Physics Opportunities at the LHeC

Emmanuelle Perez (CERN)

LHeC: A Large Hadron electron Collider at the LHC
        5-140 GeV e± on 1-7 TeV p,A

Possible "upgrade" of the LHC: add-on of an electron beam to study:

Deep-inelastic scattering ep and eA at
- unprecedented energy
- with an integrated luminosity of O(10 fb^{-1})

http://www.lhec.org.uk

LHeC context

The LHeC is not the first proposal for higher energy DIS, but it is the first with the potential for significantly higher luminosity than HERA ...

Lepton-Proton Scattering Facilities

DESY 06-006
Cockcroft-06-05

Deep Inelastic Electron-Nucleon Scattering
at the LHC*

J. B. Dainton[1], M. Klein[2], P. Newman[3], E. Perez[4], F. Willeke[2]

[1] Cockcroft Institute of Accelerator Science and Technology,
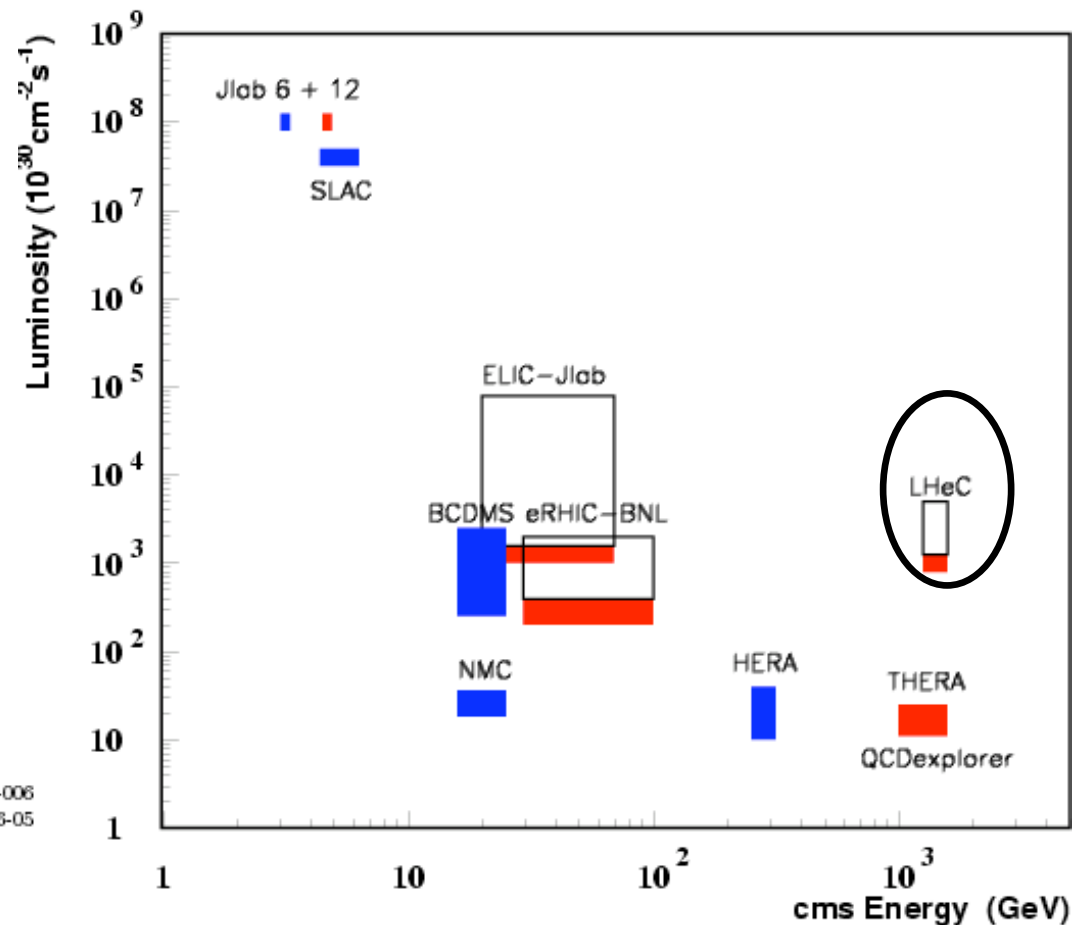Daresbury International Science Park, UK
[2] DESY, Hamburg and Zeuthen, Germany
[3] School of Physics and Astronomy, University of Birmingham, UK
[4] CE Saclay, DSM/DAPNIA/Spp, Gif-sur-Yvette, France

... achievable with a new electron accelerator at the LHC ...

[JINST 1 (2006) P10001]

… after further studies, discussions with CERN accelerator experts and a presentation to plenary ECFA :

Summary and Proposal as endorsed by ECFA (30.11.2007)

As an add-on to the LHC, the LHeC delivers in excess of 1 TeV to the electron-quark cms system. It accesses high parton densities 'beyond' what is expected to be the unitarity limit. Its physics is thus fundamental and deserves to be further worked out, also with respect to the findings at the LHC and the final results of the Tevatron and of HERA.

First considerations of a ring-ring and a linac-ring accelerator layout lead to an unprecedented combination of energy and luminosity in lepton-hadron physics, exploiting the latest developments in accelerator and detector technology.

It is thus proposed to hold two workshops (2008 and 2009), under the auspices of ECFA and CERN, with the goal of having a Conceptual Design Report on the accelerator, the experiment and the physics. A Technical Design report will then follow if appropriate.

… a working group structure agreed and convenors invited …

First ECFA-CERN Workshop on the LHeC Divonne 1.-3.9.08

Accelerator Design [RR and LR]
Oliver Bruening (CERN),
John Dainton (CI/Liverpool)
Interaction Region and Fwd/Bwd
Bernhard Holzer (DESY),
Uwe Schneeekloth (DESY),
Pierre van Mechelen (Antwerpen)
Detector Design
Peter Kostka (DESY),
Rainer Wallny (UCLA),
Alessandro Polini (Bologna)
New Physics at Large Scales
Emmanuelle Perez (CERN),
Georg Weiglein (Durham)
Precision QCD and Electroweak
Olaf Behnke (DESY),
Paolo Gambino (Torino),
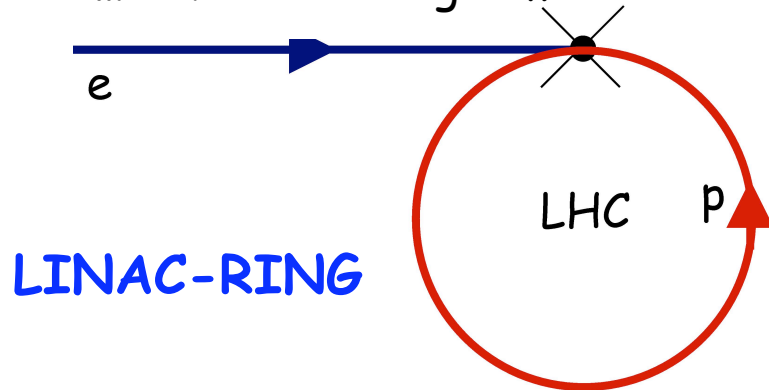Thomas Gehrmann (Zuerich)
Physics at High Parton Densities
Nestor Armesto (CERN),
Brian Cole (Columbia),
Paul Newman (B'ham),
Anna Stasto (MSU)

… first workshop took place in September 2008, Divonne. Eclectic mix of accelerator experts, experimentalists and theorists (~ 90 participants).

How could ep be done with LHC

... whilst allowing simultaneous ep and pp running ...

LINAC-RING

• Previously considered as `QCD explorer' (also THERA)

• Reconsideration (Chattopadhyay, Zimmermann et al.) recently

• Main advantages: low interference with LHC, $E_e \rightarrow$ 140 GeV, LC relation

See next talk by Max Klein !

RING-RING
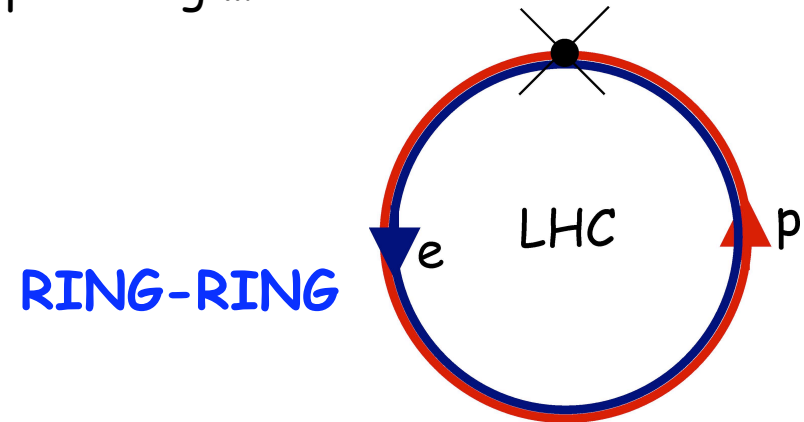
• First considered (as LEPxLHC) in 1984 ECFA workshop

• Recent detailed re-evaluation with new e ring (Willeke)

• Main advantage: high peak lumi obtainable.

• synchrotron limits e beam energy (70GeV)

Kinematics & Motivation (70 GeV x 7 TeV ep)
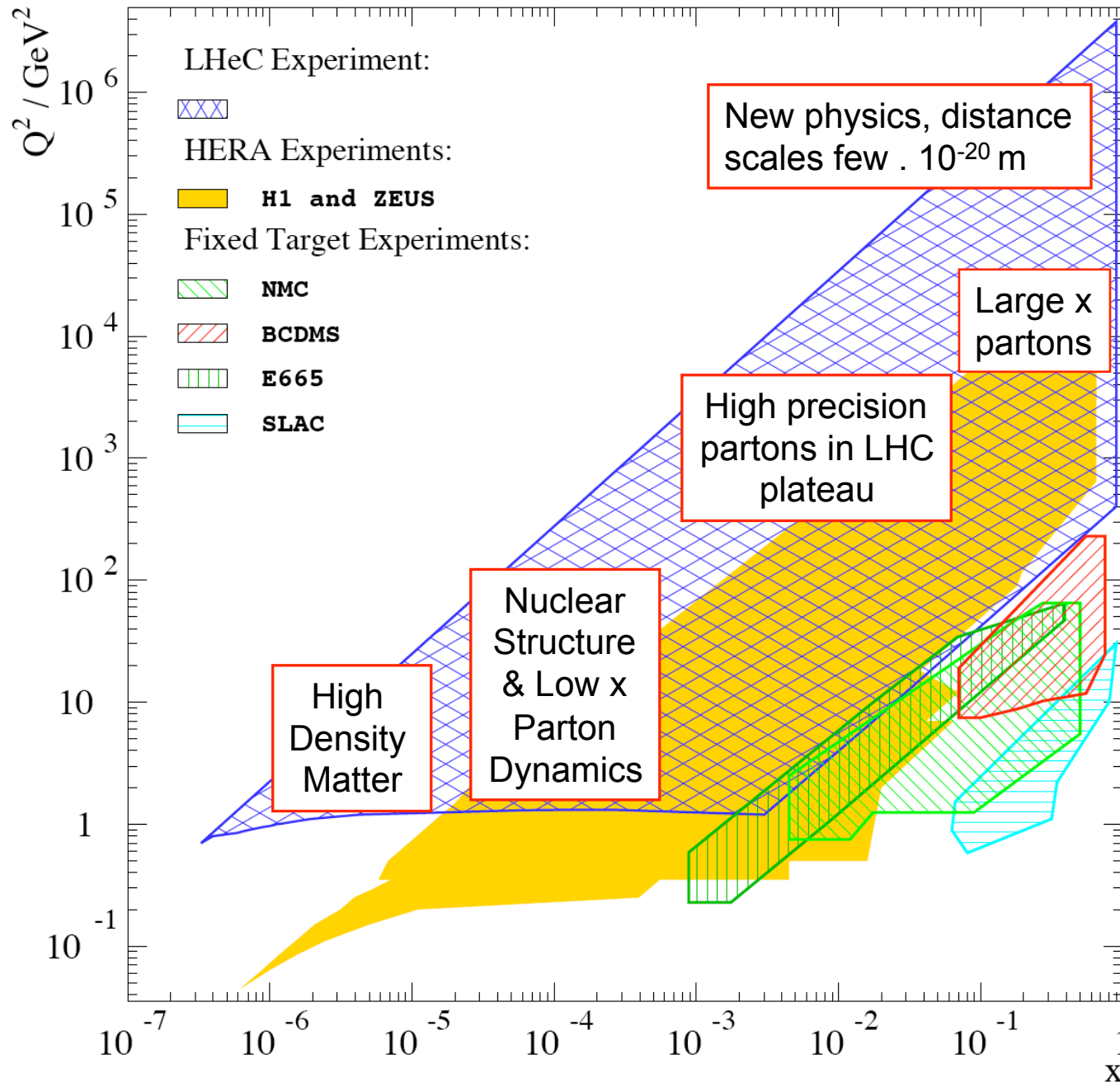
$\sqrt{s}$=1.4V Te

- High mass (M_{eq}, Q^2) frontier

- EW & Higgs

- Q^2 lever-arm at moderate & high x → PDFs

- Low x frontier [x below 10^{-6} at Q^2 ~ 1 GeV²] → novel QCD ...

TH Institute, Feb 09

New Physics at the LHeC

Wide range of basic physics

- **Lepto-Quark Production and Decay** (s and t-channel effects)

Maximum $W < 1.4$ TeV
for $E_e = 140$ GeV, $E_p = 7$ TeV

- **Squarks and Gluinos**

- **ZZ, WZ, WW elastic and inelastic collisions**

- **Technicolor**

- **Novel Higgs Production Mechanisms**

- **Composite electrons**

- **Lepton-Flavor Violation**

- **QCD at High Density in ep and eA collisions**

- **Odderon**

Broad physics goals (to be discussed at the Workshop)

- Proton structure and QCD physics in the domain of x and Q² of LHC experiments

- Small-x physics in eP and eA collisions

- Probing the e±-quark system at ~TeV energy
  eg leptoquarks, excited e*'s, mirror e, SUSY with no R-parity......

- Searching for new EW currents
  eg RH W's, effective eeqq contact interactions...

G. Altarelli

J.Bartels: Theory on low x

New Physics at High Scales

In general, unlikely that a discovery at LHeC is invisible at the LHC. But:

- Following a discovery at the LHC, LHeC may provide information about the underlying theory, examples :

    - electron-quark resonances
    - new Z' boson : couplings → underlying model
    - structure of a eeqq contact interaction
    - study of new leptons (sleptons, excited leptons)

- A better knowledge of the proton structure may be needed

    - to better study new bosons
    - to establish unambiguously new physics effects

    (Remember excess of high ET jets at CDF in 1995)

Electron-quark resonances

- "Leptoquarks" (LQs) appear in many extensions of SM
- Scalar or Vector color triplet bosons
- Carry both L and B, frac. em. Charge
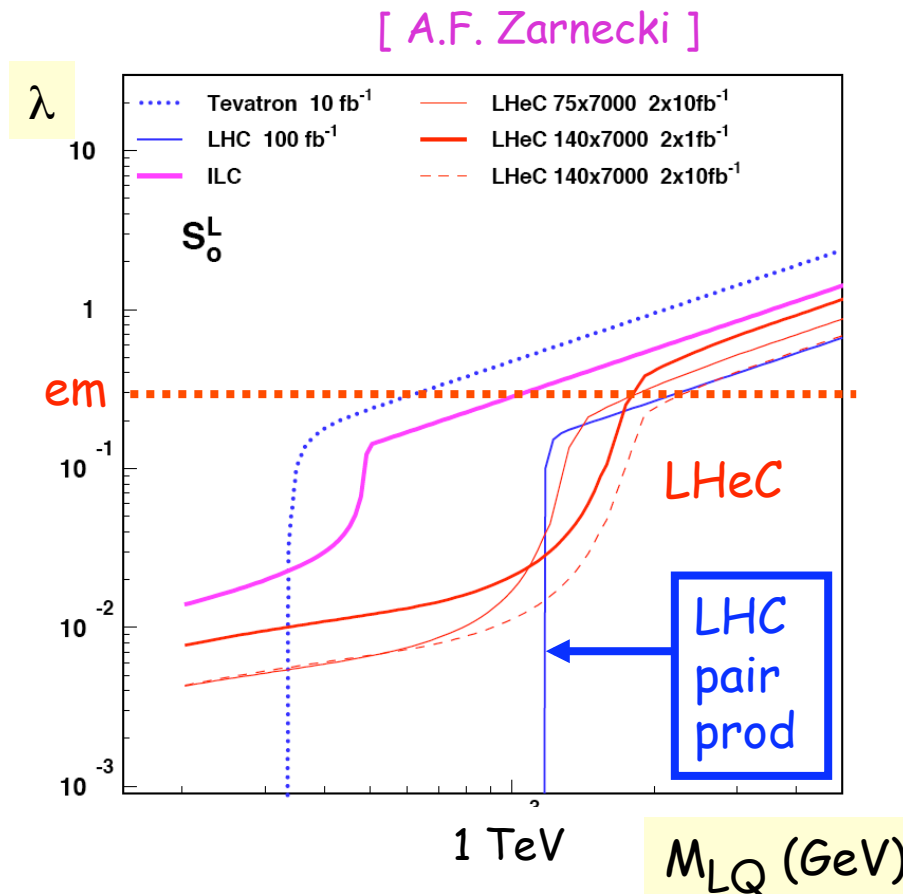- Also squarks in R-parity violating SUSY

pp

ep
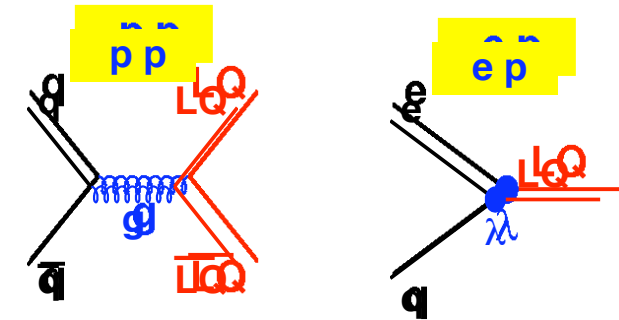
λ (unknown) coupling l-q-LQ

[A.F. Zarnecki]

LQ decays into (lq) or (νq) :

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

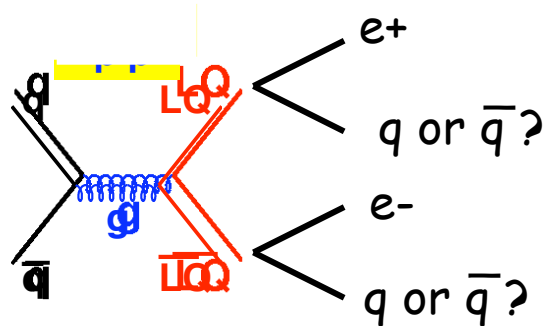LHC could discover eq resonances with a mass of up to 1.5 – 2 TeV via pair production.

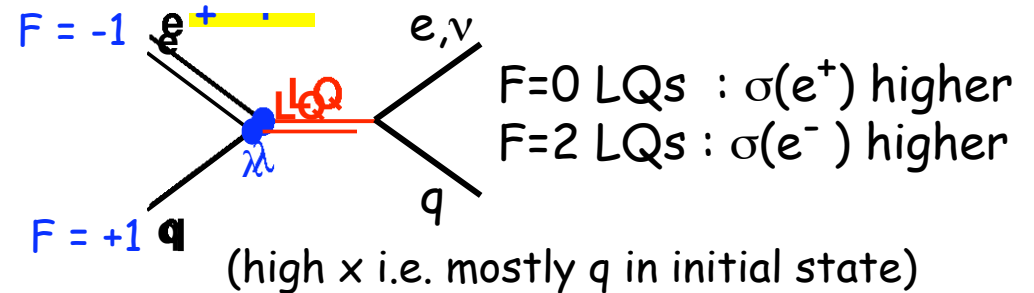Quantum numbers ? Might be difficult to determine in this mode.

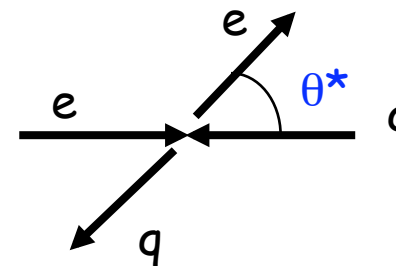# Determination of LQ properties

pp, pair production	ep, resonant production

• Fermion number

e+

q or $\bar{q}$?

e-

q or $\bar{q}$?

F = -1

F = +1

e, ν

q

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

(high x i.e. mostly q in initial state)

• Scalar or Vector

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

e

e

θ^*

q

q

$\cos(\theta^*)$
distribution
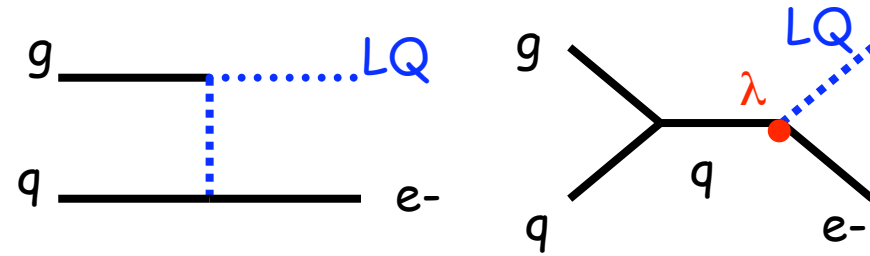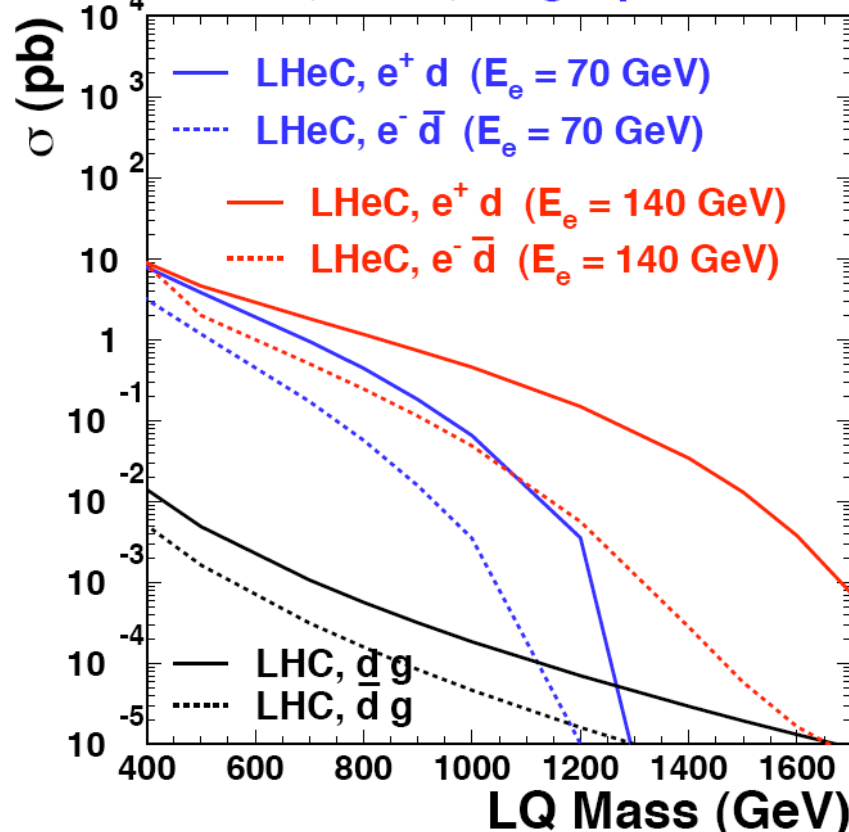gives the
LQ spin.

• Chiral couplings

?

Play with lepton beam
polarisation.

Single LQ production at LHC

Single LQ production is better suited to study "LQ spectroscopy".

Also possible in pp :

($\gamma \to ee$ followed by $eq \to LQ$ not considered yet.
Work in progress.)

Scalar LQ, λ=0.1, single production

Legend:
- LHeC, $e^+ d$ (E_e = 70 GeV)
- LHeC, $e^- \bar{d}$ (E_e = 70 GeV)
- LHeC, $e^+ d$ (E_e = 140 GeV)
- LHeC, $e^- \bar{d}$ (E_e = 140 GeV)
- LHC, $\bar{d}$ g
- LHC, $\bar{d}$ g

Axes: σ (pb) vs LQ Mass (GeV)

But with a much smaller x-section than at LHeC.
And large background from Z + 1 jet.

Not much considered yet by LHC experimental groups.

Pheno. study focusing on the extension of the discovery potential:
A.S. Belyaev et al, JHEP 0509 (2005) 005

## Determination of LQ properties in single production: e.g. Fermion Number

In pp: look at signal separately when resonance is formed by (e^+ + jet) and (e^- + jet) :

$\sigma(e^+_{out}) > \sigma(e^-_{out})$
for F=0
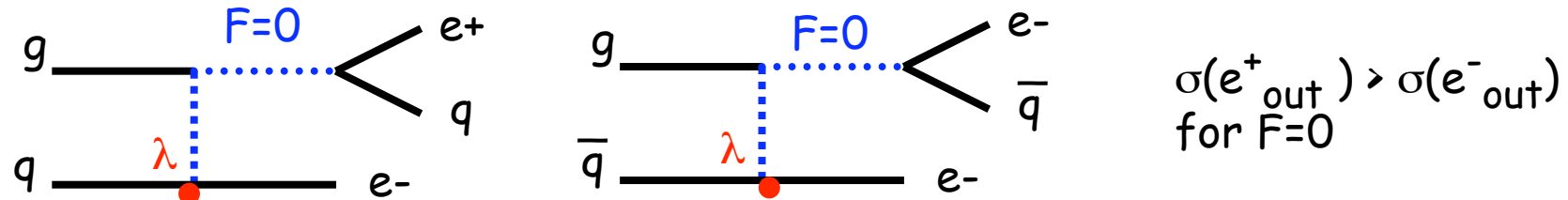
Sign of the asymmetry gives F, but could be statistically limited at LHC. (*)

Easier in ep ! Just look at the signal with incident e+ and incident e-, build the asymmetry between $\sigma(e^+_{in})$ and $\sigma(e^-_{in})$.

If LHC observes a LQ-like resonance, M < 1 - 1.5 TeV, with indications (single prod) that λ not too small, LHeC would solve the possibly remaining ambiguities.
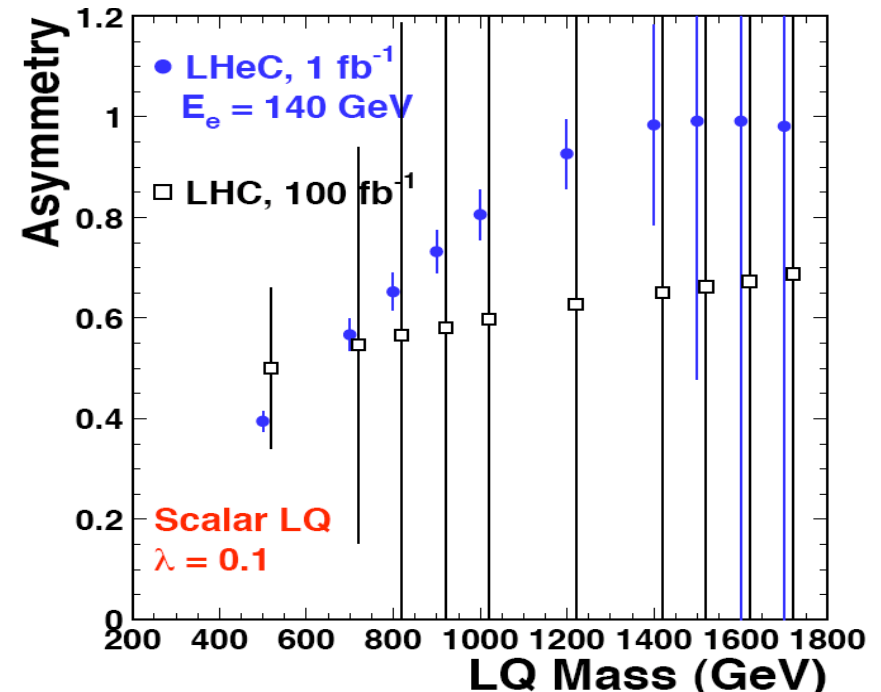

(*) First rough study done for the 2006 paper. Need to check / refine with a full analysis of signal and backgrounds.

Other examples of new physics in eeqq amplitudes

• **new Z' boson**: pp measurements alone do not allow for a model-independent determination of all of the Z' couplings ($g_{L,R}^e$, $g_{L,R}^{u,d}$)

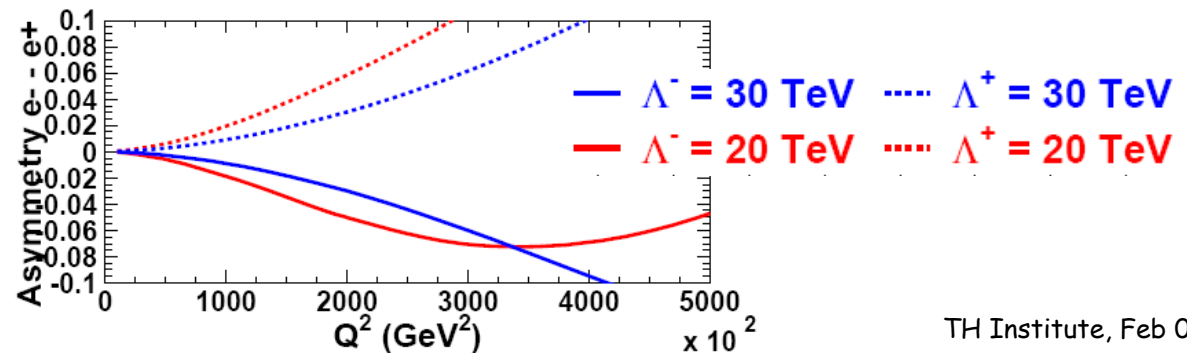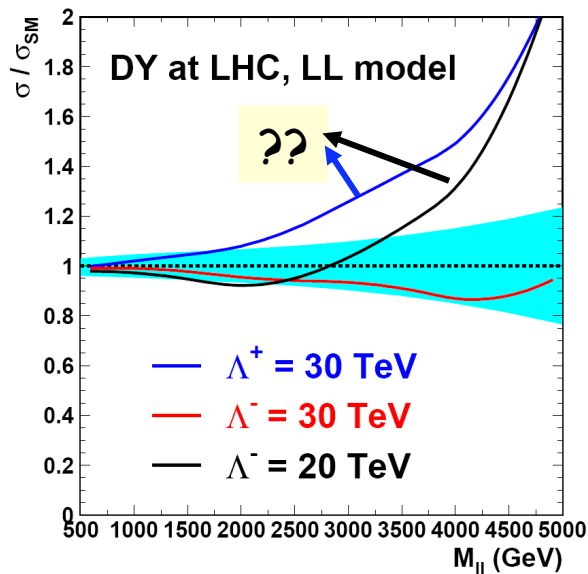LHeC data may bring the necessary complementary information, before a LC.

T. Rizzo, PRD77 (2008) 115016

L/R asym. for e−

SSM

SM

ALRM

√s = 1.5 TeV, M(Z') = 1.2 TeV
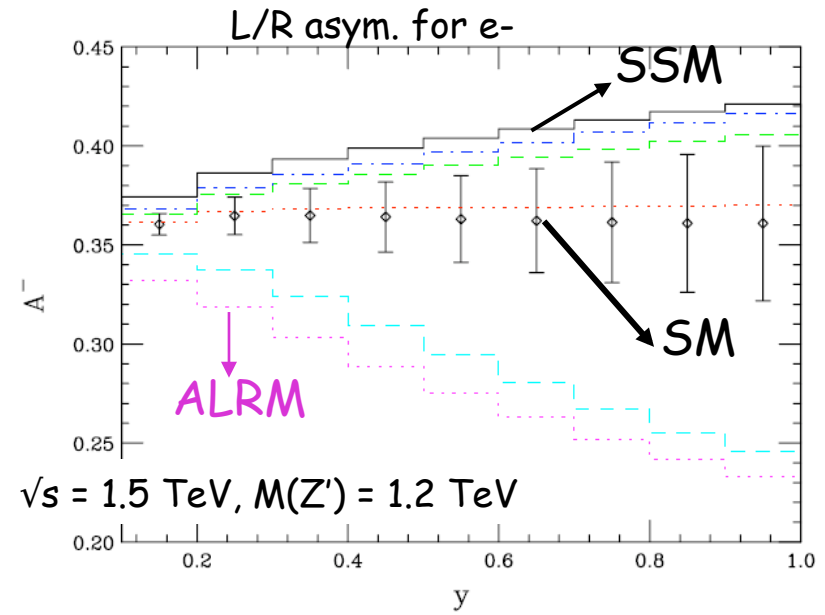
• **Contact Interactions:**

$$\mathcal{L}_{CI} = \sum_{i,j=L,R} \varepsilon_{ij}^{eq} \frac{4\pi}{\Lambda^2} (\bar{e}_i \gamma^\mu e_i)(\bar{q}_j \gamma_\mu q_j)$$

At LHeC, sign of the interference can be determined by looking at the asym. between σ/SM in e⁻ and e⁺.

DY at LHC, LL model

??

Λ^+ = 30 TeV
Λ^- = 30 TeV
Λ^- = 20 TeV

— Λ^- = 30 TeV ····· Λ^+ = 30 TeV
— Λ^- = 20 TeV ····· Λ^+ = 20 TeV

Supersymmetry (R-parity conserved)

Pair production via t-channel exchange of a neutralino.
Cross-section sizeable when ΣM below ~ 1 TeV.
Such scenarios are "reasonable".
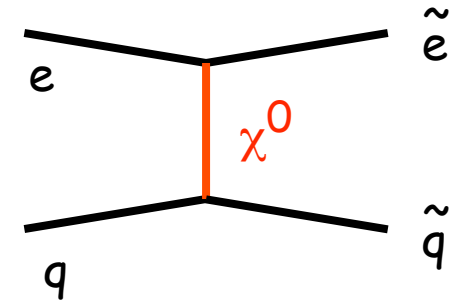
E.g. global SUSY fit to EW & B-physics observables
plus cosmological constraints (O. Buchmueller et al, 2008),
within two SUSY models (CMSSM & NUHM) leads to masses
of ~ (700, 150) GeV.

SUSY cross-section at LHeC:
about 15 fb for these scenarios.

Added value w.r.t. LHC to be studied :

- could extend a bit over the
  LHC slepton sensitivity
- precise mass measurements ?
    → study mass reco. at LHeC,
  using variables worked out for
  LHC (MT, MT2, etc...).
- relevant information on χ^0 sector ?
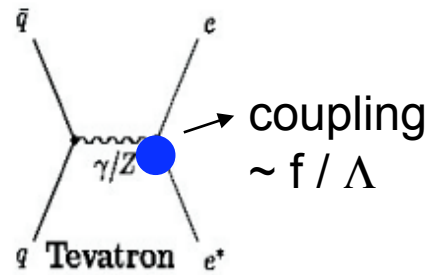   e.g. from charge / polar. asymmetries

E. Perez

$\tan \beta = 10$, $M_2 = 380$ GeV, $\mu = -500$ GeV
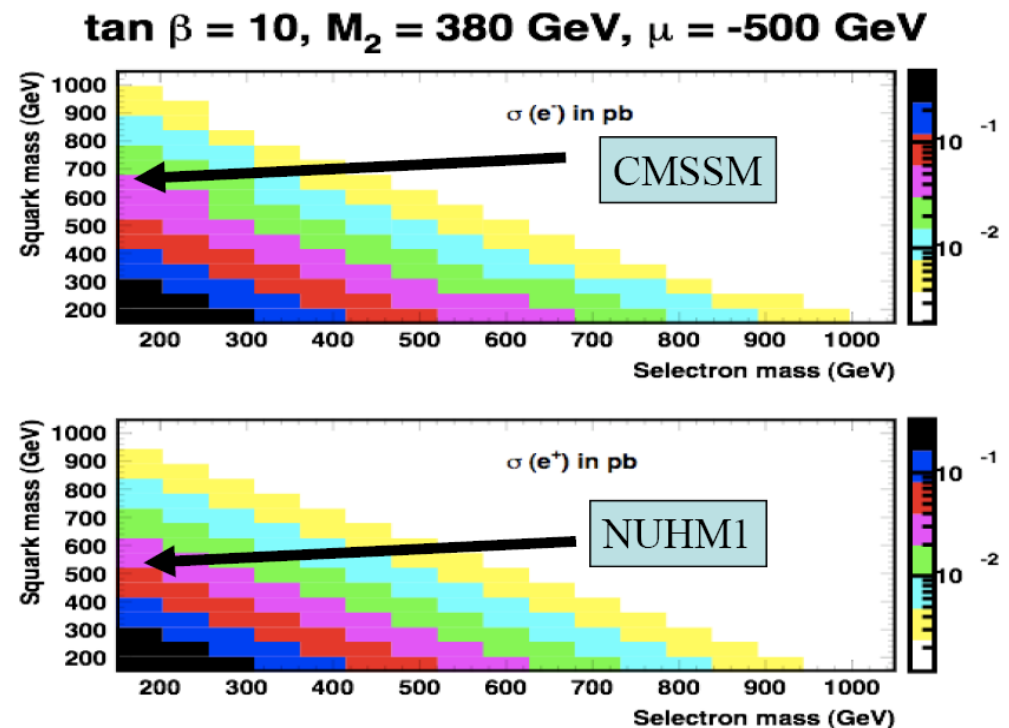
Electron-boson resonances: excited electrons
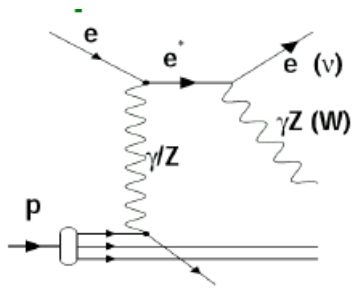
[Hagiwara et al. ZPC 29(1985)115]

[Boudjema et al. ZPC 57(1990)425]

coupling $\sim f / \Lambda$
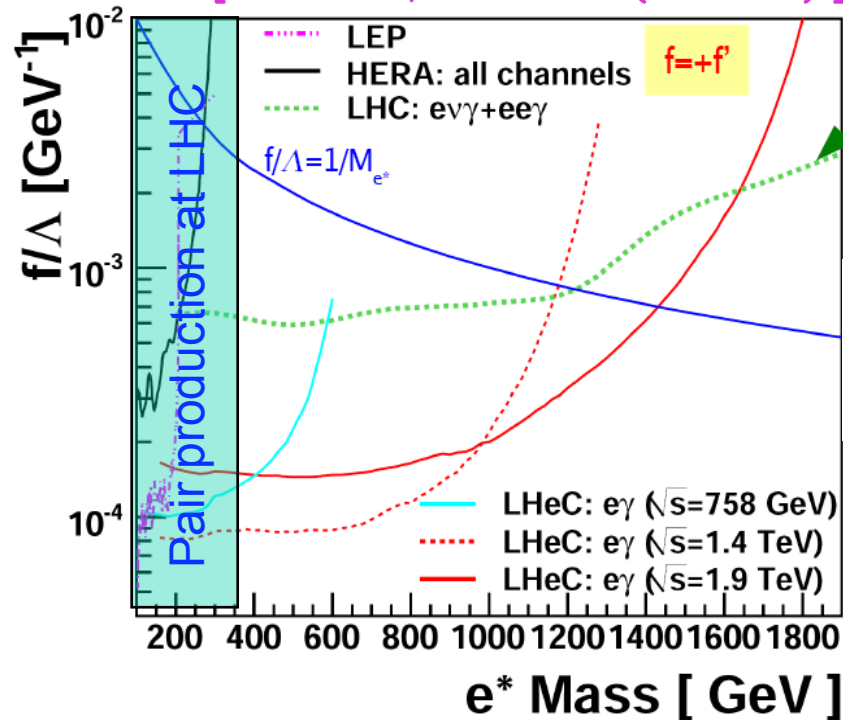
Single e* production x-section
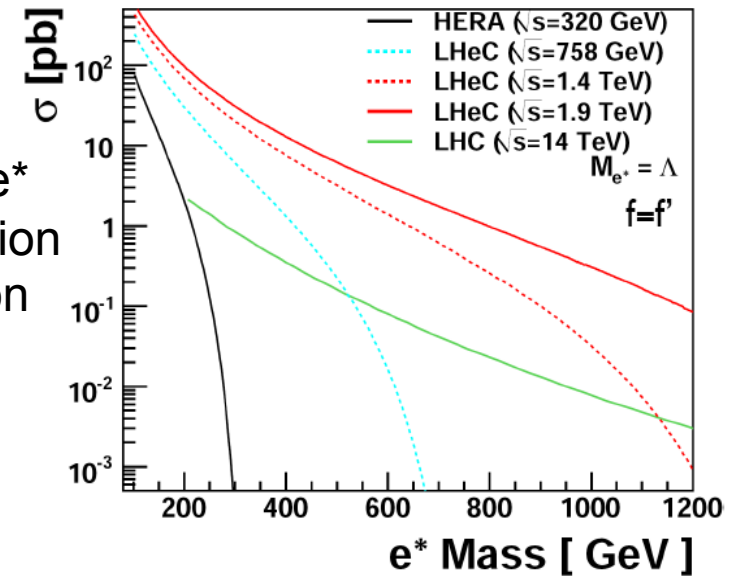
[N. Trinh, E. Sauvan (Divonne)]

[Phys. Rev D 65 (2002) 075003]

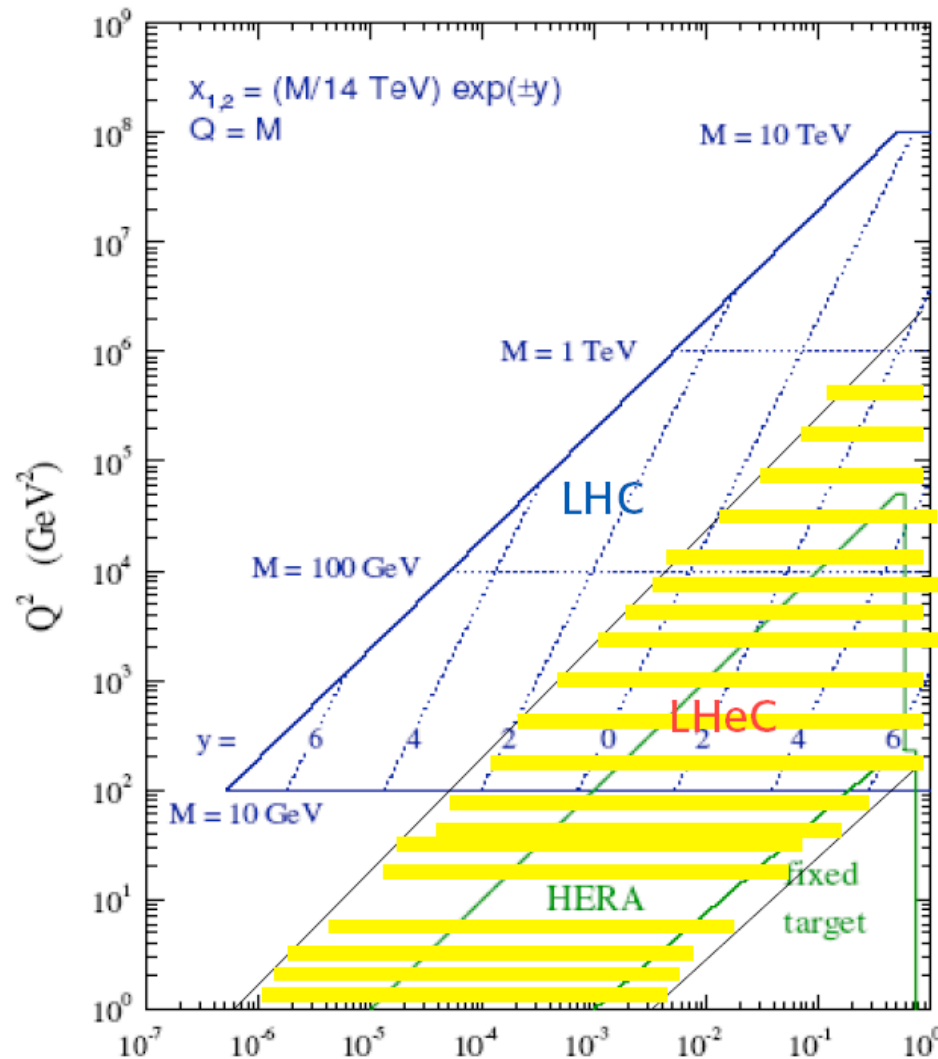LHeC prelim. analysis, looking at e* → eγ

- If LHC discovers (pair prod) an e*: LHeC would be sensitive to much smaller f/Λ couplings.
  Possible determination of QNs [cf LQs]

- Discovery potential for higher masses

LHeC sensitivity,
 with L=10 fb⁻¹ for Ee=70/20 GeV
with L=1 fb⁻¹ for Ee=140 GeV

TH Institute, Feb 09

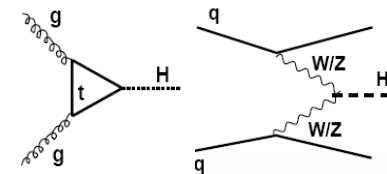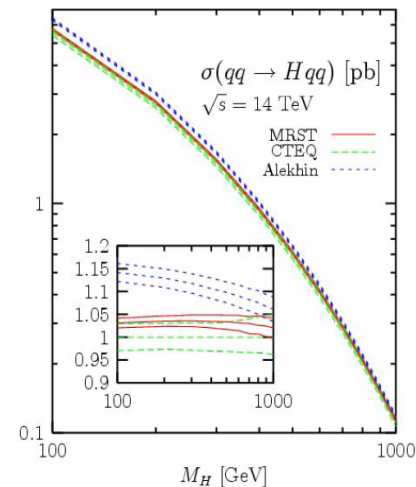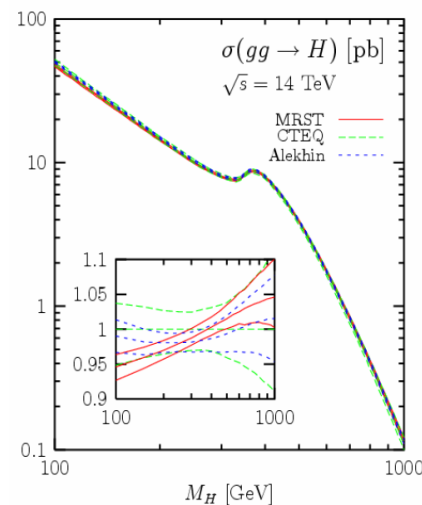# Precision physics at LHeC: better pdfs for LHC ?

- Larger overlap than HERA with the LHC domain.

- large luminosities would bring in constraints in domains which are currently poorly known

To which extent do we need a better knowledge of p structure for the interpretation of LHC data ?

Pdfs for LHC processes : do we know them "well enough" ?

- In general not too bad.

  e.g. Higgs prod.
  at the LHC:
  Pdf uncertainty
  ~ 10%.

$\sigma(gg \to H)$ [pb]
$\sqrt{s} = 14$ TeV
MRST
CTEQ
Alekhin

$\sigma(qq \to Hqq)$ [pb]
$\sqrt{s} = 14$ TeV
MRST
CTEQ
Alekhin

A. Djouadi & S. Ferrag,
PLB 586 (2004) 345.
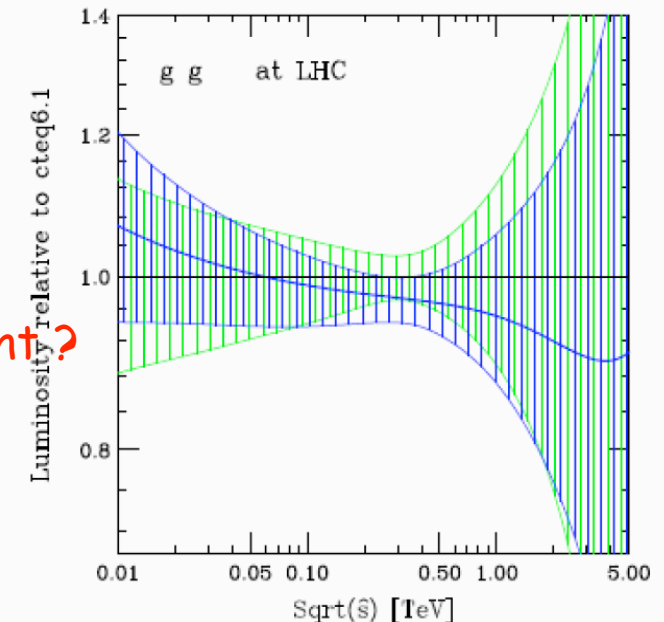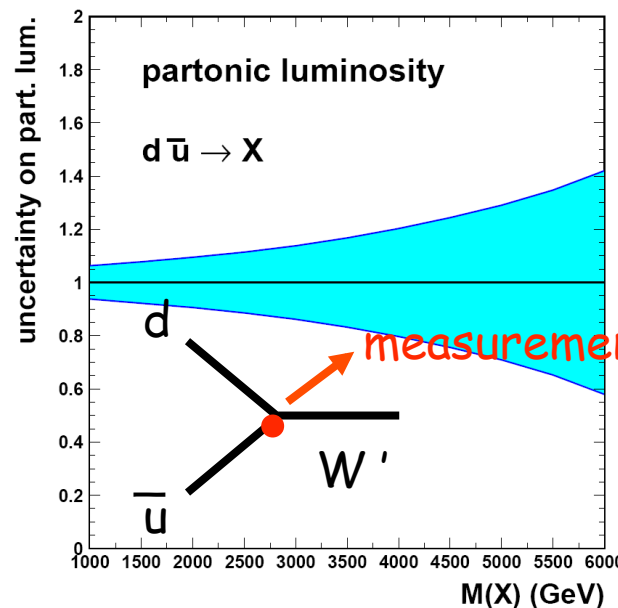
- However, limited knowledge at low x (g) and at large x (g & quarks)

Relative uncertainties
on partonic
luminosities vs.
M = √ŝ at the LHC.

$$\mathcal{L}_{ab} = C_{ab} \int_{\tau}^{1} \frac{dx_a}{x_a} f_a(x_a) f_b(\tau/x_a)$$

$$\sigma = \sum_{a,b} \mathcal{L}_{ab} \, \hat{\sigma}(ab \to M; \hat{s} = \tau s).$$

e.g. 40% for a 6 TeV W'
(within LHC reach if g_{SM})

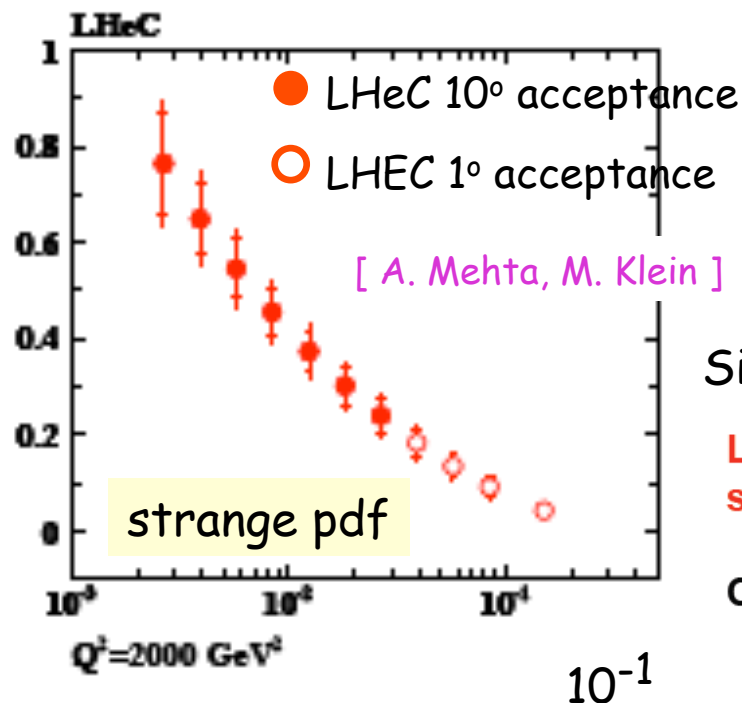partonic luminosity

d ū → X

measurement?

W'

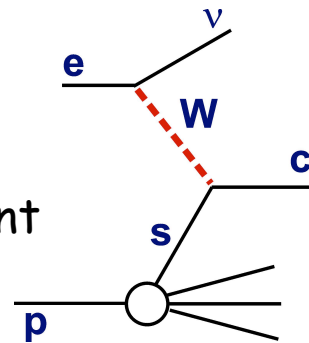g g   at LHC

Improved determination of pdfs from LHeC

NC and CC rates allow a much improved determination of pdfs over the whole domain in x.

Flavour decomposition: e.g. from High precision c, b measurements. Systematics at 10% level
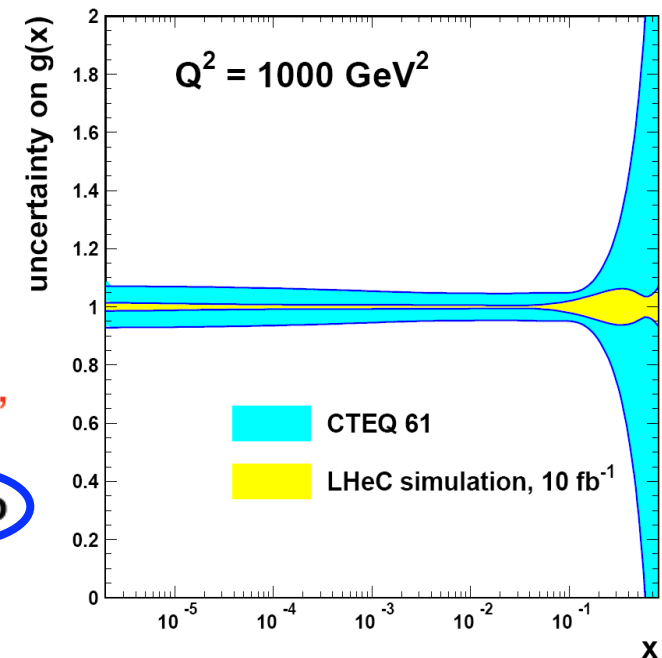
→s (& sbar) from charged current

ν

e

W

c

s

p

[T. Kluge, M. Klein, EP]

uncertainty on d(x)

Q^2 = 10000 GeV^2

CTEQ 61

LHeC simulation, 10 fb^{-1}

x

LHeC

● LHeC 10° acceptance

○ LHEC 1° acceptance

[A. Mehta, M. Klein]

strange pdf

Q^2=2000 GeV^4

10^{-1}

Similarly Wb → t ?

LHeC is a single top and single tbar quark `factory'

CC t cross section O(5)pb

uncertainty on g(x)

Q^2 = 1000 GeV^2

CTEQ 61

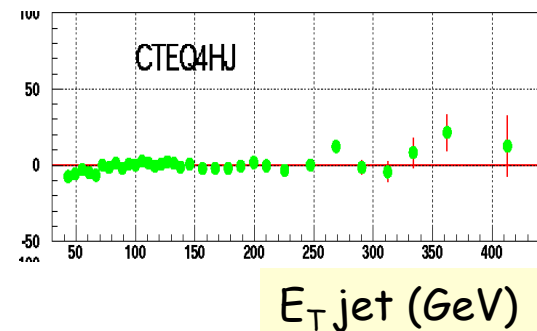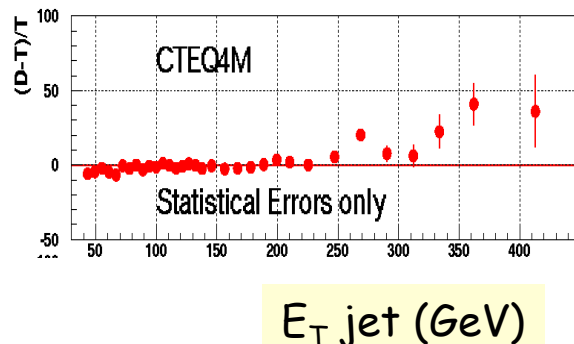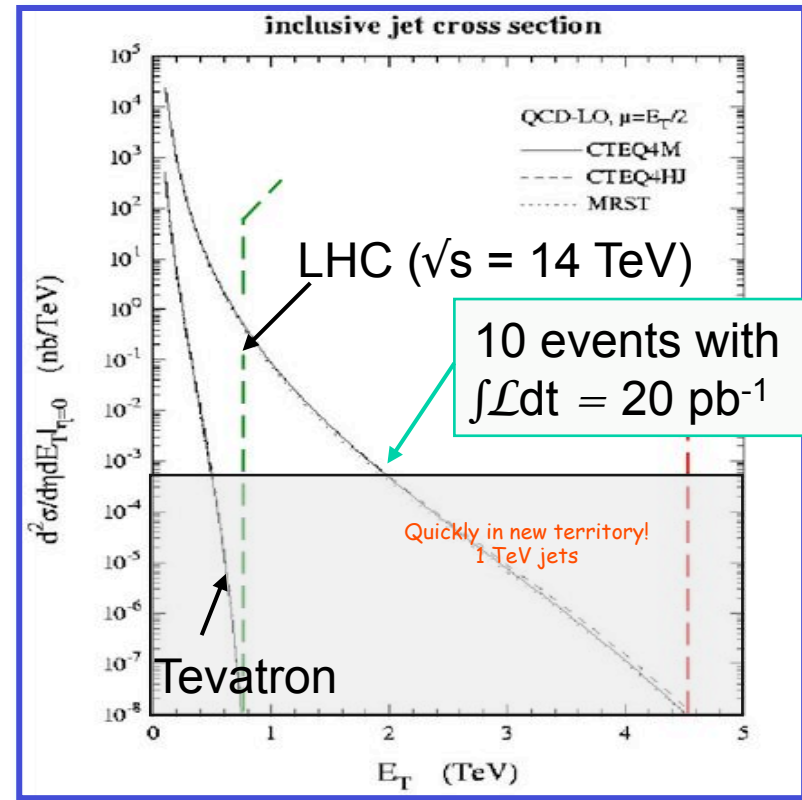LHeC simulation, 10 fb^{-1}

x

E. Perez

18
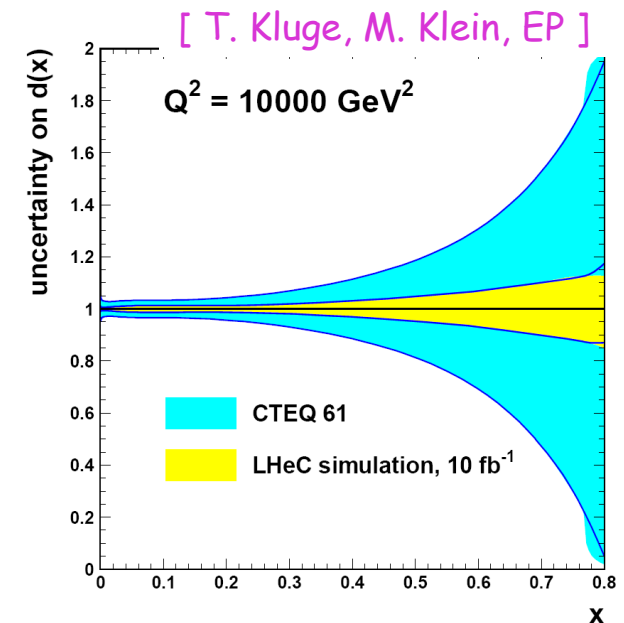
Could pdf effects "fake" new physics at the LHC ?

- One possible signal of compositeness is the production of high p_T jets.

  Quickly a new territory with TeV jets !

- At one point there was a disagreement between theory and experiment at the Tevatron.

- Not new physics but too little high-x gluon in the PDFs.

inclusive jet cross section

QCD-LO, $\mu = E_T/2$
— CTEQ4M
--- CTEQ4HJ
····· MRST

LHC ($\sqrt{s}$ = 14 TeV)

10 events with $\int \mathcal{L} dt$ = 20 pb^{-1}

Quickly in new territory!
1 TeV jets

Tevatron

$\frac{d^2\sigma/d\eta dE_T|_{\eta=0}}{}$ (nb/TeV)

E_T (TeV)

CTEQ4M

Statistical Errors only

(D-T)/T

E_T jet (GeV)

CTEQ4HJ

E_T jet (GeV)

CDF, 1995

High Mass Drell-Yan at the LHC

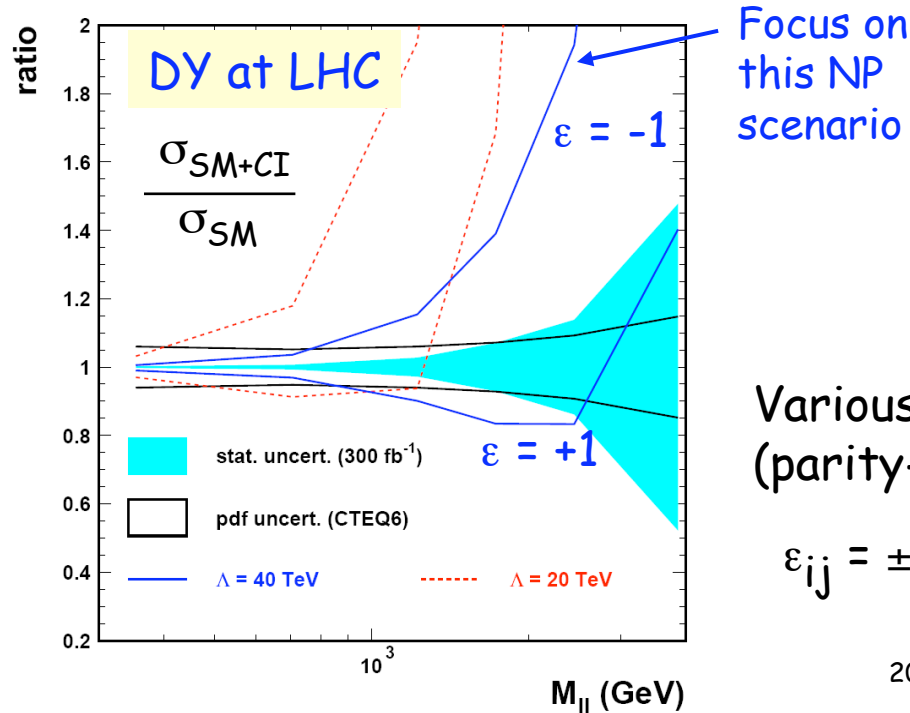Drell-Yan with M_{ll} ~ TeV involves quarks and antiquarks with x_{Bj} ~ 0.1
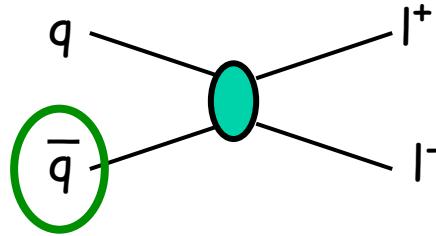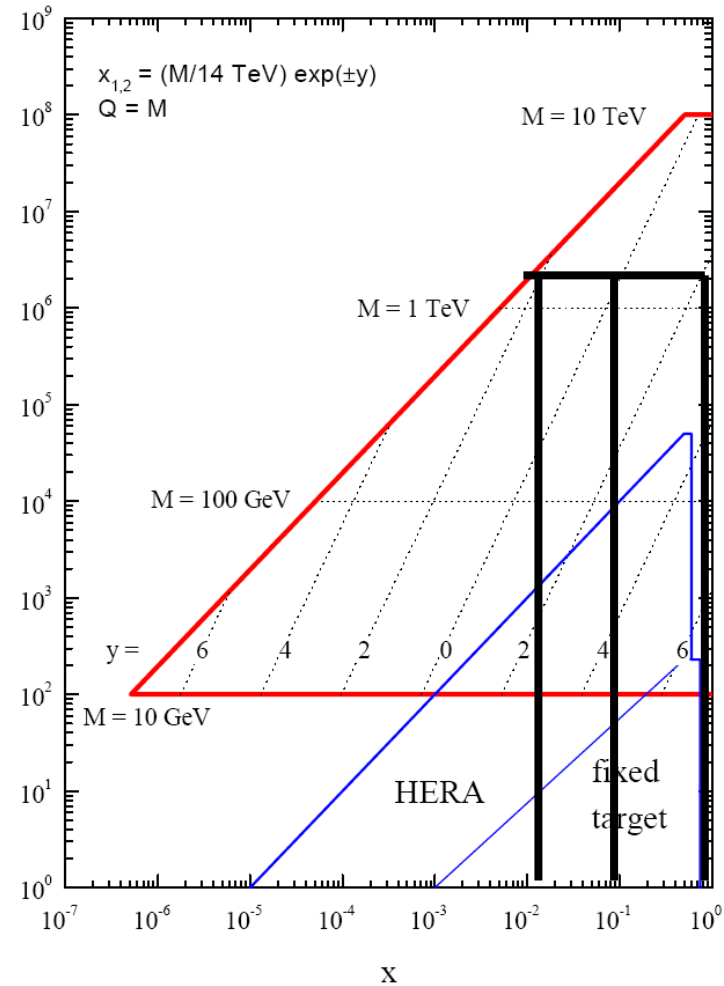
Generic approach for new physics in DY final states : contact interactions

$$\mathcal{L}_{CI} = \sum_{i,j=L,R} \varepsilon_{ij}^{eq} \frac{4\pi}{\Lambda^2} (\bar{e}_i \gamma^\mu e_i)(\bar{q}_j \gamma_\mu q_j)$$

LHC parton kinematics

$x_{1,2} = (M/14\ \text{TeV}) \exp(\pm y)$
$Q = M$

M = 10 TeV

M = 1 TeV

M = 100 GeV

M = 10 GeV

y = 6 4 2 0 2 4 6

HERA

fixed target

x

Focus on this NP scenario

DY at LHC

$\dfrac{\sigma_{SM+CI}}{\sigma_{SM}}$

$\varepsilon = -1$

$\varepsilon = +1$

ratio

stat. uncert. (300 fb⁻¹)

pdf uncert. (CTEQ6)

Λ = 40 TeV   Λ = 20 TeV

M_{ll} (GeV)

Various models, look e.g. at "VV" model (parity-conserving).

$\varepsilon_{ij} = \pm 1$ for i,j = L,R

20

VV model, Λ = 40 TeV

CTEQ4HJ

DGLAP fits :
- to HERA and BCDMS (μp and μd data) : "reference fit"
- and including in addition LHC toy-data, assuming new physics contributions to the Drell Yan.

This NP scenario looks quite different from SM, even when taking into account the stat. uncertainty of the data, and the pdf uncertainty of the SM prediction.

Λ = 40 TeV, ε = -1

- **LHC pseudo-data**
— SM fit
--- SM fit, pre-LHC
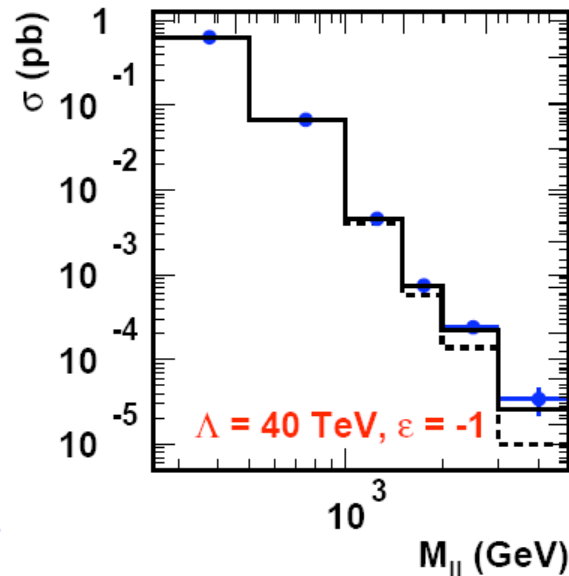
However, the effects of this scenario can easily be accommodated within DGLAP ! [in this fit]

A fit including these LHC "data" does describe well all datasets ! χ^2 / df = 0.93
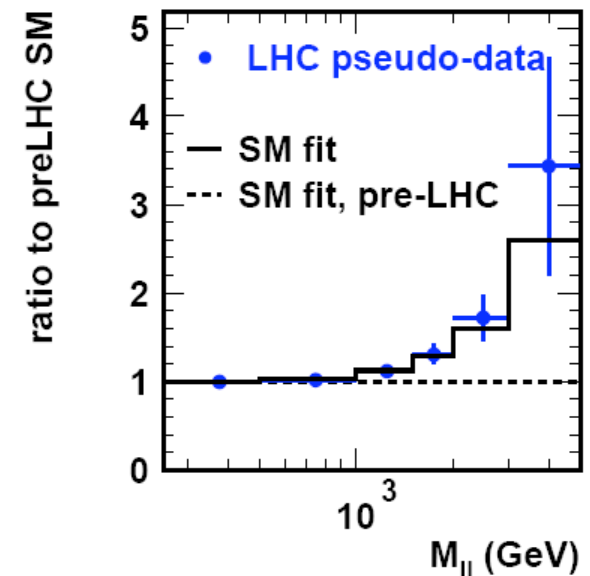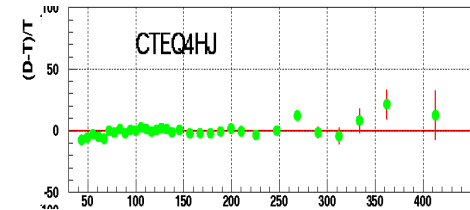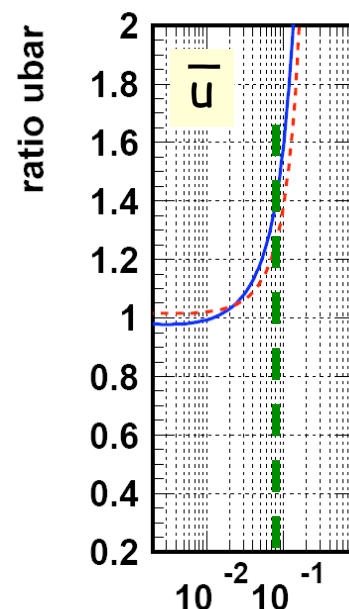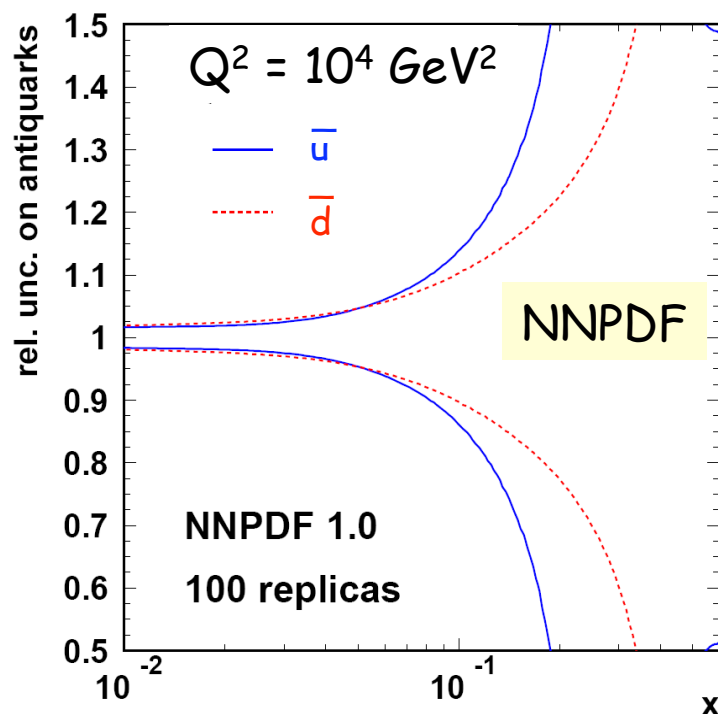
EP, LHeC workshop, September 08

(work in progress…)

The plots show ratios to the "reference" fit.

In the "region of interest", x ~ 0.1, the fit including the LHC NP-data mainly changes the antiquarks.

Reason: currently, big uncertainty on x ~ 0.1 antiquarks...

rel. unc. on antiquarks

$Q^2 = 10^4$ GeV^2

—— $\bar{u}$

----- $\bar{d}$

NNPDF

NNPDF 1.0

100 replicas

ratio ubar — $\bar{u}$

ratio utot — u

—— $Q^2 = 4$ GeV^2

- - - $Q^2 = 10000$ GeV^2

ratio dbar — $\bar{d}$

ratio dtot — d

22
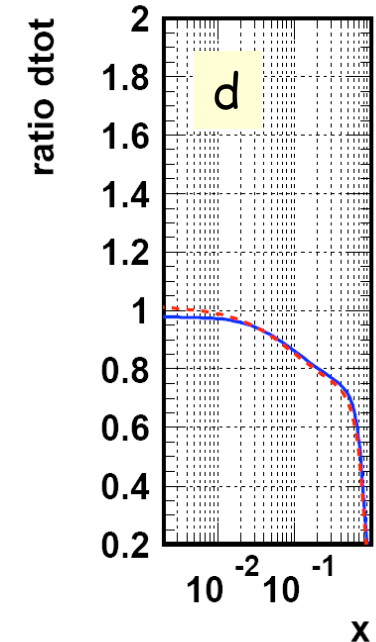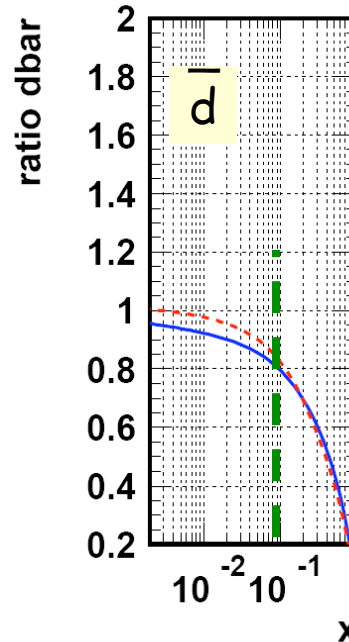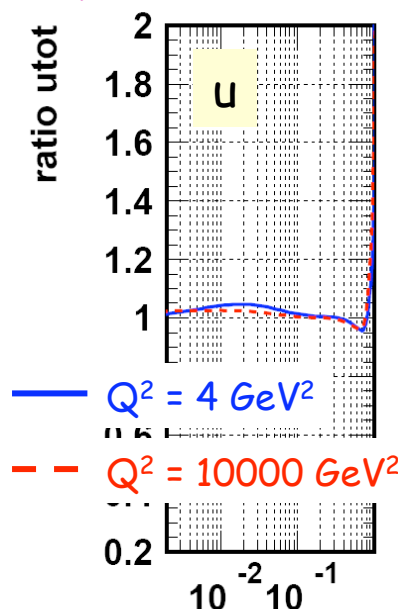
What LHeC would bring in this scenario

Blue & red data points = NP scenario (Λ = 40 TeV)
Black curve = SM cross-sections

DIS: largest contribution to the cross-section at high x & Q^2 comes from the u-quark (not anti-u) which is already well constrained.

i.e. new physics in
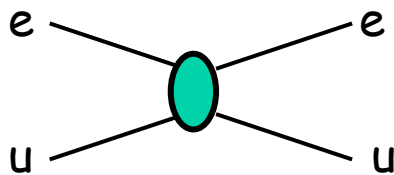
would be easy to disentangle from pdf effects.

Indeed: DGLAP fit including LHeC data with Λ = 40 TeV, ε = –1 fails:

Dataset	χ^2	N_{points}
MB 97	40.3	45
96-97	75.5	80
NC 94-97	95.2	130
CC 94-97	26.6	25
NC 98-99	112.2	126
CC 98-99	18.2	28
HY 98-99	5.0	13
NC 99-00	142.7	147
CC 99-00	49.0	28
BCDMS p	145.1	134
BCDMS n	154.6	159
LHeC e+	145.1	134
LHeC e-	295.7	135

e⁻ p cross sections

i.e. LHeC data would disentangle between the example NP scenario and modified pdfs.

E. Perez
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TH Institute, Feb 09

Precision QCD and EW: measurement of α_S

Simulation of α_s measurement at LHeC
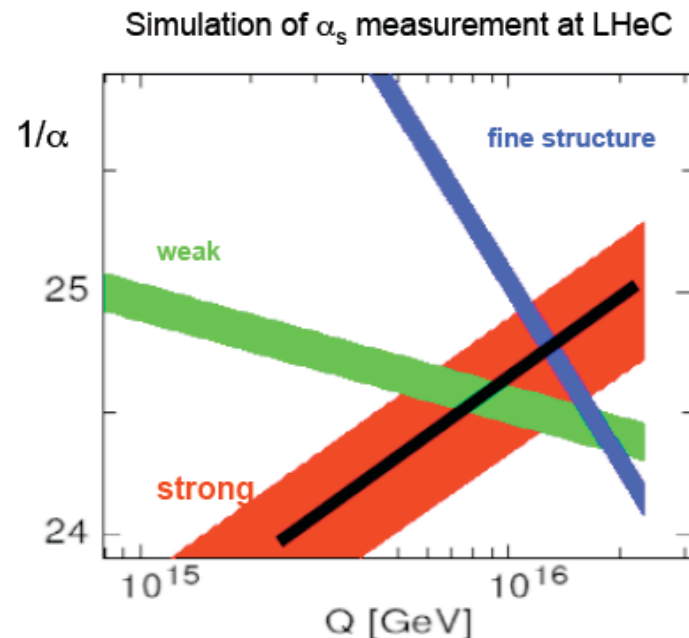
MSSM - B.Allnach et al, hep-ex/0403133

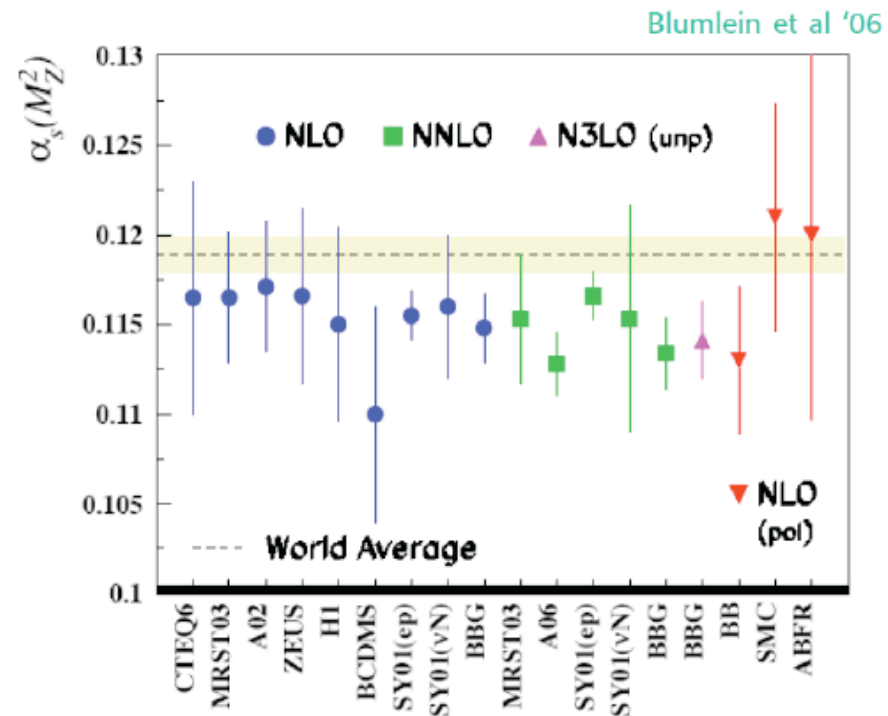| DATA	exp. error on α_s
NC e^+ only	0.48%
NC	0.41%
NC & CC	**0.23% :=**[1]
[1] $\gamma_h > 5°$	0.36% :=[2]
[1] +BCDMS	0.22%
[2] +BCDMS	0.22%
[1] stat. *= 2	0.35%

DIS08, T.Kluge

α_s least known of coupling constants
Grand Unification predictions suffer from $\delta\alpha_s$

DIS tends to be lower than world average

**LHeC: per mille accuracy indep. of BCDMS.
Challenge to experiment and to h.o. QCD**

Max Klein LHeC ECFA 11/08

LHeC and a light Higgs boson ?

ttH, 60 fb-1, Semi-lepton channel (CMS analysis)

- bb is dominant decay mode for low-mass Higgs
- Inclusive H production followed by H→bb: impossible to see at LHC, above QCD background
- ttH followed by H→bb ?

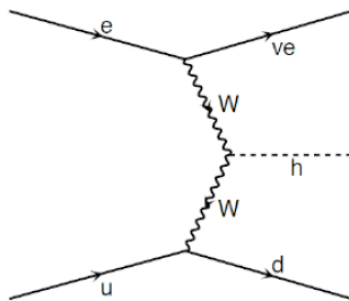| m_H (GeV/c^2)	S	S/B (%)	S/$\sqrt{B}$	S/$\sqrt{(B+dB^2)}$
115	147	7.0	3.1	0.20
120	118	5.3	2.5	0.16
130	80	3.6	1.7	0.11

Although ttH has a x-section of O(1 pb), very difficult to see the signal taking into account syst. uncertainties...
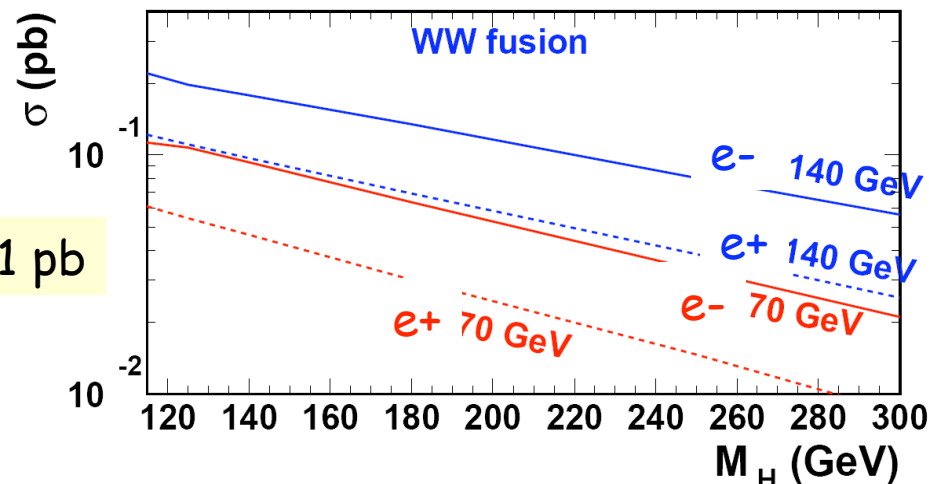
Standard unc. : JES, jet resolution, b-tagging

H production at LHeC

Information on bbH at LHeC ?

$\sigma \sim 0.1$ pb

[U. Klein, B. Kniehl, EP, M. Kuze]

E. Perez

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IH Institute, Feb 09

bbH coupling

H → bb leads to final states similar to multijet CC DIS.
Current jet very forward (lost in beam-pipe).
Requiring both b jets (from Higgs decay) to be in the central region
($10 < \theta < 170$ deg) reduces the cross-section by a factor of ~ two.　　acceptance

Divonne: First bckgd study, CC DIS only.　　[M. Kuze et al]　　HCAL resolution

For M_H = 115 GeV :

Events in 10 fb^{-1}, requiring :
  at least two jets with $P_T > 20$ GeV, $|\eta| < 3$,
  $P_{T,miss} > 25$ GeV,
  M_{jj} in a mass window around the Higgs
mass, $M_H \pm$ width

width	S	B	S/B	S/√B
10 GeV	990	39000	0.025	5.0
20 GeV	990	78000	0.013	3.5
5 GeV	990	19000	0.05	7.2

H → bb (for light H) may be seen at LHeC with
very simple cuts.
For coupling studies: b-tagging to improve S/B.

Need: High Ee,
  high luminosity,
  good acceptance,
  good resolution.

LHeC may open a unique window to access the bbH coupling.
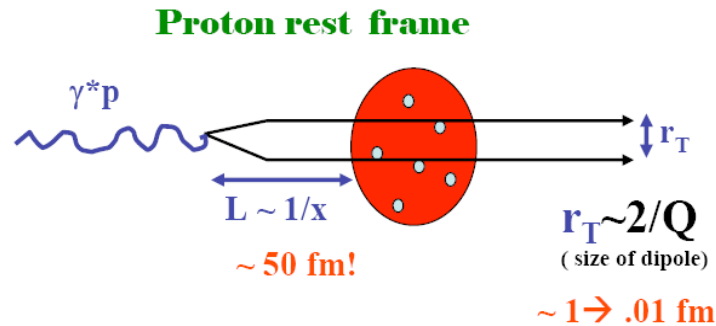
Low x : saturation of the gluon density

- Expect some saturation mechanism at low x :

(naïve estimate…)

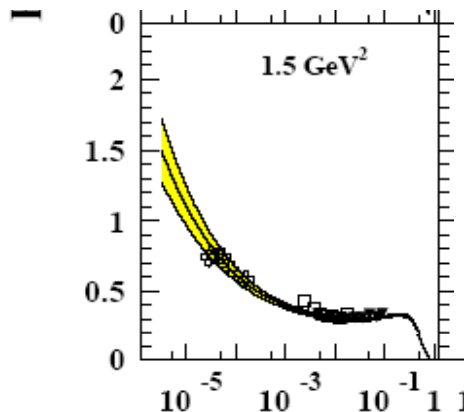Saturation, or gluon recombination, when

$$\frac{\pi}{Q^2}\, g(x, Q^2) \sim \pi\, R_p^2$$

Proton rest frame

$\gamma^* p$

$L \sim 1/x$

~ 50 fm!

$r_T \sim 2/Q$ (size of dipole)
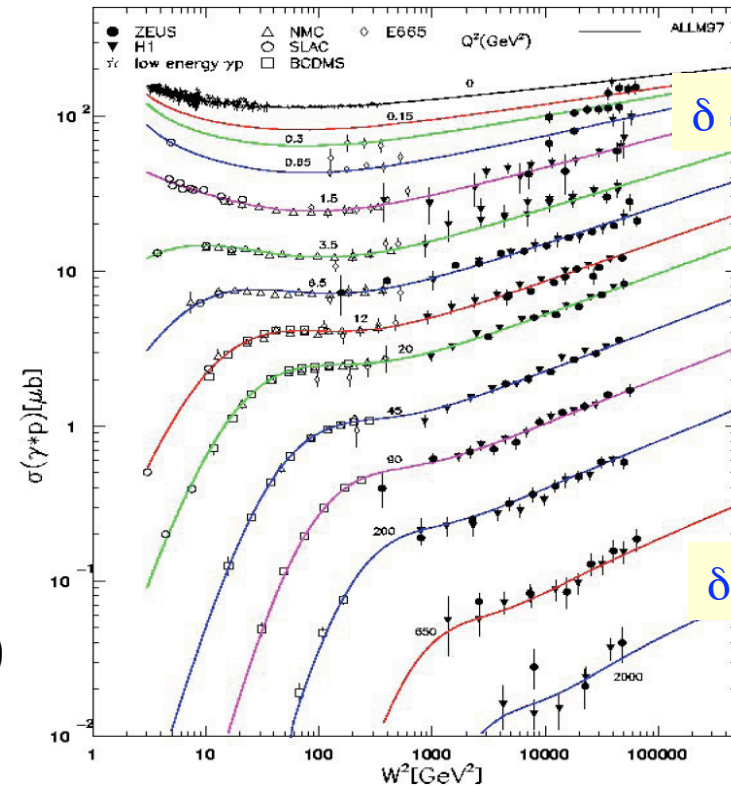
$\sim 1 \rightarrow .01$ fm

At low x, DIS can be viewed as the high energy scattering of a $q\bar{q}$ dipole with the proton. Unitarity !

$$\sigma^{\gamma^* p}(W^2, Q^2) \approx \frac{4\pi^2 \alpha}{Q^2} F_2(x, Q^2) \qquad \sim W^{2\delta}$$

$(W^2 = S_{\gamma p} \sim Q^2 / x)$

$\delta \approx 0.08$

$\delta \approx 0.4$

- However : no "taming" of the rise of F_2 at low x observed in HERA data.
  [though some "hints" of saturation may have been seen elsewhere in HERA data…]
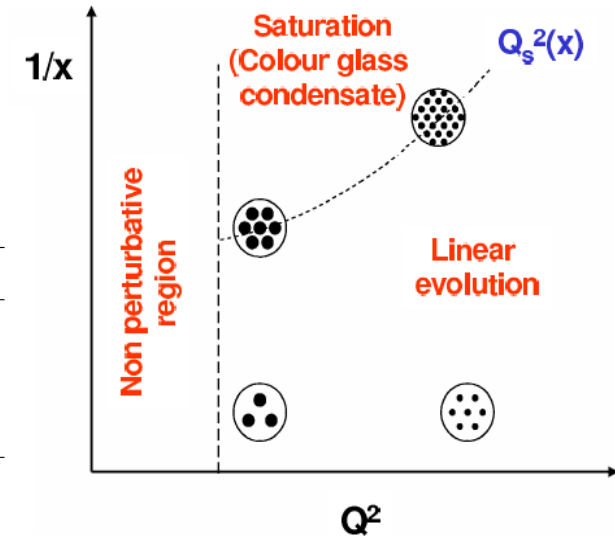
Saturation at the LHC ?

Where does saturation become important?

recent estimates of $Q_s^2(x)$ in GeV^2

$x = 10^{-4}$	$x = 10^{-6}$	Ref.
0.7	1.9	G. Soyez, 0705.3672 [hep-ph]
0.8	4.0	H. Kowalski, L. Motyka, G. Watt, hep-ph/0606272
0.8	2.0	K. Golec-Biernat, S. Sapeta, hep-ph/0607276

▶ at HERA typical $Q_s^2(x) \lesssim 1\,\mathrm{GeV}^2$
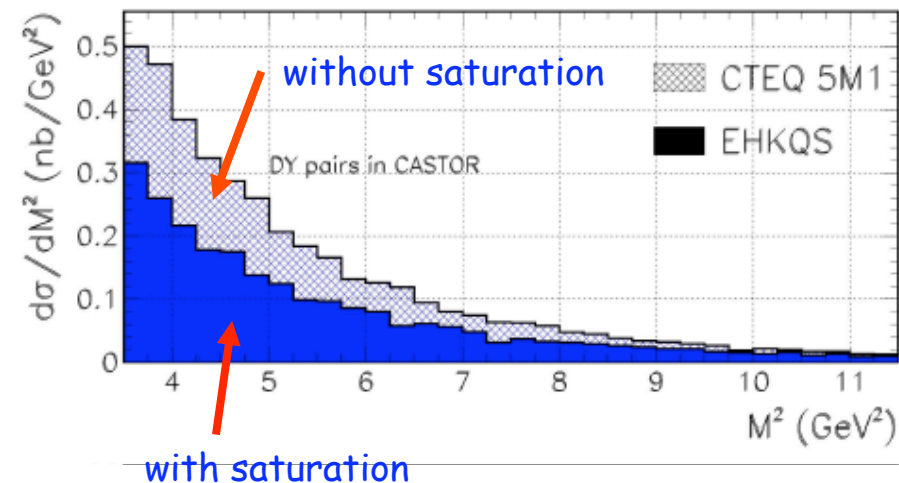

Could be seen at LHC in pp ? E.g. in Drell-Yan production with $x_1 \ll x_2$

→ one very forward lepton:

e.g. for $M_{ll} \sim 10$ GeV, $x_{Bjorken}$ down to 10^{-6} can be probed if coverage up to $\eta \sim 6$ (e.g. CASTOR calorimeter in CMS)

- Reduced event rates
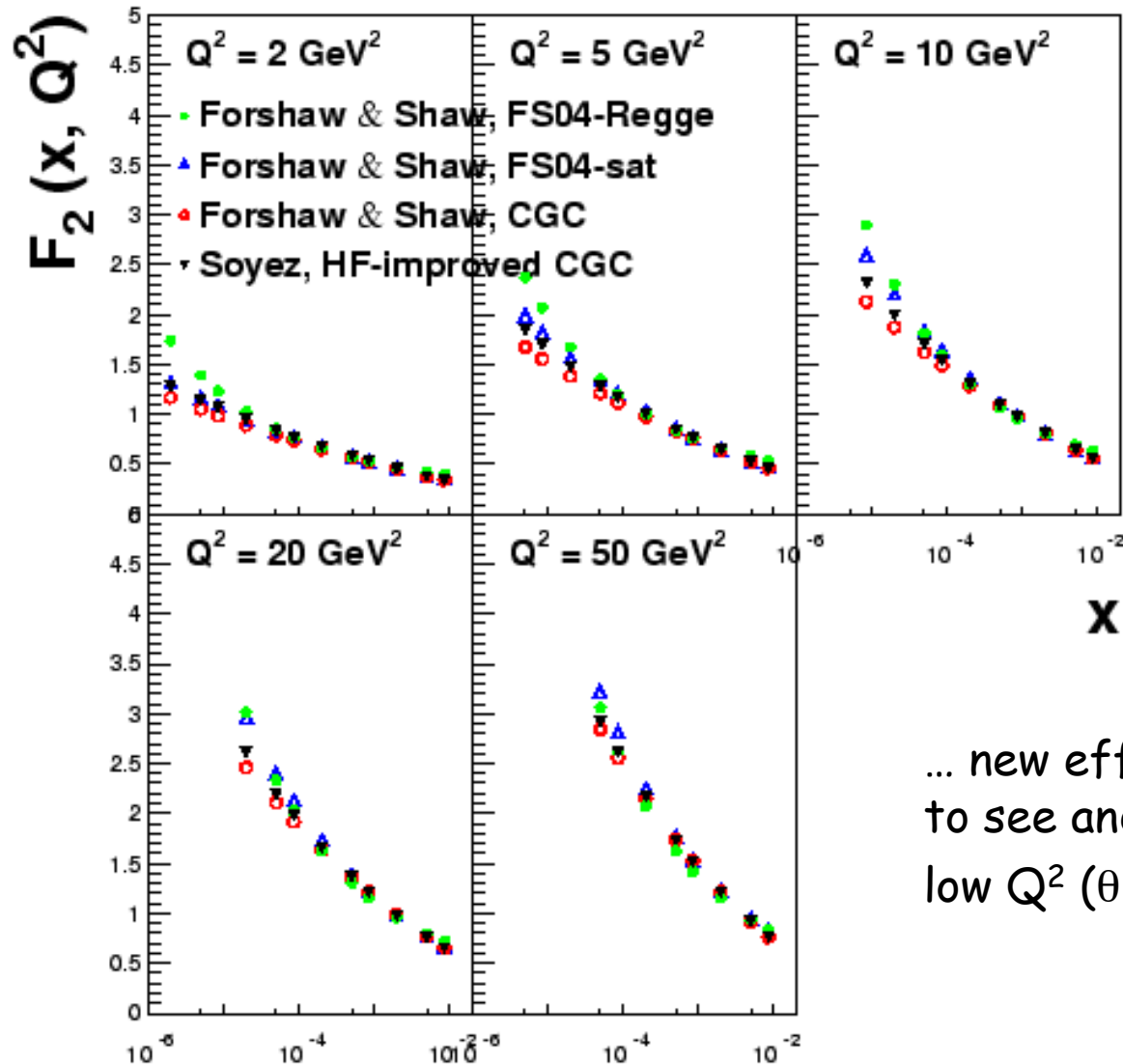- M^2 dependence different from expected

But is one observable enough to establish saturation ??

Fits to HERA data extrapolated to LHeC

With 1 fb^{-1} (1 year at 10^{33} cm^{-2} s^{-1}), 1° detector:
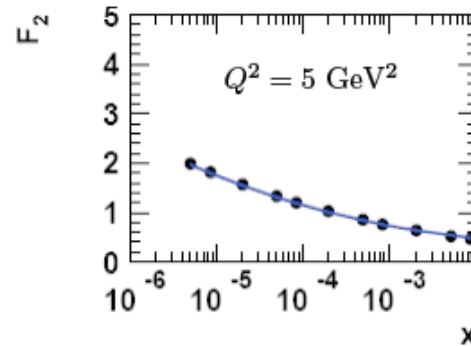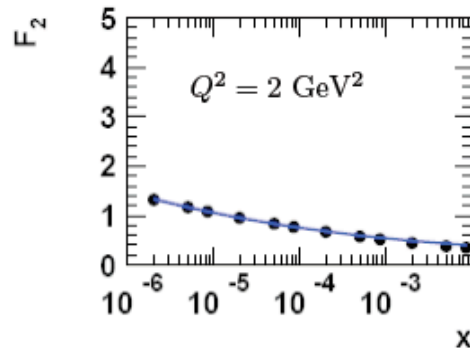stat. precision < 0.1%, syst, 1-3%

[Forshaw, Klein, PN, Soyez]

Precise data in LHeC region,
x > ~10^{-6}

FS04, CGC models including
saturation suppressed at low
x & Q^2 relative to non-sat
FS04-Regge

... new effects may not be easy
to see and will certainly need
low Q^2 ($\theta \rightarrow$ 179°) region ...

Saturation from F2 measurements ?

[J. Forshaw et al, DIS'08] FS04

Could we see DGLAP fail at $Q^2 >$ few GeV^2 ?

Can DGLAP be made to fit the data shown on the previous slide, which include saturation ?
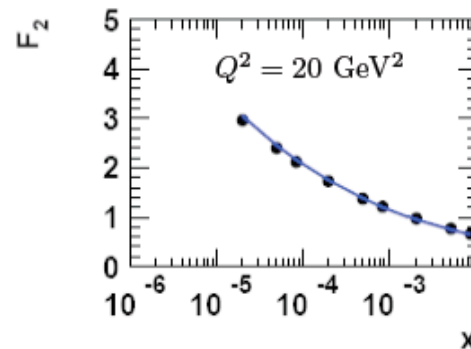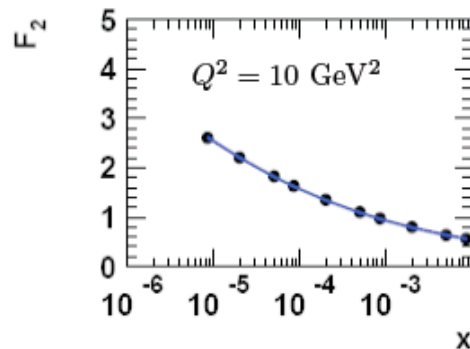
Fit to low Q^2 HERA data and to LHeC pseudo-data (FS04) with $Q^2 < 20$ GeV^2 :

$\chi^2 = 92$ for 92 data points
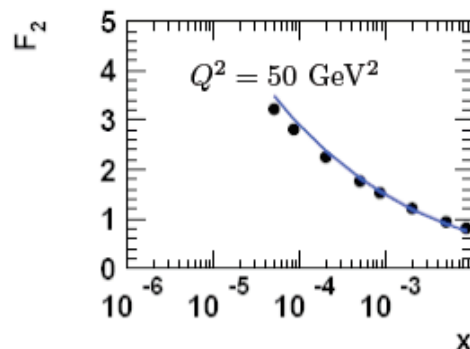
Only the 4 points at highest Q^2 and lowest x are not well described by this fit.

i.e. saturation effects may not be easy to see with F_2 data alone…

Saturation from F2 and FL

However, this fit would NOT describe F_L measurements.

These could be obtained by varying the proton beam energy as recently done at HERA.
Example for 1 year:

Ep (TeV)	Lumi (fb-1)
7	1
4	0.8
2	0.2
1	0.05

… precision typically 5%
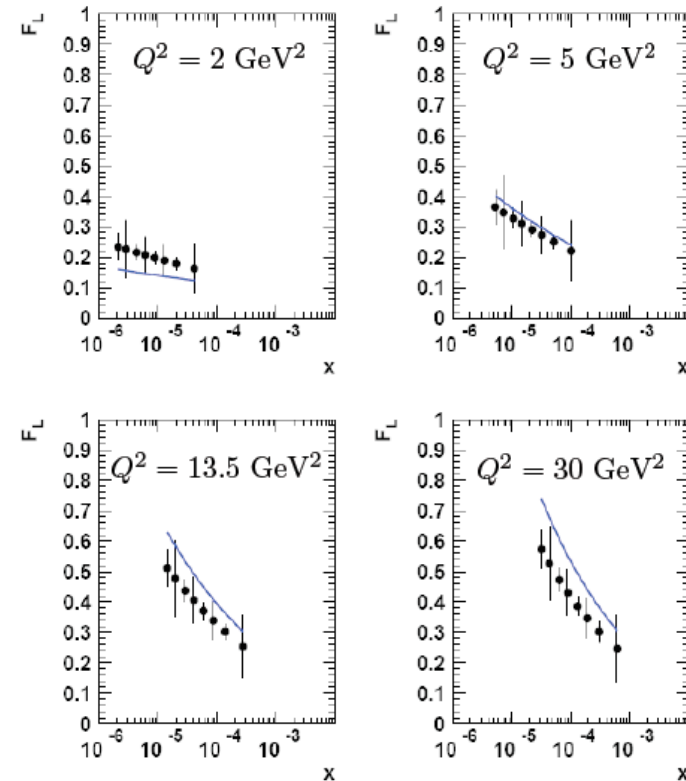
Similar conclusions within the NNPDF approach

F2 at the LHeC - Simulated data from FS04 saturation model

FL at the LHeC - Simulated data from FS04 saturation model
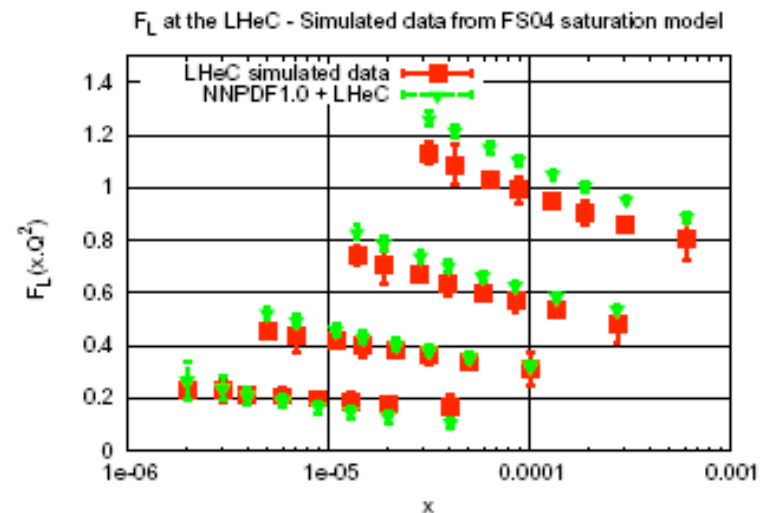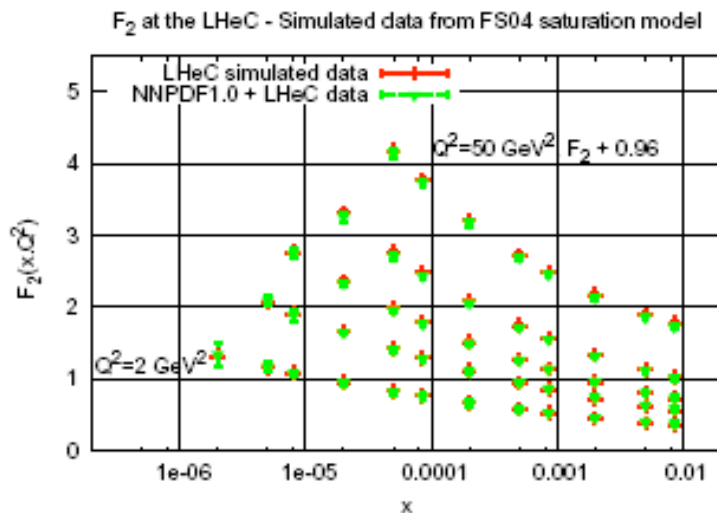
[J. Rojo, Divonne]

Saturation : conclusions

Saturation effects at LHeC (FS04-sat, CGC-sat) cannot be absorbed into a DGLAP analysis when F_2 and F_L are both fitted.

Saturation maybe much more difficult to establish unambiguously from F_2 data alone.
  → important to have measurements at various $\sqrt{s}$
  → may be also difficult to establish if we have only LHC Drell-Yan data !

Other observables at LHeC could also provide a handle: heavy quark structure functions, DVCS, exclusive vector meson production, diffractive DIS.

e.g. DVCS at LHeC, together with F2 & FL, could help disentangle between different model which contain saturation.

$Q^2 = 30 \text{ GeV}^2$

1 deg acceptance

• LHeC sim (FS04sat, 1 fb⁻¹)
• LHeC sim (CGC, 1 fb⁻¹)

Statistical precision with 1fb-1 ~ 2-11%

[Favart, Forshaw, Newman]

σ_{DVCS} / nb

W / GeV
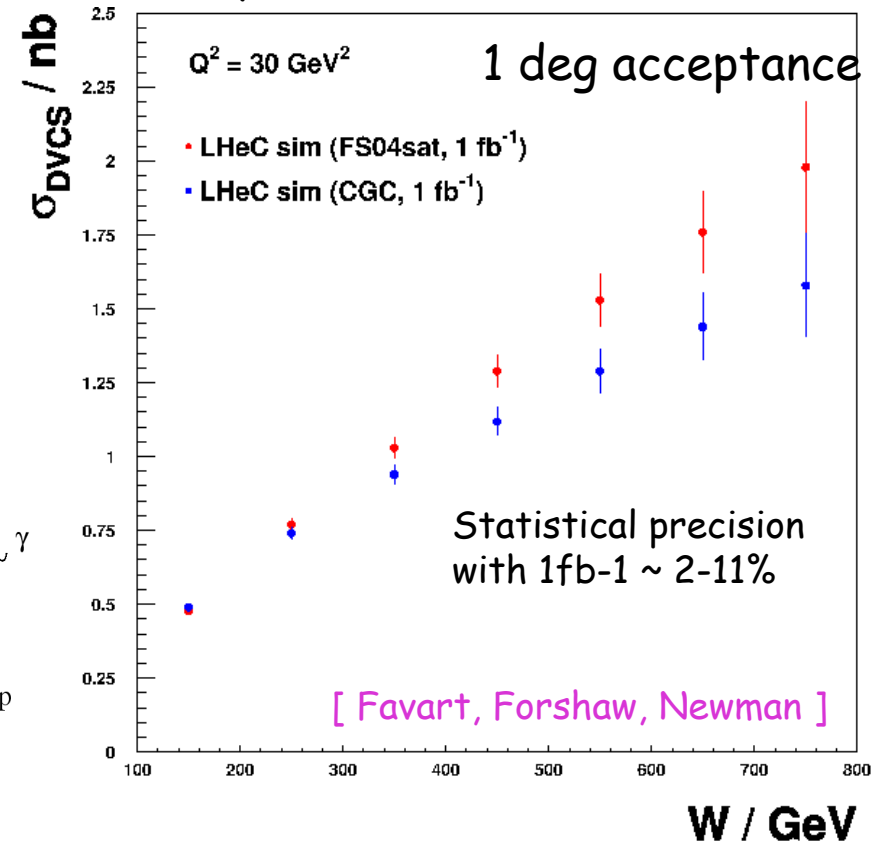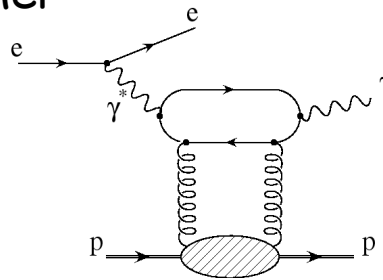
Semi-inclusive diffractive DIS

Diffractive Kinematics at $x_{IP}=0.003$

DGLAP

[Forshaw, Marquet, PN]
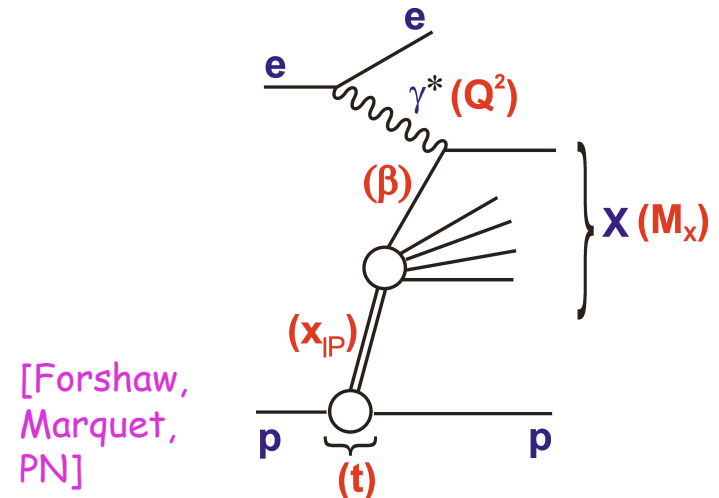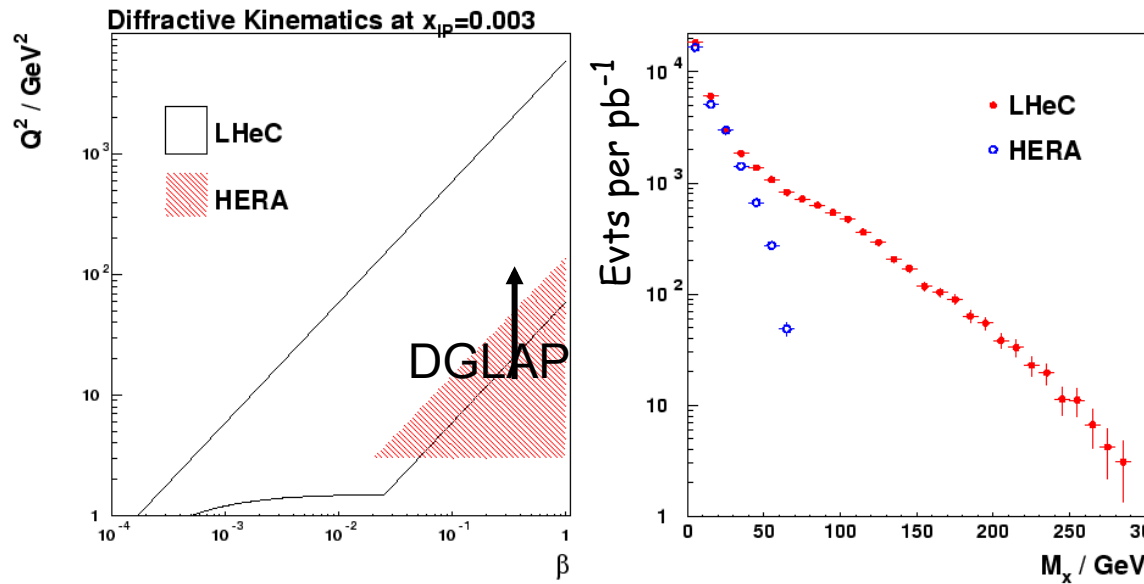
[Studies with 1° acceptance, 1 fb^{-1}]

- 5-10% data, depending on detector
- (D)PDFs / fac'n in much bigger range
- Enhanced parton satn sensitivity?
- Mx → 100 GeV with x_{IP} = 0.01 …
    → X including W, Z, b …
- Exclusive production of any 1$^-$ state
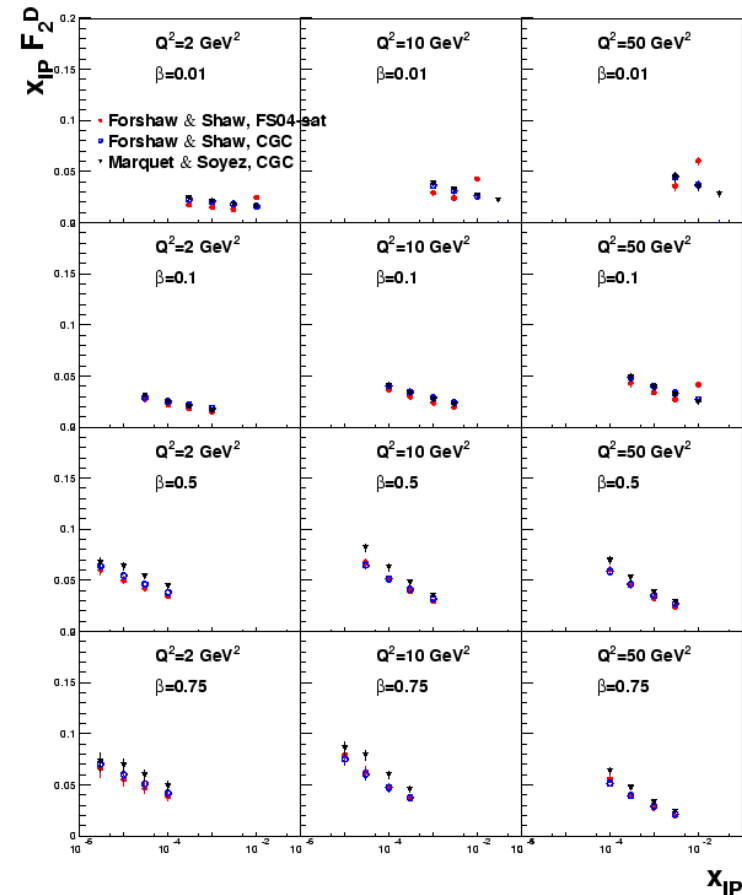
With AA at LHC, LHeC is also an eA collider

• Very limited x and Q^2 range
so far (unknown for x <~ 10^{-2},
gluon very poorly constrained)

• LHeC extends kinematic range
by 3-4 orders of magnitude

opportunity to extract and understand
nuclear parton densities in detail ...
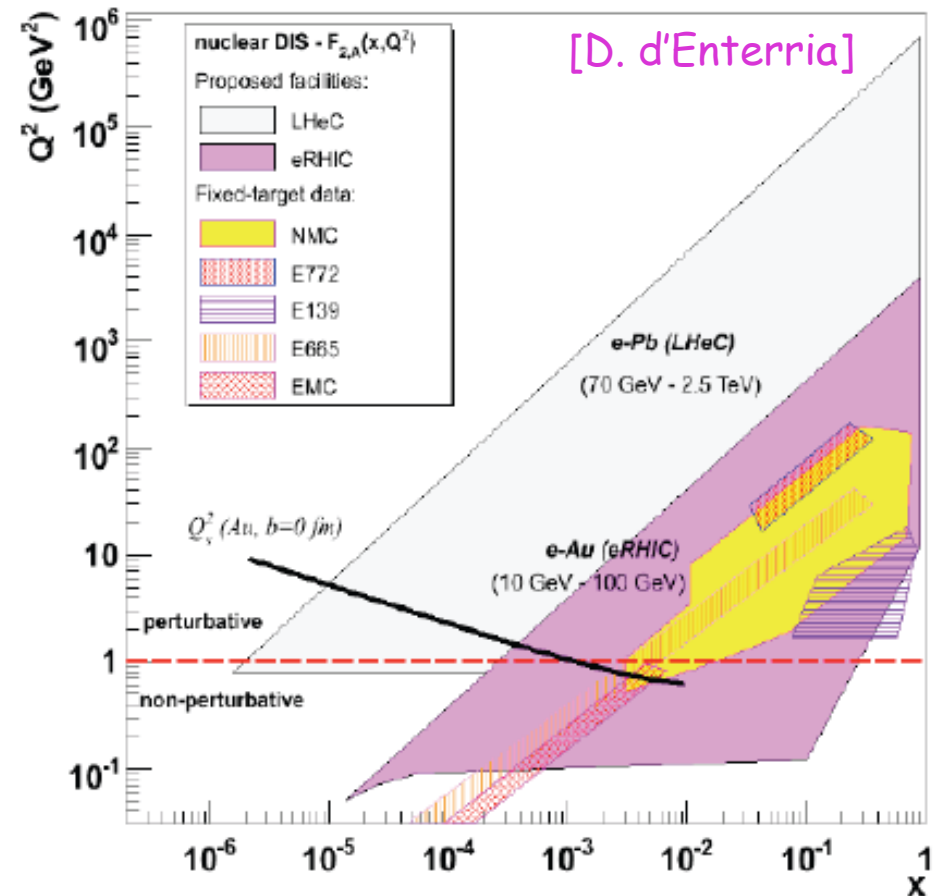
→ ~$A^{1/3}$ enhanced gluon density → additional sat^n sensitivity
→ initial state in AA quark-gluon plasma studies @ LHC / RHIC
→ relations between diffraction and shadowing
    meas. of both eA and ep at high densities to test the
    Gribov-Glauber relationship of nuclear shadowing to diff.
→ Neutron structure & singlet PDF evolution from deuterons

Very rich
physics
programme !

Need eA collider data to determine nuclear parton distributions in the kinematic range of pA/AA collisions at the LHC

NuPECC EIC-LHeC Study group

Tullio Bressani, INFN, Torino Univ.
Jens Jørgen Gaardhøje, Niels Bohr Inst.
Günther Rosner, Glasgow Univ.
Hans Ströher, FZ Juelich
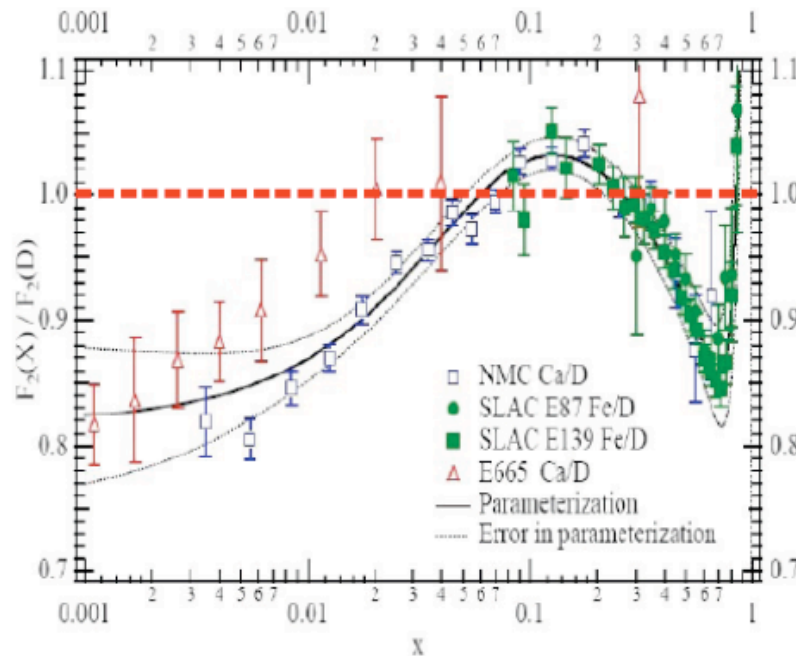
See e.g. M.Arneodo
Phys. Rept. 240 (94) 301
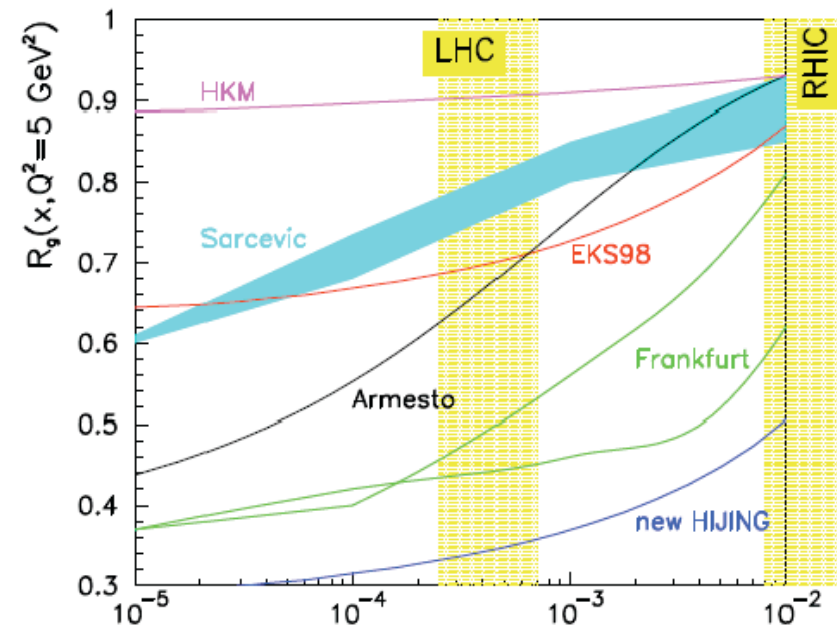
Nuclear xg(x) is unknown
for x below ~ 10^{-3} !

K.Eskola et al. JHEP 0807 (08)102

Conclusions

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

- ep data complementing pp maybe needed for the full interpretation of discoveries at the LHC.

- LHeC would lead to much better determined pdfs (p and A) in the whole domain needed for LHC.

- Would study novel QCD phenomena at low x.

- First ECFA/CERN workshop successfully gathered accelerator, theory & experimental colleagues.

- Conceptual Design Report by early 2010

Backups

DIS at highest Q^2 : towards quark substructure ?

LHeC promises to reach 10^{-19} m, i.e
1/10000 (1000) of proton (quark) radius

Assign a finite size < r > to the EW charge distributions :

$$d\sigma/dQ^2 = SM_{value} \times f(Q^2)$$

$$f(Q^2) = 1 - \frac{<r^2>}{6} Q^2$$

Global fit of PDFs and < r > using $d\sigma/dxdQ^2$ from LHeC simulation, 10 fb^{-1} per charge, Q^2 up to 500000 GeV^2 :

$$< r_q > < 8. \, 10^{-20} \text{ m}$$
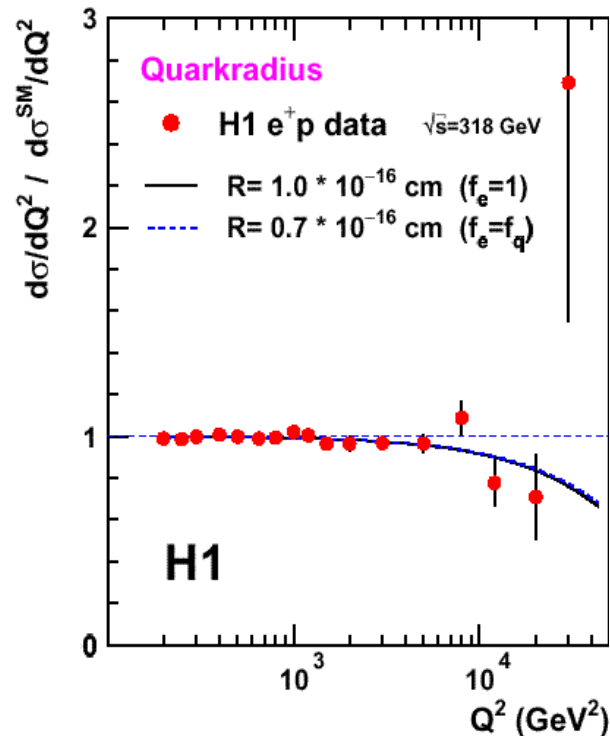
One order of mag. better than current bounds.

At LHC : quark substructure may be seen as a deviation in the dijet spectrum. Such effects could also be due to e.g. a very heavy resonance.
Could we establish quark substructure with pp data only ?

e.g. Forshaw, Sandapen, Shaw
hep-ph/0411337,0608161
... used for illustrations here

Fit inclusive HERA data
using dipole models
with and without parton
saturation effects
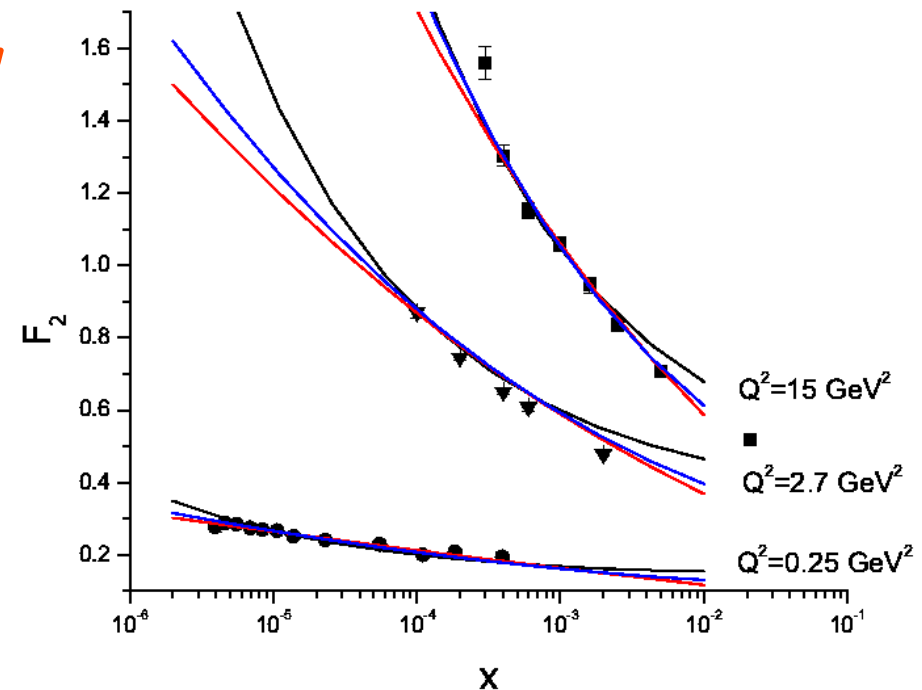
FS04 Regge (~FKS): 2 pomeron model, <u>no saturation</u>
FS04 Satn: <u>Simple implementation of saturation</u>
CGC: <u>Colour Glass Condensate version of saturation</u>

- 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

ep : golden machine to study LQ properties

F = 0 or 2 ?   Compare rates in e⁻p and e⁺p

Spin ?   Angular distributions

Chiral couplings ?   Play with polarisation of lepton beam

Couples to ν ?   Easy to see since good S/B in νj channel

Classification in the table below relies on minimal assumptions.
ep observables would allow to disentangle most of the possibilities (having
a polarised p beam would complete the picture).

	$S_{0,L}$	$S_{1,L}$	$\tilde{S}_{0,R}$	$S_{0,R}$	$S_{1/2,L}$	$\tilde{S}_{1/2,L}$	$S_{1/2,R}$
$S_{0,L}$		β_ν	P_e	P_e			
$S_{1,L}$	β_ν		P_e	P_e		e^+/e^-	
$\tilde{S}_{0,R}$	P_e	P_e		P_p			
$S_{0,R}$	P_e	P_e	P_p				
$S_{1/2,L}$						P_p	P_e
$\tilde{S}_{1/2,L}$		e^+/e^-			P_p		P_e
$S_{1/2,R}$					P_e	P_e	

(Left row groups labelled F = 2 for $S_{0,L}, S_{1,L}, \tilde{S}_{0,R}, S_{0,R}$ and F = 0 for $S_{1/2,L}, \tilde{S}_{1/2,L}, S_{1/2,R}$)

If LHC observes a LQ-like resonance, M below 1 – 1.5 TeV, LHeC could solve the possibly remaining ambiguities (if λ is not too small)

Hints for saturation in the HERA data ?

Left plot axes: σ_{γ^*p} [μb] versus x, labeled with $Q^2 = 1.5$ GeV^2, 2.5, 5, 8.5, 15, 25, 45, 90, 150, 250, 400, 650, 1000, 1500, 3000, 8000, $Q^2 = 20000$ GeV^2. Inset diagram: electron, γ, Z_0, Q^2, proton, xp, W.

Right plot: σ_{γ^*p} [μb] versus τ, "Data with x < 0.01", $\sigma \equiv \sigma_0$, $\sigma \equiv \sigma_0/\tau$.

"geometric scaling"

$$\tau \sim Q^2\, x^\lambda$$
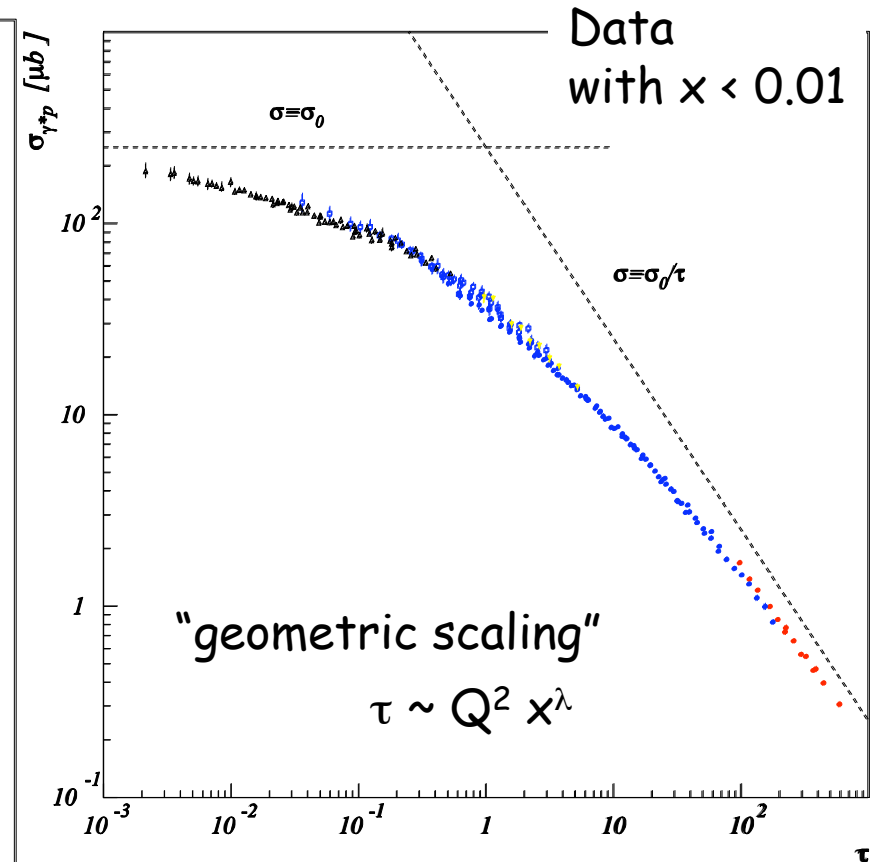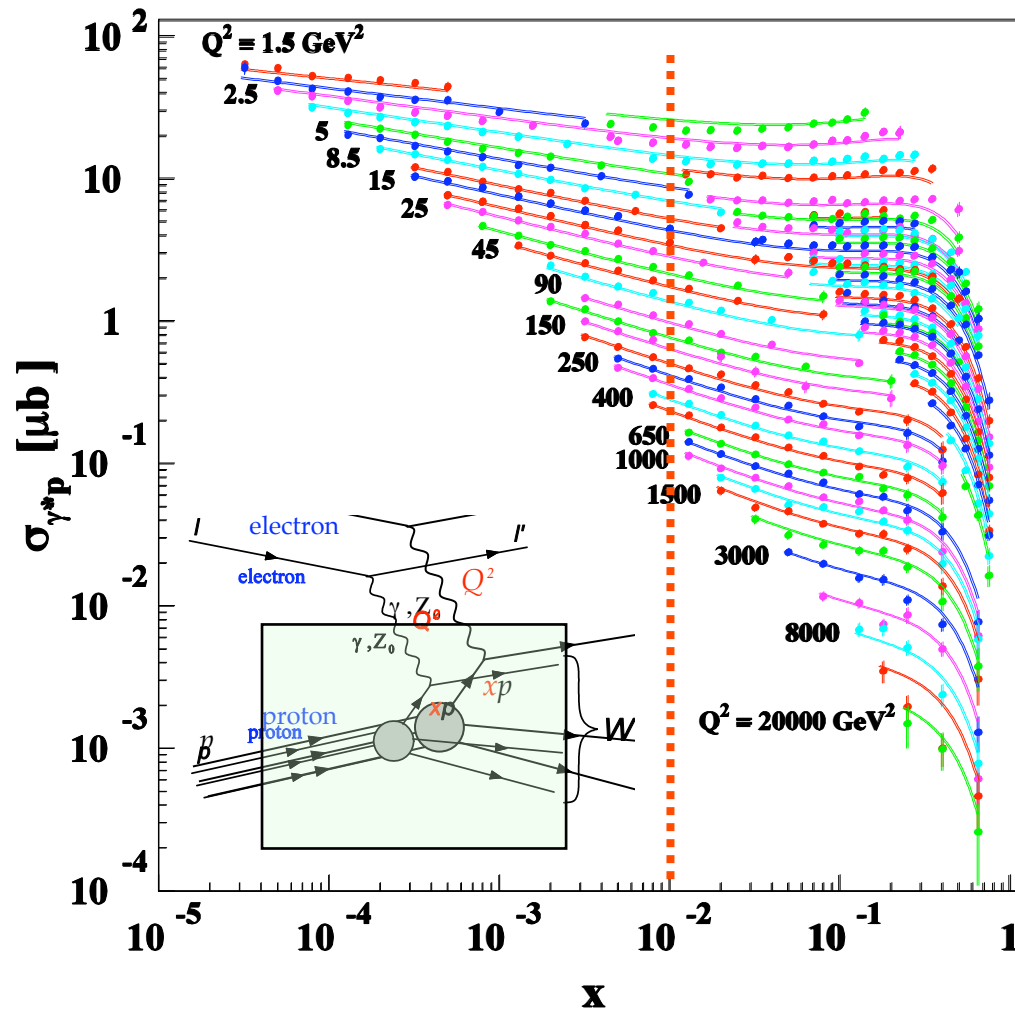
► **Saturation may be thought as something like a phase transition:**
   from free to strongly interacting partons
   from a low to a high density system

► **Some of the QCD based nonlinear equations proposed for**
   saturation accept naturally solutions with geometric scaling
   behavior

And also described well
in dipole models with
a saturating dipole-proton
cross-section.

TH Institute, Feb 09

Example: saturation in dipole models

At low x, $\gamma^* \to q\bar{q}$ and the long-lived dipole scatters from the proton

The dipole-proton cross section depends on the relative size of the dipole $r \sim 1/Q$ to the separation of gluons in the target R_0
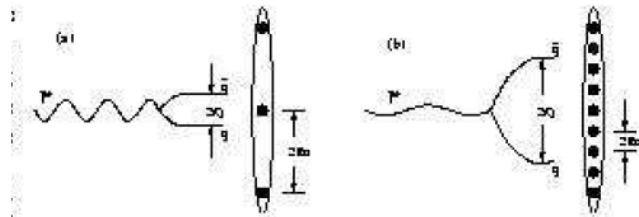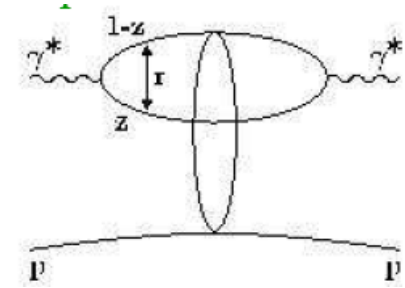

$\sigma = \sigma_0(1 - \exp(-r^2/2R_0(x)^2))$, $R_0(x)^2 \sim (x/x_0)^\lambda \sim 1/xg(x)$

r/R_0 small $\Rightarrow$ large Q^2, x
$\sigma \sim r^2 \sim 1/Q^2$

r/R_0 large $\Rightarrow$ small Q2, x
$\sigma \sim \sigma_0 \Rightarrow$ saturation of the dipole cross-section
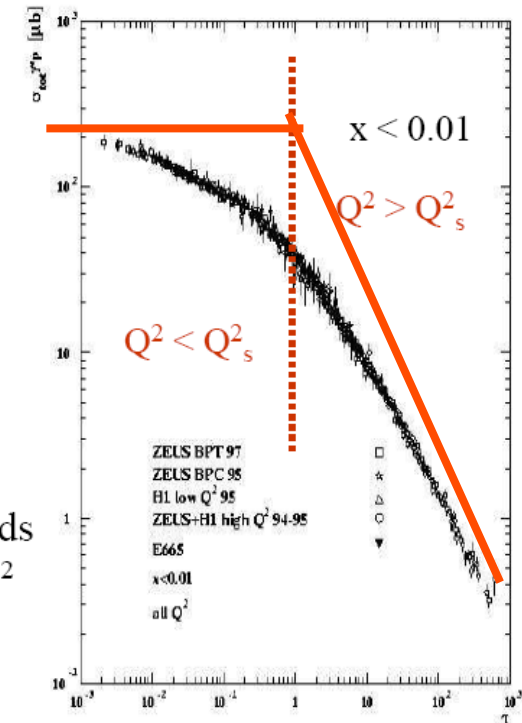
Golec-Biernat, Wustoff

$\sigma = \sigma_0 (1 - \exp(-1/\tau))$

Involves only

$\tau = Q^2 R_0^2(x)$

$\tau = Q^2/Q_0^2 \, (x/x_0)^\lambda$

And INDEED, for x<0.01, $\sigma(\gamma^*p)$ depends only on τ, not on x, Q^2 separately

x < 0.01

$Q^2 > Q^2_s$

$Q^2 < Q^2_s$

ZEUS BPT 97
ZEUS BPC 95
H1 low Q^2 95
ZEUS+H1 high Q^2 94-95
E665
x<0.01
all Q^2

Transition between $\sigma(\gamma^*p) \sim \sigma_0$ (τ small) to $\sigma(\gamma^*p) \sim \sigma_0 / \tau$ (τ large) observed indeed for $\tau \sim 1$.   Not a proof of saturation... but indicative...
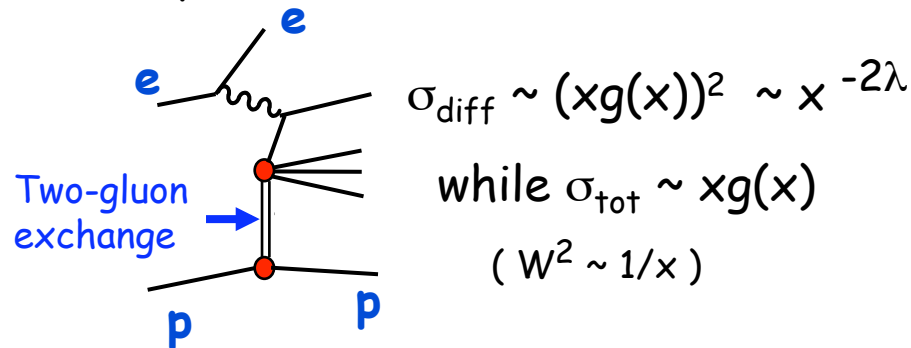
Another "hint" for saturation comes from diffractive data.

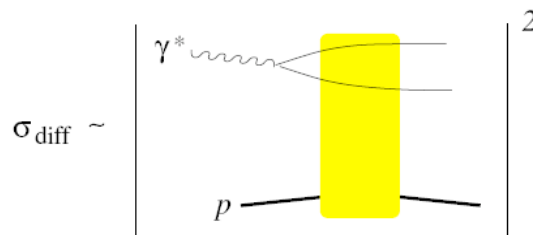σ_{diff} and σ_{tot} have the same energy dependence in the full Q^2 range !

High Q^2 : $\sigma_{tot} \sim (W^2)^\delta$ with $\delta \sim 0.4$

- not explained in Regge phenomenology :
  $\sigma_{diff} \sim (W^2)^\delta$ with $\delta \sim 0.08$

- not explained in QCD :

Two-gluon exchange

$\sigma_{diff} \sim (xg(x))^2 \sim x^{-2\lambda}$

while $\sigma_{tot} \sim xg(x)$

($W^2 \sim 1/x$)

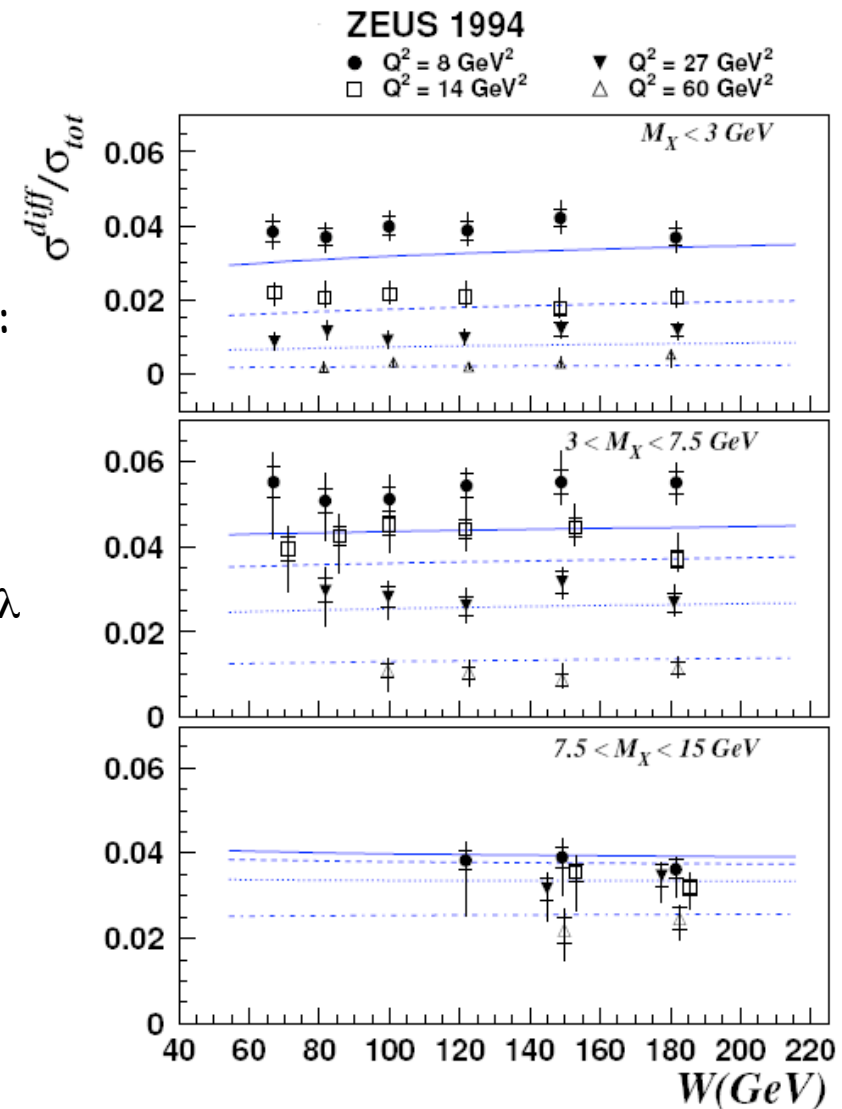- Naturally explained in dipole models with saturation

$\sigma_{diff} \sim$

e.g. with a dipole cross-section similar to that shown on two slides ago.

e.g. Golec-Biernat, Wustoff, PRD 60 (1999) 114023

ZEUS 1994

- $Q^2 = 8$ GeV^2 ▼ $Q^2 = 27$ GeV^2
- □ $Q^2 = 14$ GeV^2 △ $Q^2 = 60$ GeV^2

$\sigma^{diff}/\sigma_{tot}$

$M_X < 3$ GeV

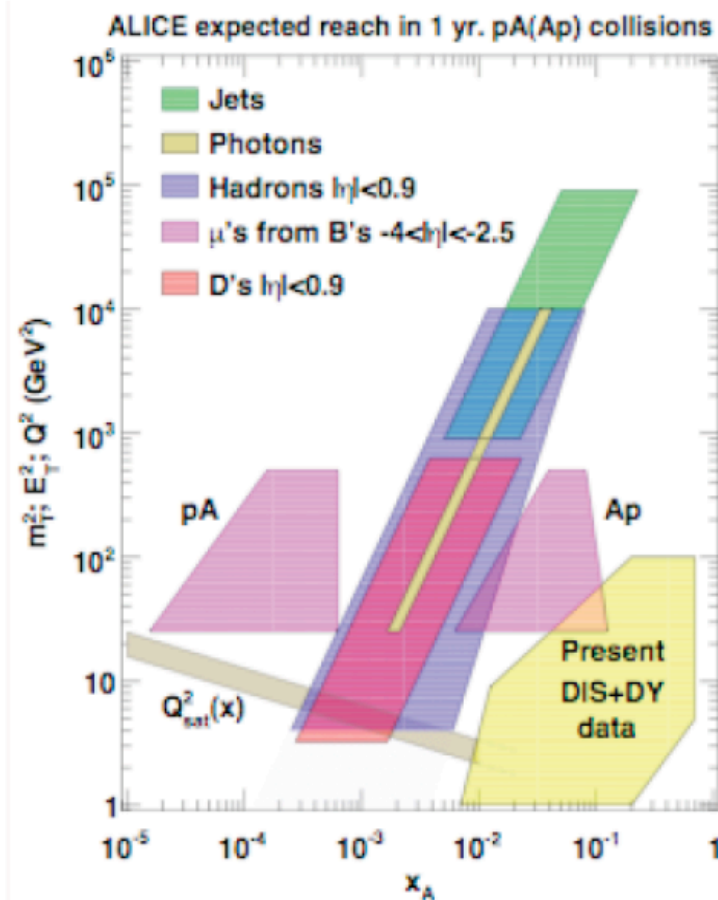$3 < M_X < 7.5$ GeV

$7.5 < M_X < 15$ GeV

$W(GeV)$

Conclusions

For "new physics" phenomena "coupling" directly electrons and quarks (e.g. leptoquarks, eeqq contact interactions) : LHeC has a sensitivity similar to that of LHC.

The further study, in ep, of such phenomena could bring important insights : leptoquark quantum numbers, structure of the "eeqq" new interaction, SUSY, Higgs coupling,.... These studies may be difficult, if possible at all, in pp.

LHC sensitivity to new (directly produced) particles not much limited by our pdf knowledge. "Contact-interactions" deviations may be more demanding.
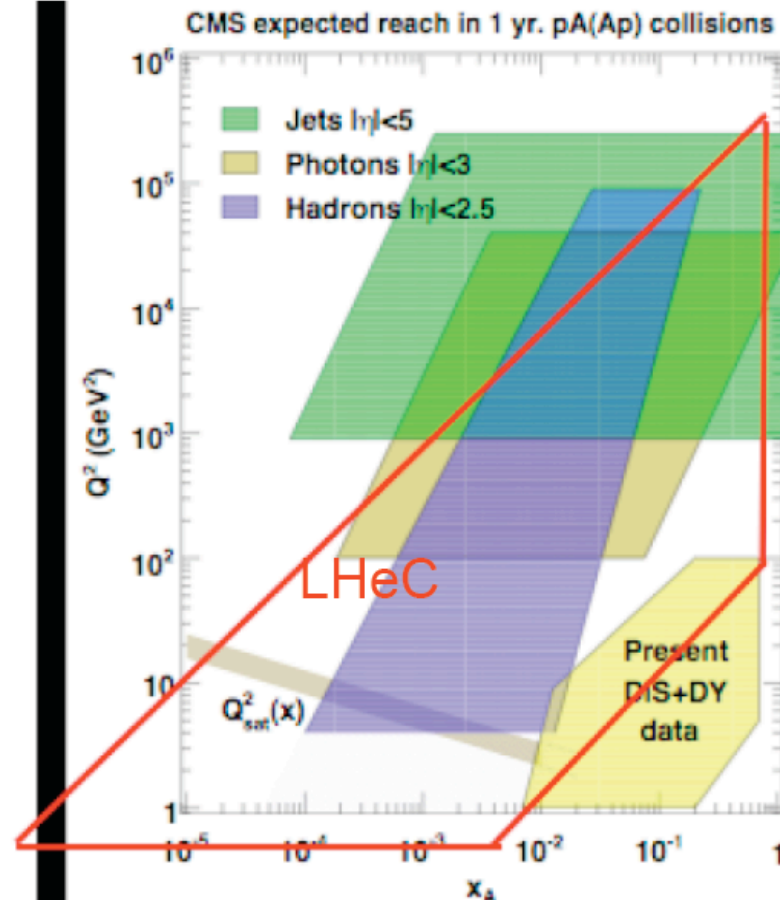
However, the interpretation of discoveries at LHC may require a better knowledge of the high x pdfs : e.g. determination of the couplings of a W ' or Z ' if "at the edge" .

Complementarity of Ap and ep

ALICE expected reach in 1 yr. pA(Ap) collisions

Jets
Photons
Hadrons |η|<0.9
μ's from B's -4<η<-2.5
D's |η|<0.9

pA

Ap

$Q^2_{sat}(x)$

Present DIS+DY data

CMS expected reach in 1 yr. pA(Ap) collisions

Jets |η|<5
Photons |η|<3
Hadrons |η|<2.5

LHeC

$Q^2_{sat}(x)$

Present DIS+DY data

D'Enterria Divonne

Max Klein LHeC ICFA08

Note that DY is not DIS

E. Perez   45   TH Institute, Feb 09