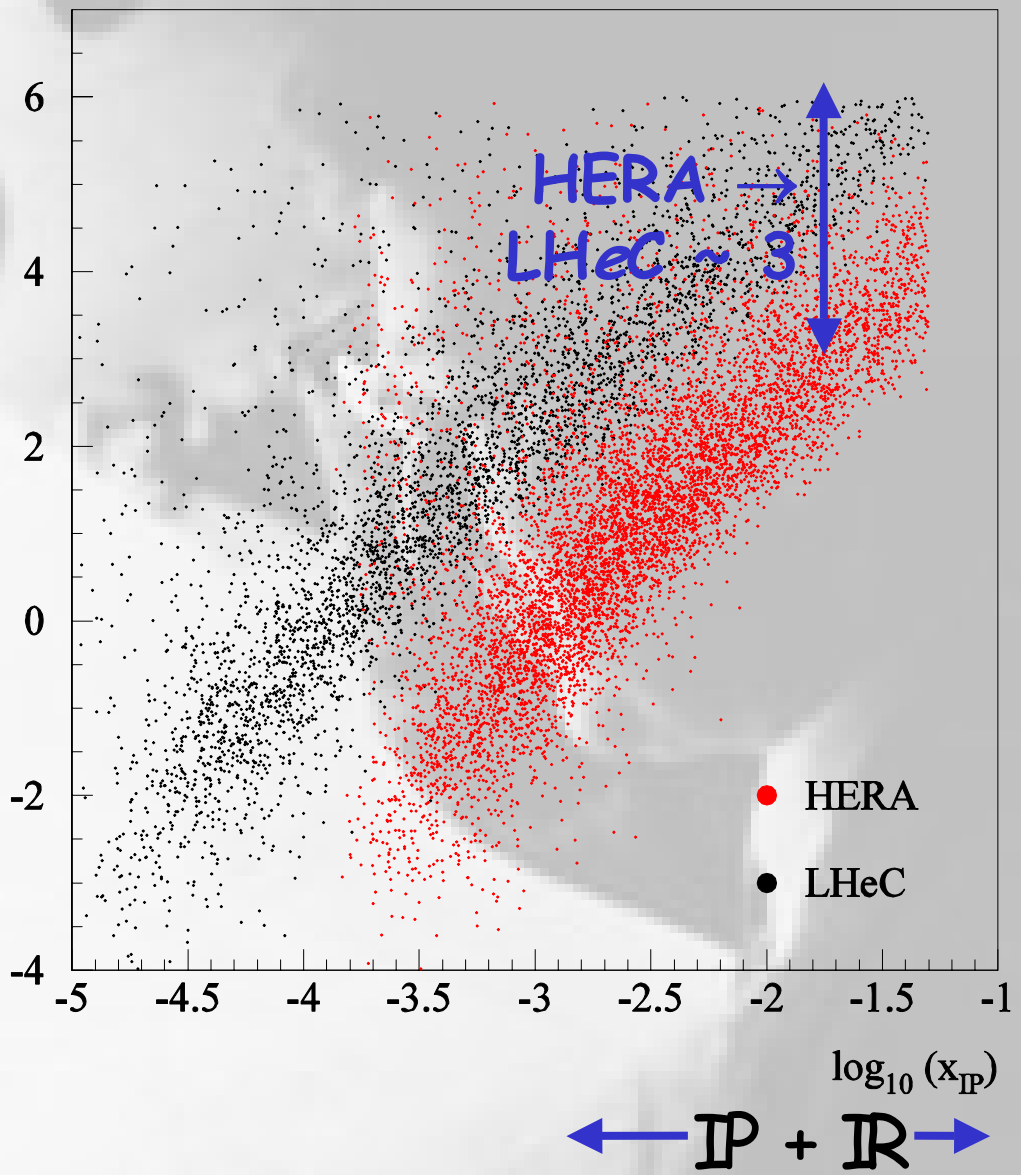
- rapgap @ LHeC ?





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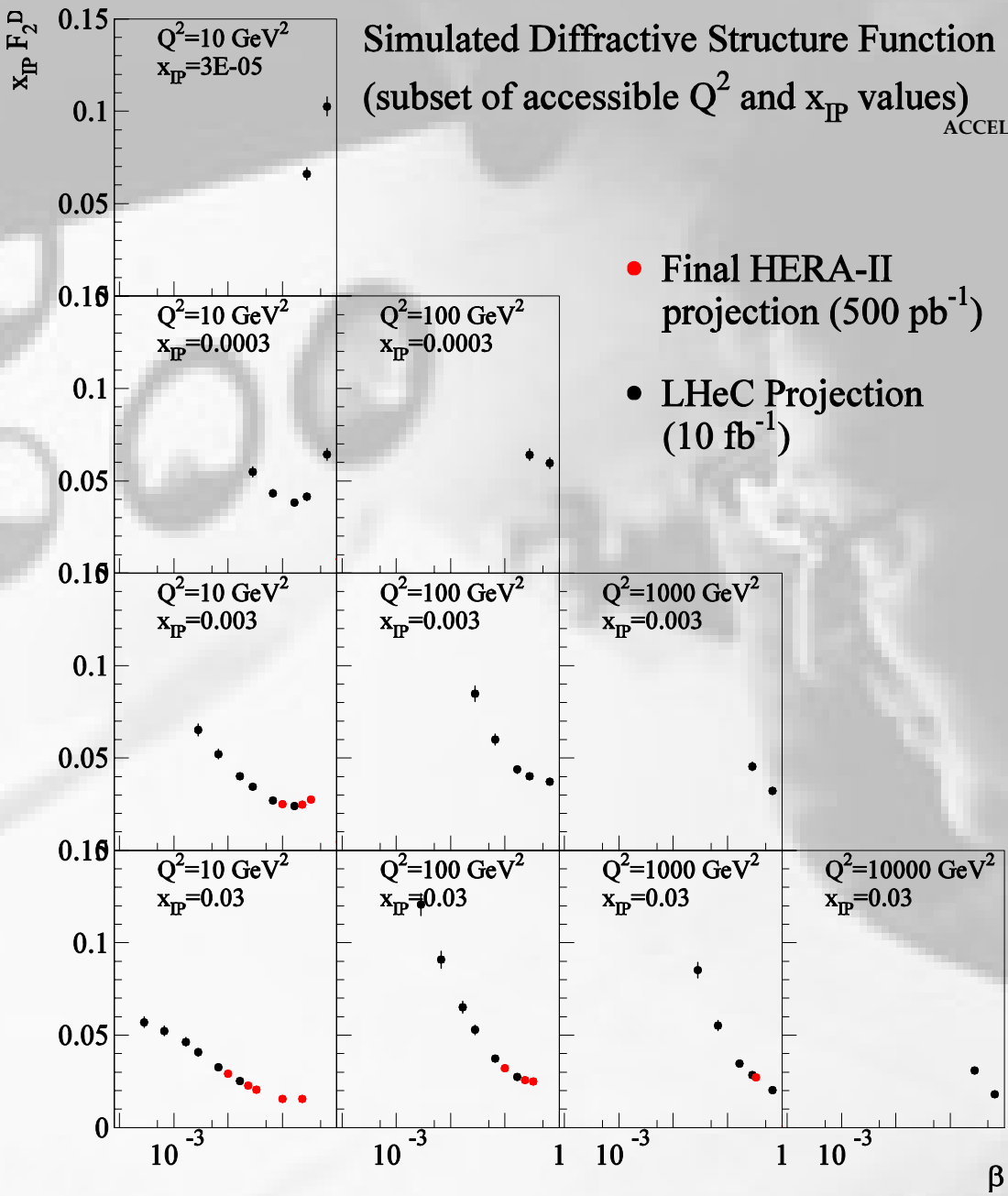
Simulated Diffractive Structure Function

(subset of accessible Q^2 and x_{IP} values)



- Final HERA-II projection (500 pb^{-1})
- LHeC Projection (10 fb^{-1})