Workshop on nuclear Parton Distribution Functions
LAPTH, Annecy-le-Vieux, February 23rd 2010

Small-x physics at the Large Hadron-electron Collider

Néstor Armesto
Departamento de Física de Partículas and IGFAE
Universidade de Santiago de Compostela
nestor.armesto@usc.es

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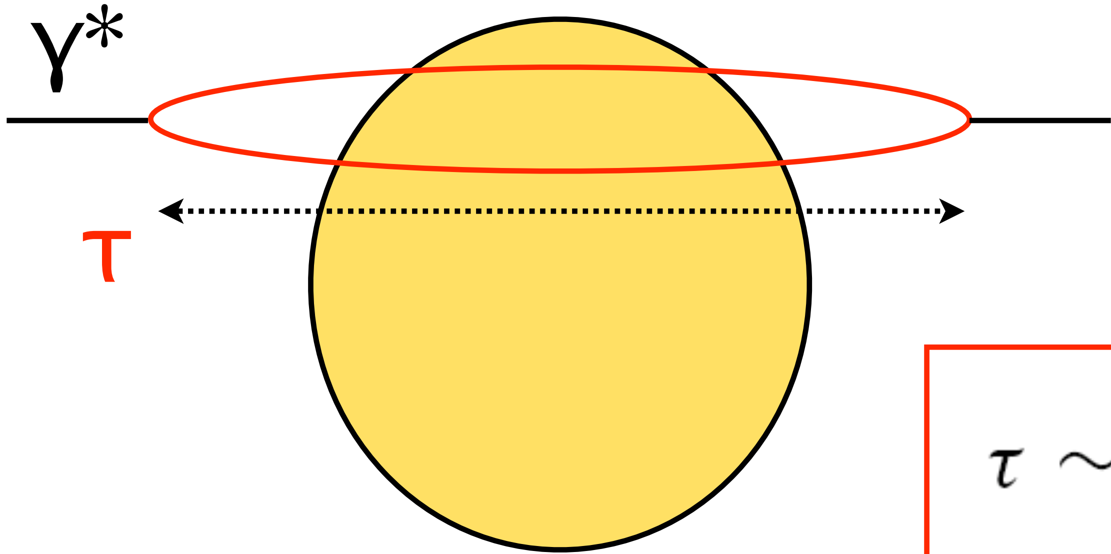
1. The problem of (n)pdf's at small x:
2. What next?: LHC, EIC, LHeC.
   - LHC.
   - EIC.
   - LHeC: the accelerator, physics goals, the detector.
3. Small-x studies with the LHeC:
   - ep inclusive pseudodata and their effect on pdf's.
   - eA inclusive pseudodata and their effect on npdf's.
   - ep, eA diffractive pseudodata.
   - F_L in eA.
4. Summary.

See the talks by P. Quiroga, D. d'Enterria and all others.

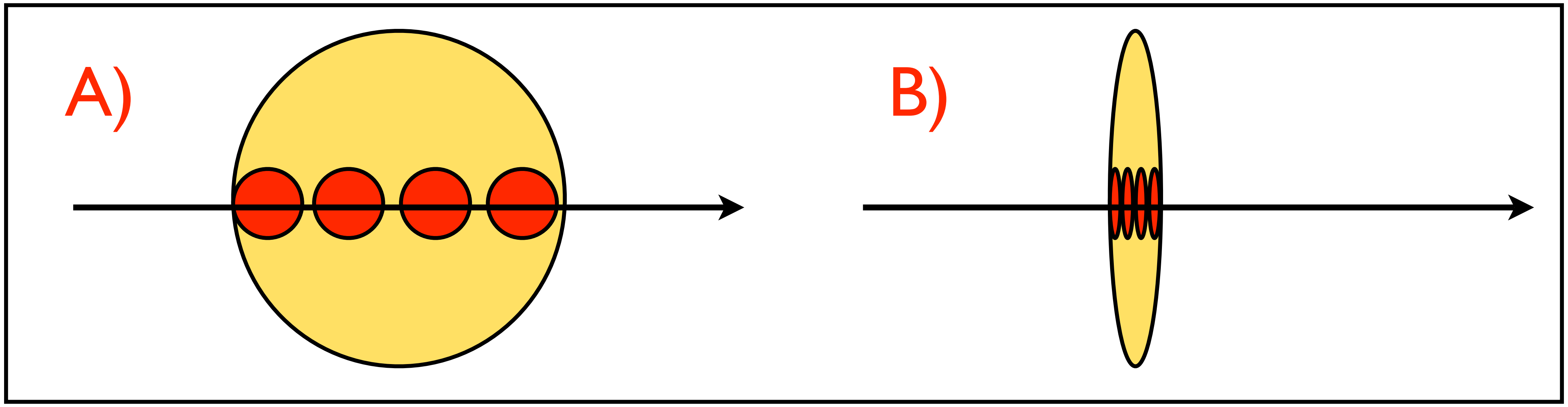
Coherence: small x



- The mean life of a fluctuation with scale Q is:

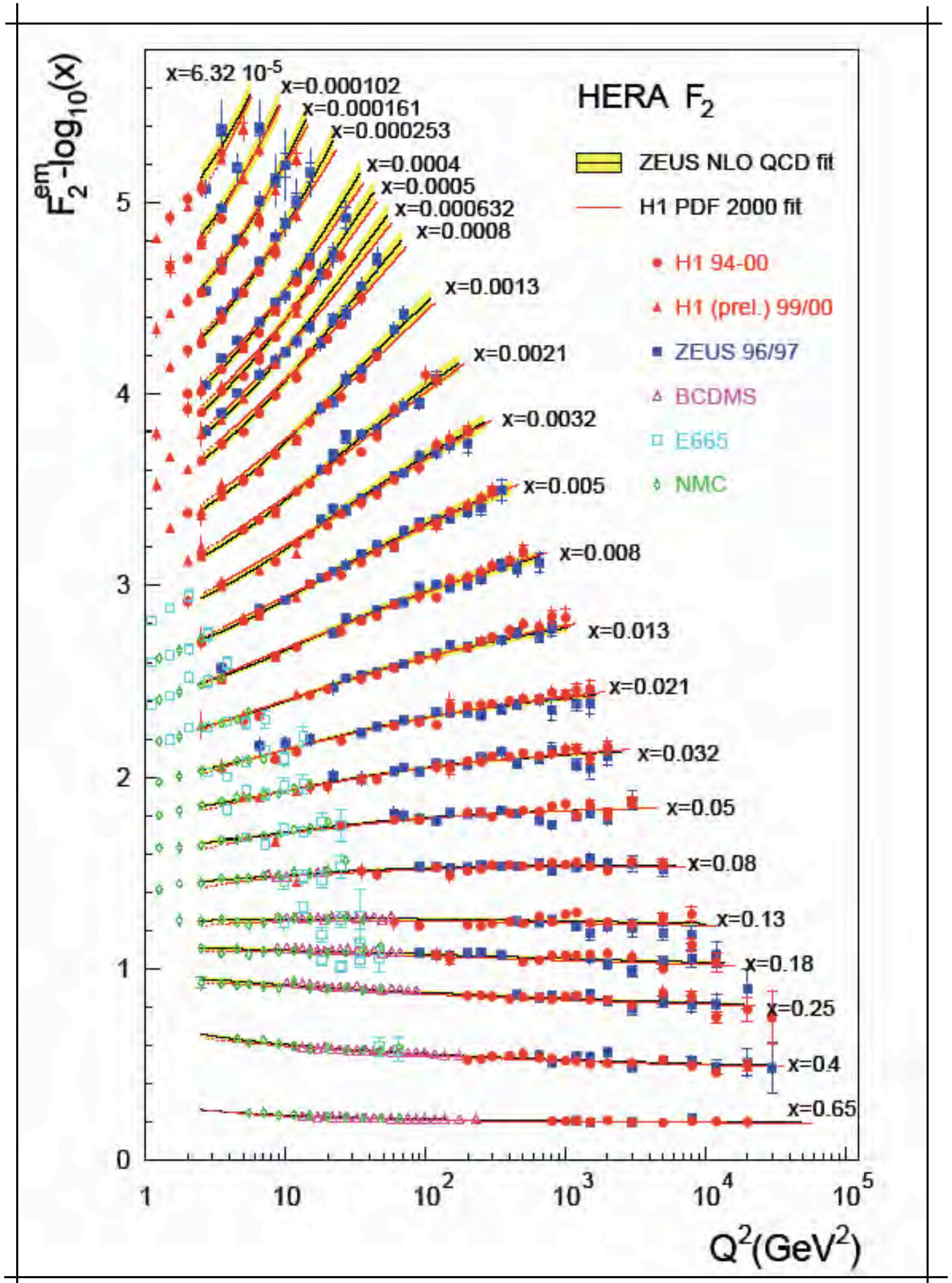
$$\tau \sim \frac{1}{Q} \times \frac{E_{\rm lab}}{Q} \simeq \frac{W^2}{2m_{\rm nucleon}Q^2} \simeq \frac{1}{2m_{\rm nucleon}x}$$

A) $x \to 1$ ($W \to m_N^2$): incoherent scattering, $\sigma_A = A\sigma^I$.
B) $x \to 0$ ($W \to \infty$): coherent scattering, $\sigma_A < A\sigma^I$.



- **Small x** is defined by $\tau \gg R_h \Rightarrow x \ll 0.1 A^{-1/3}$: coherent scattering.

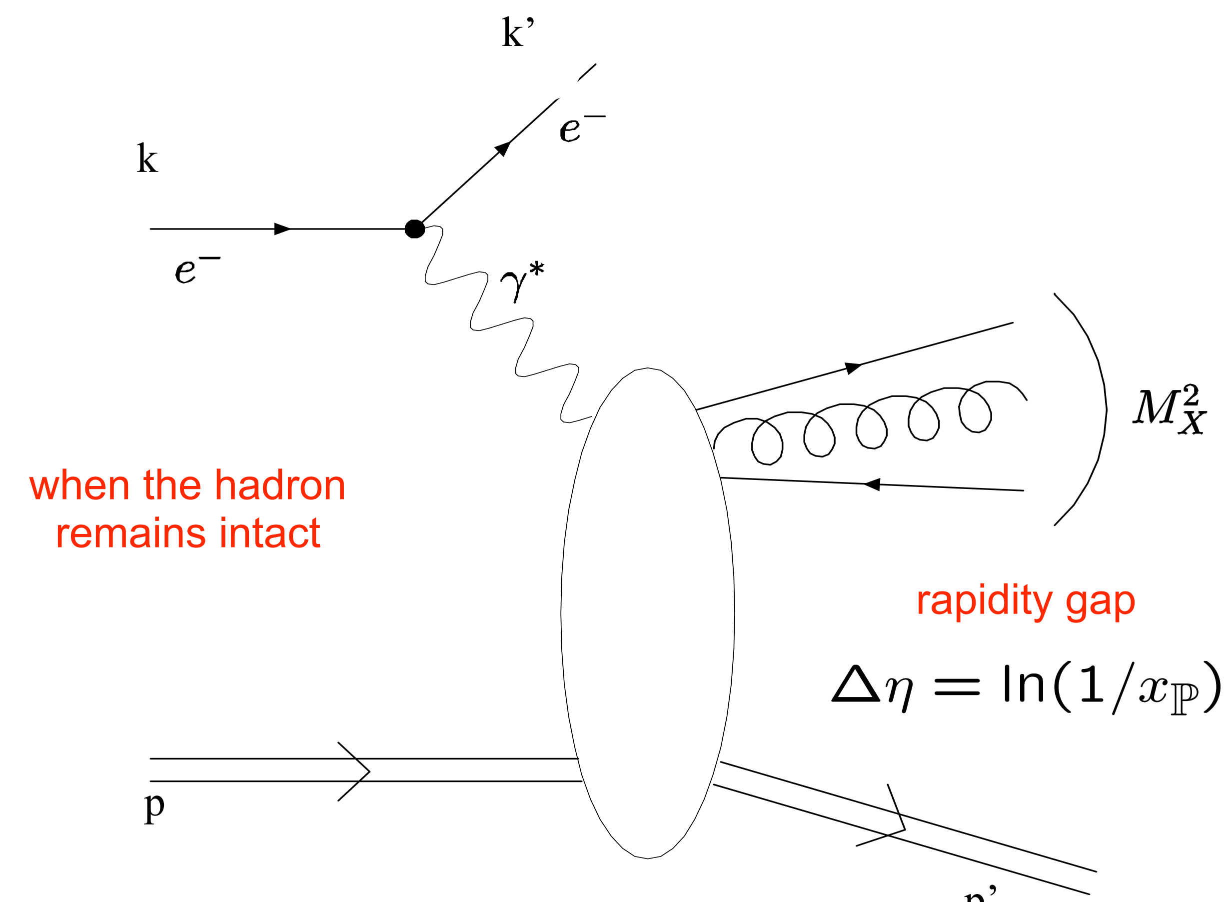
Findings at HERA:



- Most available information, above all at small x, comes from HERA:

A) $F_2 \propto x^{-0.3}$ at small x, fixed Q^2.

B) $\sigma_{diff}/\sigma_{tot}$~15 %.



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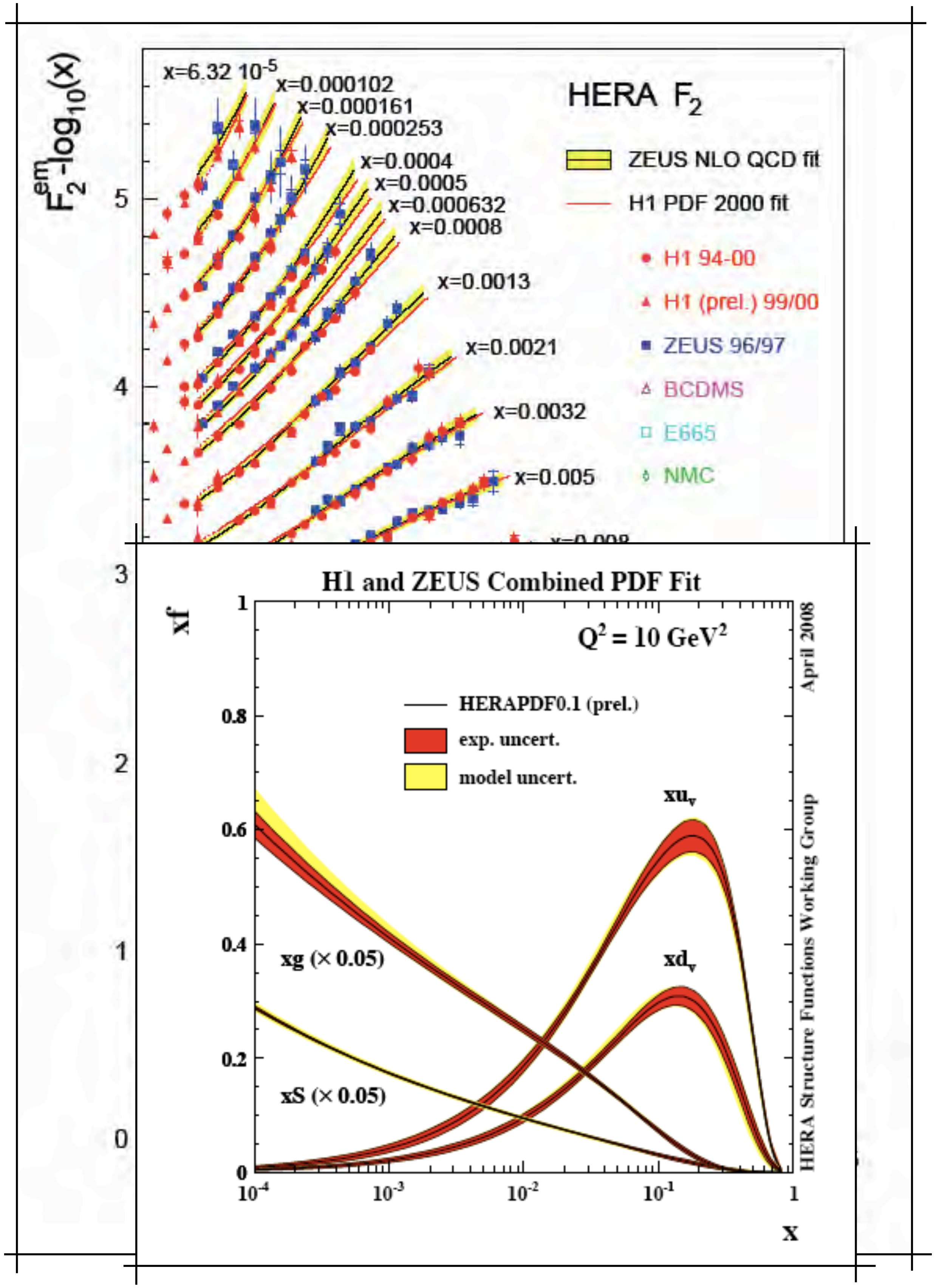

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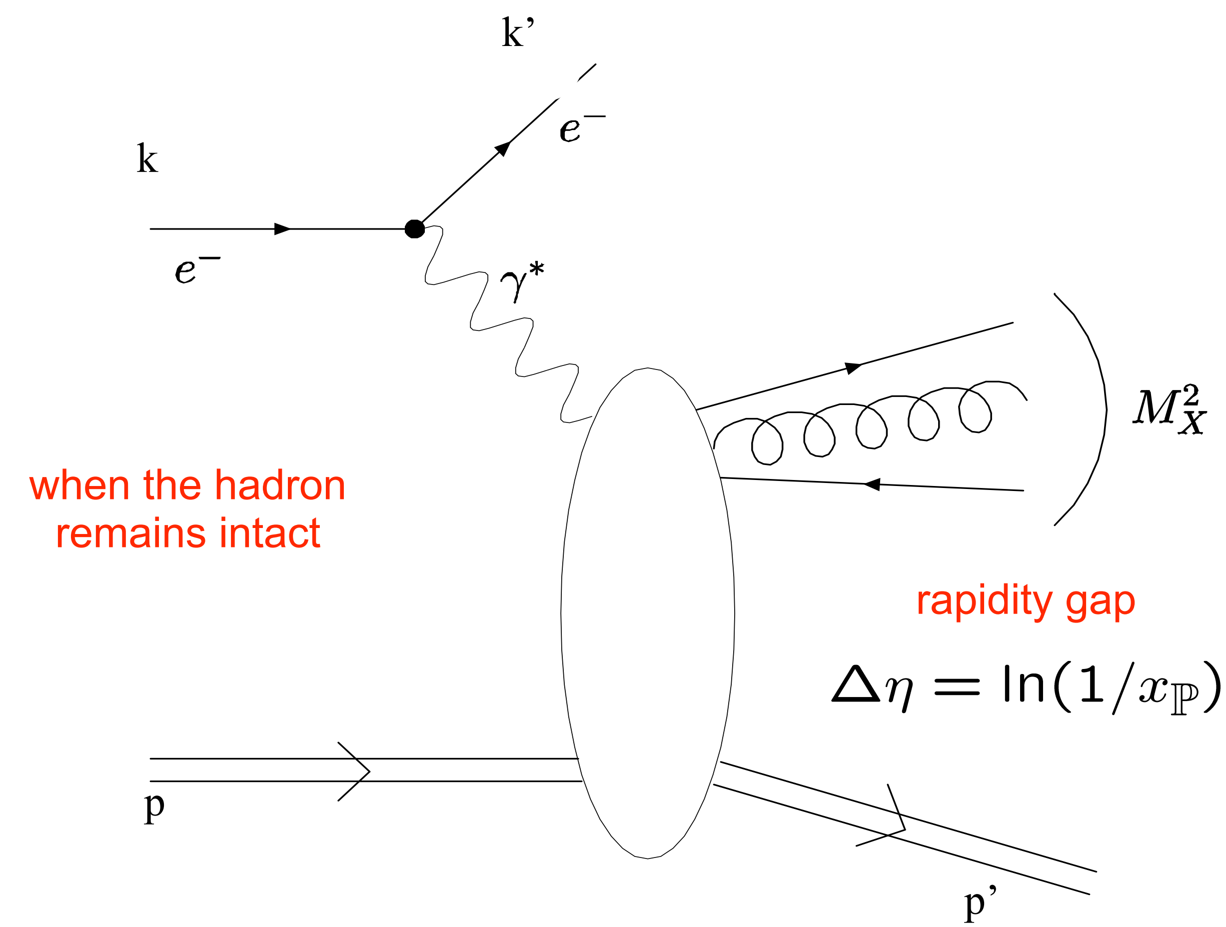


DIS on nuclei:

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

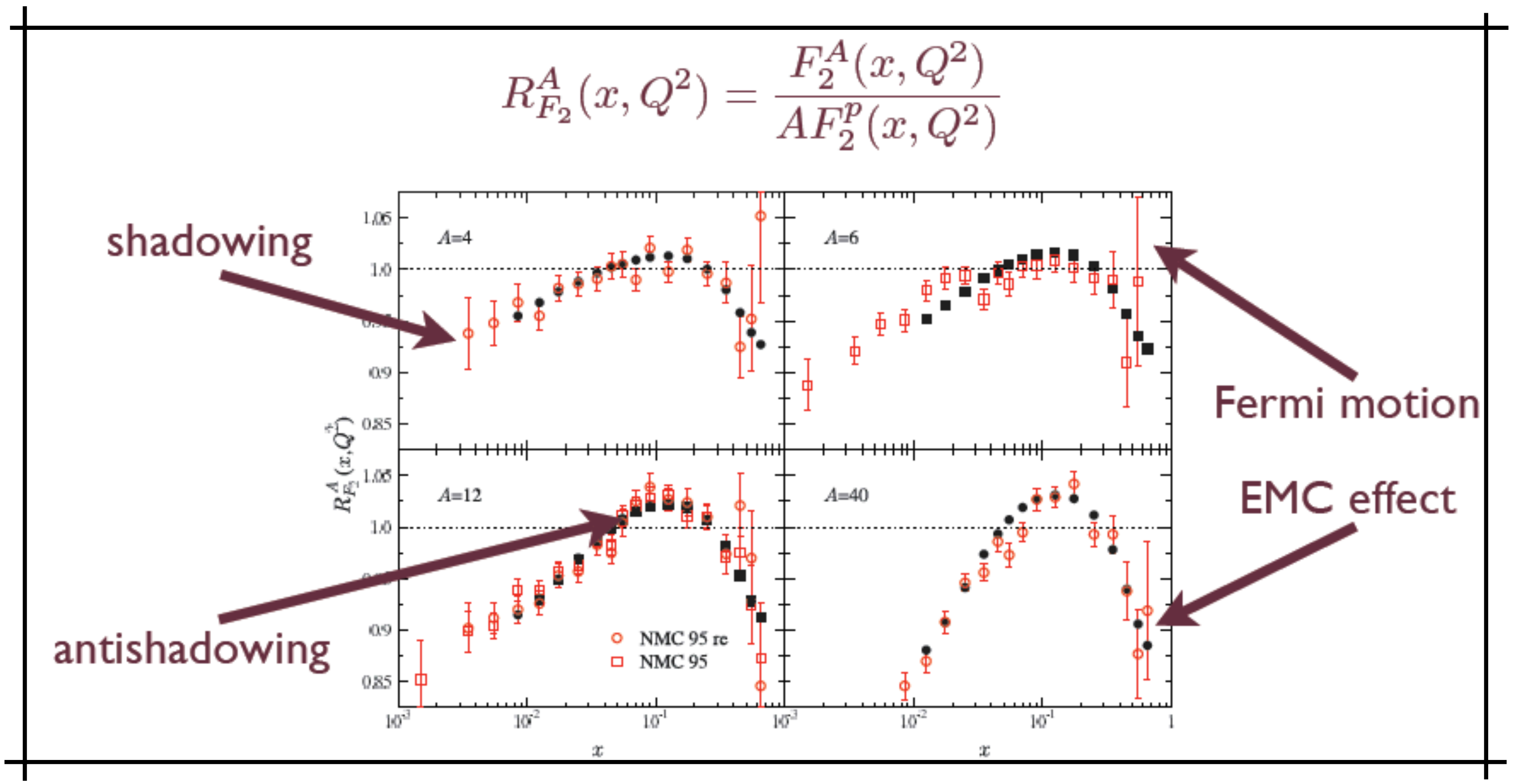
$$\sigma_r = \frac{Q^4 x}{2\pi\alpha^2[1 + (1-y)^2]} \cdot \frac{\mathrm{d}^2\sigma}{\mathrm{d}x\,\mathrm{d}Q^2}$$

$$= F_2(x, Q^2) - f(y) \cdot F_L(x, Q^2)$$

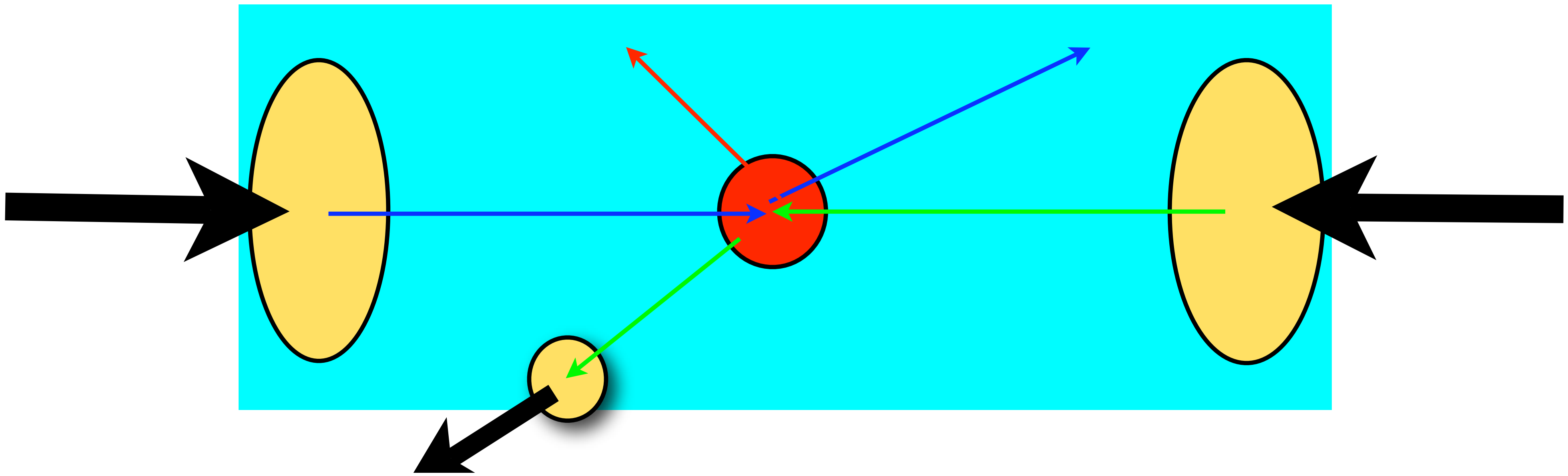
not known at small x

$$f(y) = y^2/[1 + (1-y)^2] \qquad y = Q^2/sx$$

- R=1: absence of nuclear effects.
- R≠1 discovered in the early 70's.

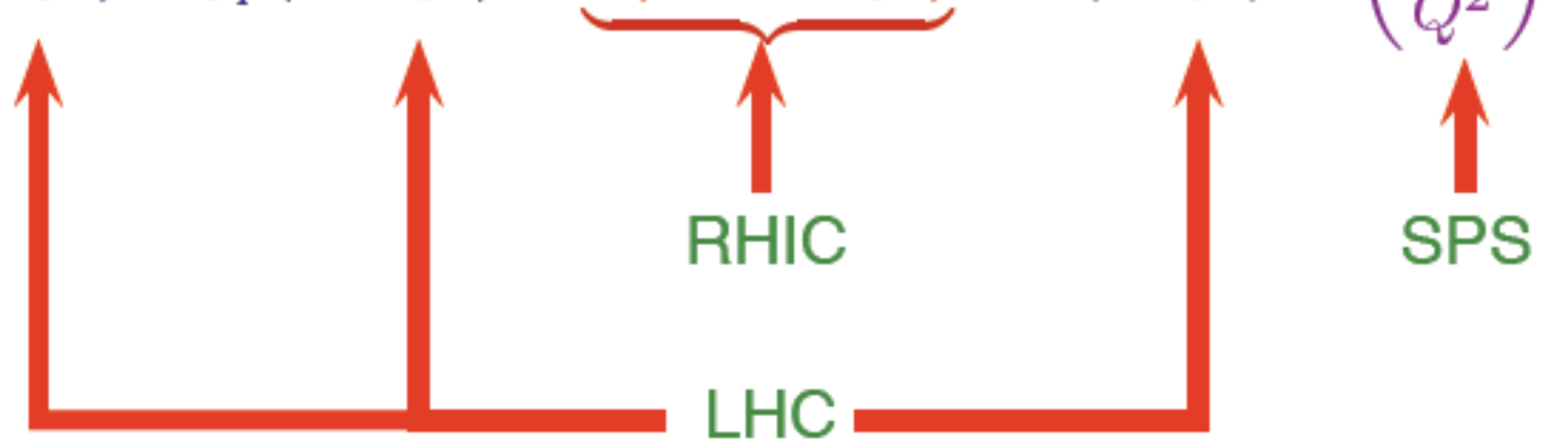


Practice: factorization



$$\sigma^{pp\to h} = f_p(x_1, Q^2) \otimes f_p(x_2, Q^2) \otimes \sigma(x_1, x_2, Q^2) \otimes D(z, Q^2) + \left(\frac{1}{Q^2}\right)^n$$

$$x_{1,2} \sim \sqrt{\frac{p_T^2 + m^2}{s}}\, e^{\pm y}$$



- The usual tool to compute particle production is collinear factorization (for $Q \sim E_{cm} >> \Lambda_{QCD}$).

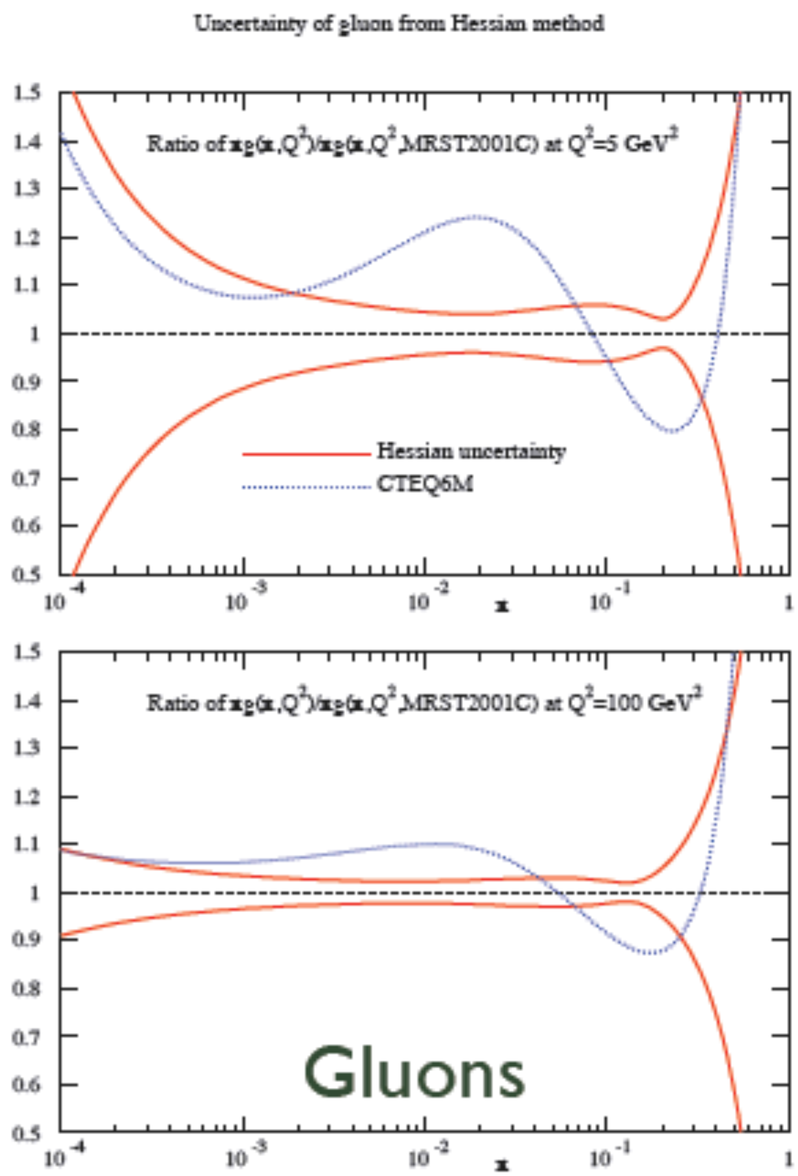
- **f_h, DGLAP-evolved, poorly known out of the measured region.**

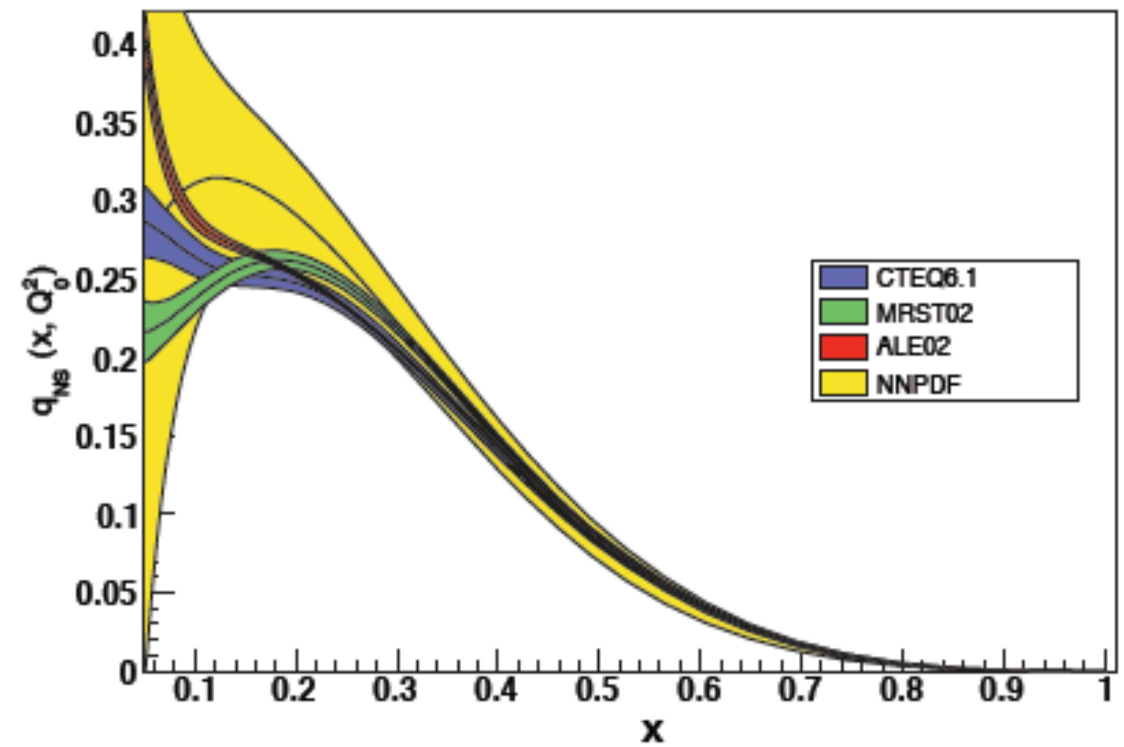
pdf's:

• Inclusive HERA data are well described by usual DGLAP analysis: CTEQ, MSTW, Alekhin, H1/ZEUS, NNPDF. Other proposals include:

1) Resummed L(1/x) schemes.

2) Saturation ideas: **unitarity**; CGC, Regge models, etc.





Non-singlet

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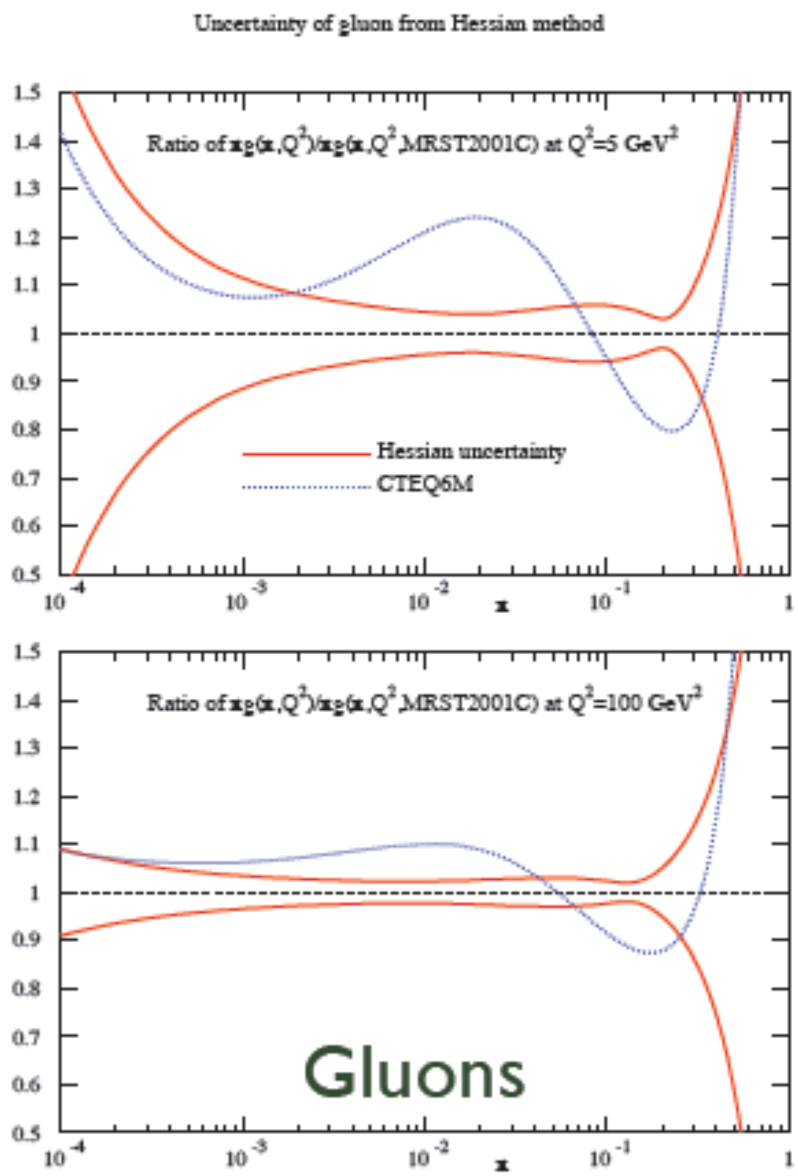
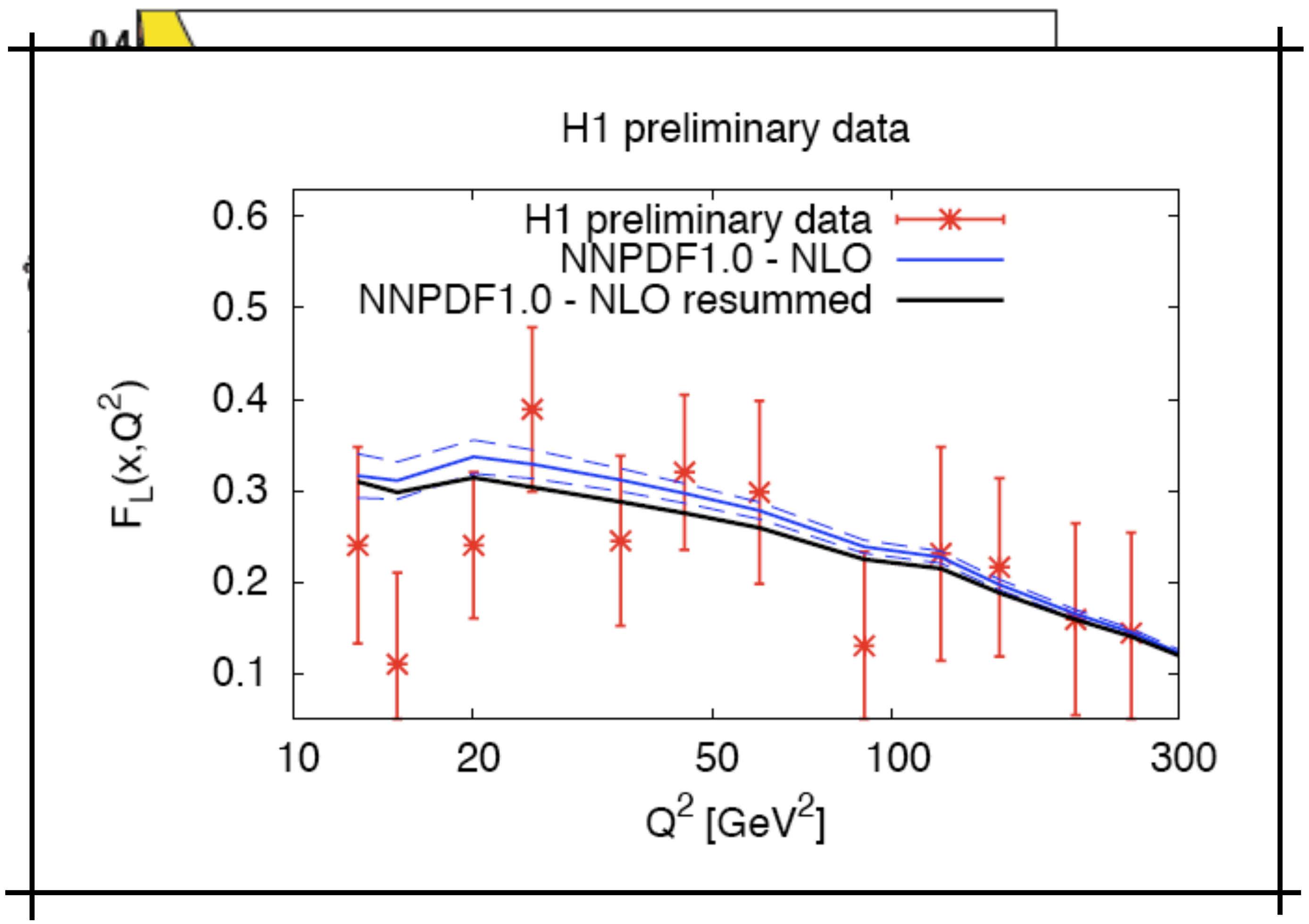
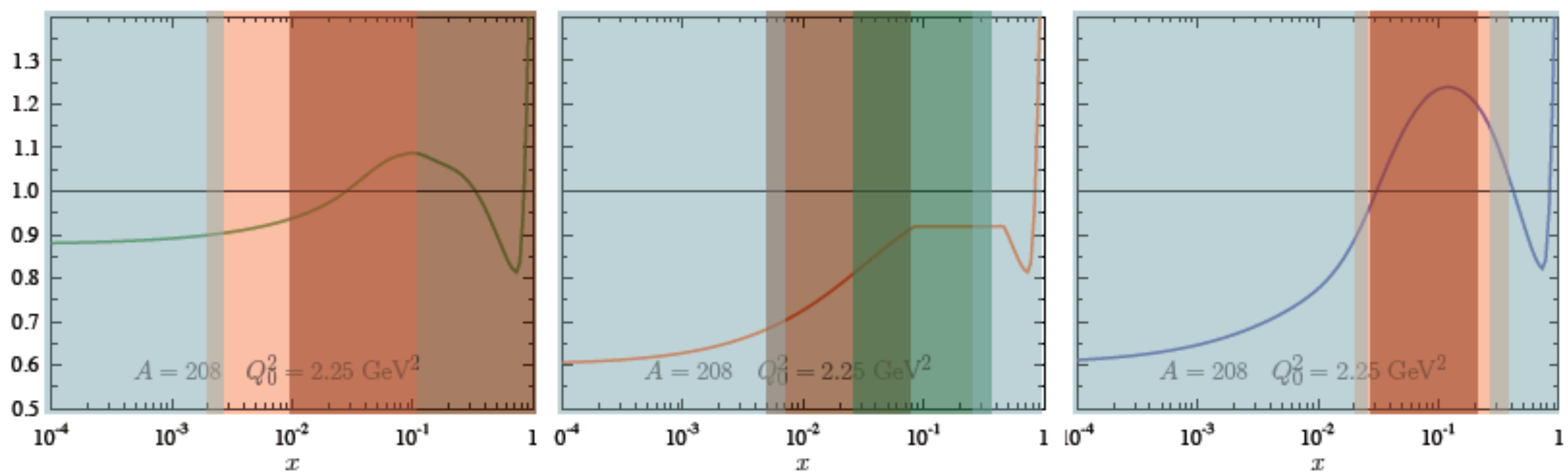


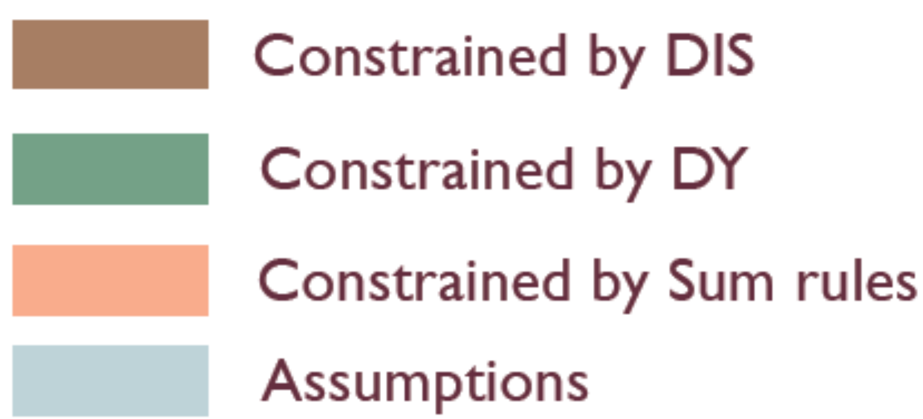


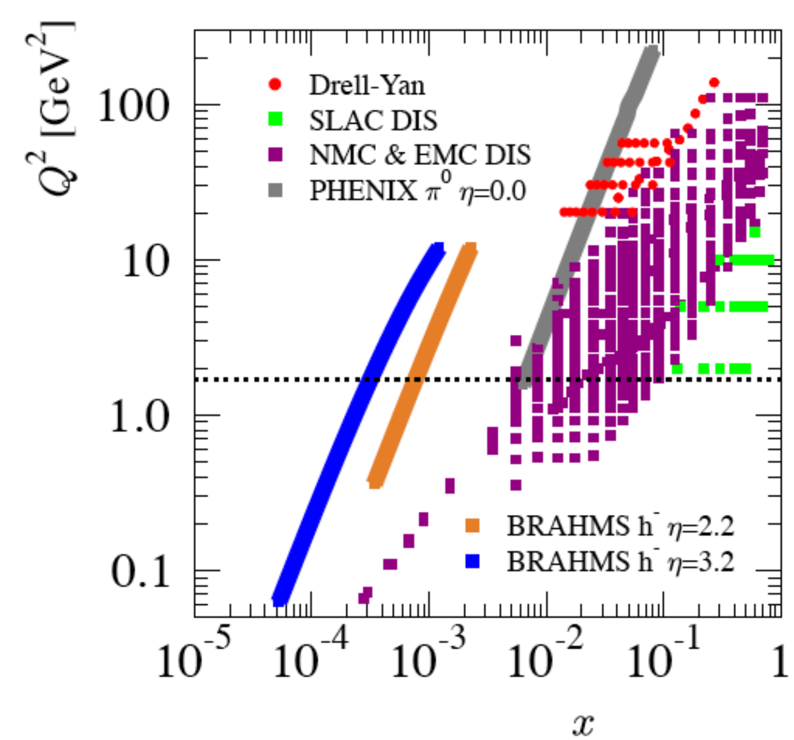
npdf's:

- Data in EPS09 (Q^2, M^2>1.69 GeV^2; p_T>1.7 GeV): 92 from DY (E-772 and 886), 20 from π^0 (PHENIX), rest up to 929 from DIS (E-135, EMC, NMC); neutrino data in CTEQ.

Valence | Sea quarks | Gluons







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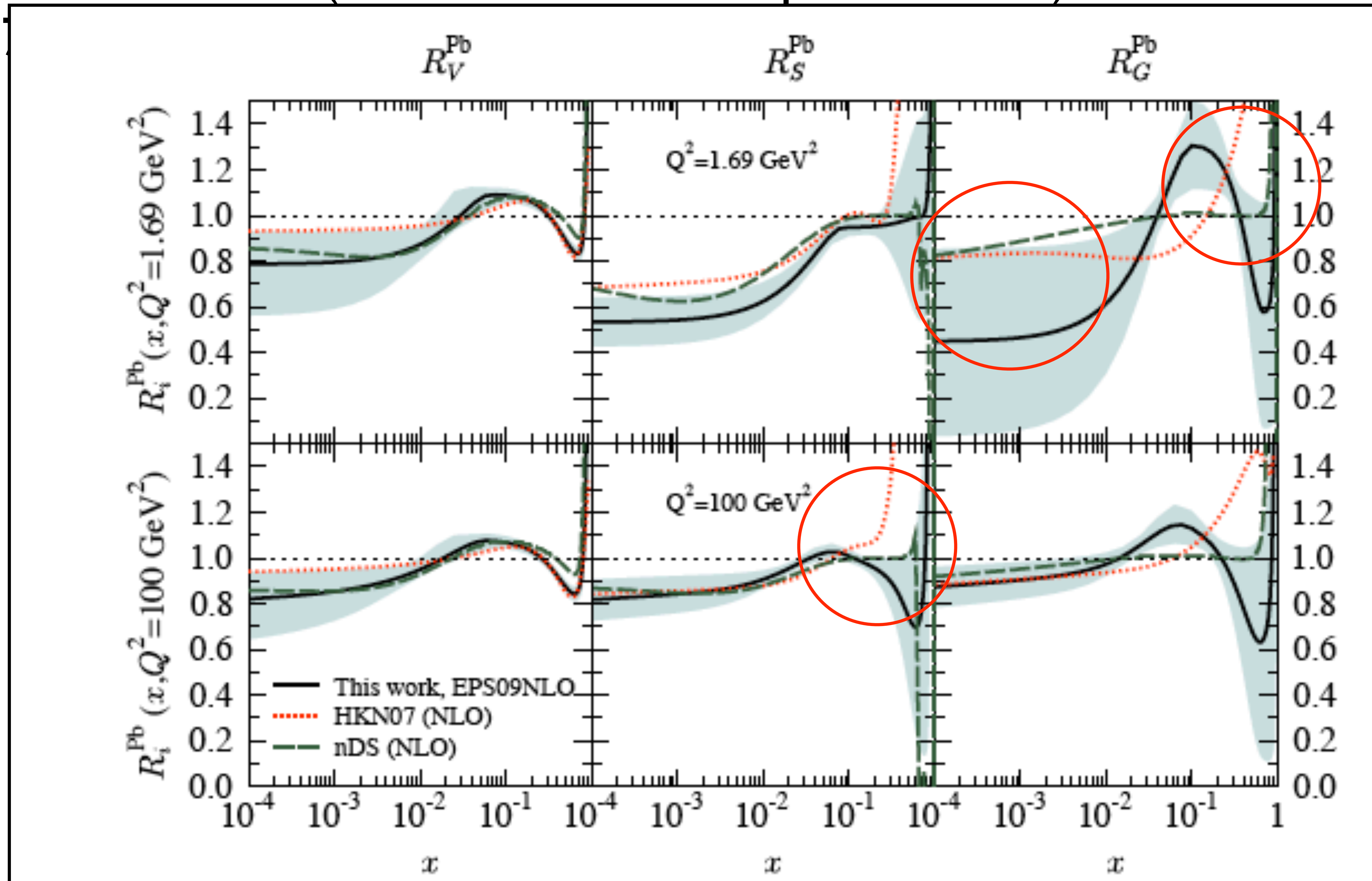

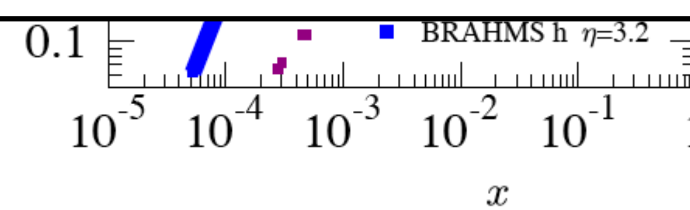

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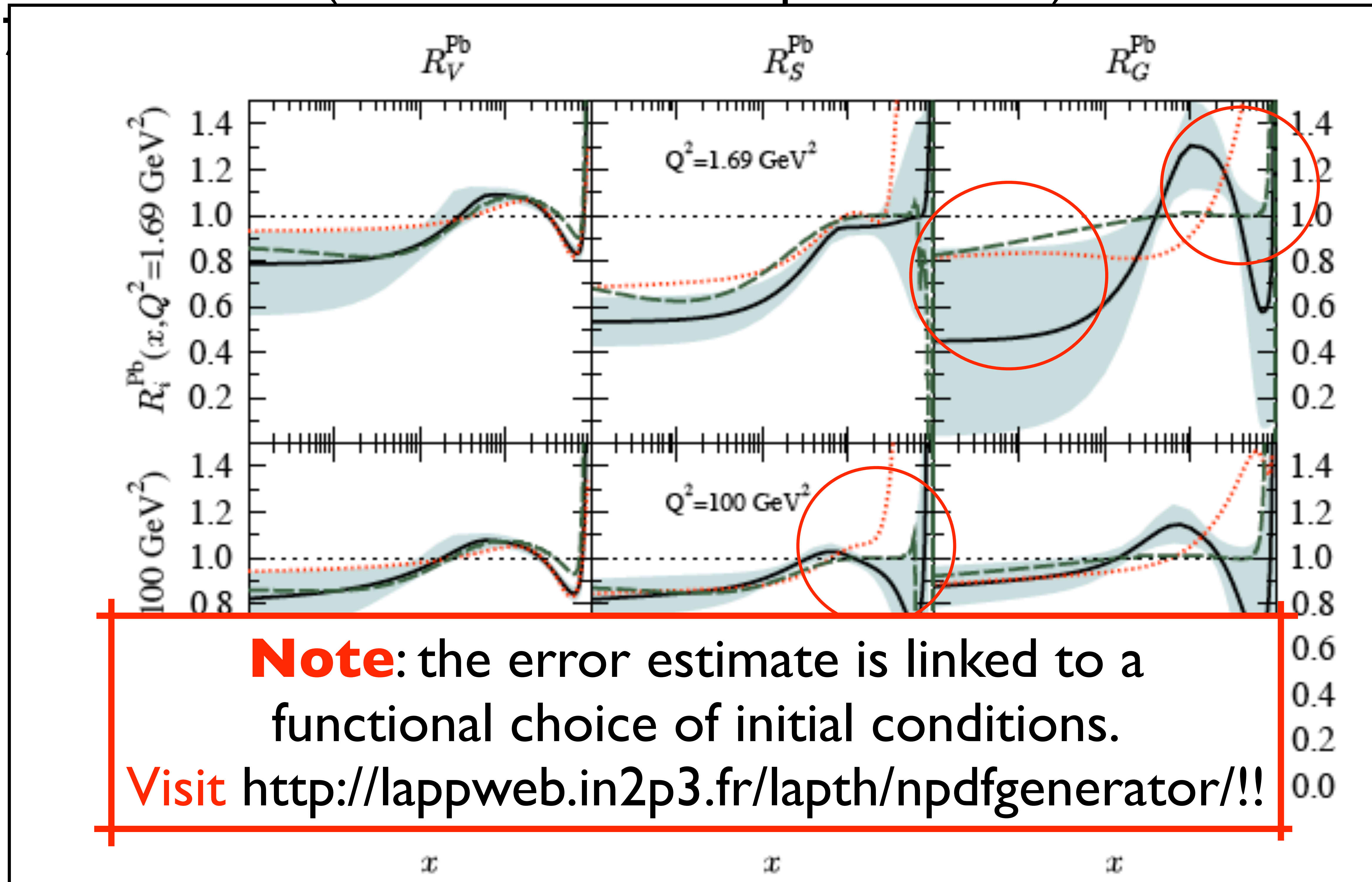
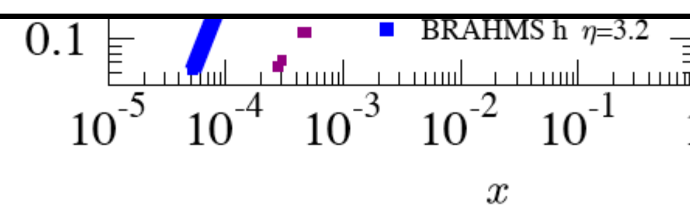
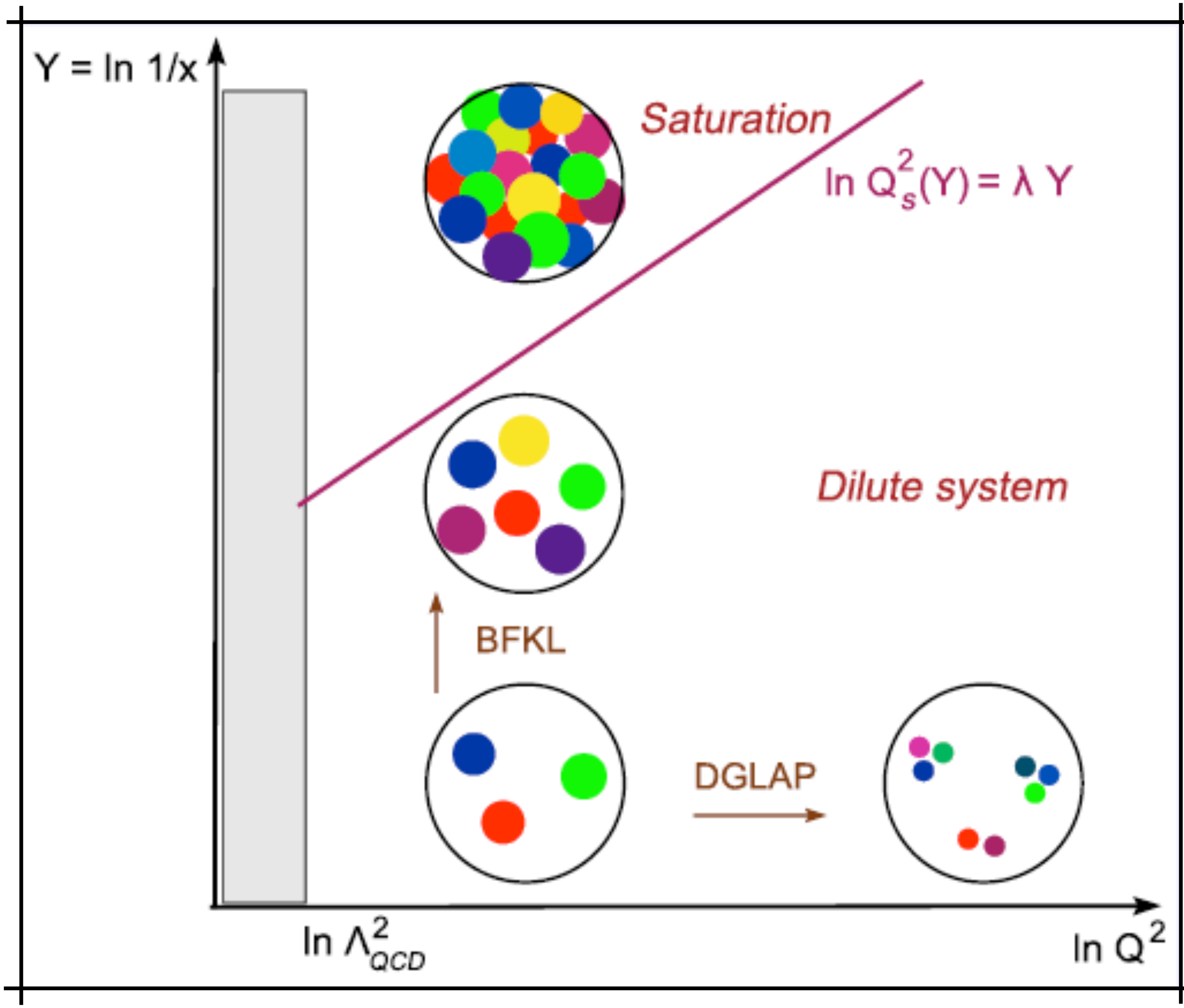


Note: the error estimate is linked to a functional choice of initial conditions.

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



Theory: high-energy QCD



Origin in the early 80's: GLR, MQ, MV.

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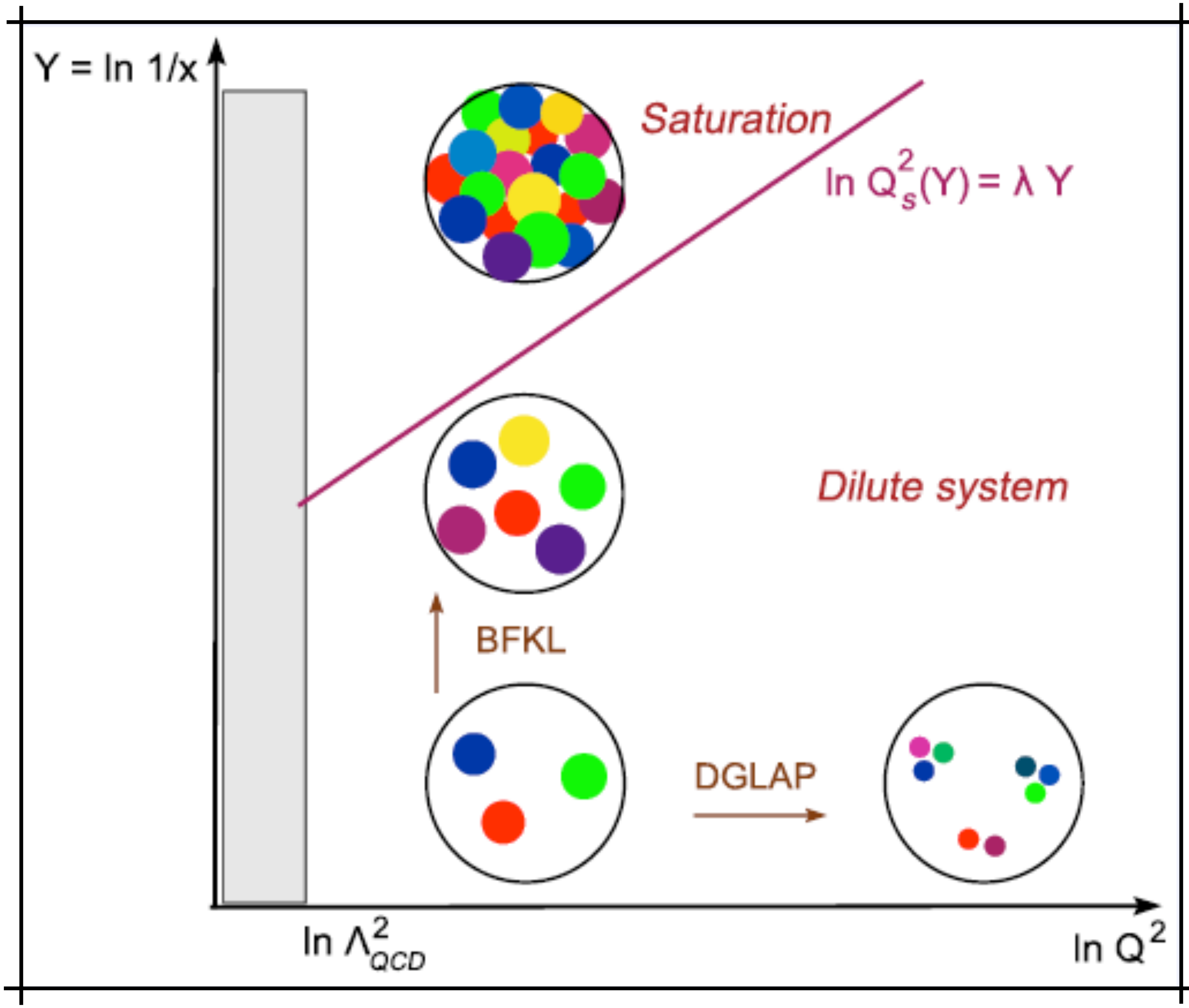
History:

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

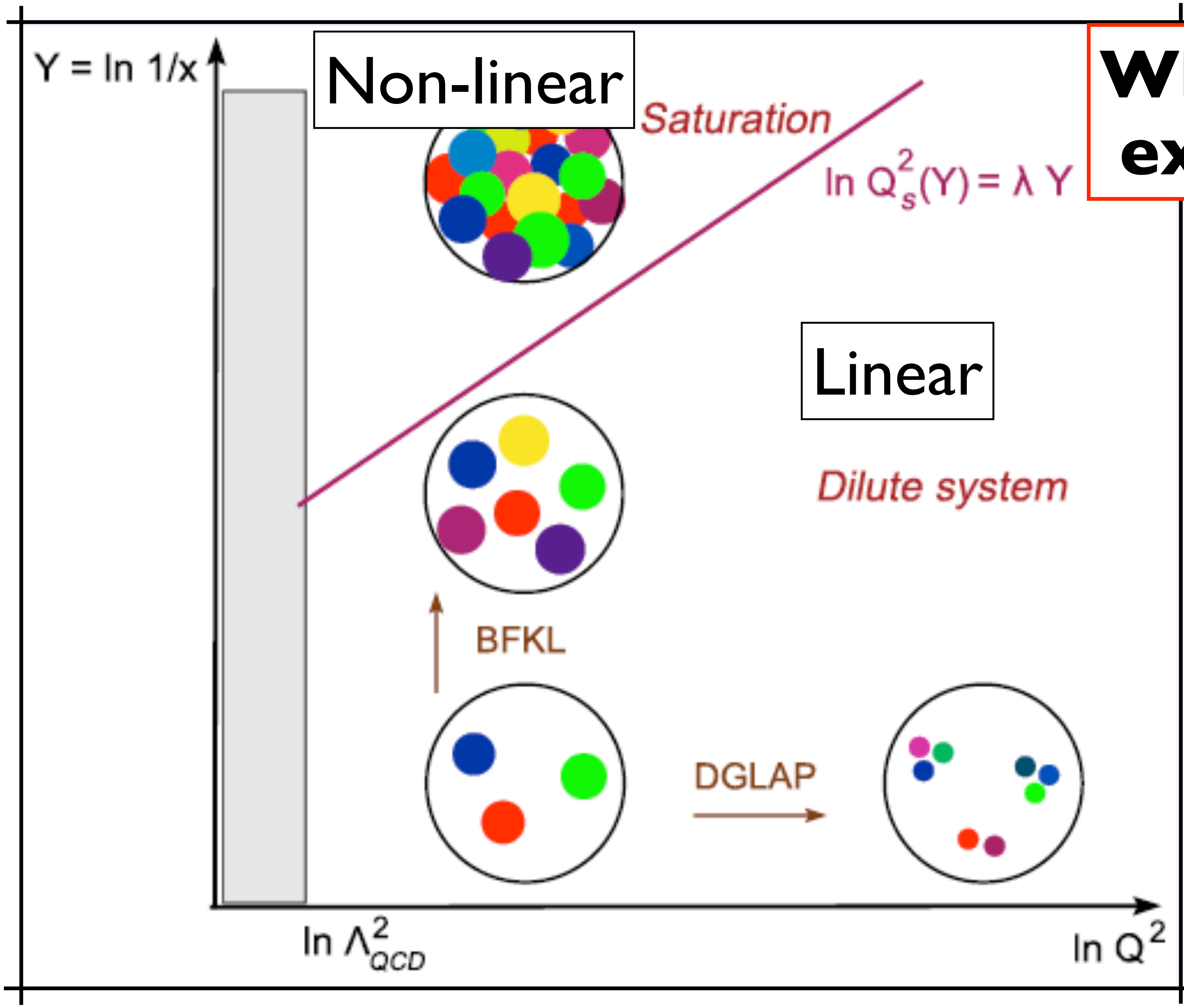


Origin in the early 80's: GLR, MQ, MV.

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

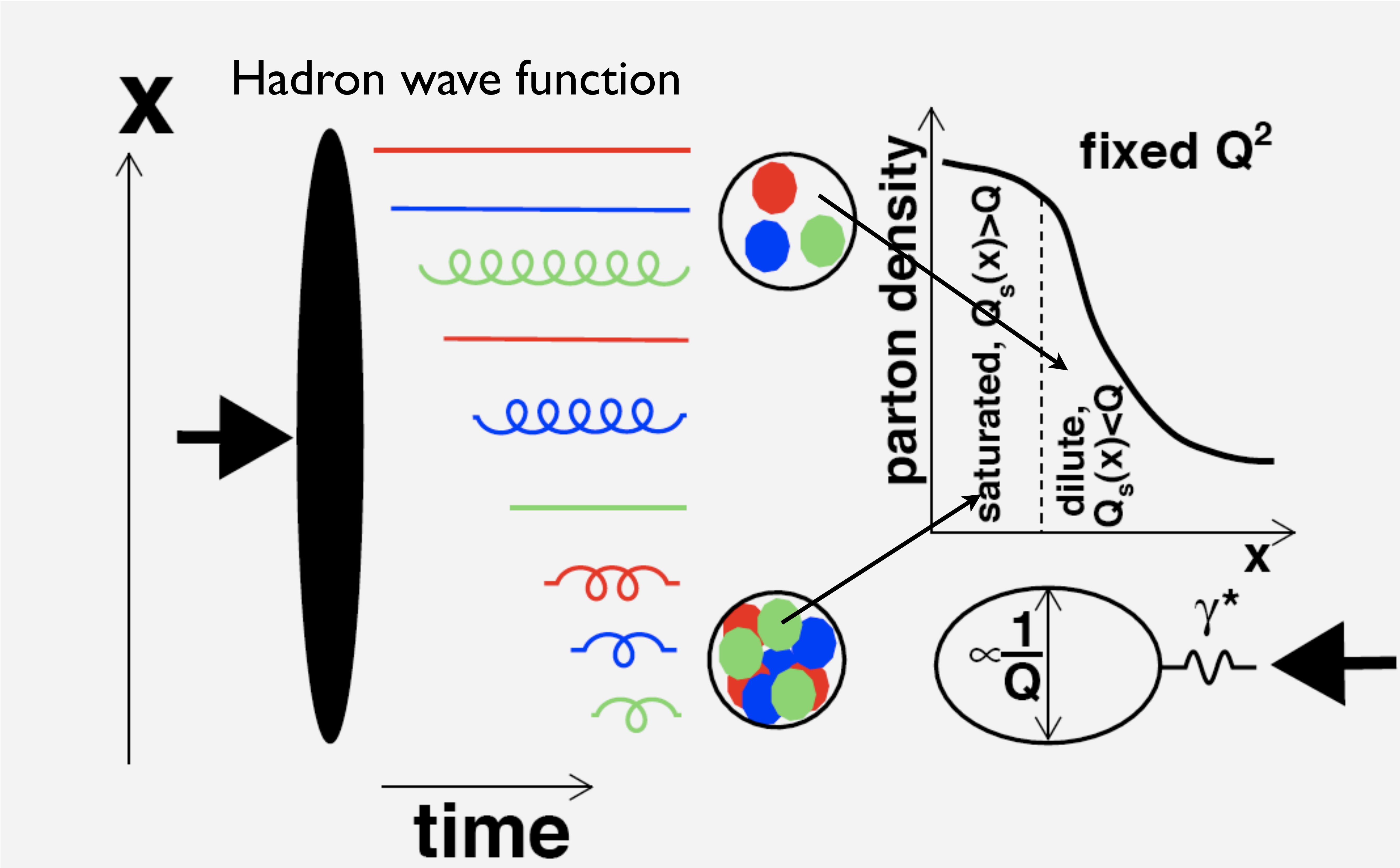


Where do the available experimental data lie?

- 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.

Origin in the early 80's: GLR, MQ, MV.

Saturation ideas: CGC



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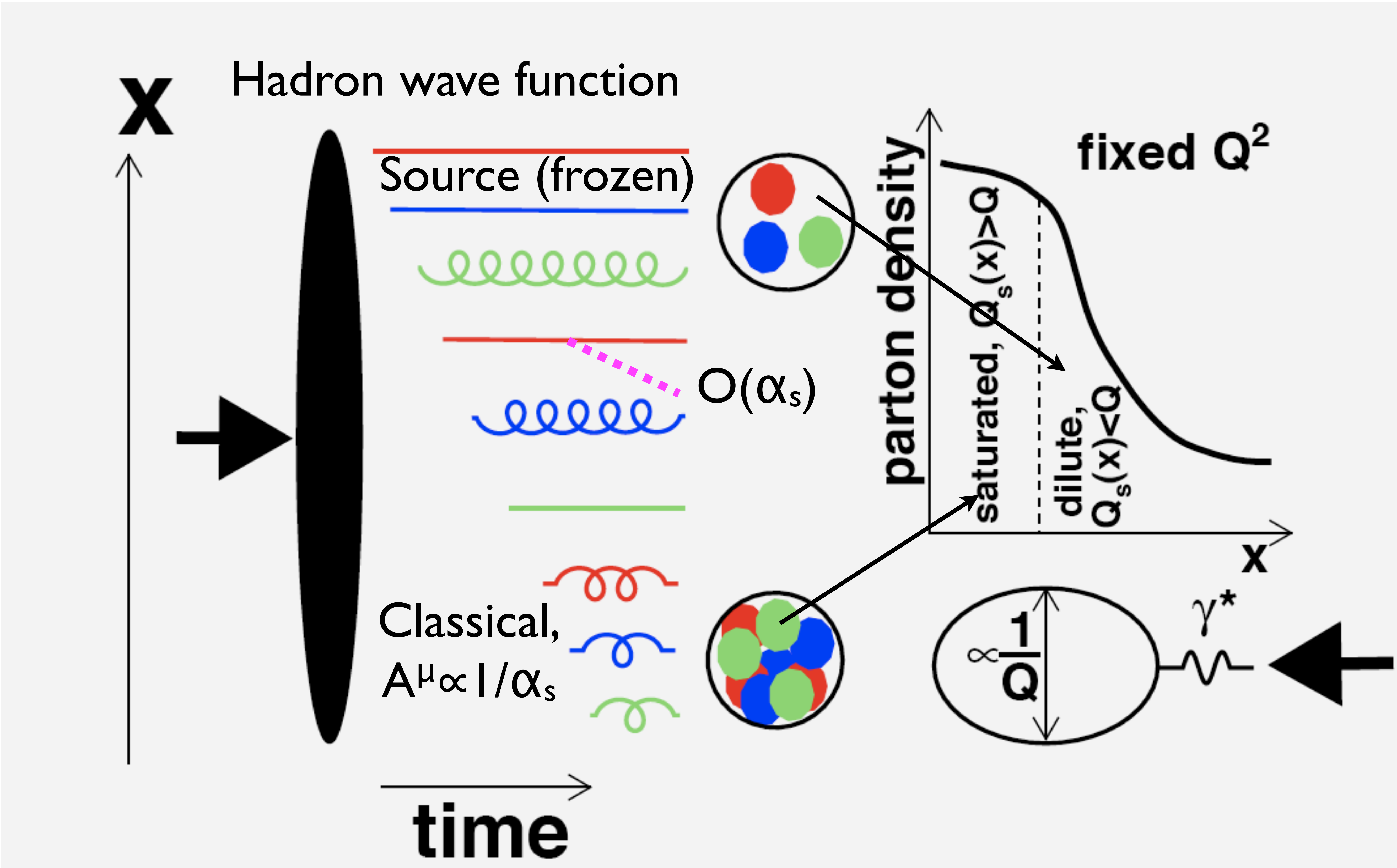
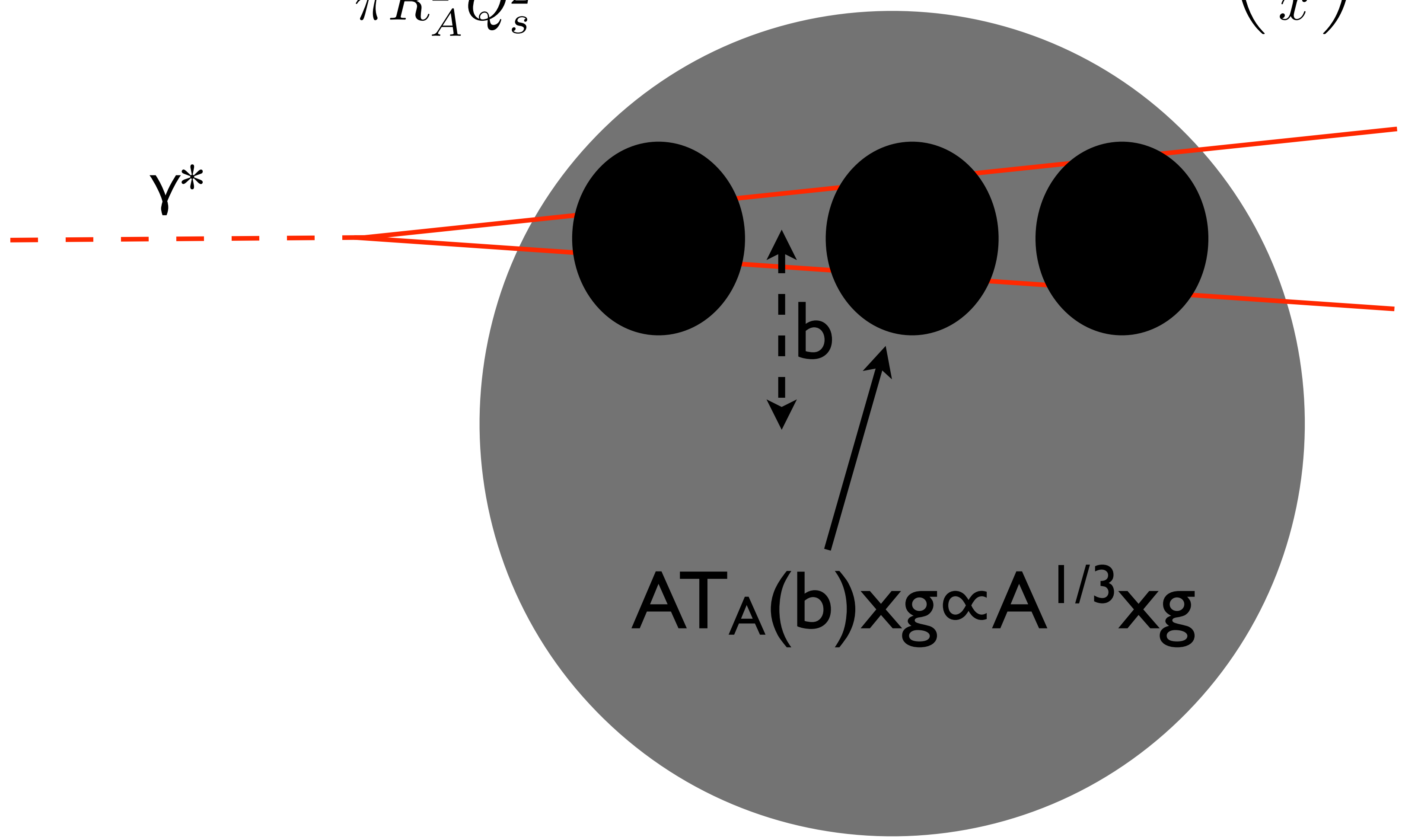
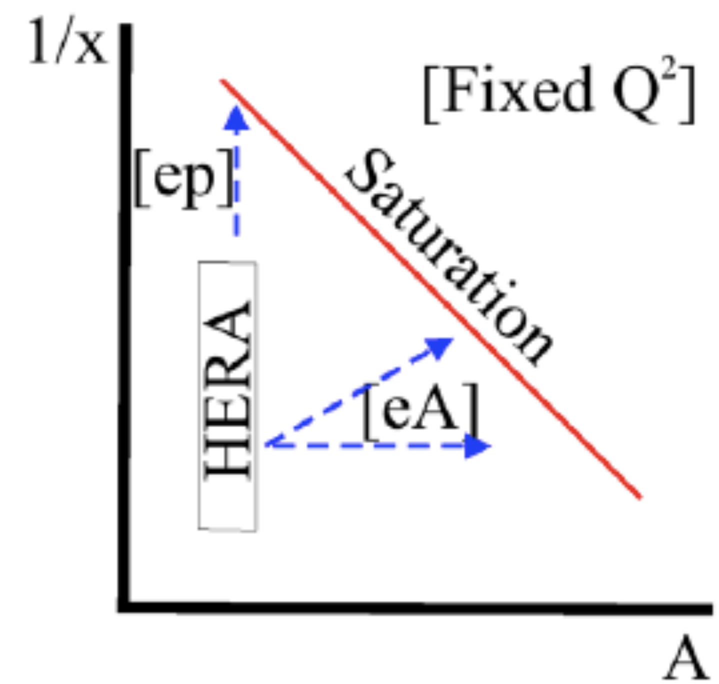


Saturation ideas: CGC

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

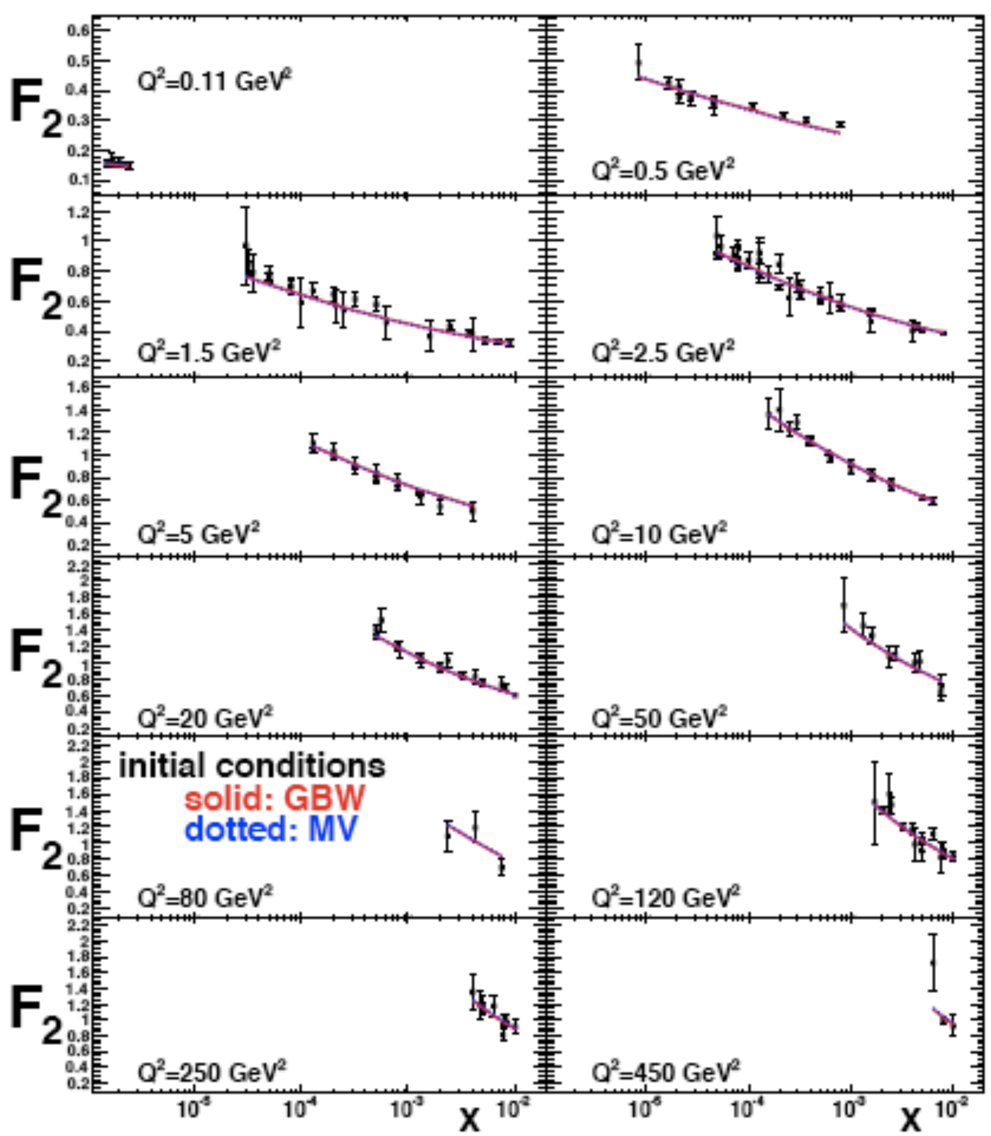


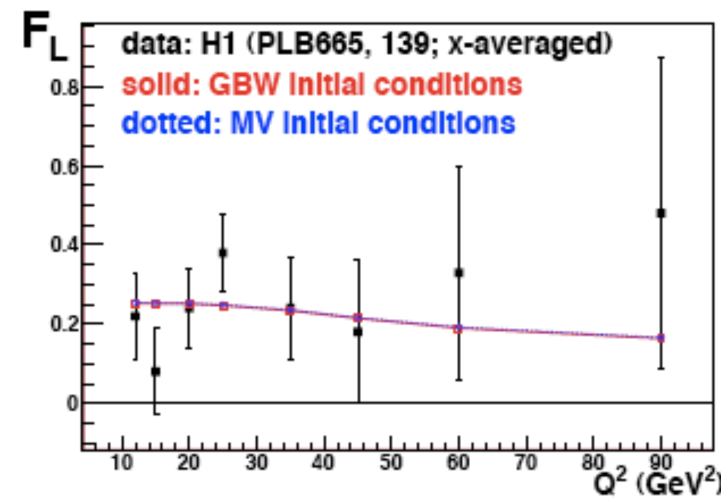
Nuclei: they offer the possibility of testing these ideas (density effect) and enhance the saturation effects for a fixed x (energy).

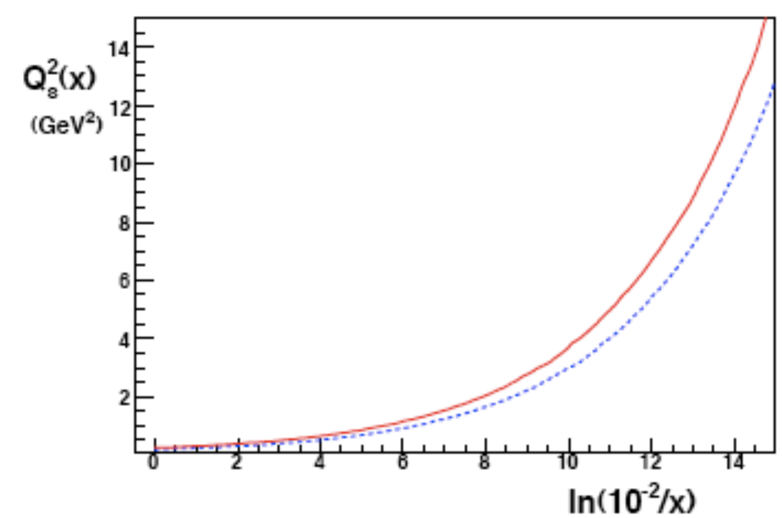


Saturation ideas: CGC

- Phenomenology based on saturation (rcBK) is successful for inclusive and diffractive DIS for small and moderate Q^2.
- Deviations from NLO DGLAP have been claimed recently (Caola, Forte, Rojo '09), incompatible with NNLO.







Status:

- DGLAP evolution (fixed order PT) is extremely successful in inclusive DIS. Diffractive DIS can be understood too, but diffractive factorization breaks when going to pp(bar).
- Resummation schemes (L(1/x): BFKL → CCFM, T, ABF, CCSS): look nearly ready to become competitive.
- CGC realization (no longer models!) is also successful.
- **Differences lie at moderate $Q^2(>\Lambda^2_{QCD})$ and small x.**
- Unitarity (non-linear effects) must be out there (maybe even already in here), the question is where 'there' is ⇒

  ☛ Theory: refine the tools and predict.

  ☛ Experiment: measure new kinematical regions: LHC, EIC, LHeC.

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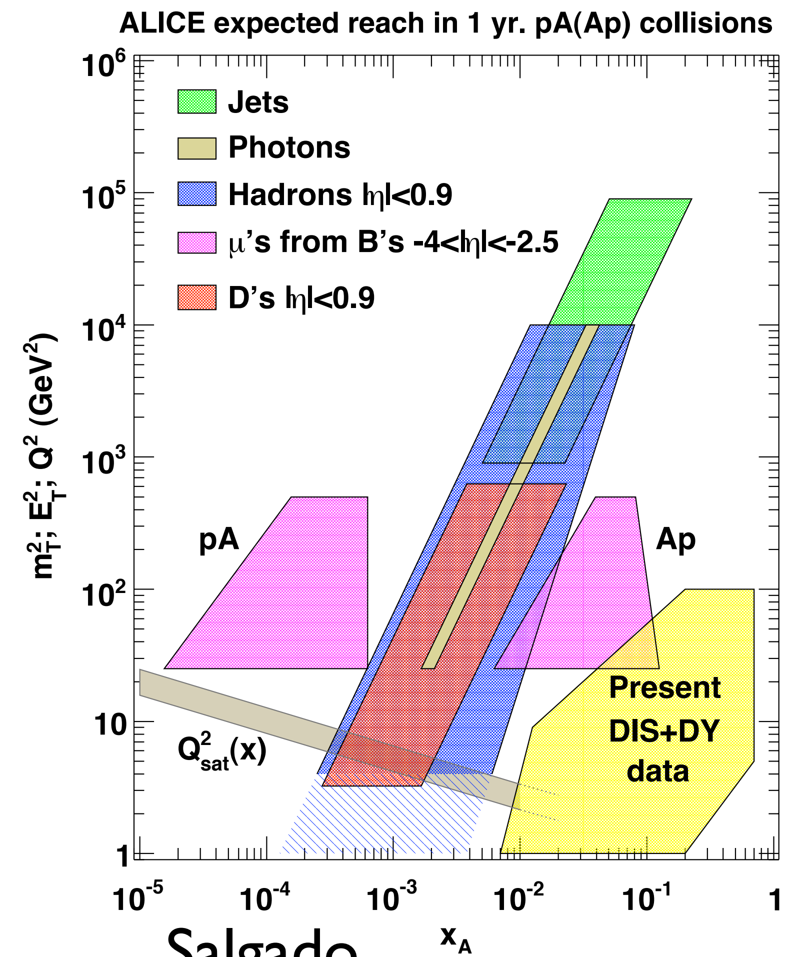
LHC:

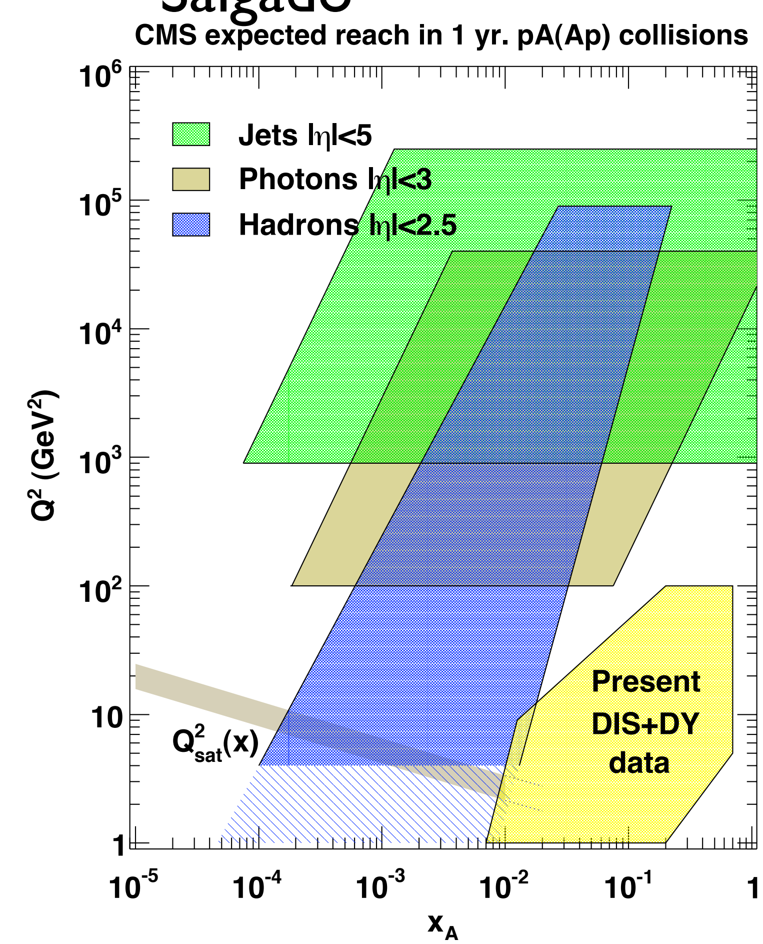
- pp at η=0 should be quite well constrained by HERA data (+ DGLAP evolution).

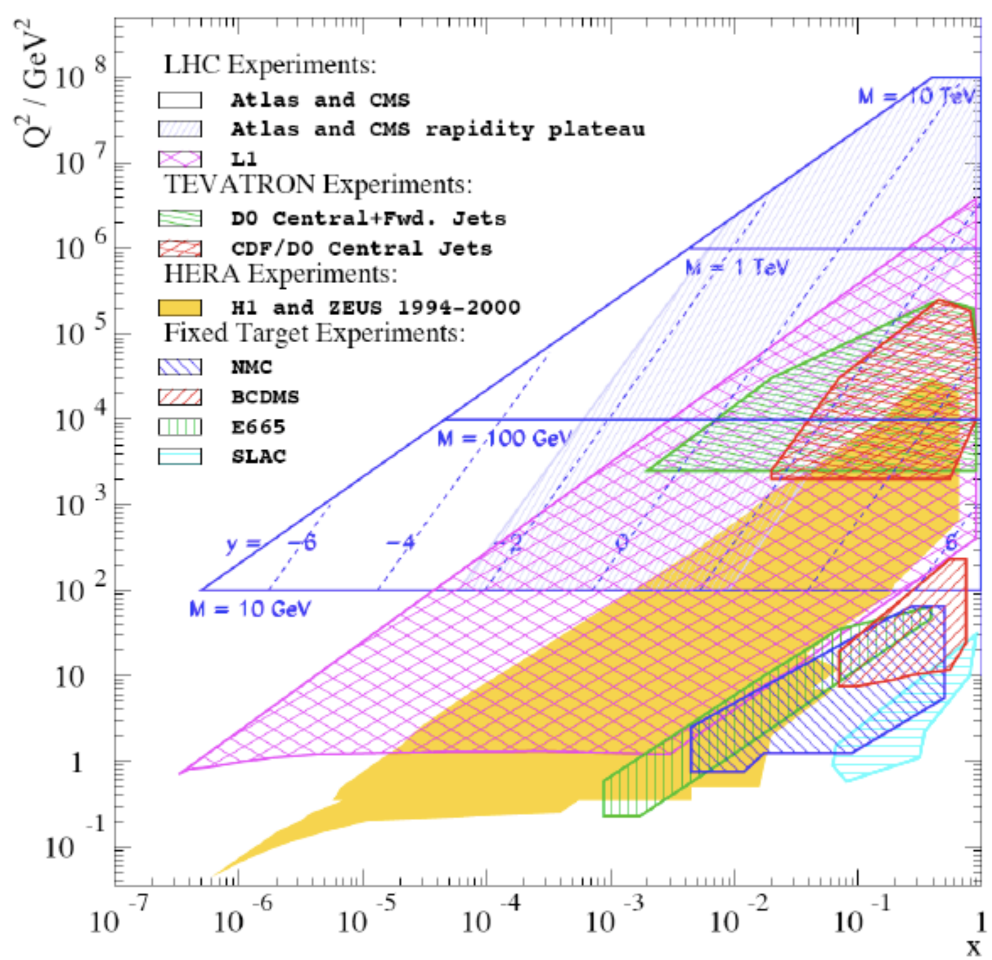
- pp at η>0 will offer constrains on pdf's

- pPb, not coming during first pp runs, would give valuable information about npdf's.



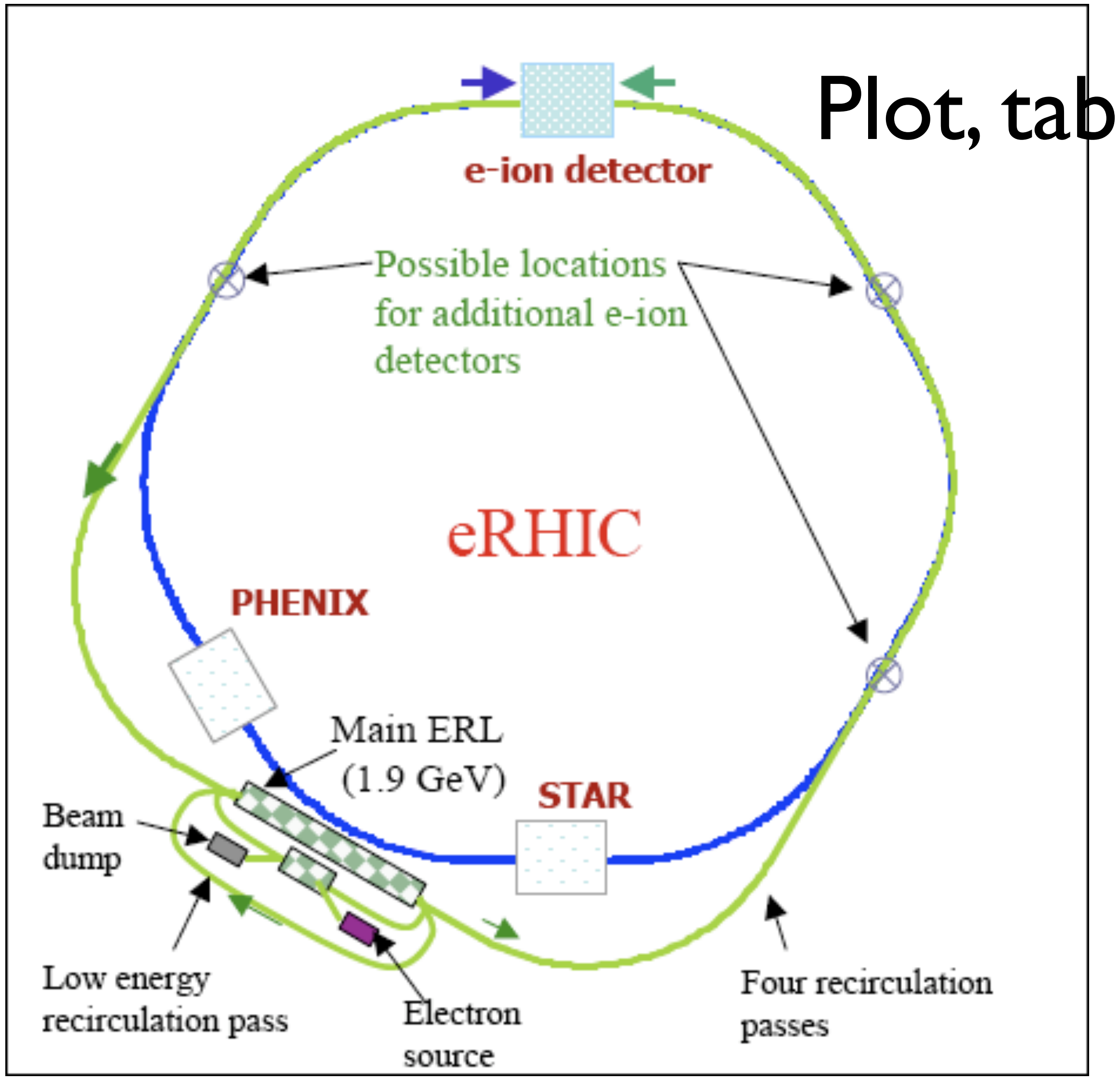
Salgado





EIC:

- Project at JLAB, uses CEBAF, need of building a proton/nucleus accelerator: larger cost and luminosity. Polarized protons?
- Project at BNL, uses RHIC (polarized protons), need of building an electron accelerator: lower cost and luminosity. Stage approach in coordination with RHIC-II.



Plot, table from 2008!!!

	High energy setup		Low energy setup	
	p	e	p	e
Energy, GeV	250	10	50	3
Number of bunches	166		166	
Bunch spacing, ns	71	71	71	71
Bunch intensity, 10^{11}	2	1.2	2	1.2
Beam current, mA	420	260	420	260
Normalized 95% emittance, π mm.mrad	6	460	6	570
Rms emittance, nm	3.8	4	19	16.5
β^*, x/y, cm	26	25	26	30
Beam-beam parameters, x/y	0.015	0.59	0.015	0.47
Rms bunch length, cm	20	1	20	1
Polarization, %	70	80	70	80
Peak Luminosity, 1.e33 $cm^{-2}s^{-1}$	2.6		0.53	
Aver.Luminosity, 1.e33 $cm^{-2}s^{-1}$	0.87		0.18	
Luminosity integral /week, pb^{-1}	530		105	

LHeC: www.lhec.cern.ch

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History and Organisation

The Large Hadron Electron Collider Project

1990: LEP*LHC (Aachen Workshop)
2001: THERA (TESLA TDR)
2005: LHeC: * DIS, Madison
2006: $10^{33}cm^{-2}s^{-1}$: 2006 JINST 1 10001
2007 CERN Council and [r]ECFA
2008 Divonne I, NuPECC, ICFA,ECFA
2009 Divonne II (1.-3.9.), ECFA 11/09

→ **2010: Conceptual Design Report**

http://www.lhec.org.uk

Please join/register for Divonne II – 1.-3.9.09

Working Group Convenors

Accelerator Design [RR and LR]
Oliver Bruening (CERN),
John Dainton (CI/Liverpool)
Interaction Region and Fwd/Bwd
Bernhard Holzer (DESY),
Uwe Schneeekloth (DESY),
Pierre van Mechelen (Antwerpen)
Detector Design
Peter Kostka (DESY),
Rainer Wallny (UCLA),
Alessandro Polini (Bologna)
New Physics at Large Scales
Emmanuelle Perez (CERN),
Georg Weiglein (Durham)
Precision QCD and Electroweak
Olaf Behnke (DESY),
Paolo Gambino (Torino),
Thomas Gehrmann (Zuerich)
Claire Gwenlan (Oxford)
Physics at High Parton Densities
Nestor Armesto (CERN),
Brian Cole (Columbia),
Paul Newman (Birmingham),
Anna Stasto (MSU)

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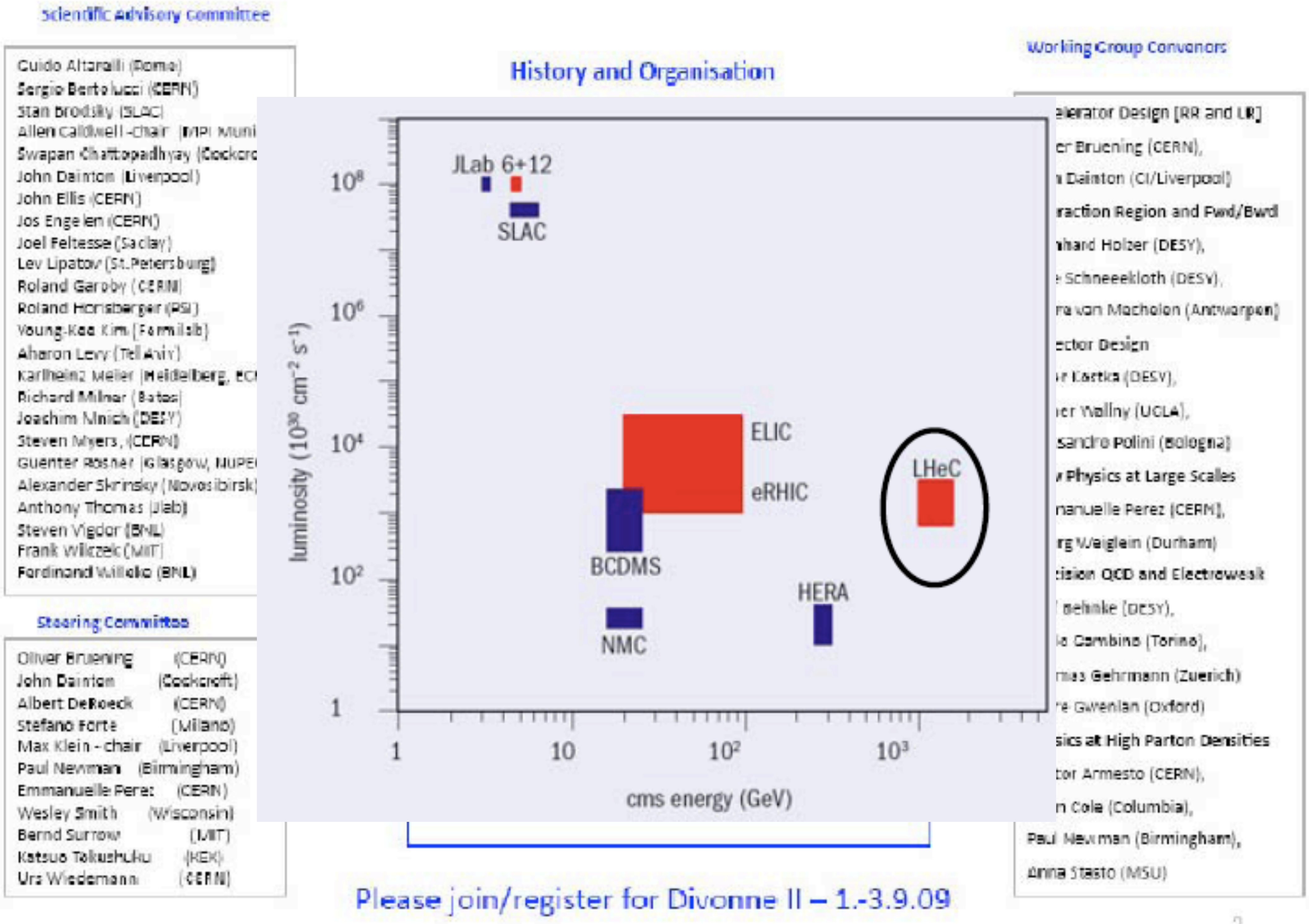
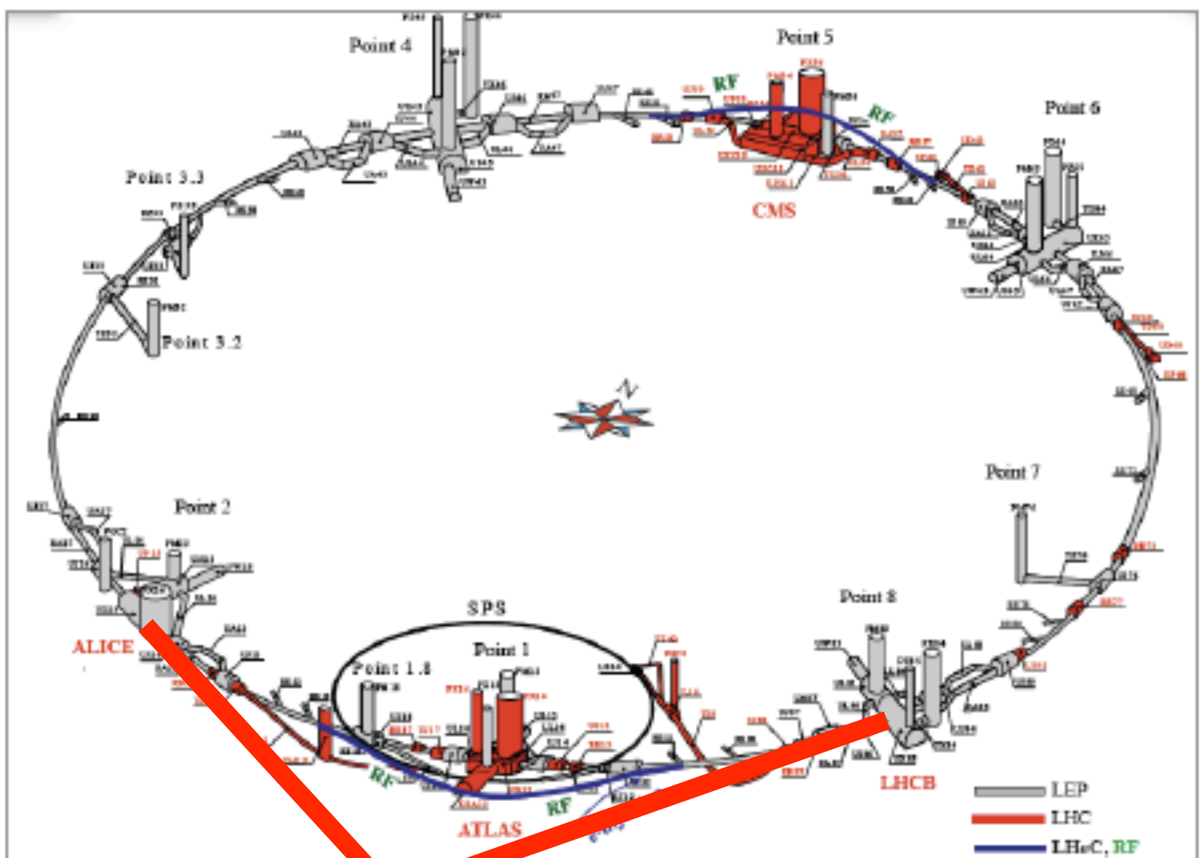
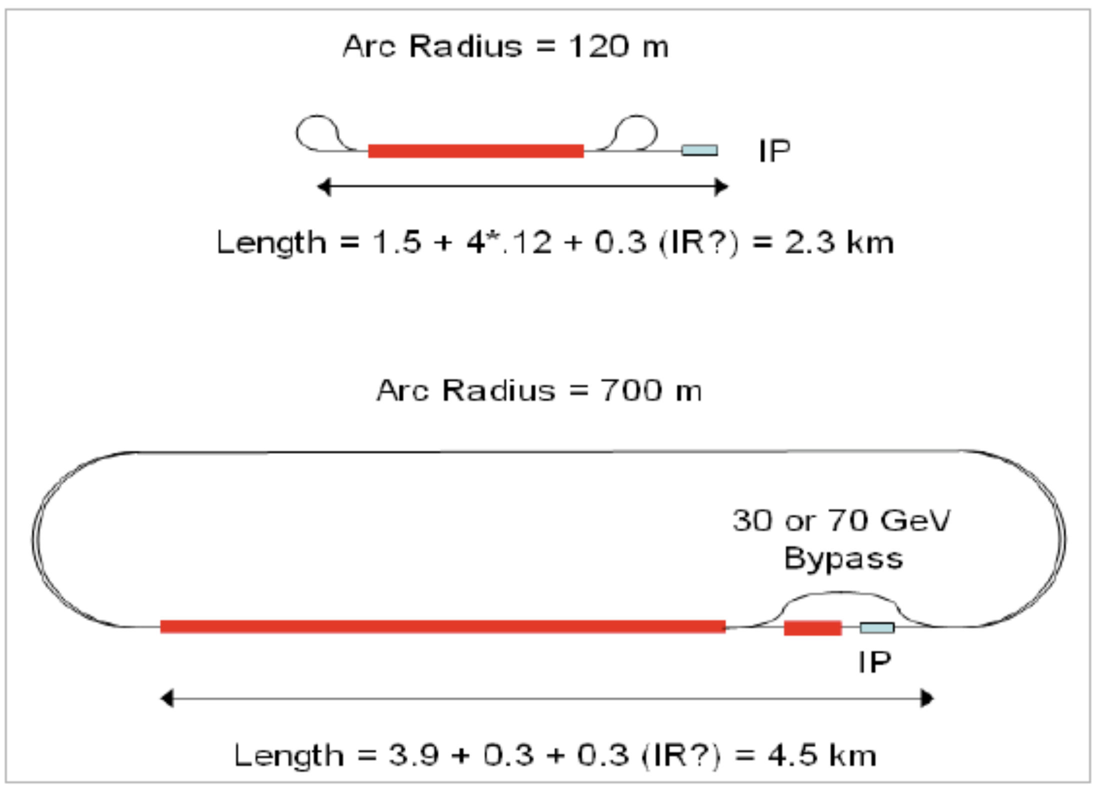


LHeC: the accelerator

- Interaction points: ALICE, LHCb.
- RR, LR options explored in the CDR.
- Luminosities in ePb comparable with those in ep!

Ring-Ring ep/eA





E_e=10 ... 70 GeV. L_{ep}~$10^{33}cm^{-2}s^{-1}$ (100 times HERA)

LHeC: the accelerator

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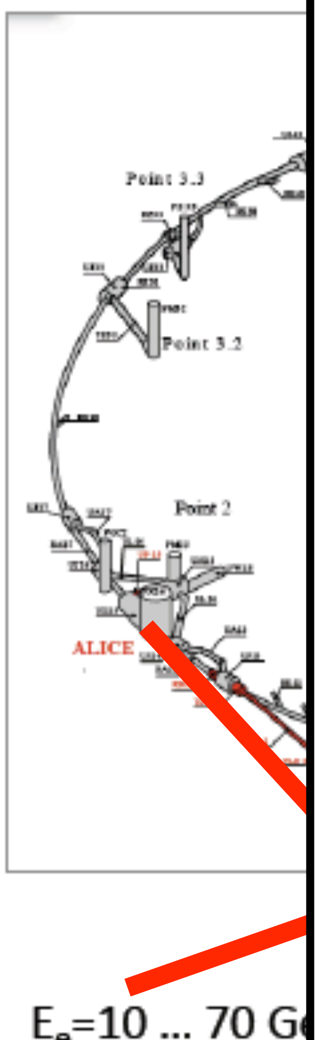
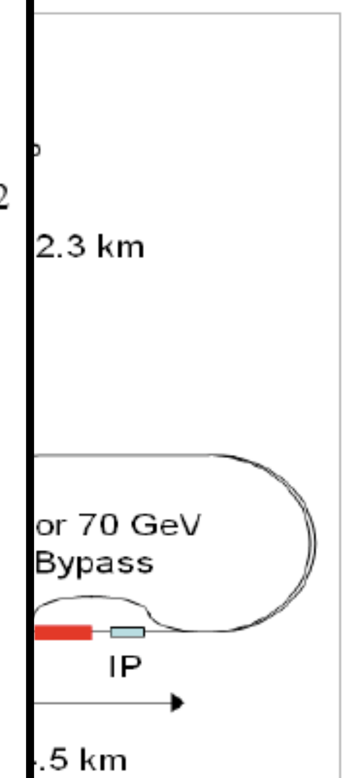


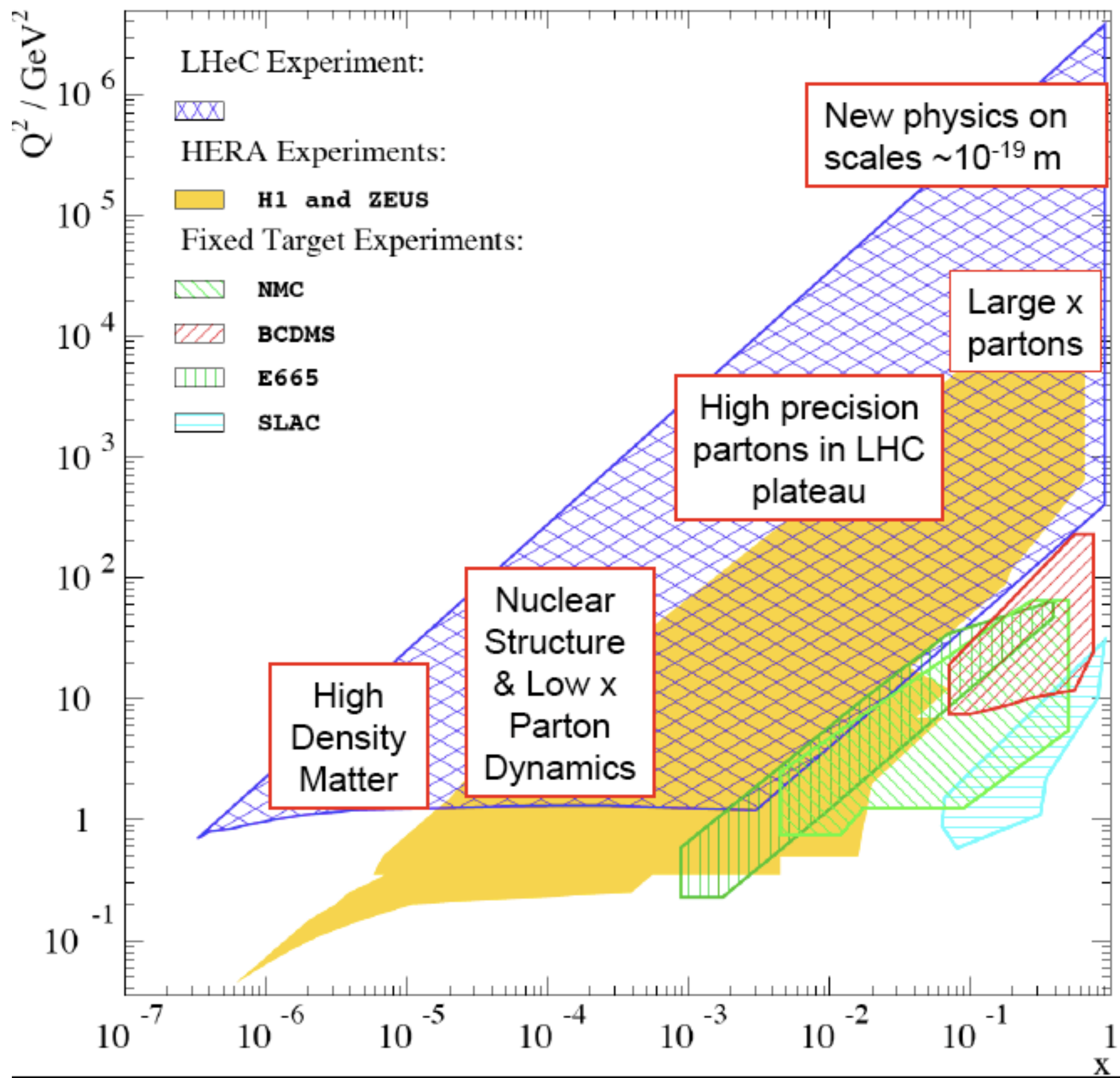
config.	E(e)	E(N)	N	$\int L(e^+)$ fb^{-1}	$\int L(e^-)$	|Pol|	$L/10^{32}$	P/MW	years	type
A	20	7	p	1	1	-	1	10	1	SPL
B	50	7	p	50	50	0.4	25	30	2	RR hiQ^2
C	50	7	p	1	1	0.4	1	30	1	RR lo x
D	100	7	p	5	10	0.9	2.5	40	2	LR
E	150	7	p	3	6	0.9	1.8	40	2	LR
F	50	3.5	D	1	1	--	0.5	30	1	eD
G	50	2.7	Pb	0.1	0.1	0.4	0.1	30	1	ePb
H	50	1	p	--	1	--	25	30	1	lowEp



LHeC: physics goals

√s=1-2 TeV:

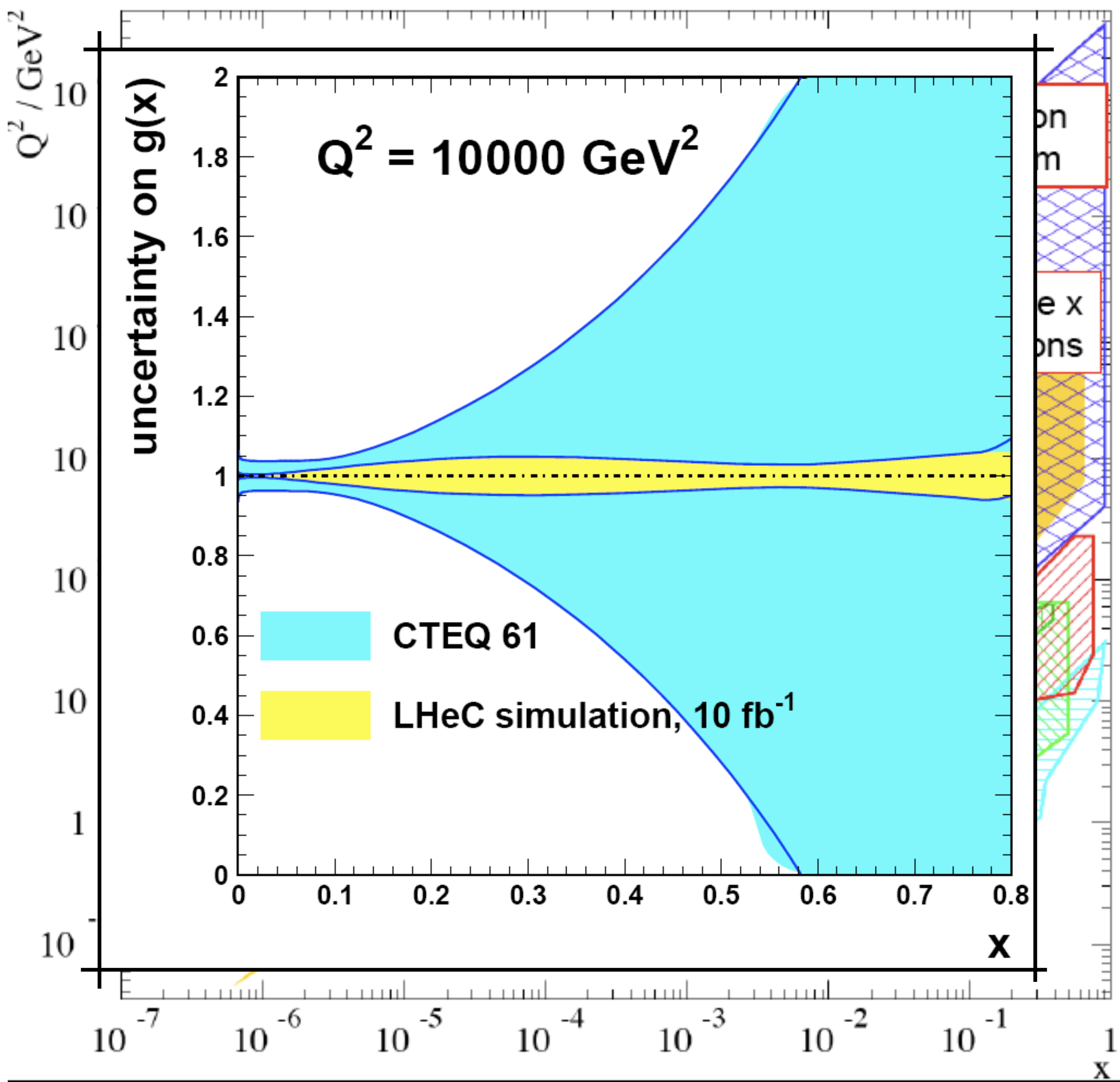
- High scale frontier (M_{lq}, Q^2).
- EW and Higgs.
- Q^2 lever-arm at moderate and high x → (n)pdf's.
- Low x and small to moderate Q^2 → high-energy QCD dynamics.



LHeC: physics goals

√s=1-2 TeV:

- High scale frontier (M_{lq}, Q^2).
- EW and Higgs.
- Q^2 lever-arm at moderate and high x → (n)pdf's.
- Low x and small to moderate Q^2 → high-energy QCD dynamics.



LHeC: the detector

Muon chambers
(fwd,bwd,central)

Coil (r=3m l=11.8m, 3.5T)
[Return Fe not drawn,
2 coils w/o return Fe studied]

Central Detector
Pixels
Elliptic beam pipe (~3cm - or smaller)

Silicon (fwd/bwd+central)
[Strip or/and Gas on Slimmed Si Pixels]
[0.6m radius for 0.03% * pt in 3.5T field]

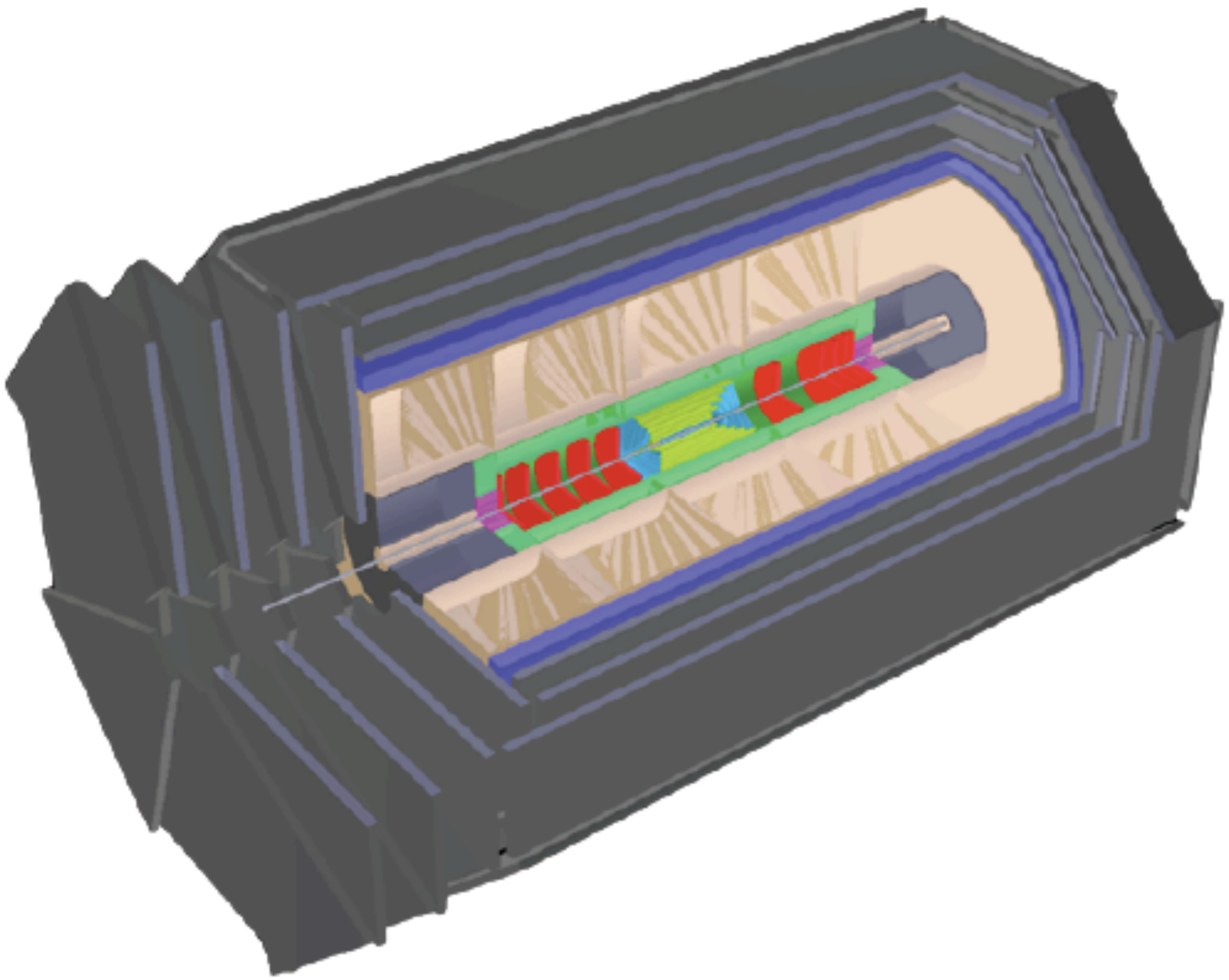
El.magn. Calo (Pb,Scint. 9-12X_0)
Hadronic Calo (Fe/LAr; Cu/Brass-Scint. ~30λ)

Fwd Detectors
(down to 1°)
Silicon Tracker
[Pix/Strip/Strixel/Pad Silicon or/and Gas on Slimmed Si Pixels]

Calice (W/Si); dual ReadOut - Elm Calo
FwdHadrCalo:
Cu/Brass-Scintillator

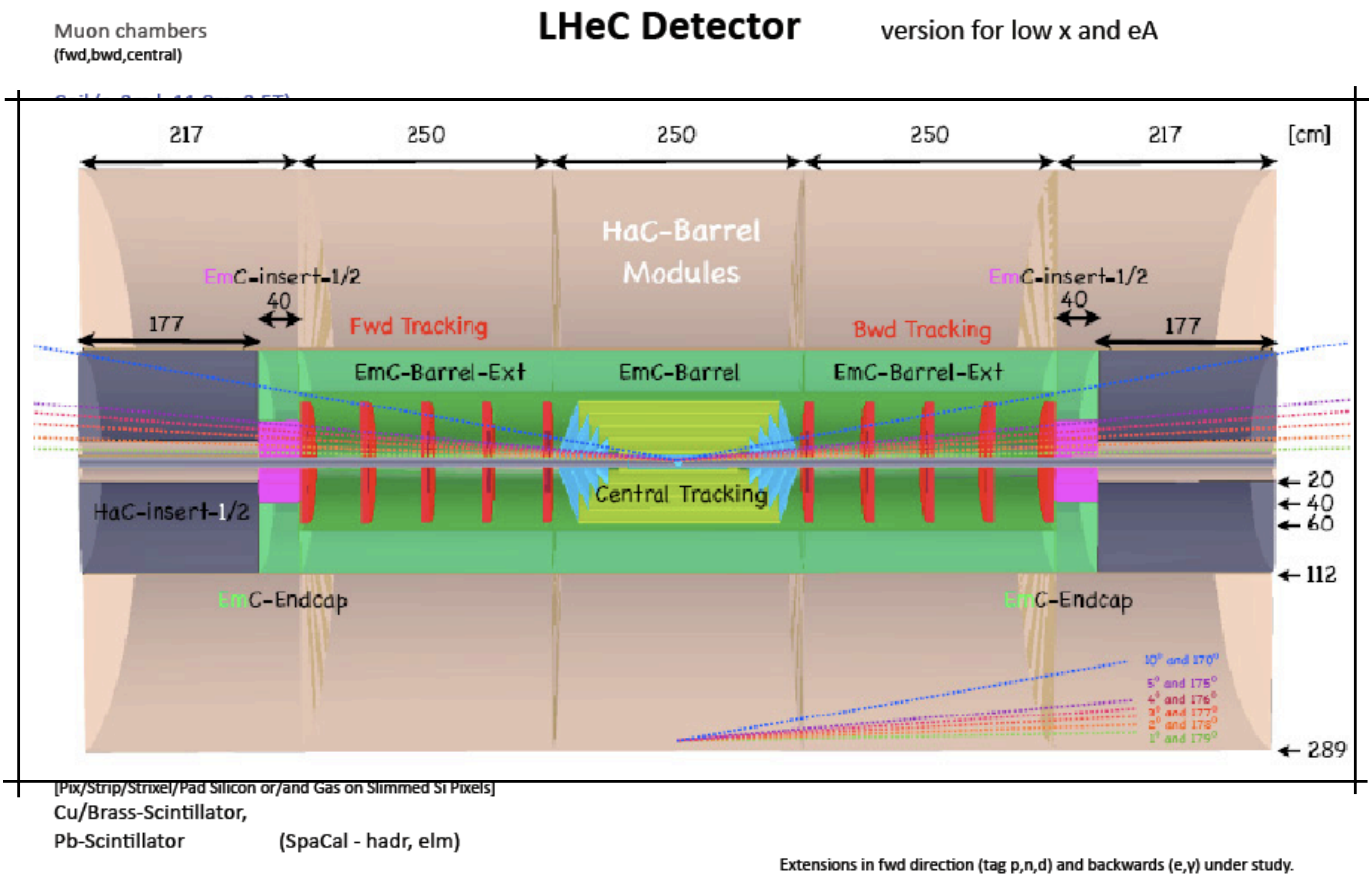
Bwd Detectors
(down to 179°)
Silicon Tracker
[Pix/Strip/Strixel/Pad Silicon or/and Gas on Slimmed Si Pixels]
Cu/Brass-Scintillator,
Pb-Scintillator (SpaCal - hadr, elm)

LHeC Detector version for low x and eA

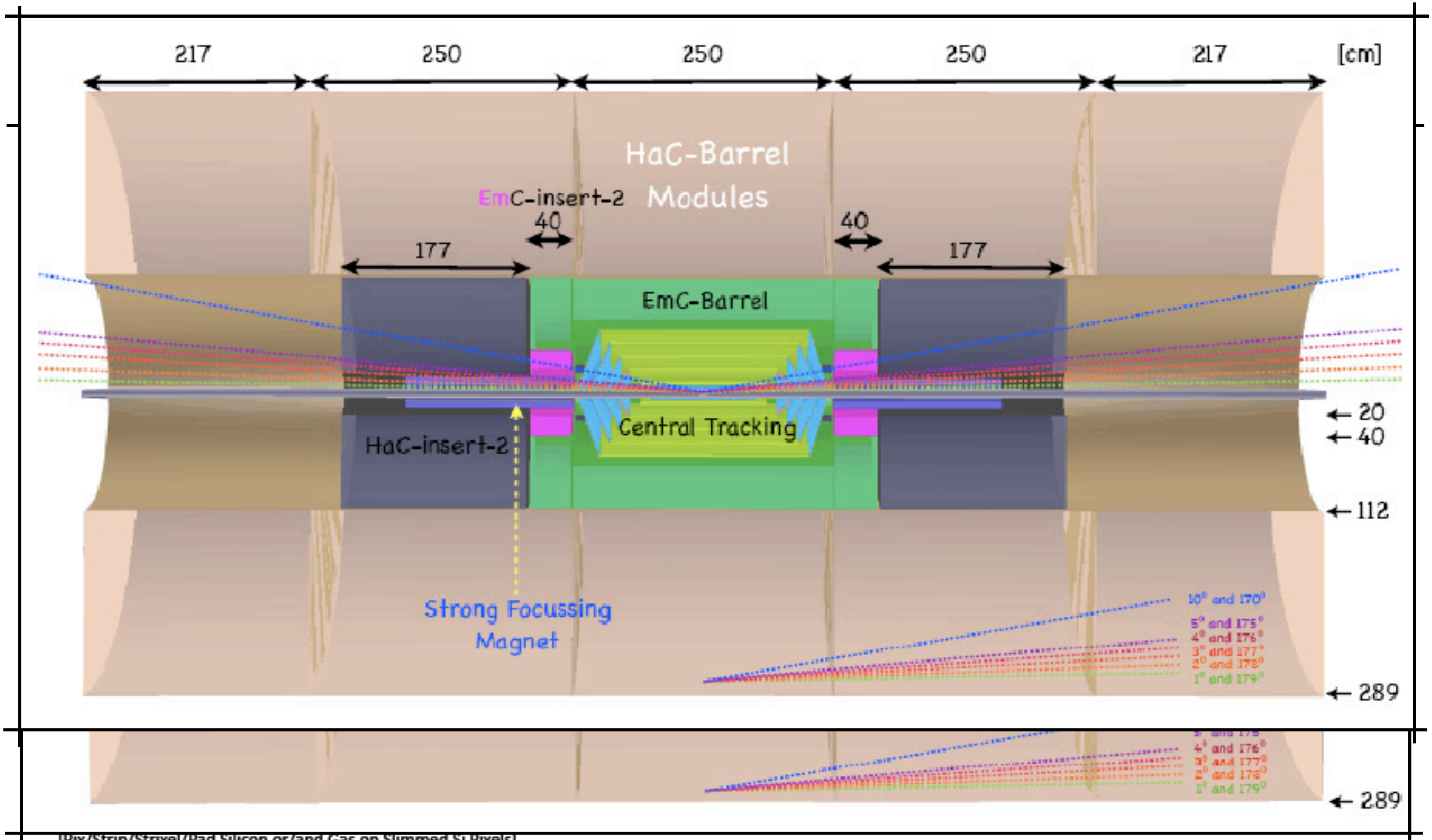


Extensions in fwd direction (tag p,n,d) and backwards (e,γ) under study.

LHeC: the detector



LHeC: the detector



[Pix/Strip/Strixel/Pad Silicon or/and Gas on Slimmed Si Pixels]
Cu/Brass-Scintillator,
Pb-Scintillator (SpaCal - hadr, elm)

Extensions in fwd direction (tag p,n,d) and backwards (e,γ) under study.

Contents:

1. The problem of (n)pdf's at small x:
2. What next?: LHC, EIC, LHeC.
    - LHC.
    - EIC.
    - LHeC: the accelerator, physics goals, the detector.
3. Small-x studies with the LHeC:
    - ep inclusive pseudodata and their effect on pdf's. (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)
    - ep, eA diffractive pseudodata. (P. Newman, G. Watt)
    - F_L in eA. (H. Paukkunen, K. Tywoniuk, NA, C.A. Salgado)
4. Summary.

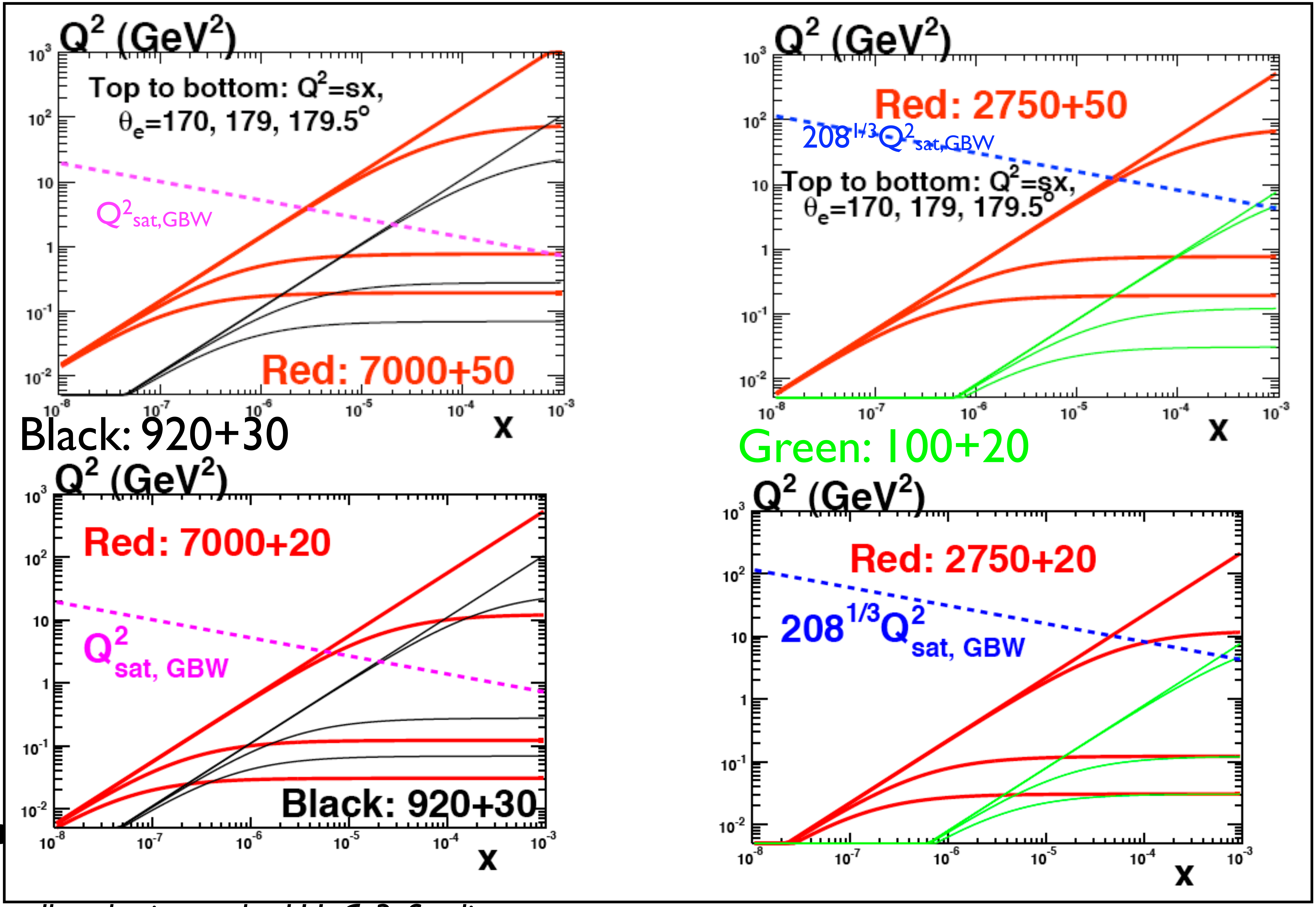
LHeC scenarios:

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	$5 \cdot 10^{-4}$		?	$5 \cdot 10^{-3}$	?	?	eCa

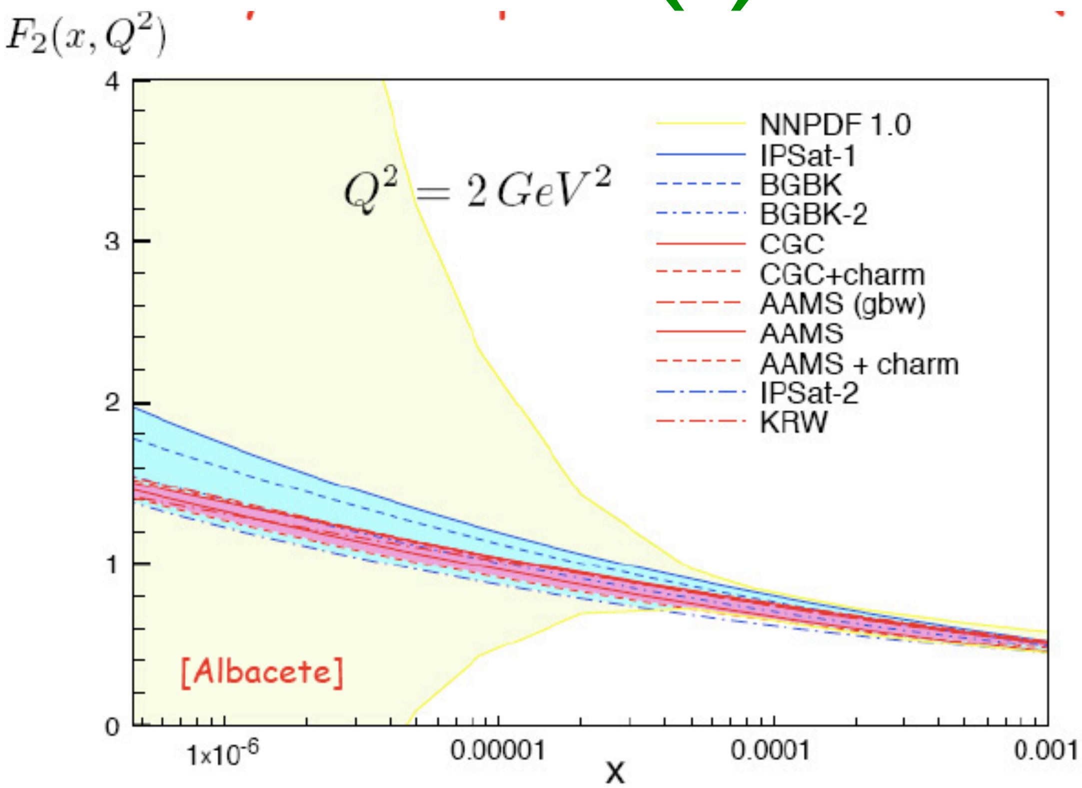
- For F_L: 10, 25, 50 + 2750 (7000); $Q^2 \leq sx$.

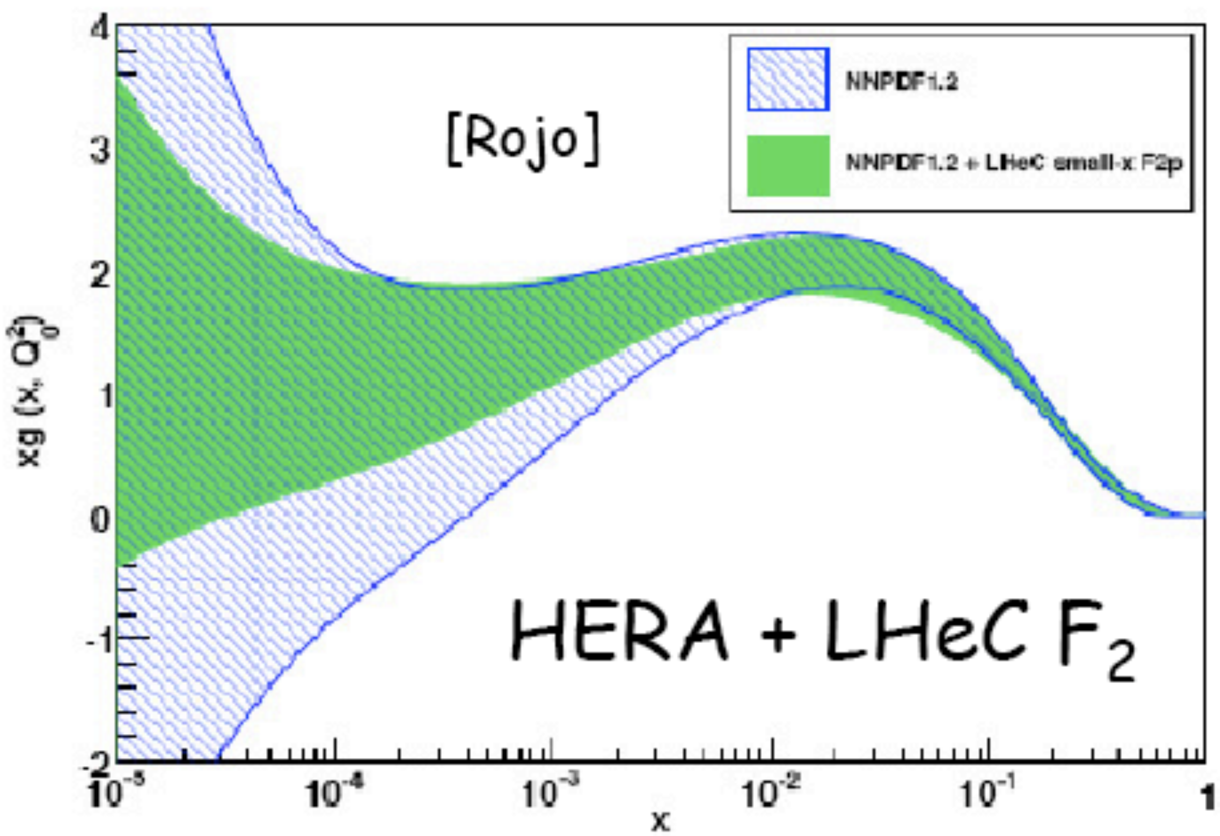
LHeC scenarios:



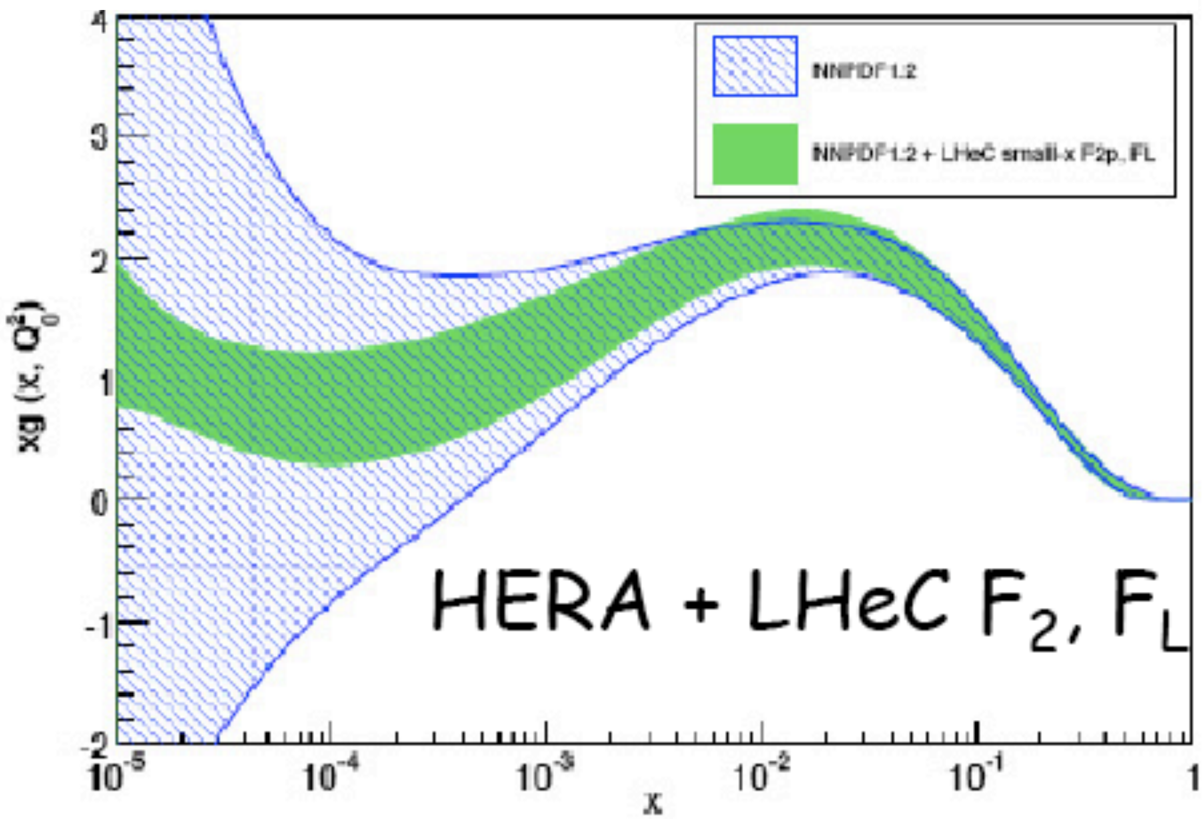
ep inclusive pseudodata (I):

- They substantially reduce the uncertainties in global fits: F_L most useful.



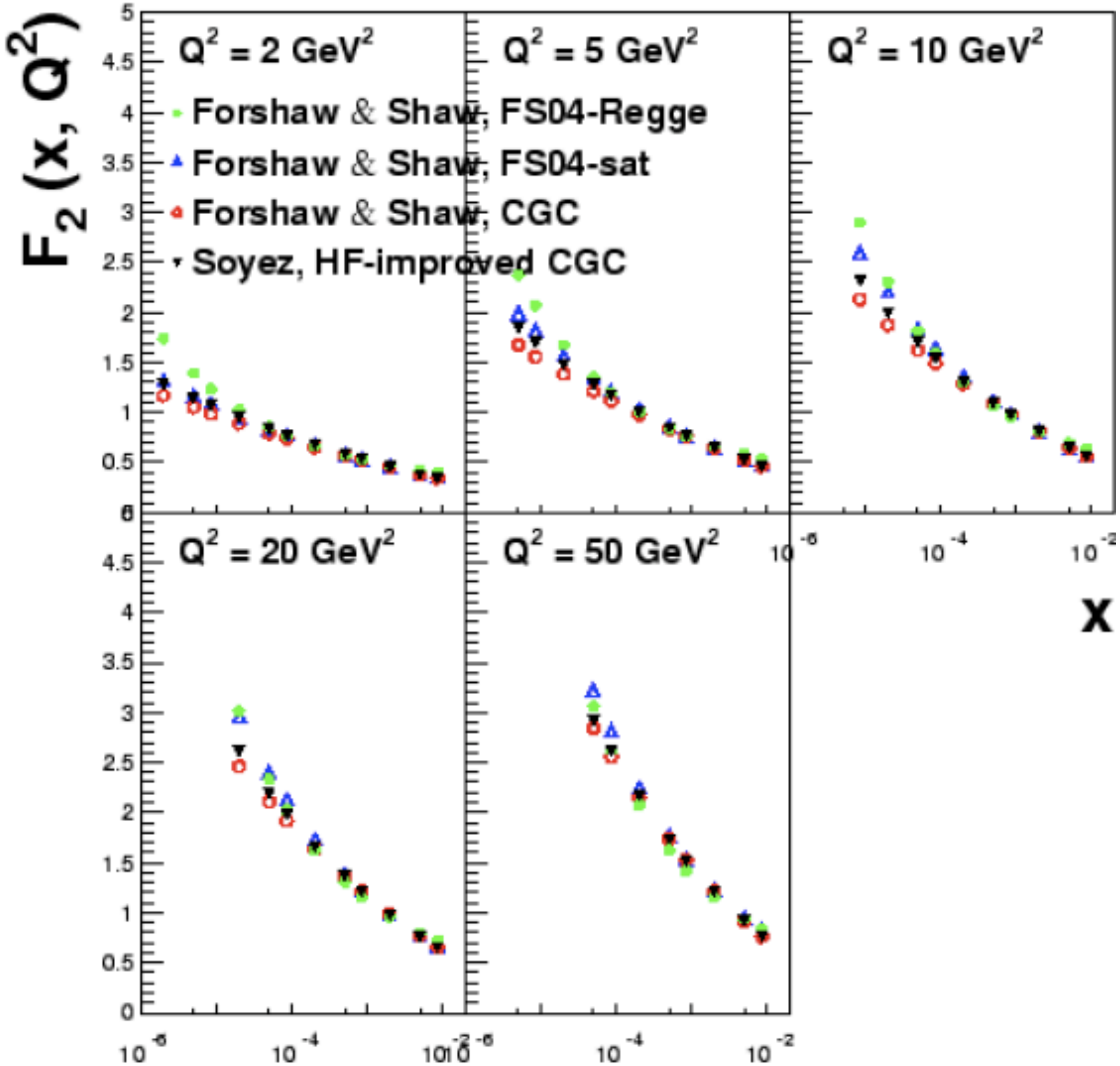


(Q^2 = 2 GeV^2)



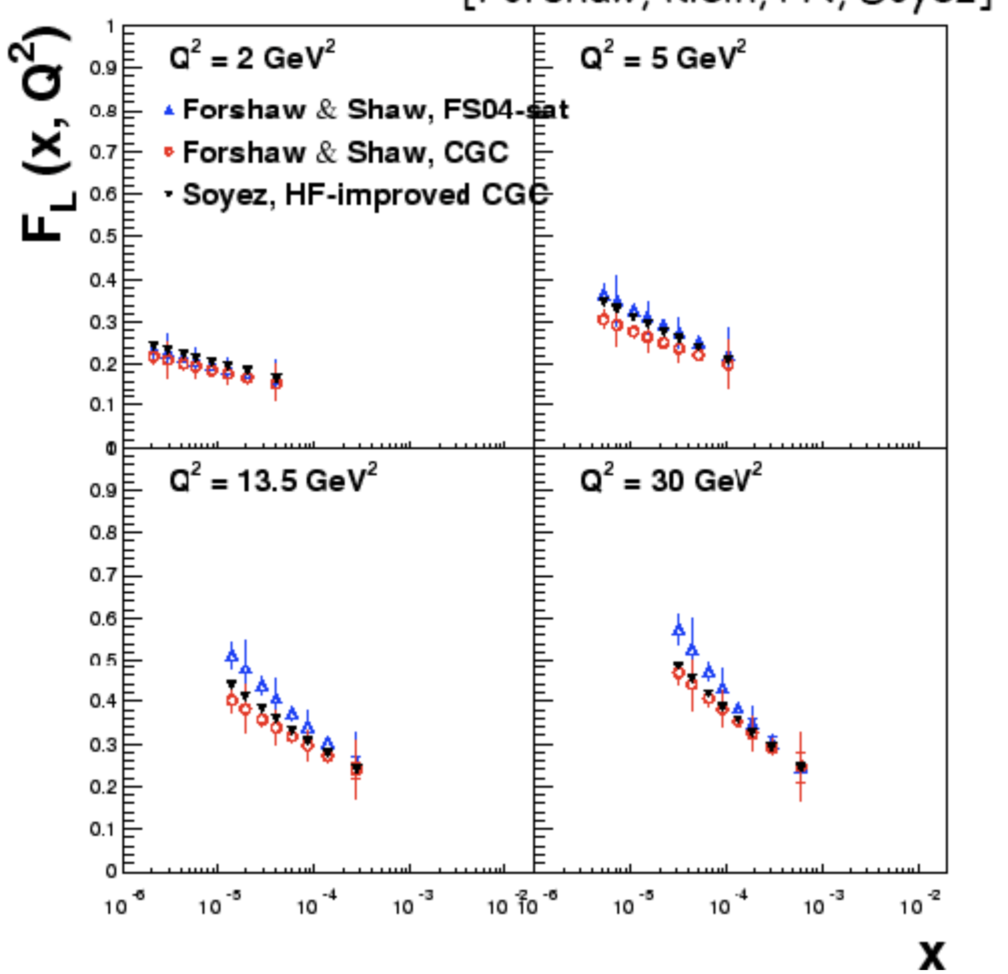
ep inclusive pseudodata (II):

[Forshaw, Klein, PN, Soyez]

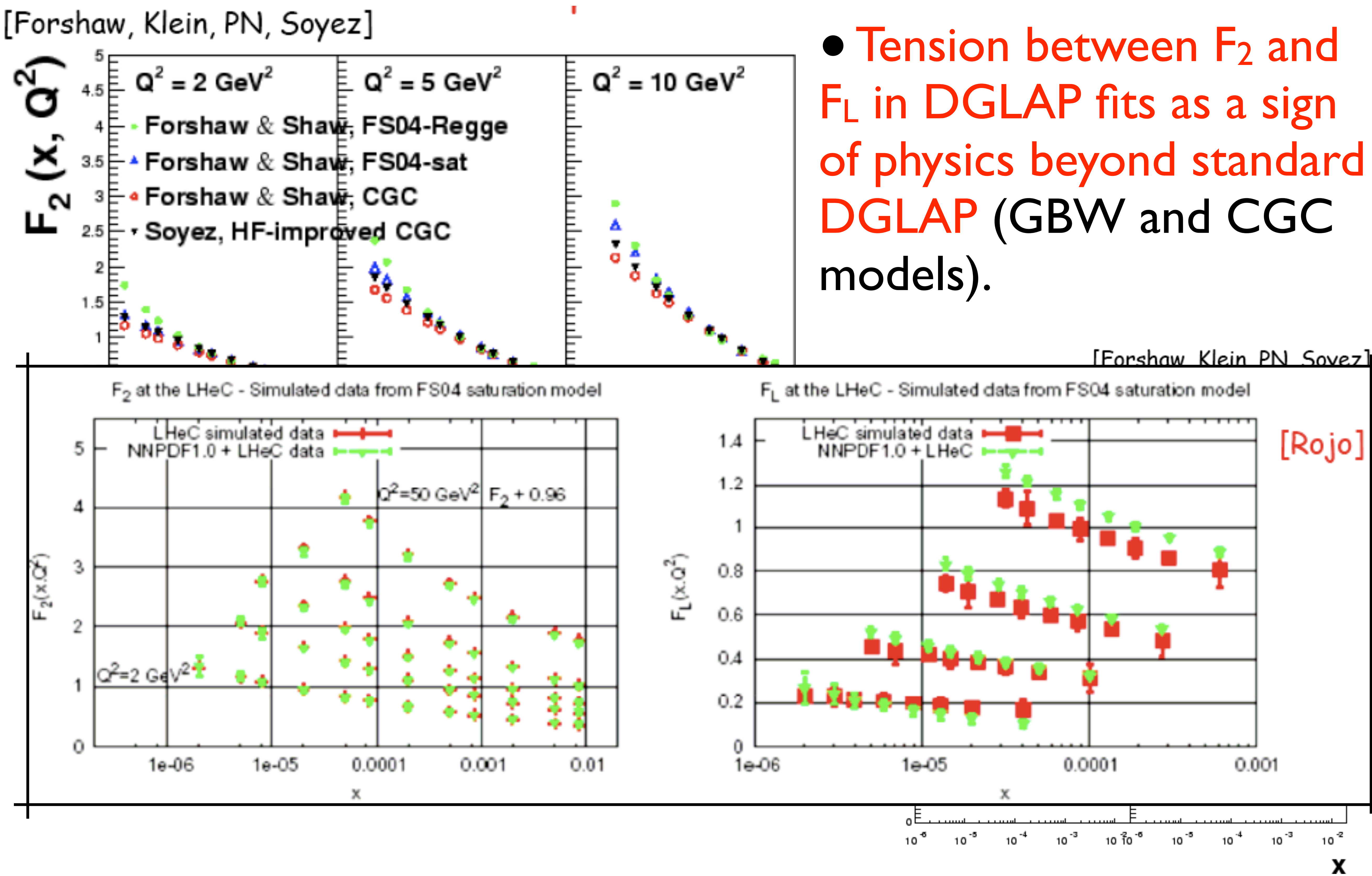


- Tension between F_2 and F_L in DGLAP fits as a sign of physics beyond standard DGLAP (GBW and CGC models).

[Forshaw, Klein, PN, Soyez]



ep inclusive pseudodata (II):

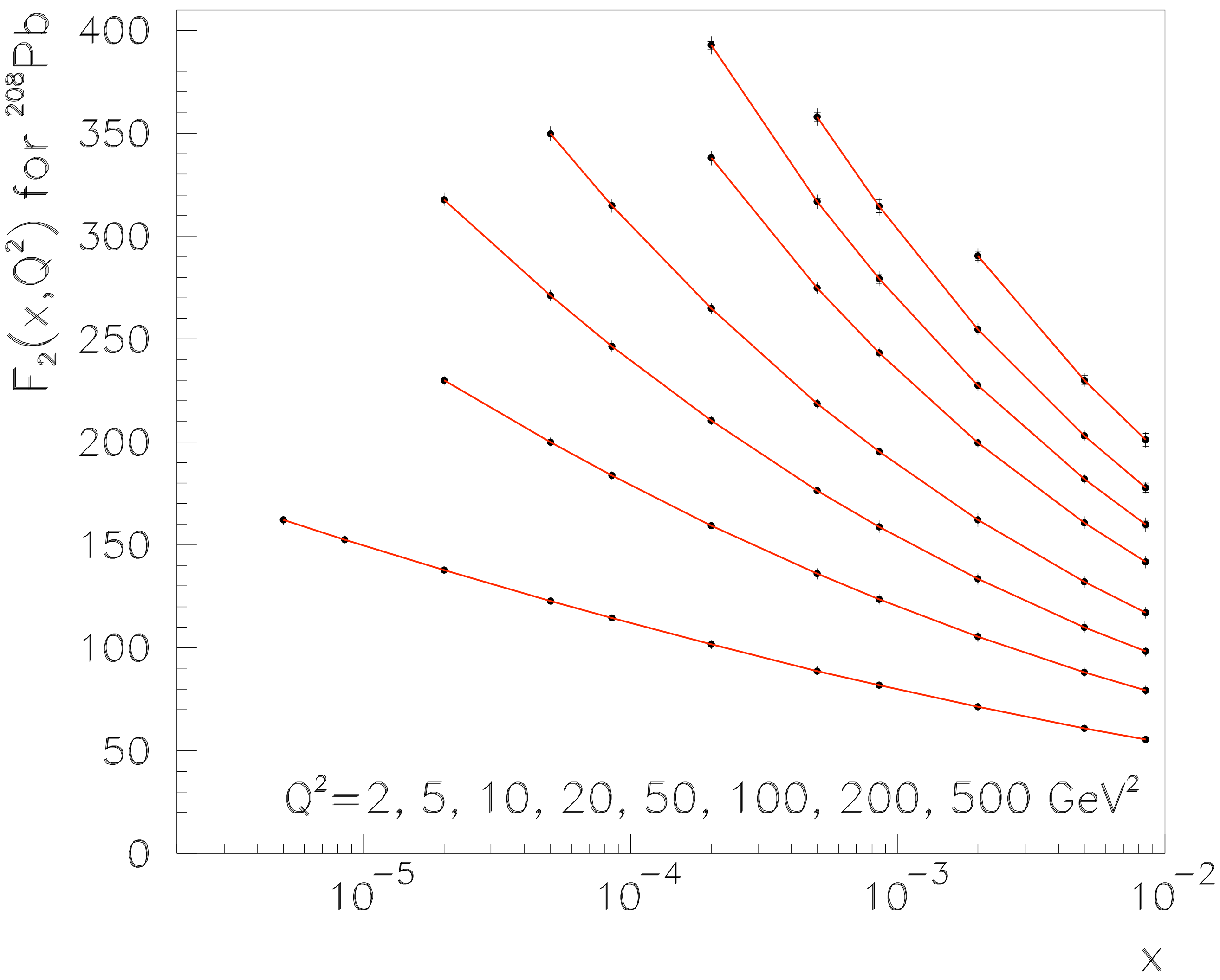


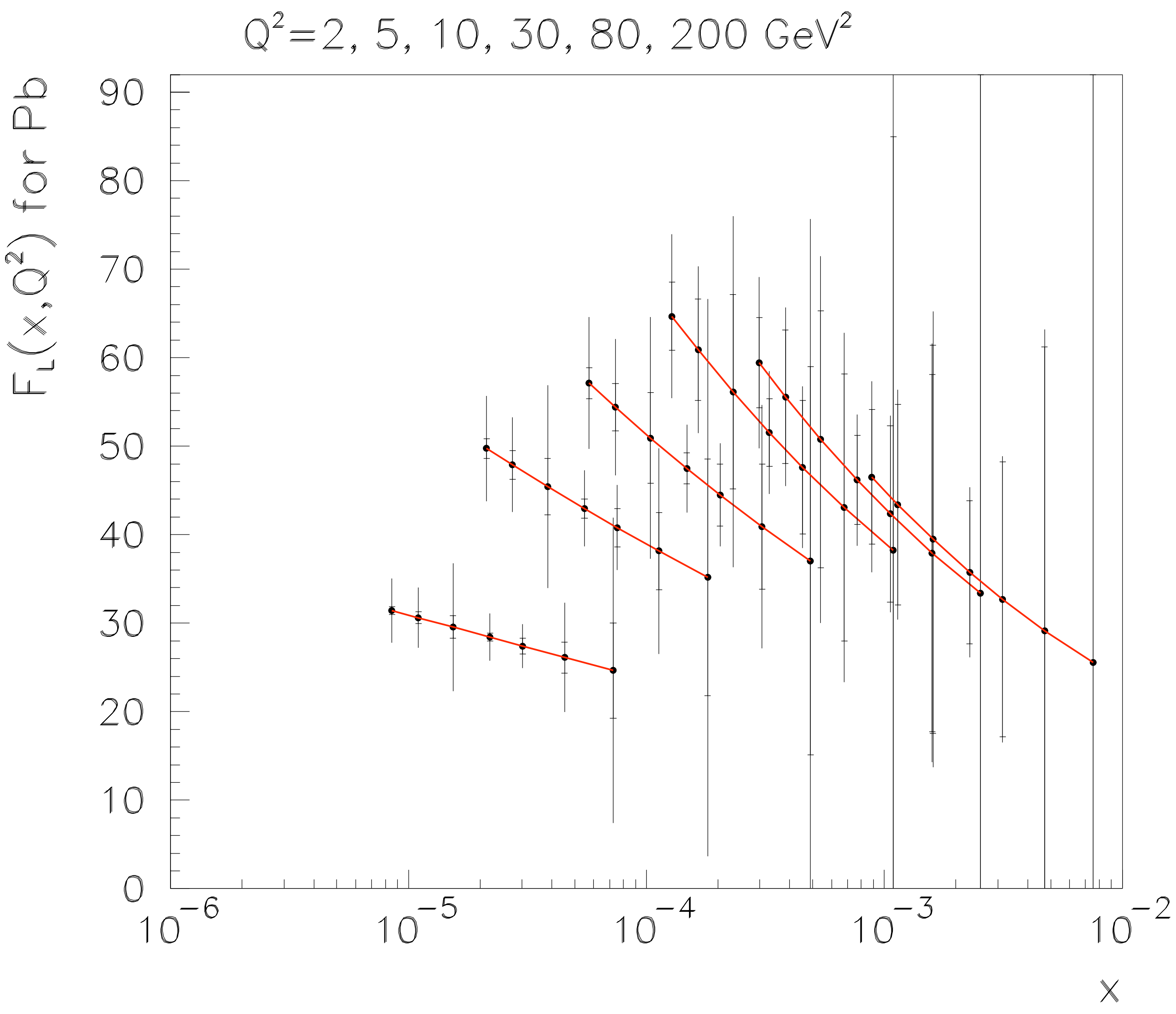
- Tension between F_2 and F_L in DGLAP fits as a sign of physics beyond standard DGLAP (GBW and CGC models).

eA inclusive pseudodata (I):

- Good precision can be obtained for F_2 and F_L at small x

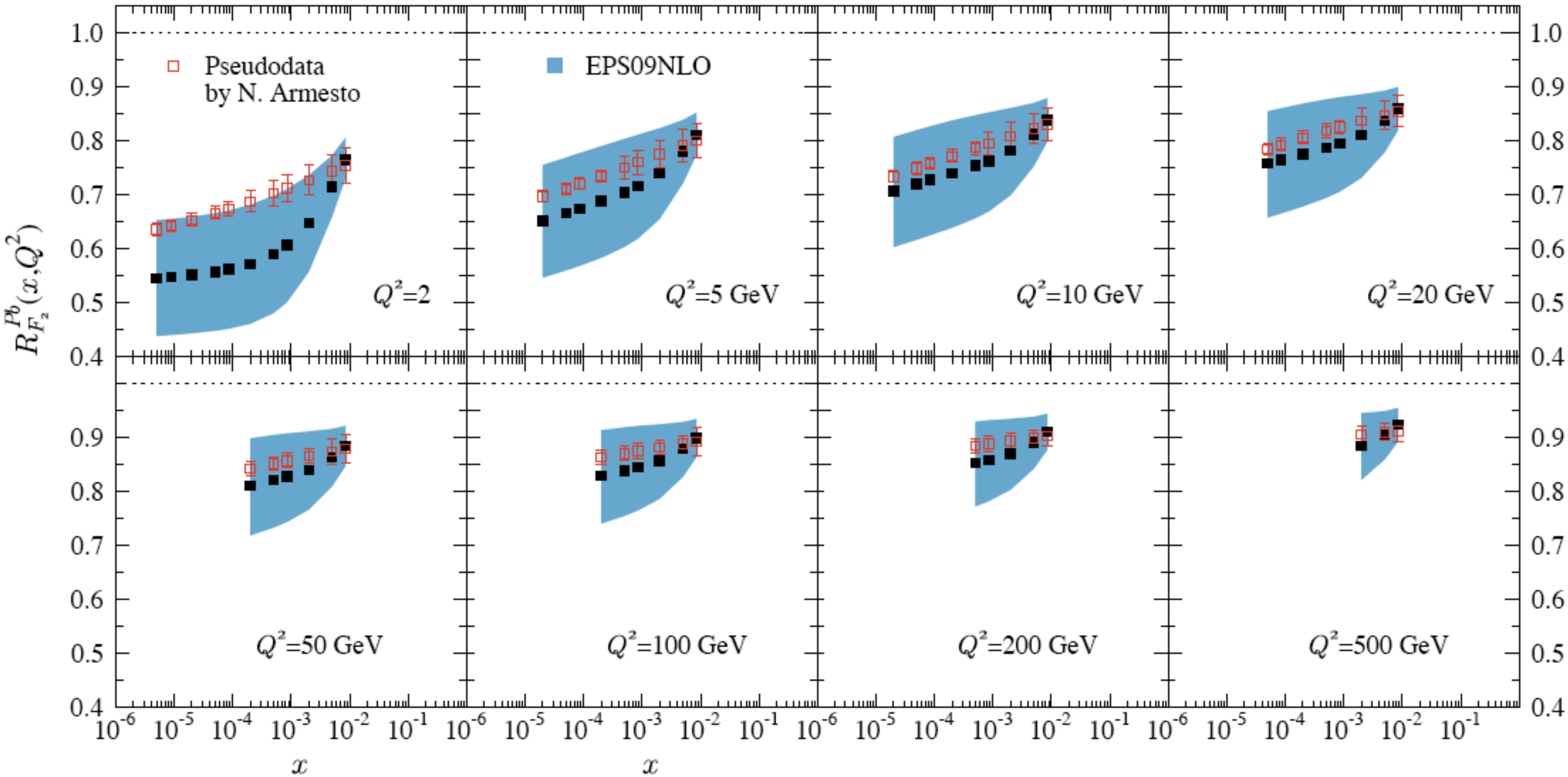
(Glauberized GBW model, NA '02).





eA inclusive pseudodata (II):

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



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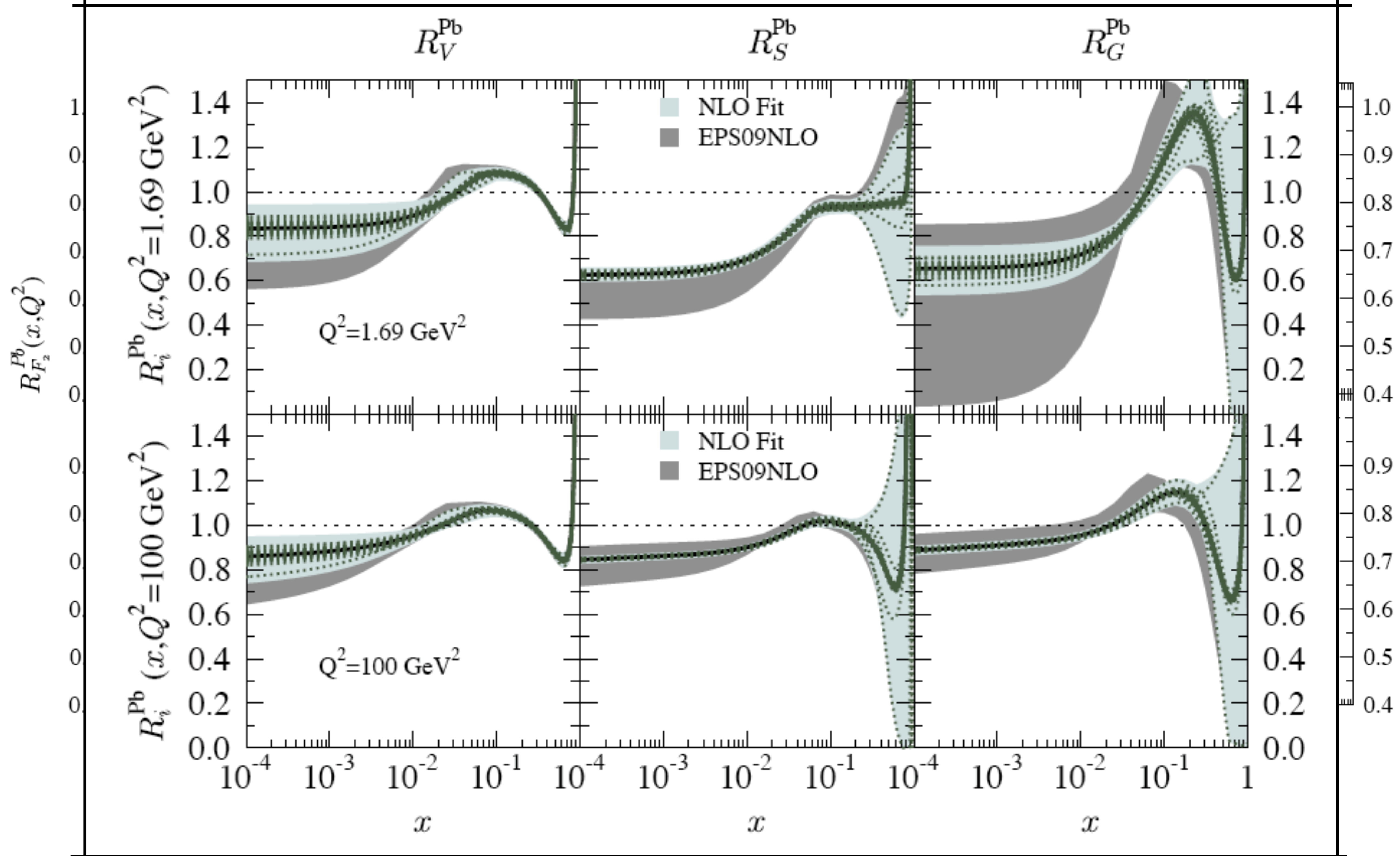
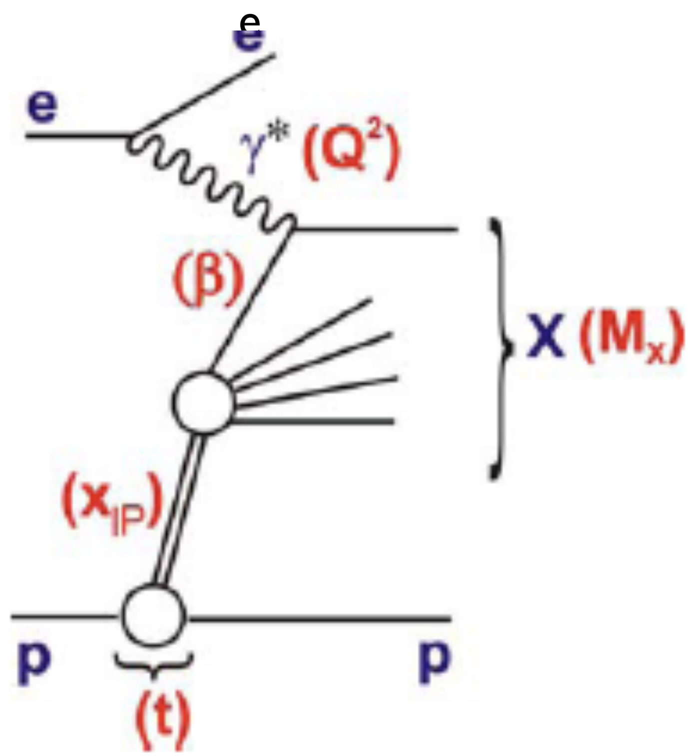
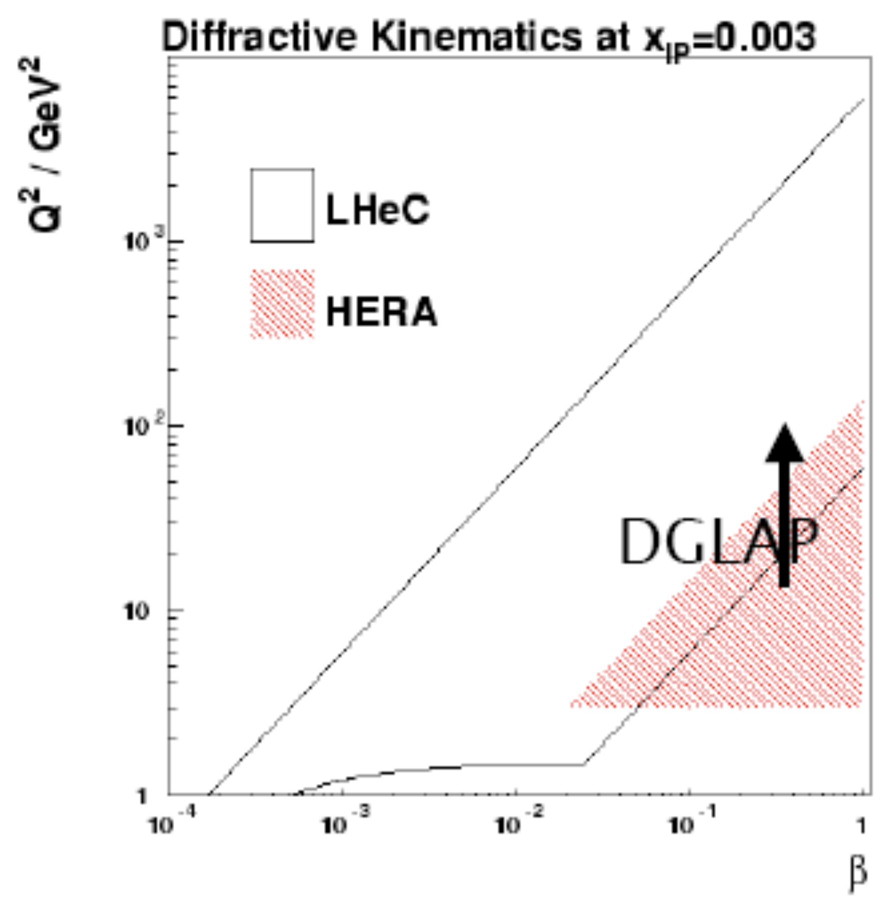
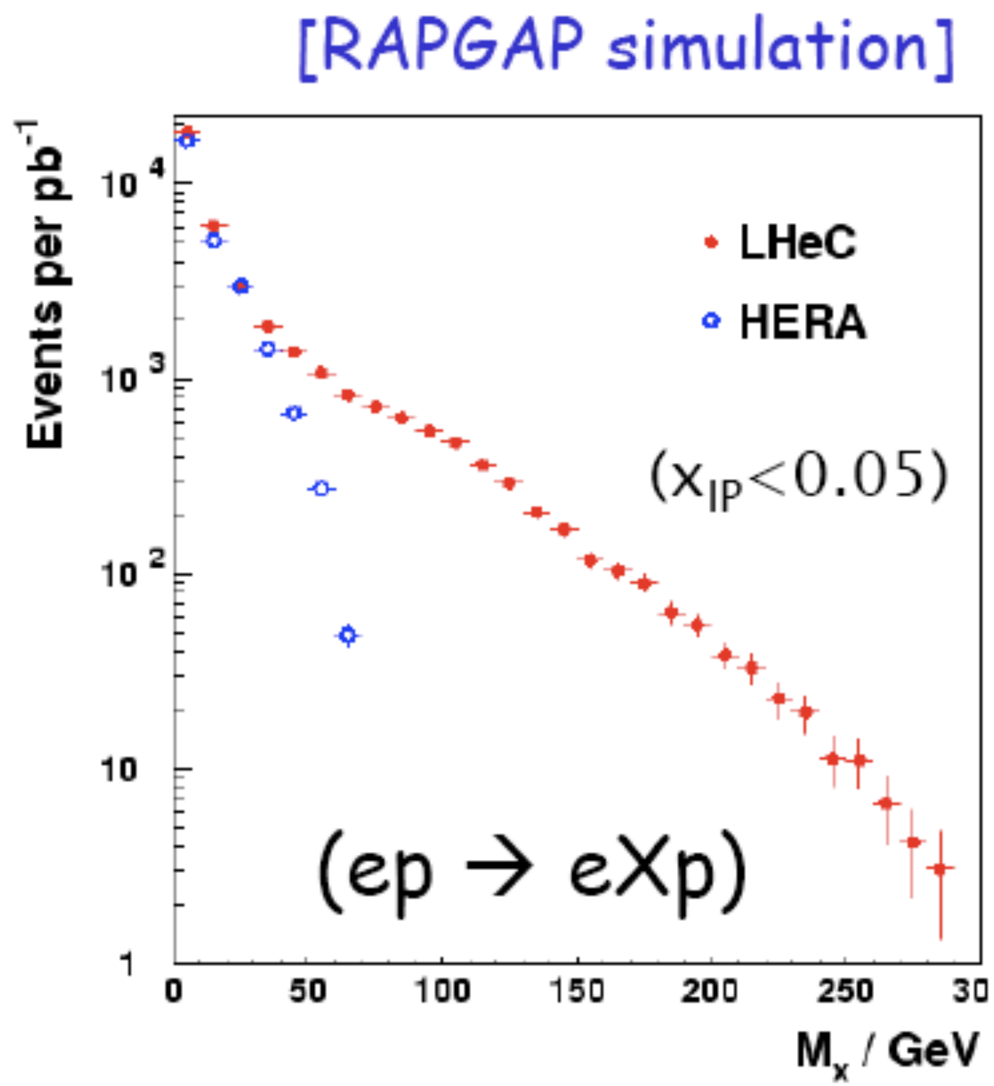


ep diffractive pseudodata (I):



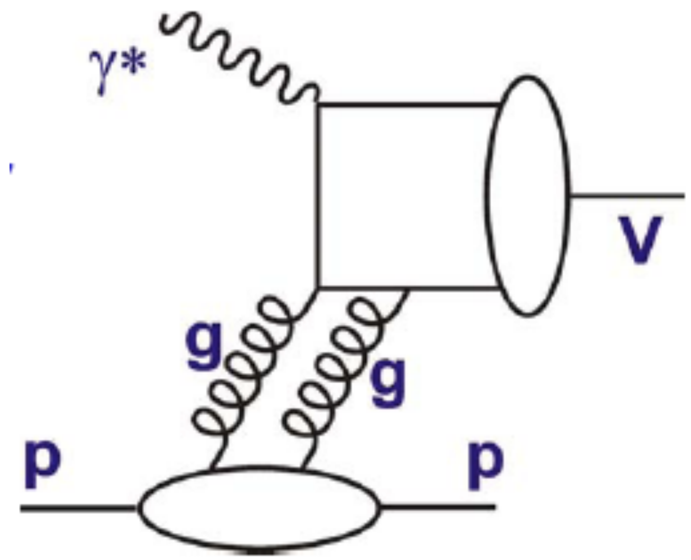
- Large increase in the M^2, $x_P=(M^2-t+Q^2)/(W^2+Q^2)$, $\beta=x/x_P$ region studied.

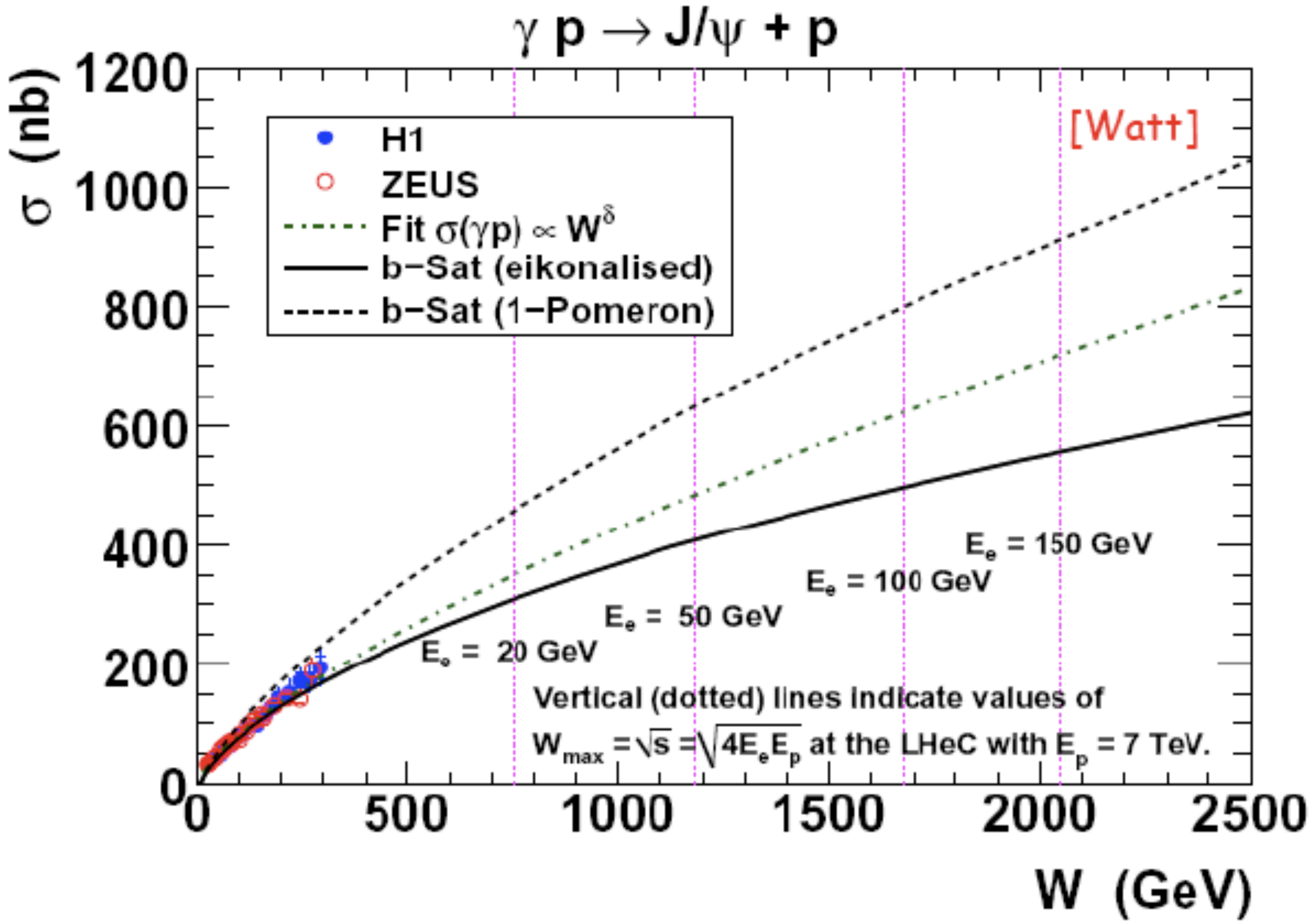


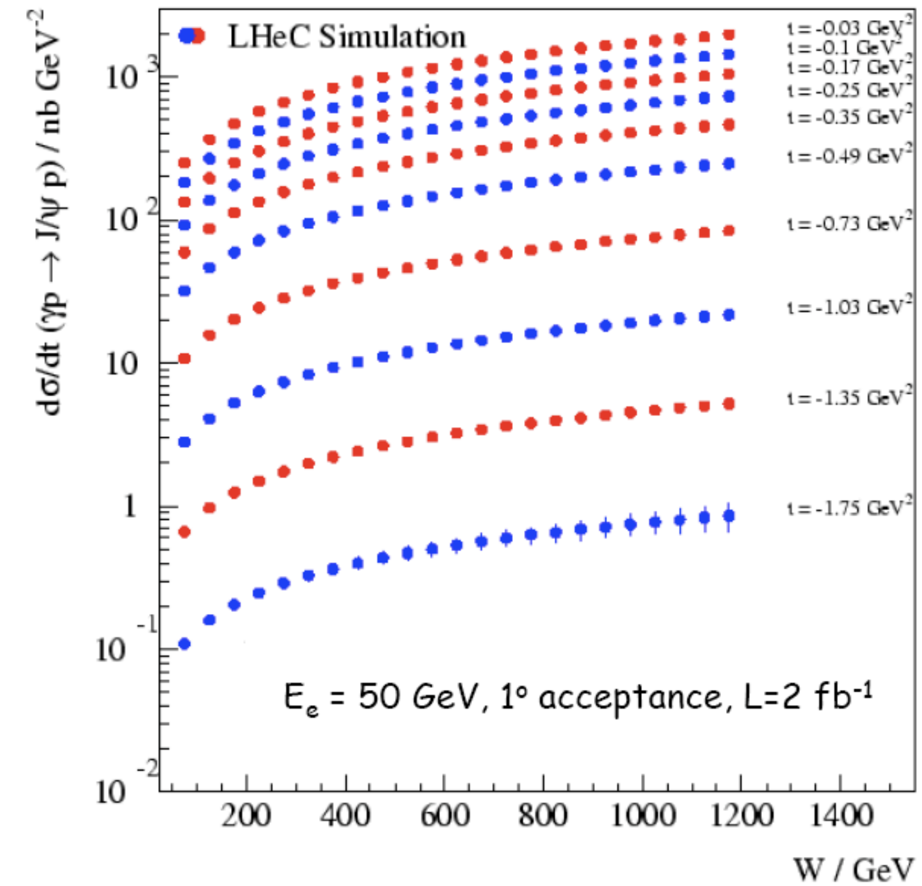


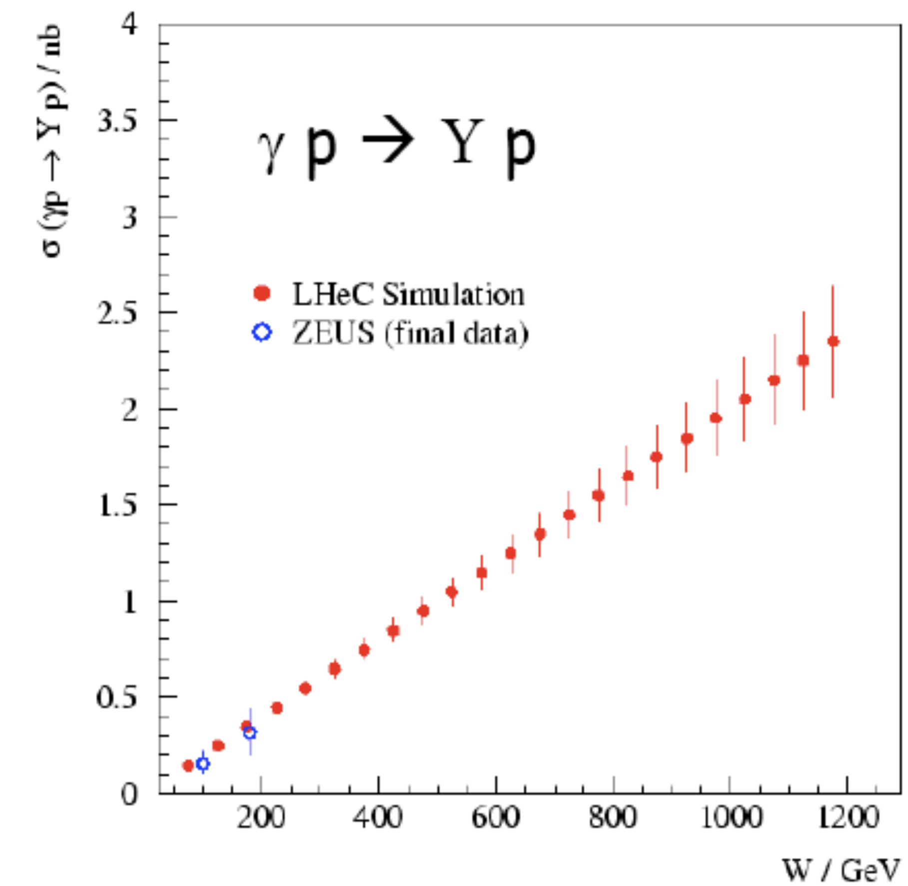
ep diffractive pseudodata (II):

- Elastic vector meson most promising.



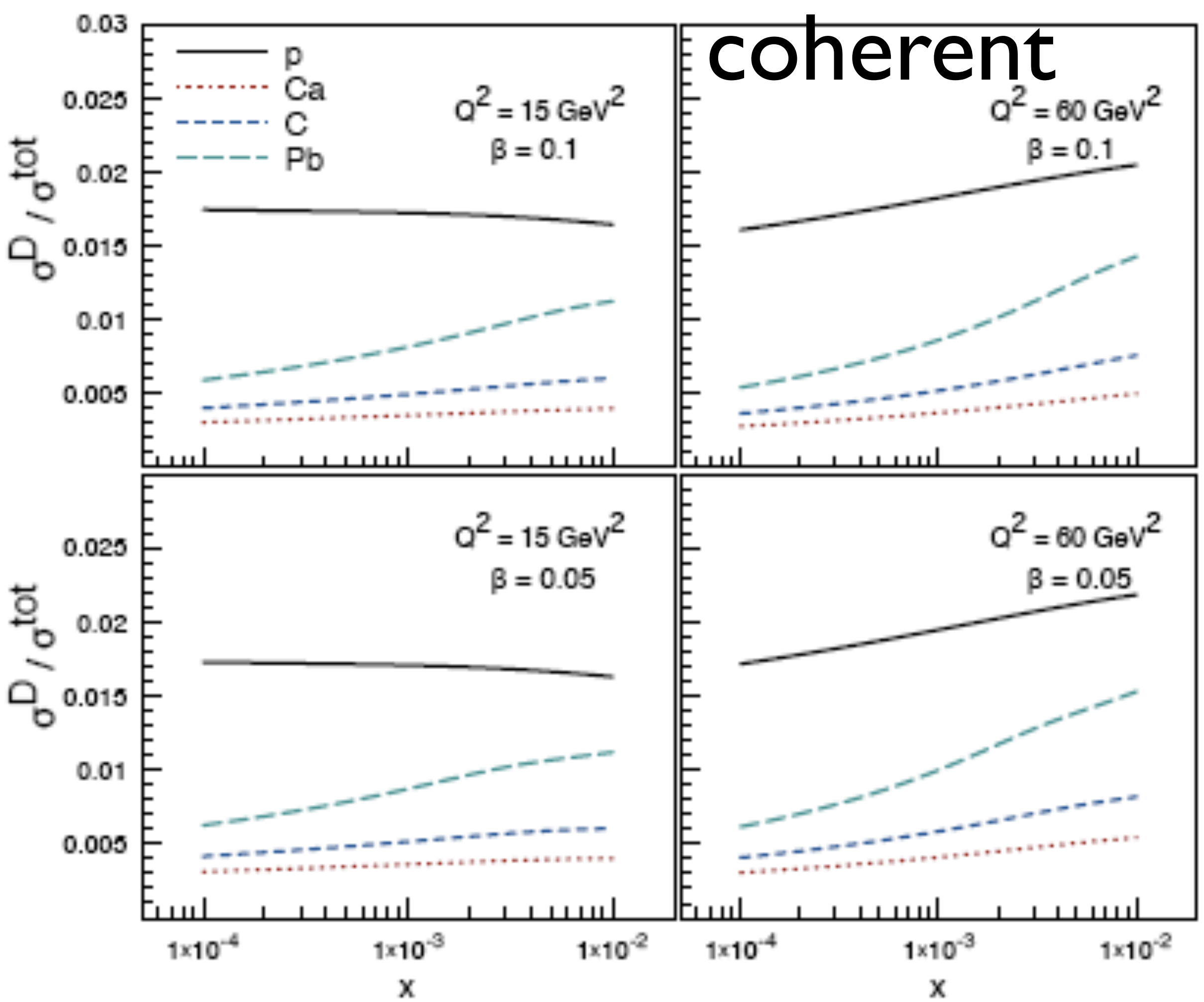




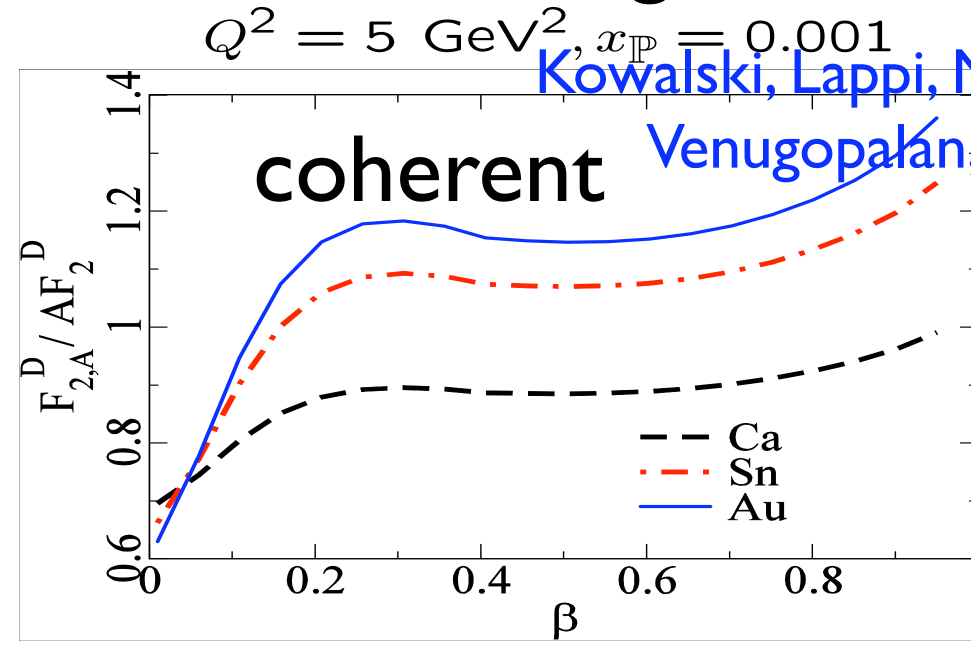


eA diffractive pseudodata:

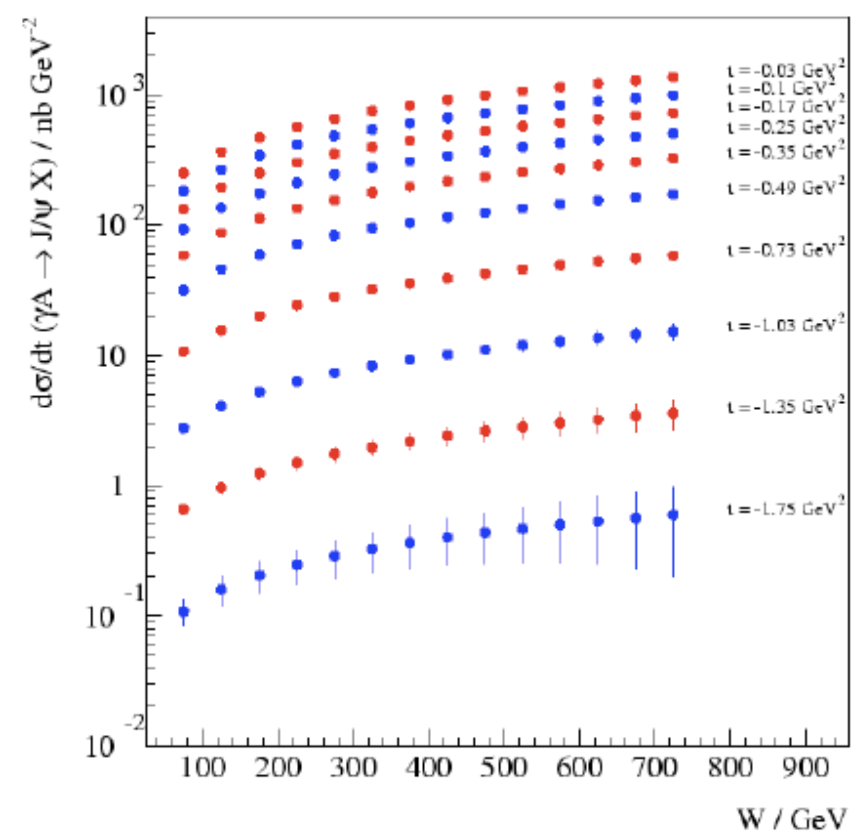
- Problem: diffraction maybe coherent (e+A→e+X+A), incoherent (e+A→e+X+Zp+(A-Z)n) and inelastic (e+A→e+X+X') ⇒ challenging experimental problem to disentangle them.



NA, Kaidalov, Salgado, Tywoniuk, preliminary



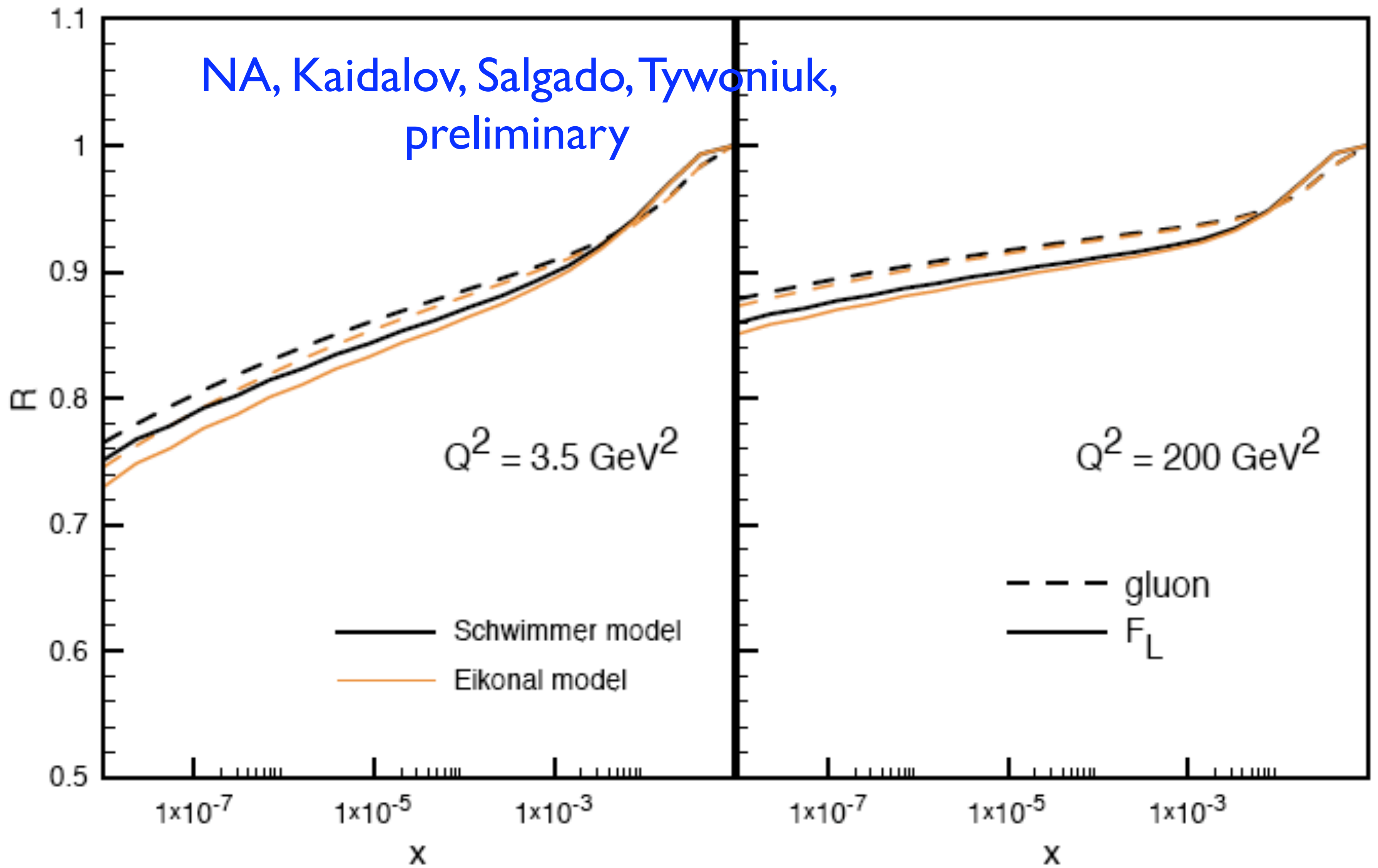
Kowalski, Lappi, Marquet, Venugopalan, '08



F_L in eA (I):

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

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

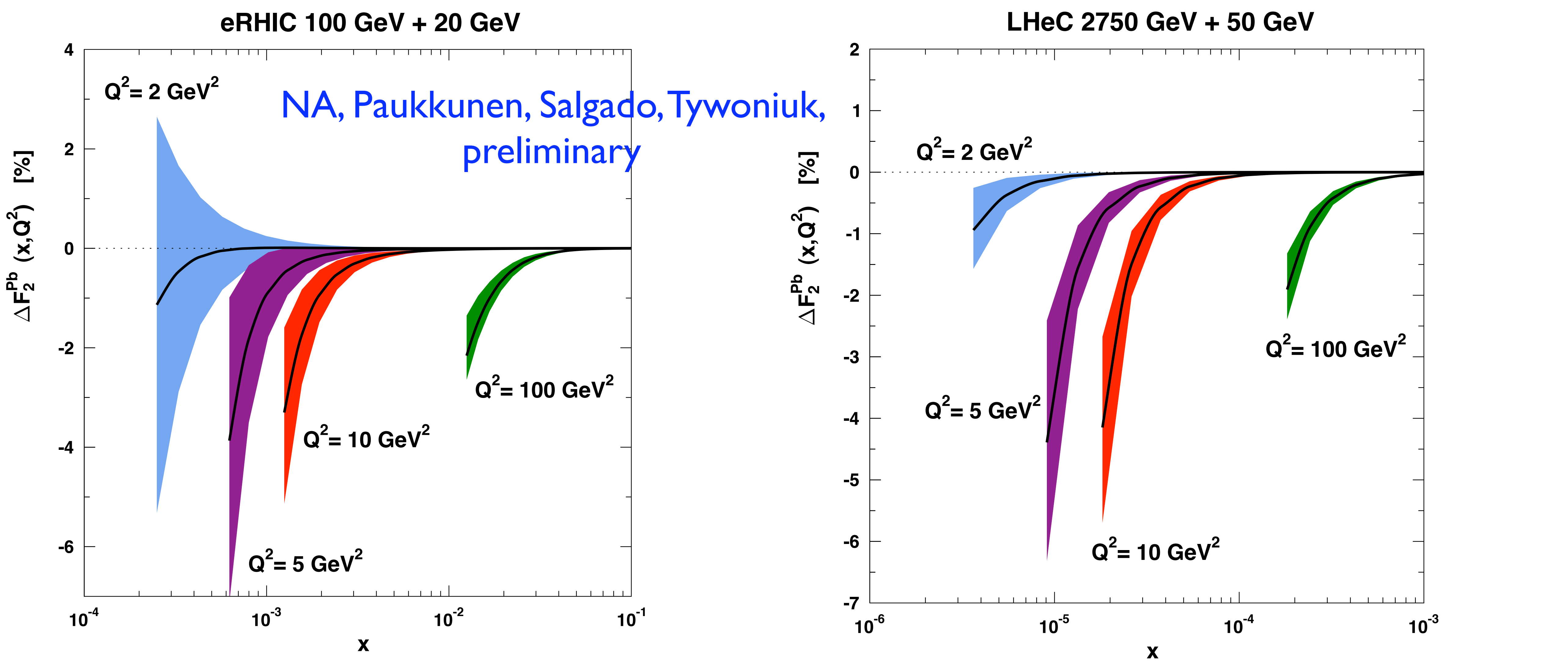


F_L in eA (II):

- 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.

$$\frac{d^2\sigma^{e^+p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[YF_2(x,Q^2) - y^2F_L(x,Q^2)\right] \qquad Y = 1 + (1-y)^2$$

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



Summary

• Many issues remain open about small x physics: behavior of the hadron wave function at small x.

• 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; I have only shown some of them (e.g. no FSI).

• The challenge, both theoretically (heavy flavors, role of radiative corrections,...) and experimentally (forward detection,...), is immense

⇒ **much to learn, stay tuned!**