QCD at the LHeC

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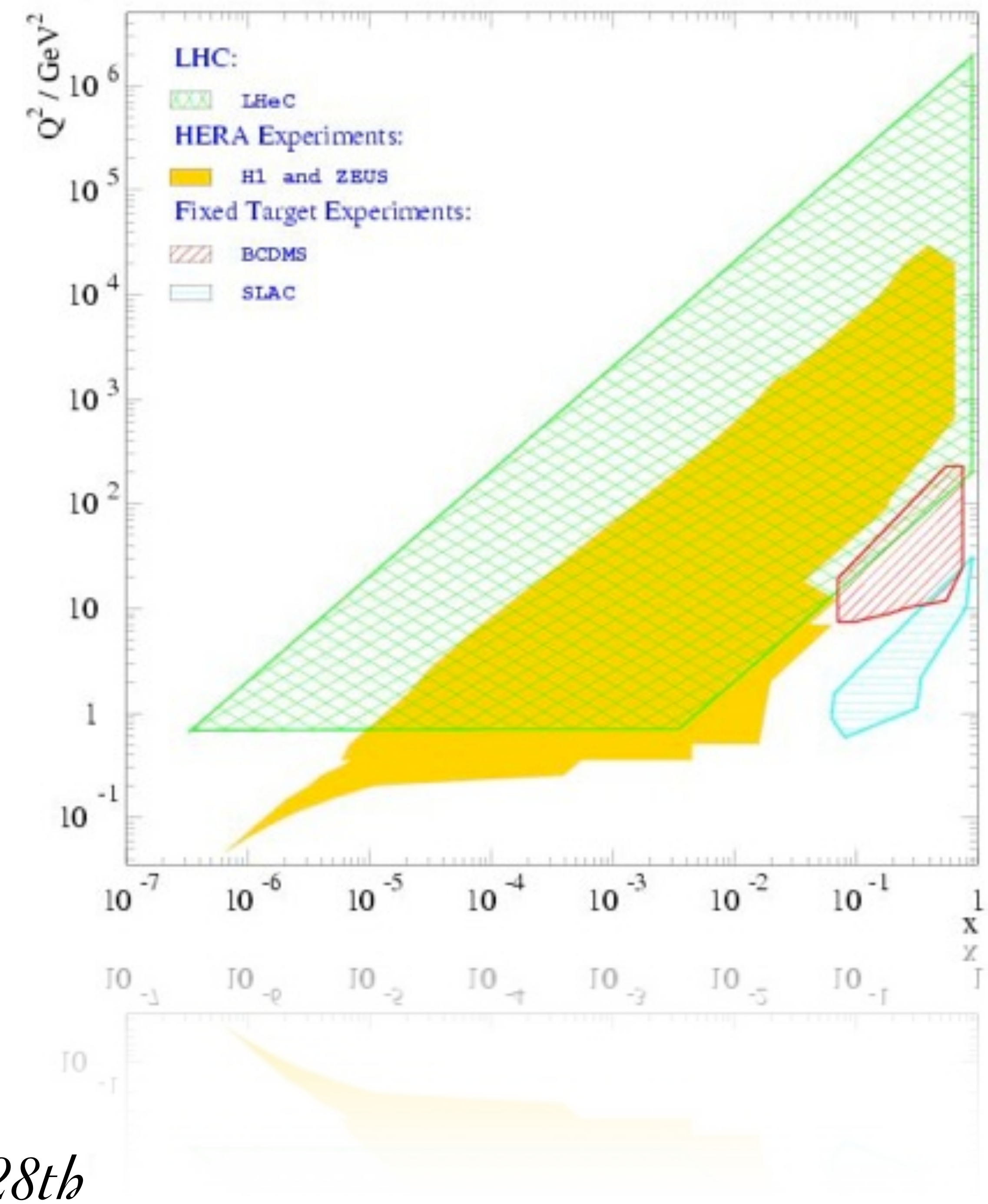
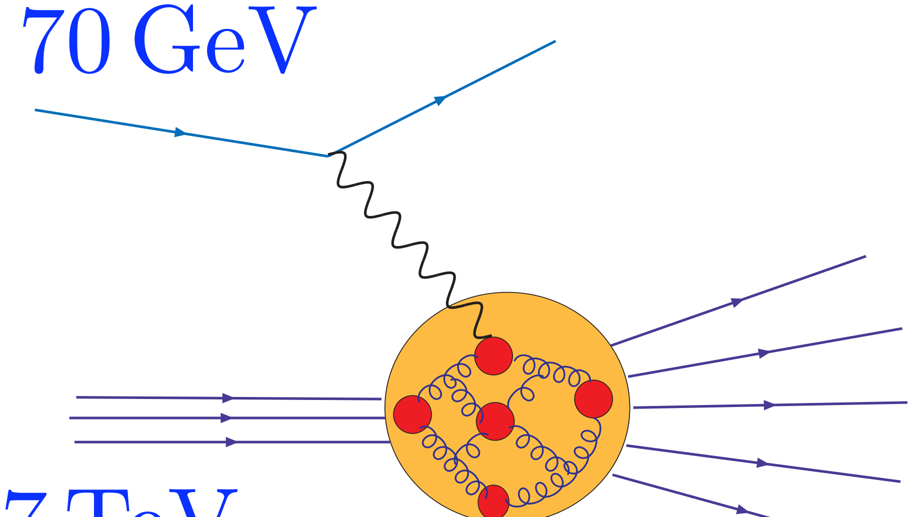
Working group: Low x and high densities in ep and eA.
Nestor Armesto, Brian Cole, Paul Newman, A.S.



$$E_e = 70\,\mathrm{GeV}$$



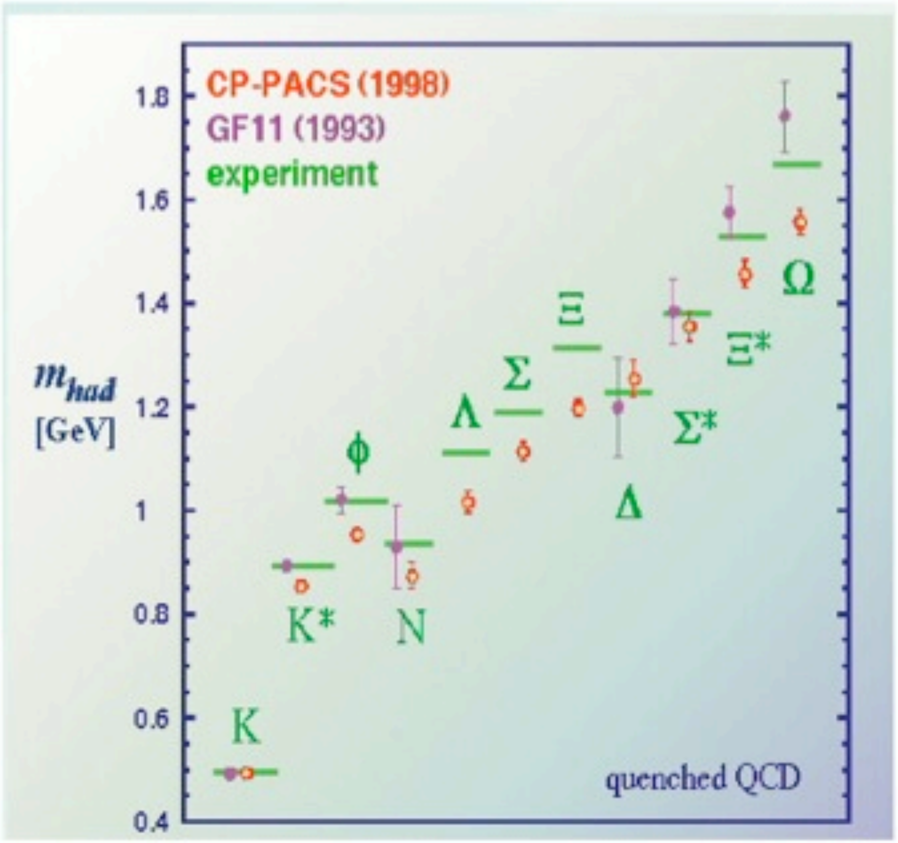
$$E_p = 7\,\mathrm{TeV}$$

DIS 2009, Madrid, April 28th

- Outstanding questions in QCD at low x and high densities
- LHeC potential
- Inclusive processes in ep and eA
- Diffraction

QCD: theory of strong interactions

- Strong interactions responsible for about 99% percent of the visible mass in the universe.
- Rich and very complicated structure due to non-linear interactions of gluons.
- Emergent phenomena: confinement, Regge trajectories, hadron spectrum.
- Complex dynamics at high energies or small x.



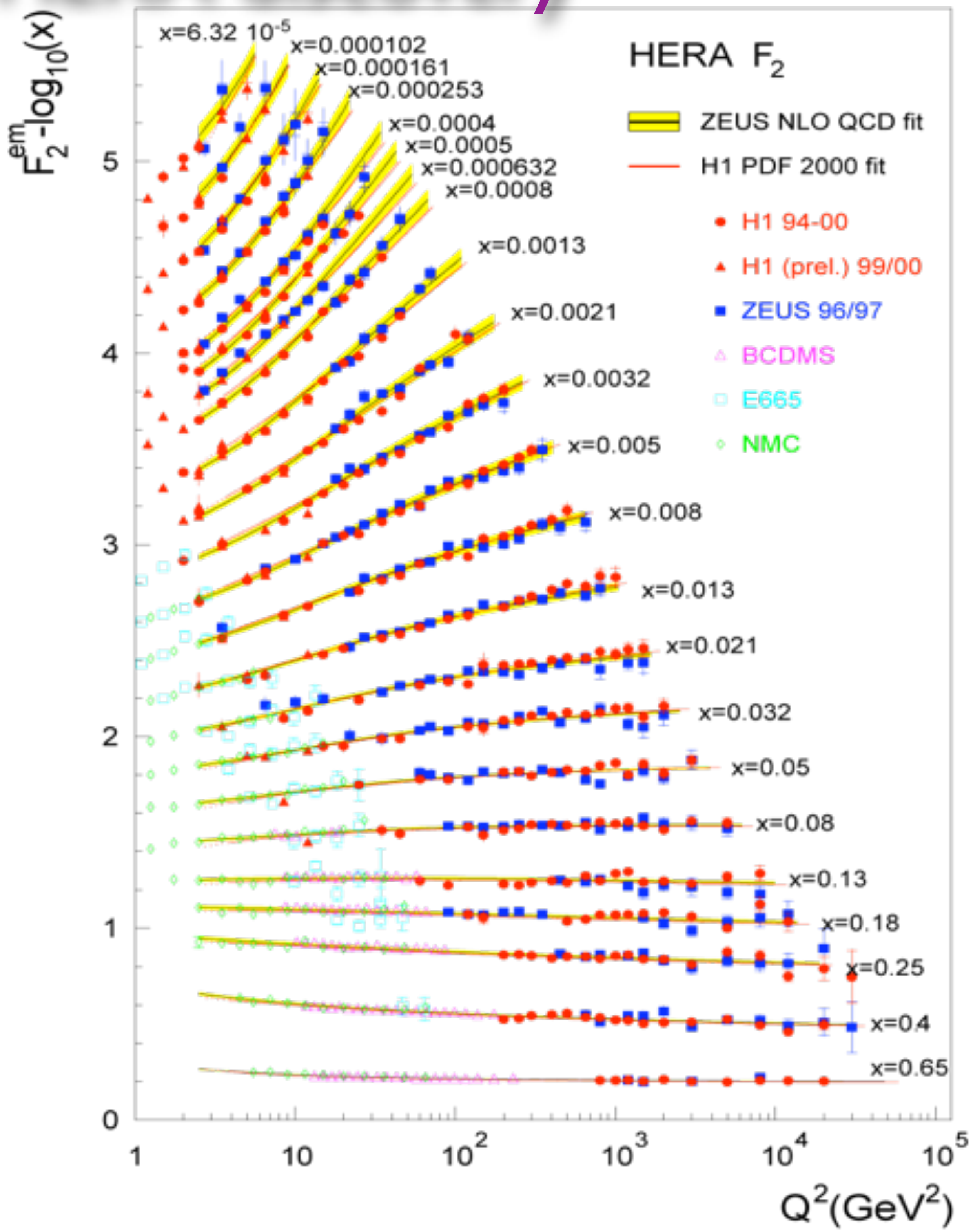
Lattice QCD reproduces hadron spectrum

Understanding of the dynamics of the gluon fields is of fundamental importance.

What we learned from HERA?

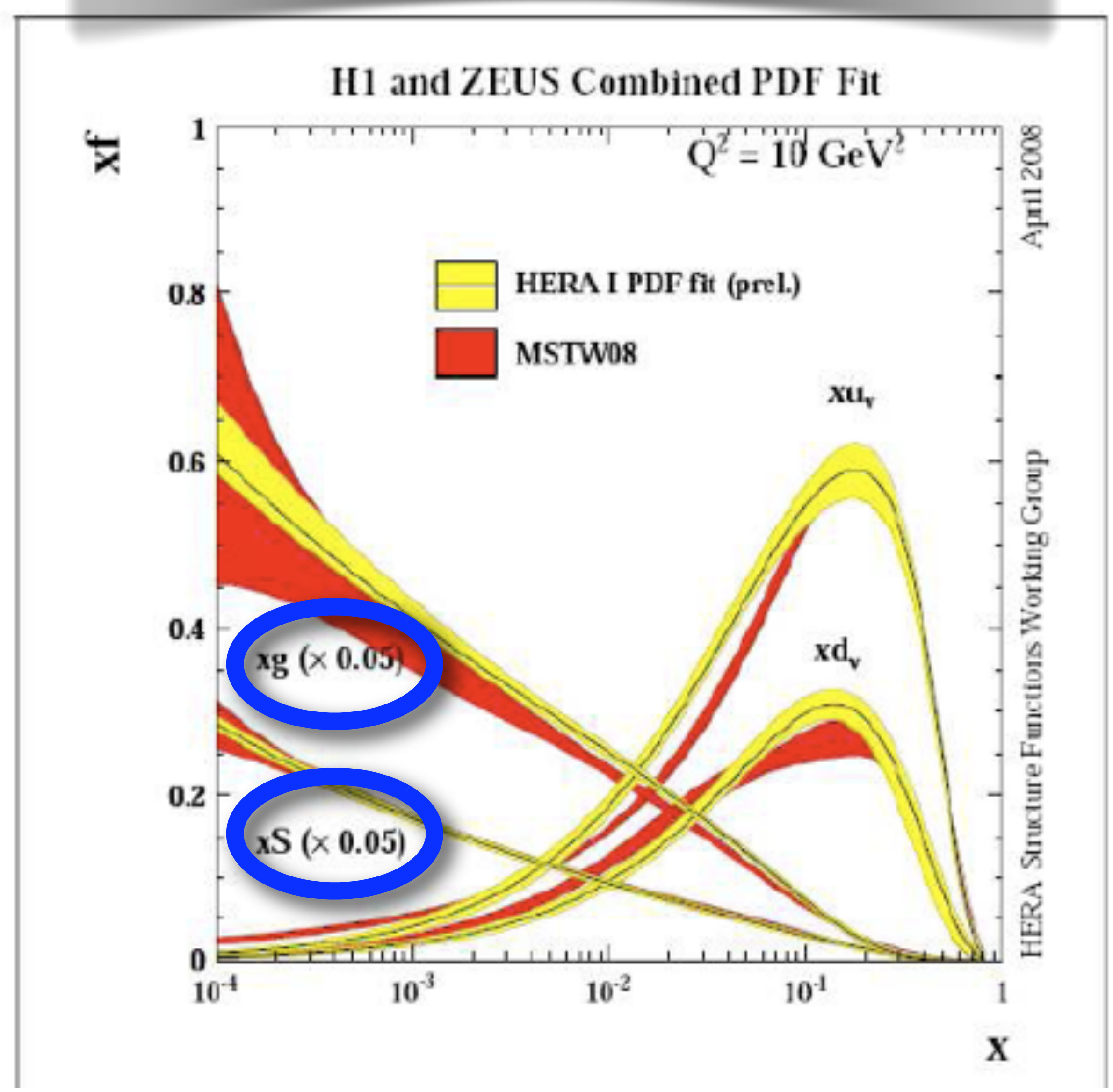
HERA discovery

Deep Inelastic Scattering:
$$\frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2_{e.m.}}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$



Observation of large scaling violations.

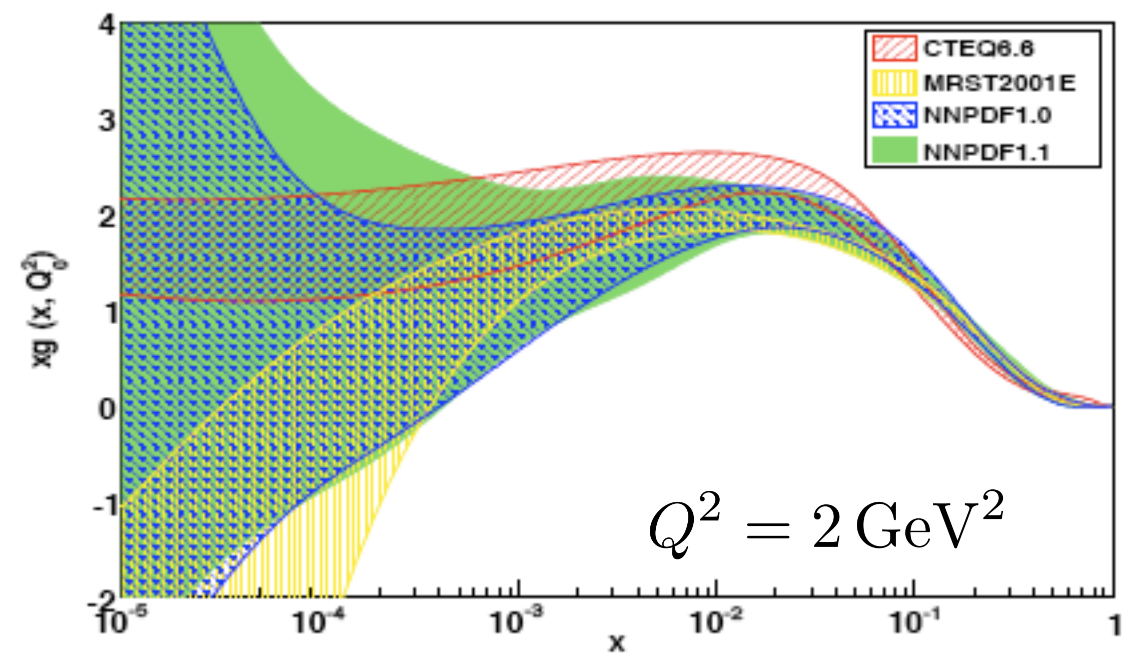
Gluon density dominates!



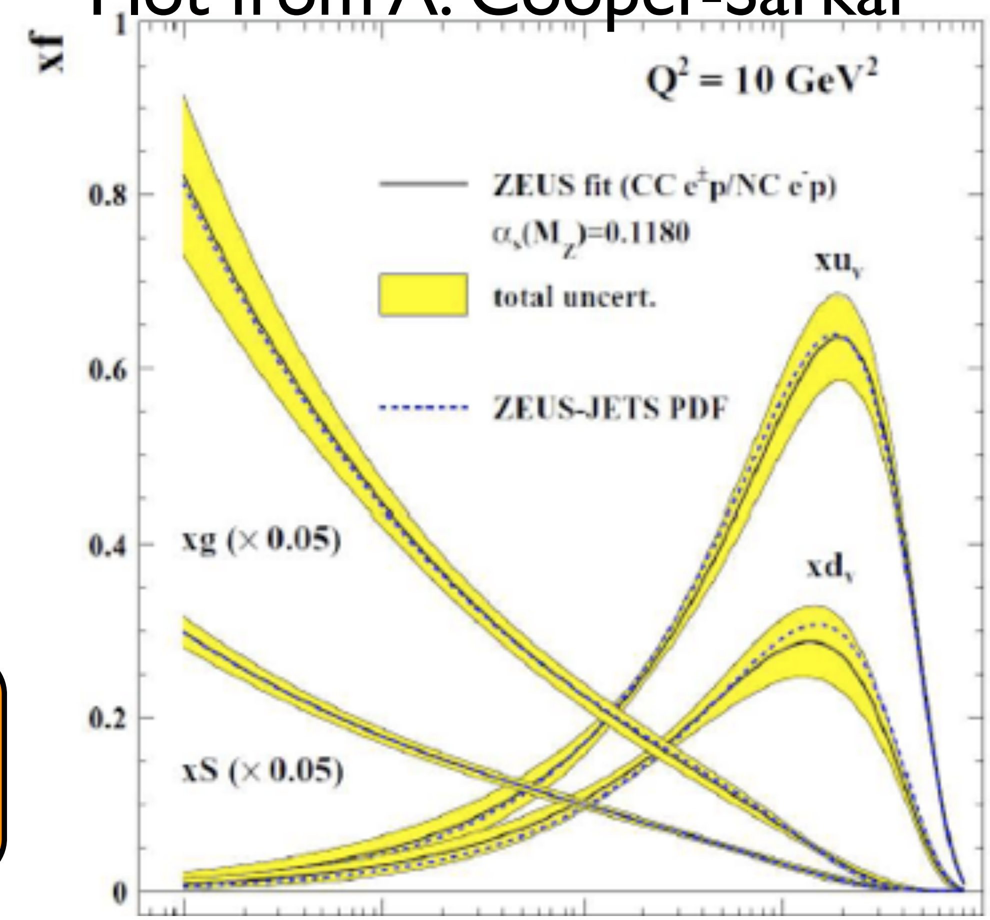
...but there are still unresolved issues...

- Strange behavior of the gluon density for small x and small Q. Implications for FL.
- Signal of the breakdown of linear DGLAP evolution?
- Higher twist/saturation, or resummation effects needed?
- Large number of diffractive events. The ratio of diffractive to inclusive constant with energy.
- What happens when the gluon density/probability of interaction becomes large?
- Unitarity has to be satisfied. When gluon density saturates?
- What is the underlying microscopic dynamics?
- Importance for the neutrino physics at high energies. Also cosmic rays.

Plot from P. Nadolsky



Plot from A. Cooper-Sarkar



LHeC has a potential for answering these questions

Parton saturation

- At small x the linear evolution gives strongly rising gluon density.
- BK/JIMWLK non-linear evolution includes the recombination effects.
- Dynamically generated scale:

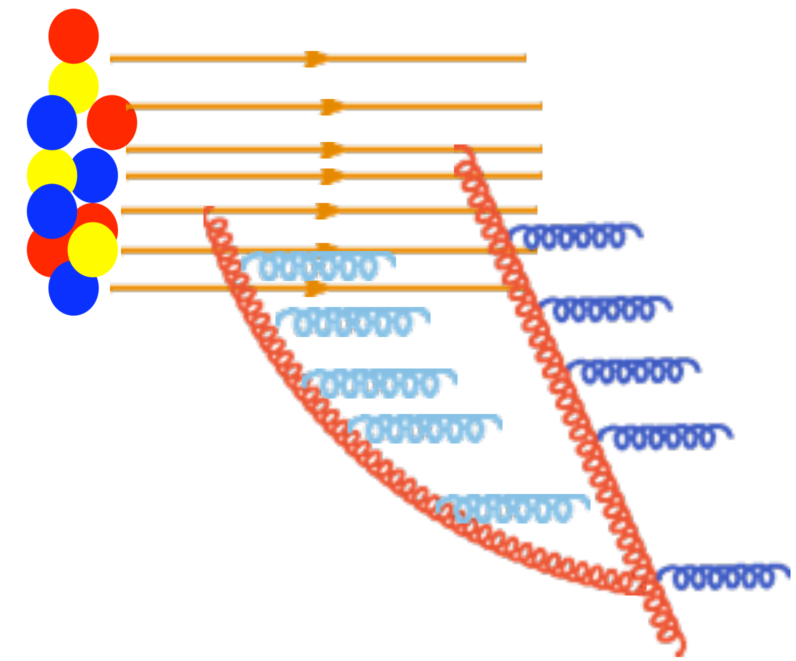
Saturation scale: $Q_s^2(x)$

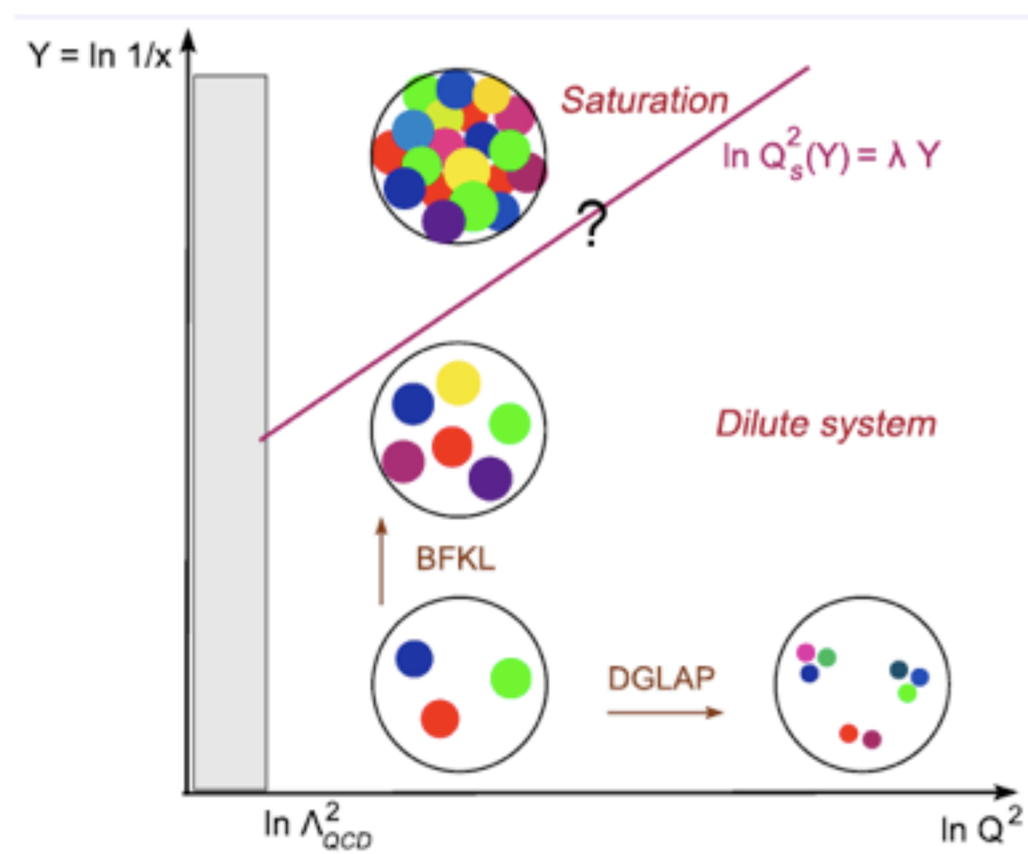
- Characterizes the boundary between the non-linear and linear regime.
- Increases with energy or with decreasing x.

Question:

- What is the relation between saturation and soft regime? Confinement?

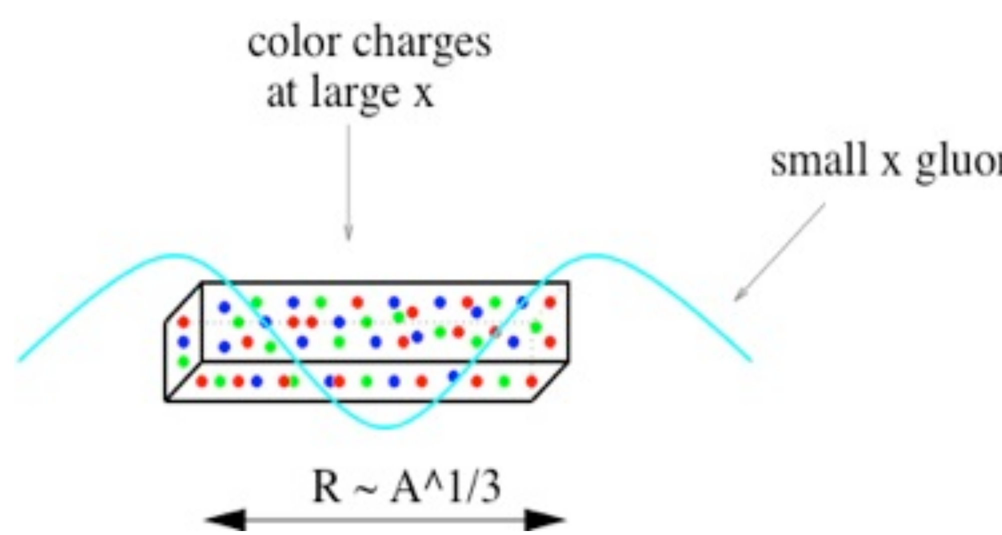
Fast proton or nucleus





Saturation scale grows with A

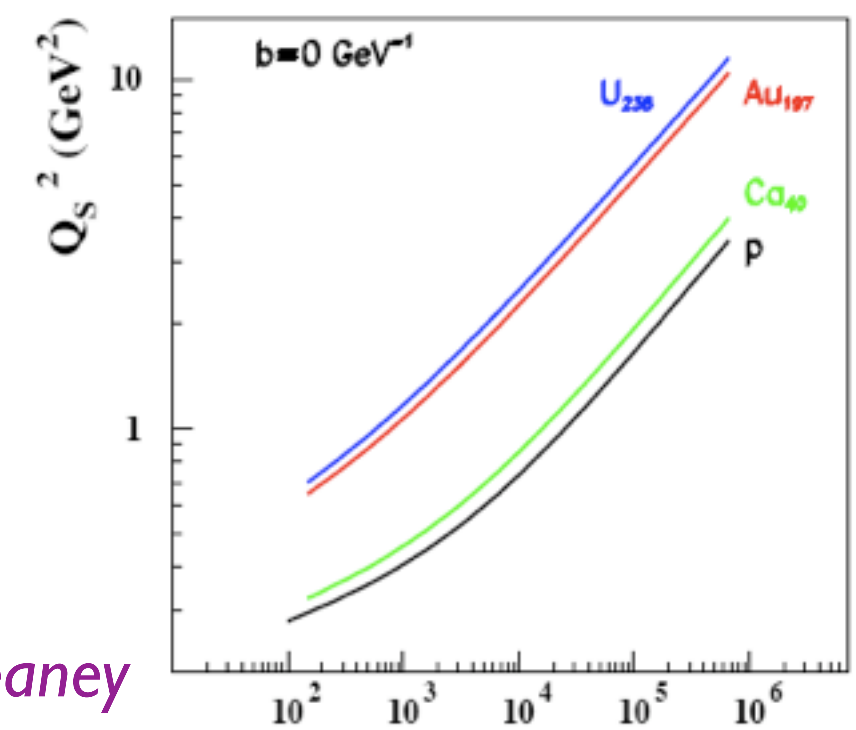
- Probes interact over distances $L \sim \dfrac{1}{2m_N x}$
- For $L > 2R_A \sim A^{1/3}$ high-energy probes interact coherently across nuclear size. Very large field strengths.



Pocket formula:

$$Q_s^2(x, A) \sim Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

Scattering off nuclei: Saturation is reached for smaller energies due to the enhancement from A.

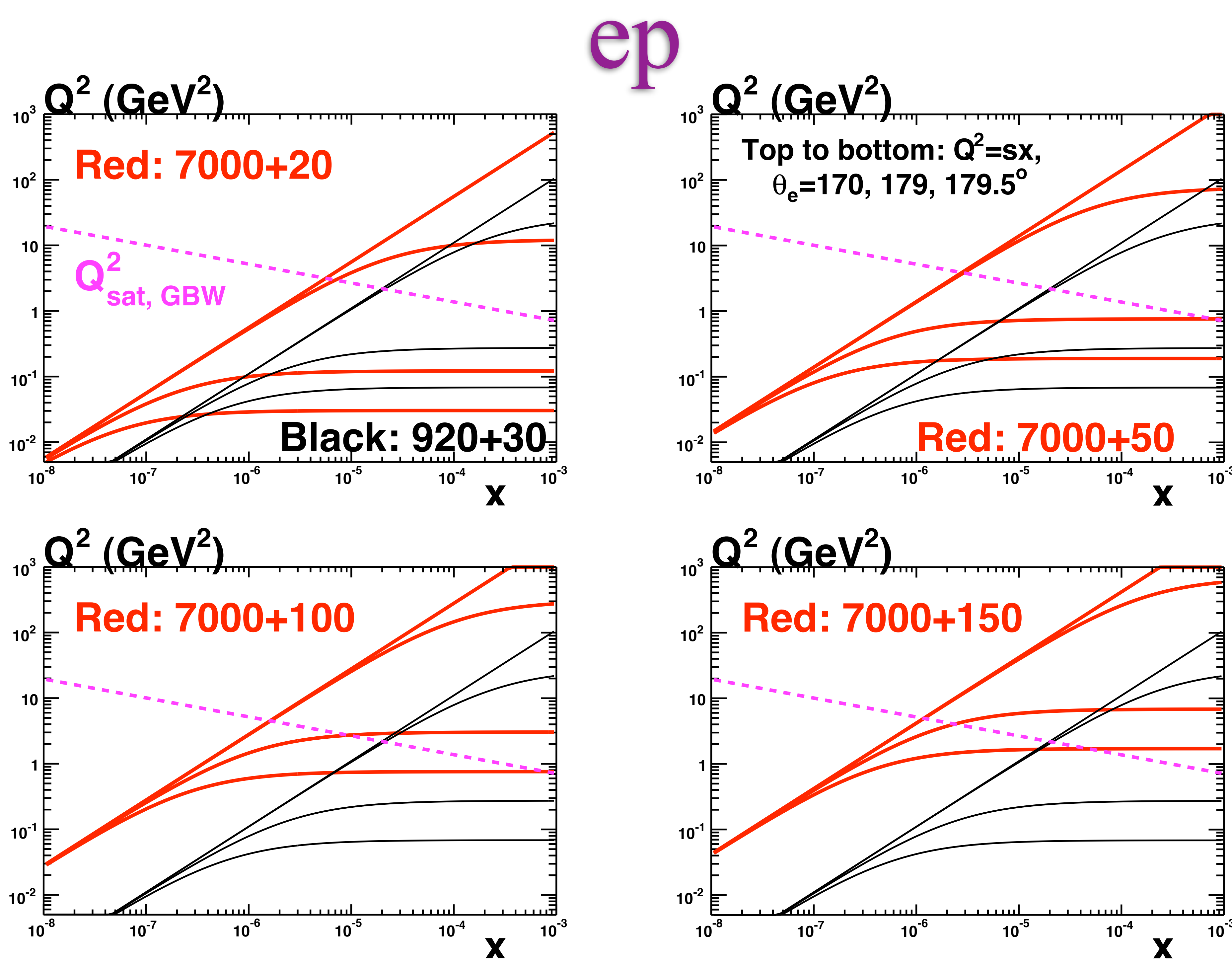


Kowalski, Teaney

LHeC kinematics

Access to Q^2=1 GeV^2 for all x > 5 x 10^{-7} IF we have acceptance to 179°

→ Without low β magnets ~ 1 fb^{-1} / yr … definitive low x facility (parton saturation ?…)



LHeC extended kinematic range will allow to probe the nonlinear regime for fixed perturbative Q while decreasing x.

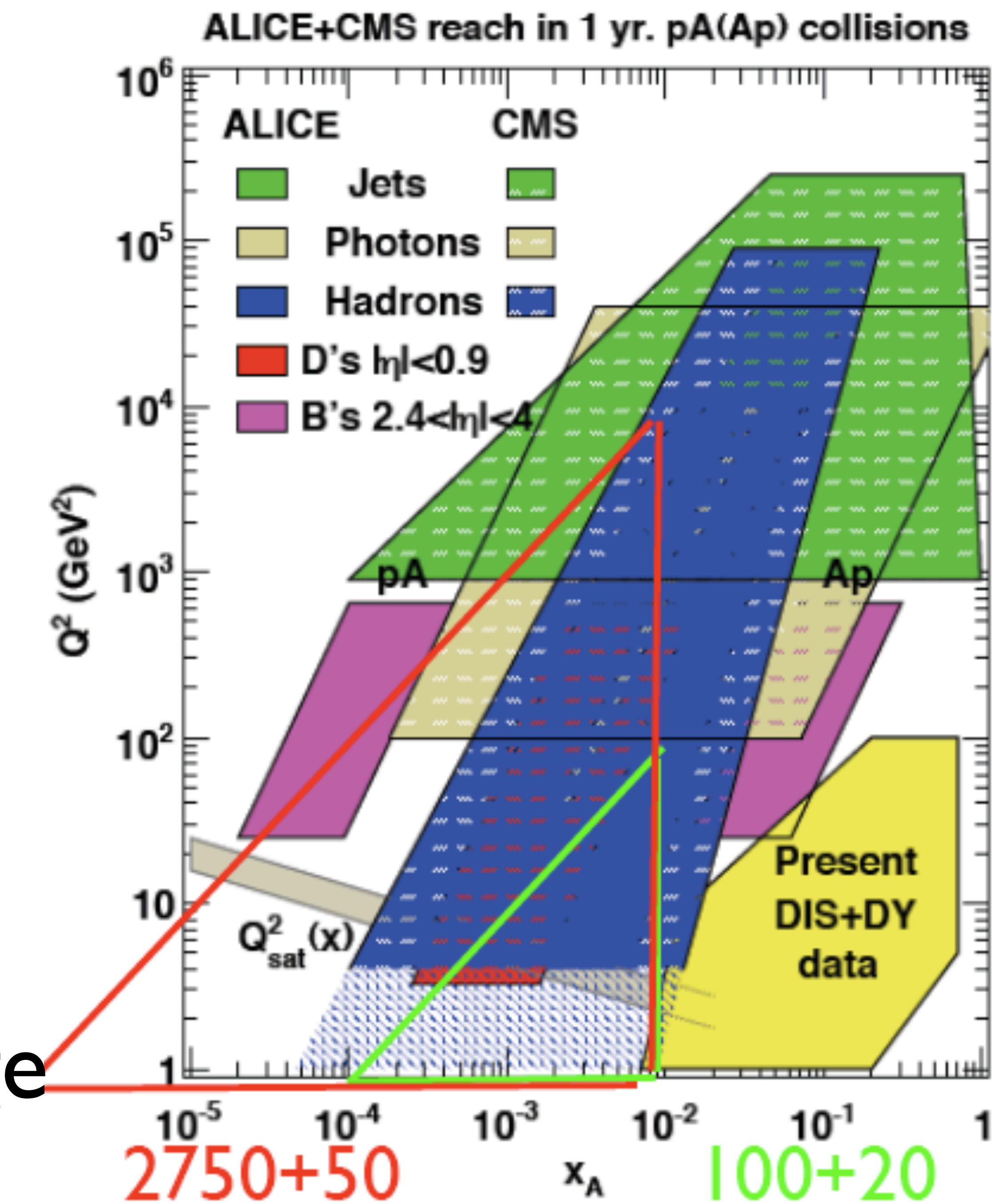
LHeC kinematics

- 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

eA LHeC will measure the initial state which is crucial for understanding the AA collisions.

eA

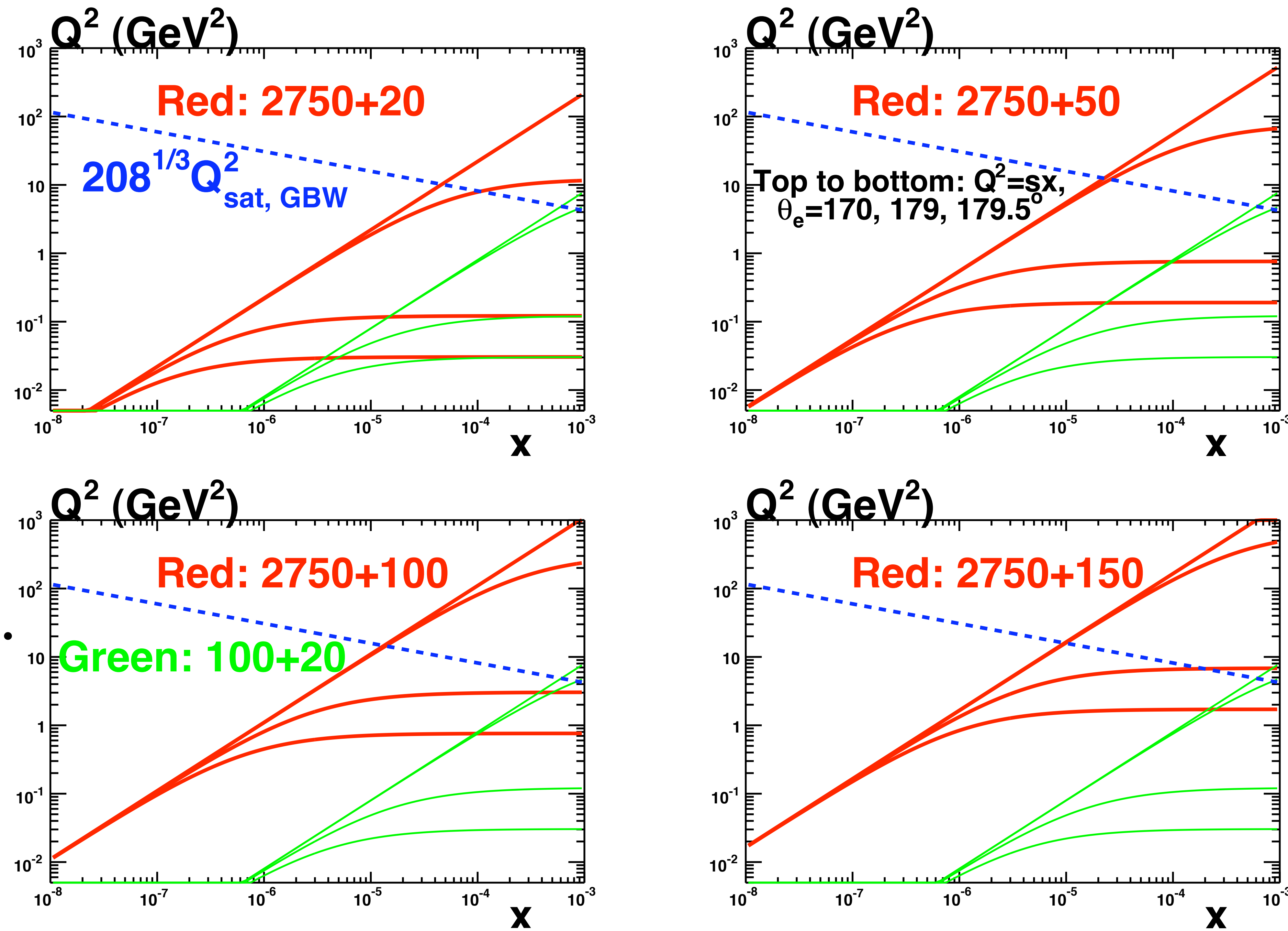


LHeC kinematics

eA

Kinematics in different scenarios.

Green: eRHIC range.

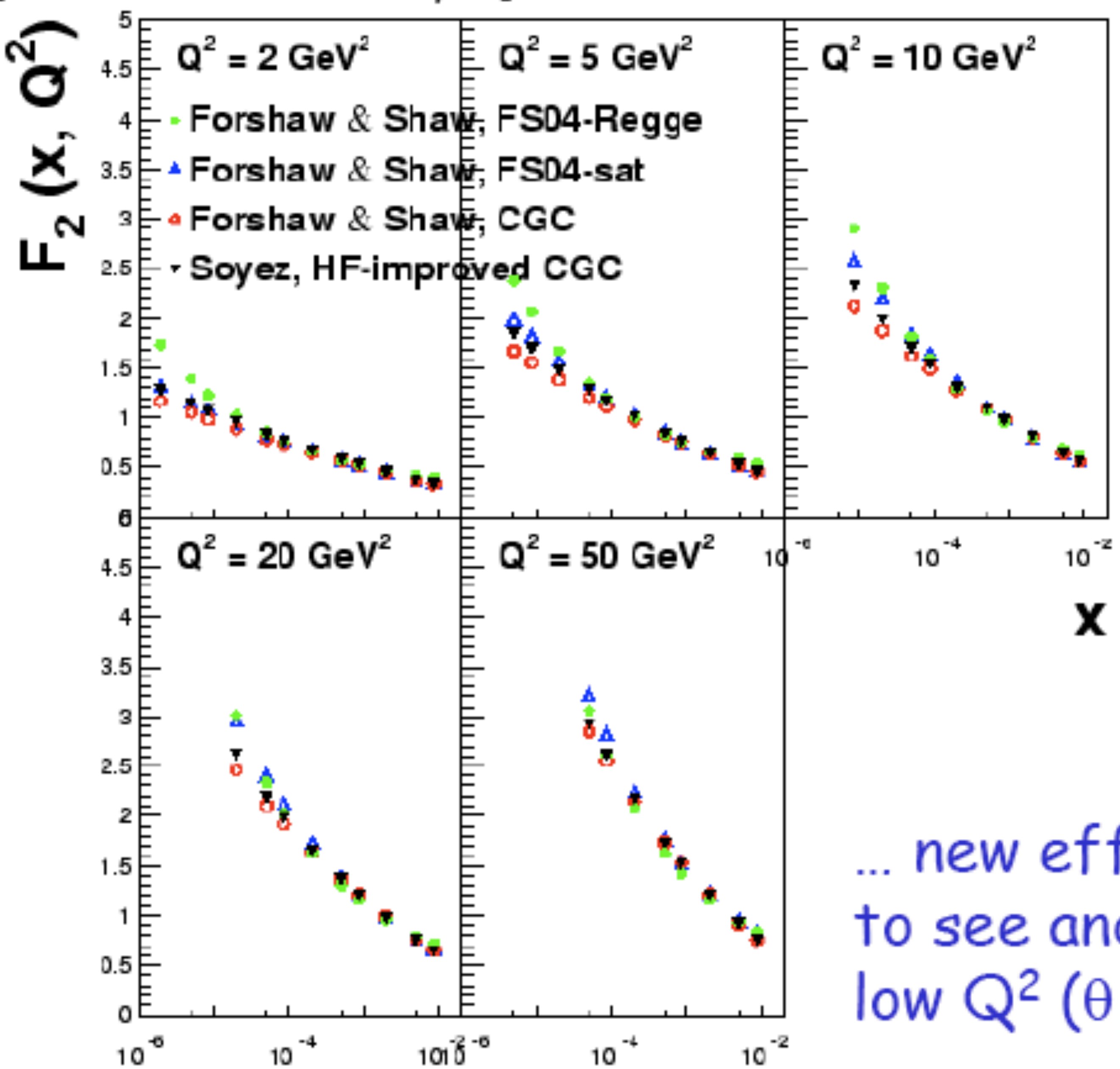


Inclusive observables

Some models of low x F_2 with LHeC Data

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}

- Extrapolated HERA dipole models …
- 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 (θ → 179°) region …

F_L Simulation

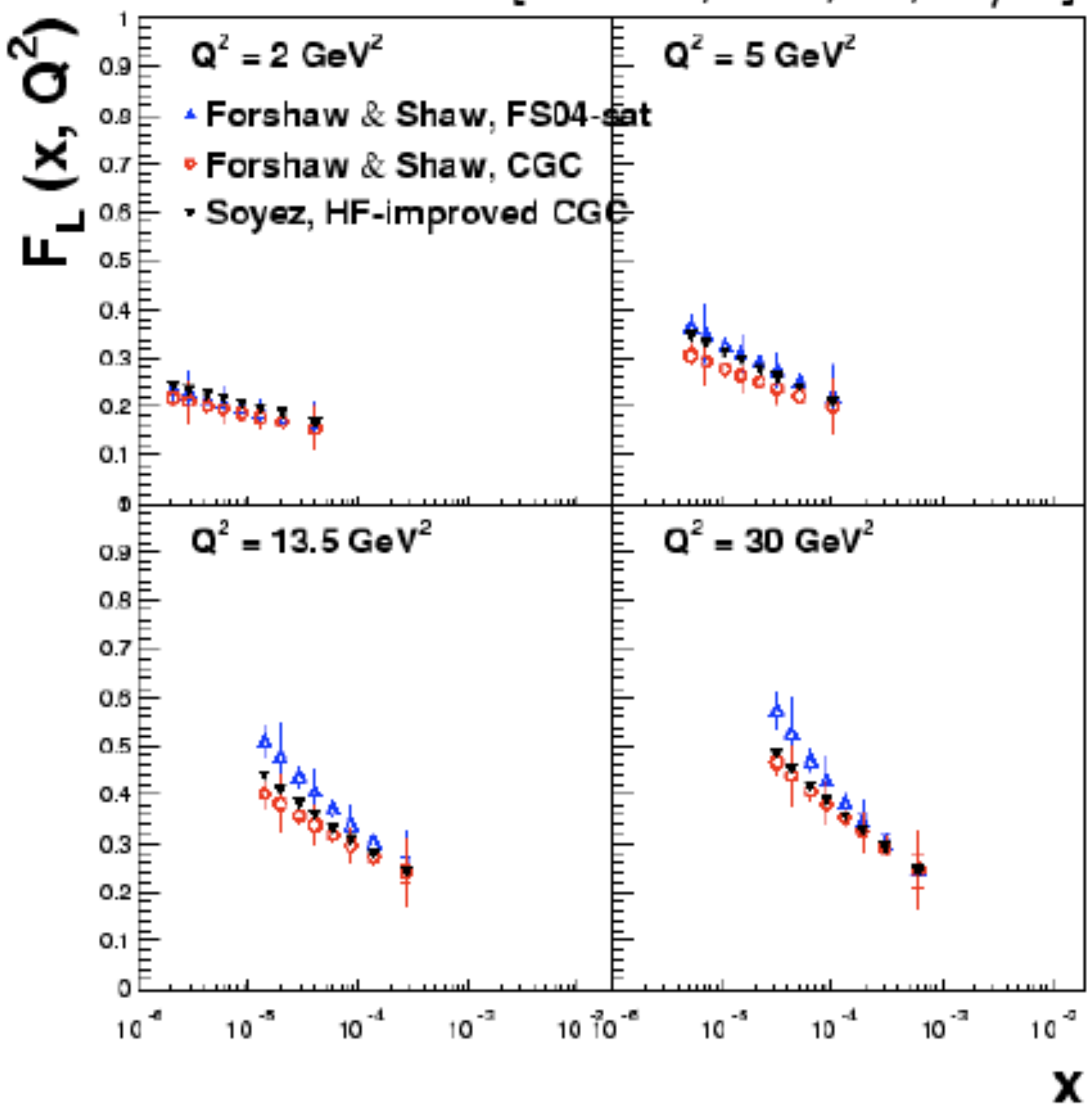
Vary proton beam energy as recently done at HERA ?...
→ example for 1 year ...

E_p (TeV)	Lumi (fb^{-1})
7	1
4	0.8
2	0.2
1	0.05
[0.45	0.01]

... precision typically 5%
... stats limited for $Q^2 > 1000\ GeV^2$

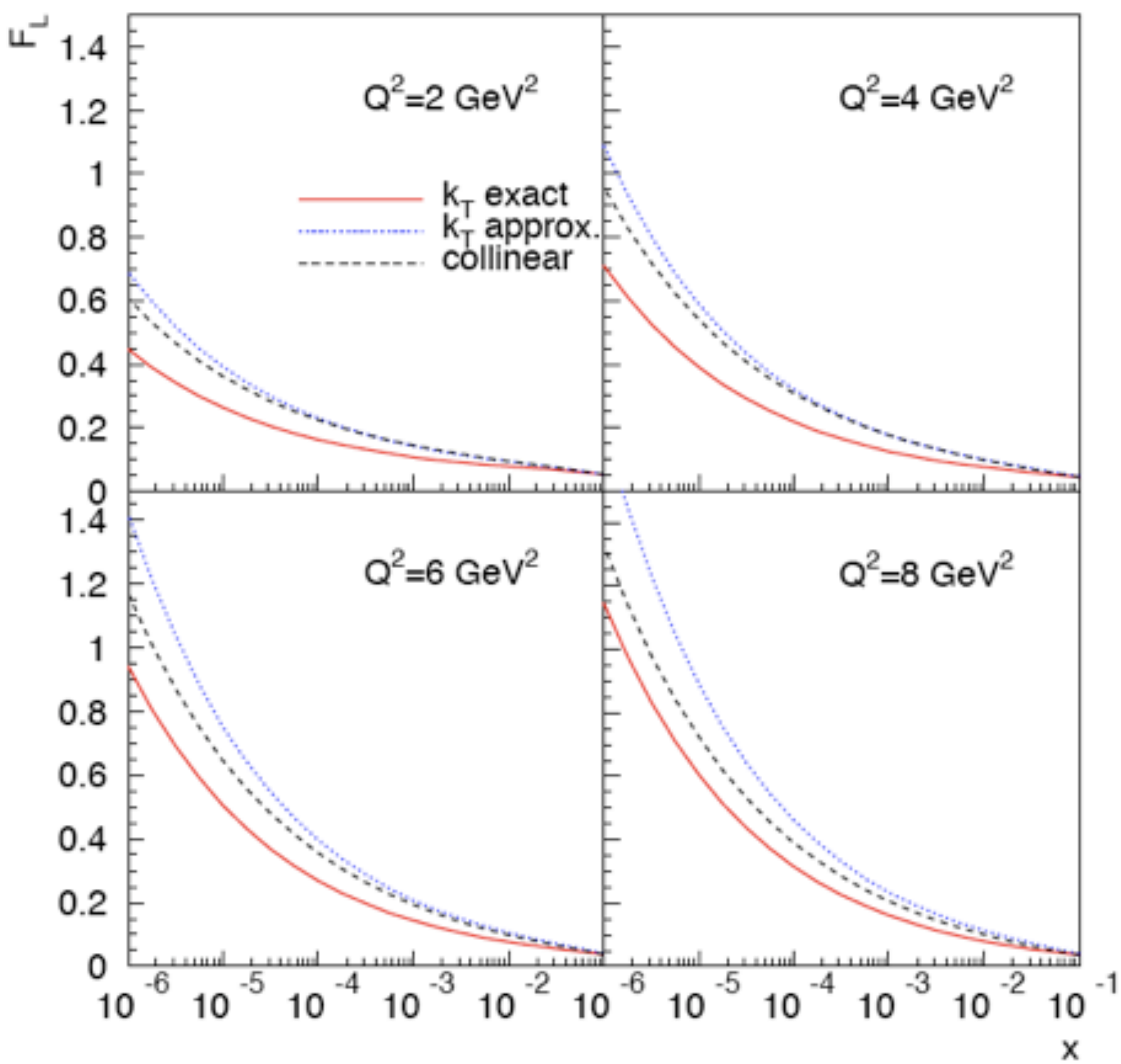
... sample lowest x data
Compared with 3 dipole models including saturation ...

[Forshaw, Klein, PN, Soyez]

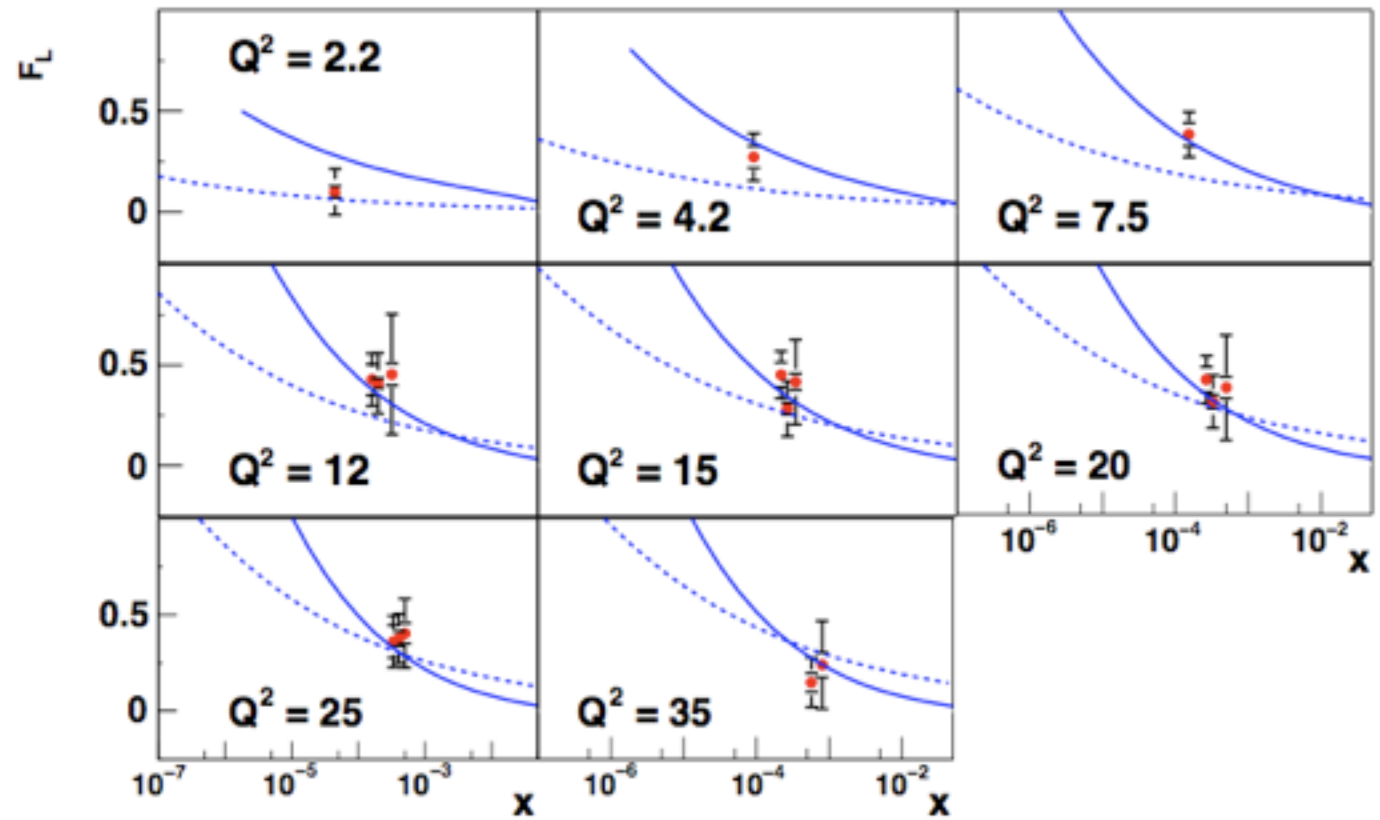


More F_L

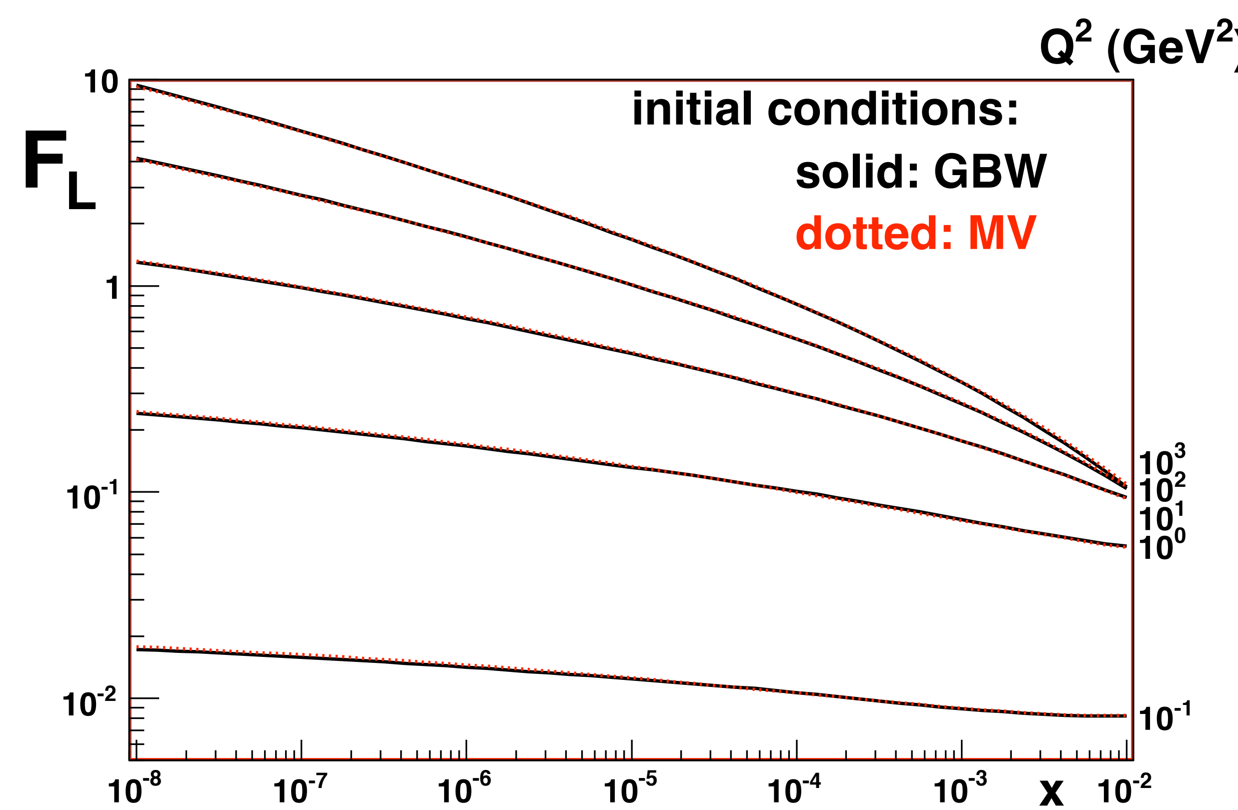
Non-saturated kt BFKL+DGLAP resummed
Golec-Biernat and Stasto



Armesto et al (dipole fit)



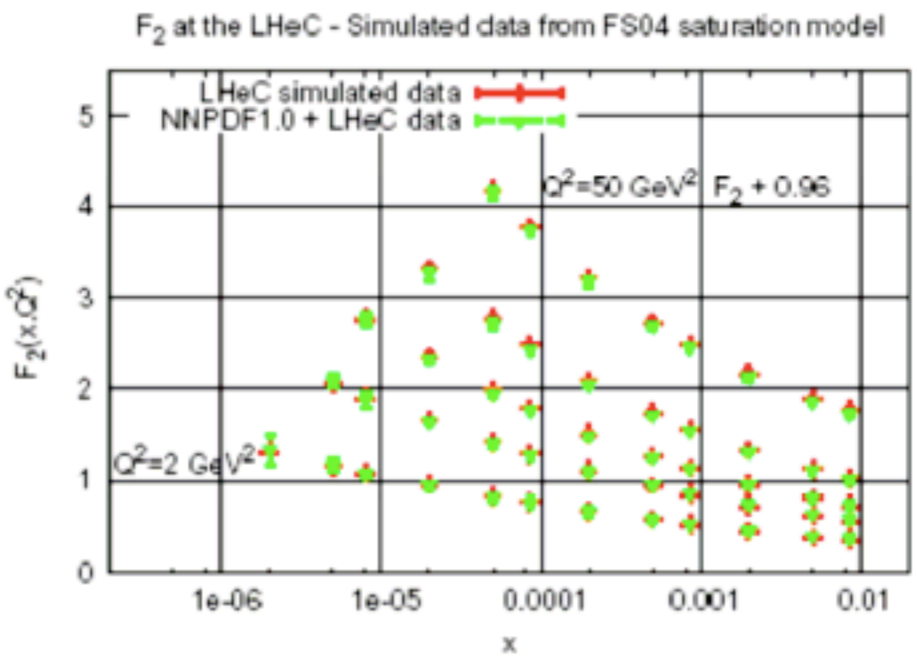
Armesto et al (NLL BK fit to F2)

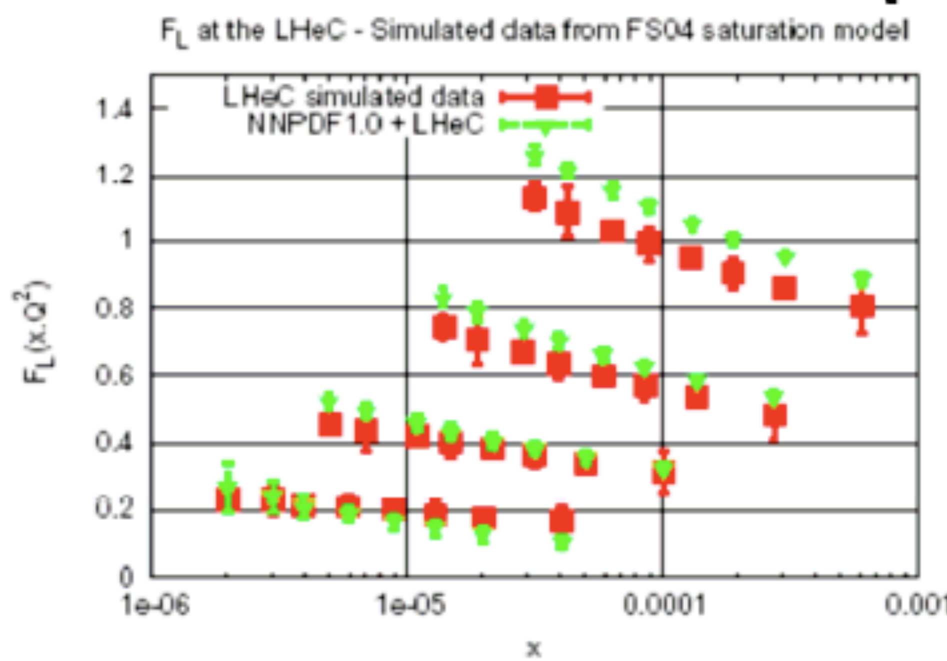


Can Parton Saturation be Established @ LHeC?

... effects may not be so large in ep → and may be hard to establish unambiguously with F_2 alone
... $A^{1/3}$ amplification in gluon in eA (~6 for Pb) may be needed
... Two first studies using F_2 and F_L in ep only ...

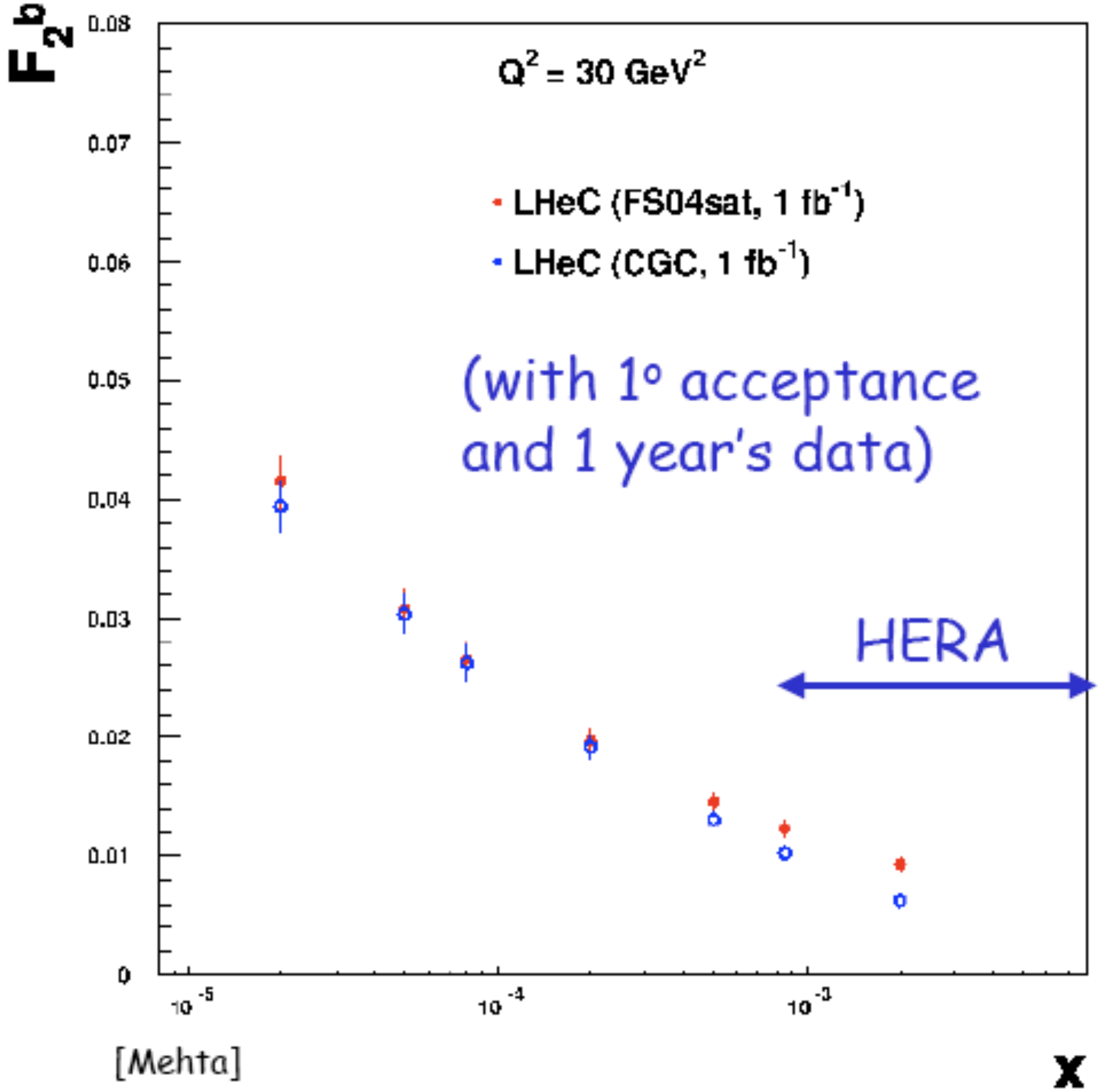
[Rojo]



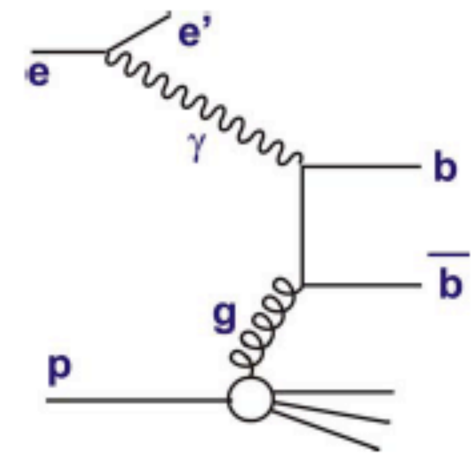


Saturation effects at LHeC (FS04-sat) cannot be absorbed into NNPDF1.0 DGLAP PDF analysis if F_2 and F_L both fitted

Jets and Heavy Flavours



[Mehta]

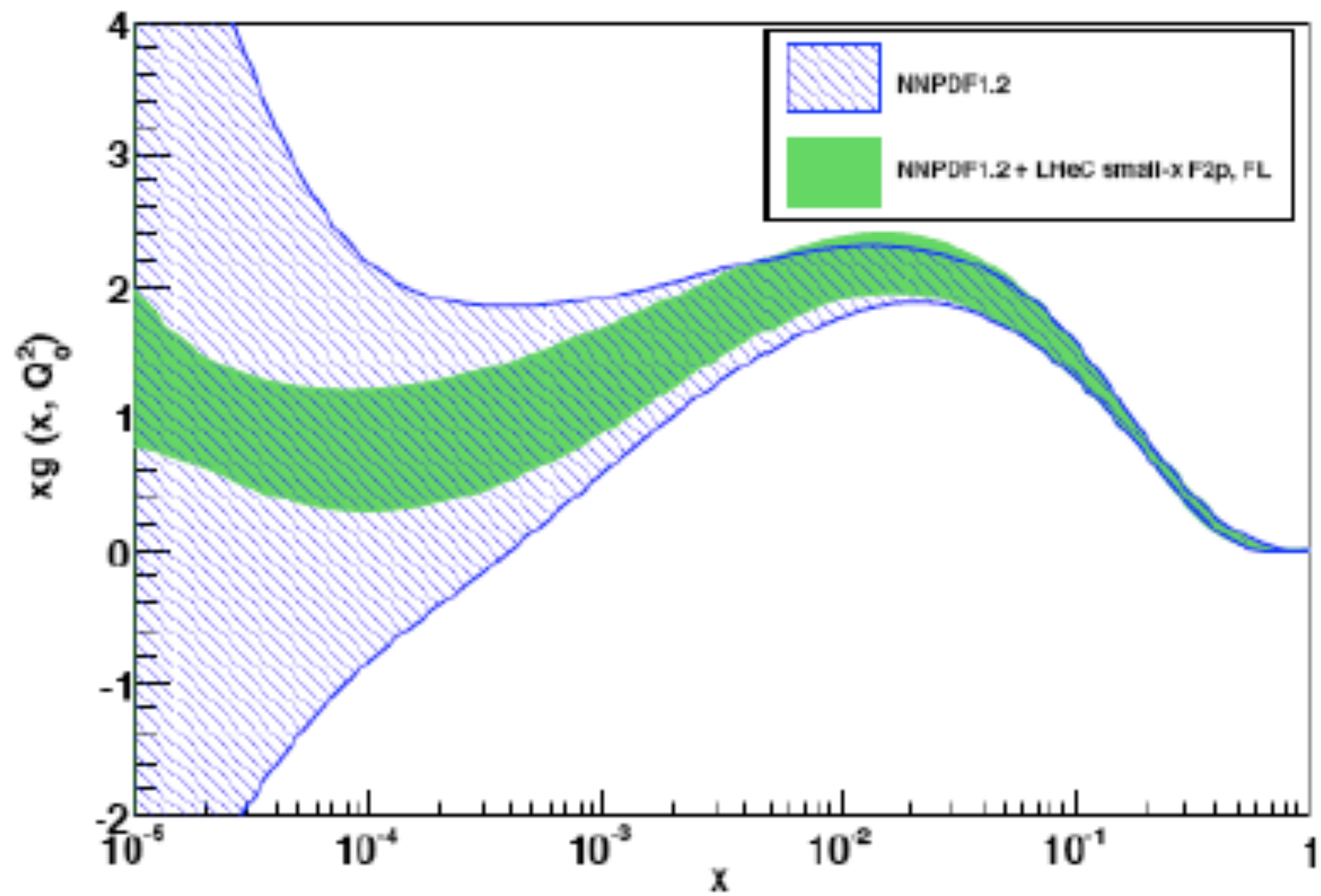


Constrain gluon (at Remarkably low x!) through jets and heavy flavour measurements

e.g. F_2^b to a few % constraining gluon down to x ~ 2.10^{-5}.

NNPDF analysis: see J .Rojo talk

F_2^p and F_2^L NLO DGLAP in NNPDF analysis:
Gluon uncertainties with F_2^p and F_L^p LHeC data



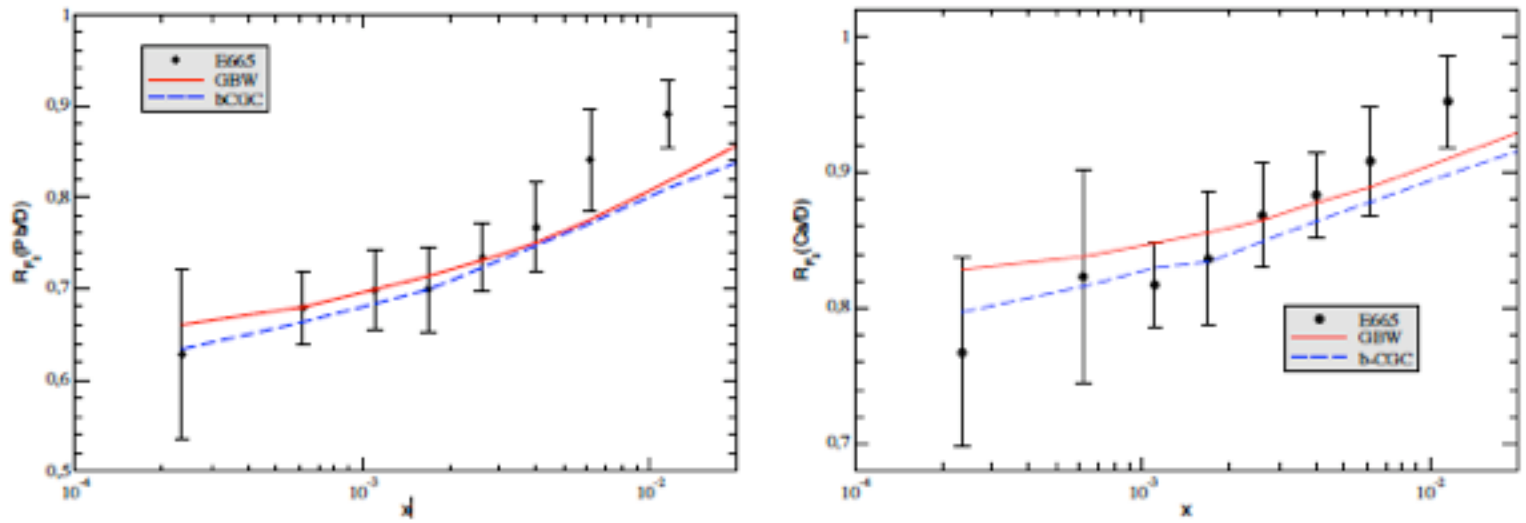
→ Sizable error reduction of gluon at small-x requires LHeC F_L data

Inclusive ratios: ep/eA

Ratio $R_{F_2} \equiv 2F_2^A / AF_2^D$ for $A = Pb$ and $A = Ca$

Data from E665 collaboration

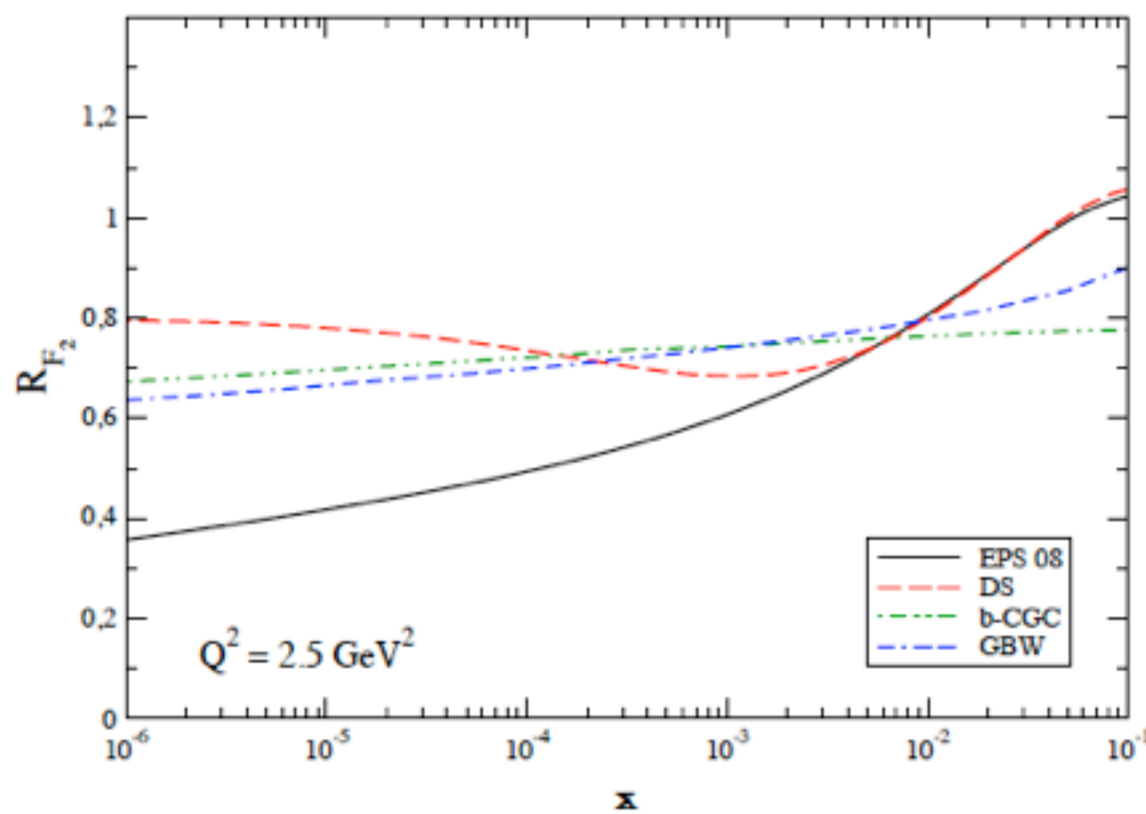
What we know now



Cazaroto, Carvalho, Goncalves, Navarra

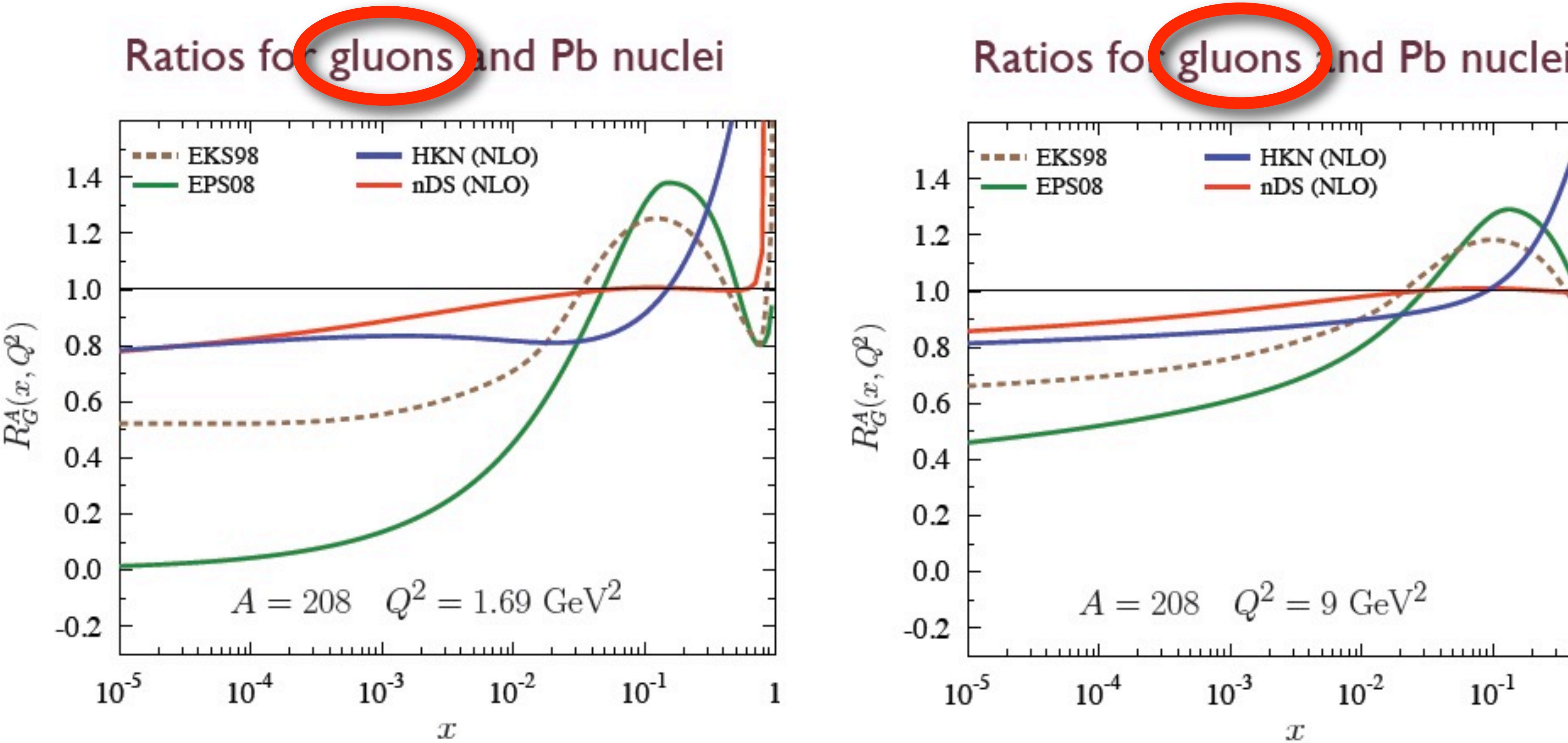
Extrapolation to lower x

A=Pb



Inclusive ratios: ep/eA

Preliminary calculations of the ratios of gluon densities from N.Armesto et al. Huge difference between models at low x



Models tell us that the ratio is not larger than 1 for small x but can be anywhere between 0 and 1...

More basics calculations specific for the LHeC regime and eA needed

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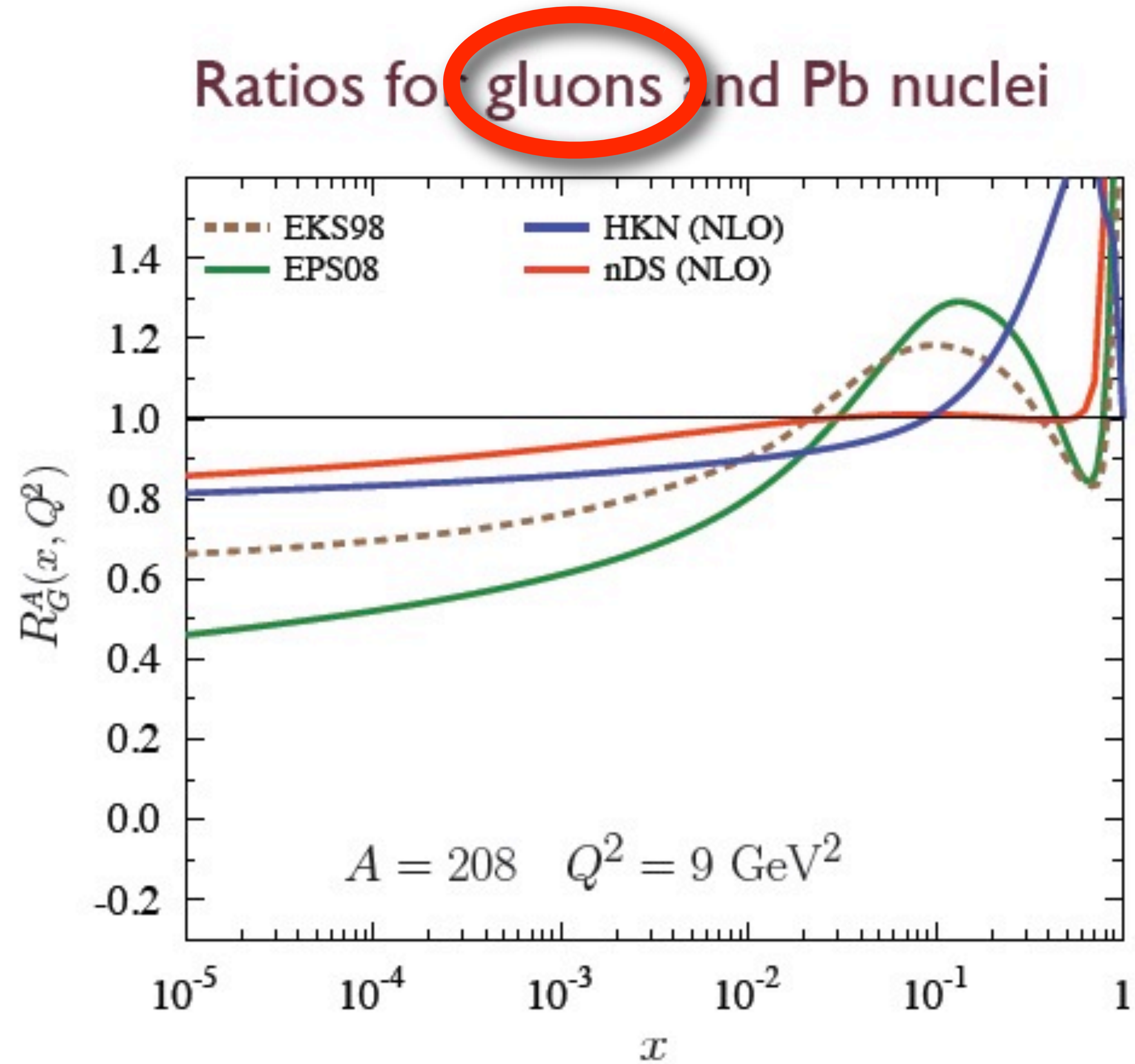

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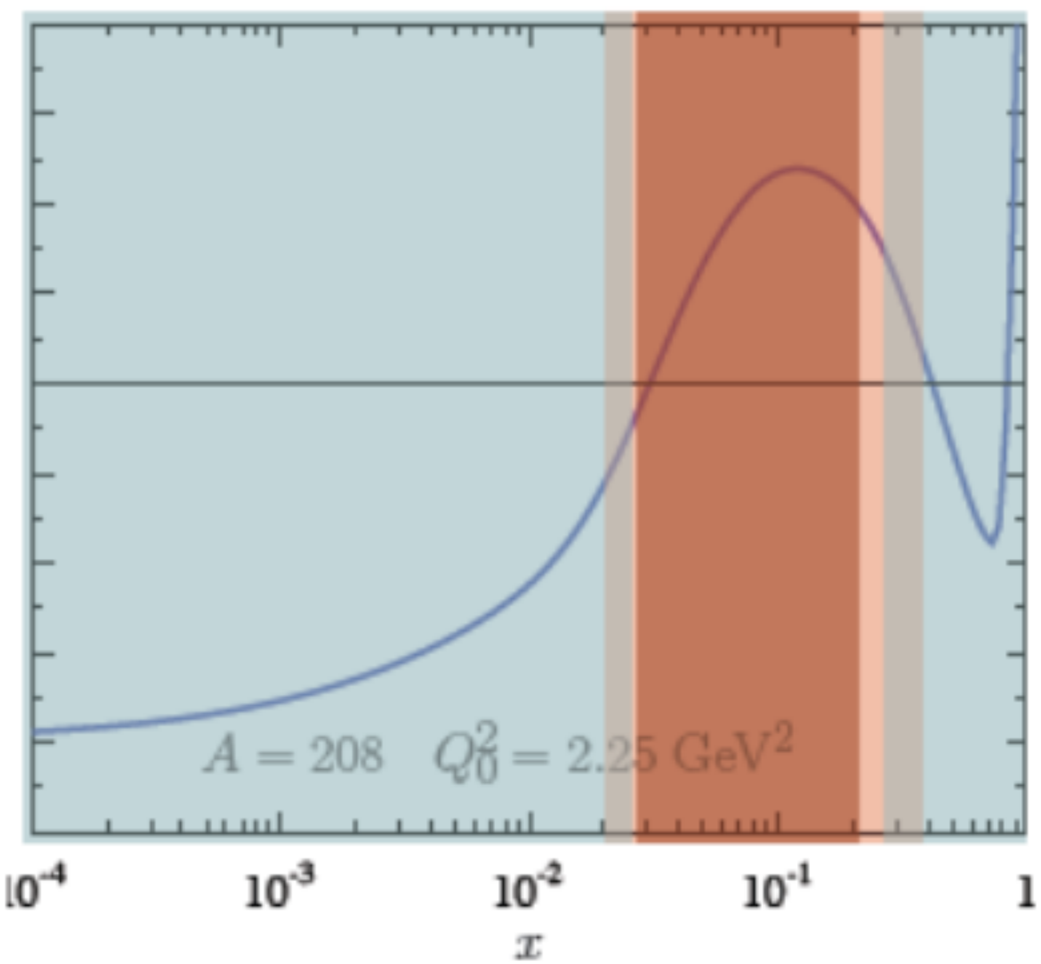

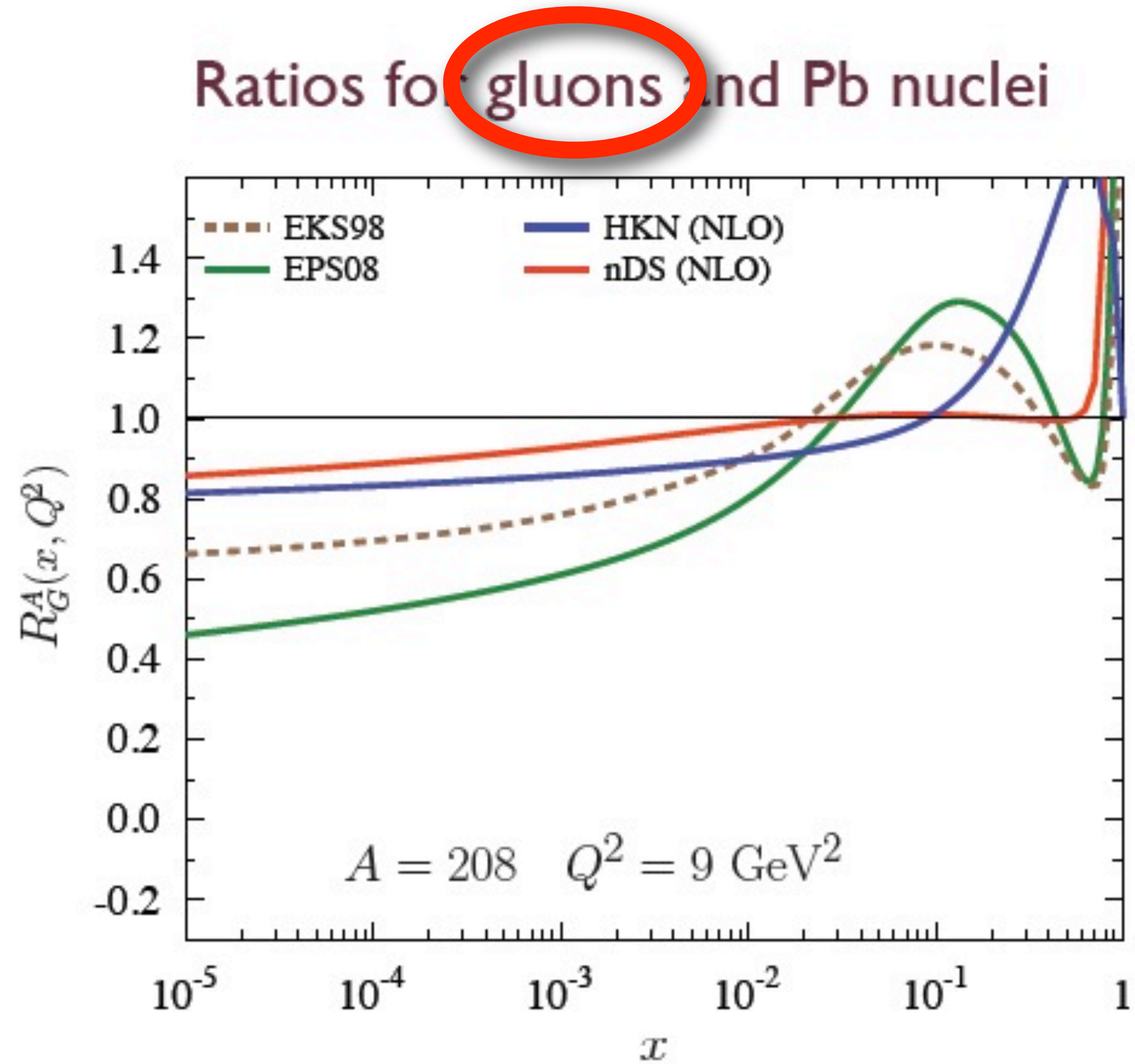

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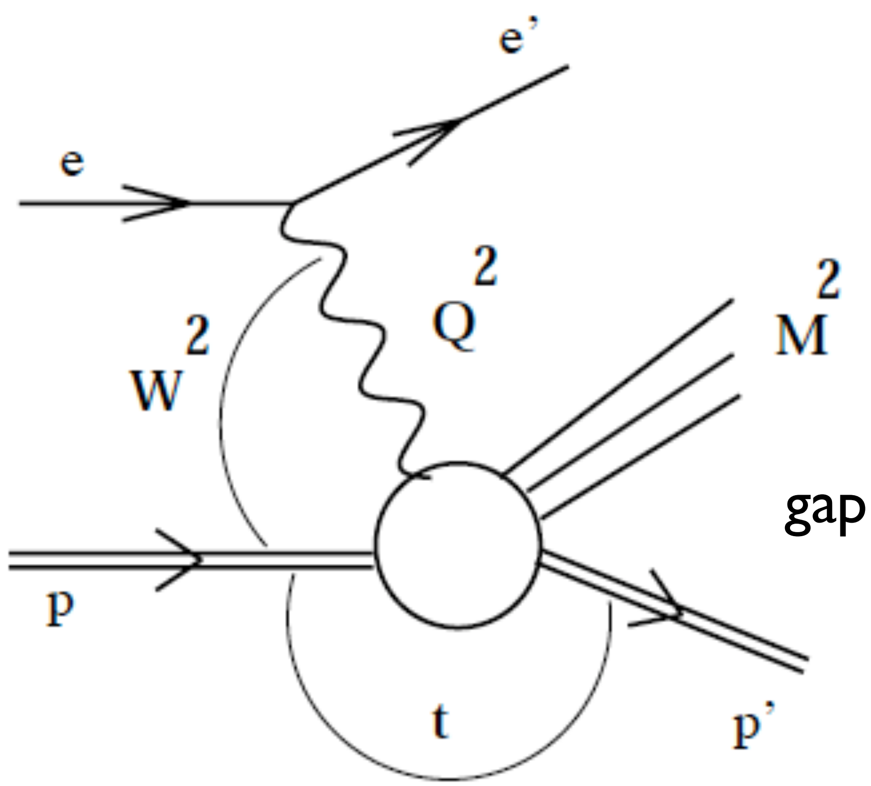
More basics calculations specific for the LHeC regime and eA needed

Diffraction in ep and eA

Diffraction



$$e + p \rightarrow e' + p' + X$$

Proton stays intact and separated by a rapidity gap

M^2 diffractive mass

$t = (p - p')^2$ momentum transfer

$\Delta\eta = \ln 1/x_{I\!P}$ Rapidity gap

$$x_{I\!P} = \frac{Q^2 + M^2 - t}{Q^2 + W^2}$$

momentum fraction of the Pomeron with respect to the hadron

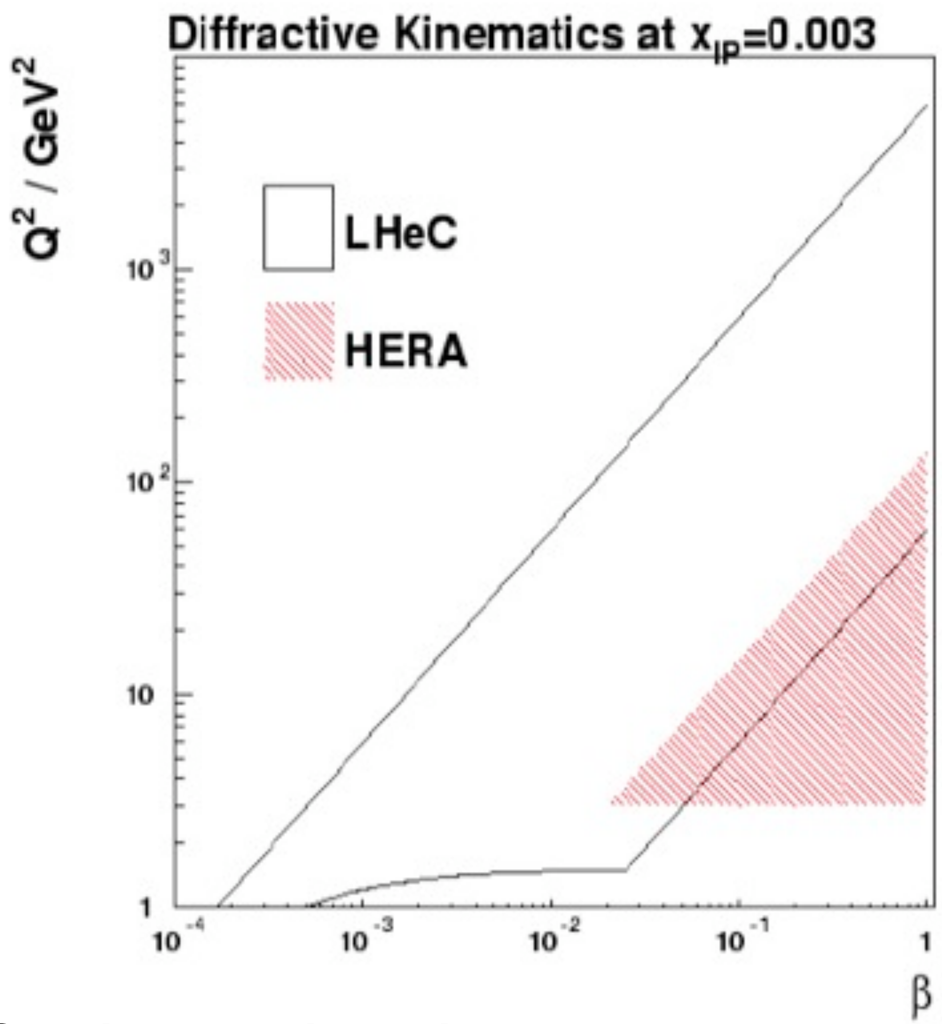
$$\beta = \frac{Q^2}{Q^2 + M^2 - t}$$

momentum fraction of the struck parton with respect to the Pomeron

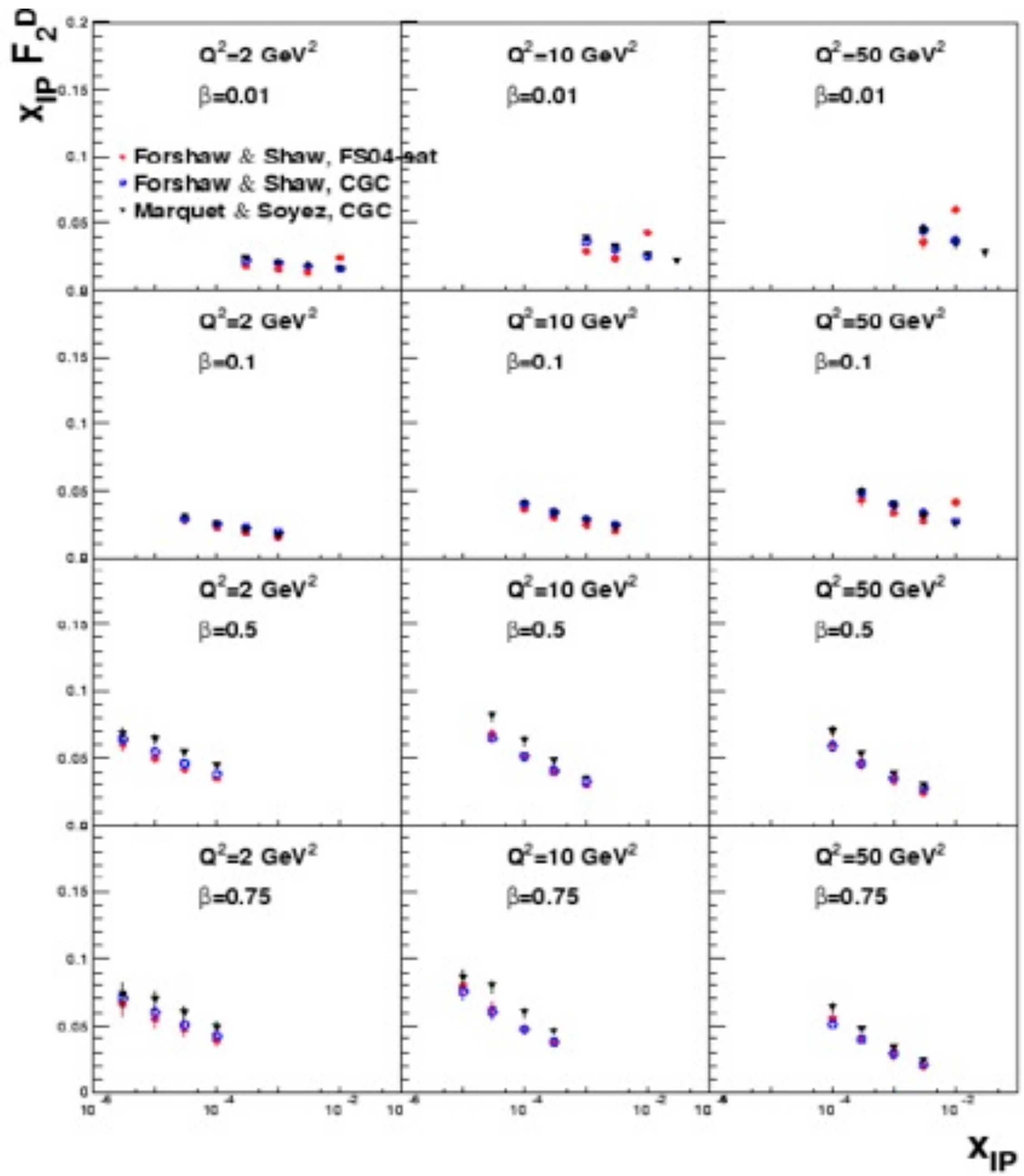
$$x = x_{I\!P}\,\beta$$

Bjorken x

Diffraction at LHeC: new possibilities



- Studies with 1 degree acceptance,
- Diffractive-PDFs
- Factorization in much bigger range
- Diffractive masses $M_X \sim 100\text{GeV}$ with $x_{I\!P} = 0.01$
- X can include W,Z,b

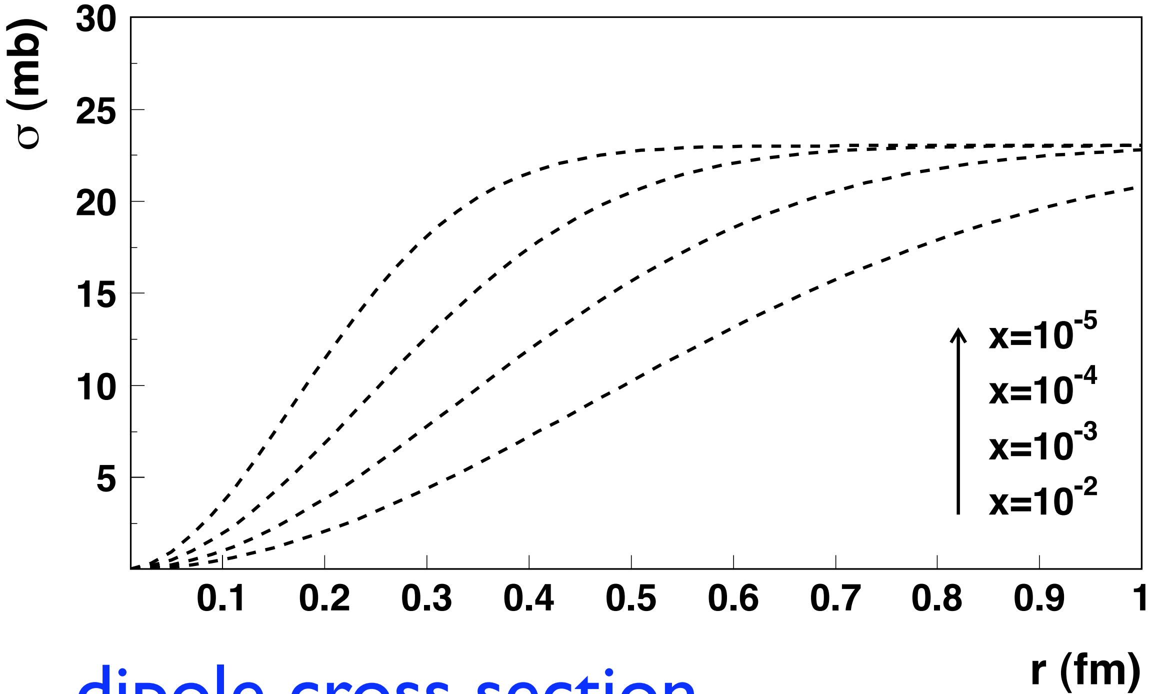


Forshaw, Marquet, Newman

Simulated diffractive data available

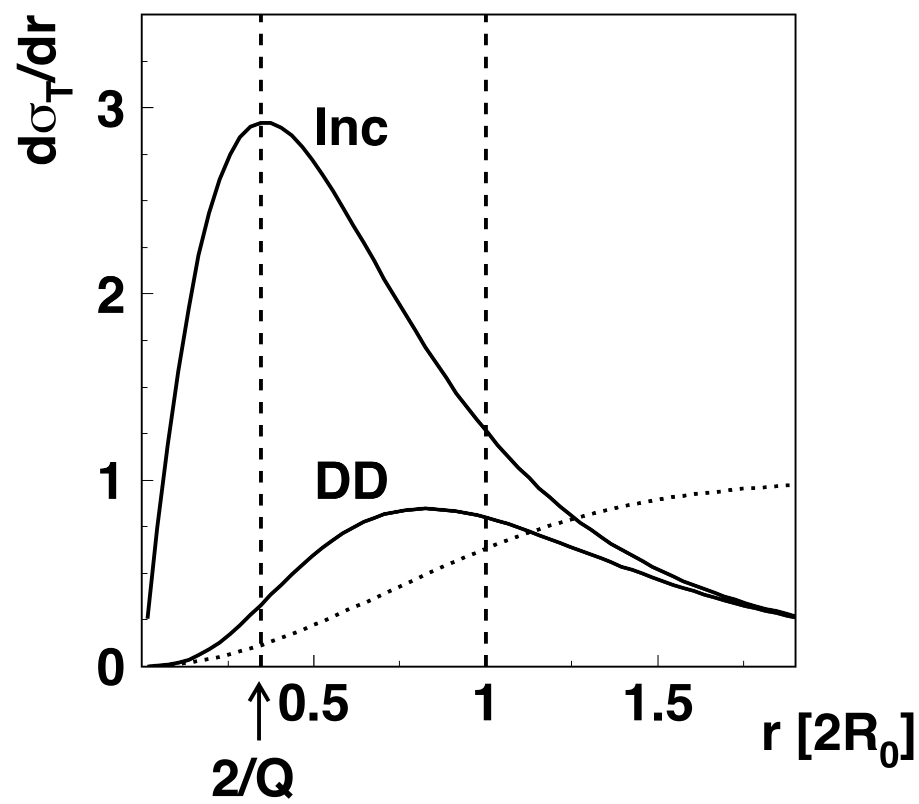
Diffraction and saturation

Golec-Biernat, Wuesthoff



dipole cross section

overlap function in the dipole model



$$\sigma_T \sim \underbrace{\frac{\sigma_0}{Q^2R_0^2}}_{r<2/Q} + \underbrace{\frac{\sigma_0}{Q^2R_0^2}\log(Q^2R_0^2)}_{2/Q<r<2R_0} + \underbrace{\frac{\sigma_0}{Q^2R_0^2}}_{r>2R_0}$$

$$\sigma_T^D \sim \underbrace{\frac{\sigma_0^2}{Q^4R_0^4}}_{r<2/Q} + \underbrace{\frac{\sigma_0^2}{Q^2R_0^2}}_{2/Q<r<2R_0} + \underbrace{\frac{\sigma_0^2}{Q^2R_0^2}}_{r>2R_0} \qquad R_0 = \frac{1}{Q_s}$$

$$\sigma_L^D \sim \underbrace{\frac{\sigma_0^2}{Q^4R_0^4}}_{r<2/Q} + \underbrace{\frac{\sigma_0^2}{Q^4R_0^4}\log(Q^2R_0^2)}_{2/Q<r<2R_0} + \underbrace{\frac{\sigma_0^2}{Q^4R_0^4}}_{r>2r_0}.$$

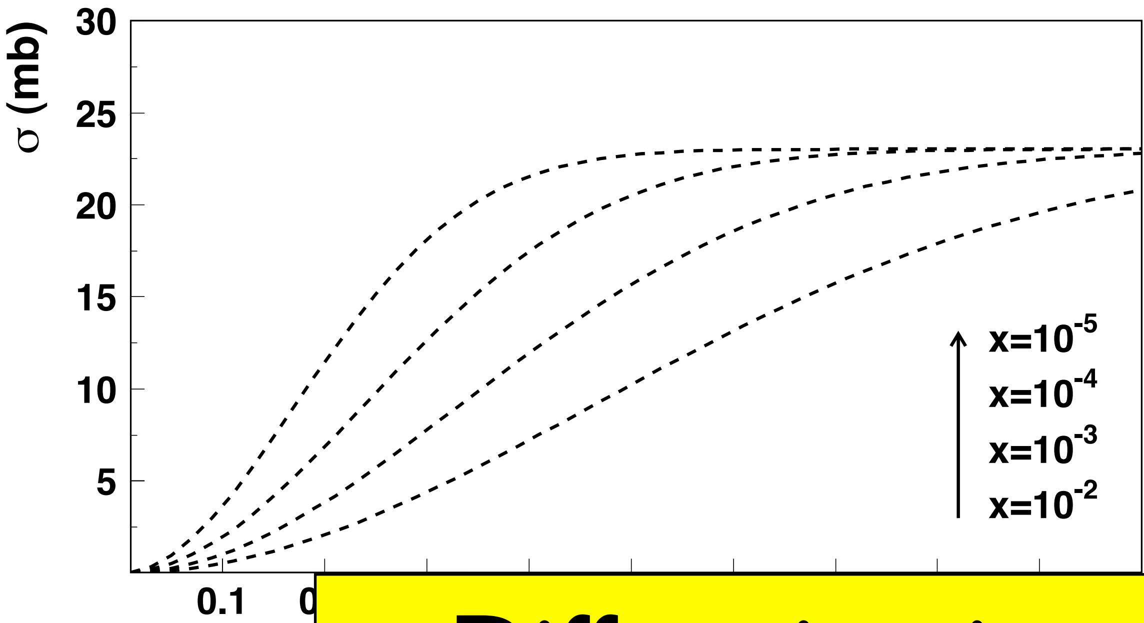
contribution of different dipole sizes

Inclusive: dominated by relatively hard component

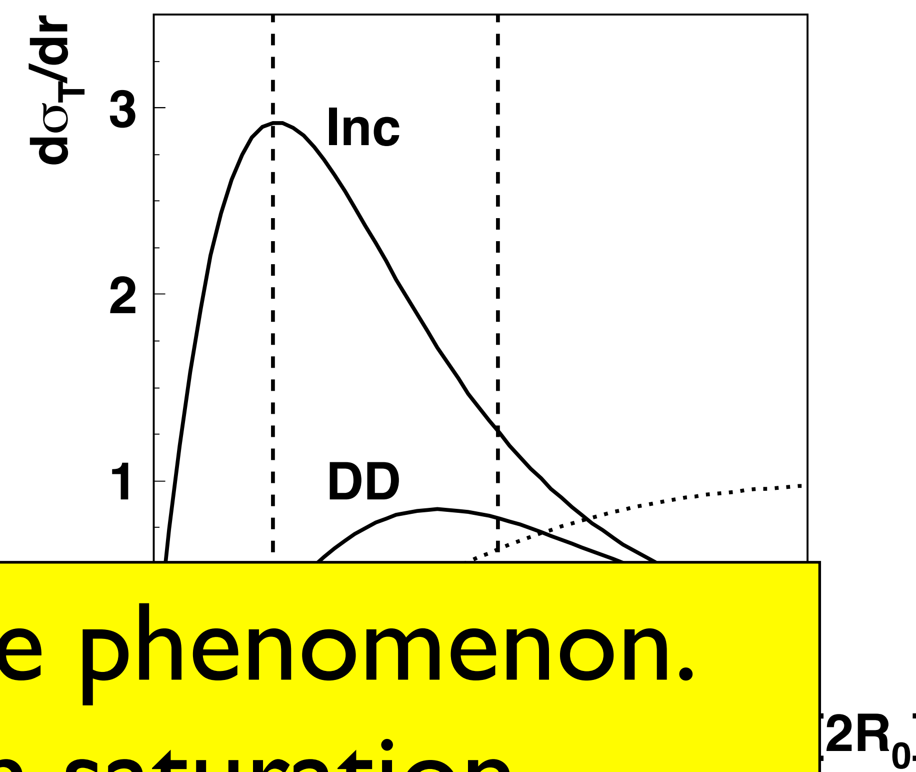
Diffractive: dominated by the semi-hard momenta

Diffraction and saturation

Golec-Biernat, Wuesthoff



overlap function in the dipole model



Diffraction is a collective phenomenon.
Explore relation with saturation.

dipole c

$$\sigma_T \sim \underbrace{\frac{\sigma_0}{Q^2 R_0^2}}_{r<2/Q} \quad \underbrace{\qquad}_{2/Q<r<2R_0} \quad \underbrace{\qquad}_{r>2R_0}$$

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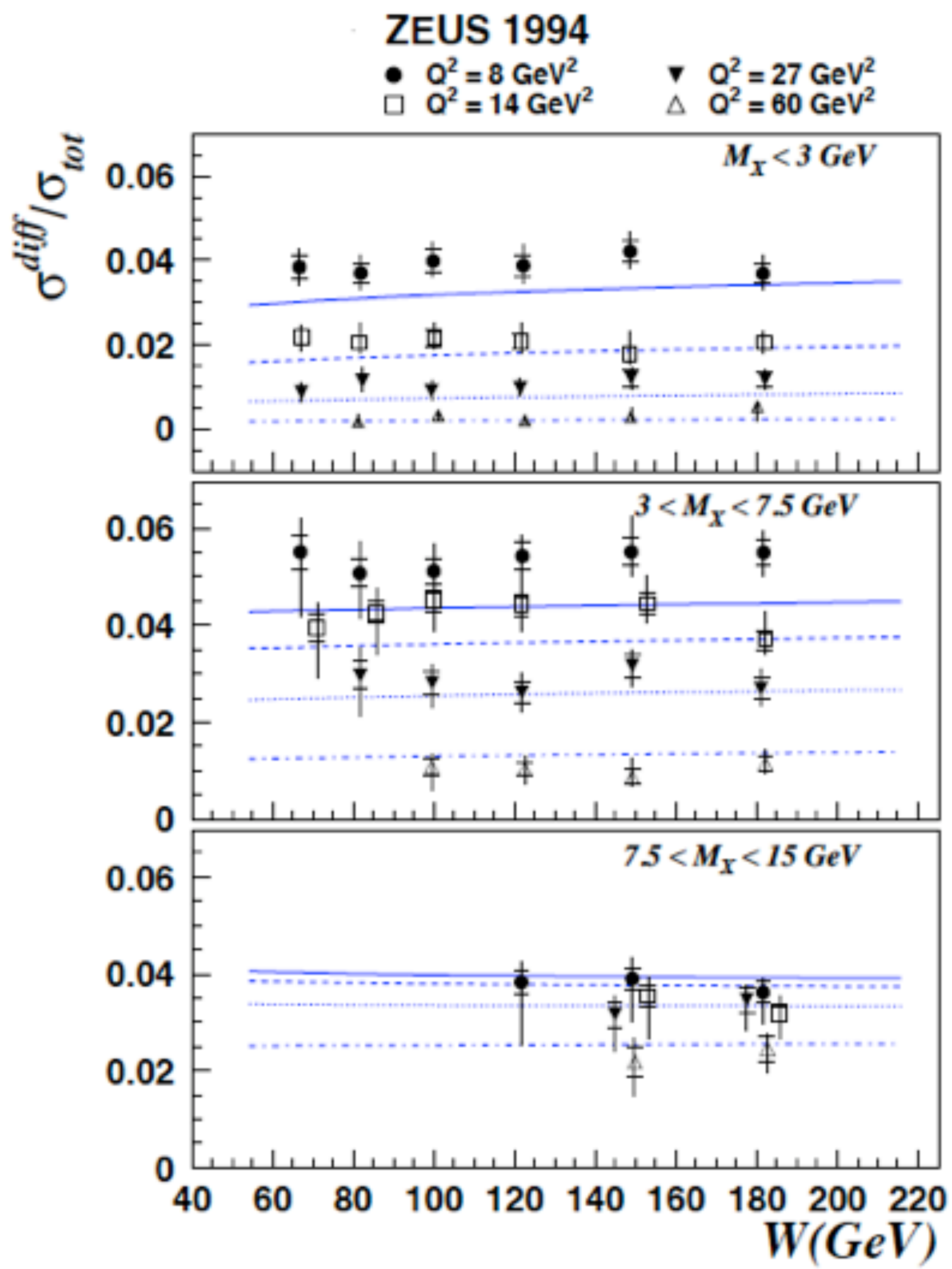
contribution of different dipole sizes

Inclusive: dominated by relatively hard component

Diffractive: dominated by the semi-hard momenta

Diffractive to inclusive ratio in ep



Golec-Biernat, Wuesthoff

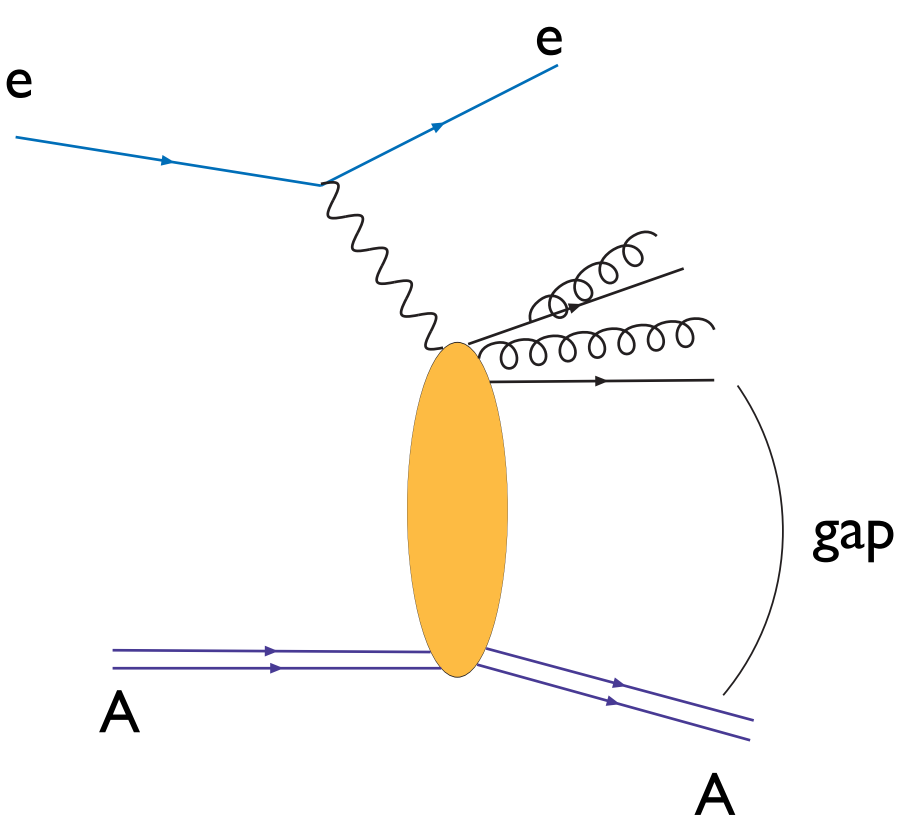
Constant ratio naturally explained in the saturation model.

Is it the same ratio and still constant at higher energy?

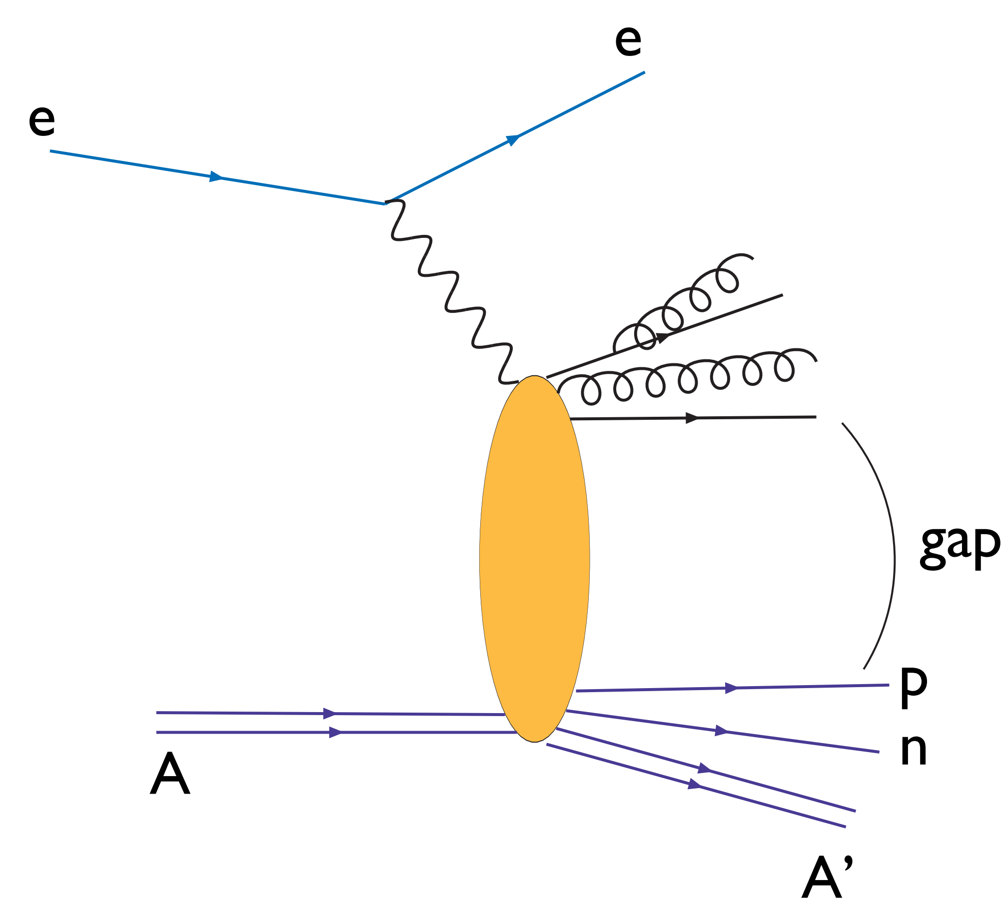
Need specific calculations for the LHeC regime (extrapolations of dipole models etc.)

Diffraction in eA

Two possibilities for the diffractive events in nuclei:

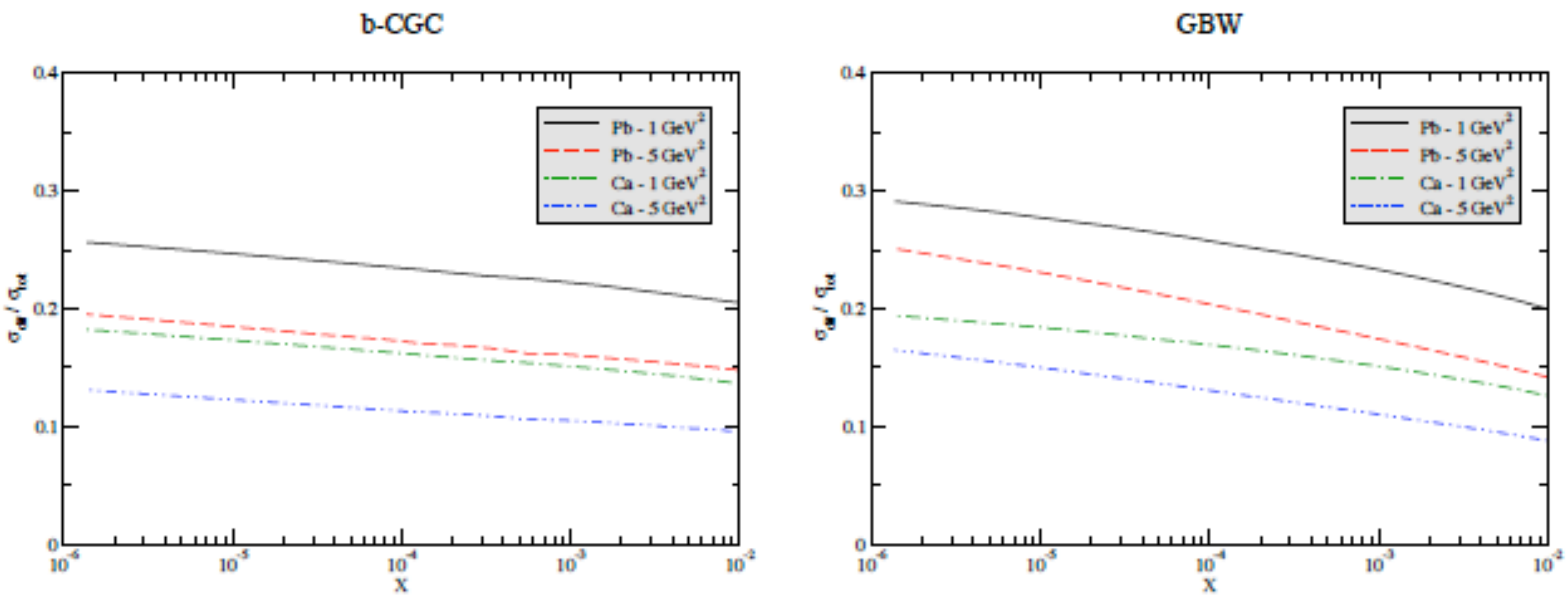


Coherent
No-breakup



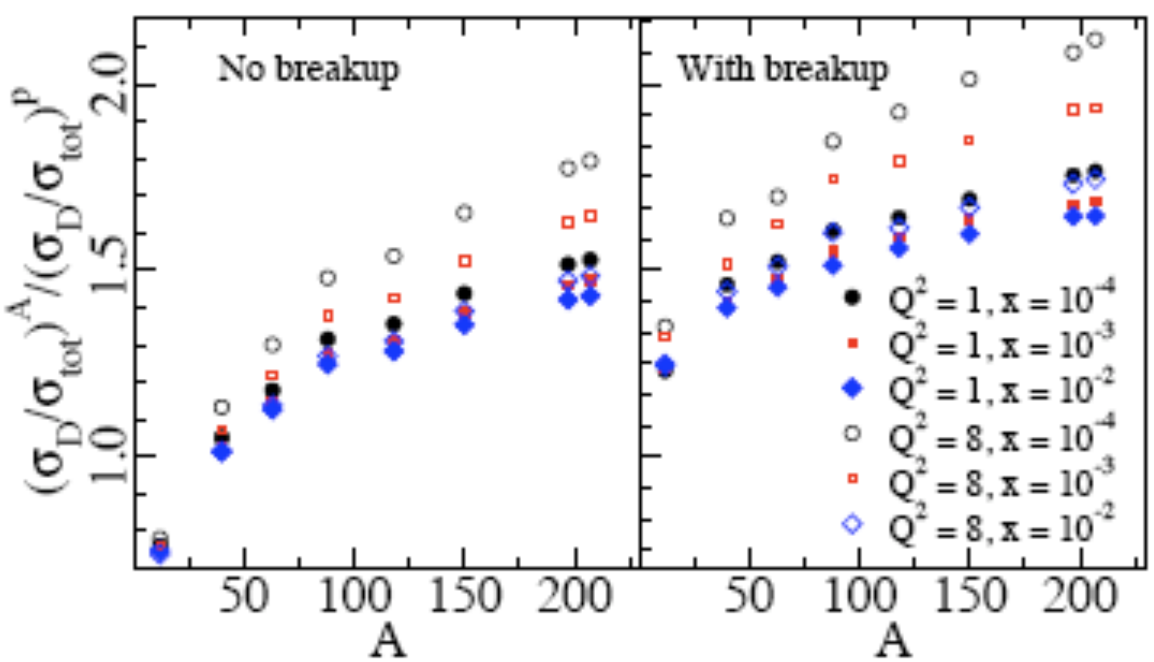
Incoherent
With breakup into nucleons
The gap is still there

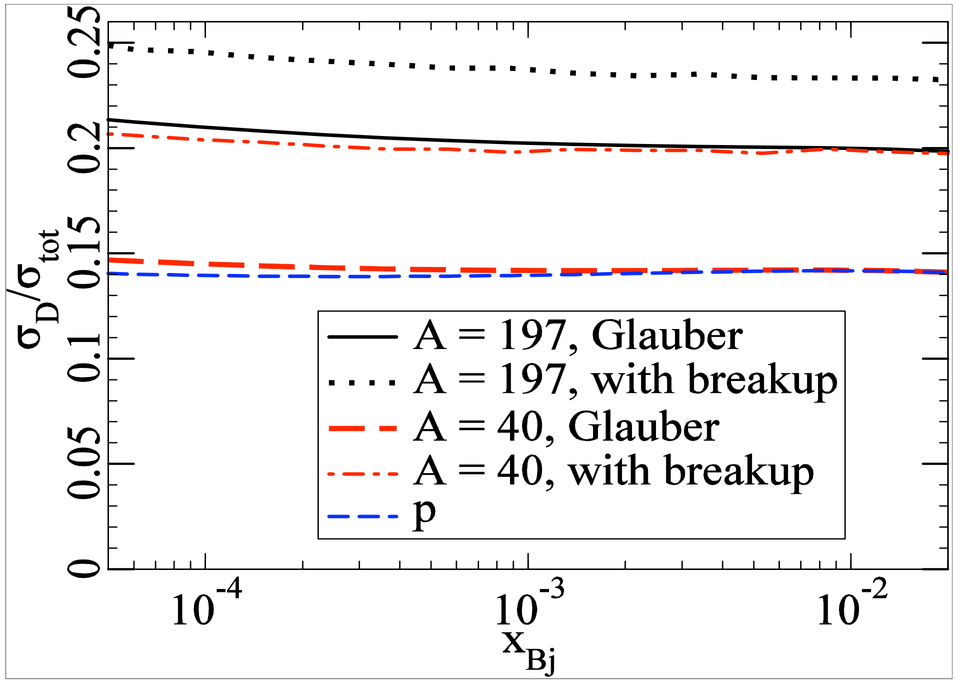
Diffractive to inclusive ratio in eA



Predictions give 20%-40% for $\sigma_{\rm diff}/\sigma_{\rm tot}$ in the regime down to 10^{-6}

Cazaroto,Carvalho, Goncalves, Navarra





Kowalski, Lappi, Venugopalan

Need specific calculations for the LHeC regime and eA (extrapolations)

Exclusive diffraction of VM

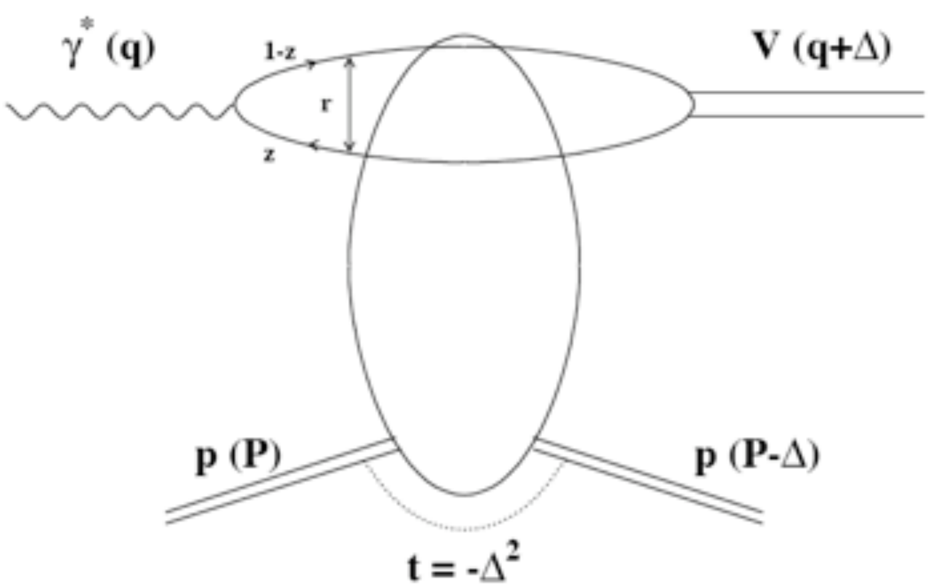
- Exclusive diffractive production of VM is an excellent process for extracting the dipole amplitude

- Suitable process for estimating the ‘blackness’ of the interaction.

- t-dependence provides an information about the impact parameter profile of the amplitude.

Differential cross section for exclusive VM production

$$\frac{d\sigma}{dt} = \frac{1}{16\pi}|\mathcal{A}_{\rm el}(x,\Delta,Q)|^2$$



Amplitude for elastic scattering

$$\mathcal{A}_{\rm el}(x,\Delta,Q) = \sum_{h,\bar{h}} \int d^2\mathbf{r}\, dz\, \psi_{\gamma^*}^{h,\bar{h}*}(z,\mathbf{r};Q)\, A_{\rm el}^{q\bar{q}-p}(x,\mathbf{r},\Delta)\, \psi_V^{h,\bar{h}}(z,\mathbf{r})$$

Elementary amplitude for elastic scattering

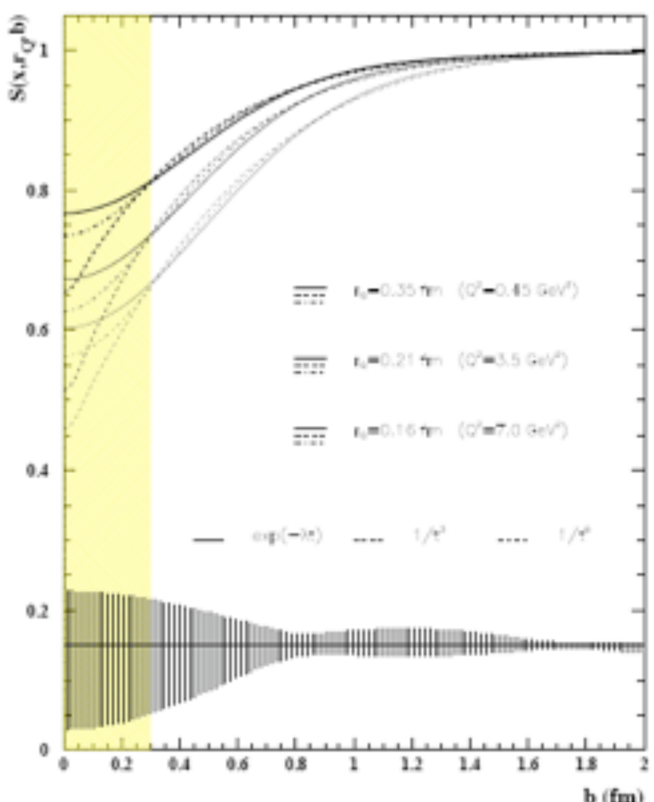
$$A_{\rm el}^{q\bar{q}-p}(x,\mathbf{r},\Delta) = \int d^2\mathbf{b}\, \tilde{A}_{\rm el}^{q\bar{q}-p}(x,\mathbf{r},\mathbf{b}) e^{i\mathbf{b}\Delta} = 2\int d^2\mathbf{b}\, [1 - S(x,\mathbf{r},\mathbf{b})] e^{i\mathbf{b}\Delta}$$

Optical theorem

$$\sigma_{\rm tot}^{q\bar{q}-p}(x,\mathbf{r}) = \mathcal{I}m\, i A_{\rm el}^{q\bar{q}-p}(x,\mathbf{r},\Delta=0)$$

Impact parameter profile

Munier, Stasto, Mueller

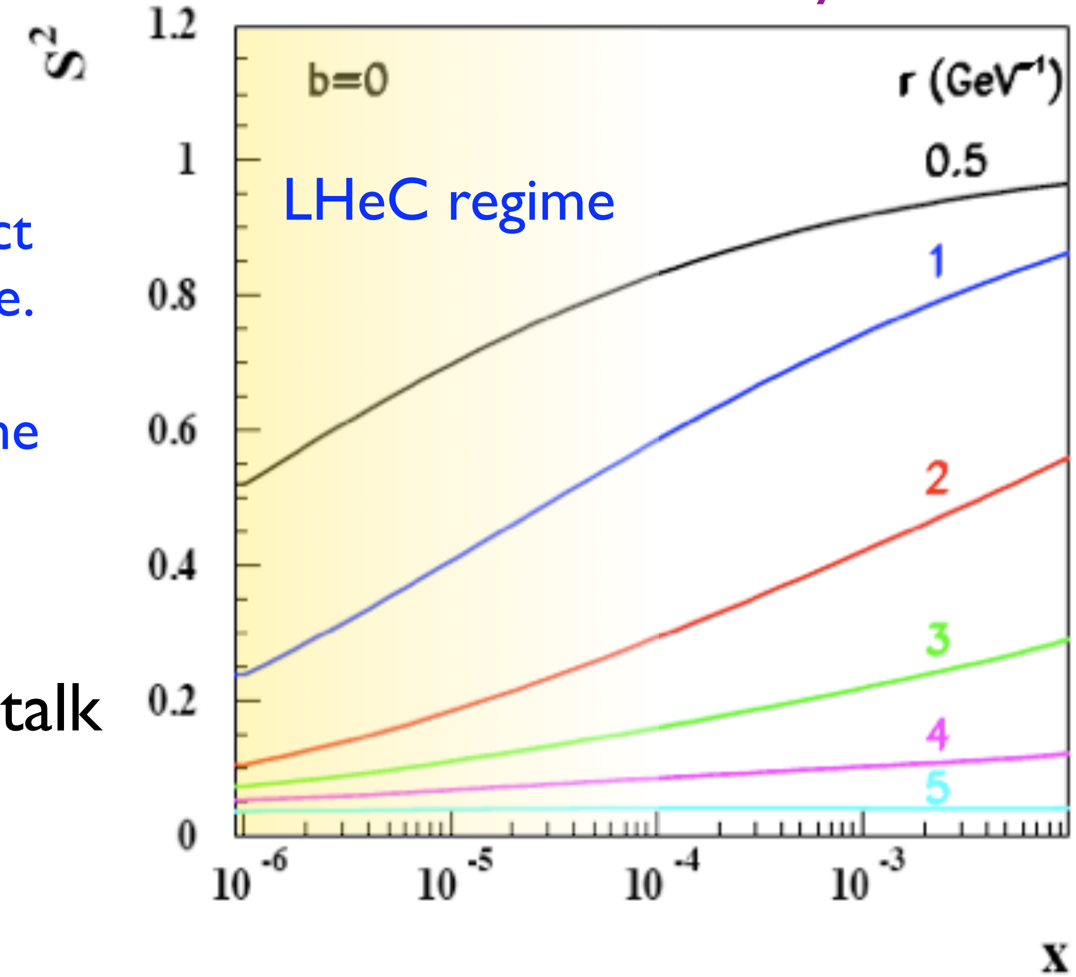


Profile extracted from the HERA data

t-dependence vs impact parameter dependence. What is the characteristic size of the proton in strong interactions?

see also A.Caldwell talk

Kowalski, Teaney



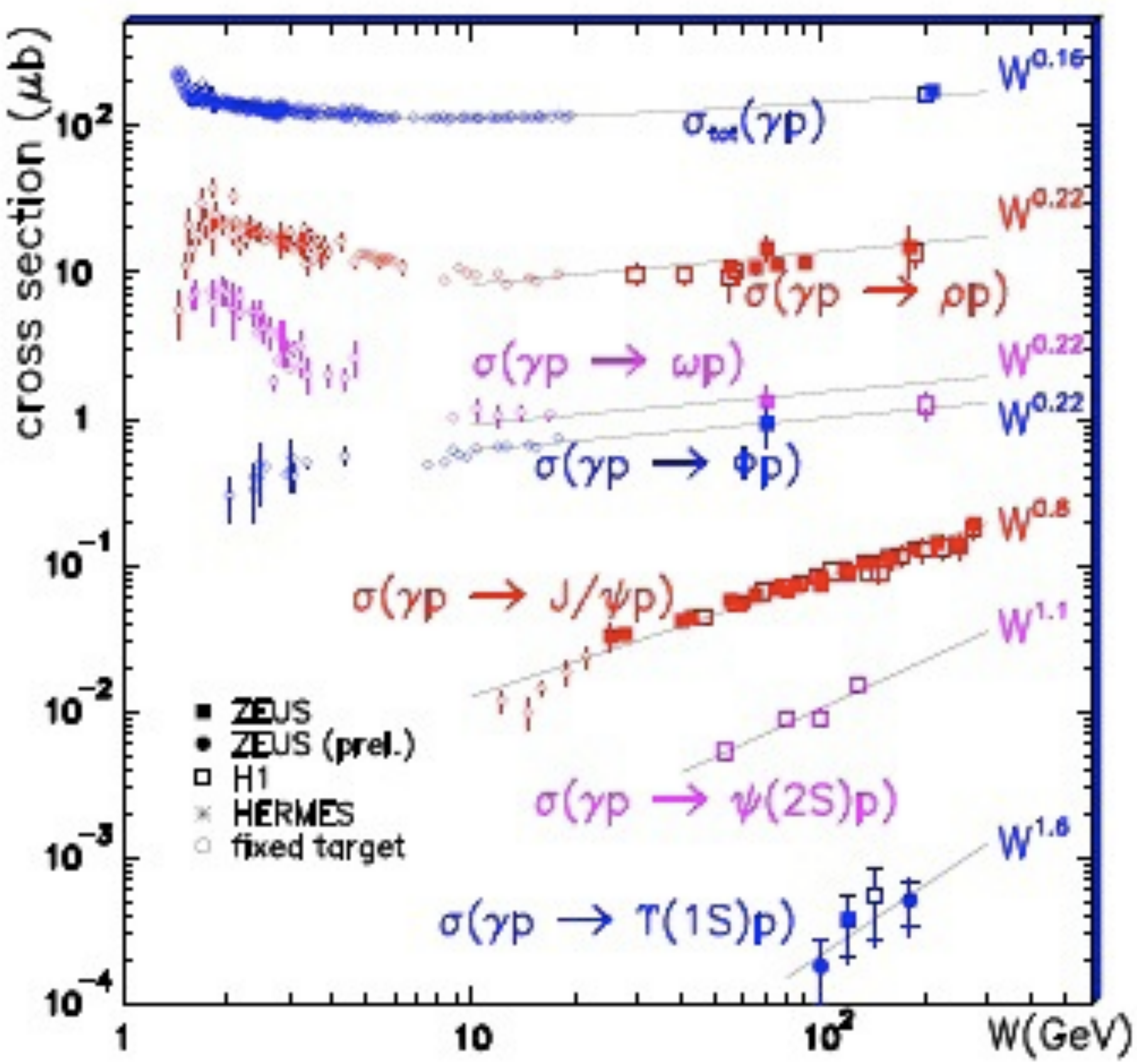
Extrapolations of the S matrix towards lower values of x

$1 - S^2$ probability that a dipole passing the proton will induce an inelastic reaction at the given impact parameter

Models indicate significant 'blackness' for central impact parameter

$Q^2 \sim 5 \text{ GeV}^2$ $x = 10^{-5} - 10^{-6}$

Exclusive vector mesons



What is the behavior of the VM production cross section for higher energies?
Is the energy dependence for VM in eA the same/different as in ep ?

Need specific calculations for the LHeC regime :
both in ep and eA

Other interesting topics

- QCD evolution and resummation at small x. There are several hints that the small x resummation is necessary and we have procedures how to perform it. Matching different expansions and gaining information about the all order QCD evolution. DGLAP/BFKL (LO +NLO) and possibly CCFM. For this one needs both sea and glue constrained (FL!).Hints from resummation: better direction in the evolution, respecting constraints from kinematics, combination of x and kt? Altarelli et al, Ciafaloni et al, Thorne and White

- Transverse momentum dependence of the parton densities. Unintegrated parton distributions. Both from Monte Carlo as well as possibility of extraction from the resummed approaches.Forward jet production. Azimuthal jet decorrelations as an indication of the transverse momentum dependence. Jung,Kutak; Stasto...

- Transition to the photoproduction region. What is the rate of increase of the photoproduction cross section as compared to electroproduction and what it tells us about the unitary limit? Total cross section measurement.

- Jet correlations: do we have hot spots in the proton? How are multiple scatterings correlated (need impact parameter description)? J. Bartels at Divonne.

- Leading neutron production. Absorptive correction. F2_pion. Relation to cosmic rays.

- Fragmentation functions: what is the space-time evolution of the off-shell parton. Constraining the proton fragmentation for z>0.5. Lots more work needed.

Done so far

Working group on Physics at High Parton Densities (ep and eA)

Conveners: N. Armesto, B. Cole, P. Newman, A. Stasto

- Fair amount of different computations for inclusive quantities, structure functions with saturation.
- Diffractive and DVCS simulated data.
- Regular EVO meetings every 2-3 weeks.
- Meeting of 'low x and high density group' at CERN in February:
  - We have outlined the CDR for the low x, high density section.
  - Contacted people who could contribute to the specific topics.

Low x section CDR outline

I. Introduction

II. Unitarity/BBL

a. QCD and unitary/black-body limit: saturation
b. Recombination, saturation models, saturation scale (GLR, color glass condensate and JIMWLK, BK)
c. Dipole models
d. Nuclear targets
e. Significance for heavy ion program
f. Significance for the ultrahigh energy neutrino interactions

III. Lepton probes and main signatures

a. Low-x physics at LHC, limitations
b. Why electron probes
c. F_2: quark sensitive
d. Diffraction, why a good starting point, A and b sensitivity
e. Exclusive diffraction
f. other gluon sensitive measurements

IV. HERA data ↔ saturation models

a. K-GB-W fits to HERA data
b. Updated dipole models and uncertainties
c. Regge models

d. Saturation in nuclei: A-dependence, LT shadowing, distinguishing saturation

V. Diffraction

1. Exclusive vector meson
   a. Forward tagging (neutron, proton, dissociating p/n)
   b. Plot of $\sigma(w)$ for different Q^2 proton and Pb, also for heavy flavor
   c. Plot of A(mplitude) vs b for different W, proton and Pb
2. Inclusive
   a. Deconstructing 50% diffractive/total
   b. Question: is diffractive/total more interesting (ideal) w/ nuclear targets
   c. Interesting question about DGLAP failure in evolution of F_2^d H1 data
   d. Semi-inclusive F_2^d/F_2 ratio (charm, jets)
   e. Unitarity limit on the dipole scattering amplitudes versus b
   f. Leading twist versus multiple scattering contributions to nuclear shadowing and diffraction on nuclei
   g. Understanding the Gribov limit in dF_2^d/dM^2

VI. Inclusive measurements, structure functions

a. F_2, F_L statistical, systematic errors for proton, Pb vs (x, Q^2) for varying electron beam energies
b. Dipole model with saturation, fit with DGLAP (PDF flexibility, resummed approach)
c. Tests of violation of DGLAP evolution
d. Jets, heavy flavor as alternative measure of $G(x, Q^2)$

VII. Jet and multi-jet observables, parton dynamics

a. Forward di-jets, angular docorrelation
b. Unintegrated PDFs

VIII. Experimental issues

a. Nuclear radiative corrections, systematic errors
b. Forward acceptance
c. Forward electron, photon tagging
d. Forward neutron tagging
e. Forward proton tagging

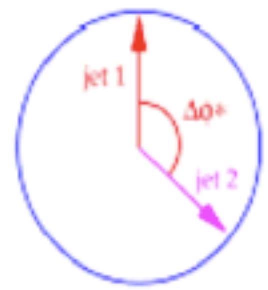
To be done: plans for CDR

- Need results for inclusive diffraction, ratios for eA/ep, coherent and incoherent processes.
- Calculations for VM (and possibly DVCS).
  - Dipole model extrapolations. Non-dipole models too.
  - Energy dependence of the J/Psi (other VMs too) cross section.
  - t-dependence. Profile amplitudes in impact parameter for ep and eA.
- Inclusive: simulations with the small x resummation.
- Parton dynamics: results for forward jets, angular de-correlation, unintegrated parton distributions.
- Monte Carlo calculations!
- Continue EVO discussions every 2-3 weeks

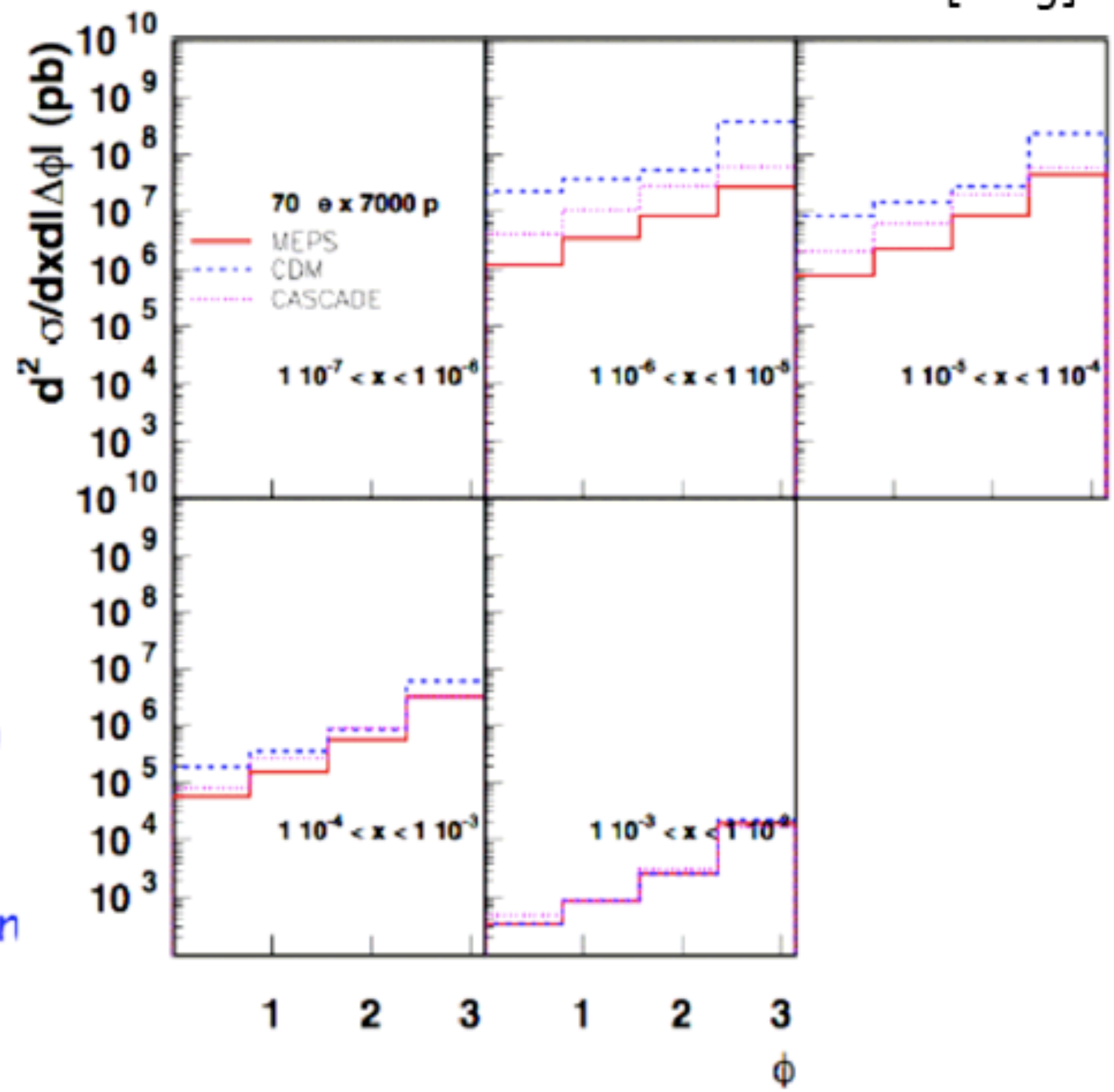
Proposed next meeting: Thur.-Sat., June 25th-27th at CERN prior to Blois conference for working meeting on Low-x part of CDR

Backup

Azimuthal (de)correlations between Jets



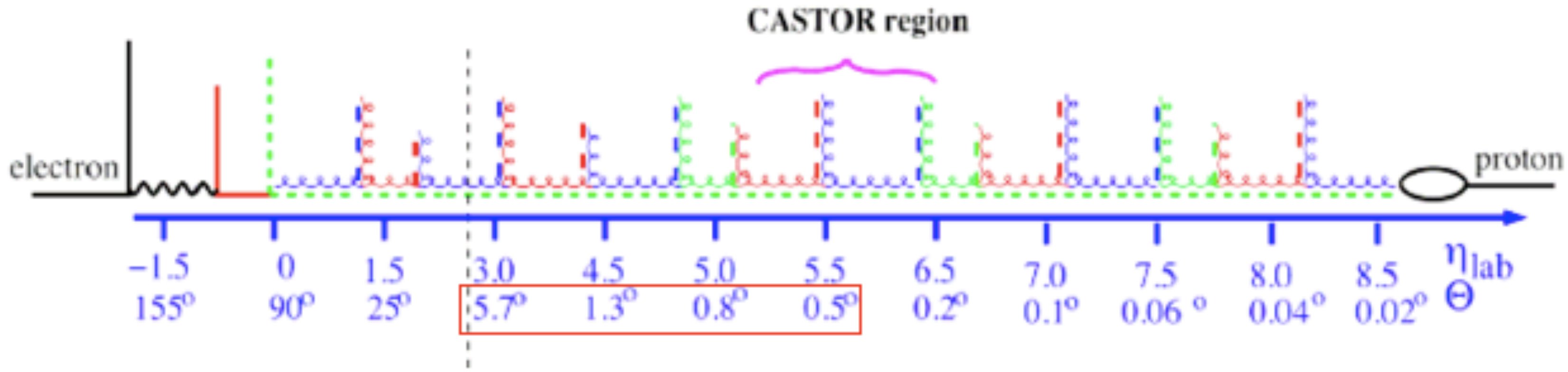
[Jung]



- $5 < Q^2 < 100\ \mathrm{GeV}^2$
  $-1 < \eta < 2.5$
  $E_T > 5\ \mathrm{GeV}$
- small $k_t \rightarrow \Delta\phi \sim 180$
- large k_t from evolution

Forward Instrumentation and Jets

[Jung]



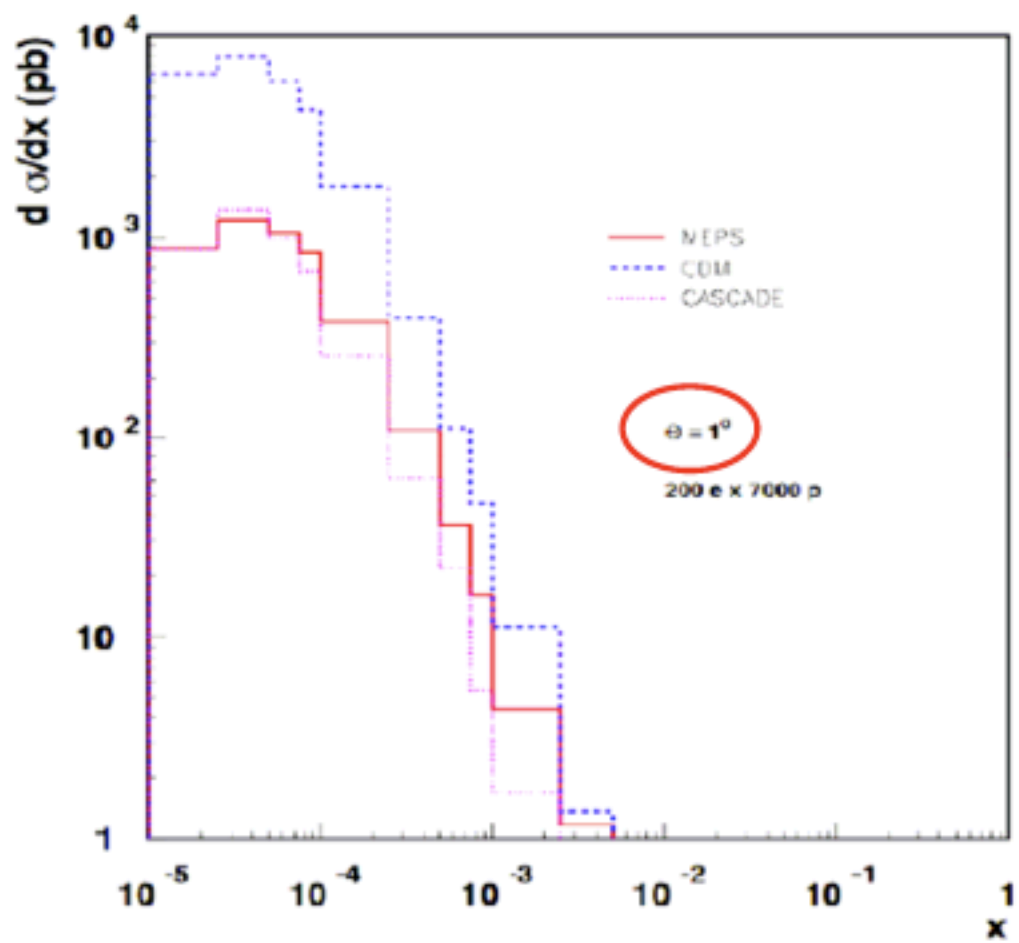
- DIS and forward jet:

$x_{jet} > 0.03$

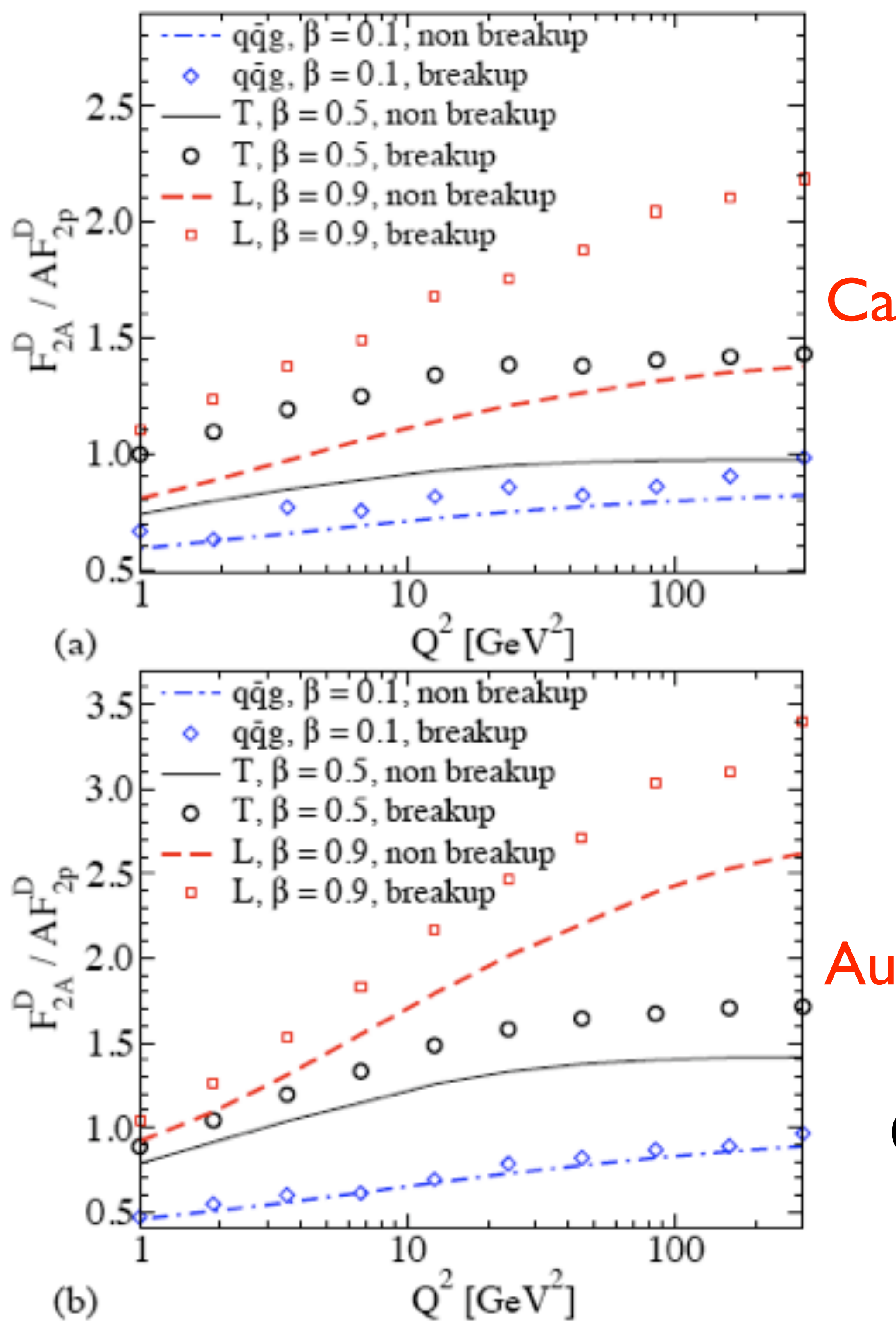
$0.5 < \frac{p_{t\ jet}^2}{Q^2} < 2$

x range (and sensitivity to novel QCD effects) strongly depend on θ cut

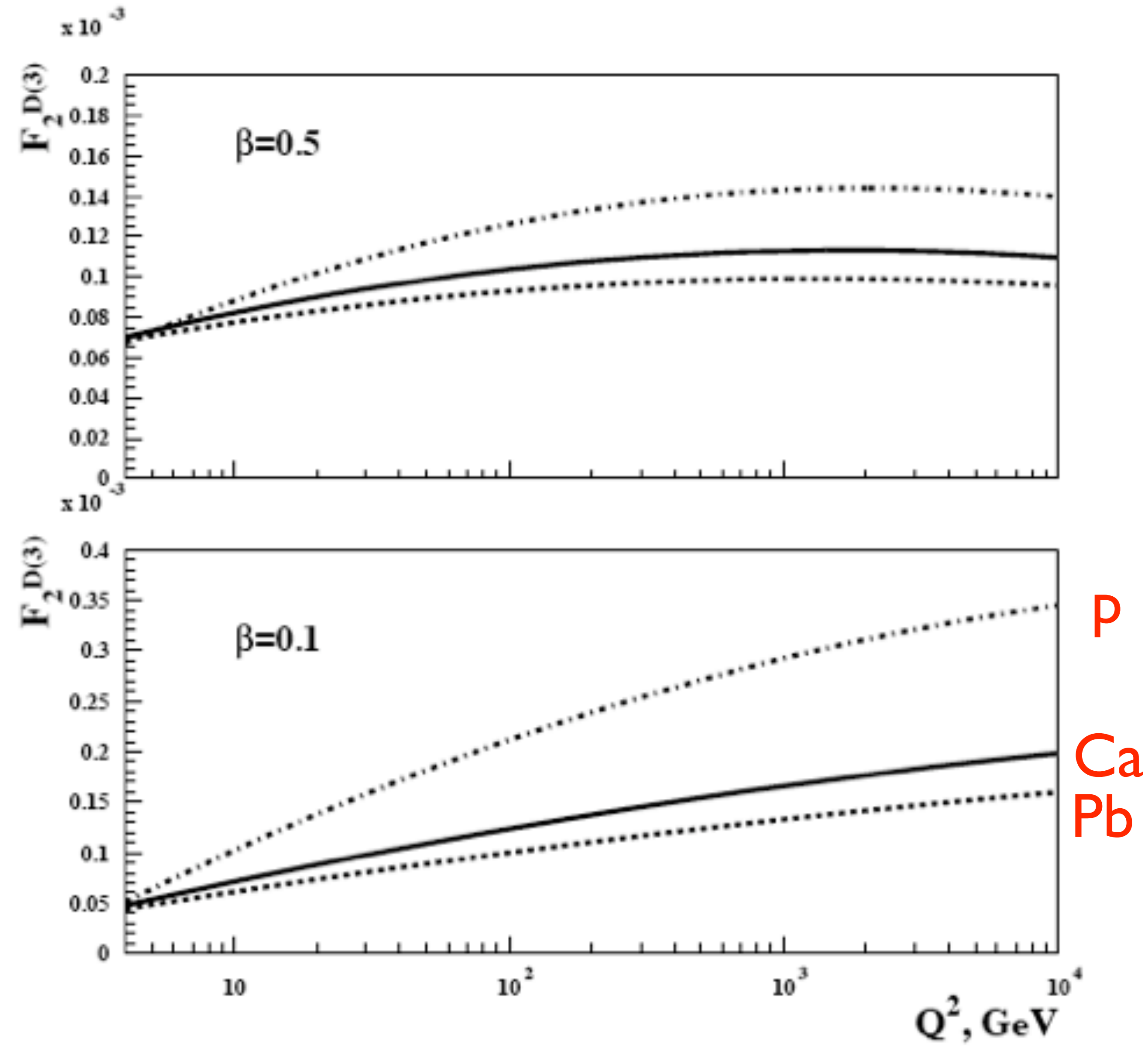
Similar conclusions for Δϕ decorrelations between jets



Inclusive diffraction in eA and ep



Kowalski, Lappi, Marquet, Venugopalan



$x_P = 10^{-3}$

Frankfurt, Guzey, Strikman

Different behavior at large values of β

suspension
or enhancement?