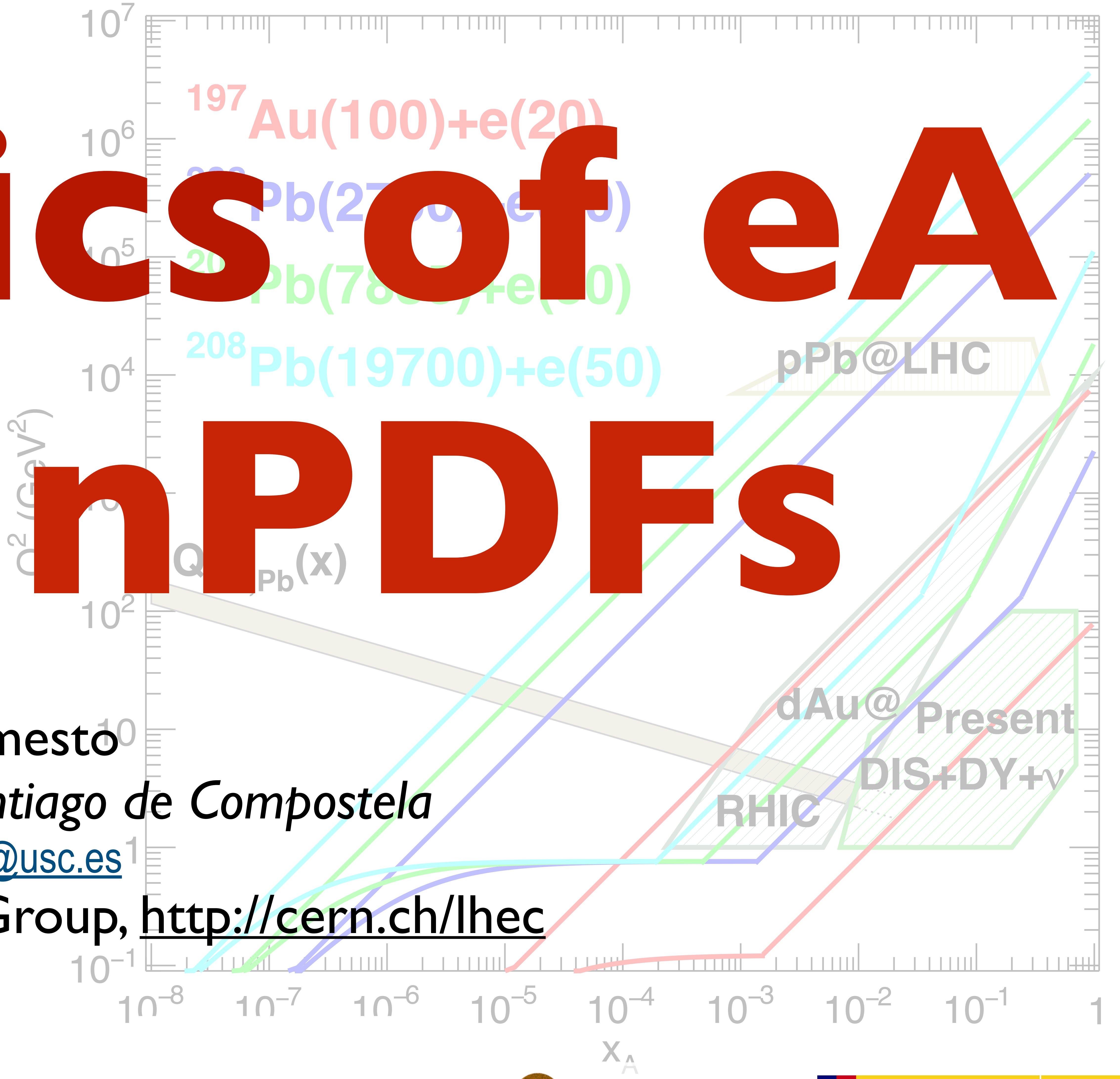
Electrons for the LHC: Workshop on the LHeC, FCC-eh and PERLE
Chavannes-des-Bogis, Switzerland, October 25th 2019

Physics of eA and nPDFs



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Contents:

1. Introduction (see the talk by Brian Cole).

2. Nuclear PDFs:
   - ➜ Pseudodata (Max Klein).
   - ➜ Global fit: EPPS16* (Hannu Paukkunen).
   - ➜ Fit to a single nucleus: xFitter (also FCC-eh) (P. Agostini, NA).

3. Further topics (see the talks by Anna Stasto and Paul Newman):
   - ➜ Small x.
   - ➜ Diffraction.
   - ➜ Correlations.

4. Summary and writeup.

See also the talk by Monica D'Onofrio.

Note: additional topics (QCD radiation and hadronisation, jets) covered in the 2012 CDR, not addressed here.

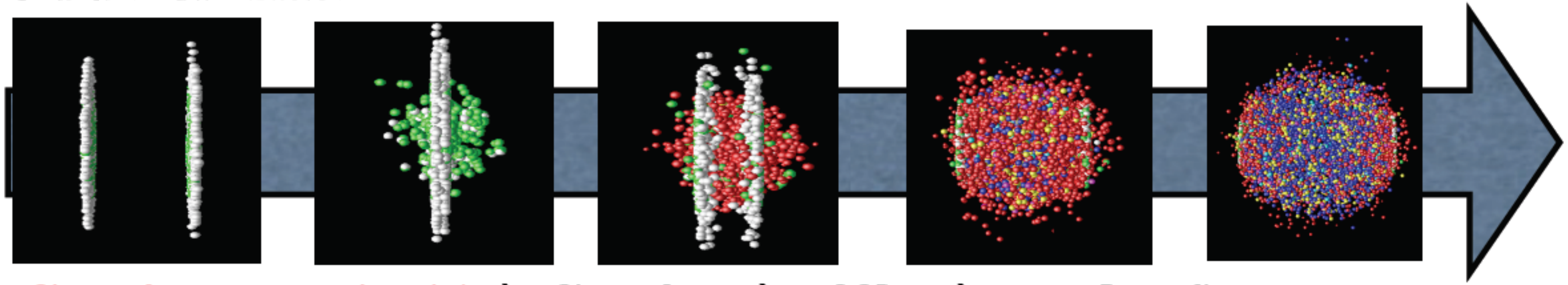
Dynamics in pA/AA:

• Nucleus ≠ Zp+(A-Z)n.
• Particle production at large scales similar to pp (dilute regime).

• Medium behaves very early like a low viscosity liquid: macroscopic description.

• Medium is very opaque to coloured particles traversing it.

[B. Cole]



Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

• Lack of information about small-x partons, correlations and transverse structure.
• We do not understand the dense regime.

• How isotropised the system becomes?
• Why is hydro effective so fast, which dynamics?

• Dynamical mechanisms for such opacity? Weak or strong coupling?
• How to extract accurately medium parameters?

→ Nuclear WF and mechanism of particle production.

→ Initial conditions; how small can a system become and still show "collectivity"?

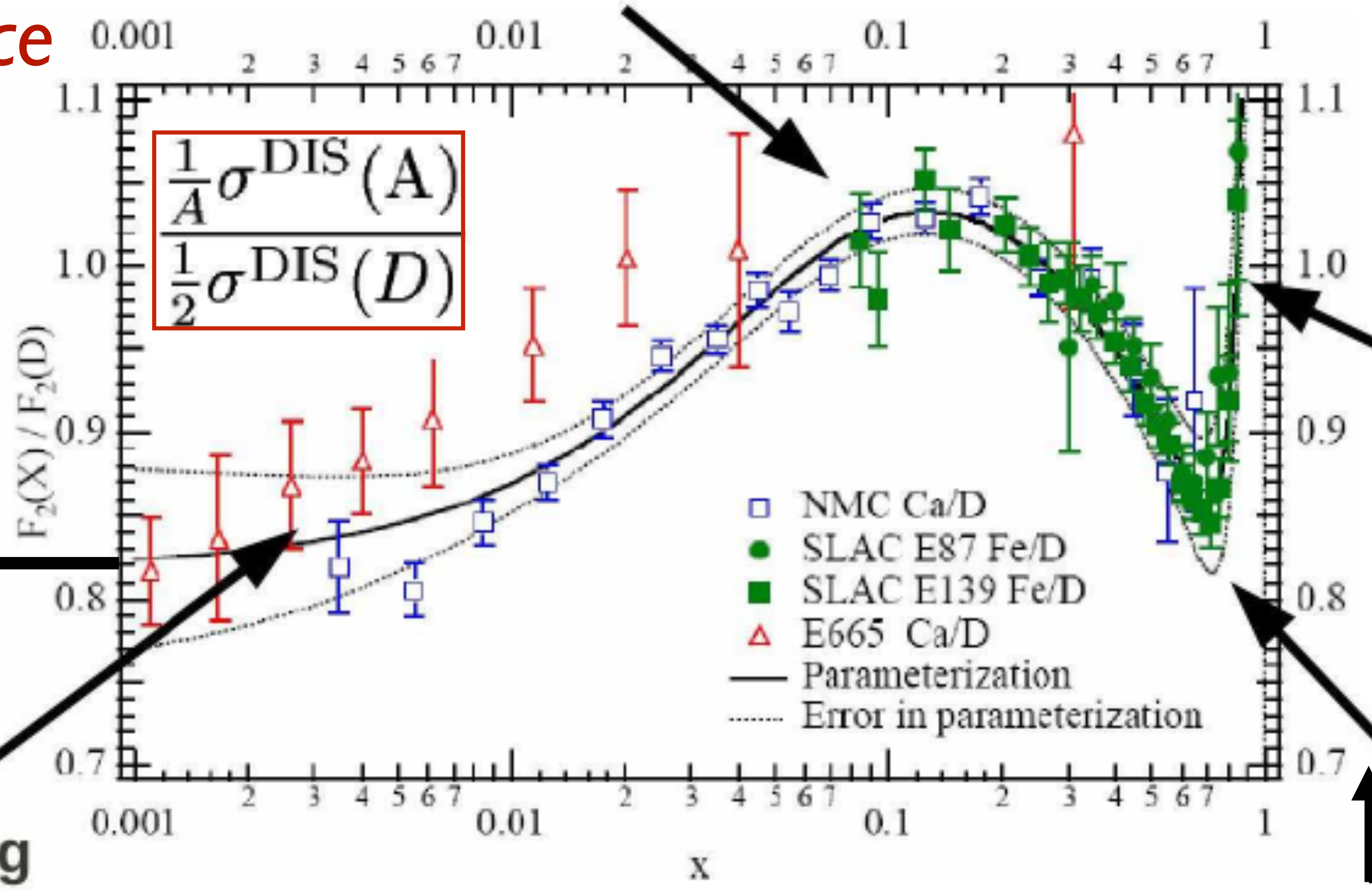
→ In-medium QCD radiation, cold nuclear effects on hard probes.

Nuclear structure functions:

Flavour dependence?; relation with shadowing and coherence

How much does the structure of a hadron change when it is immersed in a nuclear medium?

Anti-shadowing



eAu at EIC

ePb at LHeC/ FCC-eh

Fermi-motion

Short versus long range correlations, pion cloud, intrinsic charm,…

Multiple scattering, saturation,…; high-energy QCD

Shadowing

EMC-effect

Superfast quarks

- Bound nucleon $\neq$ free nucleon: search for process independent nPDFs that realise this condition, within collinear factorisation.

$$\sigma_{DIS}^{\ell+A\to\ell+X} = \sum_{i=q,\bar{q},g} f_i^A(\mu^2) \otimes \hat{\sigma}_{DIS}^{\ell+i\to\ell+X}(\mu^2)$$

Nuclear PDFs, obeying the standard DGLAP

Usual perturbative coefficient functions

$$f_i^{p,A}(x,Q^2) = R_i^A(x,Q^2) f_i^p(x,Q^2)$$

$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$

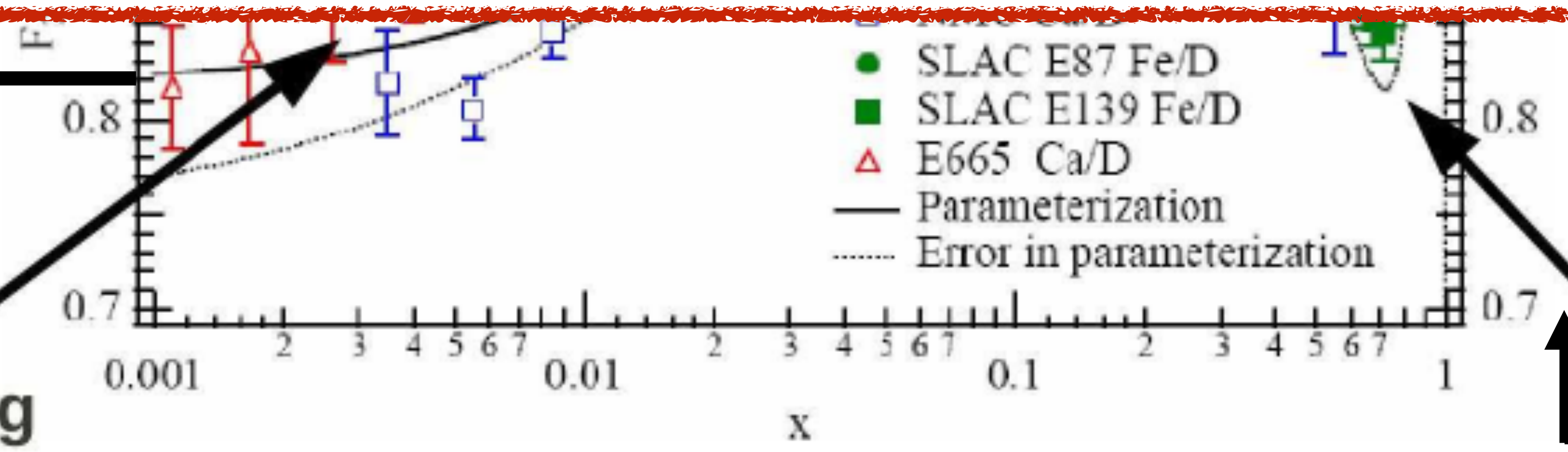
Nuclear structure functions:

- At an ep/eA collider:
  - ➜ PDF of a single nucleus possible, no need of ratios that would be obtained a posteriori.
  - ➜ Same method of extraction in both ep and eA.
  - ➜ Physics beyond standard collinear factorisation can be studied in a single setup, with size effects disentangled from energy effects and a large lever arm in x at perturbative Q^2.

EIC

Multiple scattering, saturation,…; high-energy QCD

Shadowing



Short versus long range correlations, pion cloud, intrinsic charm,…

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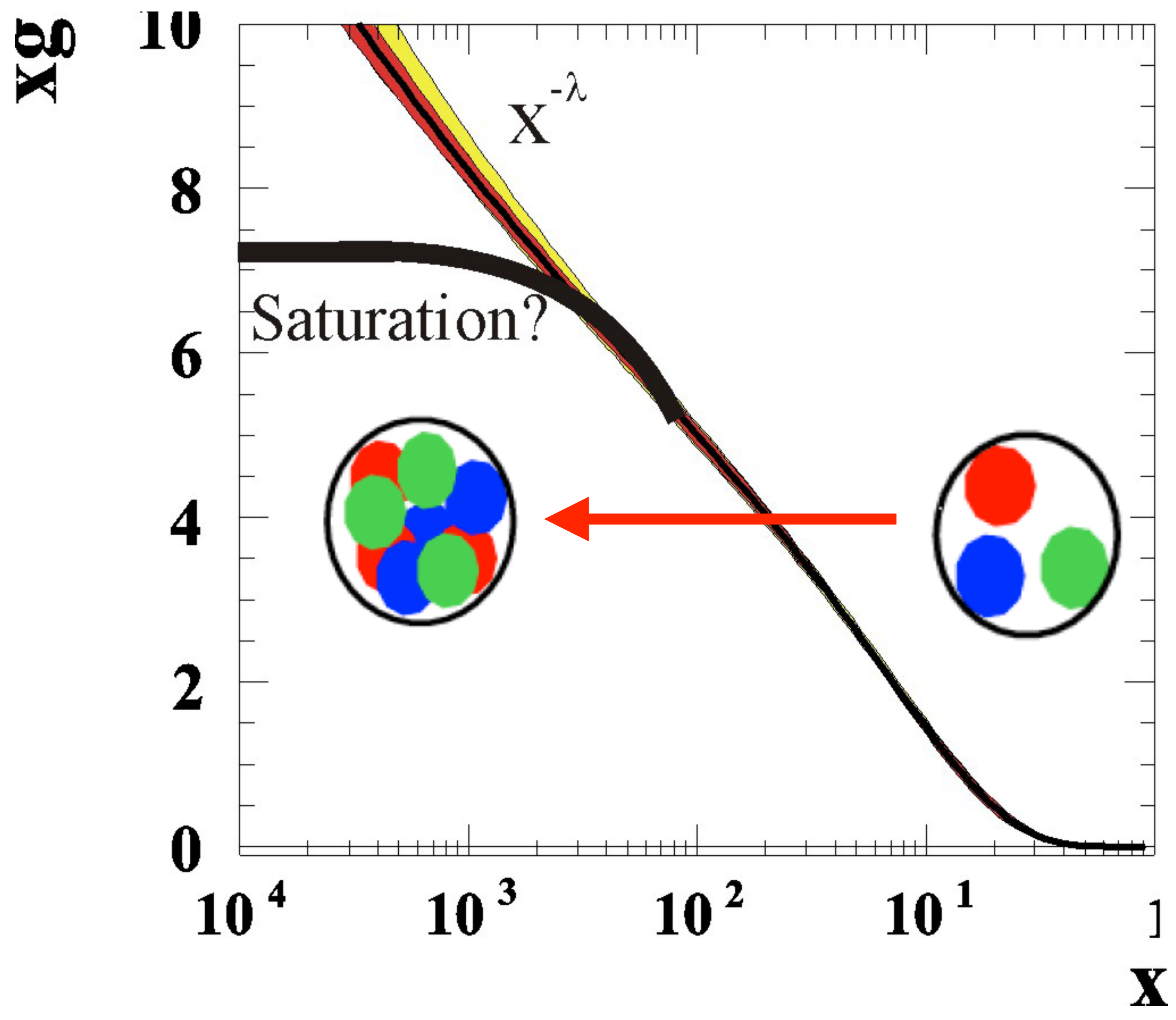
Small-x physics:

- HERA found xg α $x^{-0.3}$.
- Present data can be described by:
  - ➜ Linear evolution approaches, either DGLAP or resummation at low x.
  - ➜ Non-linear approaches - weak coupling but high density: saturation.

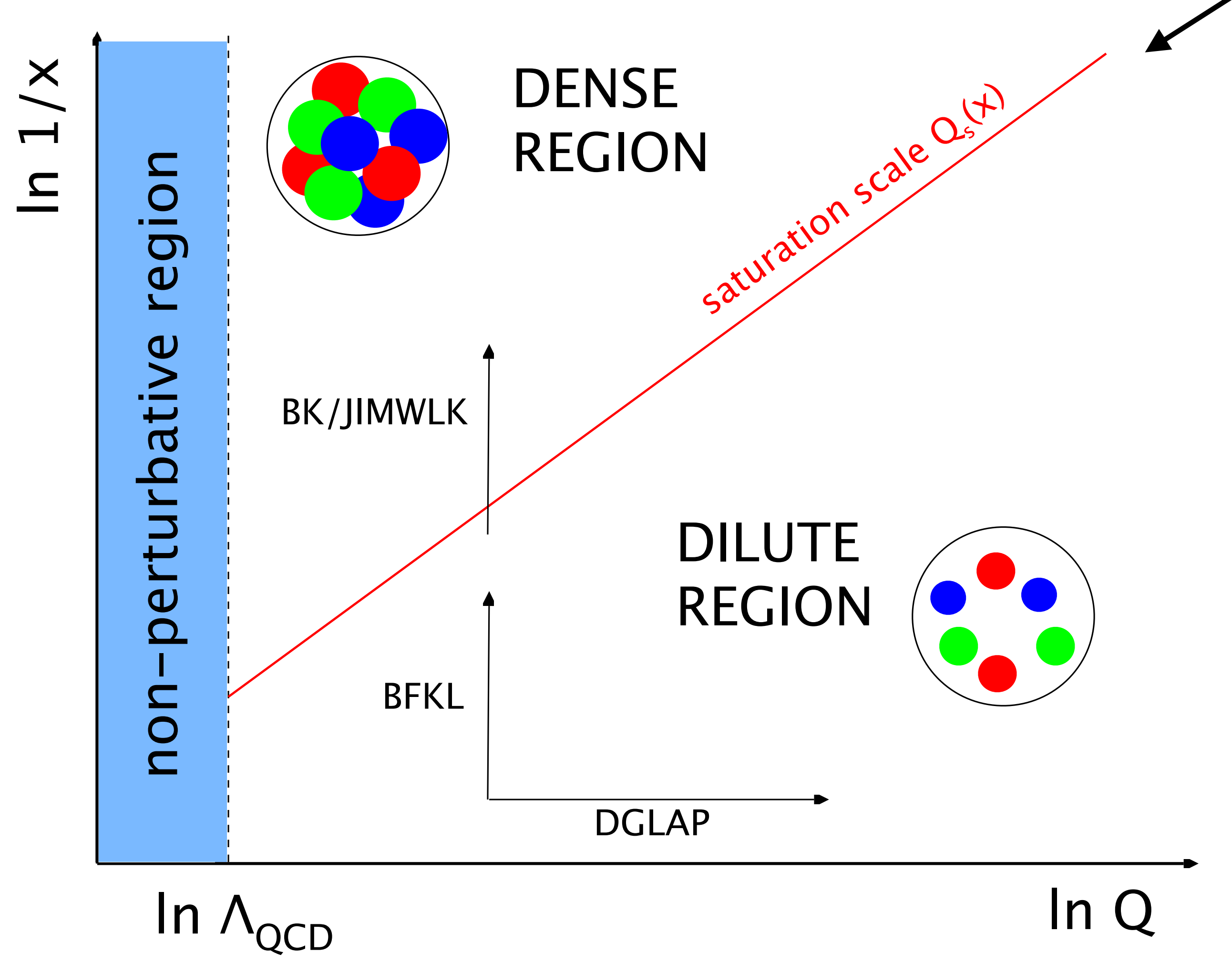
- Theory: at high energies (i.e. small x), non-linear dynamics must be present. **Where is it?** At HERA:
  - ➜ Hints of failure of DGLAP at small x, Q^2, resummation?
  - ➜ No ridge azimuthal structures yet found.

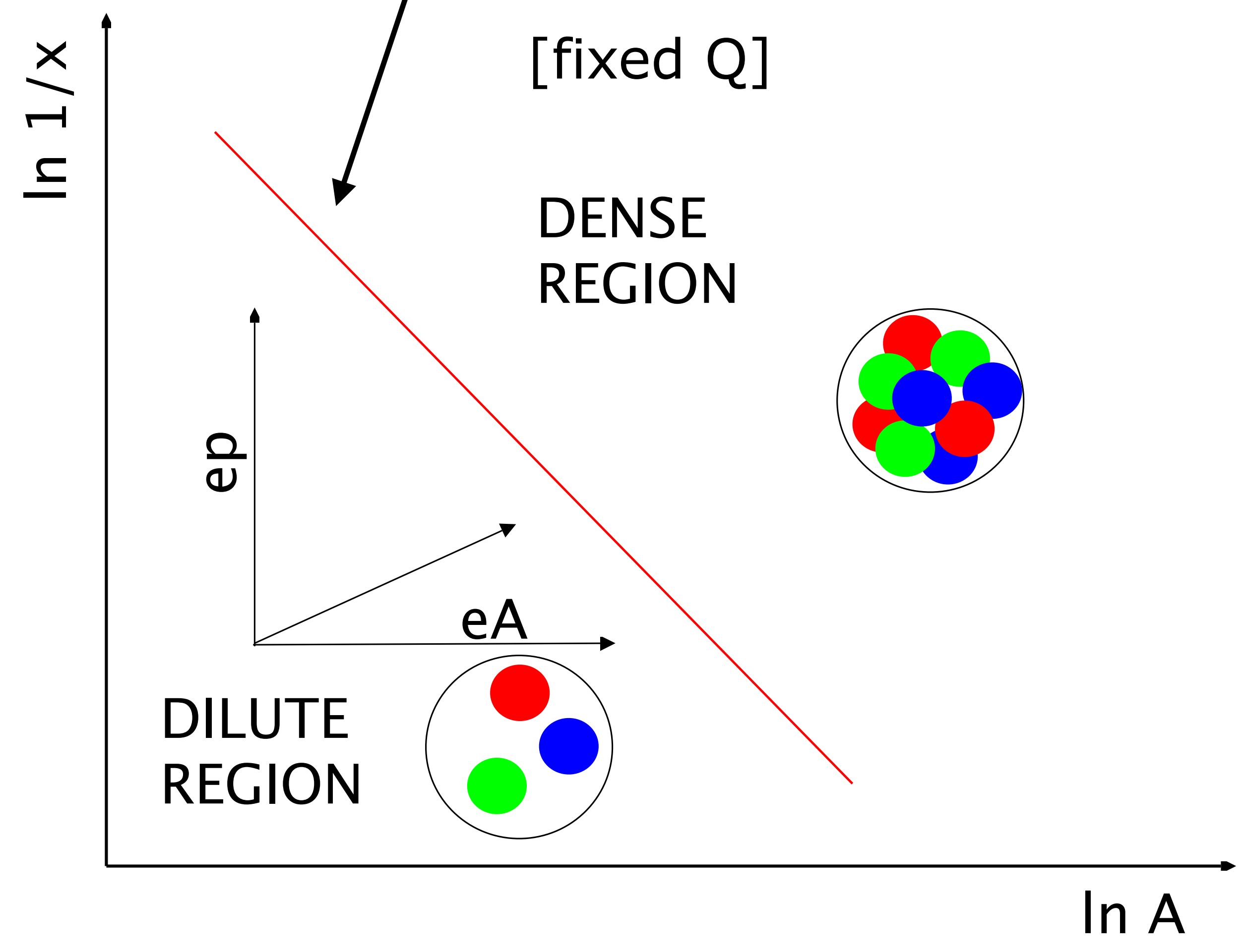
- Saturation is density-driven: ↓x/↑A ⇒

ep&eA + range in 1/x & Q² essential for full understanding.



$$\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{\sim -0.3}$$





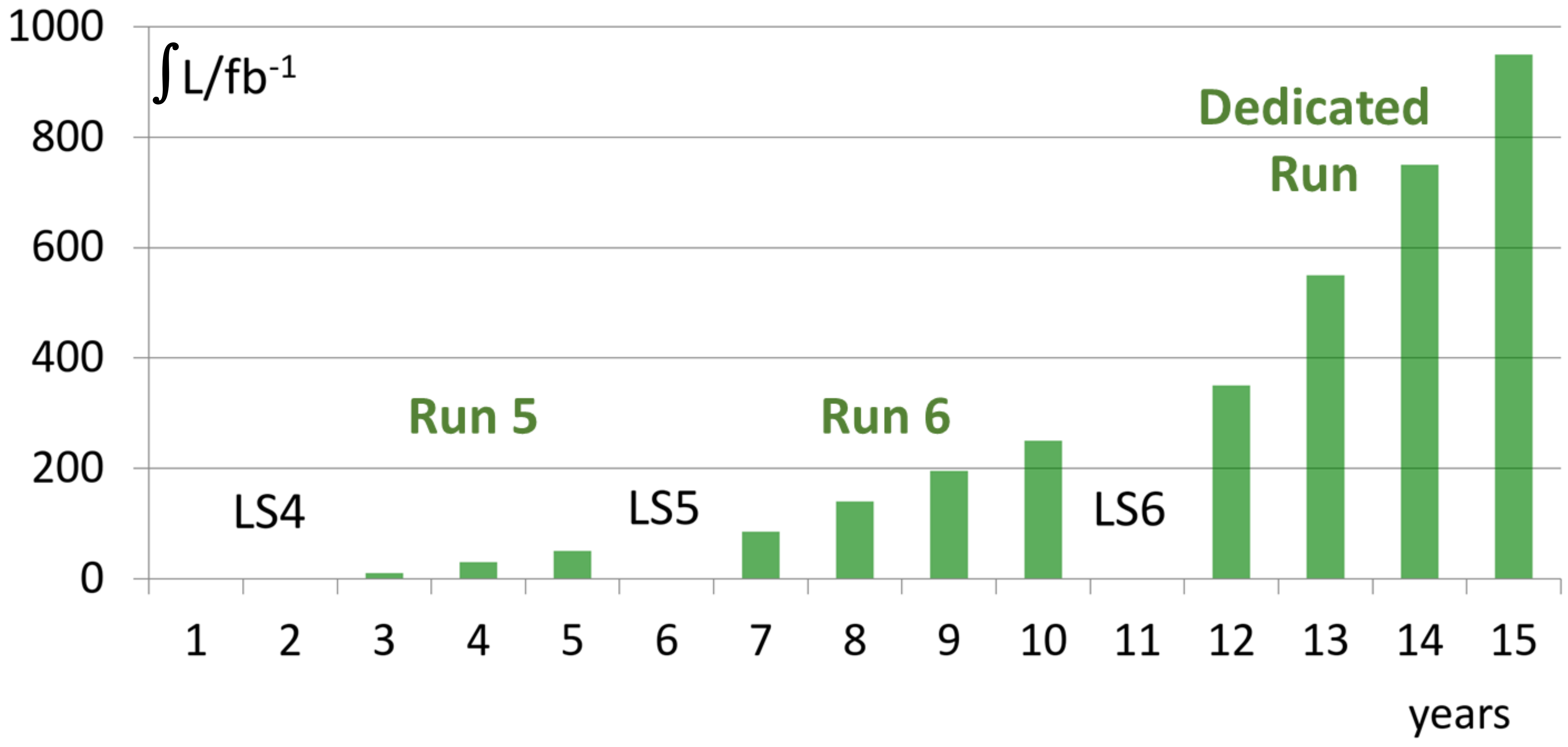
Luminosities:

Parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	13.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
Bunch spacing [ns]	25	25	25	25
Protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
Electrons per bunch [10^9]	1	2.3	3.0	3.0
Electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
Hourglass factor H_{geom}	0.9	0.9	0.9	0.9
Pinch factor H_{b-b}	1.3	1.3	1.3	1.3
Proton filling H_{coll}	0.8	0.8	0.8	0.8
Luminosity [10^{33} cm^{-2}s^{-1}]	1	8	12	15

ep

parameter [unit]	LHeC (HL-LHC)	eA at HE-LHC	FCC-he
E_{Pb} [PeV]	0.574	1.03	4.1
E_e [GeV]	60	60	60
$\sqrt{s_{eN}}$ electron-nucleon [TeV]	0.8	1.1	2.2
Bunch spacing [ns]	50	50	100
No. of bunches	1200	1200	2072
Ions per bunch [10^8]	1.8	1.8	1.8
$\gamma\epsilon_A$ [μm]	1.5	1.0	0.9
Electrons per bunch [10^9]	4.67	6.2	12.5
Electron current [mA]	15	20	20
IP beta function β_A^* [cm]	7	10	15
Hourglass factor H_{geom}	0.9	0.9	0.9
Pinch factor H_{b-b}	1.3	1.3	1.3
Bunch filling H_{coll}	0.8	0.8	0.8
Luminosity [10^{32} cm^{-2}s^{-1}]	7	18	54

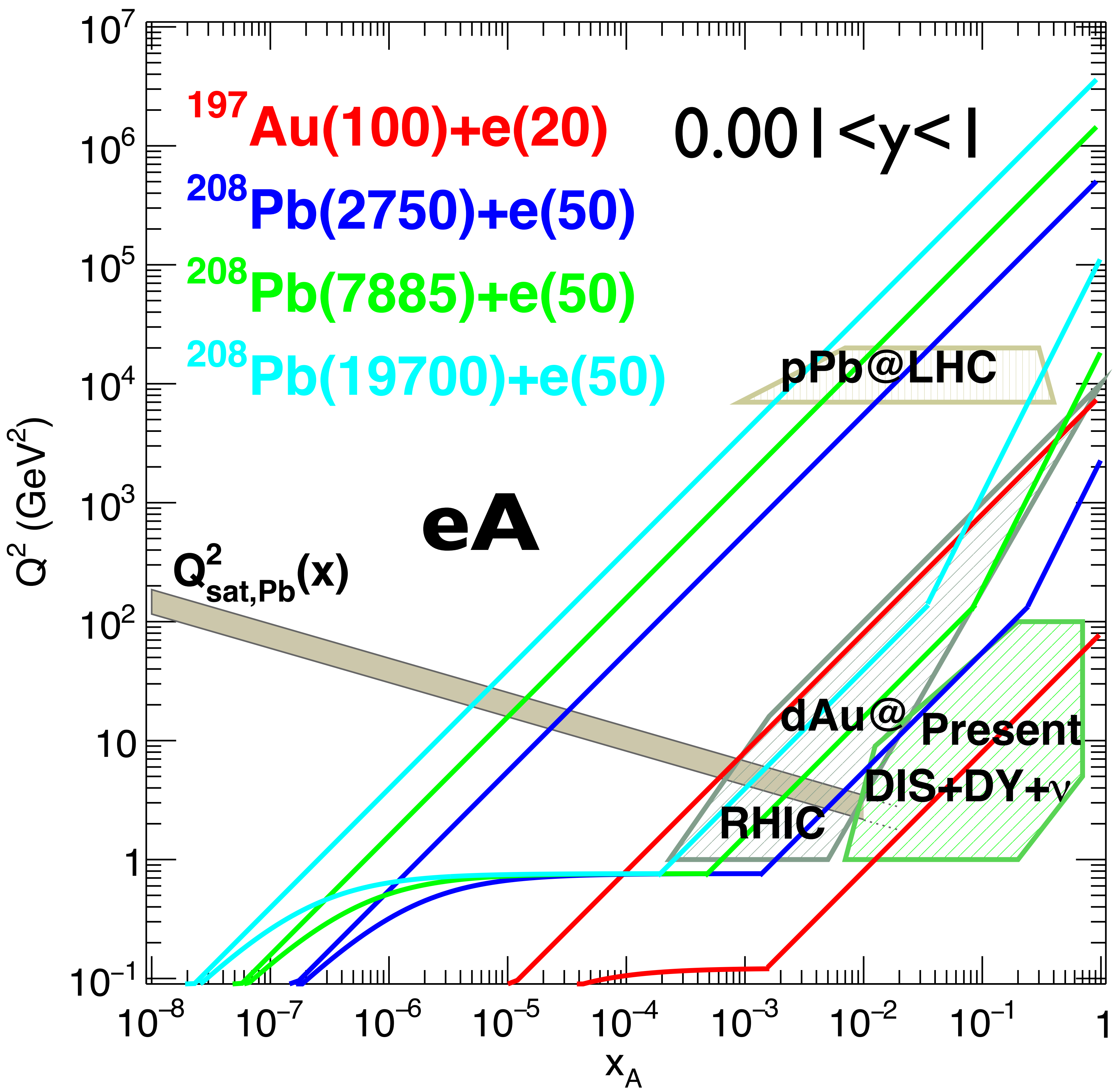
ePb



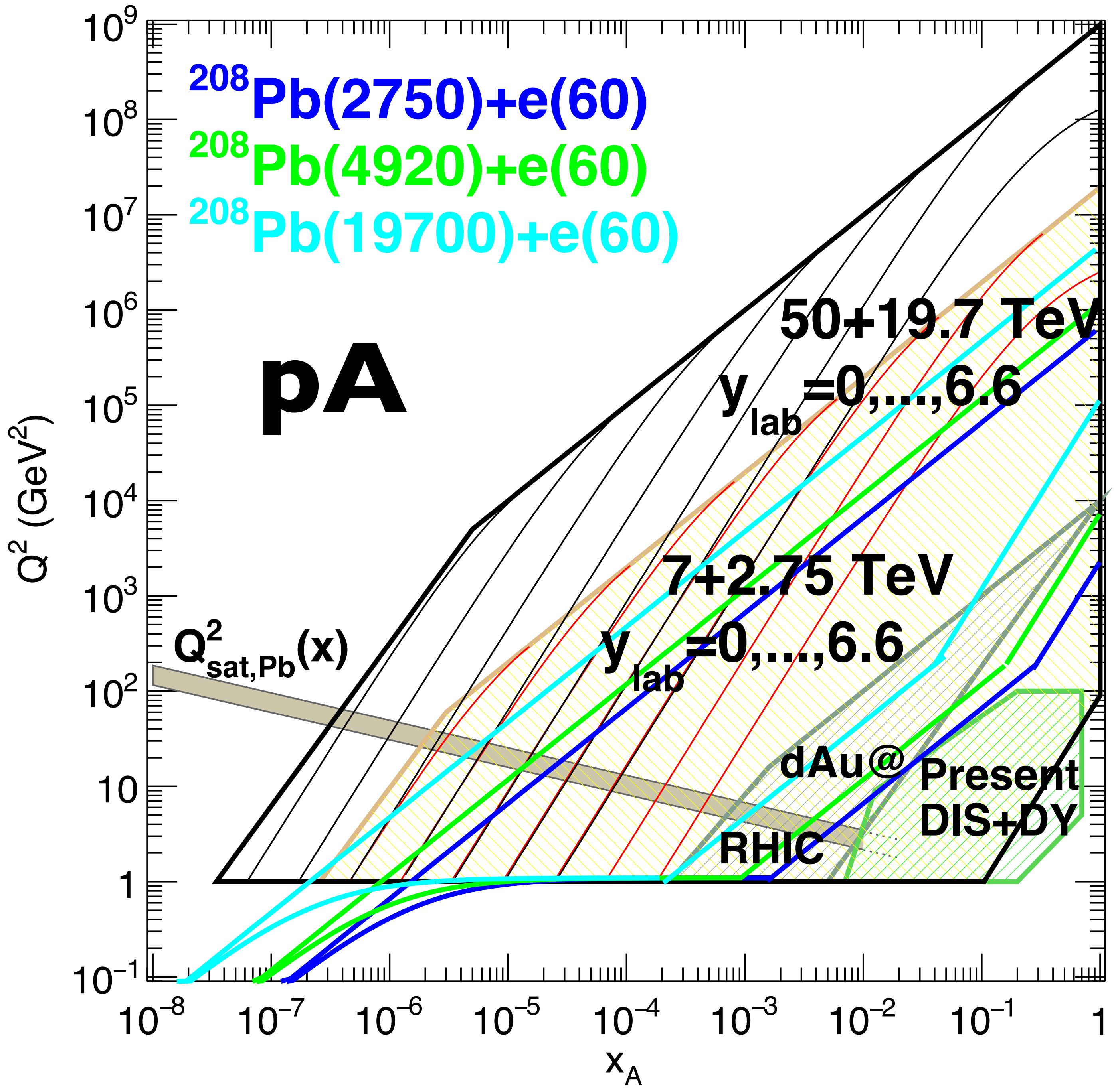
1810.13022; O. Brüning at EPS-HEP 2019 and talk here

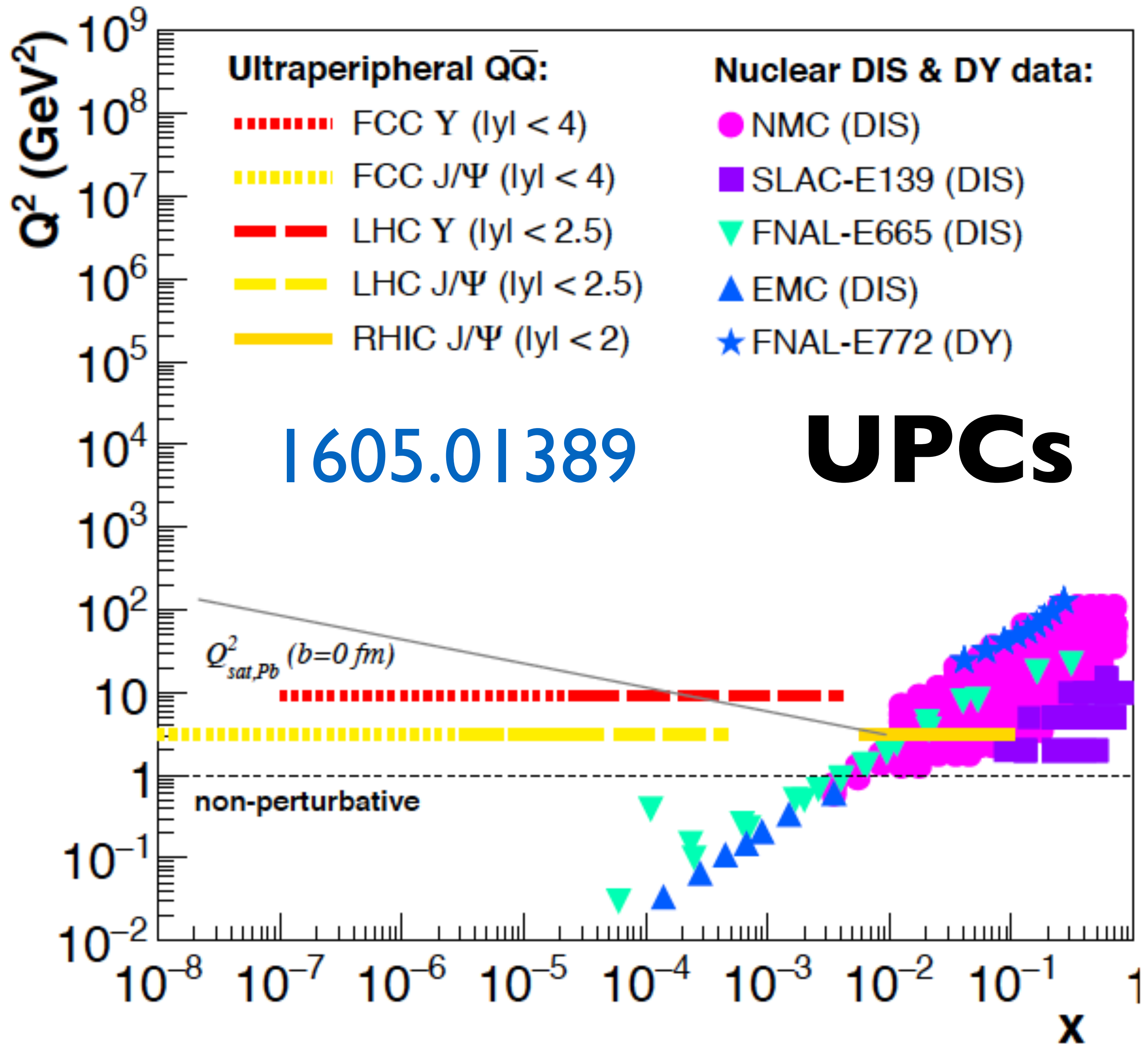
- P=±0.8 (electrons).
- Positrons: P=0, 1/100 luminosity.
- FCC-eh could deliver integrated luminosities ~2 ab^{-1}, depending on pp operation.
- ePb integrated luminosities can be estimated 1/100 those in ep (~10 times smaller luminosity times ~10 times smaller running time).

Kinematics:



- DIS offers:
  - ➜ A clean experimental environment: low multiplicity, no pileup, fully constrained kinematics;
  - ➜ A more controlled theoretical setup: many first-principles calculations in collinear and non-collinear frameworks.





- Extension up to 4-5 orders of magnitude in x and Q^2 wrt. existing DIS data 2-3 wrt. EIC.

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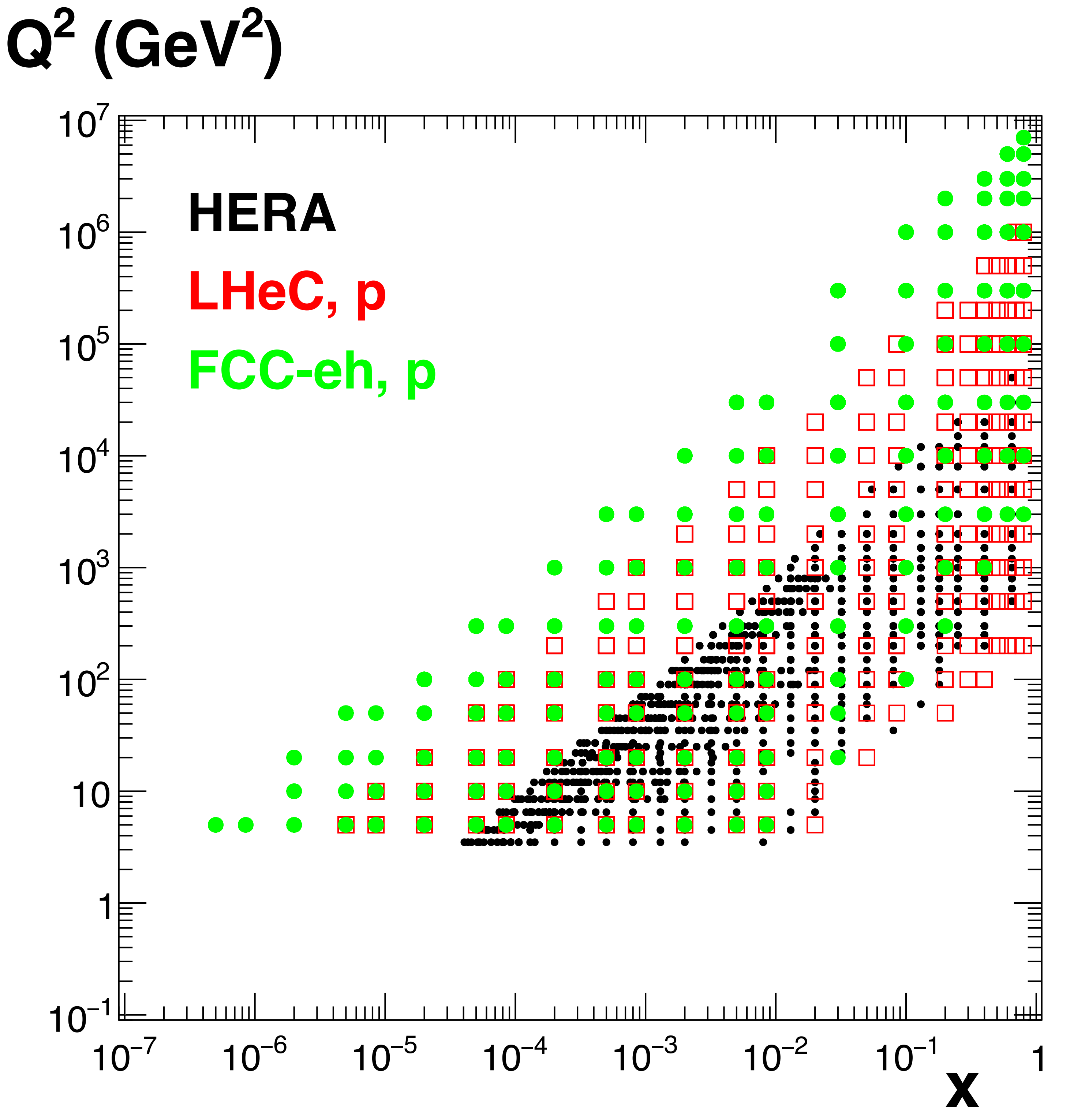
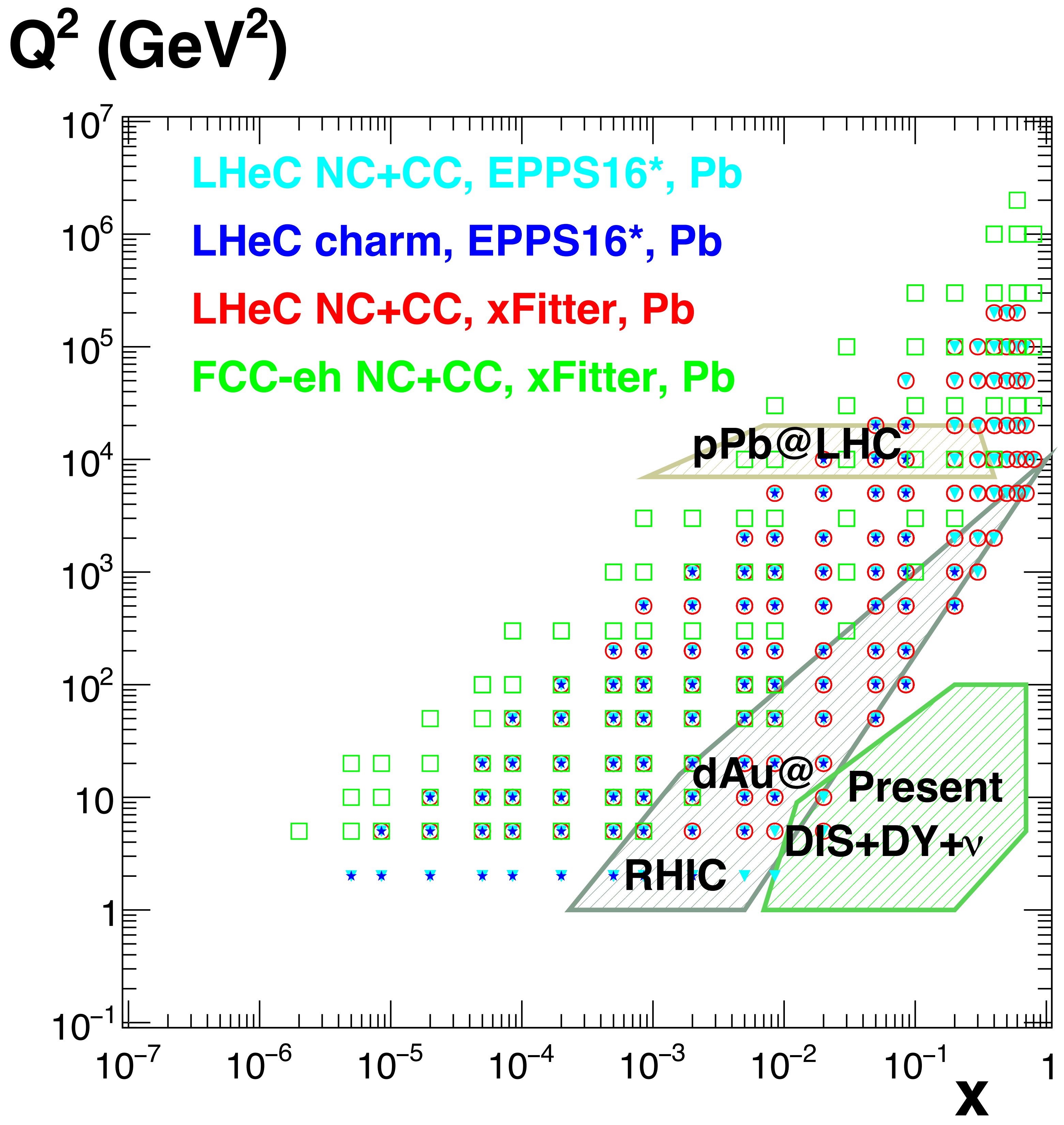
Note: additional topics (QCD radiation and hadronisation, jets) covered in the 2012 CDR, not addressed here.

Pseudodata:



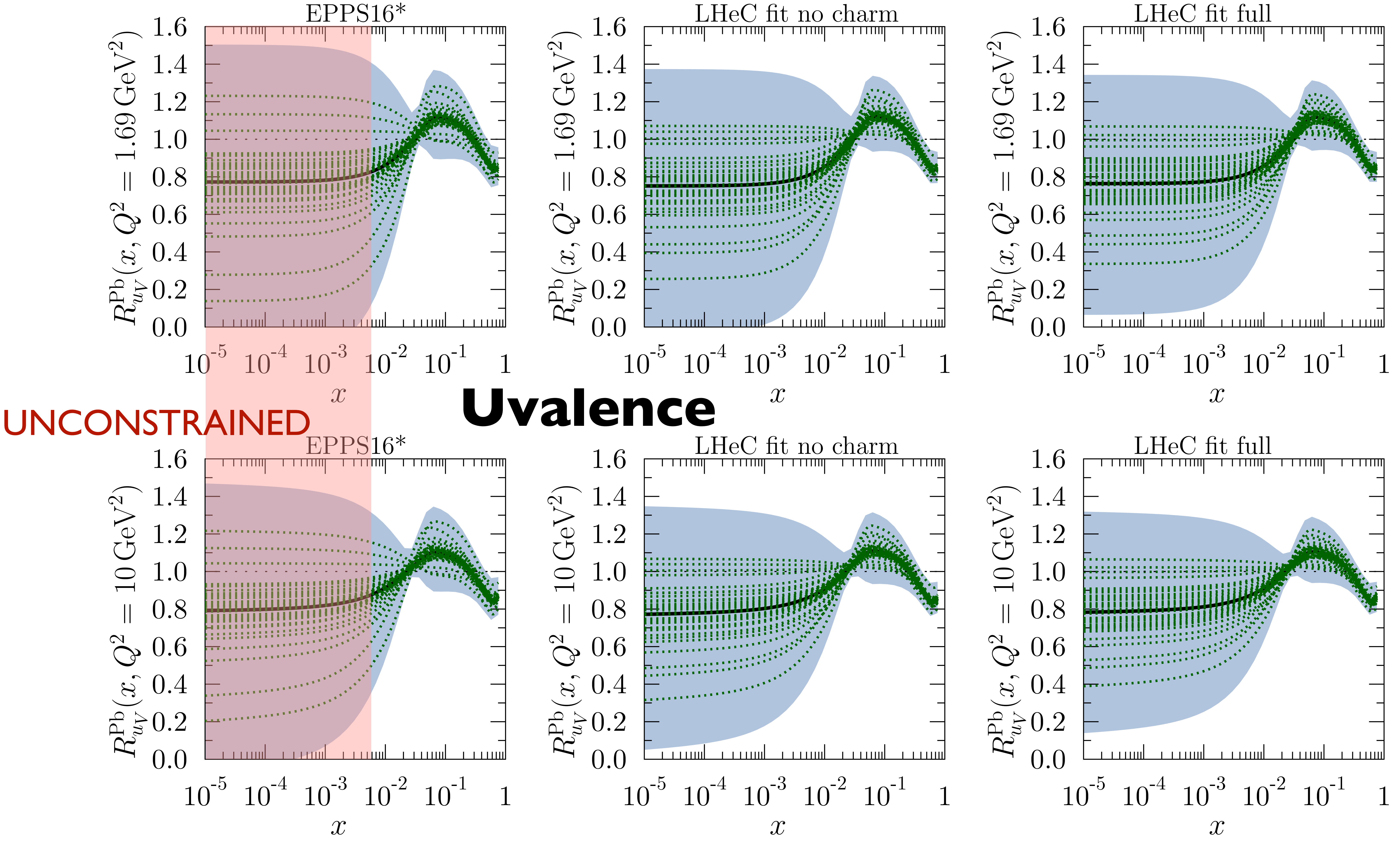


- Pseudodata generated using a code (Max Klein) validated with the H1 MC.
- Cuts: $|\eta_{max}|$=5, 0.95< y< 0.001.
- Error assumptions ~ factor 2 better than at HERA (luminosity uncertainty kept aside).

Source of uncertainty	Error on the source or cross section
scattered electron energy scale	0.1 %
scattered electron polar angle	0.1 mrad
hadronic energy scale	0.5 %
calorimeter noise ($y < 0.01$)	1-3 %
radiative corrections	1-2 %
photoproduction background	1 %
global efficiency error	0.7 %

EPPS16*: results

- Large effect of NC+CC LHeC pseudodata, and of charm on the glue at small x.
- Limitation on u/d decomposition inherent to almost isospin symmetric nuclei (u/d difference suppressed by 2Z/A-1).



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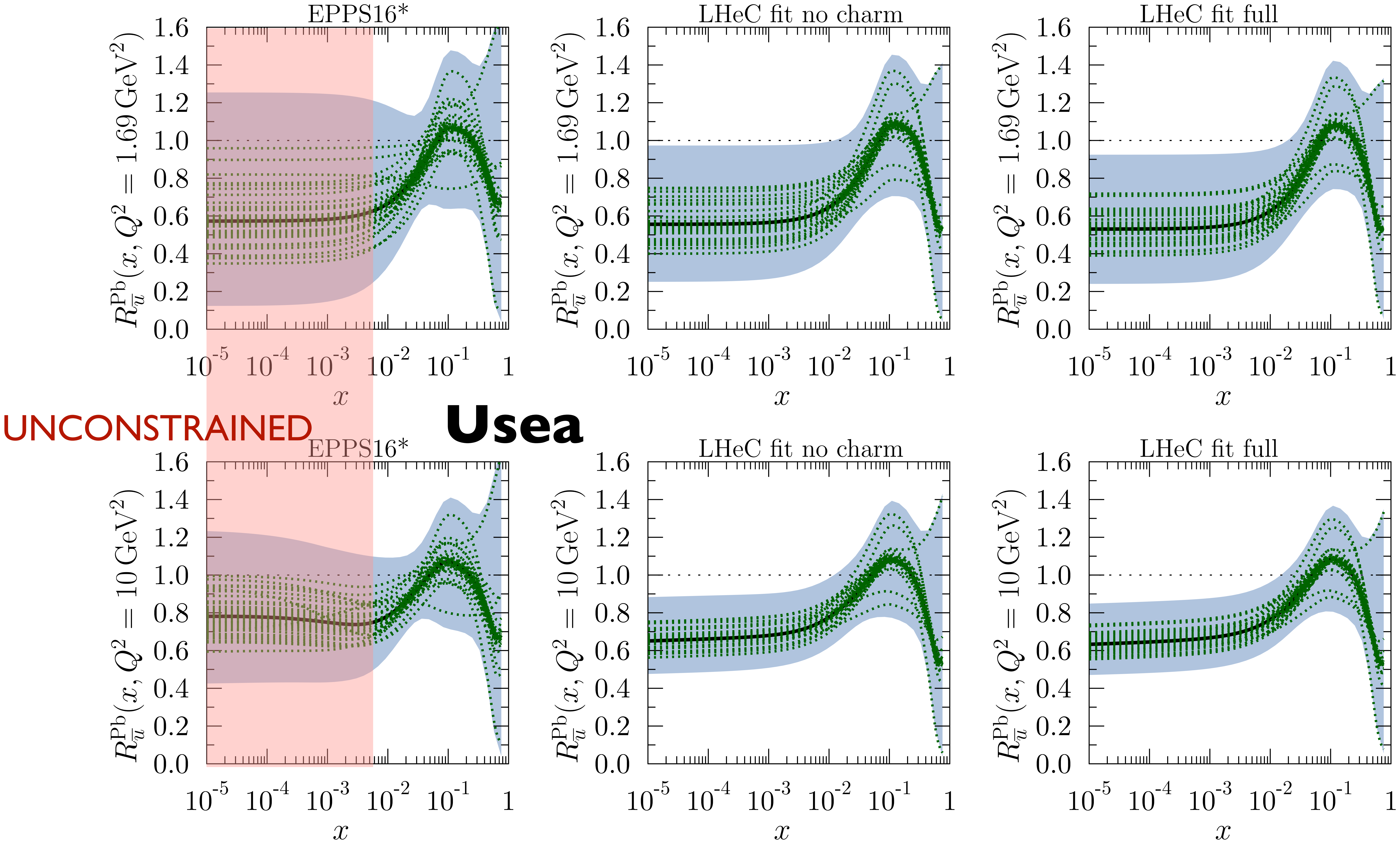

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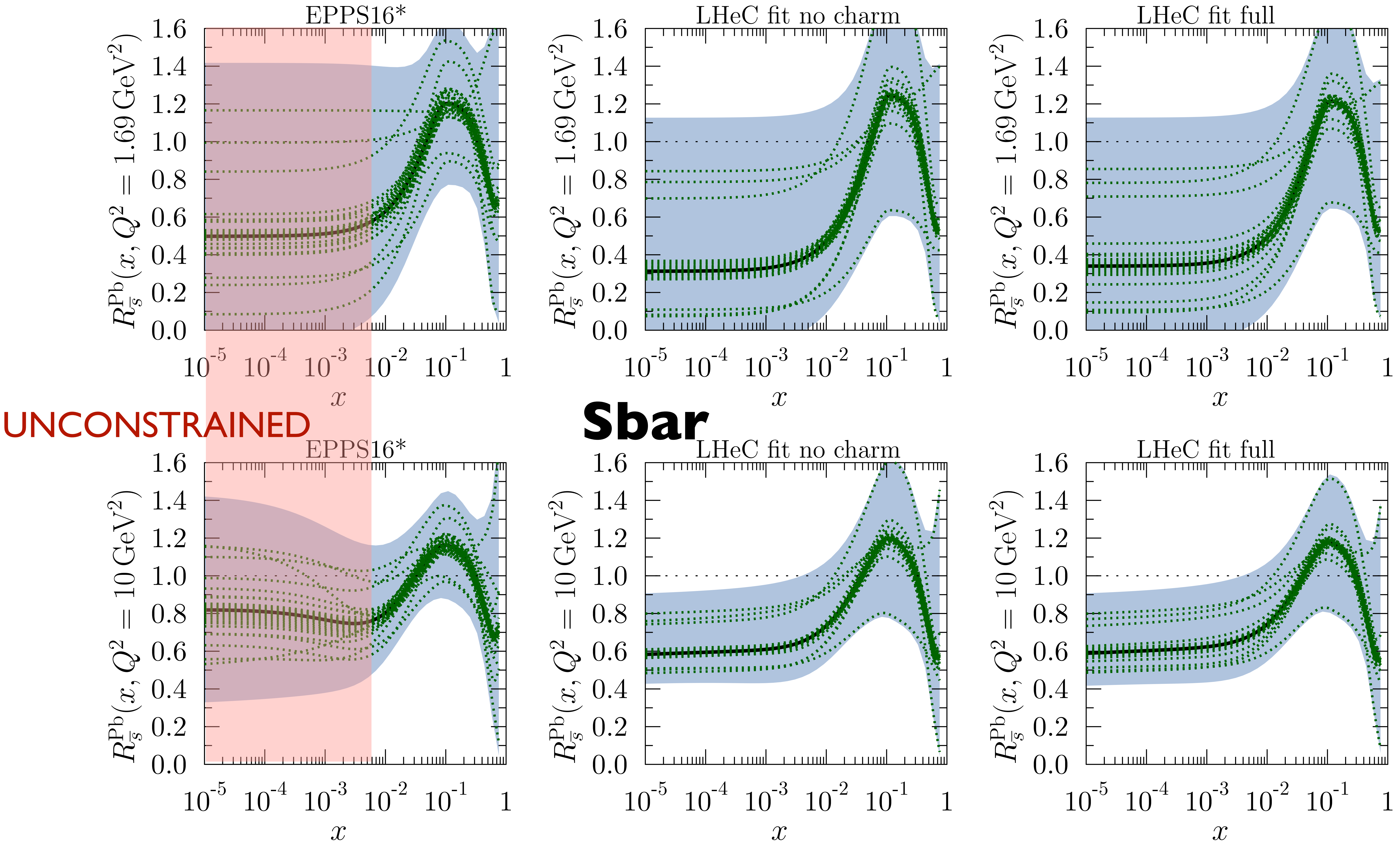

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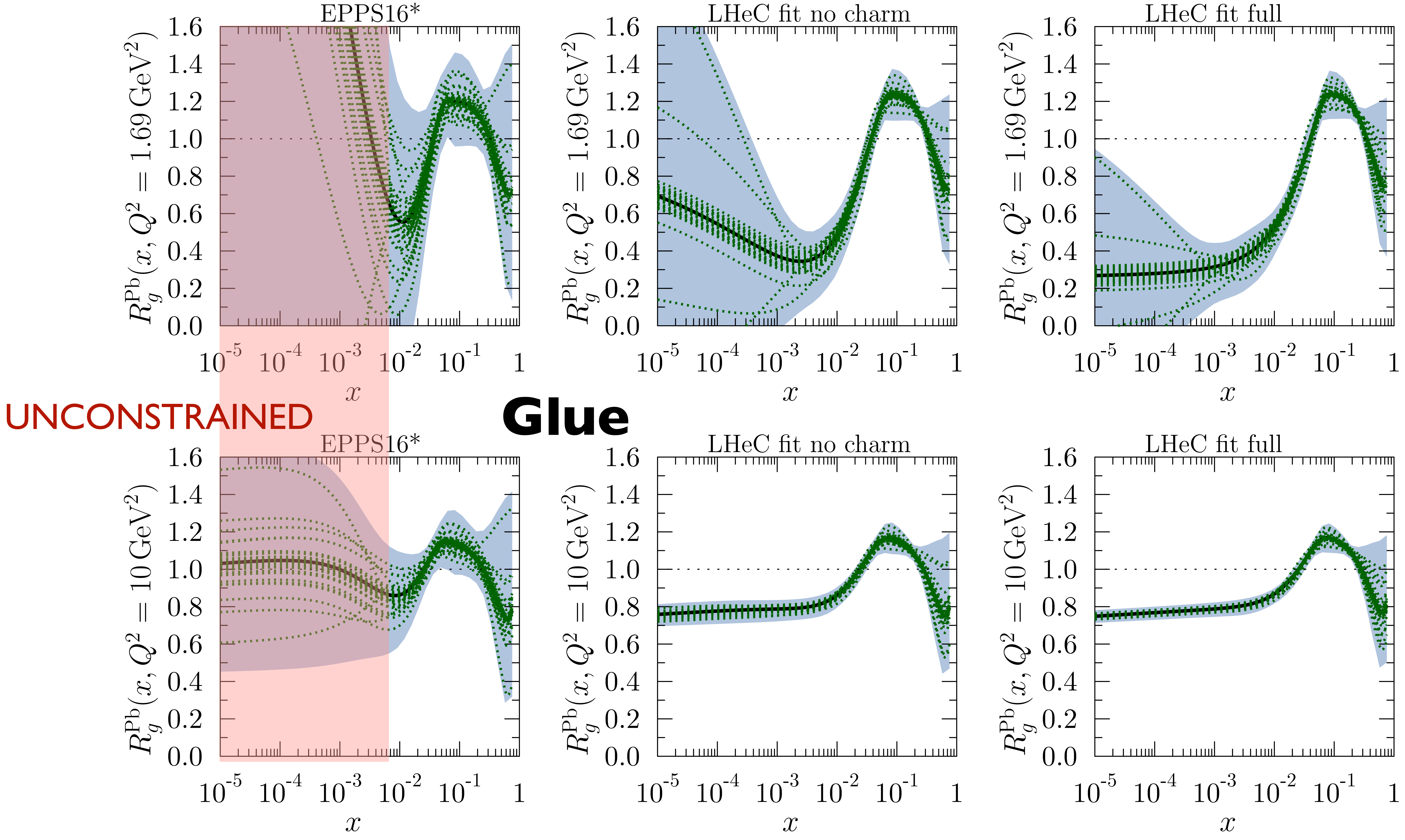

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- Large effect of NC+CC LHeC pseudodata, and of charm on the glue at small x.
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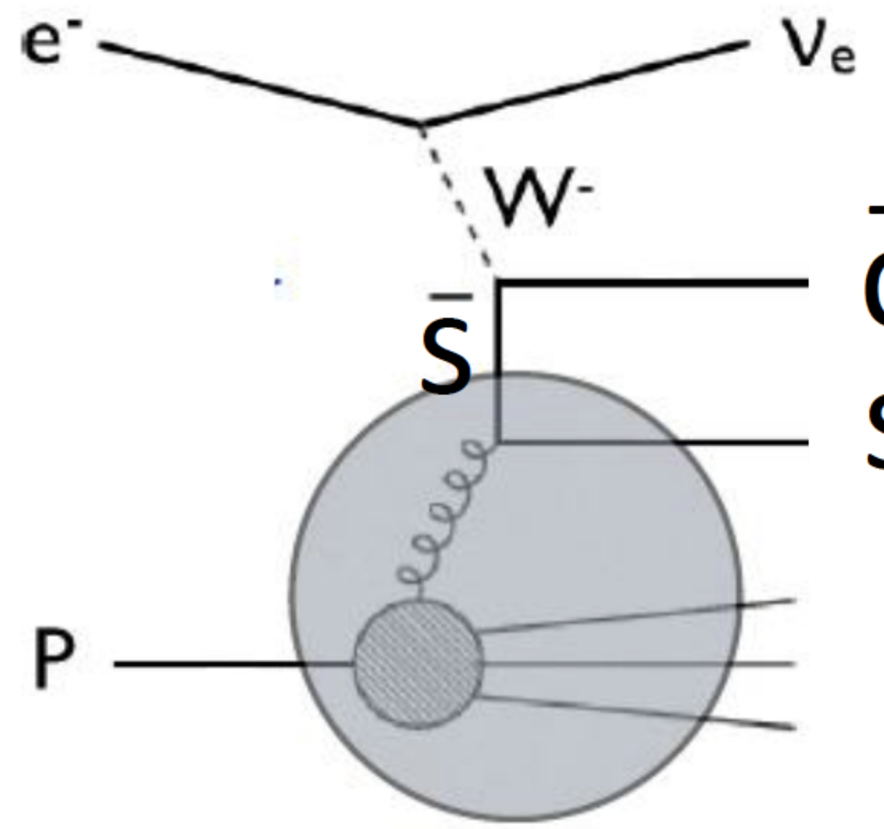
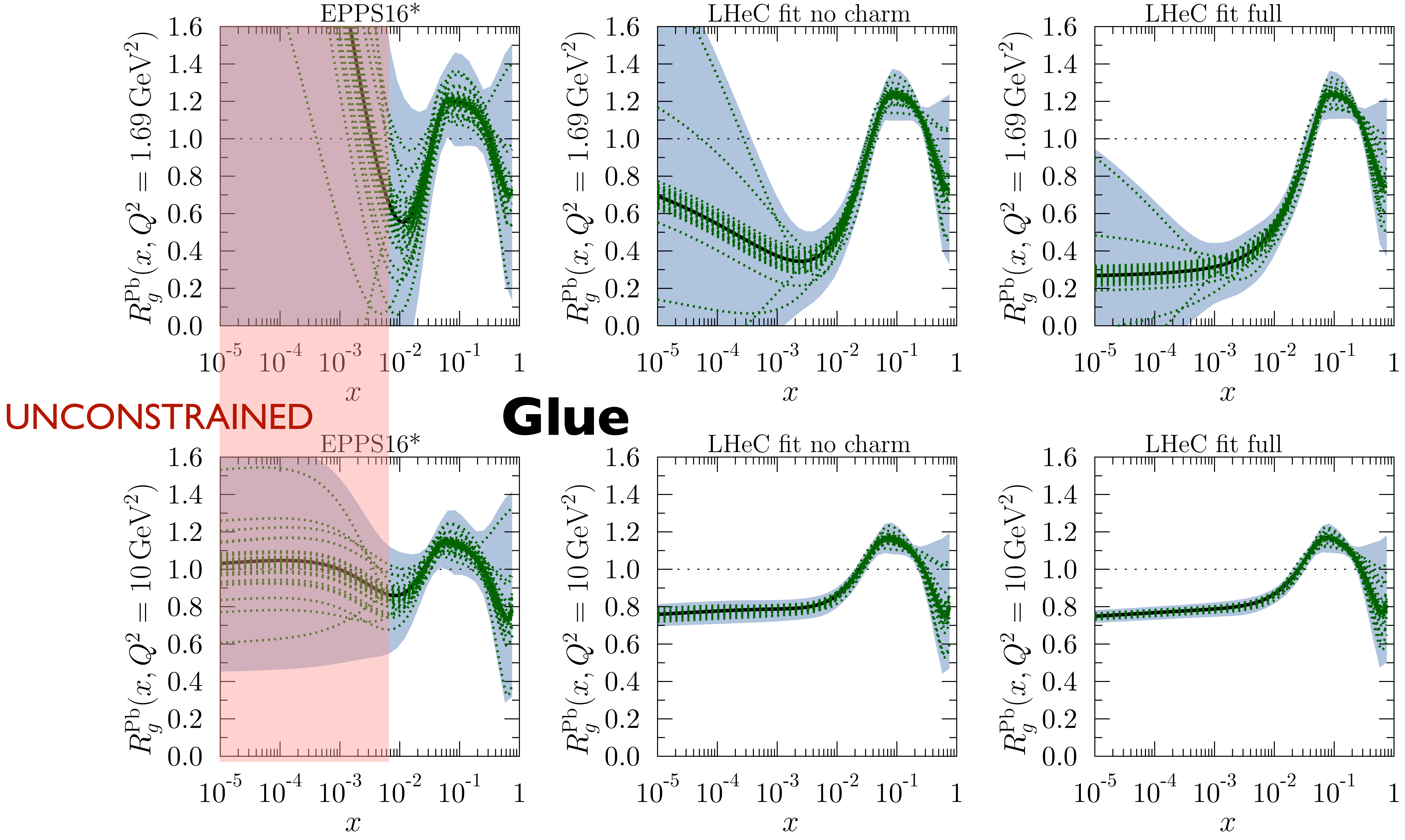
- Possible further improvements: beauty, c-tagged CC for strange.





xFitter: method

- Extraction of **Pb-only** PDFs by fitting NC+CC pseudodata, using xFitter (1410.4412)1.2.2 to estimate the uncertainties coming solely from the achievable experimental precision.

➜ HERAPDF2.0-type parametrisation (1506.06042, 14 parameters), NNLO evolution, RTOPT mass scheme, α_s=0.118.

$$xU = xu + xc\,, \qquad x\bar{U} = x\bar{u} + x\bar{c}\,, \qquad xD = xd + xs\,, \qquad x\bar{D} = x\bar{d} + x\bar{s}$$

$$\begin{aligned} xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}, \\ xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right), \\ xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\ x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\left(1+D_{\bar{U}}x\right), \\ x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}. \end{aligned}$$

See the talk by Claire Gwenlan.

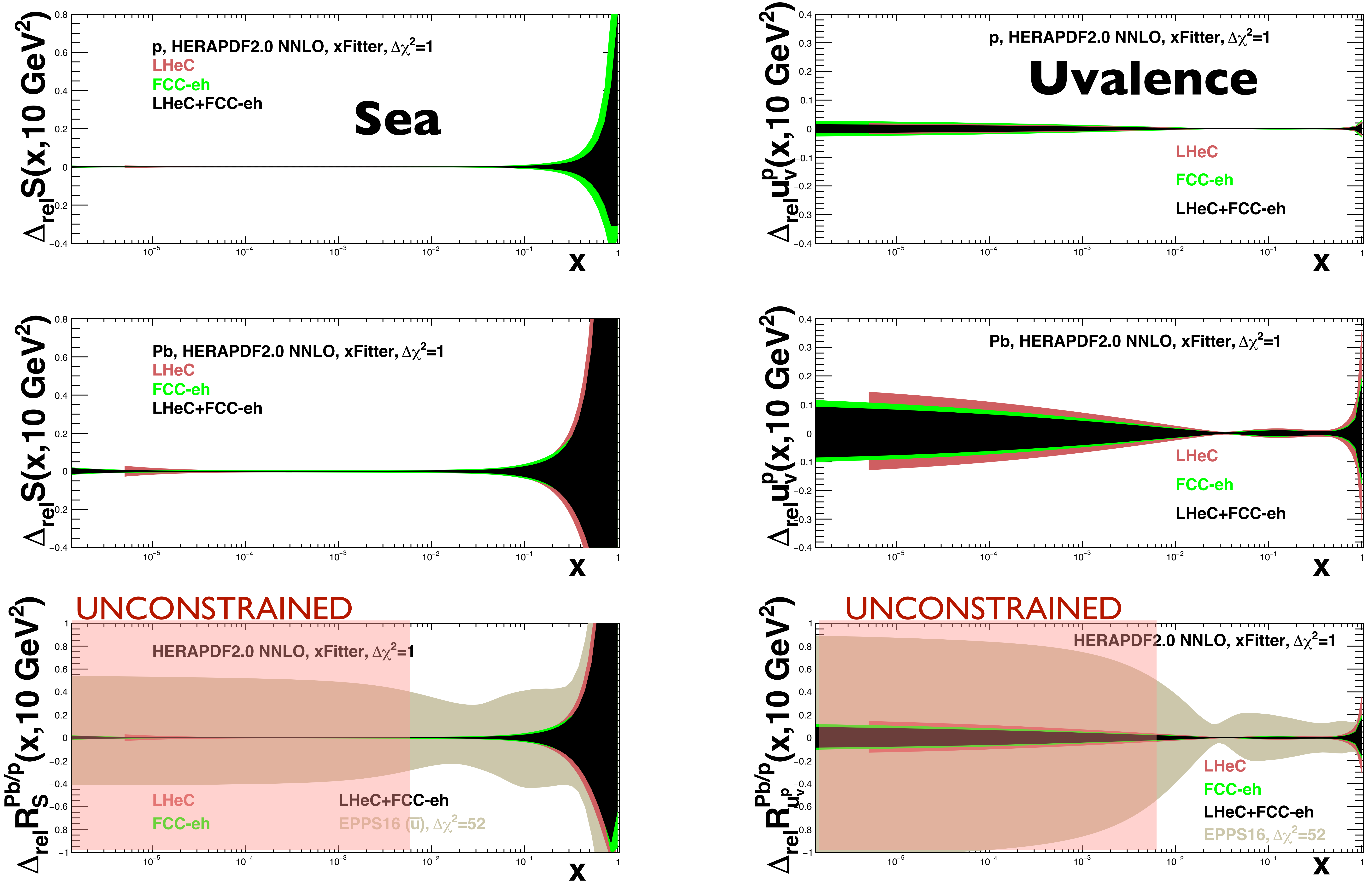
➜ Central pseudodata values from HERAPDF2.0: neither parametrisation bias nor theory uncertainties.

➜ Standard xFitter/HERAPDF treatment of correlated/uncorrelated systematics; tolerance $\Delta\chi^2$=1 (note $\Delta\chi^2$=52 in EPPS16*).

➜ Only data with $Q^2 \geq 3.5$ GeV^2, initial evolution scale 1.9 GeV^2.

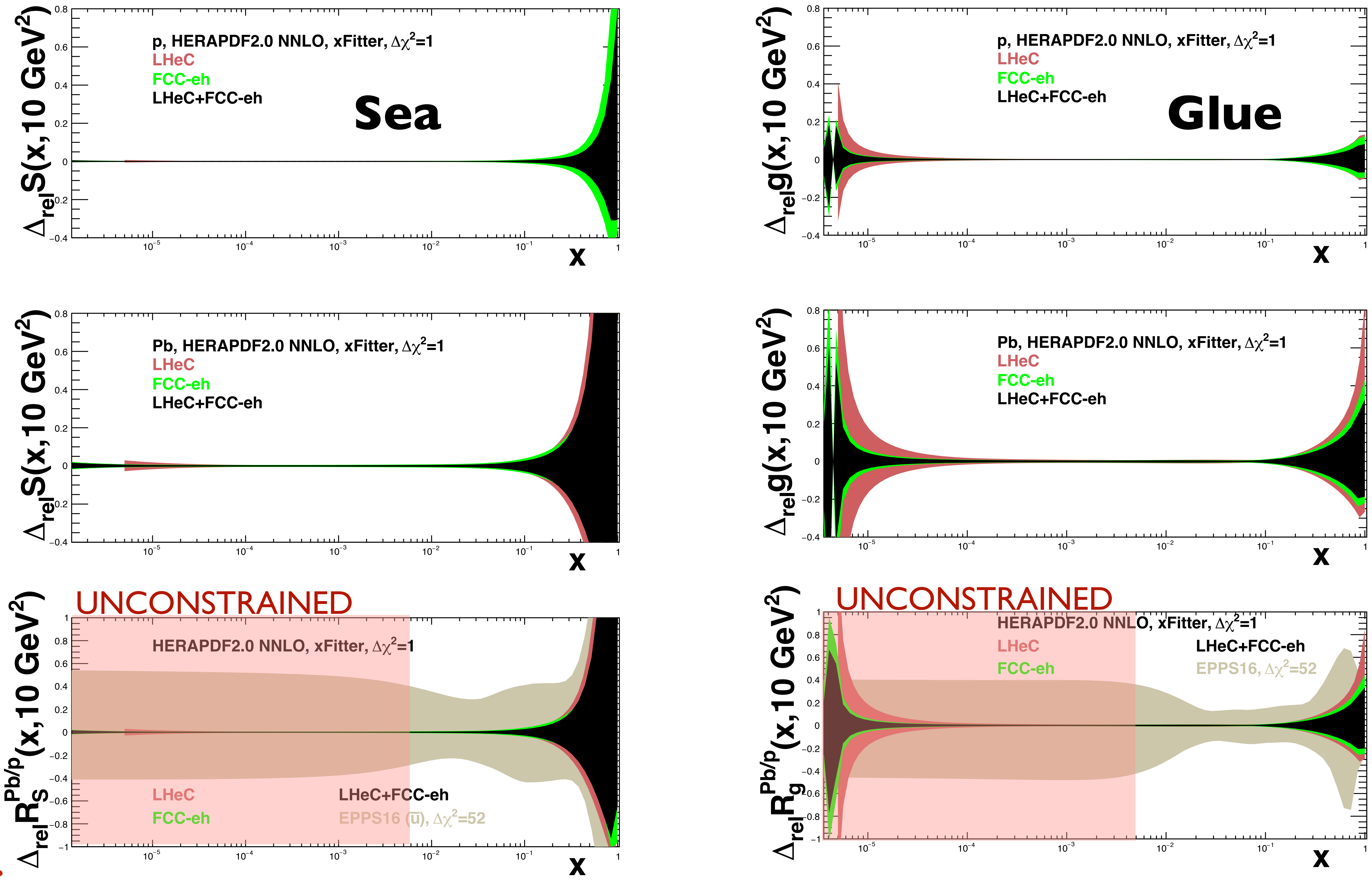
➜ Proton PDFs extracted in the same setup for consistency.

xFitter: results



xFitter: results

- Large improvements at all x, particularly for the glue, but note the different tolerances.
- Fit to a single nucleus possible: get rid of A-parametrizations, precise tests of factorisation.
- Possible improvements: charm, beauty, c-tagged CC for strange, more flexible functional forms at small x?
- Test of factorisation in pA.



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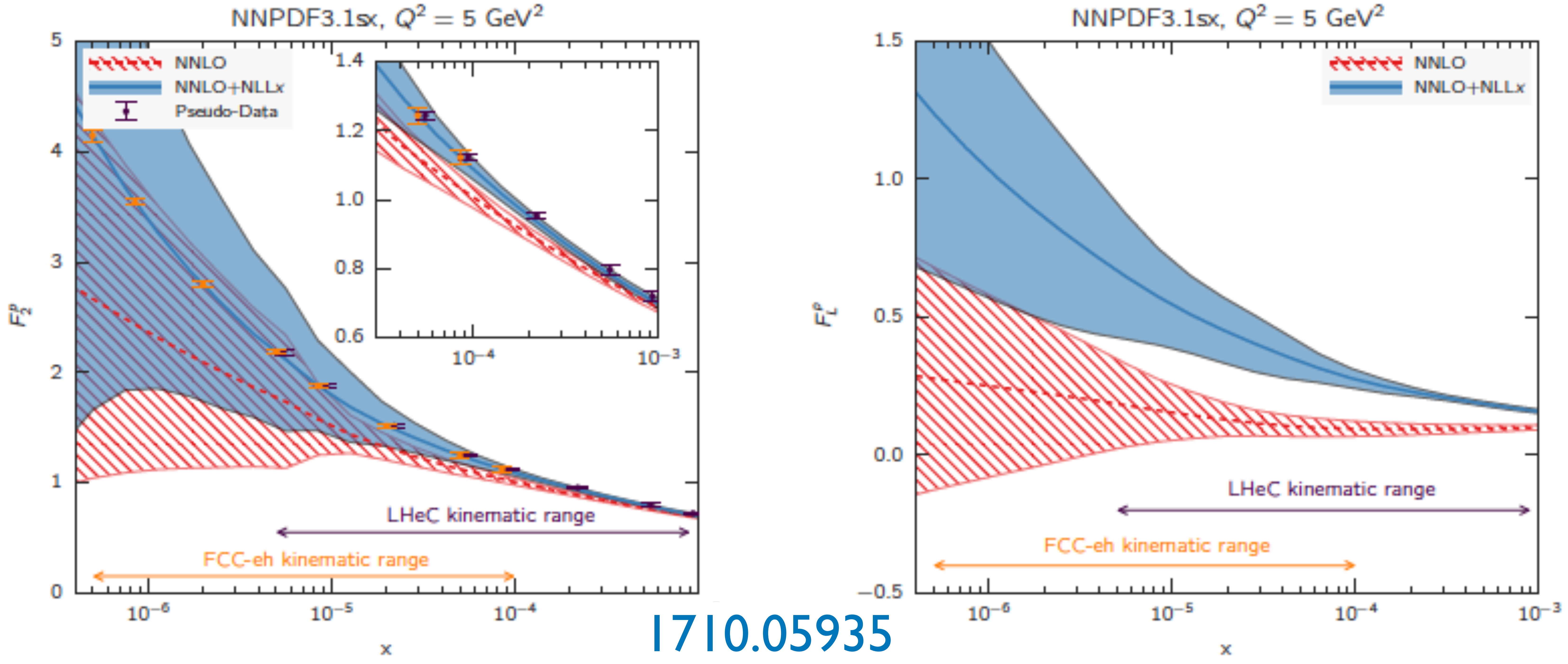
Saturation: inclusive observables

- Searching for this new dynamics requires:

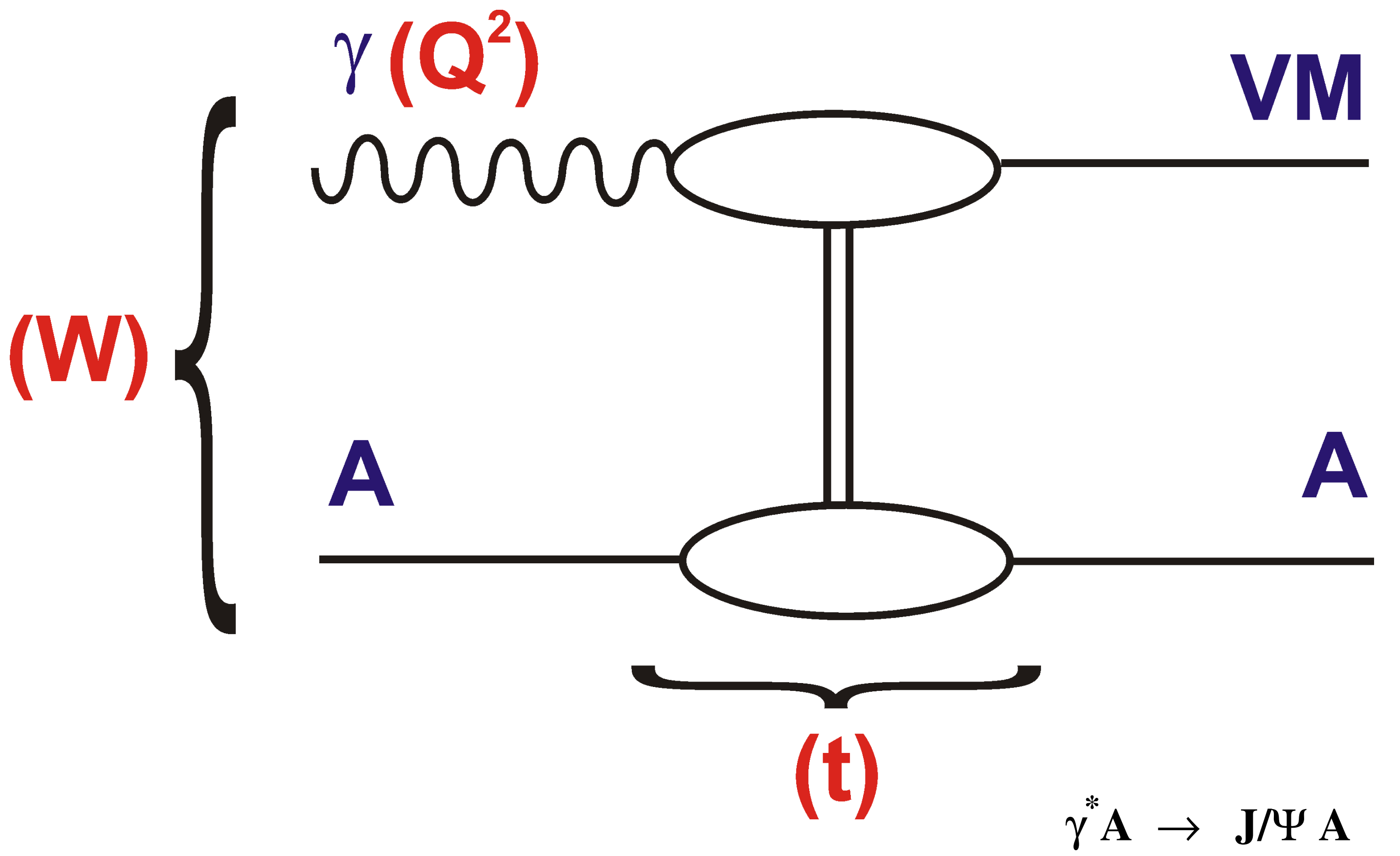
➜ Kinematic reach - lever arm in Q^2 at small x to look for the tension between observables (F_2, F_L, F_2^{HQ}): new studies confirm that linear evolution cannot accommodate saturation even at NNLO or NNLO+NLLx. Note that precision at high Q^2 helps!

➜ **Varying nuclear size to definitively disentangle resummation from non-linear dynamics** (see some attempts in 1702.00839 which show the need of lever arm!).

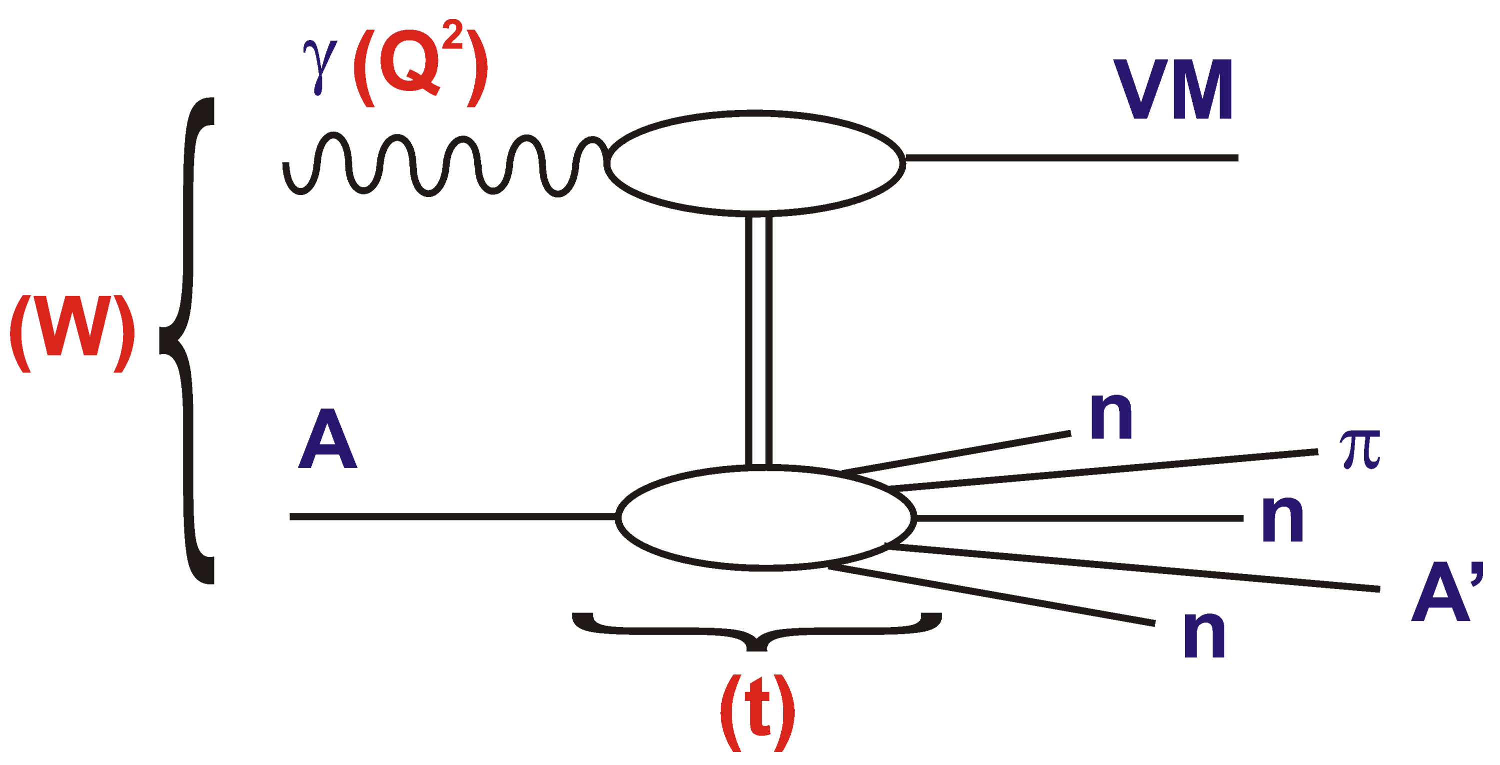


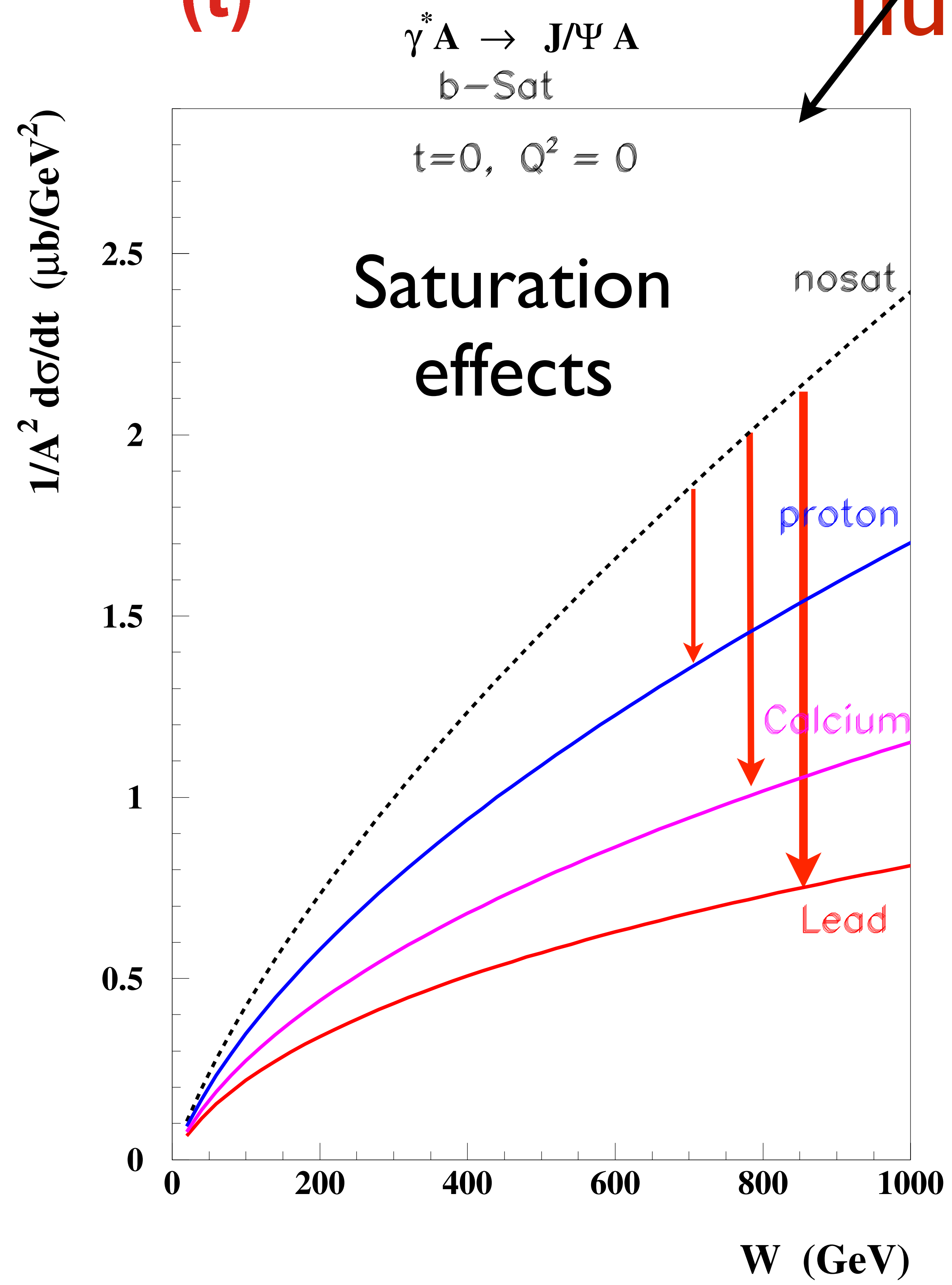
1710.05935

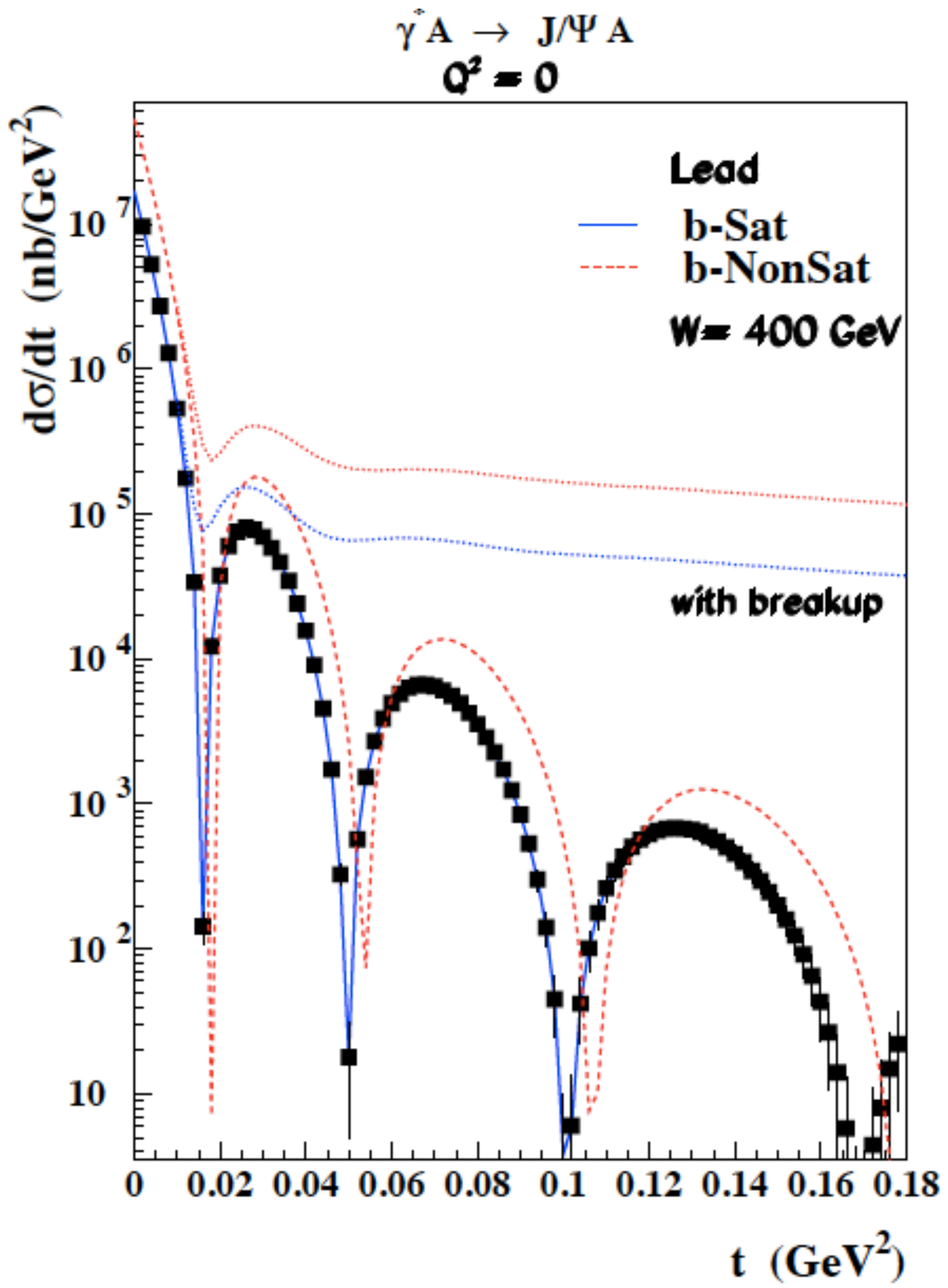
Elastic VM production:



- Challenging experimental problem.
- Coherent case: energy dependence and dips.
- Incoherent case: sensitivity to fluctuations.





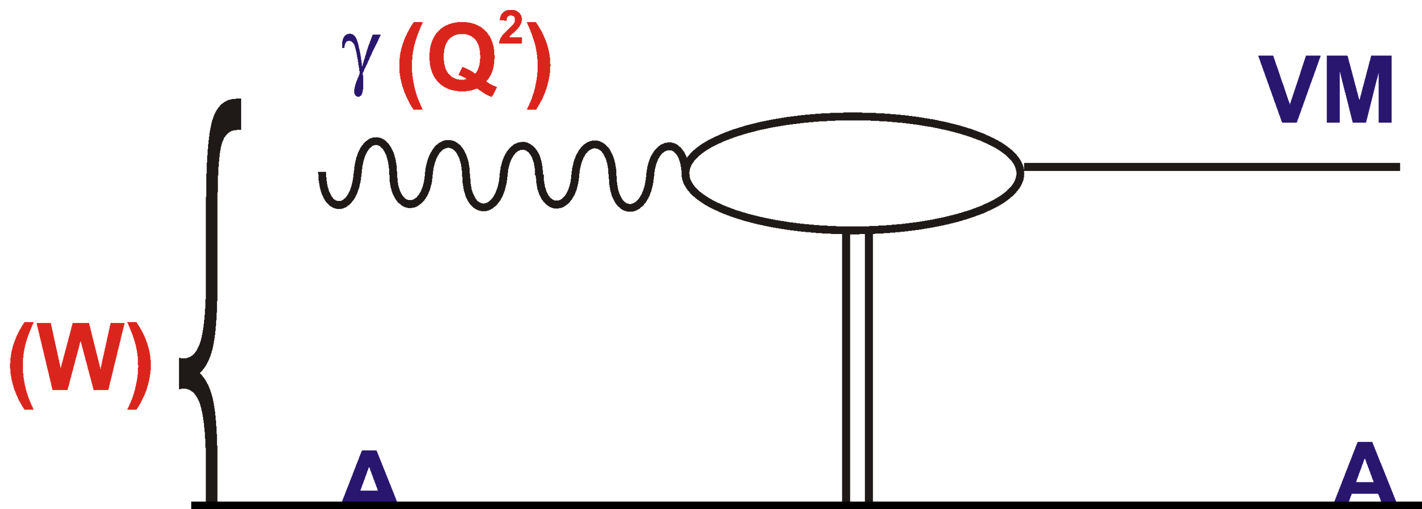


$$\Delta t = 2\sqrt{-t}\Delta p_T(J/\Psi)$$

$$\Delta p_T < 10 \text{ MeV}$$

$$\Delta t < 0.01 \text{ GeV}^2$$

Elastic VM production:



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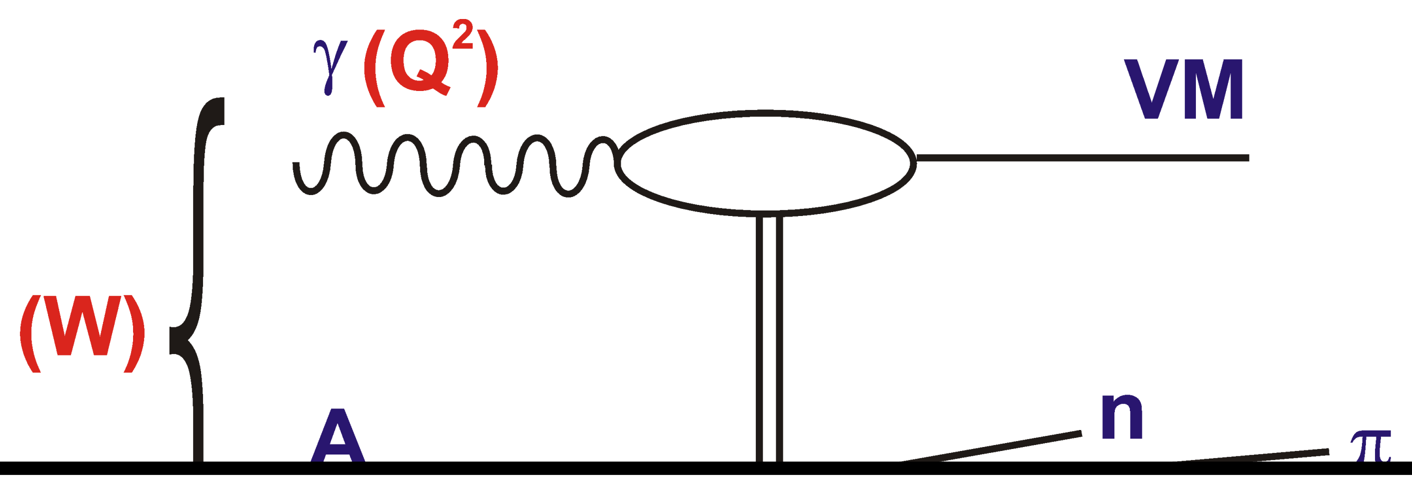

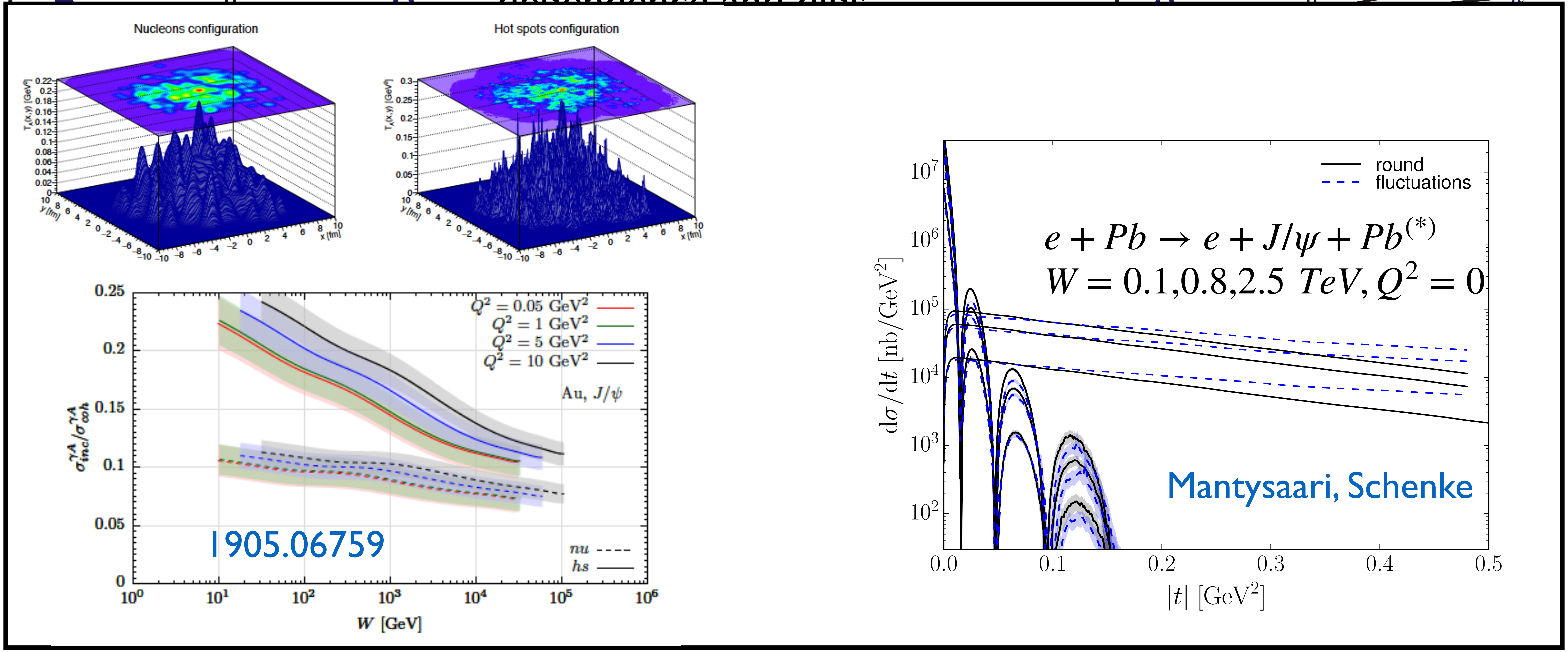

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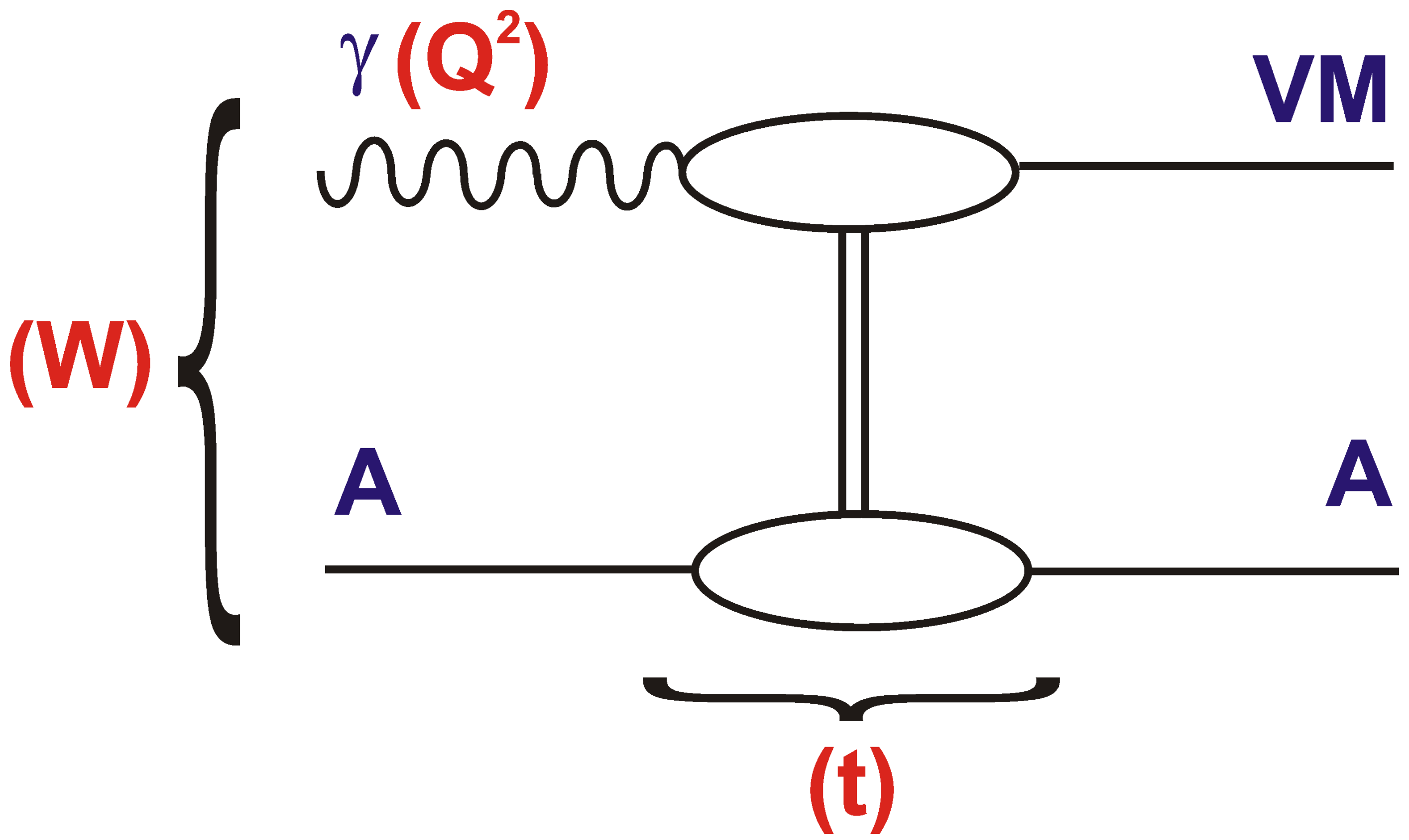

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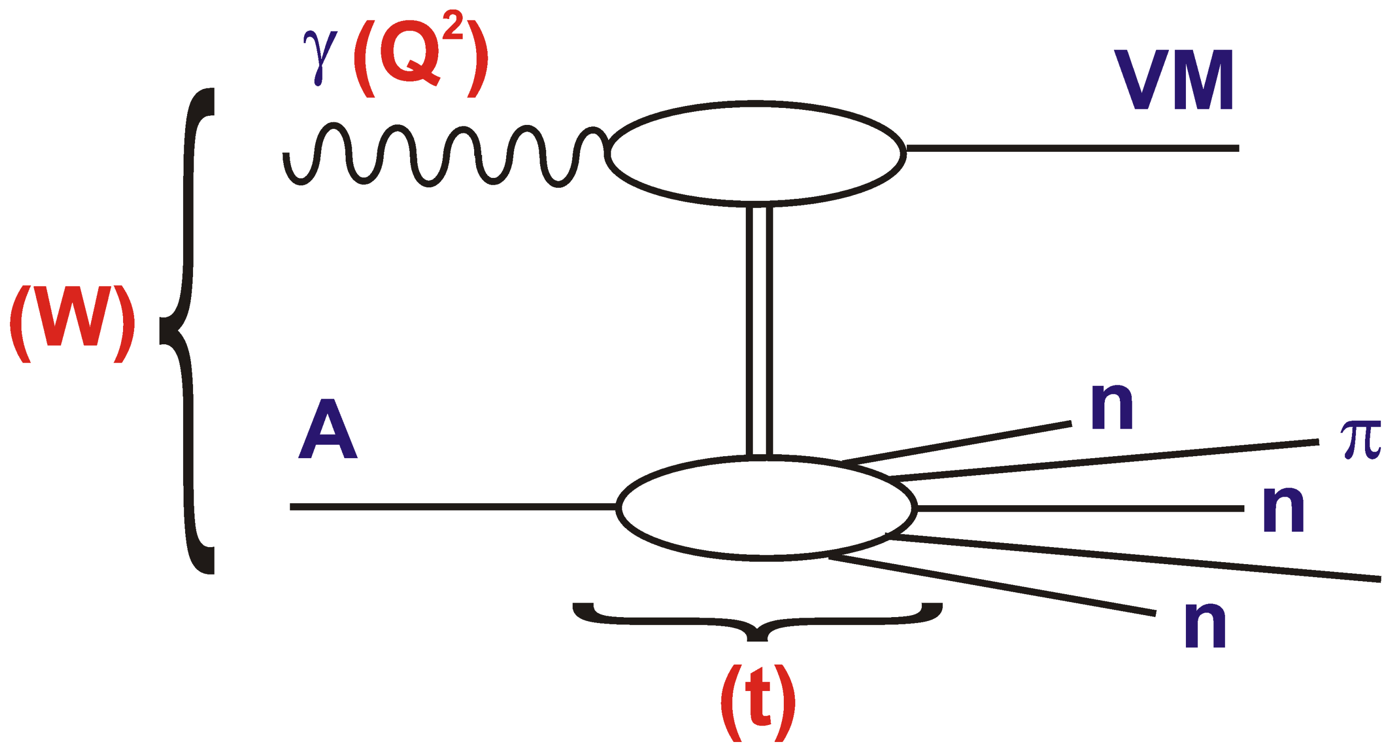
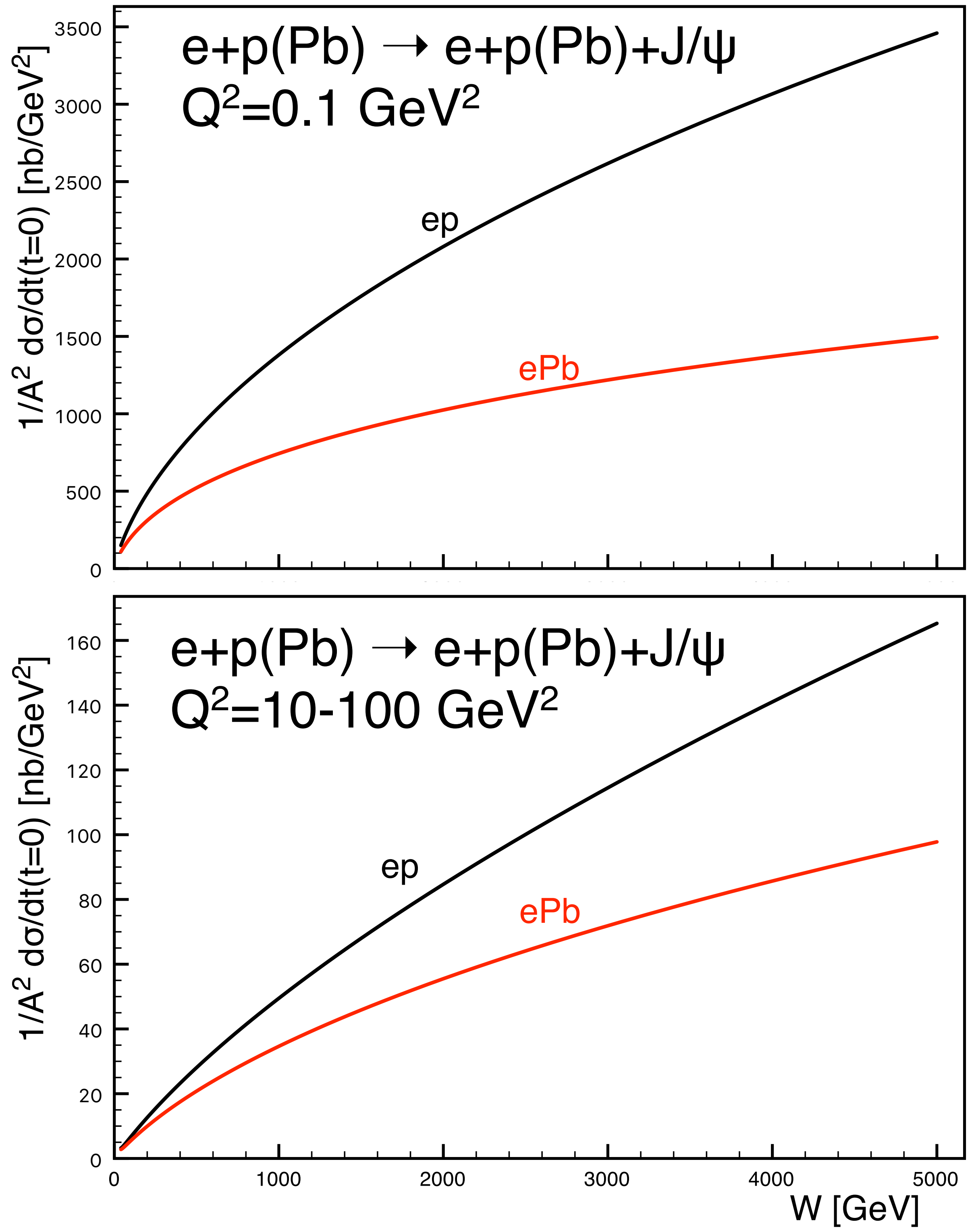
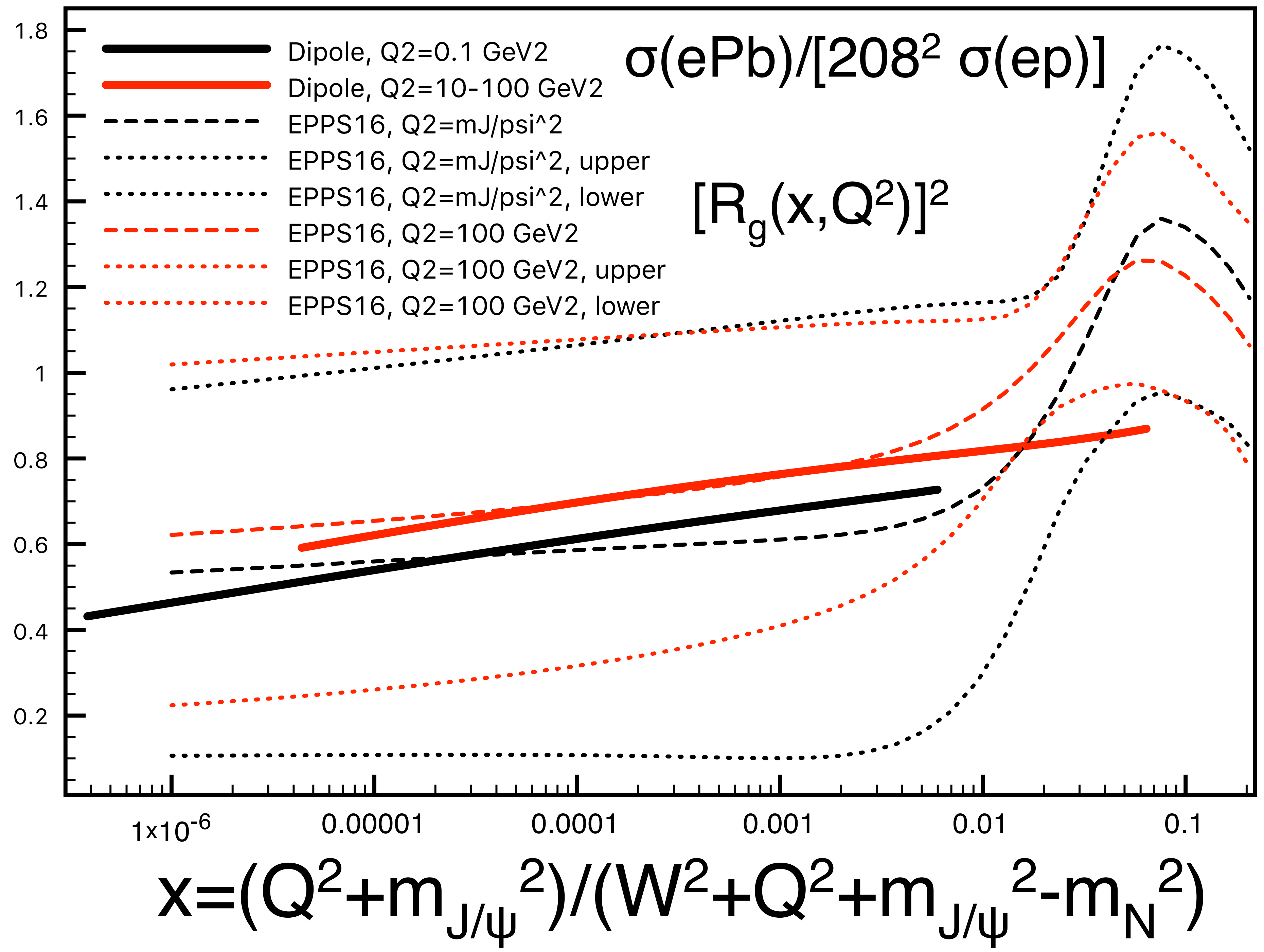




- Will nuclear effects alone disentangle saturation?



Mantysaari, Paukkunen

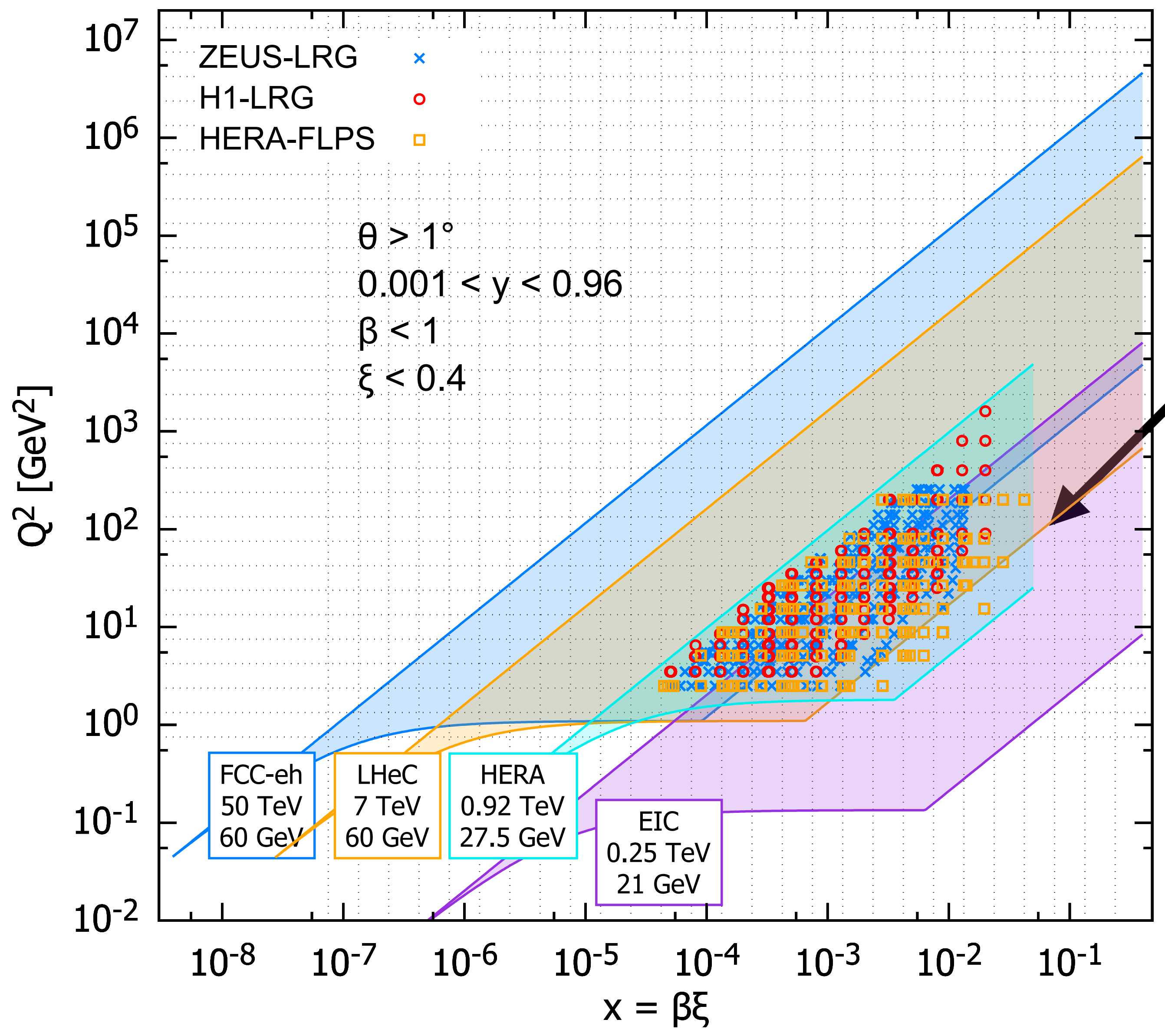
Nuclear diffractive PDFs:

- Diffractive PDFs give the conditional probability of measuring a parton in the hadron with the hadron remaining intact: ~10 % events at HERA are diffractive!
- Never measured in nuclei (enhancement expected), incoherent diffraction dominant above relatively small -t: interplay between multiple scattering and survival probability of the colourless exchange (rapidity gap), relation between diffraction in ep and nuclear shadowing ⇒ MPIs, CEP.

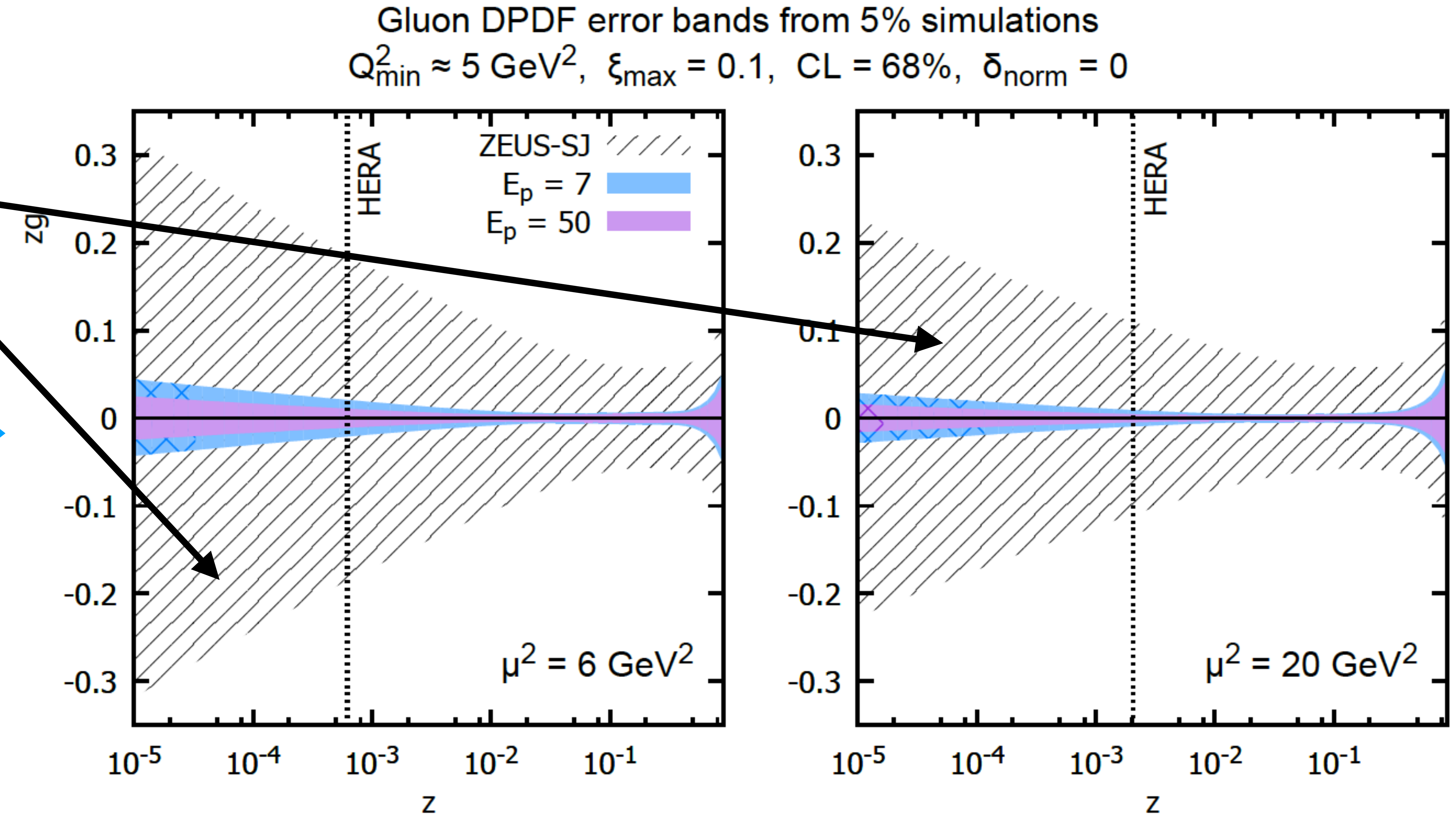
- At the LHeC/FCC-eh, **extractable in nuclei with the same accuracy as in proton**.

LHeC/FCC-eh, coherent diffraction

1901.09076: NA, PN, AS, Wojtek Slominski

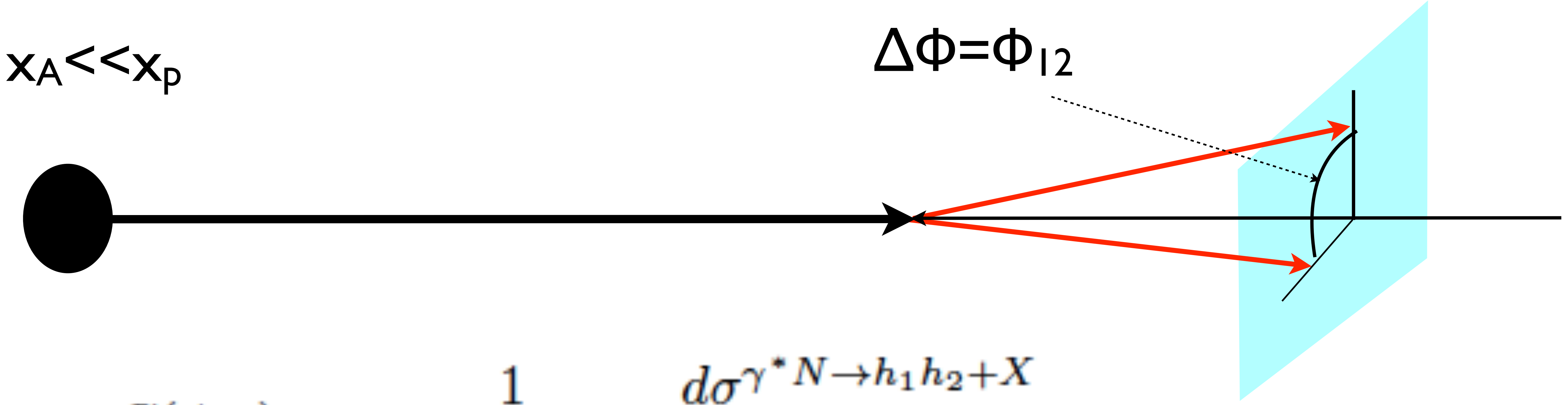


Not existing in nuclei

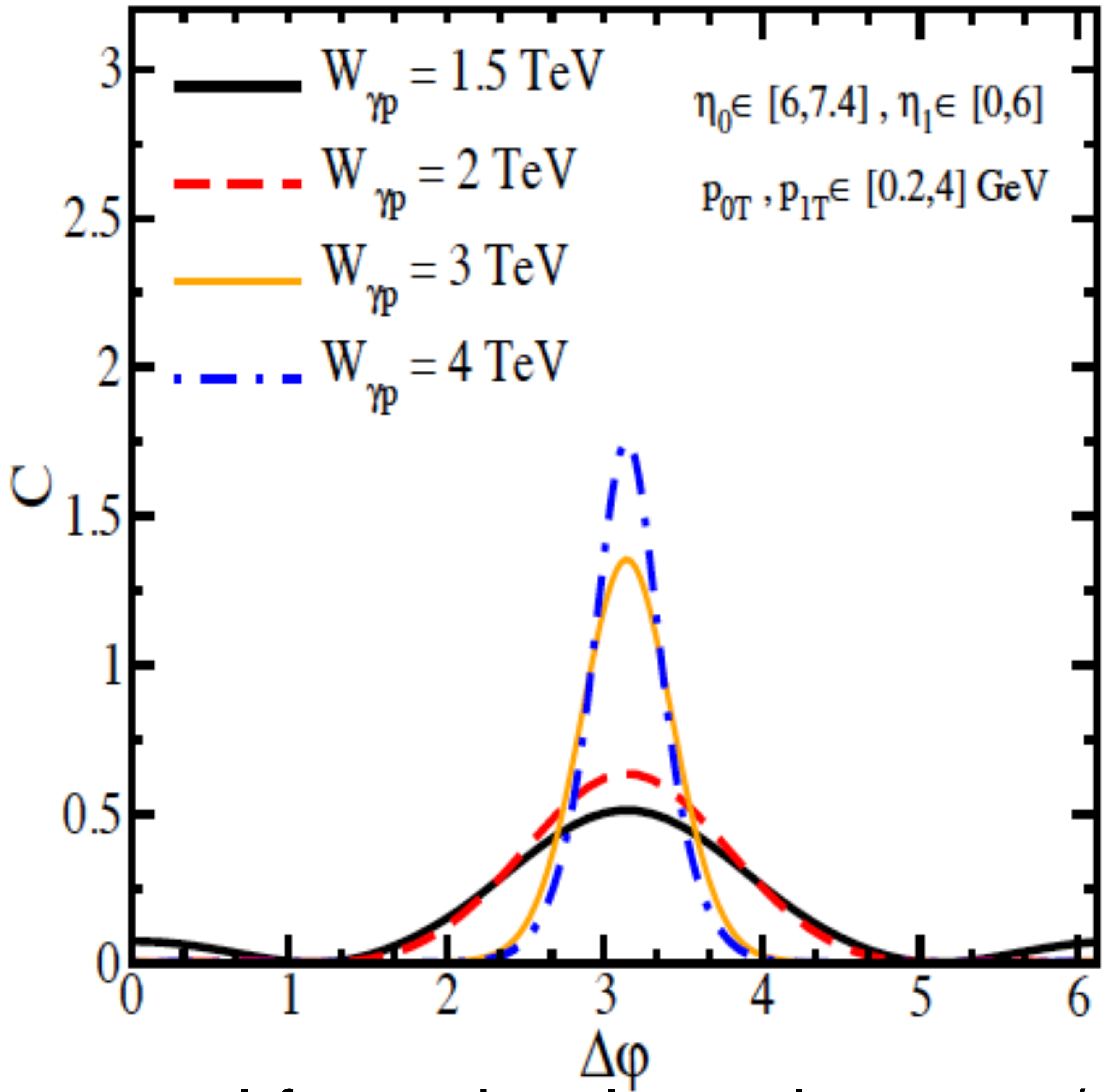


Azimuthal correlations:

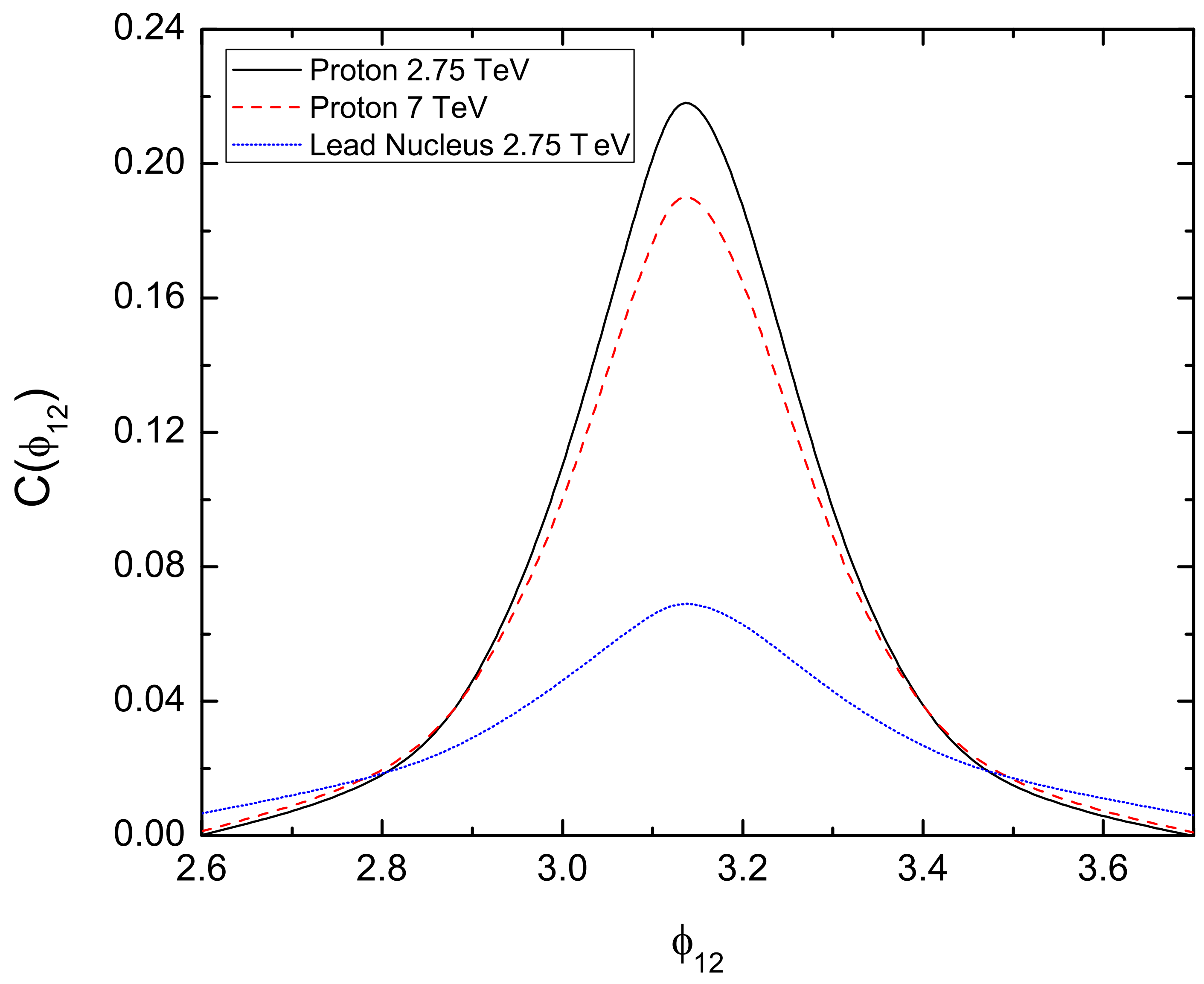
- Dihadron **azimuthal decorrelation:** currently discussed at RHIC as suggestive of saturation.
- To be studied far from kinematical limits.



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



central-forward exclusive dijets in ep/eA, 1511.07452

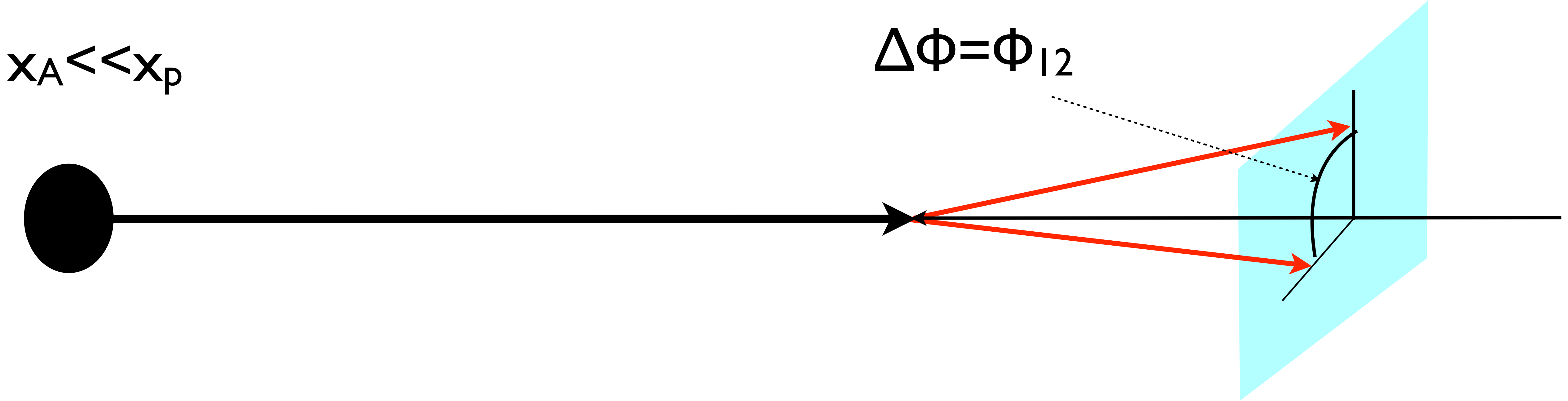


h-h in ePb

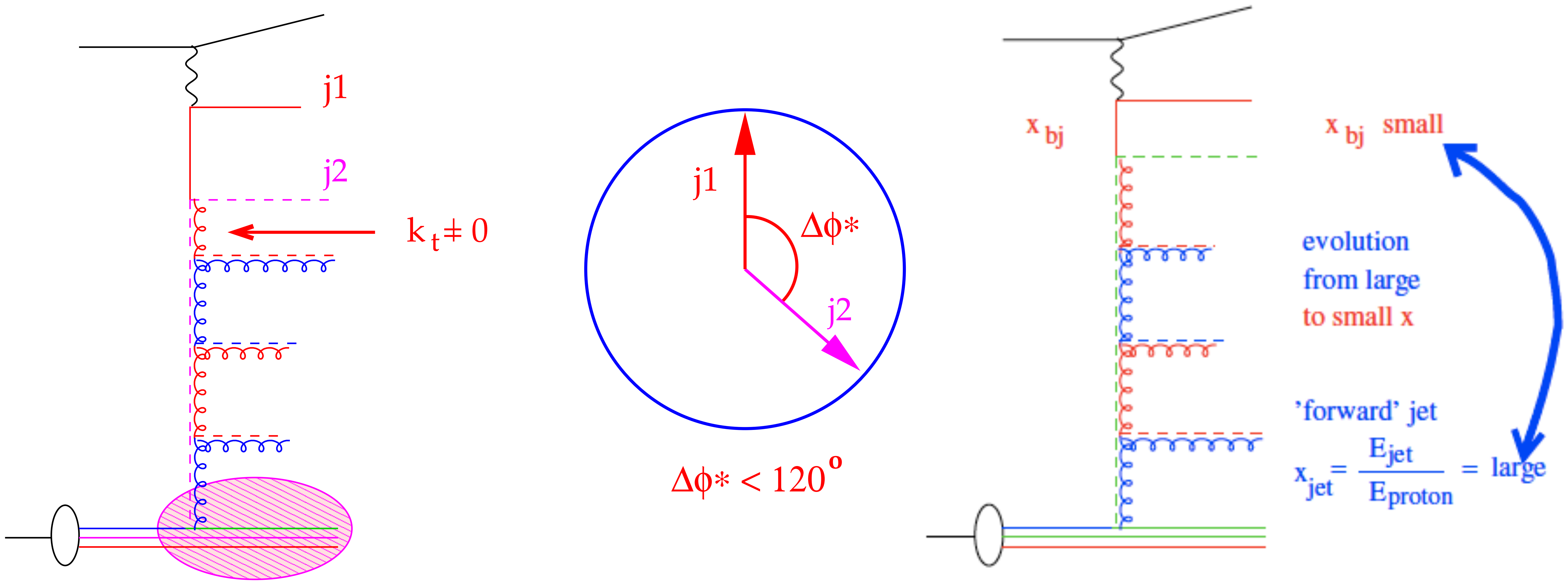
p_T^{lead}>3 GeV
p_T^{ass}>2 GeV
$z_{lead} = z_{ass} = 0.3$
y=0.7
$Q^2 = 4\ GeV^2$

Azimuthal correlations:

• Dihadron azimuthal decorrelation: currently discussed at RHIC as suggestive of saturation.
• To be studied far from kinematical limits.



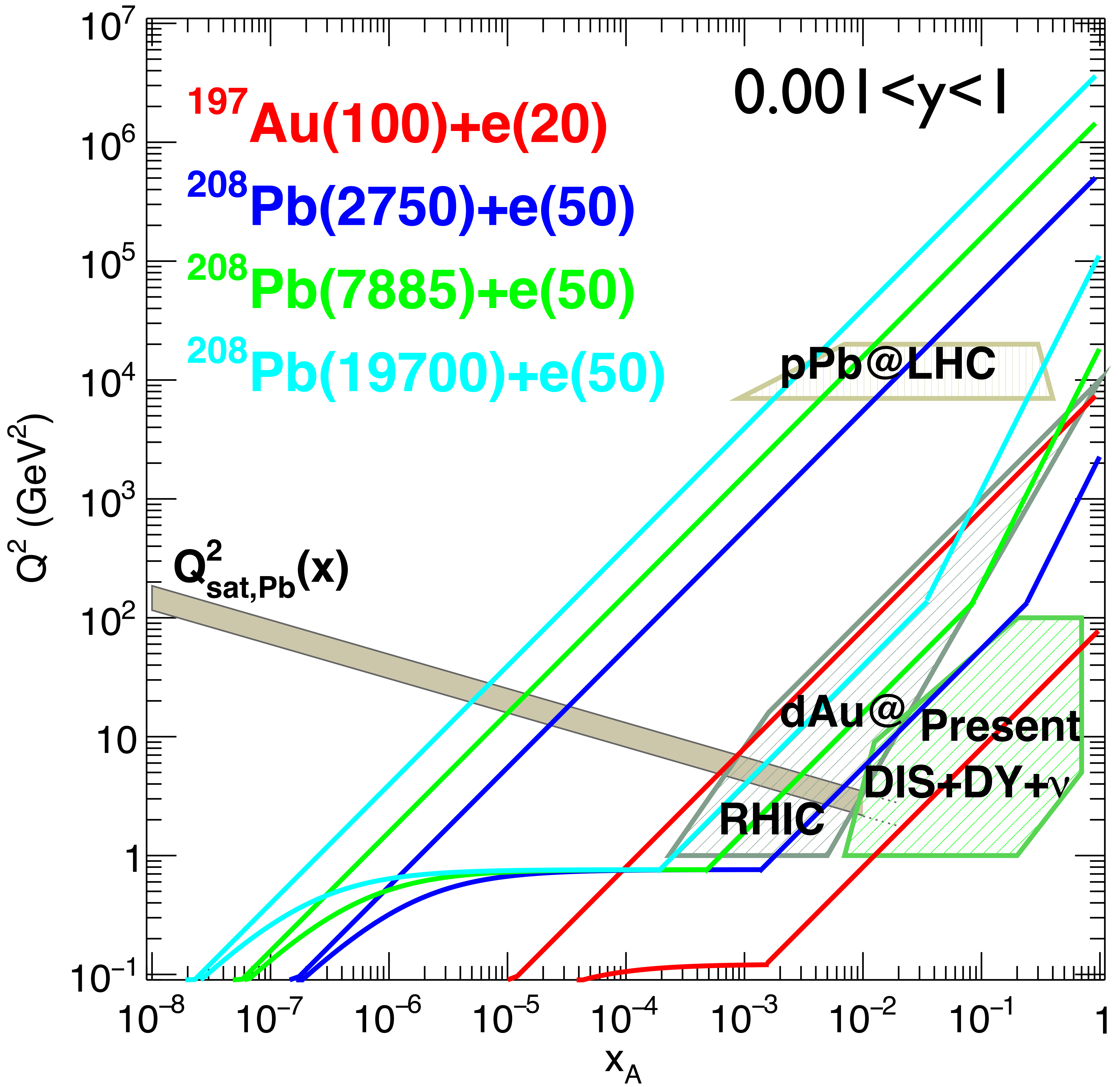
• **Nuclear and saturation effects on usual BFKL signals** (e.g. dijet azimuthal decorrelation, Mueller-Navelet jets) has not been extensively addressed in pA, less in DIS: A-dependence? (see the talk by Francesco Hautmann)



Summary:

- The LHeC (and the FCC-eh) will explore a completely new region in the x-Q^2 plane, enlarging the one presently explored in DIS by ~4 orders of magnitude down in x and up in Q^2.
  - ➜ A precise determination of nPDFs and nDPDFs will be possible, that cannot be matched at hadron colliders ⇒ factorisation.
  - ➜ Tests of small-x dynamics by studying both ep and eA.
  - ➜ Studies of the transverse structure of p and A.

Therefore: <u>precision</u> (for understanding nuclear structure in a totally new kinematic domain and for its use in present and future pA/AA) & <u>discovery</u> (of a genuinely new regime of QCD).



- For the update of the 2012 CDR:
  - ➜ nPDFs, nDPDFs, elastic VM done.
  - ➜ Writing is advanced but ideas welcome!!!

Status of the writeup:

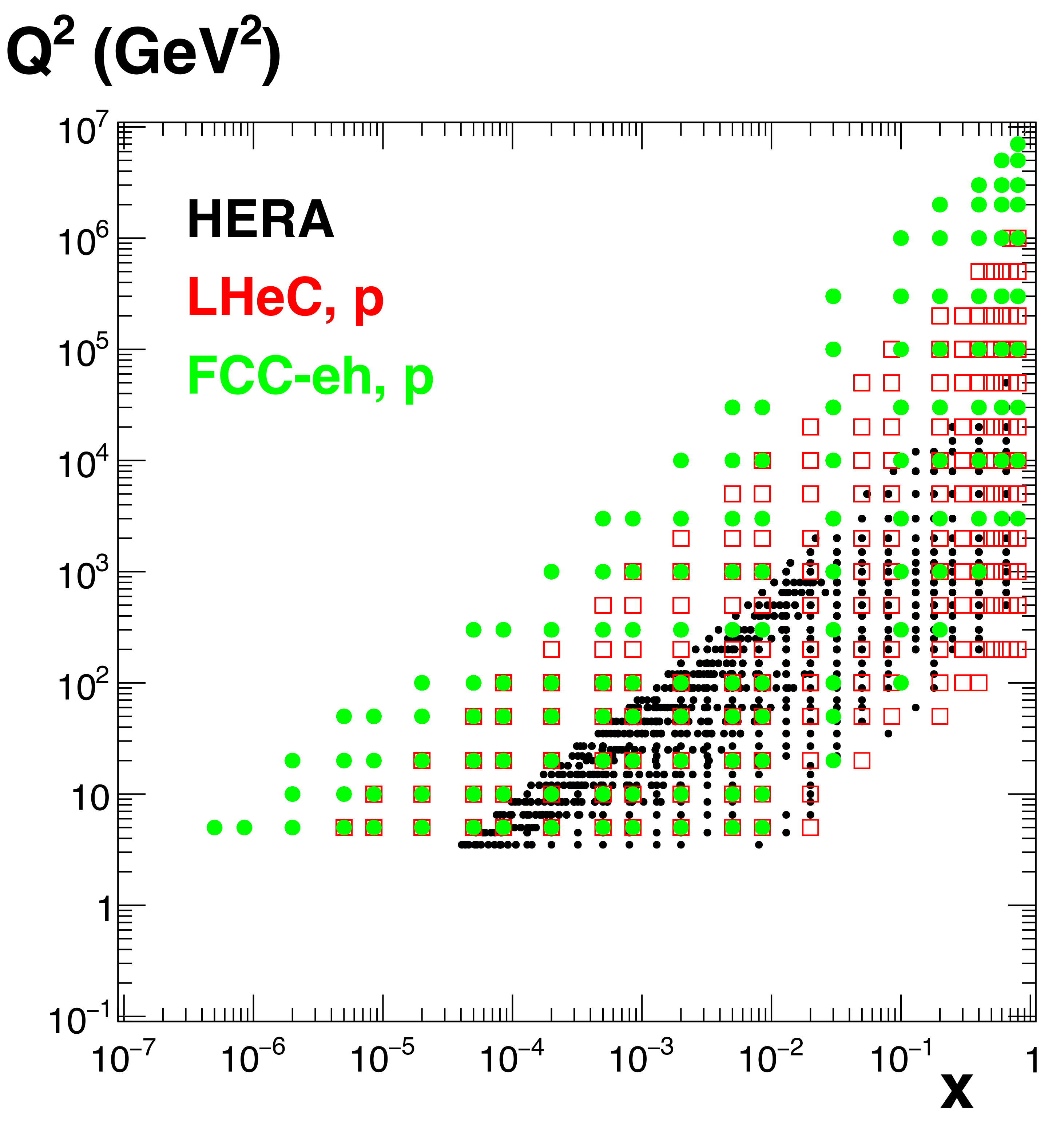
<u>Additional contributors beyond those already in the update</u>: Pedro Agostini, Liliana Apolinario, Brian Cole, Guilherme Milhano, Ilkka Helenius, Heikki Mantysaari, Pia Zurita,…

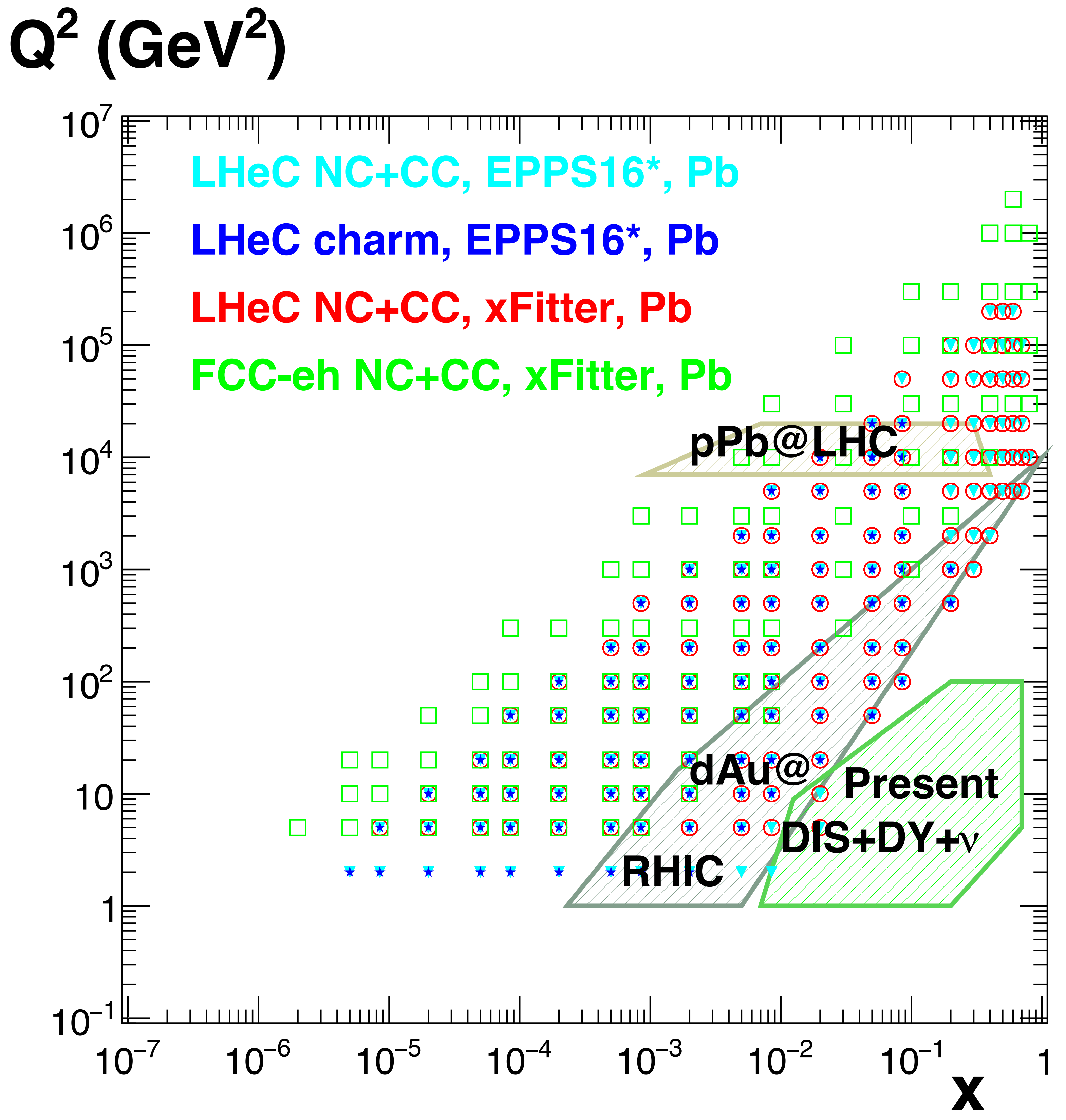
Backup:

Pseudodata:

	E_e (GeV)	E_h (TeV/nucleon)	Polarisation	Luminosity (fb^{-1})	NC/CC	# data
ep@LHeC, 1005 data points for $Q^2 \geq 3.5$ GeV^2	60 (e^-)	1 (p)	0	100	CC	93
	60 (e^-)	1 (p)	0	100	NC	136
	60 (e^-)	7 (p)	-0.8	1000	CC	114
	60 (e^-)	7 (p)	0.8	300	CC	113
	60 (e^+)	7 (p)	0	100	CC	109
	60 (e^-)	7 (p)	-0.8	1000	NC	159
	60 (e^-)	7 (p)	0.8	300	NC	159
	60 (e^+)	7 (p)	0	100	NC	157
ePb@LHeC, 484 data points for $Q^2 \geq 3.5$ GeV^2	20 (e^-)	2.75 (Pb)	-0.8	0.03	CC	51
	20 (e^-)	2.75 (Pb)	-0.8	0.03	NC	93
	26.9 (e^-)	2.75 (Pb)	-0.8	0.02	CC	55
	26.9 (e^-)	2.75 (Pb)	-0.8	0.02	NC	98
	60 (e^-)	2.75 (Pb)	-0.8	1	CC	85
	60 (e^-)	2.75 (Pb)	-0.8	1	NC	129
ep@FCC-eh, 619 data points for $Q^2 \geq 3.5$ GeV^2	20 (e^-)	7 (p)	0	100	CC	46
	20 (e^-)	7 (p)	0	100	NC	89
	60 (e^-)	50 (p)	-0.8	1000	CC	67
	60 (e^-)	50 (p)	0.8	300	CC	65
	60 (e^+)	50 (p)	0	100	CC	60
	60 (e^-)	50 (p)	-0.8	1000	NC	111
	60 (e^-)	50 (p)	0.8	300	NC	110
	60 (e^+)	50 (p)	0	100	NC	107
ePb@FCC-eh, 150 data points for $Q^2 \geq 3.5$ GeV^2	60 (e^-)	20 (Pb)	-0.8	10	CC	58
	60 (e^-)	20 (Pb)	-0.8	10	NC	101

Pseudodata:

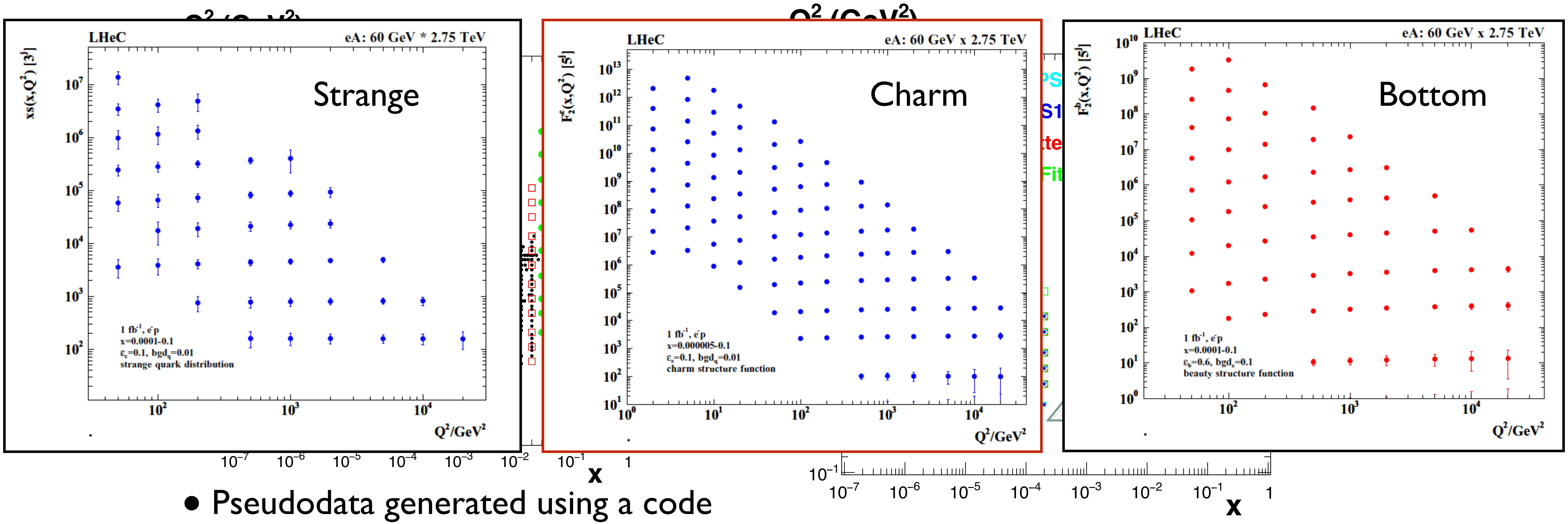




- Pseudodata generated using a code (Max Klein) validated with the H1 MC.
- Cuts: $|\eta_{max}|$=5, 0.95< y< 0.001.
- Error assumptions ~ factor 2 better than at HERA (luminosity uncertainty kept aside).

Source of uncertainty	Error on the source or cross section
scattered electron energy scale	0.1 %
scattered electron polar angle	0.1 mrad
hadronic energy scale	0.5 %
calorimeter noise ($y < 0.01$)	1-3 %
radiative corrections	1-2 %
photoproduction background	1 %
global efficiency error	0.7 %

Pseudodata:



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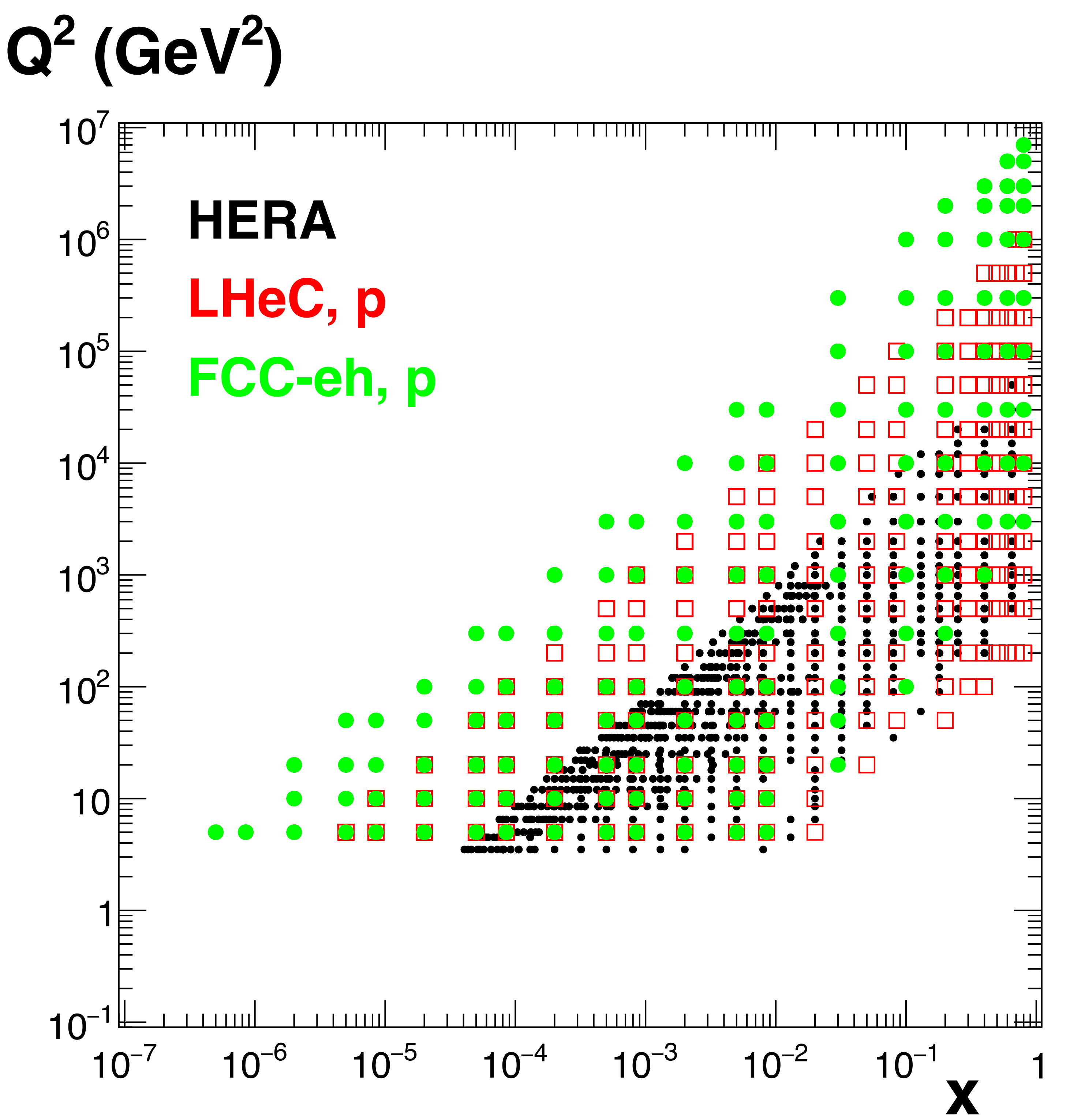

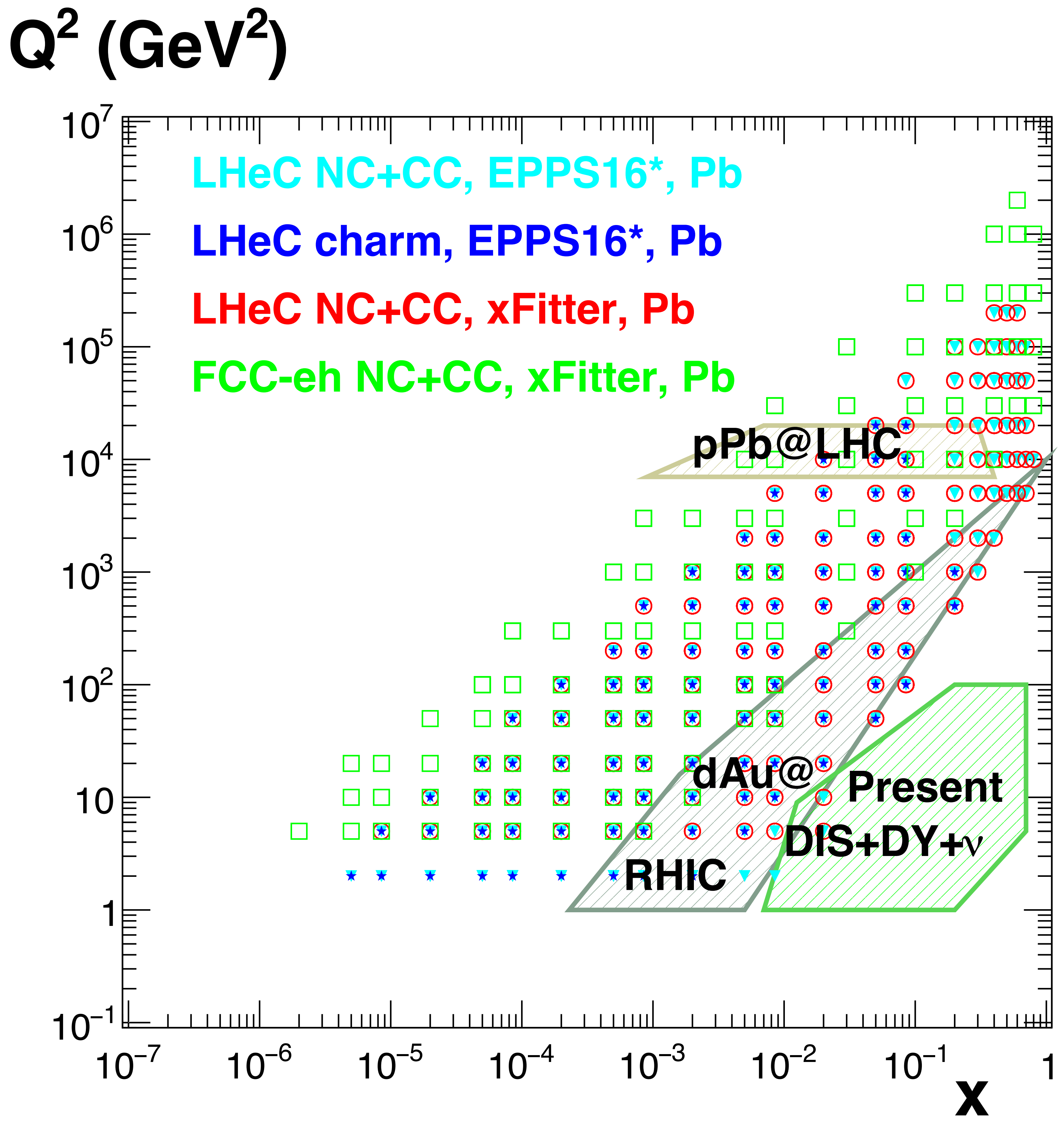

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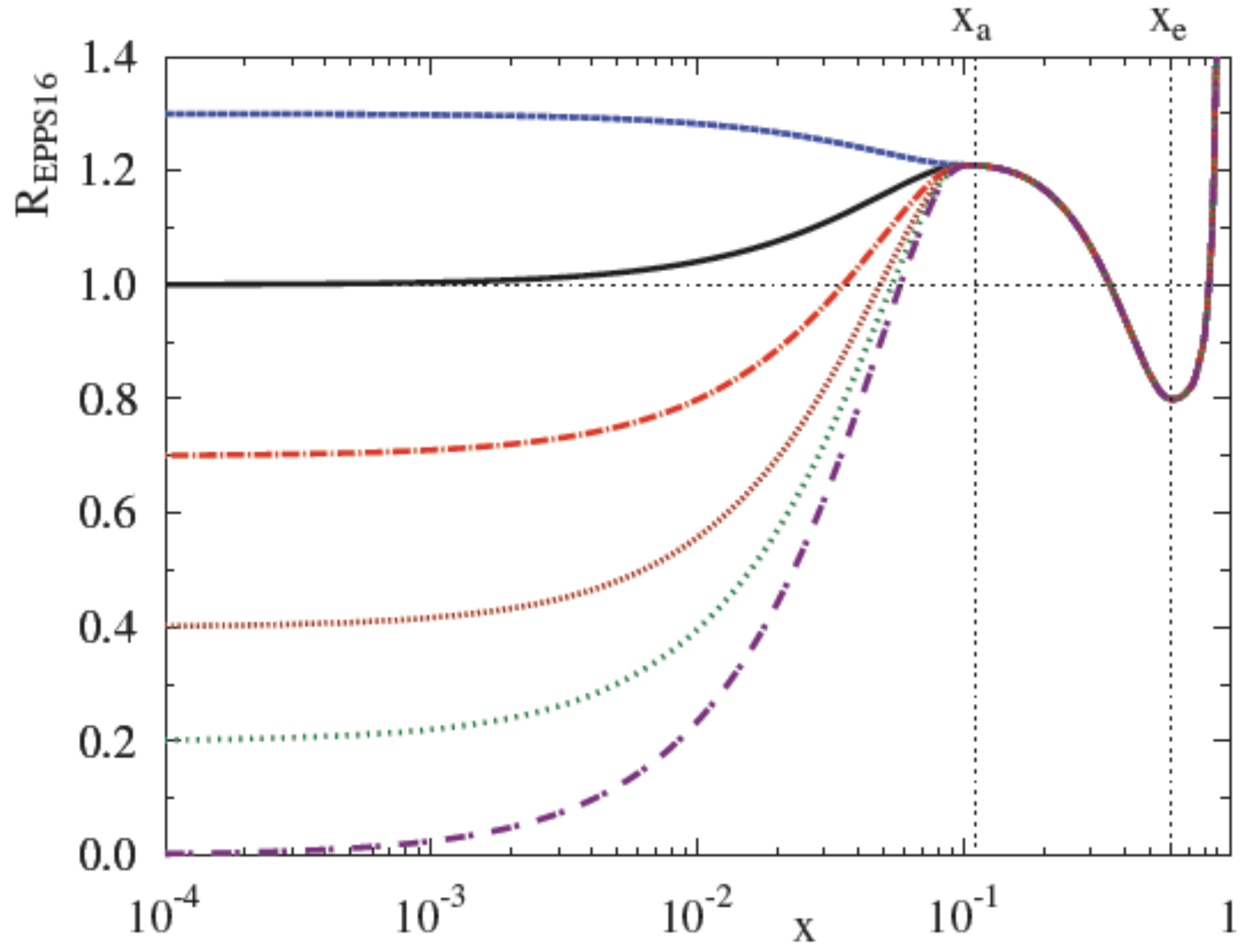
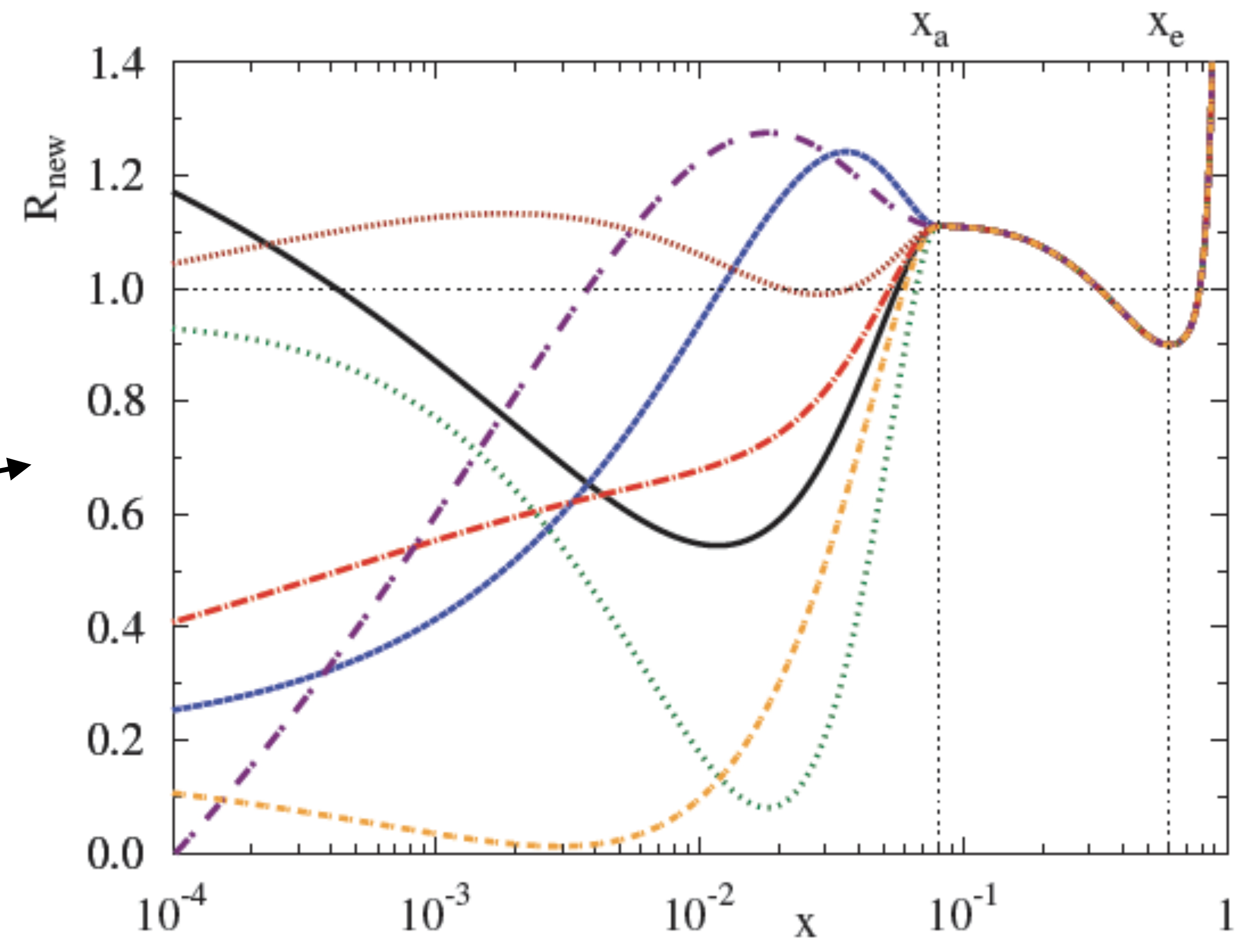
EPPS16*: setup

- EPPS16-like analysis updated, with the same data sets plus LHeC NC, CC and charm reduced cross sections.
- Central values generated using EPS09.
- Same methods and tolerance ($\Delta\chi^2$=52) as in EPPS16, but more flexible functional form at small x.

$$R_{\mathrm{EPPS16}}(x) = \begin{cases} a_0 + a_1(x - x_a)^2 & x \le x_a \\ b_0 + b_1 x^{\alpha} + b_2 x^{2\alpha} + b_3 x^{3\alpha} & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1 - x)^{-\beta} & x_e \le x \le 1. \end{cases}$$

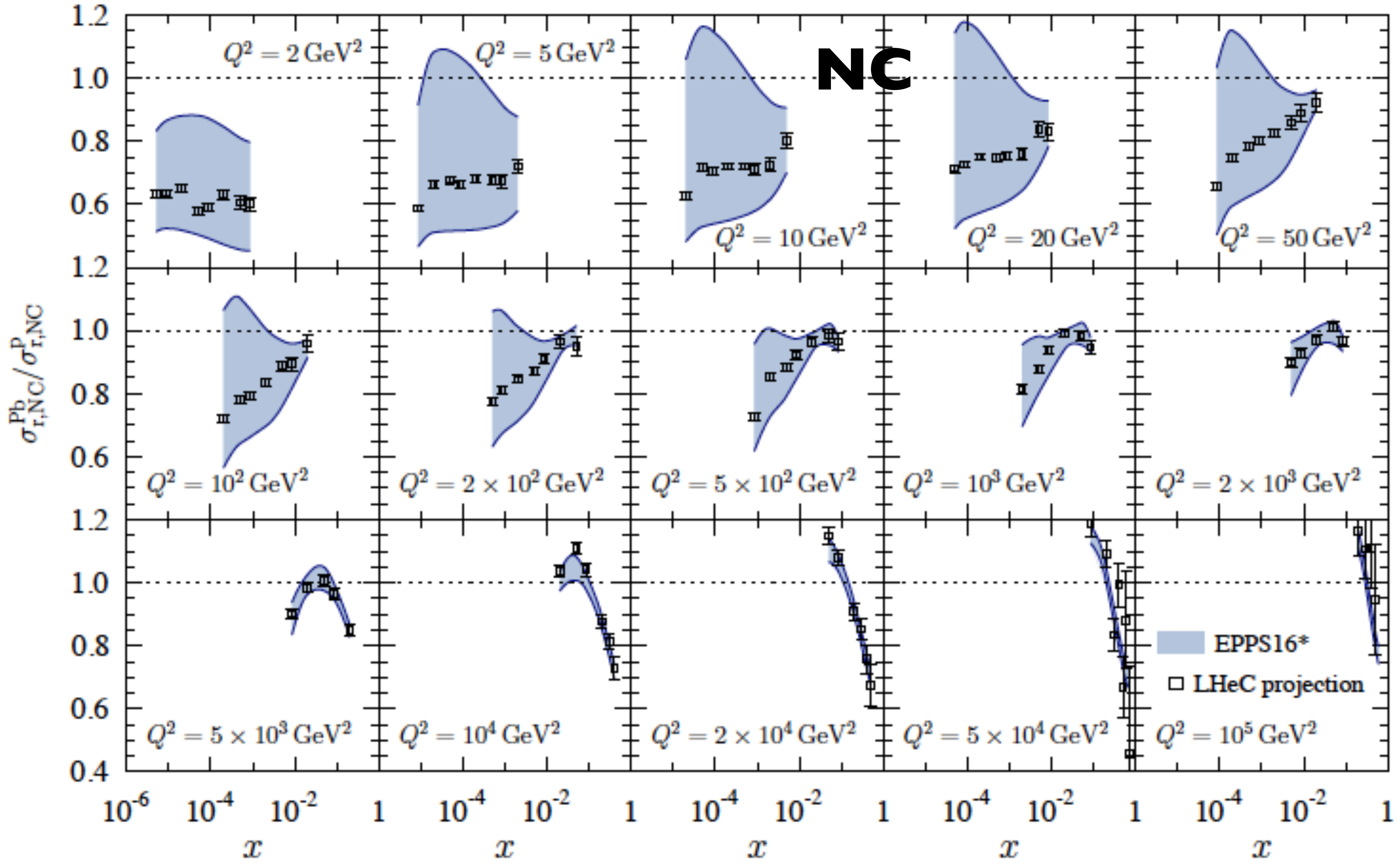


$$R_{\mathrm{new}}(x \le x_a) = a_0 + (x - x_a)^2 \left[a_1 + \sum_{k=1}^{2} a_{k+2} x^{k/4} \right]$$



EPPS16*: results

- Large effect of NC+CC LHeC pseudodata, and of charm on the glue at small x.
- Limitation on u/d decomposition inherent to almost isospin symmetric nuclei (u/d difference suppressed by 2Z/A-1).



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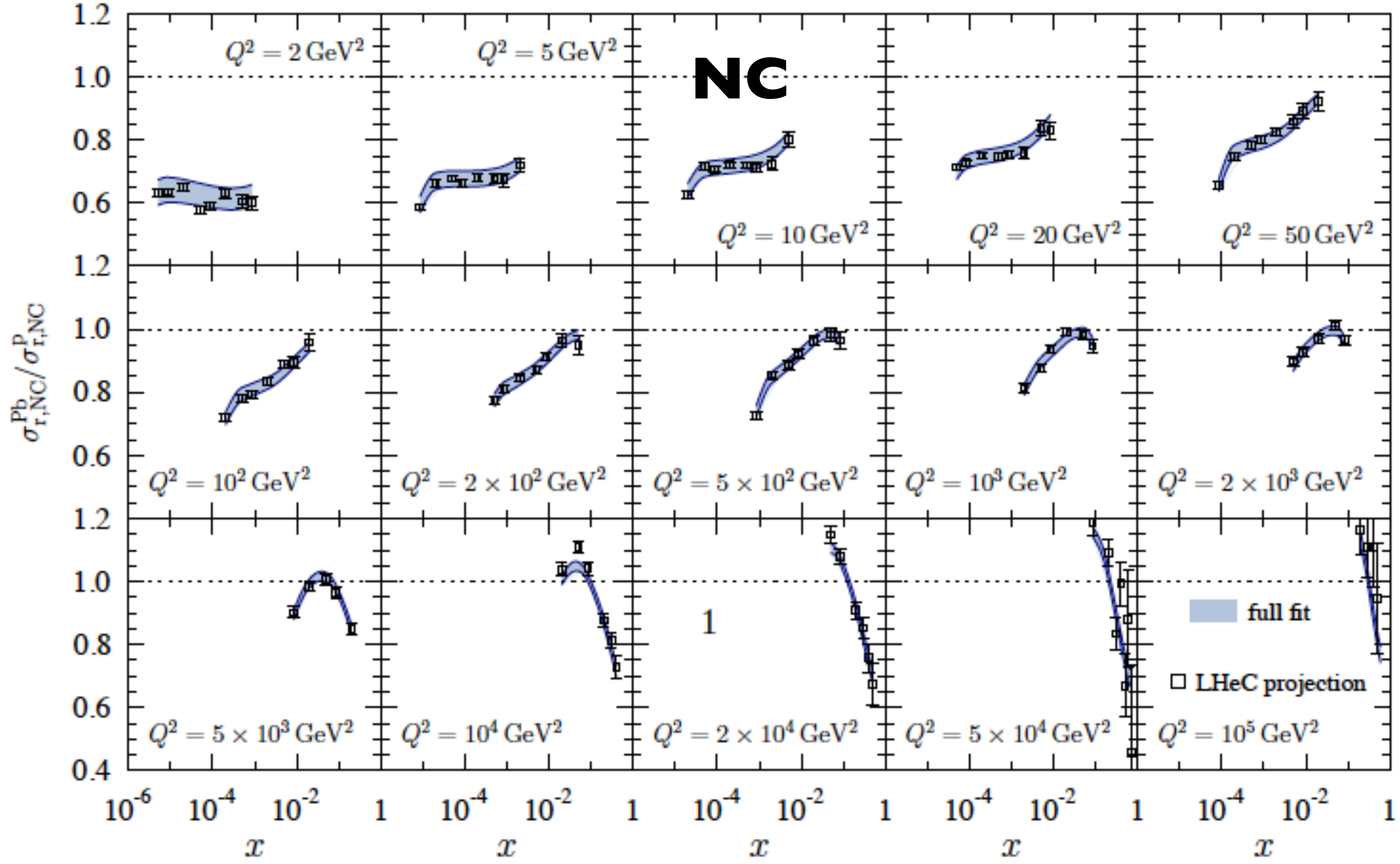

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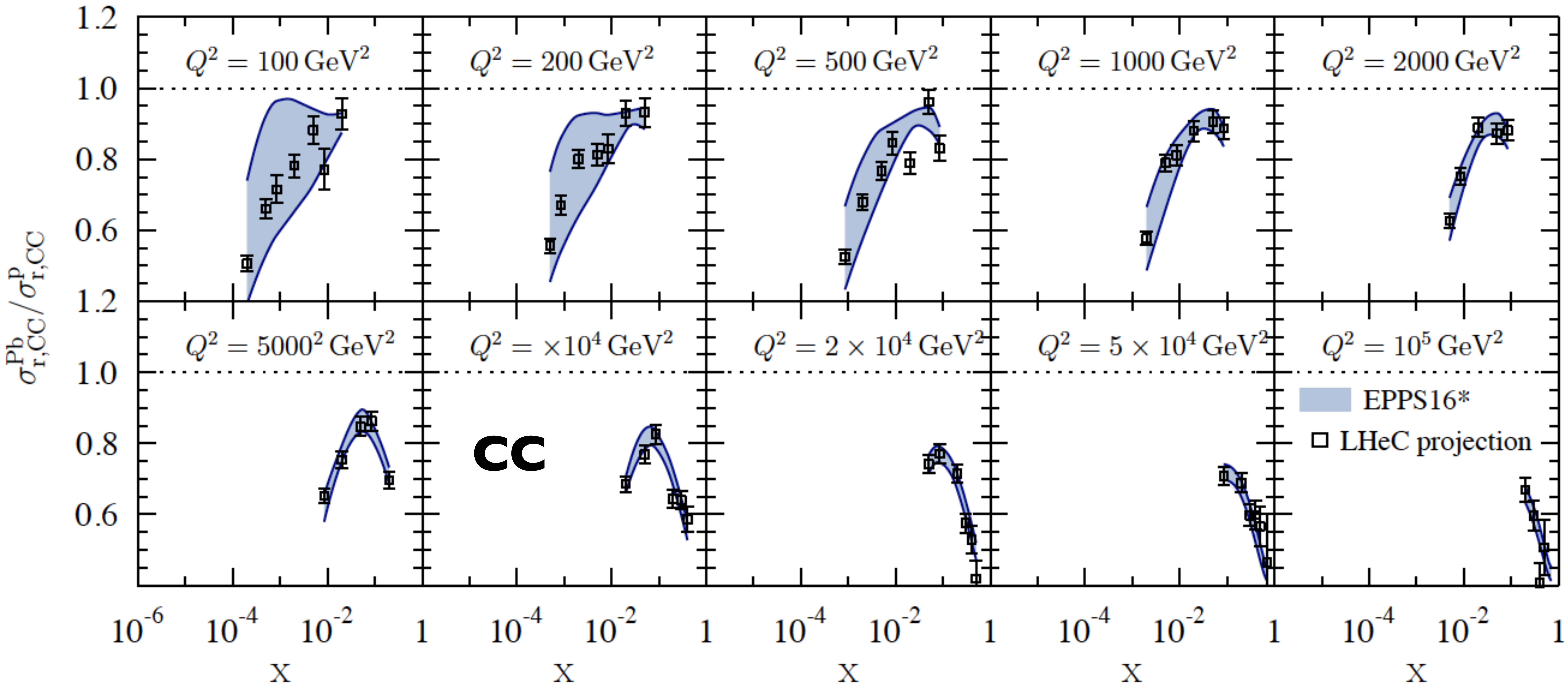

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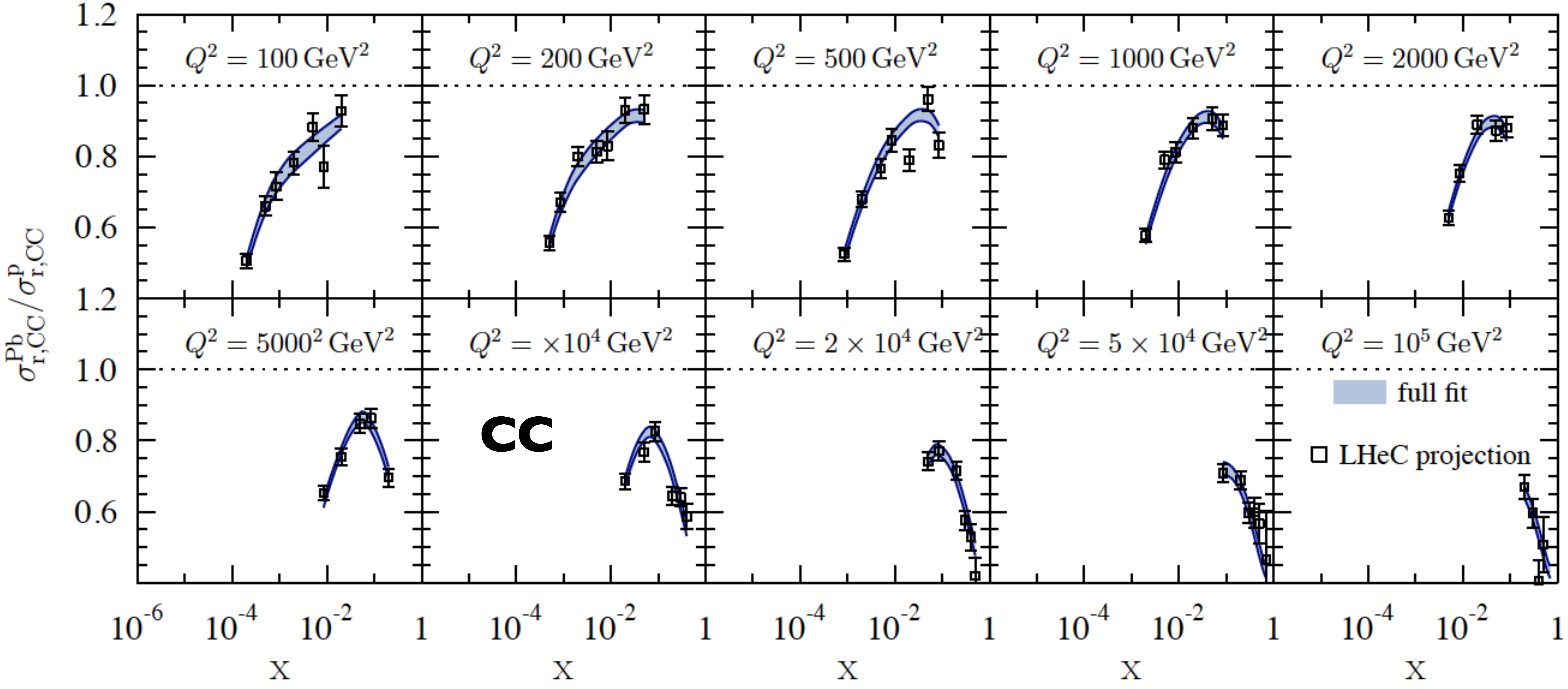

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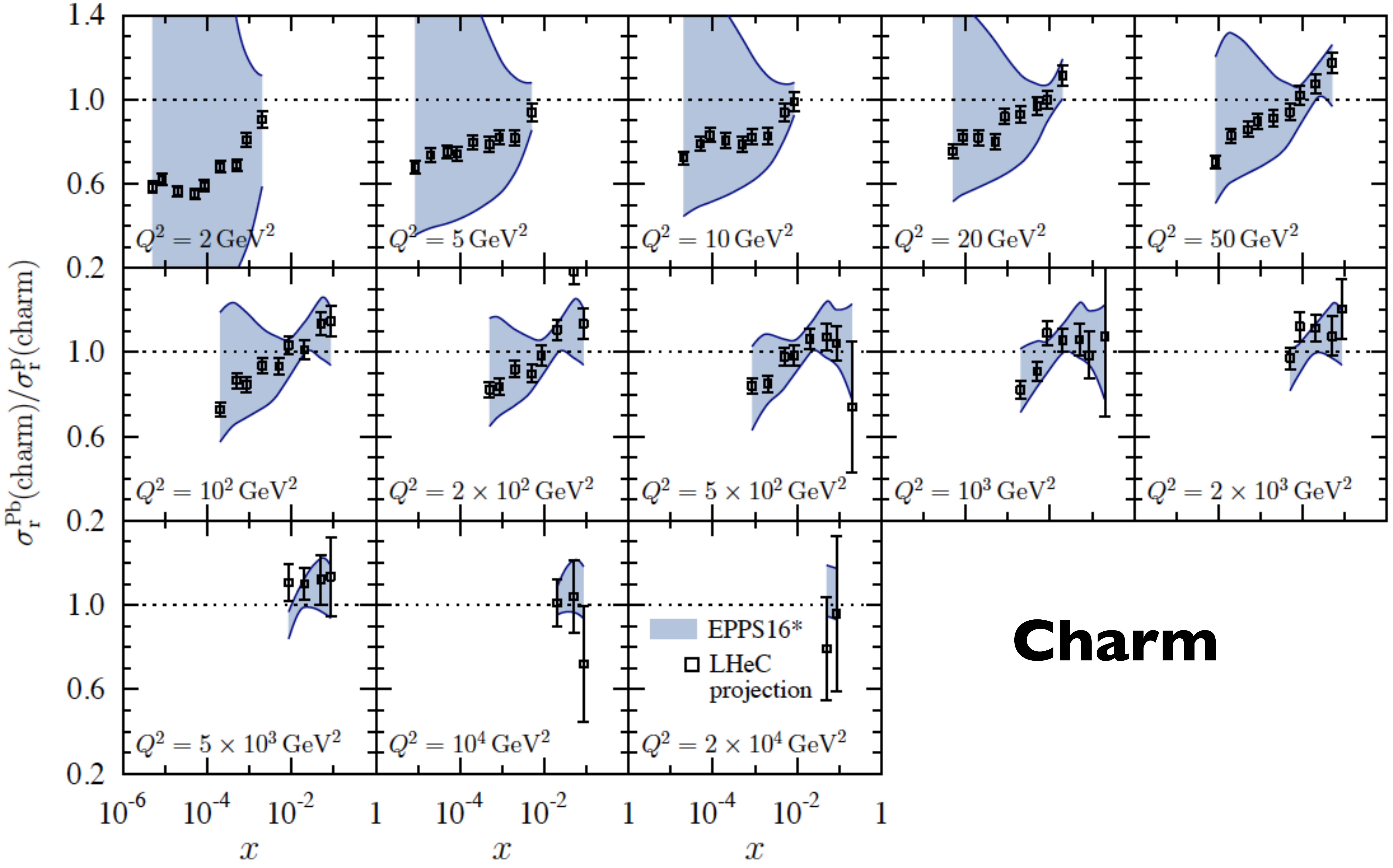

Charm

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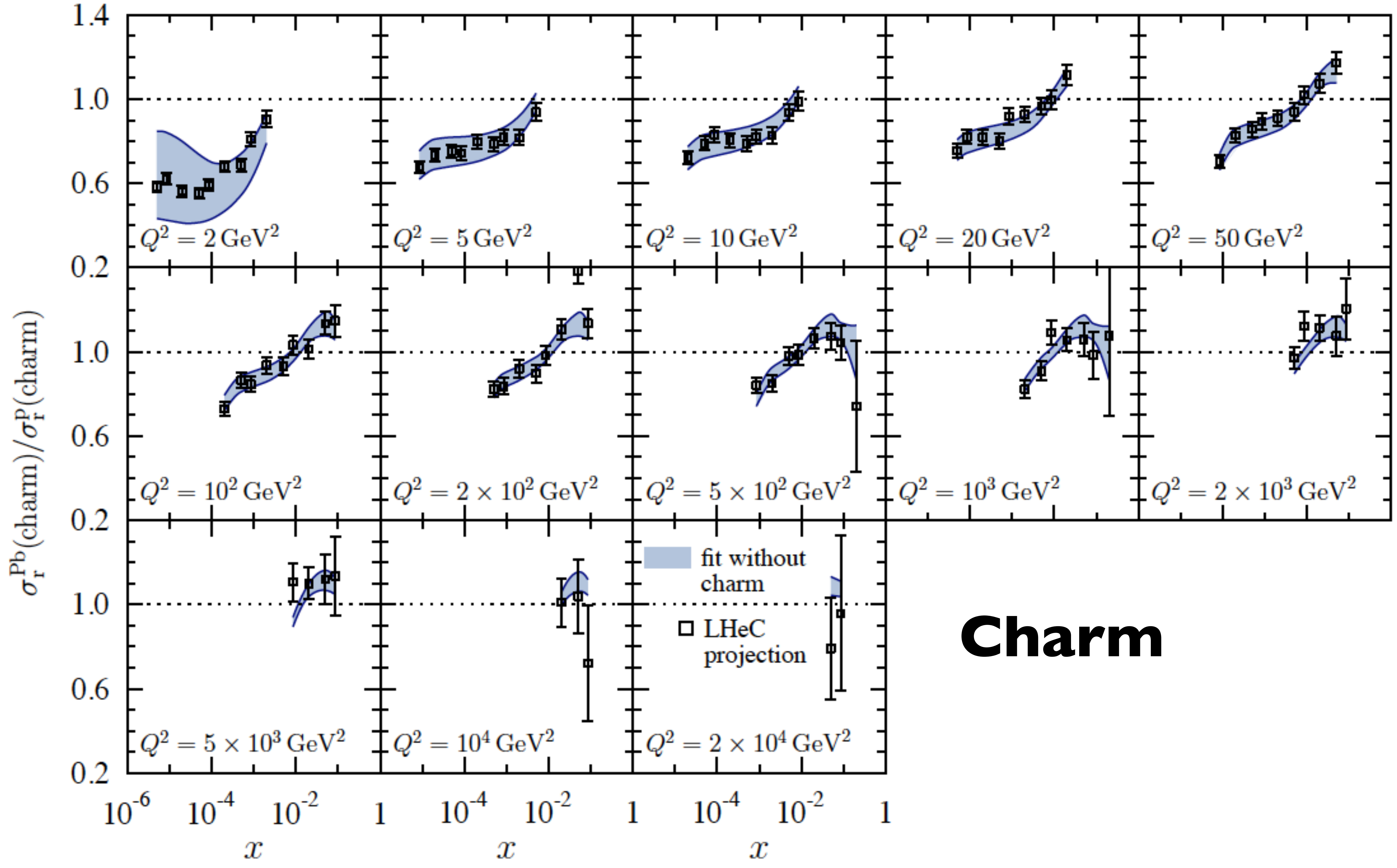

Charm

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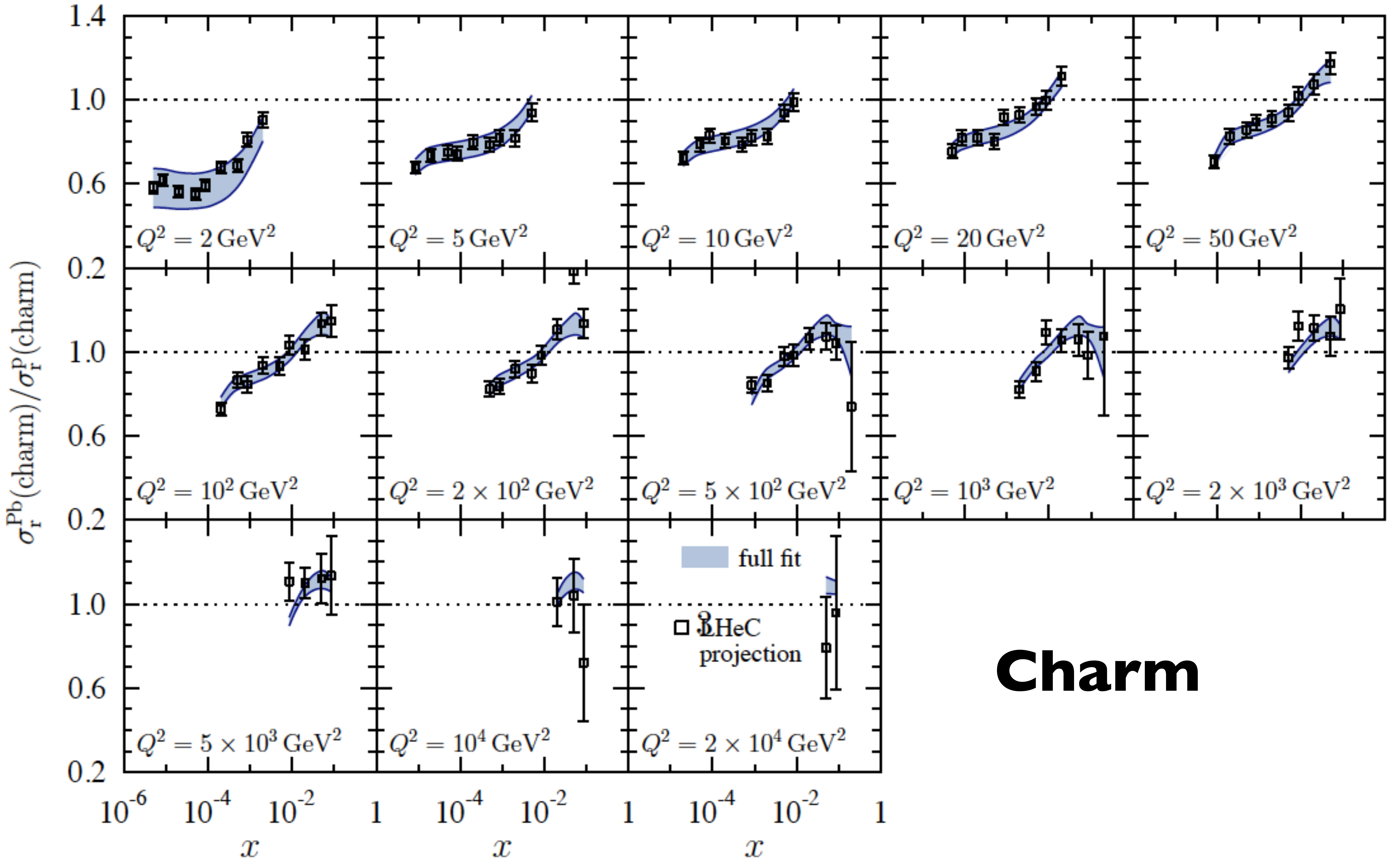
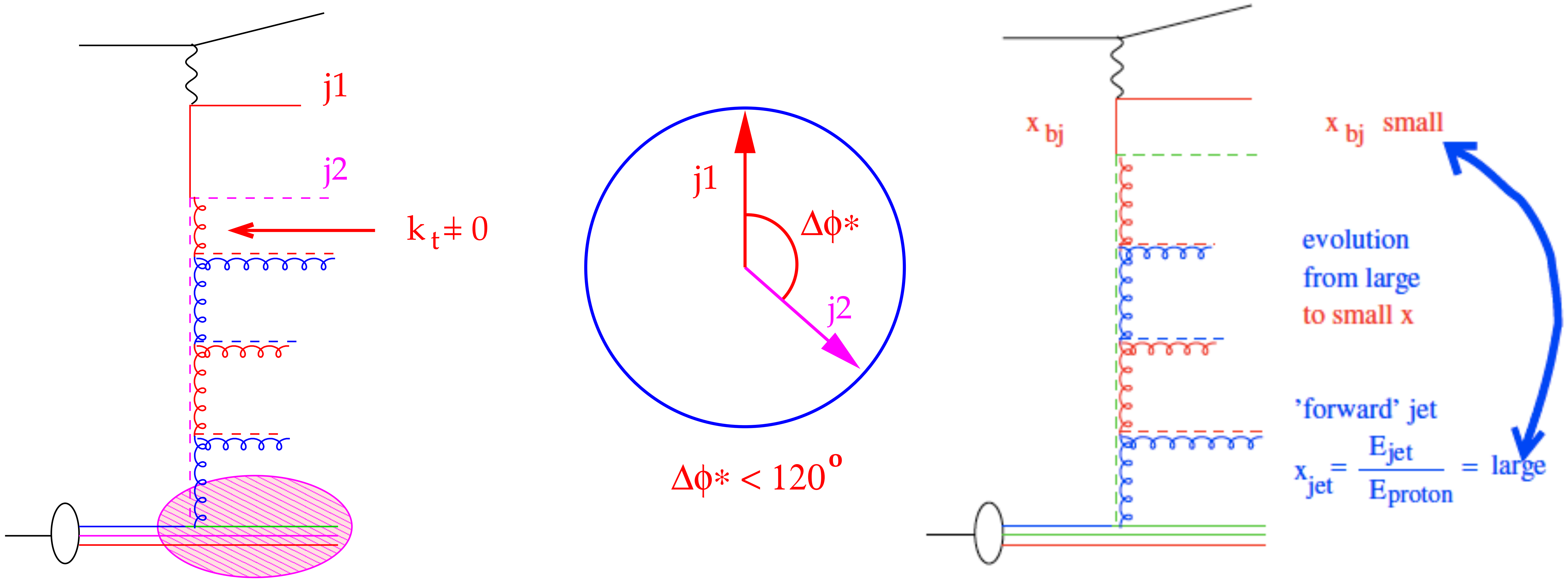


Charm

Azimuthal correlations (II):

- Studying dijet azimuthal decorrelation or forward jets ($p_T \sim Q$) in ep/eA/pp/pA would allow to understand the mechanism of radiation:
  - ➜ k_T-ordered: DGLAP.
  - ➜ k_T-disordered: BFKL.
  - ➜ Saturation?
- Further imposing a rapidity gap (diffractive jets) is most interesting.

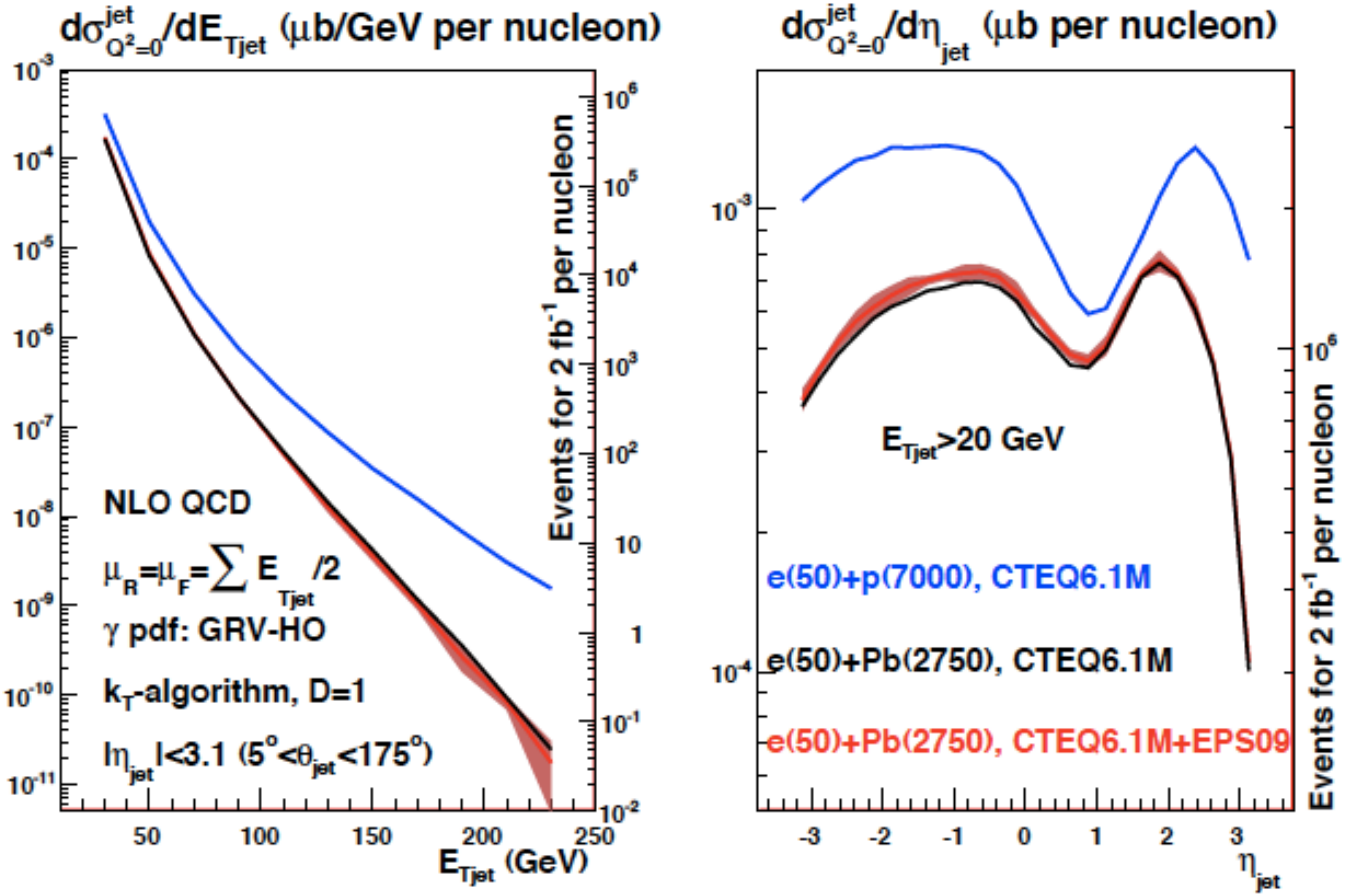


- **Nuclear and saturation effects on usual BFKL signals** (e.g. dijet azimuthal decorrelation, Mueller-Navelet jets) has not been extensively addressed (Kovchegov-Jalilian-Marian, see also the talk by A. Ramnath and K. Kutak): A-dependence?

Jets:

- Jet observables in AA: energy loss + response of the medium must be disentangled for characterisation of the medium.
- Jets not suppressed in pPb @ LHC: compatibility with softer observables? → **small systems**.
- Jets (inclusive and diffractive) abundantly produced in eA up to sizeable E_T, they can be used to **test factorisation and for precision studies of changes of QCD radiation in the nuclear environment ⇒ hard probes of the QGP.**

LHeC CDR 1206.2913

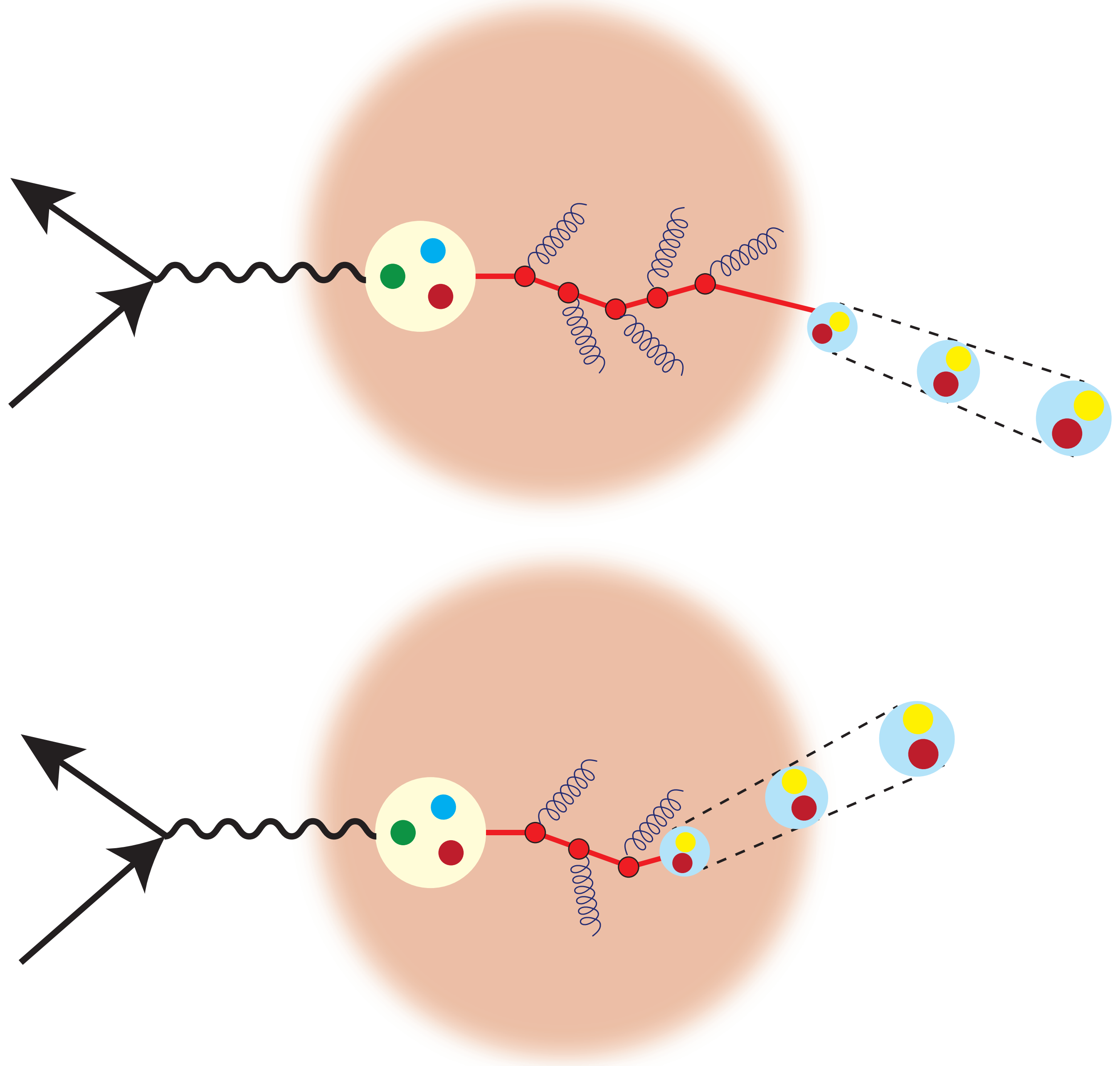


Fragmentation functions:

- eA: dynamics of QCD radiation and hadronization for light and heavy particles (energy loss of light and heavy, and quarkonium production and suppression), **relevant for particle production off nuclei** (nPDF determination in pA) **and for QGP analysis in AA.**

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

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



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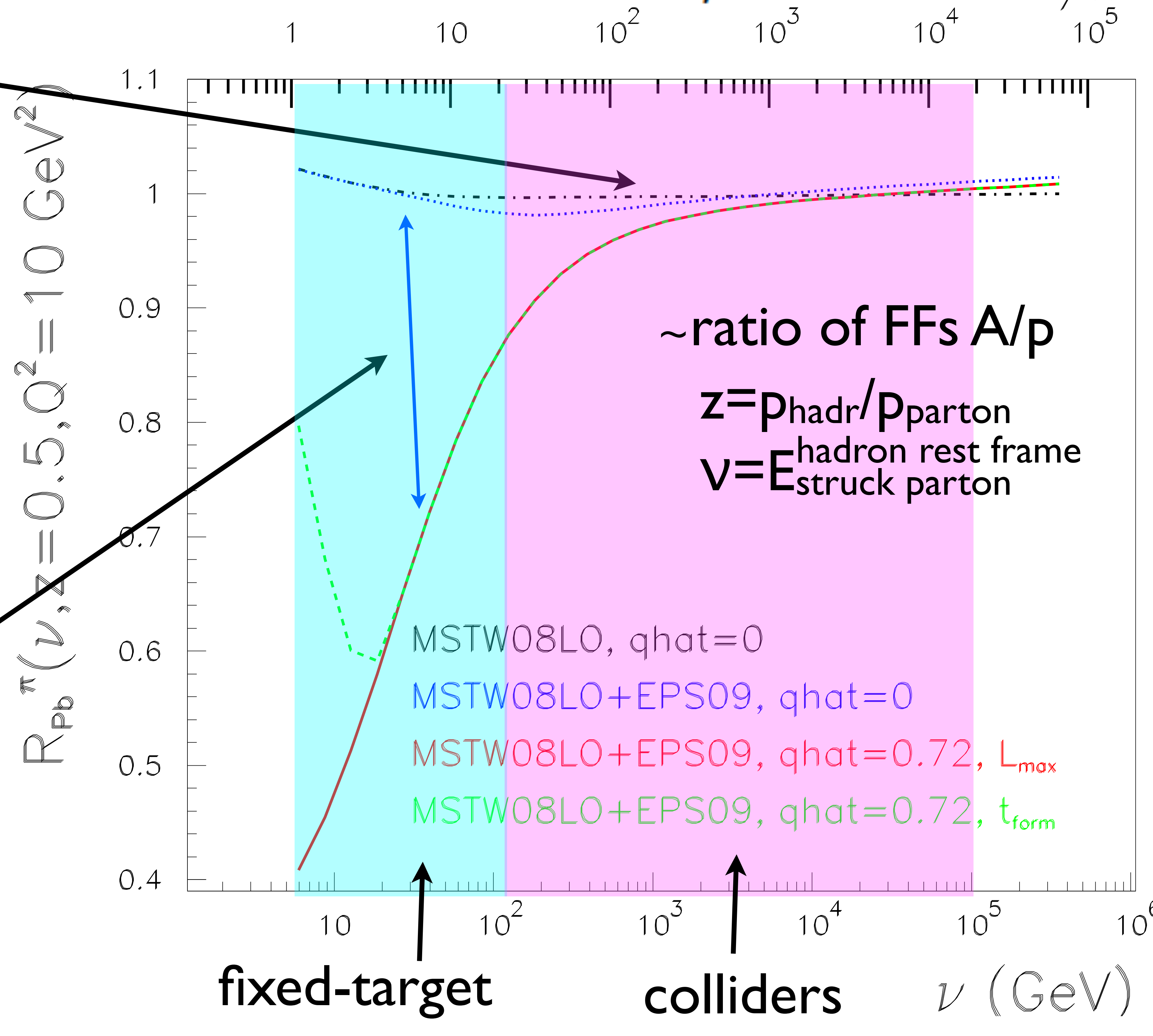

➜ Low energy: hadronization inside → formation time, (pre-)hadronic absorption,...