Physics at high parton densities

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on behalf of the conveners of the working group on
Physics at high parton densities (ep and eA)

Nestor Armesto(Santiago de Compostela), Brian Cole(Columbia Univ.), Paul Newman(Birmingham Univ.),

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3rd CERN-ECFA-NuPECC Workshop On The LHeC, November 13, 2010, Chavannes-de-Bogis

Contents of the chapter

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1. Physics at small x:

Introduction

2. Prospects at the LHeC:

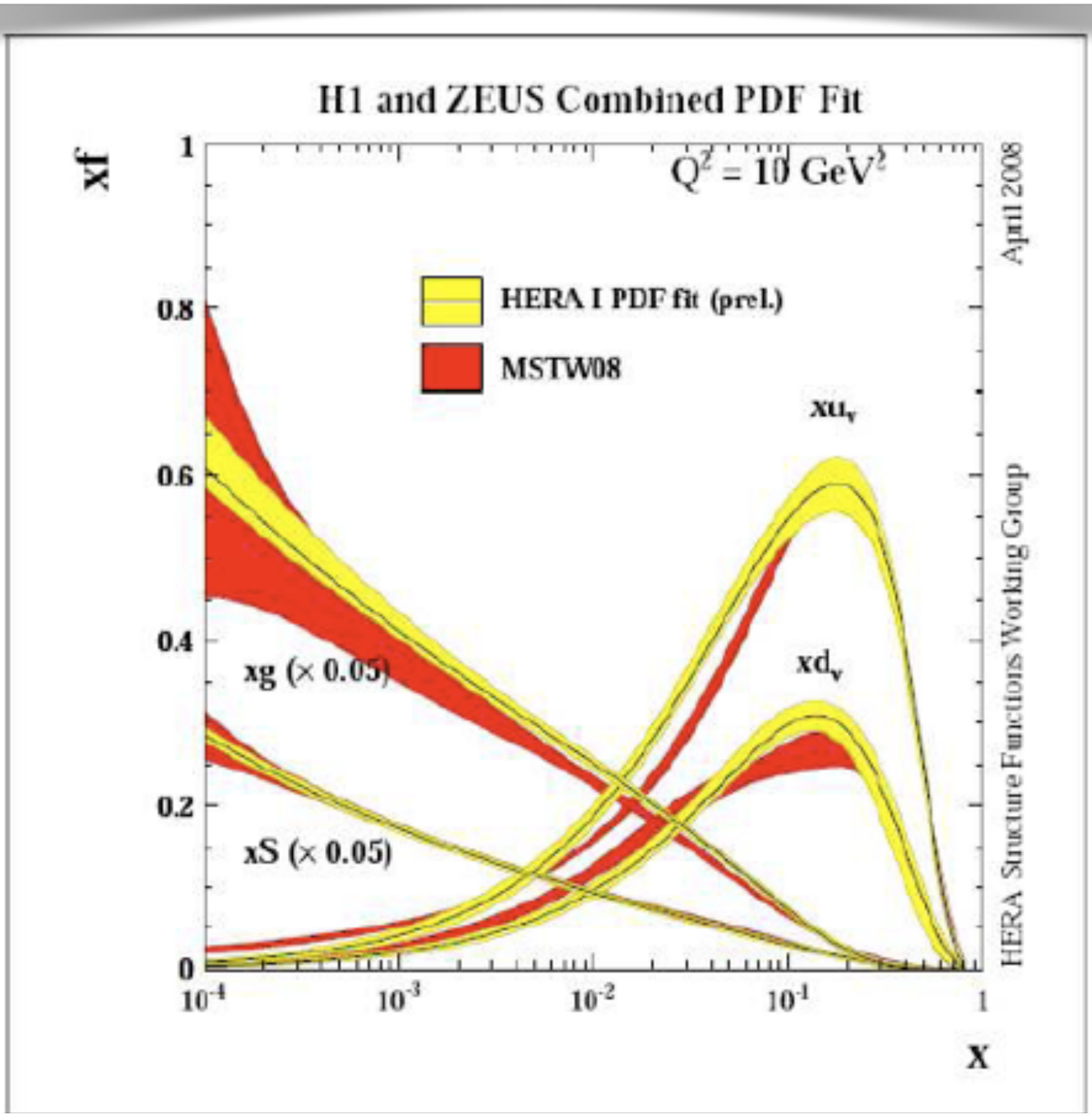
Highlights

Why small x is so interesting?

Deep inelastic scattering is a classic scattering process in which one probes the structure of the hadron most precisely.

Important lesson from HERA : Observation of large scaling violations of the structure function F2.

Gluon density dominates at small x!



HERA established strong growth of the gluon density towards small x.

On the theoretical side: there is a divergence of the parton densities/cross sections at high energies/small x.

Increasing number of partonic fluctuations in the hadron wave function. Many body system.

New phenomena expected: dense parton regime, possibly new emergent phenomena, different effective degrees of freedom...

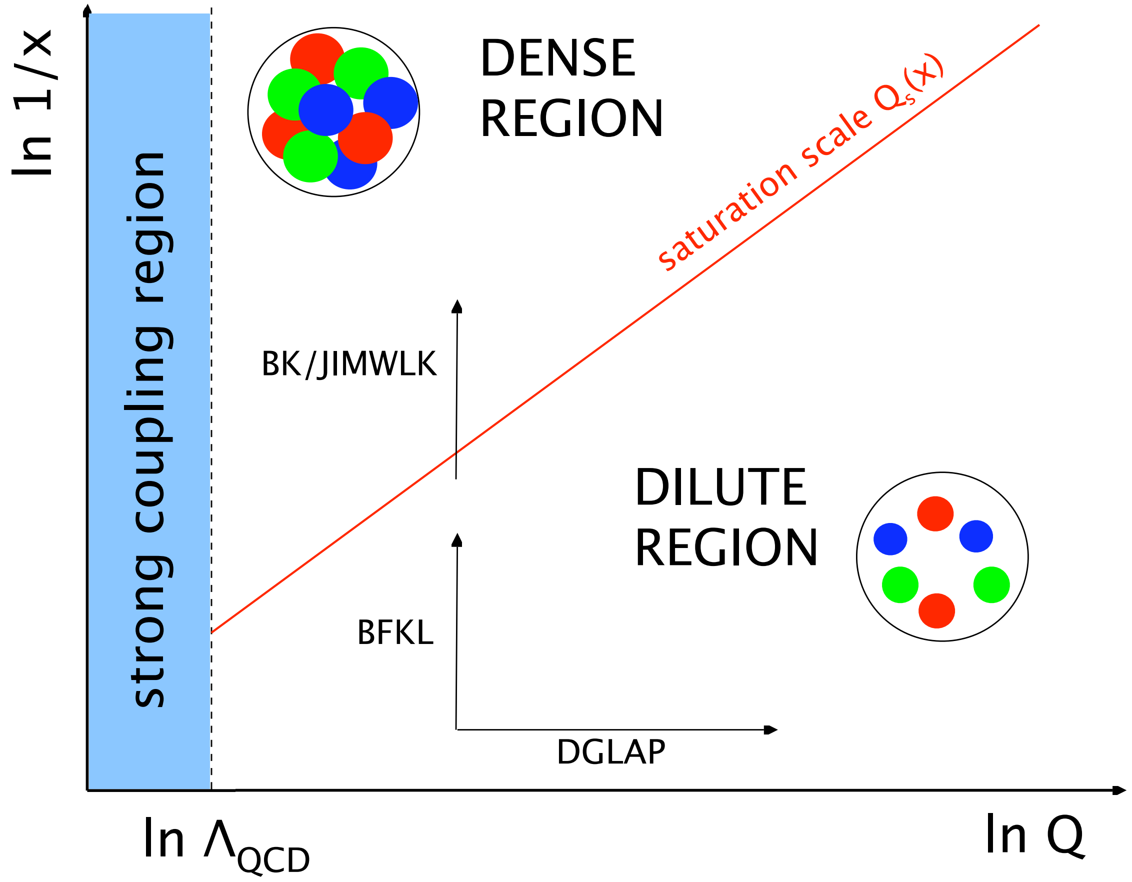
Unitarity must be preserved, how it is realized in microscopic terms?

New regime at small x: high parton density

- At small x the linear evolution gives strongly rising gluon density.
- Parton evolution needs to be modified to include the gluon recombination effects (in the dipole language it corresponds to multiple scatterings).
- 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.



The boundary between the two regimes needs to be determined experimentally.

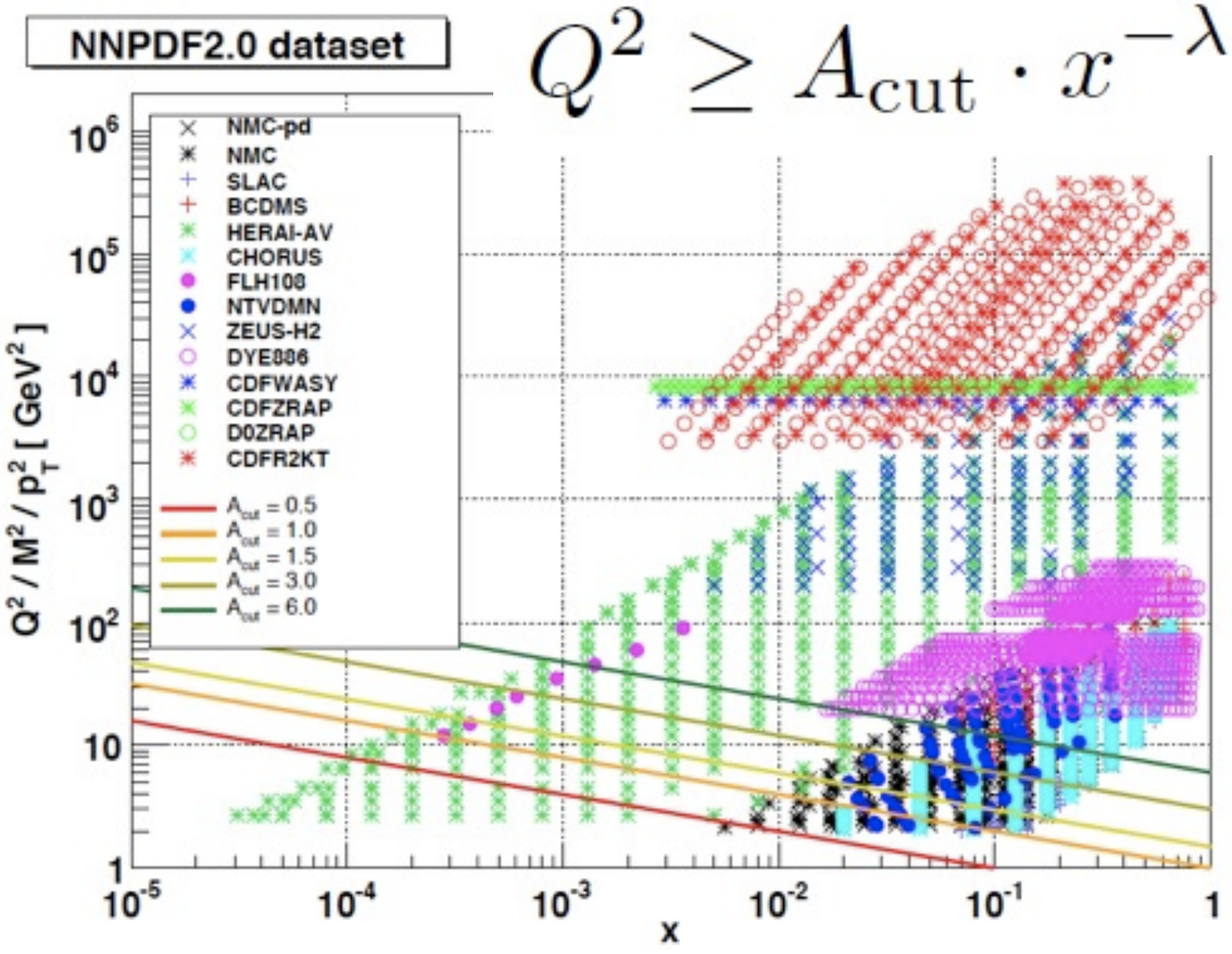
Unique feature of the LHeC: can access the dense regime at fixed, semihard scales Q, while decreasing x.

Hints from HERA

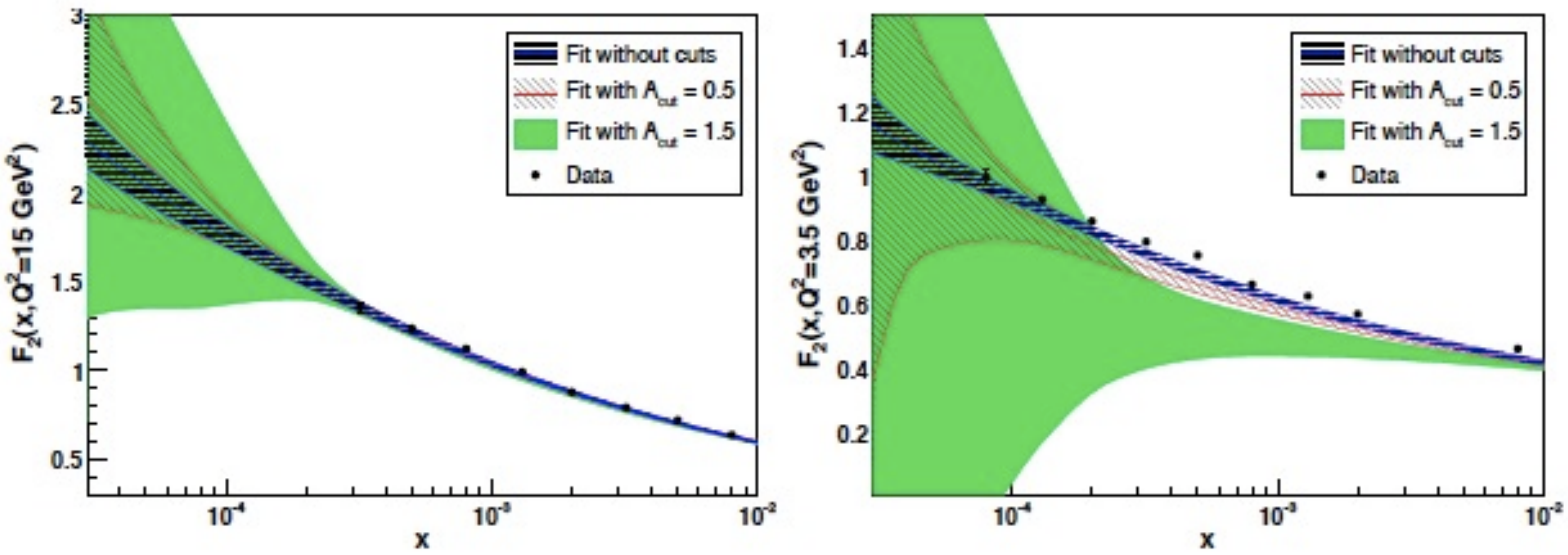
- Tension in data at small x and Q^2 when introduced in a global fit (NNPDF2.0).

- Deviation incompatible with NNLO → resummation or non-linear effects.

$$Q^2 \geq A_{\mathrm{cut}} \cdot x^{-\lambda}$$



Forte,Rojo



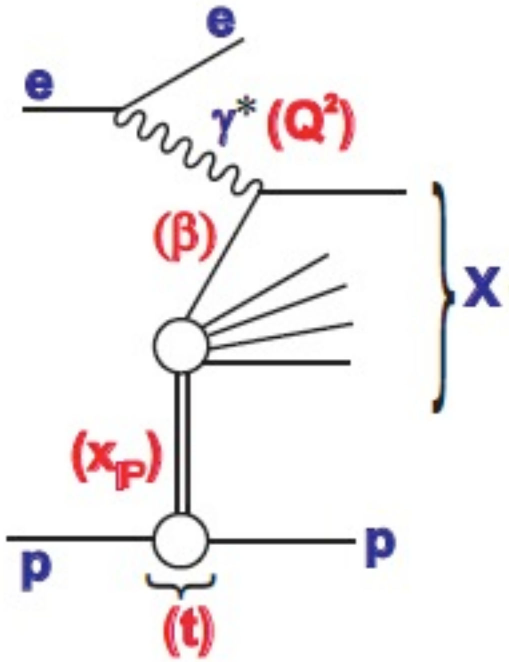
The importance of diffraction

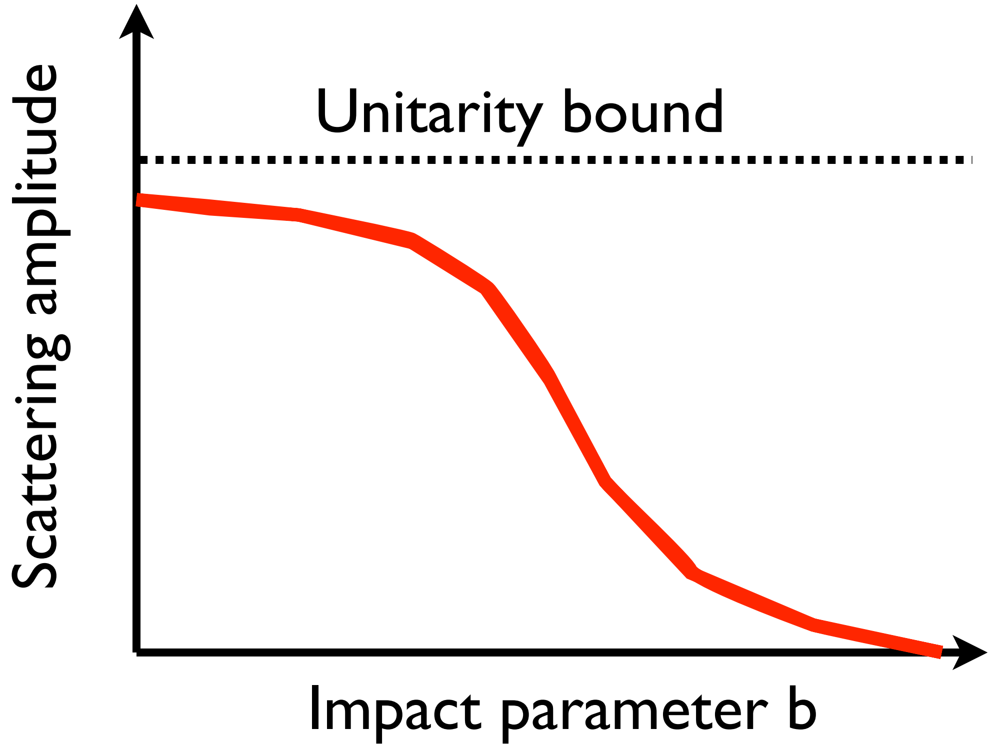
- Diffraction i.e. events with a rapidity gap due to the exchange of a color neutral object, are ~10 % of the total cross section at HERA.

- Diffraction is characterized by softer scales than inclusive measurements: additional possibility to check saturation ideas at same Q.

- Diffraction is a collective phenomenon; explore relation with saturation.

- A scanning in momentum transfer t provides an impact parameter ($t \propto 1/b$) scan of the hadron: unitarity and saturation effects expected to be larger in the center of the hadron (density effect).



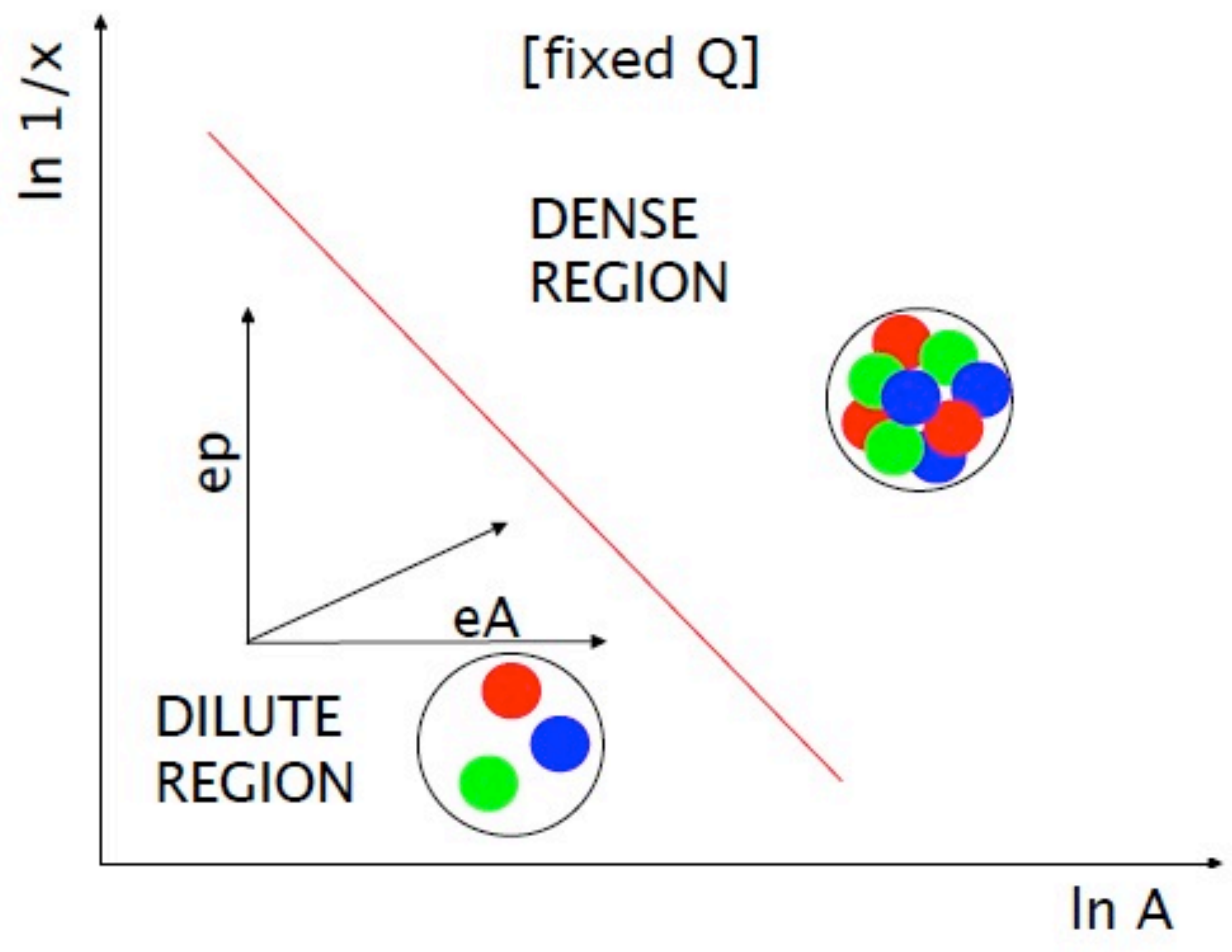


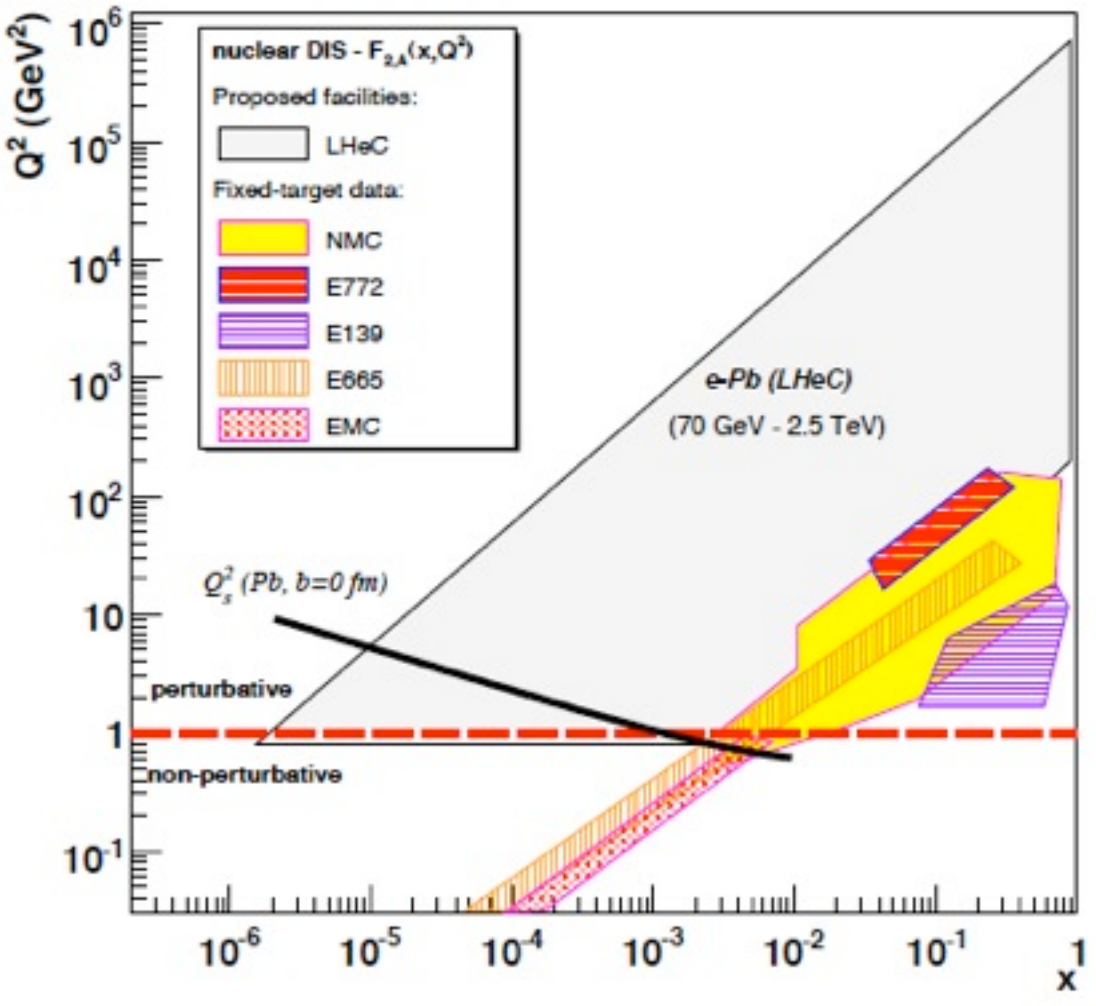
The importance of nuclei

With non-linear phenomena (saturation) being a density effect, the nuclear size offers the possibility of testing it.

$$\frac{A \times xg(x,Q_s^2)}{\pi A^{2/3}} \times \frac{\alpha_s(Q_s^2)}{Q_s^2} \sim 1 \implies Q_s^2 \sim A^{1/3} Q_0^2 \left(\frac{1}{x}\right)^{\lambda}$$

Exploration of the partonic structure of nuclei at high energies.





Contents:

1. Physics at small x:

1.1 Unitarity and QCD. ok

1.2 Status following HERA data. ok

1.3 Low-x physics at the LHC. work in progress

1.4 Nuclear targets. work in progress

2. Prospects at the LHeC:

2.1 Strategy: decreasing x and increasing A. work in progress

2.2 Inclusive measurements (ep and eA). ok

2.3 Exclusive production. ok

2.4 Exclusive vector meson production. work in progress

2.5 DVCS and GPDs. ok

2.6 Inclusive diffraction. work in progress

2.7 Jet and multi-jet observables, parton dynamics and fragmentation. work in progress

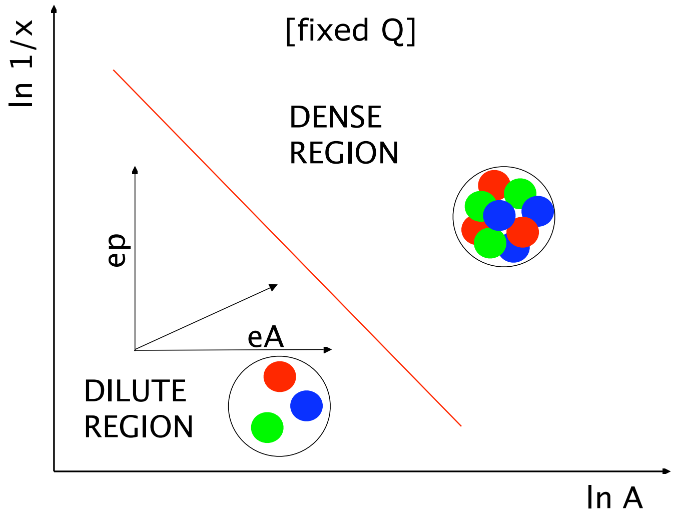
2.8 Photoproduction physics. ok

2.9 Implications for the ultra-high energy neutrino interactions. ok

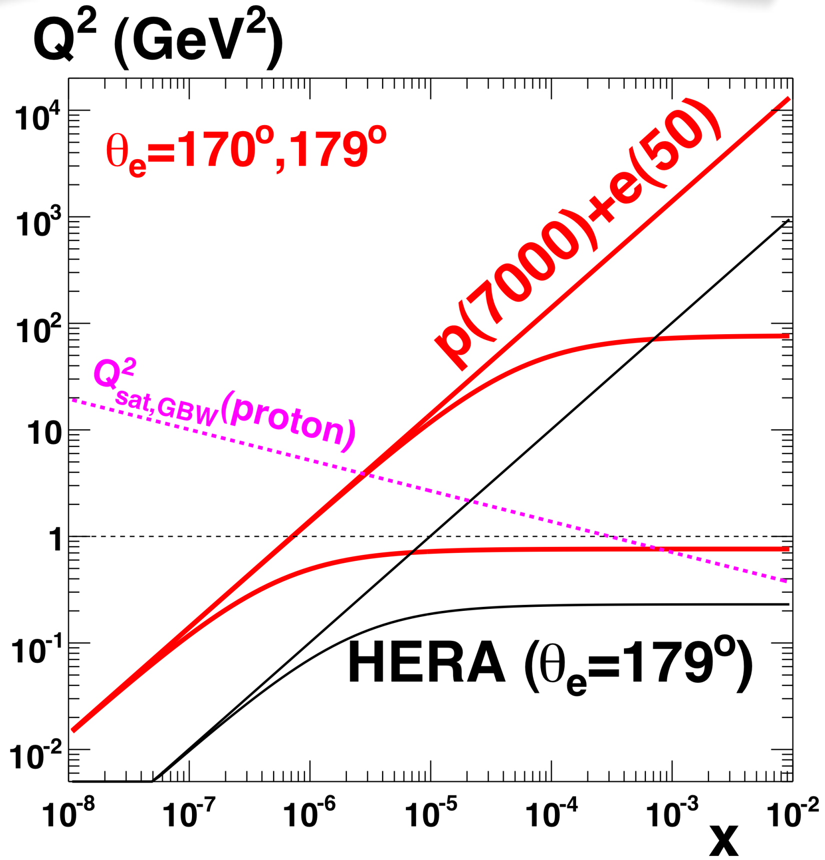
Strategy: decreasing x and/or increasing A

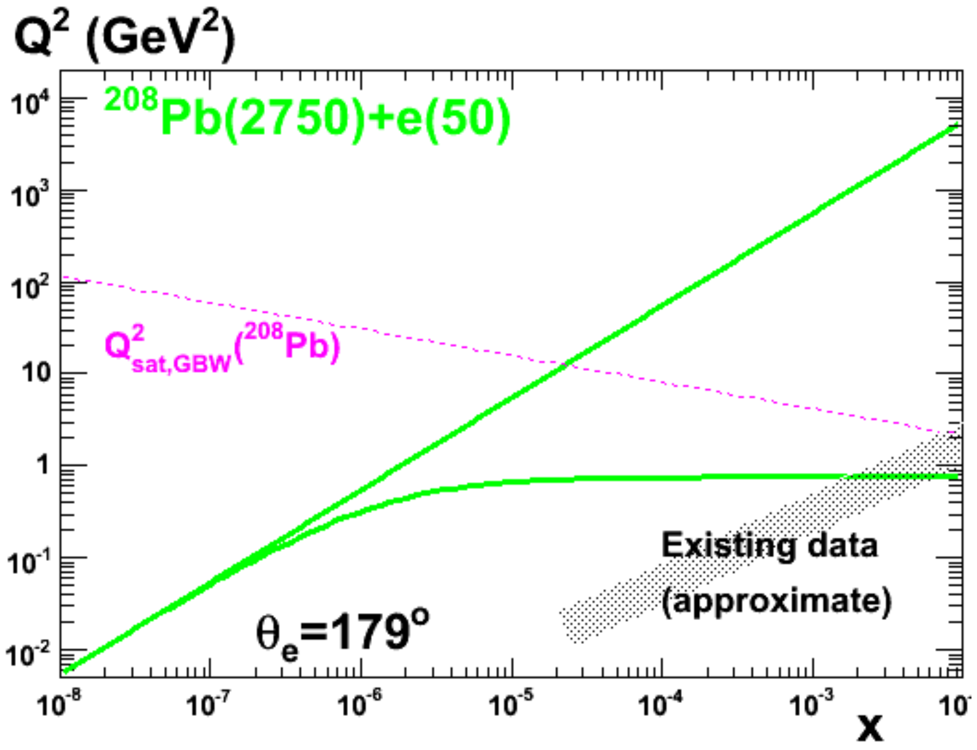
LHeC would deliver a two-pronged approach:

Probing lower x in ep. Evolution of a single source



More nucleons: eA scattering. Many sources overlapping in impact parameter .



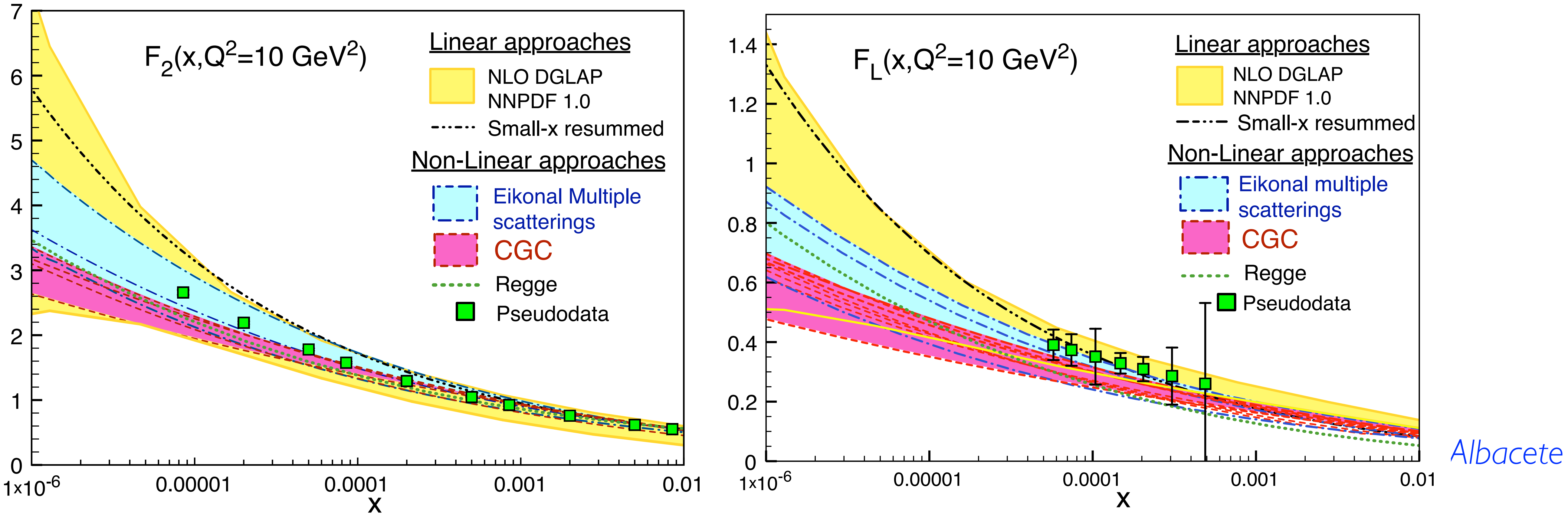


Inclusive measurements

- Predictions for the proton. ok
- Testing non-linear dynamics. ok
- Predictions for nuclei: impact on nuclear DGLAP analyses. ok

Predictions for the proton

DGLAP approaches have large uncertainties at low x and even at moderate Q (larger uncertainties as Q is decreased)



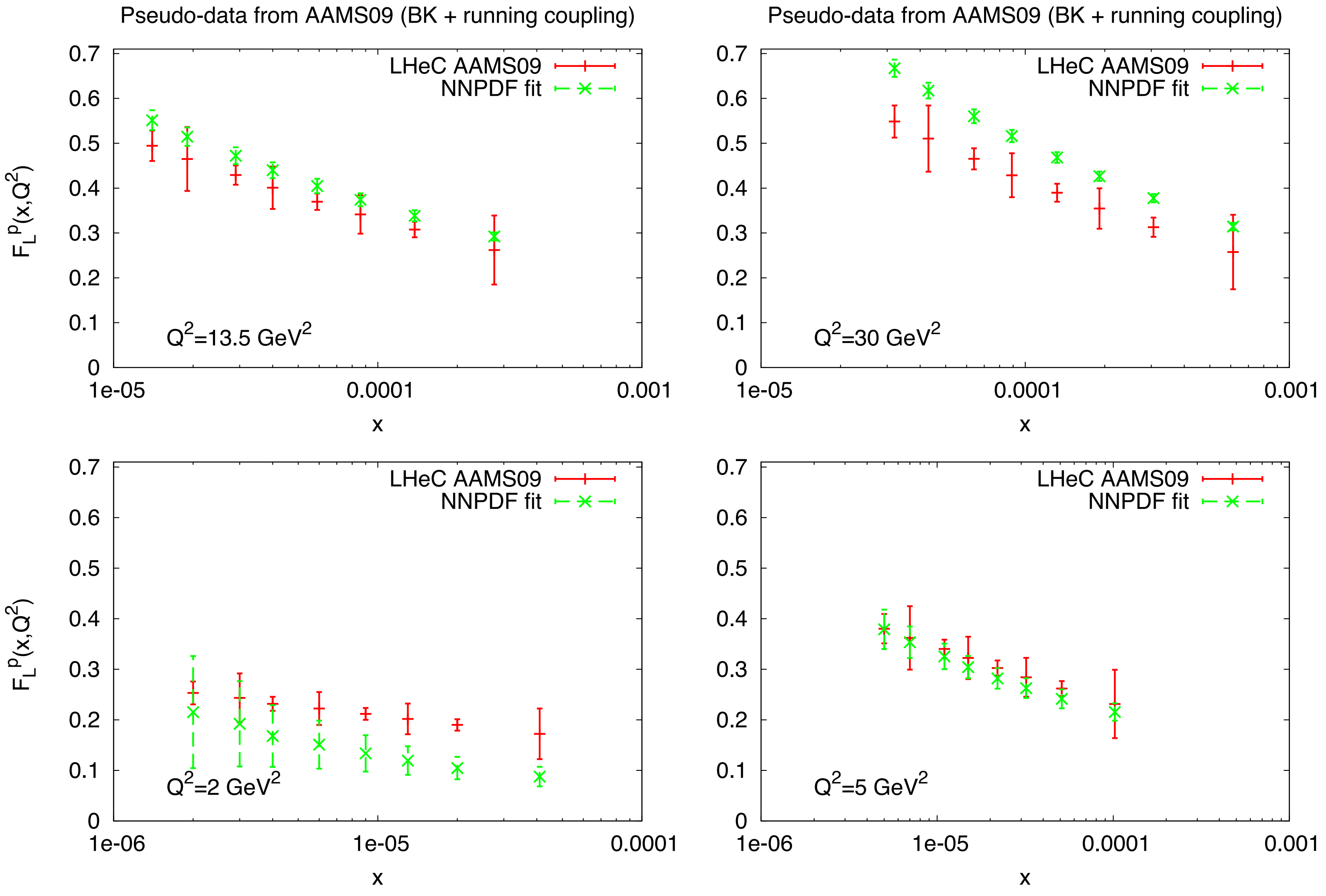
Interestingly, rather small band of uncertainties for models based on saturation as compared with the calculations based on the linear evolution. Possible cause: the nonlinear evolution washes out any uncertainties due to the initial conditions, or too constrained parametrization used within the similar framework.

approx. 2% error on the F2 pseudodata, and 8% on the FL pseudodata ,should be able to rule out many of the scenarios.

Testing nonlinear dynamics in ep

Simulated LHeC data using the nonlinear evolution which leads to the parton saturation at low x.

DGLAP fits (using the NNPDF) cannot accommodate the nonlinear effects if F2 and FL are simultaneously fitted.

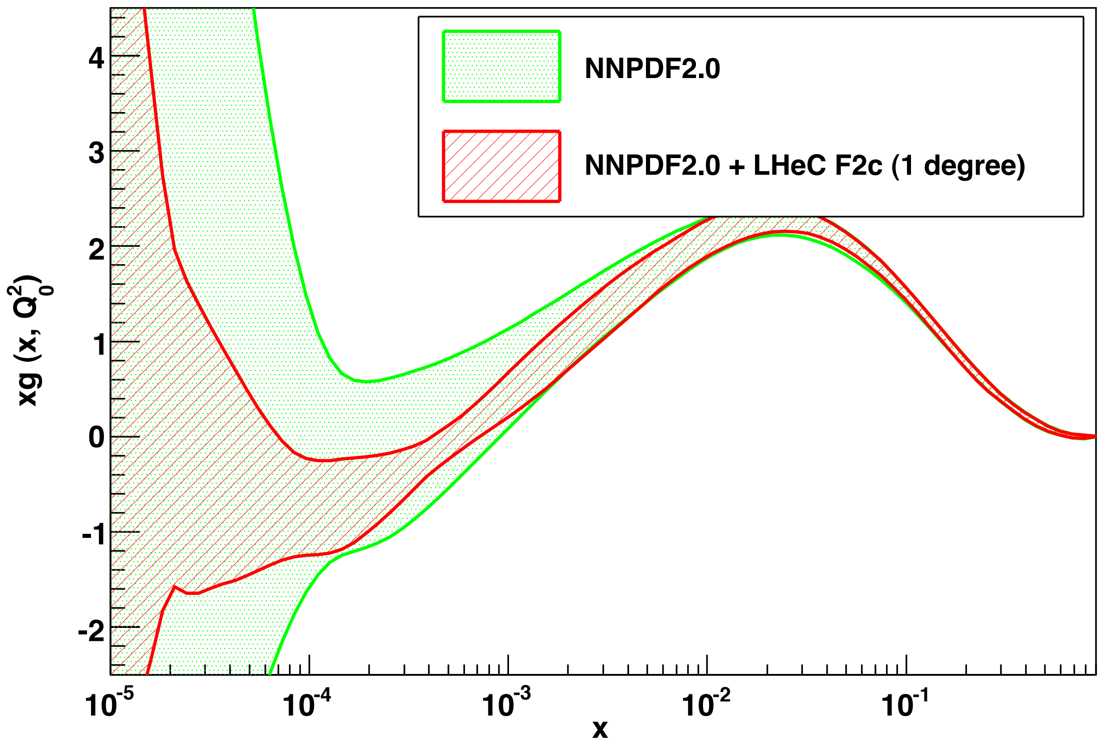


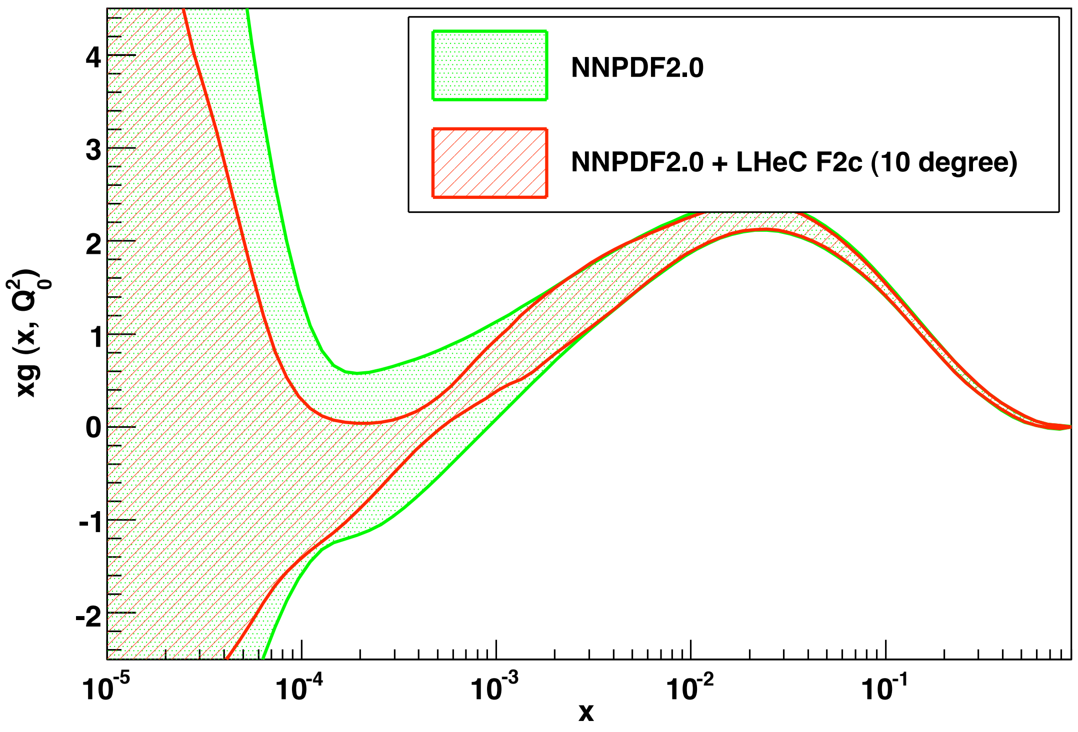
Albacete,Rojo

FL provides important constraint on the gluon density at low x.

Testing nonlinear dynamics in ep

Longitudinal structure function difficult to measure. Possibility of using charm structure function to constrain the gluon distribution function.





Rojo

Charm structure function F2c can be used in addition to F2 to constrain the gluon density (red band corresponds to the analysis with the LHeC data on F2charm).

The advantage of 1 degree scenario is also illustrated.

Conclusion: for a better discrimination between models, especially involving nonlinear dynamics, two observables are necessary.

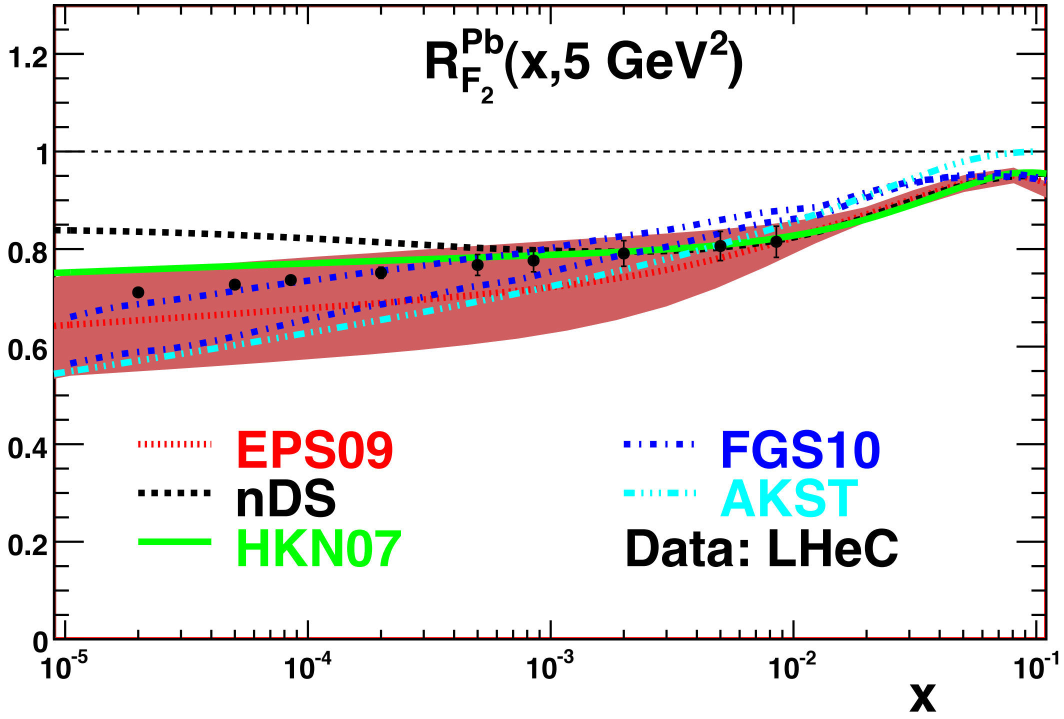
Impact of LHeC on nuclear structure functions

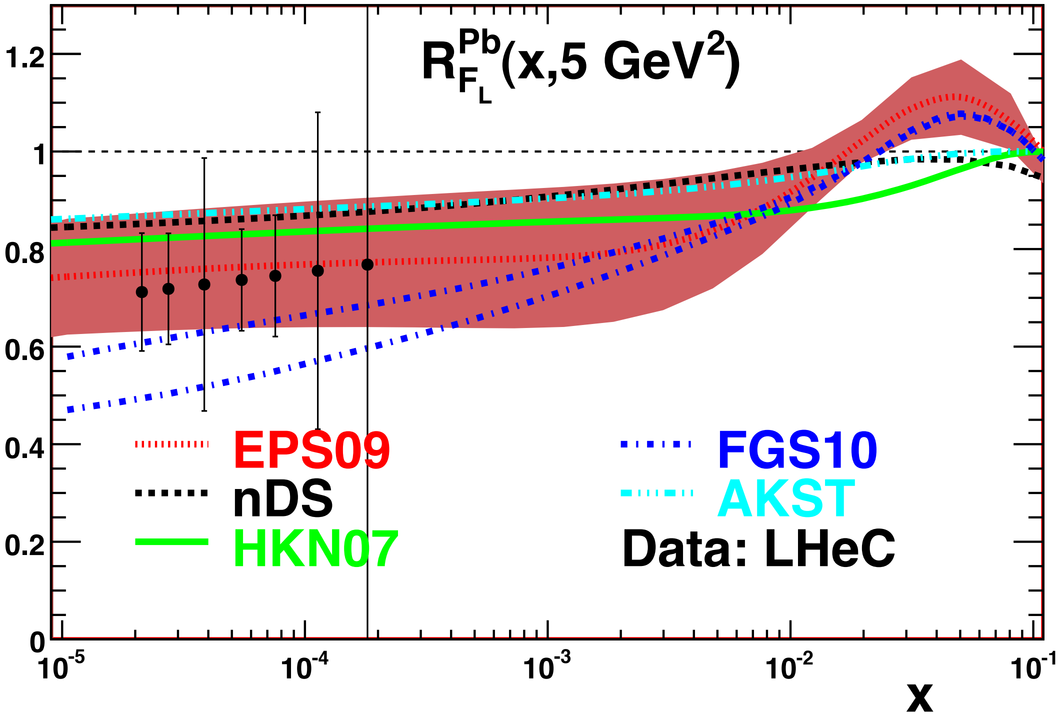
Nuclear ratio for structure function or a parton density.

$$R_f^A(x,Q^2) = \frac{f^A(x,Q^2)}{A \times f^N(x,Q^2)}$$

Nuclear effects $R^A \neq 1$

LHeC potential: precisely measure partonic structure of the nuclei at small x.



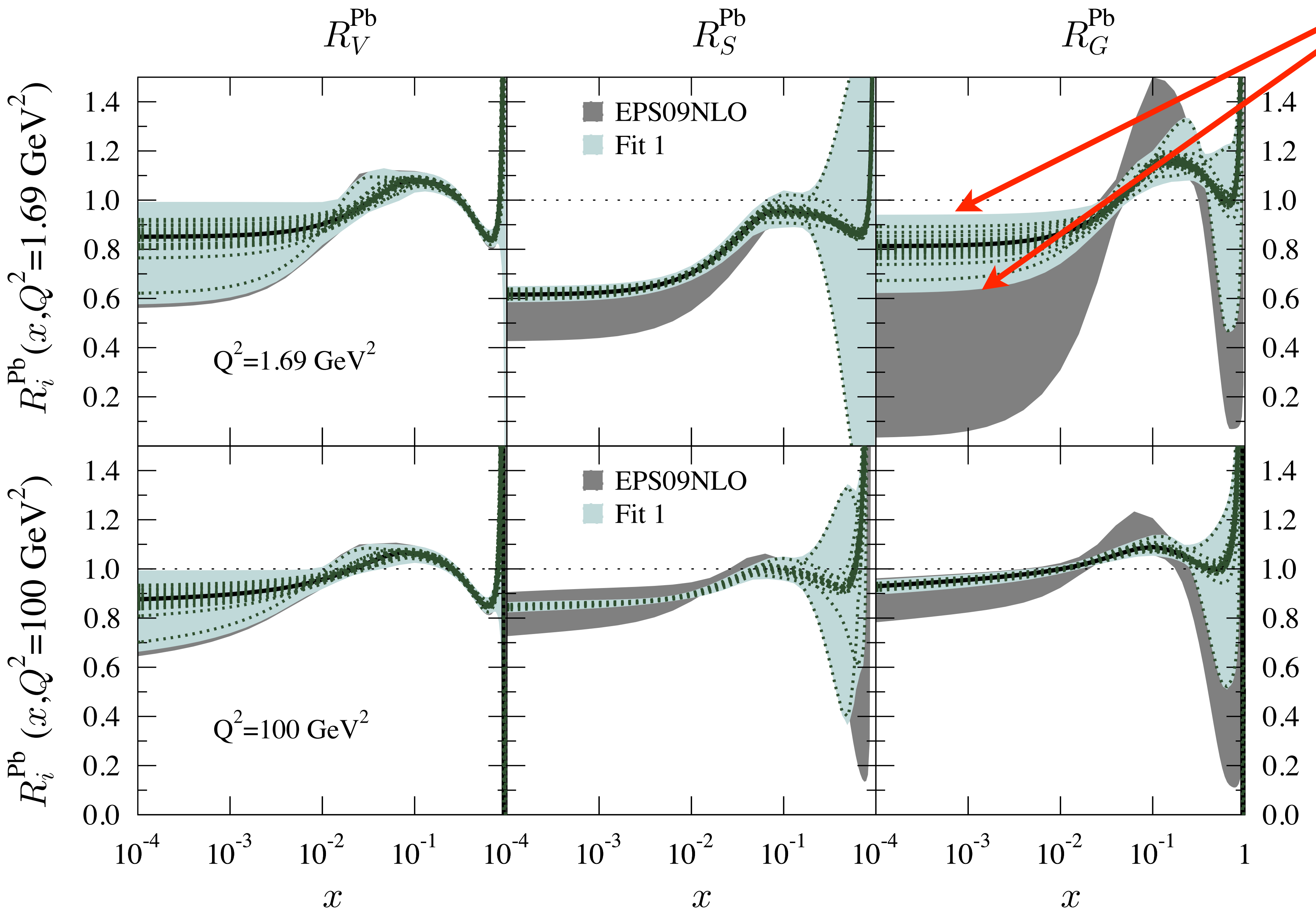


Armesto

Nuclear structure functions measured with very high accuracy.

Impact of LHeC on nuclear parton distributions

Global NLO fit with the LHeC pseudodata included



Much smaller uncertainties.

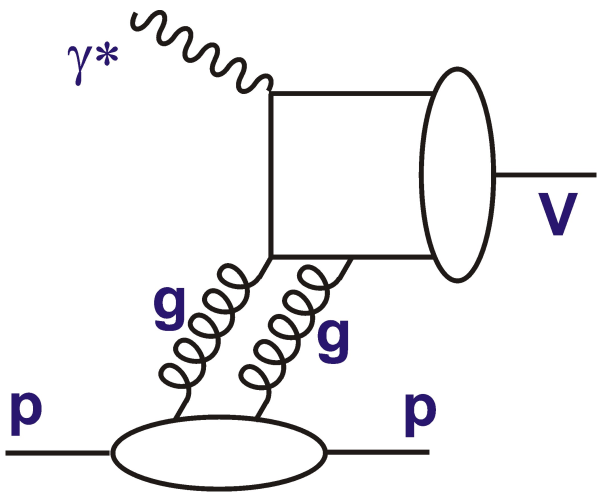
- Very large constraint on the low x gluons and sea quarks after the inclusion of the LHeC pseudodata in the fits.

Salgado

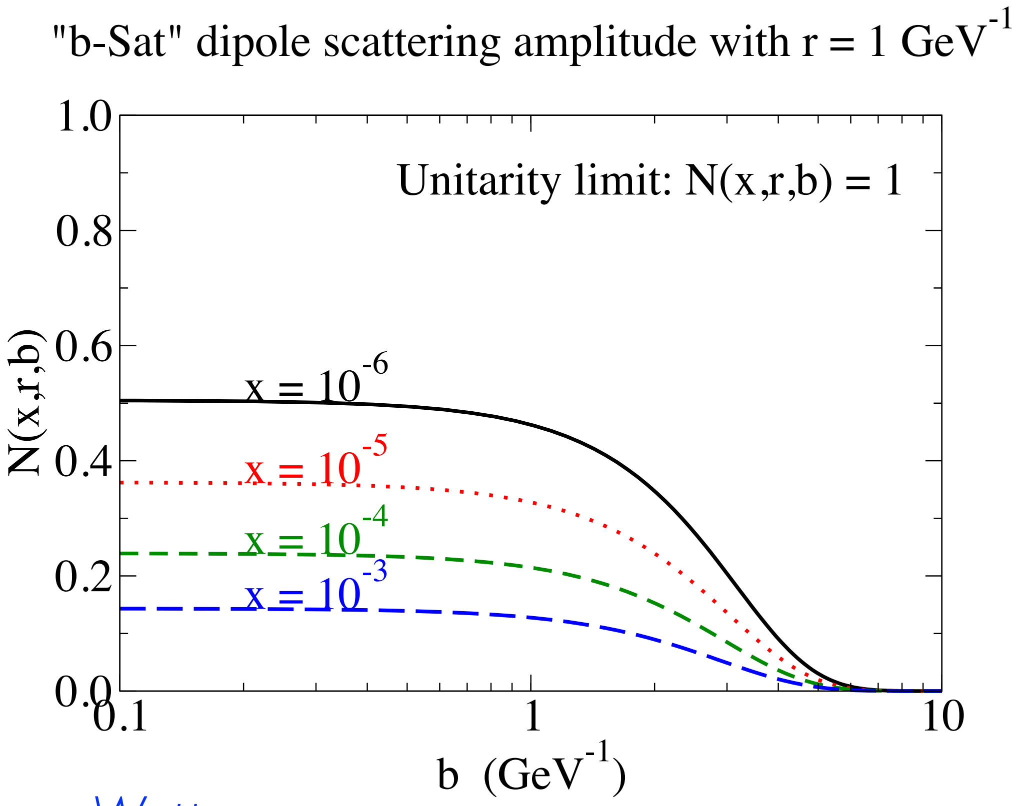
Exclusive production

- Exclusive Vector Meson production.
  - Introduction. ok
  - $\sigma(W)$ for protons. ok
  - Momentum transfer t - dependence. ok
  - Diffractive VM production from nuclei. work in progress
- Deeply Virtual Compton Scattering and Generalized Parton Distributions
  - Current DVCS perspectives. ok
  - DVCS simulation at the LHeC. ok

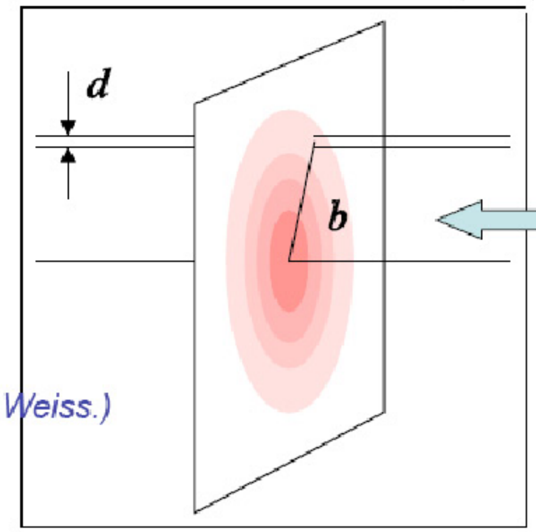
Exclusive diffraction



- 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.



Watt



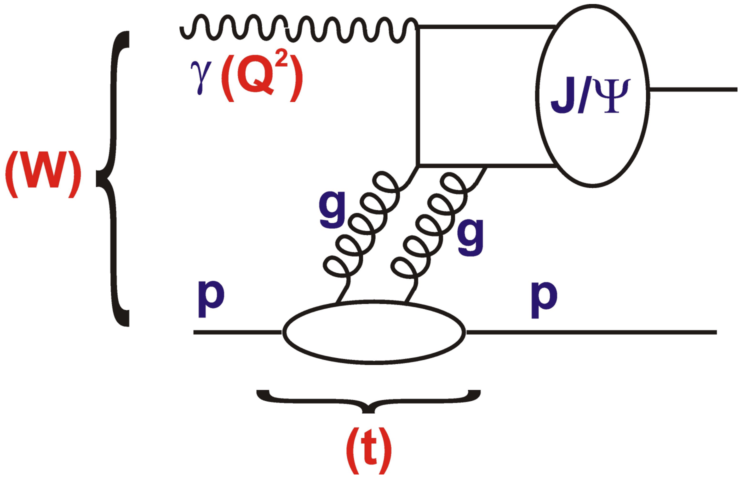
(figure from C. Weiss.)

Central black region growing with decrease of x.

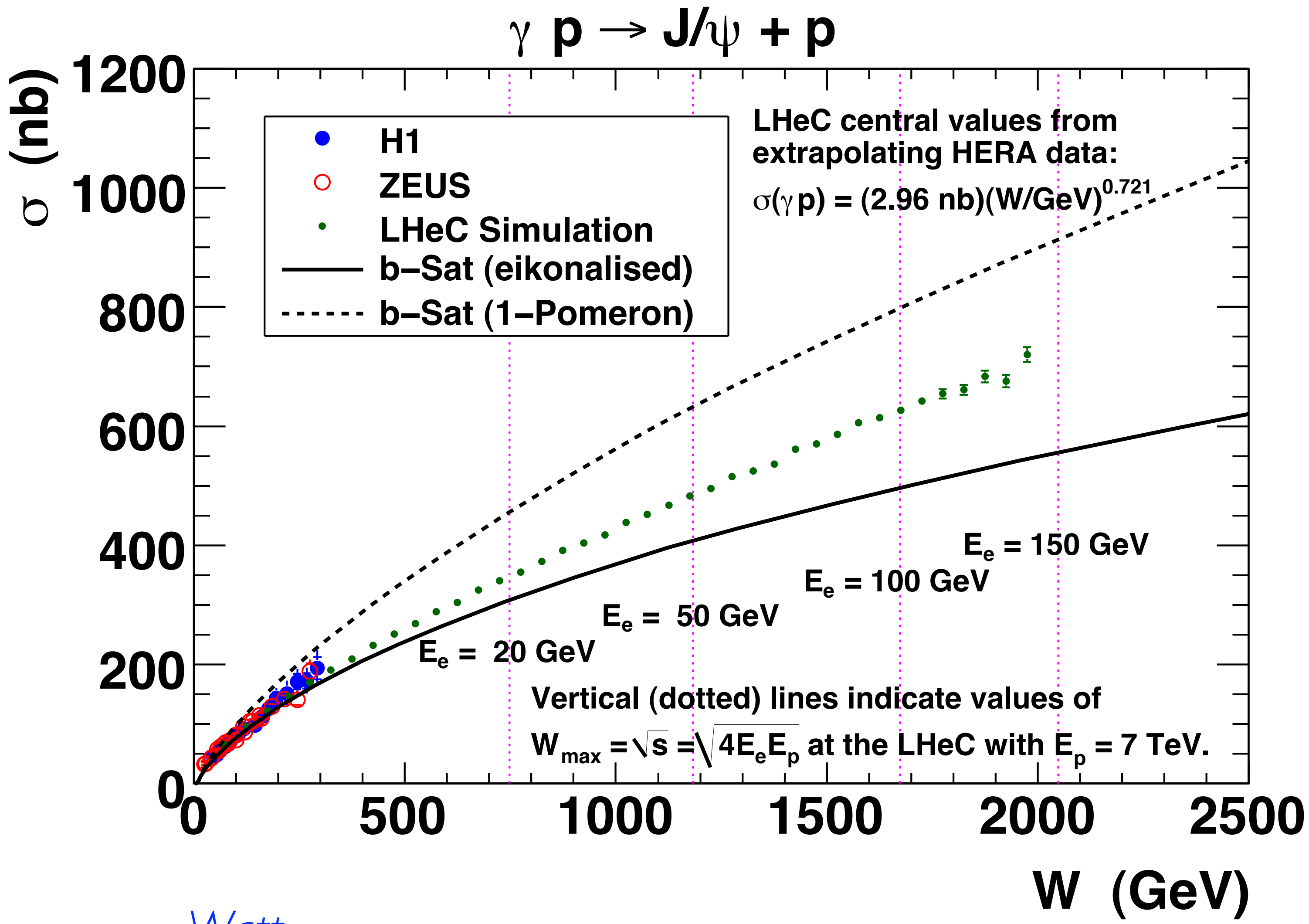
Large momentum transfer t probes small impact parameter where the density of interaction region is most dense.

Exclusive diffraction: predictions

$$\sigma^{\gamma p\rightarrow J/\Psi+p}(W)$$



- b-Sat dipole model (Golec-Biernat, Wuesthoff, Bartels, Motyka, Kowalski, Watt)
- eikonalised: with saturation
- 1-Pomeron: no saturation

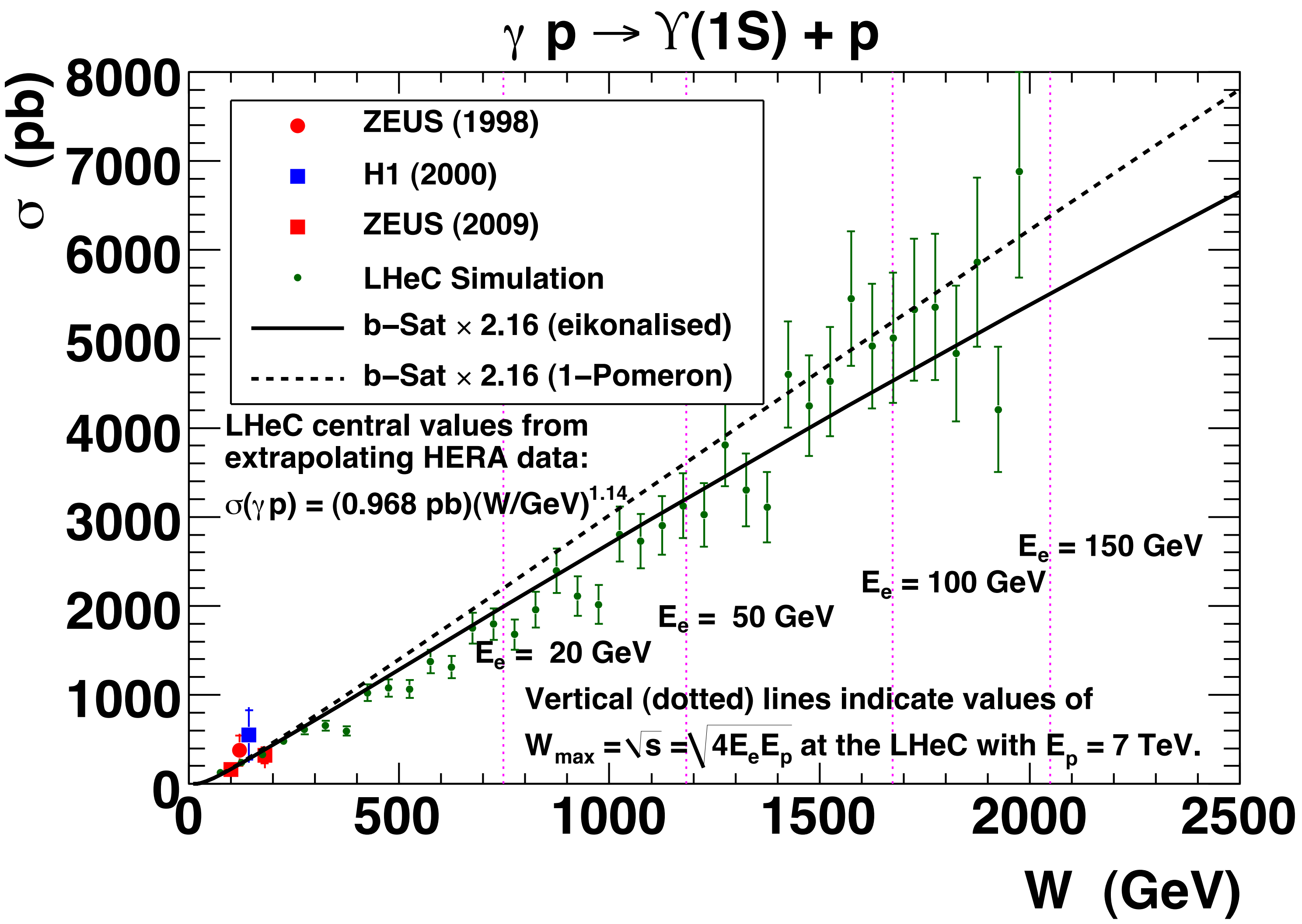


Watt

- Significant effects even for the t-integrated observable.
- Different W behavior depending whether saturation is included or not.
- Simulated data are from extrapolated fit to HERA data
- LHeC can distinguish between the different scenarios.

Exclusive diffraction: predictions

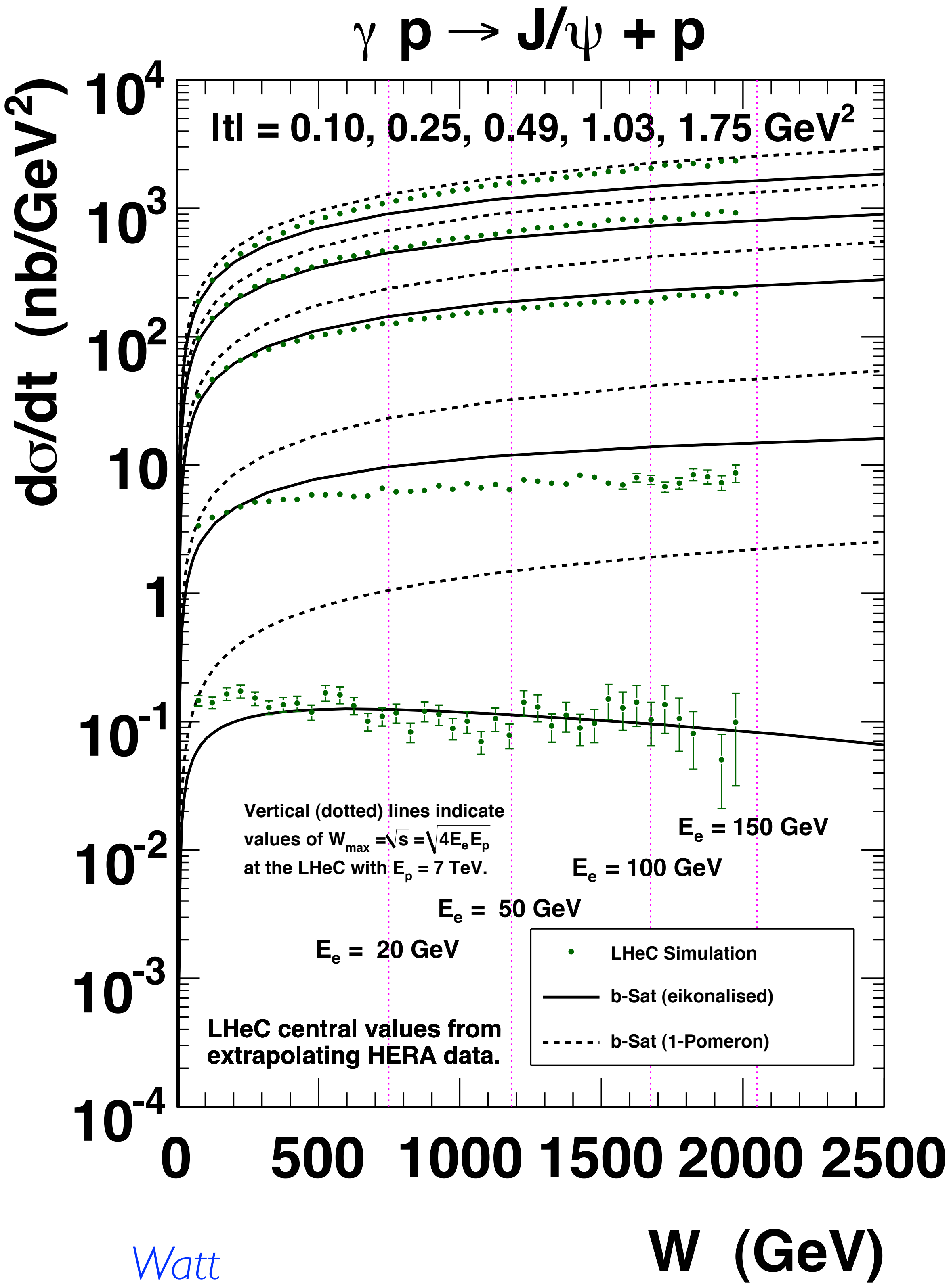
$$\sigma^{\gamma p\rightarrow \Upsilon + p}(W)$$



- Similar analysis for heavier states.
- Smaller sensitivity to the saturation effects. But models do have large uncertainty. Normalization needs to be adjusted to fit the current HERA data.
- Precise measurements possible in the regime well beyond HERA kinematics.

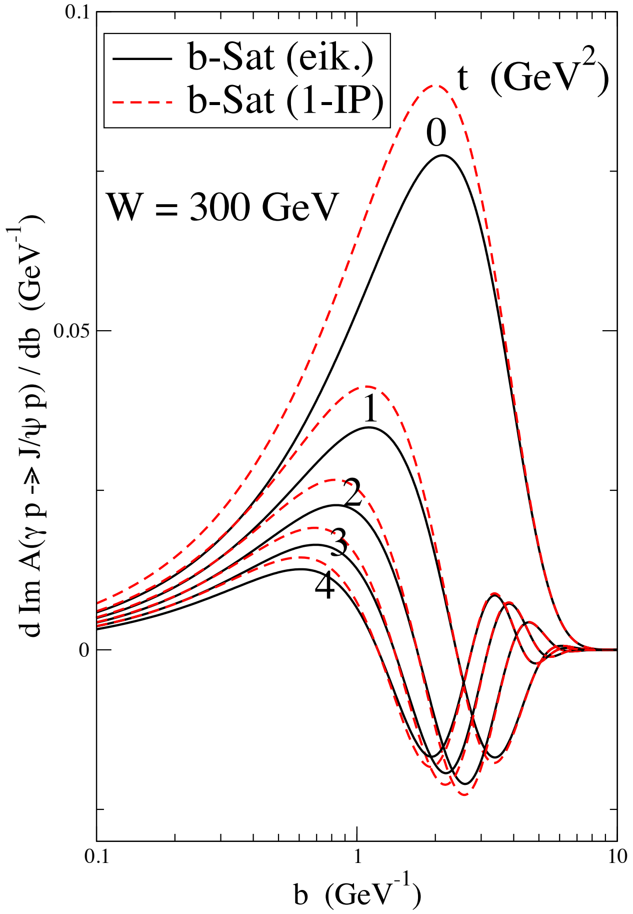
Watt

Exclusive diffraction: momentum transfer dependence



Watt

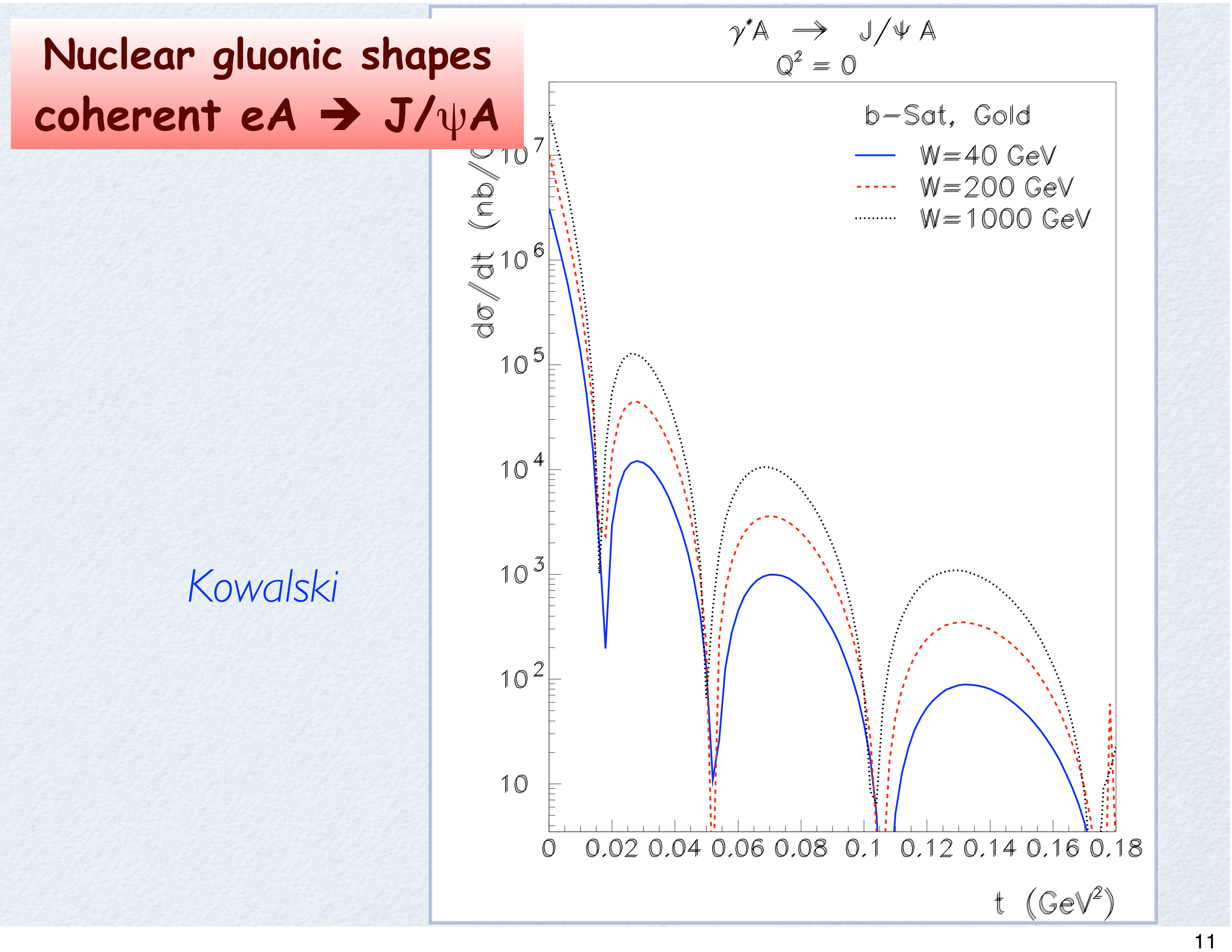
- Photoproduction in bins of W and t.
- Already for small values of t and smallest energies large discrepancies between the models. LHeC can discriminate.
- Large values of t : increased sensitivity to small impact parameters.



Amplitude as a function of the impact parameter.

Exclusive diffraction: nuclear case

Possibility of using the same principle to learn about the gluon distribution in the nucleus. Challenges: need to distinguish between coherent and incoherent diffraction. Possible nuclear resonances at small t?

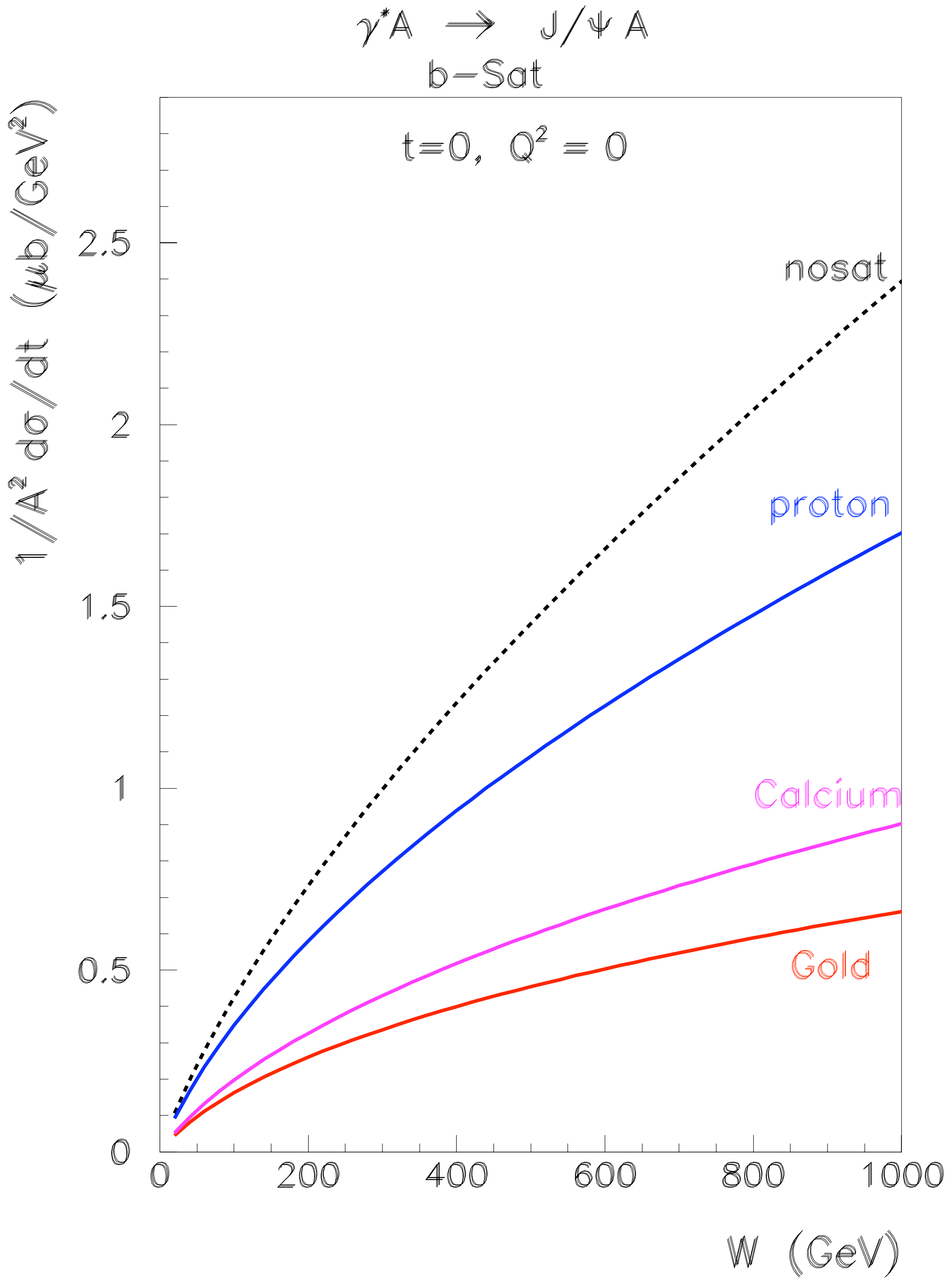


Nuclear gluonic shapes coherent eA → J/ψA

Kowalski

t-dependence: characteristic dips

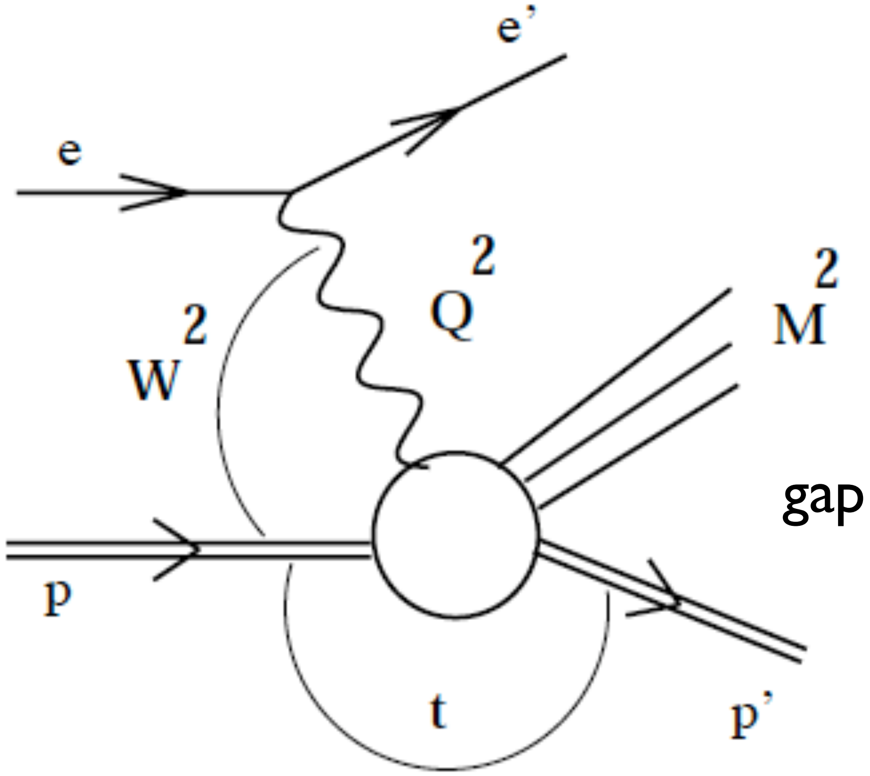
Energy dependence is also very informative



Inclusive diffraction:

- Diffractive Deep Inelastic Scattering. ok
- Diffractive Parton Densities. ok
- Diffractive DIS, Dipole Models and Sensitivity to Non-linear Effects . ok
- Predicting nuclear shadowing from inclusive diffraction in ep. ok
- Predictions for inclusive diffraction on nuclear targets. work in progress

Inclusive diffraction



$$\boxed{e + p \rightarrow e' + p' + X}$$

Proton stays intact and separated by a 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

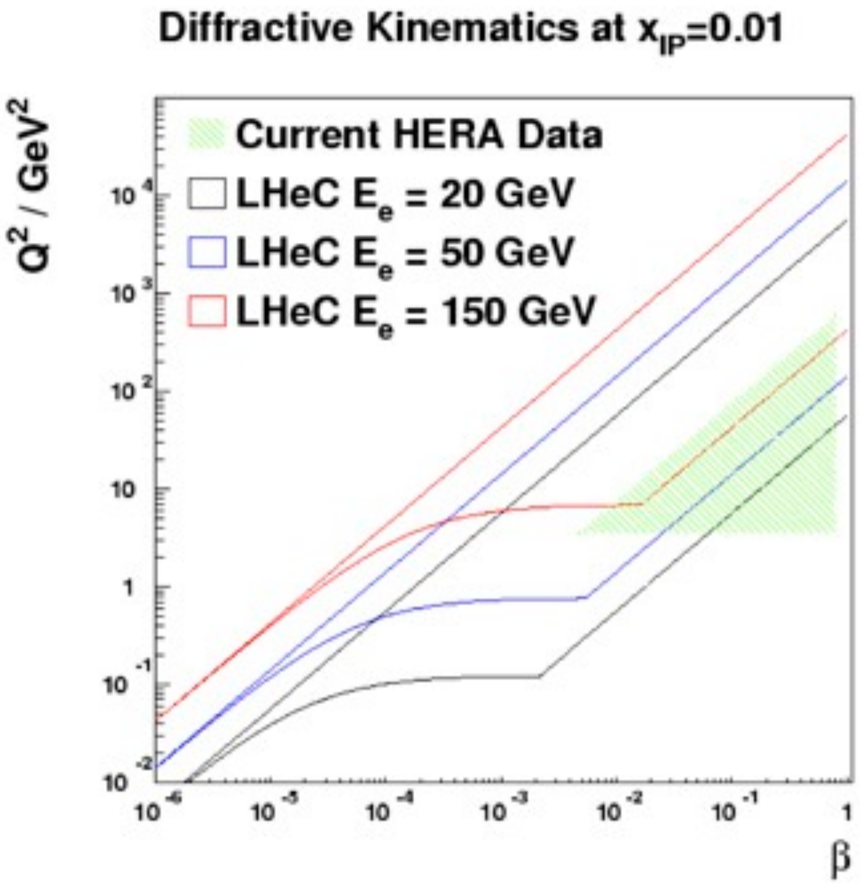
$$\Delta\eta = \ln 1/x_{I\!P}$$

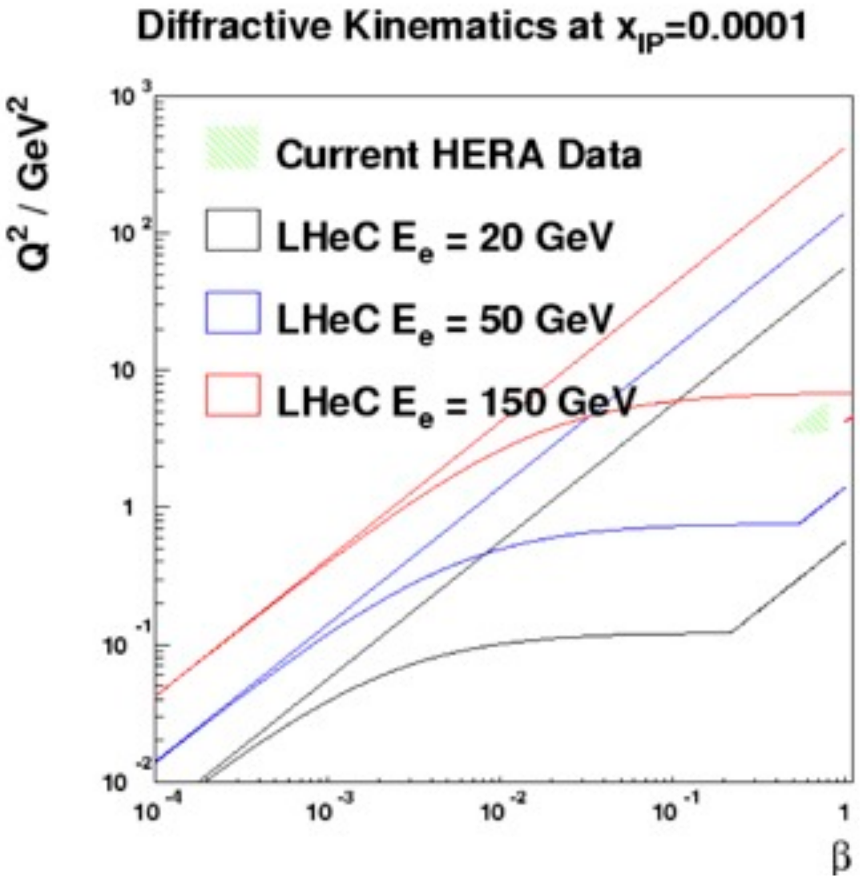
Rapidity gap

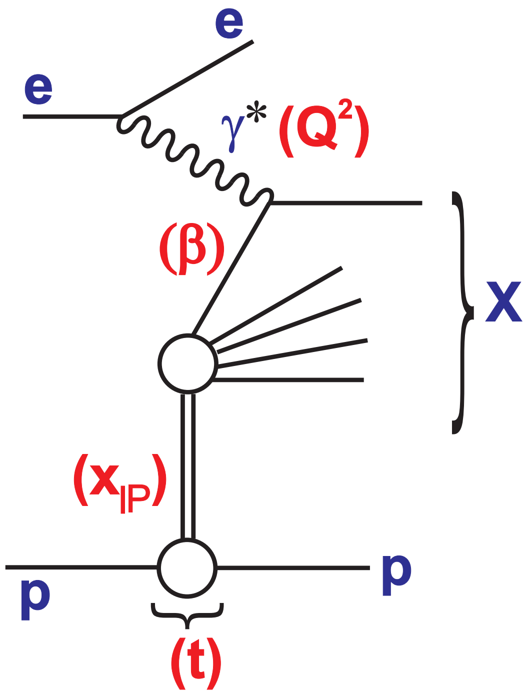
LHeC :

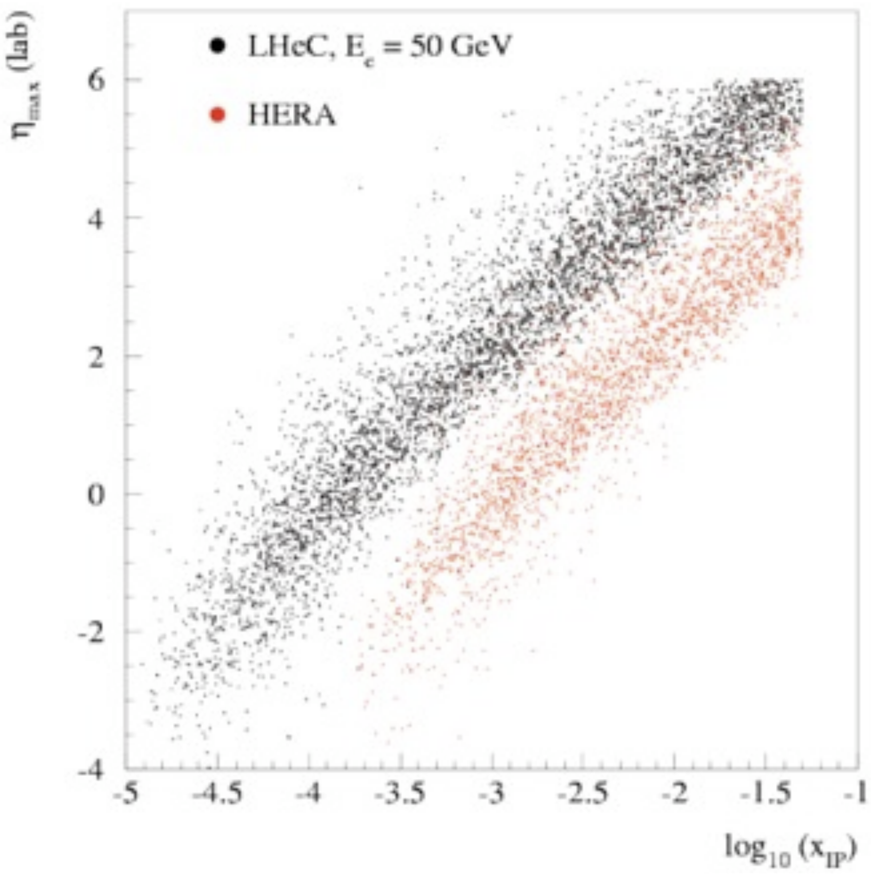
- Enhanced sensitivity to semi-hard regime
- Explore relation with saturation at unprecedented low x
- Test factorization (or lack of it)
- Gap survival issues
- Additional momentum transfer dependence allows access to measure the impact parameter profile of the interaction region

Inclusive diffraction: new possibilities


Diffractive Kinematics at $x_{IP}=0.01$


Diffractive Kinematics at $x_{IP}=0.0001$

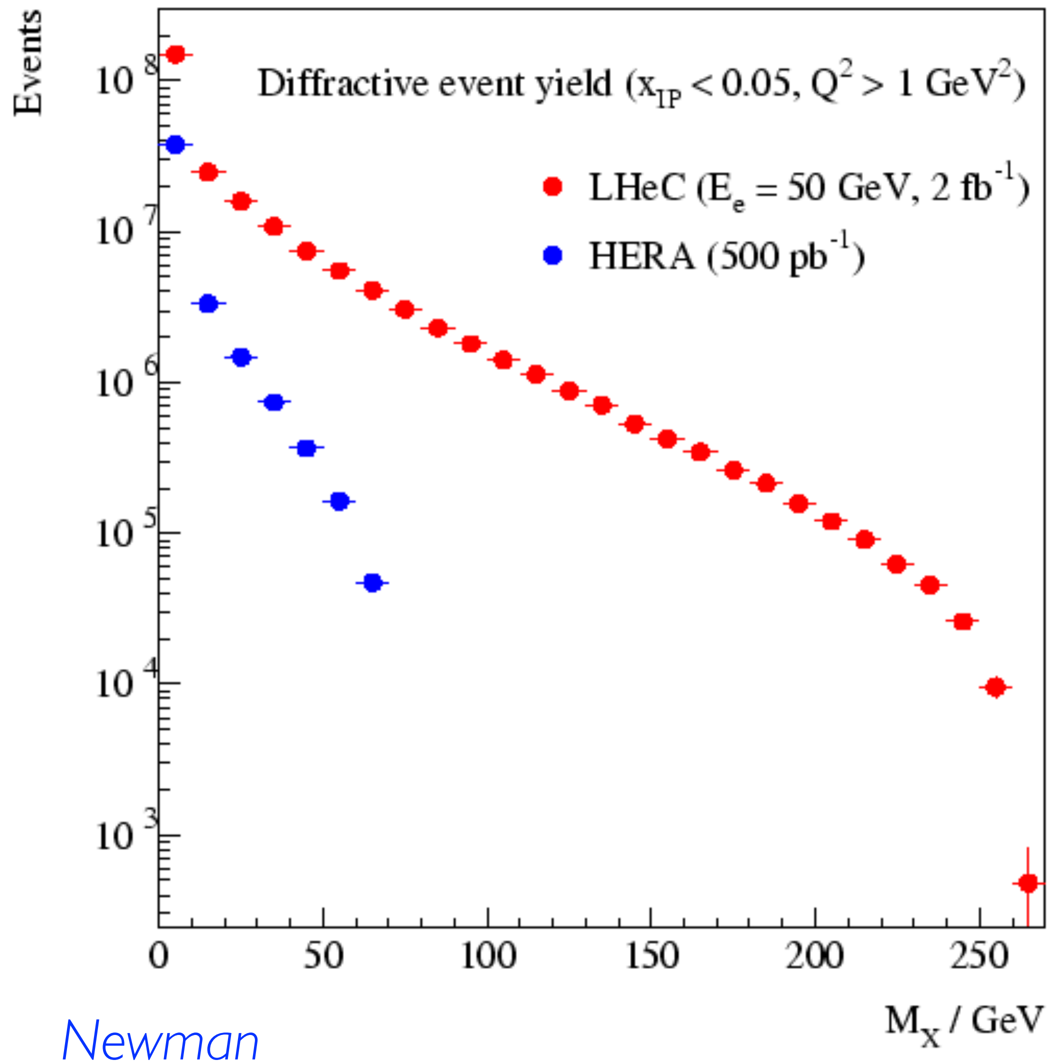




- Studies with 1 degree acceptance,
- Constraints on diffractive-PDFs
- Factorization (tests) in much bigger kinematics range.
- Diffraction is much more sensitive to the semi-hard regime.
- Enhanced sensitivity to nonlinear/saturation effects.

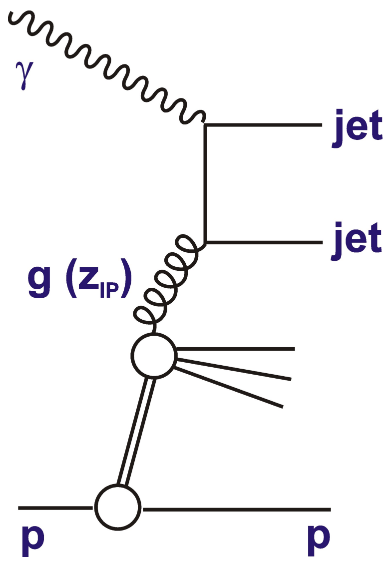
Inclusive diffraction: final states

Diffractive masses up to hundreds of GeV can be produced with low x_{IP}



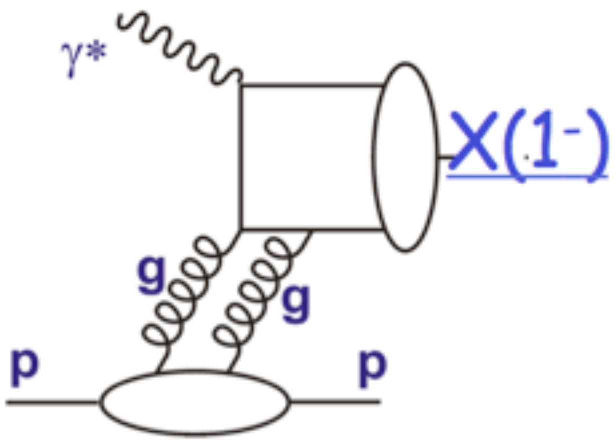
Newman

Precise tests of the diffractive PDFs and factorization possible. Final states (jets) with high p_T



New diffractive channels (W/Z/beauty/Higgs?...)

Unfold quantum numbers precisely, measure new 1^- exclusive final states

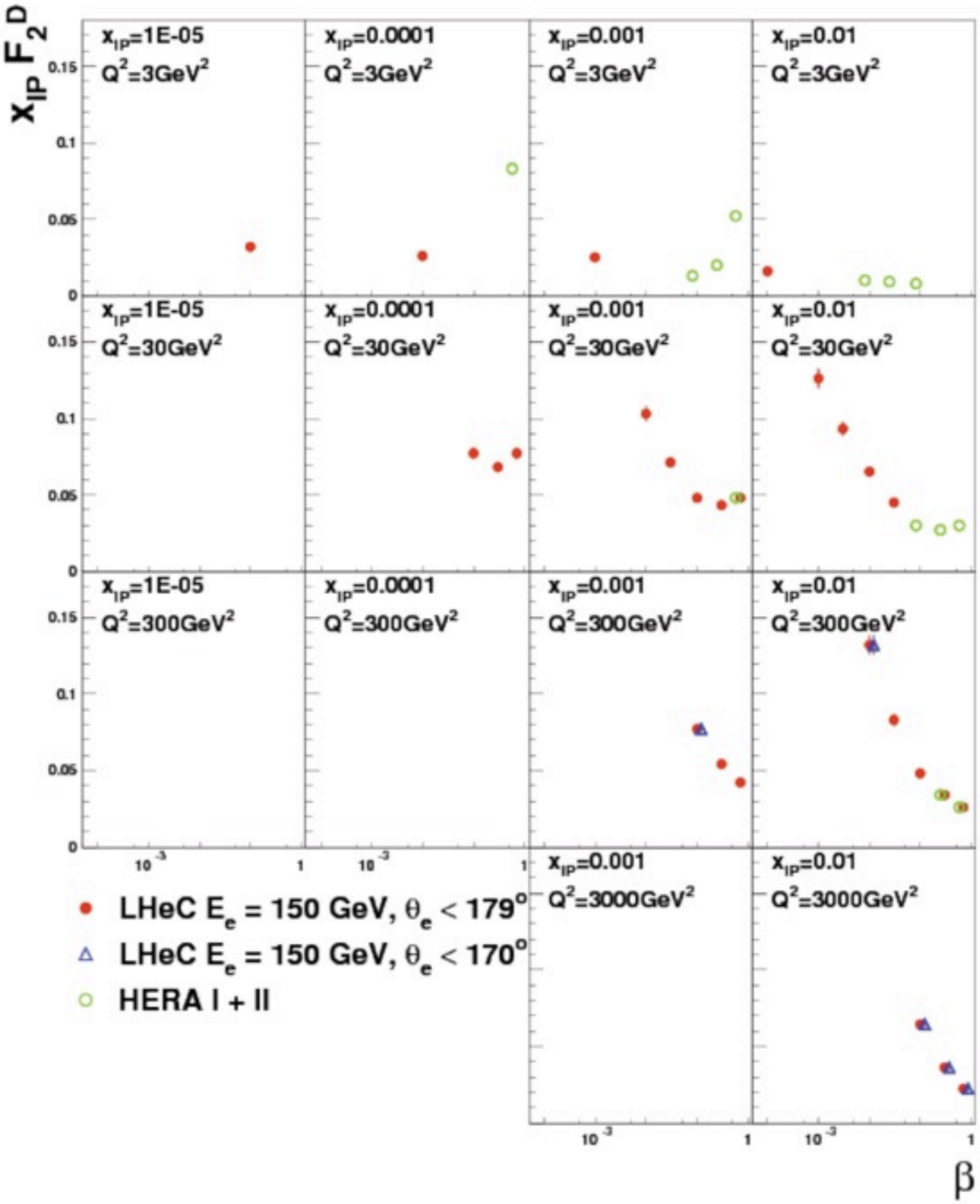


Inclusive diffraction

- The diffractive structure function can be described in theory using factorization framework and parton distribution functions.

- LHeC: precise characterization of dpdf’s, much wider range than HERA.

- Benchmark for factorization breaking in hard diffraction in hadron colliders (gap survival).

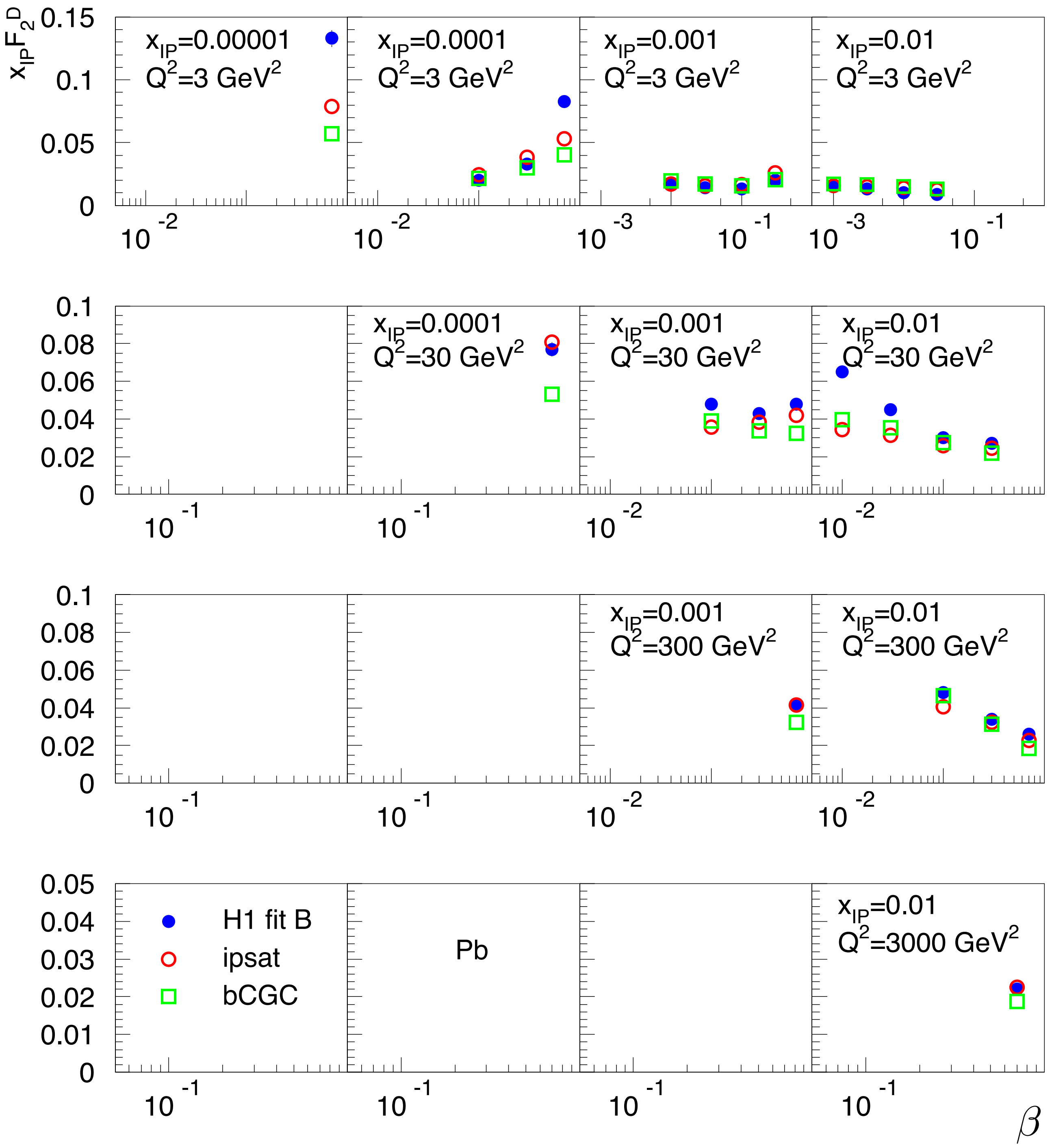


Newman

Inclusive diffraction in ePb

- In the nuclear case two scenarios possible: coherent (nucleus stays intact) and incoherent diffraction (nuclear breakup into nucleons).
- Diffractive structure functions in electron-lead collisions. Dipole model predictions compared with the H1 fit B extrapolation. Predictions for the coherent case.
- Detailed Monte Carlo simulations of the nuclear breakup necessary.

Lappi



Jet and multi-jet observables, parton dynamics and fragmentation:

Forward jets, dijets, angular decorrelation. work in progress

Unintegrated PDFs: theoretical introduction. ok

Perturbative and non-perturbative aspects of final state radiation and hadronization. work in progress

Photoproduction physics:

The total photoproduction cross section. ok

Jet photoproduction. ok

Photon Structure : probably covered in QCD/EW chapter - to discuss.

Photoproduction cross section

- Photoproduction cross section.

- Explore dual nature of the photon: pointlike interactions or hadronic behavior.

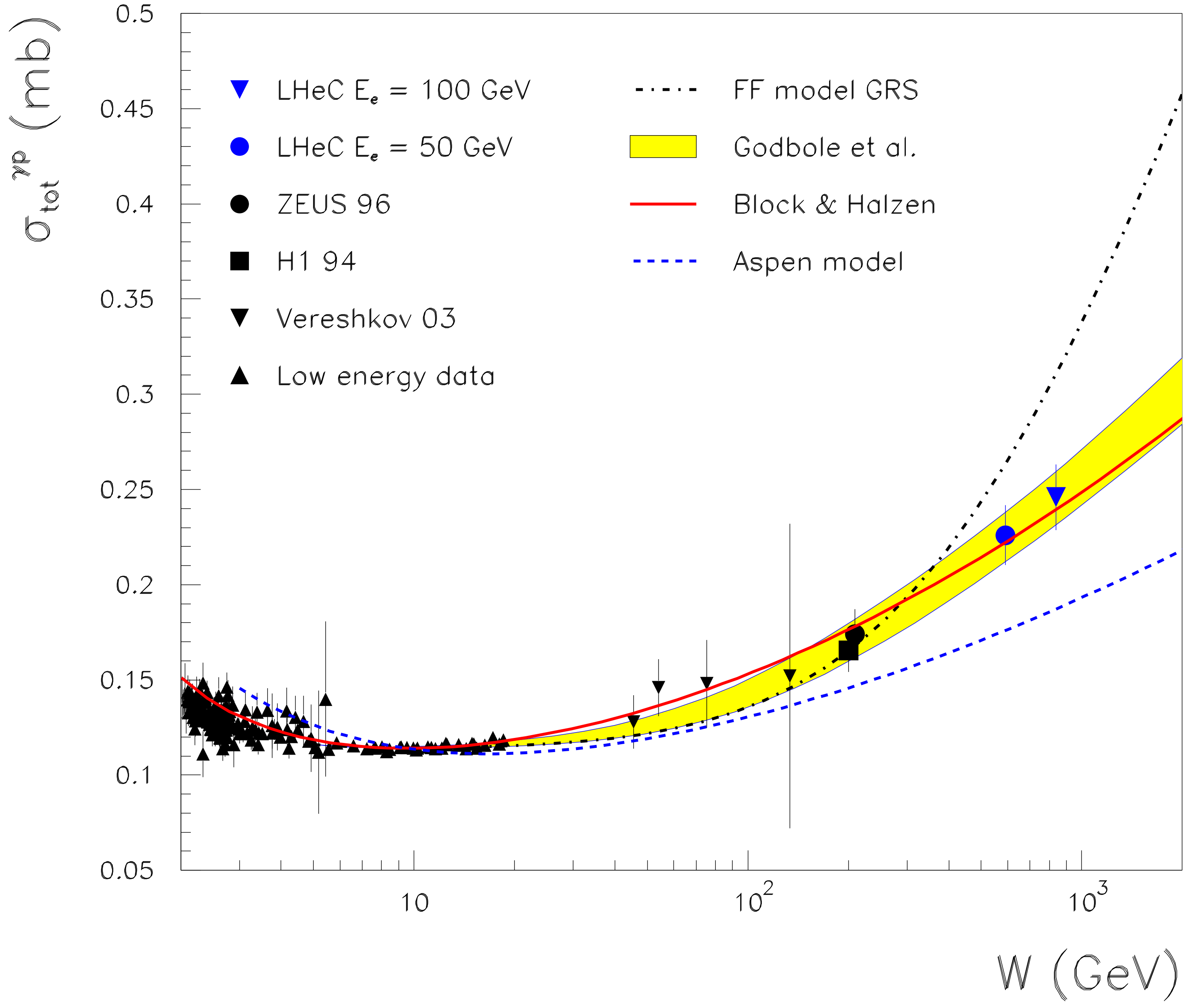
- Testing universality of hadronic cross sections, unitarity, transition between perturbative and nonperturbative regimes.

- Large divergence of the theoretical predictions beyond HERA measurements.

- Dedicated detectors for small angle scattered electrons at 62m from the interaction point.

- Events with $y \sim 0.3$ $\quad Q^2 \sim 0.01$ could be detected

Pancheri

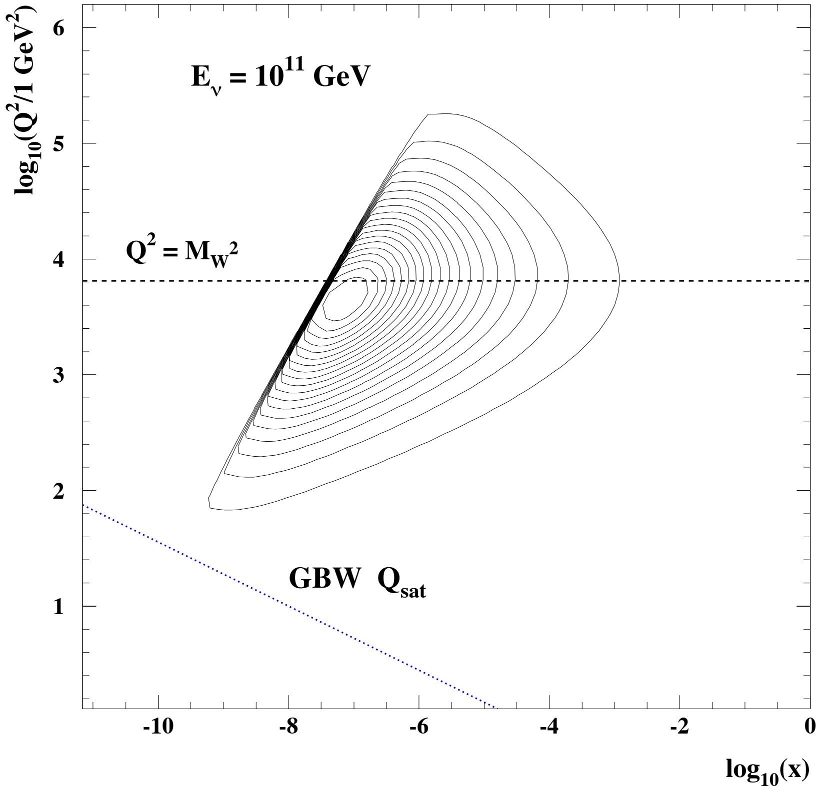


Systematics is the limiting factor here. Assumed 7% for the simulated data as in H1 and ZEUS.

Relevance of LHeC for neutrino interactions

Contours enclose $5\%, 10\%, 15\%, \ldots$

contribution to the differential cross section $\dfrac{d^2\sigma^{\nu N}}{dx dQ^2}$



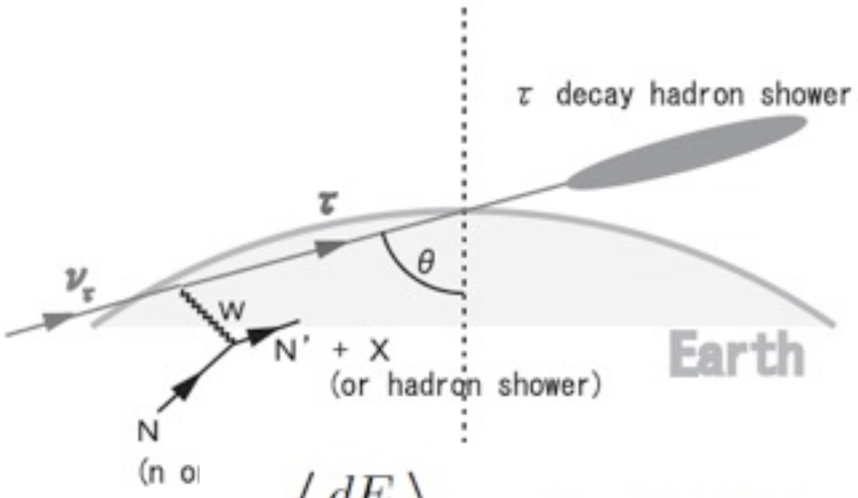
High energy neutrino interactions probe extremely small values of x

$$x \sim 10^{-7}$$

Cross section dominated by large Q

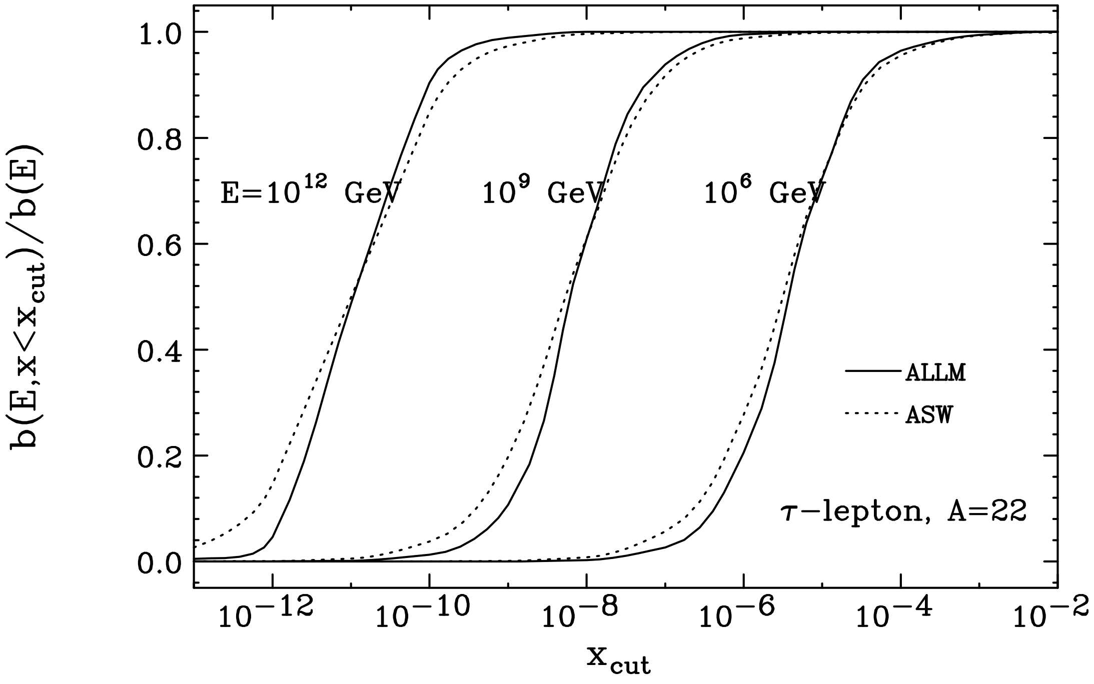
$$Q^2 \sim M_W^2$$

Search for Earth skimming tau neutrinos



$$-\left\langle \frac{dE}{dX} \right\rangle = a(E) + b(E)E$$

$$b(E) = \frac{N_A}{A} \int dy\, y \int dQ^2 \frac{d\sigma^{lA}}{dQ^2 dy}$$



Energy loss of tau again dominated by small x region.

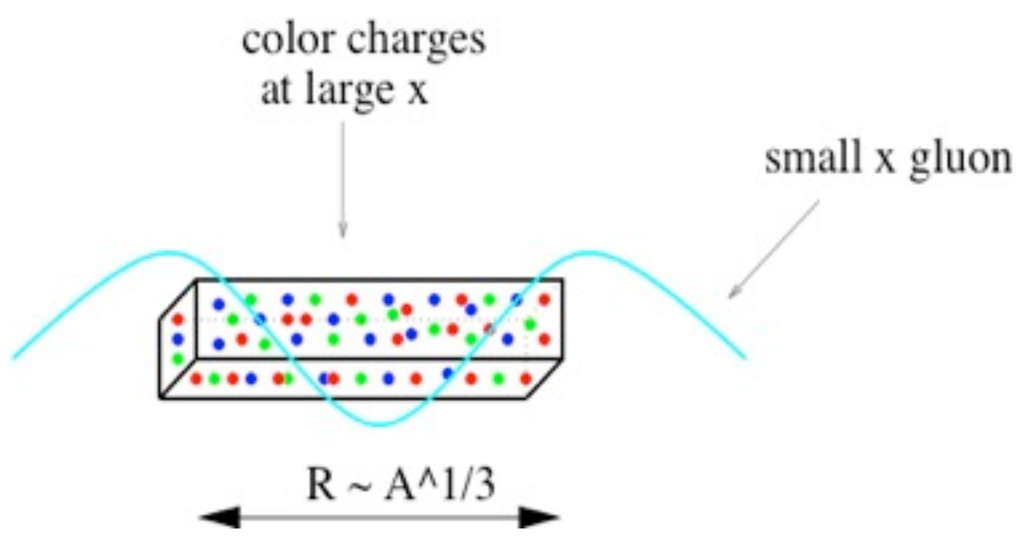
Summary of activities and plans

- Currently 50 pages submitted on the svn with 160 references. Almost a first complete draft of the chapter.
- Contributions from about 25 people.
- The complete chapter will be about 60 pages.
- Needs still a lot of editing work.
- Plans:
  - Continue on weekly EVO meetings.
  - Meeting of the conveners, around December or January.
  - Comments/remarks/critique welcome, please contact one of the conveners.

Backup

Saturation scale grows with A

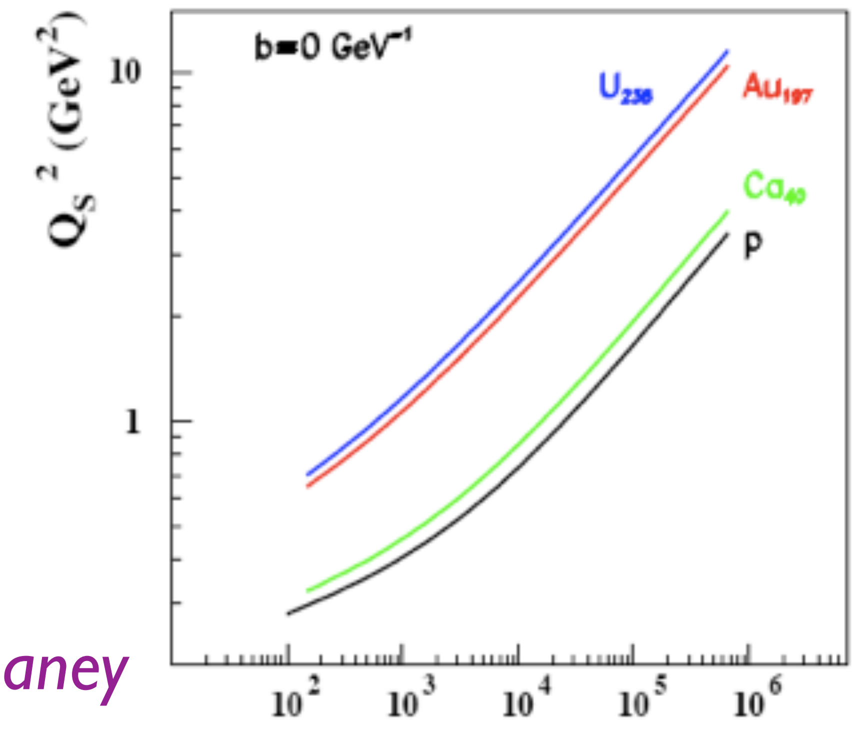
- Probes interact over distances $L \sim \frac{1}{2m_N x}$
- For $L > 2R_A \sim A^{1/3}$ high-energy probes interact coherently across nuclear size. Very large field strengths.



Pocket formula:

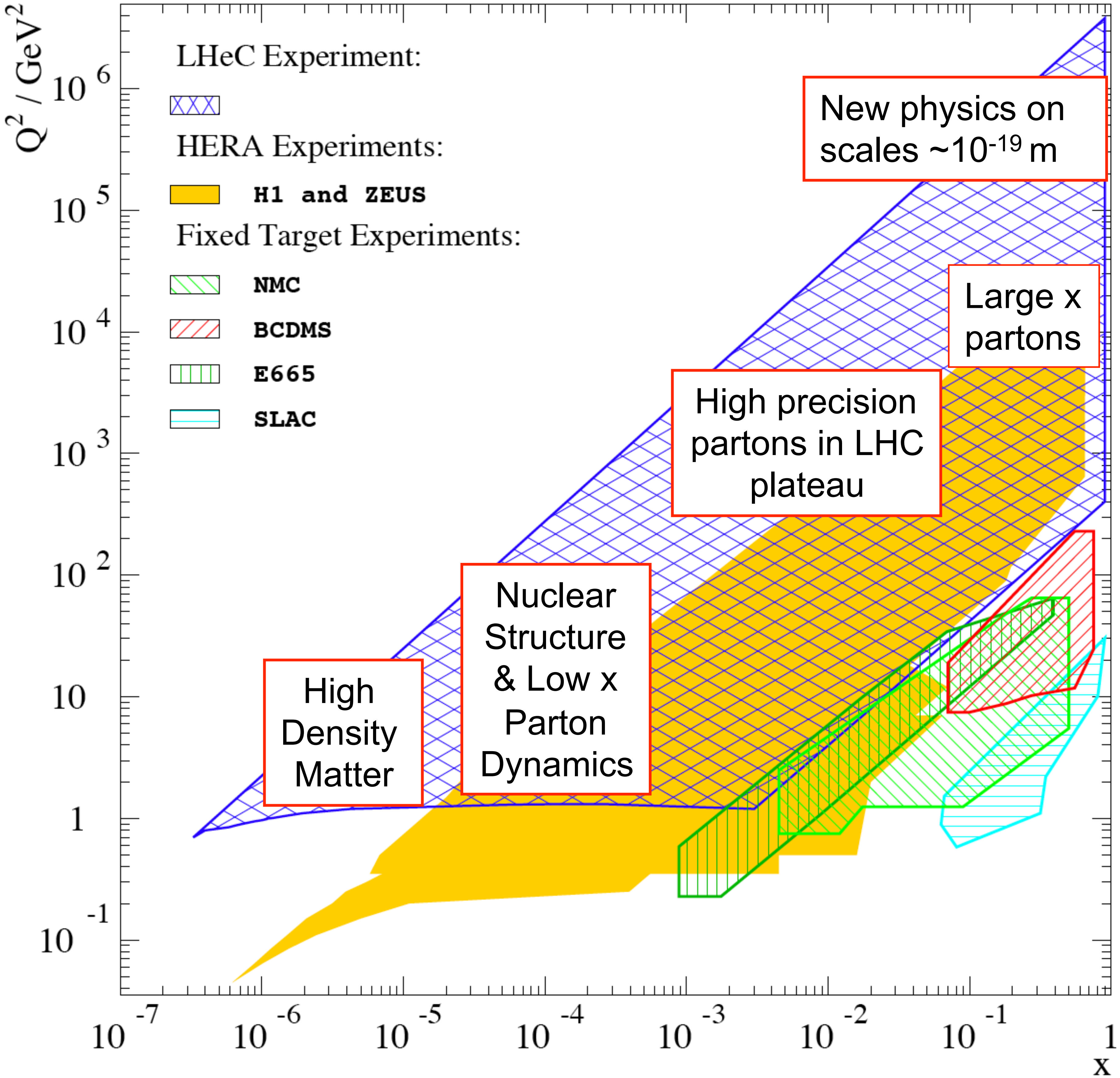
$$\boxed{Q_s^2(x, A) \sim Q_0^2 \left(\frac{A}{x}\right)^{1/3}}$$

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



Kowalski, Teaney

Kinematics & Motivation (140 GeV x 7 TeV)



New physics on scales ~10^{-19} m

Large x partons

High precision partons in LHC plateau

Nuclear Structure & Low x Parton Dynamics

High Density Matter

$$\sqrt{s} = 2 \text{ TeV}$$

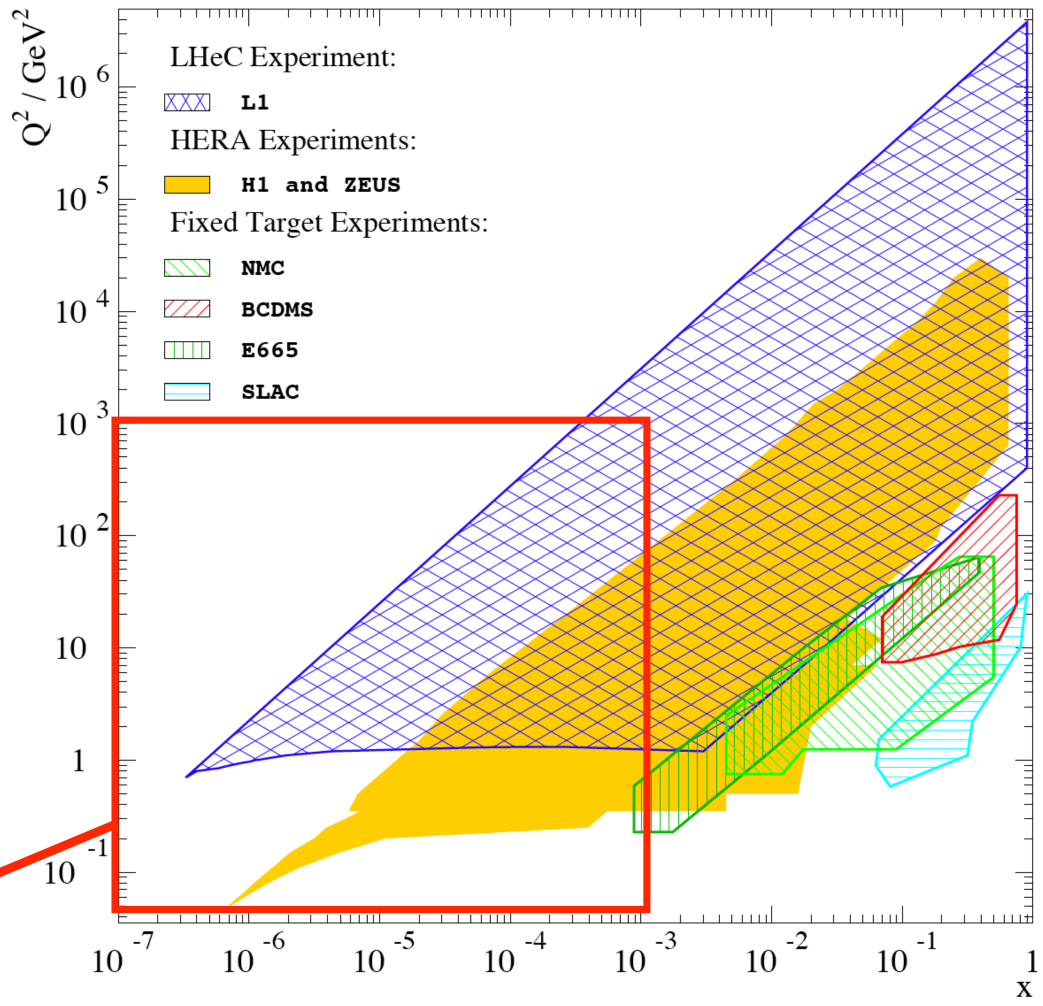
- High mass (M_{eq}, Q^2) frontier
- EW & Higgs
- Q^2 lever-arm at moderate & high x → PDFs
- Low x frontier → novel QCD …

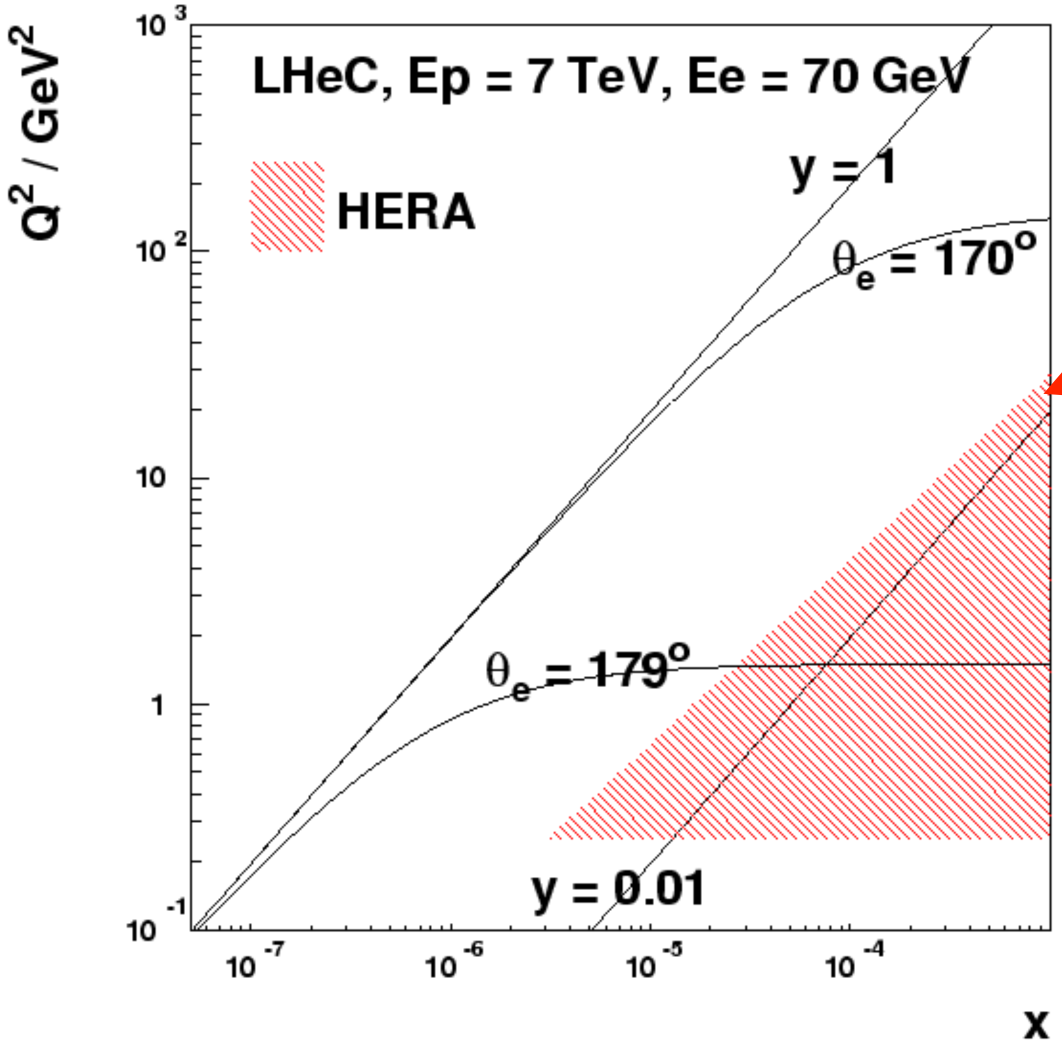
$$x \geq 5.10^{-7} \text{ at } Q^2 \leq 1 \text{ GeV}^2$$

Basic Inclusive Kinematics / Acceptance

Access to Q^2=1 GeV^2 in ep mode for all x > 5 x 10^{-7} IF we have acceptance to 179° (and @ low E_e')

Nothing fundamentally new in LHeC low x physics with θ<170°





… low x cross sections are large!

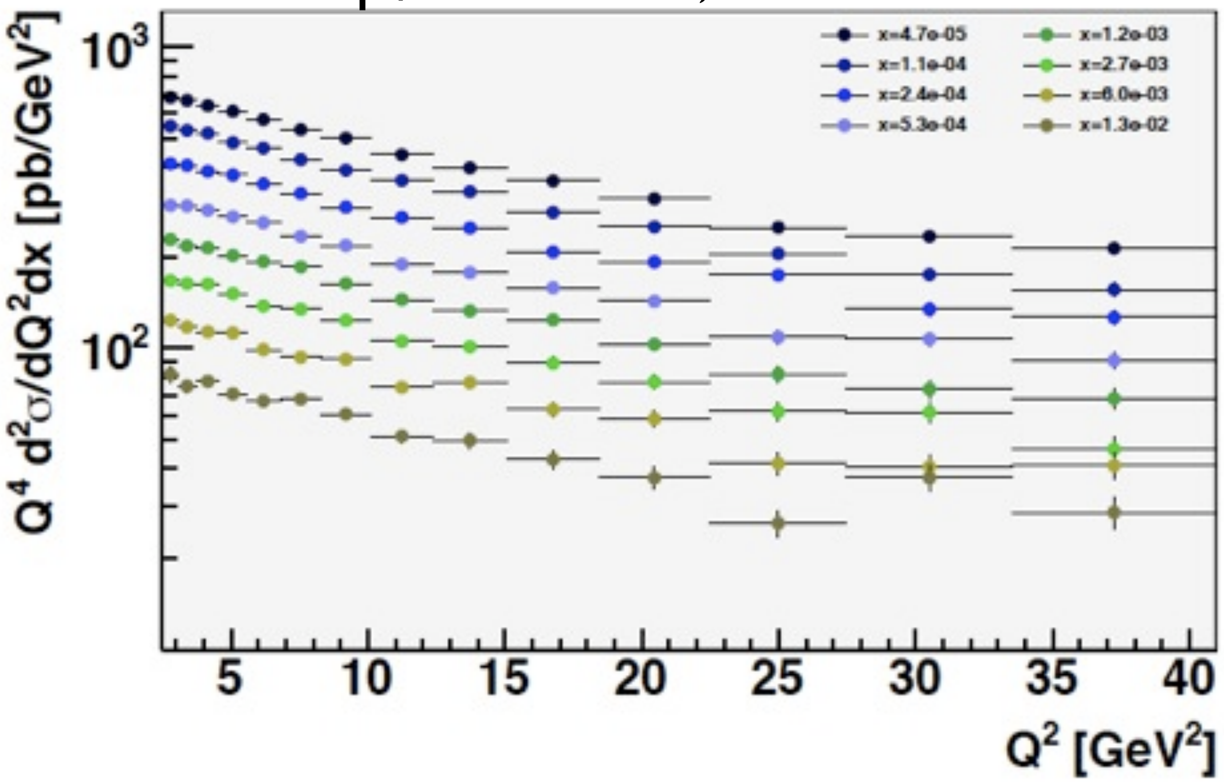
… luminosity in all realistic scenarios ample for most low x measurements

2.5 DVCS and GPDs:

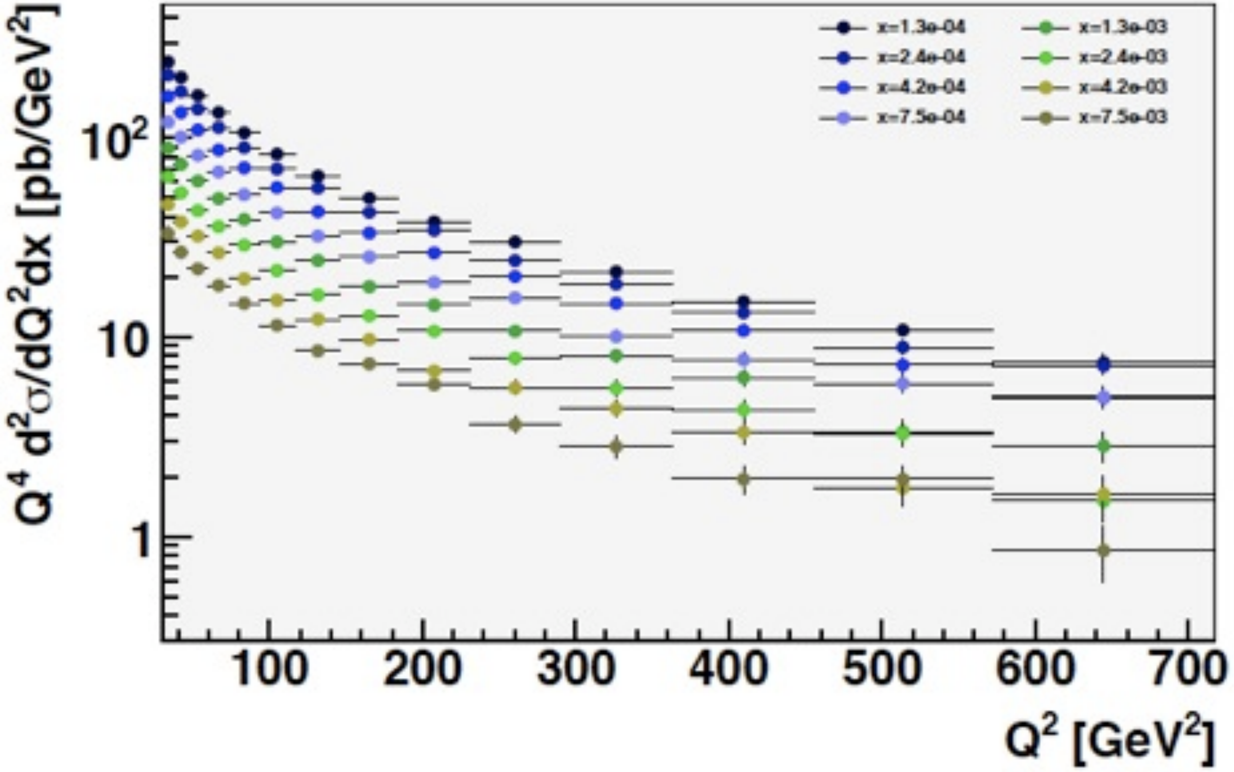
- Exclusive processes like $\gamma^*+h\to(\rho,\phi,\gamma)+h$ give information of GPDs, whose Fourier transform gives a transverse scanning of the hadron: key importance for both non-perturbative and perturbative aspects, like the possibility of non-linear dynamics.

- Only small-x case where higher luminosity really helps!!! (even lepton polarization and charge asymmetries).

DVCS, E_e=50 GeV, 1°,
$p_T^{\gamma,cut}$=2 GeV, 1 fb^{-1}

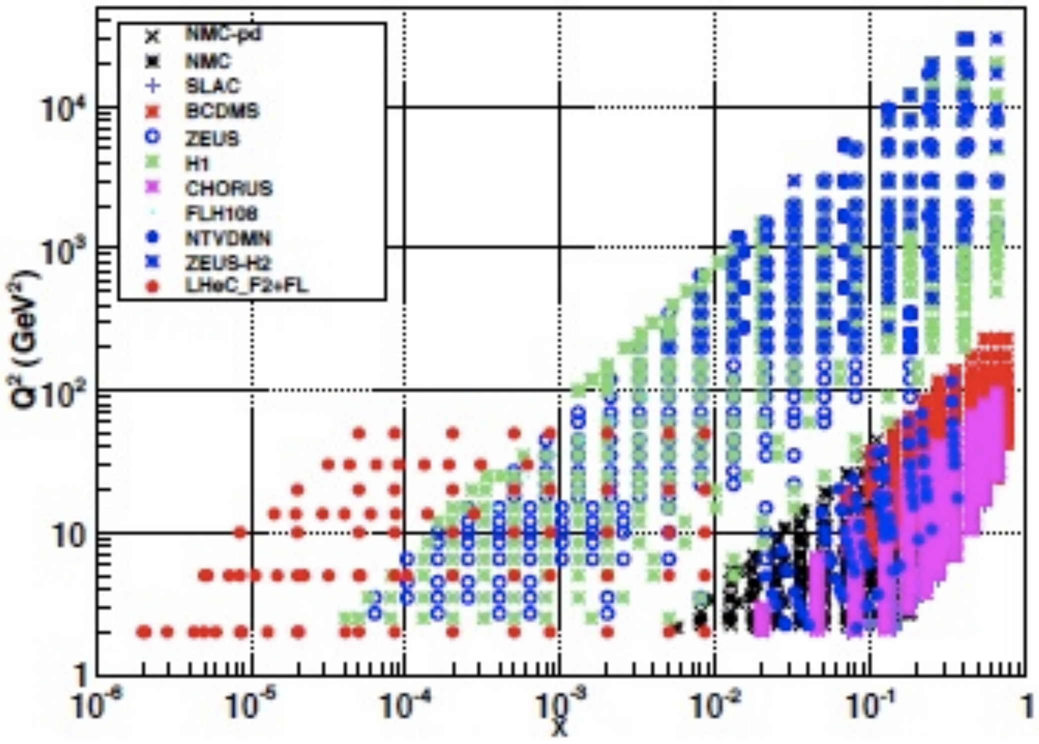


DVCS, E_e=50 GeV, 10°,
$p_T^{\gamma,cut}$=5 GeV, 100 fb^{-1}

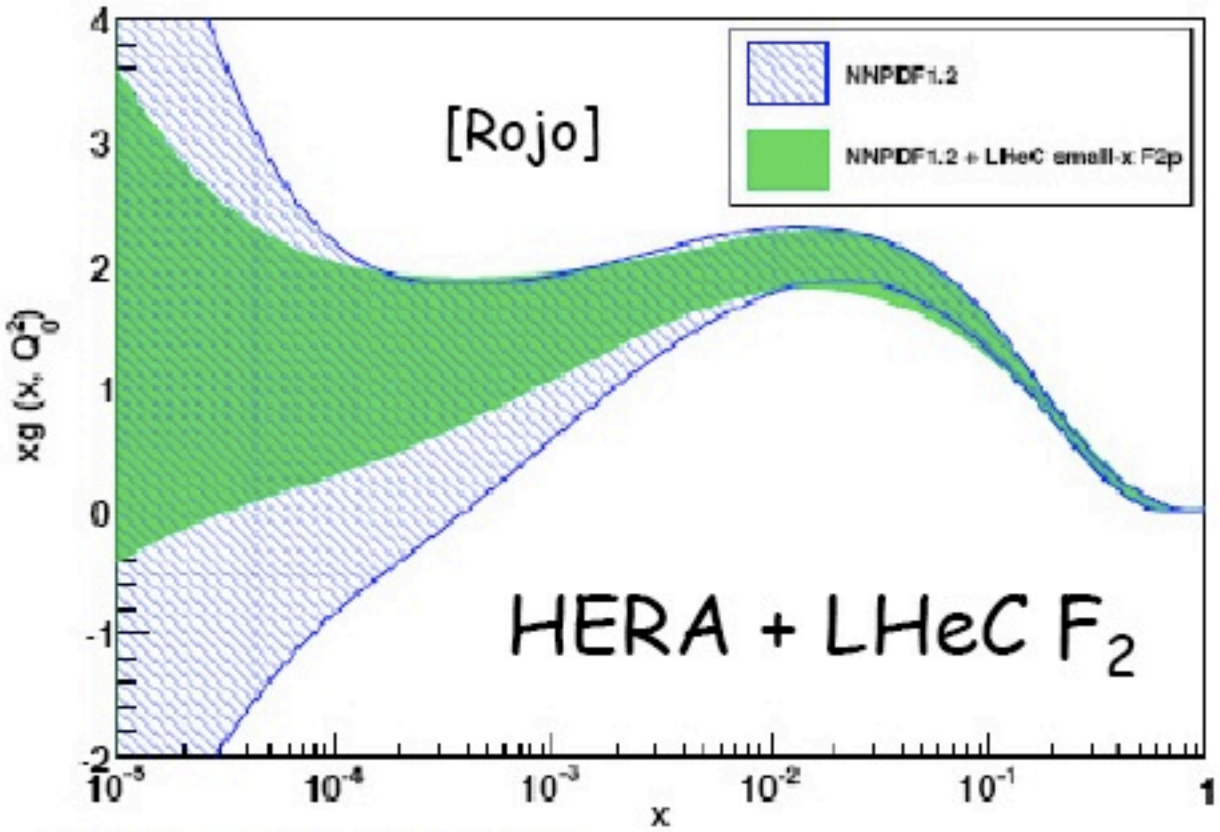


Impact on DGLAP for p: F_2, F_L

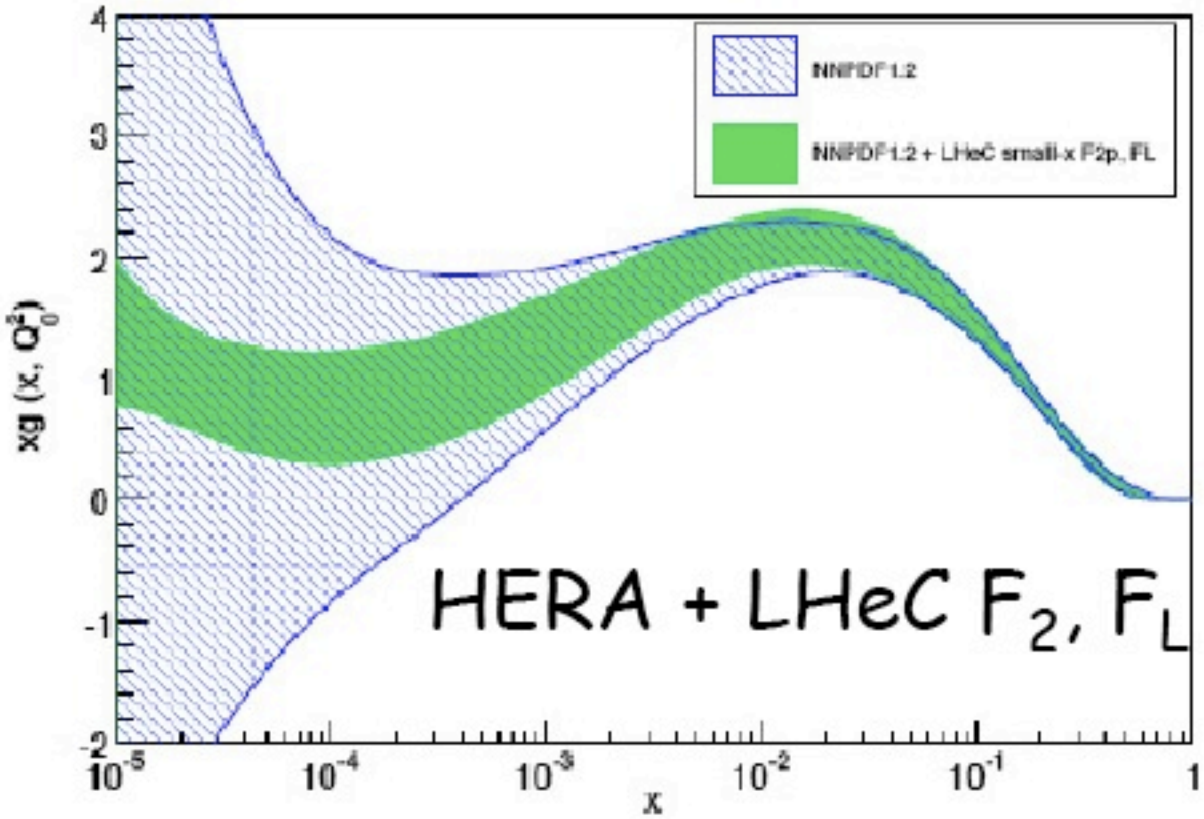
- Inclusion of LHeC pseudodata for F_2, F_L in DGLAP fits improves the determination of the glue at small x.



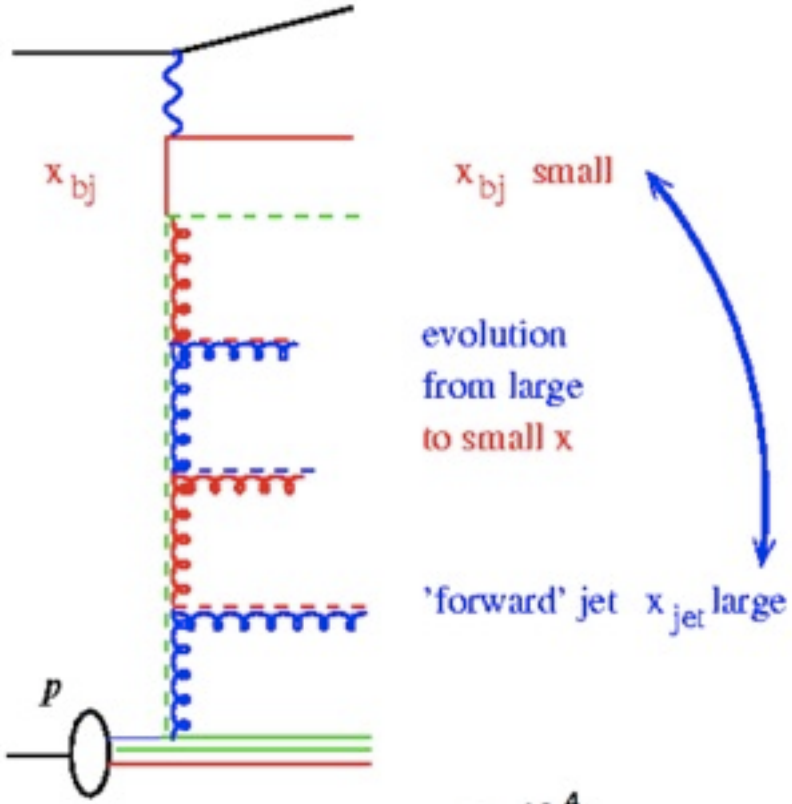
Rojo



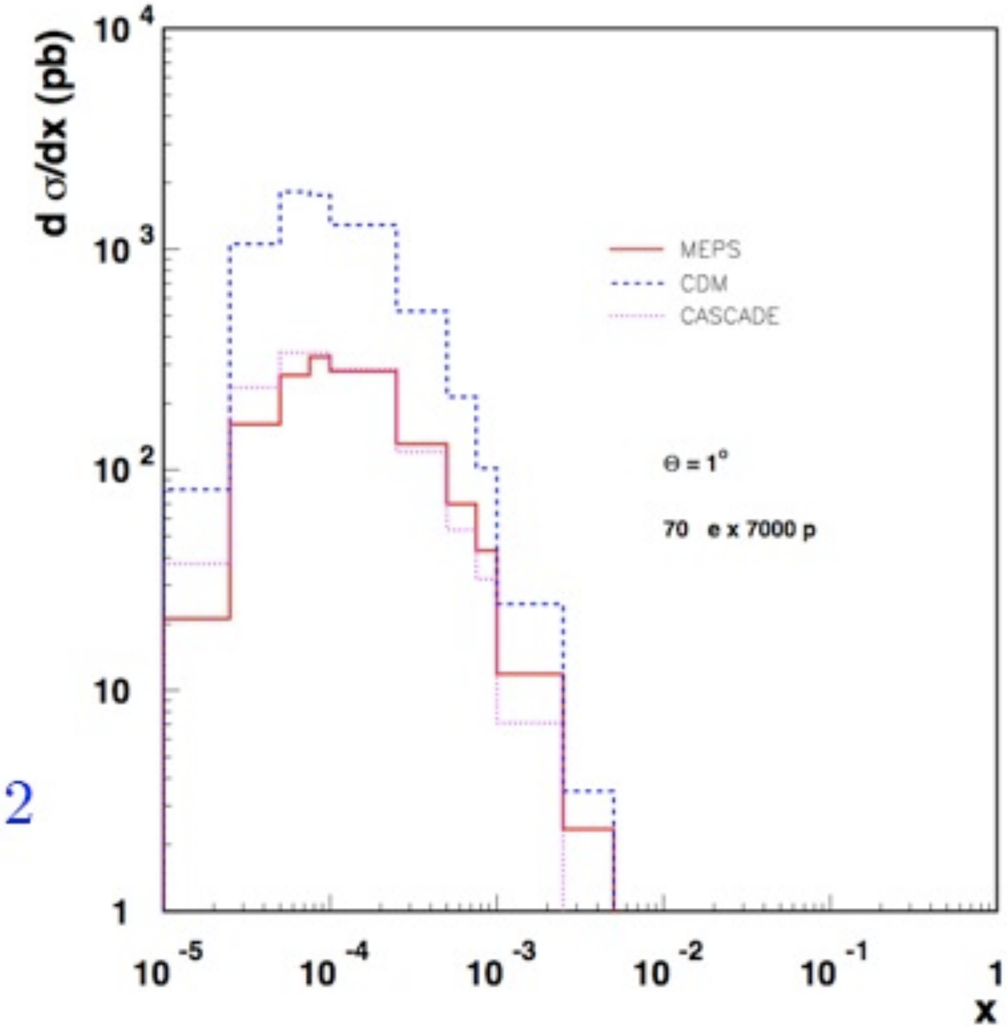
(Q^2 = 2 GeV^2)



Forward jets:



Jung at Divonne'08



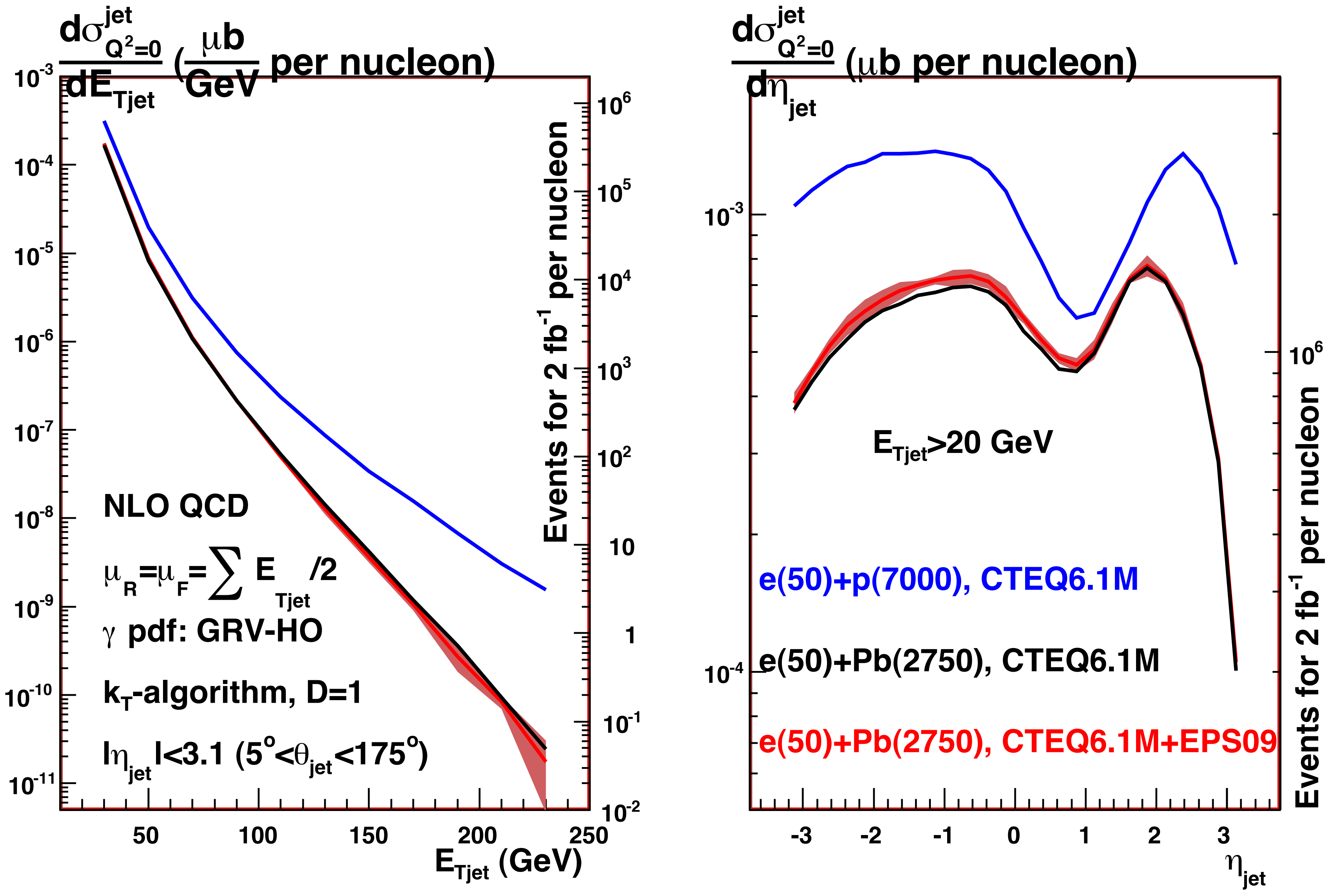
$$x_{jet} > 0.03$$

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

- Studying forward jets ($p_T \sim Q$) would allow to understand the mechanism of radiation:
  → k_T-ordered: DGLAP.
  → k_T-disordered: BFKL.
  → Saturation?

- Further imposing a rapidity gap (diffractive jets) would be most interesting: perturbatively controllable observable.

Jet photoproduction:



- Jets: large E_T even in eA.

- Useful for studies of parton dynamics in nuclei (hard probes), and for photon structure.

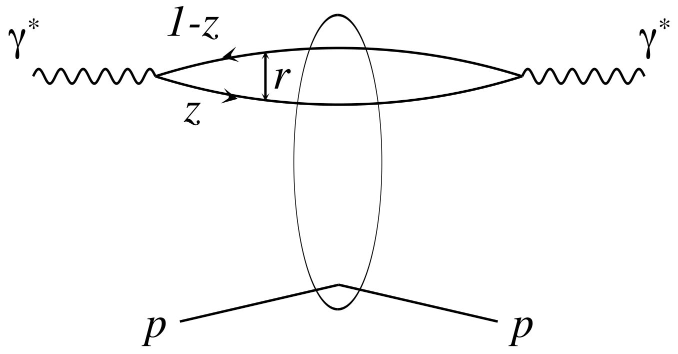
- Background subtraction, detailed reconstruction pending.

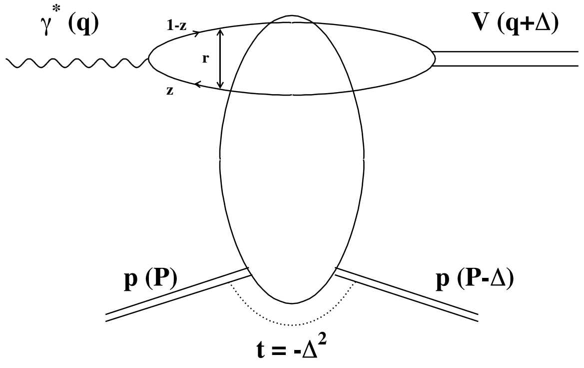
Overview of the HPD chapter: 2.8 Photoproduction Physics.

Diffraction and saturation

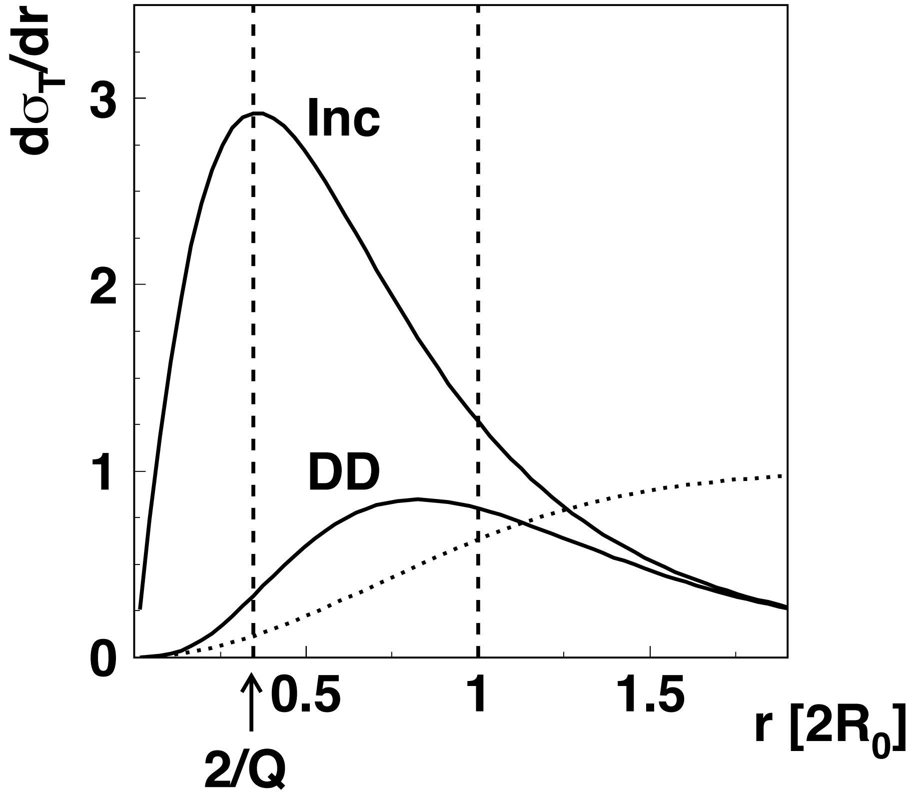
Dipole model at high energy: photon fluctuates into qqbar pair and undergoes an interaction with the target

$$\sigma_{T,L}(x,Q^2) \;=\; \int d^2\mathbf{r} \int_0^1 dz \, \sum_f \, |\Psi^f_{T,L}(\mathbf{r},z,Q^2)|^2 \; \hat\sigma(x,\mathbf{r})\,.$$





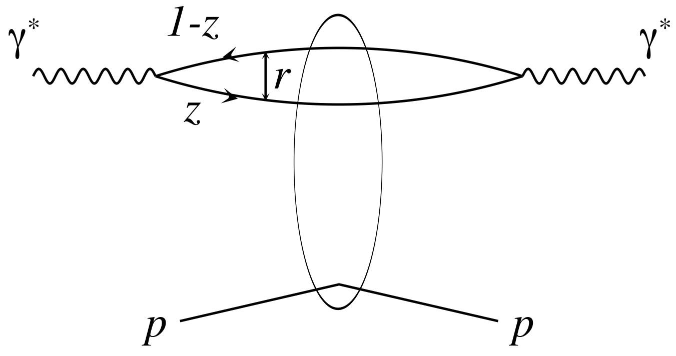
overlap function in the dipole model
typical dipole sizes involved in the process



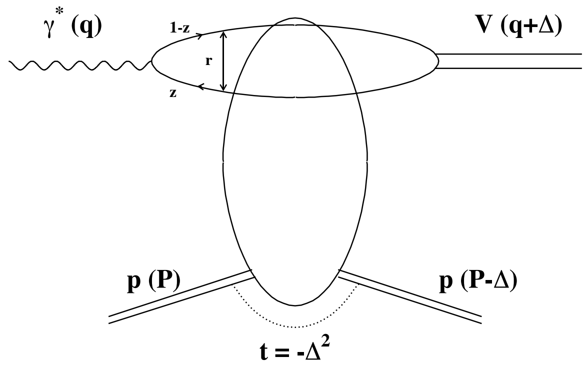
Diffraction and saturation

Dipole model at high energy: photon fluctuates into qqbar pair and undergoes an interaction with the target

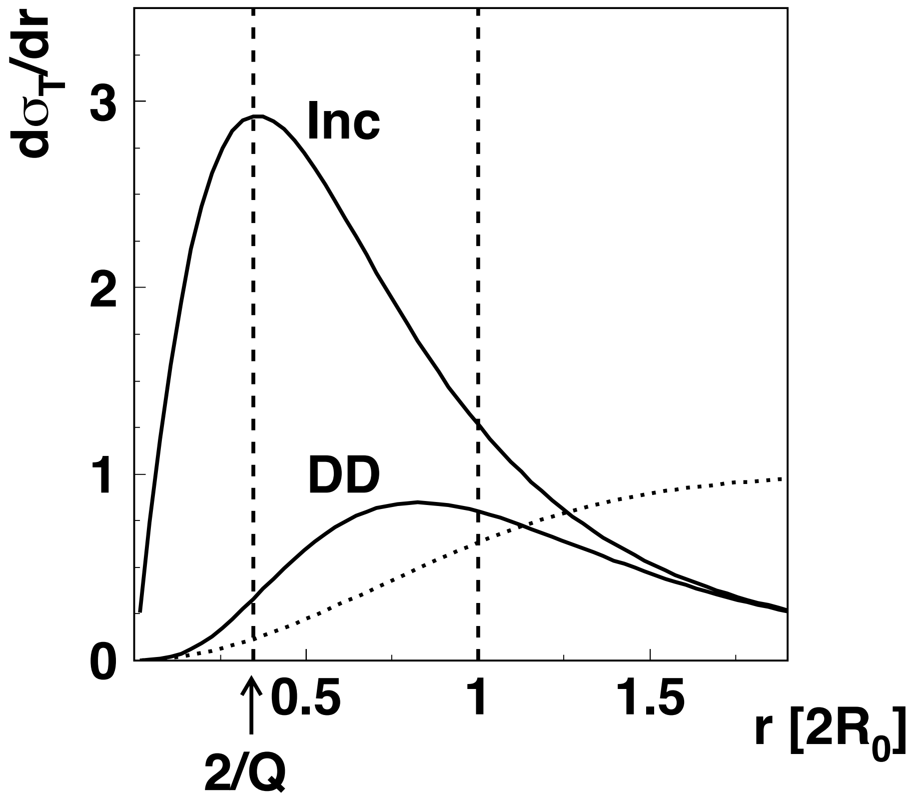
$$\sigma_{T,L}(x,Q^2) \;=\; \int d^2\mathbf{r} \int_0^1 dz \,\sum_f \,|\Psi^f_{T,L}(\mathbf{r},z,Q^2)|^2 \;\hat{\sigma}(x,\mathbf{r})\,.$$



Inclusive: dominated by relatively hard component



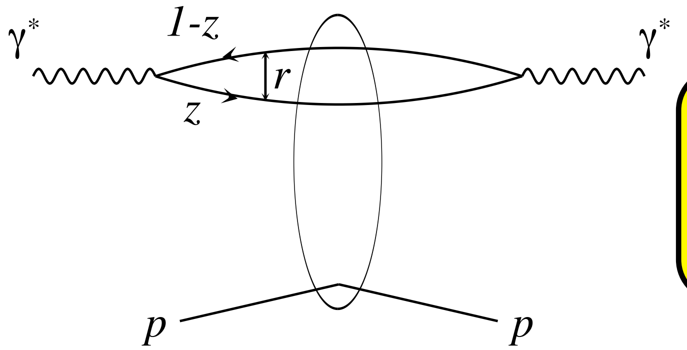
overlap function in the dipole model
typical dipole sizes involved in the process



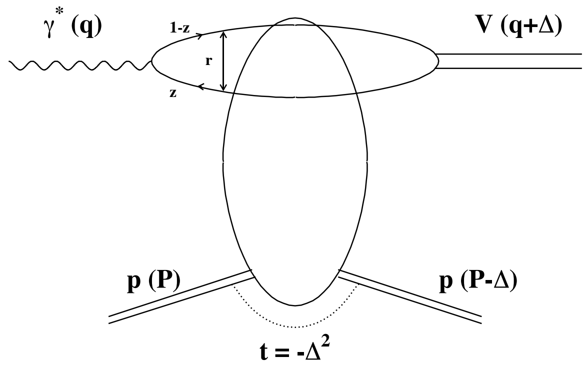
Diffraction and saturation

Dipole model at high energy: photon fluctuates into qqbar pair and undergoes an interaction with the target

$$\sigma_{T,L}(x,Q^2) = \int d^2\mathbf{r} \int_0^1 dz \sum_f |\Psi^f_{T,L}(\mathbf{r},z,Q^2)|^2 \, \hat{\sigma}(x,\mathbf{r}) \, .$$

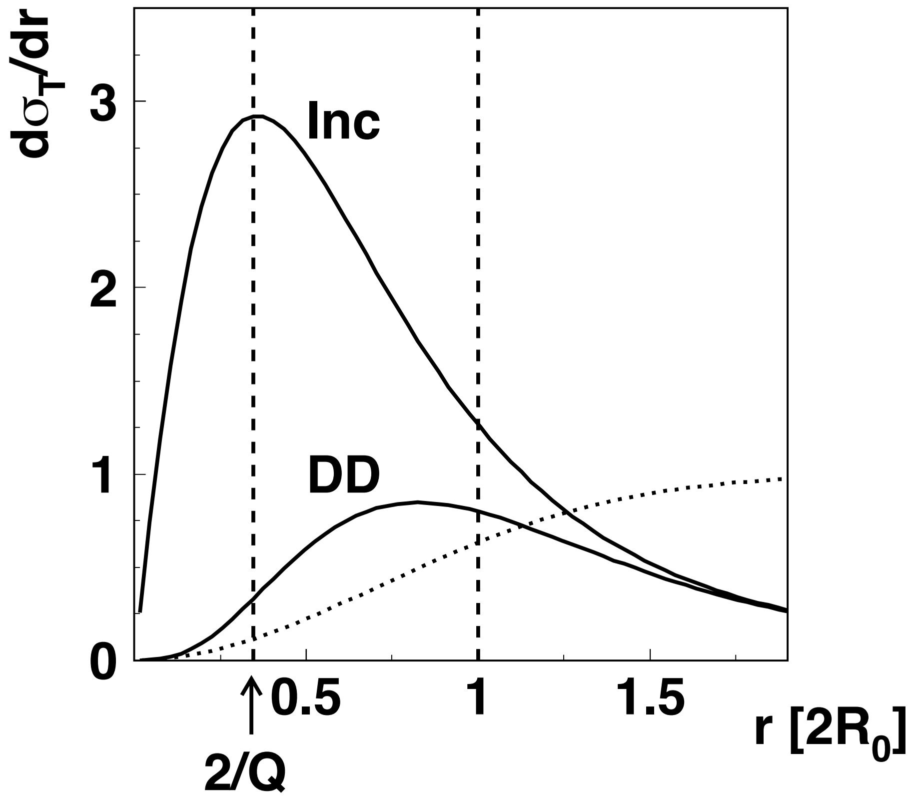


Inclusive: dominated by relatively hard component



Diffractive: dominated by the semi-hard momenta

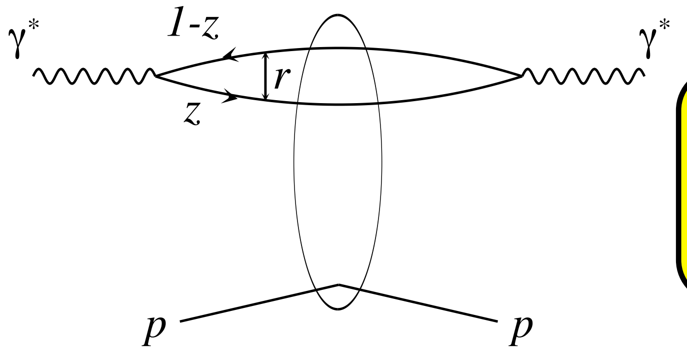
overlap function in the dipole model
typical dipole sizes involved in the process



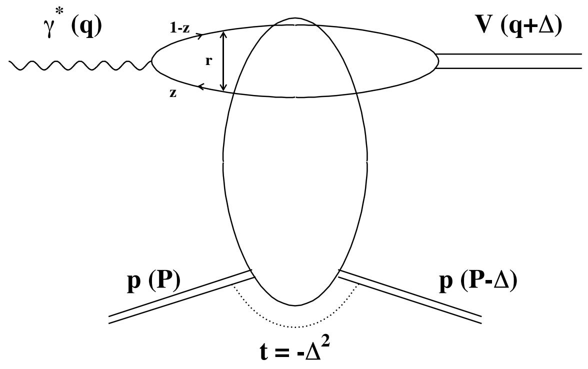
Diffraction and saturation

Dipole model at high energy: photon fluctuates into qqbar pair and undergoes an interaction with the target

$$\sigma_{T,L}(x,Q^2) \; = \int d^2\mathbf{r} \int_0^1 dz \, \sum_f \, |\Psi^f_{T,L}(\mathbf{r},z,Q^2)|^2 \; \hat{\sigma}(x,\mathbf{r})\,.$$

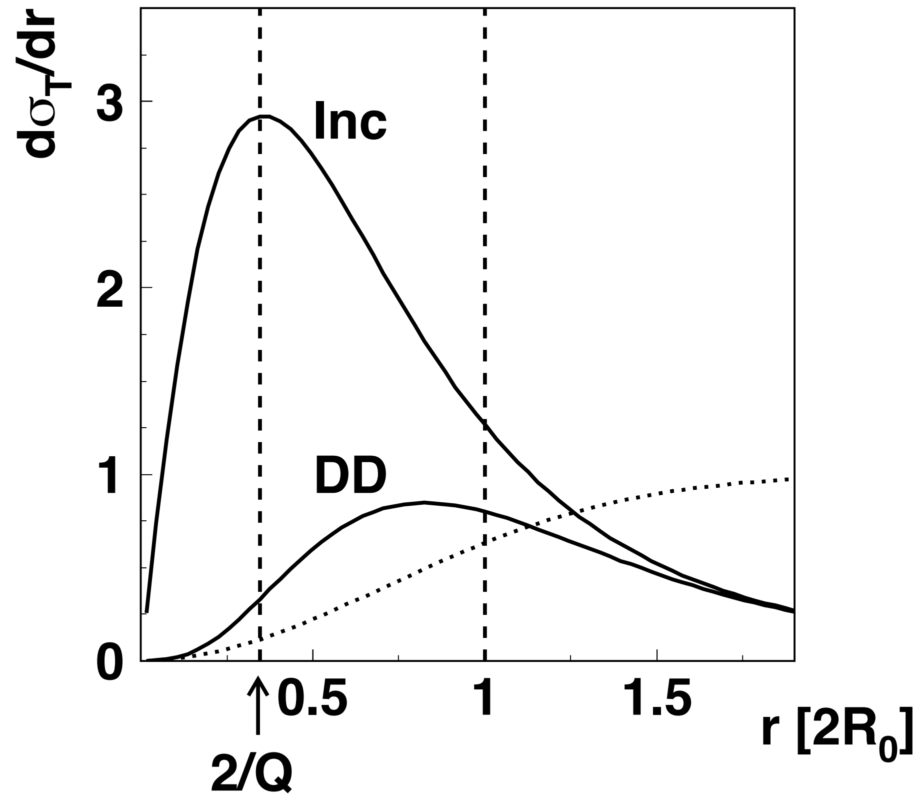


Inclusive: dominated by relatively hard component



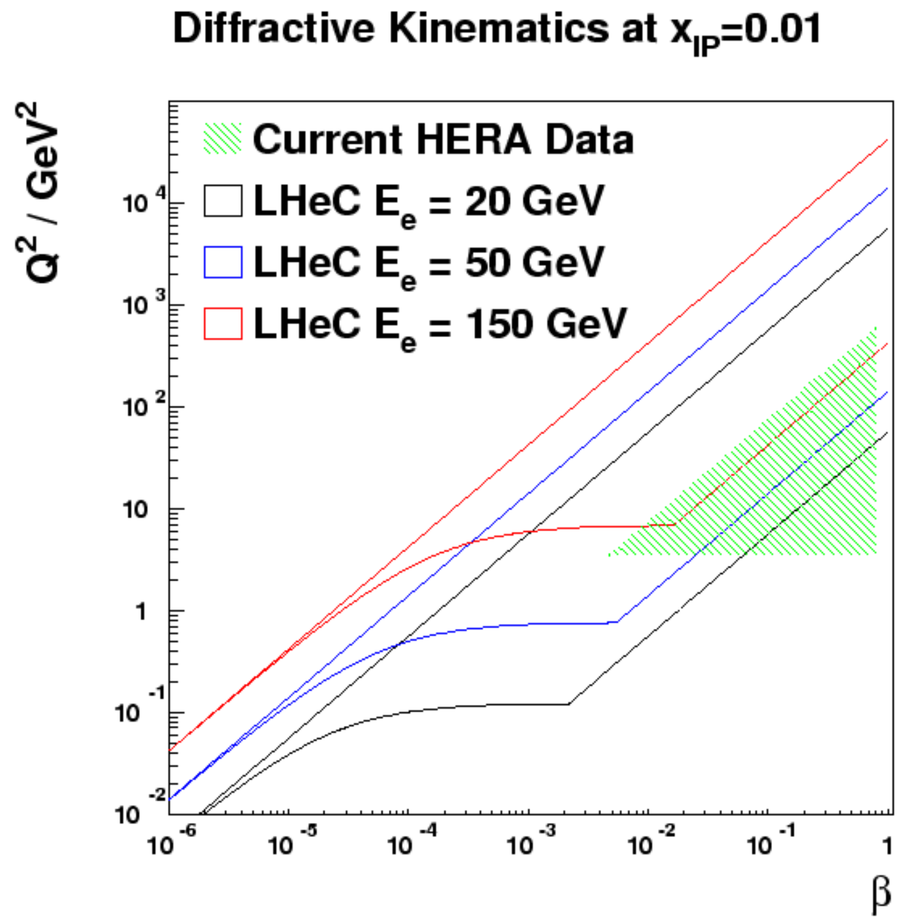
Diffractive: dominated by the semi-hard momenta

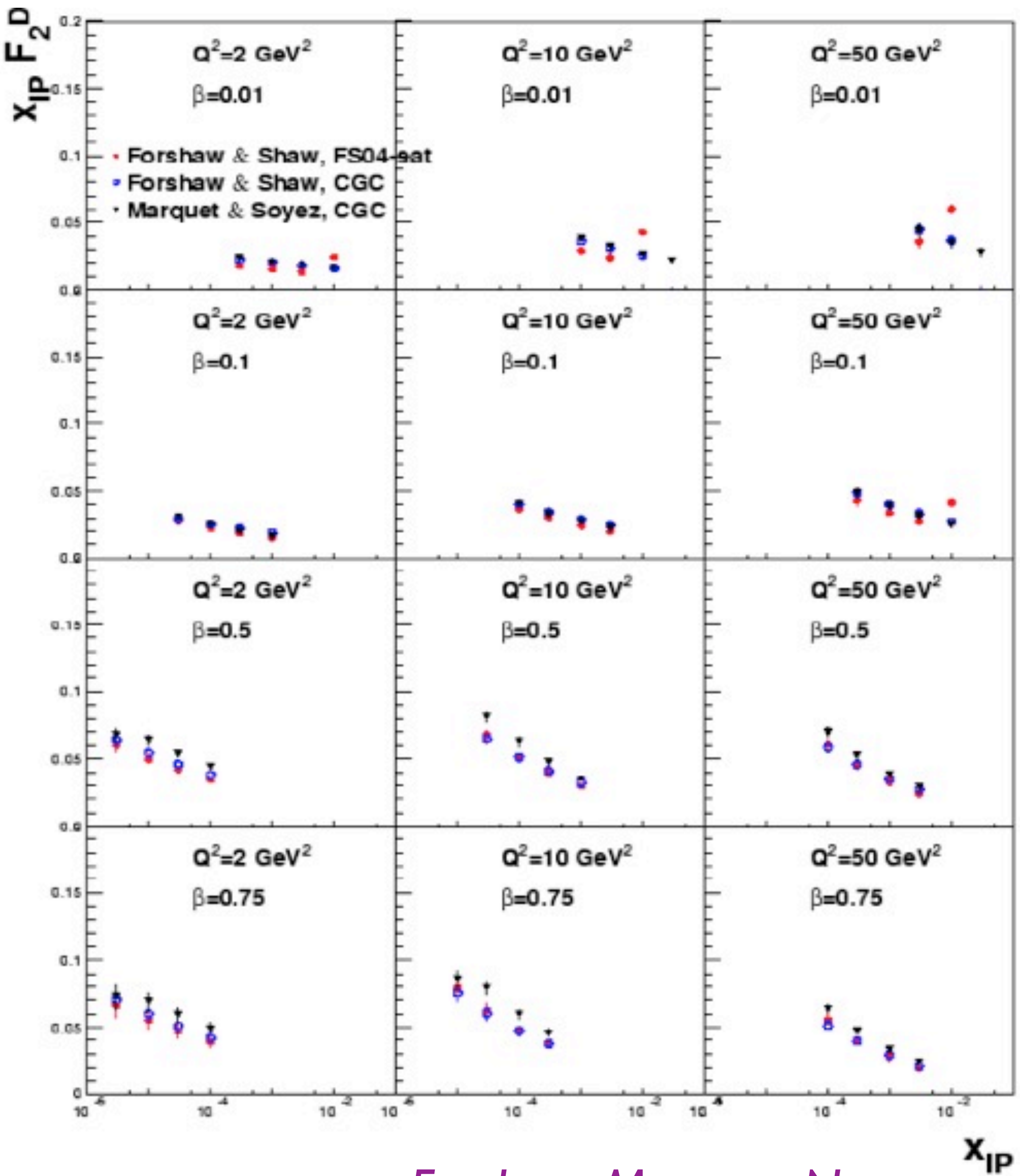
overlap function in the dipole model
typical dipole sizes involved in the process



Diffraction is a collective phenomenon. Explore relation with saturation.

Diffraction at LHeC: new possibilities



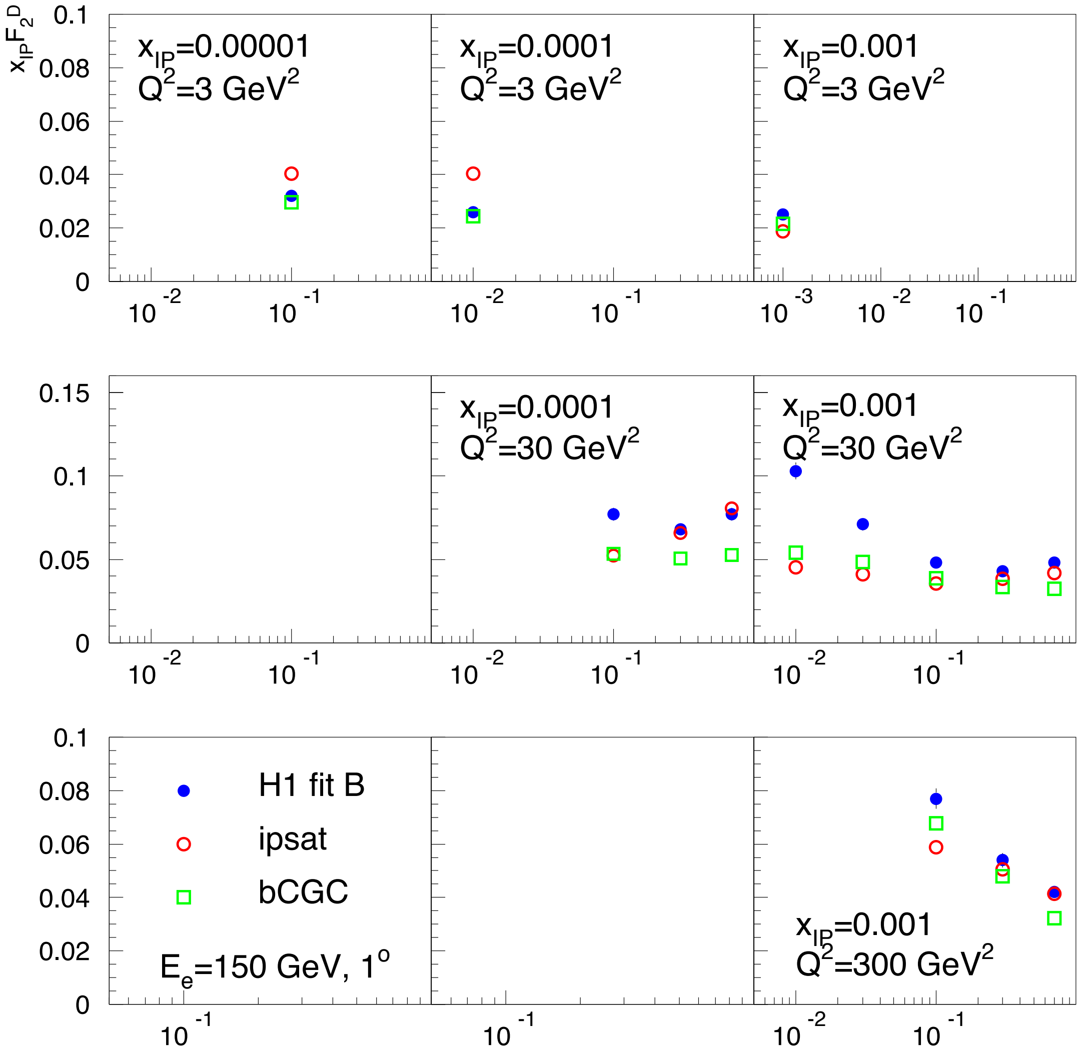


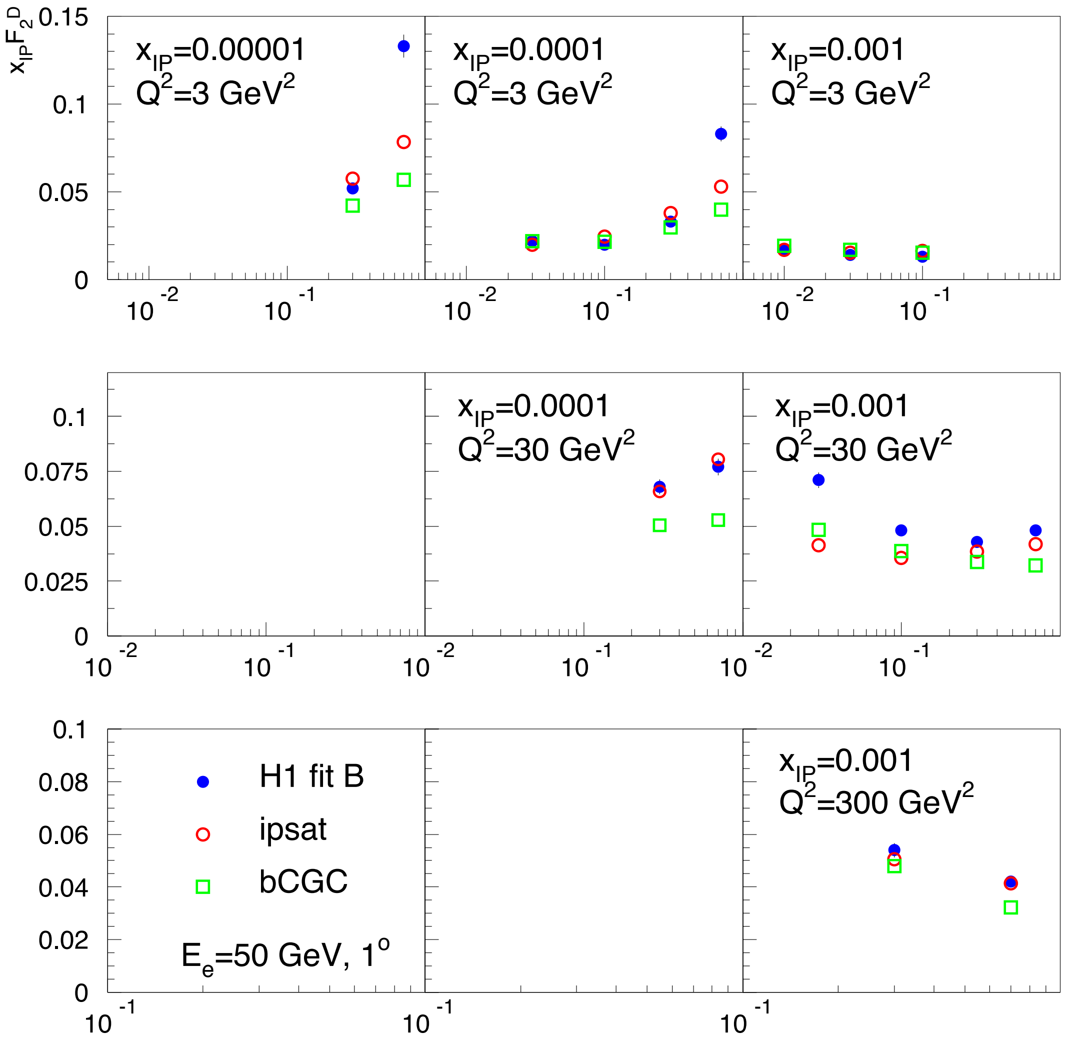
Forshaw, Marquet, Newman

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

Inclusive diffraction

Lappi

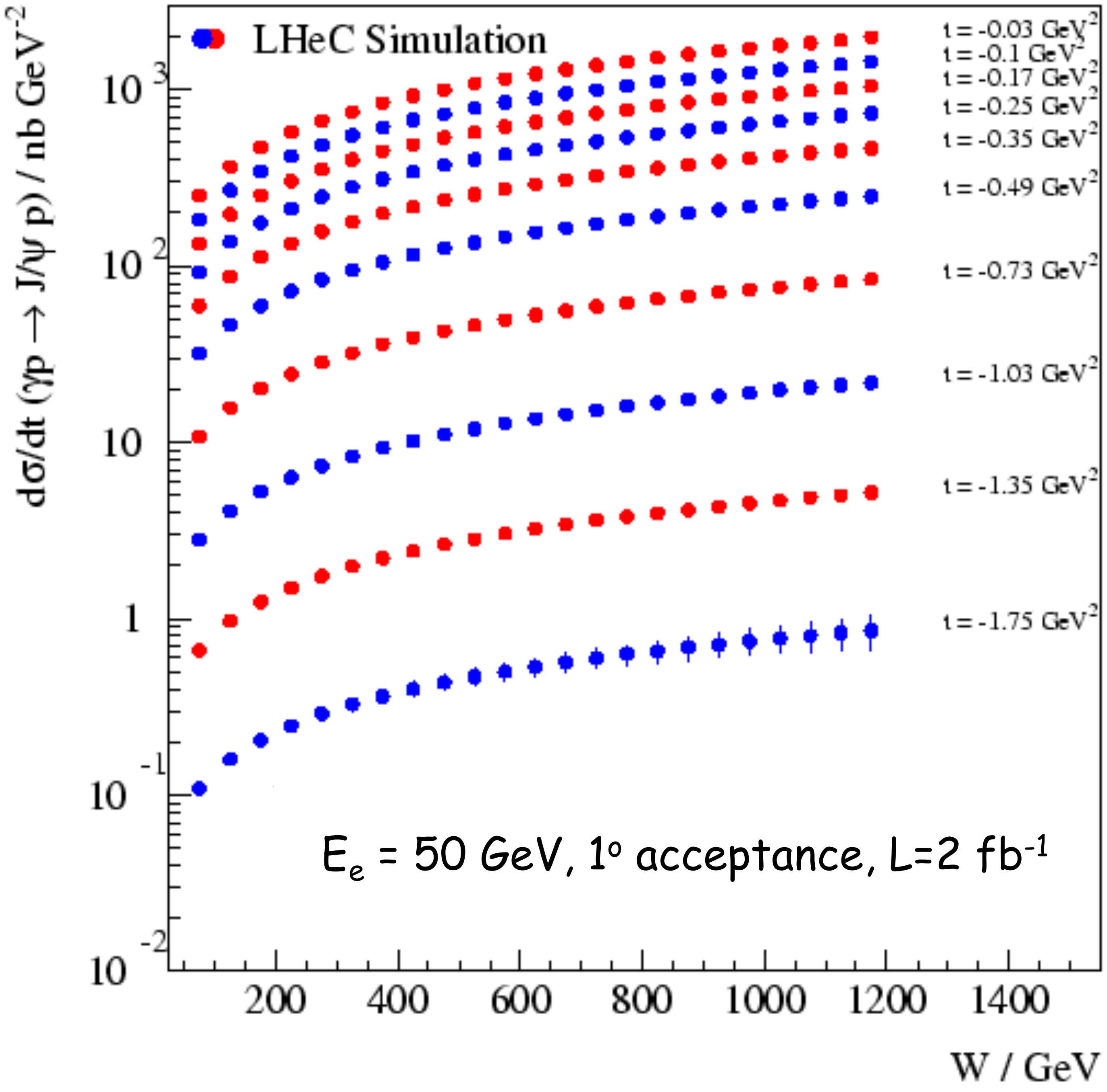




Dipole models with parton saturation effects as compared with the H1 fit extrapolations.

Exclusive diffraction in dipole model

differential cross section in bins of t



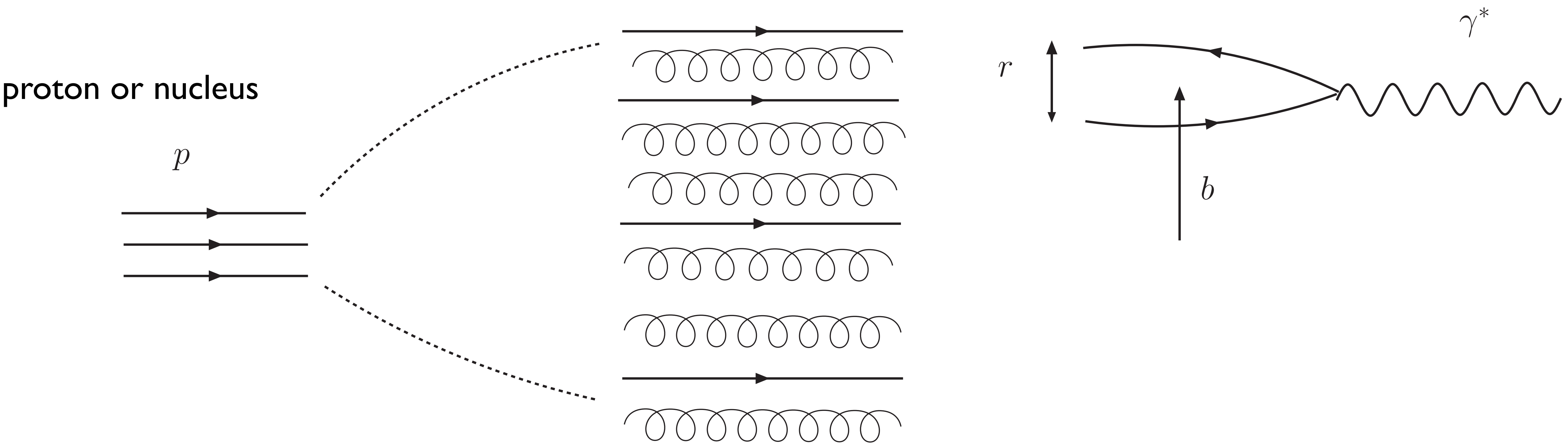
- photoproduction cross section double differential in W and t
- small x of the gluon probed
- precise t-dependence can help us map the impact parameter profile
- possible also in DIS for several Q bins and other states like Upsilon and for DVCS process.

DIS in a different frame

DIS at small x can be viewed as an interaction of the qqbar dipole (photon fluctuation) with the small x partons of the evolved target (proton or nucleus)

virtual photon

qqbar probe (a microscope)



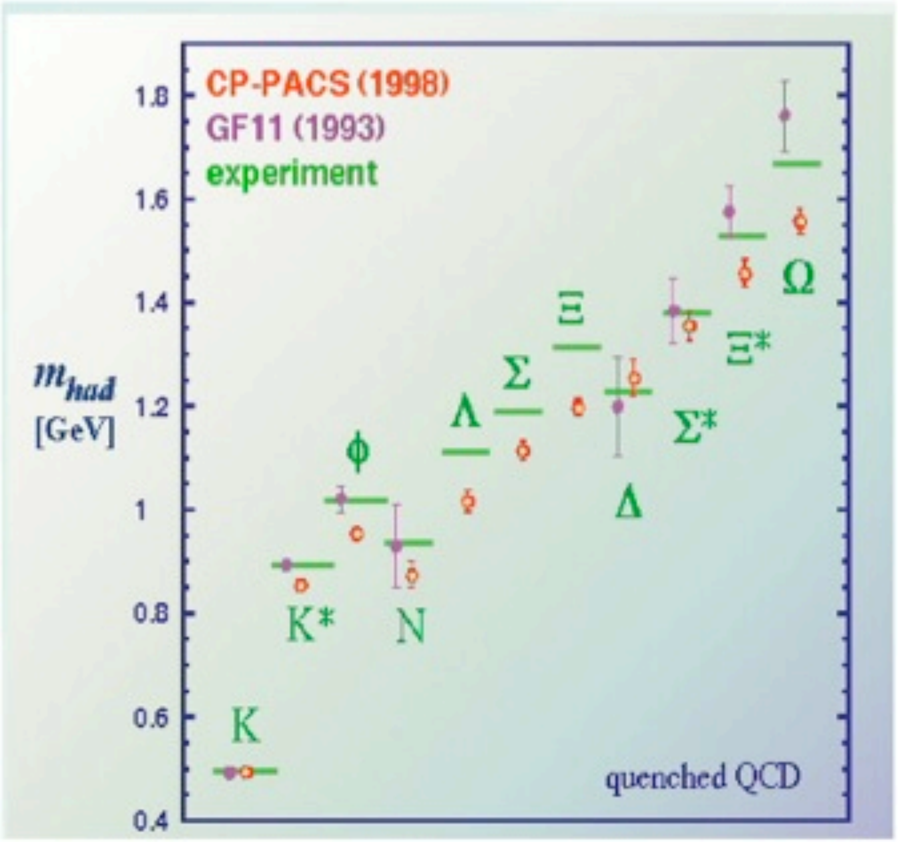
proton or nucleus

Small x components of the proton

b	impact parameter
r	dipole size

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.