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eA collisions at the Large Hadron-electron Collider

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for the **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:

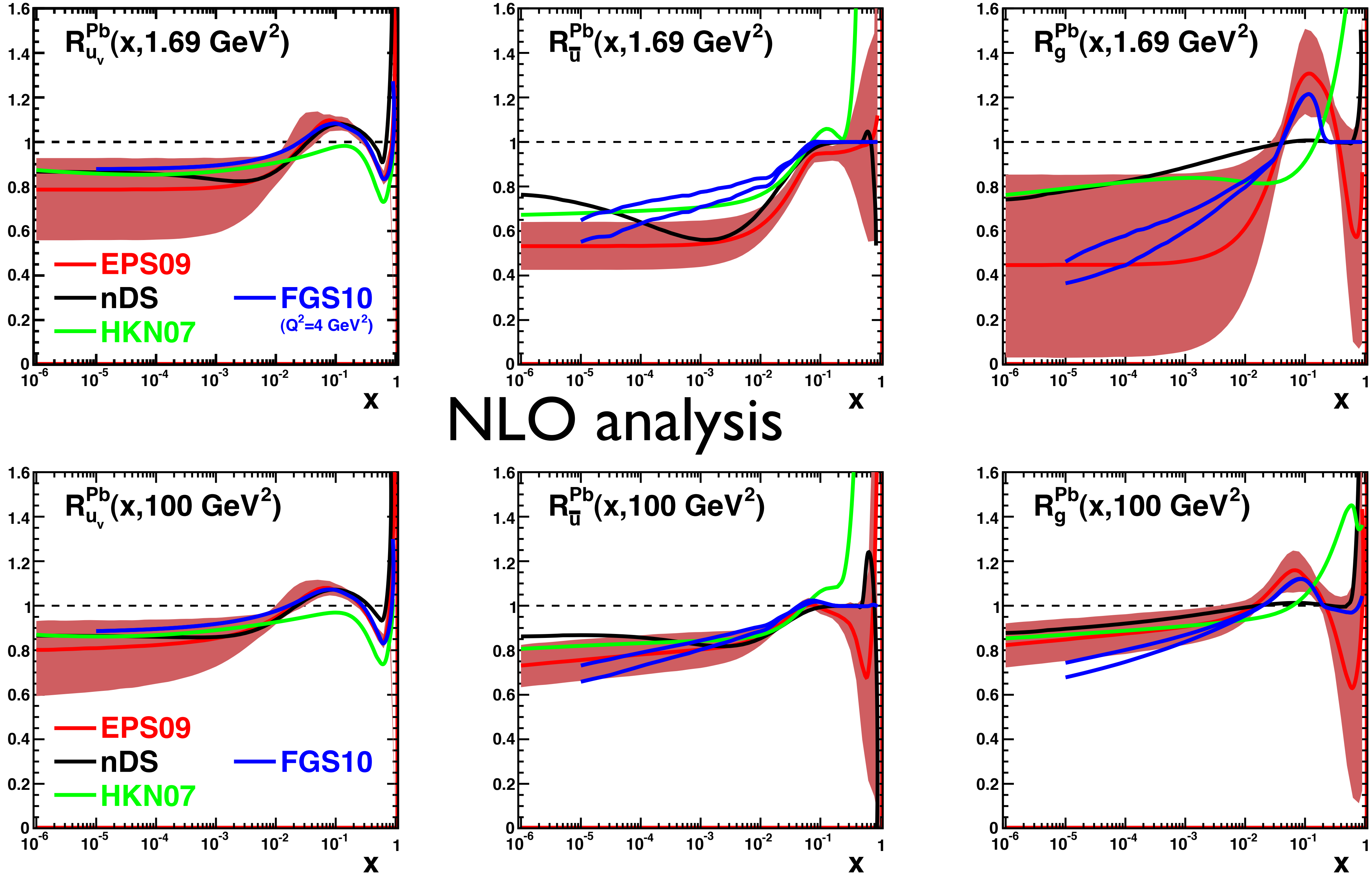
1. Introduction.
2. The Large Hadron-electron Collider.
3. Inclusive observables:
   - ep inclusive pseudodata and their effect on pdf's.
   - eA inclusive pseudodata and their effect on npdf's.
4. Diffractive observables:
   - ep diffractive pseudodata.
   - Exclusive vector meson production.
   - Nuclear diffraction.
5. Final states.
6. Summary.

See the talks by J. Albacete, F. Arleo, C. Salgado, A. Stasto and T. Ullrich, and the LHeC talks at DIS 2011 (https://wiki.bnl.gov/conferences/index.php/DIS-2011).

Uncertainties in DGLAP npdf's:

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

Problem for benchmarking in hard probes!!!



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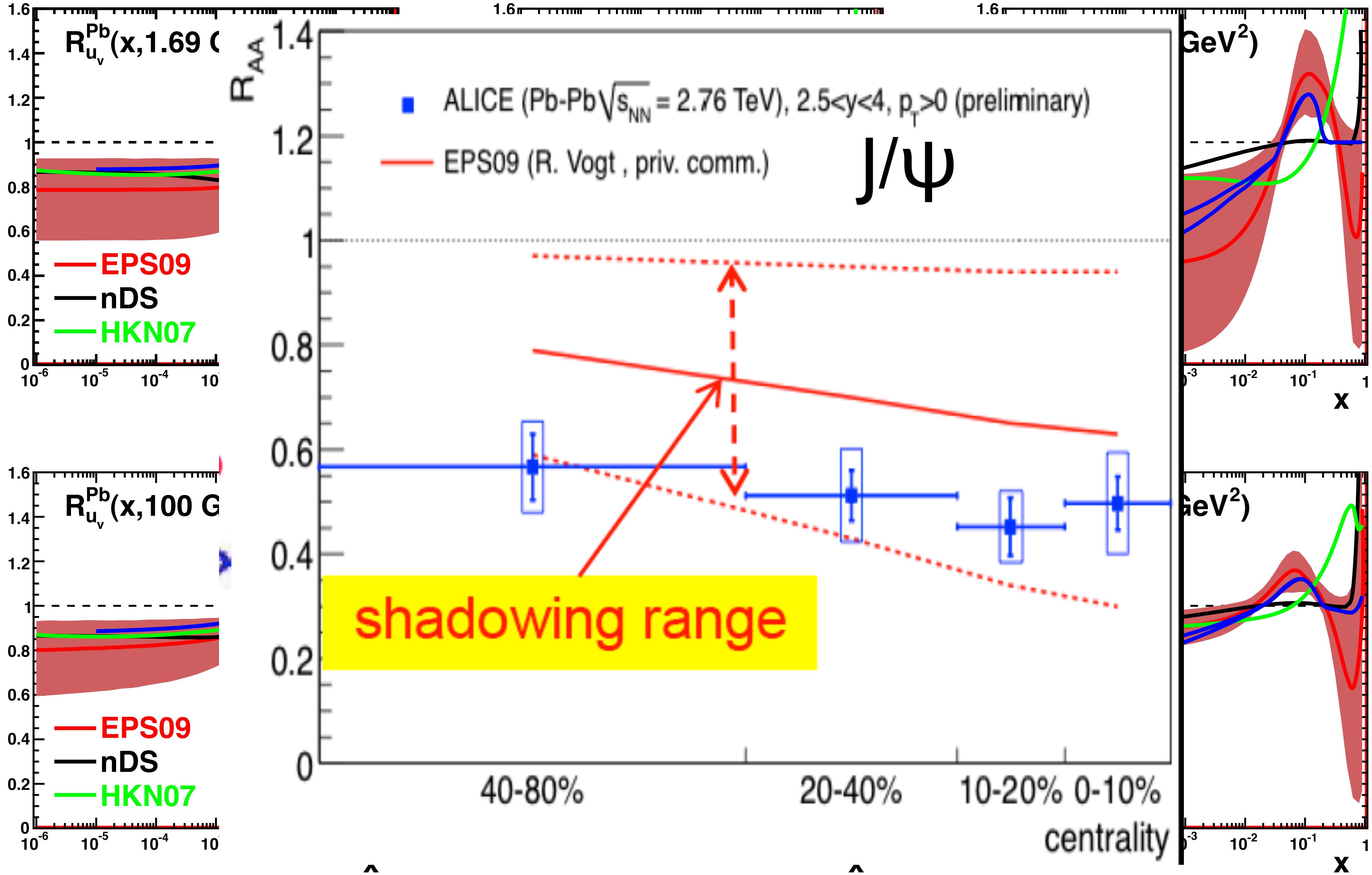
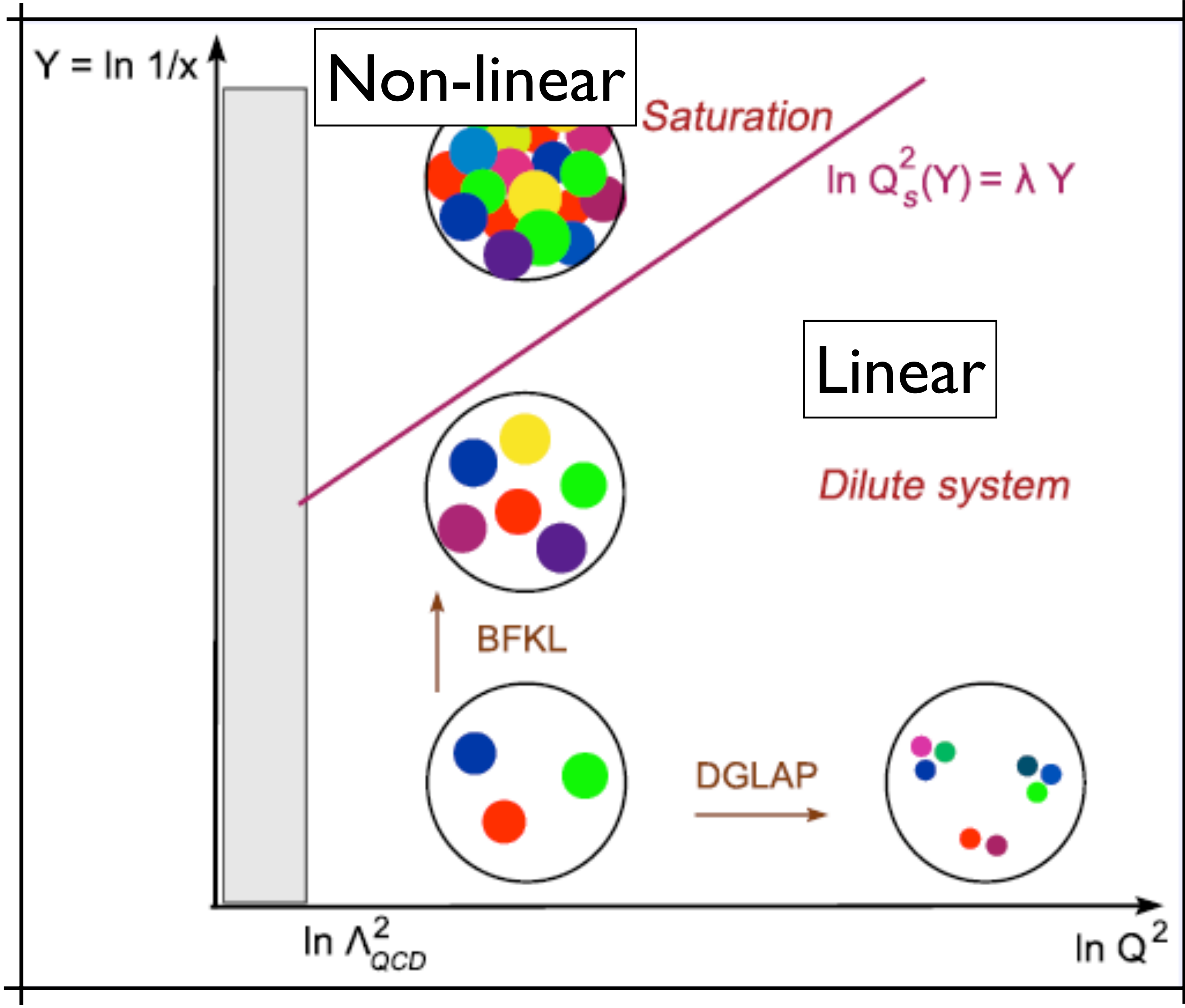


High-energy QCD:

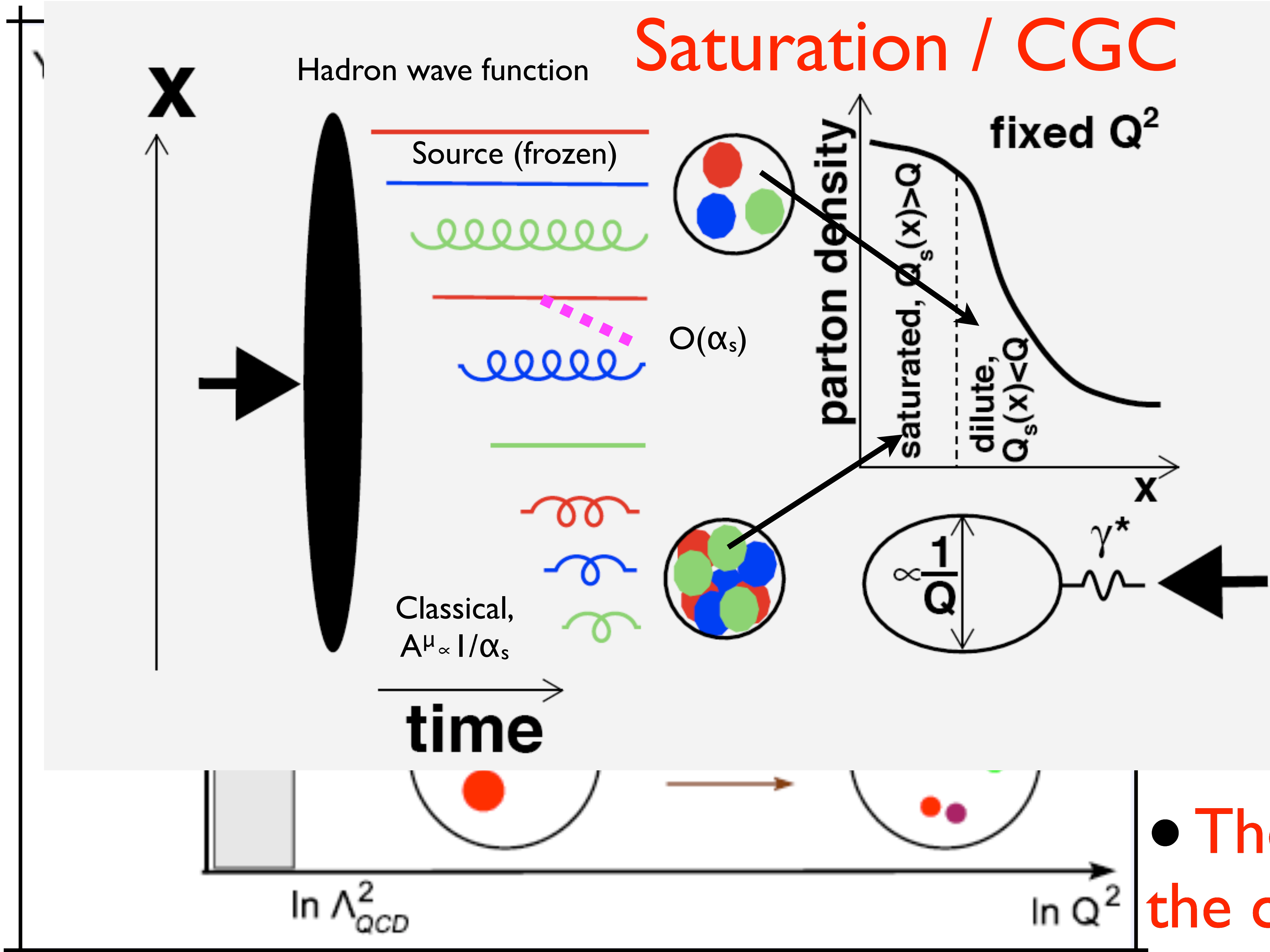


Where do the available experimental data lie?

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.

High-energy QCD:



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

Where do the available experimental data lie?

Status:

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

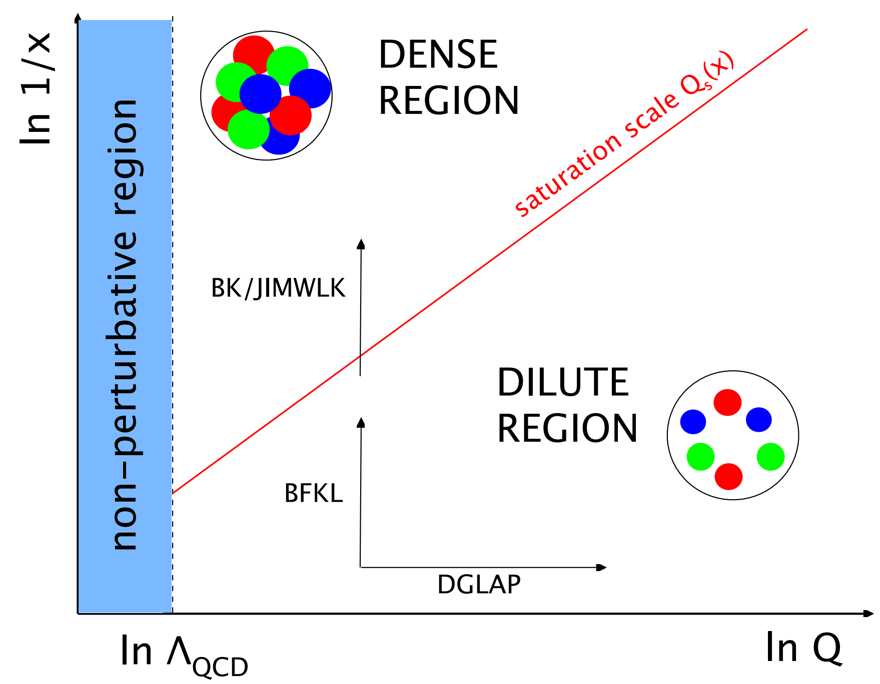
→ DGLAP evolution (fixed order PT).

→ Resummation schemes.

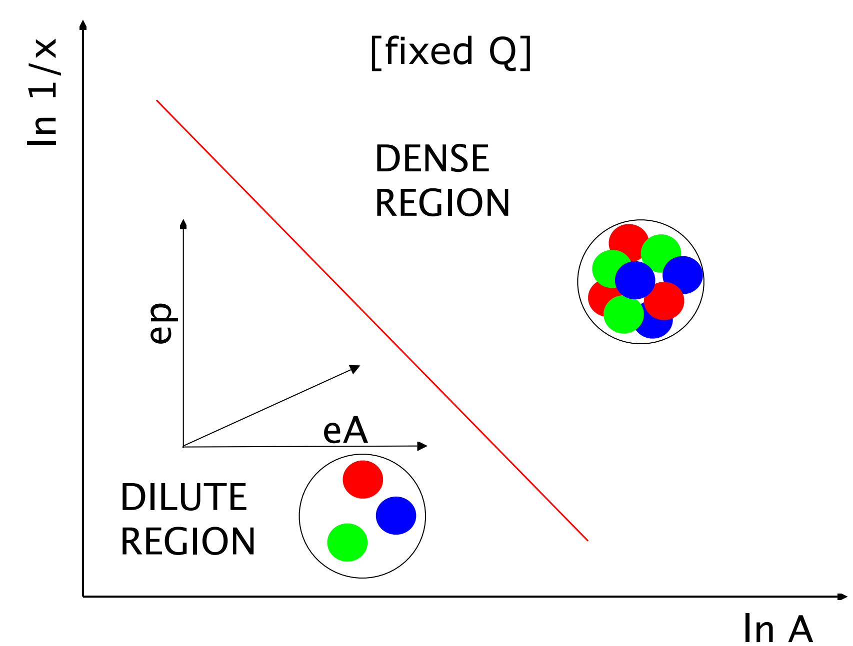
→ CGC (dipole models and rcBK).

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?



Two-pronged approach: ↓ x / ↑ A. **eA**: test/ enhance density effects.

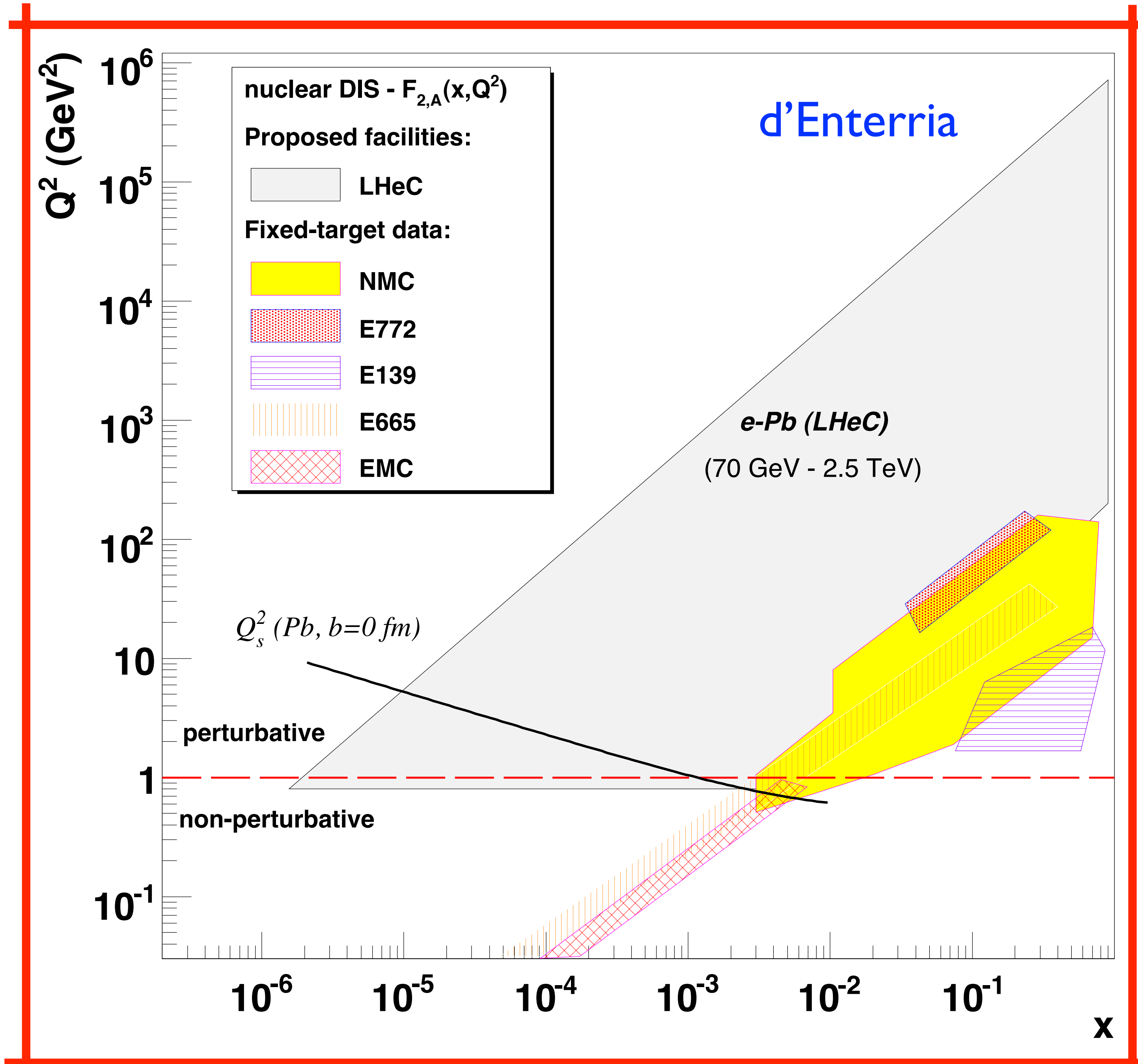


Contents:

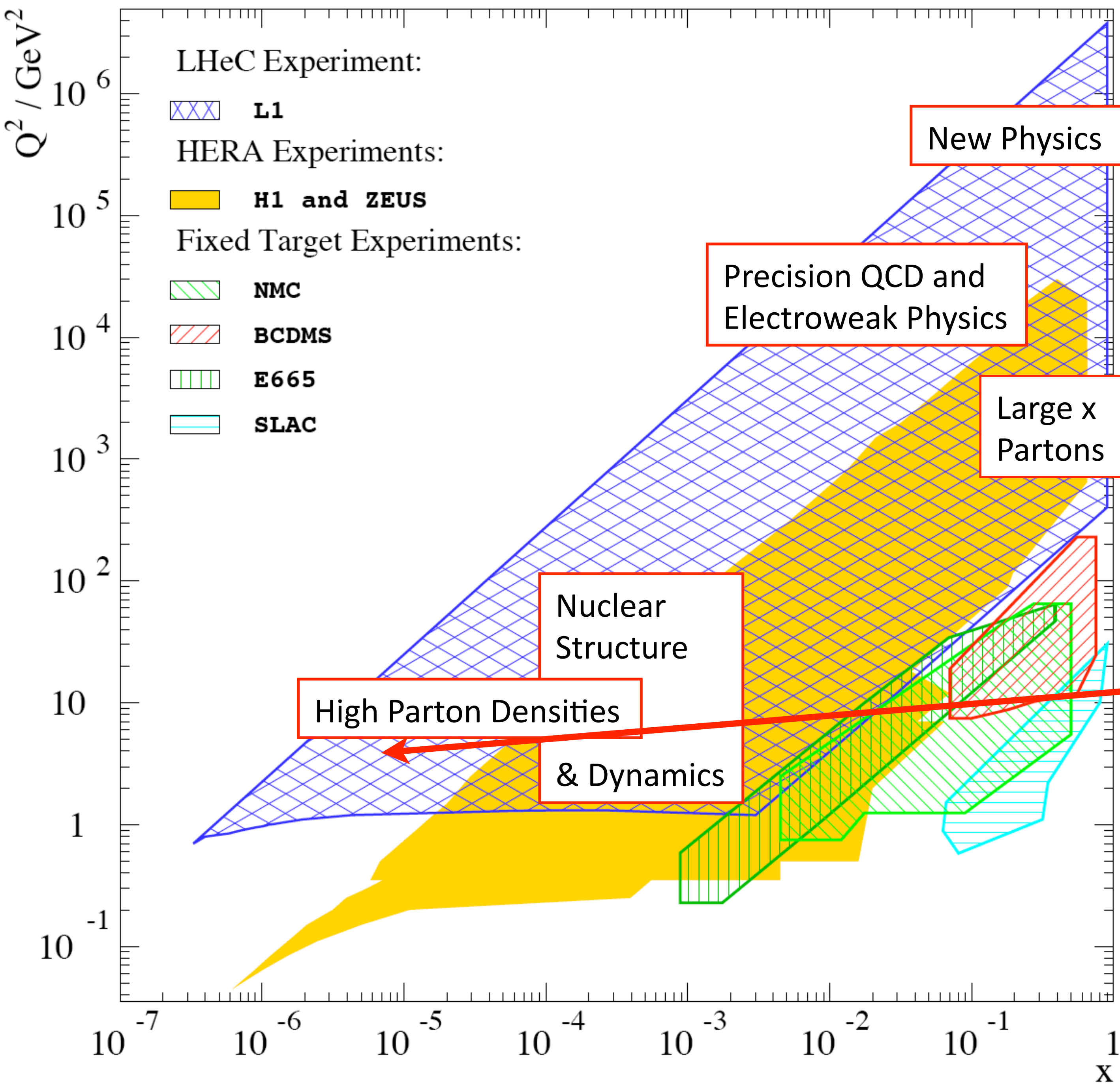
Project:

- **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.

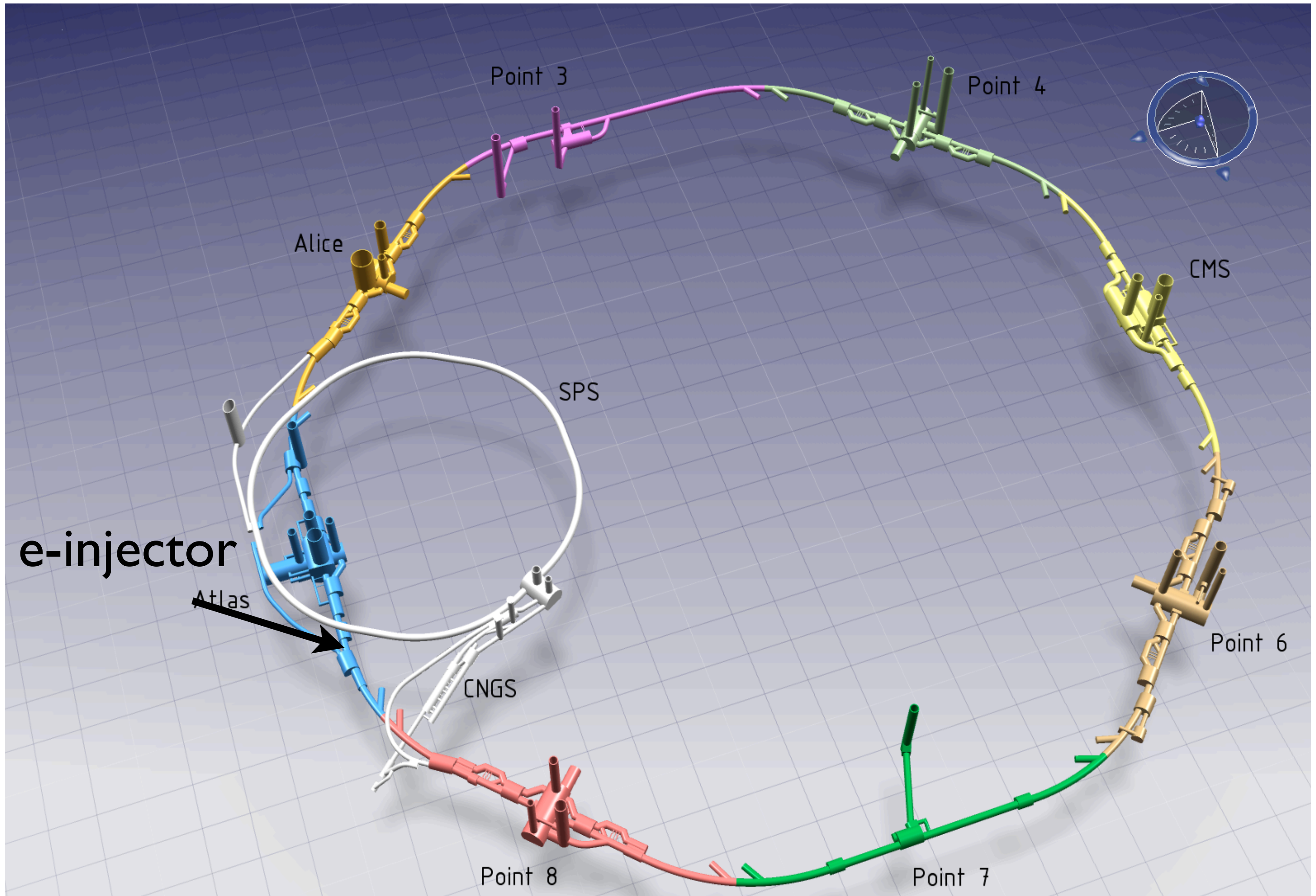


Physics goals:

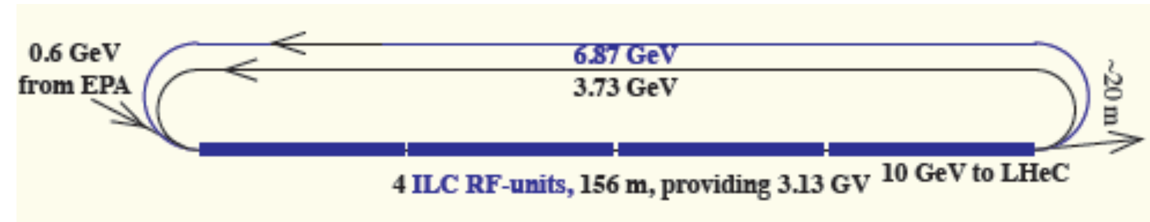


- Proton structure to a few 10^{-20} m: Q^2 lever arm.
- Precision QCD/EW physics.
- High-mass frontier (leptoquarks, excited fermions, contact interactions).
- Unambiguous access, in ep and eA, to a **qualitatively novel regime of matter predicted by QCD**.
- Substructure/parton dynamics inside nuclei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

The machine: Ring-Ring option

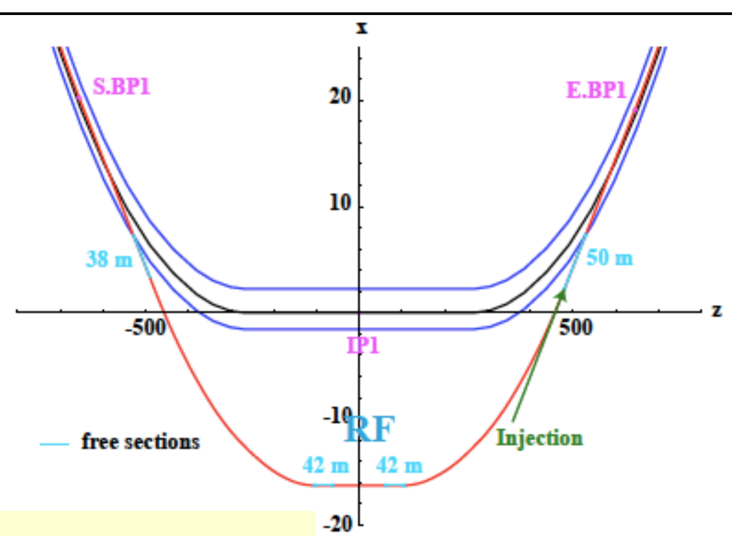


Preliminary; Fitterer@DIS11

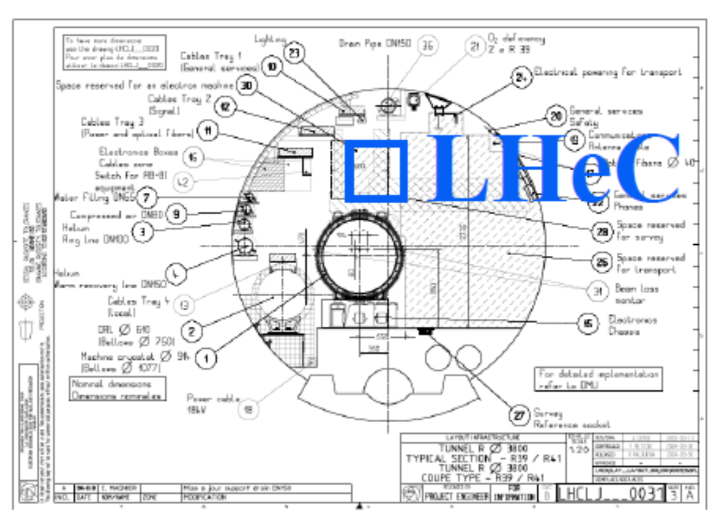


High Acceptance (1 Degree)

	Electrons	Protons
β_x	0.4 m	4.05 m
β_y	0.2 m	0.97 m
l*	6 m	22.96 m
σ_x	45 µm	
σ_y	22 µm	
Crossing angle	1 mrad	
Luminosity	$8.54\ 10^{32}$ cm^{-2} s^{-1}	
Luminosity loss factor	86%	
Luminosity	$7.33\ 10^{32}$ cm^{-2} s^{-1}	
P_γ	51 kW	
E_c	163 keV	



BYPASS

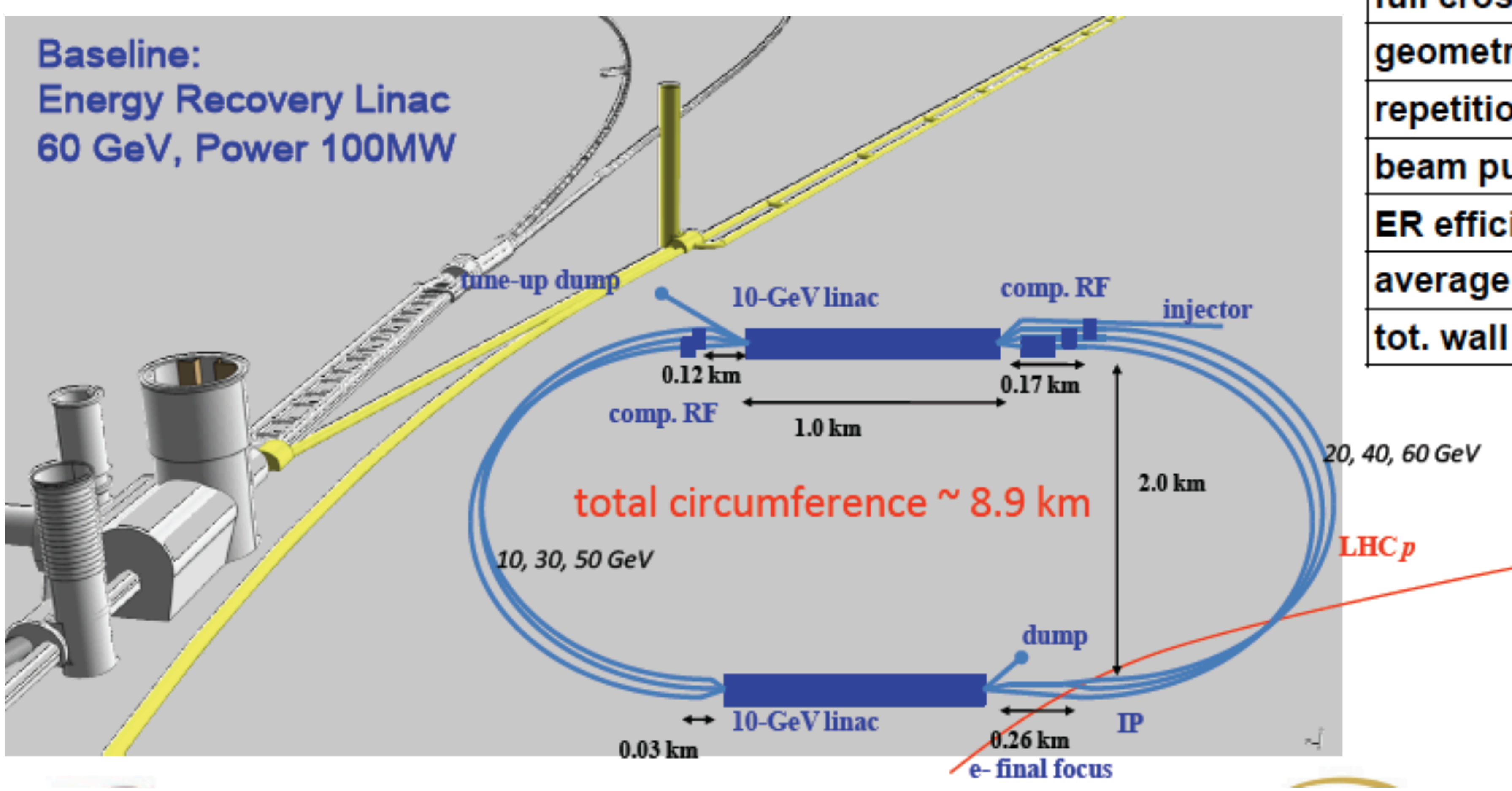


L-difference 1→10 degree < factor 2.
eA: $L_{en}\sim 10^{32}$ cm^{-2}s^{-1}.

The machine: Linac-Ring option

Preliminary; Bogacz@DIS11

electron beam	LR ERL	LR
e- energy at IP[GeV]	60	140
luminosity [10^{32} $cm^{-2}s^{-1}$]	10	0.44
polarization [%]	90	90
bunch population [10^9]	2.0	1.6
e- bunch length [mm]	0.3	0.3
bunch interval [ns]	50	50
transv. emit. $\gamma\varepsilon_{x,y}$ [mm]	0.05	0.1
rms IP beam size $\sigma_{x,y}$ [μm]	7	7
e- IP beta funct. $\beta^*_{x,y}$ [m]	0.12	0.14
full crossing angle [mrad]	0	0
geometric reduction H_{hg}	0.91	0.94
repetition rate [Hz]	N/A	10
beam pulse length [ms]	N/A	5
ER efficiency	94%	N/A
average current [mA]	6.6	5.4
tot. wall plug power[MW]	100	100

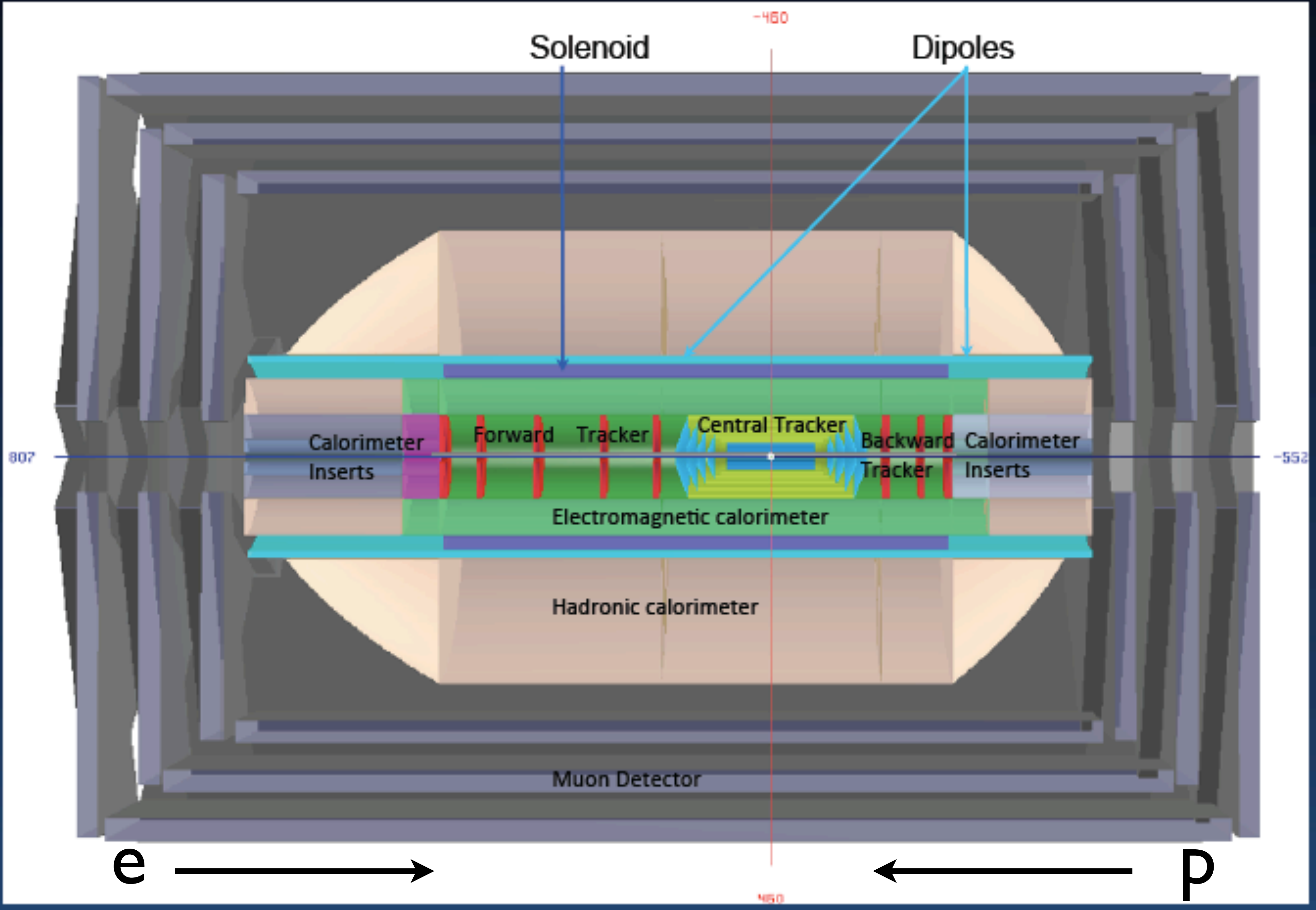


eA: L_{en} expected similar to RR.

The detector: low-x/eA setup

High Acceptance LR Option

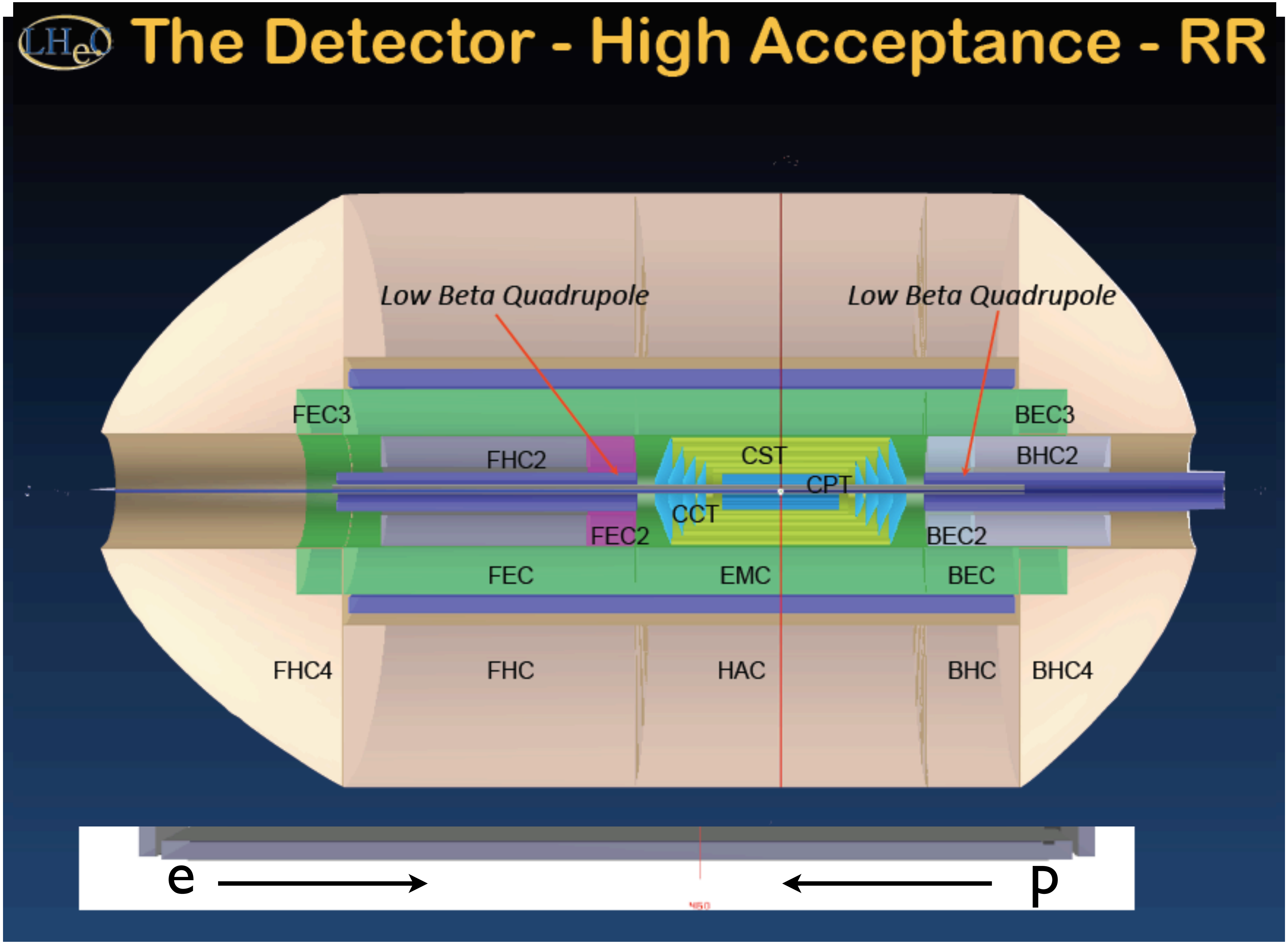
- Size of detector: 14 x 9m²



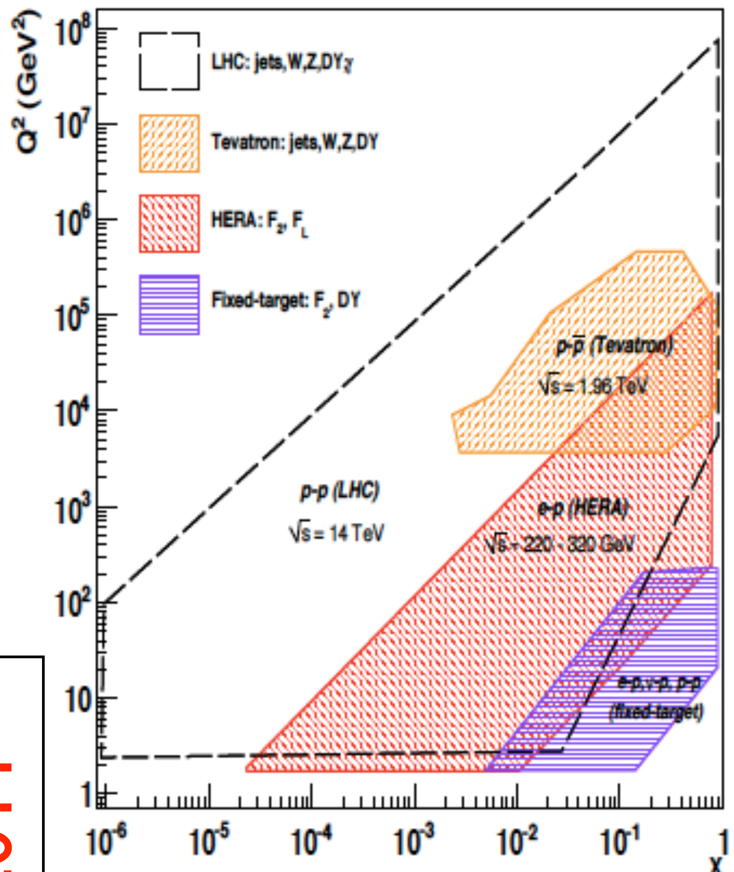
Preliminary; Kotska@DIS11

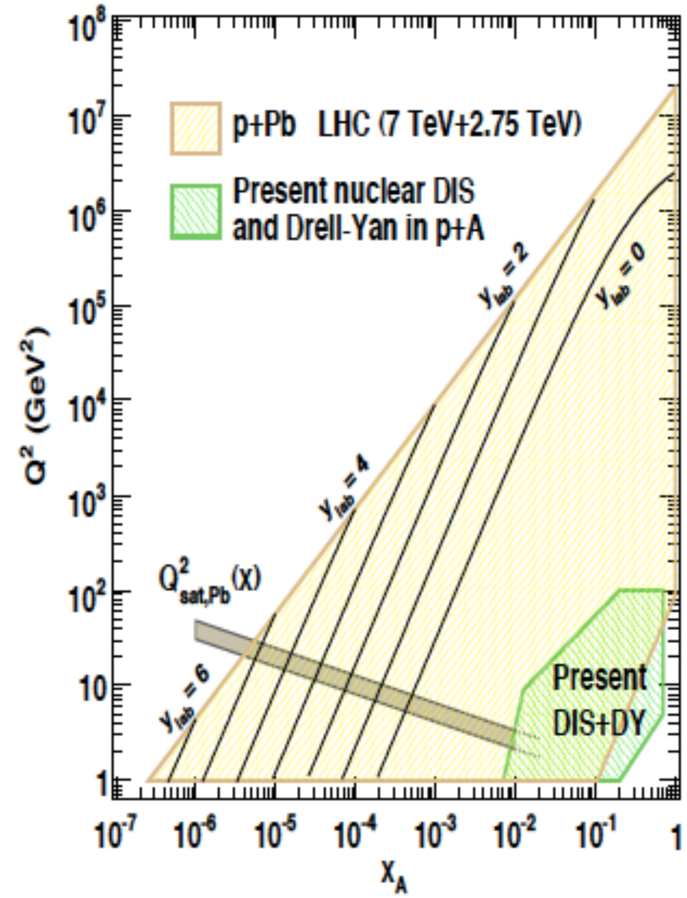
The detector: low-x/eA setup

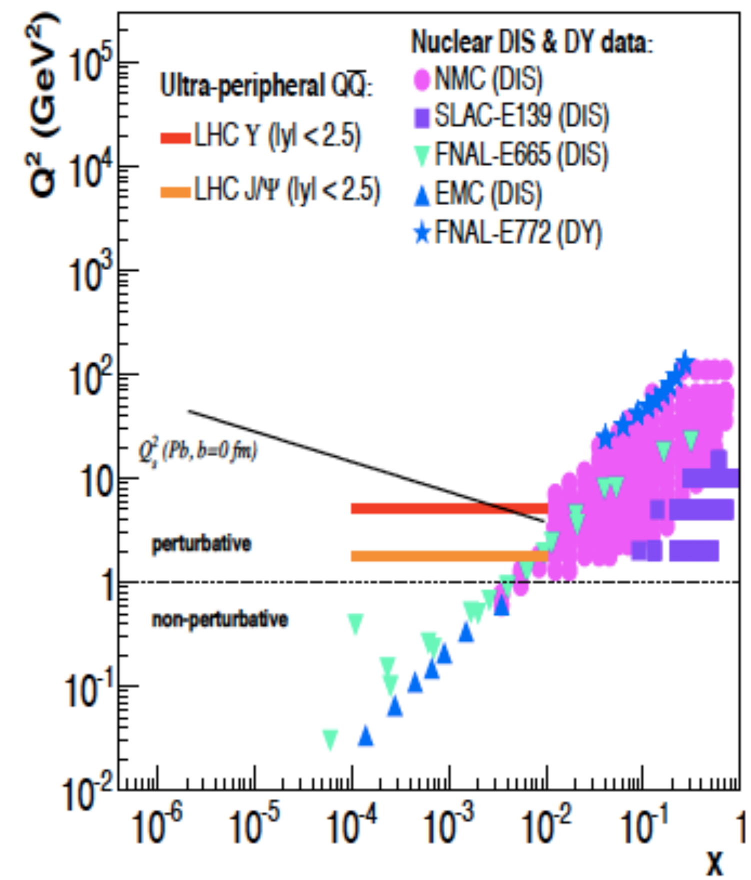
Preliminary; Kotska@DIS11



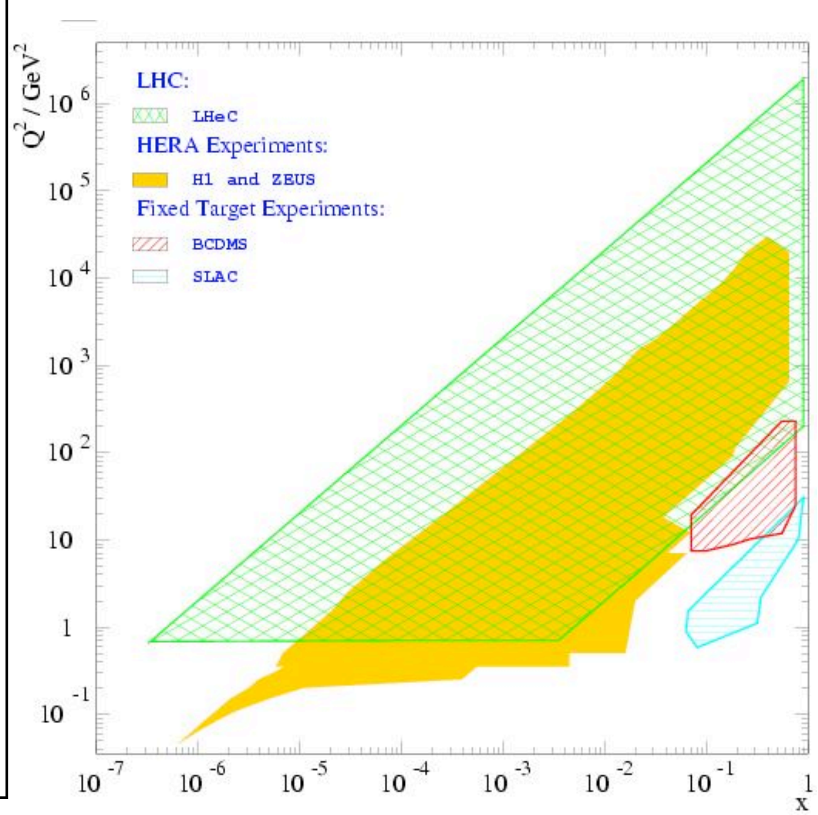
Kinematics: LHC vs. LHeC



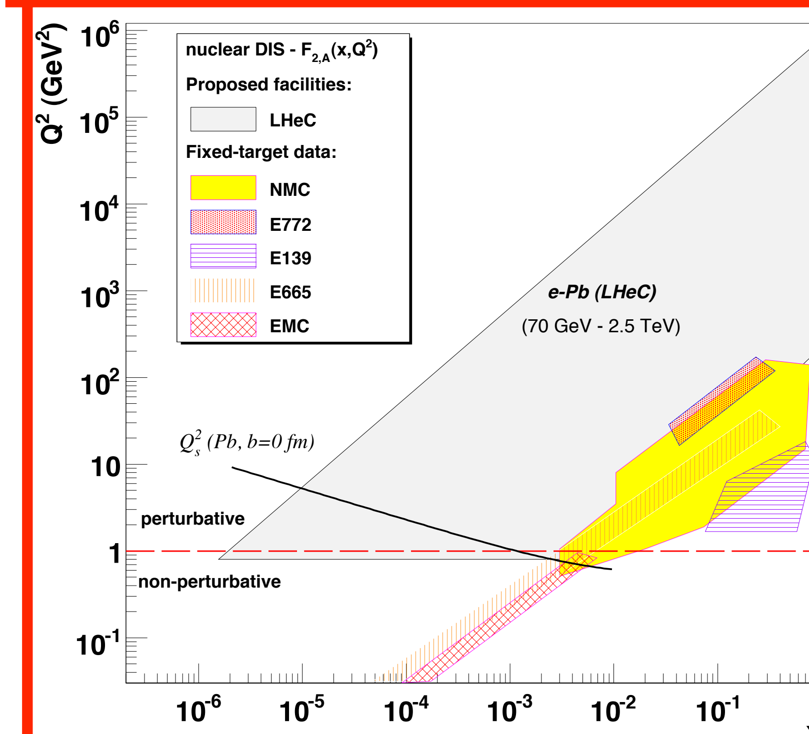




Preliminary; LHeC Design Study Report, CERN 2011



- Existing ep: pp@LHC at y=0; eA: not even dAu@RHIC.
- LHeC: clean scan of the LHC x-Q^2 domain.



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   - eA inclusive pseudodata and their effect on npdf's. (M. Klein, NA, H. Paukkunen, K. Eskola, C. A. Salgado)
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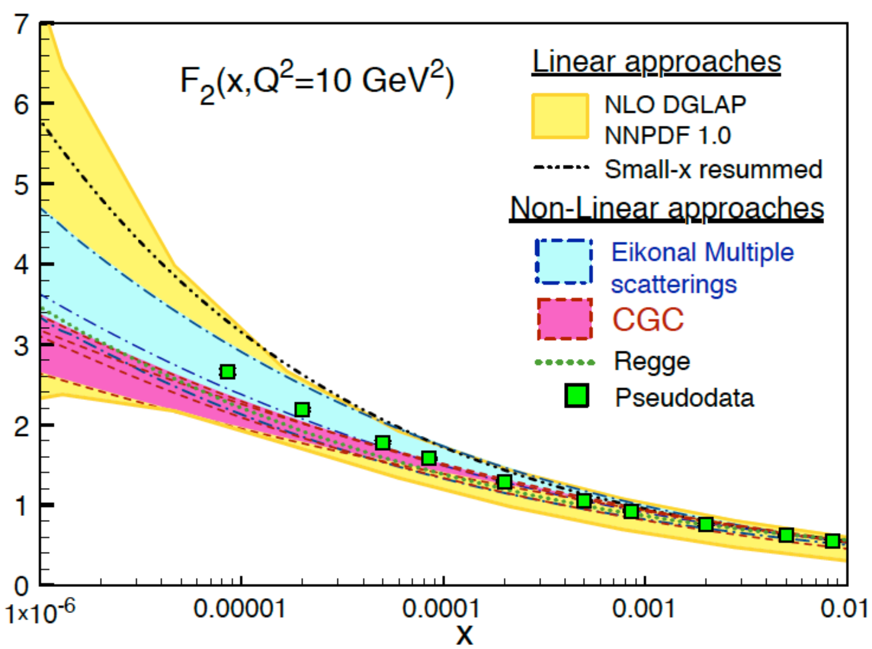
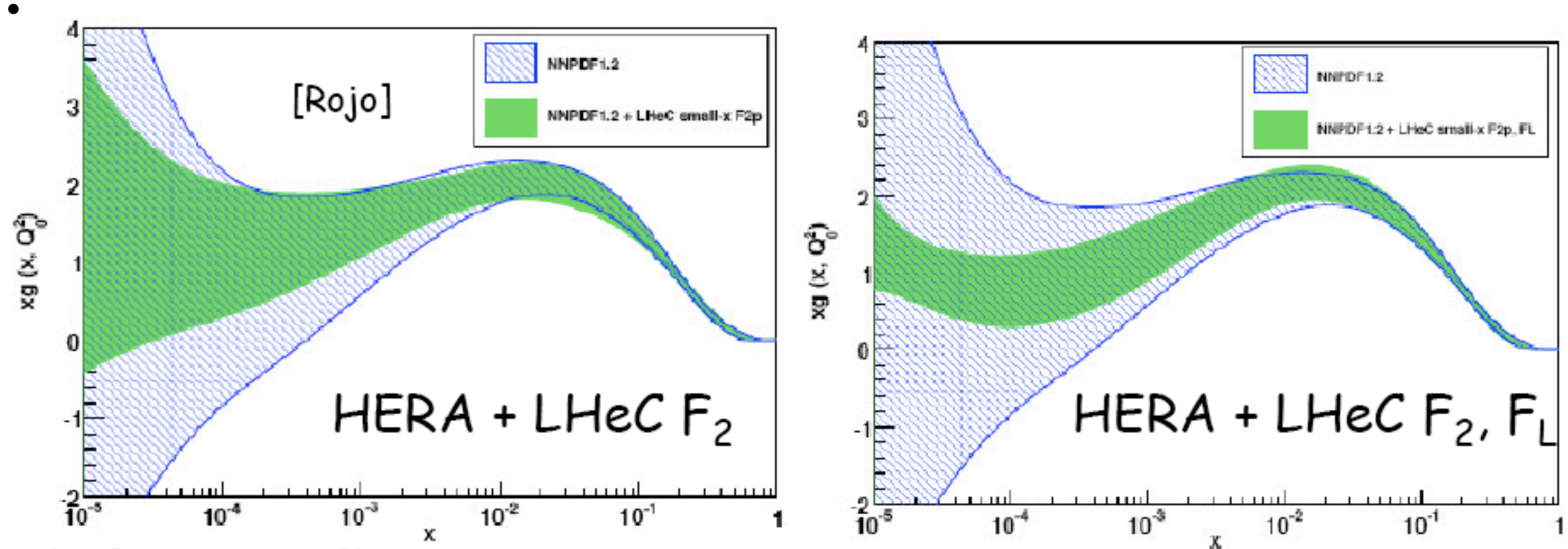
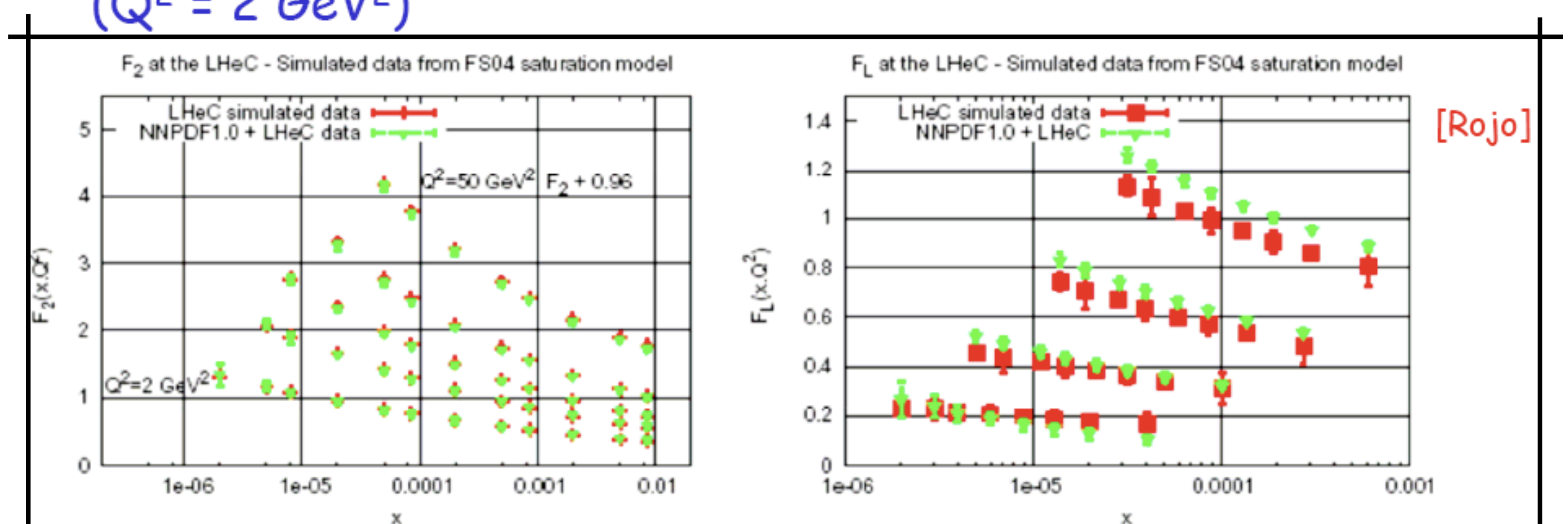
ep inclusive pseudodata:

- LHeC will have discriminative power on models.
- LHeC substantially reduces the uncertainties in global fits: F_L and heavy flavor decomposition most useful.
- Tension between F_2 and F_L in DGLAP fits as a sign of physics beyond standard DGLAP.





(Q^2 = 2 GeV^2)



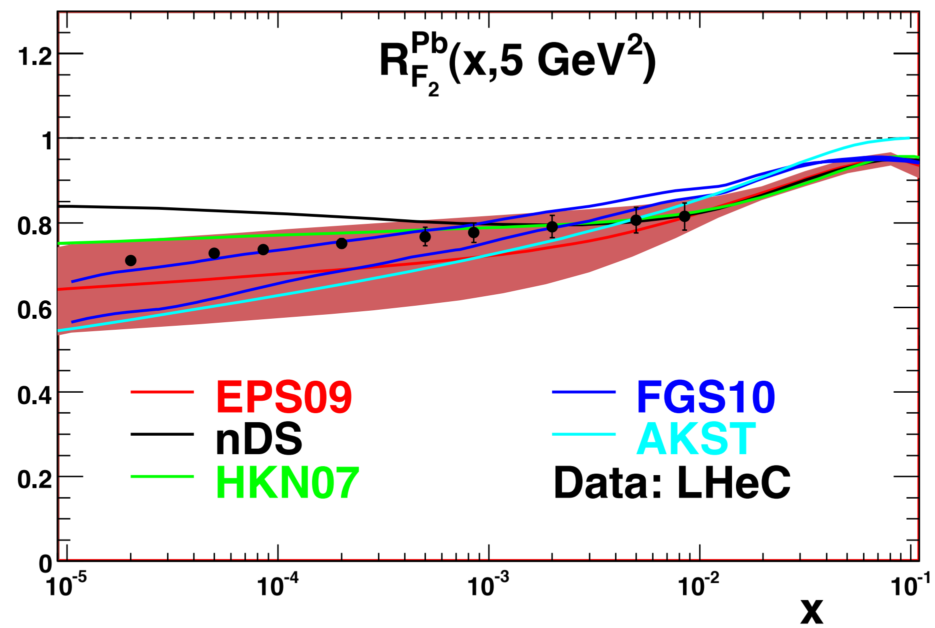
Preliminary; LHeC Design Study Report, CERN 2011

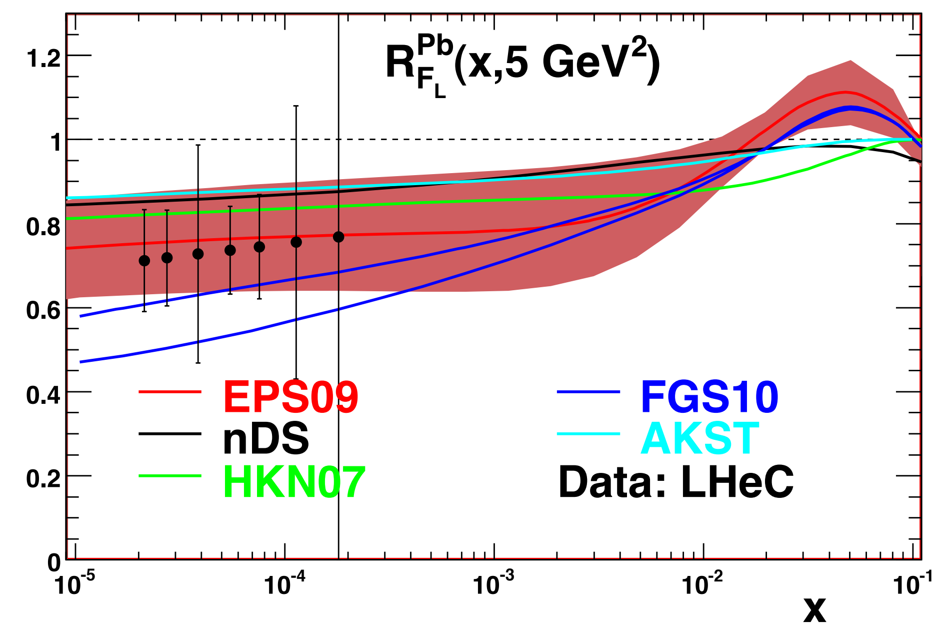
eA inclusive pseudodata (I):

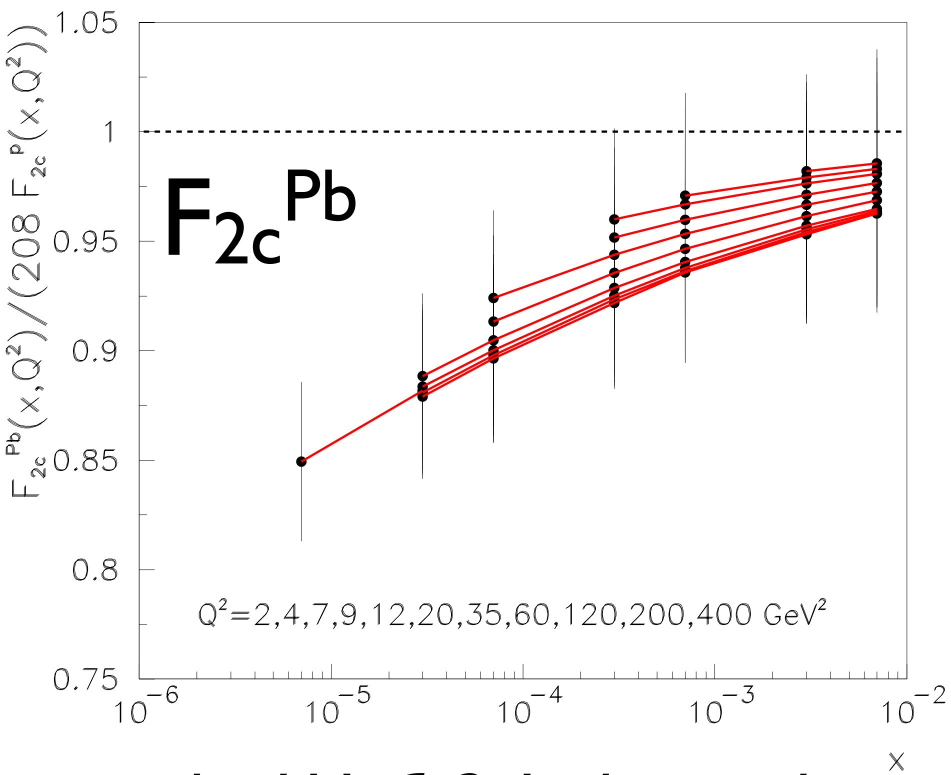
- Good precision can be obtained for $F_{2(c,b)}$ and F_L at small x

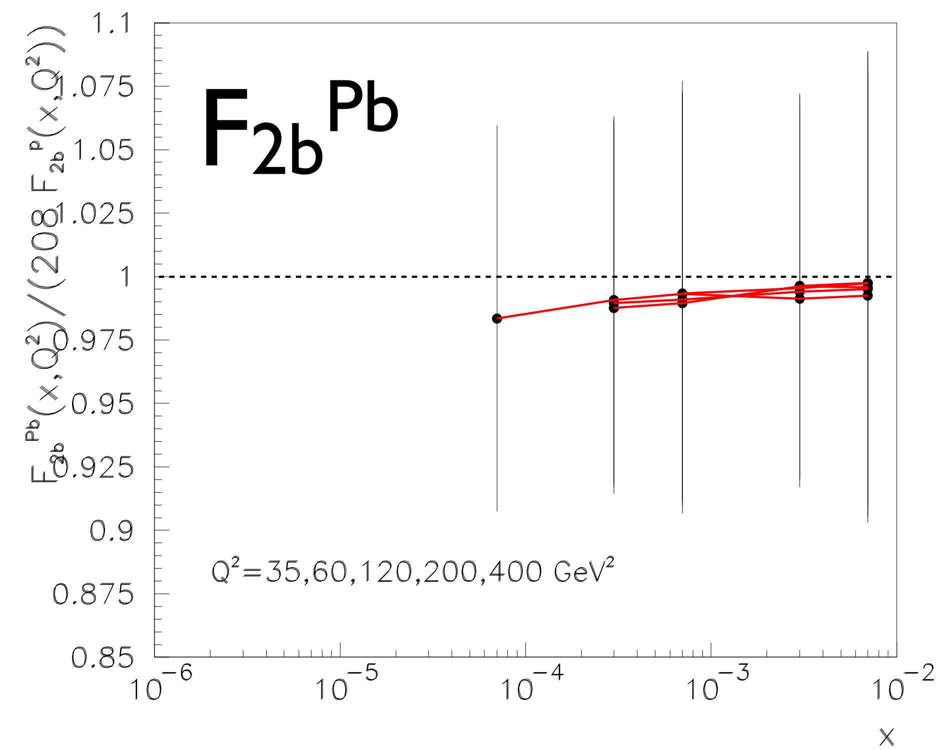
(Glauberized 3-5 flavor GBW model, NA ’02).

Preliminary; LHeC Design Study Report, CERN 2011



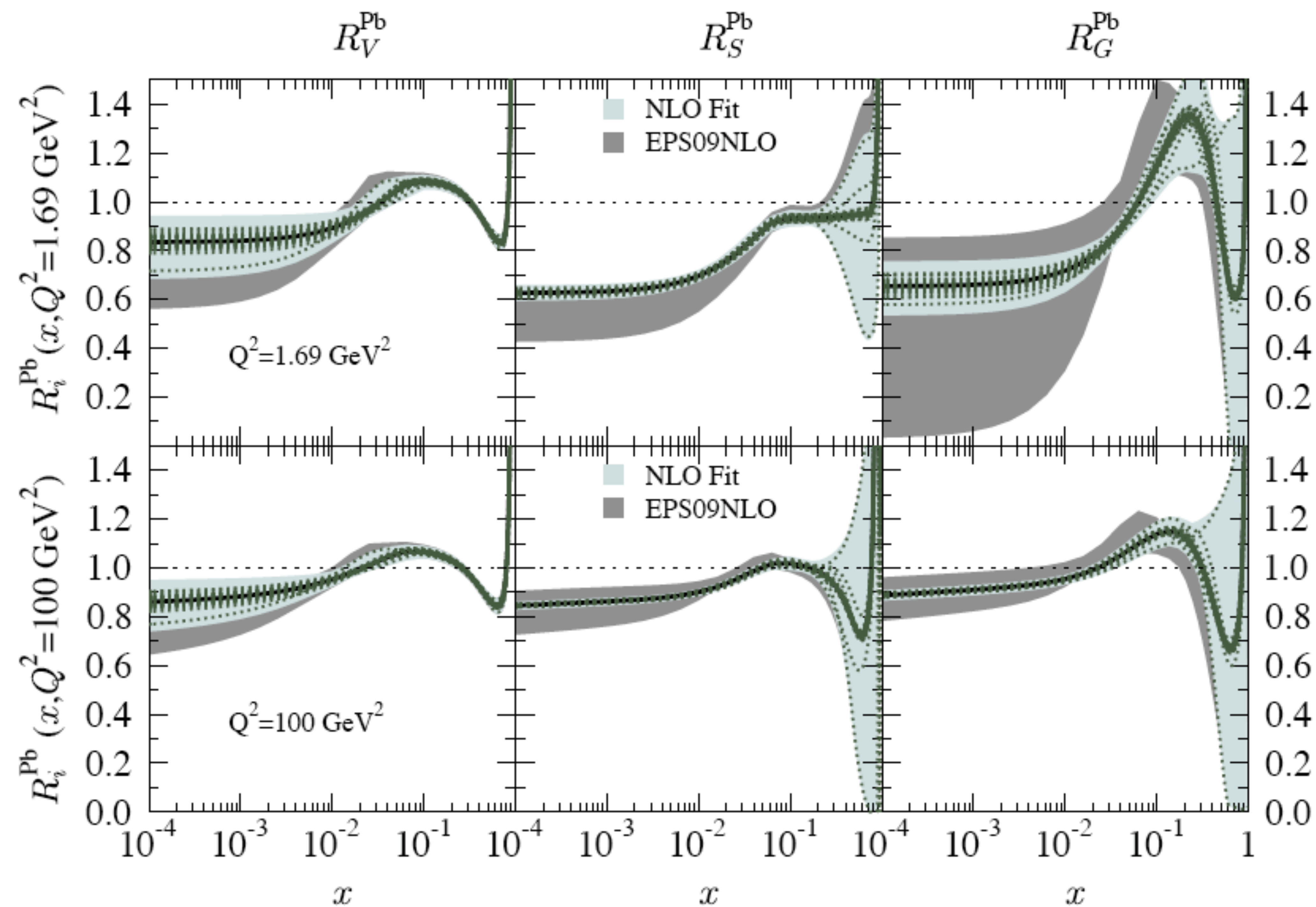






eA inclusive pseudodata (II):

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



Preliminary; LHeC Design Study Report, CERN 2011

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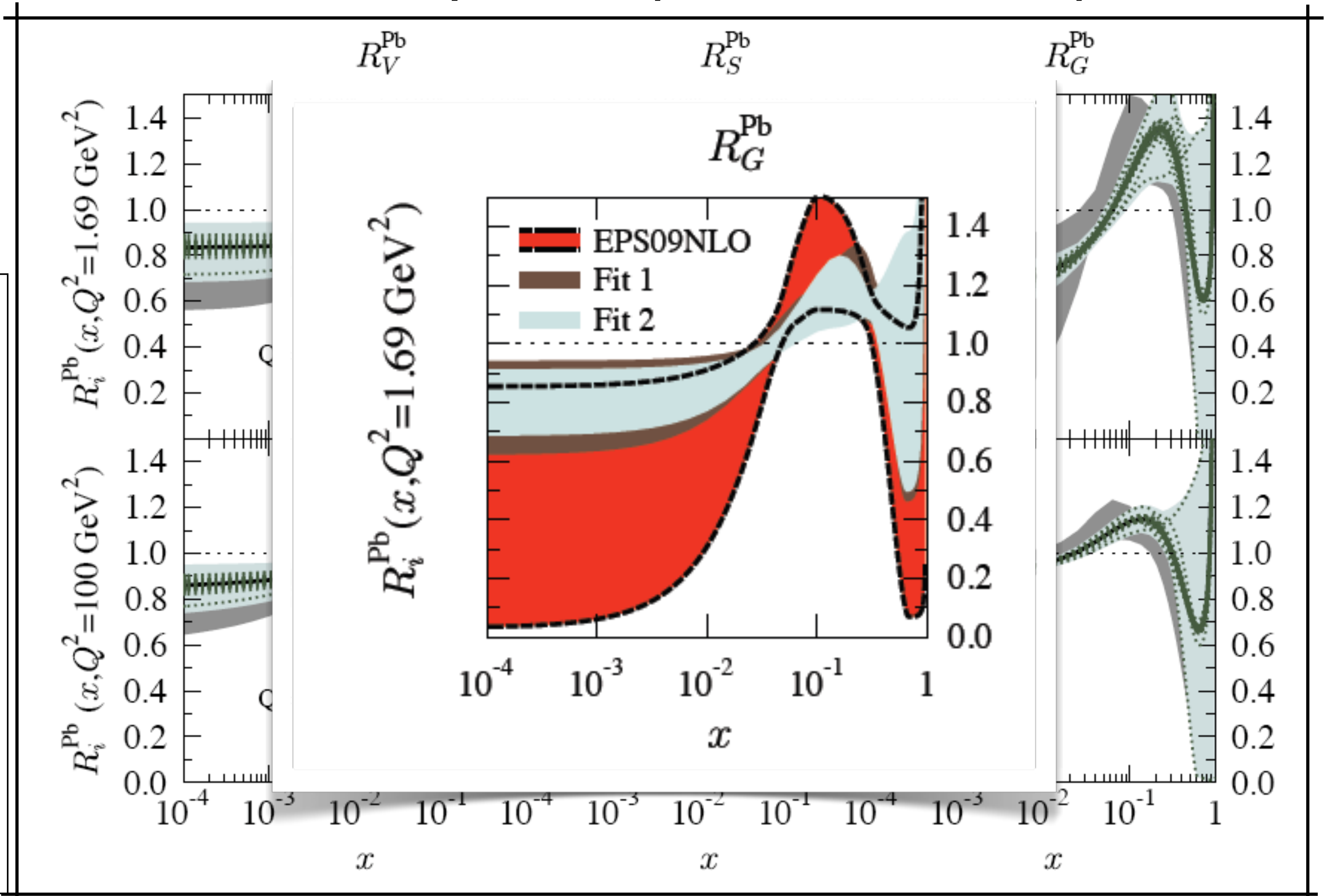

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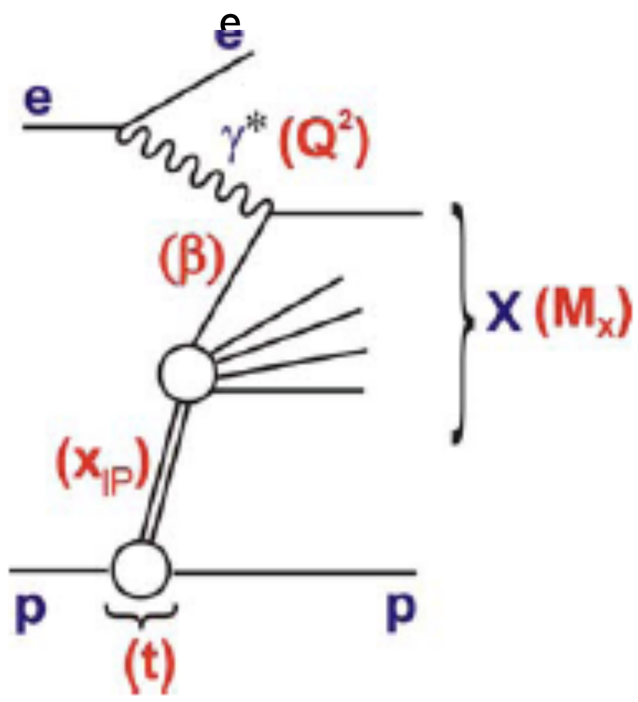
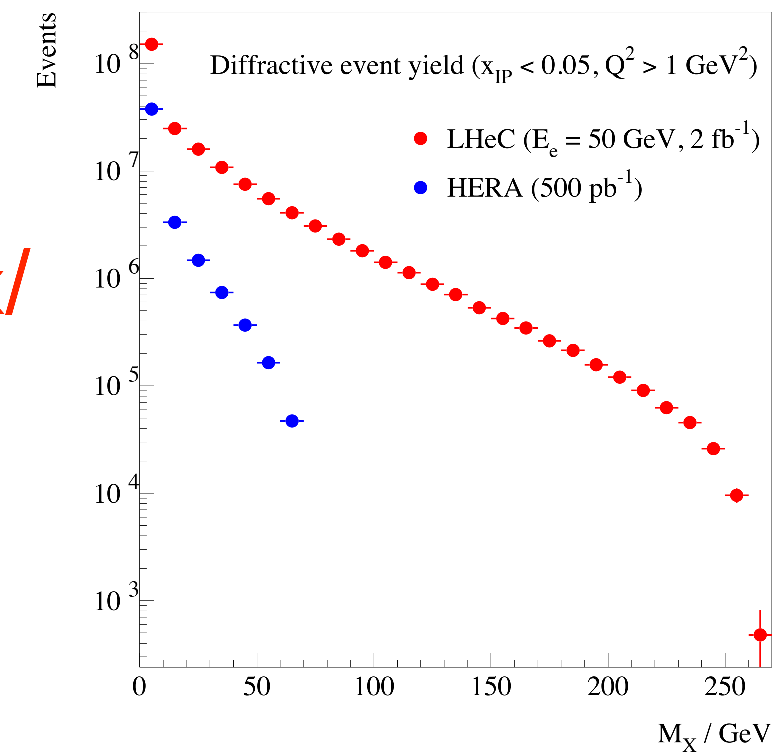
ep diffractive pseudodata:

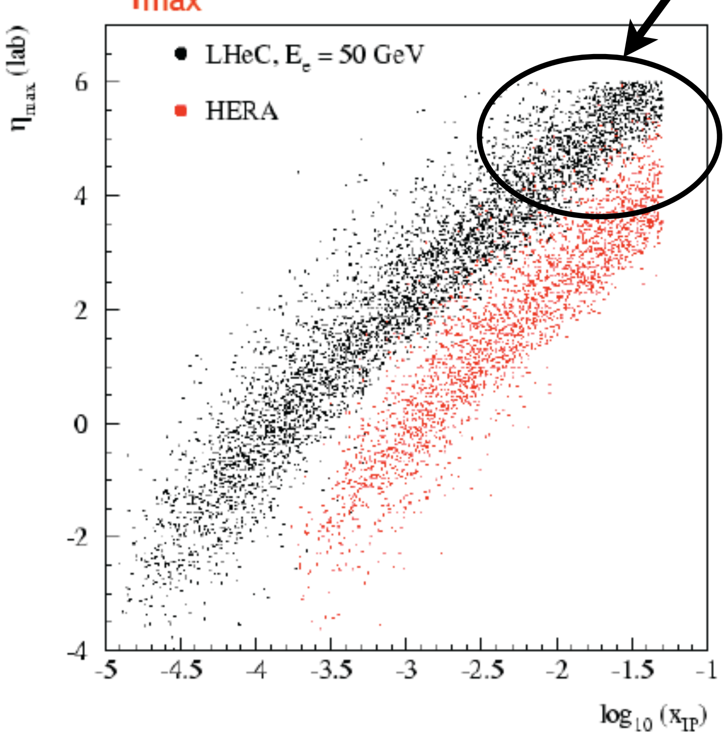


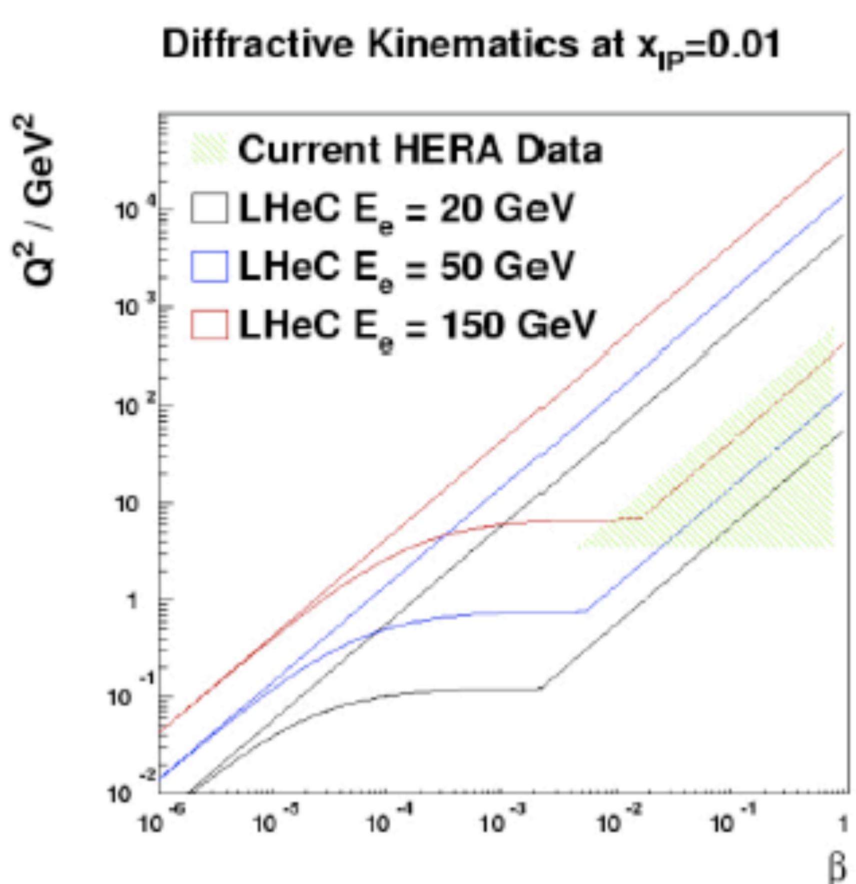
- Large increase in the M^2, $x_P=(M^2-t+Q^2)/(W^2+Q^2)$, $\beta=x/x_P$ region studied.
- Possibility to combine LRG and LPS.

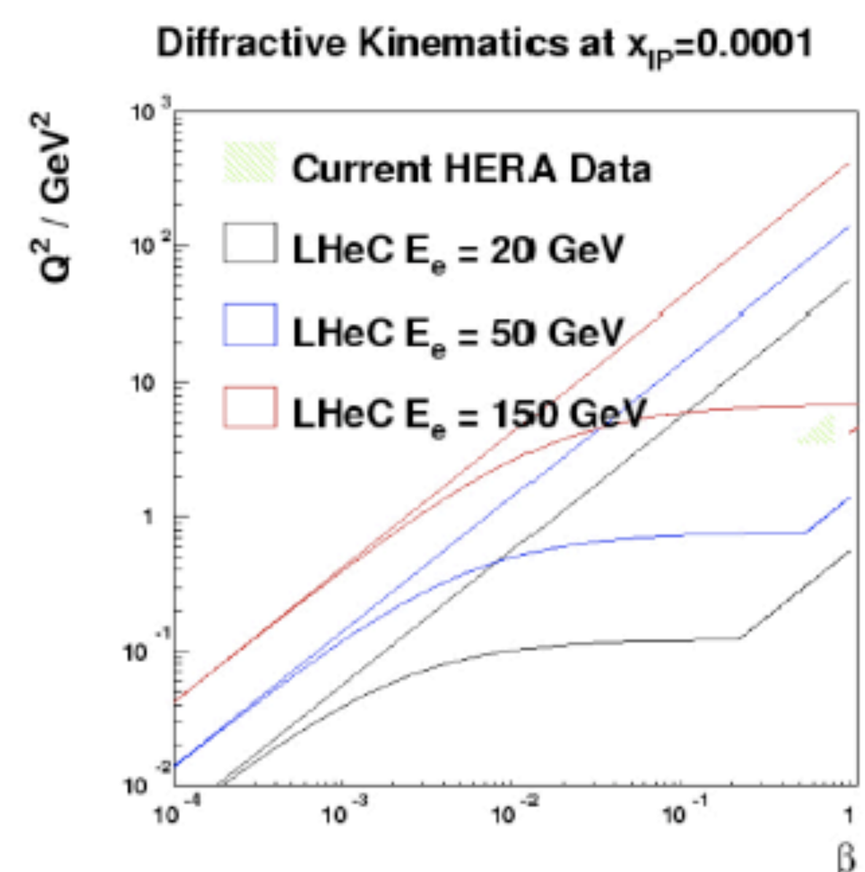


Preliminary; LHeC Design Study Report, CERN 2011

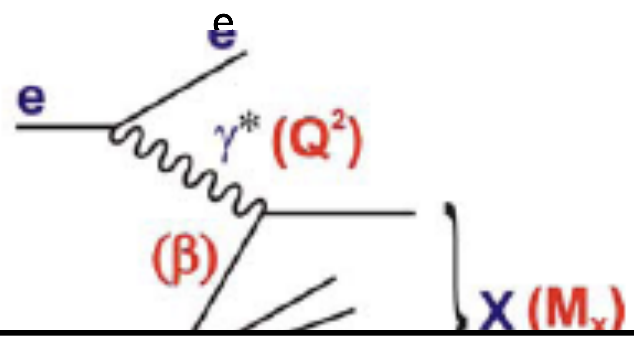
η_{max} from LRG selection ..



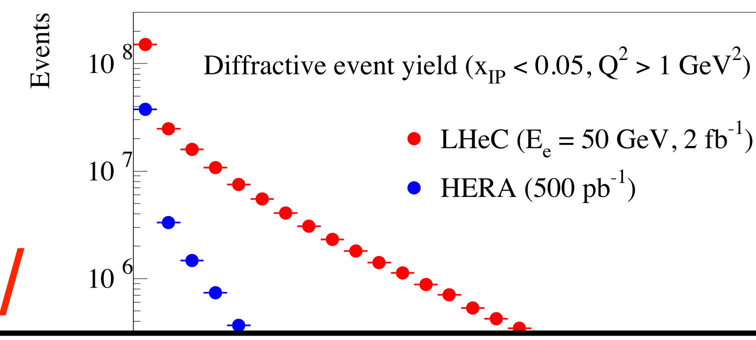




ep diffractive pseudodata:

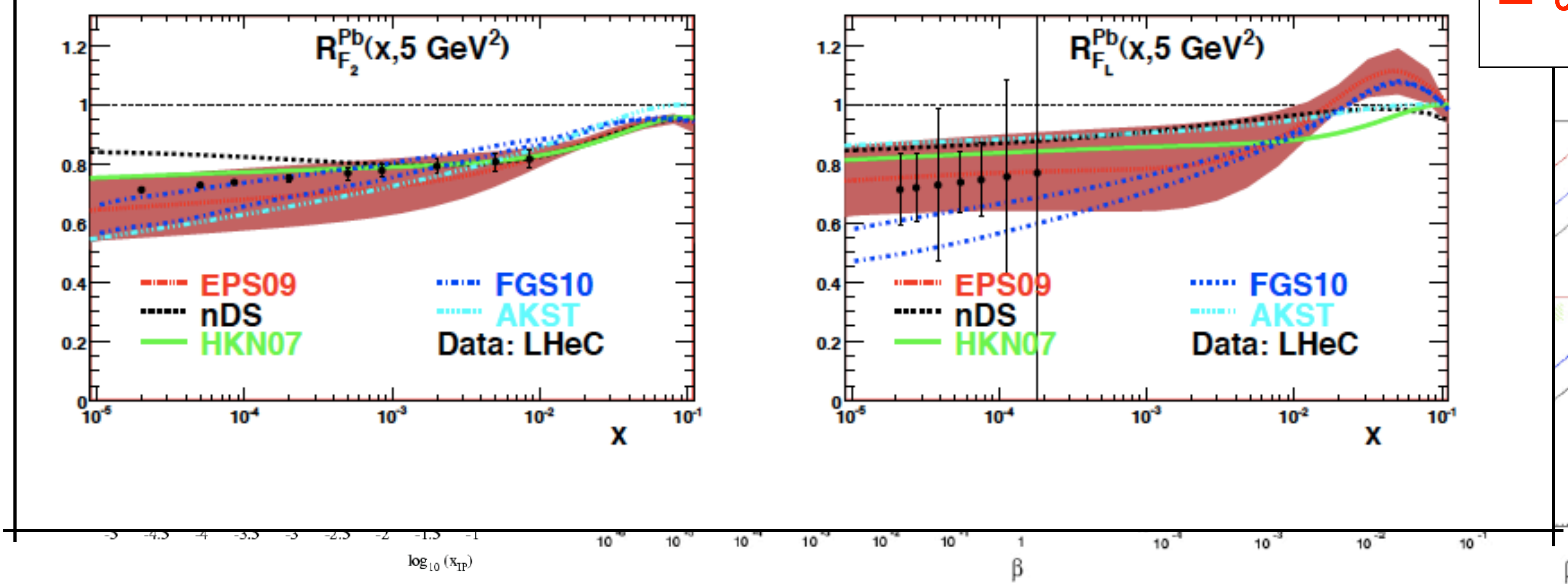


- Large increase in the M^2, $x_P=(M^2-t+Q^2)/(W^2+Q^2)$, $\beta=x/$



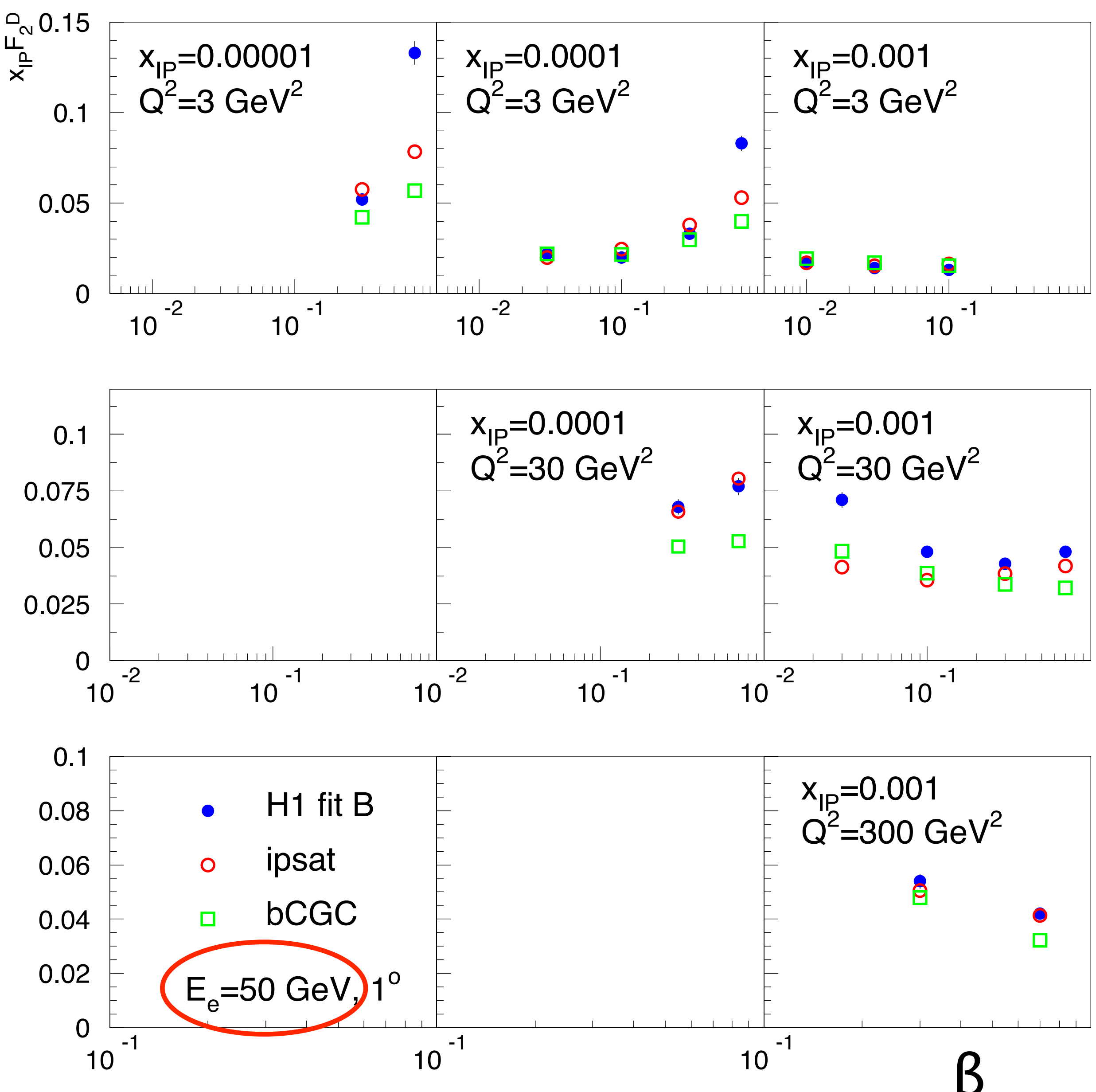
Preliminary; LHeC Design Study Report, CERN 2011

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

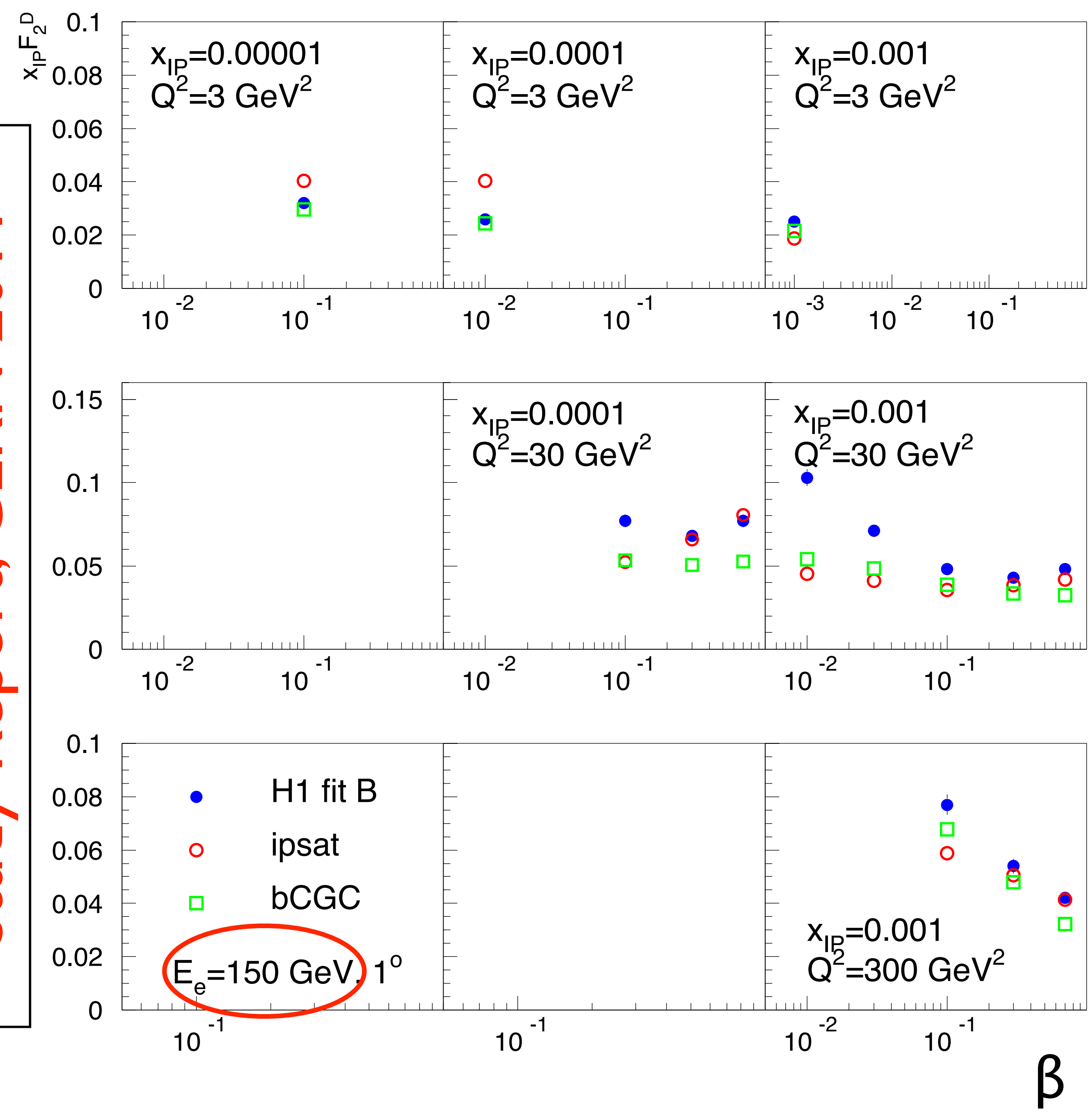


LHeC Diffraction and non-linear dynamics:

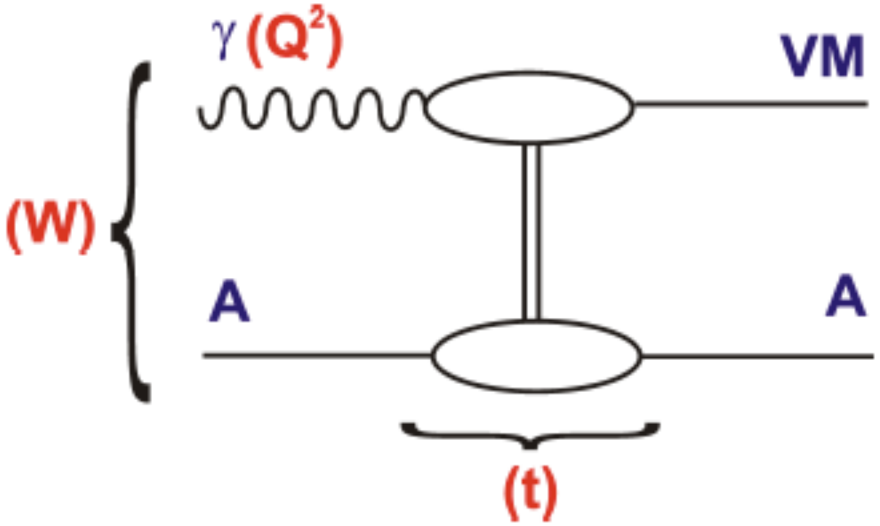
- Dipole models show differences with linear-based extrapolations (HERA-based ddpdf's) and among each other: possibility to check saturation and its realization.

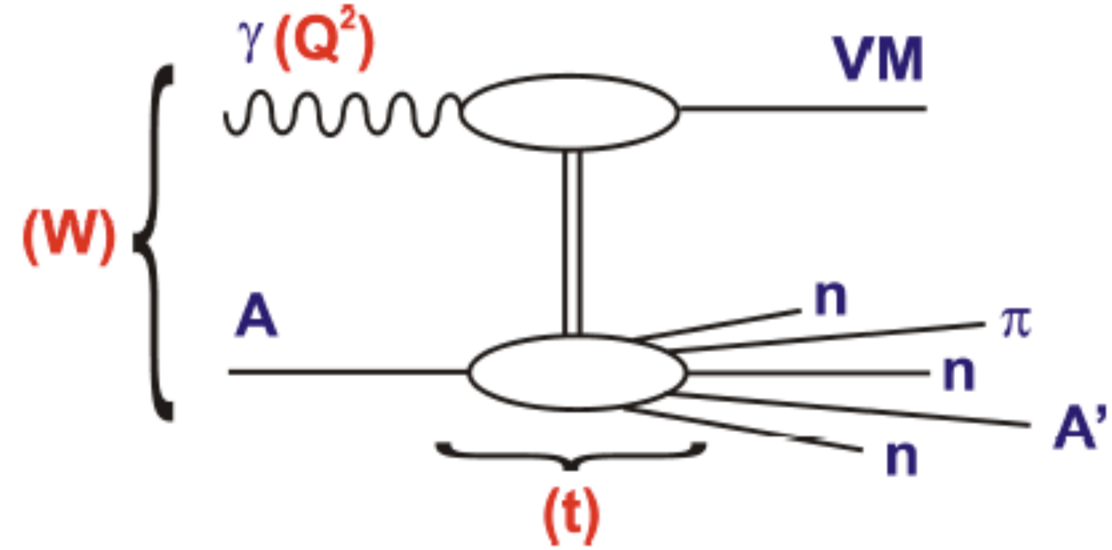


Preliminary; LHeC Design Study Report, CERN 2011



Diffractive DIS on nuclear targets:

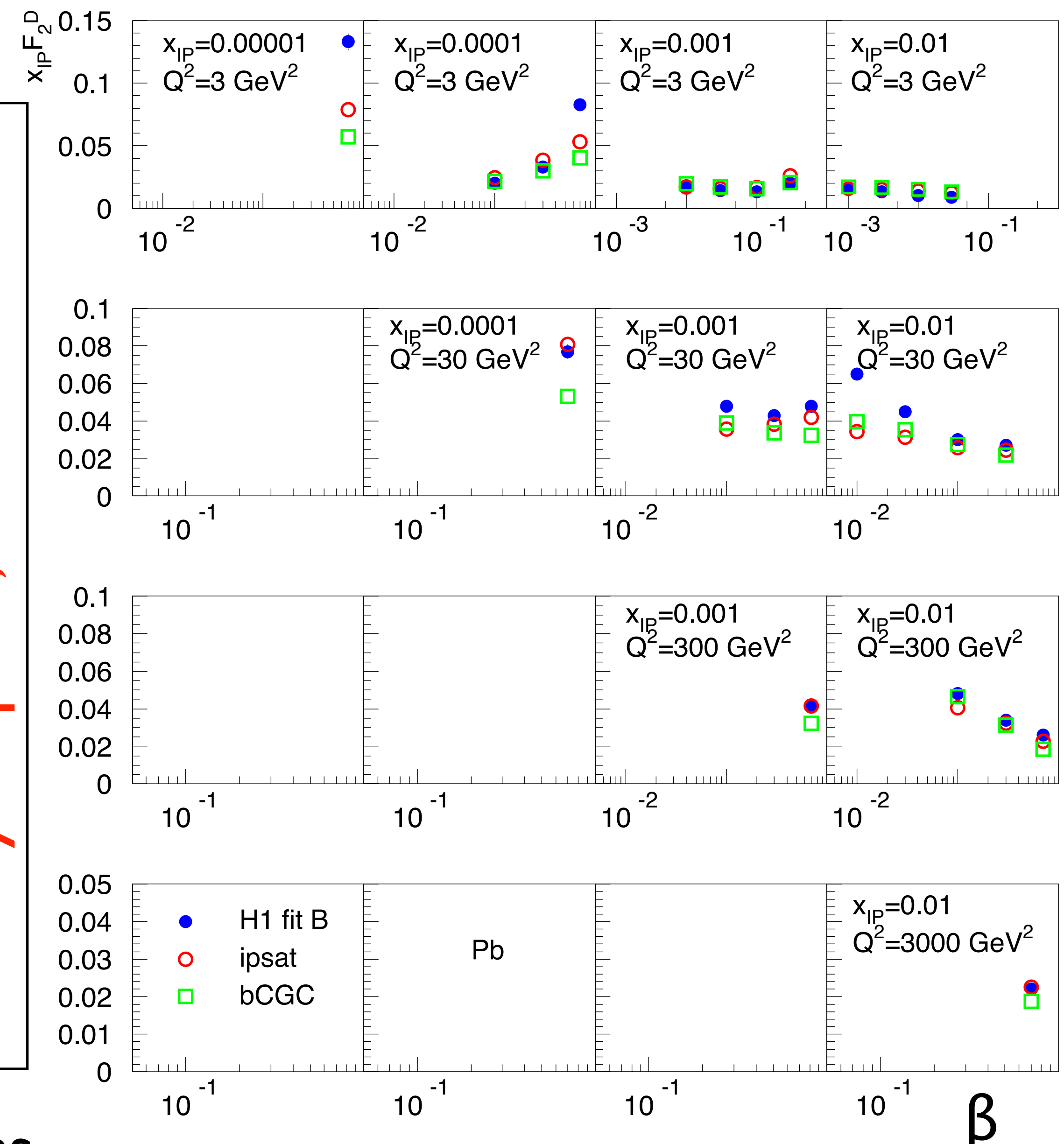




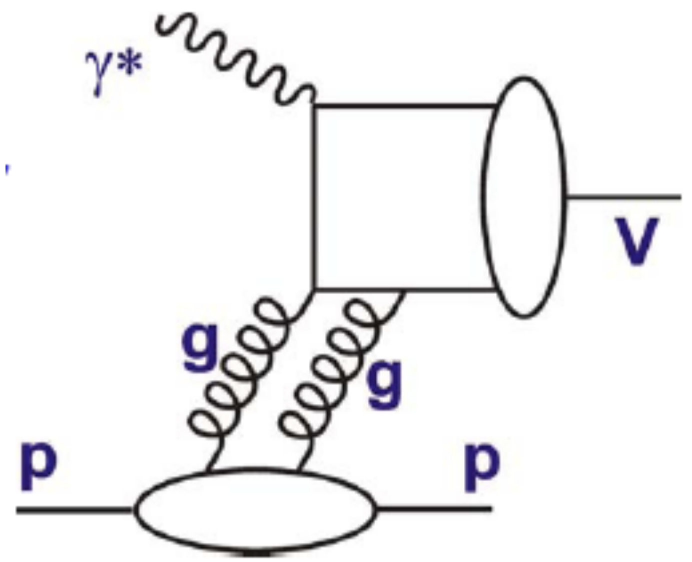
- Challenging experimental problem, requires Monte Carlo simulation with detailed understanding of the nuclear break-up.

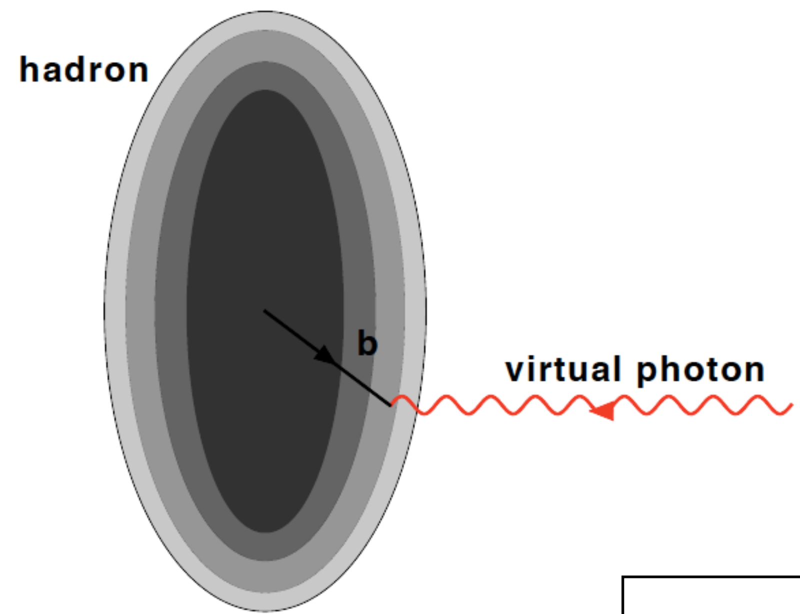
- For the coherent case, predictions available.

Preliminary; LHeC Design Study Report, CERN 2011

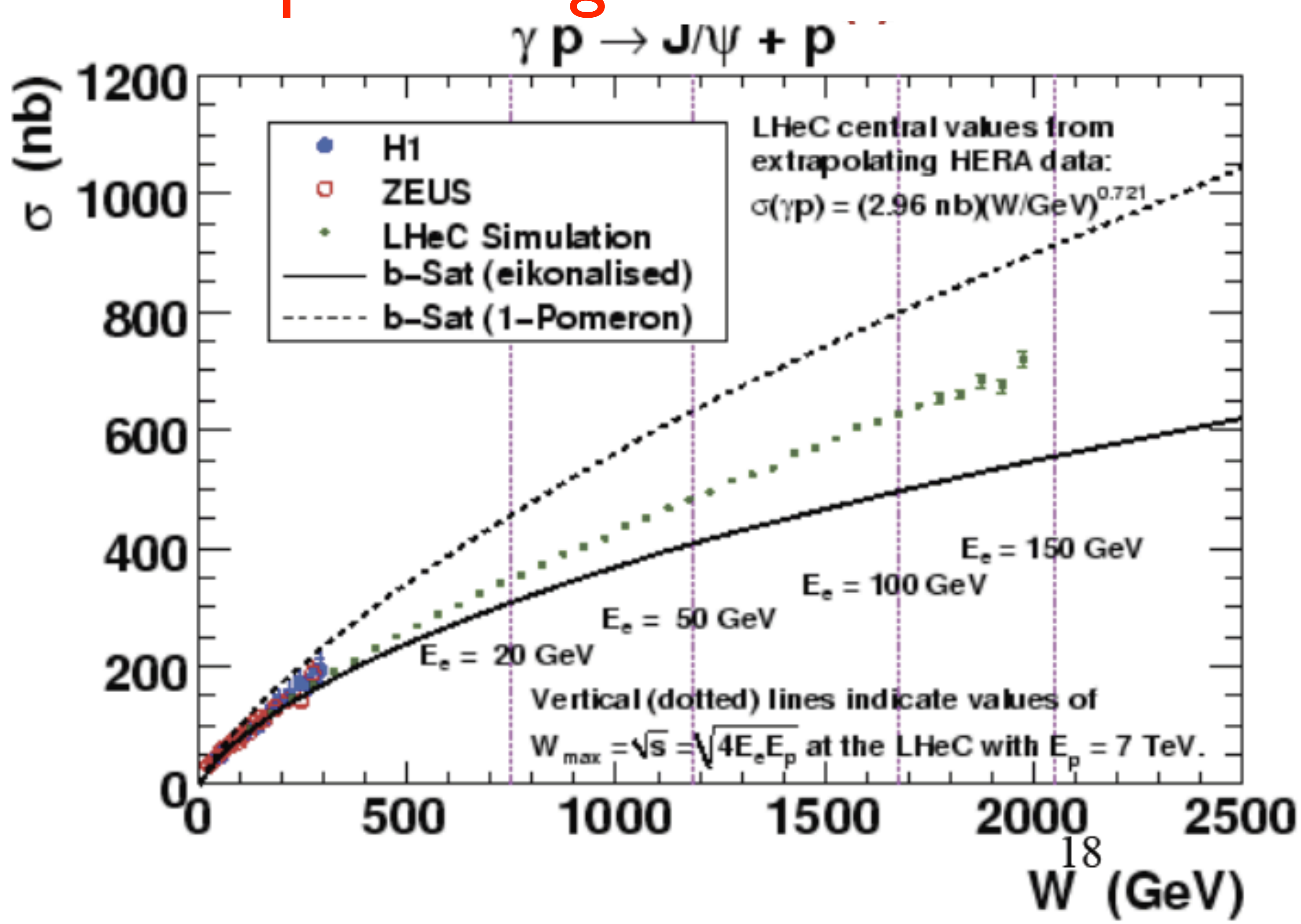


Elastic VM production (I):





- Most promising!!!



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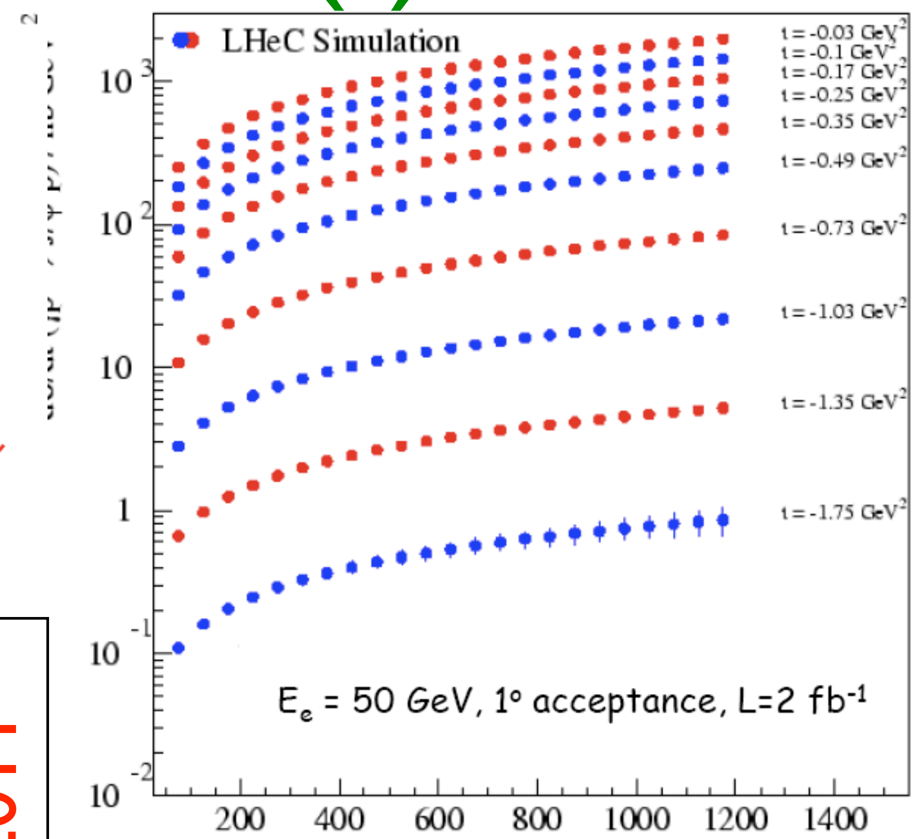
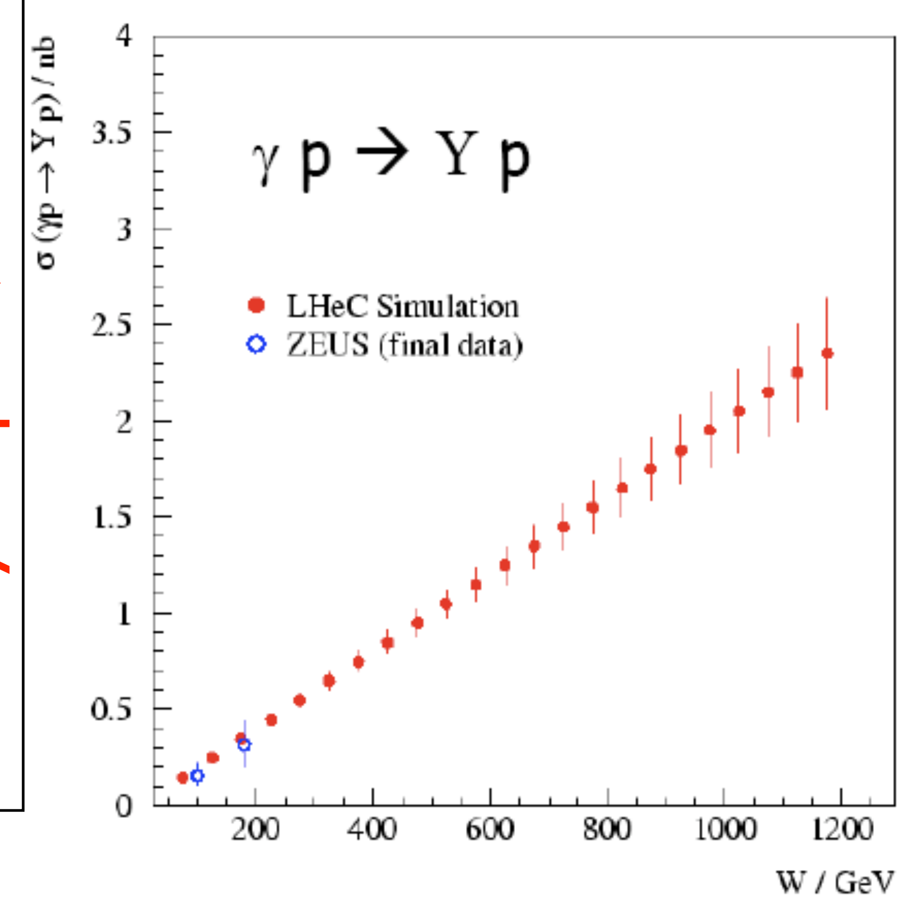


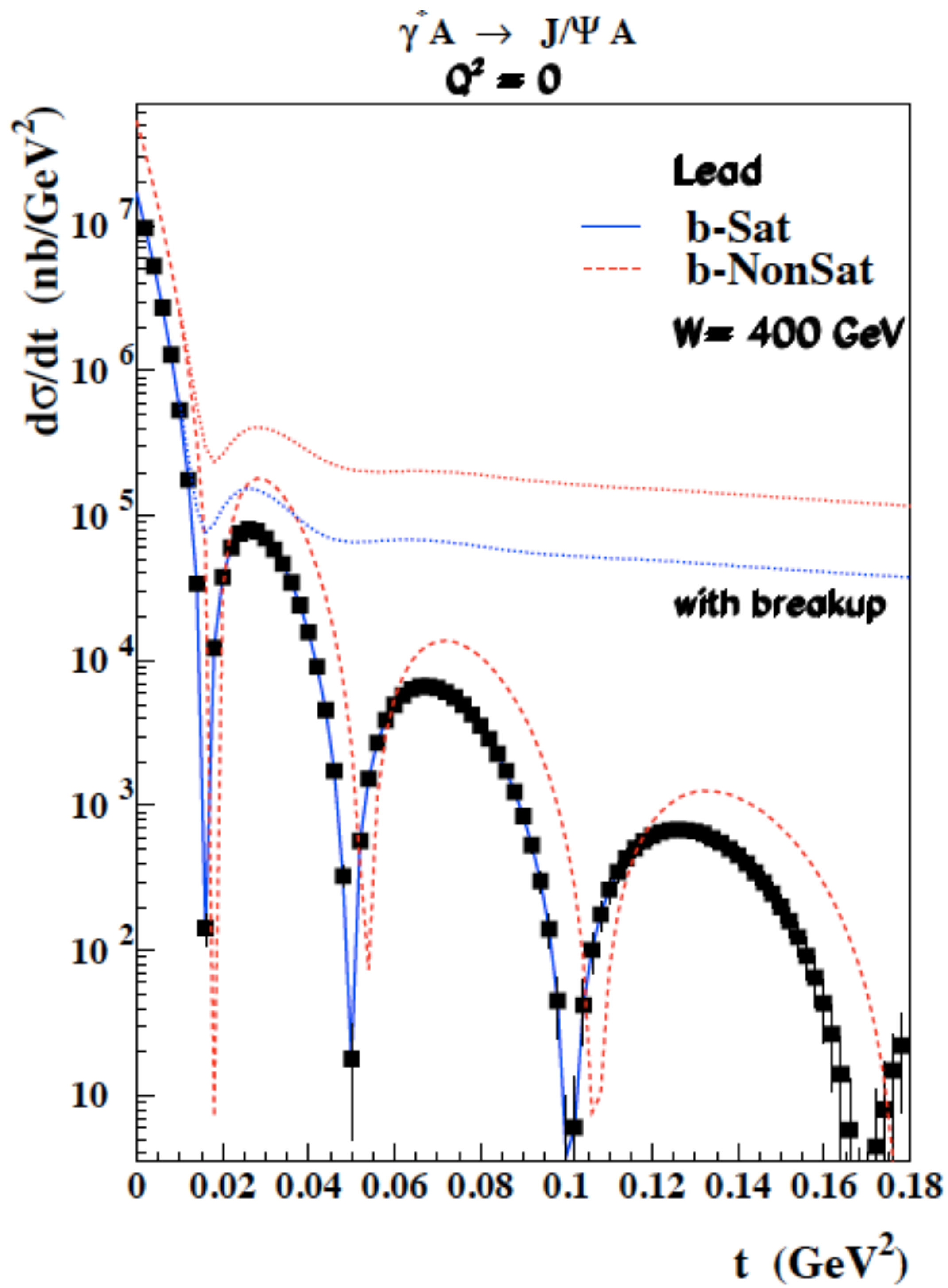


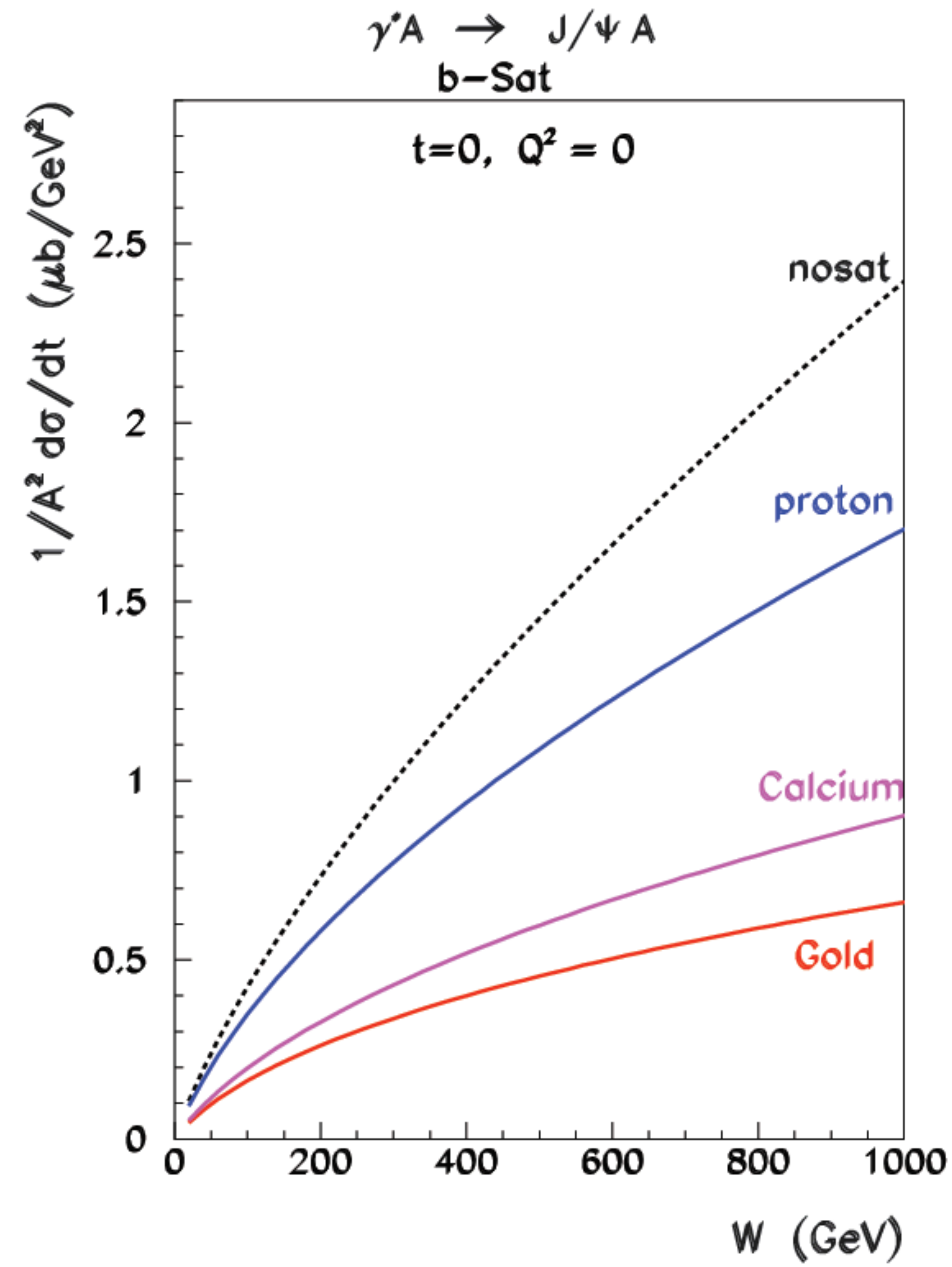
Elastic VM production (II):

- Many interesting features in the nuclear case

(see also Lappi et al '10, Horowitz '11).

Preliminary; LHeC Design Study Report, CERN 2011



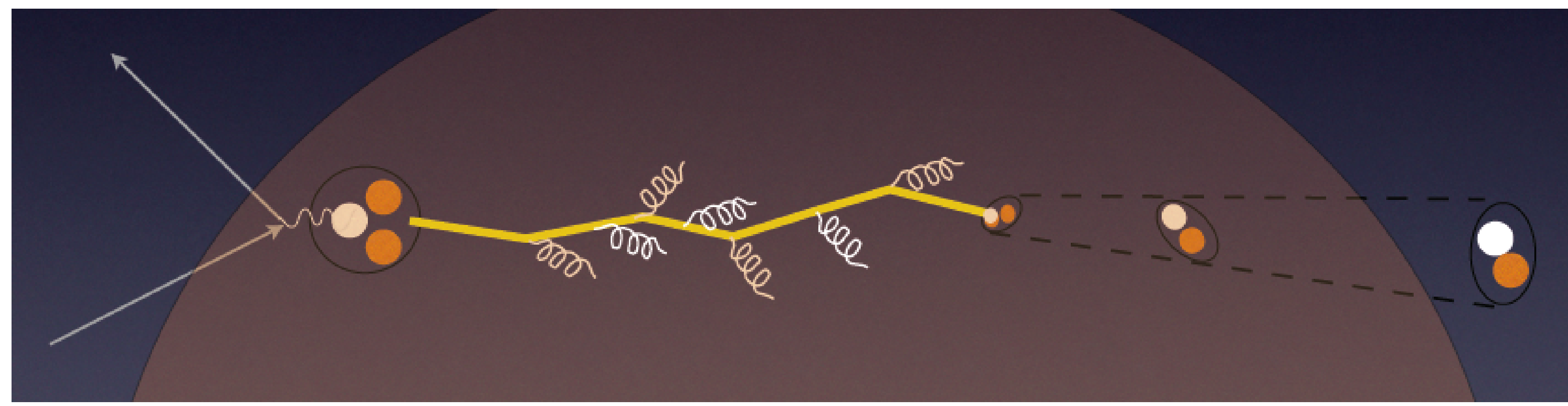


Contents:

In-medium hadronization:

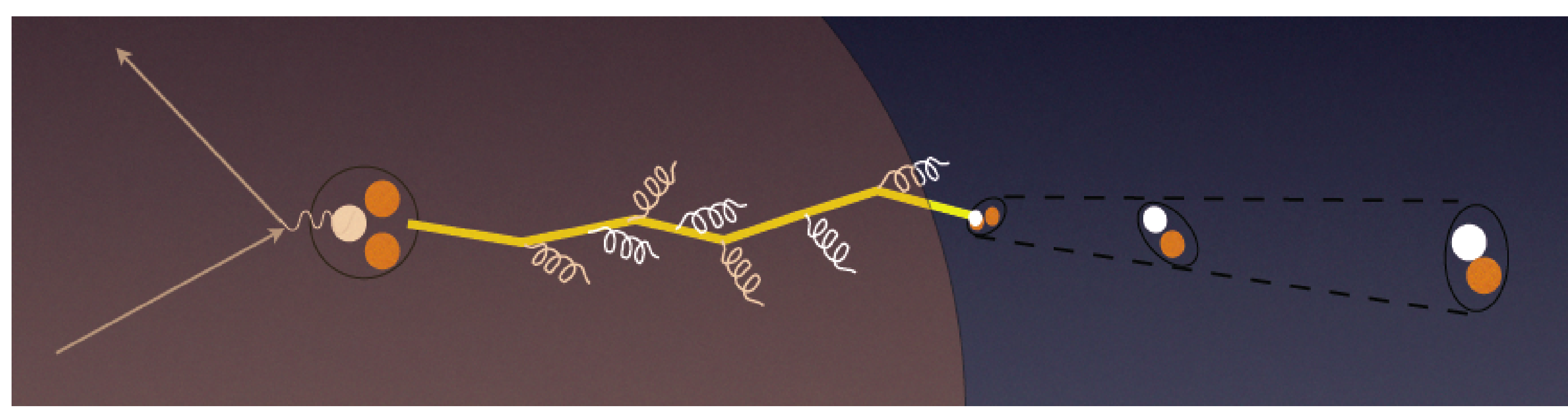
- The LHeC (ν_{max}~10^5 GeV) would allow to study the dynamics of hadronization, testing the parton/hadron eloss mechanism by introducing a length of colored material which would modify its pattern (length/nuclear size, chemical composition).

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

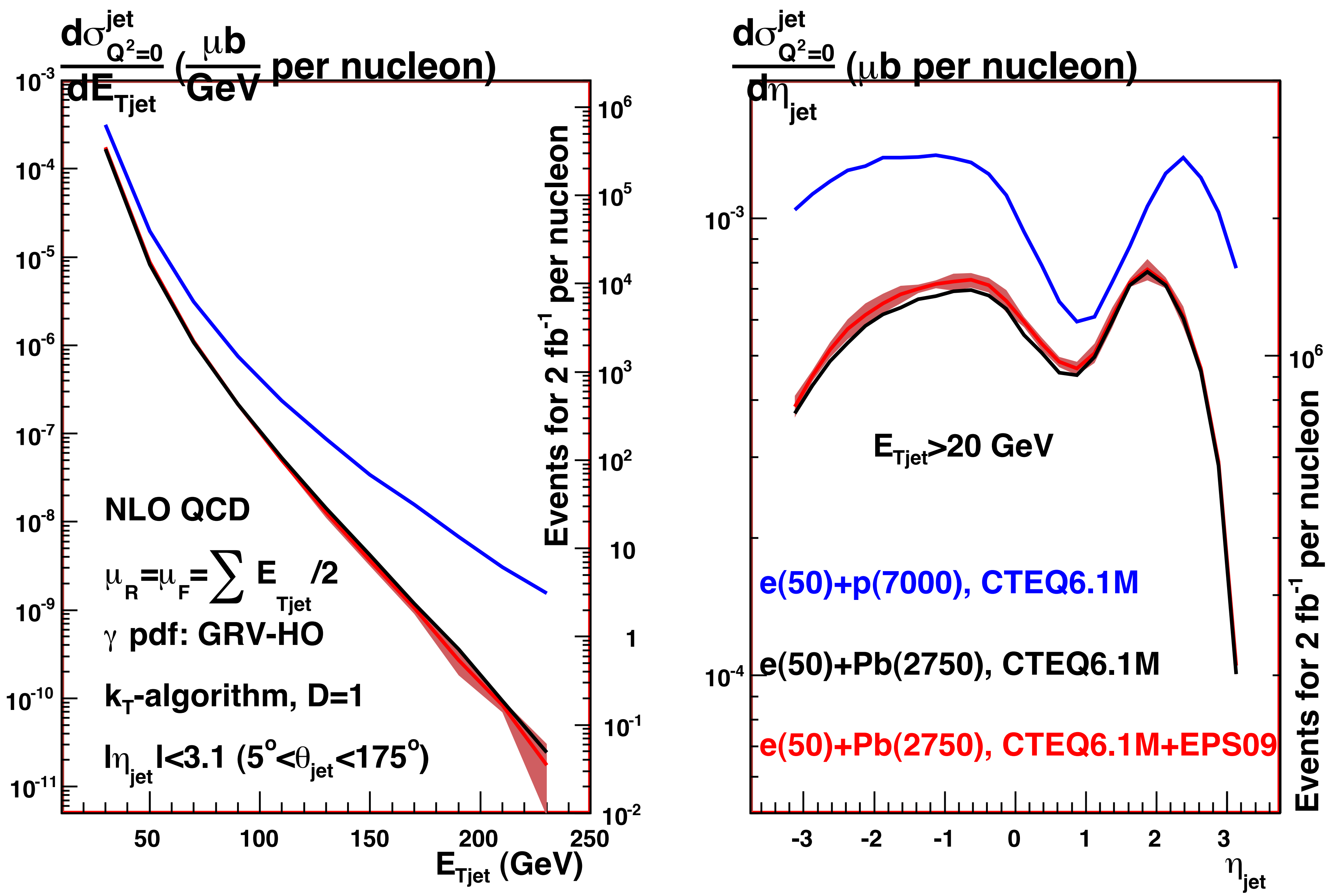


Brooks at Divonne'09

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



Jet photoproduction:



Preliminary; LHeC Design Study Report, CERN 2011

- 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.

Summary:

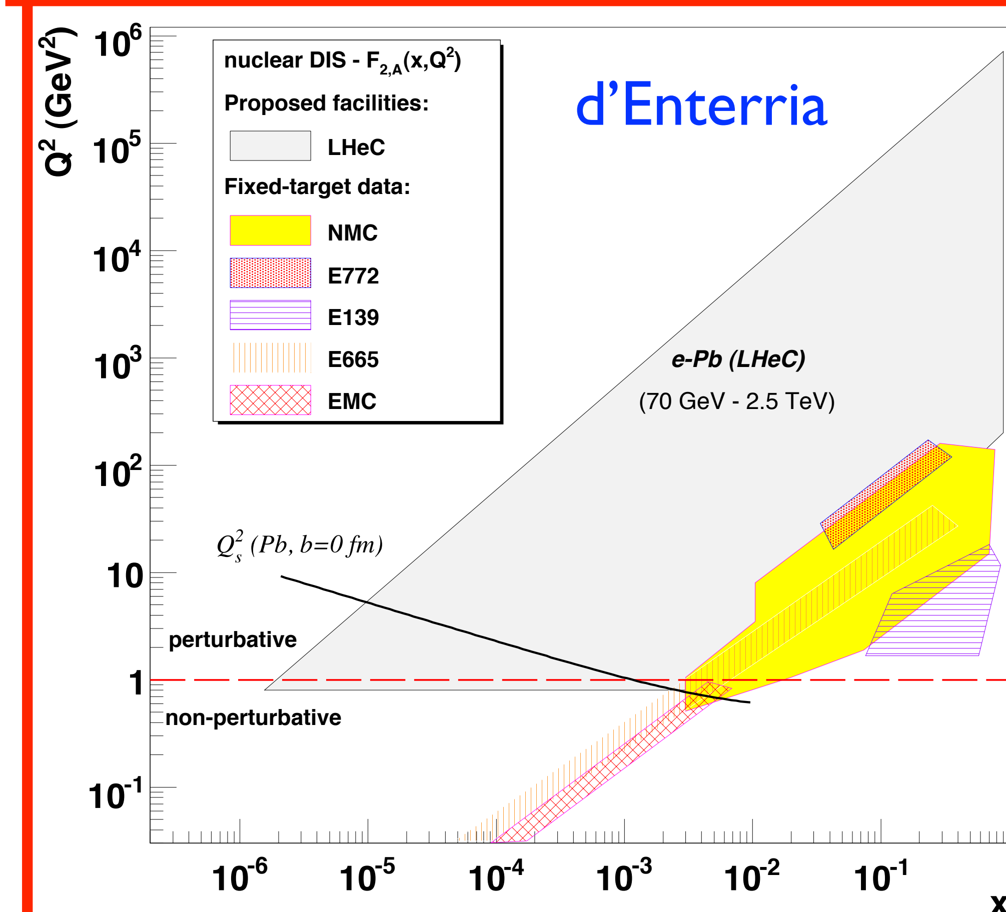
- Many issues remain open about small-x physics (behavior of the hadron wave function at small x): describable by pQCD?, need of resummation/onset of unitarity in the accessible kinematical regions?

- 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 to be published this year.



Plans for the CDR:

Organization for the CDR

Scientific Advisory Committee

Guido Altarelli (Rome)
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Stan Brodsky (SLAC)
Allen Caldwell -chair (MPI Munich)
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Georg Weiglein (Durham)

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Claire Gwenlan (Oxford)

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BSM:
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Ring-Ring Design
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Linac-Ring Design
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Energy Recovery
Georg Hoffstatter, Ilan Ben Zvi

Magnets
Neil Marx, Martin Wilson

Installation and Infrastructure
Sylvain Weisz

Preliminary; Klein@DIS11

Plans for the CDR:

Organization for the CDR

Draft **CDR Authorlist** 11.4.11

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Subject to personal ok

LHeC

Plans for the CDR:

Many thanks to Max Klein, Brian Cole, Paul Newman, Anna Stasto, Urs Wiedemann, Peter Kotska, Miriam Fitterer, Alex Bogacz, 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!!!

Preliminary; Klein@DIS11

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A.F. Zarnecki (Warsaw)
F. Zimmermann (CERN)

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No one full time – THANK YOU

Backup:

Plans for the CDR:

Organization for the CDR

Draft **CDR Authorlist** 11.4.11

Next Steps of the LHeC Project

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

2011

1. Complete CDR Draft
2. Workshop on positron intensity (20.5.11 at CERN)
3. Referee Process (5-9/11)
4. Update and Print and Hand in to ECFA/NuPECC/CERN
5. Workshop on Linac vs Ring (Fall 2011) [main features, R+D design]

2011/12

1. Participation in European Strategy Process (EPS Grenoble … 2012 conclusion)
2. Update physics programme when LHC Higgs/SUSY results consolidate (DIS12)
3. Form an international accelerator development group based at CERN
4. Build an LHeC Collaboration for preparation of LoI on the Detector

No one full time – THANK YOU

D. Schulte (CERN)

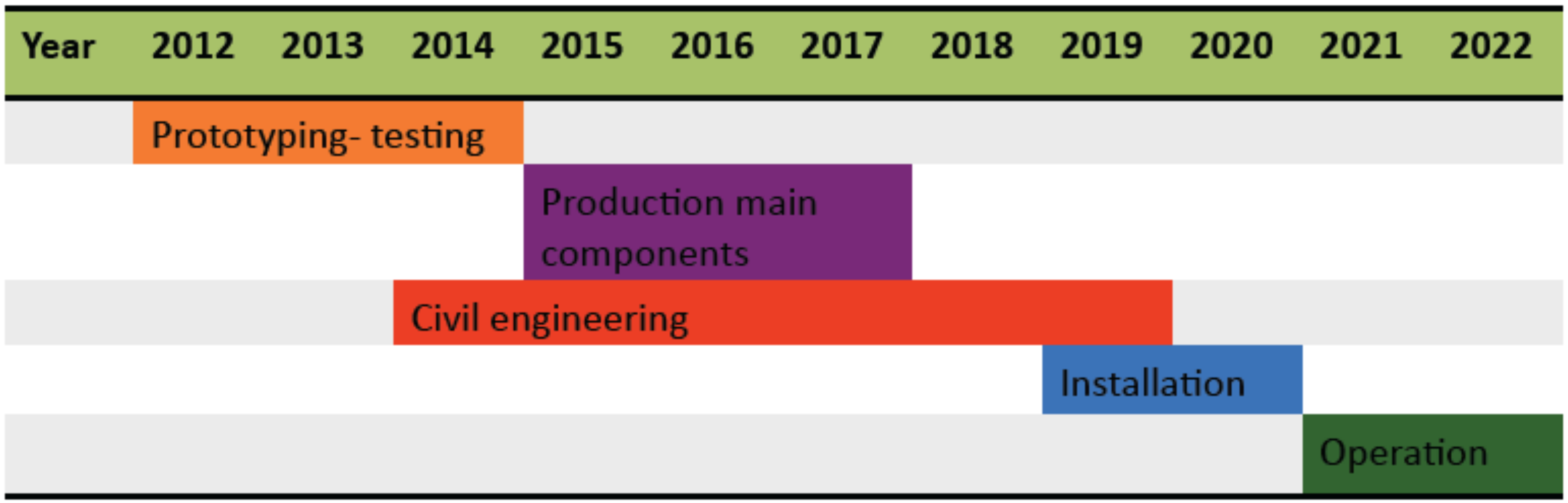
A.F. Zarnecki (Warsaw)
F. Zimmermann (CERN)

Preliminary; Klein@DIS11

Tentative timeline:

LHeC_DRAFT_Timeline

Based on LHC constraints, ep/A programme, series production, civil engineering etc



Variations on timeline:

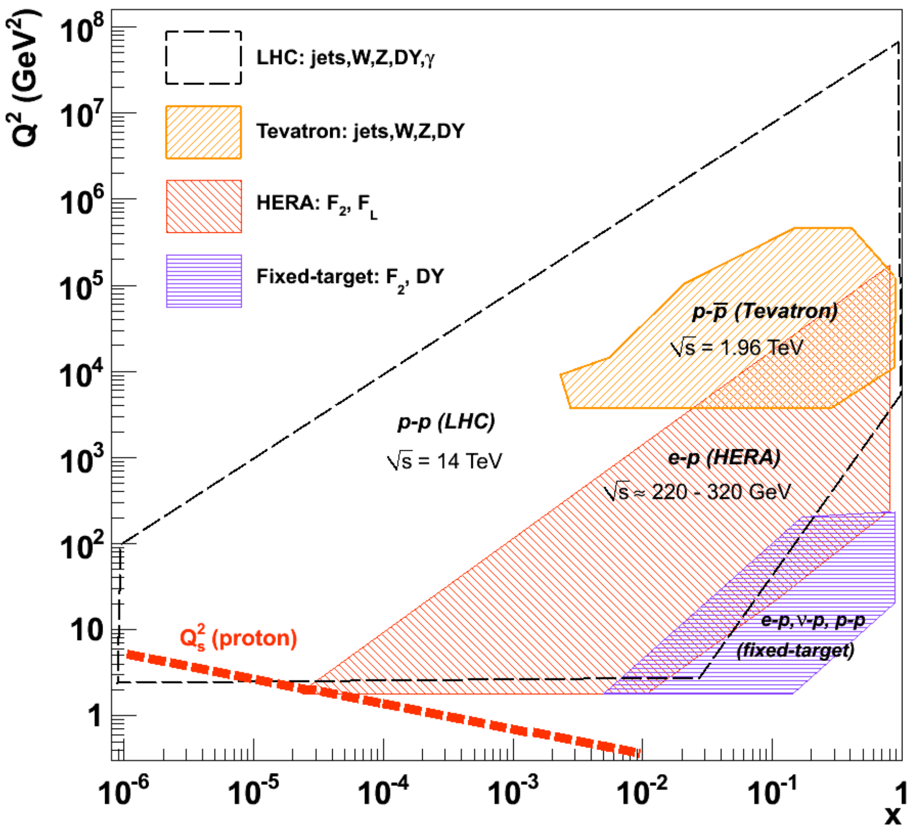
- ➔ production of main components can overlap with civil engineering
- ➔ Installation can overlap with civil engineering
- ➔ Additional constraints from LHC operation not considered here
- ➔ in any variation, a start by 2020 requires launch of prototyping of key components by 2012

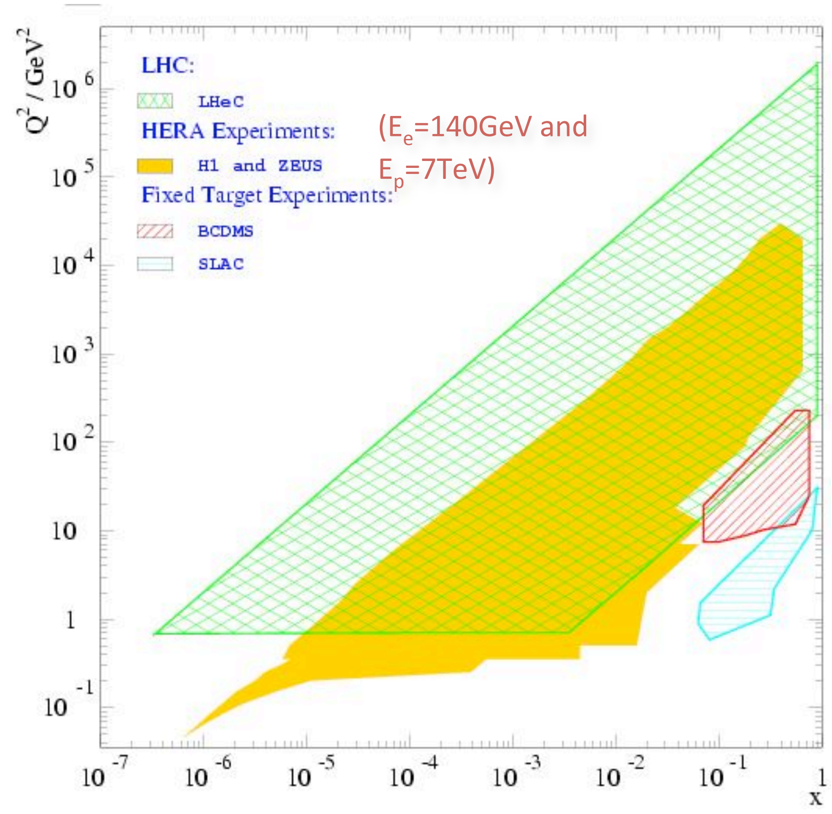
[shown to ECFA 11/2010: mandate to 2012]

Preliminary; Klein@DIS11

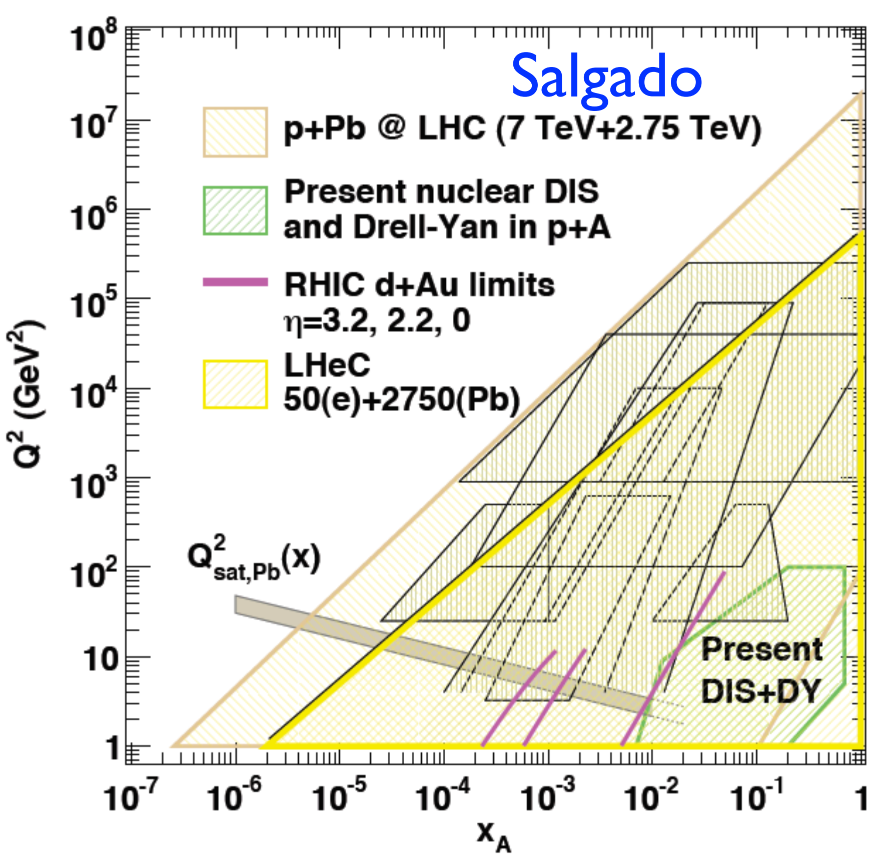
Kinematics: LHC vs. LHeC

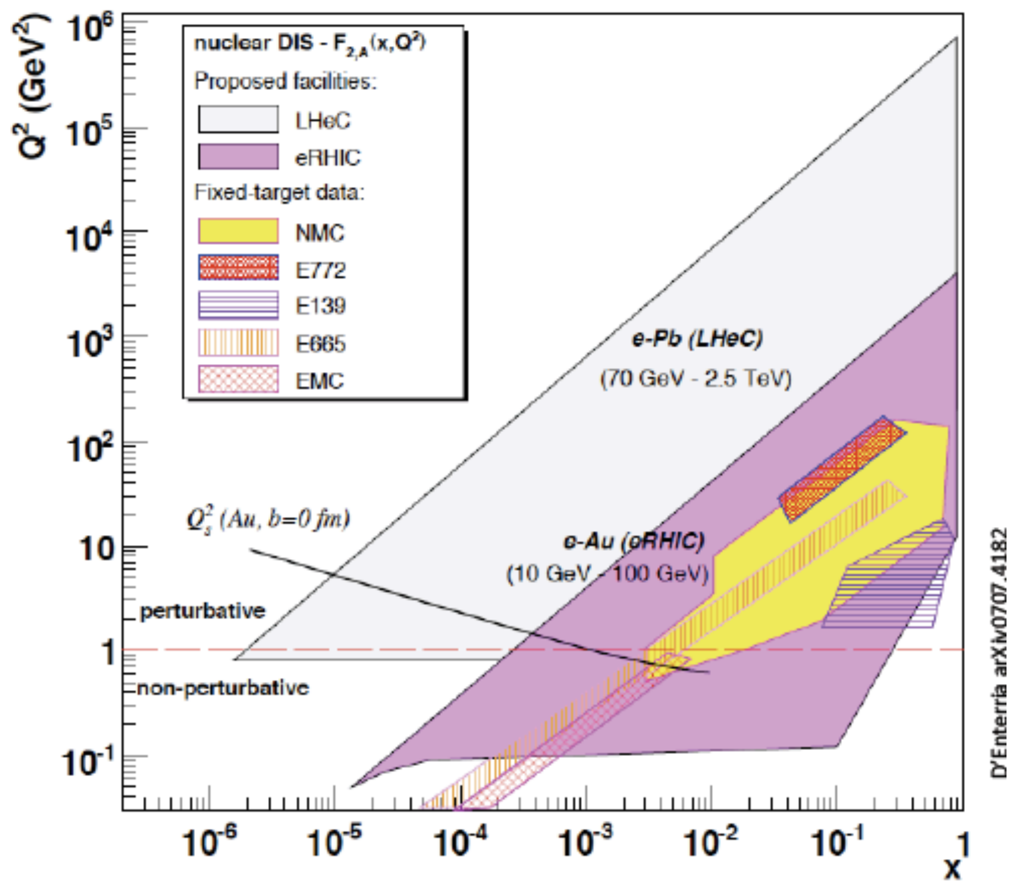
d'Enteria



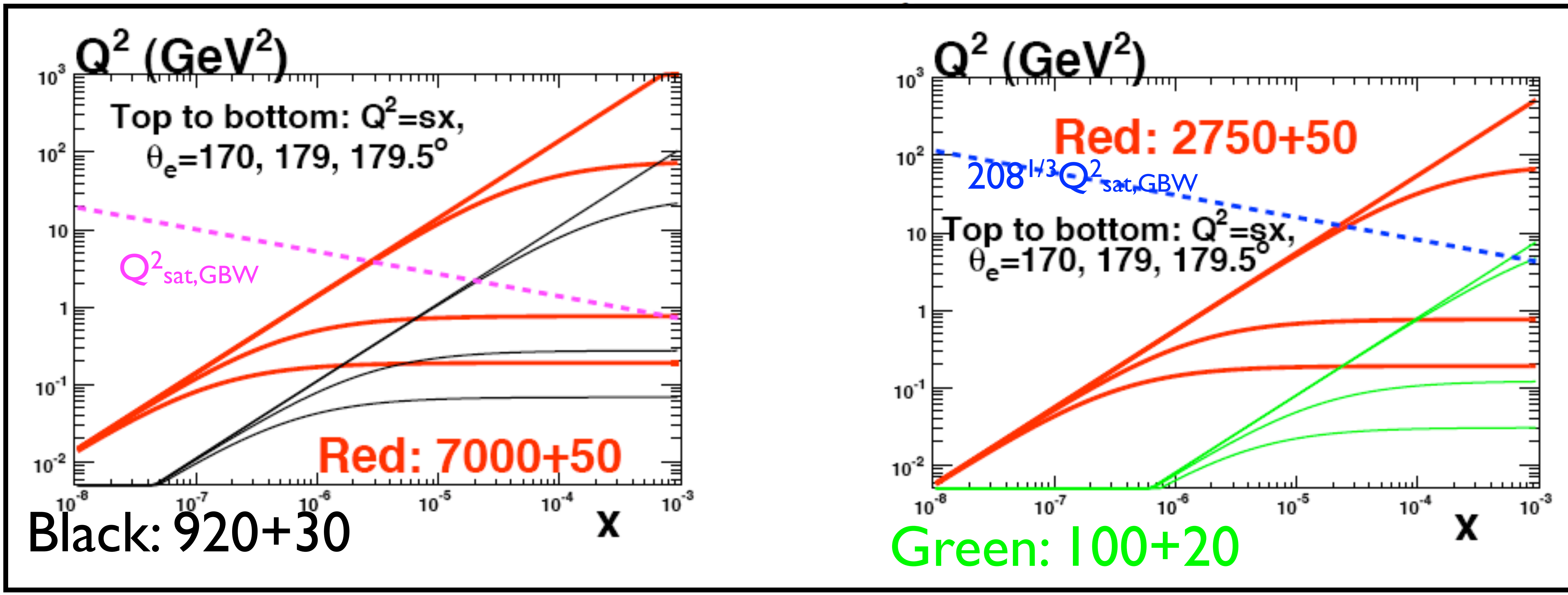


Salgado

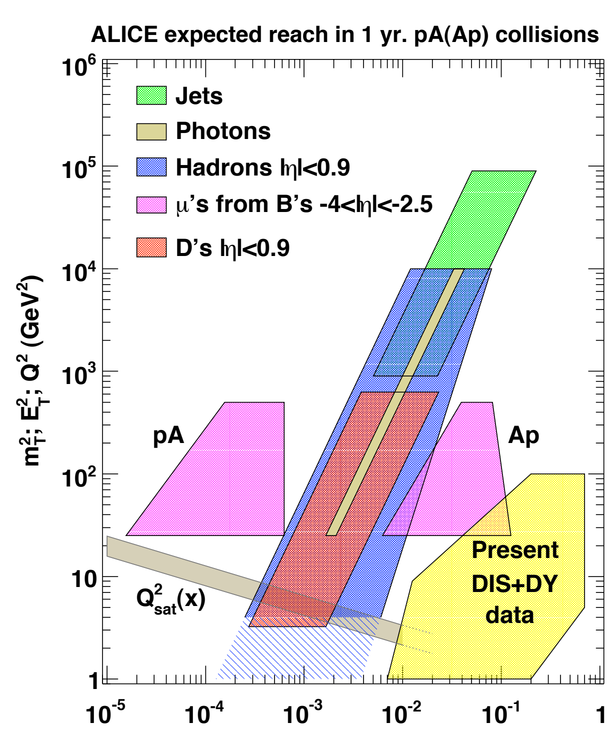


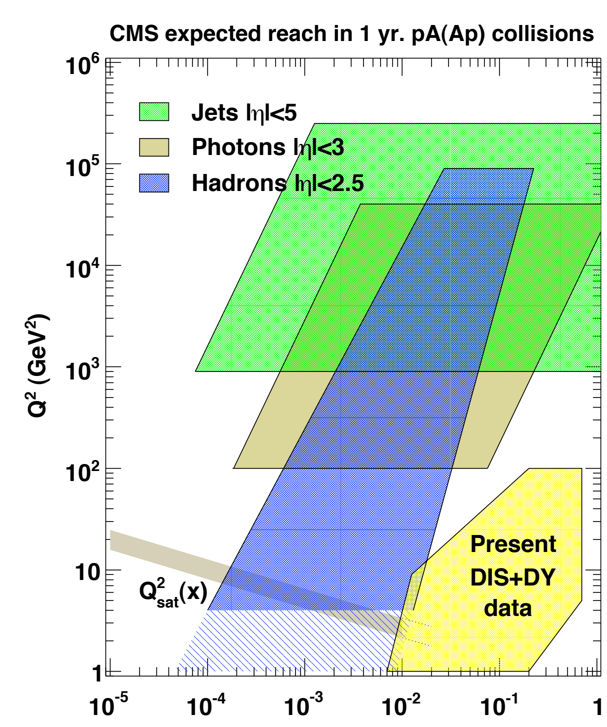


Kinematics:



- 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:

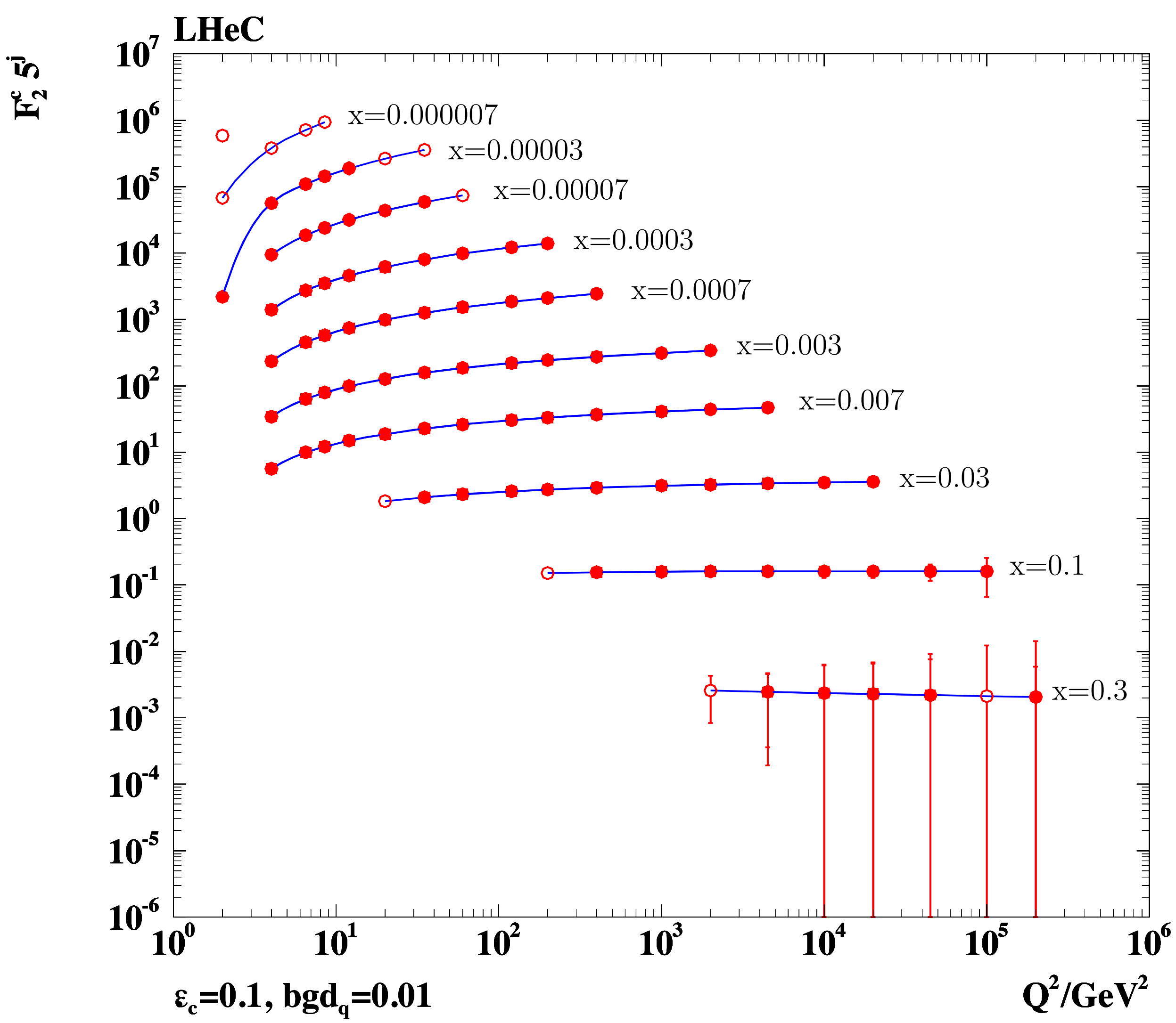
For F_2

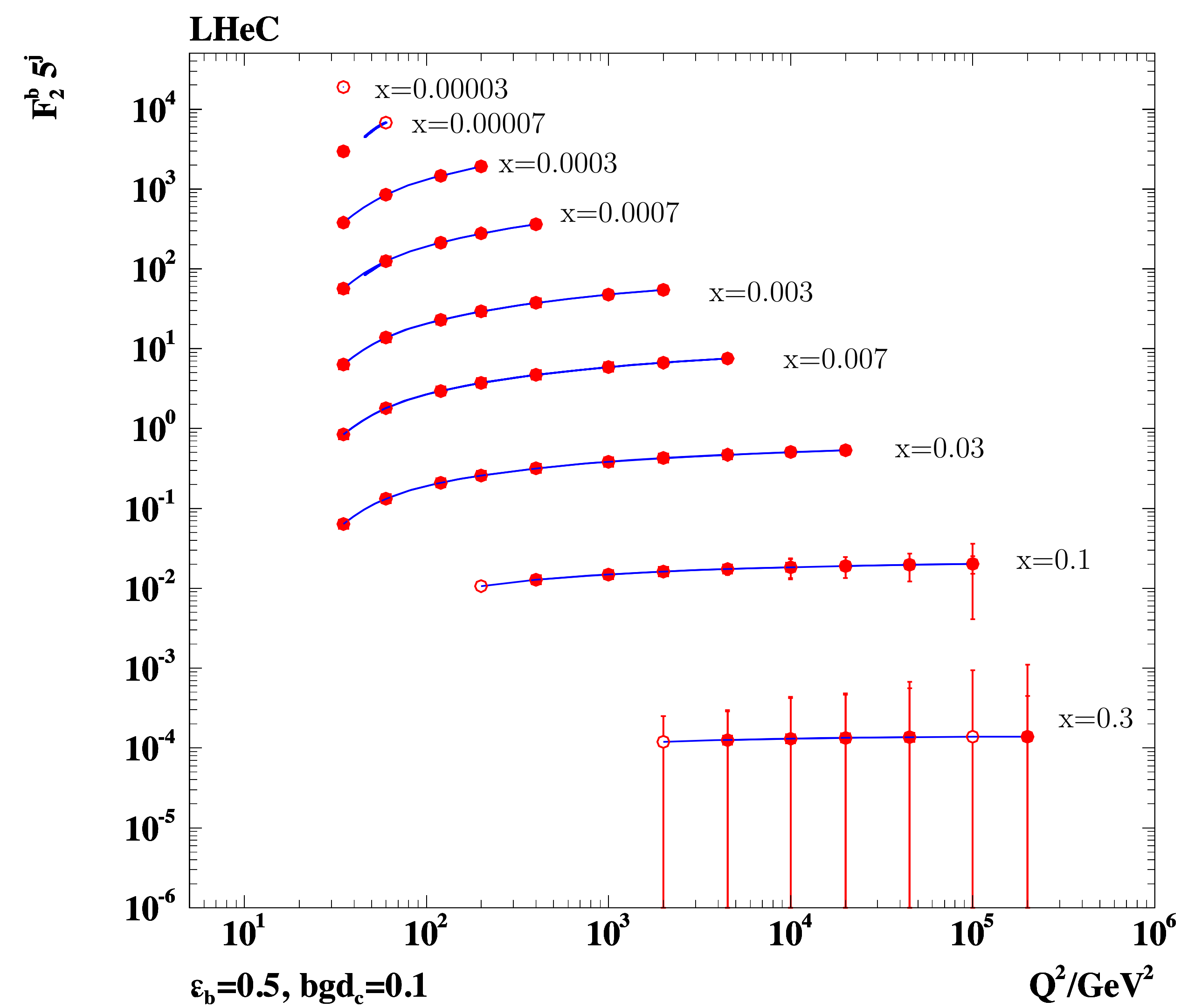
config.	E(e)	E(N)	N	$\int L(e^+)$	$\int L(e^-)$	|Pol|	$L/10^{32}$	P/MW	years	type
A	20	7	p	1	1	-	1	10	1	SPL
B	50	7	p	50	50	0.4	25	30	2	RR hiQ^2
C	50	7	p	1	1	0.4	1	30	1	RR lo x
D	100	7	p	5	10	0.9	2.5	40	2	LR
E	150	7	p	3	6	0.9	1.8	40	2	LR
F	50	3.5	D	1	1	--	0.5	30	1	eD
G	50	2.7	Pb	10^{-4}	10^{-4}	0.4	10^{-3}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

ep inclusive pseudodata (0):

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

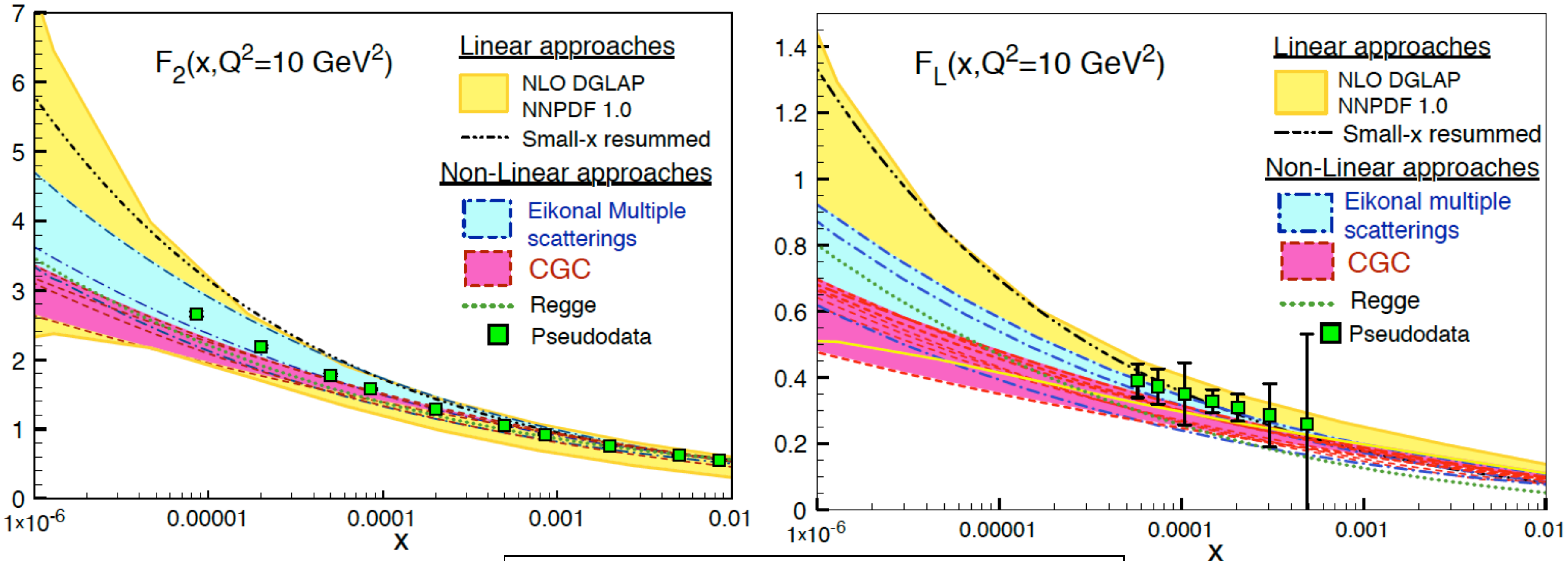




Preliminary; LHeC Design Study Report, CERN 2011

ep inclusive pseudodata (I):

- Extensive model comparison (Albacete): LHeC will have discriminative power.



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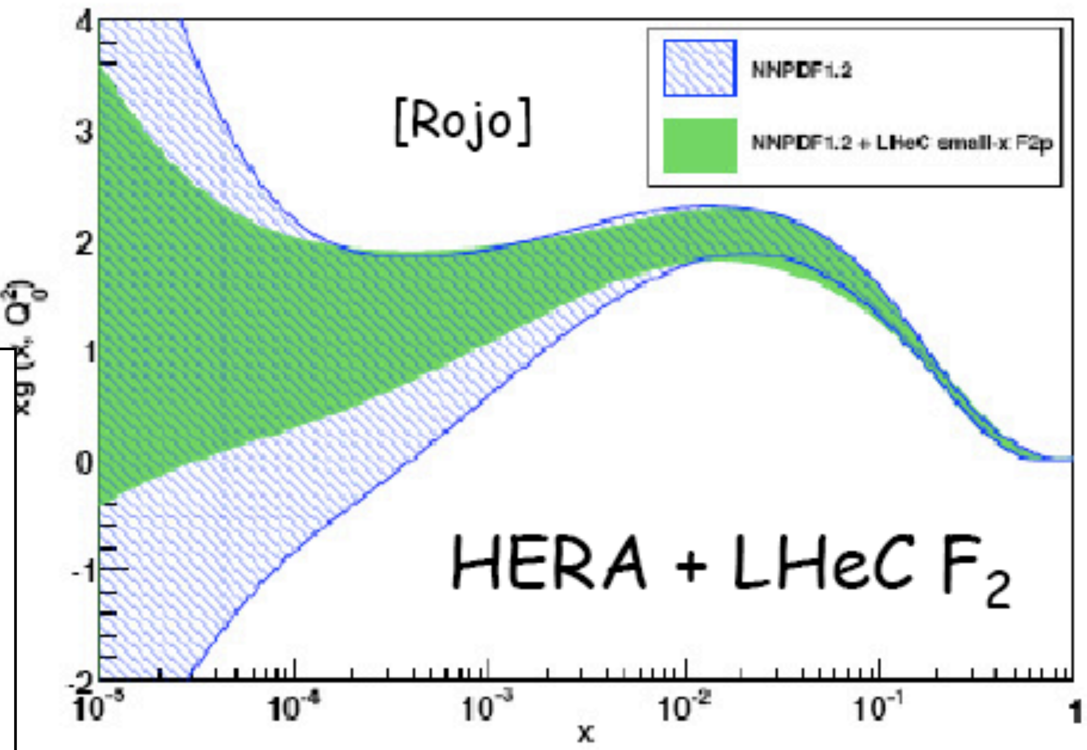
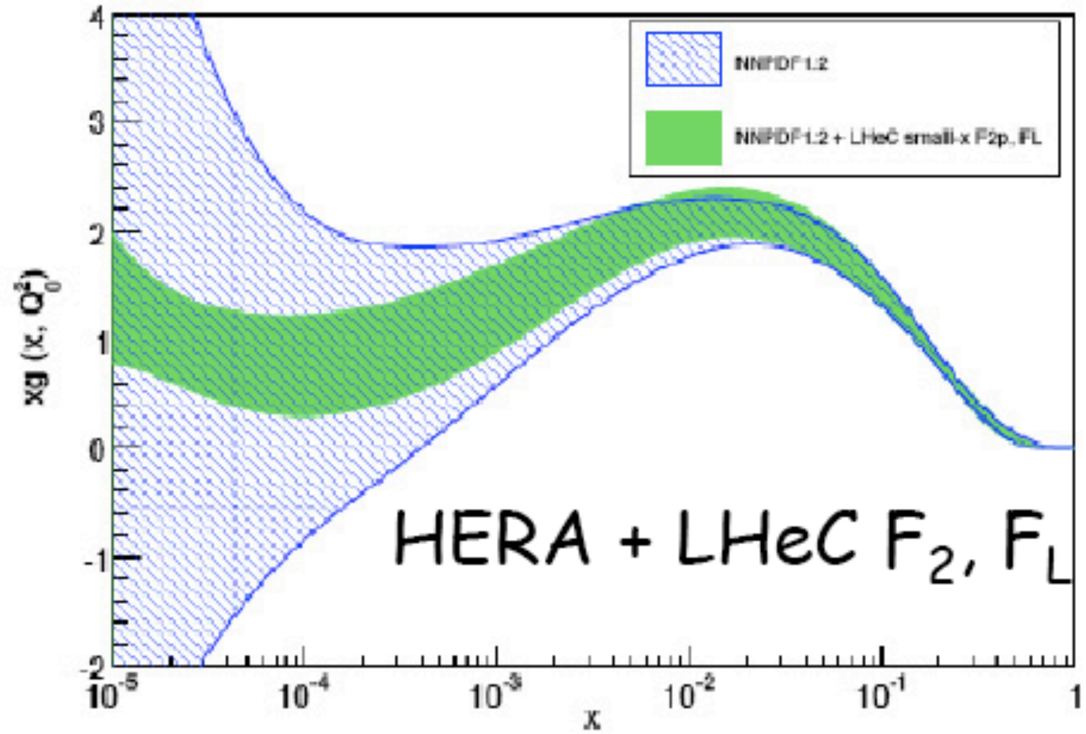
ep inclusive pseudodata (II):

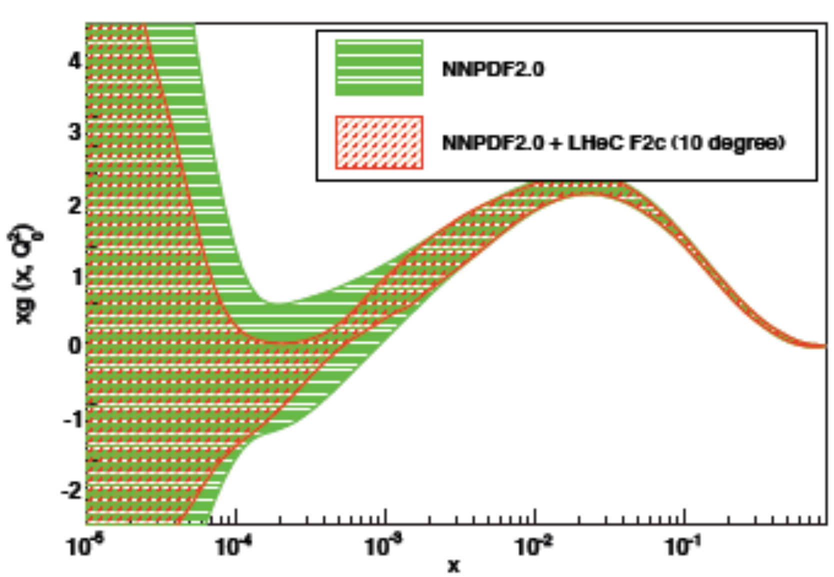


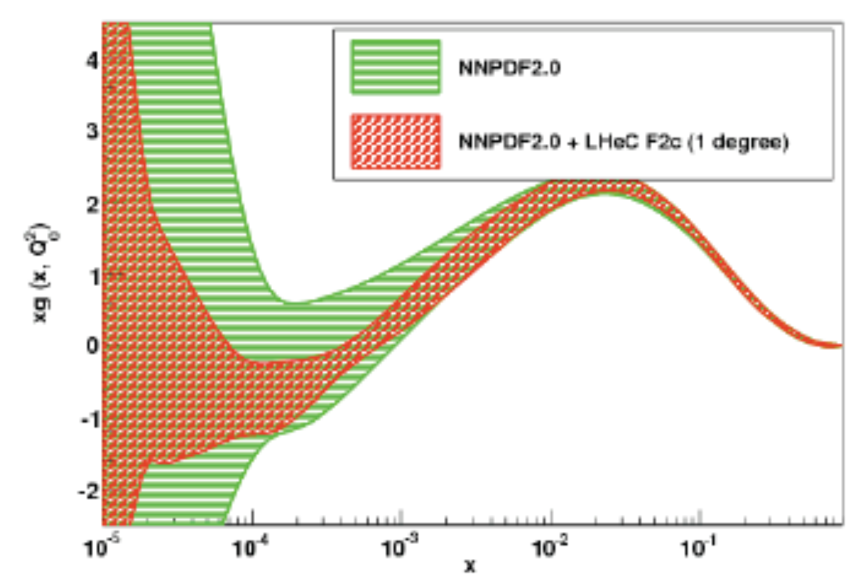


(Q^2 = 2 GeV^2)

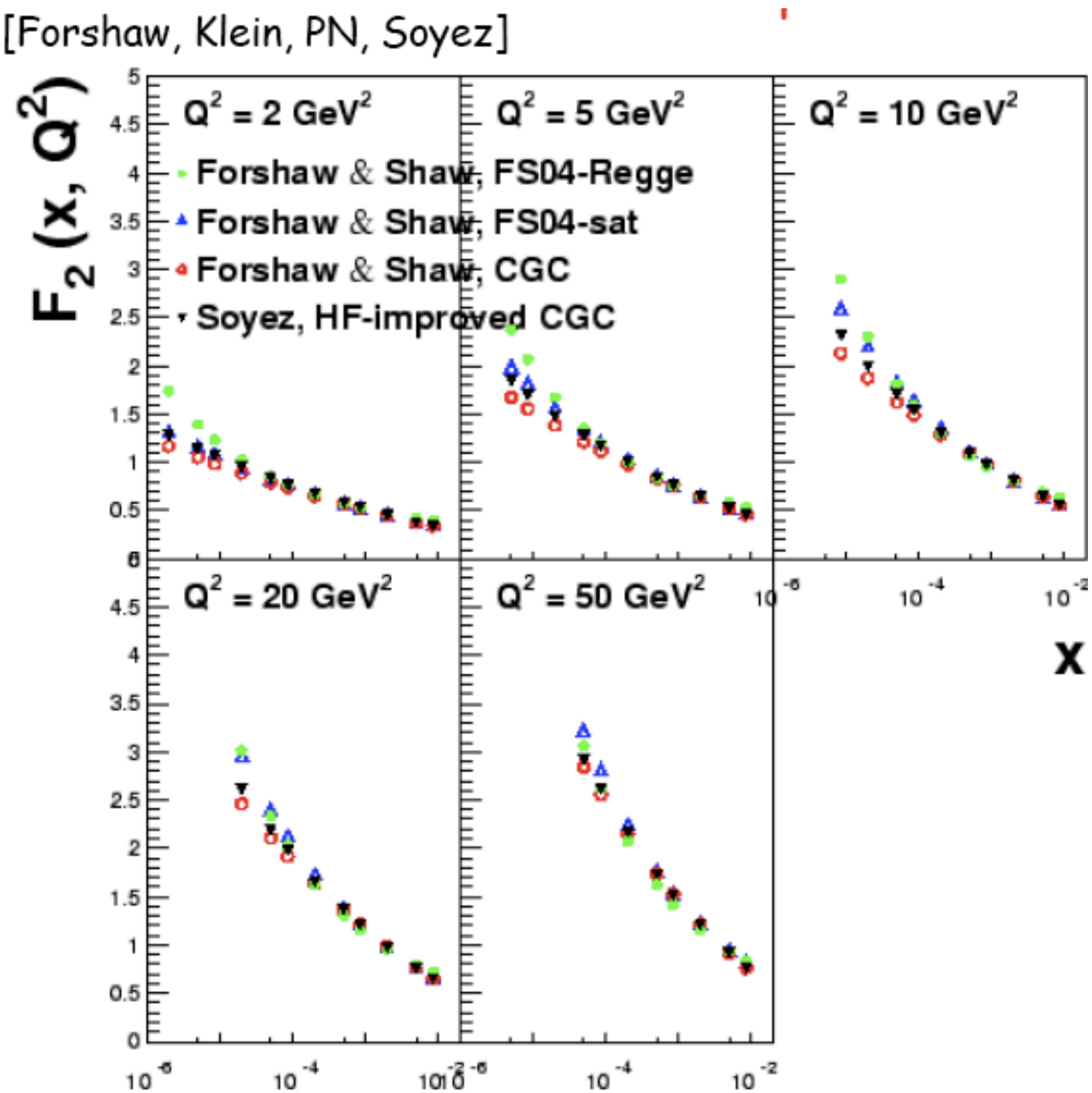
Preliminary; LHeC Design Study Report, CERN 2011

- LHeC substantially reduces the uncertainties in global fits: F_L and heavy flavor decomposition most useful.

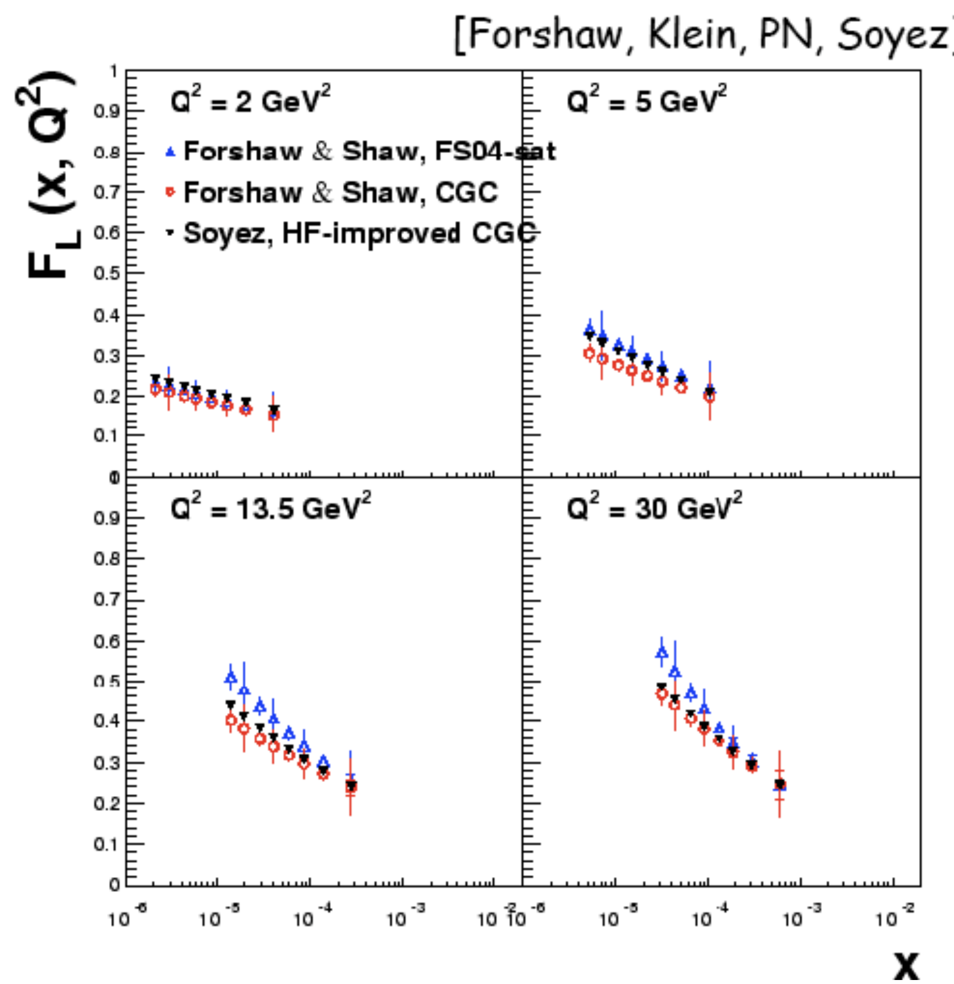




ep inclusive pseudodata (III):



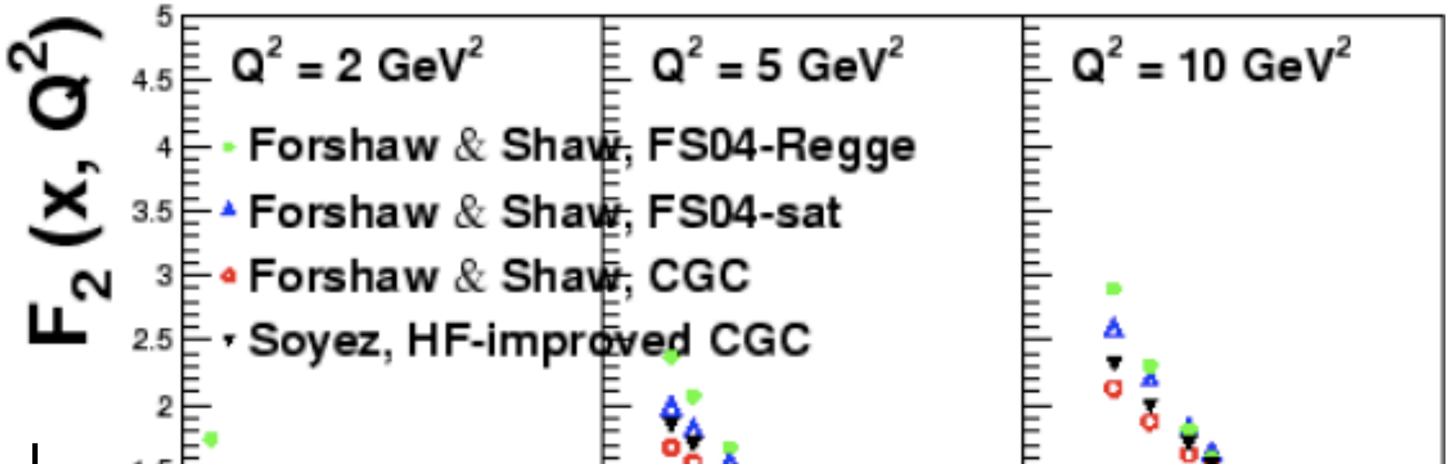
- Tension between F_2 and F_L in DGLAP fits as a sign of physics beyond standard DGLAP (GBW and CGC models).



Preliminary; LHeC Design Study Report, CERN 2011

LHeC ep inclusive pseudodata (III):

[Forshaw, Klein, PN, Soyez]



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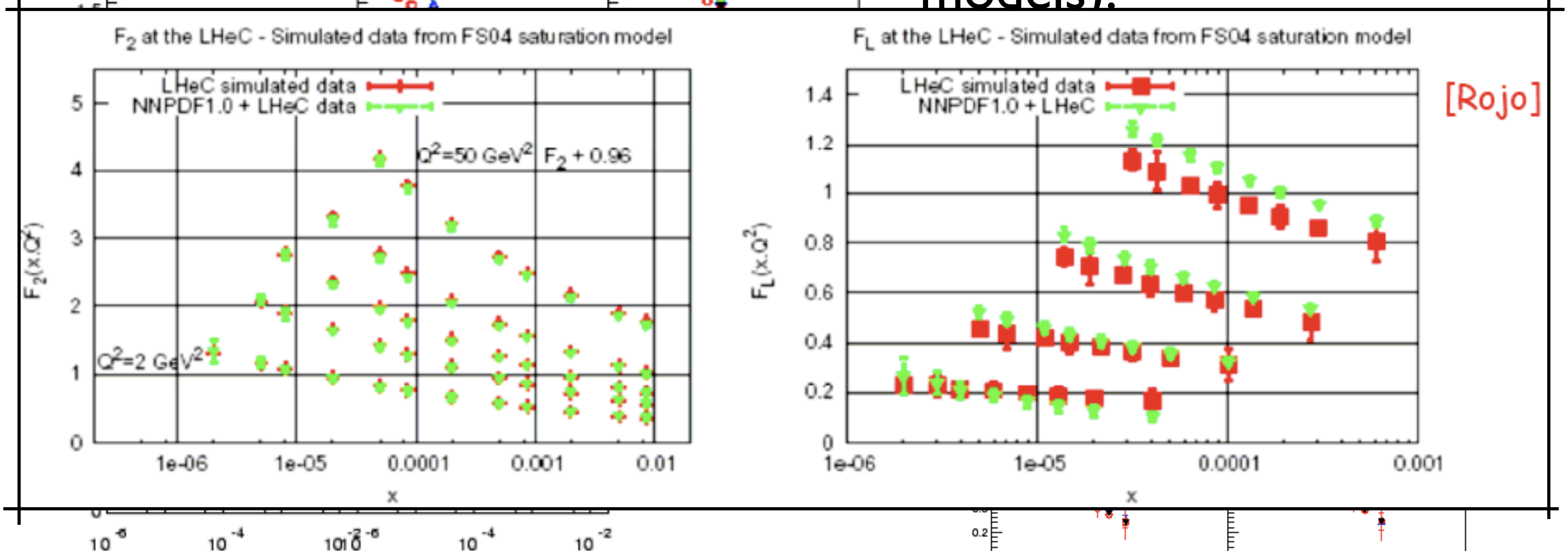
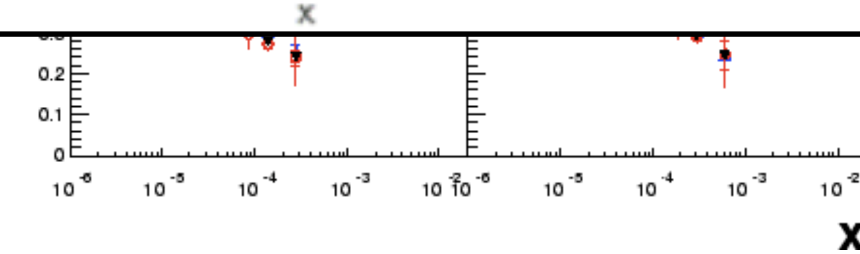
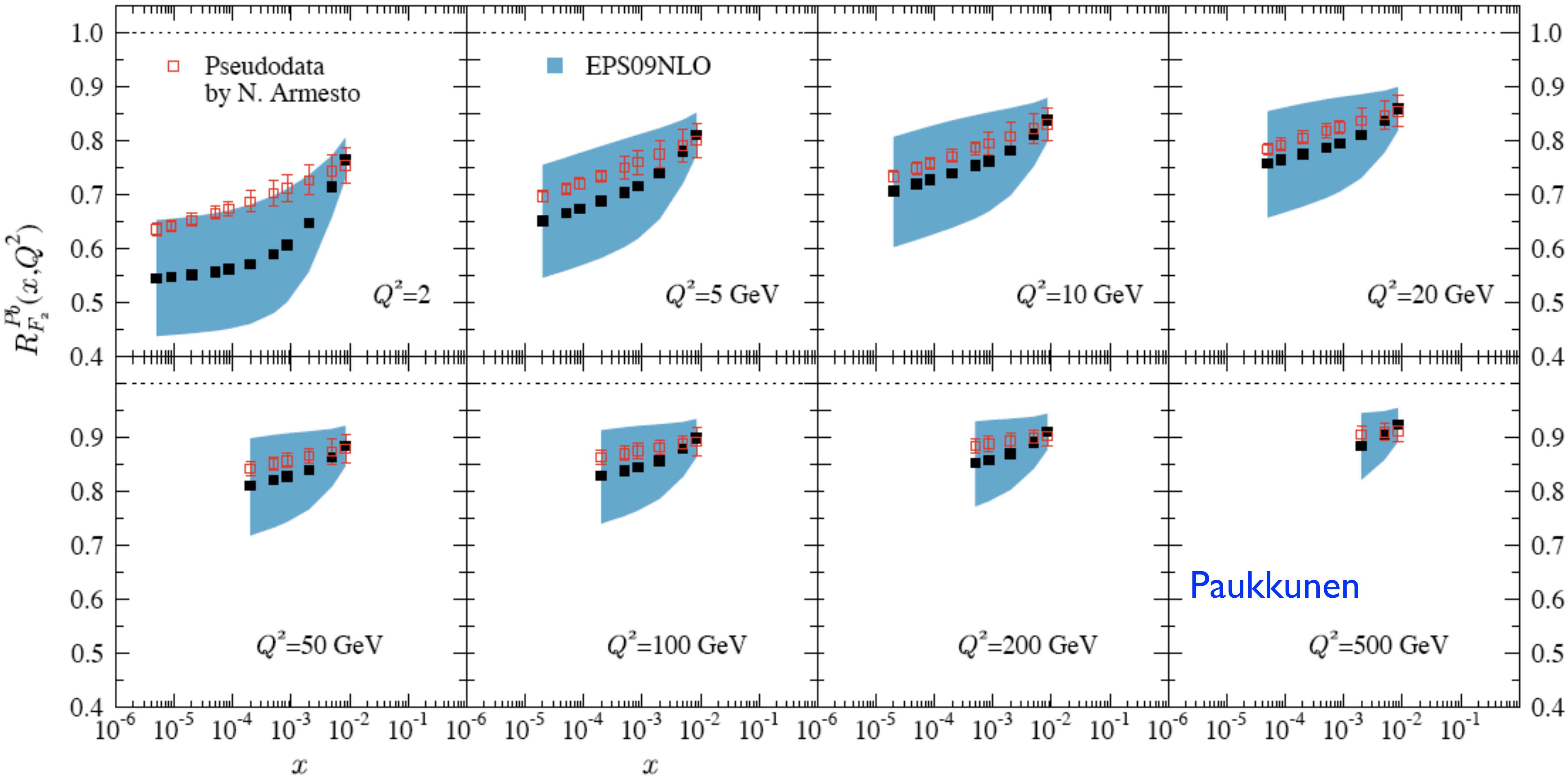




Preliminary; LHeC Design Study Report, CERN 2011

eA inclusive pseudodata (0):

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



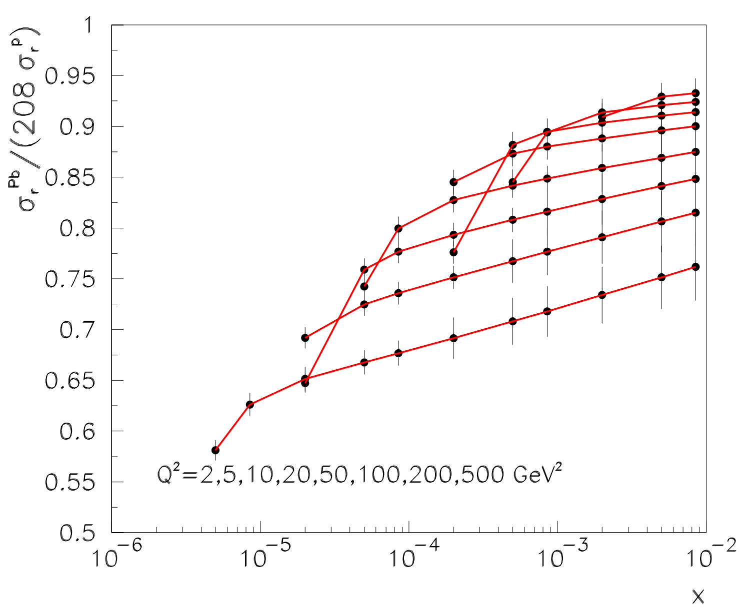
Paukkunen

Note: F_L in eA

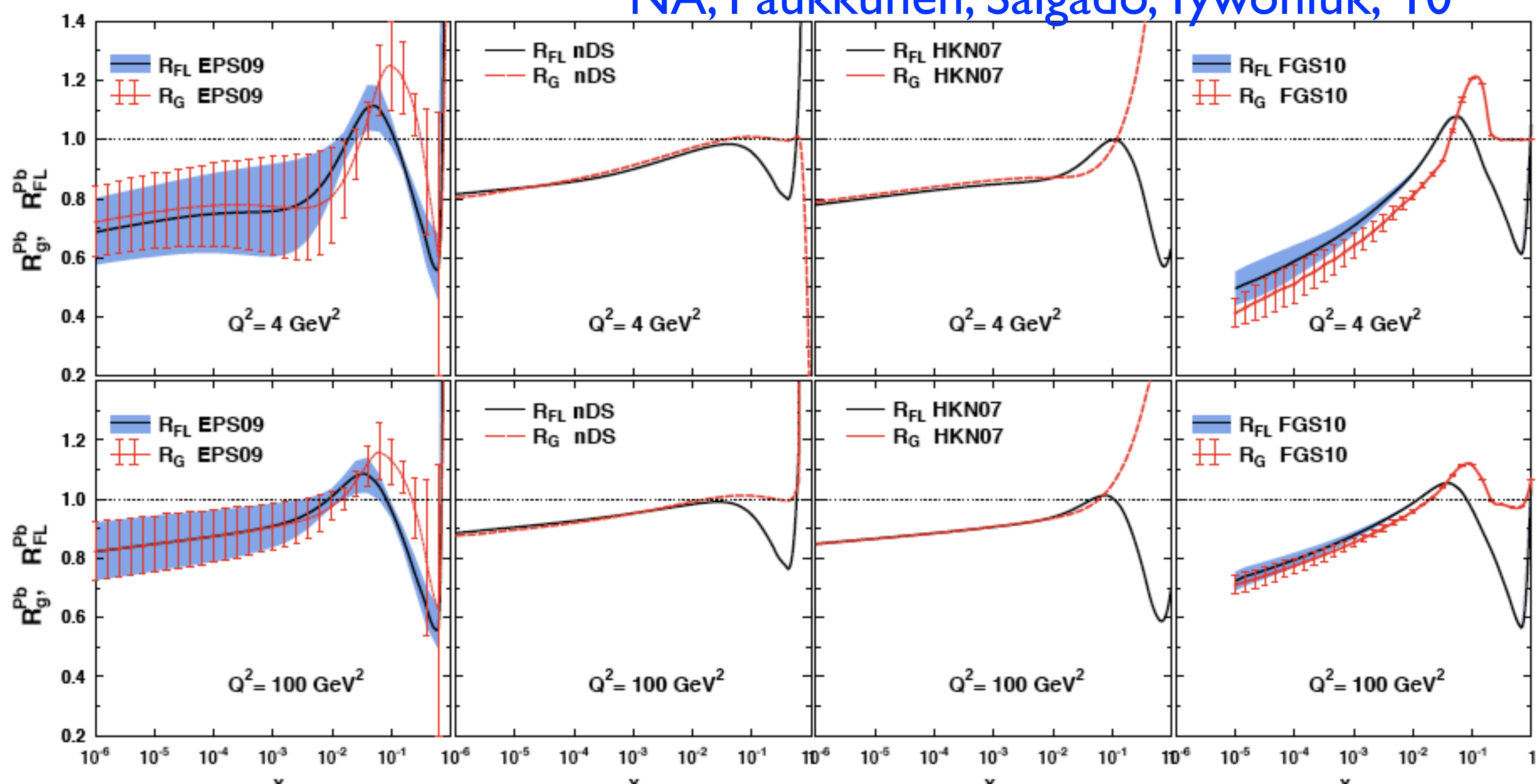
$$\sigma_r^{NC} = \frac{Q^4 x}{2\pi\alpha^2 Y_+} \frac{d^2\sigma^{NC}}{dx dQ^2} = F_2 \left[1 - \frac{y^2}{Y_+} \frac{F_L}{F_2} \right], \qquad Y_+ = 1 + (1-y)^2$$

- 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

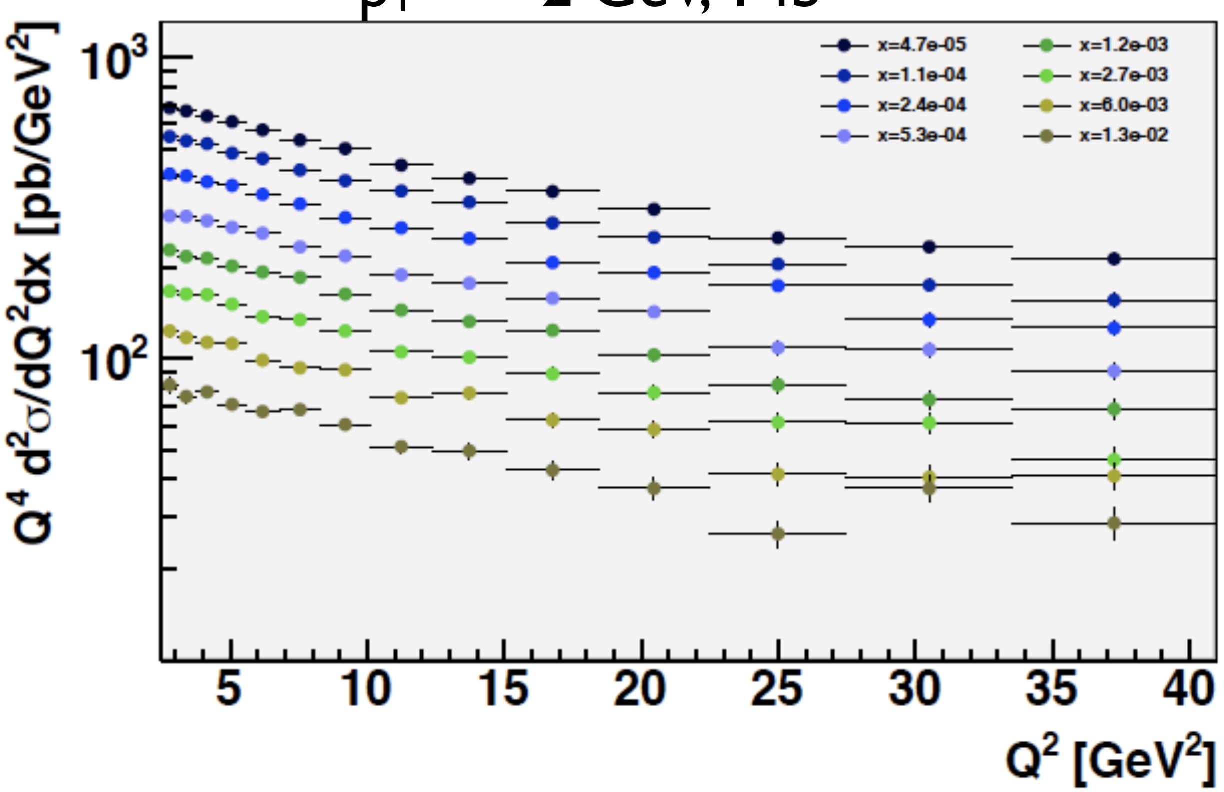


DVCS and GPDs:

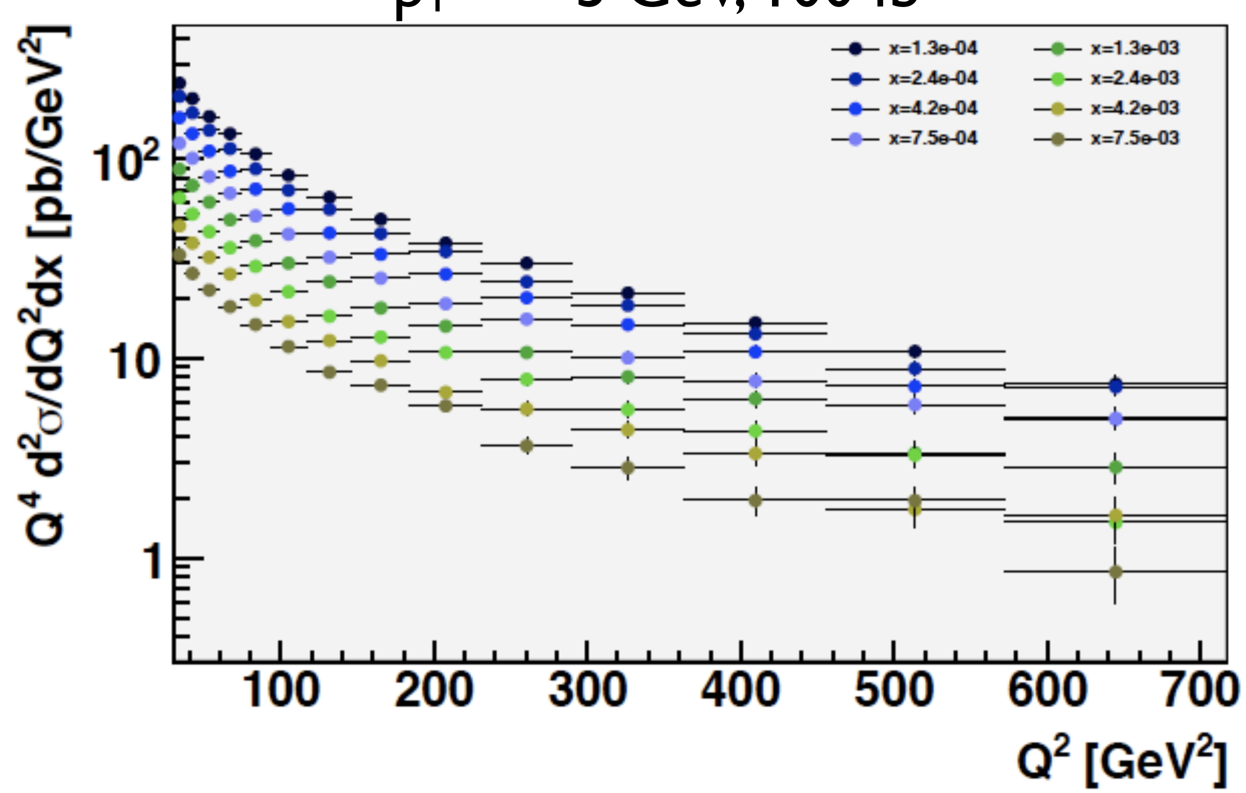
- Exclusive processes like $\gamma^*+h \to \rho,\phi,\gamma+h$ give information of GPDs, whose Fourier transform gives a tranverse scanning of the hadron: key importance for both non-perturbative and perturbative aspects, like the possibility of non-linear dynamics.

- Only small-x case where higher luminosity really helps!!!

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}

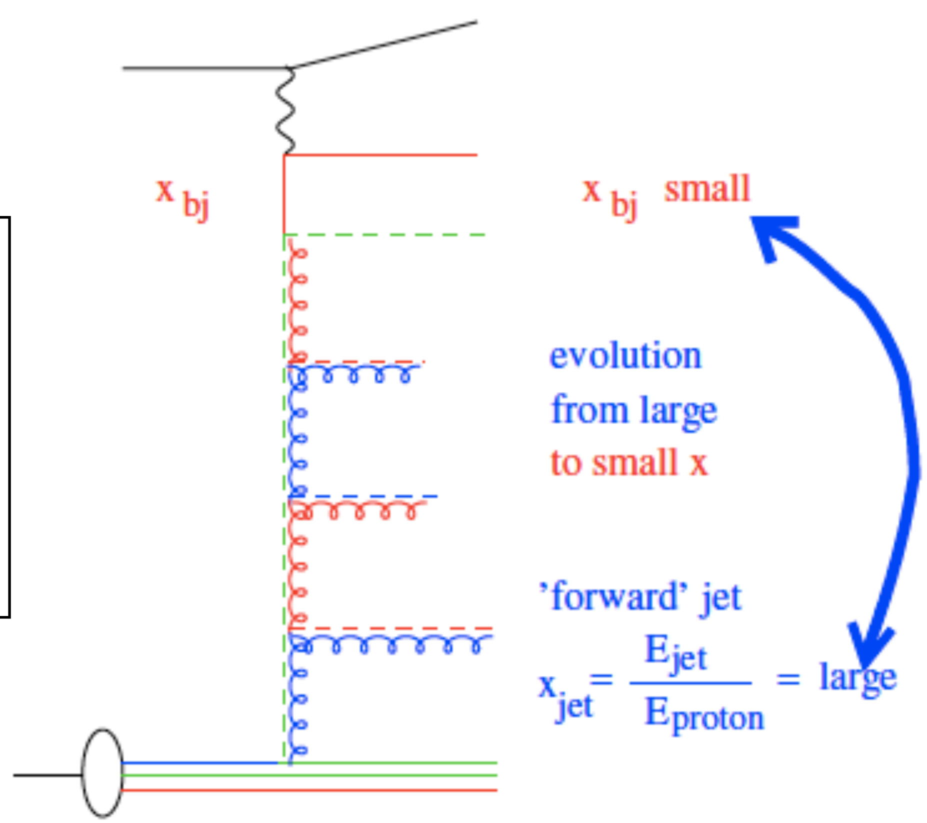


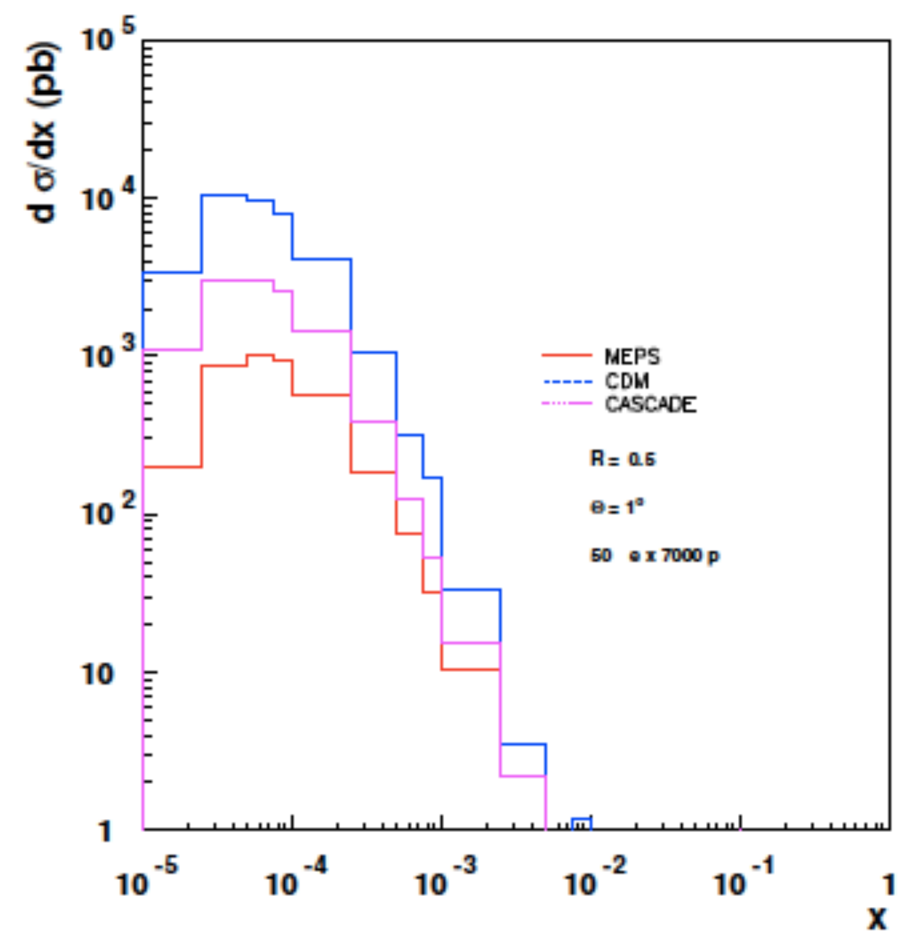
Preliminary; LHeC Design Study Report, CERN 2011

Forward jets:

- Studying forward jets (p_T~Q) or dijet decorrelation 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.

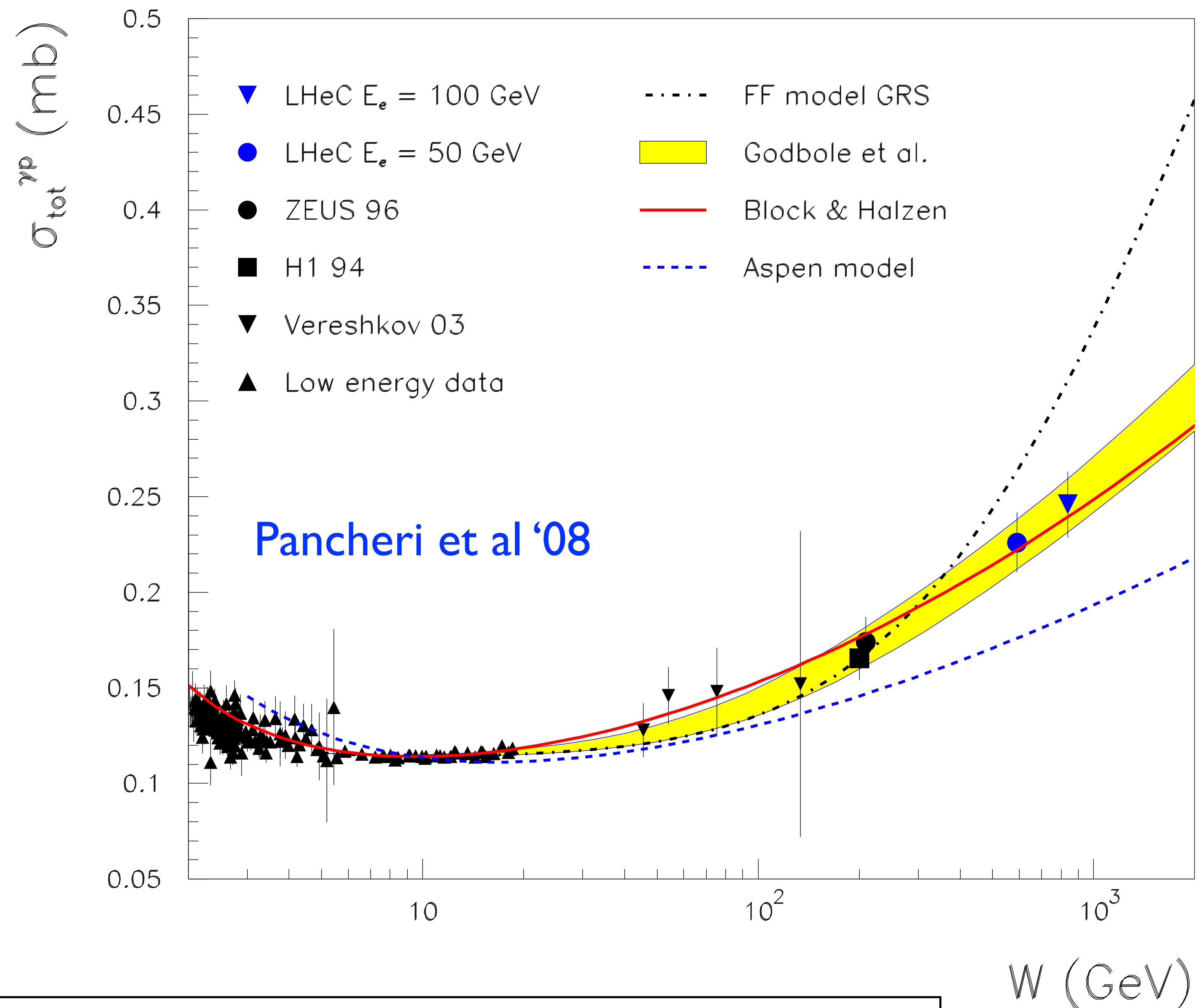
Preliminary; LHeC Design Study Report, CERN 2011





Total γp cross section:

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



Preliminary; LHeC Design Study Report, CERN 2011