Conference on Flavour Physics and CP violation (FPCP) 2020
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Nuclear PDFs: status and prospects

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

Contents:

1. Introduction.

2. Present status and perspectives at the LHC.

3. nPDFs at an eIC.

4. Summary.

Disclaimer: I concentrate on collinear PDFs, skipping GPDs/TMDs/3D-structure, diffractive PDFs, shape fluctuations,… (see the backup).

References:

- *Future Circular Collider: Vol. 1 Physics opportunities, CERN-ACC-2018-0056, and 1605.01389;*
- *1812.06772 (HL-LHC with ions);*
- *1901.09076 (diffraction in ep and eA);*
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- *EIC Physics White paper, 1212.1701; YR (CDR) for the end of the year.*
- *2019 LHeC and FCC-eh workshop, https://indico.cern.ch/event/835947/;*
- *LHeC and EIC talks at DIS 2019, https://indico.cern.ch/event/749003/.*
- *Fixed target program at the HL-LHC, 1807.00603;*
- *Update of the 2012 LHeC CDR to appear.*

Nuclear structure functions:

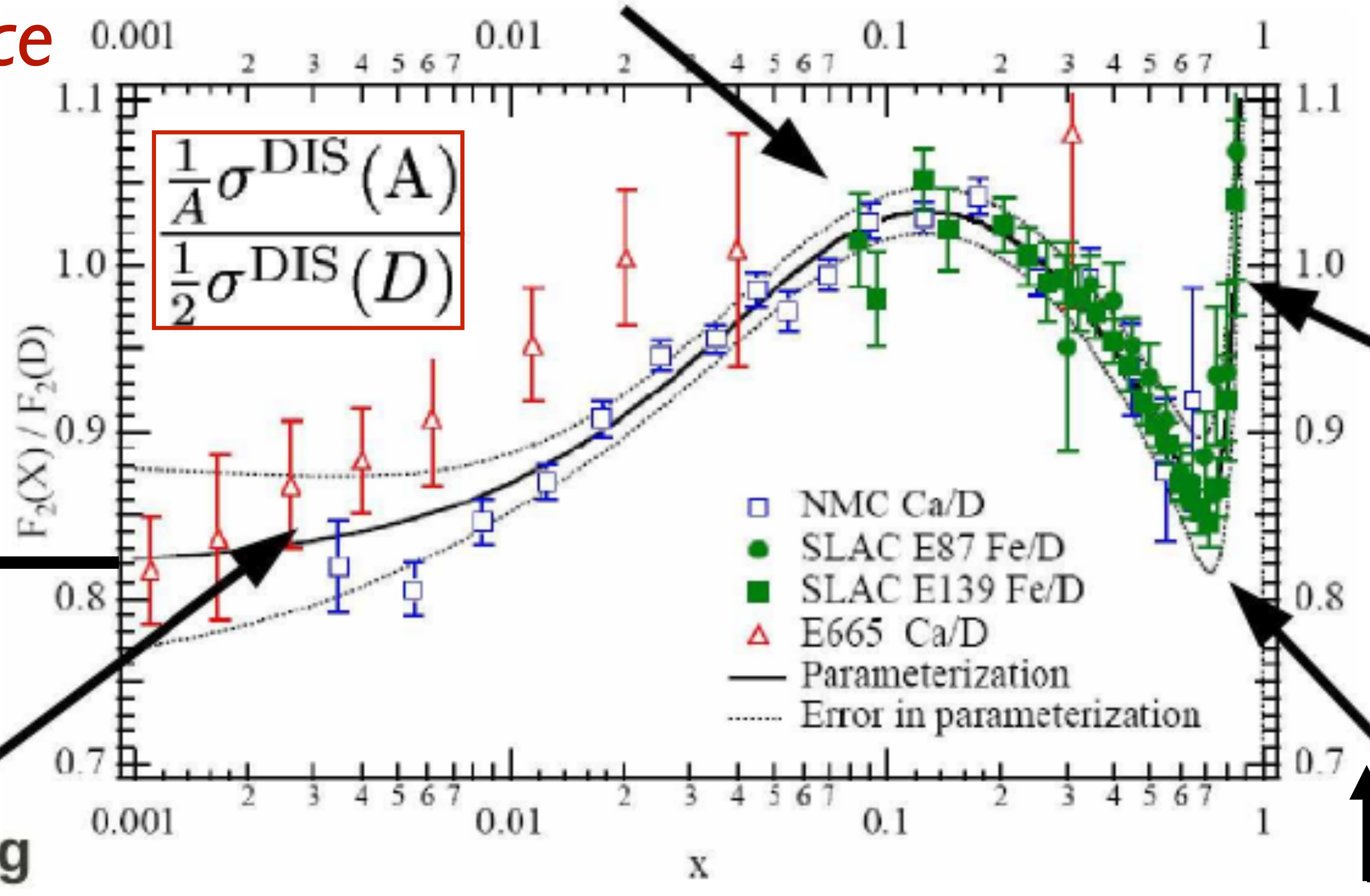
Flavour dependence?; relation with shadowing and coherence

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, within collinear factorisation.

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

Nuclear PDFs, obeying the standard DGLAP

Usual perturbative coefficient functions

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

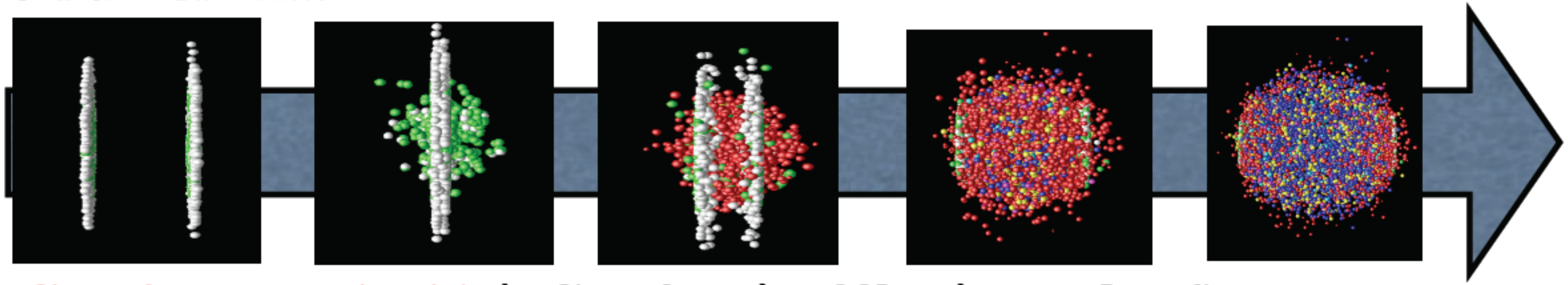
$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$

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.



- 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.

Dynamics in pA/AA:

- Nucleus ≠ Zp+(A-Z)n.
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- Medium is very opaque to

The small system problem:

➜ QGP in small systems?

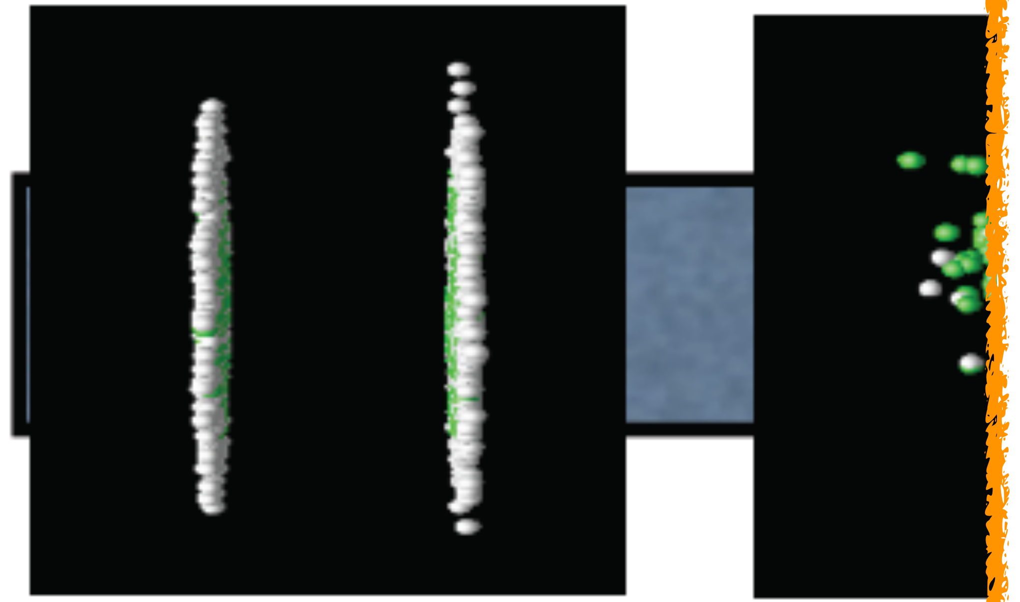
➜ Microscopic dynamics versus hydro?

➜ Strong (AdS/CFT, models) versus weak (transport) explanations?; are there quasiparticles?

➜ …

What do we mean by QGP?

[B. Cole]



Gluons from saturated nu

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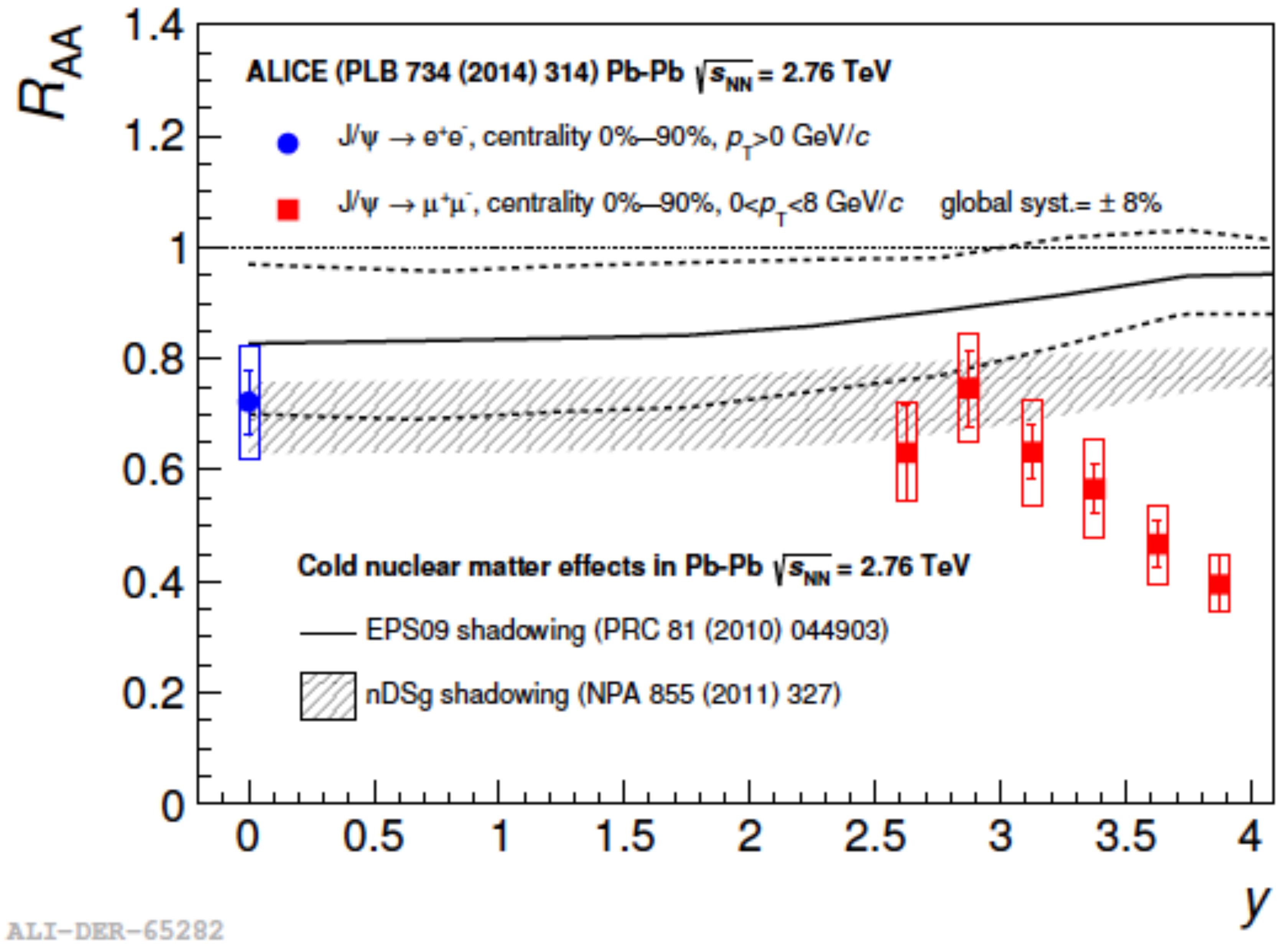
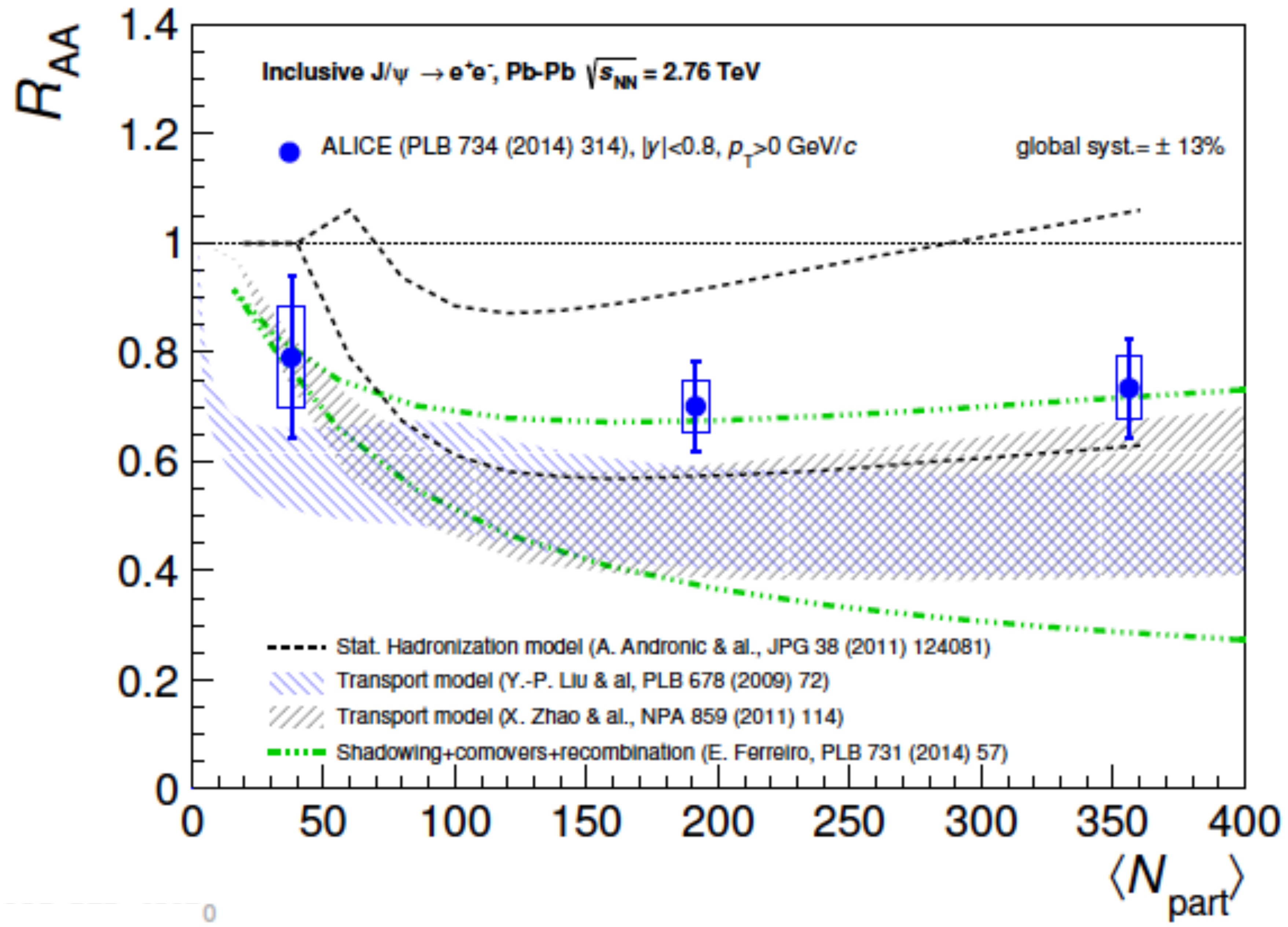
➜ In-medium QCD radiation, cold nuclear effects on hard probes.

nPDFs: implications on HI physics

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

- 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.





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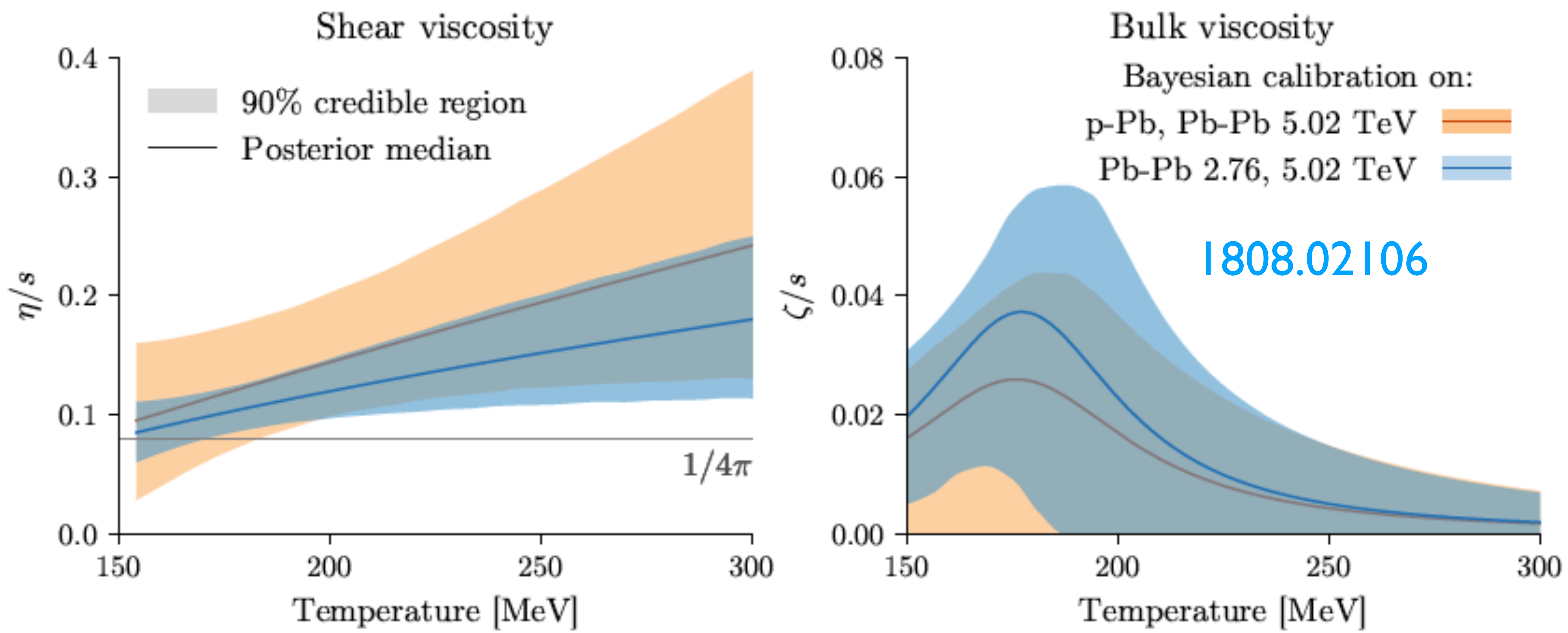
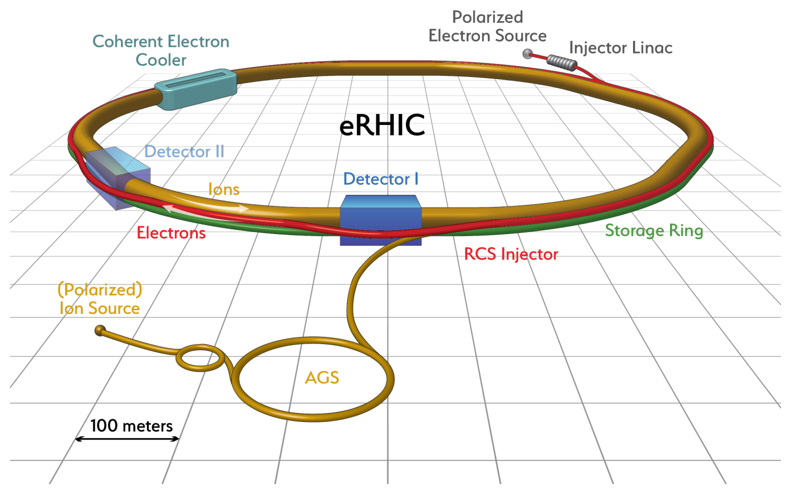
nPDFs: implications on HI physics

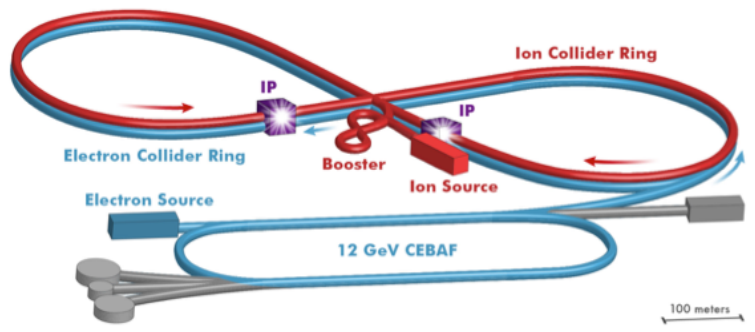


- Extraction of transport properties and hydrodynamisation times finds its key limitation in the uncertainties in the initial conditions for hydrodynamical evolution.

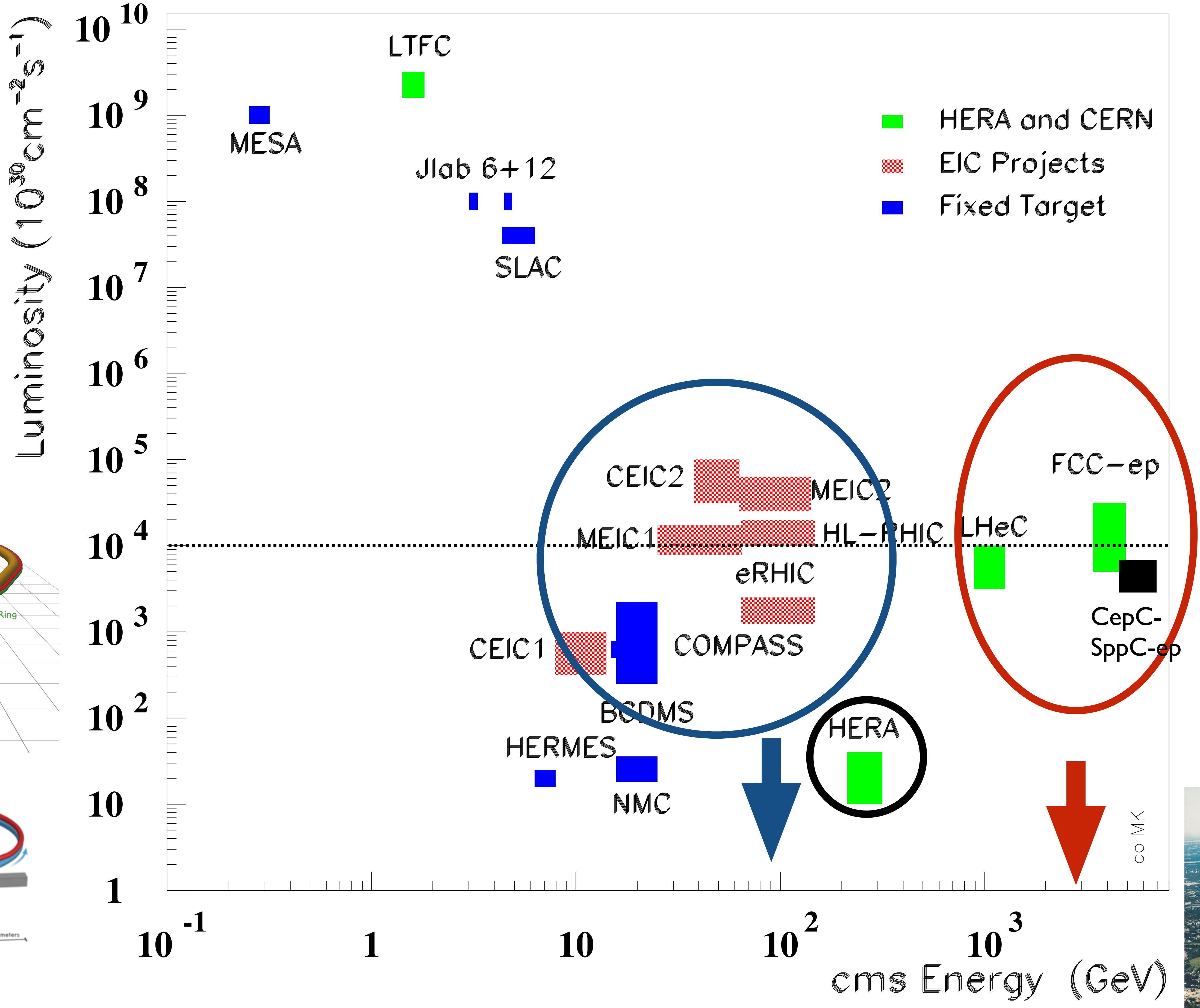
Machines: ep/eA

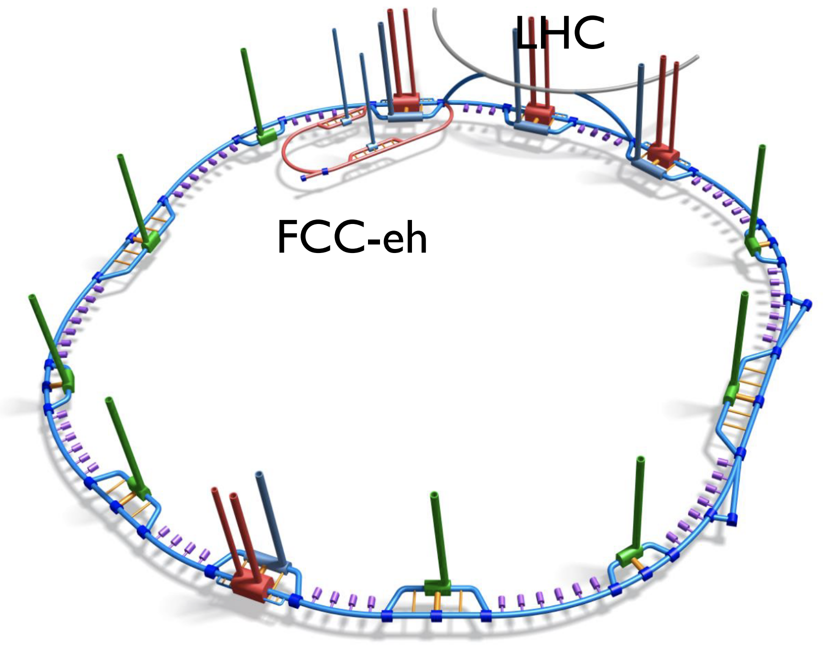
- Projects of eA colliders with $E_{cm} \sim \mathcal{O}(0.1)$ TeV/A (EICs at US and China) and $\mathcal{O}(1)$ TeV/A (LHeC and FCC-eh at CERN) addressing different physics.

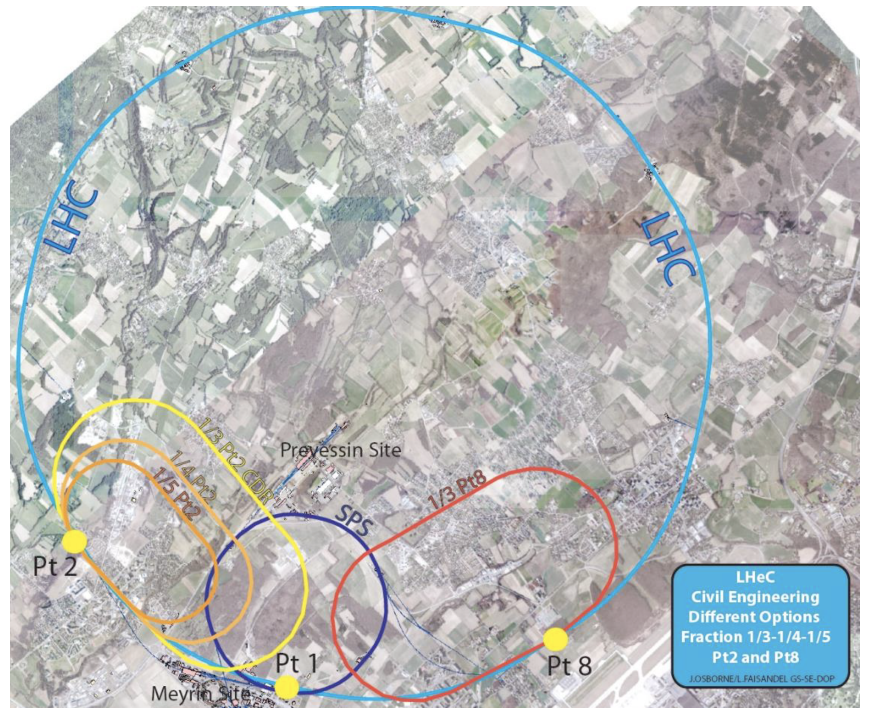




Lepton-proton/nucleus scattering facilities







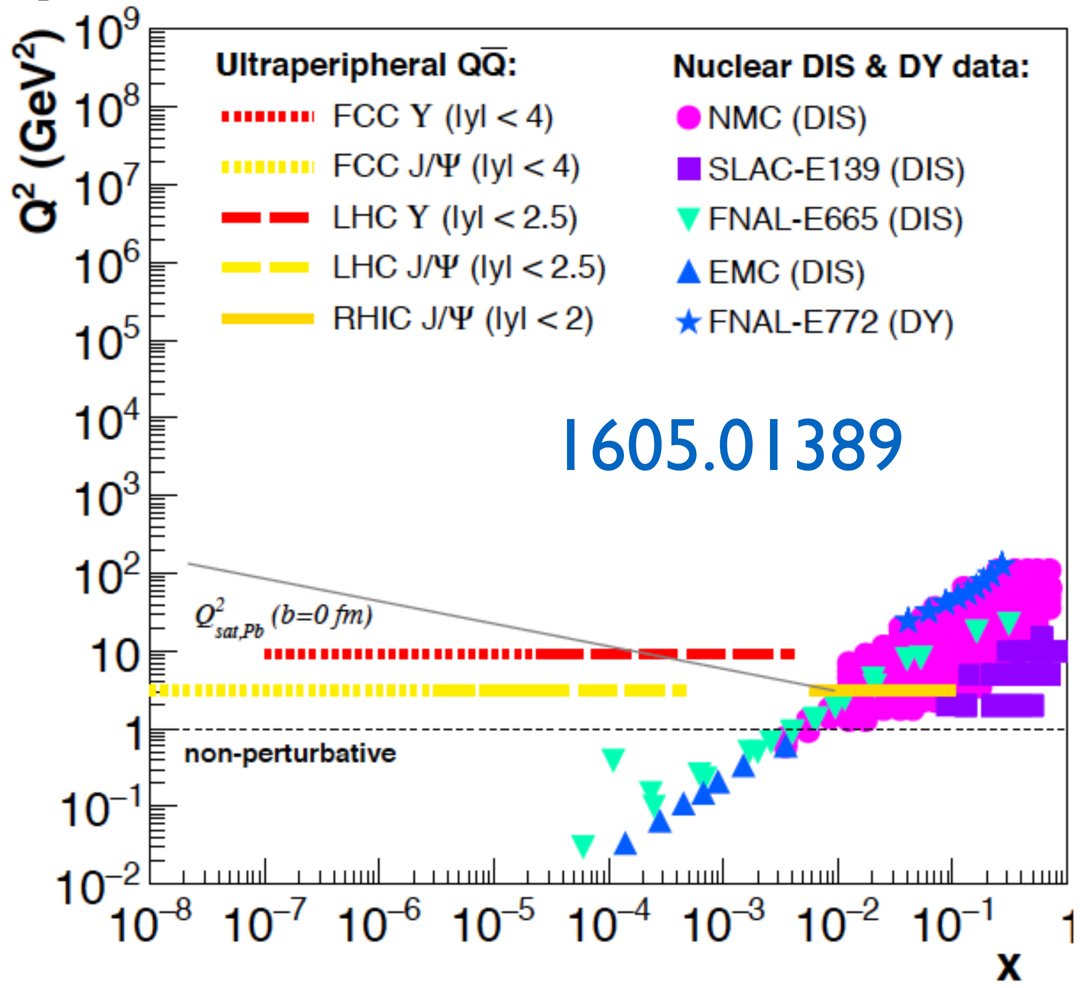
- Extension of several orders of magnitude in x and Q² w.r.t. existing DIS data.
- **DIS versus hh**:

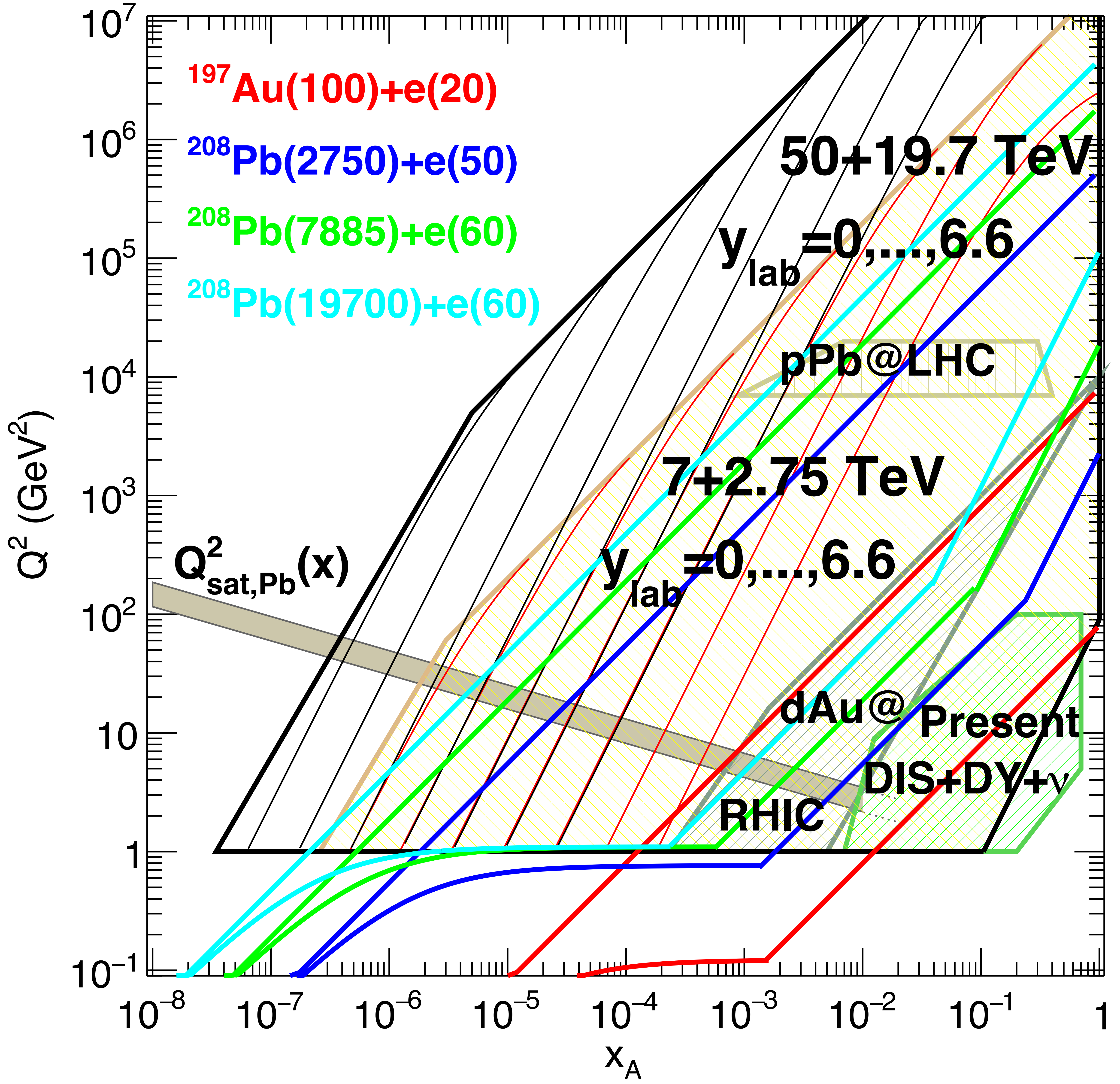
➜ pA/AA covers largest range in kinematics.

➜ **DIS offers**:

- ➤ A clean experimental environment - low multiplicity, no pileup, fully constrained kinematics x,Q² reconstructing the outgoing lepton;
- ➤ A more controlled theoretical setup - many first-principles calculations, factorisation tests.

UPCs





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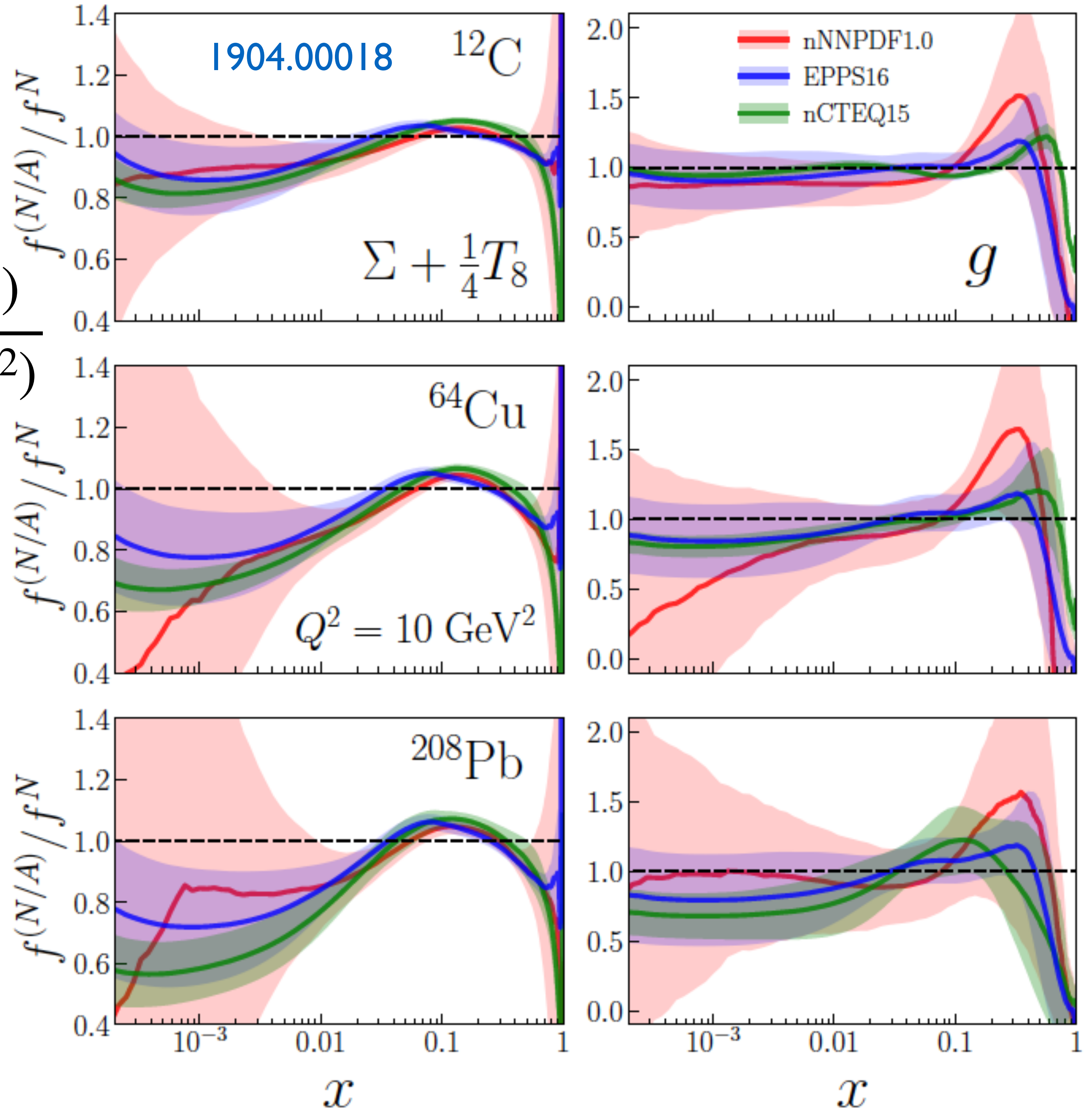
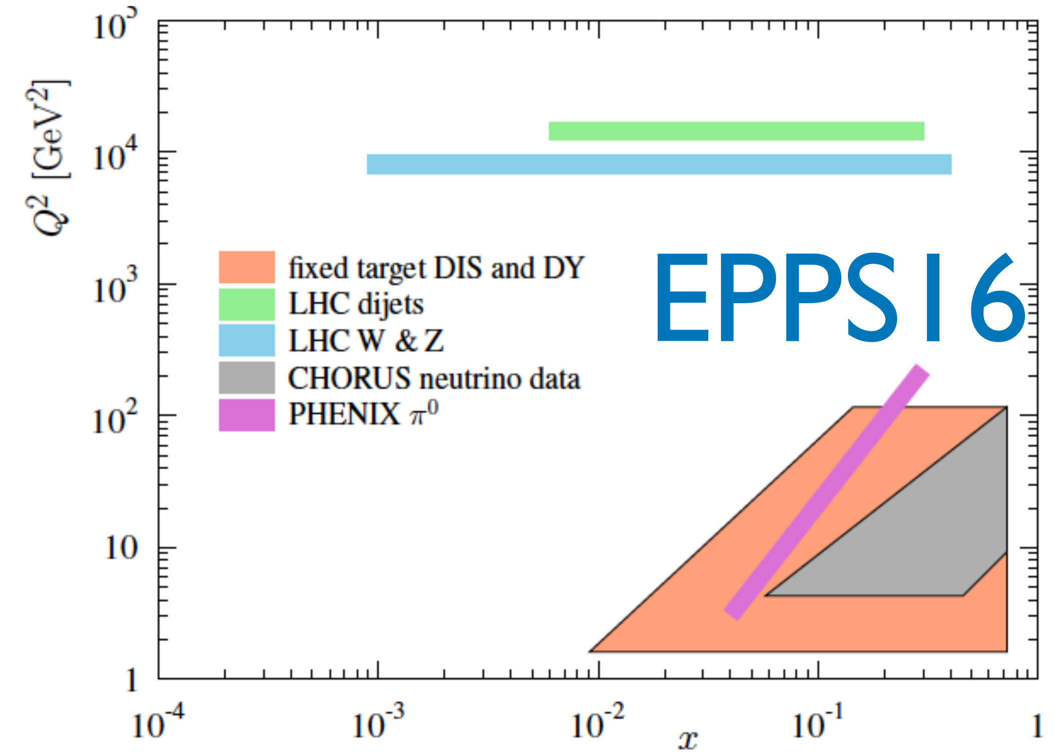
nPDFs: status

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

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



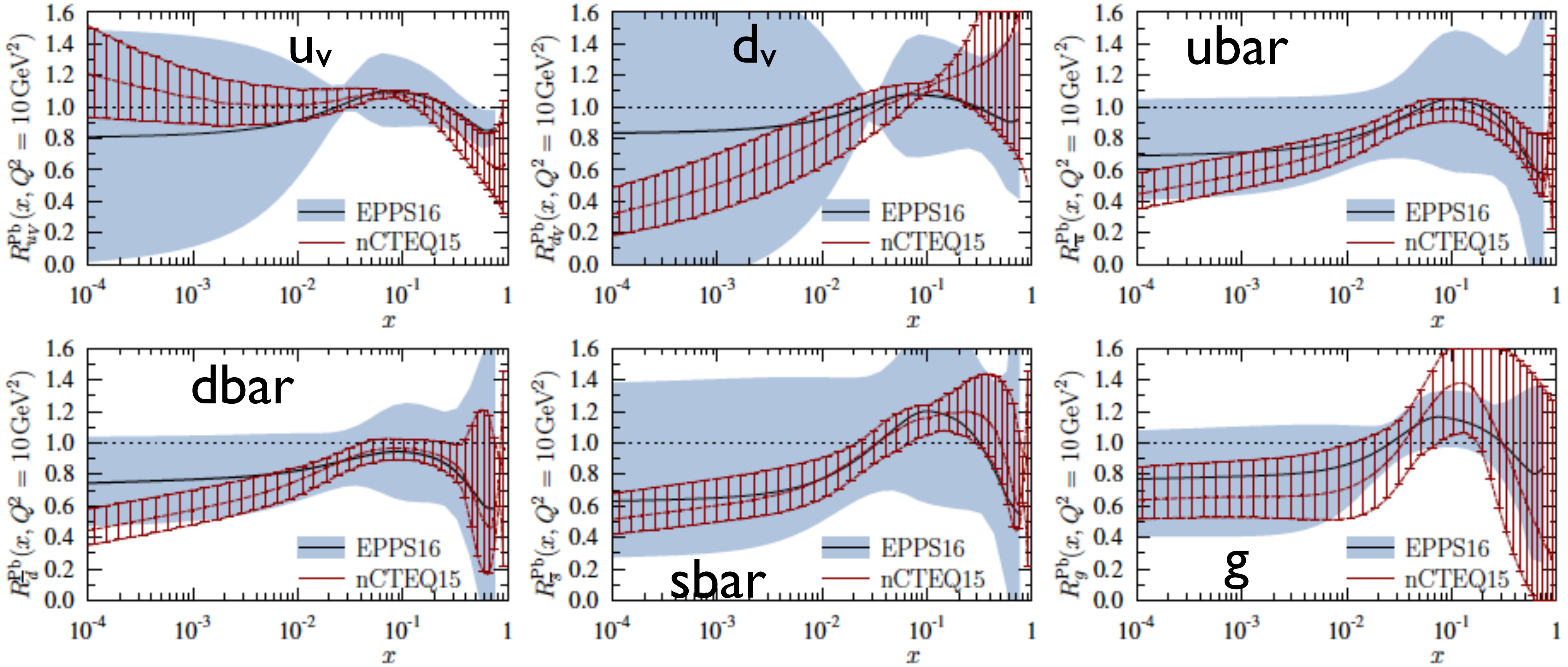
- Large uncertainties for x<0.01 and for large x glue (parametrisation biases); small impact of LHC data (large-x glue).
- Few data for any single A e.g. Pb (15 DIS+30 pPb+νA): A-dependence of I.C. mandatory; flavour decomposition weakly constrained (~ isoscalarity).
- Impact parameter dependence modelled.

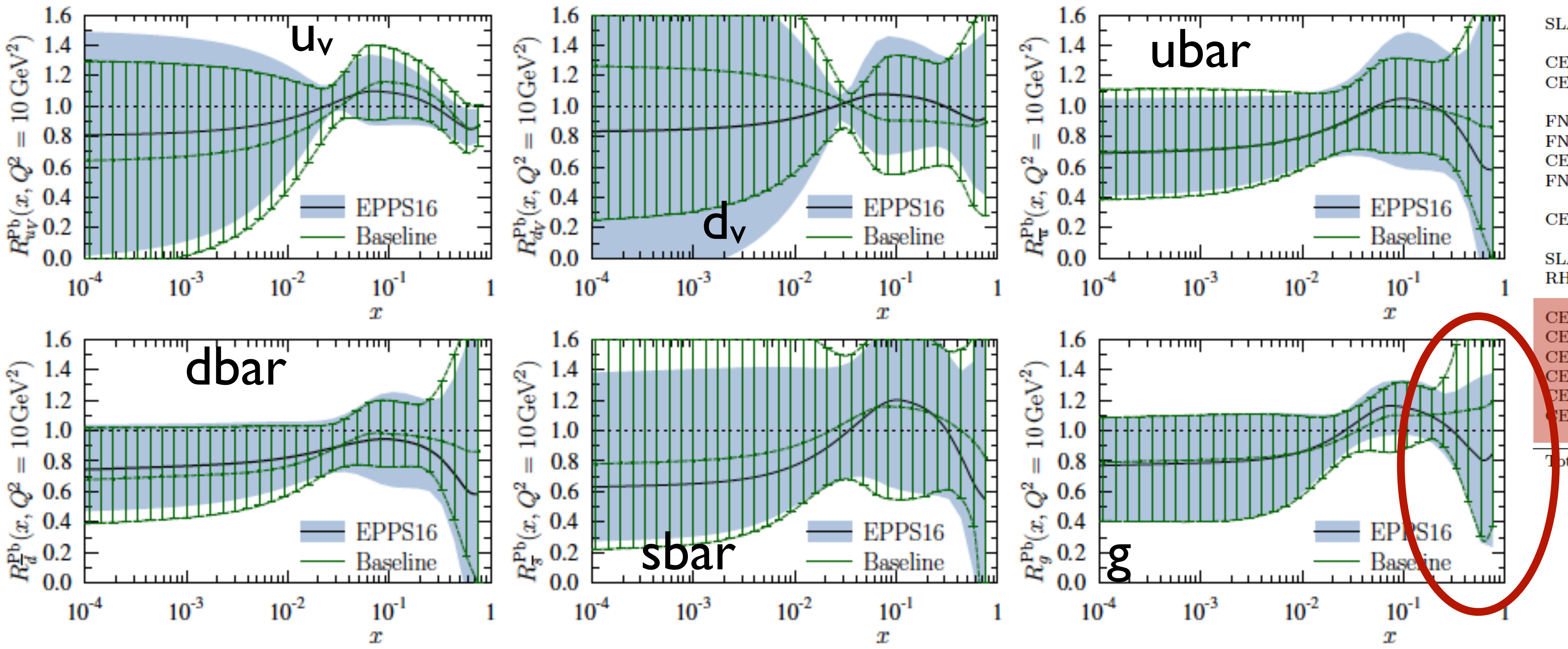


nPDFs: status

- nCTEQ15 vs. EPPS16: note the parametrisation bias.

- Presently available LHC (dijets, W/Z in pPb) data seem not to have a large effect: large-x glue (baseline=no ν, no LHC data).

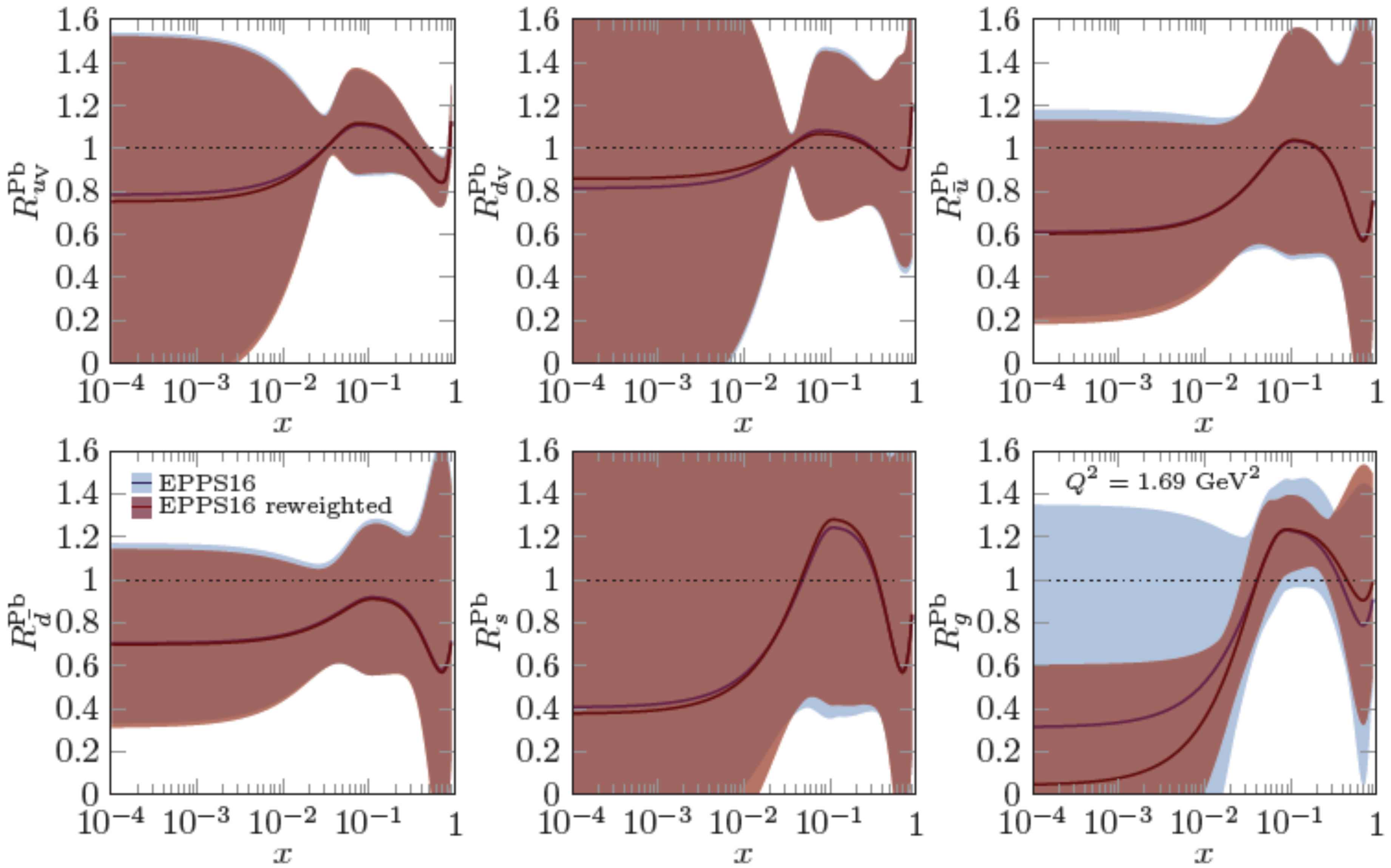




Experiment	Observable	Collisions	Data points	χ^2	Ref.
SLAC E139	DIS	e^-He(4), e^-D	21	12.2	[69]
CERN NMC 95, re.	DIS	μ^-He(4), μ^-D	16	18.0	[70]
CERN NMC 95	DIS	μ^-Li(6), μ^-D	15	18.4	[71]
CERN NMC 95, Q^2 dep.	DIS	μ^-Li(6), μ^-D	153	161.2	[71]
SLAC E139	DIS	e^-Be(9), e^-D	20	12.9	[69]
CERN NMC 96	DIS	μ^-Be(9), μ^-C	15	4.4	[72]
SLAC E139	DIS	e^-C(12), e^-D	7	6.4	[69]
CERN NMC 95	DIS	μ^-C(12), μ^-D	15	9.0	[71]
CERN NMC 95, Q^2 dep.	DIS	μ^-C(12), μ^-D	165	133.6	[71]
CERN NMC 95, re.	DIS	μ^-C(12), μ^-D	16	16.7	[70]
CERN NMC 95, re.	DIS	μ^-C(12), μ^-Li(6)	20	27.9	[70]
FNAL E772	DY	pC(12), pD	9	11.3	[73]
SLAC E139	DIS	e^-Al(27), e^-D	20	13.7	[69]
CERN NMC 96	DIS	μ^-Al(27), μ^-C(12)	15	5.6	[72]
SLAC E139	DIS	e^-Ca(40), e^-D	7	4.8	[69]
FNAL E772	DY	pCa(40), pD	9	3.33	[73]
CERN NMC 95, re.	DIS	μ^-Ca(40), μ^-D	15	27.6	[70]
CERN NMC 95, re.	DIS	μ^-Ca(40), μ^-Li(6)	20	19.5	[70]
CERN NMC 96	DIS	μ^-Ca(40), μ^-C(12)	15	6.4	[72]
SLAC E139	DIS	e^-Fe(56), e^-D	26	22.6	[69]
FNAL E772	DY	e^-Fe(56), e^-D	9	3.0	[73]
CERN NMC 96	DIS	μ^-Fe(56), μ^-C(12)	15	10.8	[72]
FNAL E866	DY	pFe(56), pBe(9)	28	20.1	[74]
CERN EMC	DIS	μ^-Cu(64), μ^-D	19	15.4	[75]
SLAC E139	DIS	e^-Ag(108), e^-D	7	8.0	[69]
CERN NMC 96	DIS	μ^-Sn(117), μ^-C(12)	15	12.5	[72]
CERN NMC 96, Q^2 dep.	DIS	μ^-Sn(117), μ^-C(12)	144	87.6	[76]
FNAL E772	DY	pW(184), pD	9	7.2	[73]
FNAL E866	DY	pW(184), pBe(9)	28	26.1	[74]
CERN NA10★	DY	π^-W(184), π^-D	10	11.6	[49]
FNAL E615★	DY	π^+W(184), π^-W(184)	11	10.2	[50]
CERN NA3★	DY	π^-Pt(195), π^-H	7	4.6	[48]
SLAC E139	DIS	e^-Au(197), e^-D	21	8.4	[69]
RHIC PHENIX	π^0	dAu(197), pp	20	6.9	[28]
CERN NMC 96	DIS	μ^-Pb(207), μ^-C(12)	15	4.1	[72]
CERN CMS★	$W^\pm$	pPb(208)	10	8.8	[43]
CERN CMS★	Z	pPb(208)	6	5.8	[45]
CERN ATLAS★	Z	pPb(208)	7	9.6	[46]
CERN CMS★	dijet	pPb(208)	7	5.5	[34]
CERN CHORUS★	DIS	νPb(208), $\overline{\nu}$Pb(208)	824	998.6	[47]
Total			1811	1789	

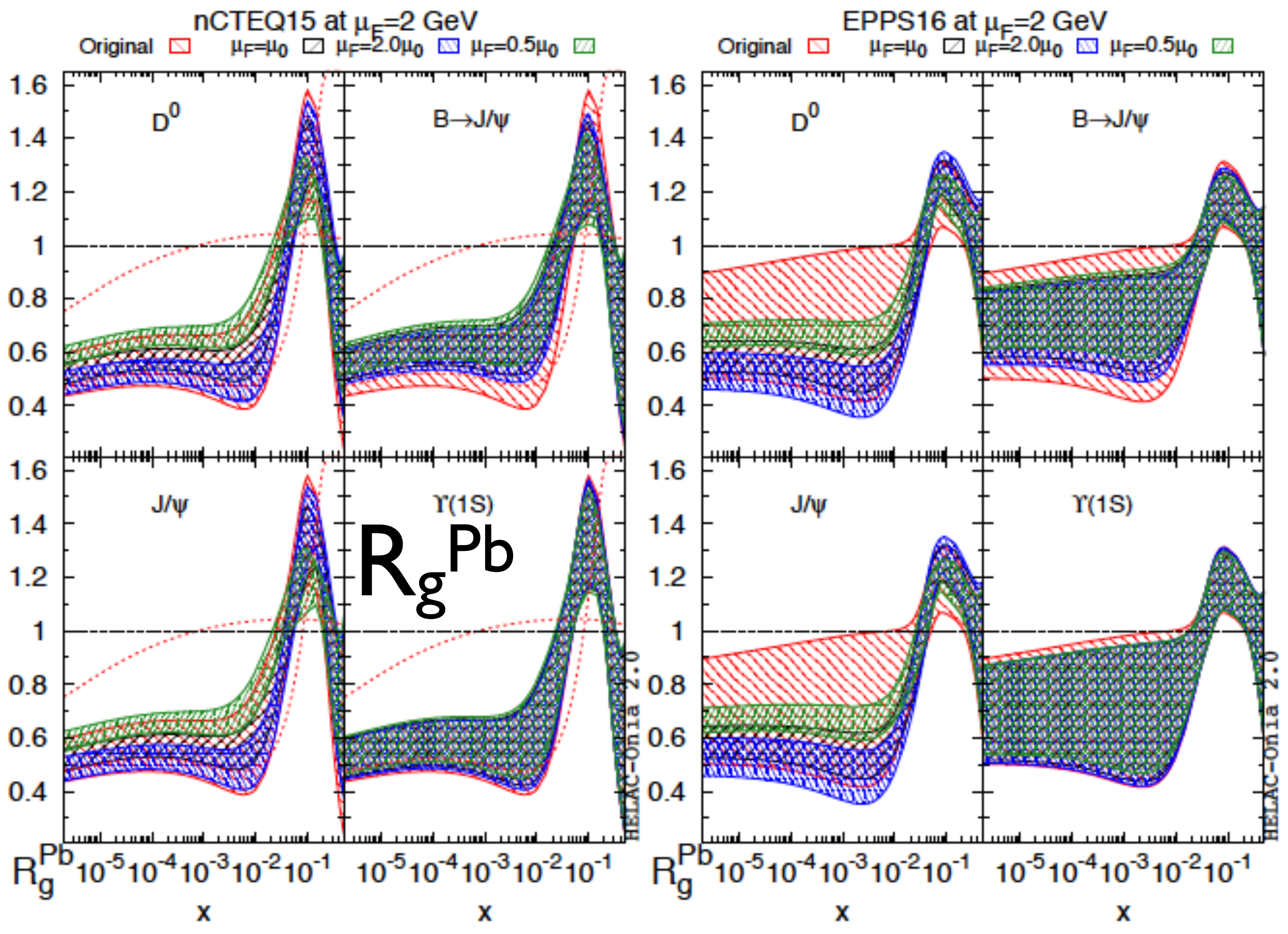
EPPS16

nPDFs @ LHC: present



D mesons, 1906.02512

- Theoretical control in PT over forward D or J/ψ under debate: scales, DPS, non-linear dynamics, … E.g. quarkonium: superposition of nPDFs + eloss/absorption + comovers for ψ',…
- Collectivity (flow for D in pPb as for charged hadrons in pPb and PbPb?) would challenge the use of low p_T data for extraction of nPDFs.



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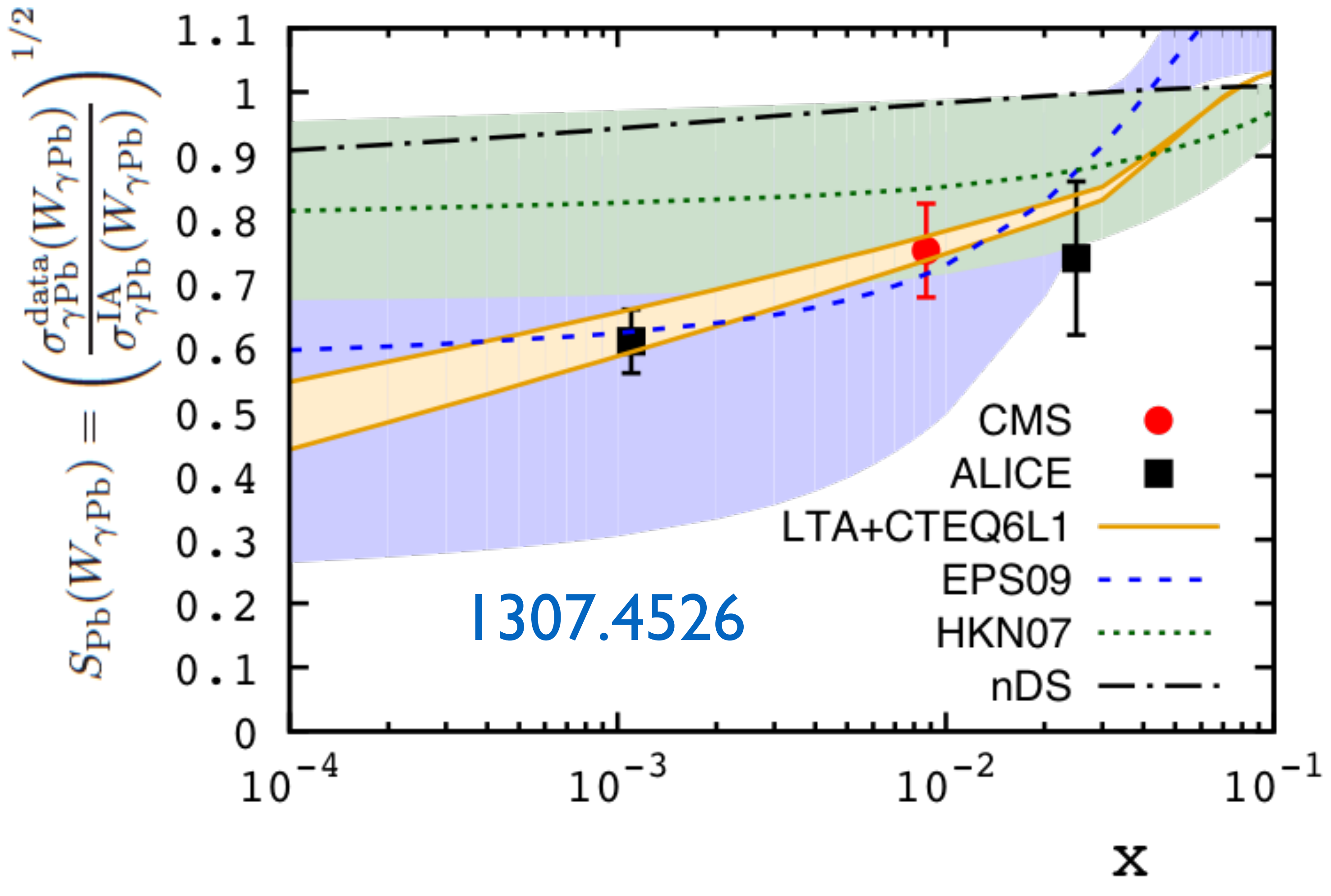
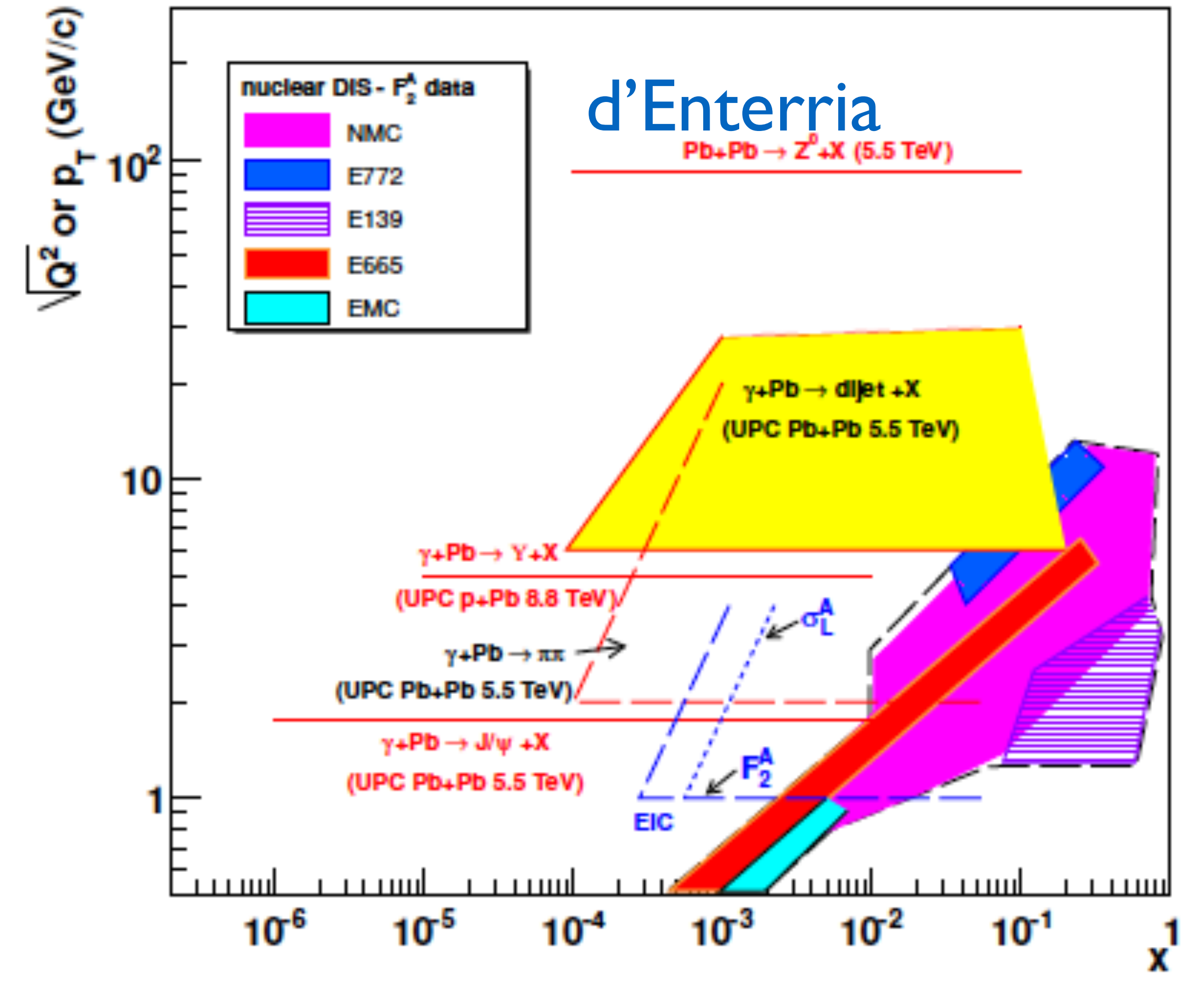
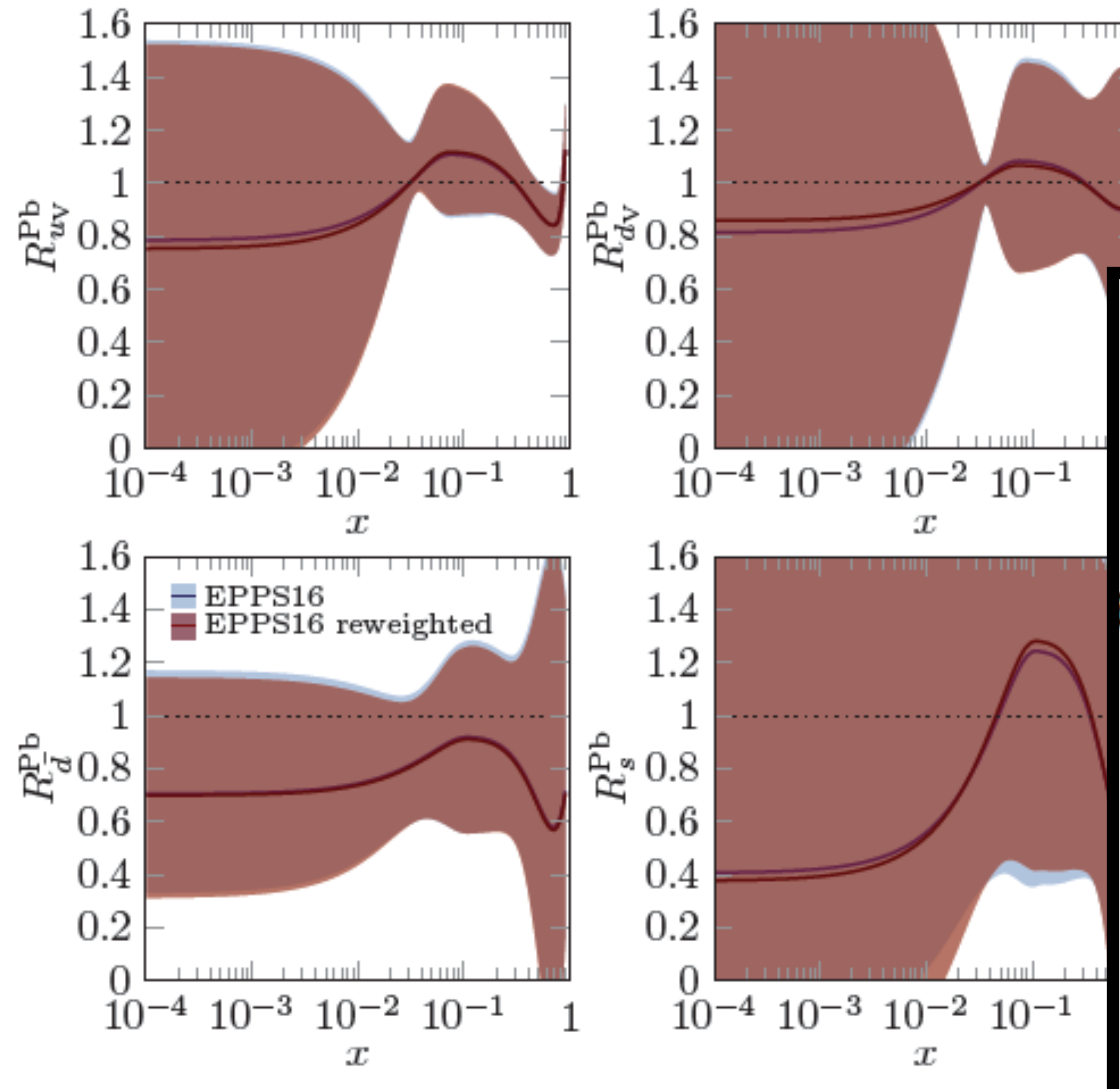
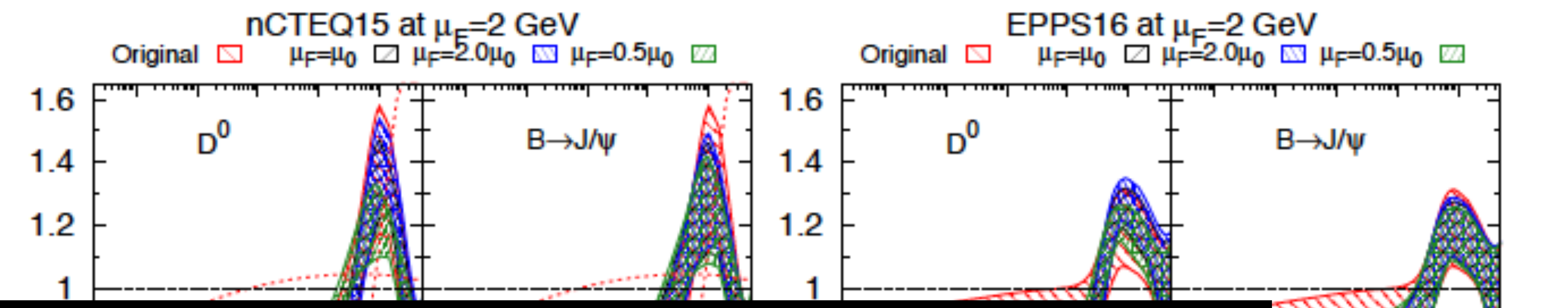


- UPCs offer possibilities for constraining nPDFs: they were the first indication of nuclear shadowing.



nPDFs @ LHC: present





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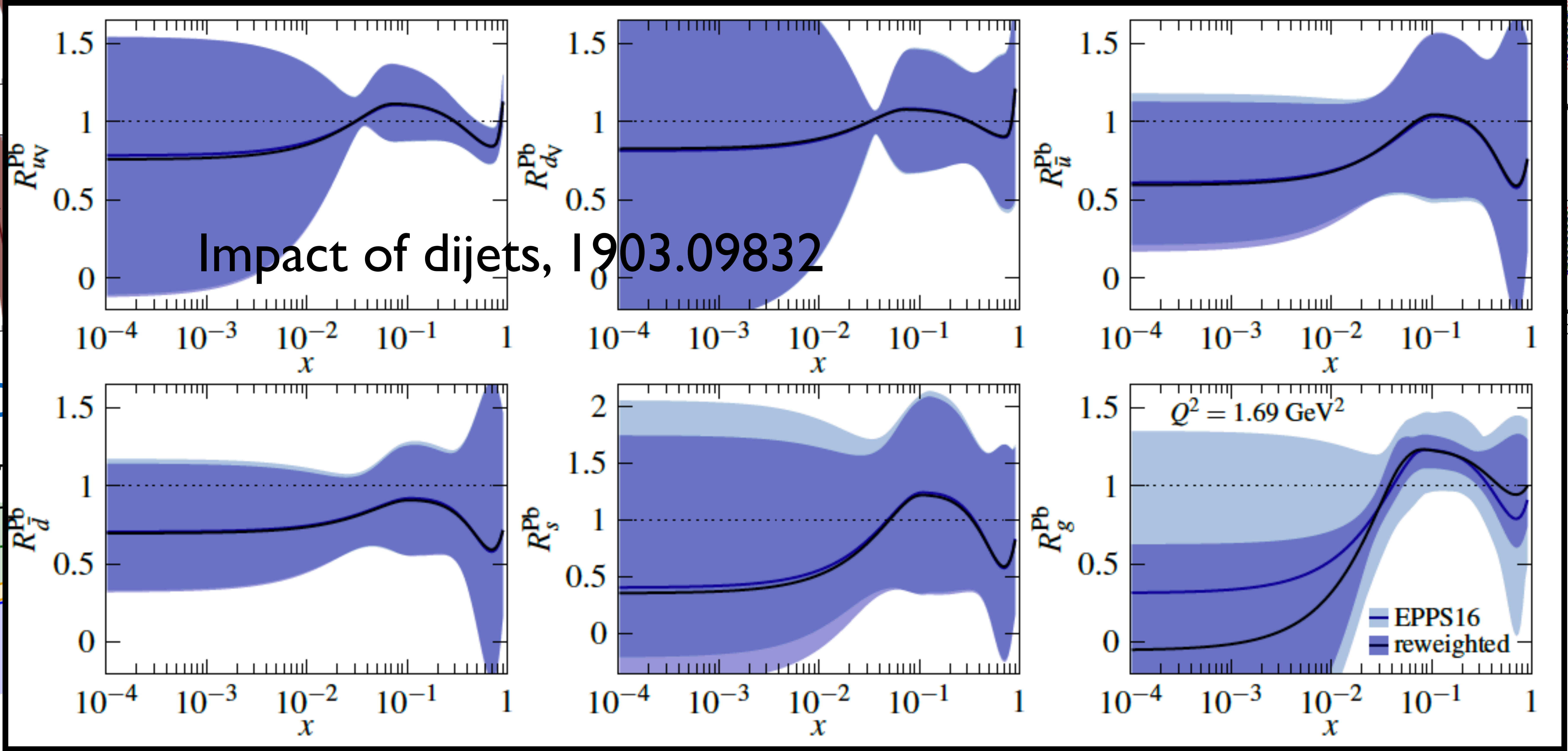
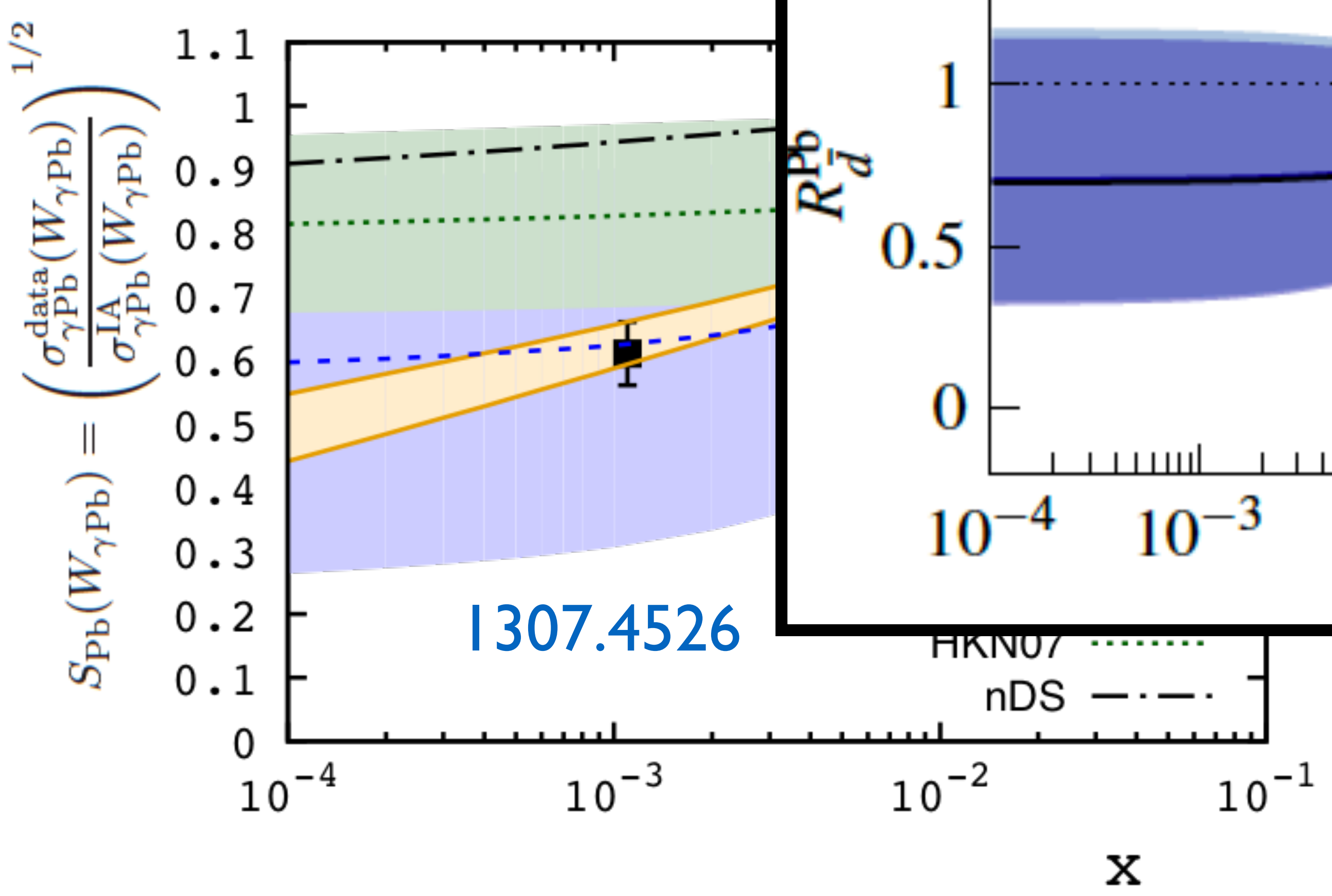
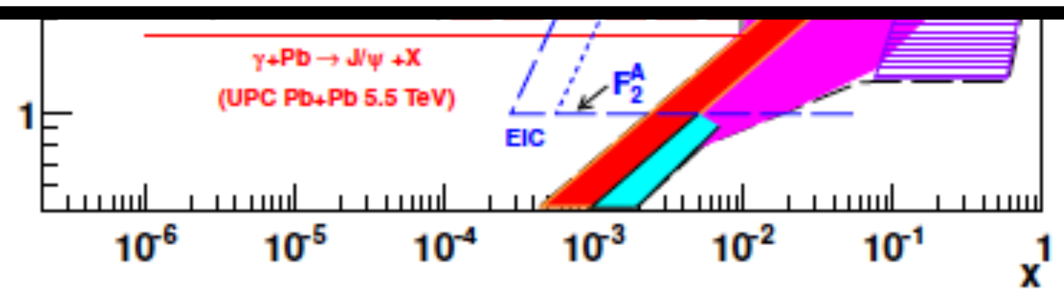


D mesons, 190

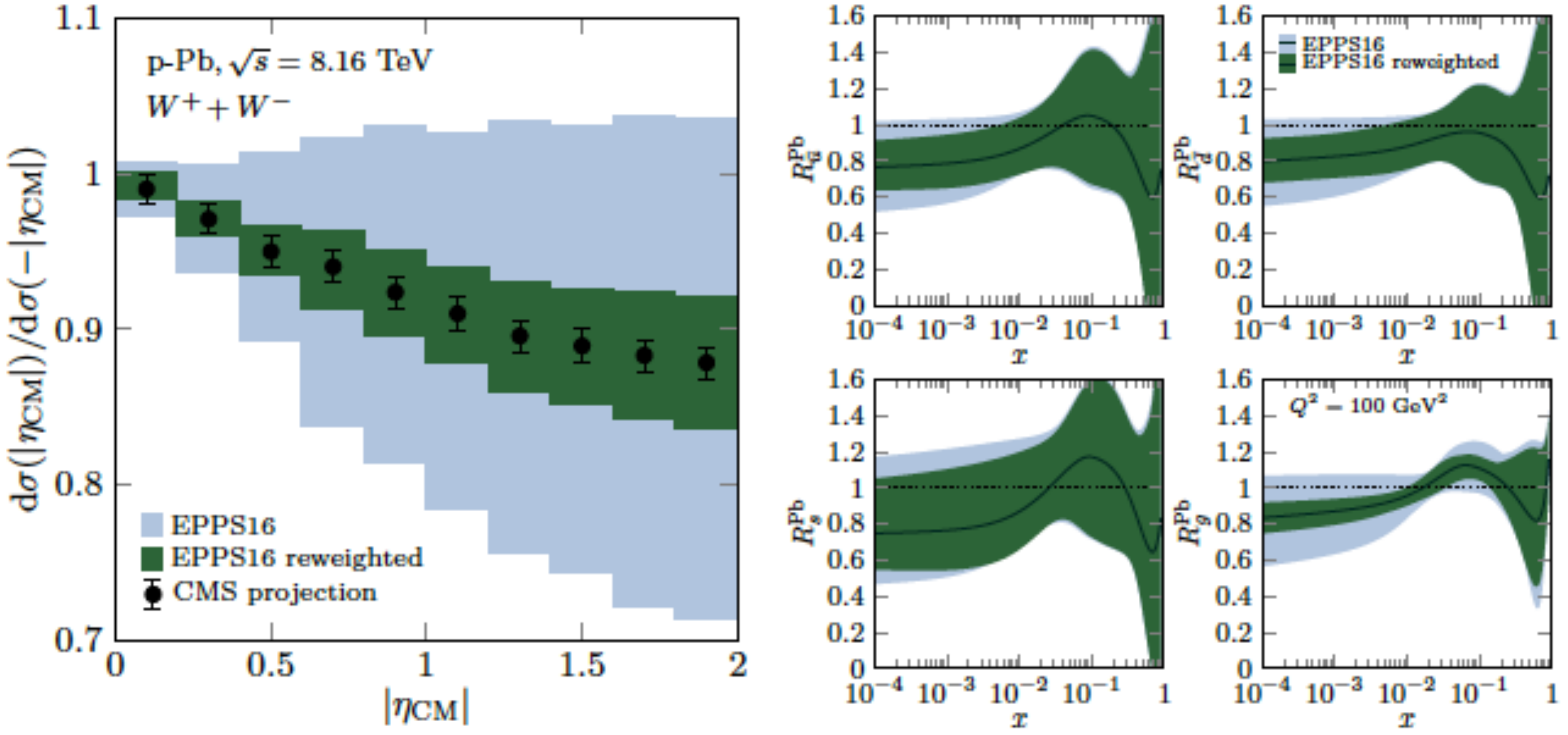


shadowing.



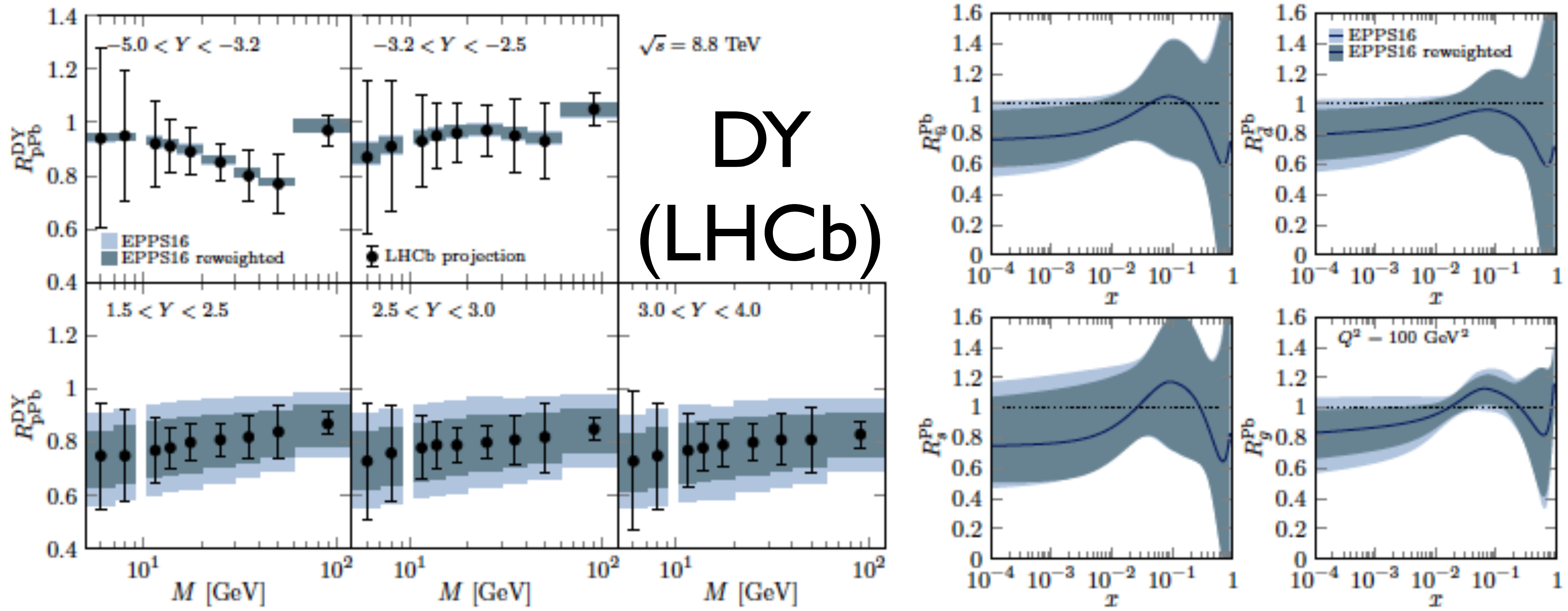
nPDFs @ HL-LHC:

W

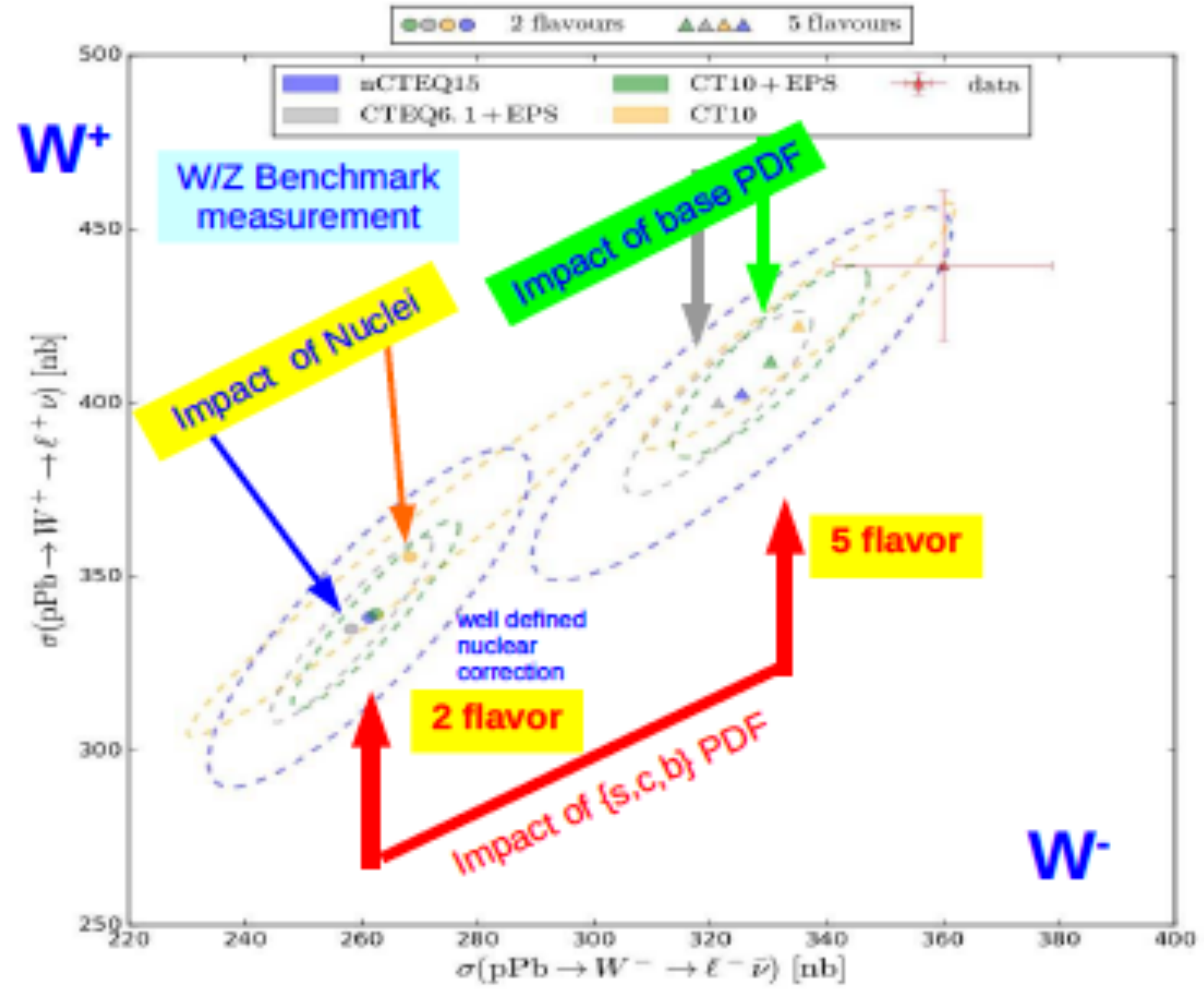


- Inclusive W for s/u.
- Dijets for glue.
- Z and γ at forward rapidity (glue).
- W asymmetries for gluon (evolution).
- Low mass forward DY for sea and gluon.
- Top requires higher statistics: lighter ions in the 30's?
- UPCs will also contribute: quarkonium, inclusive dijets (1902.05126).

1812.06772

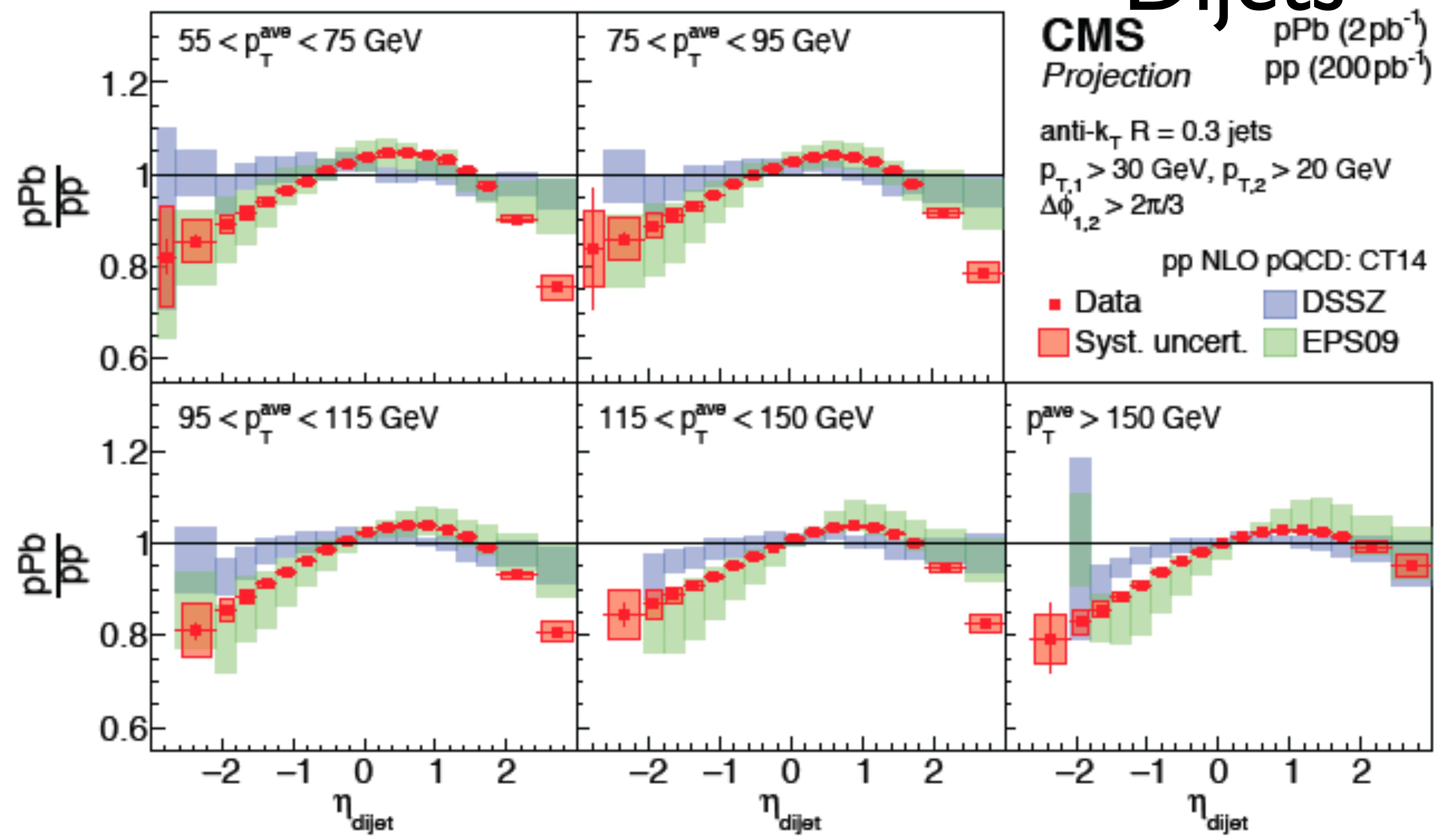


DY (LHCb)



nPDFs @ HL-LHC:

Dijets



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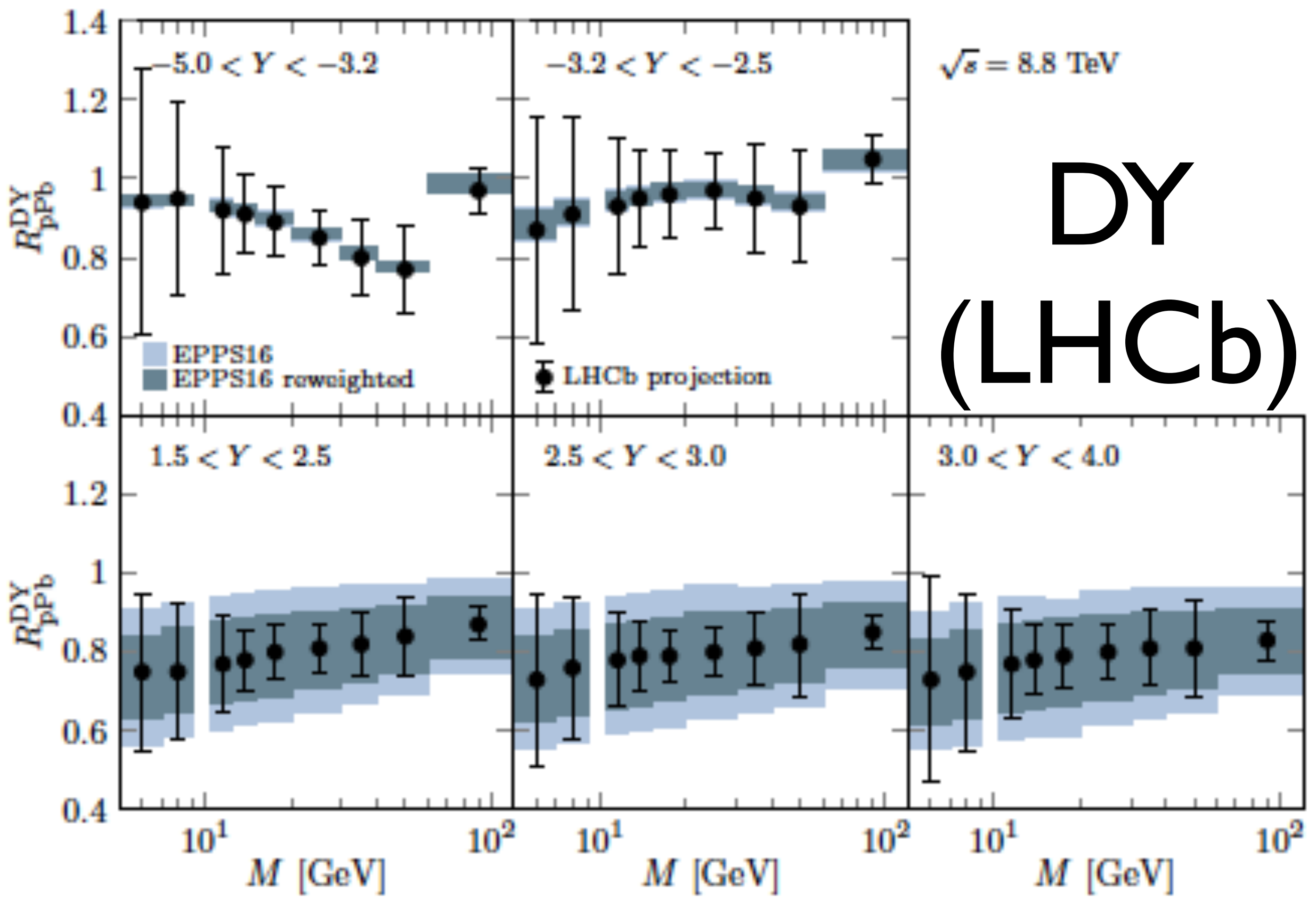

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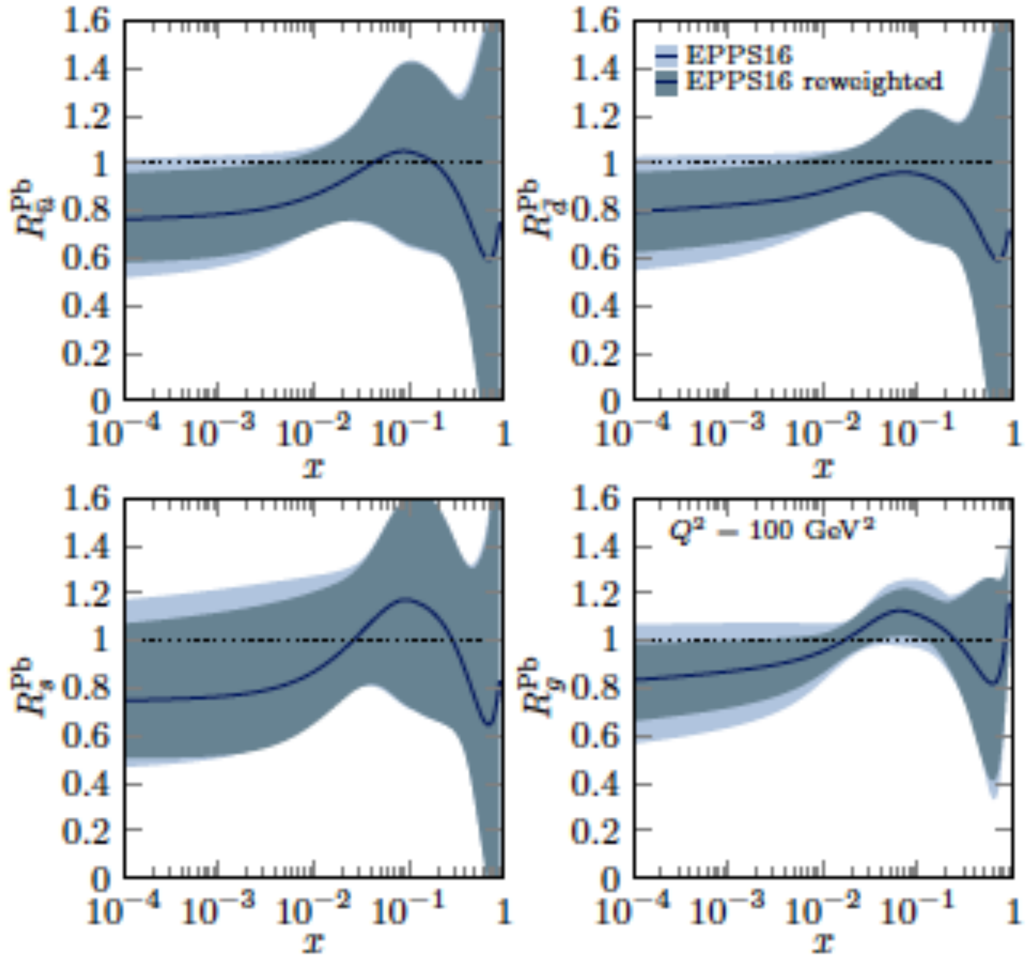
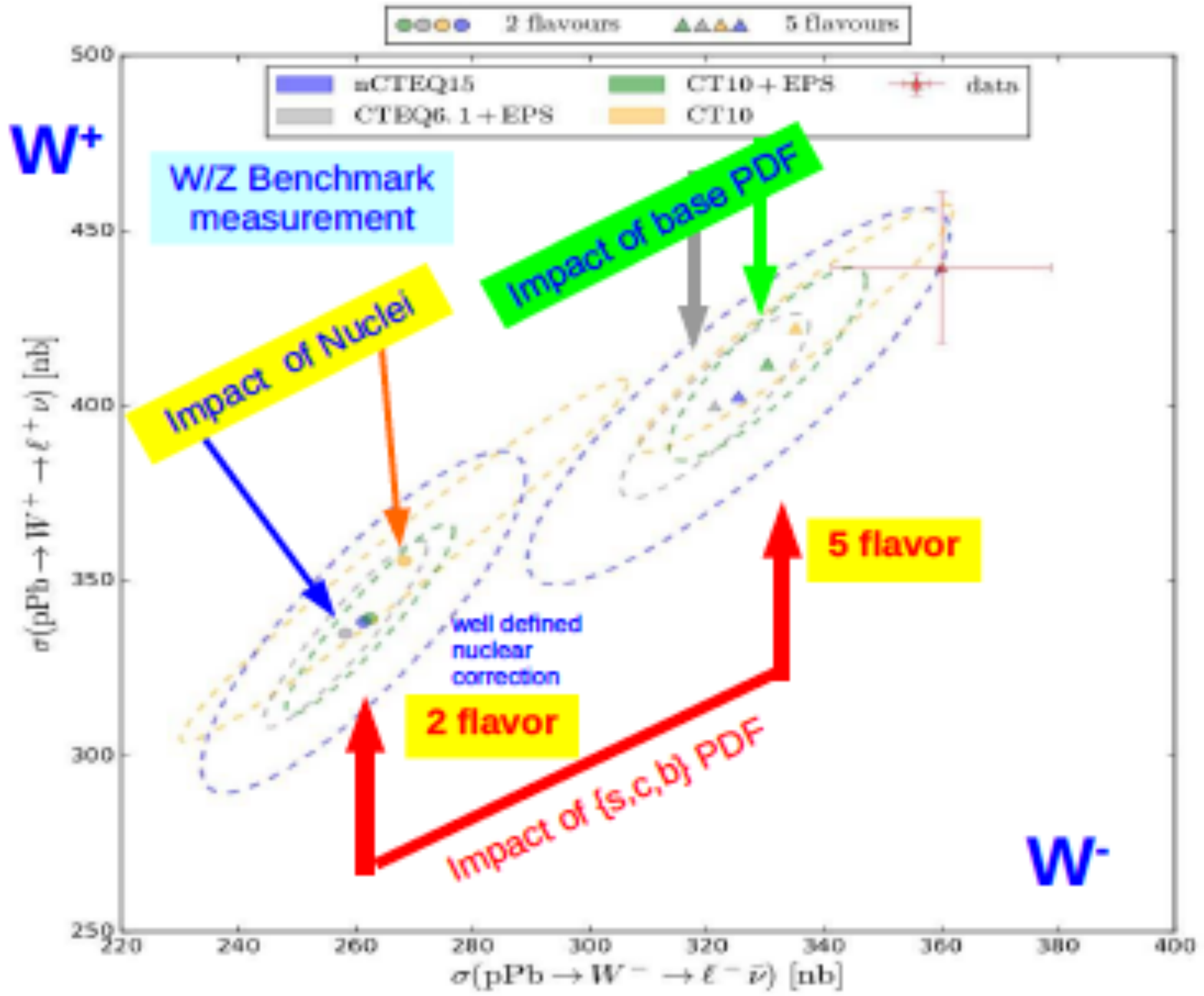
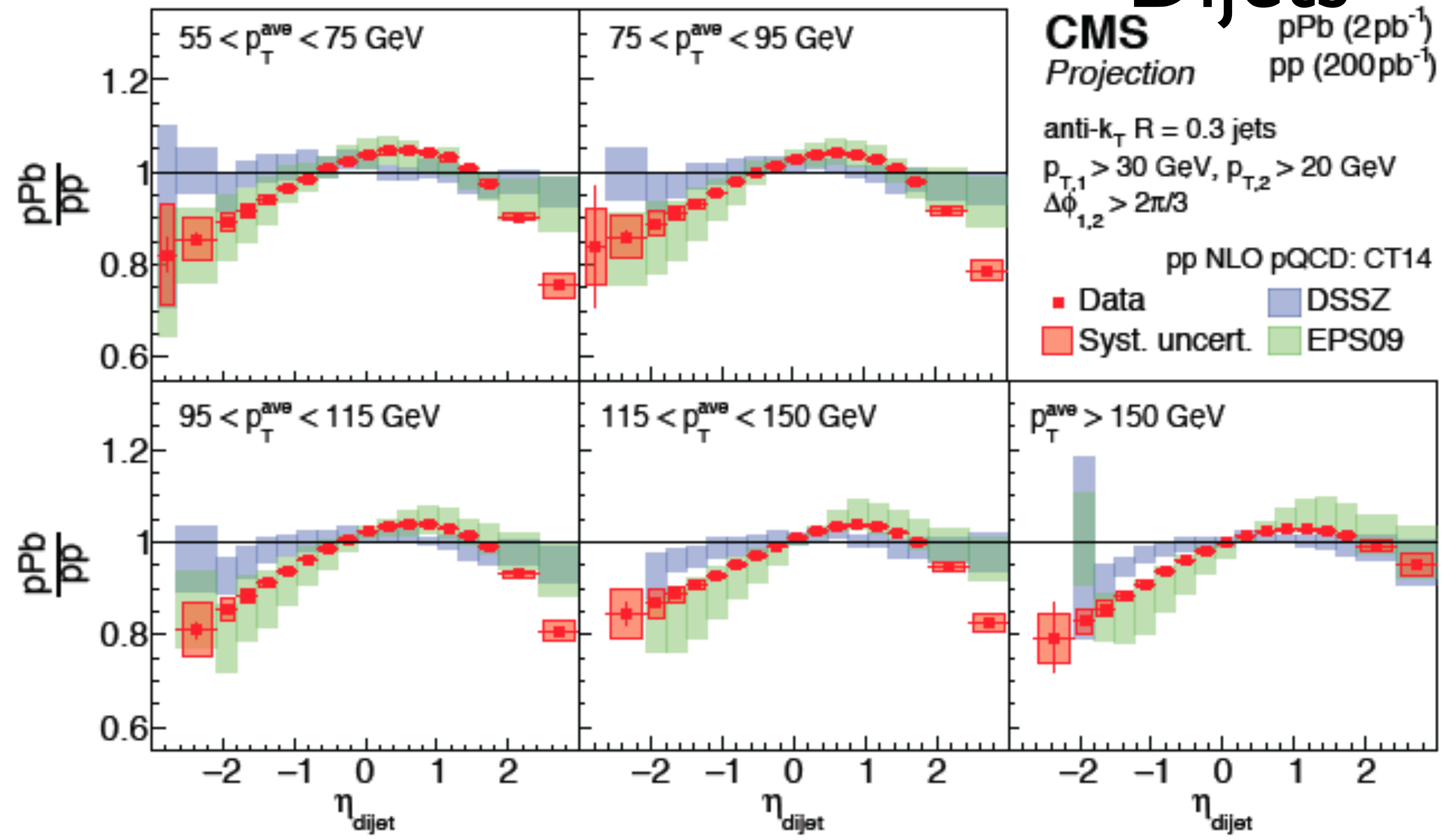




nPDFs @ HL-LHC:

Dijets



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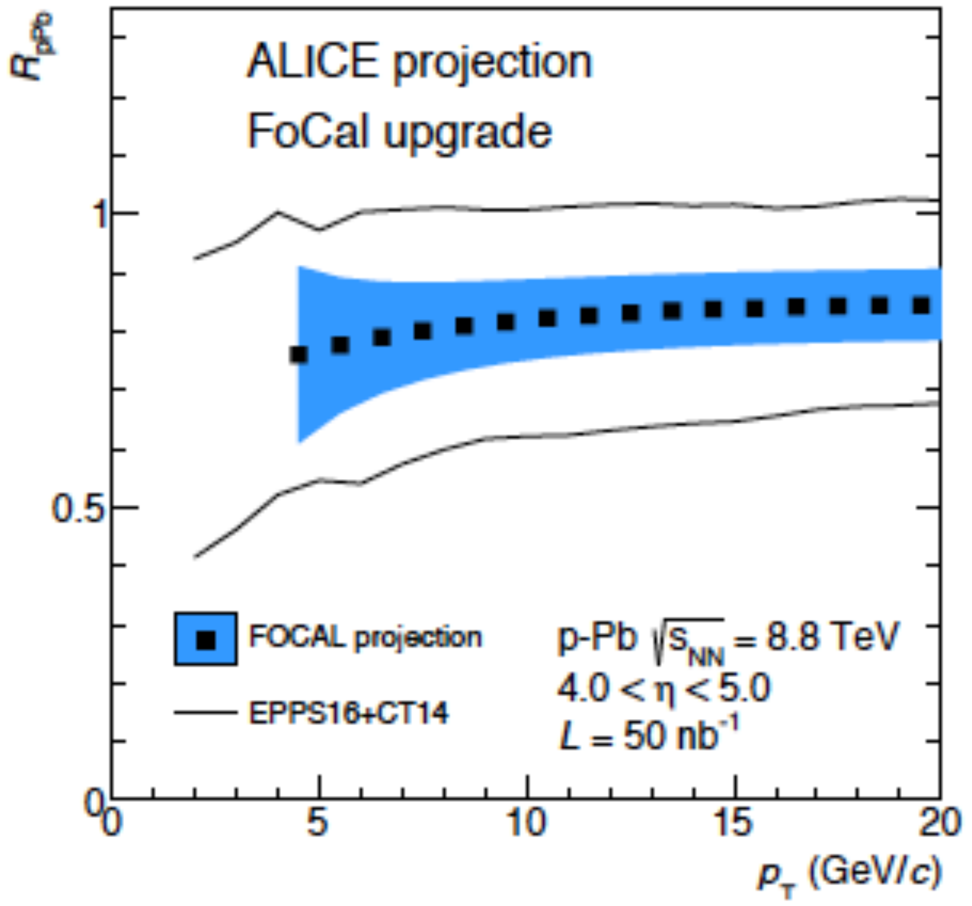
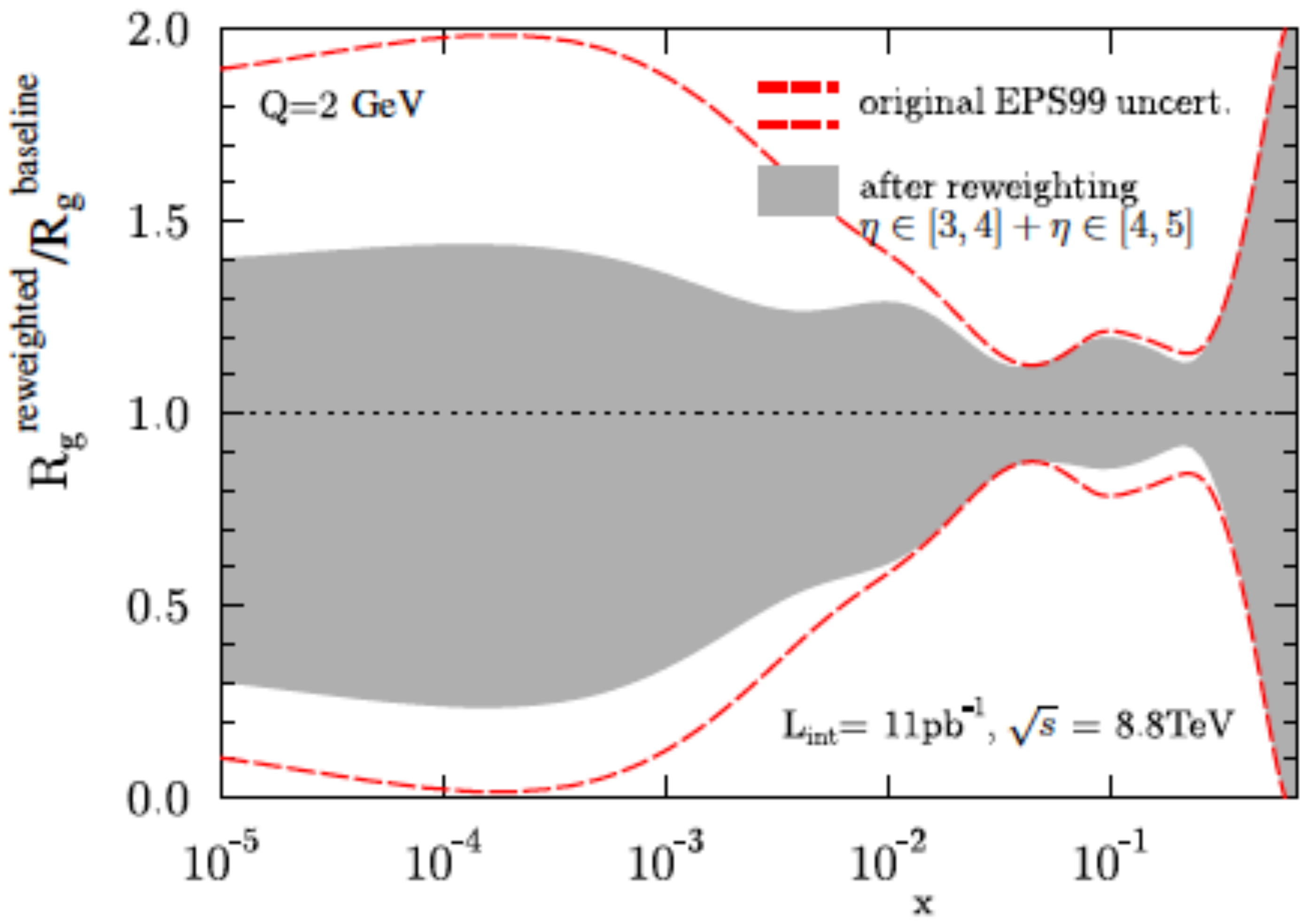
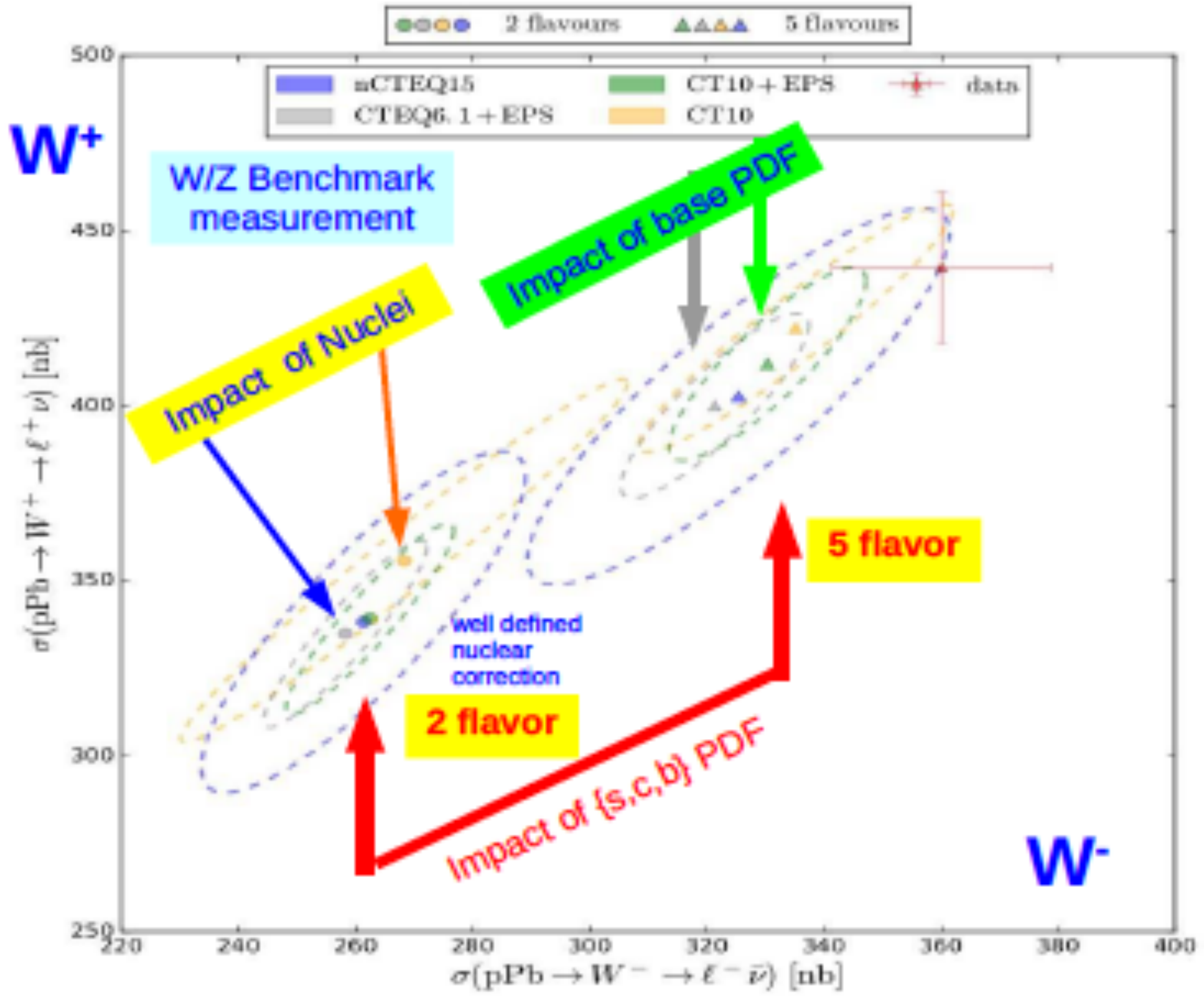
Photons

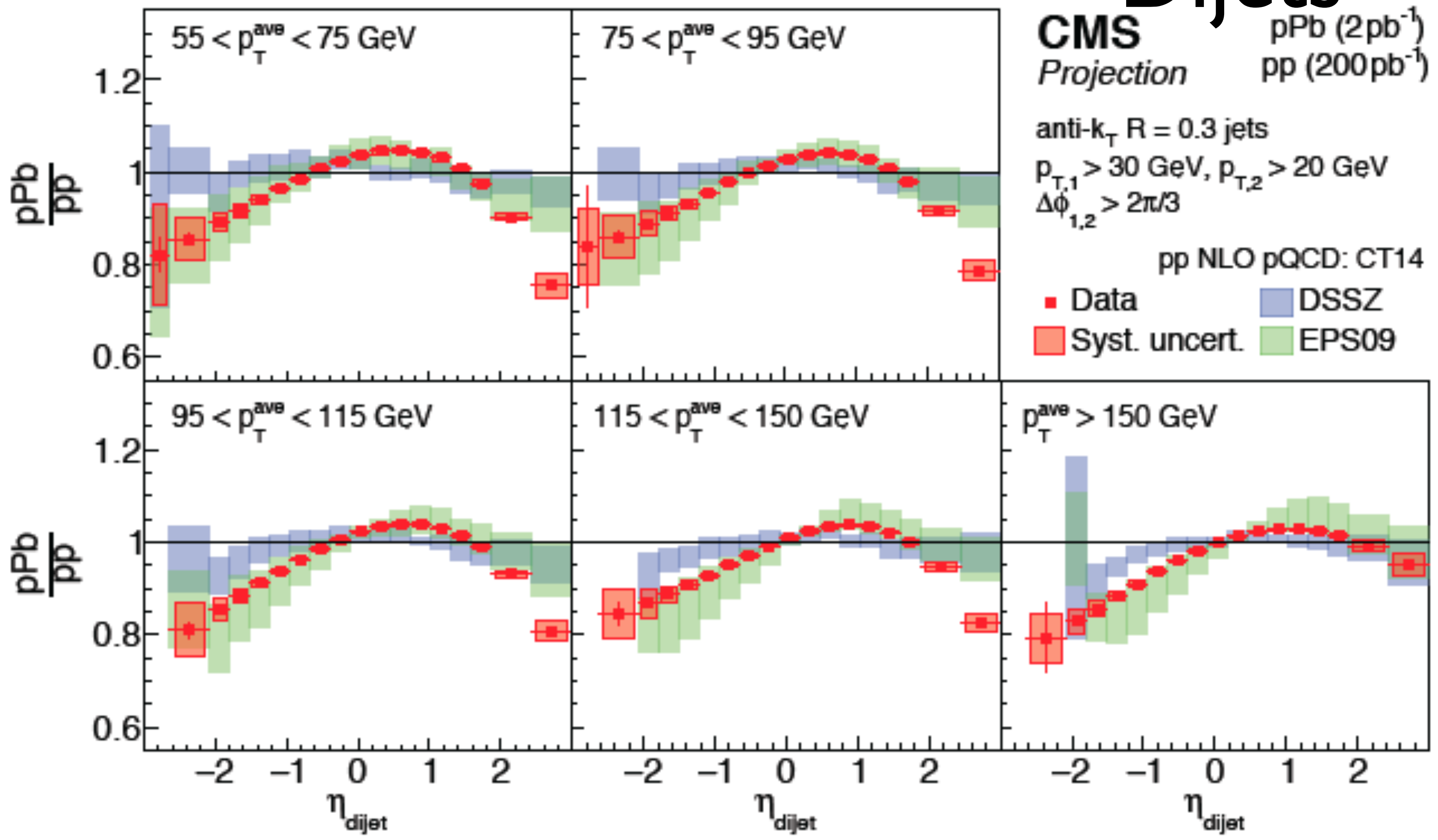






nPDFs @ HL-LHC:

Dijets



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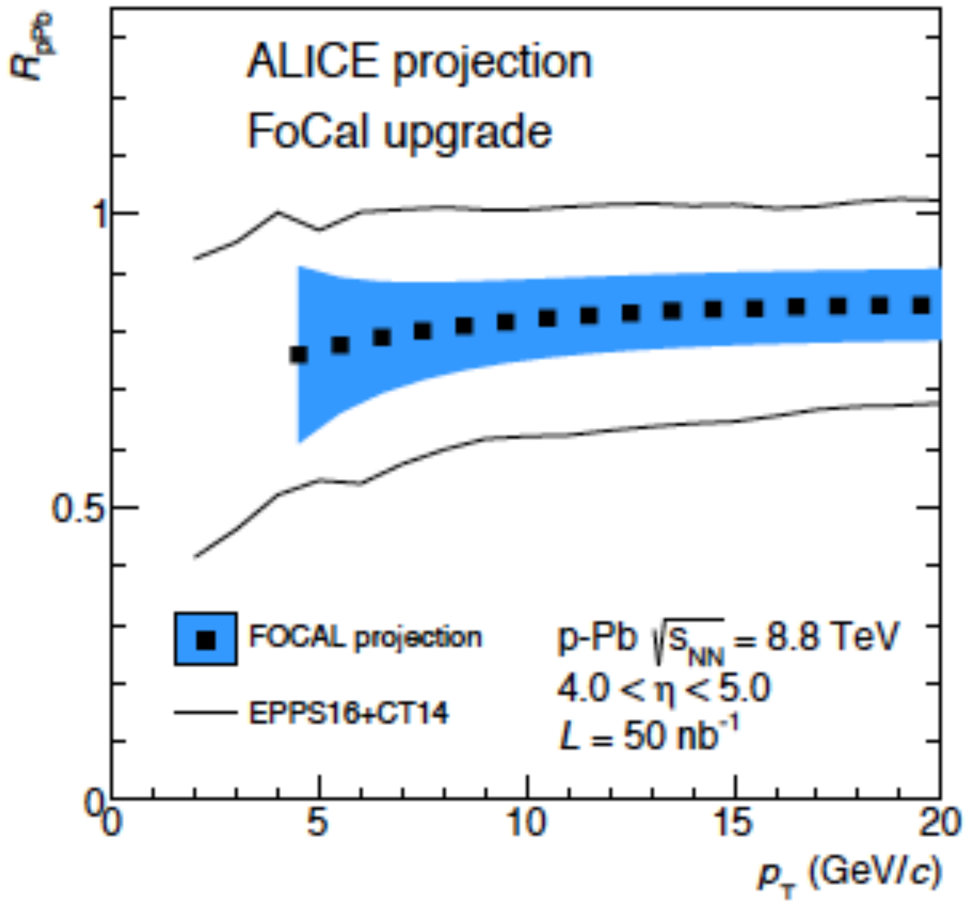
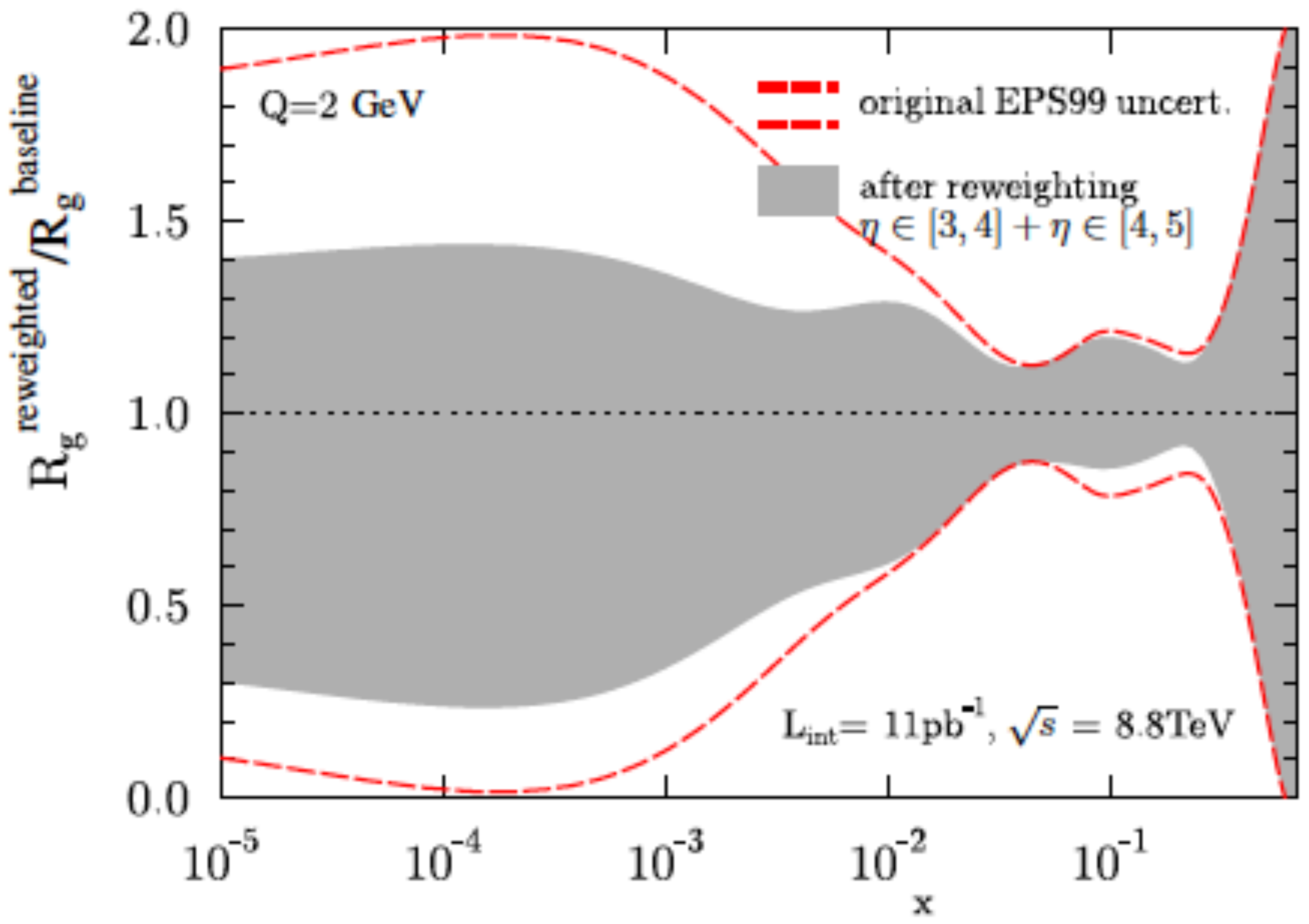
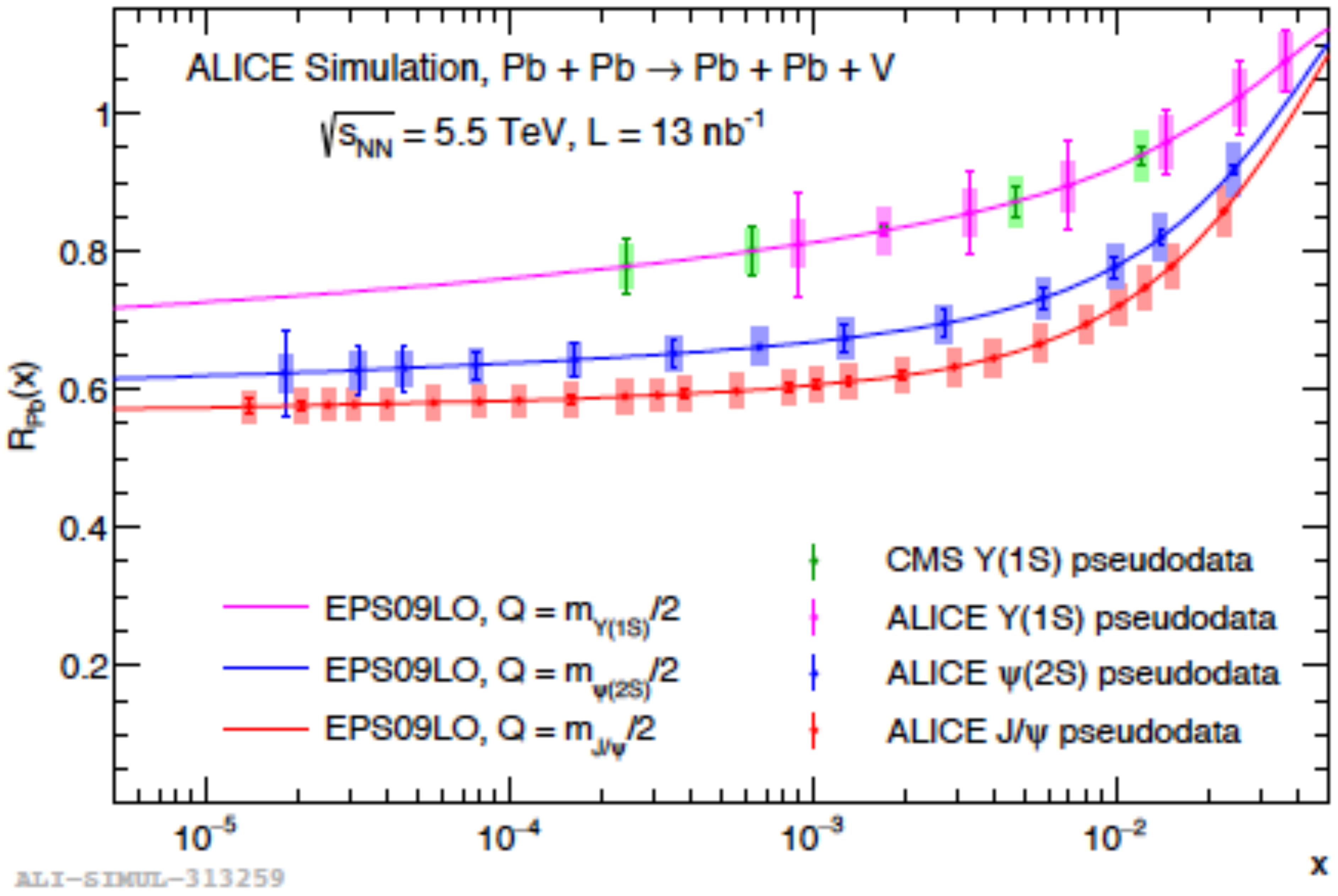
- Low mass forward DY for sea and gluon.
- Top requires higher statistics: lighter ions in the 30's?
- UPCs will also contribute: quarkonium, inclusive dijets (1902.05126).

1812.06772

Photons

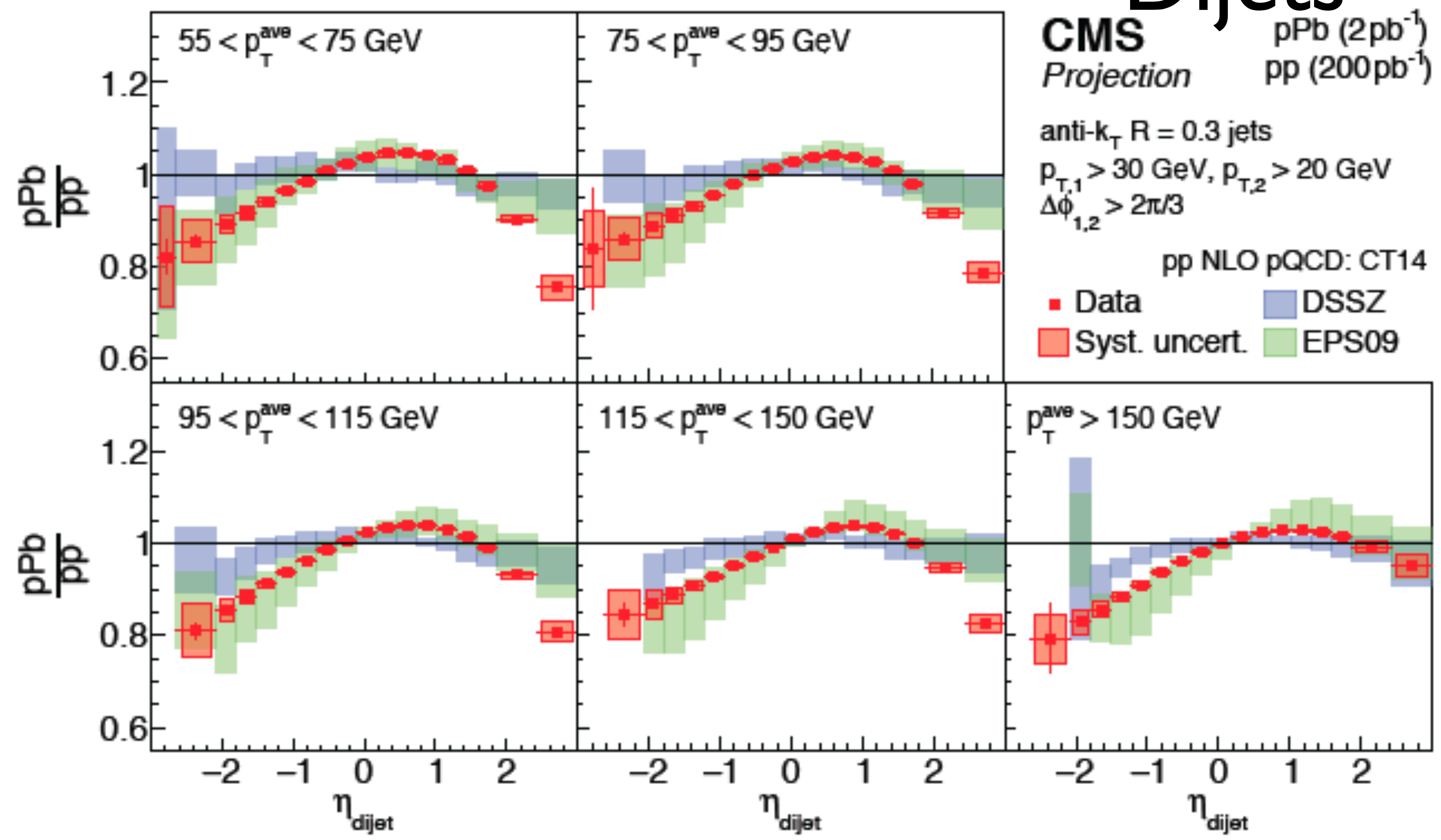






nPDFs @ HL-LHC:

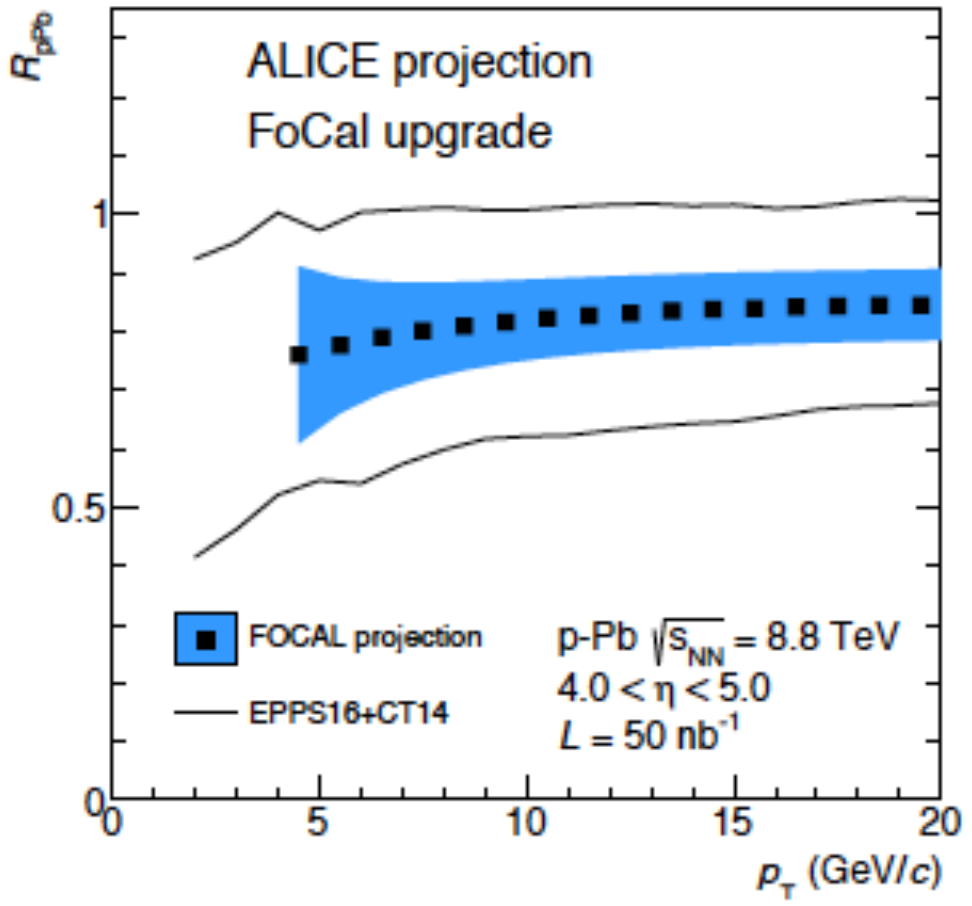
Dijets

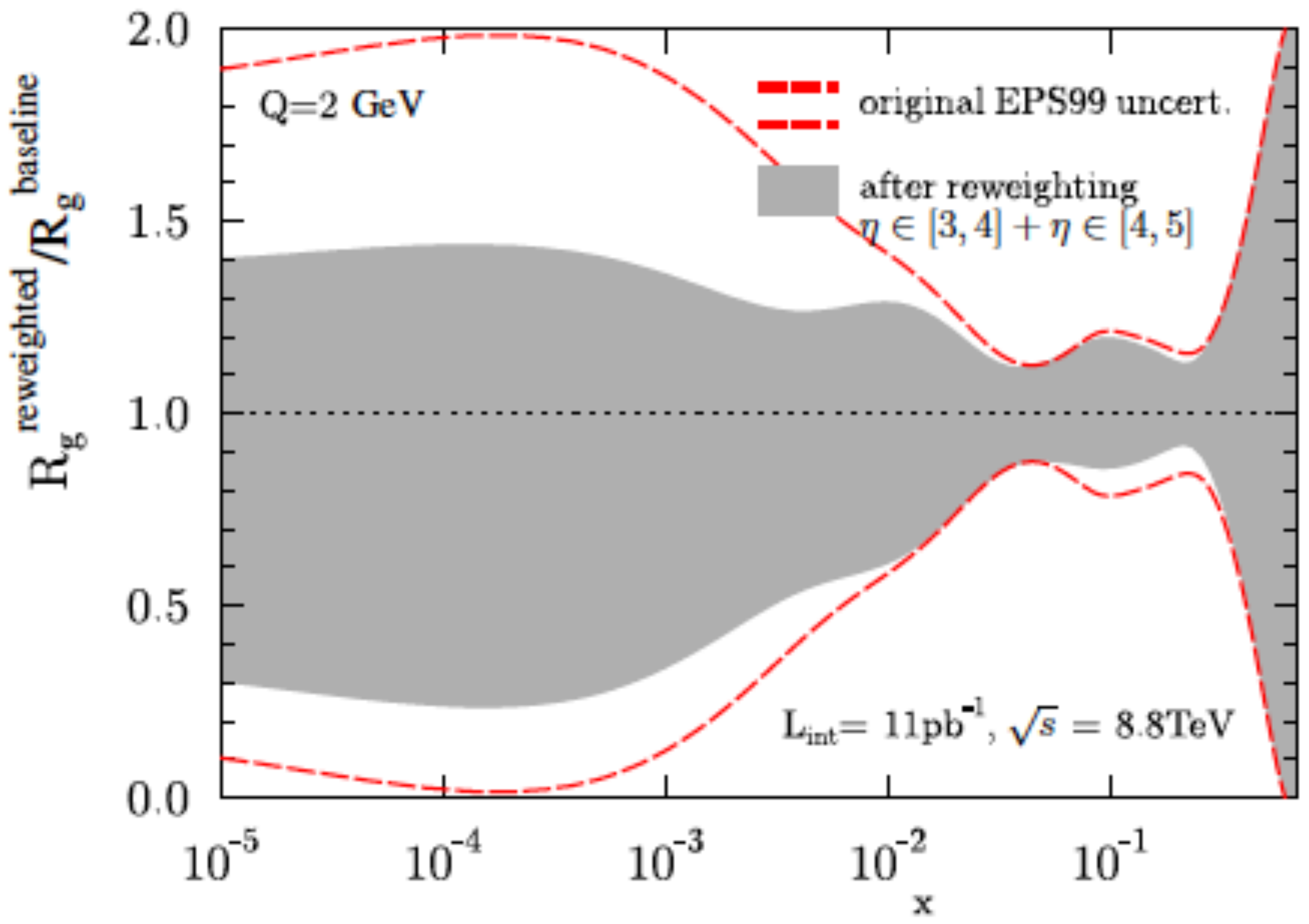


- Inclusive W for s/u.
- Dijets for glue.
- Z and γ at forward rapidity (glue).
- W asymmetries for gluon (evolution).
- Low mass forward DY for sea and gluon.
- Top requires higher statistics: lighter ions in the 30's?
- UPCs will also contribute: quarkonium, inclusive dijets (1902.05126).

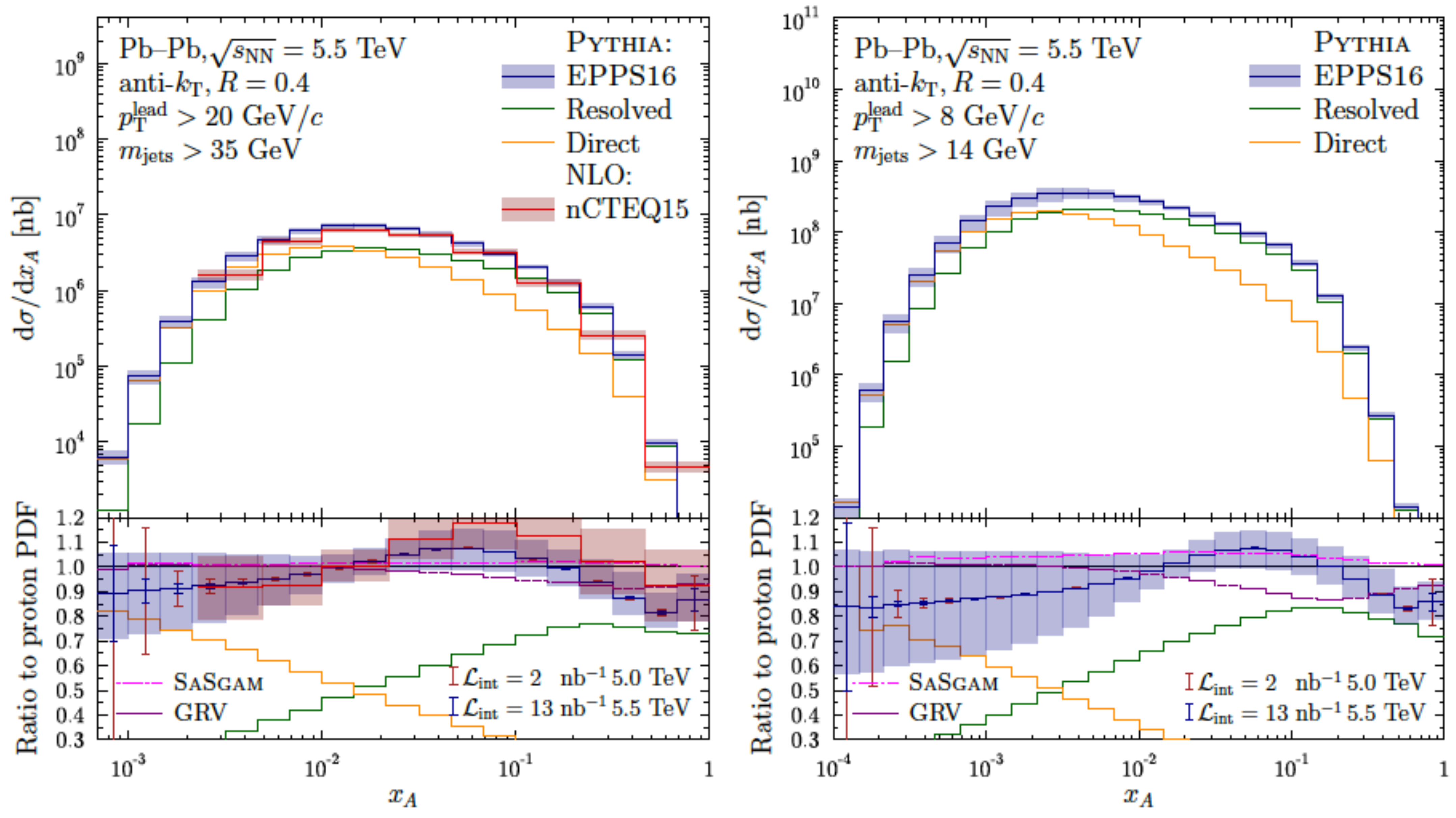
1812.06772

Photons

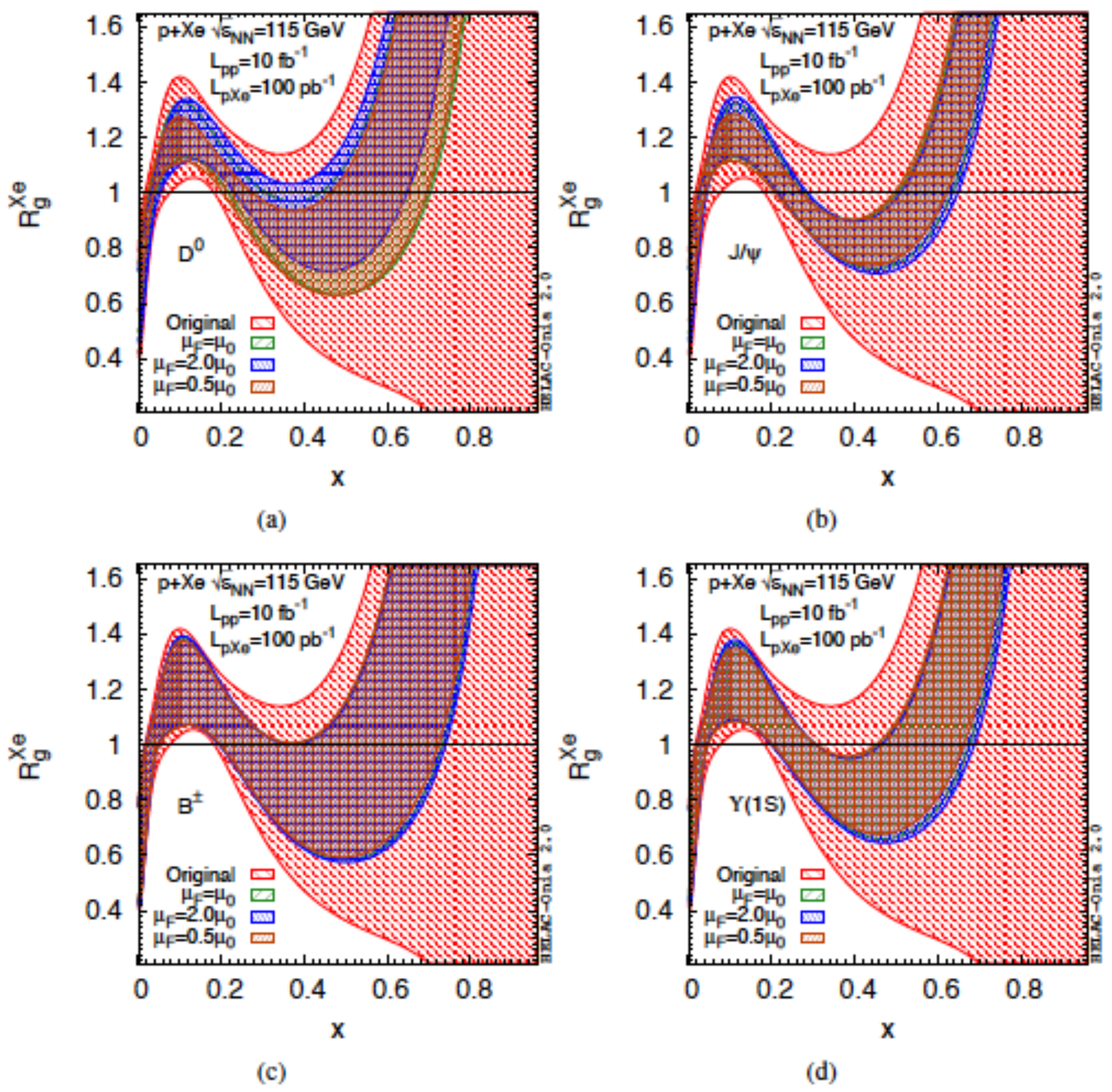




Dijets in UPCs

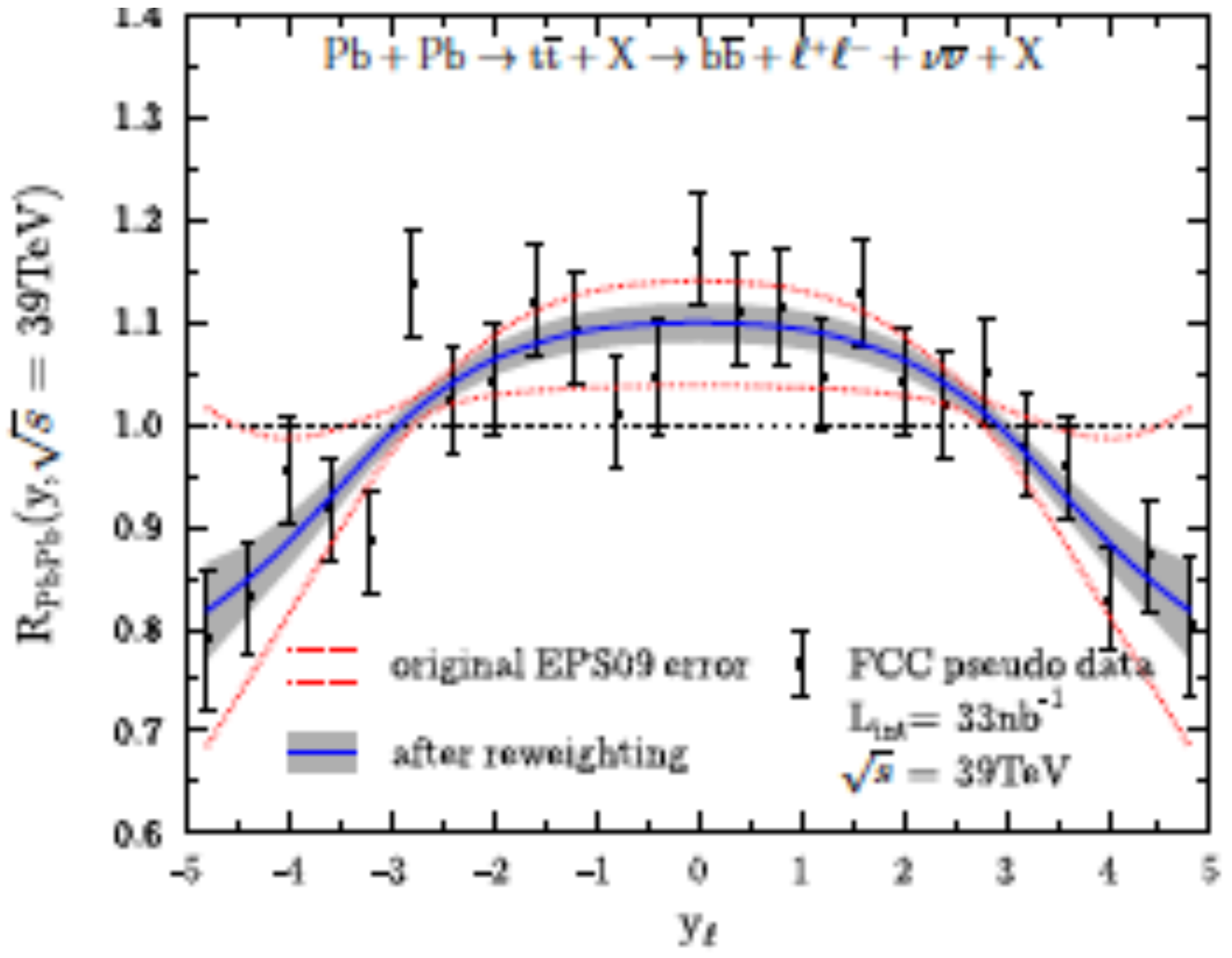


nPDFs in pA beyond HL-LHC:

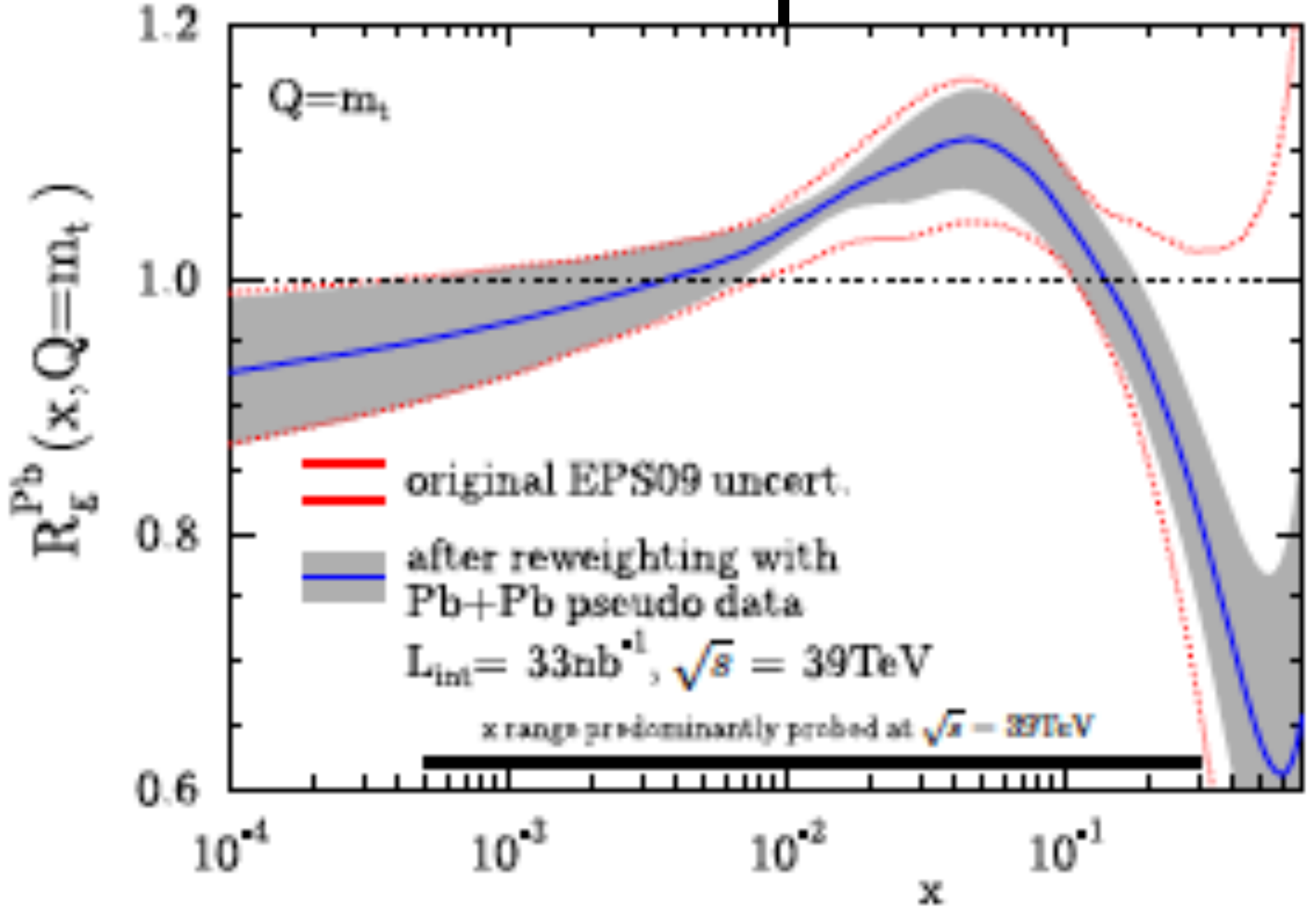


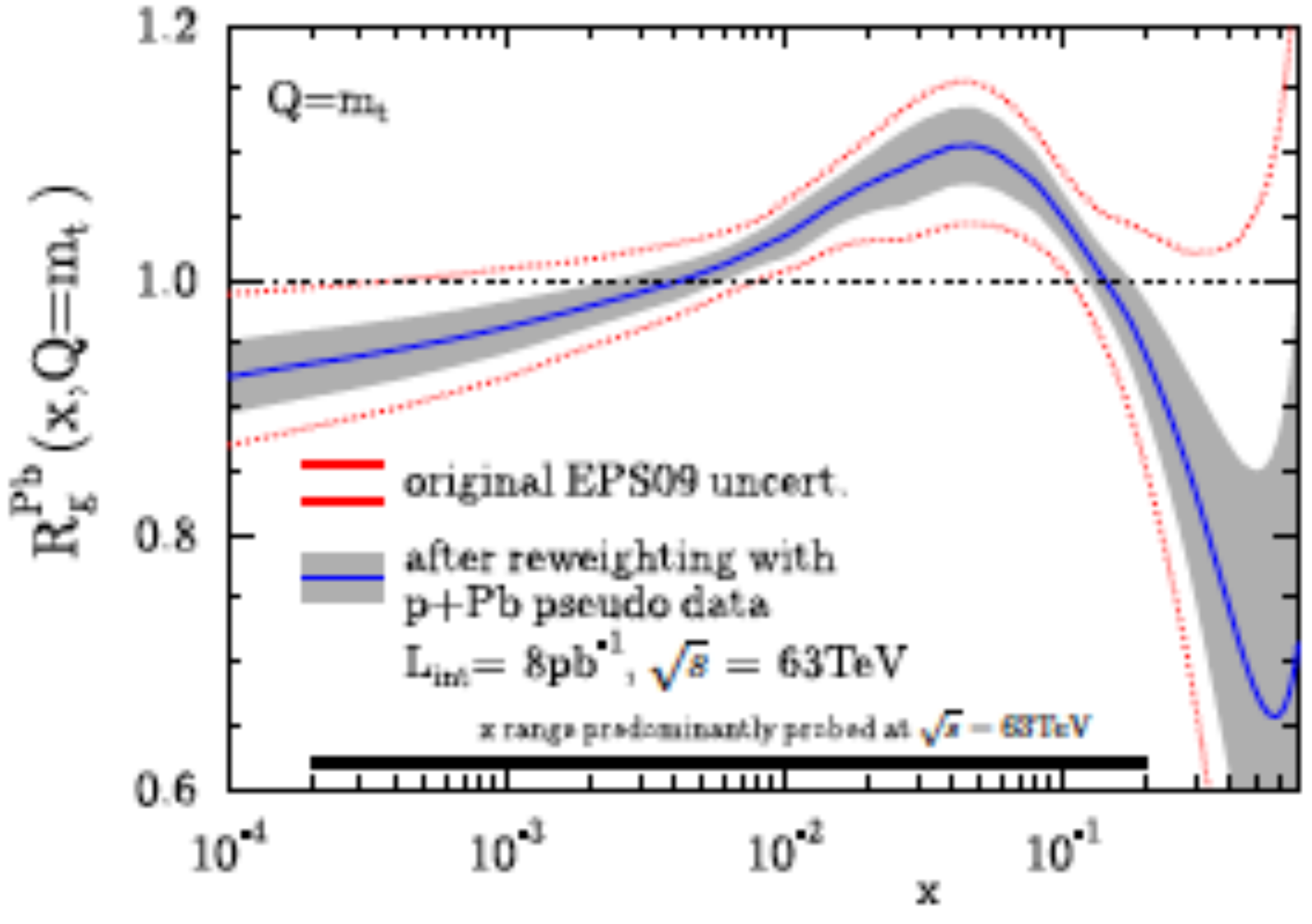
D, B mesons and quarkonia in pXe in FT mode

- Top studies become feasible at the FCC: gluon in pPb (1501.05879).
- UPCs will also contribute: quarkonium, inclusive dijets (1902.05126).
- Fixed target mode to constrain the high-x glue.



Top



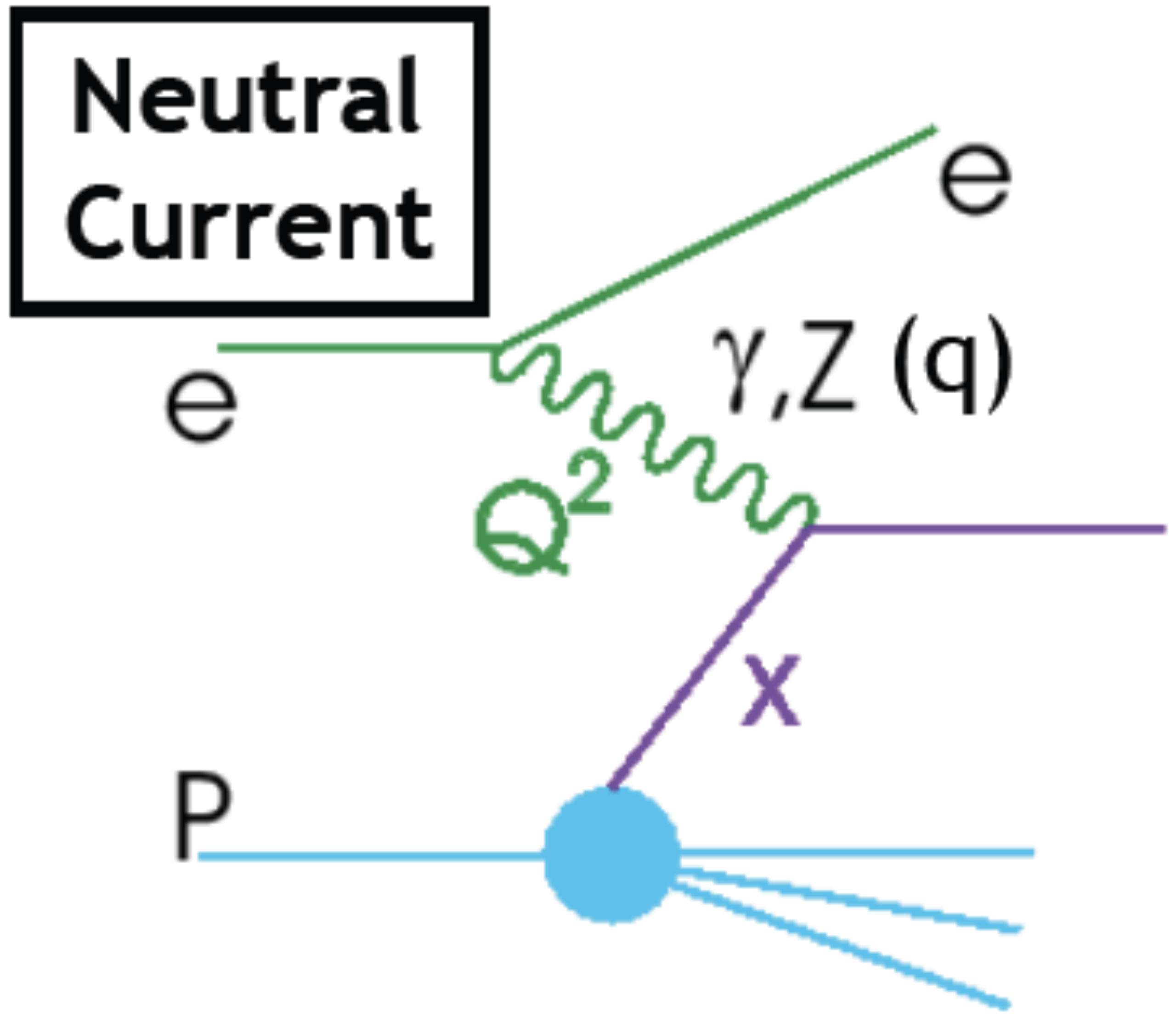


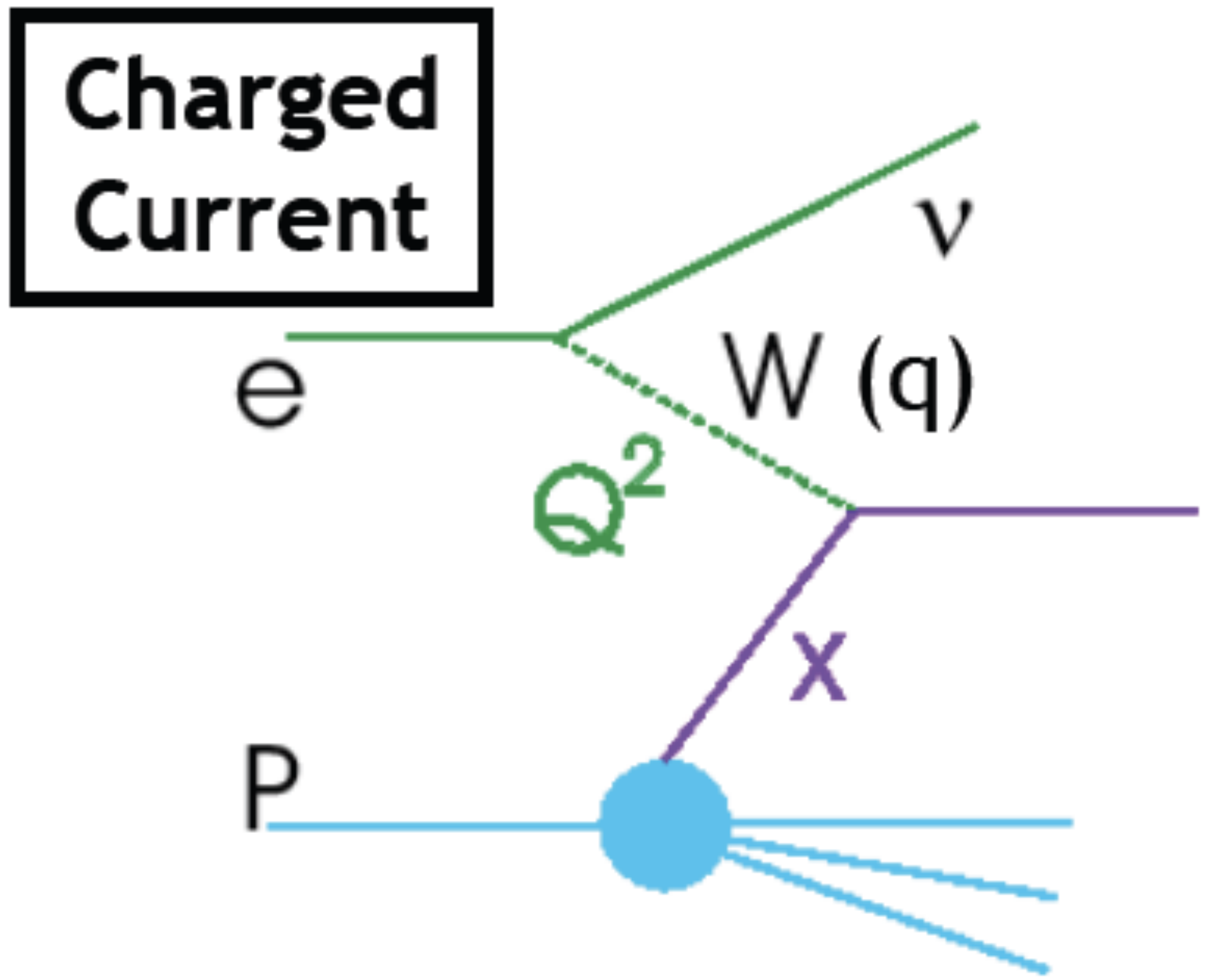
Contents:

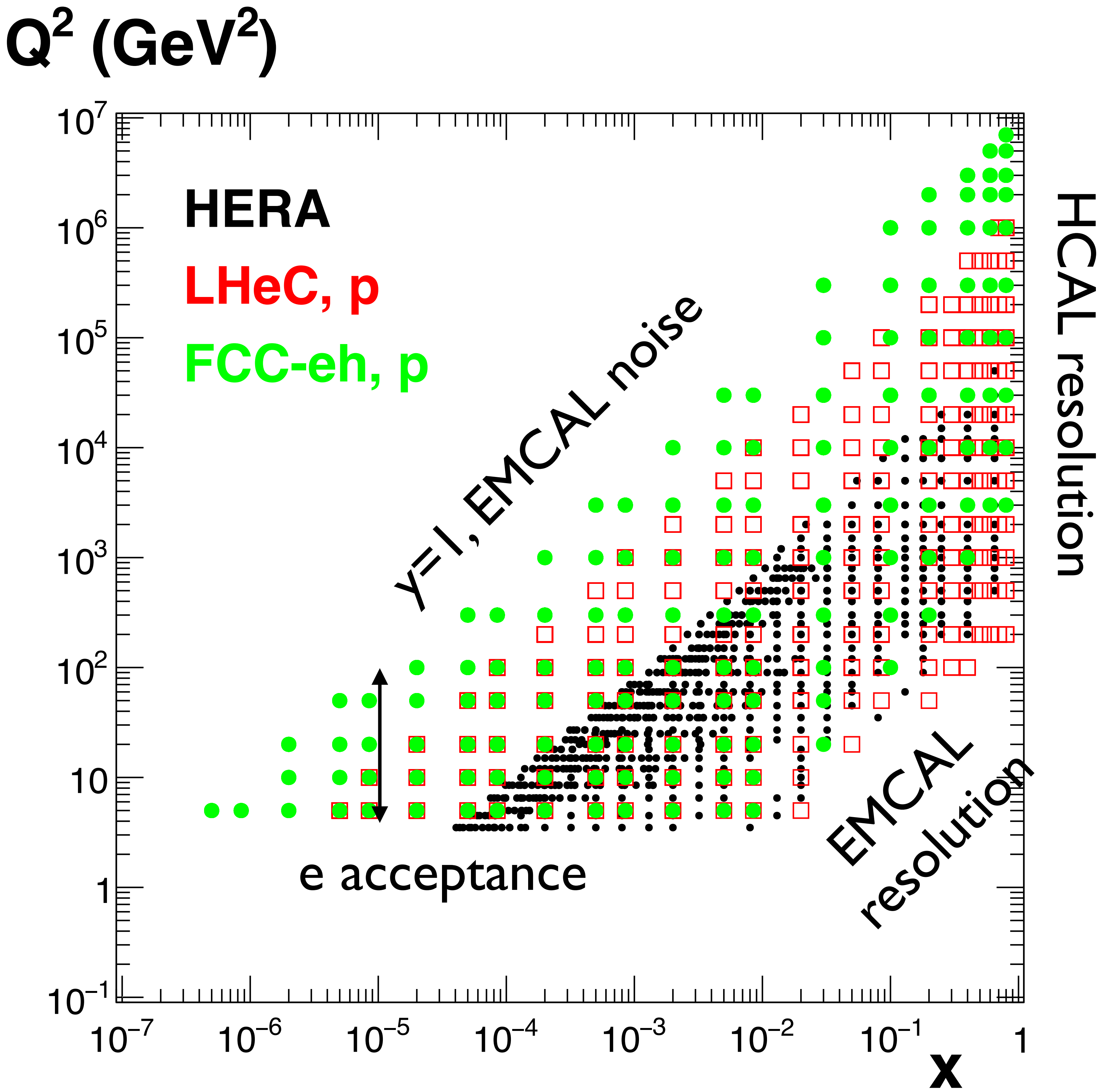
References:

- *Future Circular Collider: Vol. 1 Physics opportunities, CERN-ACC-2018-0056, and 1605.01389;*
- *1812.06772 (HL-LHC with ions);*
- *1901.09076 (diffraction in ep and eA);*
- *LHeC CDR, 1206.2913;*
- *EIC Physics White paper, 1212.1701; YR (CDR) for the end of the year.*
- *2019 LHeC and FCC-eh workshop, https://indico.cern.ch/event/835947/;*
- *LHeC and EIC talks at DIS 2019, https://indico.cern.ch/event/749003/.*
- *Fixed target program at the HL-LHC, 1807.00603;*
- *Update of the 2012 LHeC CDR to appear.*

DIS observables:







$F_2(x,Q^2) \propto \sum xq(x,Q^2)$ → determines directly valence (large x) and sea (low x)

$\dfrac{\partial F_2(x,Q^2)}{\partial \log Q^2} \propto xg(x,Q^2)$ → determines glue via DGLAP, $\mathcal{O}(\alpha_s)$: requires lever arm in Q^2.

$F_L(x,Q^2) \propto xg(x,Q^2) - F_2(x,Q^2)$ → determines the glue via DGLAP, $\mathcal{O}(\alpha_s)$: requires lever arm in E_{cm} (different y, $Q^2=xy\, E_{cm}^2$, at fixed x,Q^2, use σ_{red}).

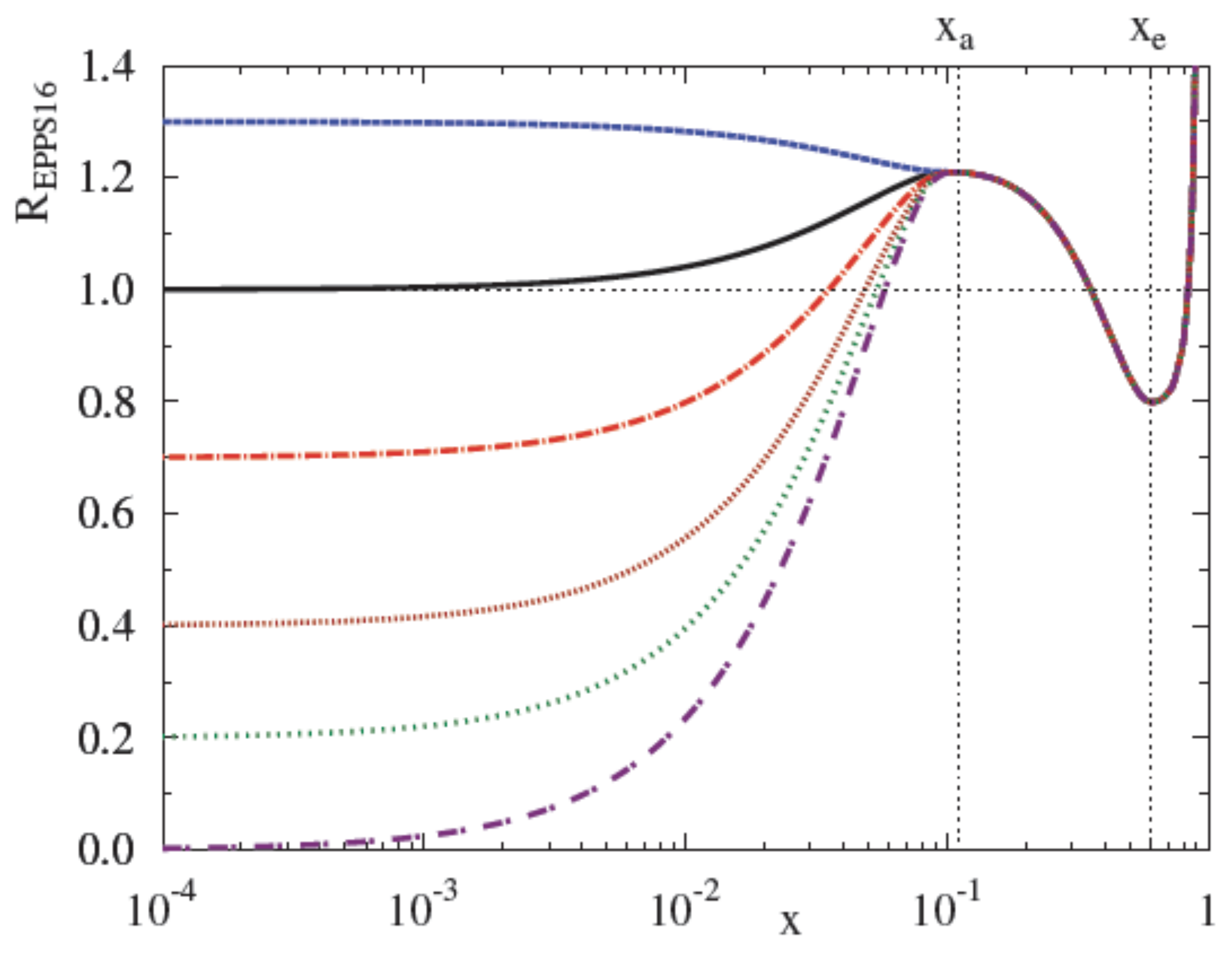
$F_2^{c,b,t}(x,Q^2)$ → determines heavy flavour PDFs: requires HQ ID.

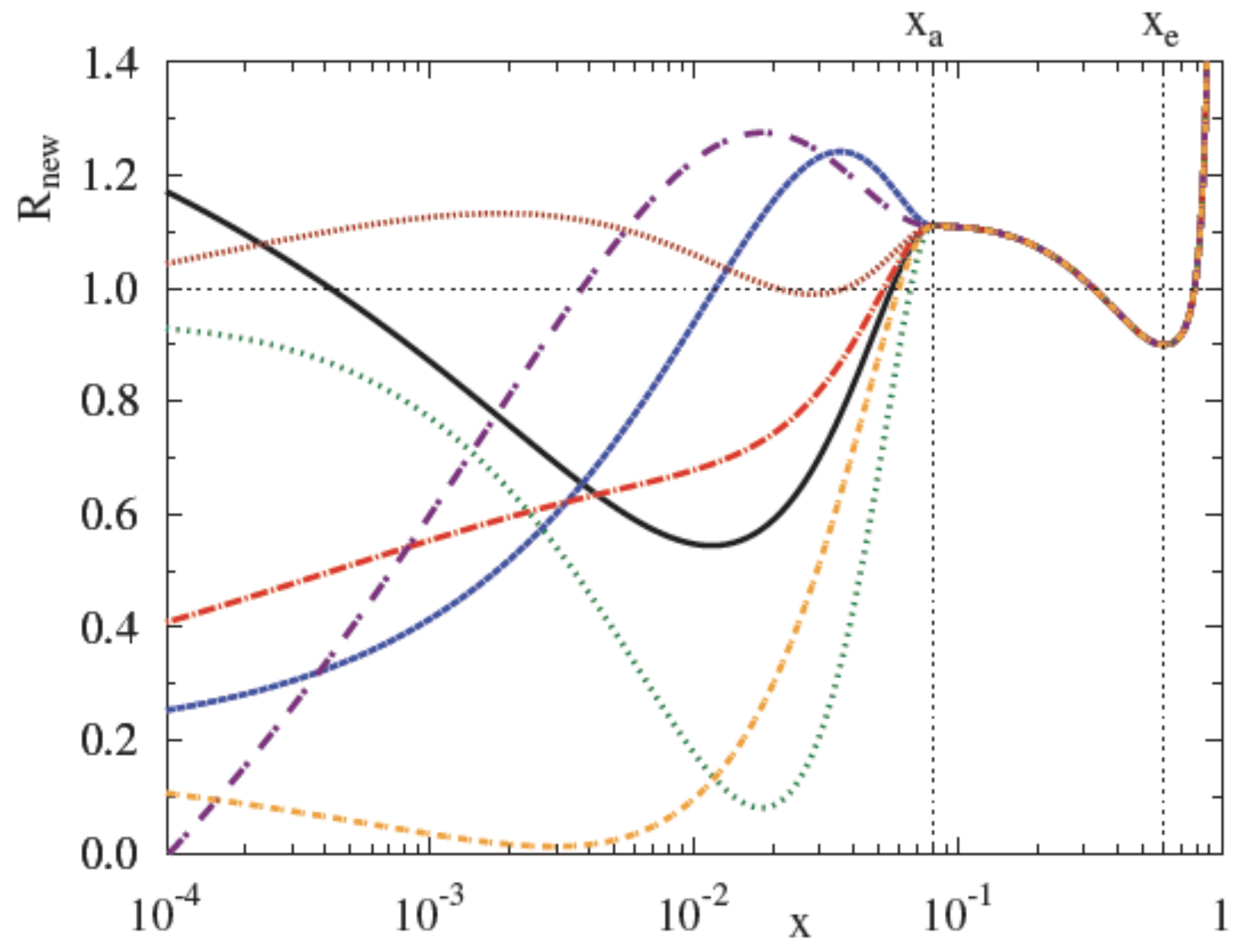
σ_r^{CC} → determines strange PDFs: requires HQ ID and measurement of missing energy.

- Besides: SIDIS, jets,…

Global analysis: EPPS16

- EPPS16-like analysis, with the same data sets as in EPPS16 plus EIC or 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 for the glue to better estimate the uncertainties (parametrisation bias).





Global analysis: EPPS16 @ EIC

- EPPS16-like analysis, with the same data sets as in EPPS16 plus EIC NC, CC and charm reduced cross sections.
- Central values generated using EPS09.
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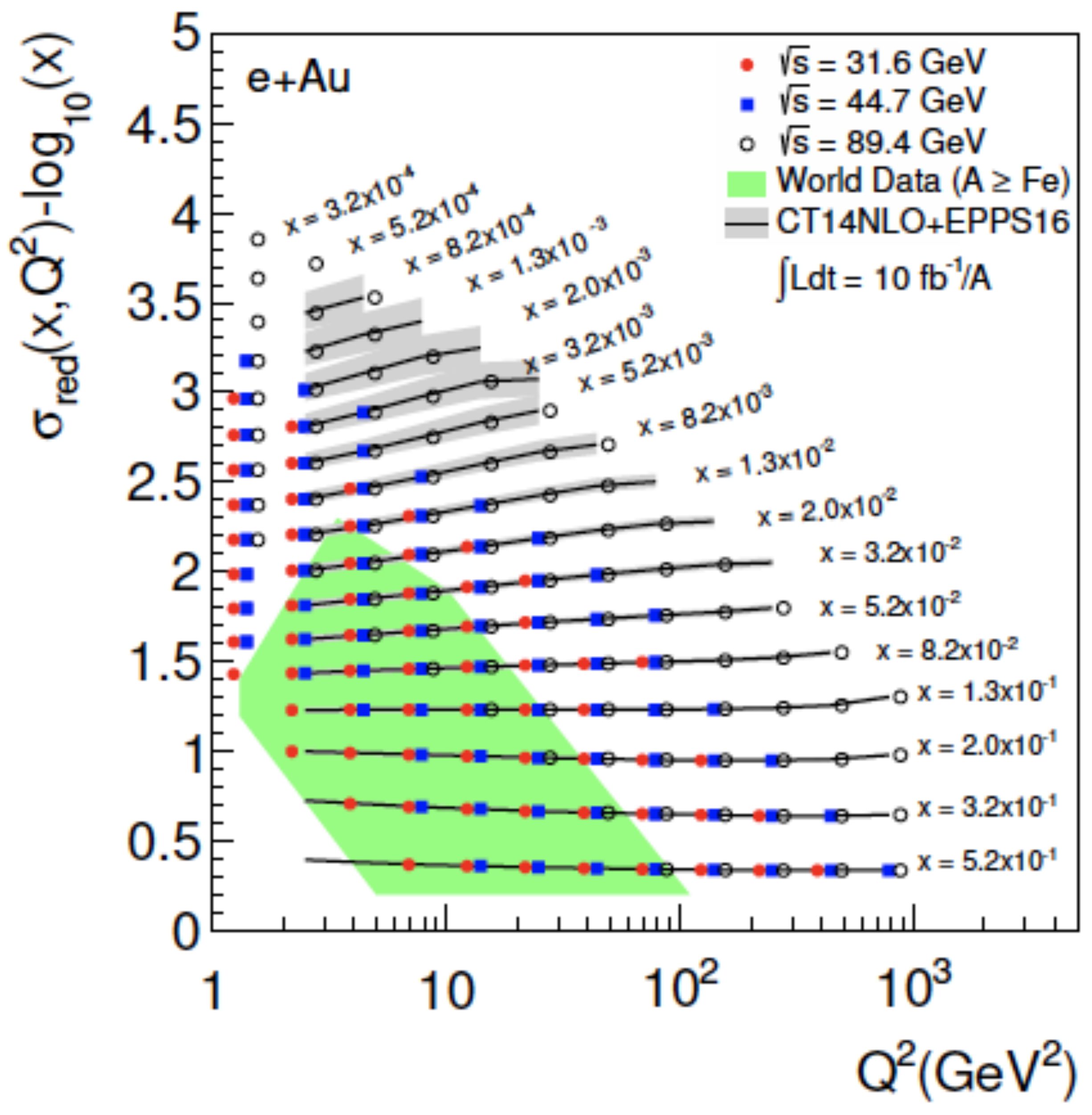
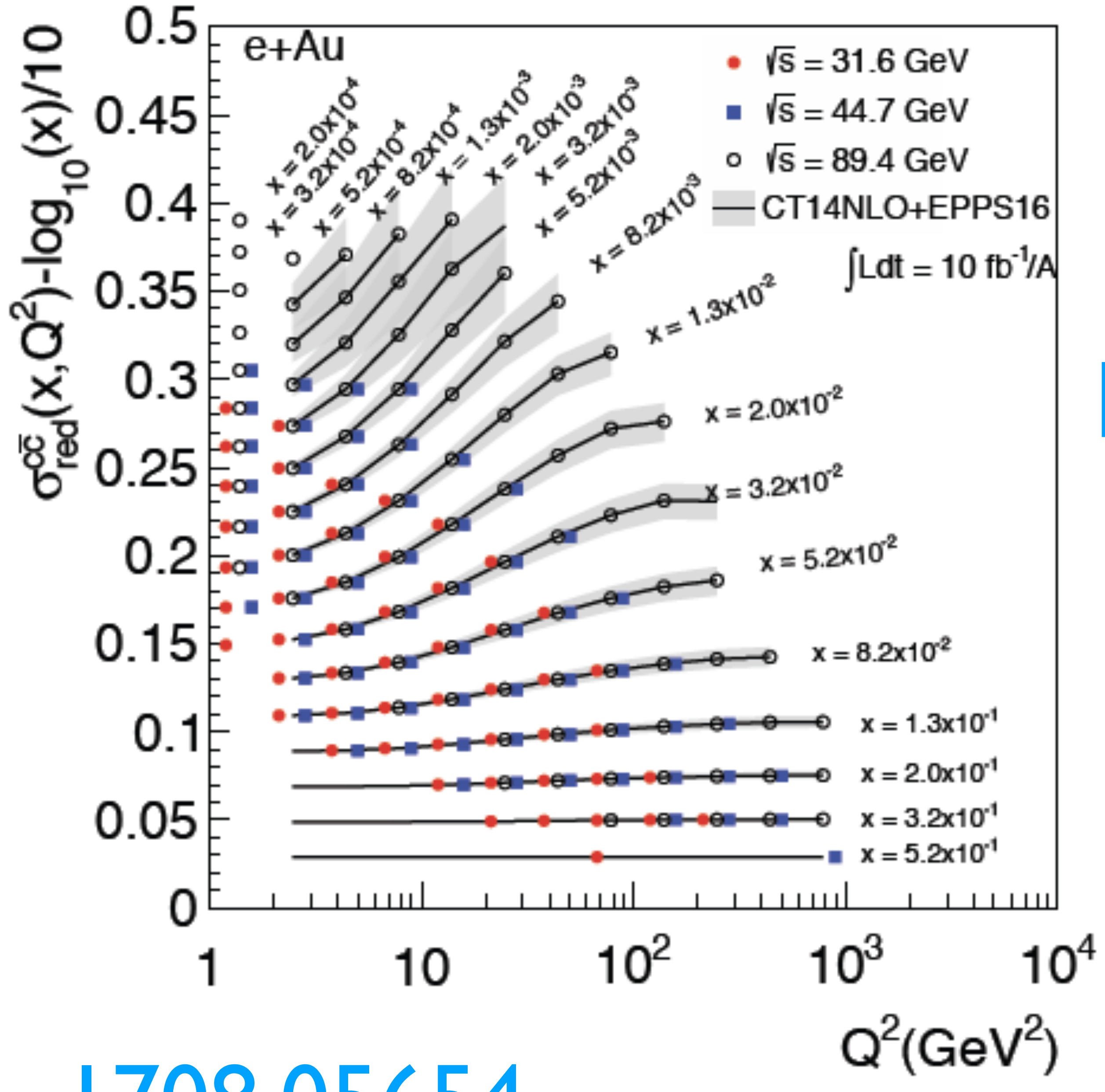
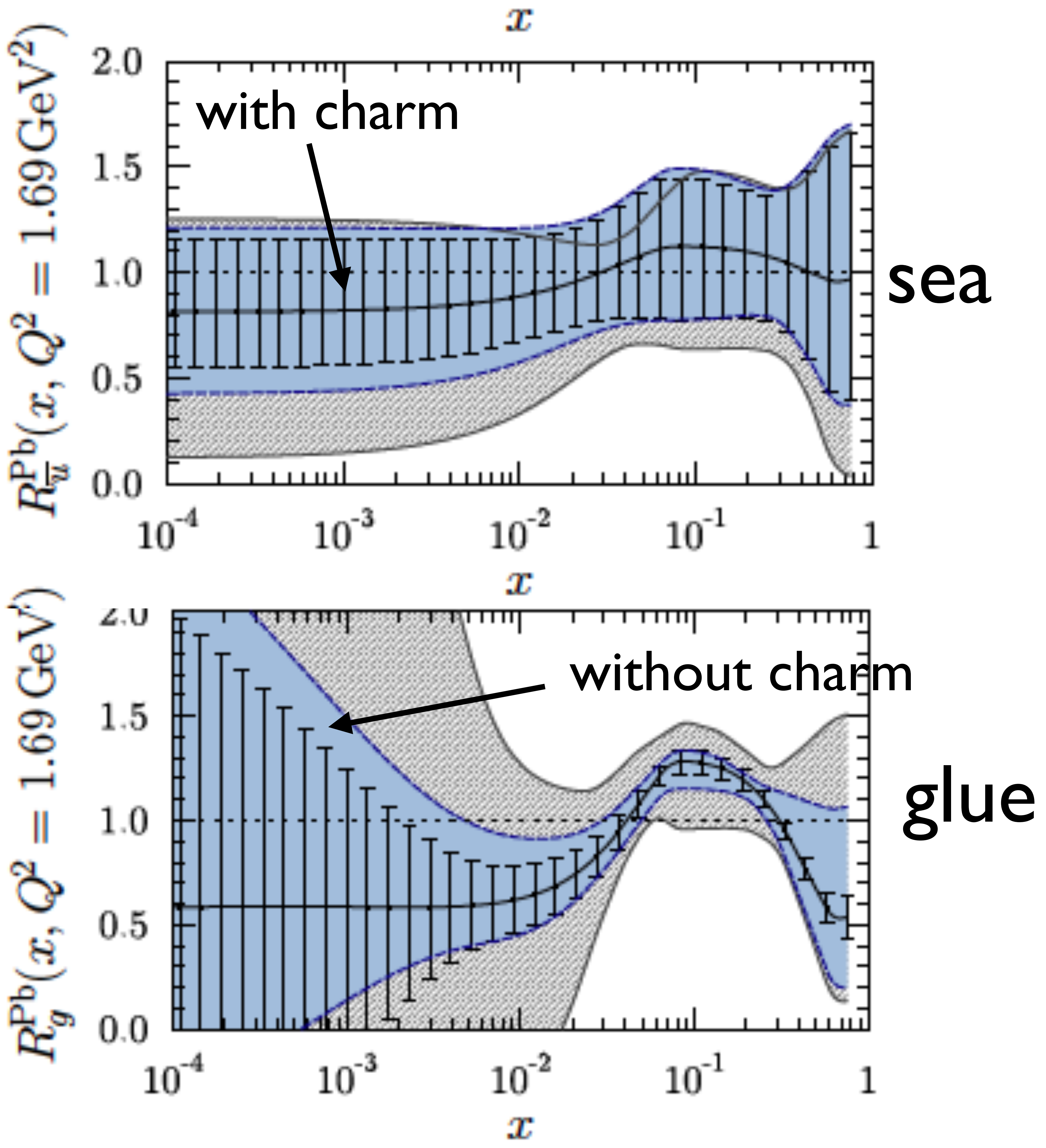




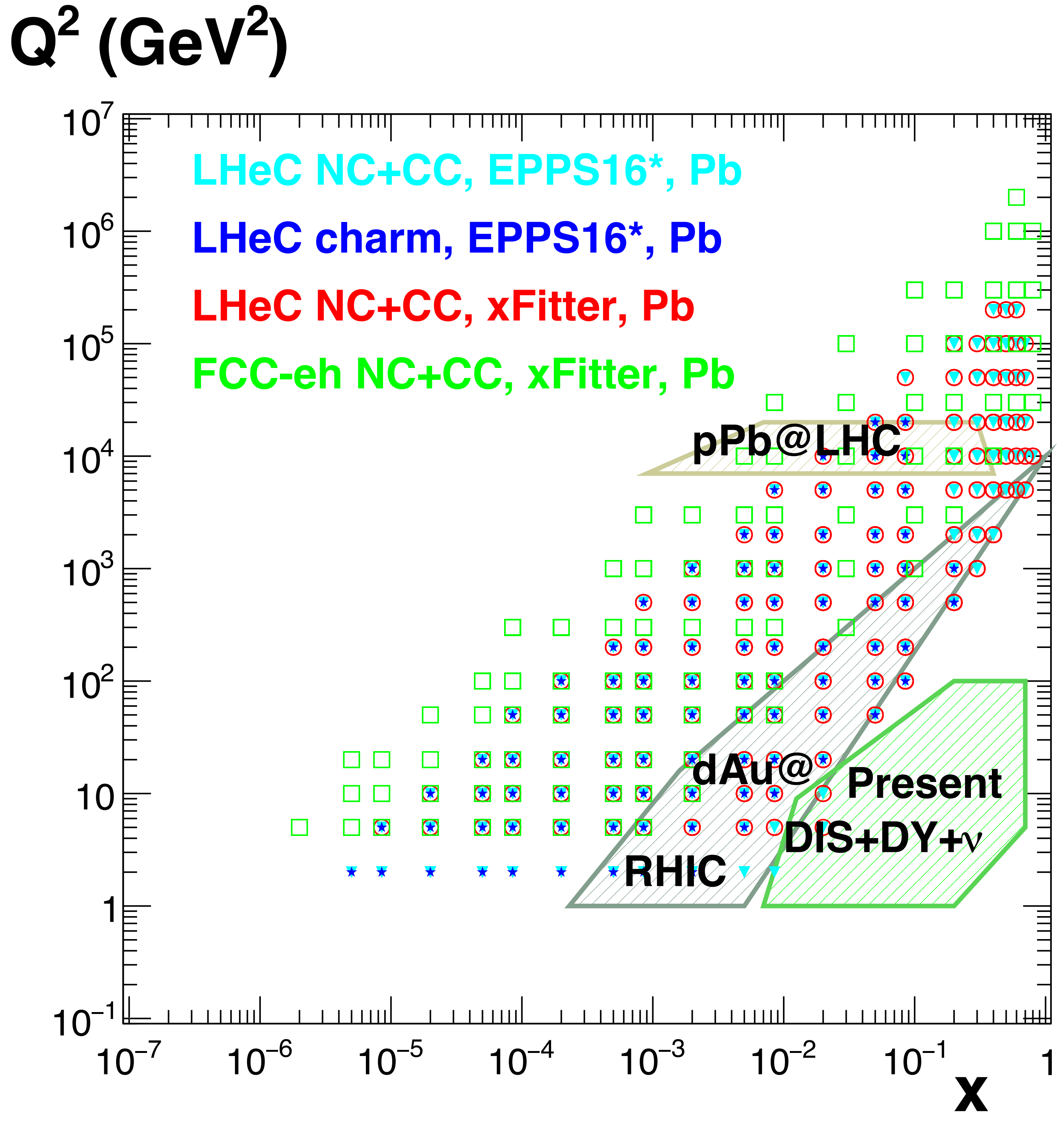
1708.05654



Global analysis: EPPS16 @ LHeC

- EPPS16-like analysis, with the same data sets as in EPPS16 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 to better estimate the uncertainties (parametrisation bias).

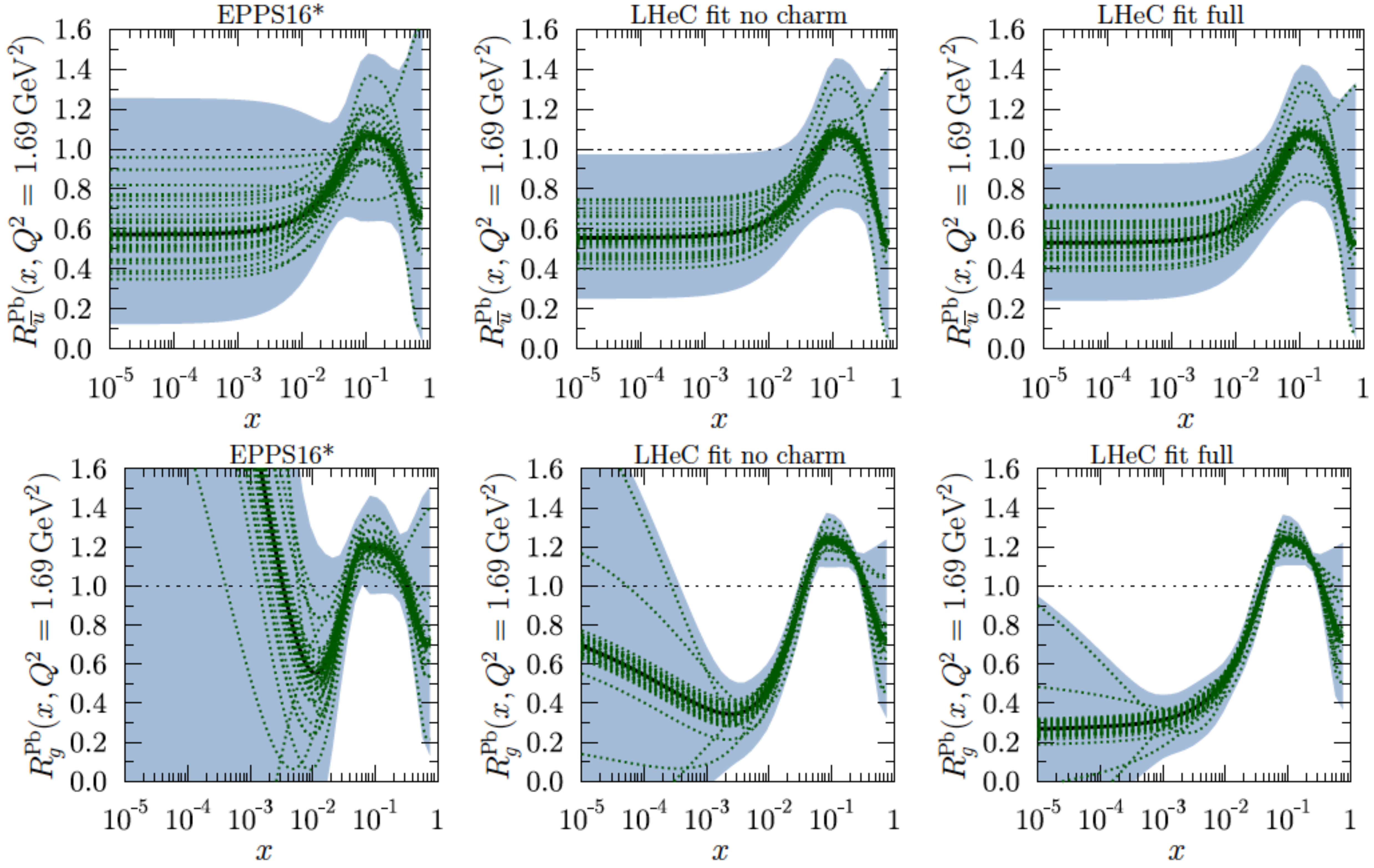
In both cases large impact:
- HF has sizeable impact (on glue).
- Not yet included: beauty, c-tagged CC for strange.



Update of the LHeC CDR; 1709.08342

sea

glue



Pb-only DIS fit:

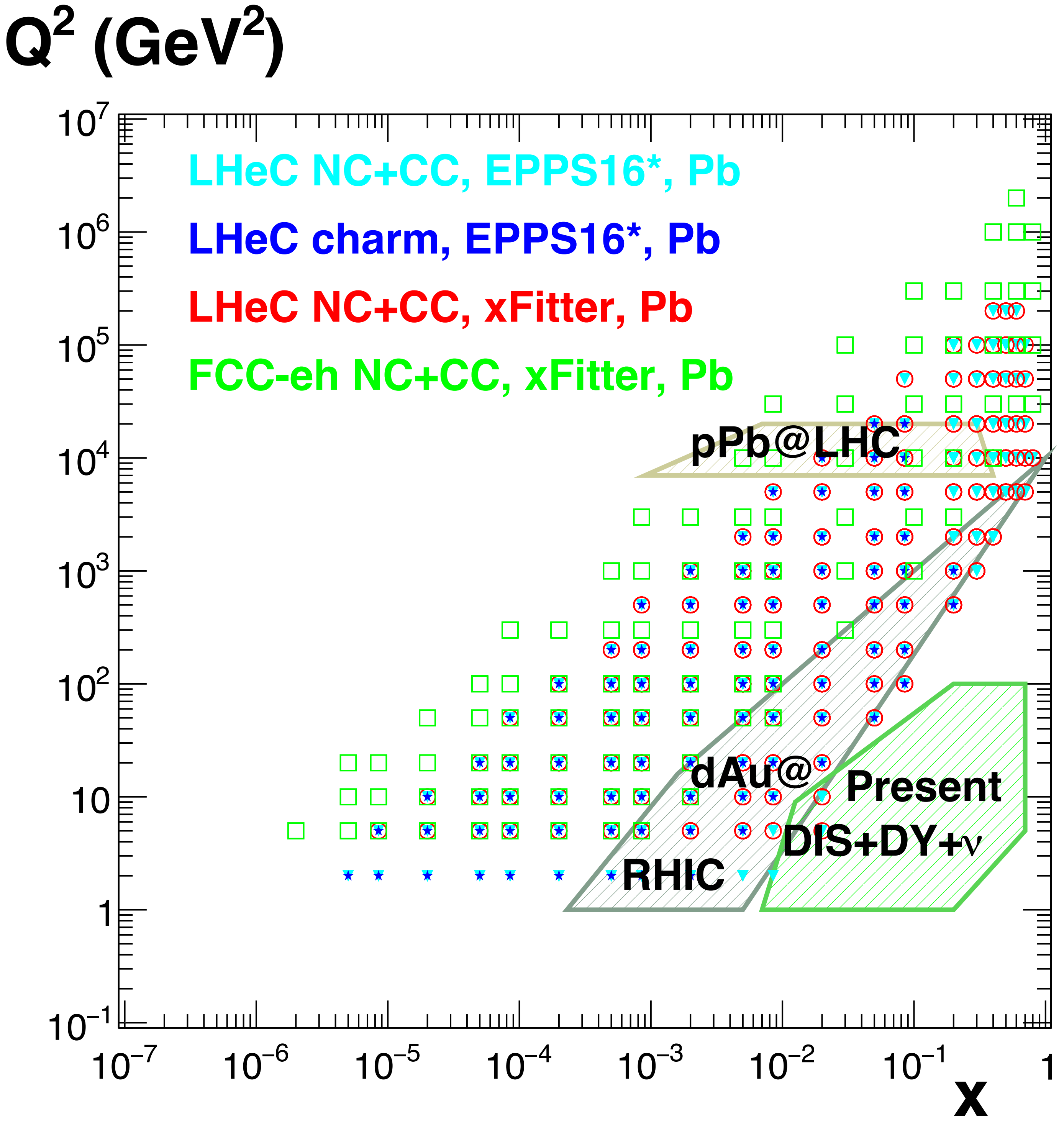
- **Pb-only** PDFs from NC+CC at LHeC and FCC-eh, using xFitter (1410.4412)1.2.2.

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

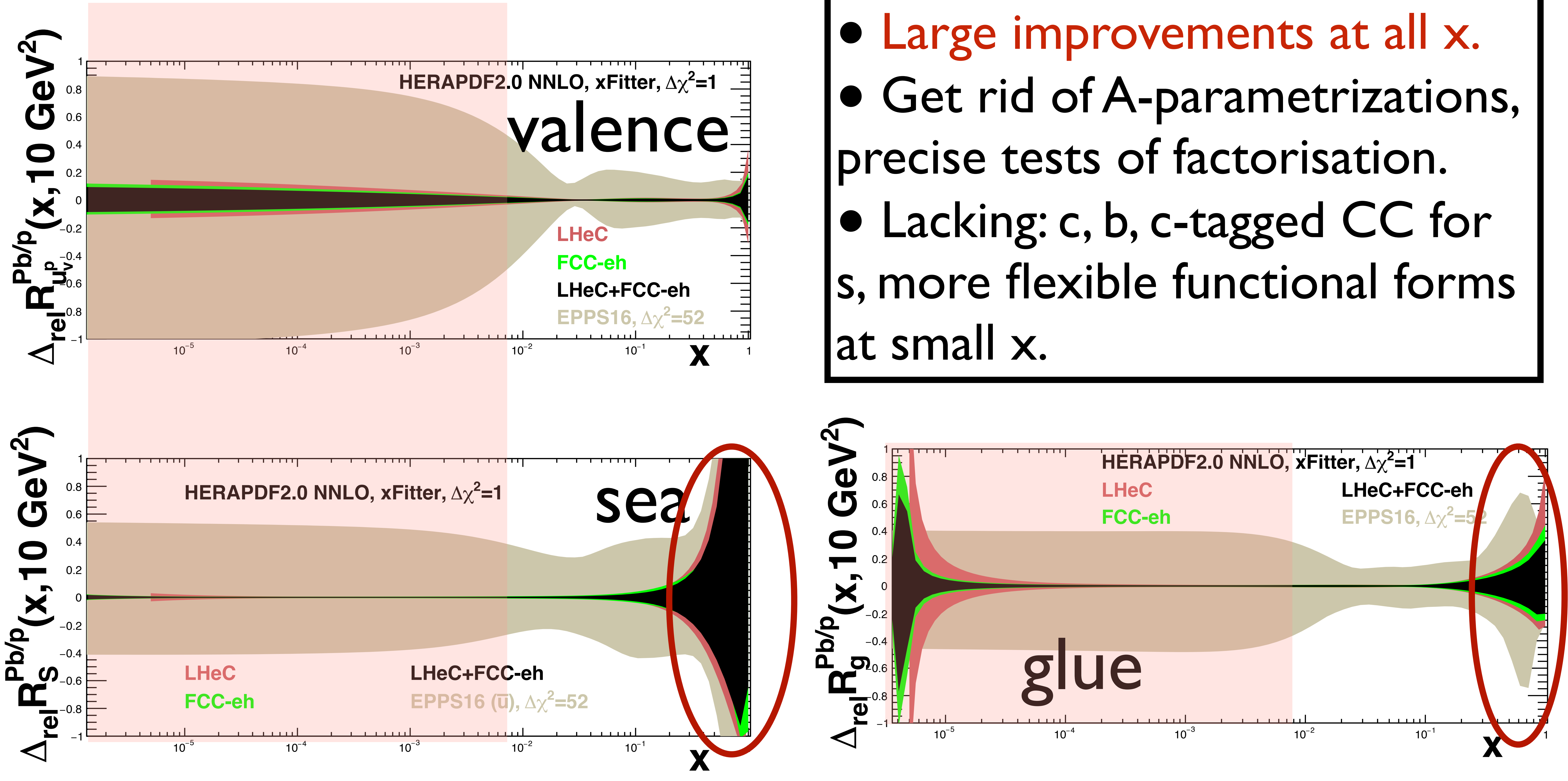
➜ Central values from HERAPDF2.0: neither parametrisation bias nor theory uncertainties.

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

➜ Only data with $Q^2 \geq 3.5$ GeV², initial evolution scale 1.9 GeV².



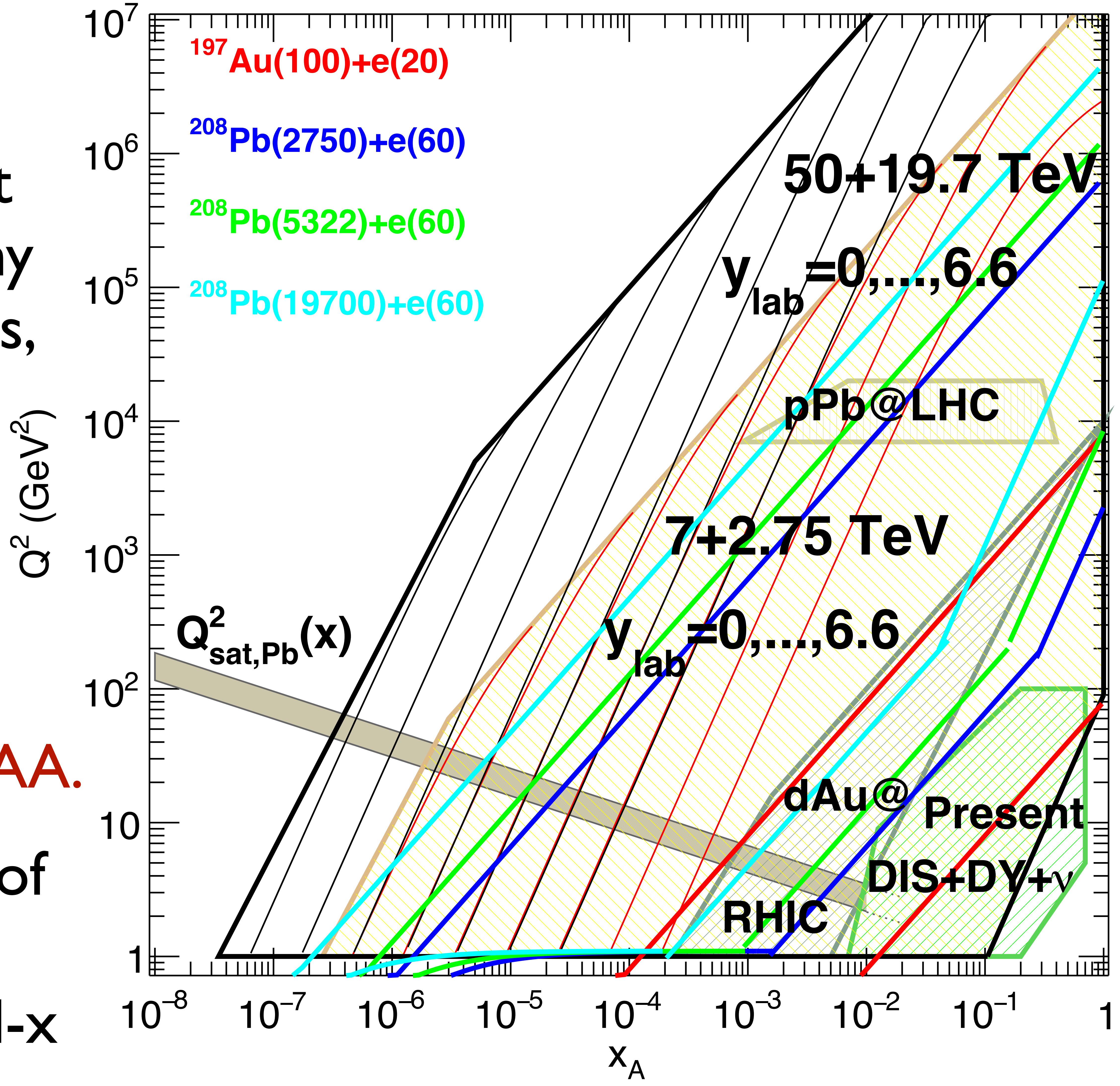
NA at DIS18 and DIS19



- Large improvements at all x.
- Get rid of A-parametrizations, precise tests of factorisation.
- Lacking: c, b, c-tagged CC for s, more flexible functional forms at small x.

Summary:

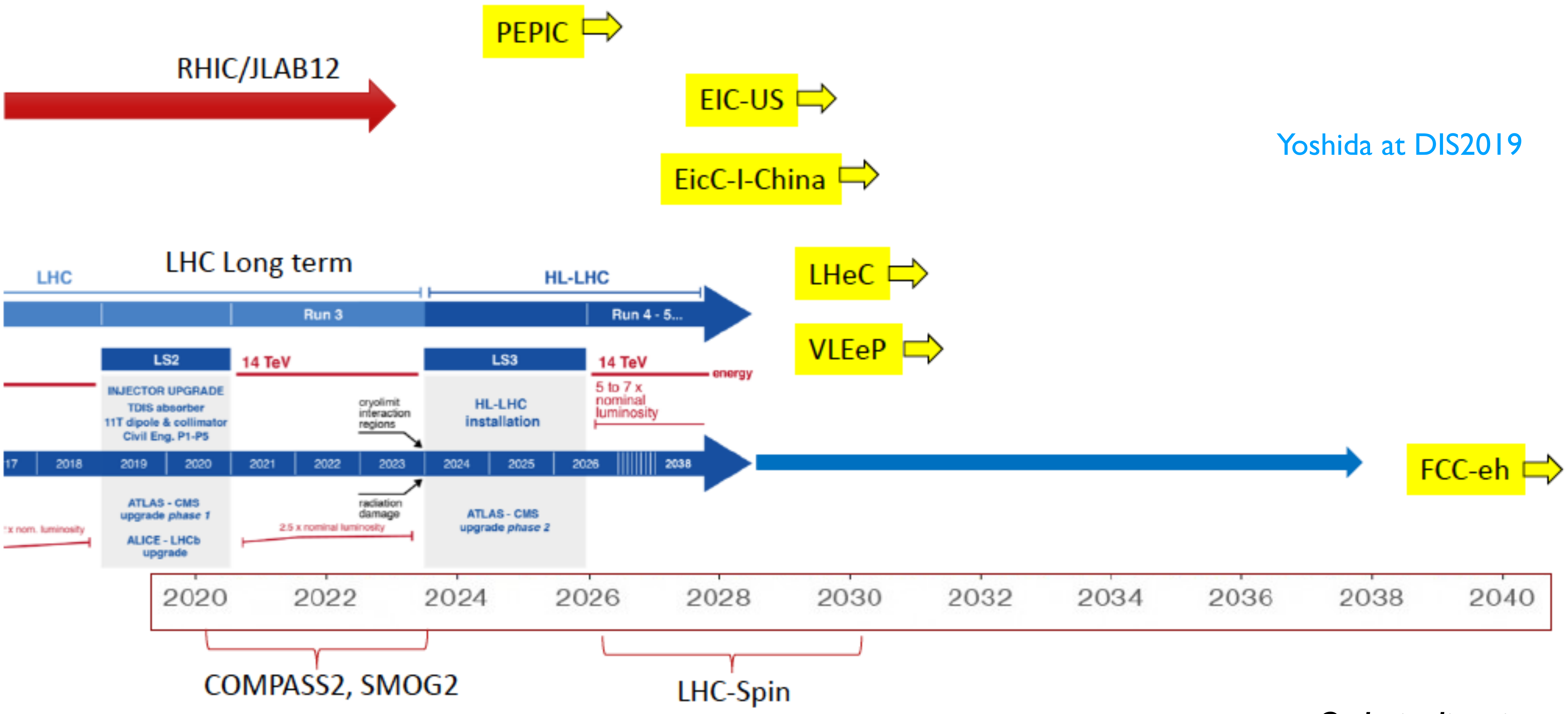
- Nuclear PDFs are basicly unknown for x<0.008, and the glue at large x: large implications on HICs.
- Extractions from LHC will improve the situation but they rely on factorisation and demand reconciling many experiments/observables: A-dependence of parameters, large tolerances.
- Extractions from EICs will greatly improve the situation in their available kinematic region. Note that DIS is experimentally (kinematic reconstruction, no pileup, no large tolerance) and theoretically (factorisation) cleaner ⇒ limits of factorisation in pA/AA.
- Hadron/DIS machines are complementary in terms of 'reach'/'precision'.
- Besides: diffraction, GPDs/TMDs/3D structure, small-x studies,…



Thanks for the invitation and your attention!

Backup

Timeline:

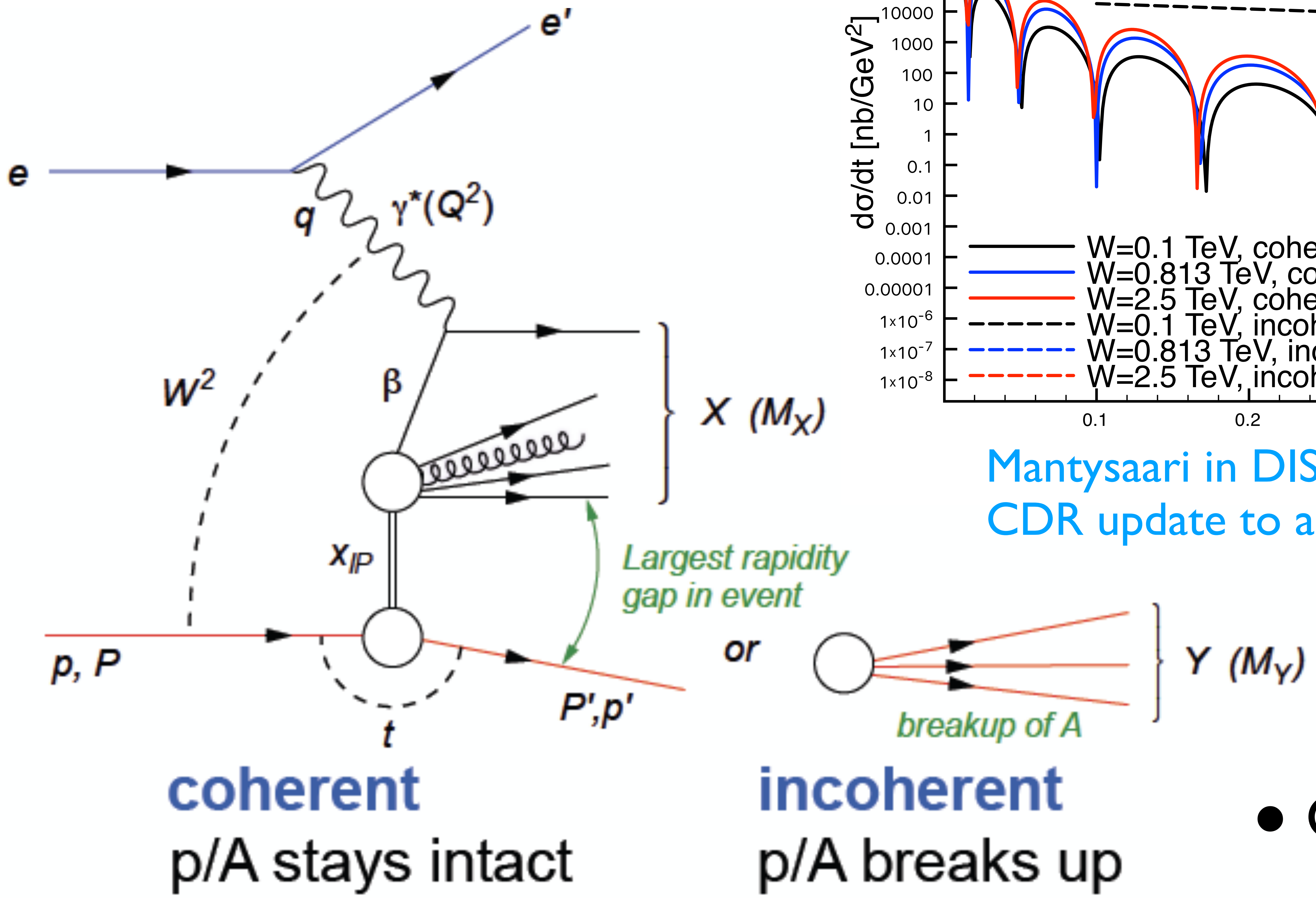


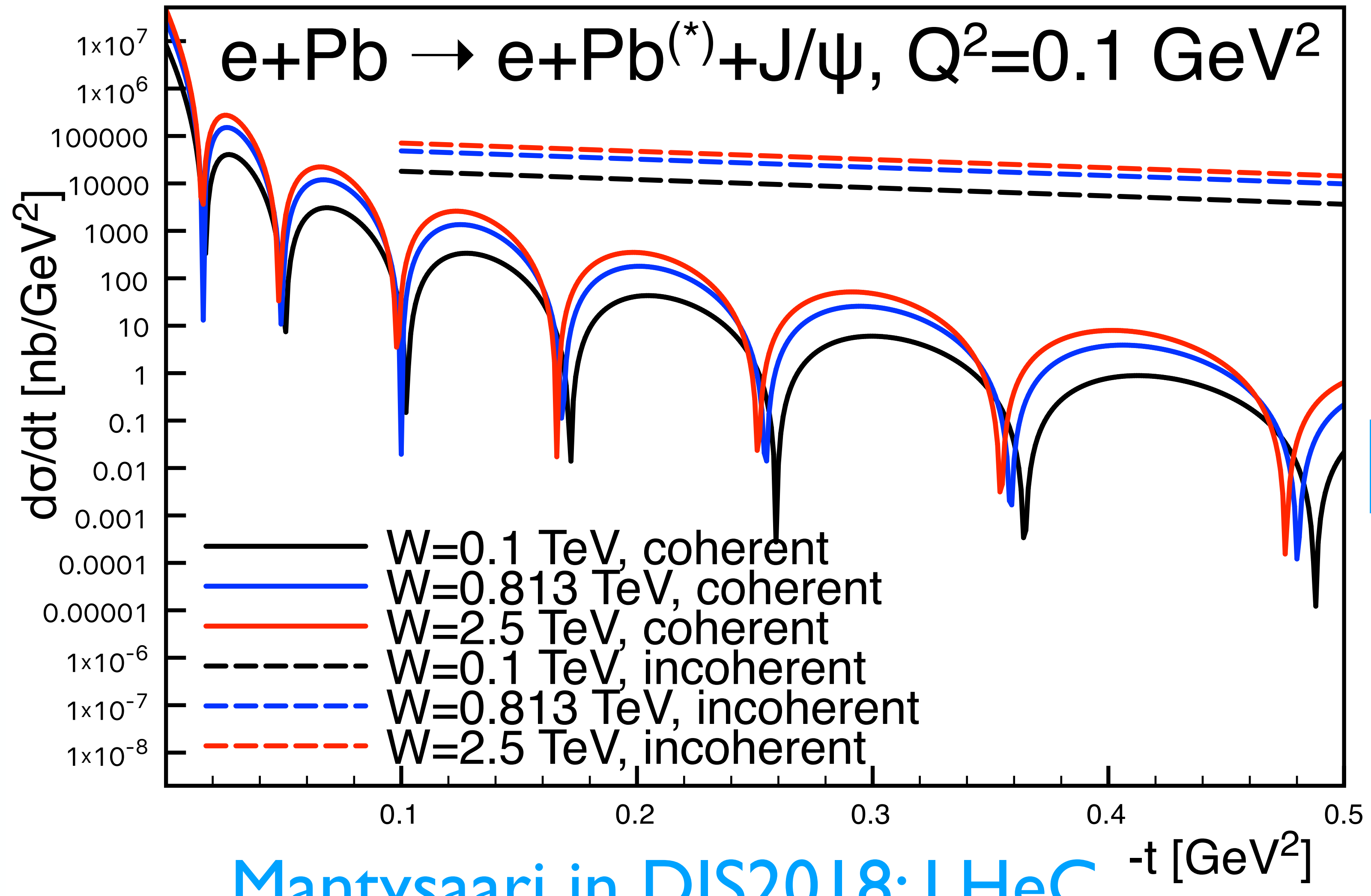
Yoshida at DIS2019

Only indicative…

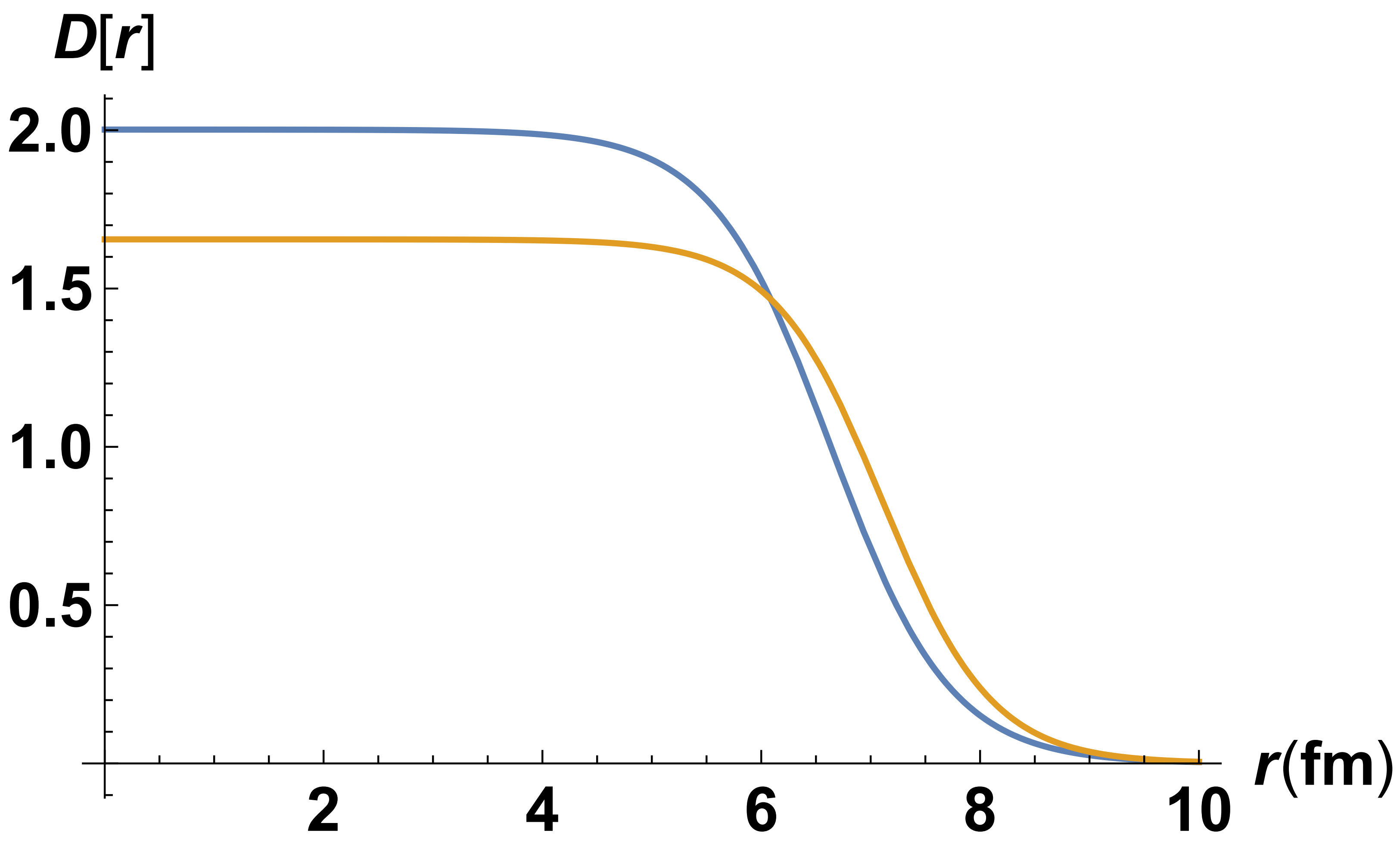
3D - GPDs and TMDs (I):

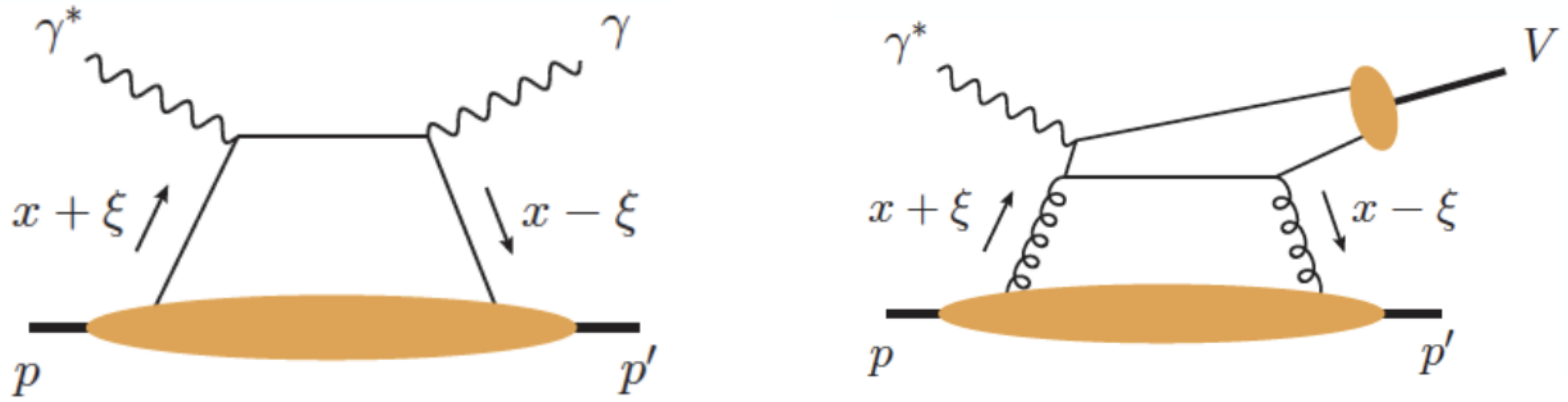
- The extraction of 3D-structure (GPDs and TMDs and their evolution equations) is a huge undergoing program: scarcely known in the proton, **mostly unknown in nuclei**.





Mantysaari in DIS2018; LHeC CDR update to appear





- Coherent exclusive production (γ/VM) ⇒ q/g GPDs, transverse profile.

- It can be done at the EIC/LHeC/FCC-eh in a large range of x and Q² ⇒ evolution.

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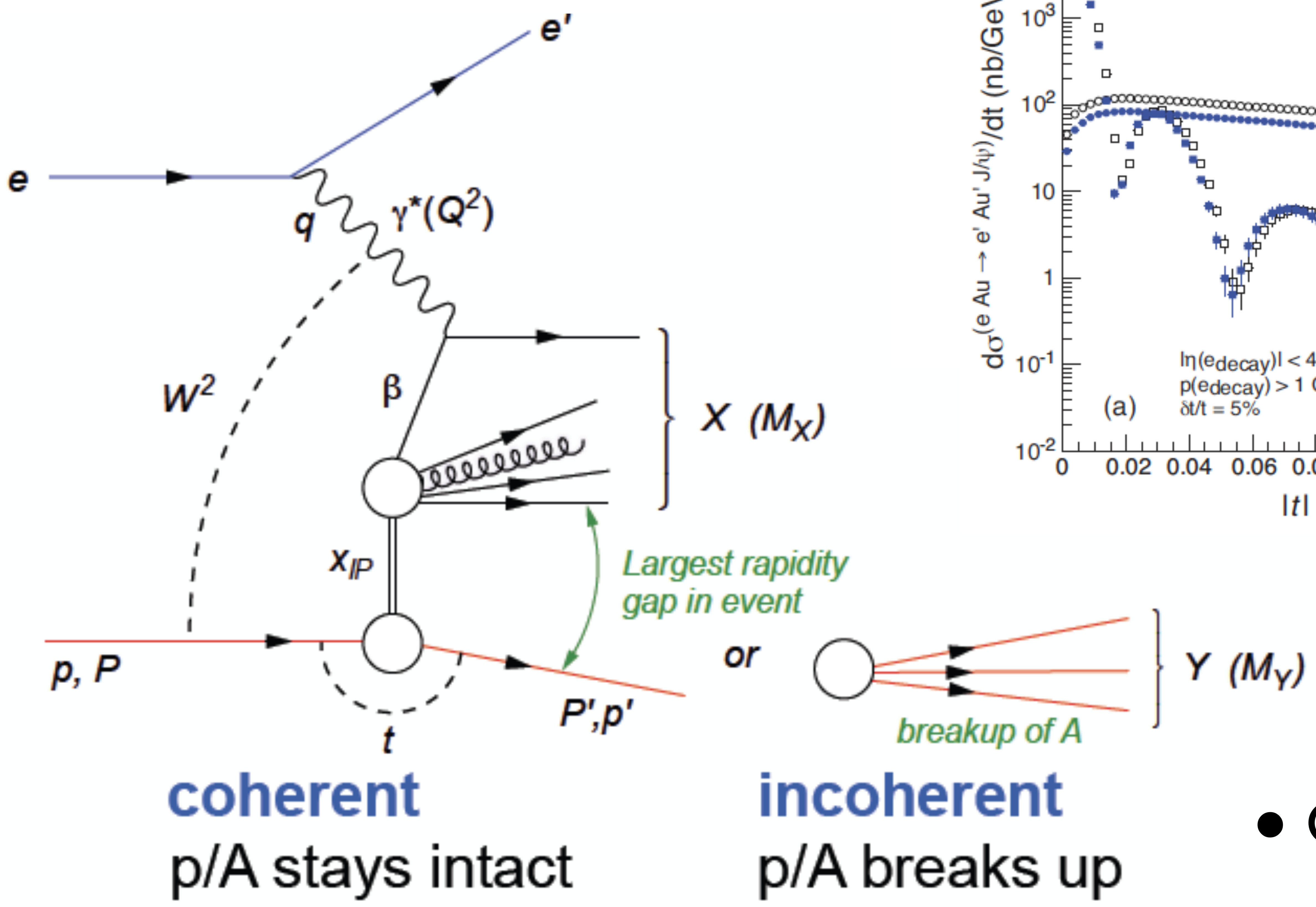
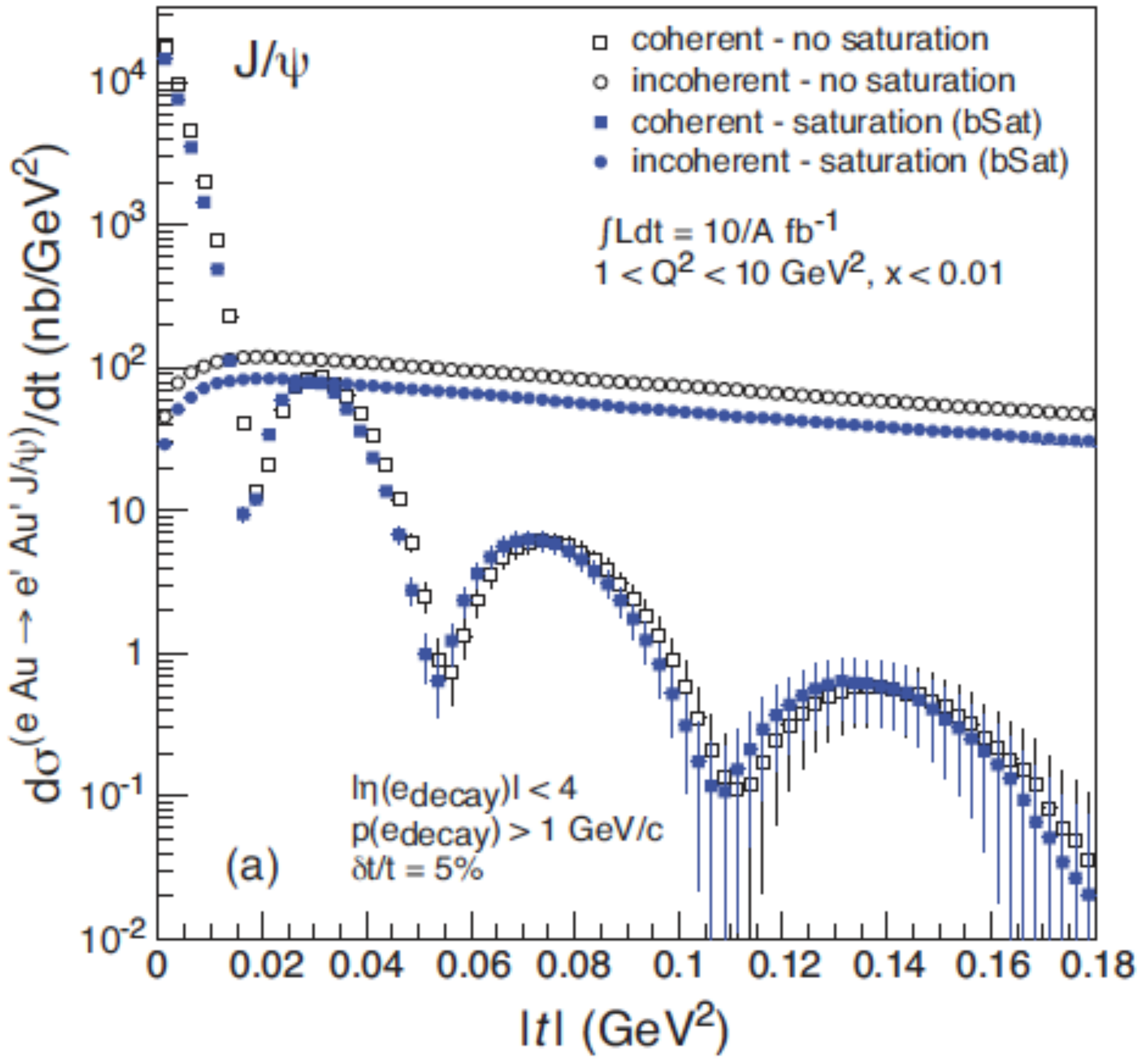
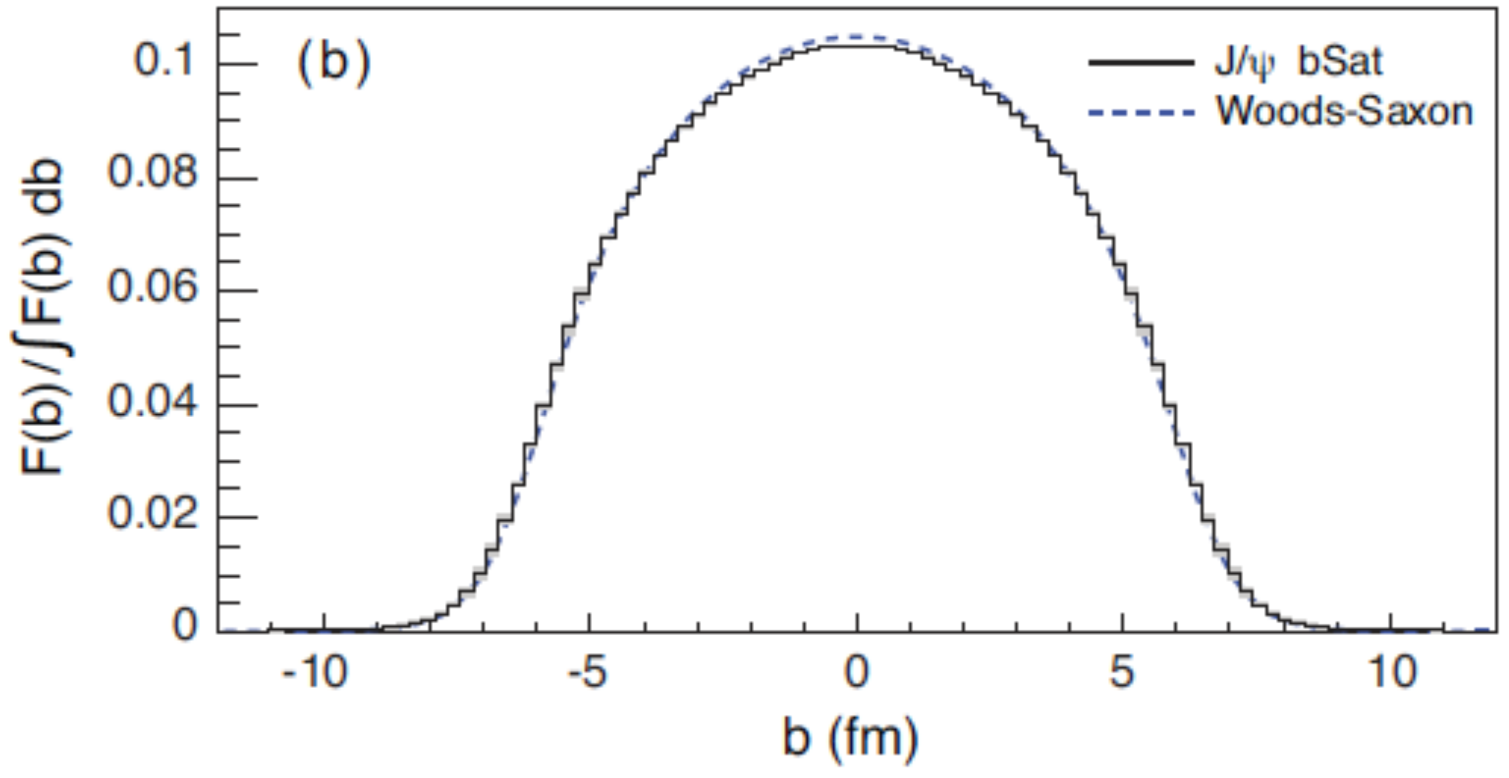
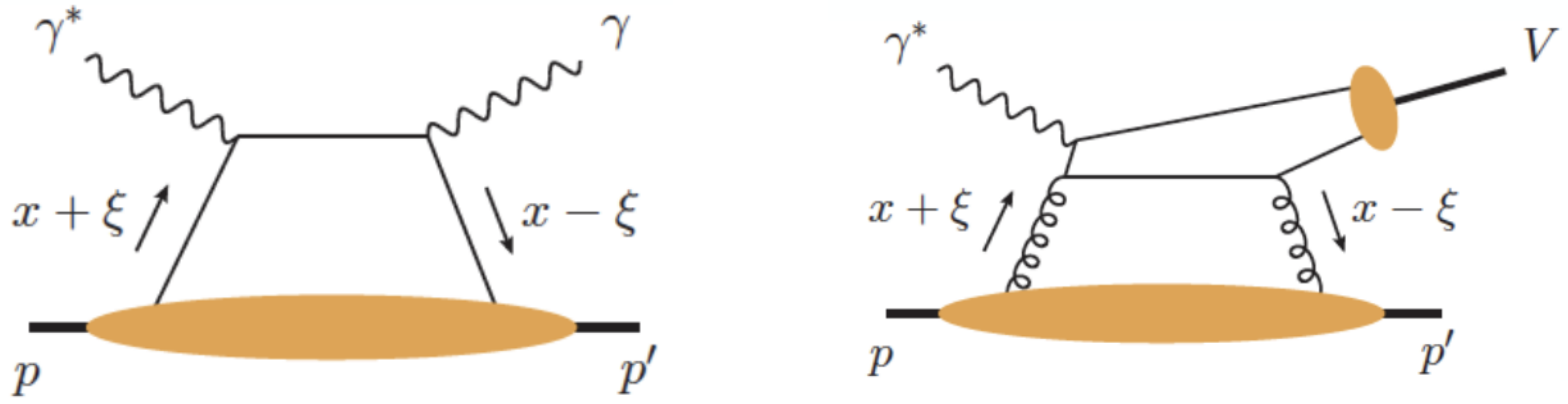




eAu at EIC, 1211.3048





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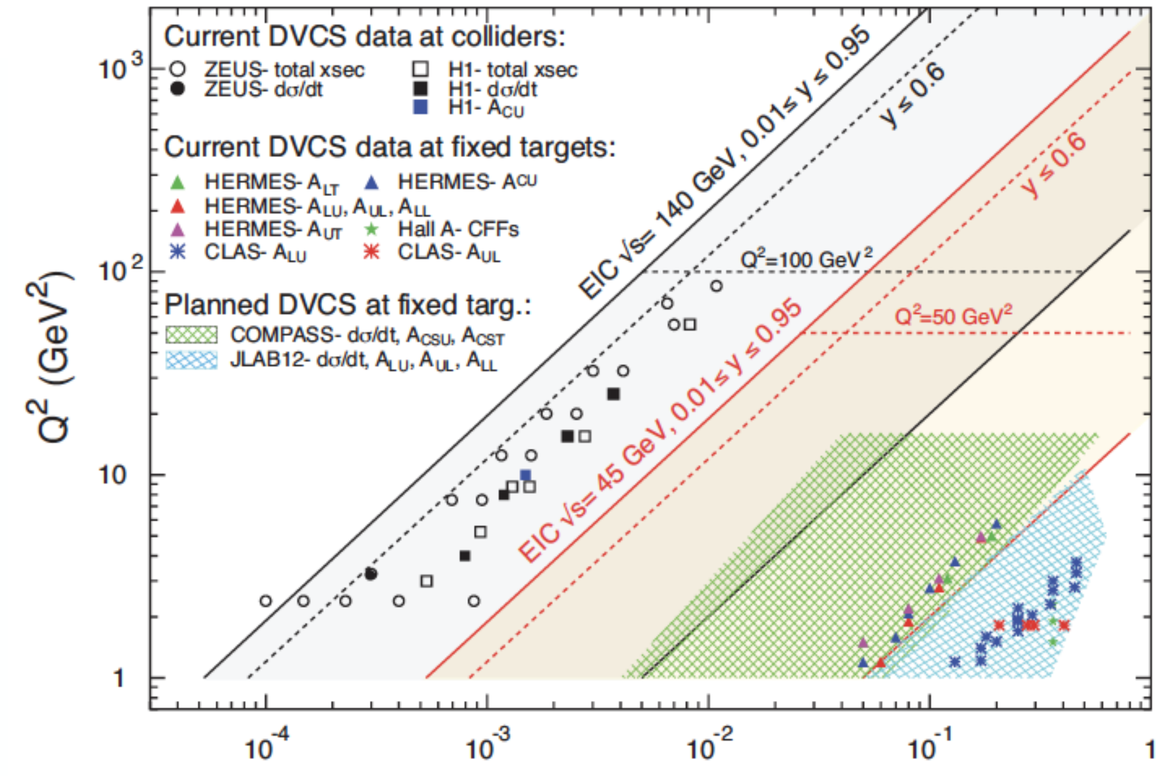
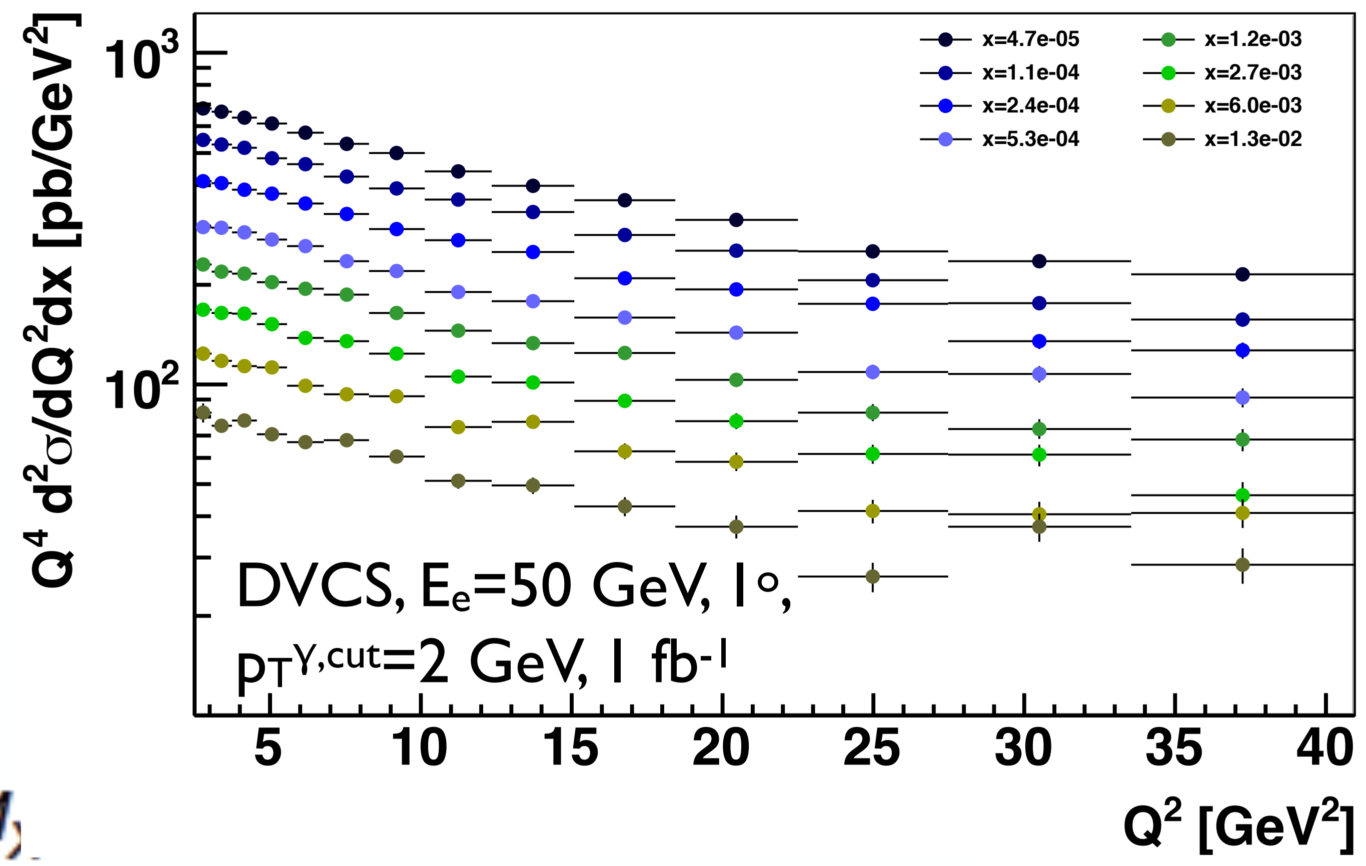
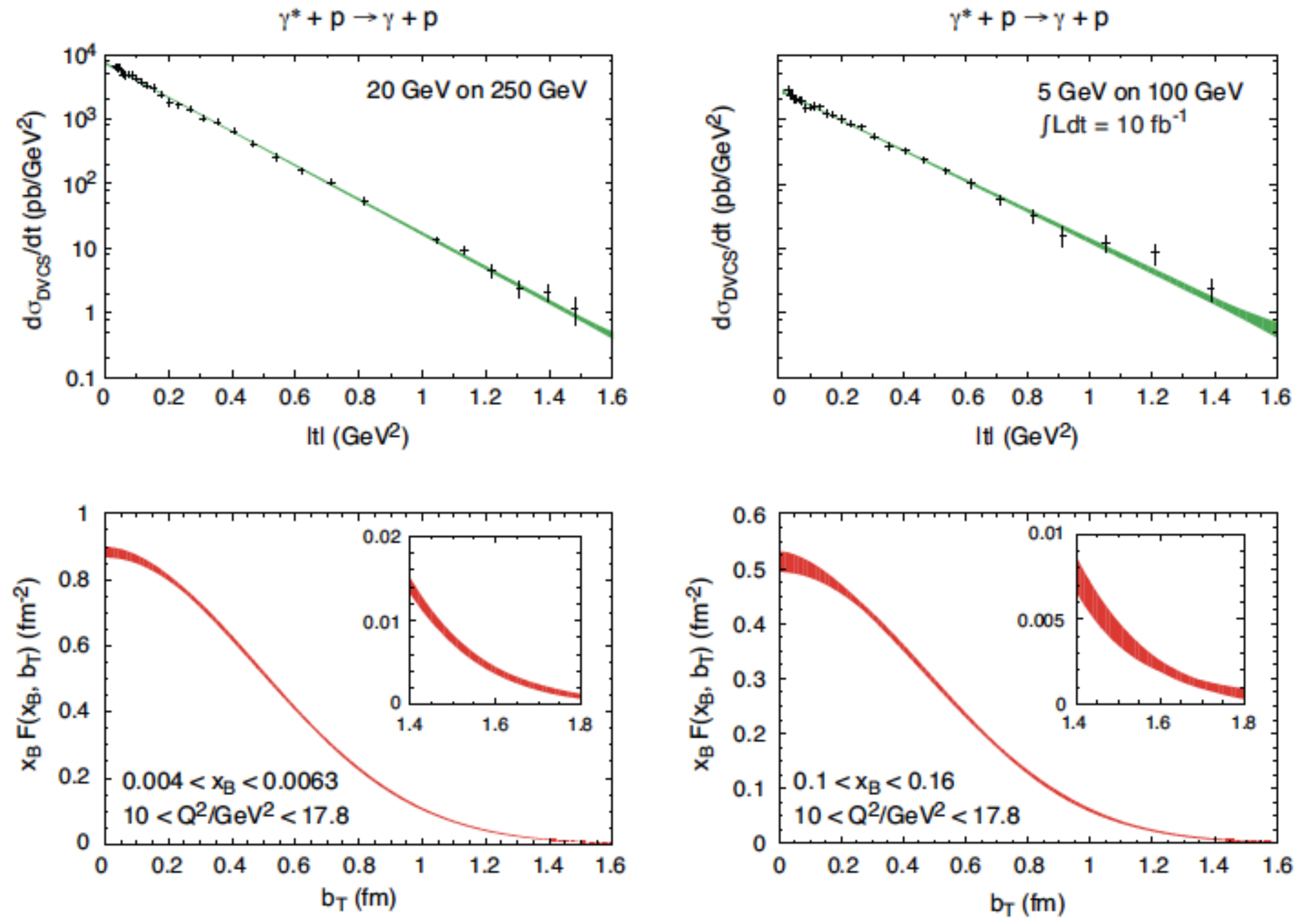
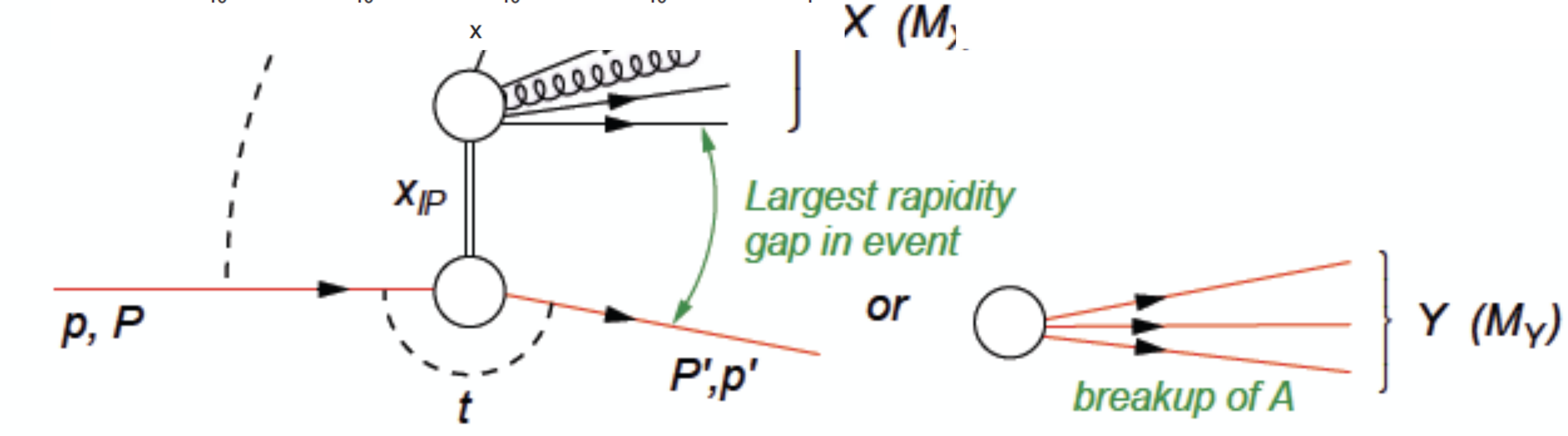
EIC, 1212.1701



LHeC 1206.2913

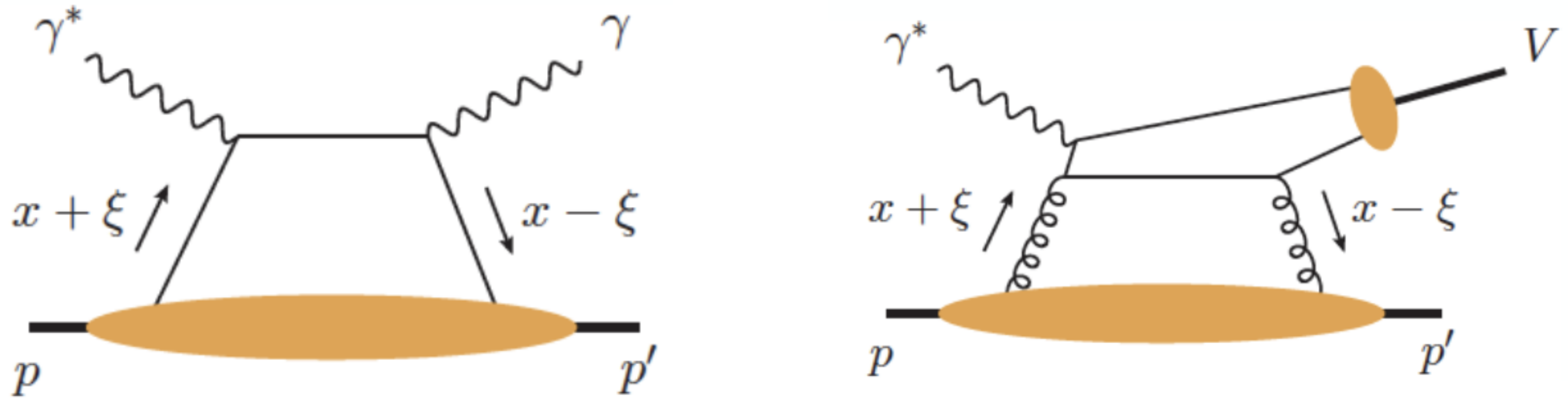






coherent
p/A stays intact

incoherent
p/A breaks up



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- It can be done at the EIC/LHeC/FCC-eh in a large range of x and Q^2 ⇒ evolution.

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, 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