IGFAE

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Light Cone 2010
Universidad Internacional Menéndez Pelayo
Valencia, June 17th 2010

Small-x physics at the Large Hadron-electron Collider

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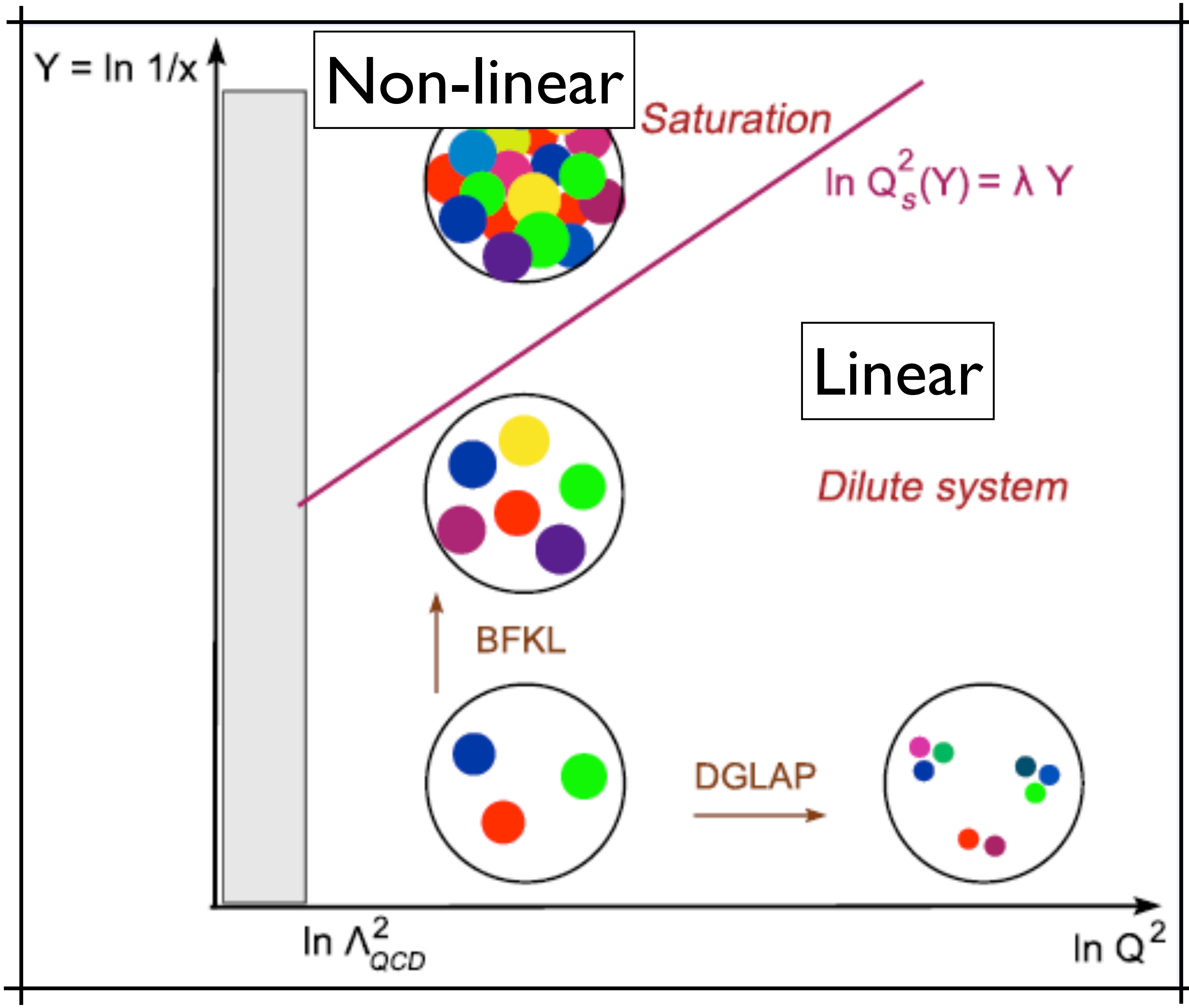
LHeC Study Group, http://cern.ch/lhec
Working group on *Physics at High Parton Densities in ep and eA* (with Brian Cole, Paul Newman and Anna Stasto)

Contents:

See the talk by David d'Enterria.

Theory: high-energy QCD

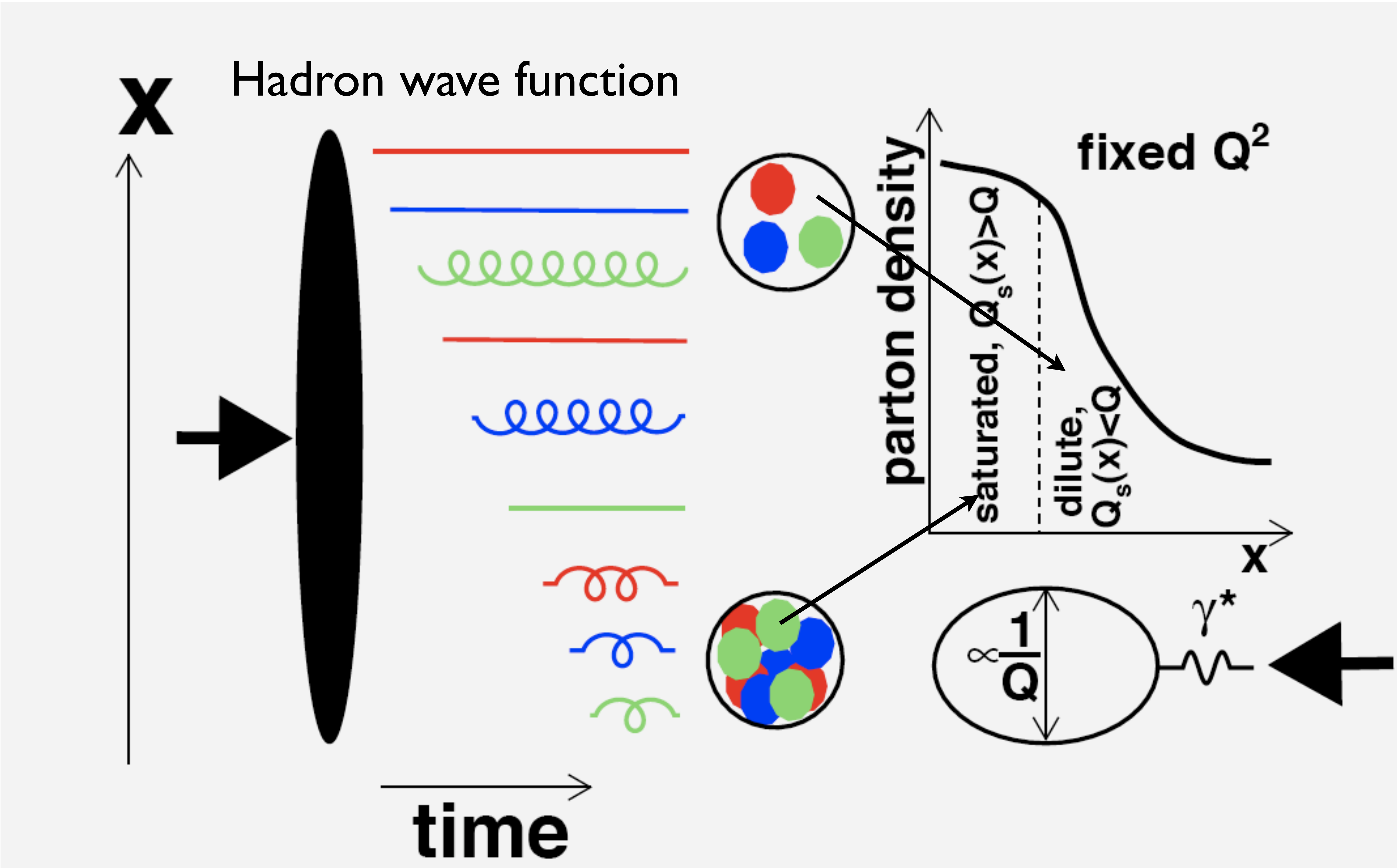


Where do the available experimental data lie?

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.

Saturation ideas: CGC



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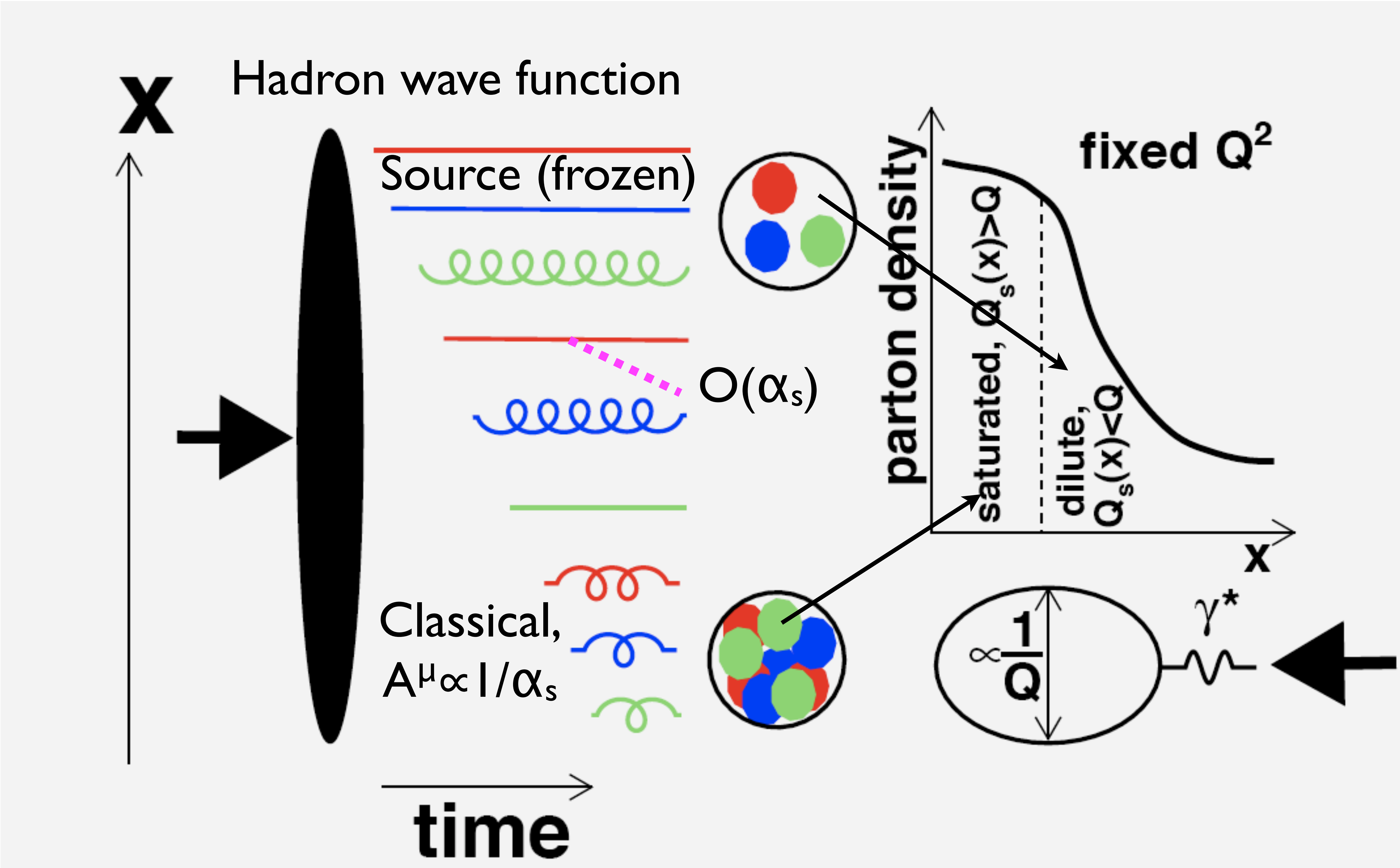
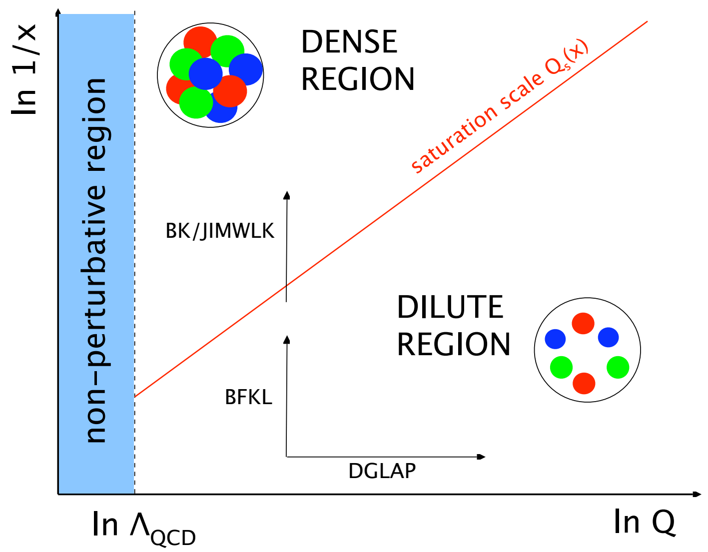
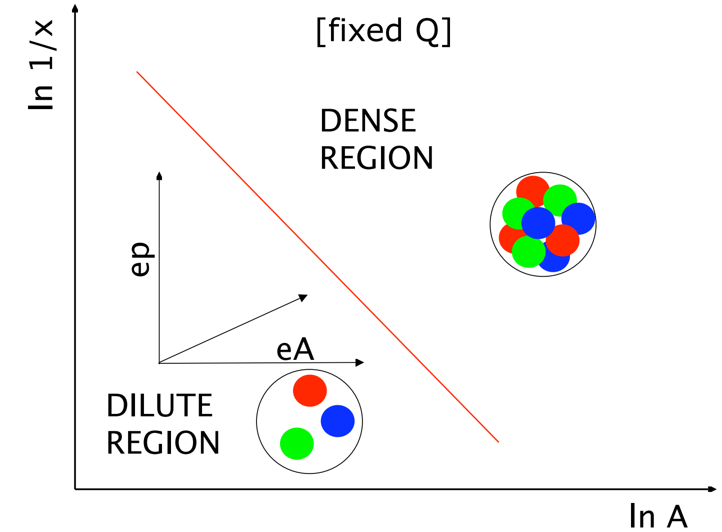


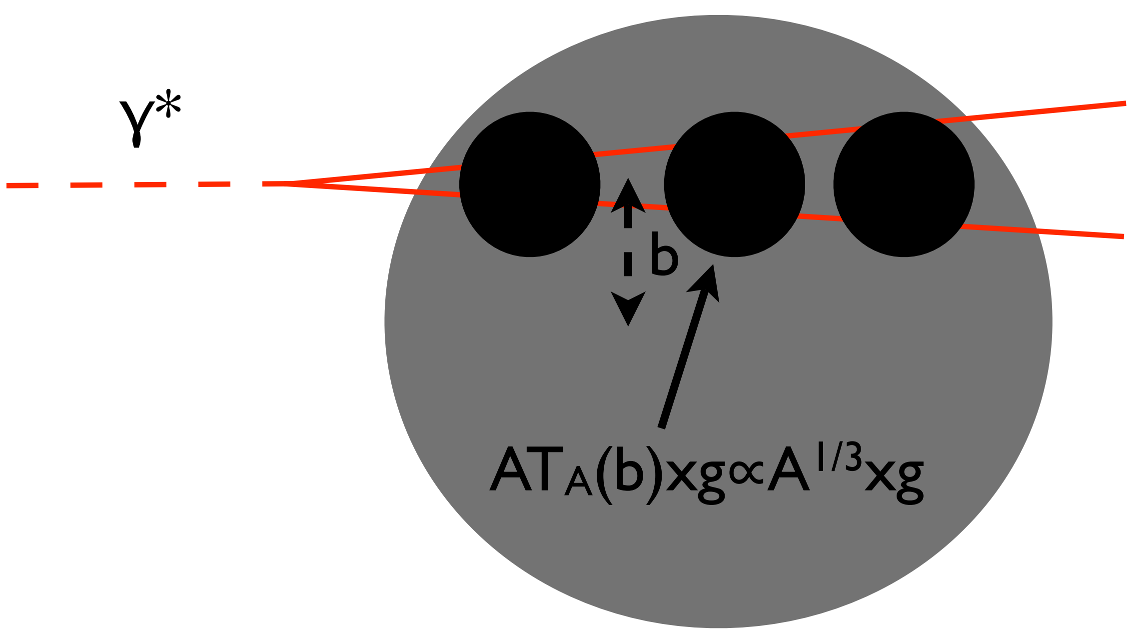
Saturation:





Two-pronged approach: ↓ x / ↑ A.

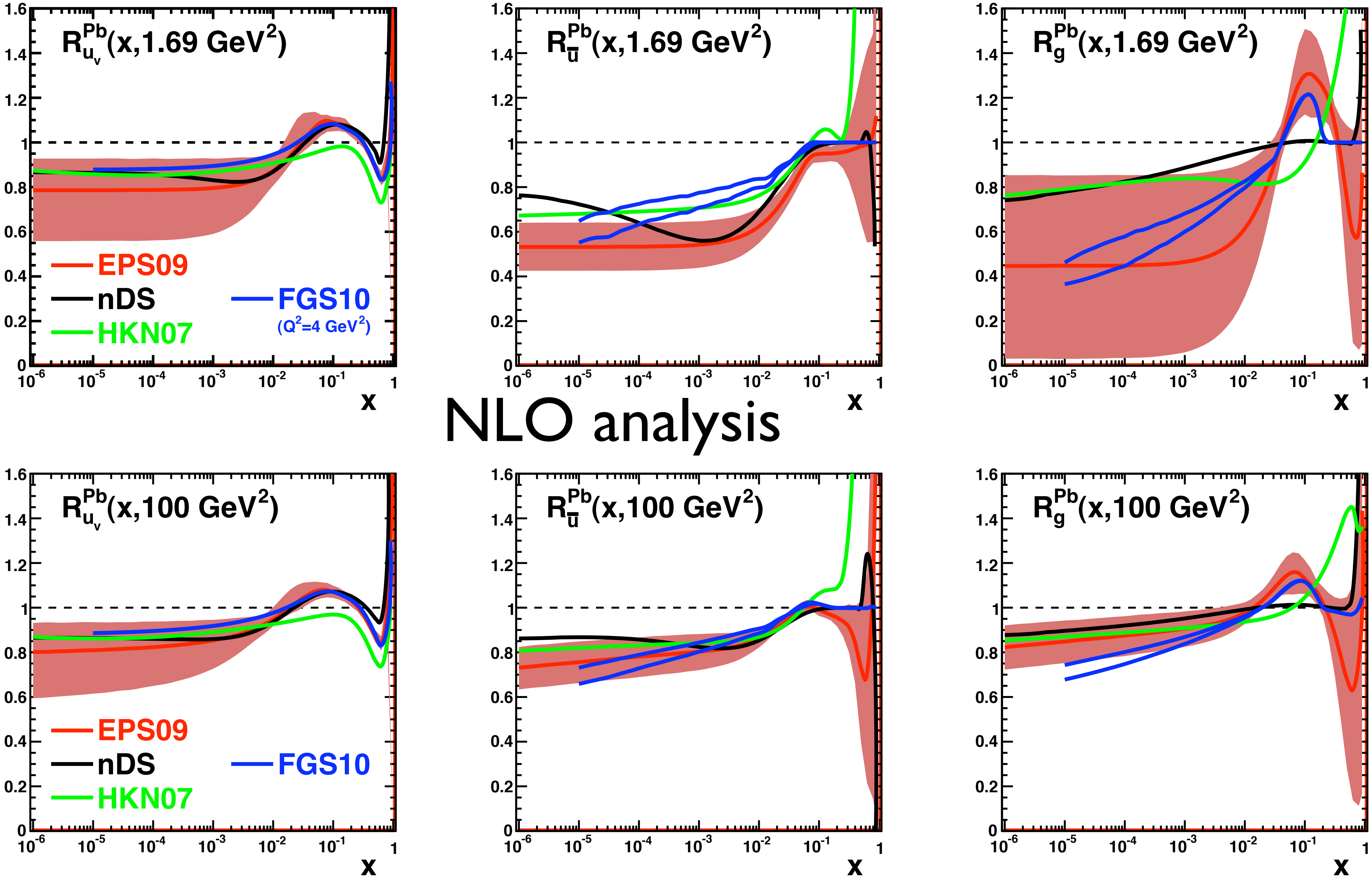
$$\sigma\rho \sim 1 \Longrightarrow \frac{Axg(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{-\lambda} \sim \left(\frac{A}{x}\right)^{1/3}$$



eA complementary to ep: nuclei offer the possibility of testing these ideas (density effect) and enhance the saturation effects for a fixed x (energy).

DGLAP analysis of npdf's:

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



Status:

Albacete et al '09

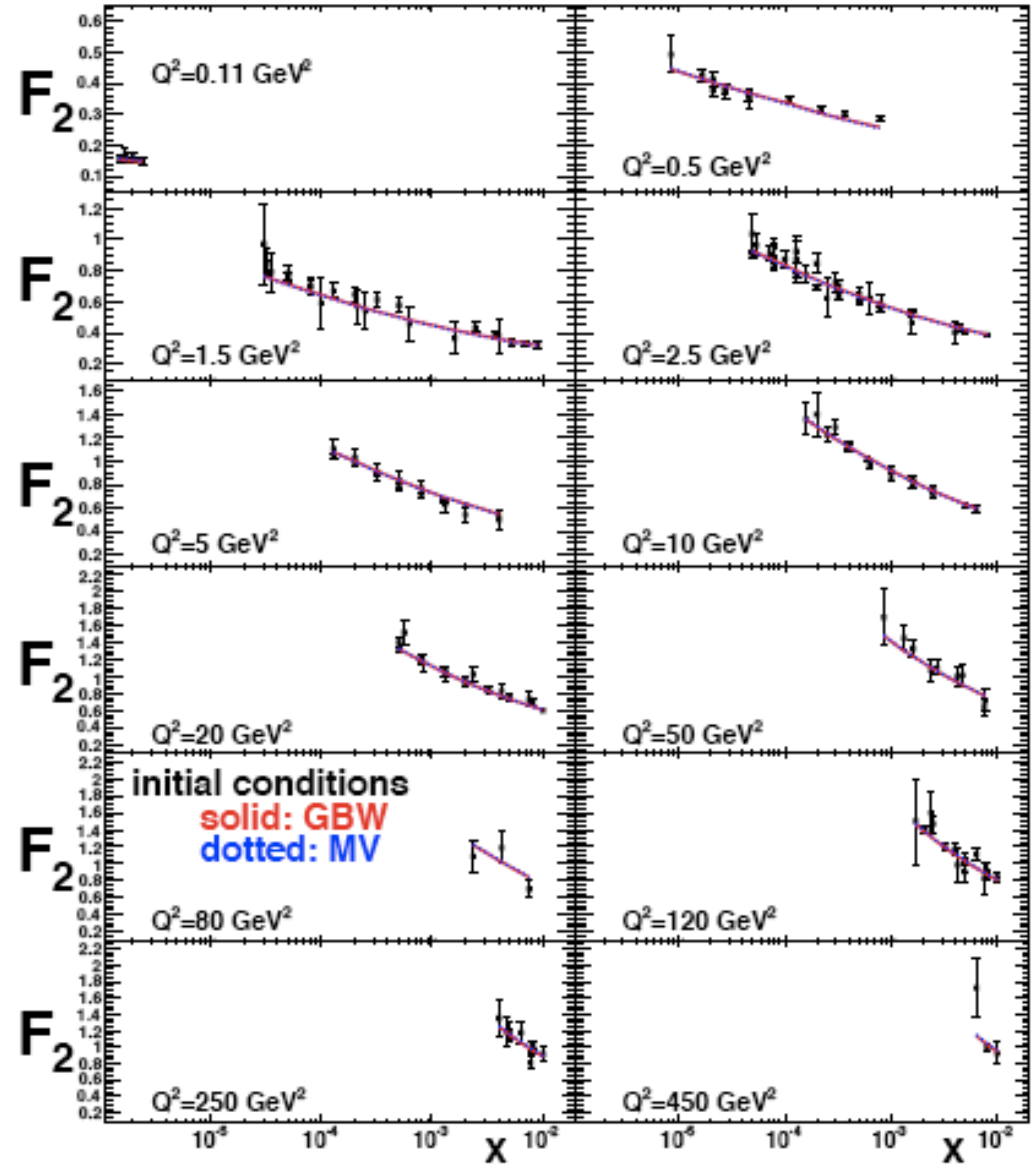
- Three pQCD-based alternatives to describe small-x ep and eA data:

→ DGLAP evolution (FO PT).

→ Resummation schemes.

→ CGC (dipole models and rcBK).

(Other: NA, Kaidalov, Salgado, Tywoniuk '10.)

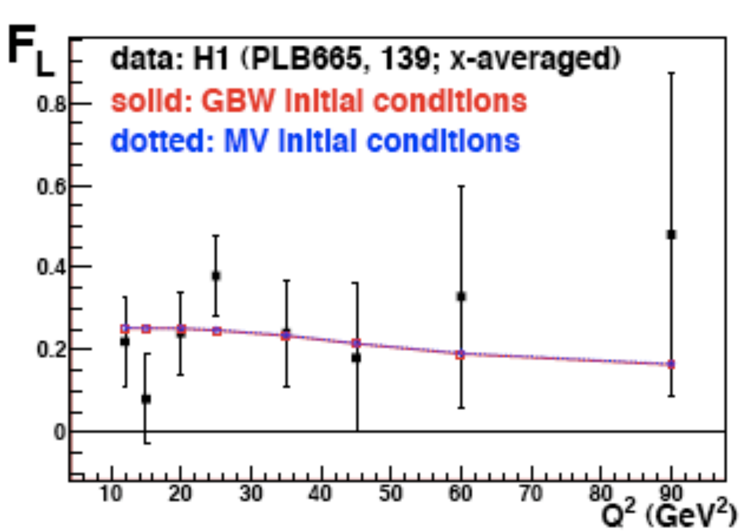


- **Differences lie at moderate $Q^2(>\Lambda^2_{QCD})$ and small x.** Hints of deviations from NLO DGLAP at small x (Caola et al '09).

- Unitarity (non-linear effects): where is it? ⇒

  ☛ Theory: refine the tools and predict.

  ☛ Experiment: LHC, EIC, LHeC.



Contents:

Project:

- **LHeC@CERN** → ep/eA experiment using p/A from the LHC: E_p=7 TeV, E_A=(Z/A)E_p=2.75 TeV/nucleon for Pb.
- New e^+/e^- accelerator: E_{cm}~1-2 TeV/nucleon (E_e=50-150 GeV).
- Requirements:

* Luminosity~10^{33} $cm^{-2}s^{-1}$.

* Acceptance: 1-179 degrees (low-x ep/eA).

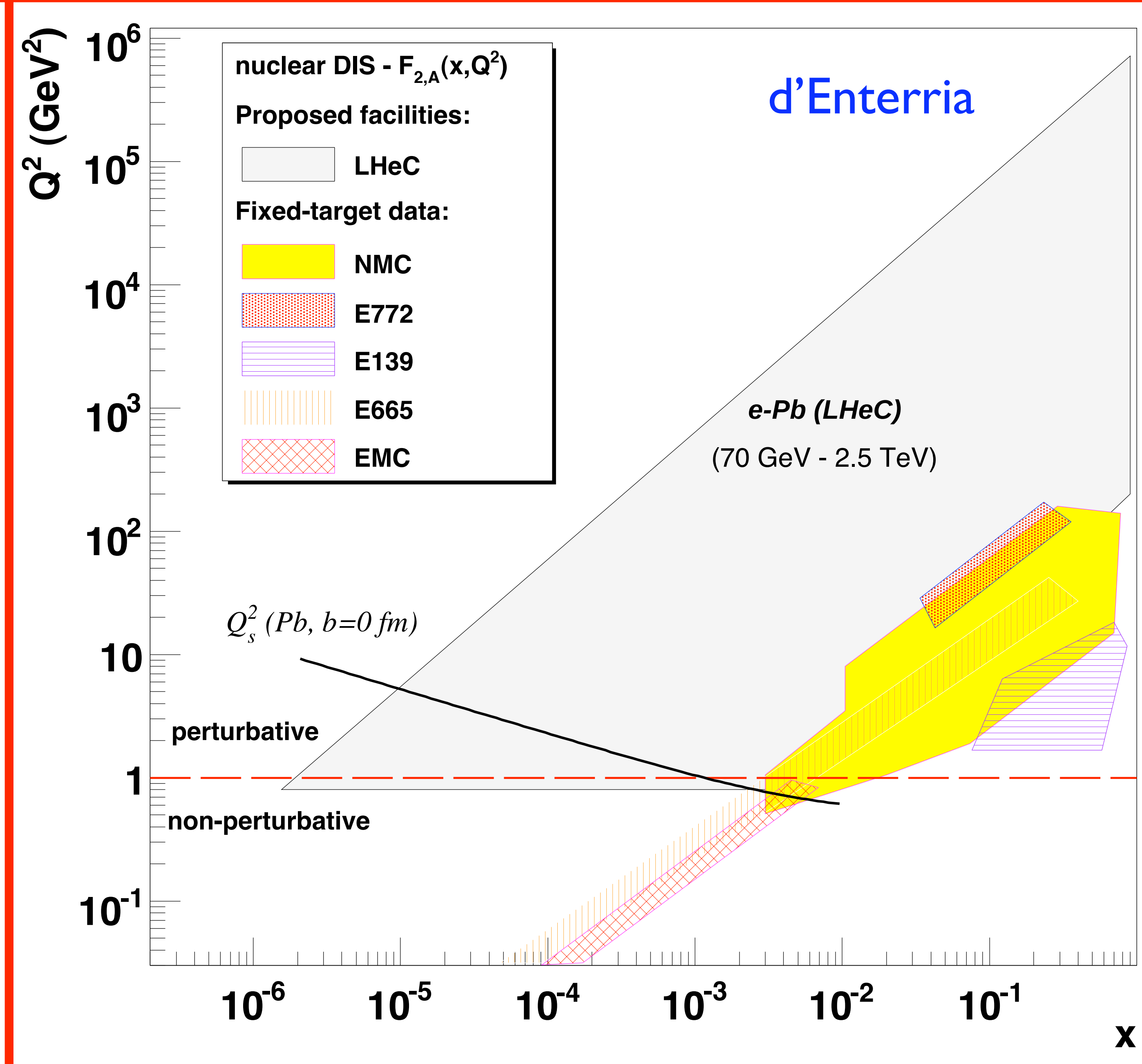
* Tracking to 1 mrad.

* EMCAL calibration to 0.1 %.

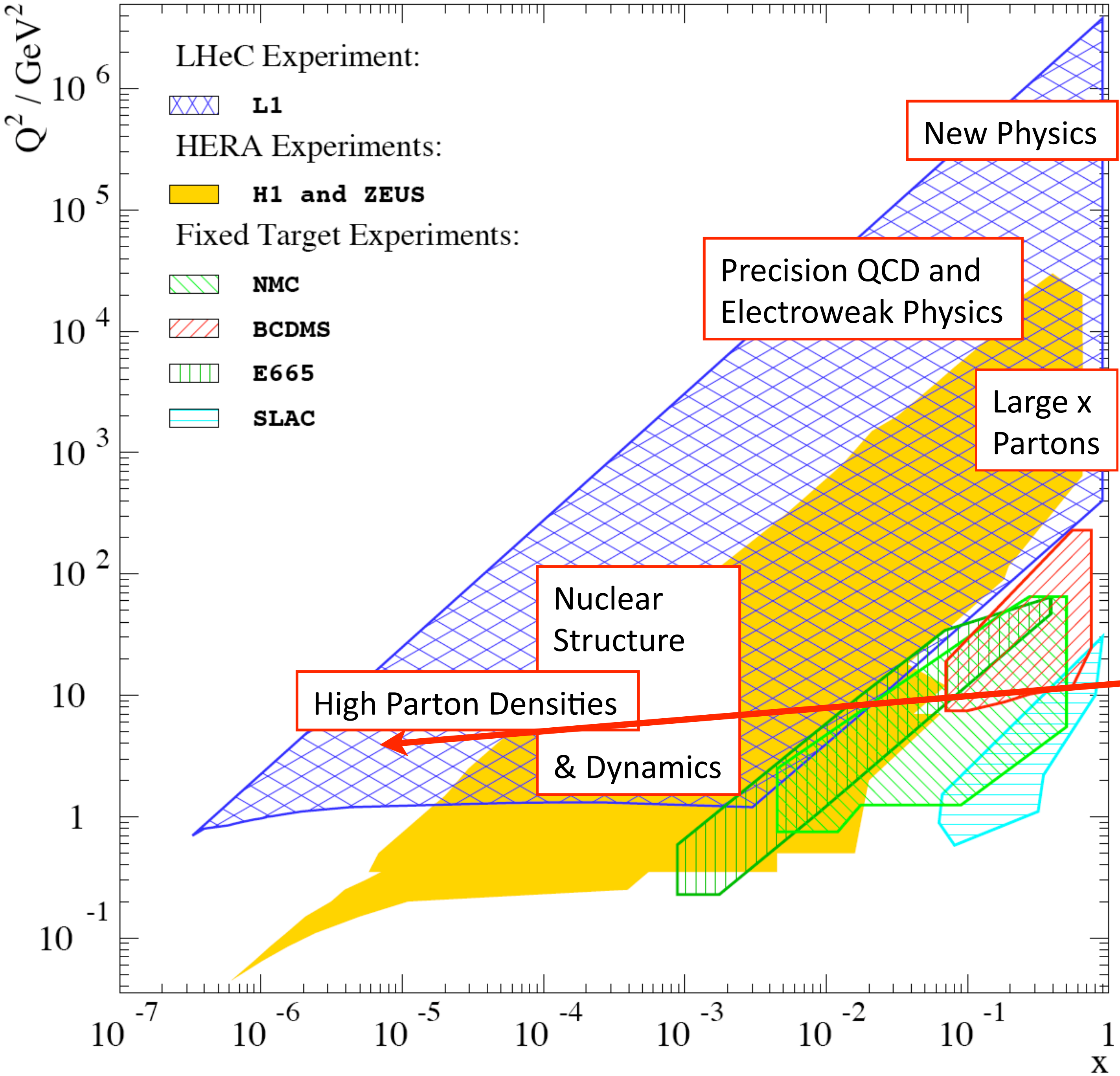
* HCAL calibration to 0.5 %.

* Luminosity determination to 1 %.

* Compatible with LHC operation.

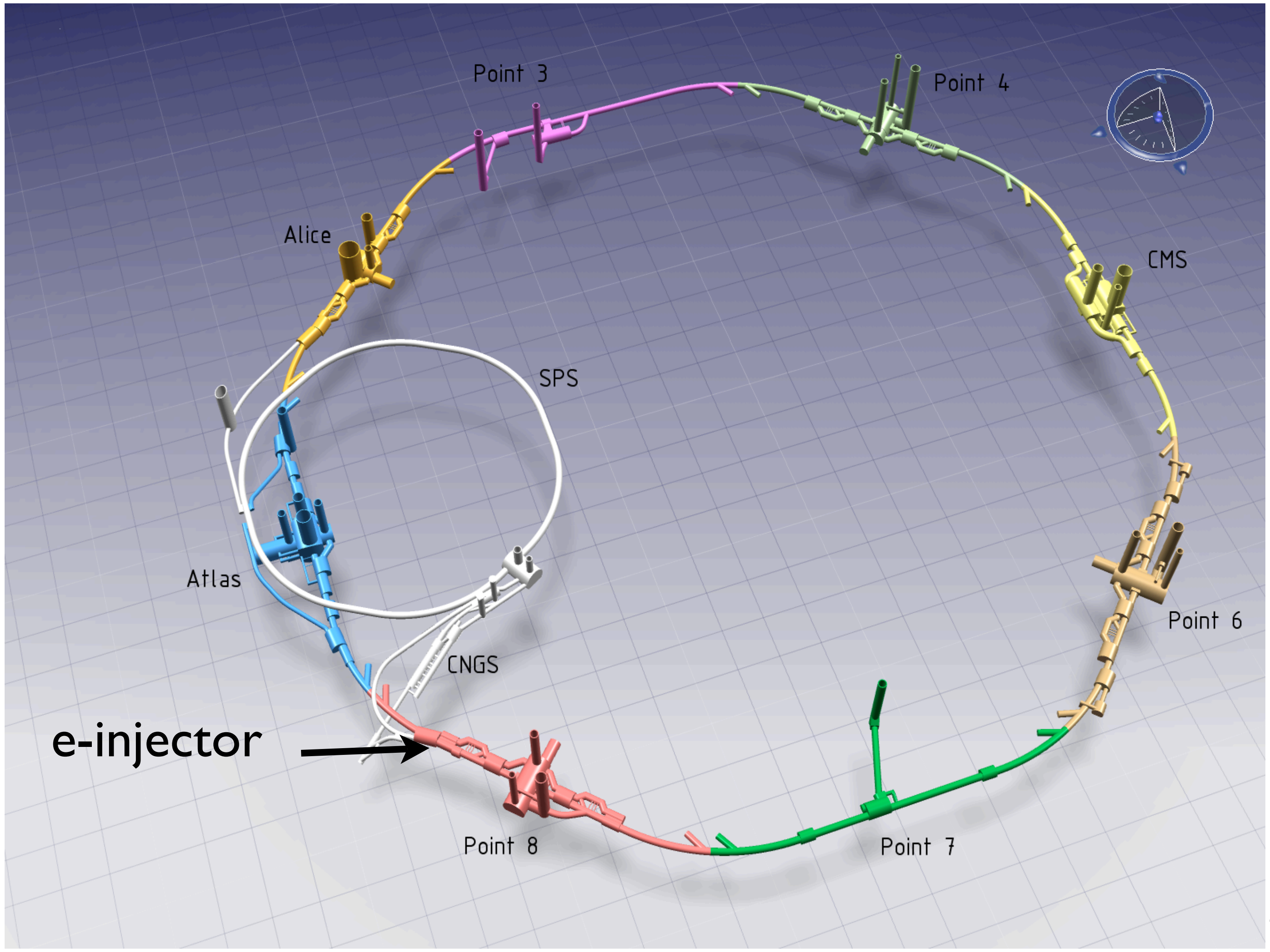


Physics goals:

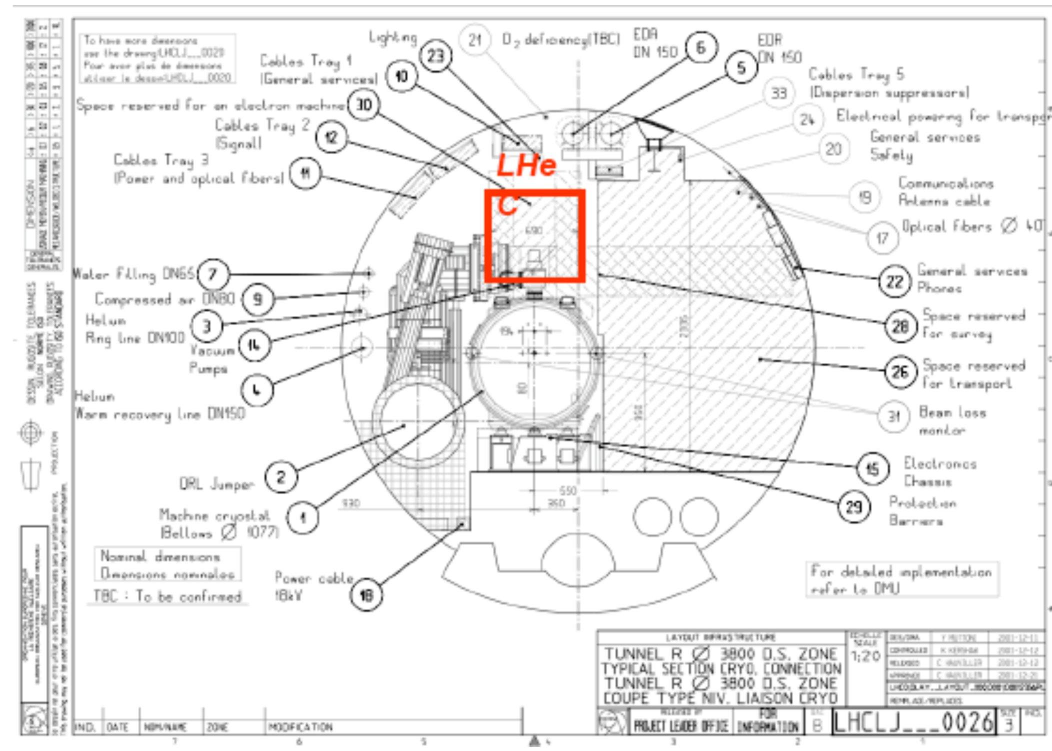


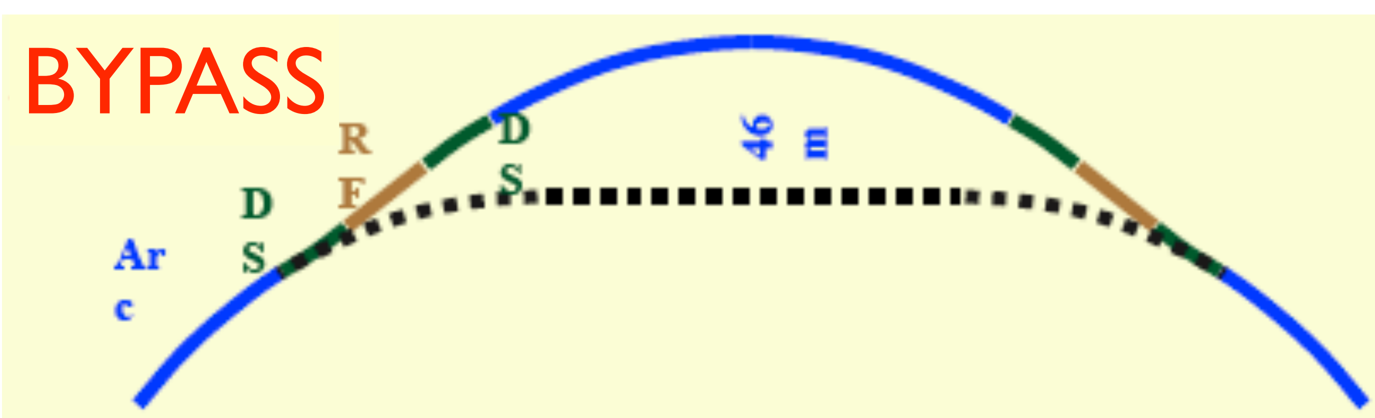
- Proton structure to a few 10^{-20} m: Q^2 lever arm.
- Precision QCD/EW physics.
- High-mass frontier (leptoquarks, excited fermions, contact interactions).
- Unambiguous access, in ep and eA, to a **qualitatively novel regime of matter predicted by QCD**.
- Substructure/parton dynamics inside nuclei with strong implications on QGP search.

The machine: Ring-Ring option



Holzer, 20.05.2010



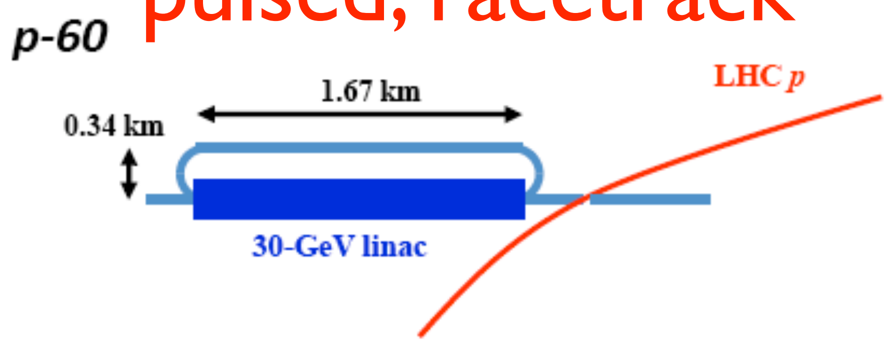


Standard	Protons	Electrons
Parameters	$N_p=1.15*10^{11}$	$N_e=1.4*10^{10}$
	$E_p=7$ TeV	$E_e=60$ GeV
	$n_b=2808$	$n_b=2808$
	$I_p=582$mA	$I_e=111$mA
Optics	$\beta_{xp}=180$cm	$\beta_{xe}=12.7$cm
	$\beta_{yp}=50$cm	$\beta_{ye}=7.1$cm
	$\varepsilon_{xp}=0.5$nm rad	$\varepsilon_{xe}=7.6$nm rad
	$\varepsilon_{yp}=0.5$nm rad	$\varepsilon_{ye}=3.8$nm rad
Beam size	$\sigma_{xp}=30\ \mu m$	$\sigma_{xe}=30\mu m$
	$\sigma_{yp}=15.8\ \mu m$	$\sigma_{ye}=15.8\mu m$
Luminosity	$1.3*10^{33}\ cm^{-2}\ s^{-1}$	

The machine: Linac-Ring option

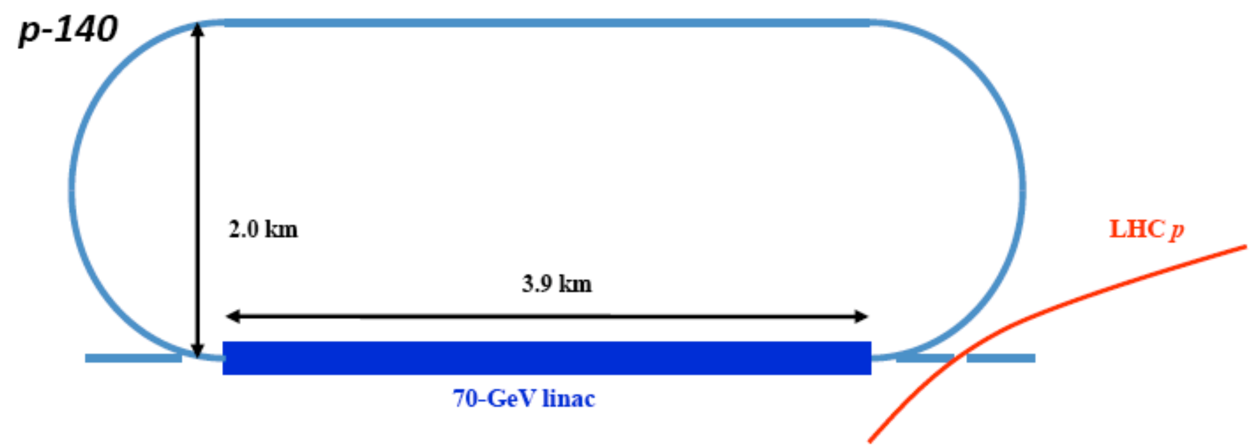
Zimmermann, 20.05.2010

pulsed, racetrack



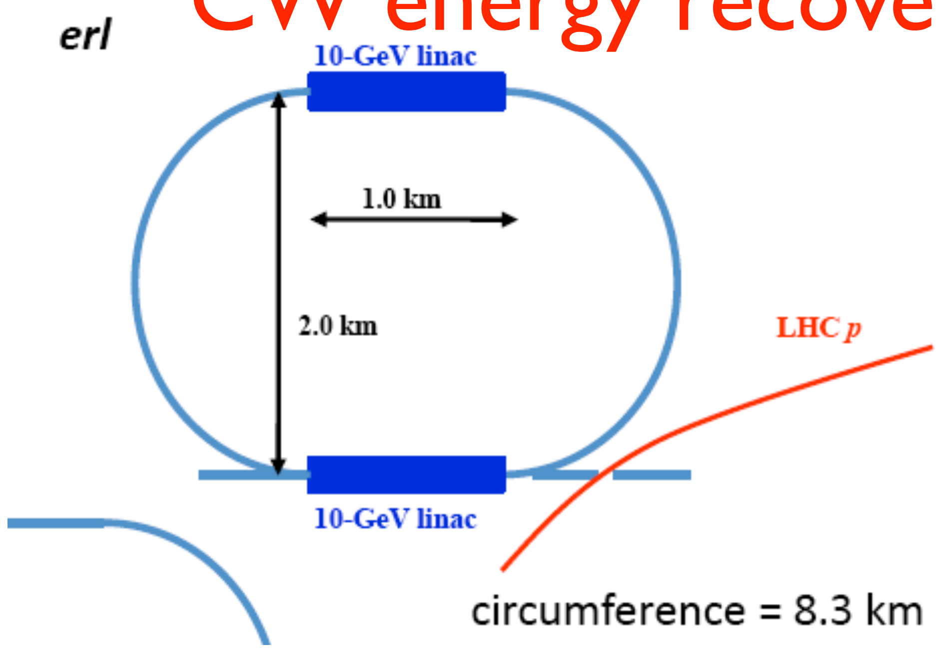
circumference = 4.4 km

highest energy racetrack



circumference = 14.1 km

CW energy recovery

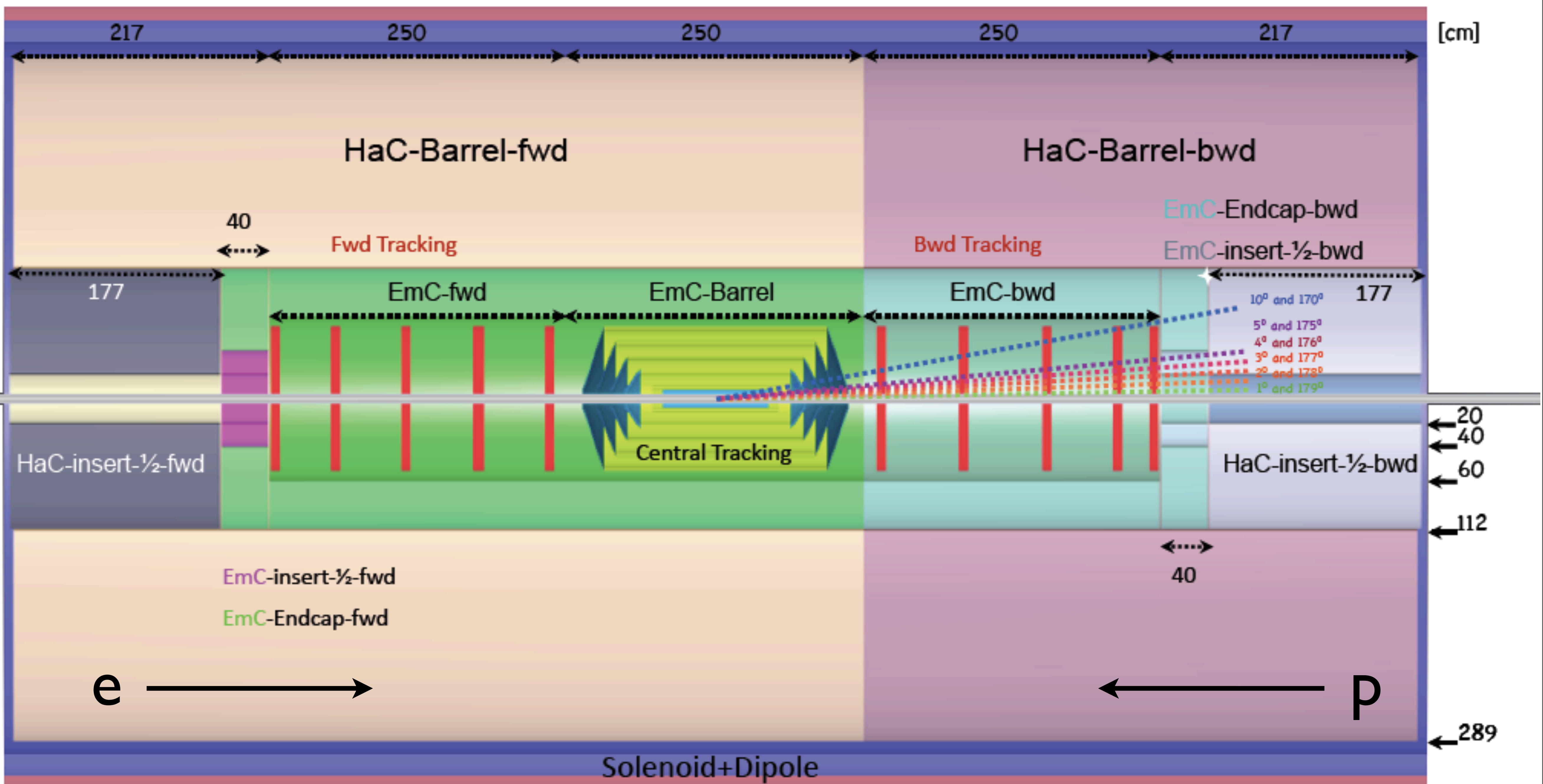


circumference = 8.3 km

	p-60	erl	p-140
e^- energy at IP [GeV]	60	60	140
luminosity [10^{32} cm^{-2}s^{-1}]	1.1	10.1	0.4
polarization [%]	90	90	90
bunch population [10^9]	4.5	2.0	1.6
e^- bunch length [μm]	300	300	300
bunch interval [ns]	50	50	50
transv. emit. $\gamma\epsilon_{x,y}$ [μm]	50	50	100
rms IP beam size [μm]	7	7	7
hourglass reduction H_{hg}	0.91	0.91	0.94
crossing angle θ_c	0	0	0
repetition rate [Hz]	10	CW	10
bunches/pulse [10^5]	1	N/A	1
pulse current [mA]	16	10	6.6
beam pulse length [ms]	5	N/A	5
ER efficiency η	0	94%	0
total wall plug power [MW]	100	100	100

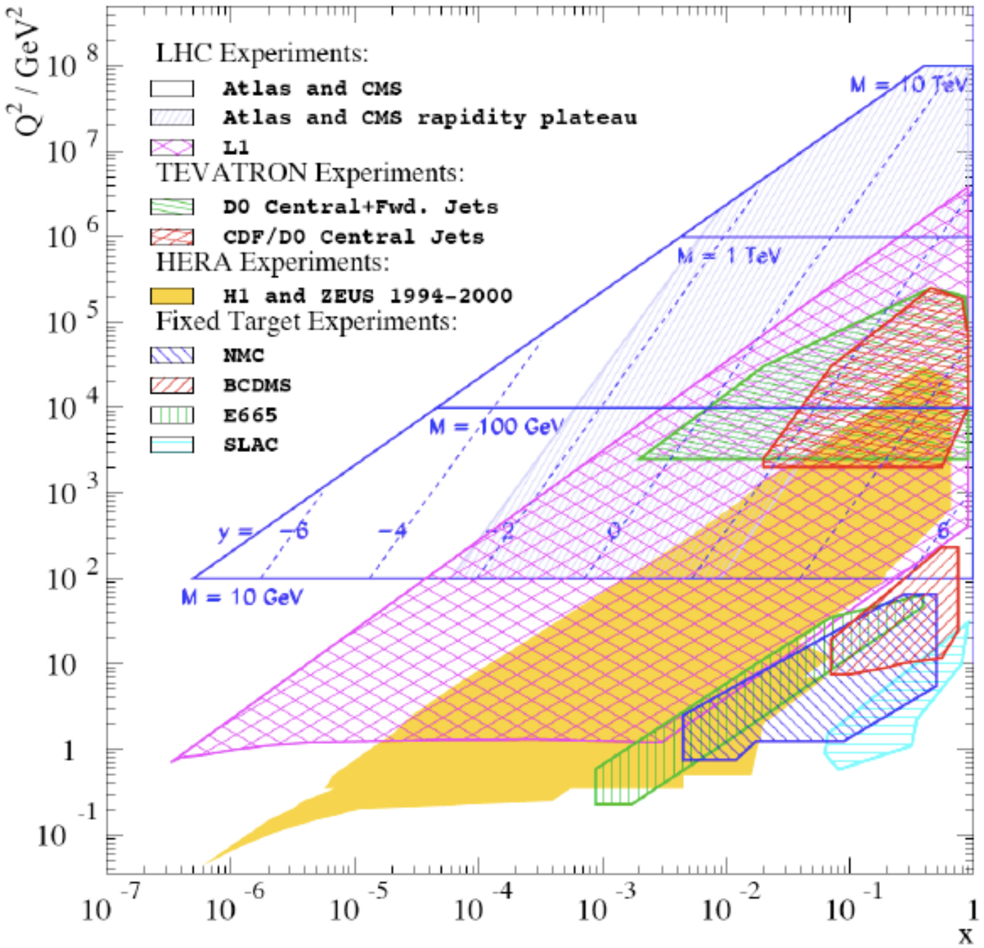
- Ions RR/LR: lumi/nucleon ~ $1\text{-}2\times10^{32}$cm^{-2}s^{-1},~ ep for 179º acceptance (low-x) (Jowett@DIS10).

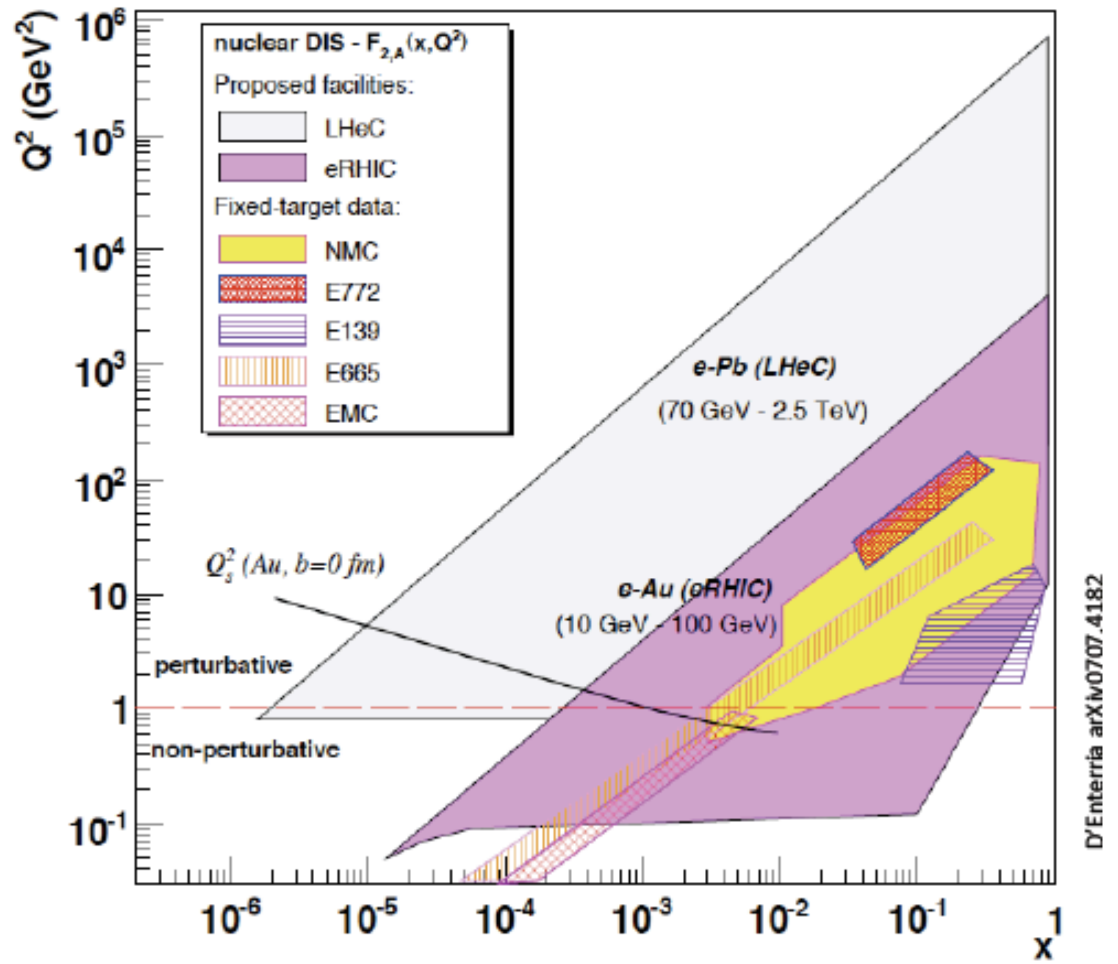
The detector: low-x/eA setup



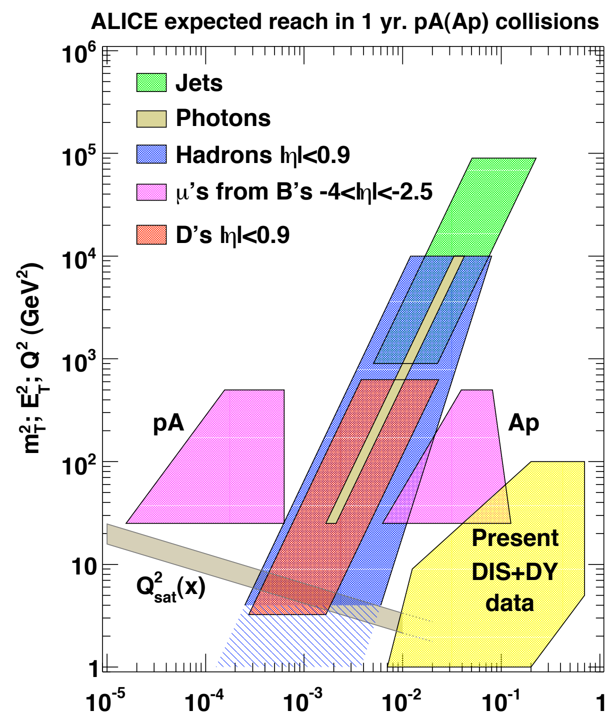
Kostka, 20.05.2010

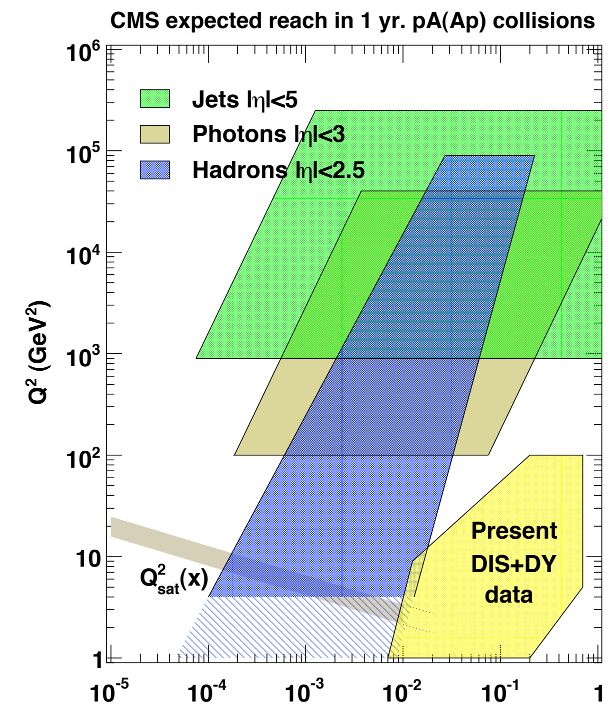
Kinematics:





- 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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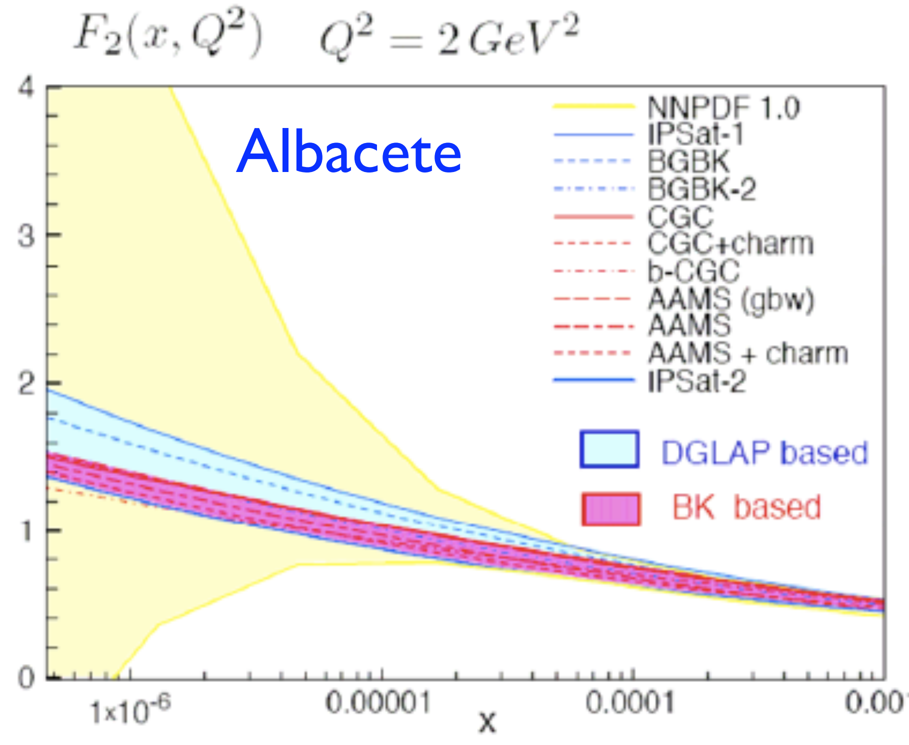
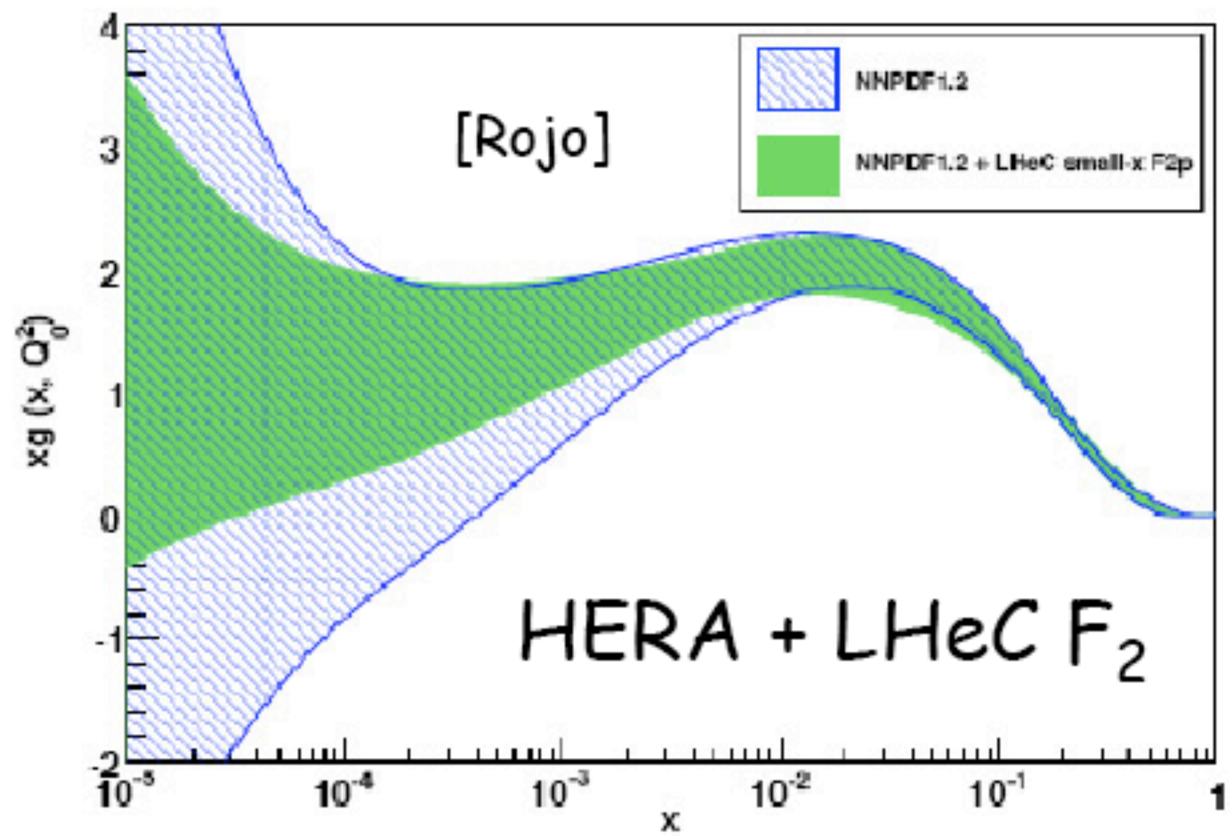
2. The Large Hadron-electron Collider.
3. Inclusive observables:
   - ep inclusive pseudodata. (M. Klein, NA, J. Rojo, P. Newman, J. Forshaw, G. Soyez)
   - eA inclusive pseudodata and their effect on npdf's. (M. Klein, NA, H. Paukkunen, K. Eskola, C. A. Salgado)
4. Diffractive observables:
   - ep diffractive pseudodata.
   - Exclusive vector meson production / DVCS.
   - Nuclear diffraction.
5. Final states.
6. Summary.

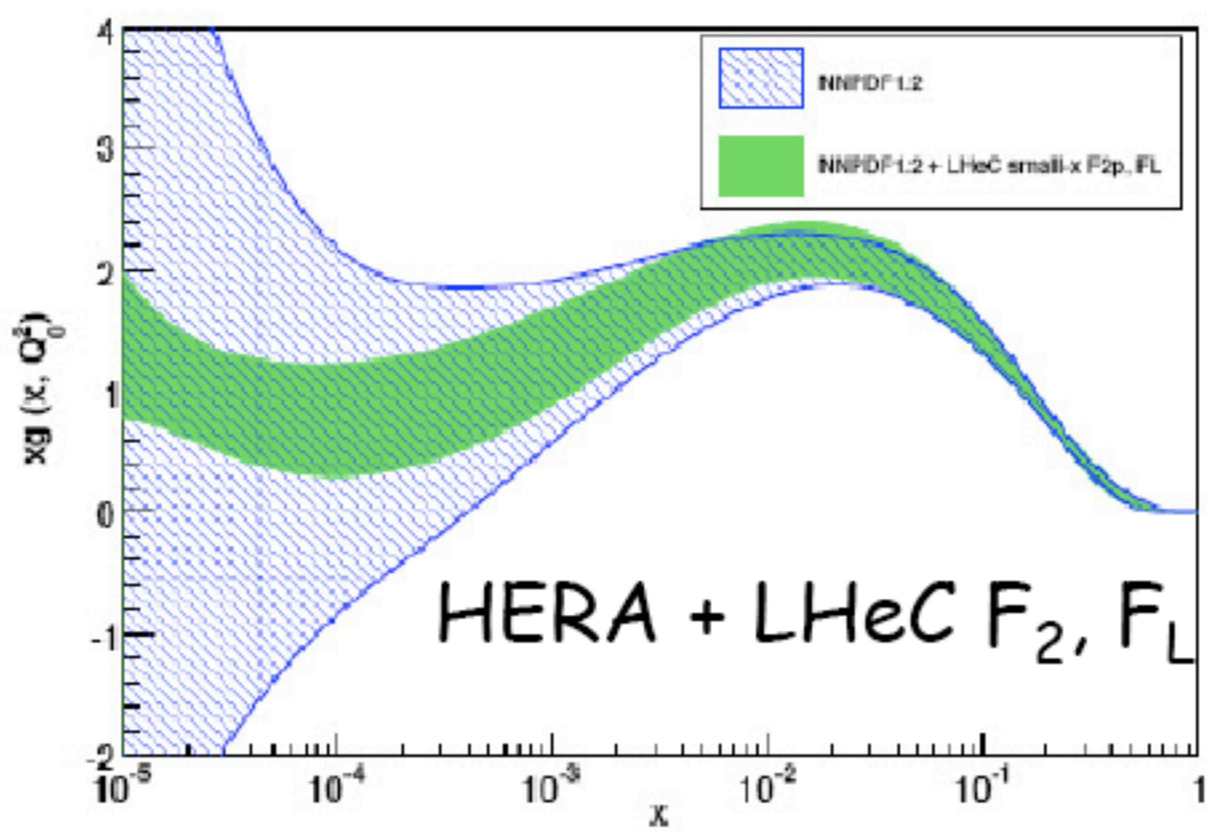
ep inclusive pseudodata (I):

- Extensive model comparison under way (Albacete).

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



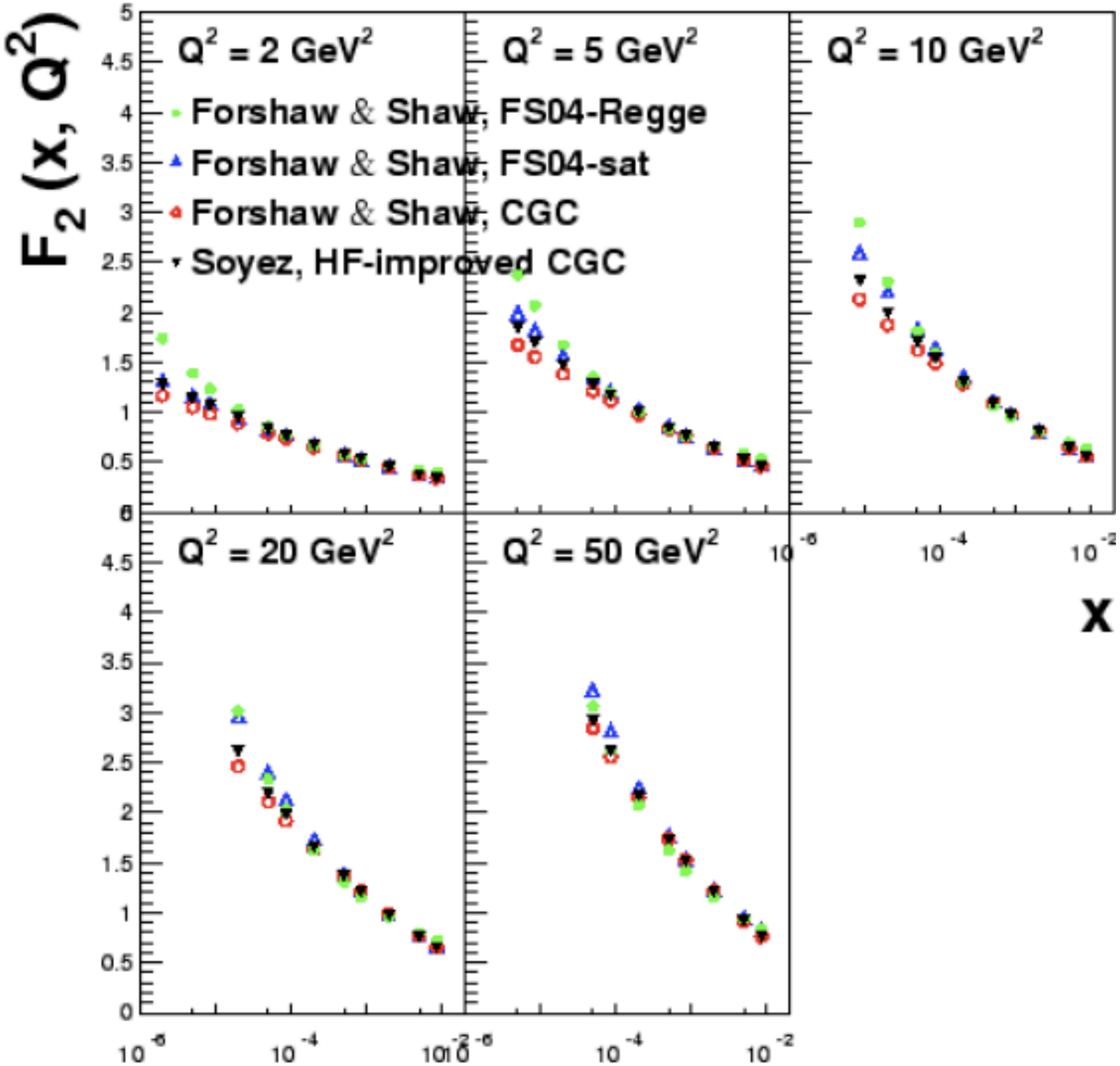




(Q^2 = 2 GeV^2)

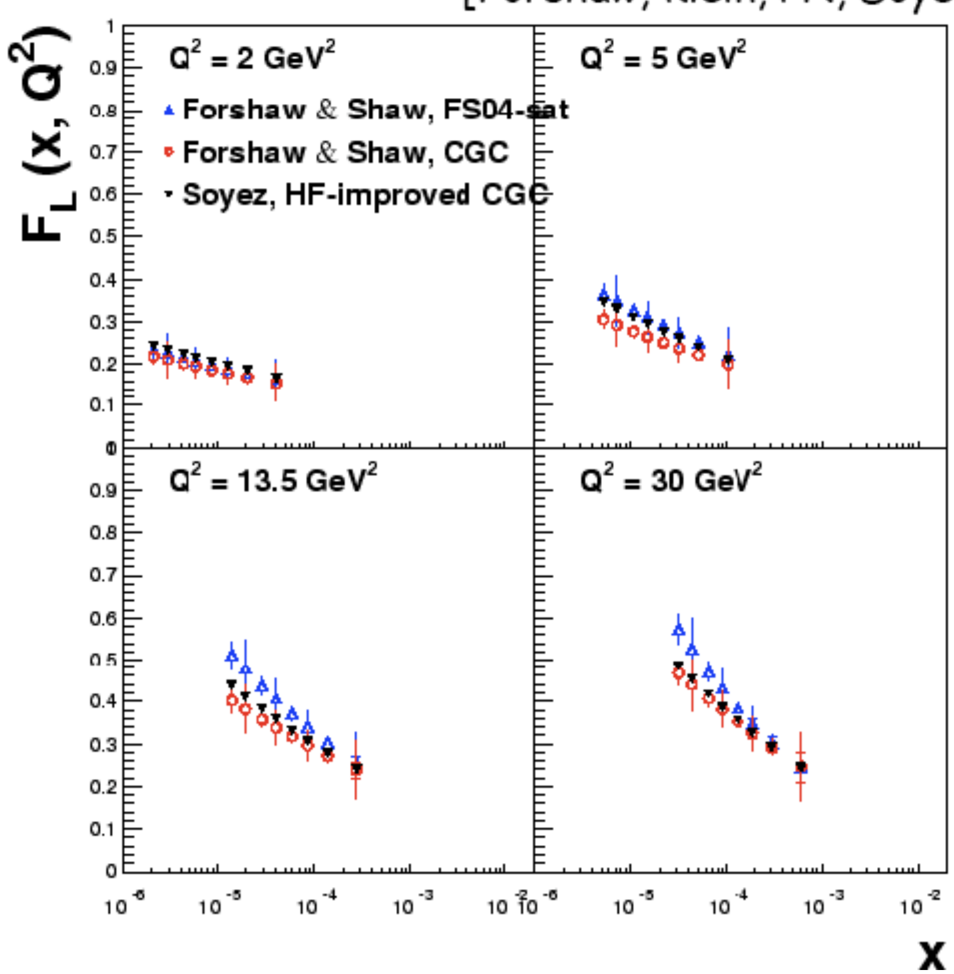
ep inclusive pseudodata (II):

[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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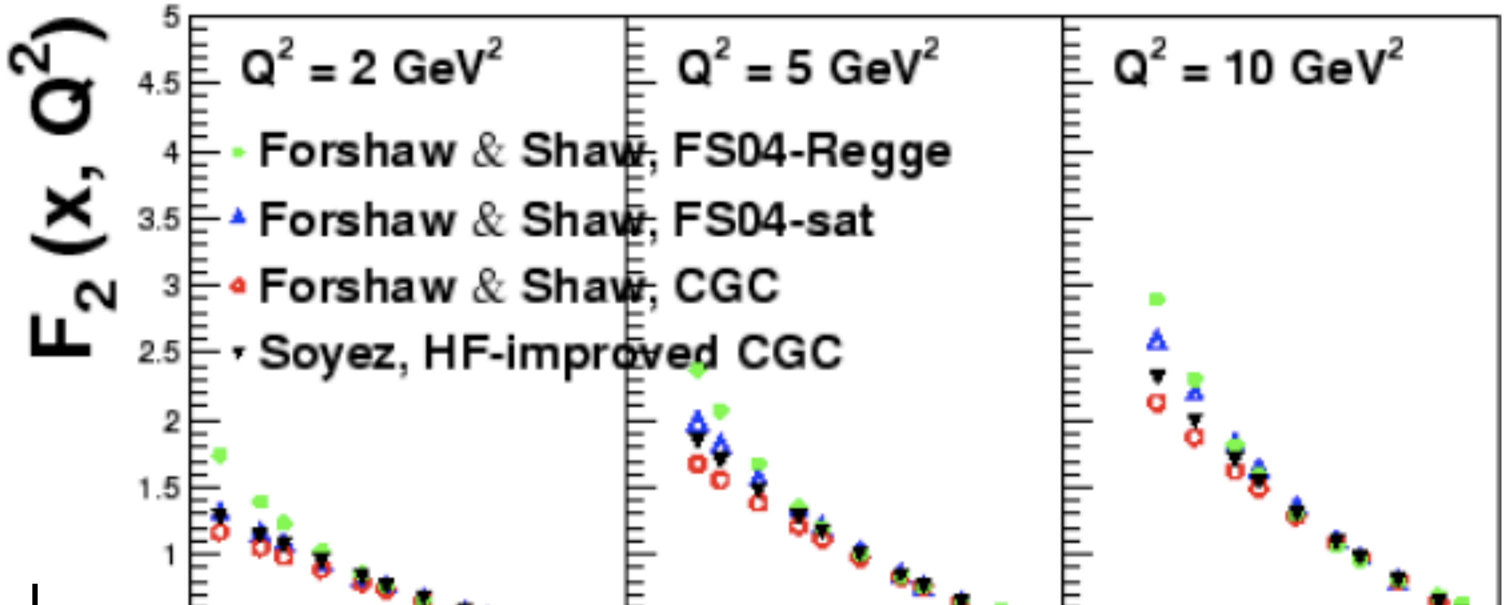

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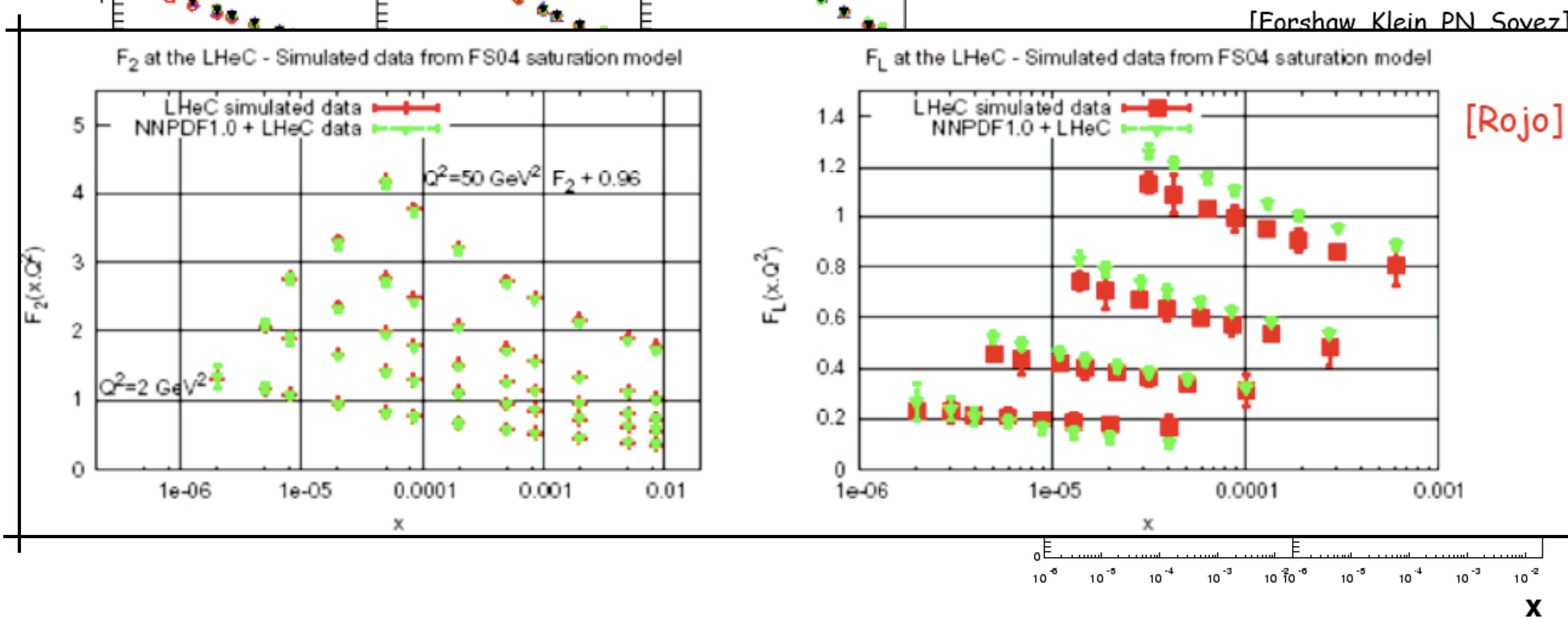
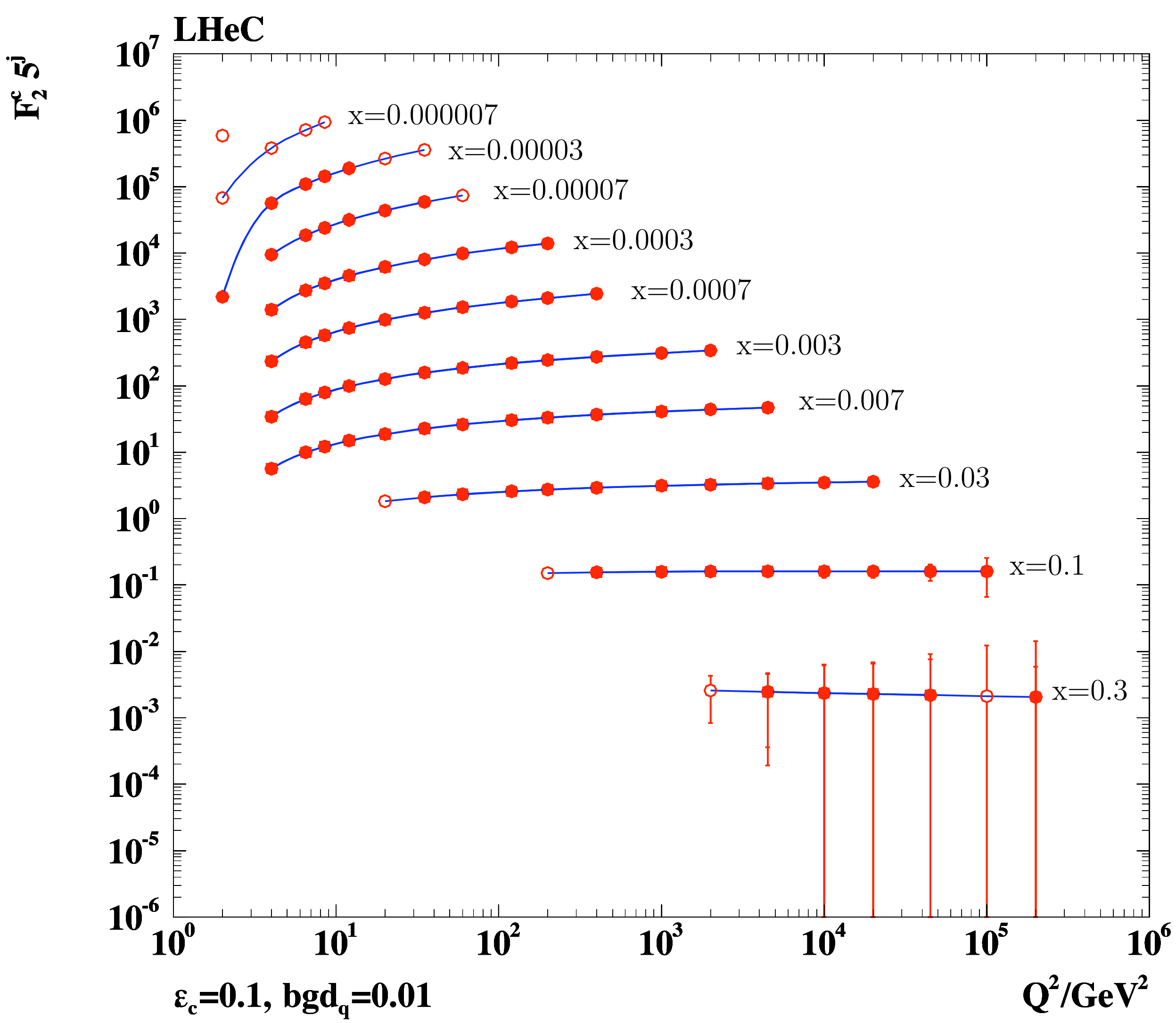
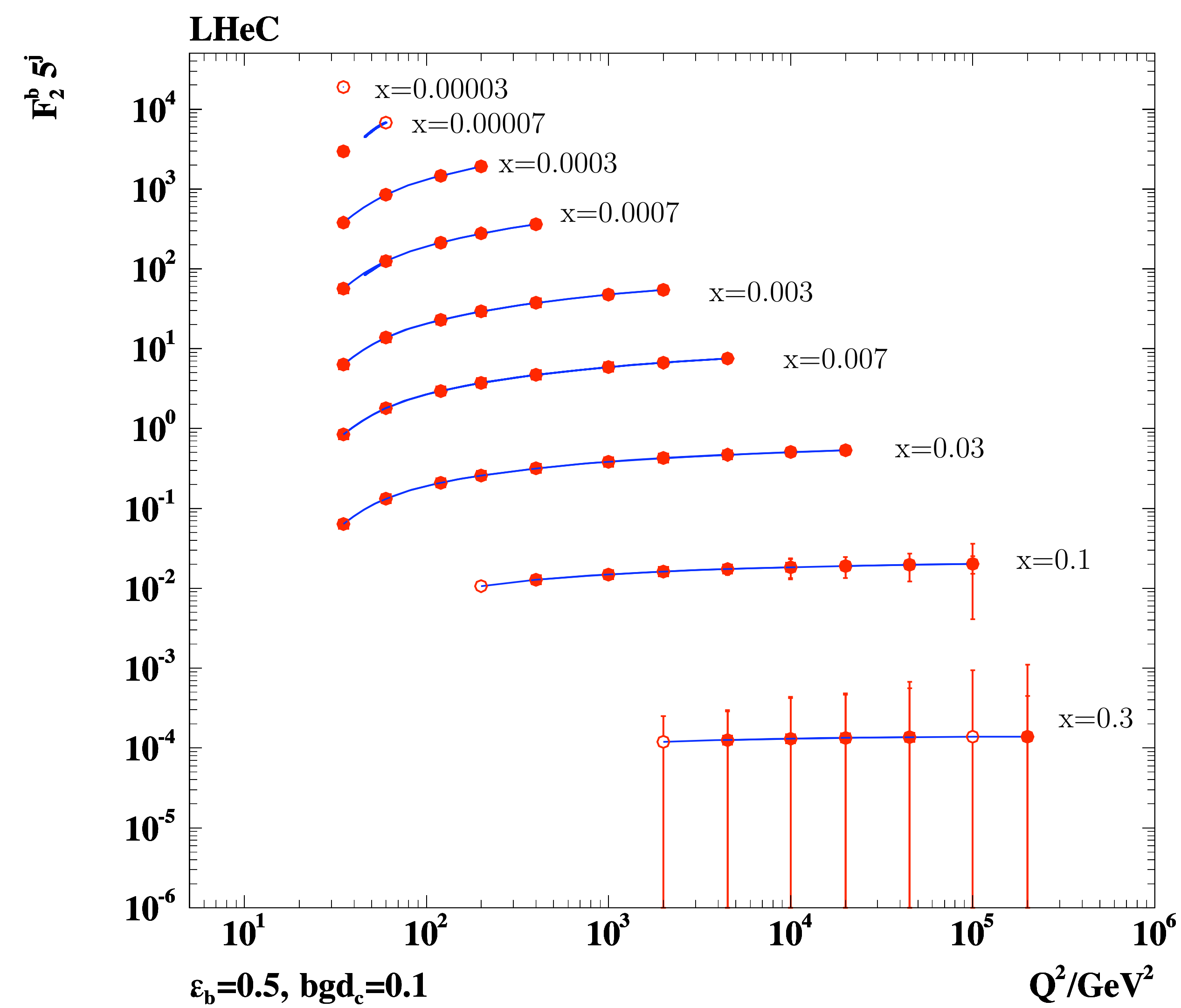


ep inclusive pseudodata (III):

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





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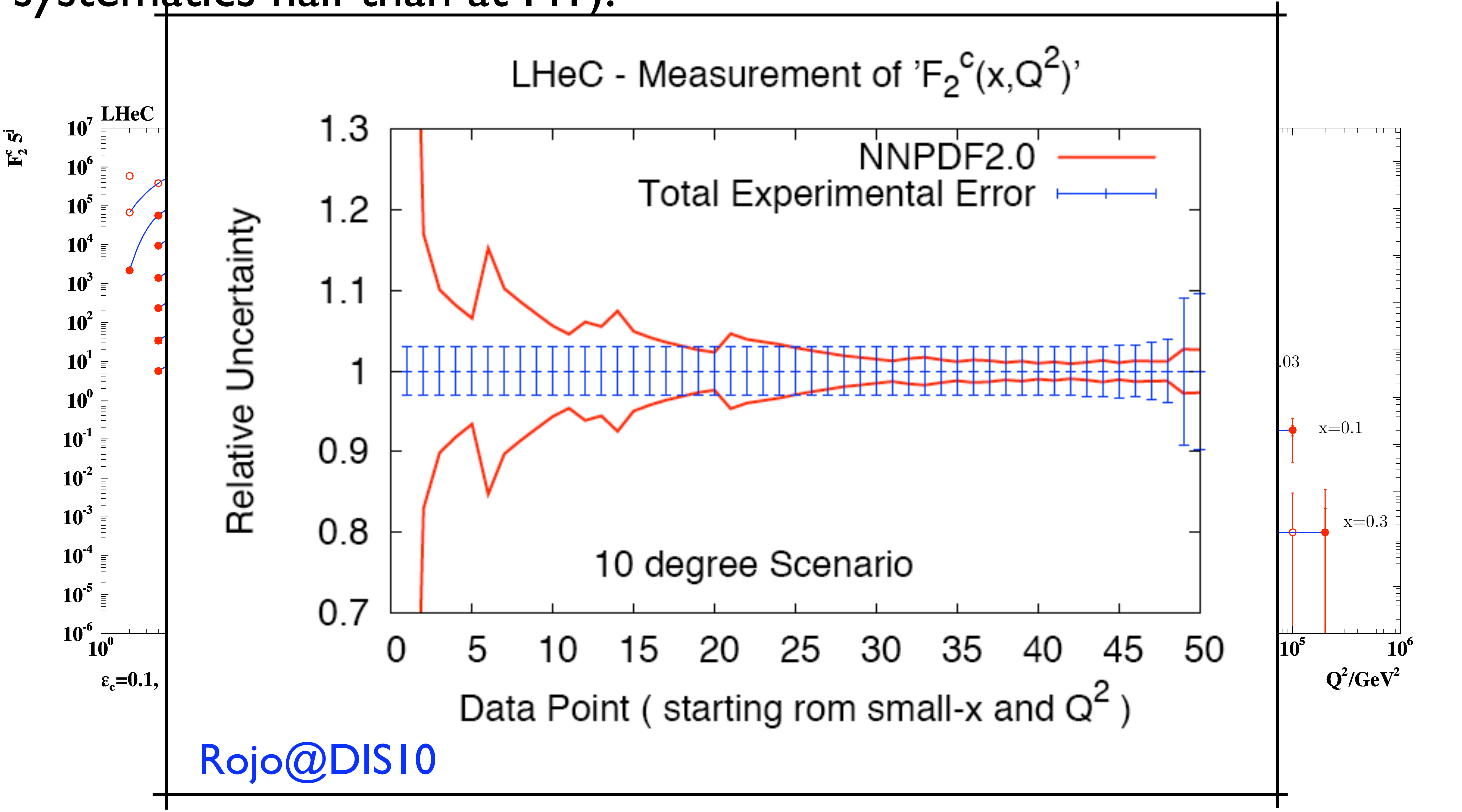
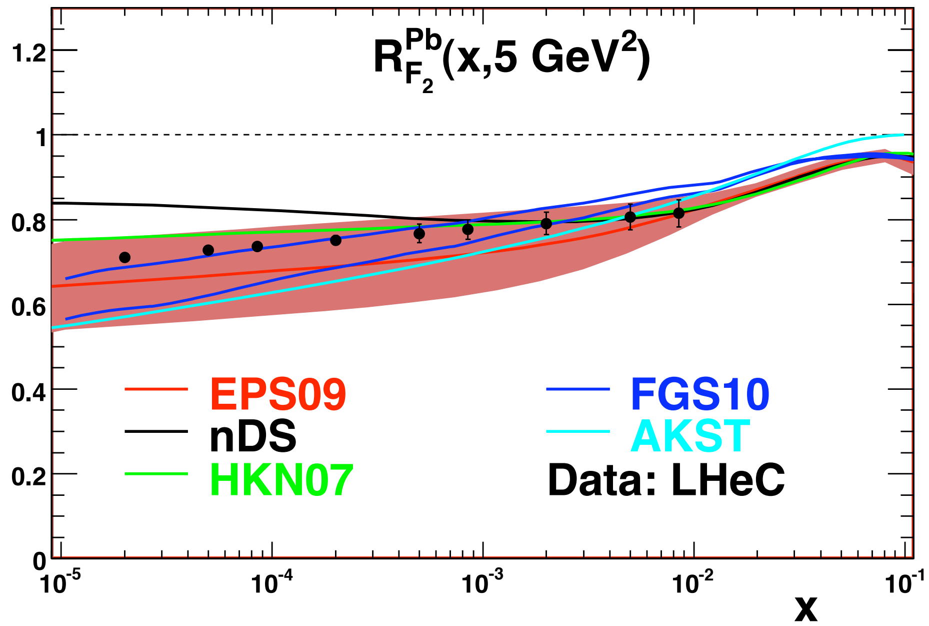
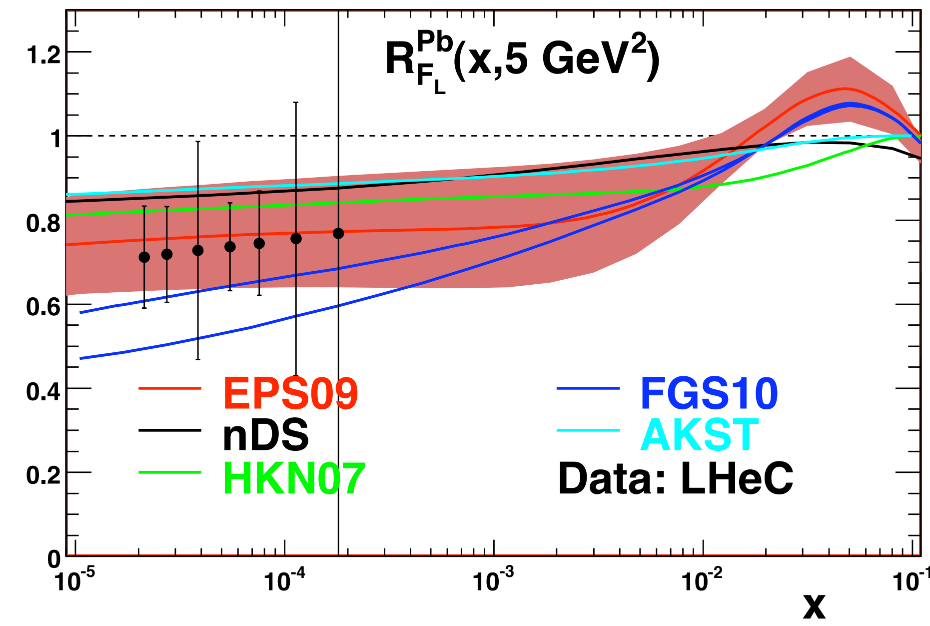


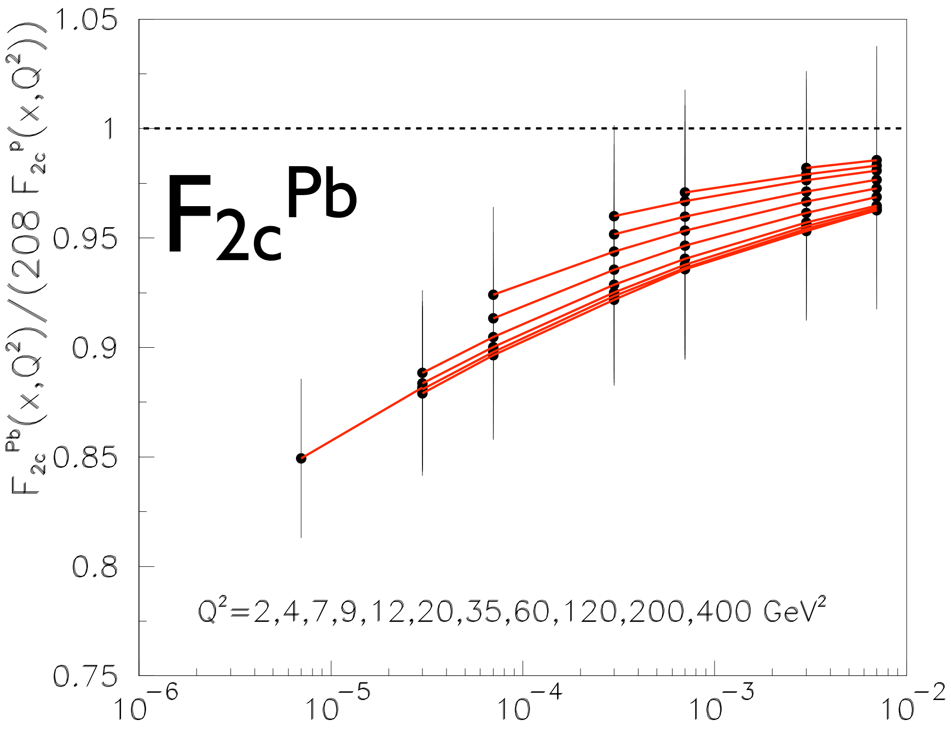
eA inclusive pseudodata (I):

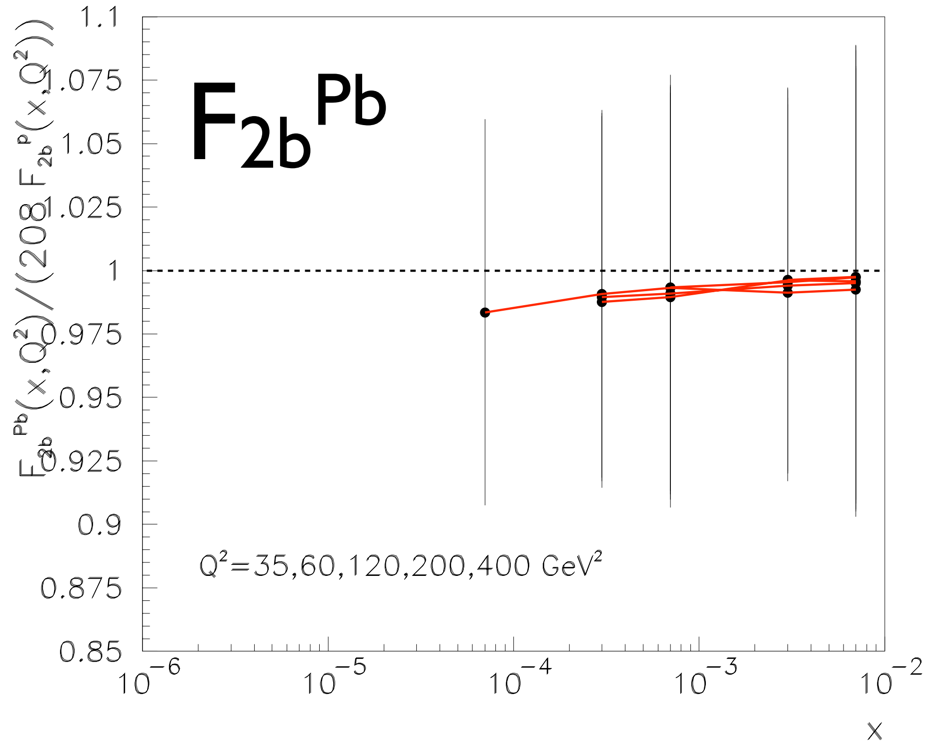
- Good precision can be obtained for $F_{2(c,b)}$ and F_L at small x

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





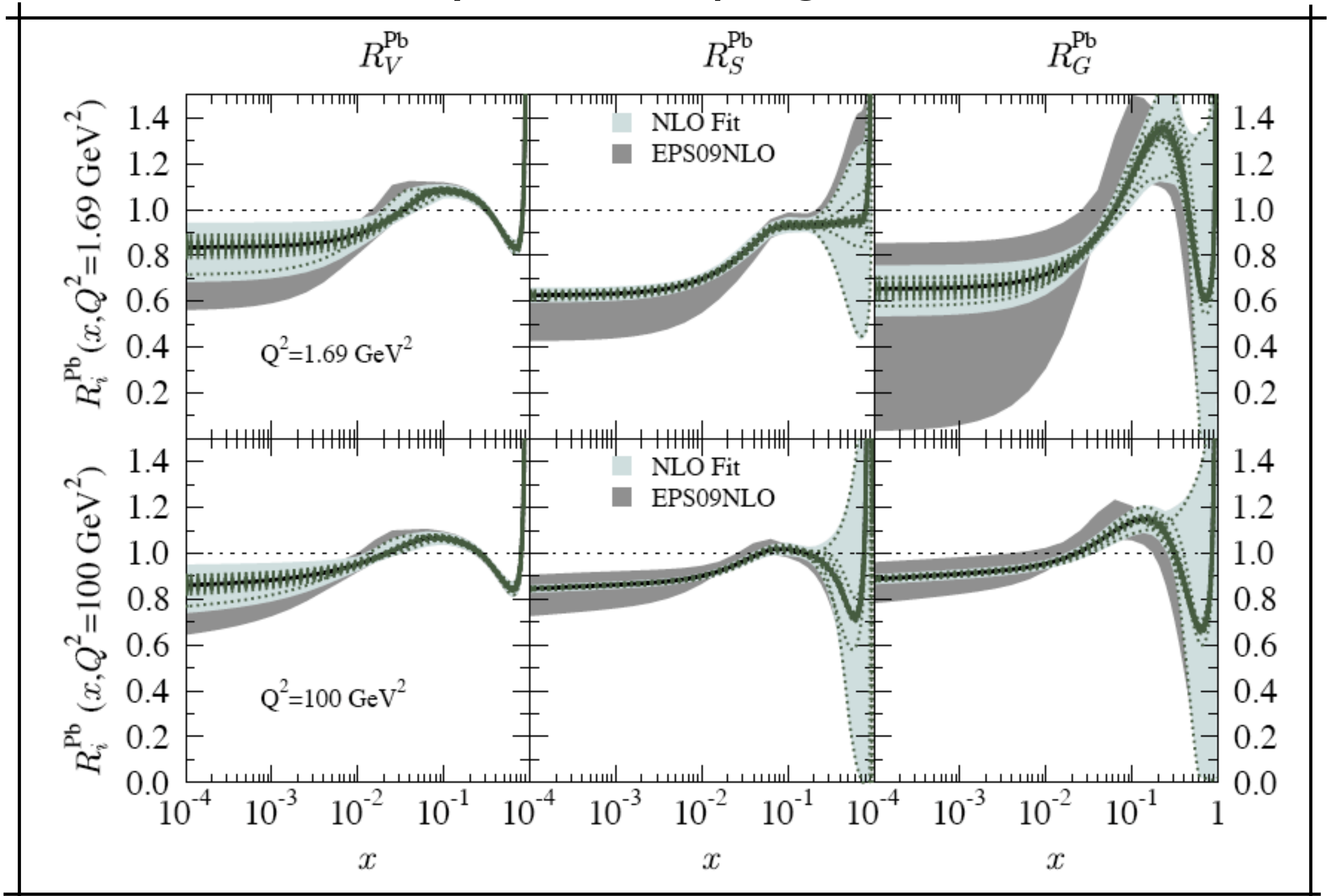




eA inclusive pseudodata (II):

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

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



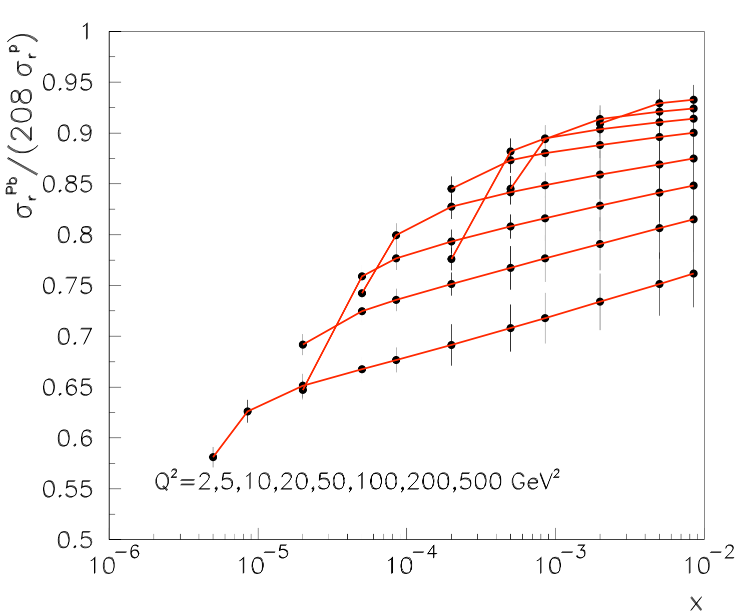
Note: F_L in eA

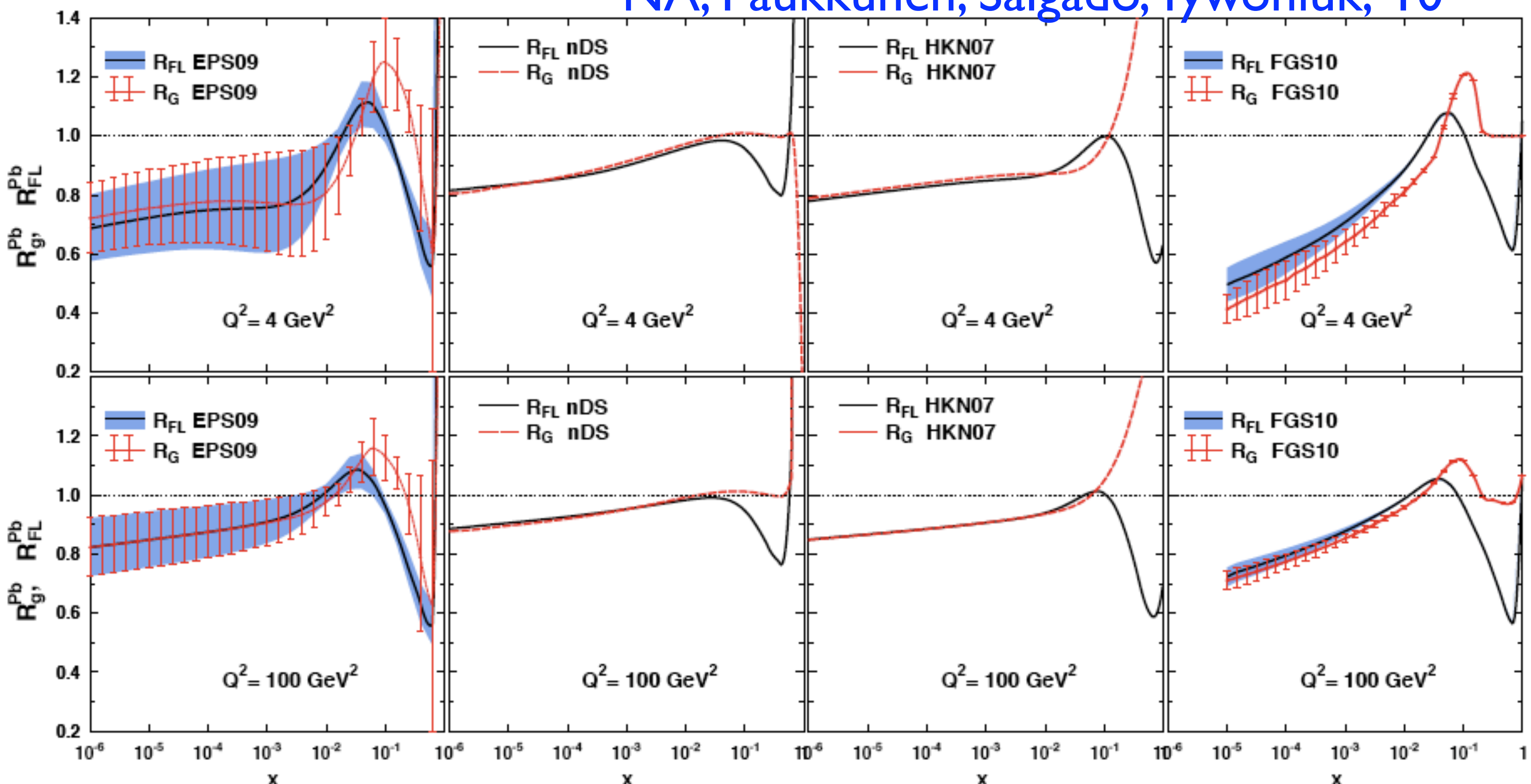
$$\sigma_r^{NC} = \frac{Q^4 x}{2\pi\alpha^2 Y_+} \frac{d^2\sigma^{NC}}{dx dQ^2} = F_2 \left[1 - \frac{y^2}{Y_+}\frac{F_L}{F_2}\right], \qquad Y_+ = 1 + (1-y)^2$$

- F_L traces the nuclear effects on the glue (Cazarotto et al '08).
- Uncertainties in the extraction of F_2 due to the unknown nuclear effects on F_L of order 5 % (larger than expected stat.+syst.) ⇒

measure F_L or use the reduced cross section (but then ratios at two energies...).

NA, Paukkunen, Salgado, Tywoniuk, '10





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   - ep diffractive pseudodata. (P. Newman)
   - Exclusive vector meson production / DVCS. (P. Newman, G. Watt, A. Stasto, L. Favart, J. Collins, C. Weiss)
   - Nuclear diffraction. (C. Marquet, K. Tywoniuk)

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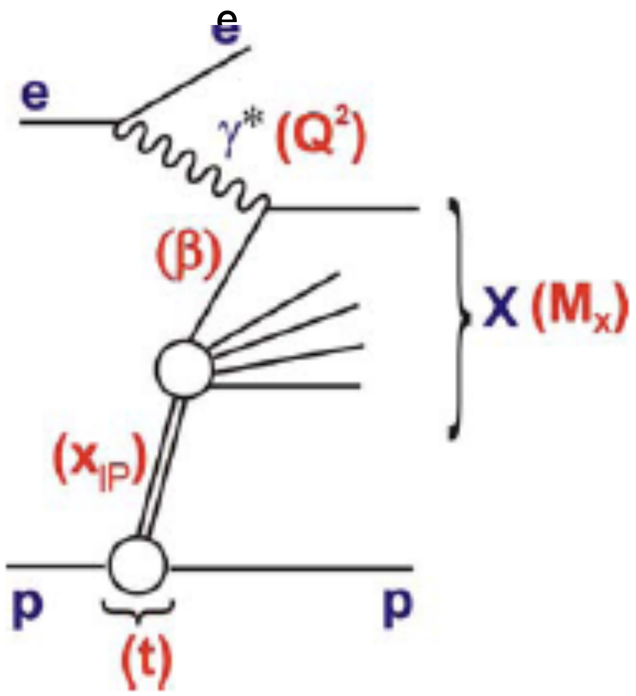
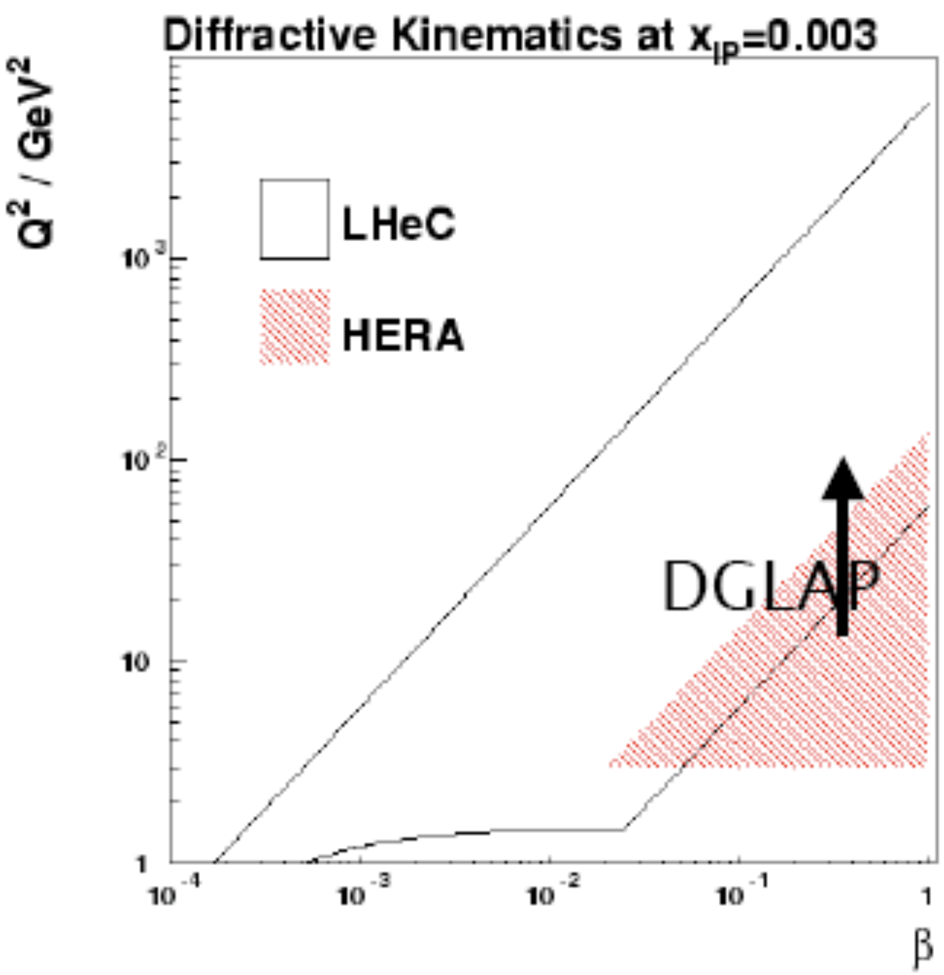
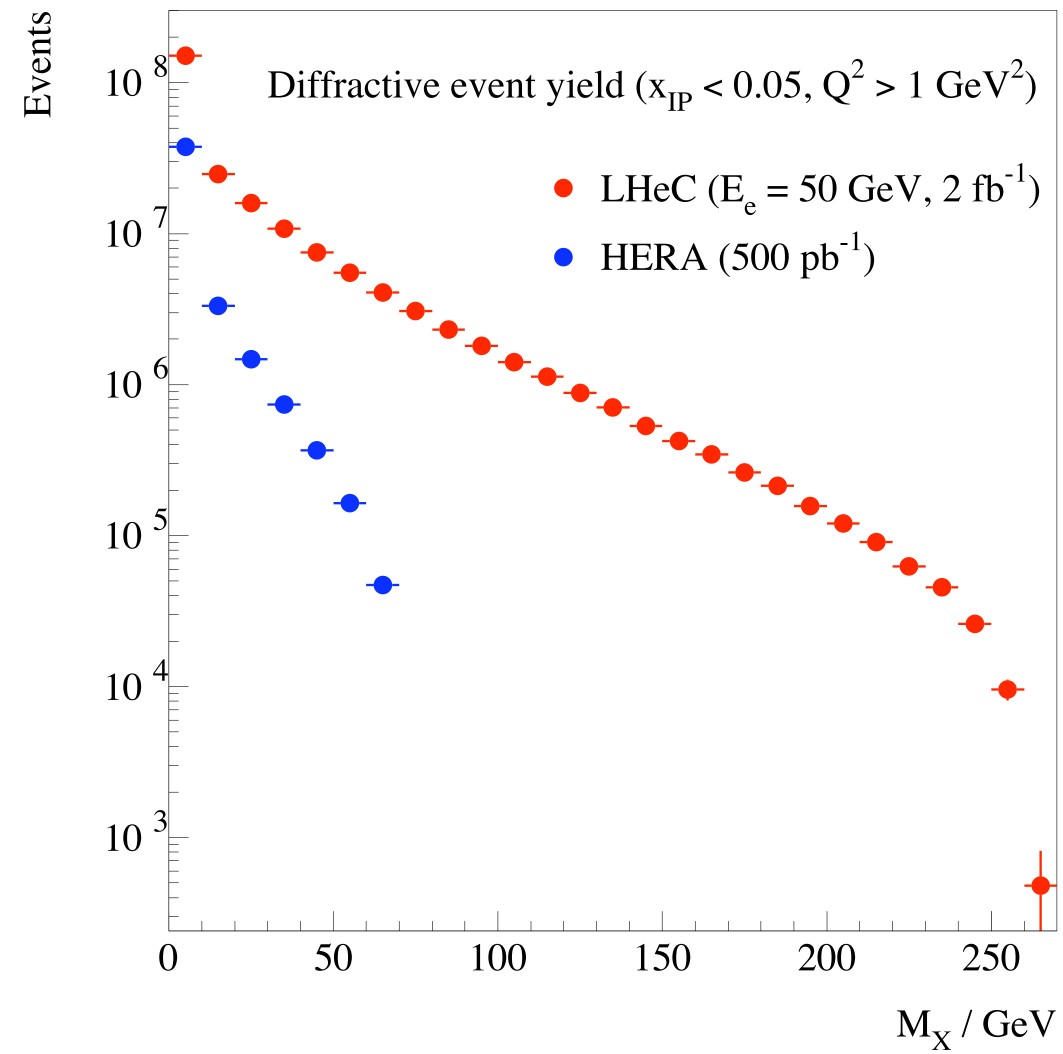
6. Summary.

ep diffractive pseudodata:





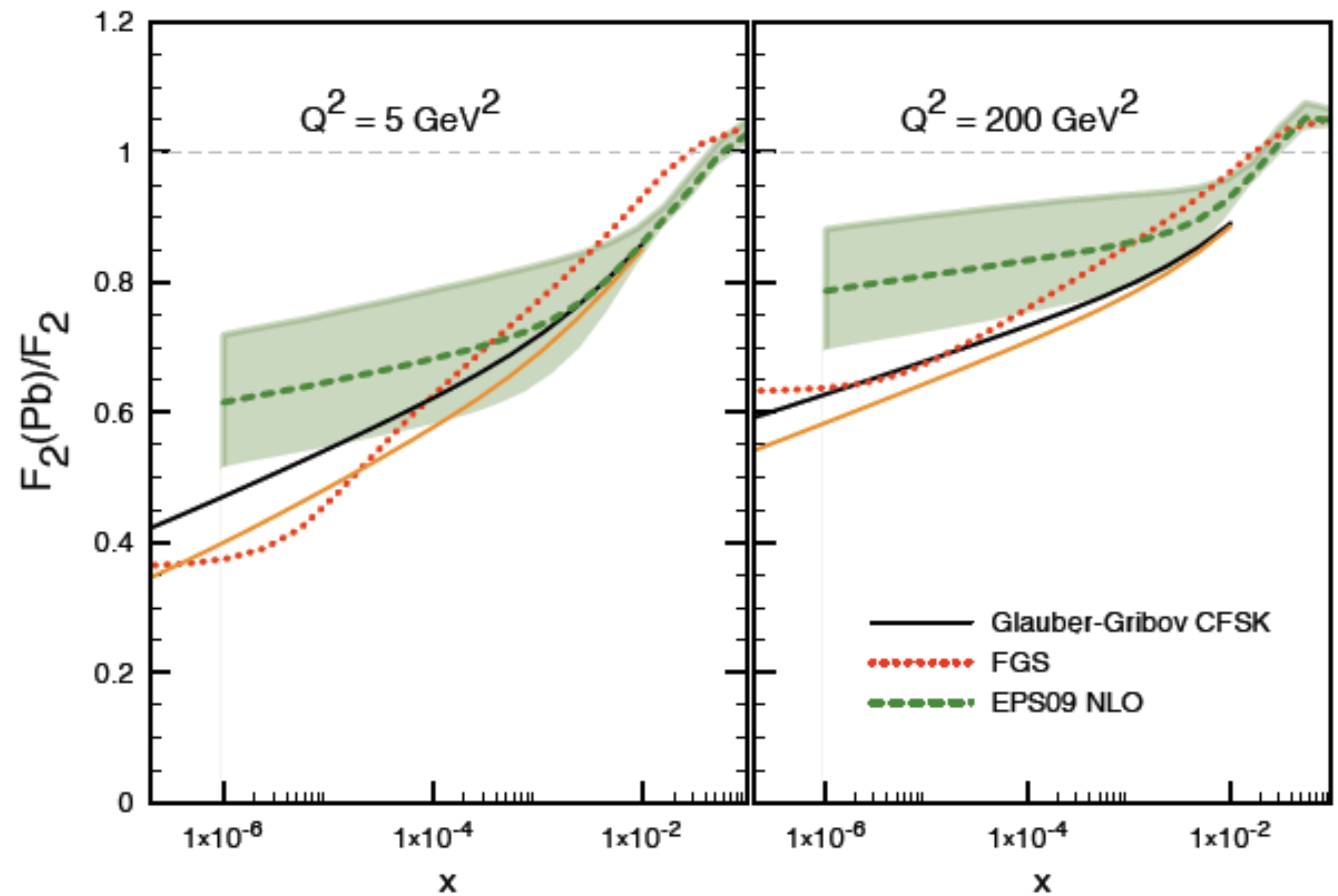
- Large increase in the M^2, $x_P=(M^2-t+Q^2)/(W^2+Q^2)$, $\beta=x/x_P$ region studied.



ep diffractive pseudodata:

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

NA, Kaidalov, Salgado, Tywoniuk, '10

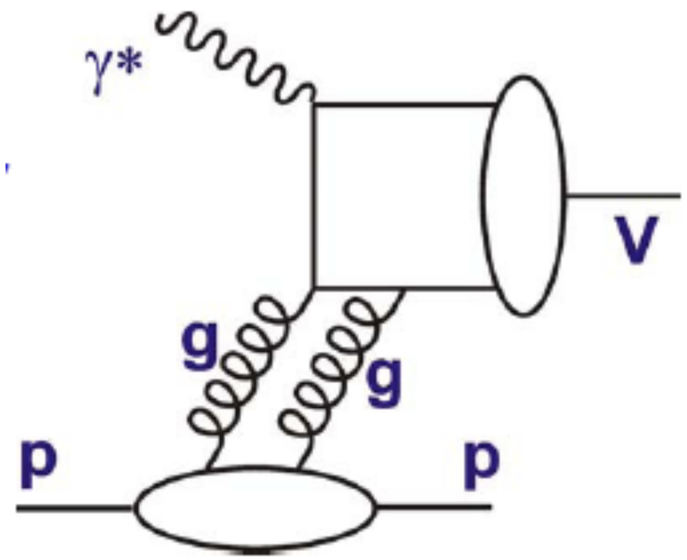


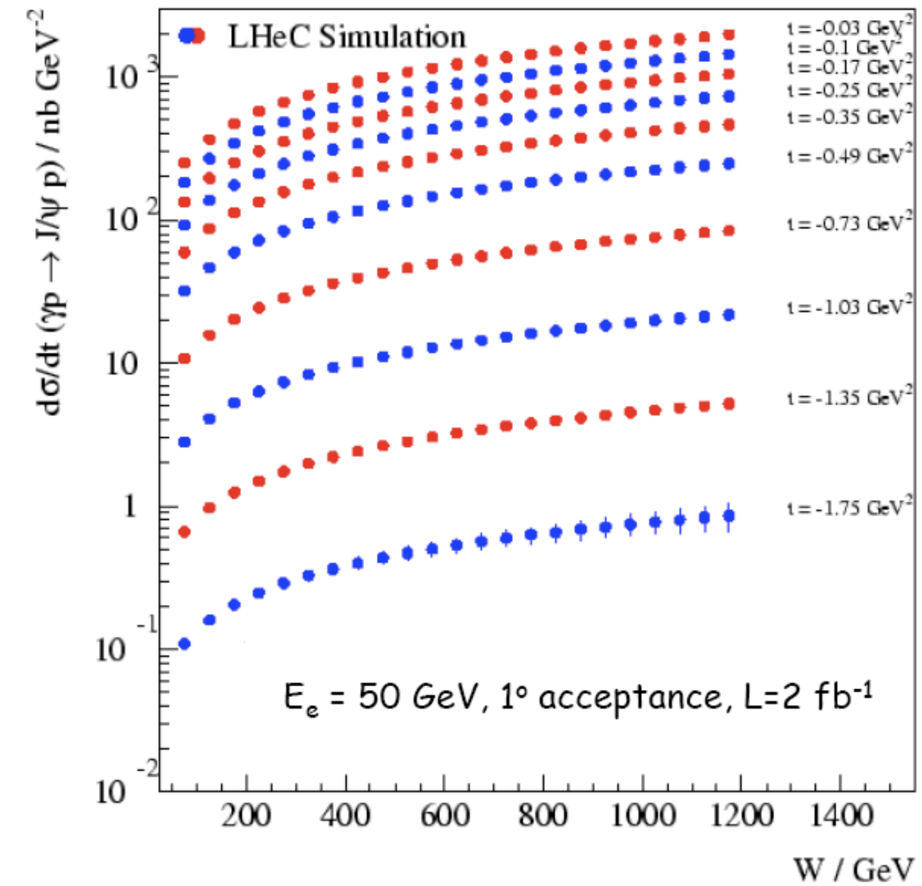
β

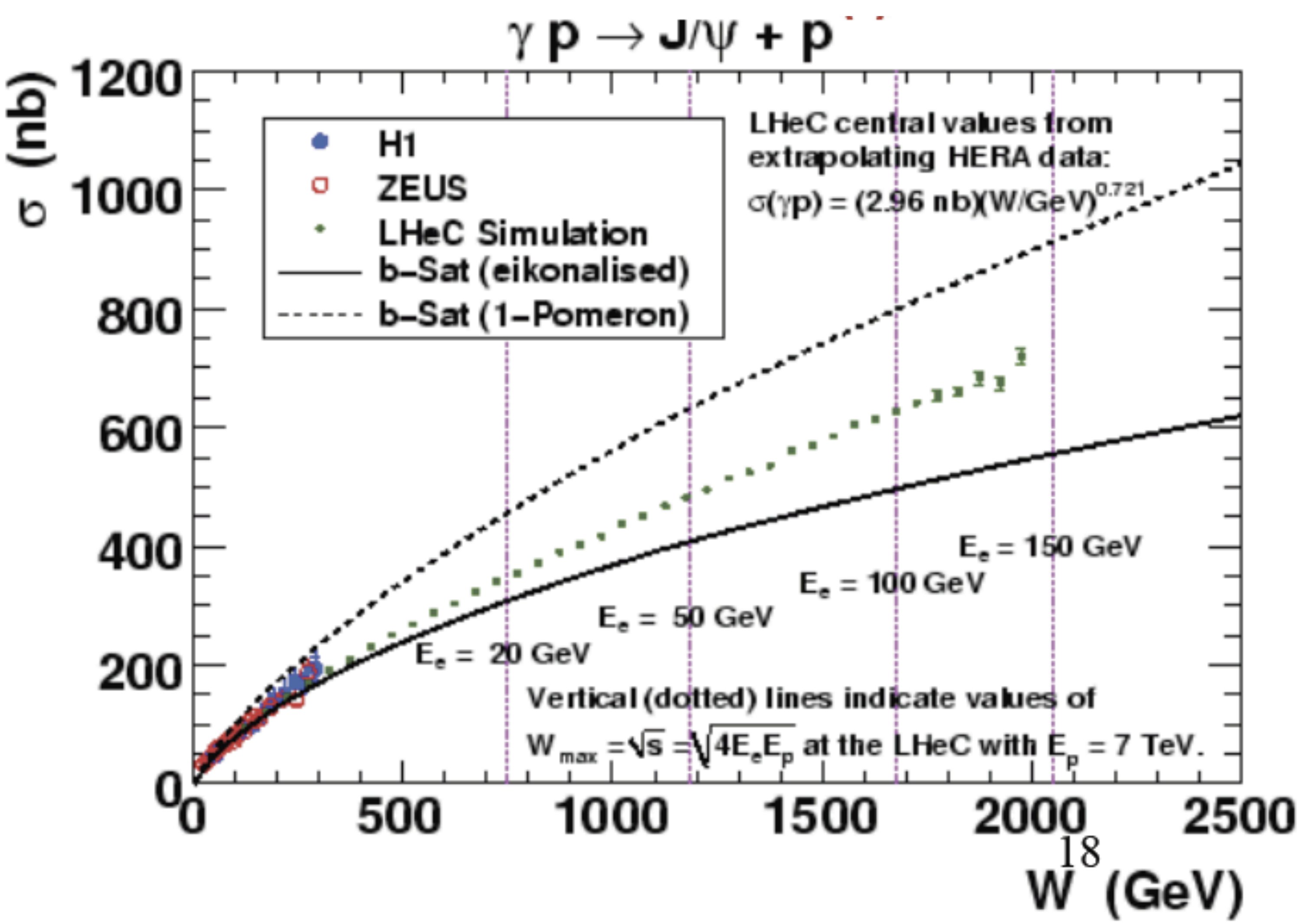
M_x / GeV

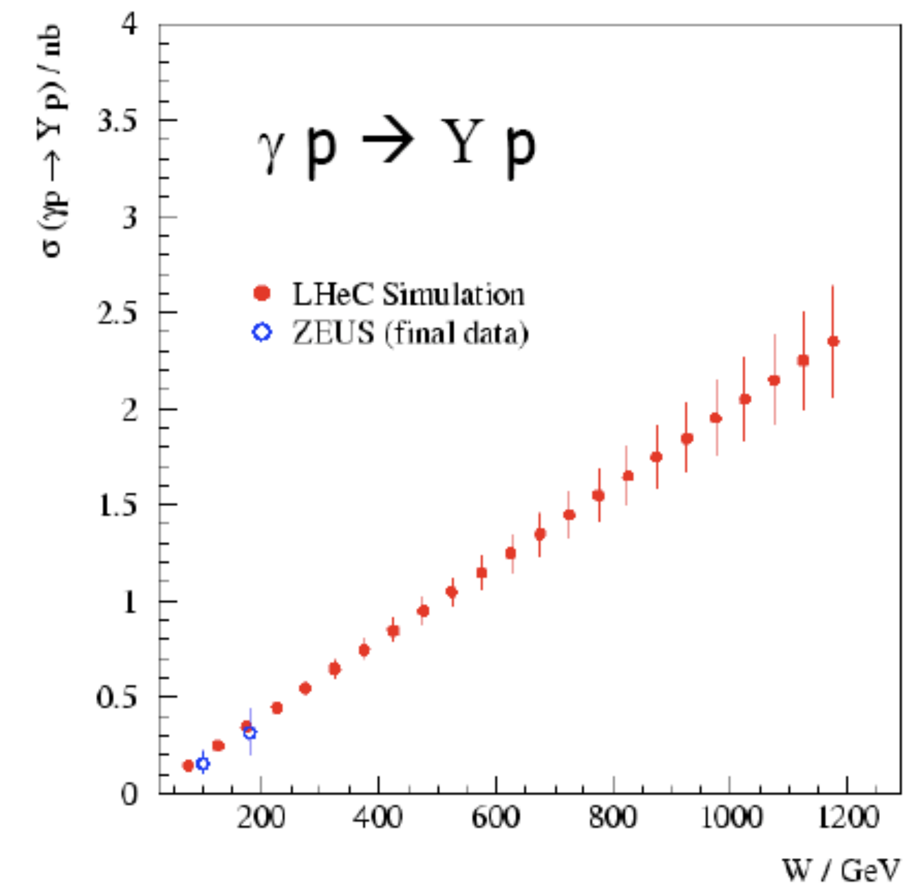
Elastic vector meson production:

- Most promising!!!



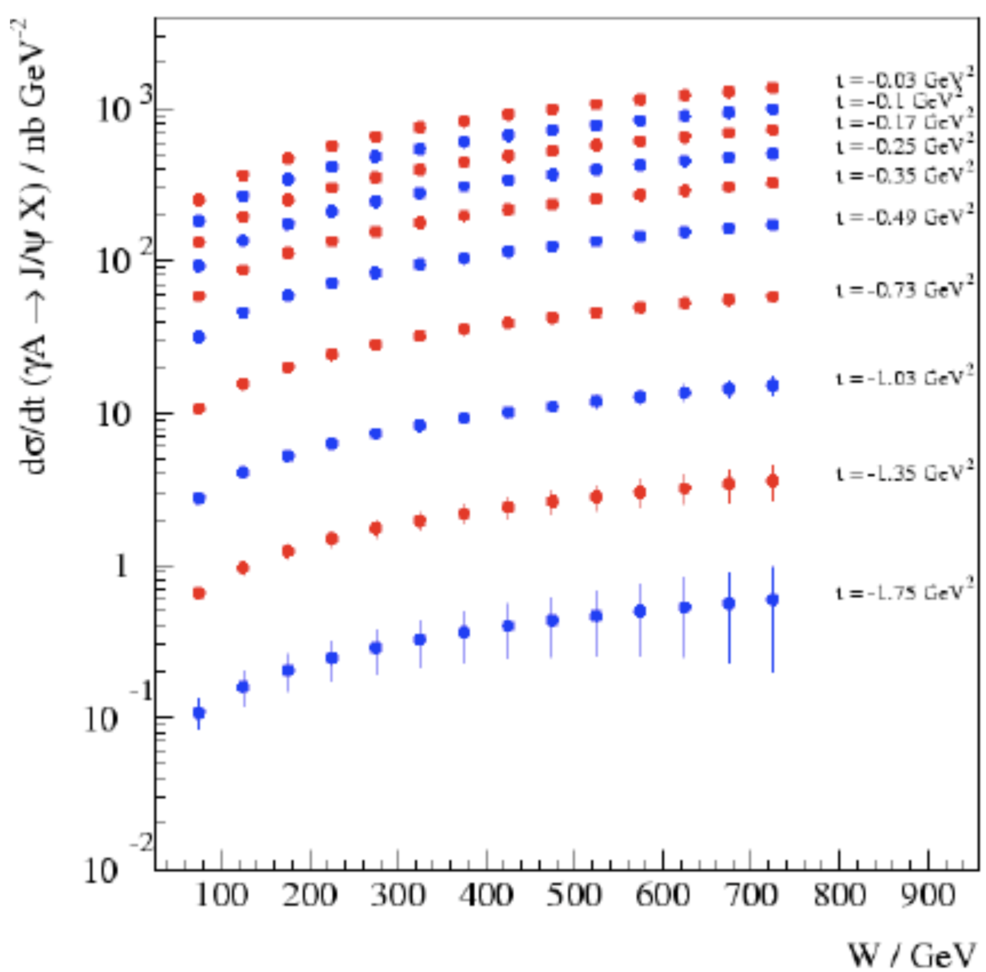




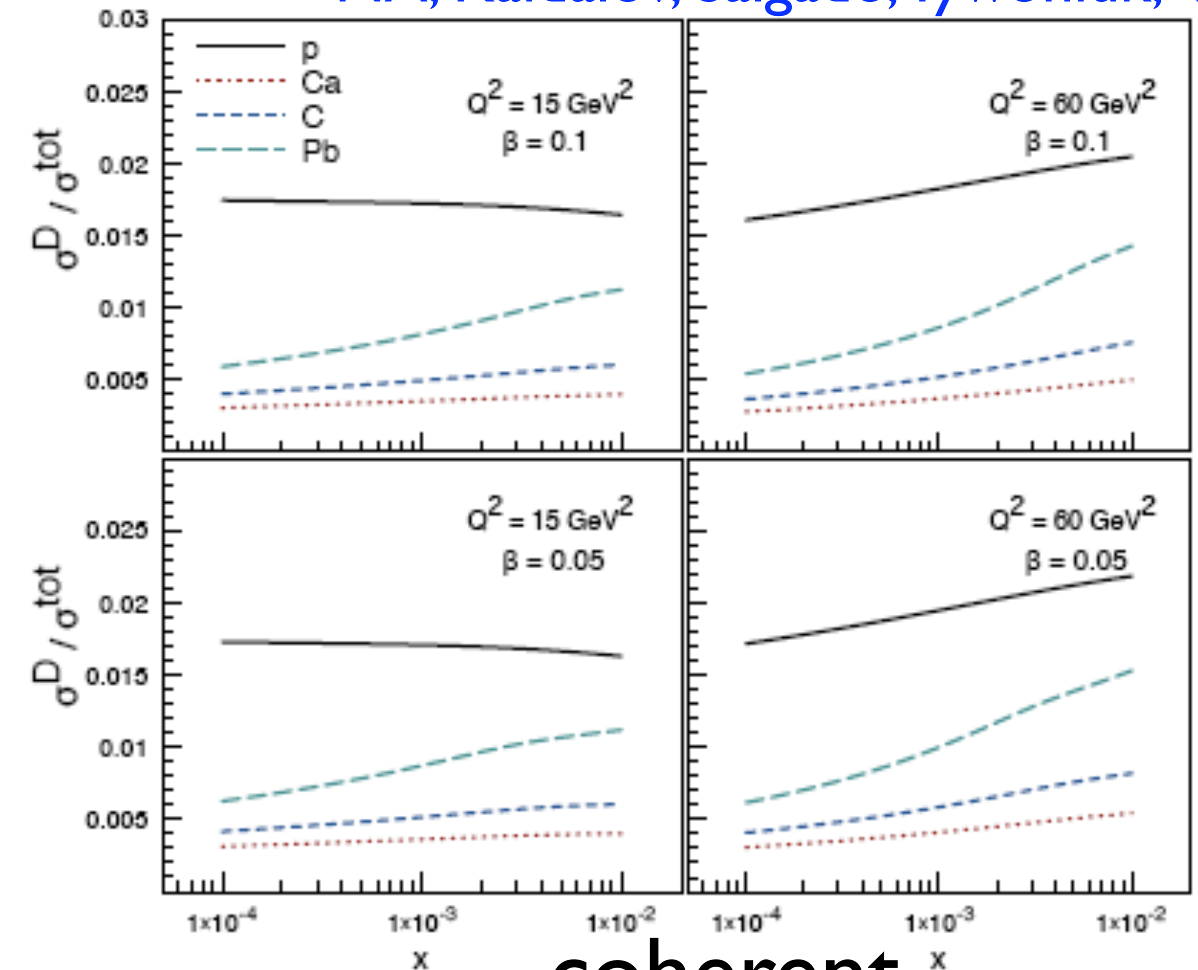


Nuclear diffraction:

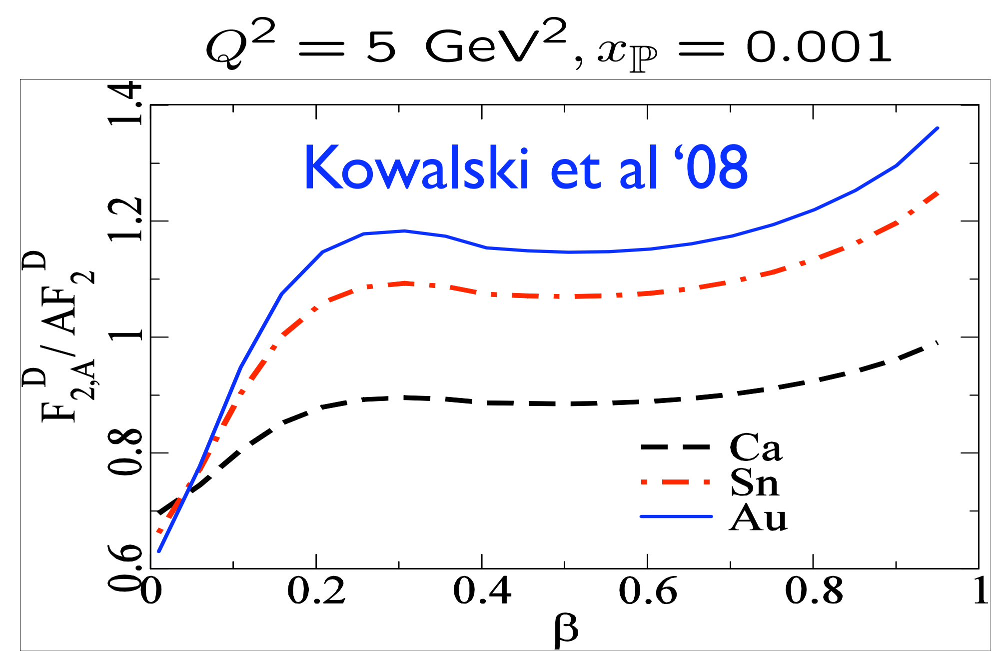
- Problem: diffraction maybe coherent (e+A→e+X+A), incoherent (e+A→e+X+Zp+(A-Z)n) and inelastic (e+A→e+X+X') ⇒ challenging experimental problem.



NA, Kaidalov, Salgado, Tywoniuk, '10



coherent



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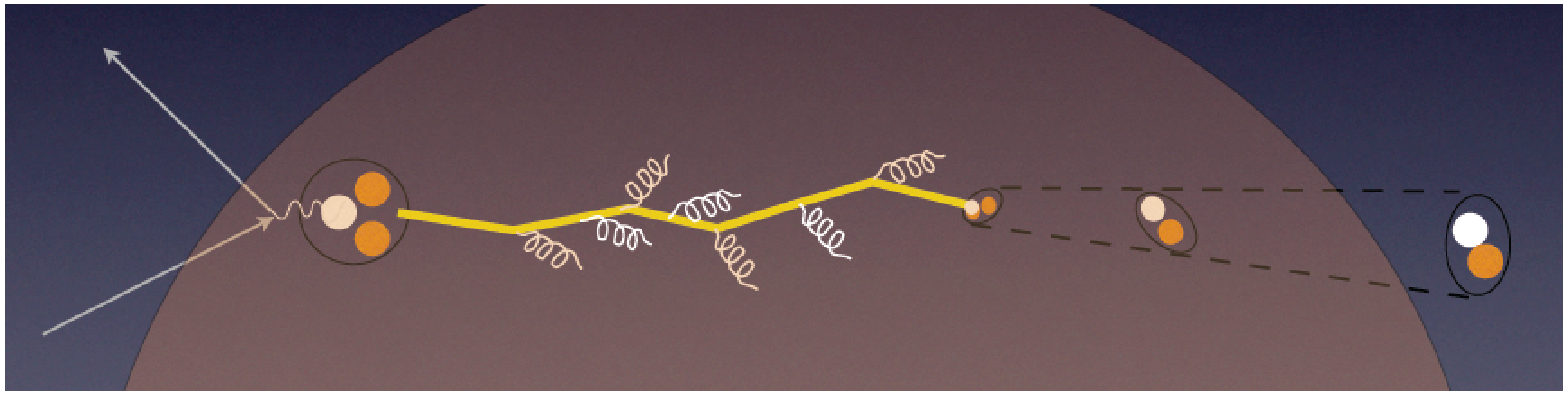
6. Summary.

In-medium hadronization:

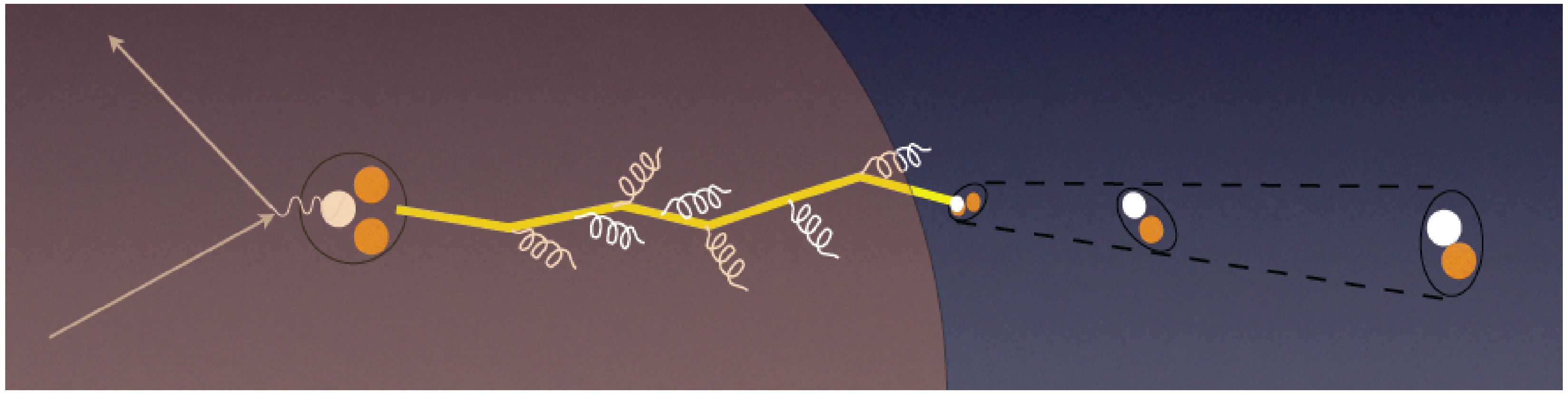
- The LHeC (ν_{max}~10^5 GeV) would allow to study the dynamics of hadronization, testing the parton/hadron eloss mechanism by introducing a length of colored material which would modify its pattern (length/nuclear size, chemical composition).

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



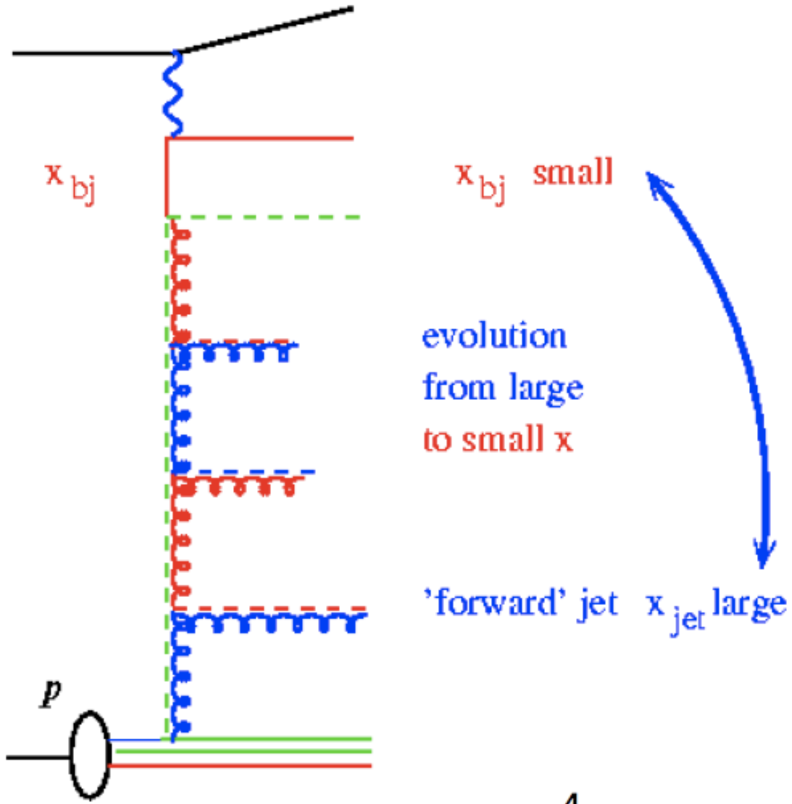
Brooks at Divonne'09

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



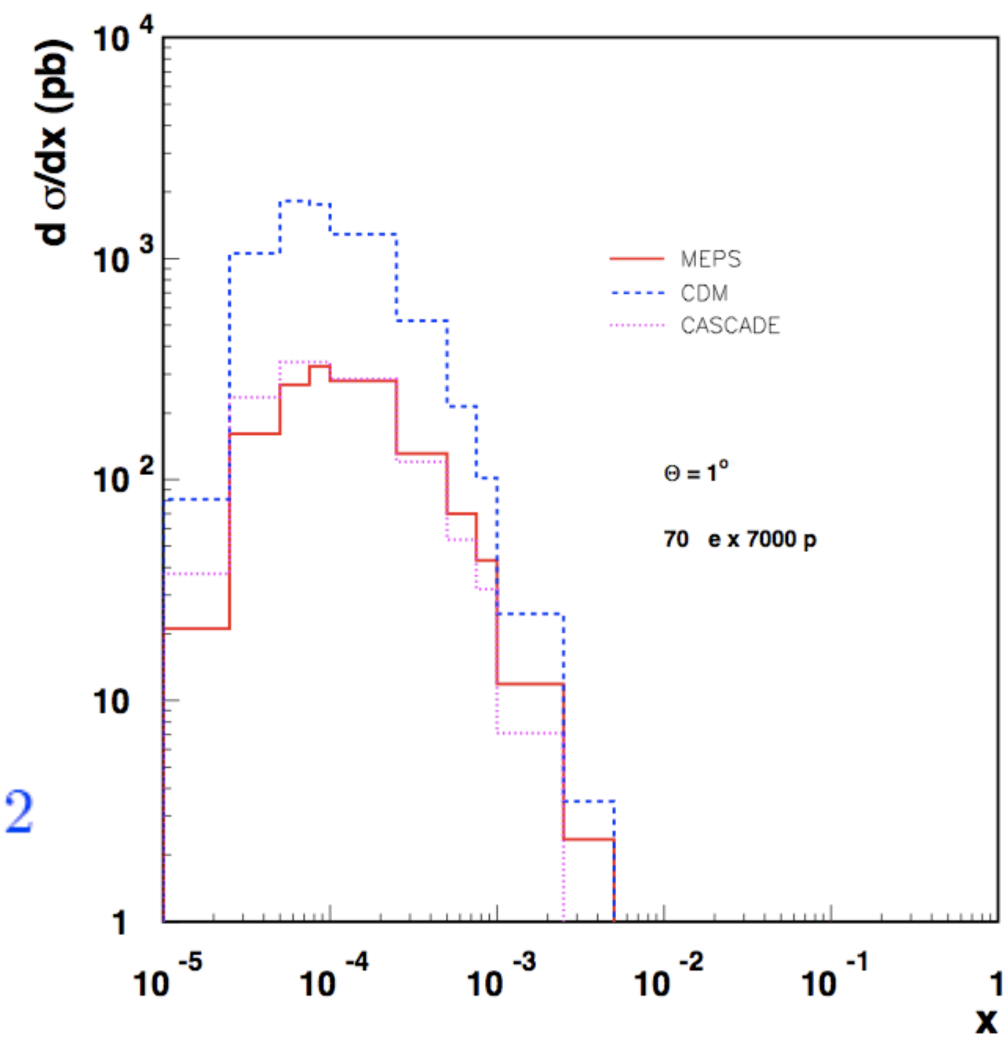
Forward jets:

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.



$$x_{jet} > 0.03$$

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

Hadronic final states:

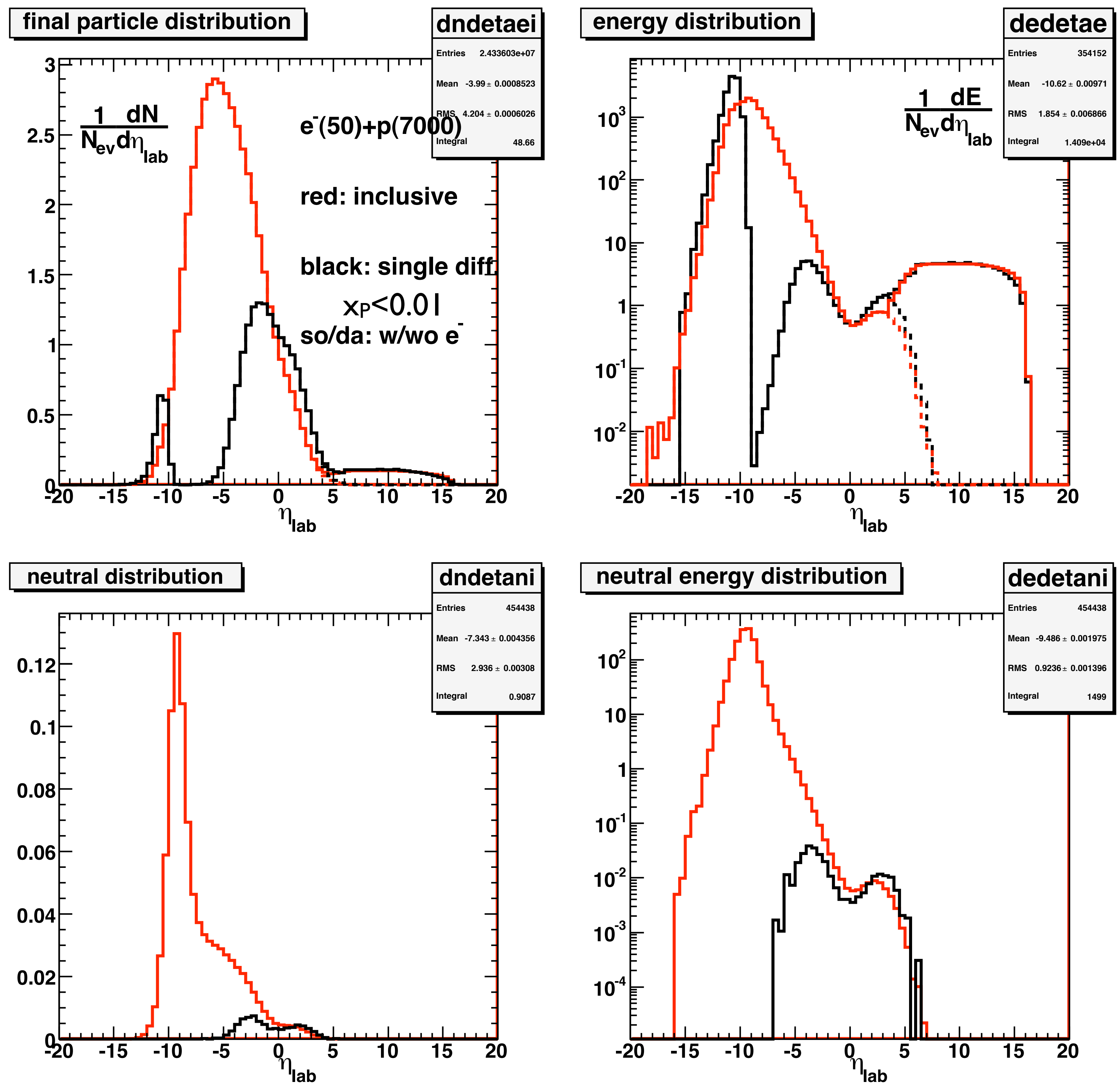
- Under study: Monte Carlo samples with DPMJET III+FLUKA for HFS, including nuclear evaporation in eA → particle/energy fluxes.
- Preliminary results for LHeC indicate:

→ ~ 2 <interactions>

in ePb: reduced rapidity gap survival.

→ ~ 1 % of events

with Pb left intact.



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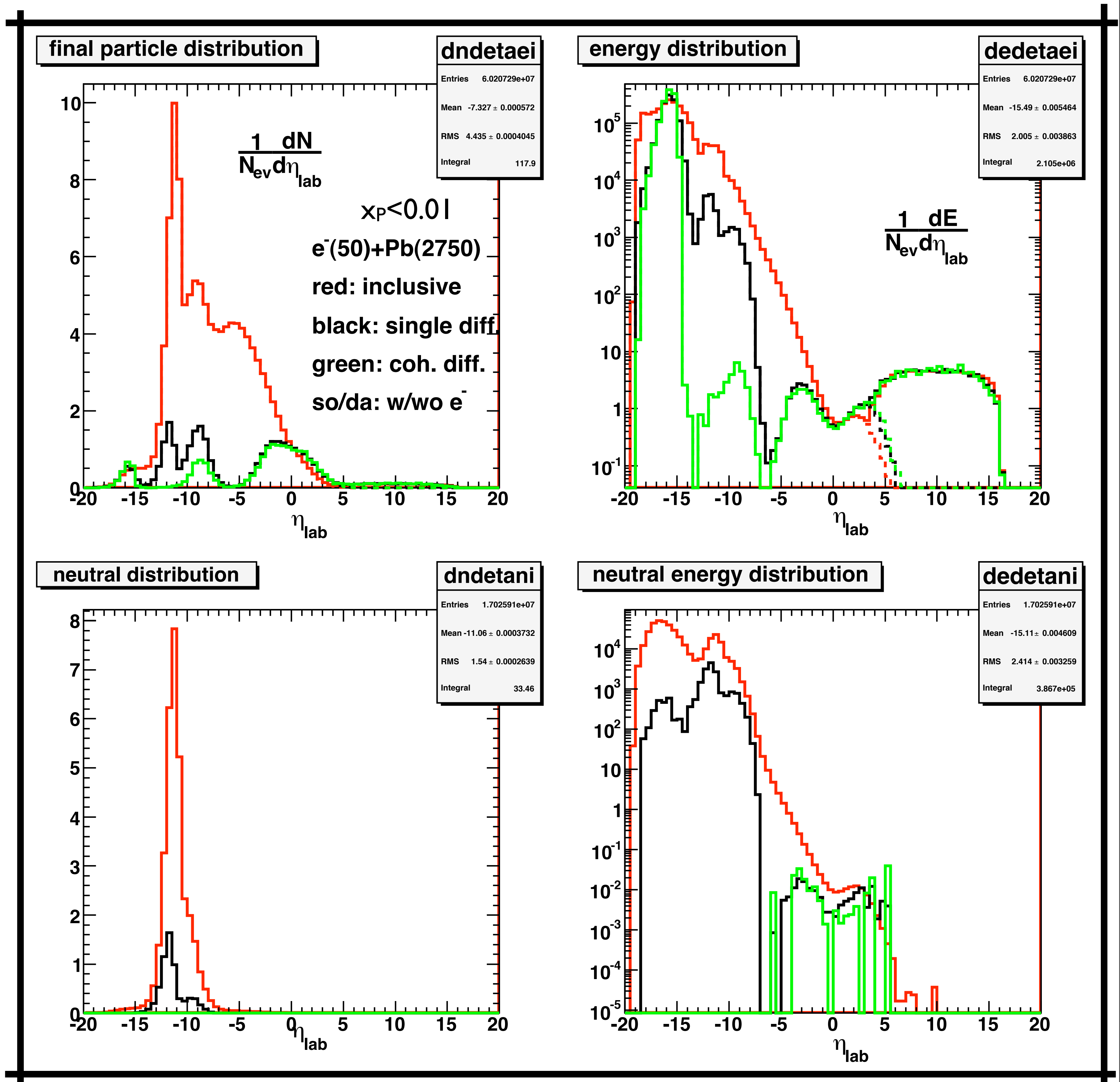


Summary:

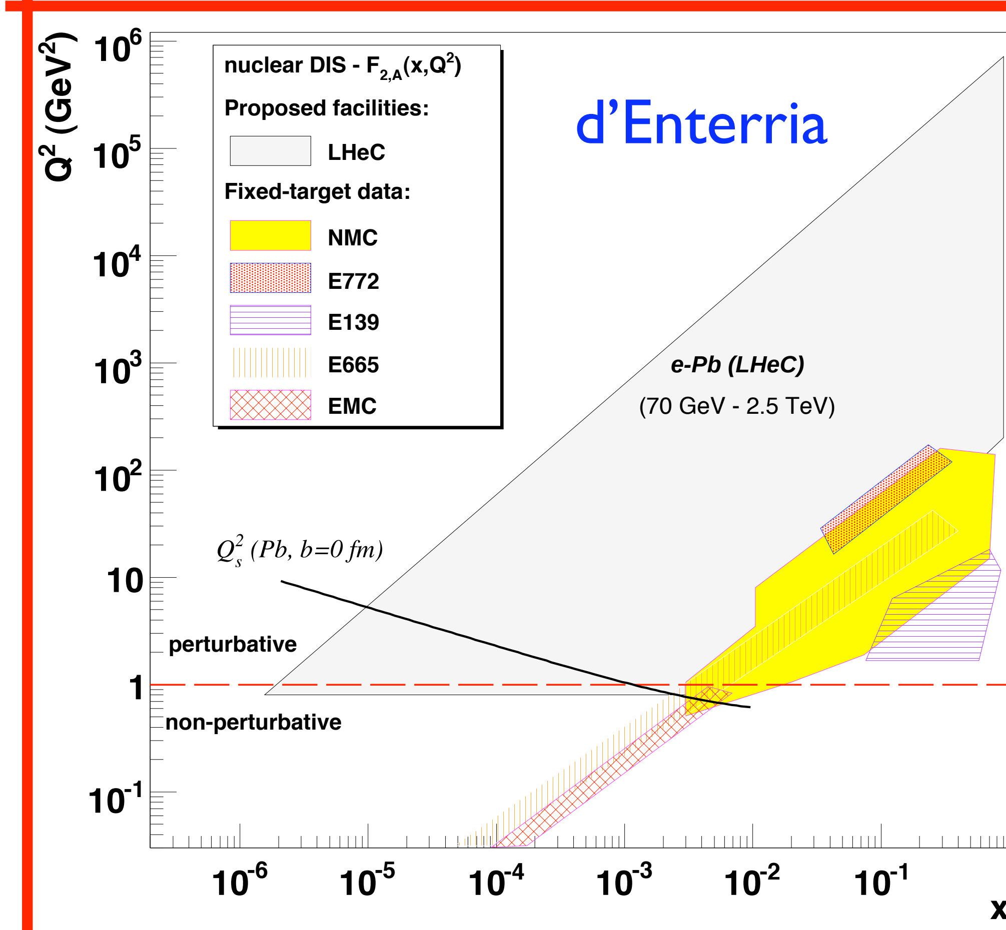
- Many issues remain open about small-x physics (behavior of the hadron wave function at small x): describable by pQCD?, need of resummation/onset of unitarity in the accessible kinematical regions?

- Current ep experiments cover pp@LHC at y=0; in eA, not even dAu@RHIC is really constrained.

- An electron-nucleon/ion collider offers huge possibilities to test our ideas about high-energy QCD. eA: amplifier of density effects; implications on UrHIC complementary to pA@LHC.

- LHeC@CERN: new facility for ep/eA at E_{cm}~1-2 TeV under design.

- LHeC could be built in 10 years, depending on LHC schedules and on us. CDR in progress.



Plans for the CDR:

Scientific Advisory Committee

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Stan Brodsky (SLAC)
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Swapan Chattopadhyay (Cockcroft)
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Wesley Smith	(Wisconsin)
Bernd Surrow	(MIT)
Katsuo Tokushuku	(KEK)
Urs Wiedemann	(CERN)
Frank Zimmermann	(CERN)

The LHeC Study Group
http://cern.ch/lhec

Steps to go in 2010

1. Finalise physics and technical studies
2. DIS10 Firenze [April] and IPACC Japan [May]
3. Draft CDR September 2010
4. Divonne 28.10.-30.10. Final Workshop
5. November 2010: Final report to ECFA
6. Submit CDR to CERN, ECFA, NuPECC

Many thanks to Max Klein, Brian Cole, Paul Newman, Anna Stasto, Urs Wiedemann, Peter Kotska, Javier Albacete, David d’Enterria, Kari Eskola, Cyrille Marquet, Hannu Paukkunen, Carlos Salgado, Mark Strikman, Konrad Tywoniuk and all other collaborators in the preparation of the CDR!!!

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Accelerator Design [RR and LR]
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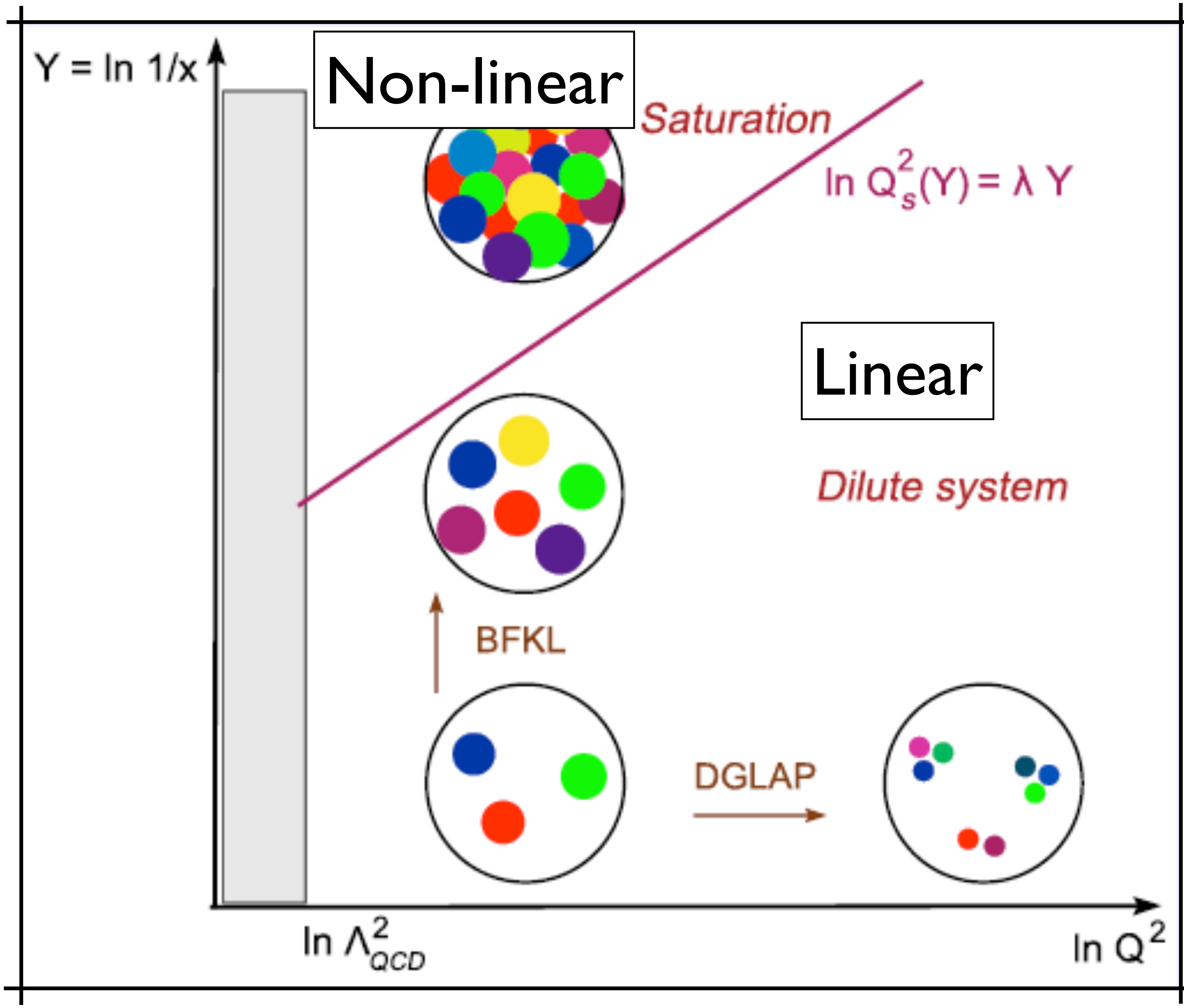
Paolo Gambino (Torino),
Thomas Gehrmann (Zuerich)
Claire Gwenlan (Oxford)

Physics at High Parton Densities
Nestor Armesto (Santiago),
Brian Cole (Columbia),
Paul Newman (Birmingham),
Anna Stasto (PennState)

Theory: high-energy QCD



Where do the available experimental data lie?

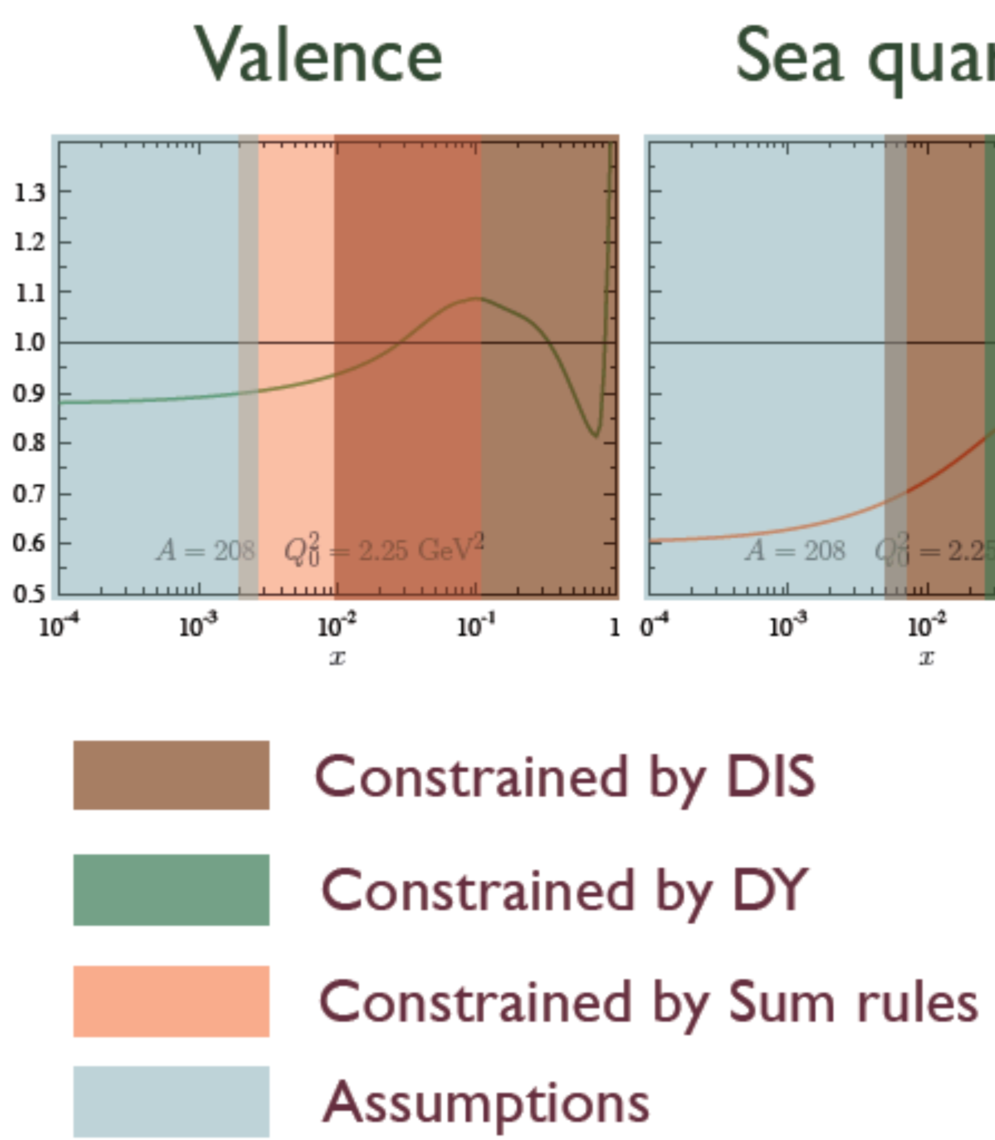
Our aims: understanding

- 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.

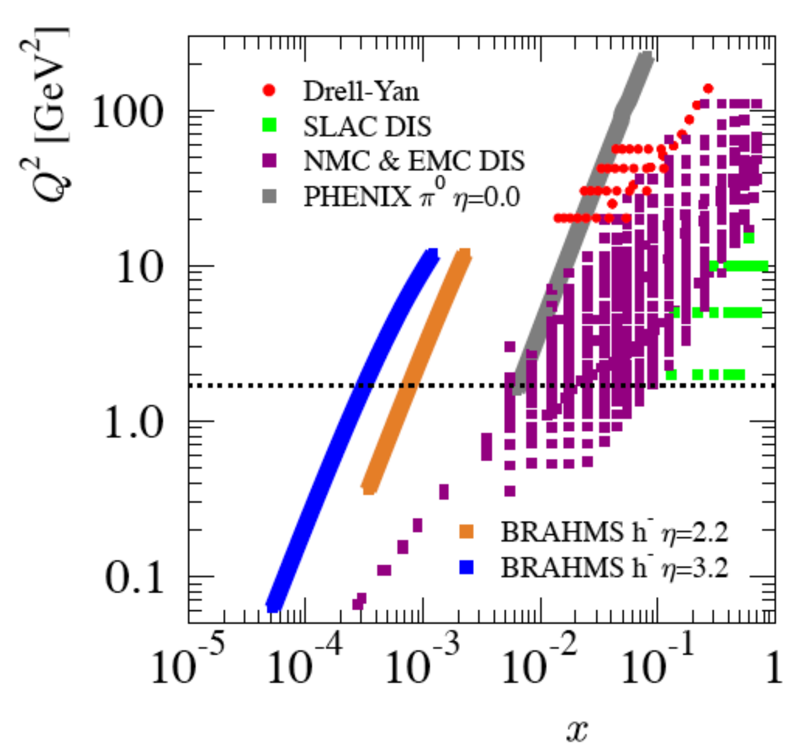
DGLAP analysis of npdf's:

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

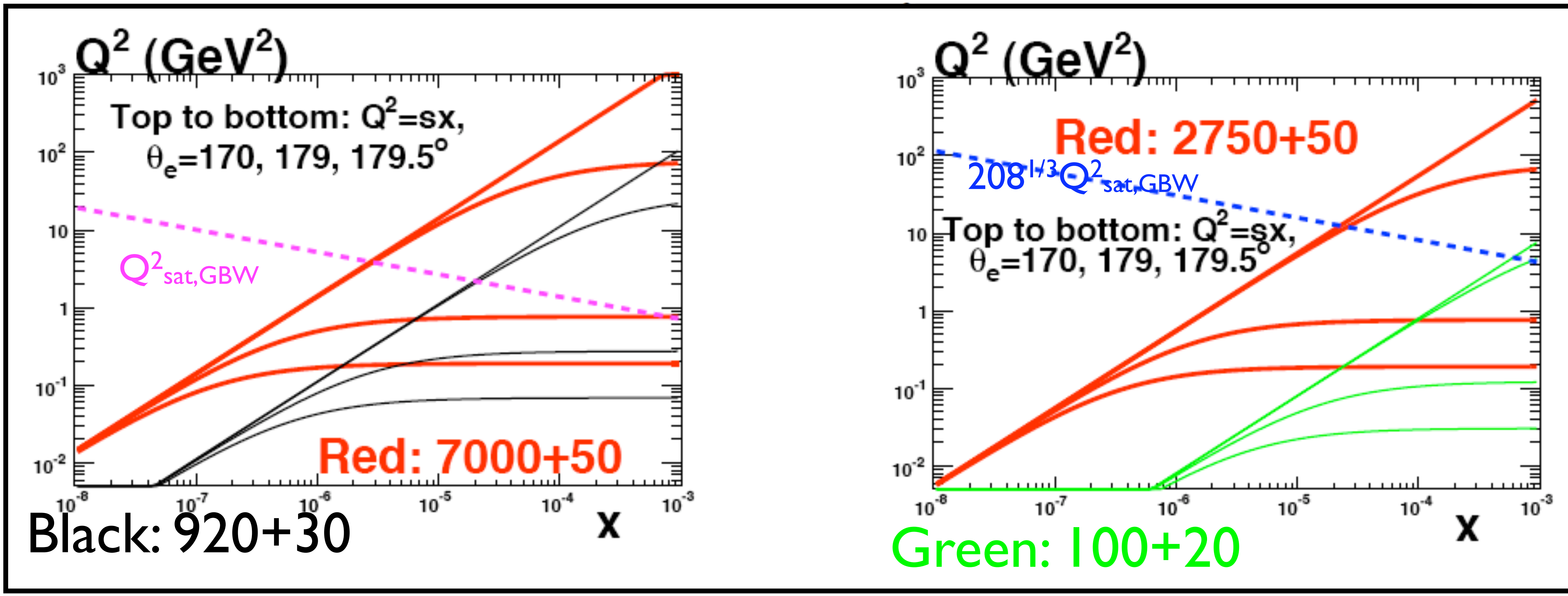
neutrino data under discussion (see CTEQ '09, Paukkunen-Salgado '10).



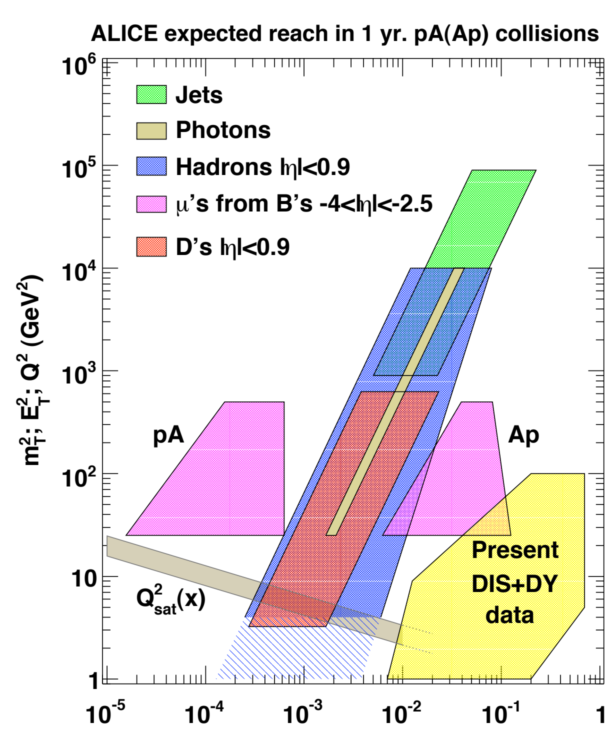
Salgado

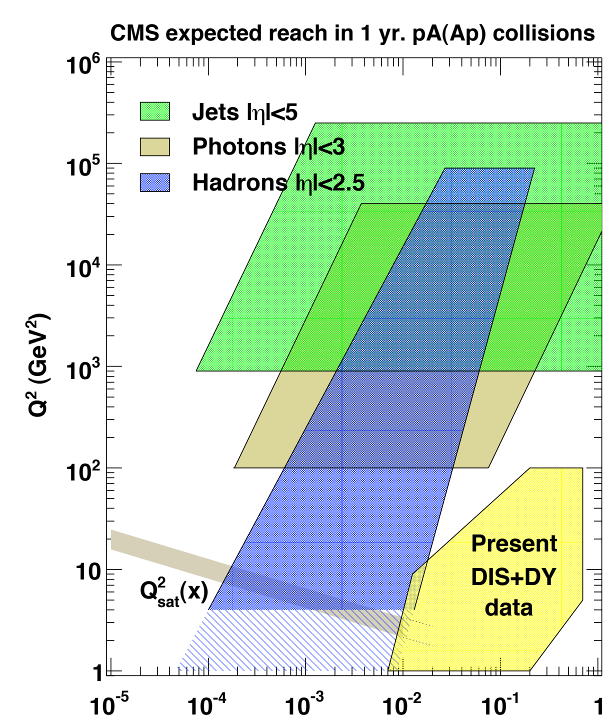


Kinematics:



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





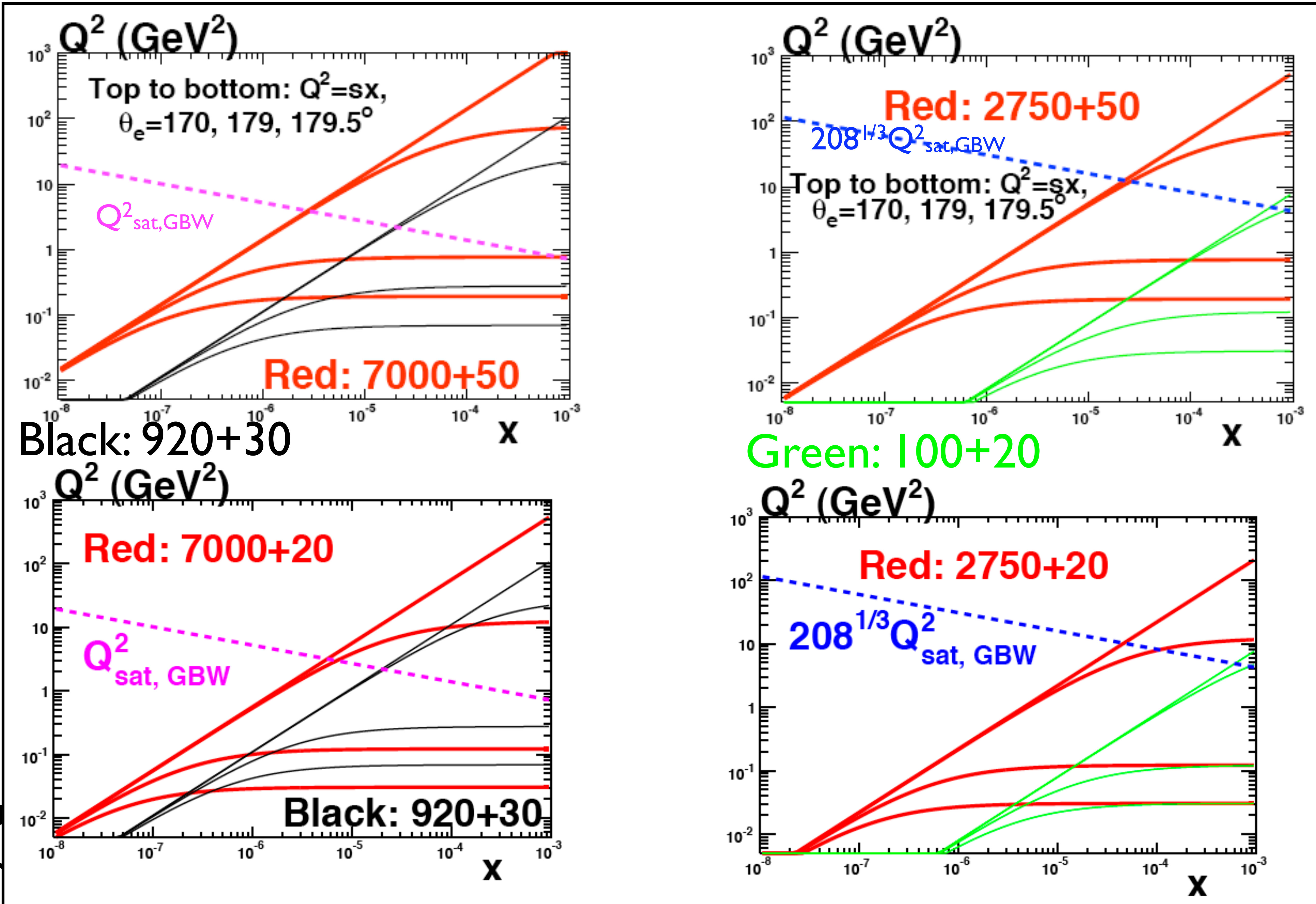
LHeC scenarios:

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

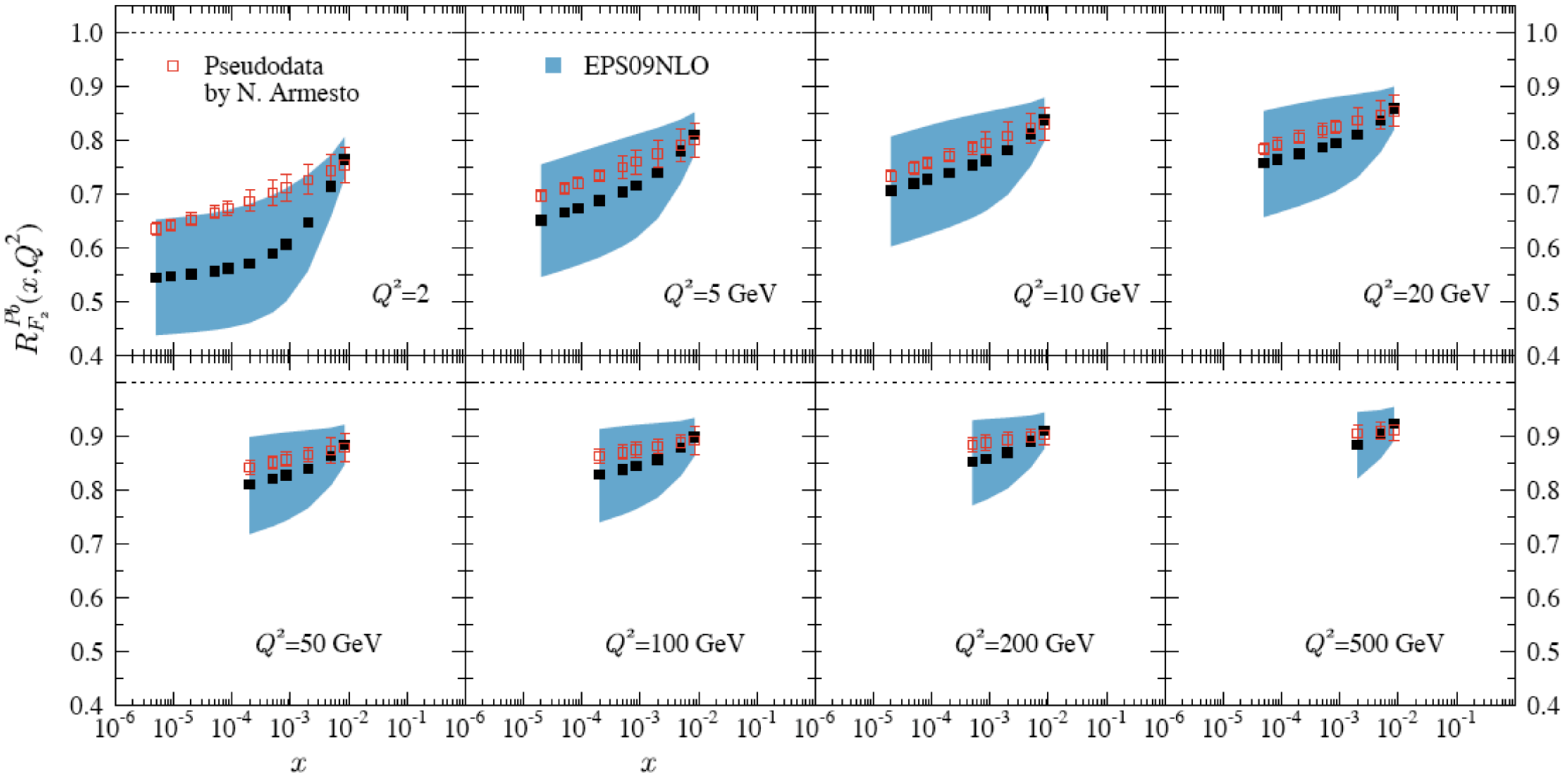
- For F_L: 10, 25, 50 + 2750 (7000); $Q^2 \leq sx$; Lumi=5,10,100 pb^{-1} respectively; charm and beauty: same efficiencies in ep and eA.

LHeC scenarios:

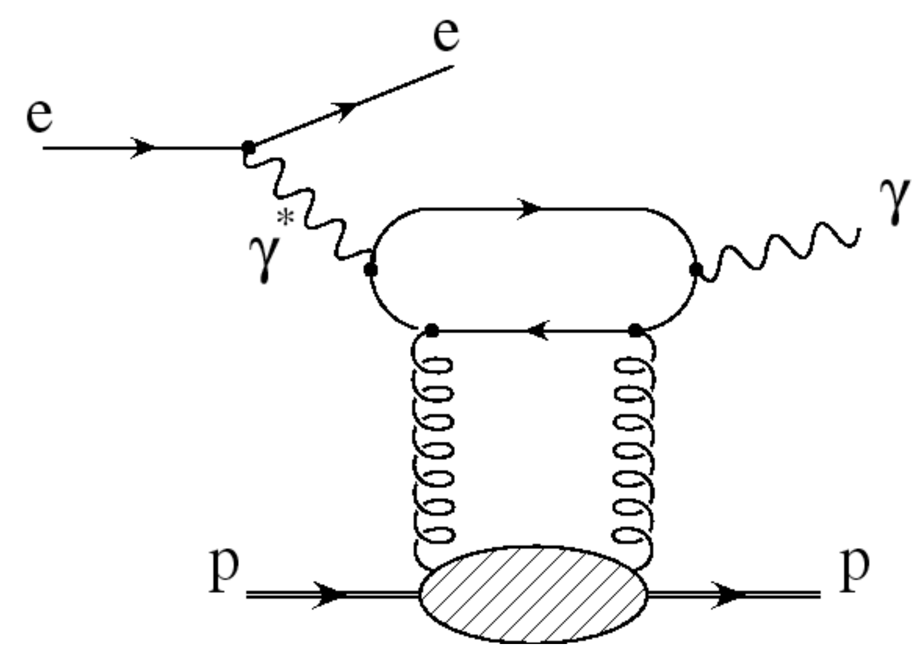


eA inclusive pseudodata (II):

- F_2 data substantially reduce the uncertainties in DGLAP analysis; inclusion of charm, beauty and F_L in progress.



DVCS:



- Large kinematical extent compared to HERA.