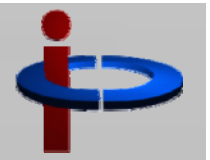
DIS07
Munich
April 2007

LHeC



THE COCKCROFT INSTITUTE *of*
ACCELERATOR SCIENCE and TECHNOLOGY

John Dainton

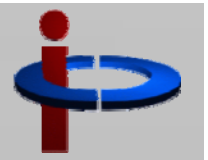
Cockcroft Institute and Univ Liverpool,
Daresbury Science and Innovation Campus, GB
and the University of Liverpool, GB

with M Klein (Univ Liverpool)
P Newman (Univ Birmingham),
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



1. Why?

Why: Leptons ↔ Quarks ?

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- how are leptons and quarks related ?

THE UNCONFINED QUARKS AND GLUONS

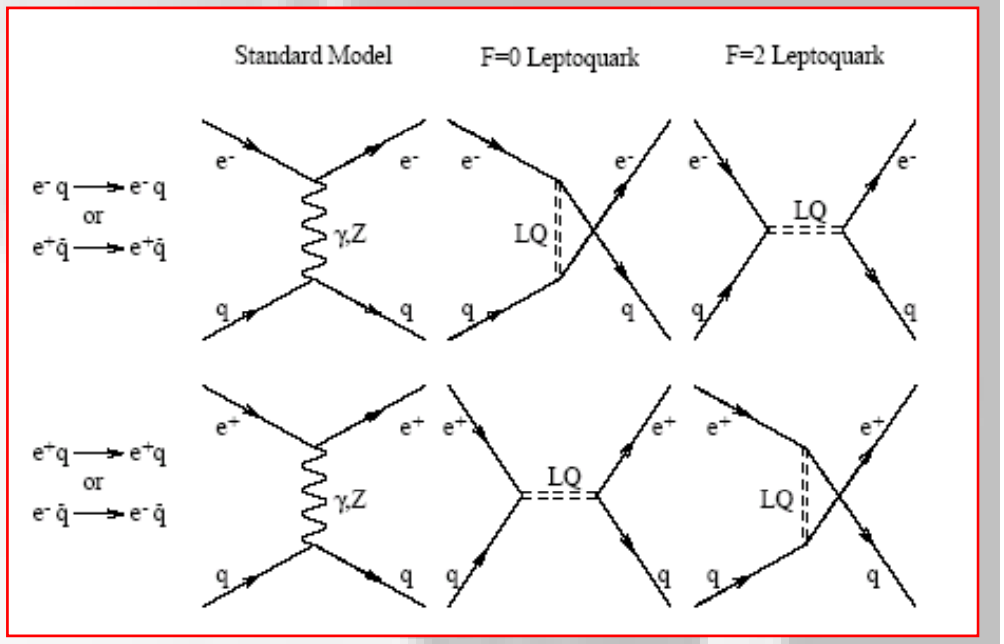
Abdus Salam

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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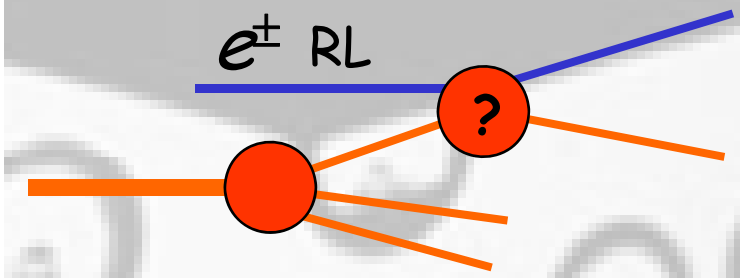
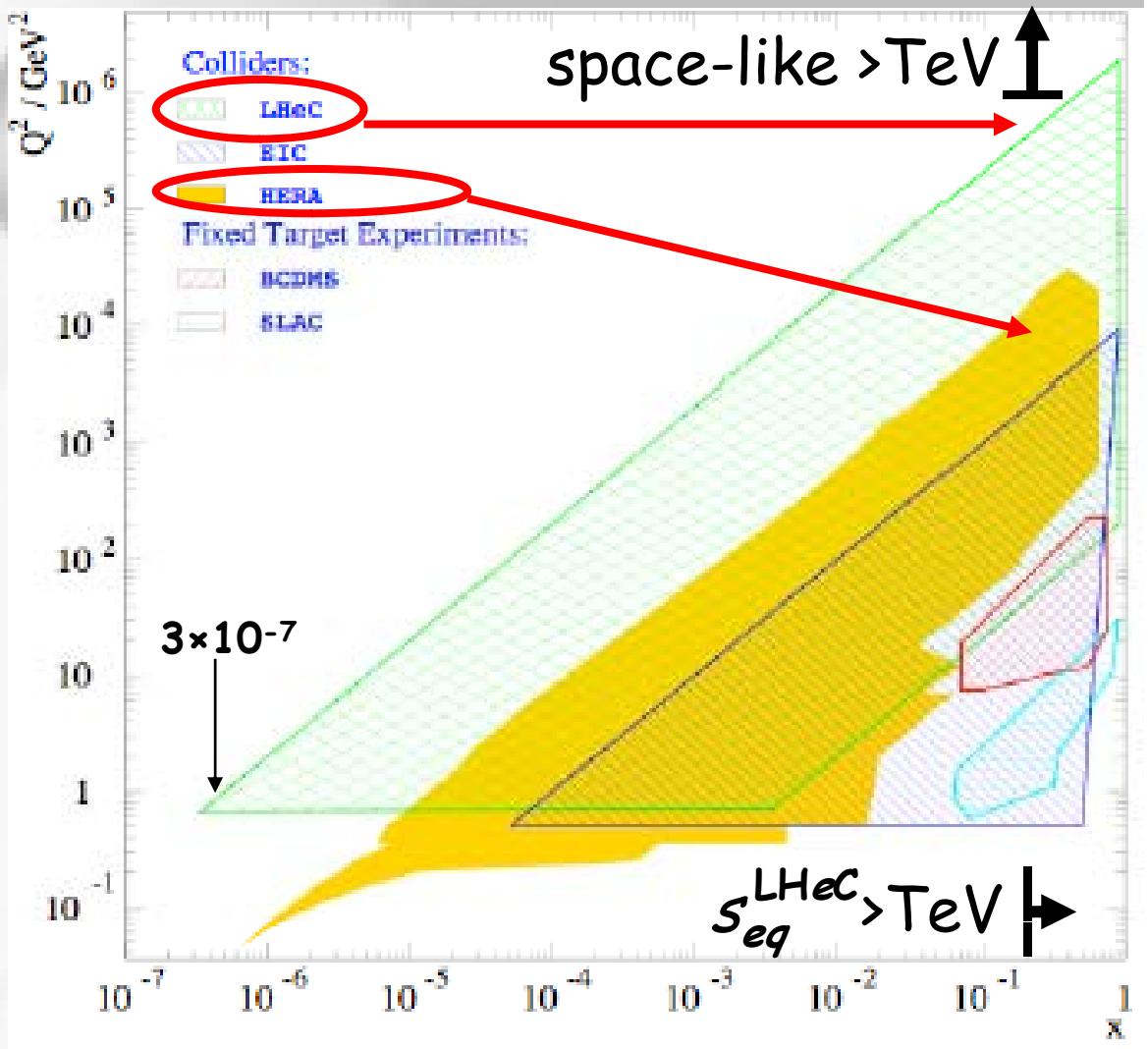


- 2007: HERA
  - $Q^2 \leq 30{,}000\ GeV^2$
  - $s_{eq} \leq (300\ GeV)^2$
    in ~ 0.7 am
- ≥2016?: LHeC
  - $Q^2 \leq 2\times10^6\ GeV^2$
  - $s_{eq} \leq (2000\ GeV)^2$
    in ~ 0.1 am !



Lepton+quark @ TeV

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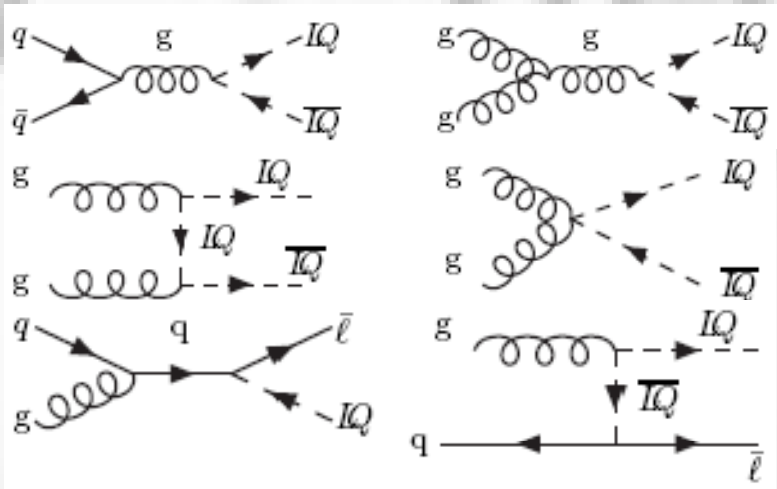
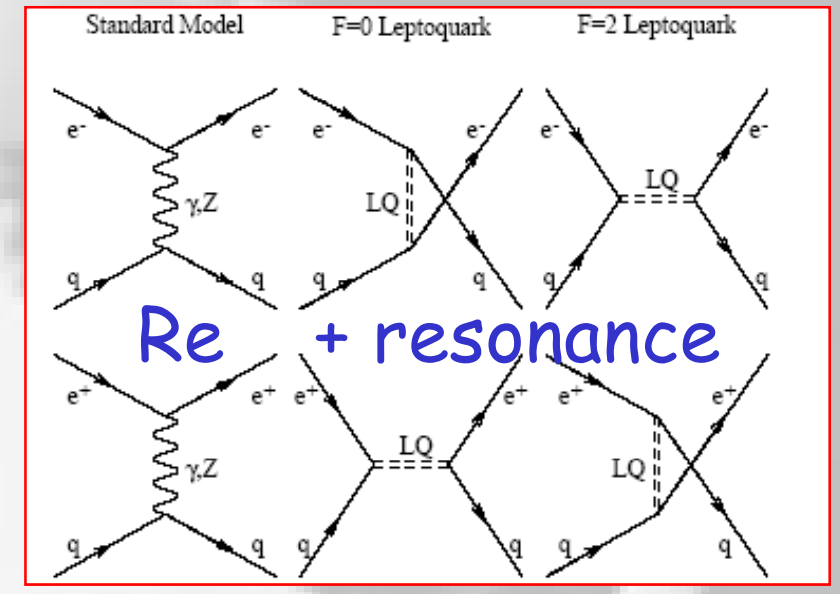
- leptoquark systems – new physics +SM

LHC



LHeC



SM (hadronic) + signal

LqLq productionS

~ few × 0.1 fb (Λ=0.1)

SM (electroweak) + signal

Lq formation

~ 100 fb (Λ=0.1)

Lepton+quark @ TeV

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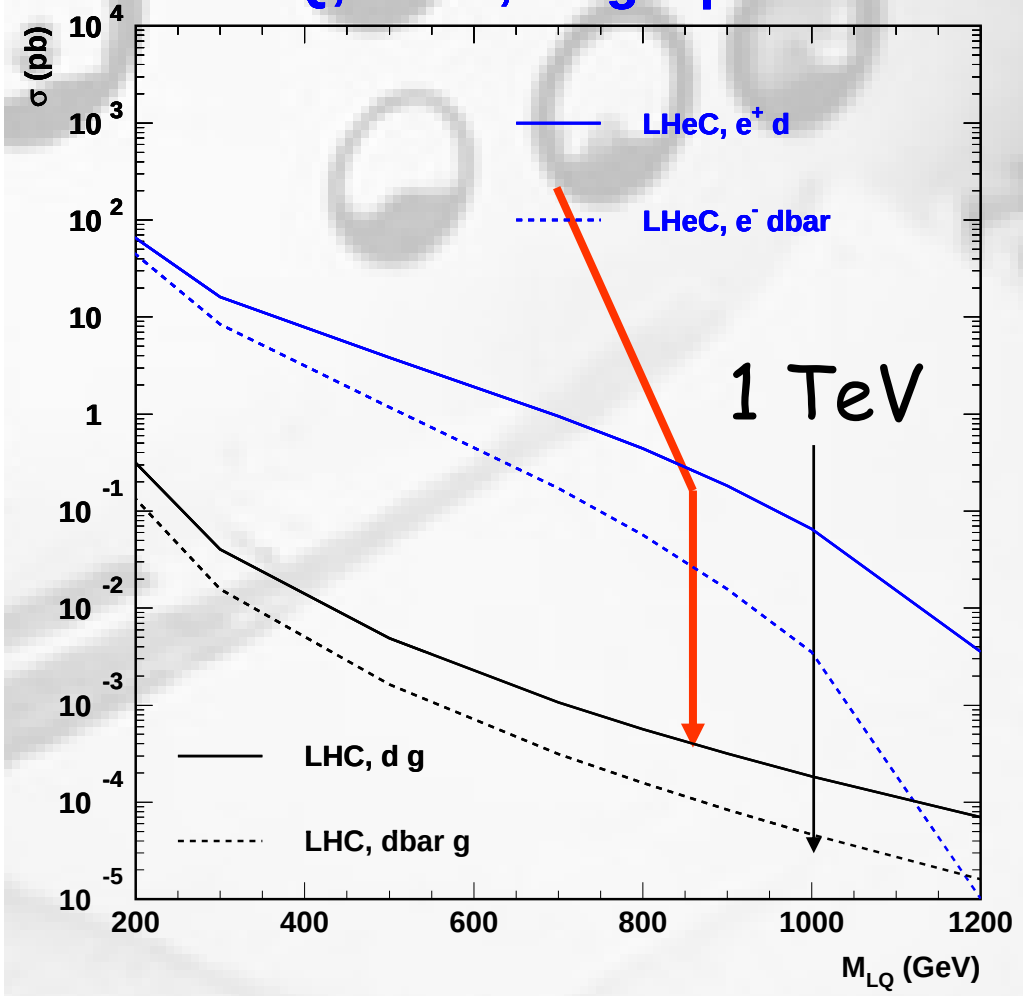
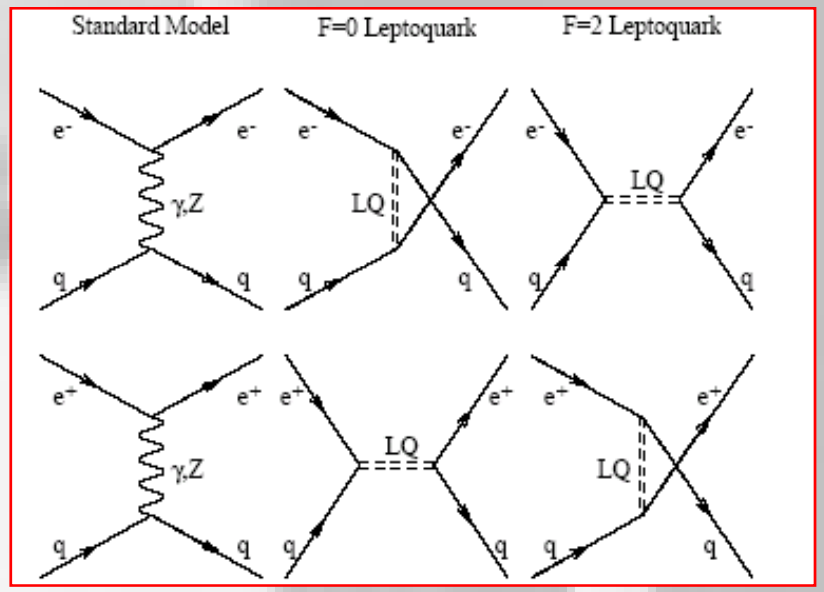
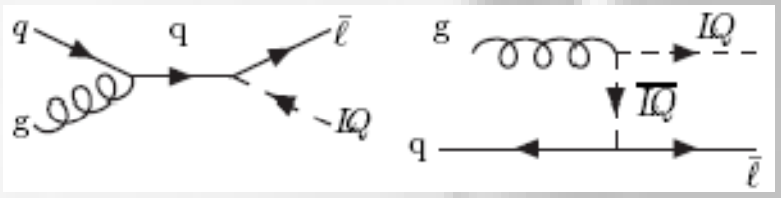
- leptoquark systems – new physics +SM

Scalar LQ, λ=0.1, single production







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Lepton+quark @ TeV

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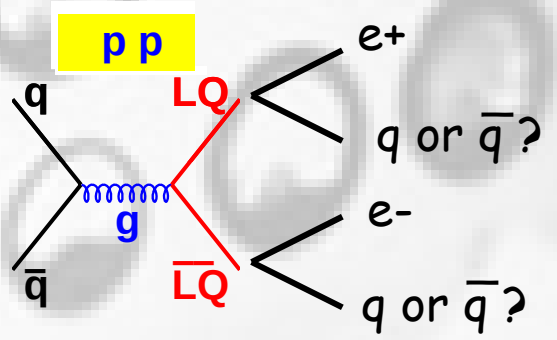
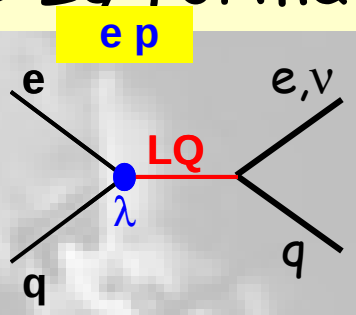
LHC *Lq* pairs



LHeC *Lq* formation+decay



e+ F=0
e- F=2

fermion number

spin parity and chirality

exp^{l}_sig

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

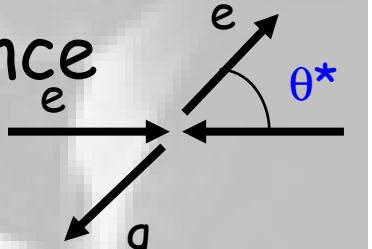
production mechanism ?

disentangle mass spectrum ?

jets + leptons

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

inclusive coherence



unique PWA

SM + signal + interference

jet+(lepton)+p_T (im)balance

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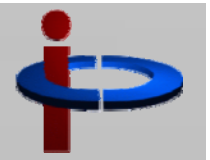
Lepton+quark @ TeV



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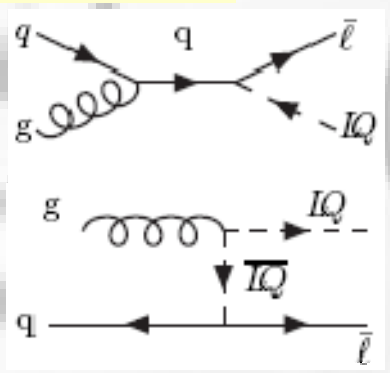
LHC *Lq*



fermion number

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

spin parity and chirality

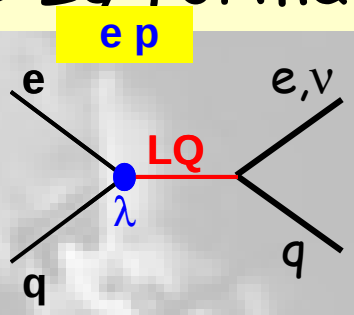
production mechanism ?

disentangle mass spectrum ?

exp^{l}_sig

jet + leptons

LHeC *Lq* formation+decay



e+ F=0

e- F=2

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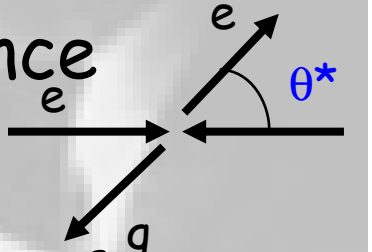

unique PWA

SM + signal + interference

jet+(lepton)+p_T (im)balance

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Structure of Matter @ TeV

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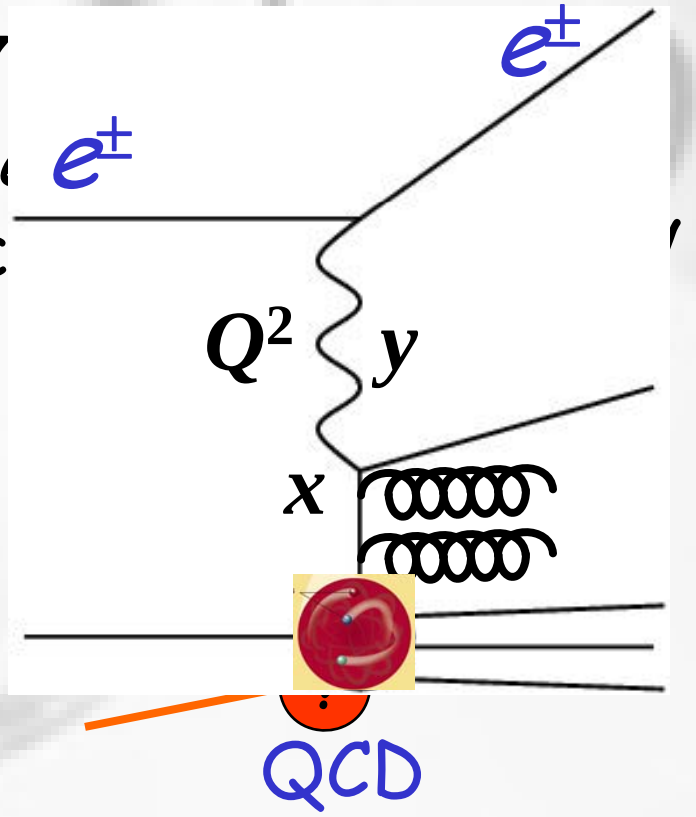
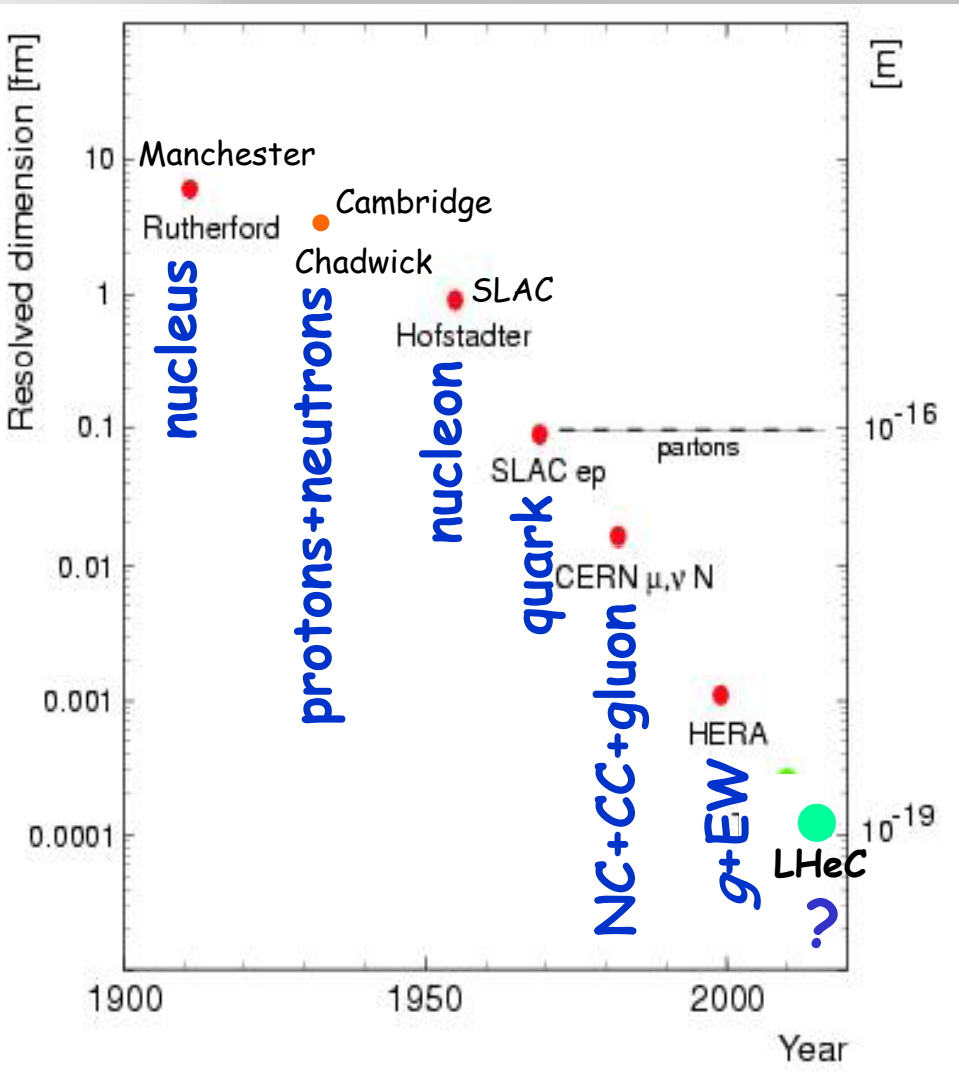
- unique chiral probe @ 0.0001 fm ?
- 7



S SM + q structure s
@ @ ~ 0.0001 fm ?



Unification ?

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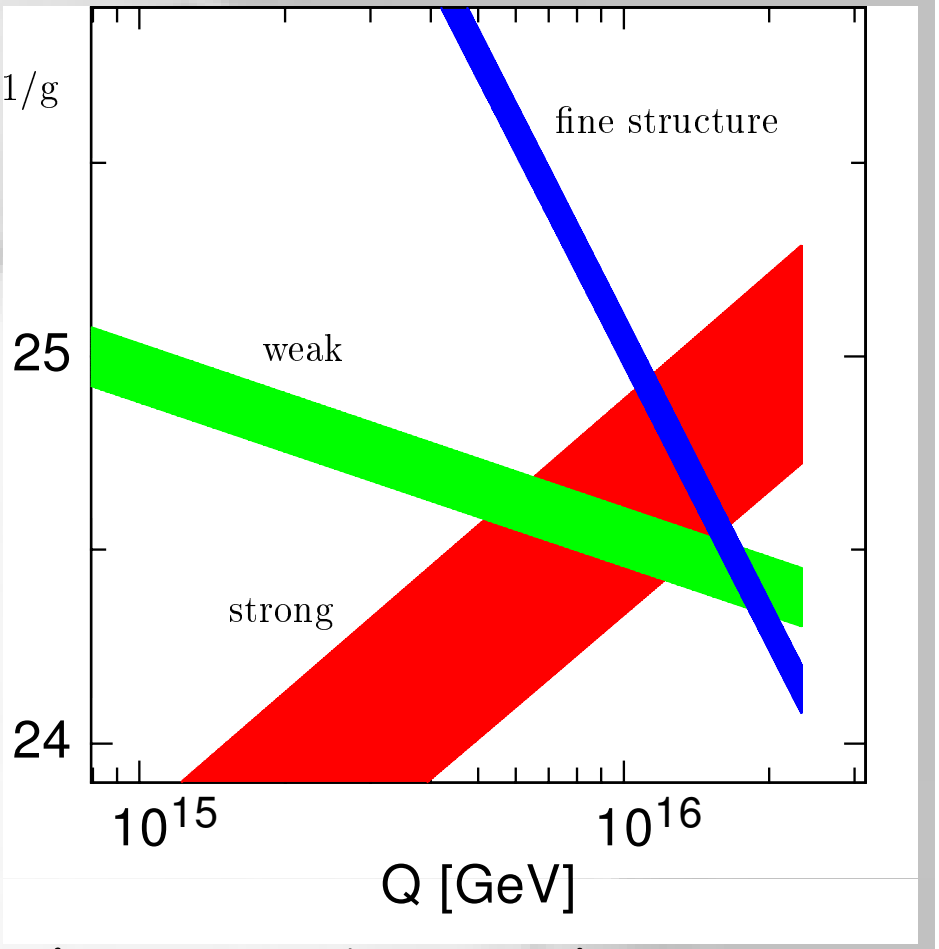
- precision → QCD at highest energy
- short distance structure of SM+
  - 2006 α @ 10^{-9}
  - 2006 G_F @ 10^{-5}
  - 2006 G @ 0.1%
  - 2006 α_s @ 1-2%
  - LHeC + detector
    → α_s few/mil



precision → discovery

probe new chromodynamic physics – beyond SM ?

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Heavy Flavour in Hadron Chromodynamics

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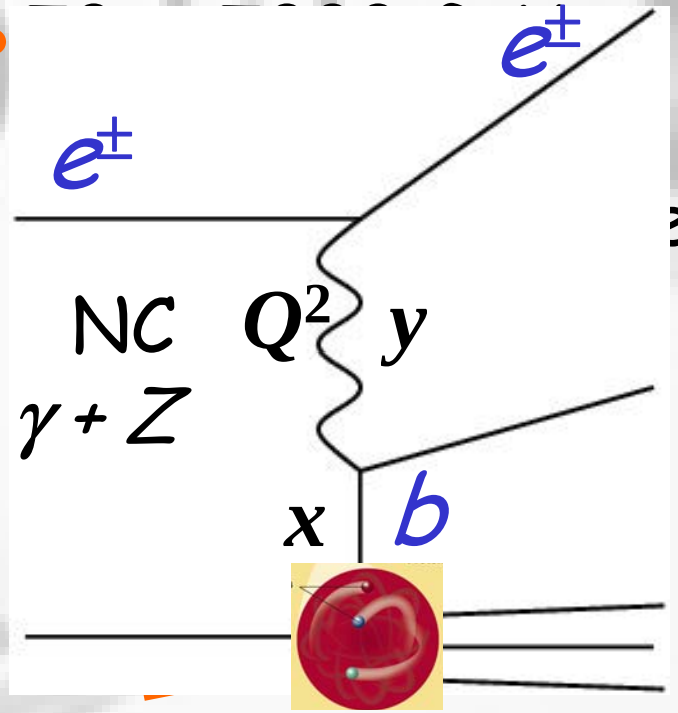
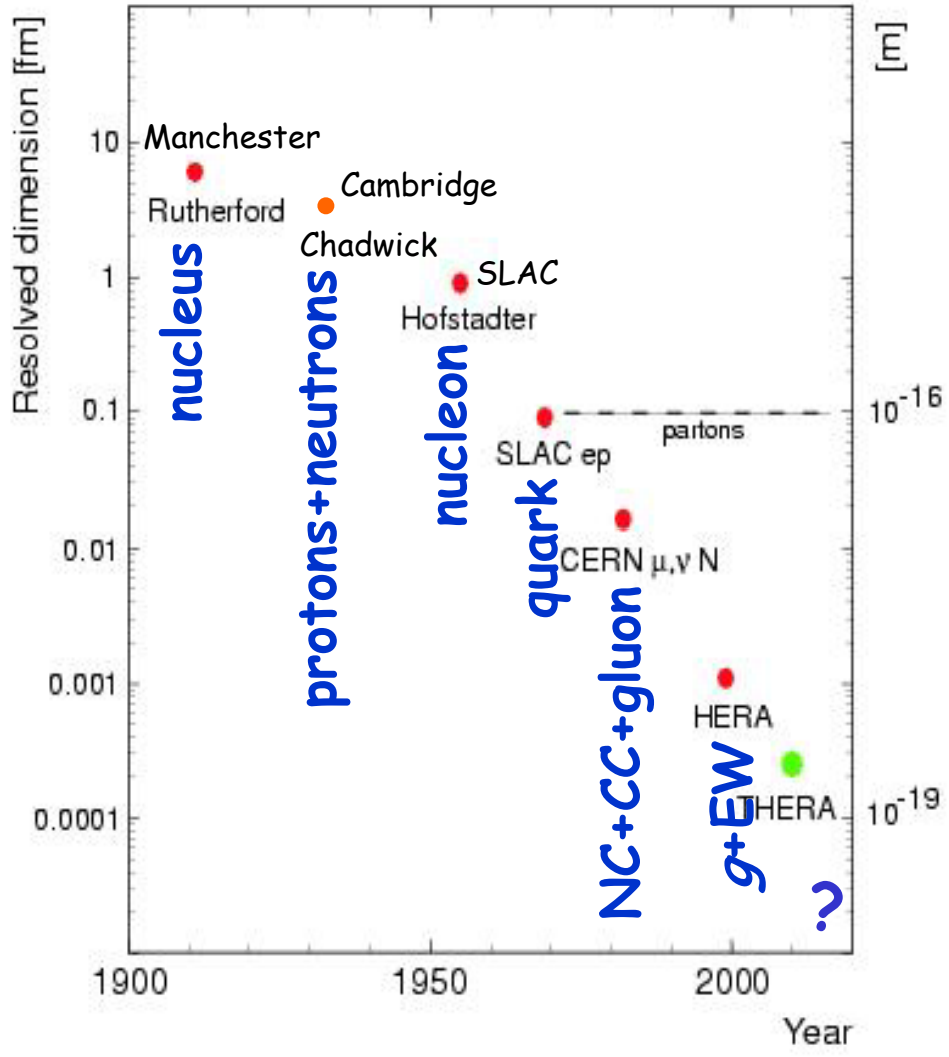
- unique chiral probe @ 0.0001 fm ?



: SM @ ~ 0.0001 fm
(heavy flavour



..... underpins discovery

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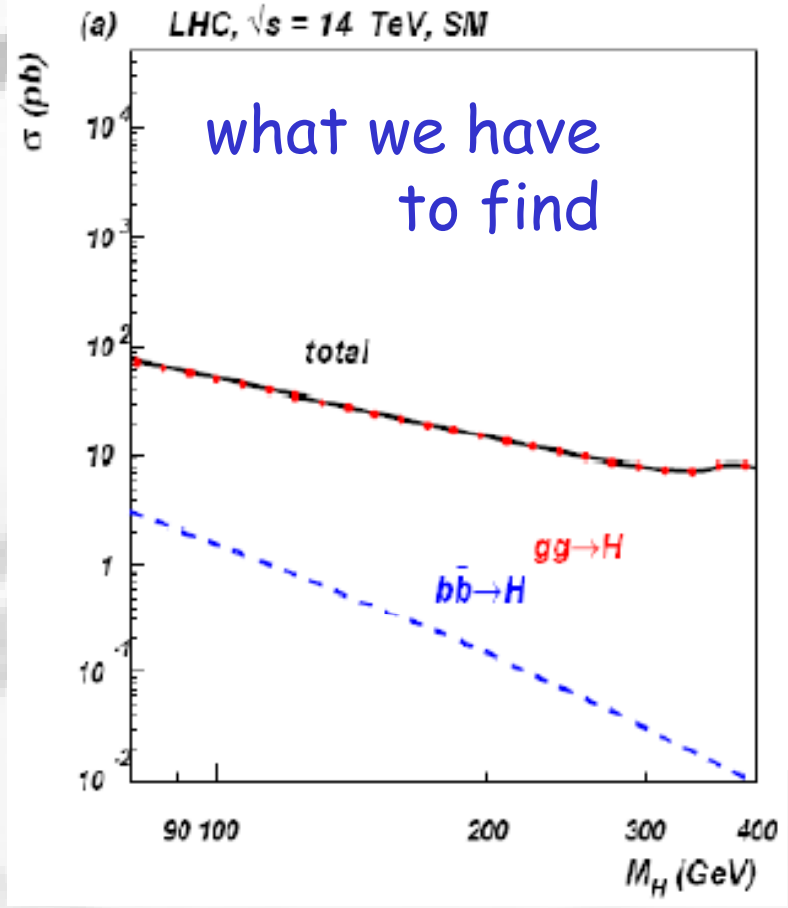
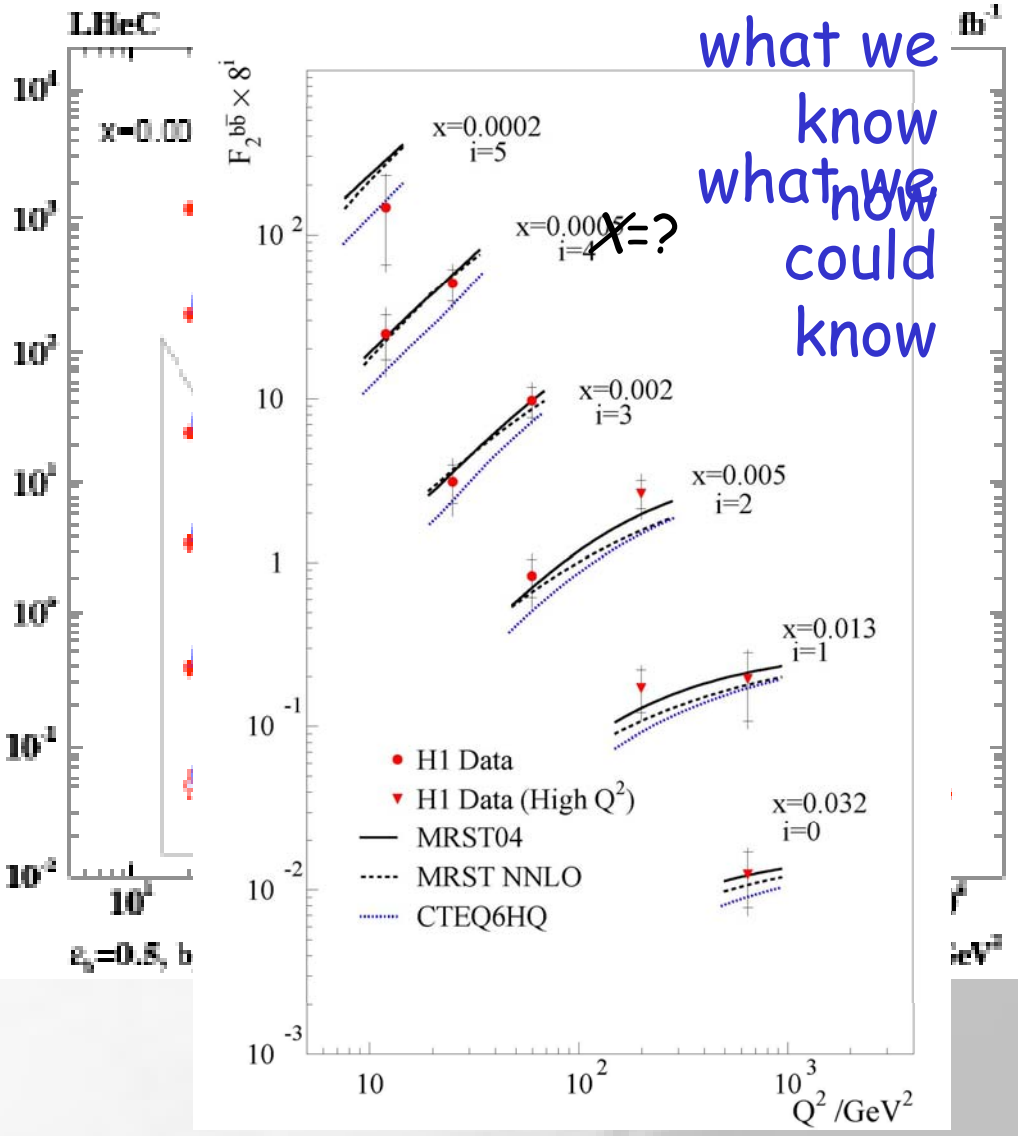
- Higgs at LHC



what we have to find



what we know
what we ~~know~~ X=?
now could know

Why: Dense Colour ?

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- the origin of mass in the Universe

  "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 at lowest Bjørken-x

Growing Field Energy Density

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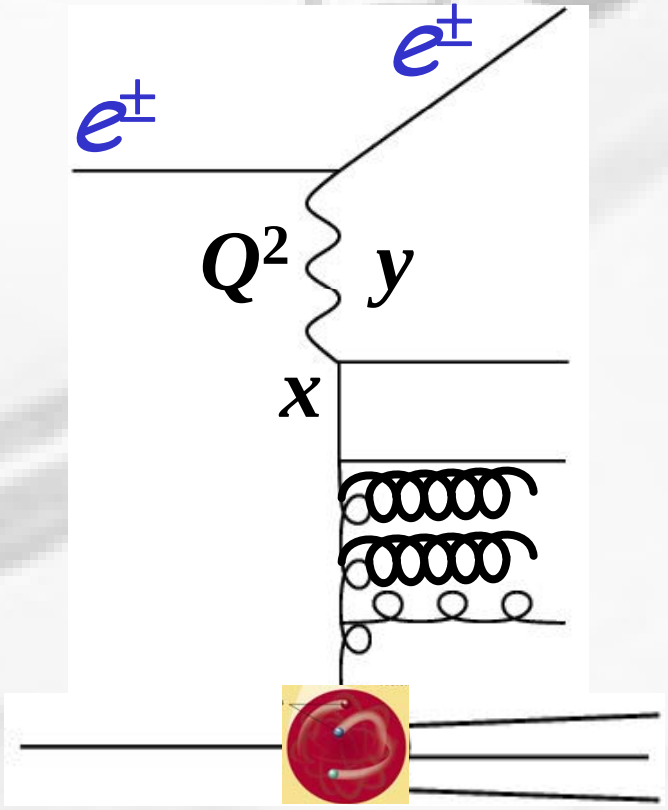
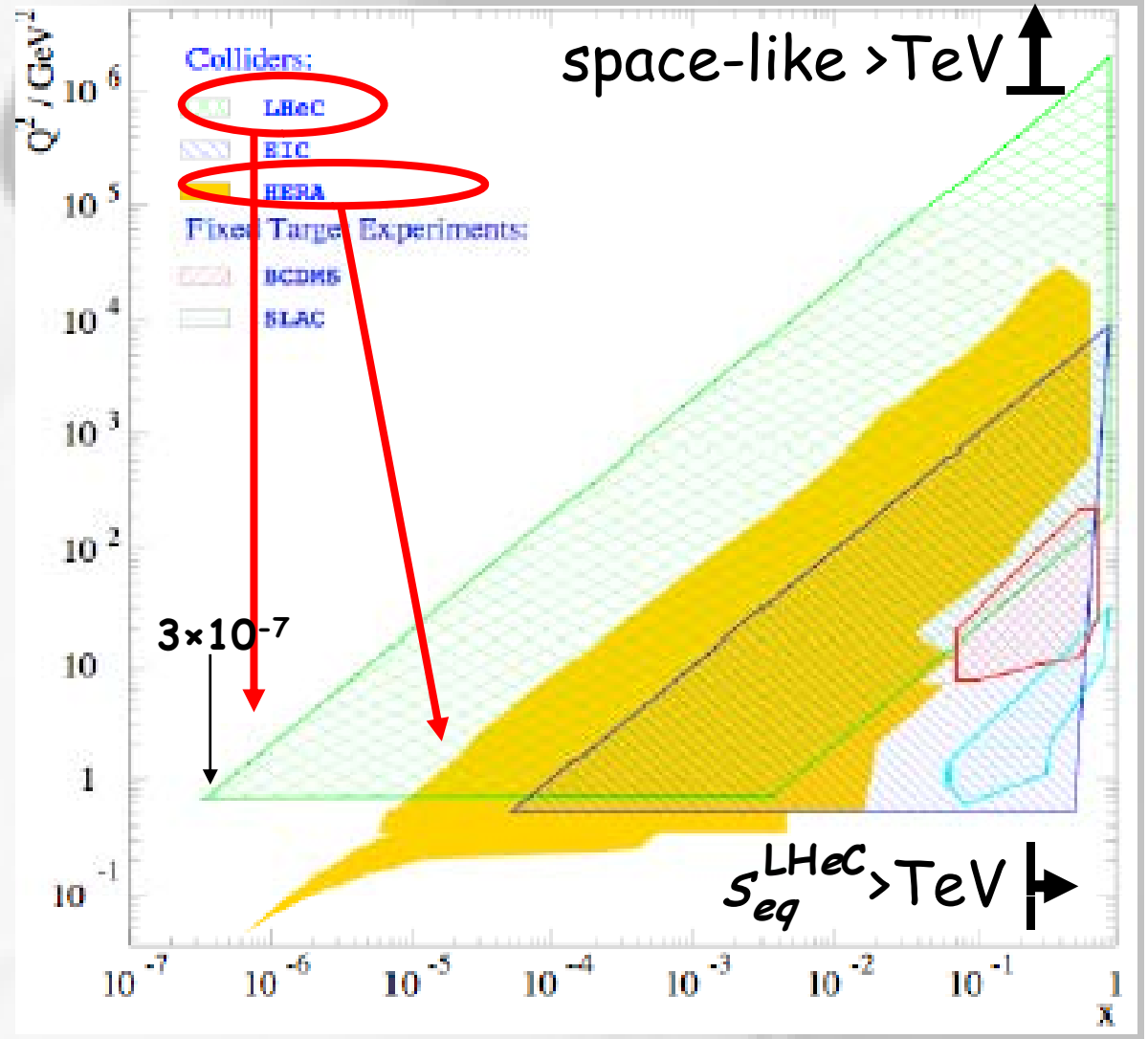
- 2001?: HERA
  - $Q^2 \geq 1\ GeV^2$
  - $x_{Bj} \geq 5\times10^{-5}$





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Gluon recombination

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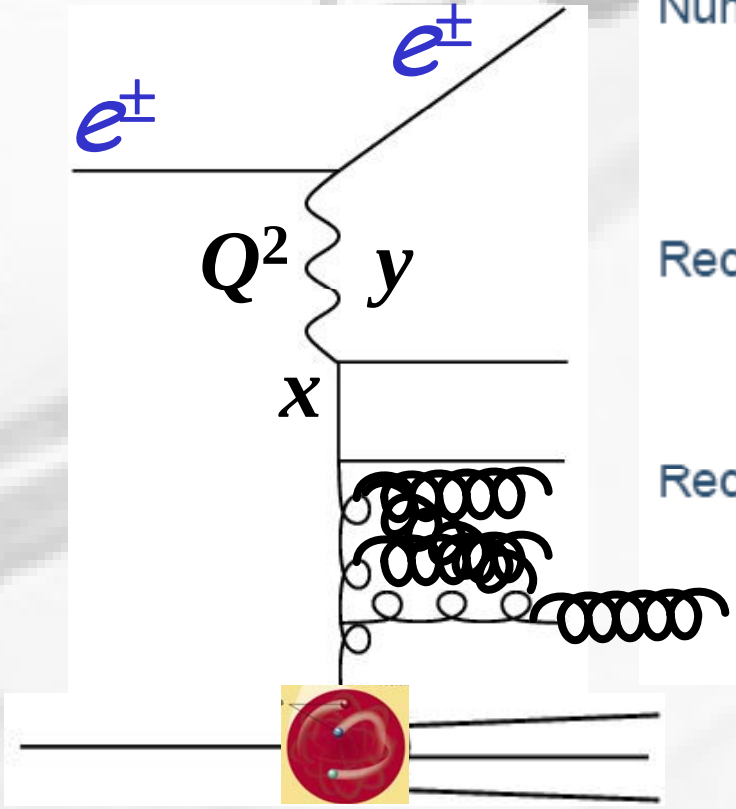
- ≥2016?: LHeC
  - $Q^2 \geq 1\ GeV^2$
  - $x_{Bj} \geq 5\times10^{-7}$

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



Number of gluons per unit area:

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

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 @ LHeC

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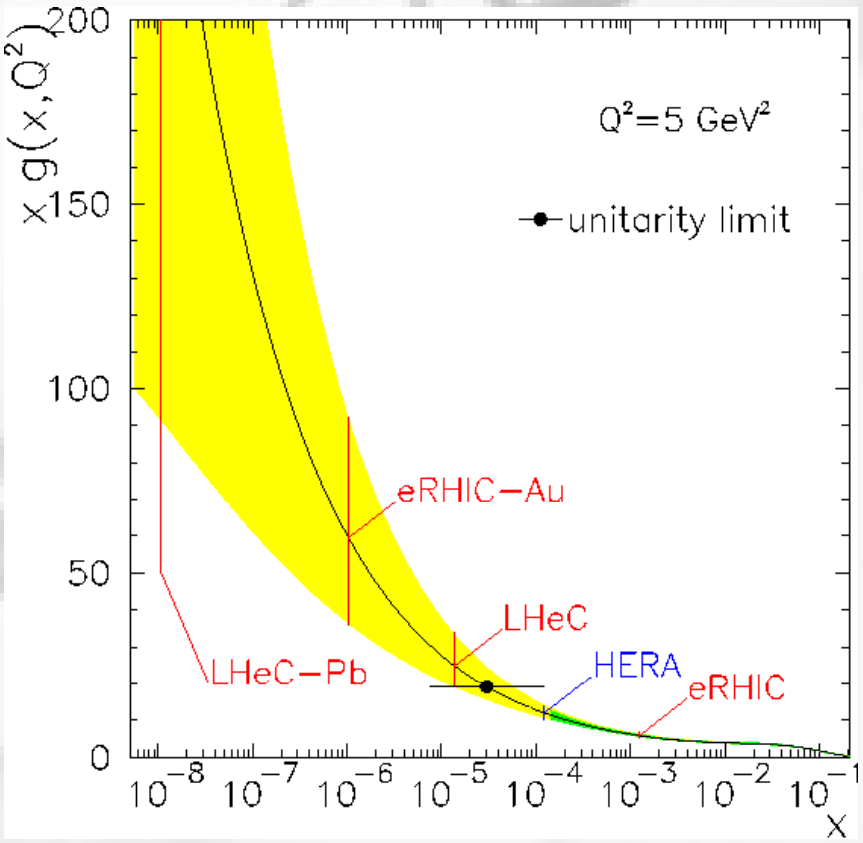
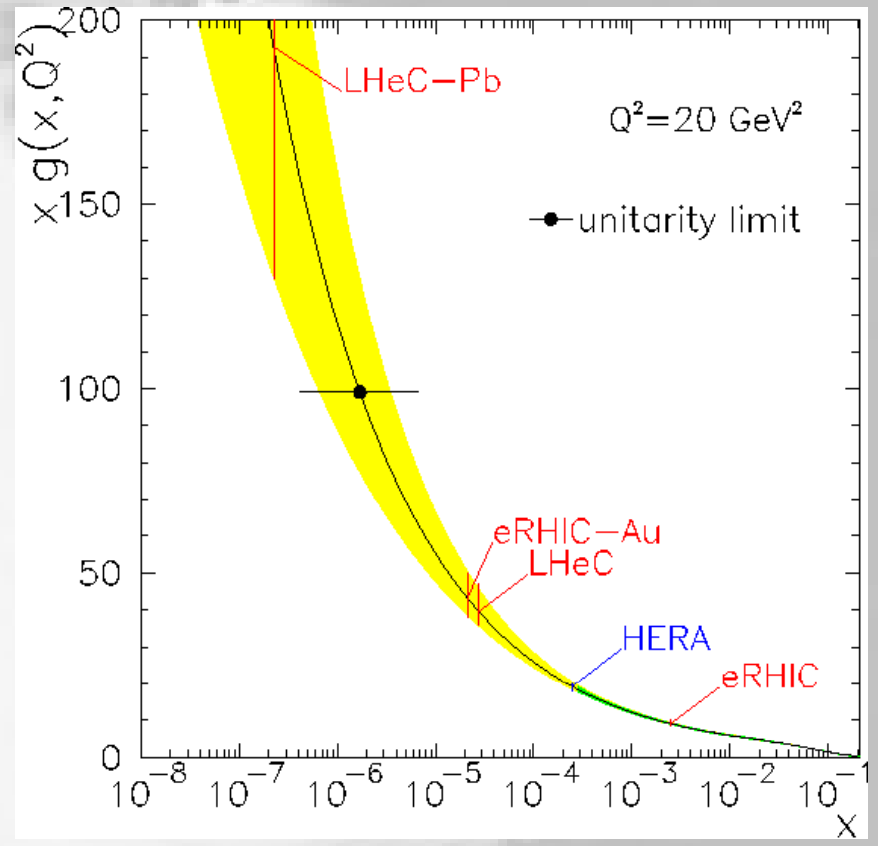
- *ep* saturation $Q^2 \leq 5$ GeV^2

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





Dense Chromodynamics

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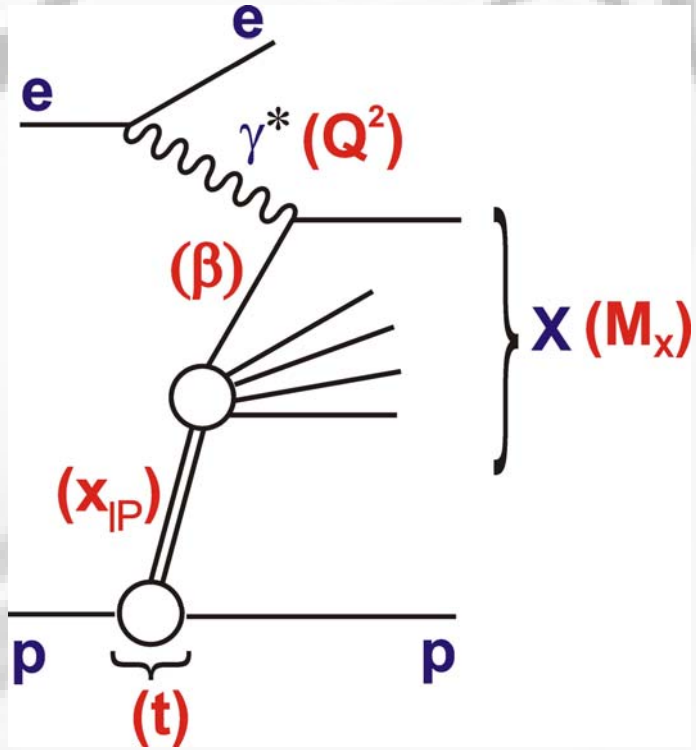
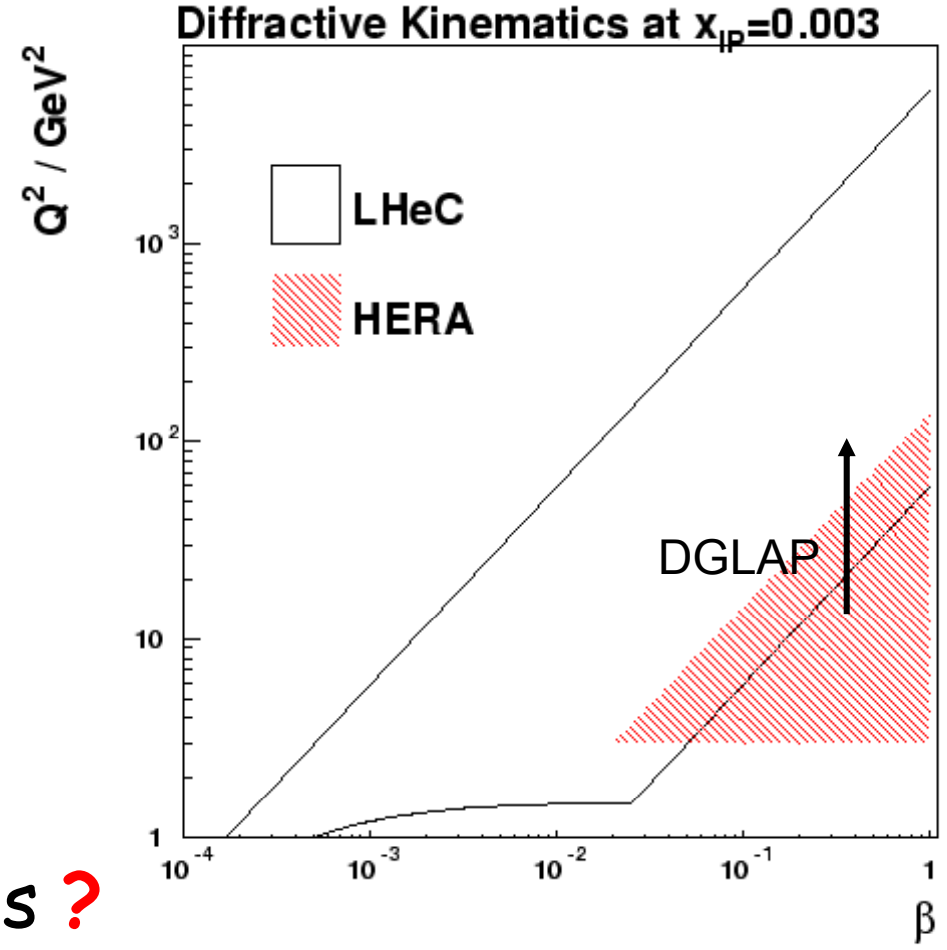
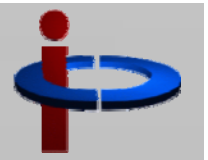
- low-x rise of F_2
  - LHeC: precision eg $x > 3\times10^{-3}$ @ $Q^2=10000$ GeV^2

$x = \beta x_{IP}$





- low x $\mathbb{P}$ physics
  QCD $\leftrightarrow$ reggeon calculus ?



2.How?

Proton beam

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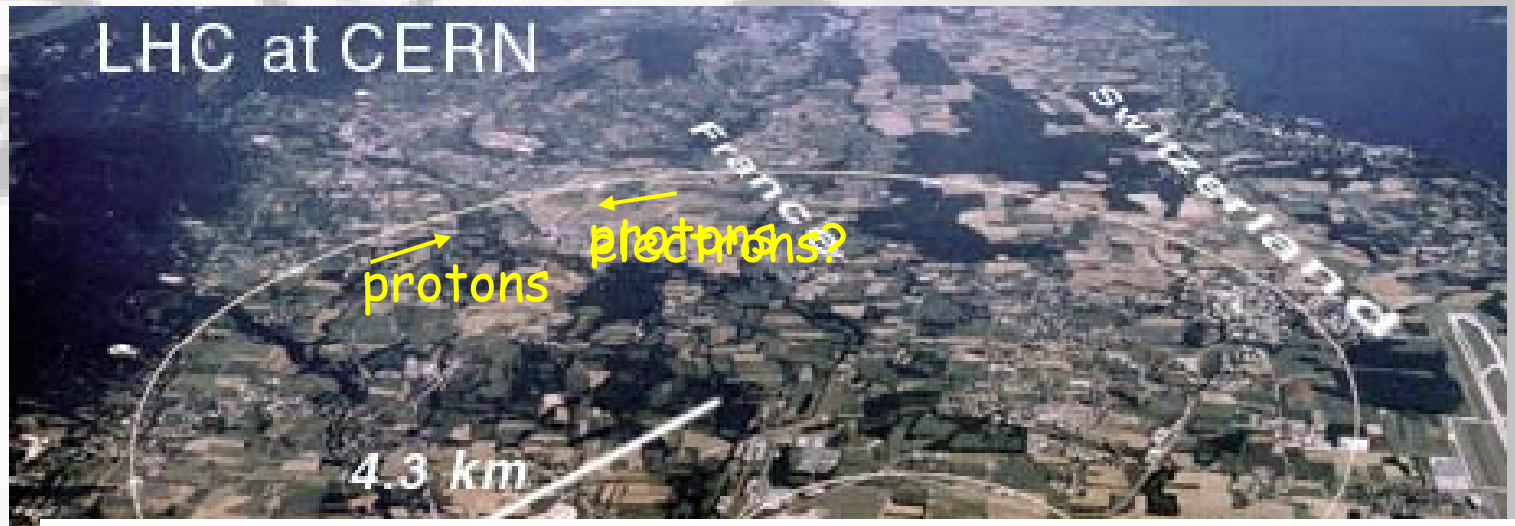
- "standard" LHC protons … with electrons?



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

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

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

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

$e^{\pm}p$ Luminosity

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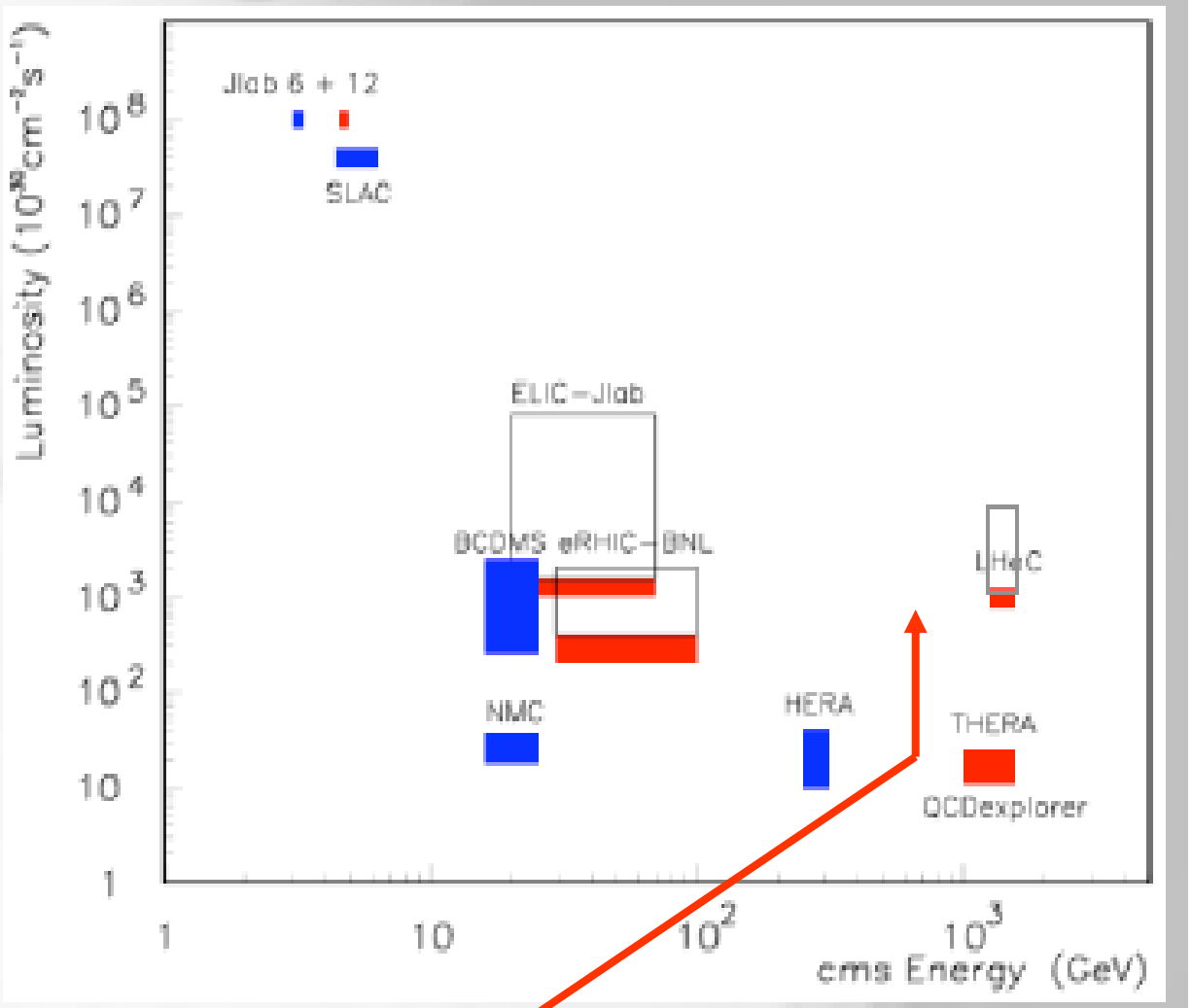
- astounding !
- $\times 10^2$ L_{NMC} μp @ 0.01 fm
- L_{eRHIC} $e_{pol}p_{pol}$ eA @ 0.007 fm
- $\times 10^2$ L_{HERA} $e_{pol}p$ @ 0.001 fm
- L_{LHeC} $e^{\pm}p$ eA @ 0.00014 fm



indisputably a next step … is it feasible ?

Lepton Ring

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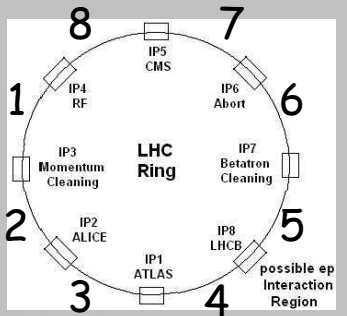

- in LEP tunnel … so like LEP
  - FODO in eight arcs
    β-tron phase advance φ_H=108° φ_V=90°
  - bending radius 3133.3 m
  - $(\delta E/E_{beam})_{rms}$ = 1.1×10^{-3}
  - SR 26 W/cm (E_c=254 KeV)

    LEP=9 W/cm
    HERA=13.5 W/cm
  - scRF @ 1GHz resonators @ 12 MV/m

    scRF proven @ > 6 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

ep Collisions

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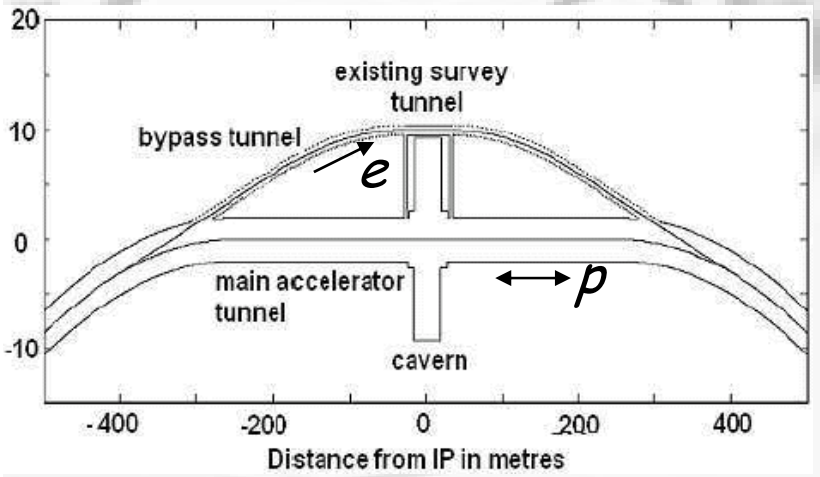
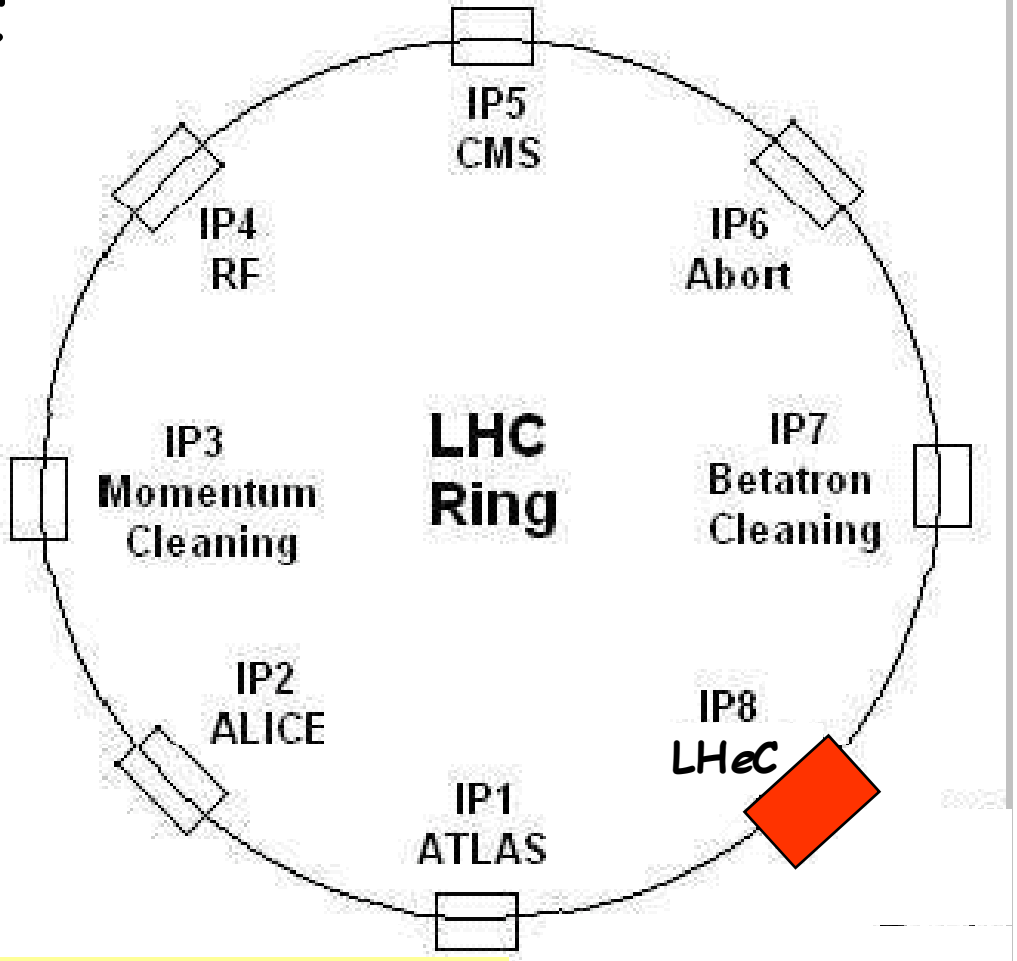
- after *B* physics @ LHC



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



ep alongside *pp* data-taking @ LHC

Interaction Region

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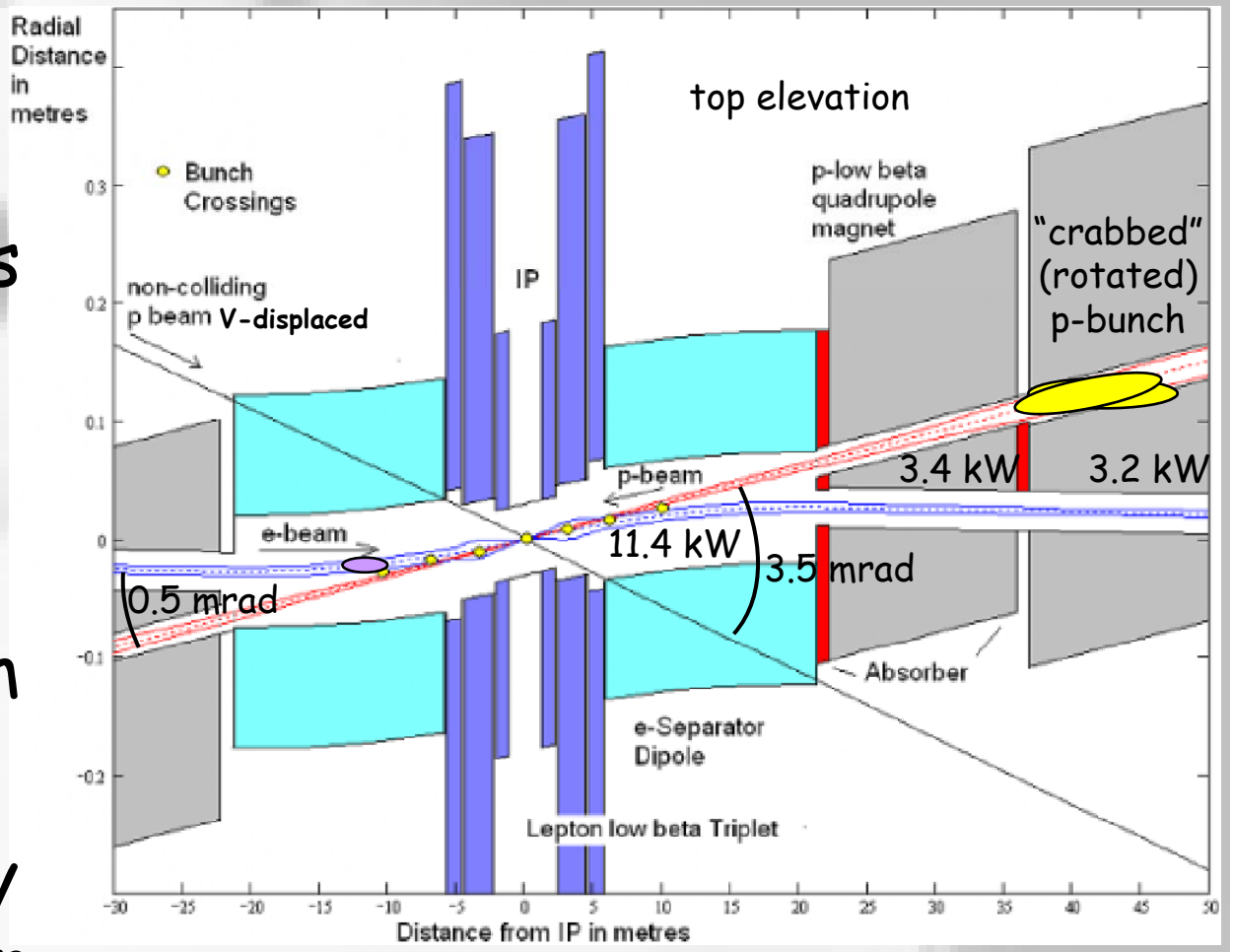
- highest lumi
  - low β_e
    - close sc quads
  - low X-ing angle
    - "hard" bend
      - SR fan
        - → sc *p*-beam
        - « HERA
  - "crab" RF cavity
    p-bunch rotation



- 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

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

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

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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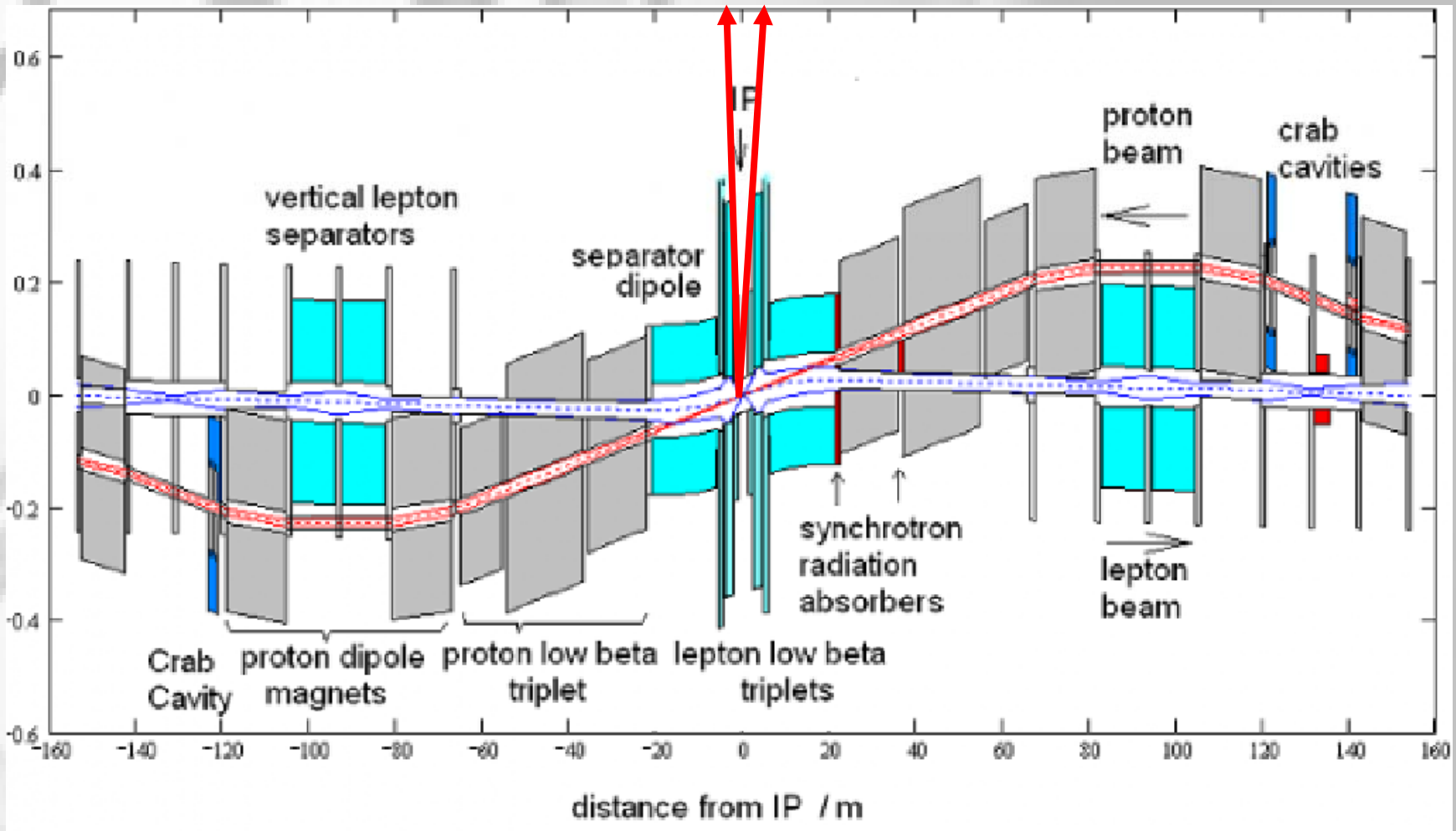
- IR ±many m
- IR ≥9.4° around beam



Asymmetric Collider

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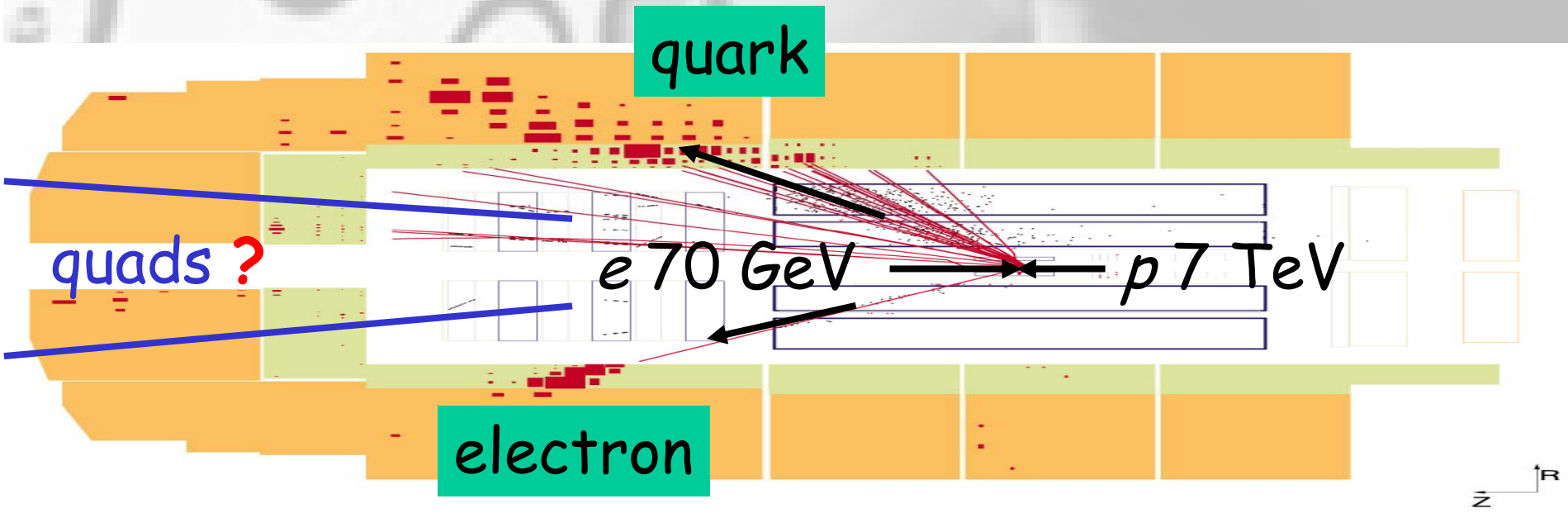
- asymmetric beam momenta: LHeC

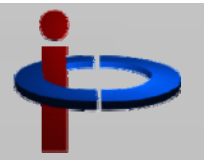
  ~ TeV



- "forward" hemisphere detection to multiTeV

  topological challenge

  precision challenge



3. When?

Timeline

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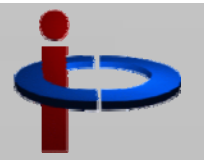
- 2007: form working groups + steering committee
  initial meeting of conveners + committee
  SAC overview
- 2008: workshop I
- 2009: workshop II

  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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1. Accelerator (injector, ring)
2. Interaction region
3. Detector
4. The new physics
5. High precision QCD
6. Low x physics
7. *eA*

tbc (SAC)

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LHeC Scientific Advisory Committee

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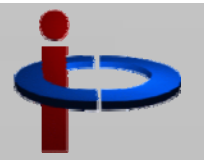
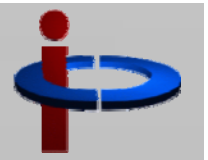
Joel Feltesse (Saclay/DESY)
Guido Altarelli (Roma)
Rolf Heuer (DESY)
Aharon Levy (Tel Aviv)
Lev Lipatov (Petersburg)
Allen Caldwell (MPI Muenchen)
Young-Kee Kim (Fermilab)
Jos Engelen (CERN)
Roland Horisberger (PSI)
Stephen Myers (CERN)
Stan Brodsky (SLAC)
Roland Garoby (CERN)
Ferdinand Willeke (DESY/BNL)
Swapan Chattopadhyay (Cockcroft Institute)
Peter Bond (BNL)
Richard Milner (MIT)
John Dainton (University of Liverpool)



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
    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!

Lepton-Parton and Parton-Parton ?

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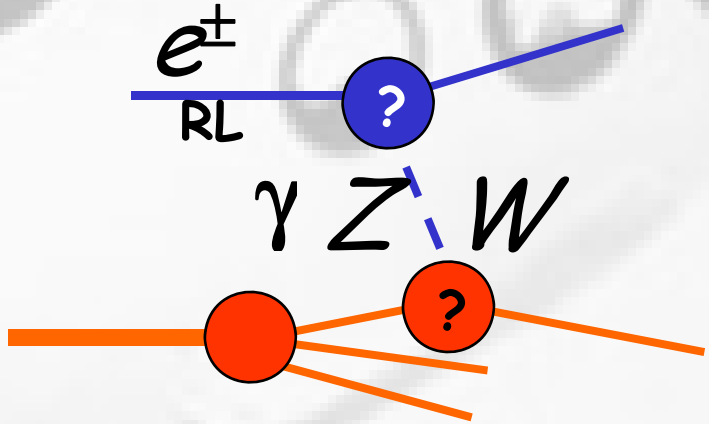
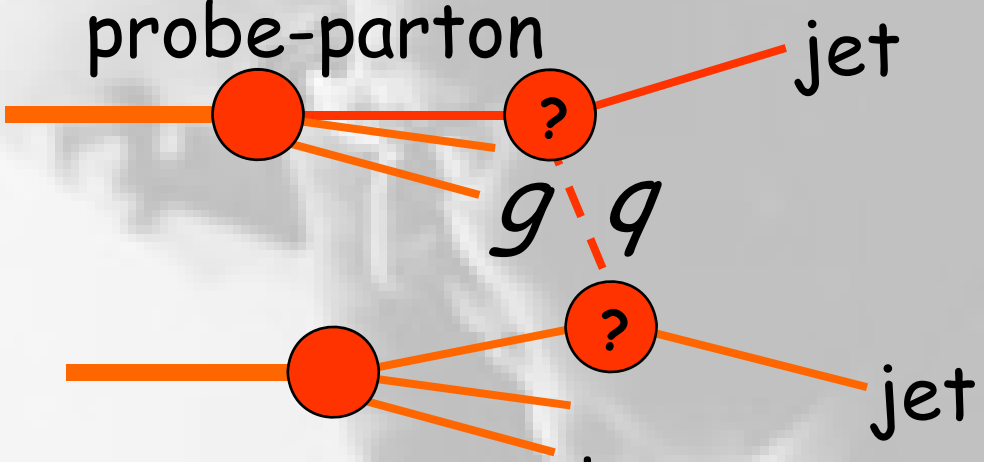
- $ep \rightarrow eX$



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

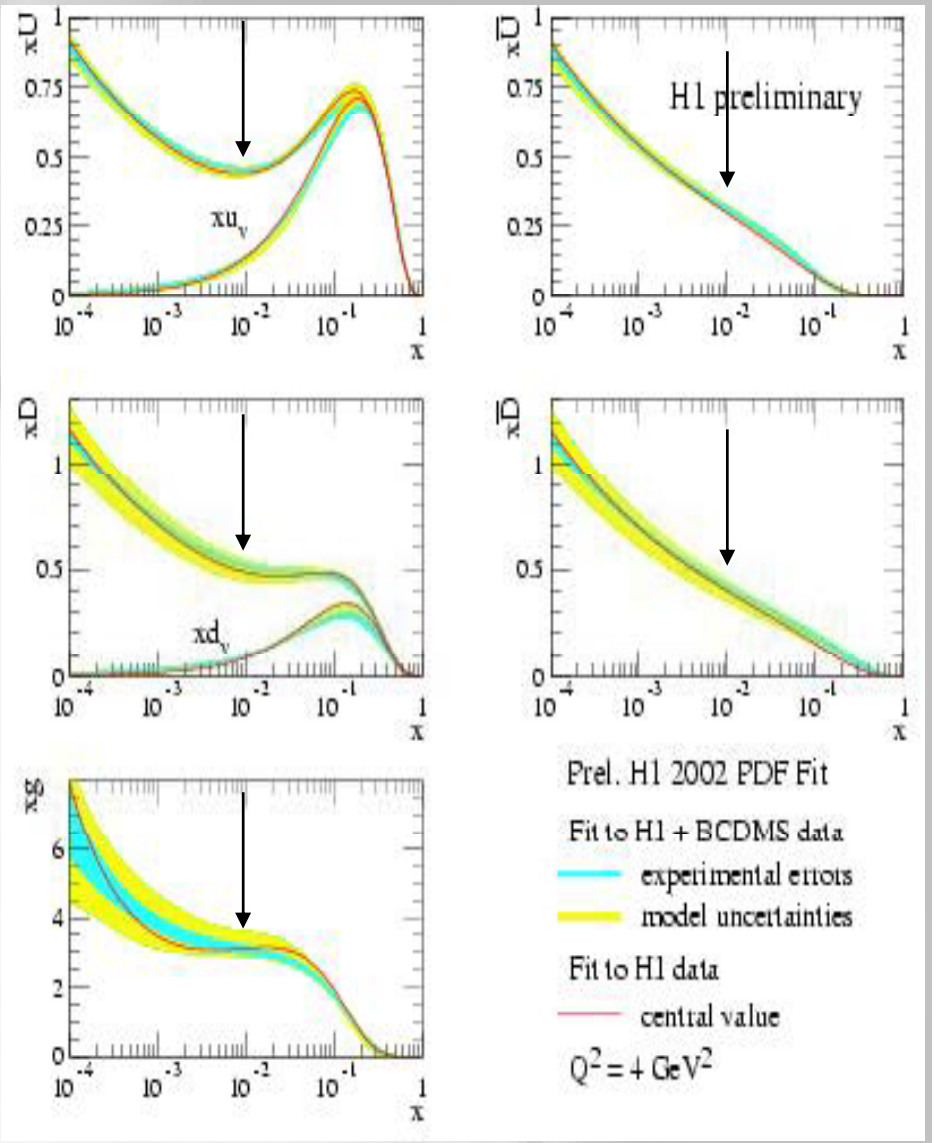
$g : q \sim 2:1$

- probe-parton @ $x \gg 0.01$

$g : q \to 0$

"mixed" LHC probe
@ LHeC energy

q LHC probe
@ LHC top energy



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Lepton-Parton and Parton-Parton

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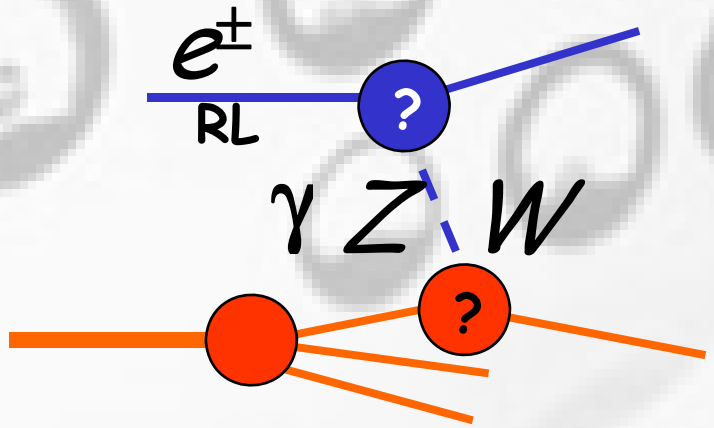
- $ep \rightarrow eX$

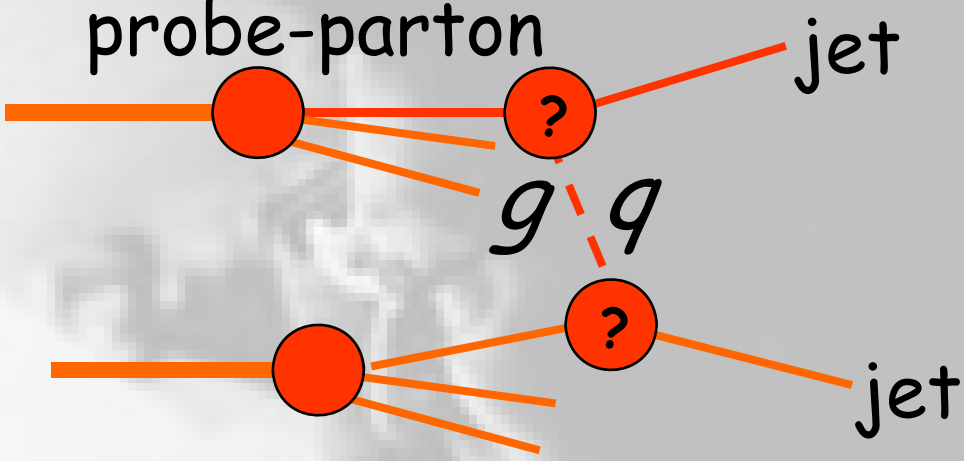


- precise probe e
- precise kinematics
- smaller kinematic reach

  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

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Dense Chromodynamics

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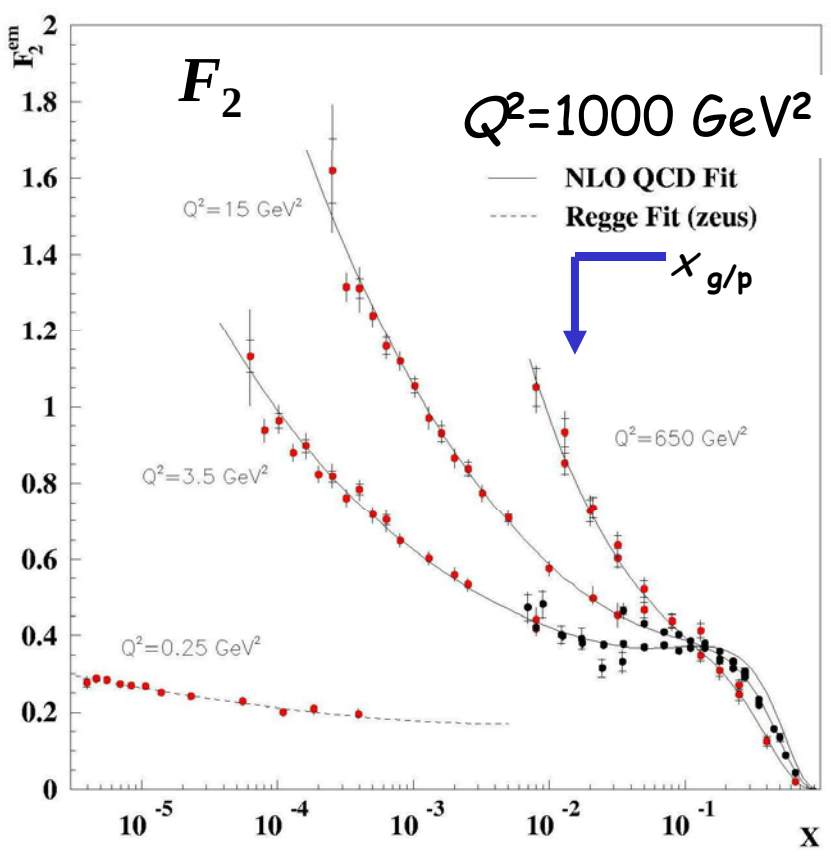
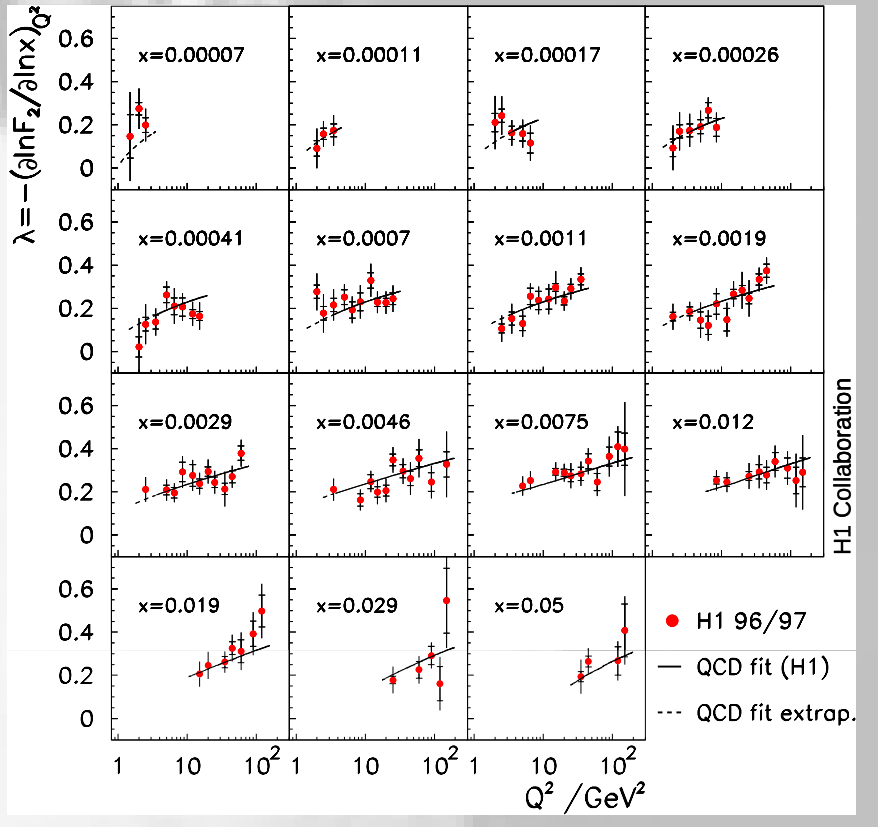
- relentless low-x rise of F_2
  - saturation? partons must someday recombine
  - LHeC: precision eg $x > 2\times10^{-4}$ @ Q^2=1000 GeV²





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Dense Chromodynamics

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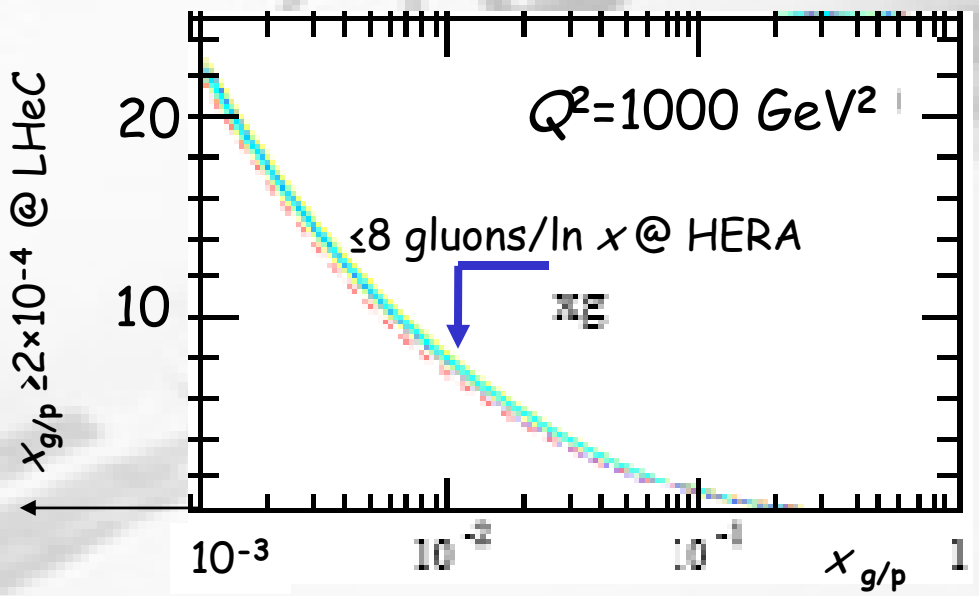
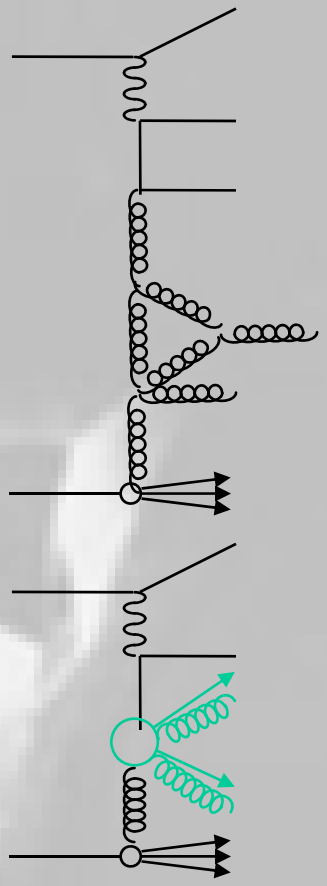
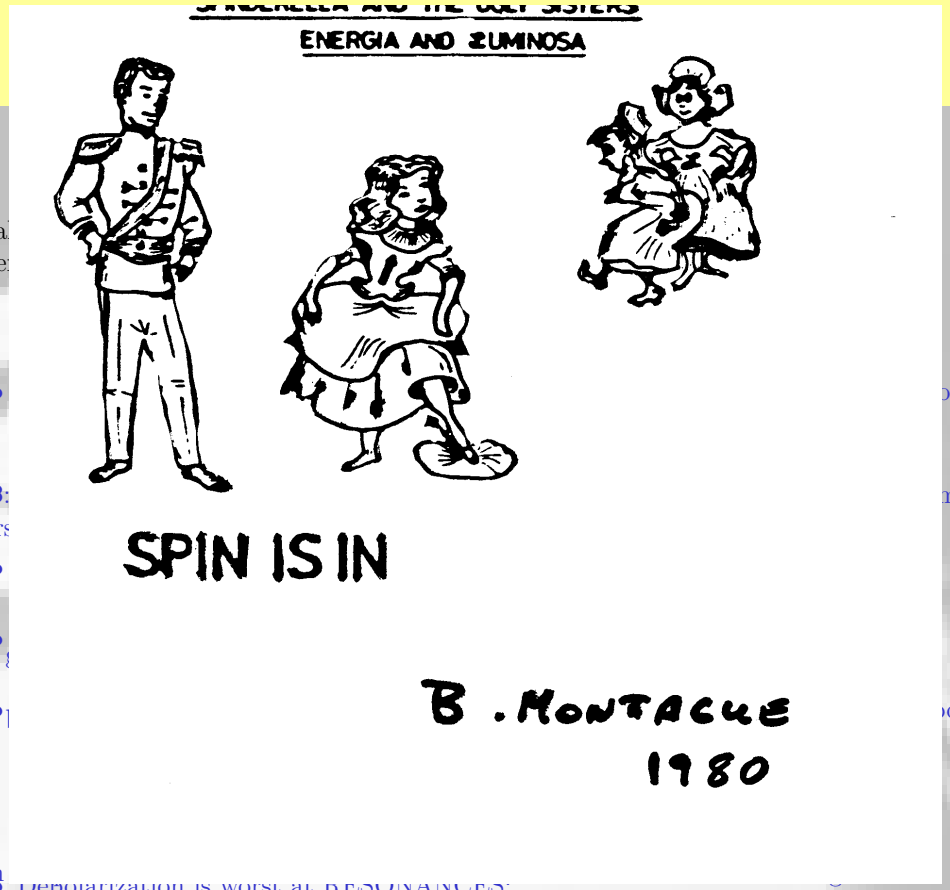
- relentless low-x rise of F_2
  - LHeC: precision for $x > 2\times10^{-4}$ @ Q^2=1000 GeV^2



- precision pdfs
  - BFKL? CCFM ?
- high density
  - recombination
  - saturation ?
  - instantons ?
  - other "ons" ?
  - condensates ?
  - other "ates" ?



≥ 20 g/nucleon/ln x @LHeC
… in heavy ion ?



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Barber

Recal… well
unde…

- …otron

LEP:… many
hours…

- …

- The …

- The …olar-

Plan…

- Depolarization is worst at RESONANCES:

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

Begin NOW with intense careful study based on experience to investigate tricks.

At high energy the synchrotron sideband resonances take control:

- Need very good alignment – better than at LEP!
  Strength scale: $\epsilon \sim (\frac{a\gamma\ \sigma_\delta}{Q_s})^2$
- Siberian Snakes to suppress the effect of energy spread and synchrotron motion on spin motion?
- Overall, roughly at each energy:
  $\tau_{dep} \propto$ (a polynomial in γ) $\times \tau_{st}$
  These are essential in proton rings to suppress depolarizing resonances during acceleration (e.g., RHIC).
- For longitudinal polarization the polarization vector must be rotated into the longitudinal direction before the IP!! and back to the vertical afterwards ===> spin rotators.
- Depolarizing can be strongly enhanced by misalignments, regions where the polarization vector is in the horizontal plane (spin rotators etc, etc.....

What's been achieved

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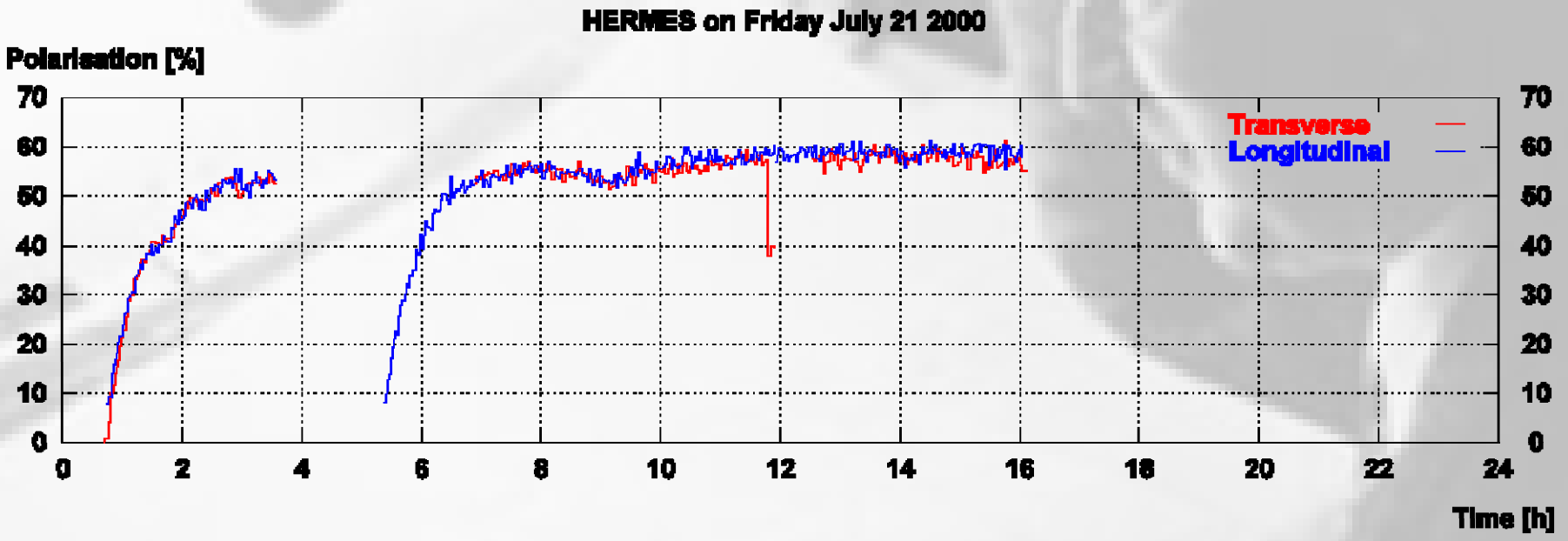
- Sokolov-Ternov + spin-rotators @ HERA



What's been achieved

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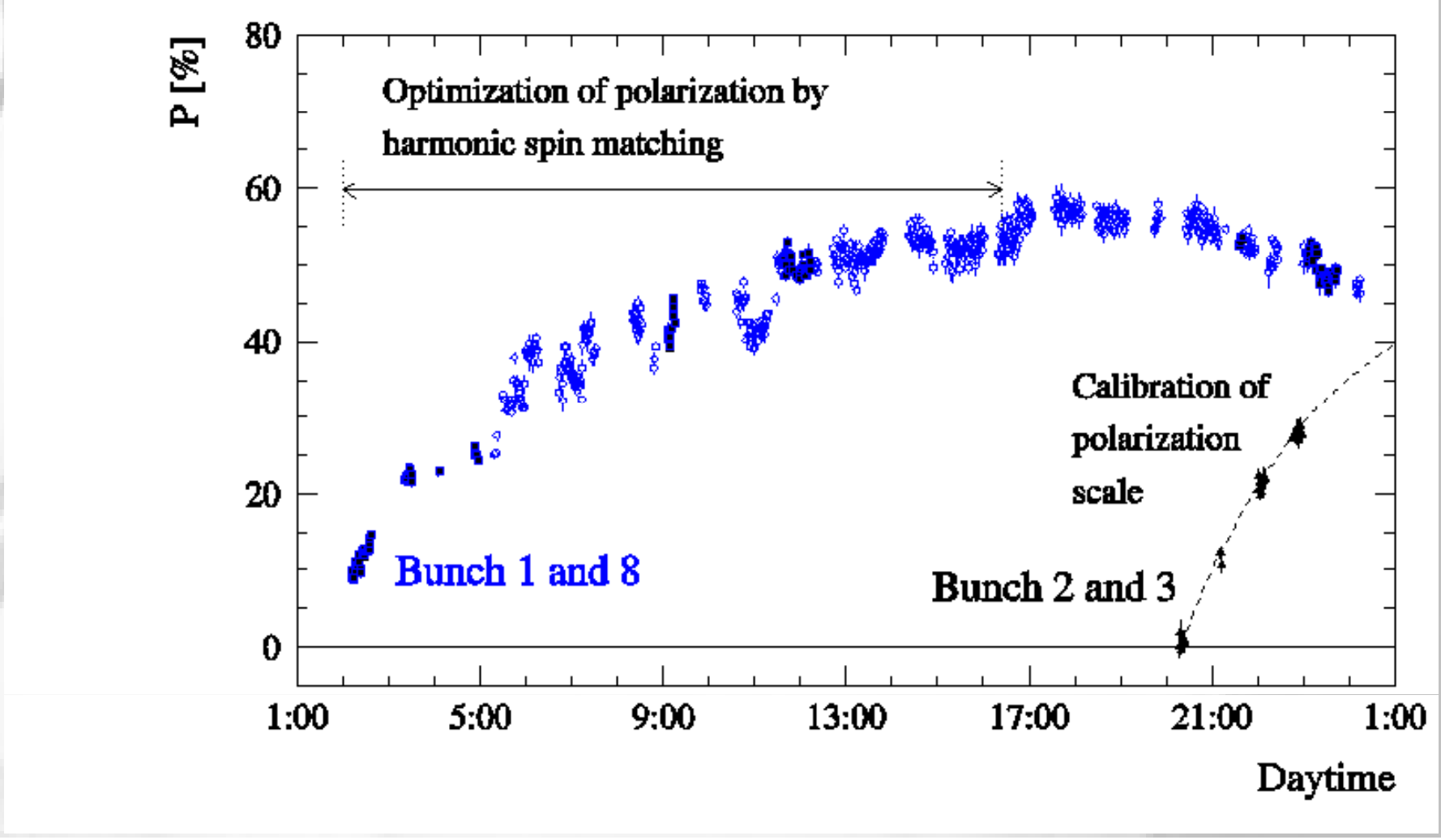
- Sokolov-Ternov @ $LEP_{70\ GeV}$



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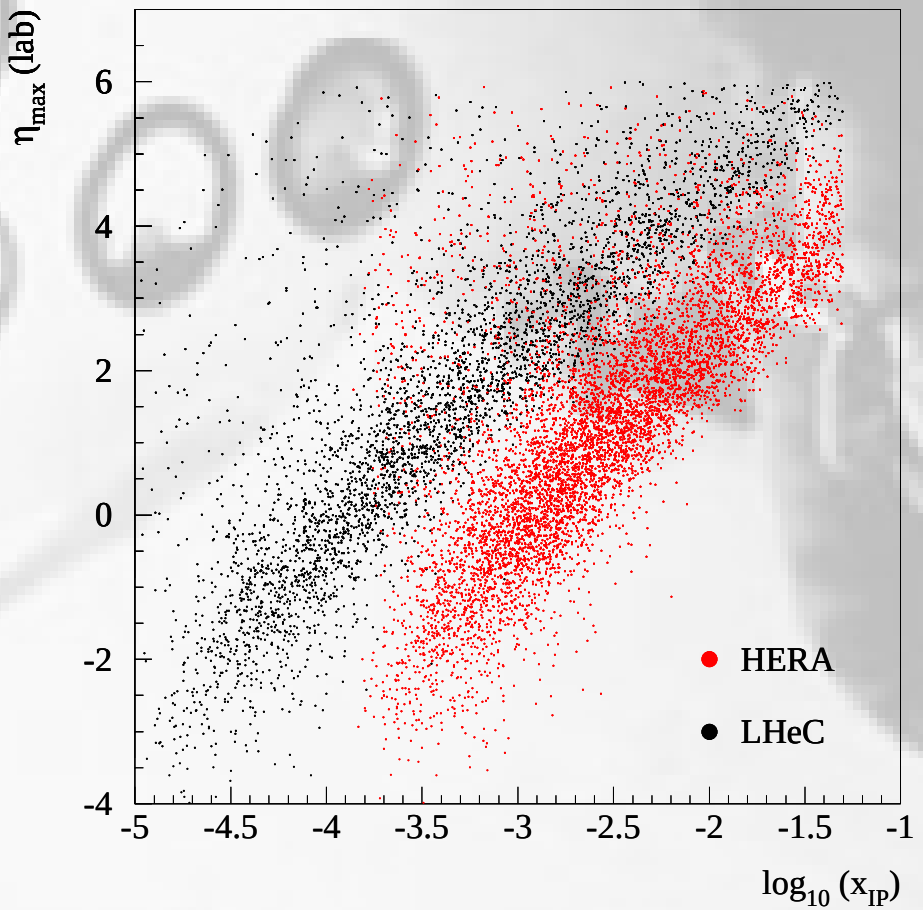

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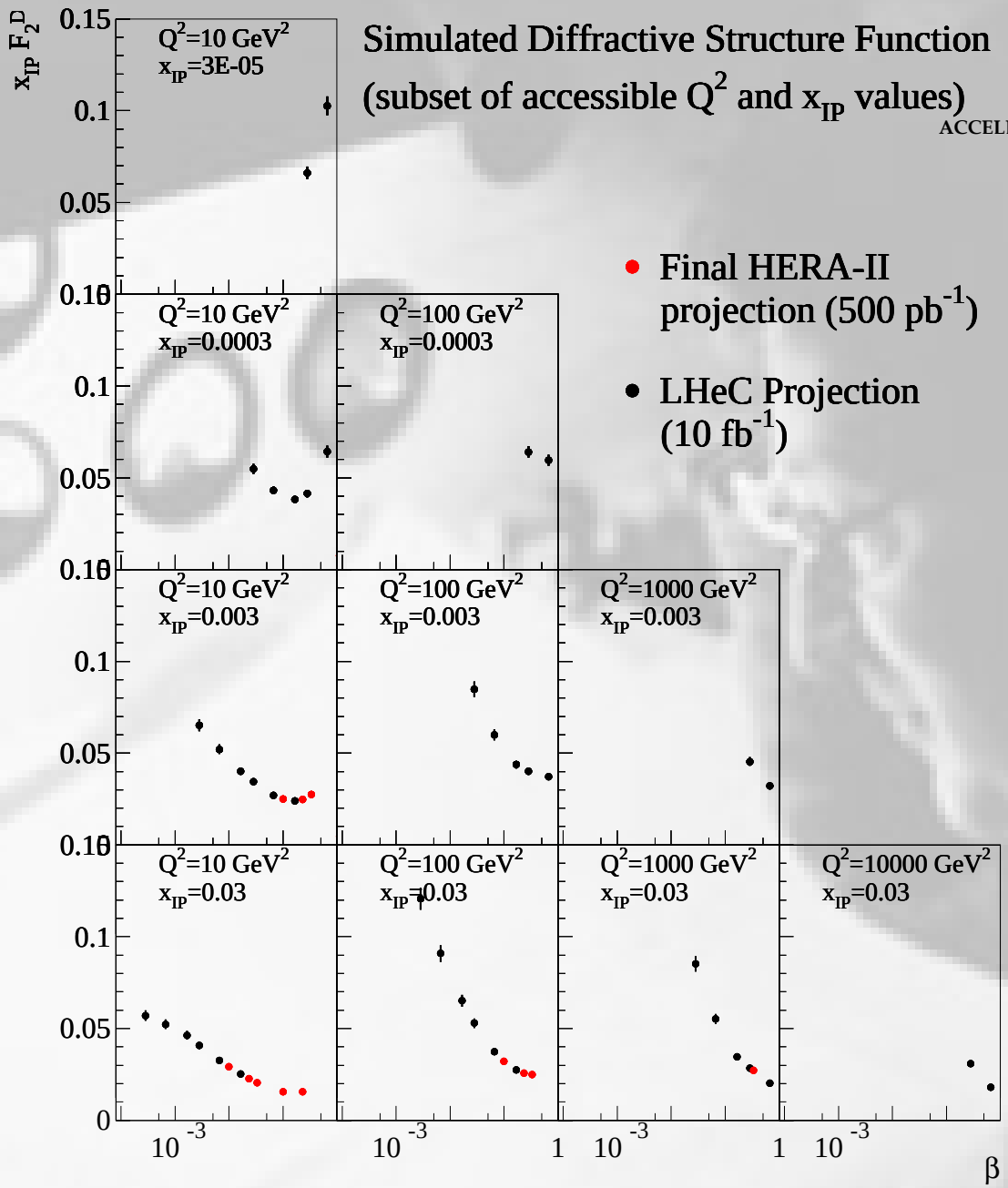
Simulated Diffractive Structure Function (subset of accessible Q^2 and x_{IP} values)



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