Physics Opportunities at the LHeC

Henri Kowalski
on behalf of Max Klein
Slides from Emmanuelle Perez, CERN Feb 2009

LHeC: A Large Hadron electron Collider at the LHC
5-140 GeV $e^{\pm}$ 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

… 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)

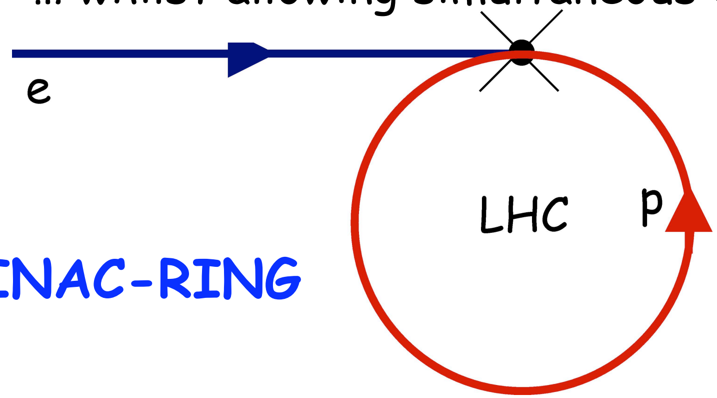
Physics at High Parton Densities
Nestor Armesto (CERN),
Brian Cole (Columbia),
Paul Newman (B'ham),
Anna Stasto (MSU)

… 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 ...

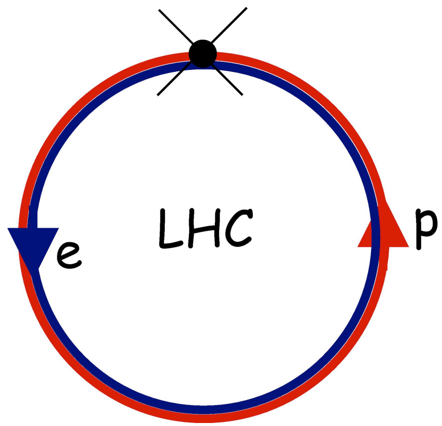
LINAC-RING



- 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

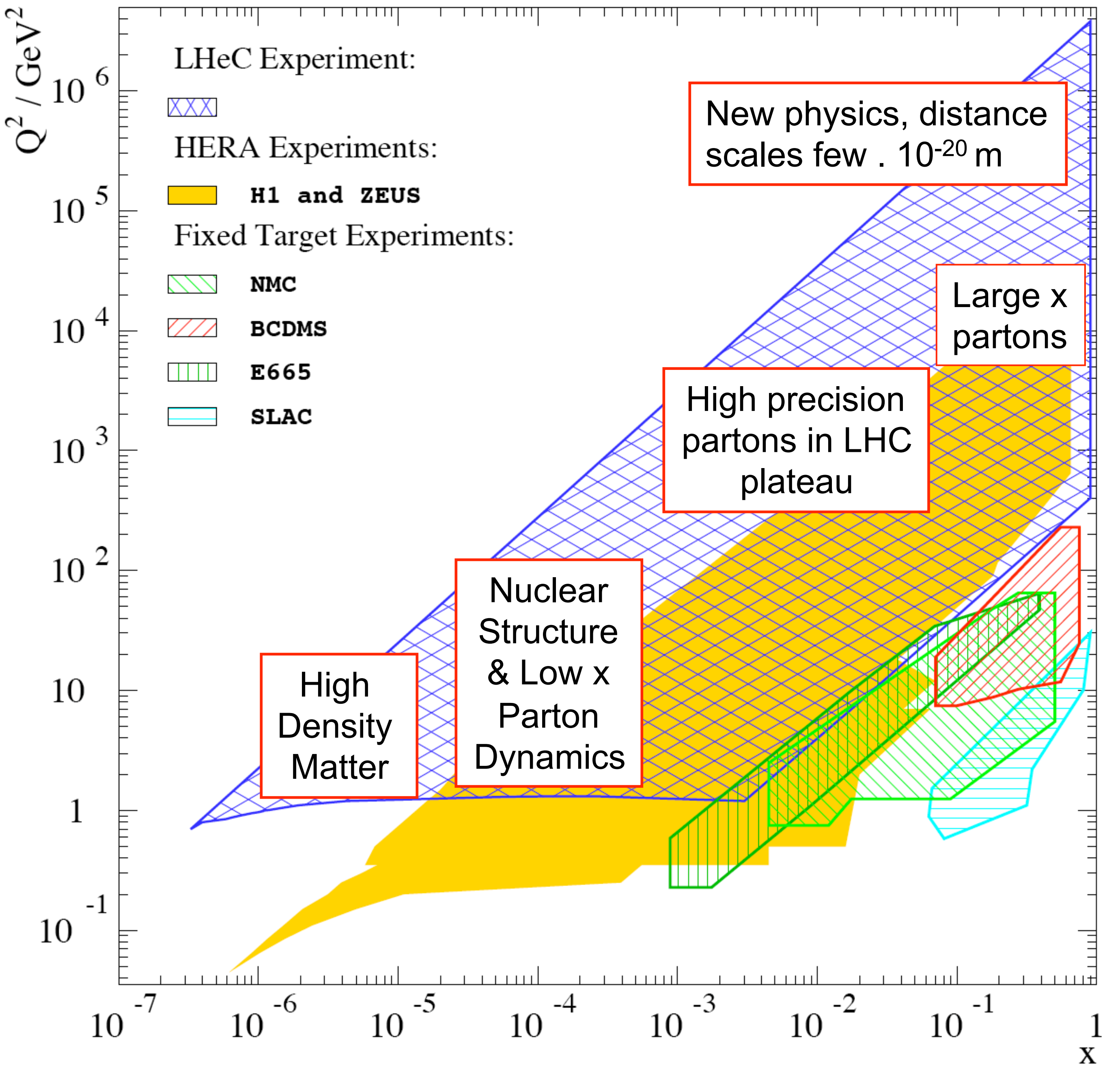
See next talk by Uwe Schneekloth !

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)



$\sqrt{s} = 1.4$ TeV

- 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 $Q^2 \sim 1$ GeV^2] → novel QCD …

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 Q^2 of LHC experiments
- Small-x physics in eP and eA collisions
- Probing the $e^{\pm}$-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)

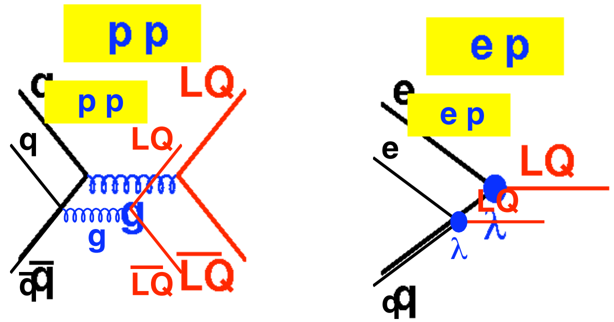
- A better knowledge of the proton structure may be needed

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

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

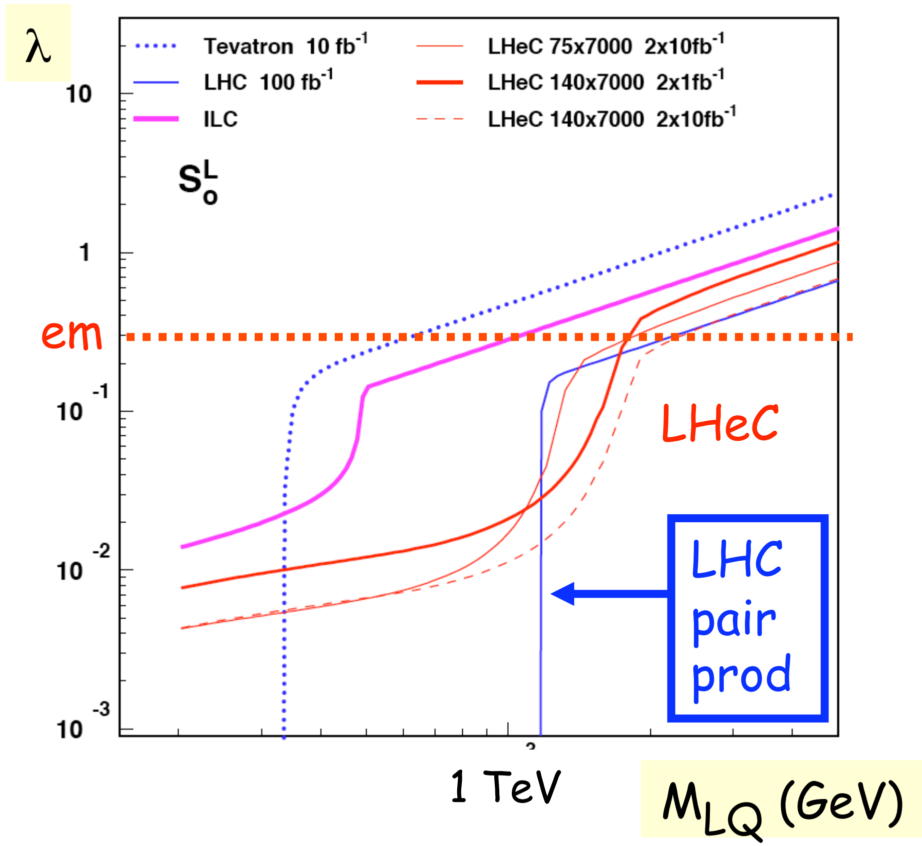
Electron-quark resonances

- "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



λ (unknown) coupling l-q-LQ

[A.F. Zarnecki]



LQ decays into (lq) or (νq) :

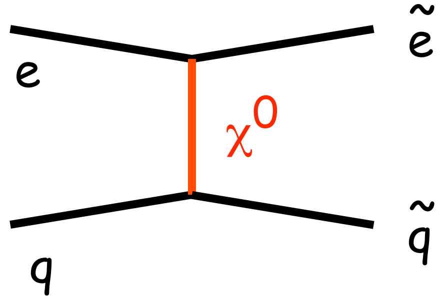
- ep : resonant peak, ang. distr.
- pp : high E_T lljj events

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.

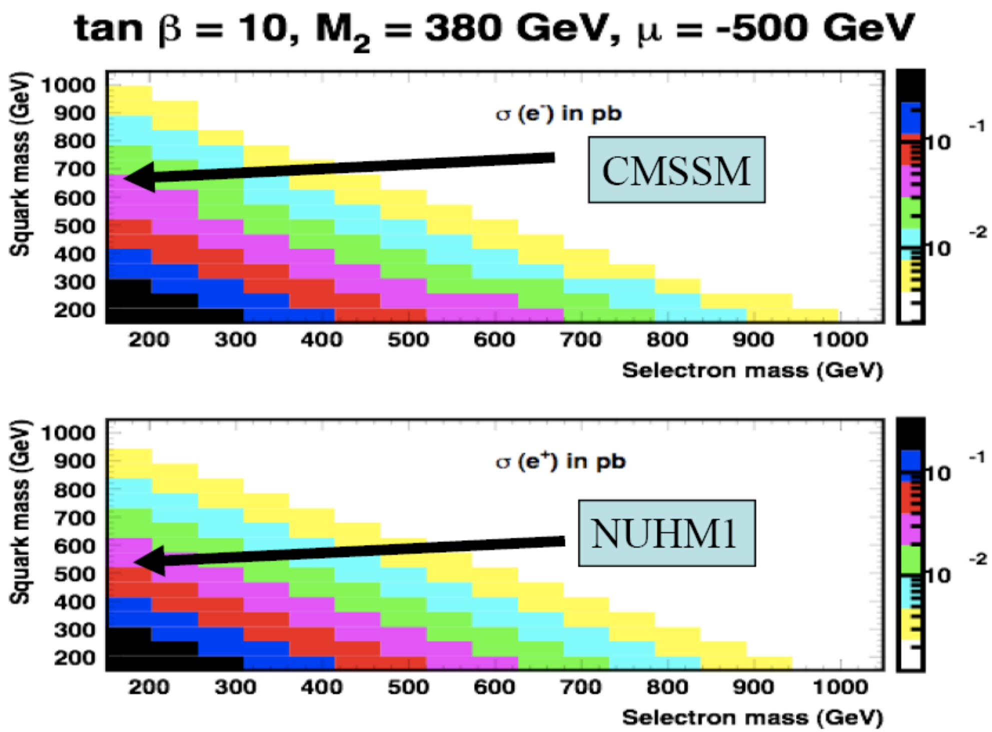
Supersymmetry (R-parity conserved)

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 :

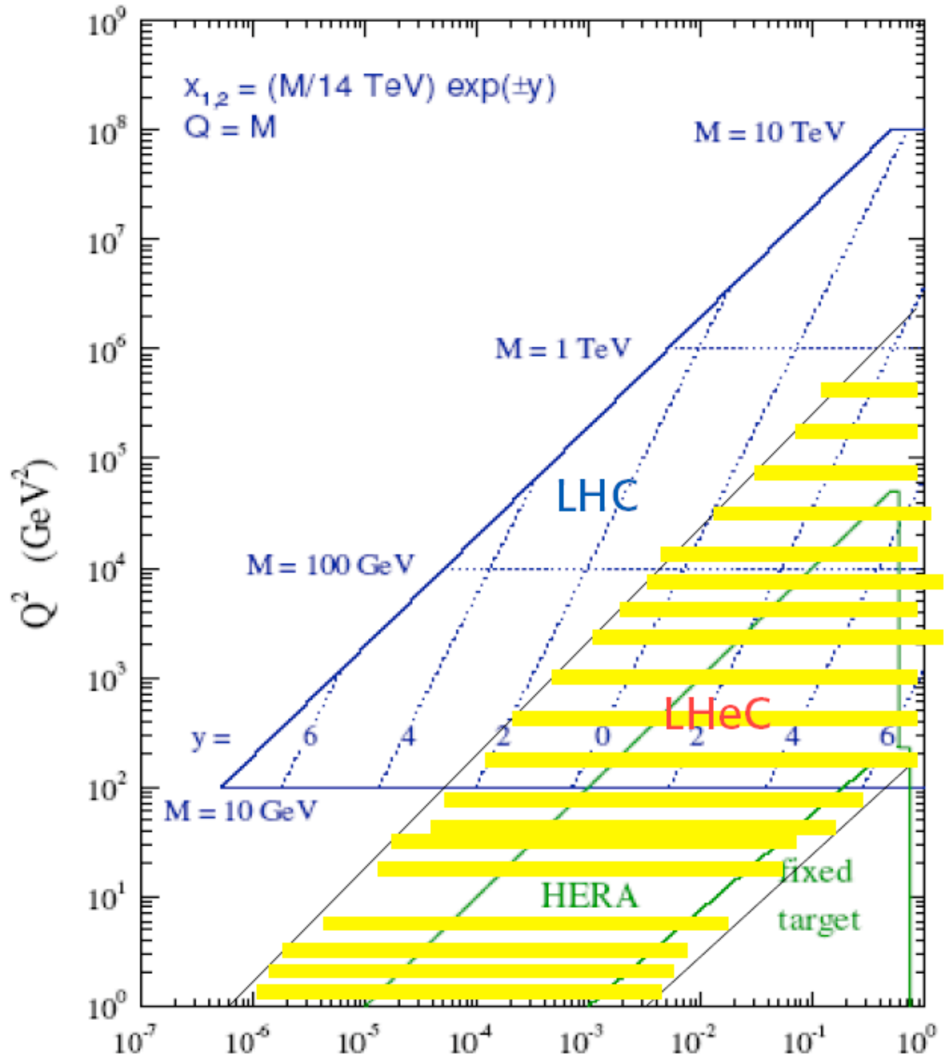
- could extend a bit over the LHC slepton sensitivity
- precise mass measurements ?

  → 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

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 ?

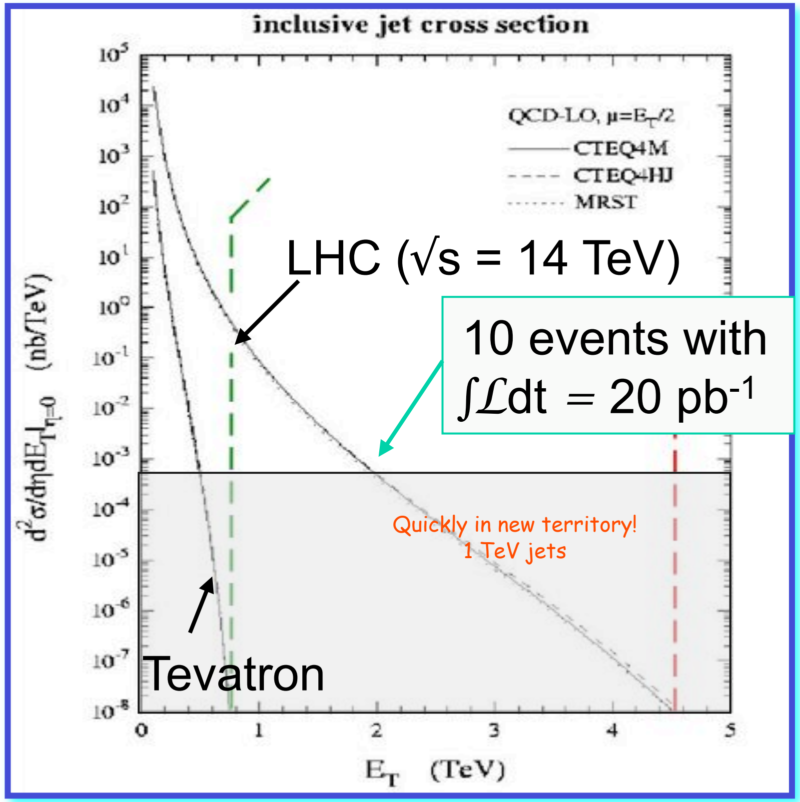
Could pdf effects "fake" new physics at the LHC ?

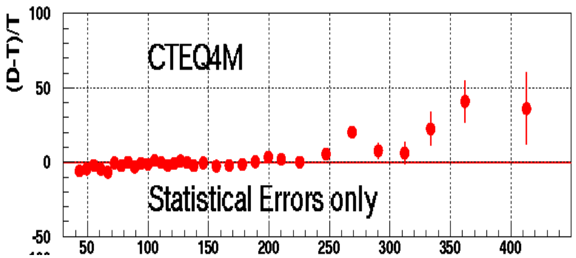
- One possible signal of compositeness is the production of high p_T jets.

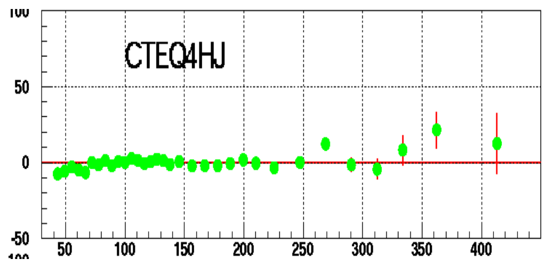
Quickly a new territory with TeV jets !

- 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.



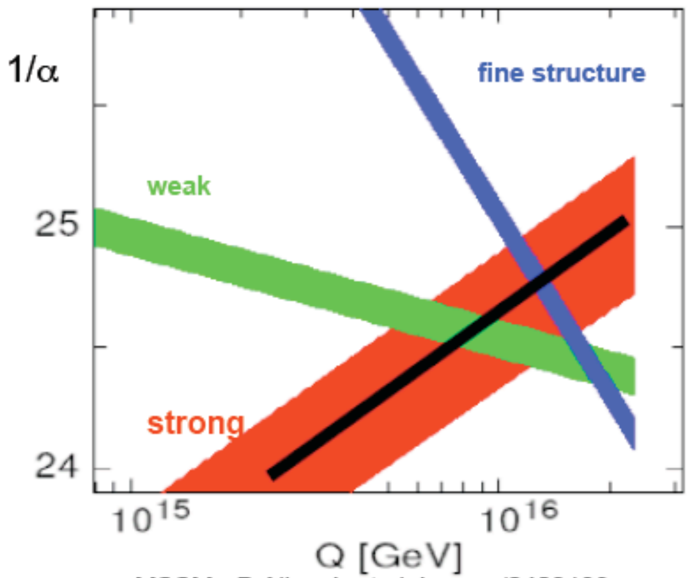




CDF, 1995

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) γ_h>5°	0.36% :=⁽²⁾
(1) +BCDMS	0.22%
(2) +BCDMS	0.22%
(1) stat. *= 2	0.35%

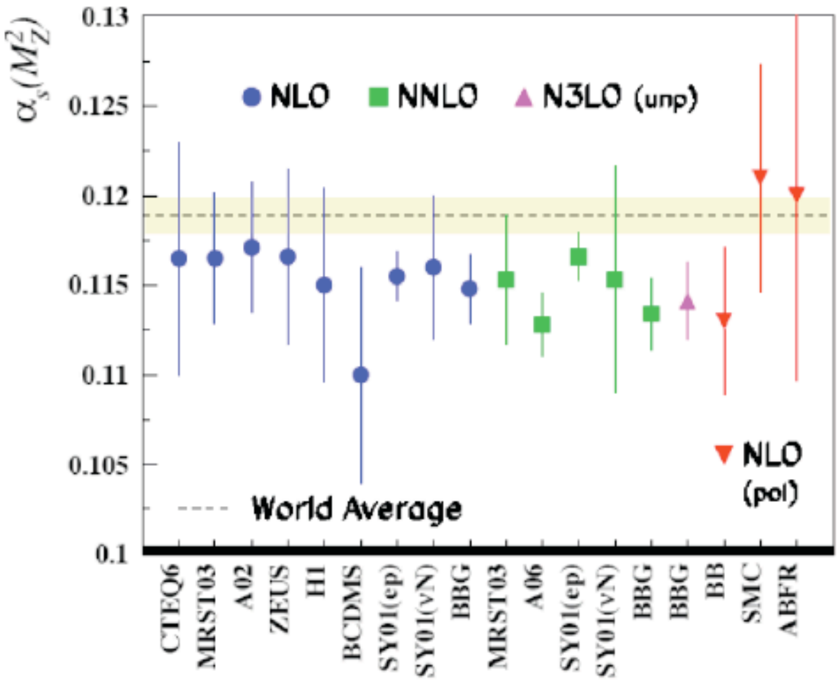
DIS08, T.Kluge

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

Blumlein et al '06



LHeC and a light Higgs boson ?

- 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 ?

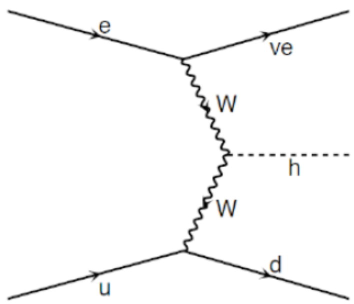
ttH, 60 fb-1, Semi-lepton channel (CMS analysis)

m_H (GeV/c^2)	S	S/B (%)	S/√B	S/√(B+dB²)
115	147	7.0	3.1	0.20
120	118	5.3	2.5	0.16
130	80	3.6	1.7	0.11

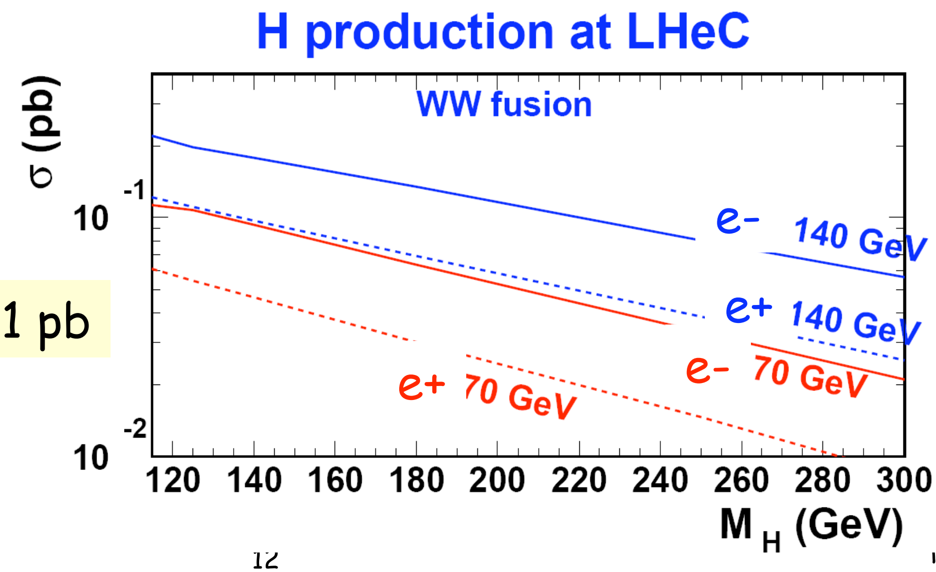
Standard unc. : JES, jet resolution, b-tagging

Although ttH has a x-section of O(1 pb), very difficult to see the signal taking into account syst. uncertainties…

Information on bbH at LHeC ?



σ ~ 0.1 pb



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

bbH coupling

$H \rightarrow bb$ 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

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

For $M_H = 115$ GeV :

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

$H \rightarrow bb$ (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.

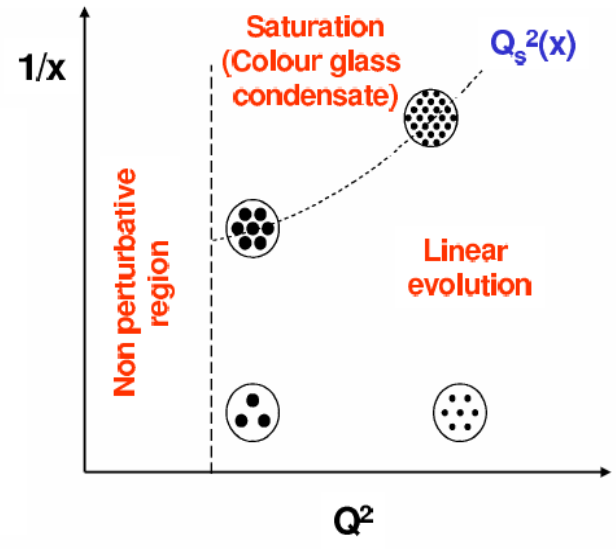
Saturation at the LHC ?

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 $Q_s^2(x) \lesssim 1\,\mathrm{GeV}^2$

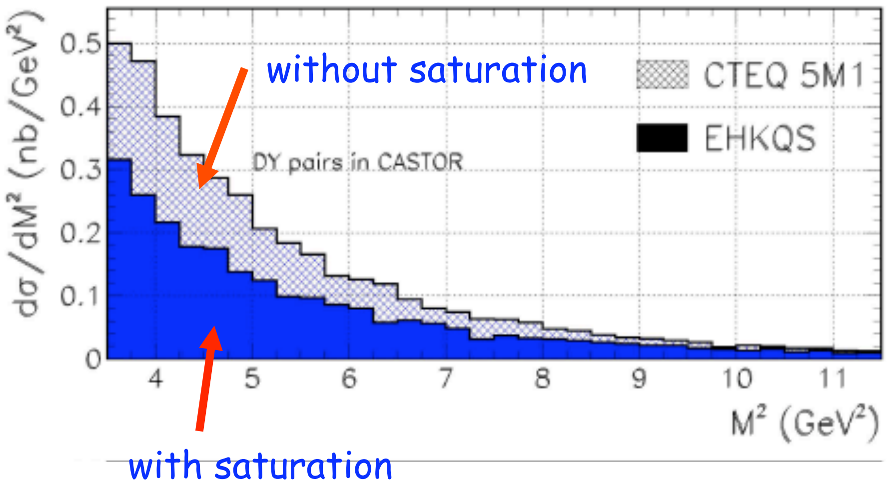


Could be seen at LHC in pp ? E.g. in Drell-Yan production with $x_1 \ll x_2$

→ one very forward lepton:

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

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

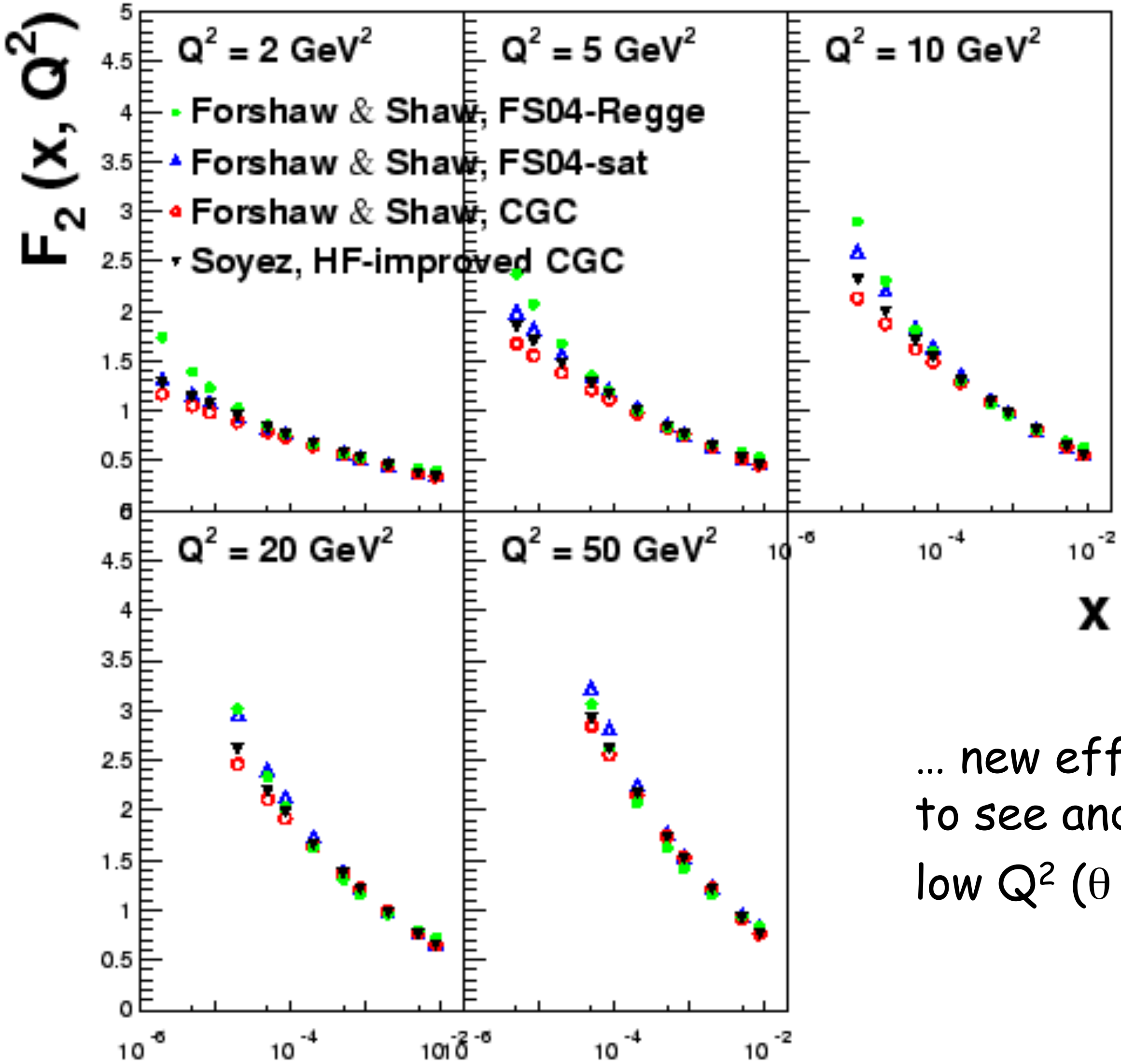


But is one observable enough to establish saturation ??

Fits to HERA data extrapolated to LHeC

With 1 fb^{-1} (1 year at 10^{33} cm^{-2} s^{-1}), 1^{o} 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 ($\theta \rightarrow 179^{o}$) region …

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.

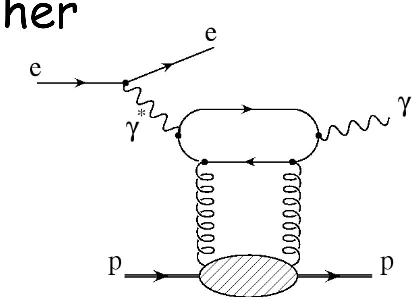
Saturation maybe much more difficult to establish unambiguously from F_2 data alone.

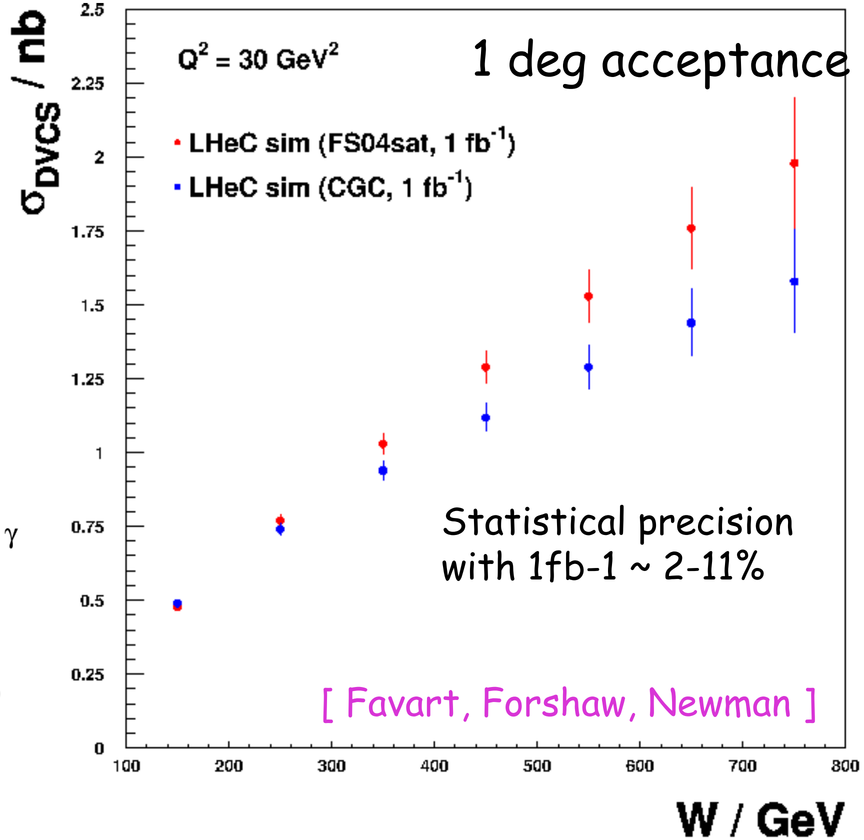
→ important to have measurements at various √s

→ may be also difficult to establish if we have only LHC Drell-Yan data !

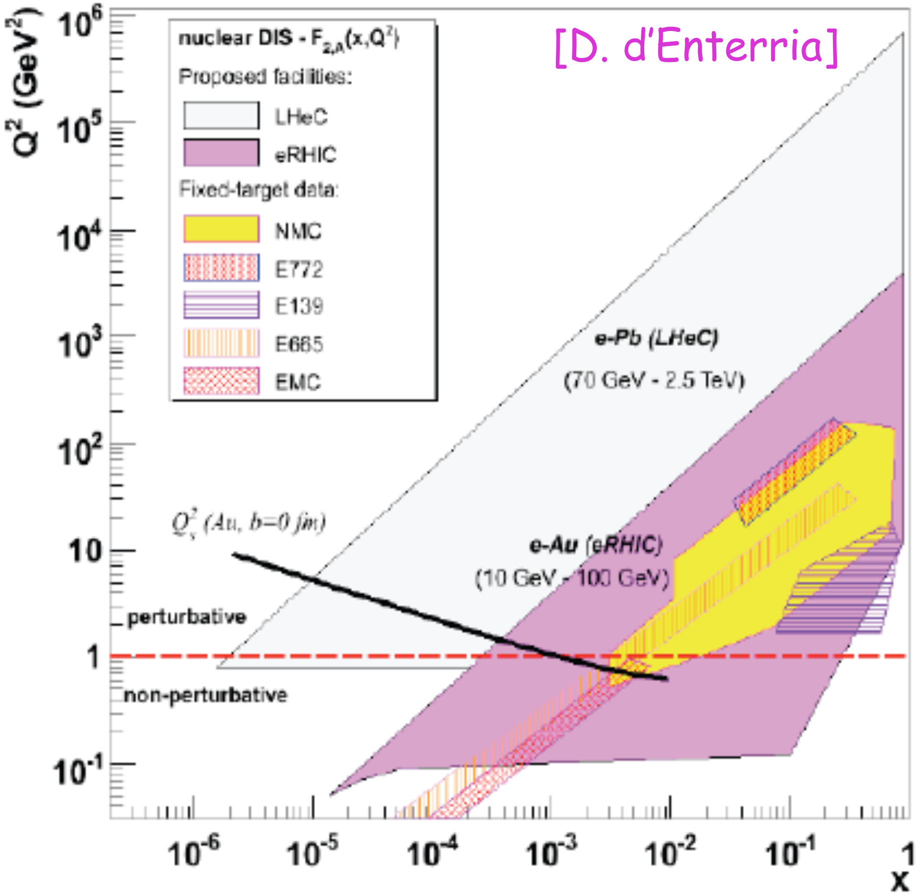
Other observables at LHeC could also provide a handle: heavy quark structure functions, DVCS, exclusive vector meson production, diffractive DIS.

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





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 …

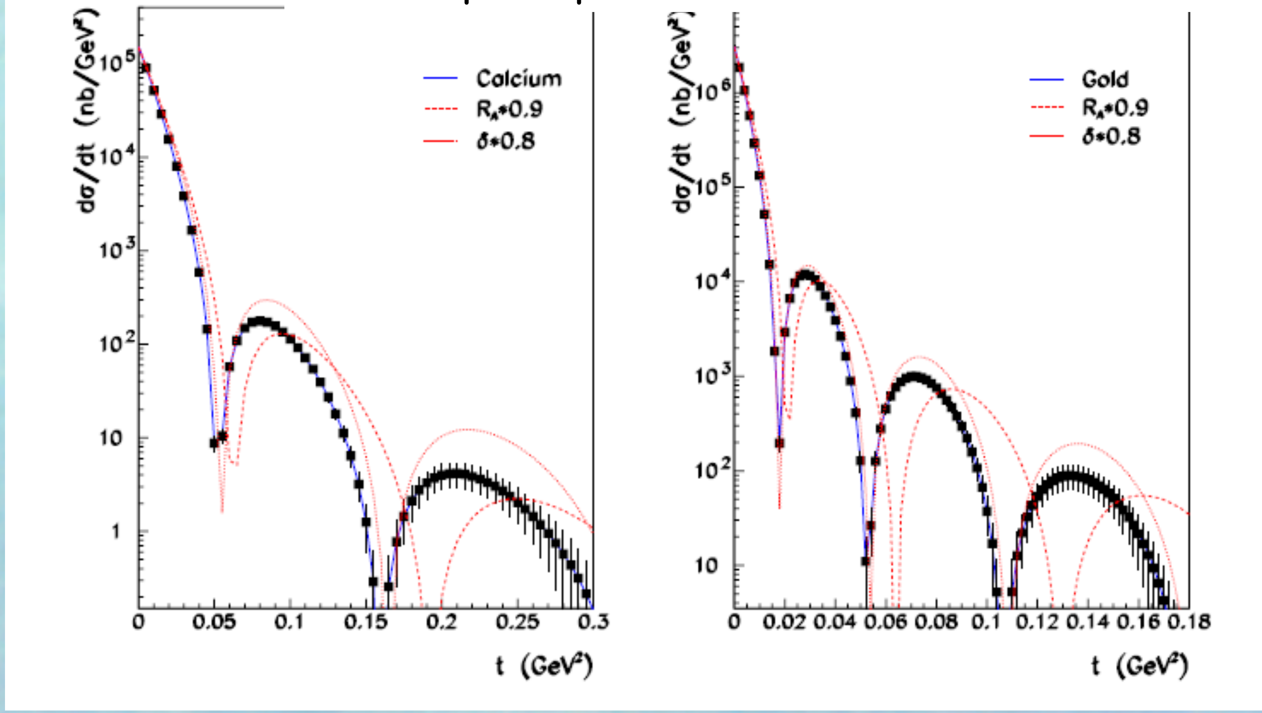
→ ~$A^{1/3}$ enhanced gluon density → additional sat^n sensitivity
→ initial state in AA quark-gluon plasma studies @ LHC / RHIC
→ relations between diffraction and shadowing
meas. of both eA and ep at high densities to test the Gribov-Glauber relationship of nuclear shadowing to diff.
→ Neutron structure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

Very rich physics programme !

Nuclear gluonic shapes at EIC and LHeC

Coherent eA ➔ J/ψA production

photoproduction



$\Delta p_T \sim 10$ MeV

p_T resolution depends on the measurement of leptons only

electron beam has similar proper. at LHeC as at EIC

Look into inner arrangements of nucleons in nucleus?

Incoherent exclusive J/y production
- Nucleus disintegrates

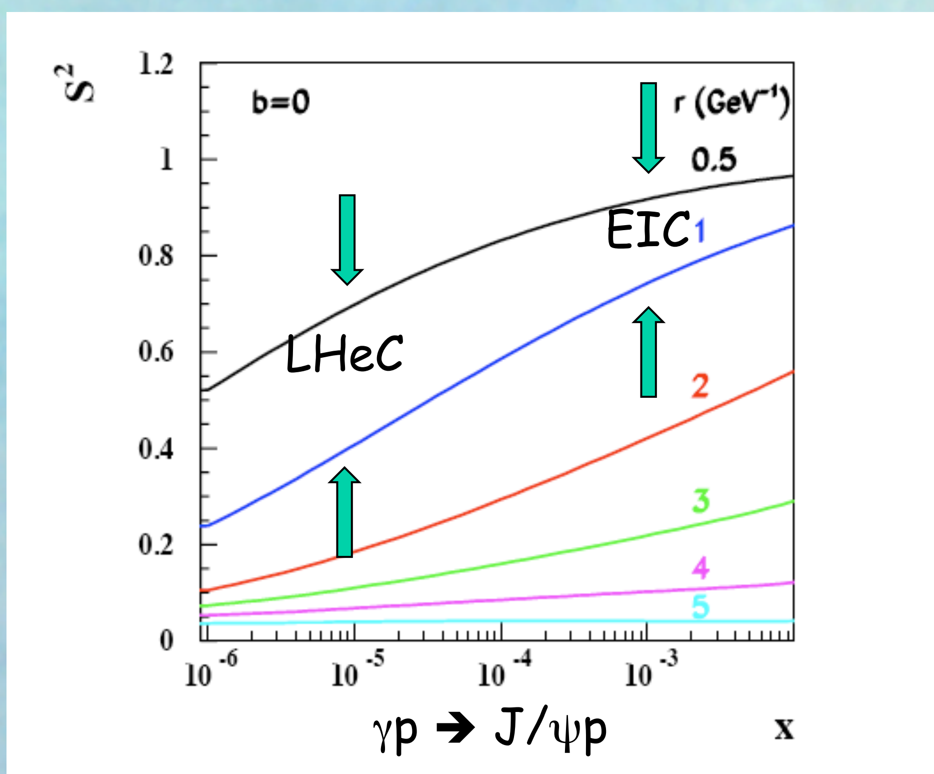
The measurement of the t-distribution correlated with the number and momenta of the breakup neutrons and protons can become an invaluable source of information about the nuclear forces

LHeC is complementary to EIC; it is more difficult to measure the momenta of breakup protons and neutrons but the saturation effects are more pronounced

Impact dependent saturation studies with J/ψ

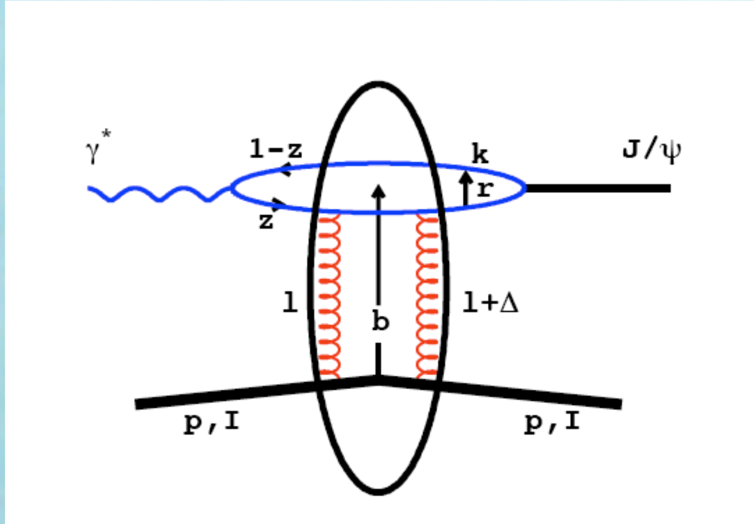
Saturation leads to a clear distortion of a proton or nuclear shape

Survival Probability S^2 $d\sigma_{qq}/d^2b = 2[1 - \Re S(b)]$



Munier, Stasto,Mueller
Kowalski,Teaney

J/psi p_T resolution



J/psi p_T can be determined from the momentum of ee or μμ decay pair

no measurement of the proton or ion momentum necessary

p_T resolution for J/psi - O(2) MeV for a TPC with 1m radius
beam electron p_T < 1 MeV
scattered electron can be easily detected in the forw. det.

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.

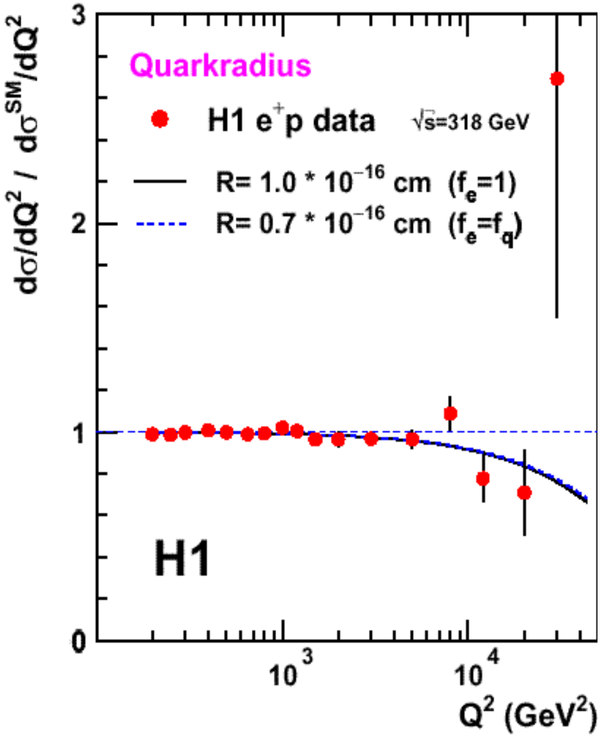
- First ECFA/CERN workshop successfully gathered accelerator, theory & experimental colleagues.

- 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 :

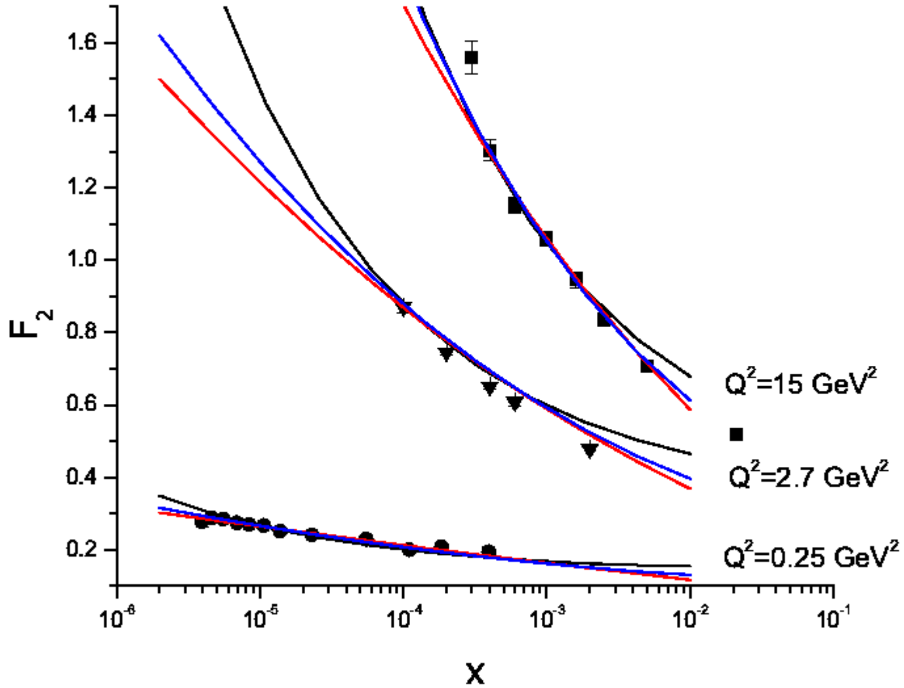
$$< r_q > < 8.\ 10^{-20}\ m$$

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, no saturation
FS04 Satn: Simple implementation of saturation
CGC: Colour Glass Condensate version of saturation

- 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

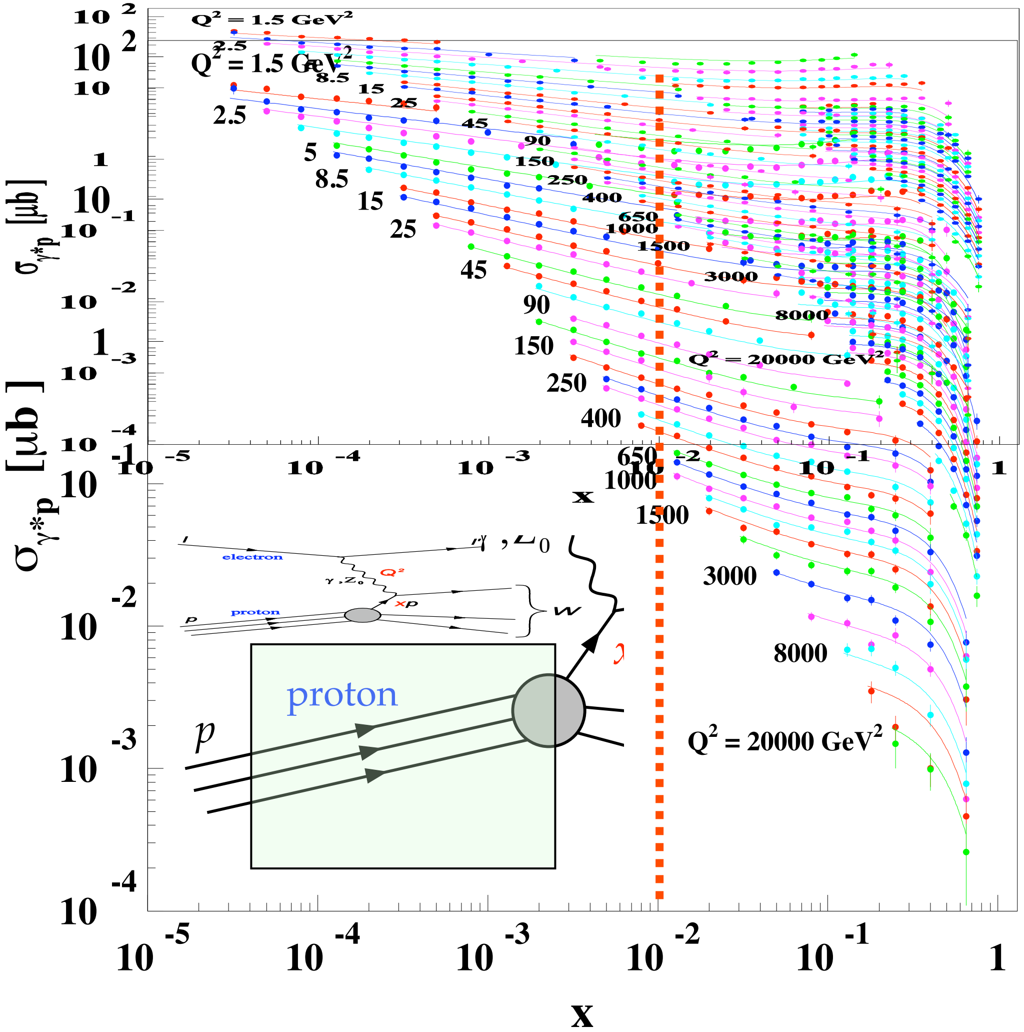
- F = 0 or 2 ? — Compare rates in e^-p and e^+p
- Spin ? — Angular distributions
- Chiral couplings ? — Play with polarisation of lepton beam
- Couples to ν ? — Easy to see since good S/B in νj channel

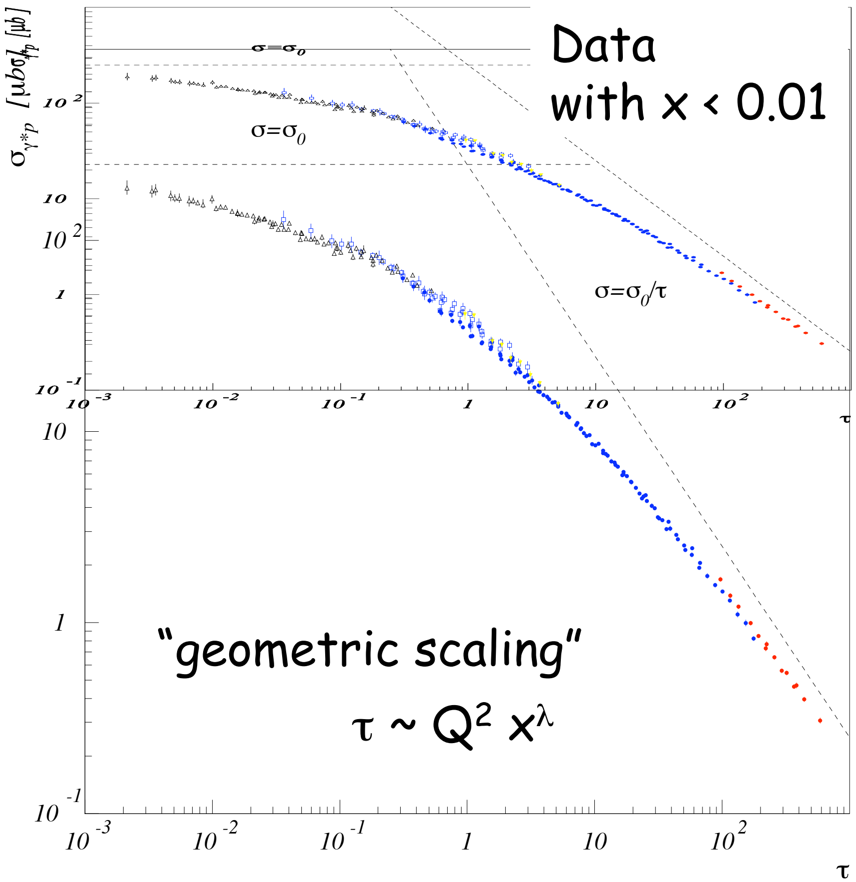
Classification in the table below relies on minimal assumptions.
ep observables would allow to disentangle most of the possibilities (having a polarised p beam would complete the picture).

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

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 ?



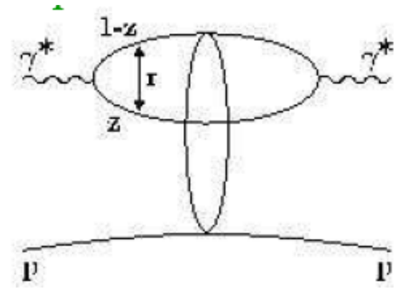


- ► Saturation may be thought as something like a phase transition:
  from free to strongly interacting partons
  from a low to a high density system
- ► Some of the QCD based nonlinear equations proposed for saturation accept naturally solutions with geometric scaling behavior

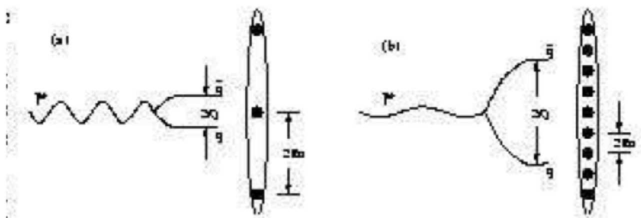
And also described well in dipole models with a saturating dipole-proton cross-section.

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

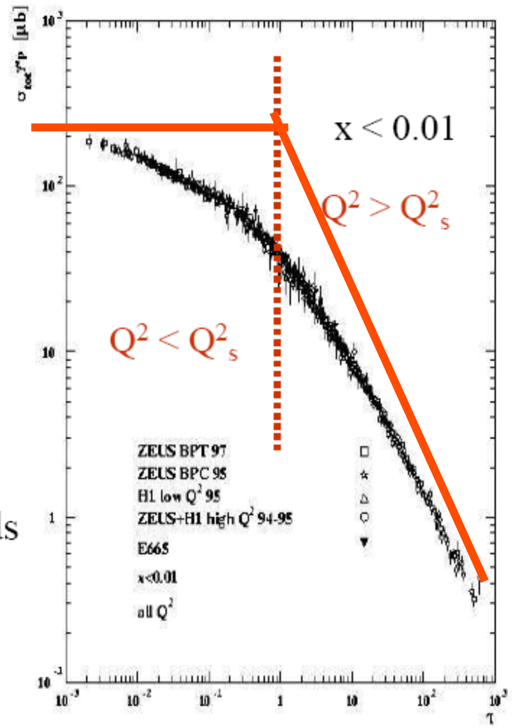
$\sigma = \sigma_0 (1 - \exp(-1/\tau))$

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



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…

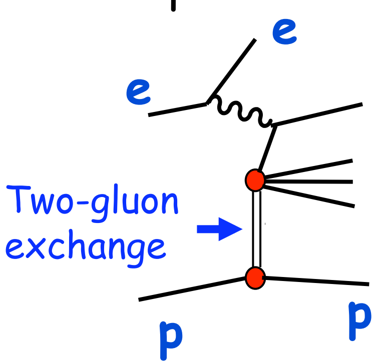
Another "hint" for saturation comes from diffractive data.

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 $\delta \sim 0.08$

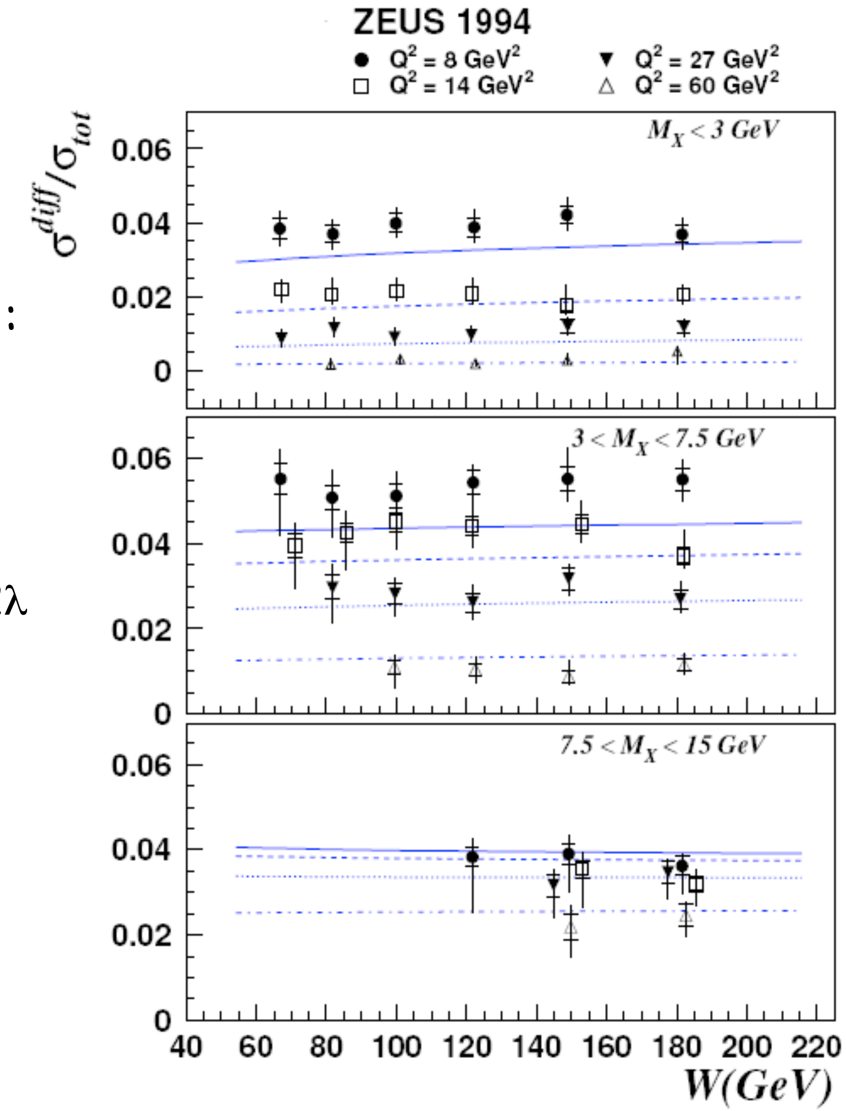
- not explained in QCD :



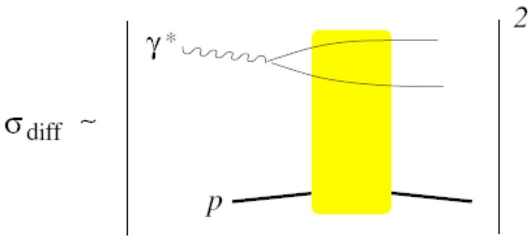
$\sigma_{diff} \sim (xg(x))^2 \sim x^{-2\lambda}$

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

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



- Naturally explained in dipole models with saturation



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

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

Conclusions

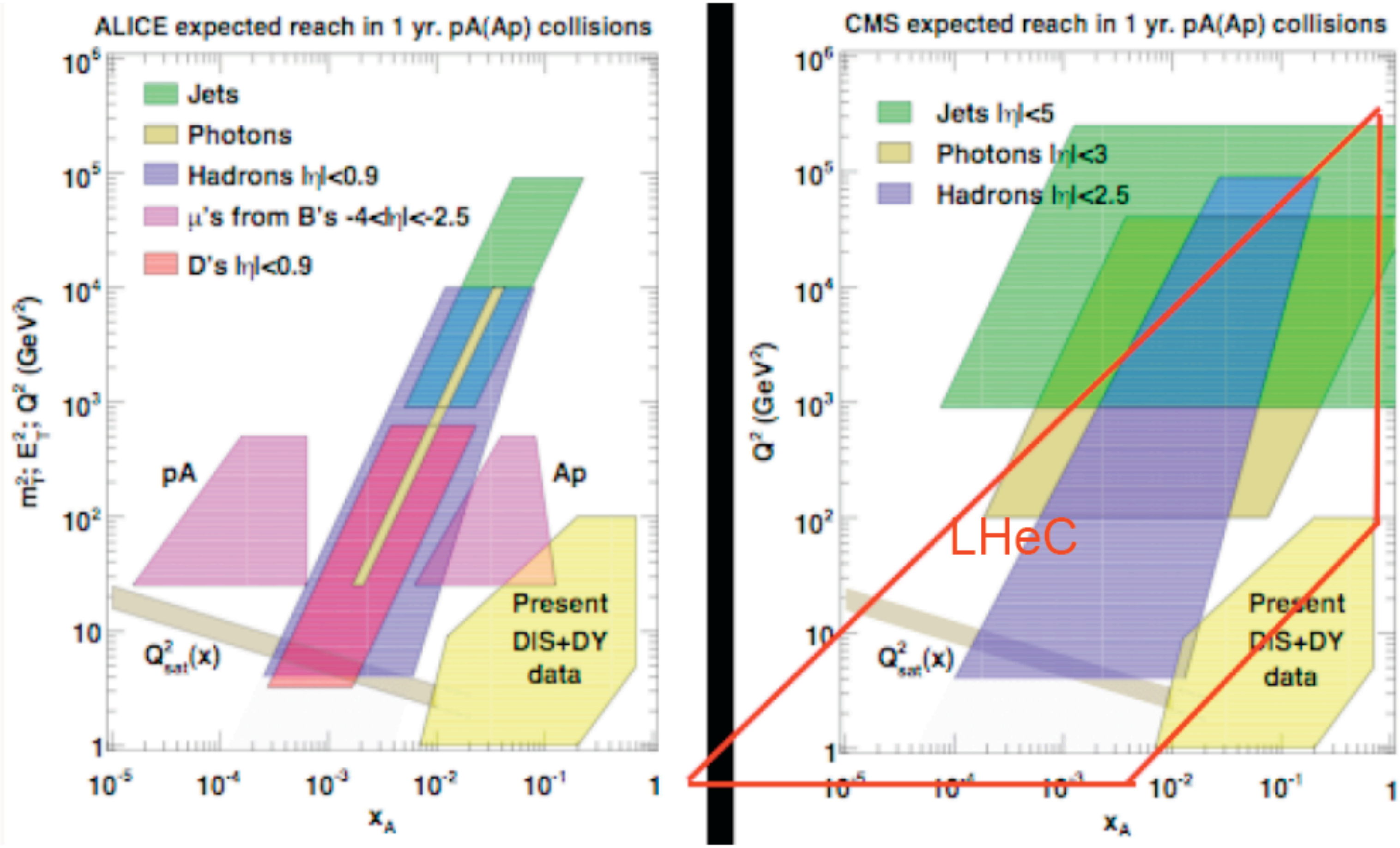
For "new physics" phenomena "coupling" directly electrons and quarks (e.g. leptoquarks, eeqq contact interactions) : LHeC has a sensitivity similar to that of LHC.

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



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Note that DY is not DIS