CERN Council Open Symposium on the Update of European Strategy for Particle Physics
Granada, Spain, May 15th 2019

Strong interaction physics at future eA colliders

Néstor Armesto
IGFAE, Universidade de Santiago de Compostela
nestor.armesto@usc.es

Contents:

1. Introduction:
   - ➜ Nuclear structure functions.
   - ➜ Small-x physics.
   - ➜ Implications on pA/AA.
   - ➜ Machines and kinematics.

2. Partonic structure of the nucleus:
   - ➜ Collinear nPDFs.
   - ➜ Diffractive nPDFs.

3. New dynamics at small x:
   - ➜ Inclusive observables.
   - ➜ Diffractive observables.
   - ➜ Correlations.

4. Nuclear effects in the final state:
   - ➜ Jets.
   - ➜ Fragmentation functions.

Not yet final!

5. Community.

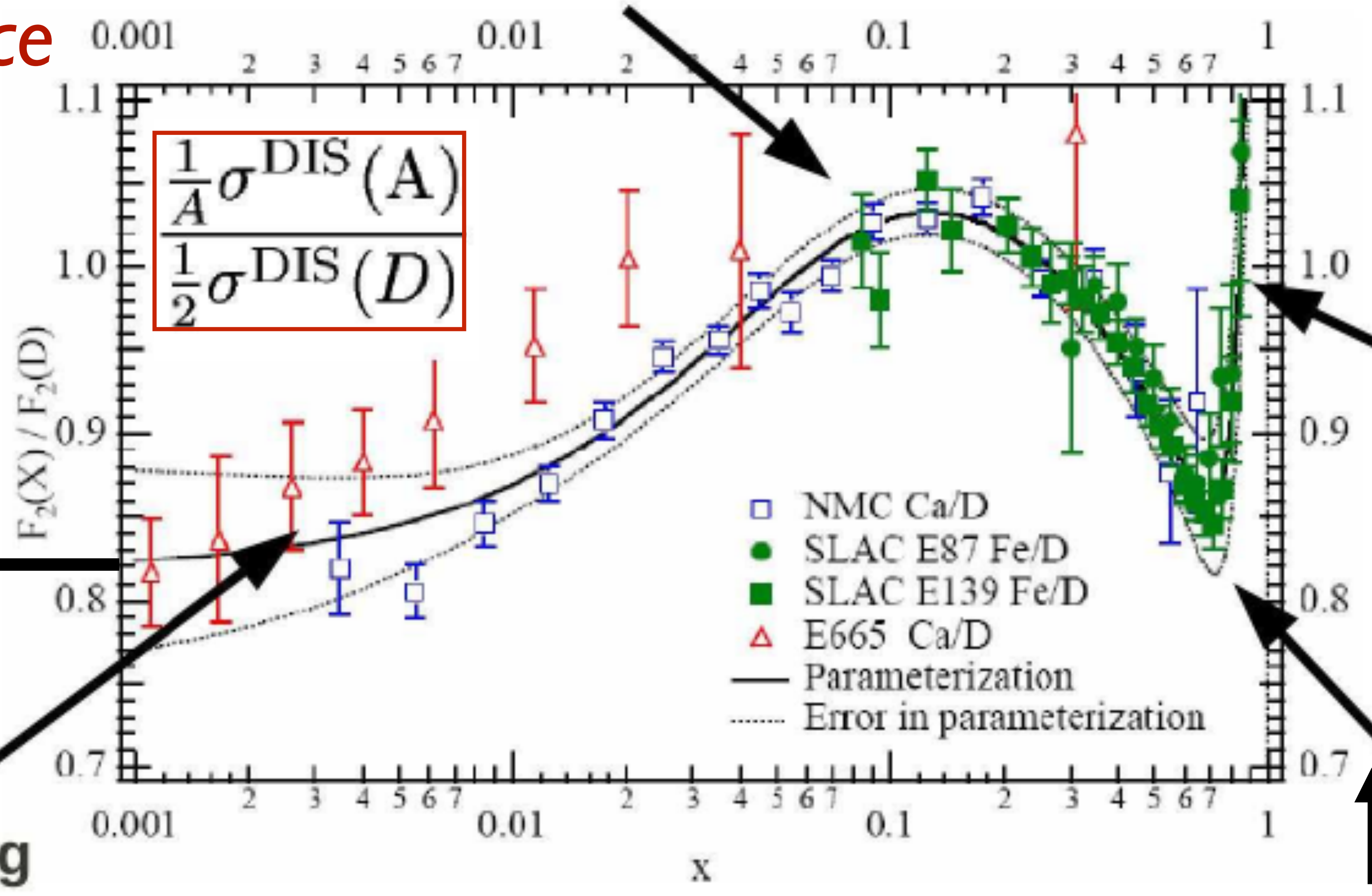
6. Summary/recommendations.

Note: this is a personal selection of topics; for additional discussions and supplemental material (e.g. on spin and relations with other fields), see Thomas Gehrmann, Urs Wiedemann, Uta Klein and Gavin Salam's talks, and the backup.

Nuclear structure functions:

Flavour dependence?; relation with shadowing and coherence

Anti-shadowing



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

ePb at LHeC/ FCC-eh

eAu at EIC

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, assuming collinear factorisation.

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

Nuclear PDFs, obeying the standard DGLAP

Usual perturbative coefficient functions

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

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

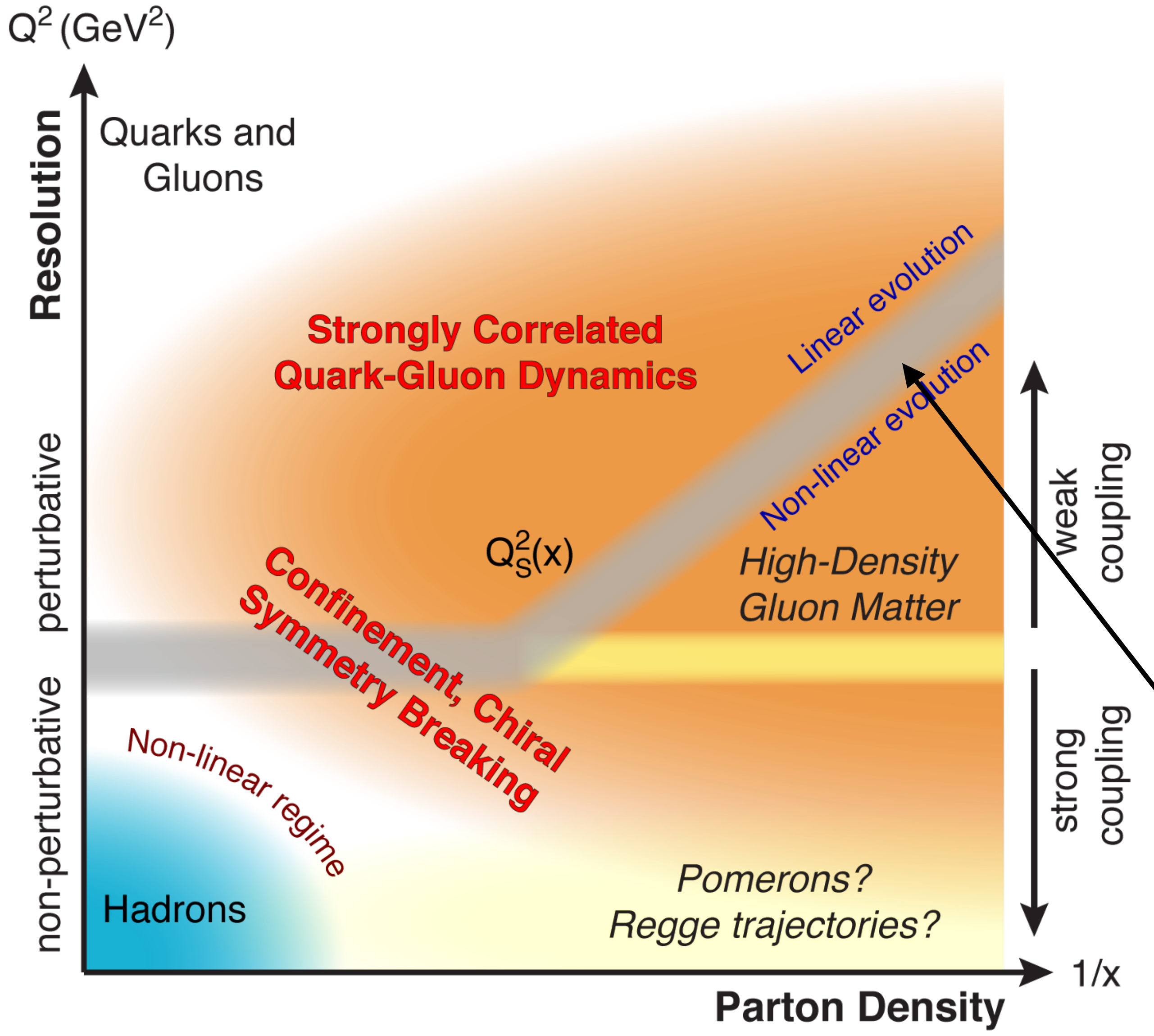
Small-x physics:

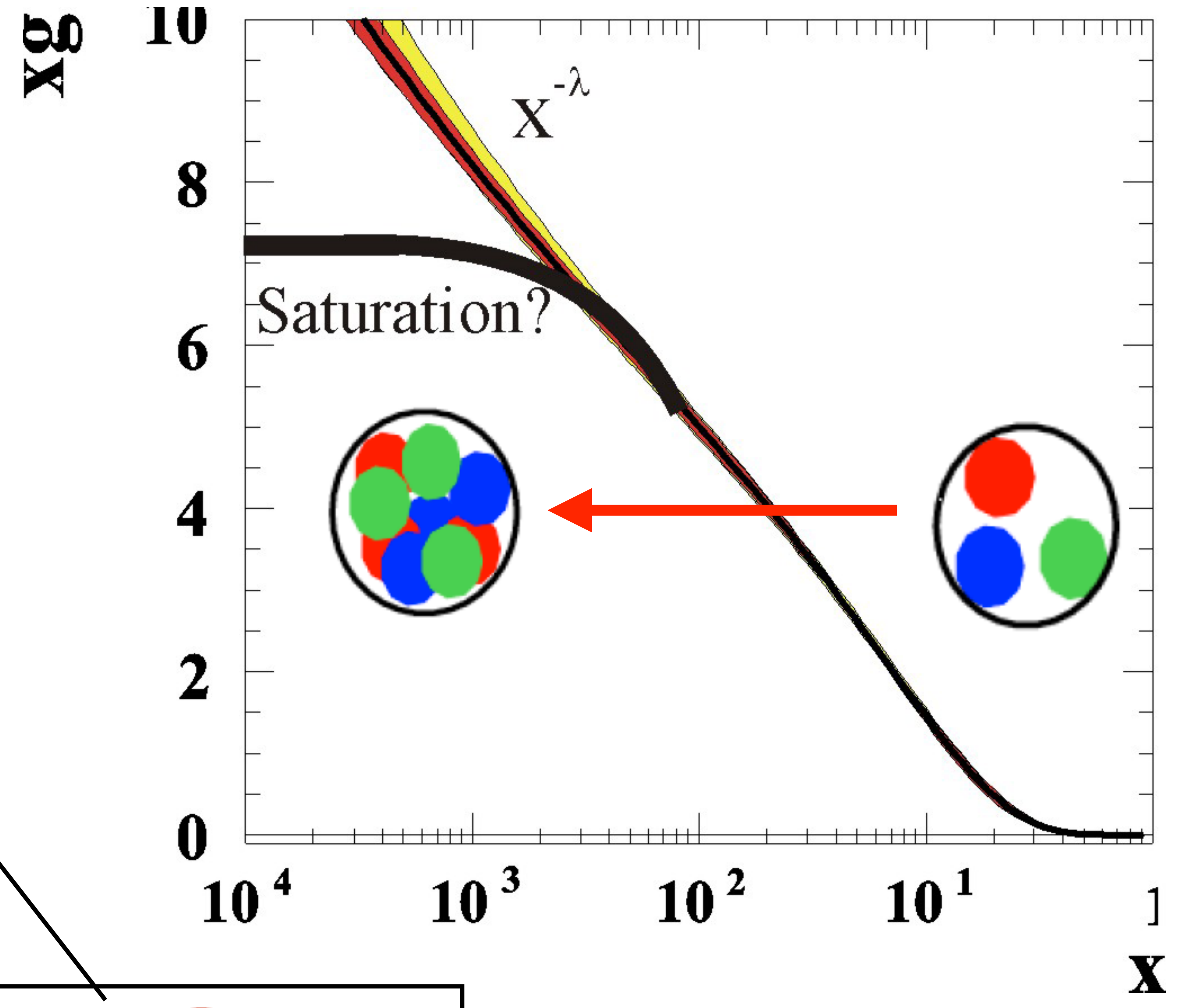
- HERA found $xg \propto x^{-0.3}$.
- Present data can be described by:
  - ➜ Linear evolution approaches, either DGLAP or resummation at low x.
  - ➜ Non-linear approaches: saturation.

- Theory: at very high energies (i.e. small x), non-linear dynamics must be present.

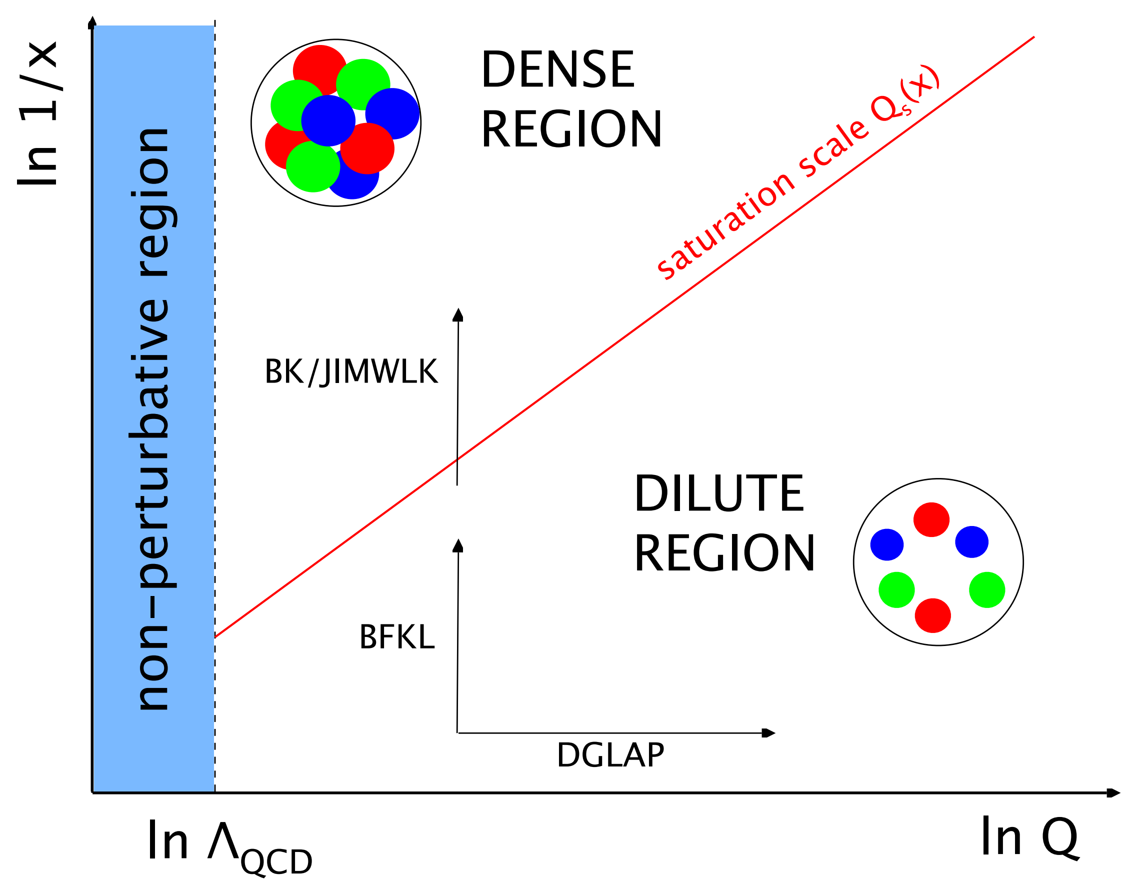
Where is it? At HERA:
  - ➜ Hints of failure of DGLAP at small x, Q^2, resummation?
  - ➜ No azimuthal structures (ridge) found for Q^2>5 GeV^2.

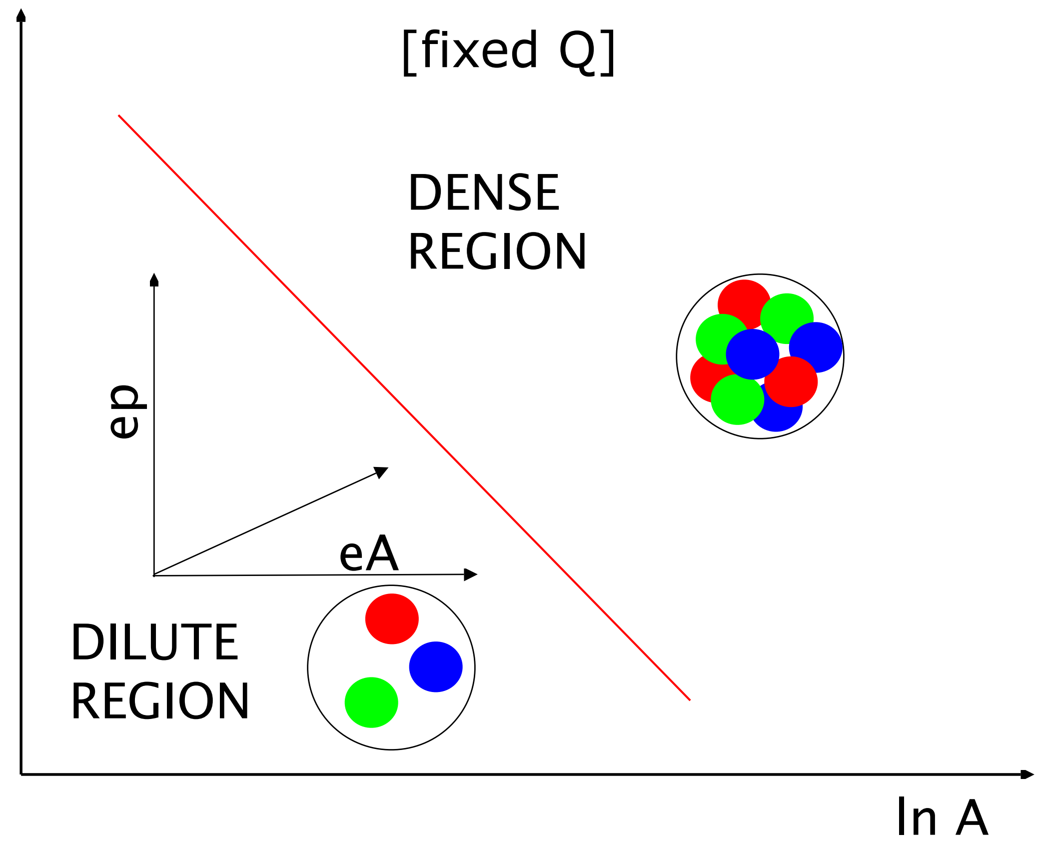
- Non-linear dynamics density-driven: ↓x/↑A ⇒ **ep & eA, large range in 1/x & Q^2, essential.**





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





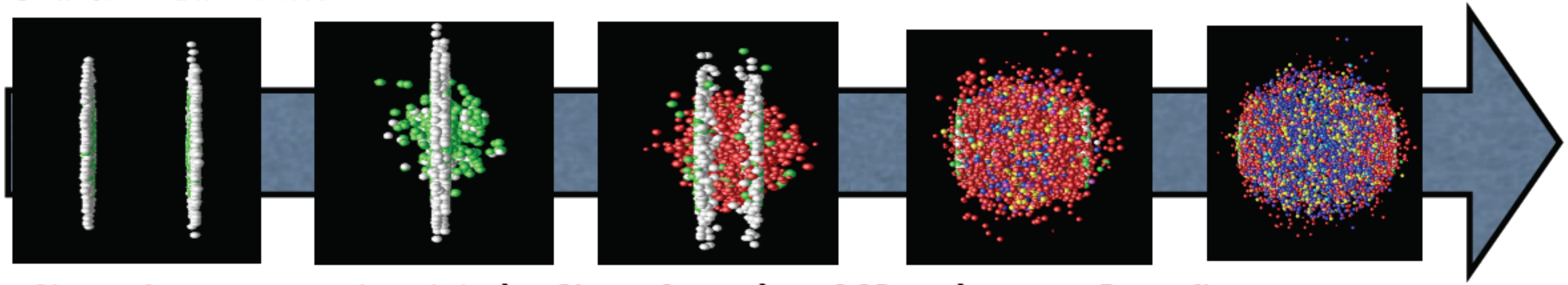
Implications on pA/AA:

- 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?

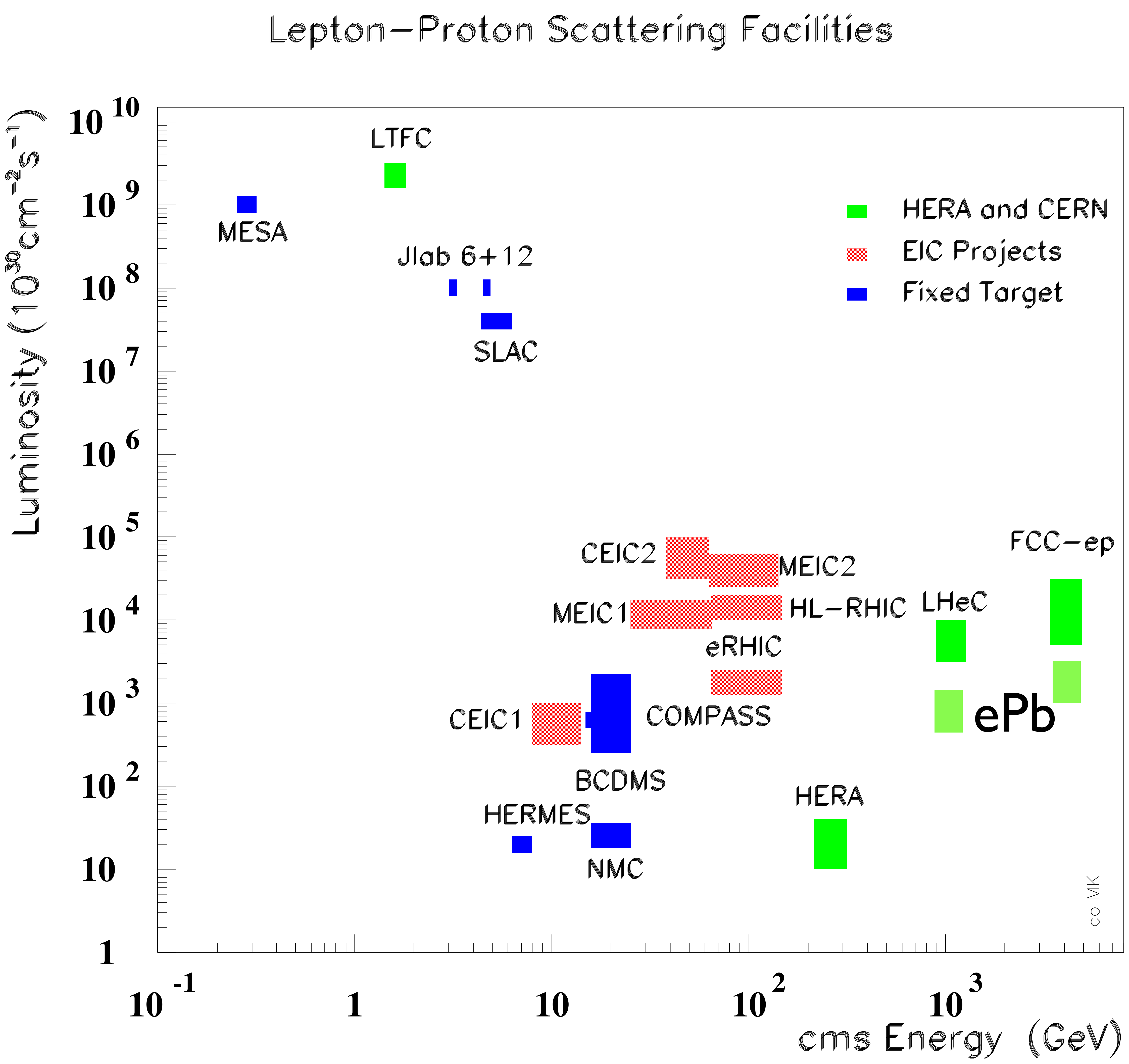
- Dynamical mechanisms for such opacity? Weak or strong coupling?
- How to extract accurately medium parameters?

➜ eA: nuclear WF and mechanism of particle production.

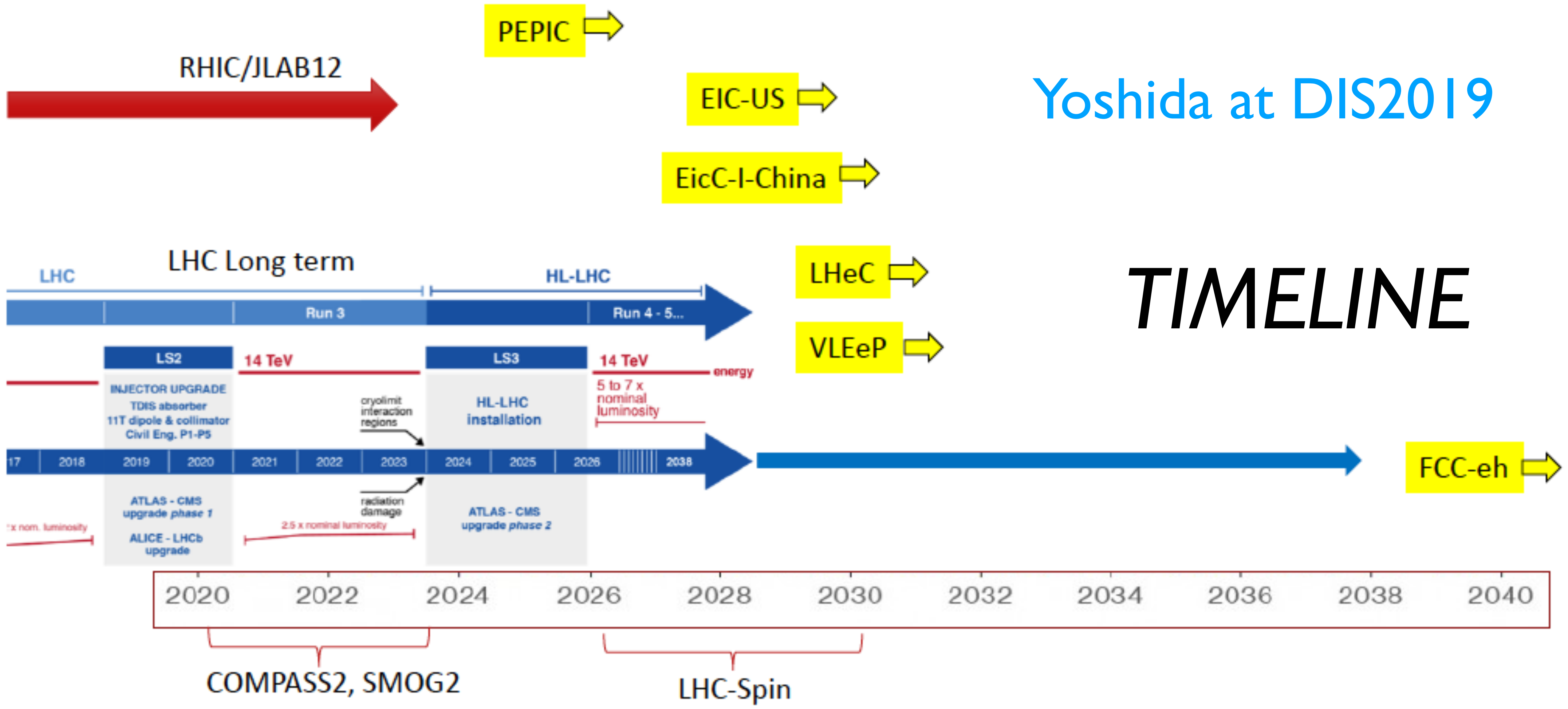
➜ eA: initial conditions; how small can a system become and still show ‘collectivity’?

➜ eA: in-medium QCD radiation, cold nuclear effects on hard probes.

Machines:

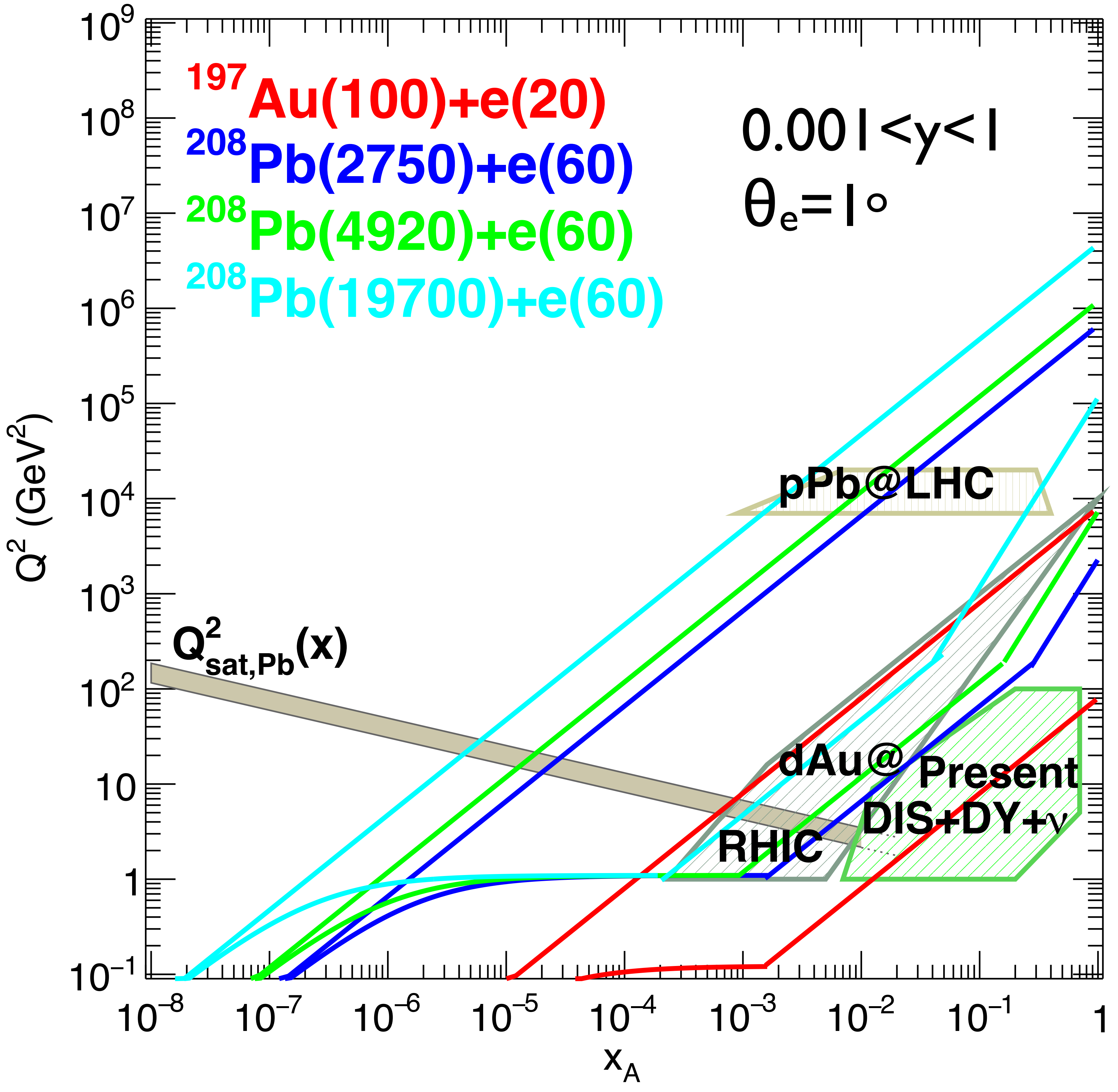


- ***Projects of eA colliders with E_{cm} ~ 0.1 (US and Ch EIC) and 1 (LHeC and FCC-eh) TeV/A addressing different physics.***



Kinematics:

EIC/LHeC



- **EIC/LHeC-FCC-eh**: extension of 2/4-5 orders of magnitude in x and Q^2 wrt existing DIS data.

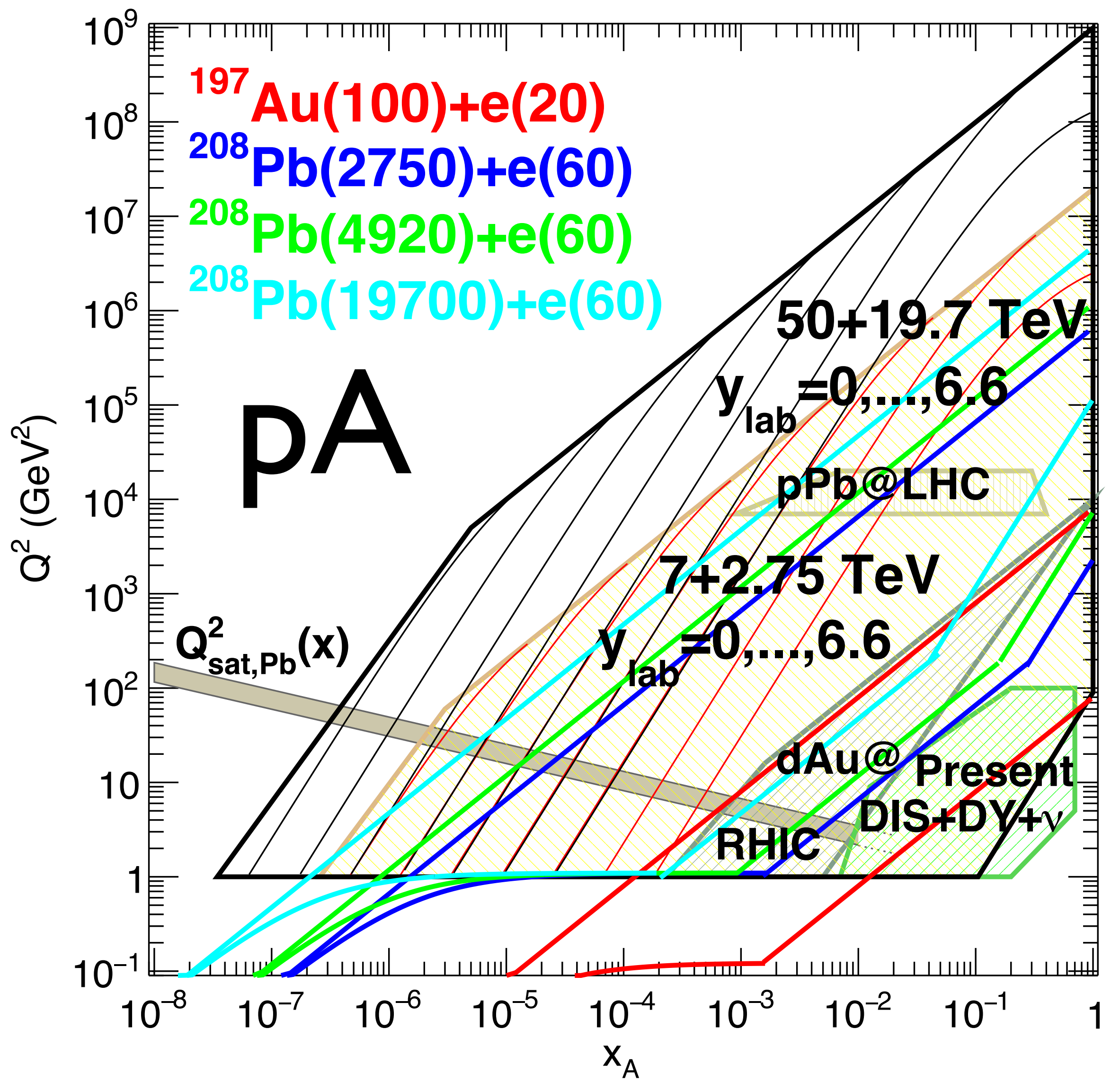
- **EIC/LHeC versus hh**:

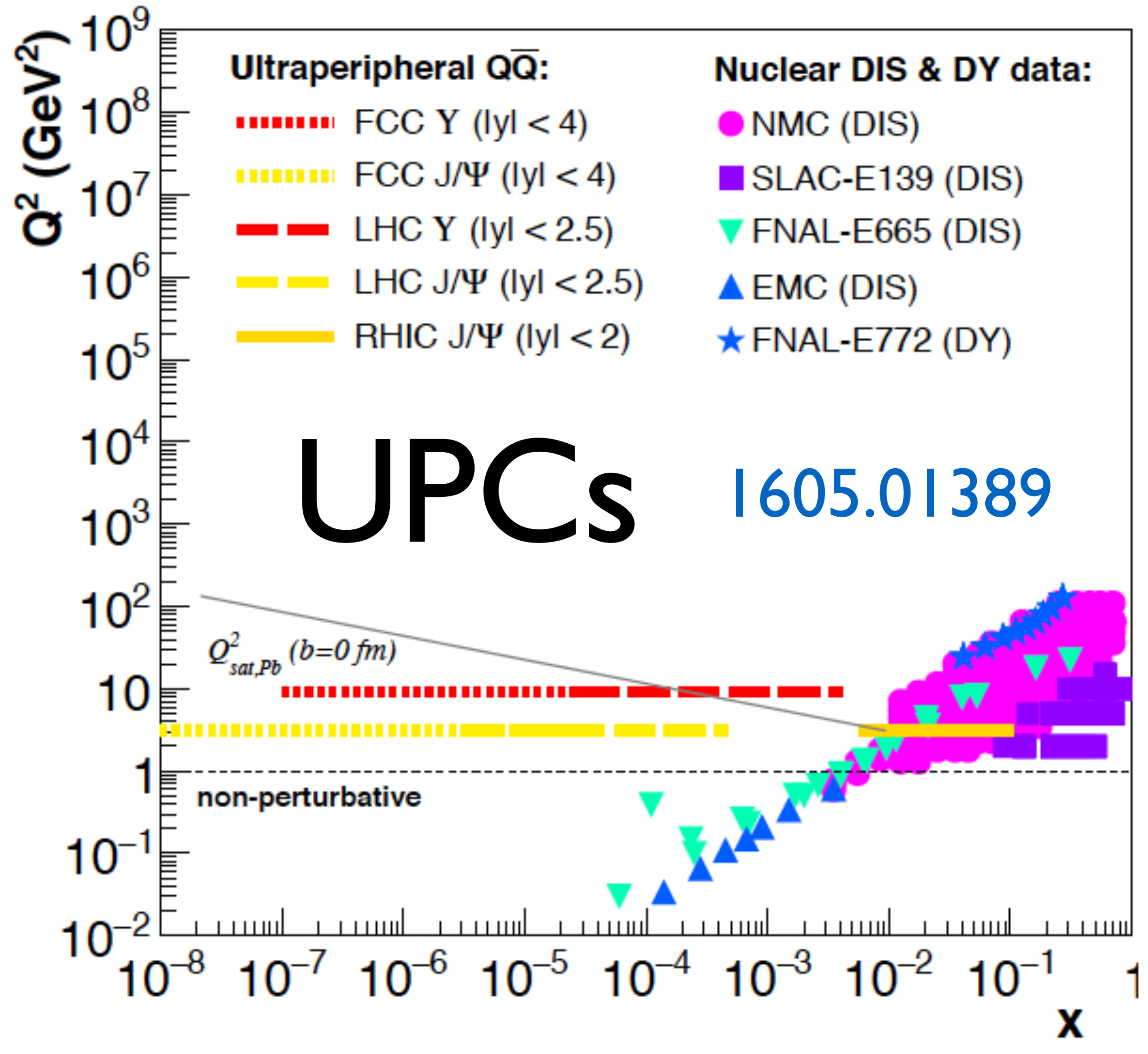
➜ pA/AA covers largest range in kinematics.

➜ **DIS offers**:

➤ A clean experimental environment - low multiplicity, no pileup, fully constrained kinematics x,Q^2 reconstructing the outgoing lepton;

➤ A more controlled theoretical setup - many 1st-principles calculations, factorisation tests.





Contents:

1. Introduction:
   - ➜ Nuclear structure functions.
   - ➜ Small-x physics.
   - ➜ Implications on pA/AA.
   - ➜ Machines and kinematics.

2. Partonic structure of the nucleus:
   - ➜ Collinear nPDFs.
   - ➜ Diffractive nPDFs.

3. New dynamics at small x:
   - ➜ Inclusive observables.
   - ➜ Diffractive observables.
   - ➜ Correlations.

4. Nuclear effects in the final state:
   - ➜ Jets.
   - ➜ Fragmentation functions.

Not yet final!

5. Community.

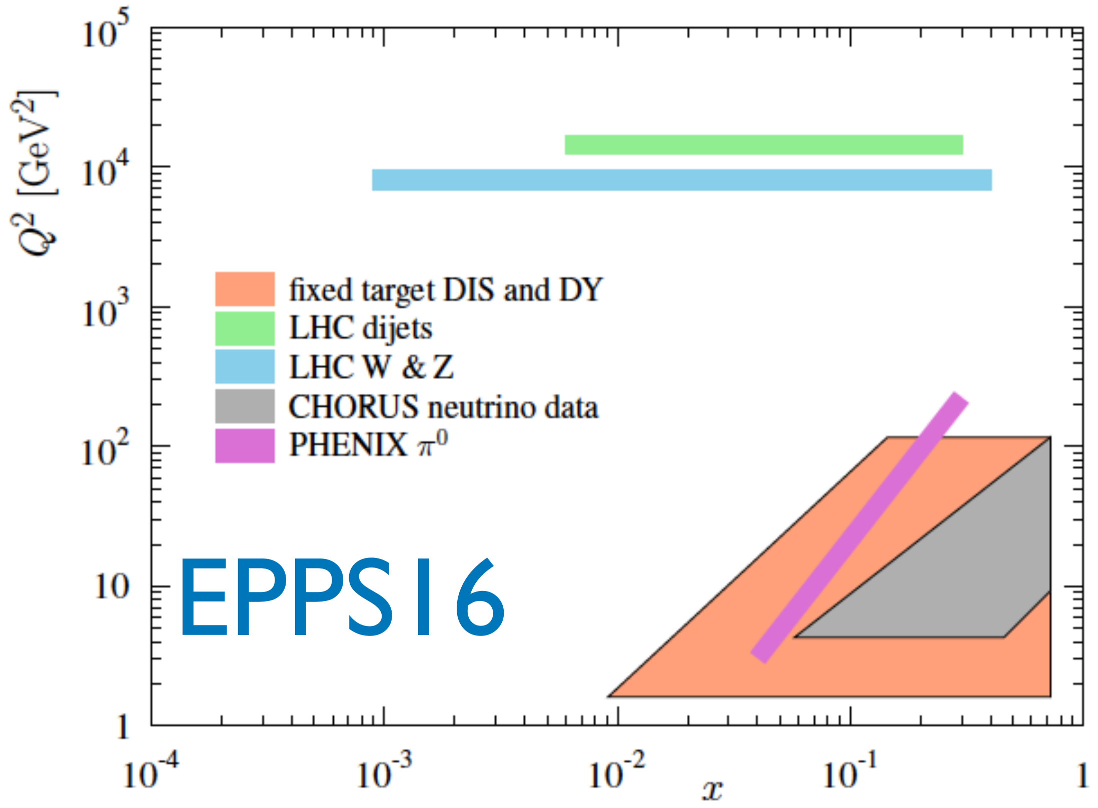
6. Summary/recommendations.

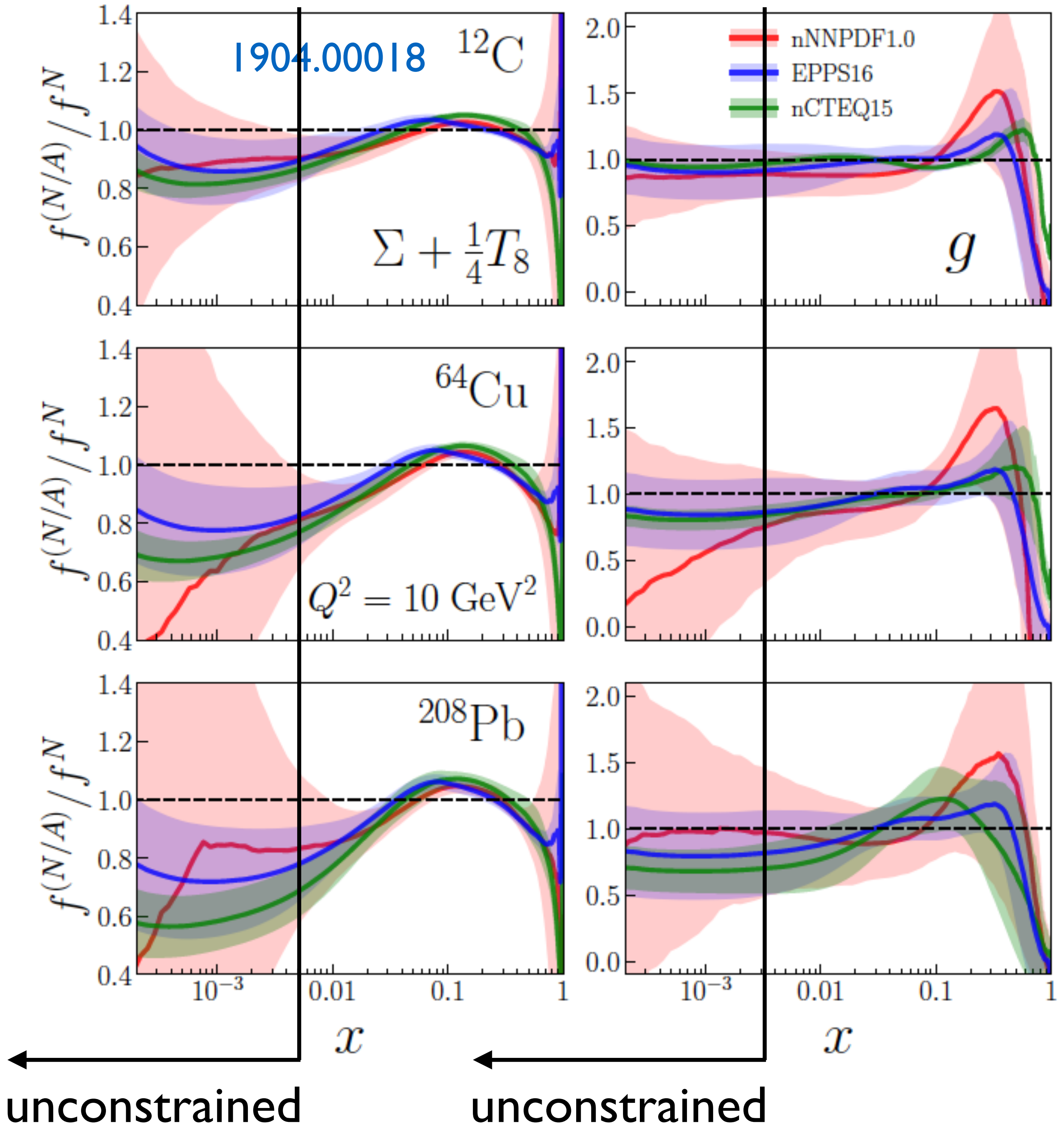
Note: this is a personal selection of topics; for additional discussions and supplemental material (e.g. on spin and relations with other fields), see Thomas Gehrmann, Urs Wiedemann, Uta Klein and Gavin Salam's talks, and the backup.

nPDFs: status

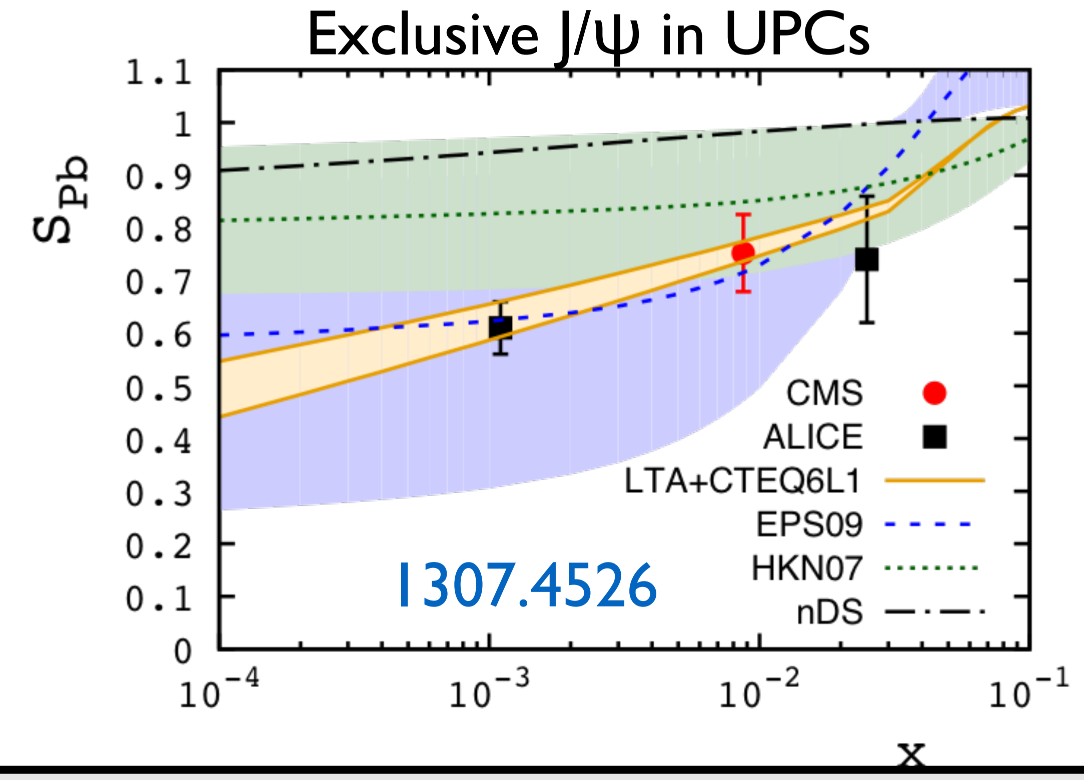
- **Large uncertainties** for x<0.01 and for large x glue (parametrisation biases, weakly constrained flavour decomposition and impact parameter dependence); small impact of present LHC data.
- **Few data for any <u>single A</u>** e.g. Pb (15 DIS+30 pPb+νA): A-dependence of initial conditions.
- **Sizeable impact on precision in hard probes of the QGP.**

$$R_{i/A}(x,Q^2) = \frac{f_{i/A}(x,Q^2)}{A f_{i/p}(x,Q^2)}$$





- **HL-LHC data to provide additional constrains**, see 1812.06772: heavy quarks (including top) and quarkonium (inclusive, and exclusive in UPCs) under study.
- **eA will provide precise nPDFs to be contrasted with pA/AA**: checks of factorisation in the nuclear environment required for hard probes of the QGP.

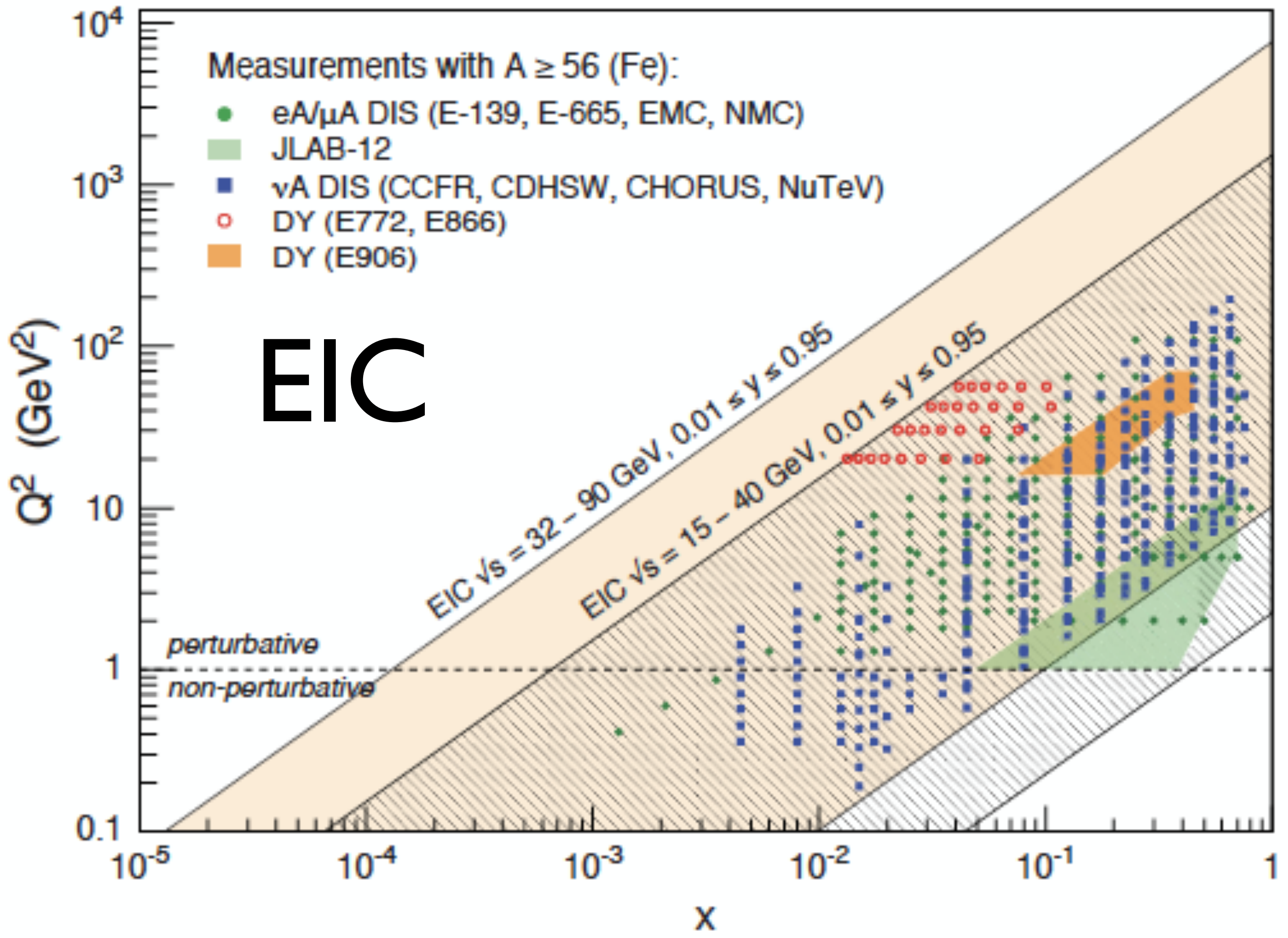


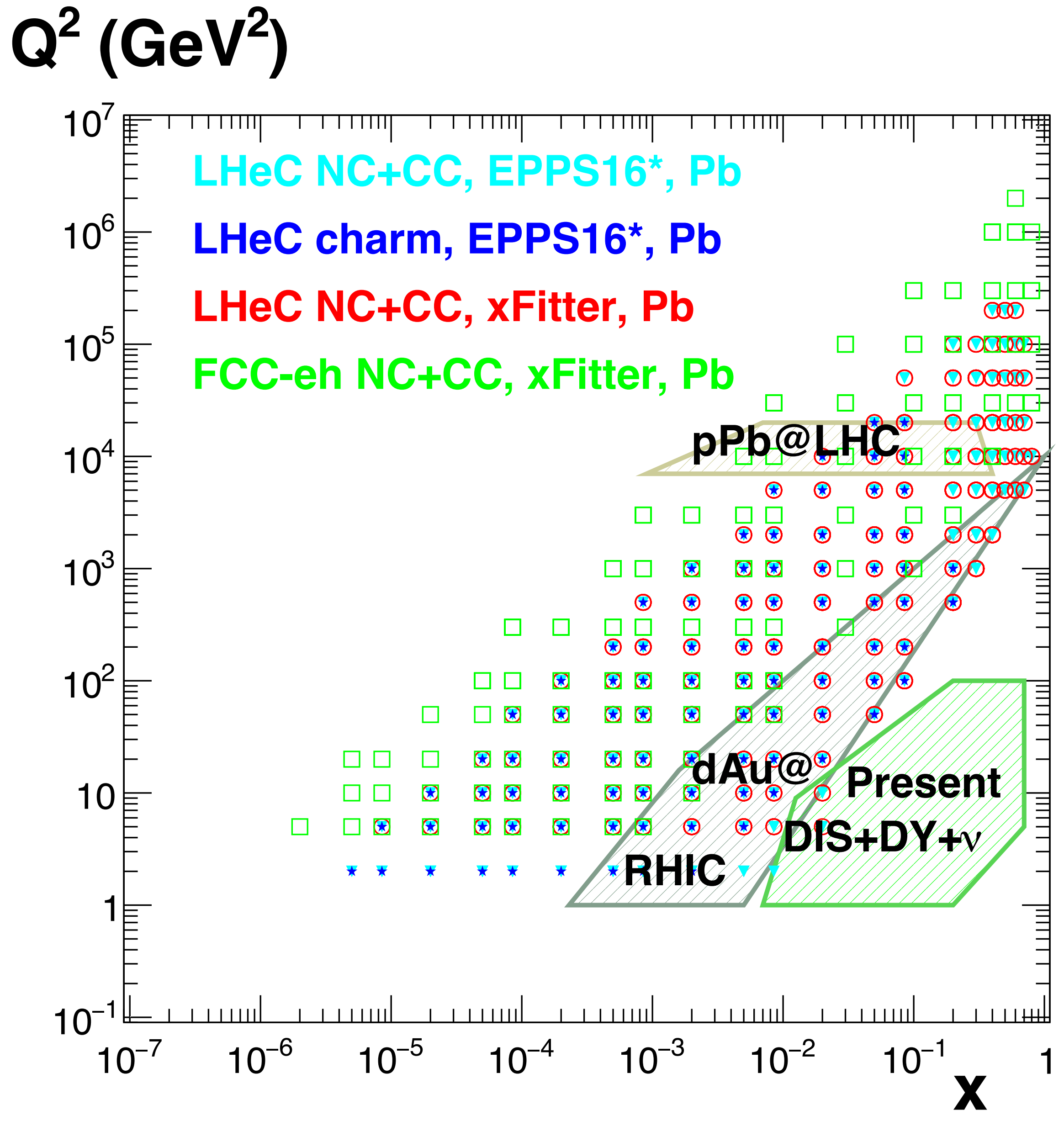
nPDFs: fits to a single nucleus

- LHeC/FCC-eh ePb and EIC eAu pseudodata included in EPPS16-like global fits and HERAPDF DIS-only fits: **large reduction of uncertainties in a completely new kinematical region.**

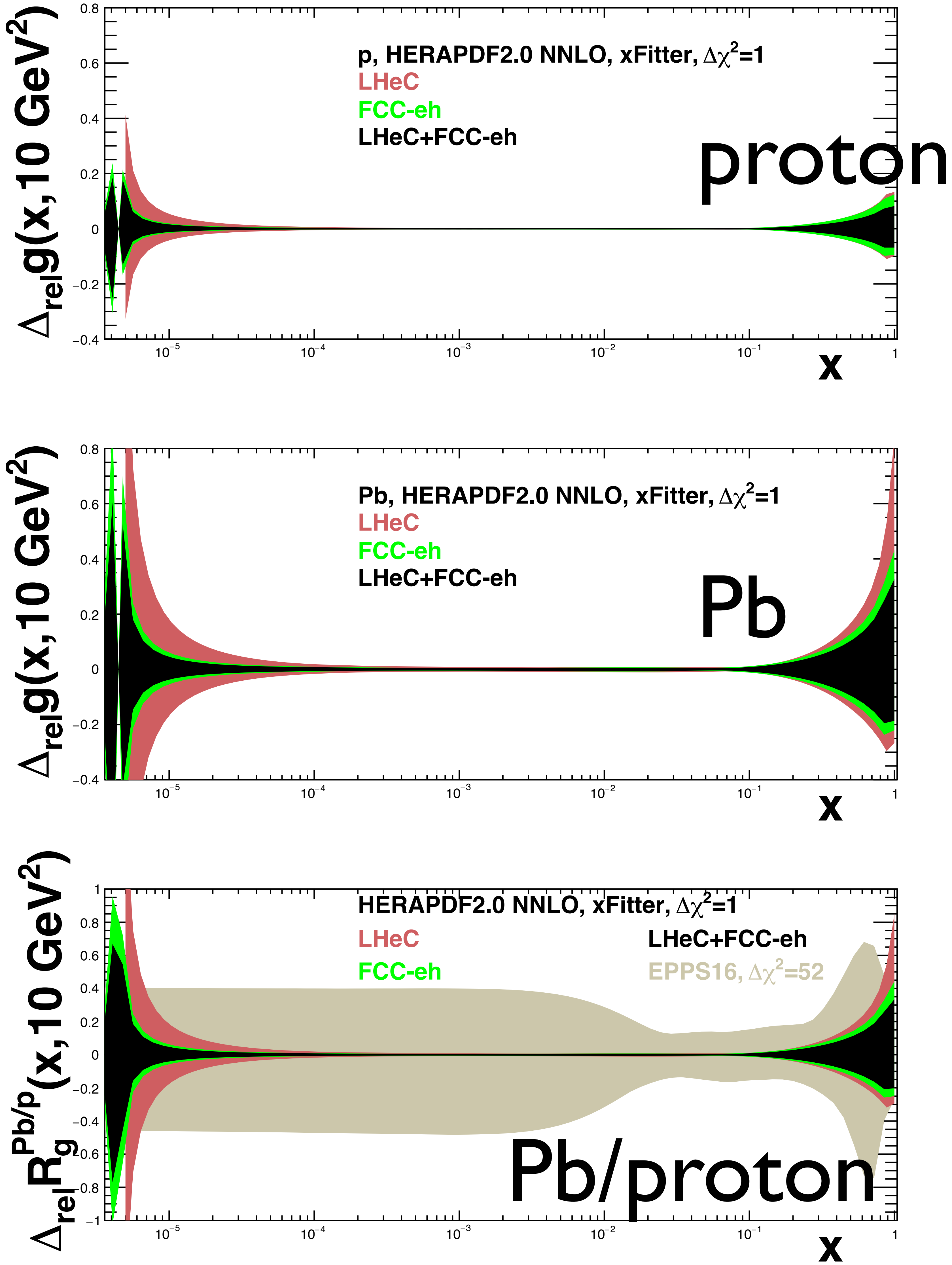
- Fit to a single nucleus possible: no A-dependence.
- Charm, beauty, c-tagged CC for strange (not yet in) ⇒ complete unfolding of different parton species.

1708.05654



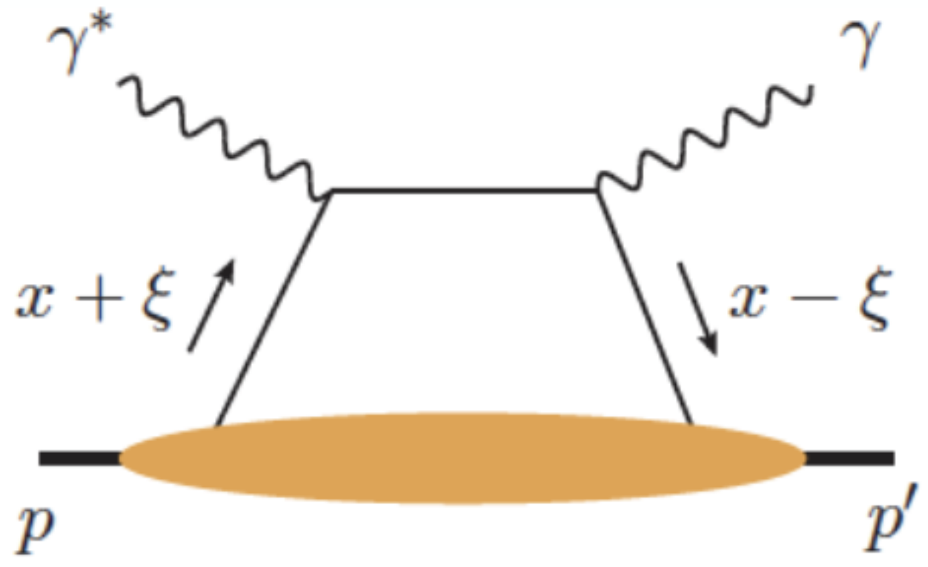


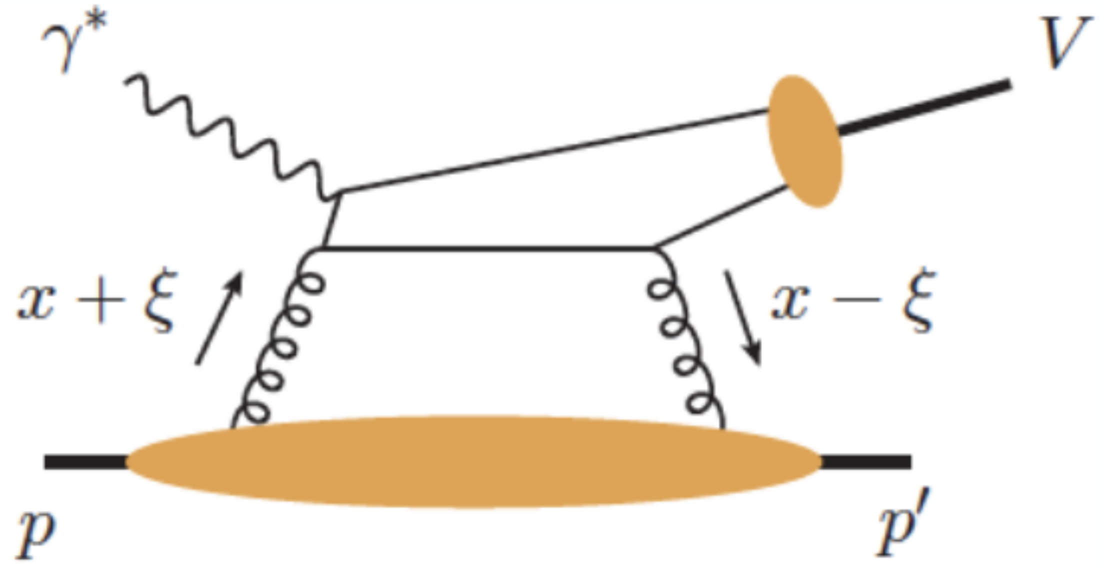
LHeC/FCC-eh

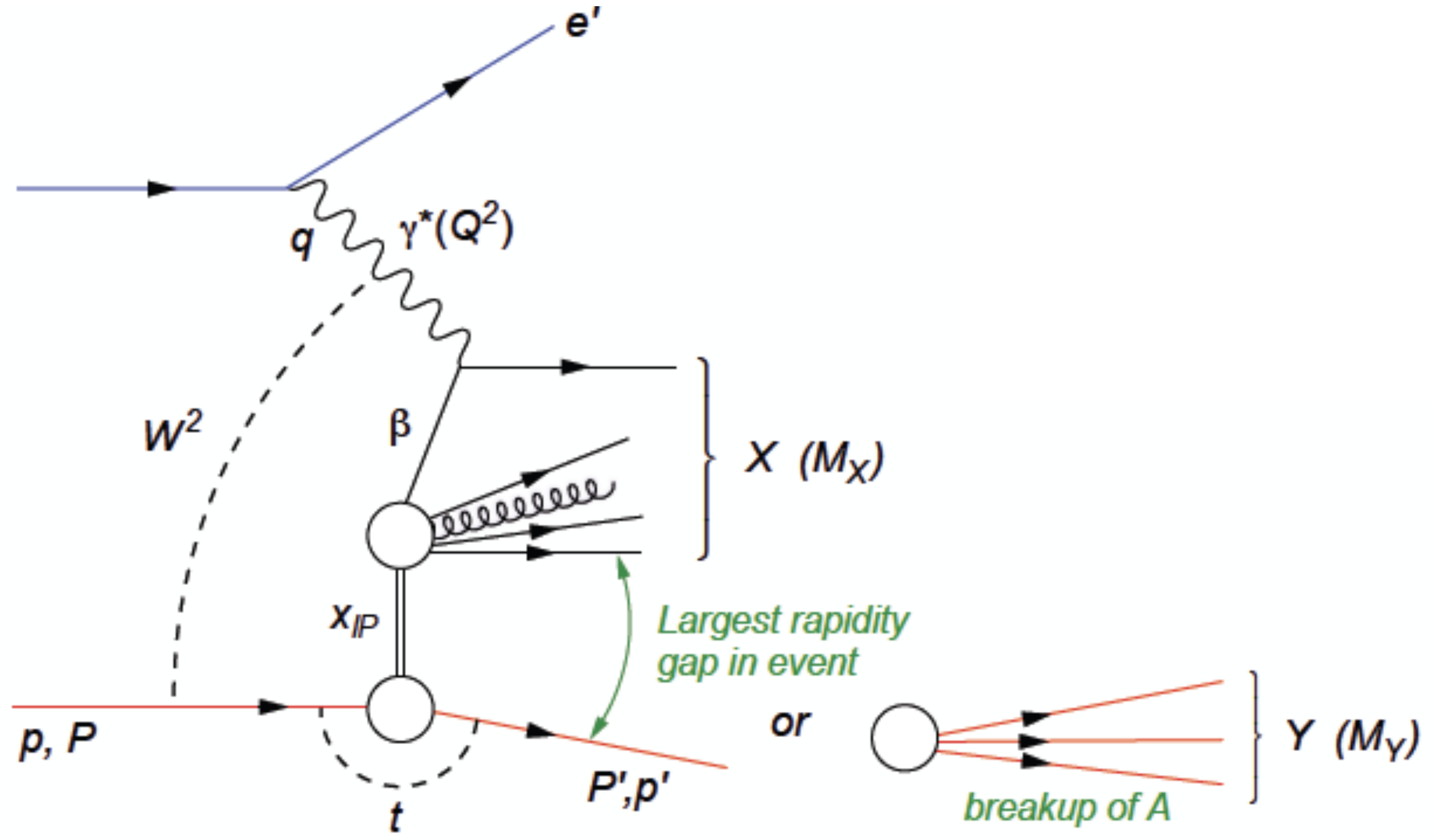


GPDs and TMDs:

- The extraction of GPDs and TMDs and of their evolution equations is a huge undergoing program: scarcely known in the proton, **nuclear effects are mostly unknown**.







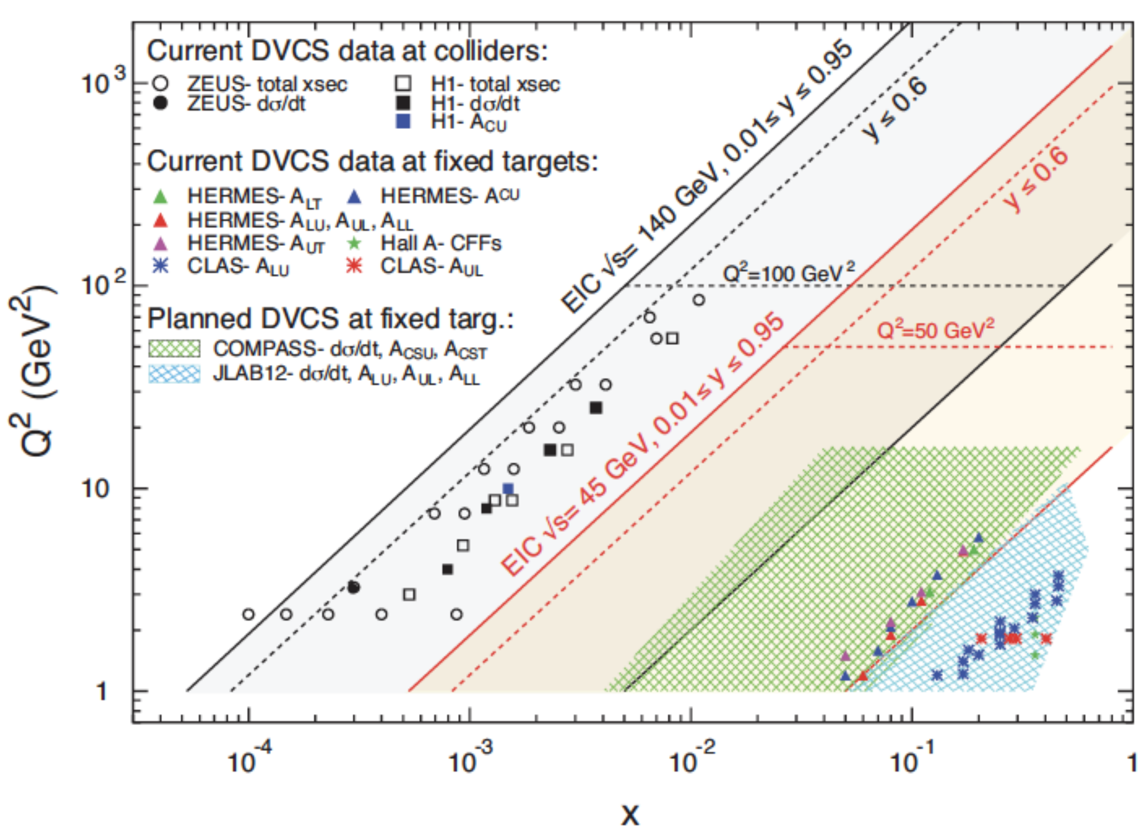
coherent
p/A stays intact

incoherent
p/A breaks up

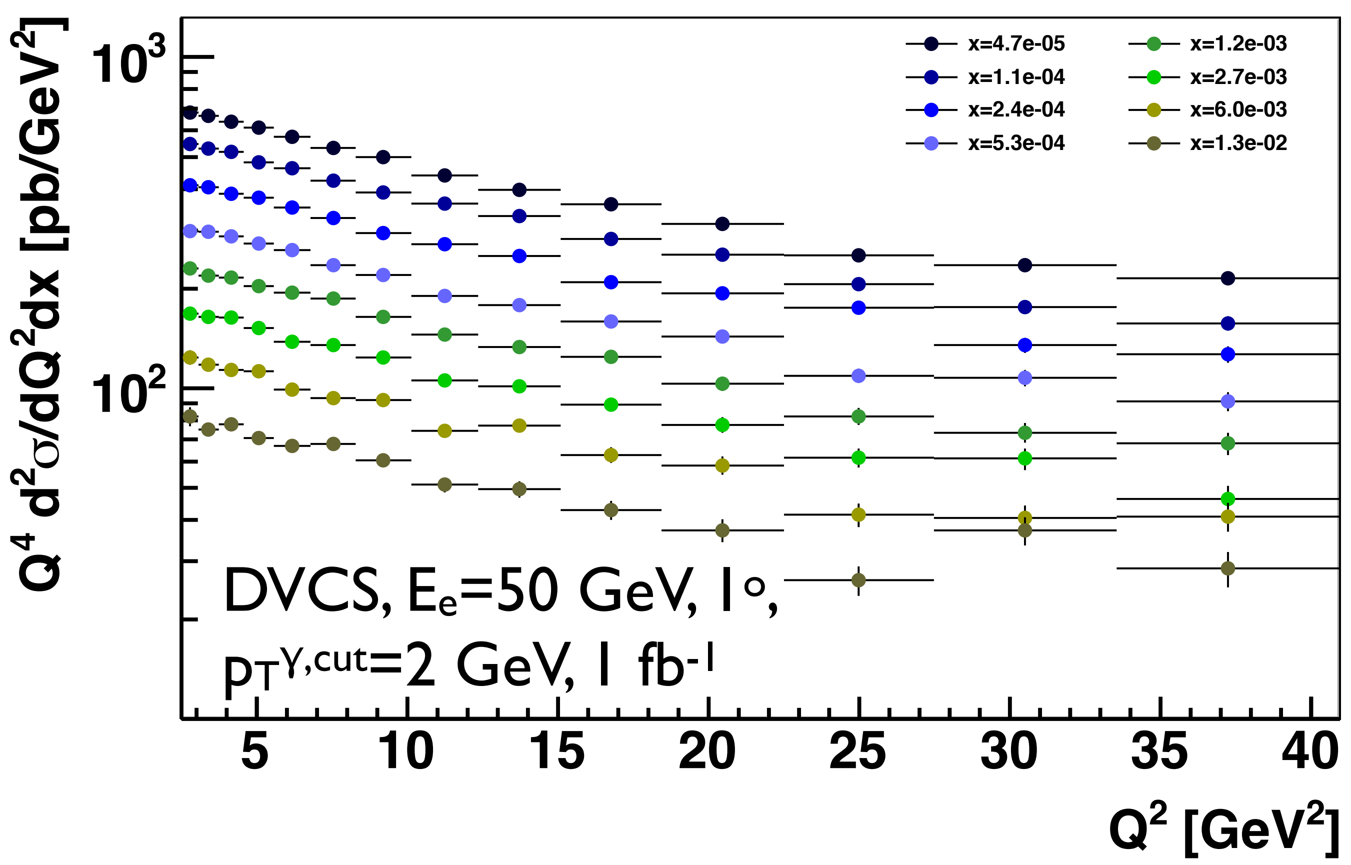
- Coherent exclusive production of γ and VM yields information about q and g GPDs.

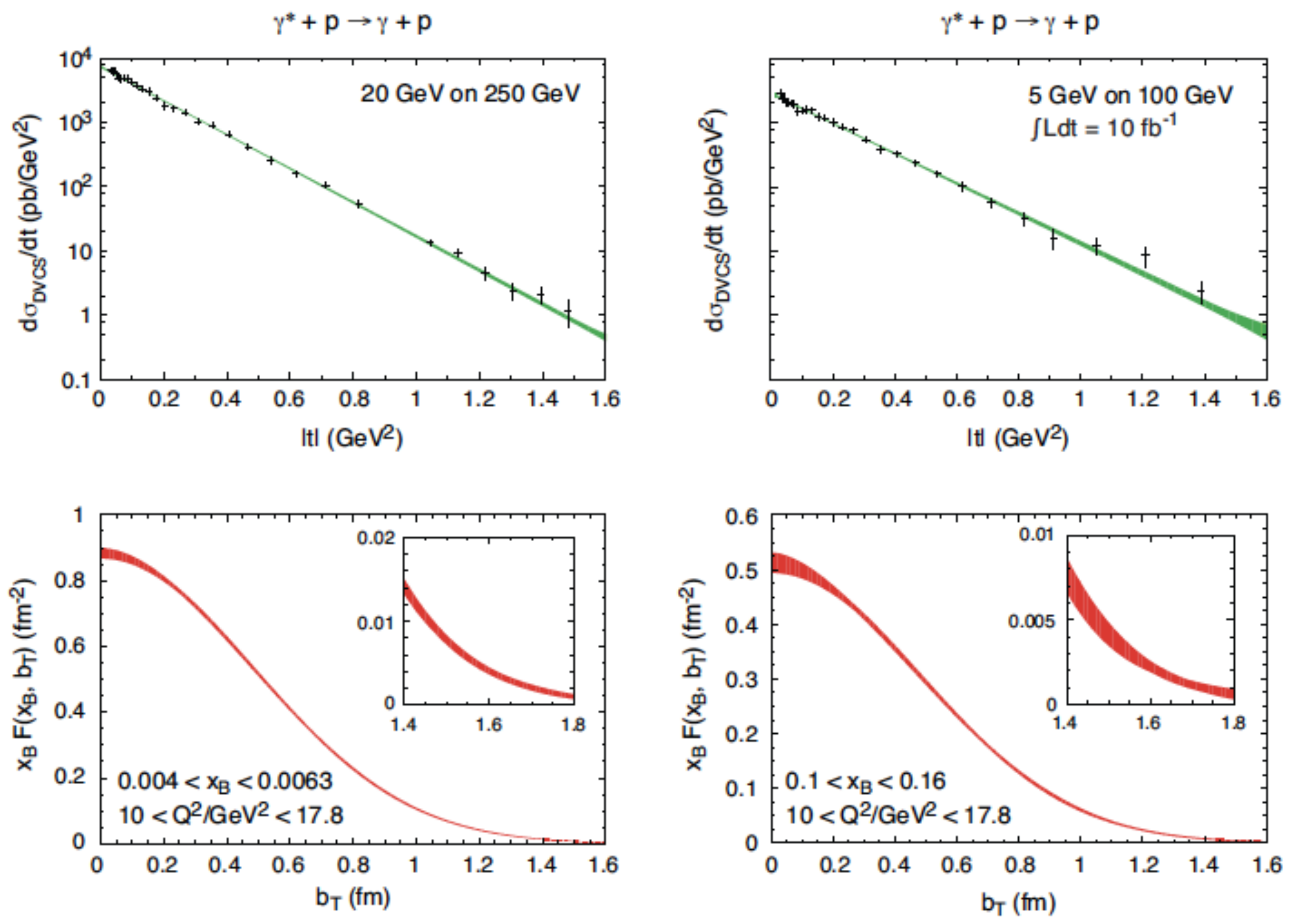
1212.1701

EIC



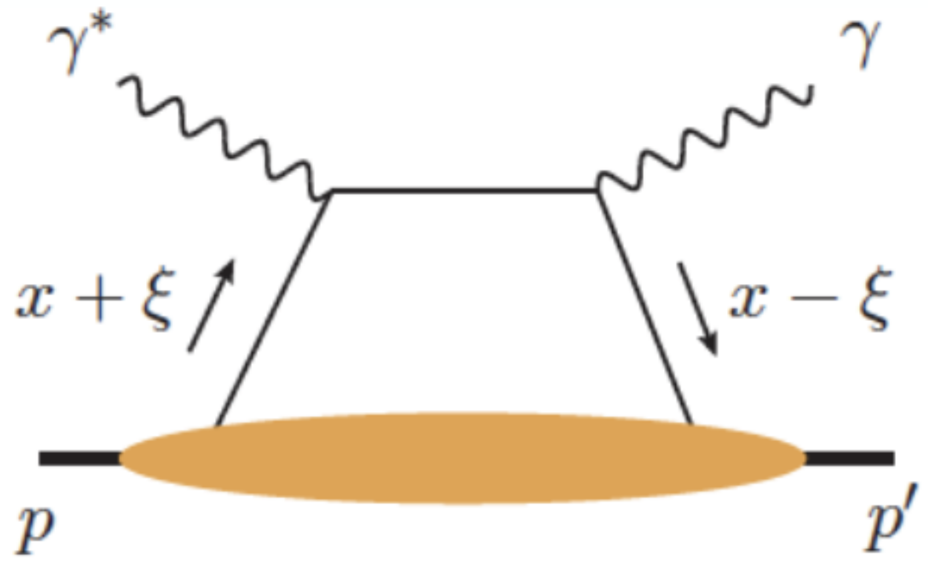
LHeC

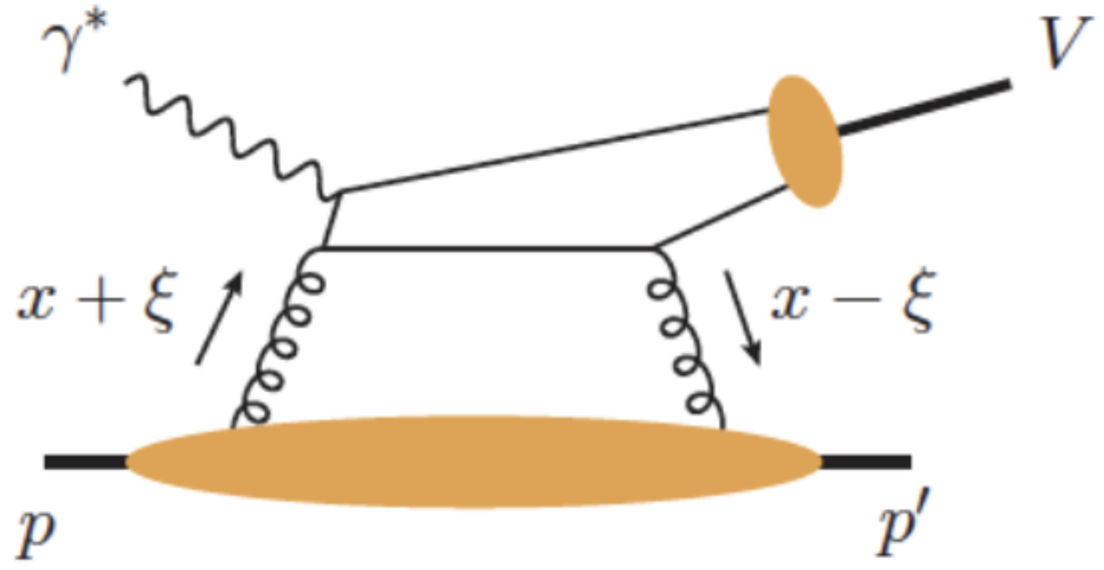


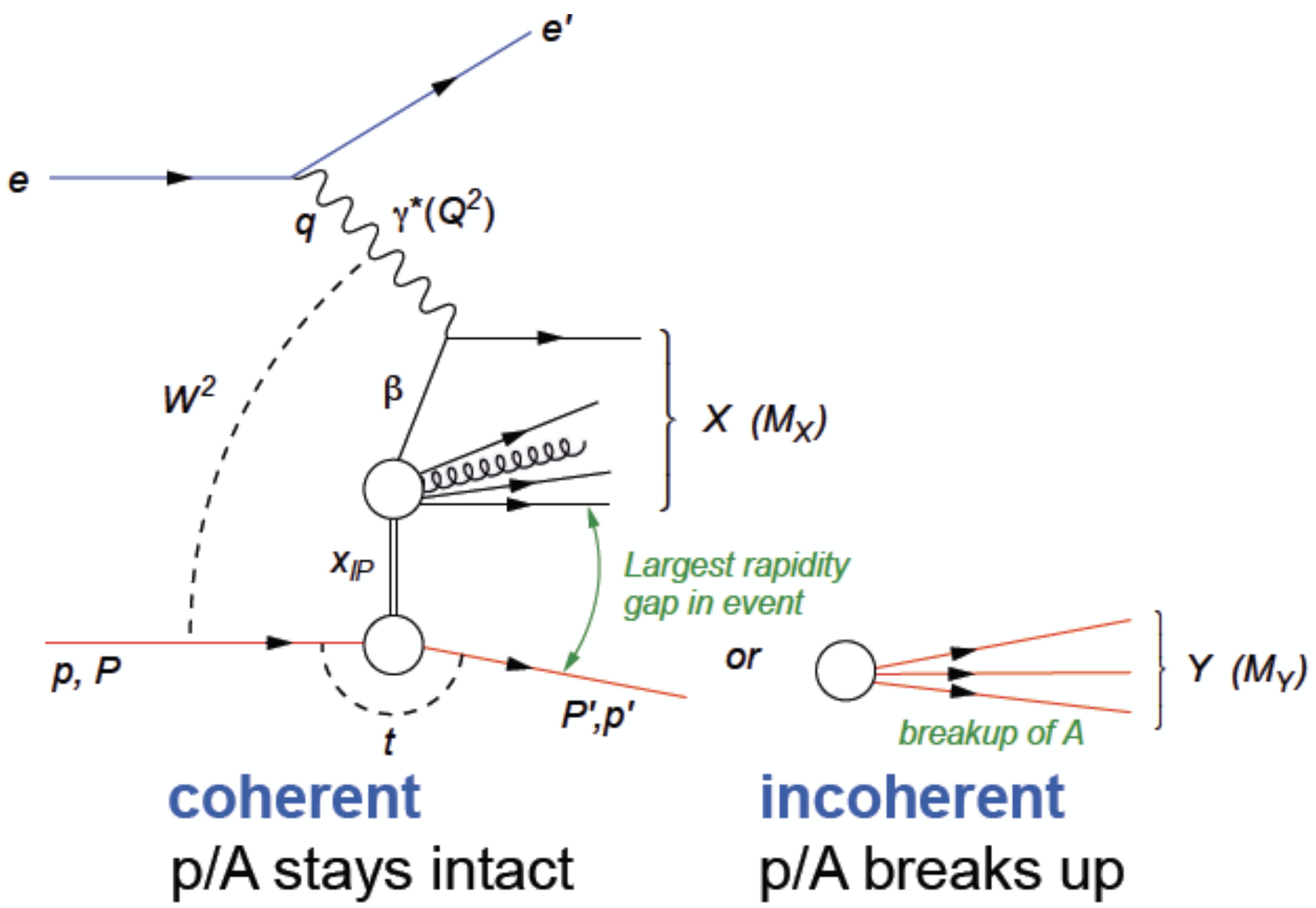


GPDs and TMDs:

- The extraction of GPDs and TMDs and of their evolution equations is a huge undergoing program: scarcely known in the proton, **nuclear effects are mostly unknown**.

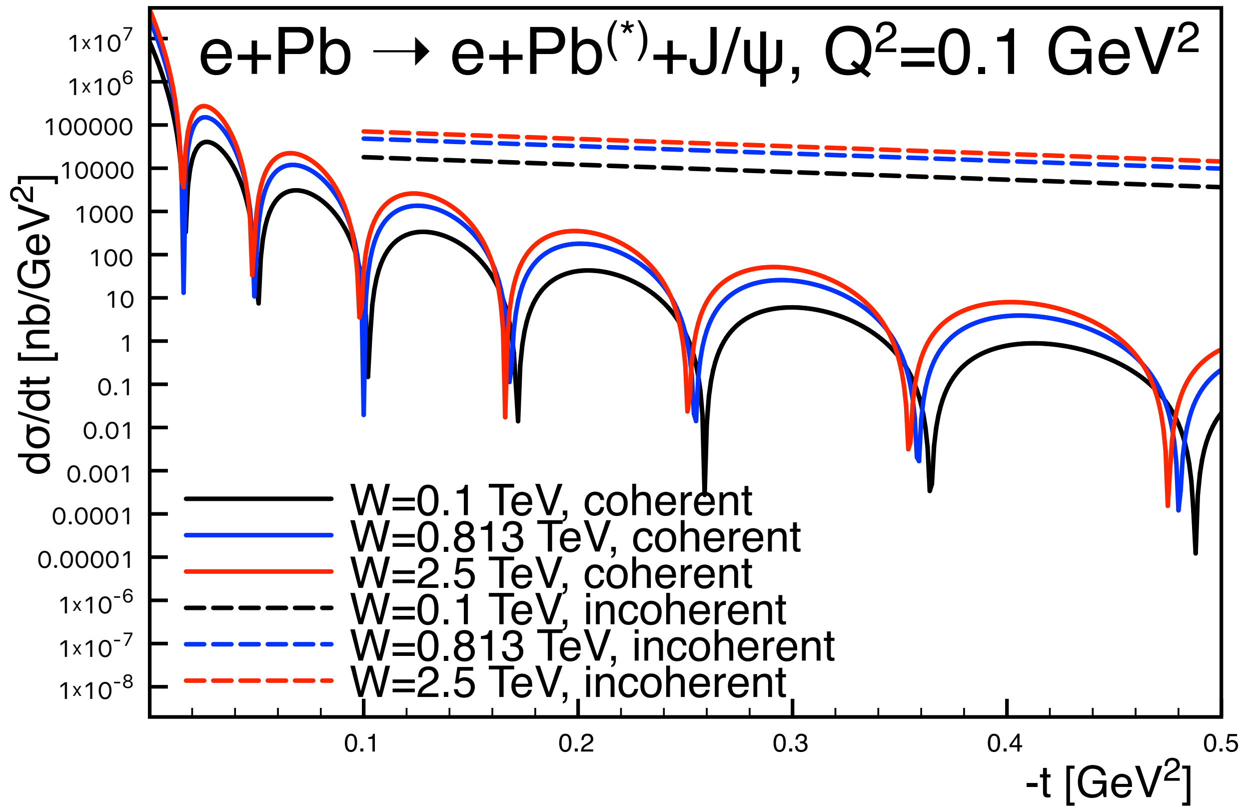


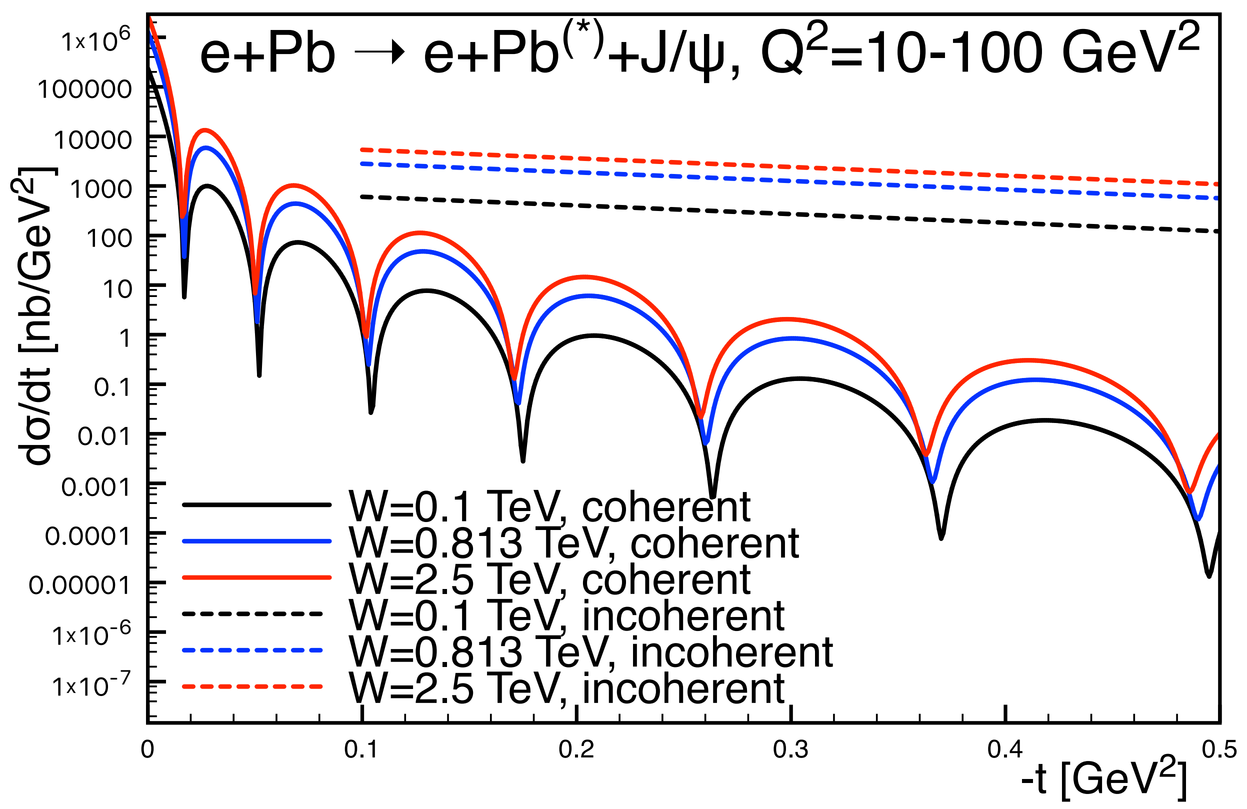




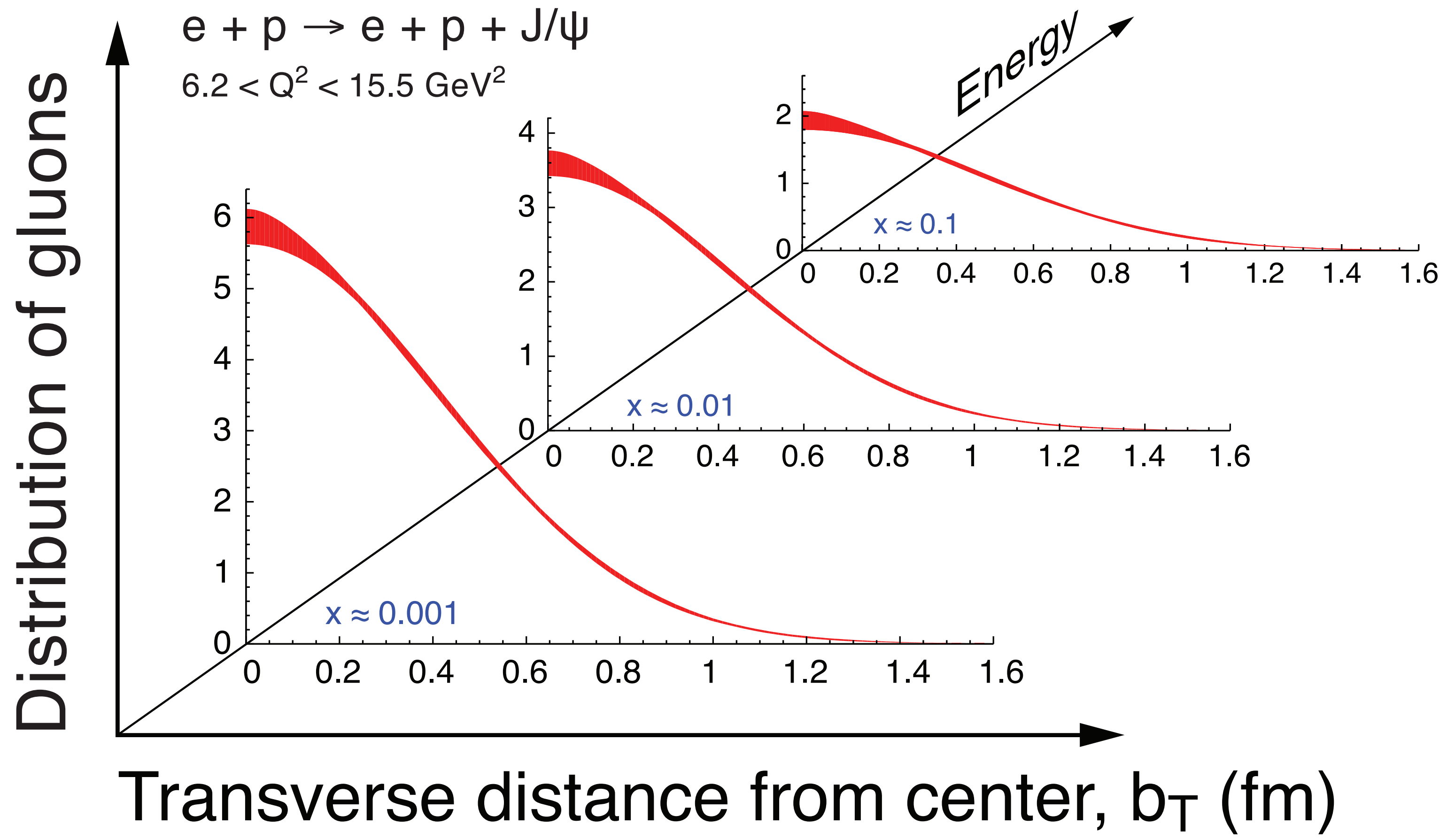
- Coherent exclusive production of γ and VM yields information about q and g GPDs.

1212.1701



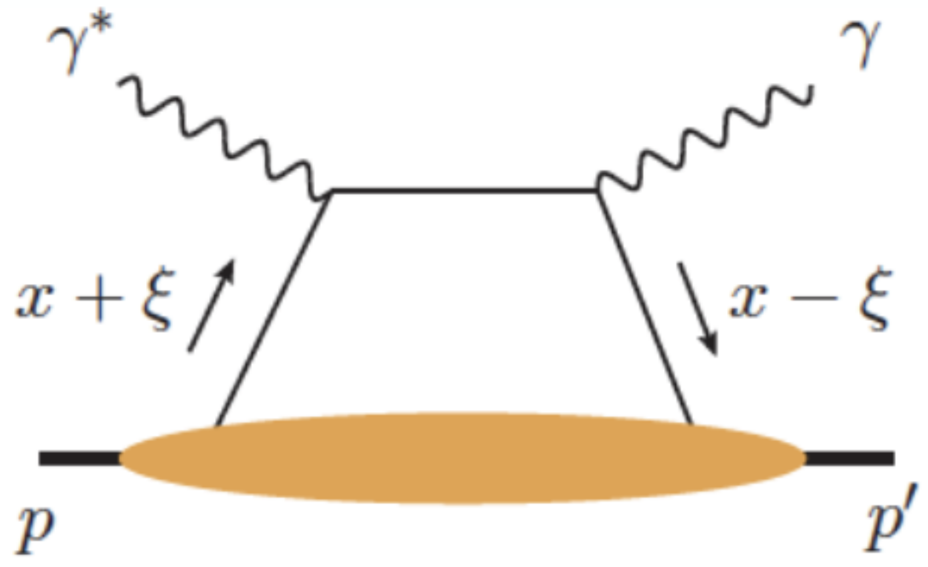


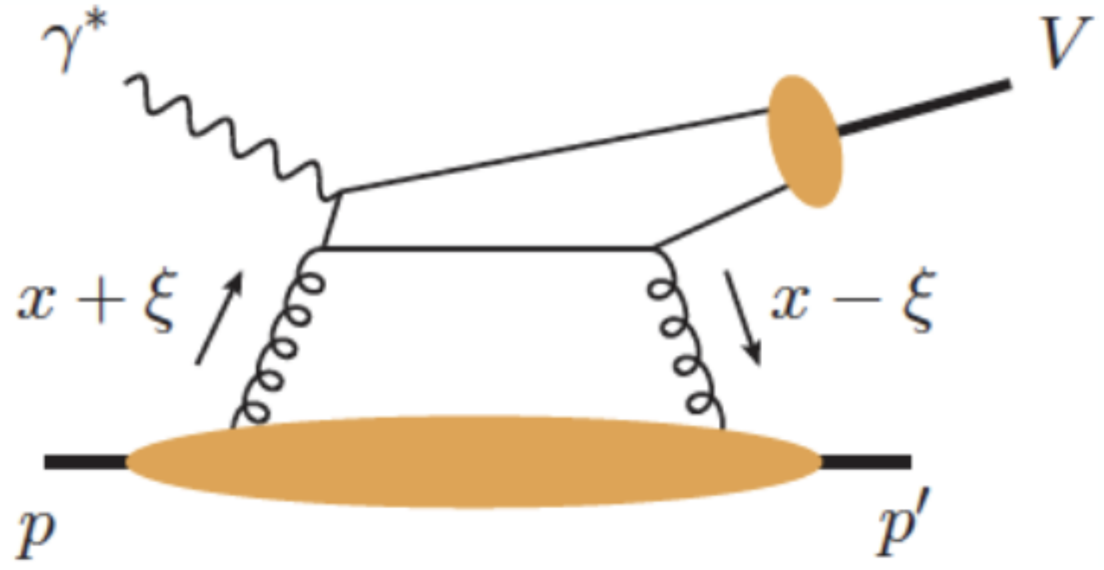
Mantysaari, 1011.1988, IPsat

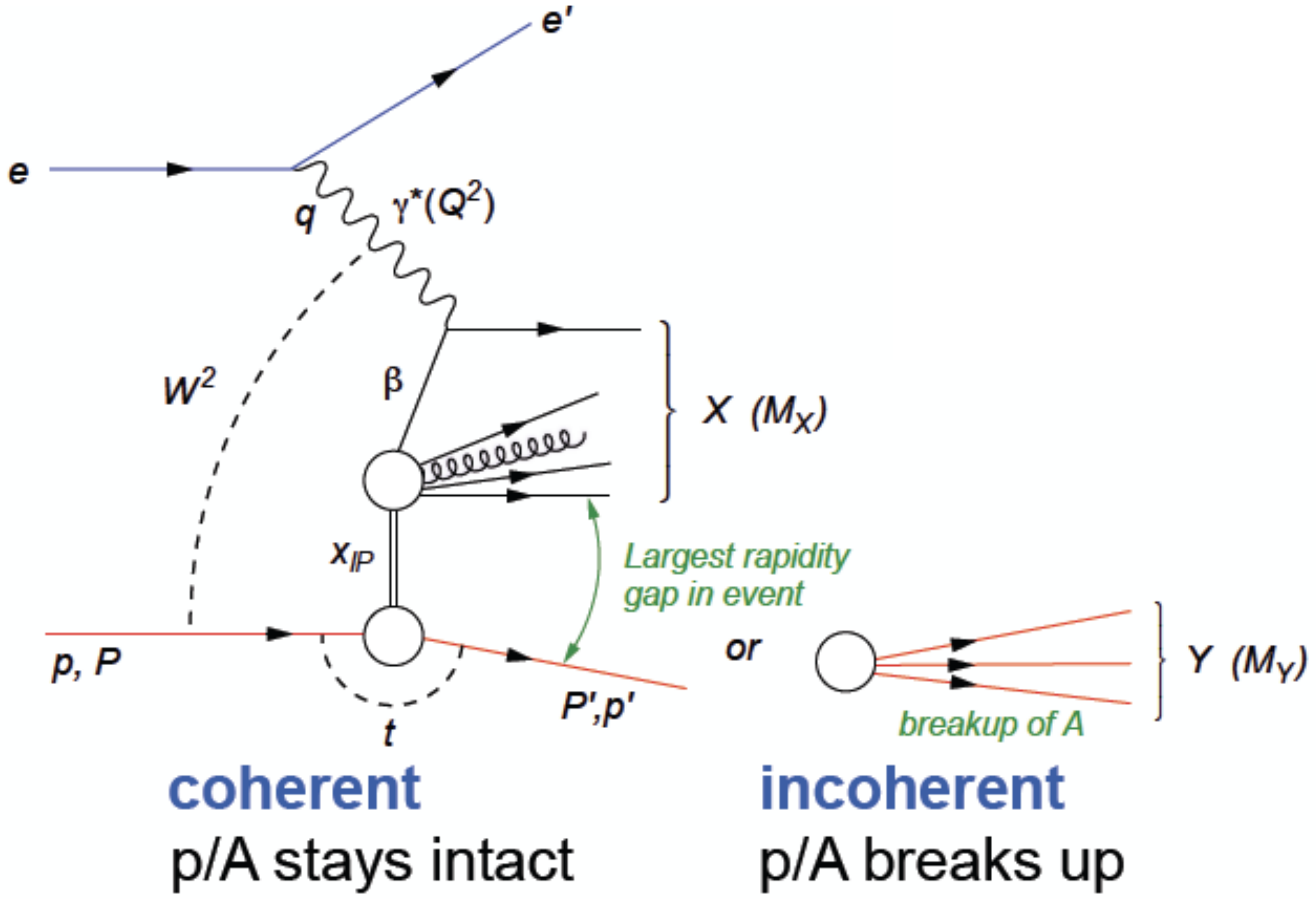


GPDs and TMDs:

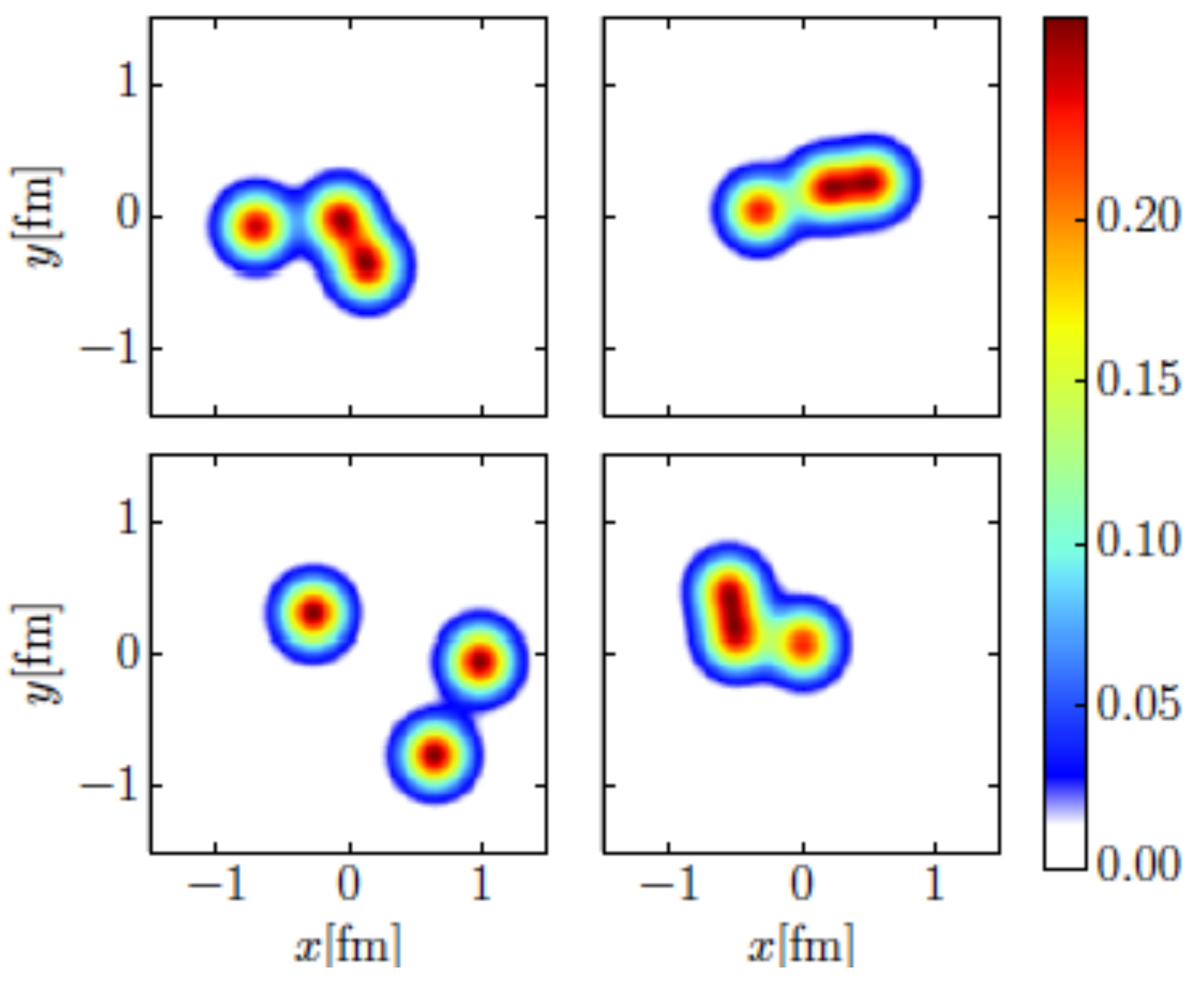
- The extraction of GPDs and TMDs and of their evolution equations is a huge undergoing program: scarcely known in the proton, **nuclear effects are mostly unknown**.

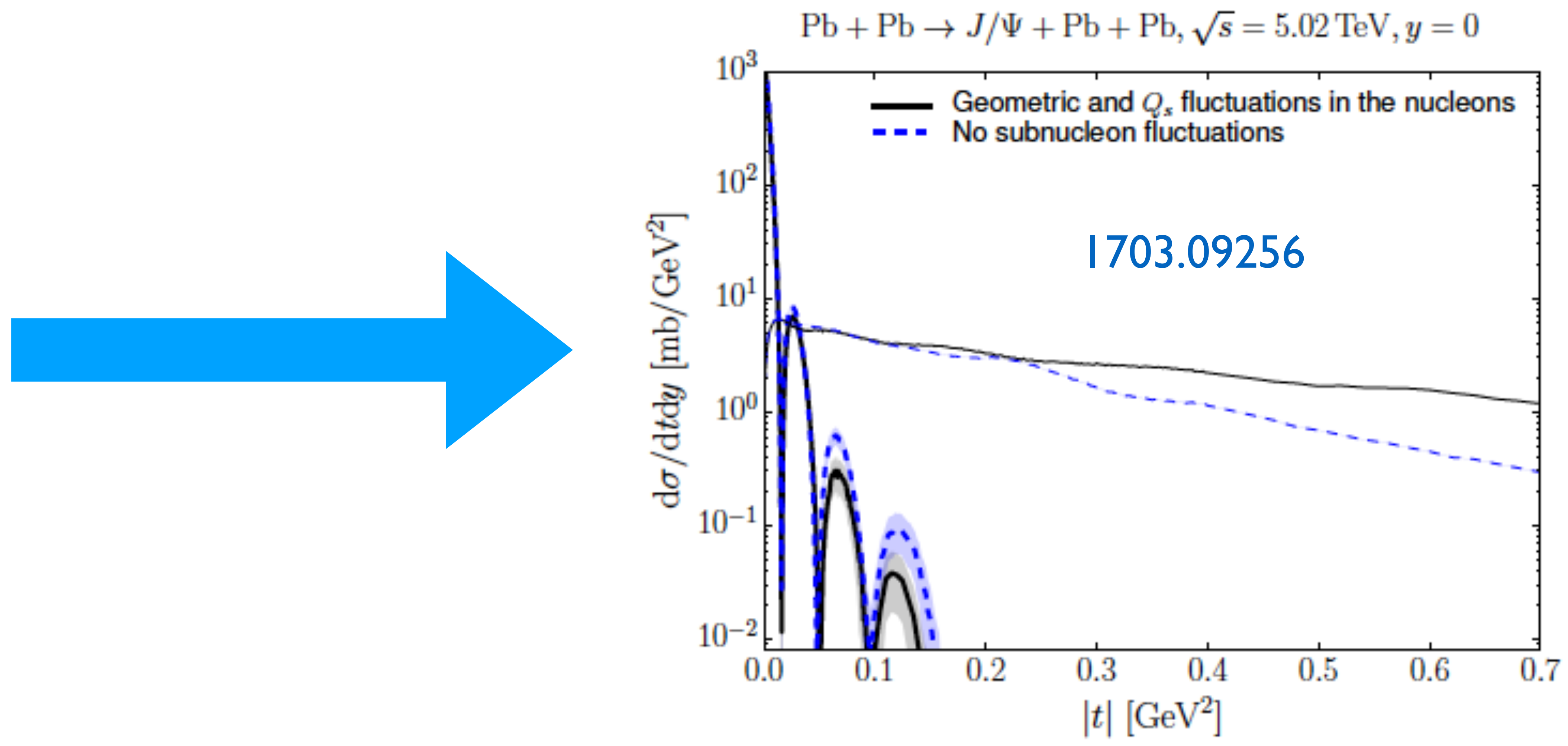






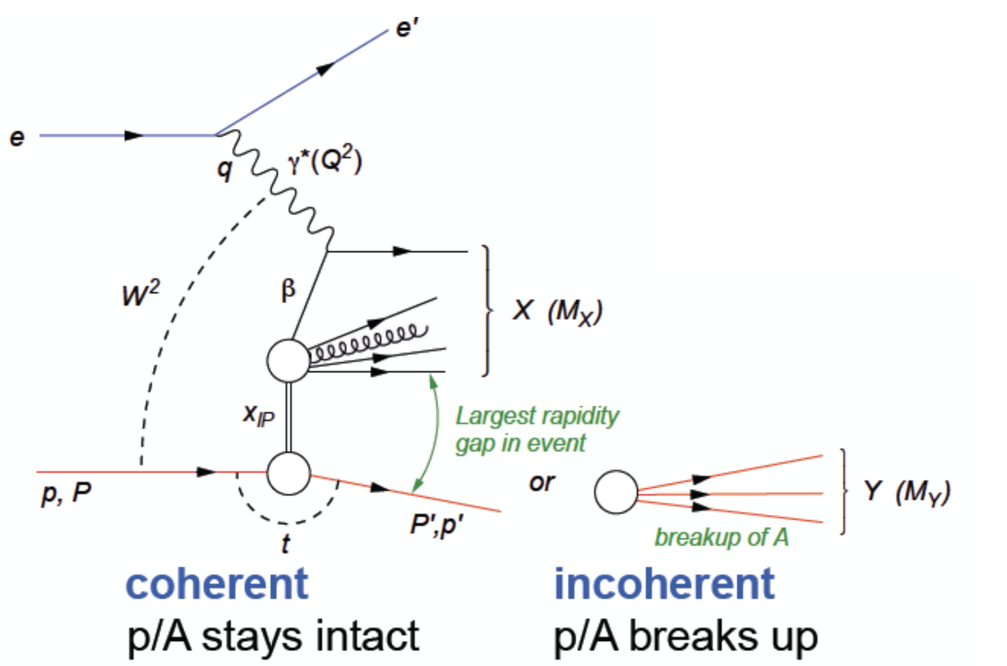
- Coherent exclusive production of γ and VM yields information about q and g GPDs.
- Incoherent exclusive production yields information about fluctuations: hot spots ⇒ MPIs.



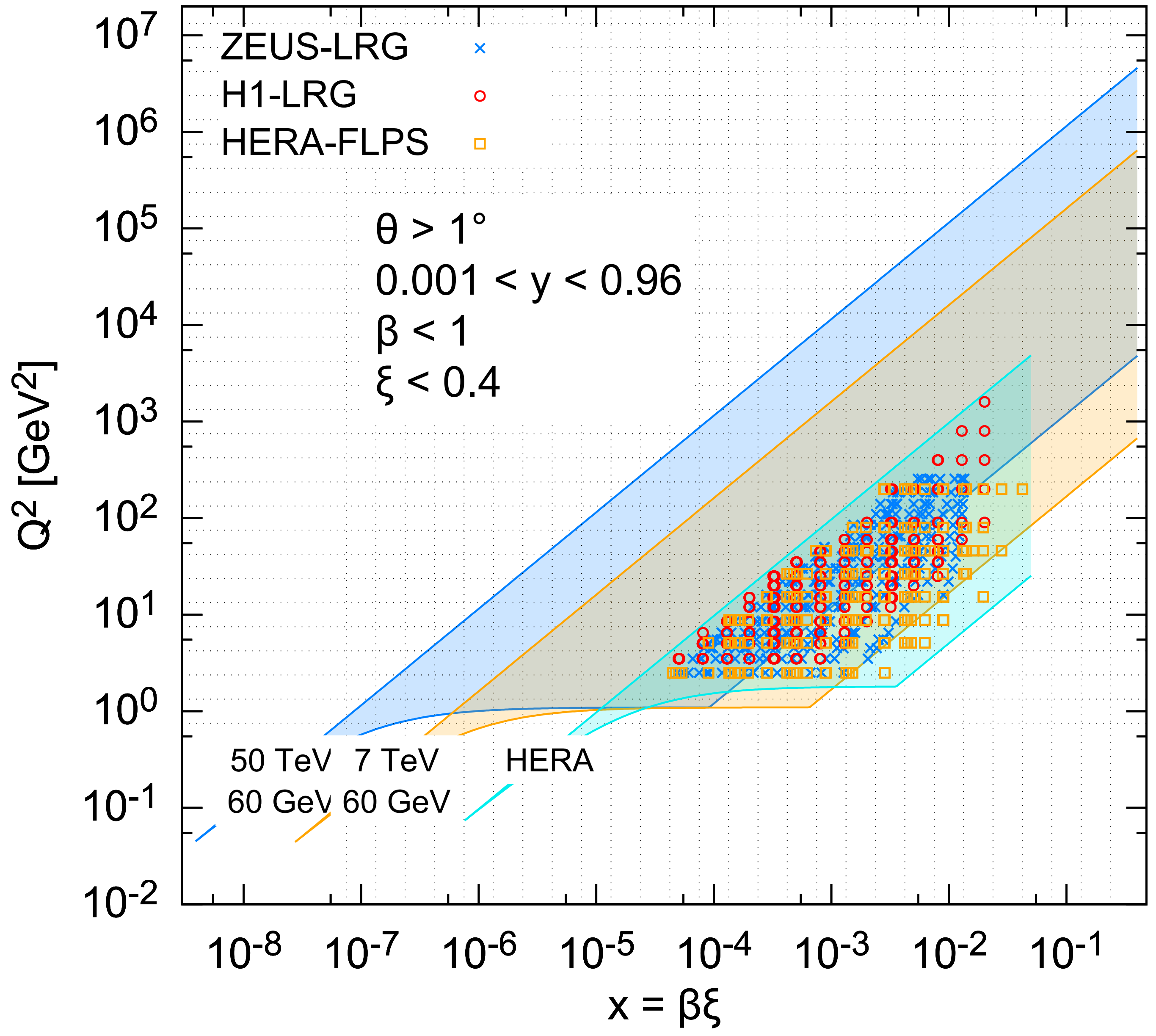


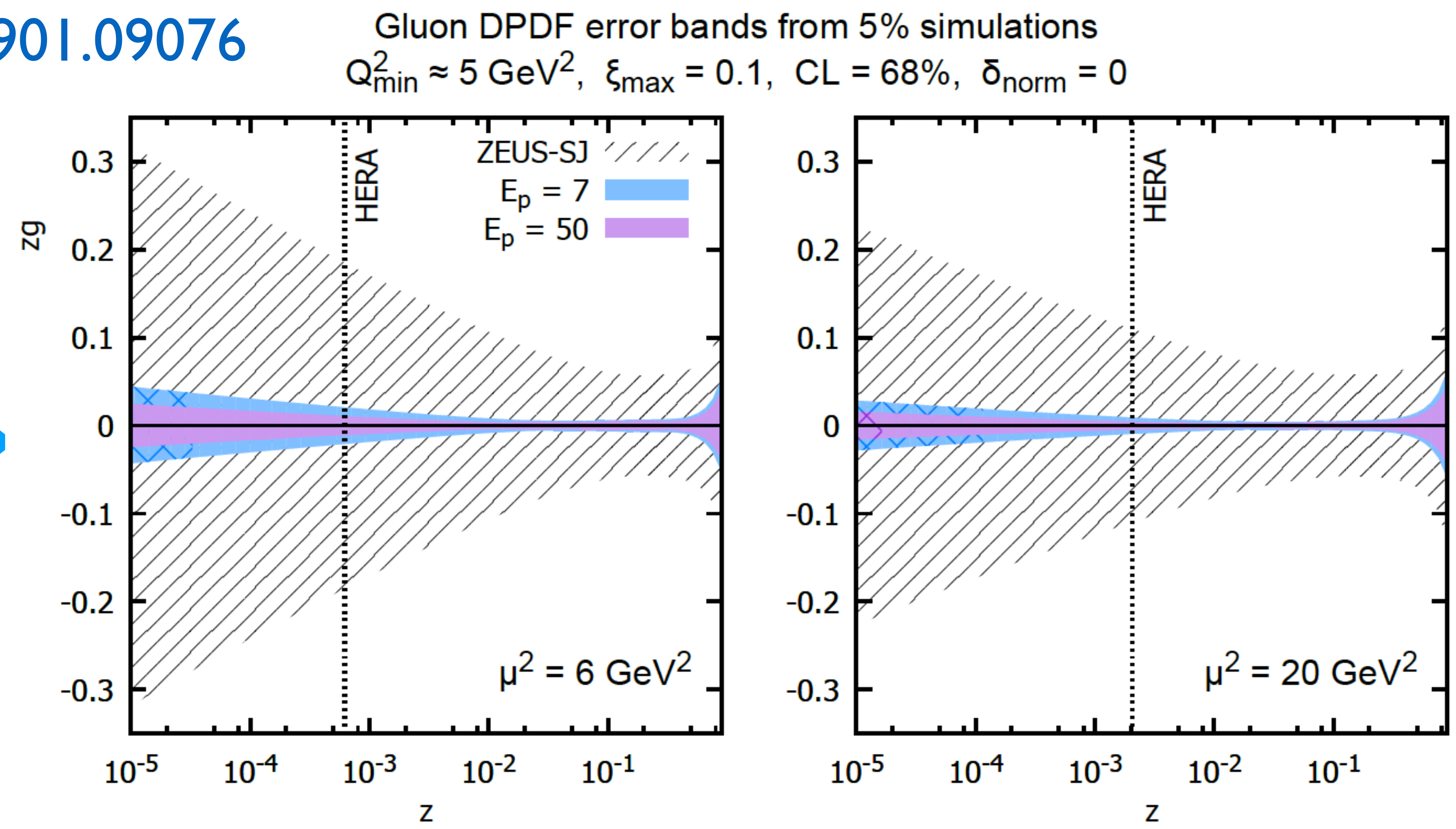
Nuclear diffractive PDFs:

- 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, with 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**.
- **Extractable in nucleus with the same accuracy as in proton**.



LHeC/FCC-eh, coherent diffraction, 1901.09076





Contents:

1. Introduction:
   - ➜ Nuclear structure functions.
   - ➜ Small-x physics.
   - ➜ Implications on pA/AA.
   - ➜ Machines and kinematics.

2. Partonic structure of the nucleus:
   - ➜ Collinear nPDFs.
   - ➜ Diffractive nPDFs.

3. New dynamics at small x:
   - ➜ Inclusive observables.
   - ➜ Diffractive observables.
   - ➜ Correlations.

4. Nuclear effects in the final state:
   - ➜ Jets.
   - ➜ Fragmentation functions.

Not yet final!

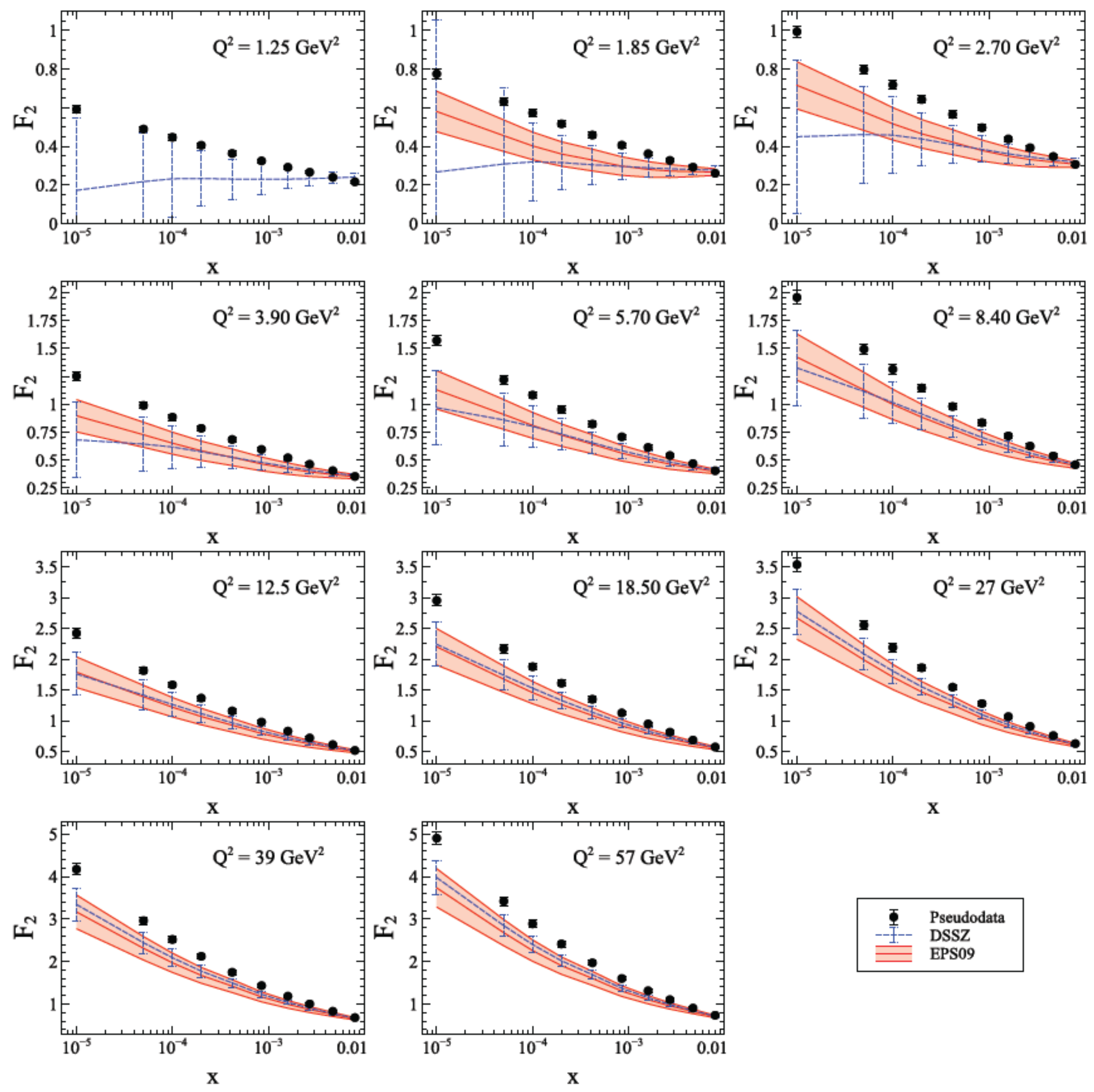
5. Community.

6. Summary/recommendations.

Note: this is a personal selection of topics; for additional discussions and supplemental material (e.g. on spin and relations with other fields), see Thomas Gehrmann, Urs Wiedemann, Uta Klein and Gavin Salam's talks, and the backup.

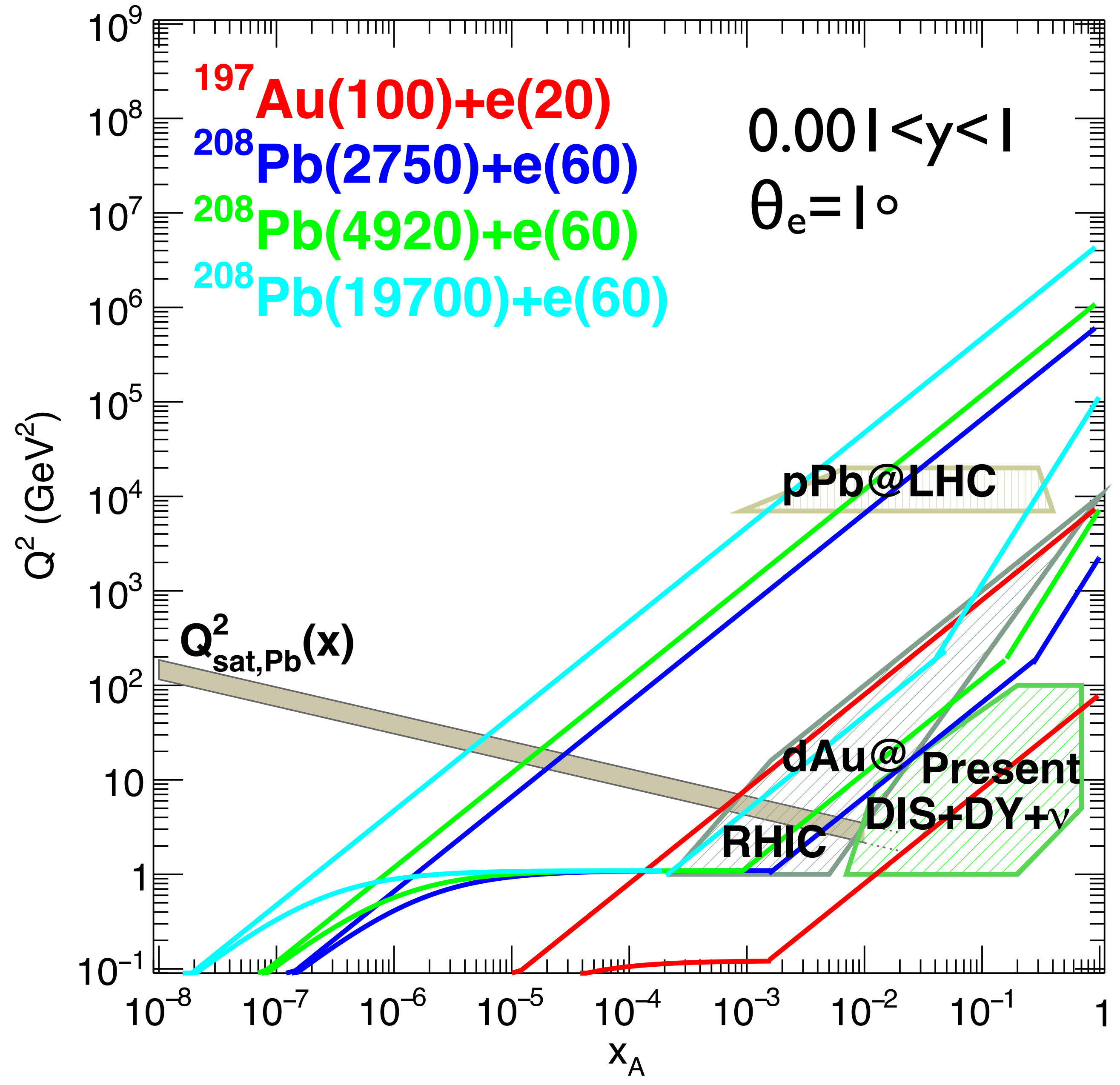
Search for new parton dynamics at small x:

- Saturation modifies evolution: tension between the description in linear evolution of different inclusive observables (with different sensitivities to the gluon and the sea, e.g. F_2 and F_L or σ_r^{HQ}), **if enough lever arm in Q^2 is available at small enough x**.



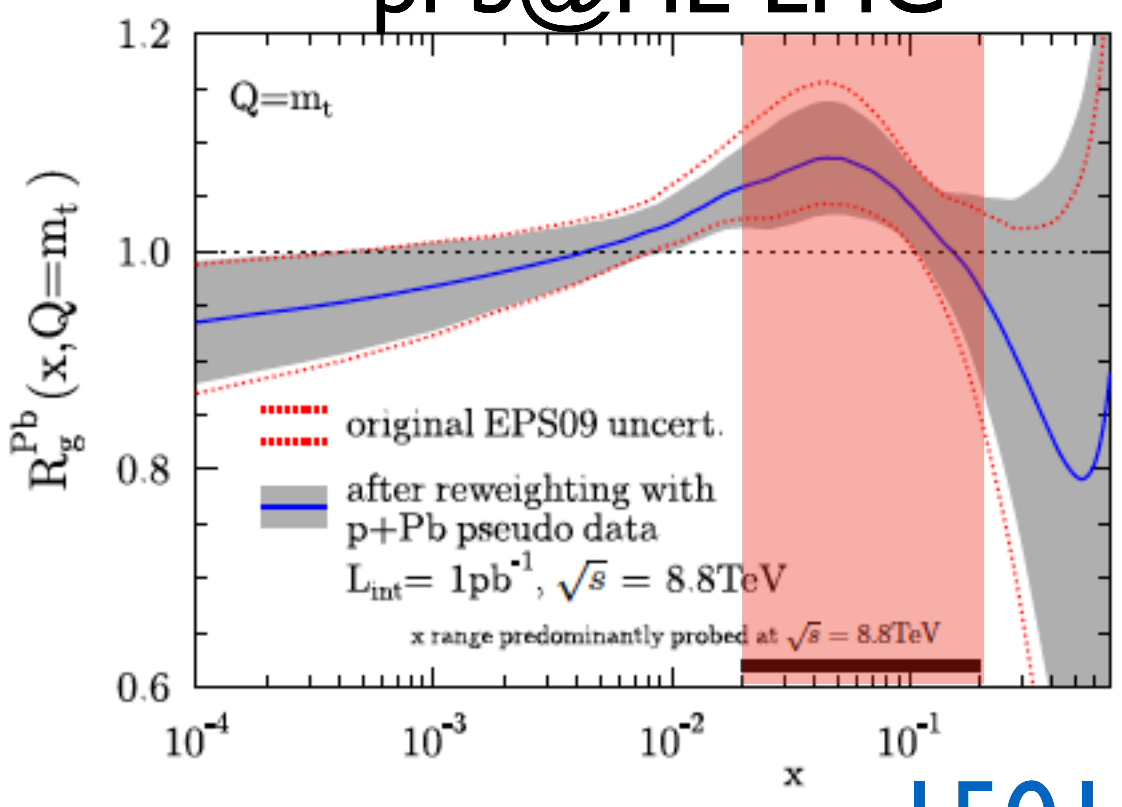
1702.00839

eAu@EIC

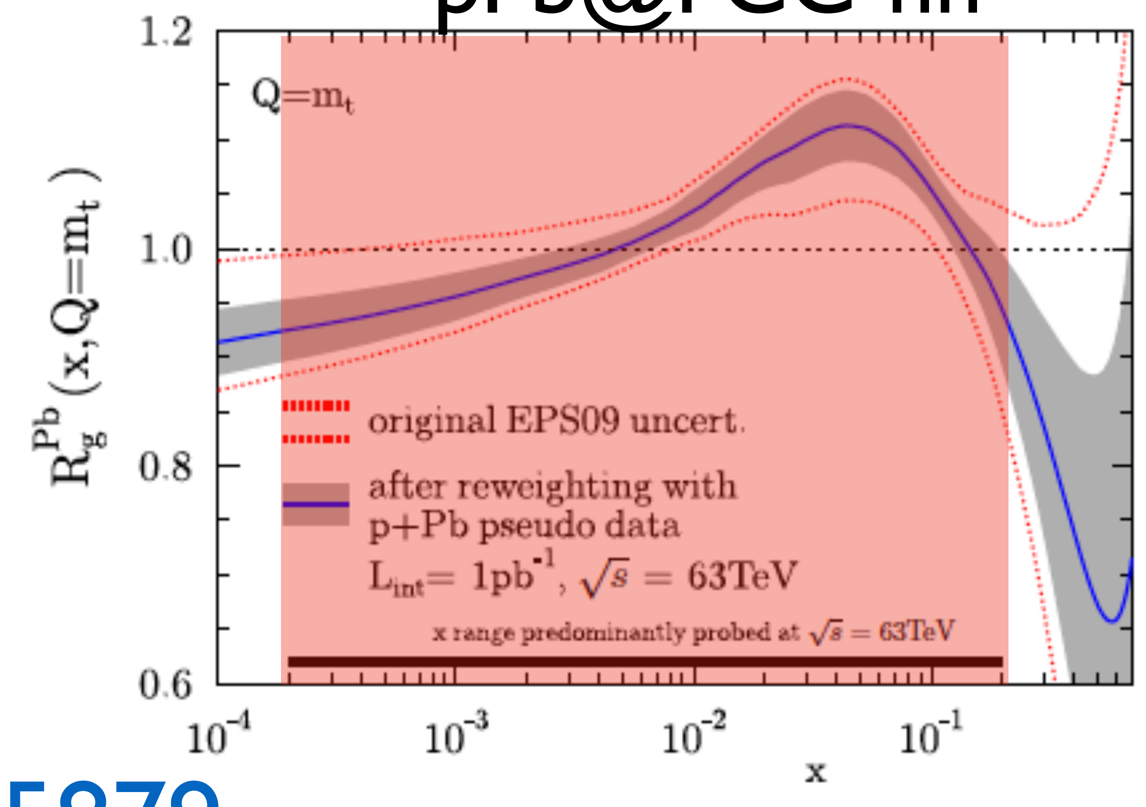


- High scales are small x at the FCC-AA.

pPb@HL-LHC



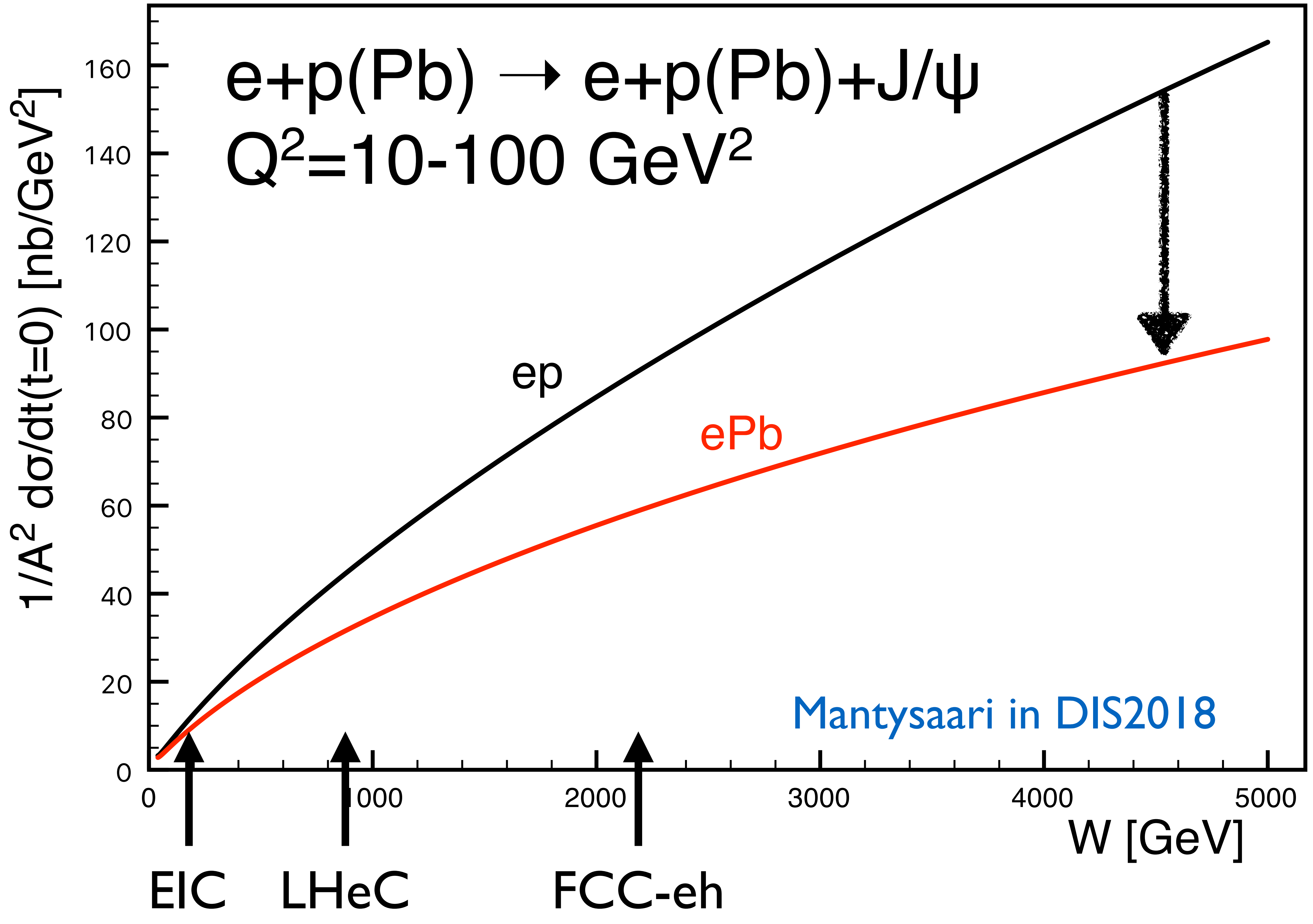
pPb@FCC-hh



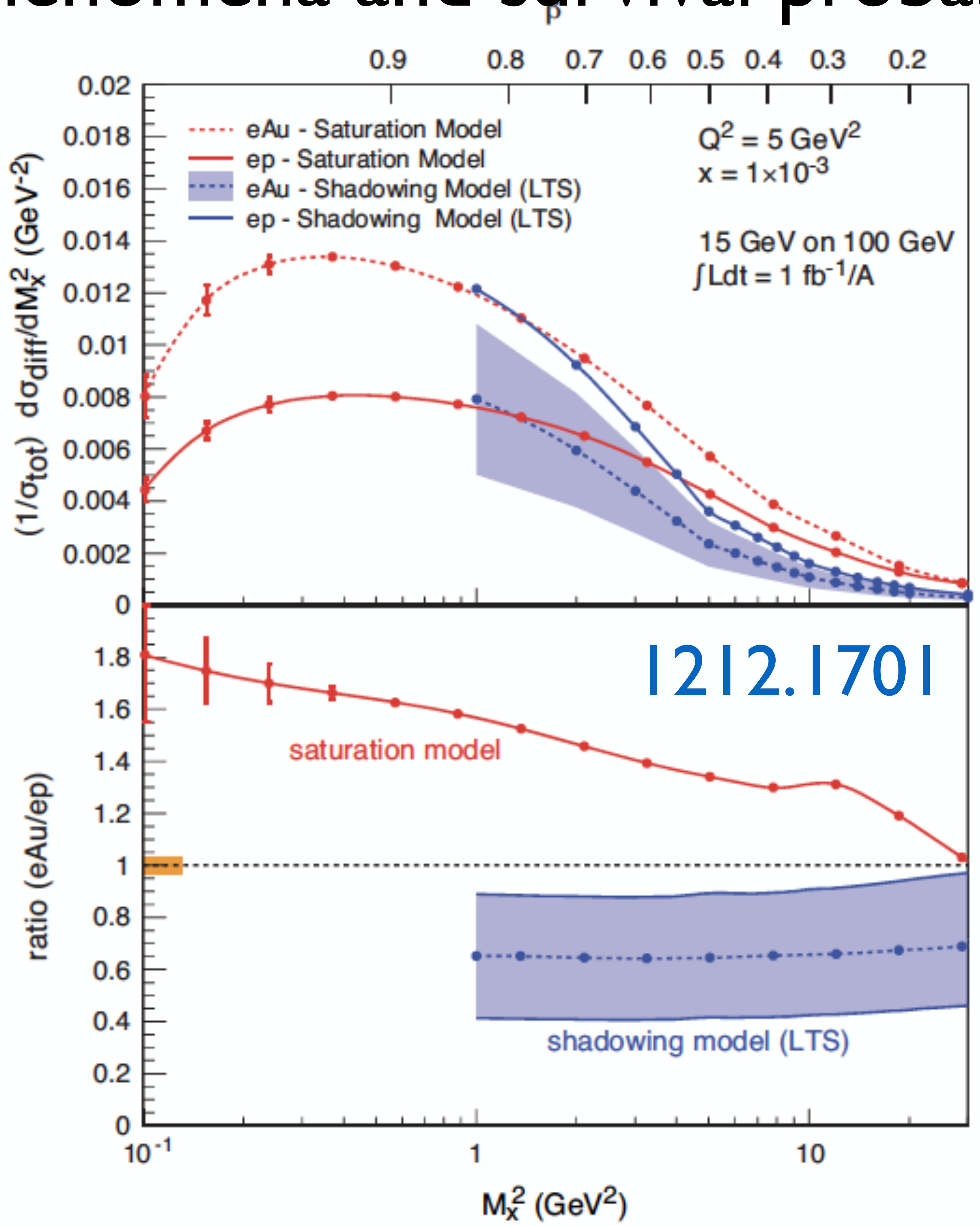
1501.05879

Diffractive observables:

- Saturation (the approach to the black disk limit) affects both the energy and the t (impact parameter)-dependence of coherent exclusive VM production: smaller energy dependence, shrinking of the diffractive peak.

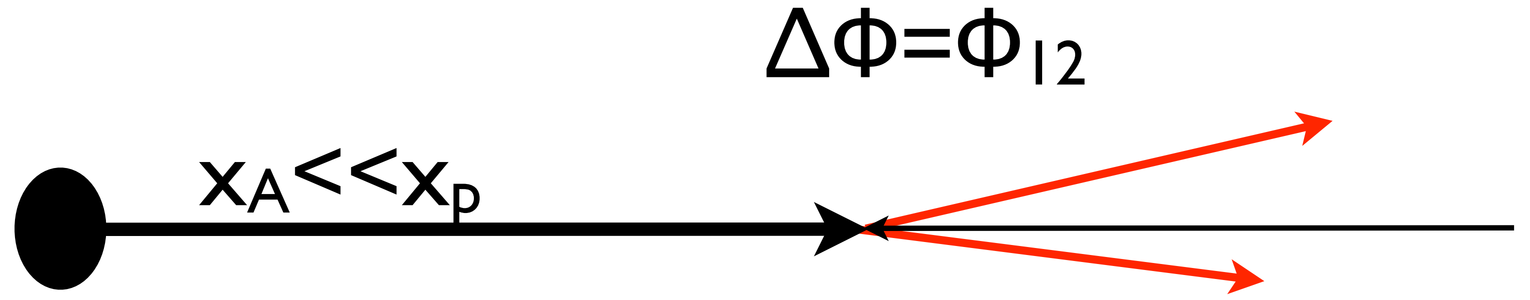


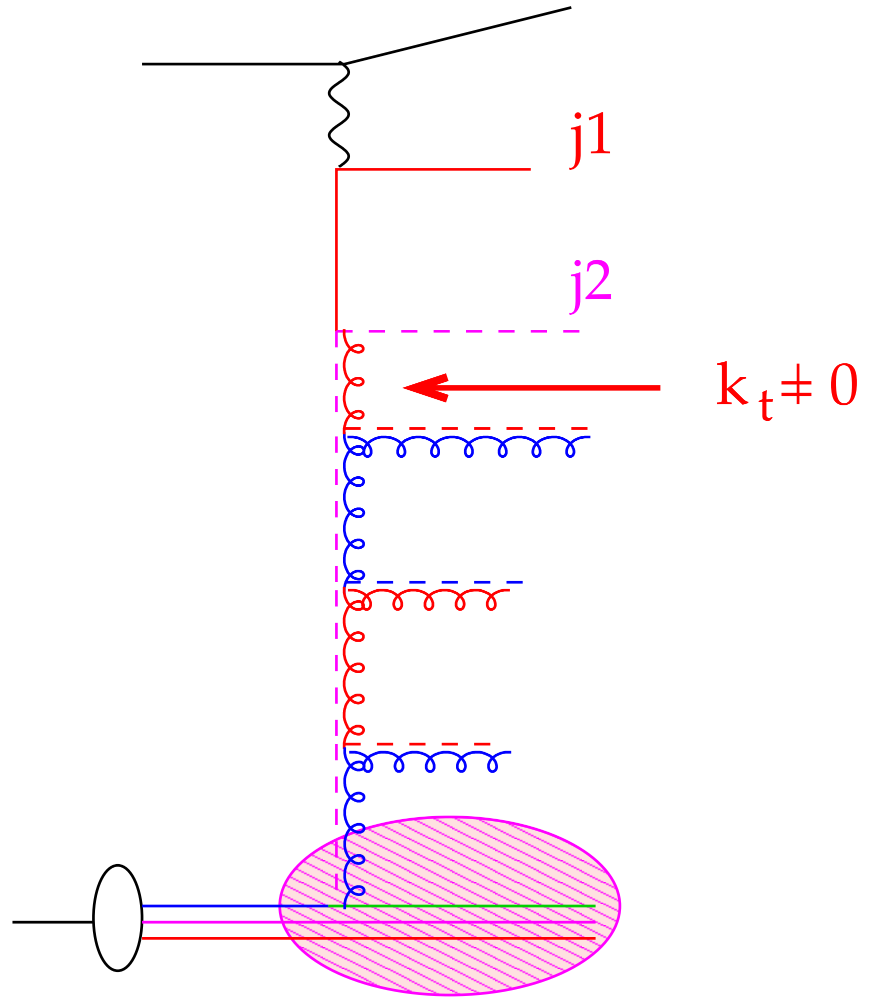
- Saturation results in a larger diffractive over inclusive cross section: interplay between non-linear phenomena and survival probability.

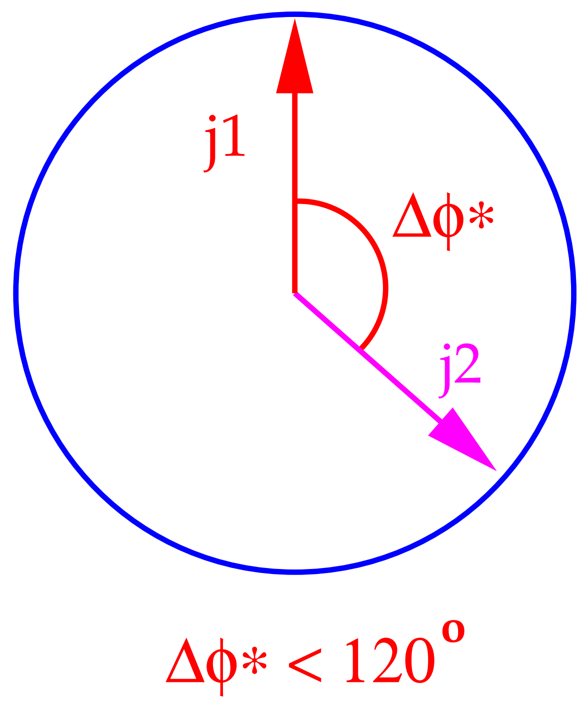


Correlations:

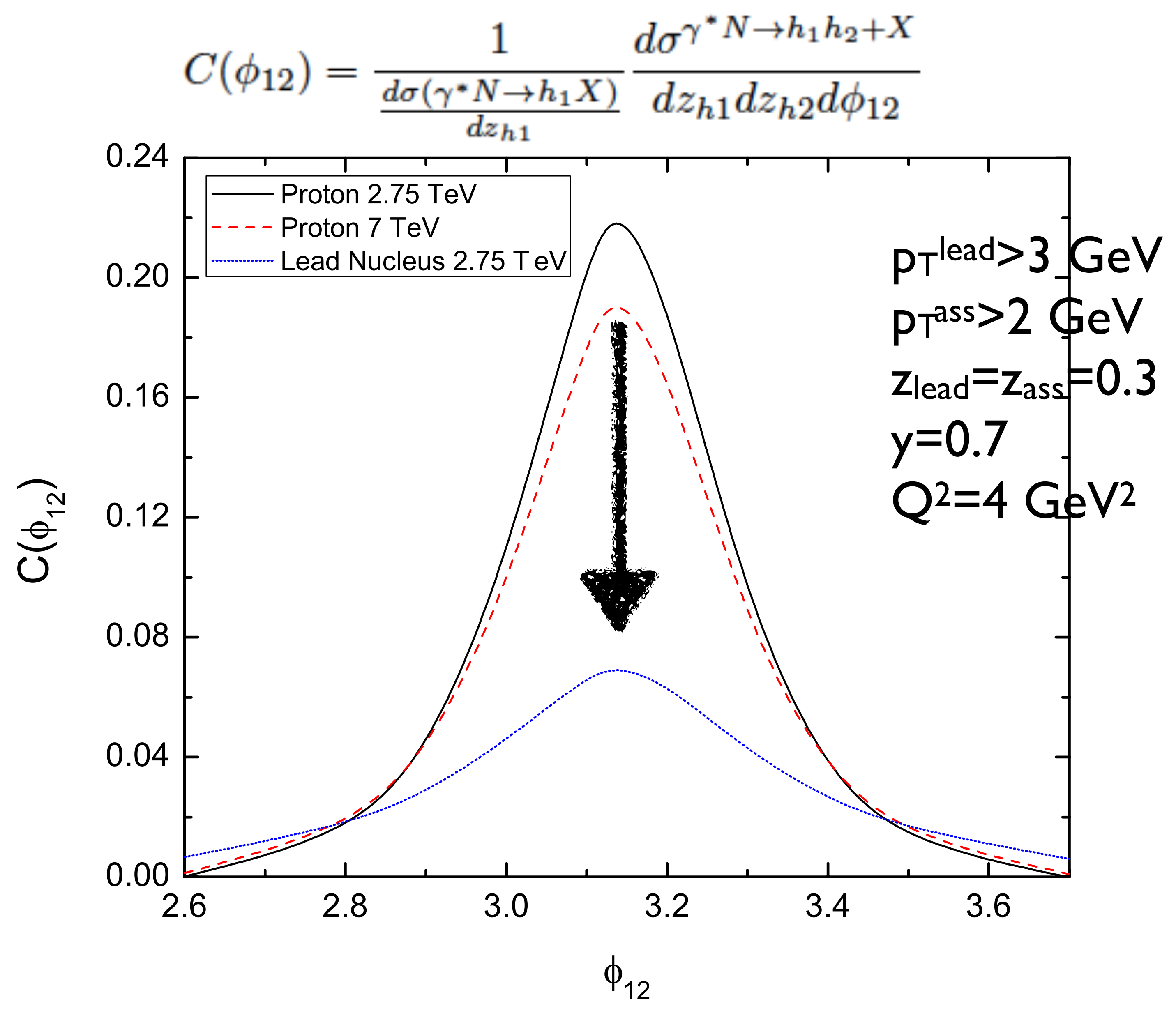
- Dihadron azimuthal decorrelation: currently discussed at RHIC as suggestive of saturation.
- **To be studied at EIC & LHeC far from kinematical limits**.
- **Nuclear and saturation effects on usual BFKL signals** (e.g. dijet azimuthal decorrelation, Mueller-Navelet jets) has not been extensively addressed: A-dependence contrary to linear resummation?







LHeC CDR



- HL-LHC and higher energy hh/AA colliders: many of these signals can be considered (nuclear modification factors at small-x, exclusive vector meson production in UPCs, particle and jet decorrelation), but larger uncertainties will remain: collectivity, factorisation,… **DIS would be decisive to set the existence of a new regime of QCD**.

Contents:

1. Introduction:
   → Nuclear structure functions.
   → Small-x physics.
   → Implications on pA/AA.
   → Machines and kinematics.

2. Partonic structure of the nucleus:
   → Collinear nPDFs.
   → Diffractive nPDFs.

3. New dynamics at small x:
   → Inclusive observables.
   → Diffractive observables.
   → Correlations.

4. Nuclear effects in the final state:
   → Jets.
   → Fragmentation functions.

Not yet final!

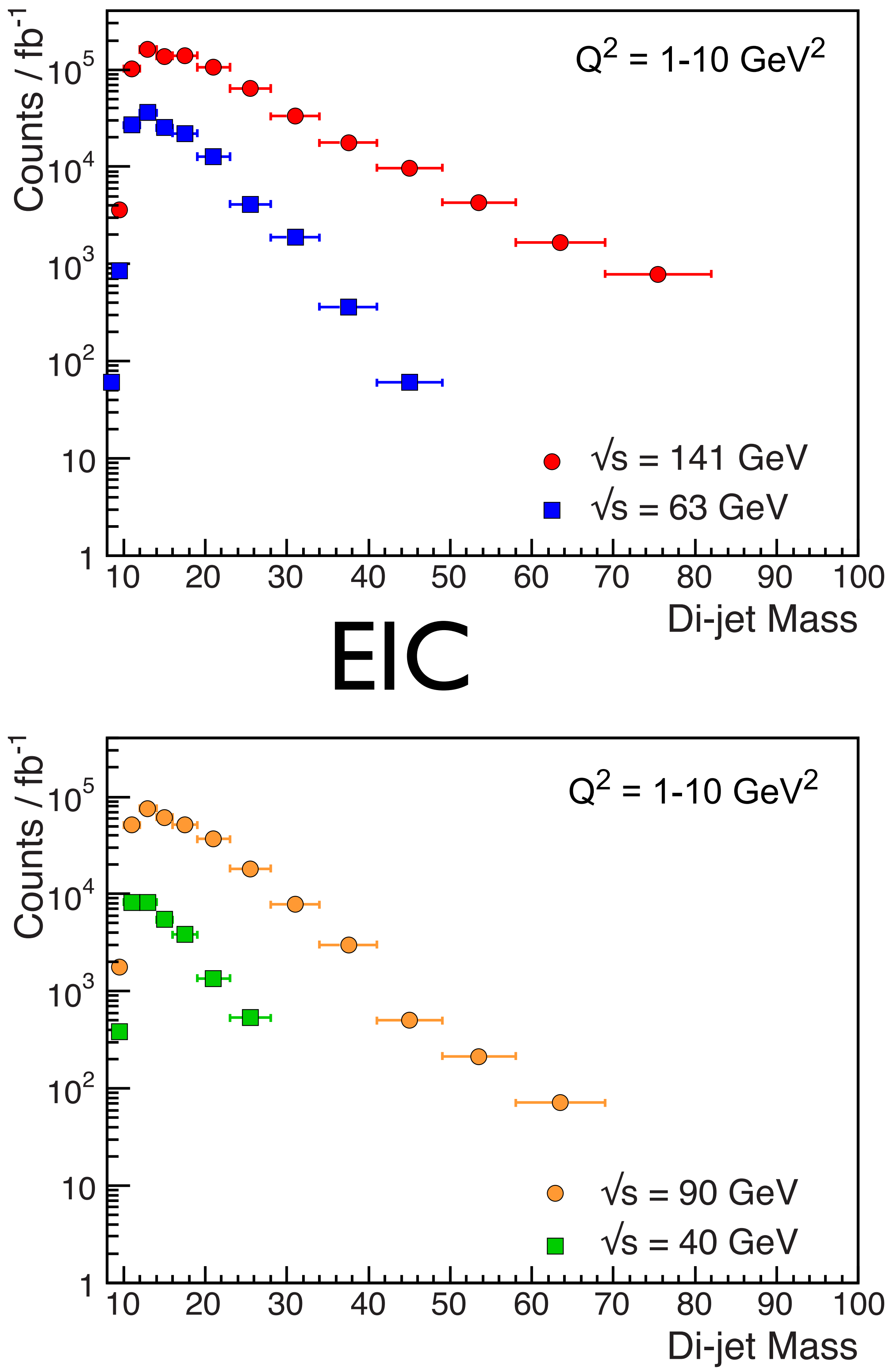
5. Community.

6. Summary/recommendations.

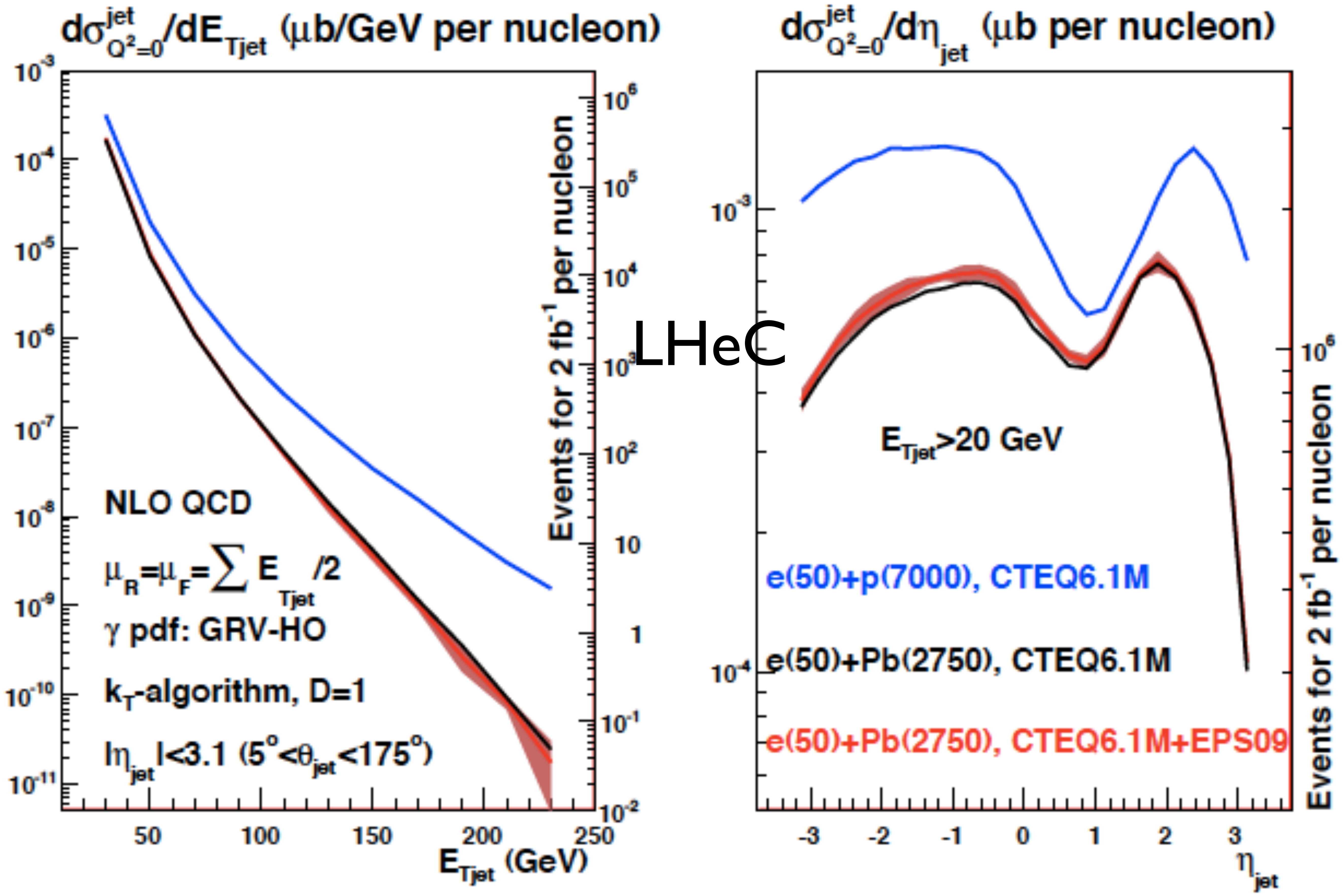
Note: this is a personal selection of topics; for additional discussions and supplemental material (e.g. on spin and relations with other fields), see Thomas Gehrmann, Urs Wiedemann, Uta Klein and Gavin Salam's talks, and the backup.

Jets:

- Jets not suppressed in pPb @ LHC: compatibility with softer observables? → small systems.
- Jets will be abundantly produced in eA colliders 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.**

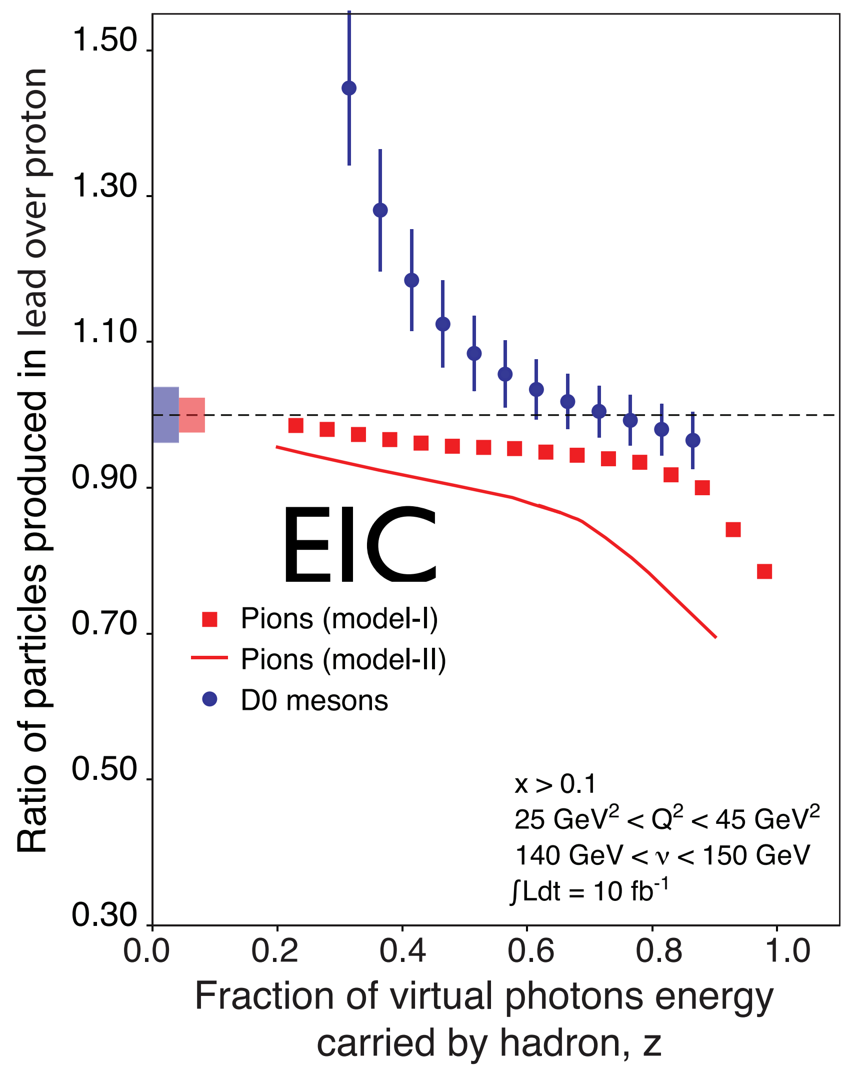


EIC

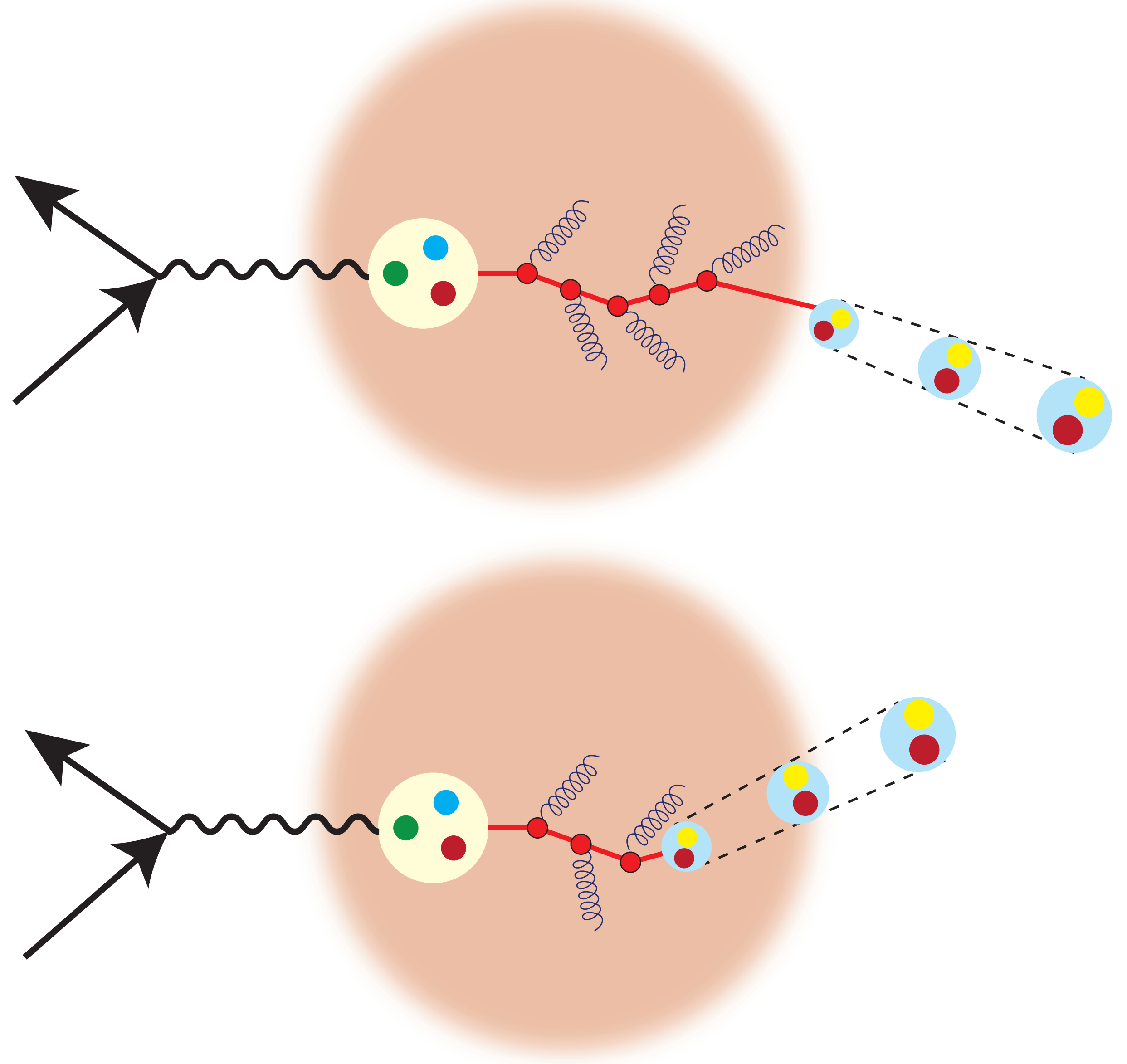


Fragmentation functions:

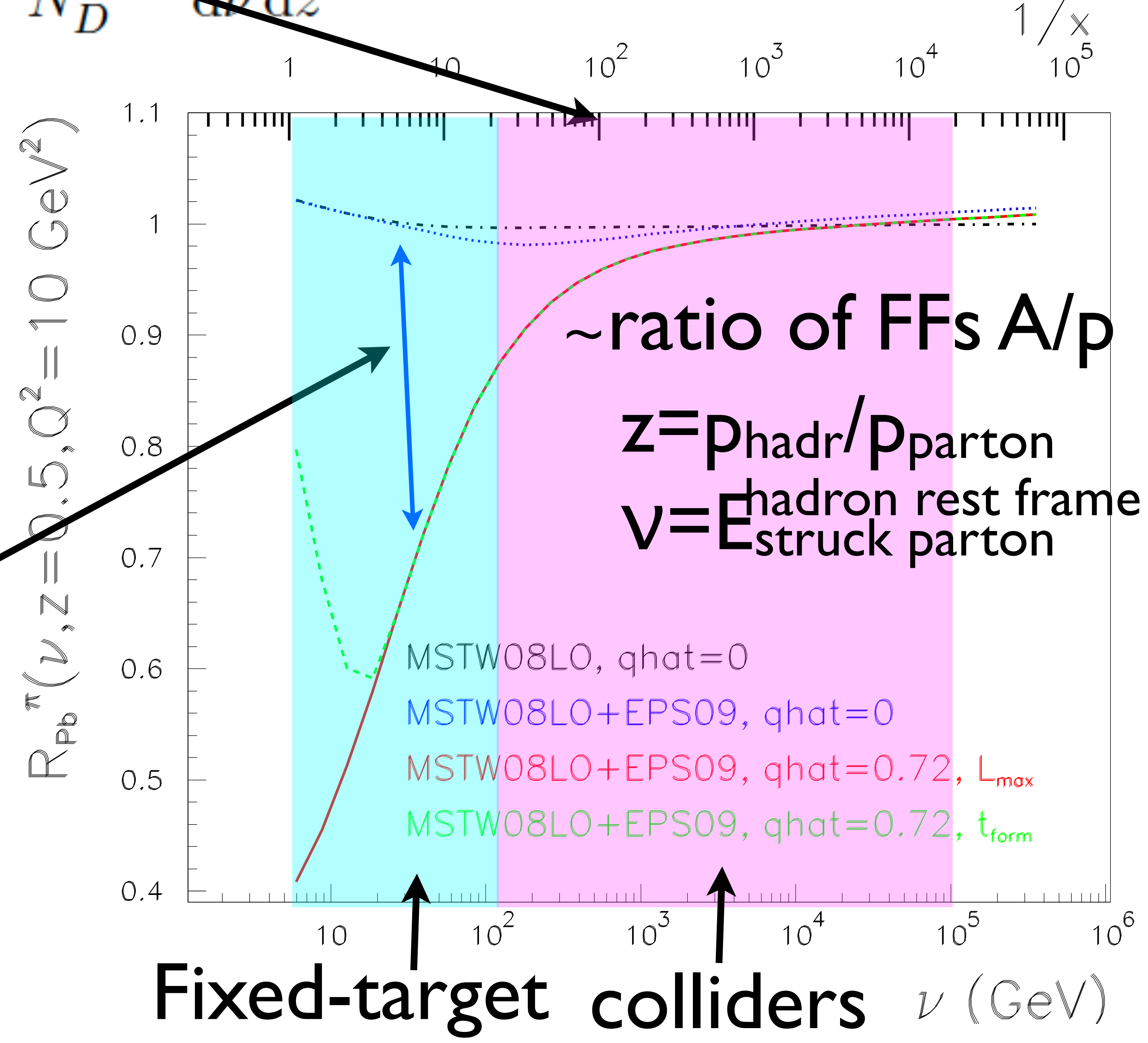
- eA: dynamics of QCD radiation and hadronization for light and heavy particles (energy loss of light and heavy, and quarkonium production and suppression), **most relevant for particle production off nuclei** (nPDF determination in pA) **and for QGP analysis in AA.**



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



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



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

Community:

Summary / recommendations:

- eA colliders offer huge possibilities for QCD physics in new kinematic and dynamics domains:

  ➜ Determination of nuclear partonic structure with high precision: collinear nuclear PDFs, nuclear GPDs/TMDs (3D-structure), diffractive nuclear PDFs, to be contrasted with pA and AA.

  ➜ Searches of signals of a new regime of QCD - saturation - in inclusive and diffractive observables, and through correlations; both ep & eA are required to discover it and understand the underlying dynamics.

  ➜ Modifications of particle production, hadronisation and QCD radiation in the nuclear environment.

Support further studies of the eA physics case at the largest possible energy and the implications on pp/pA/AA.

- The EIC and the LHeC are complementary (except for spin in which EIC is unique):

  ➜ PDFs for future AA colliders and the study of saturation demand the highest possible energy.

  ➜ 3D-structure and hadronisation/QCD radiation will be studied in complementary domains.

Support the exploitation of the synergies and complementarities between the EIC and the LHeC/FCC-eh.

- All these aspects are very relevant for the heavy-ion program:

  ➜ Benchmarking of hard probes.

  ➜ Initial conditions for collective behaviour.

  ➜ Understanding of the onset of collectivity: small systems, MPIs, …

Encourage the development of a QCD program in the 2030's consisting of pp/pA/AA and ep/eA.

Backup

Purpose:

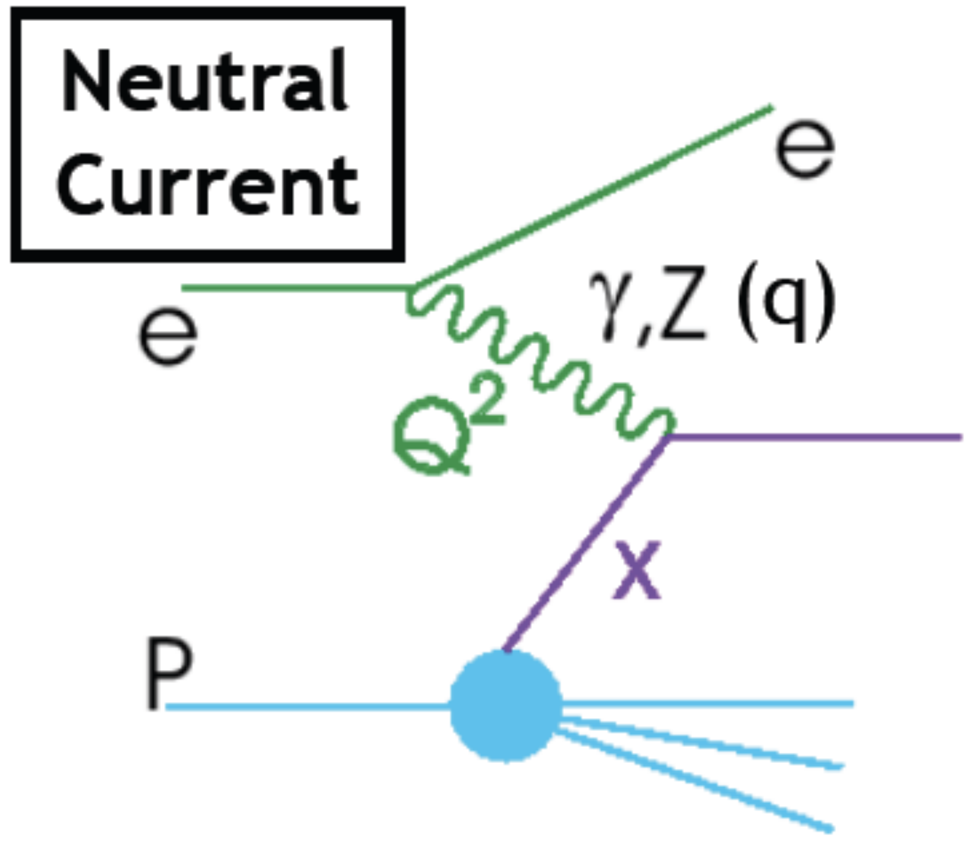
- To cover: Prospects and Challenges for Electron-Ion Collider, also from the perspectives of the US-EIC, to trigger our understanding of the rich variety of structures at the subatomic scale.

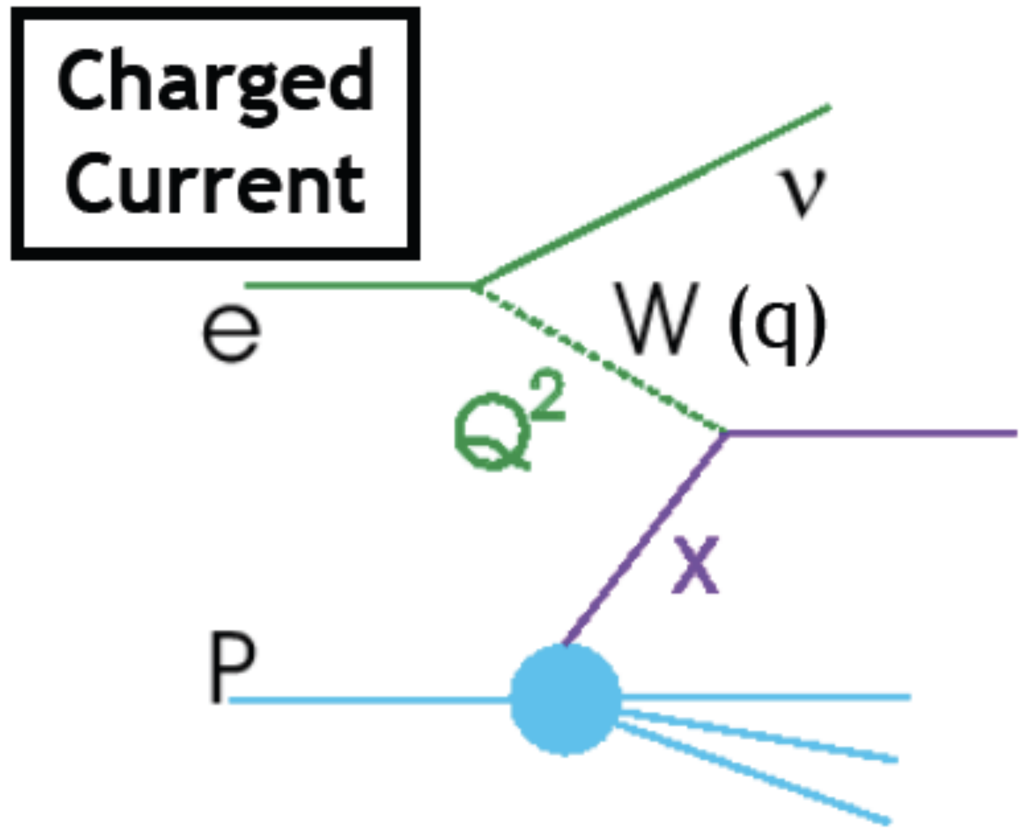
- Related contributions submitted to the ESPPU:

ID	Title
159	LHeC/PERLE
99	US-based EIC
103	DIS
152	QCD/HI at HL-LHC
135	QCD/HI at FCC-hh and FCC-eh
163	QCD theory
148	NuPECC
21	INFN hadron
114	MC generators
33	Germany HEP

DIS:

- Consider the process of lepton (e, μ, ν) scattering on a proton (or neutron or nucleus).





Standard DIS variables:

electron-proton cms energy squared:
$$s = (k + p)^2$$

photon-proton cms energy squared:
$$W^2 = (q + p)^2$$

inelasticity
$$y = \frac{p \cdot q}{p \cdot k}$$

Bjorken x
$$x = \frac{-q^2}{2p \cdot q}$$

(minus) photon virtuality
$$Q^2 = -q^2$$

- For charged lepton scattering and neglecting Z exchange,

$$\frac{d^2\sigma_{NC}}{dx dQ^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x} \cdot \sigma_{r,NC}$$

$$\frac{\mathrm{d}^2\sigma^{\pm}_{CC}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{1 \pm P}{2} \cdot \frac{G_F^2}{2\pi x} \cdot \left[\frac{M_W^2}{M_W^2 + Q^2}\right]^2 Y_+ \cdot \sigma_{r,CC}$$

$$Y_{\pm} = 1 \pm (1 - y)^2$$

$$\sigma_{r,NC} = \mathbf{F_2} + \frac{Y_-}{Y_+}\mathbf{xF_3} - \frac{y^2}{Y_+}\mathbf{F_L},$$

$$\sigma^{\pm}_{r,CC} = W_2^{\pm} \mp \frac{Y_-}{Y_+} x W_3^{\pm} - \frac{y^2}{Y_+} W_L^{\pm}$$

$$\mathbf{F_2^{\pm}} = F_2 + \kappa_Z(-v_e \mp P a_e) \cdot F_2^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2 \pm 2P v_e a_e) \cdot F_2^Z$$

$$\mathbf{xF_3^{\pm}} = \kappa_Z(\pm a_e + P v_e) \cdot xF_3^{\gamma Z} + \kappa_Z^2(\mp 2 v_e a_e - P(v_e^2 + a_e^2)) \cdot xF_3^Z$$

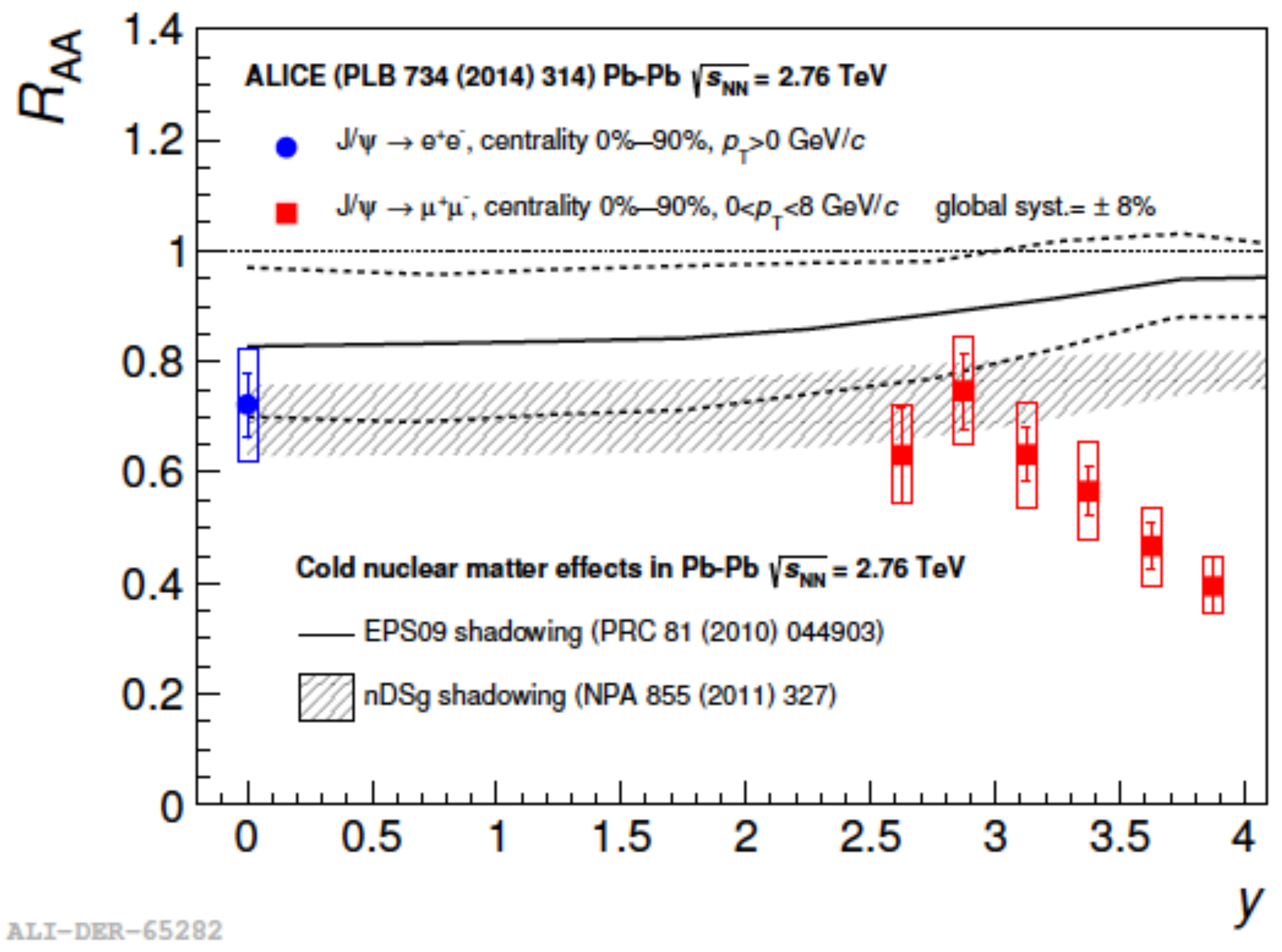
nPDFs: status

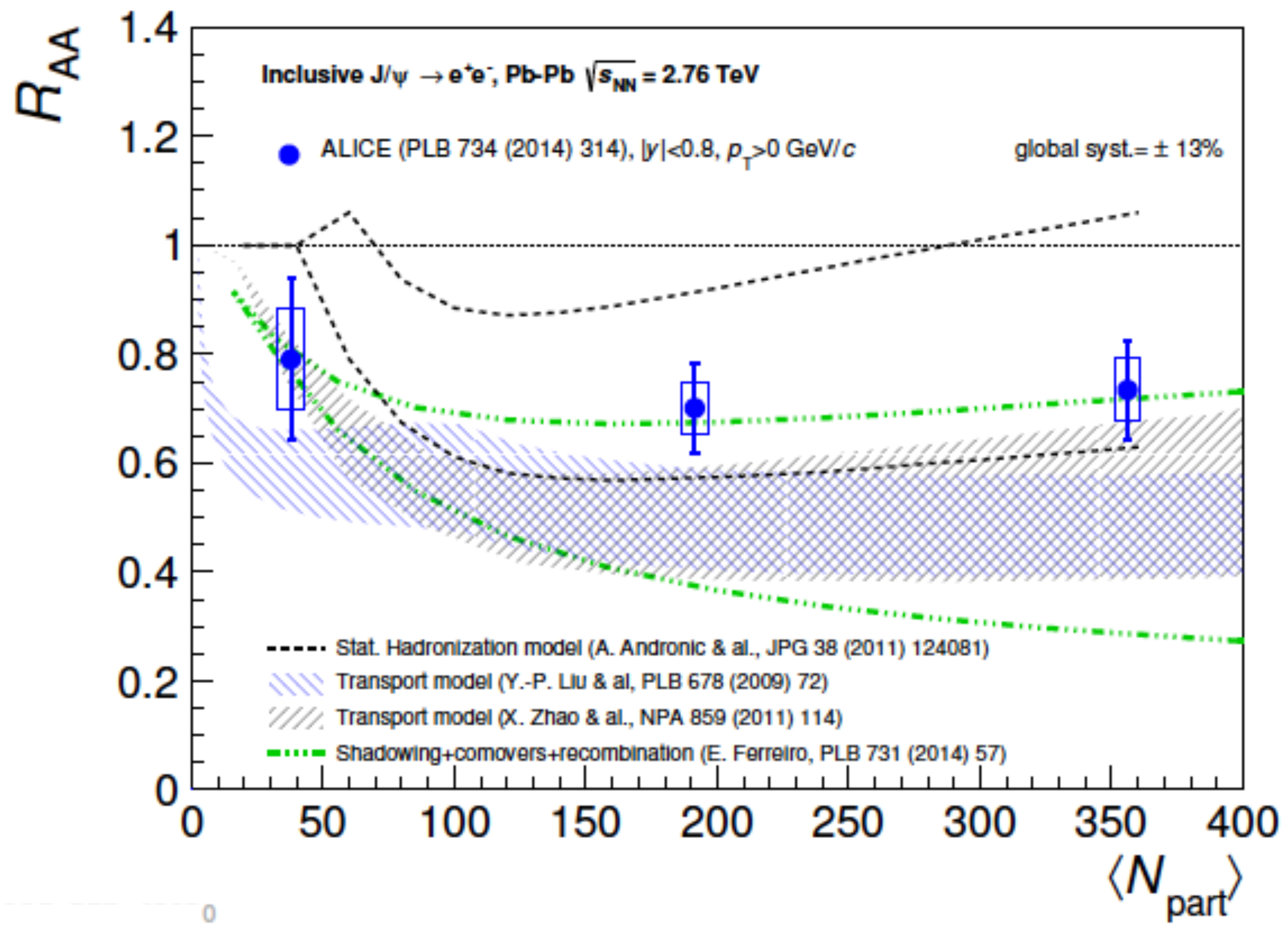
SET		EPS09 JHEP 0904 (2009) 065	DSSZ PRD85 (2012) 074028	nCTEQ15 PRD93 (2016) 085037	KA15 PRD93 (2016) 014036	EPPS16 EPJC C77 (2017)163	nNNPDF1.0 1904.00018
data	eDIS	✔	✔	✔	✔	✔	✔
	DY	✔	✔	✔	✔	✔	✘
	π^0	✔	✔	✔	✘	✔	✘
	νDIS	✘	✔	✘	✘	✔	✘
	pPb	✘	✘	✘	✘	✔	✘
# data		929	1579	740	1479	1811	451
order		NLO	NLO	NLO	NNLO	NLO	NNLO
proton PDF		CTEQ6.1	MSTW2008	~CTEQ6.1	JR09	CT14NLO	NNPDF3.1
mass scheme		ZM-VFNS	GM-VFNS	GM-VFNS	ZM-VFNS	GM-VFNS	FONLL-B
comments		$\Delta\chi^2$=50, ratios, huge shadowing-antishadowing	$\Delta\chi^2$=30, ratios, medium-modified FFs for π^0	$\Delta\chi^2$=35, PDFs, valence flavour sep., not enough sensitivity	PDFs, deuteron data included	$\Delta\chi^2$=52, flavour sep., ratios, LHC pPb data	NNPDF methodology, isoscalarity assumed

nPDFs: status

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

- Lack of data ⇒ large uncertainties for the nuclear glue at small scales and x: problem for benchmarking in HIC in order to extract medium parameters.



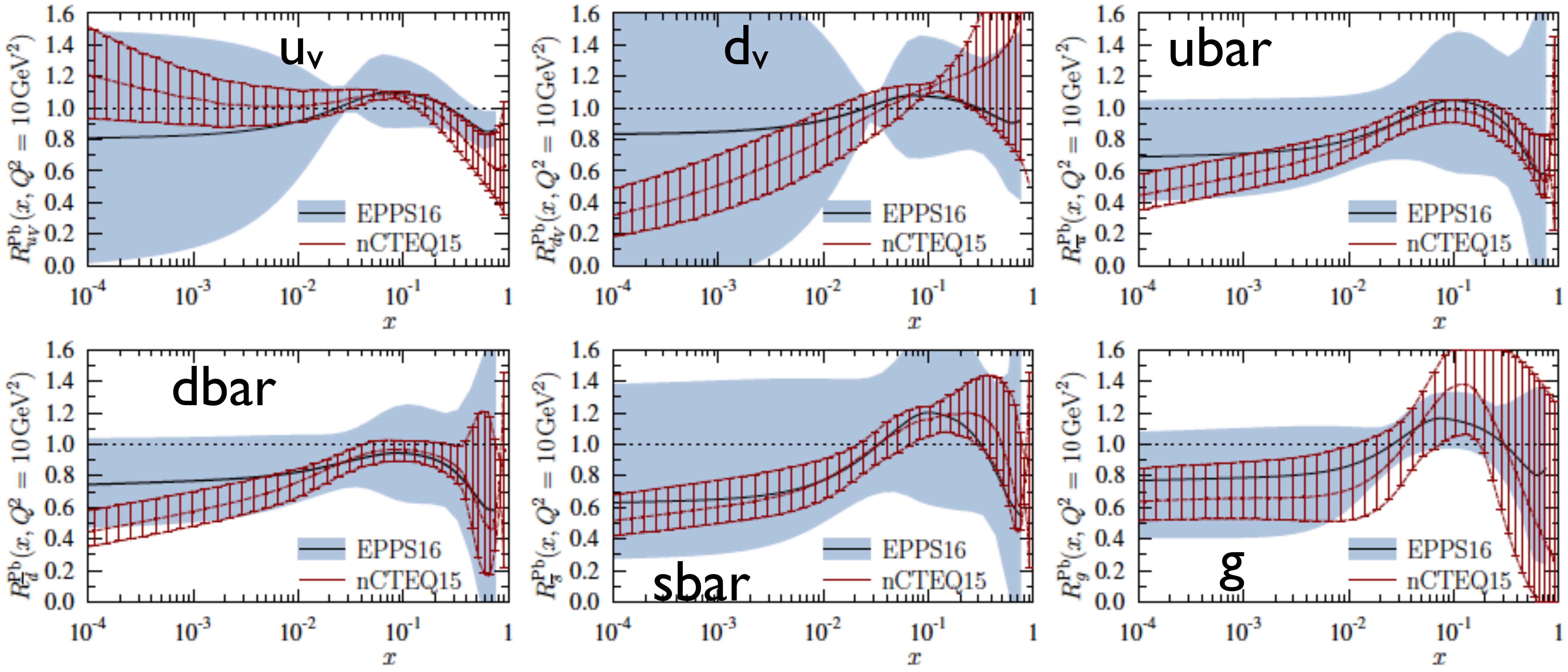


1506.03981

nPDFs: status

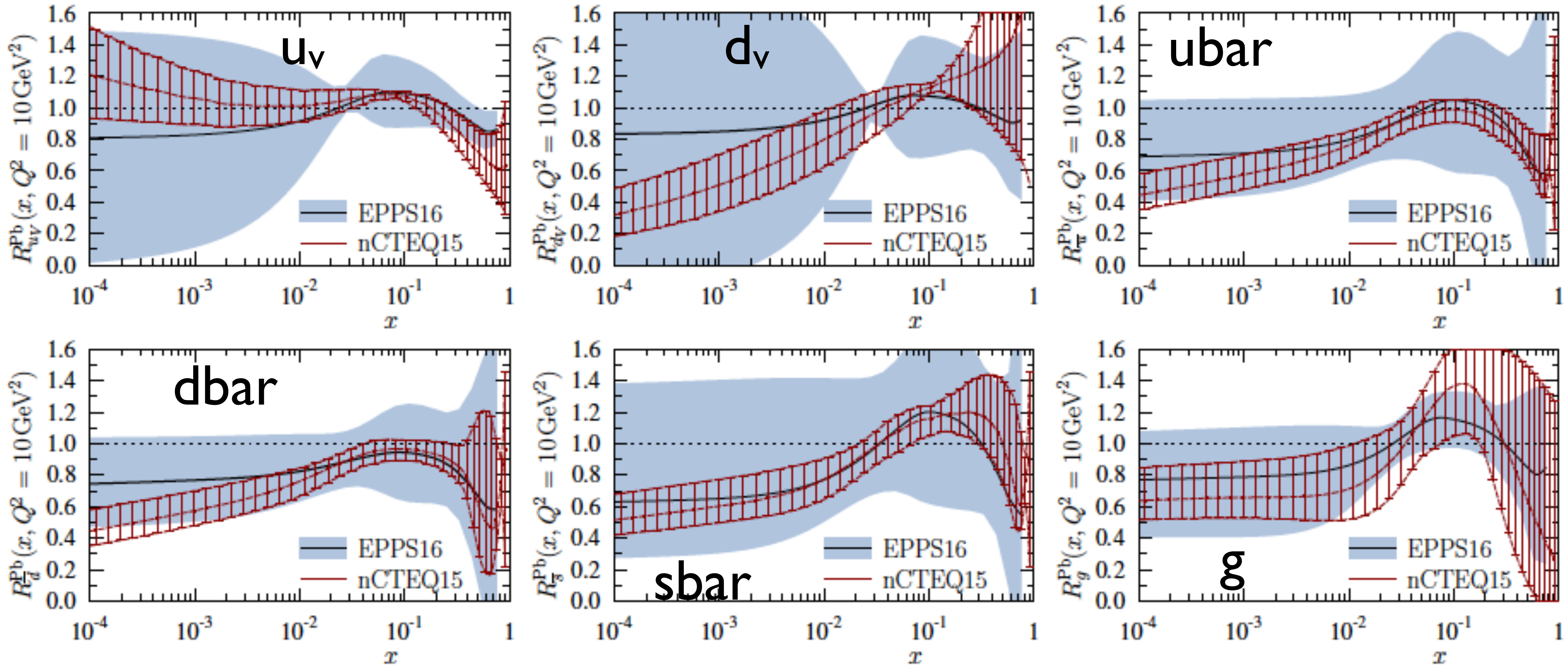
nPDFs: status

- nCTEQ15 vs. EPPS16: note the parametrisation bias.

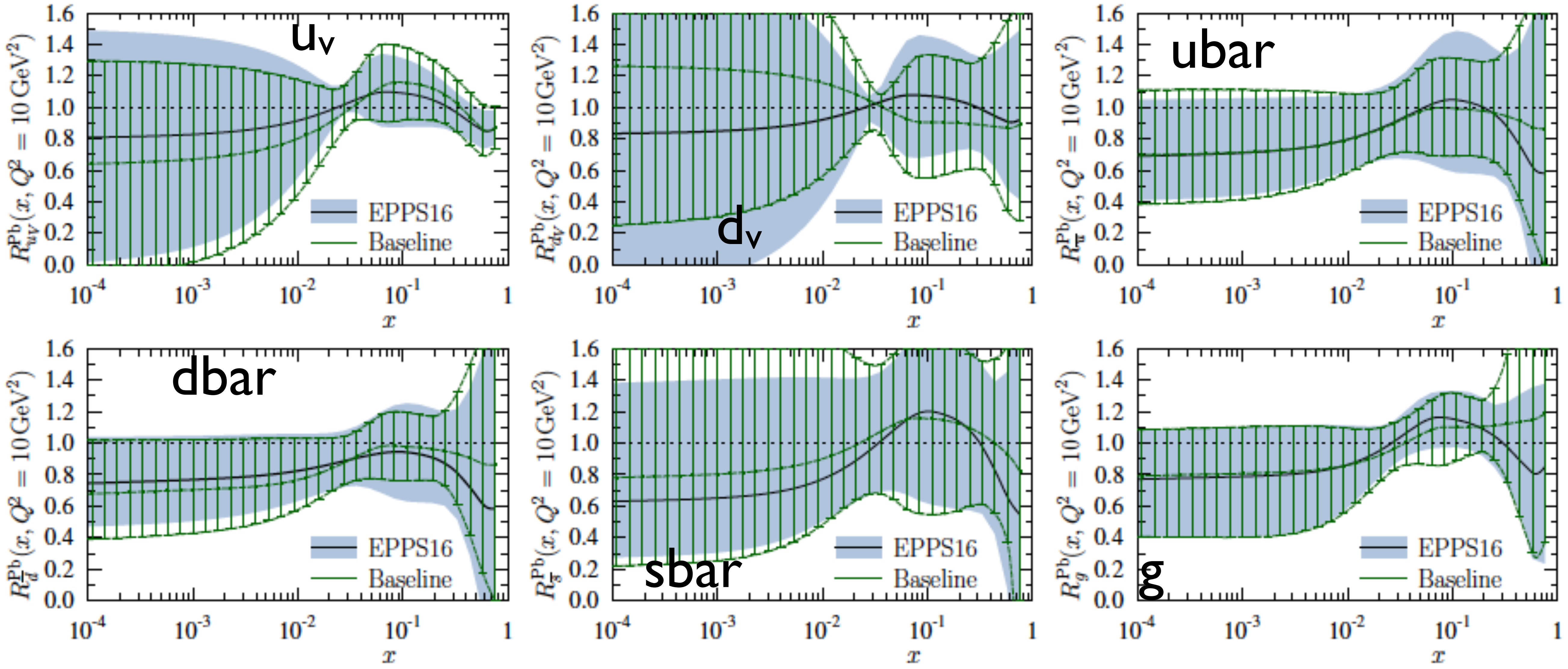


nPDFs: status

- nCTEQ15 vs. EPPS16: note the parametrisation bias.

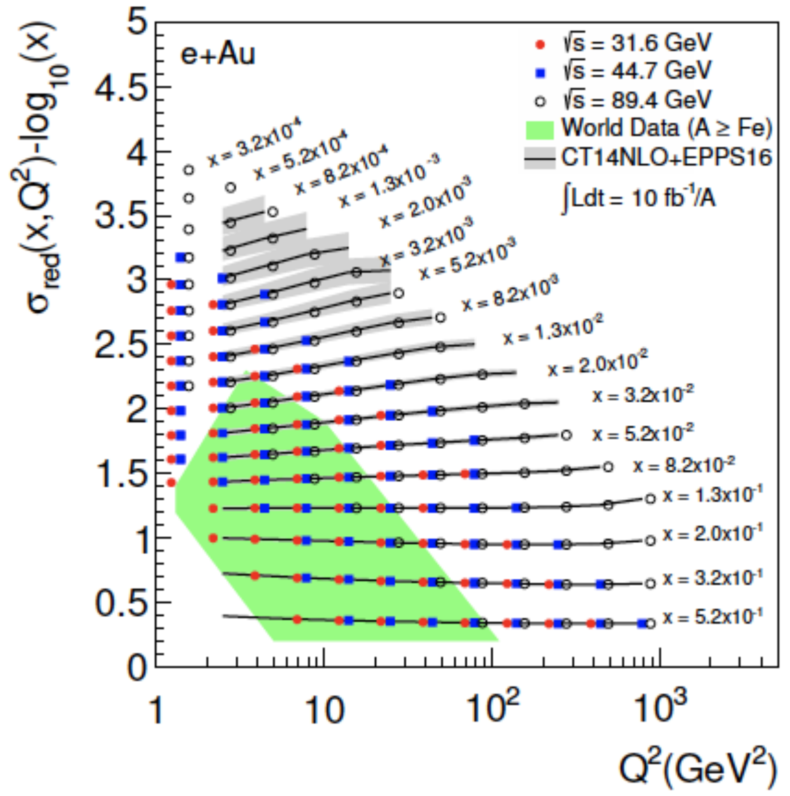


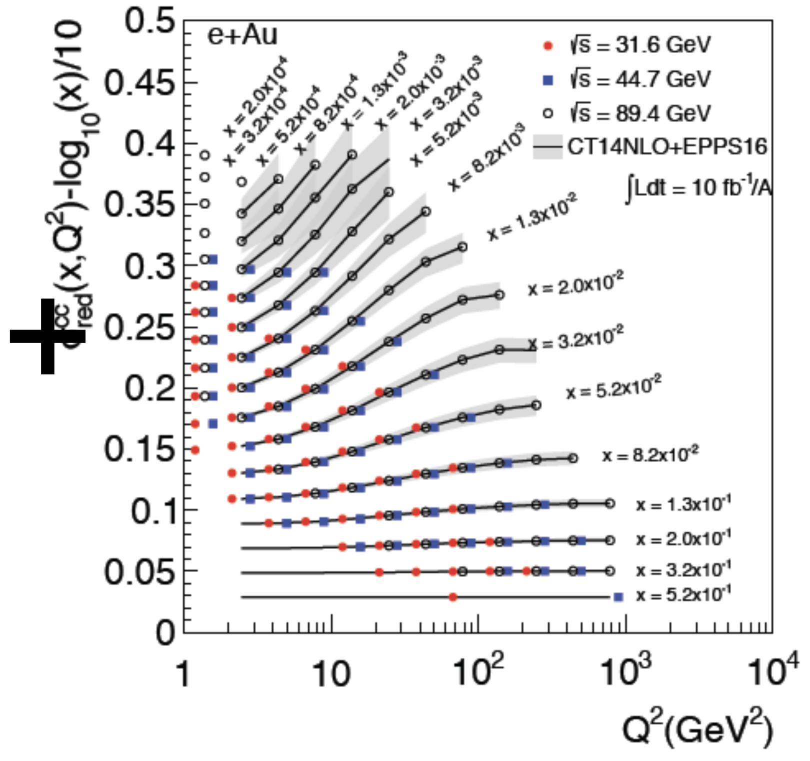
- Presently available LHC data seem not to have a large effect: large-x glue (baseline=no ν, no LHC data).



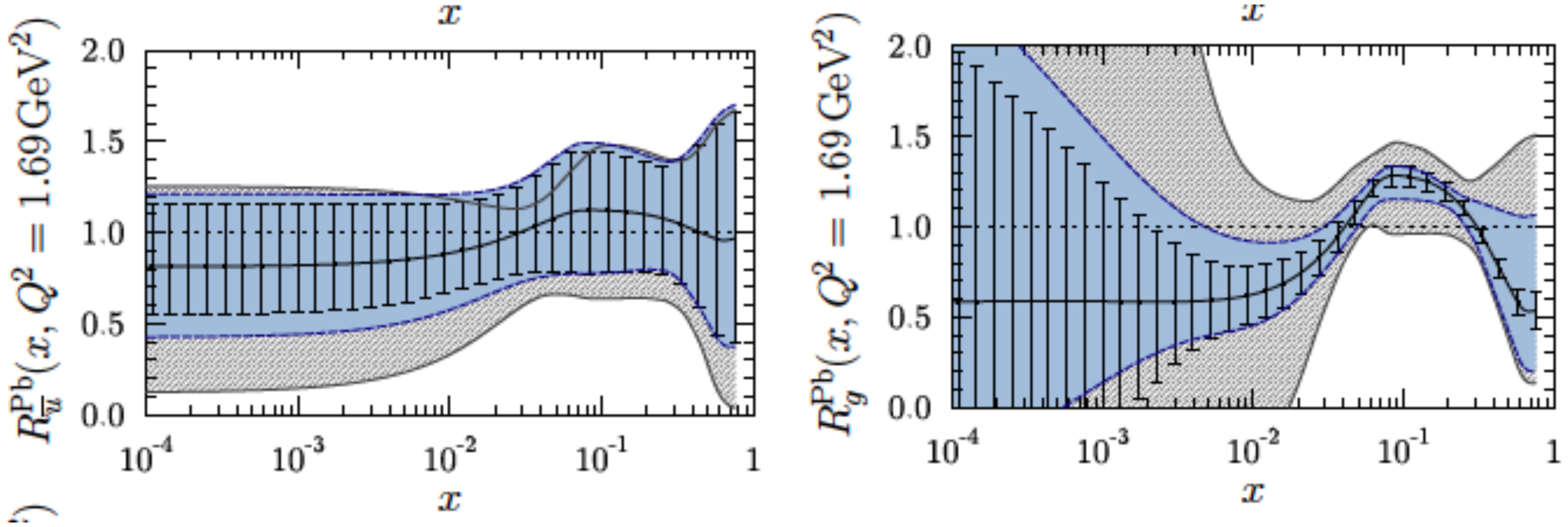
nPDFs: fits

- LHeC/FCC-eh ePb and EIC eAu pseudodata included in EPPS16-like global fits: large impact.

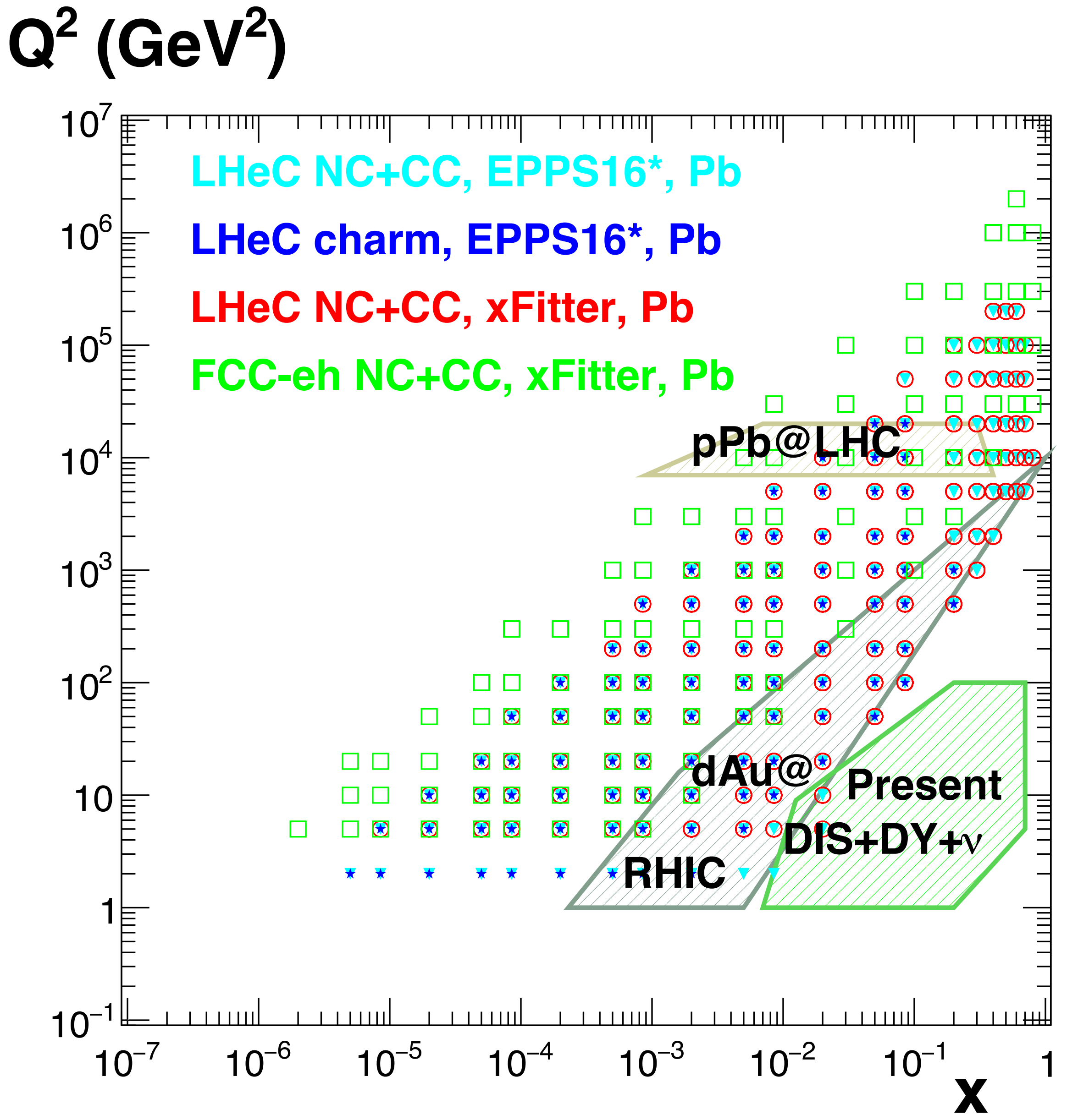




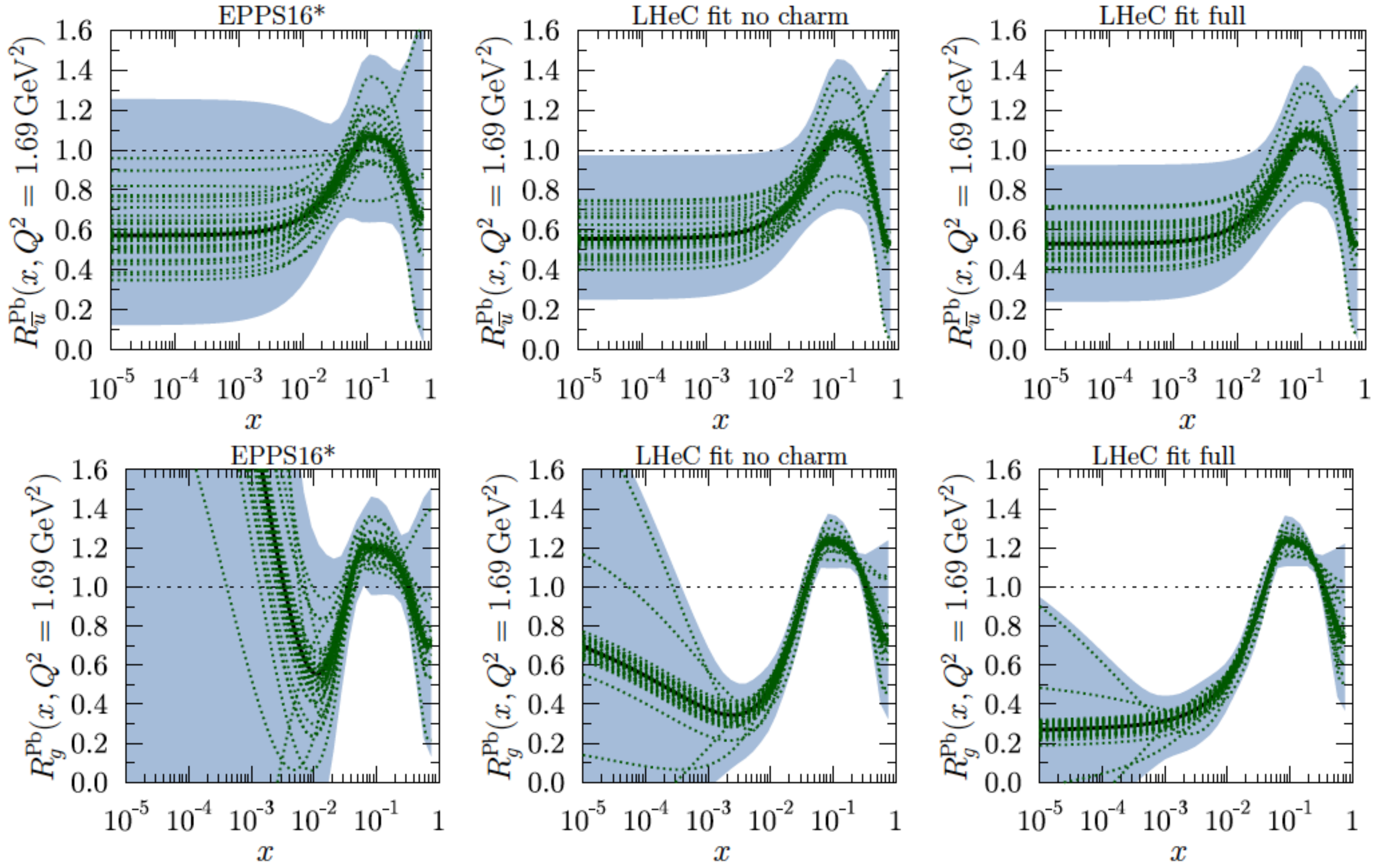
1708.05654
EIC



- HF separation has sizeable impact (on glue).



LHeC



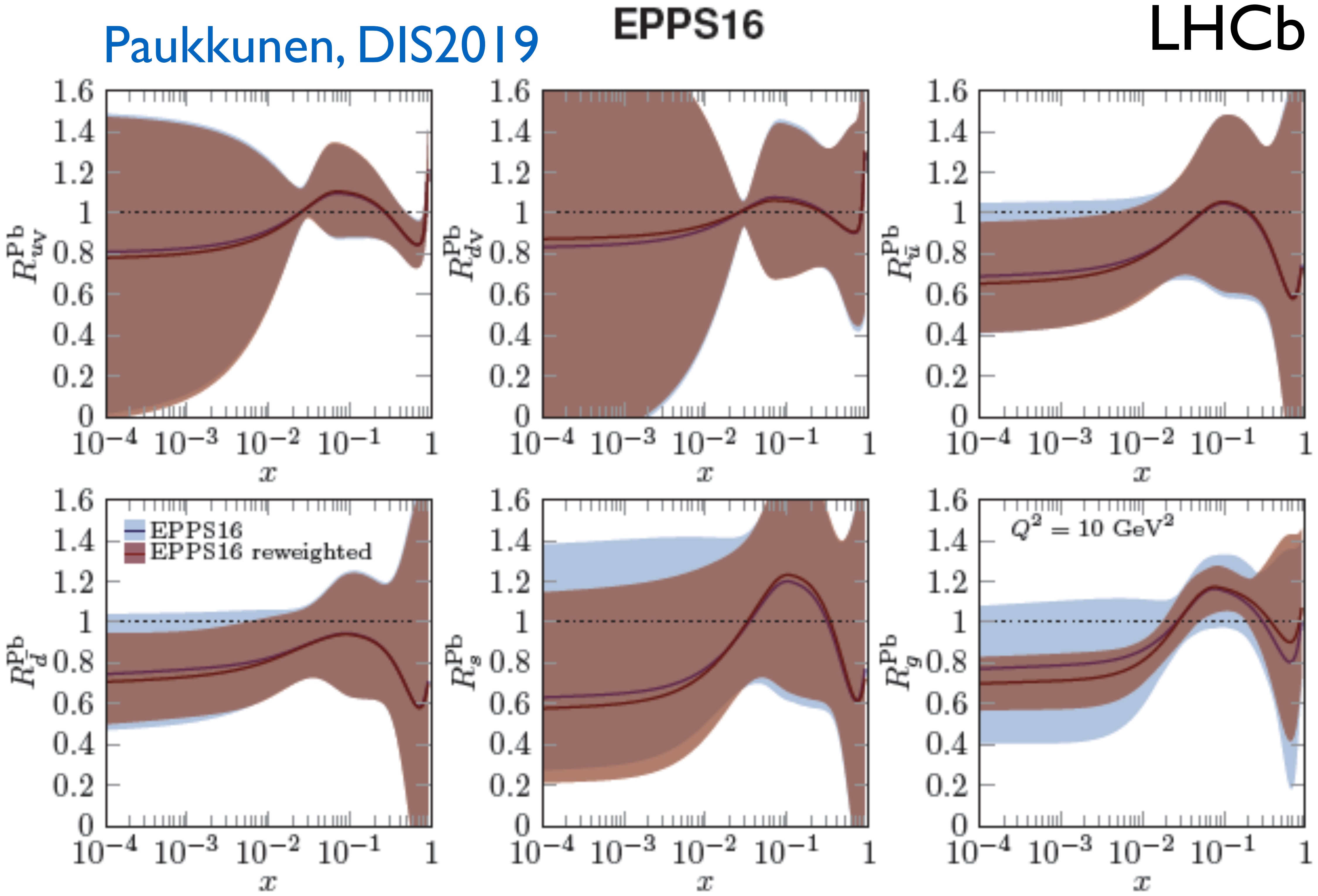
- Not yet included: beauty, c-tagged CC for strange.

nPDFs: HL-LHC

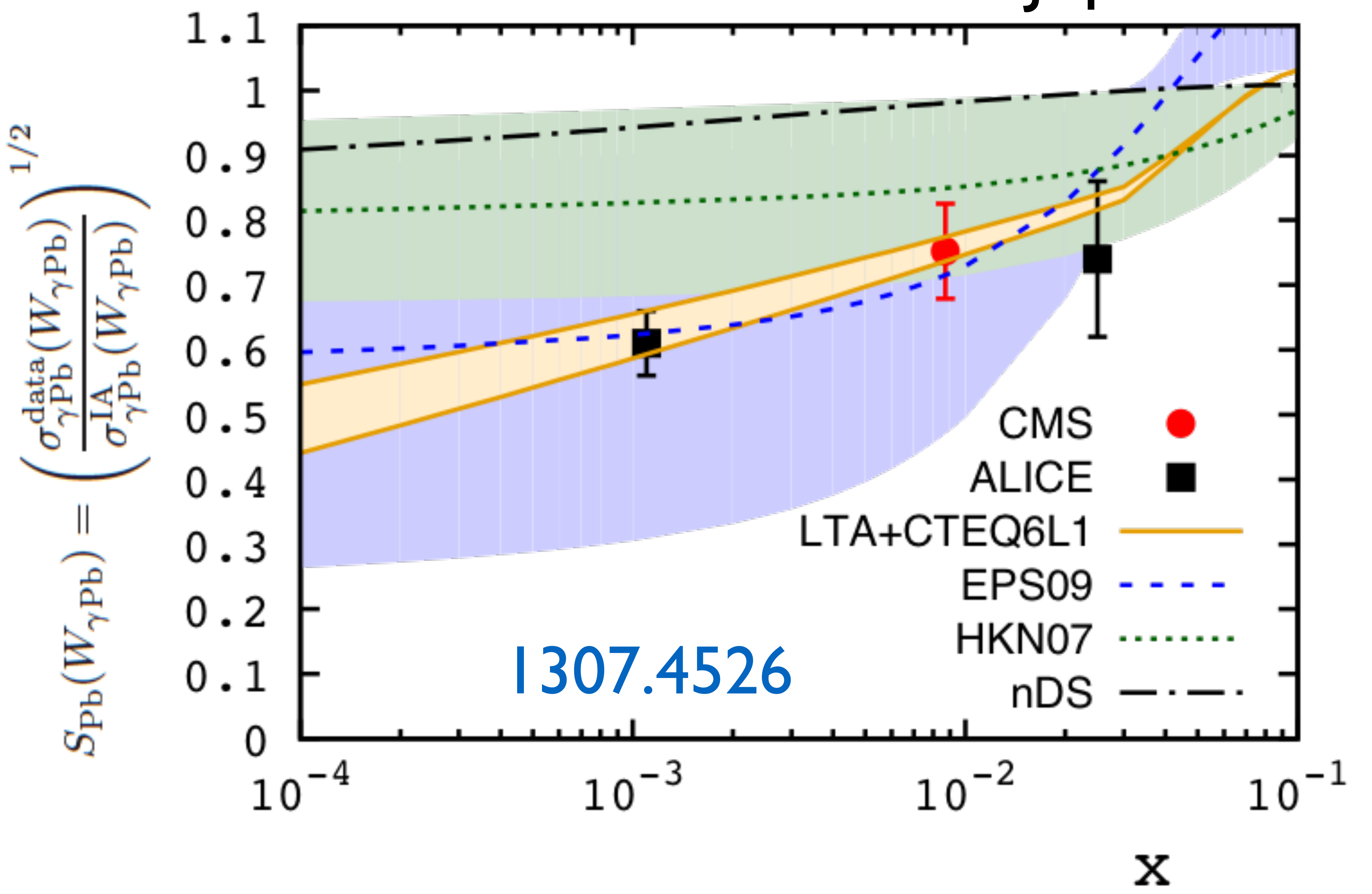
- Presently, only dijet and W/Z data from pPb at the LHC are used in global fits.
- Use of heavy quarks (including top) and quarkonium under study. See 1812.06772.

Paukkunen, DIS2019

LHCb D-mesons

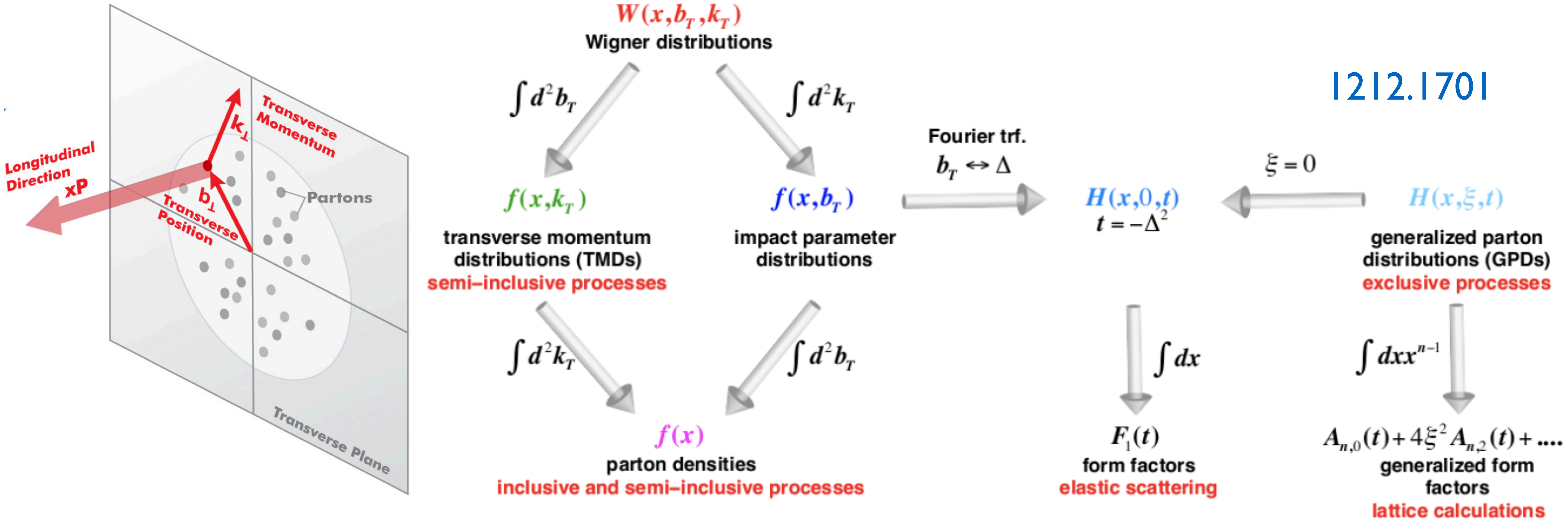


Exclusive J/ψ in UPCs



- Also exclusive vector meson production in UPCs - additional assumptions are required.
- **nPDFs from eA to be contrasted with pA/AA**: precise checks of factorisation in the nuclear environment.

3D-structure of hadrons and nuclei:



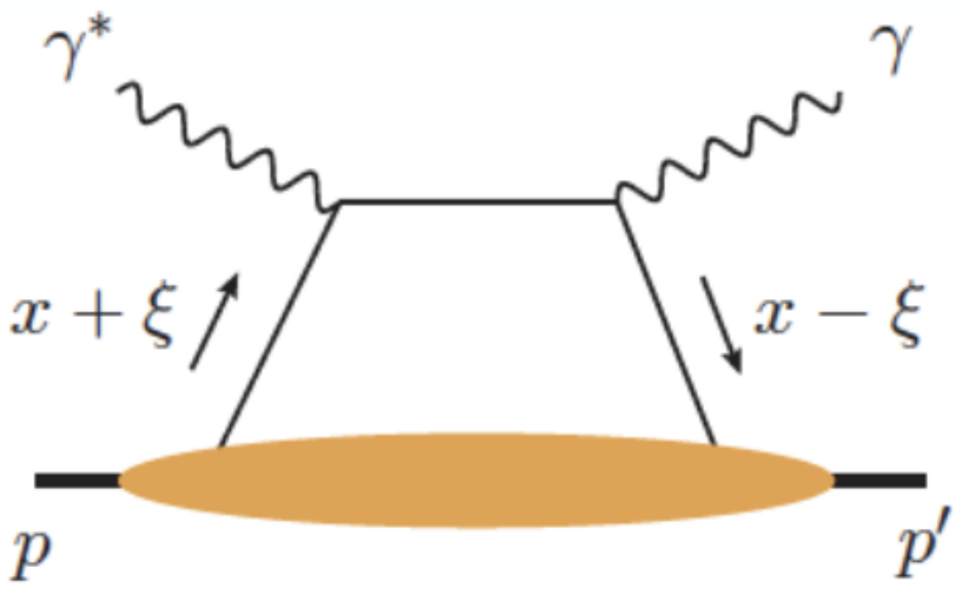
1212.1701

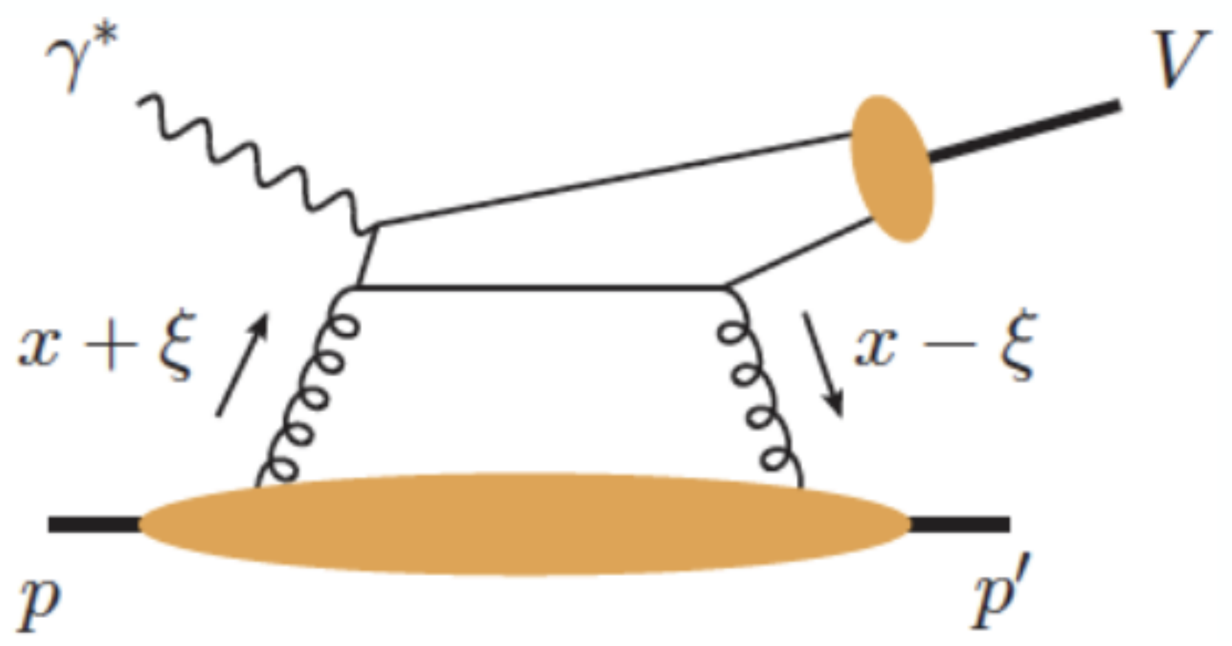
Two-scale processes

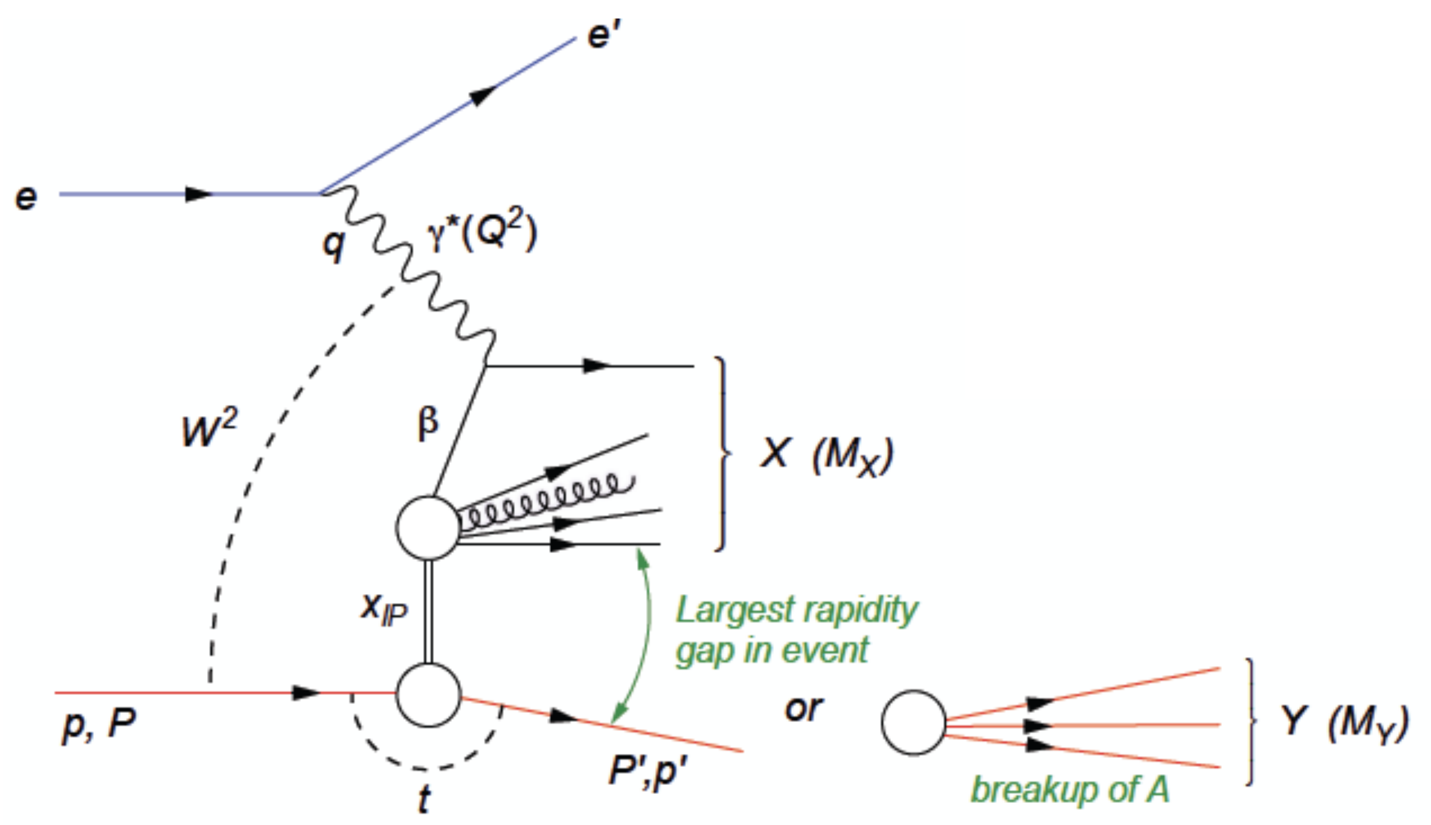
One-scale processes

- New kinds of factorisation (or lack of it), new evolution equations.
- Directly related with spin.
- Most of these quantities can be ideally explored in EIC and LHeC; they also can be explored in fixed target programs (talks by Lansberg and Schnell) and UPCs (at Q=0).

Quark and gluon GPDs:





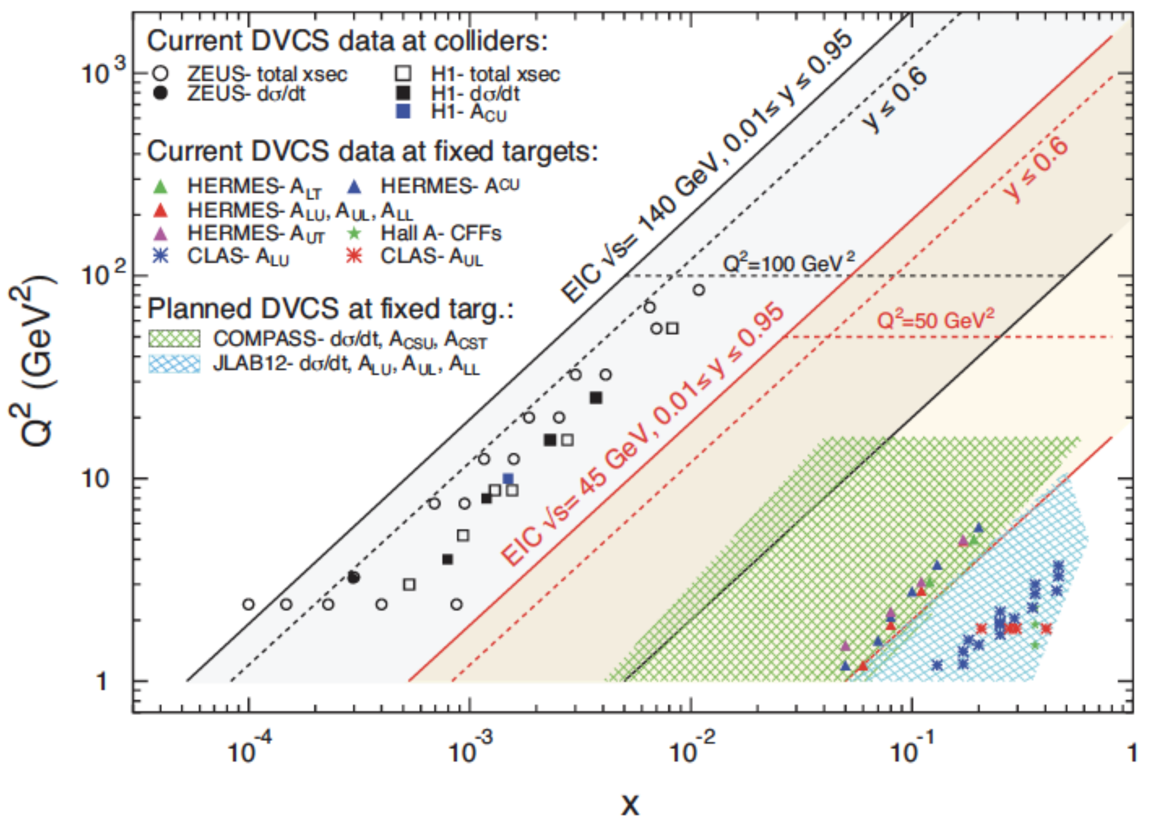


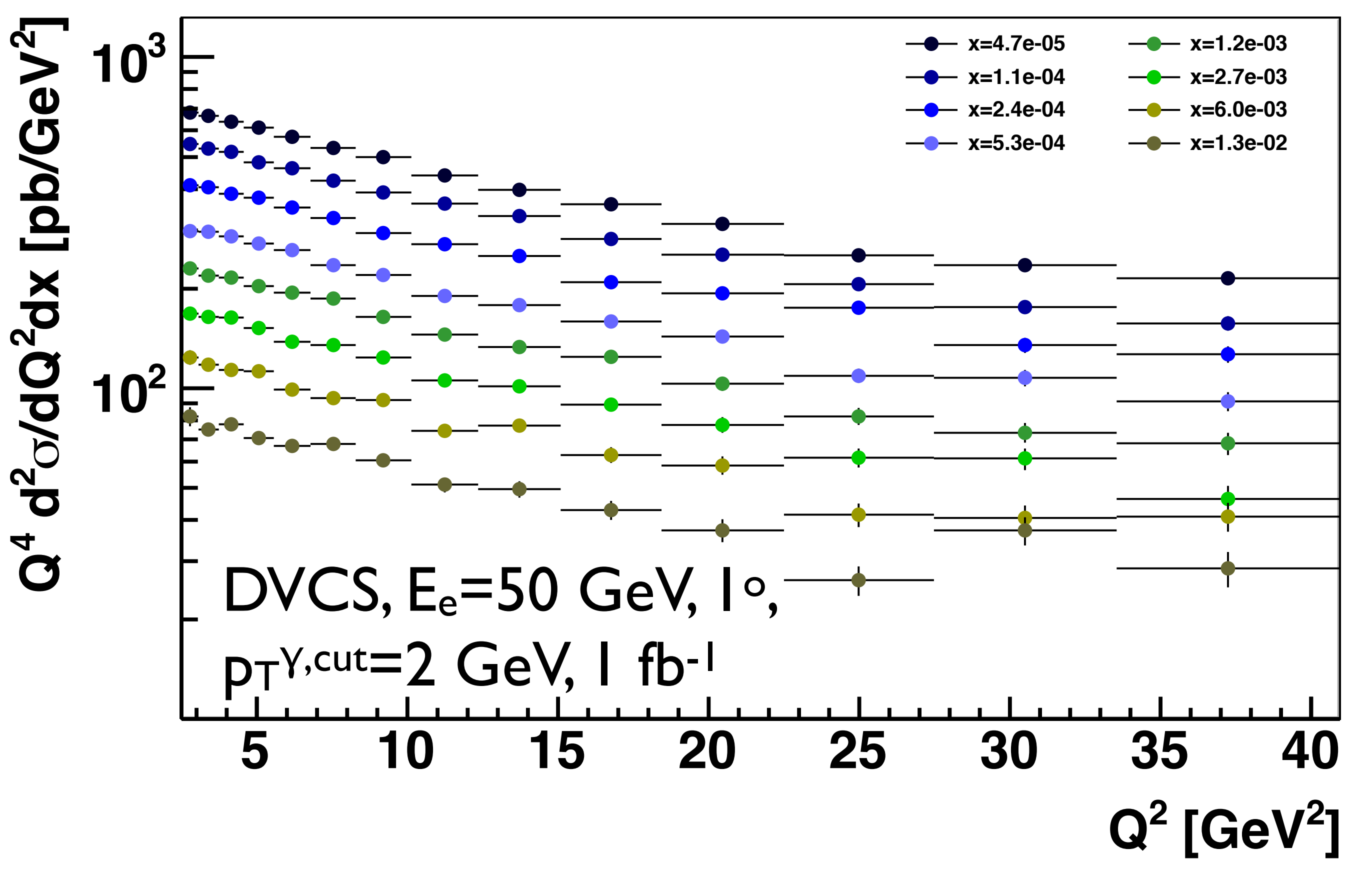
$$\int \frac{dw^-}{2\pi} e^{-i\xi P^+ w^-} \left\langle P' \middle| T\overline{\psi}_j\left(0,\frac{1}{2}w^-,\mathbf{0}_T\right)\frac{\gamma^+}{2}\psi_j\left(0,-\frac{1}{2}w^-,\mathbf{0}_T\right)\middle| P\right\rangle_c$$

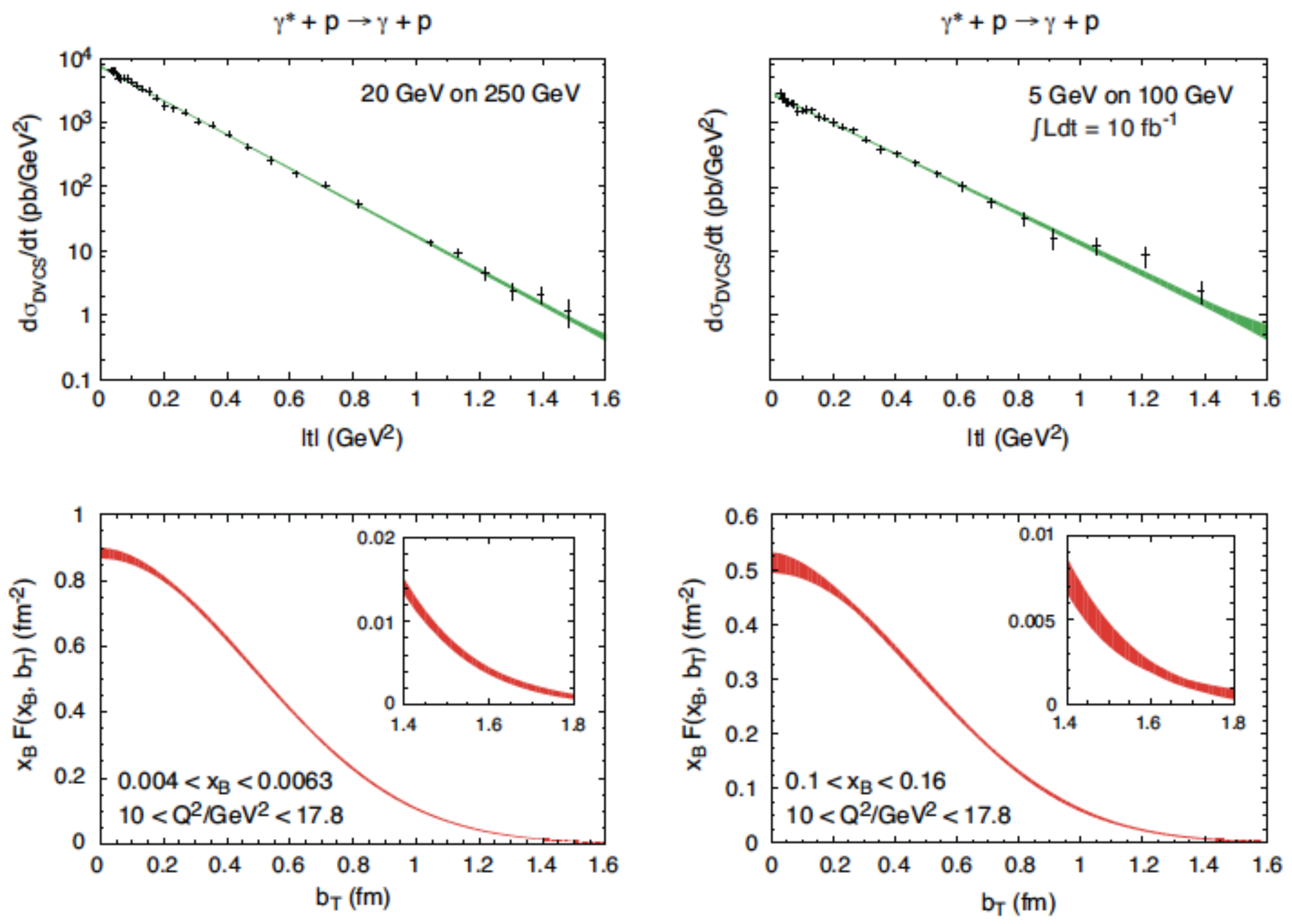
coherent
p/A stays intact

incoherent
p/A breaks up

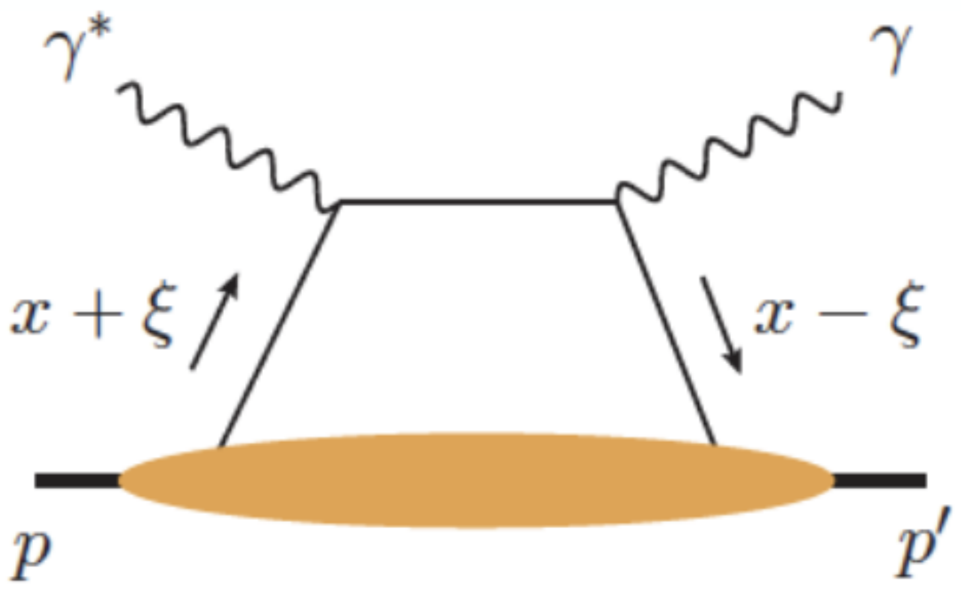
- Coherent exclusive production of γ and VM yields information about q and g GPDs.



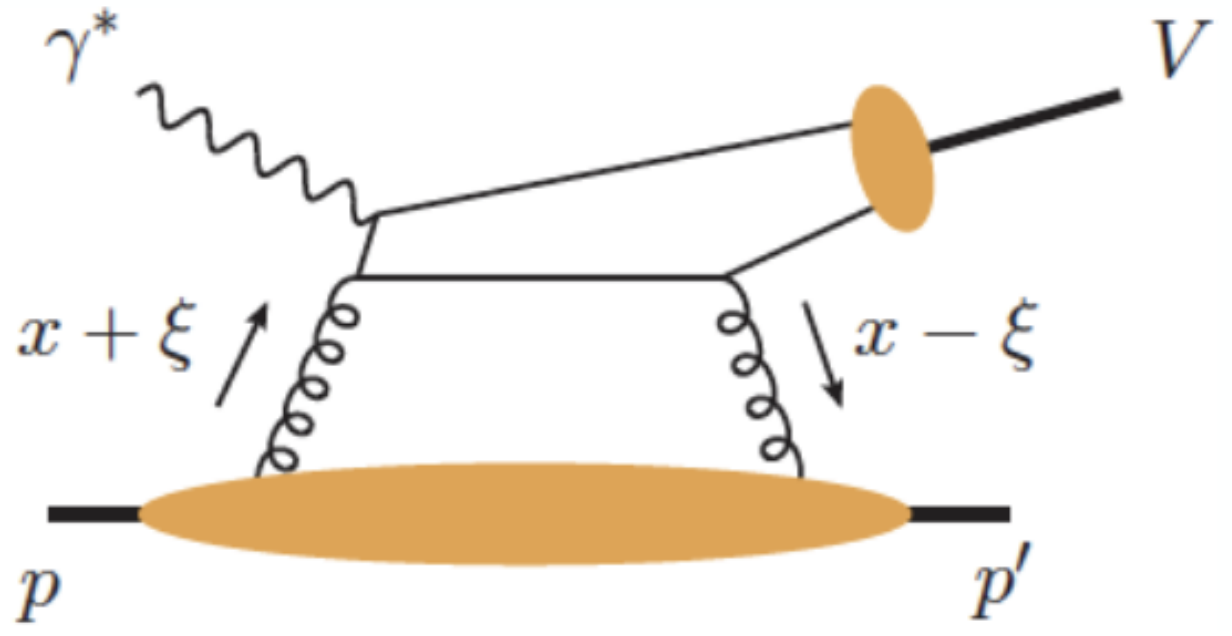


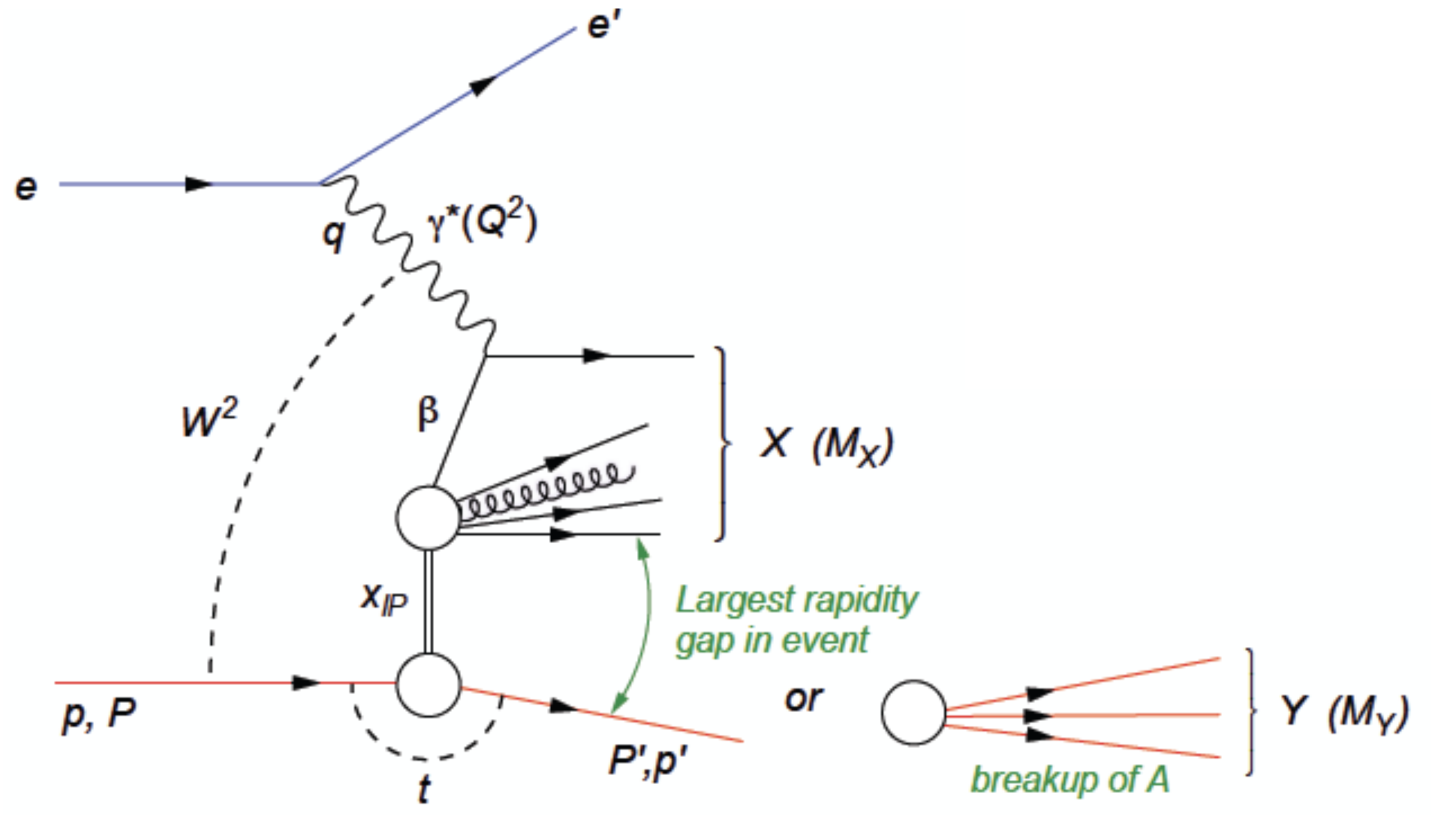


Quark and gluon GPDs:



$$\int \frac{dw^-}{2\pi} e^{-i\xi P^+ w^-} \left\langle P' \left| T \overline{\psi}_j \left(0, \frac{1}{2}w^-, \mathbf{0}_T\right) \frac{\gamma^+}{2} \psi_j \left(0, -\frac{1}{2}w^-, \mathbf{0}_T\right) \right| P \right\rangle_c$$

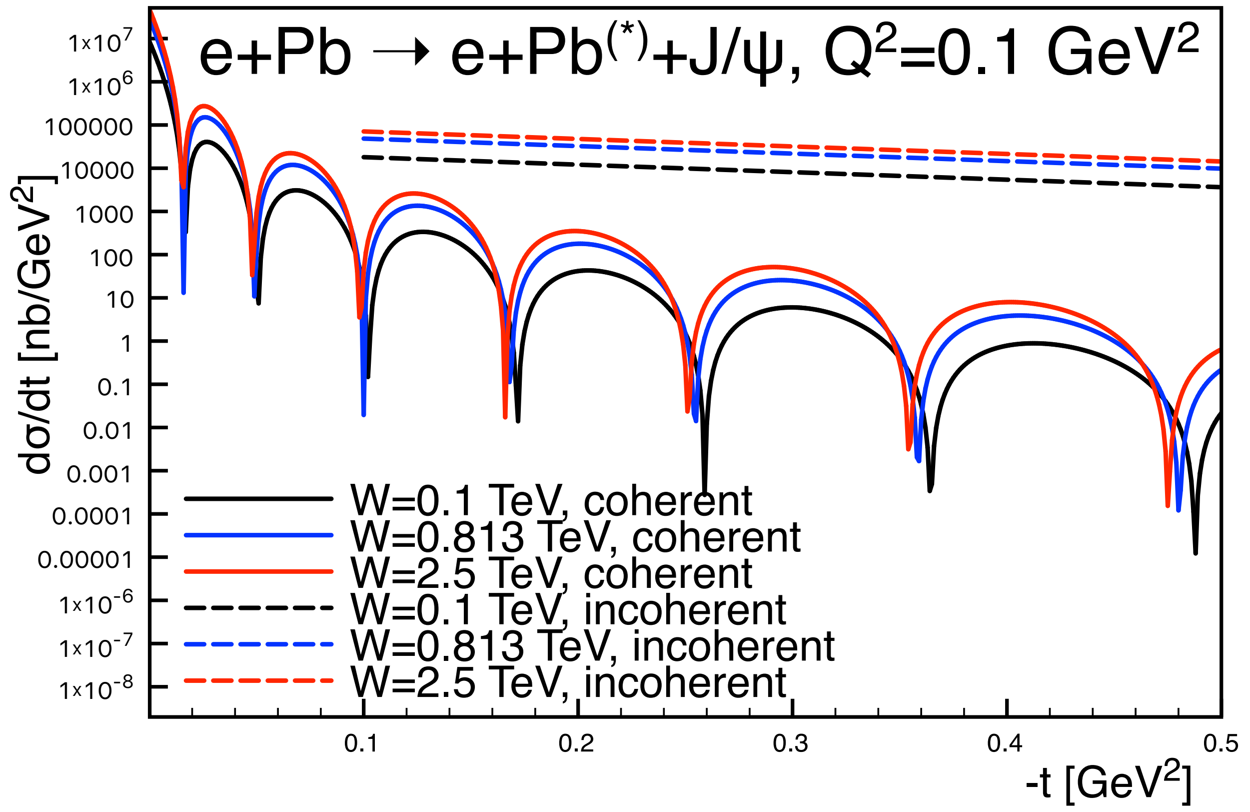


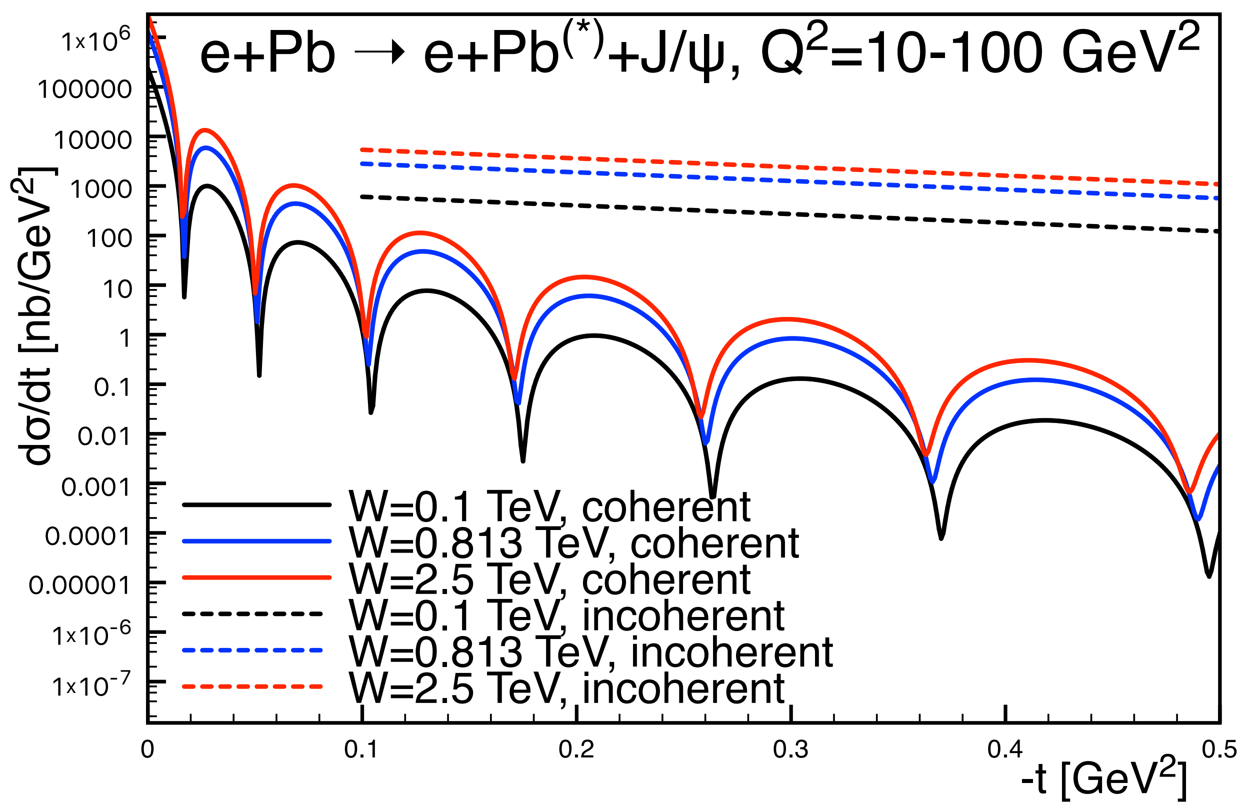


coherent
p/A stays intact

incoherent
p/A breaks up

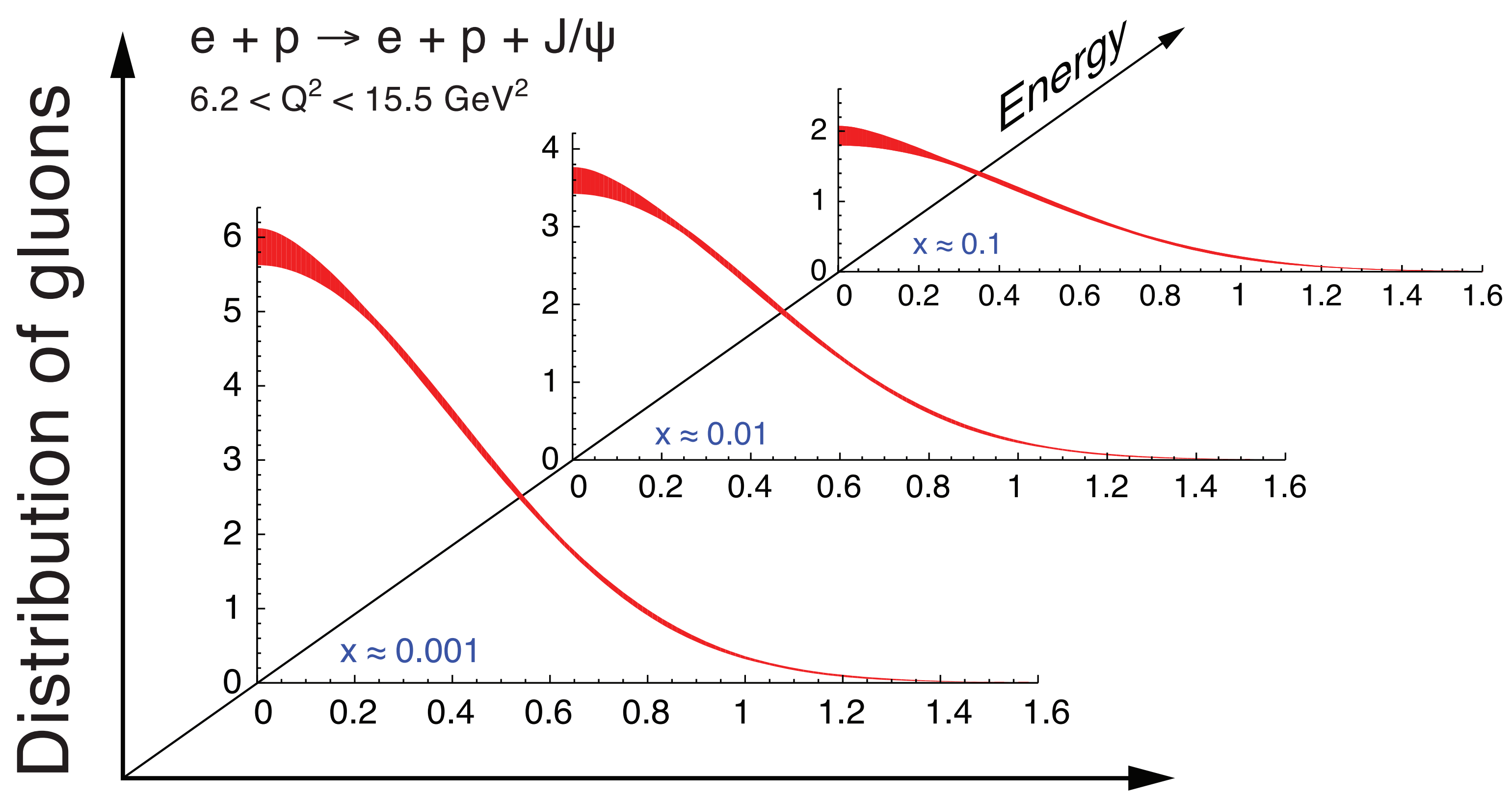
- Coherent exclusive production of γ and VM yields information about q and g GPDs.



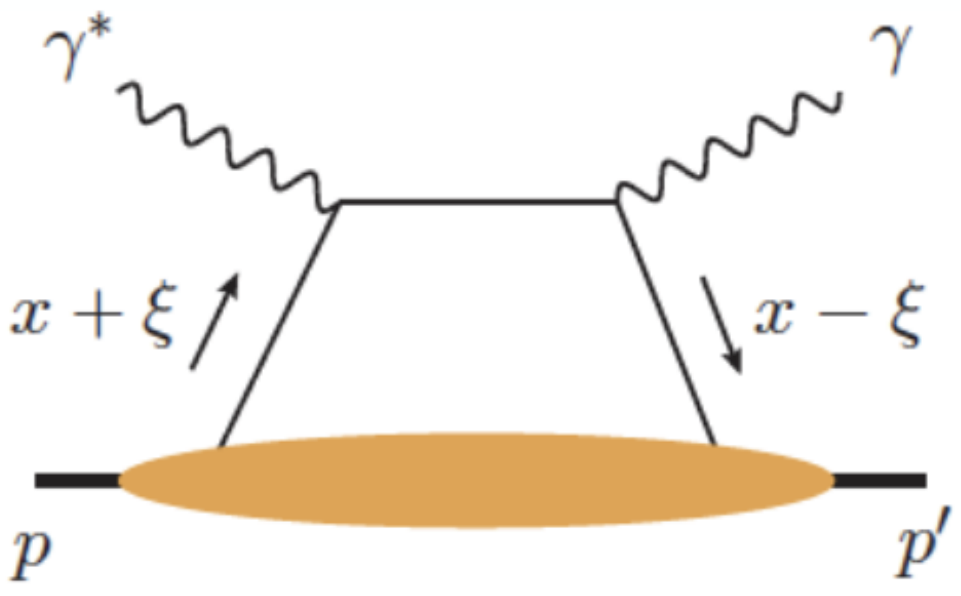


Mantysaari, 1011.1988, IPsat

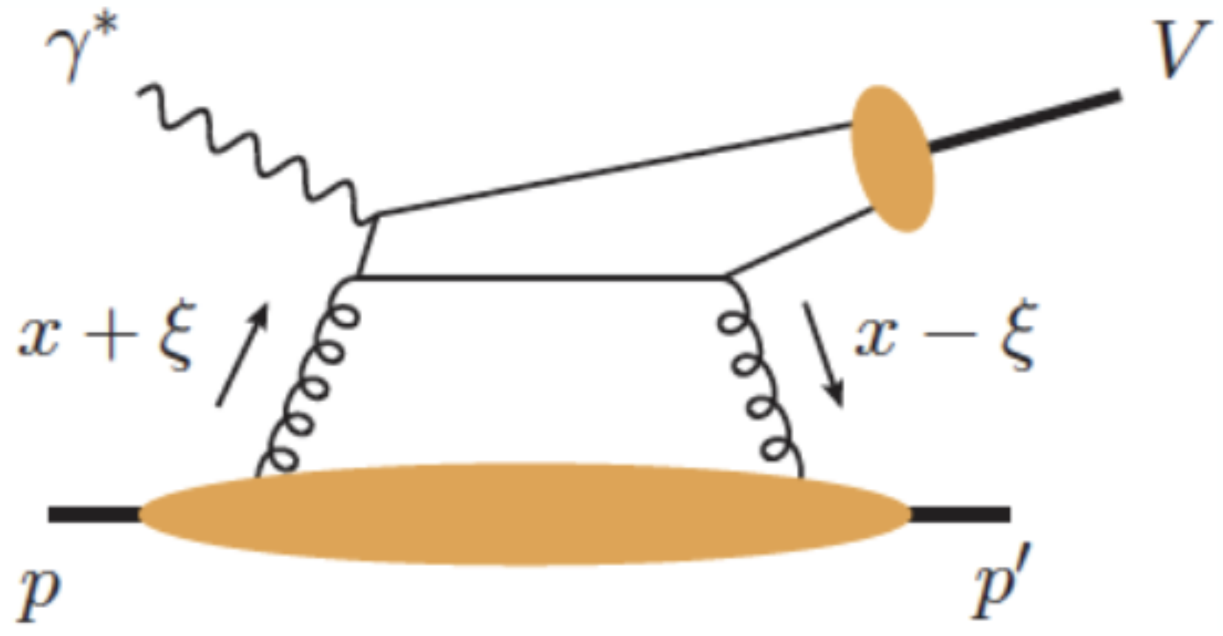
1212.1701

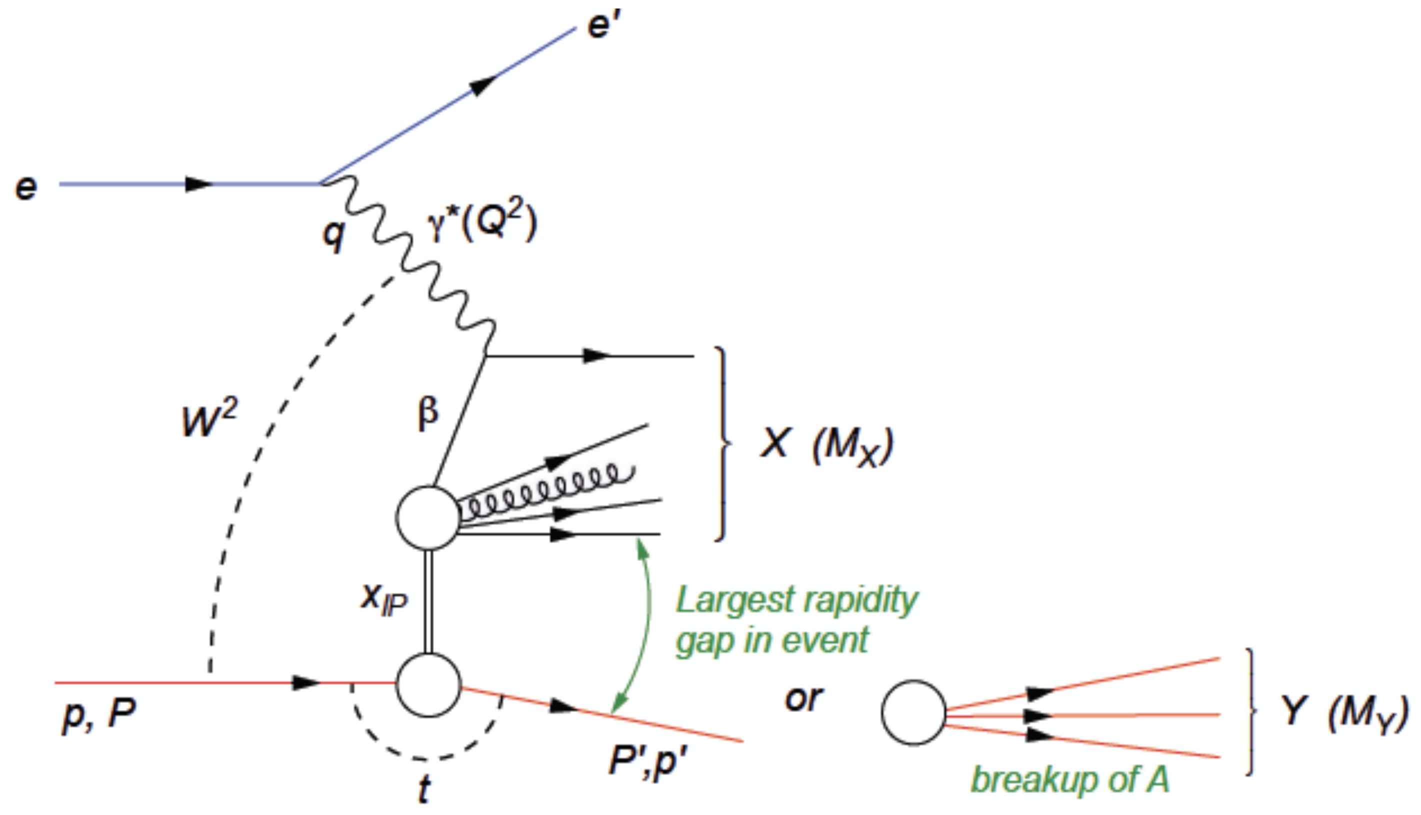


Quark and gluon GPDs:



$$\int \frac{\mathrm{d}w^-}{2\pi} e^{-i\xi P^+ w^-} \left\langle P' \middle| T \overline{\psi}_j \left(0, \frac{1}{2} w^-, \mathbf{0}_\mathrm{T}\right) \frac{\gamma^+}{2} \psi_j \left(0, -\frac{1}{2} w^-, \mathbf{0}_\mathrm{T}\right) \middle| P \right\rangle_\mathrm{c}$$

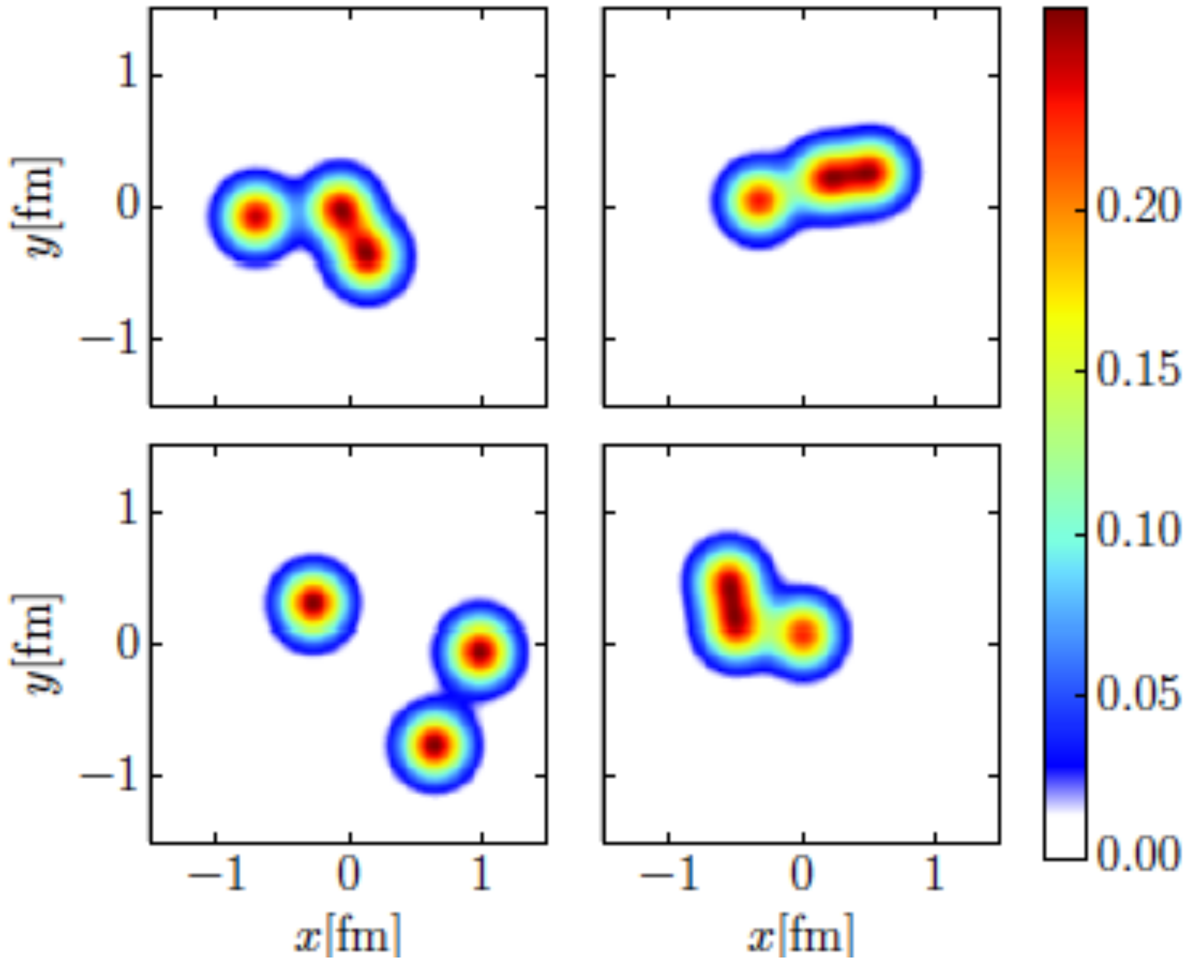


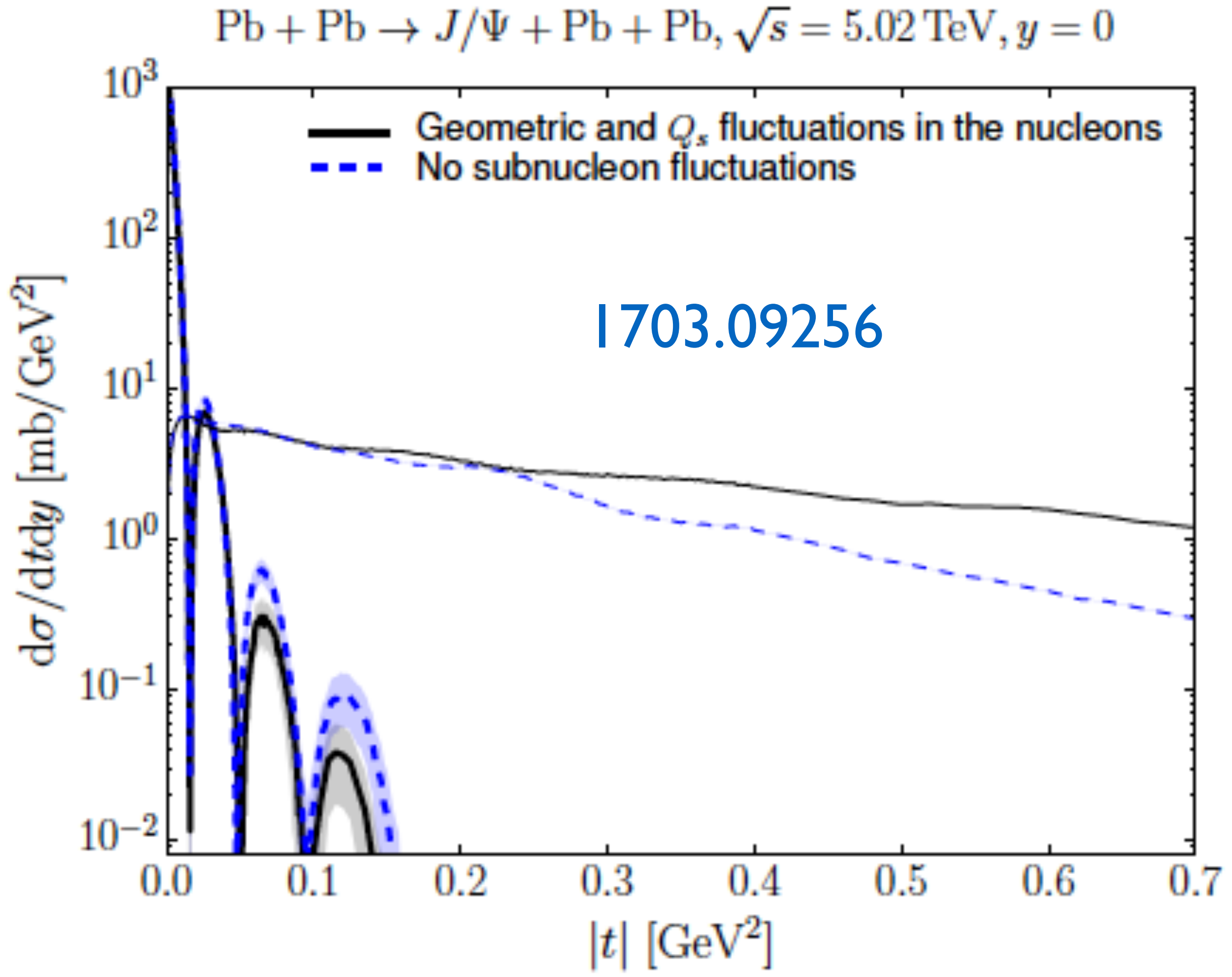


coherent
p/A stays intact

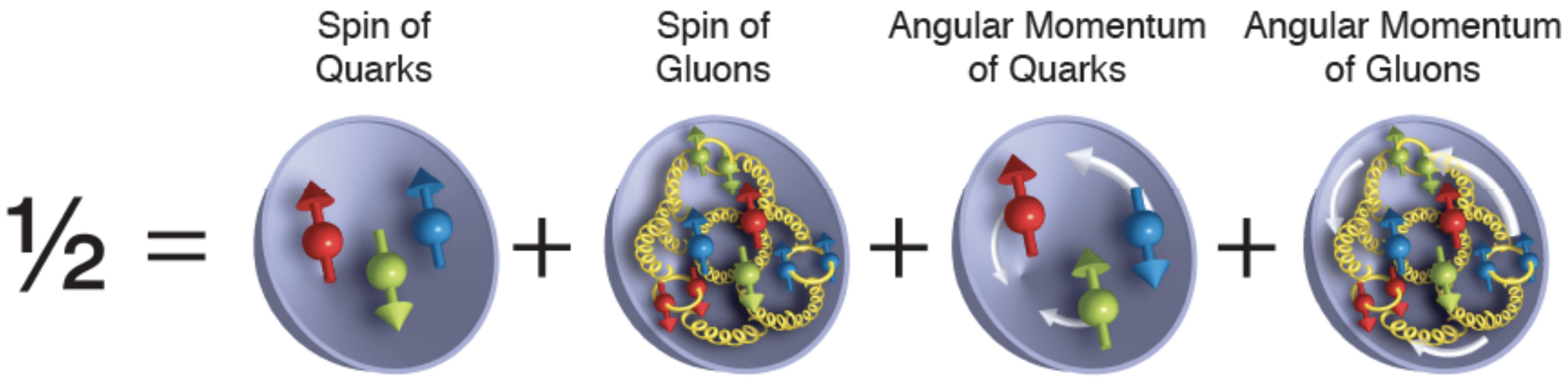
incoherent
p/A breaks up

- Coherent exclusive production of γ and VM yields information about q and g GPDs.
- Incoherent exclusive production yields information about fluctuations: hot spots.





Spin:



- The origin of proton spin has been an open issue for several decades: schematically speaking, quarks account for ~30 %, gluons for ~ 20 % (known in a limited x-range), the rest?

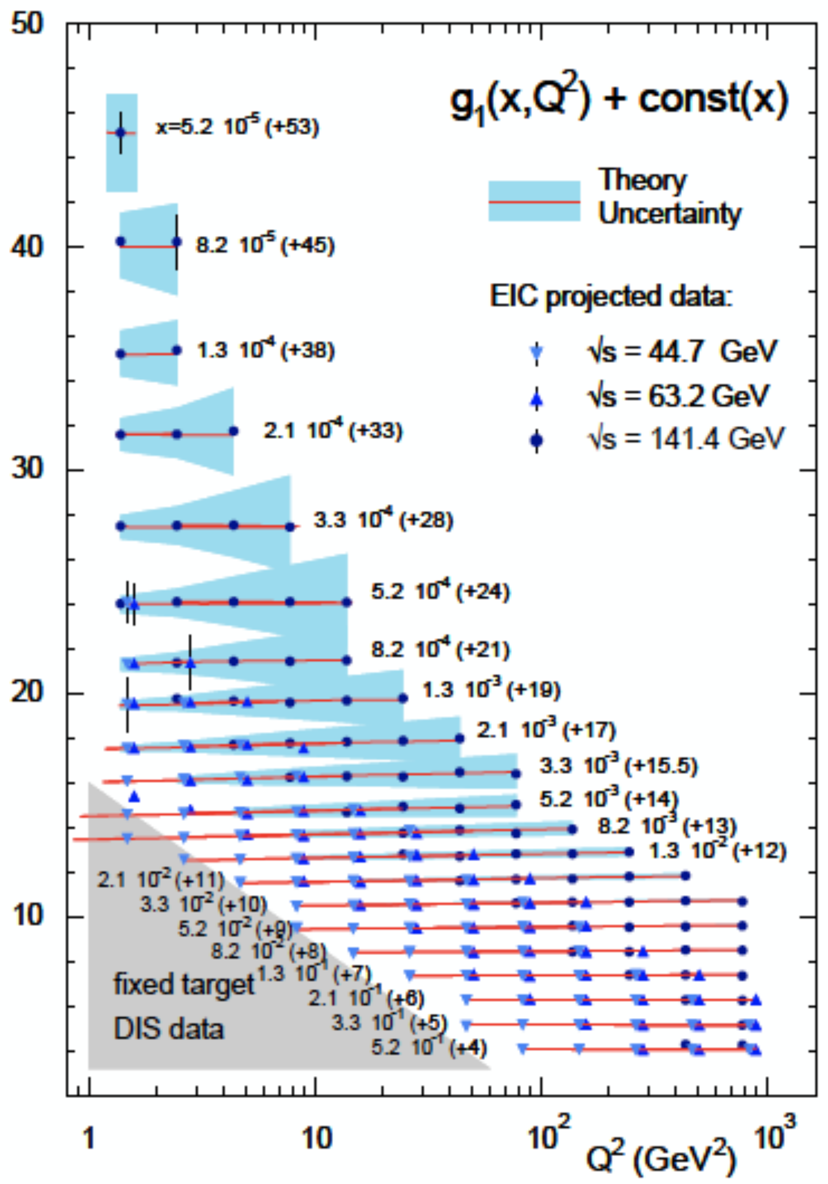
Inclusive Measurement: $\frac{1}{2}\left[\frac{\mathrm{d}^2\sigma^{\rightleftarrows}}{\mathrm{d}x\,\mathrm{d}Q^2}-\frac{\mathrm{d}^2\sigma^{\rightrightarrows}}{\mathrm{d}x\,\mathrm{d}Q^2}\right]\simeq\frac{4\pi\,\alpha^2}{Q^4}y\,(2-y)\,g_1(x,Q^2)$

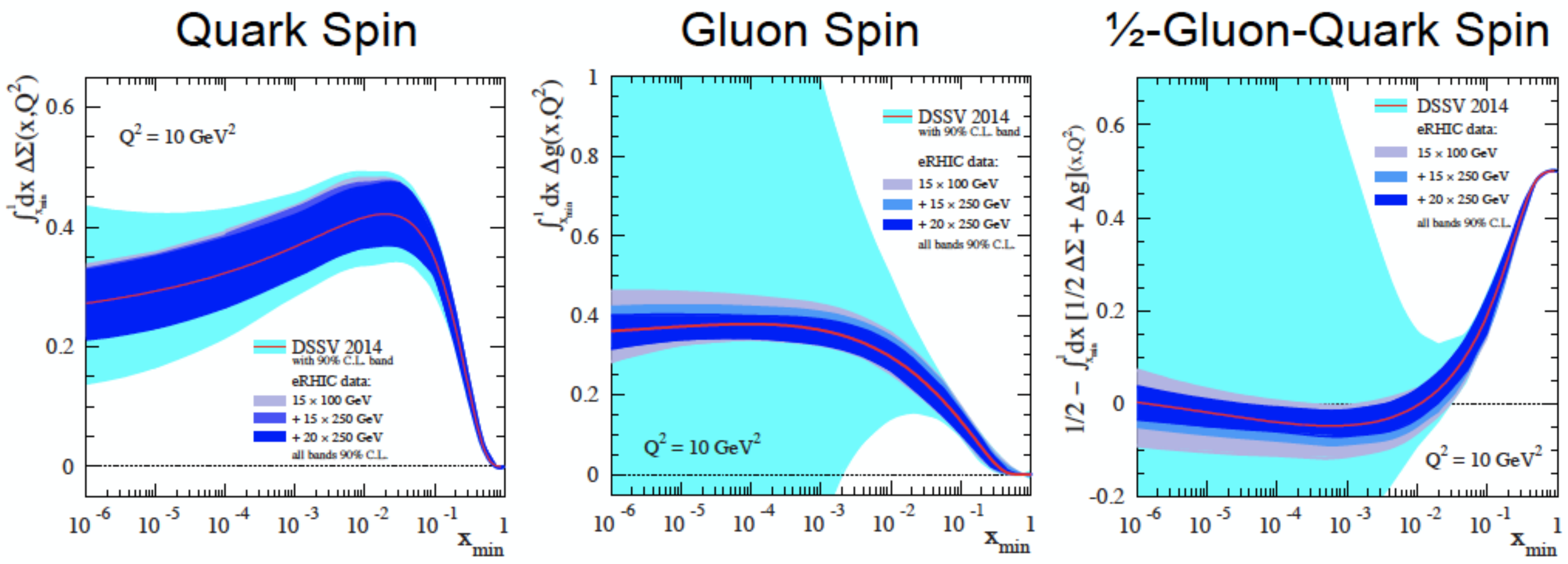
e+p → e'+X

Leading Order: $g_1(x,Q^2)=\frac{1}{2}\sum e_q^2\left[\Delta q(x,Q^2)+\Delta\bar{q}(x,Q^2)\right]$

$$\Delta\Sigma(Q^2)=\int_0^1 dx\ g_1(x,Q^2)$$ (Quark Spin)

Higher Order: $\frac{dg_1}{d\log Q^2}\propto\Delta g(x,Q^2)$ (Gluon Spin)





- Inclusive measurements with both e and p polarised (**EIC**): huge improvement at low x.

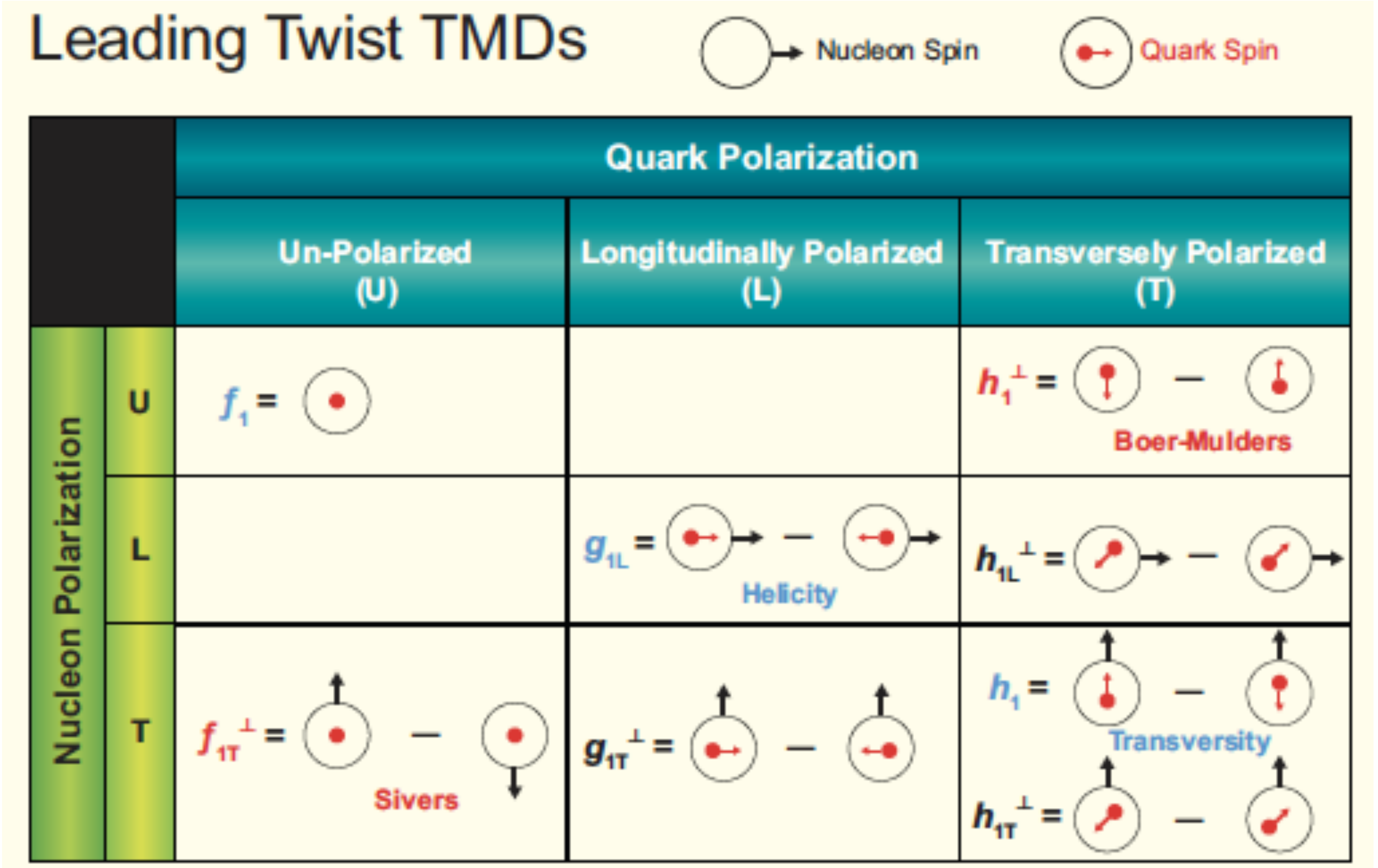
1509.06489, 1206.6014, 1212.1701

TMDs and spin:

• Several TMDs to be determined by different observables: beyond inclusive DIS, further possibilities are SIDIS (FFs required), CC,…

• Besides, polarised light nuclei, diffraction,…

• TMD factorisation can be tested in non-polarised collisions: dijets, charm,… Relation at small x with CGC.



1509.06489,1206.6014, 1212.1701