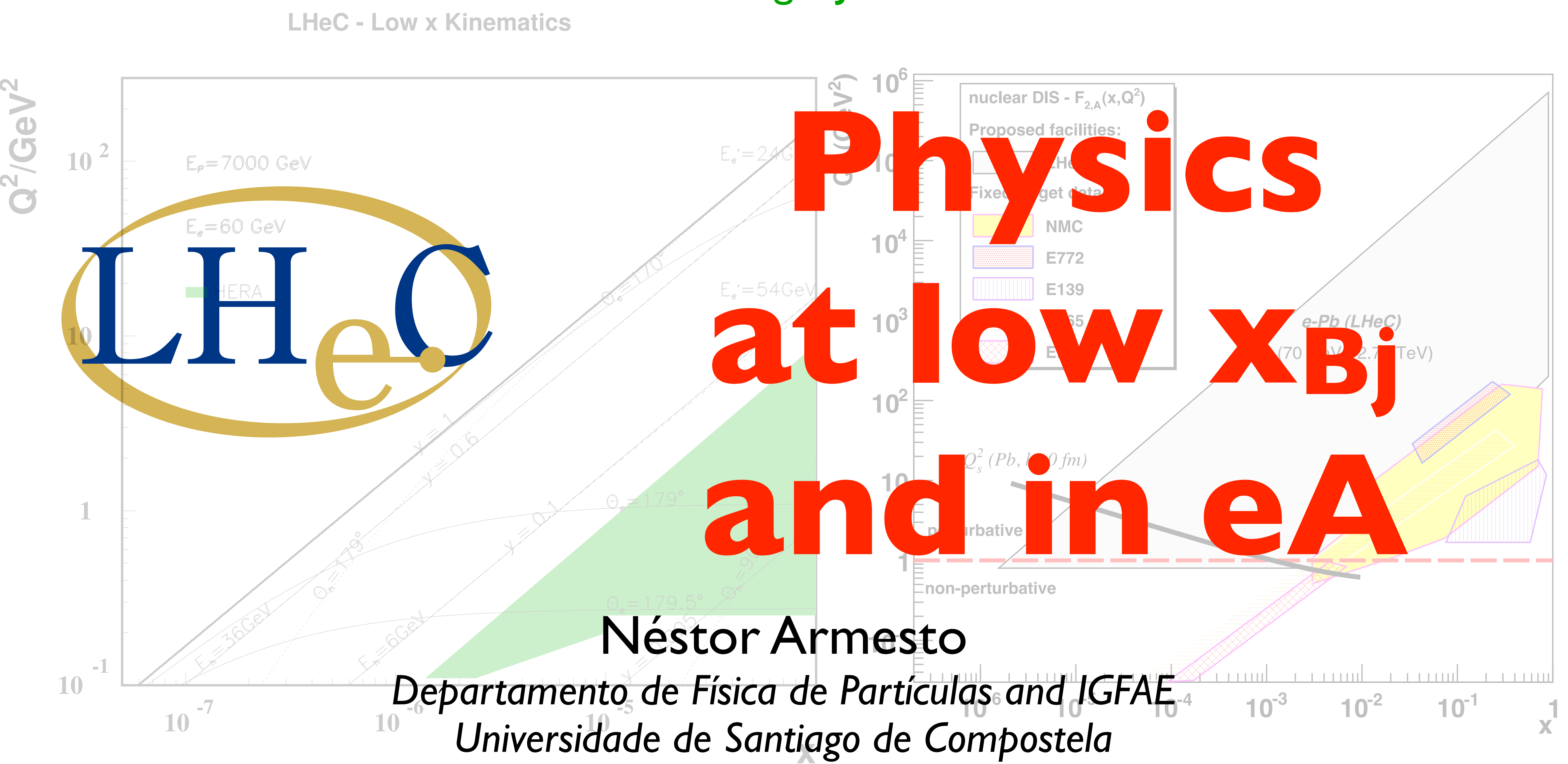
2012 CERN-ECFA-NuPECC Workshop on the LHeC
Chavannes-de-Bogis, June 14th 2012



Physics at low x_{Bj} and in eA

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Contents:

1. CDR, Chapter 4: *Physics at High Parton Densities.*

2. Highlights:
   - 'Benchmarking' for pp/pA/AA: PDFs at small x.
   - 'Discovery': novel regime of QCD at small x?
   - Transverse scan of the hadron at small x.
   - Dynamics of QCD radiation and hadronization.

3. Summary and outlook.

CDR, arXiv:1206.2913, submitted to JPG

CDR, Chapter 4:

- 81 pages (JPG format).
- 34 authors (thanks!!!).
- 4 conveners.
- 3(+2) referees.

J.L.Abelleira Fernandez[16,23], C.Adolphsen[57], A.N.Akay[03], H.Aksakal[39], J.L.Albacete[52], S.Alekhin[17,54], P.Allport[24], V.Andreev[34], R.B.Appleby[14,30], E.Arikan[39], N.Armesto[53,a], G.Azuelos[33,64], M.Bai[37], D.Barber[14,17,24], J.Bartels[18], O.Behnke[17], J.Behr[17], A.S.Belyaev[15,56], I.Ben-Zvi[37], N.Bernard[25], S.Bertolucci[16], S.Bettoni[16], S.Biswal[41], J.Blümlein[17], H.Böttcher[17], A.Bogacz[36], C.Bracco[16], G.Brandt[44], H.Braun[65], S.Brodsky[57,b], O.Brüning[16], E.Bulyak[12], A.Buniatyan[17], H.Burkhardt[16], I.T.Cakir[02], O.Cakir[01], R.Calaga[16], V.Cetinkaya[01], E.Ciapala[16], R.Ciftci[01], A.K.Ciftci[01], B.A.Cole[38], J.C.Collins[48], O.Dadoun[42], J.Dainton[24], A.De.Roeck[16], D.d'Enterria[16], A.Dudarev[16], A.Eide[60], R.Enberg[63], E.Eroglu[62], K.J.Eskola[21], L.Favart[08], M.Fitterer[16], S.Forte[32], A.Gaddi[16], P.Gambino[59], H.García Morales[16], T.Gehrmann[69], P.Gladkikh[12], C.Glasman[28], R.Godbole[35], B.Goddard[16], T.Greenshaw[24], A.Guffanti[13], V.Guzey[19,36], C.Gwenlan[44], T.Han[50], Y.Hao[37], F.Haug[16], W.Herr[16], A.Hervé[27], B.J.Holzer[16], M.Ishitsuka[58], M.Jacquet[42], B.Jeanneret[16], J.M.Jimenez[16], J.M.Jowett[16], H.Jung[17], H.Karadeniz[02], D.Kayran[37], A.Kilic[62], K.Kimura[58], M.Klein[24], U.Klein[24], T.Kluge[24], F.Kocak[62], M.Korostelev[24], A.Kosmicki[16], P.Kostka[17], H.Kowalski[17], G.Kramer[18], D.Kuchler[16], M.Kuze[58], T.Lappi[21,c], P.Laycock[24], E.Levichev[40], S.Levonian[17], V.N.Litvinenko[37], A.Lombardi[16], J.Maeda[58], C.Marquet[16], B.Mellado[27], K.H.Mess[16], A.Milanese[16], S.Moch[17], I.I.Morozov[40], Y.Muttoni[16], S.Myers[16], S.Nandi[55], Z.Nergiz[39], P.R.Newman[06], T.Omori[61], J.Osborne[16], E.Paoloni[49], Y.Papaphilippou[16], C.Pascaud[42], H.Paukkunen[53], E.Perez[16], T.Pieloni[23], E.Pilicer[62], B.Pire[45], R.Placakyte[17], A.Polini[07], V.Ptitsyn[37], Y.Pupkov[40], V.Radescu[17], S.Raychaudhuri[35], L.Rinolfi[16], R.Rohini[35], J.Rojo[16,31], S.Russenschuck[16], M.Sahin[03], C.A.Salgado[53,a], K.Sampei[58], R.Sassot[09], E.Sauvan[04], U.Schneekloth[17], T.Schörner-Sadenius[17], D.Schulte[16], A.Senol[22], A.Seryi[44], P.Sievers[16], A.N.Skrinsky[40], W.Smith[27], H.Spiesberger[29], A.M.Stasto[48,d], M.Strikman[48], M.Sullivan[57], S.Sultansoy[03,e], Y.P.Sun[57], B.Surrow[11], L.Szymanowski[66,f], P.Taels[05], I.Tapan[62], T.Tasci[22], E.Tassi[10], H.Ten.Kate[16], J.Terron[28], H.Thiesen[16], L.Thompson[14,30], K.Tokushuku[61], R.Tomás García[16], D.Tommasini[16], D.Trbojevic[37], N.Tsoupas[37], J.Tuckmantel[16], S.Turkoz[01], T.N.Trinh[47], K.Tywoniuk[26], G.Unel[20], J.Urakawa[61], P.VanMechelen[05], A.Variola[52], R.Veness[16], A.Vivoli[16], P.Vobly[40], J.Wagner[66], R.Wallny[68], S.Wallon[43,46,f], G.Watt[16], C.Weiss[36], U.A.Wiedemann[16], U.Wienands[57], F.Willeke[37], B.-W.Xiao[48], V.Yakimenko[37], A.F.Zarnecki[67], Z.Zhang[42], F.Zimmermann[16], R.Zlebcik[51], F.Zomer[42]

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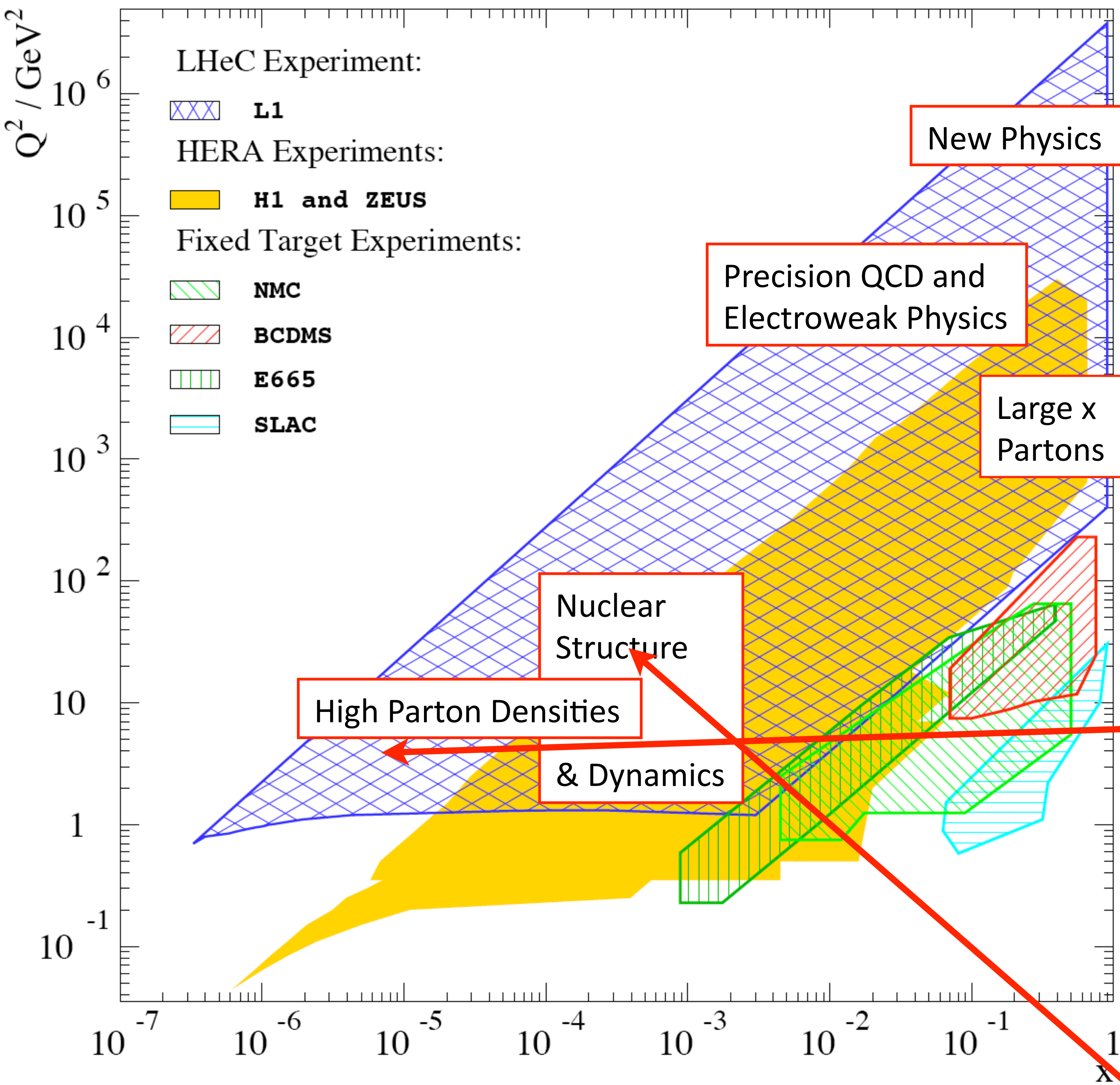
Brian A. Cole (Columbia University, New York)
Paul R. Newman (University of Birmingham)
Anna M. Stasto (Pennsylvania State University)

Michele Arneodo (INFN, Torino)
Alfred Mueller (Columbia University, New York)
Raju Venugopalan (BNL, Brookhaven)

Chapter 4: physics



- Proton structure to a few 10^{-20} m: Q^2 lever arm.
- Precision QCD/EW physics.
- High-mass frontier (leptoquarks, excited fermions, contact interactions).

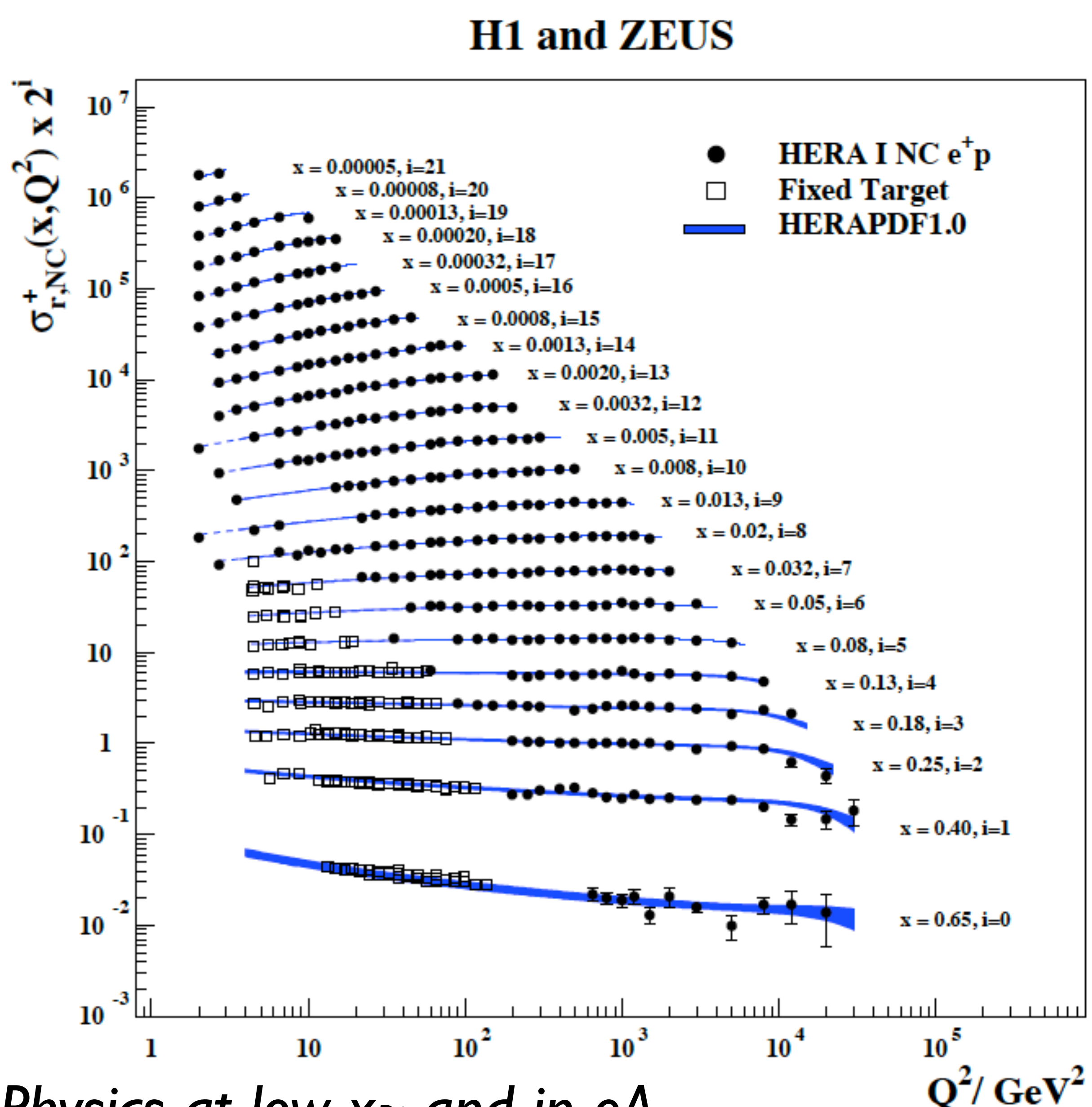
[Talk by Laycock]

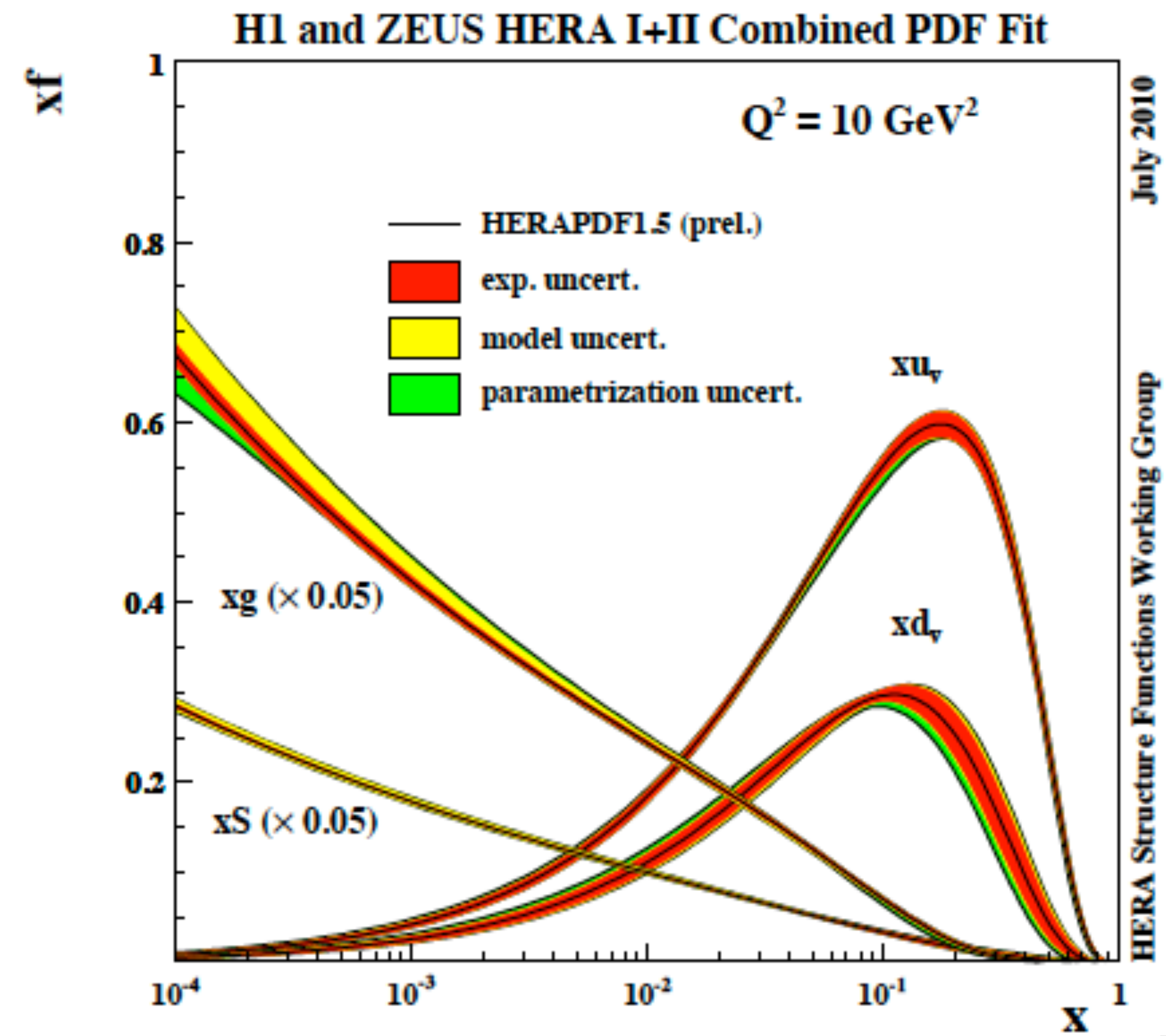
- Unambiguous access, in ep and eA, to a qualitatively novel regime of matter predicted by QCD.
- Substructure/parton dynamics inside nuclei with strong implications on QGP search.

Physics at low x_{Bj} and in eA.

Legacy from HERA:

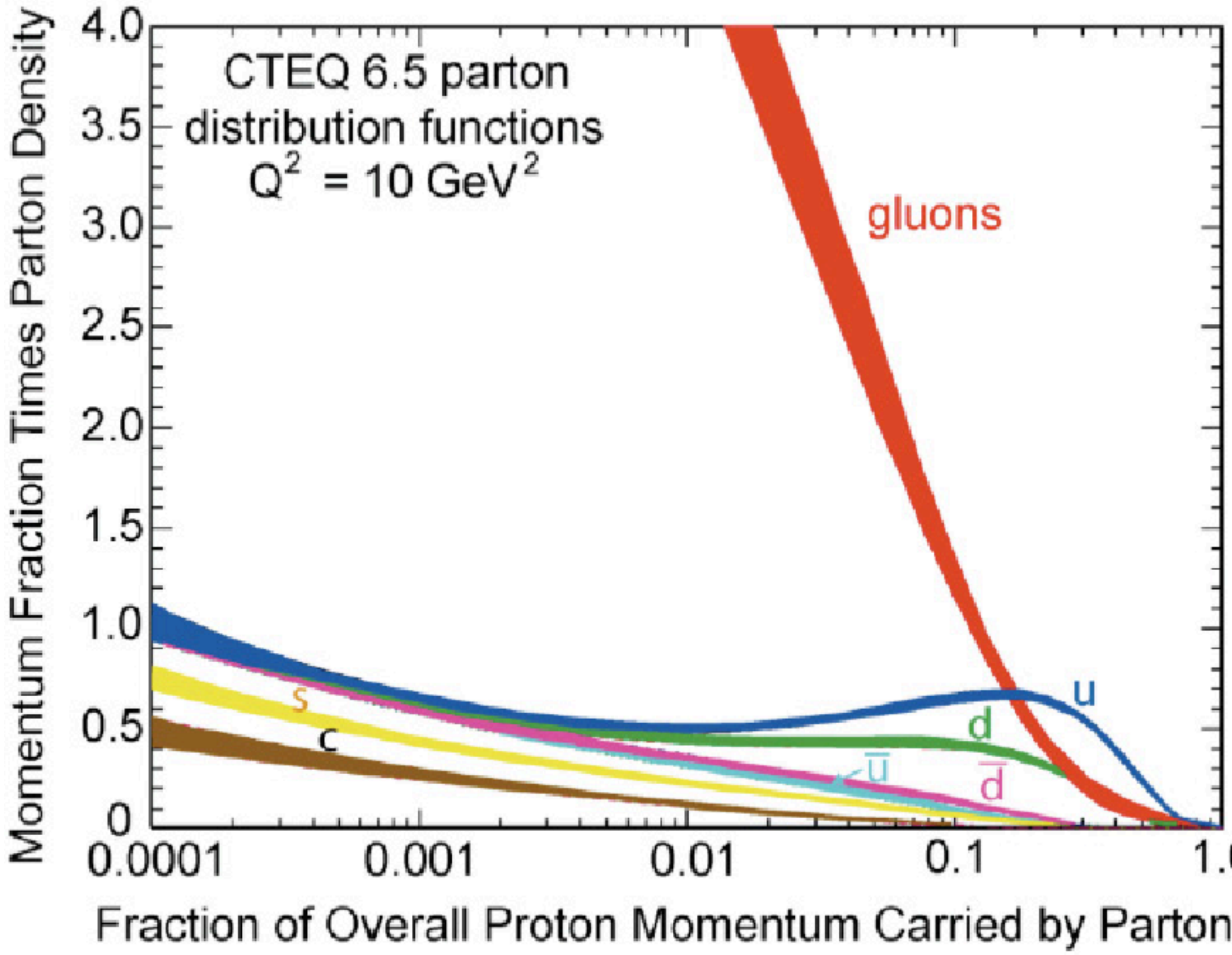
- Structure functions in an extended x-Q^2 range, xg $\propto 1/x^\lambda$, $\lambda>0$.
- Large fraction of diffraction $\sigma_{diff}/\sigma_{tot}\sim 10\%$.
- But: no eA/eD, kinematical reach at small x, luminosity at high x / for searches (odderon,...), flavour decomposition, TMDs,...

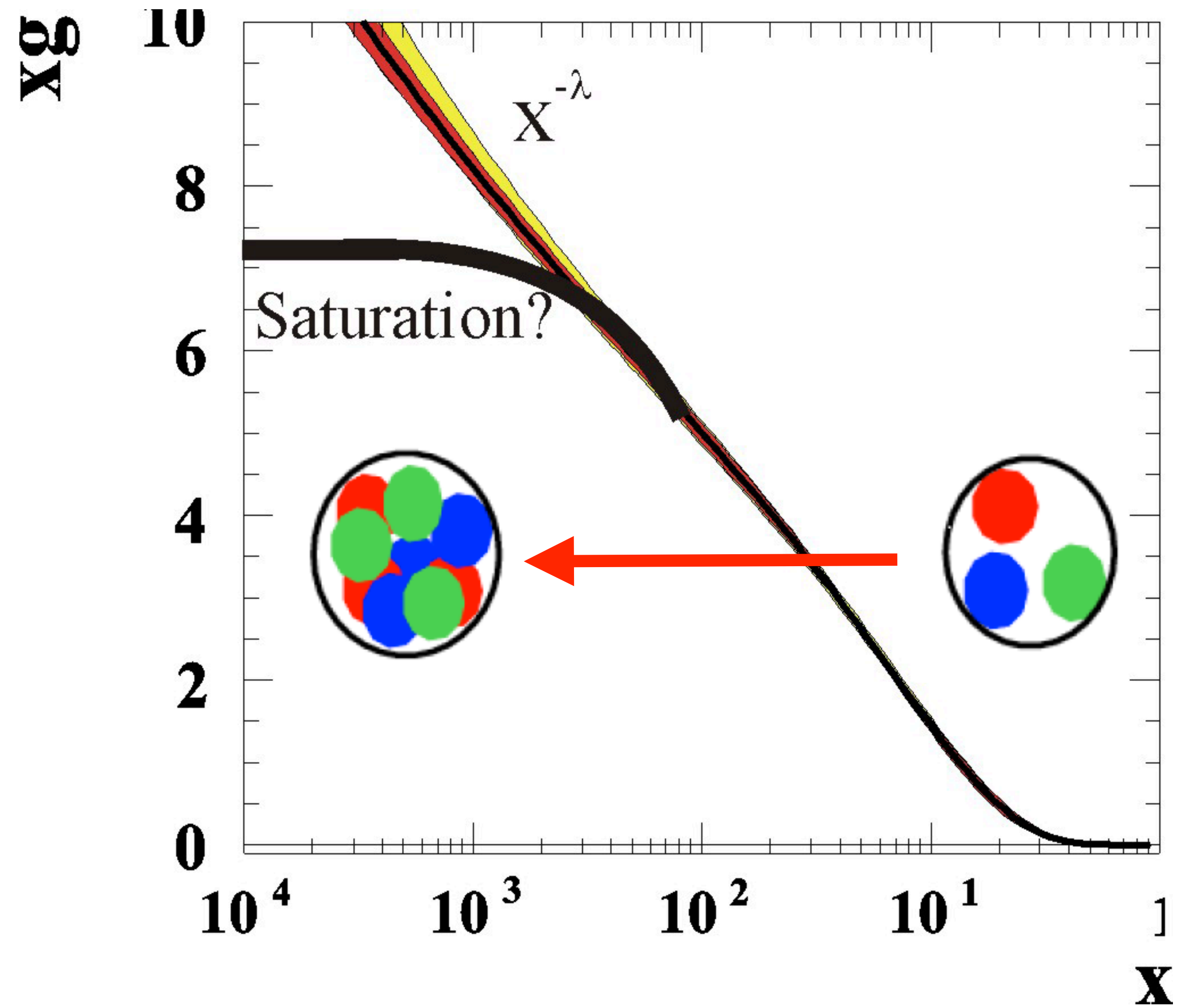




Physics at low x_{Bj} and in eA.

Small x and saturation:





- QCD radiation of partons when x decreases leads to a large number of partons (gluons), provided each parton evolves independently (linearly, $\Delta[xg] \propto xg$).
- This independent evolution breaks at high densities (<u>small x or high mass number A</u>): non-linear effects ($g \leftrightarrow gg$, $\Delta[xg] \propto xg - k(xg)^2$).

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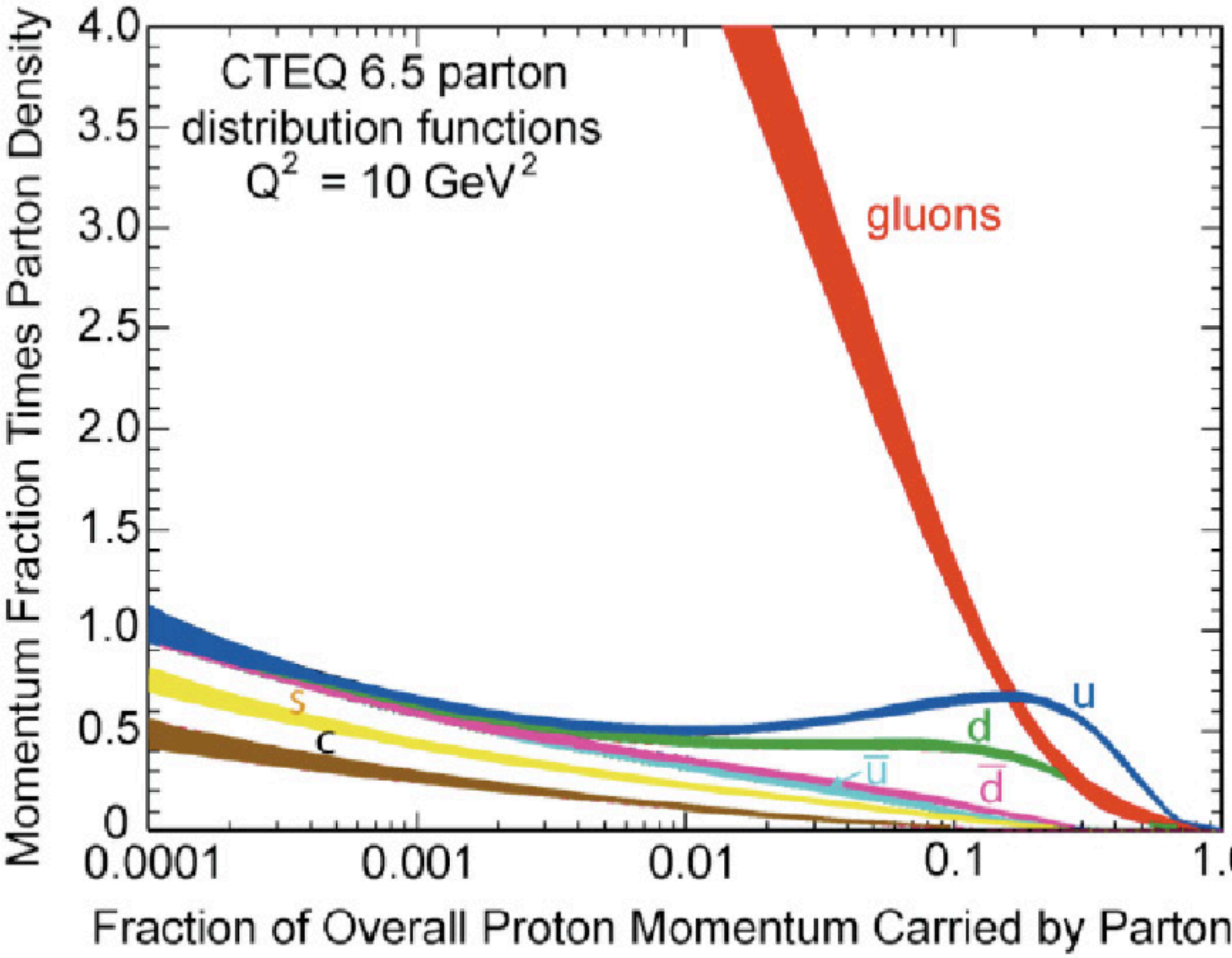

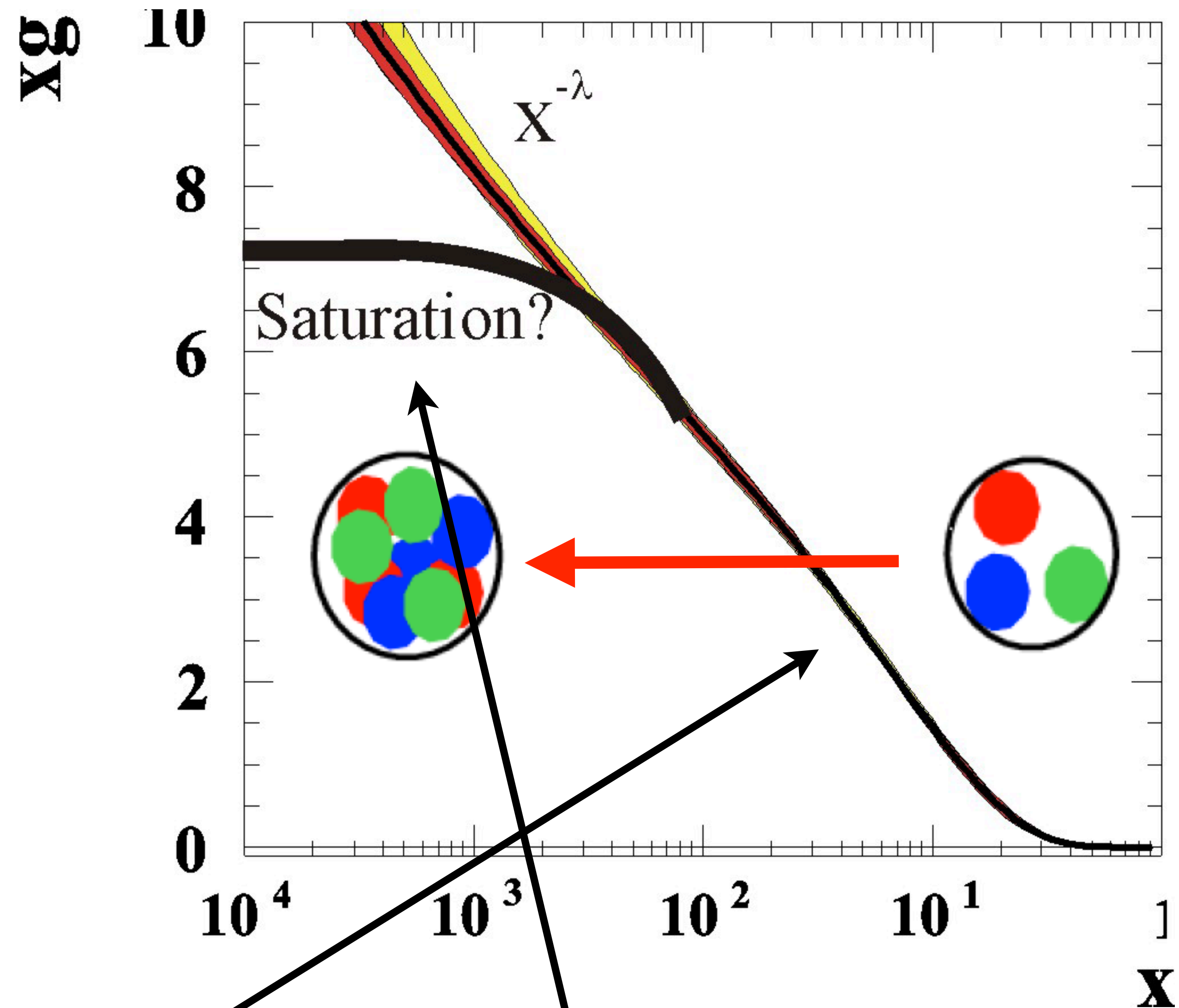

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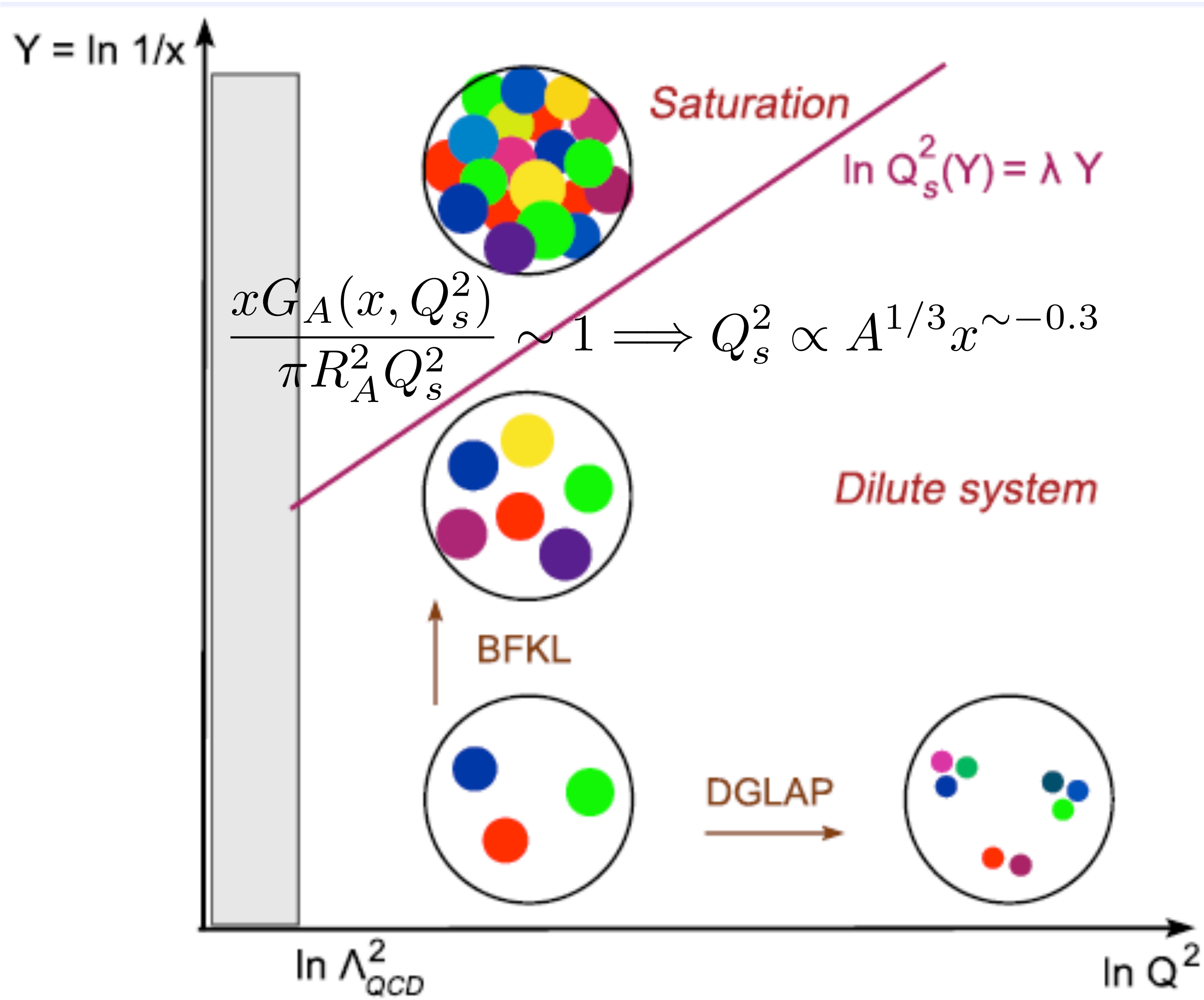
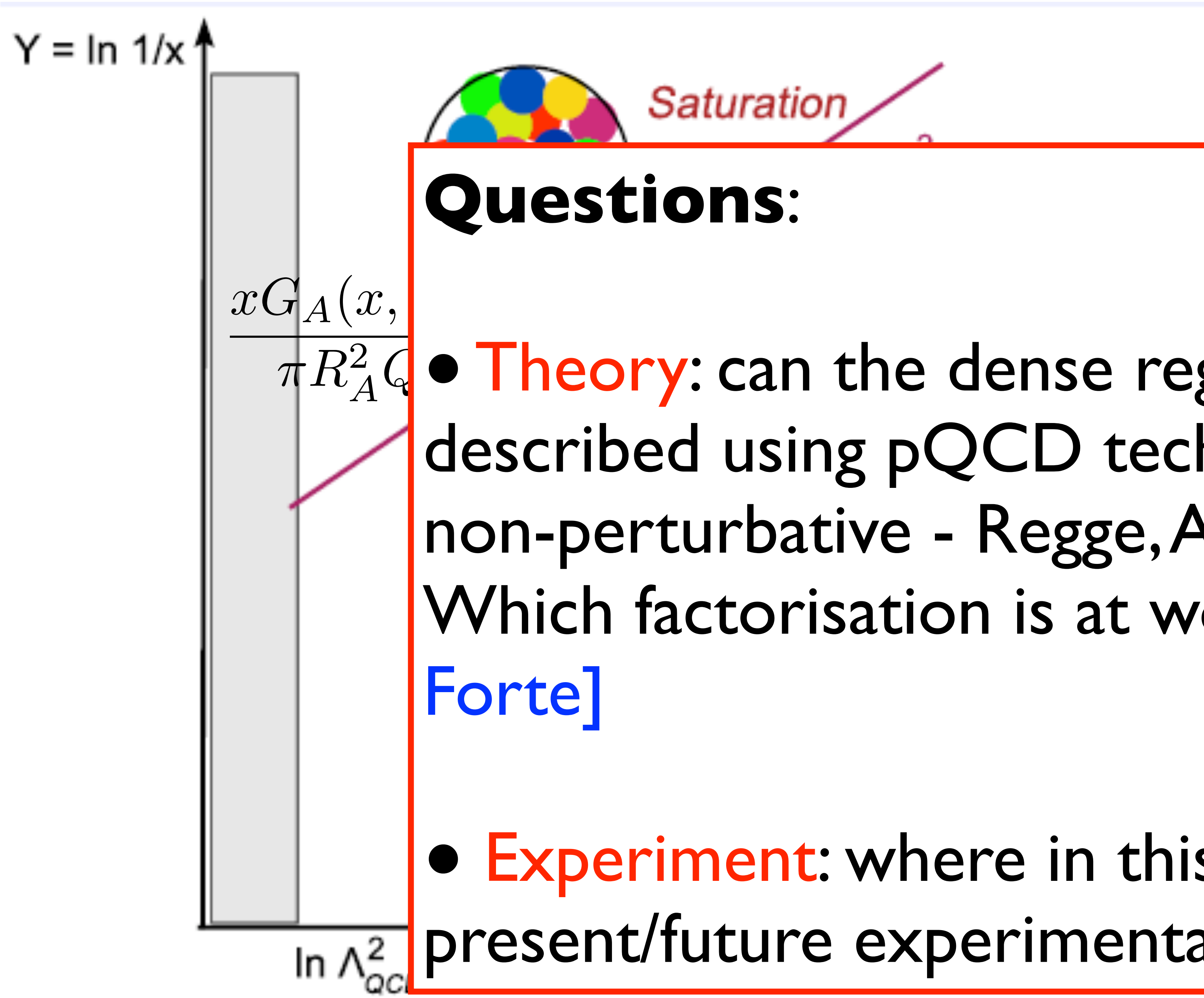


Origin in the early 80's: GLR, Mueller et al, McLerran-Venugopalan.

Our aims: understanding

- The implications of unitarity in a QFT.
- The behaviour of QCD at large energies.
- The hadron wave function at small x.
- The initial conditions for the creation of a dense medium in heavy-ion collisions.

The 'QCD phase' diagram:



Questions:

• Theory: can the dense regime be described using pQCD techniques? Or non-perturbative - Regge, AdS/QCD,...? Which factorisation is at work? [talk by Forte]

• Experiment: where in this plane do present/future experimental data lie?

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• The initial conditions for the creation of a dense medium in heavy-ion collisions.

Status of small-x physics:

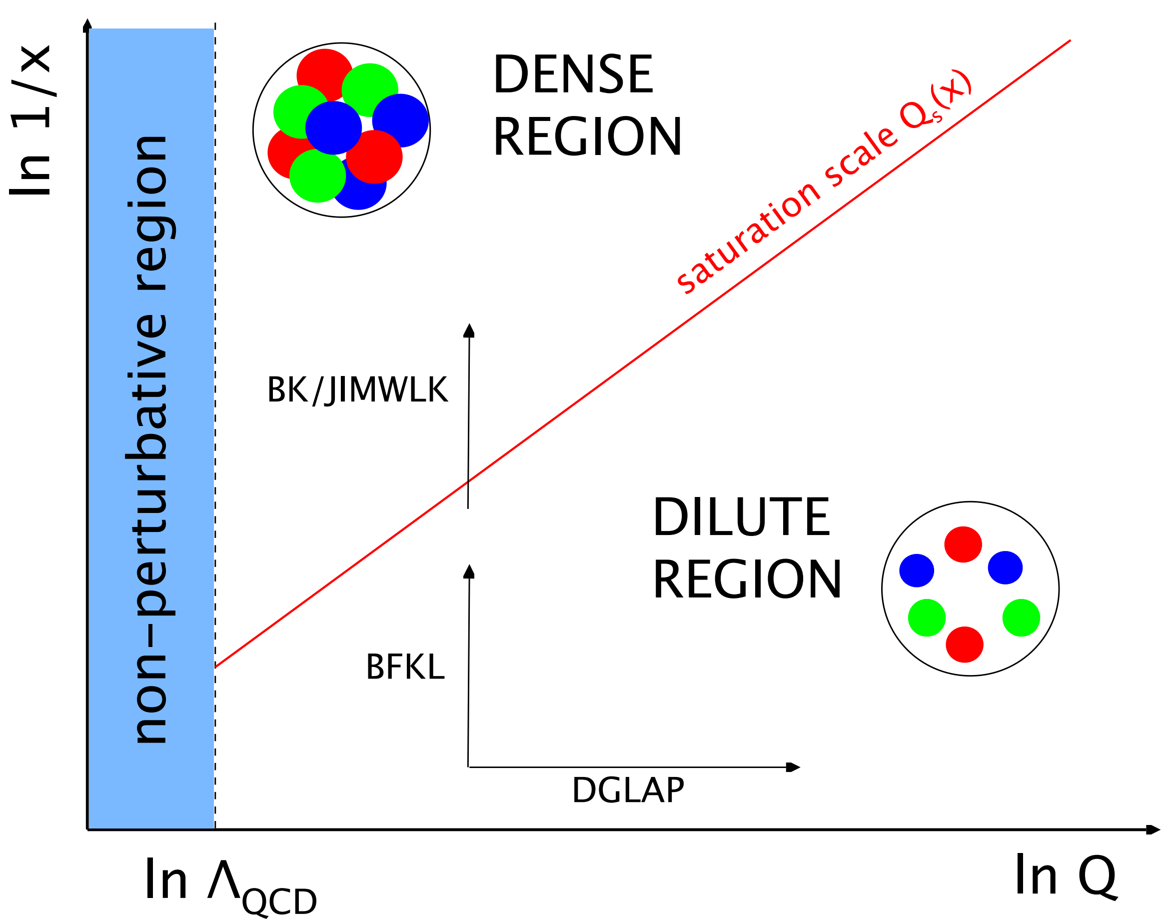
- Three pQCD-based alternatives to describe small-x ep and eA data (differences at moderate $Q^2(>\Lambda^2_{QCD})$ and small x):

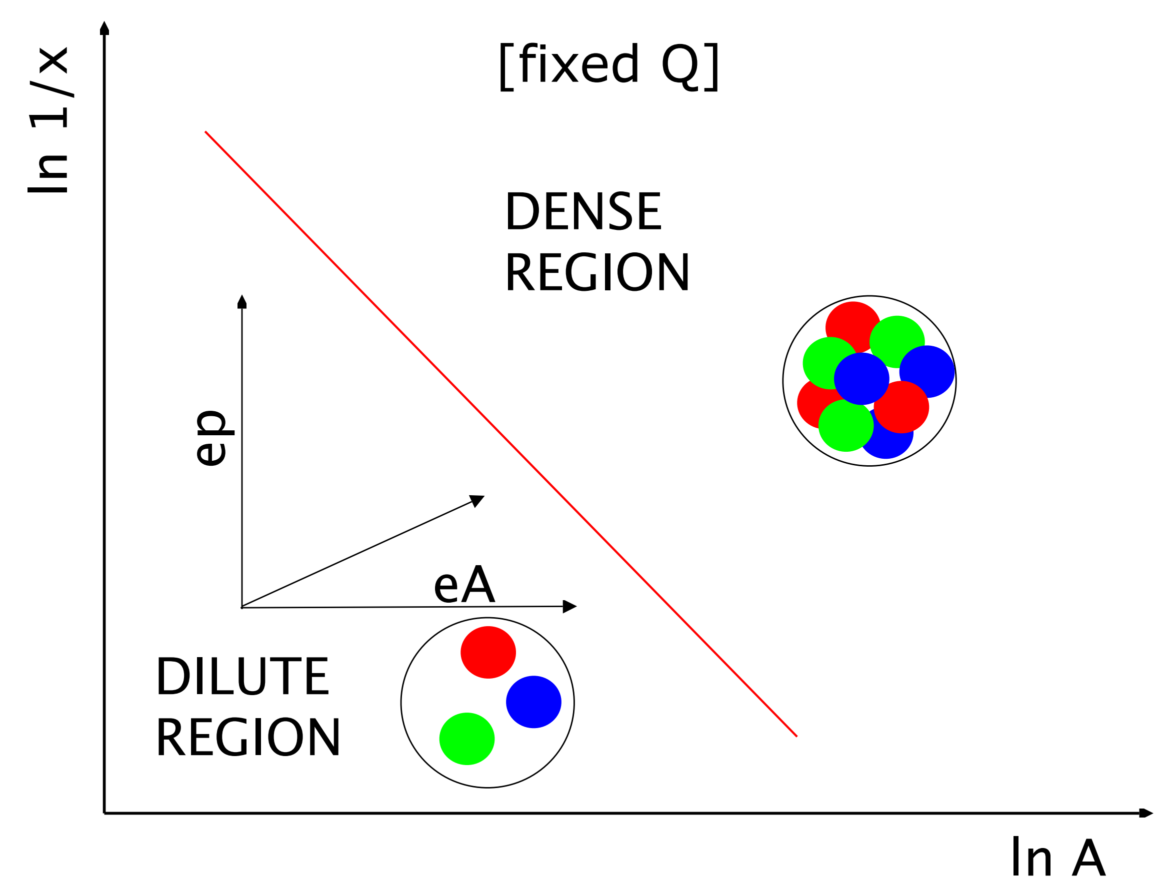
→ DGLAP evolution (fixed order PT).

→ Resummation schemes.

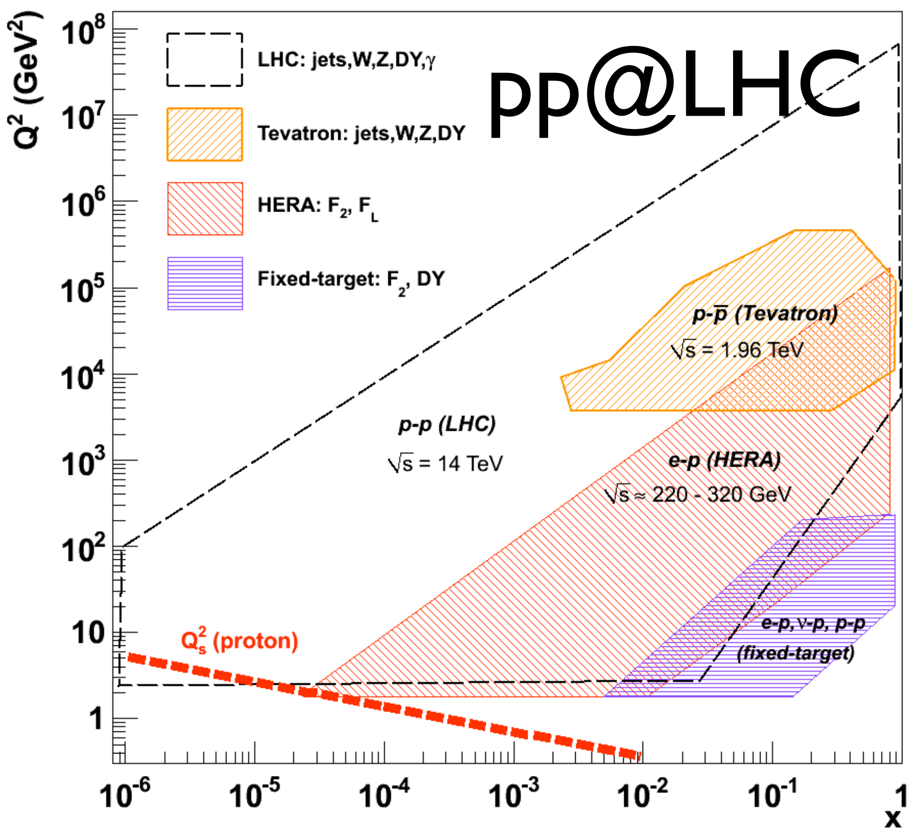
→ Saturation (CGC, dipole models).

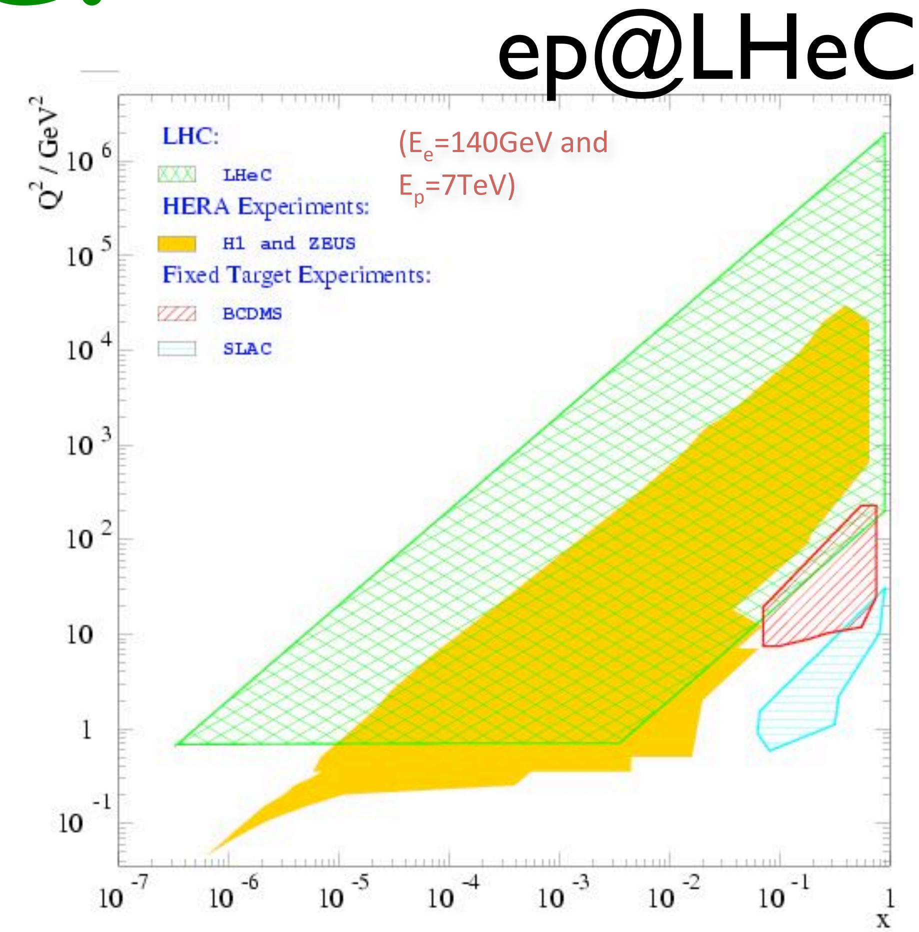
- **Non-linear effects** (unitarity constraints) are density effects: where? ⇒ **two-pronged approach at the LHeC**: ↓ x / ↑ A.

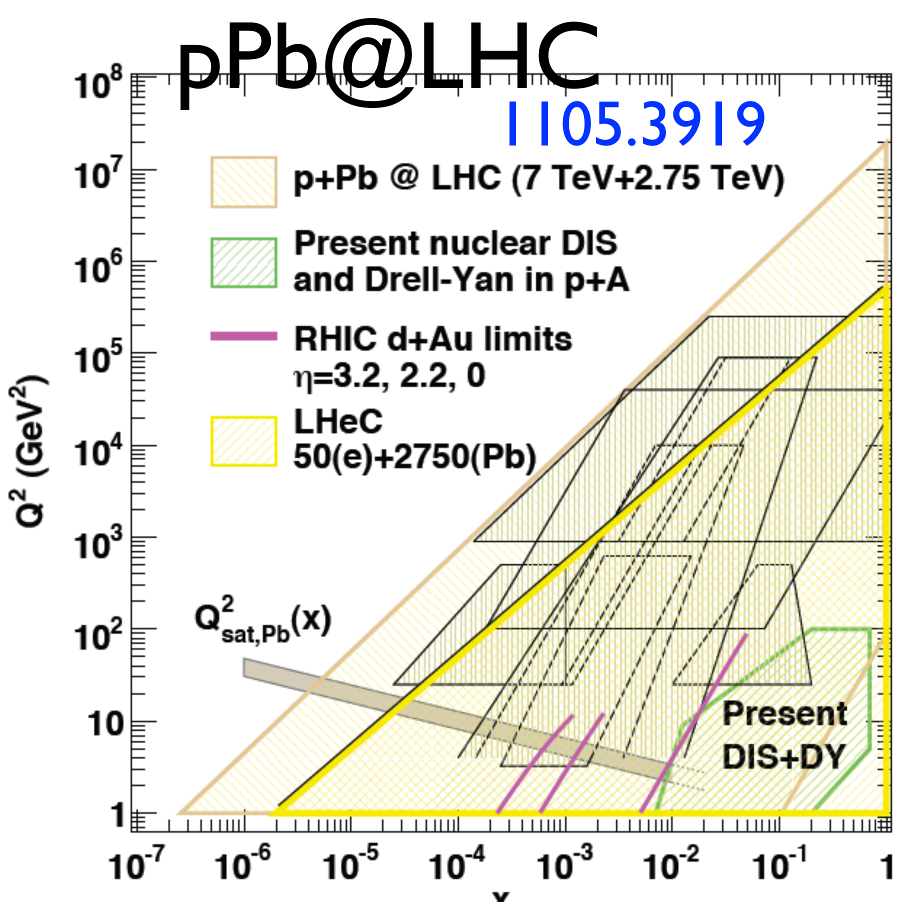




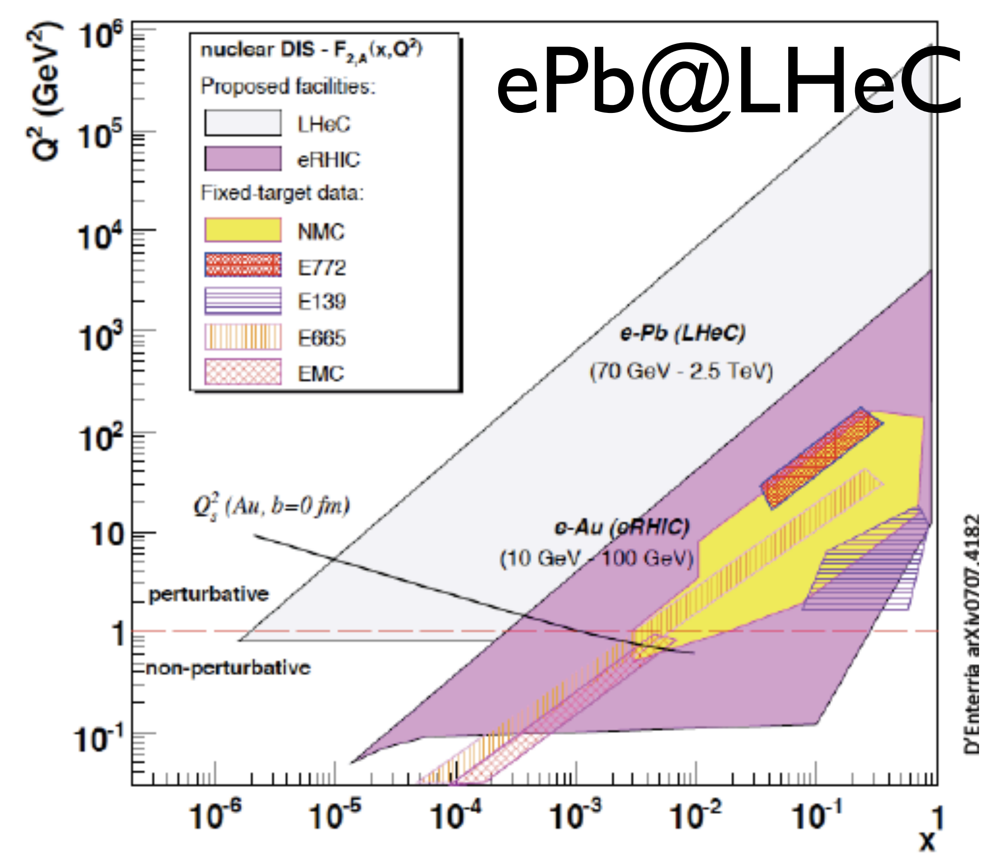
LHC vs. LHeC:







- The LHeC will explore a region overlapping with the LHC but in a much cleaner manner.



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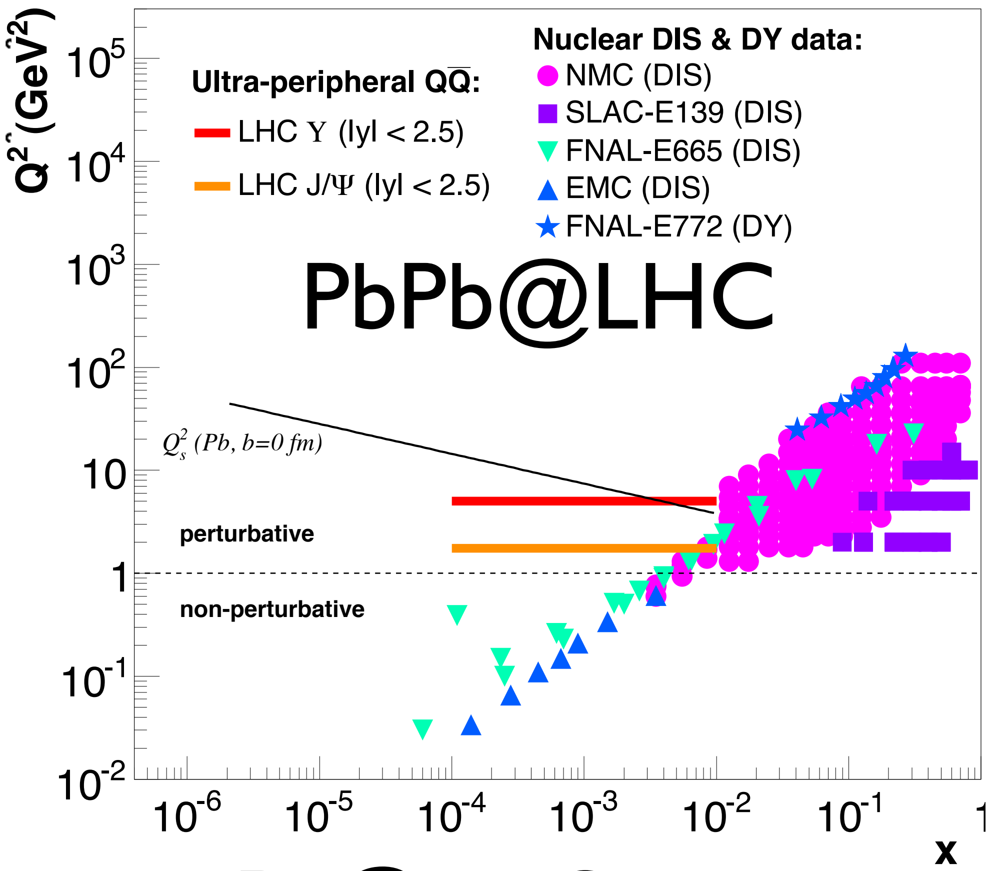
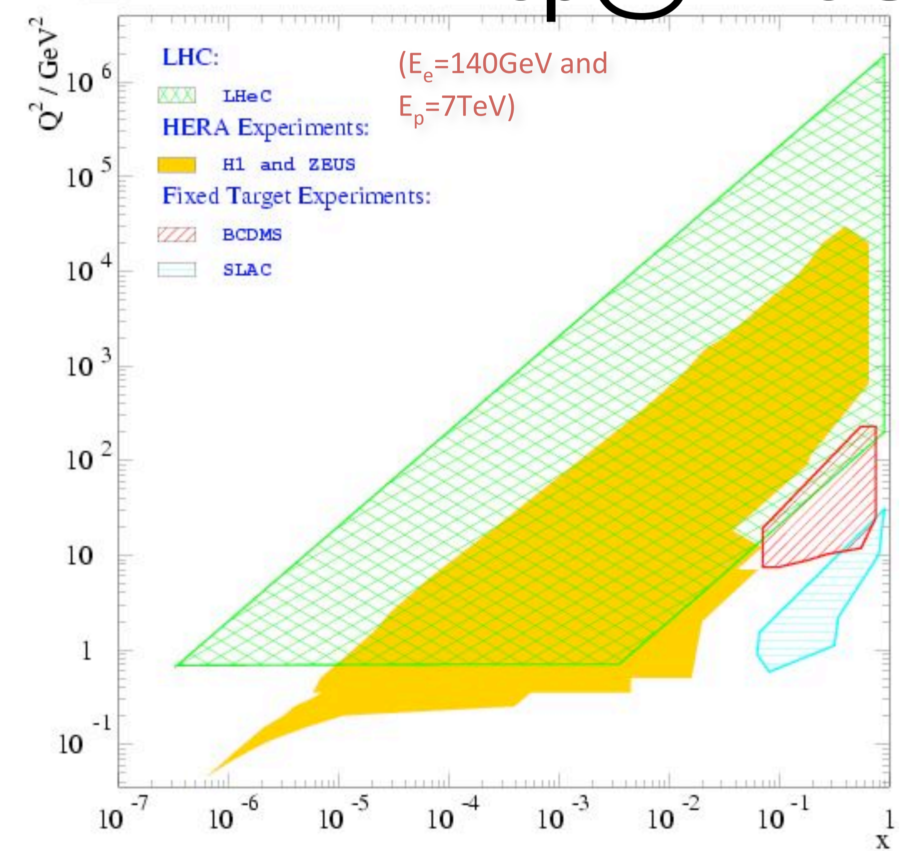


ep@LHeC



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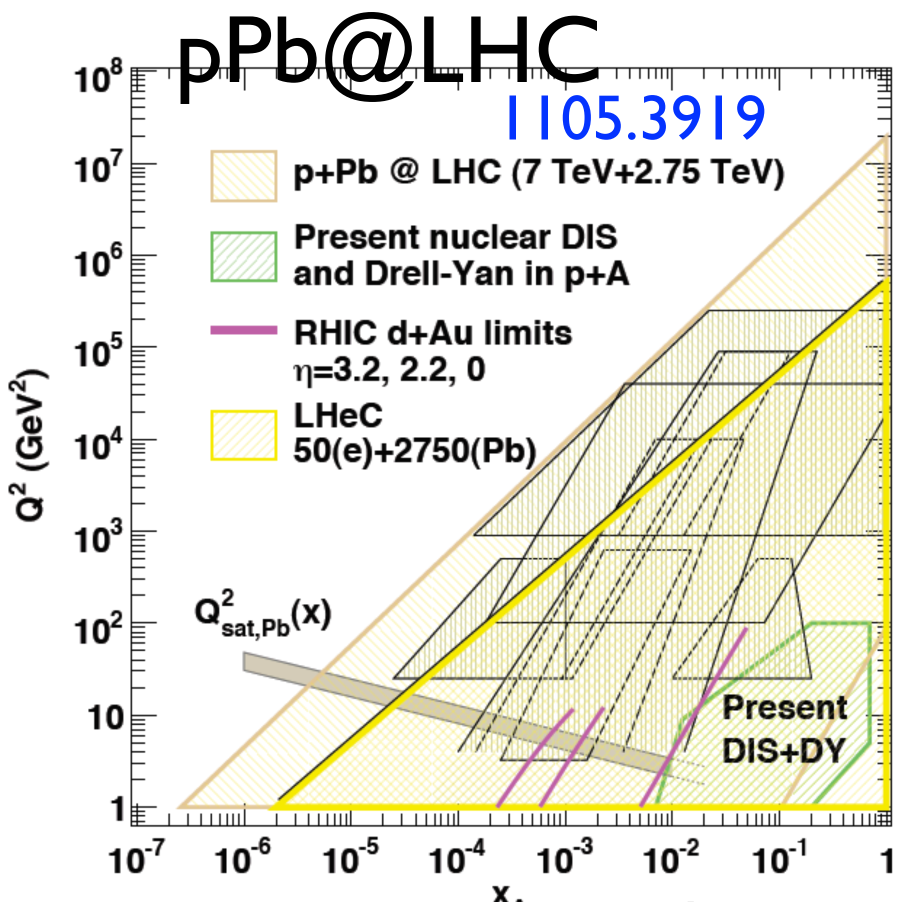
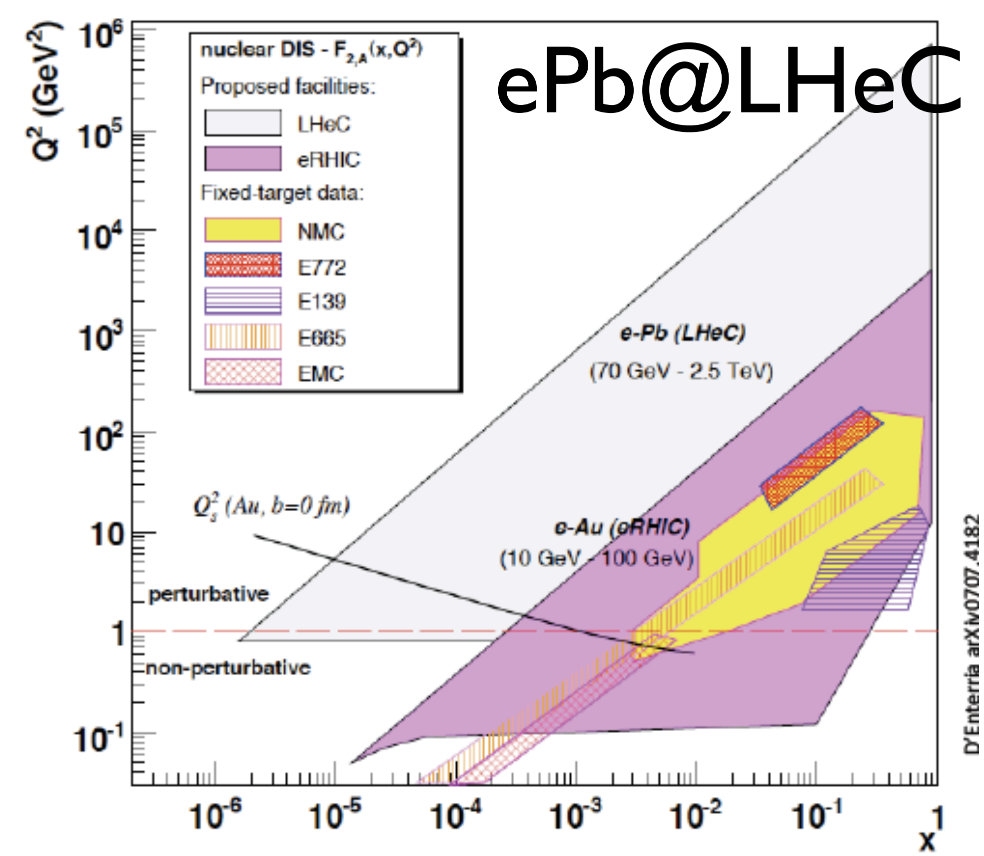
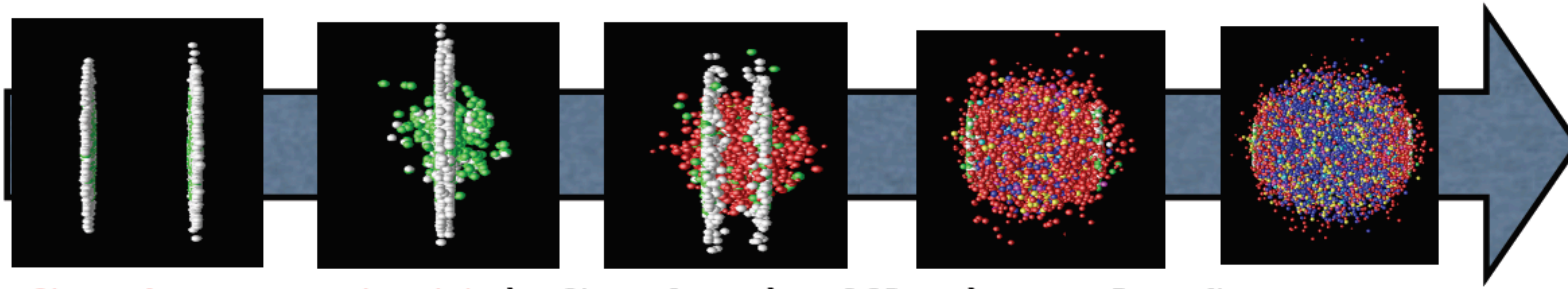




Physics at low x_{Bj} and in eA.

Relevance for the HI program:



- Nuclear wave function at small x: nuclear structure functions.

- Particle production at the very beginning: which factorisation in eA?

- How does the system behave as ~ isotropised so fast?: initial conditions for plasma formation to be studied in eA.

- Probing the medium through energetic particles (jet quenching etc.): modification of QCD radiation and hadronization in the nuclear medium.

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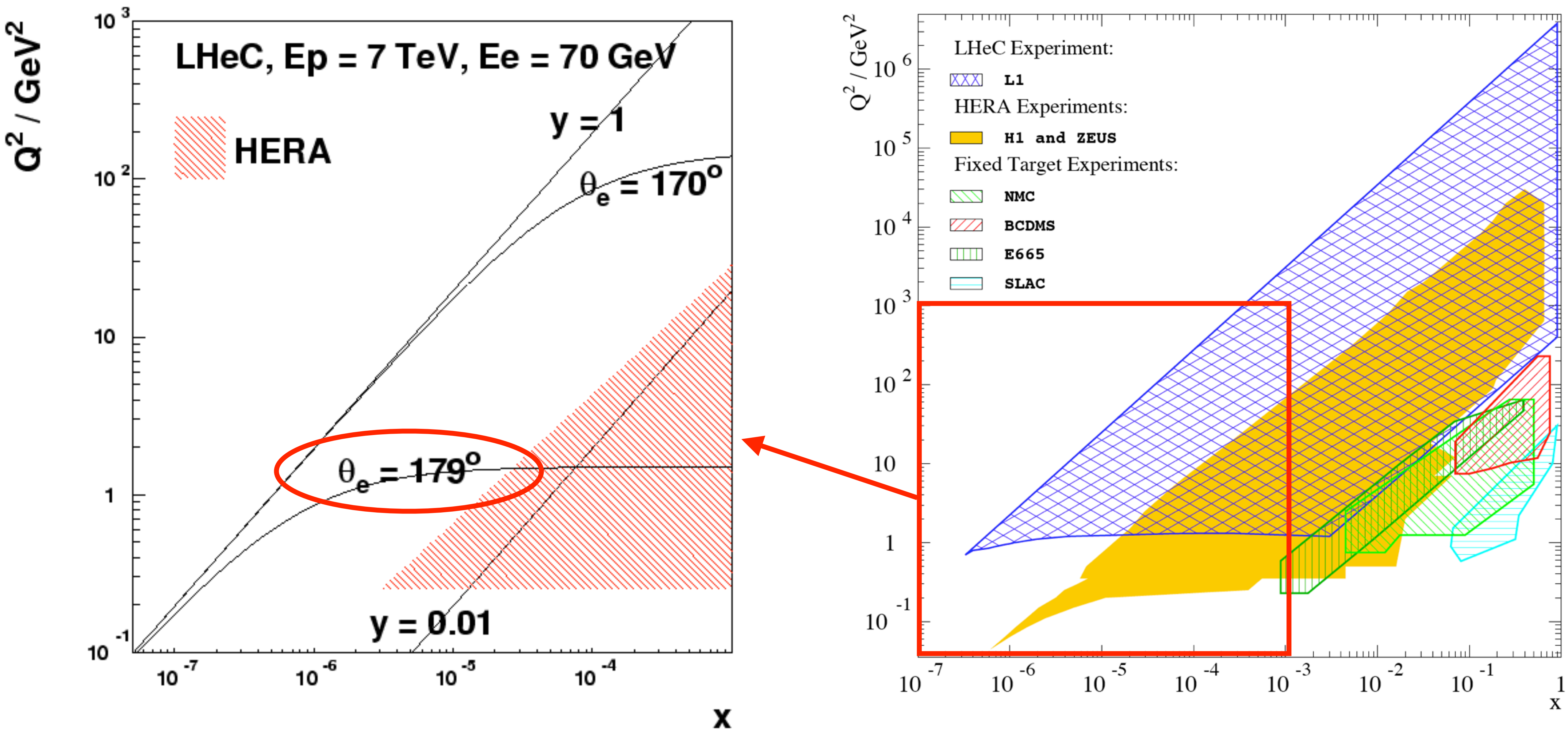
Proton PDFs at small x:

- Parton densities poorly known at small x and small to moderate Q^2 [talks by Laycock and Radescu]: uncertainties in predictions.
- LHeC will substantially reduce the uncertainties in global fits: F_L and heavy flavour decomposition most useful.



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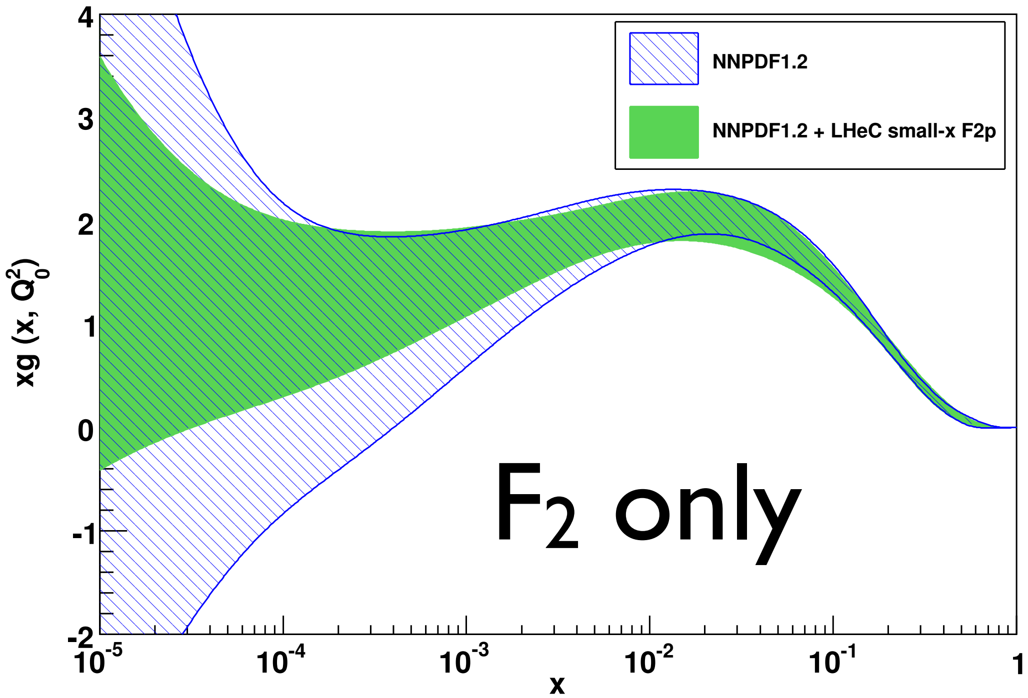
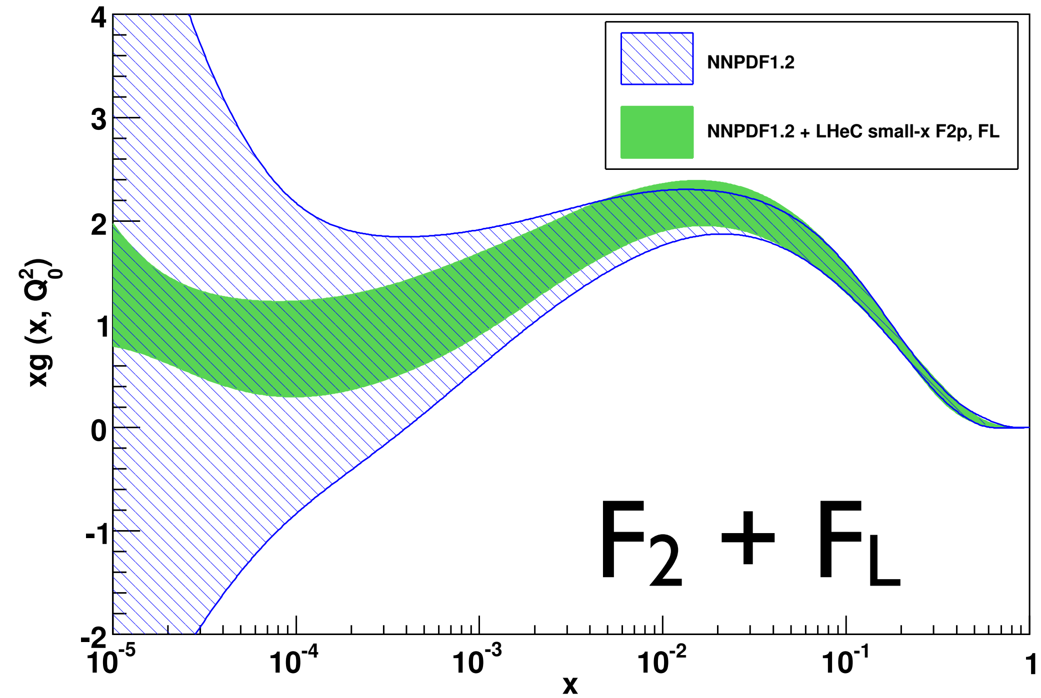
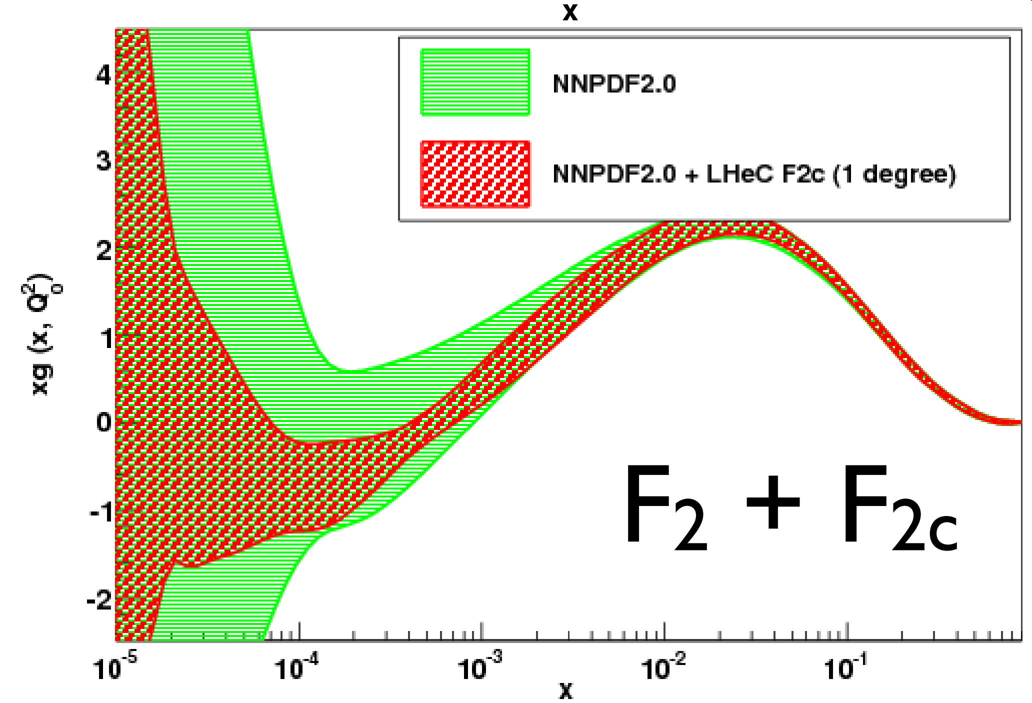


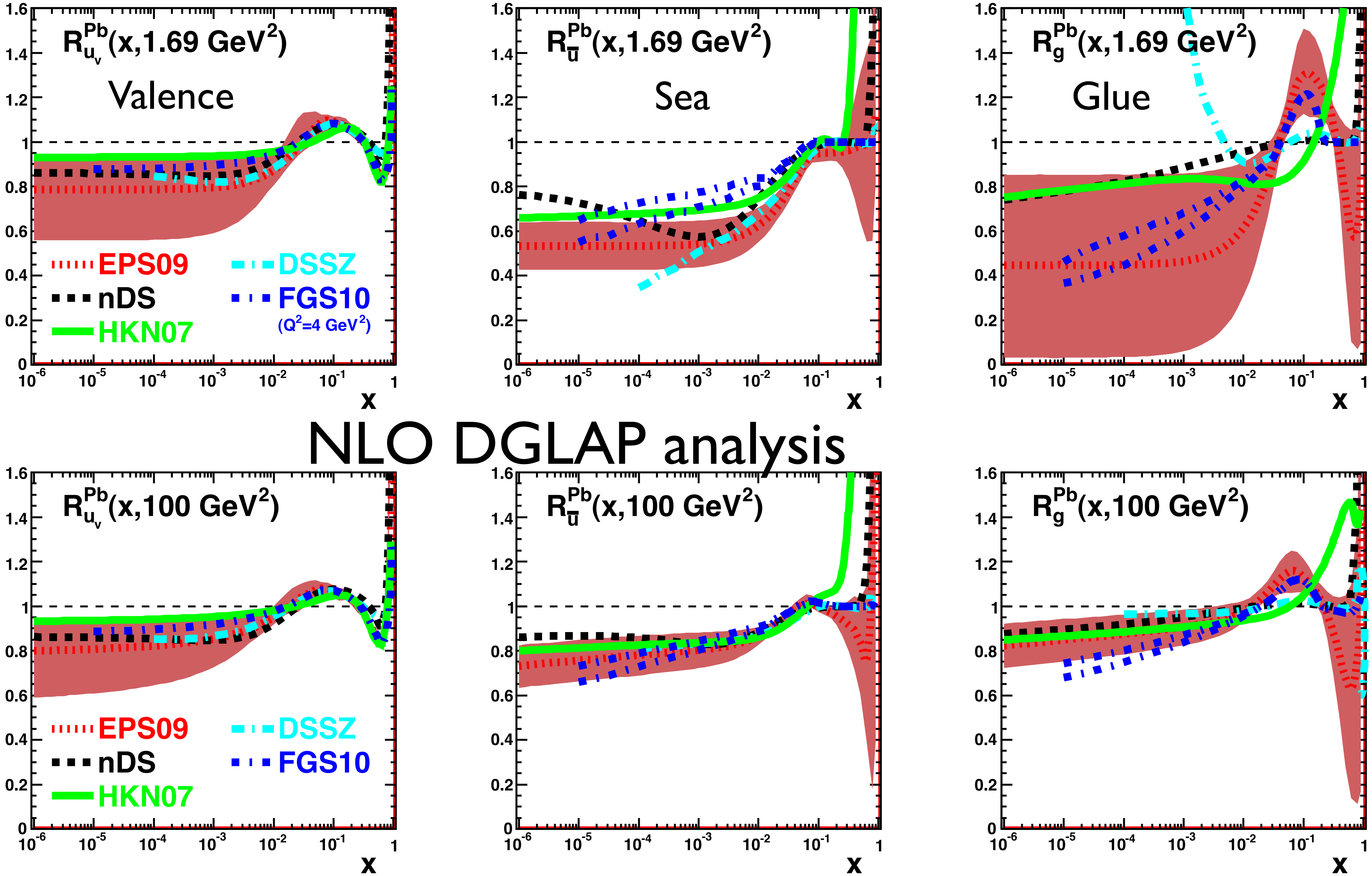


Q_0^2=2 GeV^2



Nuclear PDFs at small x (I):

- Parton densities unconstrained at small x and small to moderate Q^2 [talk by Zurita] ⇒ uncertainties in the predictions for observables within collinear factorisation: pPb@LHC.



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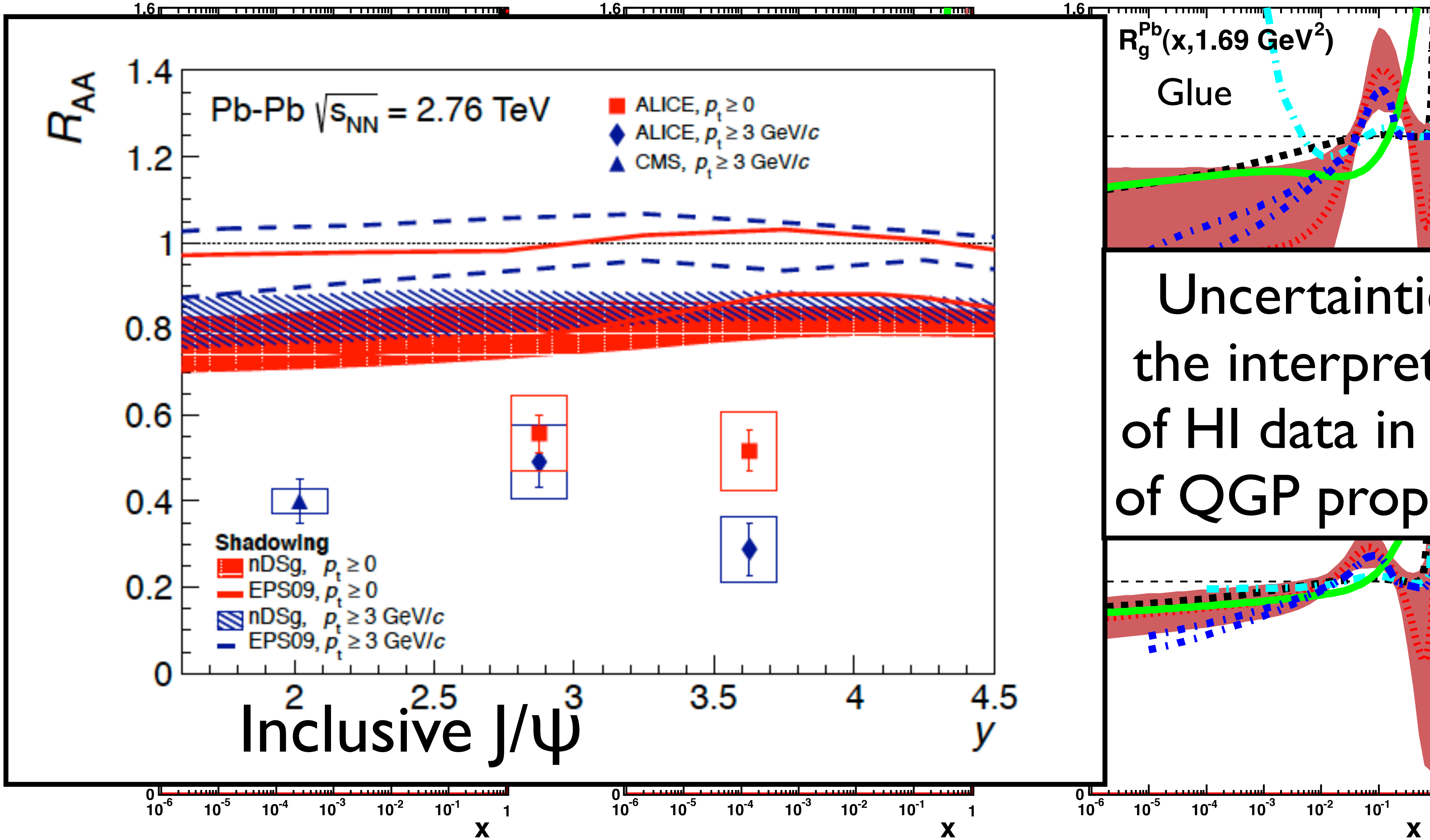
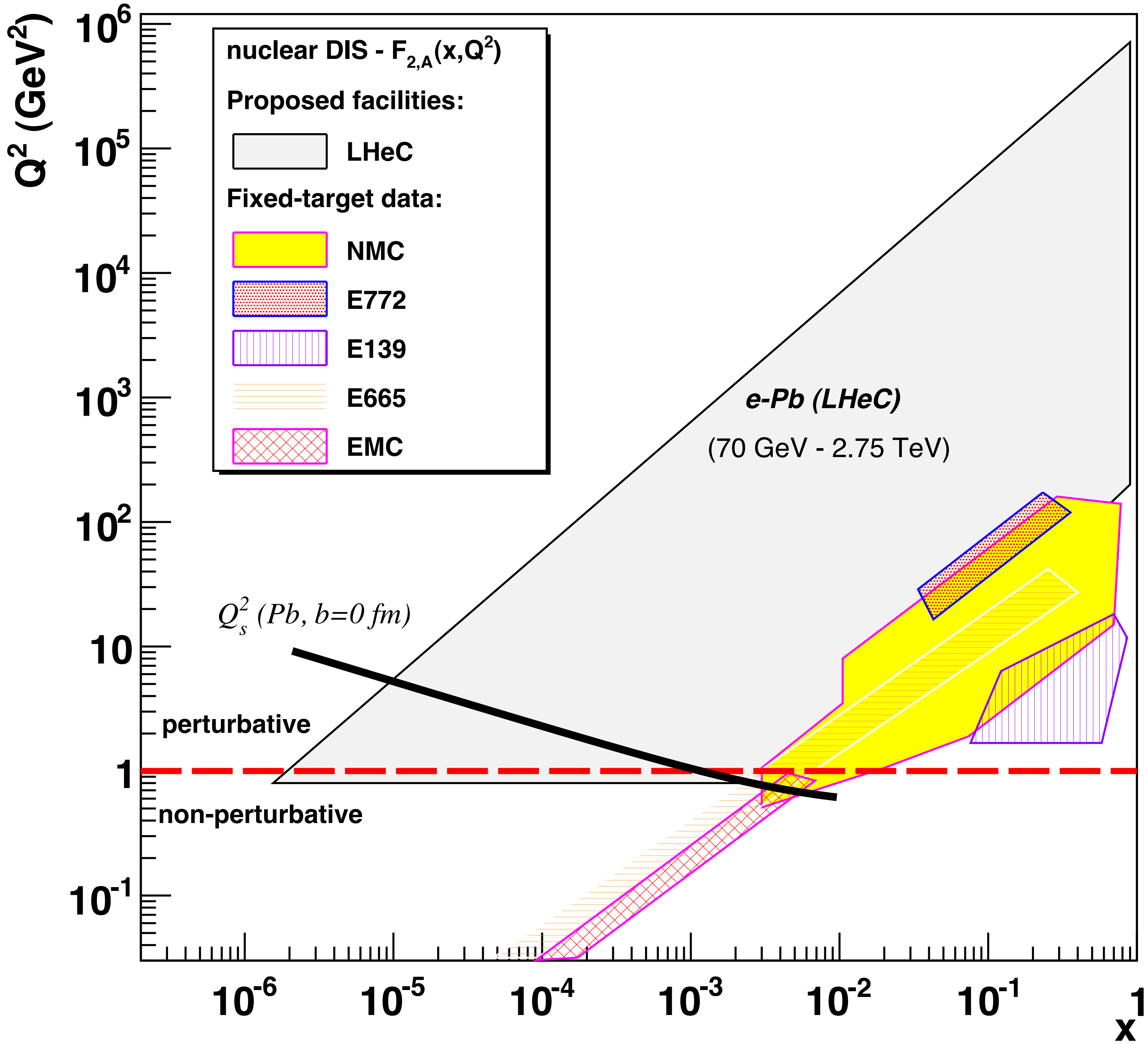


Uncertainties in the interpretation of HI data in terms of QGP properties.

Nuclear PDFs at small x (II):

- F$_2$ data substantially reduce the uncertainties in DGLAP analysis; inclusion of charm, beauty and F$_L$ also produce improvements.



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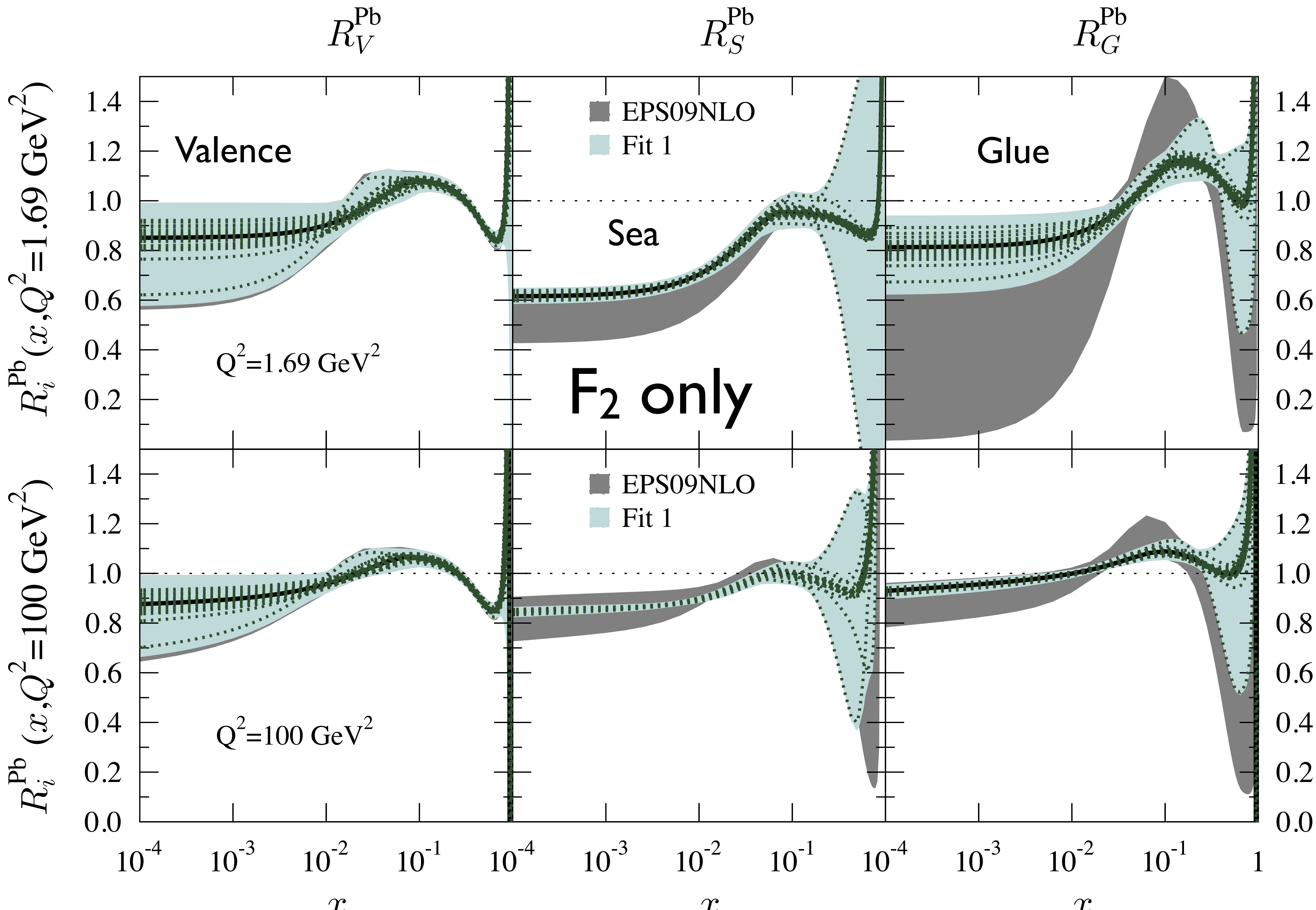

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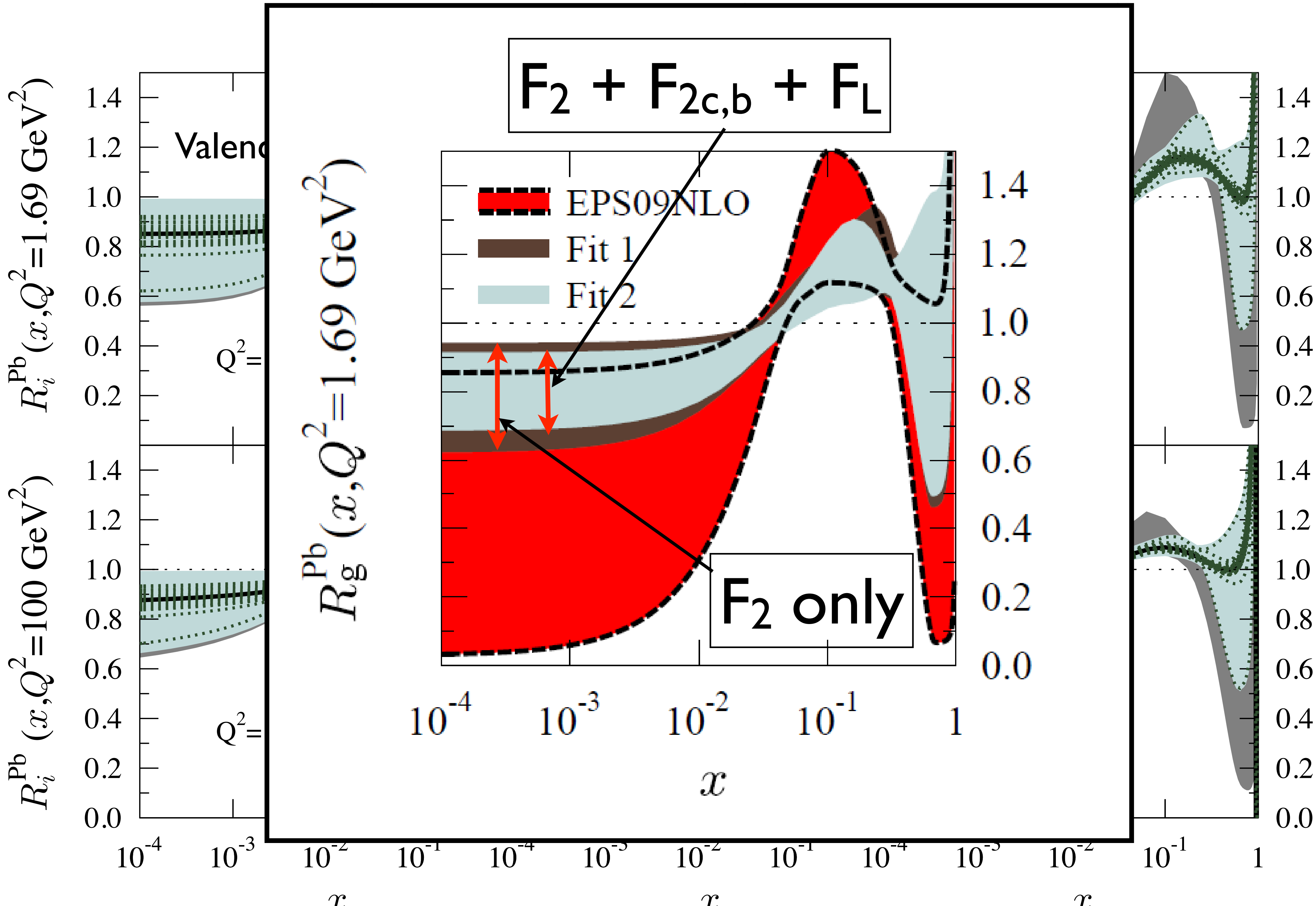
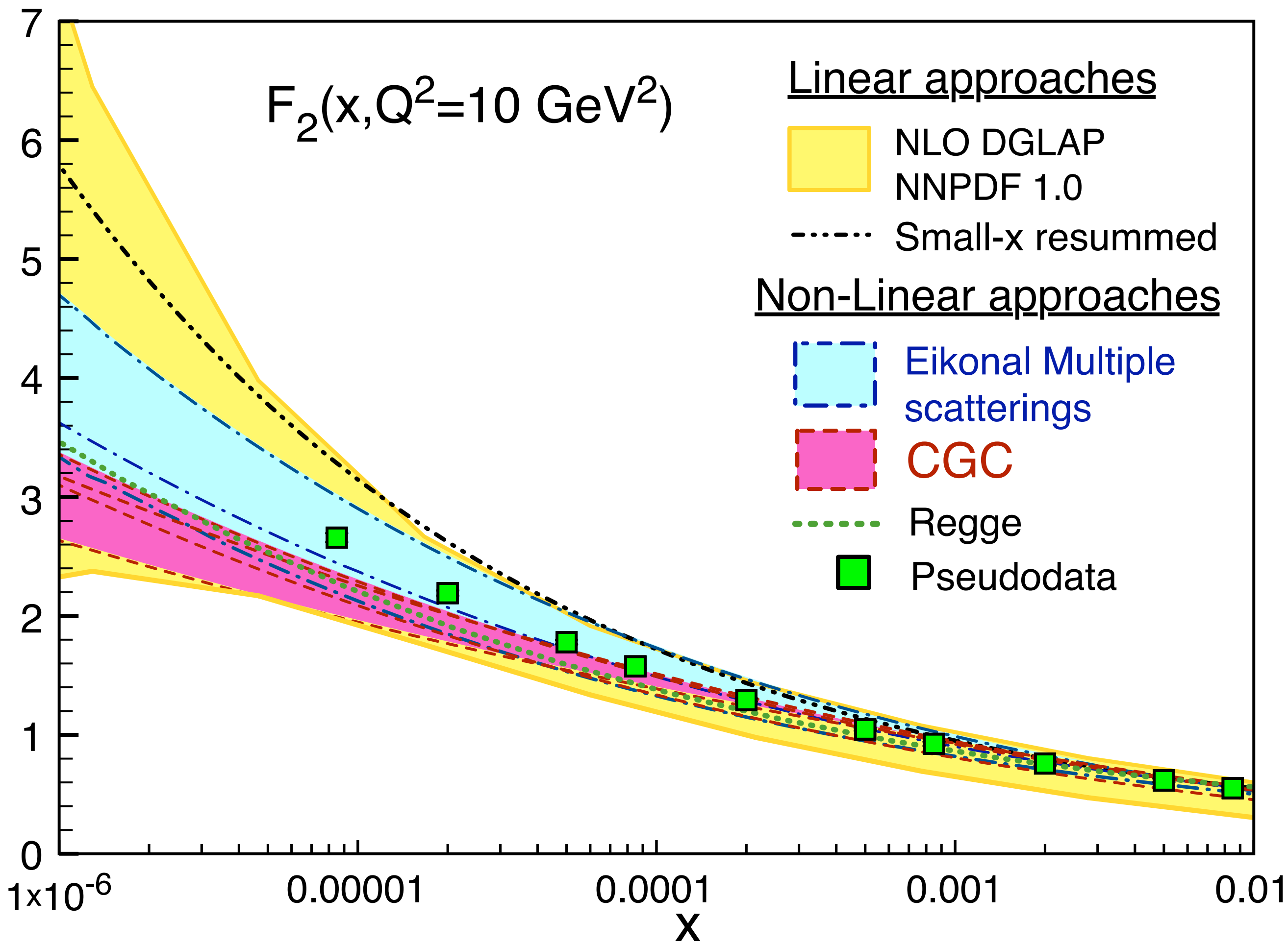
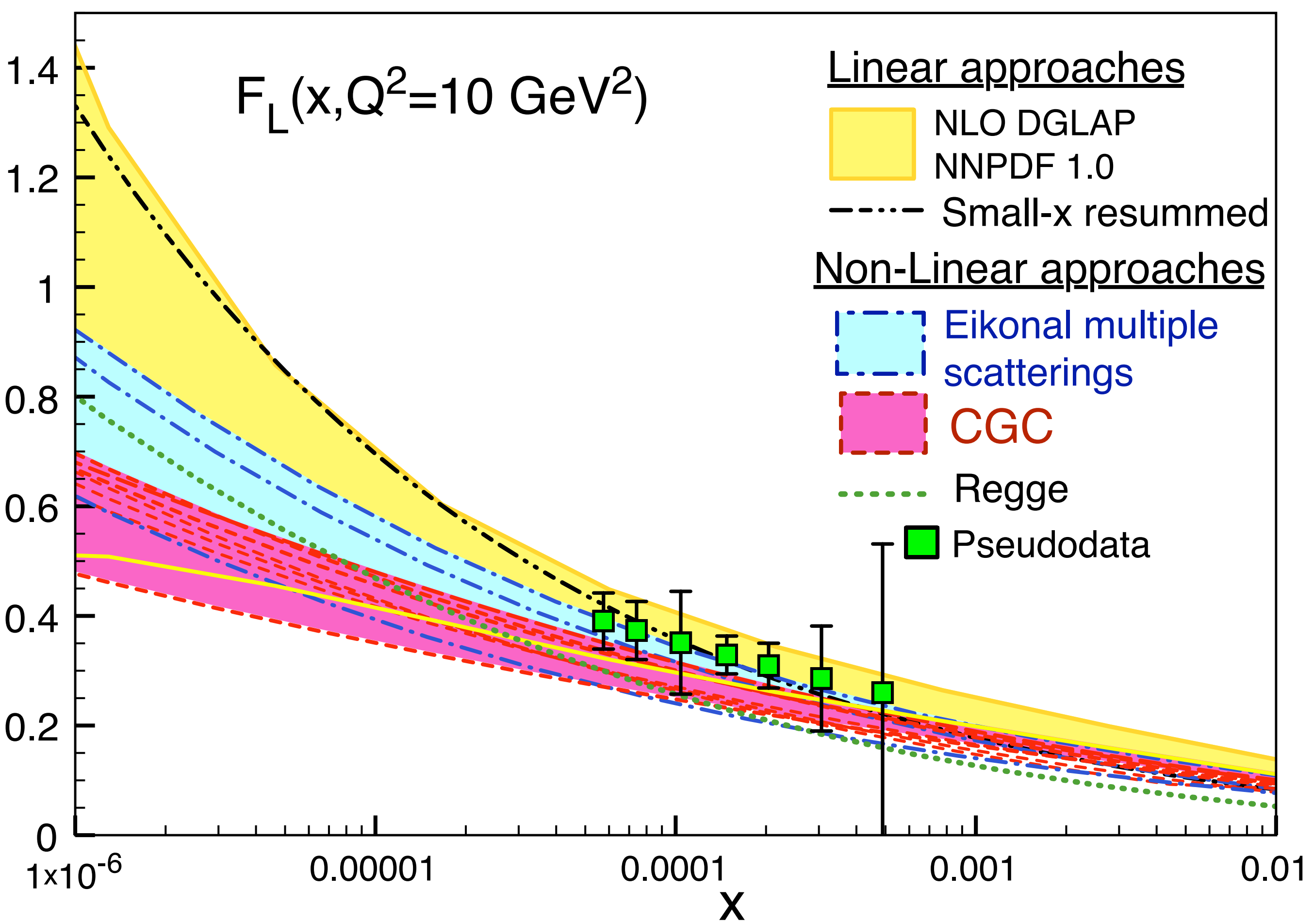


Effects beyond DGLAP?:

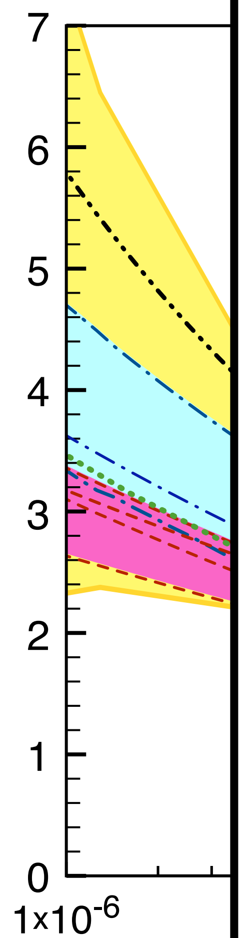


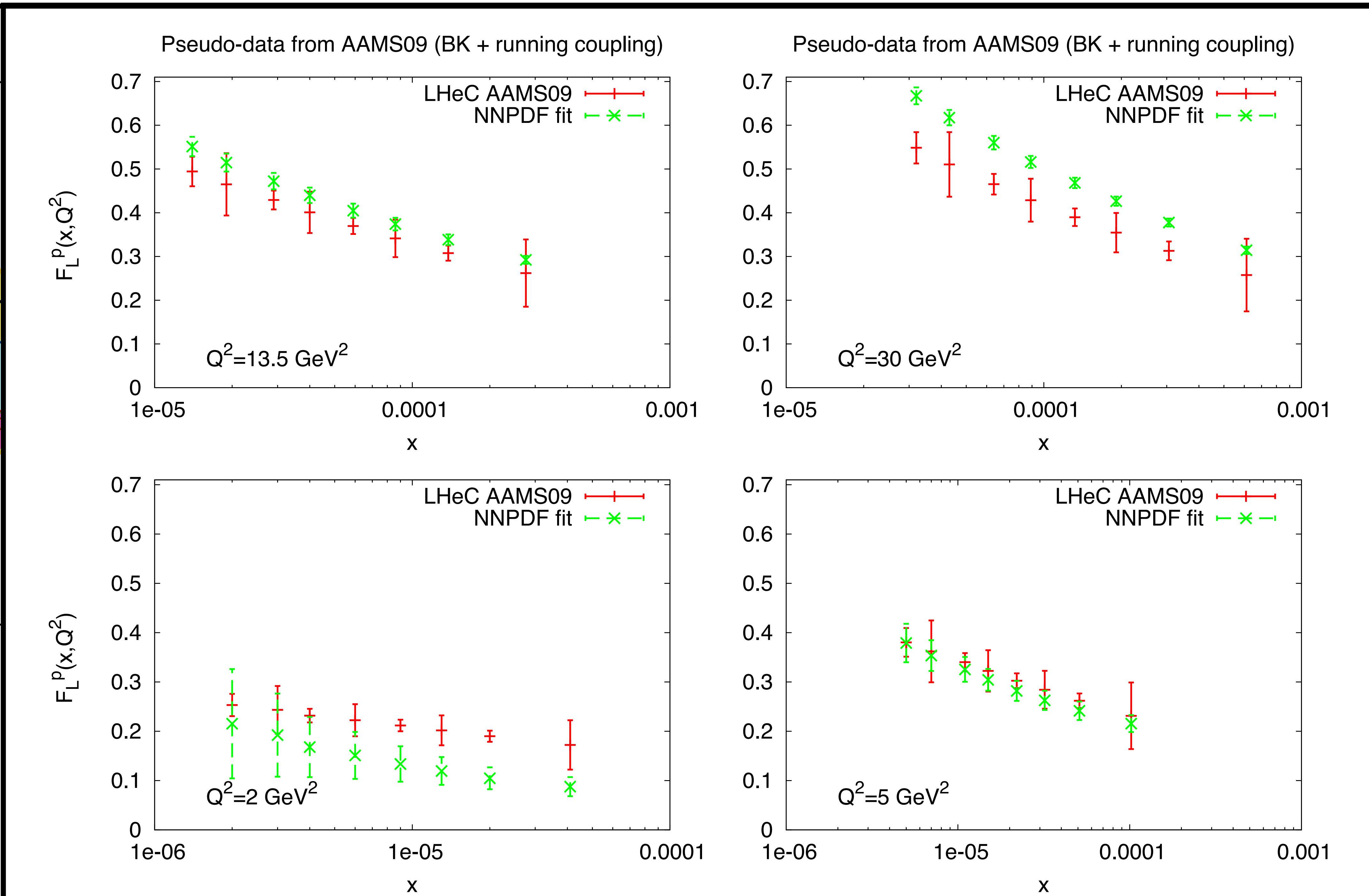


- LHeC F_2 and F_L data will have discriminatory power on models.

Effects beyond DGLAP?:

NLO DGLAP cannot simultaneously accommodate LHeC F_2 and F_L data if saturation effects included according to current models.

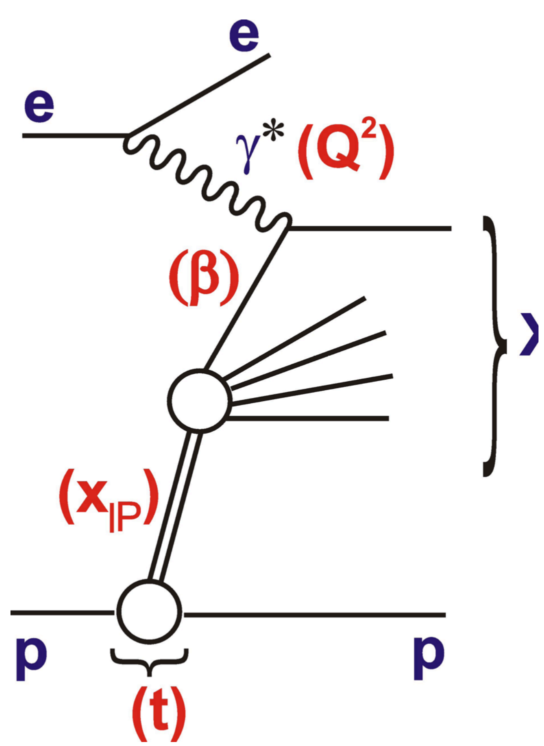


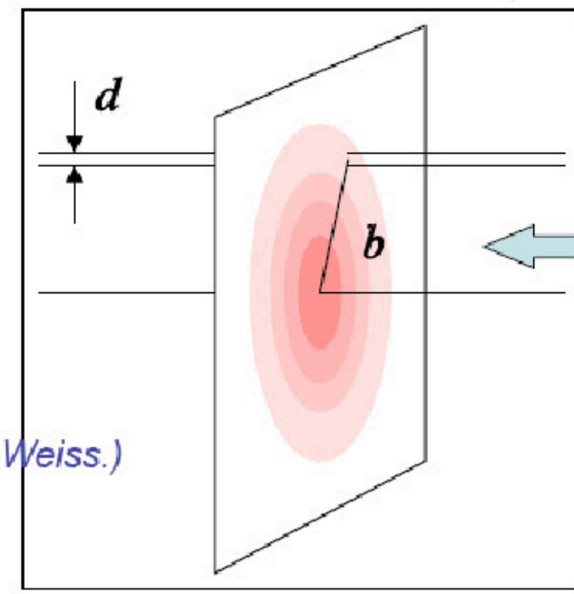


- LH … odels.

Diffraction:

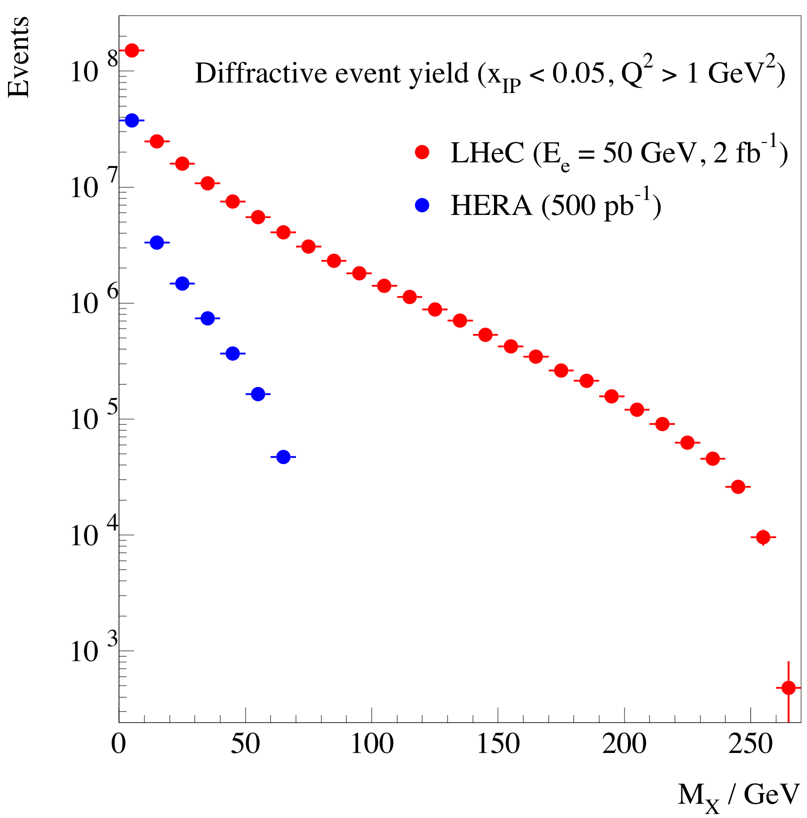
- t conjugate to b: transverse scan of the hadron.
- Large increase in M^2, x_P, β range.

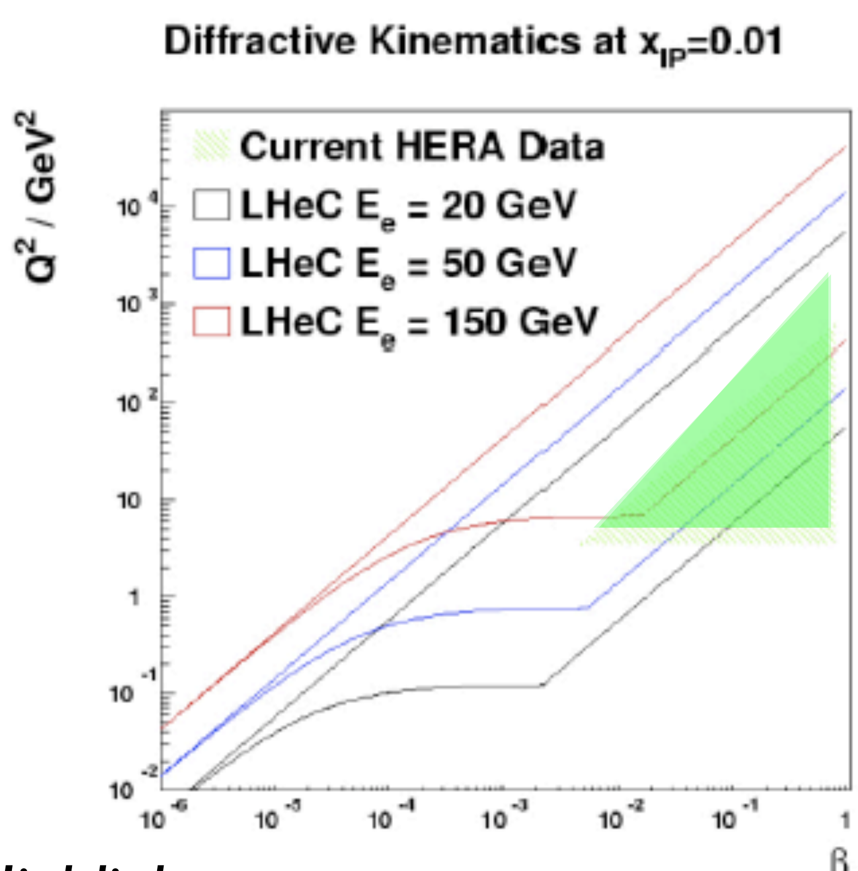


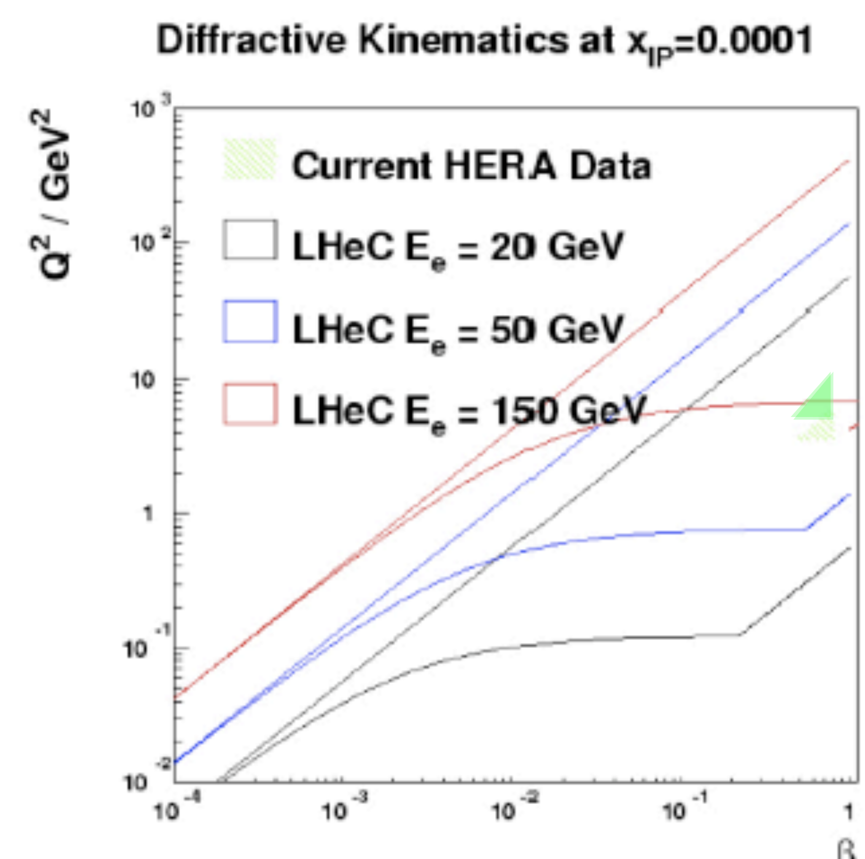


(figure from C. Weiss.)

Central black region growing with decrease of x.







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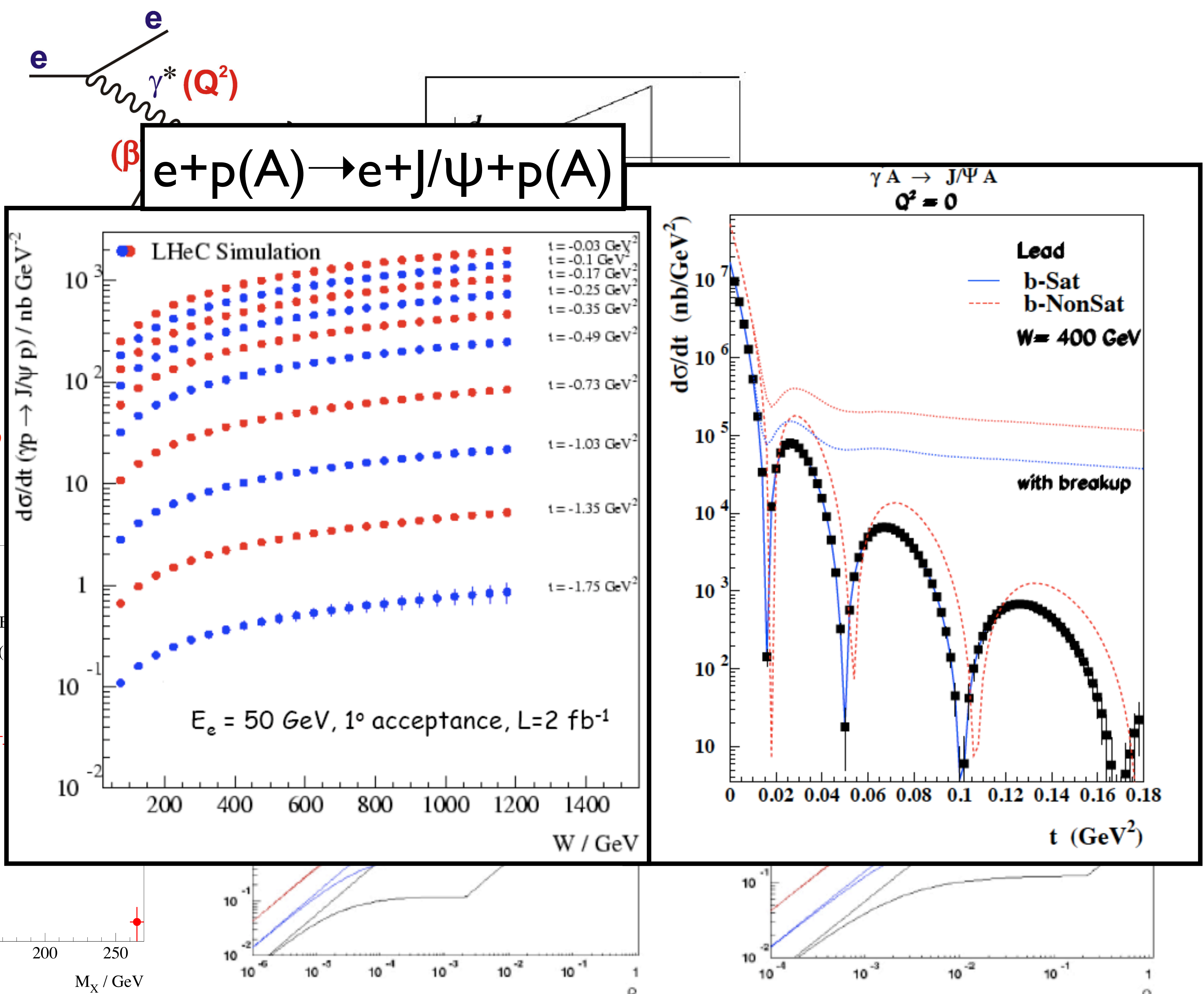
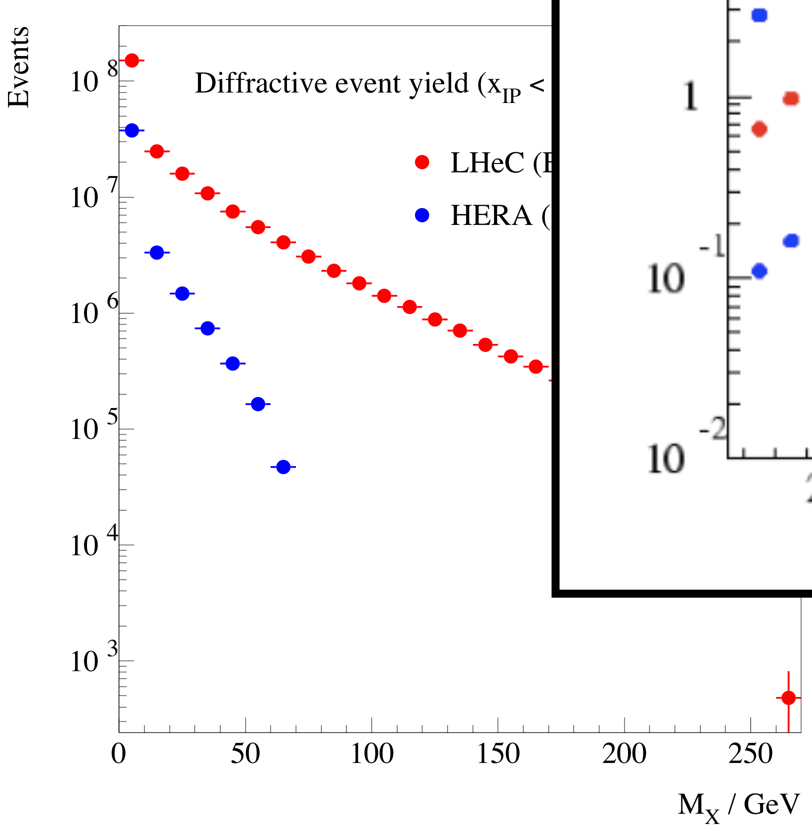
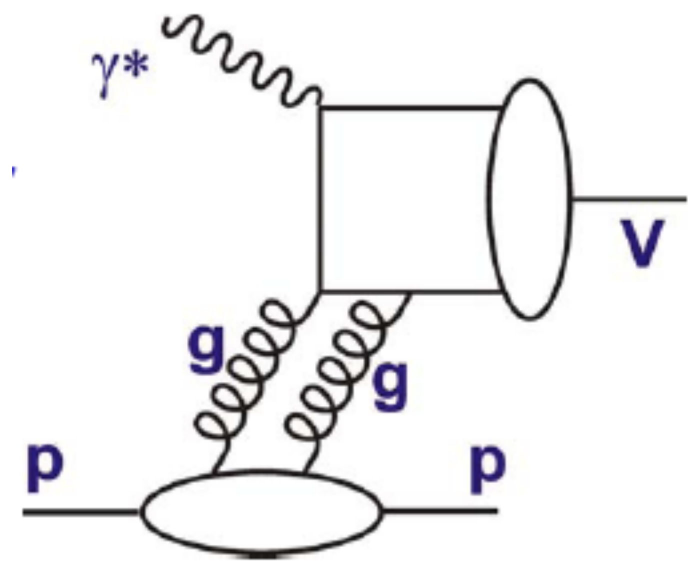
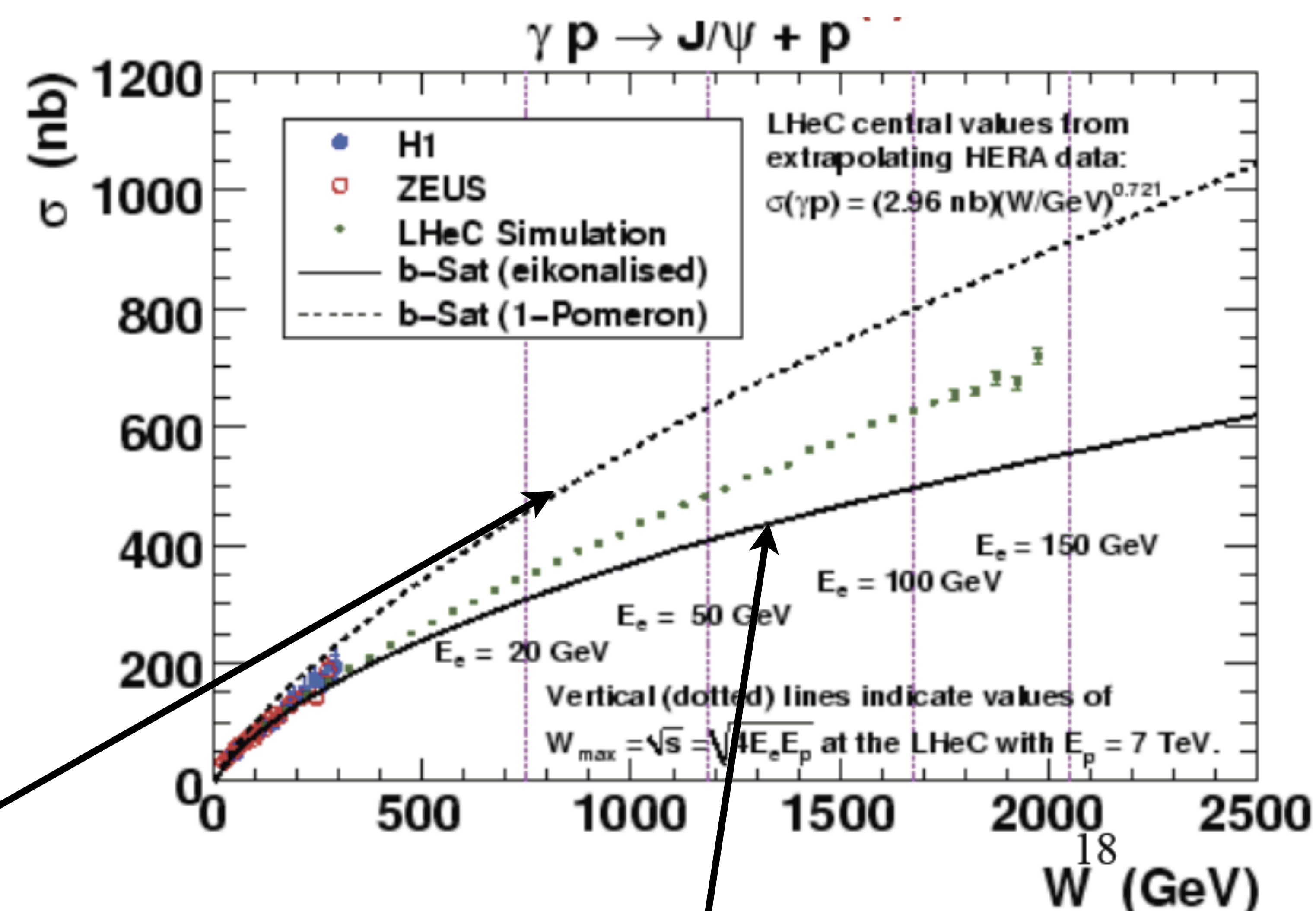




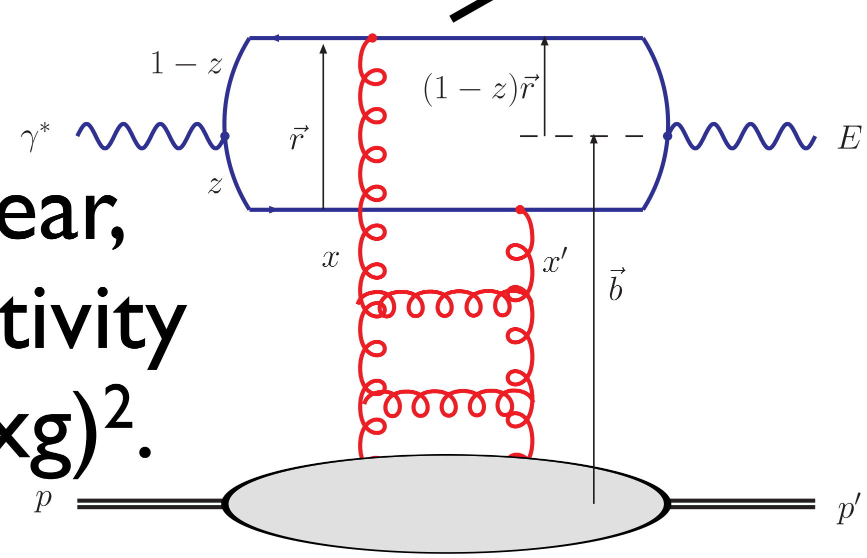
Elastic VM production in ep:

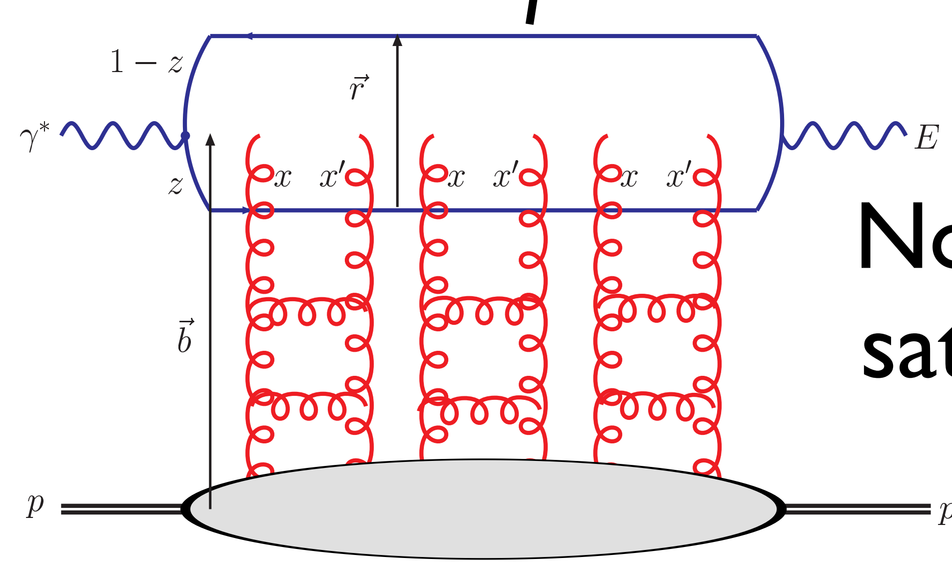




- Elastic J/ψ production appears as a candidate to signal saturation effects at work!!!

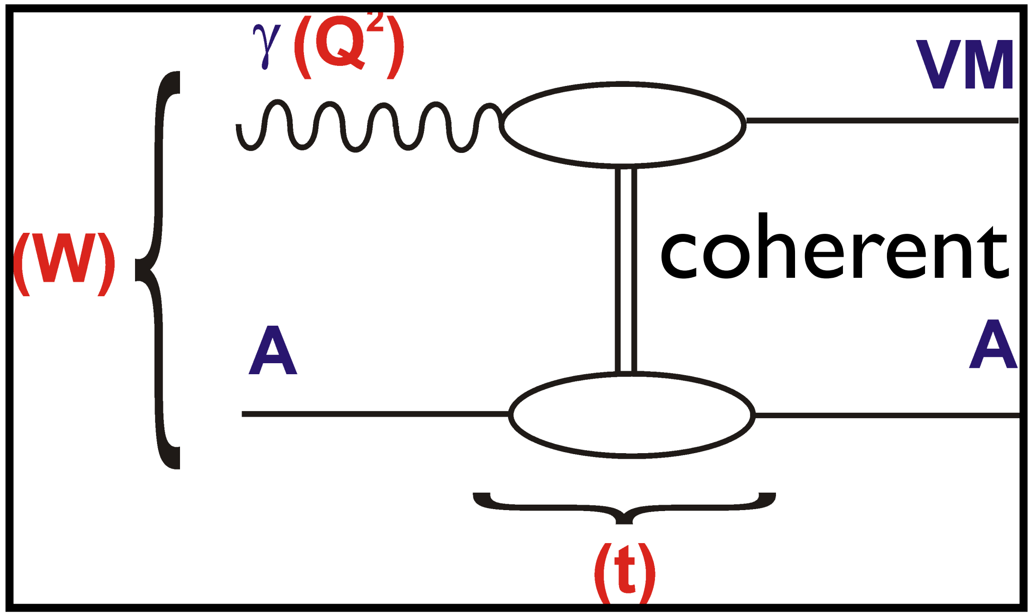
Linear, sensitivity to $(xg)^2$.





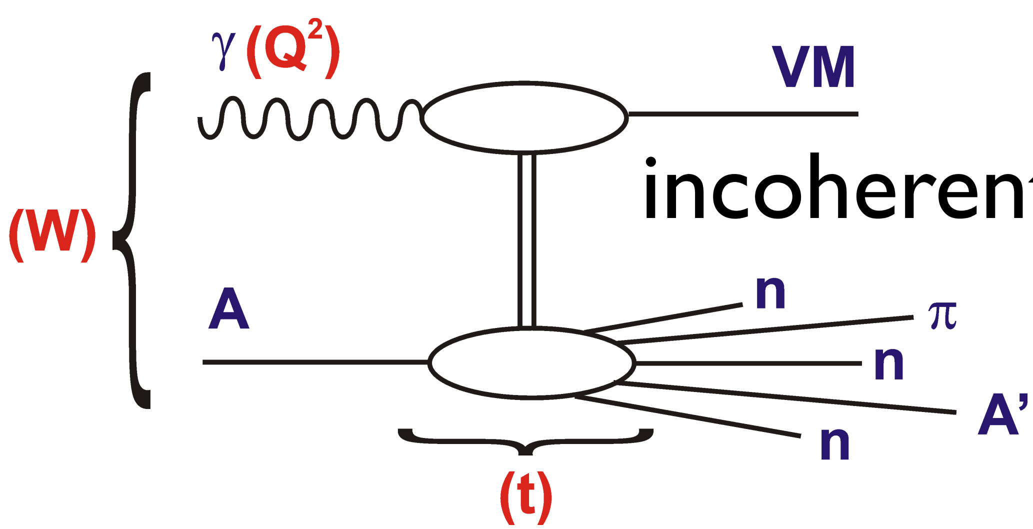
Non-linear, saturation.

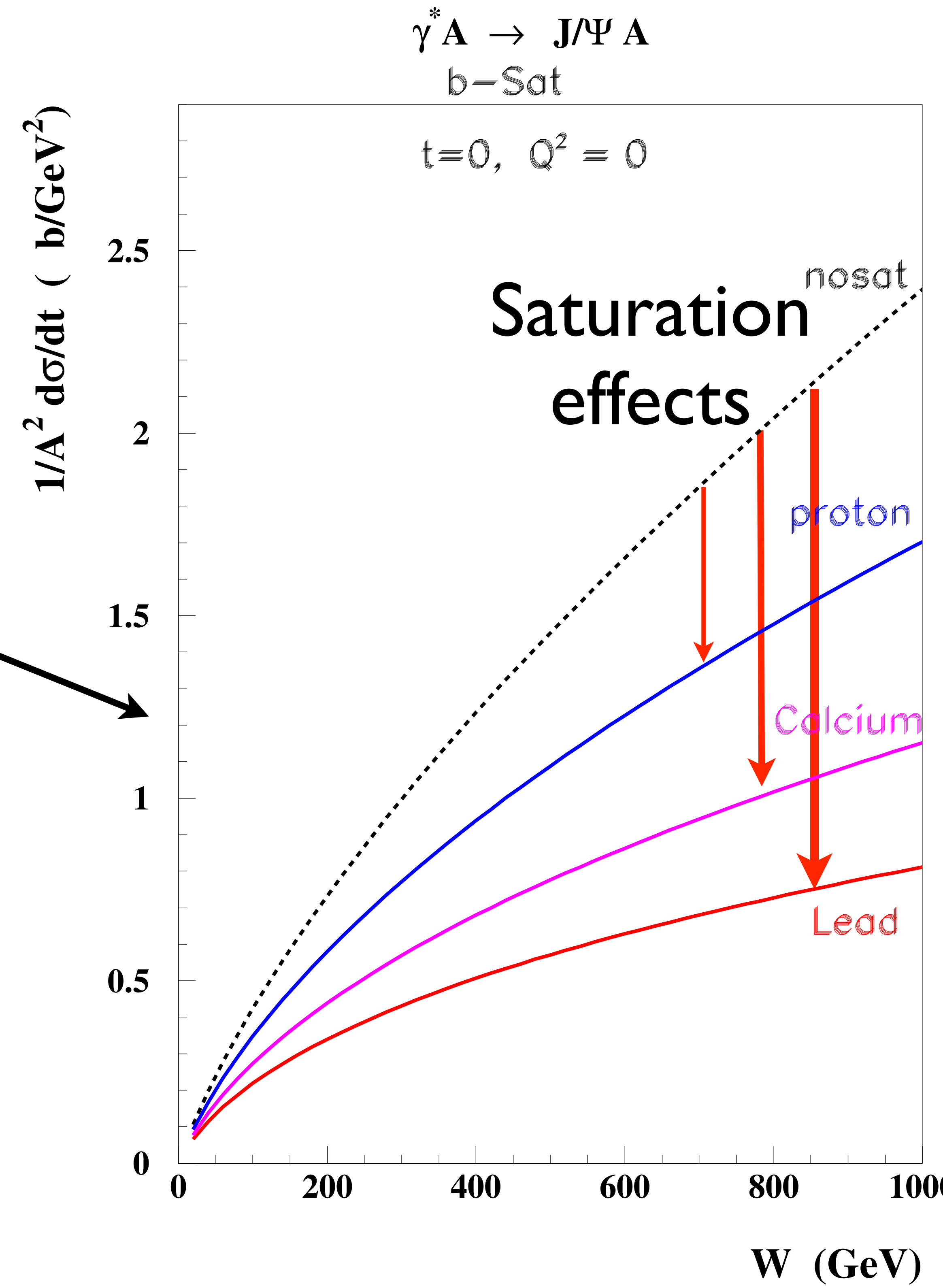
Elastic VM production in eA:



- For the coherent case, predictions available.

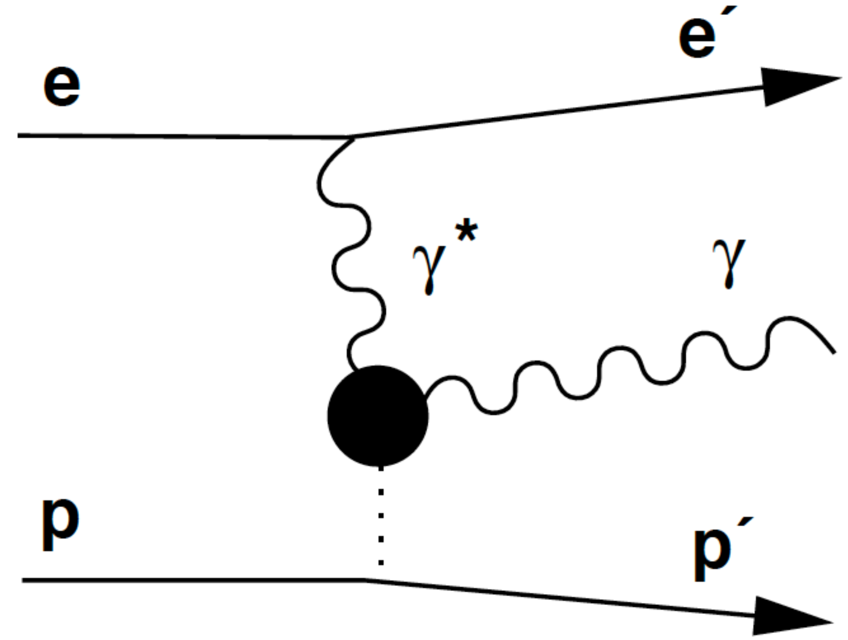
- Challenging experimental problem.



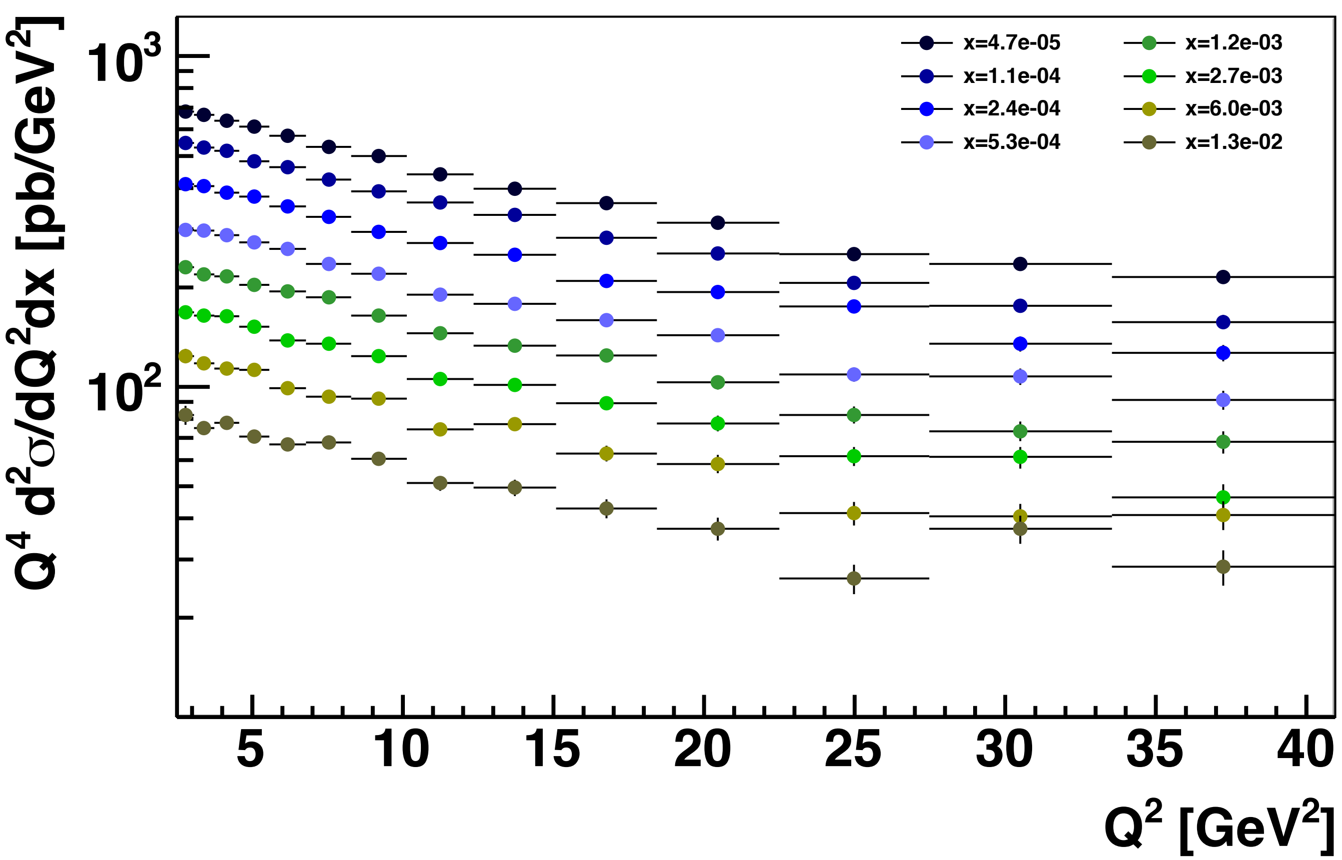


DVCS:

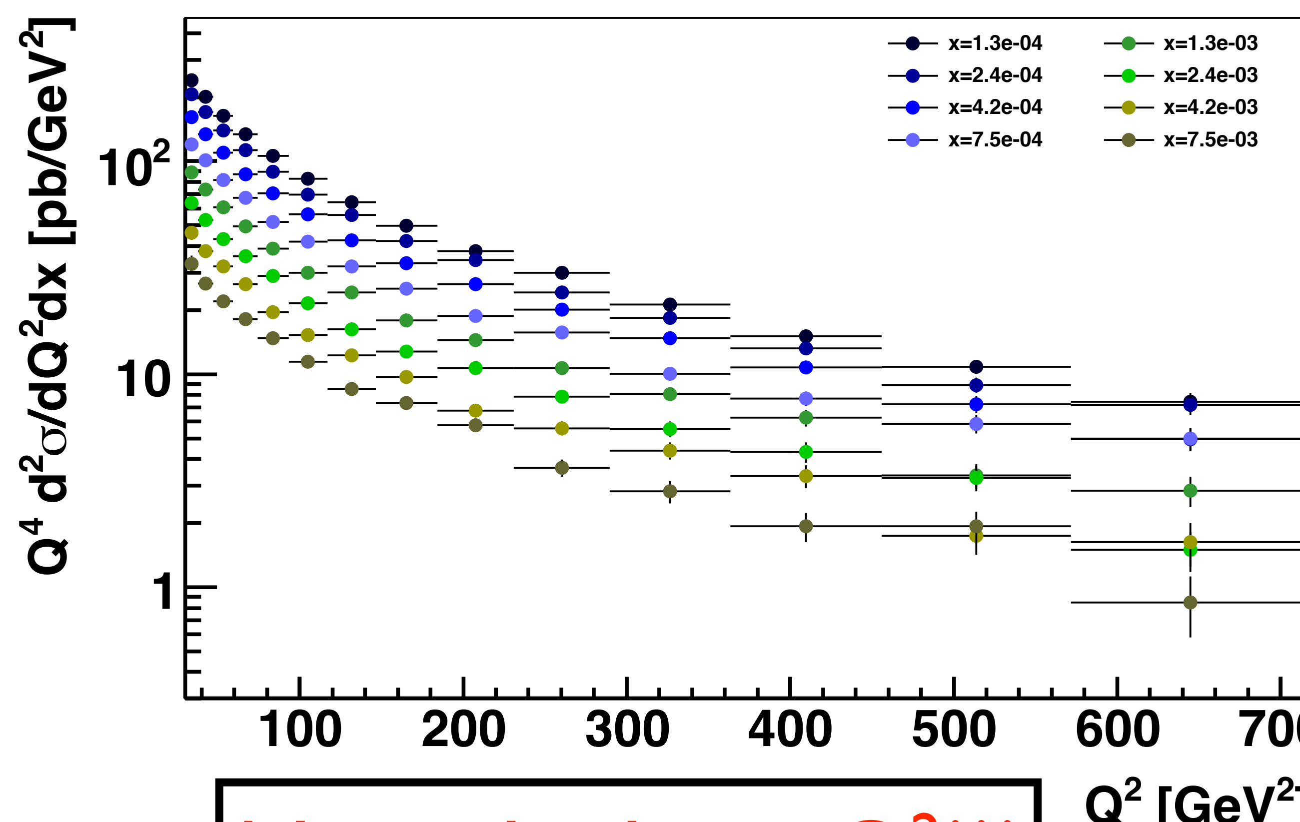
- Exclusive processes give information about GPDs, whose Fourier transform gives a tranverse scan of the hadron: DVCS sensitive to the singlet.
- Sensitive to dynamics e.g. non-linear effects.



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}



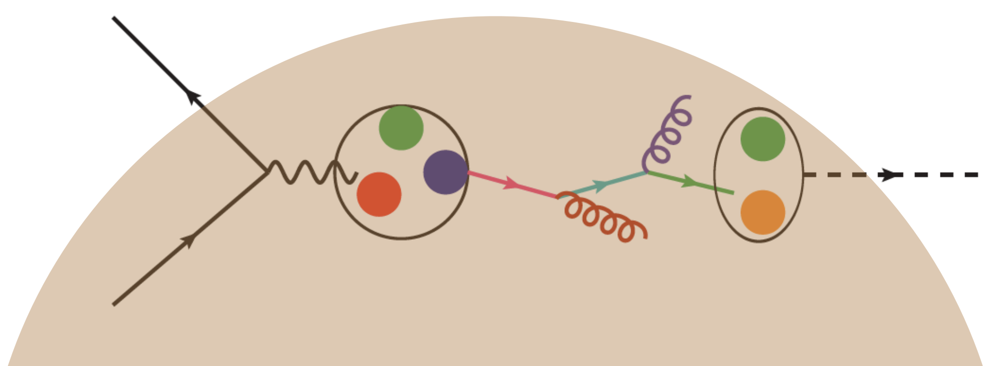
Note the huge Q^2!!!

Radiation and hadronization:

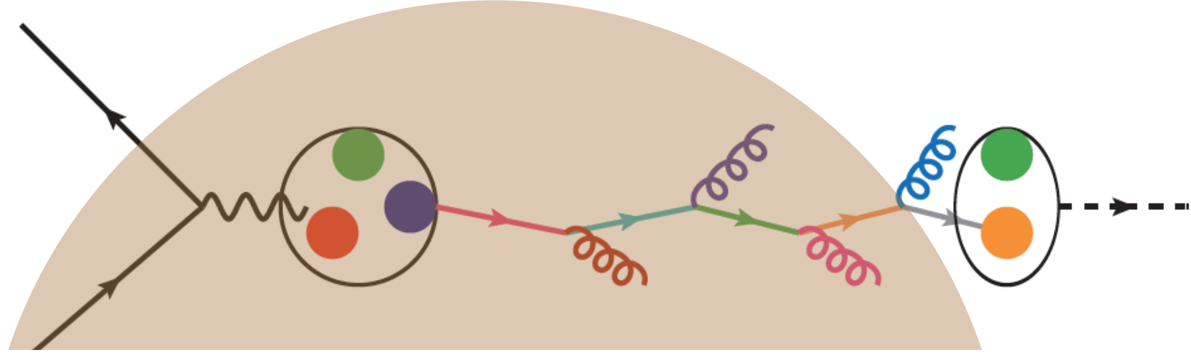
- LHeC: dynamics of QCD radiation and hadronization.
- Most relevant for particle production off nuclei and for QGP analysis in HIC.

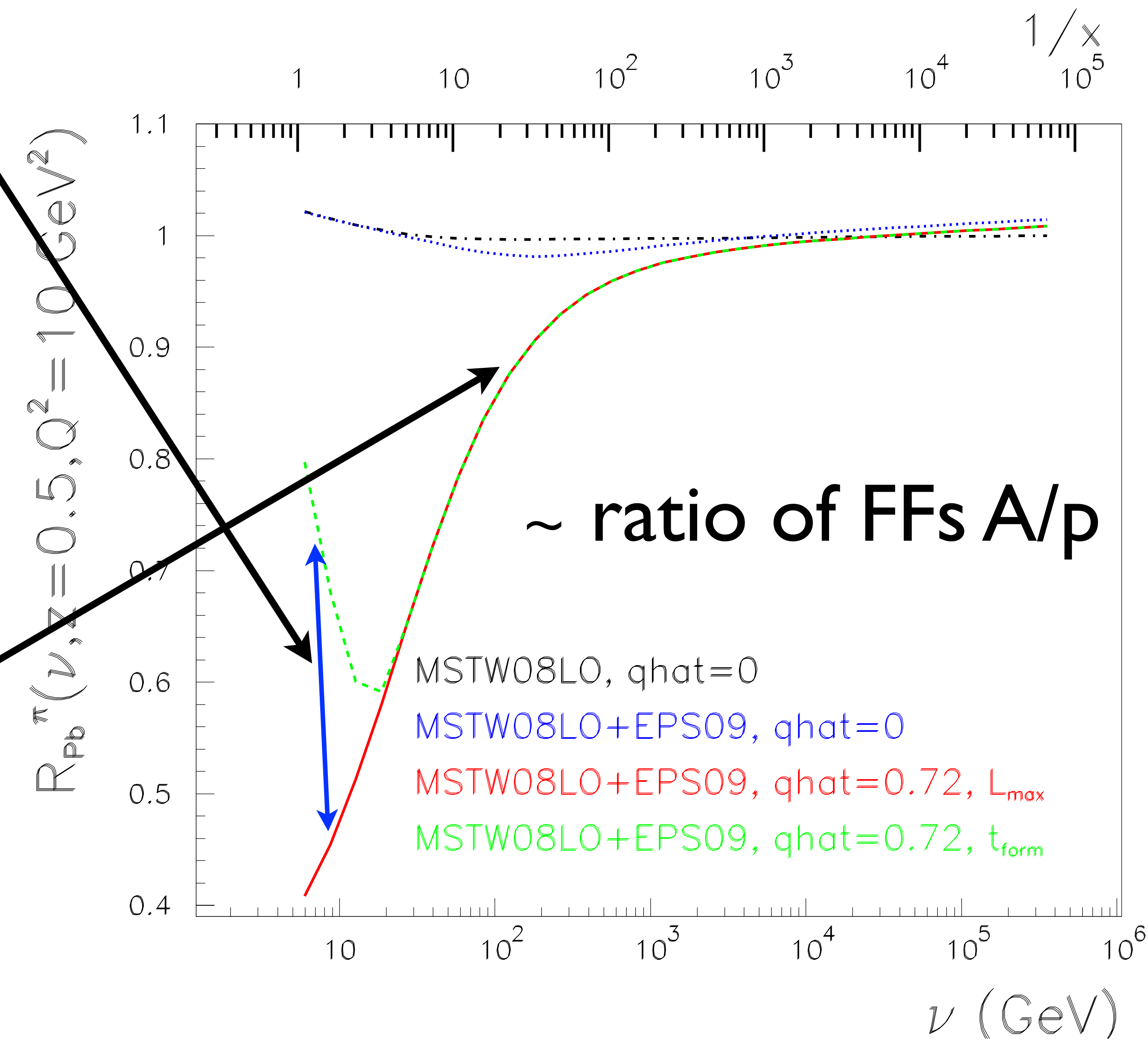
$$R_A^h(z,\nu) = \frac{1}{N_A^e}\frac{dN_A^h(z,\nu)}{d\nu\, dz} \Big/ \frac{1}{N_D^e}\frac{dN_D^h(z,\nu)}{d\nu\, dz}$$

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



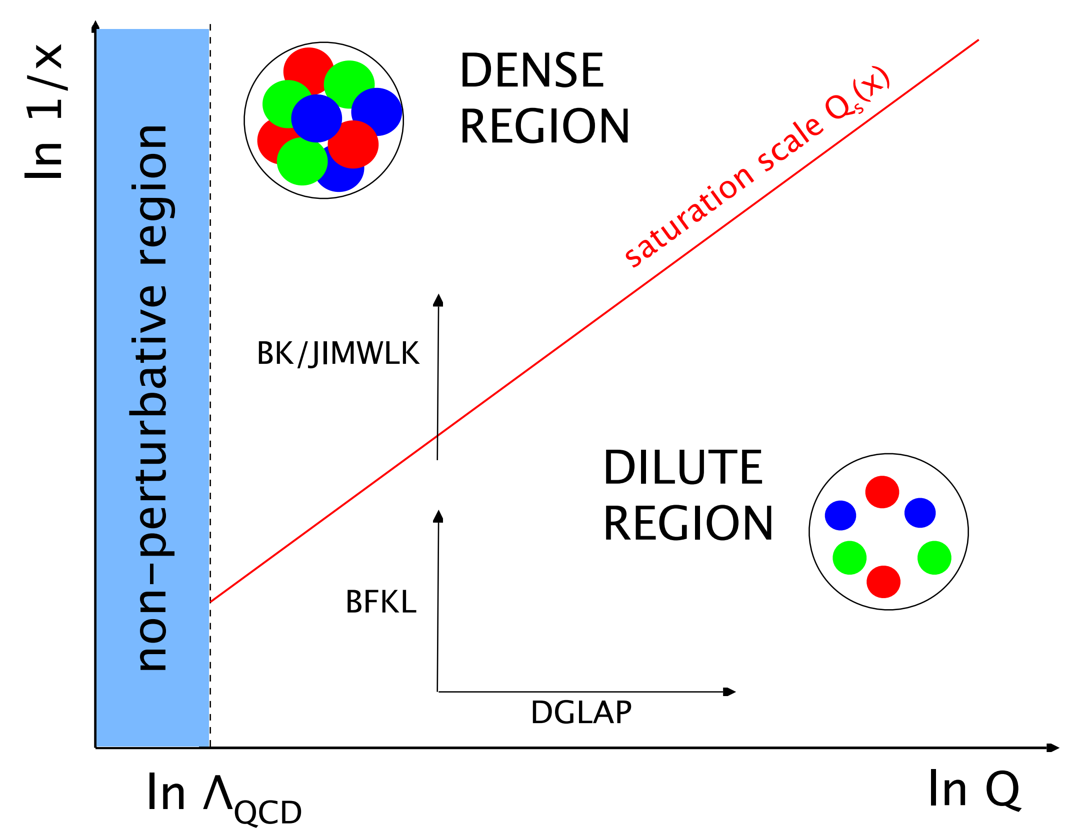
- High energy: partonic evolution altered in the nuclear medium.

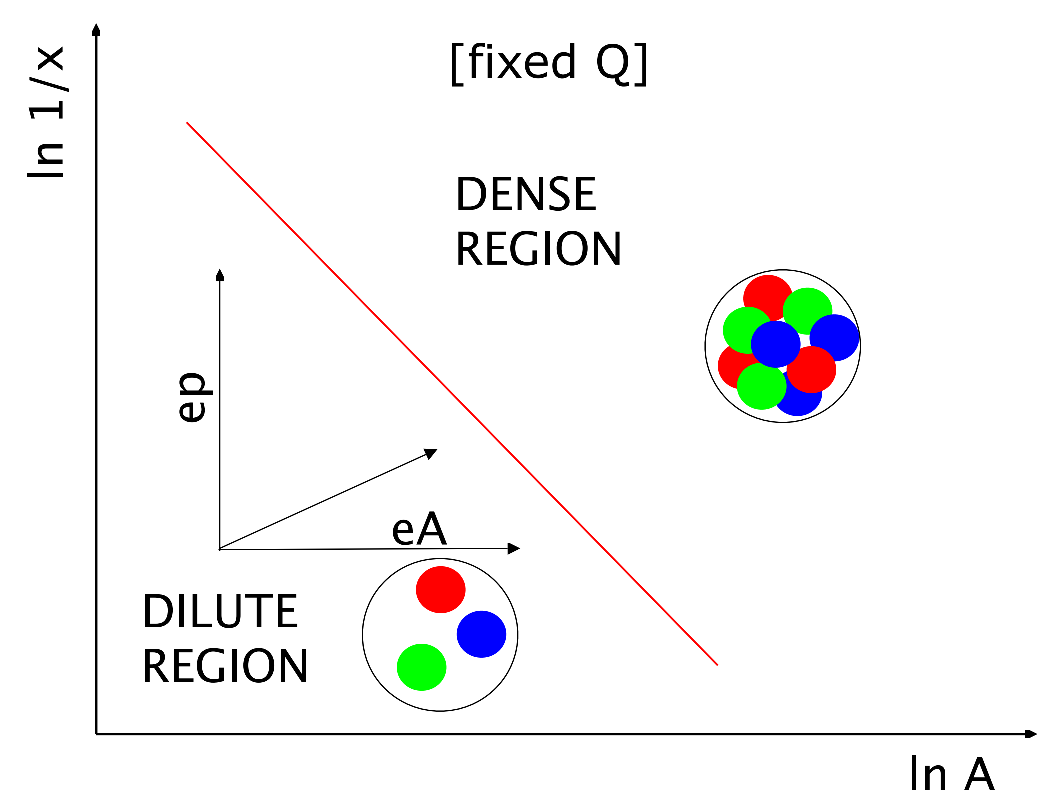




Summary:

- ***At an LHeC@CERN***:
  - ➜ Unprecedented access to small x in p and A for PDFs.
  - ➜ Novel sensitivity to physics beyond standard pQCD.
  - ➜ Stringent tests of QCD radiation and hadronization.
  - ➜ High precision tests of collinear factorization(s).
  - ➜ Transverse scan of the hadron at small x.
  - ➜ ...
- **The LHeC will answer the question of saturation/ non-linear dynamics. For that, ep AND eA essential!!!**





Physics at low x_{Bj} and in eA.

Outlook: pending issues

➜ Monte Carlo model for inclusive, semi-inclusive, diffractive and exclusive processes in ep and eA (with nuclear breakup) [talk by Plaetzer].

➜ Separation of coherent diffraction off nuclei.

Thanks to Anna, Max and Paul!!!

➜ Radiative corrections [talk by Spiesberger].

➜ More realistic estimates of measurables yields: effects of backgrounds on jets, asymmetries for the odderon,...

➜ Detailed program for sensitivity to non-linear effects and for GPDs.

➜ Constraints from pp/pA/AA at the LHC [talk by Salgado].

➜ ...

Possibilities of synergies with other projects.

Changes and additions (I):

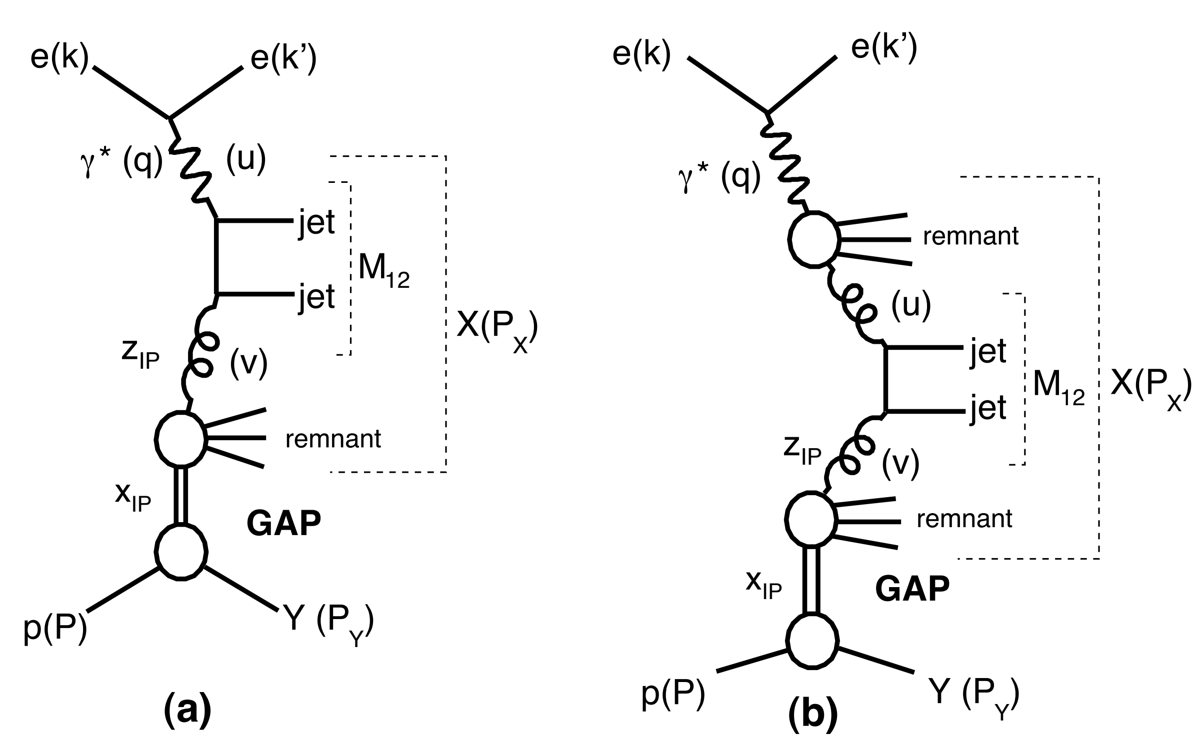
- Chapter moved before *BSM*, right after *Precision QCD and EW.*

- Introduction refined: resummation moved, now
DGLAP → resummation → non-linear equations and saturation.

- GPD-related content enlarged [talk by Pire]:
  - ◆ Theoretical introduction.
  - ◆ Possibilities of measurement of helicity-flip GPDs through exclusive production

$$ep(p_2) \to e'\gamma^{(*)}_{L/T}(q)\ \ p(p_2) \to e'\rho^0_{L,T}(q_\rho)\ \ \rho_T(p_\rho)\ N'(p_{2'})$$

- Diffractive dijets included
as a test of hard collinear factorisation [talk by Zlebcik].



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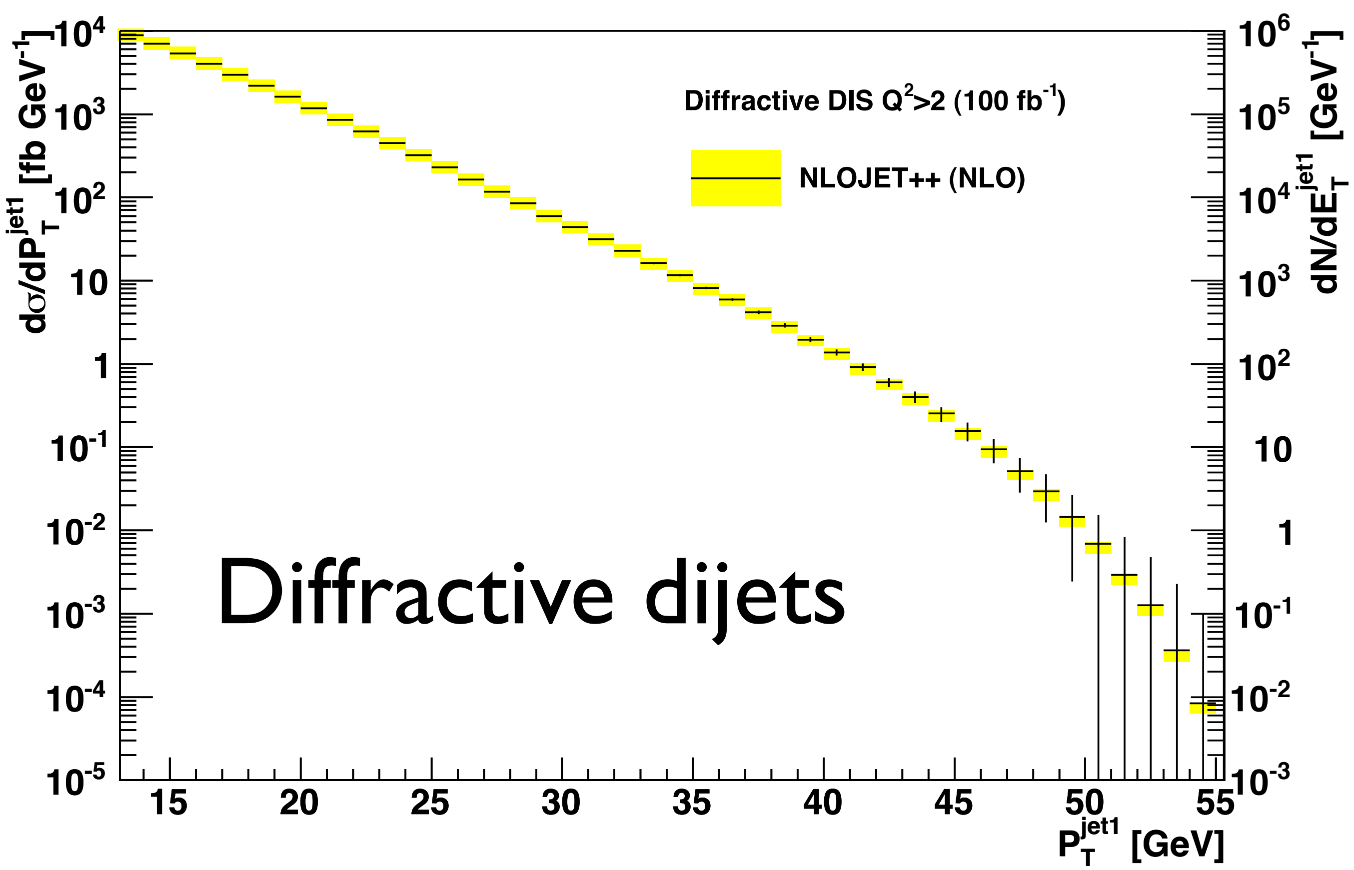


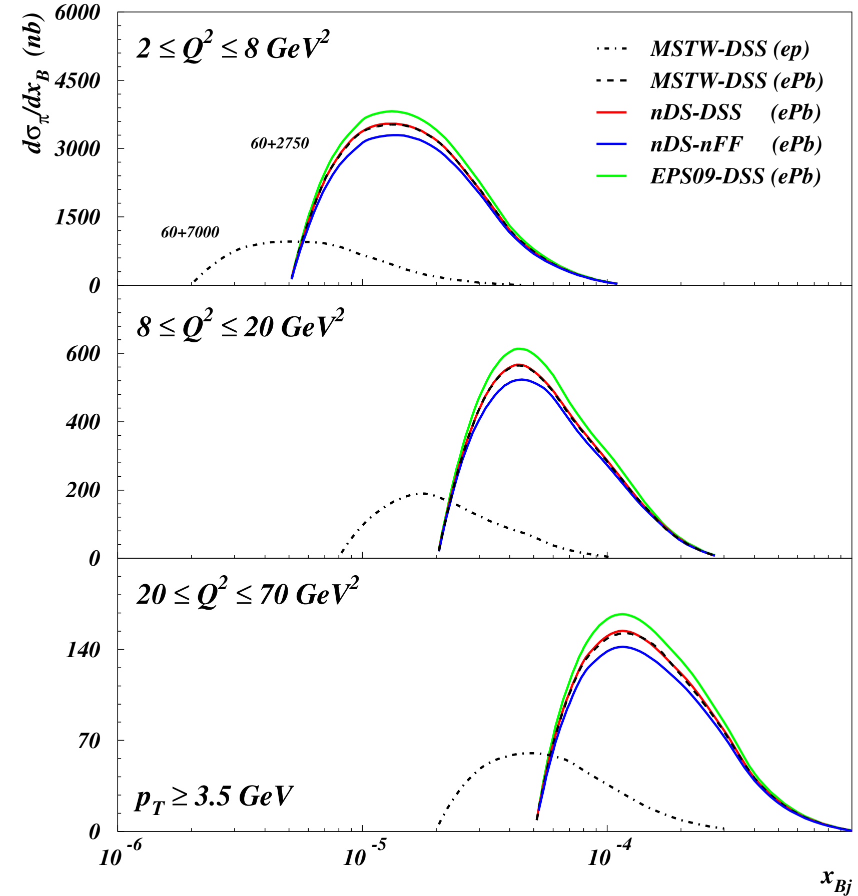
Changes and additions (II):

- Predictions for searching the odderon in $ep \rightarrow e\pi^+\pi^- p$.

- SIDIS: yields and nuclear effects considered.

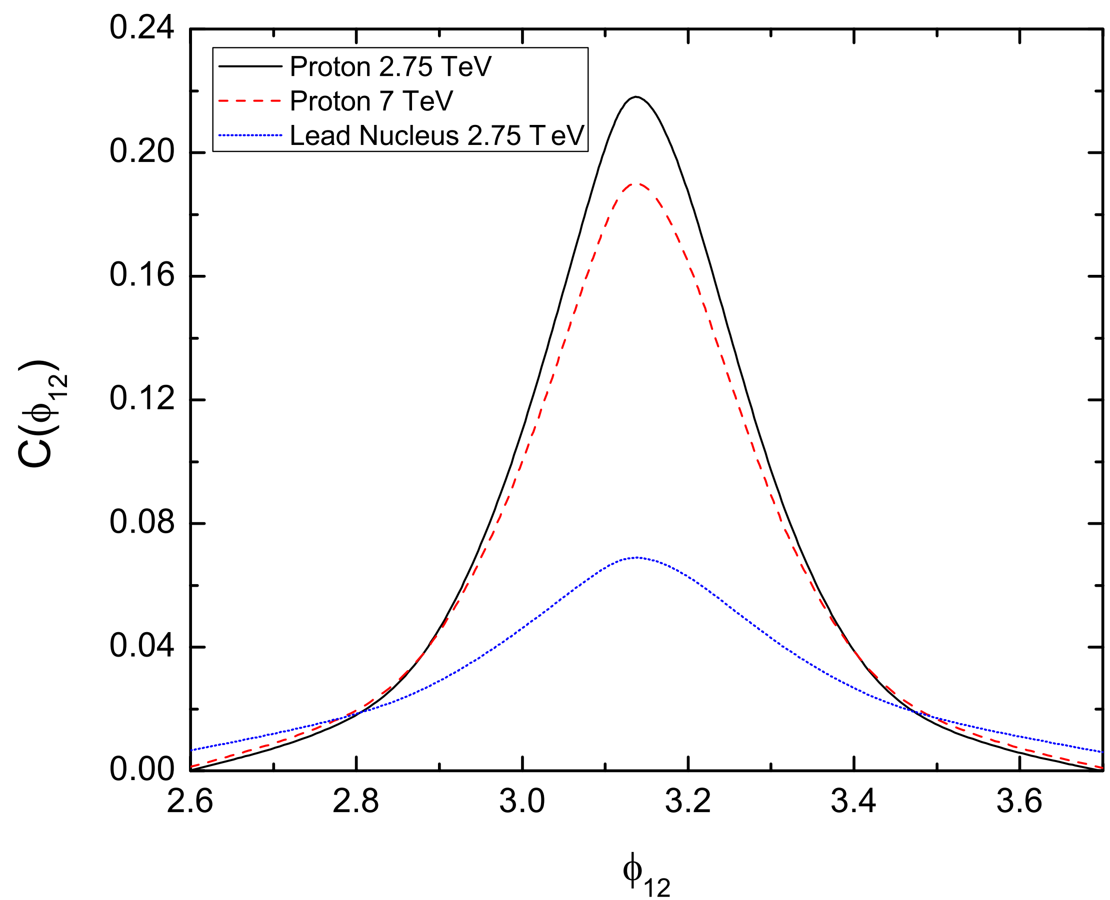
- Dihadron azimuthal correlations studied as a possible signal of saturation.

- Section on nuclear diffraction rewritten and comments on the black disk limit added.



π^0 spectrum

$5° < \theta_\pi < 25°$,
$x_\pi = E_\pi/E_p > 0.01$



Dihadron azimuthal correlation

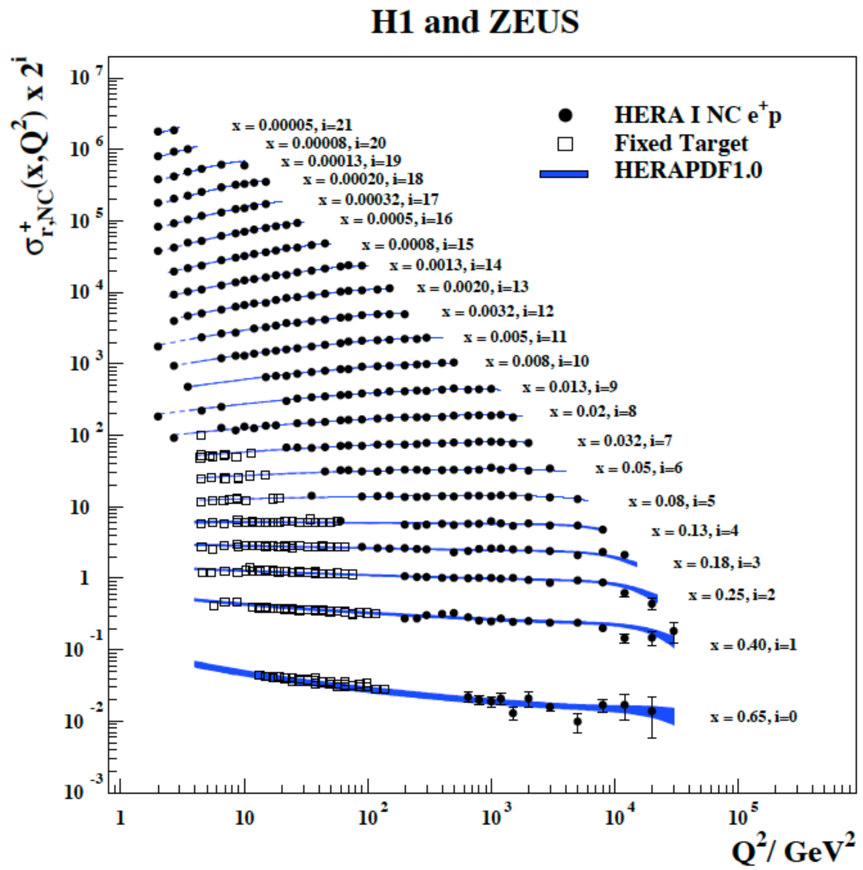
$p_T^{lead} > 3$ GeV
$p_T^{ass} > 2$ GeV
$z_{lead} = z_{ass} = 0.3$
$y = 0.7$
$Q^2 = 4$ GeV^2

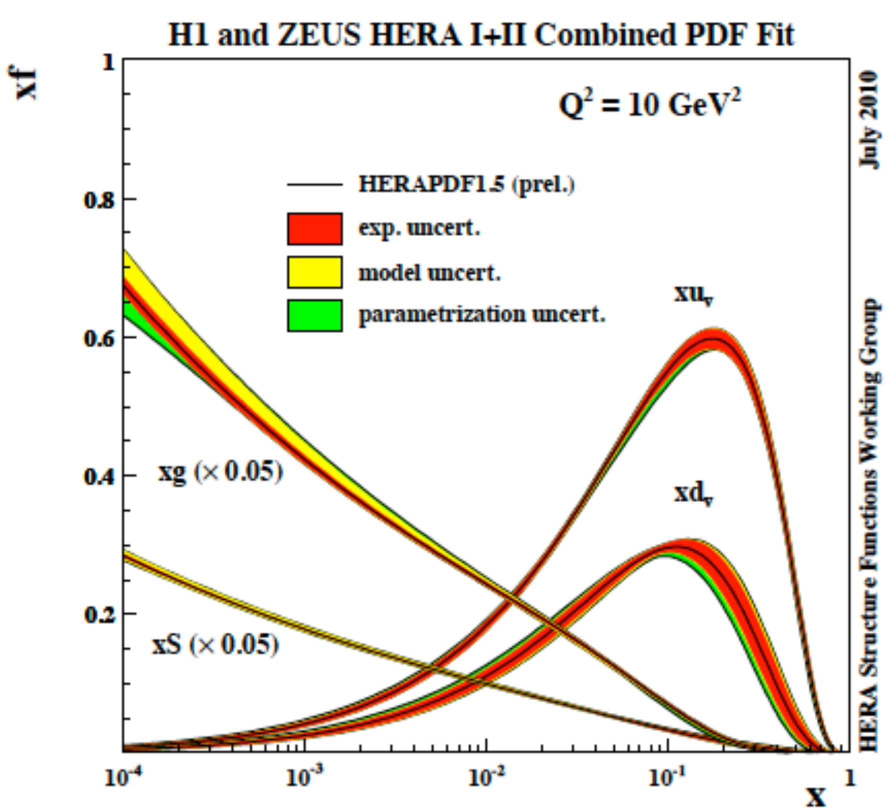
Backup:

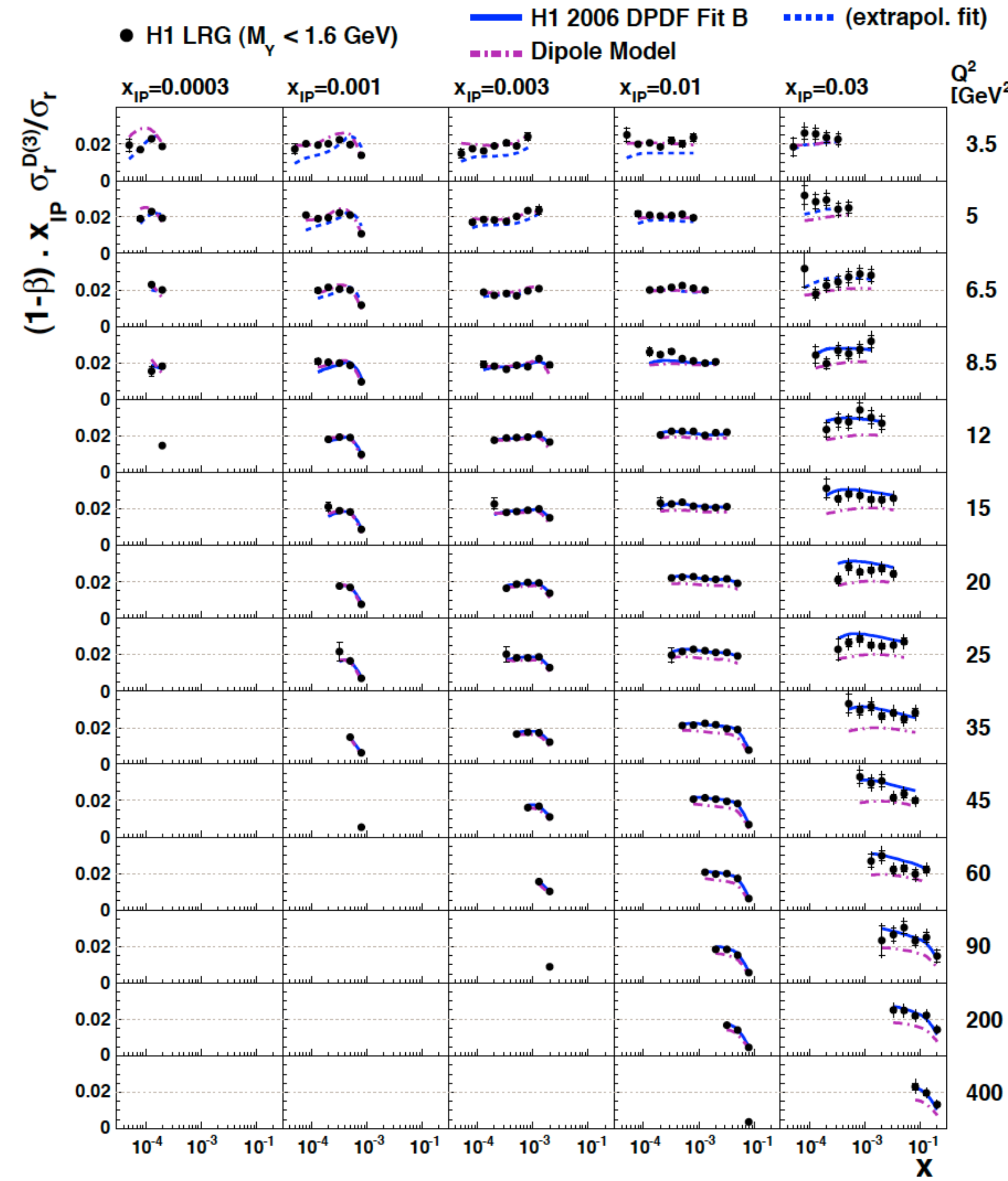
Messages from HERA:

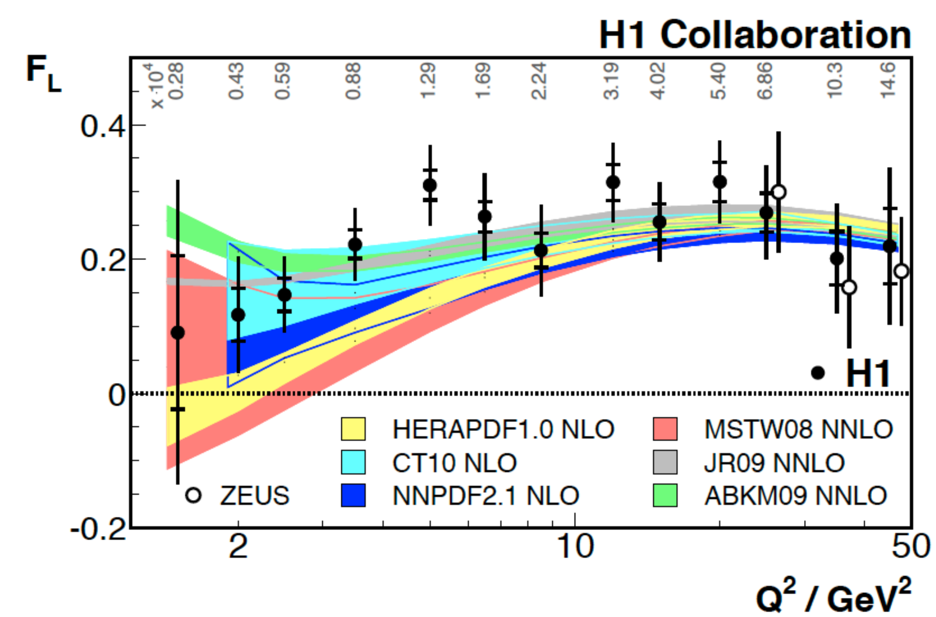
- Very good description of $F_{2(c,b)}$ (F_L?) within DGLAP, steep gluon in 1/x.

- Large fraction of diffraction $\sigma_{diff}/\sigma_{tot}$~10% (Cooper-Sarkar, 1206.0984).









Physics at low x_{Bj} and in eA.

LHeC scenarios:

For F_2

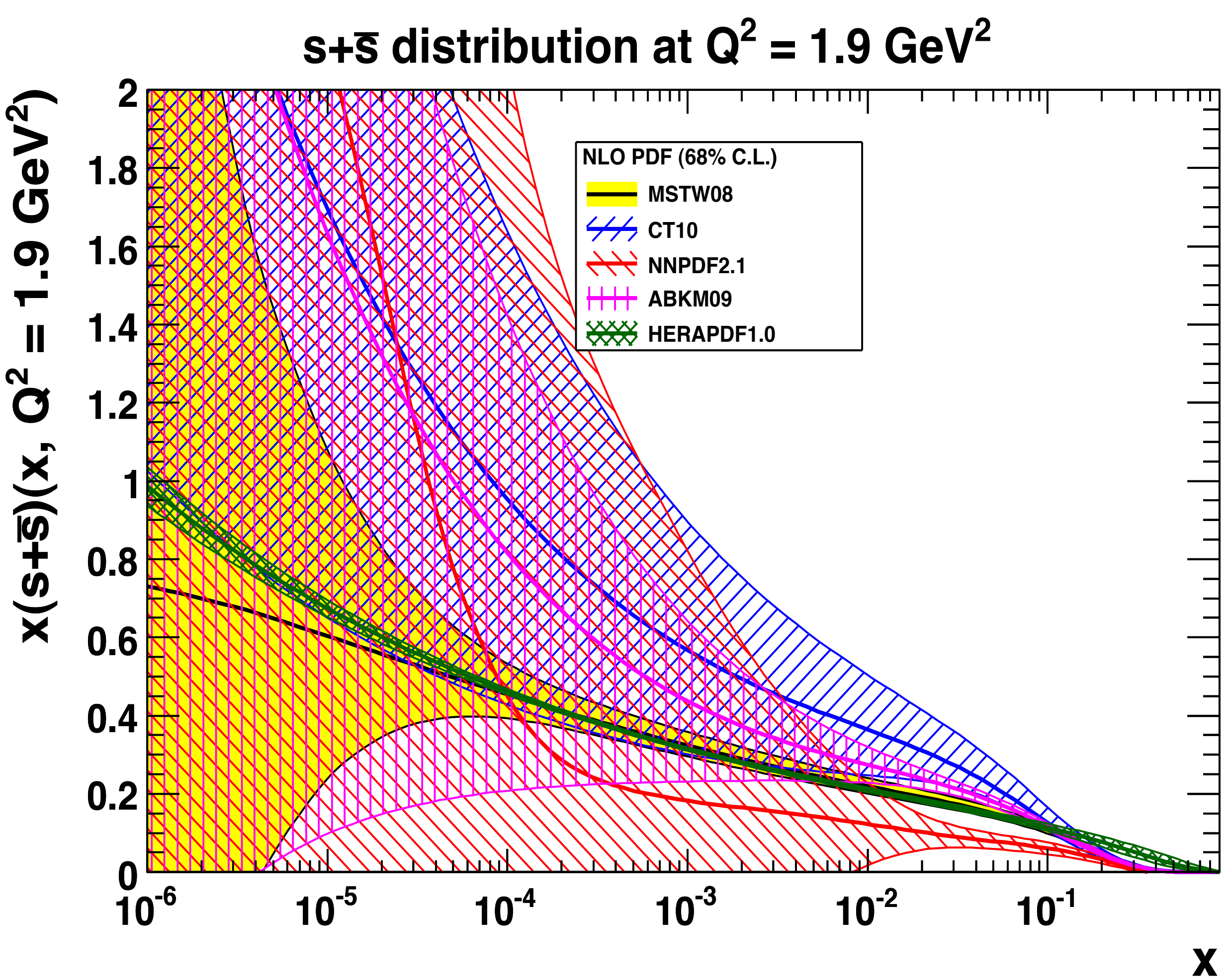
config.	E(e)	E(N)	N	$\int L(e^+)$	$\int L(e^-)$	|Pol|	$L/10^{32}$	P/MW	years	type
A	20	7	p	1	1	-	1	10	1	SPL
B	50	7	p	50	50	0.4	25	30	2	RR hiQ^2
C	50	7	p	1	1	0.4	1	30	1	RR lo x
D	100	7	p	5	10	0.9	2.5	40	2	LR
E	150	7	p	3	6	0.9	1.8	40	2	LR
F	50	3.5	D	1	1	--	0.5	30	1	eD
G	50	2.7	Pb	10^{-4}	10^{-4}	0.4	10^{-3}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

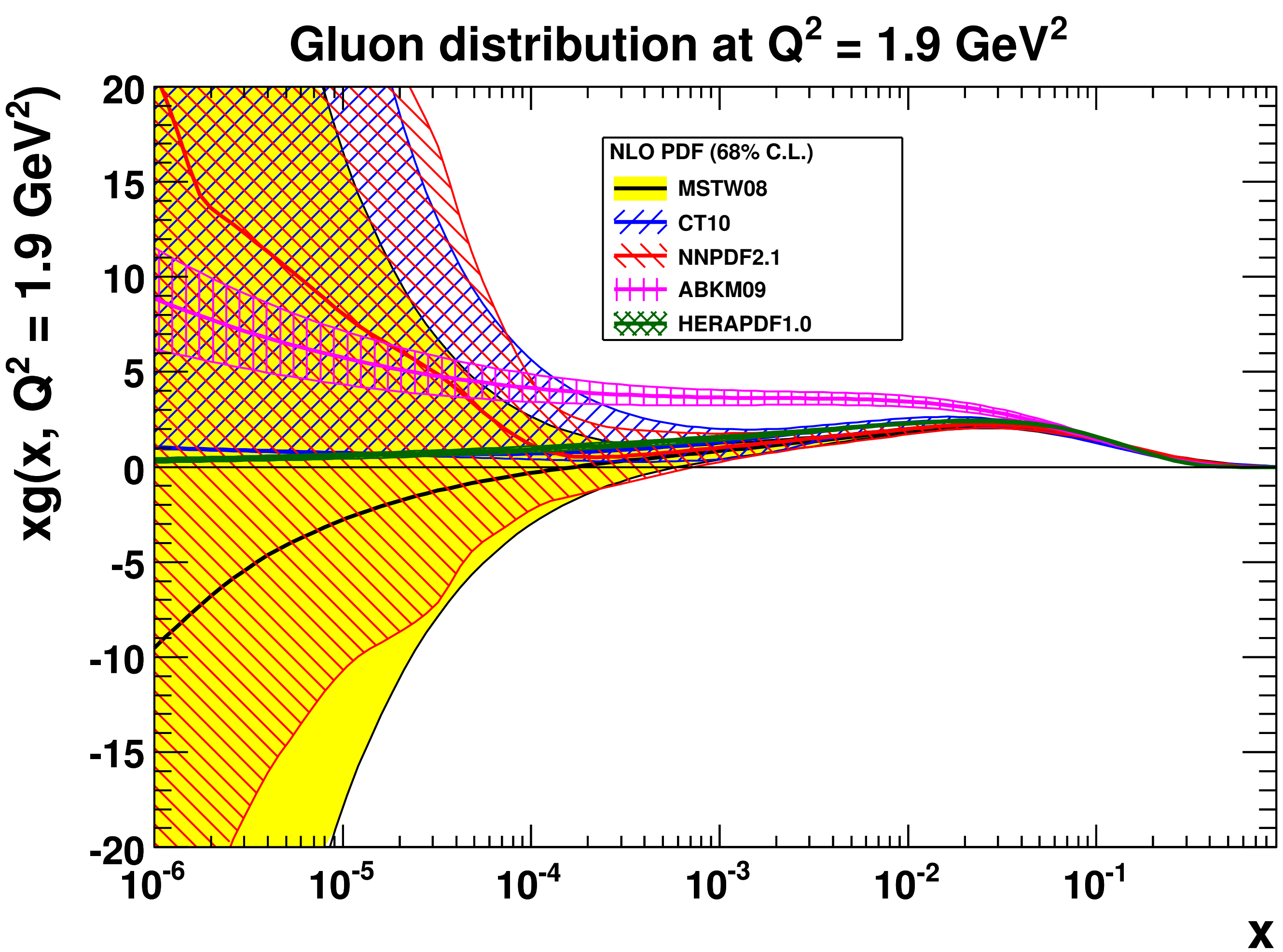
- For F_L: 10, 25, 50 + 2750 (7000); $Q^2 \leq sx$; Lumi=5,10,100 pb^{-1} respectively; charm and beauty: same efficiencies in ep and eA.

Preliminary; LHeC Design Study Report, CERN 2012

Proton PDFs at small x (I):

• Parton densities poorly determined at small x and small to moderate Q^2 [talk by Radescu] ⇒ uncertainties in the predictions for observables within collinear factorisation.





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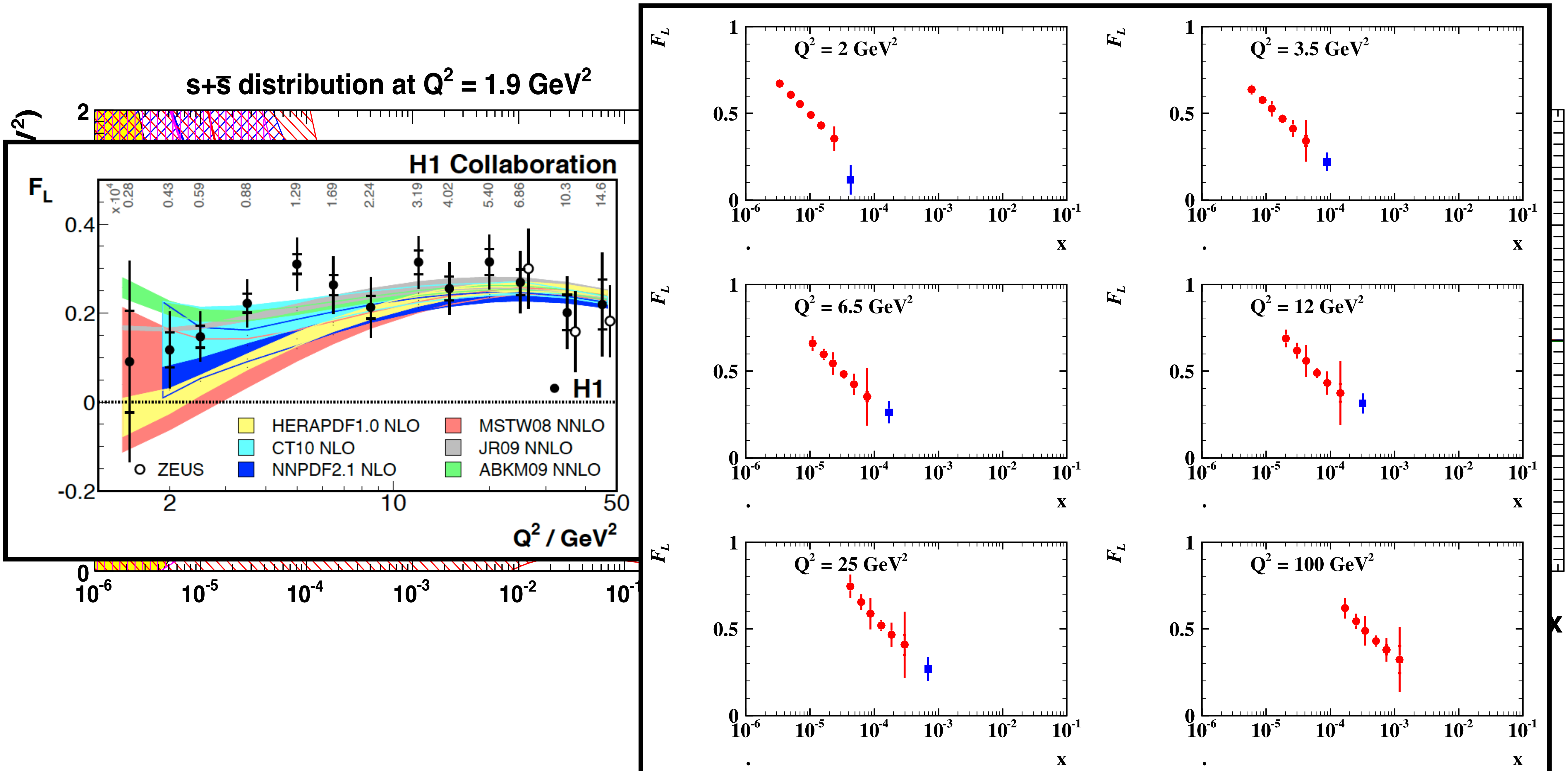
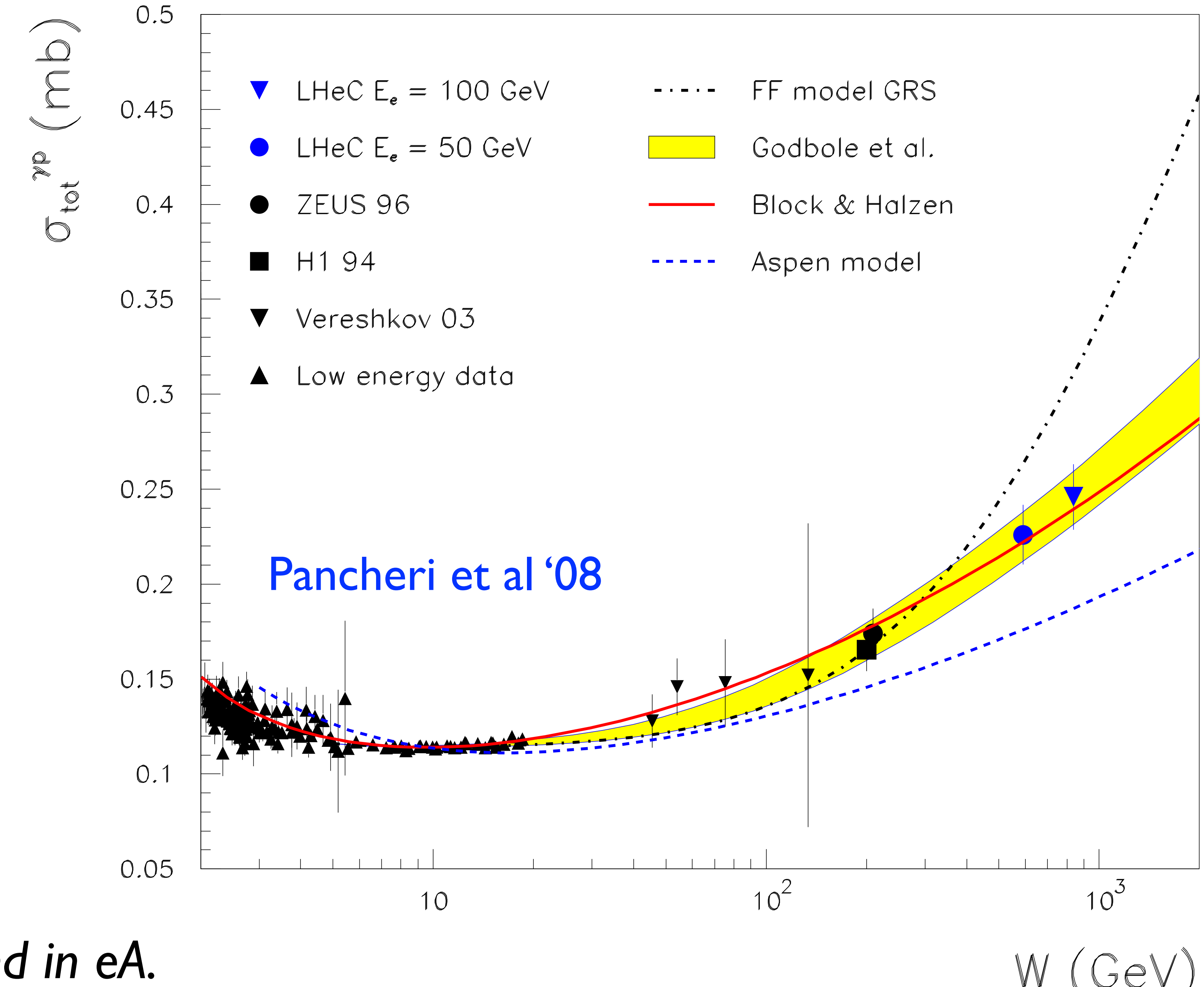


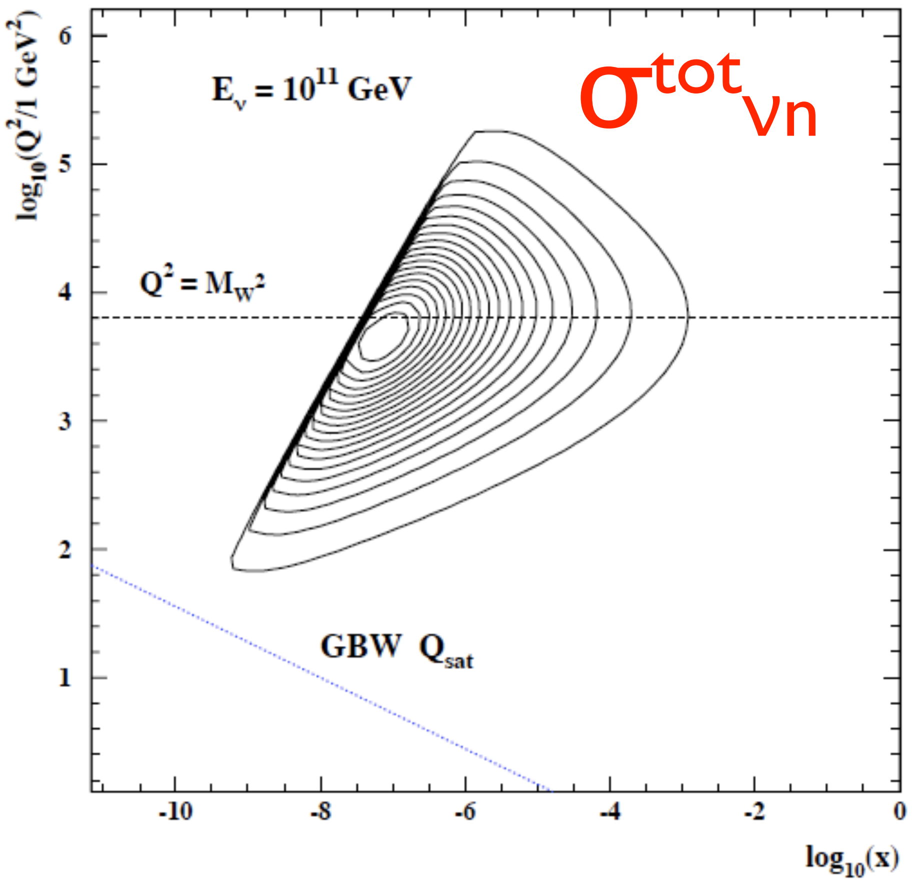
Photoproduction cross section:

- Small angle electron detector 62 m far from the interaction point: $Q^2<0.01$ GeV, $y\sim0.3 \Rightarrow W\sim0.5\sqrt{s}$.

- Substantial enlarging of the lever arm in W.

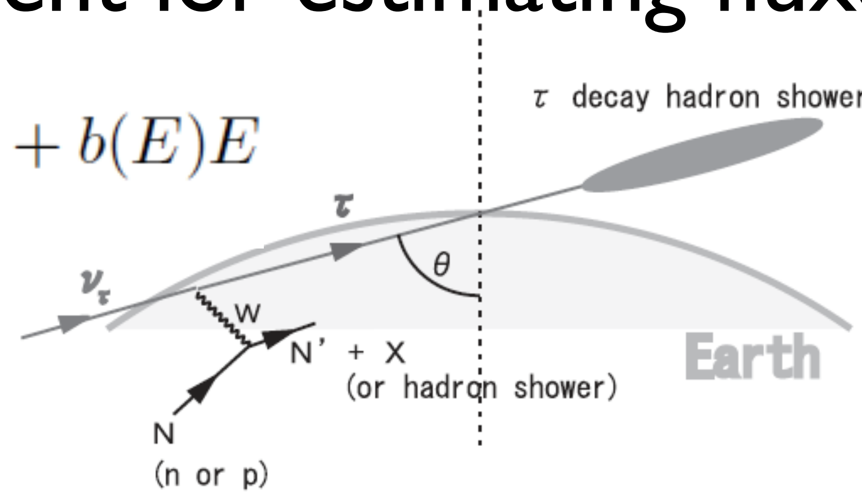


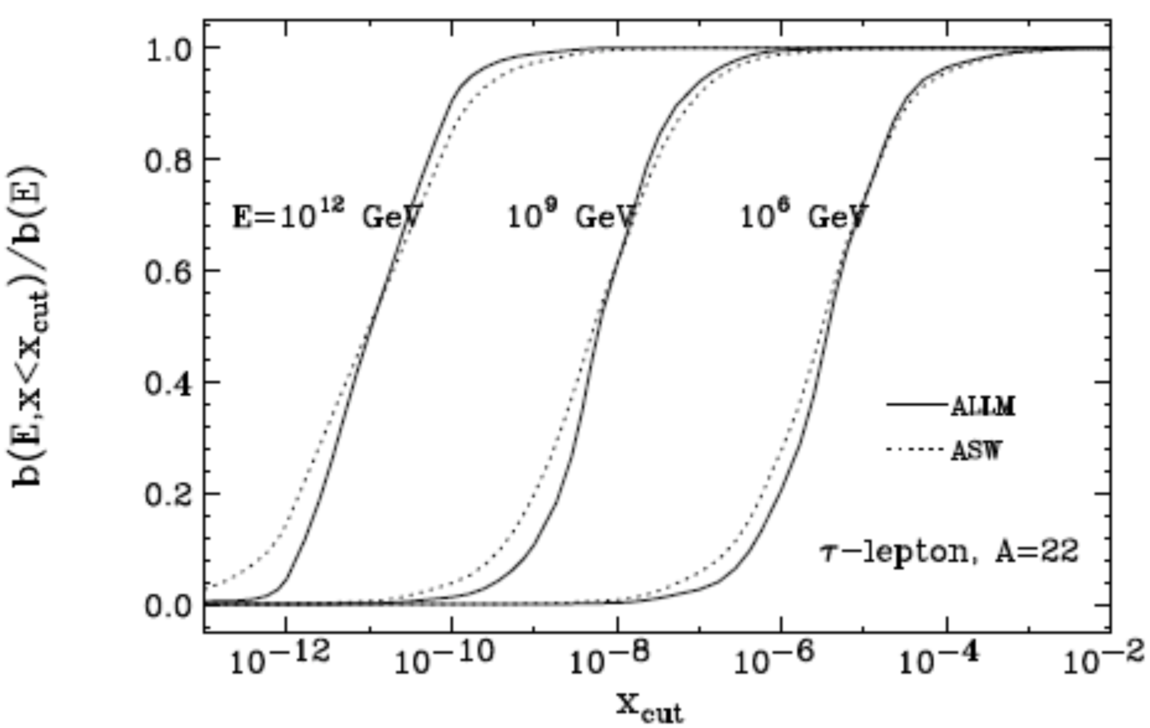
Implications for UHEν's:

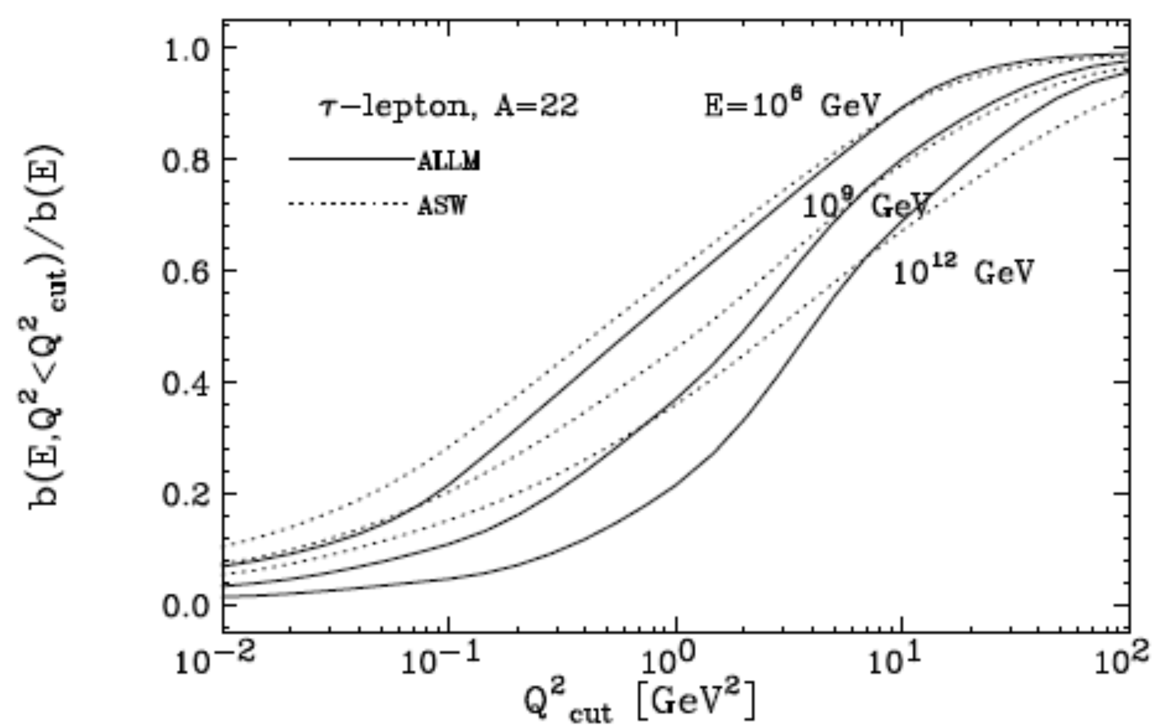


- ν-n/A cross section (τ energy loss) dominated by DIS structure functions / (n)pdfs at small-x and large (small) Q^2.
- Key ingredient for estimating fluxes.

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

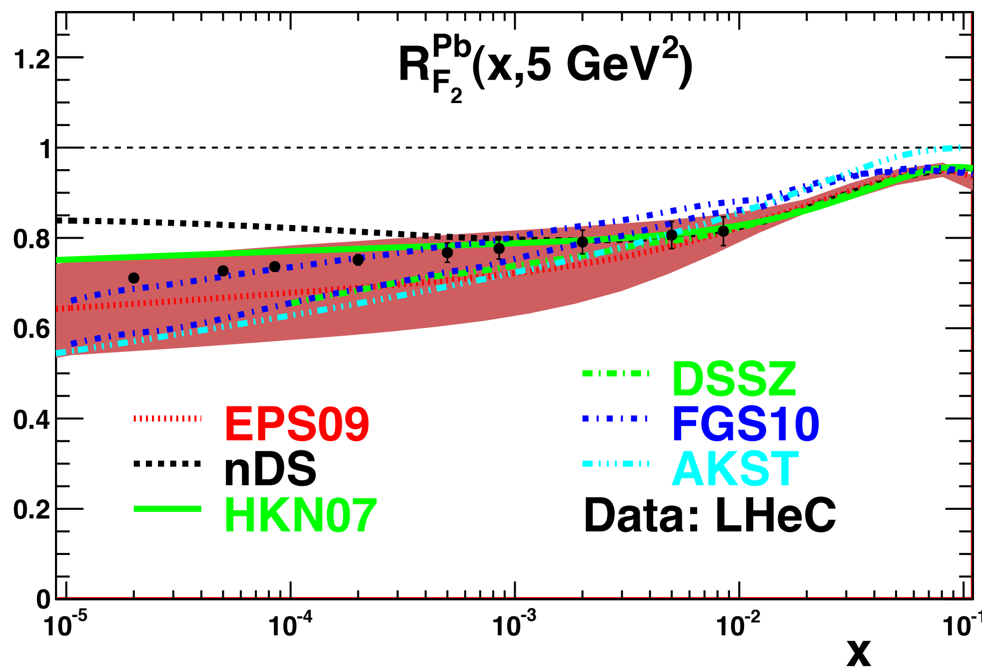


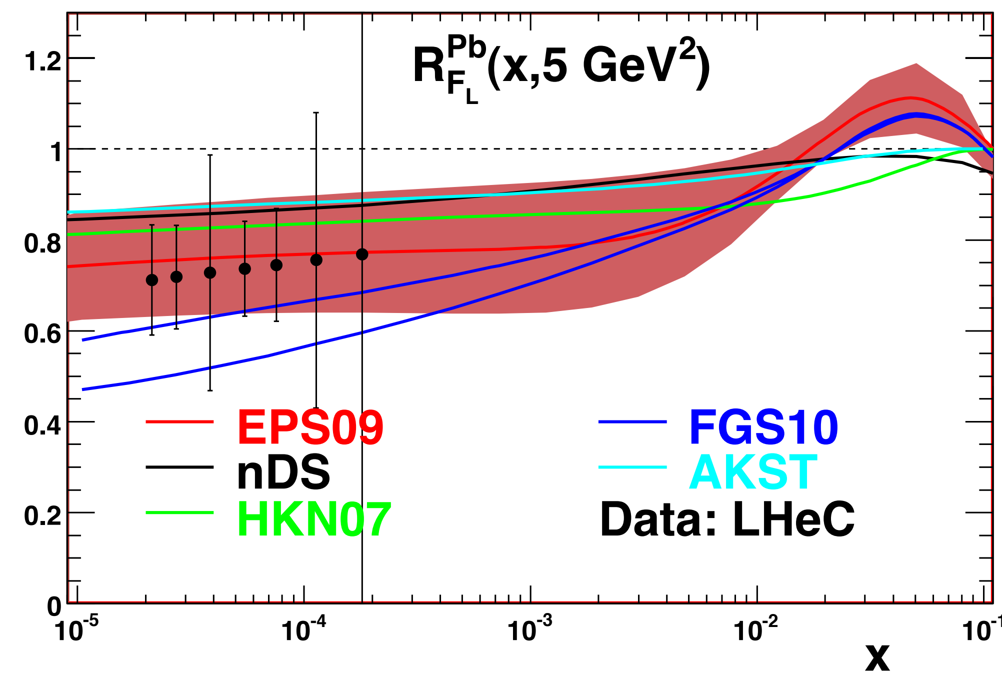


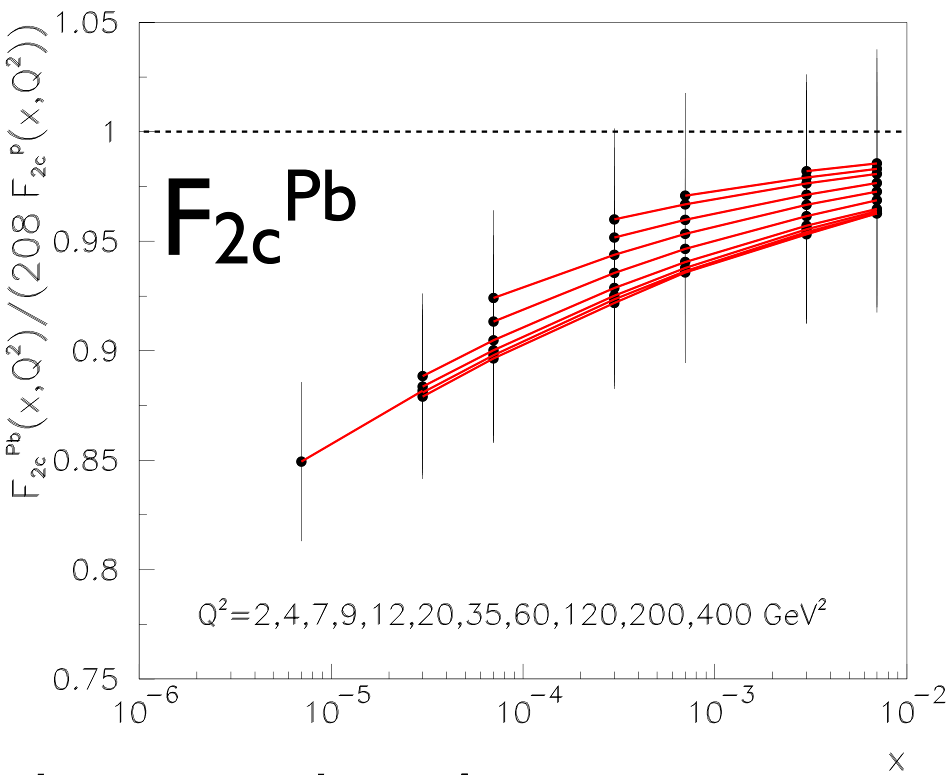


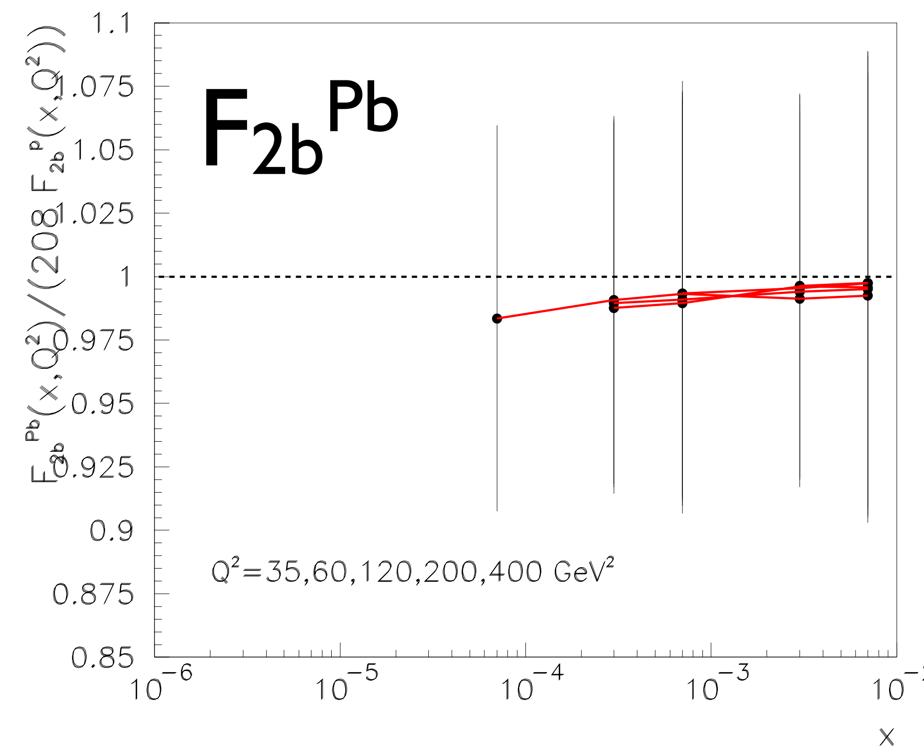
eA inclusive: comparison

- Good precision can be obtained for $F_{2(c,b)}$ and F_L at small x (Glauberized 3-5 flavor GBW model, NA '02).

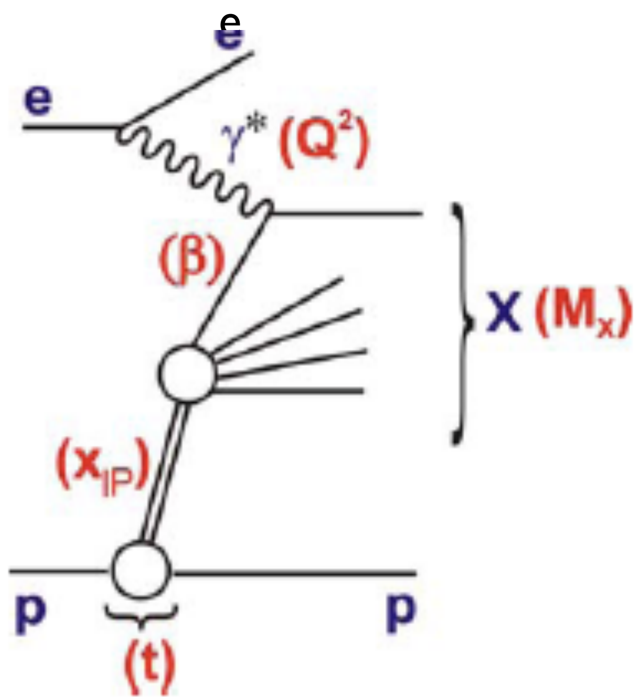




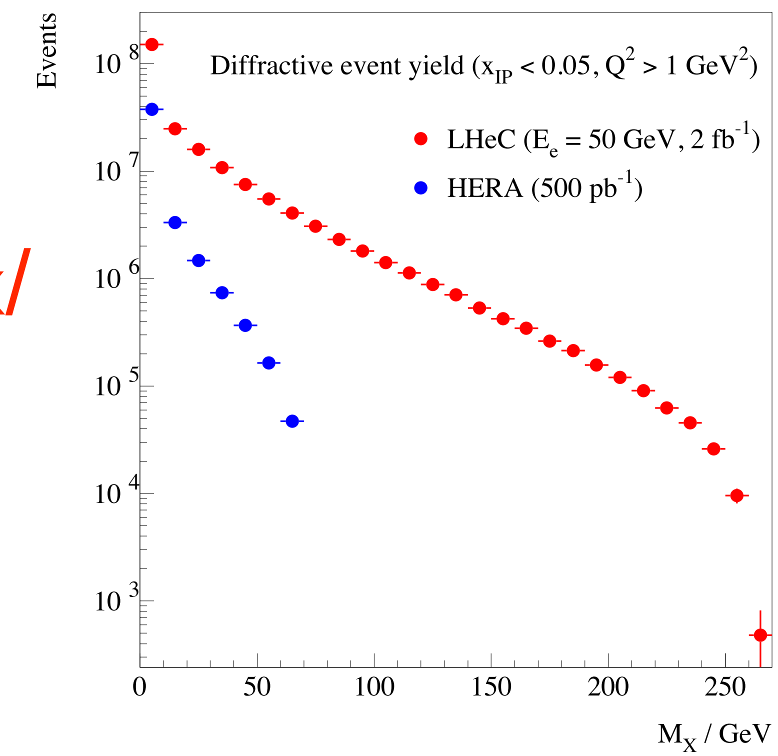


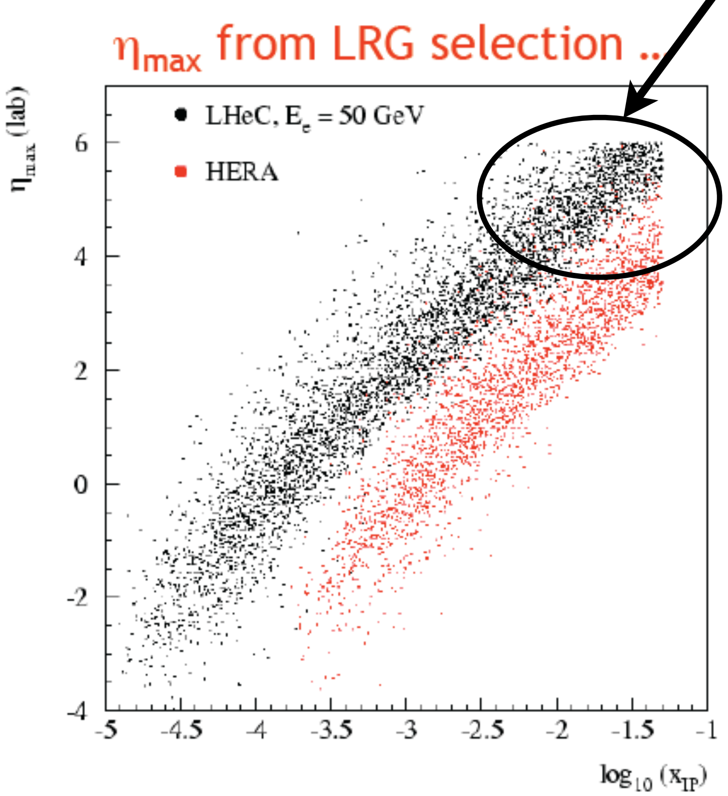


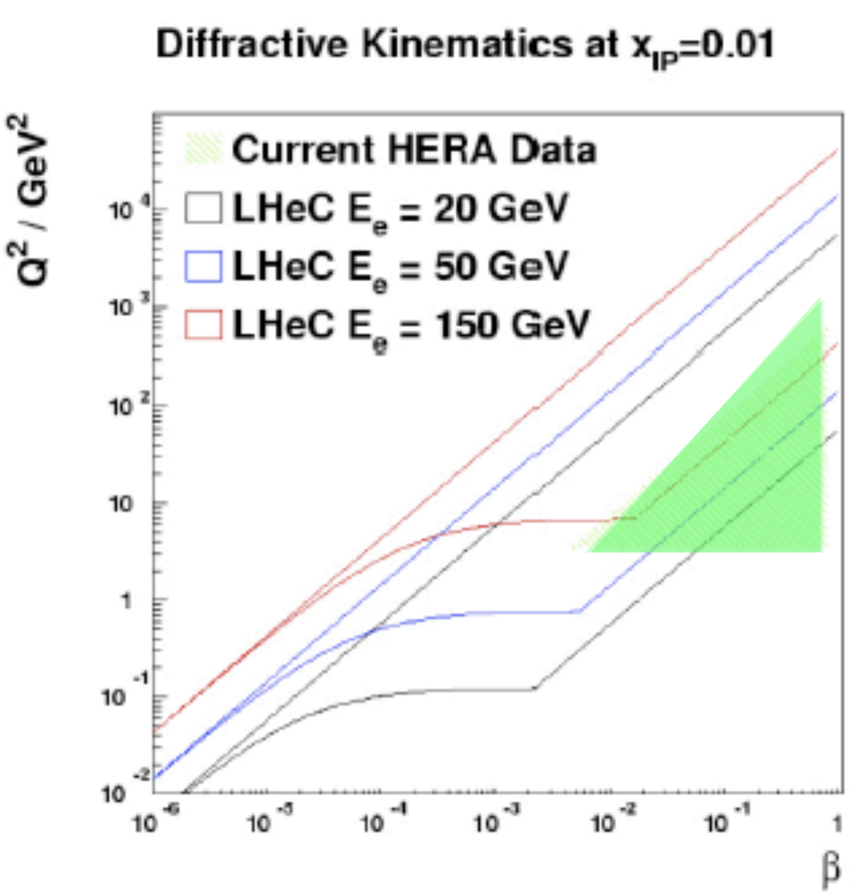
ep diffractive pseudodata:

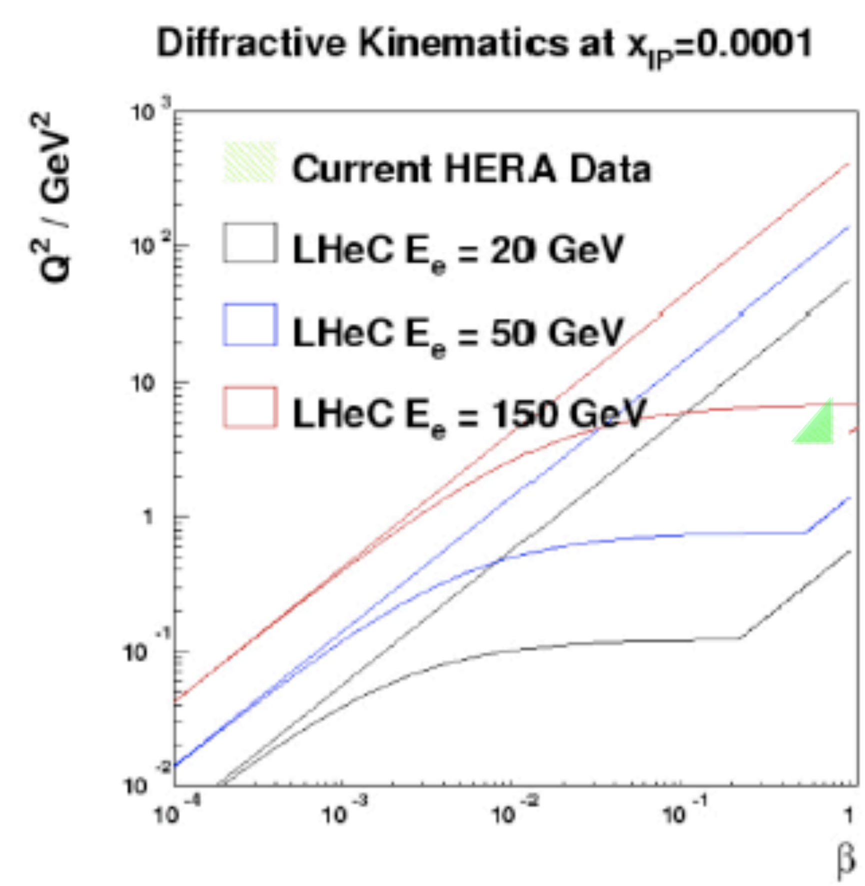


- Large increase in the M^2, $x_P=(M^2-t+Q^2)/(W^2+Q^2)$, $\beta=x/x_P$ region studied.
- Possibility to combine LRG and LPS.









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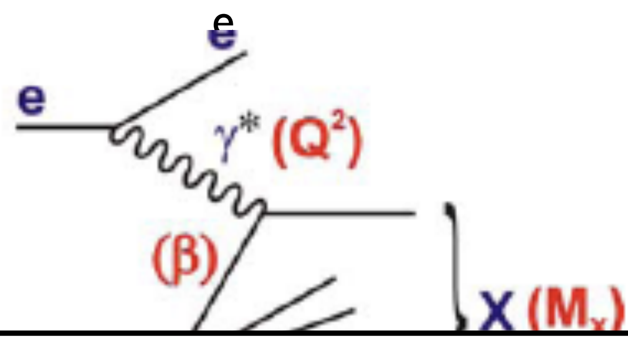
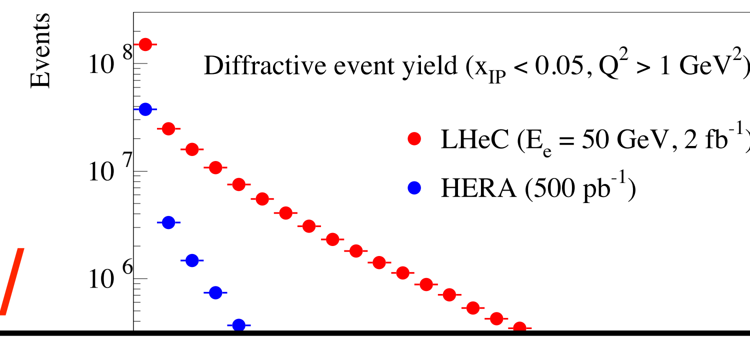
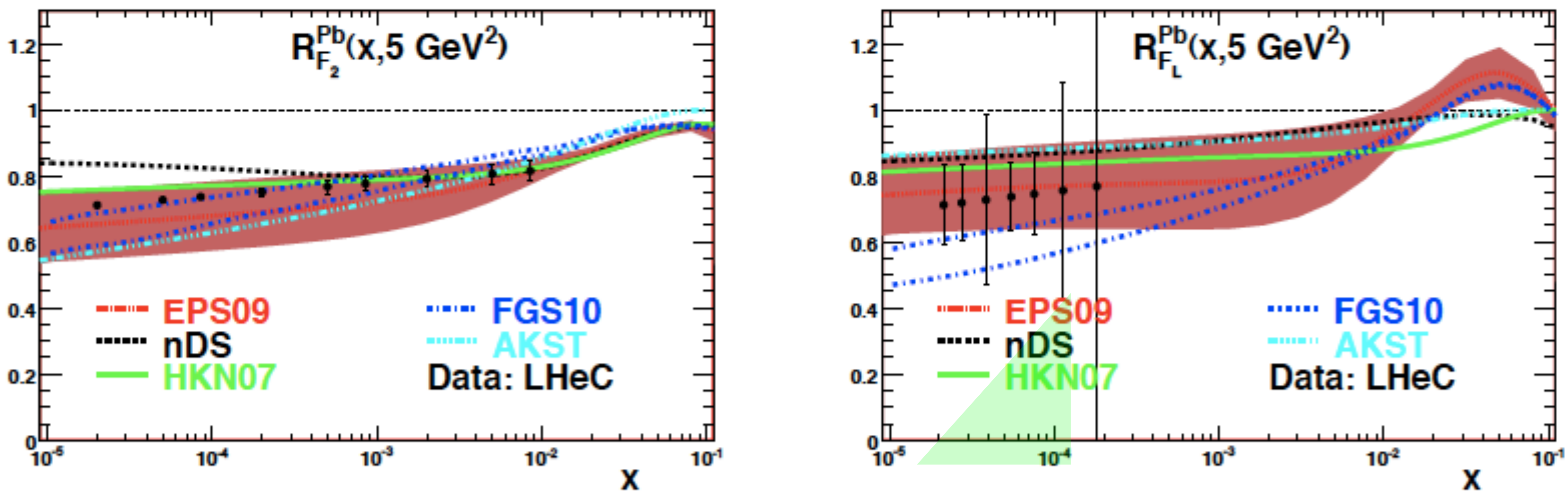
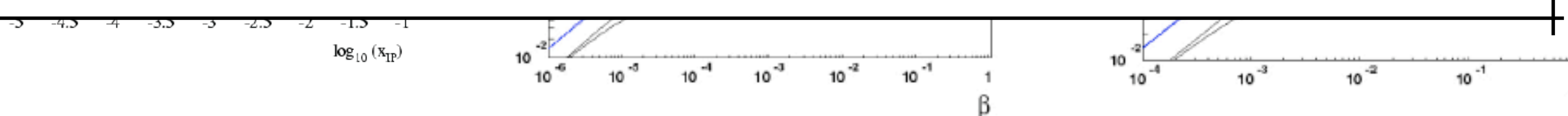


- Large increase in the M^2, $x_P=(M^2-t+Q^2)/(W^2+Q^2)$, $\beta=x/$



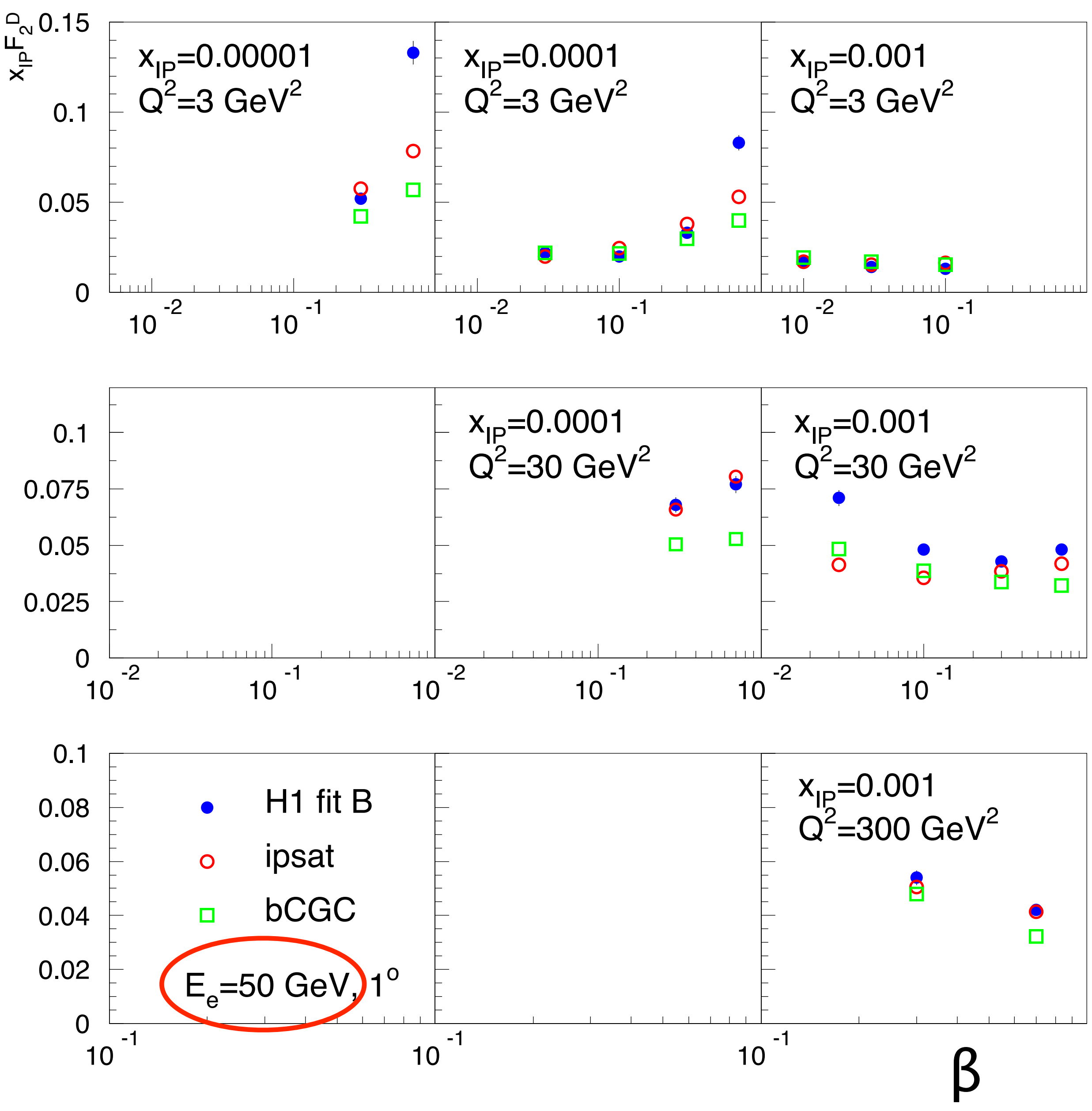
Note: diffraction in ep is linked to shadowing in eA (Gribov): FGS, Capella-Kaidalov et al,...

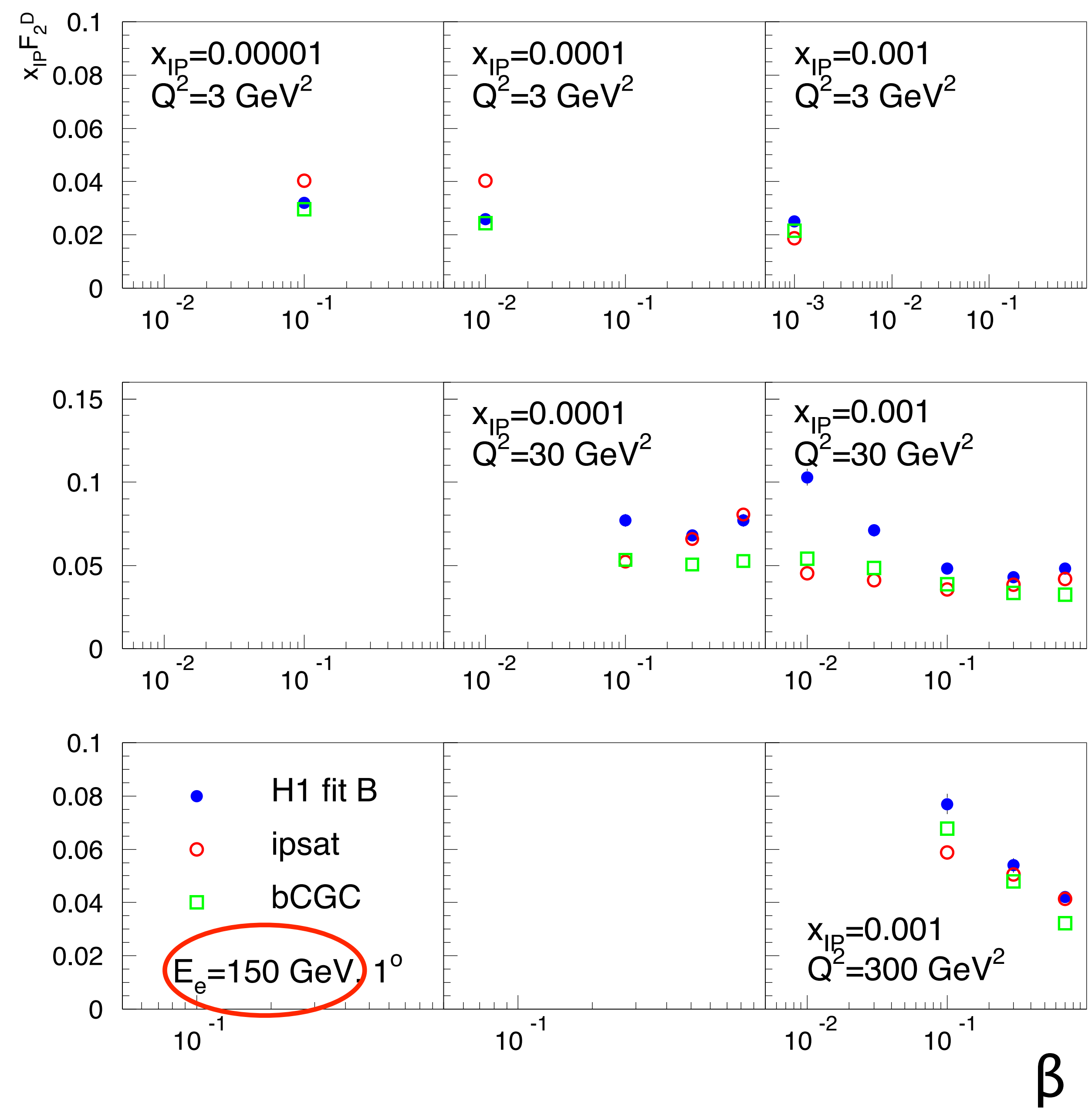




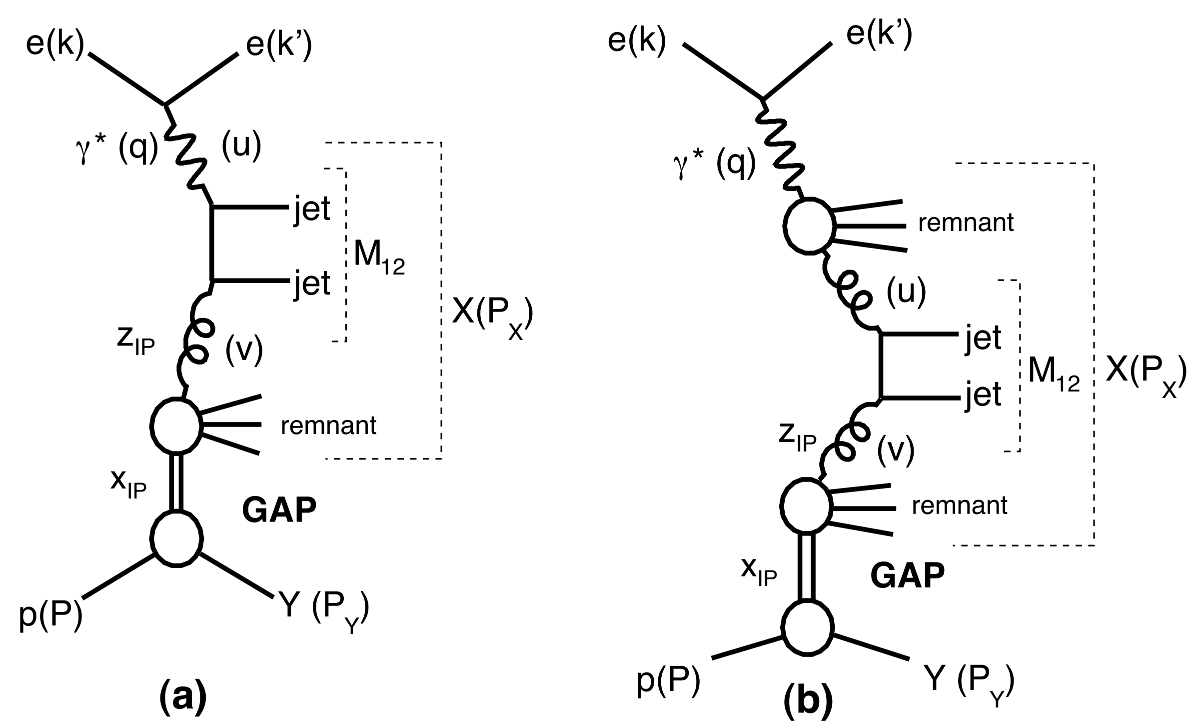
Diffraction and non-linear dynamics:

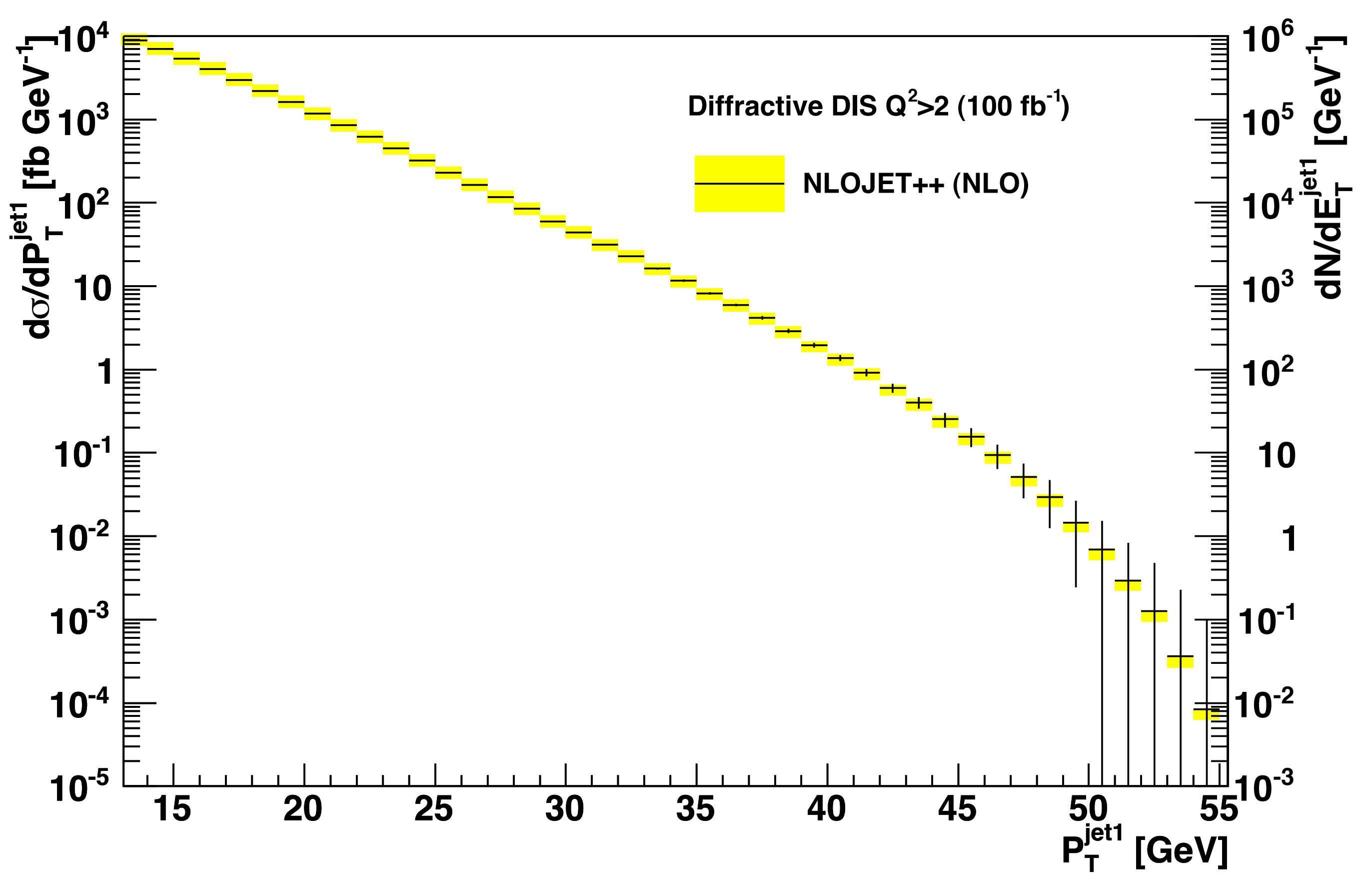
- Dipole models show differences with linear-based extrapolations (HERA-based dpdf's) and among each other: possibility to check saturation and its realization.





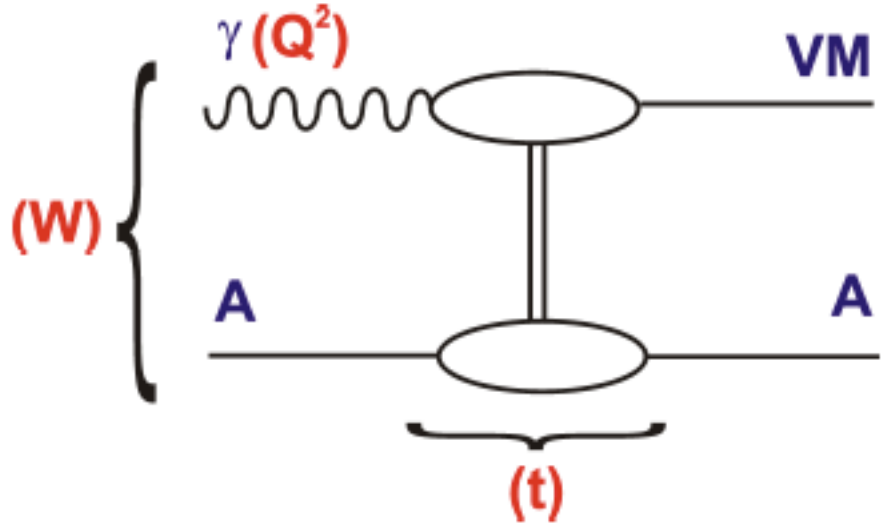
Diffractive dijets:

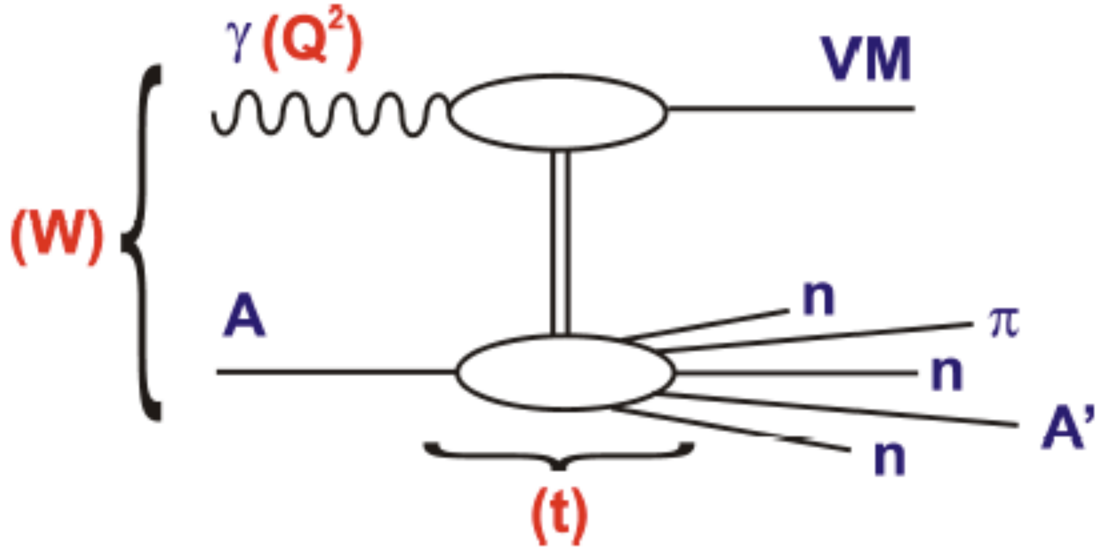




- Diffractive dijet and open heavy flavour production offer large possibilities for:
  - → Checking factorization in hard diffraction.
  - → Constraining DPDFs.
- Large yields upto large p_T^{jet}.
- Direct and resolved contributions: photon PDFs.

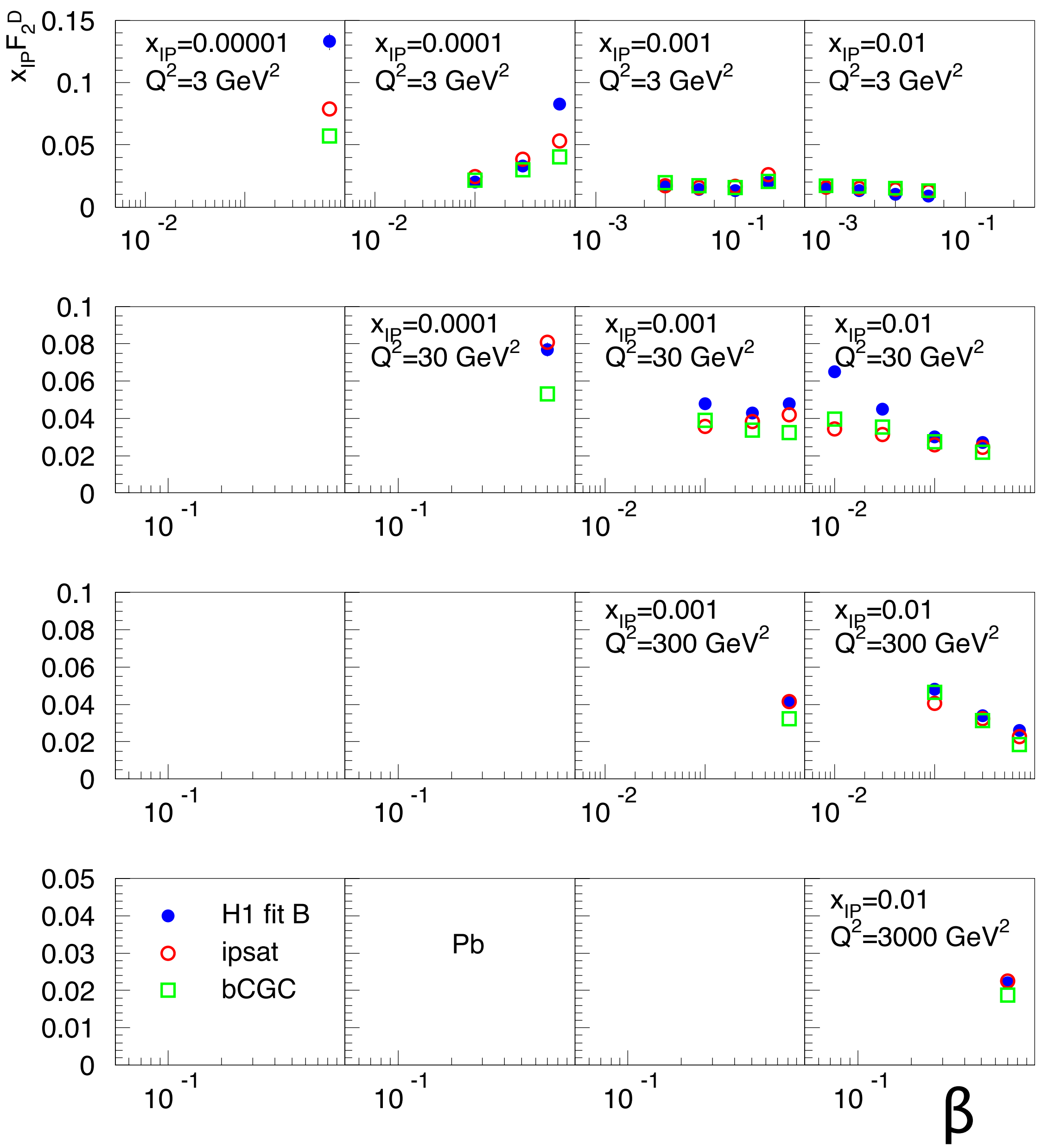
Diffractive DIS on nuclear targets:





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

- For the coherent case, predictions available.



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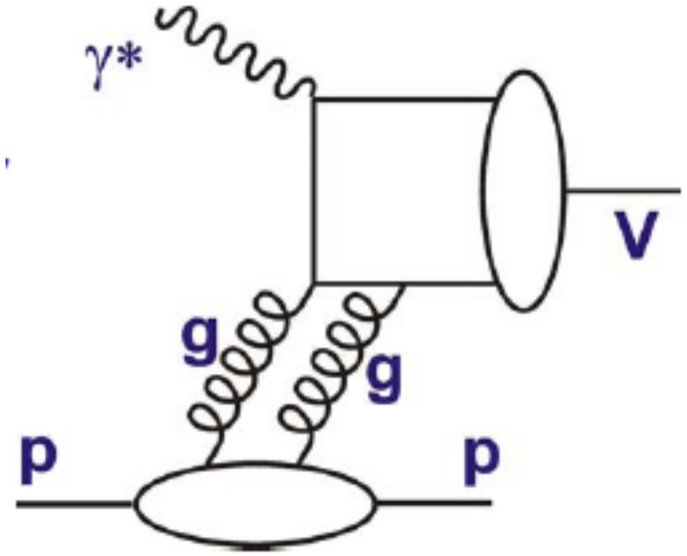
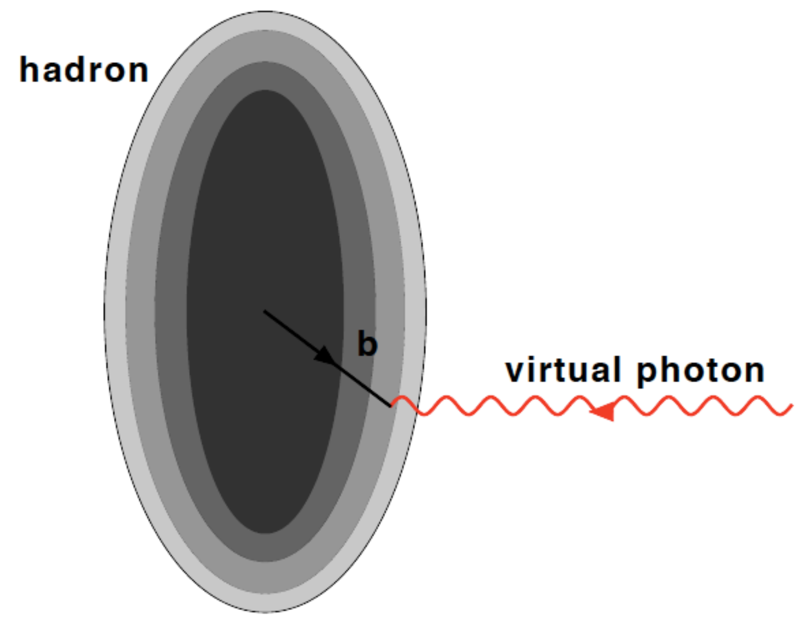
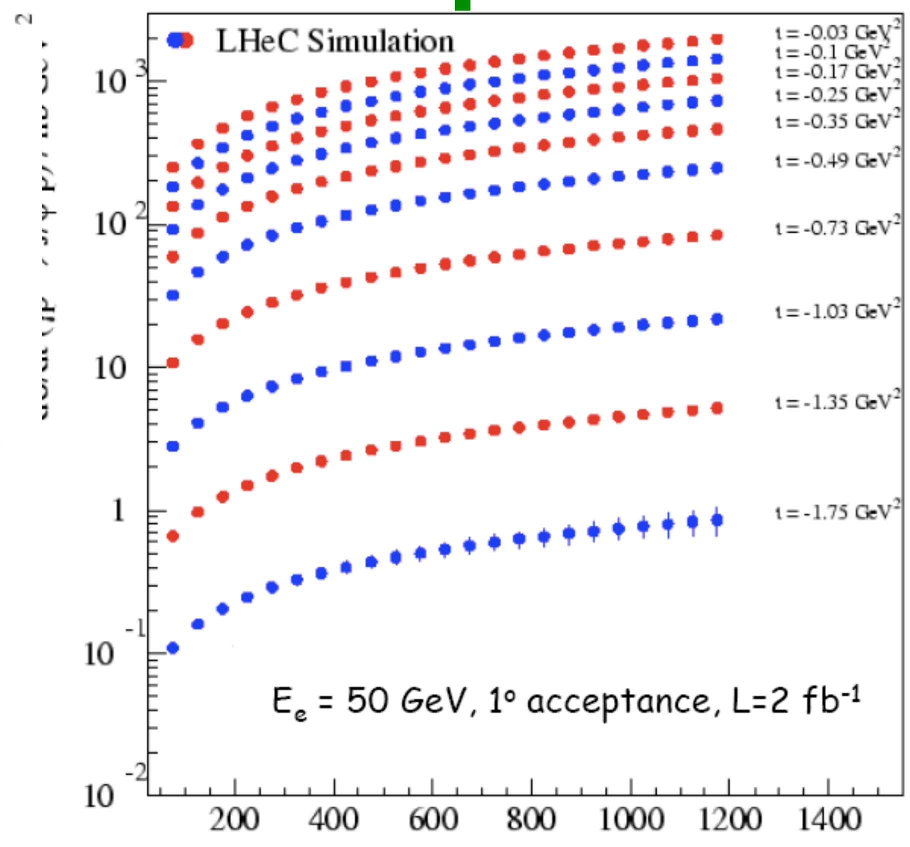
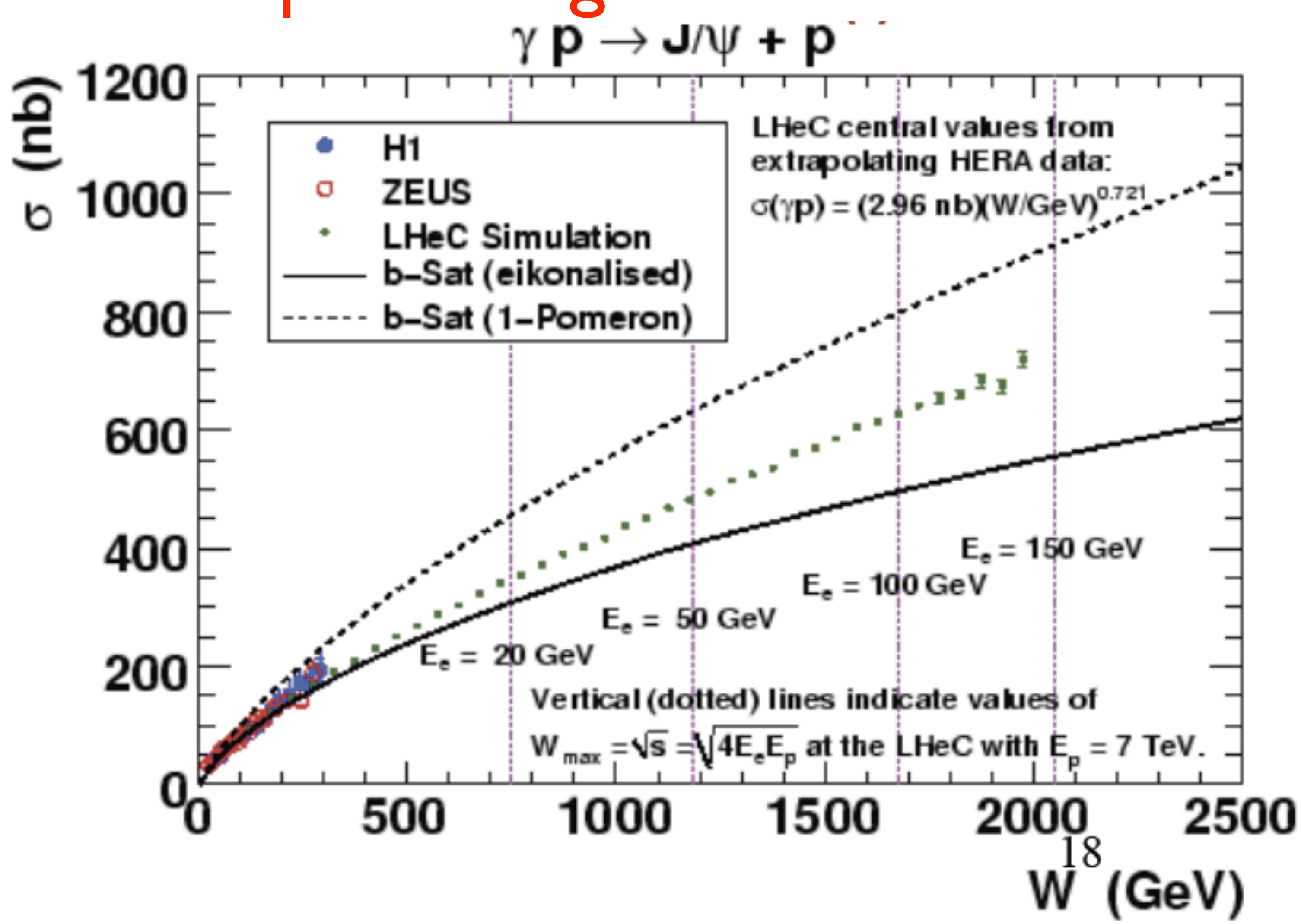
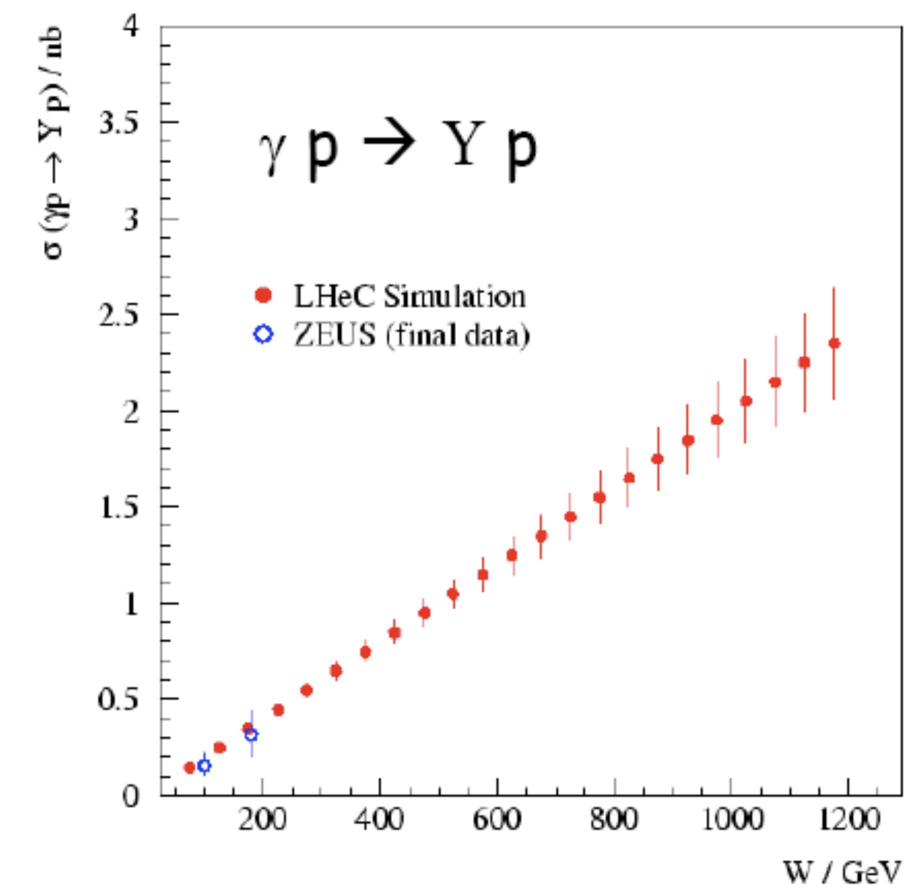






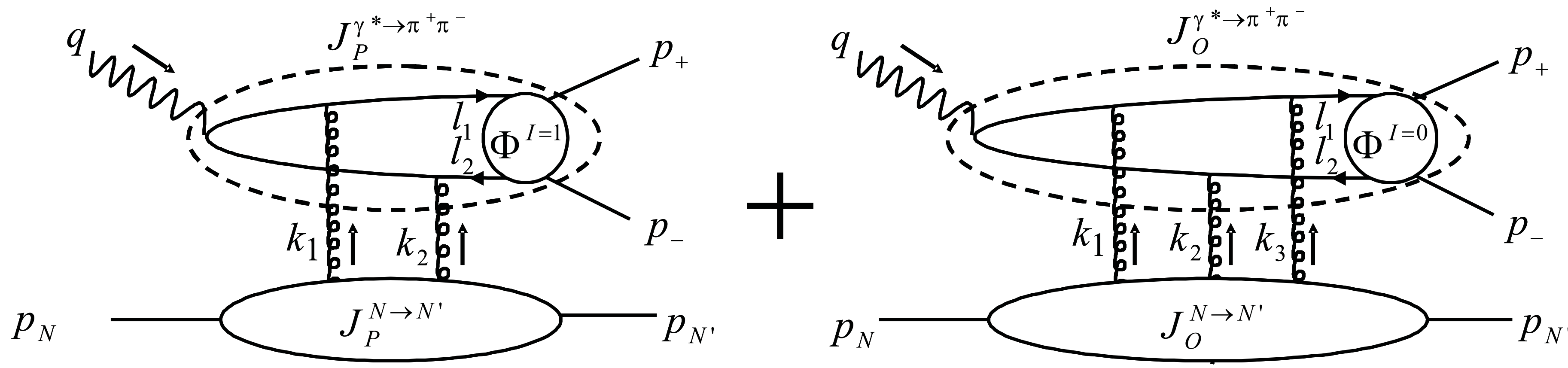
- Most promising!!!





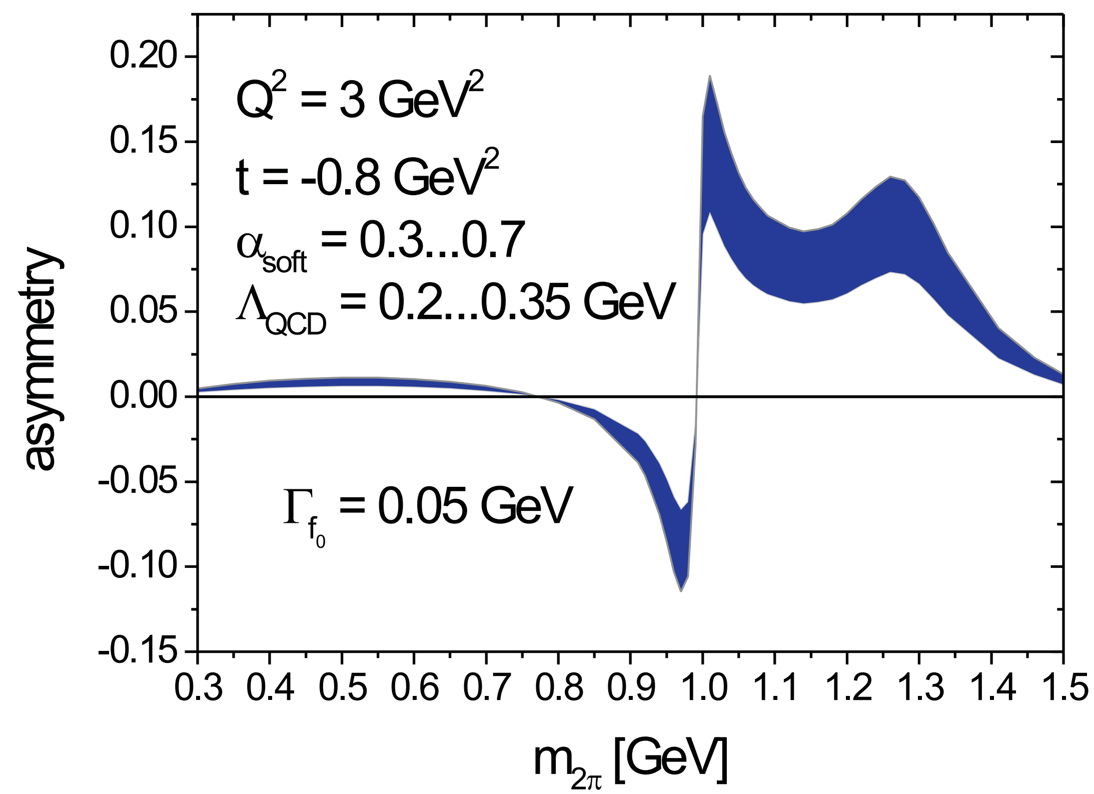
Odderon:

- Odderon (C-odd exchange contributing to particle-antiparticle difference in cross section) seached in $\gamma^{(\star)}p \to Cp$, where $C = \pi^0, \eta, \eta', \eta_c \ldots$ or through O-P interferences.



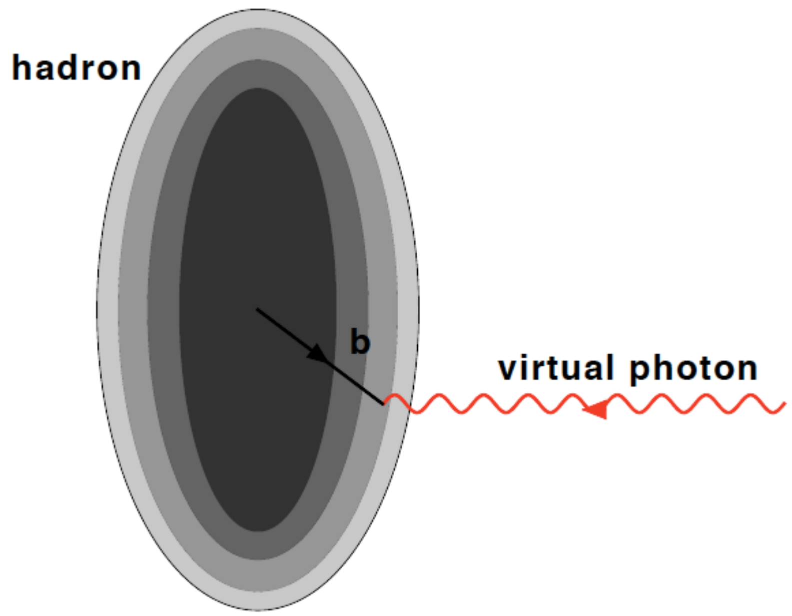
$$A(Q^2, t, m_{2\pi}^2) = \frac{\int \cos\theta \, d\sigma(W^2, Q^2, t, m_{2\pi}^2, \theta)}{\int d\sigma(W^2, Q^2, t, m_{2\pi}^2, \theta)} = \frac{\int_{-1}^{1} \cos\theta \, d\cos\theta \, 2 \, \mathrm{Re}\left[\mathcal{M}_P^{\gamma_L^*}(\mathcal{M}_O^{\gamma_L^*})^*\right]}{\int_{-1}^{1} d\cos\theta \left[|\mathcal{M}_P^{\gamma_L^*}|^2 + |\mathcal{M}_O^{\gamma_L^*}|^2\right]}$$

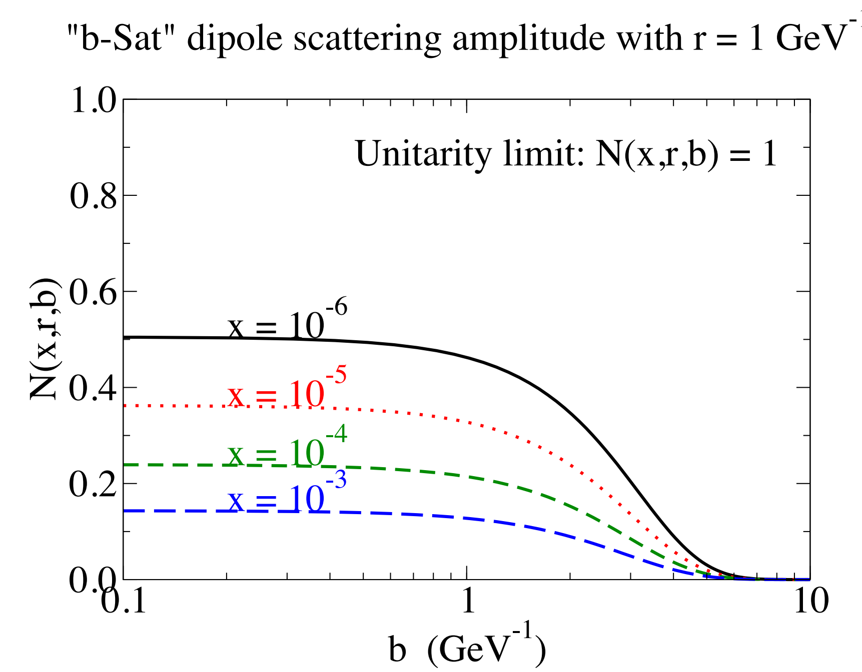
- Sizable charge asymmetry, yields and reconstruction pending.

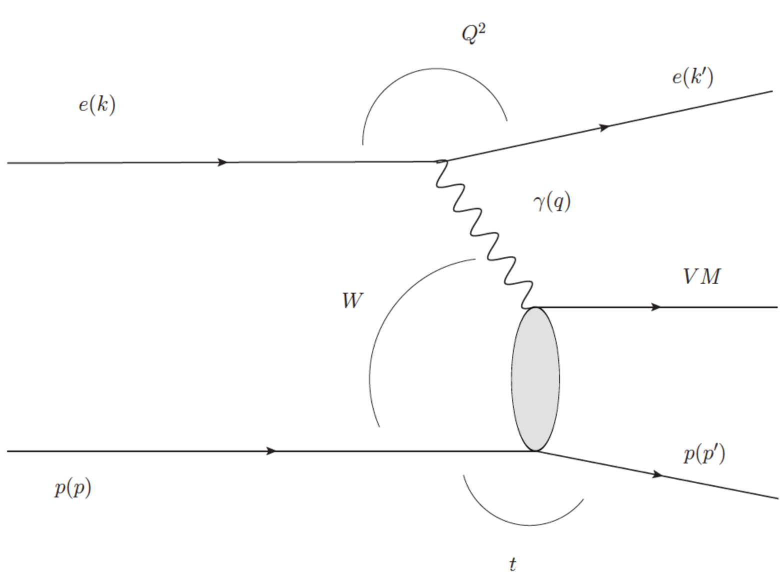


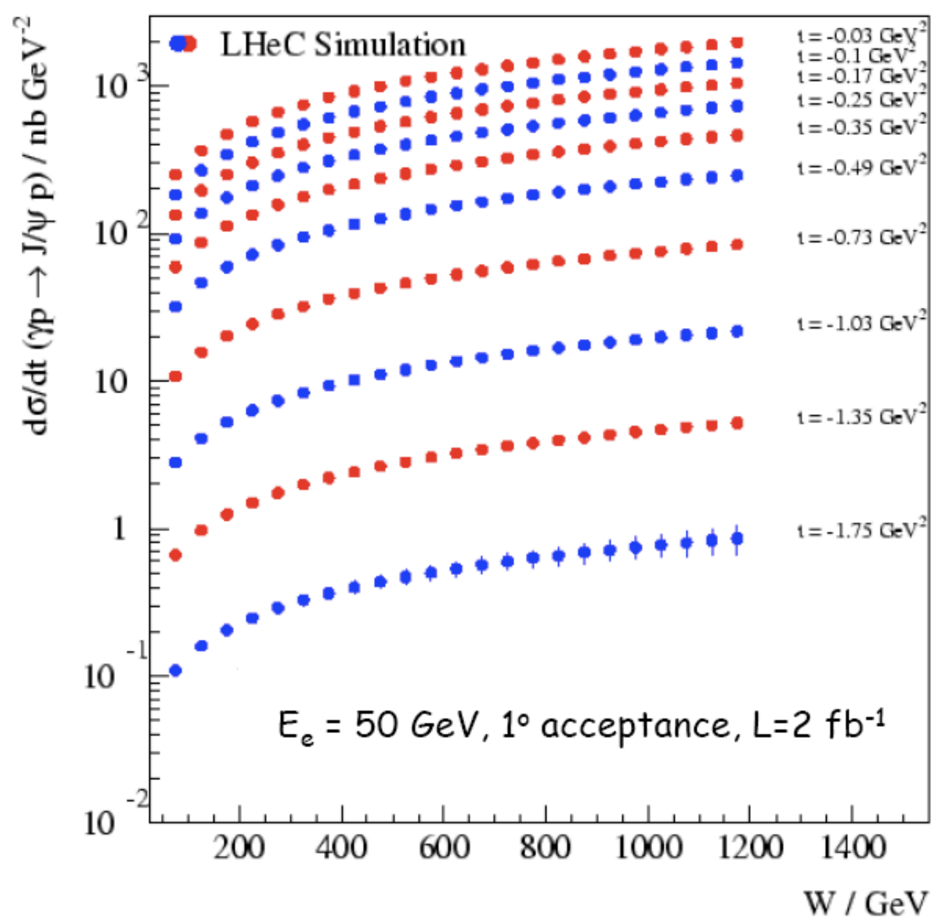
Transverse scan: elastic VM

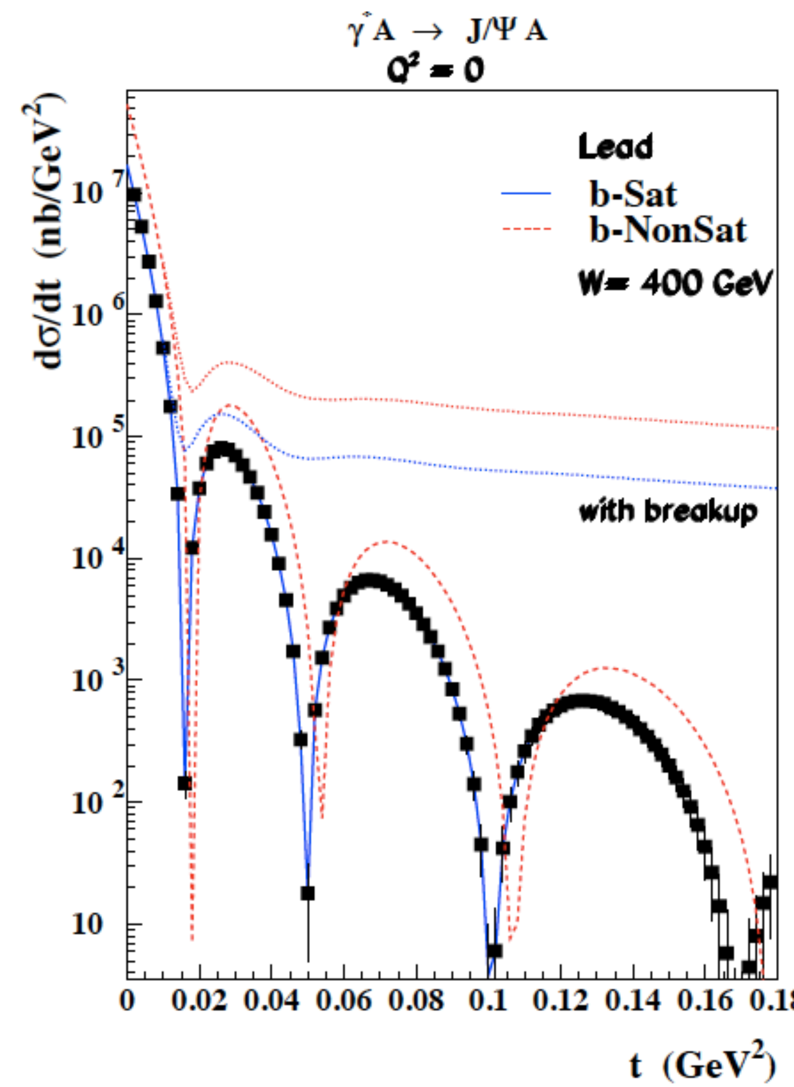
- t-differential measurements give a gluon tranverse mapping of the hadron/nucleus.







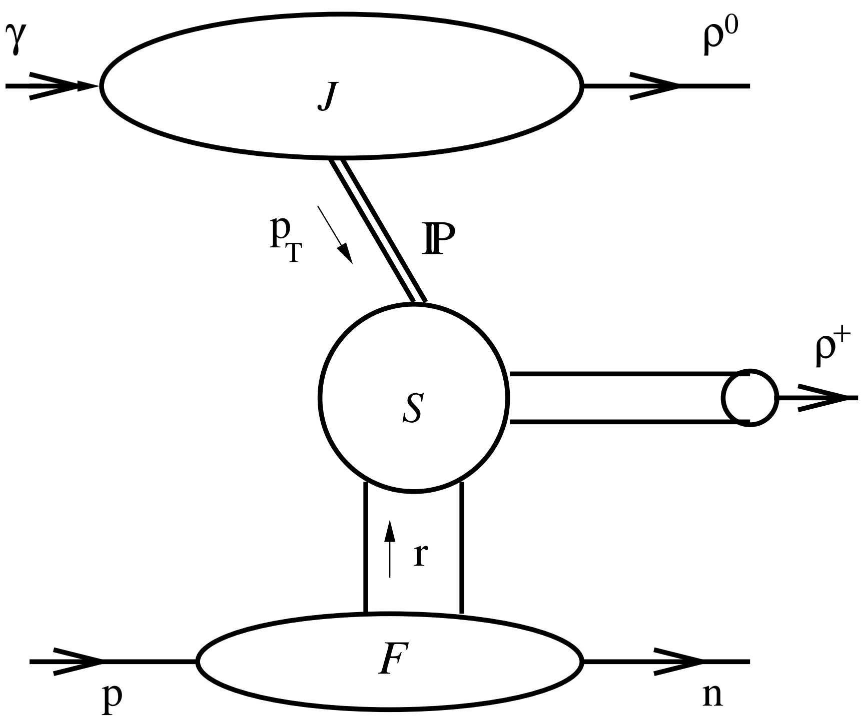




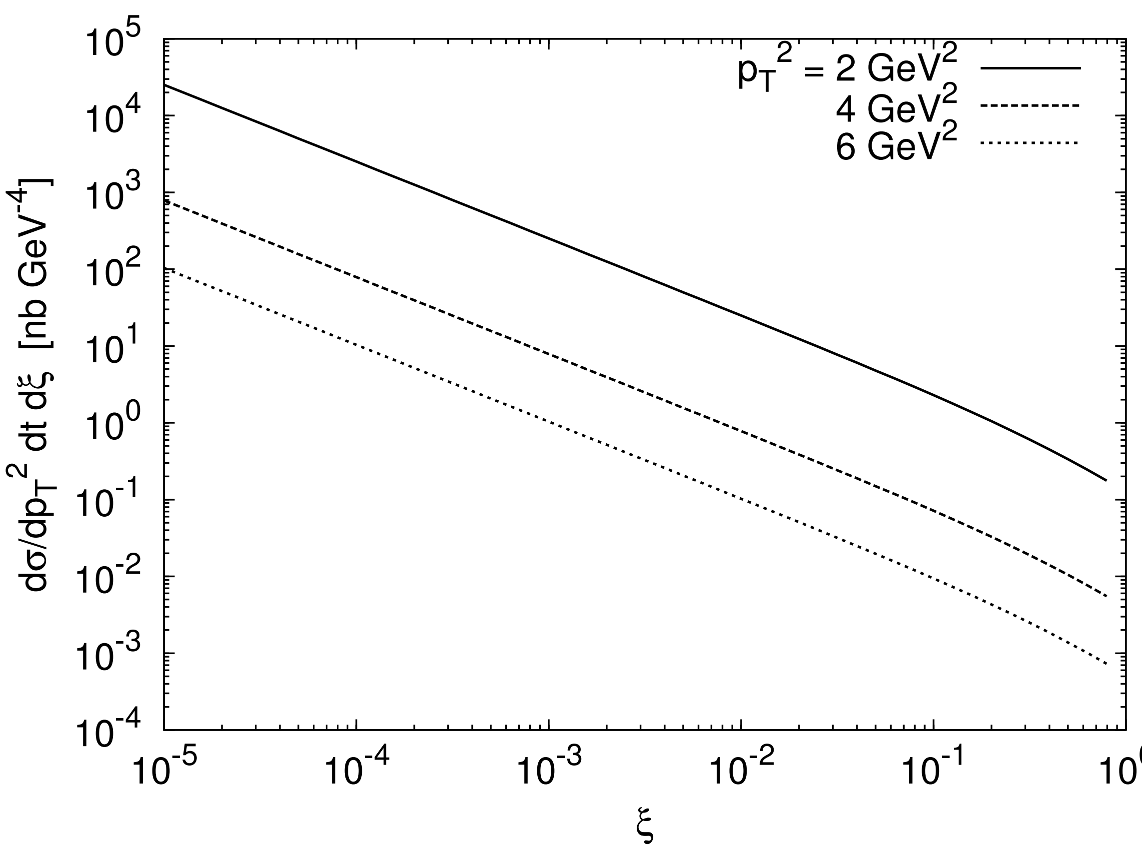
Transversity GPDs:

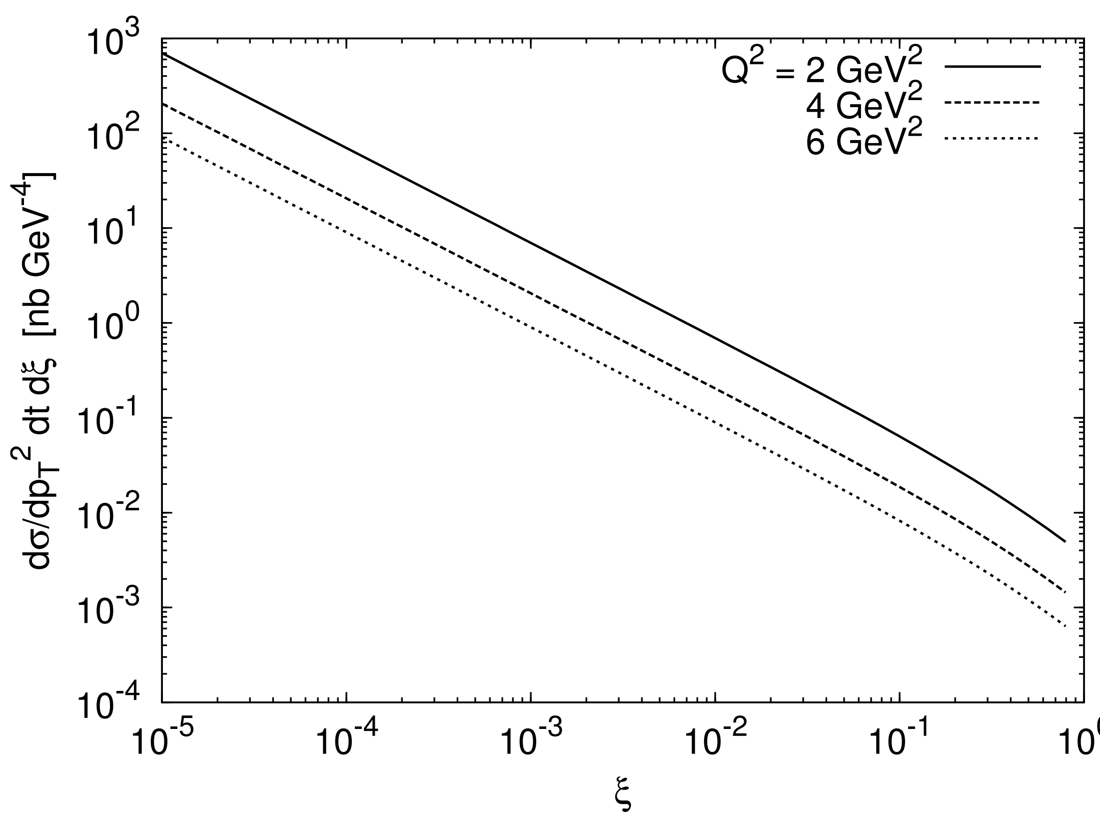
- Chiral-odd transversity GPDs are largely unknown.

- They can be accessed through double exclusive production:



$$ep(p_2) \to e'\gamma^{(*)}_{L/T}(q)\ \ p(p_2) \to e'\rho^0_{L,T}(q_\rho)\ \ \rho_T(p_\rho)\ N'(p_{2'})$$





$$\xi \approx x_B/(2-x_B)$$

Dijet azimuthal decorrelation:

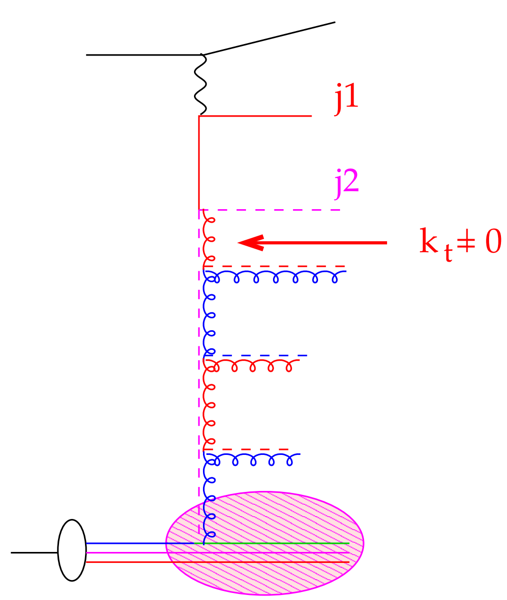
- Studying dijet azimuthal decorrelation or forward jets ($p_T \sim Q$) would allow to understand the mechanism of radiation:

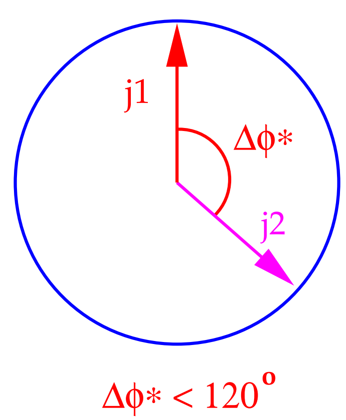
→ k_T-ordered: DGLAP.

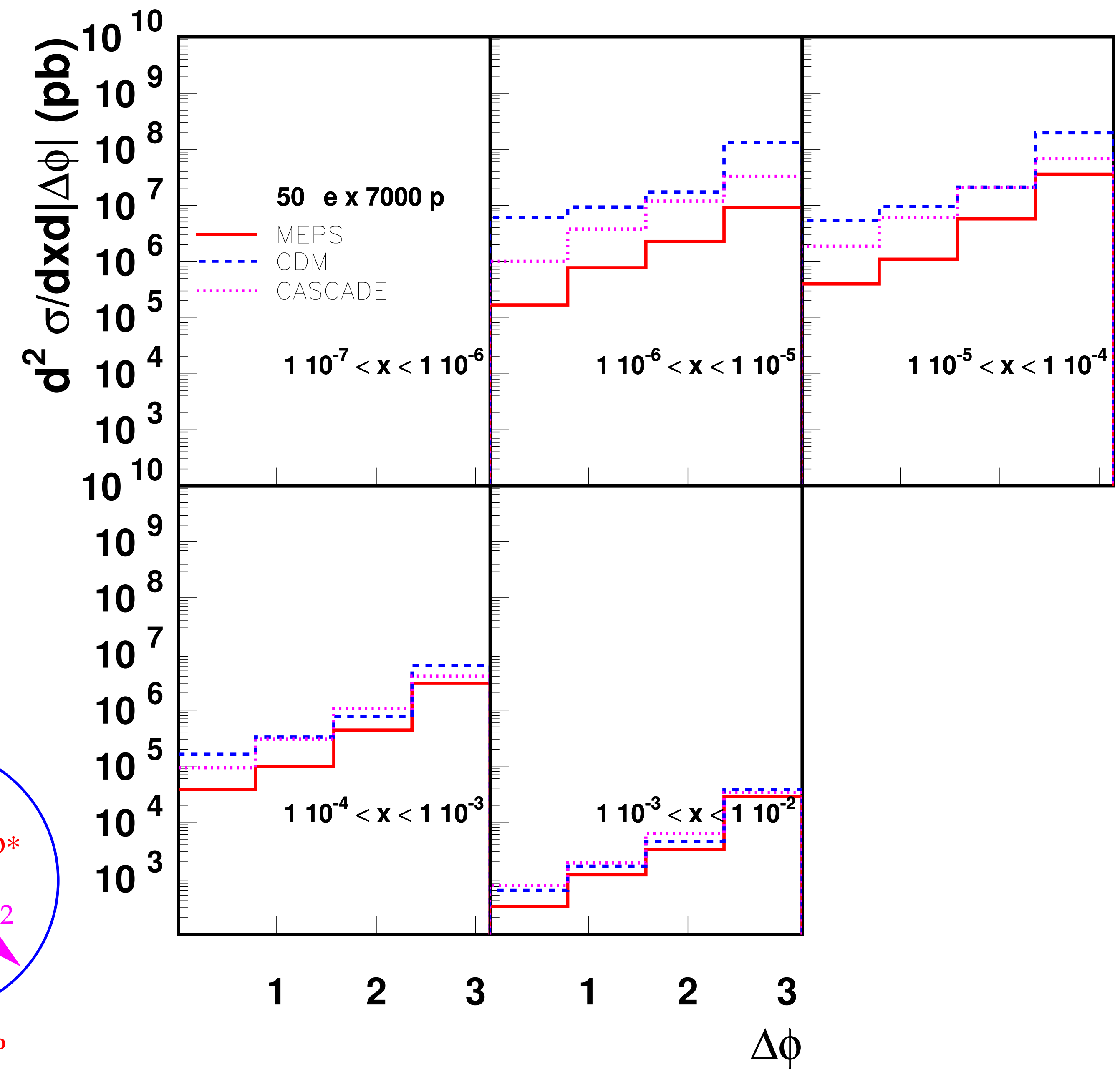
→ k_T-disordered: BFKL.

→ Saturation?

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







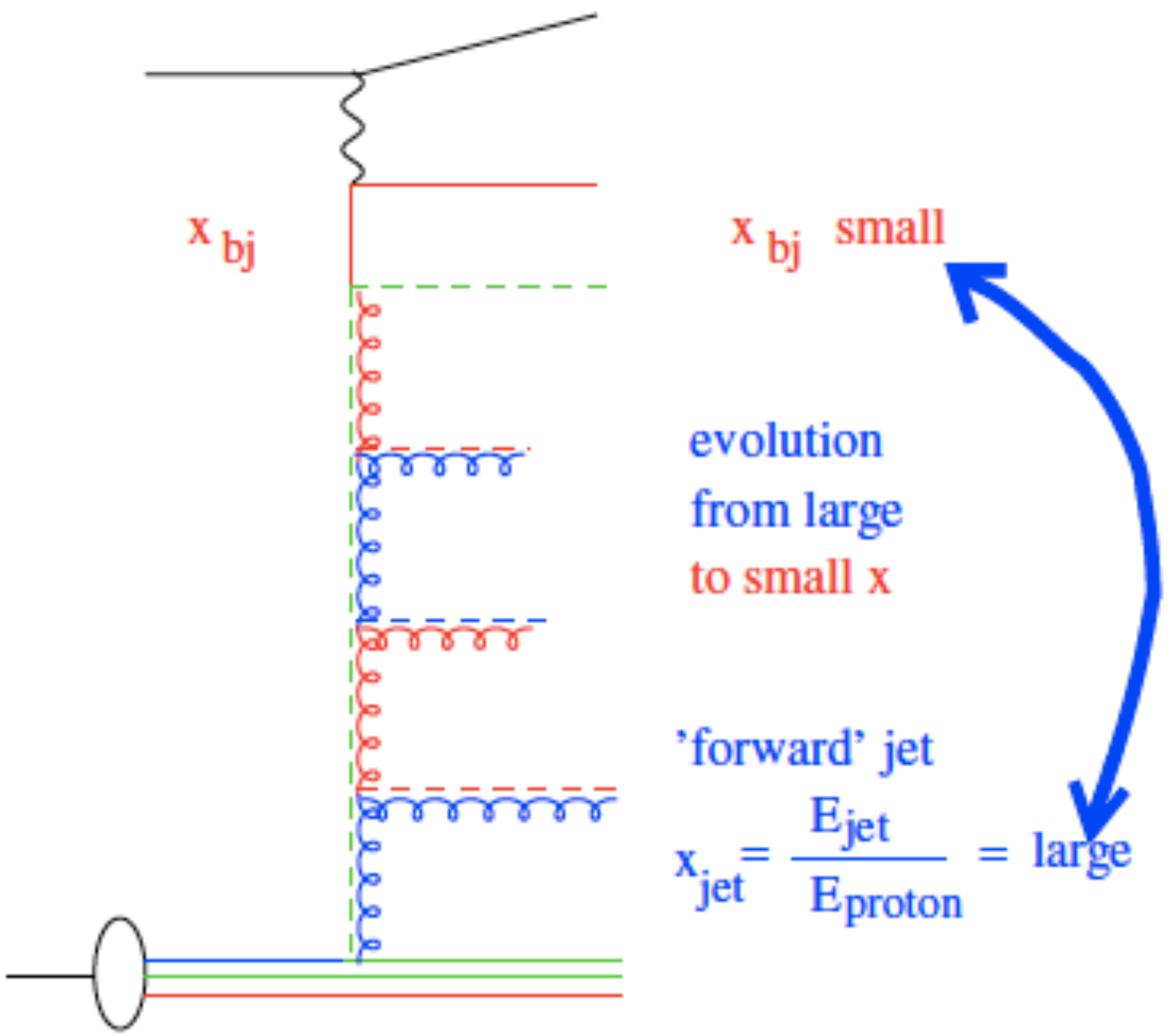
Dynamics of QCD radiation:

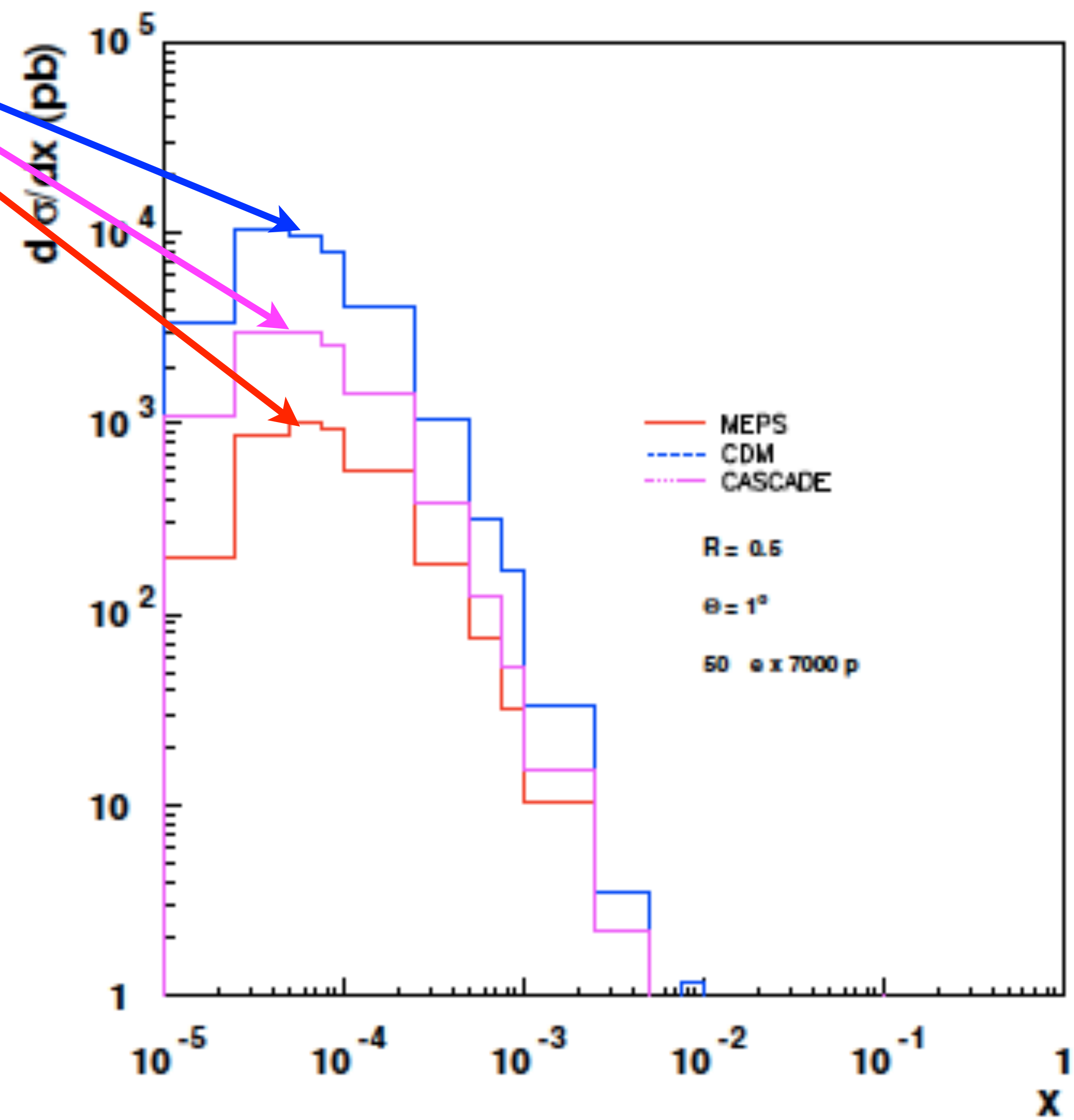
- Studying dijet azimuthal decorrelation or forward jets ($p_T \sim Q$) would allow to understand the mechanism of radiation:

→ k_T-ordered: DGLAP.

→ k_T-disordered: BFKL-like.

→ Saturation?

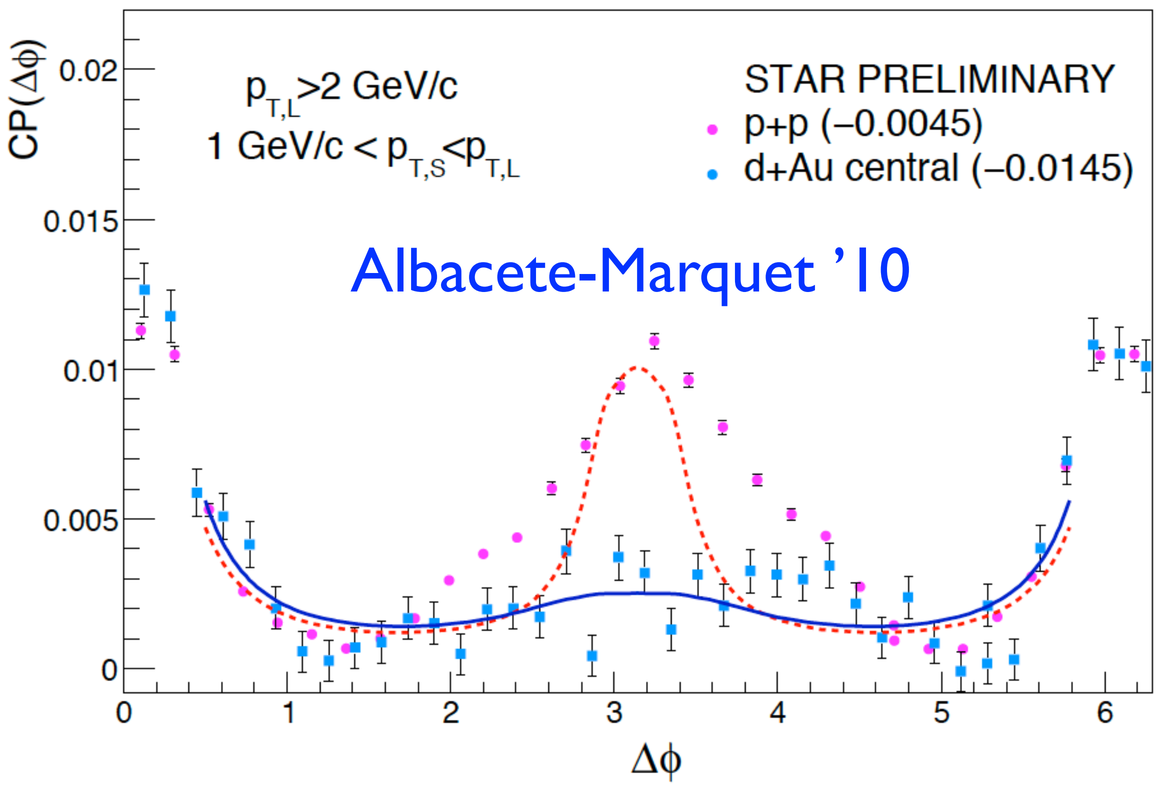




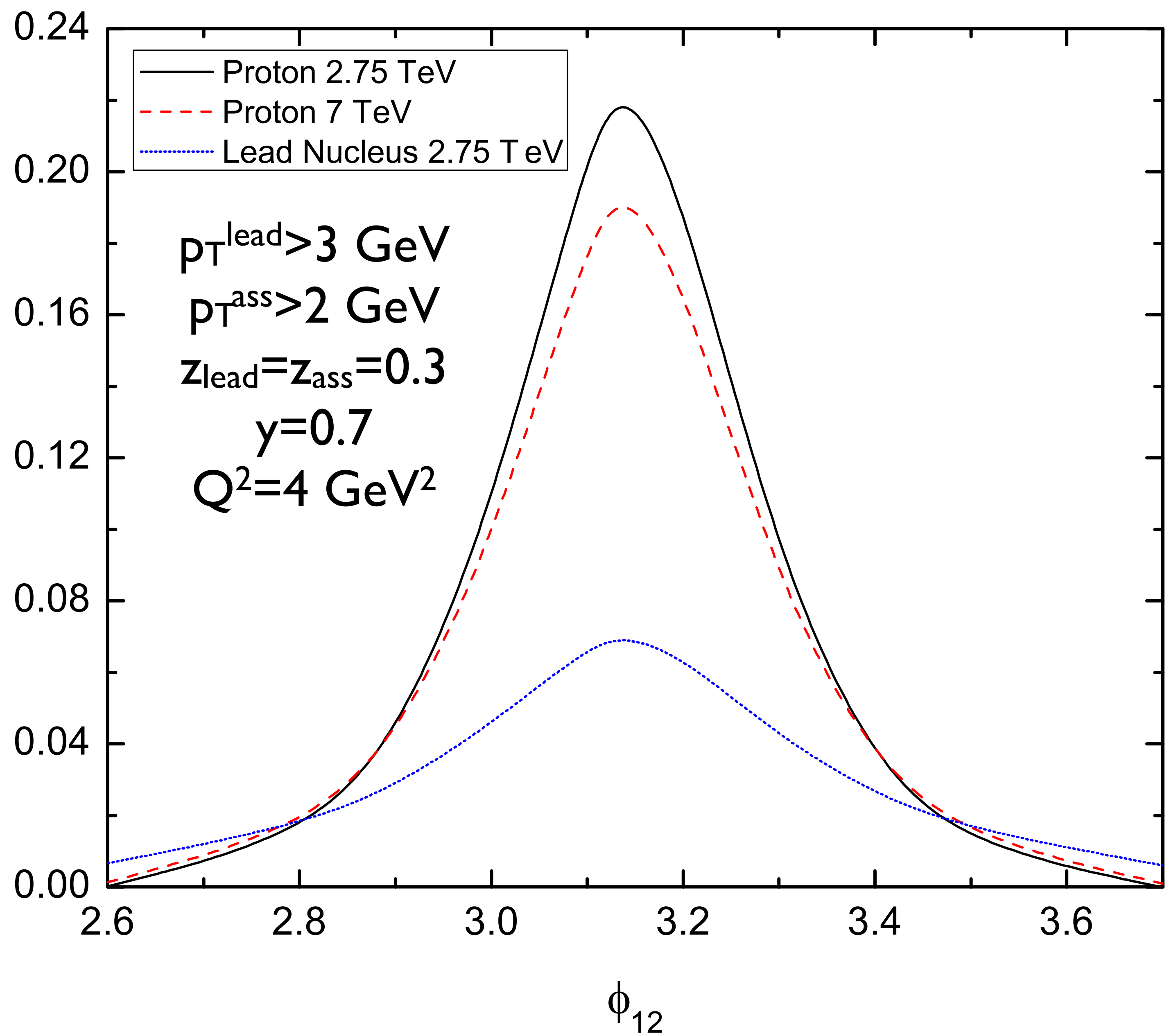
Dihadron azimuthal decorrelation:

- Dihadron azimuthal decorrelation is currently discussed at RHIC as one of the most suggestive indications of saturation.

- At the LHeC it could be studied far from the kinematical limits.



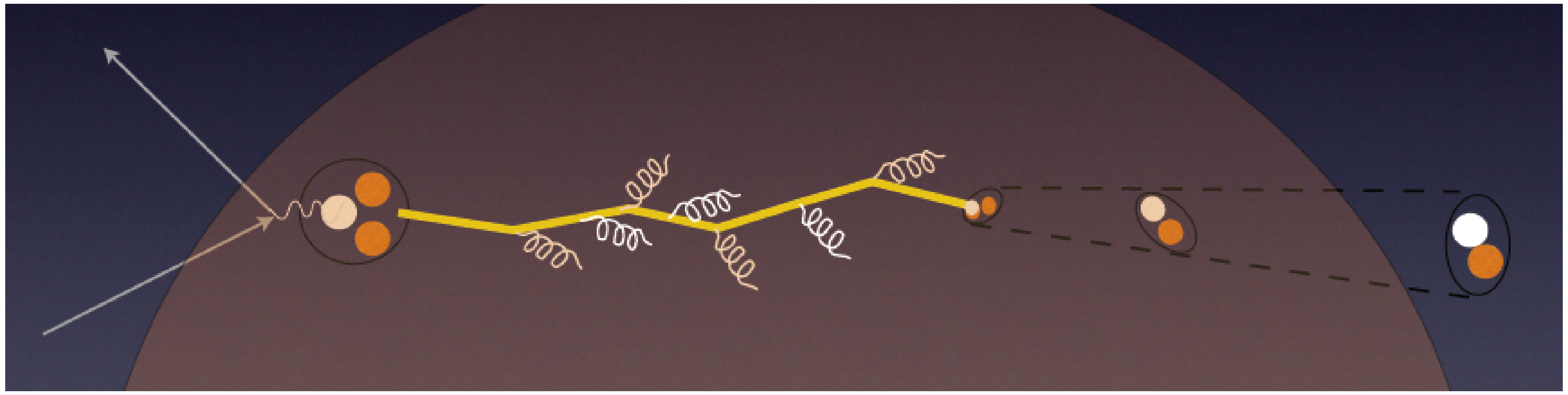
$$C(\phi_{12}) = \frac{1}{\frac{d\sigma(\gamma^* N \to h_1 X)}{dz_{h1}}} \frac{d\sigma^{\gamma^* N \to h_1 h_2 + X}}{dz_{h1} dz_{h2} d\phi_{12}}$$



In-medium hadronization (I):

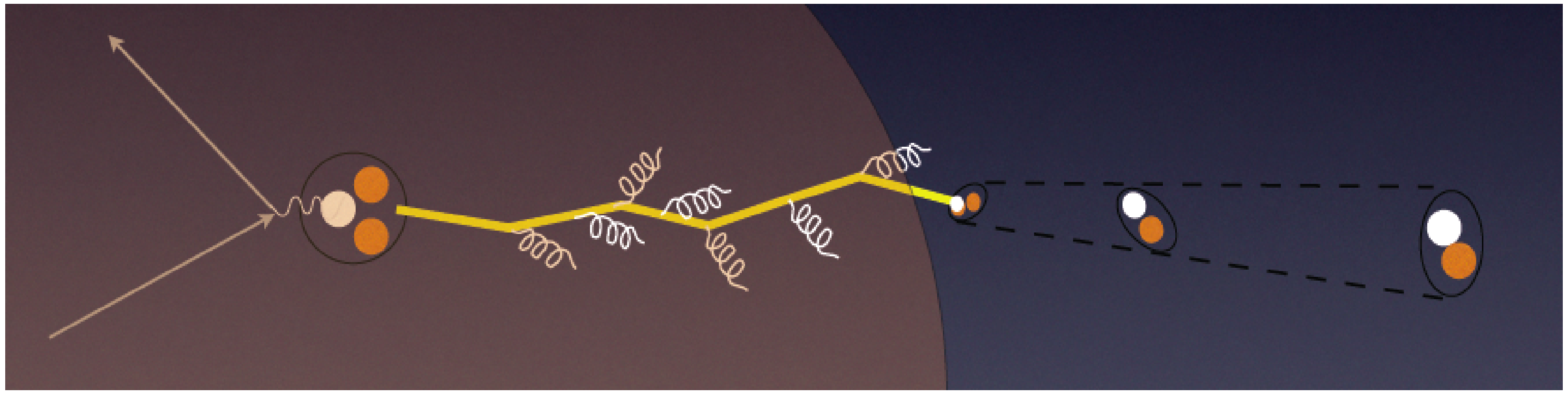
- The LHeC ($\nu_{max}\sim 10^5$ GeV) would allow to study the dynamics of hadronization, testing the parton/hadron eloss mechanism by introducing a length of colored material which would modify its pattern (length/nuclear size, chemical composition).

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



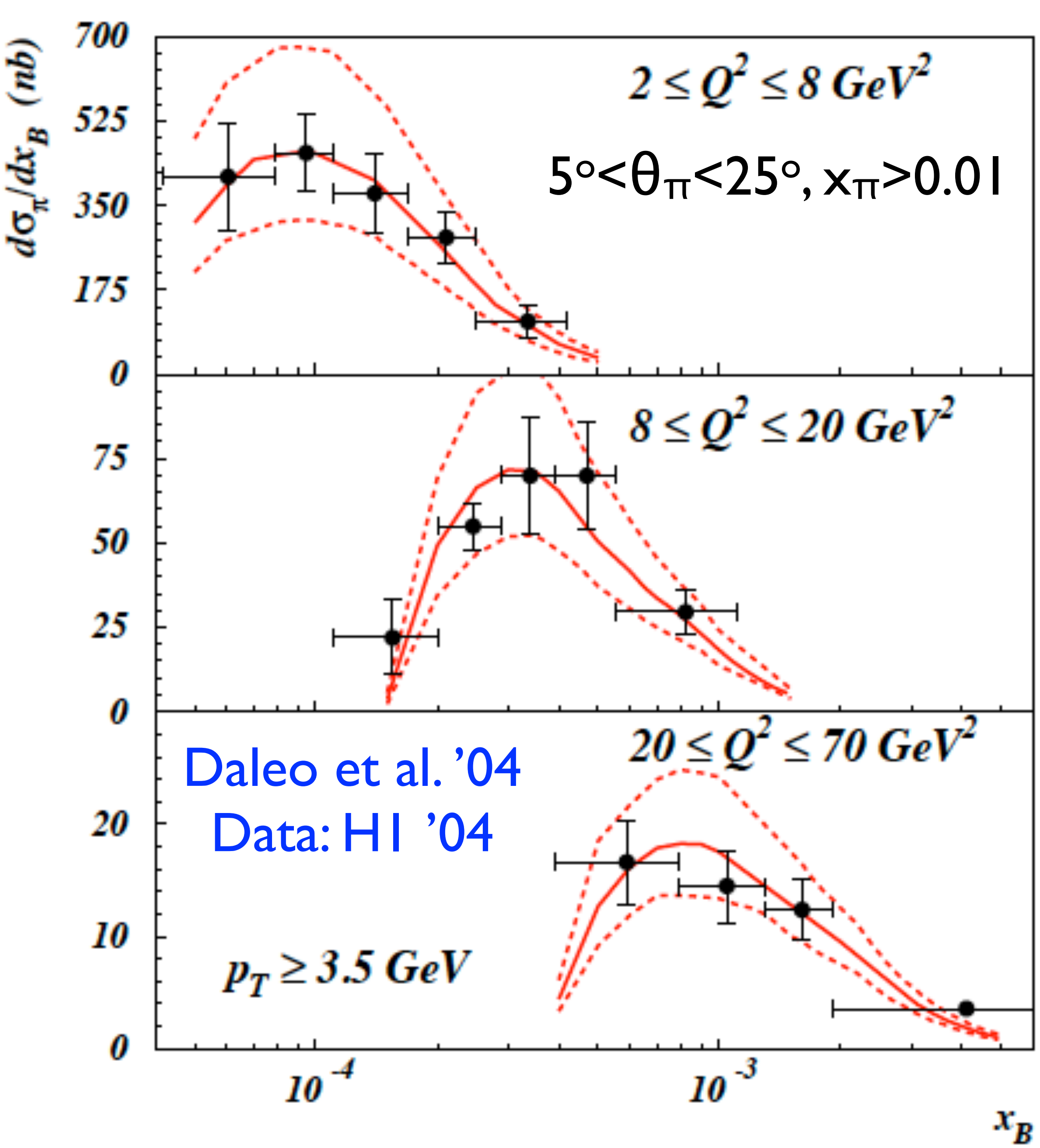
Brooks at Divonne'09

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

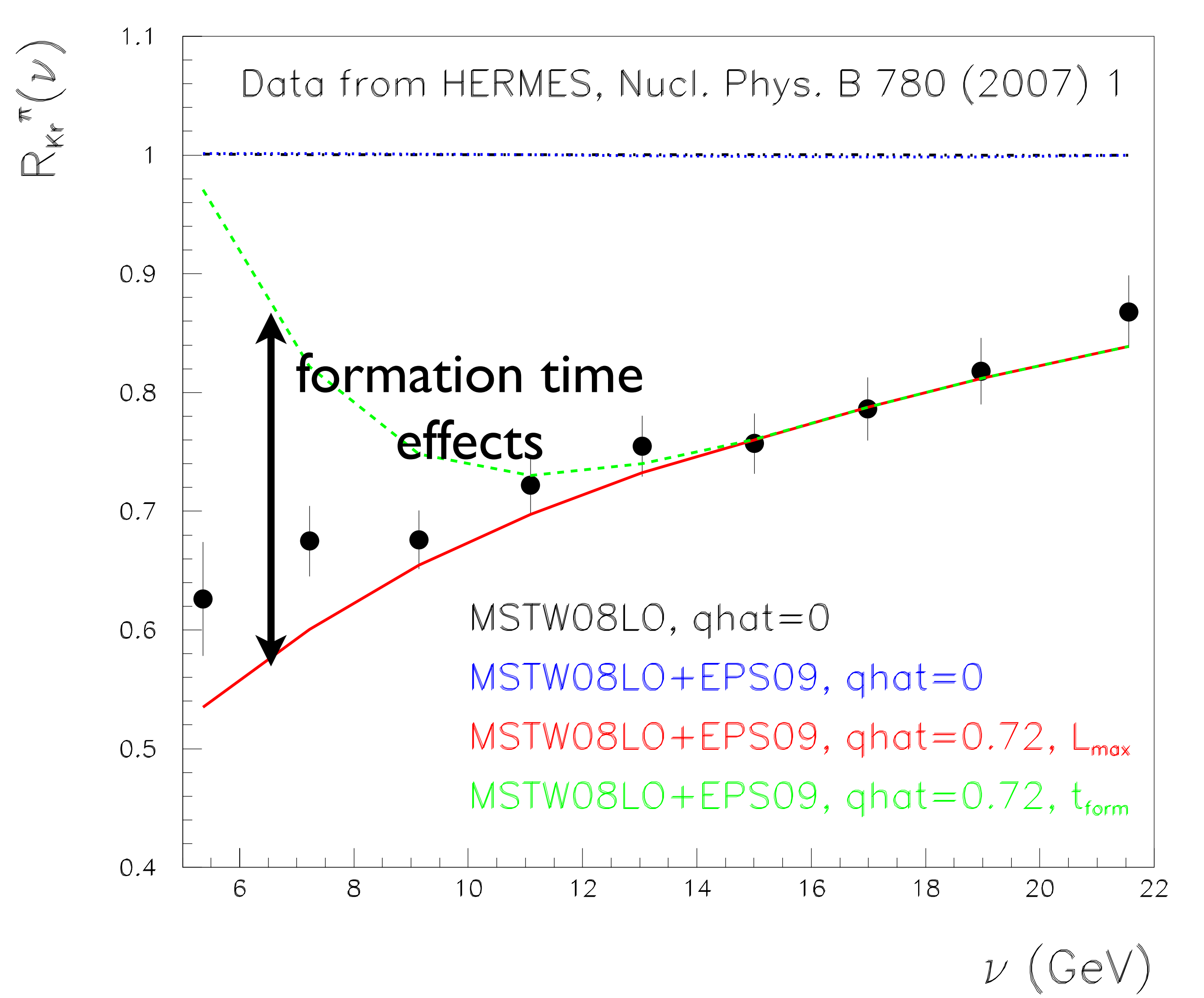


In-medium hadronization (II):

- Large (NLO) yields at small-x (H1 cuts, 3 times higher if relaxed).
- Nuclear effects in hadronization at small ν (LO plus QW, Arleo '03).



$$R_A^h(z,\nu) = \frac{1}{N_A^e}\frac{dN_A^h(z,\nu)}{d\nu\, dz} \Big/ \frac{1}{N_D^e}\frac{dN_D^h(z,\nu)}{d\nu\, dz}$$



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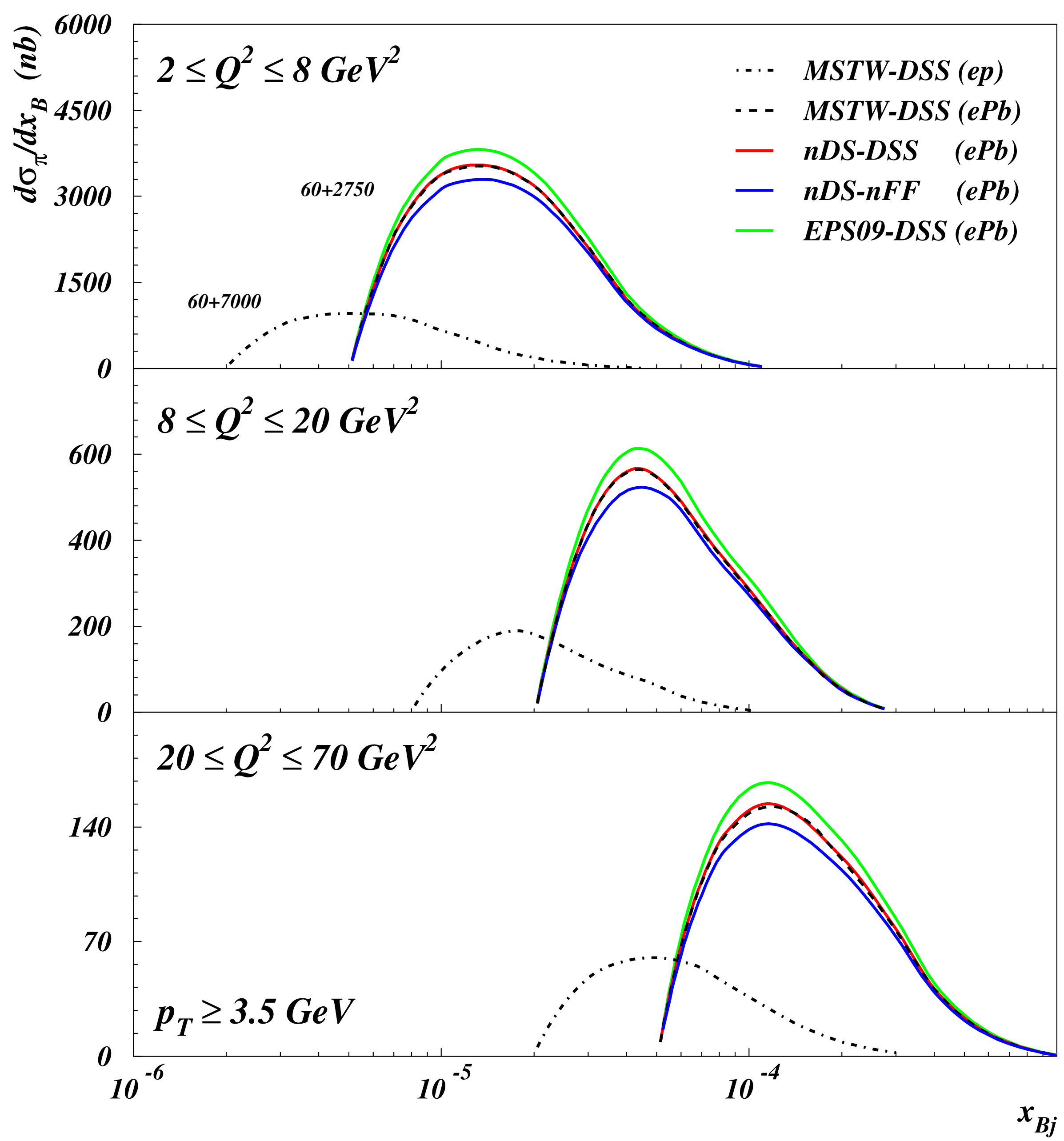

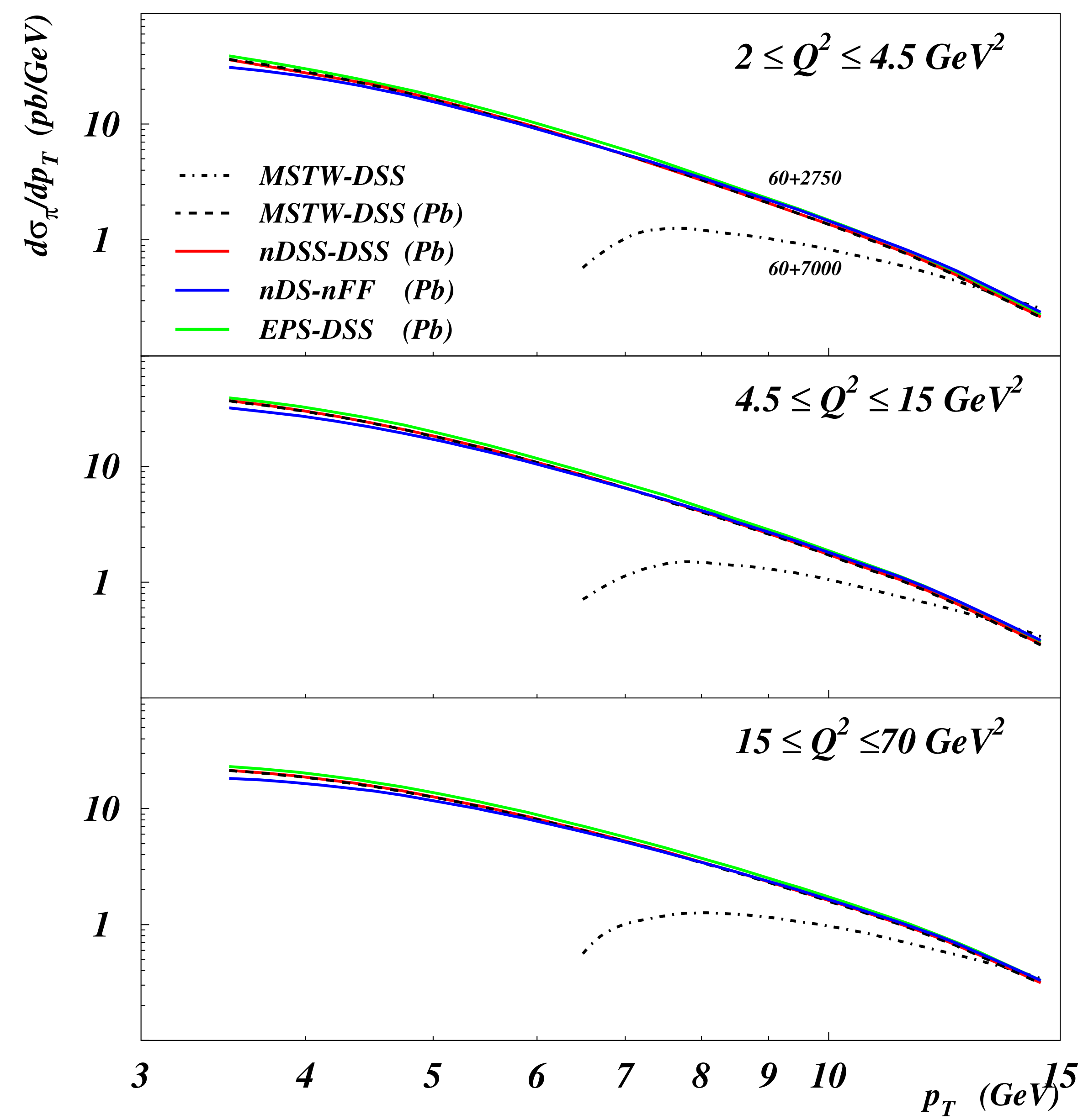

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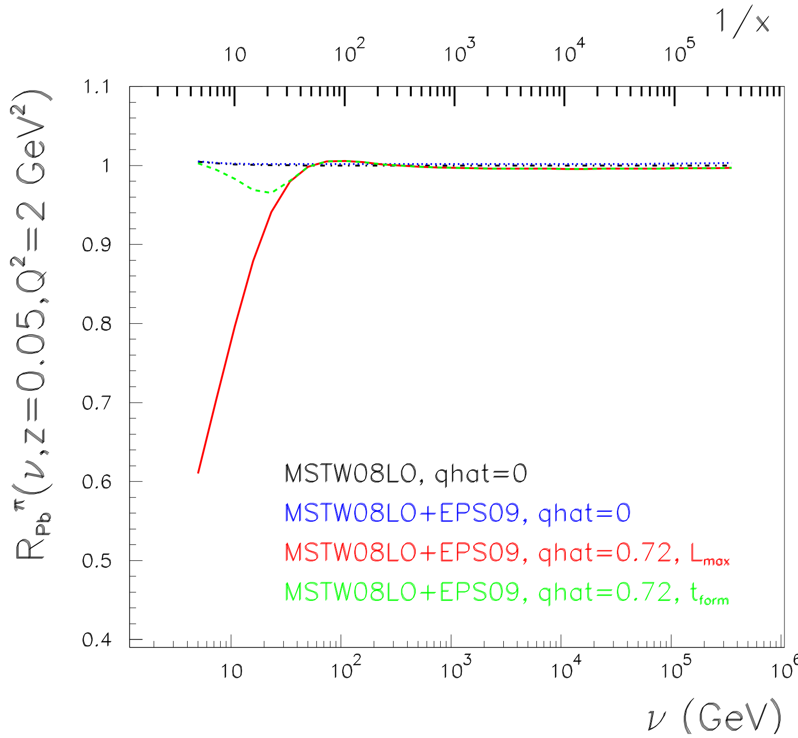

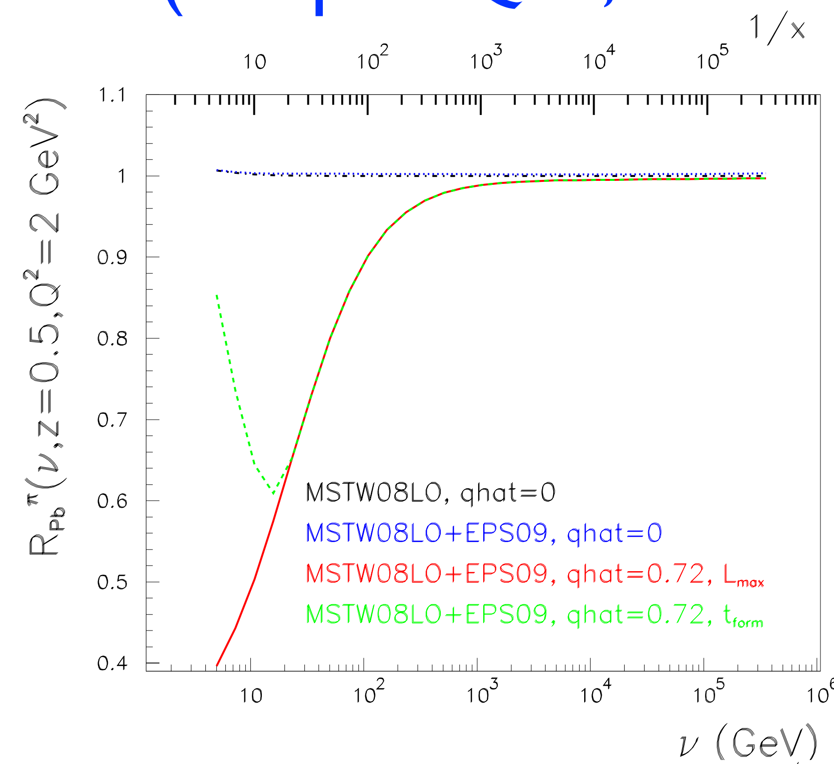

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