Diffraction and forward physics in ep collisions at the LHeC

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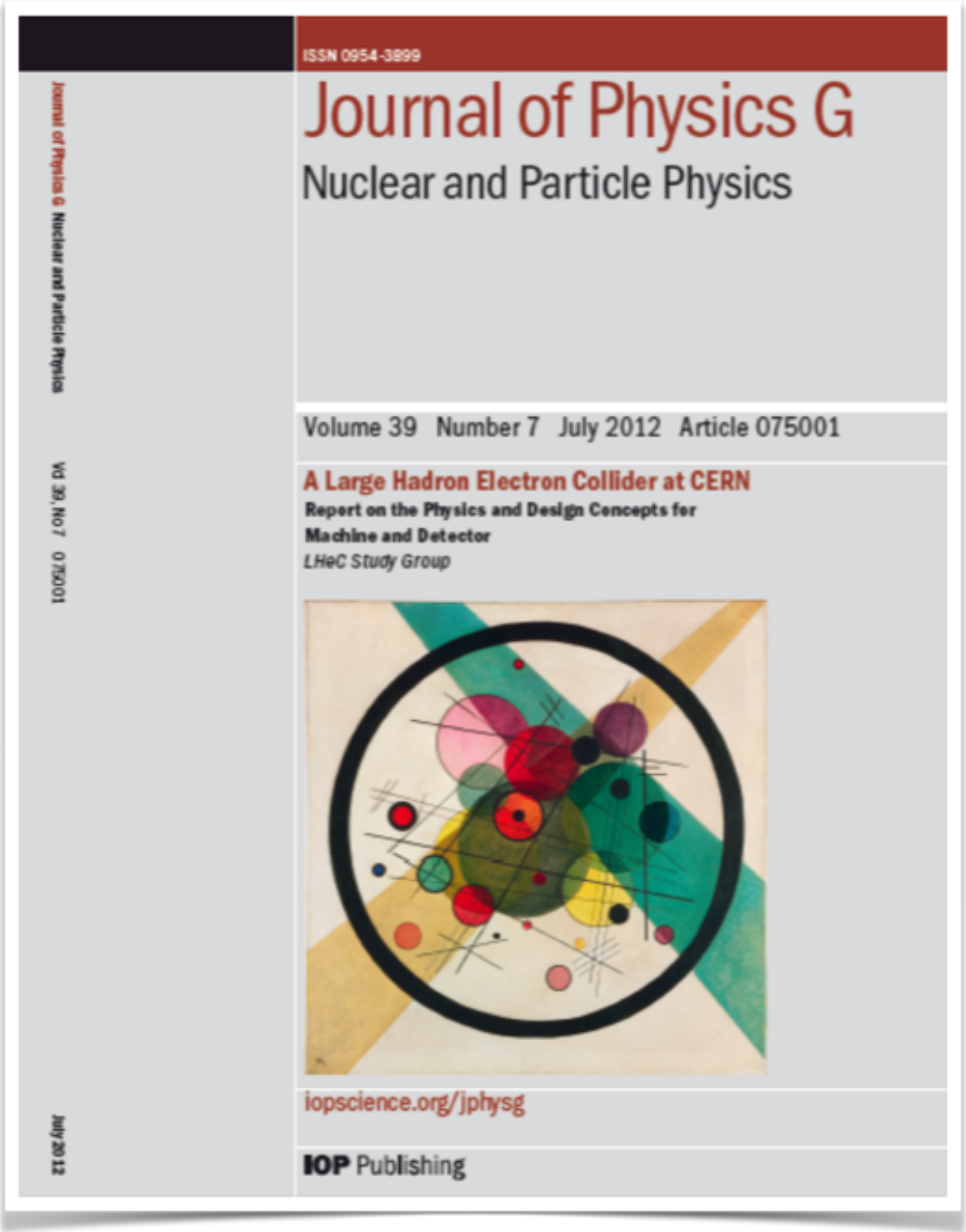
LHeC Conceptual Design Report



Forward Physics?

- Diffraction (obviously)
- Small *x* (cf. LHC)

This talk:

Physics at High Parton Densities

- Physics at small *x*
- Jet and multi-jet observables
- Inclusive diffraction
- Exclusive production

Disclaimer:
Lots of material taken from LHeC CDR
Refer to ~200 authors and 900+ bibliography contained therein

Physics at small *x*

QCD description of hadronic scattering

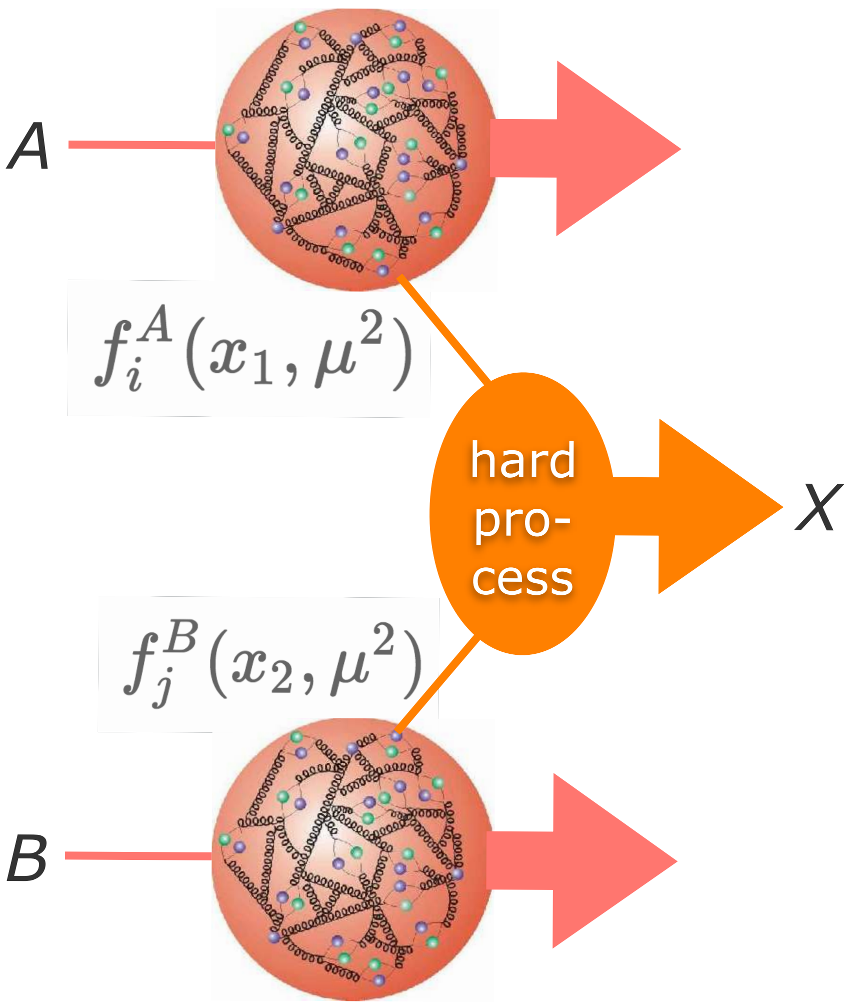
Fixed-order perturbation theory and collinear factorization

- factorization of weak and strong coupling dynamics:

matrix element @ LO, NLO, ...

$$\sigma_{pp} = f_i^A(x_1, \mu^2) \otimes \hat{\sigma}(i + j \to X) \otimes f_j^B(x_2, \mu^2)$$

Parton Density Functions (PDFs) with evolution driven by DGLAP equations: $f(x,Q^2)$ determined by $f(x_0>x, Q_0^2<Q^2)$



- collinear factorization: PDFs do not depend on parton transverse momentum $k_T \Rightarrow$ also X must be collinear with the incoming protons
- leading twist: a single parton is picked from the proton
- valid for hard momentum scales and hadrons consisting of a dilute set of partons

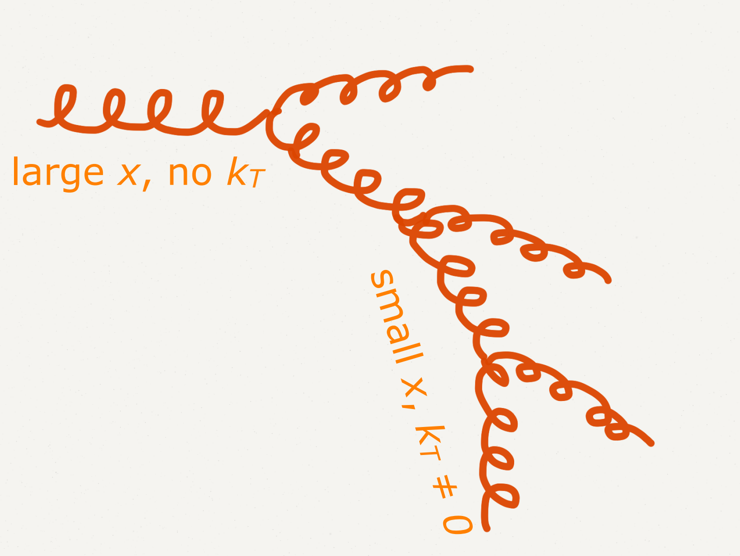
➡ **works well for inclusive cross sections!**

Implementation in Monte Carlo models

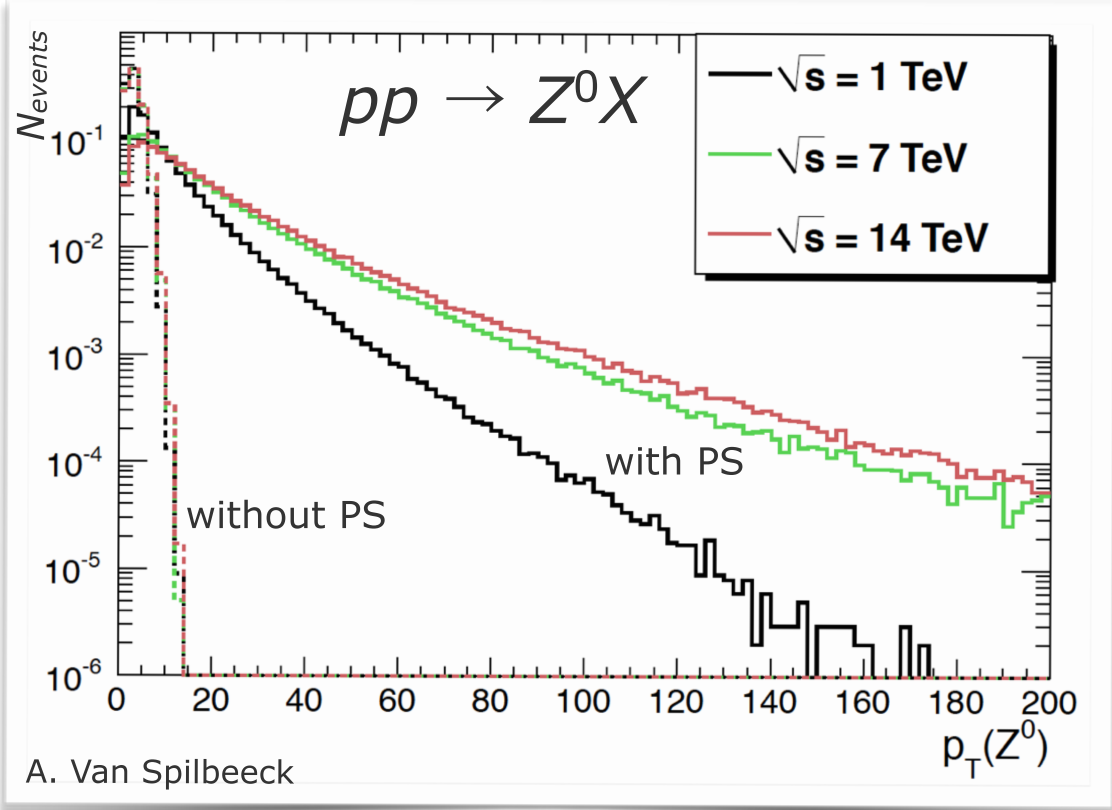
Parton Showers add transverse momentum to the final state!

- high-x partons at the starting scale radiate secondary partons via parton showers
- parton looses longitudinal momentum (decreases x) and gains transverse momentum k_T
- transverse momentum enters hard scattering system and produces final state X with p_T
- PDF4MC: possible to extract a k_T dependent PDF from DGLAP Parton Showers

$$\rightarrow f(x, k_T^2, \mu^2)$$



- in pure collinear factorization, this can only be achieved with NLO matrix elements (e.g. qg → Zq) ⇒ k_T dependent PDFs contain some higher order effects already at LO

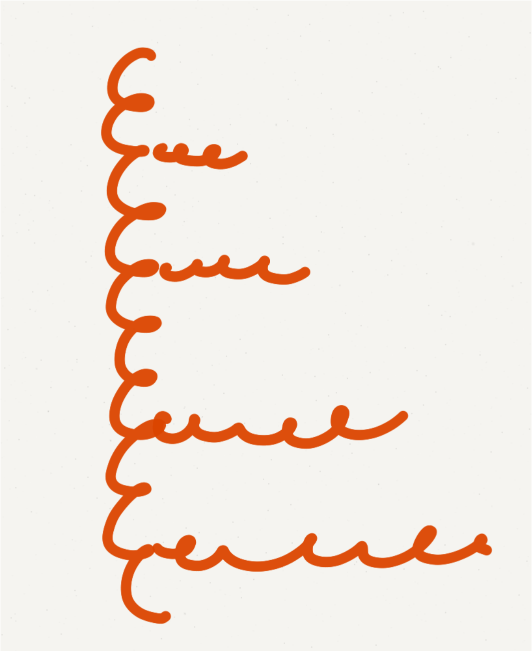


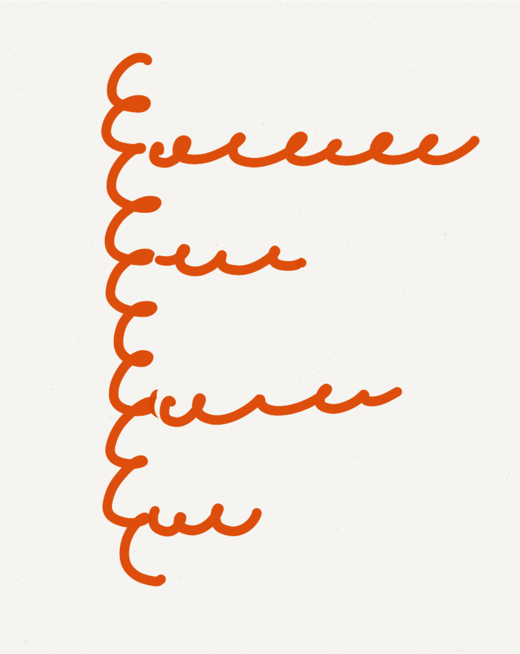
➡ ***k_T* dependent PDFs are essential in order to describe the detailed *p_T* structure of the final state**

Parton evolution schemes

DGLAP

- Valid for medium to large x, large Q^2
- Contributions leading in $\log(Q^2)$
- Parton showers strongly ordered with increasing k_T





BFKL

- Valid for low x, medium Q^2
- Re-summation of $\log(1/x)$ terms to all orders in α_S
- Parton showers exhibit random walk in k_T

  $\Rightarrow$ diffusion of k_T towards small x
- BFKL naturally incorporates unintegrated PDFs!

➡ **Any approach using unintegrated PDFs calls for a precise measurement of semi-inclusive processes in a wide kinematic range**

Saturation

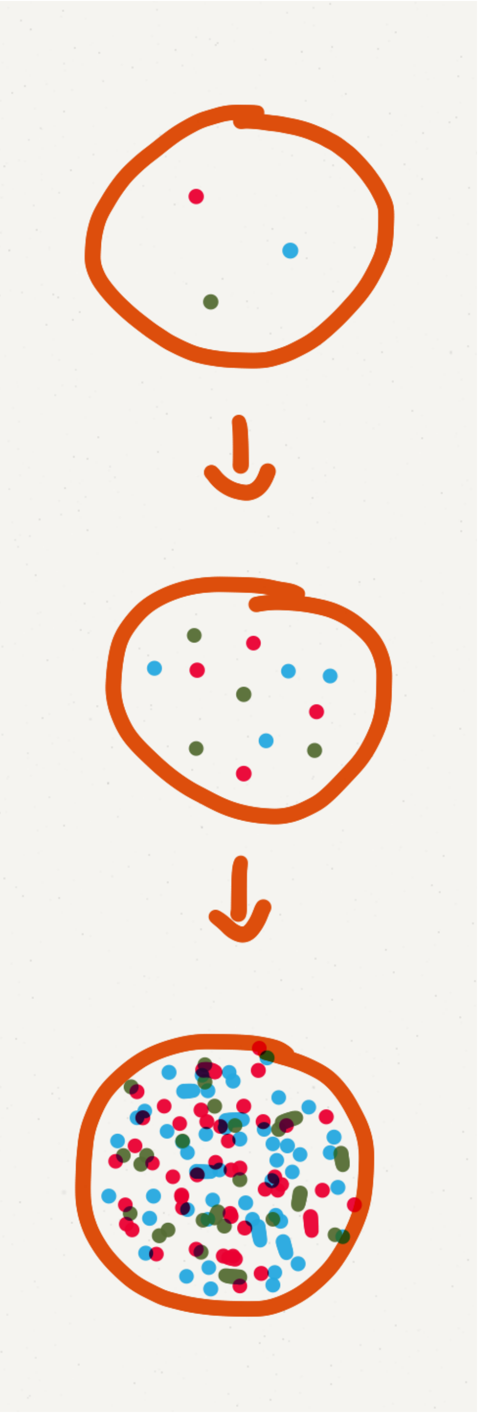
HERA: proton becomes increasingly densely packed!

- Parton densities from HERA exhibit a strong rise towards low x and fixed Q^2

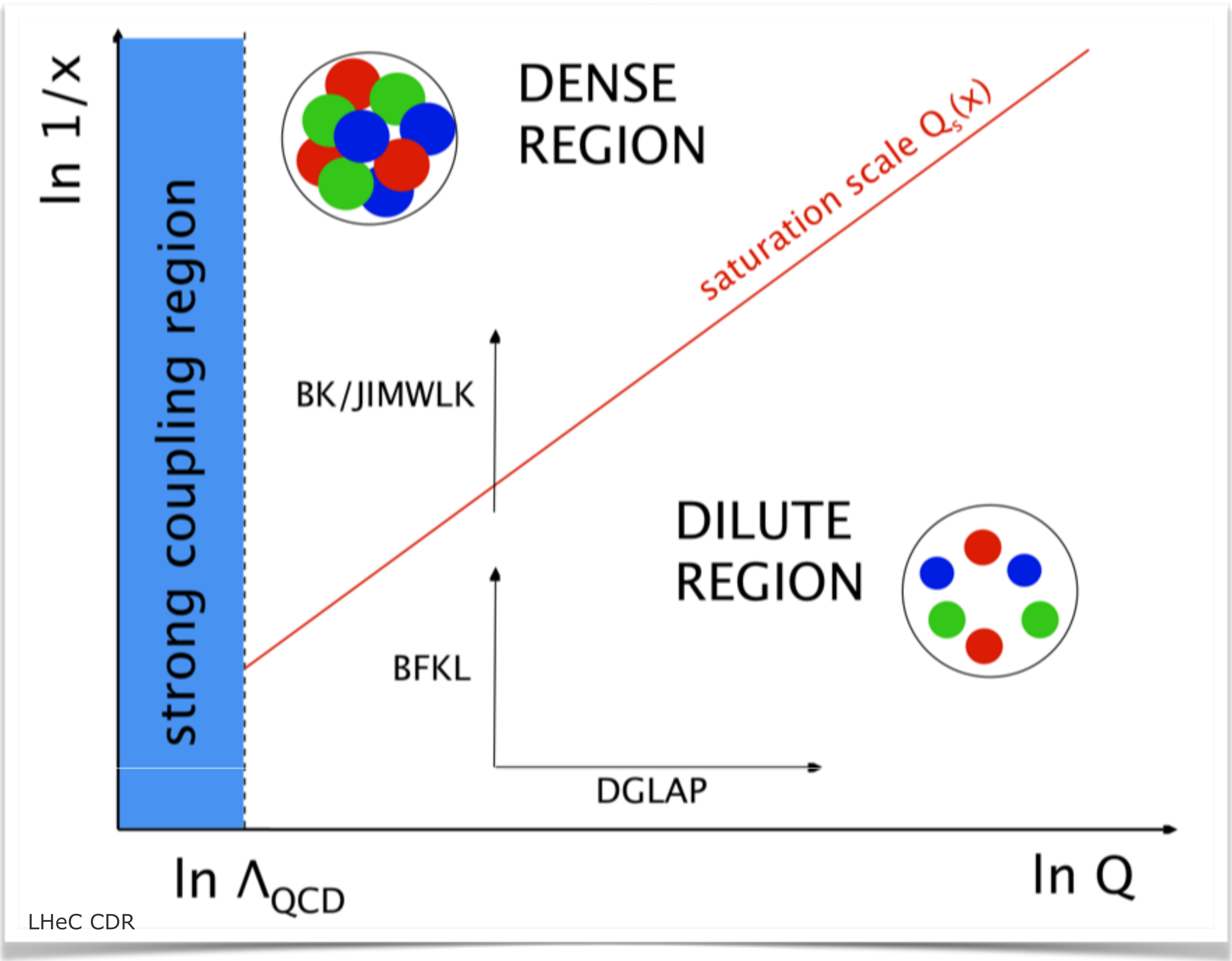
  ⇒ this will eventually violate unitarity
- Non-linear evolution must eventually become relevant and parton densities must saturate
- Parton recombinations will lead to non-linear terms in evolution equations
- Note: Q^2 is still large and the coupling is still weak

  ⇒ parton level understanding of dense limit of QCD
- Saturation scale: defined by packing factor ~ 1

$$\frac{\text{density}}{\text{unit transverse area}} \sim 1 \quad \Rightarrow \quad \frac{xg(x, Q_s^2)}{Q_s^2} \sim 1 \quad \Rightarrow \quad Q_s^2 \sim Q_0^2 \left(\frac{1}{x}\right)^{\lambda}$$



QCD phase diagram

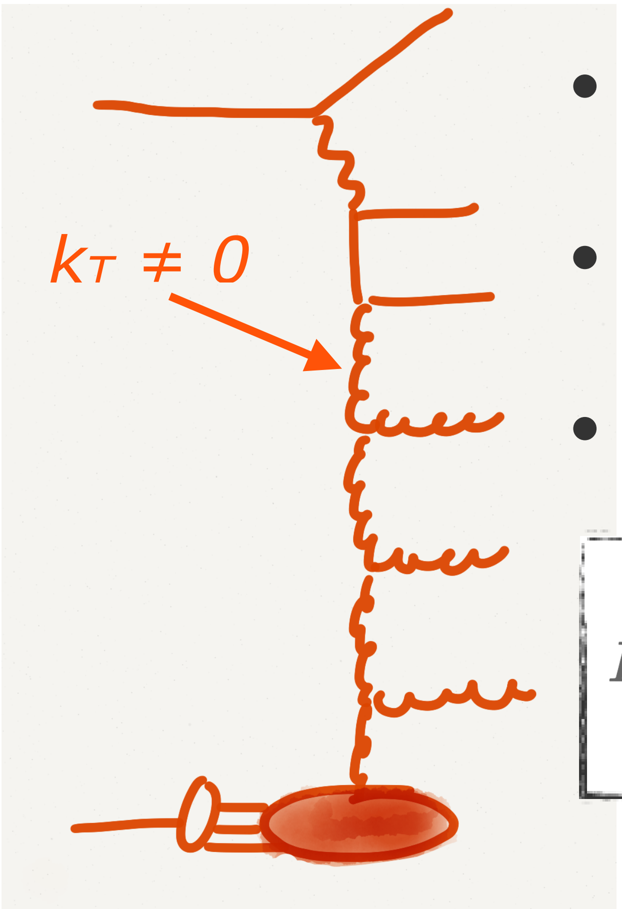


➡ **What is the interplay between re-summation (BFKL) and non-linear effects?**

Jet and multi-jet observables

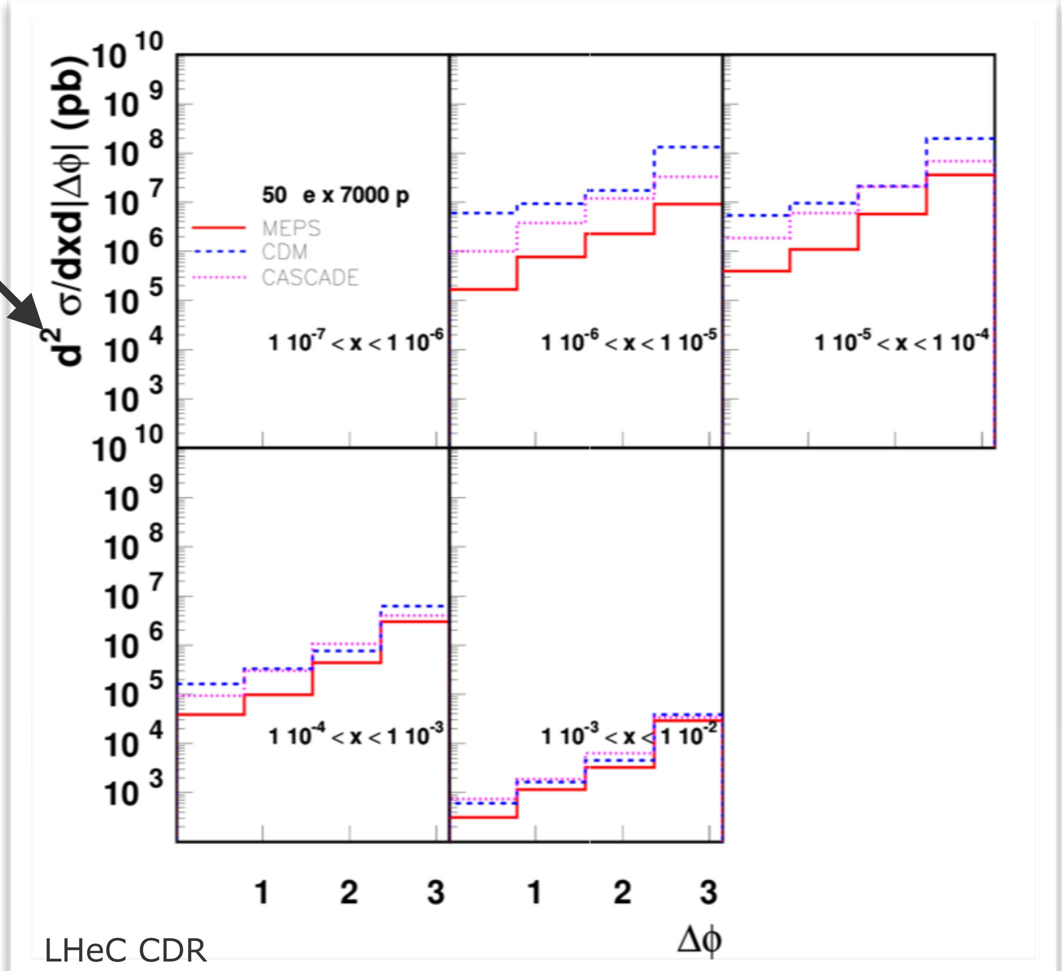
Dijet azimuthal de-correlation

Effect of parton transverse momentum



- Jets are back-to-back if no k_T is entering the hard scattering system
- A small x, gluons may gain sizable k_T through diffusion along the gluon chain
- De-correlation becomes visible in azimuthal separation $\Delta\varphi$

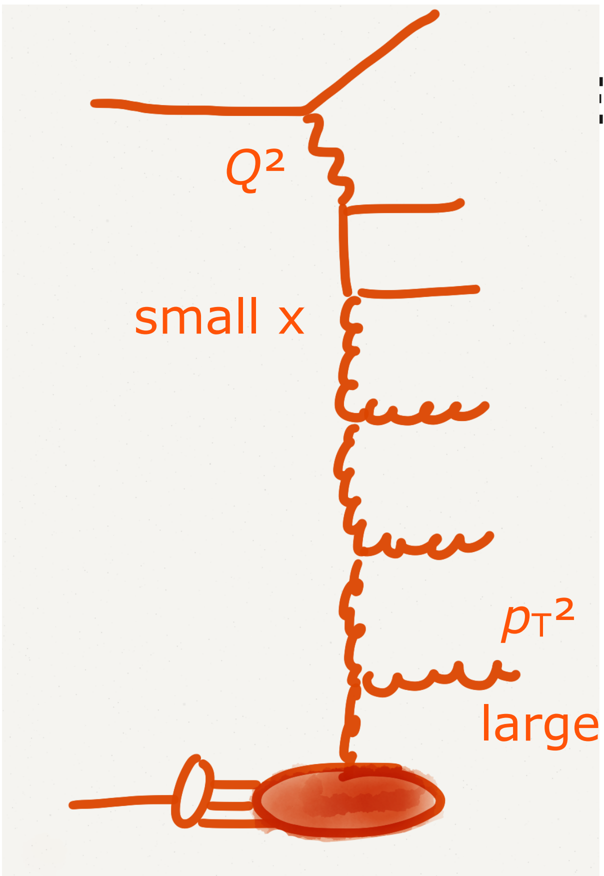
$$-1 < \eta_{\text{jet}} < 2.5,$$
$$E_{\text{T,jet1}} > 7\ \text{GeV}, E_{\text{T,jet2}} > 5\ \text{GeV},$$
$$0.1 < y < 0.6, Q^2 > 5\ \text{GeV}^2$$



- MEPS: O(α_S) ME+DGLAP parton showers
- CDM: Color Dipole Model, includes some diffusion in k_T
- CASCADE: off-shell matrix elements+CCFM
- Discrepancies become visible at low x

➡ **Azimuthal de-correlation offers direct determination of k_T-dependence of the unintegrated PDF**

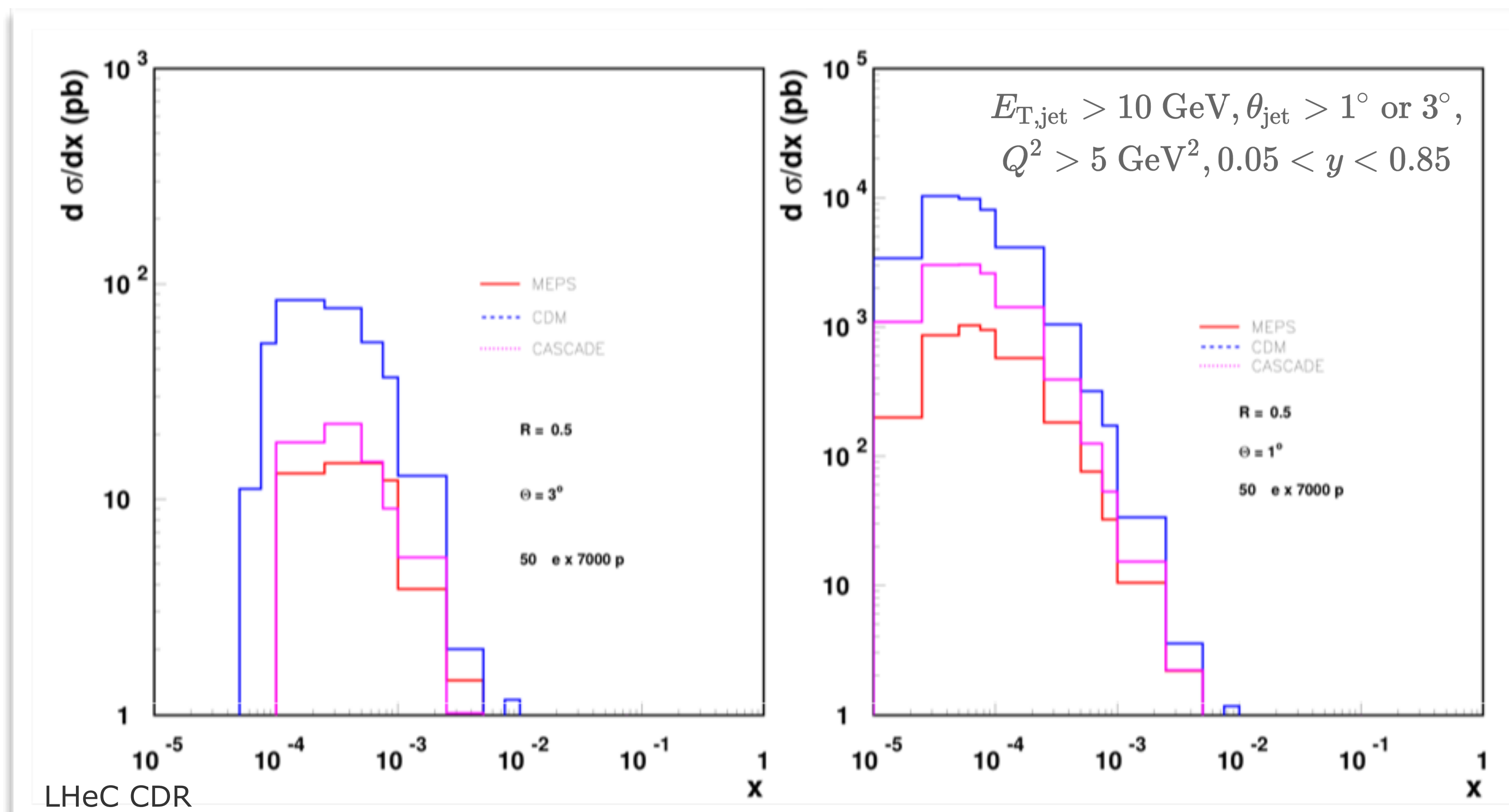
Forward jets



Effect of parton showers unordered in k_T

- $Q^2 \sim p_T{}^2 \Rightarrow$ suppress collinear (DGLAP) configurations
- Jet longitudinal momentum fraction x_J as large as possible and x/x_J as small as possible $\Rightarrow$ select BFKL phase space
- From HERA we know that standard DGLAP fails to describe the forward jet cross section

- LHeC will allow to systematically cover full phase space in x, Q^2 and p_T
- Lowest x is explored with small angle scenario for detector acceptance
- Large differences between MEPS, CDM and CASCADE



Di-hadron correlations

Effect of saturation

- Semi-inclusive di-hadron production

  ⇒ angular correlation function:

$$C(\phi_{12}) = \frac{1}{d\sigma(\gamma^* N \to h_1 X)/dz_{h1}} \frac{d\sigma(\gamma^* N \to h_1 h_2 X)}{dz_{h1} dz_{h2} d\phi_{12}}$$

$$p_{\mathrm{T,h1}} > 3\ \mathrm{GeV}, p_{\mathrm{T,h2}} > 2\ \mathrm{GeV},$$
$$z_{\mathrm{h1}} = z_{\mathrm{h2}} = 0.3,$$
$$Q^2 = 4\ \mathrm{GeV}^2, y = 0.7$$

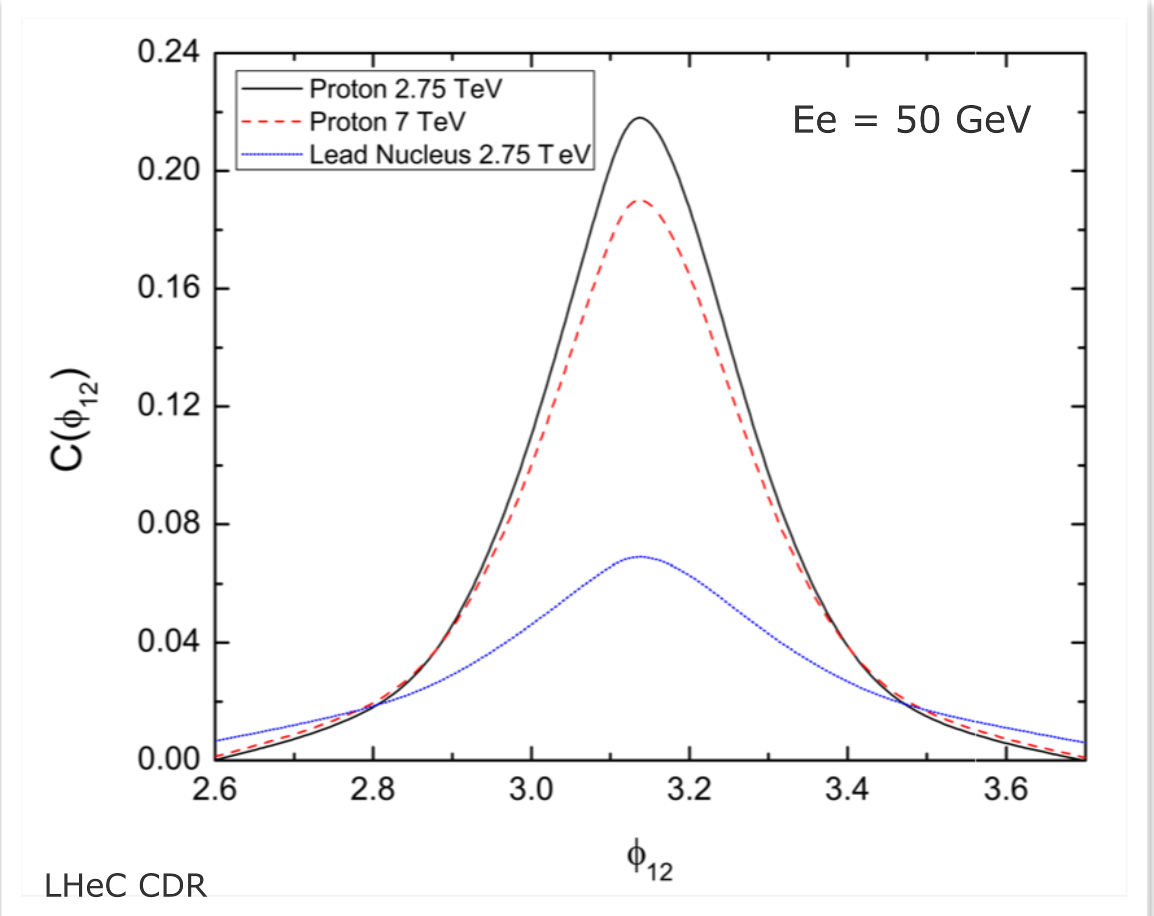
  z_h: longitudinal momentum fraction of hadrons w.r.t. photon momentum, φ_{12}: azimuthal angle between them

- GBW dipole model predicts wider correlation function for nuclei than for the proton

  ⇒ can be interpreted as due to stronger saturation in nuclei

- GBW dipole model also predicts mild dependence on proton beam energy

  ⇒ indicative of log(1/x) effects



➡ **Di-hadron correlation provides additional way to constrain unintegrated PDF**

Inclusive diffraction

Inclusive Diffraction

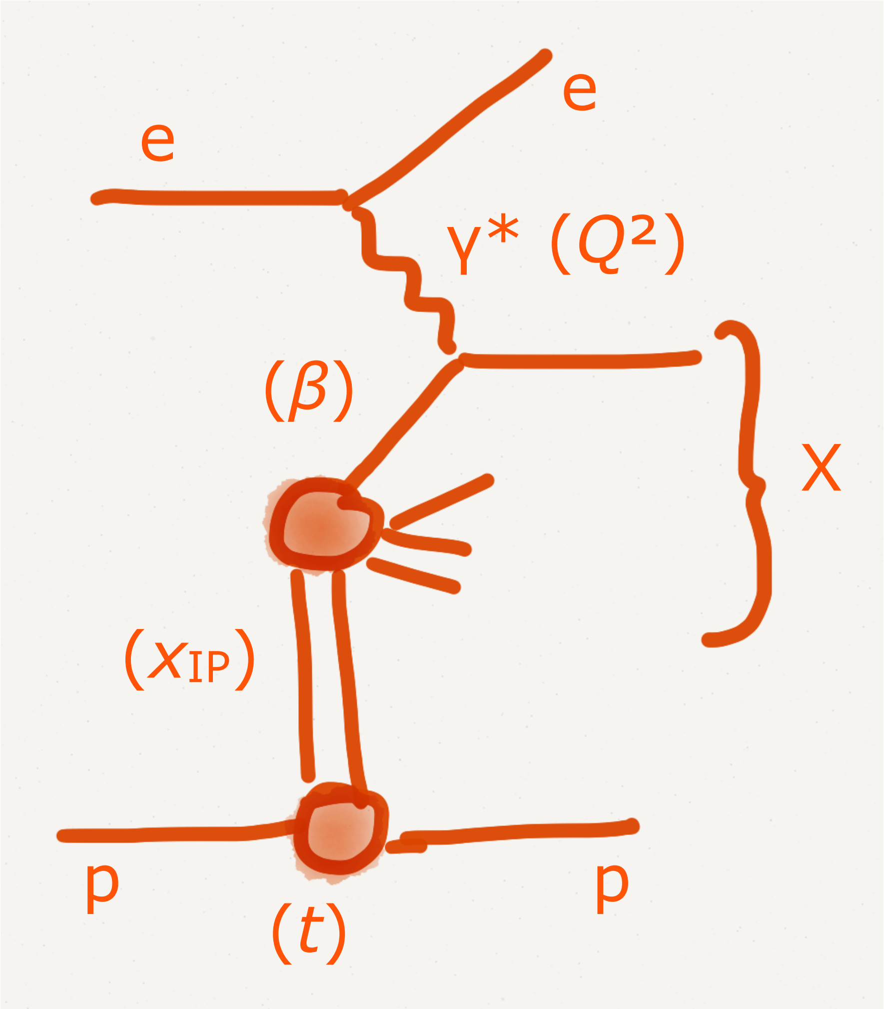
Diffractive deep inelastic scattering: a quick recap

- HERA: 10% of DIS is diffractive!

$$\mathrm{ep} \to \mathrm{eXp}$$

  with a large rapidity gap between X and p
- Can be described by the exchange of a color neutral "pomeron"
- Can be characterized via a factorization theorem by diffractive PDFs

$$f^{\mathrm{D}}(\beta, Q^2, x_{\mathbb{P}}, t)$$



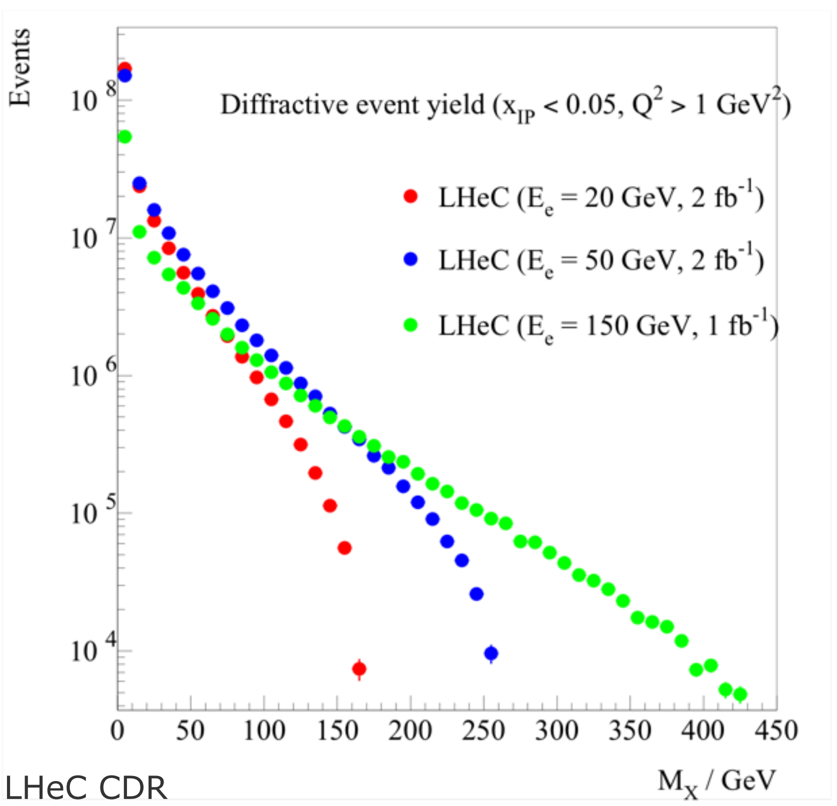
- Kinematic variables:

$$\beta = \frac{Q^2}{Q^2 + M_X^2 - t} \qquad x_{\mathbb{P}} = \frac{x}{\beta} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2 - m_p^2}$$

- At lowest order, the exchange must consist of at least two gluons
  ⇒ expect enhanced sensitivity to saturation effects!

Kinematic range at the LHeC

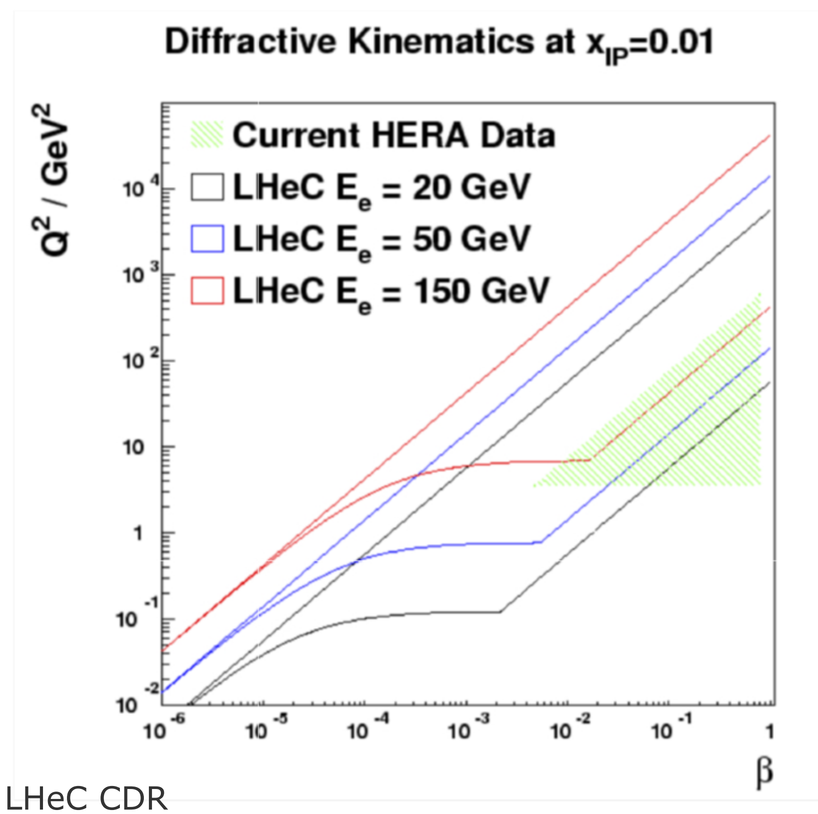
Vast increase of phase space!



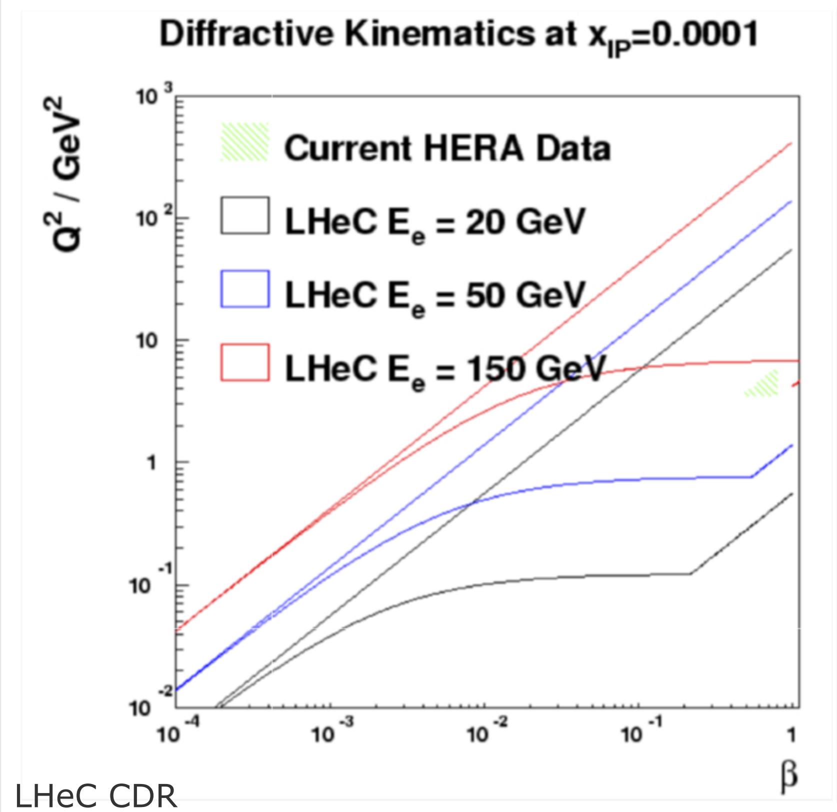
- Mass of diffractive dissociation system of **up to 250 GeV** (for E_e = 50 GeV)

  ⇒ possible to have diffractive production of beauty, W, Z, exotic states with JP=1-, ...

Accessible via leading proton detection



Accessible via large rapidity gap selection

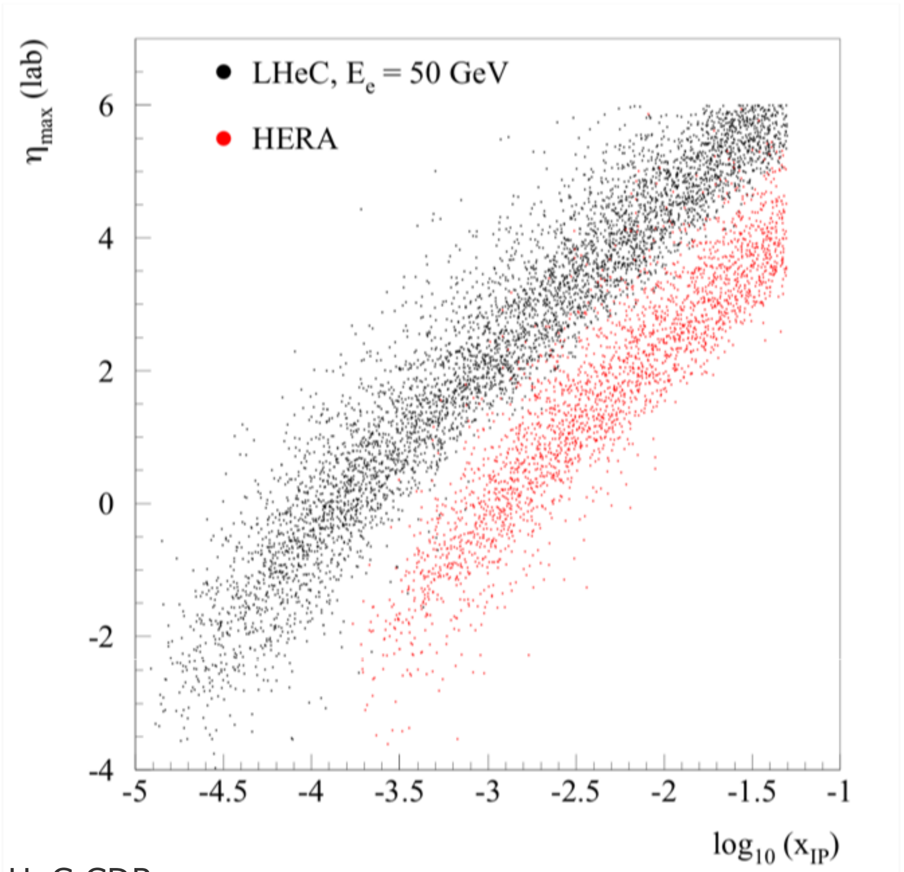


- Large Q^2 allows weak boson exchange

  ⇒ possible to do quark flavor decomposition

➡ **Testing of collinear and proton vertex factorization in significantly increased phase space domain**

Diffractive event selection



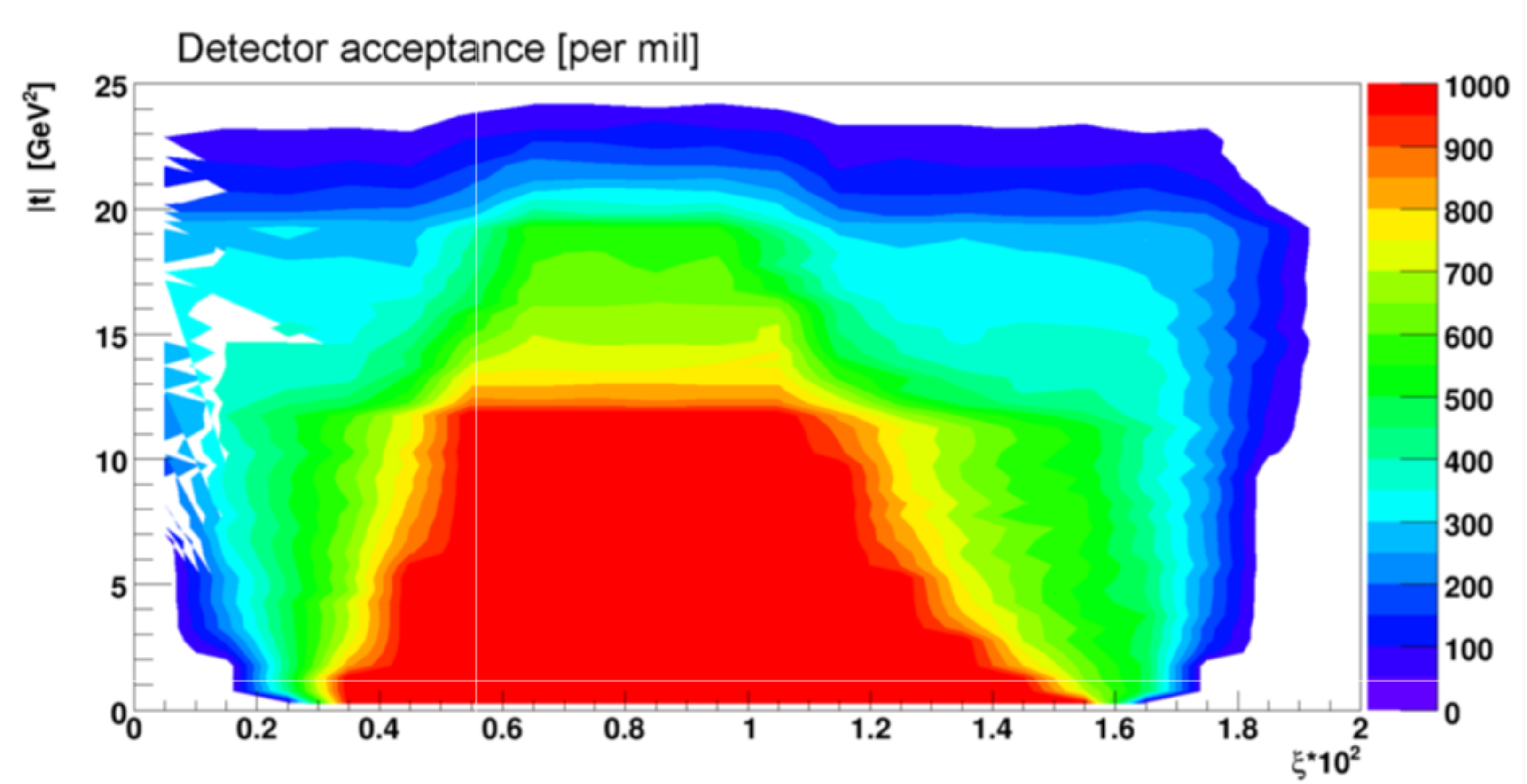
LHeC CDR

Large rapidity gap technique

- Exploit correlation between x_{IP} and rapidity of most forward particle η_{max}
- η_{max} < 5 (implying forward instrumentation down to 1°) allows measurements up to x_{IP} ~ 0.001

Leading proton detection

- Using proton spectrometer at 420 m from the interaction point
- Overlap in x_{IP} with LRG method can be used for cross-calibration



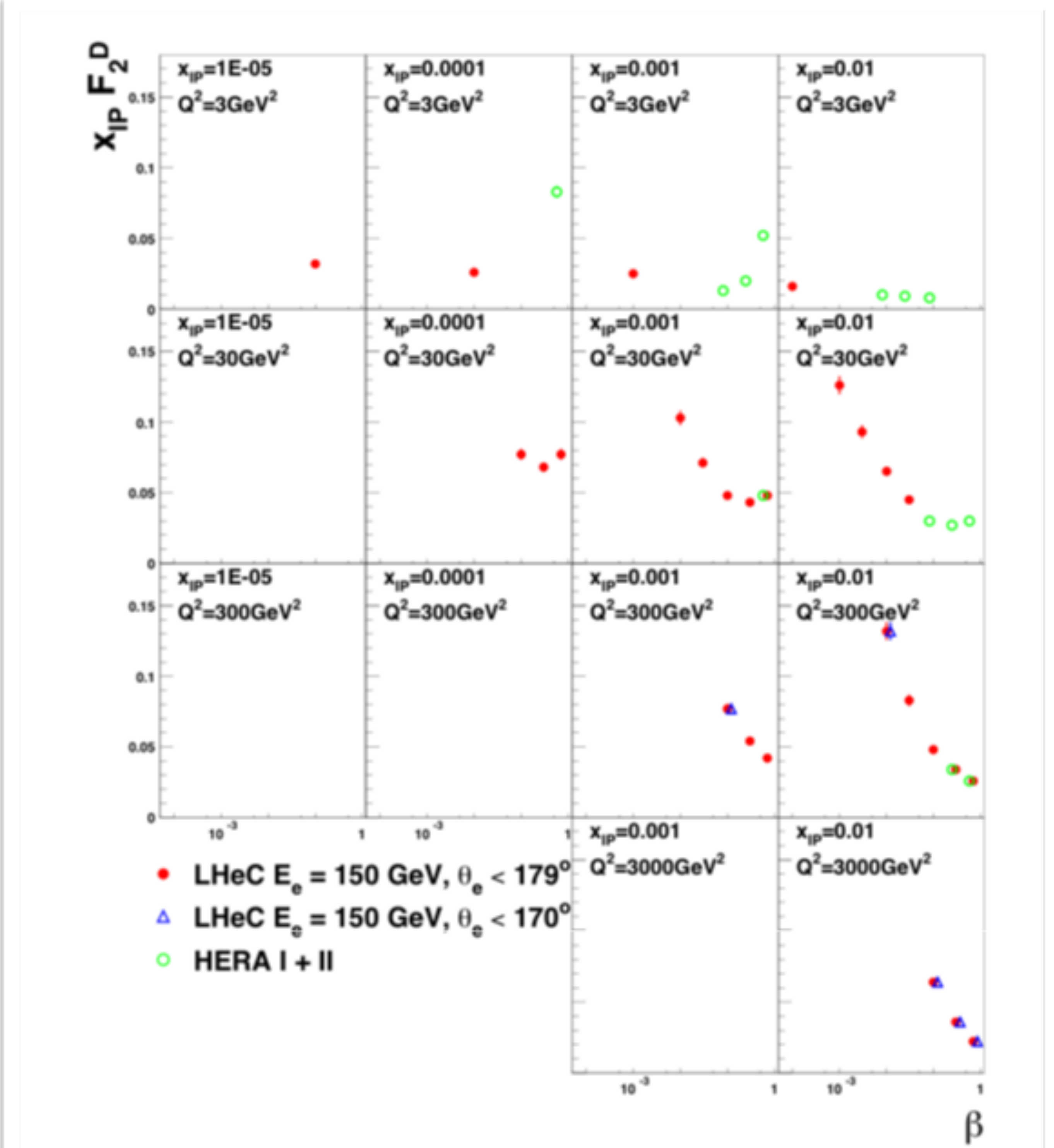
LHeC CDR

Example of diffractive F_2 measurement

LHeC pseudodata

- E_e = 150 GeV, L = 2 fb^{-1}
- Extrapolation from "H1 fit B"
- Large difference between kinematic range accessible with backward instrumentation up to 170° or 179°!

➡ **Large extension of HERA measurements!**



LHeC CDR

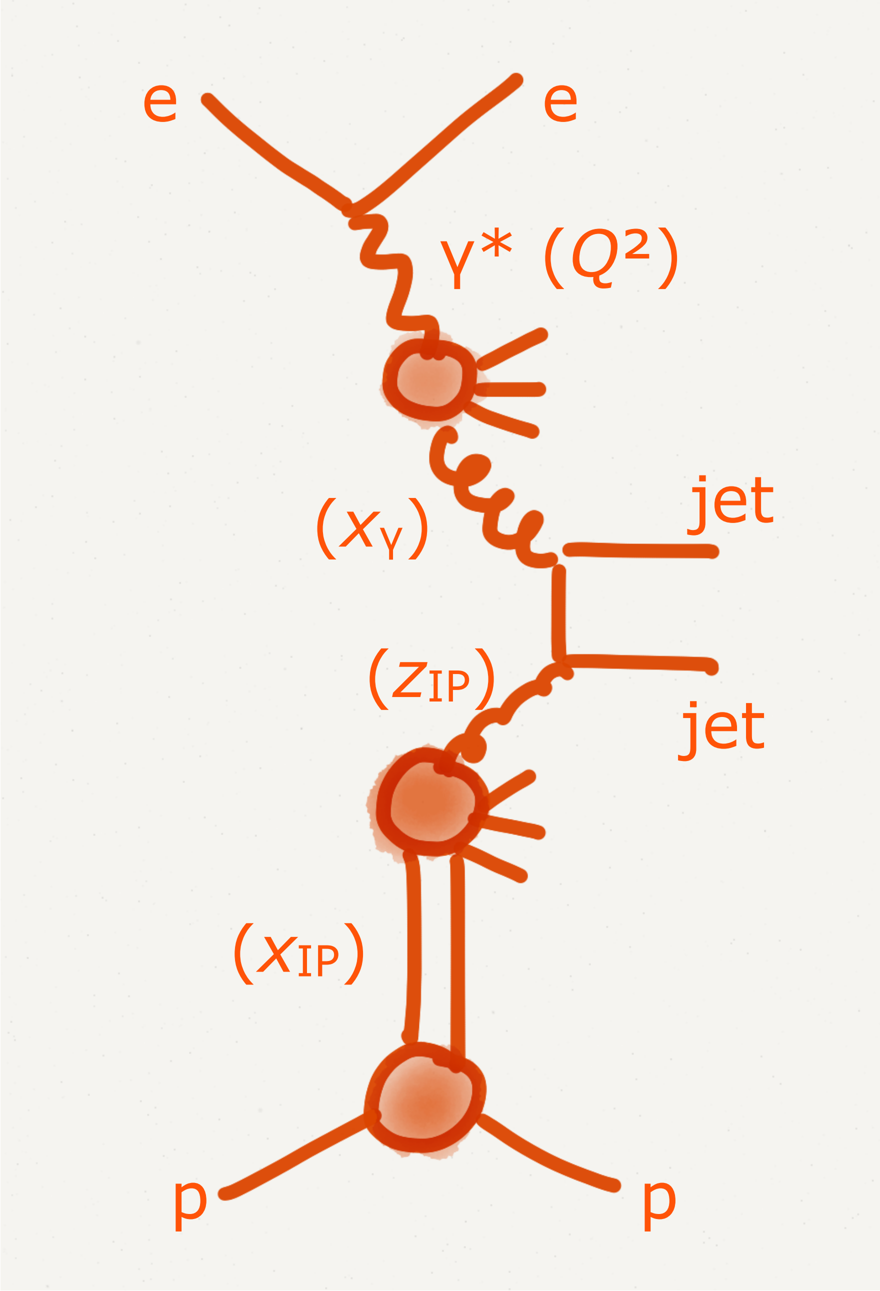
Diffractive dijet and charm production

Test of collinear factorization in diffractive ep scattering

- Experimental confirmation of factorization in diffractive dijet photoproduction from HERA is somewhat confusing
- Role of resolved photons: provides a link to diffractive hadron-hadron scattering

  ⇒ multi-parton interactions and gap survival probability
- LHeC: measurements up to p_T = 50 GeV are possible, much smaller scale uncertainties than at HERA
- LHeC gives access to much lower z_{IP}/x_γ than HERA

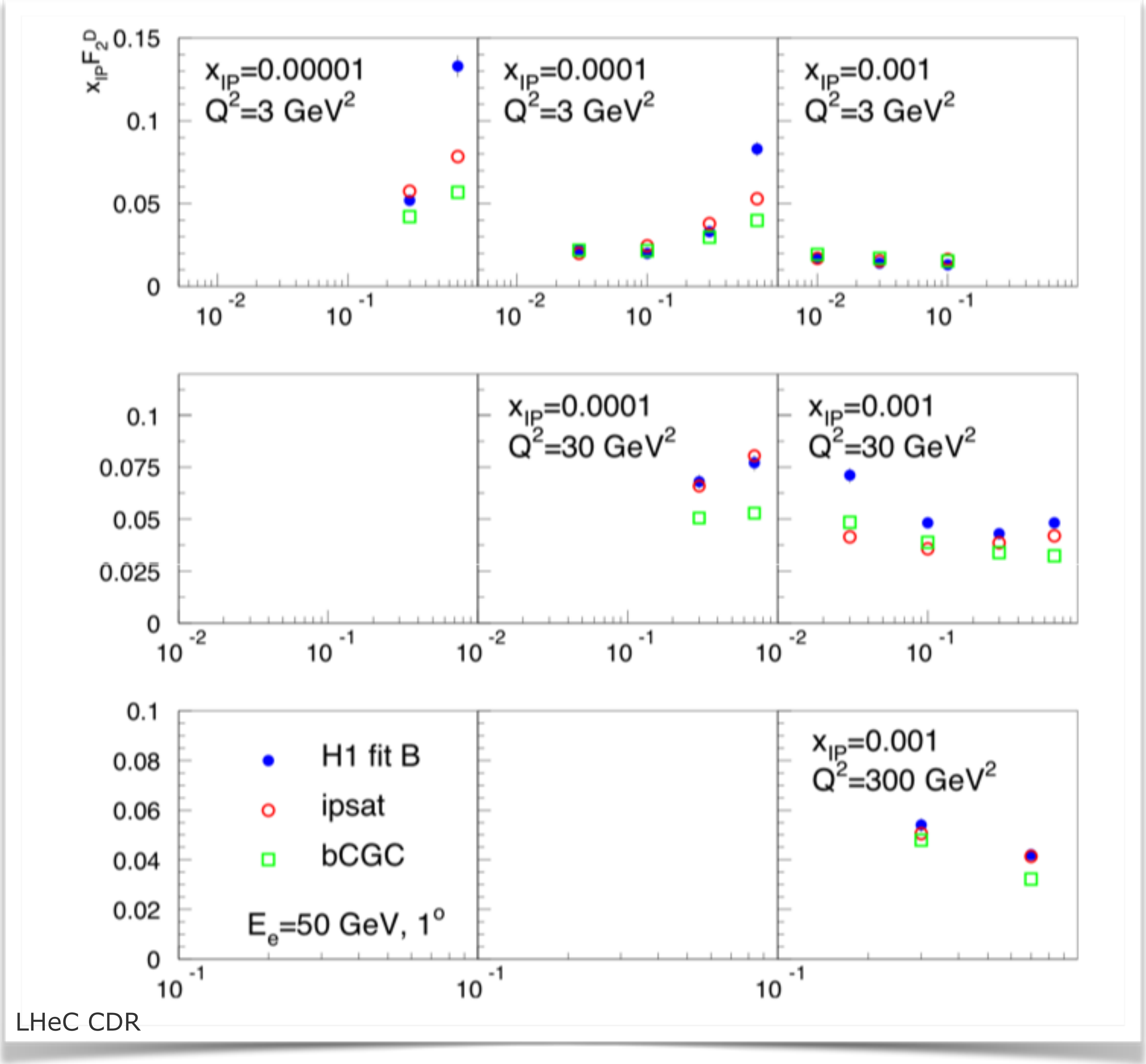
➡ **Diffractive dijet photoproduction at the LHeC is dominated by resolved photons!**



Saturation in diffraction

Looking for the onset of non-linear evolution/higher twist effects…

- Diffractive DIS sensitive to power corrections of order Q^2_{sat}/Q^2
- LHeC gives access to semi-hard regime $Q^2 < 10$ GeV² and low x
- Pseudo-data can distinguish between a range of models with and without saturation effects



LHeC CDR

Exclusive production

Exclusive J/ψ and Υ production at the LHeC

Studying the transition from dilute to dense parton densities

- Extremely clean final state: 2μ + p
- Access low *x* and Q², while varying *W* and *t*

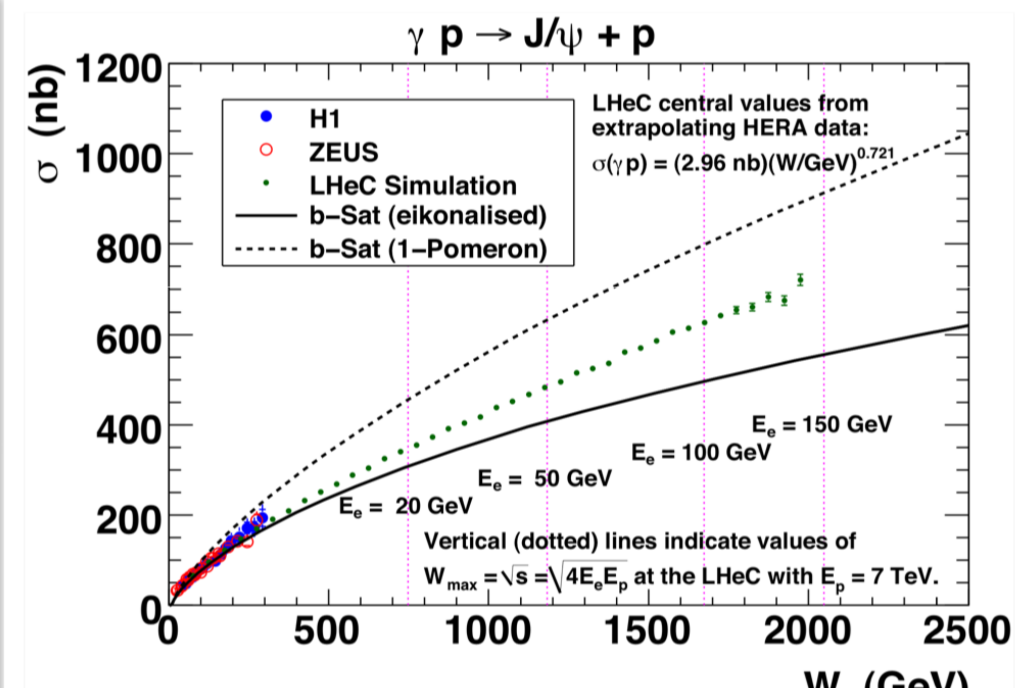
$$x_{\rm eff} = \frac{Q^2 + m_V^2}{Q^2 + W^2} \qquad Q^2_{\rm eff} = \frac{Q^2 + m_V^2}{4}$$

- Assume μ detection down to 1°

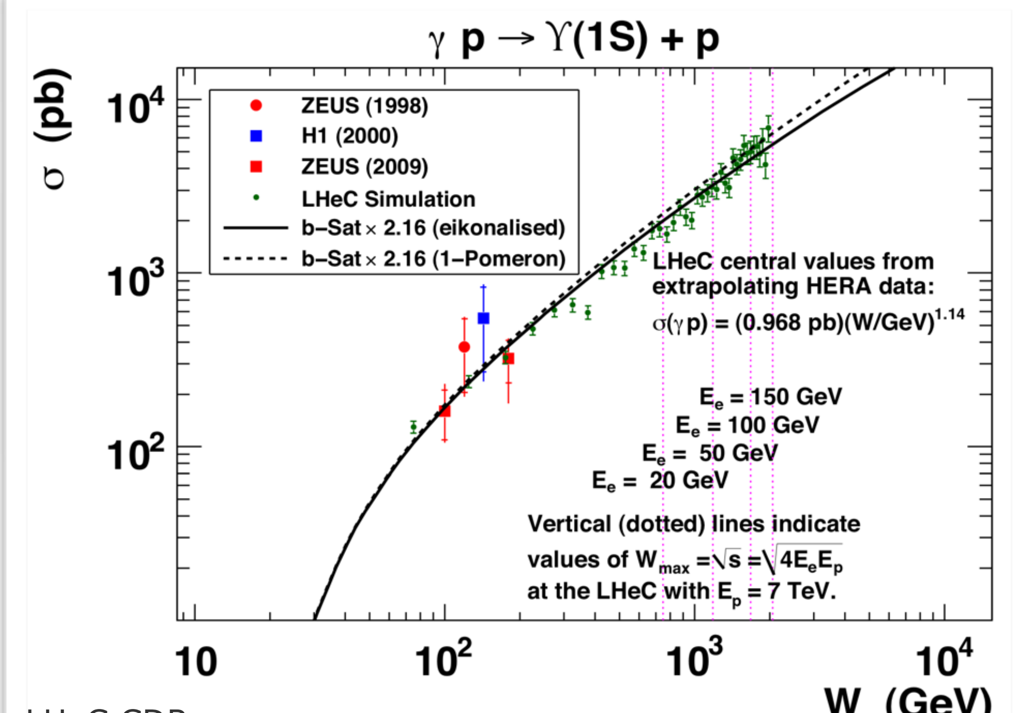
  ⇒ *W* up to 1 TeV and higher
- LHeC pseudodata obtained from power-law extrapolation, stat. error from DIFFVM
- b-sat dipole model:
  - eikonalized dipole scattering amplitude
  - including only 1-pomeron exchanges

  ⇒ importance of unitarity corrections
- Sensitivity is reduced for exclusive Υ photoproduction due to the higher mass and lower cross section

➡ **Exclusive J/ψ photoproduction may be the ideal observable to investigate unitarity corrections at a perturbative scale**



LHeC CDR



LHeC CDR

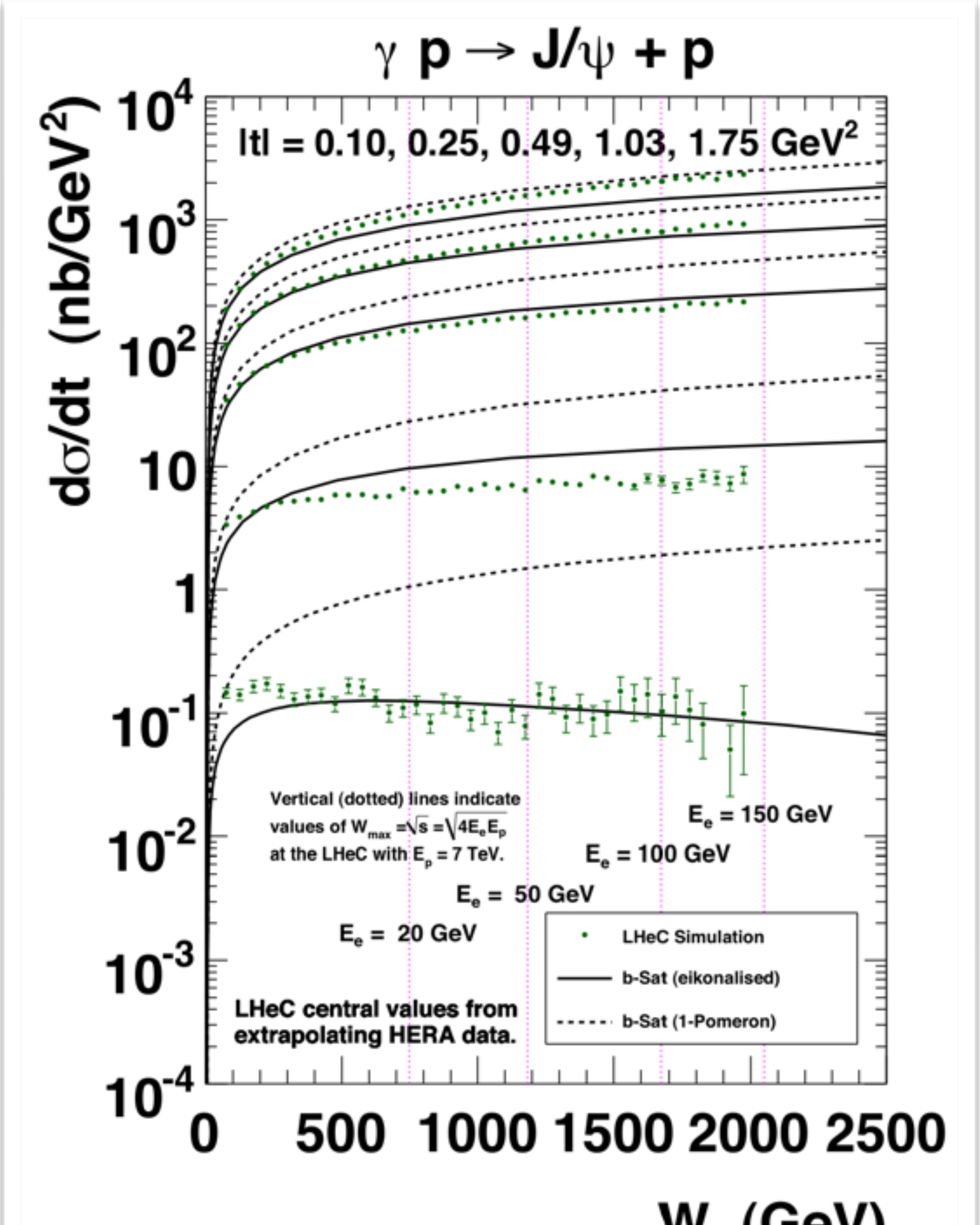
Exclusive J/ψ and Υ production at the LHeC

Impact parameter dependence

- Saturation effects are most important towards the centre of the proton

  t is the Fourier conjugate variable to impact parameter *b*
- Difference in b-sat model between fully eikonalized and 1-pomeron exchanges increases with *t*
- Errors in LHeC pseudo-data small enough to differentiate between models

➡ **measuring exclusive J/ψ production in bins of *t*, one can extract the impact parameter profile of the interaction region**



LHeC CDR

Deeply virtual Compton scattering

Generalized parton densities (GPDs)

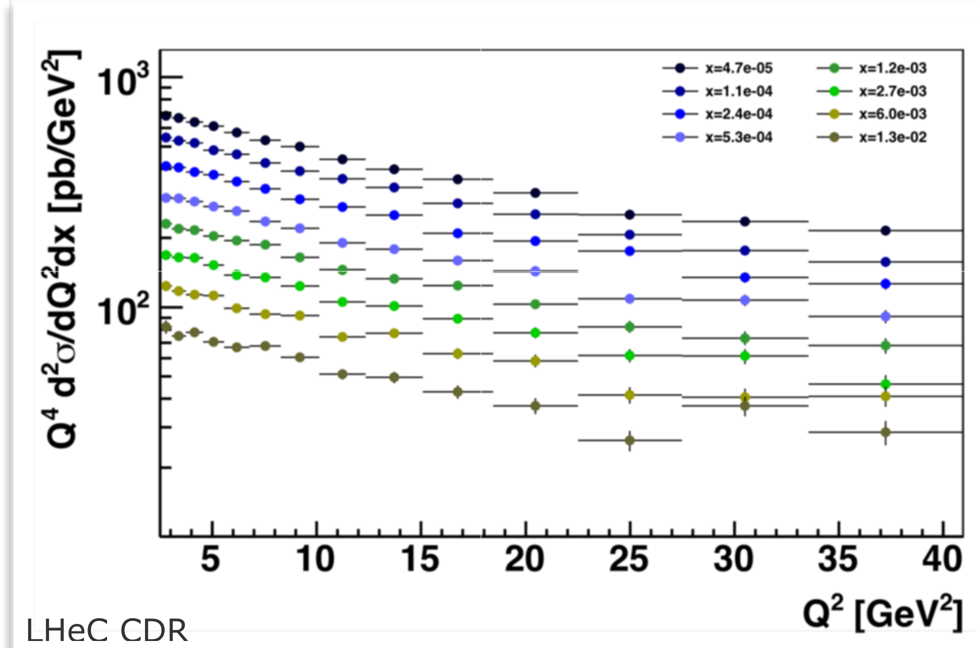
- Factorization between pQCD scattering process and universal GPDs defined as

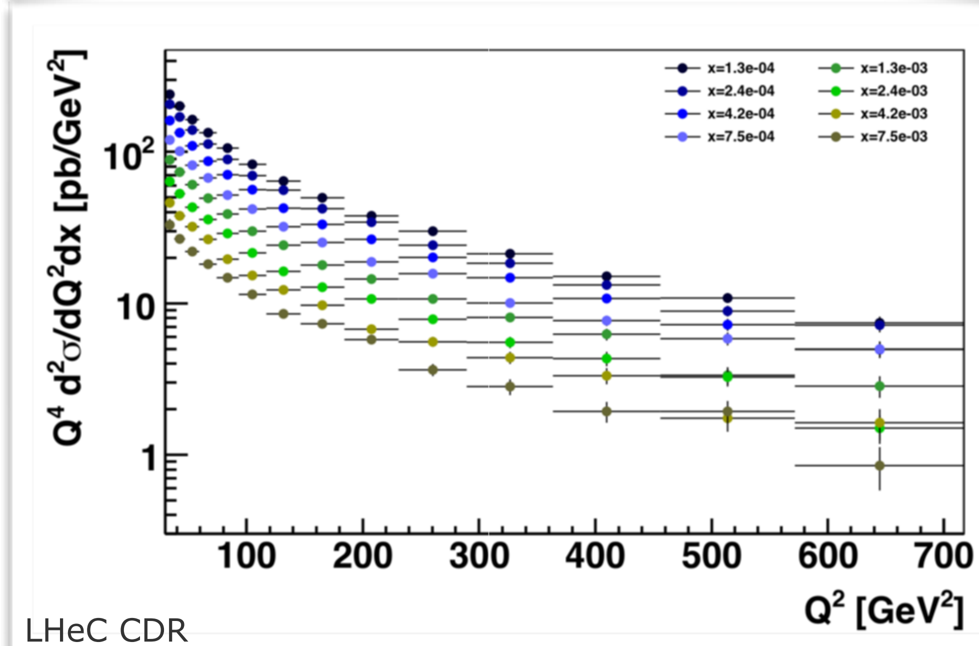
$$\langle P', \lambda' | \hat{O} | P, \lambda \rangle$$

- Fourier transform of GDP w.r.t. transverse momentum transfer ~ transverse spatial distribution of partons
  - impact parameter dependence of saturation scale
  - UE structure and rapidity gap survival probability in hard diffraction
- Need measurement up to high |t|
  - Large systematic due to proton dissociation at large |t| -> good scattered proton detection is needed

Observable processes

- VM and heavy quarkonia probe gluon GPD
- DVCS adds singlet quark GDPs





MILOU simulation

Low Q^2 (2.5 GeV^2) low x (10^{-5}) can only be reached with $p_{T,\gamma} > 2$ GeV and detector acceptance to 1°

Summary

We know that the collinear, leading twist description of hadron collisions based on DGLAP evolution is only an approximation and that it has to fail eventually...

- Re-summation -

- Saturation -

- Higher twist -

- Multi-parton interactions -

Discrepancies are expected to be seen first in **semi-inclusive and exclusive** observables

But we need high energy (low x) and/or high A to firmly establish physics beyond leading twist, collinear factorization

The LHeC is able to take us to the next step in high density QCD!