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Small-x physics at the Large Hadron-electron Collider

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Working group on *Physics at High Parton Densities in ep and eA* (with Brian Cole, Paul Newman and Anna Stasto)

Contents:

1. Introduction:

- Saturation.
- Status of npdfs.

2. Inclusive observables:

- ep inclusive pseudodata.
- eA inclusive pseudodata and their effect on npdf's.
- F_L in eA.

3. Diffractive observables:

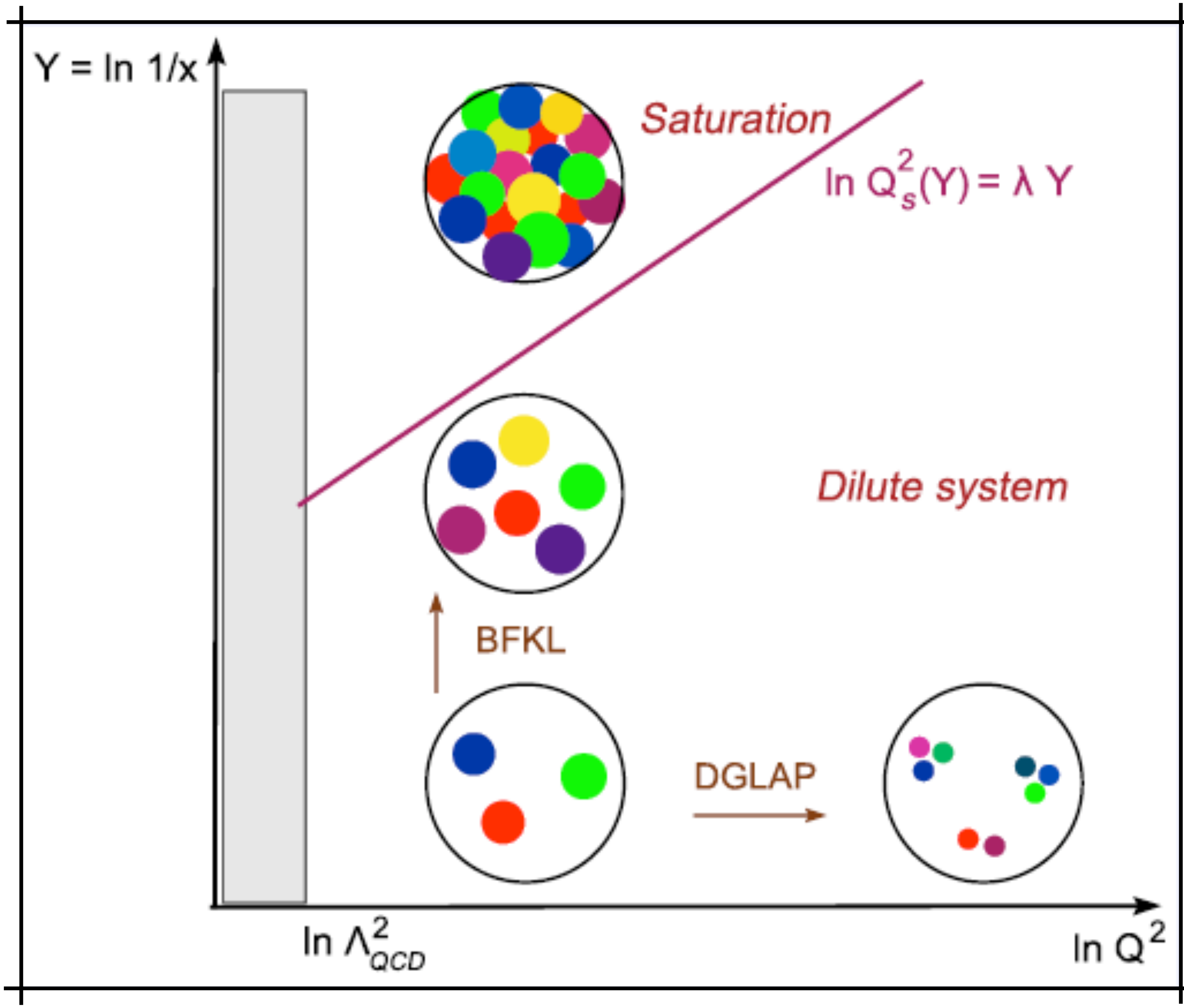
- ep diffractive pseudodata.
- Exclusive vector meson production.
- Nuclear diffraction.

4. Final states.

5. Summary.

See the other LHeC talks by G. Azuelos, O. Behnke, U. Klein, P. Kostka, K. Kutak, J. Jowett, S. Levonian and J. Rojo, and those by W. Brooks and M. Lamont.

Theory: high-energy QCD



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History:

Regge ('50's)

↓ *SLAC ('65)*

Gribov ('60's,'70's)

↓ *QCD ('73)*

Linear eqs.: DGLAP, BFKL ('77)

↓

Non-linear eqs.: GLR, MQ ('80's)

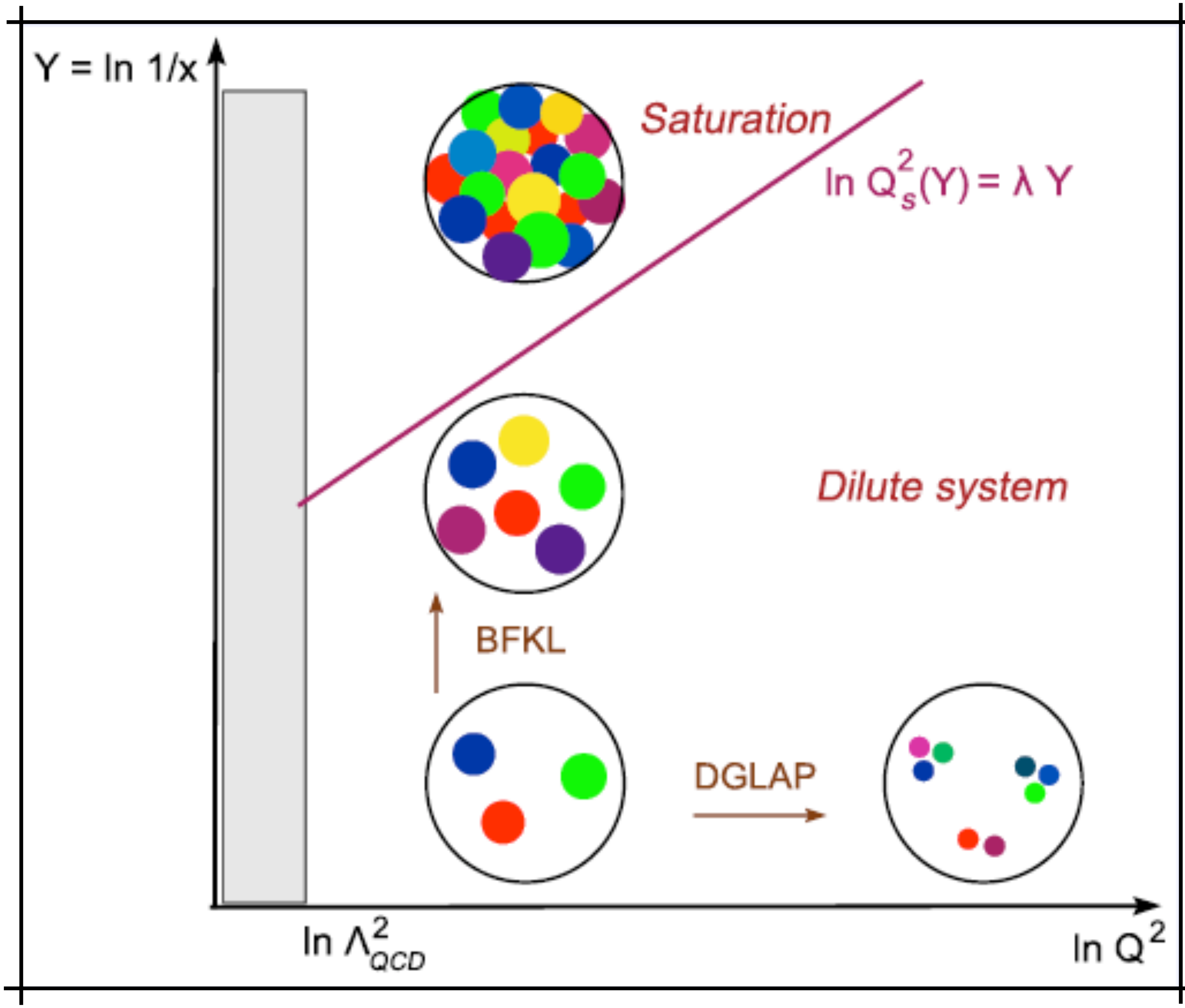
↓ *HERA ('90)*

Saturation: MV, GBW, BK ('90's,'00's)

↓ *RHIC ('00)*

… *LHC ('09)*

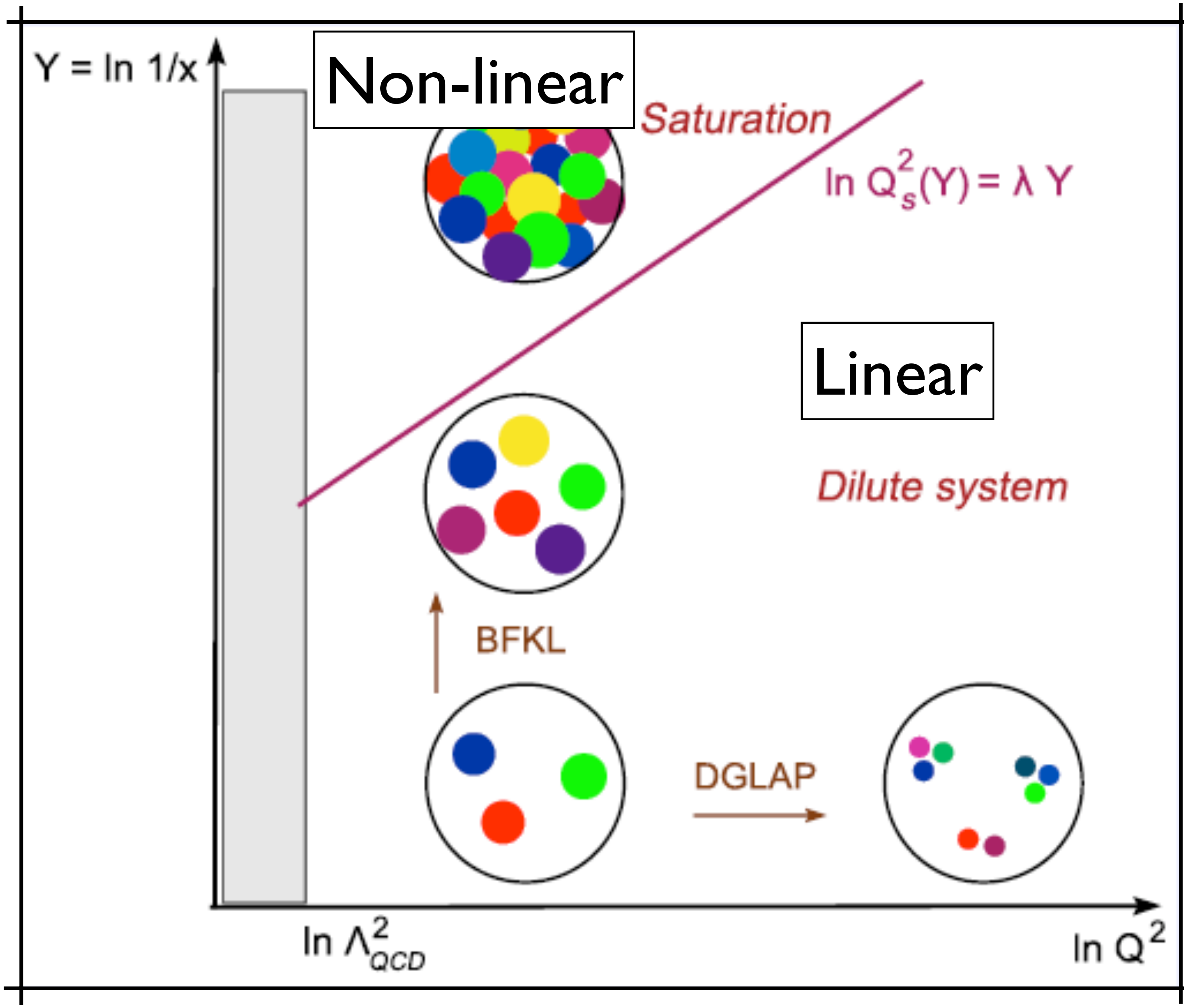
Theory: high-energy QCD



Our aims: understanding

- The implications of unitarity in a QFT.
- The behavior of QCD at large energies / hadron wave function at small x.
- The initial conditions for the creation of a dense medium in heavy-ion collisions: nuclear WF + initial stage.

Theory: high-energy QCD



Where do the available experimental data lie?

Our aims: understanding

- The implications of unitarity in a QFT.
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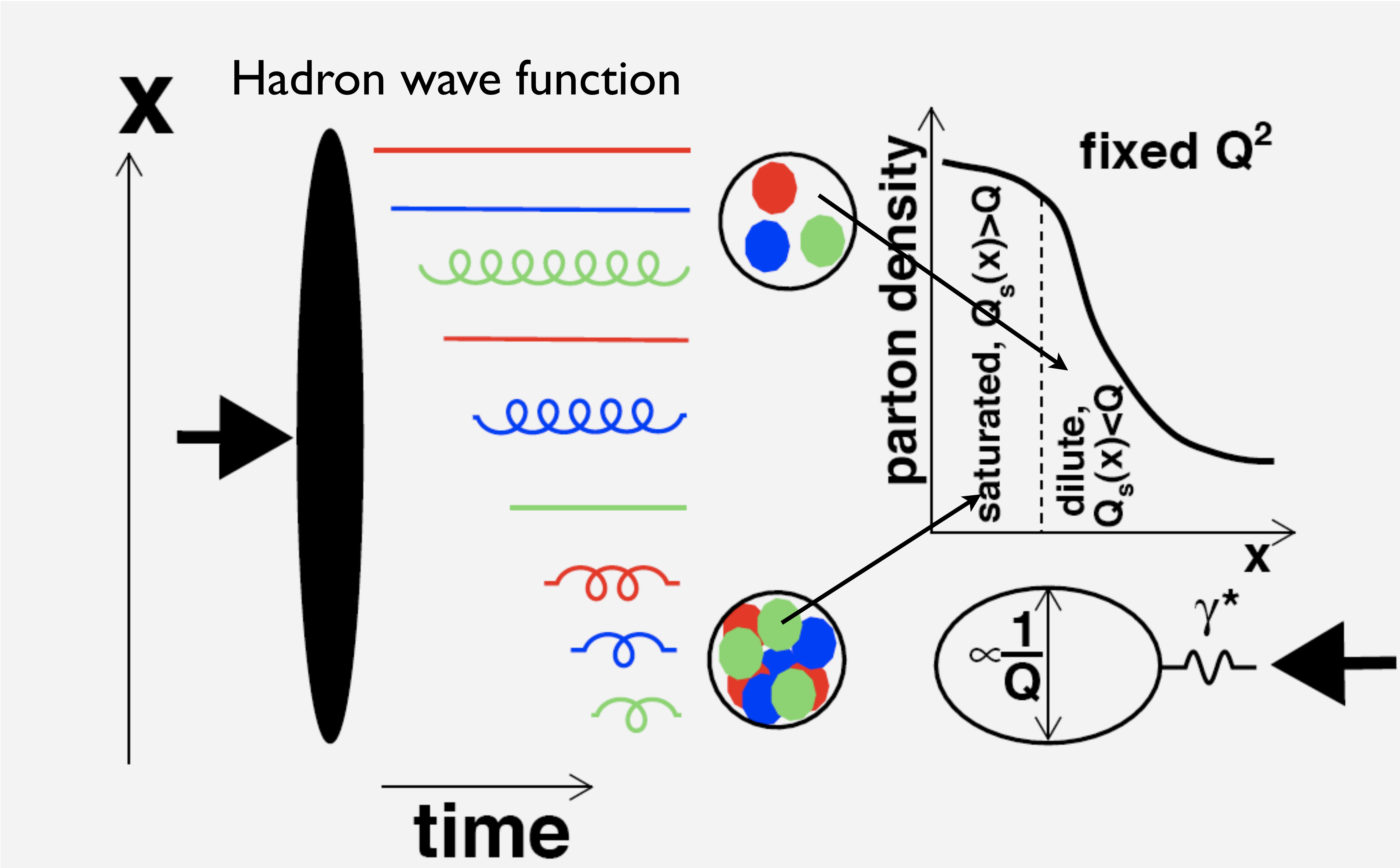
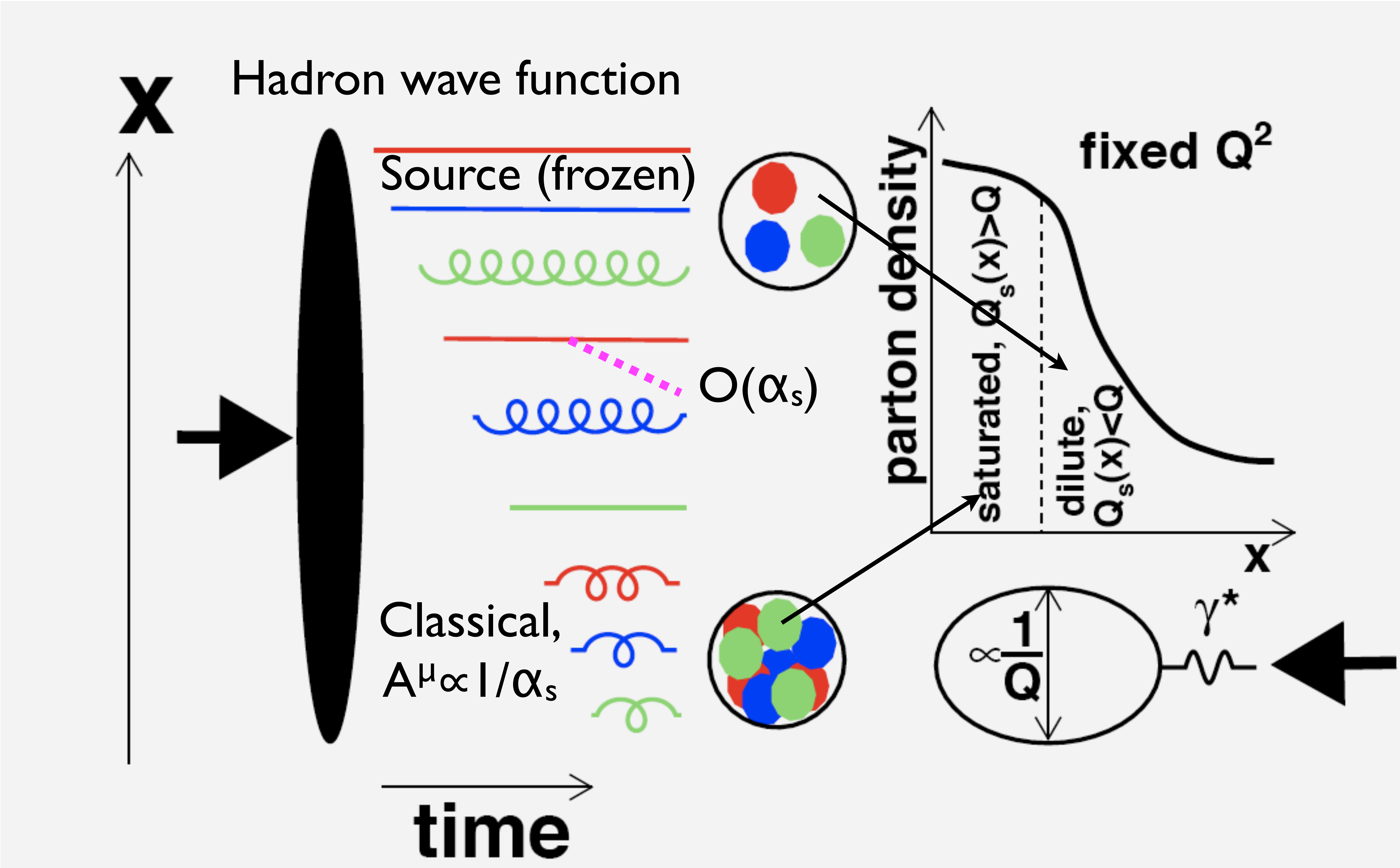
Saturation ideas: CGC

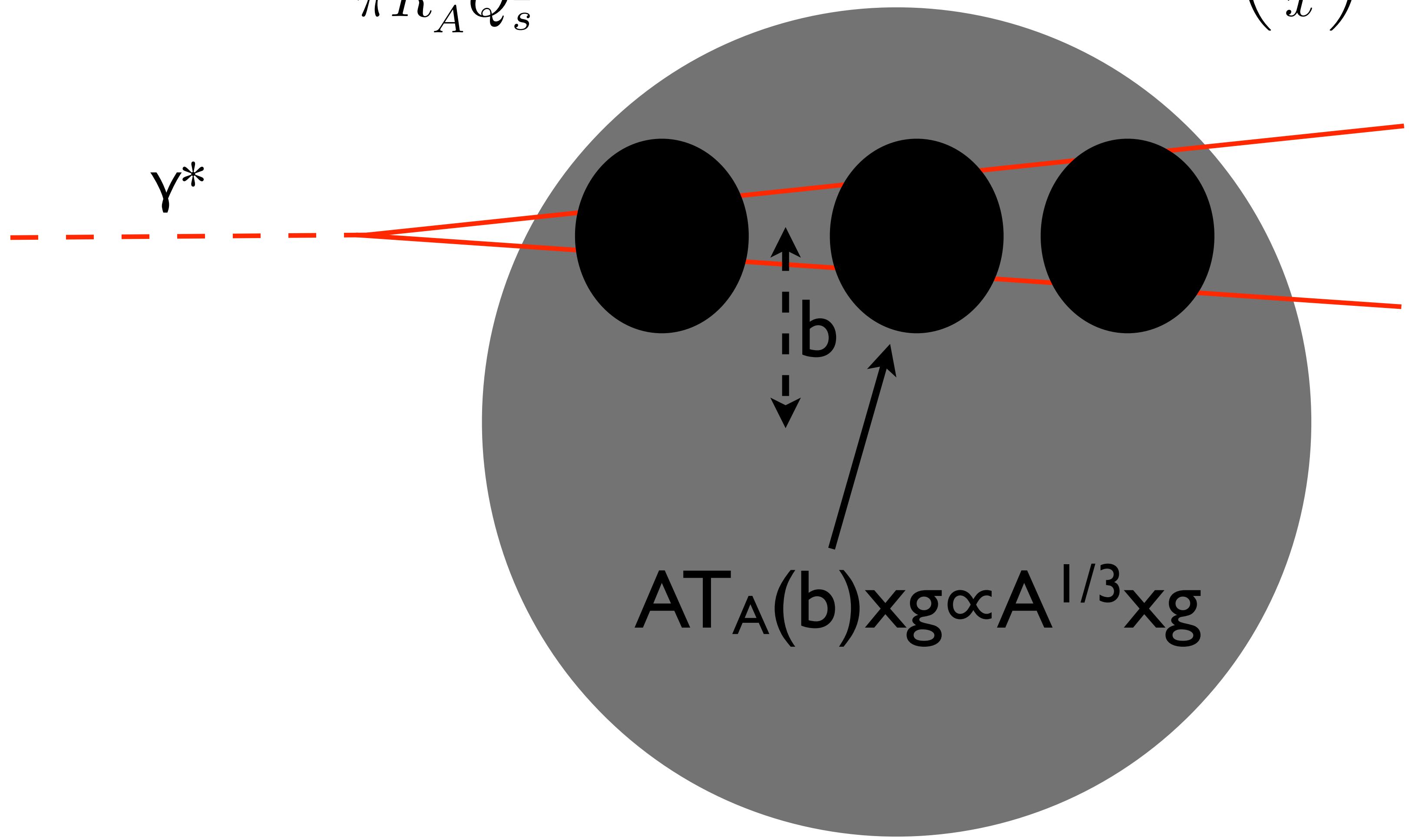


Saturation ideas: CGC

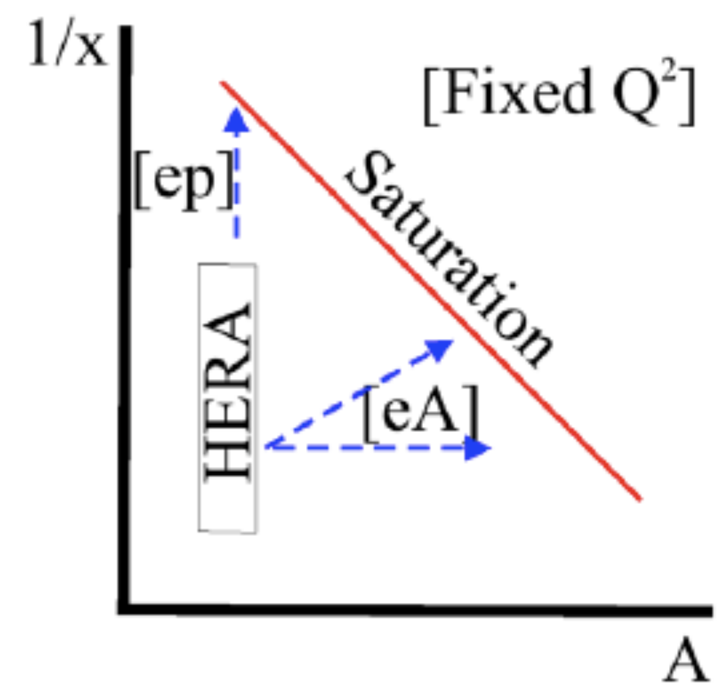


Saturation ideas: CGC

$$\sigma\rho \sim 1 \Longrightarrow \frac{Axg(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3}x^{-\lambda} \sim \left(\frac{A}{x}\right)^{1/3}$$



Nuclei: they offer the possibility of testing these ideas (density effect) and enhance the saturation effects for a fixed x (energy).

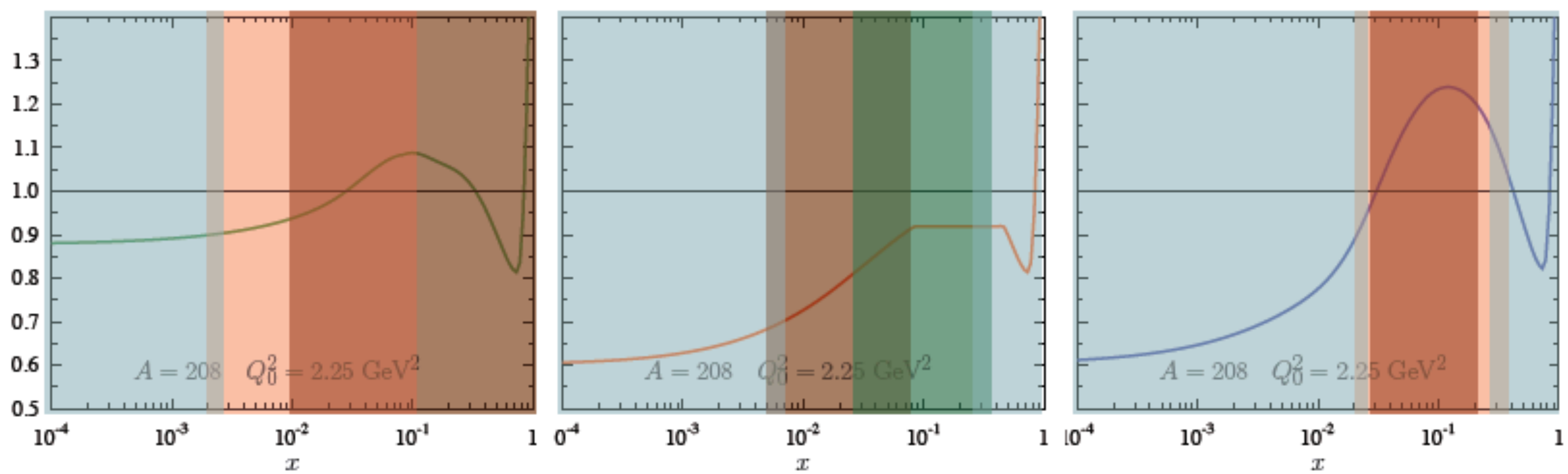


DGLAP analysis of npdf's:

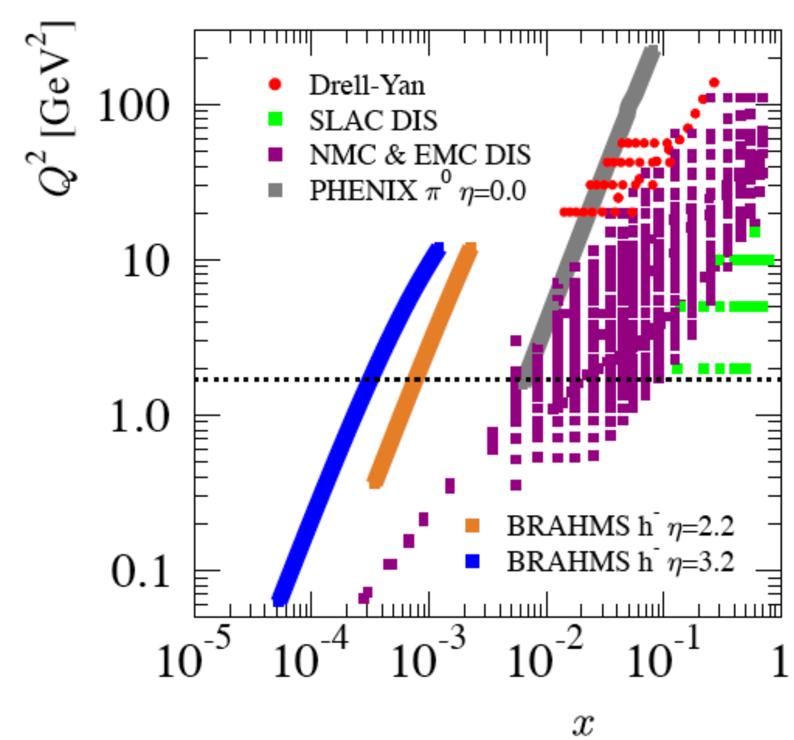
- Data sets: ~100 DY, ~20 from π^0, rest up to ~900 from NC DIS;

neutrino data under discussion (see Kovarik's and Paukkunen's talks).

Valence Sea quarks Gluons



Salgado

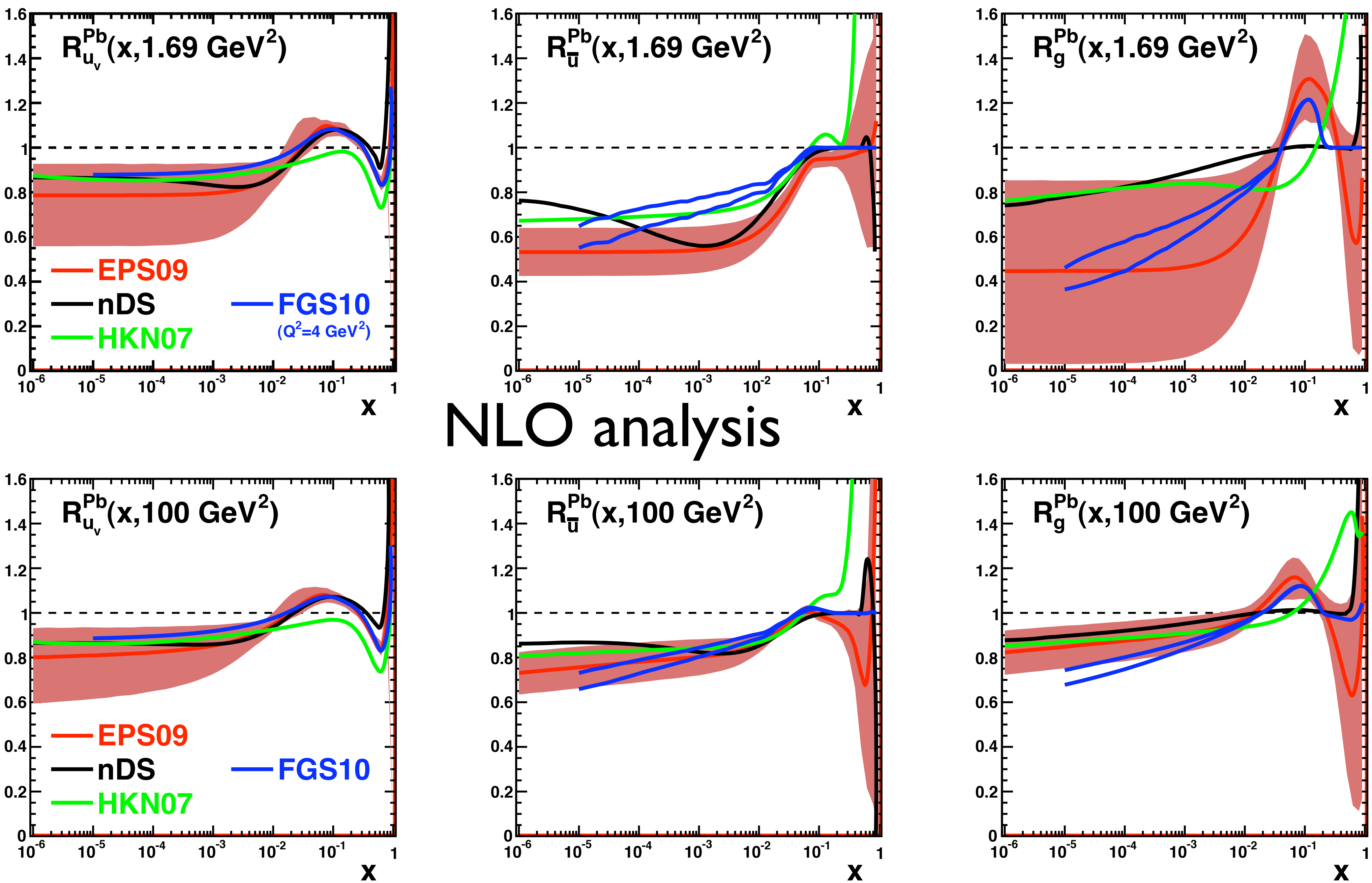


DGLAP analysis of npdf's:

- Data sets: ~100 D… ~900 from NC DIS;

neutrino data under … Paukkunen's talks).

$$R^A_{F_2}(x, Q^2) = \frac{F_2^A(x, Q^2)}{A F_2^{\text{nucleon}}(x, Q^2)}$$



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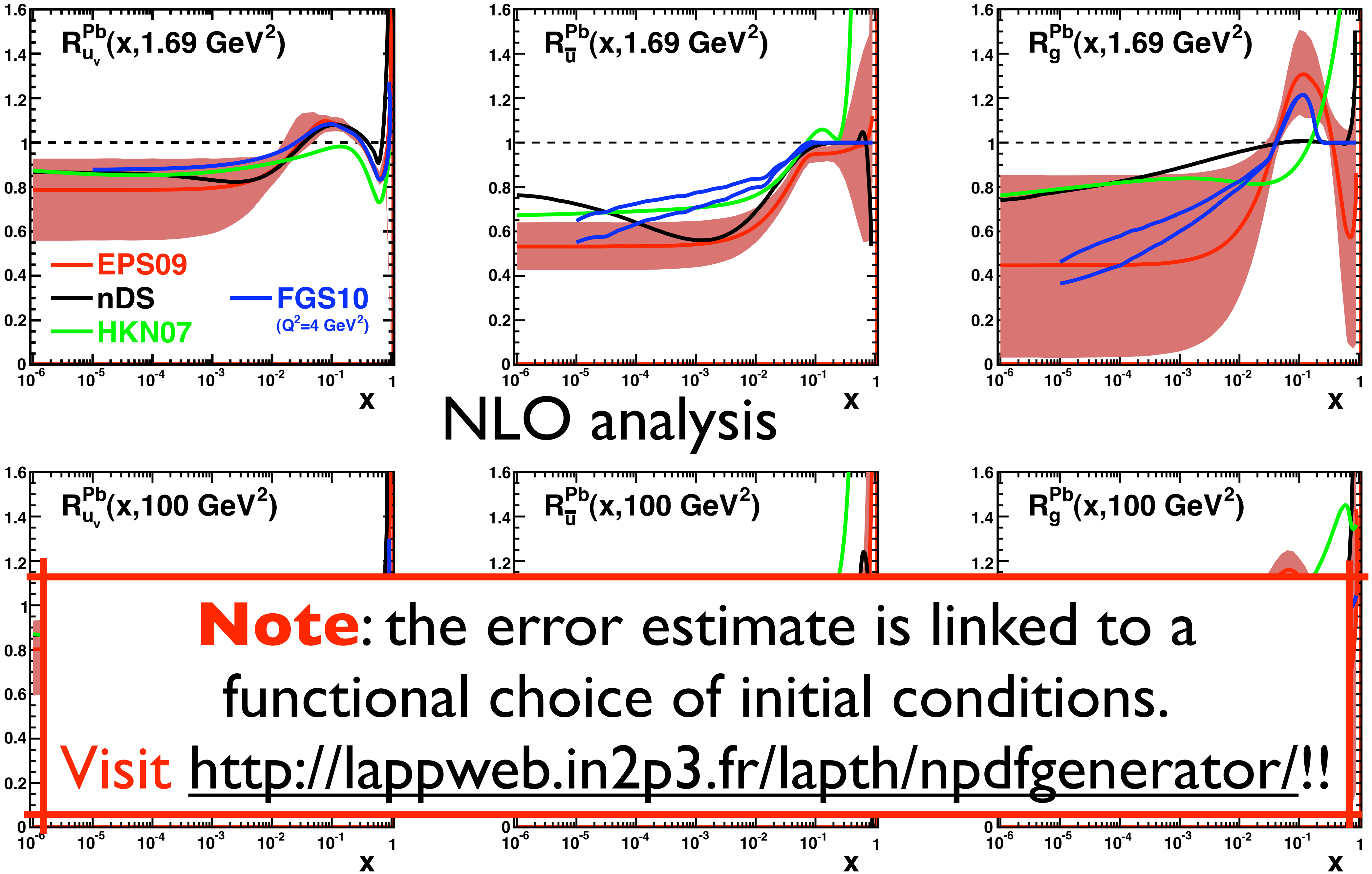


NLO analysis

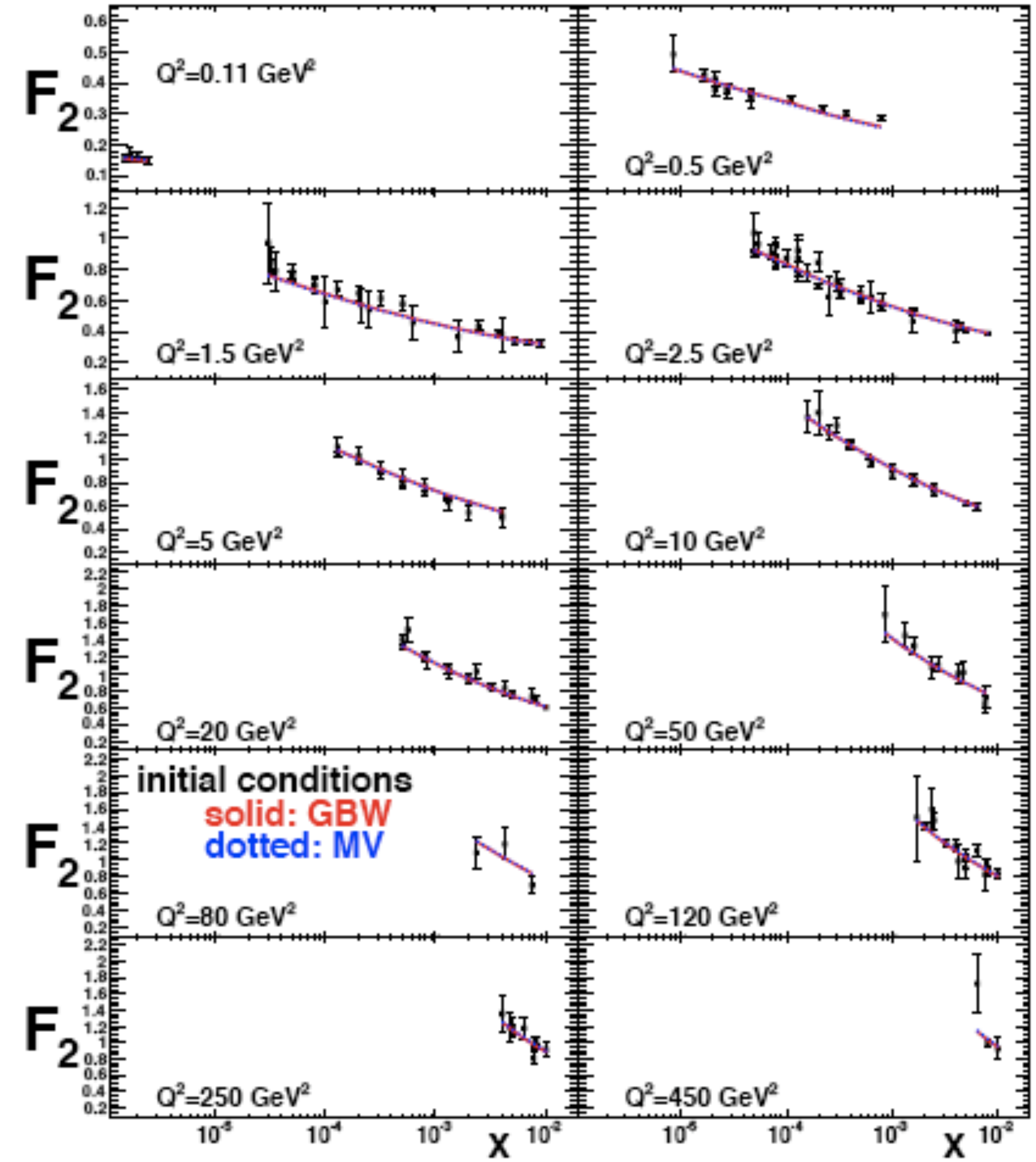
Note: the error estimate is linked to a functional choice of initial conditions.

Visit http://lappweb.in2p3.fr/lapth/npdfgenerator/!!

x

Status:

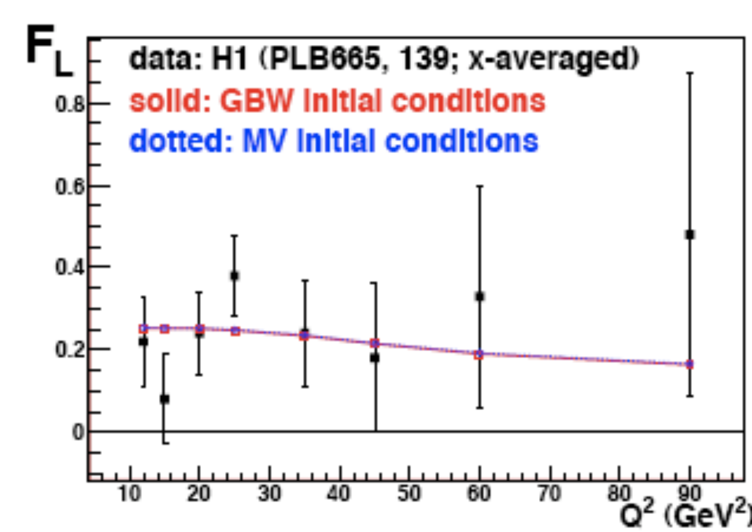
Albacete et al '09



- Three pQCD-based alternatives to describe small-x ep and eA data:
  → DGLAP evolution (FO PT).
  → Resummation schemes.
  → CGC (dipole models and rcBK).
  (See Tywoniuk's talk for other.)

- **Differences lie at moderate $Q^2 (> \Lambda^2_{QCD})$ and small x.** Hints of deviations from NLO DGLAP at small x (Caola et al '09, see Caola's talk).

- Unitarity (non-linear effects): where is it? ⇒
  - ☛ Theory: refine the tools and predict.
  - ☛ Experiment: LHC, EIC, LHeC.



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- ep inclusive pseudodata. (M. Klein, NA, J. Rojo, P. Newman, J. Forshaw, G. Soyez; see Rojo's talk)
- eA inclusive pseudodata and their effect on npdf's. (M. Klein, NA, H. Paukkunen, K. Eskola, C. A. Salgado)
- F_L in eA. (H. Paukkunen, K. Tywoniuk, NA, C. A. Salgado; see Tywoniuk's talk)

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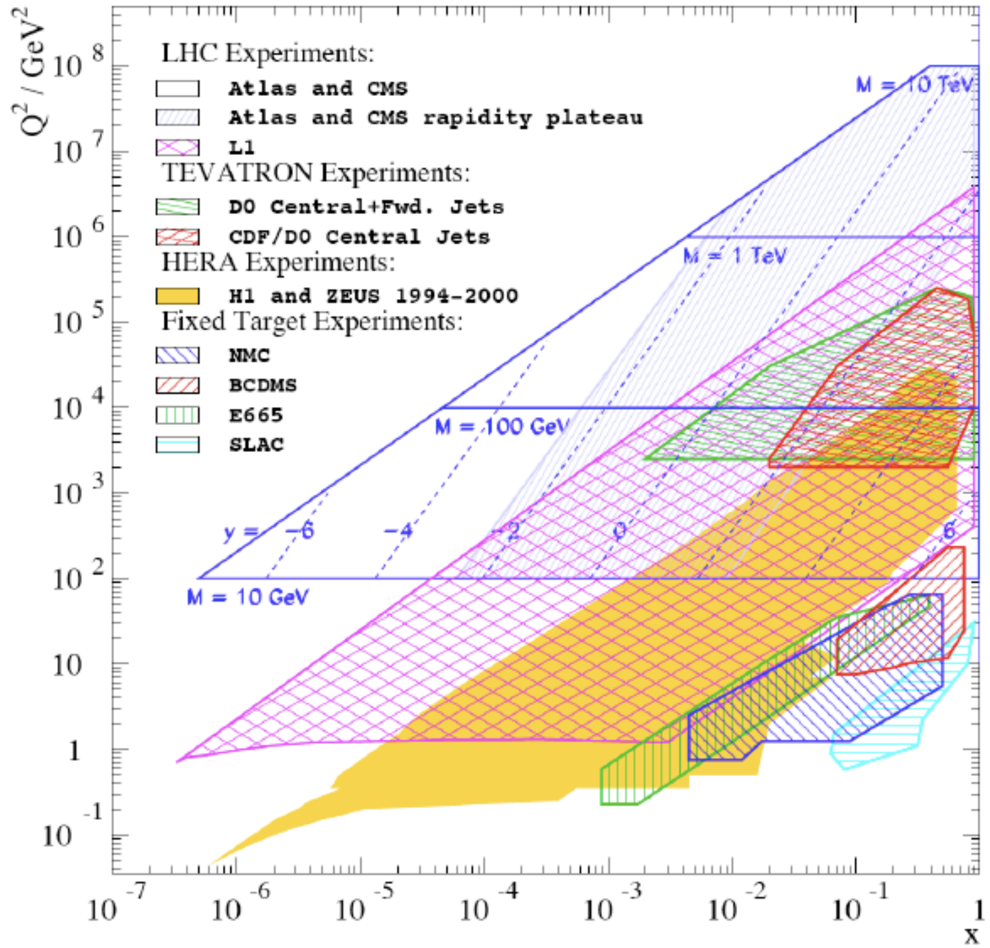
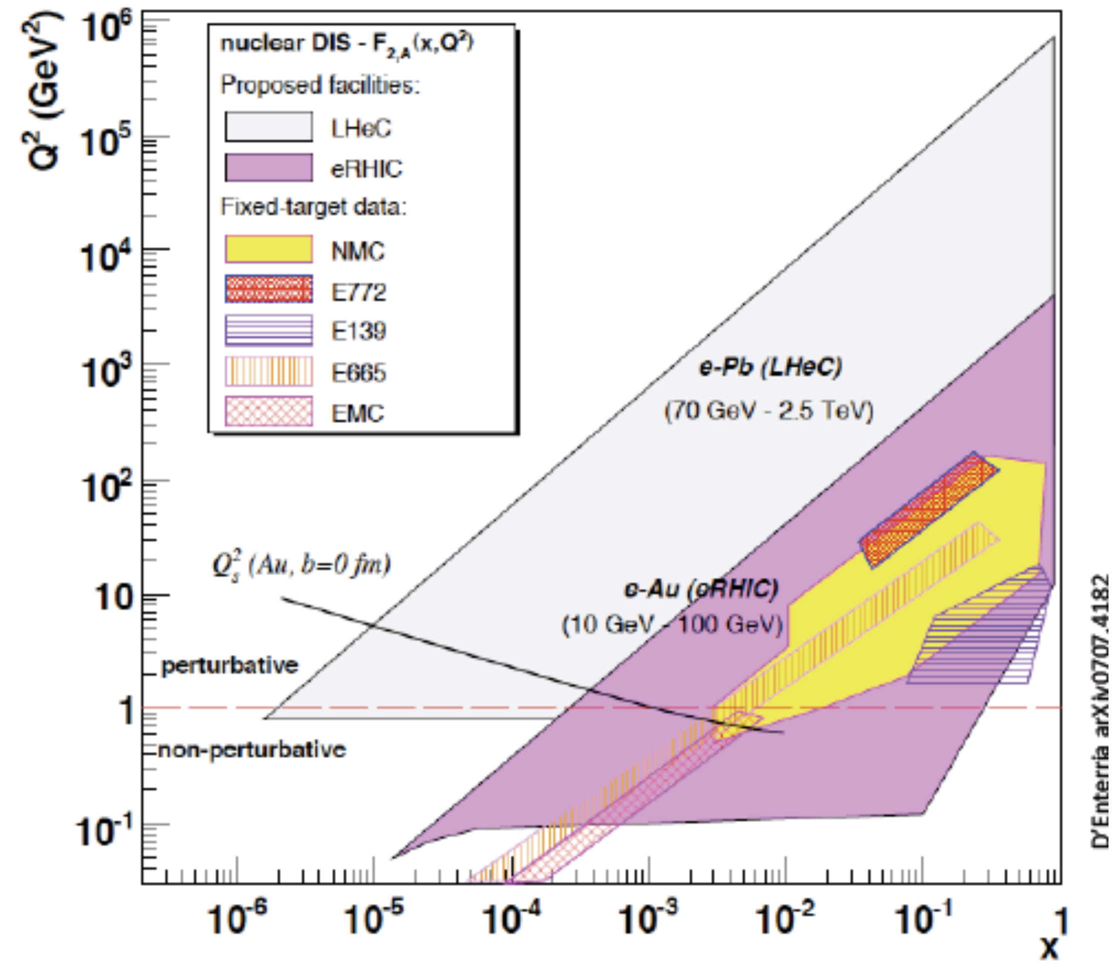
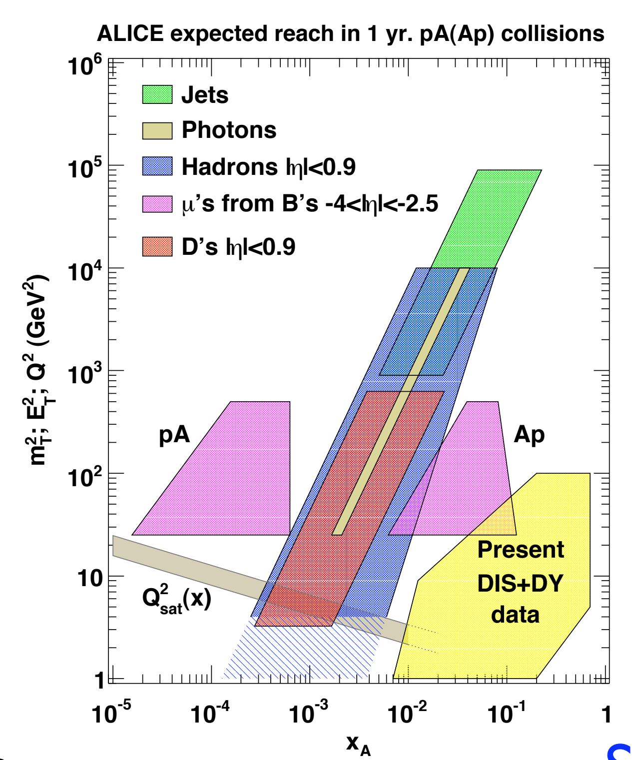
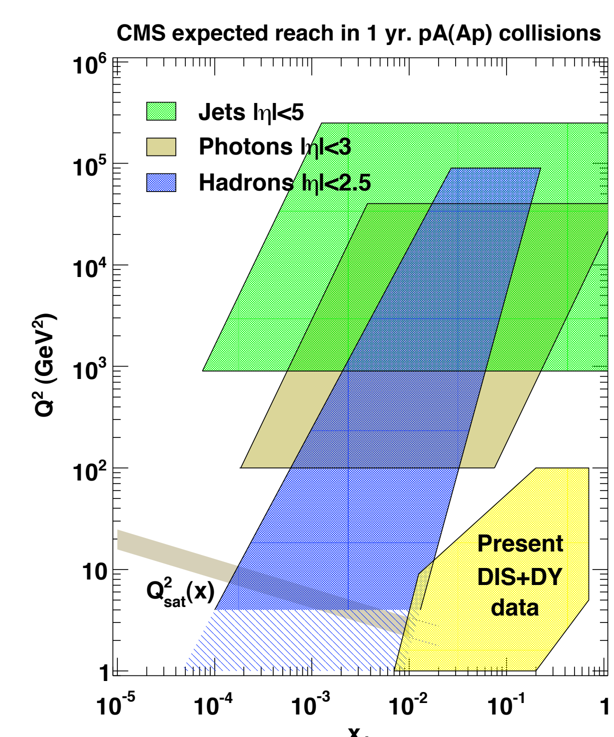
Kinematics:





- ep: access to the perturbative region below x ~ a few 10^{-5}.
- eA: new realm.
- No small-x physics without ~ 1 degree acceptance.





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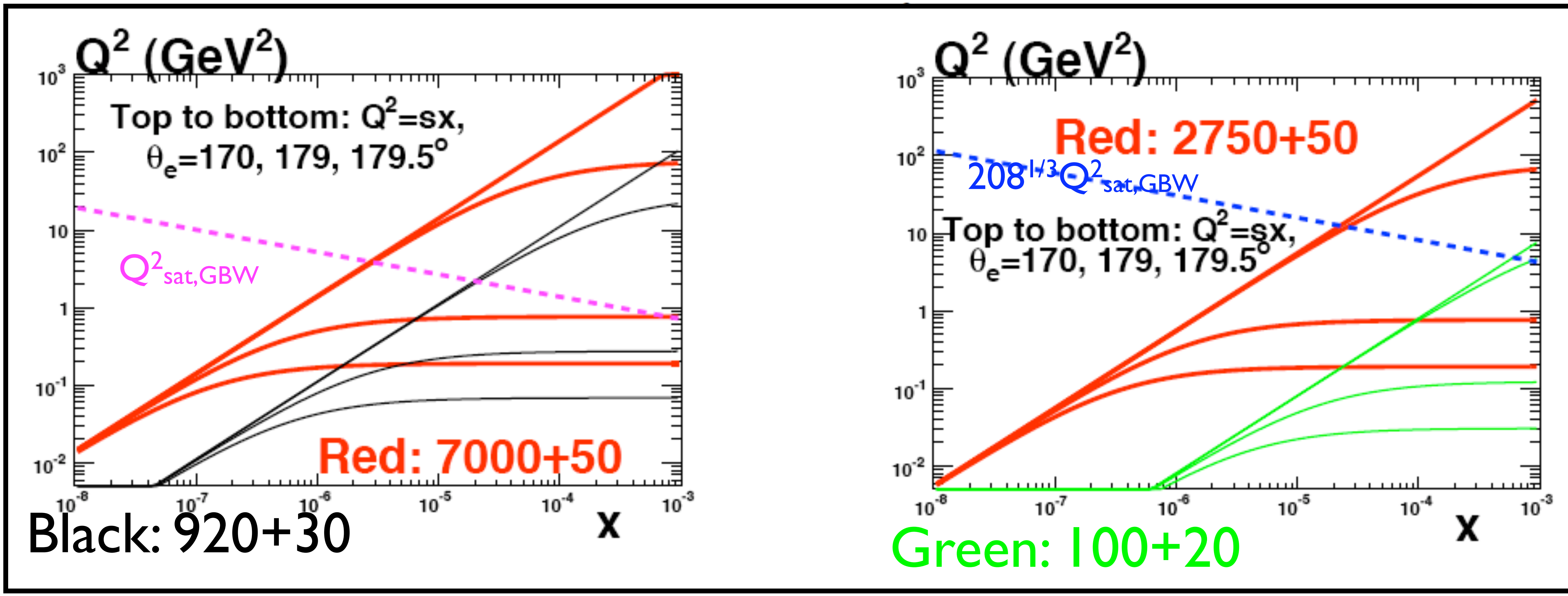

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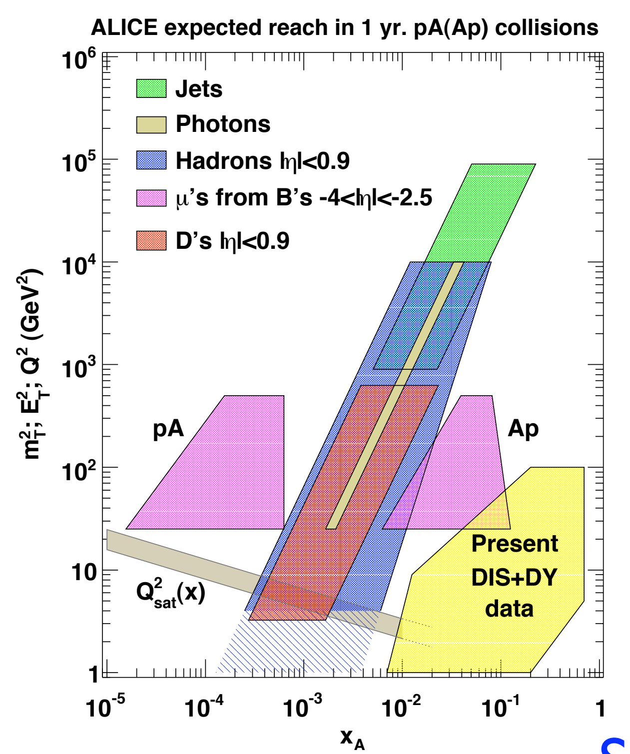
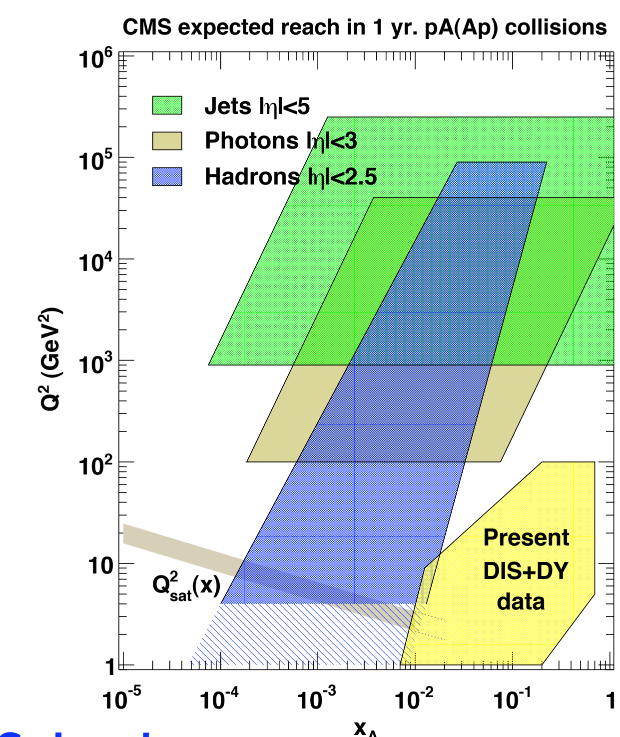


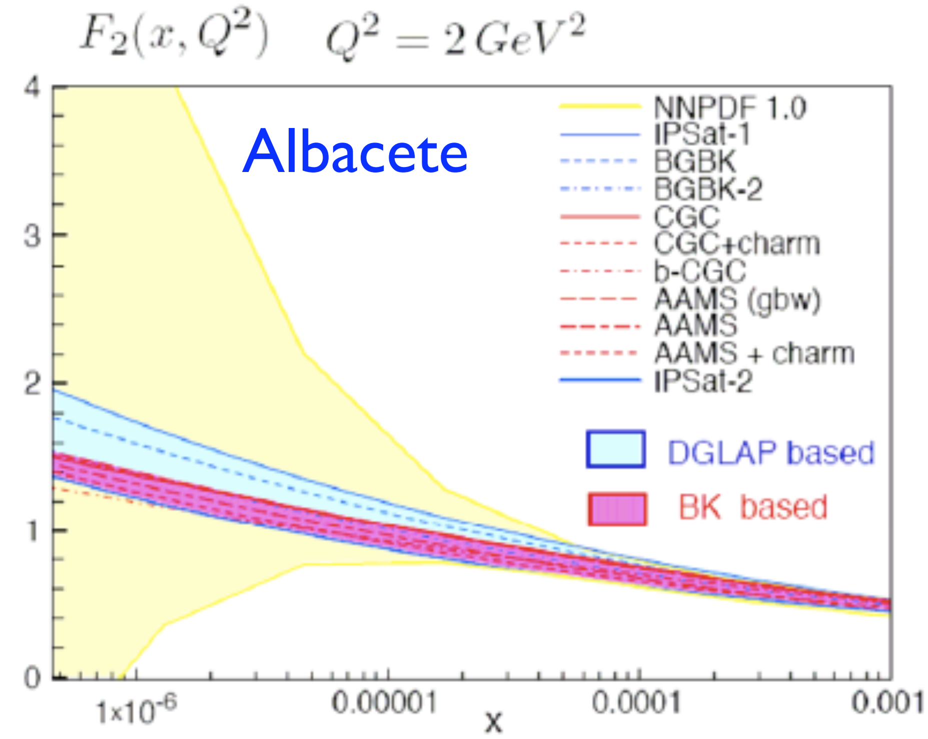


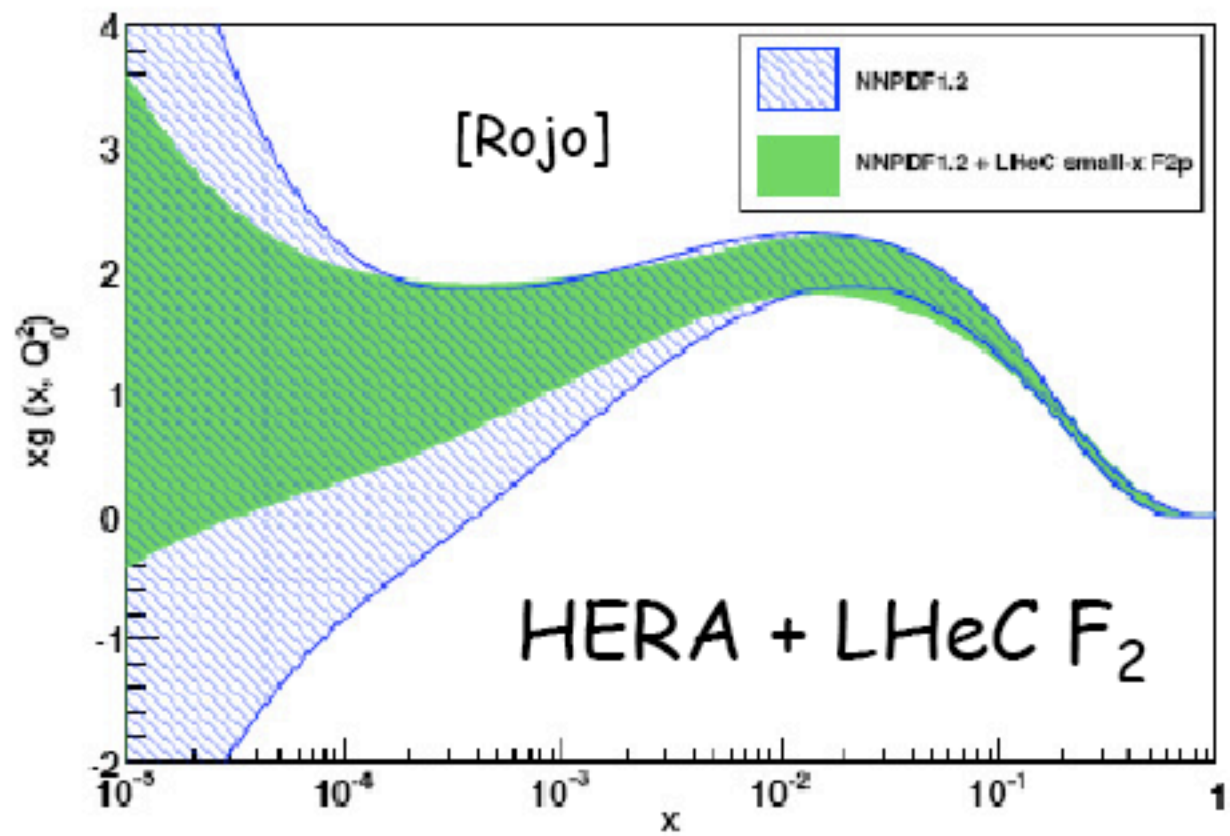
Salgado

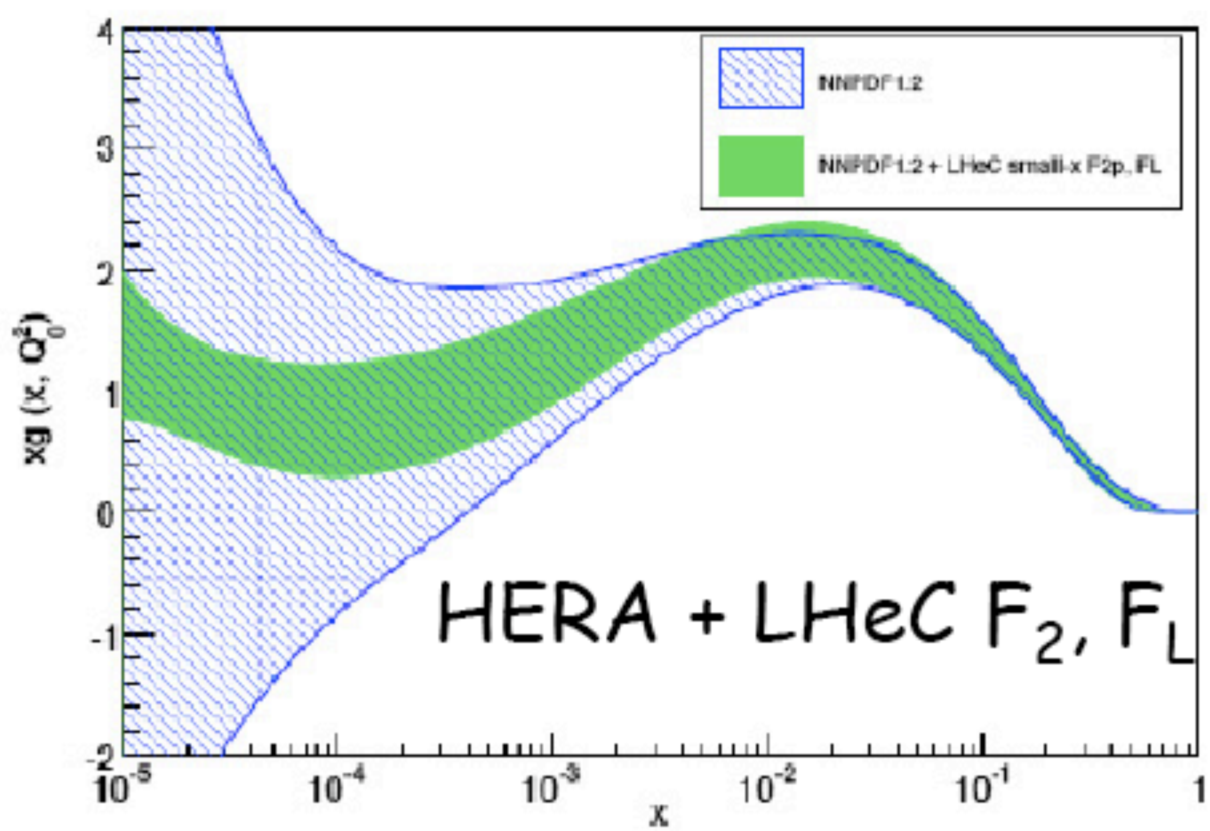
ep inclusive pseudodata (I):

- Extensive model comparison under way (Albacete).

- LHeC substantially reduces the uncertainties in global fits: F_L most useful.



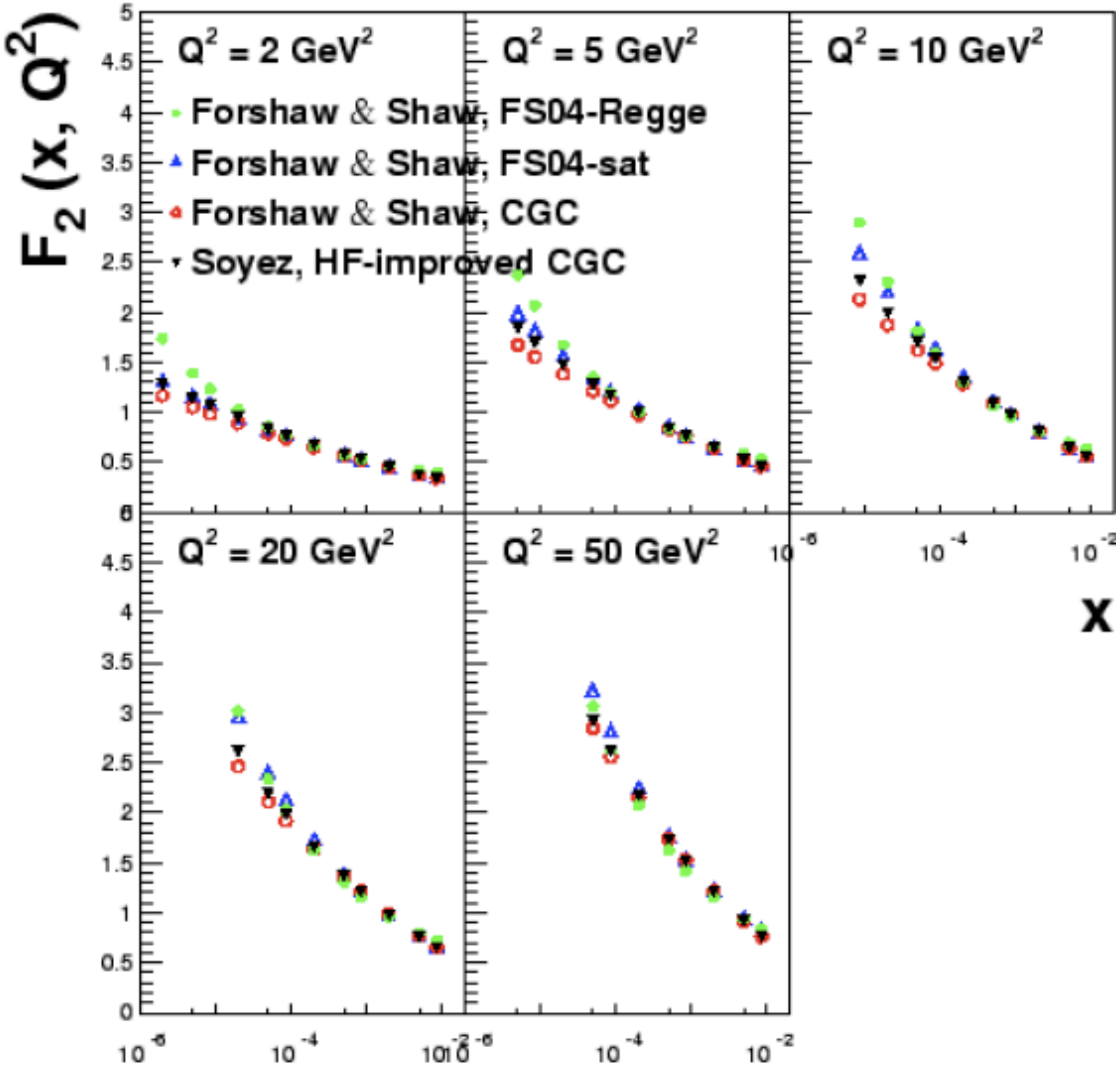




(Q^2 = 2 GeV^2)

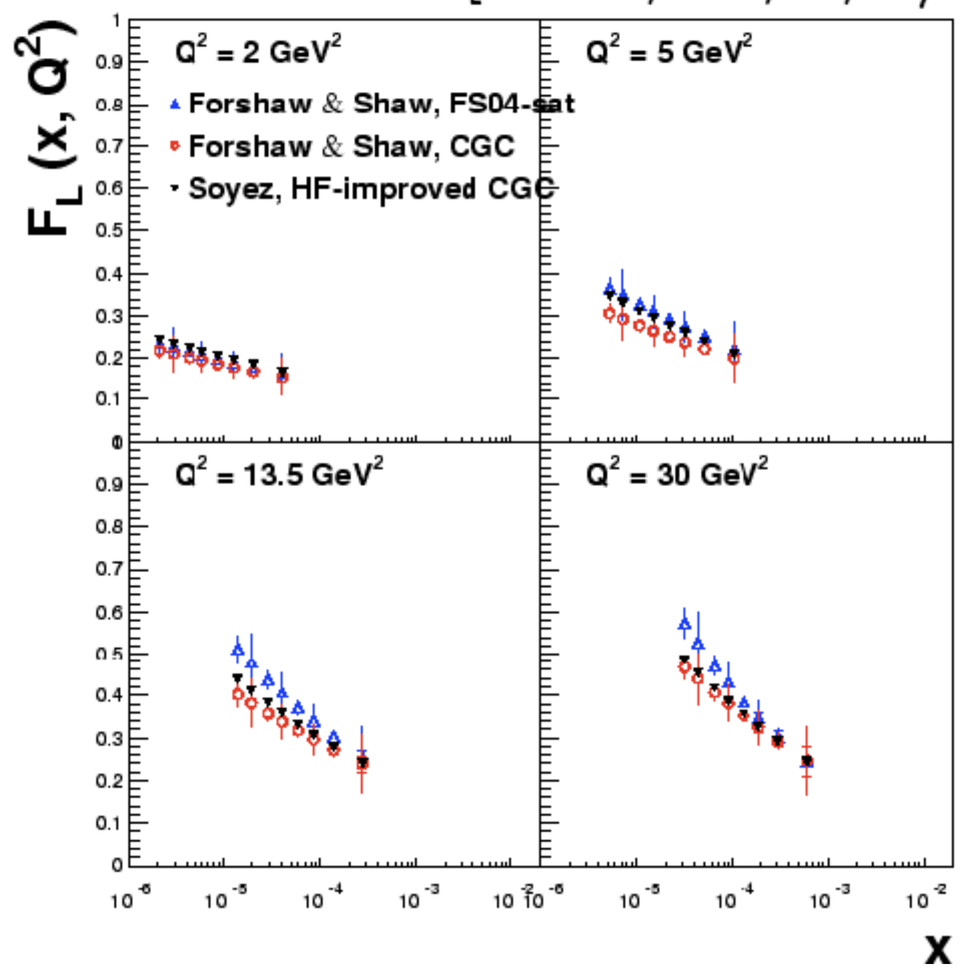
ep inclusive pseudodata (II):

[Forshaw, Klein, PN, Soyez]



- Tension between F_2 and F_L in DGLAP fits as a sign of physics beyond standard DGLAP (GBW and CGC models).

[Forshaw, Klein, PN, Soyez]



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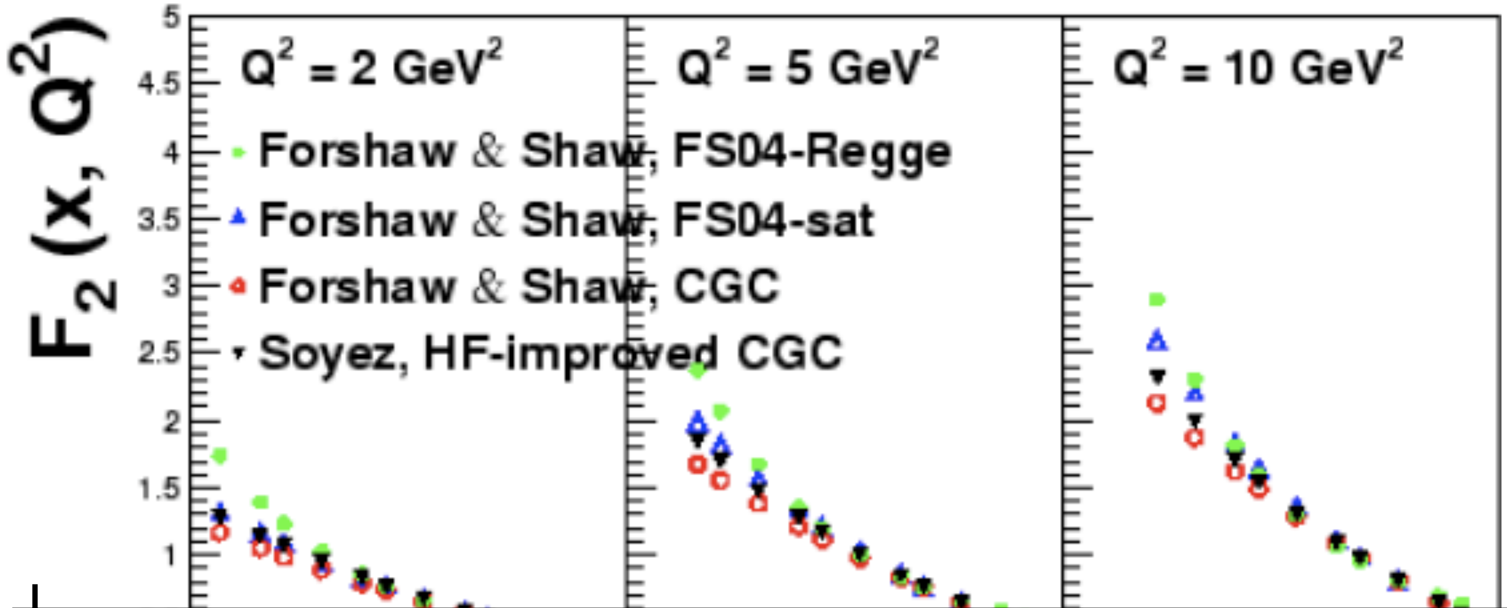

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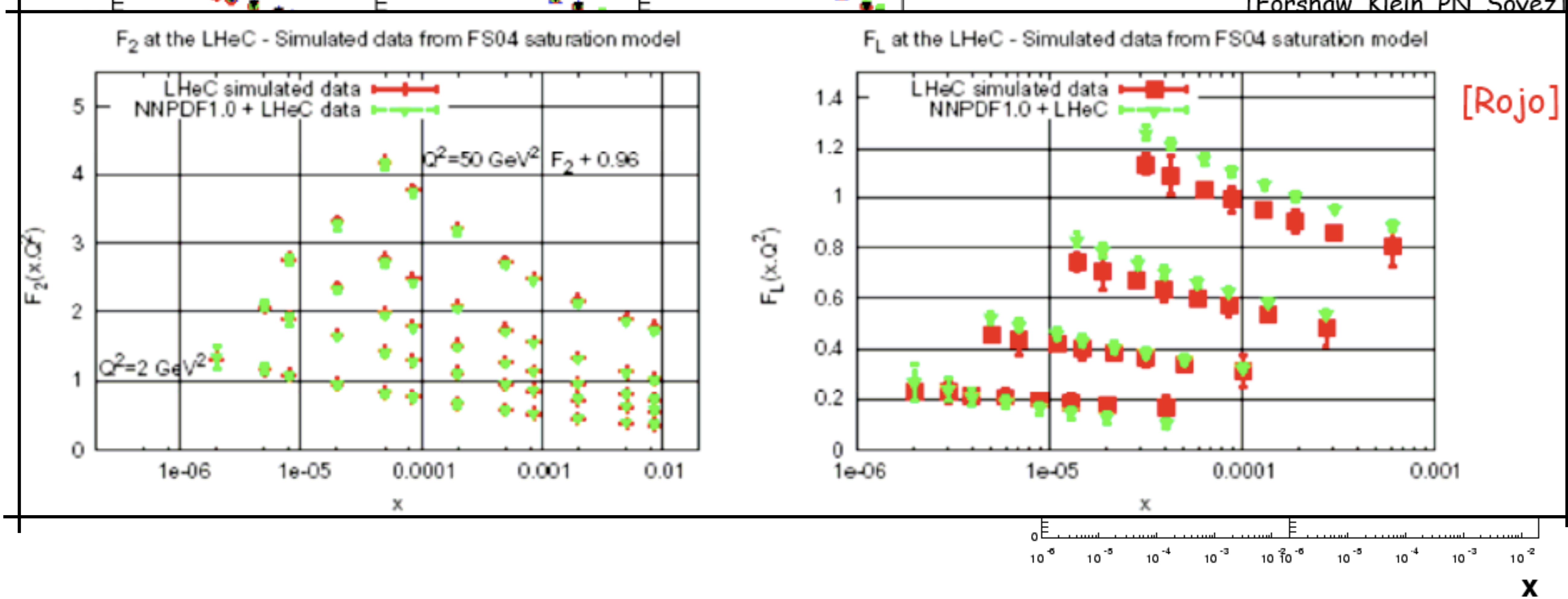
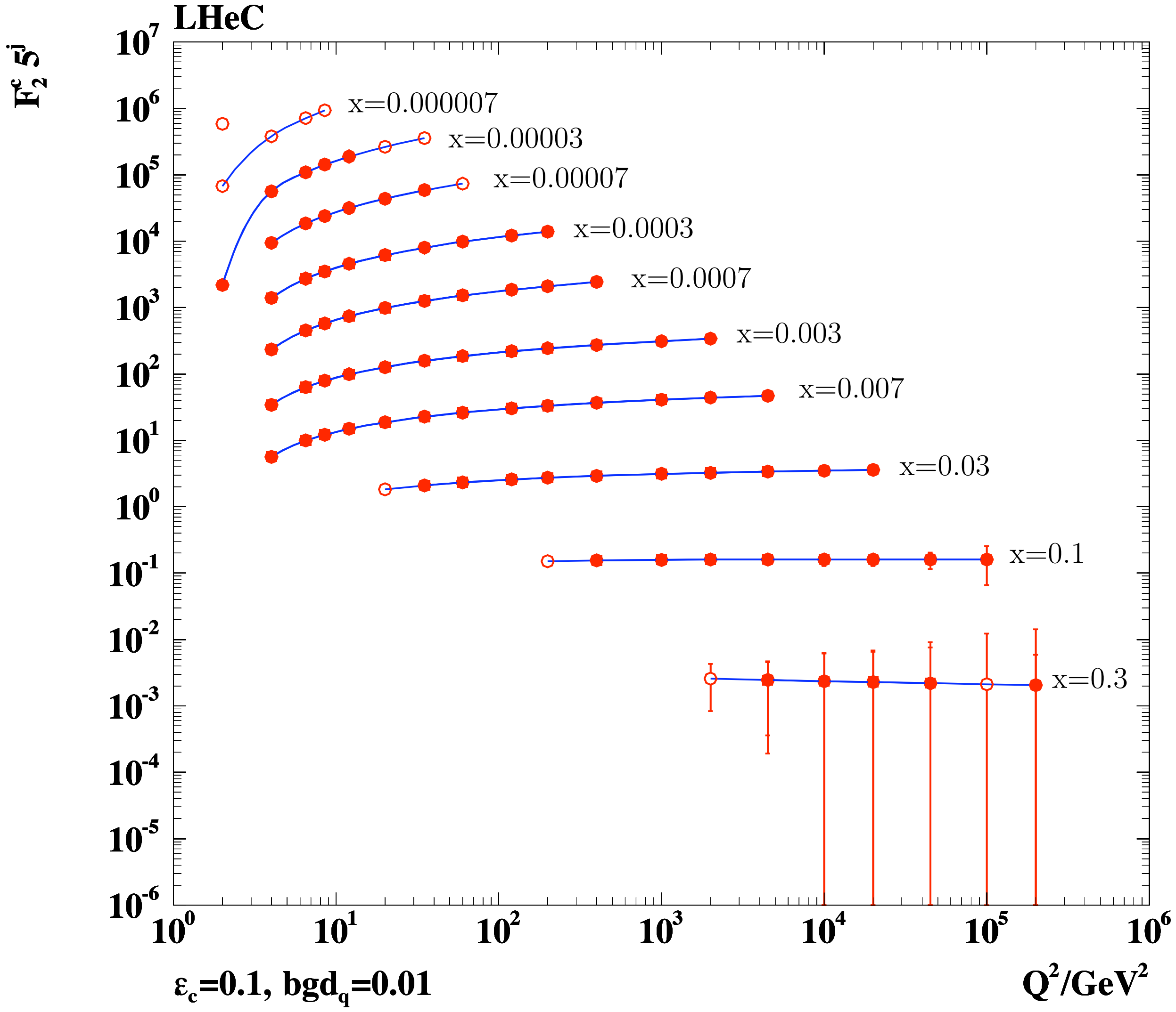
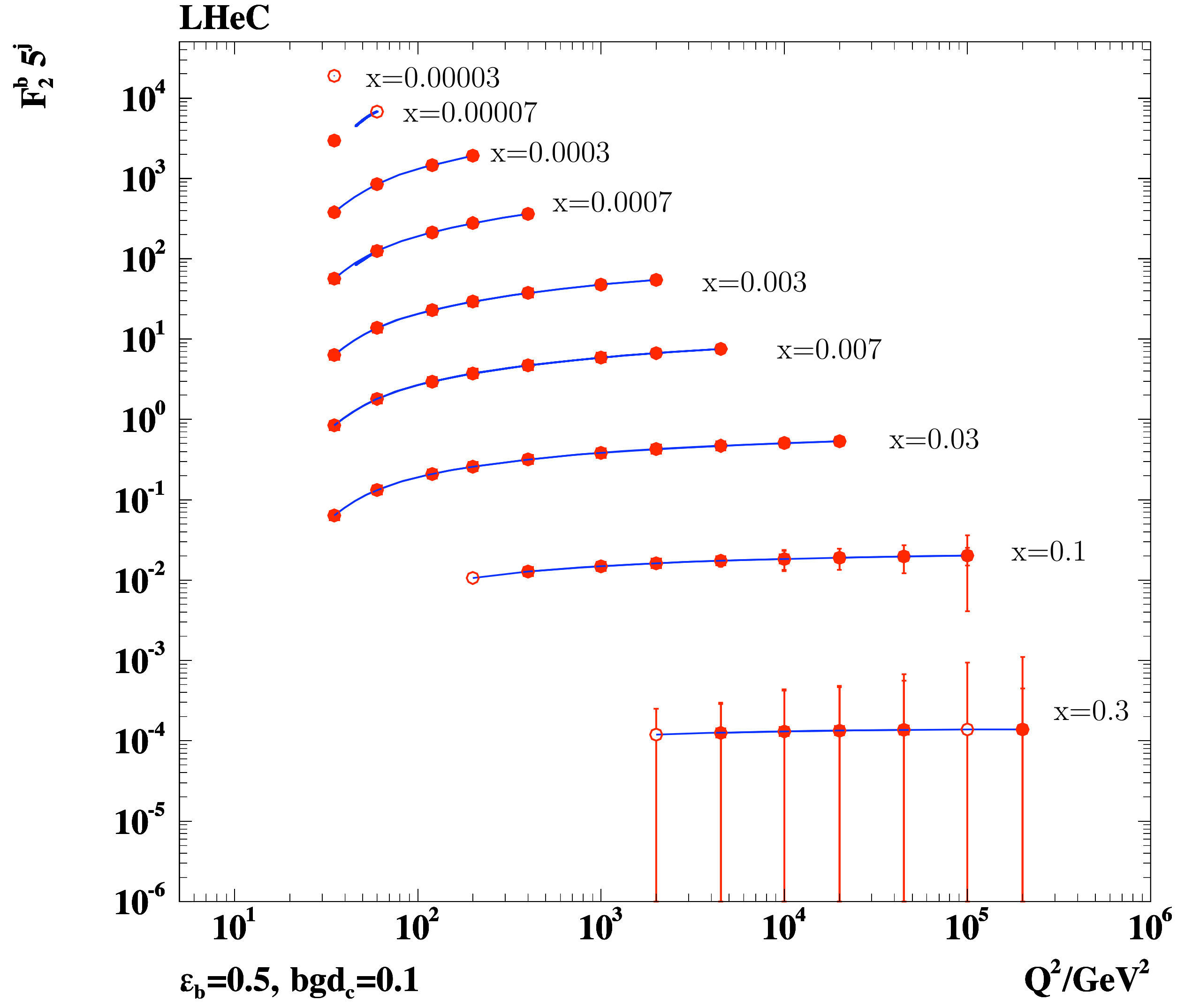


ep inclusive pseudodata (III):

- New: charm and beauty, to be included in the fits (HERApdf; systematics half than at H1).





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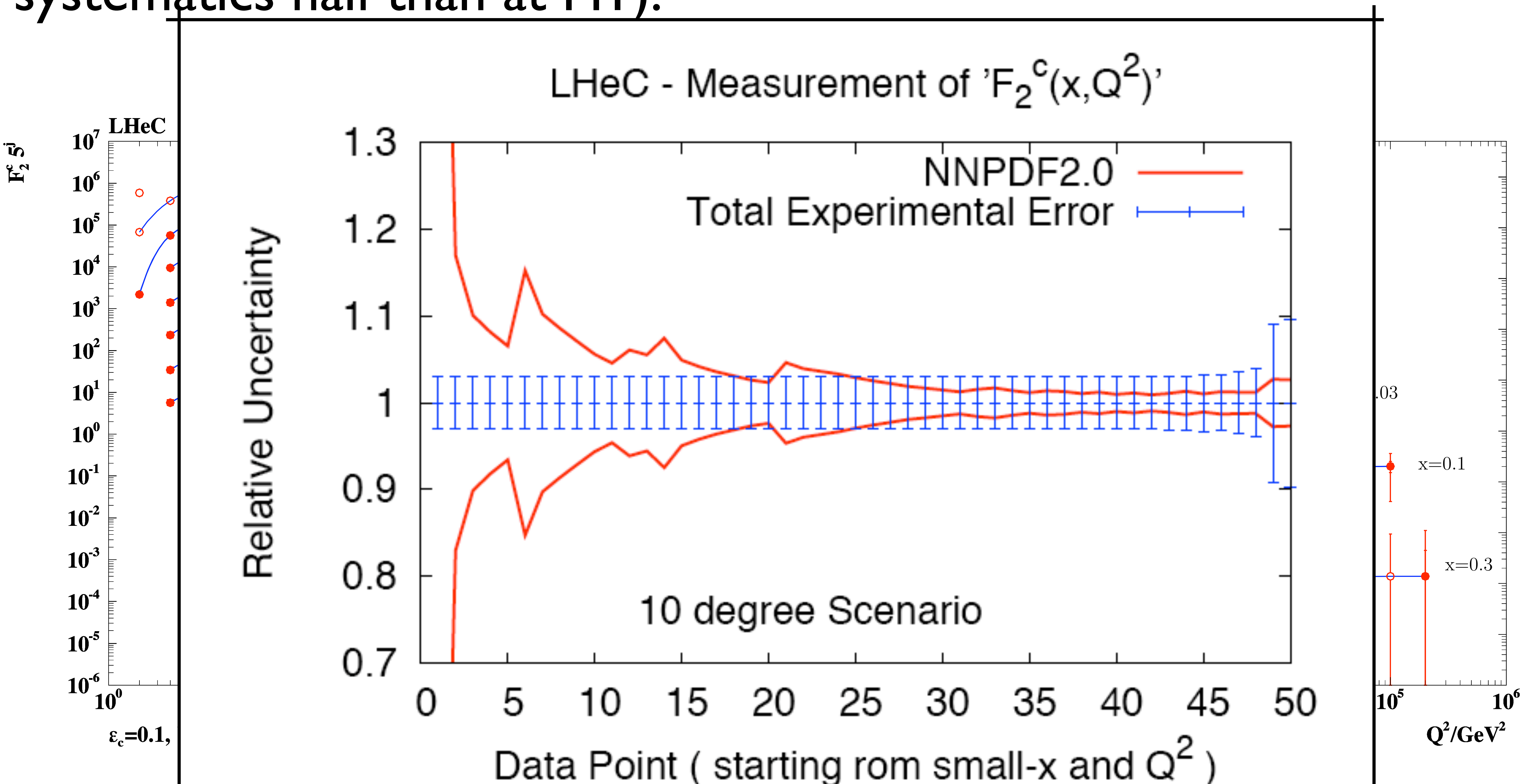
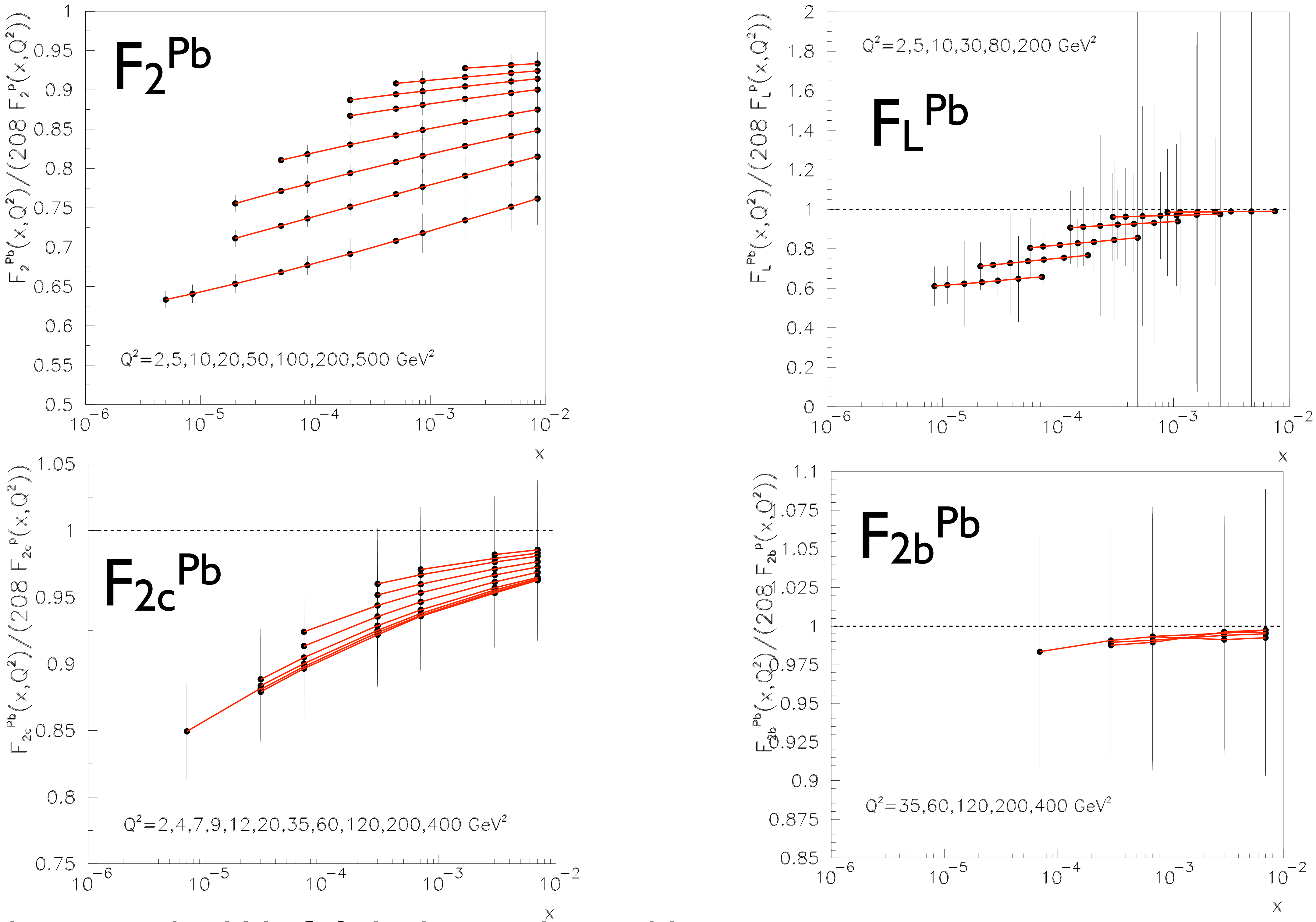


Rojo's talk

eA inclusive pseudodata (I):

- Good precision can be obtained for $F_{2(c,b)}$ and F_L at small x

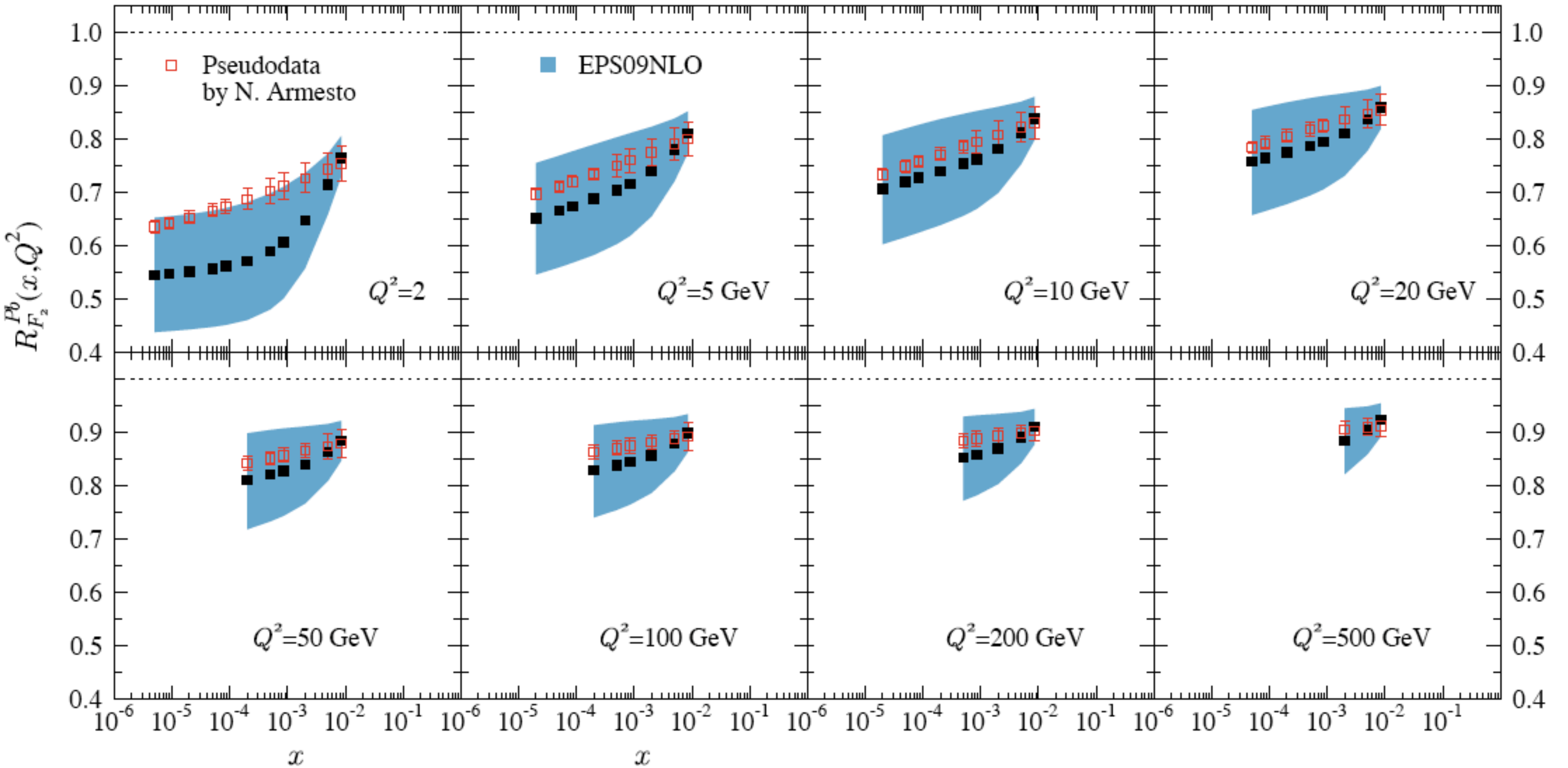
(Glauberized 3-5 flavor GBW model, NA '02).



eA inclusive pseudodata (II):

- F$_2$ data substantially reduce the uncertainties in DGLAP analysis;

inclusion of charm, beauty and F$_L$ in progress.



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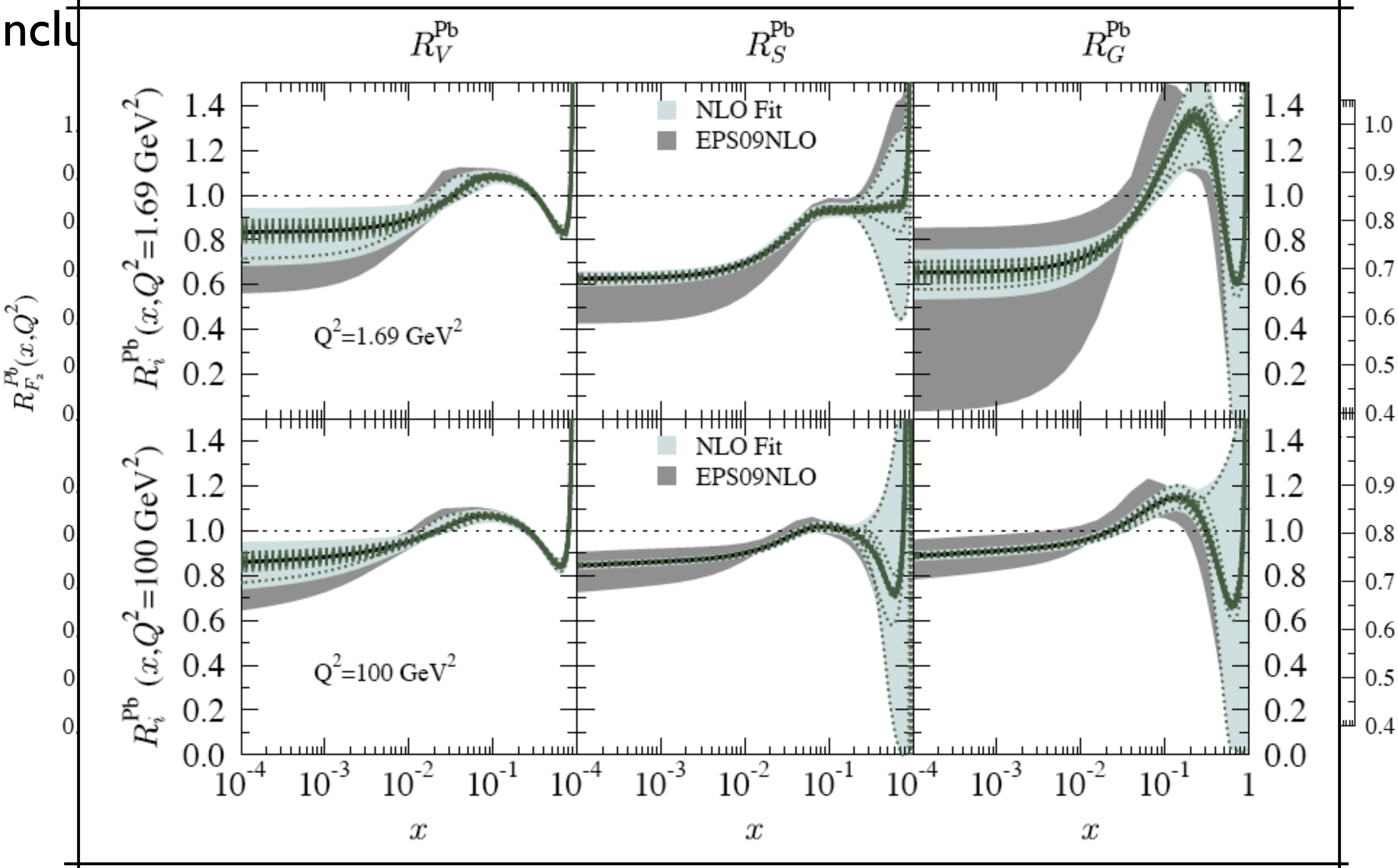
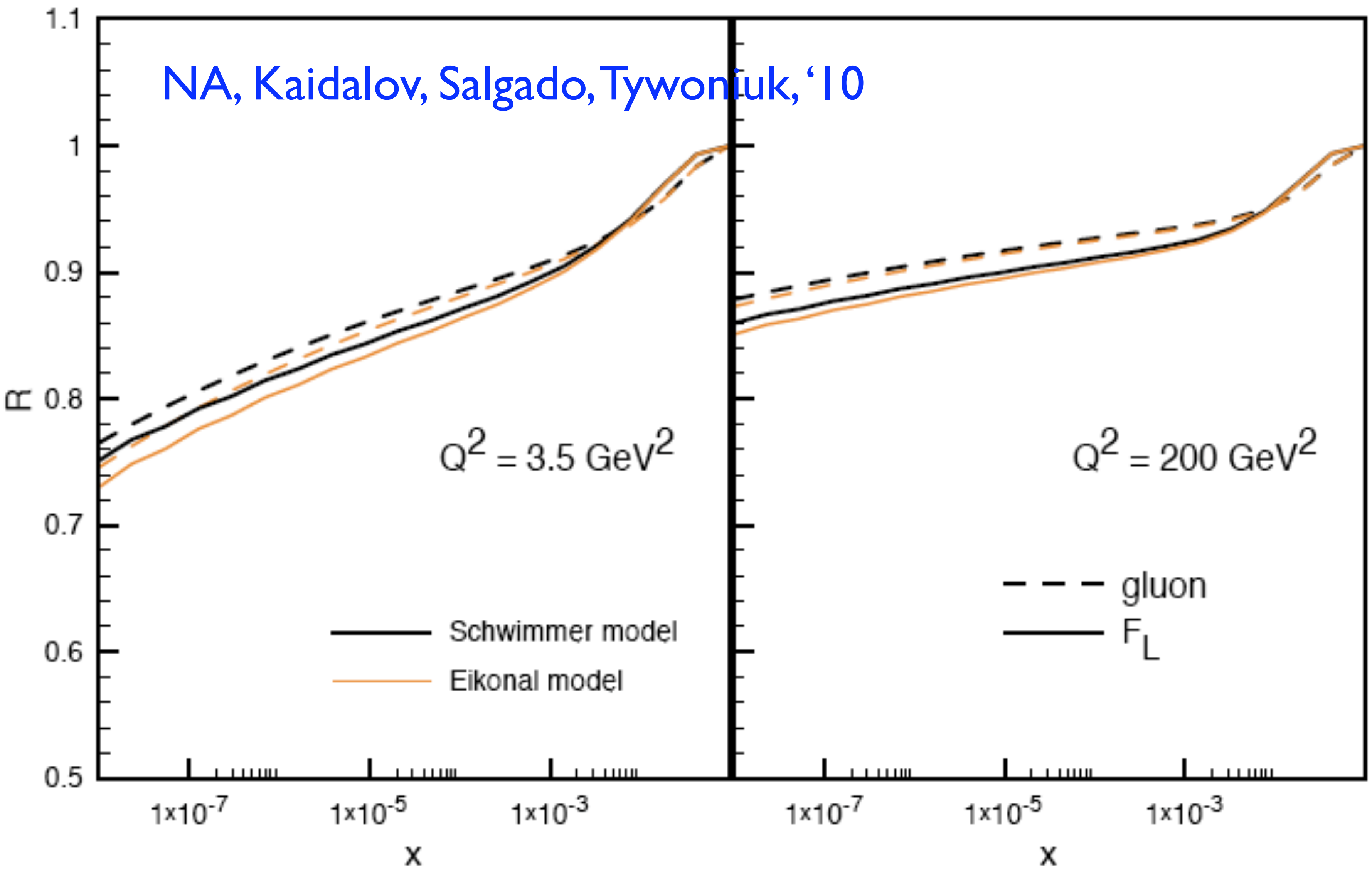


F_L in eA (I):

- F_L is very badly constrained in nuclei at small x. It traces the nuclear effects on the gluon:

$$R_{F_L} = \frac{\int_x^1 \frac{dy}{y} \left(\frac{x}{y}\right)^2 \left(\sum_{i=1}^{N_f} e_i^2 \left(1-\frac{x}{y}\right) y\, R_g(y,Q^2) g(y,Q^2) + \frac{2}{3} R_{F_2}(y,Q^2) F_2(y,Q^2)\right)}{\int_x^1 \frac{dy}{y} \left(\frac{x}{y}\right)^2 \left(\sum_{i=1}^{N_f} e_i^2 \left(1-\frac{x}{y}\right) y g(y,Q^2) + \frac{2}{3} F_2(y,Q^2)\right)}$$

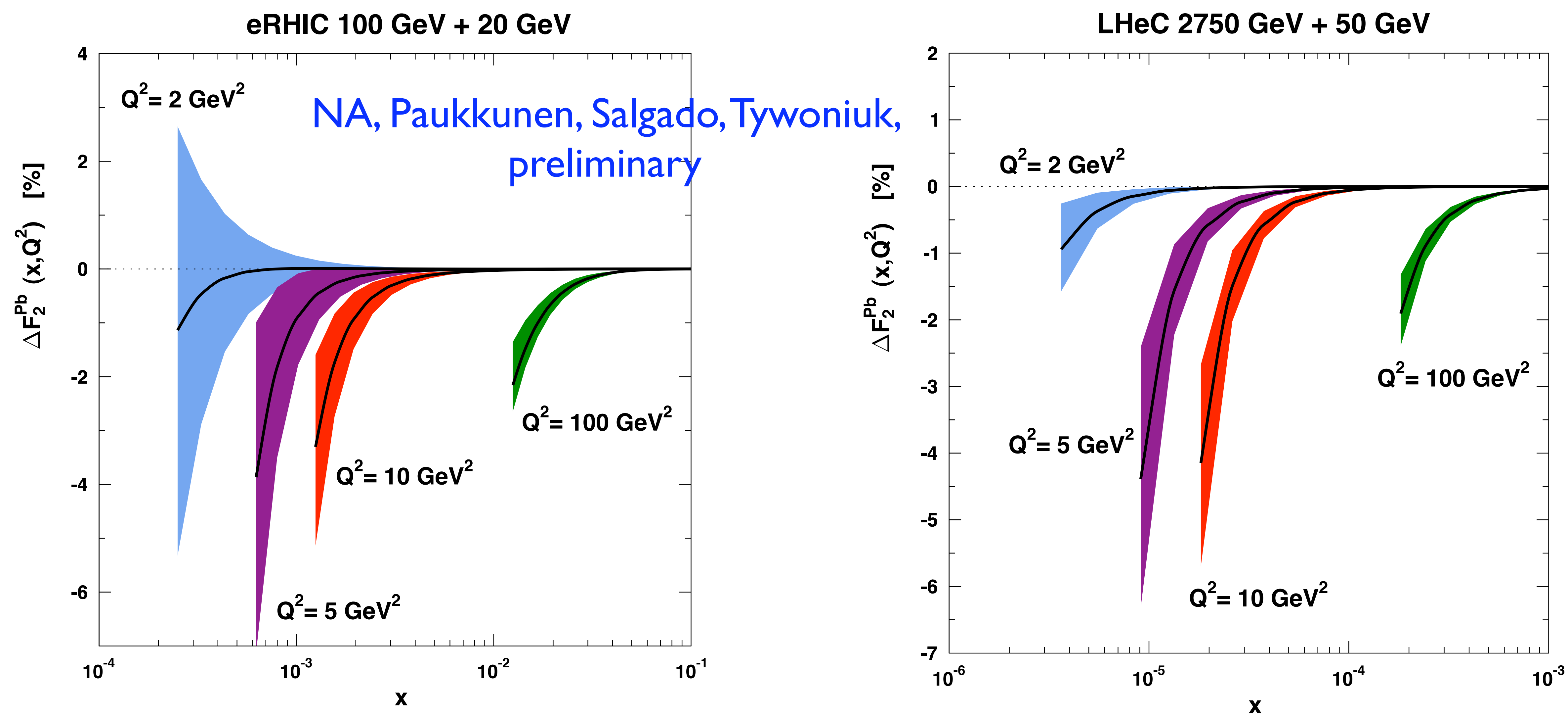


F_L in eA (II):

- F_L enters the extraction of F_2: usually F_L/F_2 is taken as A-independent i.e. the same measured in ep.

$$\sigma_r^{NC} = \frac{Q^4 x}{2\pi\alpha^2 Y_+}\frac{d^2\sigma^{NC}}{dx dQ^2} = F_2\left[1 - \frac{y^2}{Y_+}\frac{F_L}{F_2}\right], \qquad Y_+ = 1 + (1-y)^2$$

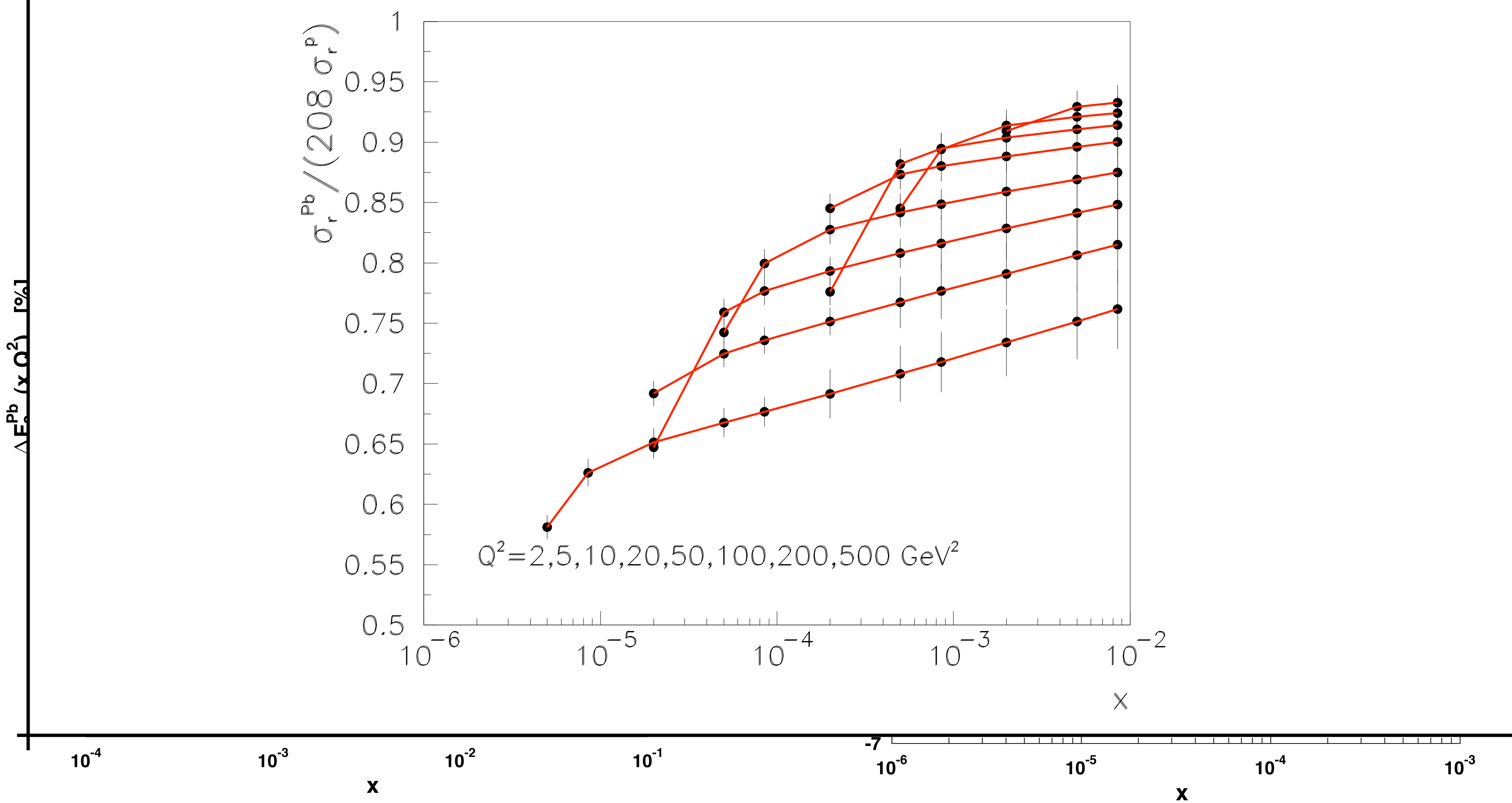
- What if not? Plot $(F_2^{CTEQ6M} - F_2^{CTEQ6M+EPS09})/F_2^{CTEQ6M}$.



NA, Paukkunen, Salgado, Tywoniuk, preliminary

F_L in eA (II):

- F_L Uncertainties of order 5 % (larger than expected stat. inde+syst.) ⇒ measure F_L or use the reduced cross section (but then ratios at two energies...).



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   - Exclusive vector meson production. (P. Newman, G. Watt)
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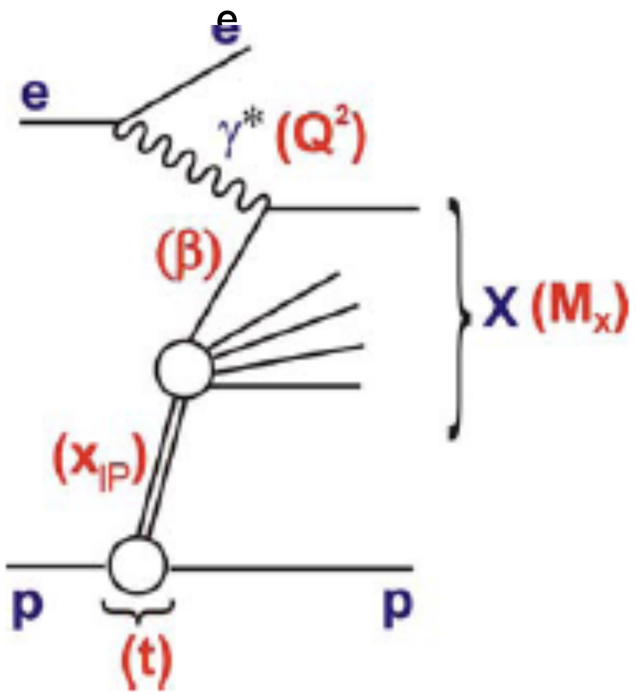
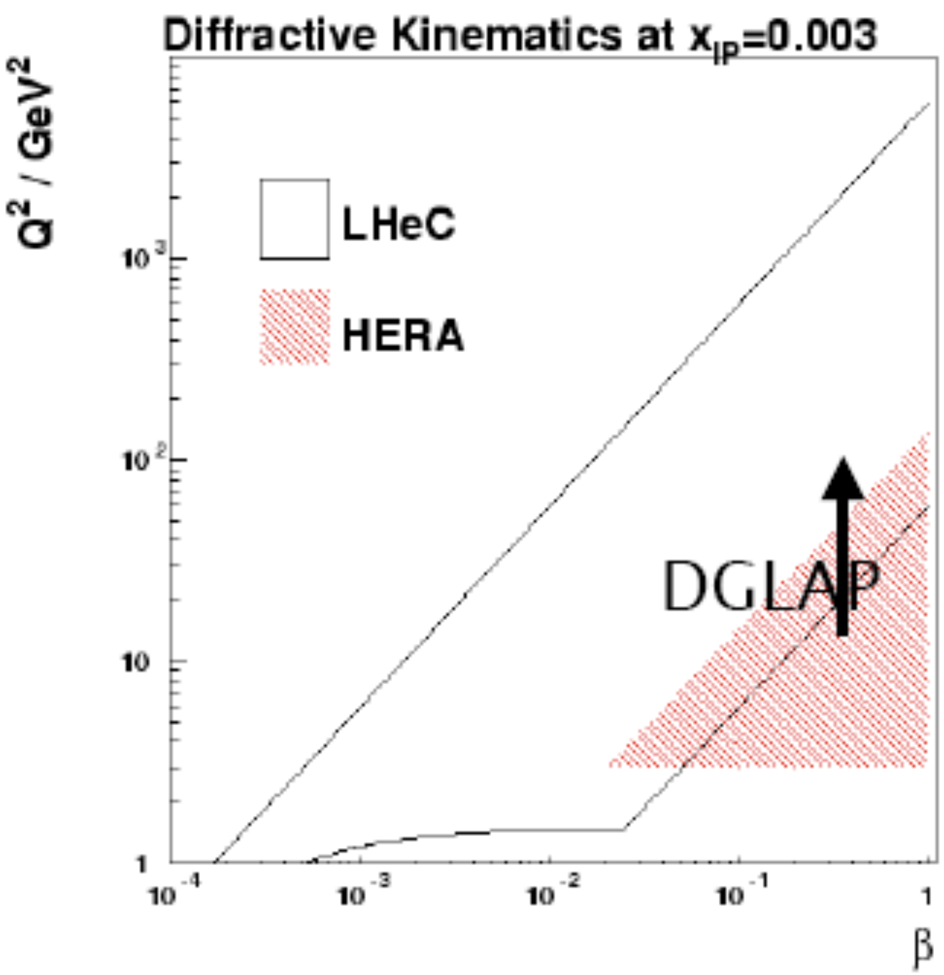
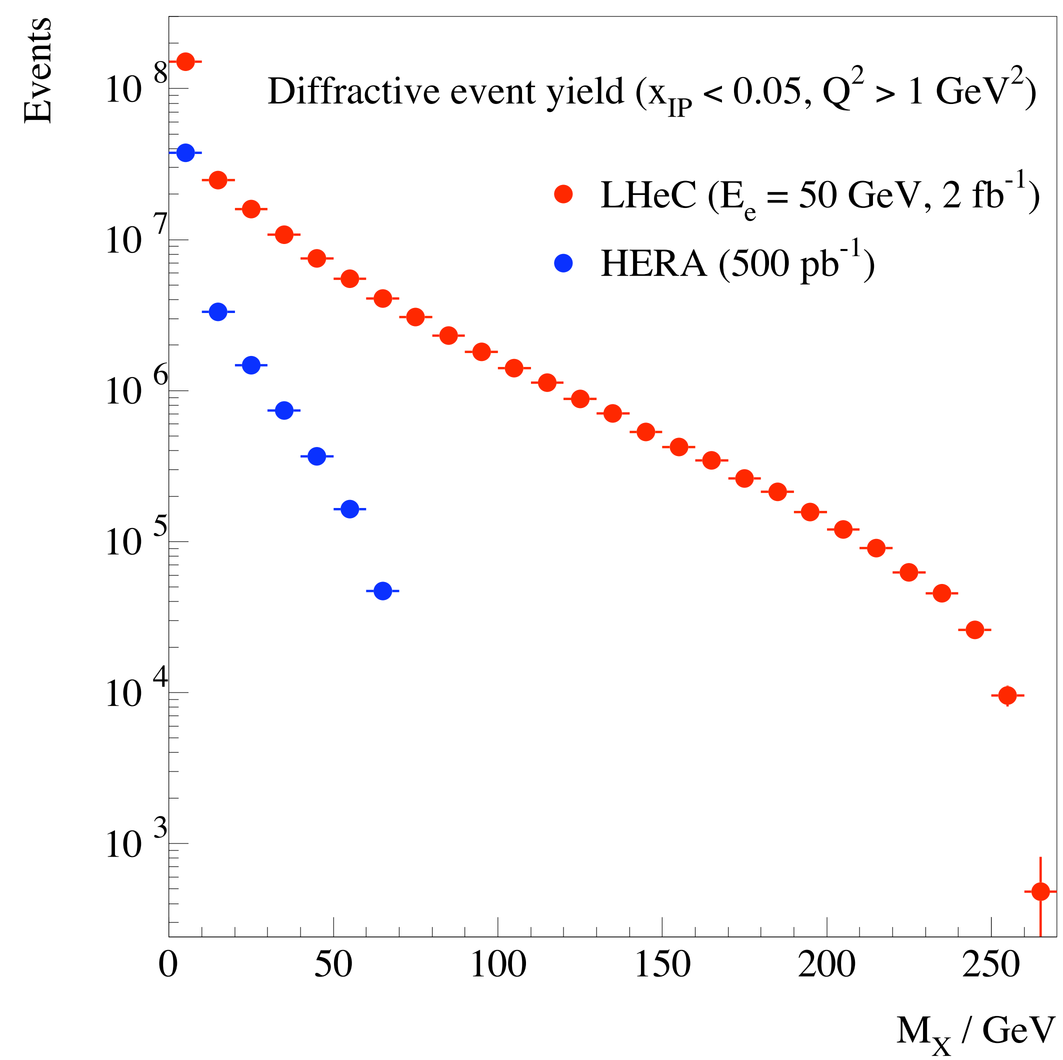
ep diffractive pseudodata:



- Large increase in the M^2, $x_P=(M^2-t+Q^2)/(W^2+Q^2)$, $\beta=x/x_P$ region studied.

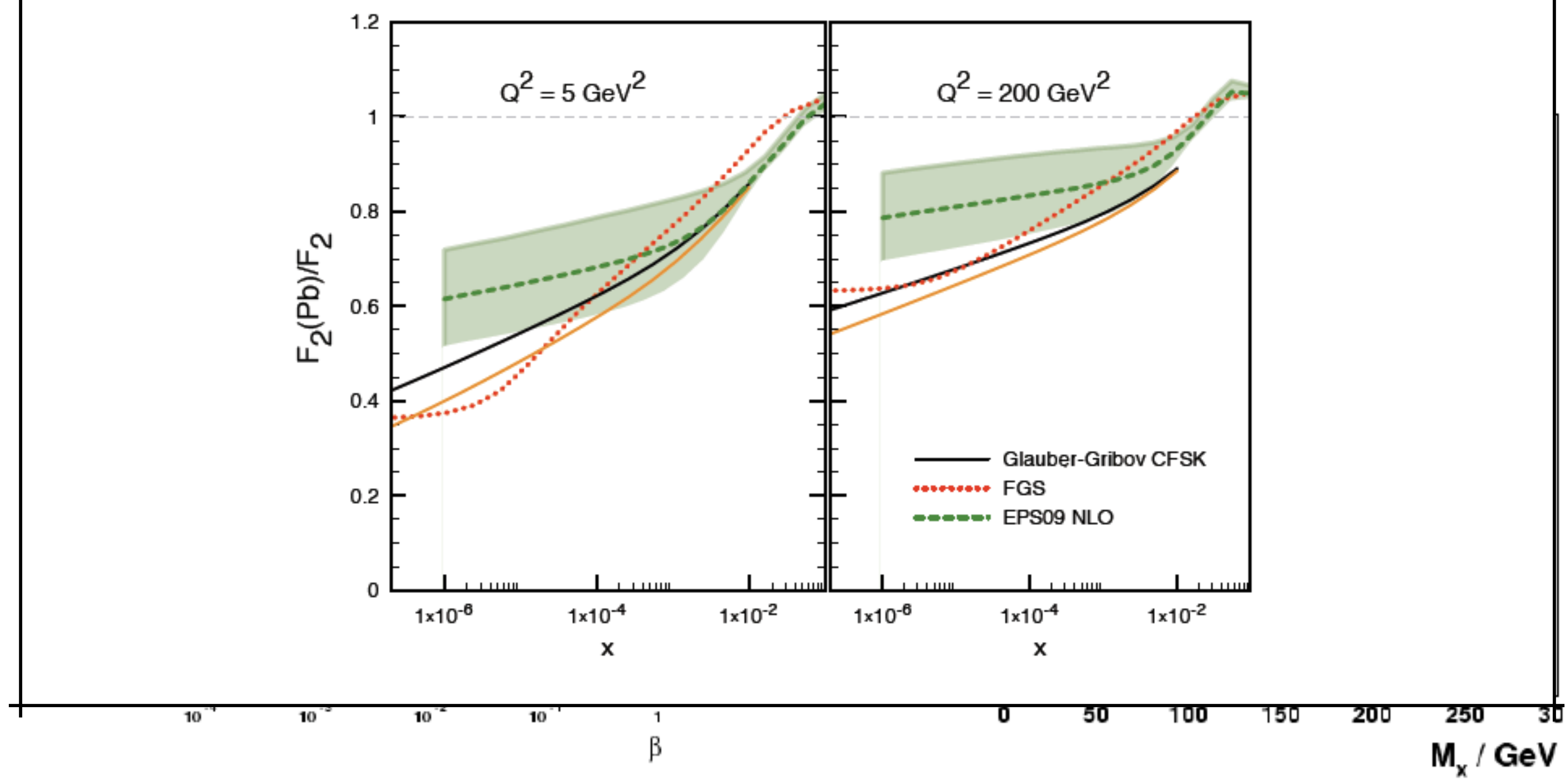




ep diffractive pseudodata:

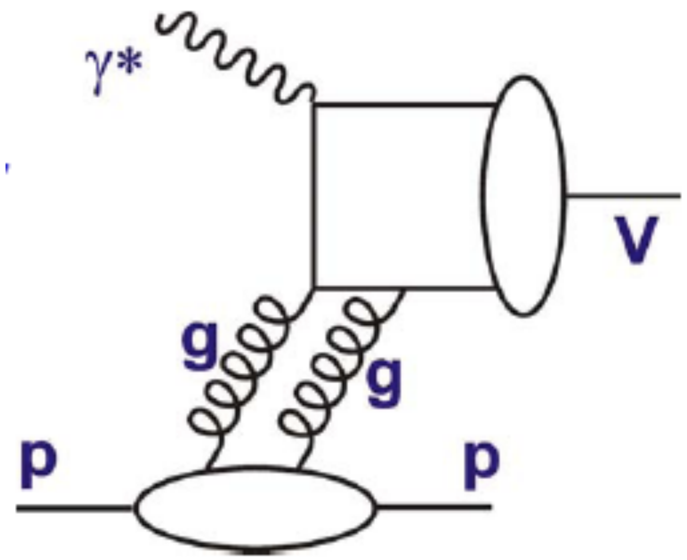
Note: diffraction in ep is linked to shadowing in eA (Gribov): FGS, Capella-Kaidalov et al,...

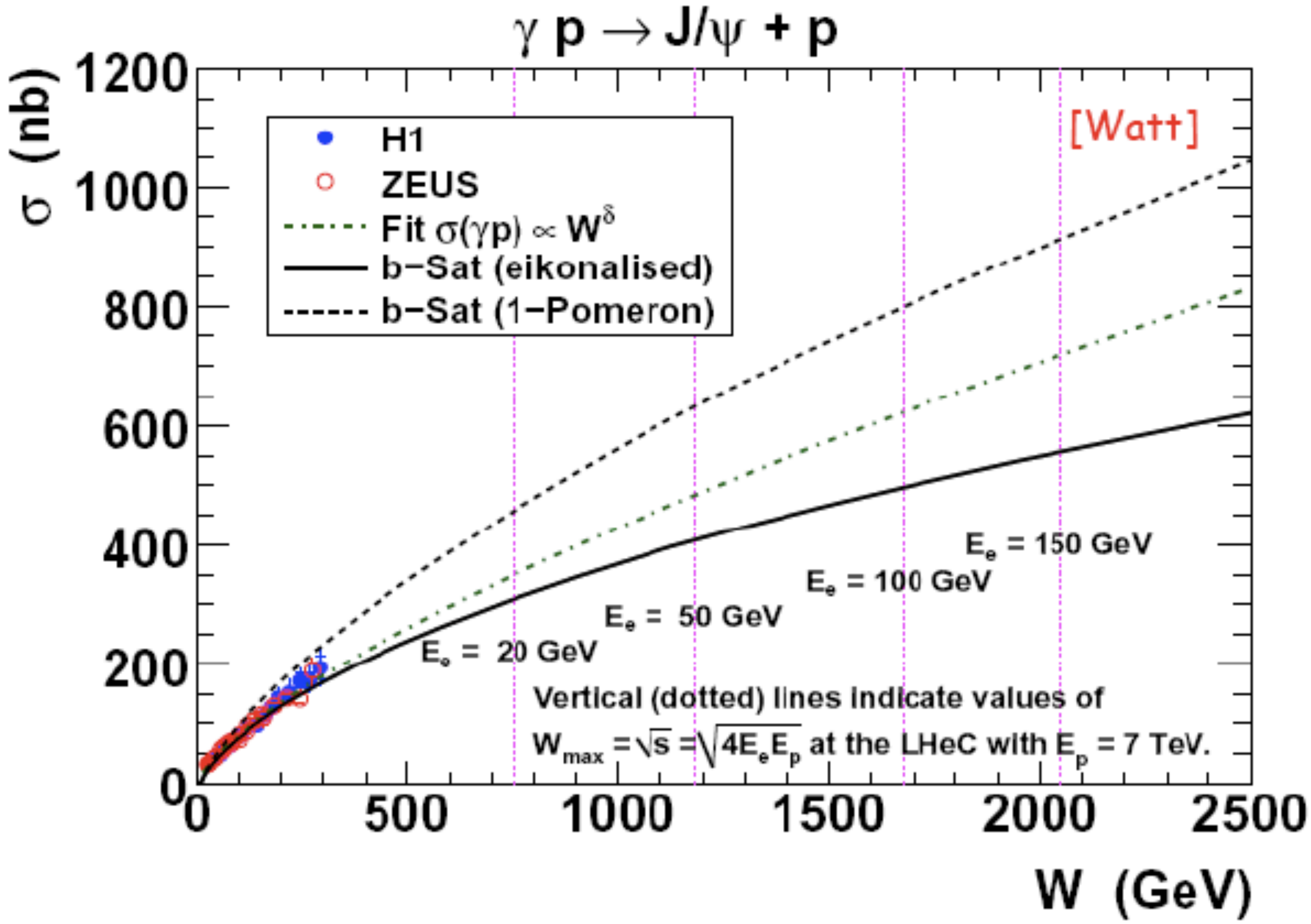
NA, Kaidalov, Salgado, Tywoniuk, '10

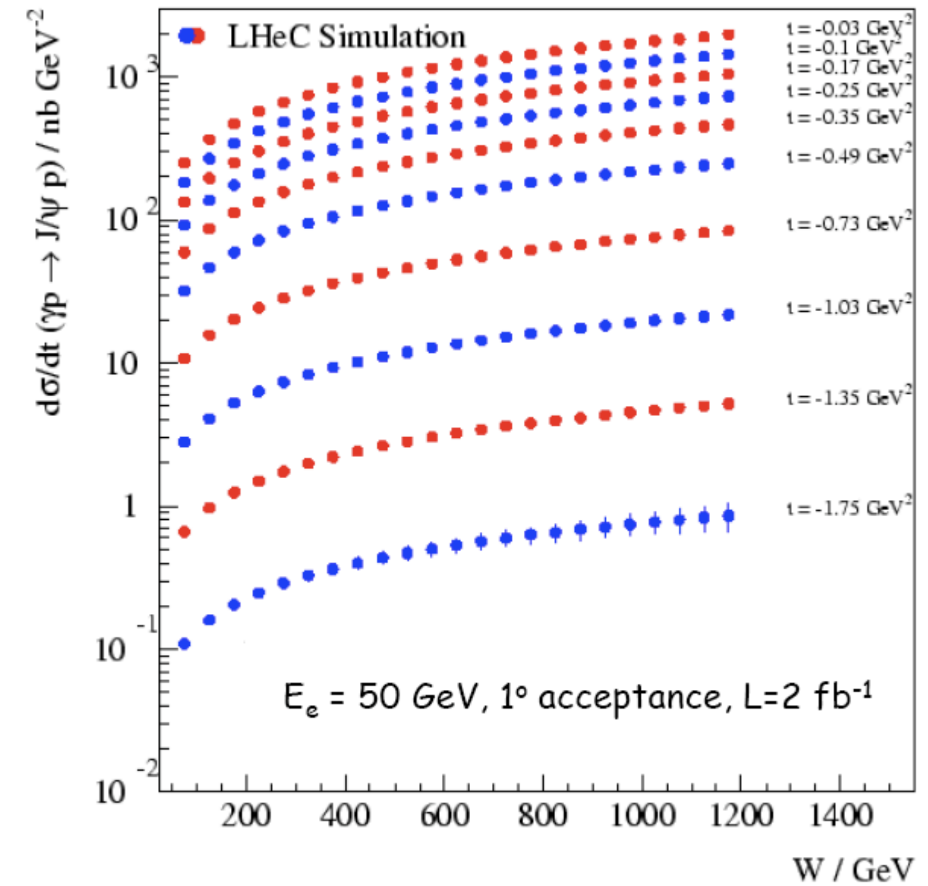


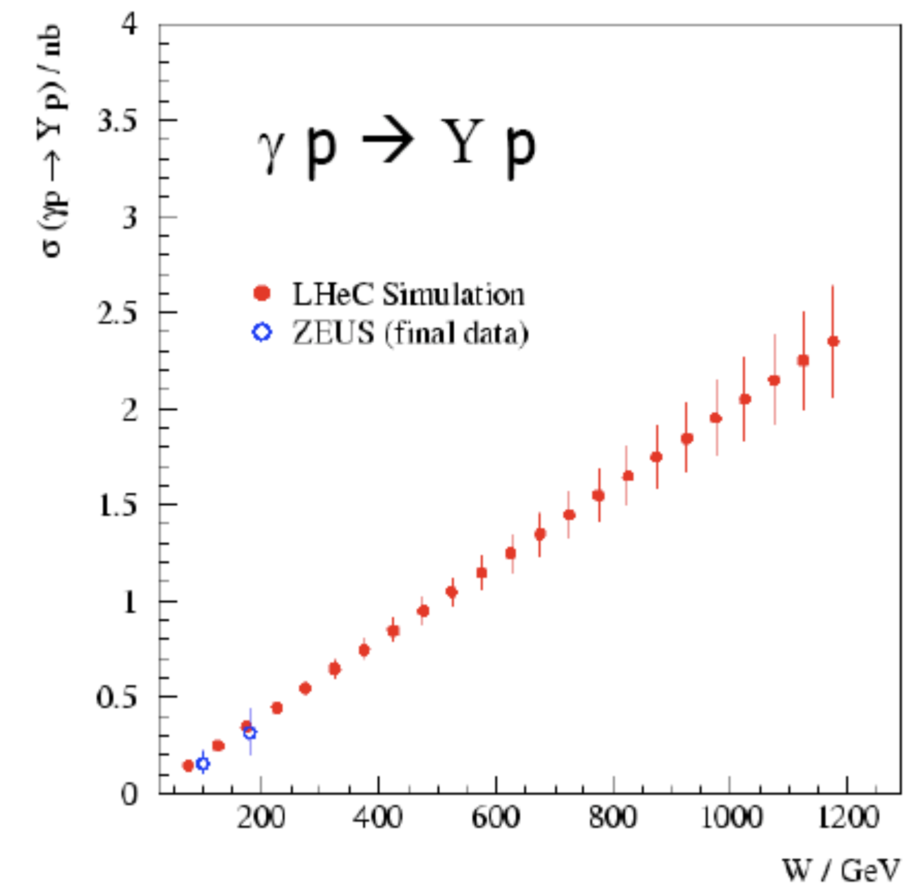
Elastic vector meson production:

- Most promising!!!





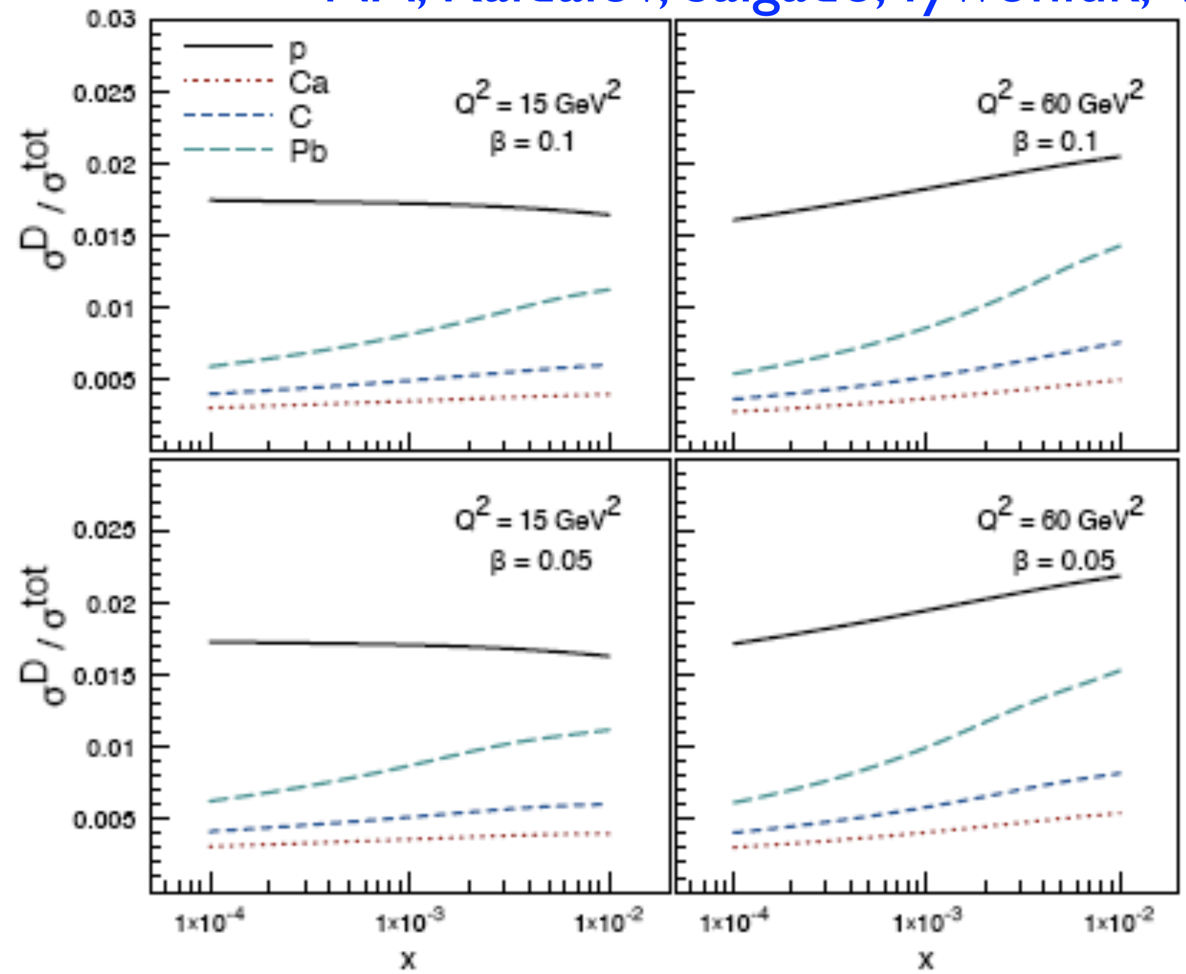


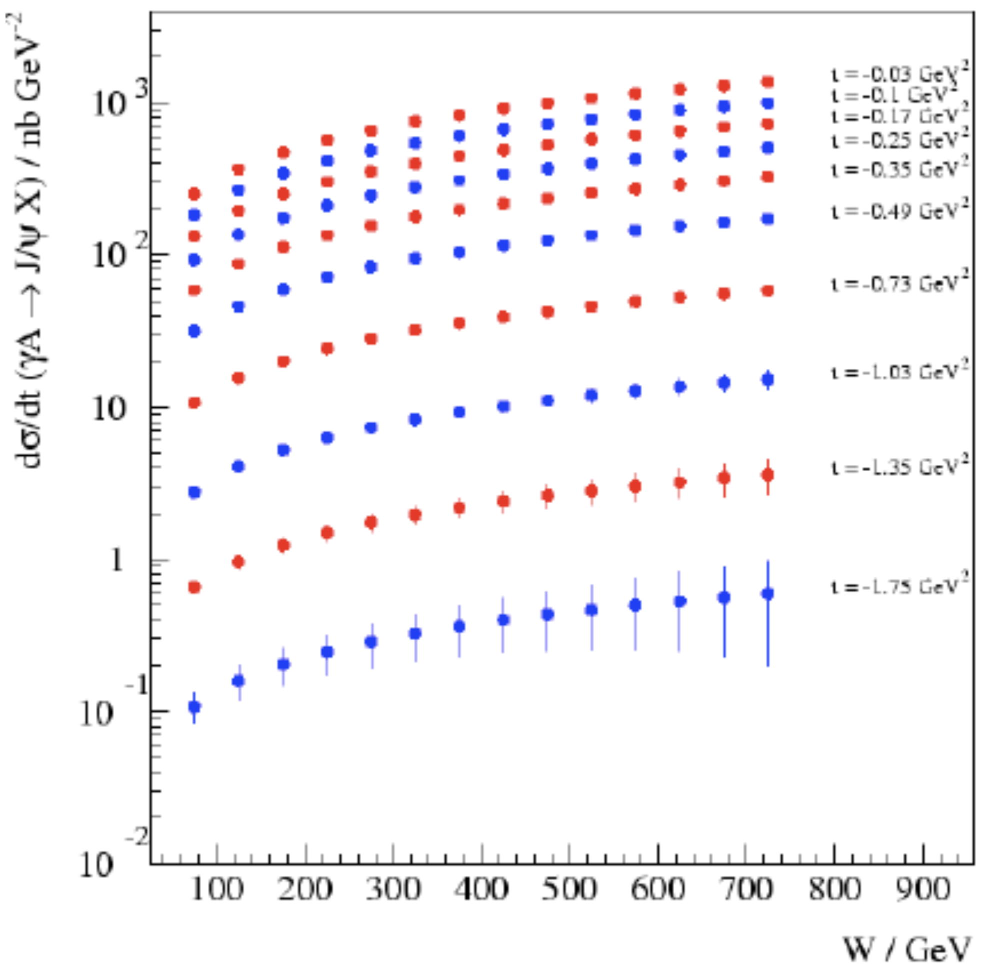


Nuclear diffraction:

- Problem: 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.

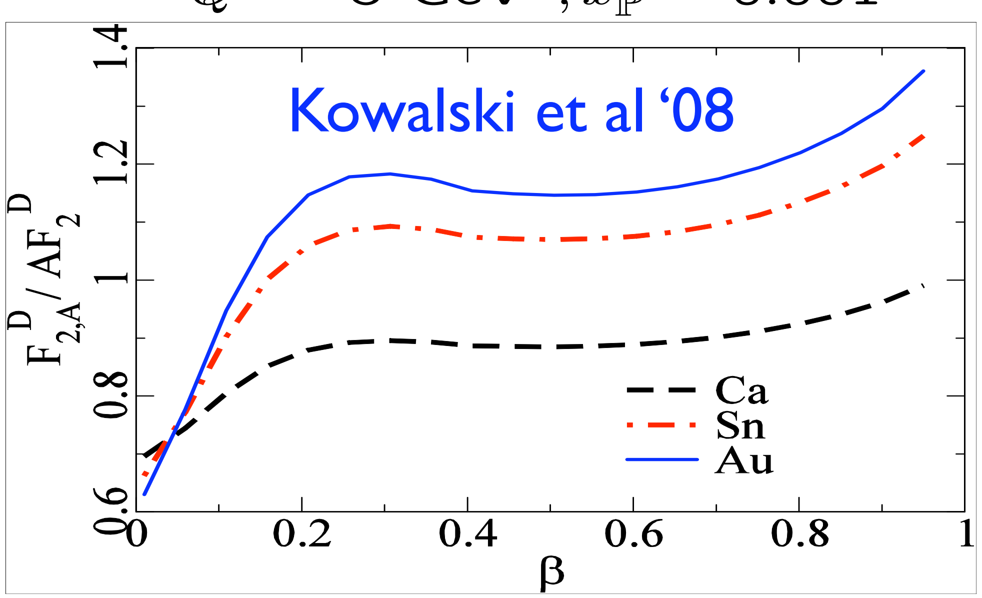
NA, Kaidalov, Salgado, Tywoniuk, '10





coherent

$Q^2 = 5\ \text{GeV}^2, x_{\mathbb{P}} = 0.001$



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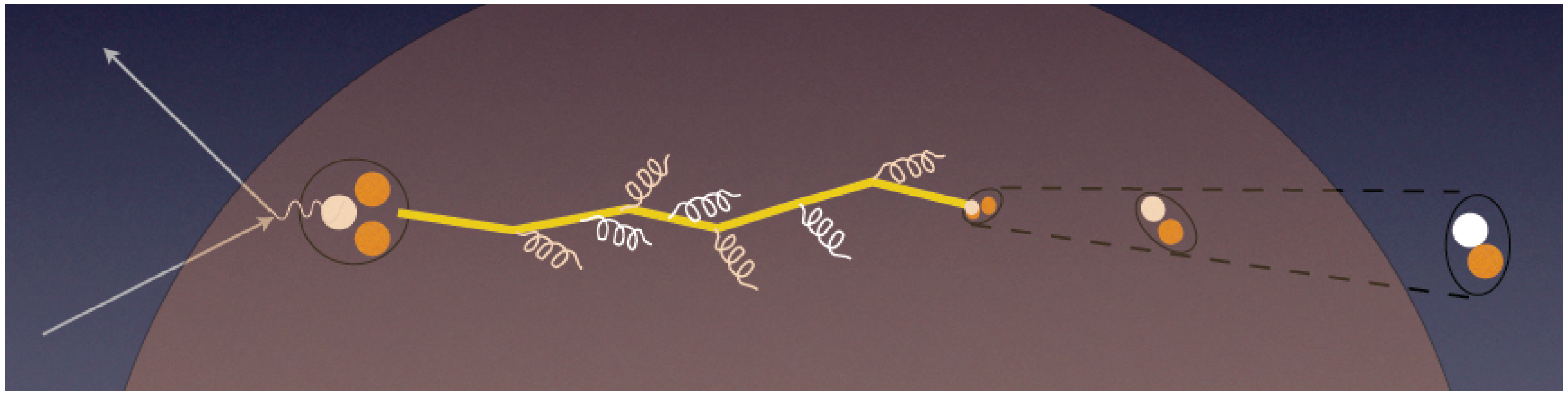
In-medium hadronization:

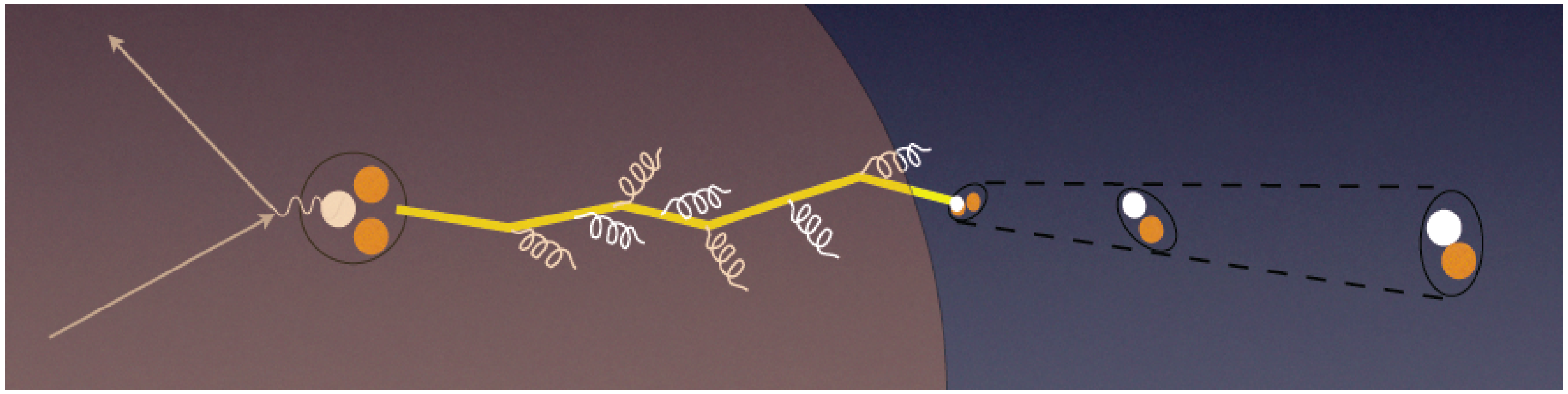
- A high energy eA collider would allow to study the dynamics of hadronization, testing the parton/hadron energy loss mechanism by introducing a length of colored material which would modify its pattern (length/nuclear size, chemical composition).

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



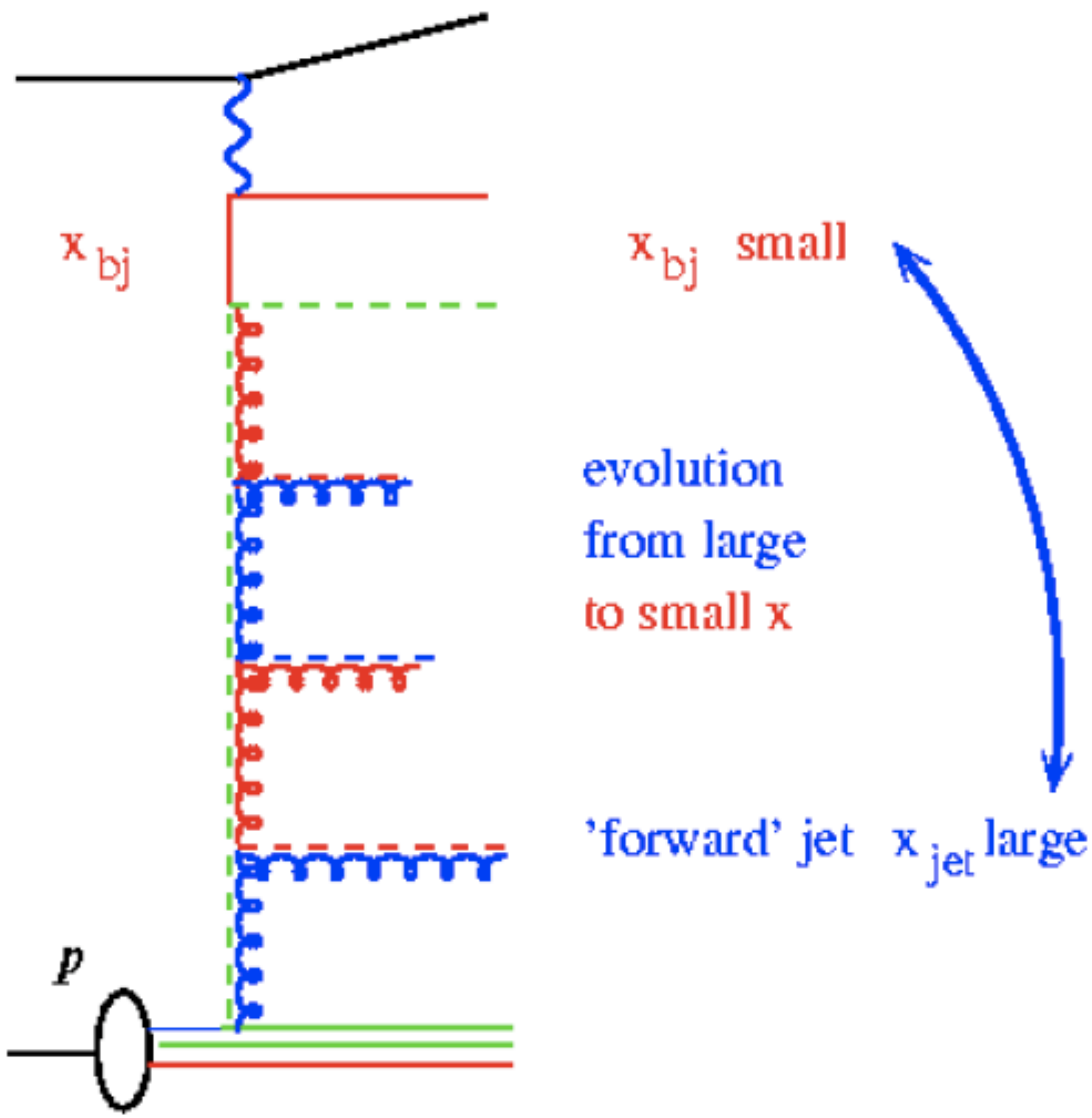
Brooks at Divonne'09

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



Forward jets:

Jung at Divonne'08



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

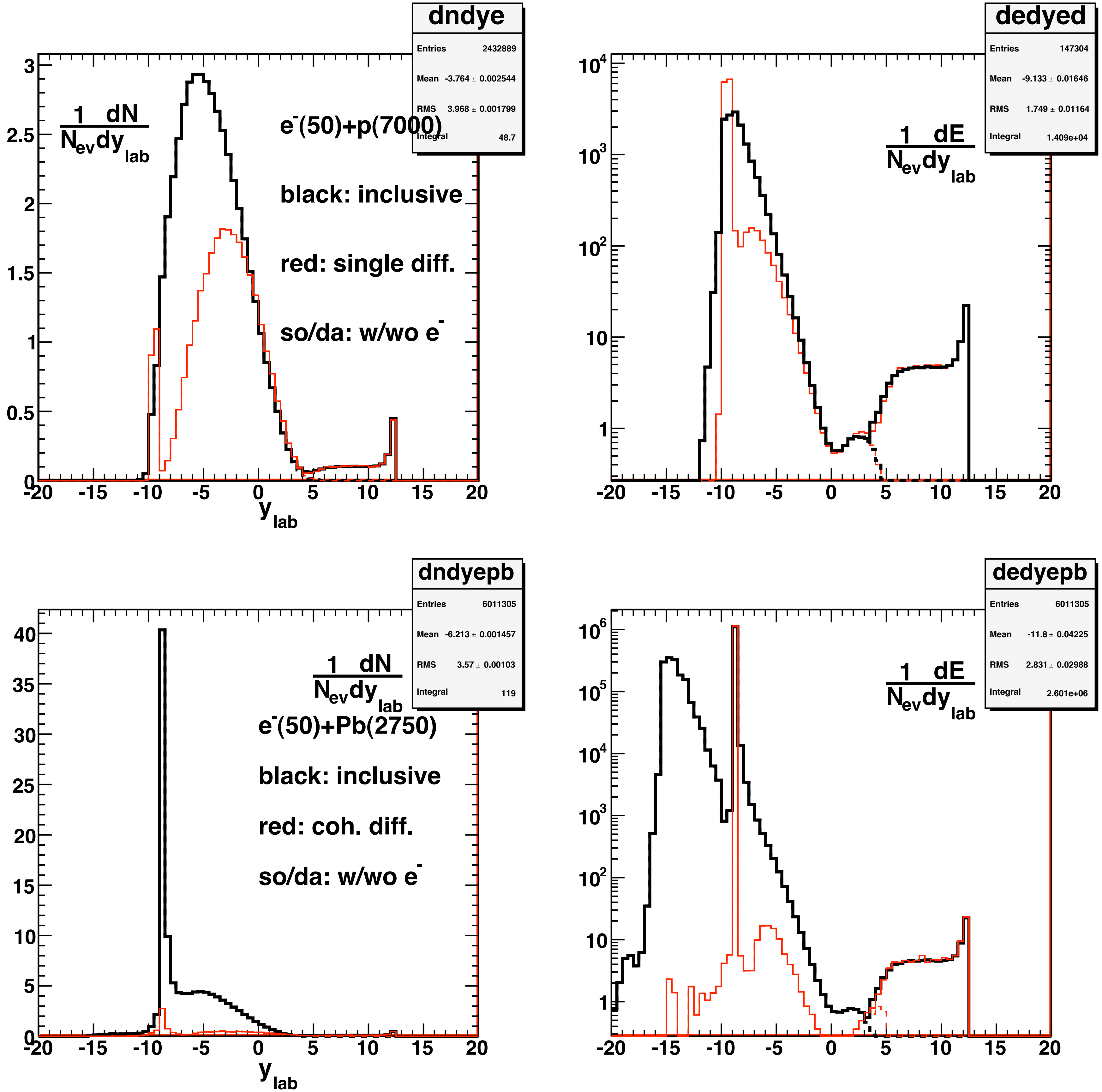
- Further imposing a rapidity gap (diffractive jets) would be most interesting: perturbatively controllable observable.

Hadronic final states:

- Under study: Monte Carlo samples with DPMJET III+FLUKA for HFS, including nuclear evaporation in eA → particle/energy fluxes.
- Preliminary results for LHeC indicate:
→ ~ 2 <interactions>

in ePb: reduced rapidity gap survival.
→ ~ 1 % of events

with Pb left intact.



Summary:

- Many issues remain open about small-x physics (behavior of the hadron wave function at small x): describable by pQCD?, need of resummation or onset of unitarity in the accessible kinematical regions?

- Current ep experiments provide information for pp@LHC at mid-rapidity; in eA, not even dAu@RHIC is covered at mid-rapidity.

- An electron-nucleon/ion collider offers huge possibilities to test our ideas about high-energy QCD; I have only shown some of them (e.g. no GPDs,...).

- eA acts as an amplifier of density effects: enlarges the lever arm for discovery and offers a testing ground.

- To do for the CDR: impact of diffractive data, updf's and GPDs, final states, radiative corrections for eA,...

LHeC scenarios:

For F_2

config.	E(e)	E(N)	N	$\int L(e^+)$	$\int L(e^-)$	|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	$5 \cdot 10^{-4}$		?	$5 \cdot 10^{-3}$	?	?	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.

LHeC scenarios: