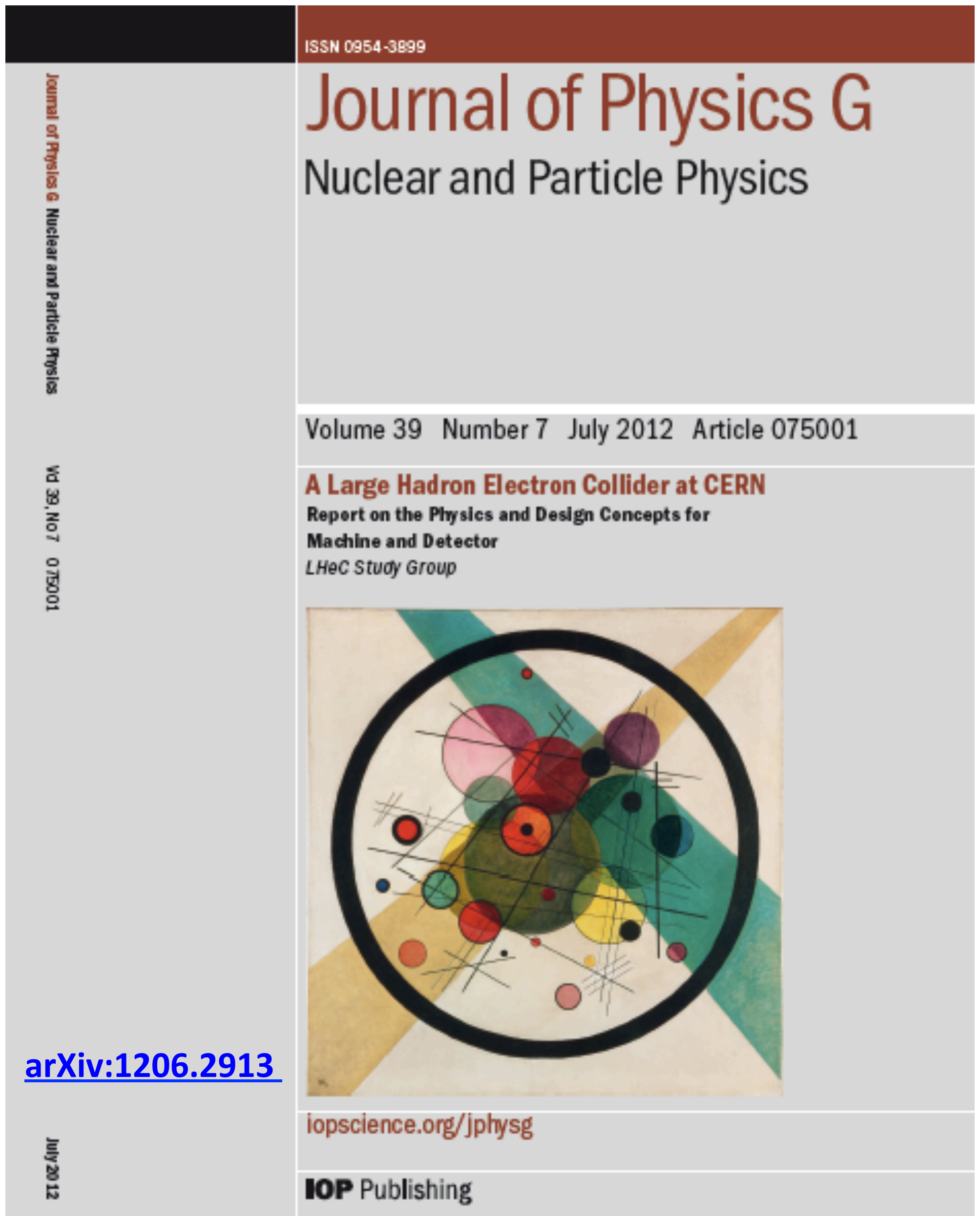
Exploring QCD at the LHeC

Anna Stasto
Penn State & RIKEN BNL & Cracow INP

April 18, 2013, CERN

Physics at low x at the LHeC



arXiv:1206.2913

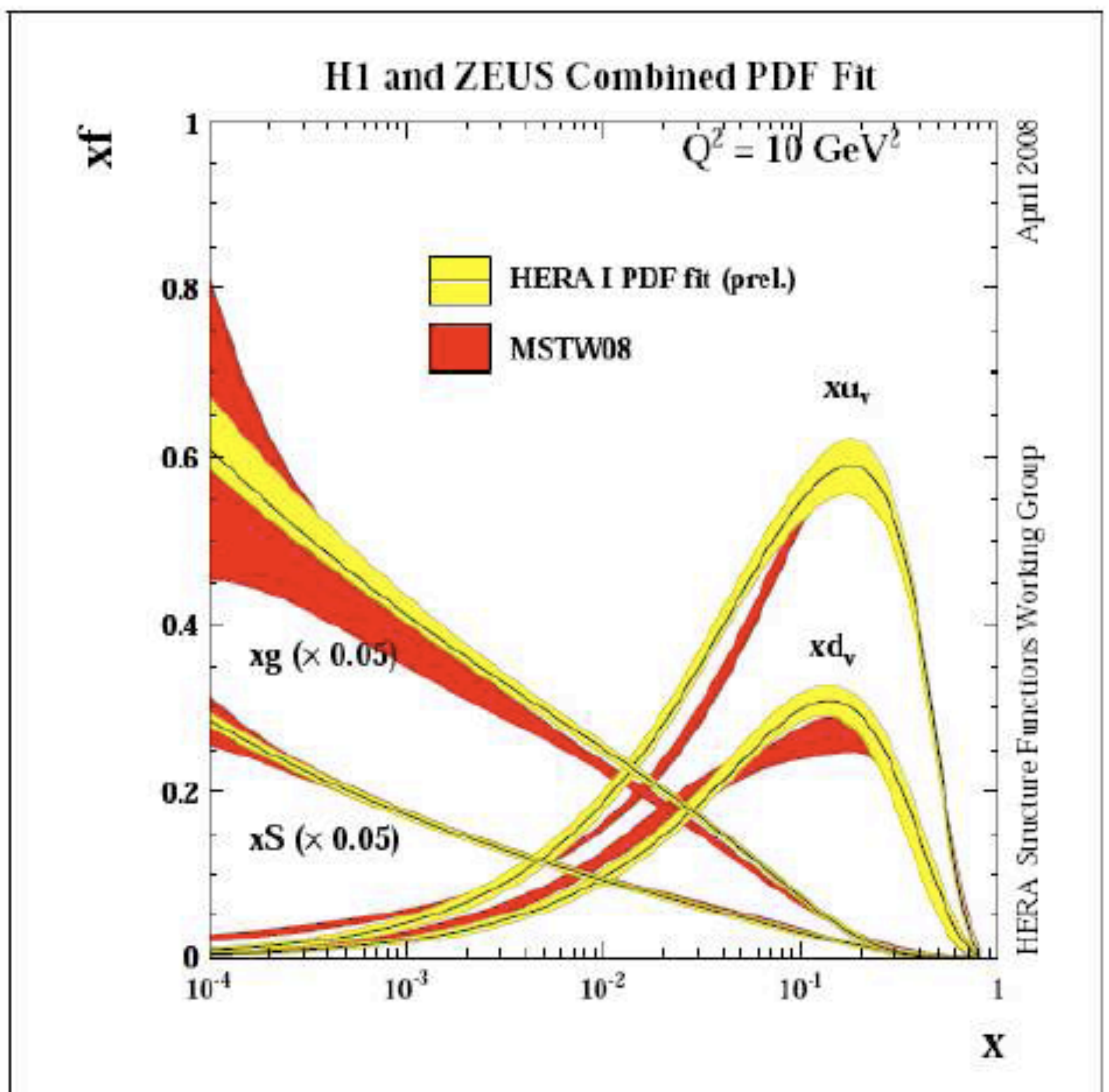
See also arXiv:1211.5102, 1211.4831

Nestor Armesto talk on eA

Why small x is 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 proton structure function.



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

Large uncertainties in the pdf extraction below x<0.0001

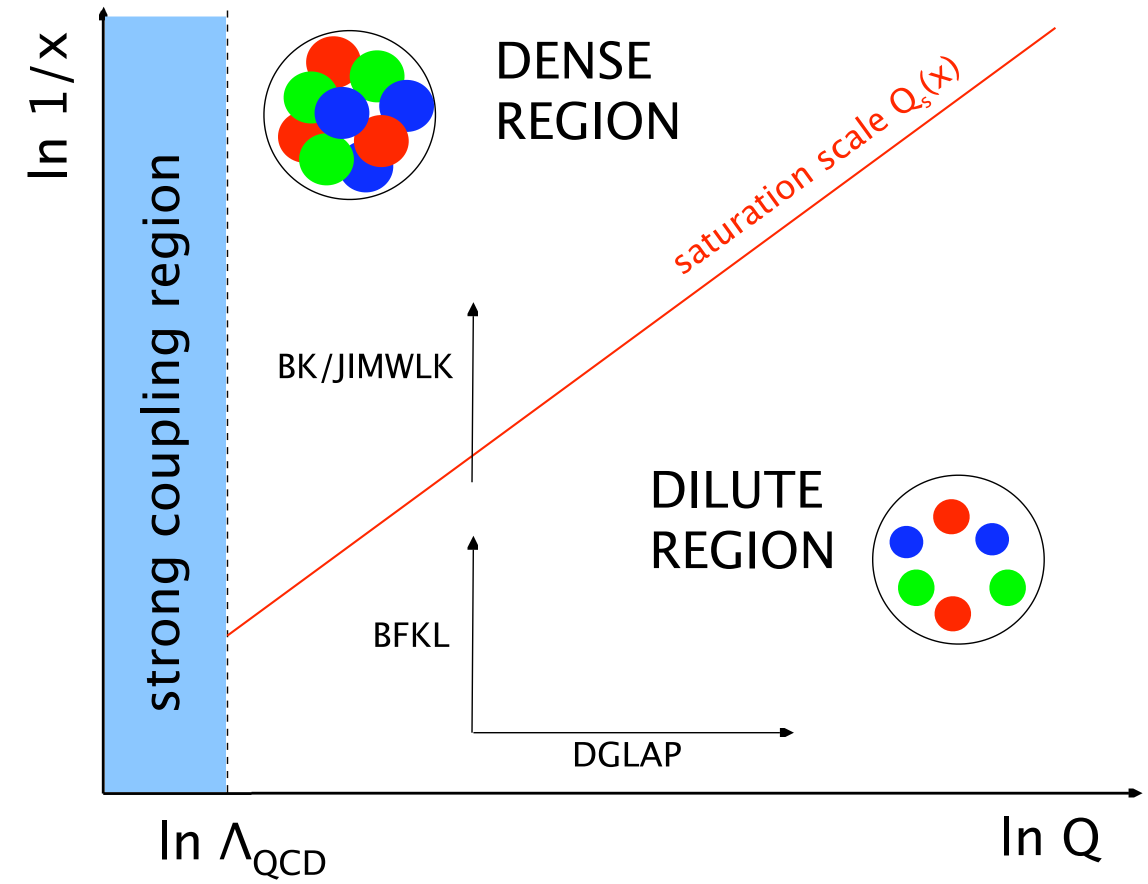
On the theoretical side: there is a divergence of the parton densities/cross sections at high energies/small x.

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...

Small x regime

- At small x the linear evolution gives strongly rising gluon density.
- Parton evolution needs to be modified to include potentially very large logs, resummation of log(1/x)
- Further increase in the energy could lead to the importance of the recombination effects.
- Modification of parton evolution by including non-linear or saturation effects in the parton density.



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.

Small x regime

- Precision inclusive measurements of structure functions: determining the gluon at low x, DGLAP/resummation BFKL,CCFM, ABF ,CCSS .../or nonlinear effect saturation? Relevance for ultrahigh energy neutrino interactions.

- Inclusive diffraction in ep: new domains of diffractive masses, large kinematic window for factorization tests.

- Exclusive processes, VM production and DVCS: determining GPDs, sensitive tests of saturation, mapping the detailed shape of the proton.

- Forward jets and dijets: constraints on unintegrated parton distributions.

LHeC kinematics

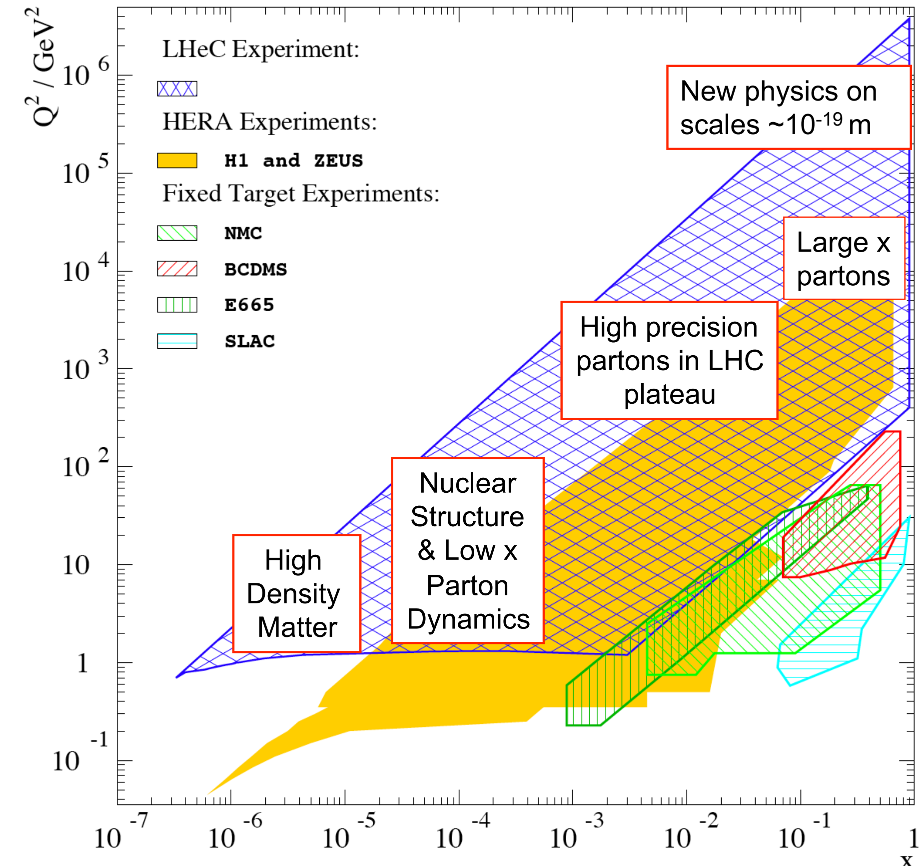
ep/ea collisions

$$E_p = 7 \text{ TeV}$$
$$E_A = 2.75 \text{ TeV/nucleon}$$
$$E_e = 60(50) - 140 \text{ GeV}$$
$$\sqrt{s} \simeq 1 - 2 \text{ TeV}$$

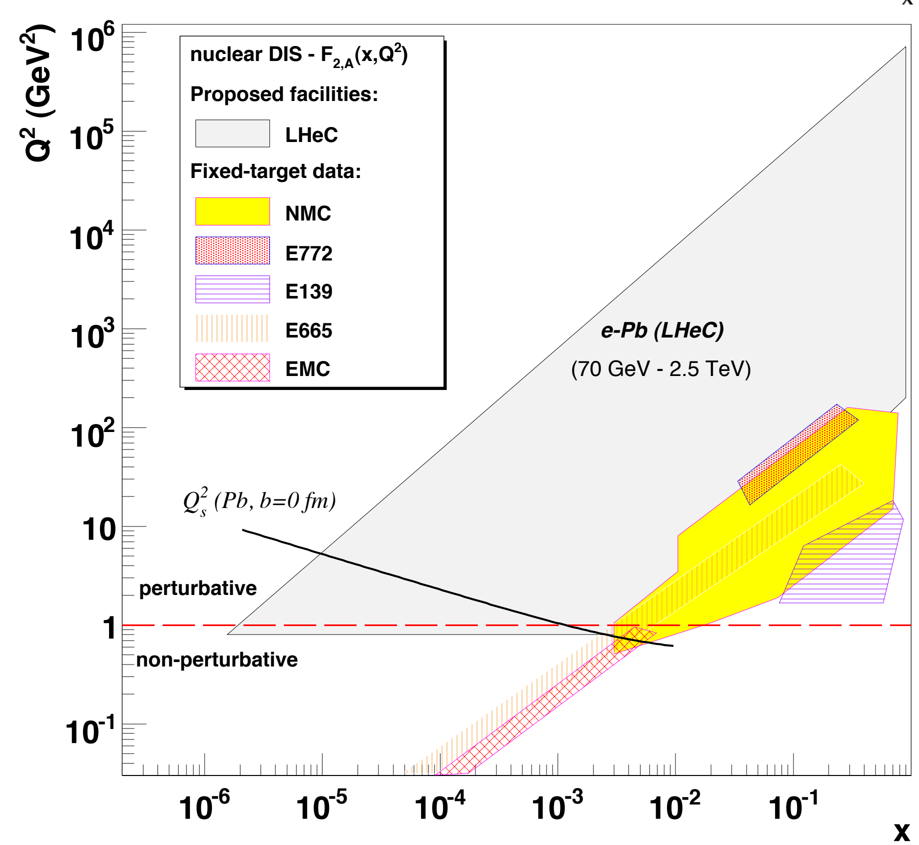
- Requirements:

* Luminosity~10^{33} $cm^{-2}s^{-1}$. eA: L_{en}~10^{32} $cm^{-2}s^{-1}$
* Acceptance: 1-179 degrees (low-x ep/eA).
* Tracking to 1 mrad.
* EMCAL calibration to 0.1 %.
* HCAL calibration to 0.5 %.
* Luminosity determination to 1 %.
* Compatible with LHC operation.

ep



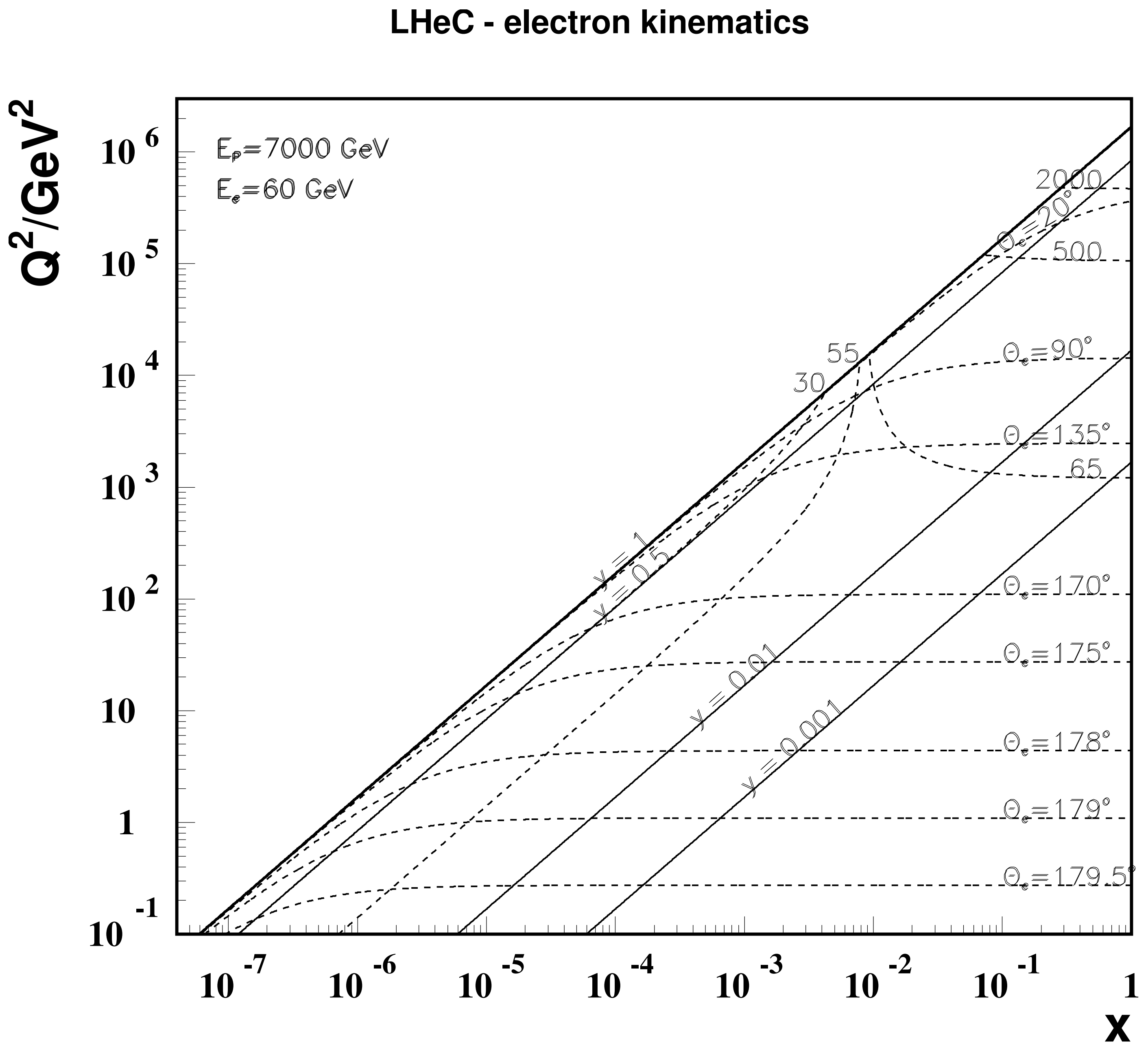
eA



LHeC kinematics: acceptance

Kinematics in ep mode

$$Q^2_{min}(x, \theta_e^{max}) \simeq [2E_e \cot(\theta_e^{max}/2)]^2.$$



Access to low x and low Q requires electron acceptance down to 179 degrees.

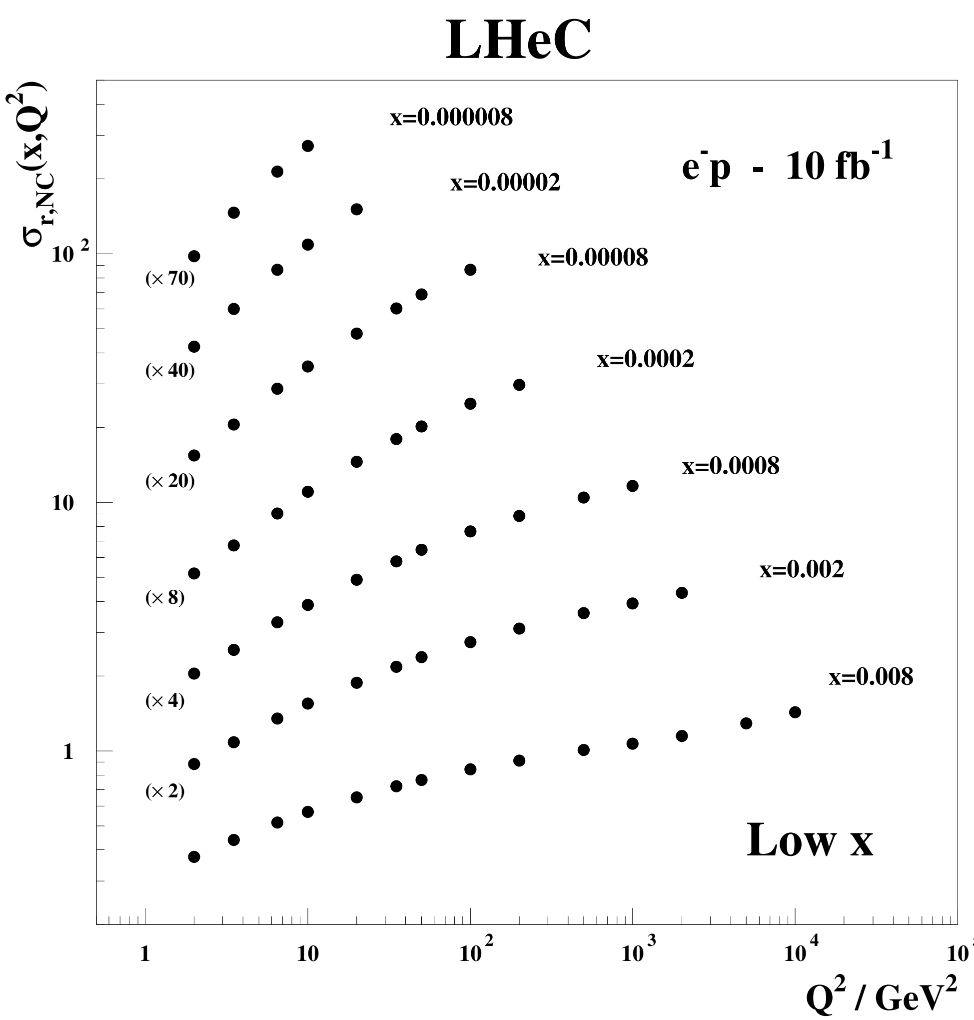
$Q^2_{\rm min} = 0.03\ \mathrm{GeV}^2$ for $E_e = 10$ GeV

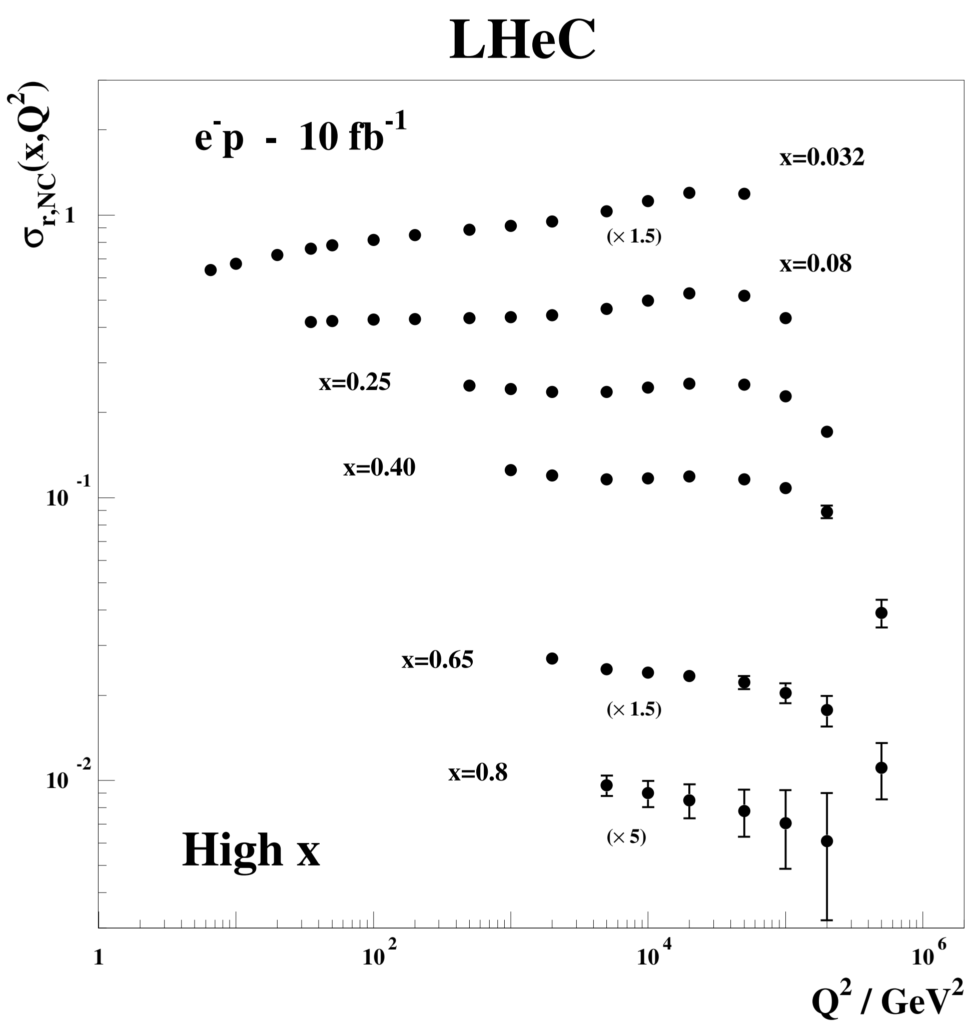
$Q^2_{\rm min} = 1\ \mathrm{GeV}^2$ for $E_e = 60$ GeV

$Q^2_{\rm min} = 6\ \mathrm{GeV}^2$ for $E_e = 140$ GeV

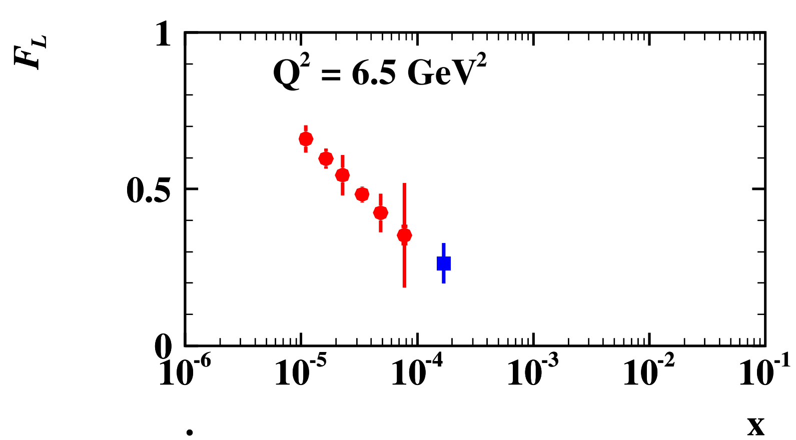
The measurement of the transition from hadronic to partonic regime would require lowering the electron energy.

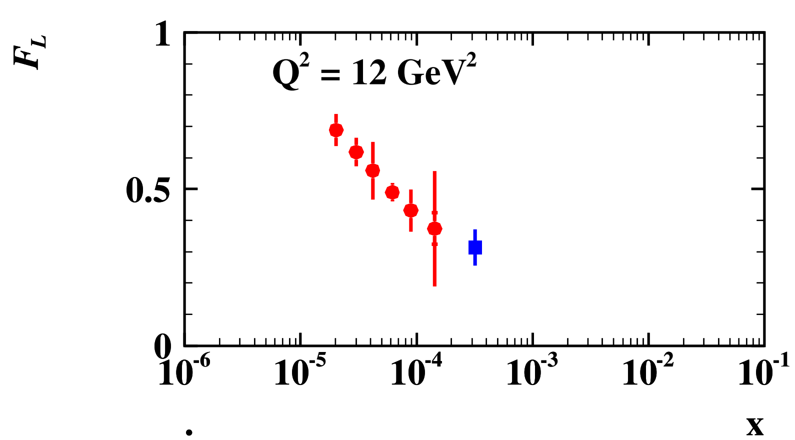
F_2,F_L structure functions





Reduced cross section: huge kinematic range and excellent accuracy

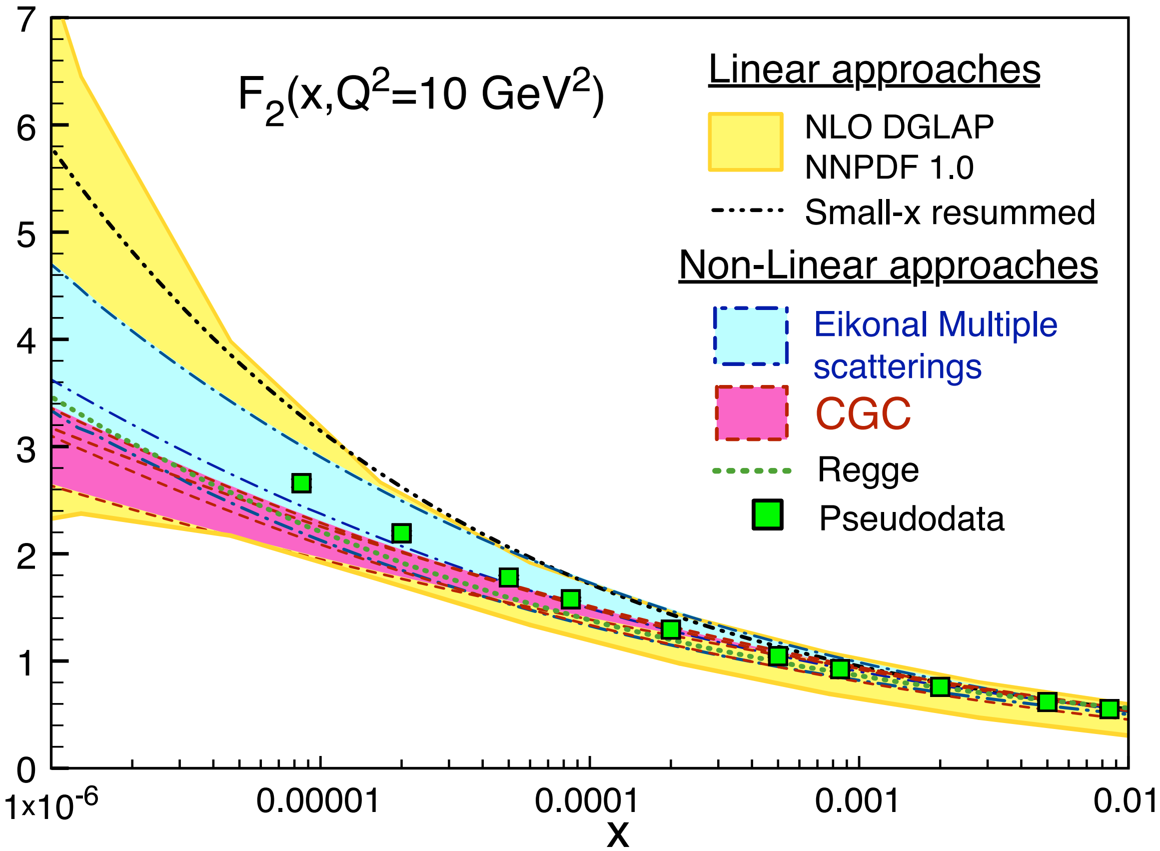


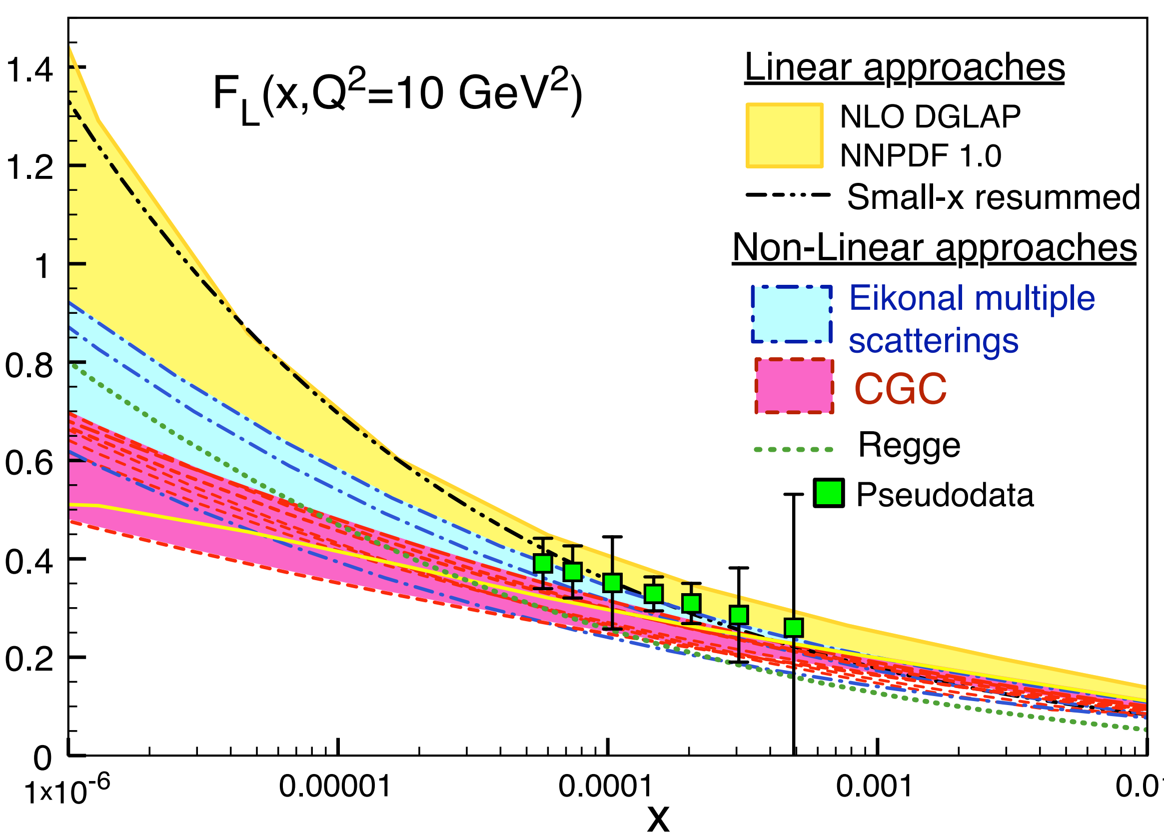


Longitudinal structure function: lowering electron energy

Predictions for the proton

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





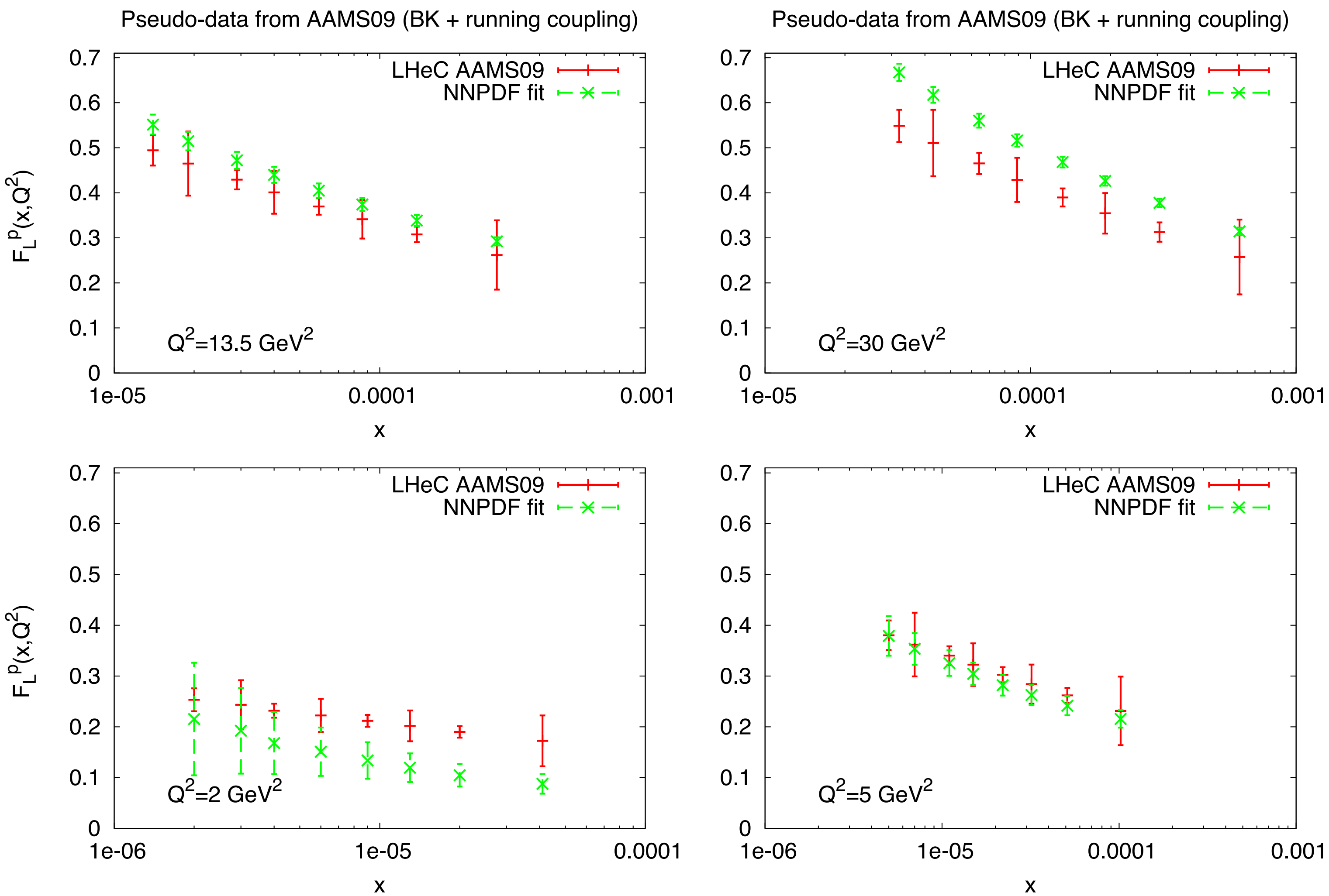
approx. 2% error on the F2 pseudodata, and 8% on the FL pseudodata ,should be able to rule out many of the scenarios.

powerful constraints on pdfs, see talk by Voica Radescu

Testing nonlinear dynamics in ep

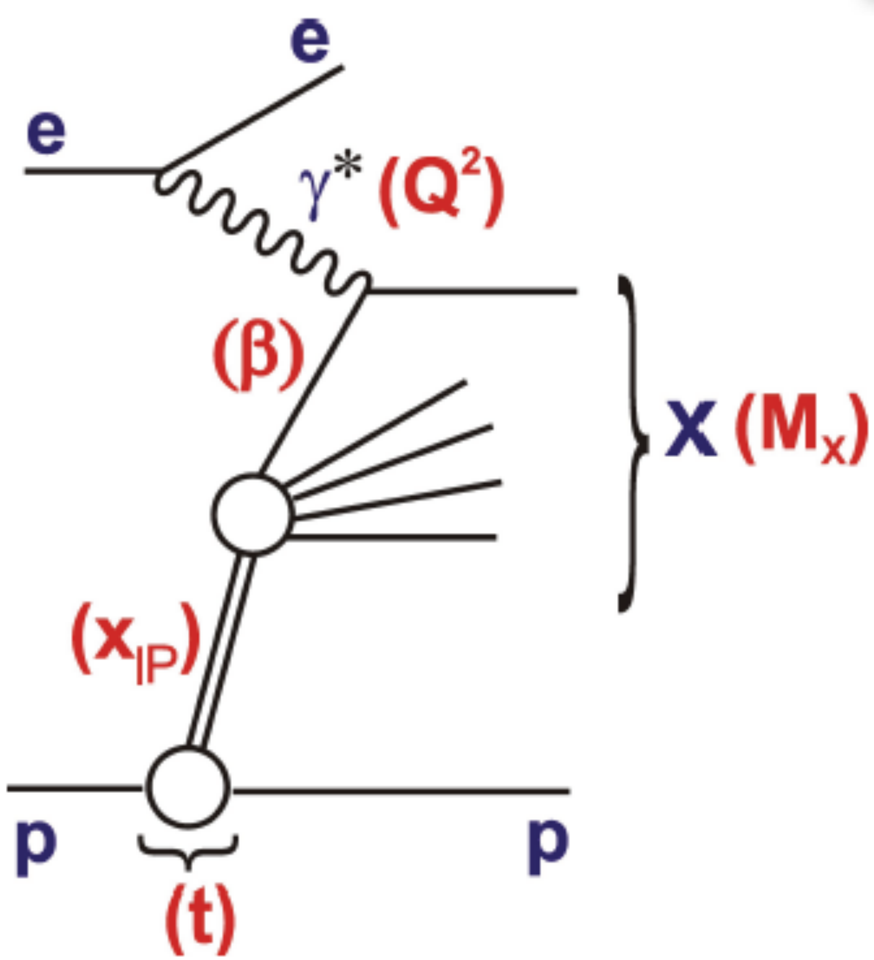
Simulated LHeC data using the nonlinear evolution which leads to the parton saturation at low x.

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



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

Diffraction



$$x_{IP} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2}$$

momentum fraction of the Pomeron w.r.t hadron

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

momentum fraction of parton w.r.t Pomeron

$$x_{Bj} = x_{IP}\beta$$

Theoretical description of such process is in terms color-less exchange : the Pomeron.

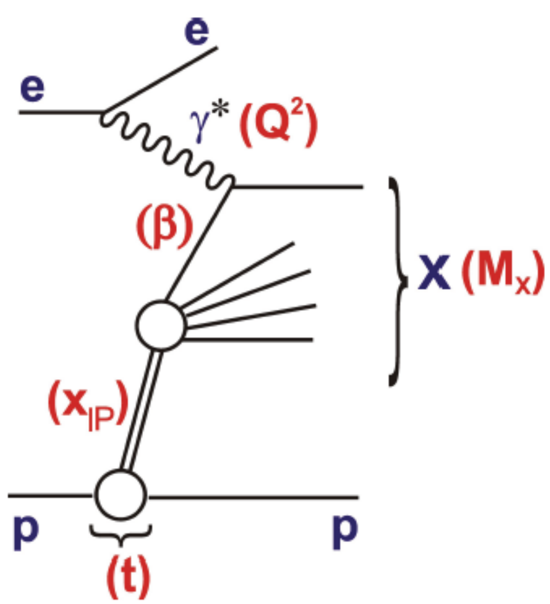
For large scales the QCD factorization was shown.

The diffractive structure functions are convolutions of diffractive pdfs and coefficient functions.

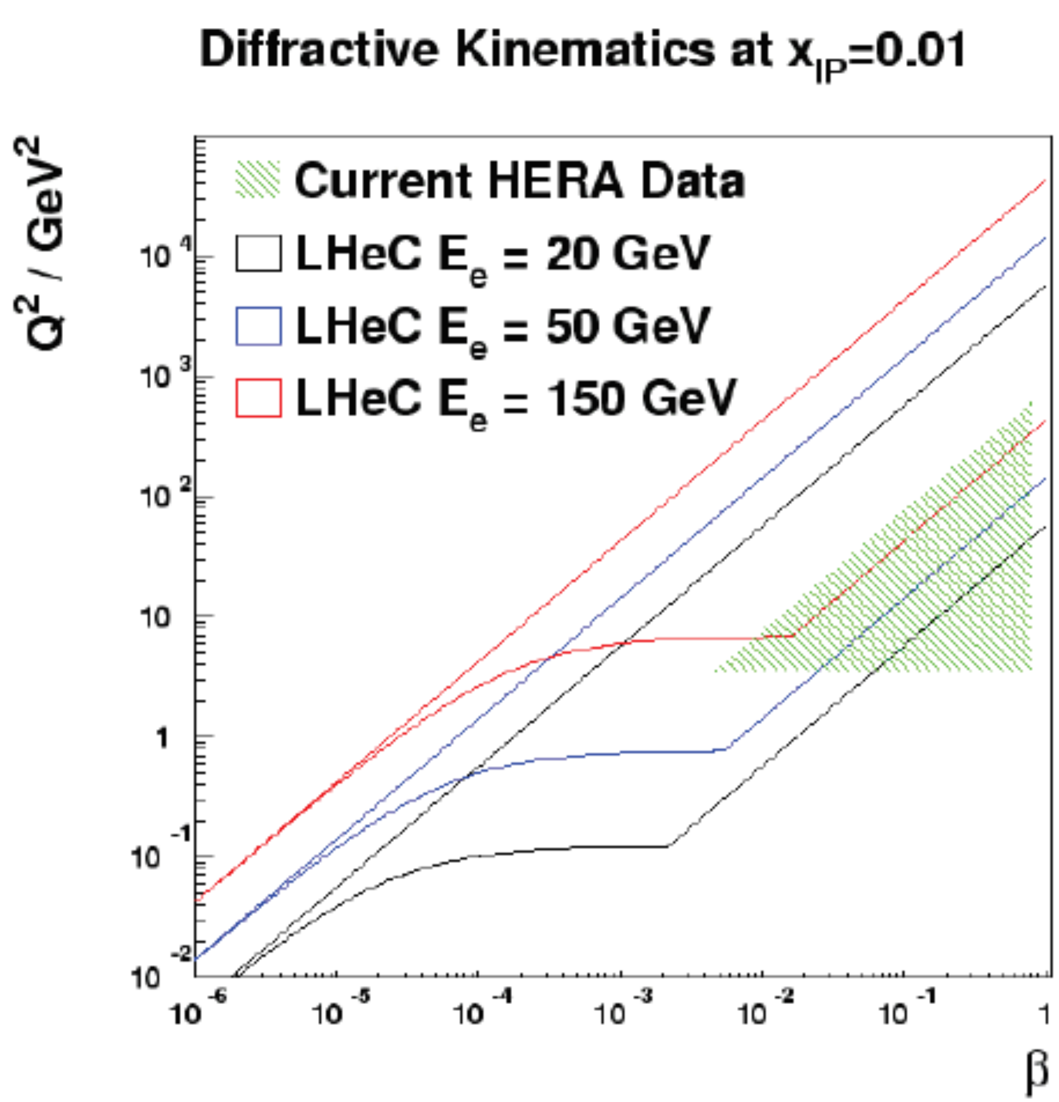
What can be done at LHeC

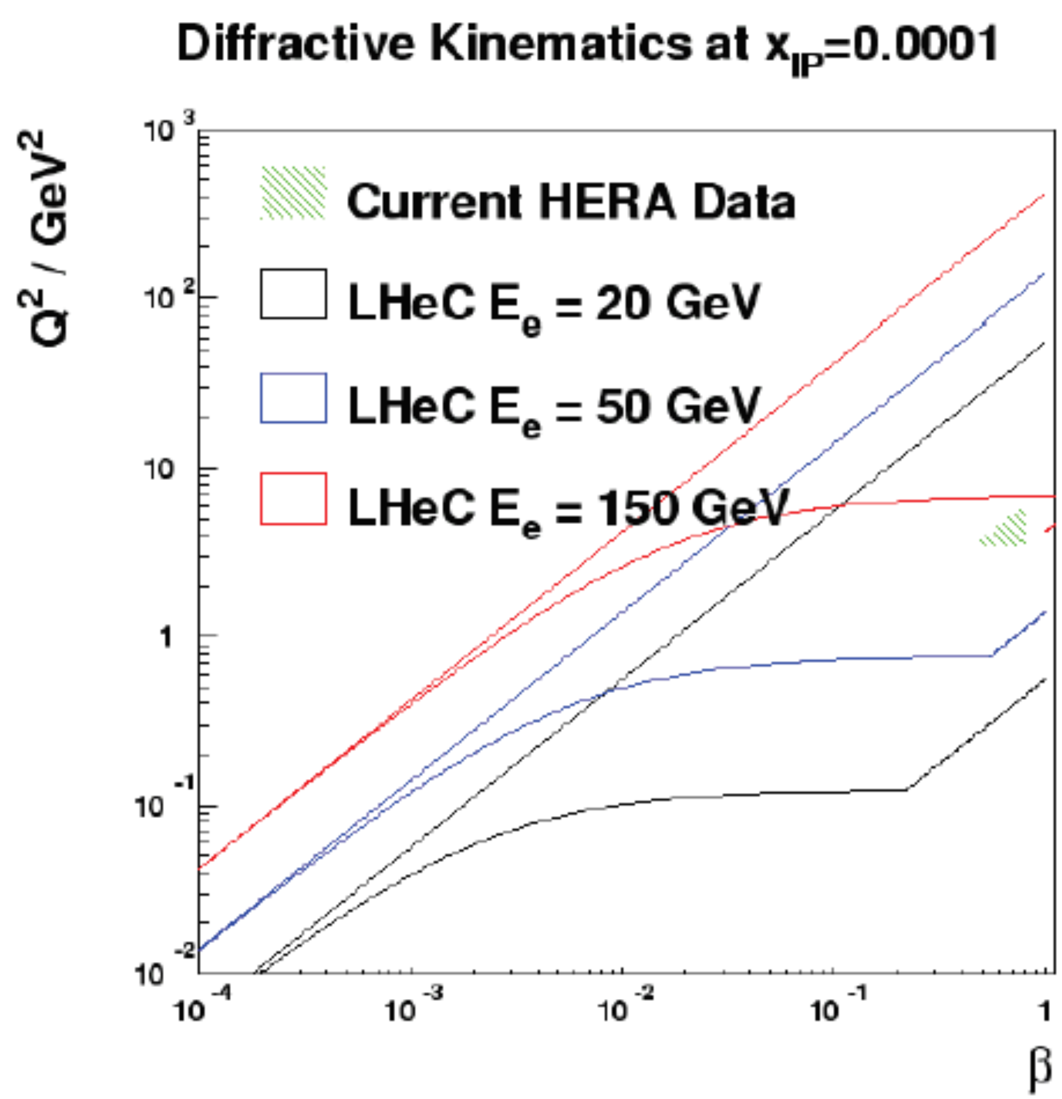
- Tests of factorization of diffractive parton distributions in an extended kinematic range (ep and eA).
- Sensitivity and relation to saturation physics (smaller scales involved).
- New domain for the diffractive masses.
- Study relation between diffraction in ep and shadowing in eA.

Diffractive kinematics



Methods for selection of diffractive events:
Leading proton tagging, large rapidity gap selection





Rapidity gap selection

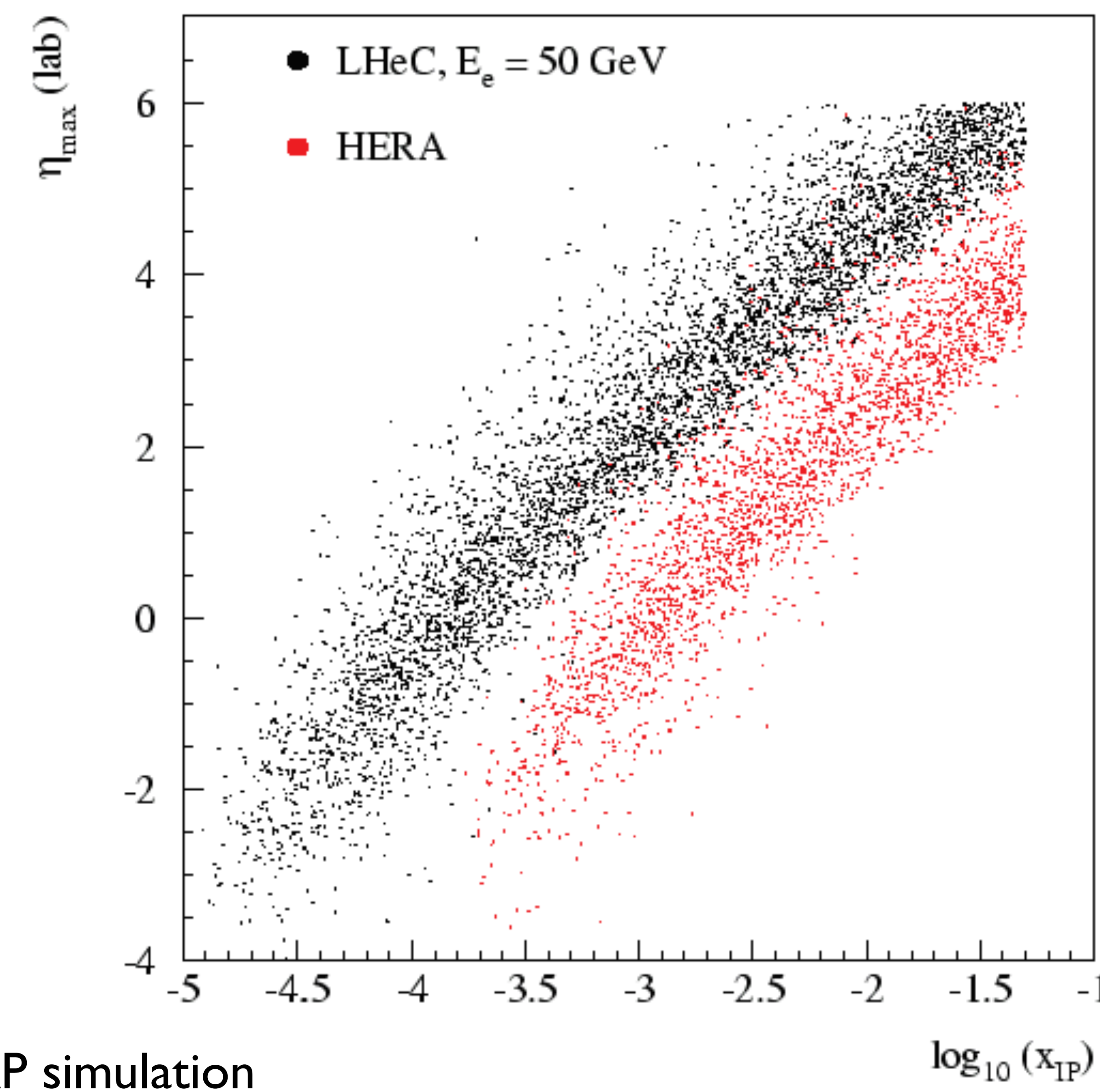
Correlation of x_{IP} with the pseudorapidity of the most forward particle in the diffractive final state $\eta_{\max}$

Cut at $\eta_{\max} = 5$

For larger x_{IP} leading proton method could be used.

Two methods are complementary with some region of common acceptance.

η_{max} from LRG selection ...



RAPGAP simulation

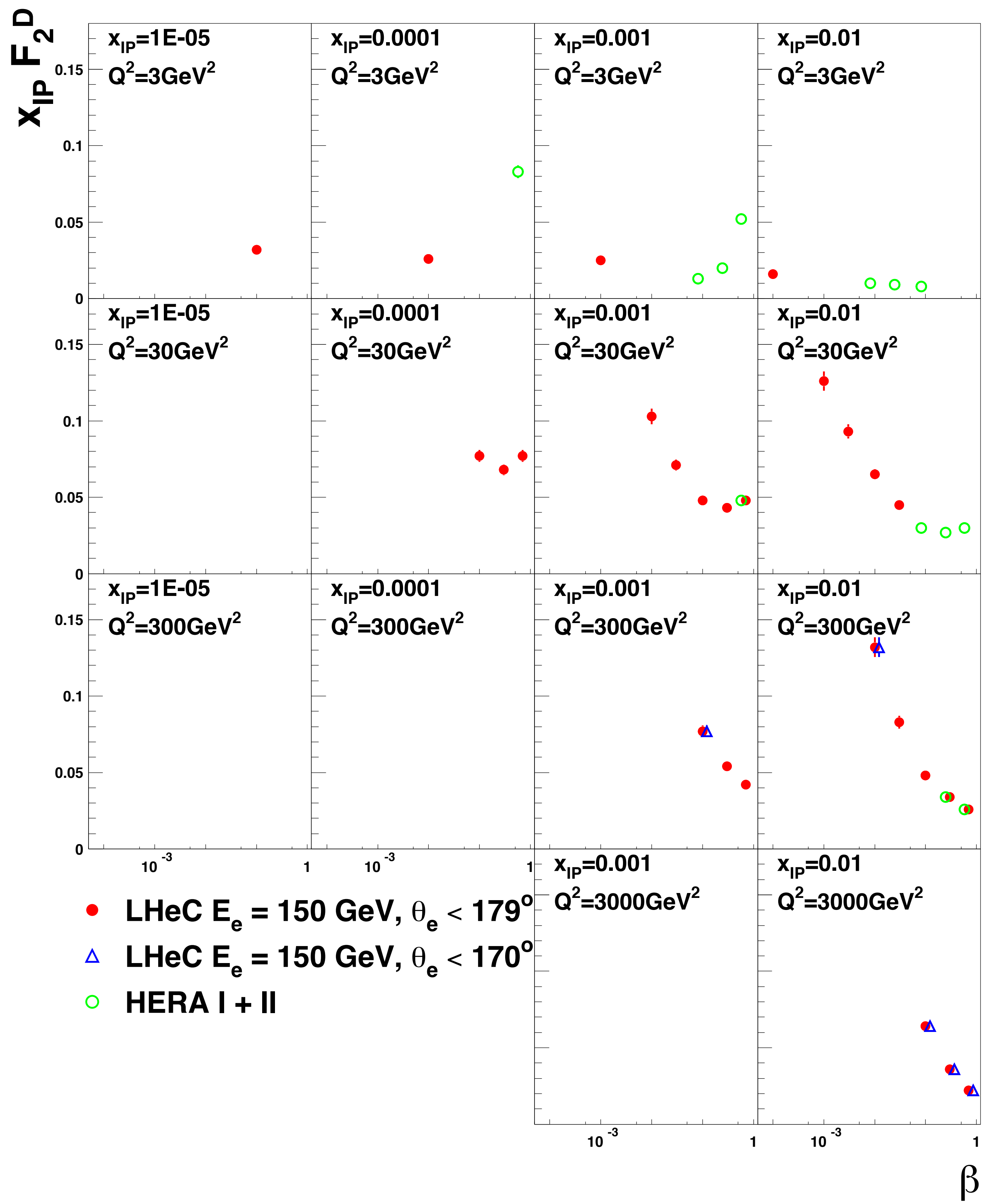
Diffractive structure function

Pseudodata simulated using the large rapidity gap method and leading proton method.

Large differences depending on the acceptance of the detector: 1 vs 10 degree.

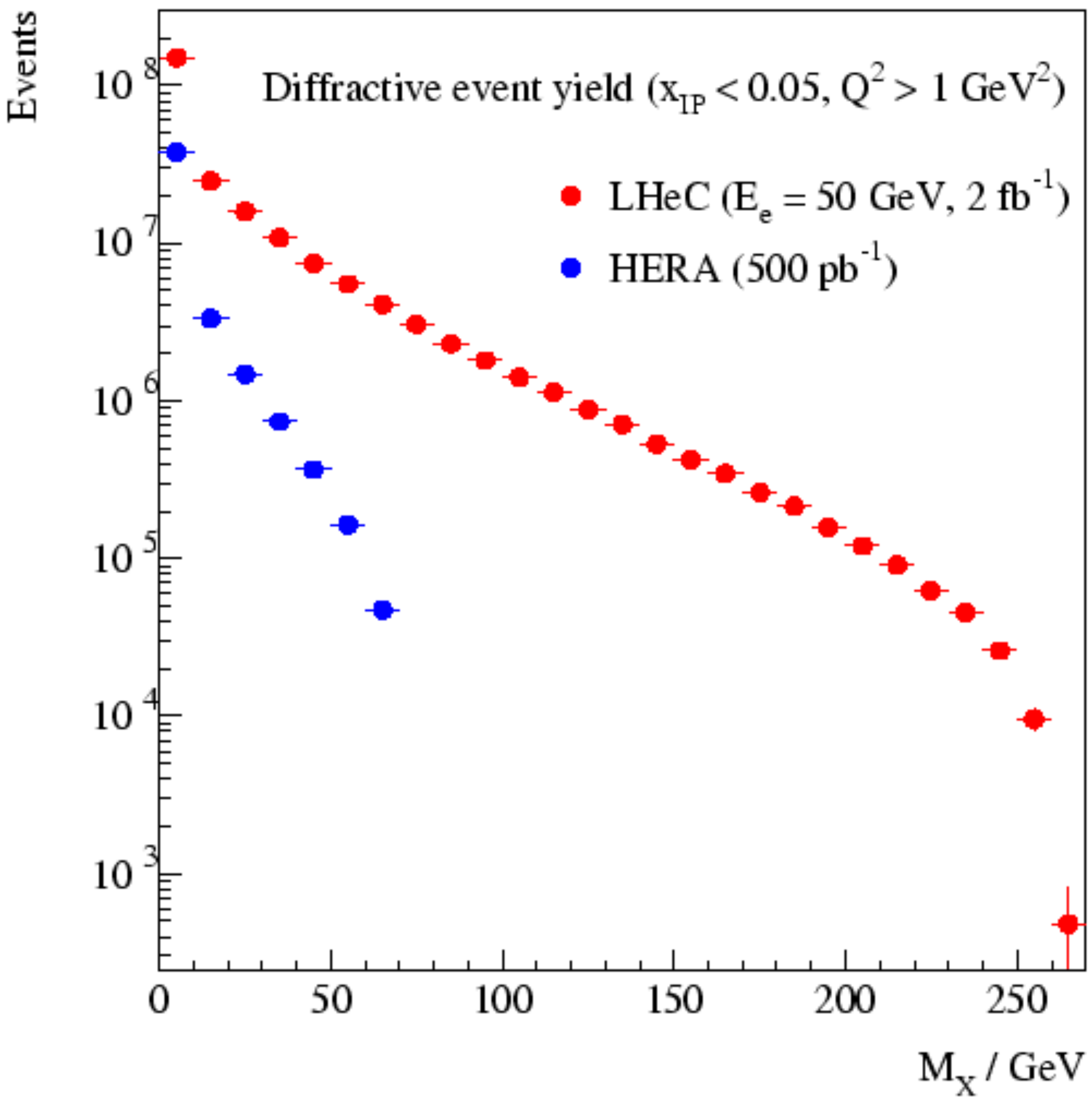
Statistical errors less than 1% for a sample luminosity of $2\ \mathrm{fb}^{-1}$

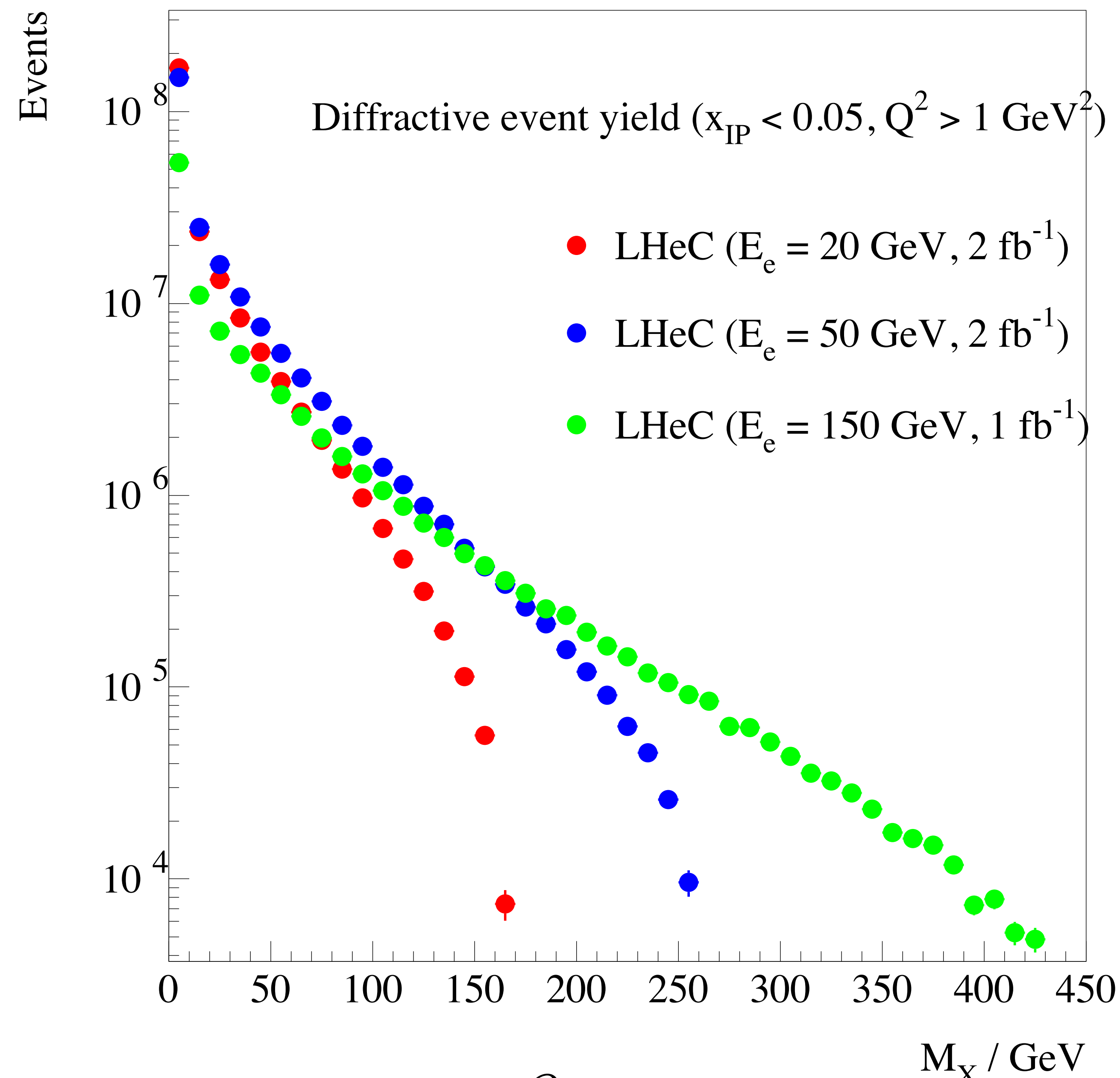
Comparison of HERA data shows huge increase in kinematic range.



Diffractive mass distribution

RAPGAP simulation



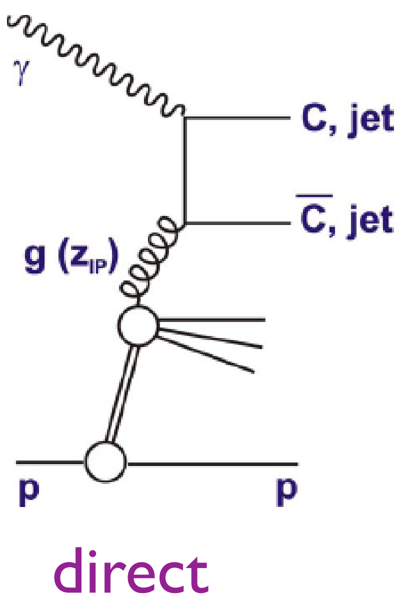


LHeC can explore very low values of β

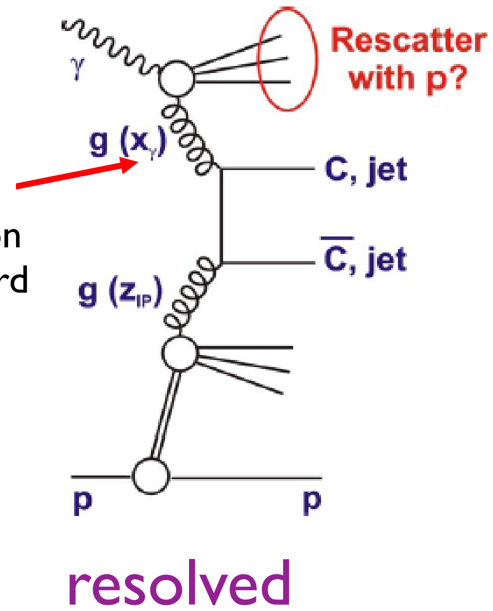
New domain of diffractive masses.

M_X can include W/Z/beauty or any state with 1^-

Diffractive dijets



fraction of photon momentum in hard subprocess



Factorization in diffraction breaks down at hadron collider.

Is factorization valid for dijet production?

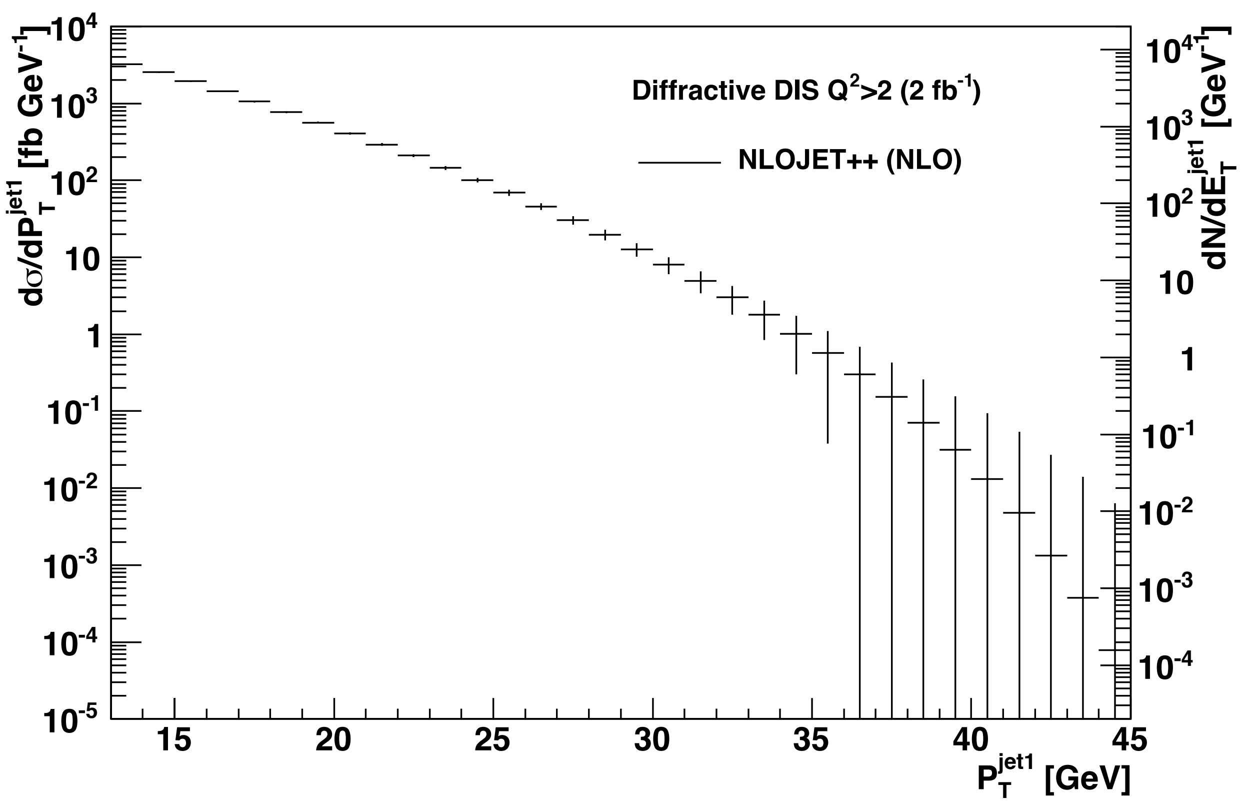
Measurement of diffractive gluon density

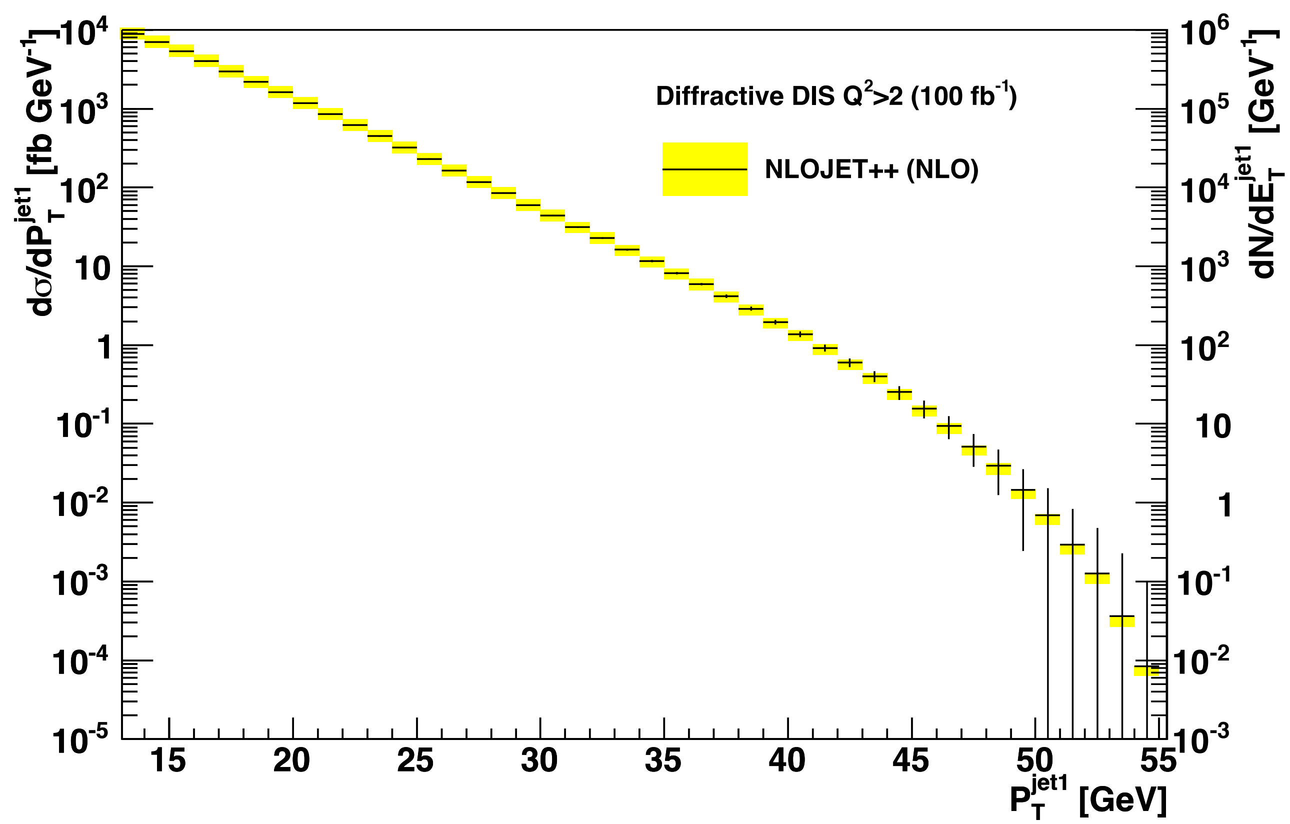
$0.2 < y < 0.4$

$x_{IP} < 0.01$

scale uncertainties $0.5\mu, 2\mu$

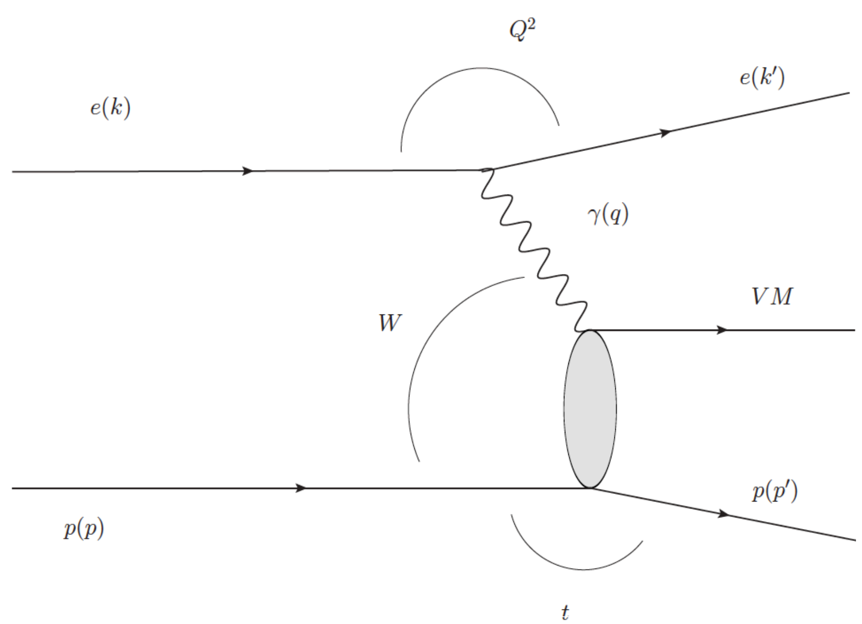
$0.1 < y < 0.7$

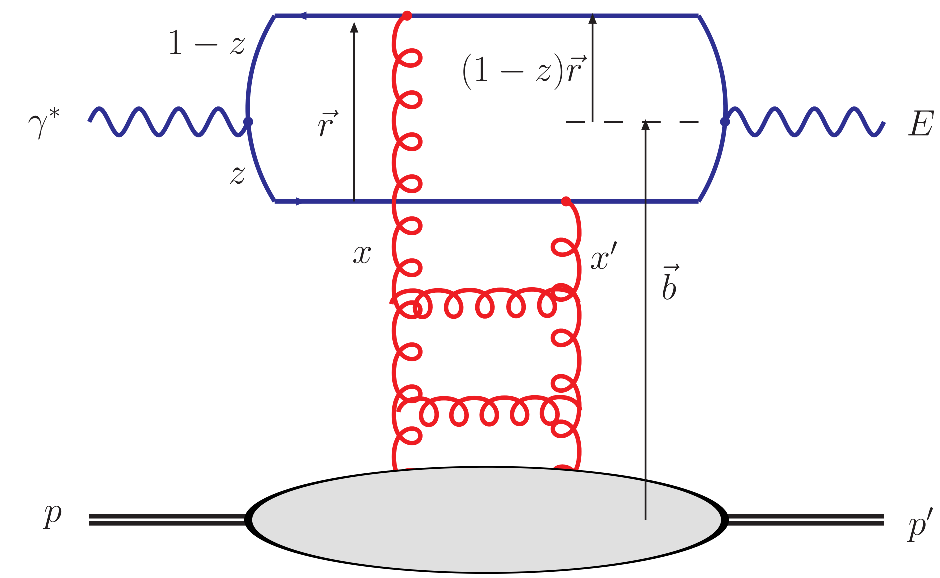




Exclusive production of vector mesons

$$\gamma^* p \to pV \qquad V = \rho, \phi, J/\Psi, \Upsilon$$





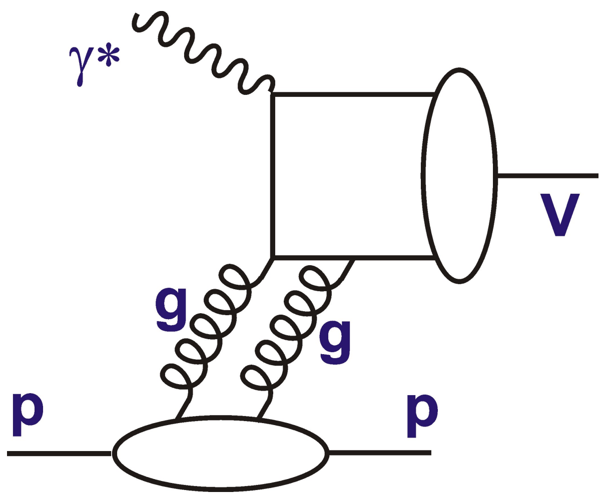
At first approximation described by two gluon exchange

HERA demonstrated that such measurements allow to probe the details of the gluonic structure of the proton.

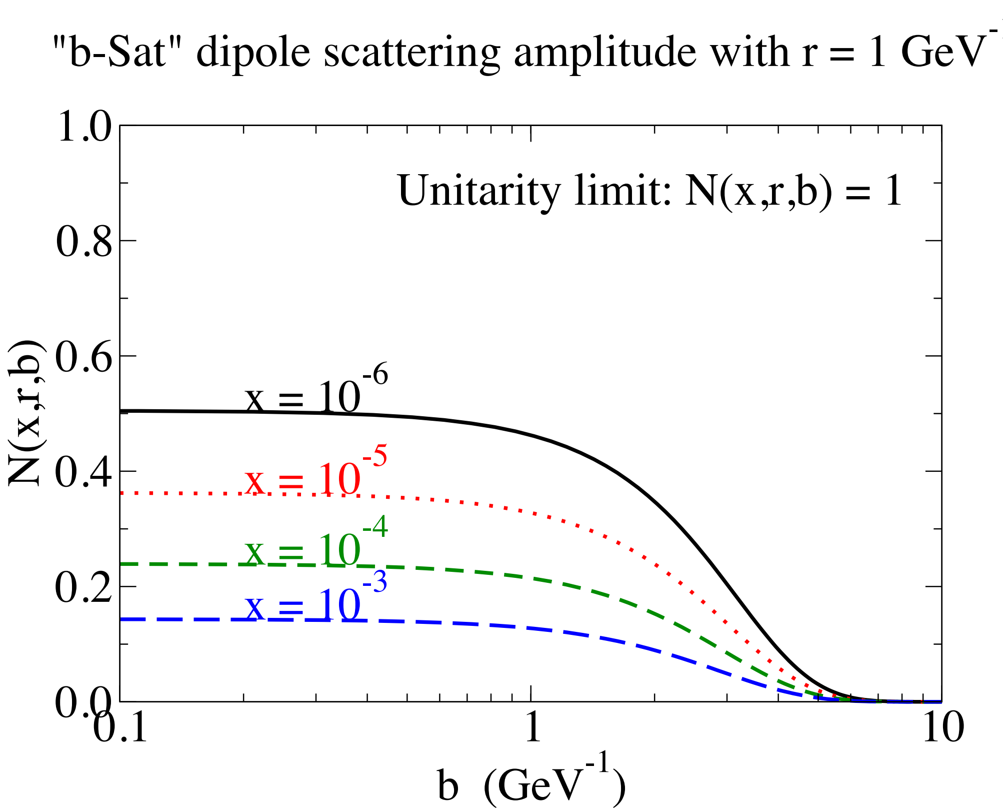
Goals for LHeC:

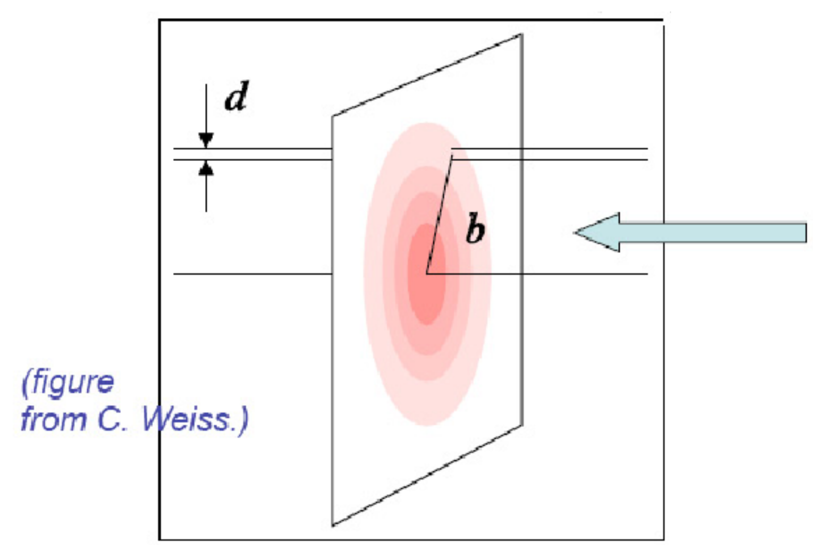
Tests of nonlinear, saturation phenomena.
Extraction of Generalized Parton Distributions. Large lever arm in Q allows to test universality of GPDs.
Impact parameter profile. Diffusion at low x.

Exclusive diffraction and saturation



- Suitable process for estimating the 'blackness' of the interaction.
- t-dependence provides an information about the impact parameter profile of the amplitude.





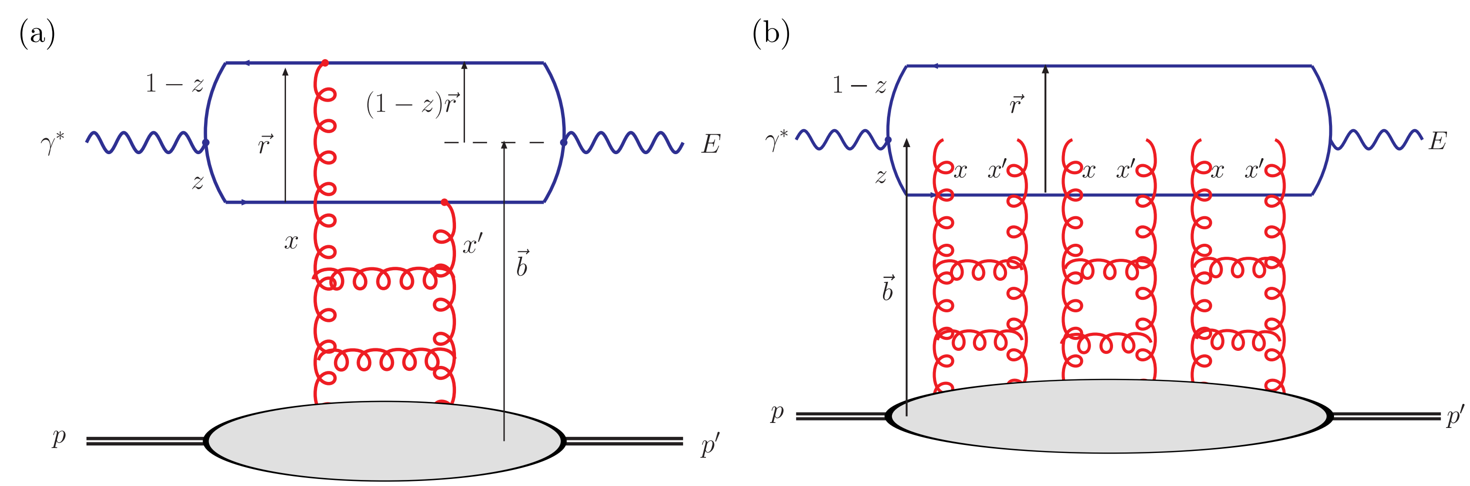
Central black region growing with decrease of x.

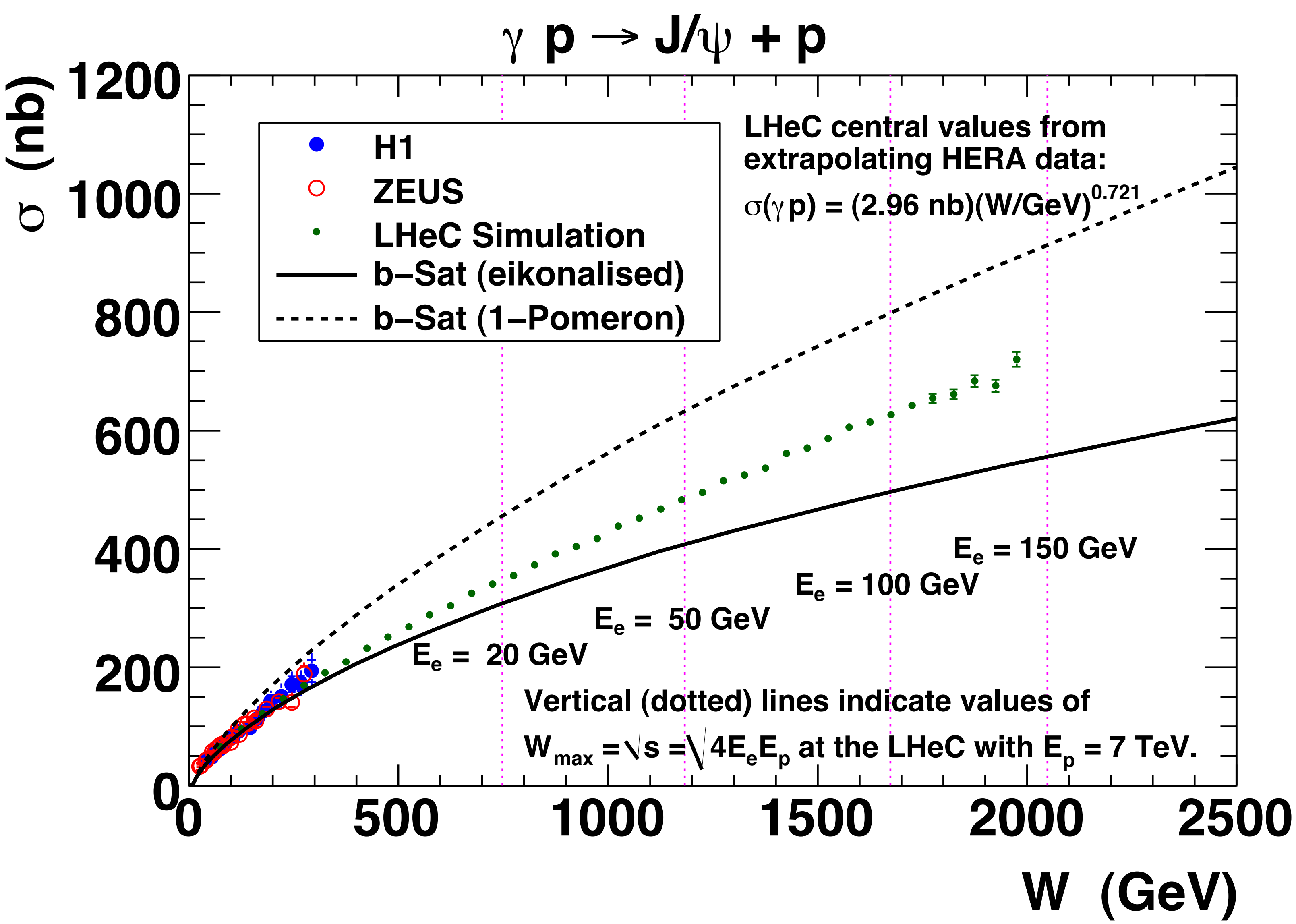
Large momentum transfer t probes small impact parameter where the density of interaction region is most dense.

Exclusive diffraction: vector mesons

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

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





Large effects even for the t-integrated observable.

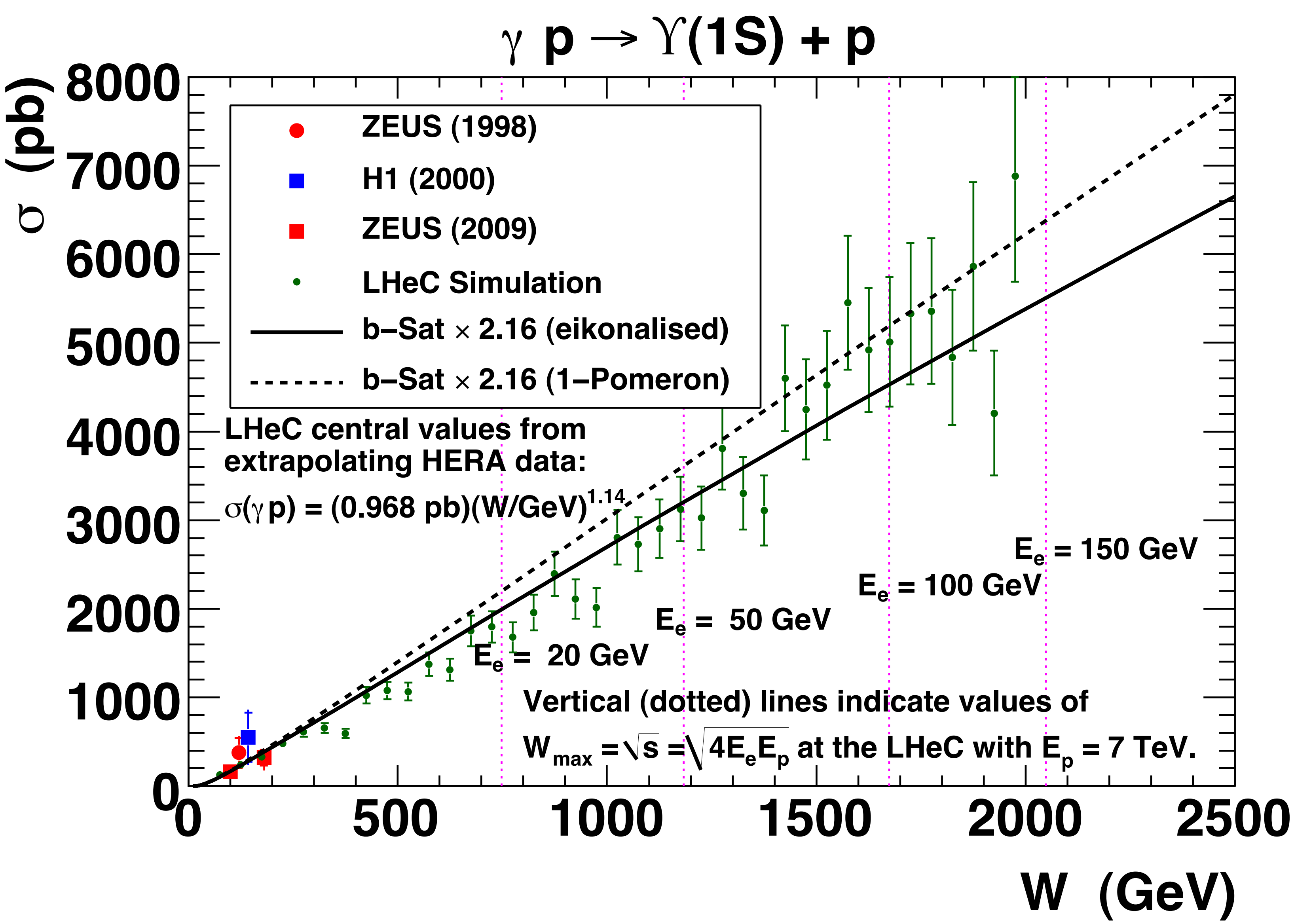
Different W behavior depending whether saturation is included or not.

Simulated data are from extrapolated fit to HERA data

LHeC can distinguish between the different scenarios.

Exclusive diffraction: vector mesons

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



Similar analysis for heavier states.

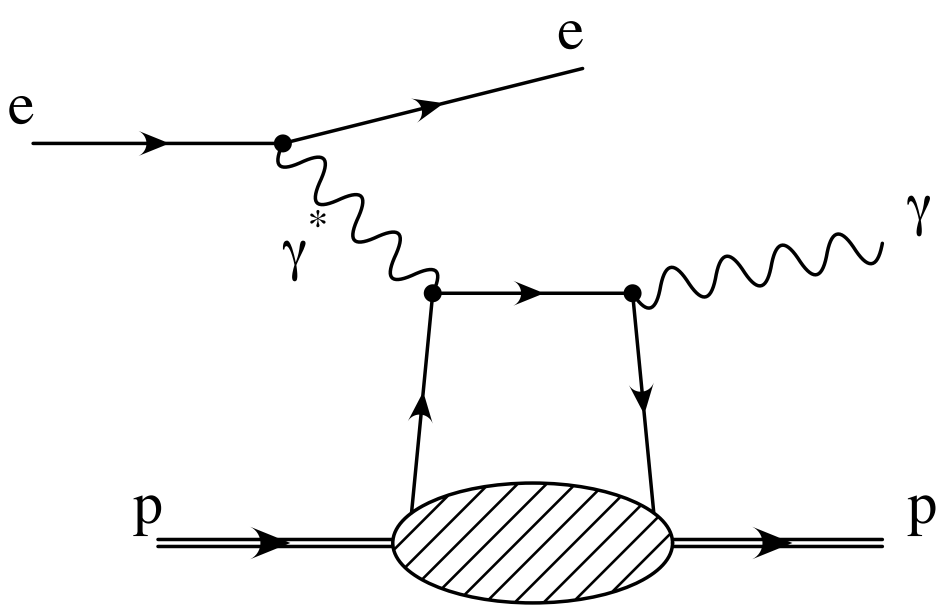
Smaller sensitivity to the saturation effects.

Models do have large uncertainty. Normalization needs to be adjusted to fit the current HERA data.

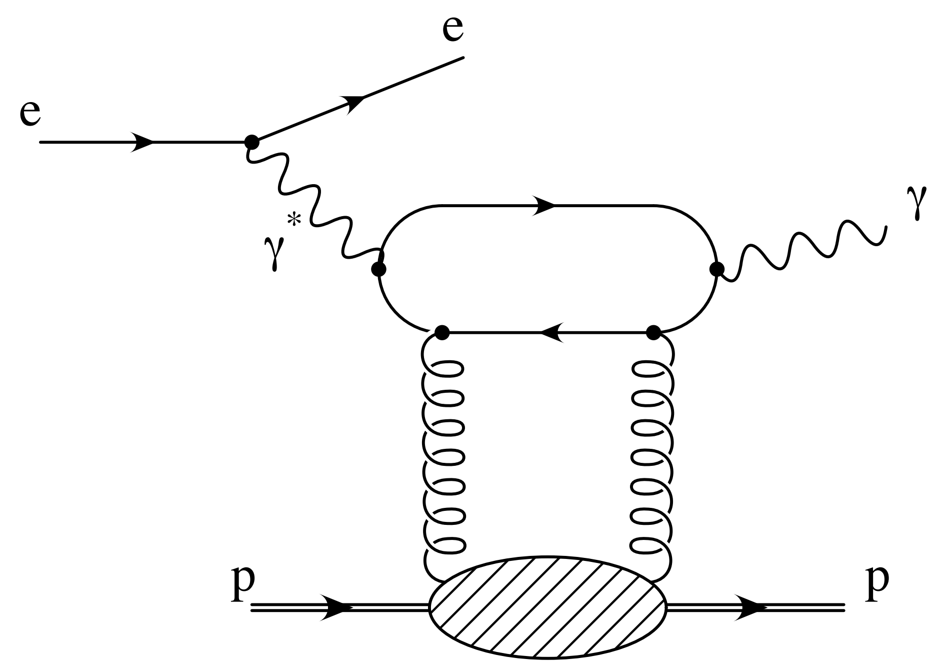
Precise measurements possible in the regime well beyond HERA kinematics.

Note: the theoretical curves have been rescaled by a factor of 2 to match the data.

Exclusive processes: DVCS



LO



NLO

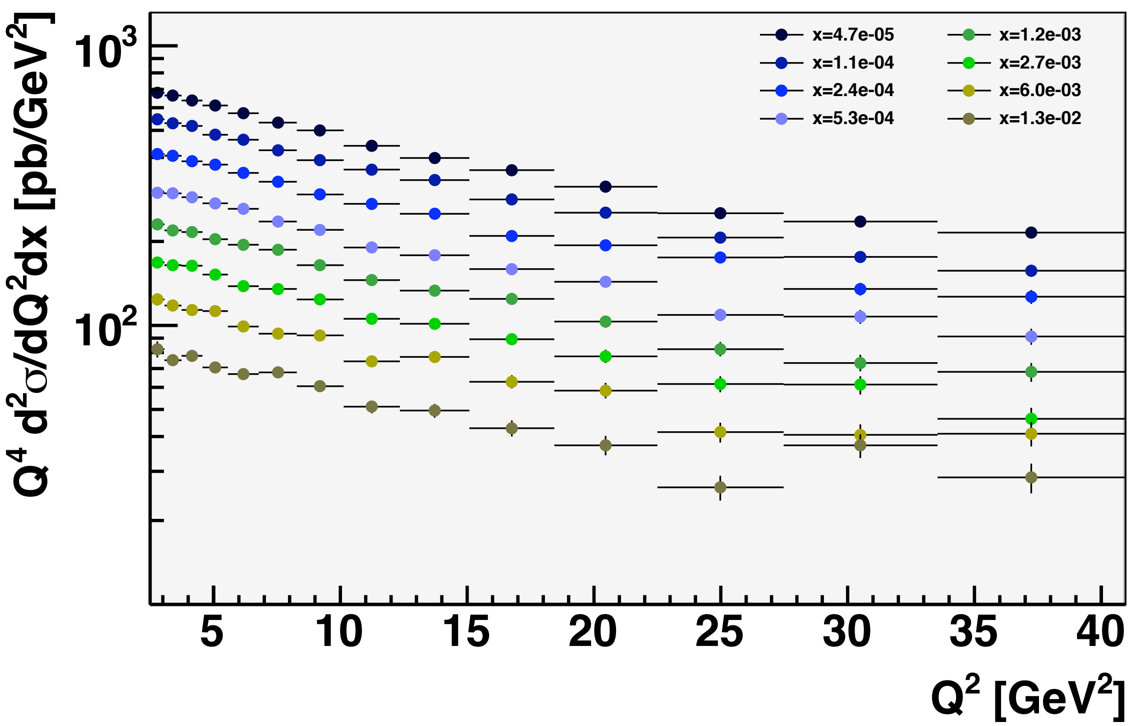
DVCS sensitive to singlet quark and gluon Generalized Parton Distribution functions

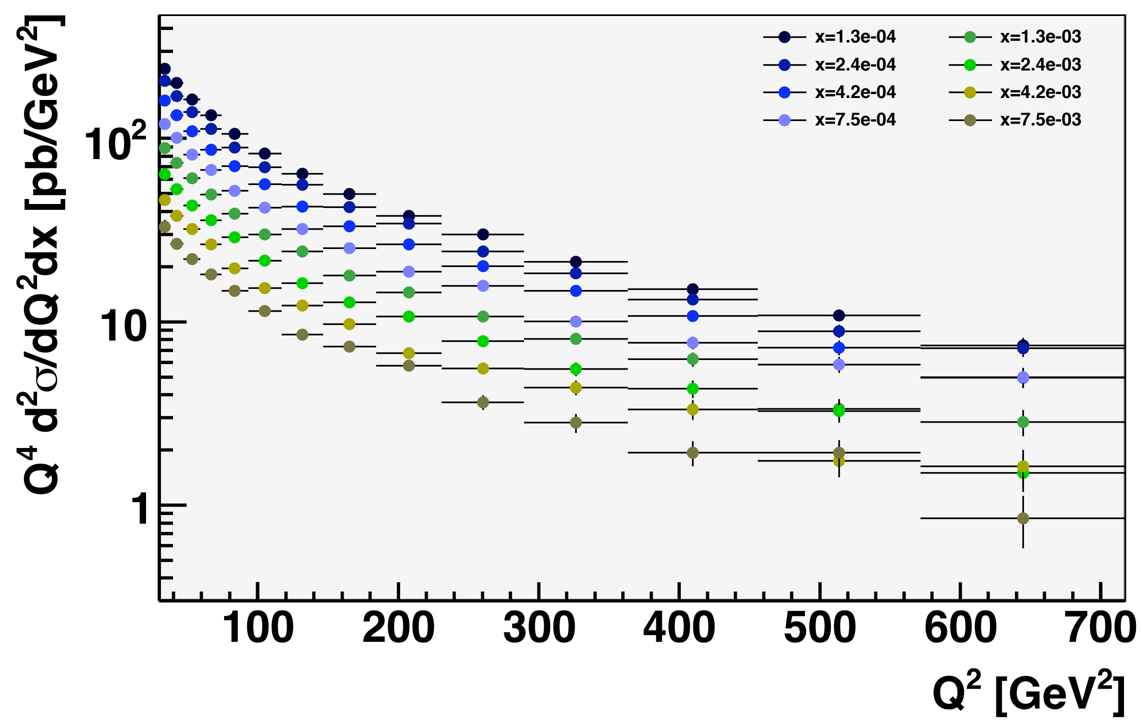
HERA indicate larger size of quark distribution than that of gluons

LHeC could determine the x evolution of both quark and gluon GPDs in a wide kinematic range.

Exclusive processes: DVCS

MILOU generator using Frankfurt, Freund, Strikman model.





$$\mathcal{L} = 1 \text{ fb}^{-1}$$

$$\theta = 1^o$$

$$p_T^\gamma = 2 \text{ GeV}$$

$$2.5 < Q^2 < 40 \text{ GeV}^2$$

low x

$$\mathcal{L} = 100 \text{ fb}^{-1}$$

$$\theta = 10^o$$

$$p_T^\gamma = 5 \text{ GeV}$$

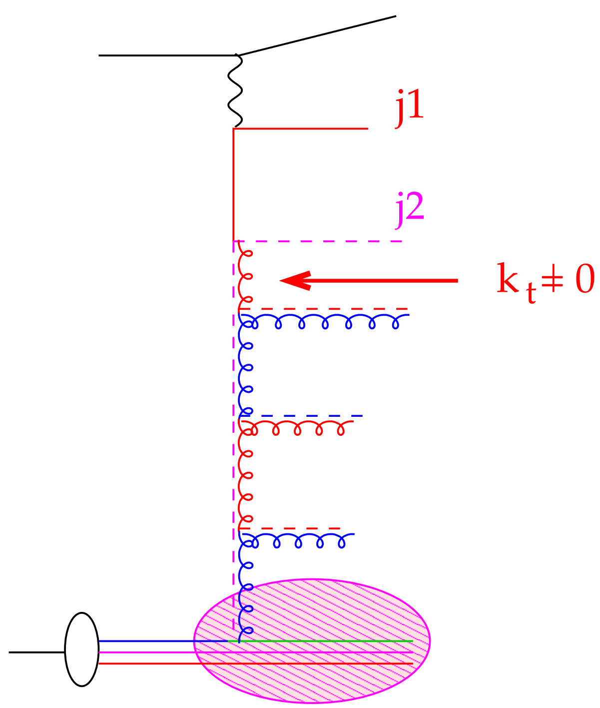
$$50 < Q^2 \simeq 500 \text{ GeV}^2$$

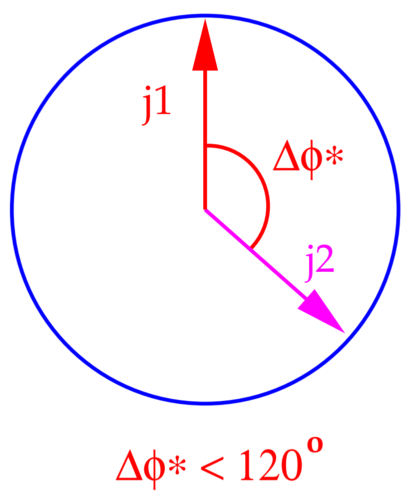
large scales

Parton dynamics

- Inclusive measurements provide constraints on the integrated parton distribution functions.
- Details of the dynamics need to be pinned down by more exclusive measurements.
- Unintegrated parton distribution functions needed, which have a better control of the kinematics of the process. LO with unintegrated pdfs descriptions are in general better than higher order terms in collinear approach.
- Angular decorrelation of dijets, forward jets, transverse energy flow, needed to constrain the parton dynamics.

Dijets in ep



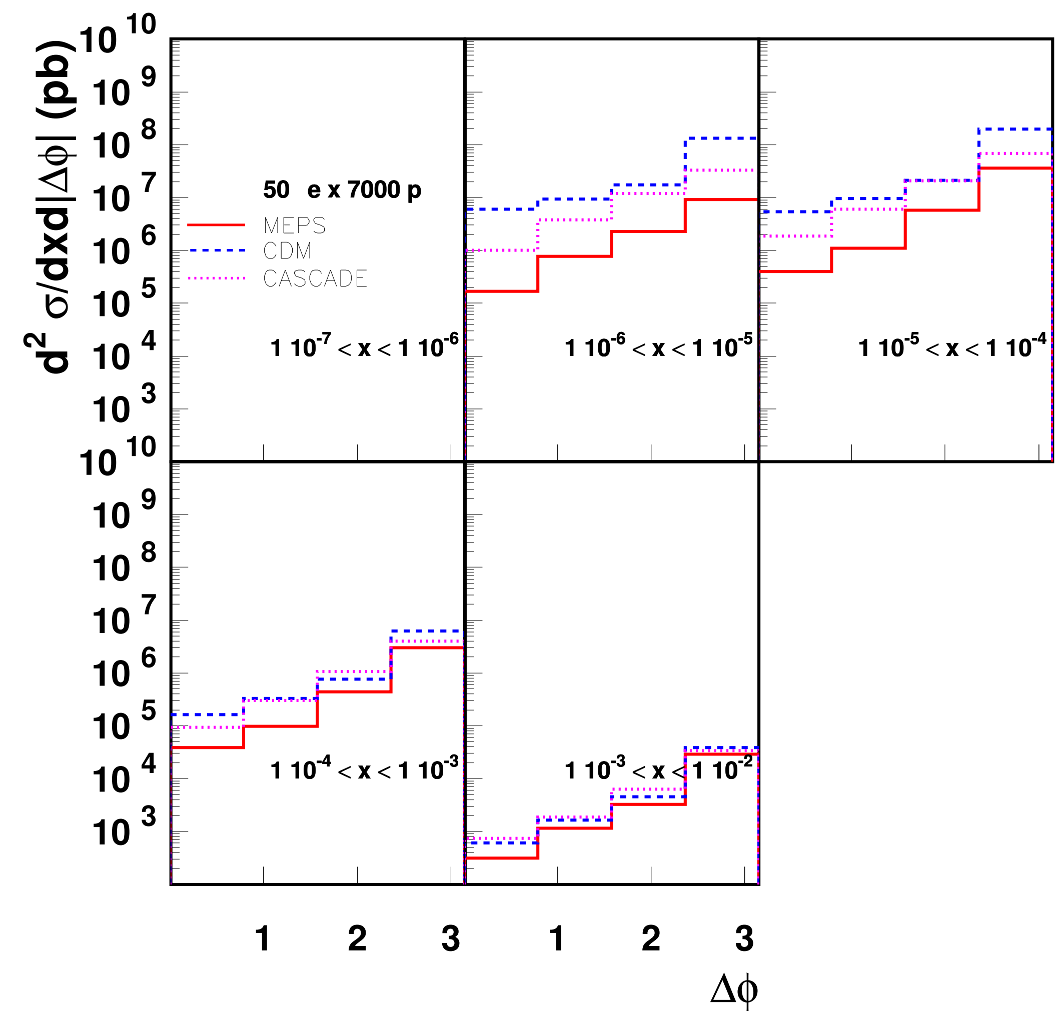


- Incoming gluon can have sizeable transverse momentum.
- Decorrelation of pairs of jets, which increases with decreasing value of x.
- Collinear approach typically produces narrow back-to-back configuration. Need to go to higher orders(NLO not sufficient).

$$-1 < \eta_{\rm jet} < 2.5 \qquad 0.1 < y < 0.6$$

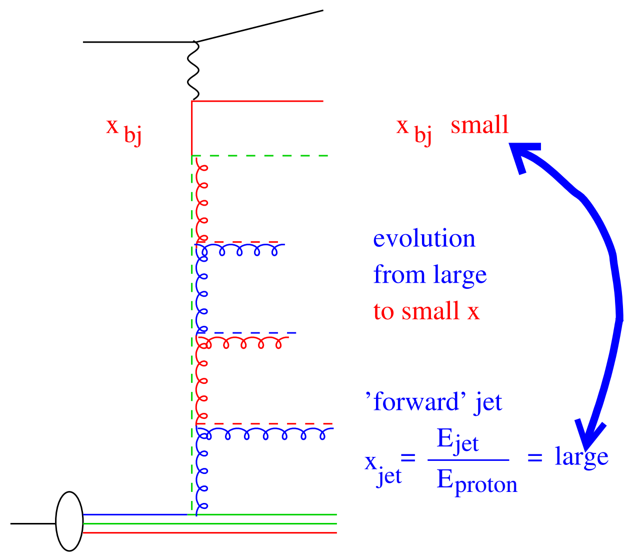
$$E_{1T} > 7 \text{ GeV} \qquad Q^2 > 5 \text{ GeV}^2$$

$$E_{2T} > 5 \text{ GeV}$$



- All simulations agree at large x.
- CDM, CASCADE give a flatter distribution at small x.

Forward jets



- Forward jet provides the second hard scale.
- By selecting it to be of the order of the photon virtuality, collinear configurations can be suppressed.
- Forward jet, large phase space for gluon emission.
- DGLAP typically underestimates the forward jet production.

Simulations for

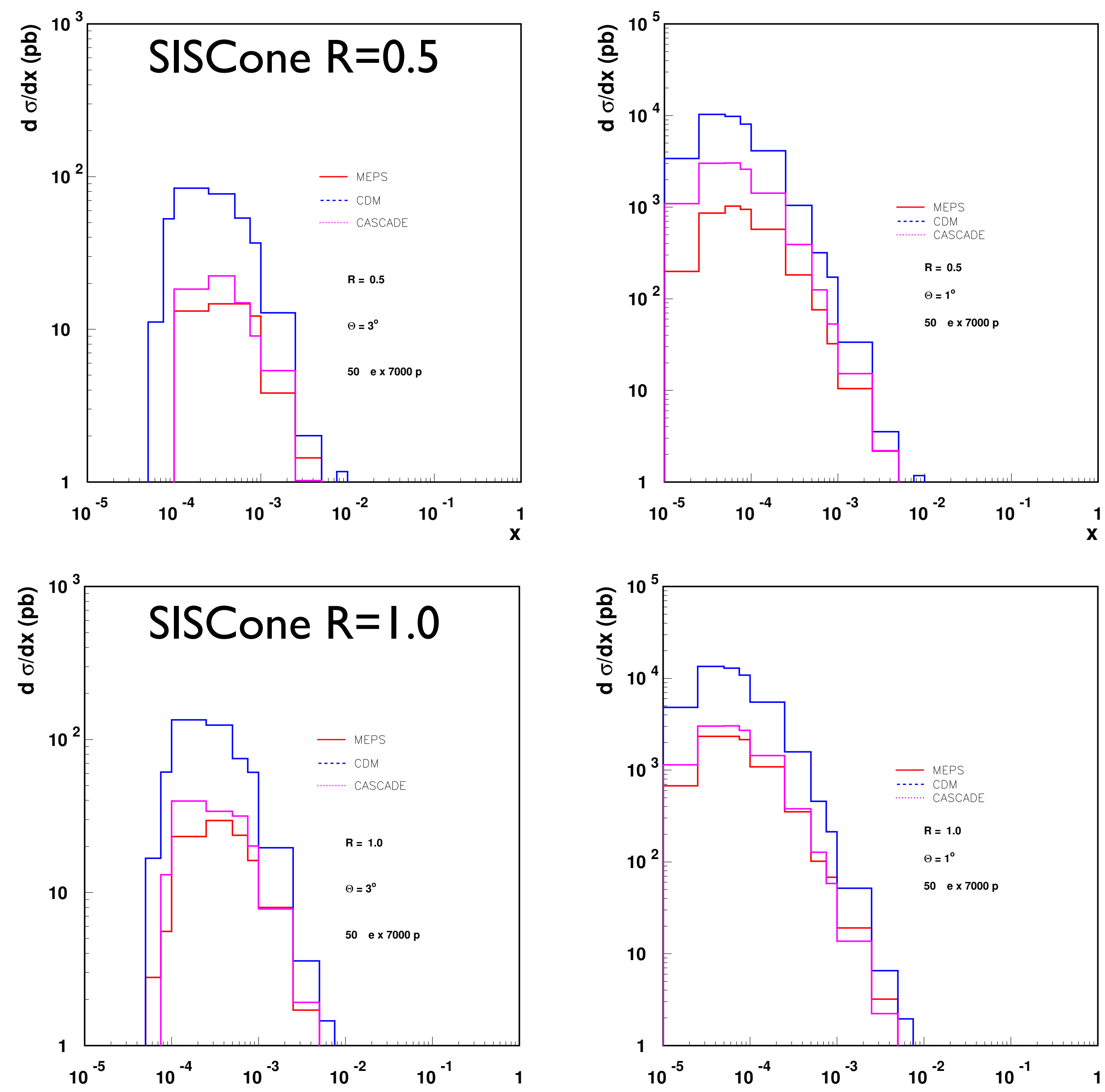
$\Theta > 3^o$ and $\Theta > 1^o$

Angular acceptance crucial for this measurement.

With $\Theta > 10^o$

all the signal for forward jets is lost.

Can explore also forward pions. Lower rates but no dependencies on the jet algorithms. Non-perturbative hadronisation effects included effectively in the fragmentation functions.



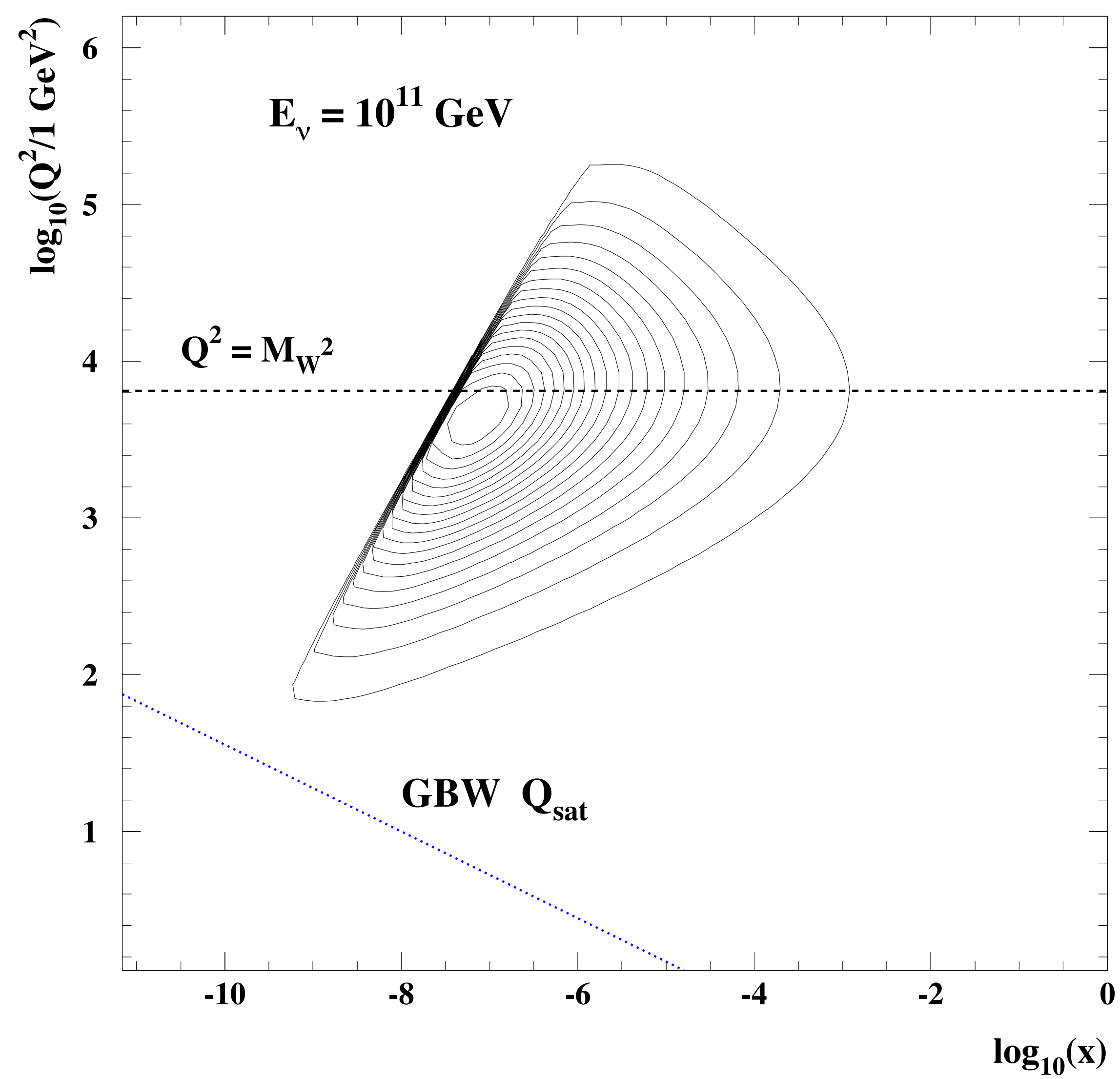
Relevance of LHeC for neutrino interactions

High energy neutrino interactions probe extremely small values of x

$$x \sim 10^{-8}$$

Smaller than constraints on pdfs from colliders

Contours enclose $5\%, 10\%, 15\%, \ldots$ contribution to the differential cross section $\dfrac{d^2\sigma^{\nu N}}{dx dQ^2}$



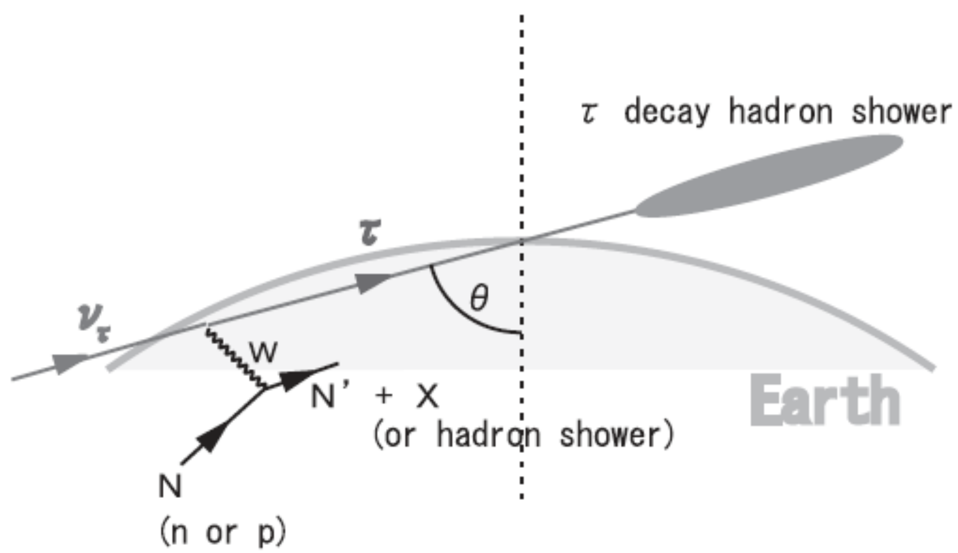
Cross section dominated by large Q

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

Relevant for UHE neutrino observatories ICECUBE

Relevance of LHeC for neutrino interactions

Oscillation enhance the possibility of direct observation of tau neutrinos at Earth. Short lifetime of tau, causes it to quickly decay in flight and produce a shower. Search for Earth skimming tau neutrinos



Energy loss of tau:

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

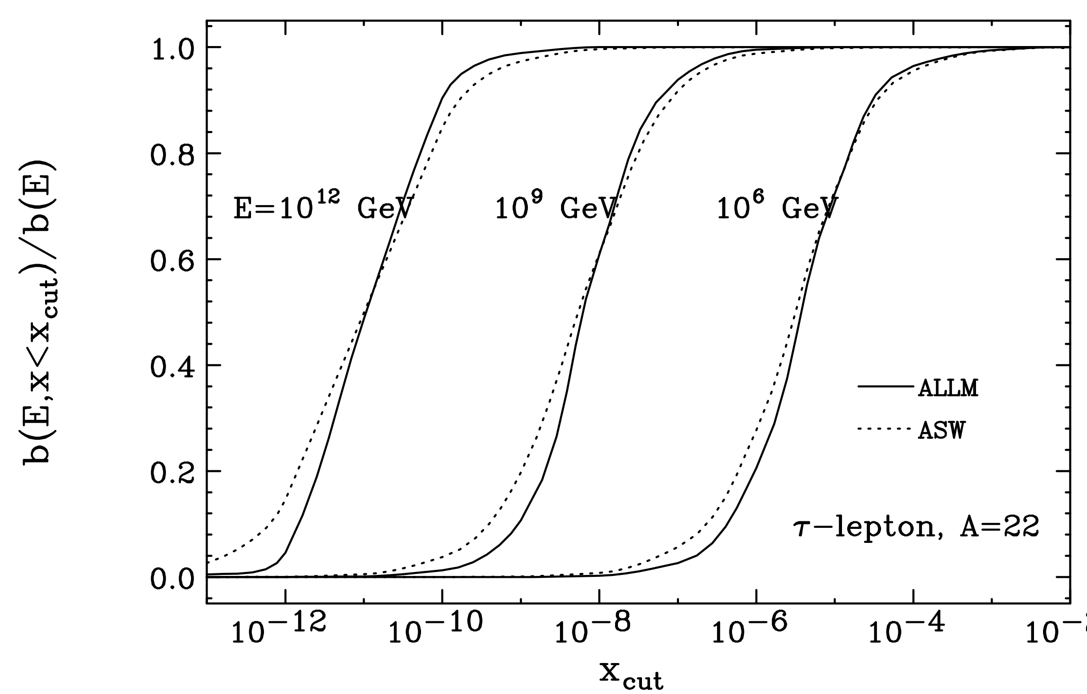
ionization

dominated by pair production, bremsstrahlung and photonuclear interactions

photonuclear contributions:

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

dominant at high energies



Armesto

Energy loss of tau again dominated by small x region.

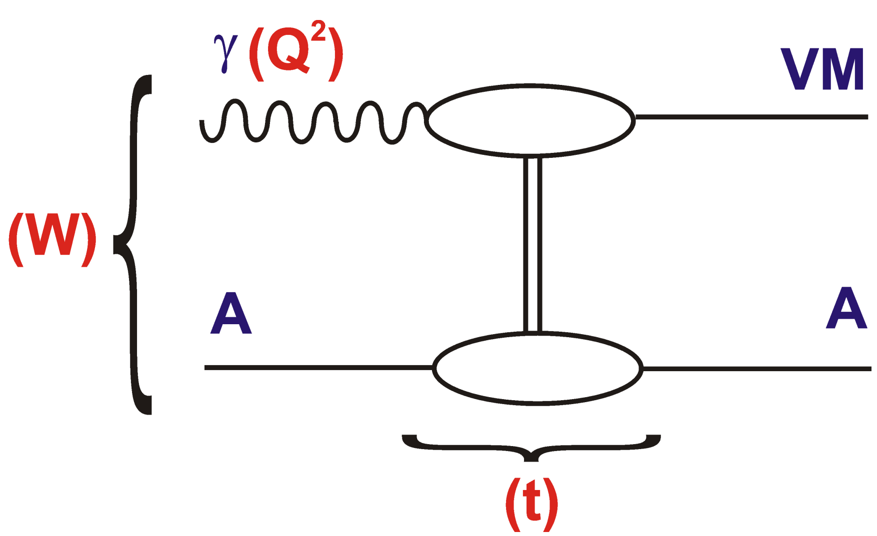
Summary

- LHeC has an unprecedented potential for exploring small x physics and high parton density regime.
- Precision measurement of inclusive structure functions provides constraint on the gluon density down to very low x. Constrain the nonlinear dynamics.
- Inclusive Diffraction: QCD factorization tests, diffractive parton densities, nonlinear effects. New domain of diffractive masses.
- Exclusive vector meson production and Deeply Virtual Compton Scattering: constraints on gluon and quark GPDs, impact parameter profile, saturation.
- Jets, ex. forward jets, dijets: probe of unintegrated parton densities (transverse momentum dependence) in a wide kinematic range.

Backup

Exclusive diffraction on nuclei

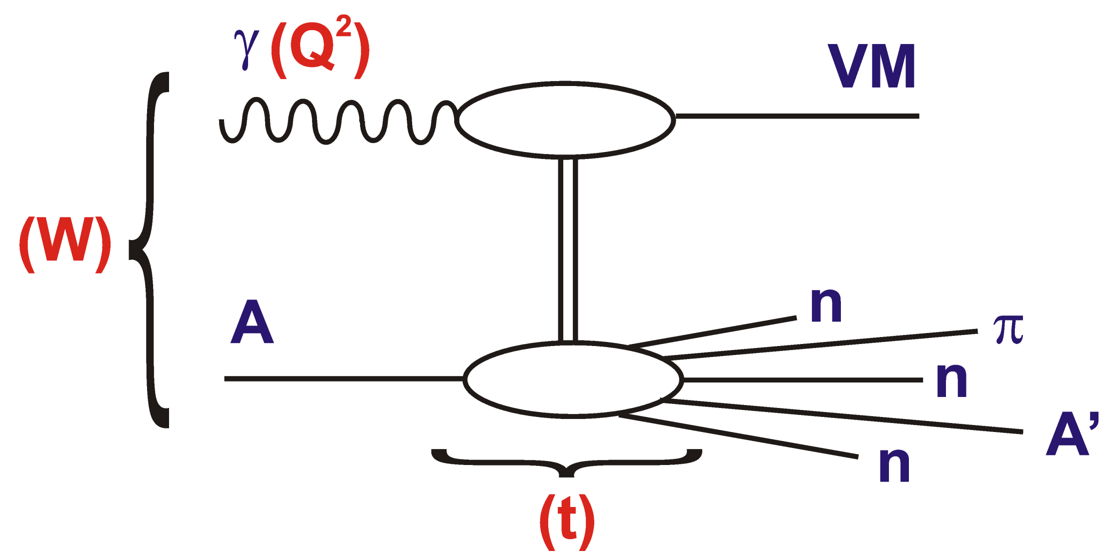
coherent



significant for

$$|t| < 0.02 \ \mathrm{GeV}^2$$

incoherent



$$0.05 < |t| < 0.7 \ \mathrm{GeV}^2$$

nuclear breakup into nucleons

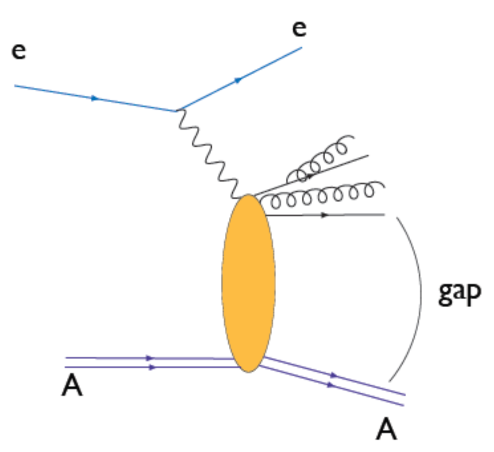
$$|t| > 0.7 \ \mathrm{GeV}^2$$

pion production
will become large

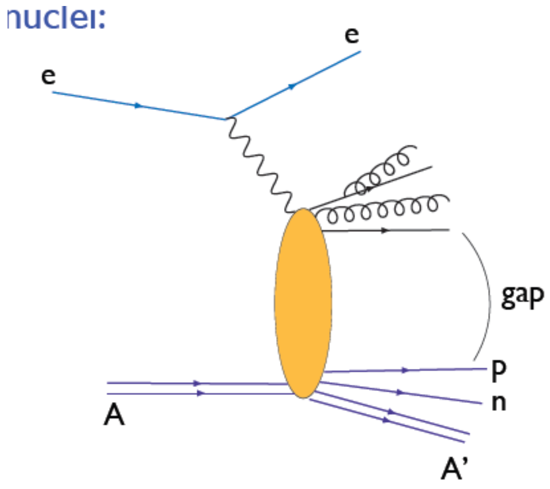
Resolving between these two requires forward instrumentation: Zero Degree Calorimeter

Inclusive diffraction in eA

Two types of events in the case of scattering off nuclei



coherent



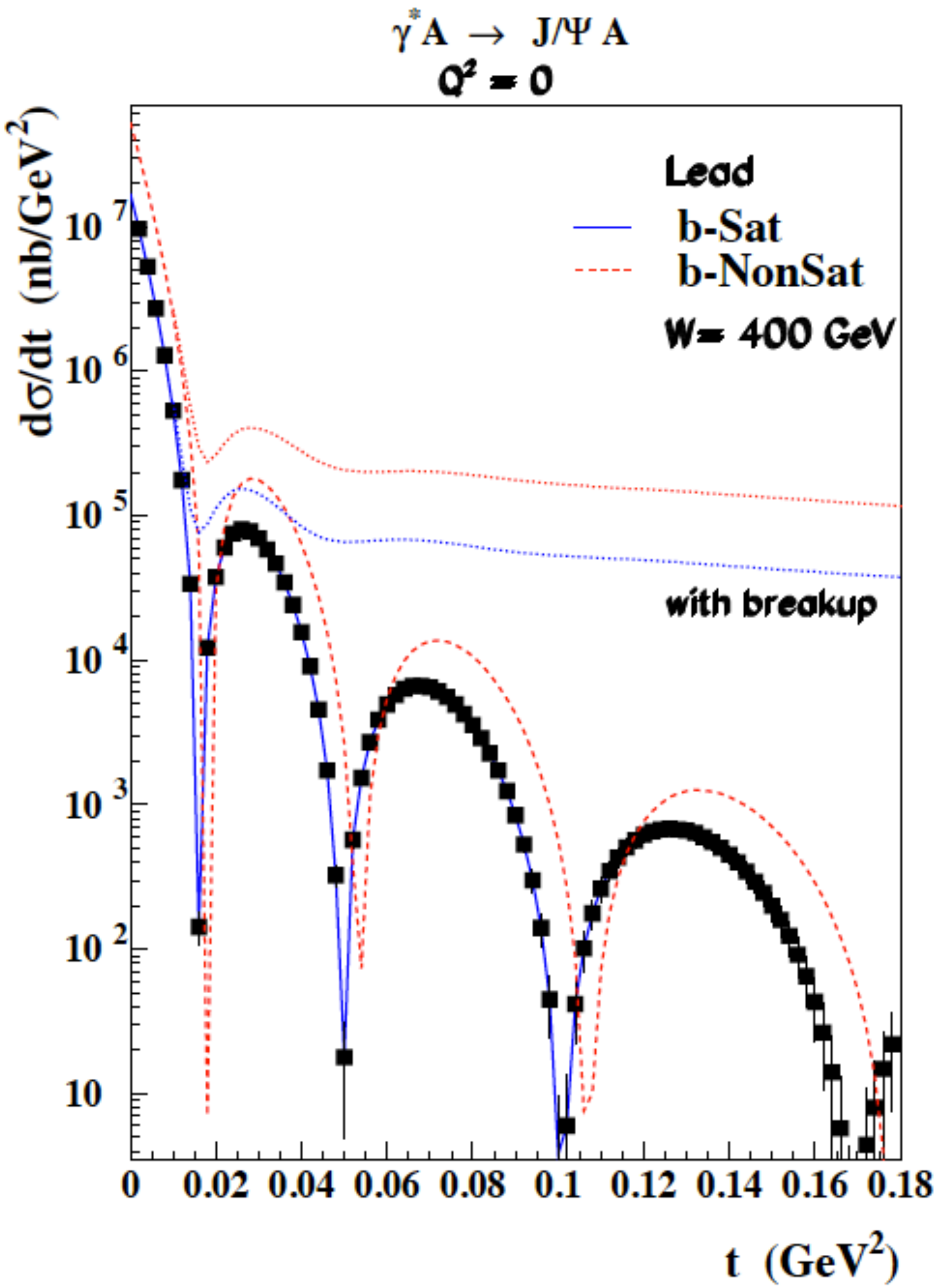
incoherent

Inclusive diffraction on nuclei is an unexplored area.

- Can one use factorization for the description of DDIS on nuclei?
- Impact parameter dependence?
- Relation between diffraction in ep and shadowing in eA.
- Current theoretical predictions vary a lot.

Exclusive diffraction on nuclei

Possibility of using this process to learn about the gluon distribution in the nucleus and its spatial distribution. Possible nuclear resonances at small t?



Incoherent production is dominant except for low |t|.

The dip structure is sensitive to details of the impact parameter profile.

Resolving the dips:

$$\Delta t = 2\sqrt{-t}\Delta p_T(J/\Psi)$$

$$\Delta p_T < 10 \text{ MeV}$$

$$\Delta t < 0.01 \text{ GeV}^2$$

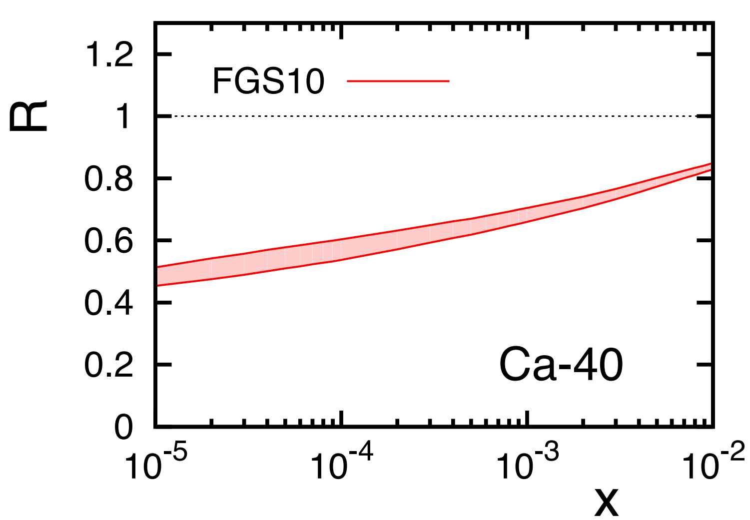
Exclusive diffraction on nuclei

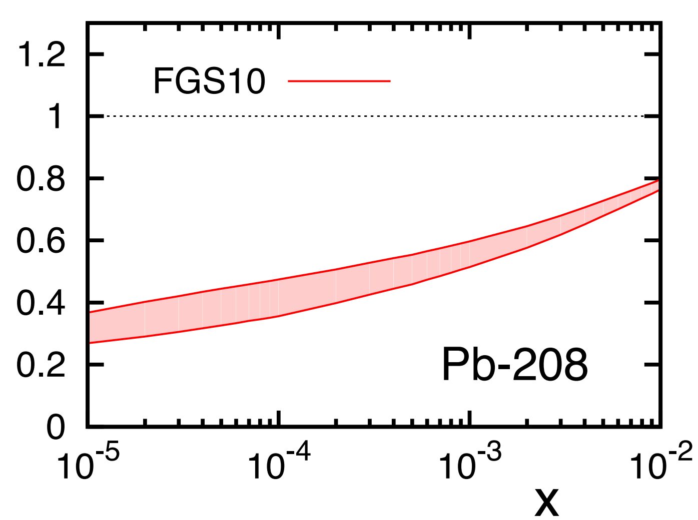
Forward t=0 coherent cross section provides also information about the gluon density in the nucleus.

Strong variation with energy and mass number A.

Large sensitivity to saturation and shadowing effects.

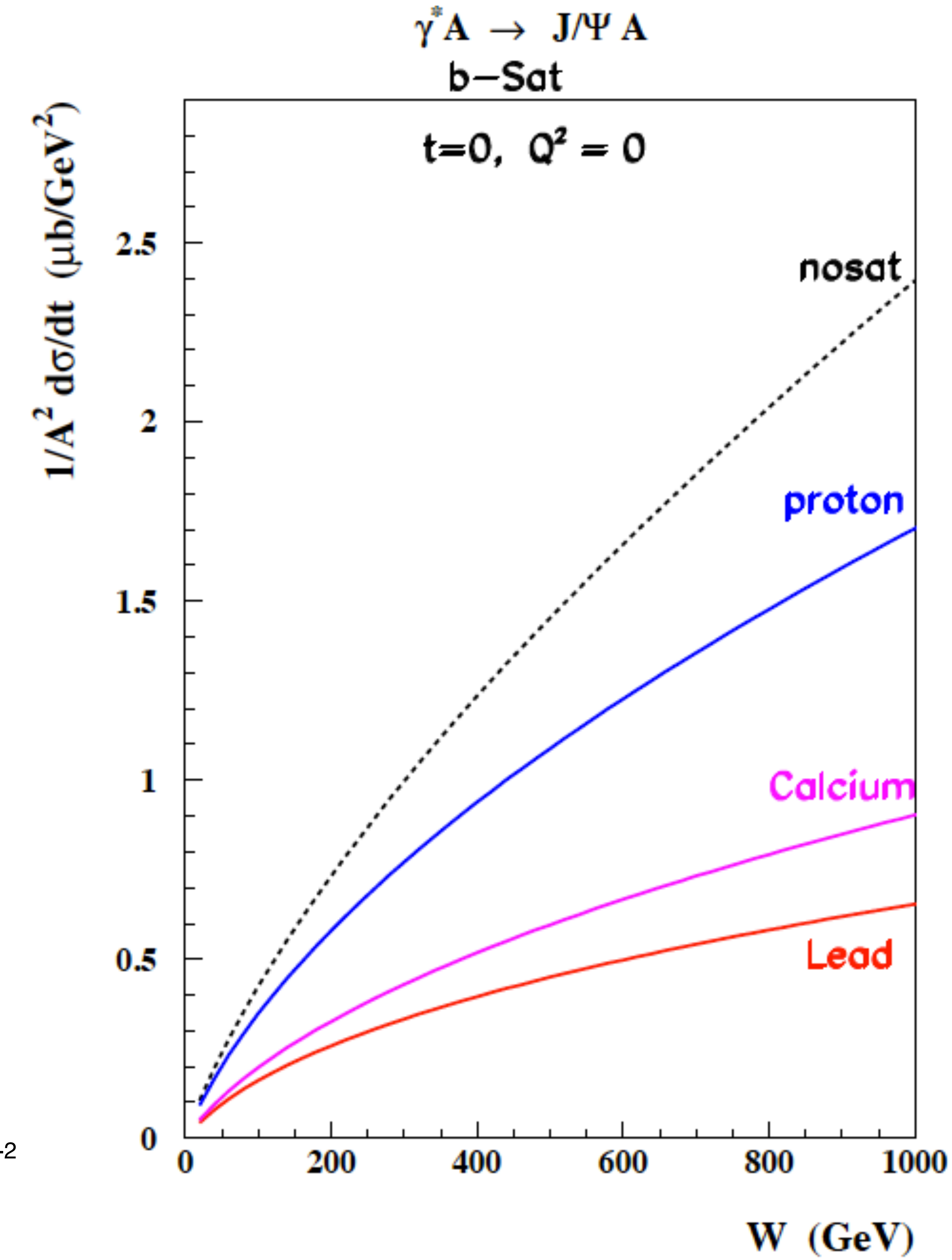
Nuclear modification ration for the gluon density squared.





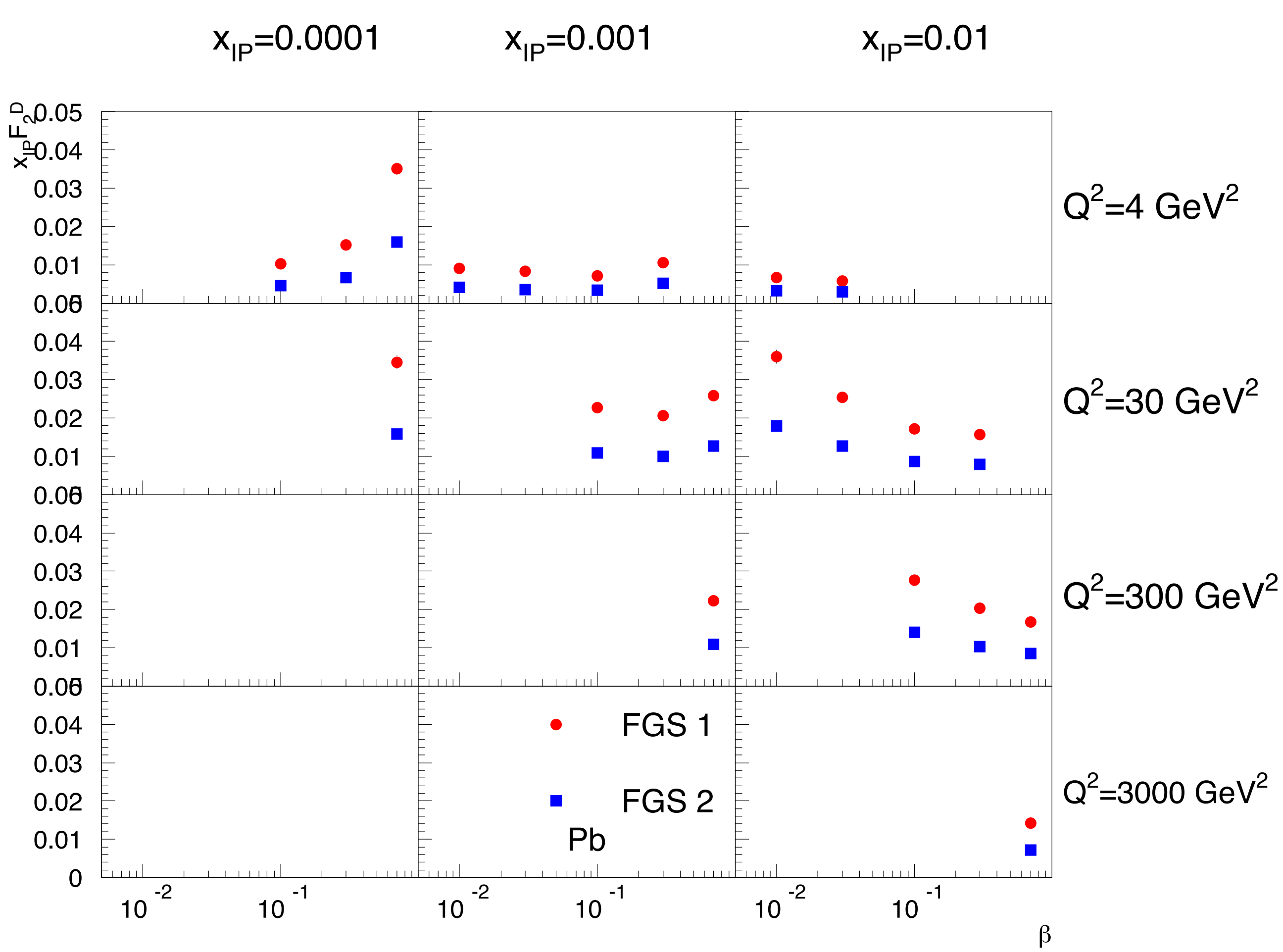
$$Q^2 = M_{J/\Psi}^2$$

Energy dependence for different targets.

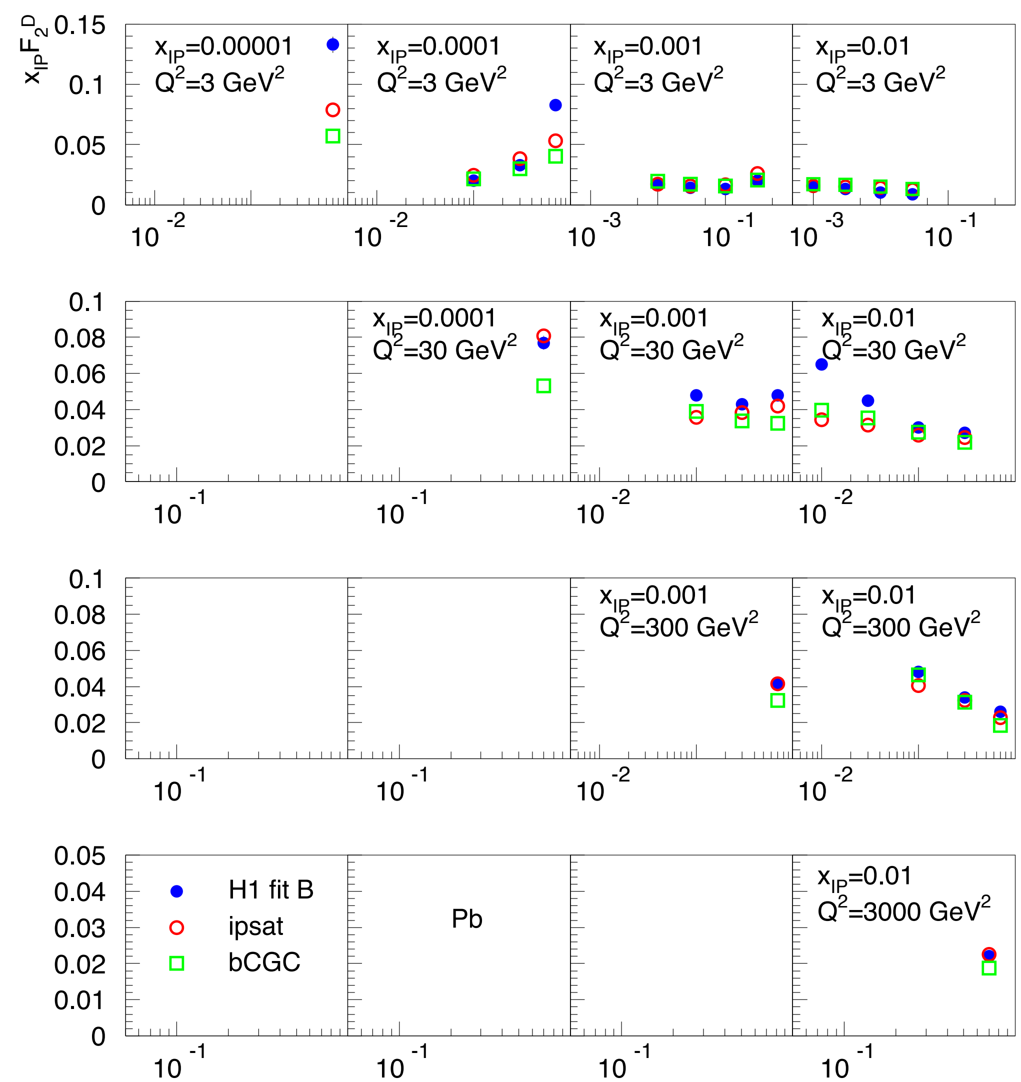


Diffractive structure func. in eA

Diffractive structure function for Pb



Frankfurt, Guzey, Strikman. Model based on leading twist shadowing.

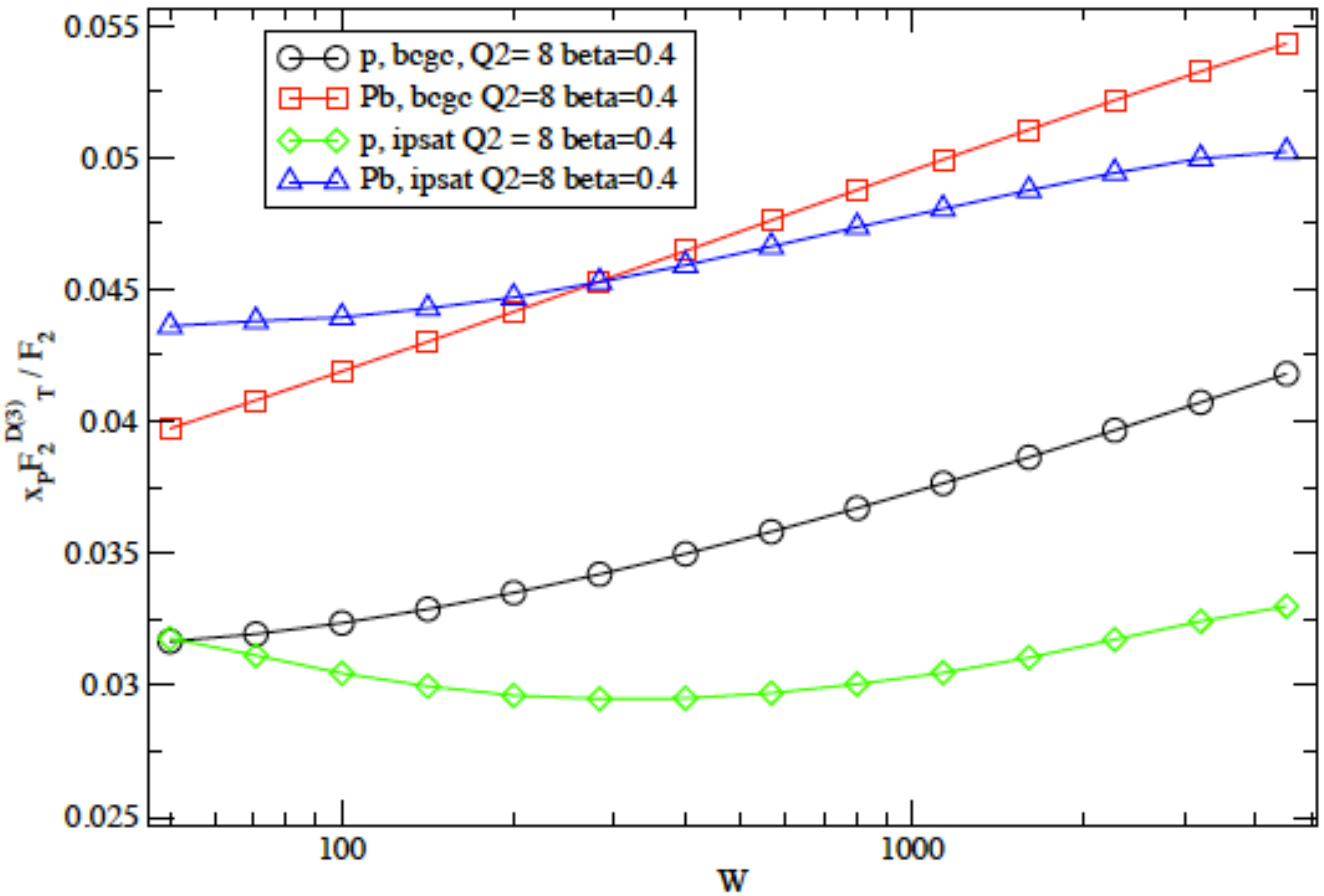


Kowalski, Lappi, Marquet, Venugopalan. Dipole model and Color Glass Condensate.

Models differ a lot in magnitude between the different scenarios within one framework as well as between different frameworks.

Diffractive structure func. in ep/eA

Diffractive to inclusive ratio for protons and Pb



The constant diffractive/total ratio as a function of W can be explained in saturation models: in the black disk limit the energy dependencies approximately cancel in diffractive/total ratio.

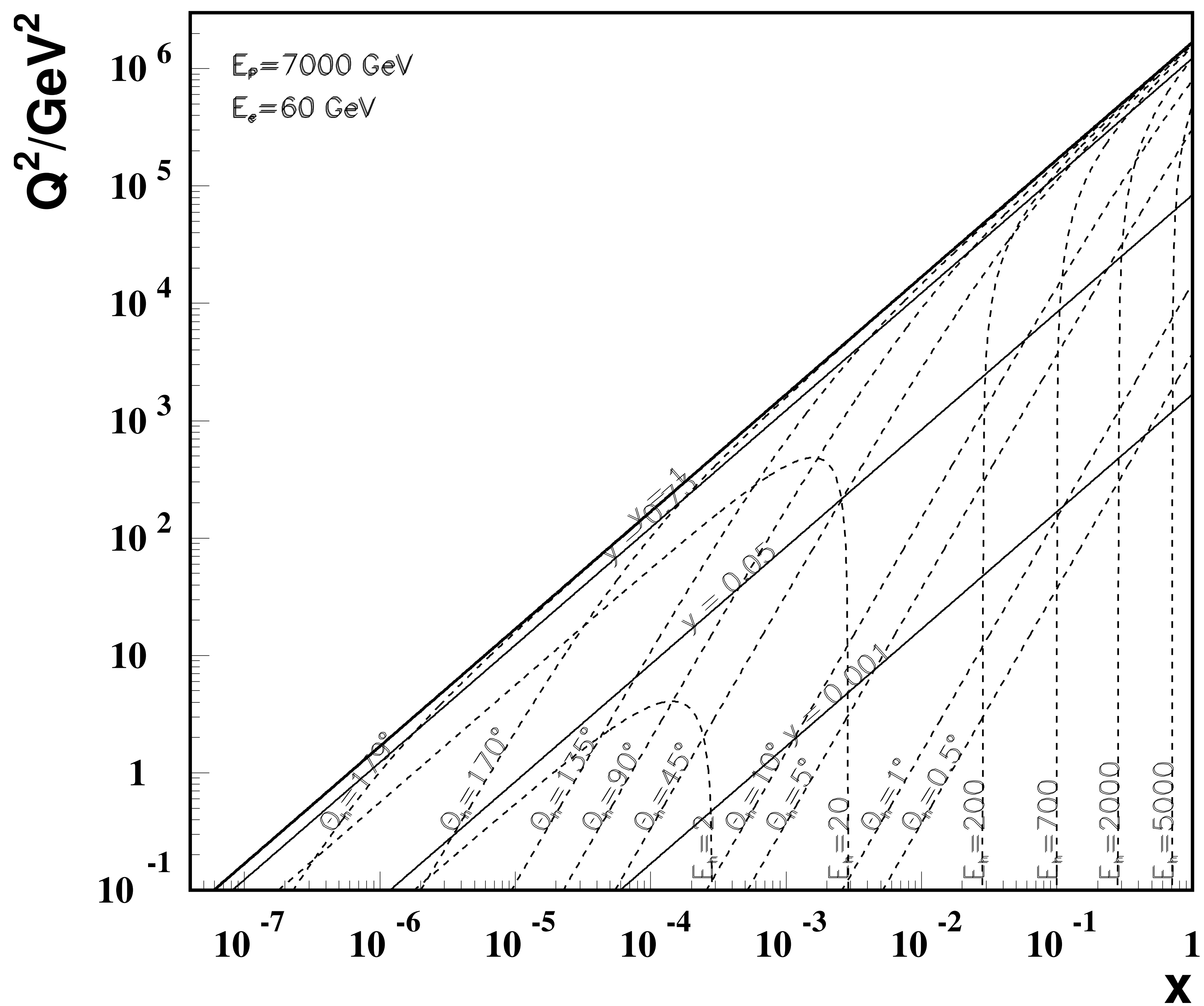
Models incorporate saturation but show variation with energy. Large differences between models. Very large sensitivity due to lack of impact parameter information.

Enhanced diffraction in the nuclear case.

LHeC can provide here essential information on the saturation limit in ep/eA and constrain impact parameter dependence.

LHeC kinematics: acceptance

Kinematics in ep



$$Q^2\ (x, \theta_{h,min}) \simeq [2E_p x \tan^2(\theta_{h,min}/2)]^2,$$

Similarly access to large x requires angle acceptance of hadrons down to 1 degree.

Photoproduction cross section

- Photoproduction cross section.

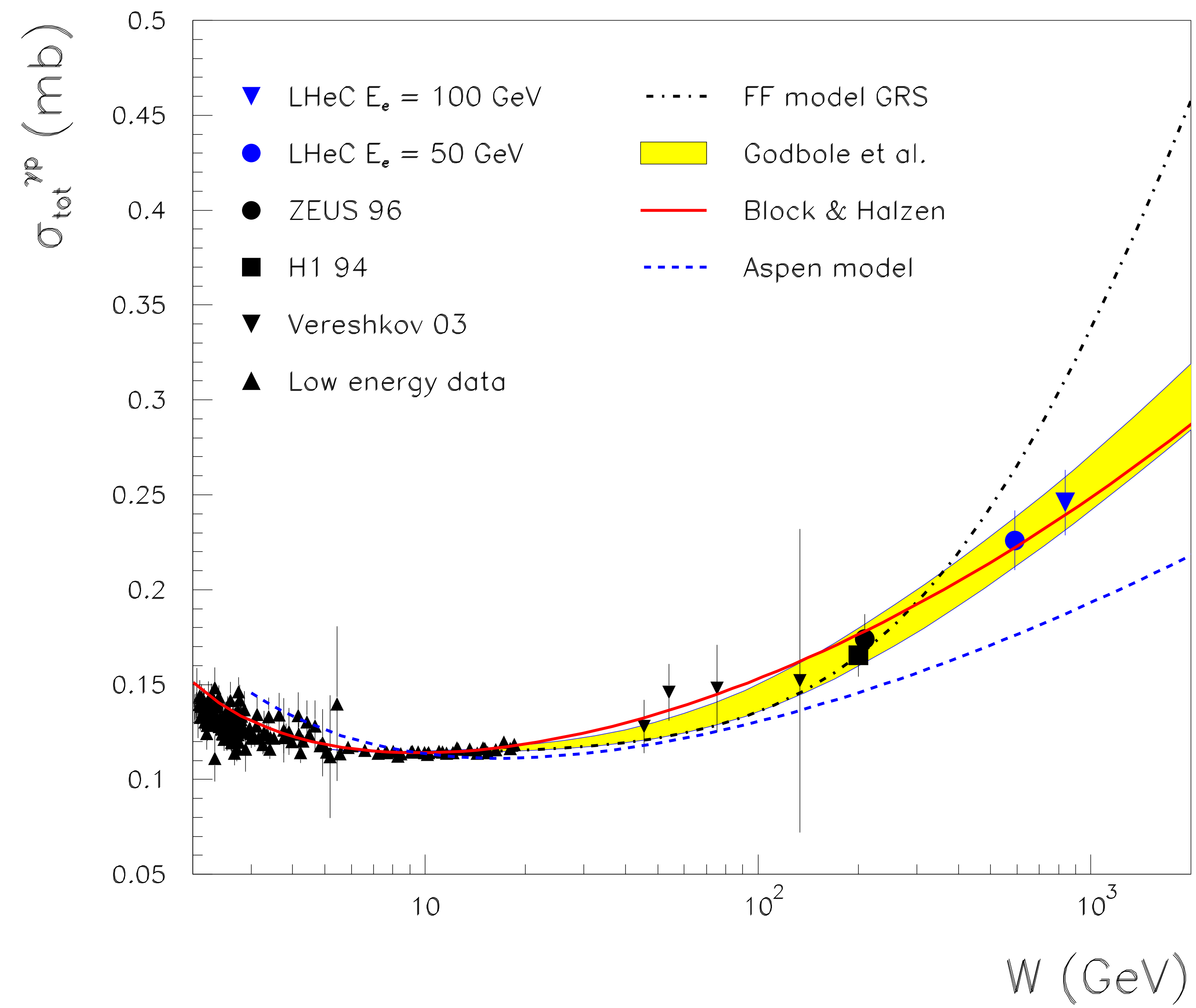
- Explore dual nature of the photon: pointlike interactions or hadronic behavior.

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

- Large divergence of the theoretical predictions beyond HERA measurements.

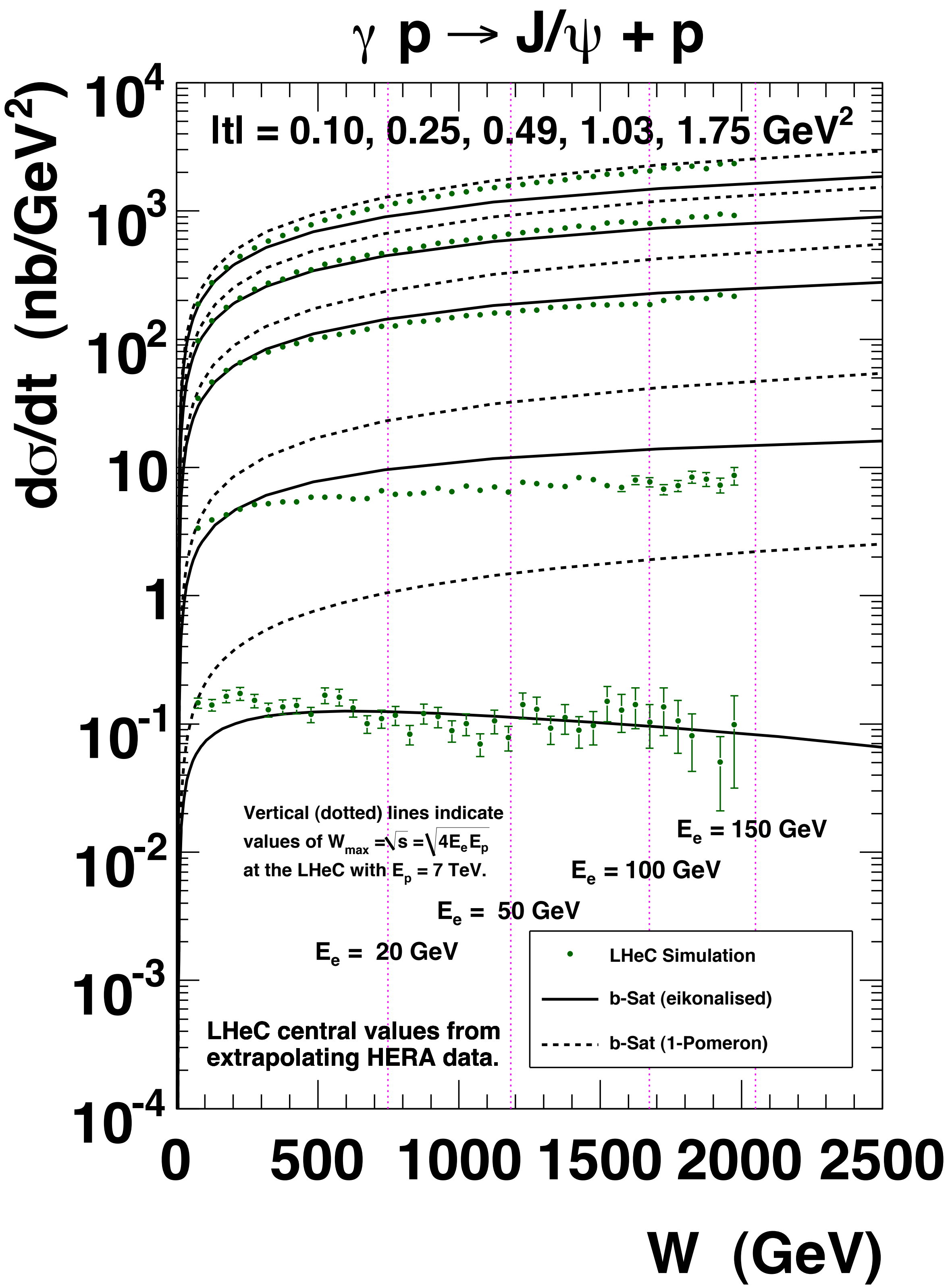
- Dedicated detectors for small angle scattered electrons at 62m from the interaction point.

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



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

Exclusive diffraction: t-dependence



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.