3rd CERN-ECFA-NuPECC Workshop on the LHeC
Chavannes-de-Bogis, Switzerland, November 12th 2010

Overview of the HPD chapter

Néstor Armesto
Santiago de Compostela
nestor.armesto@usc.es

on behalf of the conveners of the working group on ***Physics at High Parton Densities (ep and eA)***:
Brian Cole *(Columbia)* , Paul Newman *(Birmingham)* and Anna Stasto *(Penn State)*

Aim of the talk:

- Presenting the structure of the chapter of the CDR on ***Physics at High Parton Densities***.

- Showing those contents already available which will not be covered by the other speakers: David d'Enterria (small-x@LHC), Javier Albacete (predictions for F_2 and F_L in ep), Carlos Salgado (npdf's), Graeme Watt (exclusive VM in ep) or Henri Kowalski (exclusive VM in eA).

- Discussing, and refining the presentation of, the physics case for the LHeC related with Small-x Physics.

- Note: the discussion on ep and eA has been done on equal footing when possible.

- Note: already more than 50 pages long without references - some 10 more pages to be expected.

Contents:

1. Physics at small x:

1.1 Unitarity and QCD.
1.2 Status following HERA data.
1.3 Low-x physics at the LHC (David d'Enterria, also Carlos Salgado).
1.4 Nuclear targets.

2. Prospects at the LHeC:

2.1 Strategy: decreasing x and increasing A.
2.2 Inclusive measurements (Javier Albacete and Carlos Salgado).
2.3 Exclusive production (Graeme Watt).
2.4 Exclusive vector meson production (Graeme Watt and Henri Kowalski).
2.5 DVCS and GPDs.
2.6 Inclusive diffraction.
2.7 Jet and multi-jet observables, parton dynamics and fragmentation.
2.8 Photoproduction Physics.
2.9 Implications for the ultra-high energy neutrino interactions.

1.1 Unitarity and QCD:

* Introduction (J. Bartels, NA, BC,AS).

* From DGLAP to non-linear evolution equations in QCD: saturation (NA, AS).

* Linear resummation schemes (S. Forte, J. Rojo, AS).

* Saturation in perturbative QCD (NA, AS).

* Dipole models (AS).

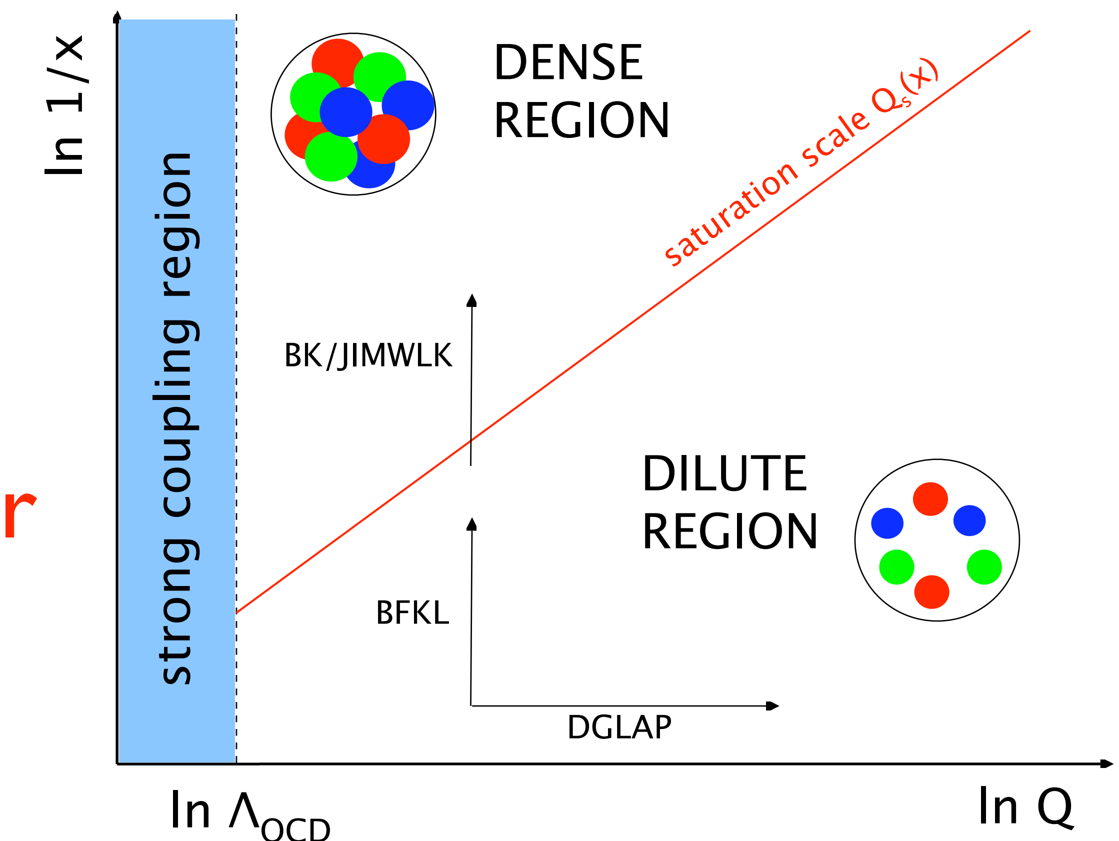
* The importance of diffraction (AS).

* The importance of nuclei (NA, BC).

Introduction & linear to NL:

- **Weak coupling** and **dilute** regime of QCD extensively tested in large scale observables - hard scattering, collinear factorization.

- Small x at HERA/forward physics in colliders (large σ) may show factorization breaking: dense regime, unitarity bound on scattering amplitudes.



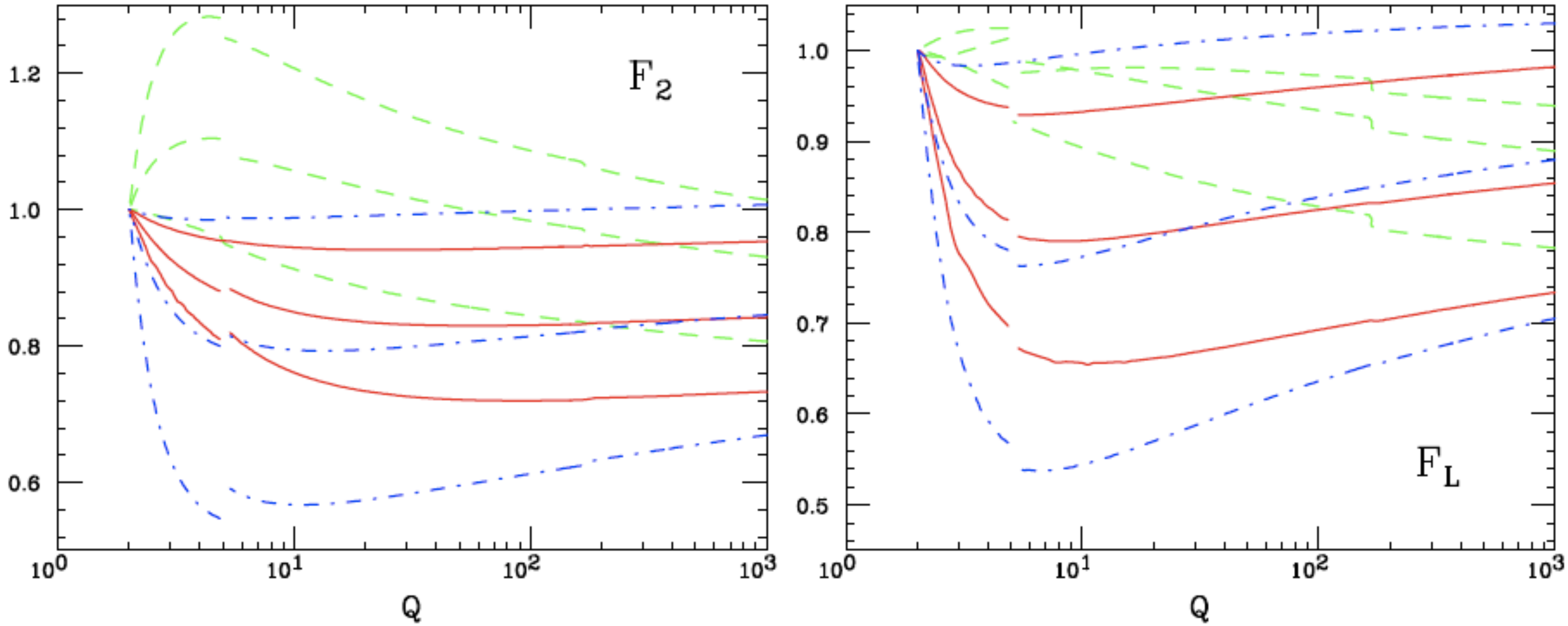
- Density implies interplay between recombination and splitting: non-linear evolution leading to saturation of partonic densities.

- Diluteness may be broken either by strong scattering (strong coupling at small Q^2) or by large density (weak coupling at moderate/large Q^2): **new qualitative regime of QCD**, perturbative realization of the unitarity bound (black disk limit).

Linear resummation schemes:

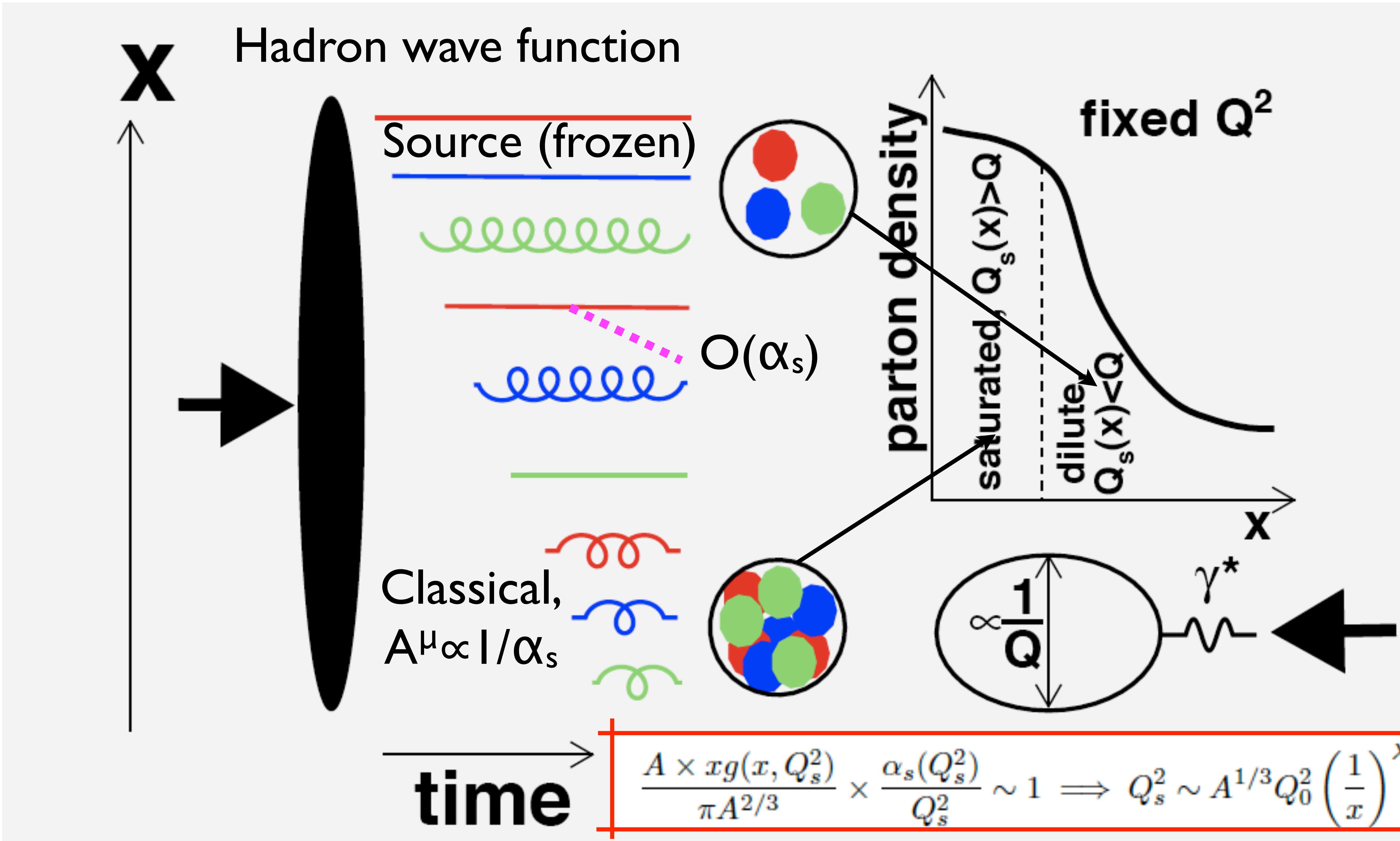
- Linear resummation (in $\alpha_s \ln x$) available (CCSS, ABF): soon in global fits (NNPDF).
- Impact opposite to NNLO.

K=(NNLO or resummed)/NLO, $x=10^{-2}, 10^{-4}, 10^{-6}$, ↑NNLO, ↓resummed.



Saturation in pQCD:

- The CGC offers a perturbative, partonic realization of saturation.



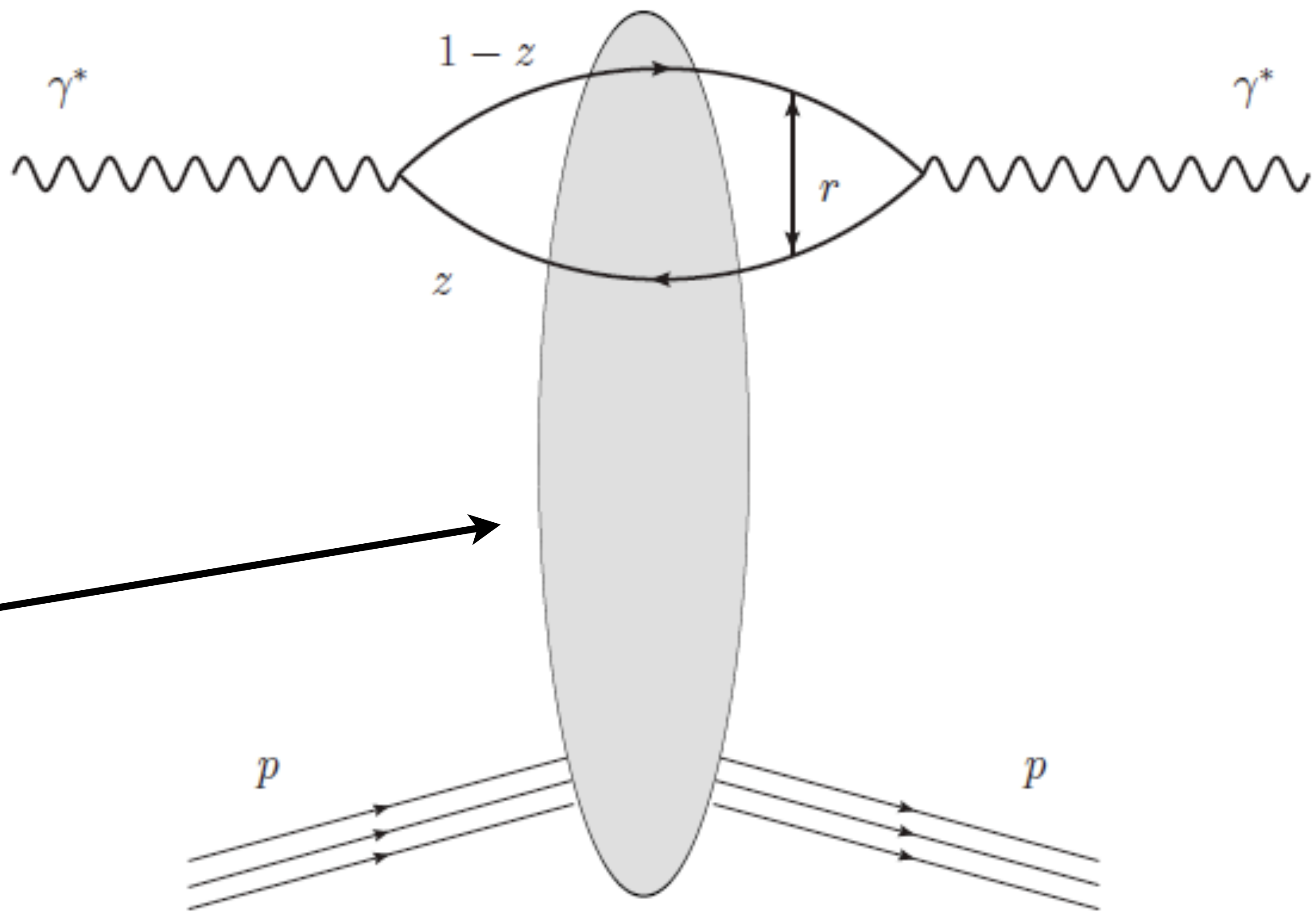
$$\frac{A \times xg(x,Q_s^2)}{\pi A^{2/3}} \times \frac{\alpha_s(Q_s^2)}{Q_s^2} \sim 1 \Longrightarrow Q_s^2 \sim A^{1/3} Q_0^2 \left(\frac{1}{x}\right)^\lambda$$

Dipole models:

- For $x<(2m_N R_A)^{-1} \sim 0.1A^{-1/3}$, lifetime of the γ^* fluctuation>R_A: frozen.

Photon WF (impact factor), available up to NLO.

Dipole-hadron cross section, linked with gluon density at large Q^2: x-evolution up to NLO or models.

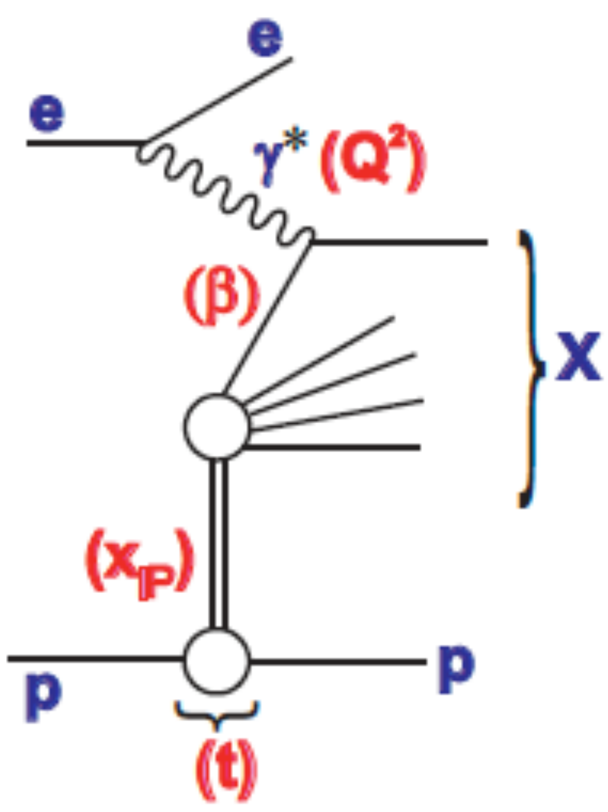


$$\sigma^{q\bar{q}}(r,x) \sim r^2\, \alpha_s(C/r^2)\, xg(x,C/r^2)$$

- Successful for inclusive and diffraction, problems with impact parameter profile.

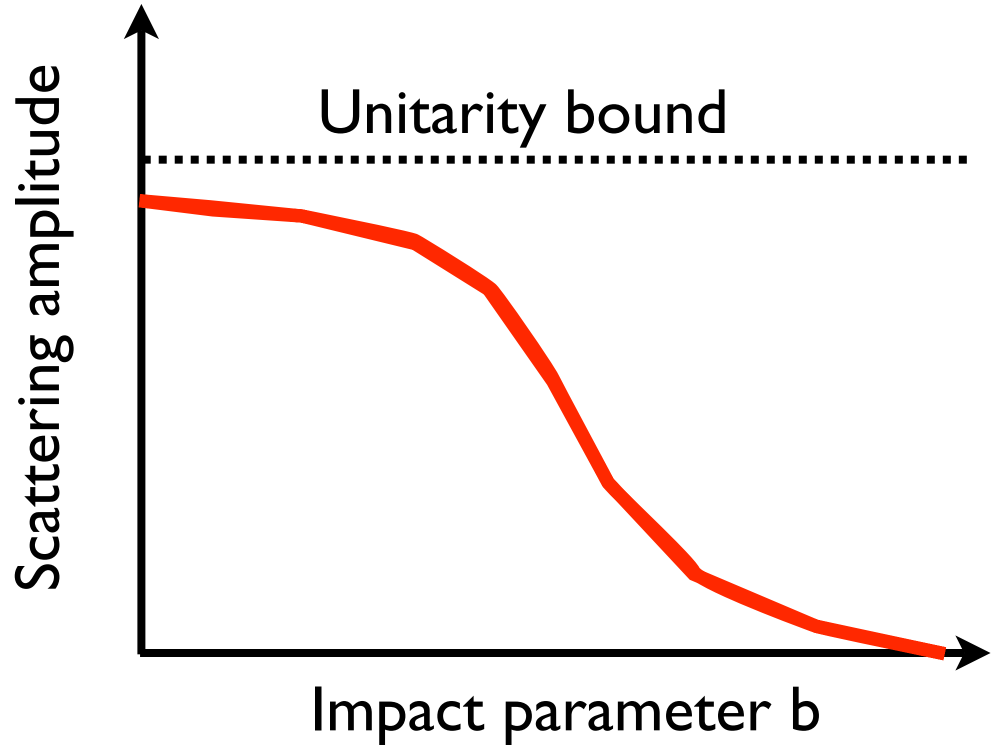
The importance of diffraction:

- 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 the same Q^2.

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

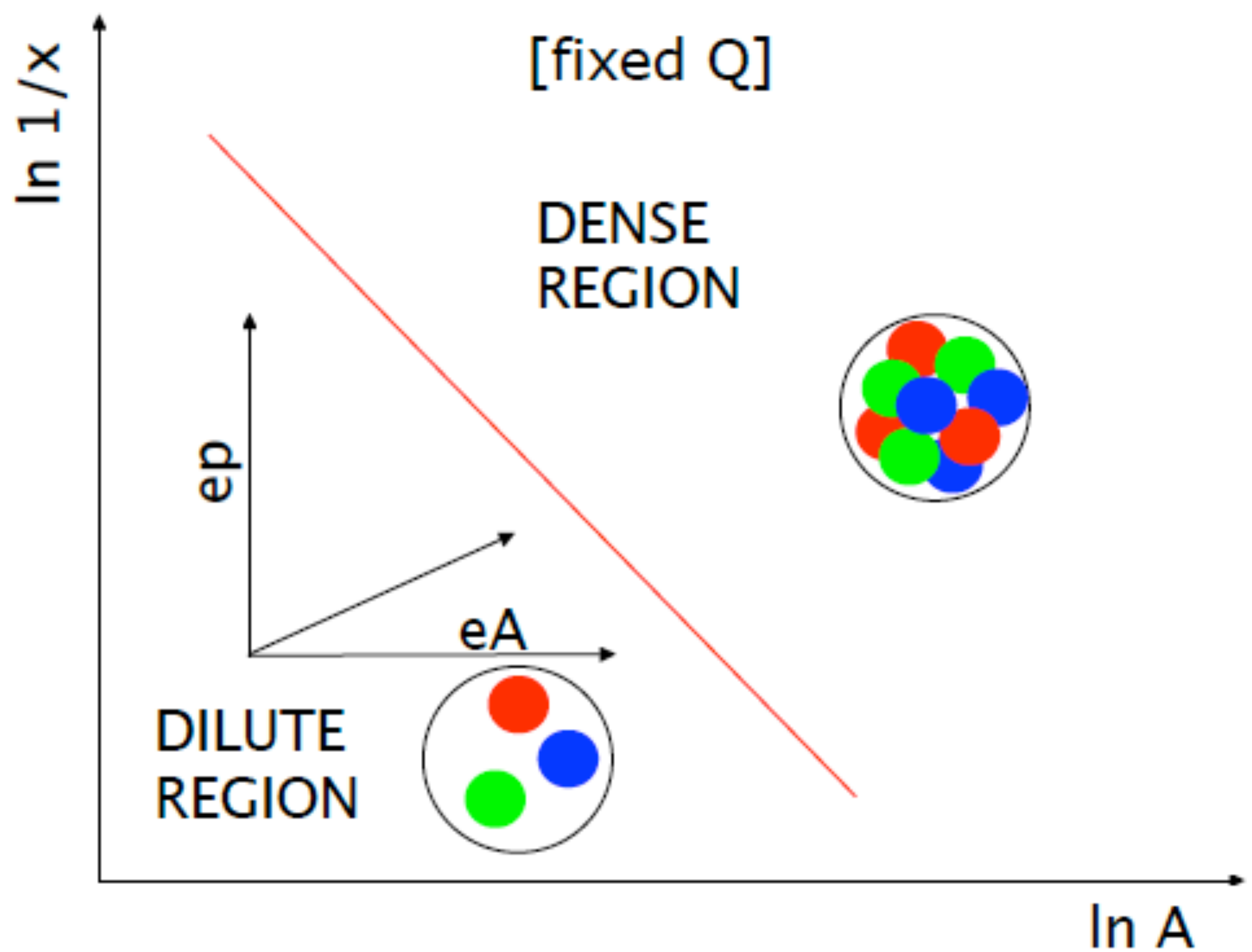


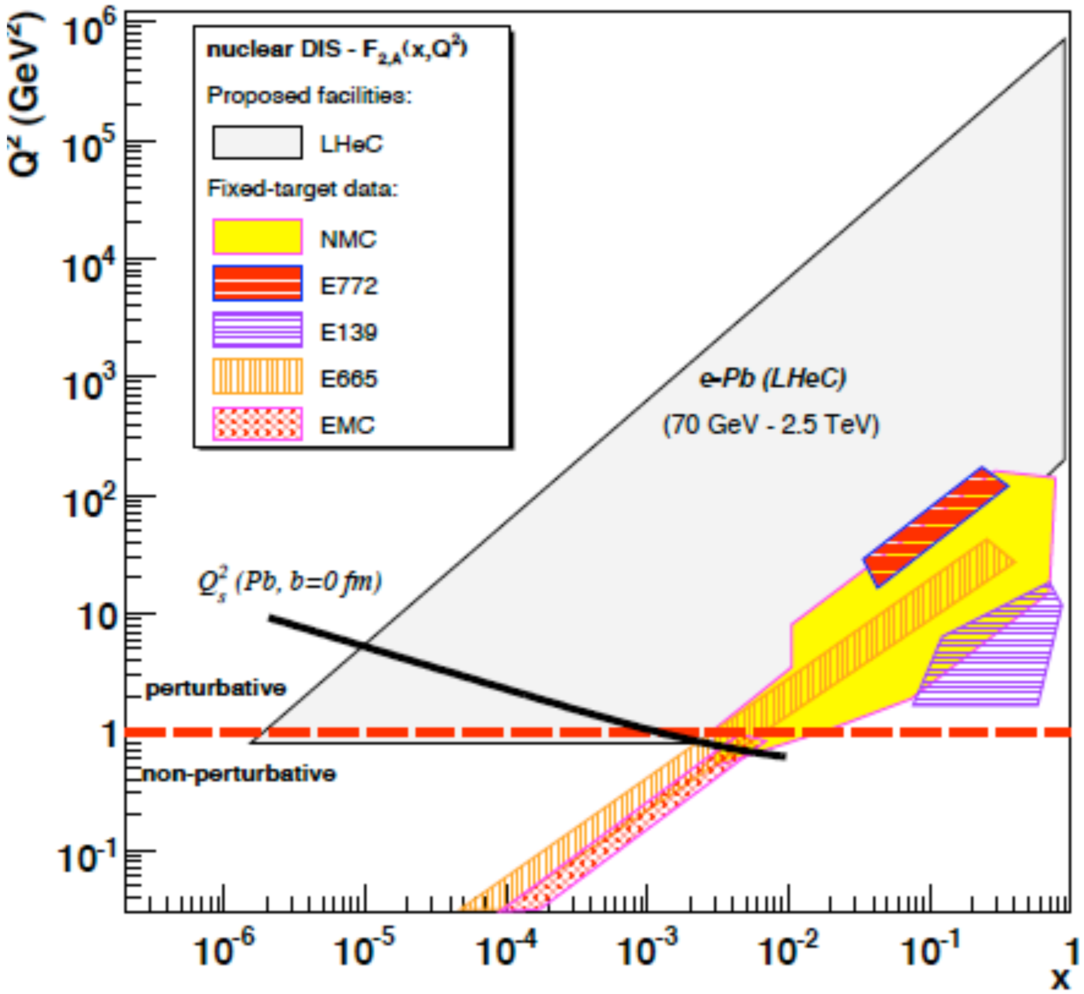
The importance of nuclei:

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

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

- Besides, we will explore a new realm in the partonic structure of nuclei.





1.2 Status following HERA data:

* Introduction (PN).

* Deviations from fixed order linear DGLAP evolution in inclusive HERA data (S. Forte, J. Rojo, PN).

Introduction:

- Three pQCD-based alternatives to describe small-x ep and eA data. **Differences lie at moderate $Q^2(>\Lambda^2_{QCD})$ and small x:**

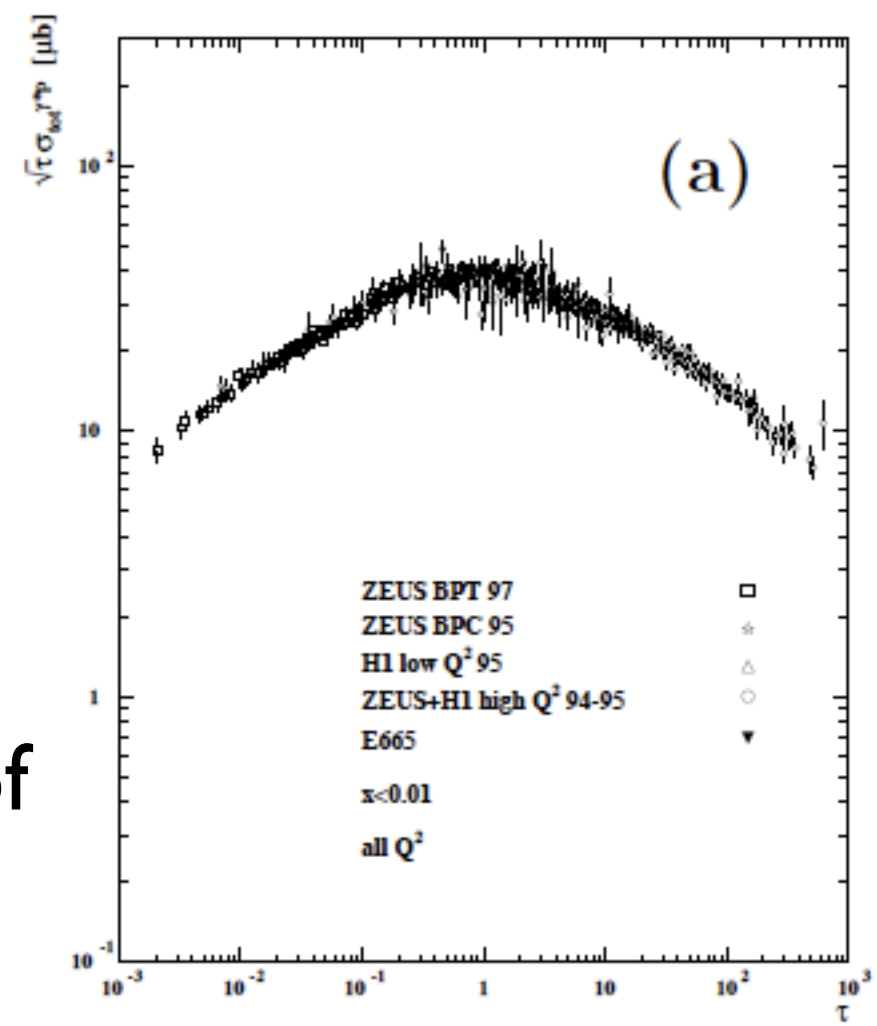
→ DGLAP evolution (FO PT).

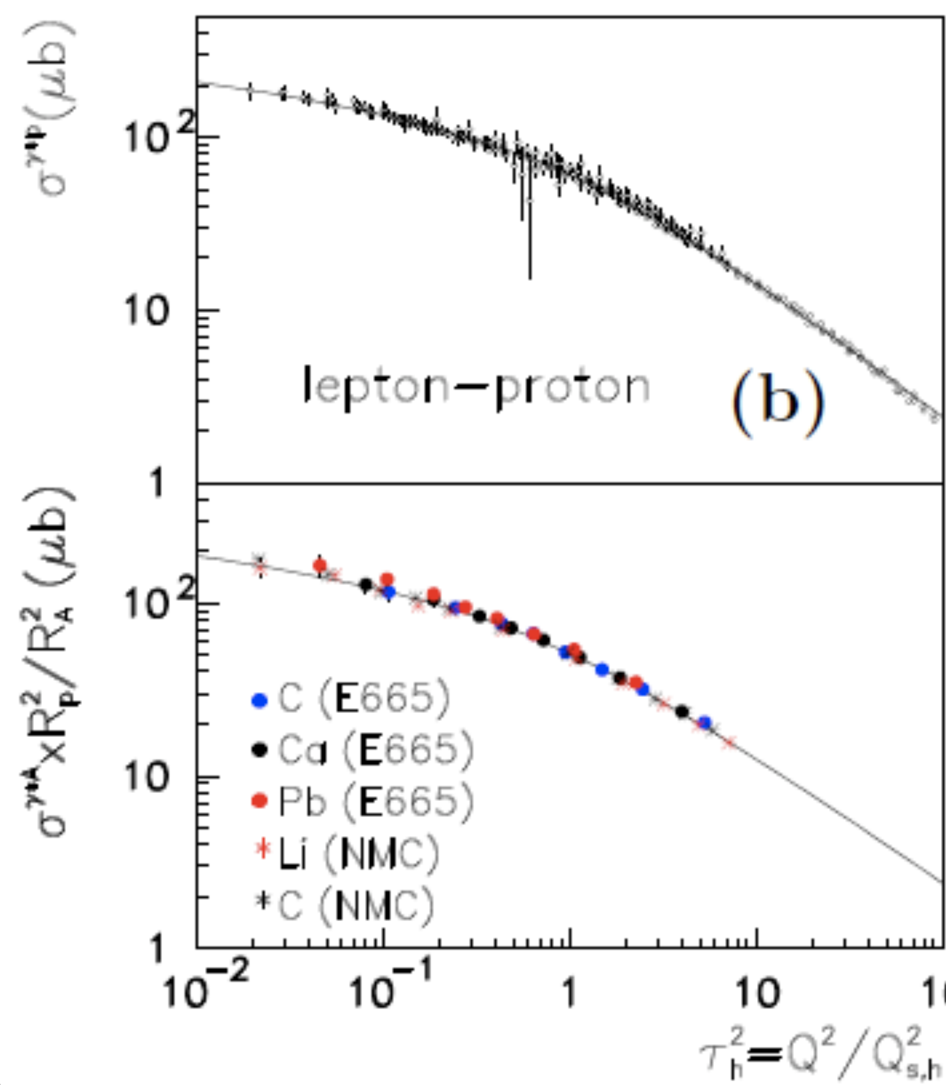
→ Resummation schemes.

→ CGC (dipole models and rcBK).

- Diffraction described in dipole models.

- Geometric scaling is a most striking feature of data.



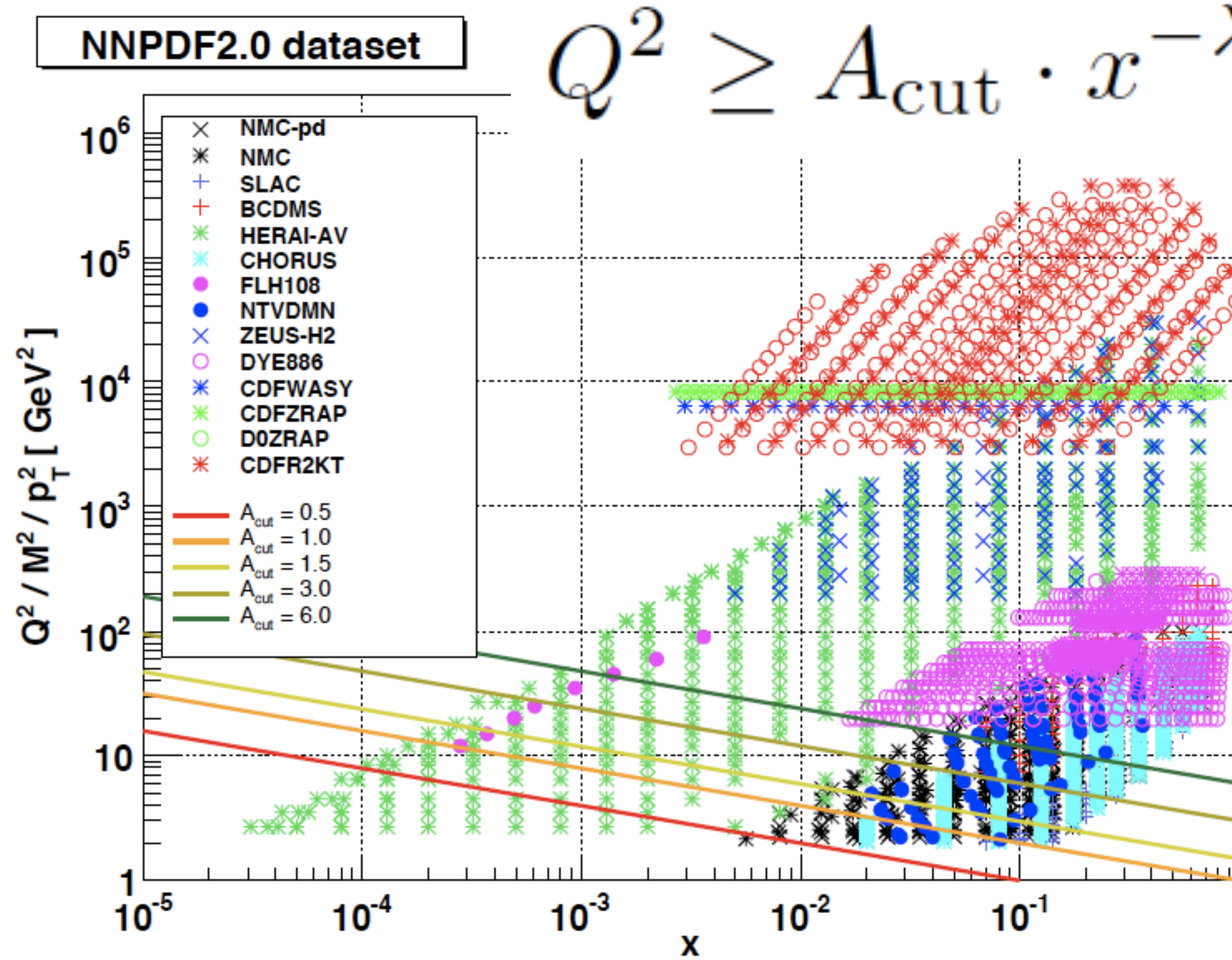


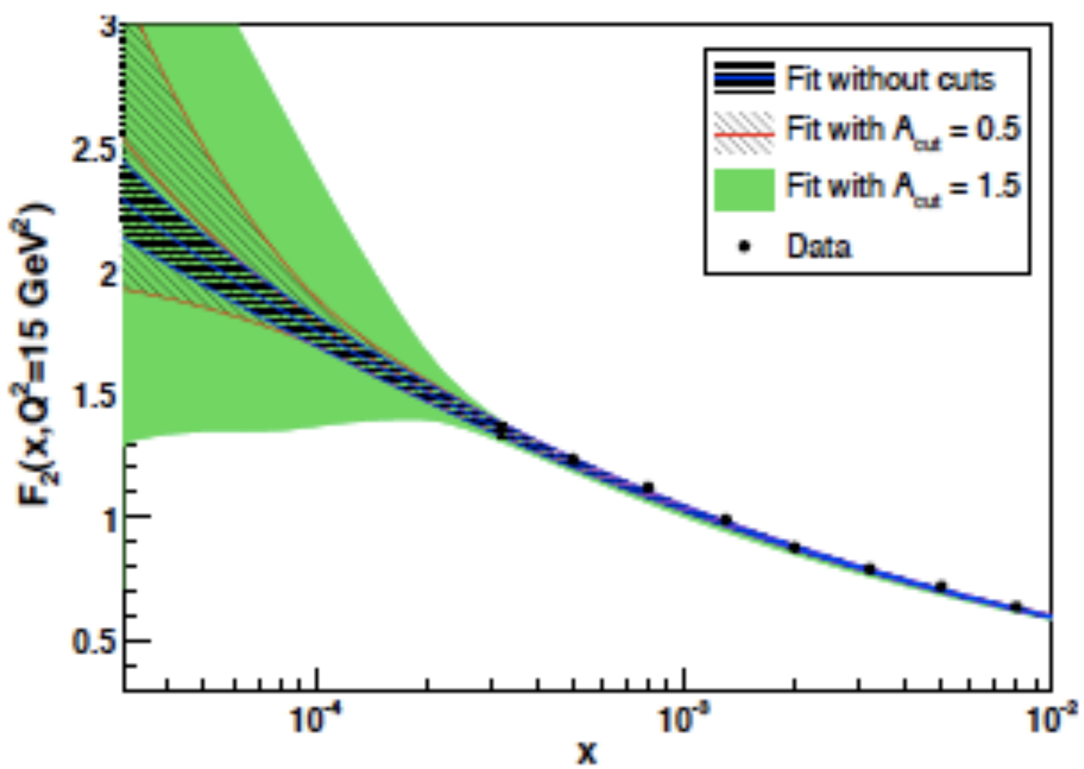
Deviations from DGLAP:

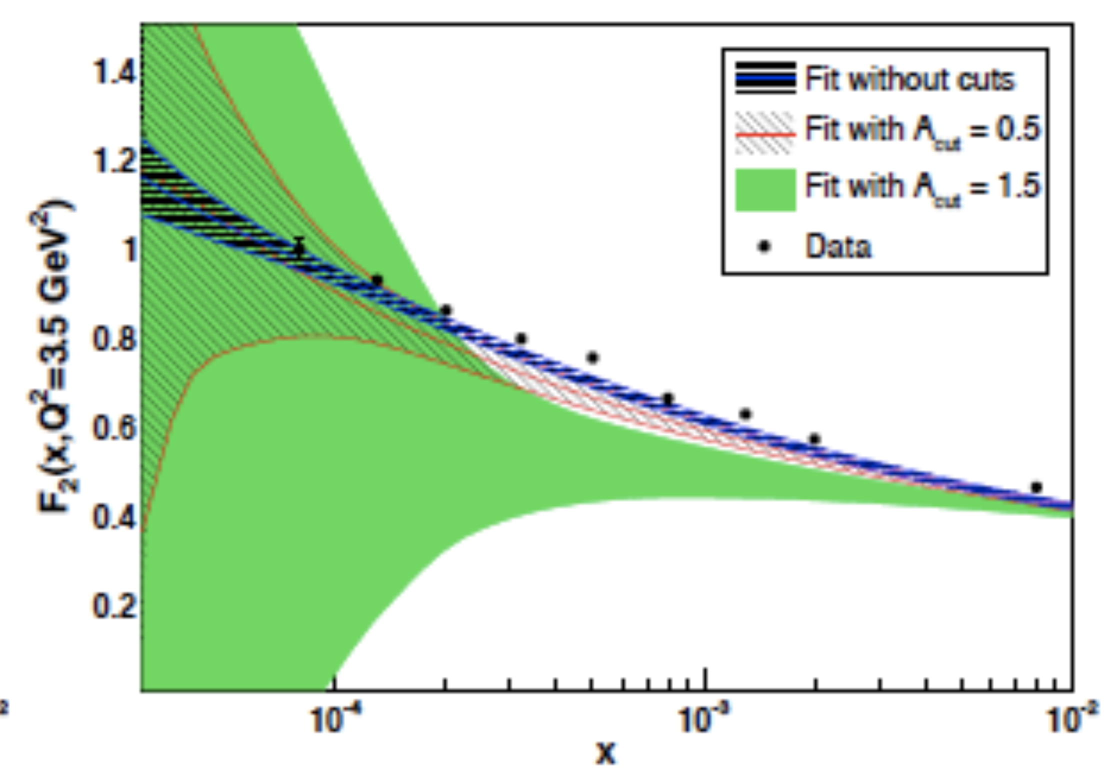
- Tension in data at small x and Q^2 when introduced in a global fit (NNPDF2.0).

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

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







Overview of the HPD chapter: 1.2 Status following HERA data.

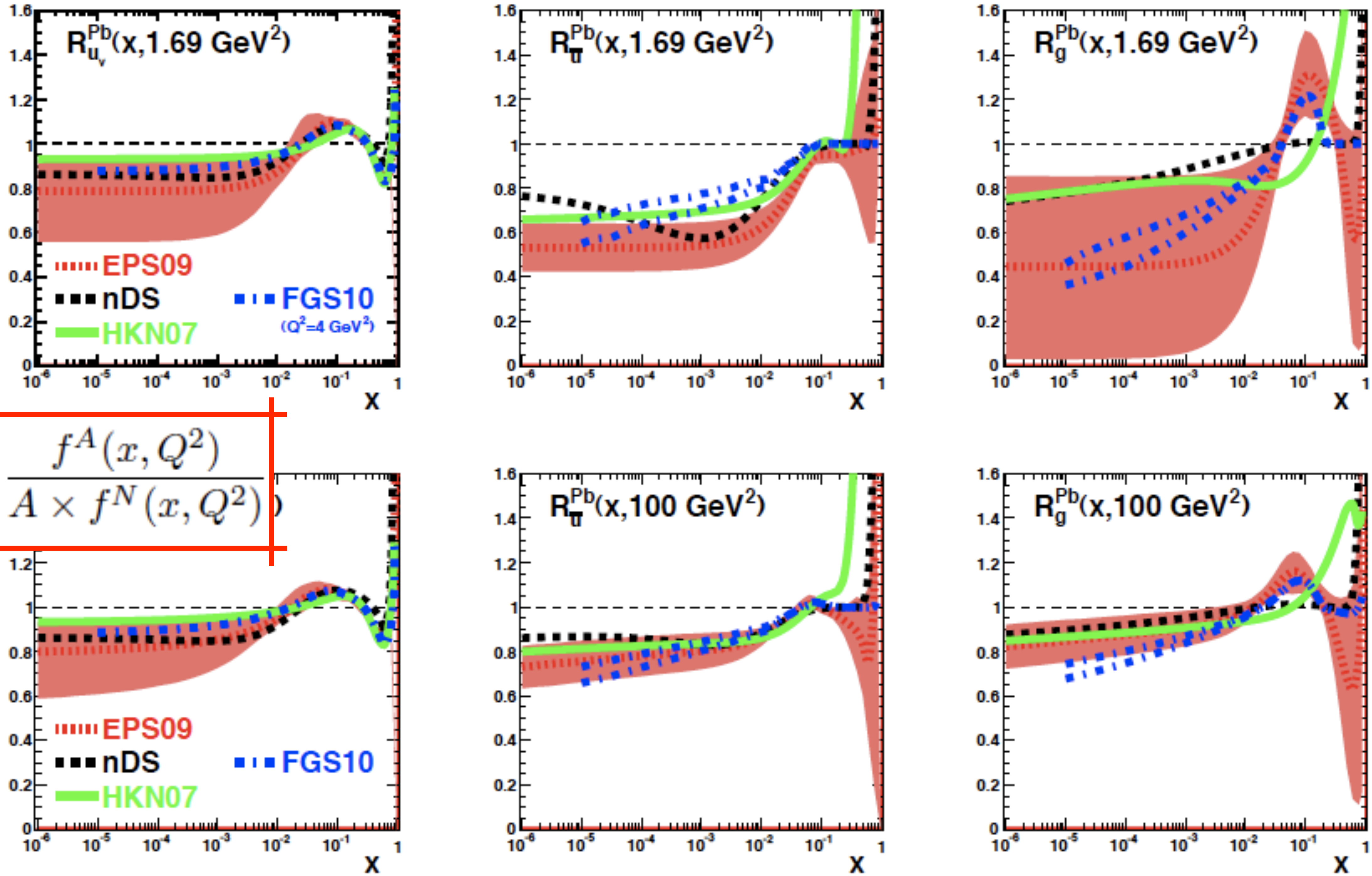
1.4 Nuclear targets:

* Comparing nuclear parton density functions (K. Eskola, M. Strikman, NA).

* Importance of LHeC measurements to ultra-relativistic heavy ion programs at RHIC and the LHC (U. Wiedemann, NA, BC).

Comparing npdf's:

- Several global analysis with NLO accuracy: DIS+DY(+dAu).
- Several ill-determined regions due to limited experimental information.



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

Overview of the HPD chapter: 1.4 Nuclear targets.

Importance for HI programmes:

• LHeC will offer most valuable information for identifying the medium created in HIC with the QGP, and to characterize it:

→ Accurate npdf's required to establish the benchmark nuclear effects for perturbative probes on top of which the effects of the medium will be studied.

→ eA offers a laboratory to study particle production which in AB will determine the initial conditions for the creation and subsequent collective properties of the medium.

→ ep to eA gives the possibility to study the non-QGP effects of the nuclear medium on QCD radiation and hadronization (large lever arm in partonic energies), whose modification in AB characterizes the created medium.

Contents:

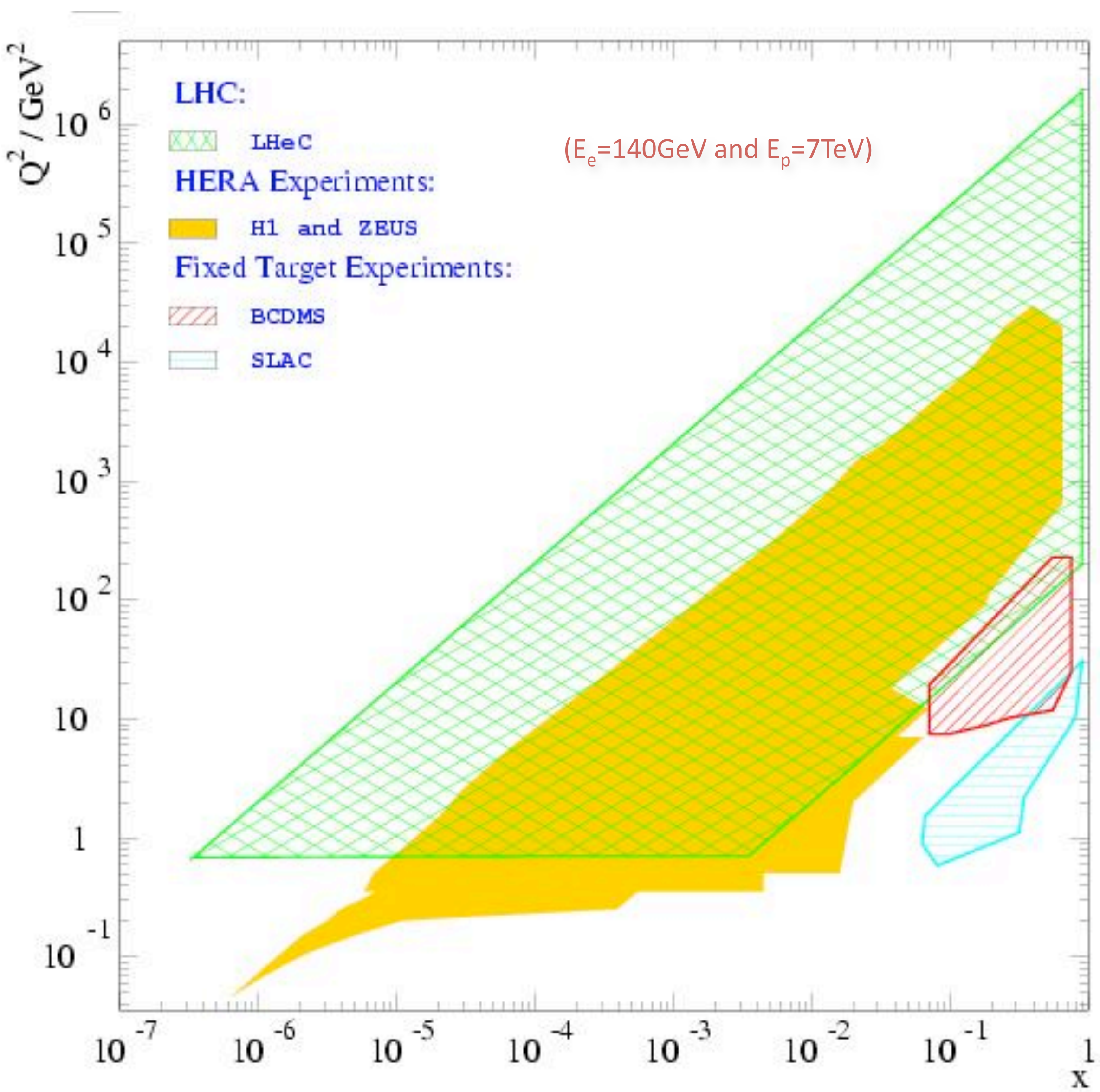
1. Physics at small x:
   - 1.1 Unitarity and QCD.
   - 1.2 Status following HERA data.
   - 1.3 Low-x physics at the LHC (David d'Enterria, also Carlos Salgado).
   - 1.4 Nuclear targets.

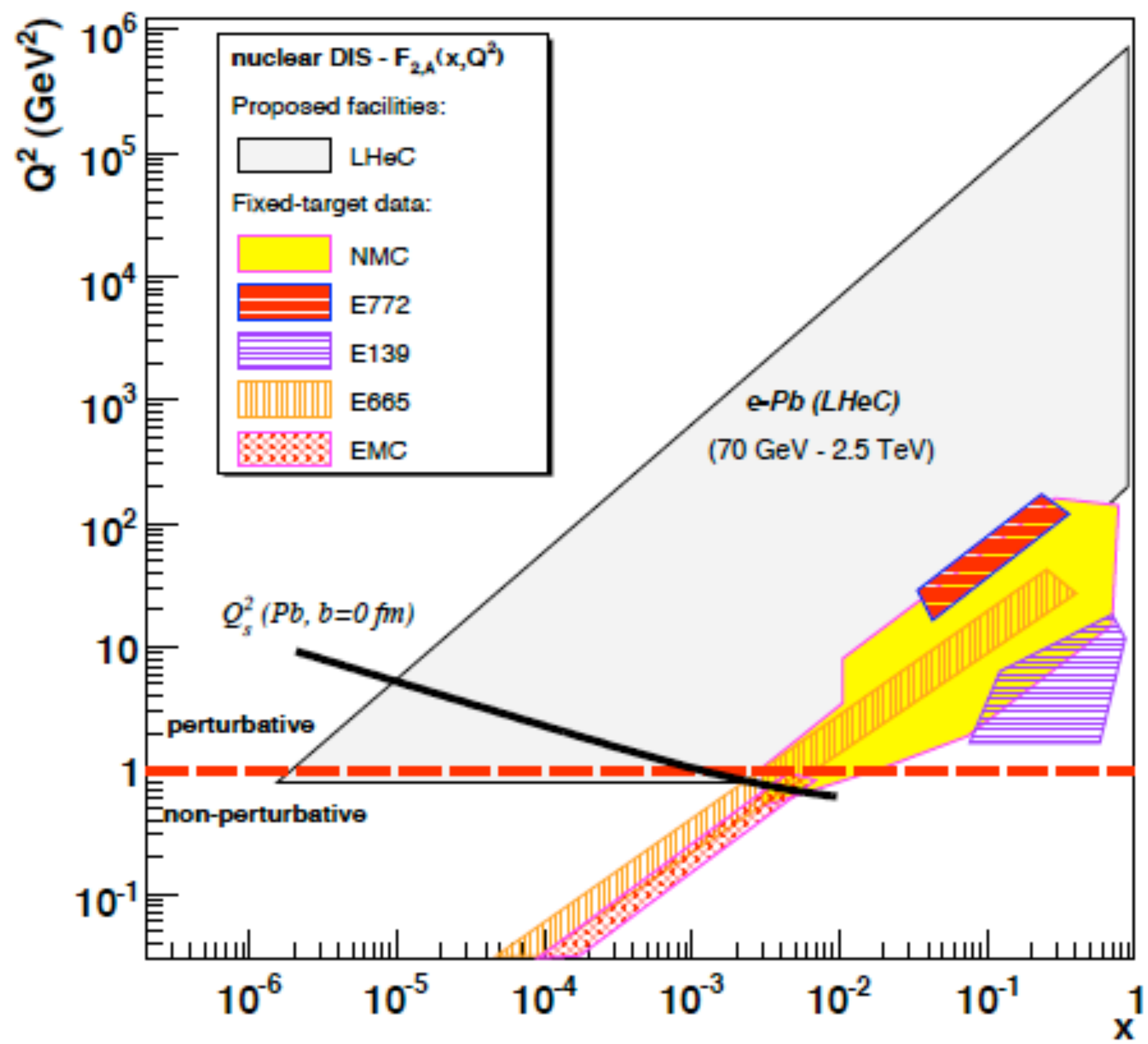
2. Prospects at the LHeC:
   - 2.1 Strategy: decreasing x and increasing A.
   - 2.2 Inclusive measurements (Javier Albacete and Carlos Salgado).
   - 2.3 Exclusive production (Graeme Watt).
   - 2.4 Exclusive vector meson production (Graeme Watt and Henri Kowalski).
   - 2.5 DVCS and GPDs.
   - 2.6 Inclusive diffraction.
   - 2.7 Jet and multi-jet observables, parton dynamics and fragmentation.
   - 2.8 Photoproduction Physics.
   - 2.9 Implications for the ultra-high energy neutrino interactions.

2.1 Strategy: decreasing x/increasing A

- A two-pronged strategy will be pursued to check that deviations from linear behavior have their origin in higher density - as expected.

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





2.2 Inclusive measurements

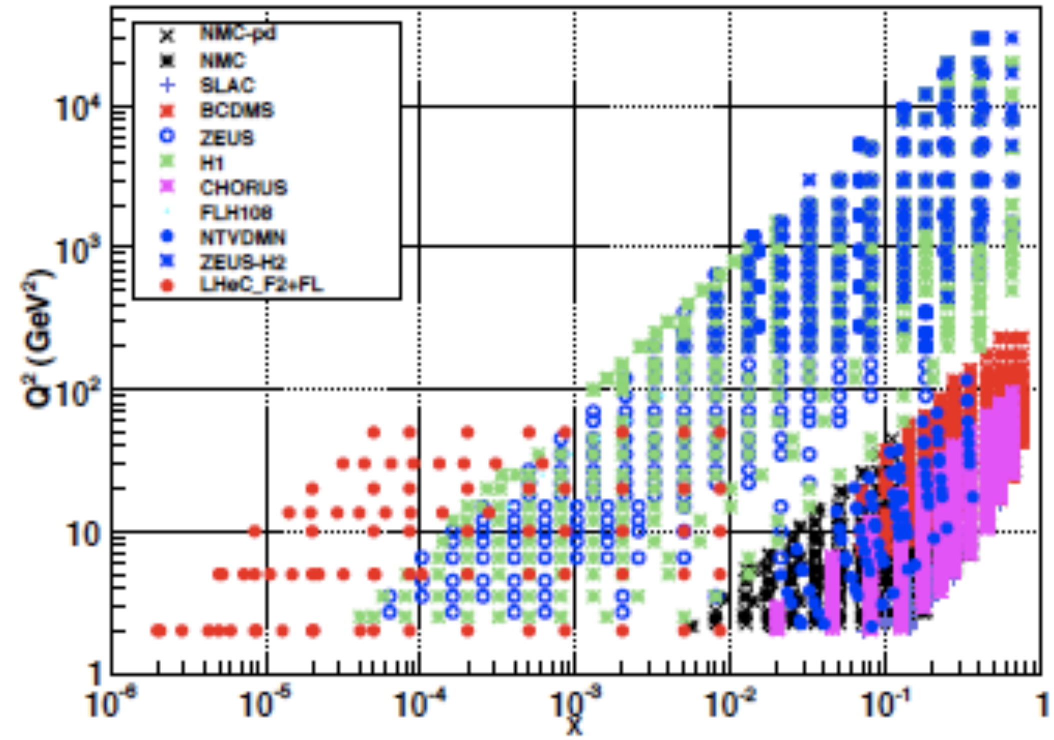
* Predictions for the proton (Javier Albacete).

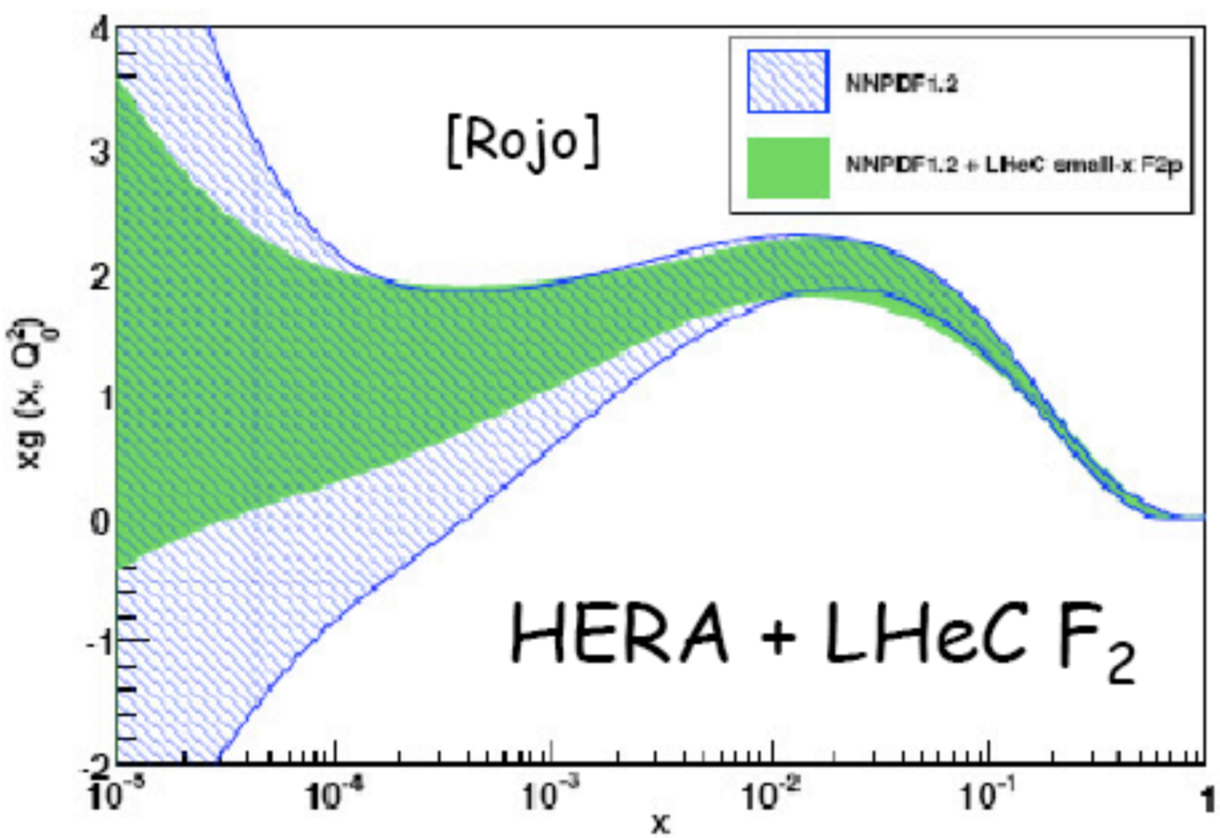
* Testing non-linear dynamics (J. Forshaw, J. Rojo, G. Soyez, PN, AS), see Javier Albacete.

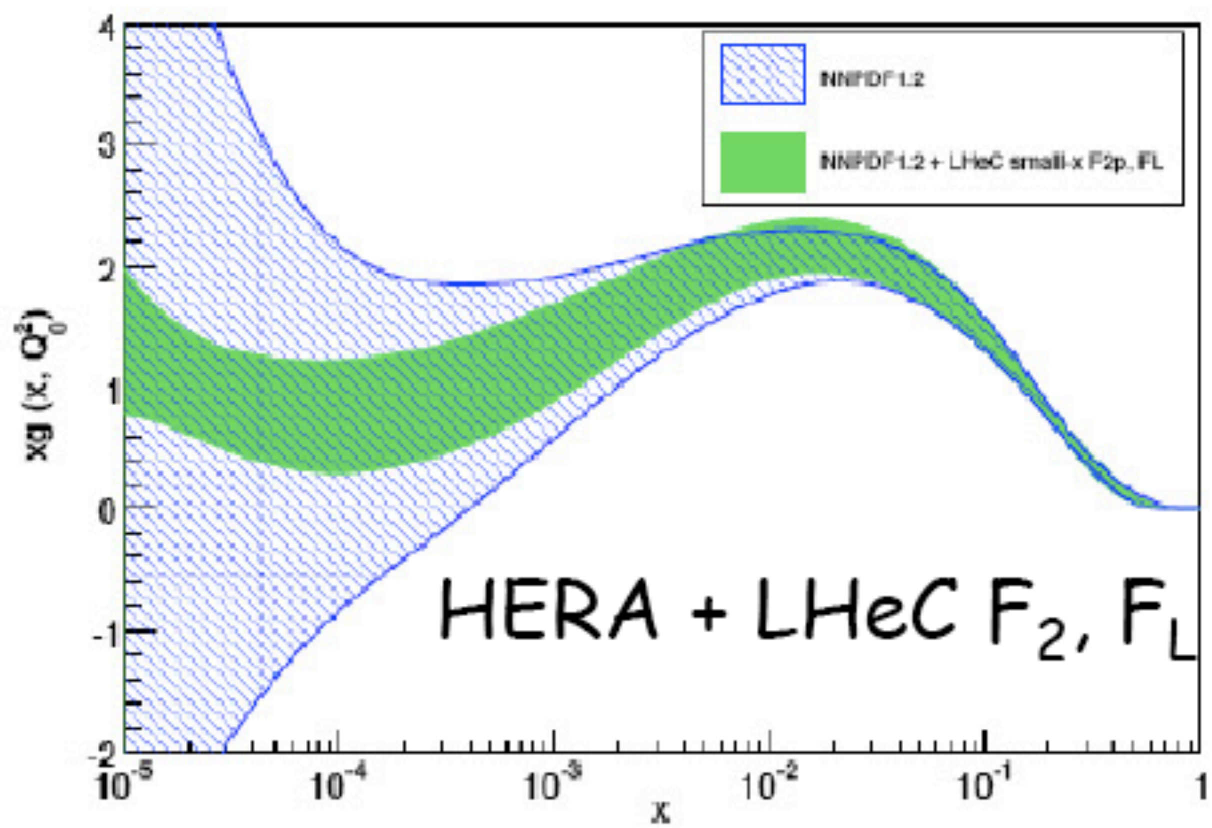
* Predictions for nuclei: impact on nuclear DGLAP analyses (K. Eskola, H. Paukkunen, C. Salgado, K. Tywoniuk, NA), see Carlos Salgado.

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.



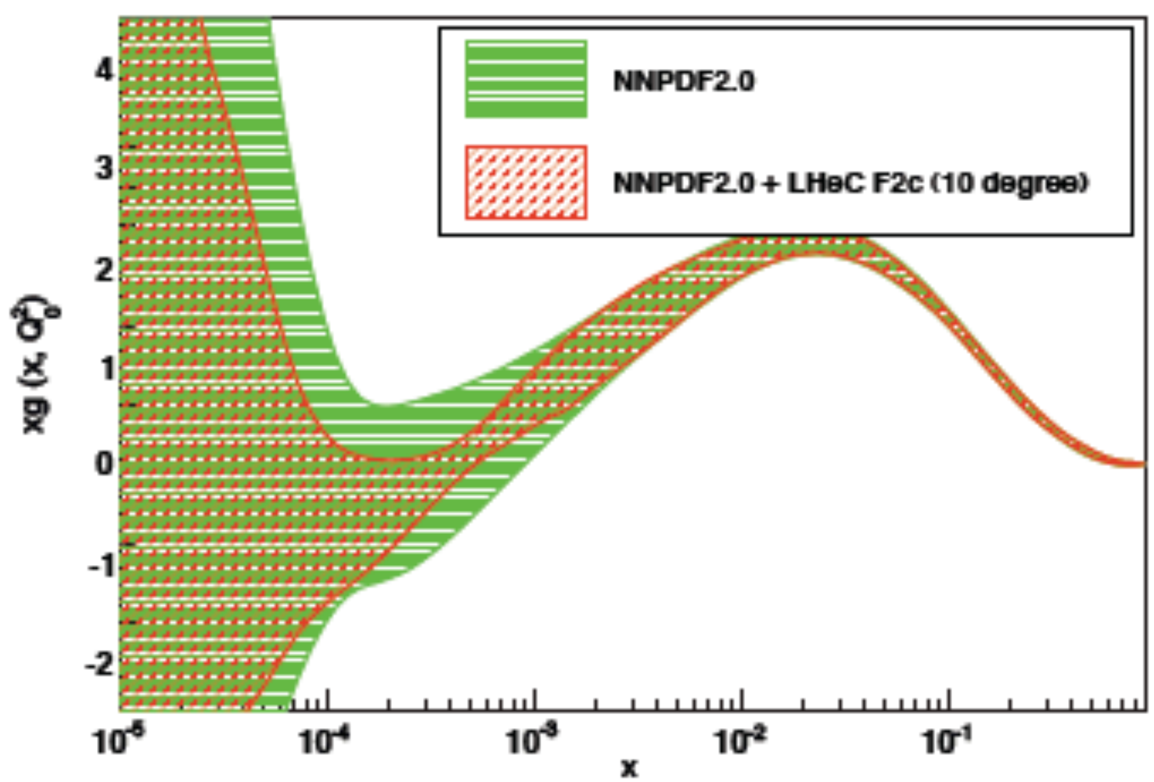


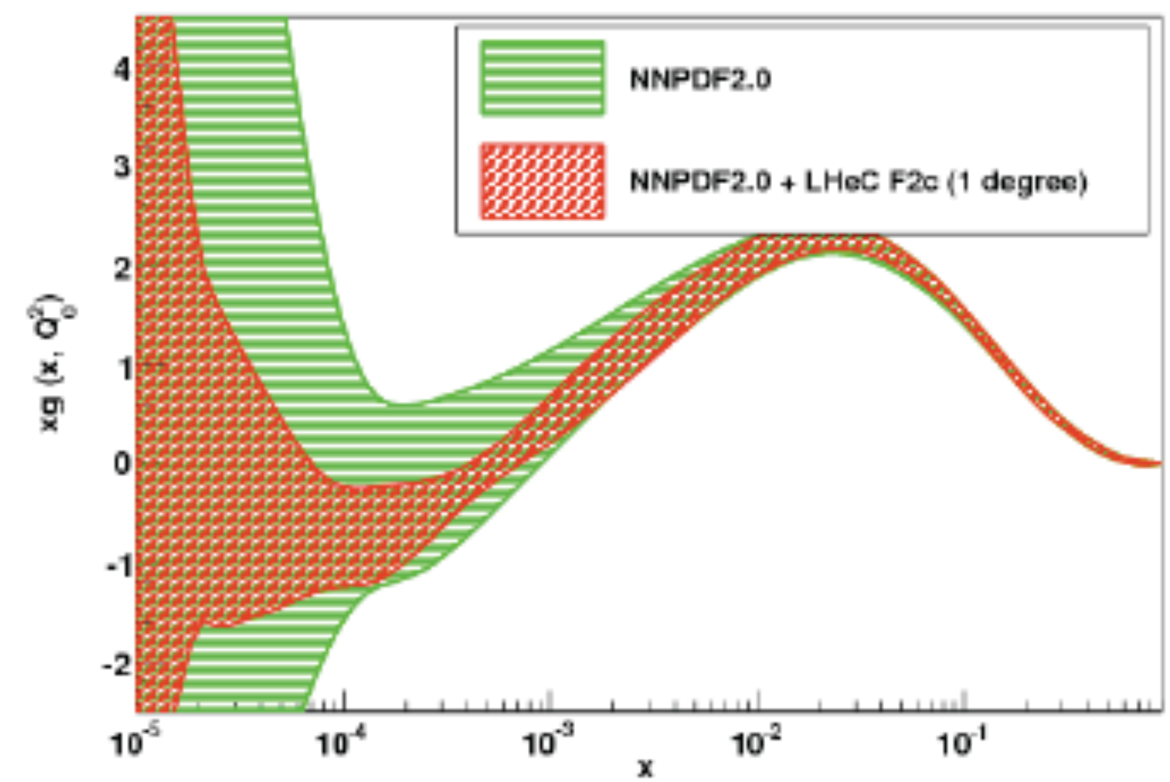


$(Q^2 = 2\ GeV^2)$

Impact on DGLAP for p: F_{2c}

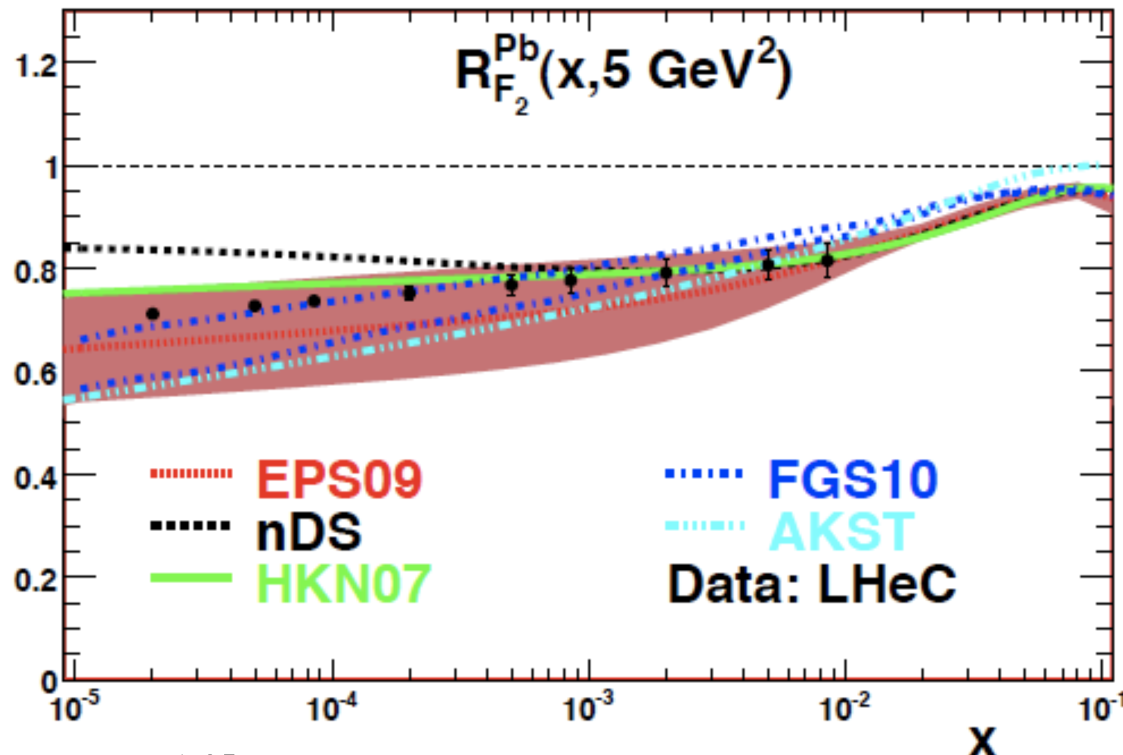
- F_{2c}: further improvement without F_L (new!!!).

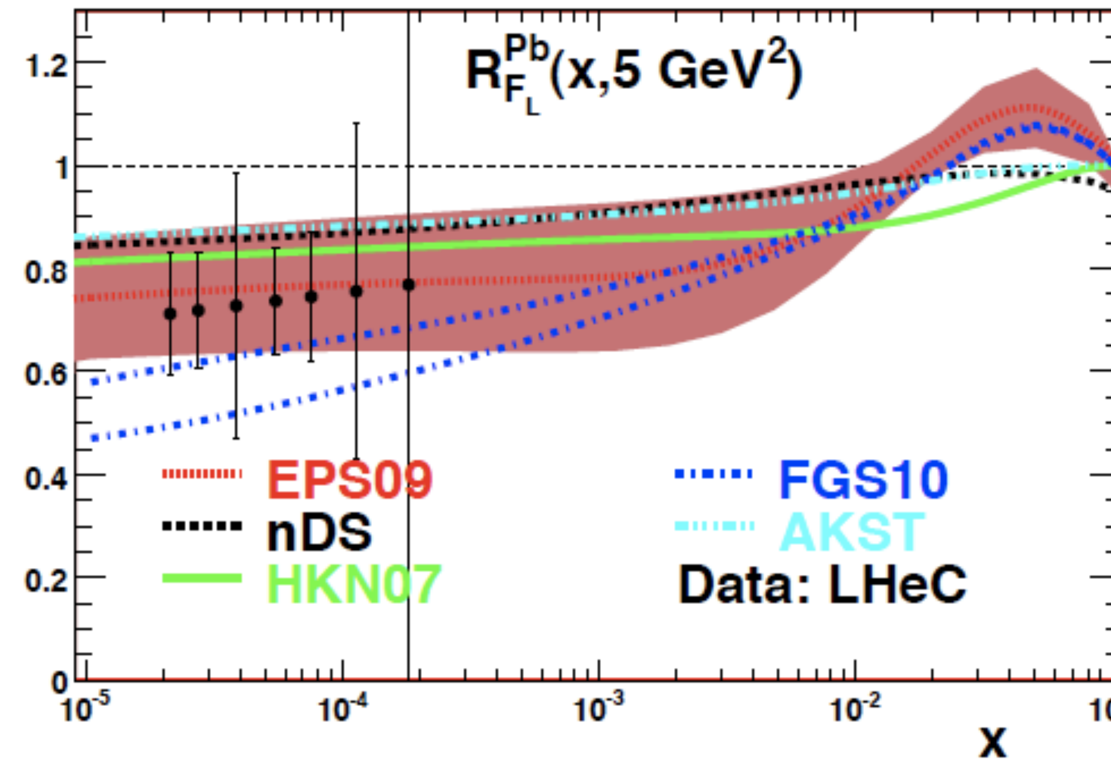


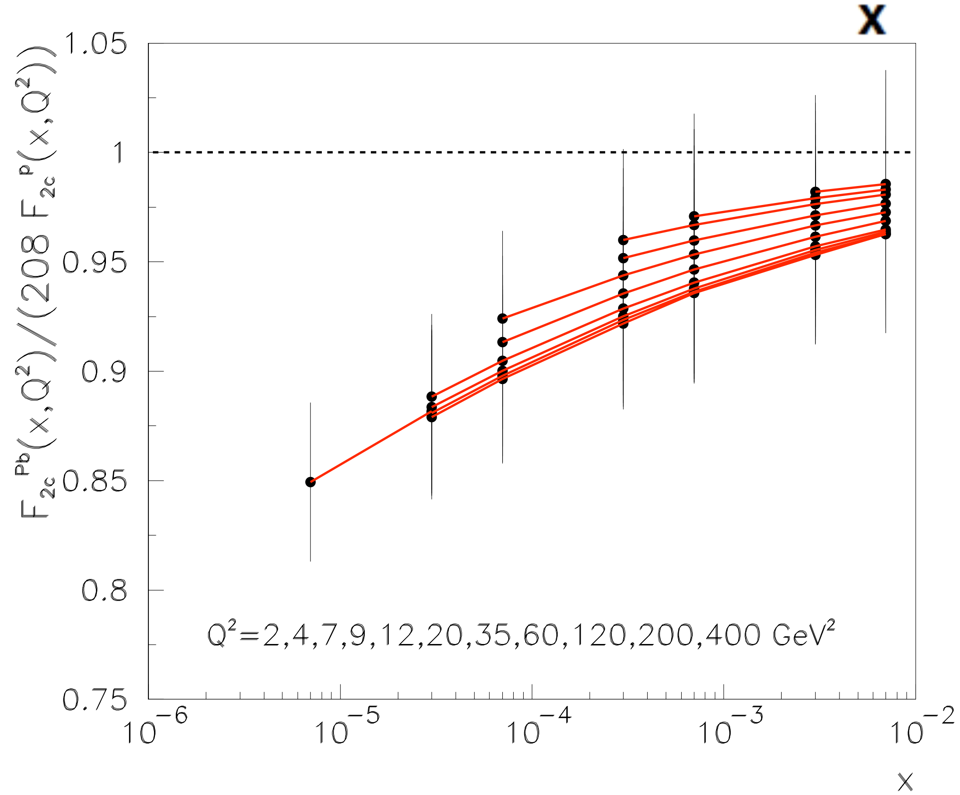


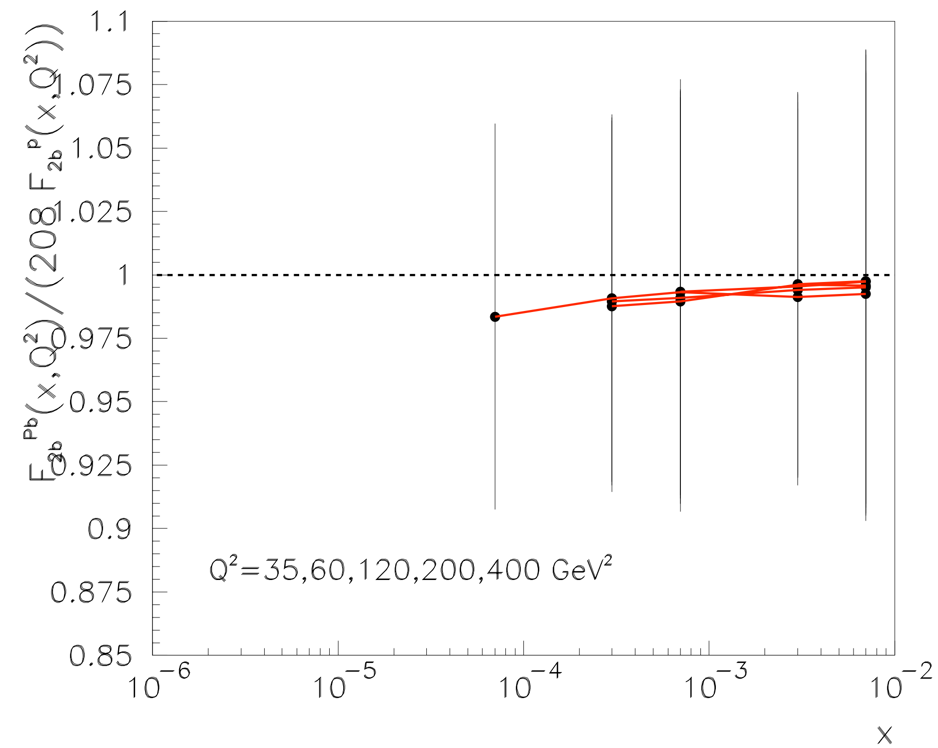
Nuclear SF:

- F_2, F_L, $F_{2c,b}$ will be measured with discriminating accuracy on existing models.









Overview of the HPD chapter: 2.2 Inclusive measurements.

2.4 Exclusive VM production:

* Introduction (PN), see Graeme Watt.

* $\sigma(W)$ for protons (G. Watt, PN, AS), see Graeme Watt.

* t-dependence (G. Watt, PN, AS), see Graeme Watt.

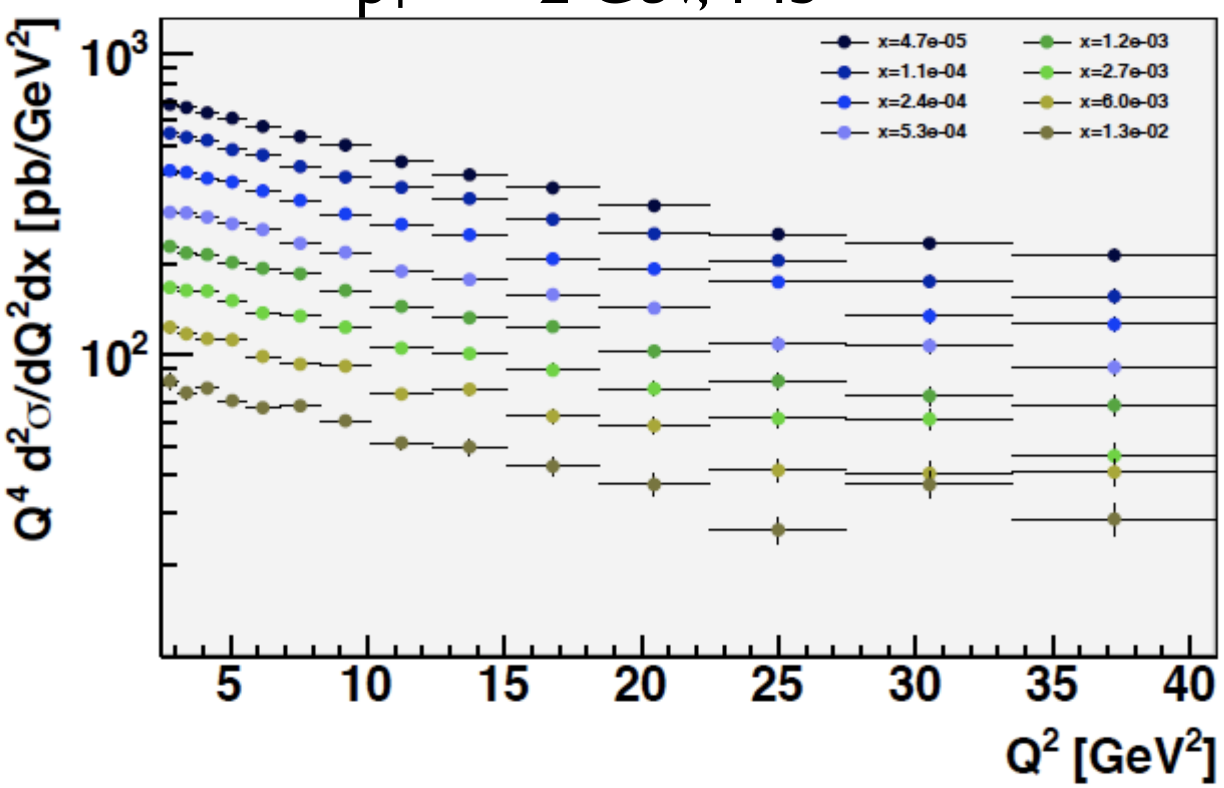
* Diffractive VM production from nuclei (Henri Kowalski).

2.5 DVCS and GPDs:

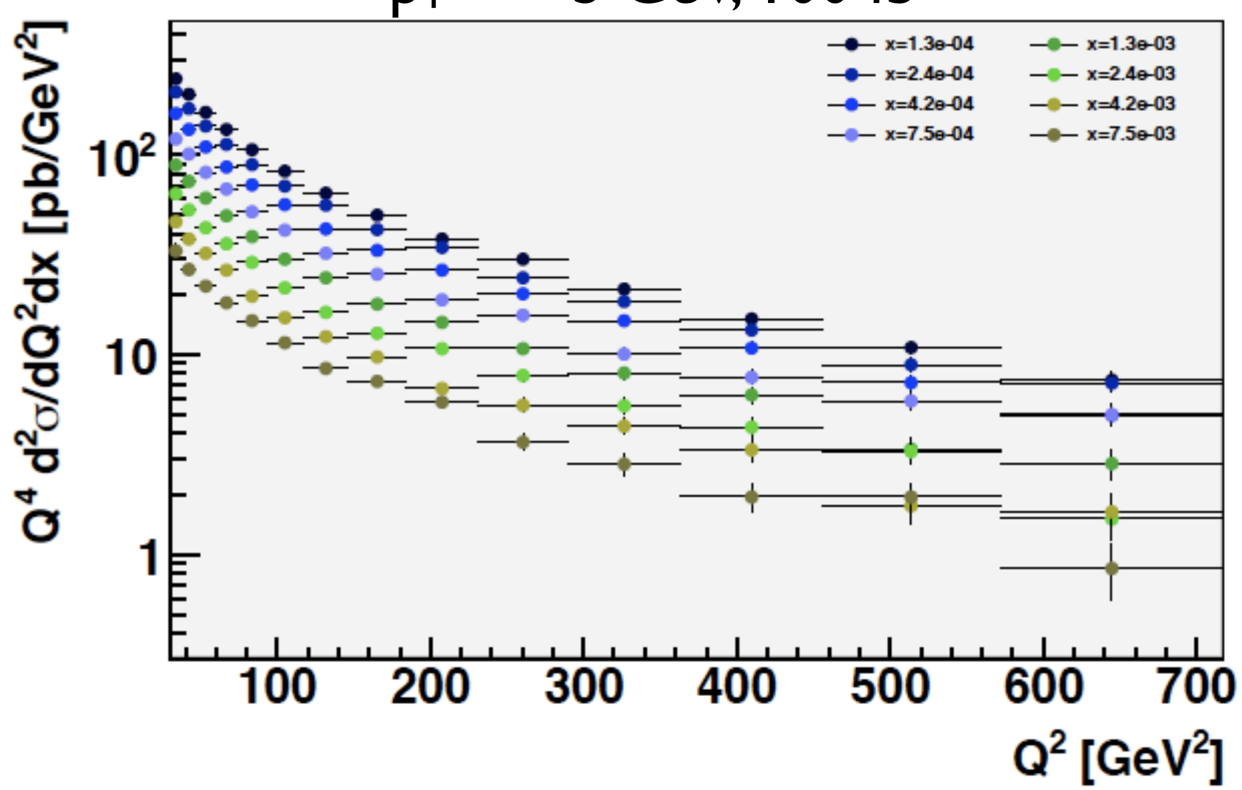
- Exclusive processes like $\gamma^* + h \rightarrow (\rho, \phi, \gamma) + h$ give information of GPDs, whose Fourier transform gives a transverse scanning of the hadron: key importance for both non-perturbative and perturbative aspects, like the possibility of non-linear dynamics.

- 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}



2.6 Inclusive diffraction:

* Diffractive Deep Inelastic Scattering (AS, PN).

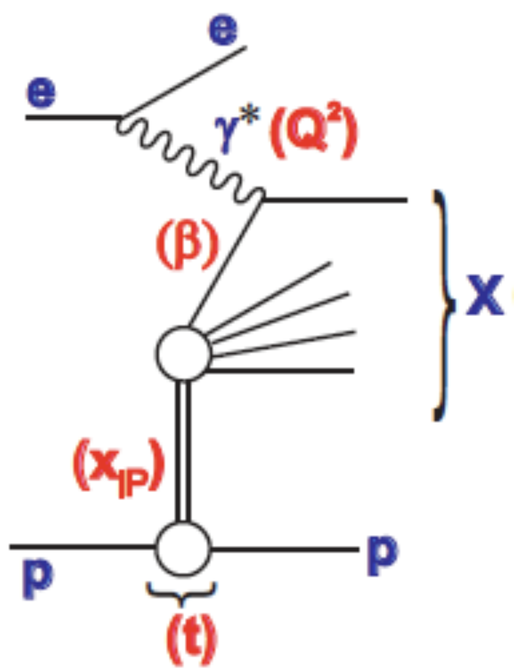
* Diffractive Parton Densities (PN).

* Diffractive DIS, Dipole Models and Sensitivity to Non-linear Effects (T. Lappi, C. Marquet, PN).

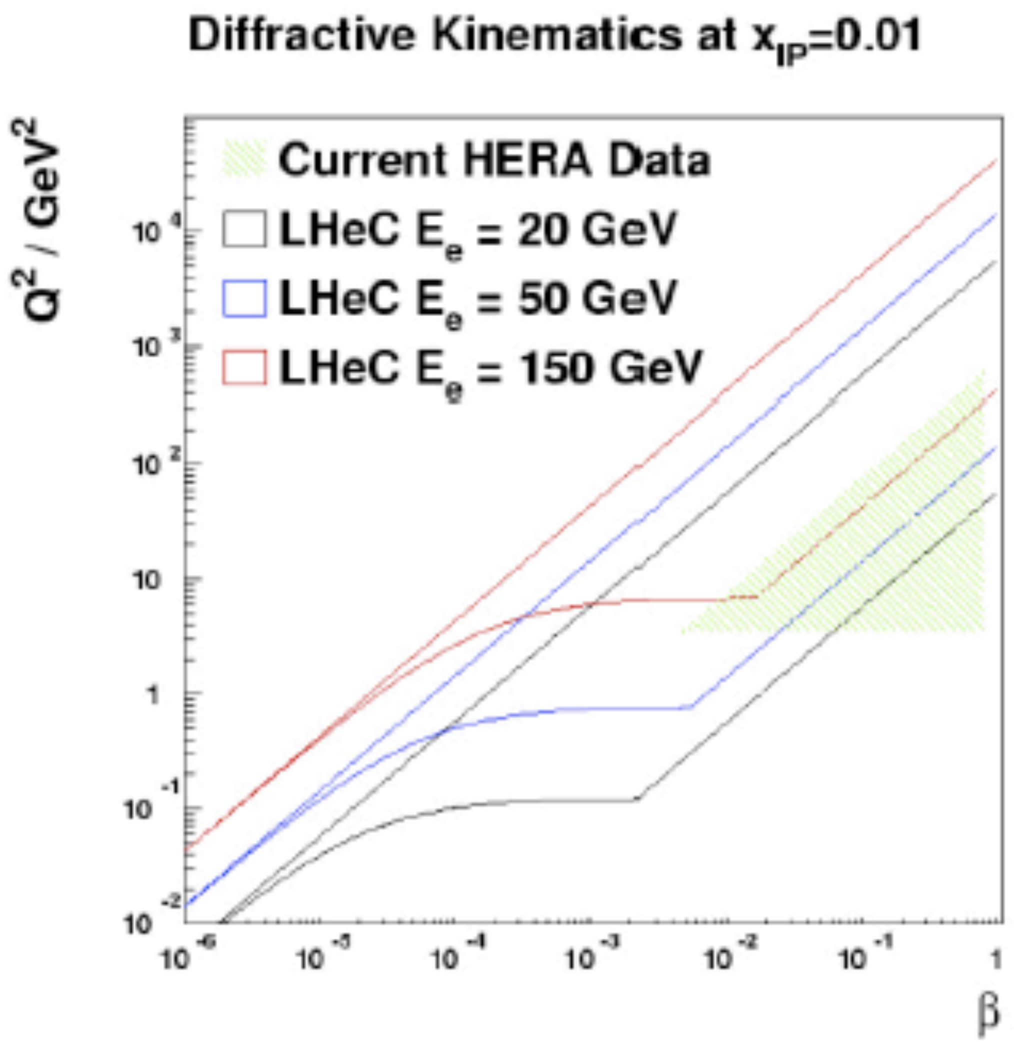
* Predicting nuclear shadowing from inclusive diffraction in ep (M. Strikman, K. Tywoniuk, NA).

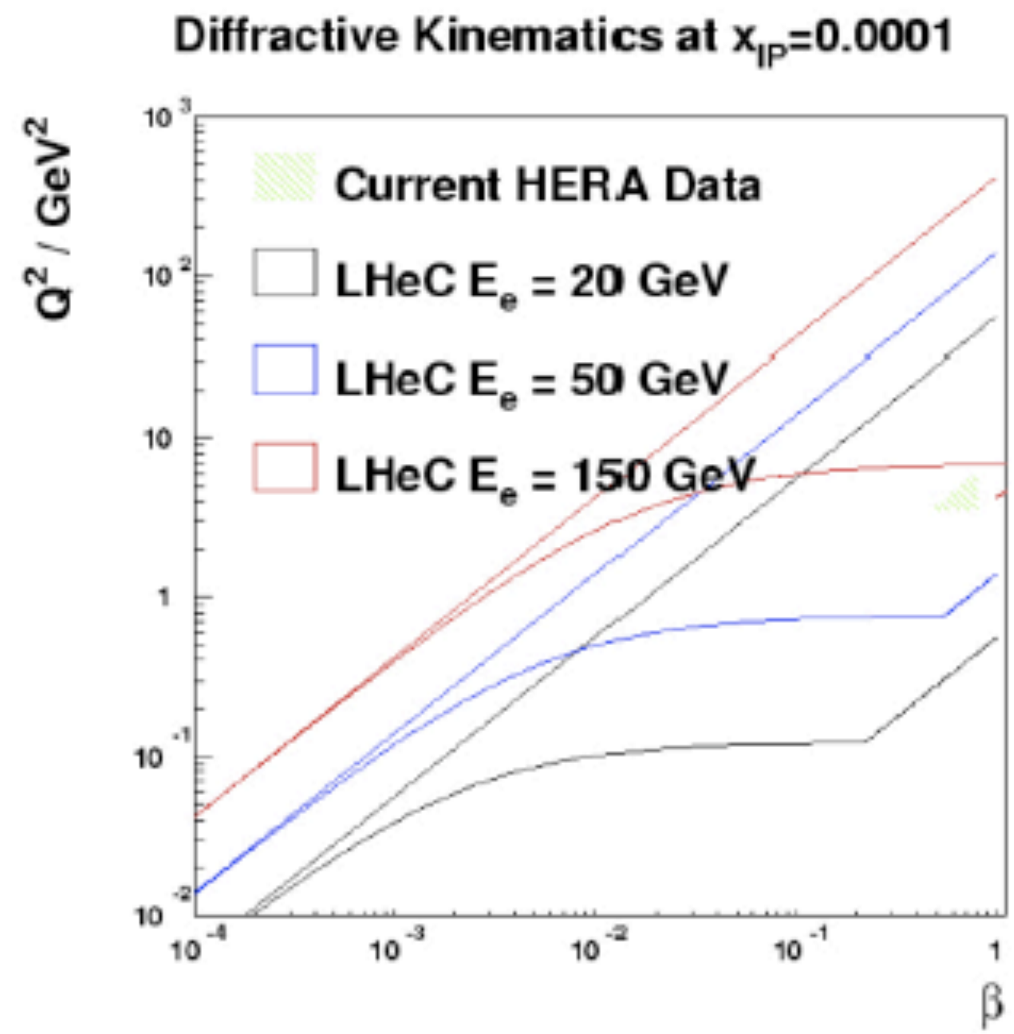
* Predictions for inclusive diffraction on nuclear targets (T. Lappi, C. Marquet, AS).

Diffractive DIS (I):



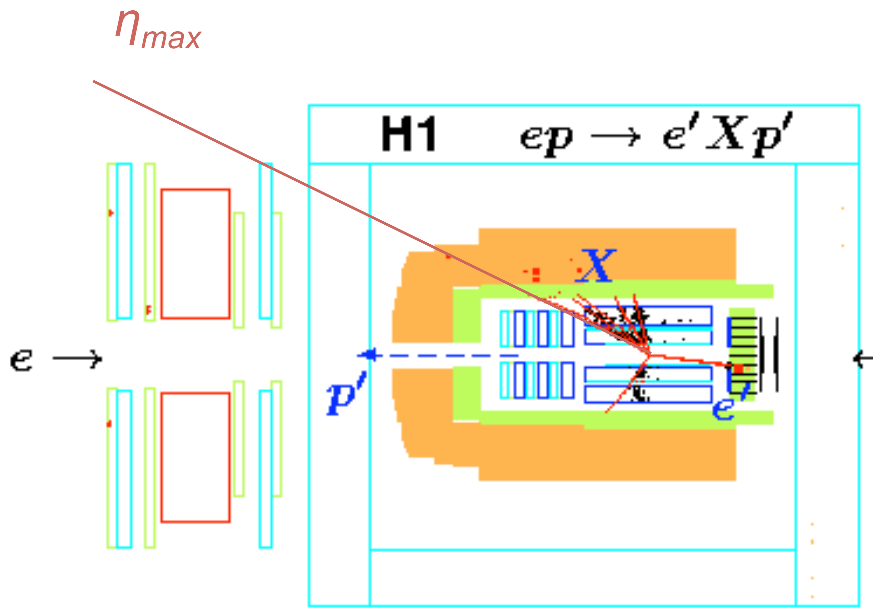
- LHeC will extend the kinematical reach in diffractive DIS (both in x_P and in β) tremendously.

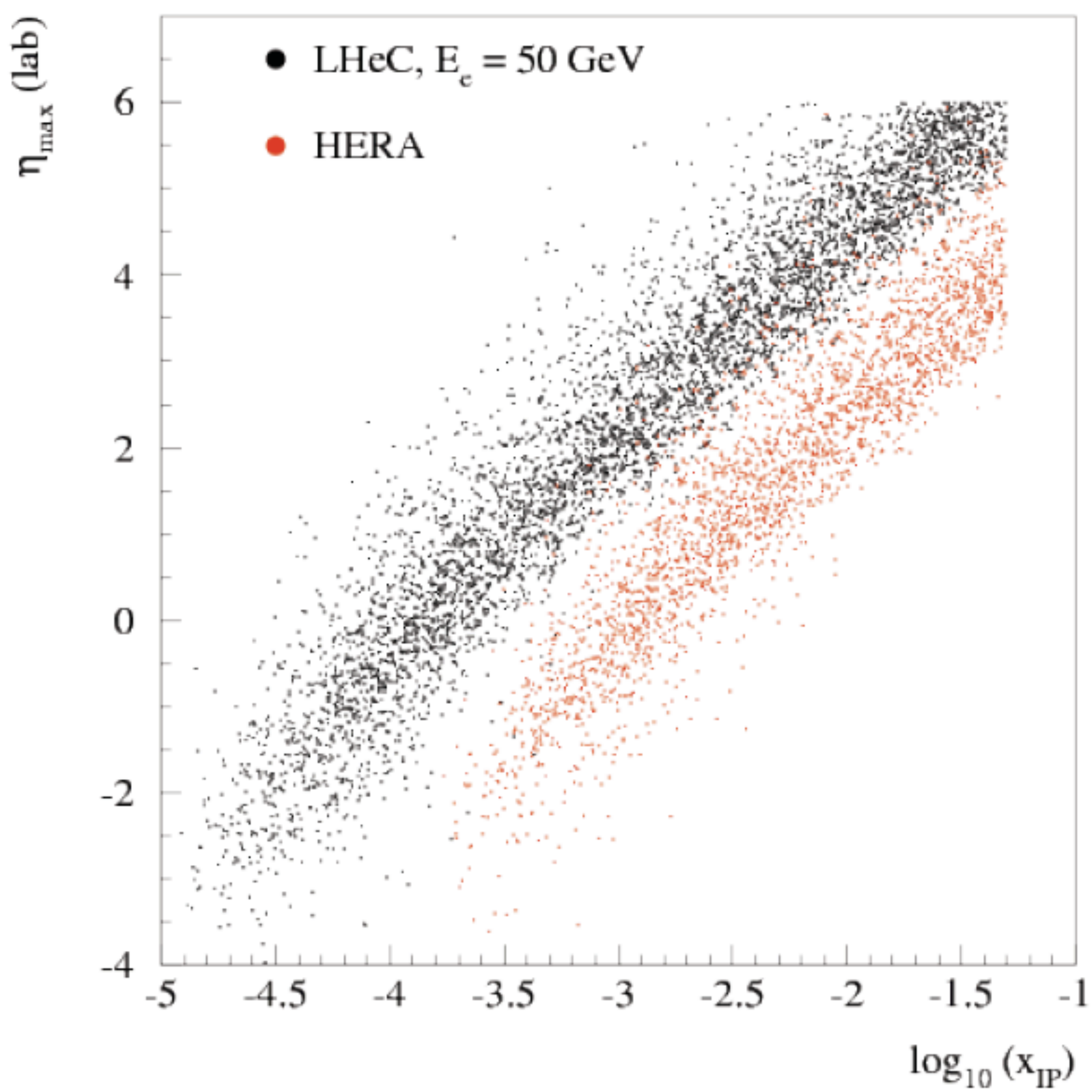




Overview of the HPD chapter: 2.6 Inclusive diffraction.

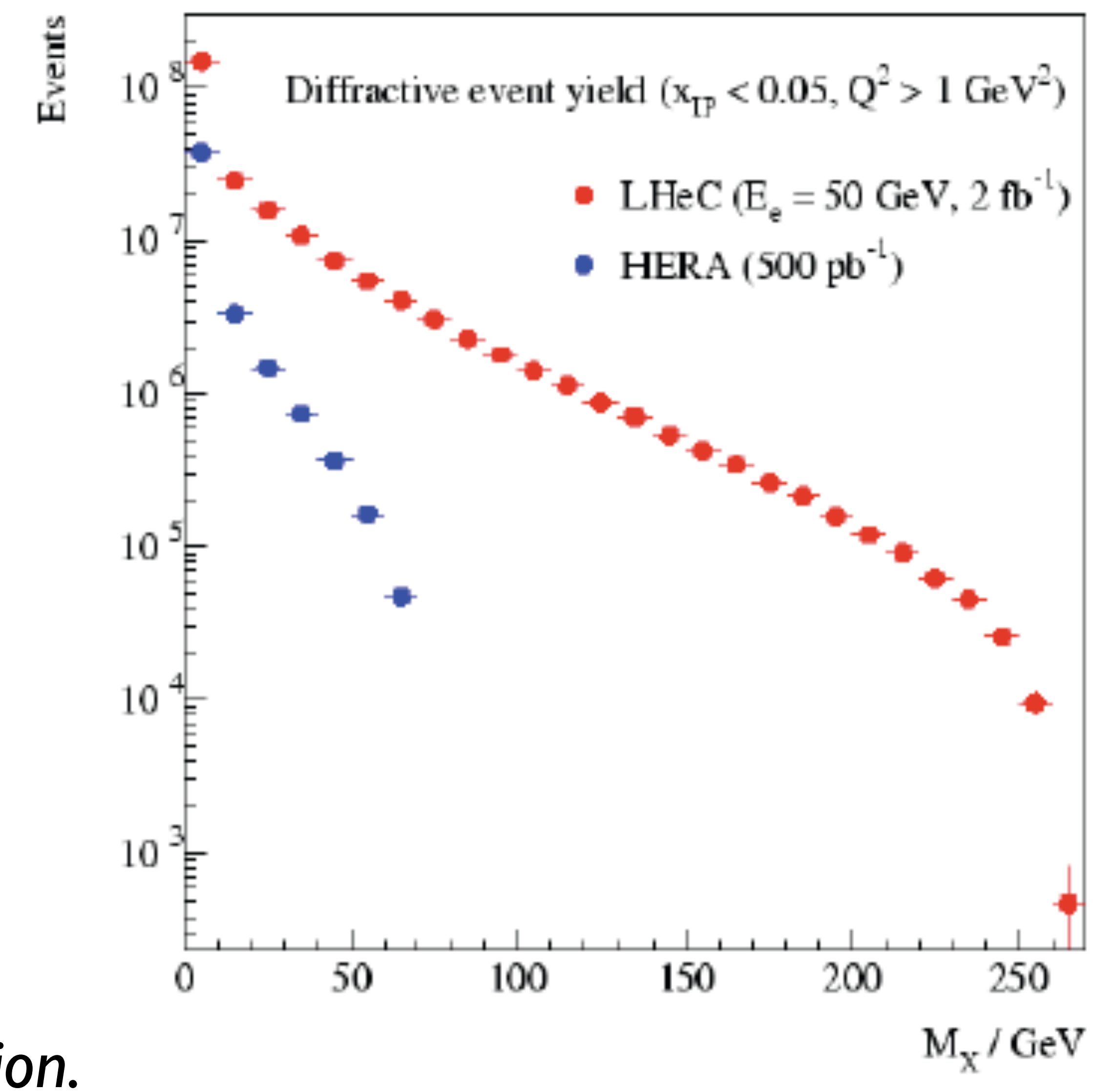
Diffractive DIS (II):





- Both the η-gap method and p-tagging considered.

- Large reach in diffractive masses: EW bosons, single top, 1⁻ exotics!!!



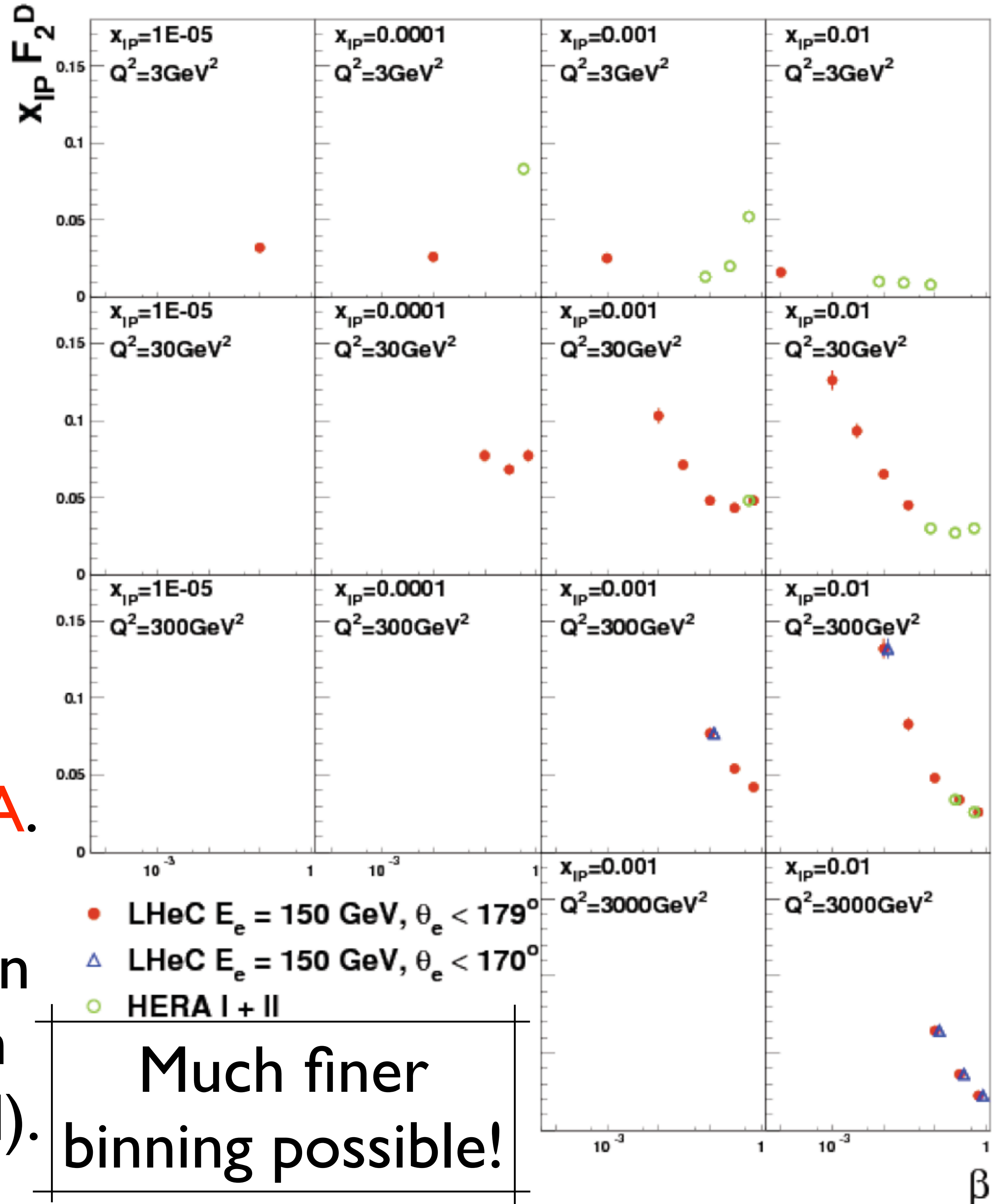
Overview of the HPD chapter: 2.6 Inclusive diffraction.

Diffractive pdf's:

- Theory shows that it is possible to factorize the x_P and β dependencies of the DDIS structure functions, respectively into a flux and a set of *diffractive* parton densities, DGLAP evolved.

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

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

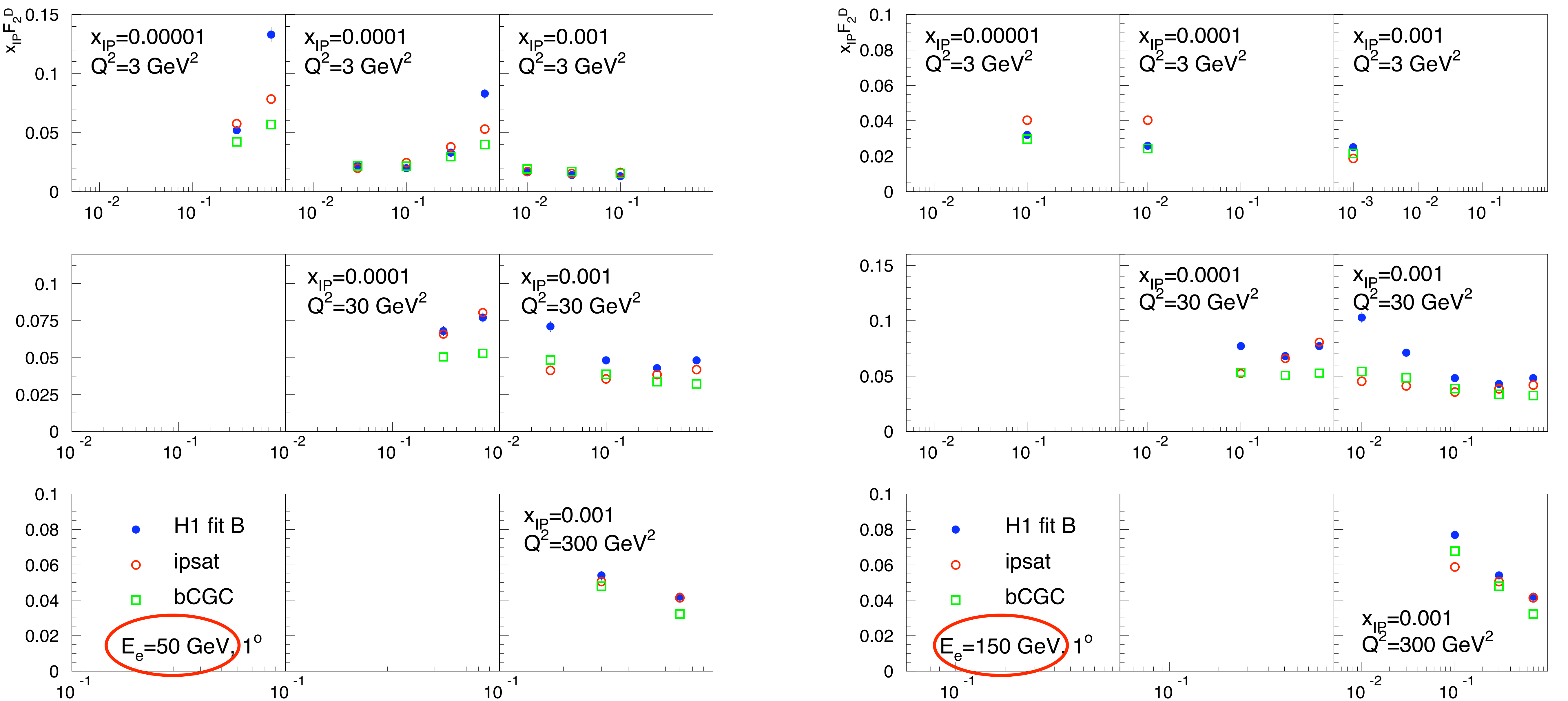


Much finer binning possible!

Overview of the HPD chapter: 2.6 Inclusive diffraction.

Sensitivity to non-linear dynamics:

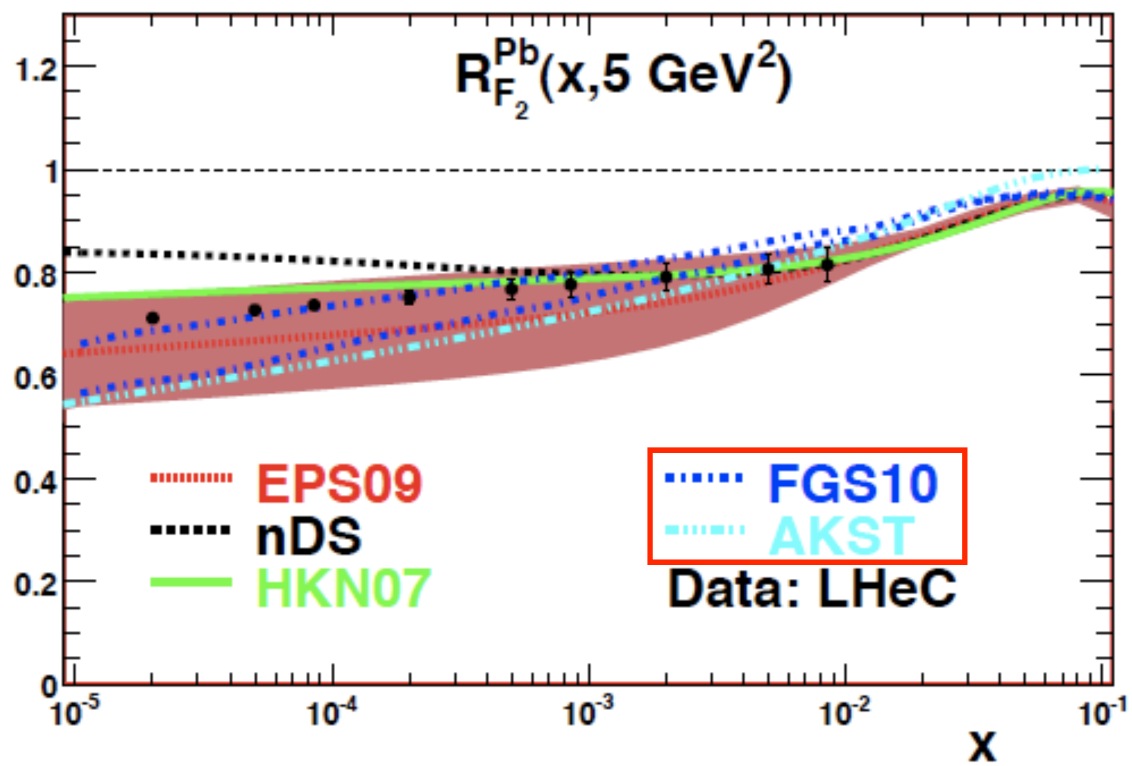
- Dipole models show differences with linear-based extrapolations (HERA-based dpdf's) and among each other: possibility to check saturation and its realization.

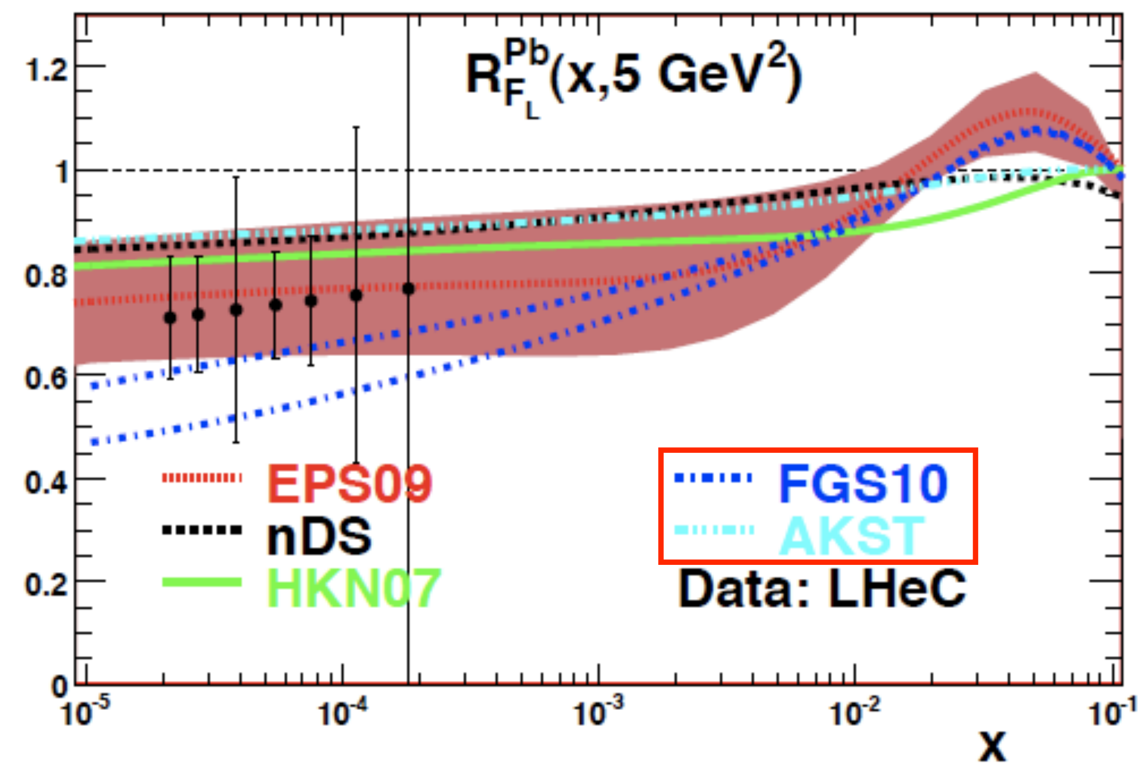


Predicting nuclear shadowing:

- Exact relation between diffraction in on a nucleon and nuclear shadowing on two nucleons (D or first contribution to nuclear shadowing for larger nuclei).

- Different extrapolations for more than two nucleons yield different results: fluctuations in the cross sections.



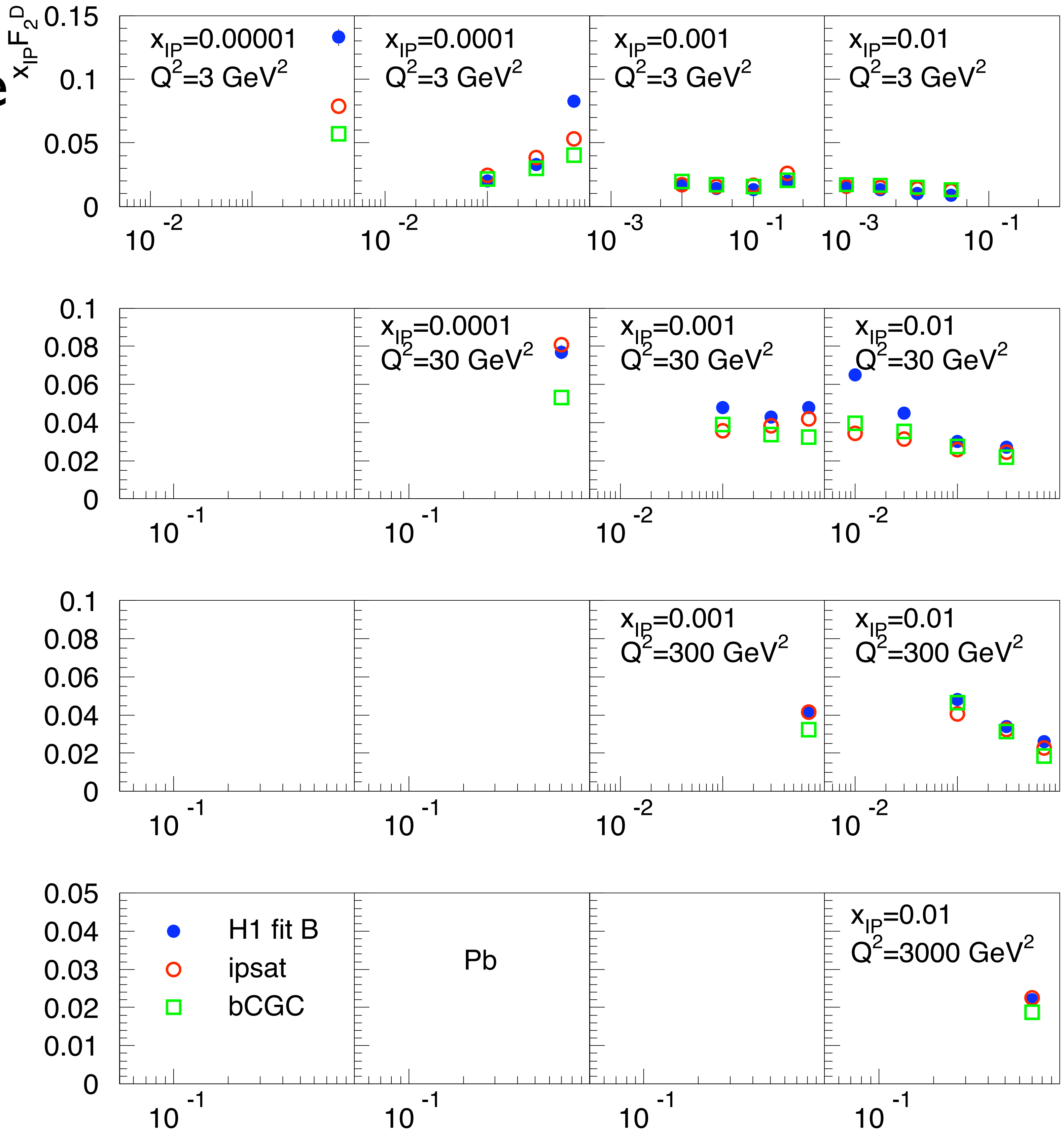


Diffractive DIS on nuclear targets:

- Nuclear diffraction maybe coherent (e+A→e+X+A), incoherent (e+A→e+X+Zp+(A-Z)n) and inelastic (e+A→e+X+X') ⇒ challenging experimental problem.

- Requires Monte Carlo simulation with detailed understanding of the nuclear break-up.

- For the coherent case, predictions available.



Overview of the HPD chapter: 2.6 Inclusive diffraction.

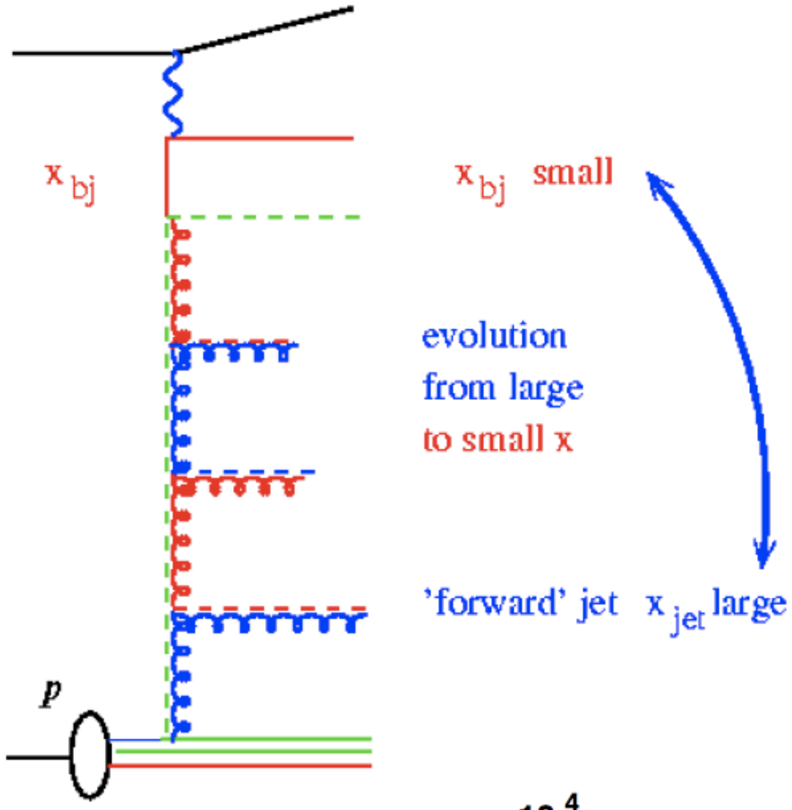
2.7 Jet and multi-jet observables, parton dynamics and fragmentation:

* Forward jets, dijets, angular decorrelation (K. Kutak, H. Jung).

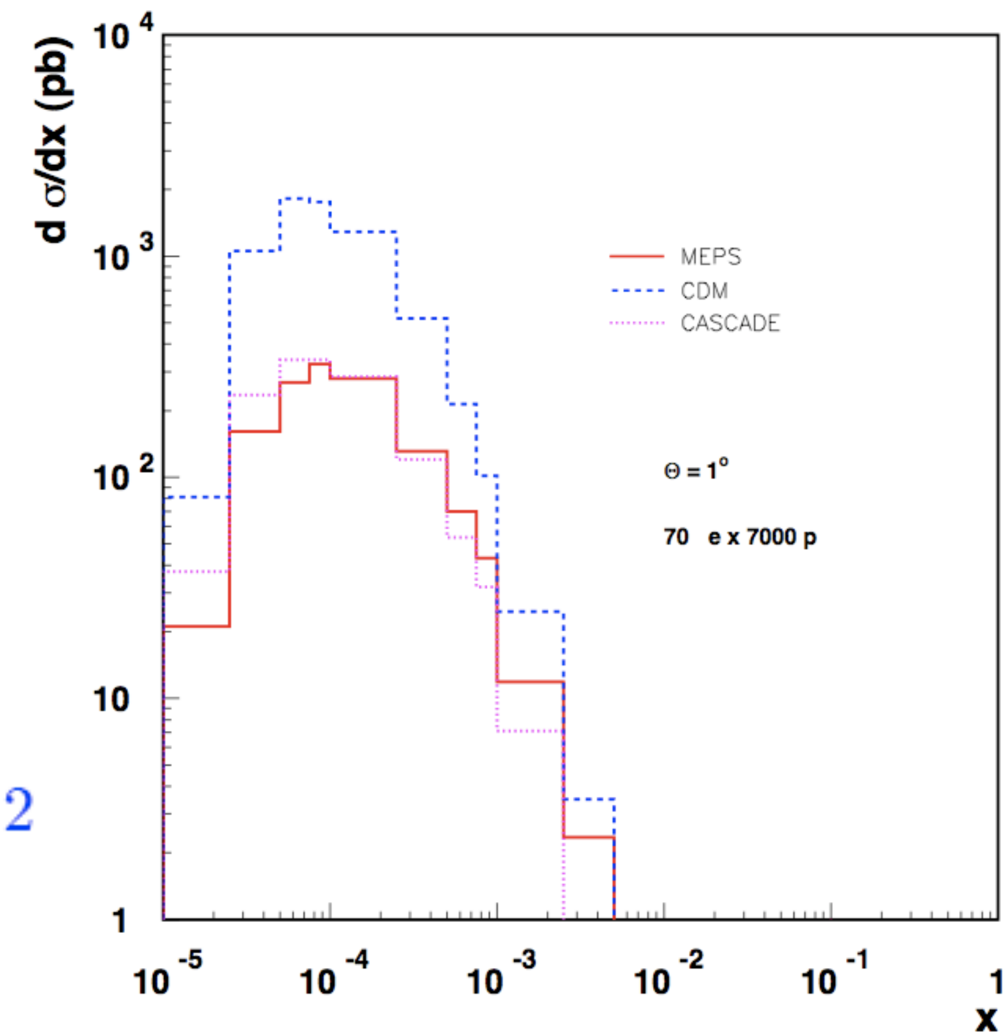
* Unintegrated PDFs (J. Collins, NA, AS): theoretical introduction.

* Perturbative and non-perturbative aspects of final state radiation and hadronization (W. Brooks, BC).

Forward jets:



Jung at Divonne'08



$$x_{jet} > 0.03$$

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

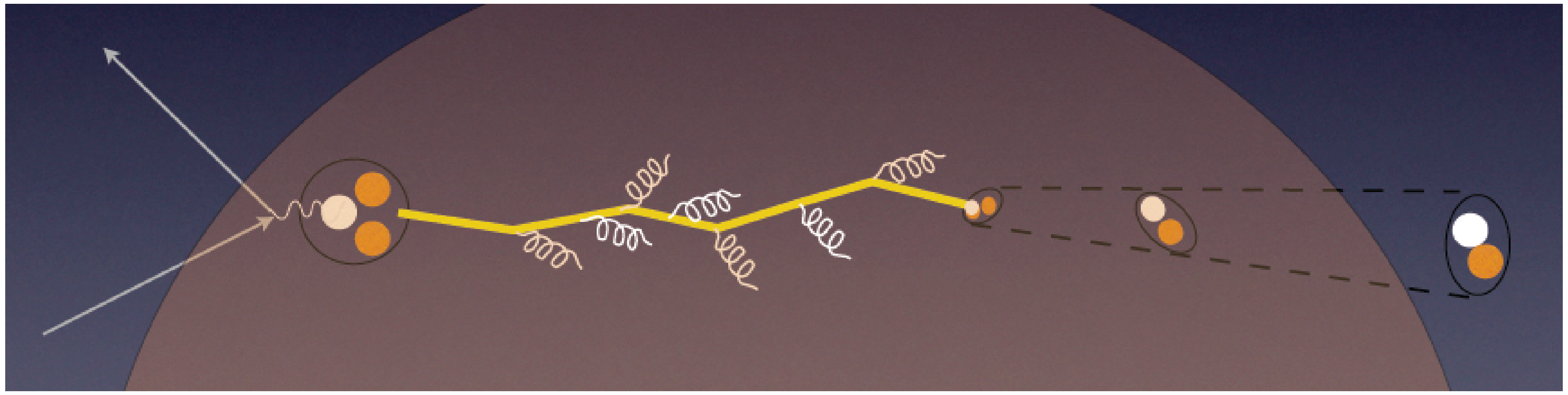
- Studying forward jets ($p_T \sim Q$) would allow to understand the mechanism of radiation:
  → k_T-ordered: DGLAP.
  → k_T-disordered: BFKL.
  → Saturation?

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

Parton dynamics, fragmentation:

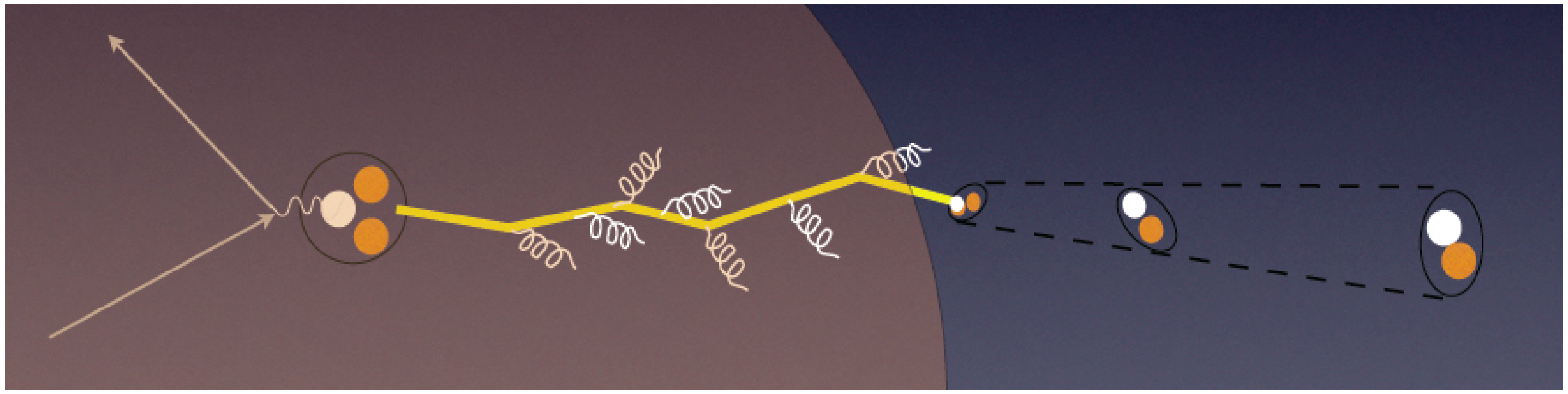
- The LHeC (ν_{max}~10^5 GeV) would allow to study the dynamics of hadronization, testing the parton/hadron eloss mechanism by introducing a length of colored material which would modify its pattern (length/nuclear size, chemical composition).

- Low energy: need of hadronization inside → formation time, (pre-) hadronic absorption,...



Brooks at Divonne'09

- High energy: partonic evolution altered in the nuclear medium, partonic energy loss.



2.8 Photoproduction Physics:

* The total photoproduction cross section (NA, PN).

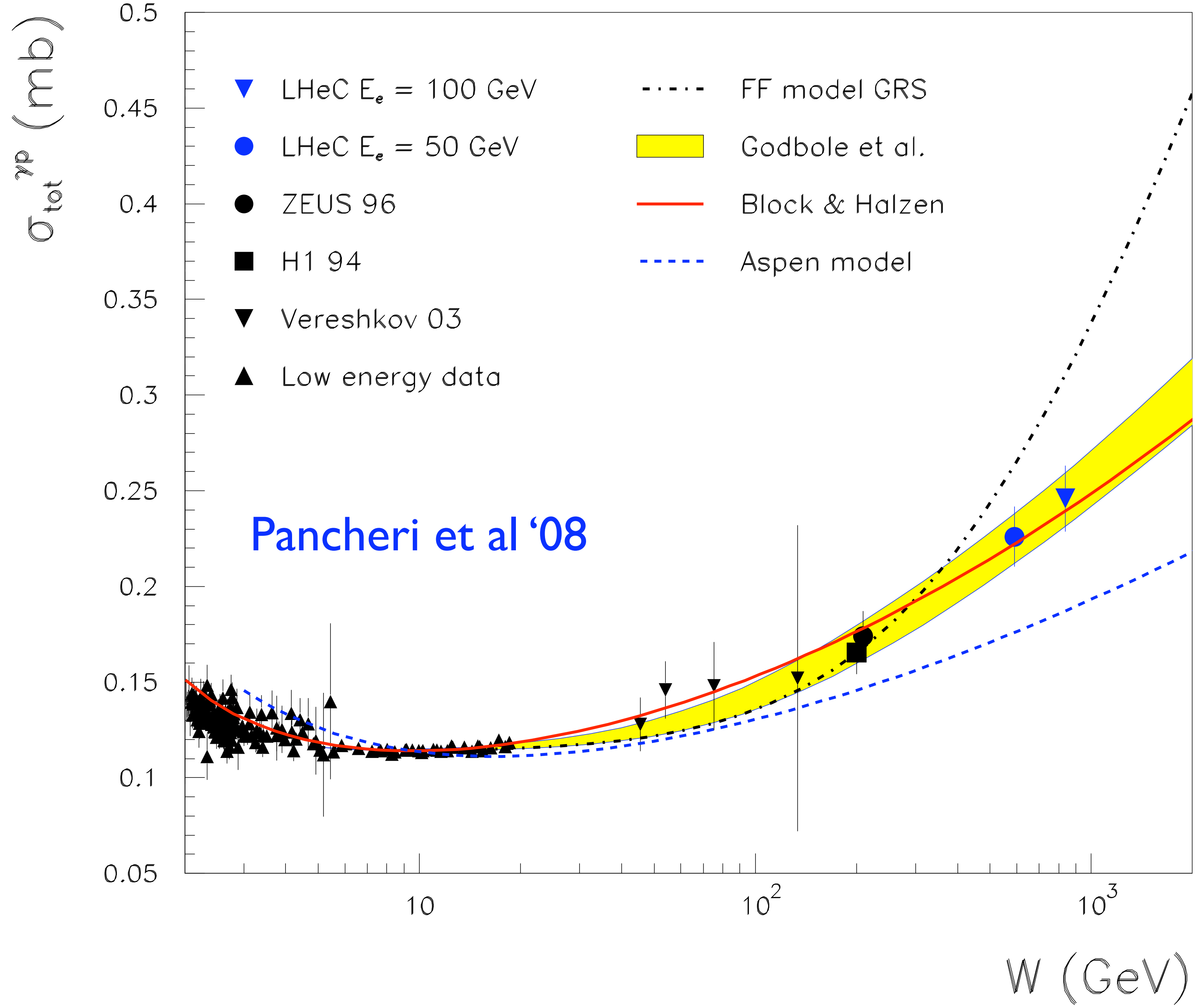
* Jet photoproduction (NA).

* Photon Structure (PN): probably covered in QCD/EW chapter
- to discuss.

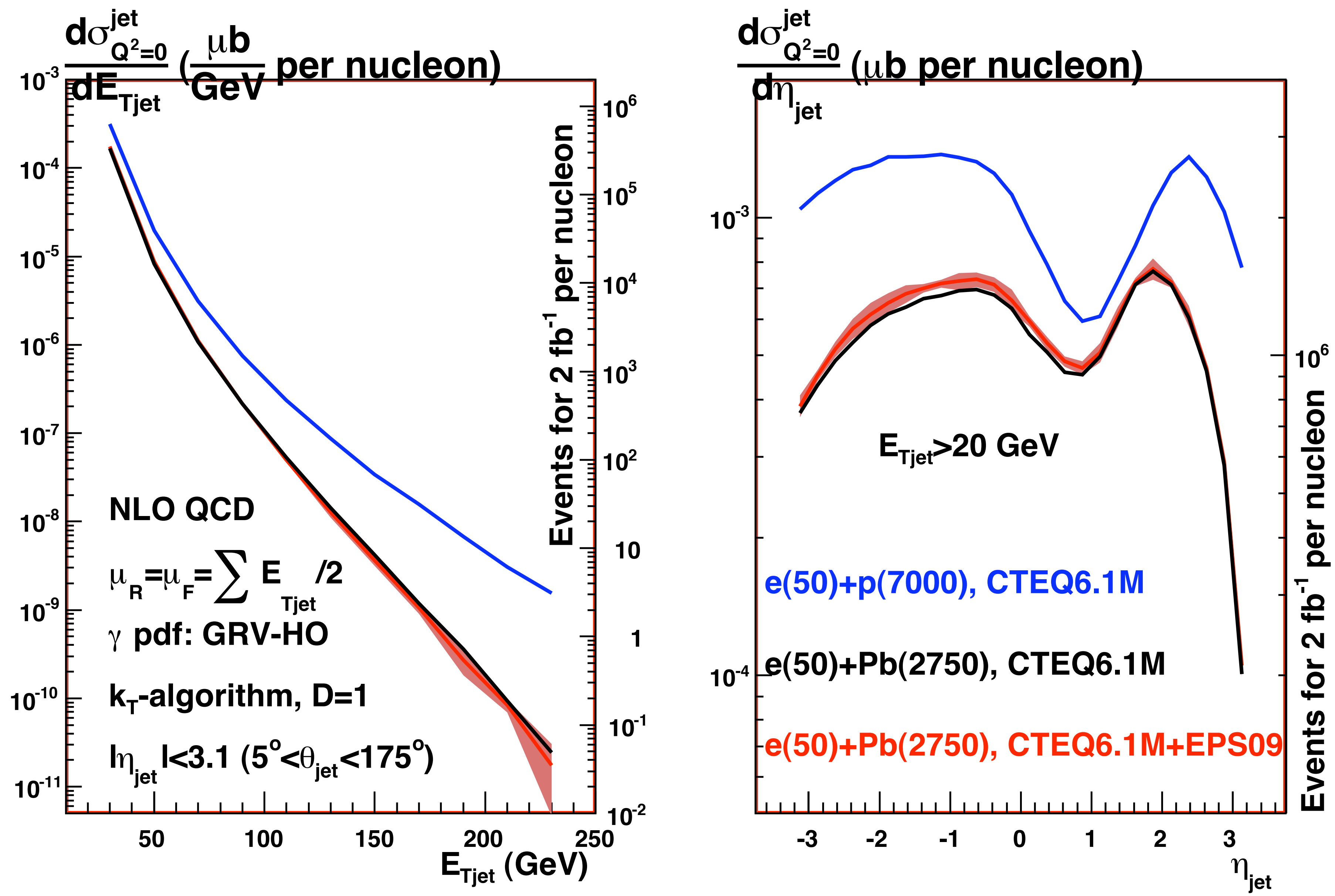
Total γp cross section:

- Small angle electron detector 62 m far from the interaction points: $Q^2<0.01$ GeV, $y \sim 0.3 \Rightarrow W \sim 0.5 \sqrt{s}$.

- Substantial enlarging of the lever arm in W.



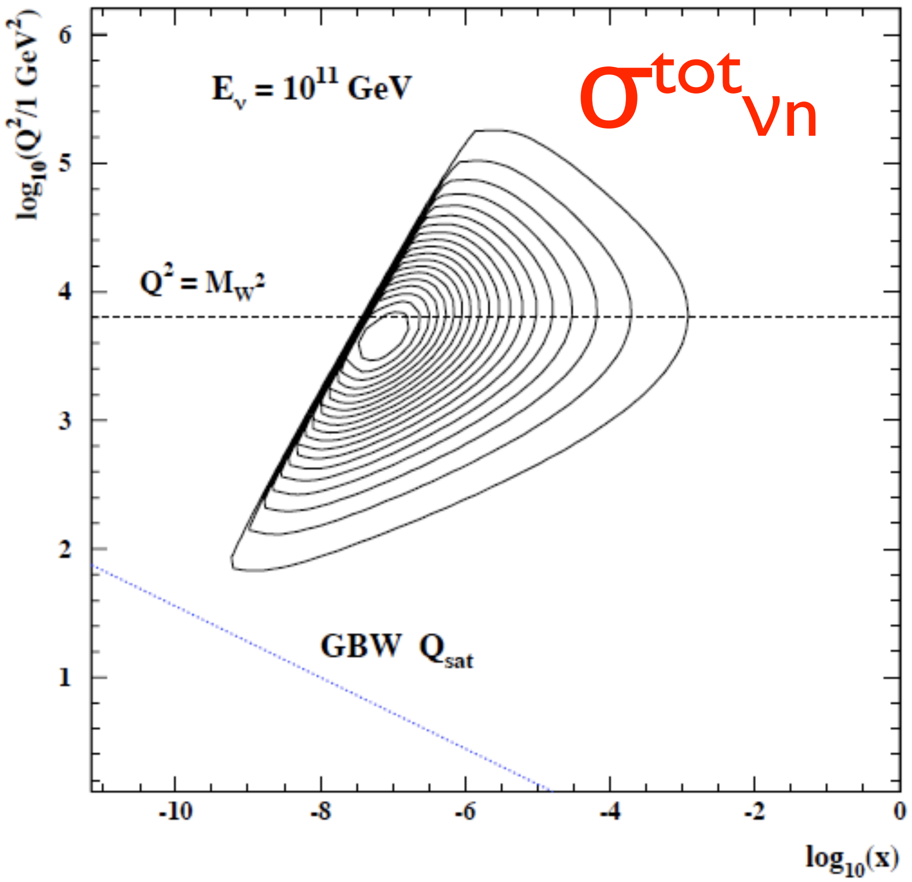
Jet photoproduction:



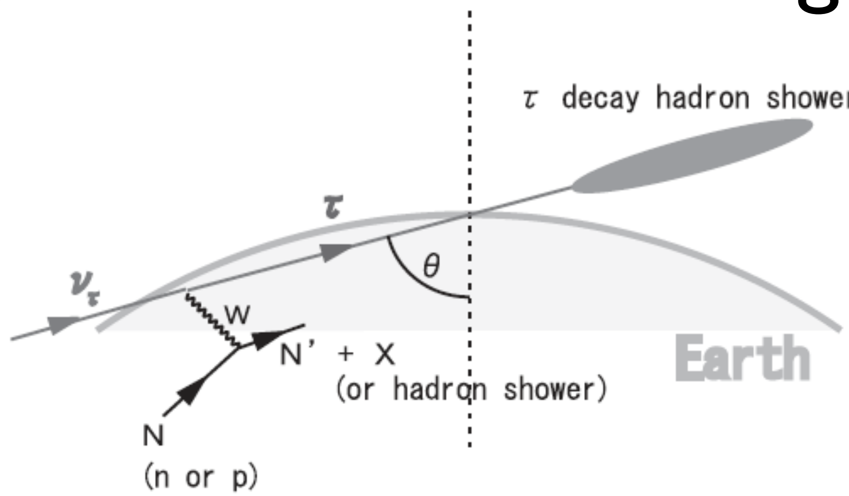
- Jets: large E_T even in eA.
- Useful for studies of parton dynamics in nuclei (hard probes), and for photon structure.
- Background subtraction, detailed reconstruction pending.

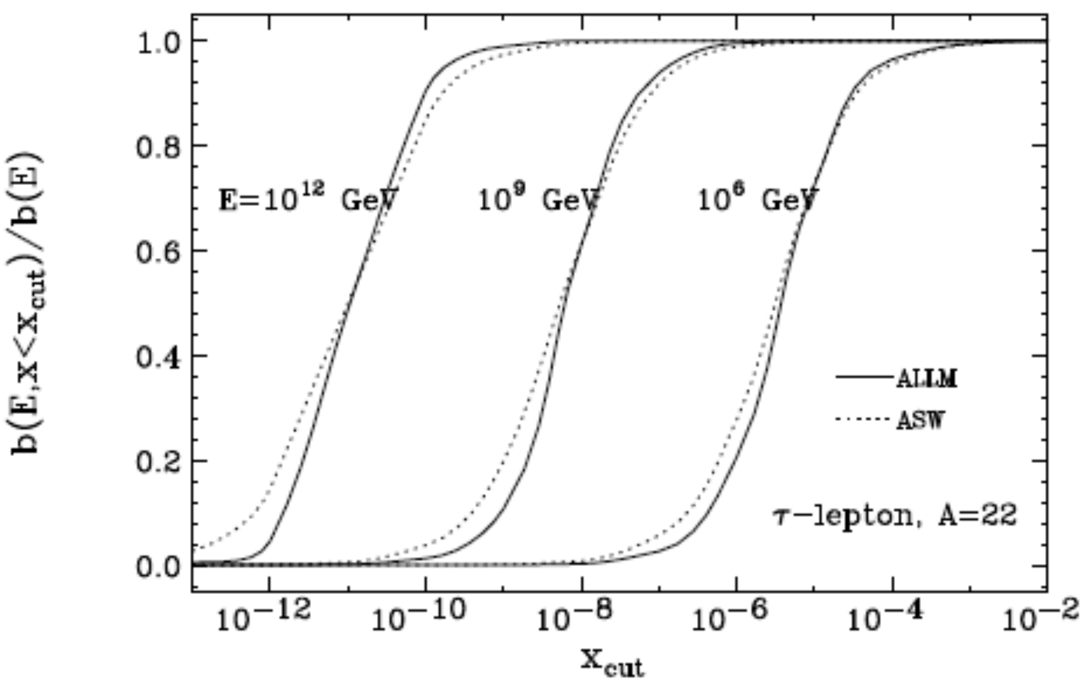
Overview of the HPD chapter: 2.8 Photoproduction Physics.

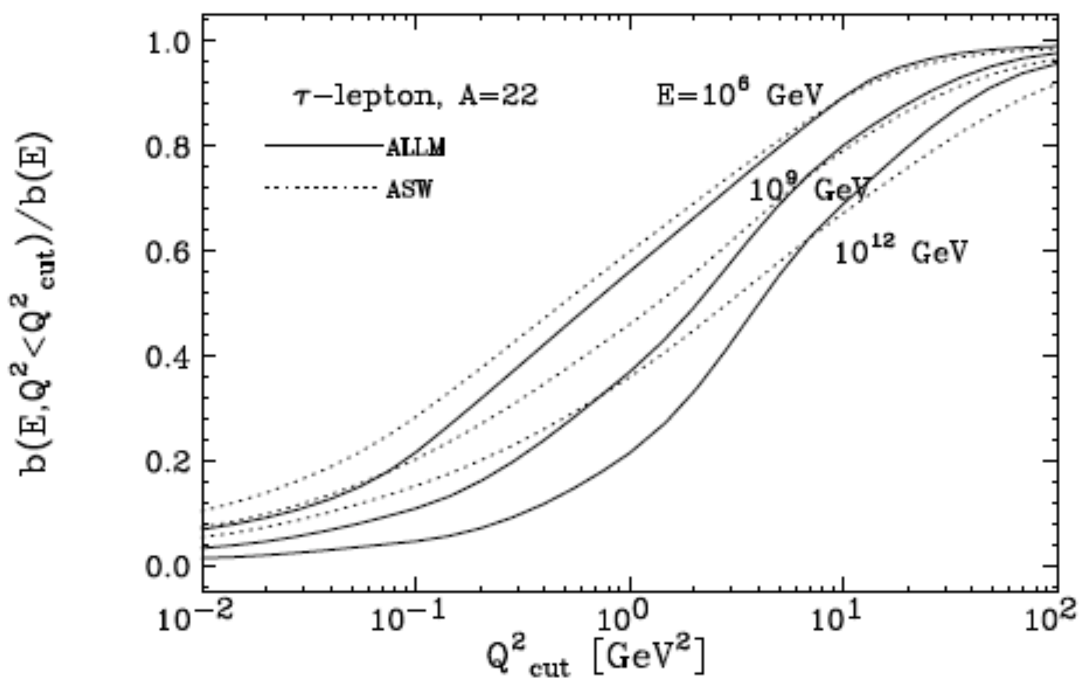
2.9 Implications for UHEν interactions:



- ν-n/A cross section (τ energy loss) dominated by DIS structure functions / (n)pdfs at small-x and large (small) Q^2.
- Key ingredient for estimating fluxes.







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

To conclude:

- Much material has been gathered: we almost have a first draft.

- Still, much editing and polishing to be done before we get a consistent chapter to be merged with the others.

- 1 degree acceptance is required for the small-x program!!!

- **Many thanks to those who have contributed, attended the workshops, presented material or made most useful remarks and suggestions!!!**

- **Many thanks to Patricia for the logistics.**

Backup:

LHeC scenarios:

For F_2

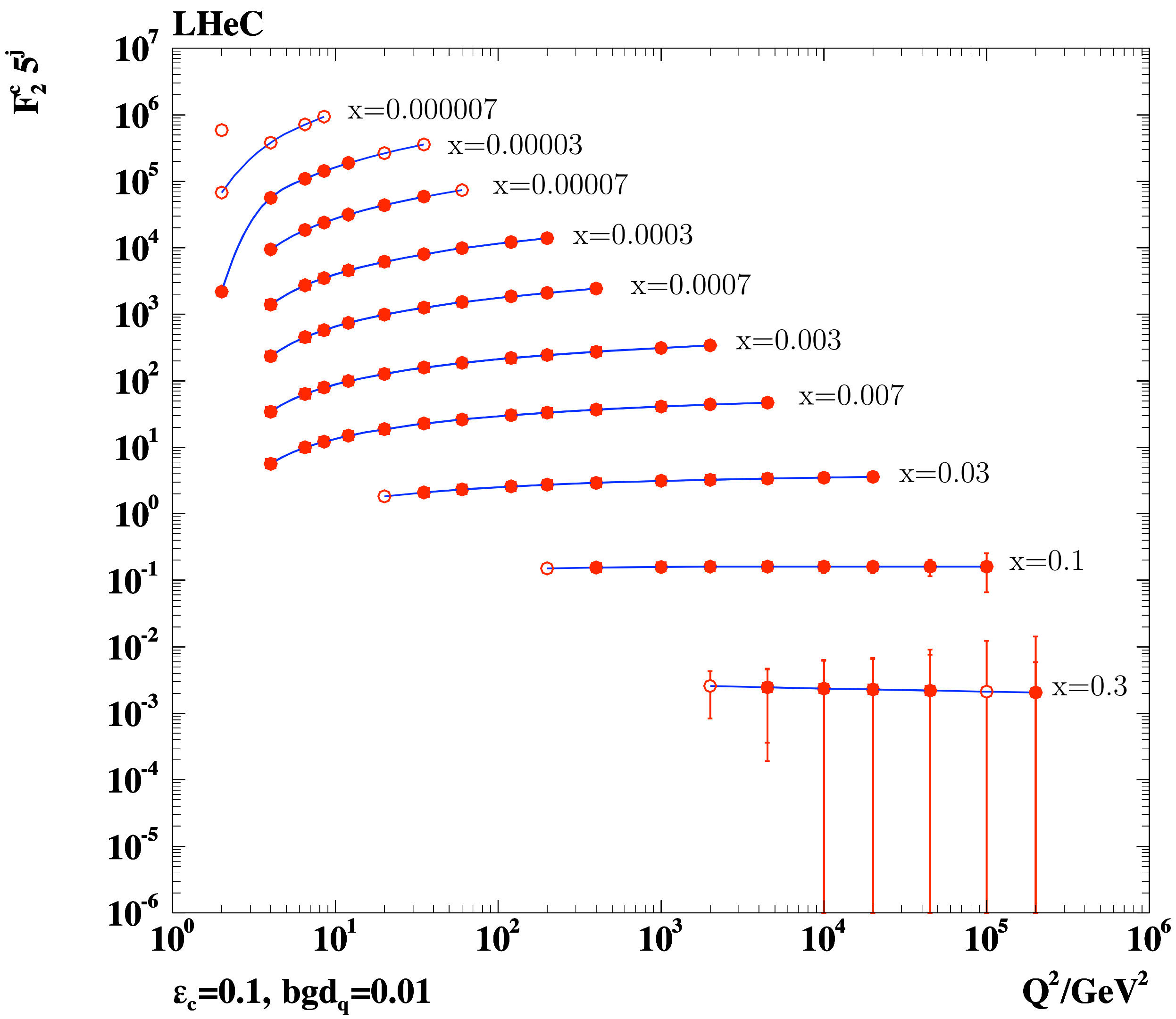
config.	E(e)	E(N)	N	∫L(e⁺)	∫L(e⁻)	|Pol|	$L/10^{32}$	P/MW	years	type
A	20	7	p	1	1	-	1	10	1	SPL
B	50	7	p	50	50	0.4	25	30	2	RR hiQ^2
C	50	7	p	1	1	0.4	1	30	1	RR lo x
D	100	7	p	5	10	0.9	2.5	40	2	LR
E	150	7	p	3	6	0.9	1.8	40	2	LR
F	50	3.5	D	1	1	--	0.5	30	1	eD
G	50	2.7	Pb	10^{-4}	10^{-4}	0.4	10^{-3}	30	1	ePb
H	50	1	p	--	1	--	25	30	1	lowEp
I	50	3.5	Ca	$5\cdot10^{-4}$		?	$5\cdot10^{-3}$	?	?	eCa

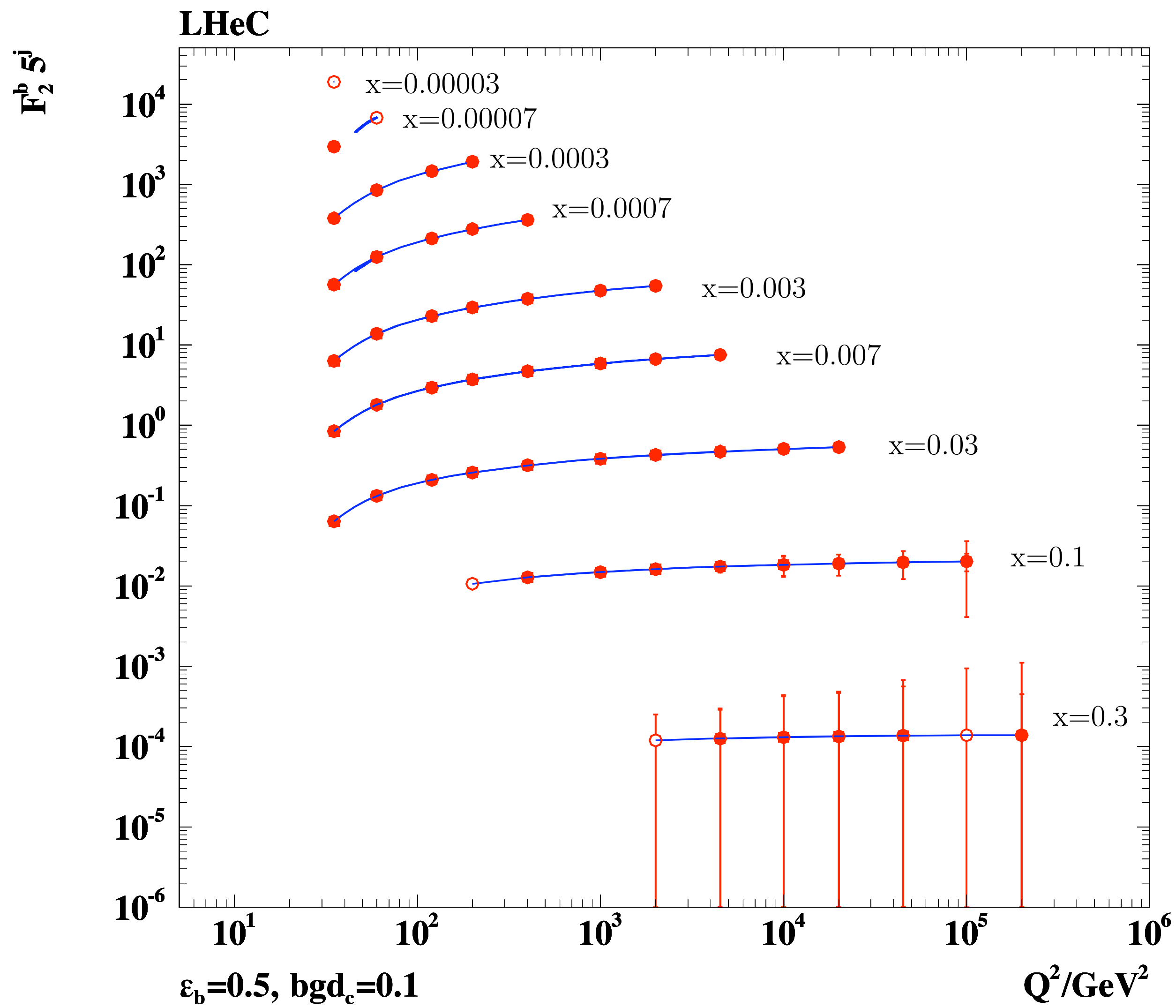
- For F_L: 10, 25, 50 + 2750 (7000); $Q^2 \leq sx$; Lumi=5,10,100 pb^{-1} respectively; charm and beauty: same efficiencies in ep and eA.

Overview of the HPD chapter.

ep inclusive pseudodata:

- Charm and beauty (HERApdf; systematics half than at H1).





Overview of the HPD chapter.