Forward Physics and Diffraction at the LHC
Dublin, June 11th 2019

Perspectives for high-density QCD with ions beyond HL-LHC: ep/eA and pA/AA

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Unión Europea
Fondo Europeo de Desarrollo Regional
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MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

Contents:

1. Introduction.

2. Partonic structure of the nucleus.

3. New dynamics at small x.

4. Evolution of the medium in pp/pA/AA.

5. Summary.

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;*
- *2018 LHeC and FCC-eh workshop, https://indico.cern.ch/event/698368/;*
- *LHeC and EIC talks at DIS 2019, https://indico.cern.ch/event/749003/.*
- *Fixed target program at the HL-LHC, 1807.00603.*

Contents:

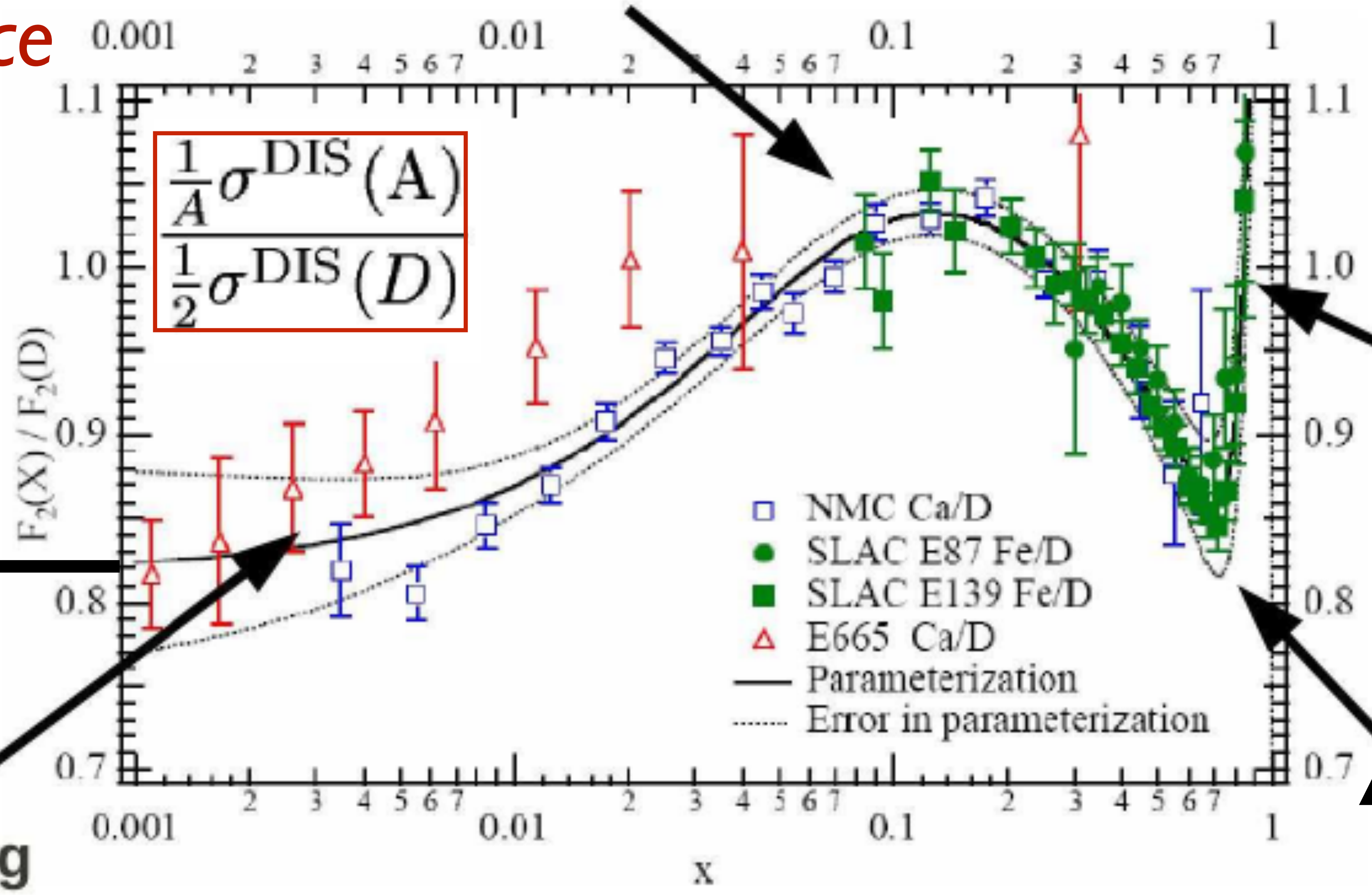
__Warnings__:

- *Although the focus is on what goes beyond LS4, I will also be talking about the perspectives at Runs 3 and 4.*
- *This is a personal review, my apologies to those who find their work misrepresented.*
- *I am not giving a full review of the heavy-ion topics at energies higher that LHC, just focus on those aspects that are more closely related to high-energy QCD, not necessarily to QGP: exploration of the initial stages and small systems.*
- *Even with these restrictions, it is too much material…*

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

Multiple scattering, saturation,…; high-energy QCD

Shadowing

Fermi-motion

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

EMC-effect

Superfast quarks

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

$$\sigma_{\rm DIS}^{\ell+A\to\ell+X} = \sum_{i=q,\overline{q},g} \underbrace{f_i^A(\mu^2)}_{\text{Nuclear PDFs, obeying the standard DGLAP}} \otimes \underbrace{\hat{\sigma}_{\rm DIS}^{\ell+i\to\ell+X}(\mu^2)}_{\text{Usual perturbative coefficient functions}}$$

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

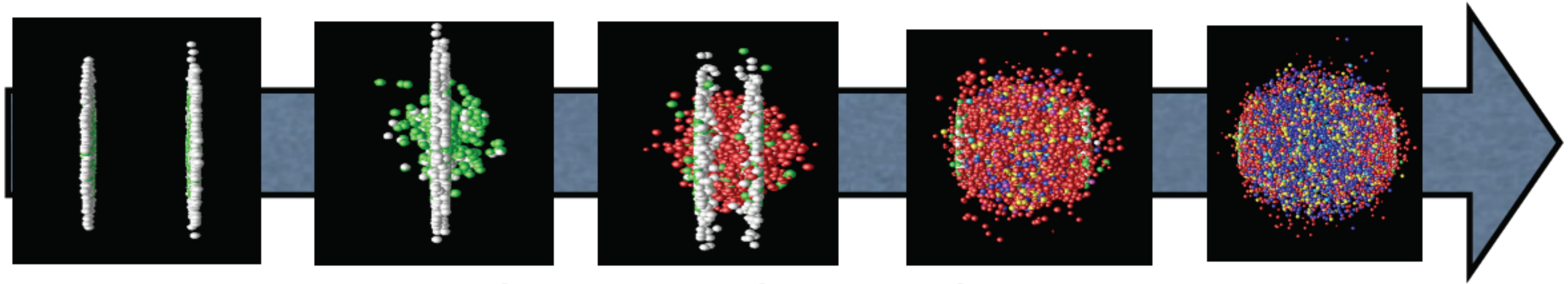
$$\boxed{R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}}$$

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.



[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.

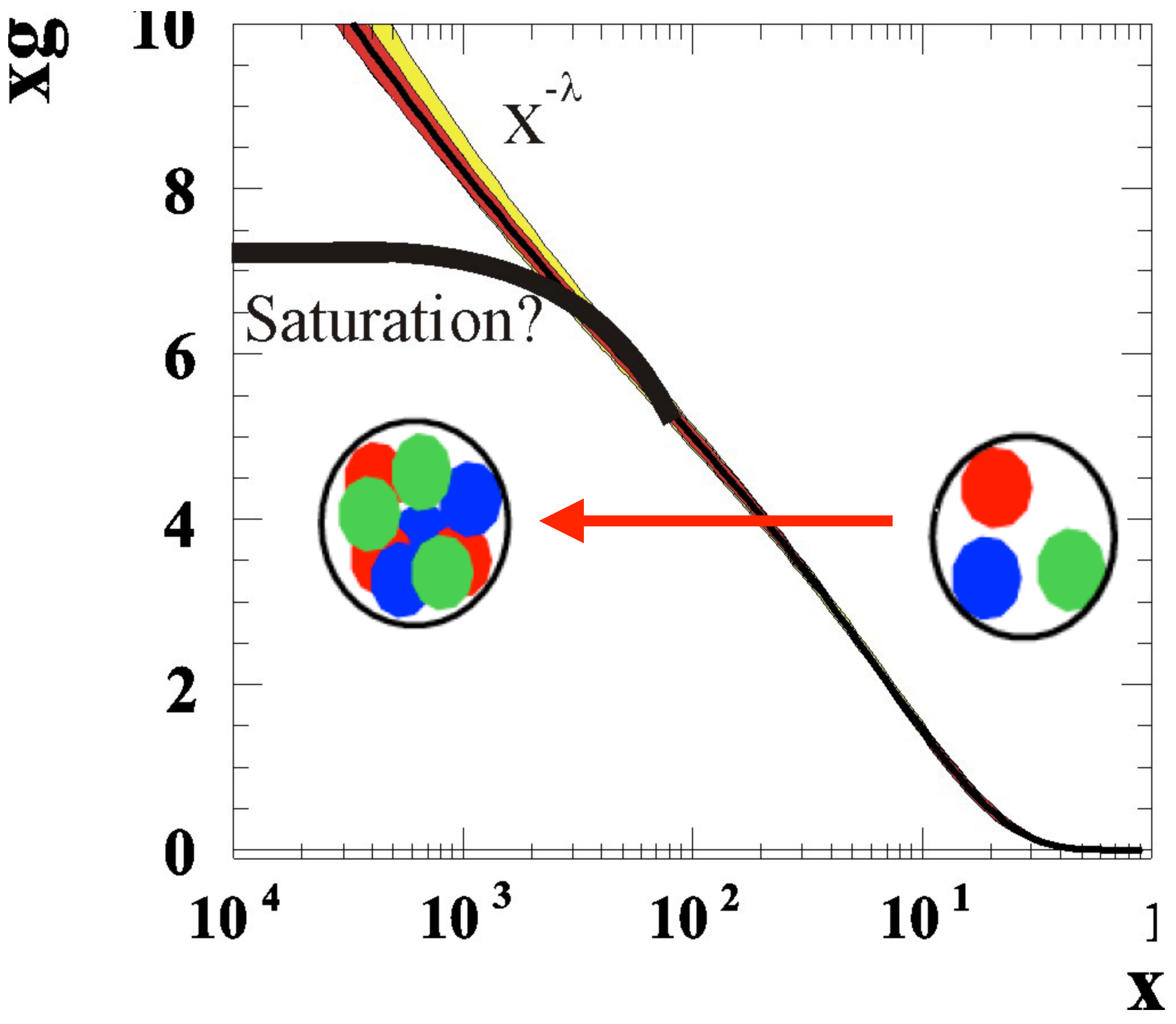
Small-x physics:

- 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 - weak coupling but high density: saturation.

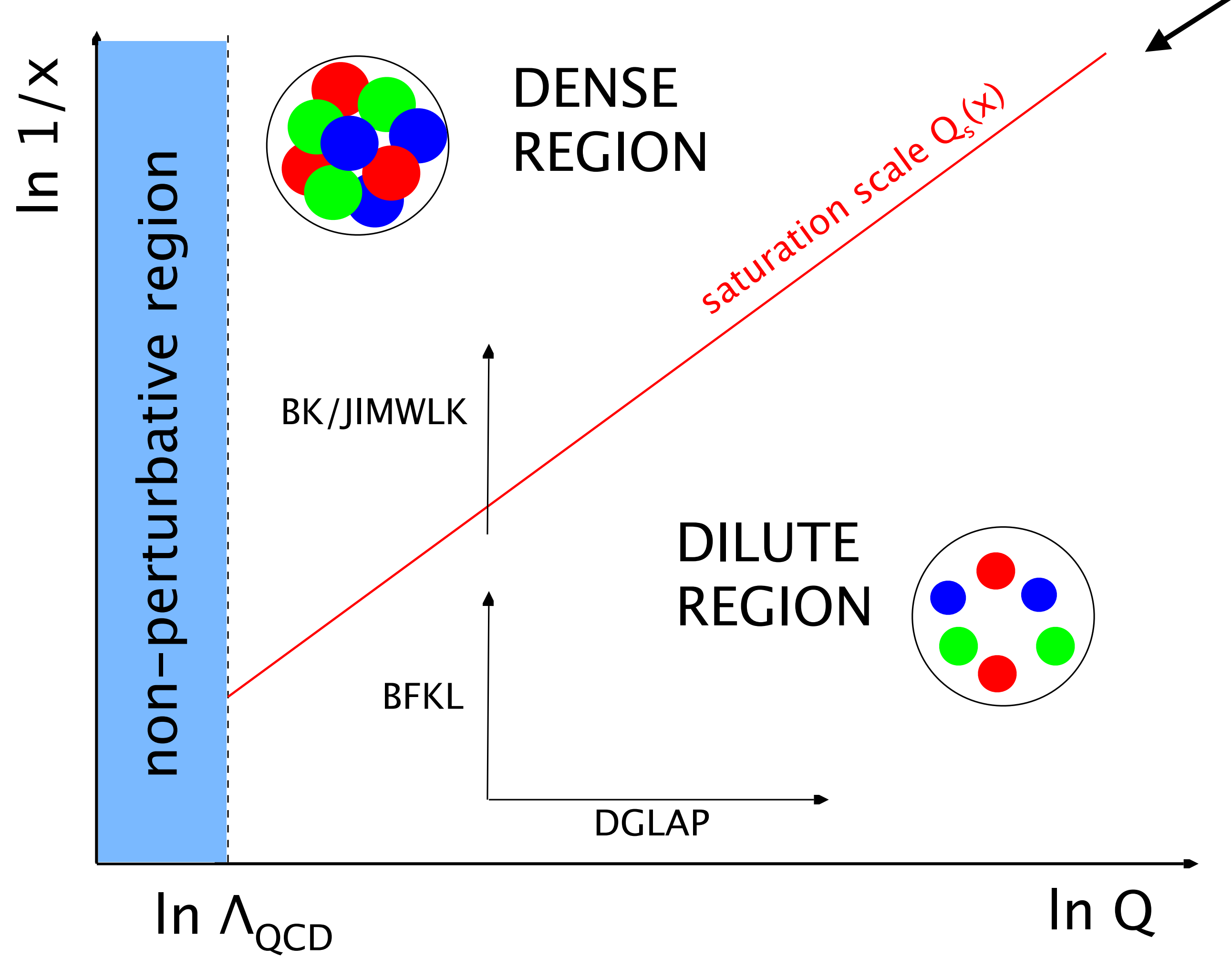
- Theory: at high energies (i.e. small x), non-linear dynamics must be present. **Where is it?** At HERA:
  ➜ Hints of failure of DGLAP at small x, Q^2, resummation?
  ➜ No ridge azimuthal structures yet found.

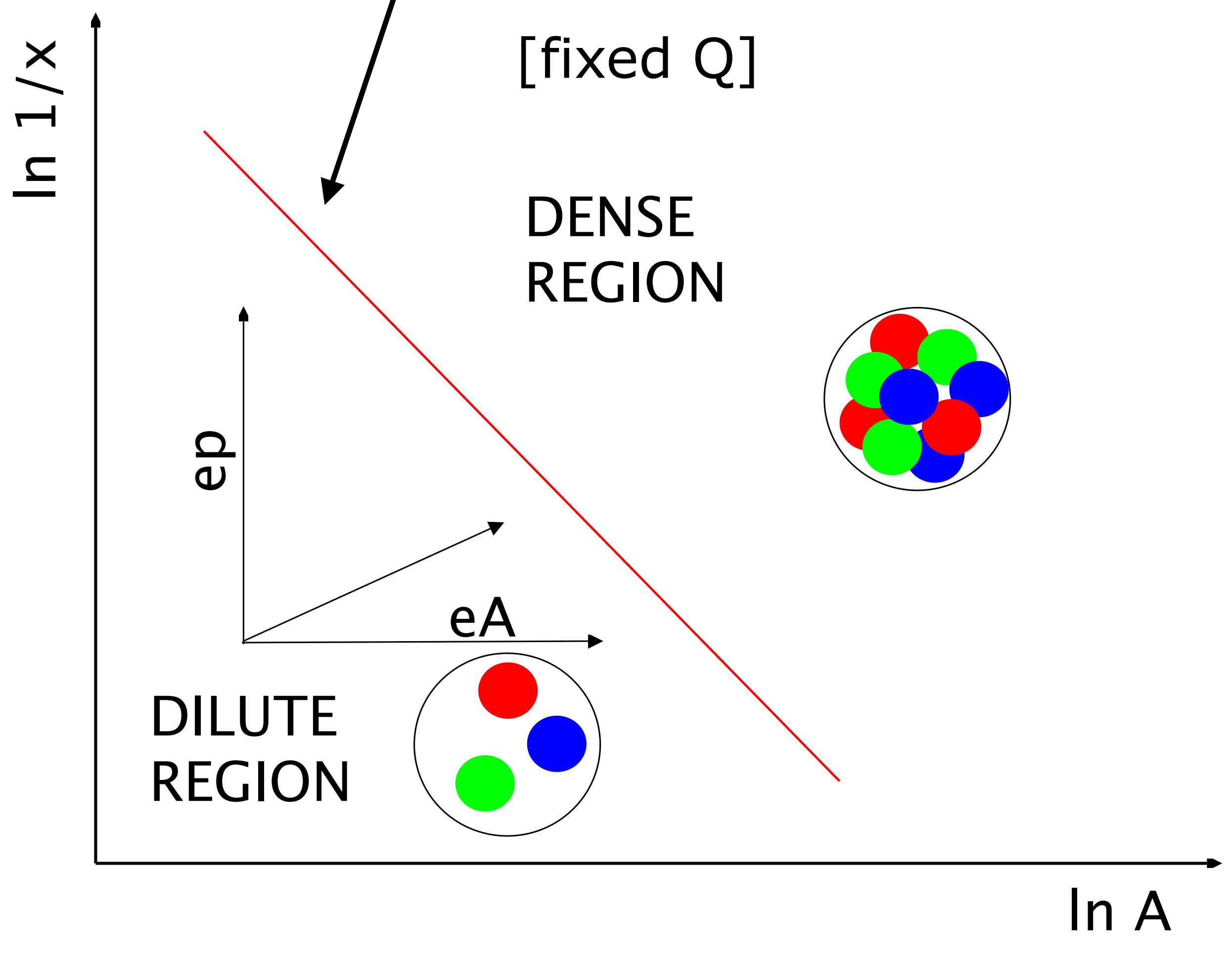
- Saturation is density-driven: ↓x/↑A ⇒

ep&eA + large range in 1/x & Q^2 essential for full understanding.



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





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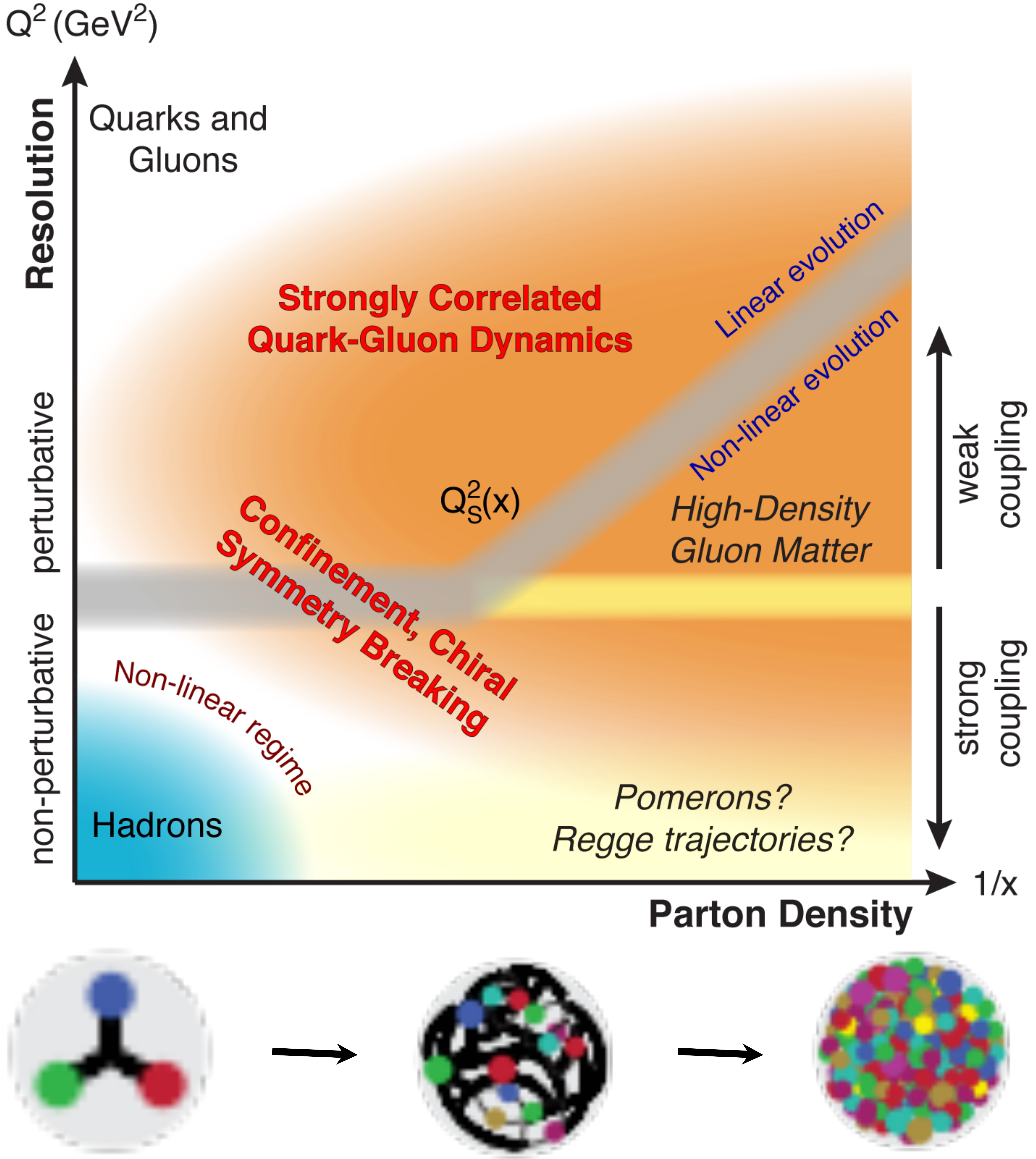
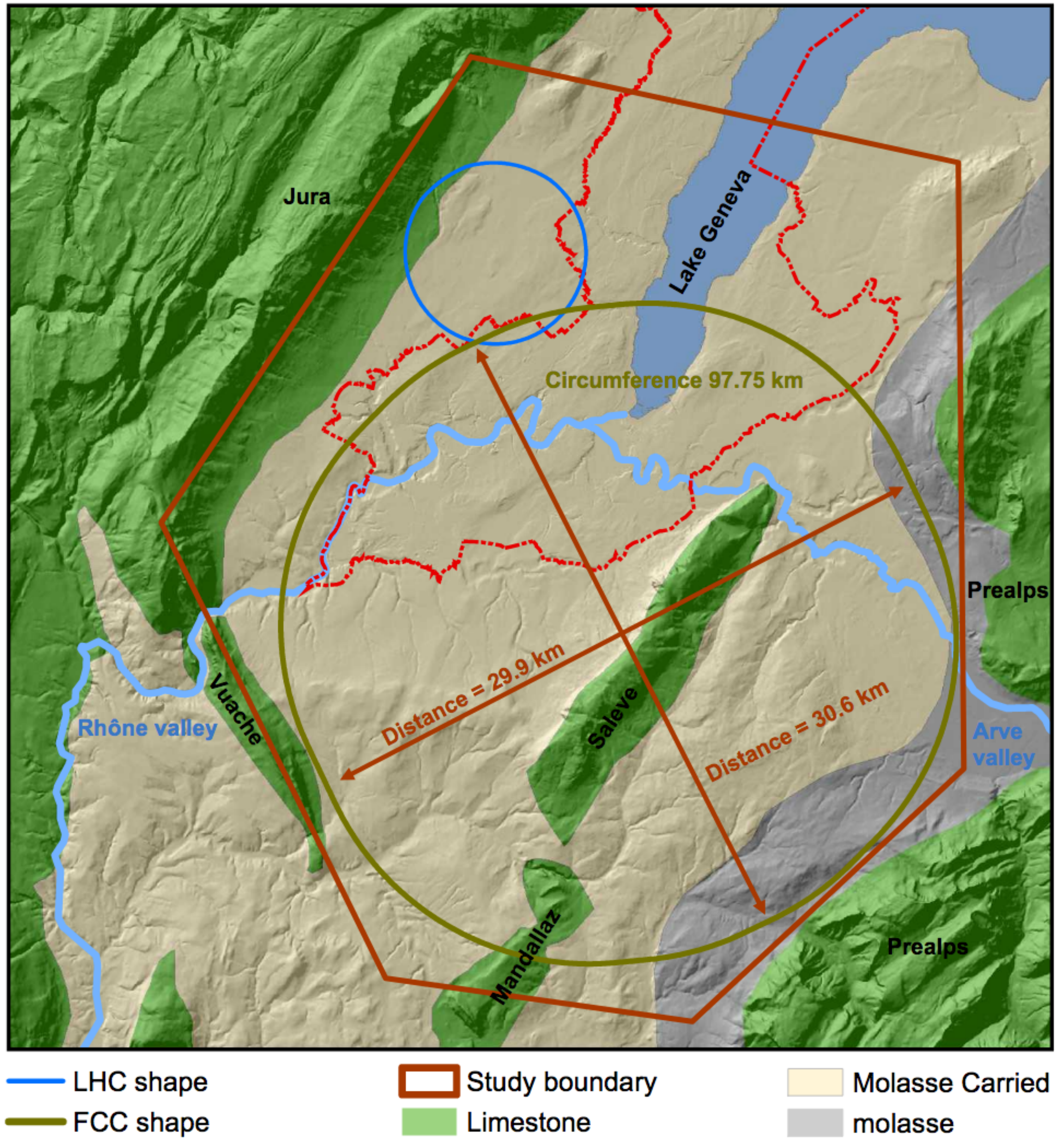


Machines: pp/pA/AA

- FCC parameters for PbPb and pPb collisions:

	Unit	FCC Injection	FCC Collision	
Operation mode		Pb	Pb–Pb	p–Pb
Beam energy	[TeV]	270	4100	50
$\sqrt{s_{\rm NN}}$	[TeV]	-	39.4	62.8
No. of bunches per LHC injection	-	518	518	518
No. of bunches in the FCC	-	2072	2072	2072
No. of particles per bunch	$[10^8]$	2.0	2.0	164
Transv. norm. emittance	$[\mu\mathrm{m}]$	1.5	1.5	3.75
Number of IPs in collision	-	-	1	1
Crossing-angle	$[\mu\mathrm{rad}]$	-	0	
Initial luminosity	$[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	-	24.5	2052
Peak luminosity	$[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	-	57.8	9918
Integrated luminosity per fill	$[\mu\mathrm{b}^{-1}]$	-	553	158630
Average luminosity	$[\mu\mathrm{b}^{-1}]$	-	92	20736
Time in collision	[h]	-	3	6
Assumed turnaround time	[h]	-	1.65	1.65
Integrated luminosity/run	$[\mathrm{nb}^{-1}]$	-	33	8000



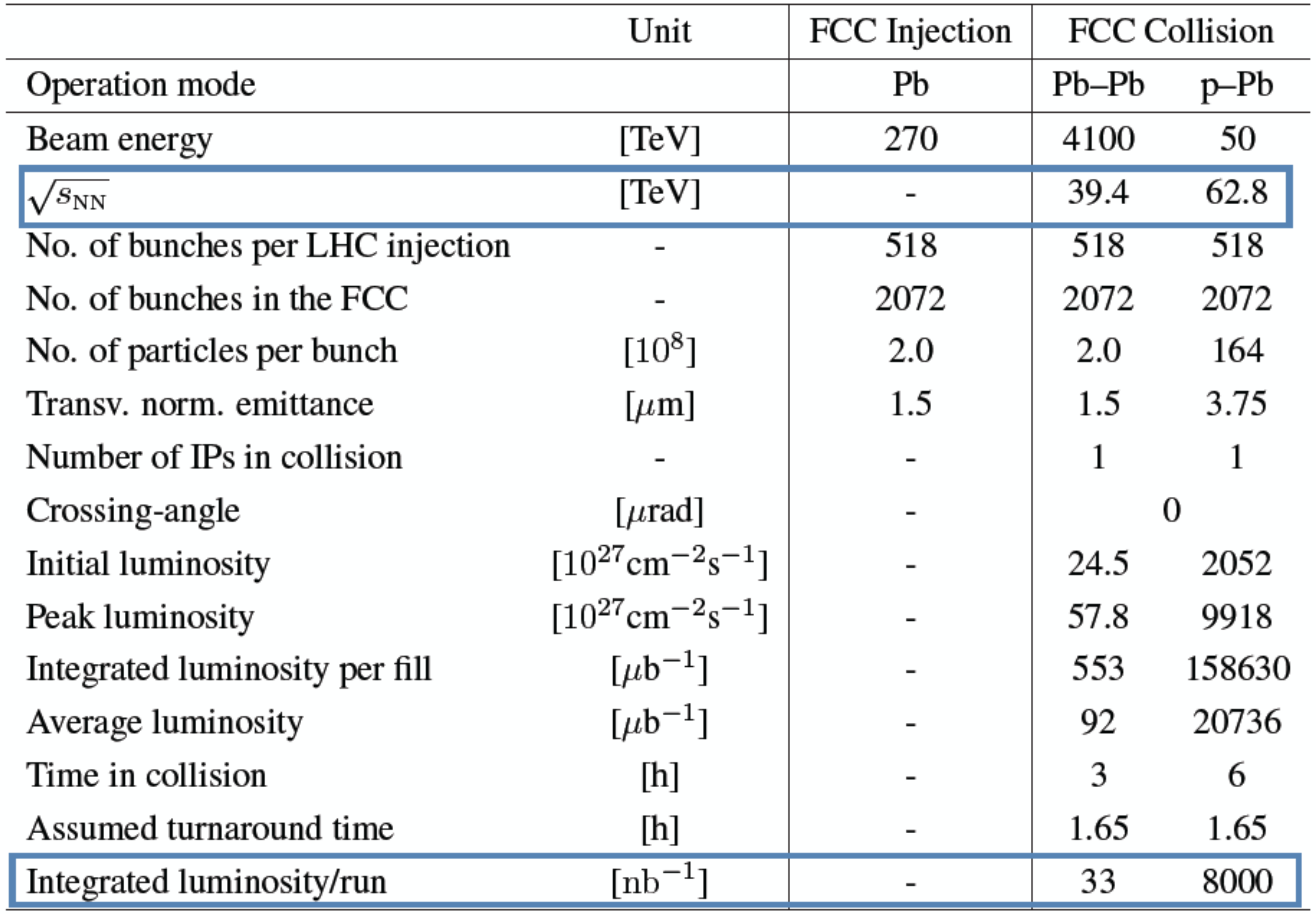
- Other ideas:

➜ HE-LHC (16 T magnets): 27.5 TeV pp.

➜ 6 T magnets in the FCC tunnel: 37.5 TeV pp.

Machines: pp/pA/AA

- FCC parameters for PbPb and pPb collisions:



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vs LHC: 5.5 (PbPb) and 8.8 (pPb)

vs LHC (total):
PbPb: ~1 (Run2); ~4 (Run3); ~4 (Run4)
pPb: 50-400 (2 weeks)

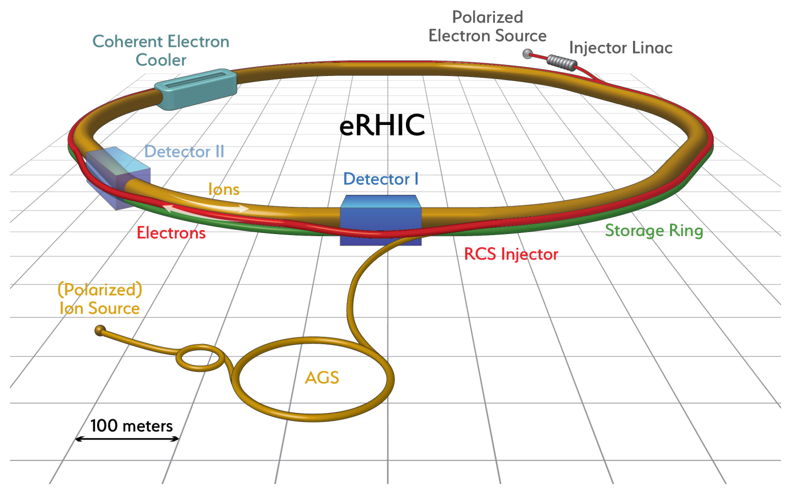
- Other ideas:

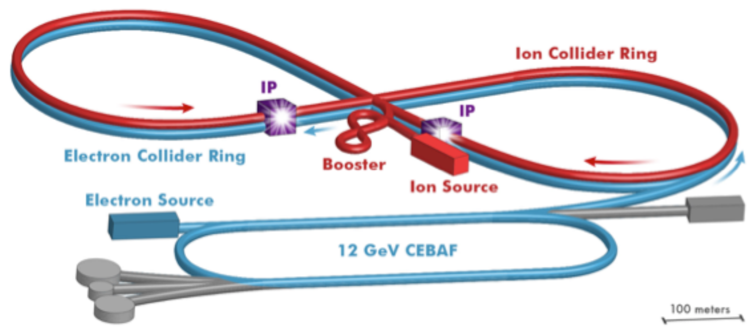
➜ HE-LHC (16 T magnets): 27.5 TeV pp.

➜ 6 T magnets in the FCC tunnel: 37.5 TeV pp.

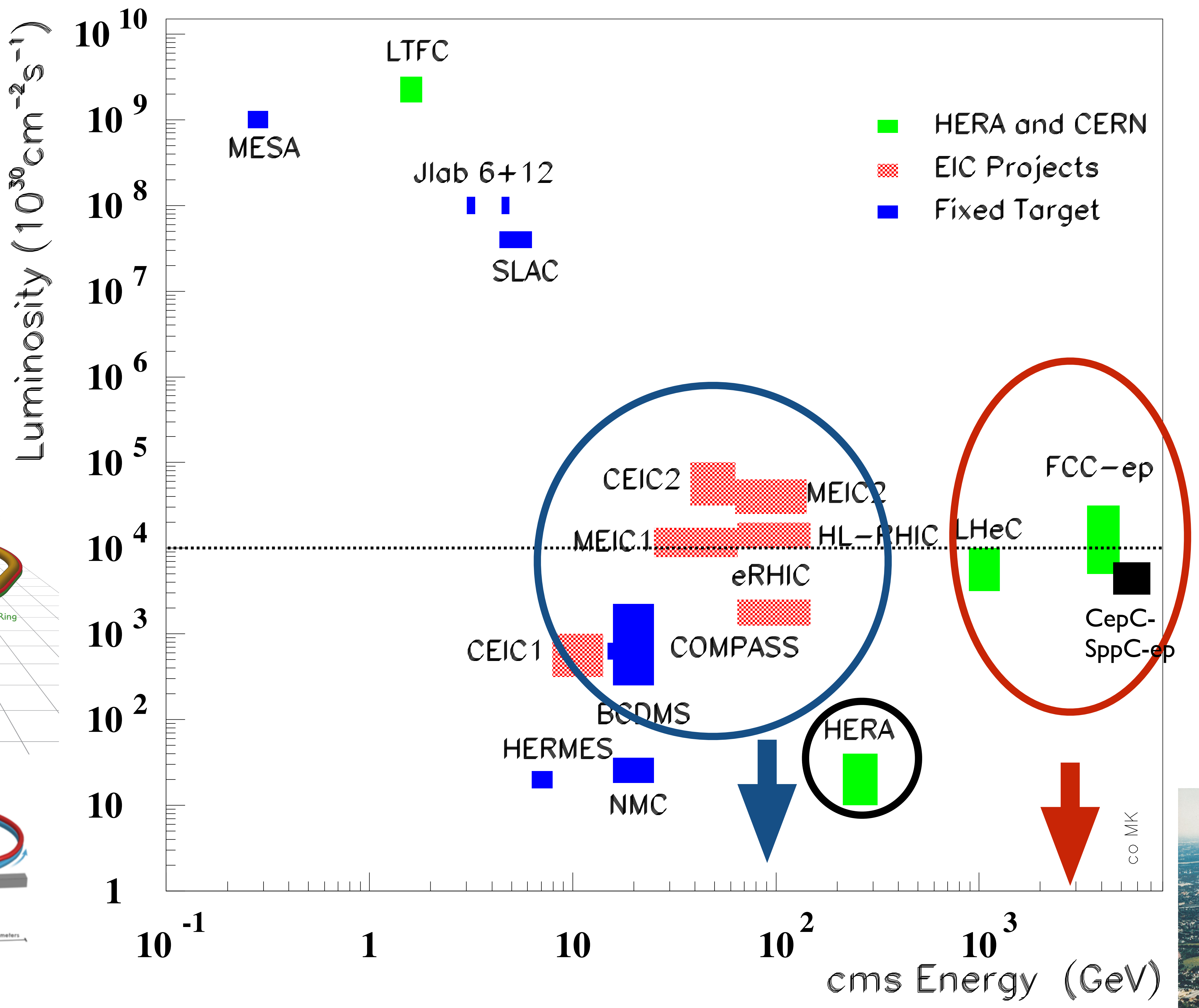
Machines: ep/eA

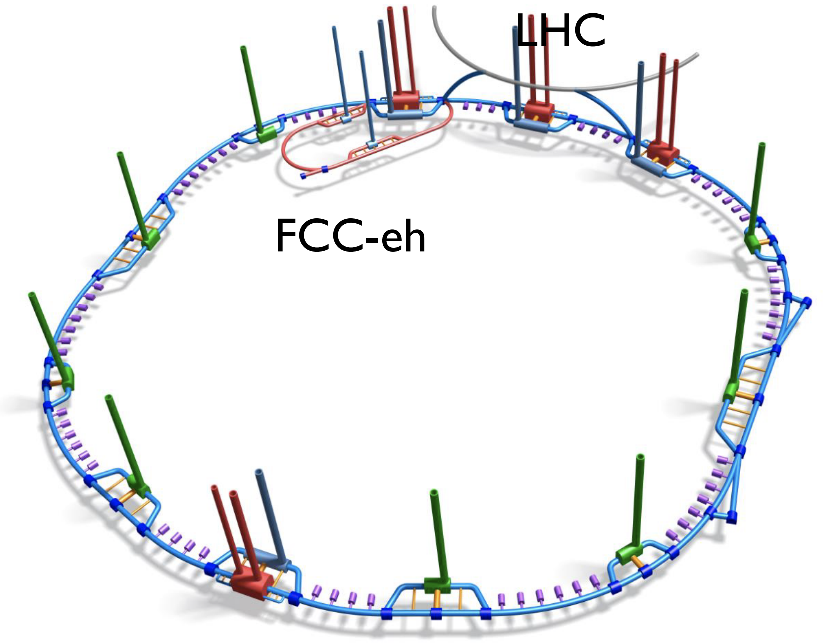
- Projects of eA colliders with $E_{cm} \sim \mathcal{O}(0.1)$ TeV/A (EICs at US and China) and $\mathcal{O}(1)$ TeV/A (LHeC and FCC-eh at CERN) addressing different physics.

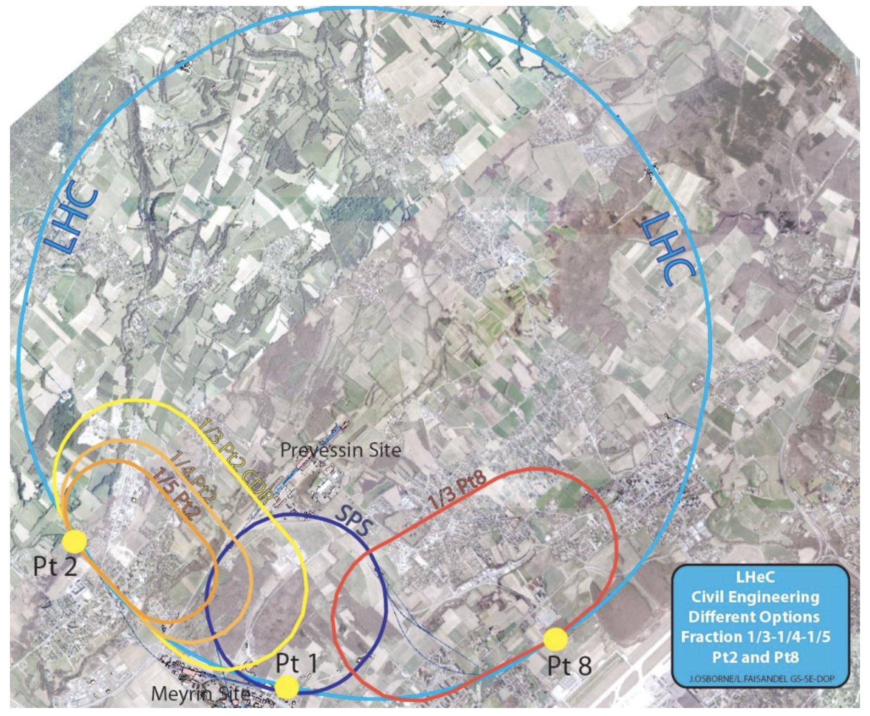




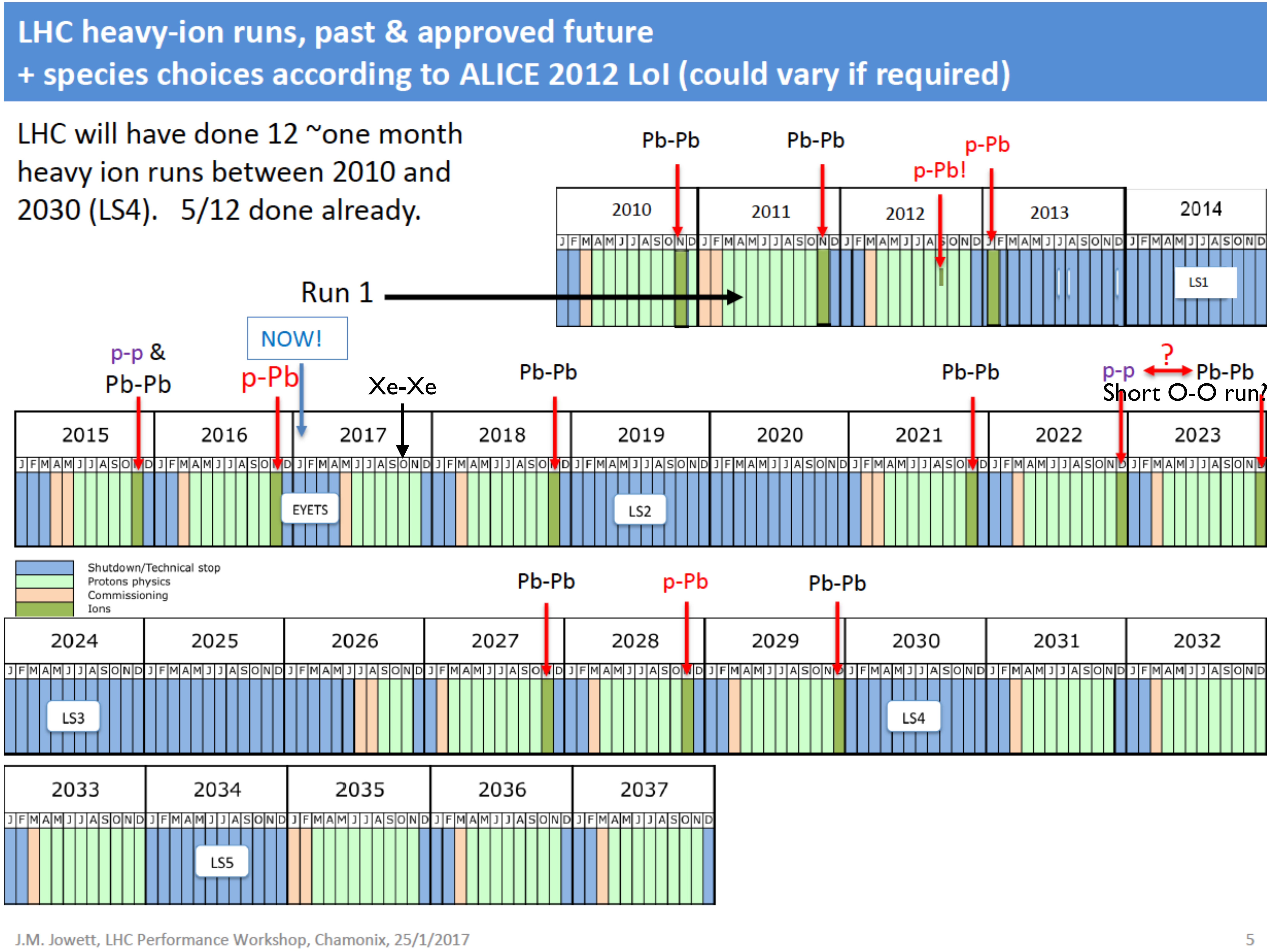
Lepton-proton/nucleus scattering facilities







Timeline:



LHC heavy-ion runs, past & approved future
+ species choices according to ALICE 2012 LoI (could vary if required)

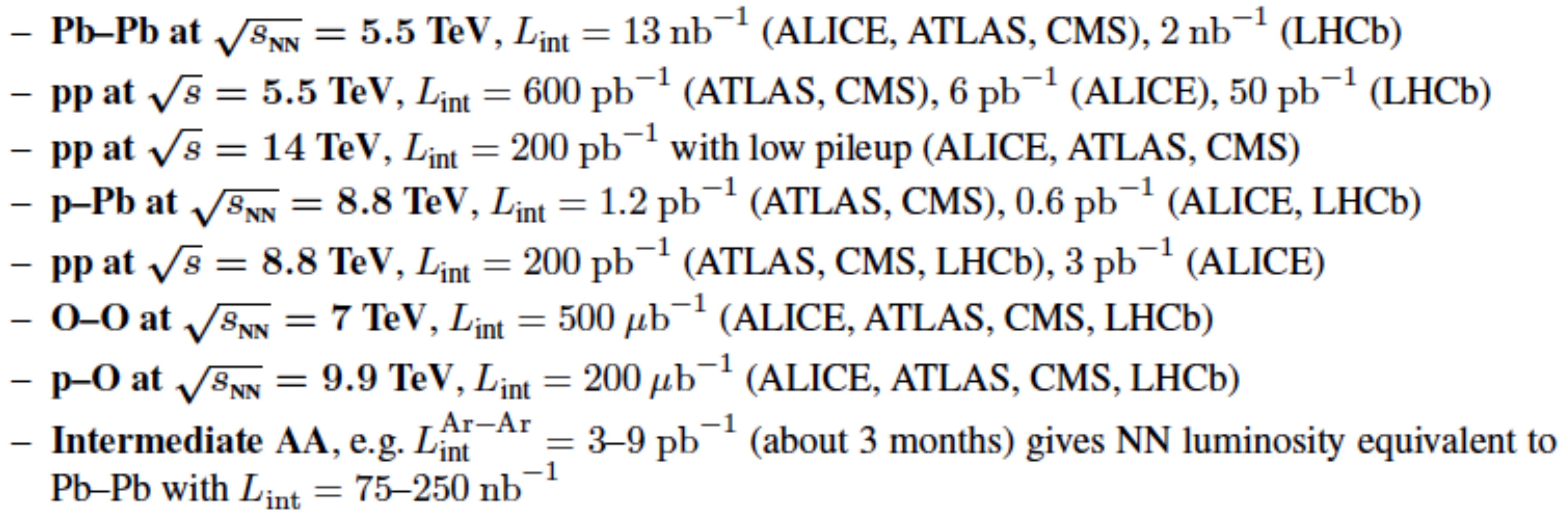
LHC will have done 12 ~one month heavy ion runs between 2010 and 2030 (LS4). 5/12 done already.

J.M. Jowett, LHC Performance Workshop, Chamonix, 25/1/2017

5

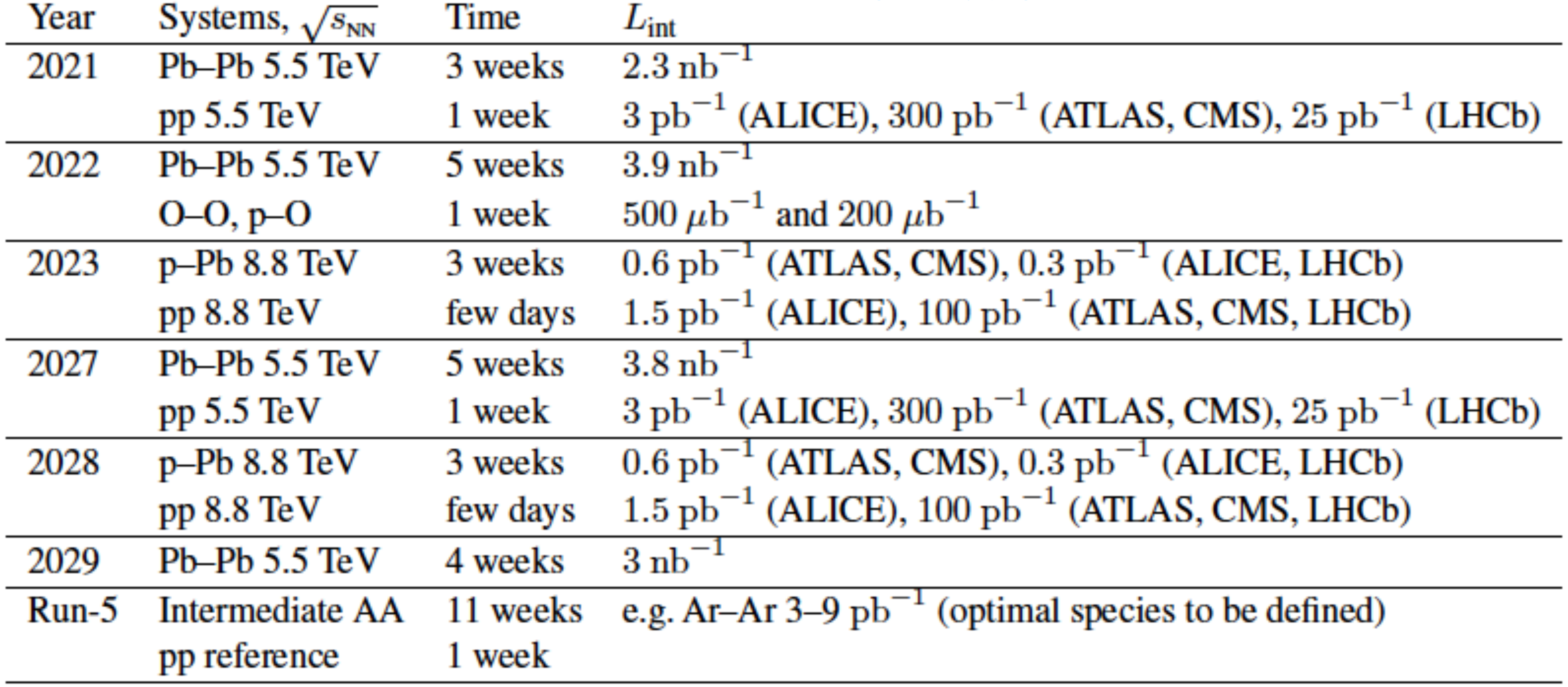
Only indicative…

Timeline:



- **Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.5$ TeV**, $L_{\mathrm{int}} = 13\ \mathrm{nb}^{-1}$ (ALICE, ATLAS, CMS), $2\ \mathrm{nb}^{-1}$ (LHCb)
- **pp at $\sqrt{s} = 5.5$ TeV**, $L_{\mathrm{int}} = 600\ \mathrm{pb}^{-1}$ (ATLAS, CMS), $6\ \mathrm{pb}^{-1}$ (ALICE), $50\ \mathrm{pb}^{-1}$ (LHCb)
- **pp at $\sqrt{s} = 14$ TeV**, $L_{\mathrm{int}} = 200\ \mathrm{pb}^{-1}$ with low pileup (ALICE, ATLAS, CMS)
- **p–Pb at $\sqrt{s_{\mathrm{NN}}} = 8.8$ TeV**, $L_{\mathrm{int}} = 1.2\ \mathrm{pb}^{-1}$ (ATLAS, CMS), $0.6\ \mathrm{pb}^{-1}$ (ALICE, LHCb)
- **pp at $\sqrt{s} = 8.8$ TeV**, $L_{\mathrm{int}} = 200\ \mathrm{pb}^{-1}$ (ATLAS, CMS, LHCb), $3\ \mathrm{pb}^{-1}$ (ALICE)
- **O–O at $\sqrt{s_{\mathrm{NN}}} = 7$ TeV**, $L_{\mathrm{int}} = 500\ \mu\mathrm{b}^{-1}$ (ALICE, ATLAS, CMS, LHCb)
- **p–O at $\sqrt{s_{\mathrm{NN}}} = 9.9$ TeV**, $L_{\mathrm{int}} = 200\ \mu\mathrm{b}^{-1}$ (ALICE, ATLAS, CMS, LHCb)
- **Intermediate AA**, e.g. $L_{\mathrm{int}}^{\mathrm{Ar-Ar}} = 3$–$9\ \mathrm{pb}^{-1}$ (about 3 months) gives NN luminosity equivalent to Pb–Pb with $L_{\mathrm{int}} = 75$–$250\ \mathrm{nb}^{-1}$

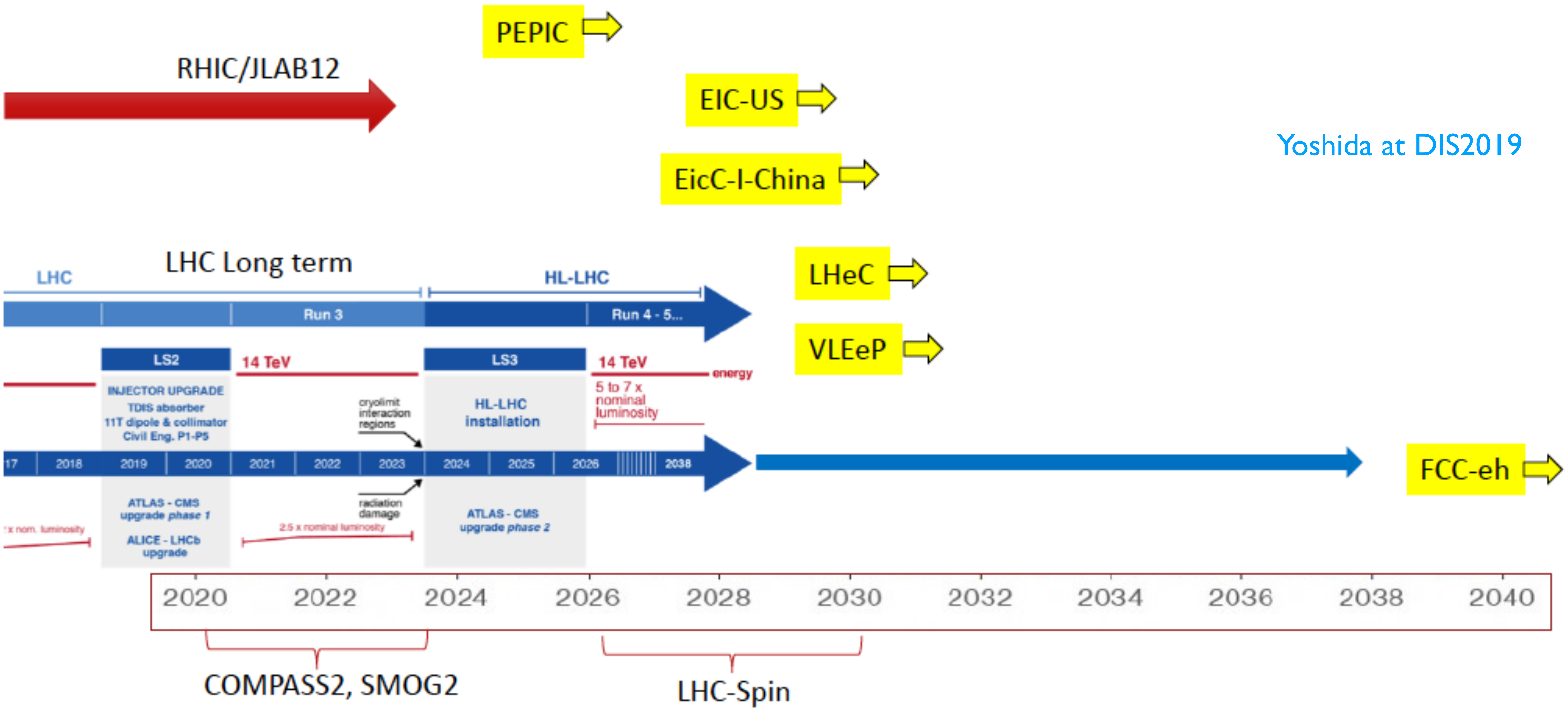
1812.06772



Year	Systems, $\sqrt{s_{\mathrm{NN}}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	$2.3\ \mathrm{nb}^{-1}$
	pp 5.5 TeV	1 week	$3\ \mathrm{pb}^{-1}$ (ALICE), $300\ \mathrm{pb}^{-1}$ (ATLAS, CMS), $25\ \mathrm{pb}^{-1}$ (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	$3.9\ \mathrm{nb}^{-1}$
	O–O, p–O	1 week	$500\ \mu\mathrm{b}^{-1}$ and $200\ \mu\mathrm{b}^{-1}$
2023	p–Pb 8.8 TeV	3 weeks	$0.6\ \mathrm{pb}^{-1}$ (ATLAS, CMS), $0.3\ \mathrm{pb}^{-1}$ (ALICE, LHCb)
	pp 8.8 TeV	few days	$1.5\ \mathrm{pb}^{-1}$ (ALICE), $100\ \mathrm{pb}^{-1}$ (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	$3.8\ \mathrm{nb}^{-1}$
	pp 5.5 TeV	1 week	$3\ \mathrm{pb}^{-1}$ (ALICE), $300\ \mathrm{pb}^{-1}$ (ATLAS, CMS), $25\ \mathrm{pb}^{-1}$ (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	$0.6\ \mathrm{pb}^{-1}$ (ATLAS, CMS), $0.3\ \mathrm{pb}^{-1}$ (ALICE, LHCb)
	pp 8.8 TeV	few days	$1.5\ \mathrm{pb}^{-1}$ (ALICE), $100\ \mathrm{pb}^{-1}$ (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	$3\ \mathrm{nb}^{-1}$
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

Only indicative...

Timeline:



Yoshida at DIS2019

Only indicative…

Kinematics:

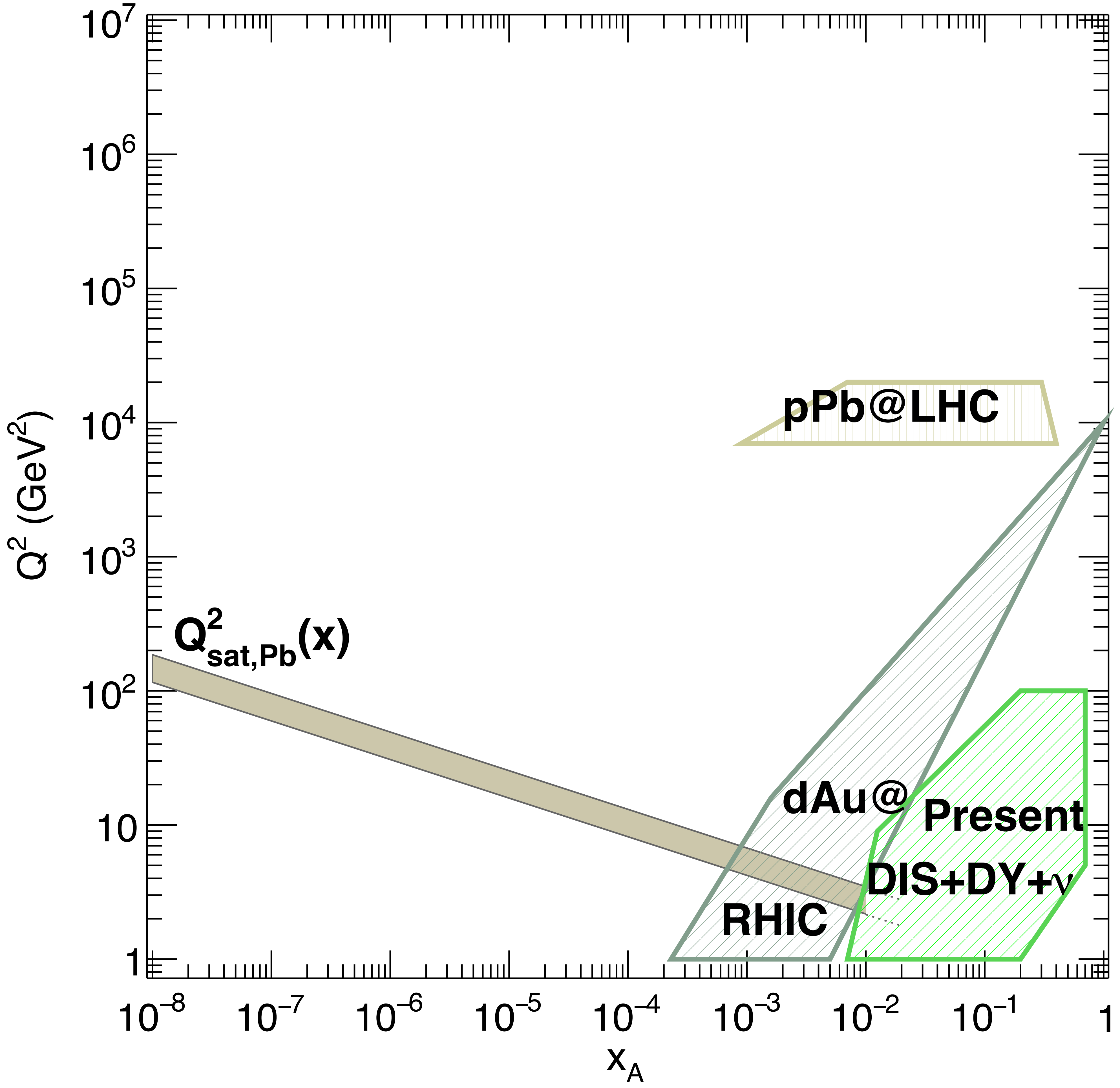
- Extension of several orders of magnitude in x and Q^2 w.r.t. existing DIS data.
- **DIS versus hh**:

➜ pA/AA covers largest range in kinematics.

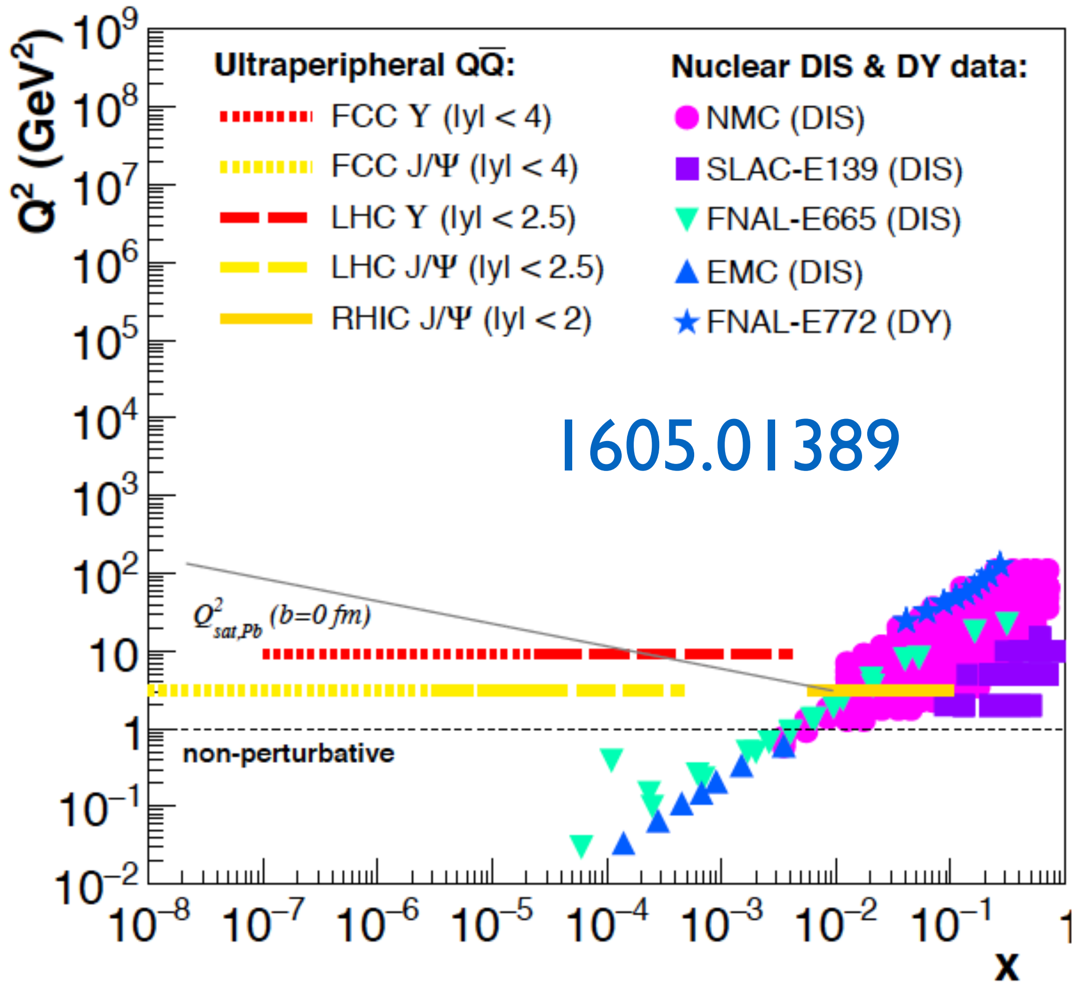
➜ **DIS offers**:

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

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



UPCs



1605.01389

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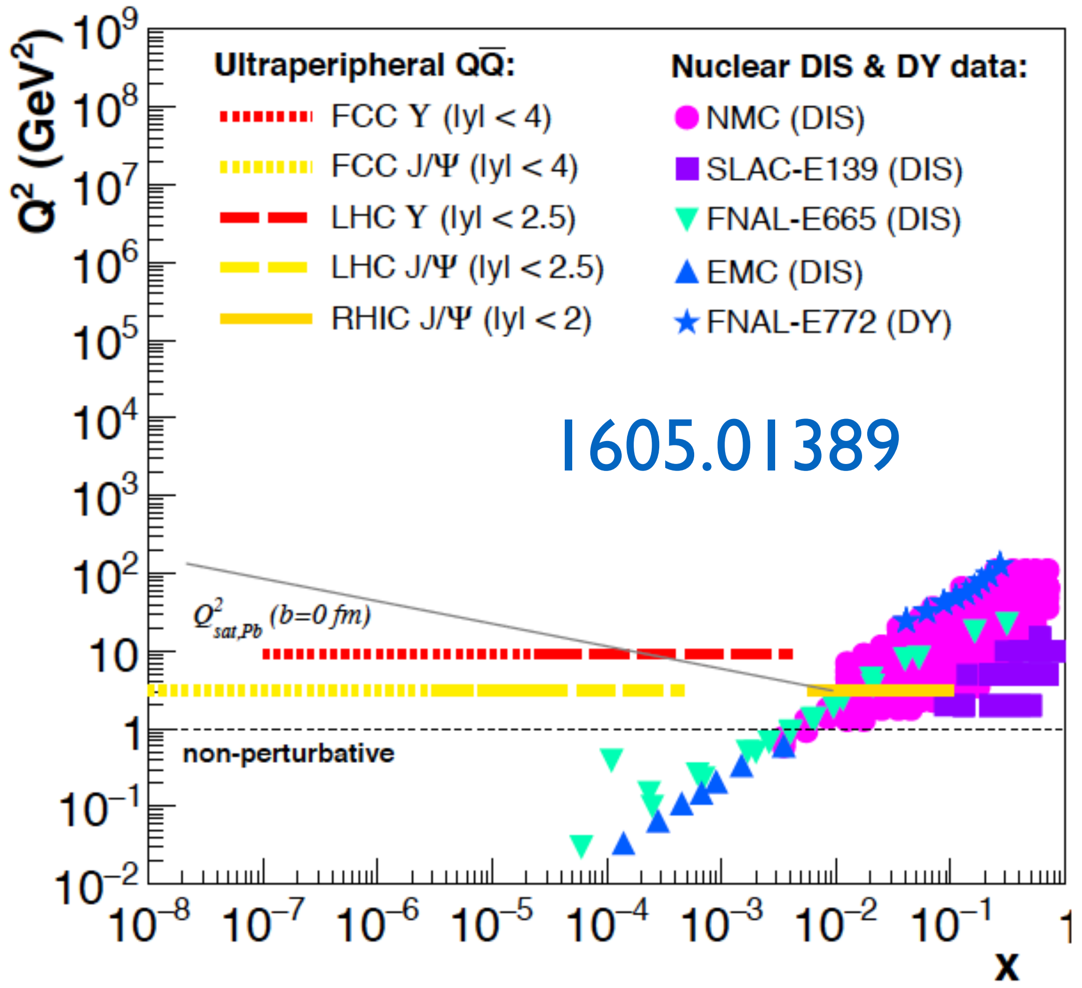

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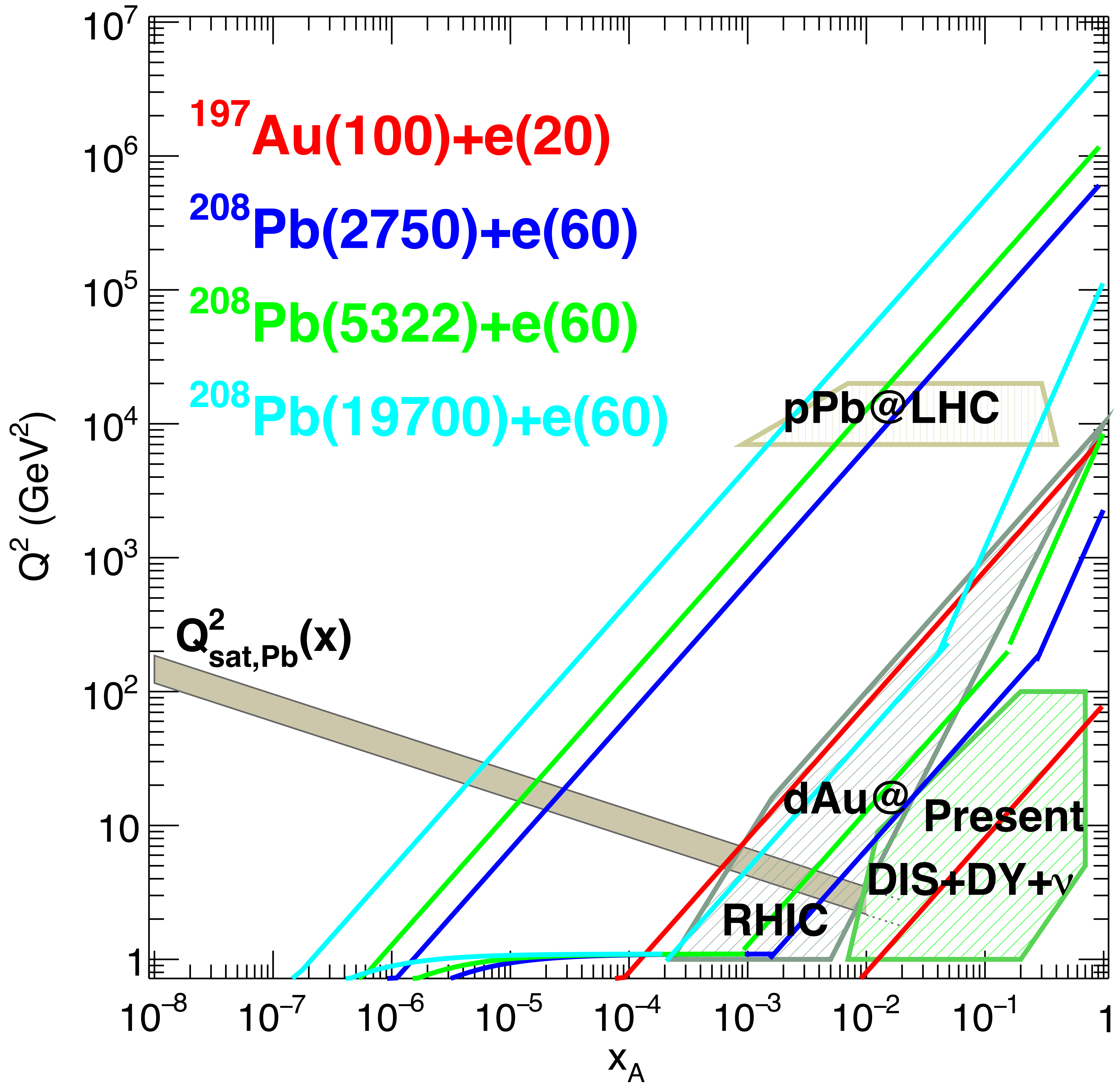

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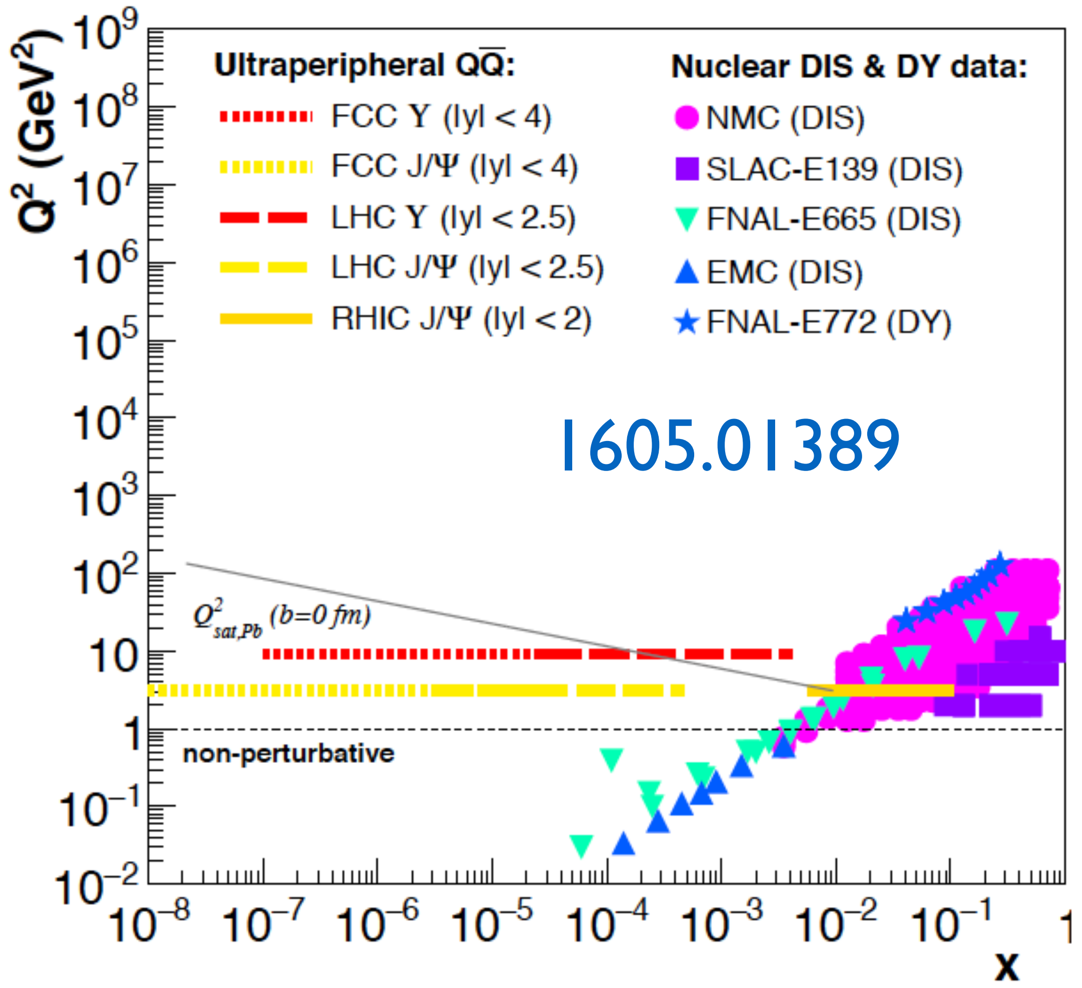

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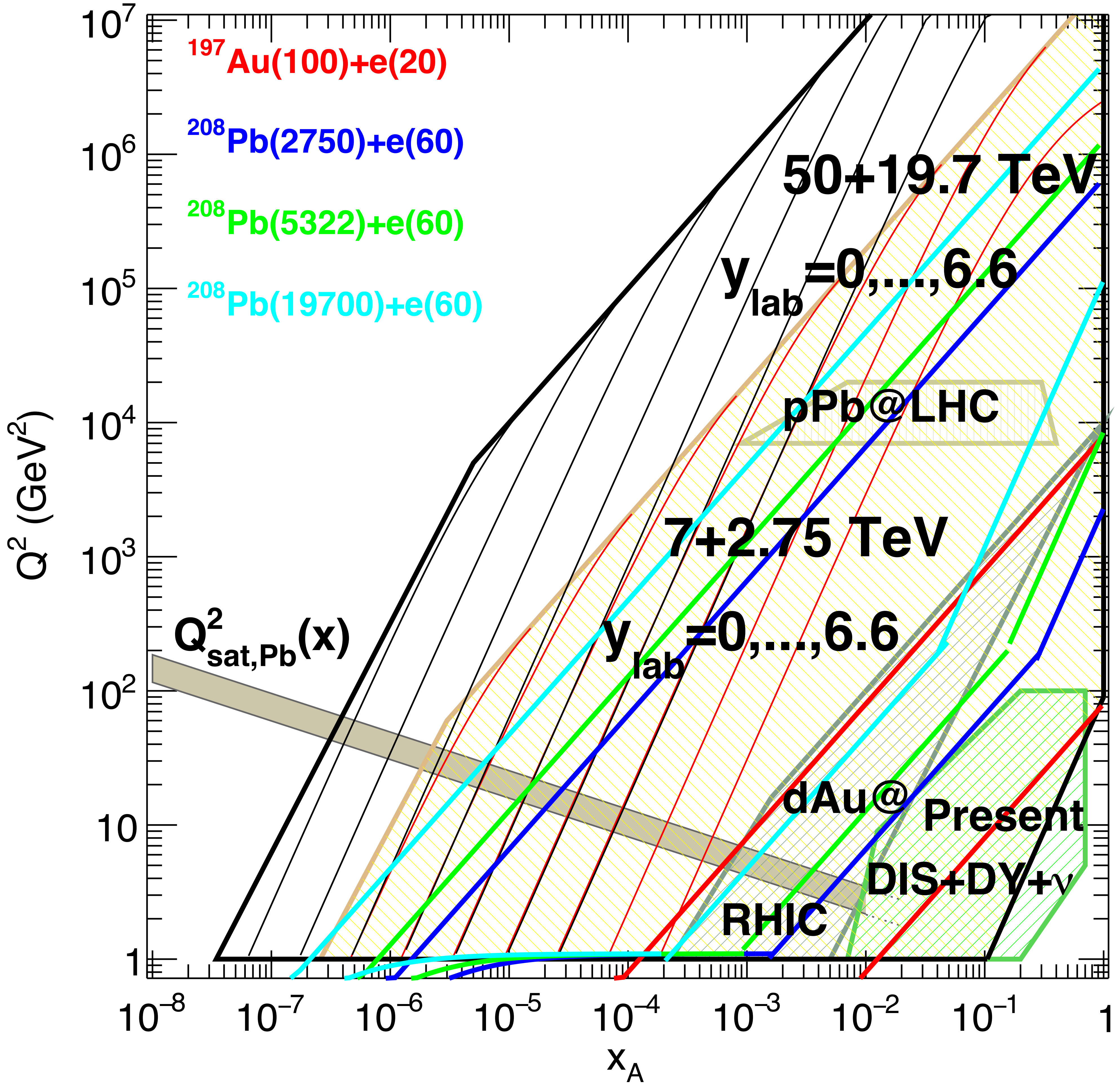

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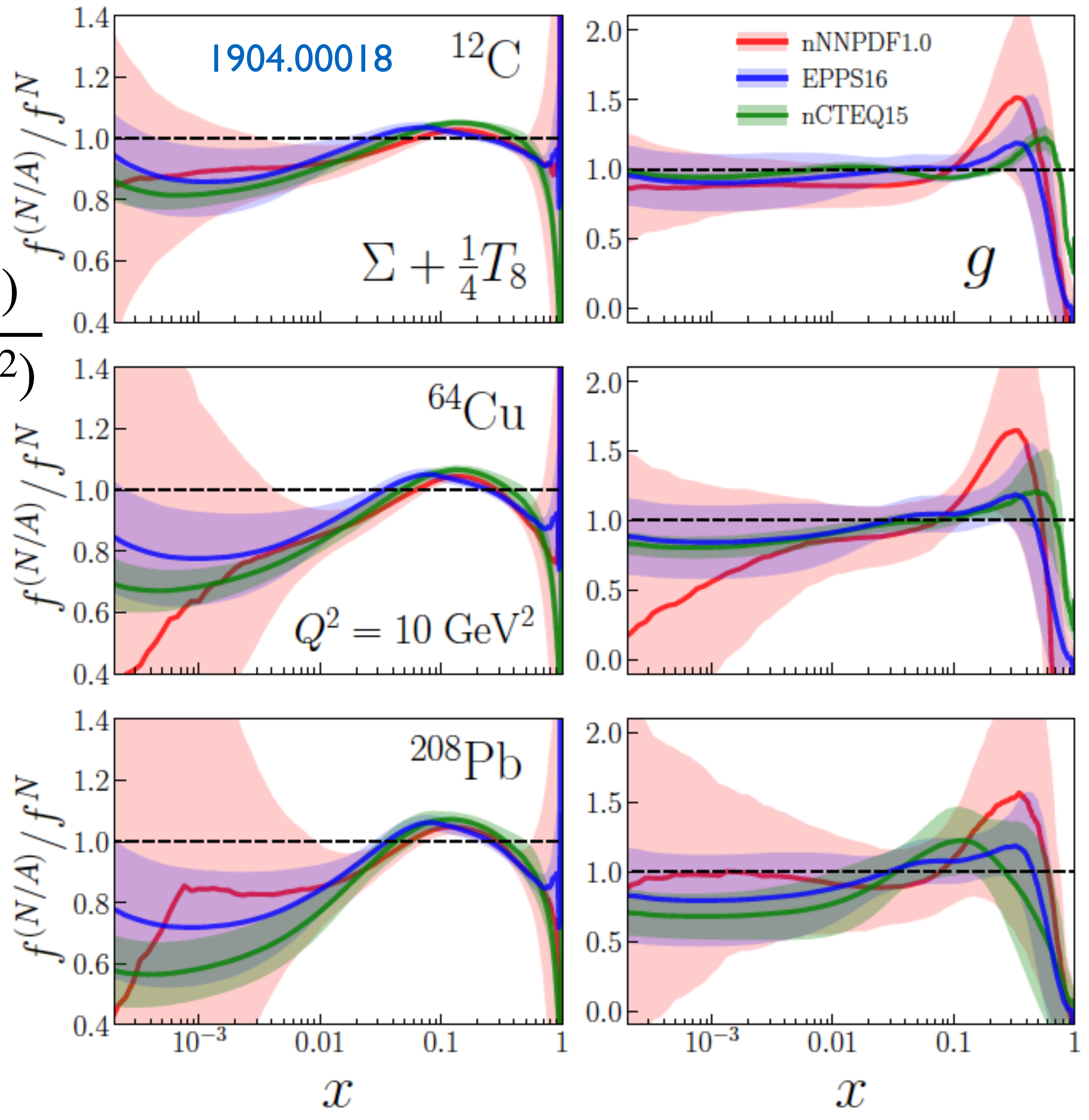
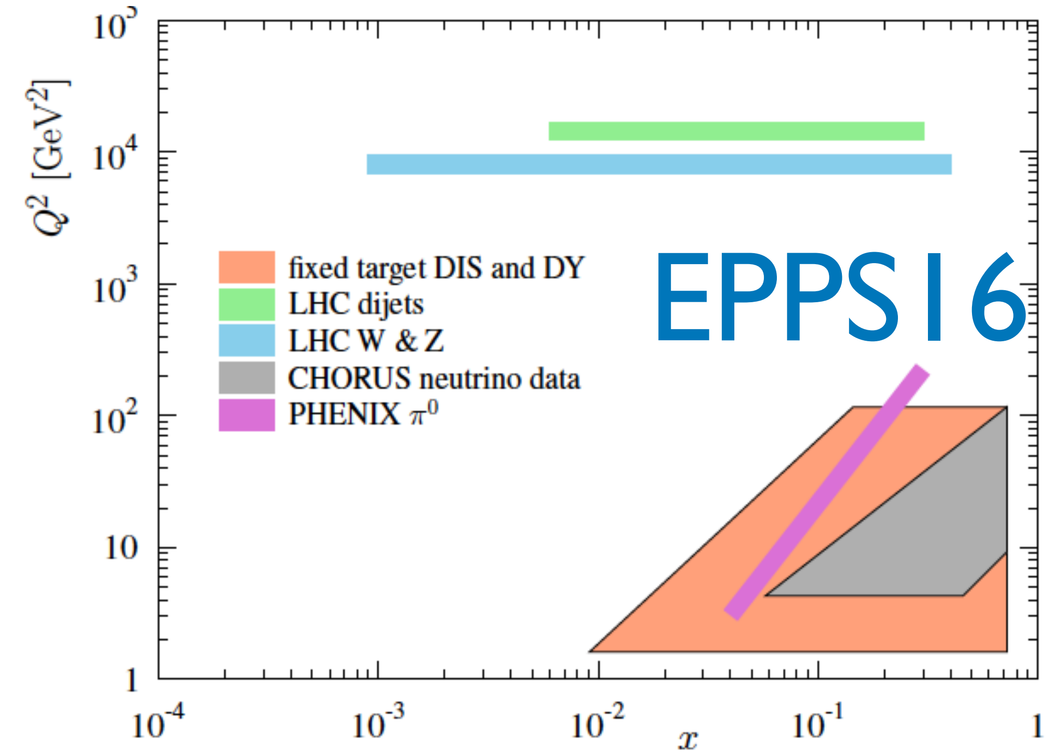
nPDFs: status

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	✔	✔	✔	✔	✔	✘
	π⁰	✔	✔	✔	✘	✔	✘
	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		Δχ²=50, ratios, huge shadowing-antishadowing	Δχ²=30, ratios, medium-modified FFs for π⁰	Δχ²=35, PDFs, valence flavour sep., not enough sensitivity	PDFs, deuteron data included	Δχ²=52, flavour sep., ratios, LHC pPb data	NNPDF methodology, isoscalarity assumed

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



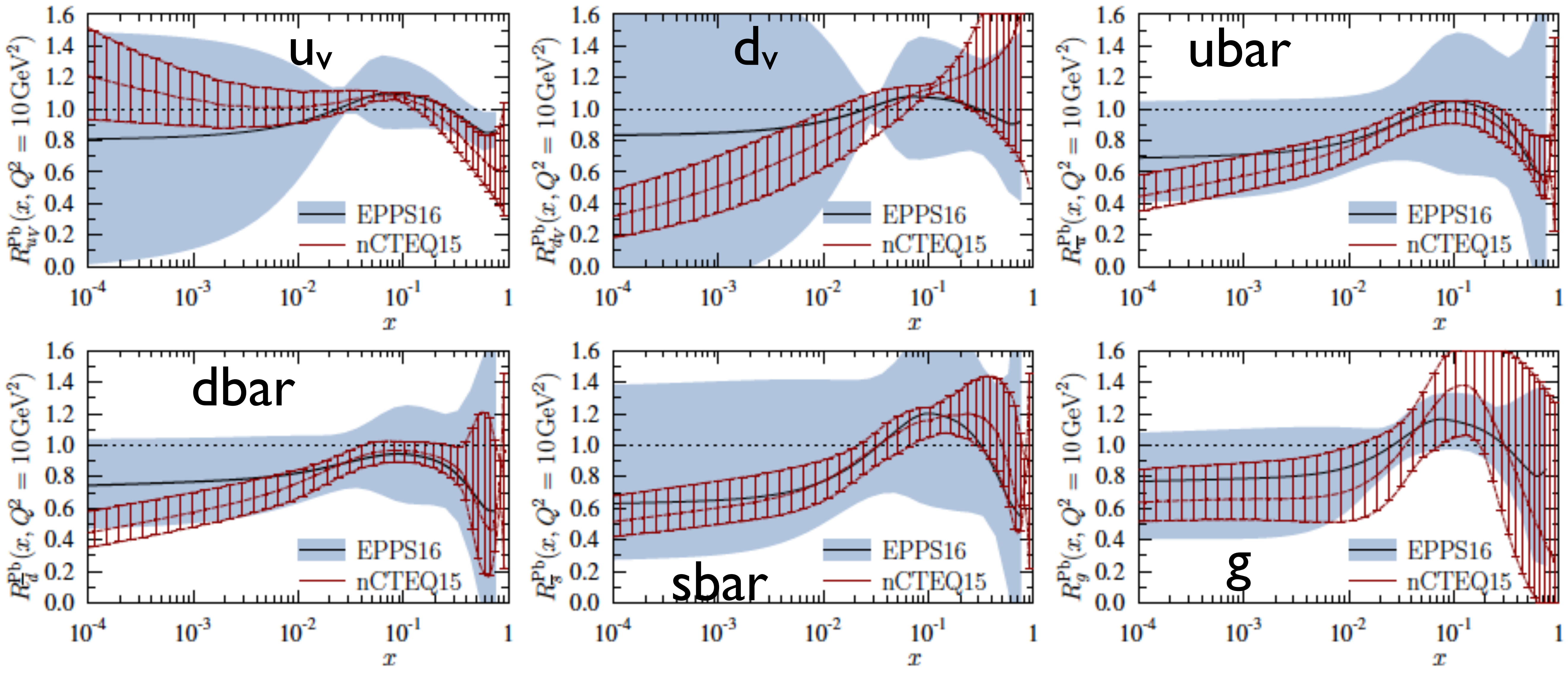


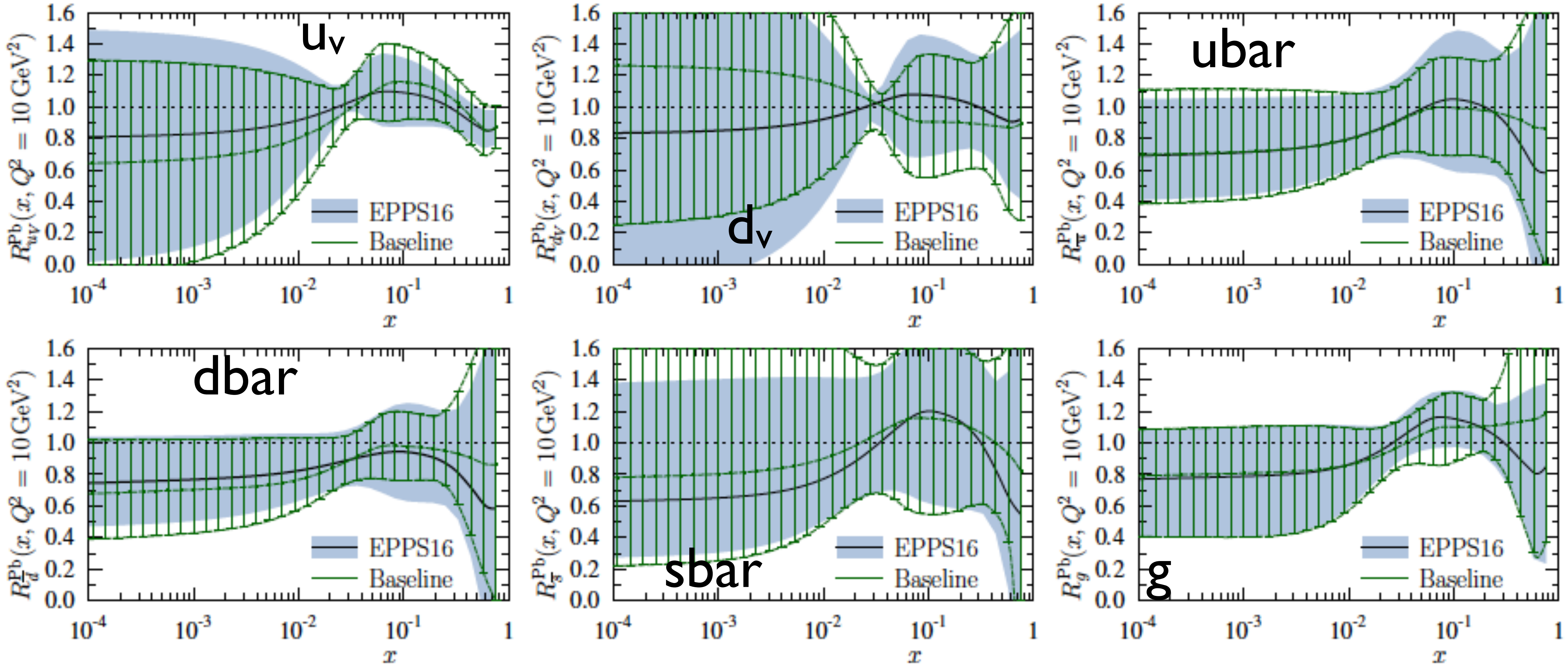
- Large uncertainties for x<0.01 and for large x glue (parametrisation biases); small impact of LHC data (large-x glue).
- Few data for any single A e.g. Pb (15 DIS+30 pPb+νA): A-dependence of I.C. mandatory; flavour decomposition weakly constrained (~ isoscalarity).
- Impact parameter dependence modelled.

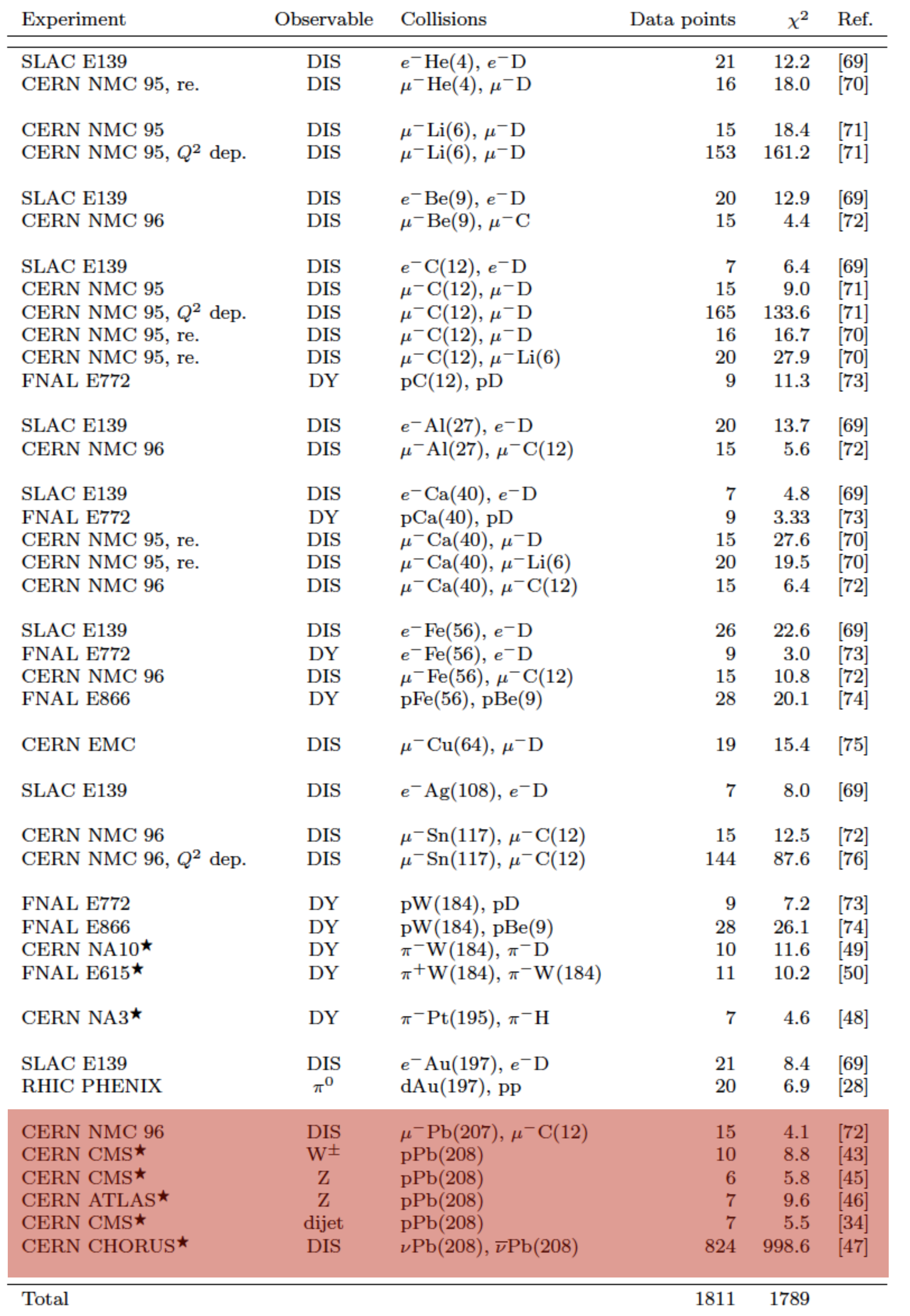
nPDFs: status

- 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).



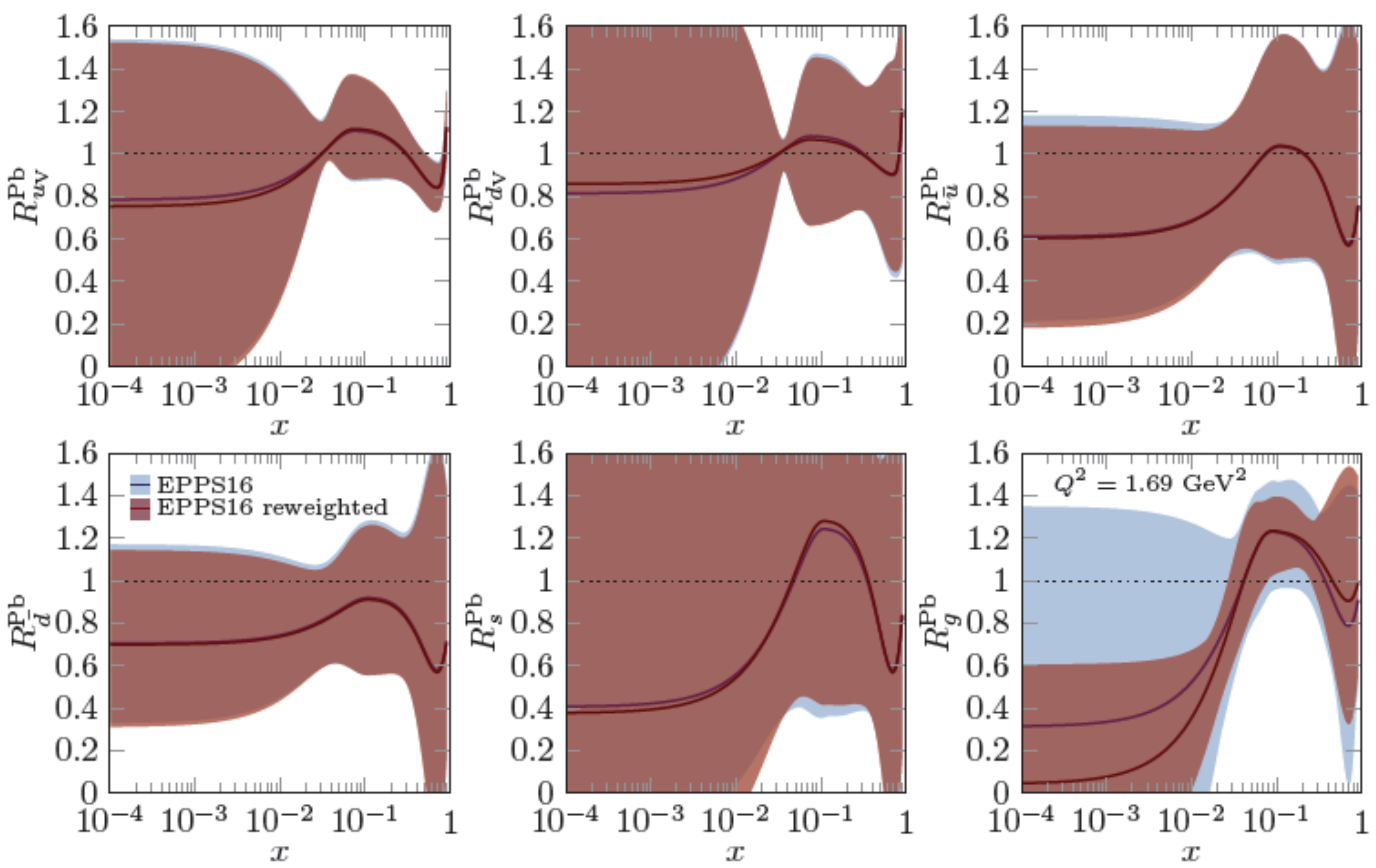




Experiment	Observable	Collisions	Data points	χ^2	Ref.
SLAC E139	DIS	e^-He(4), e^-D	21	12.2	[69]
CERN NMC 95, re.	DIS	μ^-He(4), μ^-D	16	18.0	[70]
CERN NMC 95	DIS	μ^-Li(6), μ^-D	15	18.4	[71]
CERN NMC 95, Q^2 dep.	DIS	μ^-Li(6), μ^-D	153	161.2	[71]
SLAC E139	DIS	e^-Be(9), e^-D	20	12.9	[69]
CERN NMC 96	DIS	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), $\bar{\nu}$Pb(208)	824	998.6	[47]
Total			1811	1789	

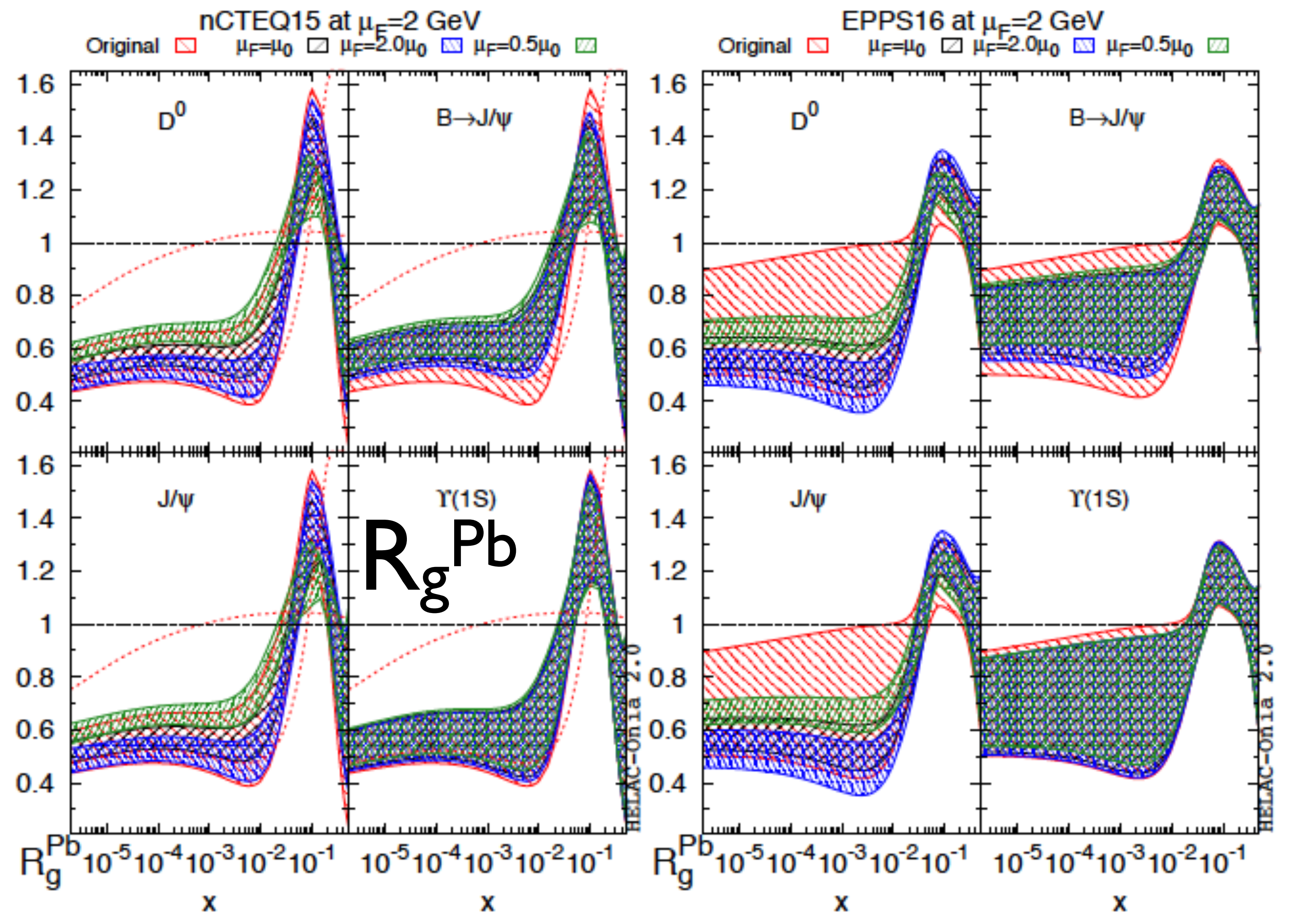
EPPS16

nPDFs @ LHC: present

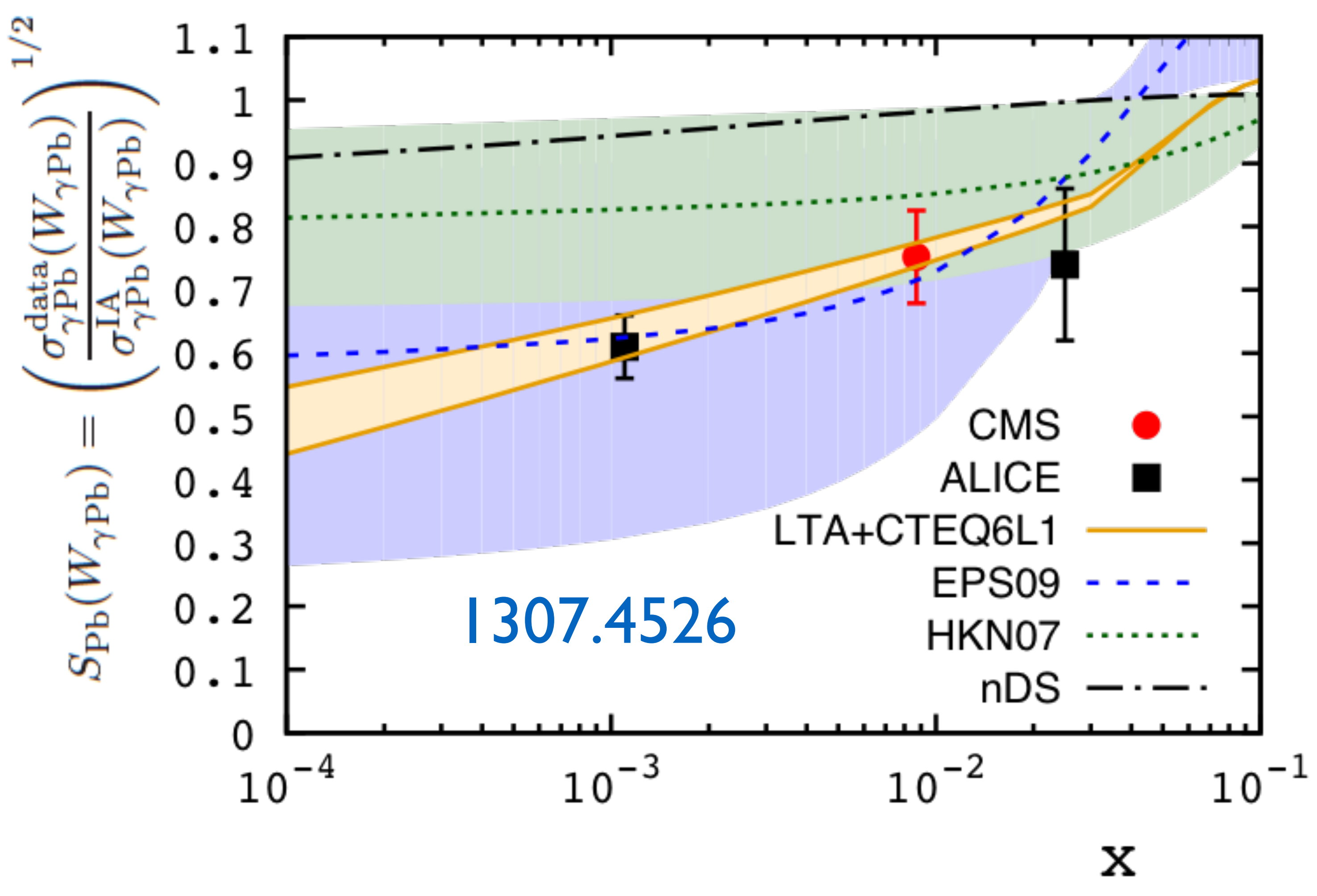


D mesons, 1906.02512

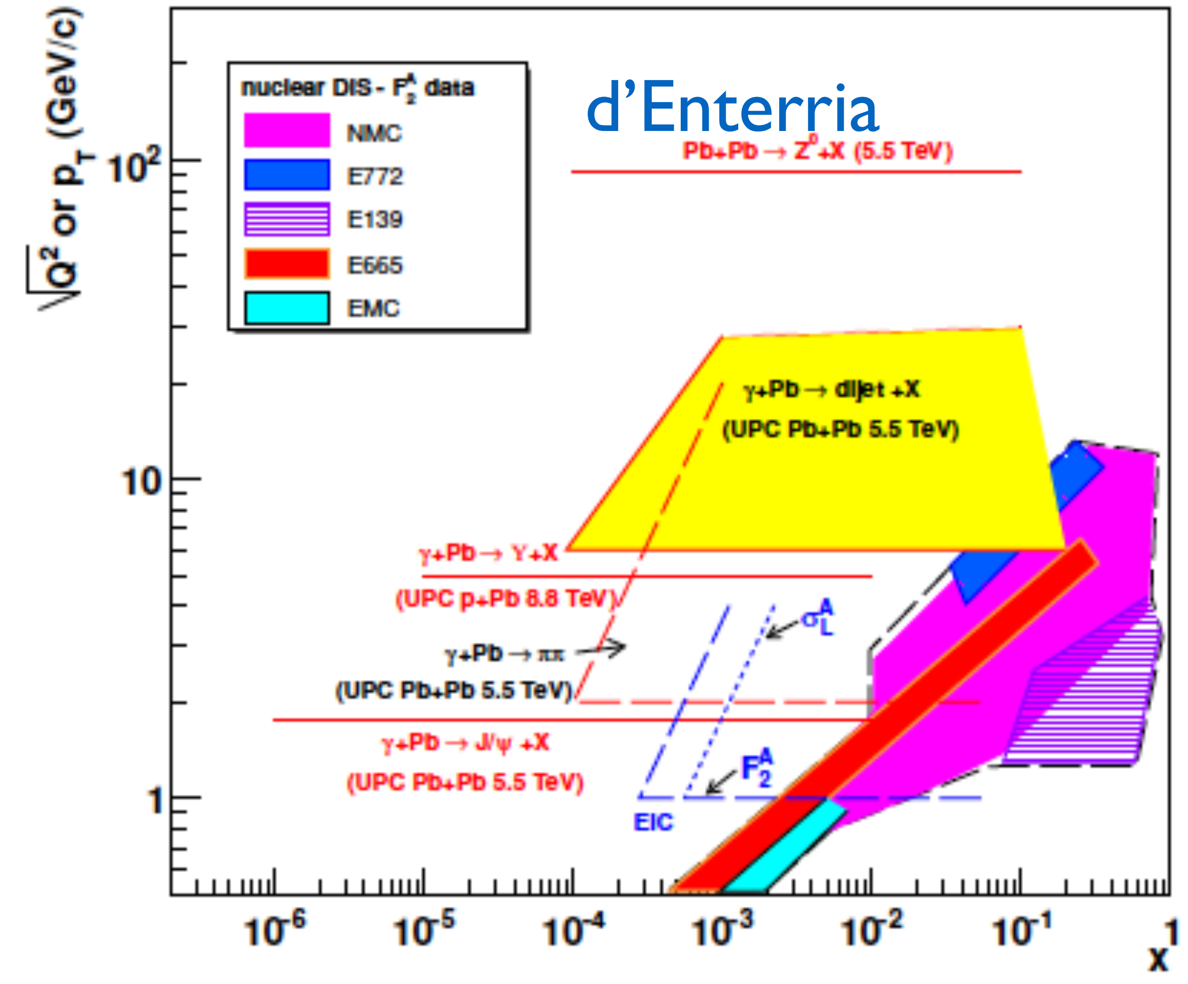
- Theoretical control in PT over forward D or J/ψ under debate: scales, DPS, non-linear dynamics, … E.g. quarkonium: superposition of nPDFs + eloss/absorption + comovers for ψ',…
- Collectivity (flow for D in pPb as for charged hadrons in pPb and PbPb?) would limit the use of low p_T data for extraction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



1712.07024

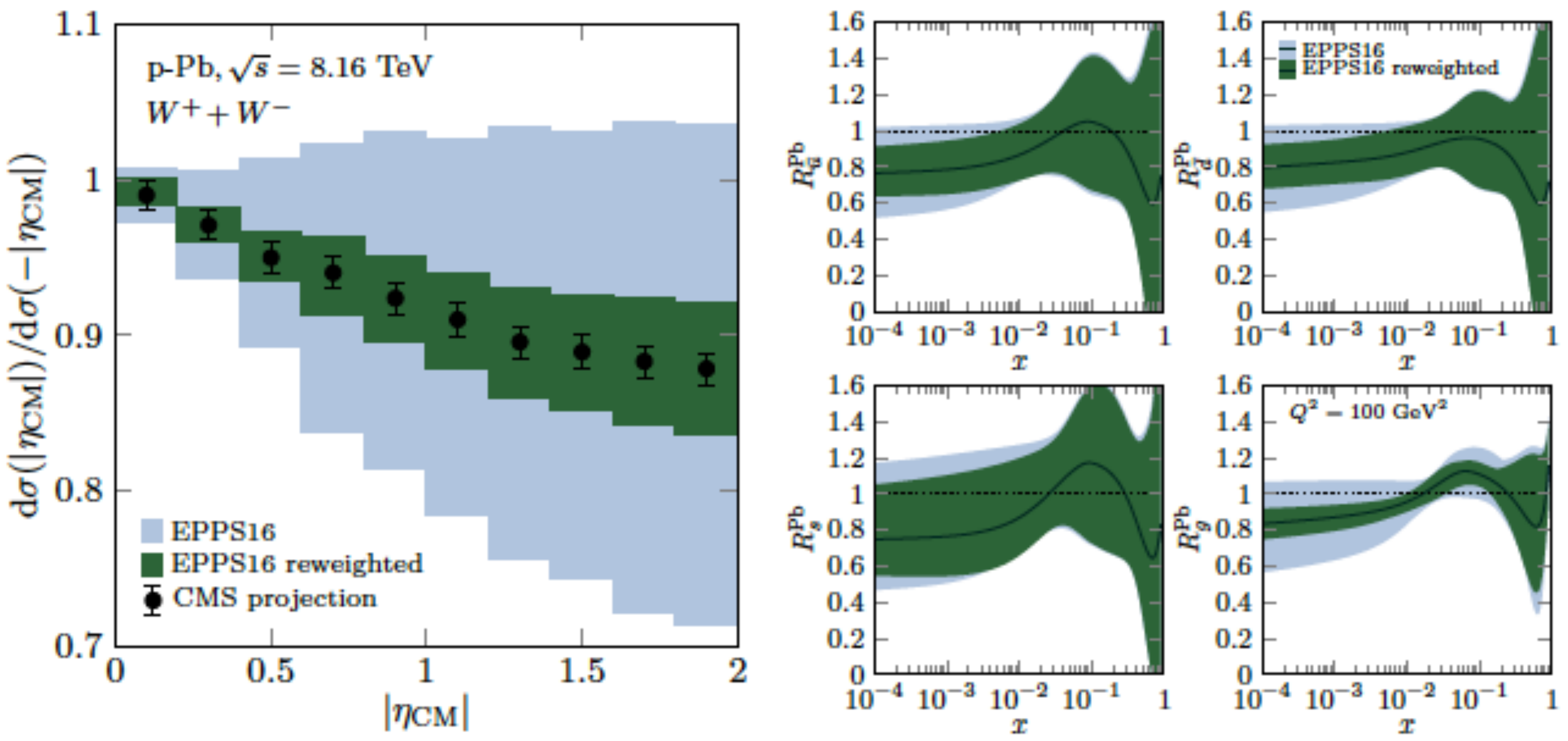


- UPCs offer possibilities for constraining both nPDFs: they were the first indication of nuclear shadowing.



nPDFs @ HL-LHC:

W



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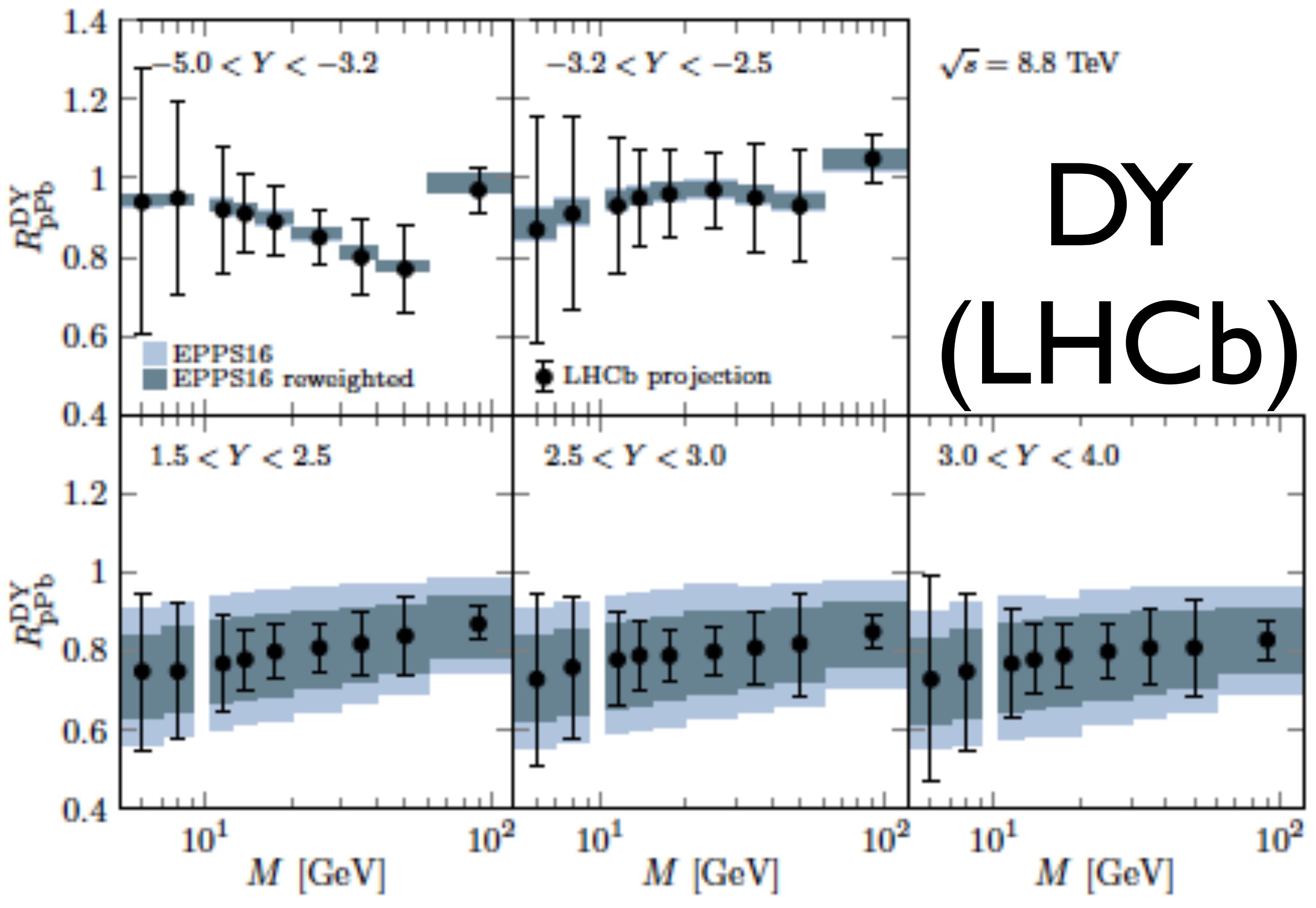
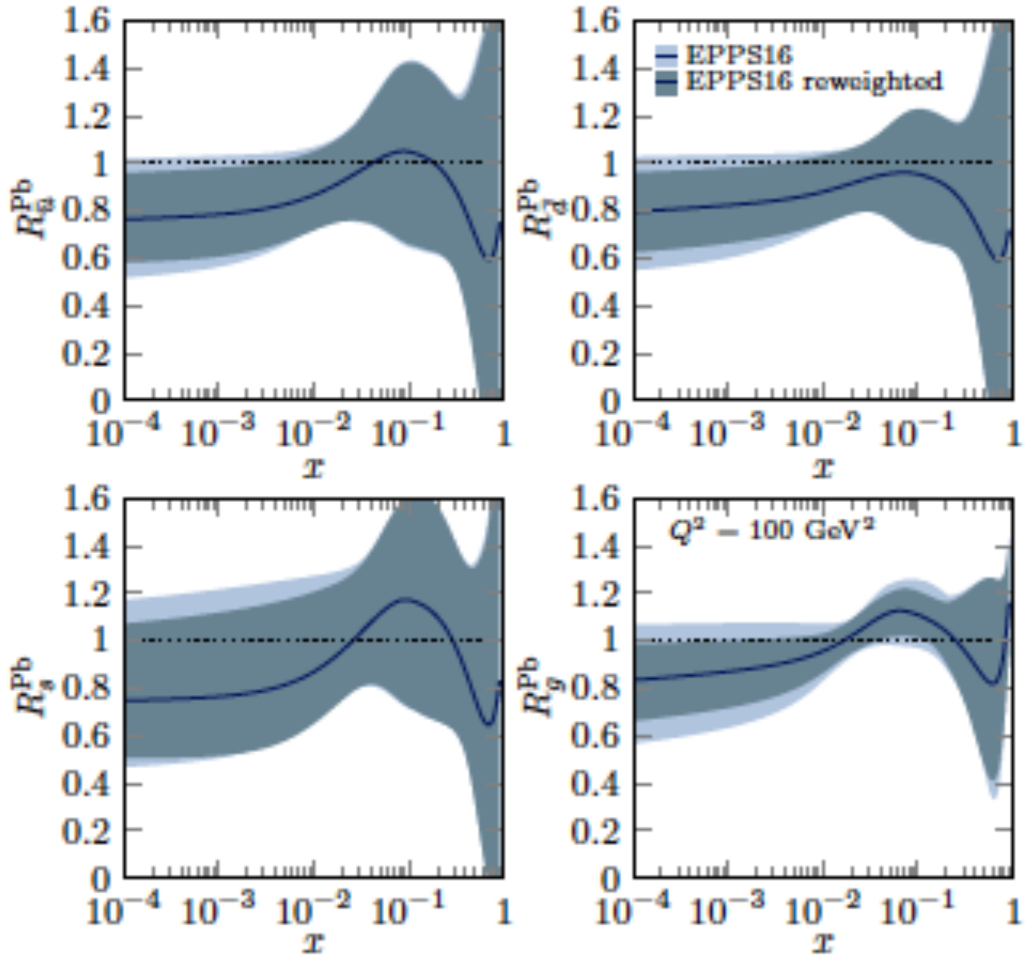
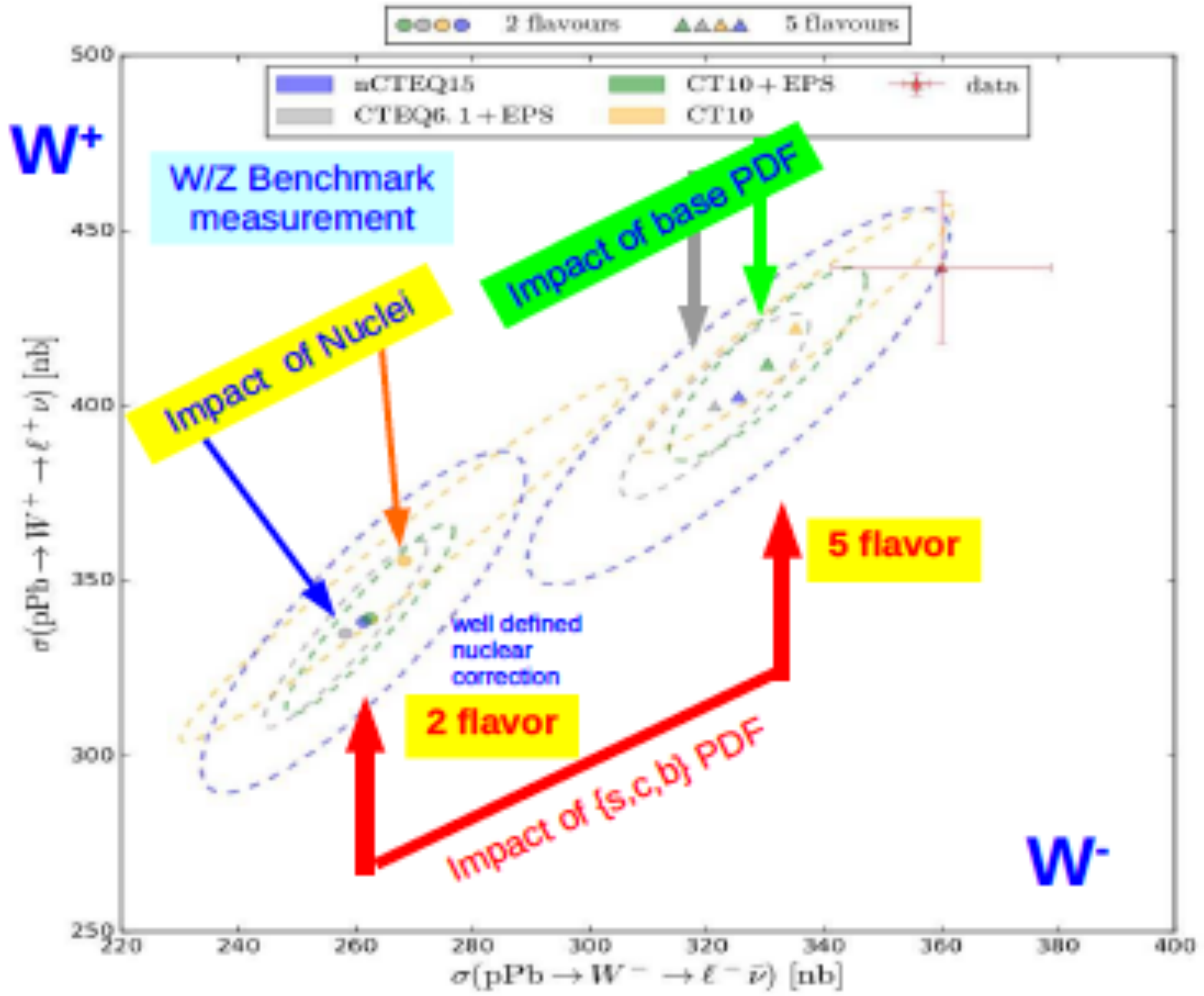
- Dijets for glue.
- Z and γ at forward rapidity (glue).
- W asymmetries for gluon (evolution).
- Low mass forward DY for sea and gluon.
- Top requires higher statistics: lighter ions in the 30’s?
- UPCs will also contribute: quarkonium, inclusive dijets (1902.05126).

1812.06772

DY (LHCb)

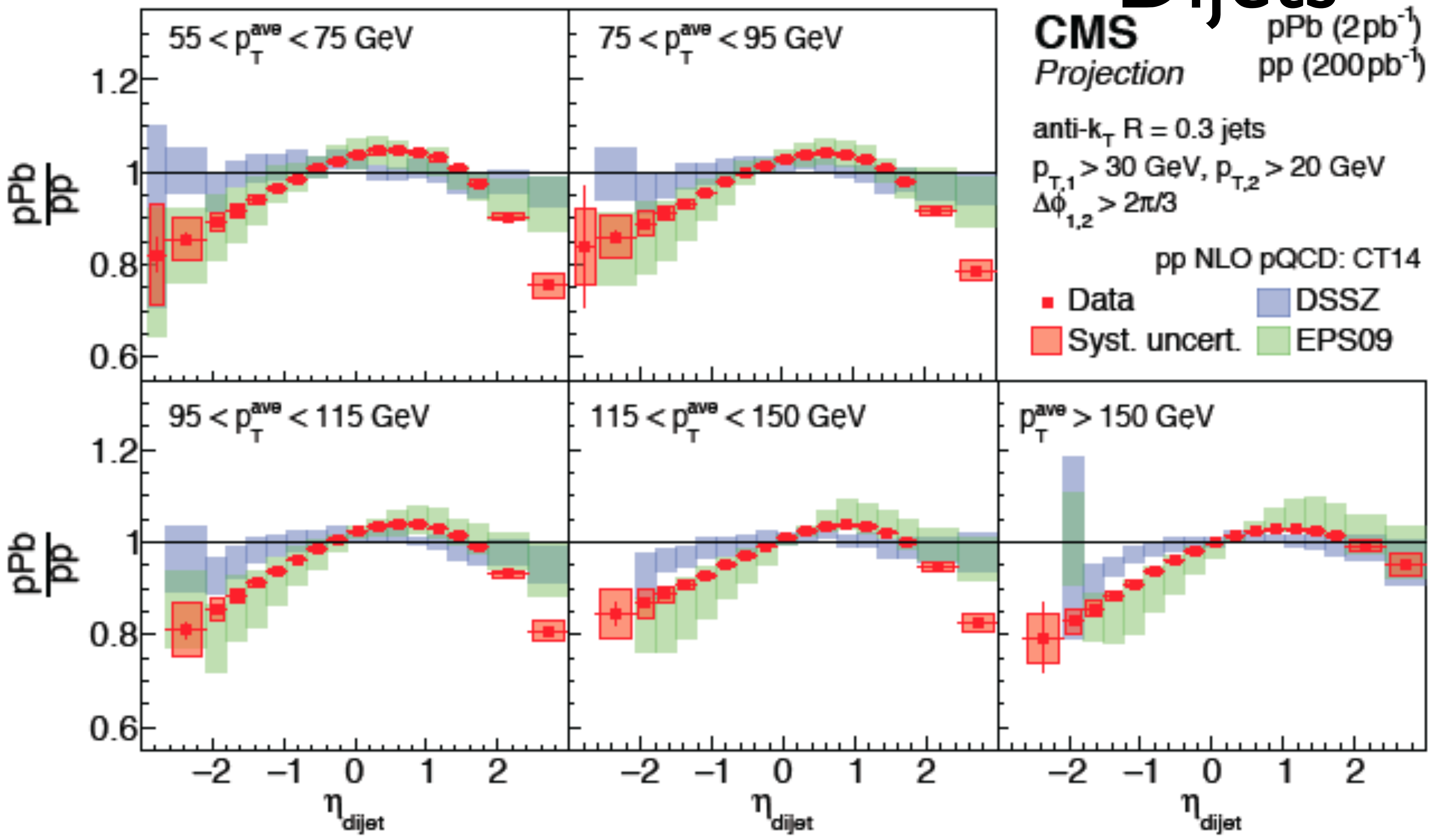






nPDFs @ HL-LHC:

Dijets



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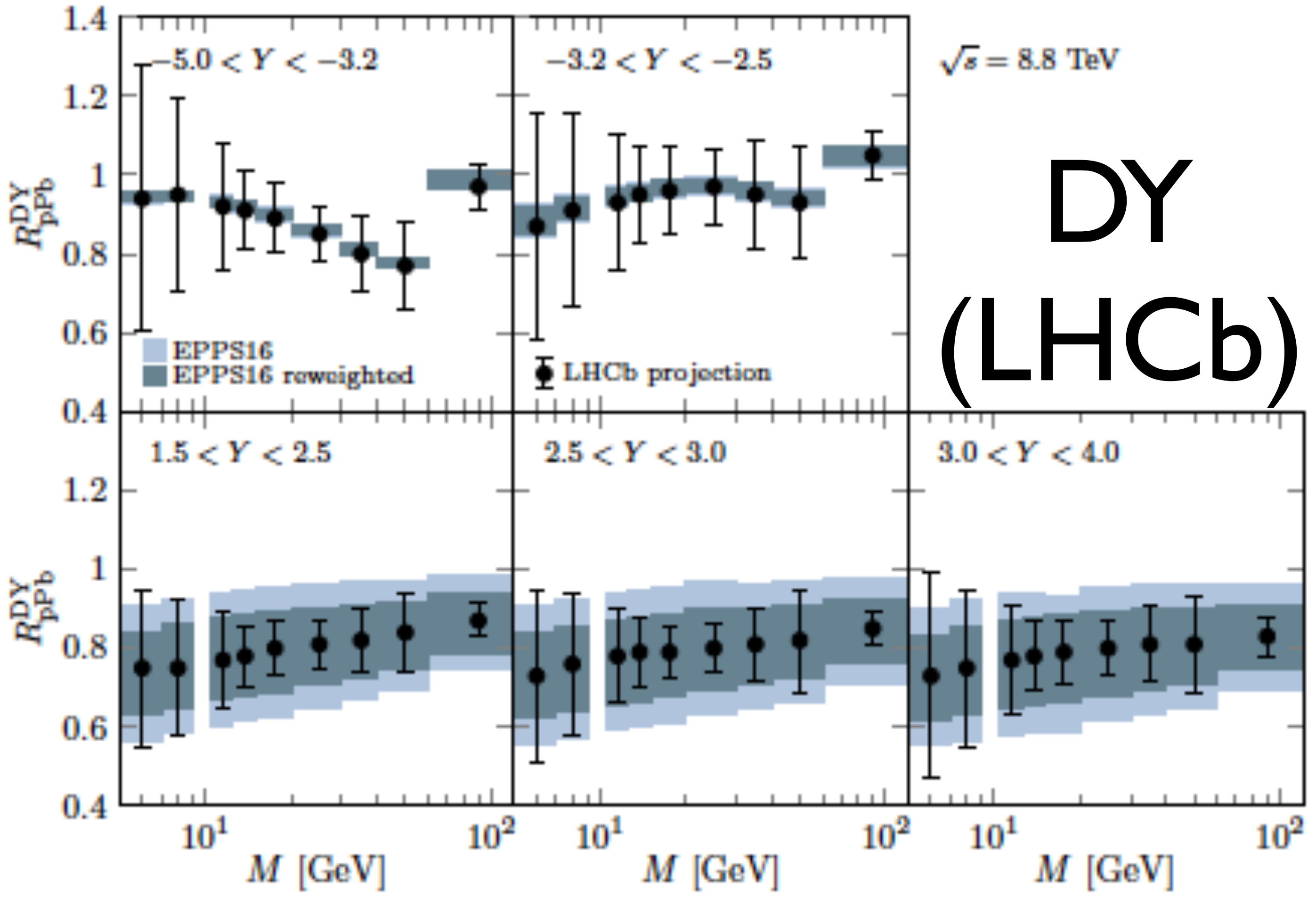
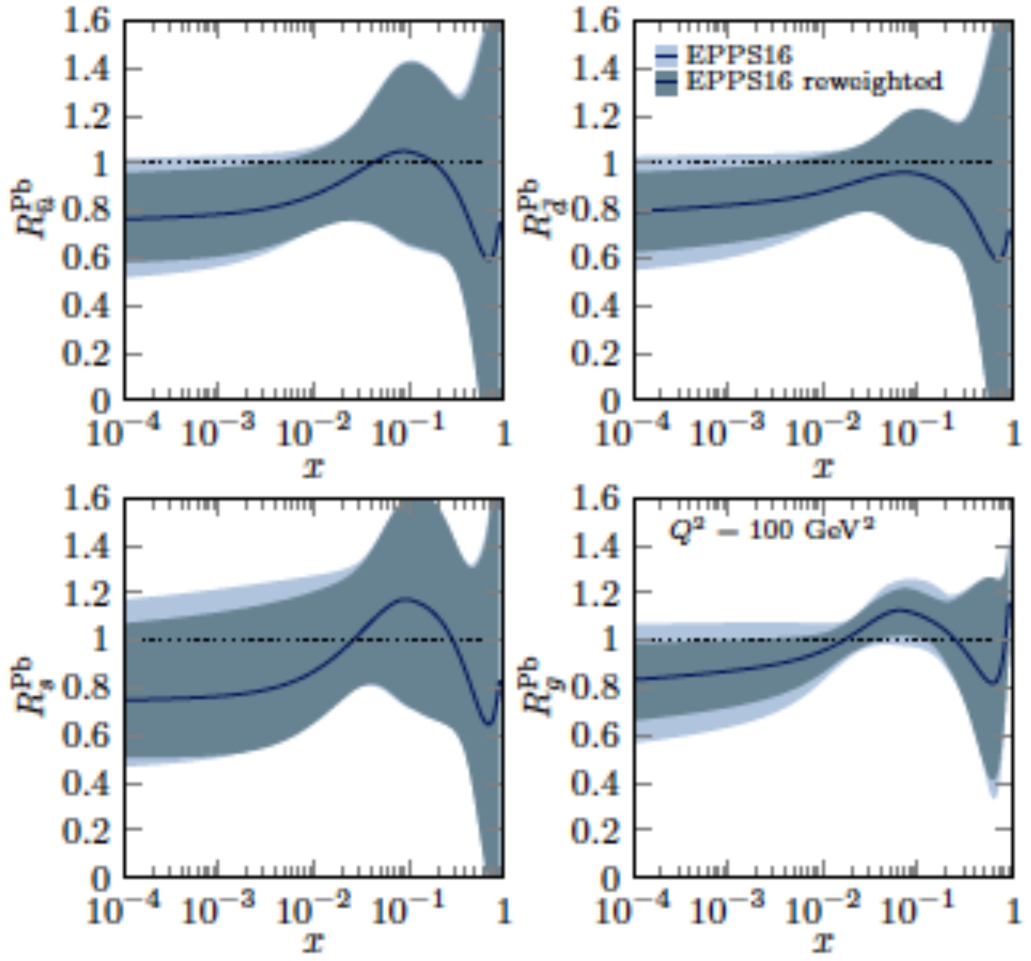
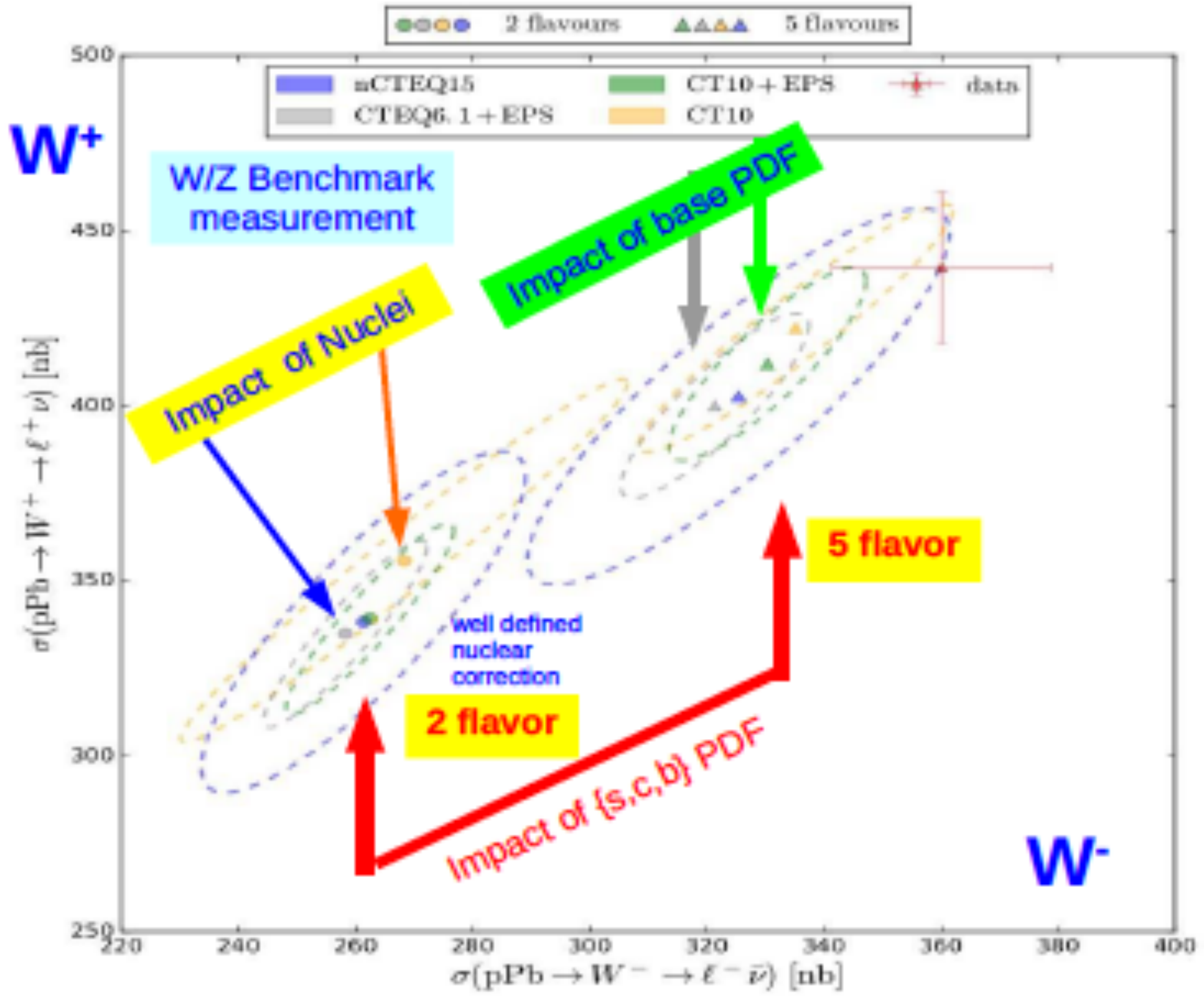


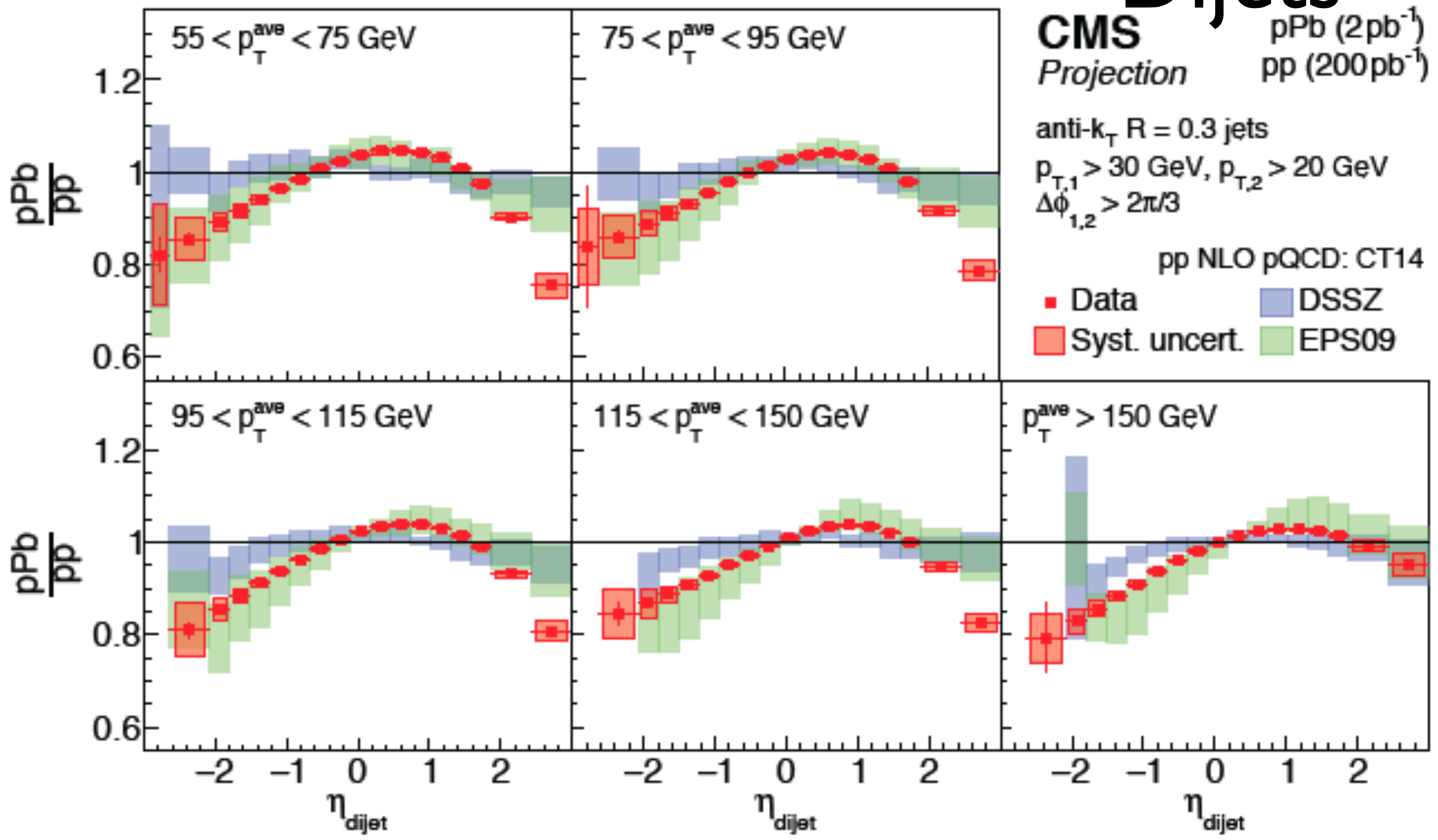
DY
(LHCb)





nPDFs @ HL-LHC:

Dijets



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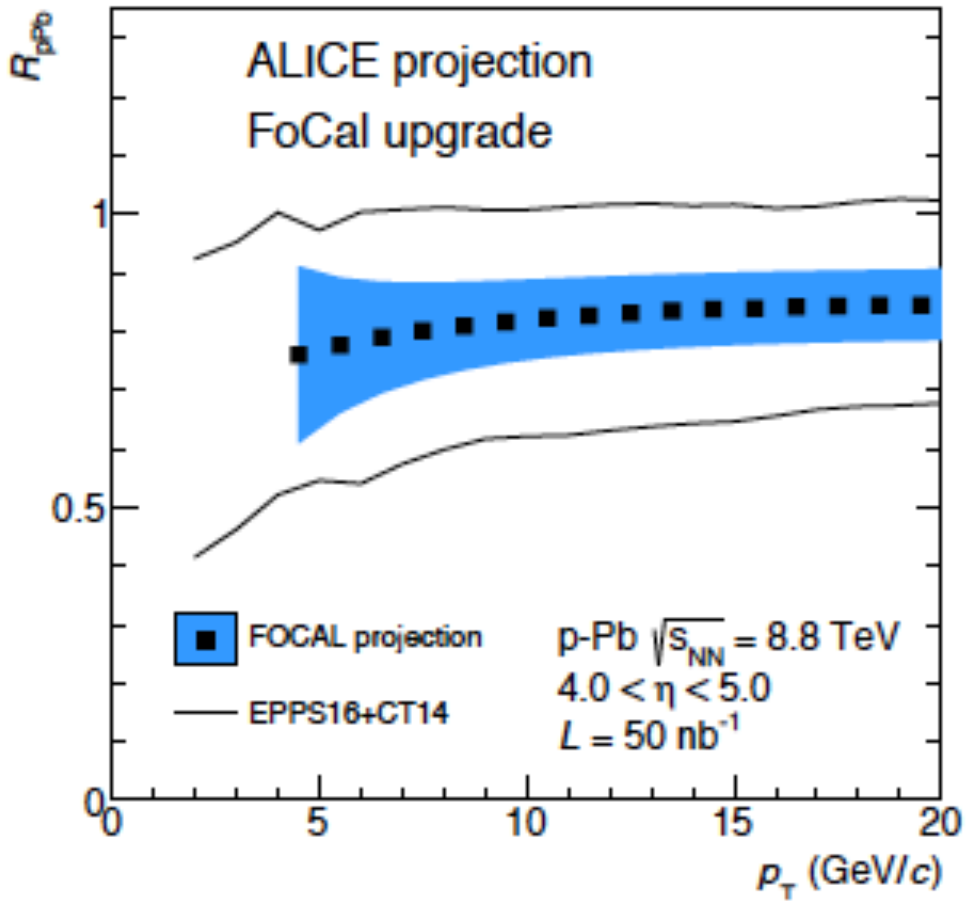
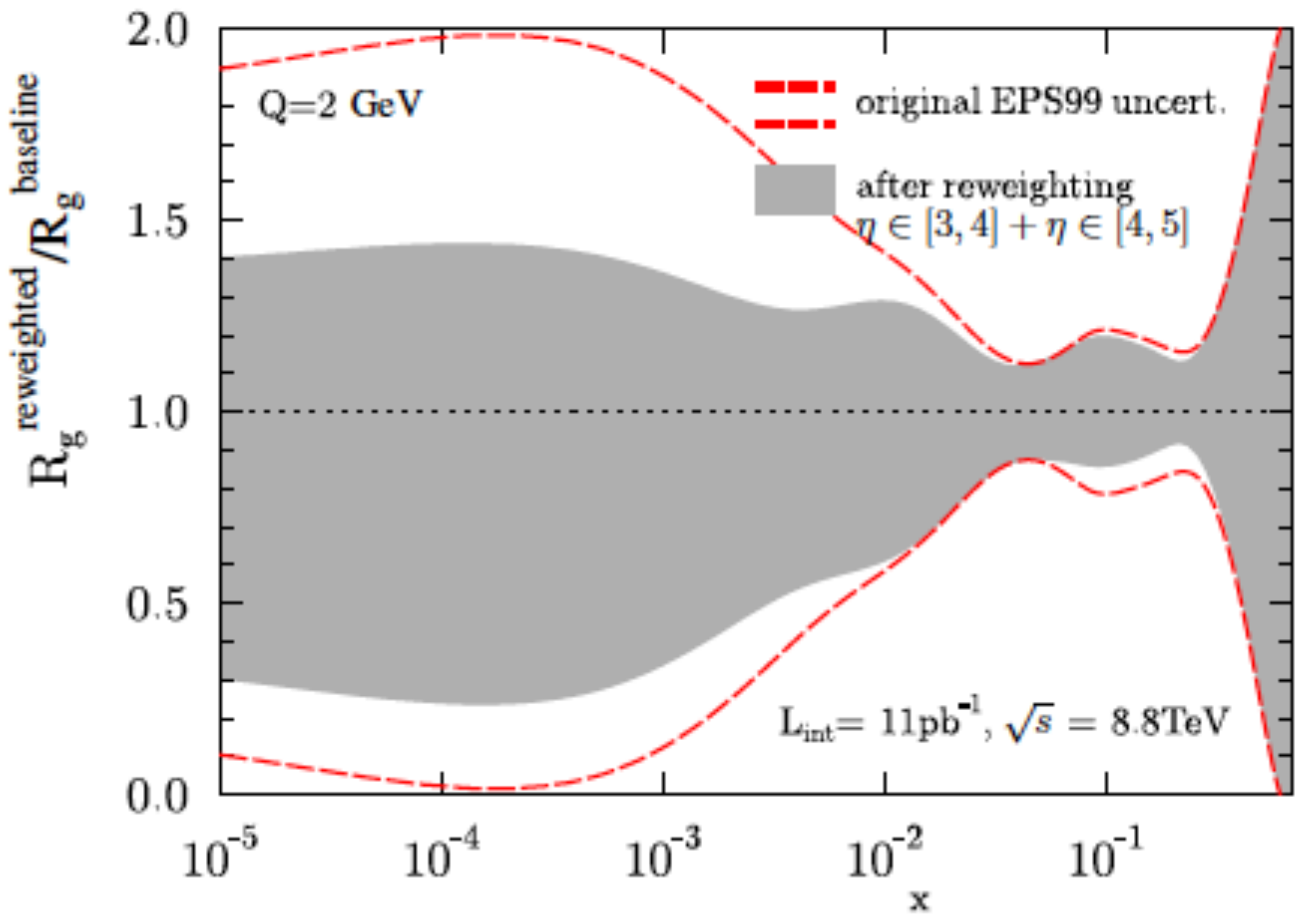
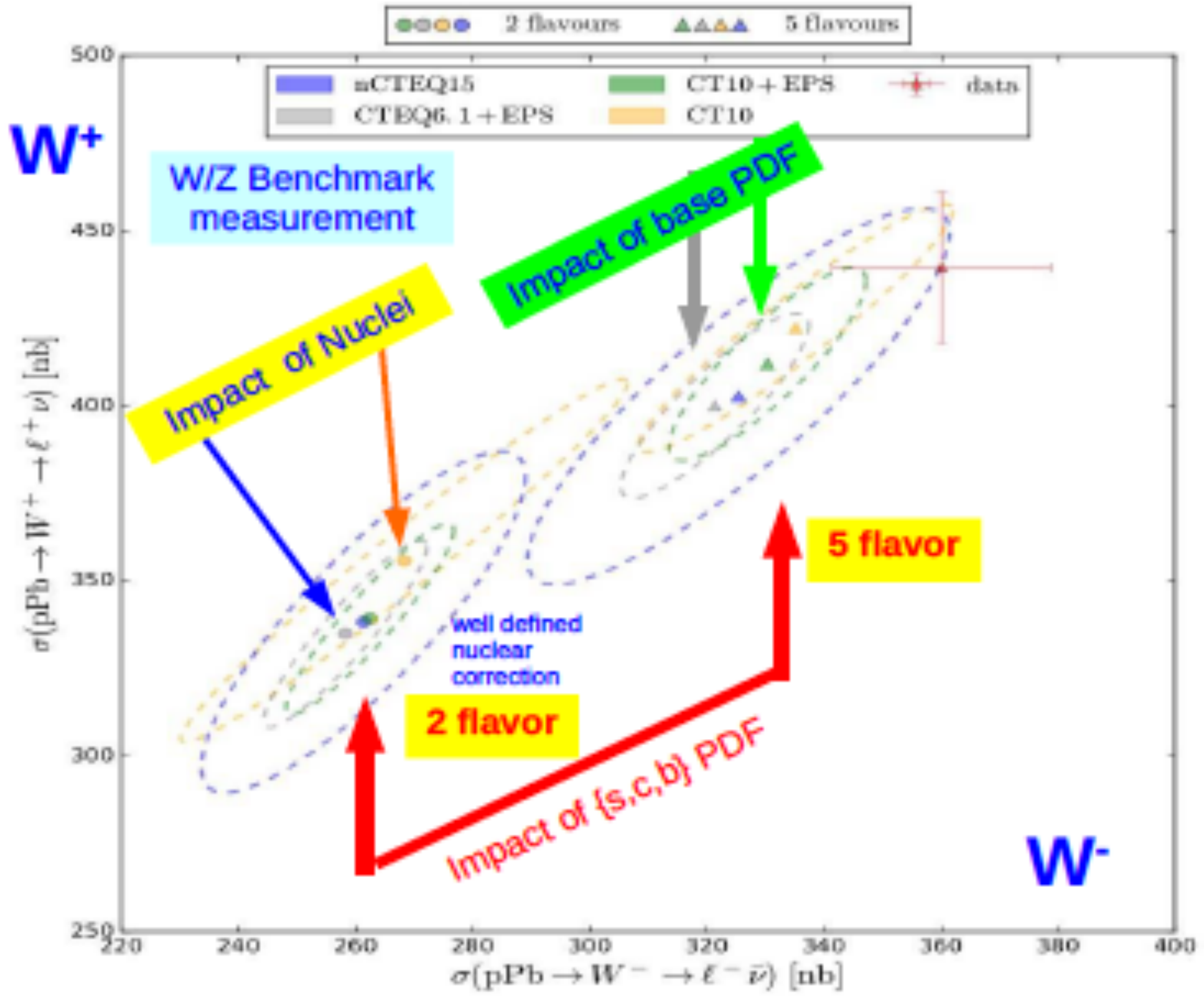
1812.06772

Photons

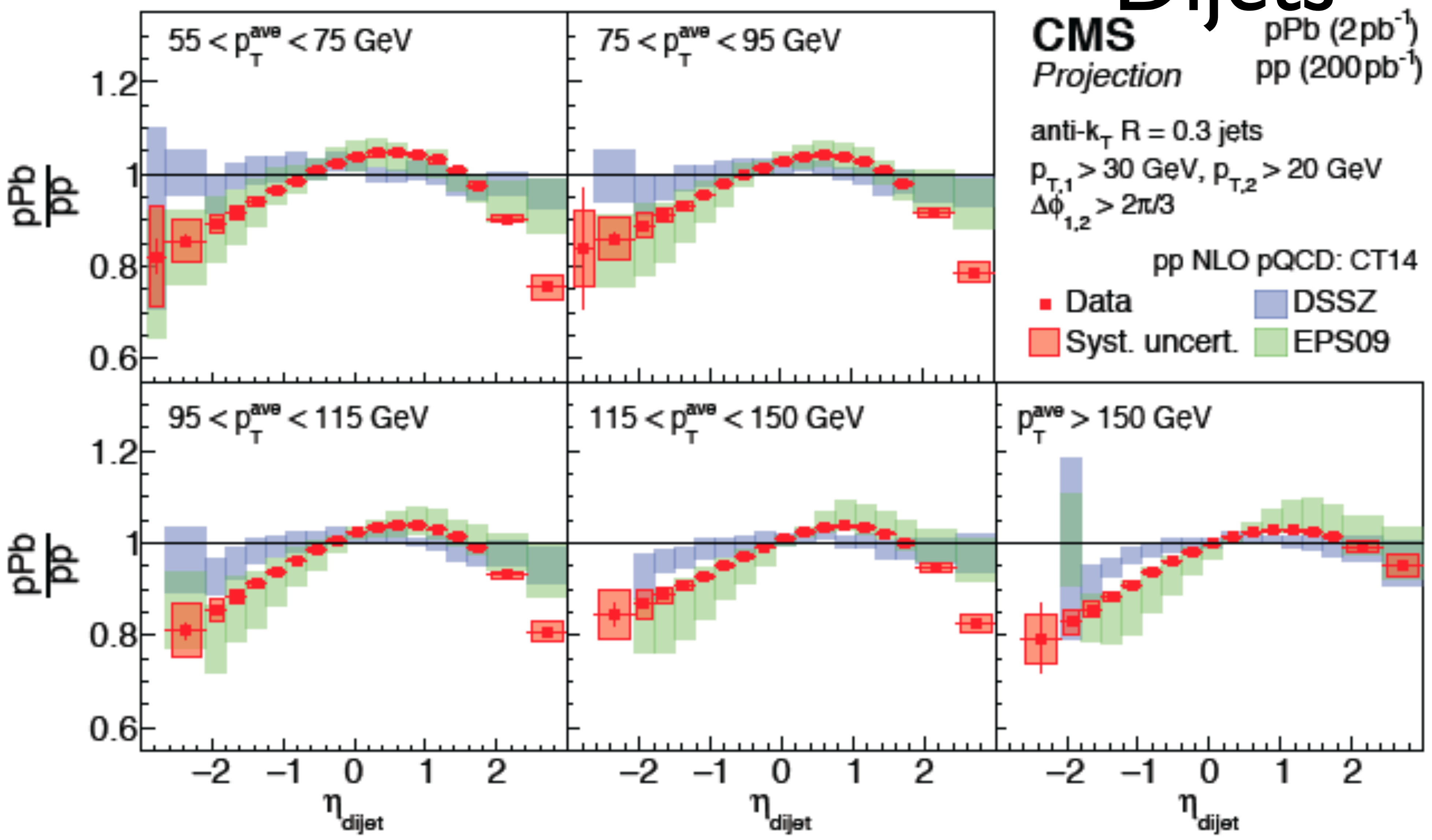






nPDFs @ HL-LHC:

Dijets



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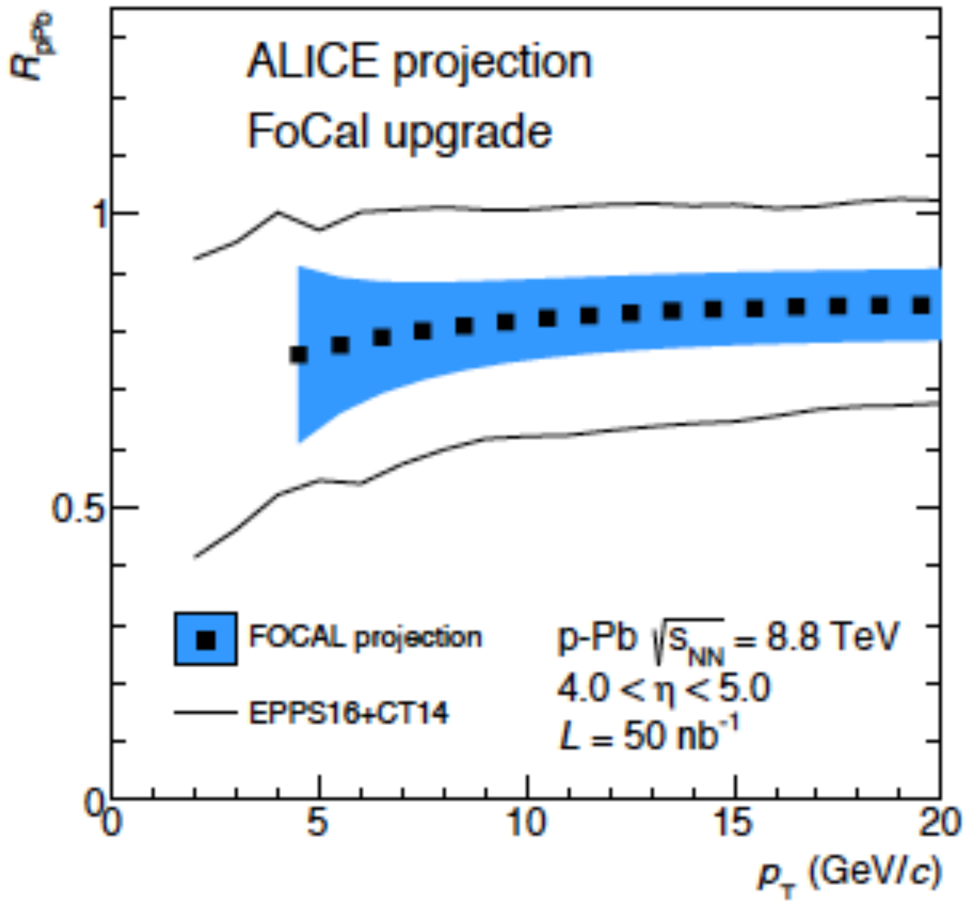
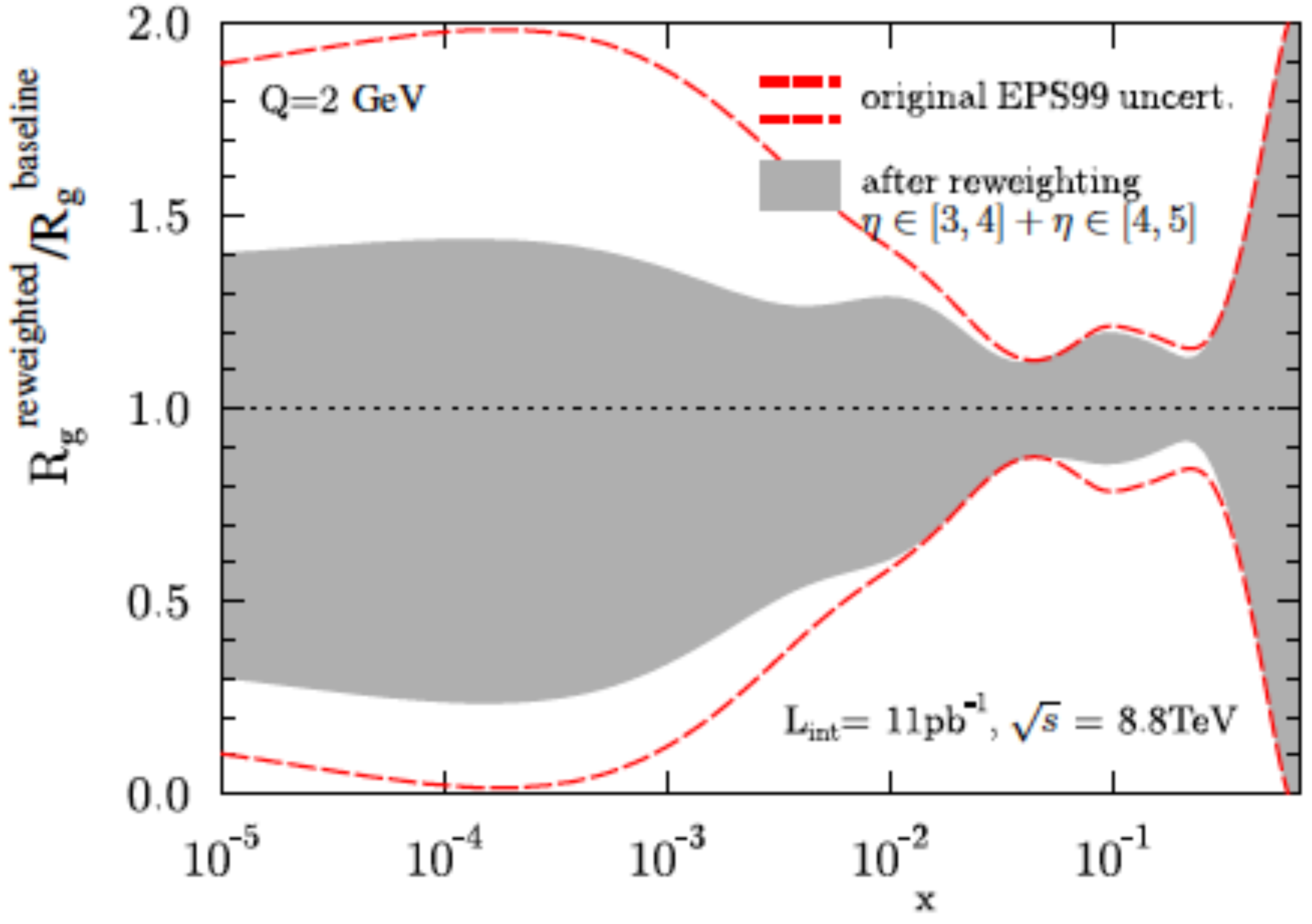
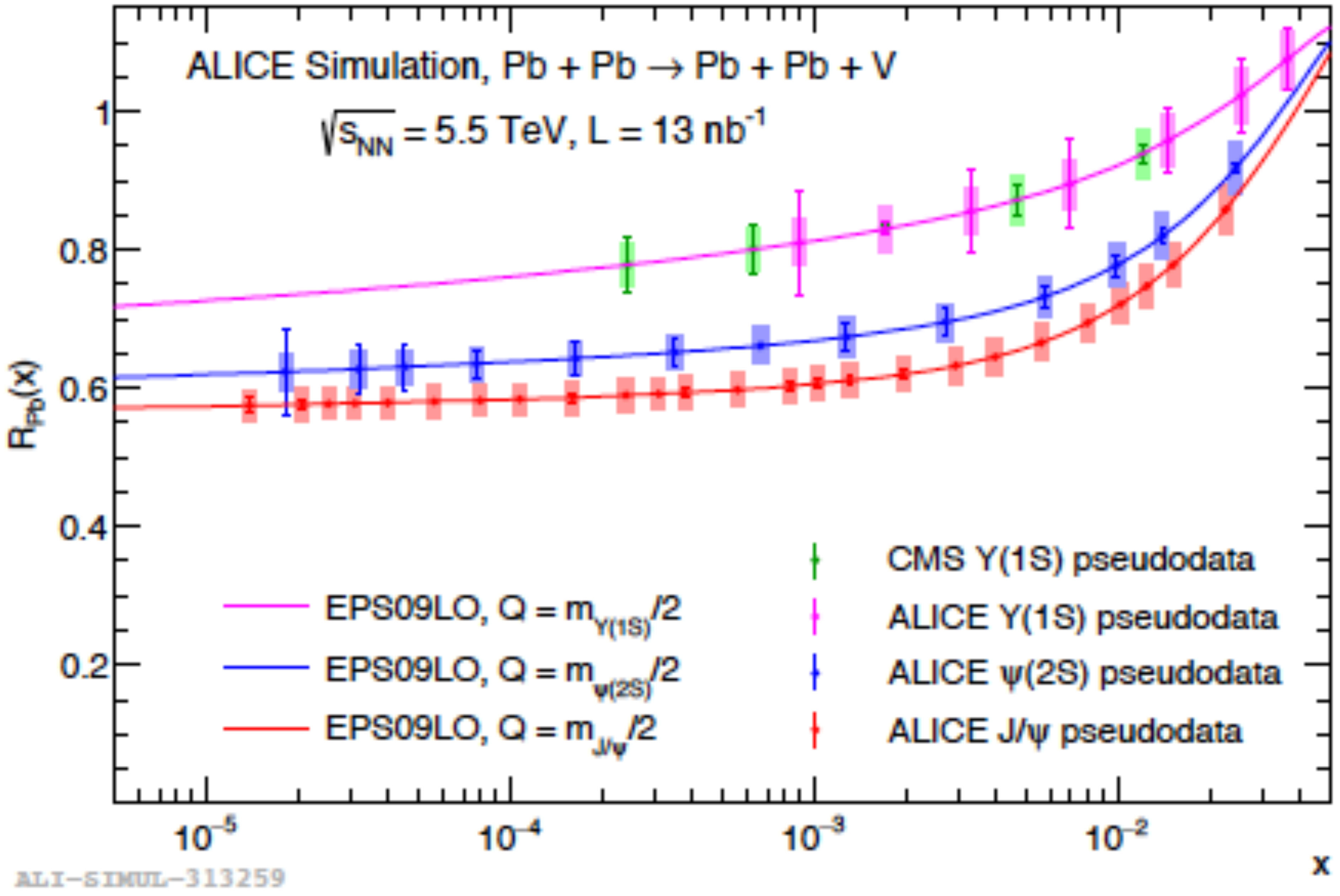
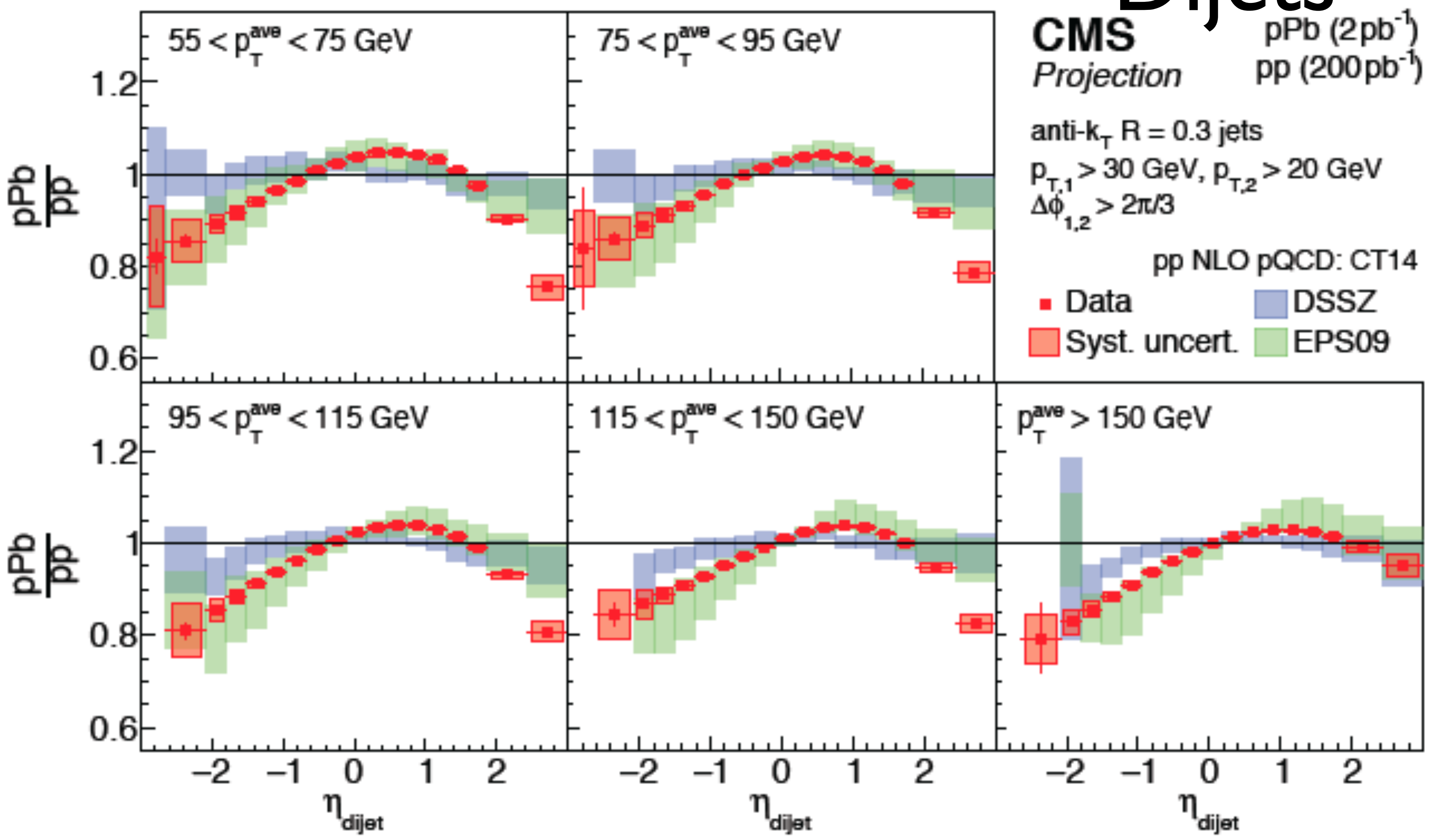






nPDFs @ HL-LHC:

Dijets



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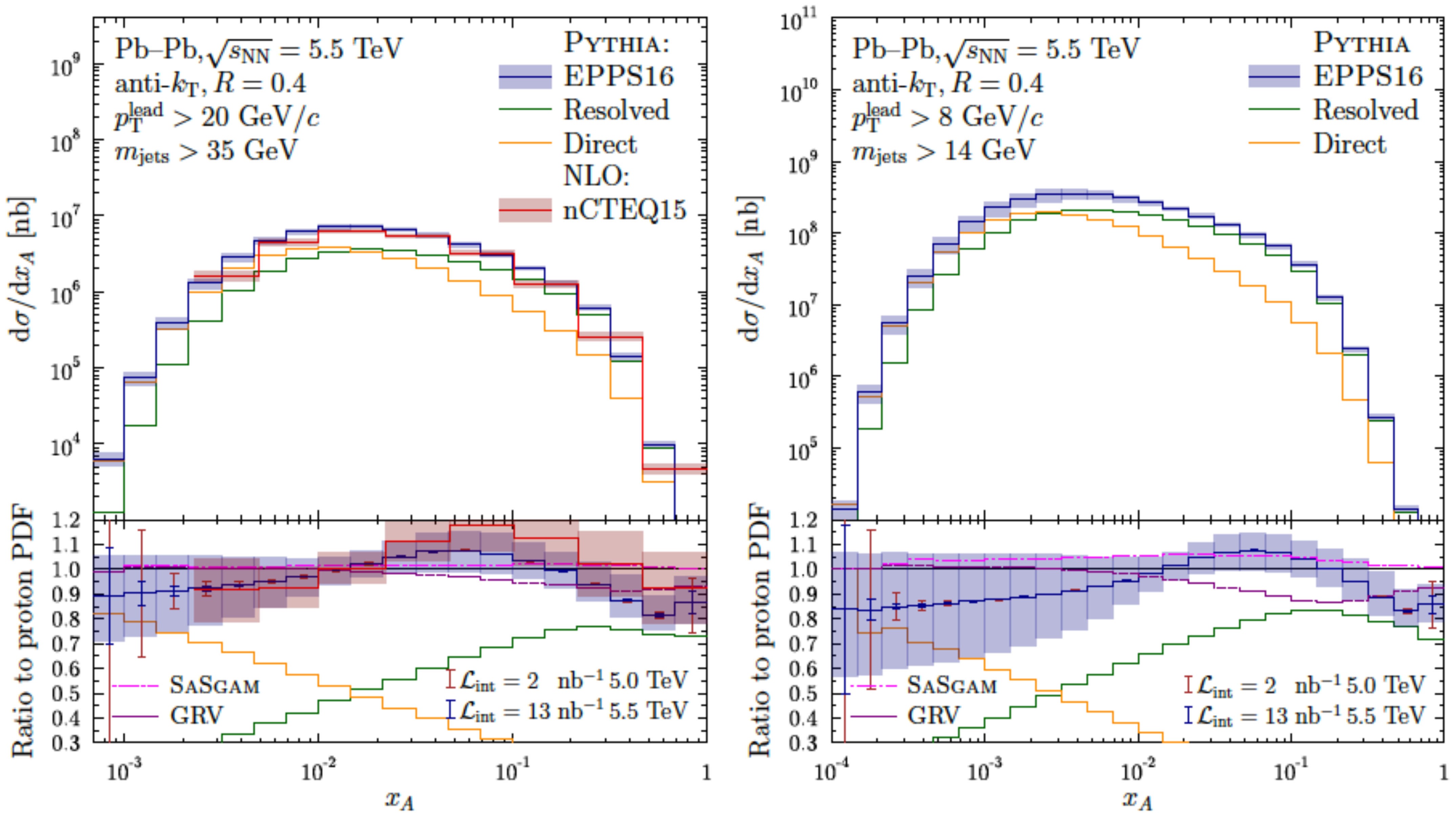
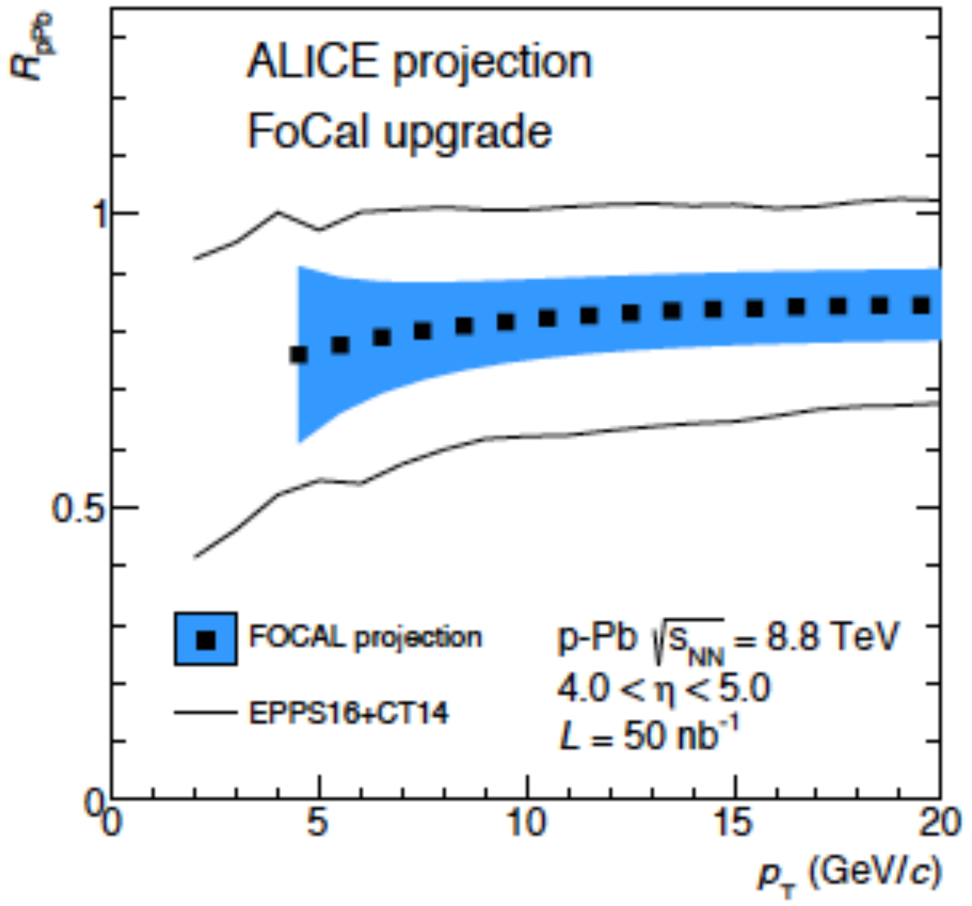
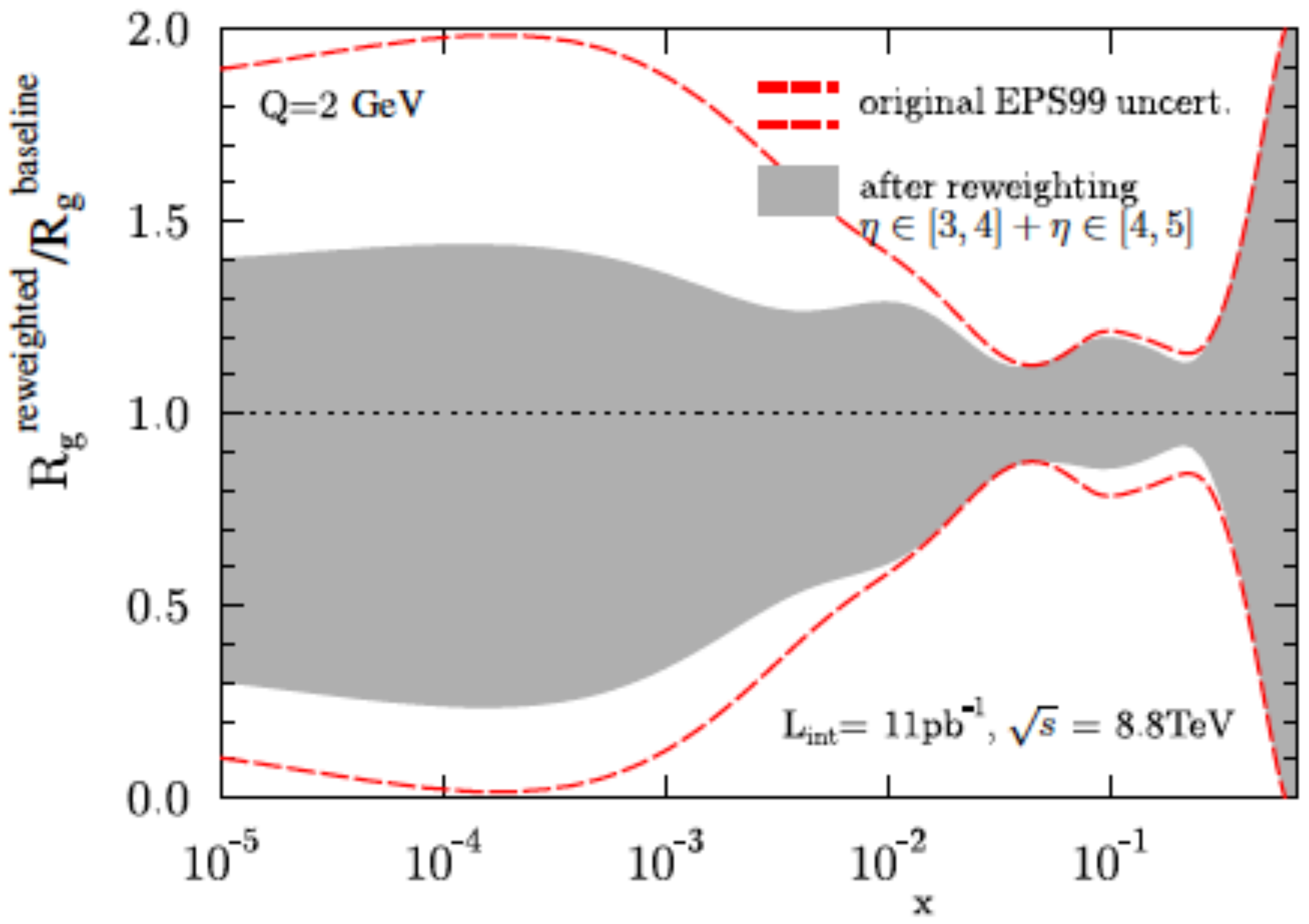
1812.06772

Dijets in UPCs

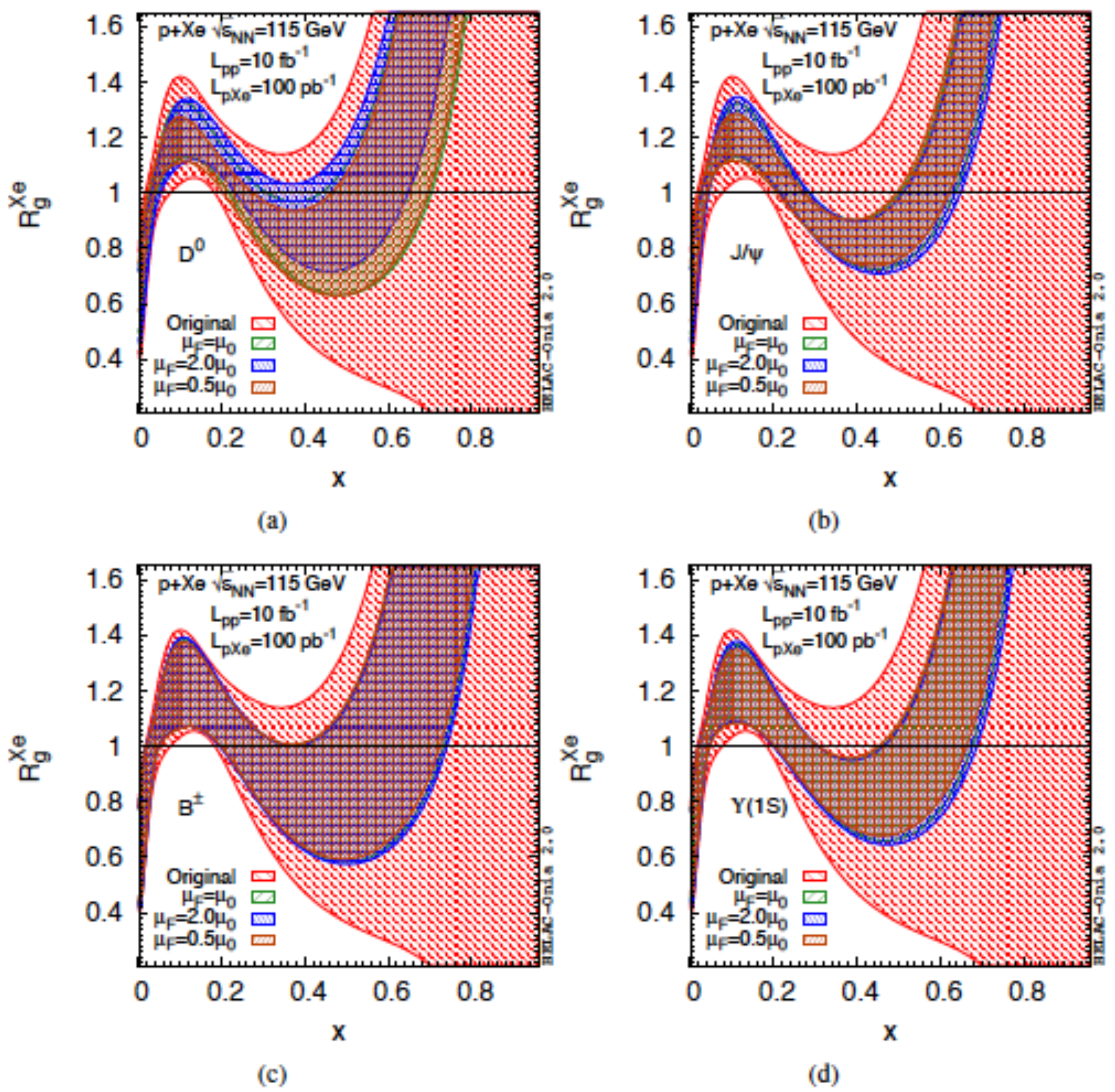


Photons





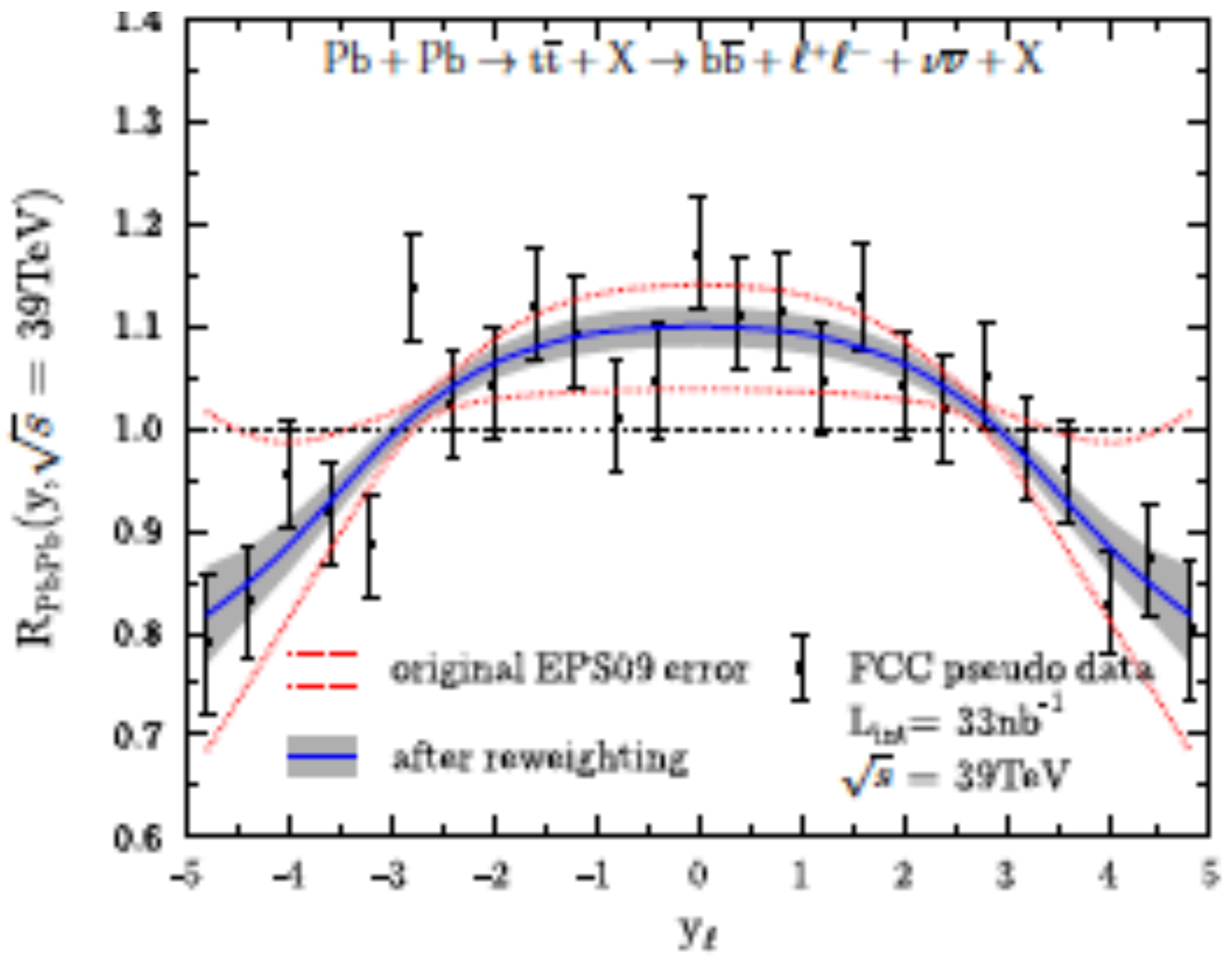
nPDFs in pA beyond HL-LHC:



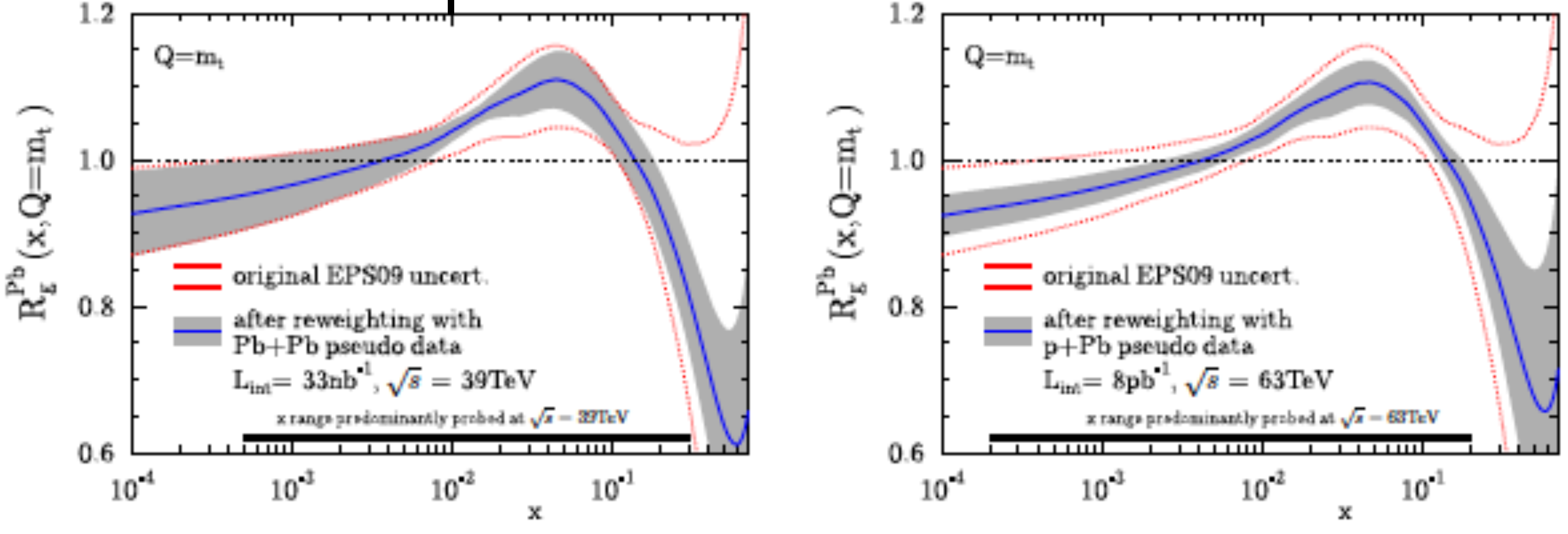
(a) (b) (c) (d)

D, B mesons and quarkonia in pXe in FT mode

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



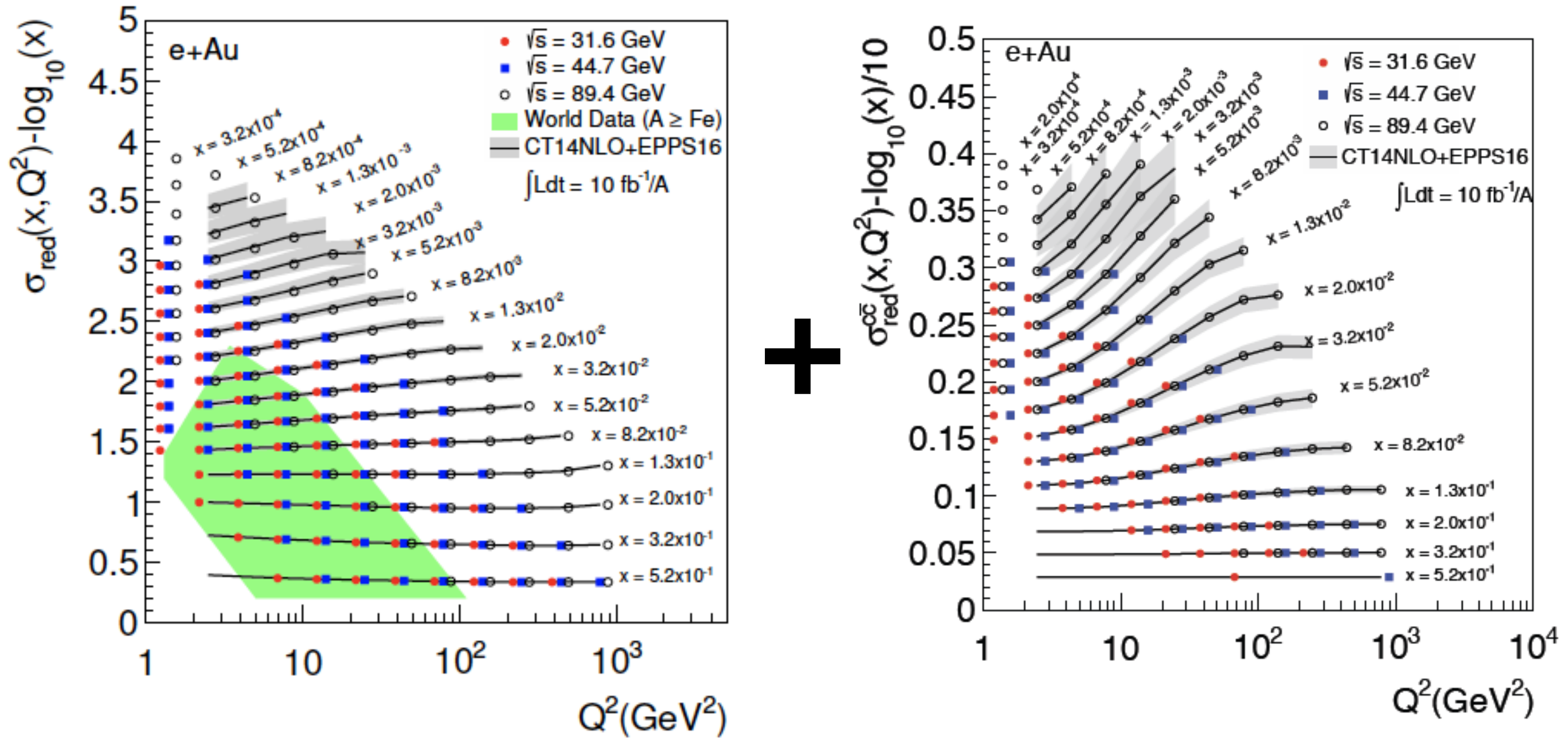
Top

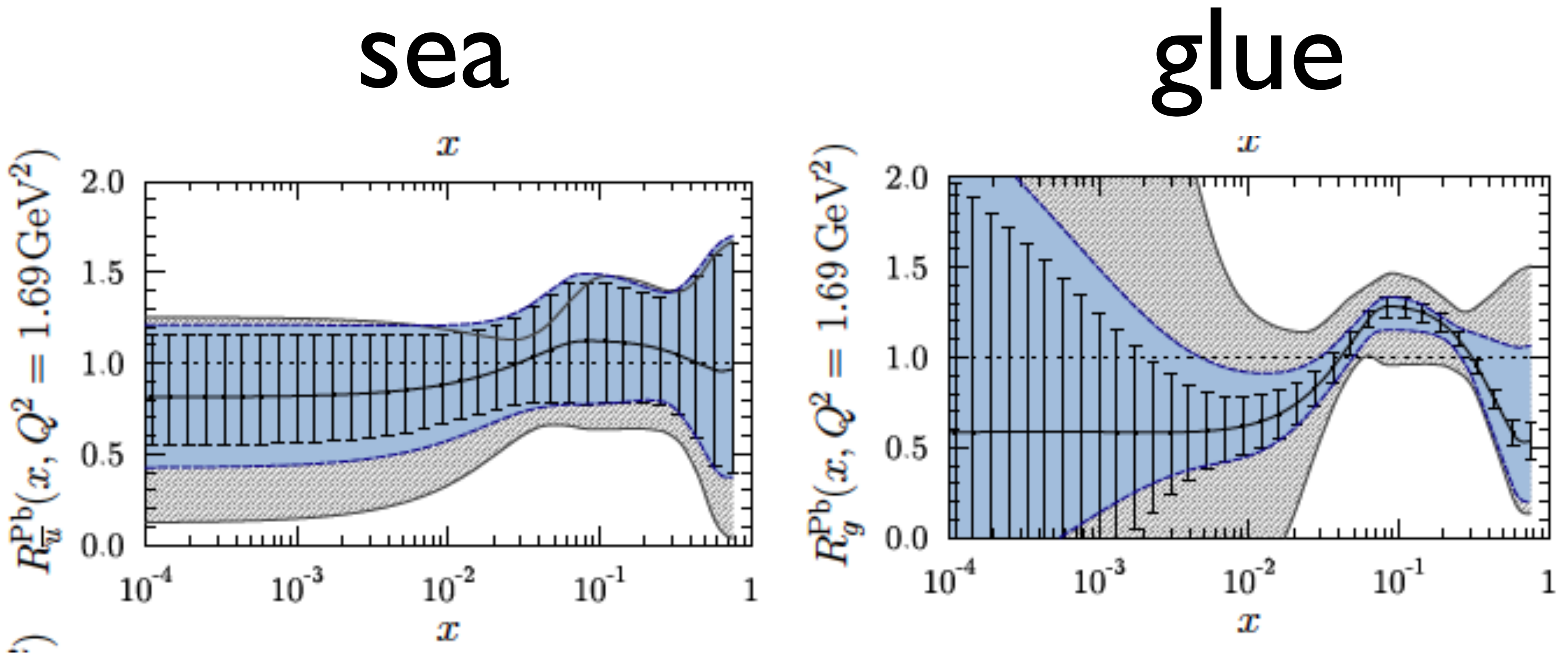


nPDFs @ eA colliders:

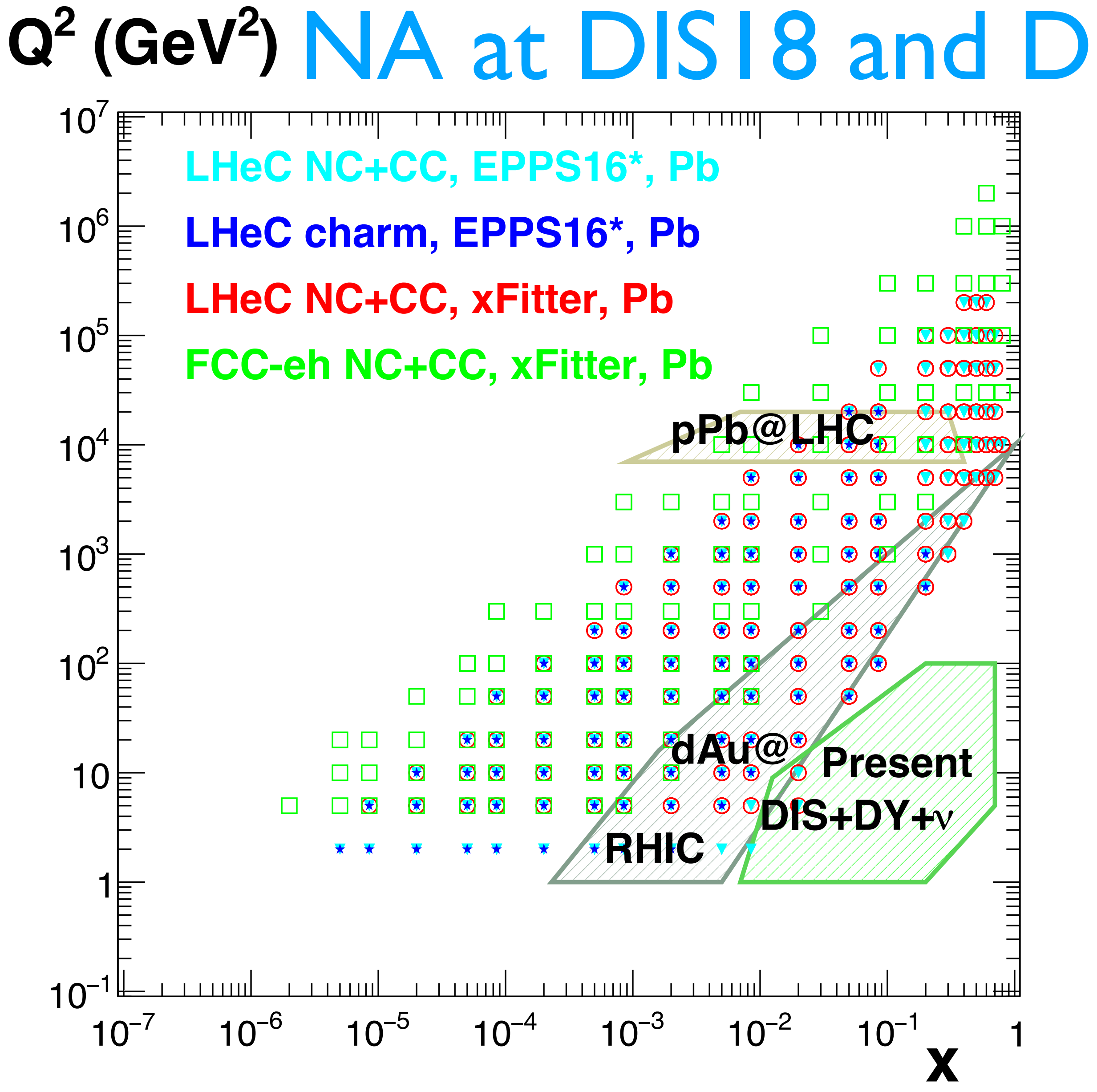
- LHeC/FCC-eh ePb and EIC eAu pseudodata included in EPPS16-like global fits and HERAPDF DIS-only fits: large impact.
- HF separation has sizeable impact (on glue).
- Not yet included: beauty, c-tagged CC for strange.

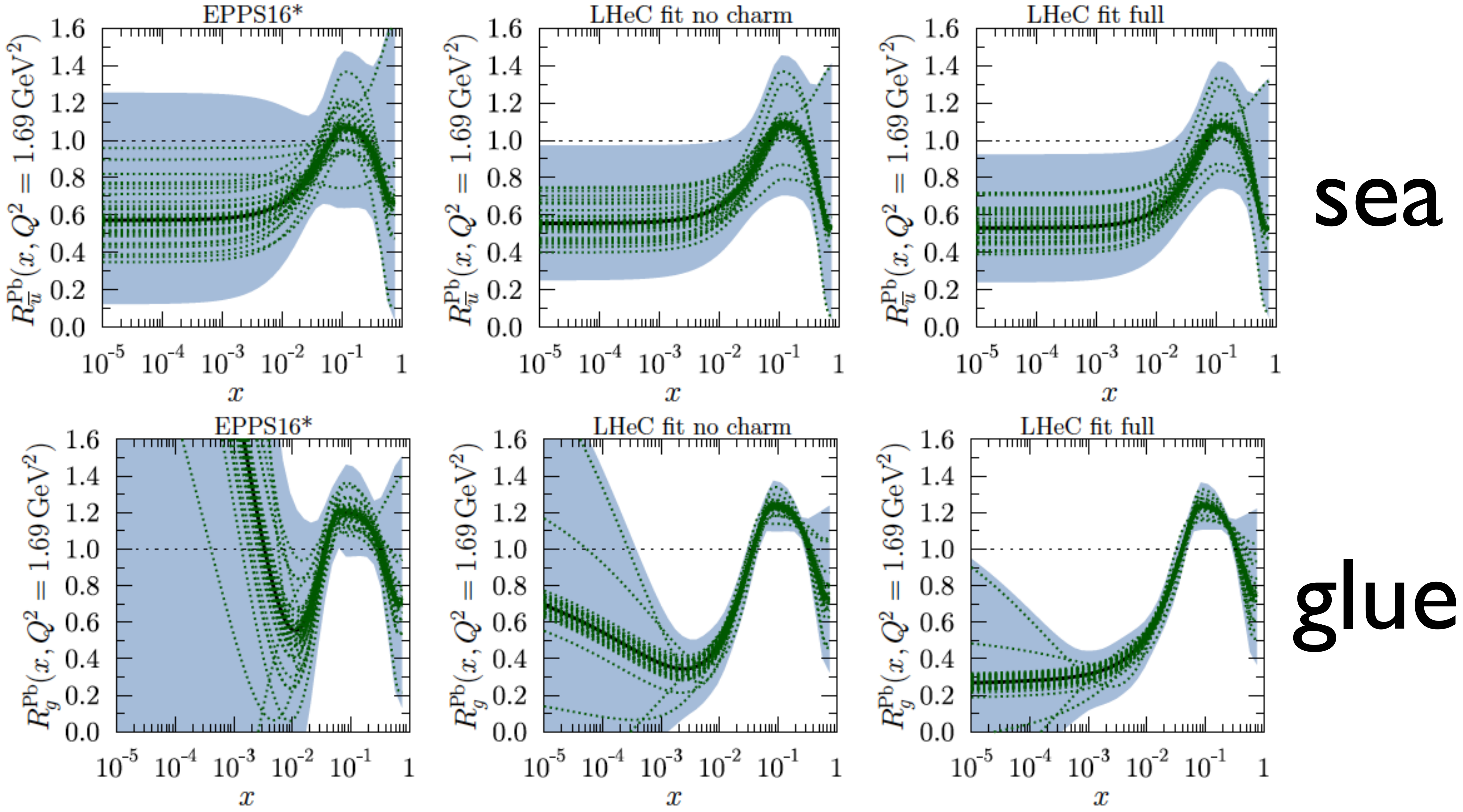
1708.05654





NA at DIS18 and DIS19





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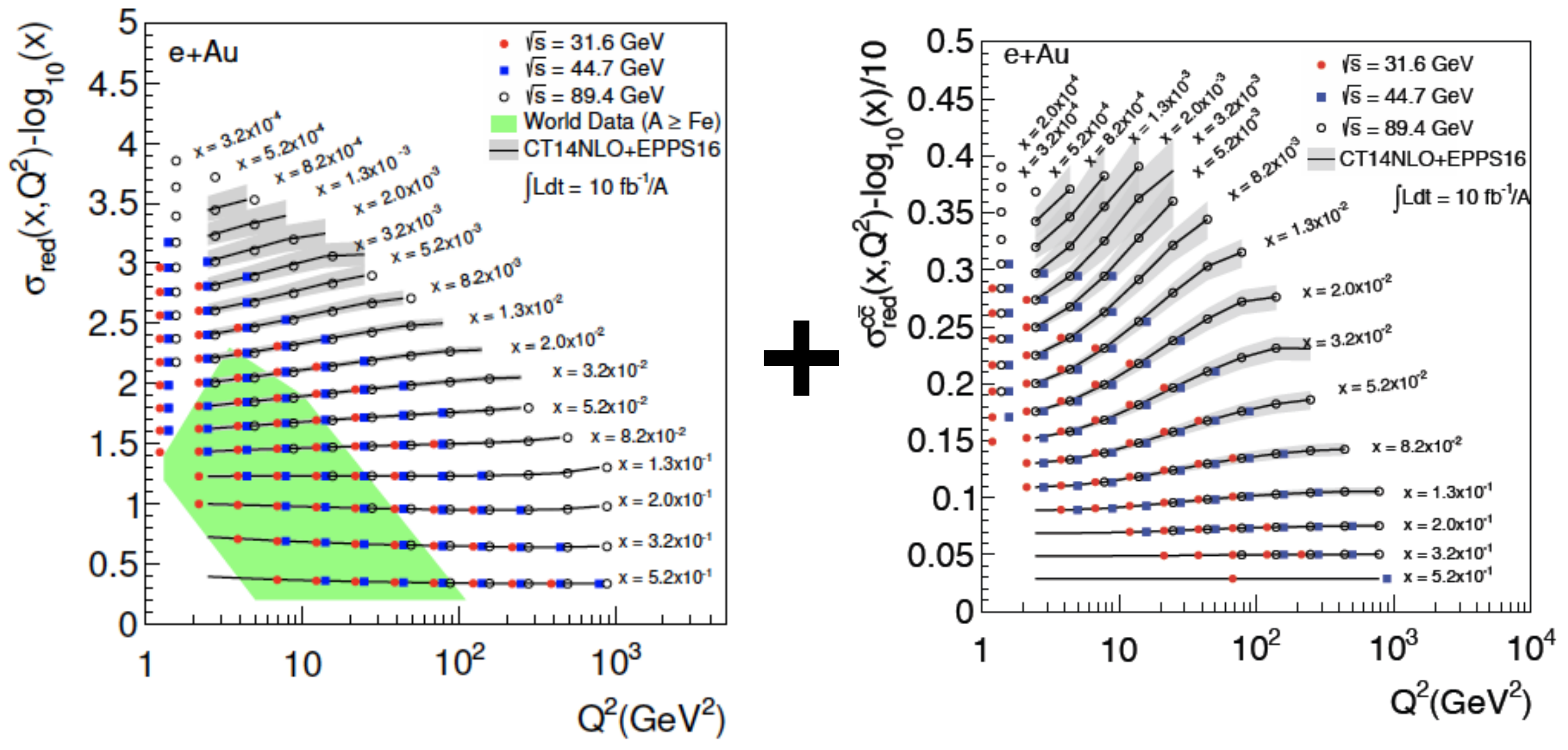

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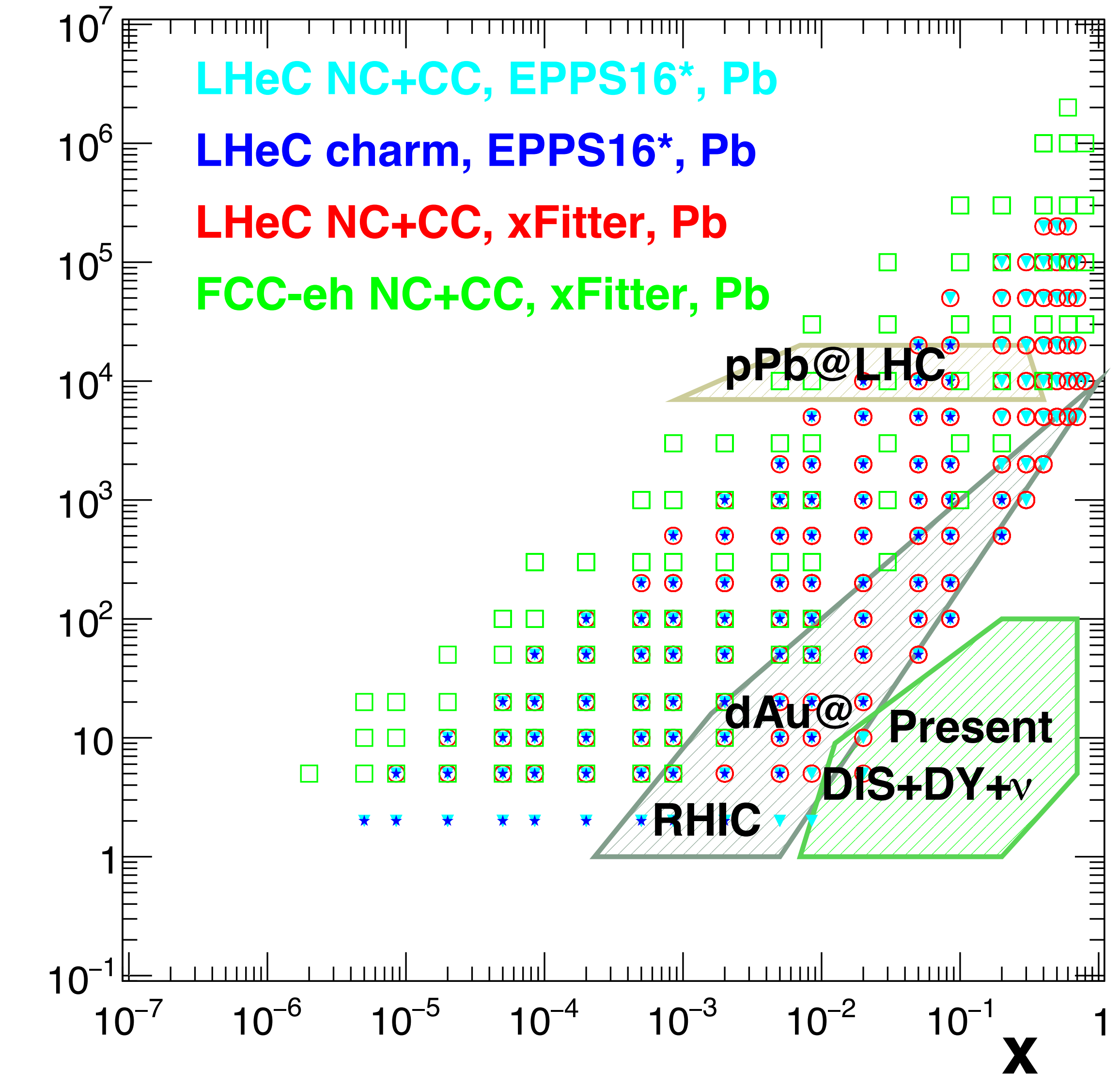
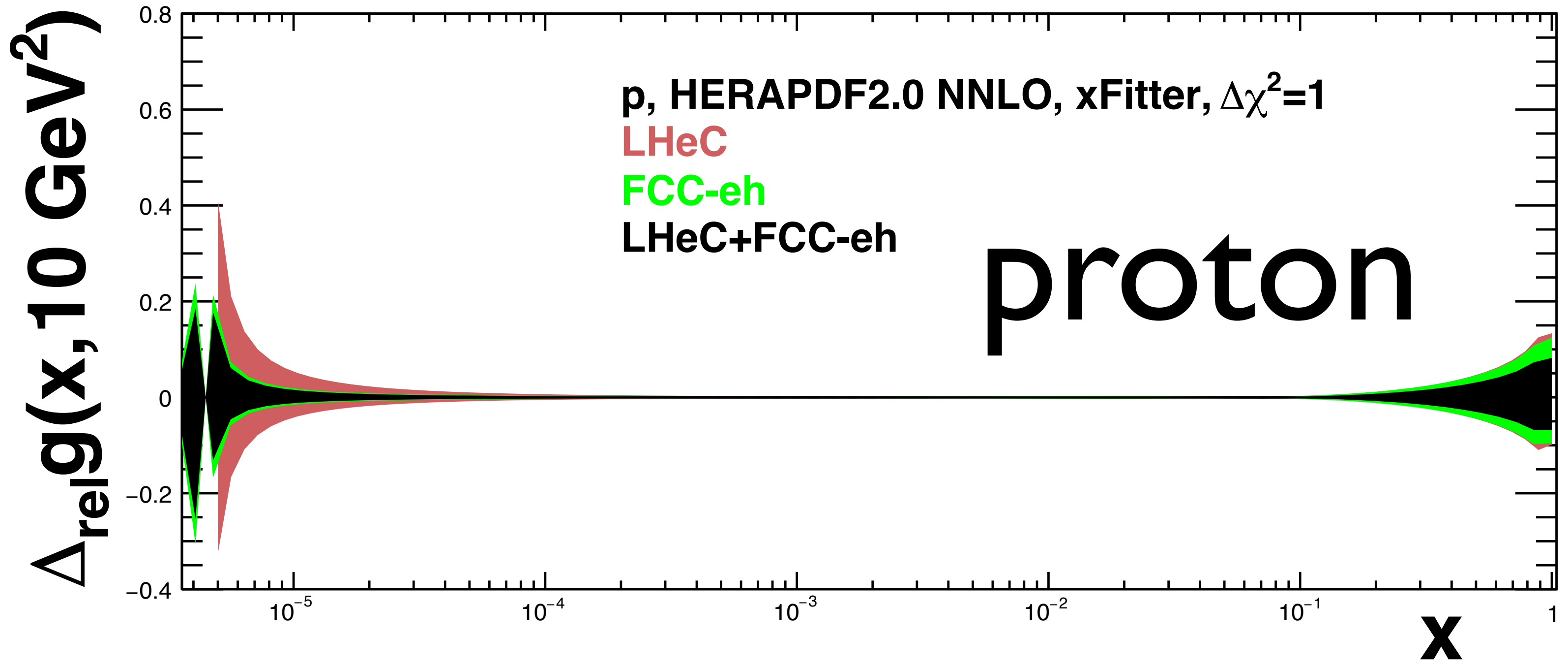
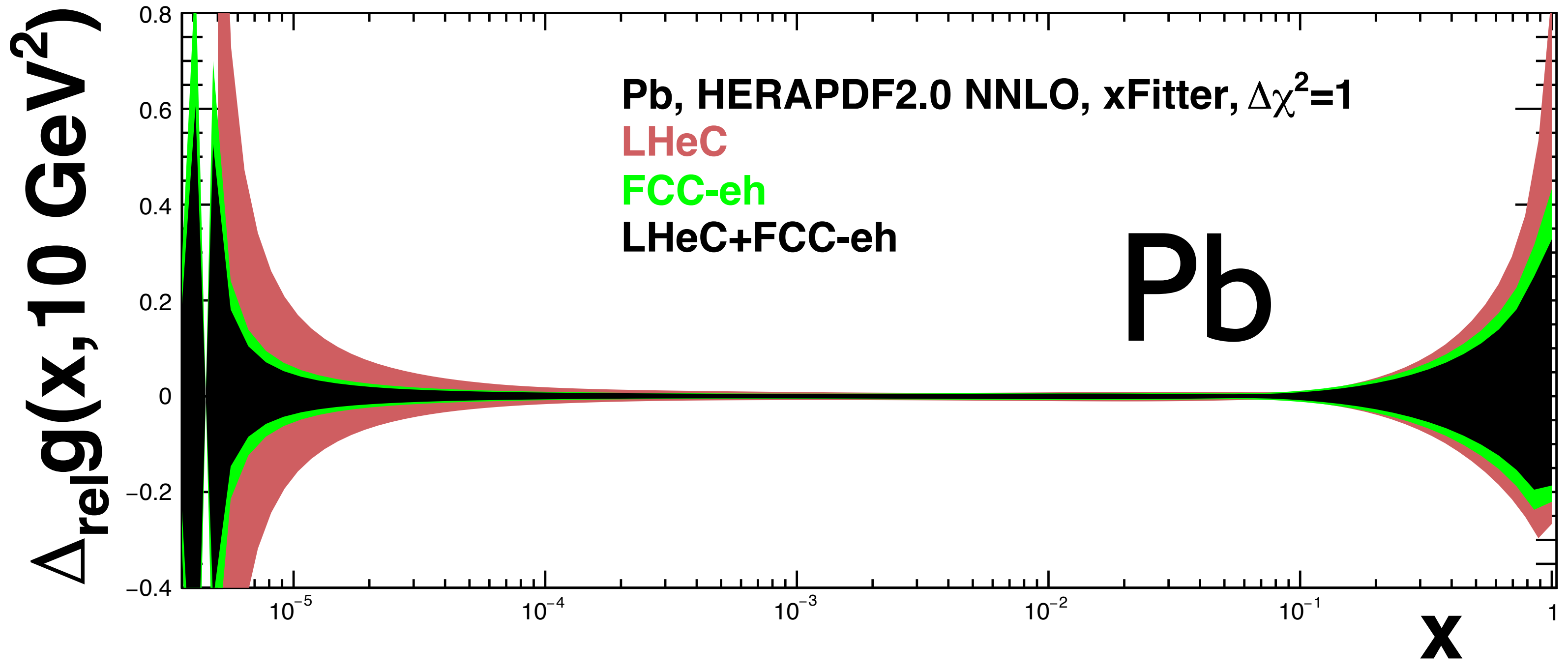
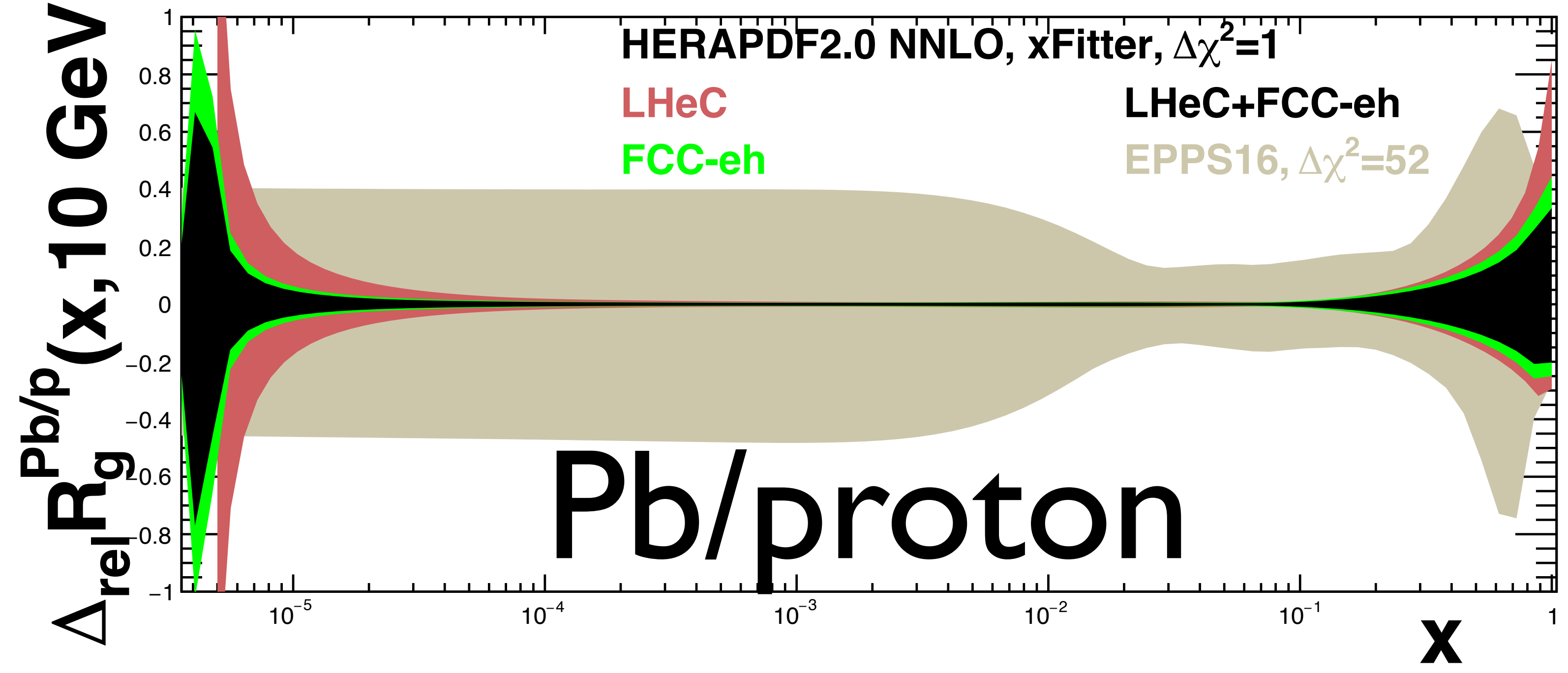


Ultimate experimental precision

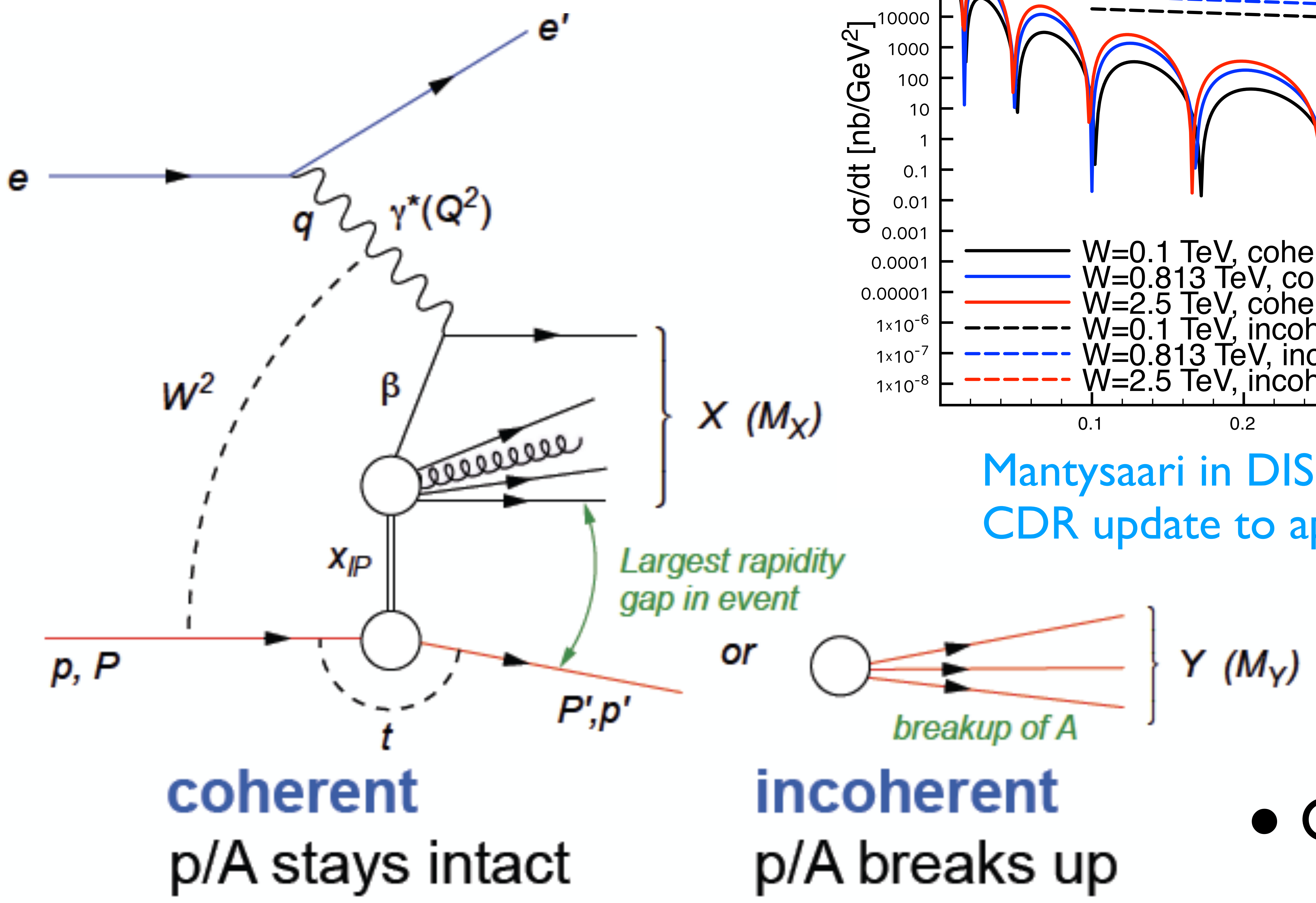


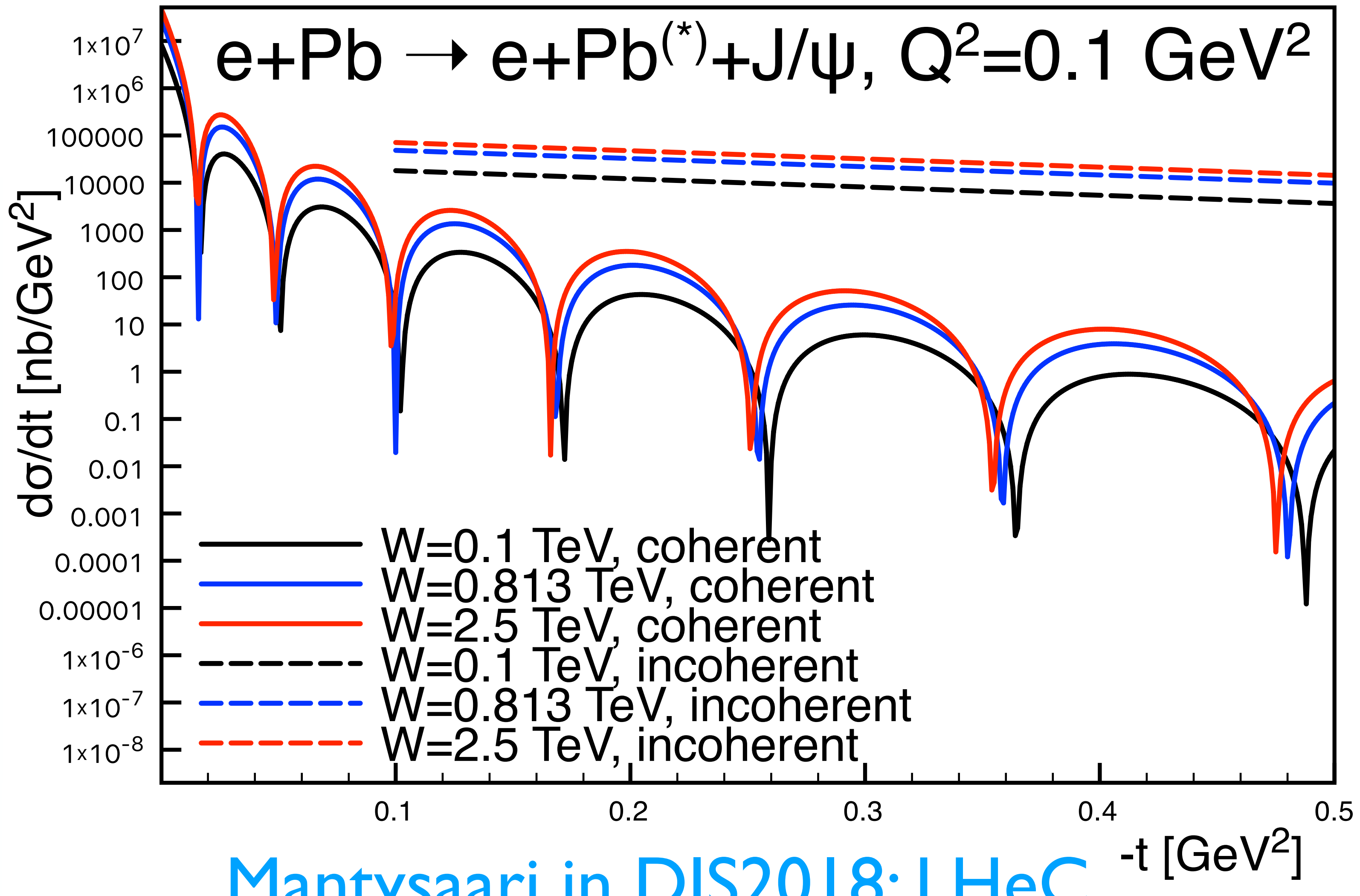




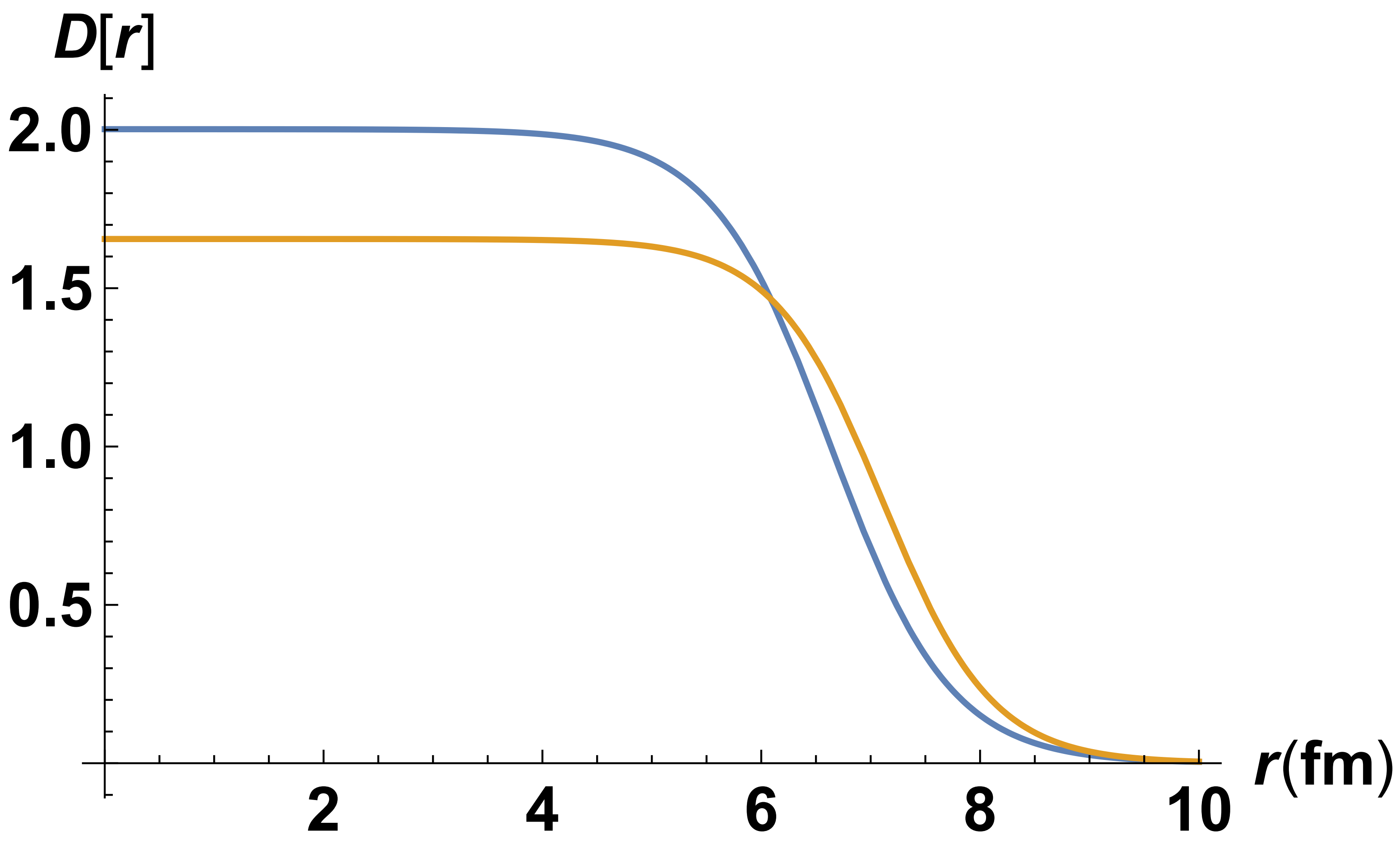
3D - GPDs and TMDs (I):

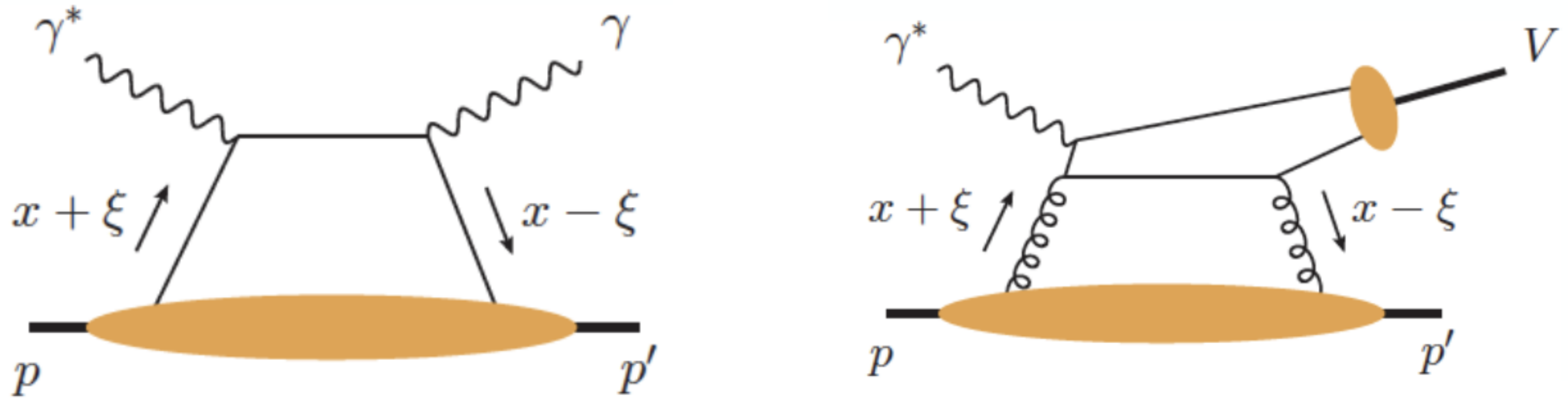
- The extraction of 3D-structure (GPDs and TMDs and their evolution equations) is a huge undergoing program: scarcely known in the proton, **mostly unknown in nuclei**.





Mantysaari in DIS2018; LHeC CDR update to appear





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

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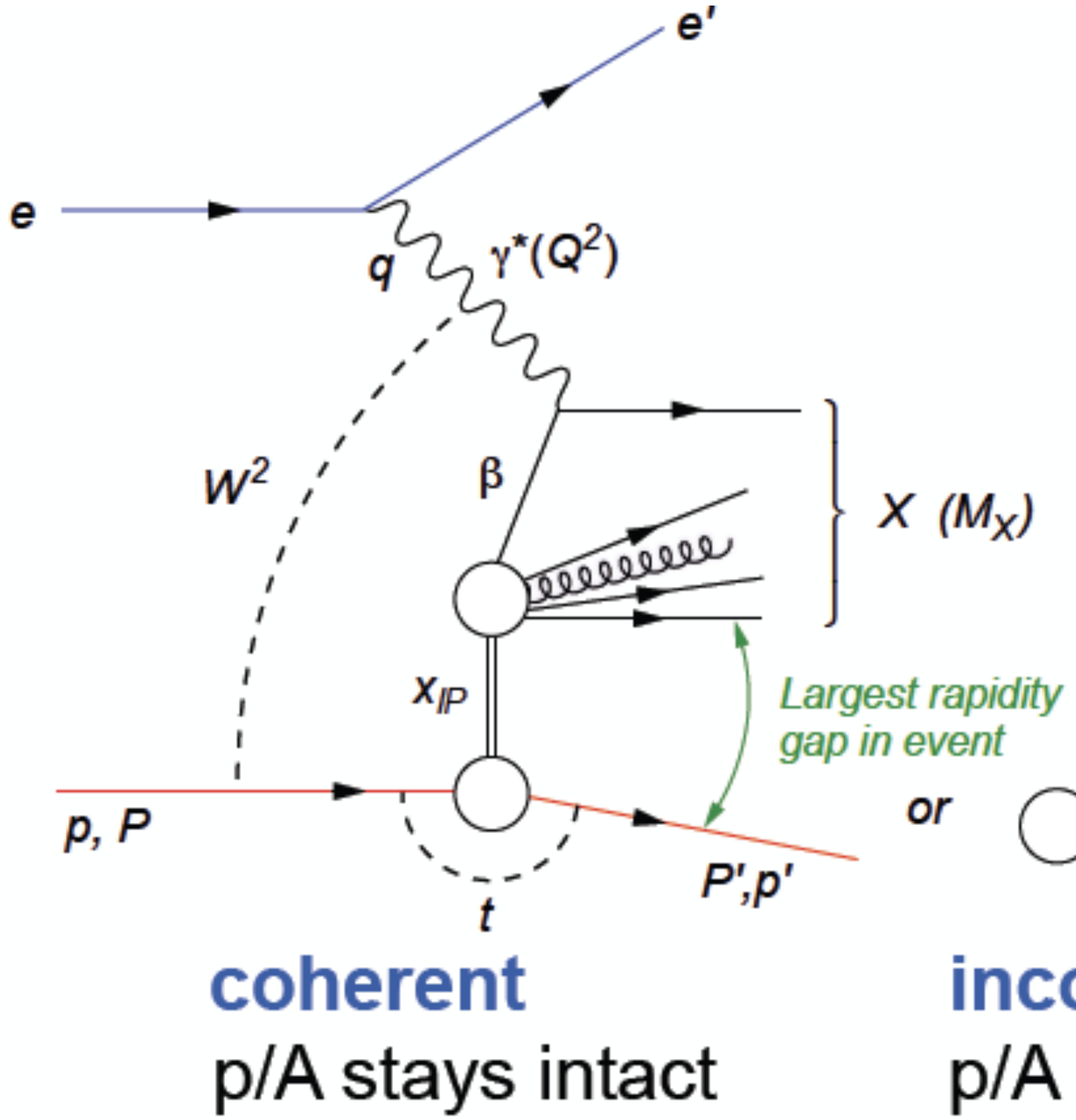
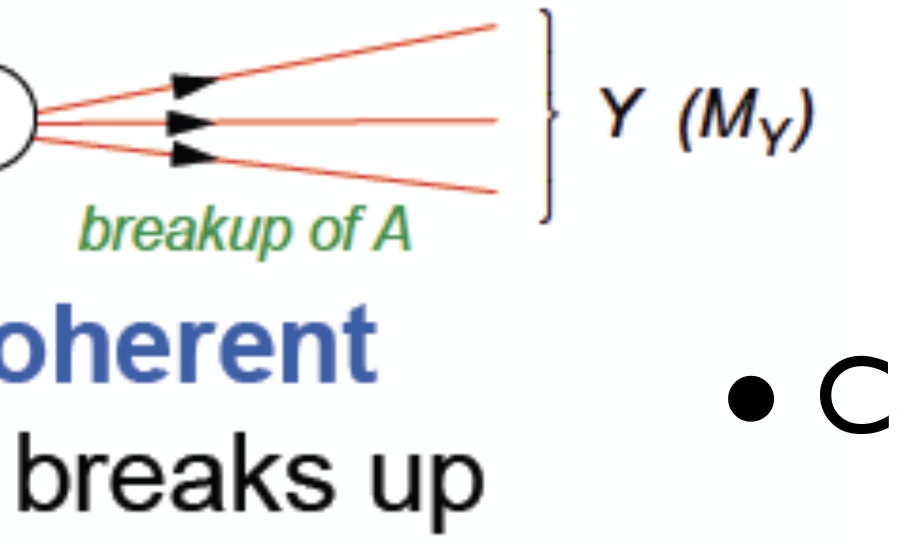
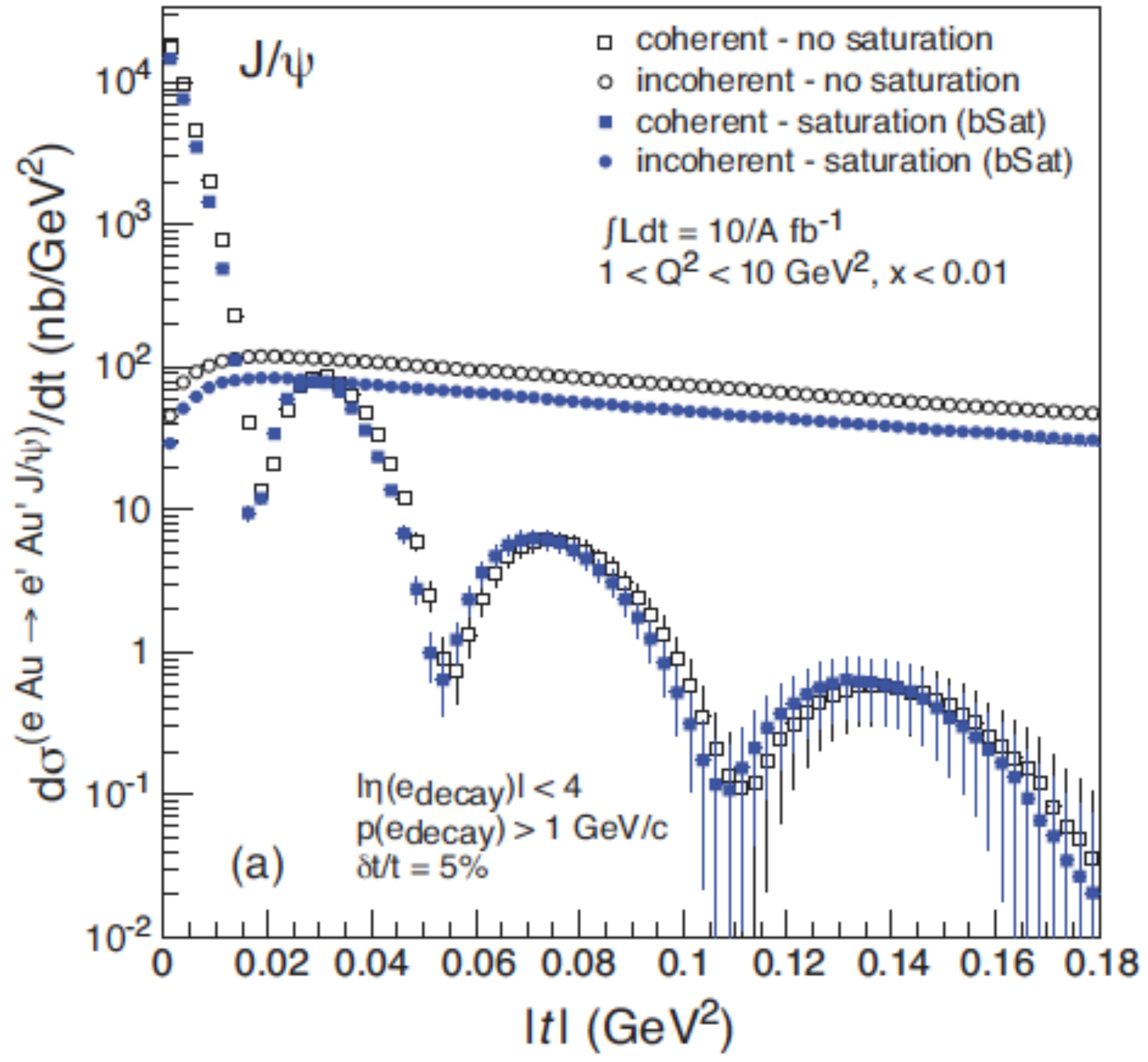
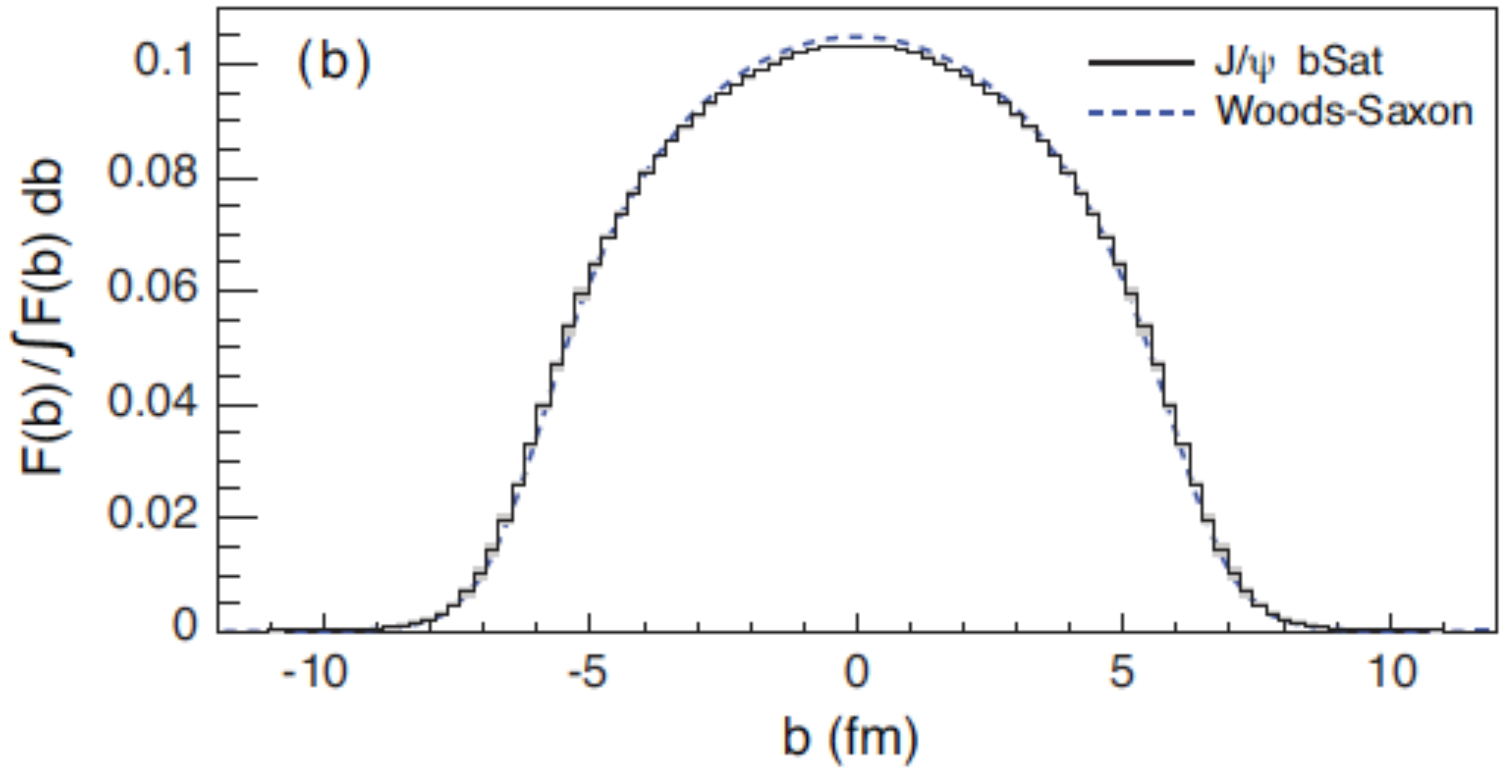
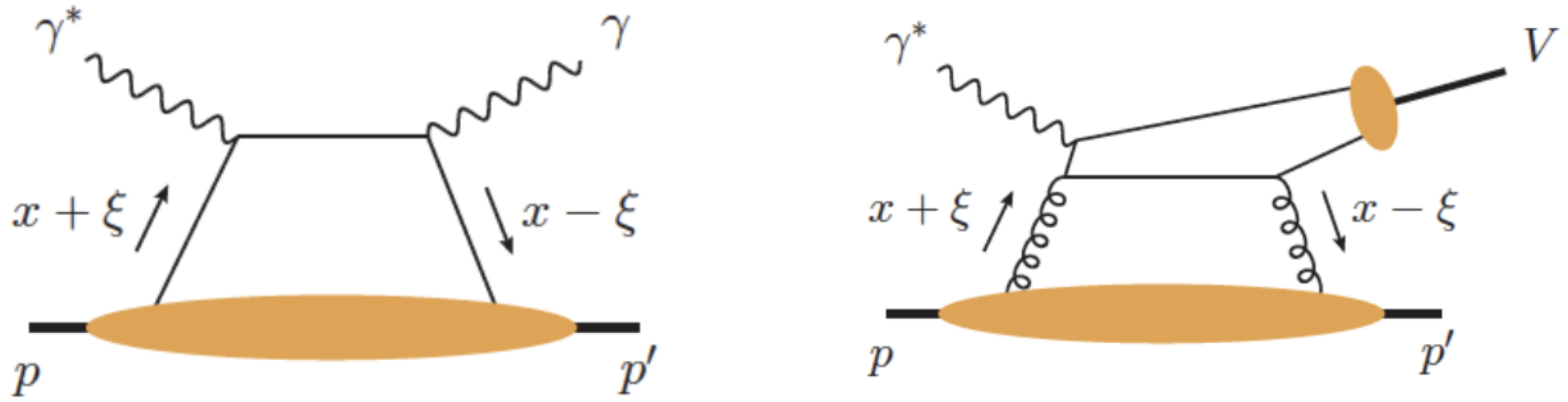






eAu at EIC, 1211.3048





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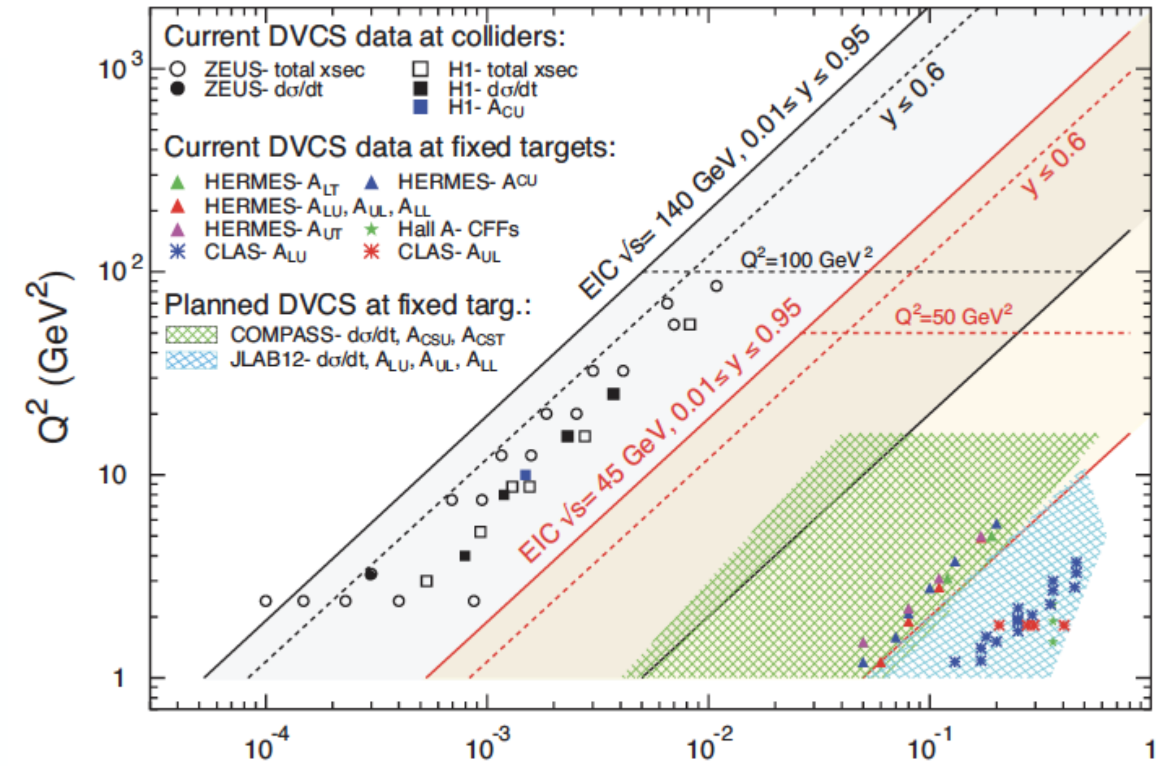
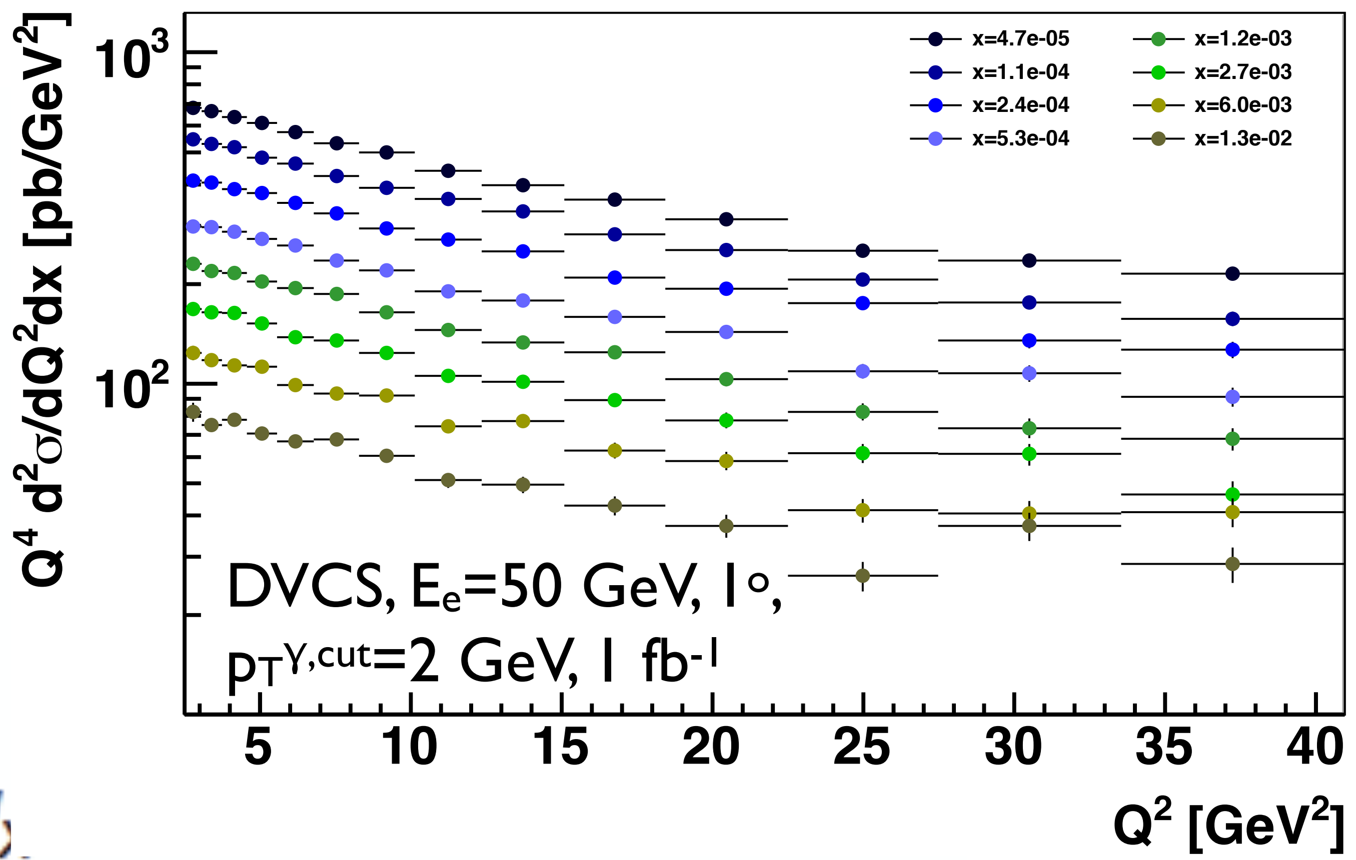
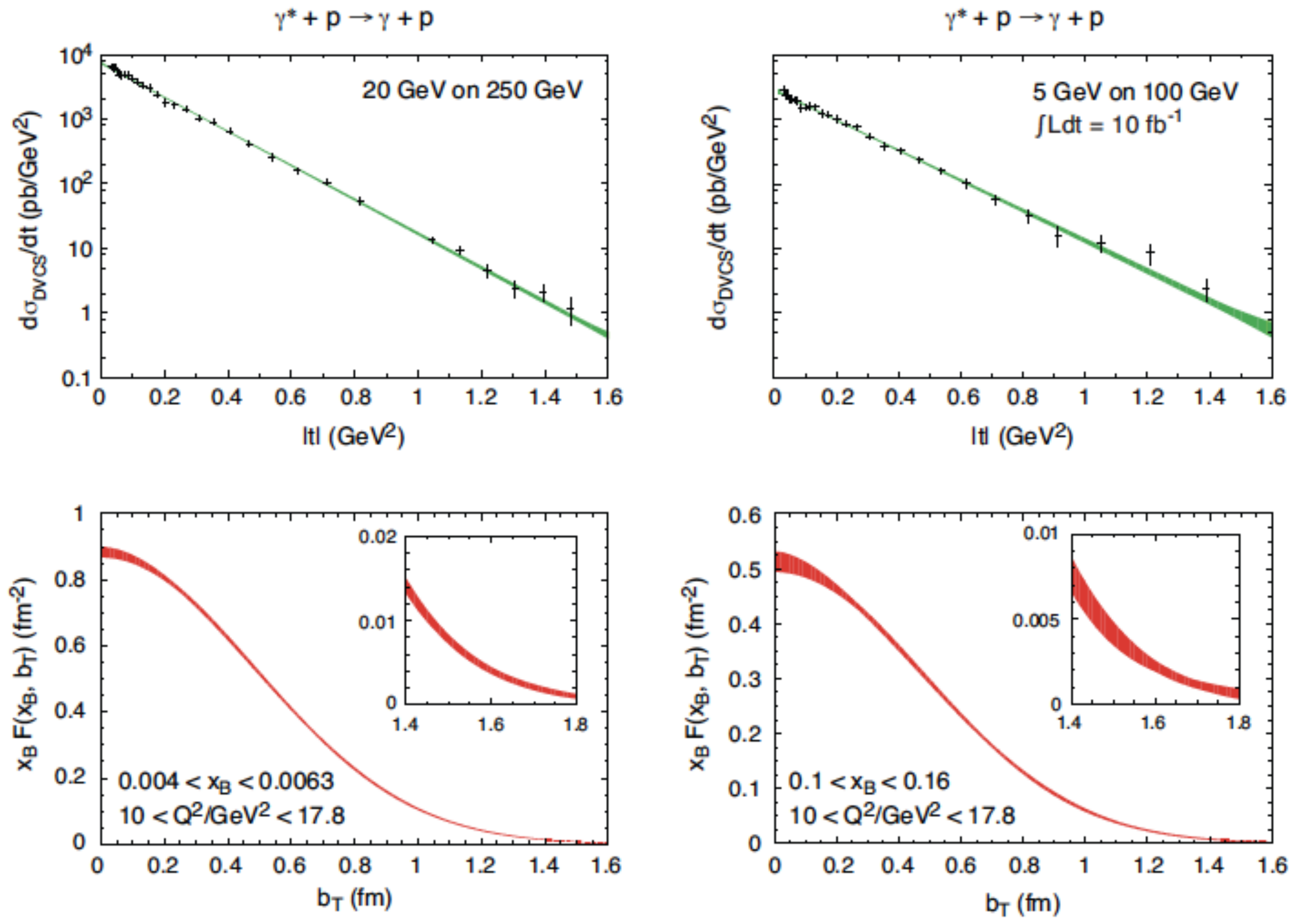
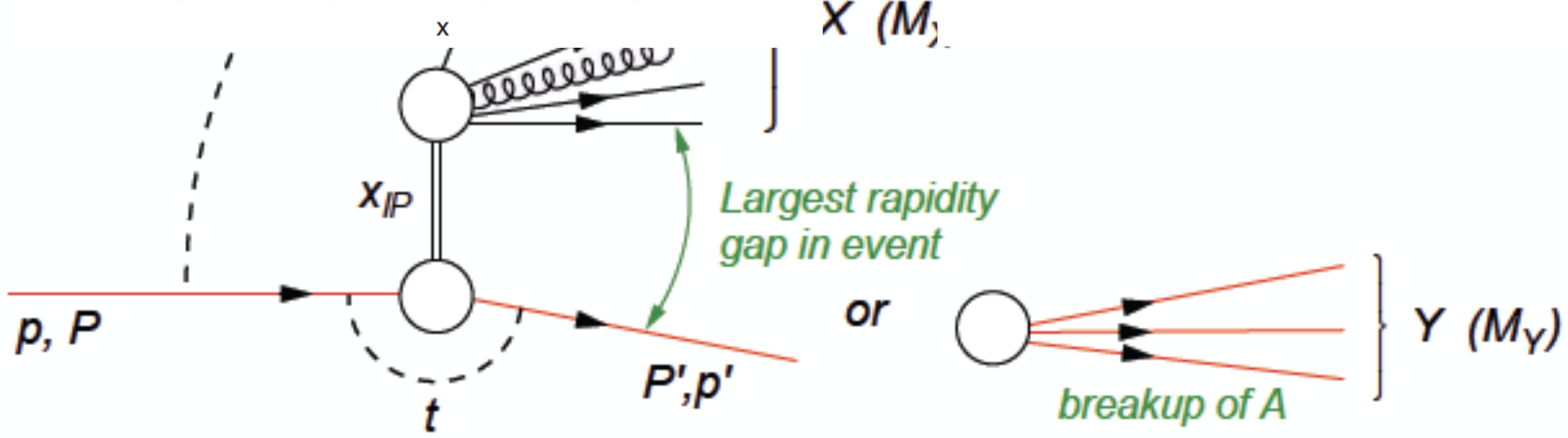
EIC, 1212.1701



LHeC 1206.2913

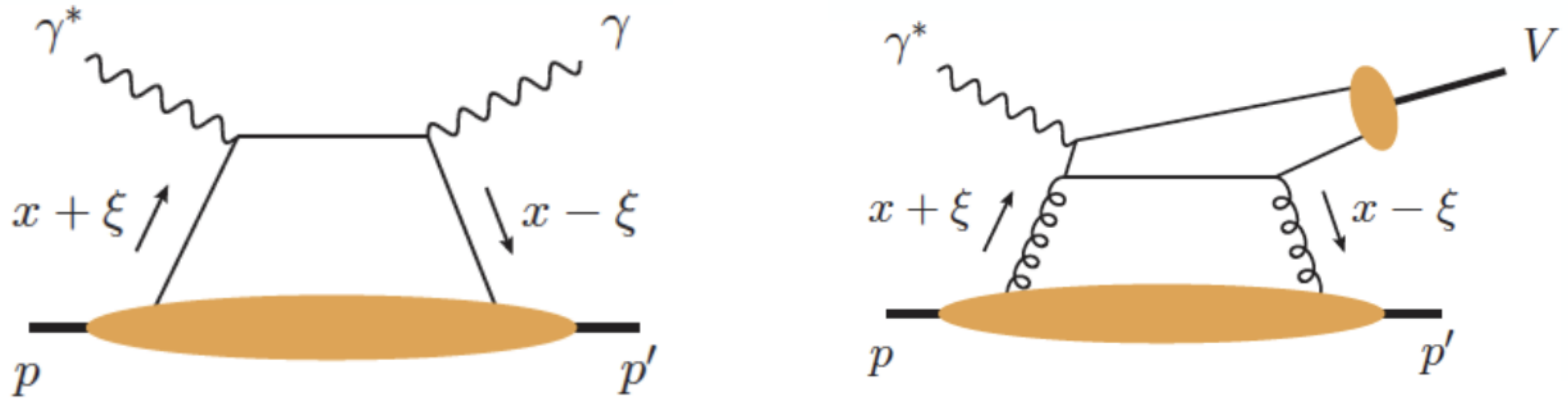






coherent
p/A stays intact

incoherent
p/A breaks up



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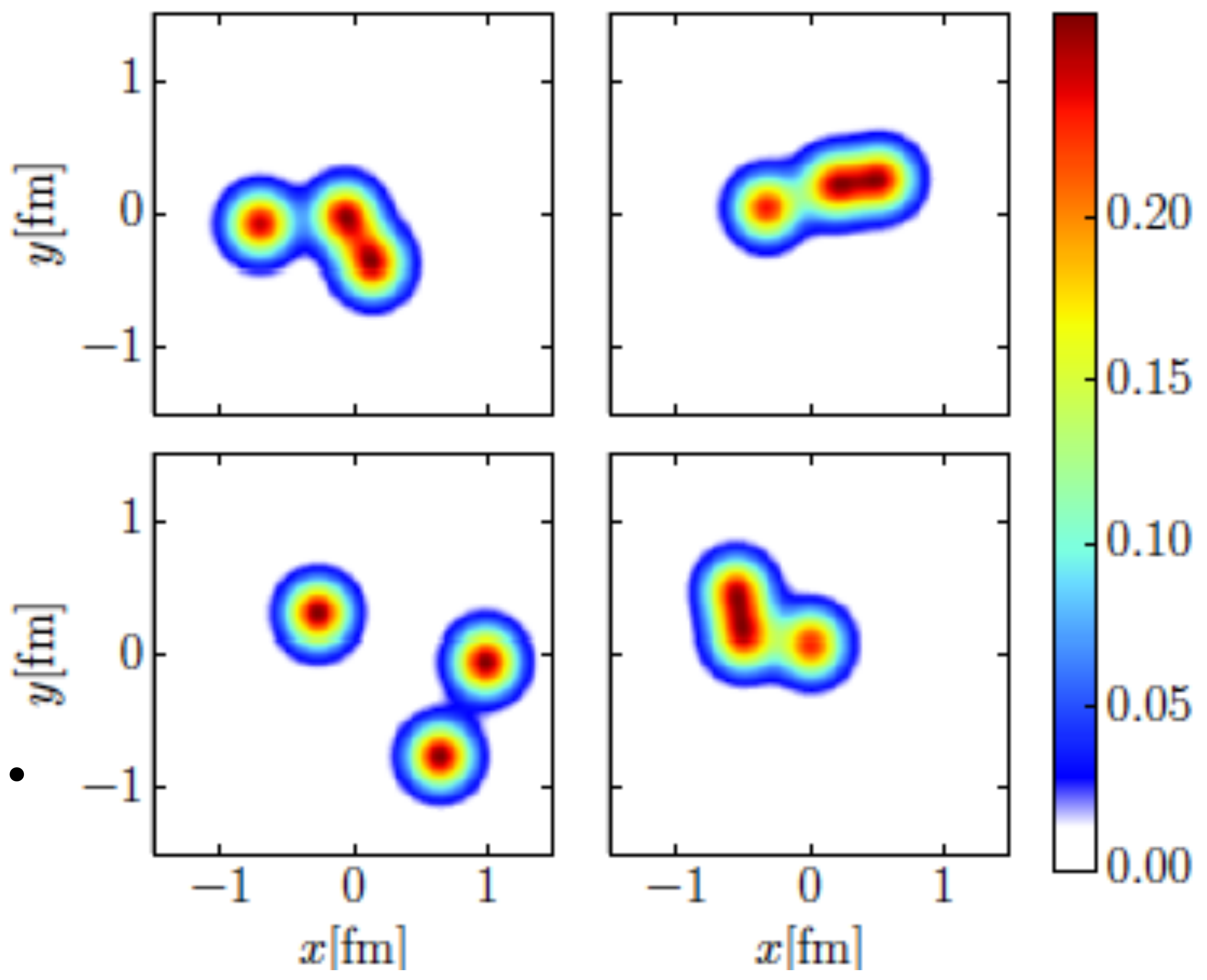
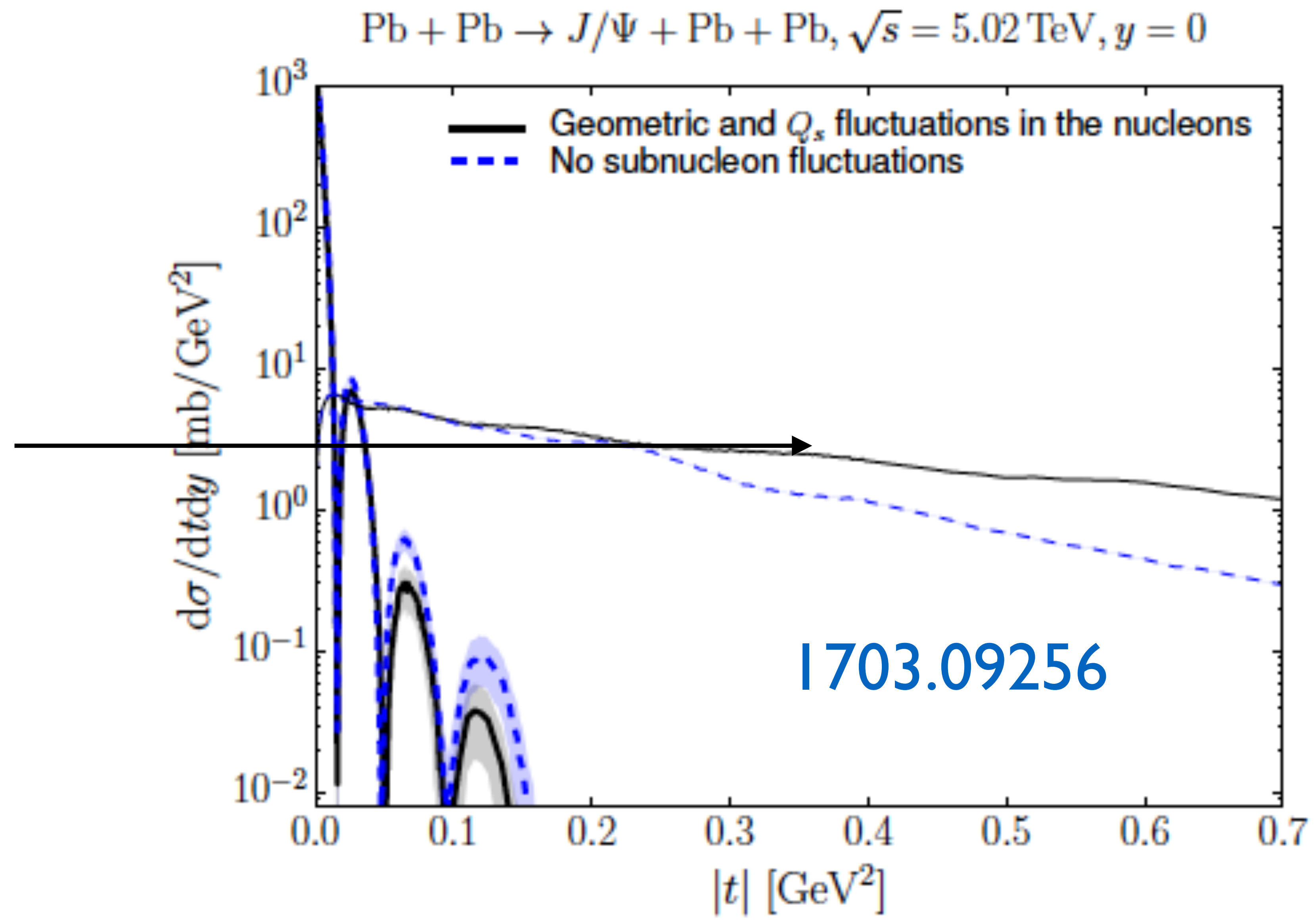
3D - GPDs and TMDs (I):

- Incoherent diffraction sensitive to fluctuations: hot spots? that determine the initial stage of HIC, the distribution of MPIs,…
- Exclusive dijet production and sensitive to the gluon Wigner distribution, forward DDbar to g TMDs.

$$\left.\frac{d\sigma(\gamma p \to \mathrm{J}/\psi p)}{dt}\right|_{T,L} = \frac{(R_g^{T,L})^2}{16\pi}\left|\left\langle A(x,Q^2,\vec{\Delta})_{T,L}\right\rangle\right|^2$$

$$\left.\frac{d\sigma(\gamma p \to \mathrm{J}/\psi Y)}{dt}\right|_{T,L} = \frac{(R_g^{T,L})^2}{16\pi}\left(\left\langle\left|A(x,Q^2,\vec{\Delta})_{T,L}\right|^2\right\rangle - \left|\left\langle A(x,Q^2,\vec{\Delta})_{T,L}\right\rangle\right|^2\right)$$





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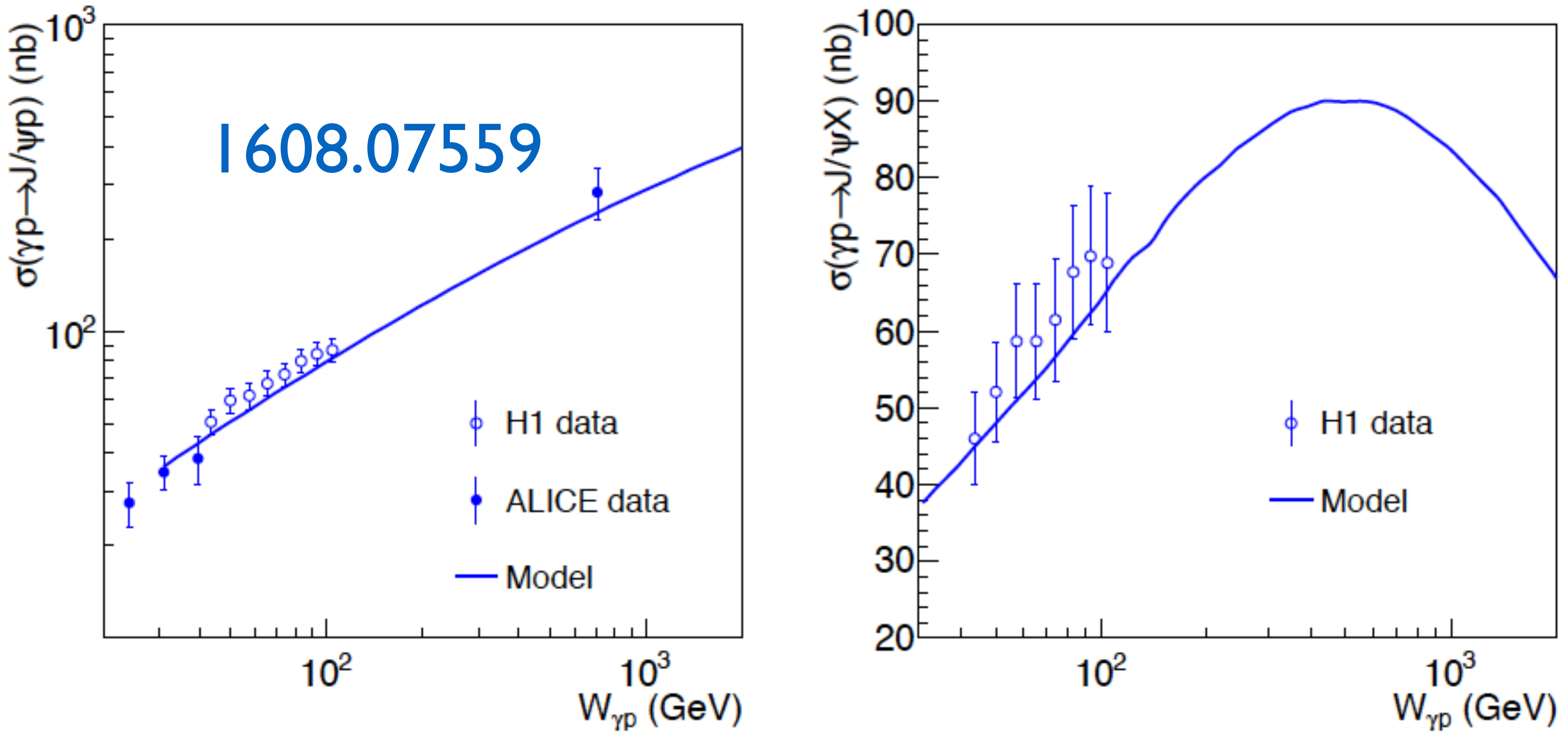


1608.07559

- Most of these observables can, in principle, be studied in UPCs, even for larger energies, but for photoproduction: separation of coherent and incoherent diffraction, reach and resolution in t,…?

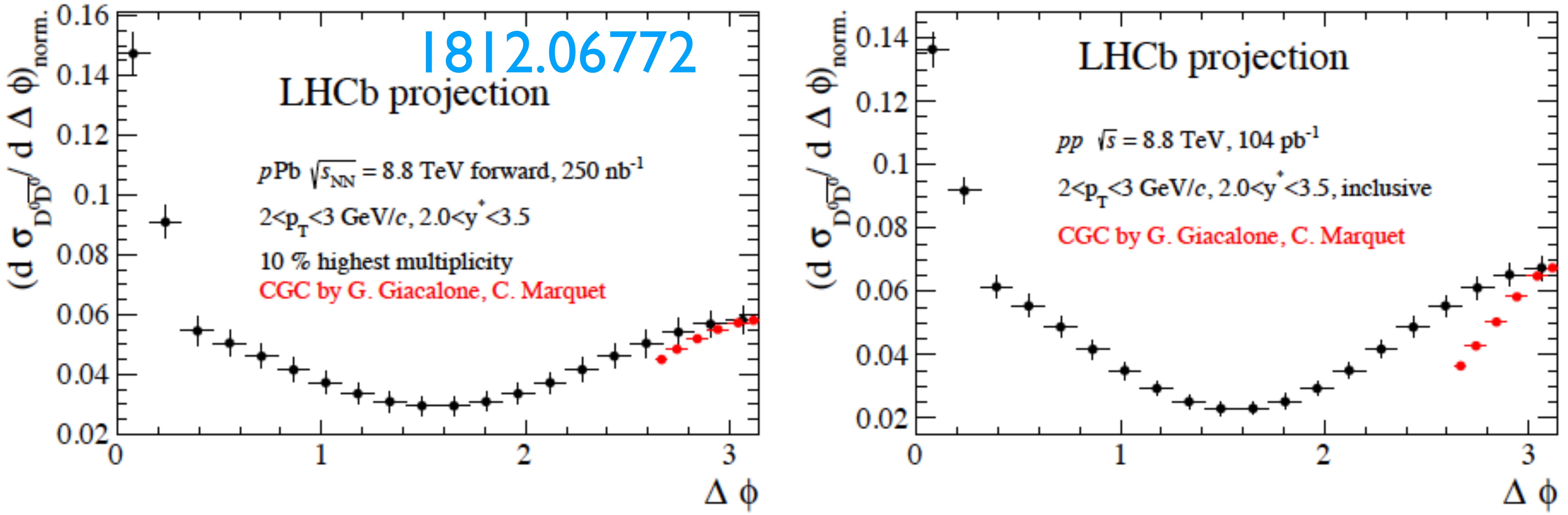
- Also extensive studies in FT mode (1807.00603), mainly focused on spin physics.

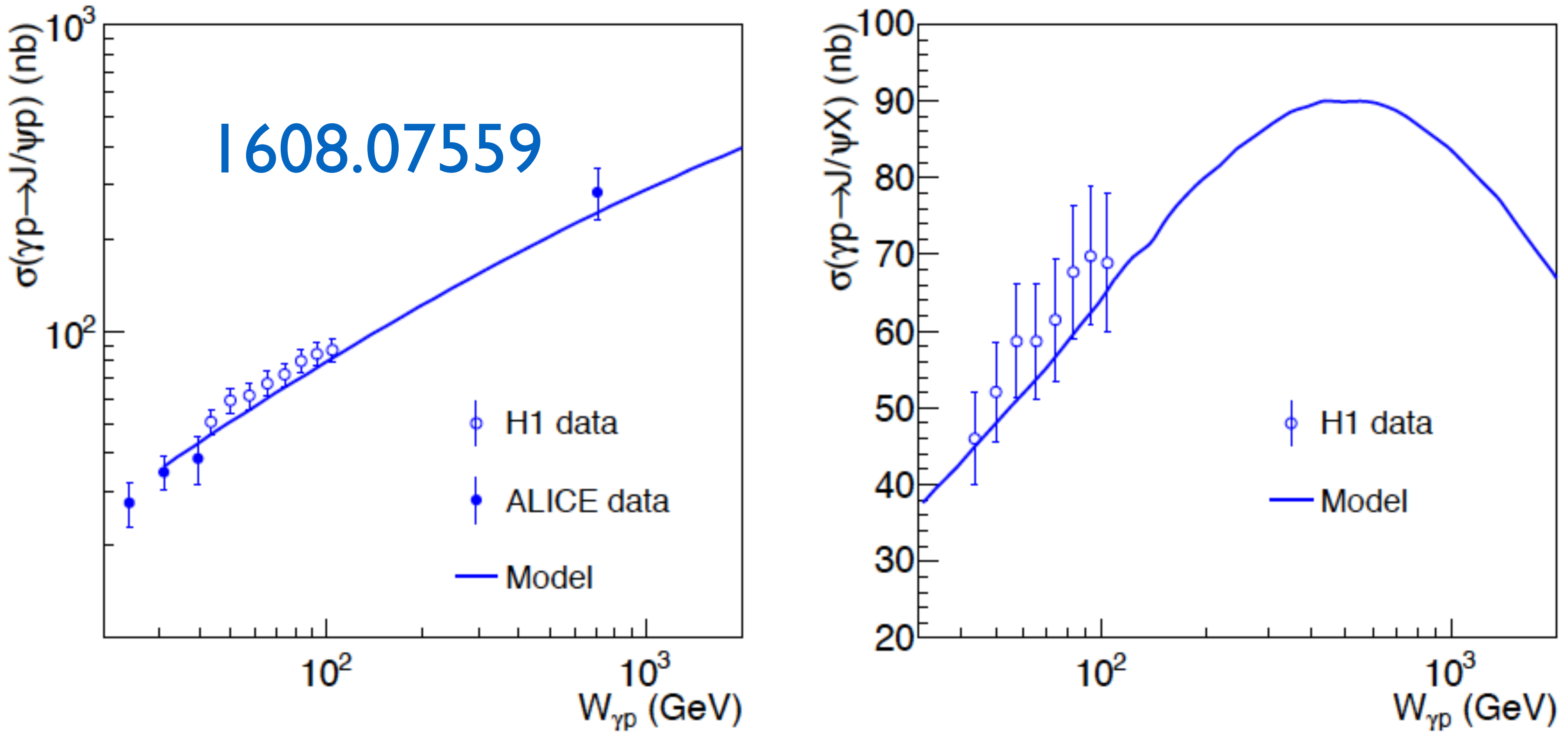
3D - GPDs and TMDs (I):

- Incoherent diffraction sensitive to fluctuations: hot spots? that determine the initial stage of HIC, the distribution of MPIs,…
- Exclusive dijet production and sensitive to the gluon Wigner distribution, forward DDbar to g TMDs.

$$\left.\frac{d\sigma(\gamma p\to \mathrm{J}/\psi p)}{dt}\right|_{T,L}=\frac{(R_g^{T,L})^2}{16\pi}\left|\left\langle A(x,Q^2,\vec{\Delta})_{T,L}\right\rangle\right|^2$$

$$\left.\frac{d\sigma(\gamma p\to \mathrm{J}/\psi Y)}{dt}\right|_{T,L}=\frac{(R_g^{T,L})^2}{16\pi}\left(\left\langle\left|A(x,Q^2,\vec{\Delta})_{T,L}\right|^2\right\rangle-\left|\left\langle A(x,Q^2,\vec{\Delta})_{T,L}\right\rangle\right|^2\right)$$





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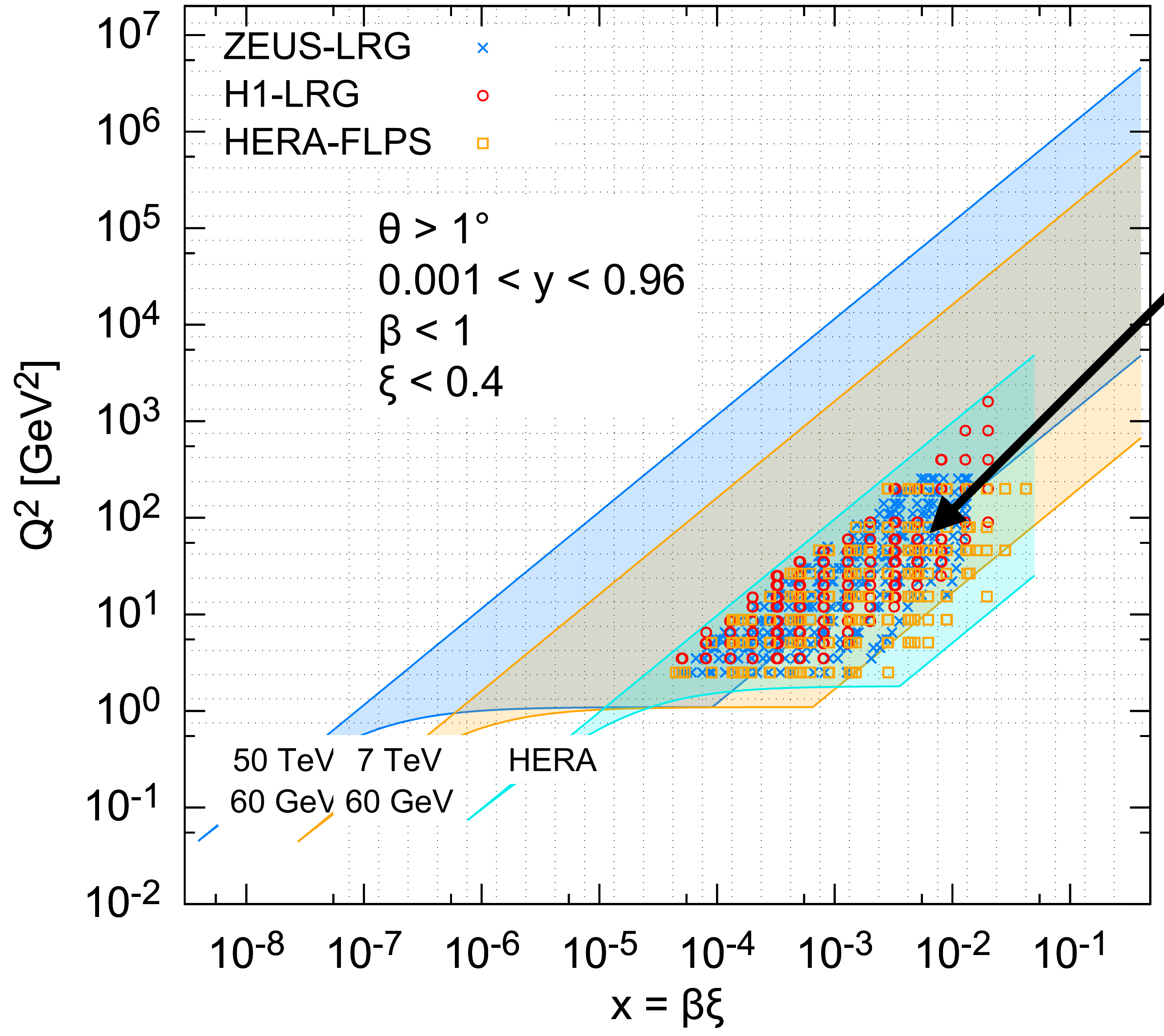
- Also extensive studies in FT mode (1807.00603), mainly focused on spin physics.

Nuclear diffractive PDFs:

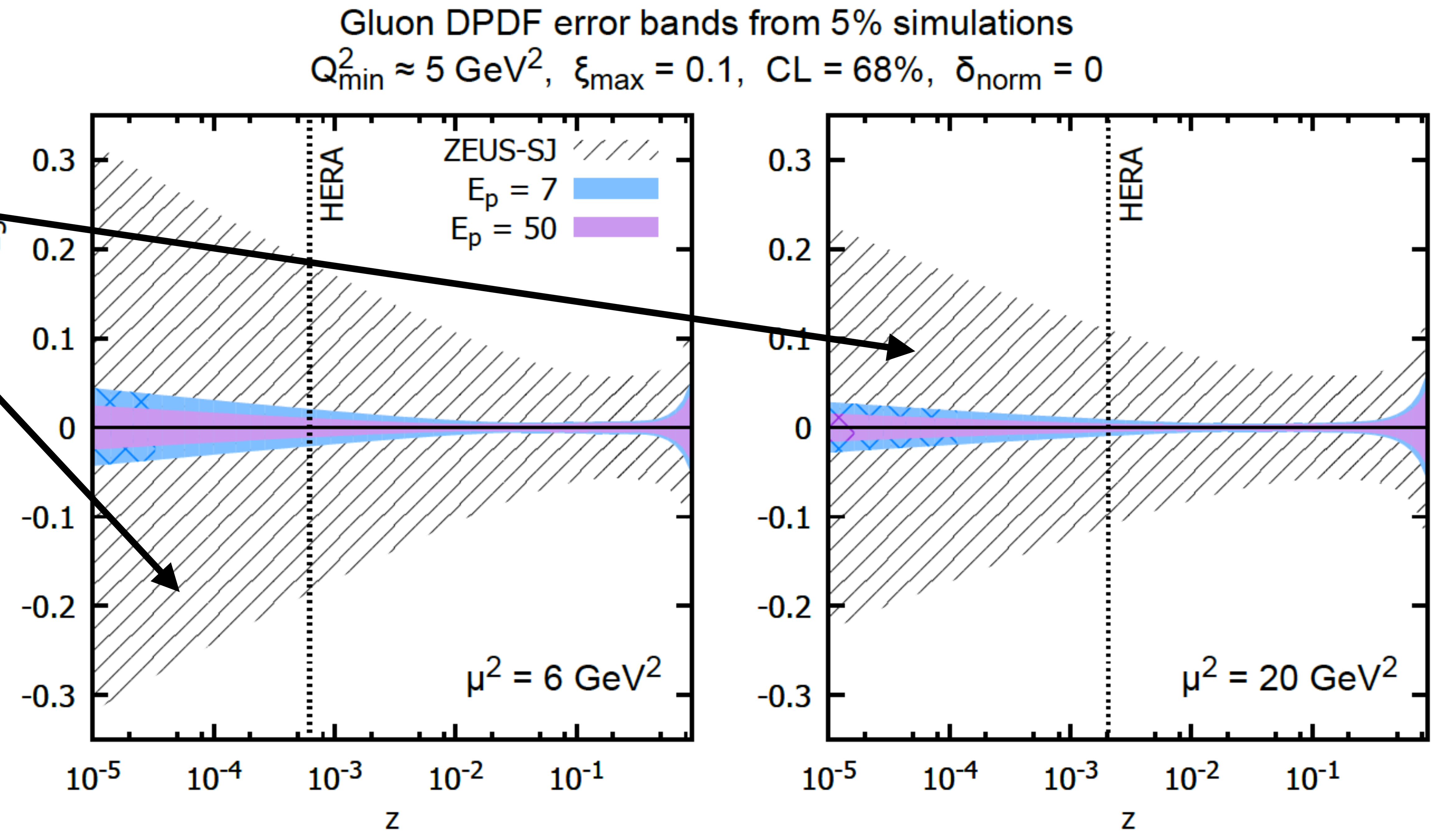
- Diffractive PDFs give the conditional probability of measuring a parton in the hadron with the hadron remaining intact: ~10 % events at HERA are diffractive!
- Never measured in nuclei, incoherent diffraction dominant above relatively small -t: interplay between multiple scattering and survival probability 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



Not existing in nuclei



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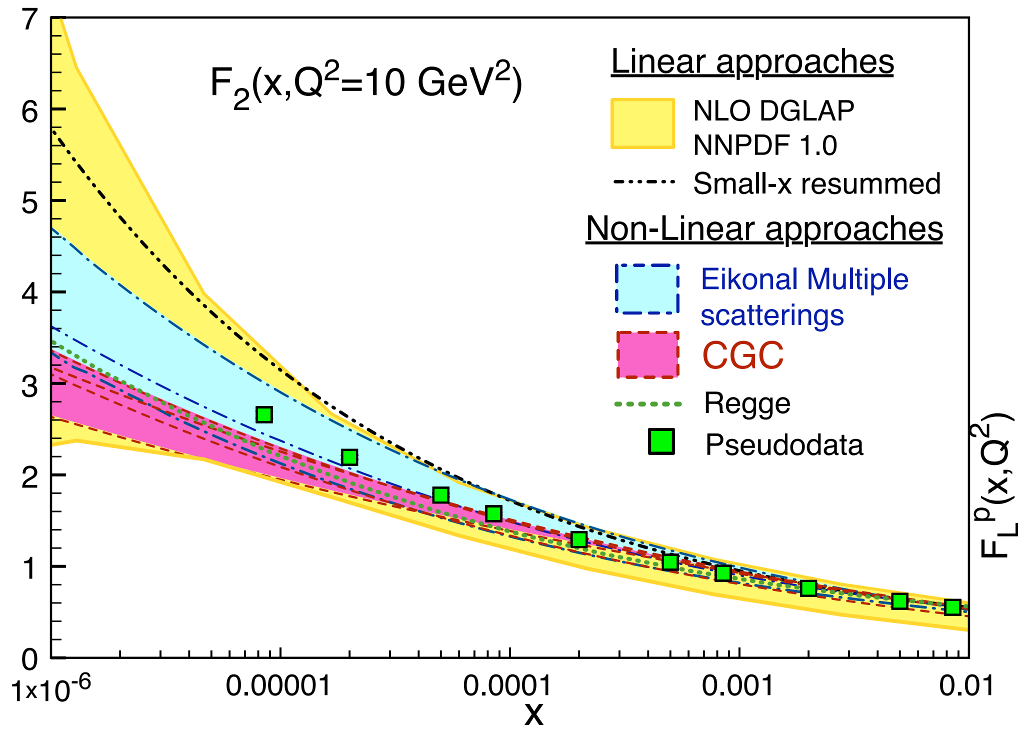
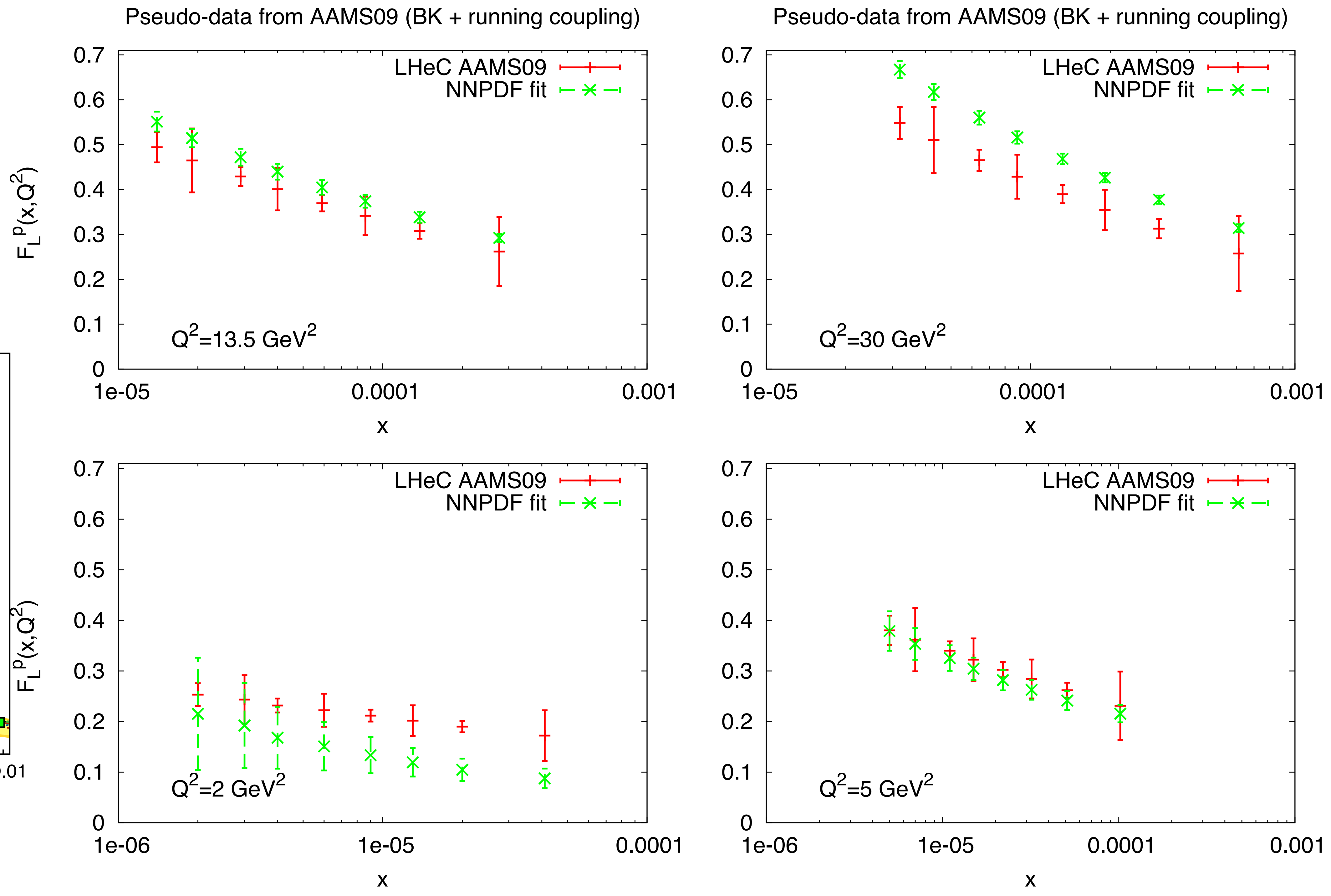
- *1812.06772 (HL-LHC with ions);*
- *1901.09076 (diffraction in ep and eA);*
- *LHeC CDR, 1206.2913;*
- *EIC Physics White paper, 1212.1701;*
- *2018 LHeC and FCC-eh workshop, https://indico.cern.ch/event/698368/;*
- *LHeC and EIC talks at DIS 2019, https://indico.cern.ch/event/749003/.*
- *Fixed target program at the HL-LHC, 1807.00603.*

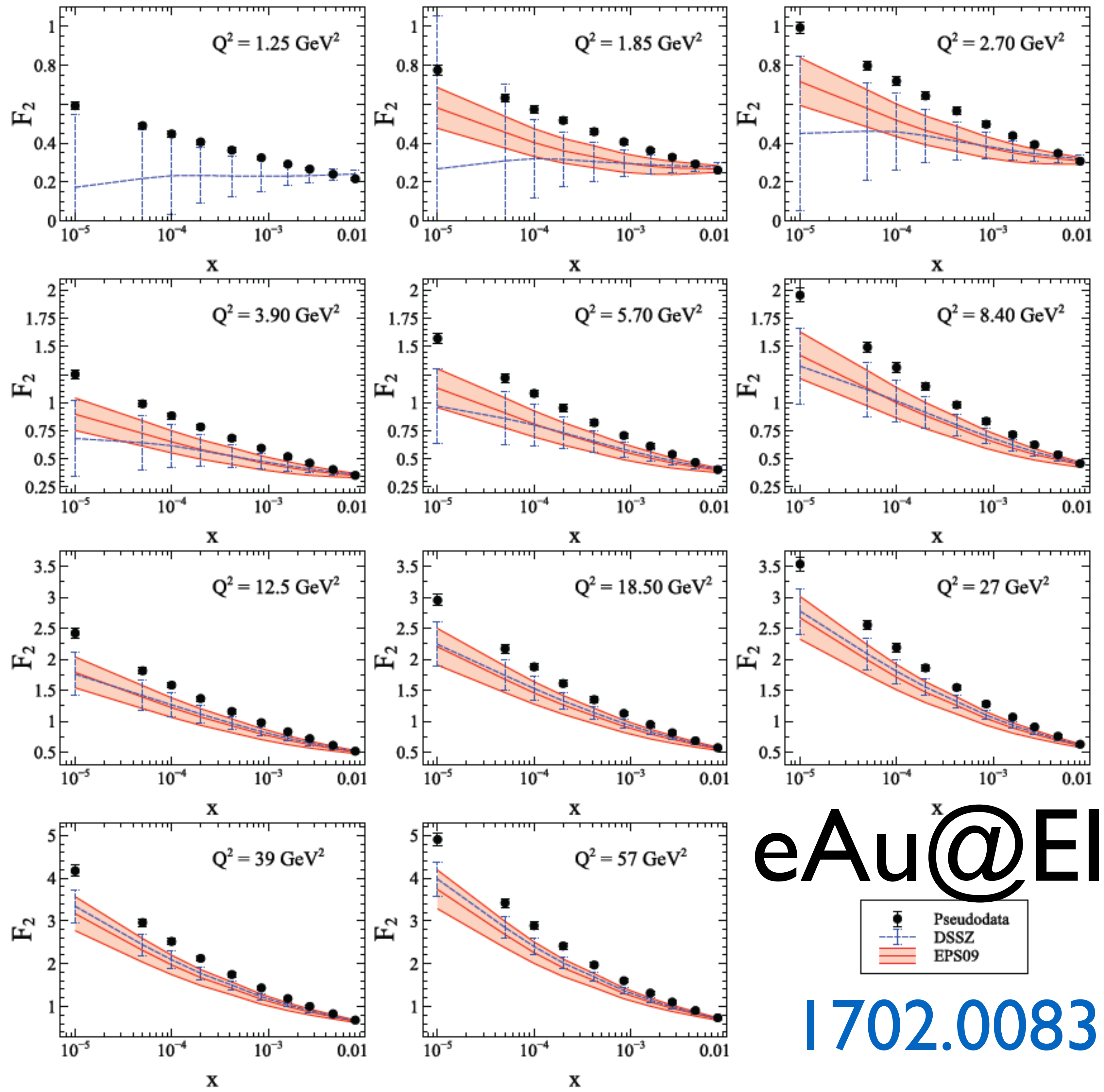
Search for new dynamics at small x in ep/eA:

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

ep@LHeC







eAu@EIC

1702.00839

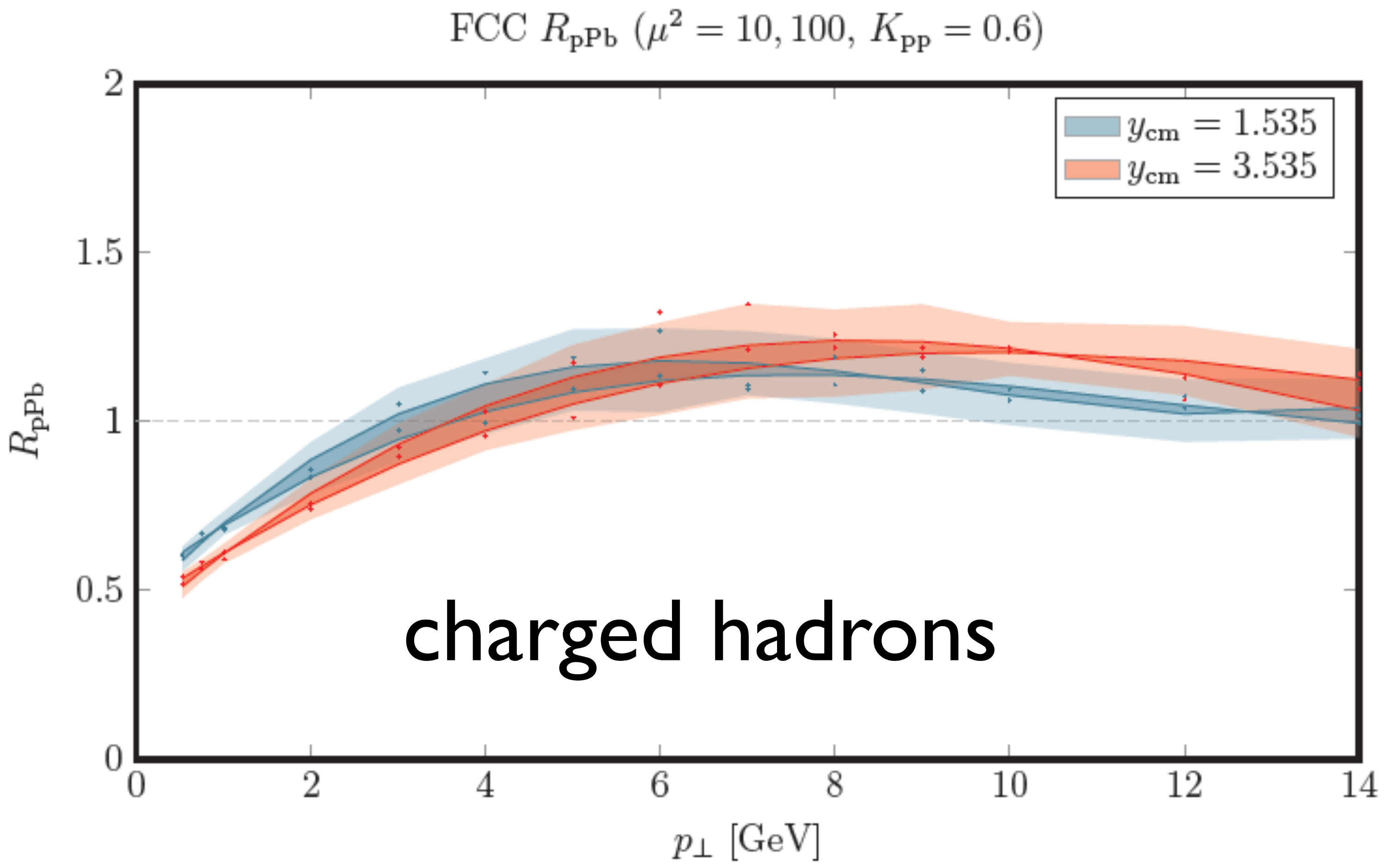
- High scales are small x at the FCC-AA: e.g. top production in pPb sensitive to x ~ 0.02-0.2 at HL-LHC and 0.0002-0.2 at the FCC-hh (1501.05879).

Search for new dynamics at small x in pA:

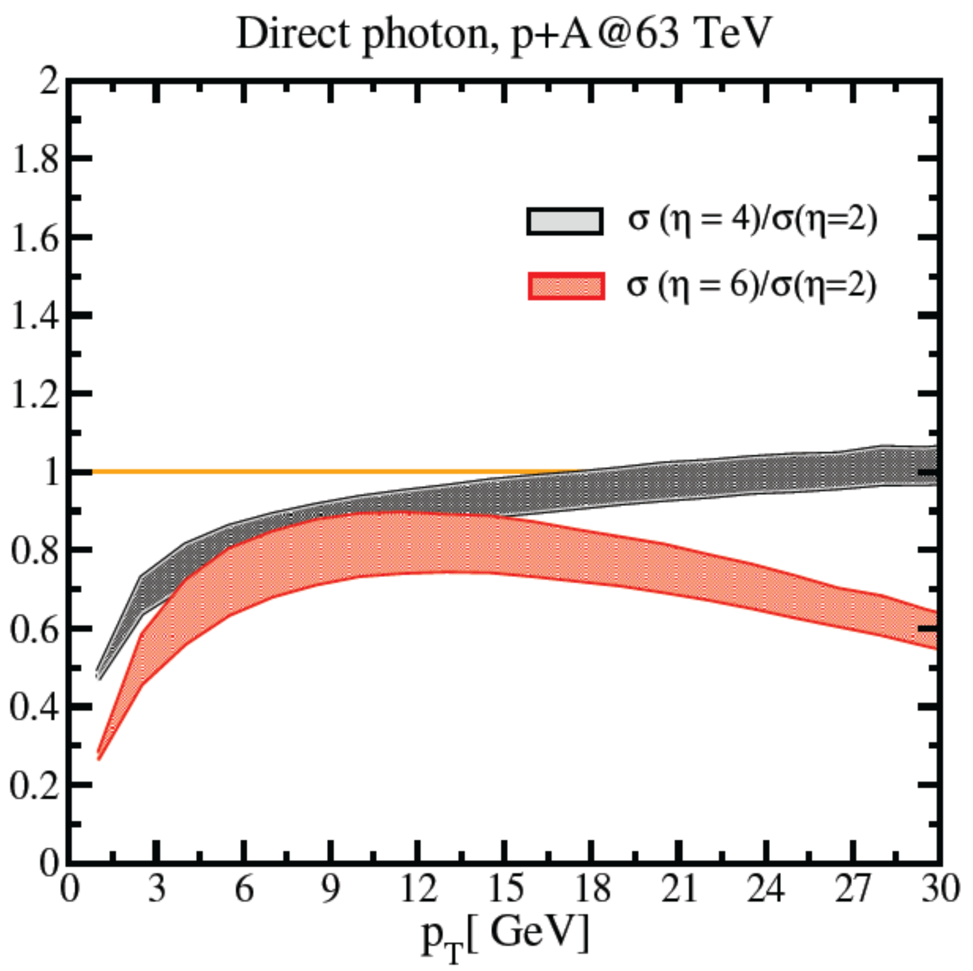
- Single particle suppression increasing with rapidity was proposed as a signal of saturation.

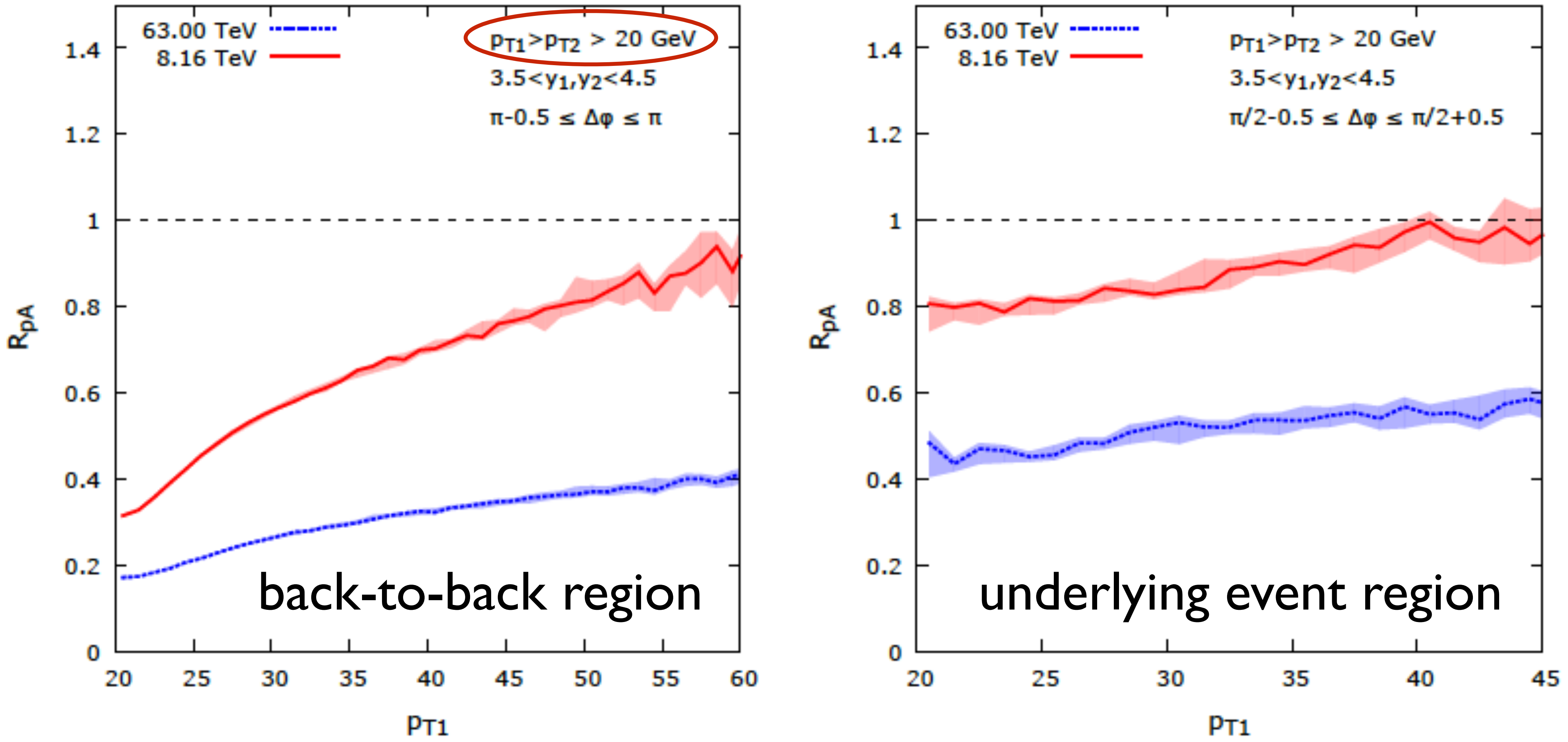
$$\boxed{R_{\mathrm{pA}} = \frac{\text{yield in eA/pA}}{\text{scaled yield in ep/pp}}}$$

- To be contrasted with an extraction of PDFs in collinear factorisation: tensions?



charged hadrons



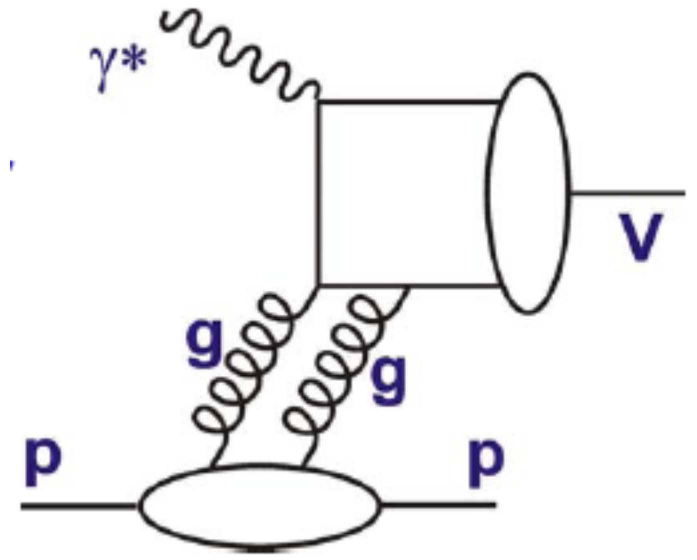


back-to-back region

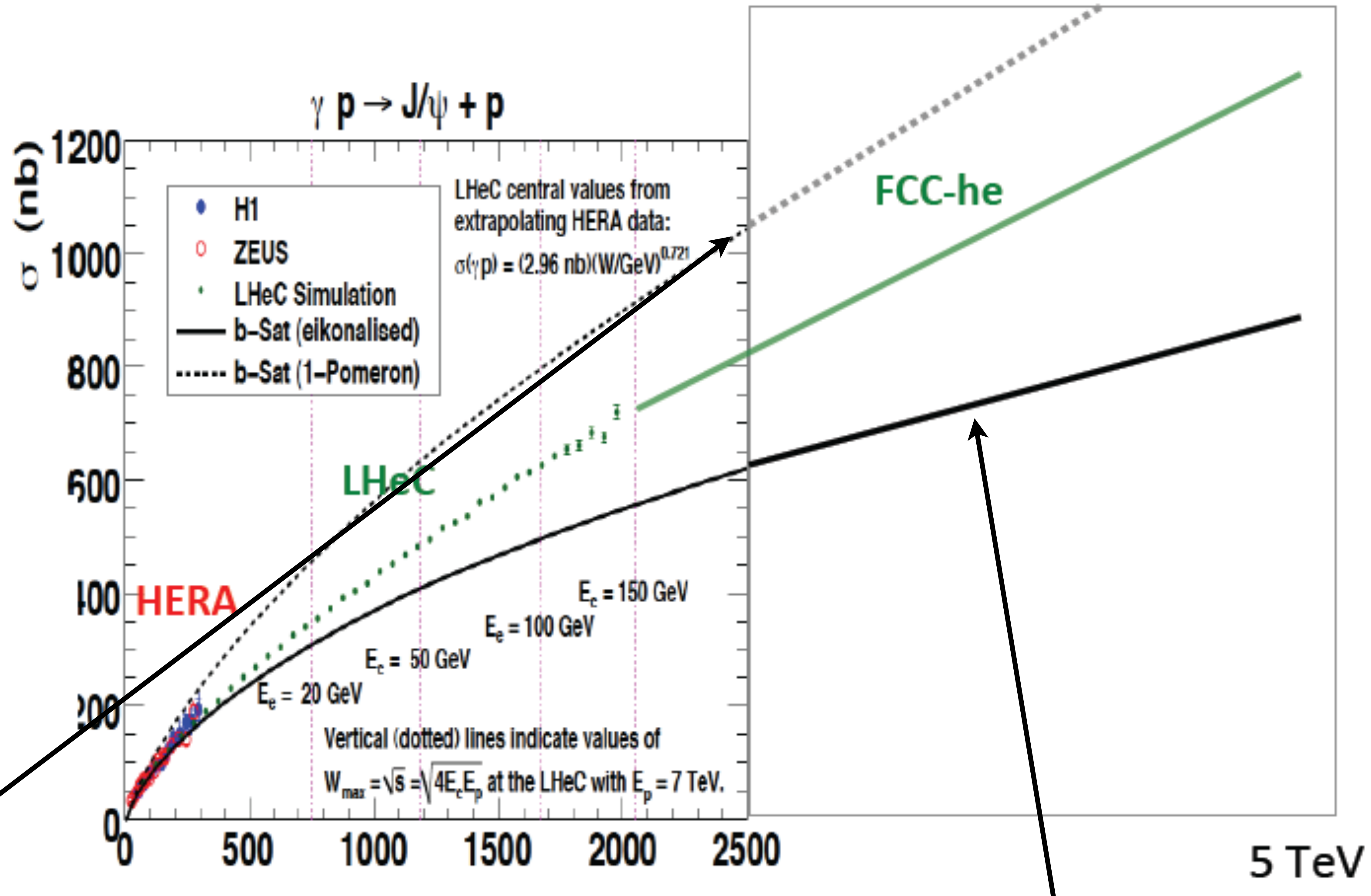
underlying event region

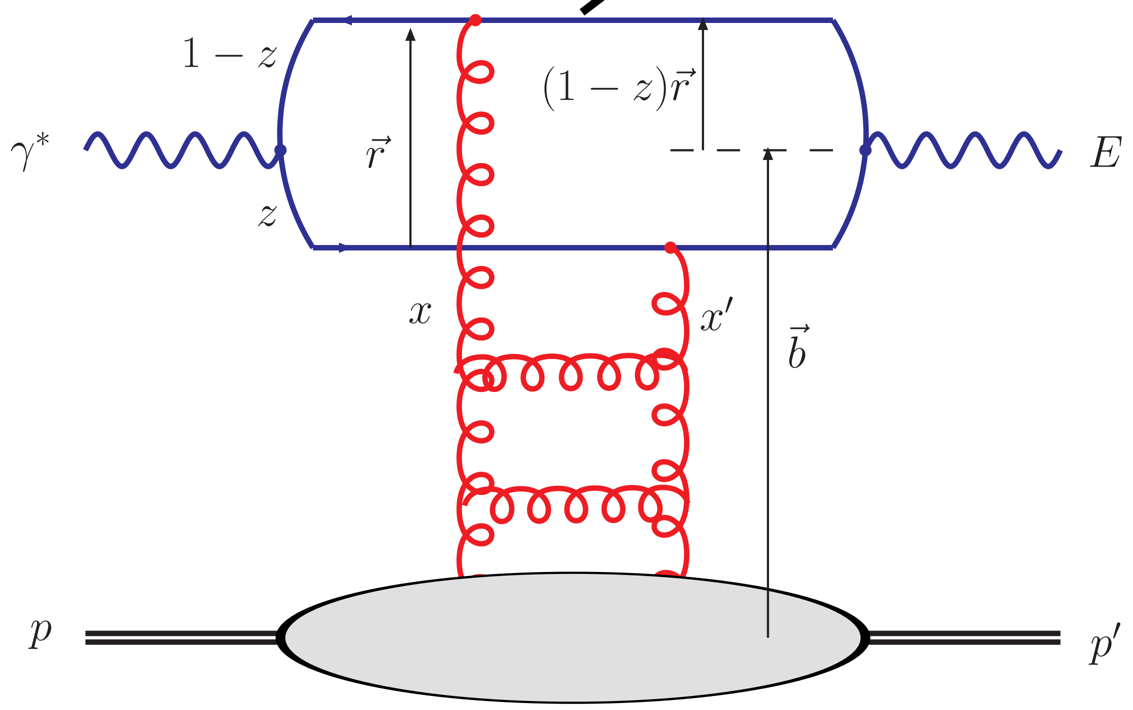
dijet yield modification pPb/pp, anti-k_T, R=0.5

Elastic VM production in ep/eA and UPCs:

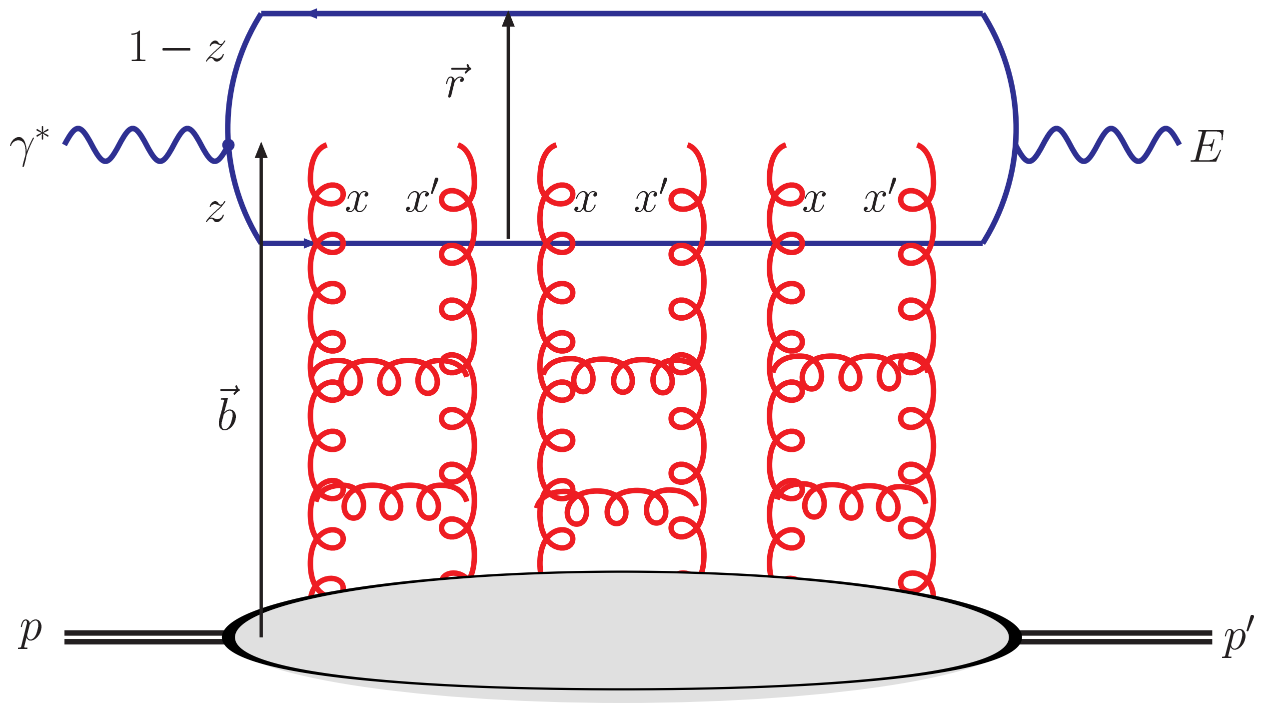


- Elastic J/ψ production may be a candidate to signal saturation effects at work.



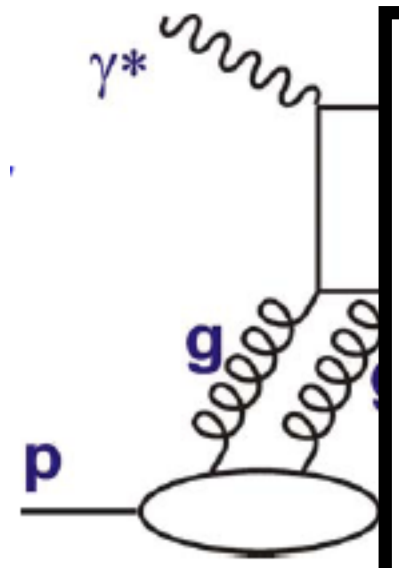


Linear, sensitivity to (xg)².

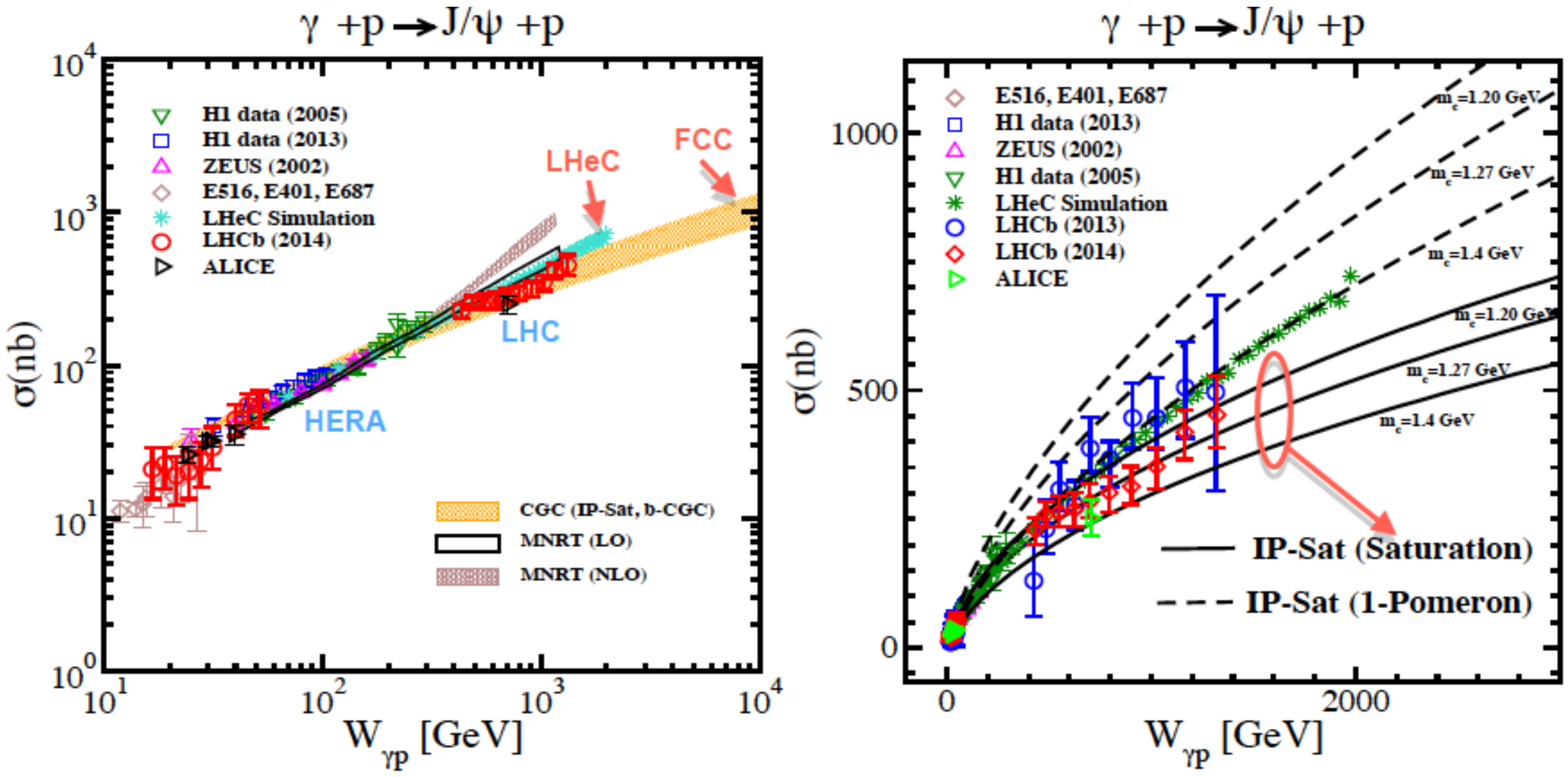


Non-linear, saturation.

Elastic VM production in ep/eA and UPCs:



- UPCs are an alternative, though less precise.
- Large uncertainties, e.g. charm mass (1402.4831).



- Elastic J/
may be a ca
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Linear,
sensitivit
to (xg)^2

n-linear,
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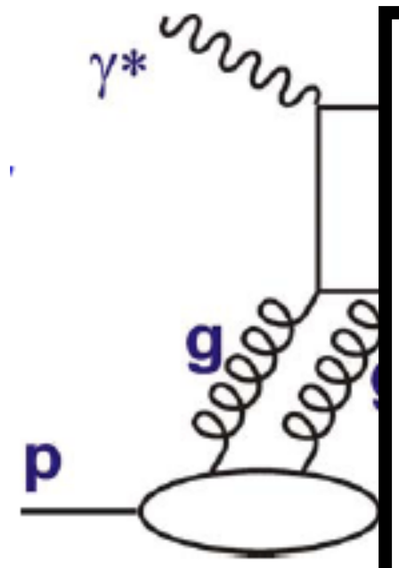

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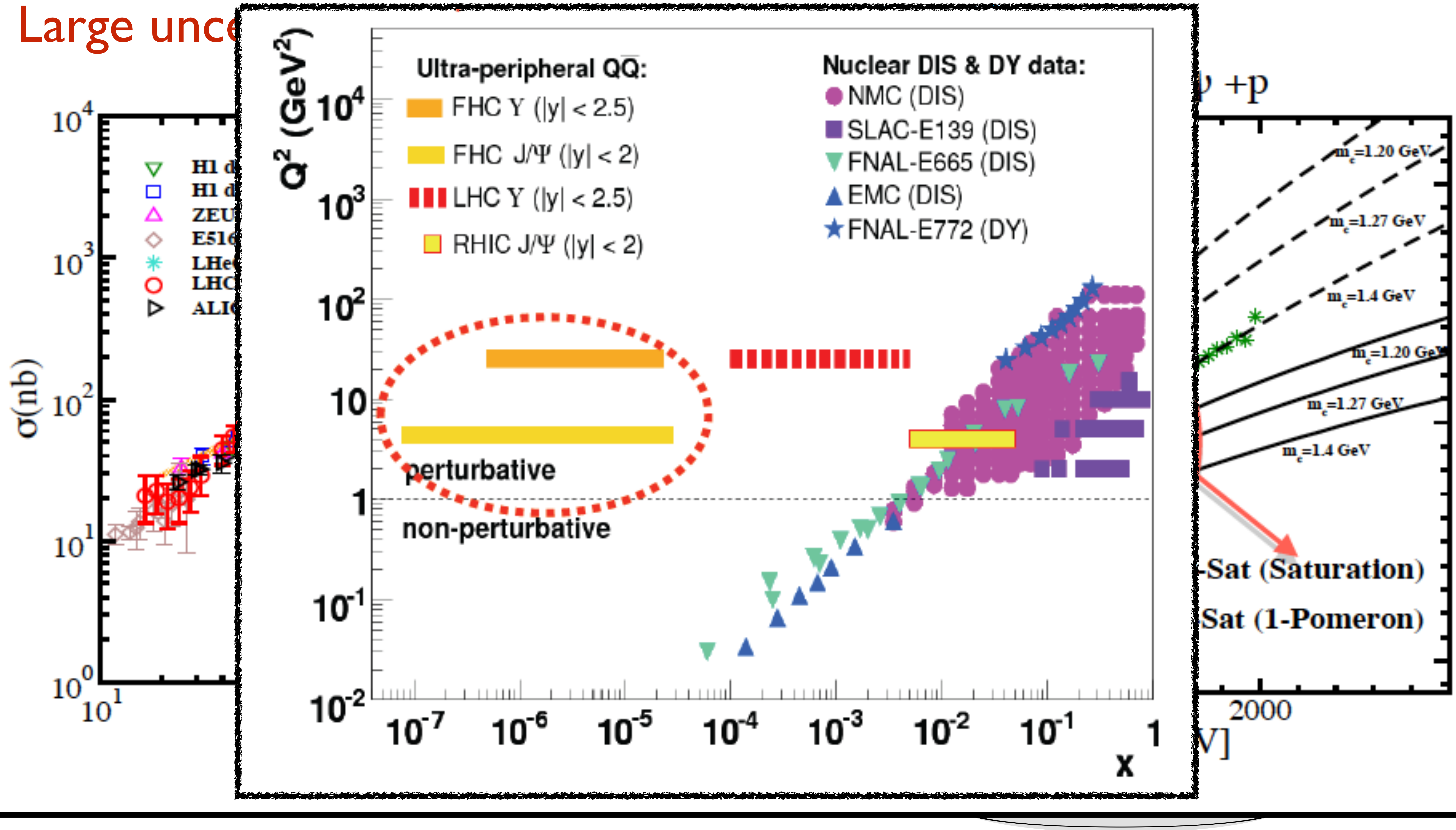

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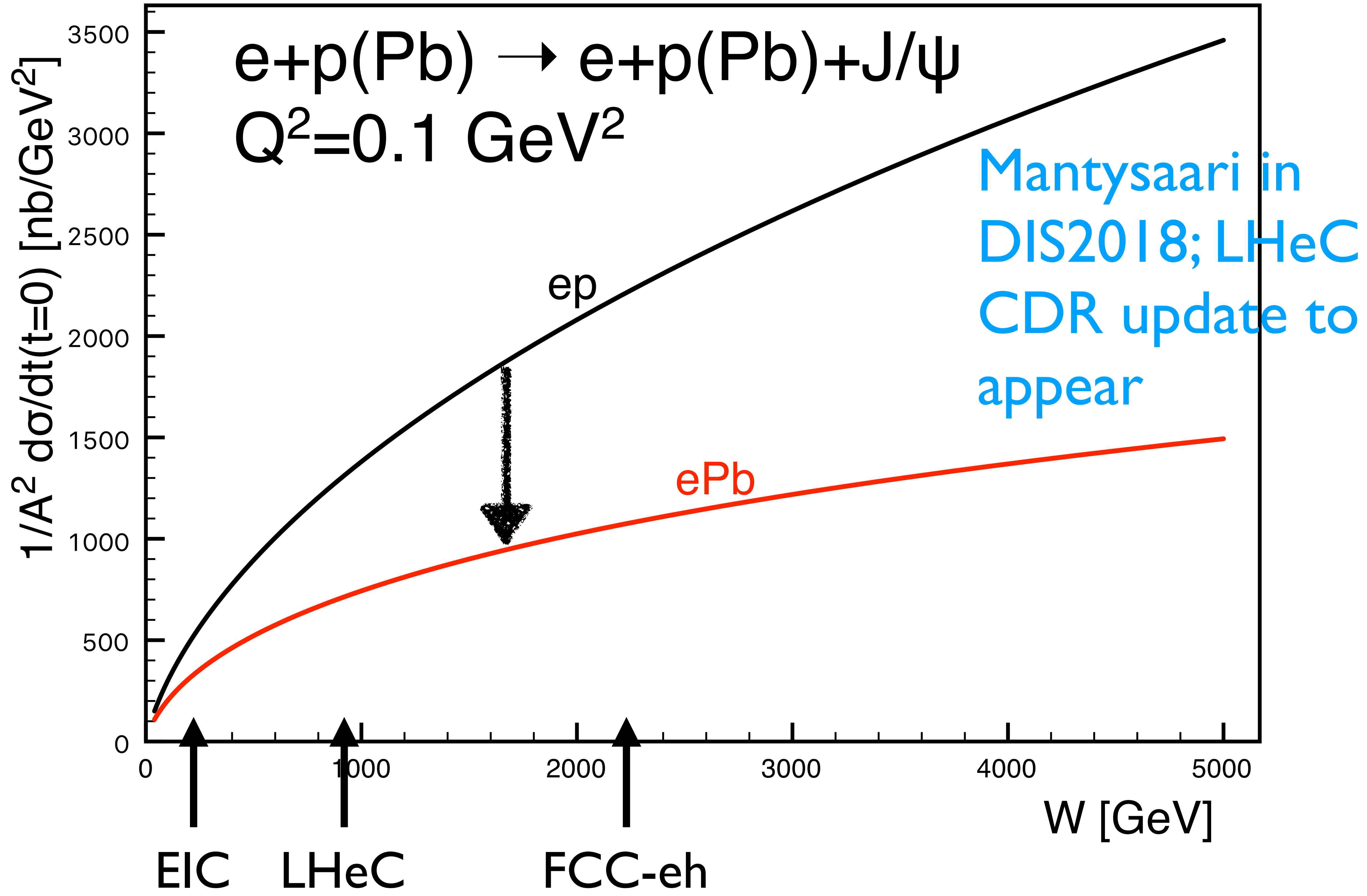
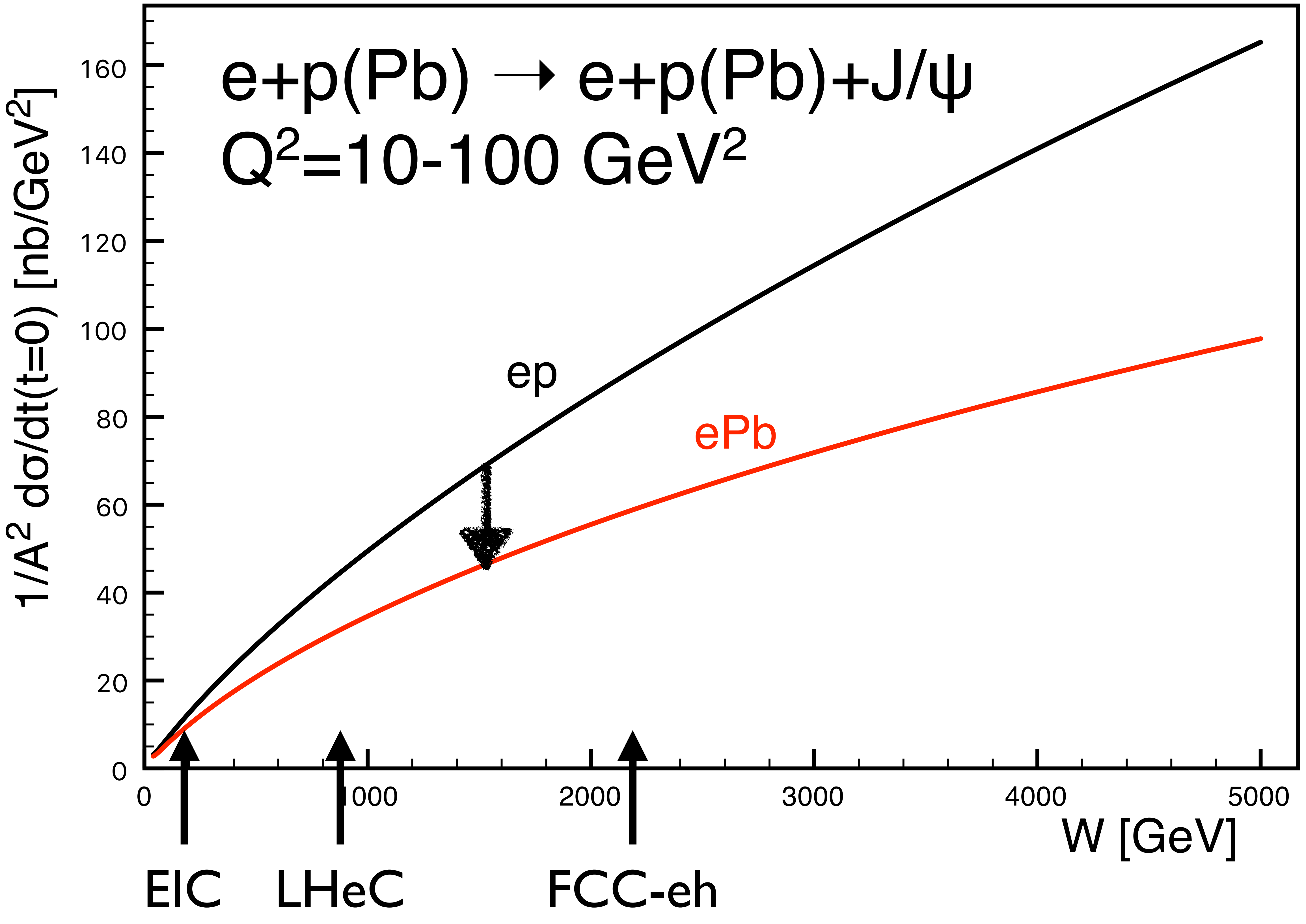
Elastic VM production in ep/eA and UPCs:

- Saturation (the approach to the black disk limit) affects both the energy and the t (impact parameter)-dependence of coherent exclusive VM production: softer energy dependence, shrinking of the diffractive peak.
- Saturation results in a larger diffractive over inclusive cross section (Nikolaev et al., Z.Phys. A351 (1995) 435): interplay between non-linear phenomena and survival probability.



Mantysaari in DIS2018; LHeC CDR update to appear



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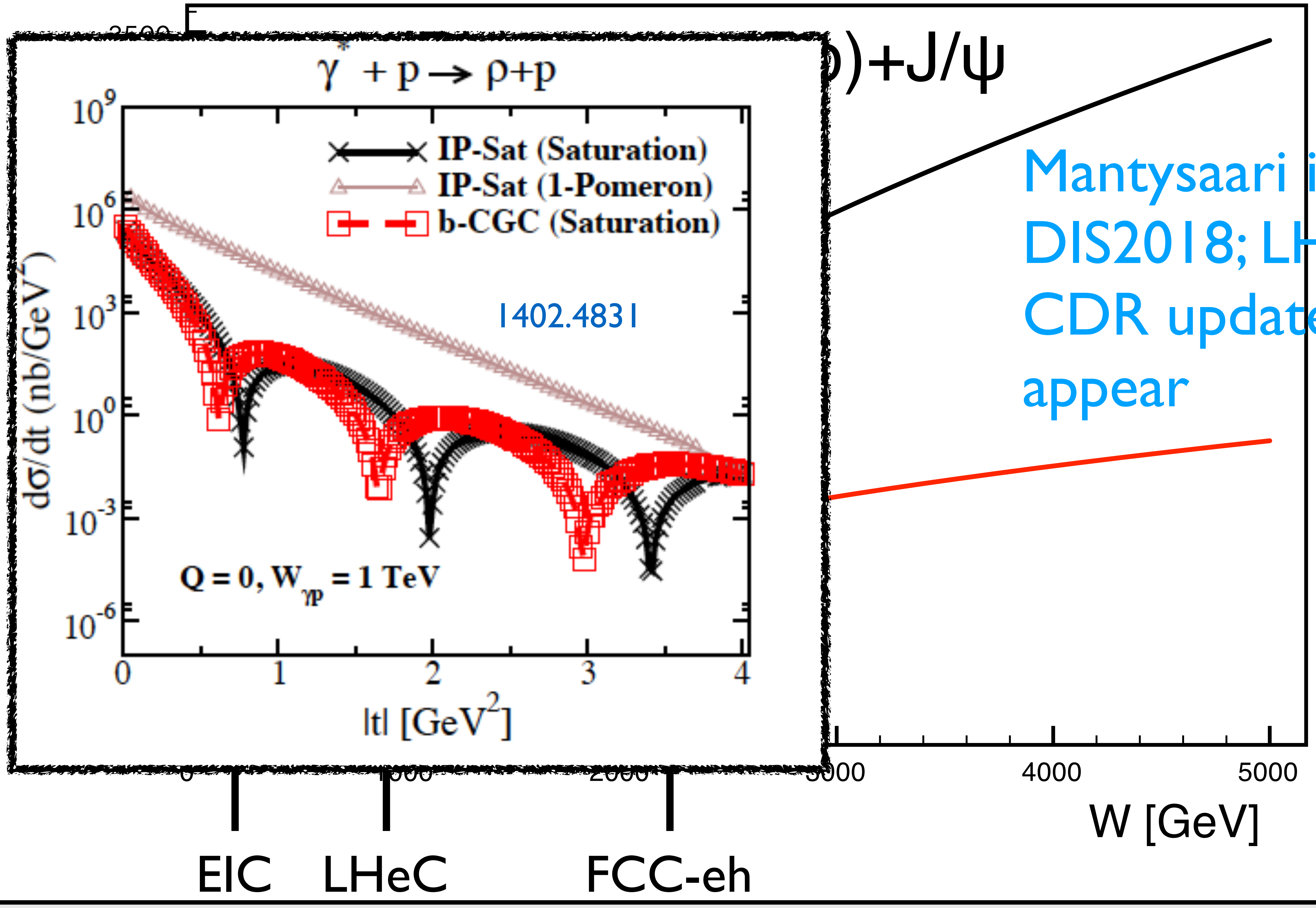

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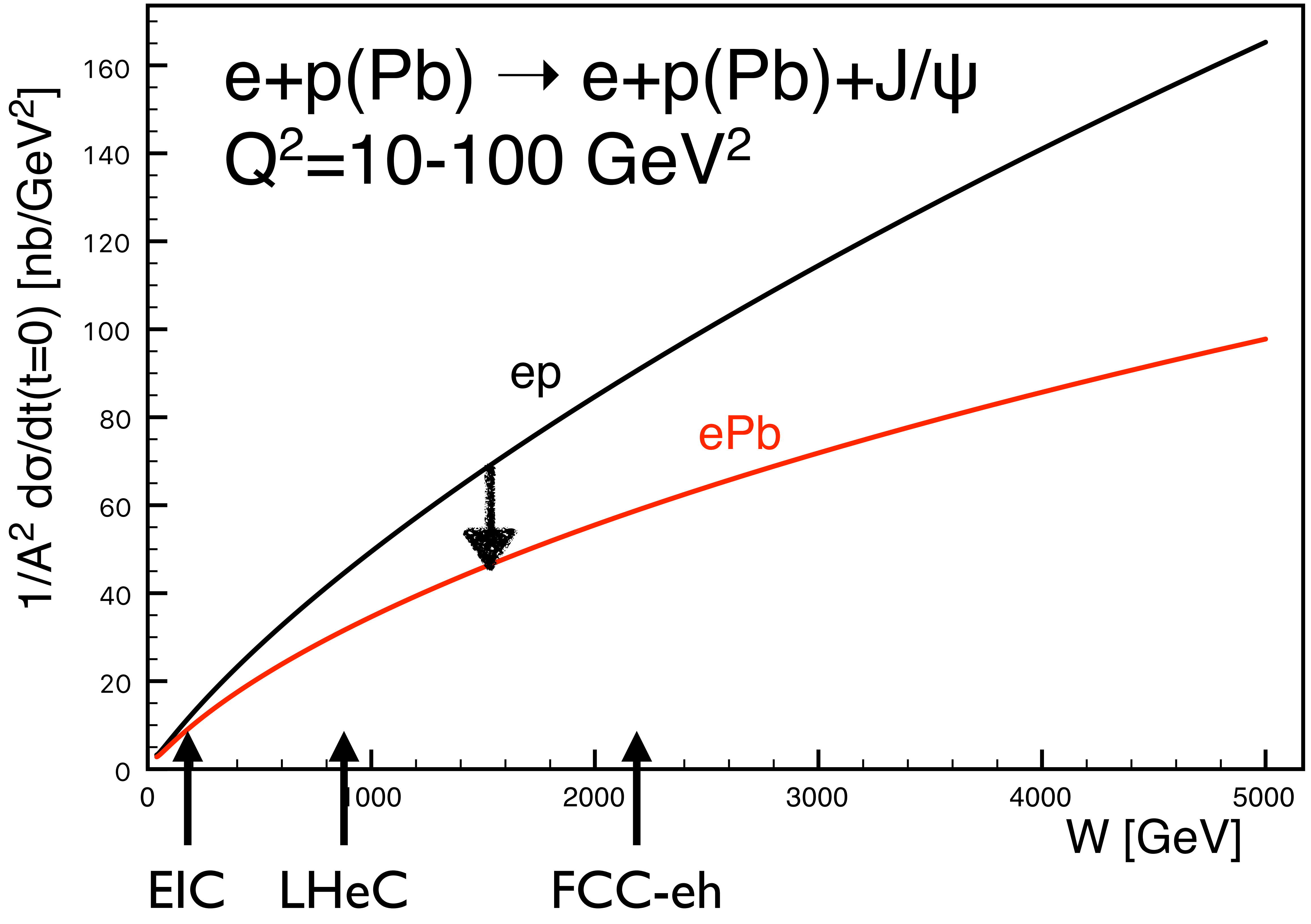

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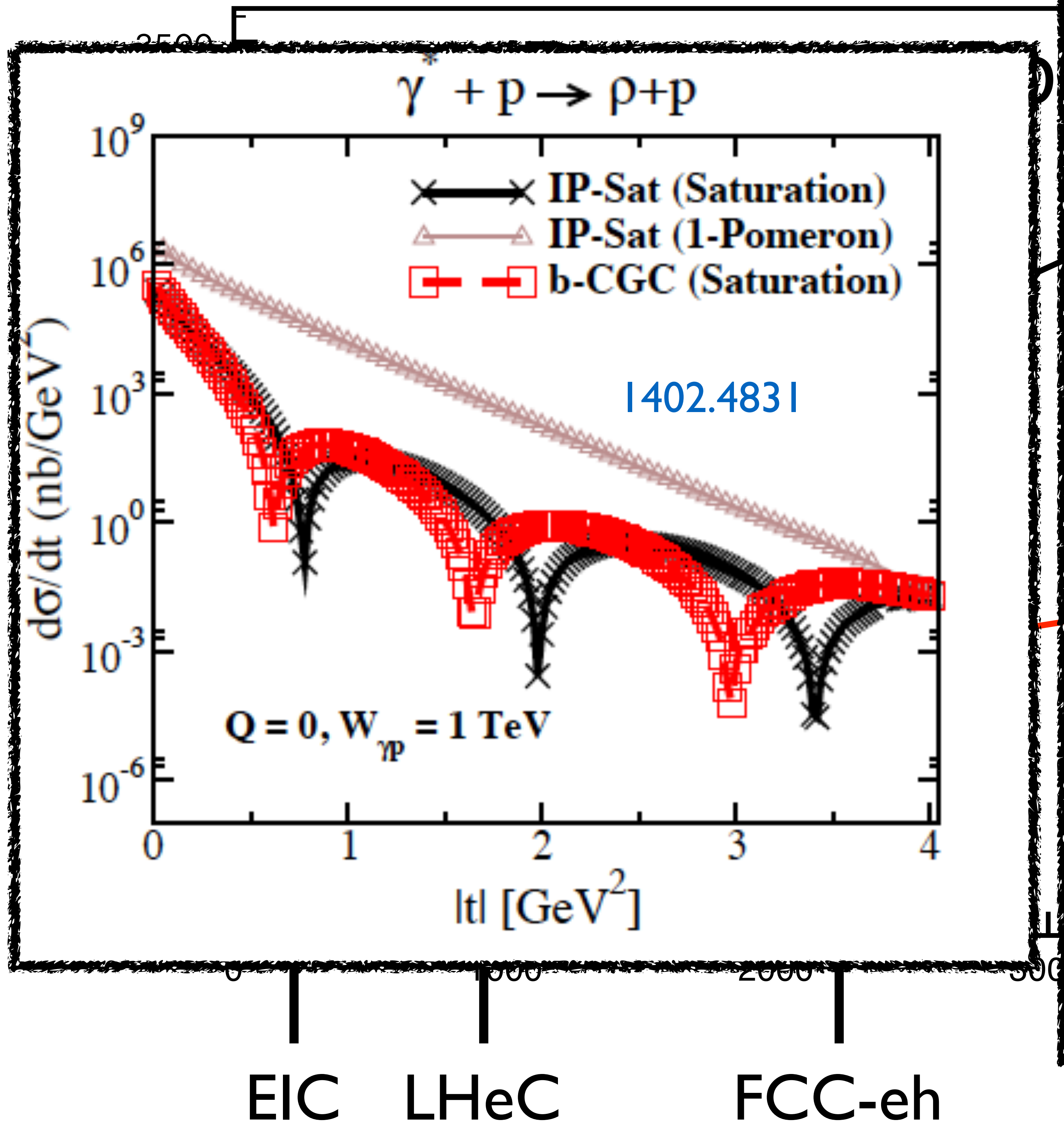
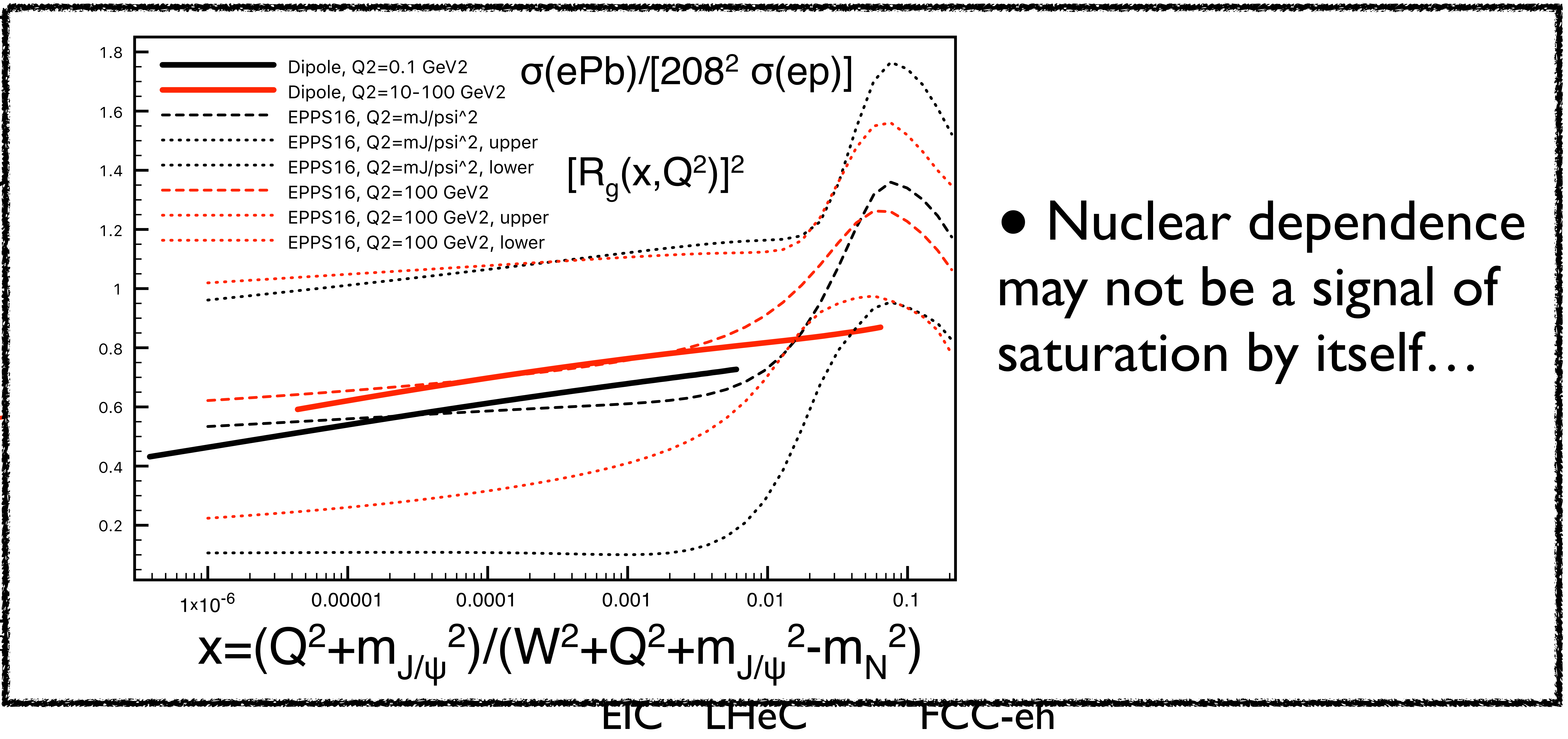
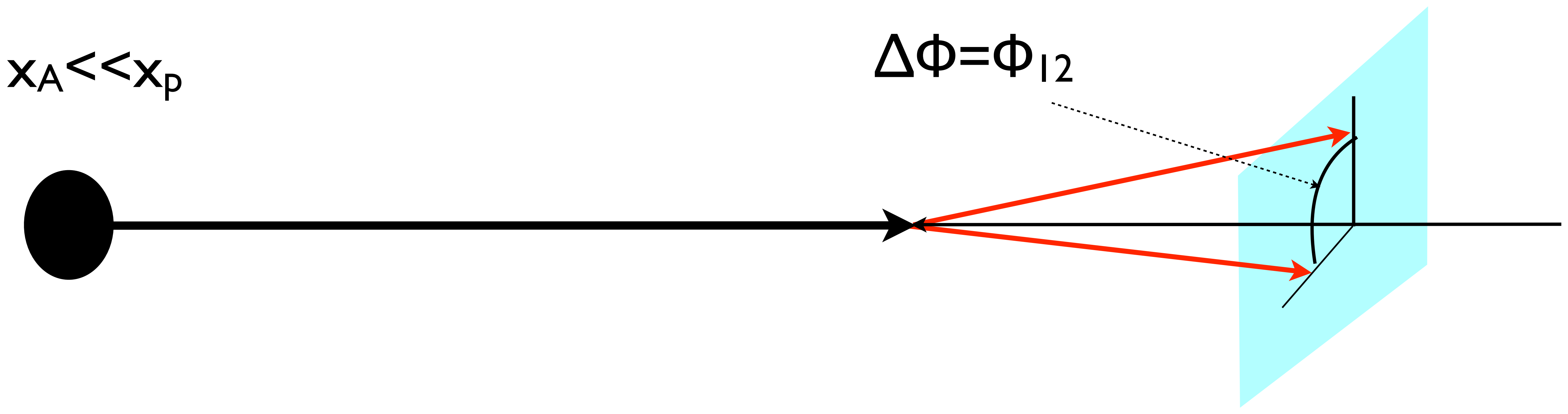




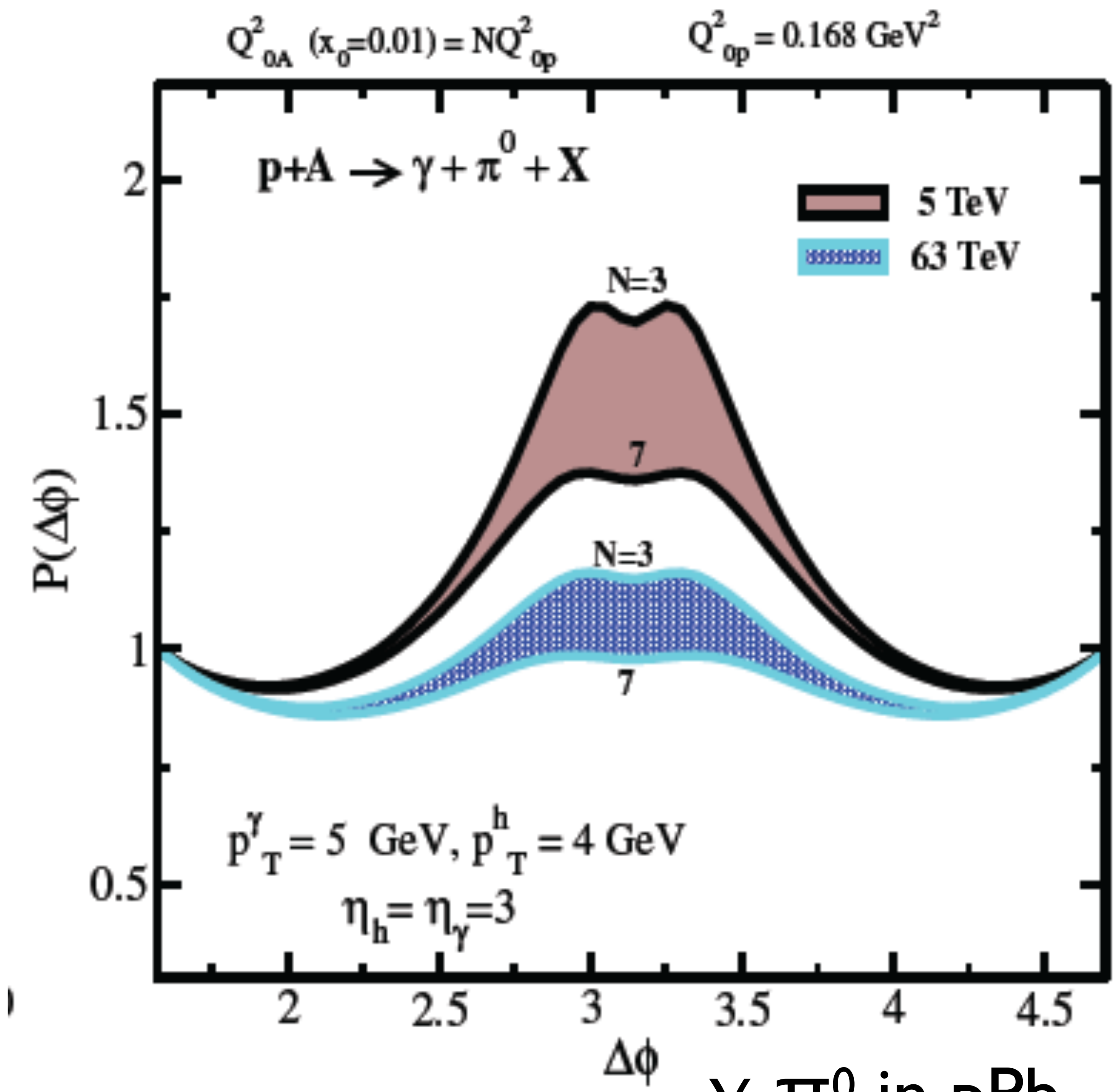
- Nuclear dependence may not be a signal of saturation by itself…

Correlations en eA/pA (I):

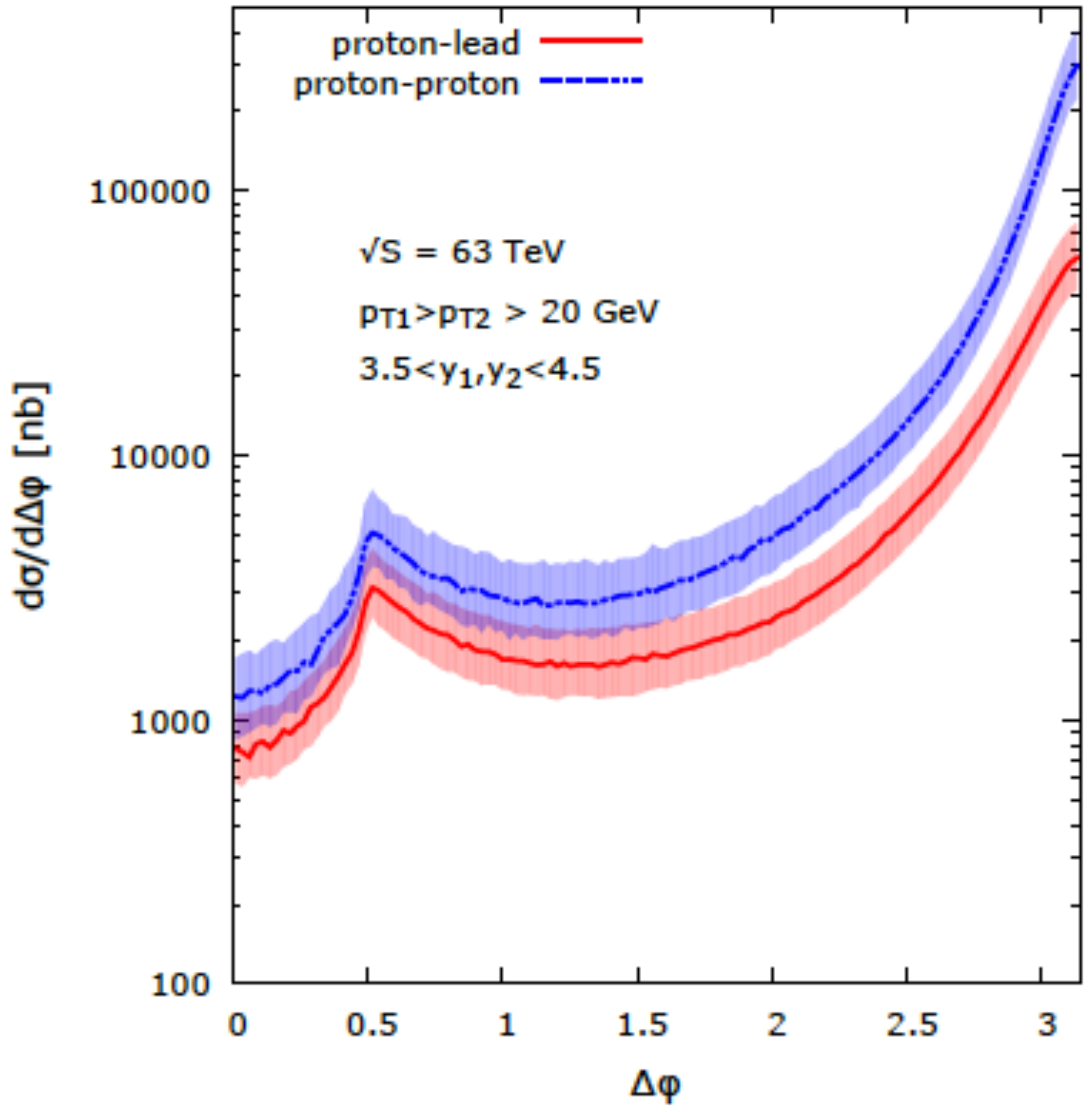
- Dihadron azimuthal decorrelation: currently discussed at RHIC as suggestive of saturation.
- To be studied far from kinematical limits.



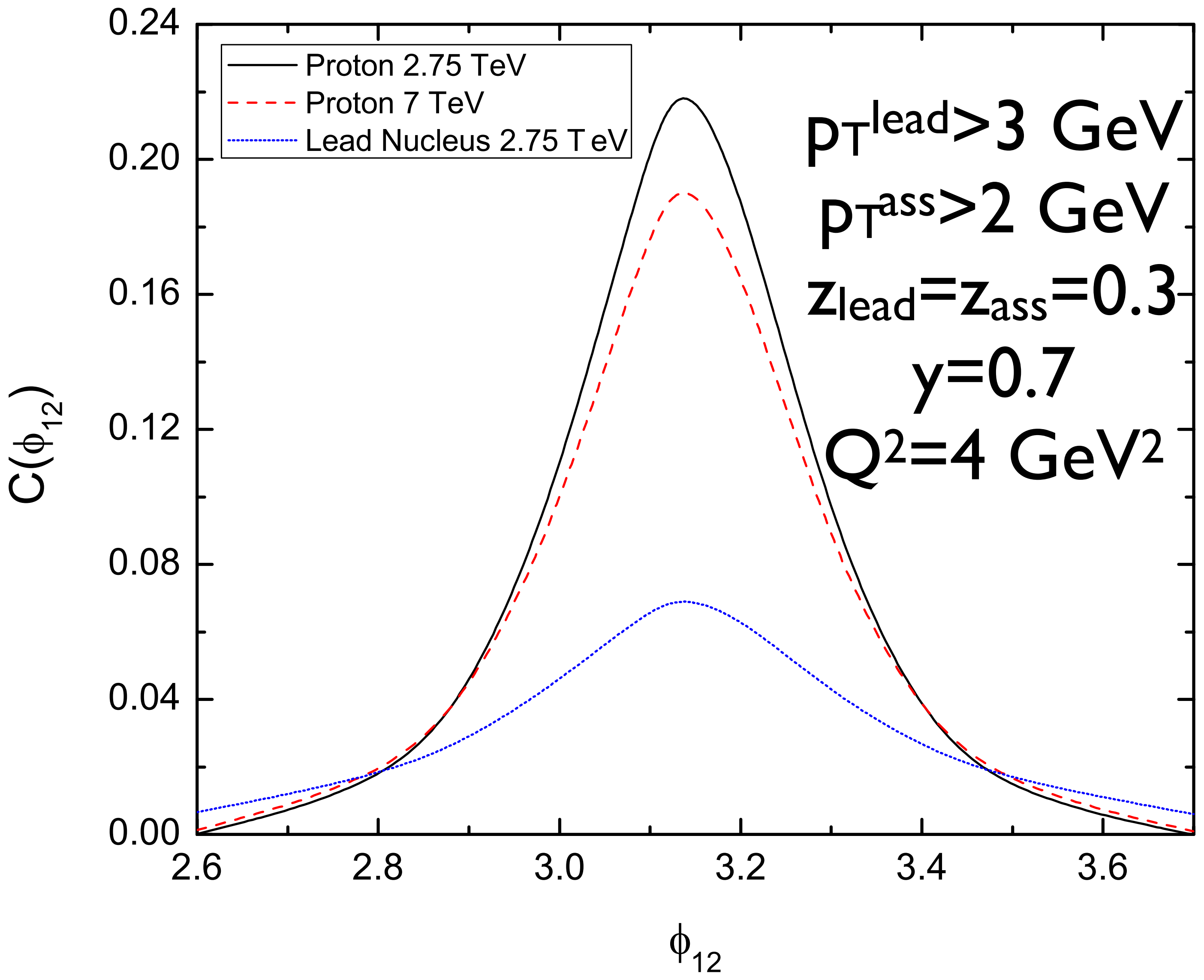
$$C(\phi_{12}) = \frac{1}{\frac{d\sigma(\gamma^* N \to h_1 X)}{dz_{h1}}} \frac{d\sigma^{\gamma^* N \to h_1 h_2 + X}}{dz_{h1} dz_{h2} d\phi_{12}}$$



γ-π⁰ in pPb



jet-jet in pPb



h-h in ePb

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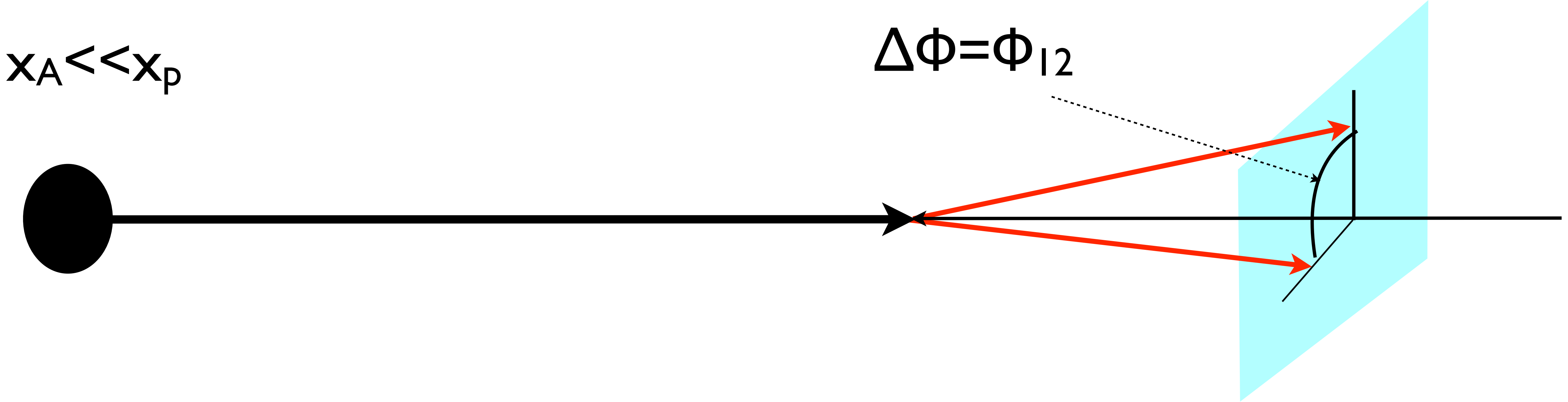

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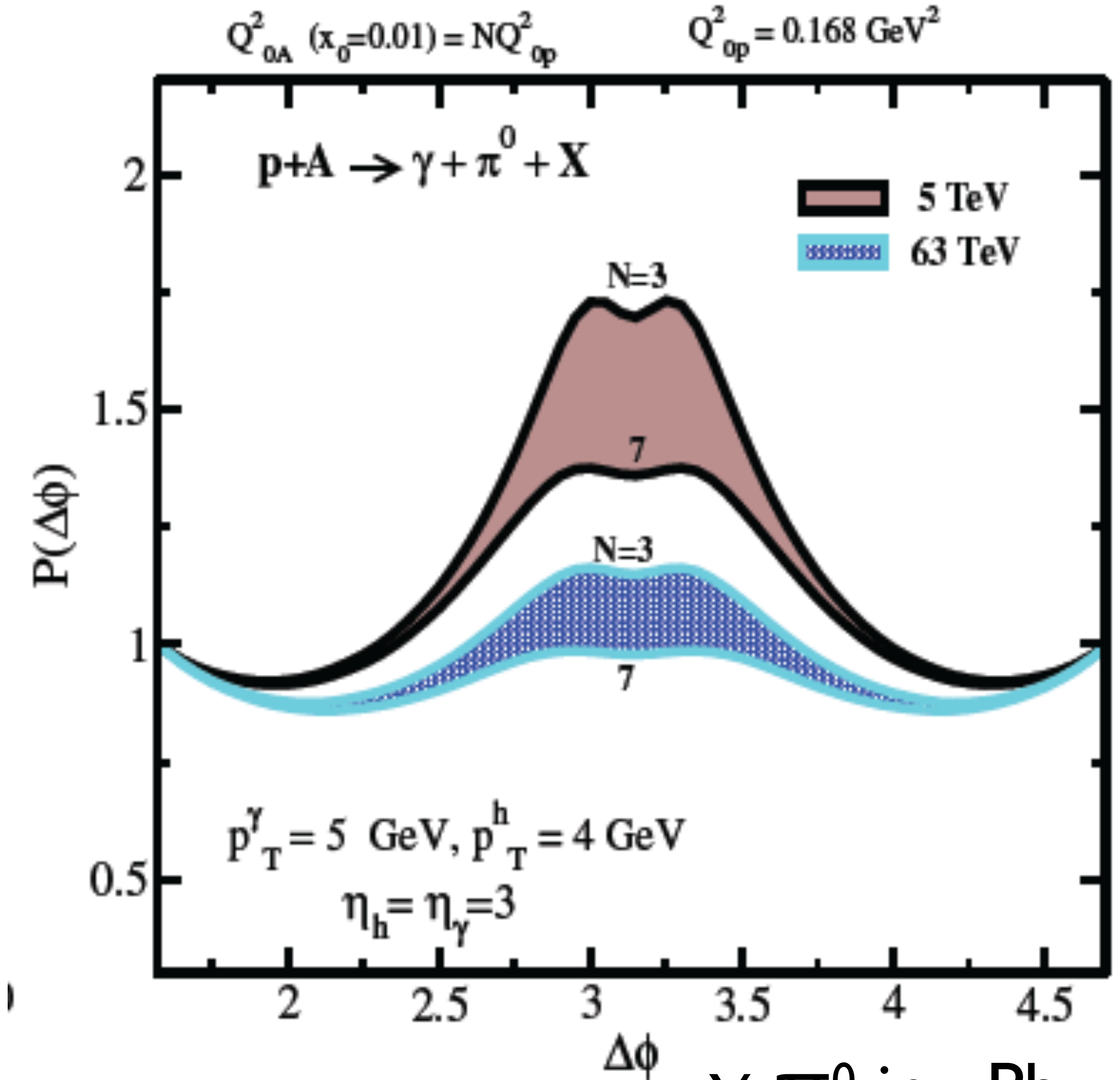
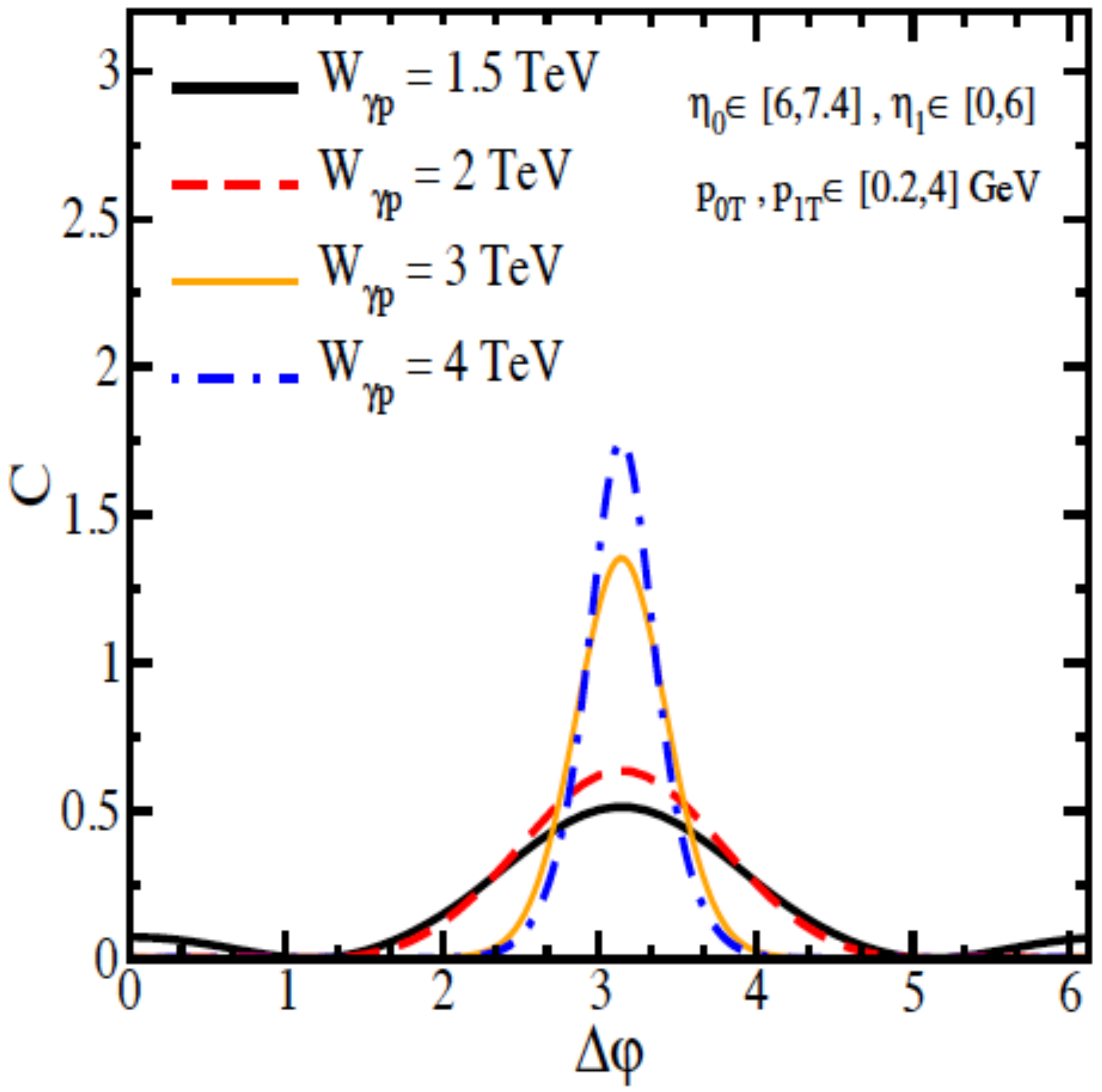
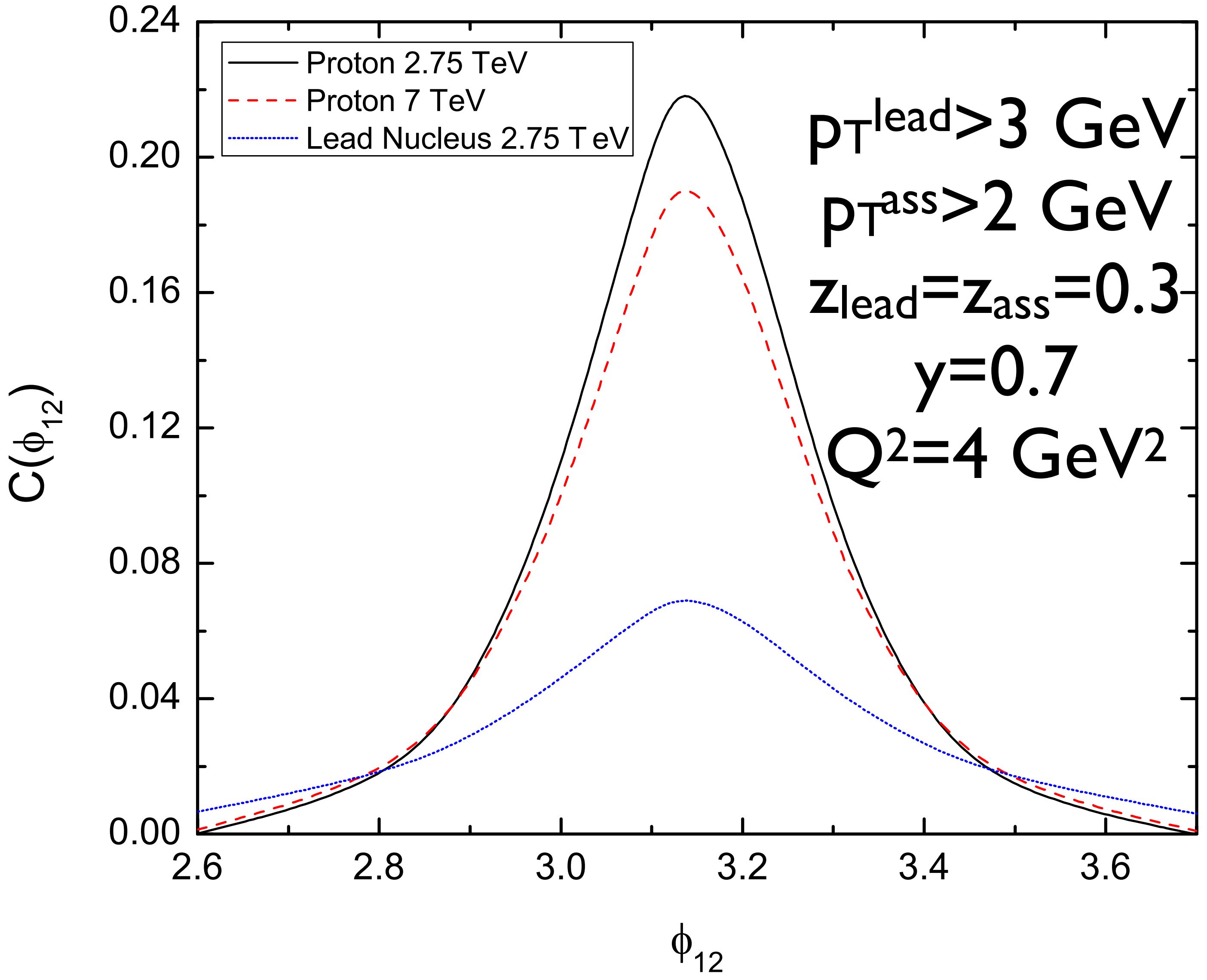


γ-π^0 in pPb



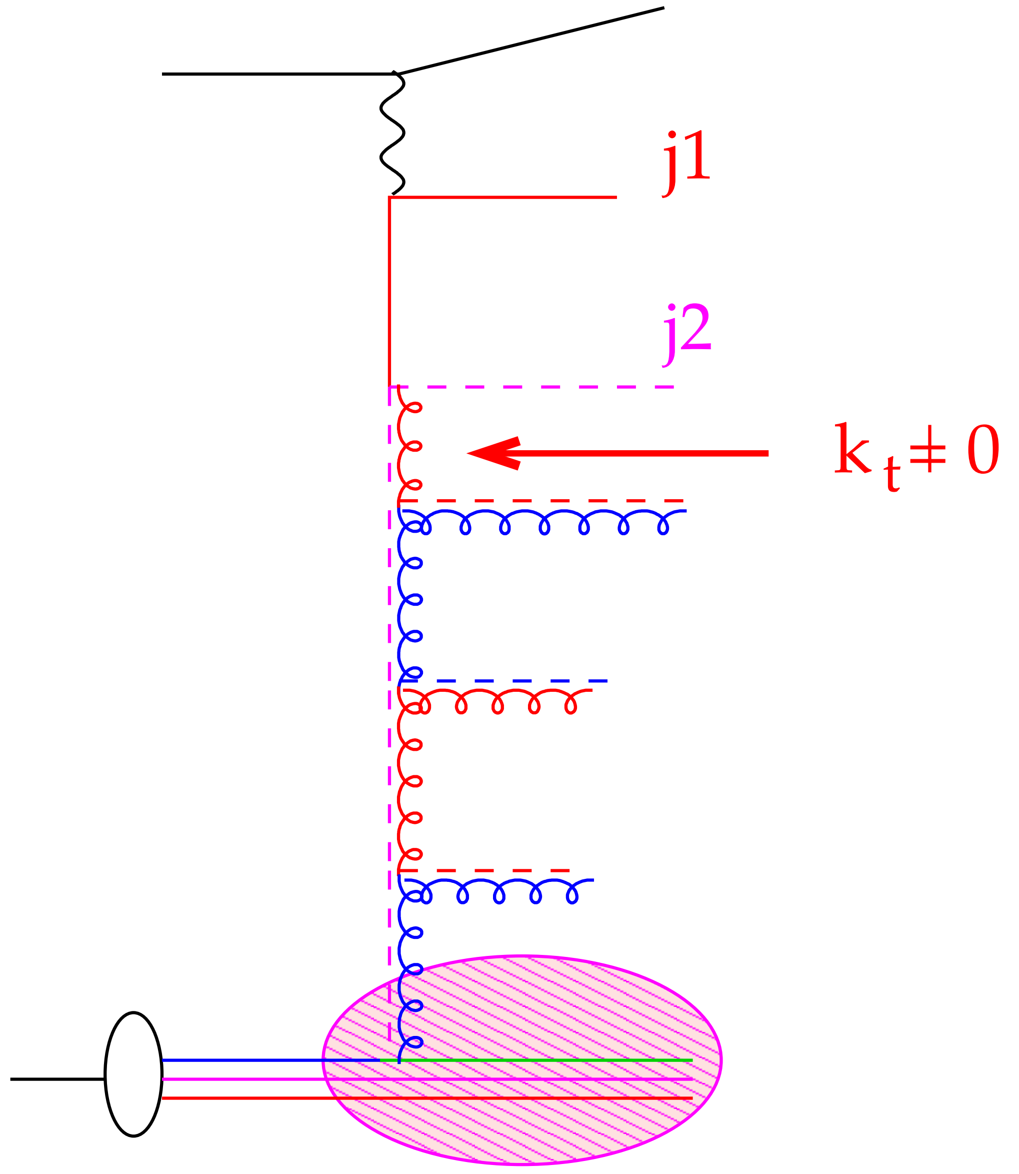
central-forward exclusive dijets in ep/eA, 1511.07452

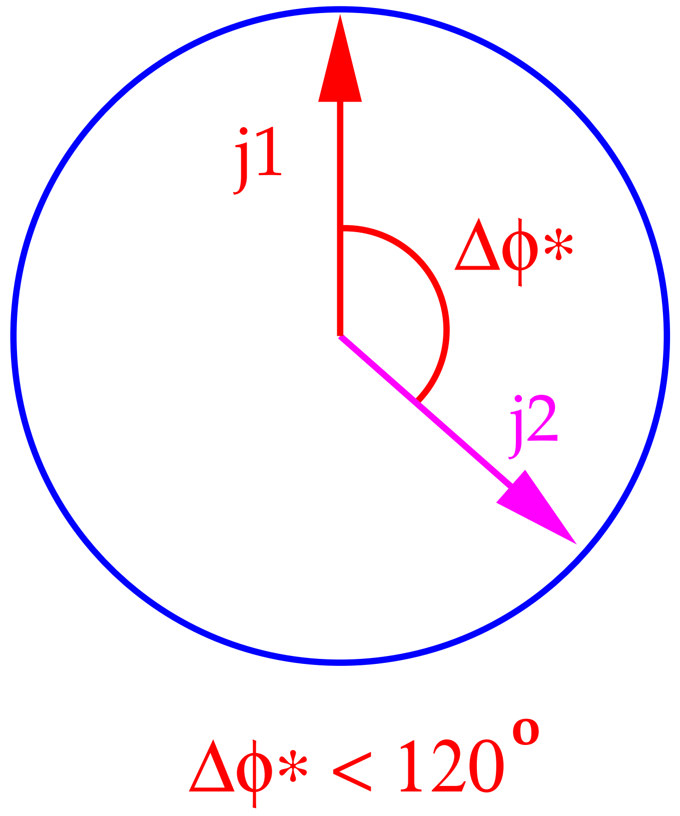


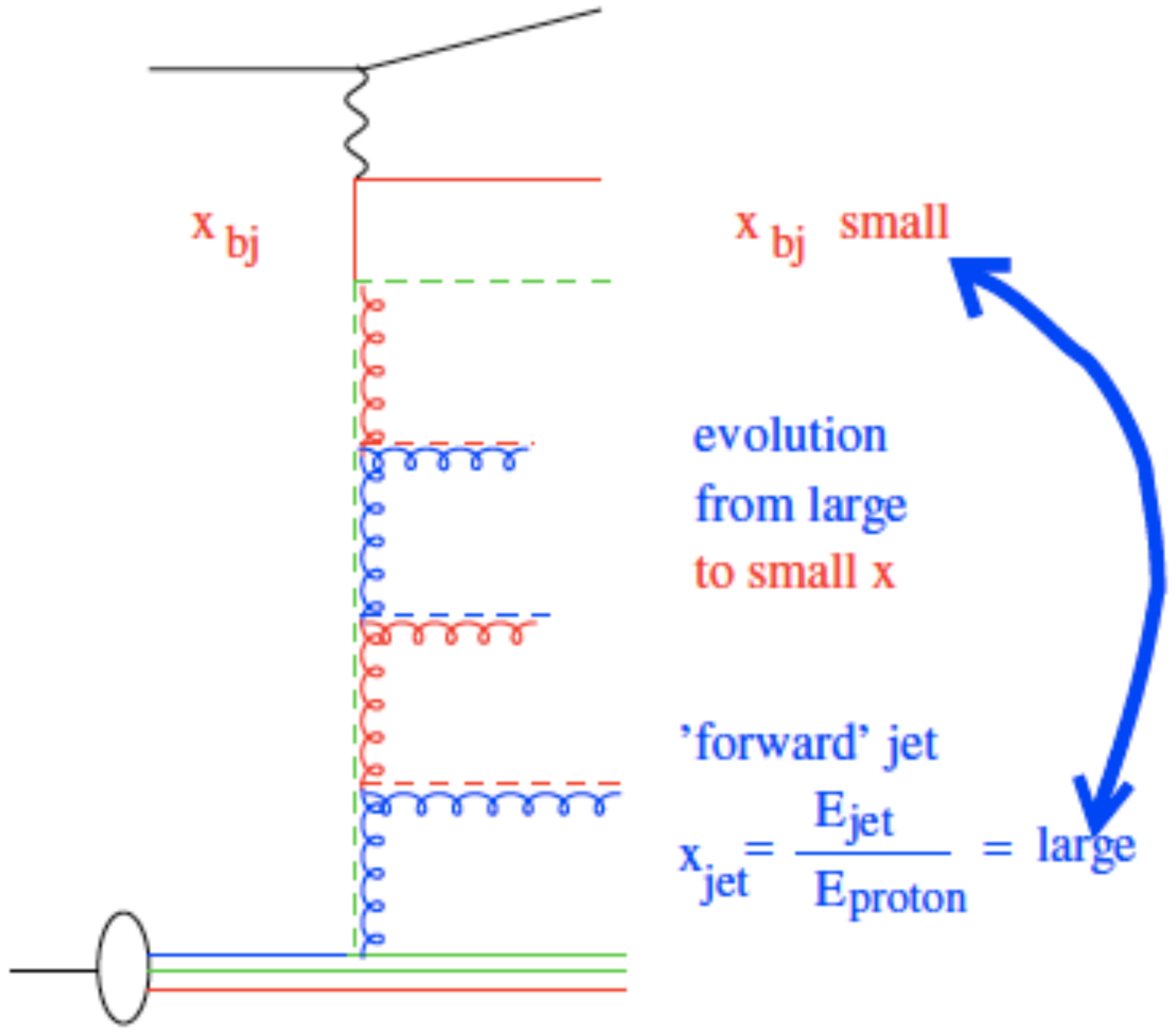
h-h in ePb

Correlations en eA/pA (II):

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







- **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?

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- *Fixed target program at the HL-LHC, 1807.00603.*

Small systems:

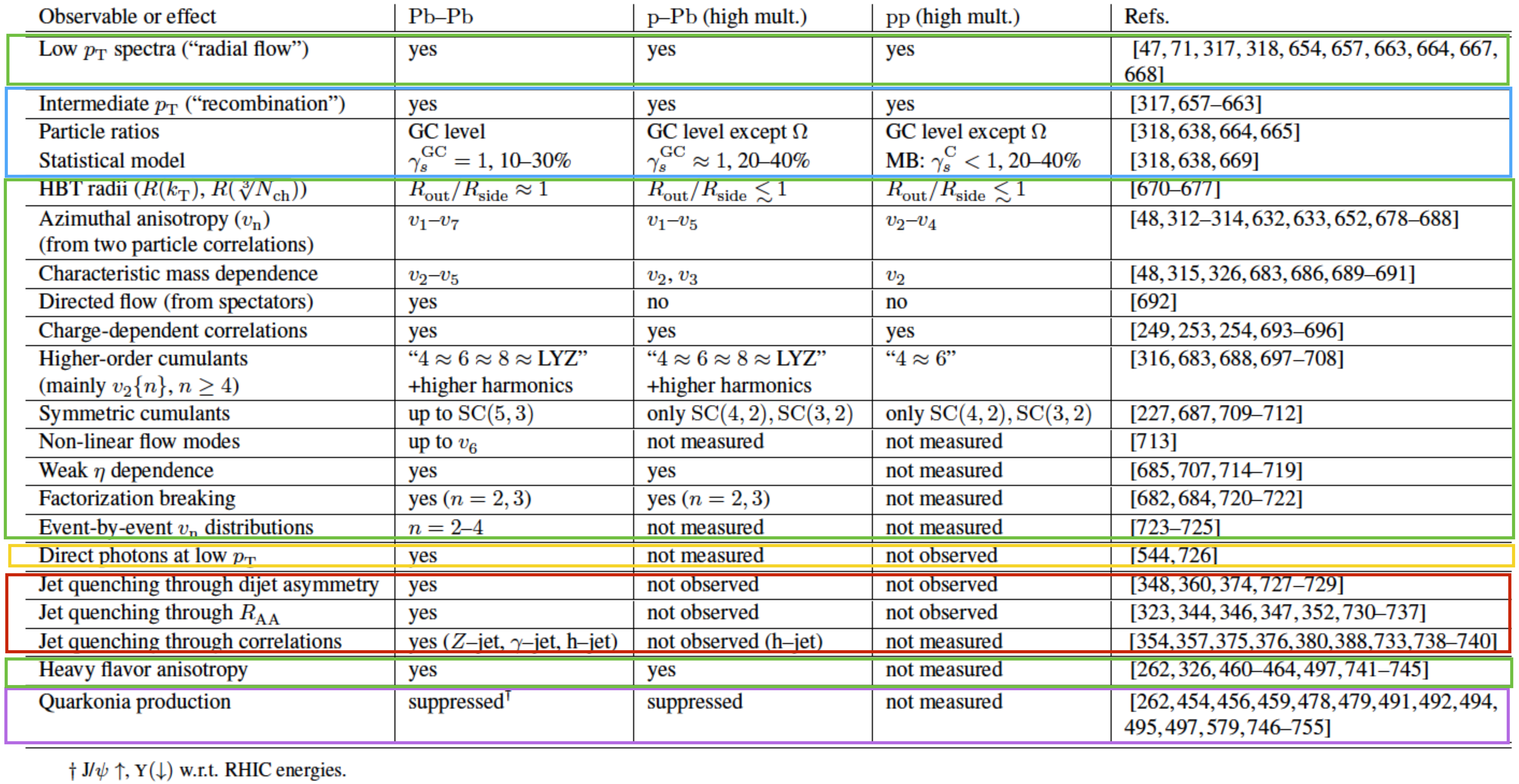
- Observables measured in small systems: pp and pA, that in AA are taken as QGP signals:

Collective hadronisation

Collective expansion (hydro-like)

Direct photons

Final state interactions (non-hydro)



Observable or effect	Pb–Pb	p–Pb (high mult.)	pp (high mult.)	Refs.
Low p_T spectra (“radial flow”)	yes	yes	yes	[47, 71, 317, 318, 654, 657, 663, 664, 667, 668]
Intermediate p_T (“recombination”)	yes	yes	yes	[317, 657–663]
Particle ratios	GC level	GC level except Ω	GC level except Ω	[318, 638, 664, 665]
Statistical model	$\gamma_s^{GC} = 1$, 10–30%	$\gamma_s^{GC} \approx 1$, 20–40%	MB: $\gamma_s^{C} < 1$, 20–40%	[318, 638, 669]
HBT radii ($R(k_T)$, $R(\sqrt[3]{N_{ch}})$)	$R_{out}/R_{side} \approx 1$	$R_{out}/R_{side} \lesssim 1$	$R_{out}/R_{side} \lesssim 1$	[670–677]
Azimuthal anisotropy (v_n) (from two particle correlations)	v_1–v_7	v_1–v_5	v_2–v_4	[48, 312–314, 632, 633, 652, 678–688]
Characteristic mass dependence	v_2–v_5	v_2, v_3	v_2	[48, 315, 326, 683, 686, 689–691]
Directed flow (from spectators)	yes	no	no	[692]
Charge-dependent correlations	yes	yes	yes	[249, 253, 254, 693–696]
Higher-order cumulants (mainly $v_2\{n\}, n \geq 4$)	“$4 \approx 6 \approx 8 \approx$ LYZ” +higher harmonics	“$4 \approx 6 \approx 8 \approx$ LYZ” +higher harmonics	“$4 \approx 6$”	[316, 683, 688, 697–708]
Symmetric cumulants	up to SC(5, 3)	only SC(4, 2), SC(3, 2)	only SC(4, 2), SC(3, 2)	[227, 687, 709–712]
Non-linear flow modes	up to v_6	not measured	not measured	[713]
Weak η dependence	yes	yes	not measured	[685, 707, 714–719]
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured	[682, 684, 720–722]
Event-by-event v_n distributions	$n = 2$–4	not measured	not measured	[723–725]
Direct photons at low p_T	yes	not measured	not observed	[544, 726]
Jet quenching through dijet asymmetry	yes	not observed	not observed	[348, 360, 374, 727–729]
Jet quenching through R_{AA}	yes	not observed	not observed	[323, 344, 346, 347, 352, 730–737]
Jet quenching through correlations	yes (Z–jet, γ–jet, h–jet)	not observed (h–jet)	not measured	[354, 357, 375, 376, 380, 388, 733, 738–740]
Heavy flavor anisotropy	yes	yes	not measured	[262, 326, 460–464, 497, 741–745]
Quarkonia production	suppressed†	suppressed	not measured	[262, 454, 456, 459, 478, 479, 491, 492, 494, 495, 497, 579, 746–755]

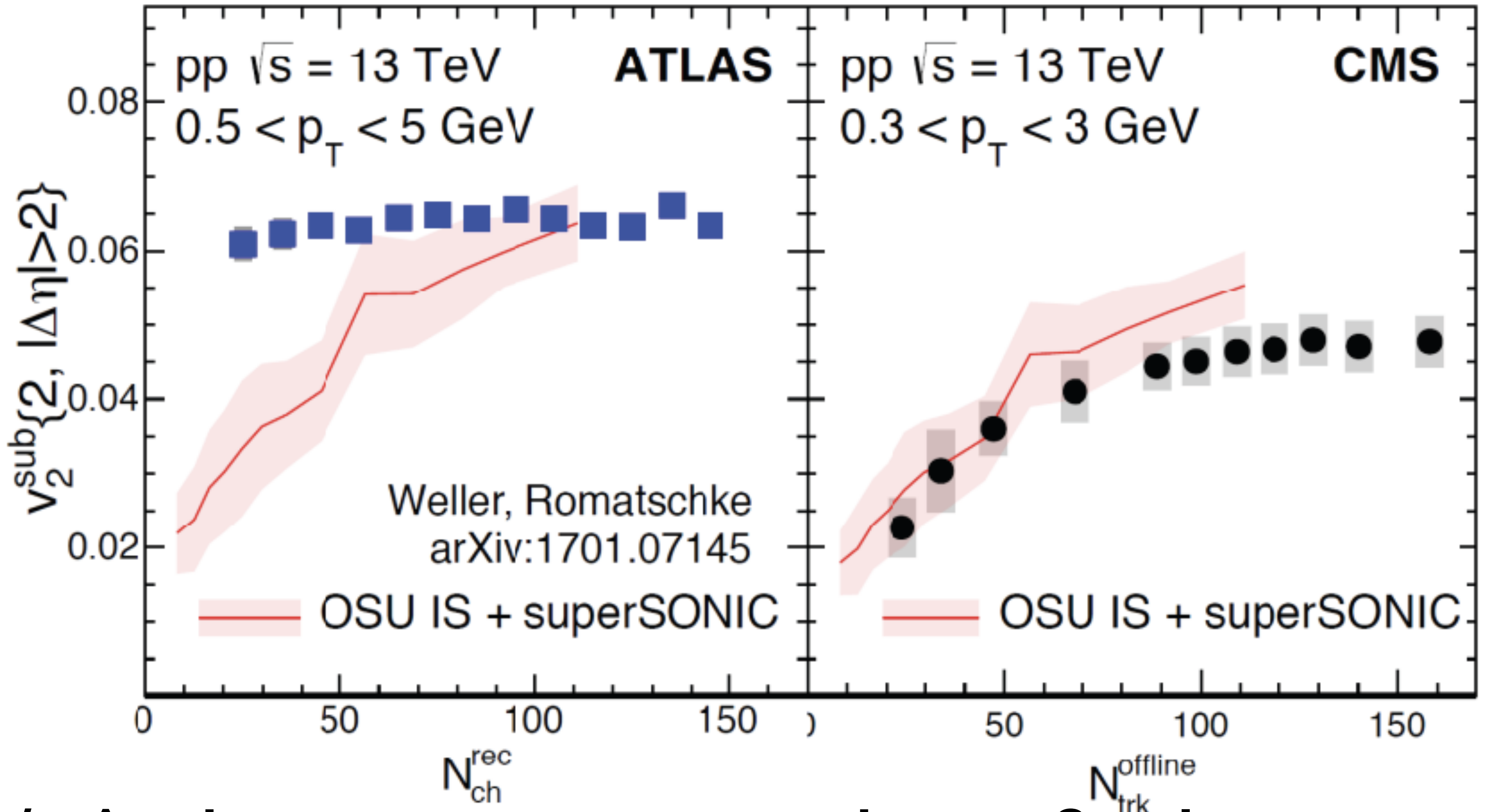
† $J/\psi \uparrow$, $\Upsilon(\downarrow)$ w.r.t. RHIC energies.

Small systems:

- Azimuthal correlations extended in η (the ridge) are found in all systems from almost minimum bias pp (10) to central AA (2000) and are describable by viscous relativistic hydro (with suitable ICs):

➜ Final state interactions, so QGP-like physics in all systems?

➜ Correlations already present in the hadron or nucleus wave functions, as in CGC calculations?



- One way to proceed: go to even smaller systems, ep/eA, down to a point where final state interactions cannot be justified.

➜ Correlations appear (e.g. in eA) for large multiplicities: final state interactions?

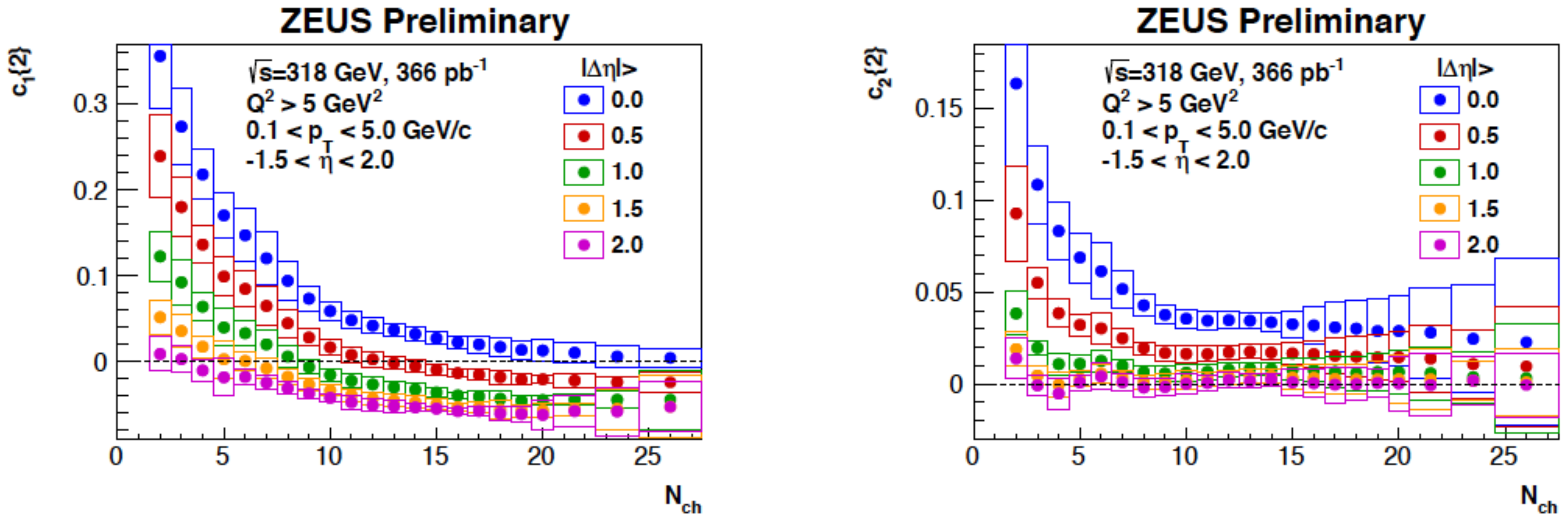
➜ No correlations: initial state effects?

- Note: preliminary analysis by ZEUS and ALEPH put strong limits on azimuthal 2-particle correlations in ep at HERA and e^+e^- at LEP.

Small systems:

Multiplicity-dependent $c_1\{2\}$ and $c_2\{2\}$ with increasing η-separation

ZEUS at DIS2019



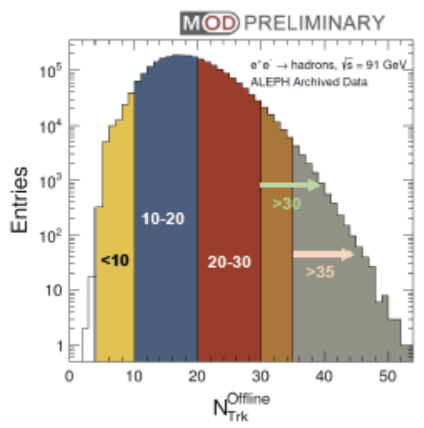
$|\Delta\eta| > 2.0$: $c_1\{2\}$ changes sign → consistent with momentum conservation.

$|\Delta\eta| > 2.0$: $c_2\{2\}$ consistent with zero.

Switching off the flow: e+e-

Talk: J-Y Lee

1906.00489



High-multiplicity events

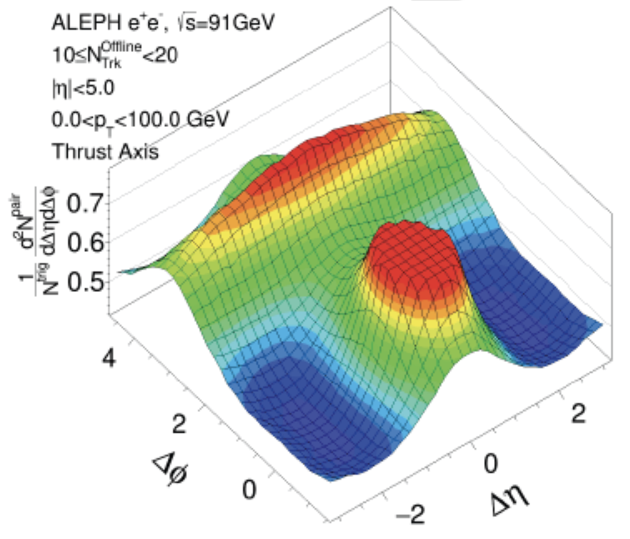
Low T; 'multi-jet'

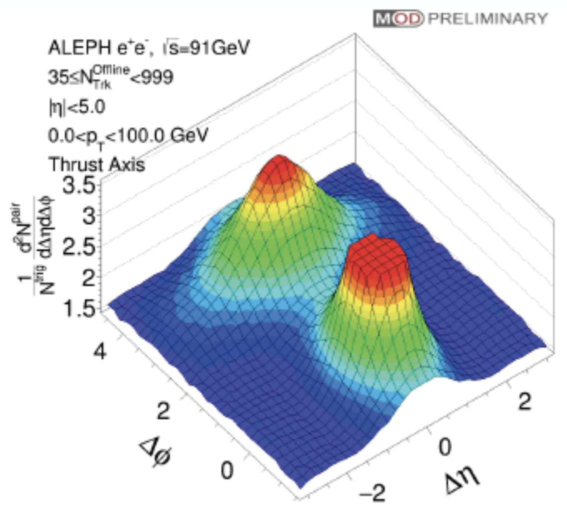
High T; 'di-jet'

10 < N < 20

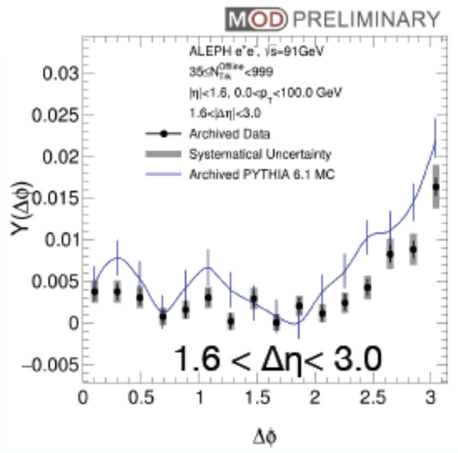
ALEPH e+e- thrust axis

N ≥ 35

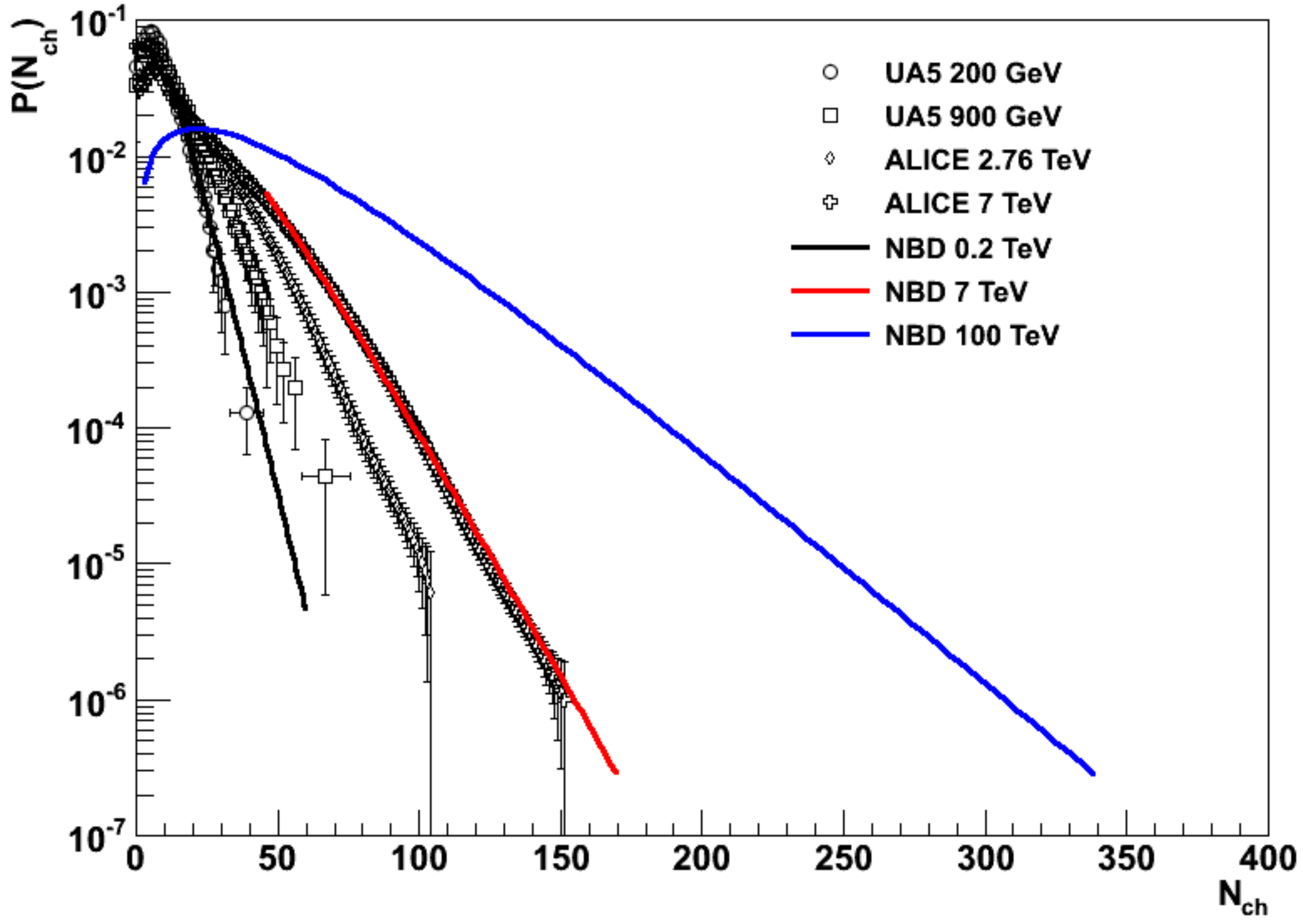




No evidence of long-range correlations beyond Pythia expectation



Charged multiplicity distribution $|\eta|<1.5$

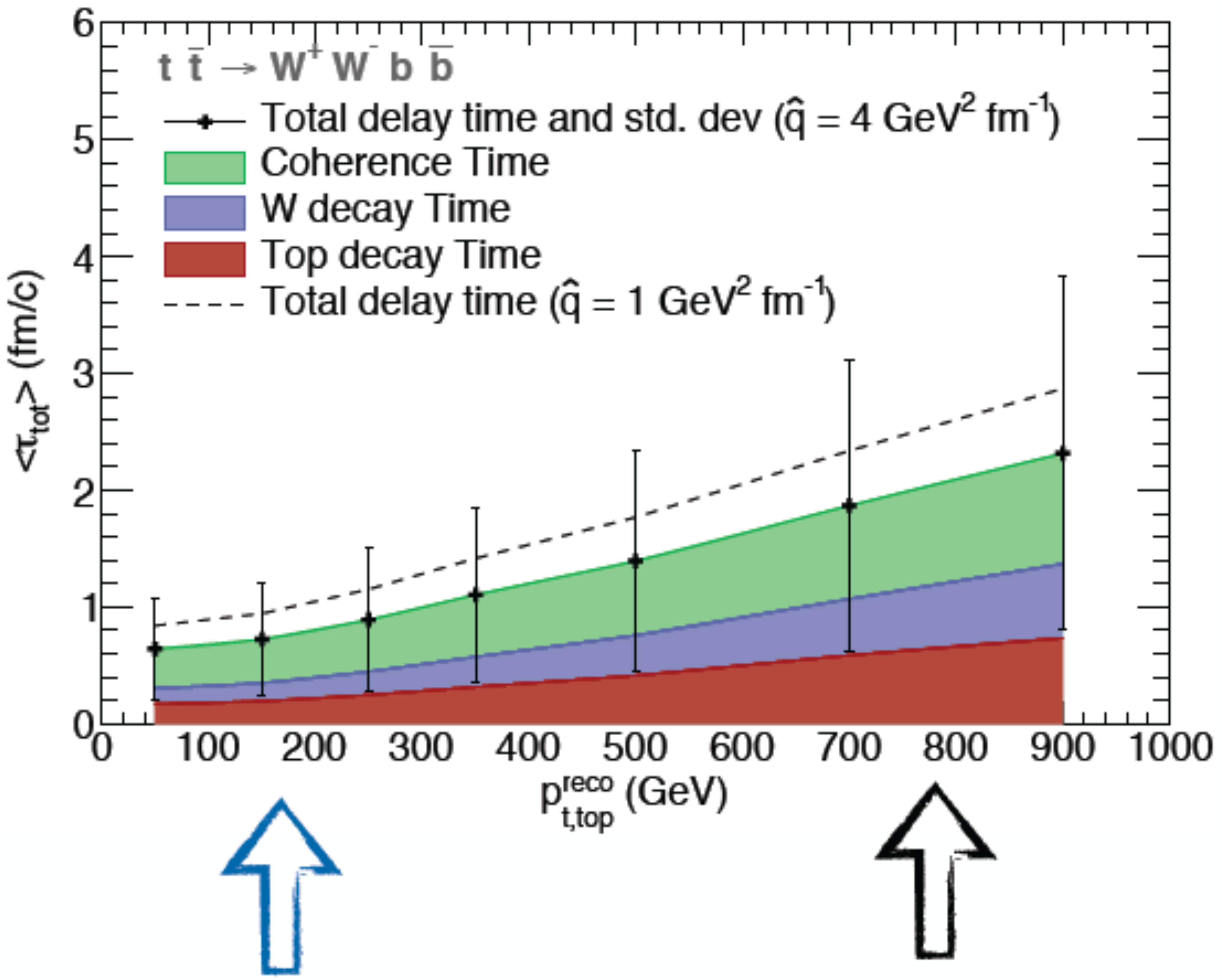


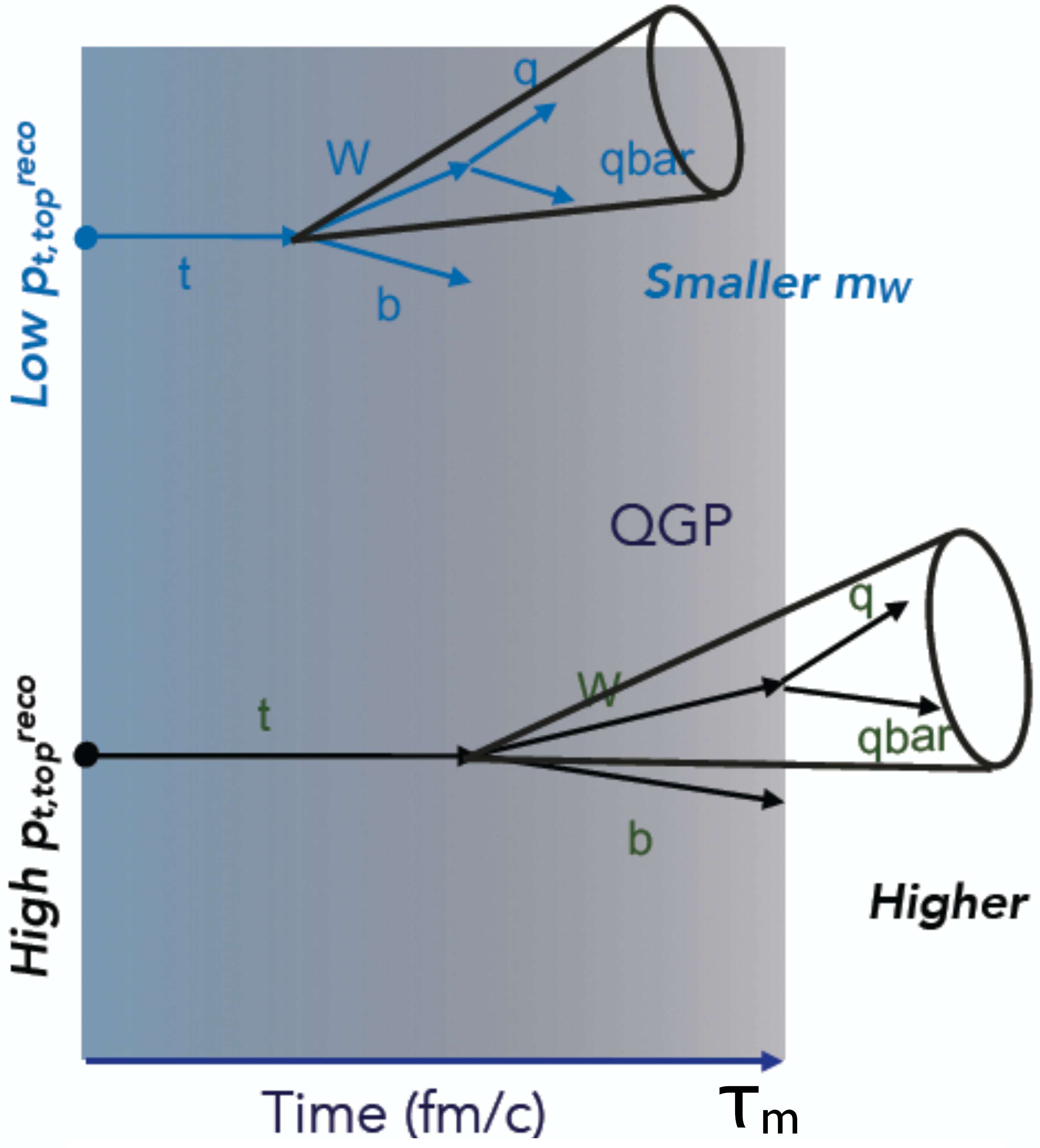
Initial stages though hard probes:

- Recent activity on the use of hard probes to study the initial stages of hadronic collisions (1902.03231).
- Large energies and statistics (lighter ions at HL-LHC?; FCC-AA) make boosted tops available (1711.03105).

Apolinario at HP2018

- Semi-leptonic decay of tt events produce jets that start interacting with the QGP only at later times





$$\langle\tau_{\rm tot}\rangle = \gamma_{t,\rm top}\tau_{\rm top} + \gamma_{t,W}\tau_W + \tau_d$$

Reconstructed W mass: m_W

will depend on the energy that is lost (medium length that jet is able to "see")

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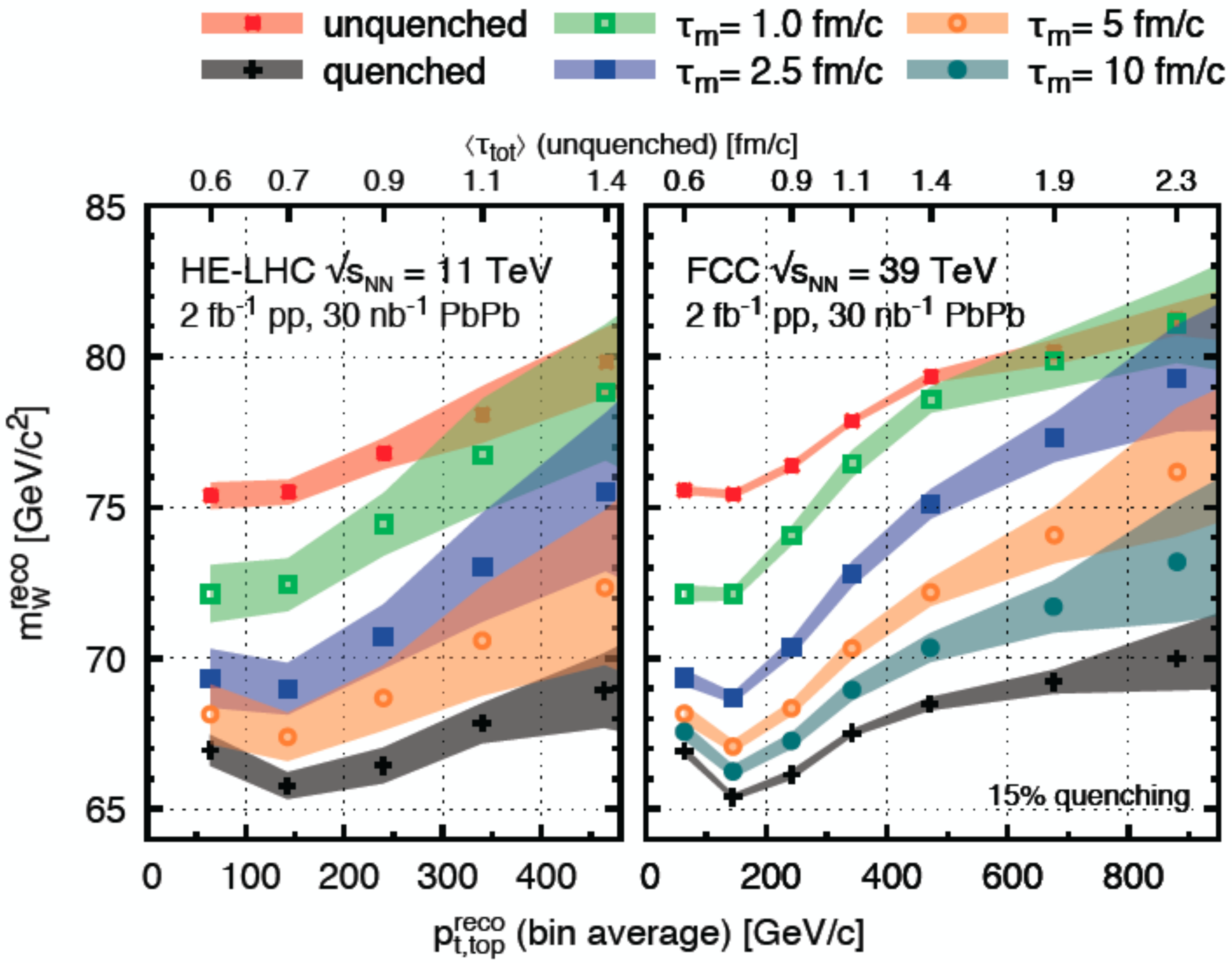
Apolinario at HP2018

- ✦ Reconstructed W Mass as a function of the top p_T:
  - ✦ Useful probe of the QGP density evolution
- ✦ QGP tomography:
  - ✦ HE-LHC: Some discrimination between short vs long lived medium
  - ✓ FCC: able to scan entire QGP lifetime!



Lighter ions in Runs 5 and 6:

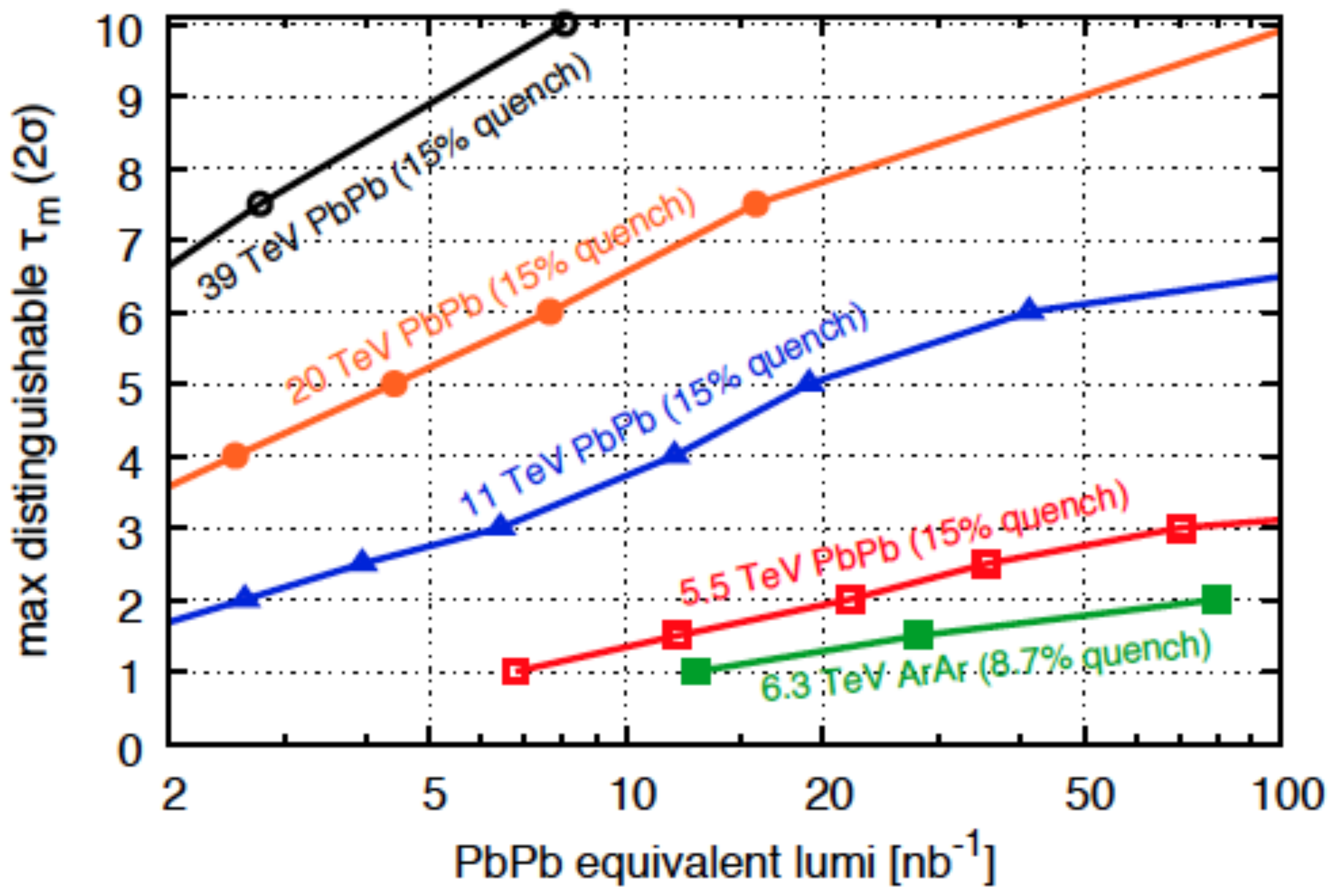
- There has been a proposal to collider lighter ions: O(Z=8,A=16), Ar(Z=18,A=40), Kr(Z=36,A=78), Xe(Z=52,A=129),…, in Runs 5 and 6 to:

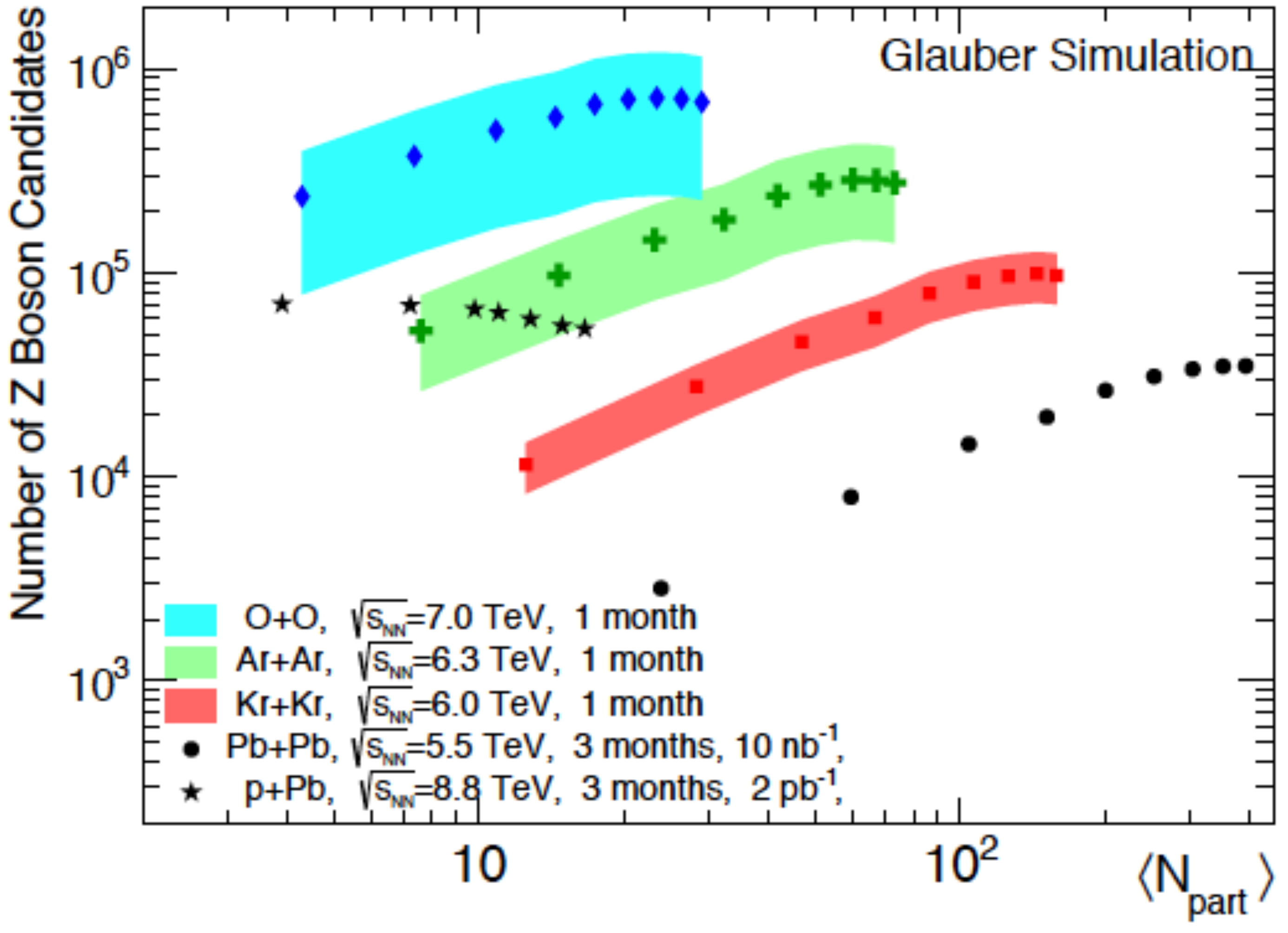
➜ Test size dependencies of QGP properties and dynamical mechanisms, getting rid of centrality definitions that introduce strong biases in peripheral collisions and pA → link to small systems.

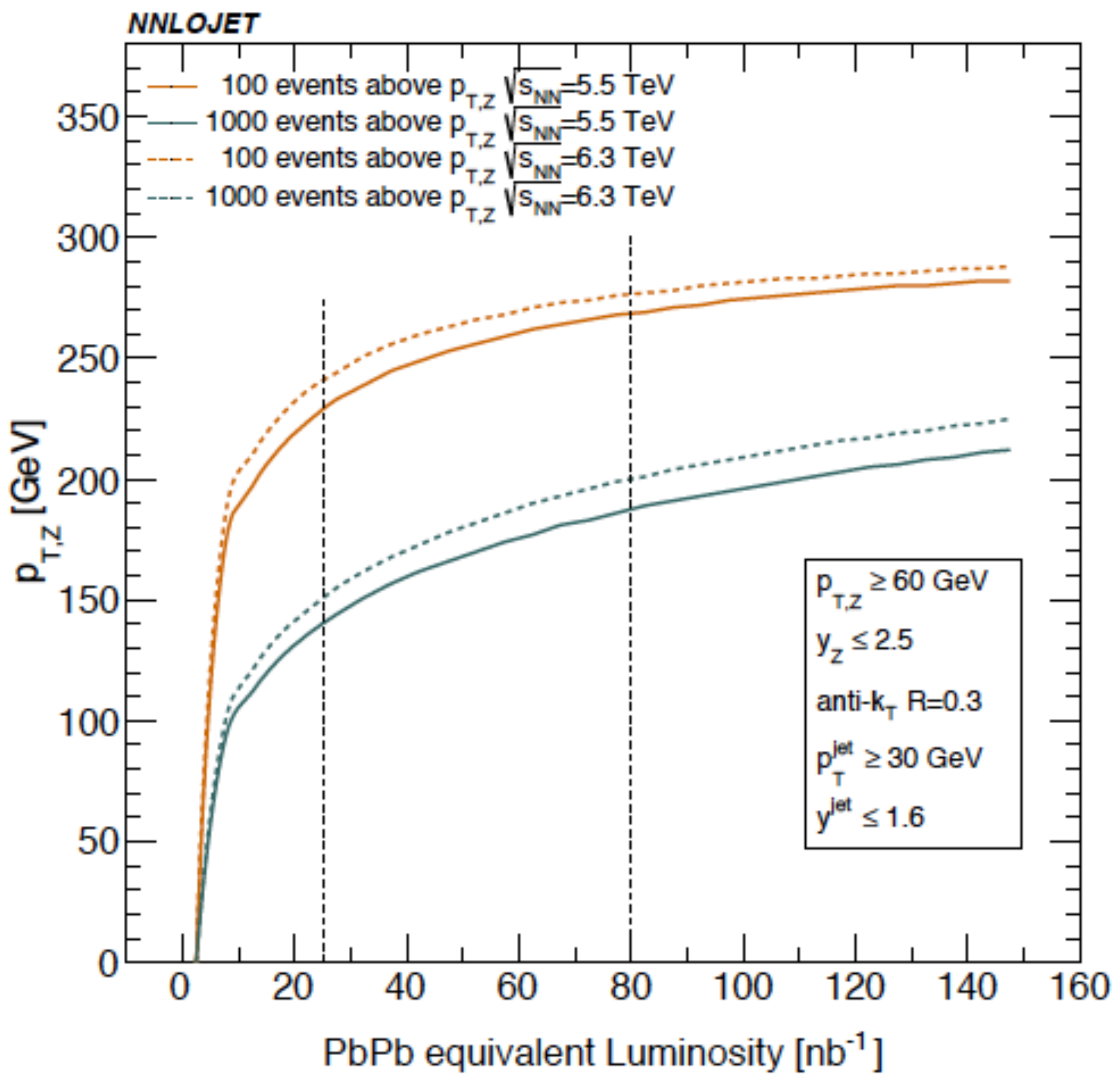
➜ Get rid of centrality dependence for nPDFs, ridge, etc., that introduce additional correlations.

➜ Get larger statistics: gains of factors 2 (Xe) to 15 (O), for e.g. top studies, Z+jet,…

- We may have new detectors/experiments there: LHCb Upgrade II, new detector in IP2 (HI detector focused on soft physics (1902.01211), or LHeC that would offer ep/eA at the same time as pp/pA/AA).







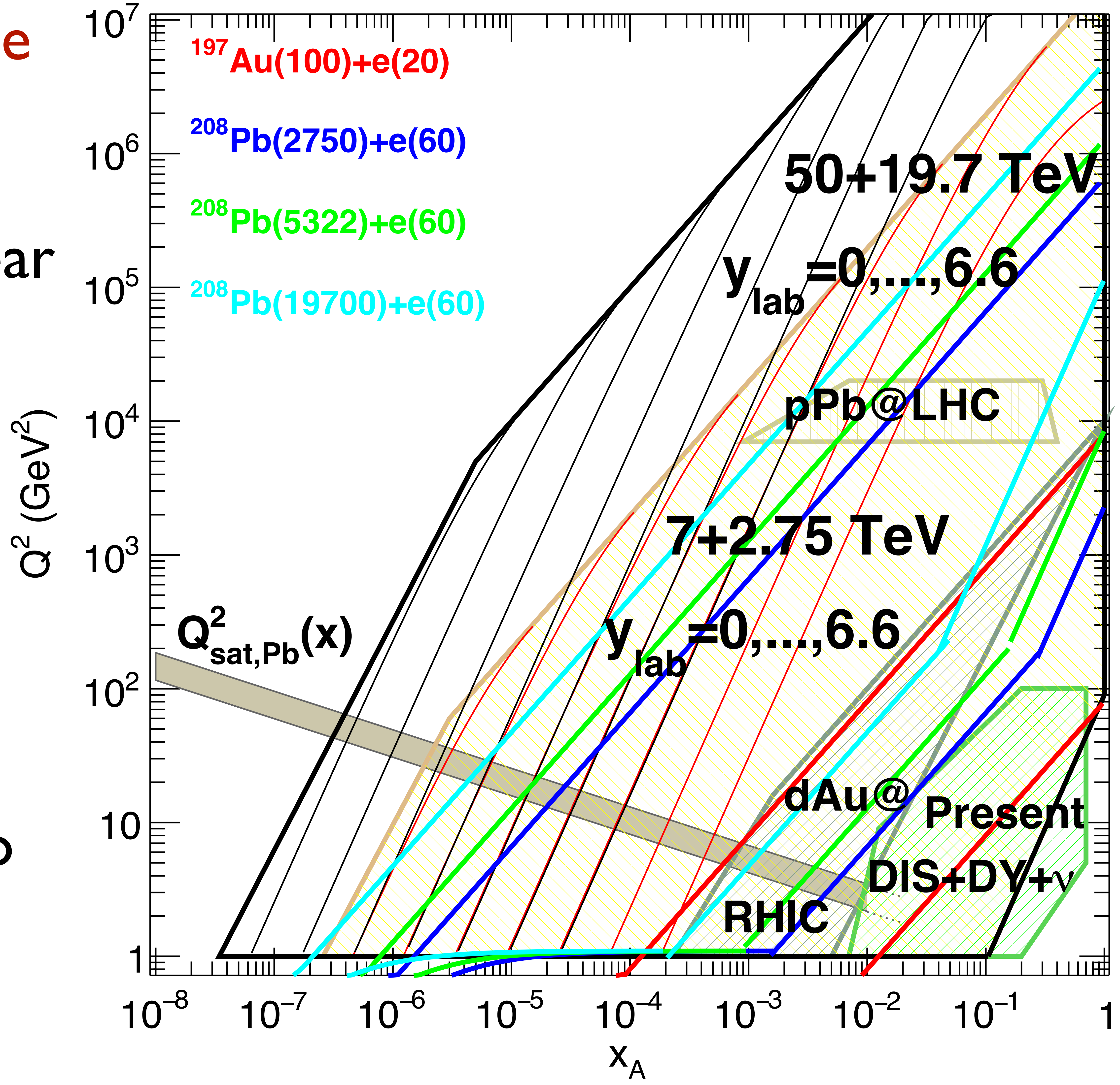
Summary:

- I have done an incomplete, **personal** overview of the possibilities for high-density QCD with ions at the HL-LHC and beyond: FCC as representative of AA colliders, ep/eA and fixed target possibilities.
  - ➜ Partonic structure of the nucleus, in the collinear framework and beyond.
  - ➜ New dynamics at small x.
  - ➜ Some discussion on medium evolution.

- Hadron/DIS machines are complementary in terms of 'reach'/'precision'.

- Both proton and nuclear targets will be required to unravel the existence of a new regime of QCD.

- Most interesting things are waiting for us!!!



Summary:

Many thanks to:

→ My HL-LHC, FCC-AA, LHeC/FCC-eh and EIC colleagues for discussions and the opportunity to work with them;

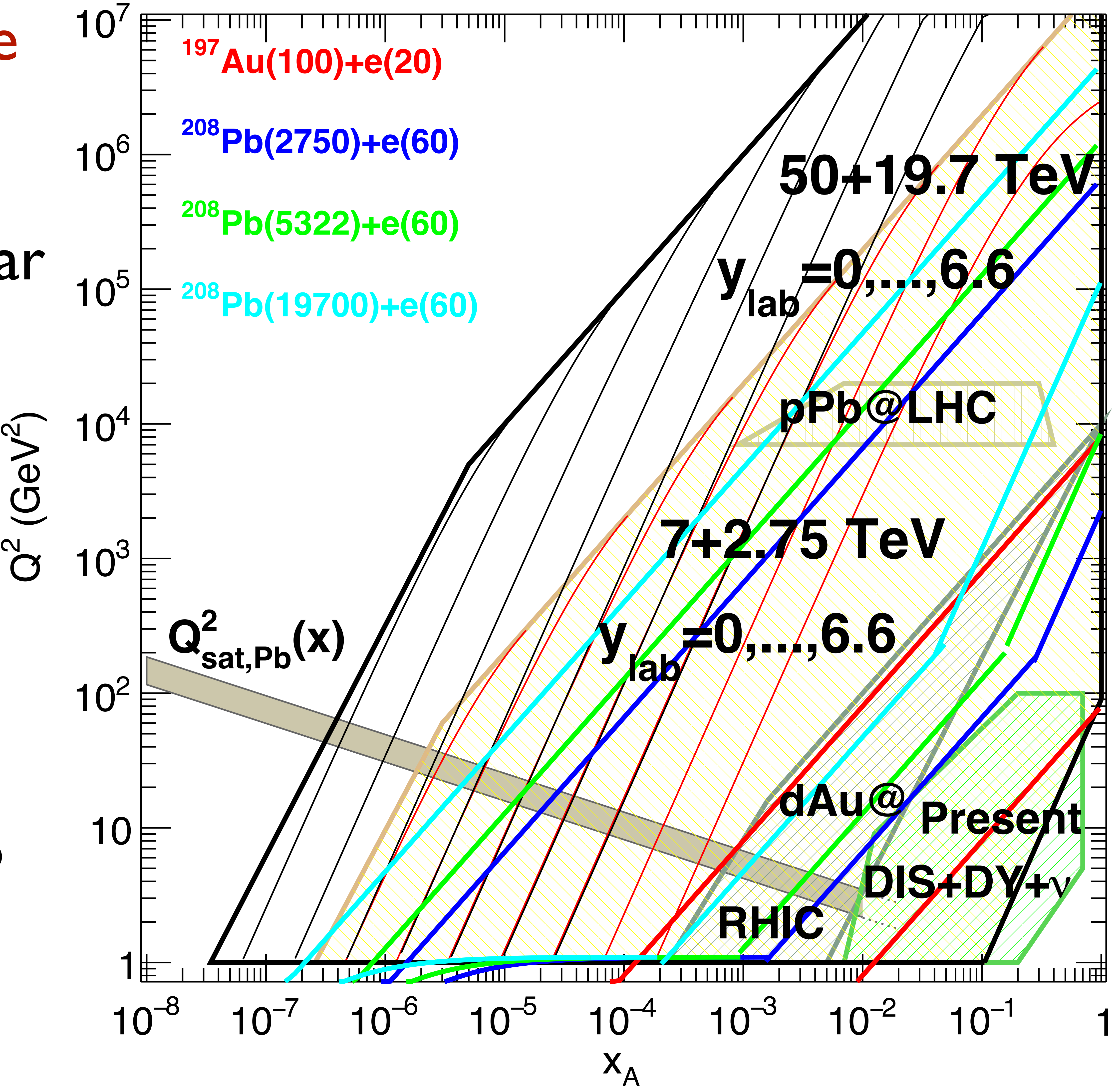
→ Christophe and Paul for the invitation to provide this talk;

→ You all for your attention.

- Hadron and DIS machines are complementary in terms of ‘discovery’/‘precision’.

- Both proton and nuclear targets will be required to unravel the existence of a new regime of QCD.

- Most interesting things are waiting for us!!!

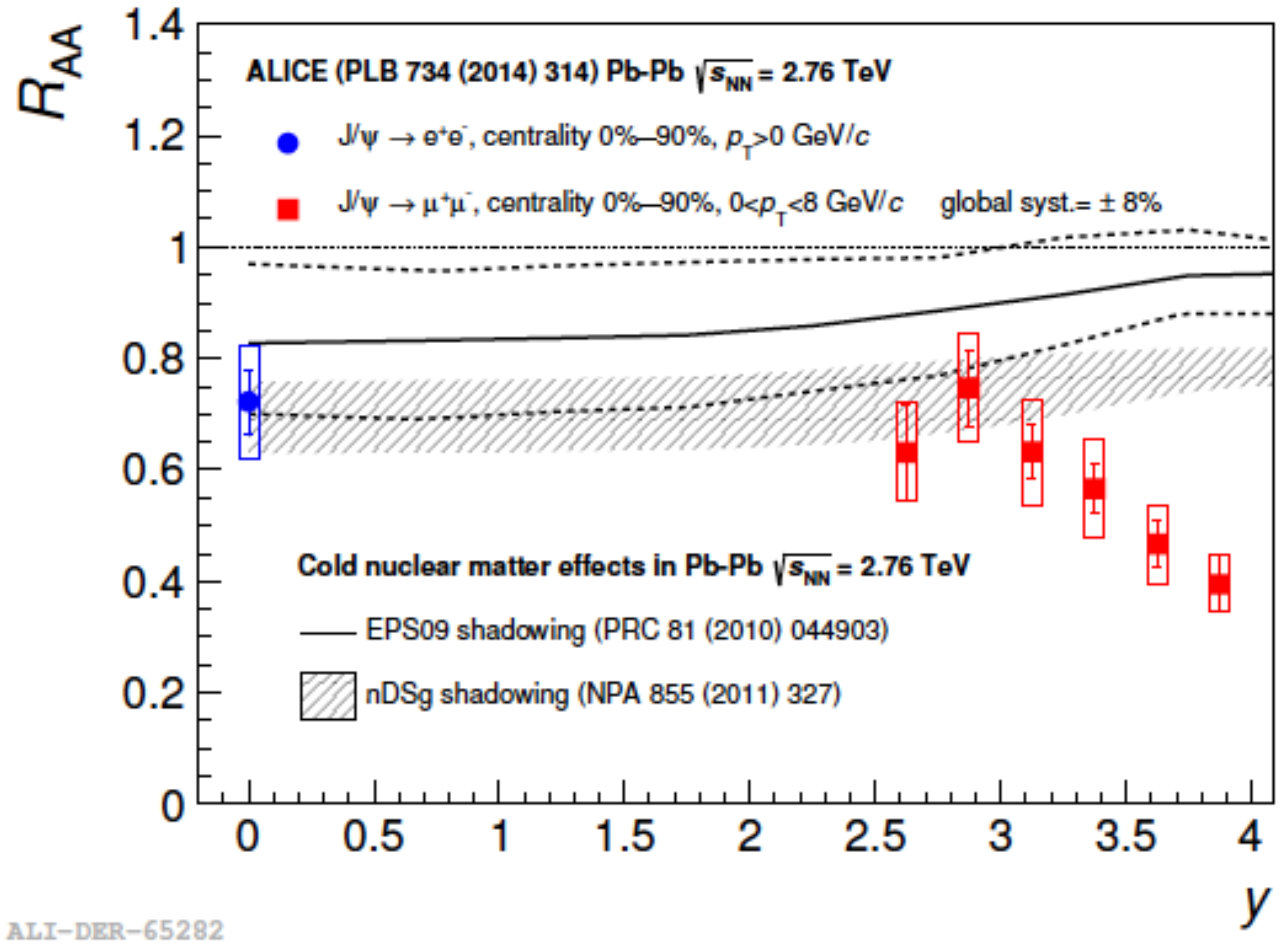


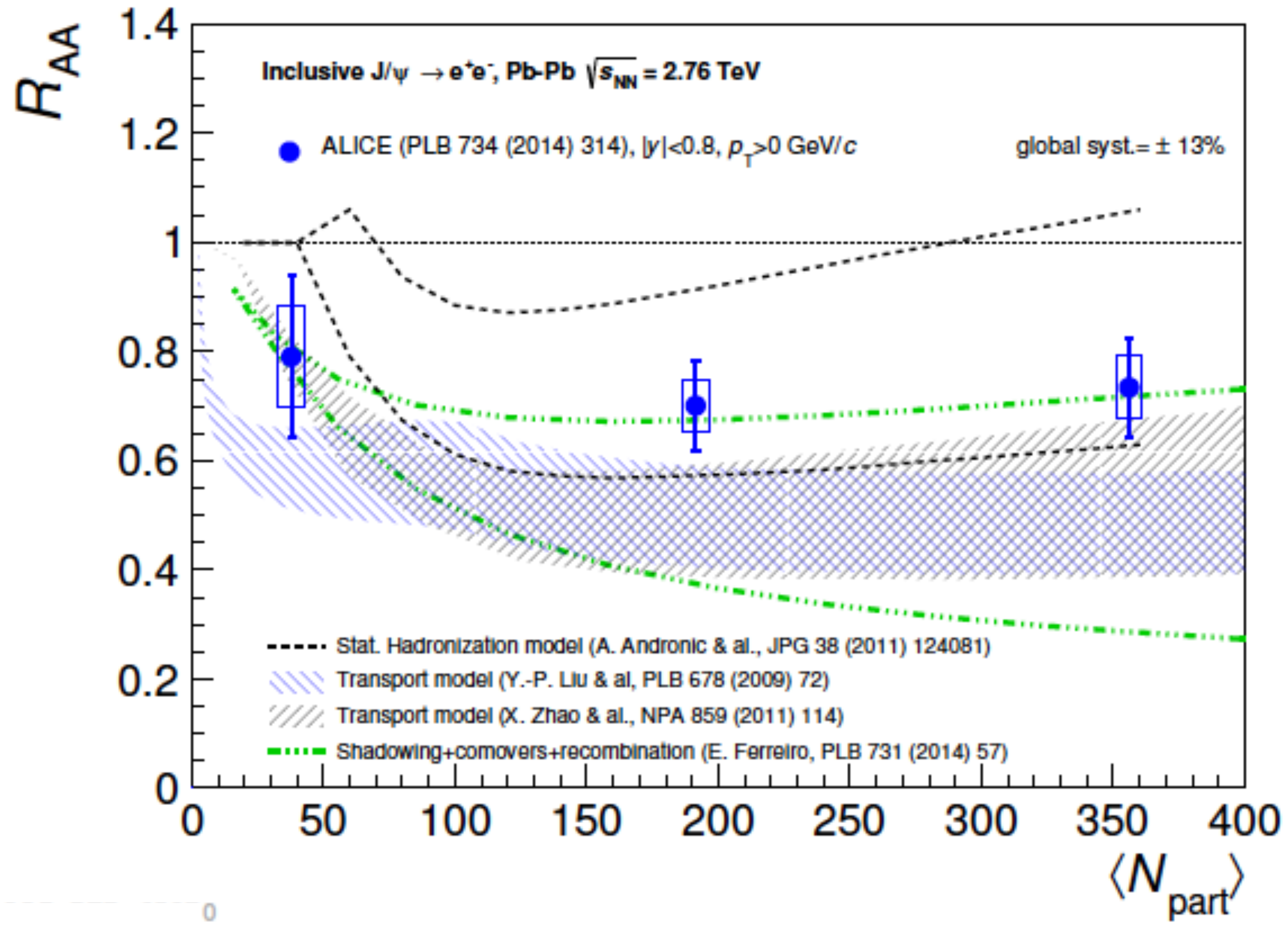
Backup

nPDFs: implications on HI physics

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

- 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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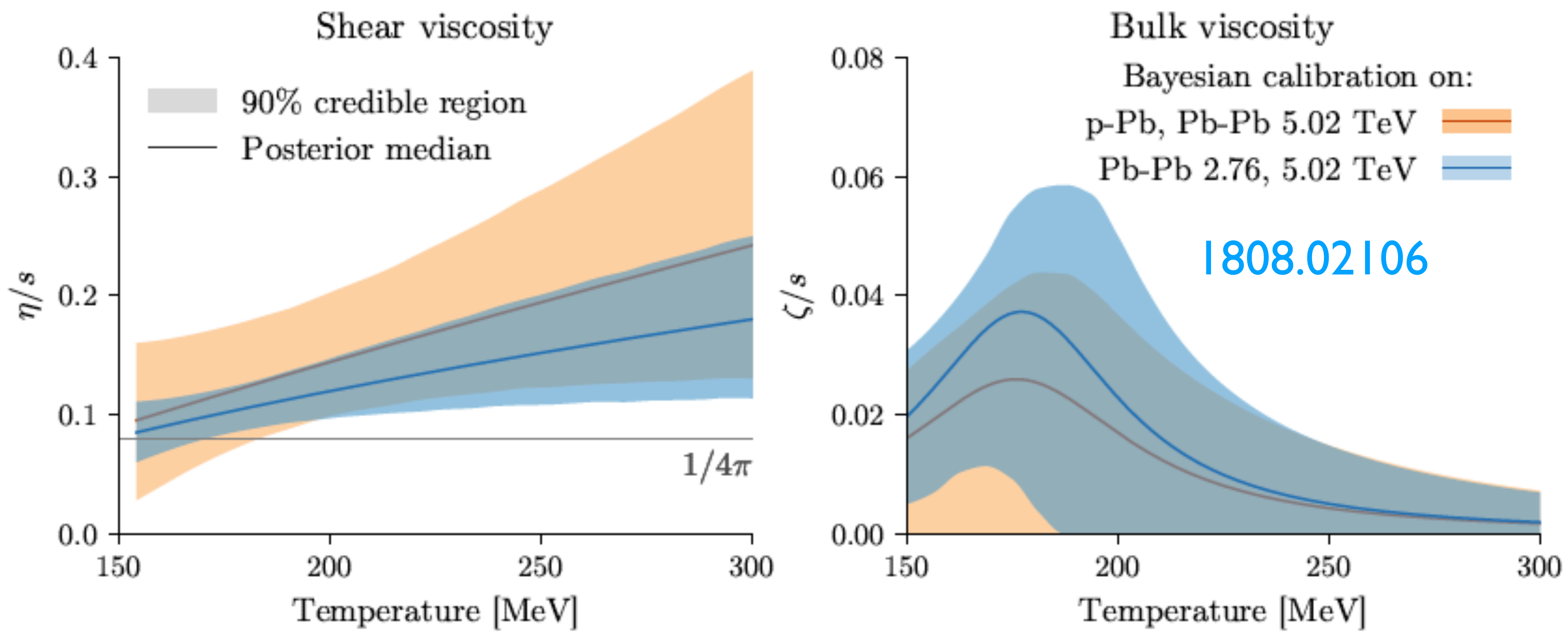
nPDFs: implications on HI physics



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