

**DIS2018: XXVIth International Workshop on Deep Inelastic
Scattering and Related Subjects
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Future of Nuclear PDFs

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Contents:

1. Introduction.

2. Present status of nPDFs.

3. Future of determination of nPDFs.

→ Kinematics.

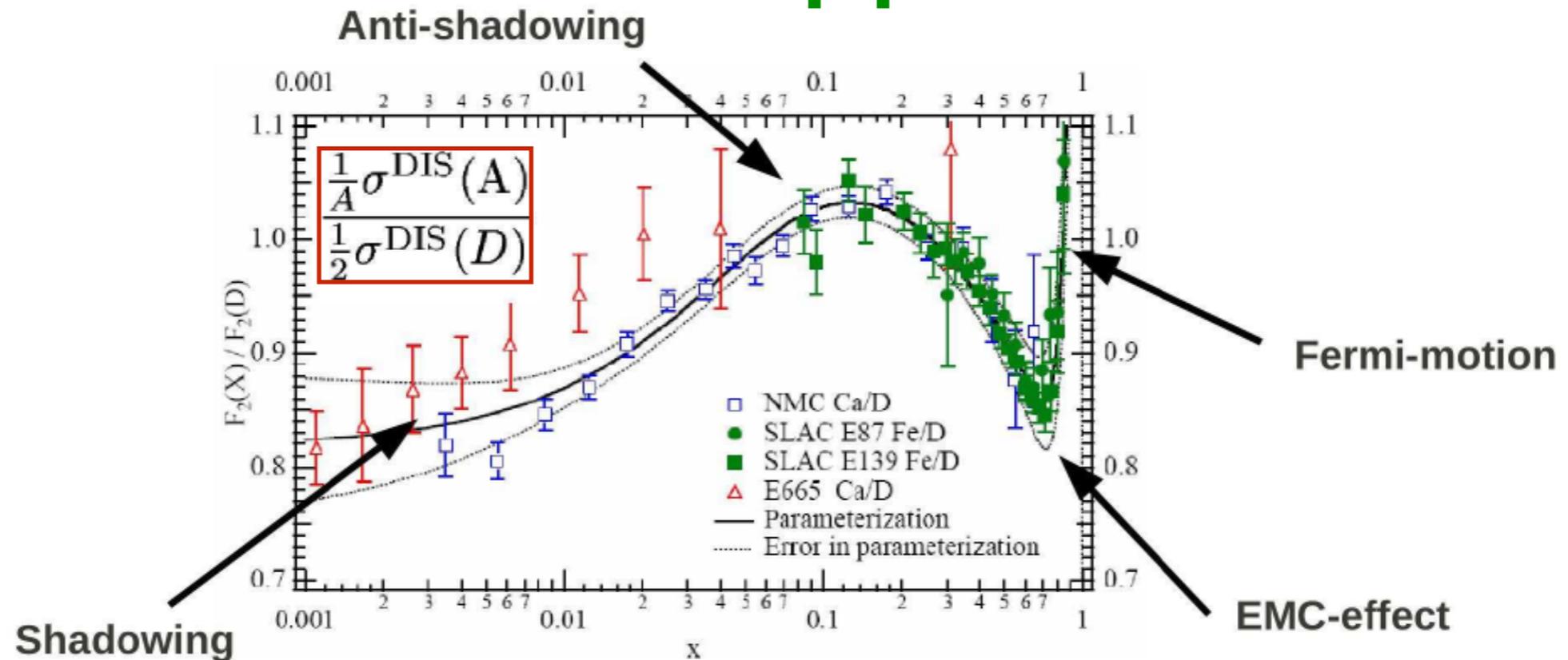
→ Constraints from the (HL-)LHC.

→ Constraints from EICs.

4. Summary.

See the talks by Ilkka Helenius, Yulia Furletova, Aleksander Kusina, Fred Olness, Petja Paakkinen and Thomas Ullrich.

Collinear approach:



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

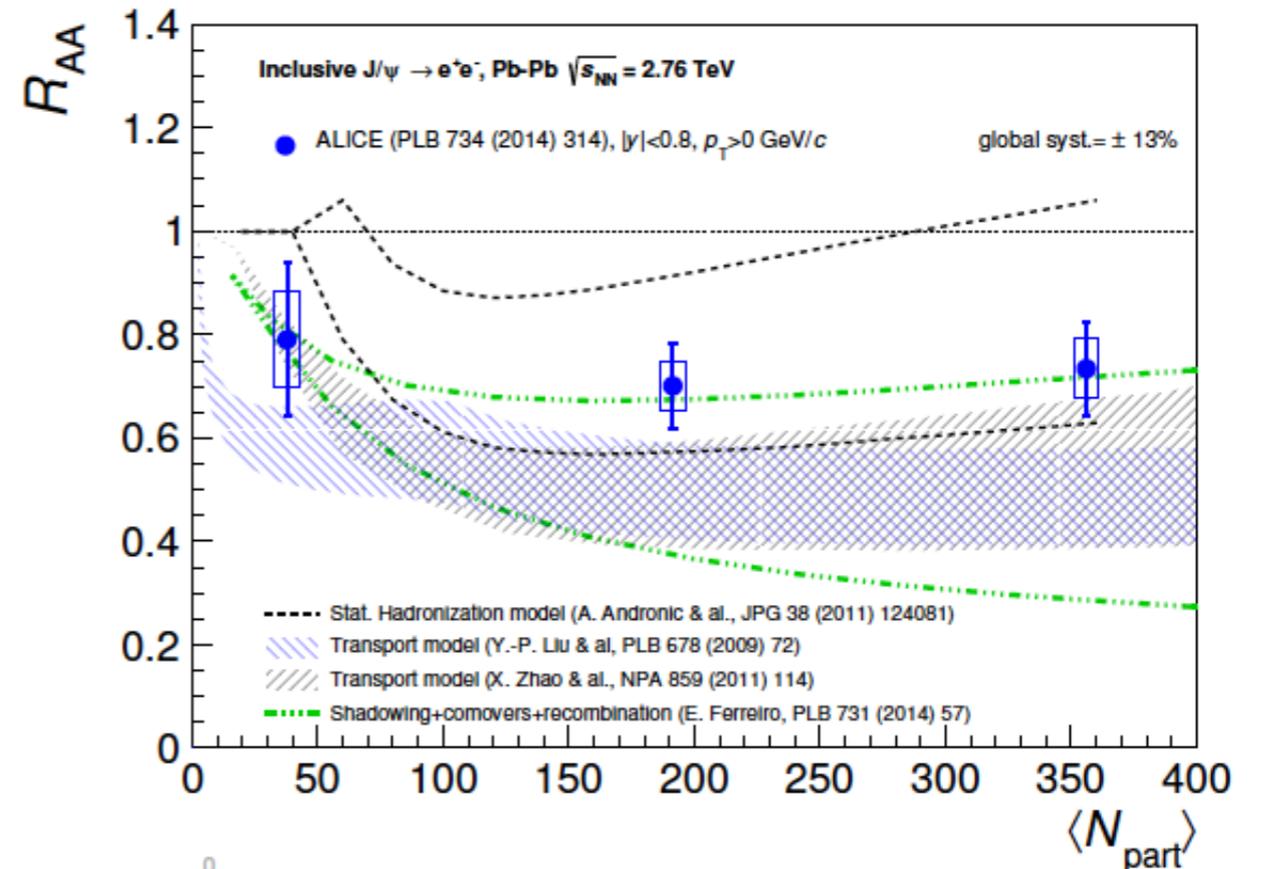
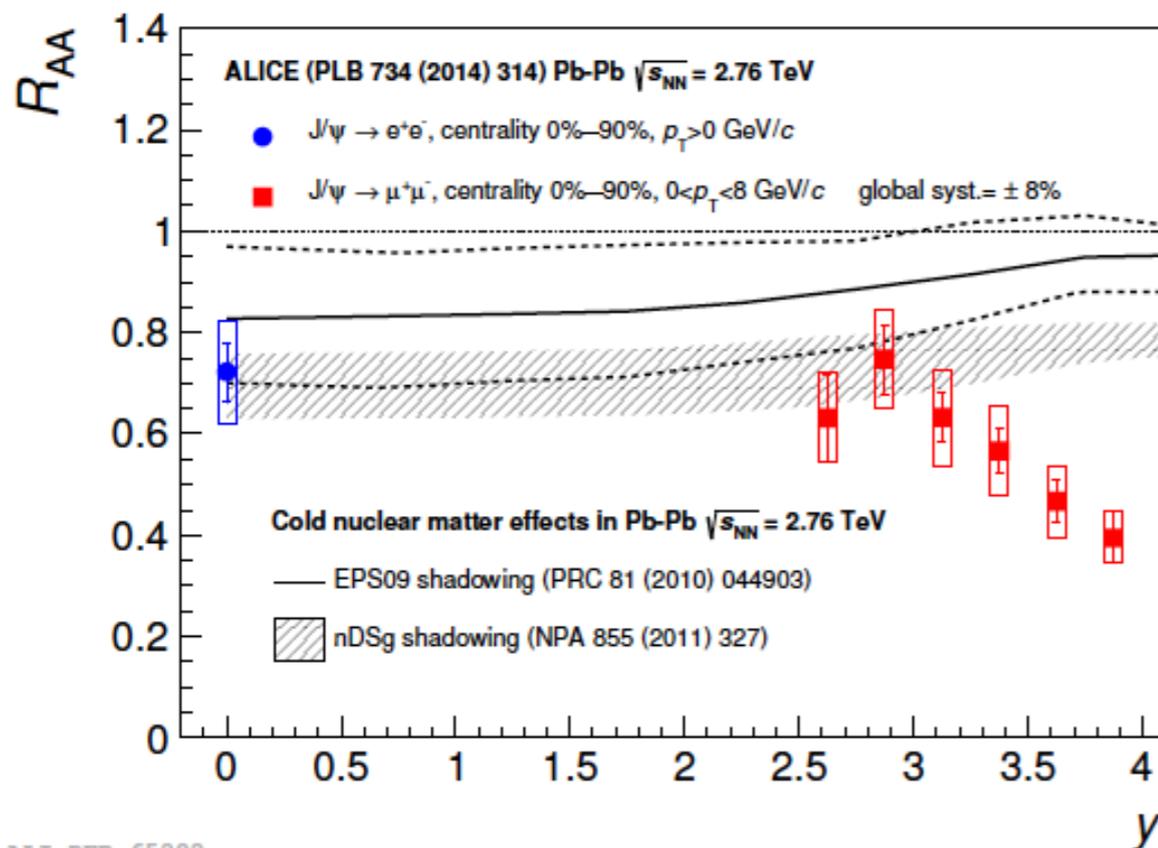
$$\sigma_{\text{DIS}}^{\ell+A \rightarrow \ell+X} = \sum_{i=q, \bar{q}, g} \underbrace{f_i^A(\mu^2)}_{\text{Nuclear PDFs, obeying the standard DGLAP}} \otimes \underbrace{\hat{\sigma}_{\text{DIS}}^{\ell+i \rightarrow \ell+X}(\mu^2)}_{\text{Usual perturbative coefficient functions}}$$

$$f_i^{p,A}(x, Q^2) = \boxed{R_i^A(x, Q^2)} f_i^p(x, Q^2) \quad \boxed{R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}}$$

nPDFs for HIC:

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

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



ALI-DER-65282

1506.03981

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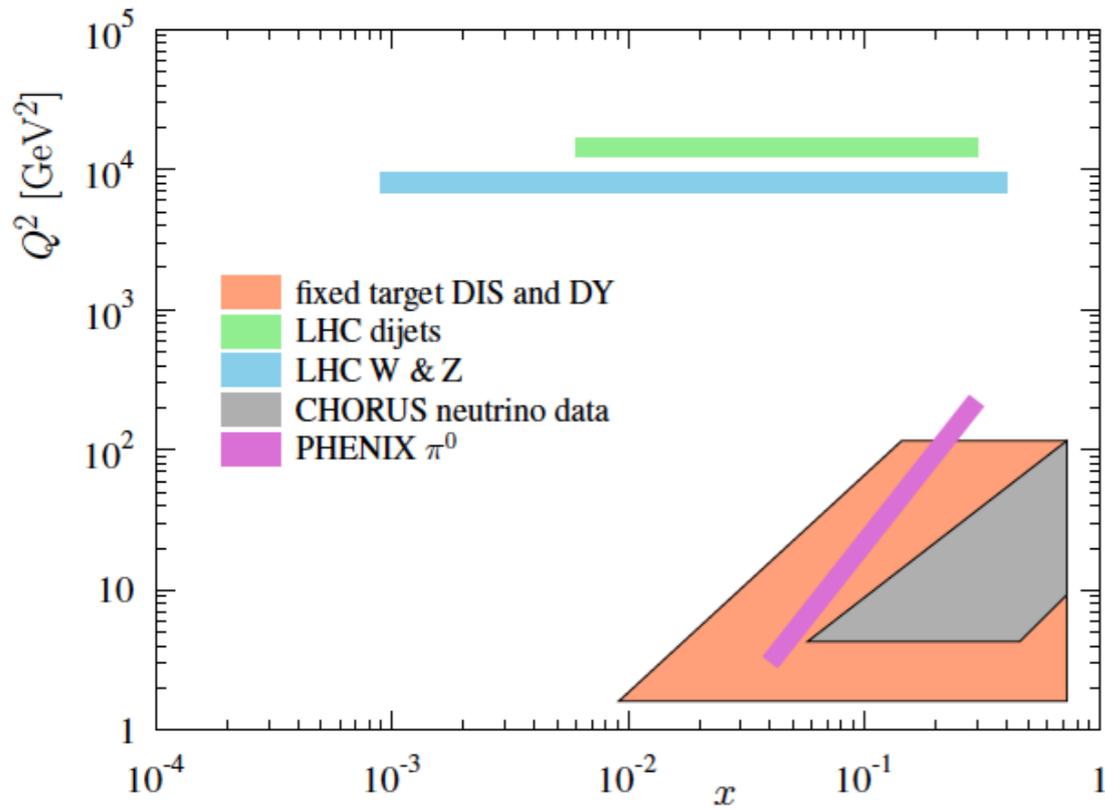
Available sets:

SET		HKN07 PRC76 (2007) 065207	EPS09 JHEP 0904 (2009) 065	DSSZ PRD85 (2012) 074028	nCTEQ15 PRD93 (2016) 085037	KAI5 PRD93 (2016) 014036	EPPS16 EPJC C77 (2017)163
data	eDIS	✓	✓	✓	✓	✓	✓
	DY	✓	✓	✓	✓	✓	✓
	π^0	✗	✓	✓	✓	✗	✓
	vDIS	✗	✗	✓	✗	✗	✓
	pPb	✗	✗	✗	✗	✗	✓
# data	1241	929	1579	740	1479	1811	
order	NLO	NLO	NLO	NLO	NNLO	NLO	
proton PDF	MRST98	CTEQ6.1	MSTW2008	~CTEQ6.1	JR09	CT14NLO	
mass scheme	ZM-VFNS	ZM-VFNS	GM-VFNS	GM-VFNS	ZM-VFNS	GM-VFNS	
comments	$\Delta\chi^2=13.7$, ratios, <u>no EMC for gluons</u>	$\Delta\chi^2=50$, ratios, <u>huge shadowing-antishadowing</u>	$\Delta\chi^2=30$, ratios, <u>medium-modified FFs for π^0</u>	$\Delta\chi^2=35$, PDFs, <u>valence flavour sep., not enough sensitivity</u>	PDFs, <u>deuteron data included</u>	$\Delta\chi^2=52$ <u>flavour sep., ratios, LHC pPb data</u>	

Available sets:

SET	HKN07 PRC76 (2007)	EPS09 JHEP 0904	DSSZ PRD85 (2012) 074028	nCTEQ15 PRD93 (2016) 085037	KAI5 PRD93 (2016) 014036	EPPS16 EPJC C77 (2017)163
<ul style="list-style-type: none"> Centrality dependence (EPS09s) not from data but from the A-dependence of the parameters. Several models provide it: Vogt et al., FGS, Ferreiro et al.,... 			✓	✓	✓	✓
			✓	✓	✓	✓
			✓	✓	✗	✓
			✓	✗	✗	✓
			✗	✗	✗	✓
			1579	740	1479	1811
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EPPS16:



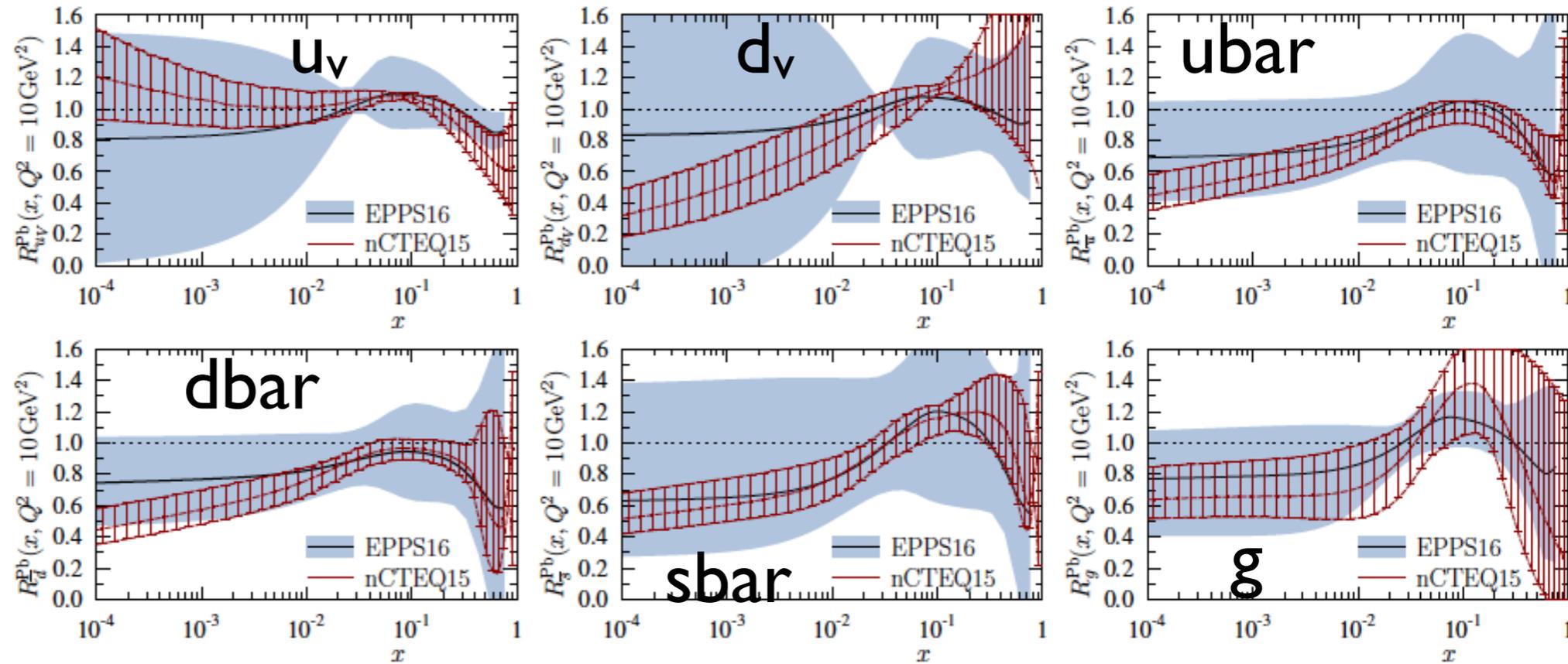
- Most Pb data from CHORUS, 30 Pb points from pPb@LHC: fit for a single nucleus not possible.

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

EPPS16:

$Q^2=10 \text{ GeV}^2$

- nCTEQ15 vs. EPPS16: note the parametrisation bias.

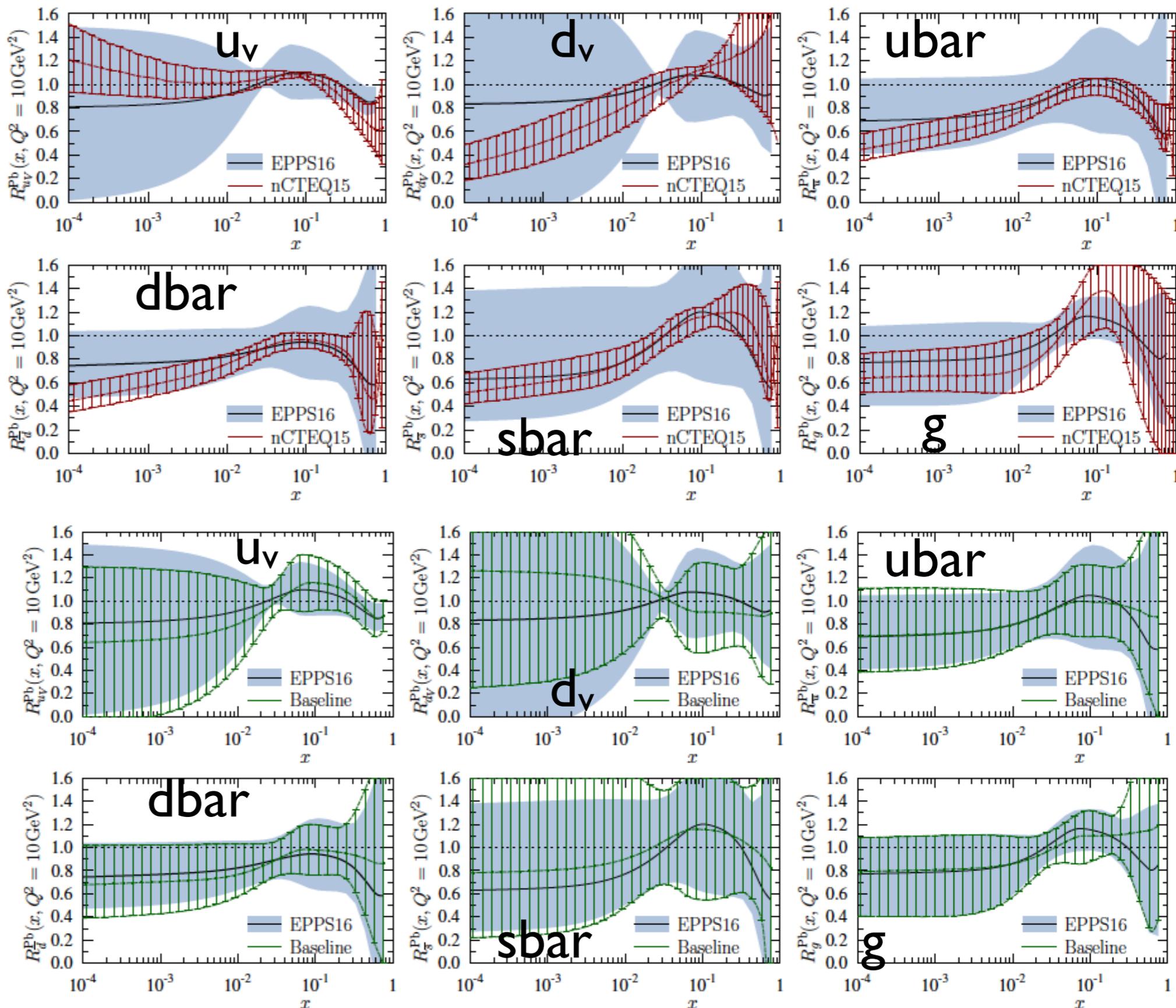


EPPS16:

$Q^2=10 \text{ GeV}^2$

- 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).



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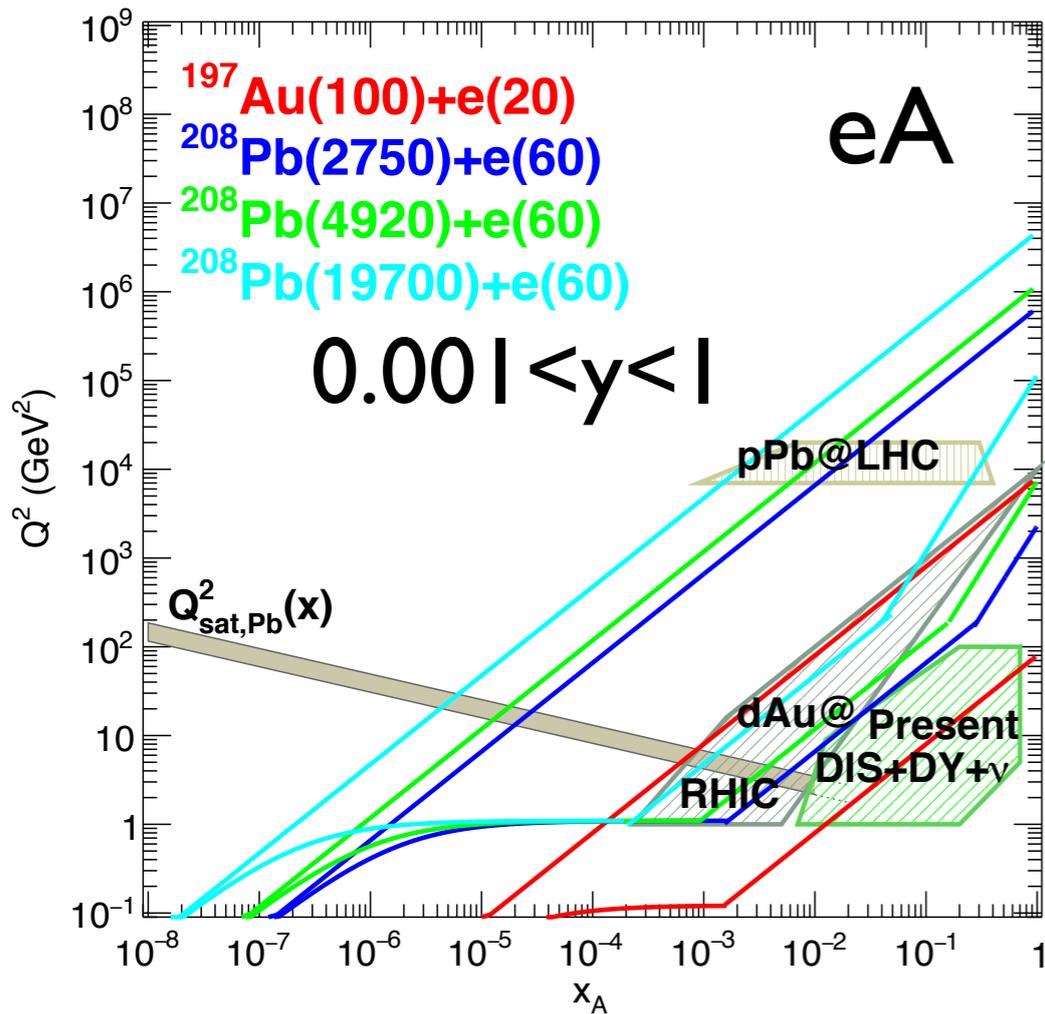
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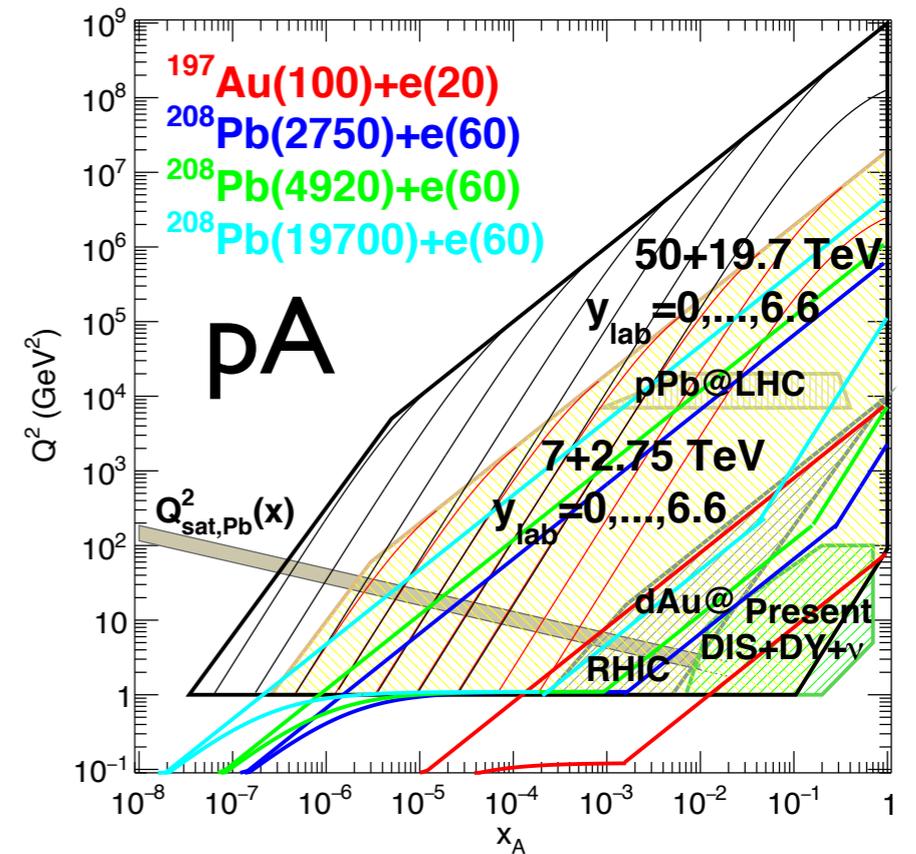
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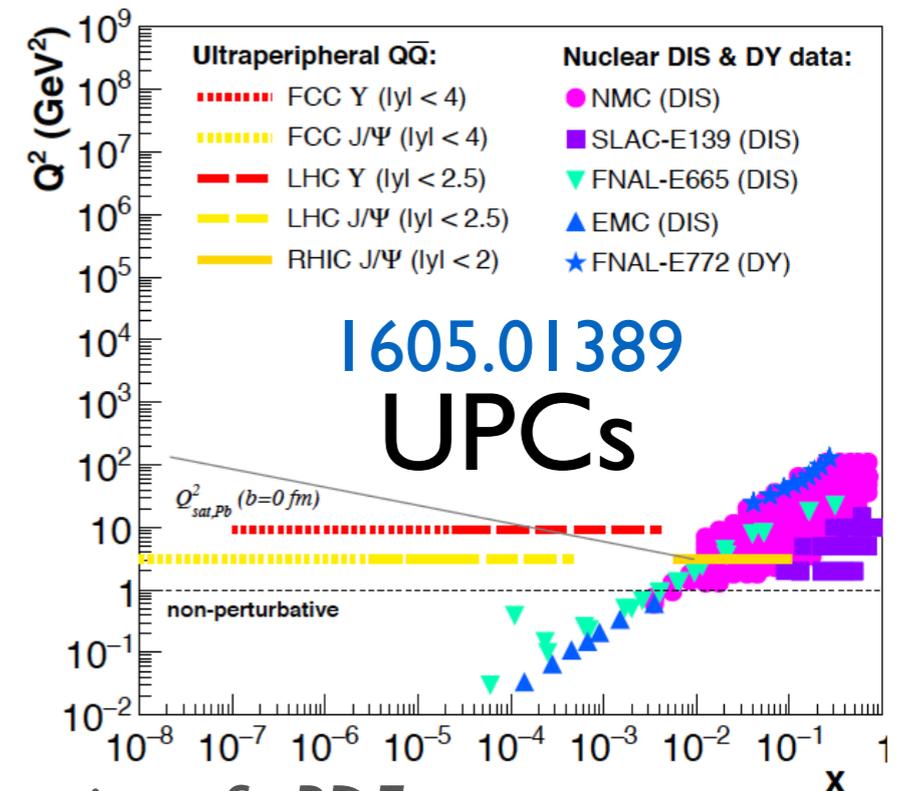
EICs versus pA:



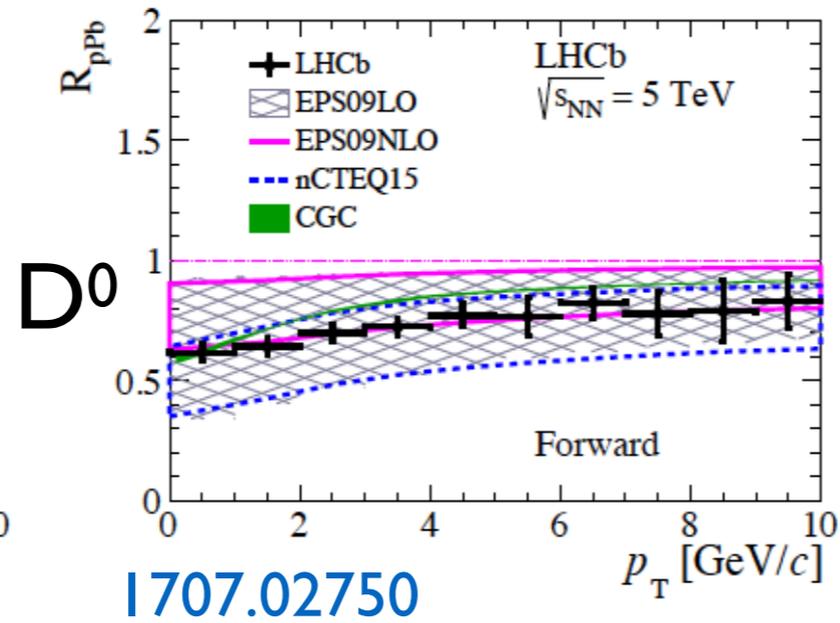
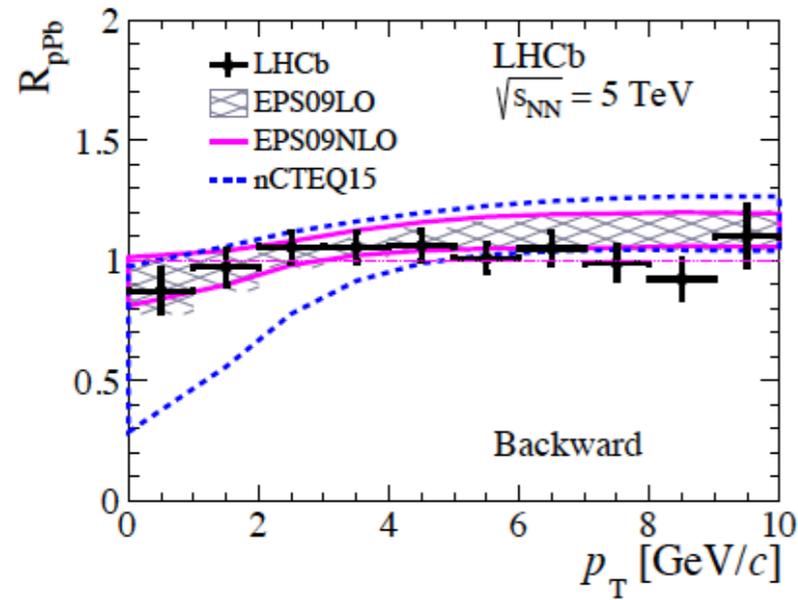
- Extension of 2 to 4-5 orders of magnitude in x and Q^2 wrt existing DIS data.
- pA unbeatable in kinematics.



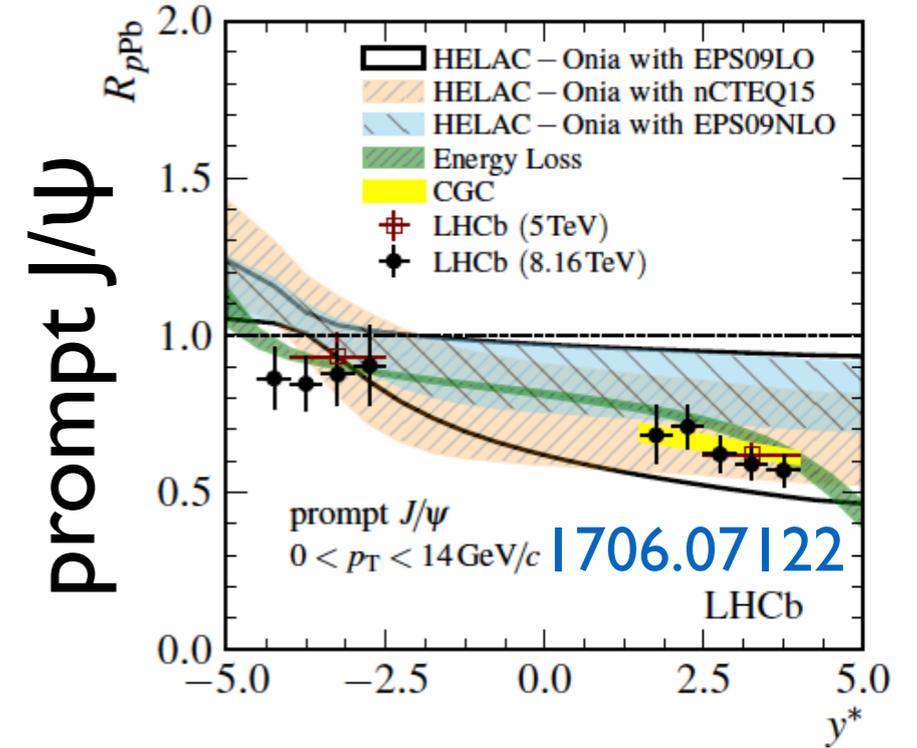
- DIS offers:
 - A clean experimental environment: low multiplicity, no pileup, fully constrained kinematics x, Q^2 by reconstructing the outgoing lepton;
 - A more controlled theoretical setup: many 1st-principles calculations.



Open charm and J/ψ :

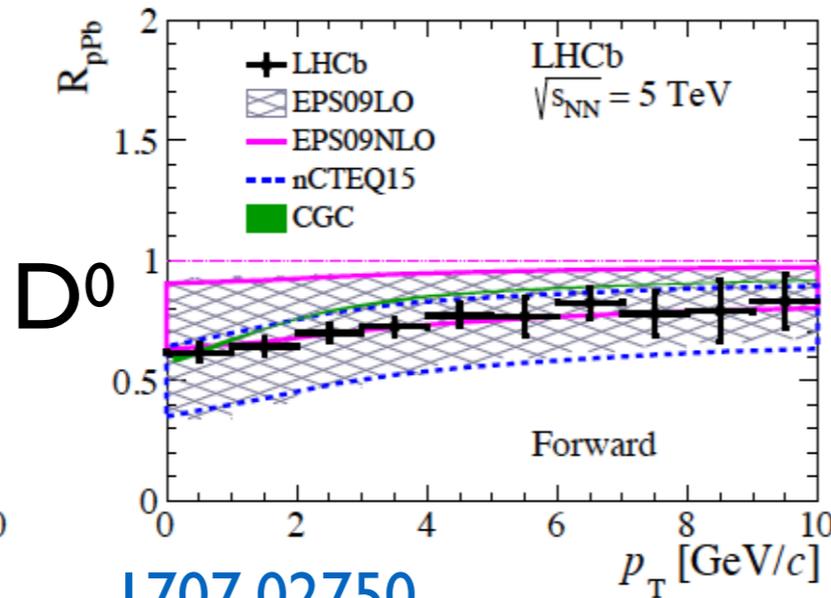
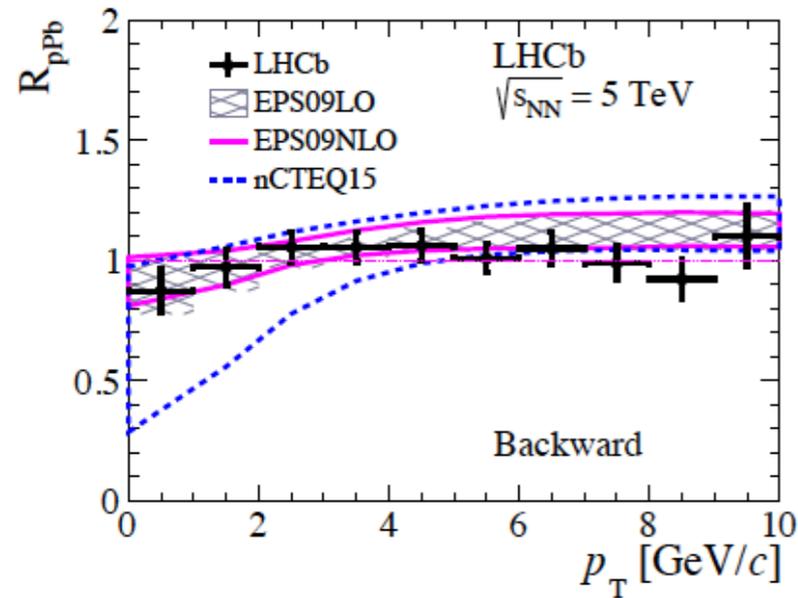


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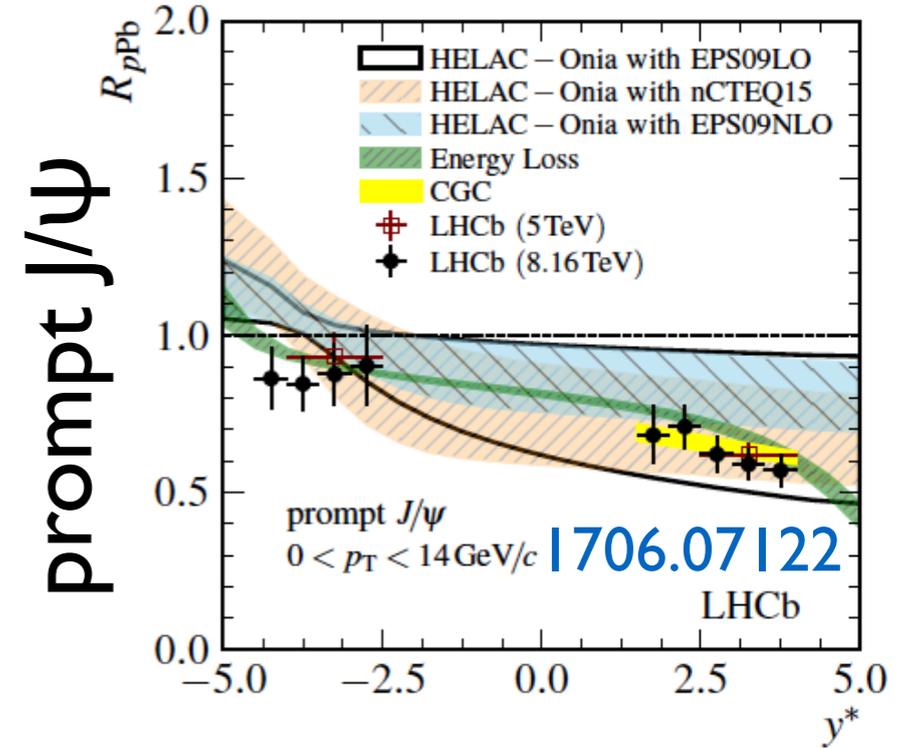


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Open charm and J/ψ :

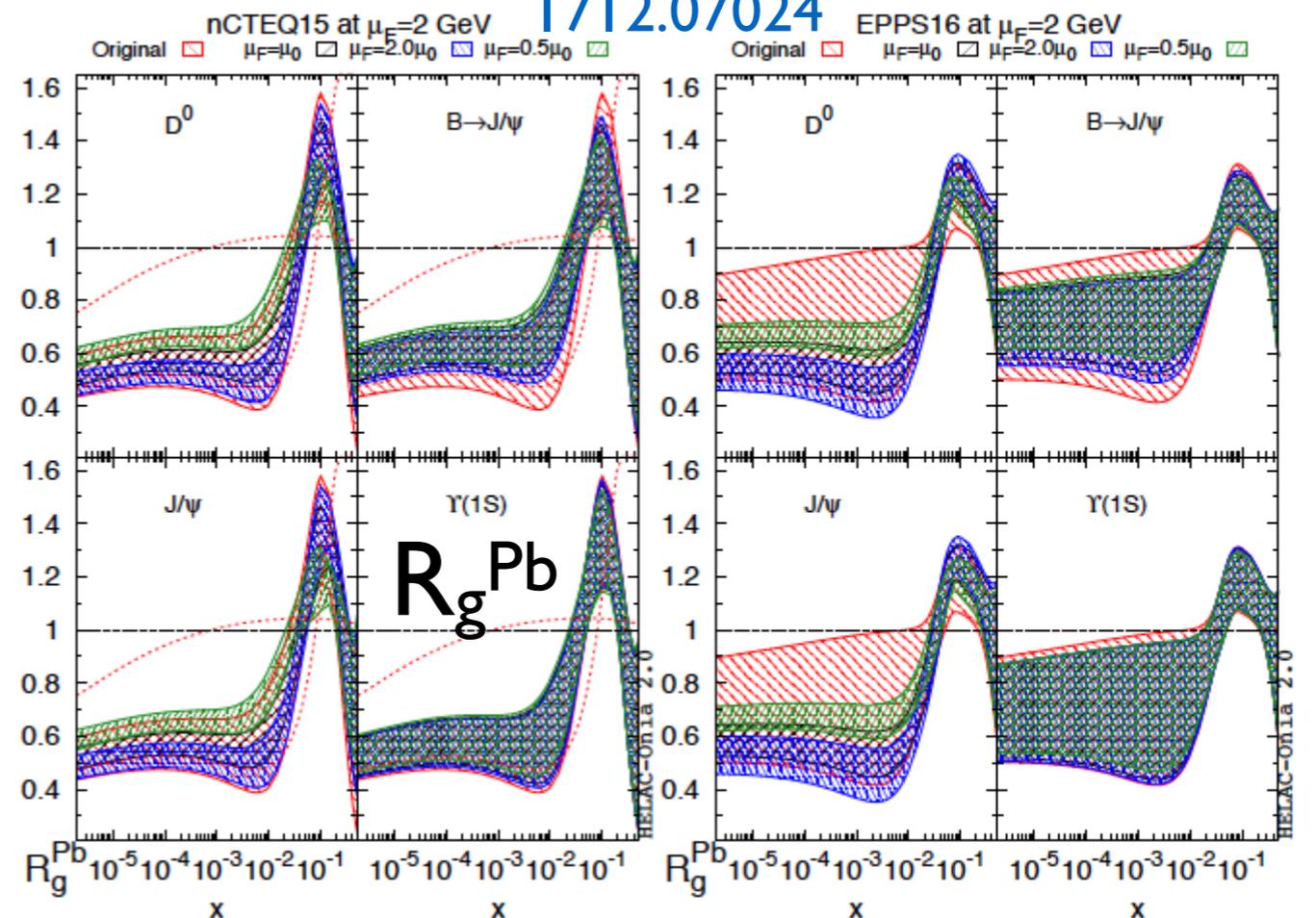


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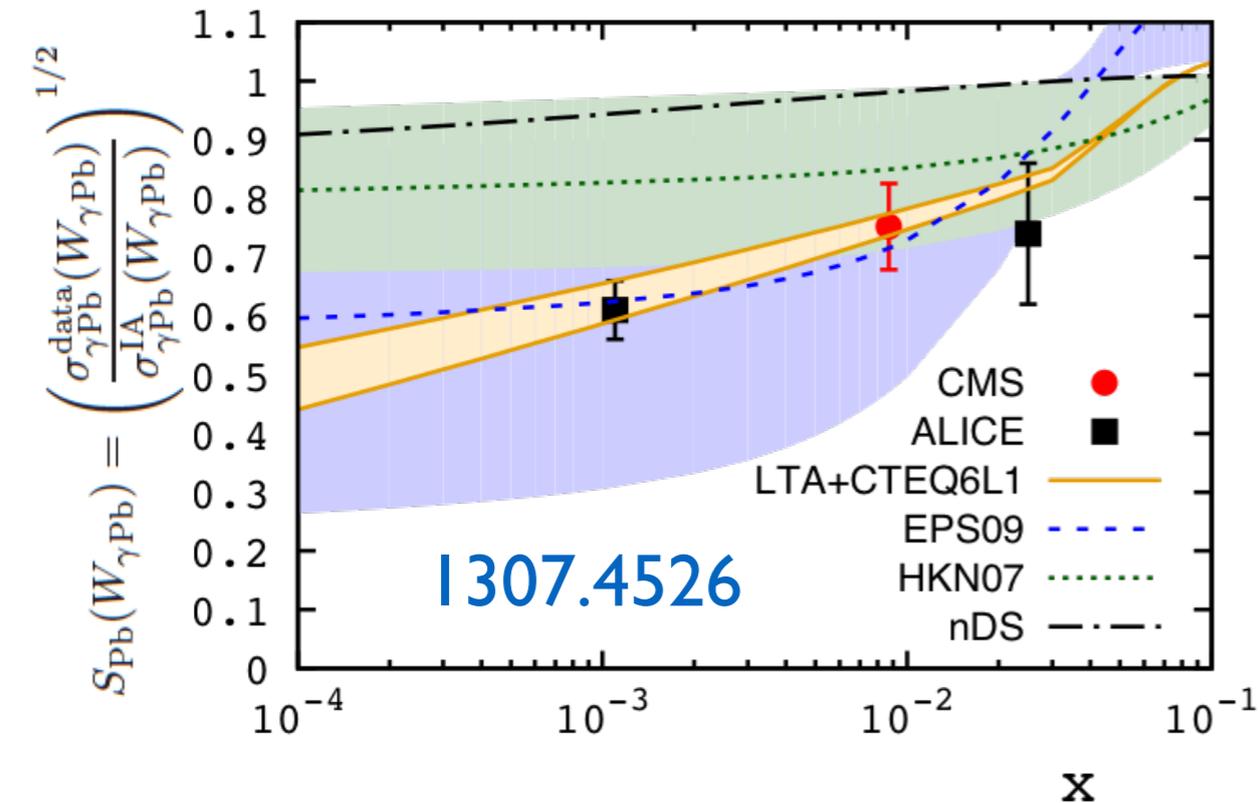


1712.07024

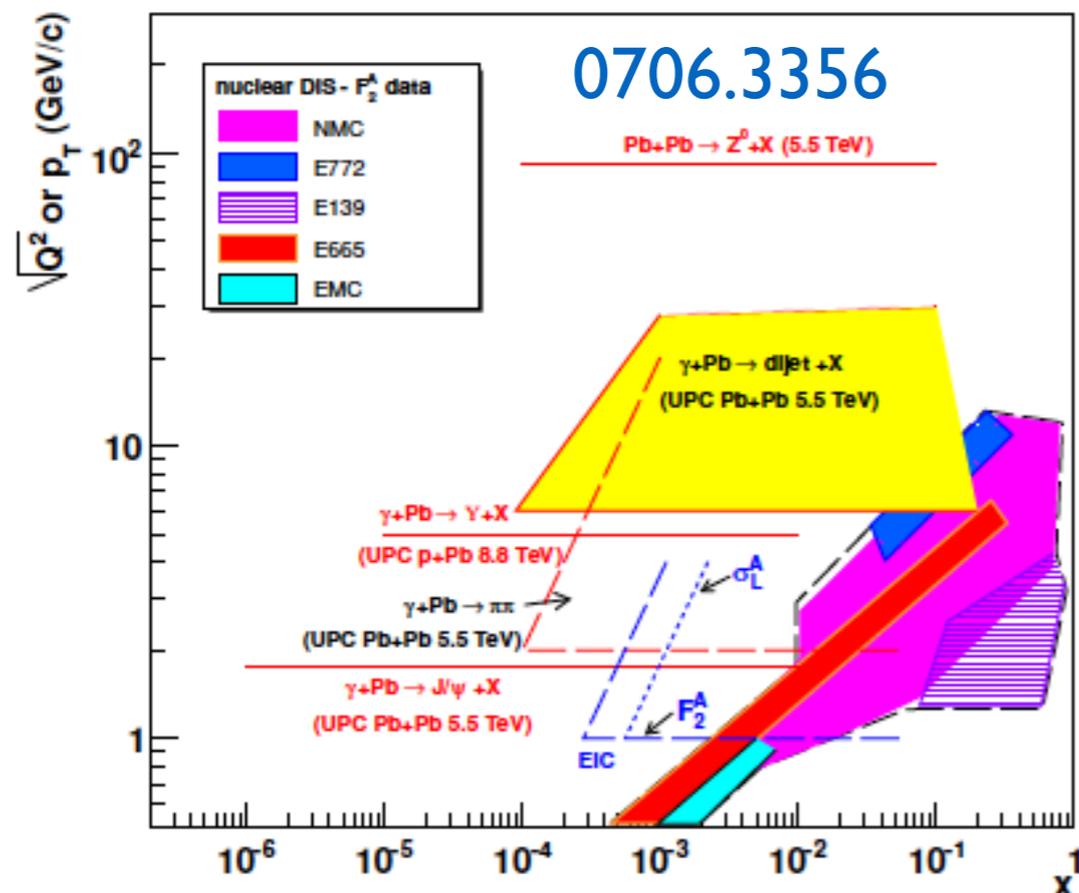
- Theoretical control in p_T over forward D or J/ψ under debate, even in pp: **scales**, DPS, non-linear dynamics, ..., see 1610.09373 vs. 1710.05935.
- E.g. quarkonium: superposition of nPDFs + eloss/absorption + comovers for ψ' + ...
- **Collectivity** (flow for D in pPb as for charged hadrons in pPb and PbPb?) would limit the use of low p_T data for extraction of nPDFs.



UPCs:

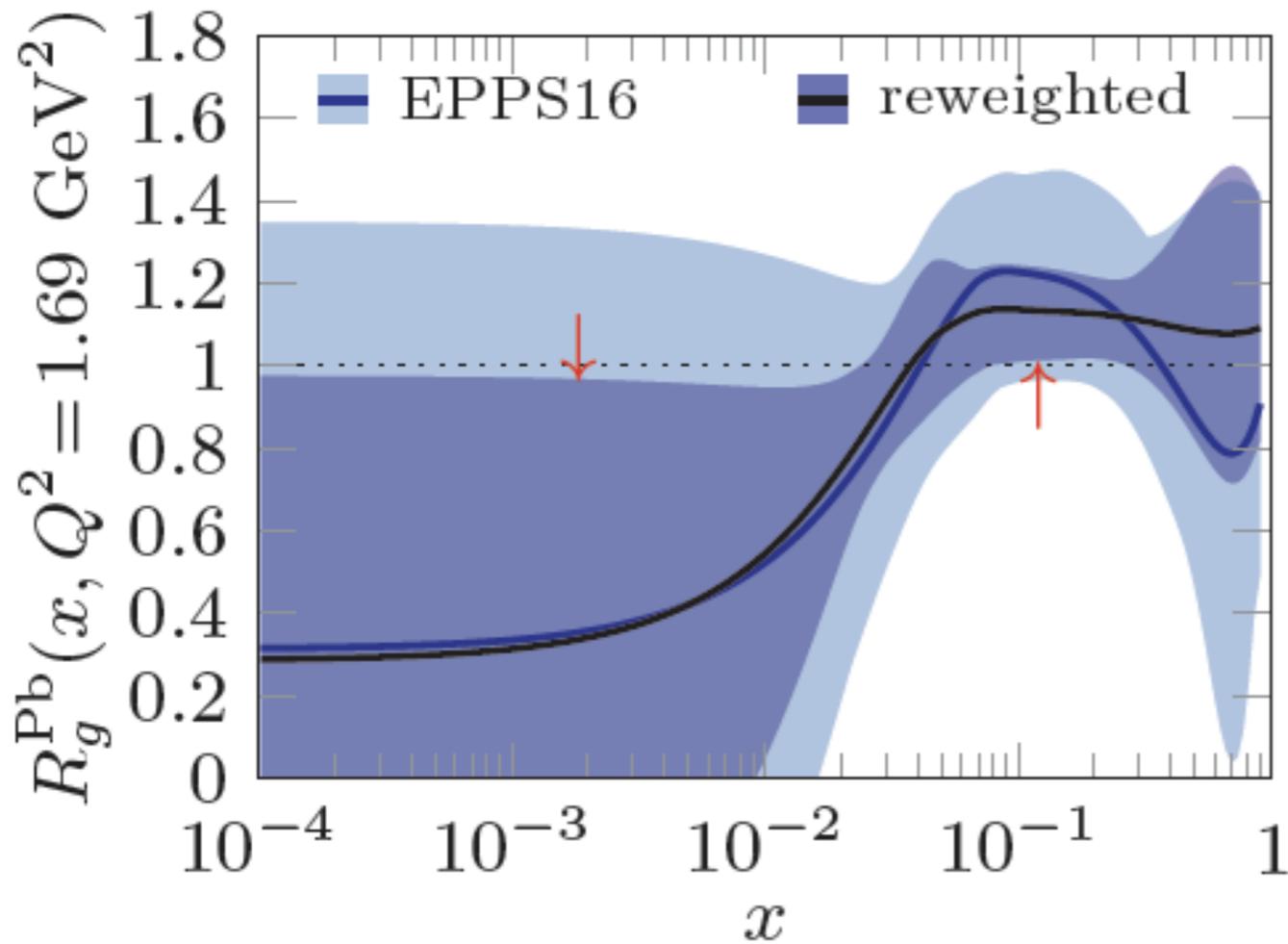


- UPCs offer possibilities for constraining nPDFs (elastic VM, jets in photoproduction): they were the first indication of nuclear shadowing.



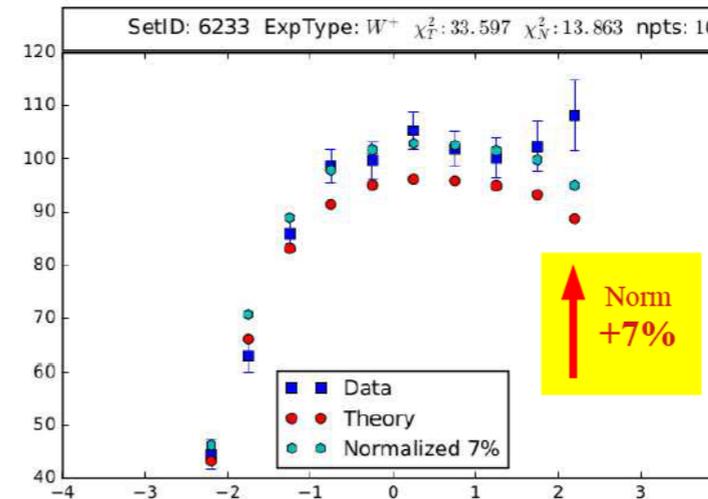
- Uncertainties on the precision and applicability of standard collinear factorisation exist for many of the processes currently studied e.g. exclusive VM production: work still required to be included in global fits. Scale?

LHC (ongoing):



P. Paakinen's talk, preliminary CMS dijet data

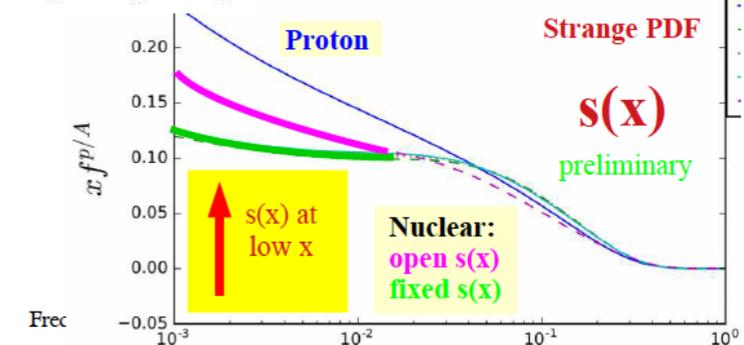
Fit to LHC W/Z Data w/ Normalization



Fit + Normalization

- Improved $\chi^2/\text{d.o.f.}$
- Seems to prefer larger strange PDF

The preliminary result is if we fit strange, the data prefers a larger $s(x)$



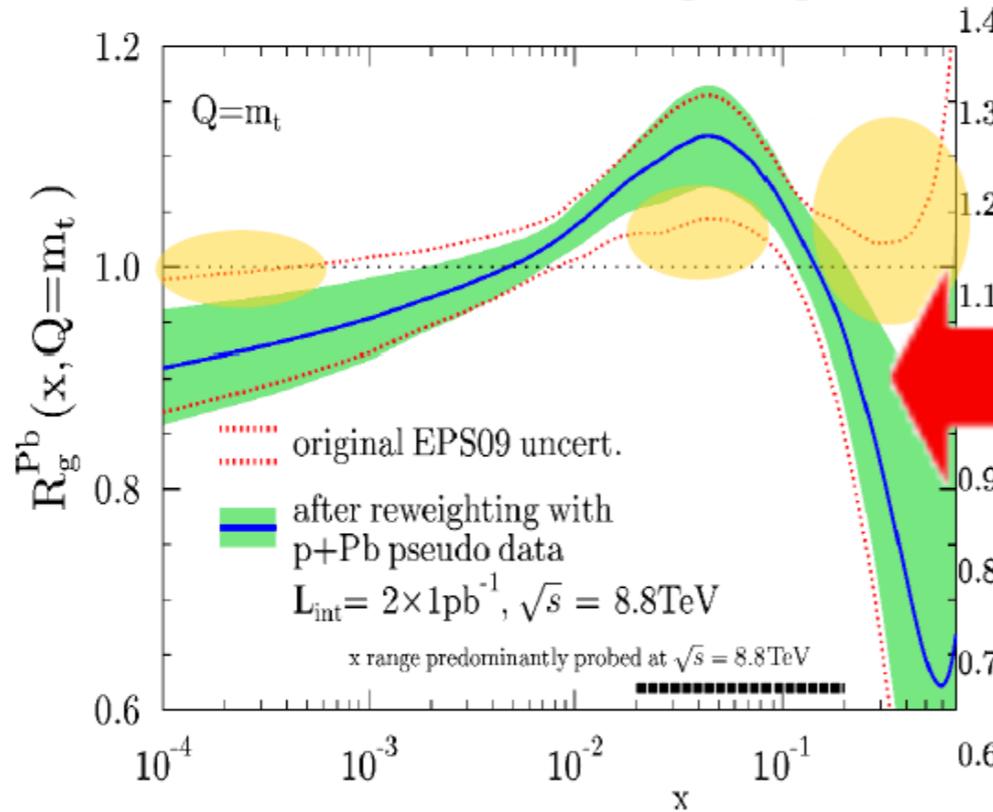
F. Olness' talk, nCTEQ15++

- News to be expected from dijets in CMS (EPPS16; problems with the description in pp, NNLO?), and from W/Z (nCTEQ15).

HL-LHC (Run 3+4):

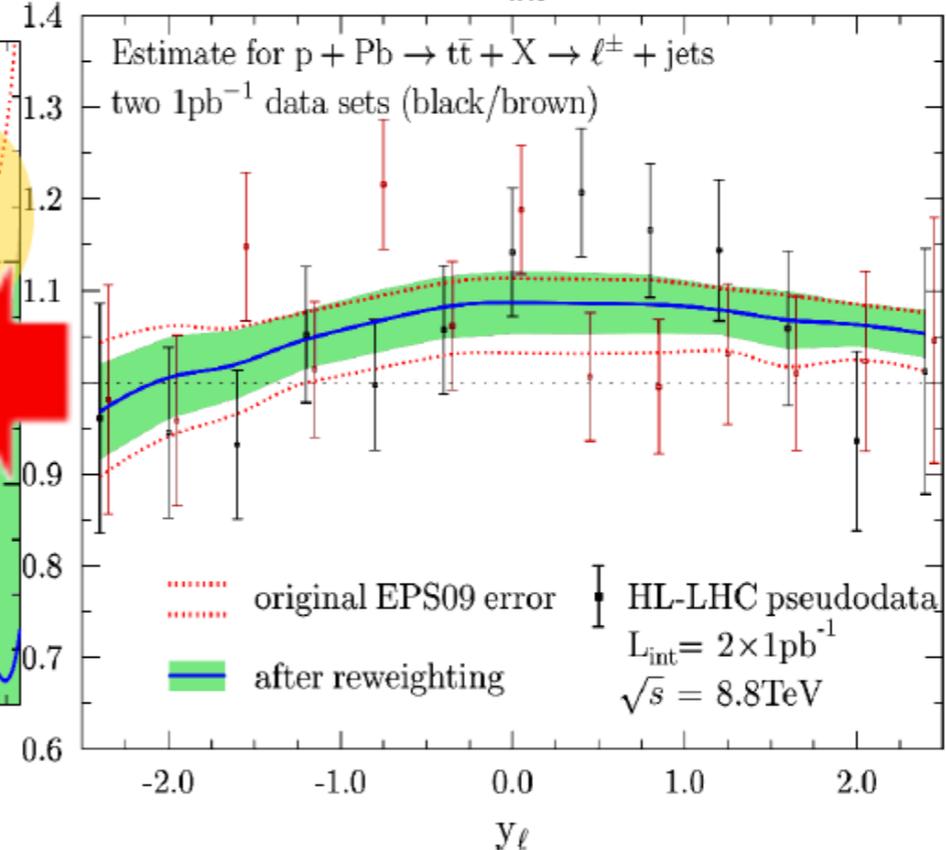
pPb \rightarrow ttbar+X (8.8 TeV): Gluon density constraints

■ Improved gluon density via Hessian PDF reweighting



■ ~50% reduction in uncertainties at antishadowing ($x \sim 0.05$) and EMC ($x \sim 0.4$) regions.

■ Isolated lepton y-distrib. after cuts: (Pseudodata for $L_{int} = 1 \text{ pb}^{-1}$)



(5% syst. uncertainties dominate now)

■ nPDF R_{pPb} effects (lepton): $\pm 10\%$

$L_{int} = 2 \times 1 \text{ pb}^{-1}$: ~35% constraining power

D. d'Enterria (CERN)

● Besides: HL-LHC (WG5), CERN March'18

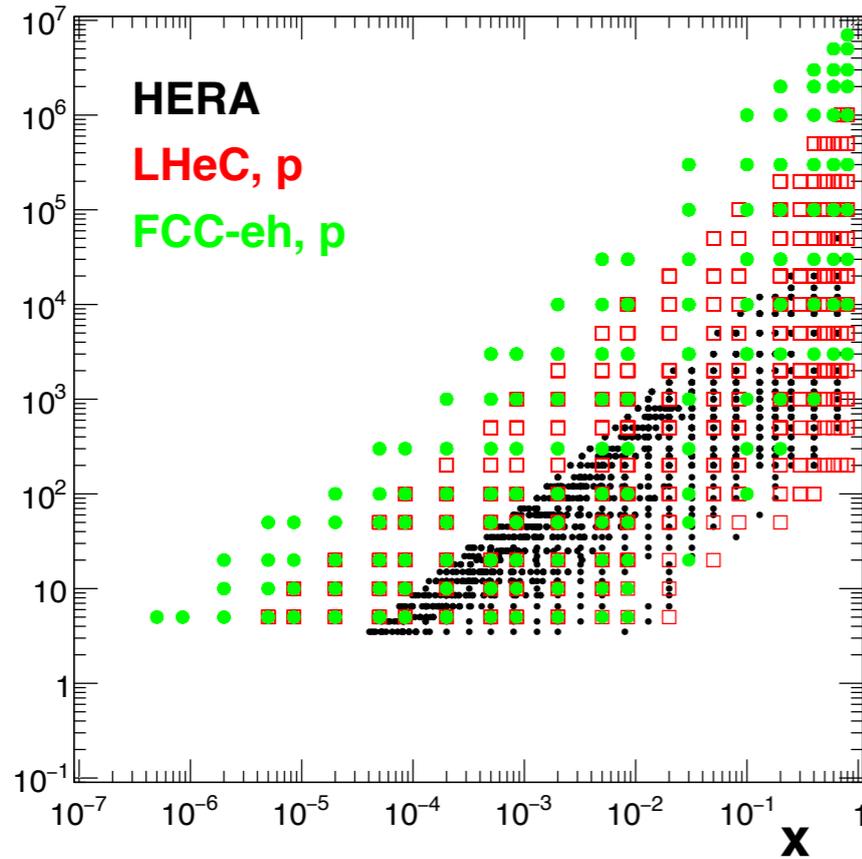
12/14

→ Prospects for using photons and jets in pPb at forward rapidities: FoCal proposal in ALICE, LHCb.

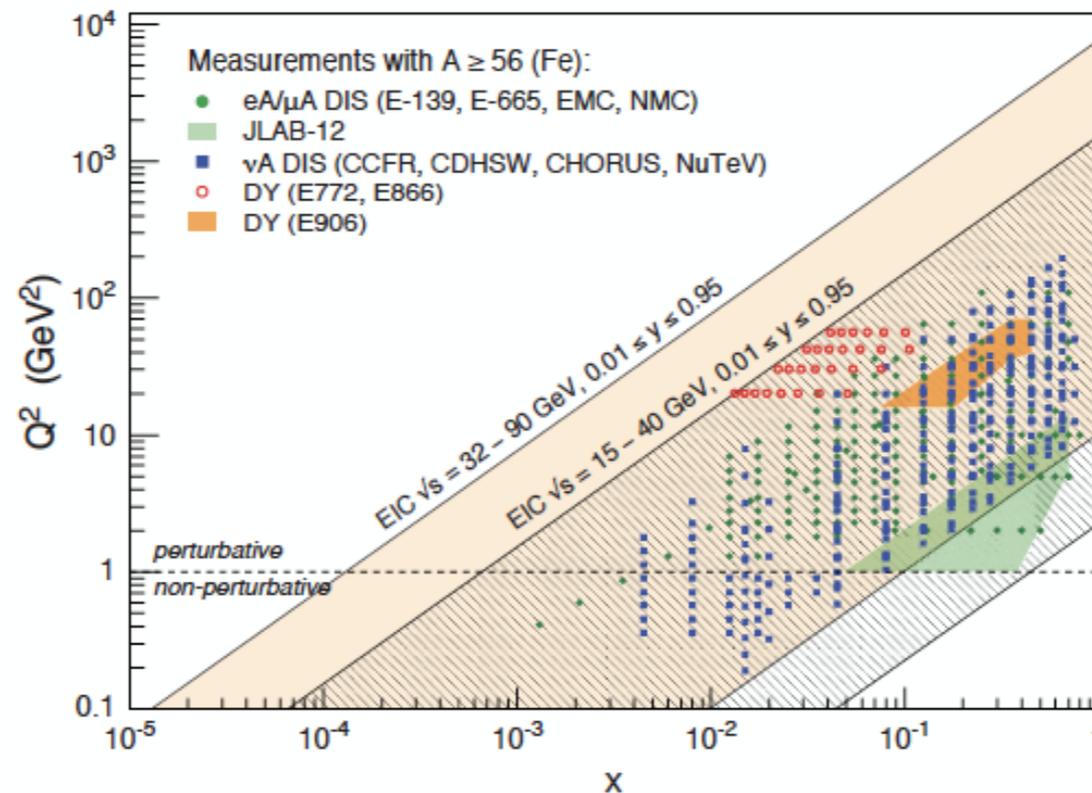
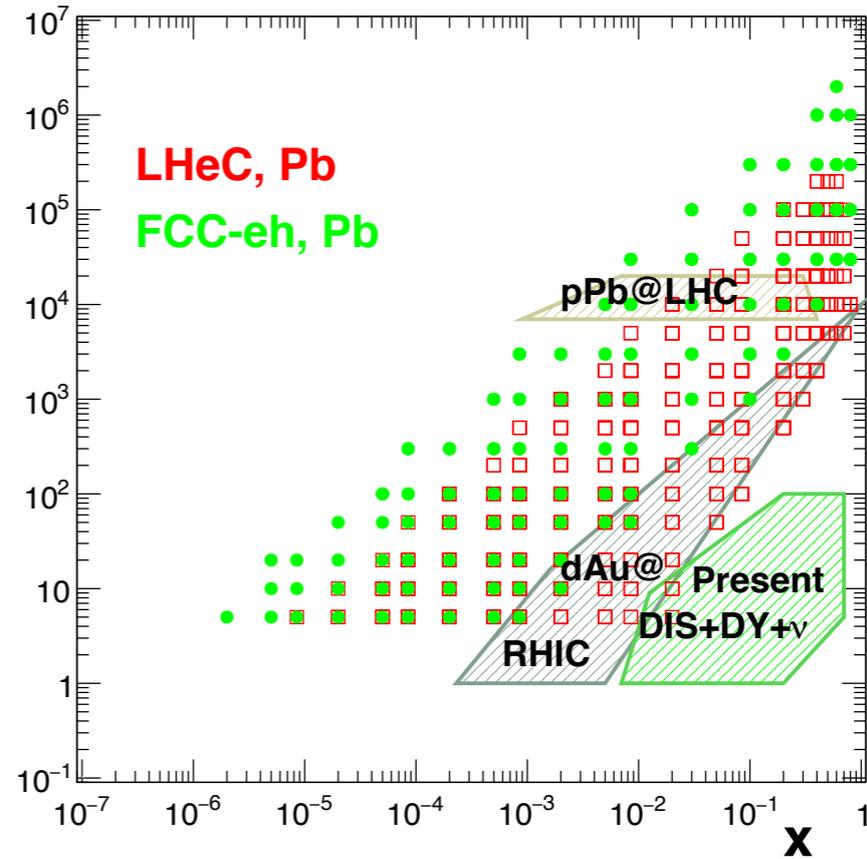
→ Present plan places next pPb run in 2028...

LHeC/FCC-eh vs. EIC:

Q^2 (GeV²)

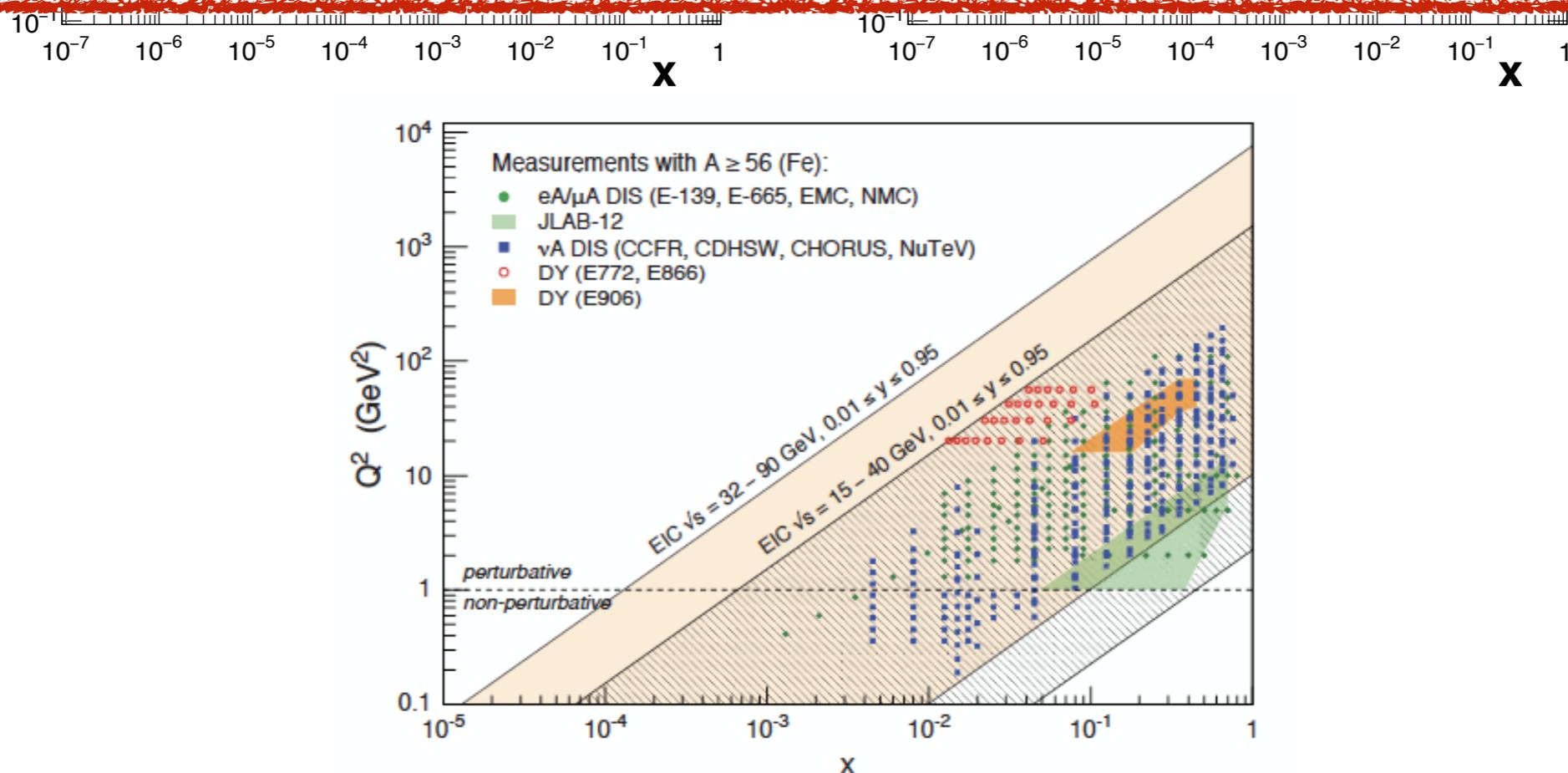


Q^2 (GeV²)



LHeC/FCC-eh vs. EIC:

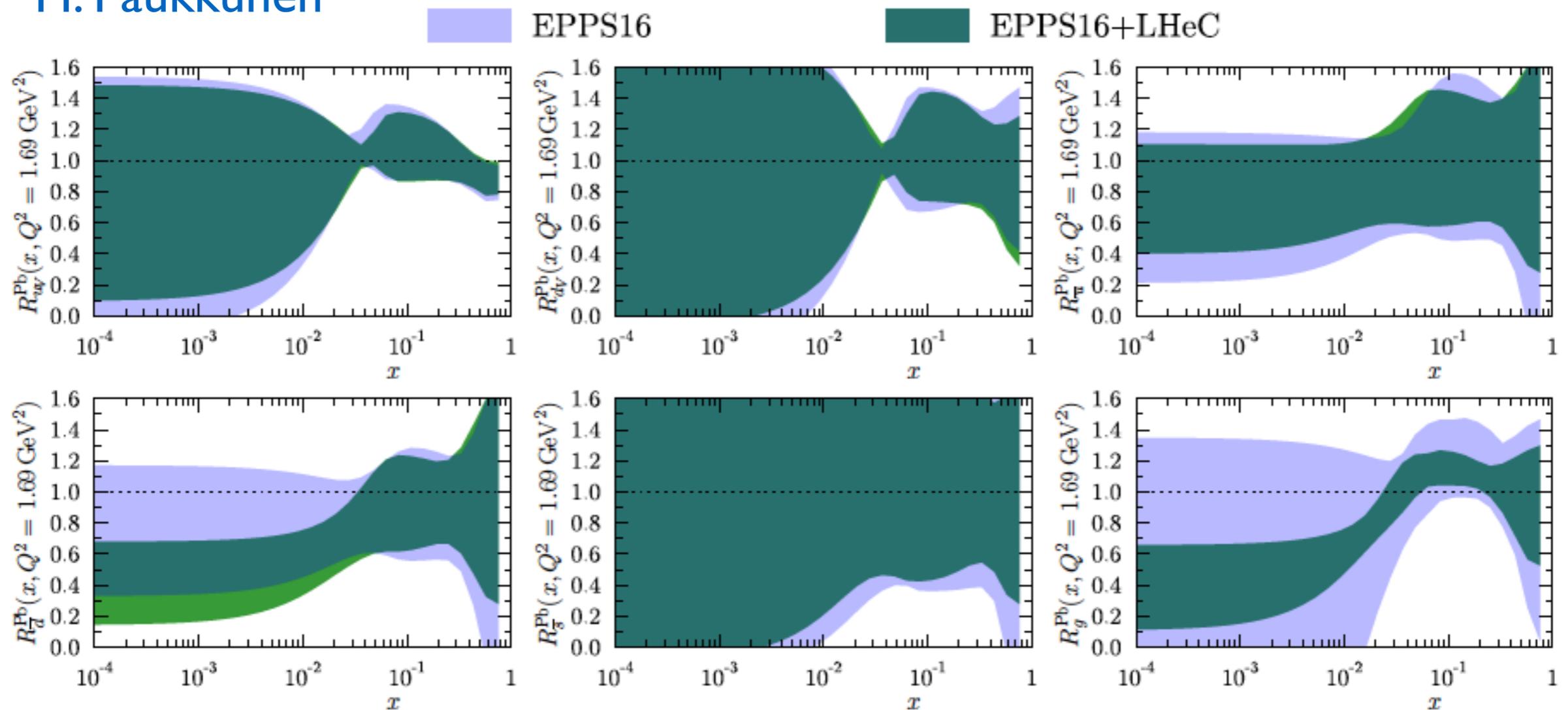
- At an ep/eA collider:
 - PDFs of a single nucleus possible (NC, CC, heavy flavours), no need of ratios that would be obtained a posteriori.
 - Same method of extraction in both ep and eA.
 - Physics beyond standard collinear factorisation can be studied in a single setup, with size effects disentangled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



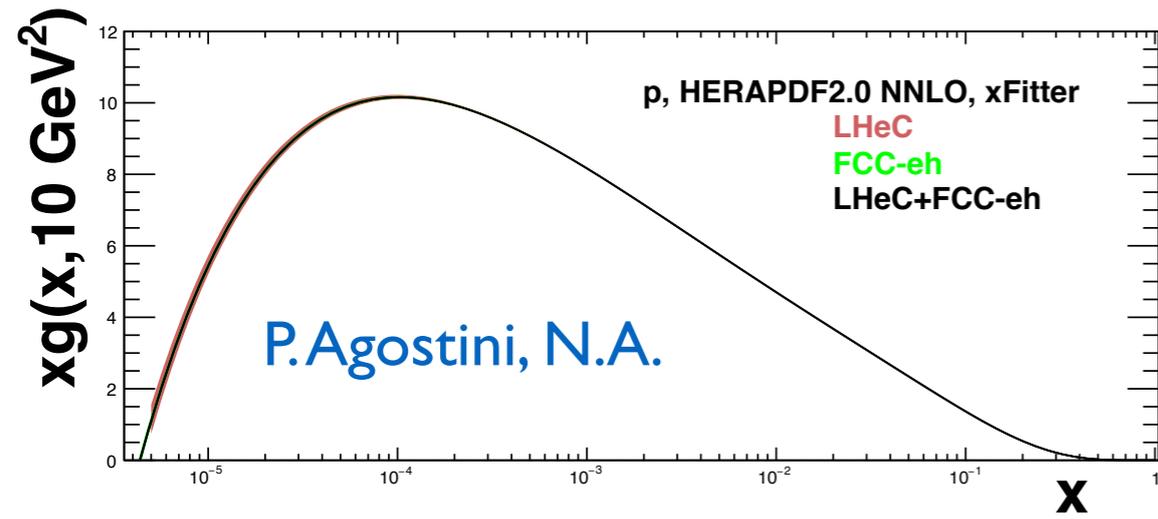
EPPS16@LHeC:

- Pseudodata generated with EPS09, 10/1 fb⁻¹ ep/ePb luminosities; uncorrelated and normalisation uncertainties considered.
- EPPS16 analysis, same method and tolerance.
 - The improvement after adding the LHeC data ($Q^2 = 1.69 \text{ GeV}^2$)

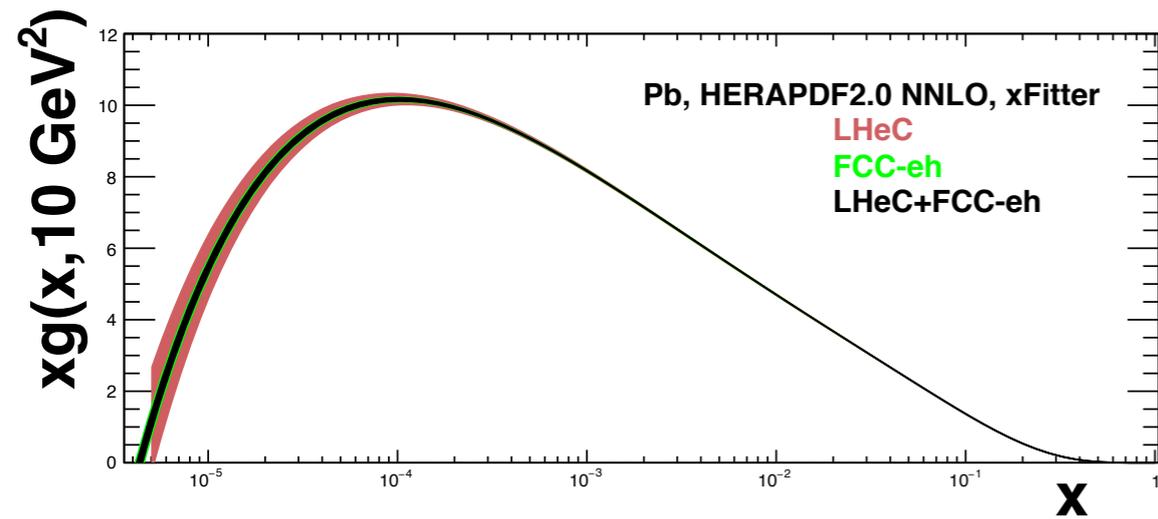
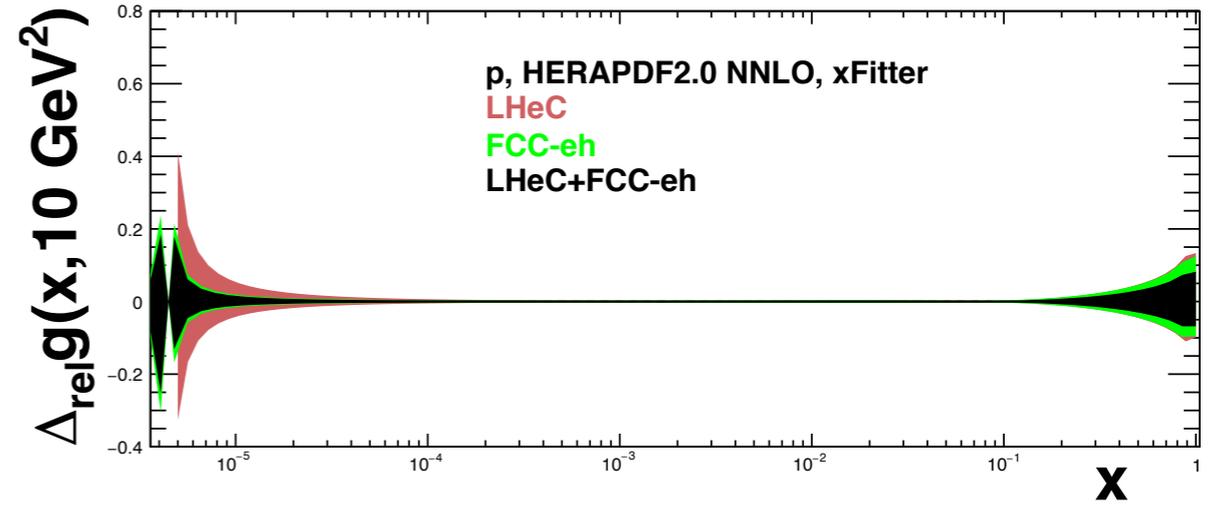
H. Paukkunen



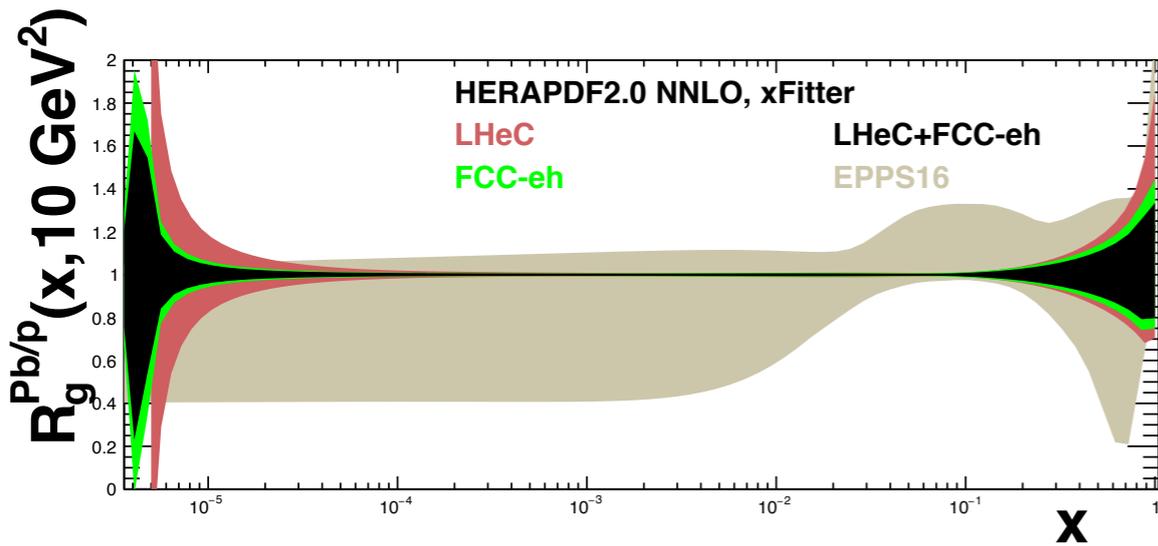
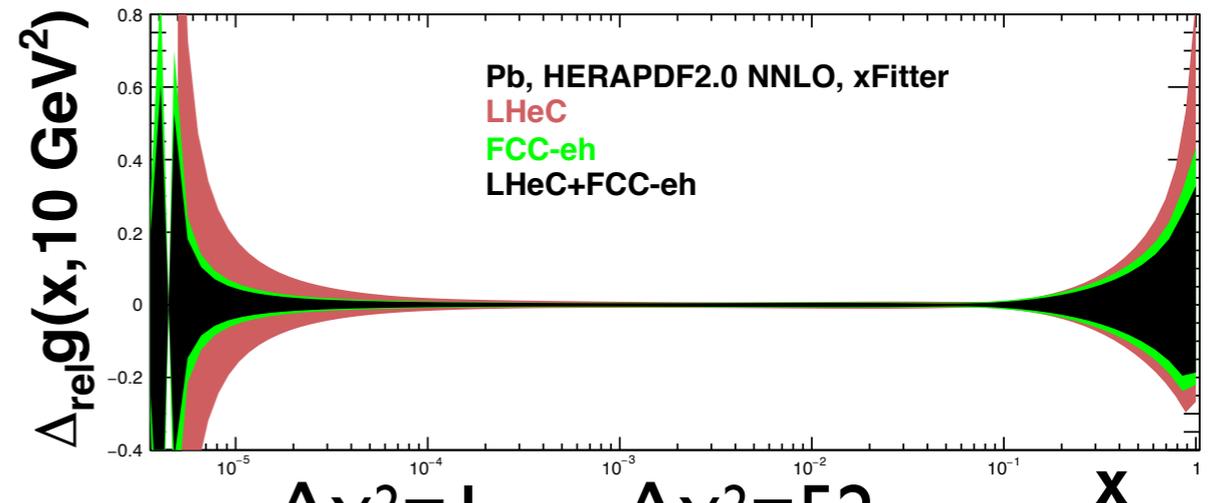
xFitter: gluon at LHeC/FCC-eh



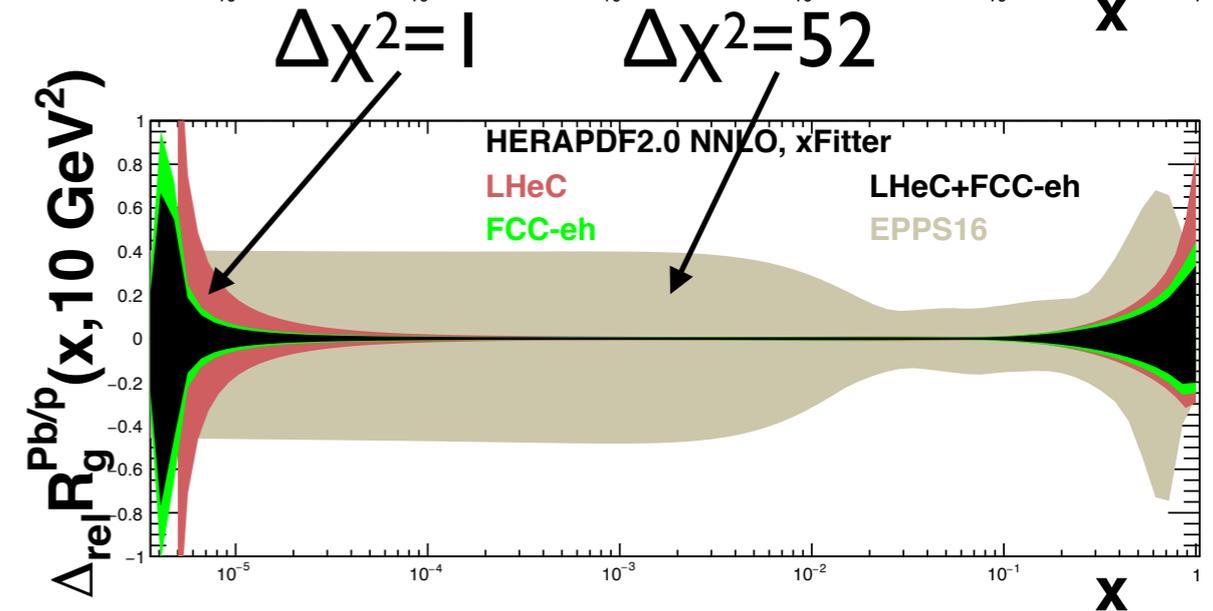
p



P_b



P_b/p

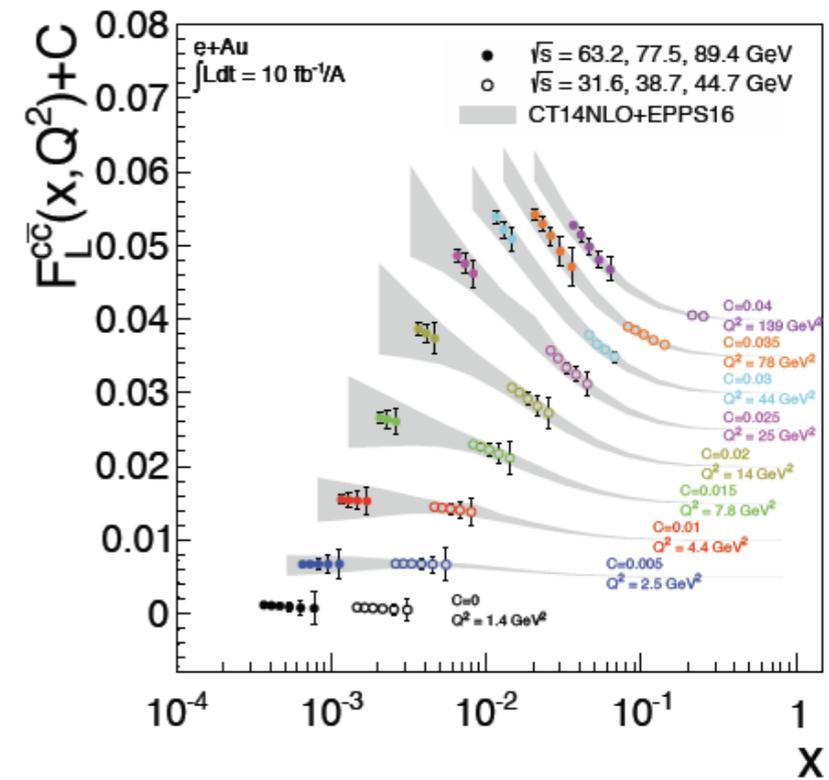
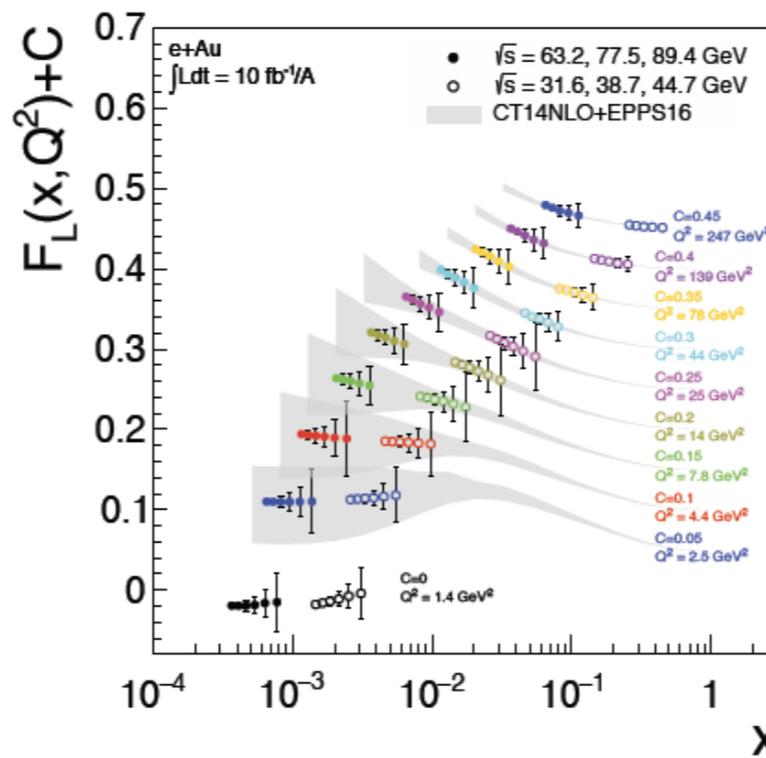
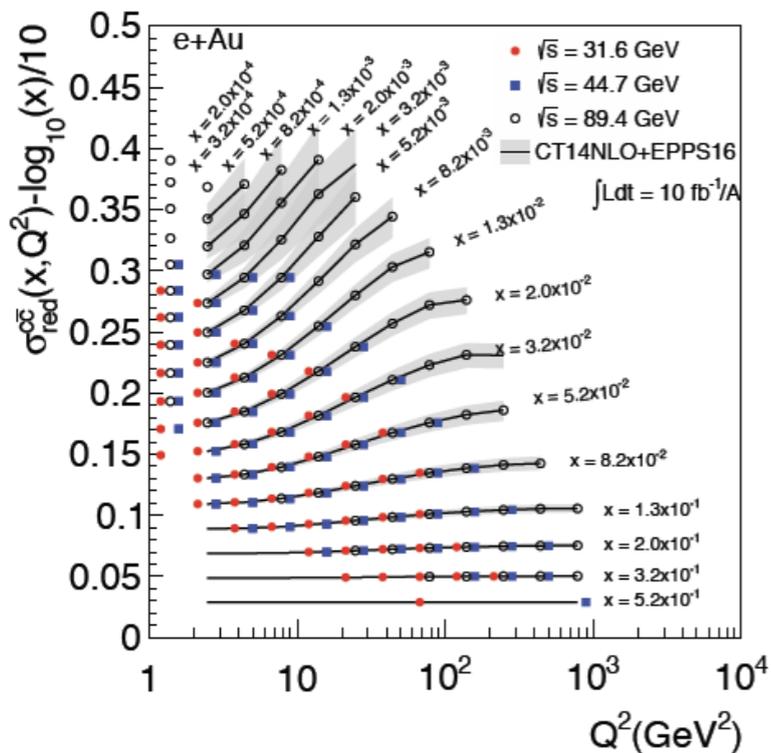
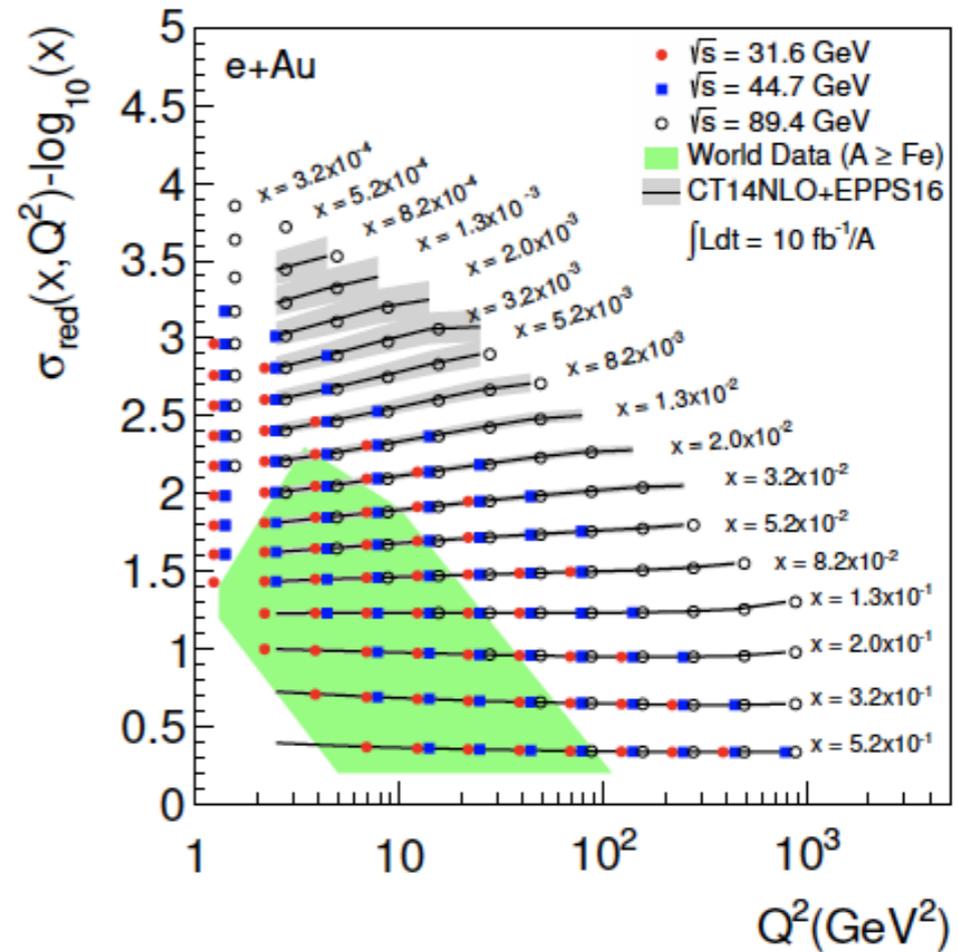


EPPS16@EIC:

● Following a very similar approach to that shown for the LHeC (1708.05654):

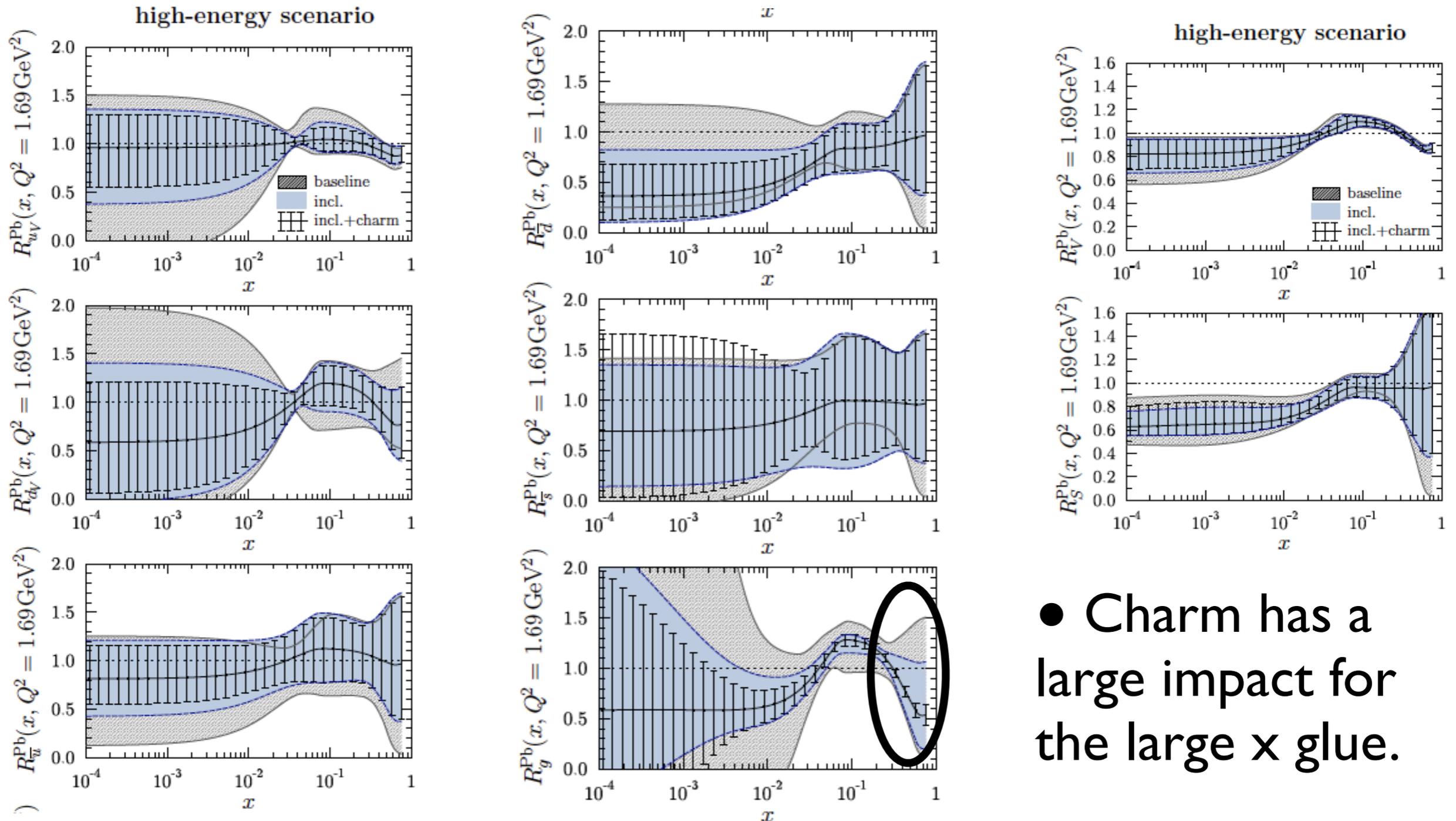
→ Pseudodata generated with EPS09, uncertainties as achieved at HERA.

→ Impact of low (5 GeV) and high (20 GeV) electron energies, and of charm.



EPPS16@EIC:

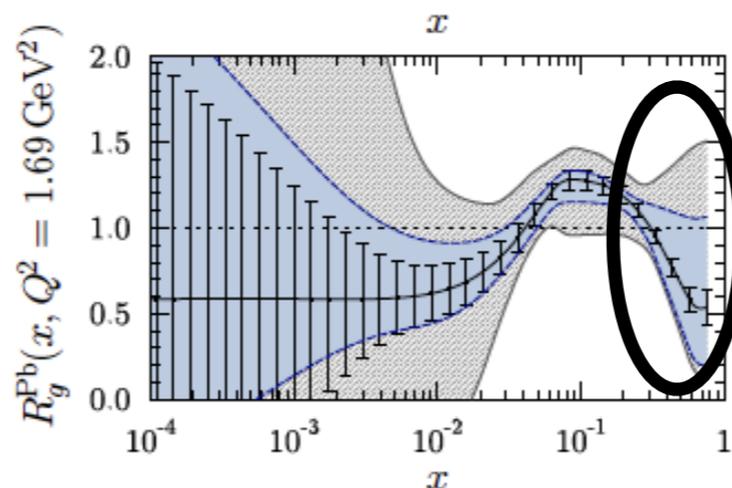
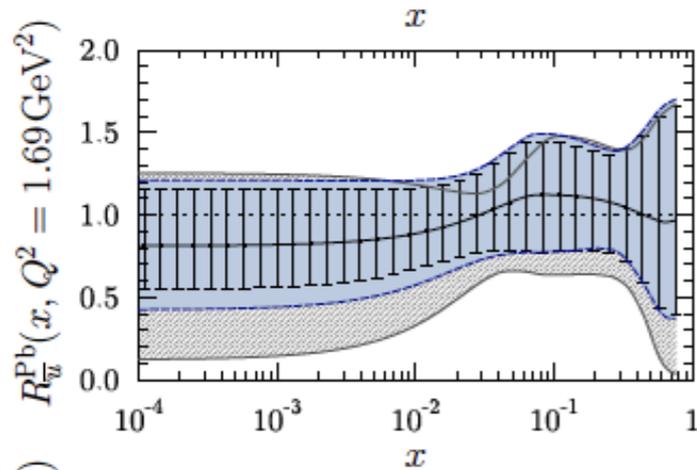
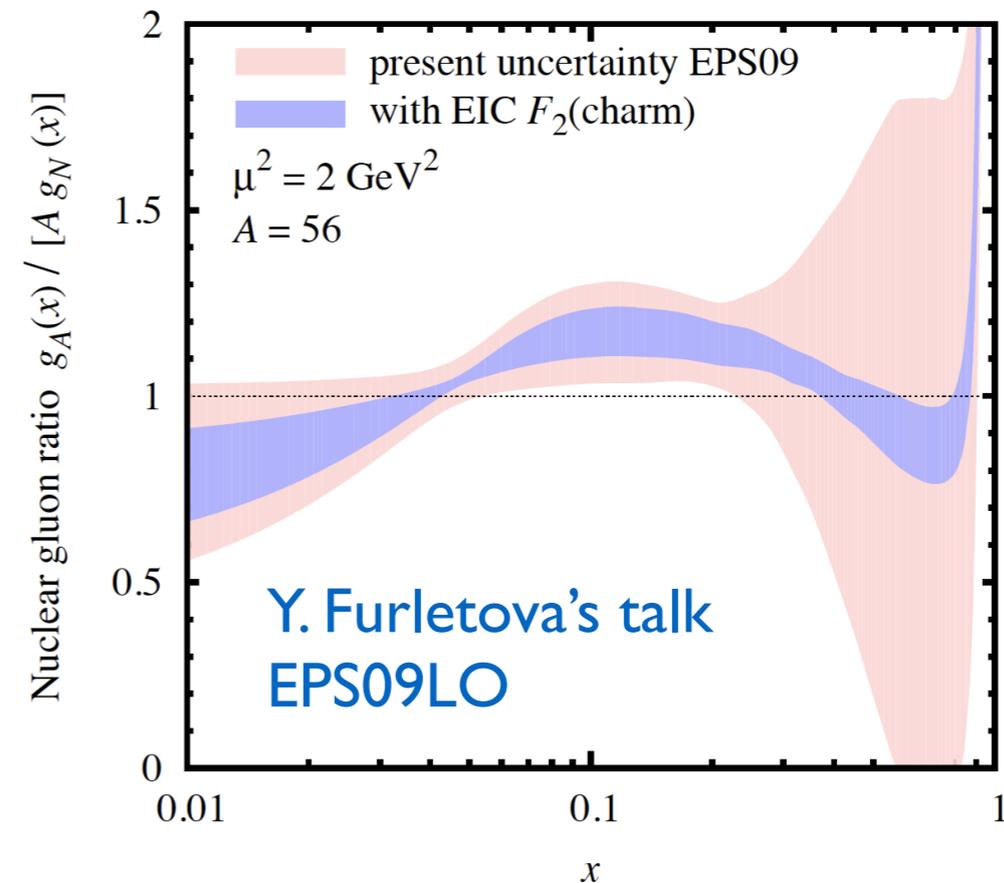
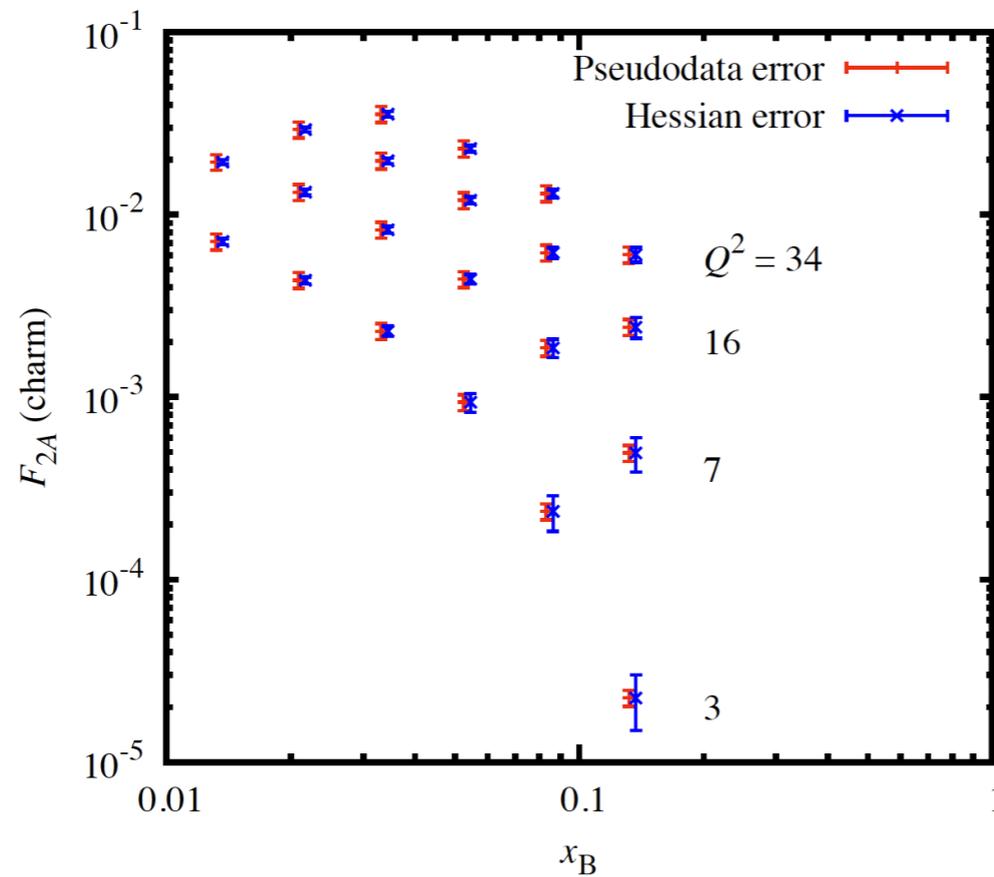
- Very similar approach to that shown for the LHeC (1708.05654):
- Pseudodata generated with EPS09, uncertainties as at HERA.
- Impact of low (5 GeV) and high (20 GeV) E_e , and of charm.



- Charm has a large impact for the large x glue.

EPPS16@EIC:

- Very similar approach to that shown for the LHeC (1708.05654):
- Pseudodata generated with EPS09, uncertainties as at HERA.
- Impact of low (5 GeV) and high (20 GeV) E_e , and of charm.



- Charm has a large impact for the large x glue.

nPDFs@EICs (I):

The effect of LHeC pseudodata

- Why it's so hard to pin down the flavor dependence?
- Take the valence up-quark distribution u_V^A as an example:

$$u_V^A = \frac{Z}{A} R_{u_V} u_V^{\text{proton}} + \frac{A-Z}{A} R_{d_V} d_V^{\text{proton}}$$

H. Paukkunen

- Write this in terms of average modification R_V and the difference δR_V

$$R_V \equiv \frac{R_{u_V} u_V^{\text{proton}} + R_{d_V} d_V^{\text{proton}}}{u_V^{\text{proton}} + d_V^{\text{proton}}}, \quad \delta R_V \equiv R_{u_V} - R_{d_V}$$

$$u_V^A = R_V \left(\frac{Z}{A} u_V^{\text{proton}} + \frac{A-Z}{A} d_V^{\text{proton}} \right) + \delta R_V \left(\frac{2Z}{A} - 1 \right) \frac{u_V^{\text{proton}}}{1 + u_V^{\text{proton}}/d_V^{\text{proton}}}$$

Leading term

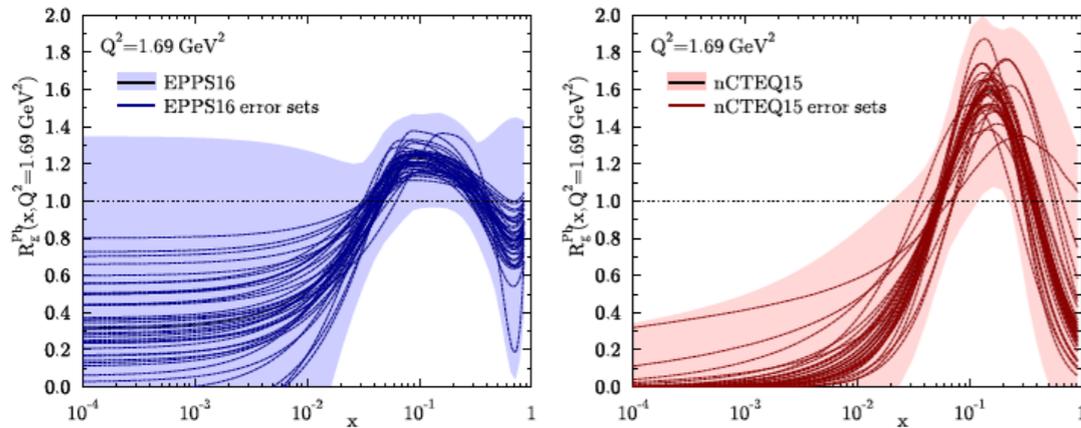
"Correction term"

- The effects of flavour separation (i.e. δR_V here) are suppressed in cross sections — but also so in most of the nPDF applications.

nPDFs@EICs (II):

$$R^{\text{EPS09}}(x) = \begin{cases} a_0 + a_1(x - x_a)^2 & x \leq x_a \\ b_0 + b_1x^\alpha + b_2x^{2\alpha} + b_3x^{3\alpha} & x_a \leq x \leq x_e \\ c_0 + (c_1 - c_2x)(1-x)^{-\beta} & x_e \leq x \leq 1 \end{cases}$$

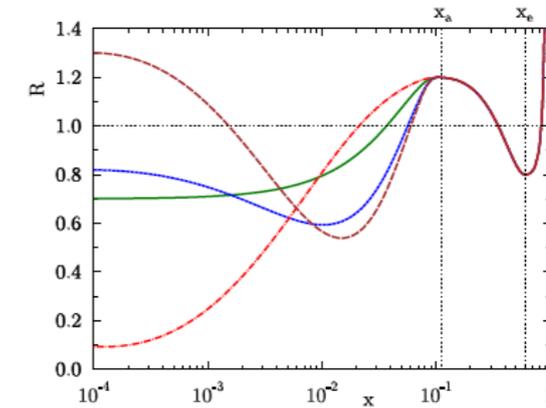
$$R^{\text{nCTEQ15}}(x) = [c_0x^{c_1}(1-x)^{c_2}e^{c_3x}(1+e^{c_4x})^{c_5}] / f^P(x)$$



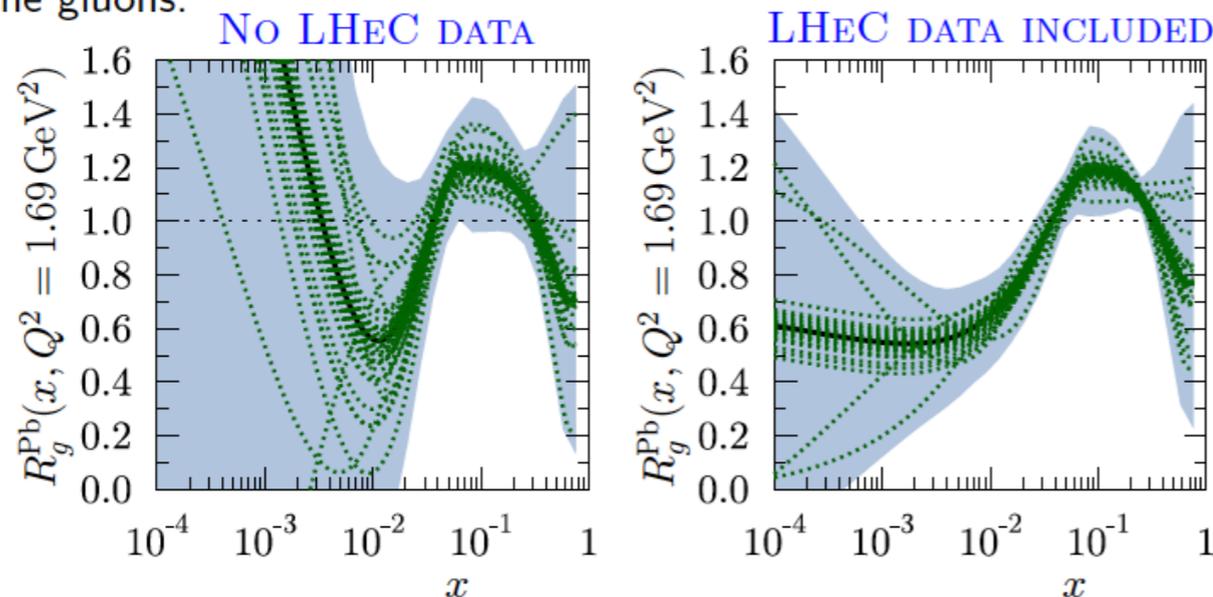
$$R(x \leq x_a) = a_0 + a_1(x - x_a)^2 + \sqrt{x}(x_a - x) \left[a_2 \log\left(\frac{x}{x_a}\right) + a_3 \log^2\left(\frac{x}{x_a}\right) + a_4 \log^3\left(\frac{x}{x_a}\right) + \dots \right]$$

or

$$R(x \leq x_a) = a_0 + (x - x_a)^2 [a_1 + a_2x^\alpha + a_3x^{2\alpha} + a_4x^{3\alpha} + \dots], \alpha \ll 1$$



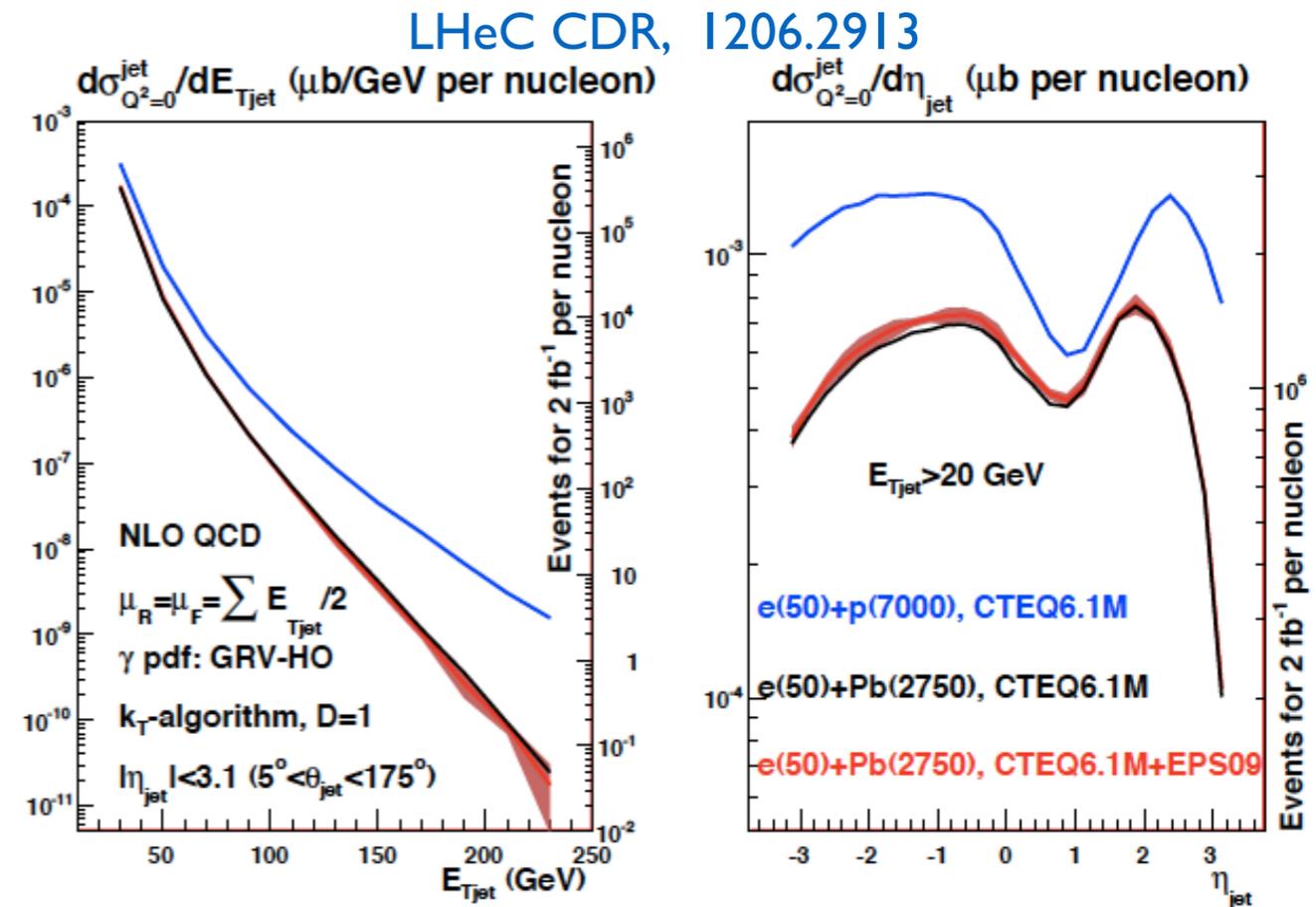
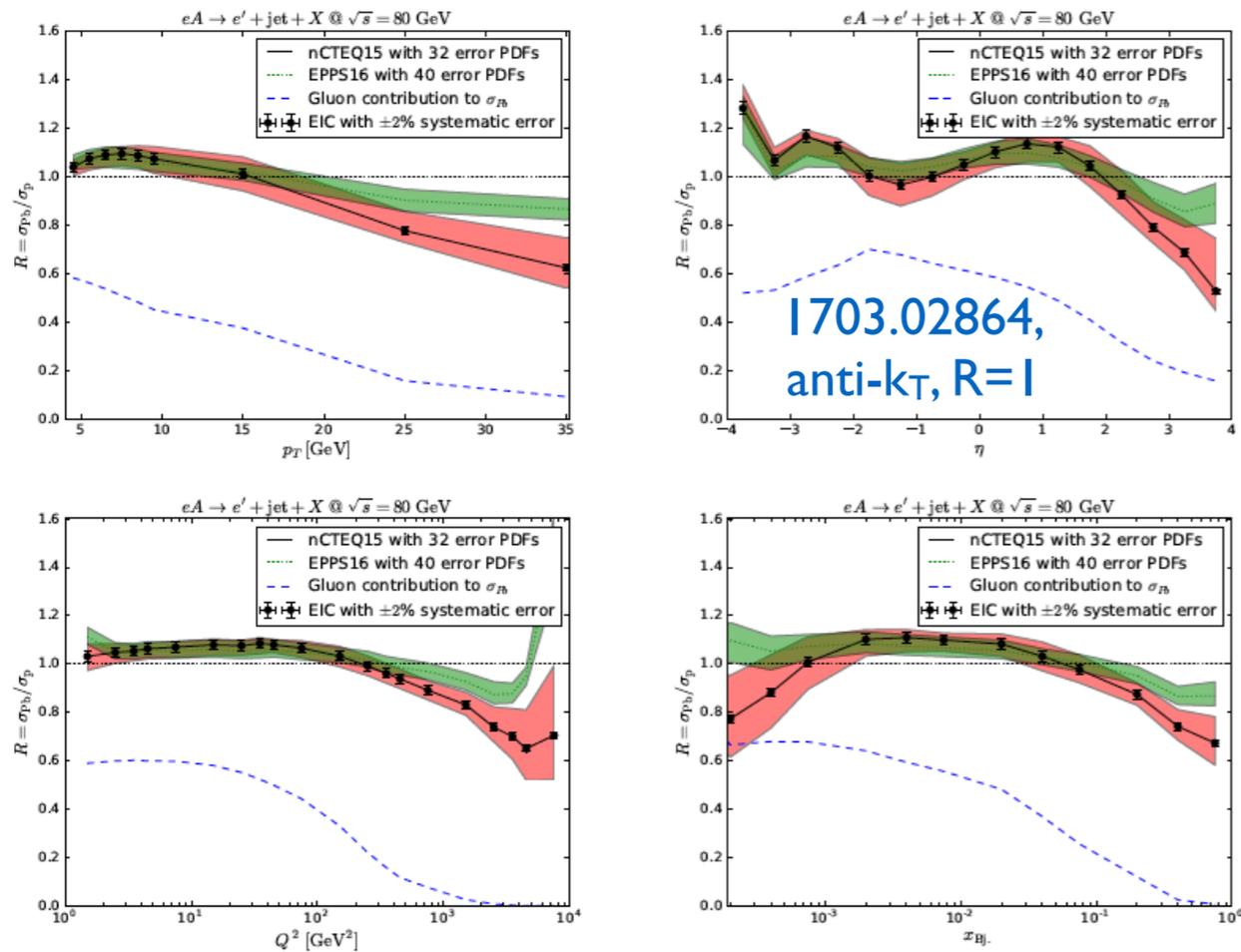
- Would need Monte-Carlo methods to more reliably map the uncertainties
 \Rightarrow Further work needed
- Despite all the shortcomings, a typical result using a more flexible form for the gluons:



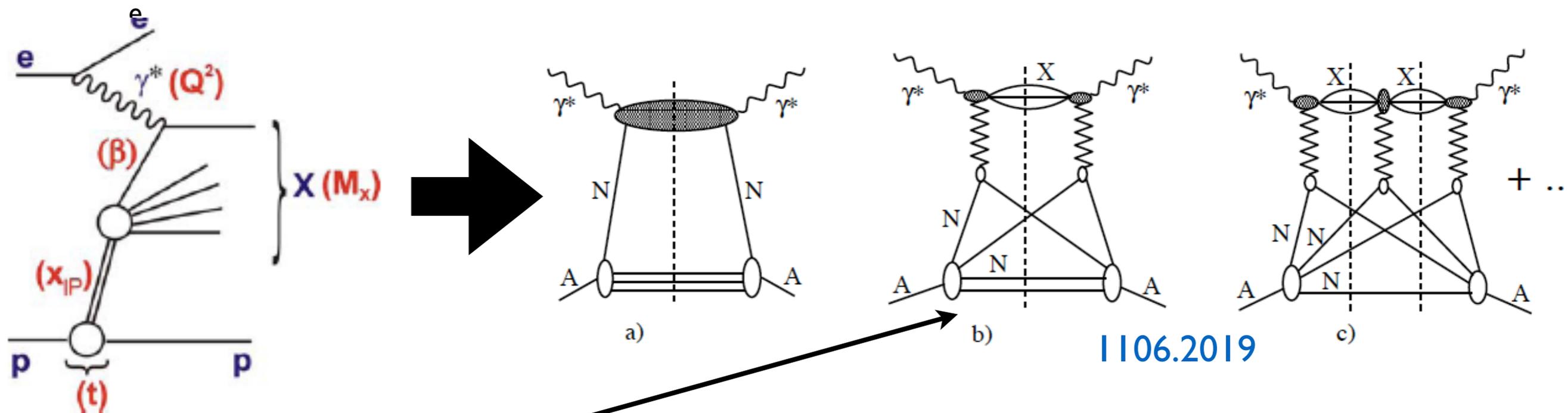
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Jets@EIC:

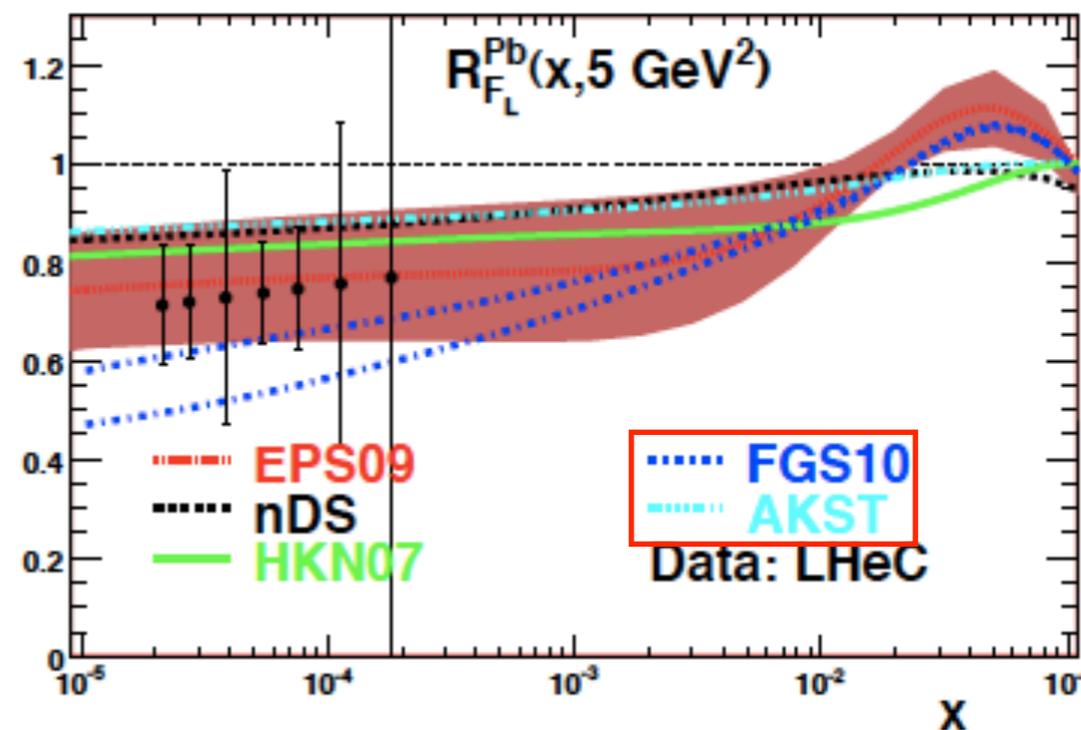
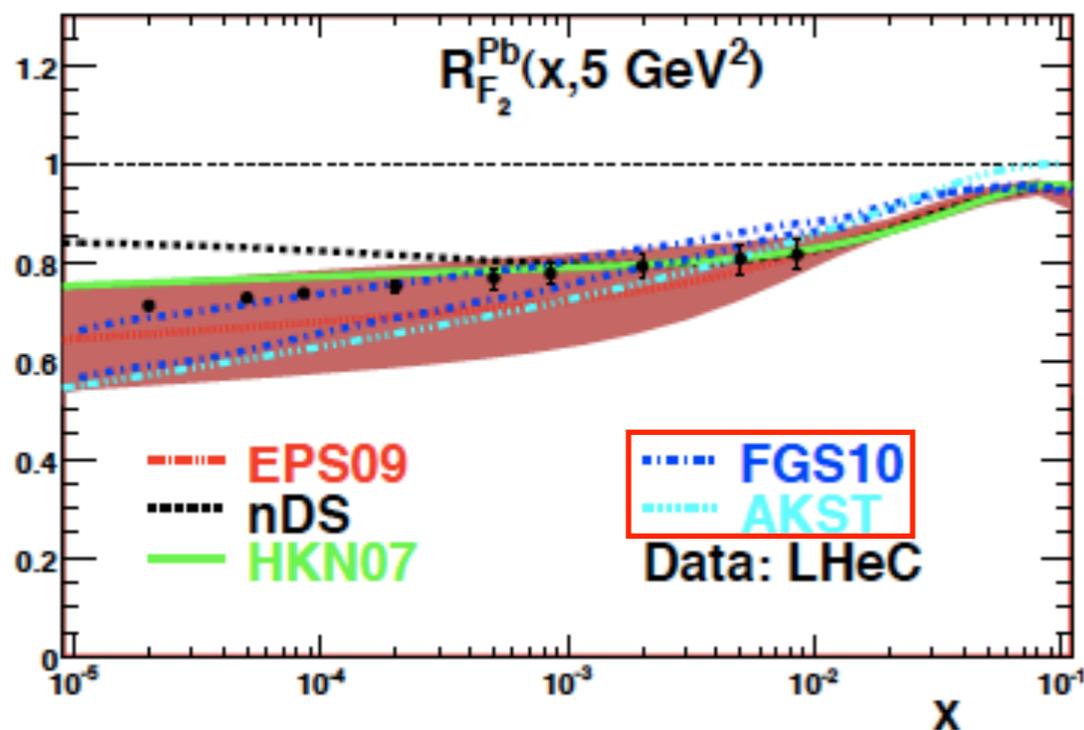
- Jets in DIS and dijets in photoproduction offer constraints on the nuclear glue, competing with LHC dijets and RHIC pions (also photon PDF).
- High integrated luminosity is required.
- At the LHeC, sizeably larger p_T achievable.



Diffraction in ep and shadowing:



- Diffraction in ep is linked to nuclear shadowing through basic QFT (Gribov): eD to test and set the ‘benchmark’ for new effects.

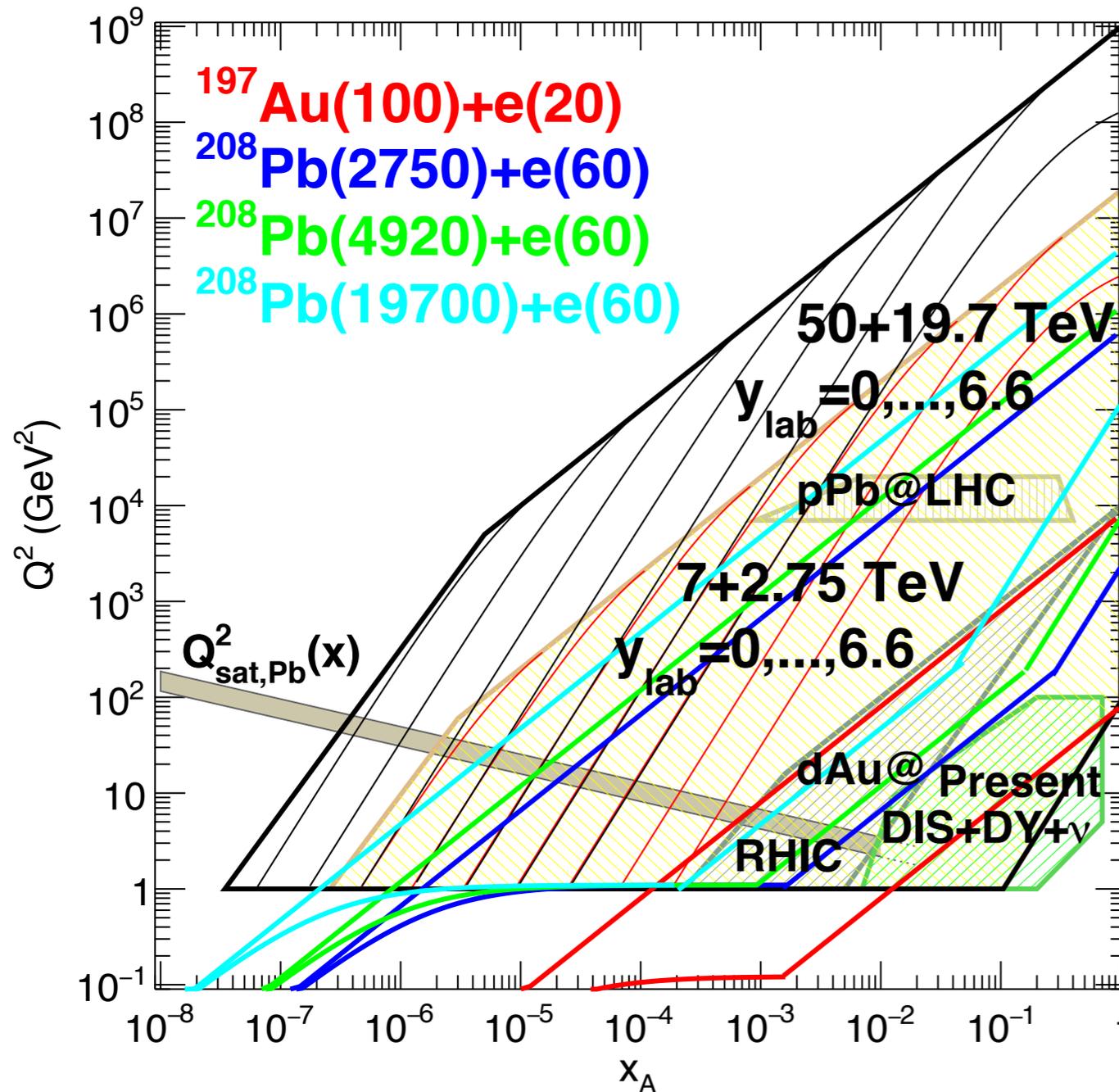


Summary:

- Present constrains on nPDFs are rather weak compared to the ones on proton PDFs (**HERA**).
- Several possibilities for constraining them in hadron colliders using forward measurements and UPCs: theoretical uncertainties, (e.g. scale dependency) are still the caveat.
- Nevertheless, pA cannot be challenged in terms of kinematics: tests of collinear factorisation and its eventual breaking.
- **EICs are the ideal places to determine the nPDFs:**
 - Fully constrained kinematics.
 - Well controlled theoretical & experimental setup.
 - Many observables, from σ_{red} in NC and CC to heavy flavours and jets.
 - Possibilities to obtain PDFs of a single nucleus without any resource to proton ones, ratios obtained a posteriori.
- **Limitation: do not cover as wide kinematics as hadronic colliders;** luminosity may be important for some observables.

Summary:

- Present constrains on nPDFs are rather weak compared to the



Many thanks to:

→ Max Klein, Fred Olness, Hannu Paukkunen, Voica Radescu, Carlos Salgado, Thomas Ullrich and Pía Zurita for many discussions and help.

→ The organisers for the invitation to provide this talk.

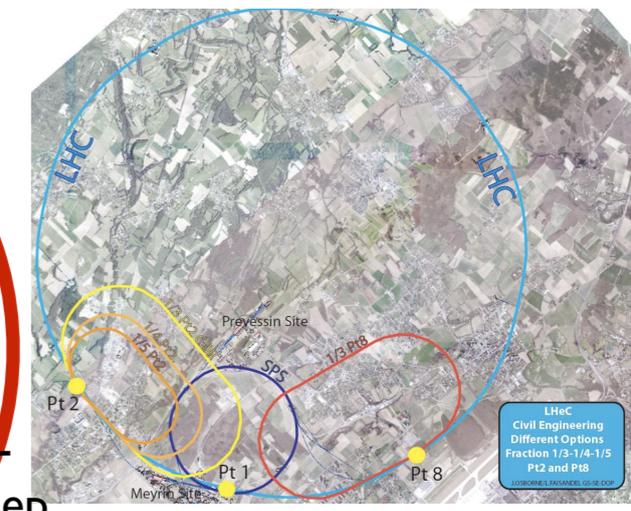
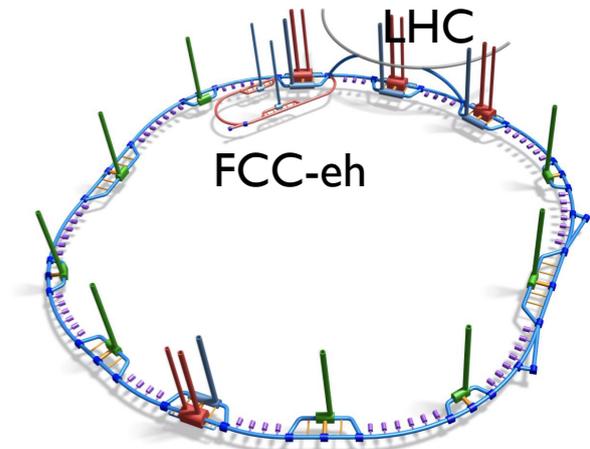
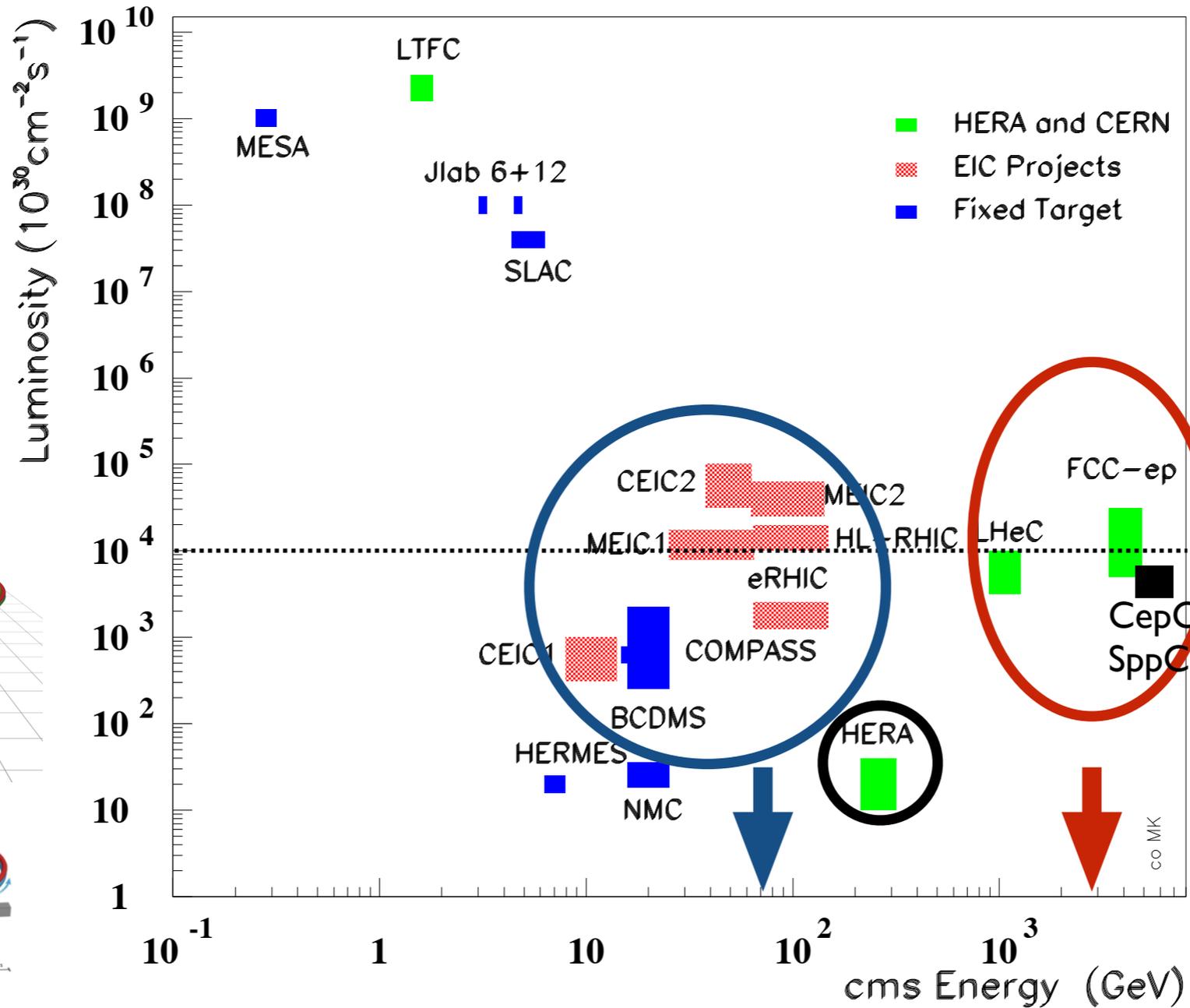
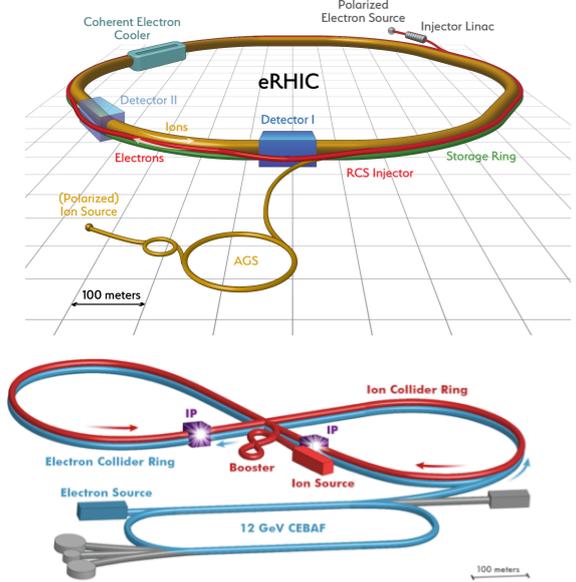
→ You all for your attention.

colliders; luminosity may be important for some observables.

Backup:

Summary of machines:

Lepton-proton/nucleus scattering facilities



h/A wave function:

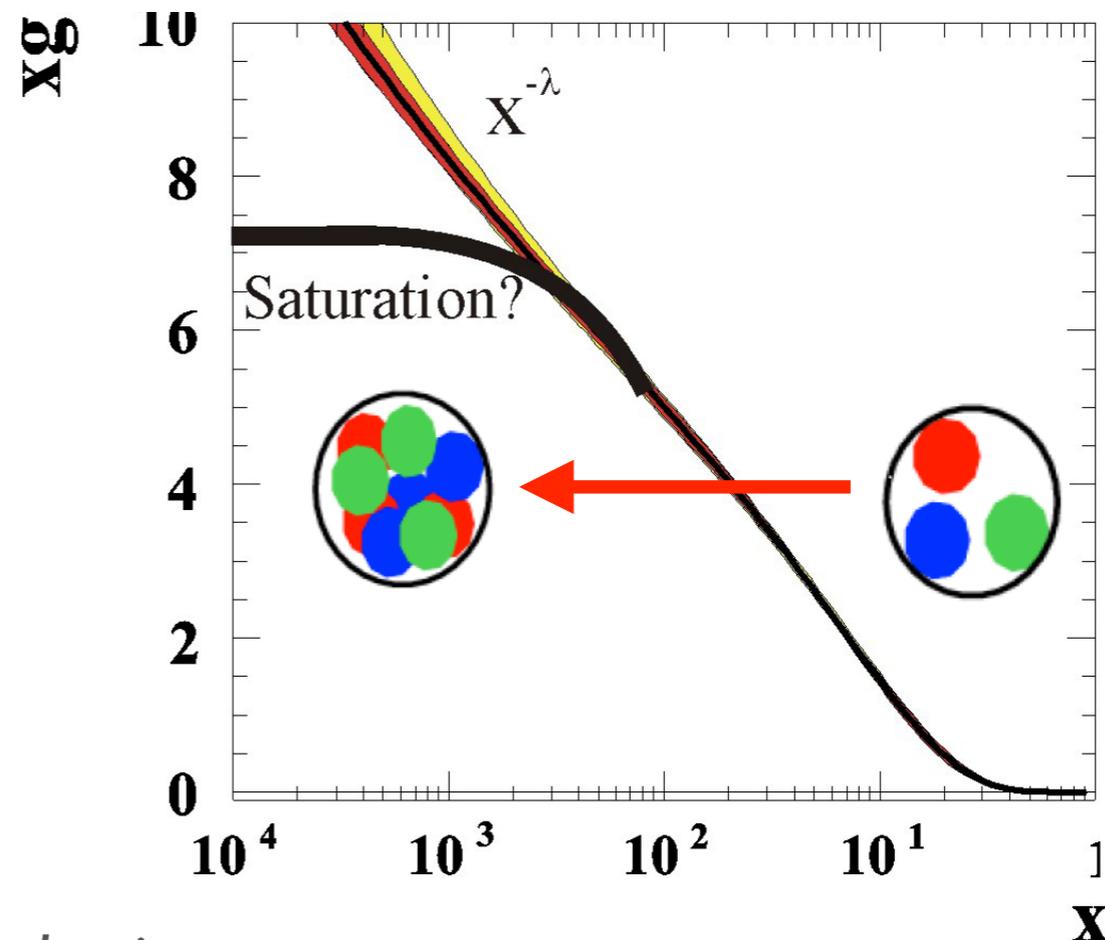
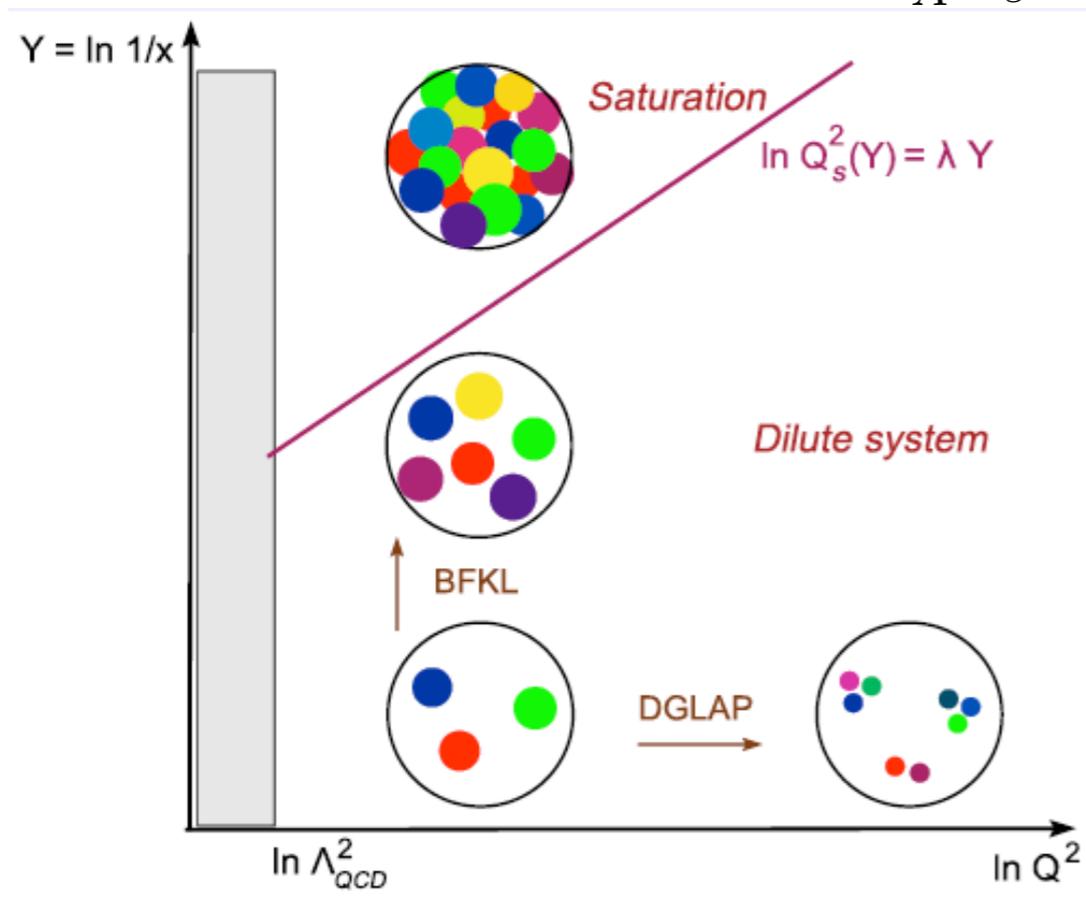
● Standard fixed-order perturbation theory (DGLAP, linear evolution) must eventually fail:

→ Large logs e.g. $\alpha_s \ln(1/x) \sim 1$: **resummation** (BFKL, CCFM, ABF, CCSS).

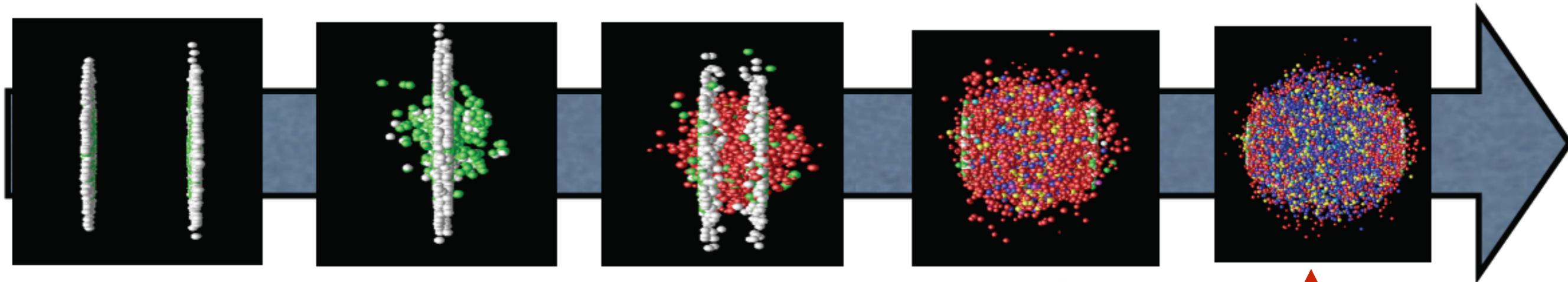
→ High-density: $x \downarrow, A \uparrow \Rightarrow$ non-linear regime, recombination

balancing splitting: **saturation**, perturbative (CGC) or non.

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



Relevance for HIC:



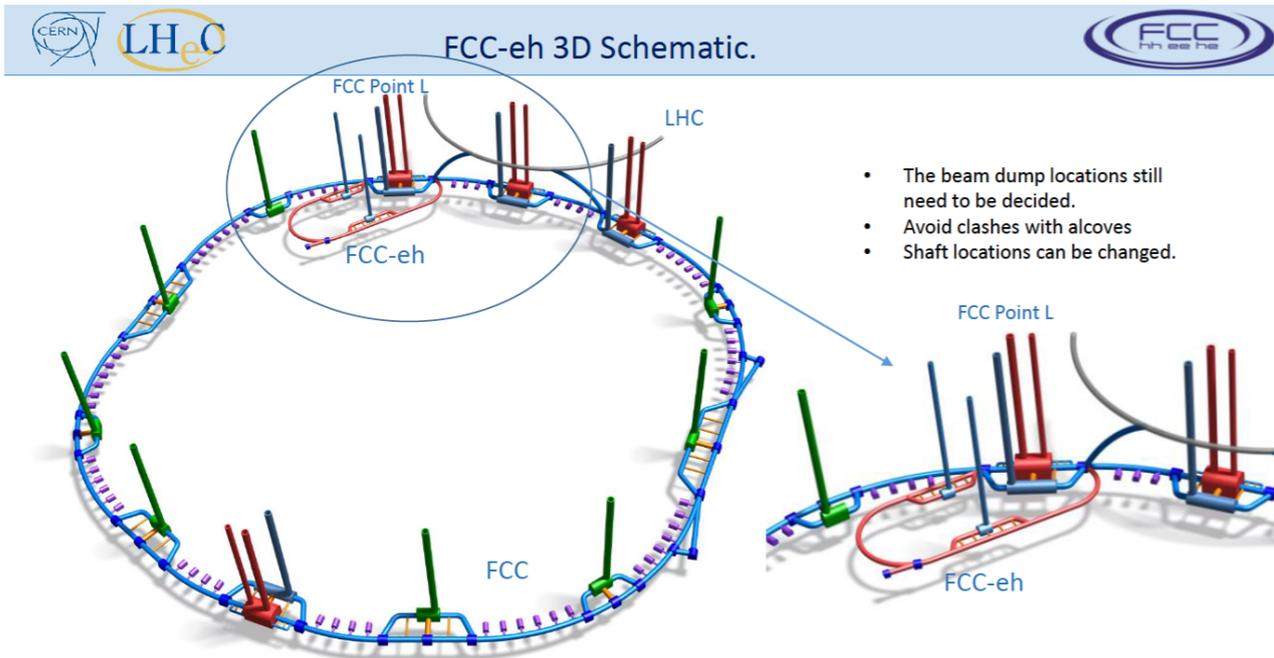
Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

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

- Particle production at the very beginning: which factorisation in eA?
- How does the system behave as \sim isotropised so fast?: initial conditions for plasma formation to be studied in eA.

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

FCC-eh (I):



- eA could run either concurrently with pA/AA or in dedicated mode.

John Osborne, Jo Stanyard & Matthew Stuart (SMB-SE-FAS)

LHeC and FCC-eh Workshop 2017

parameter [unit]	LHeC (HL-LHC)	eA at HE-LHC	FCC-he
E_{Pb} [PeV]	0.574	1.03	4.1
E_e [GeV]	60	60	60
$\sqrt{s_{eN}}$ electron-nucleon [TeV]	0.8	1.1	2.2
bunch spacing [ns]	50	50	100
no. of bunches	1200	1200	2072
ions per bunch [10^8]	1.8	1.8	1.8
$\gamma\epsilon_A$ [μm]	1.5	1.0	0.9
electrons per bunch [10^9]	4.67	6.2	12.5
electron current [mA]	15	20	20
IP beta function β_A^* [cm]	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3
bunch filling H_{coll}	0.8	0.8	0.8
luminosity [$10^{32}\text{cm}^{-2}\text{s}^{-1}$]	7	18	54
Integrated lumi. in 10 y. (fb^{-1}) $\sim\sim$	6	15	45

eD at LHEC:

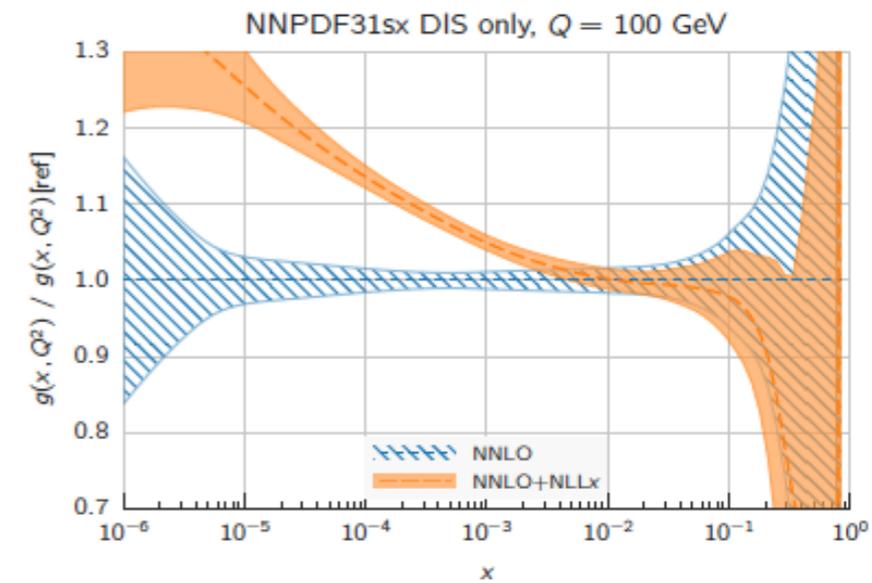
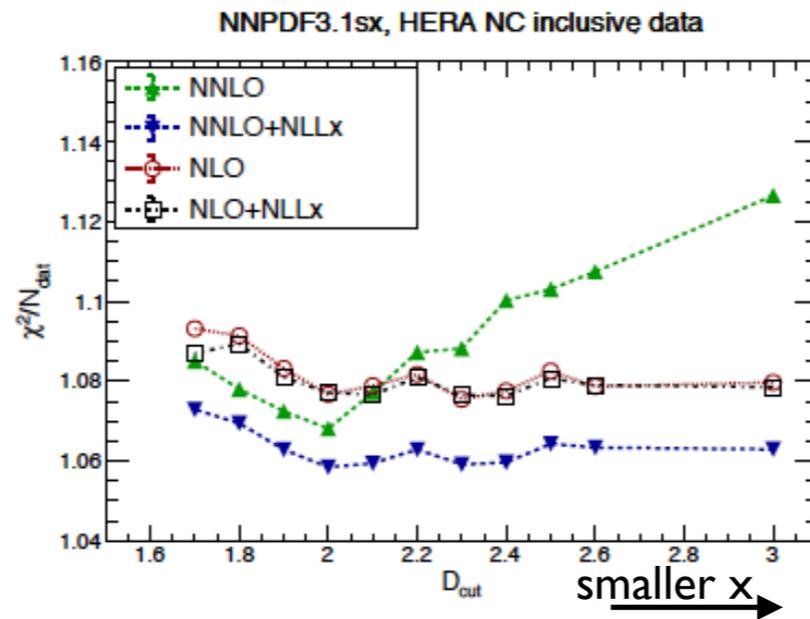
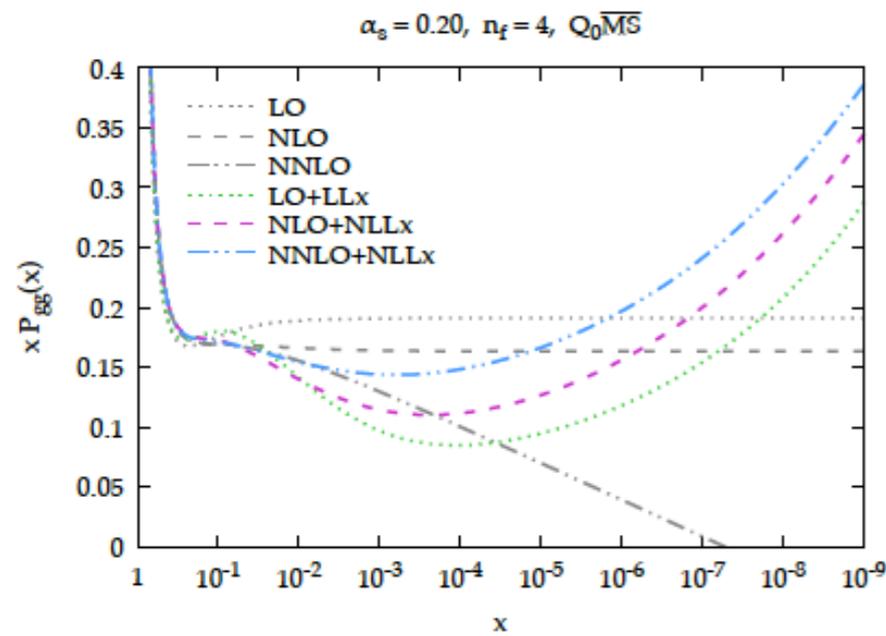
$$L_{eN} = A L_{eA} > \sim 3 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$$

(old CDR number)

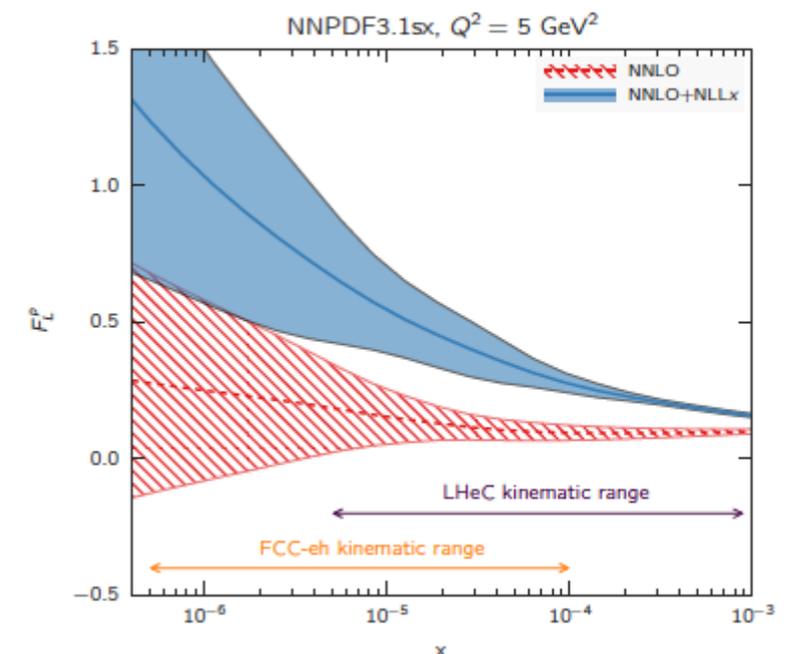
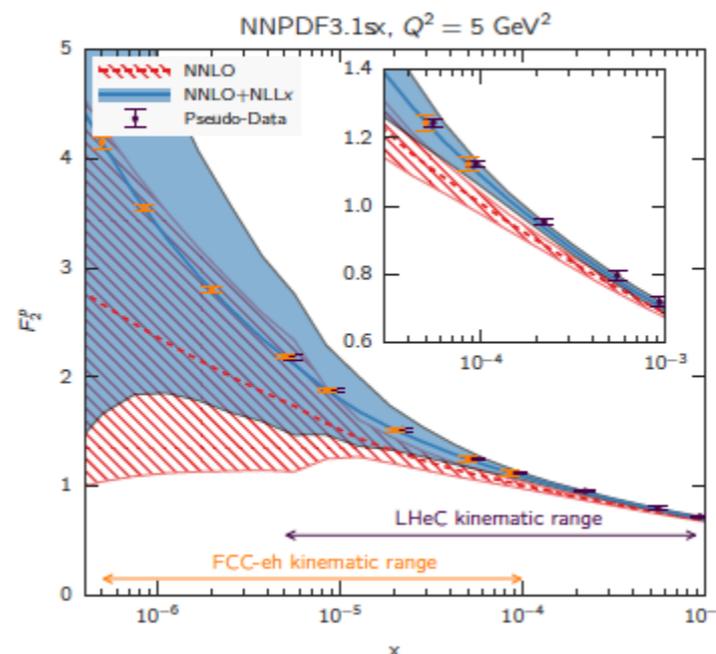
- 100 times larger luminosity than HERA, full HERA integrated luminosity in less than a month.

Resummation:

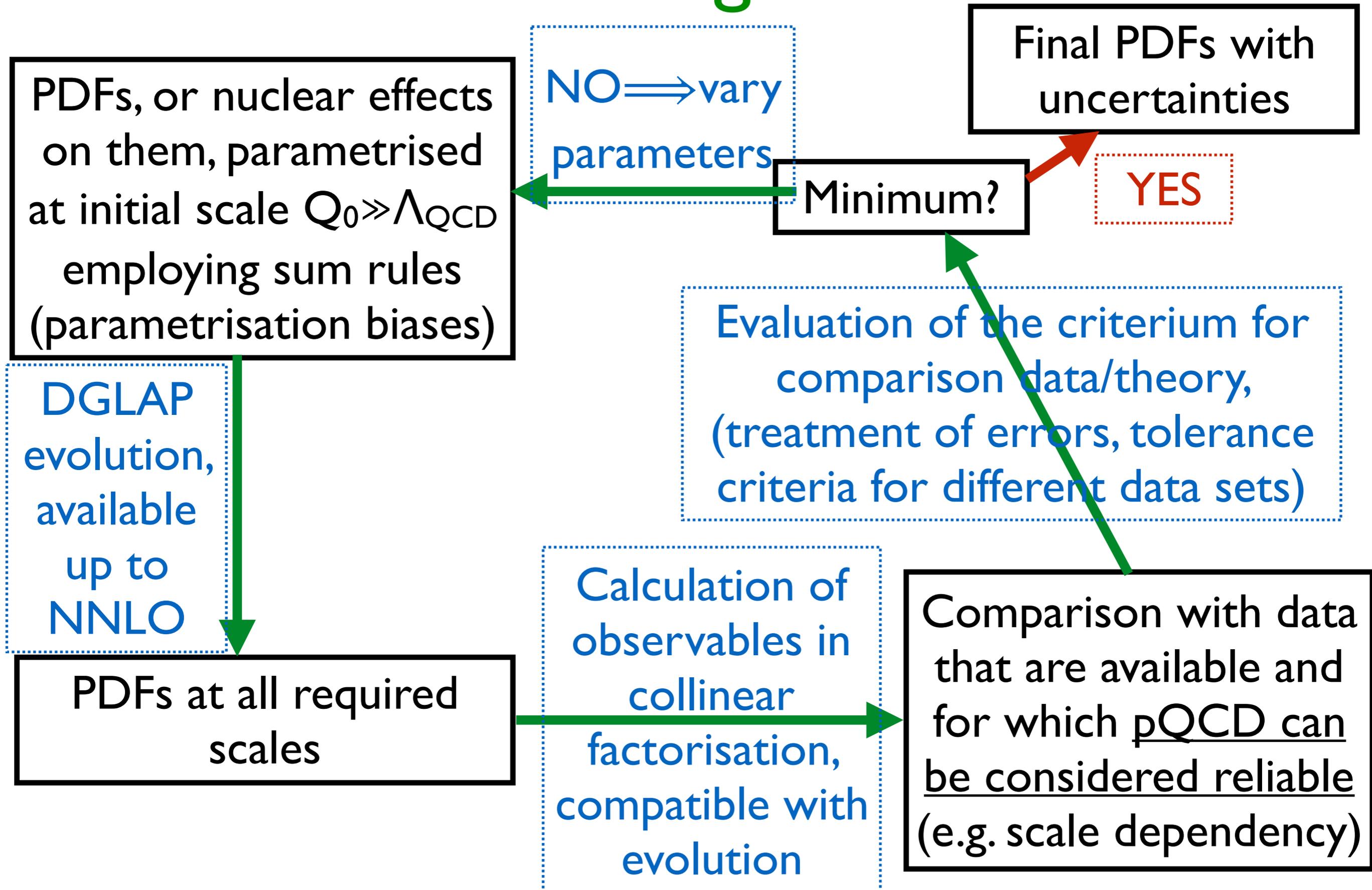
- **Resummation** has been suggested ([1710.05935](#)) to cure the problem seen in HERA data of a worsening of the PDF fit quality with decreasing x and Q^2 : the problem lies in F_L .



- This approach, and **saturation**, can be checked at smaller x through the tension between observables: F_2 , F_L , σ_r^{HQ} .

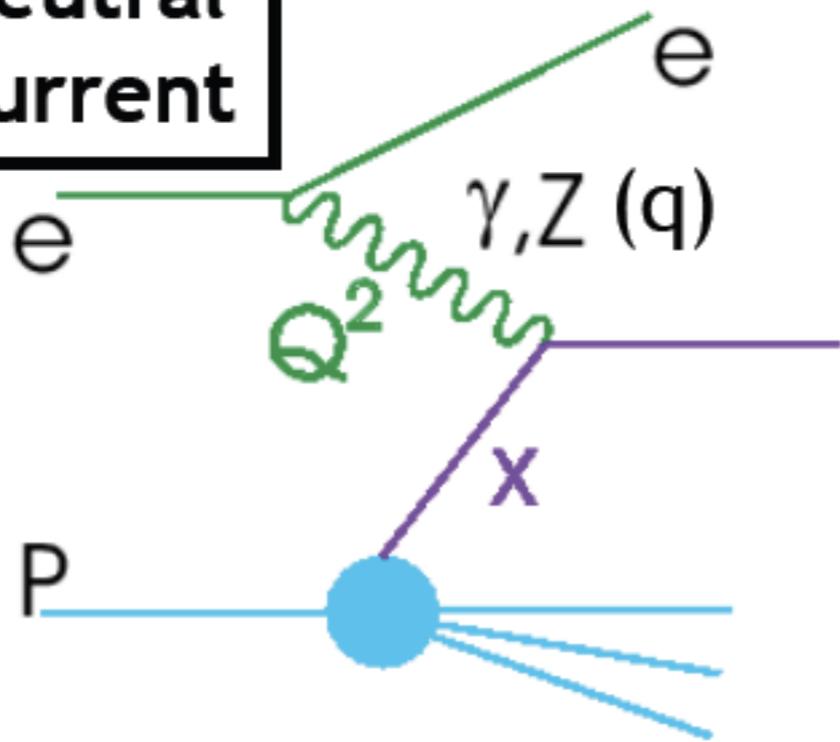


Extracting PDFs:

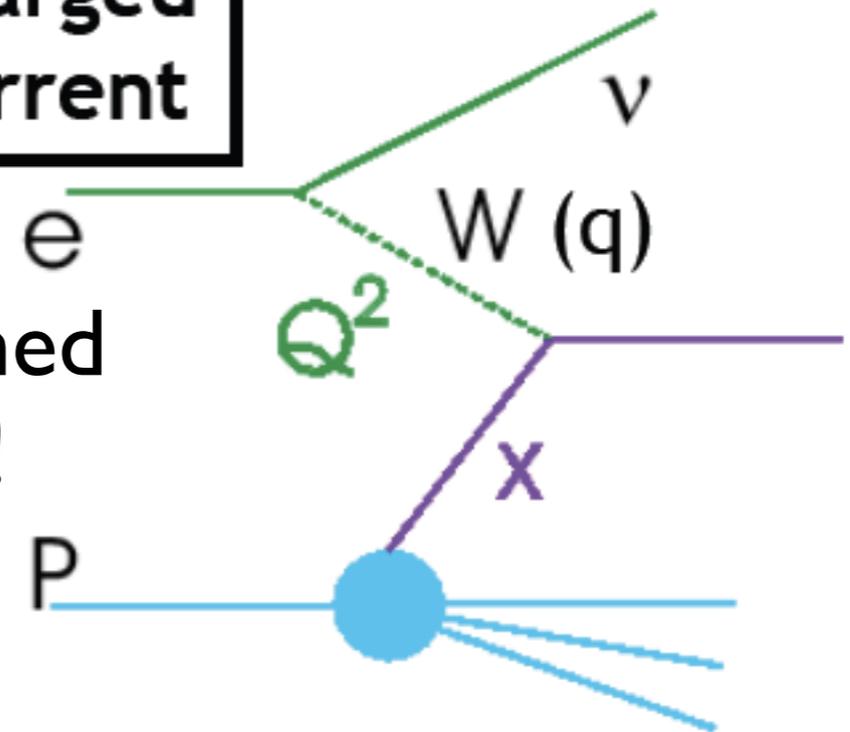


Some relations:

Neutral Current



Charged Current



Fully constrained kinematics!

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

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

$$\sigma_{r,NC} = \mathbf{F}_2 + \frac{Y_-}{Y_+} \mathbf{x} \mathbf{F}_3 - \frac{y^2}{Y_+} \mathbf{F}_L,$$

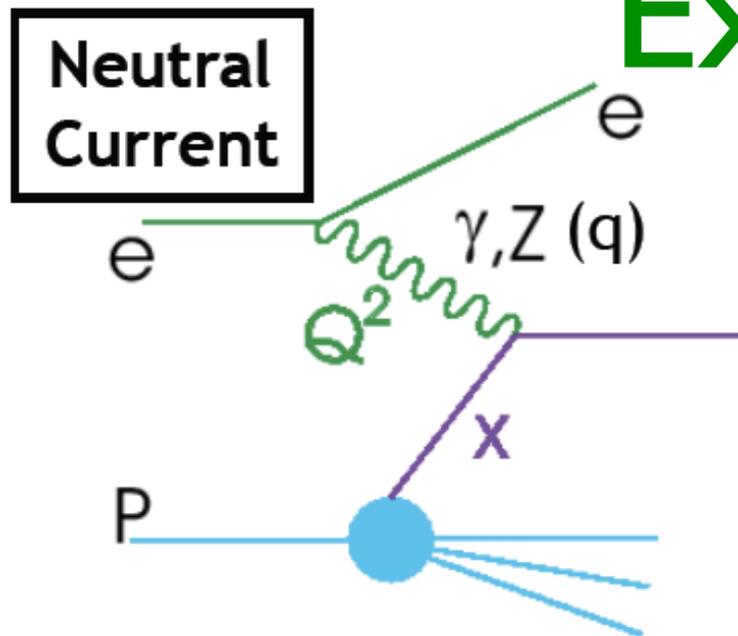
$$\sigma_{r,CC}^\pm = W_2^\pm \mp \frac{Y_-}{Y_+} x W_3^\pm - \frac{y^2}{Y_+} W_L^\pm$$

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

$$\mathbf{F}_2^\pm = F_2 + \kappa_Z (-v_e \mp P a_e) \cdot F_2^{\gamma Z} + \kappa_Z^2 (v_e^2 + a_e^2 \pm 2P v_e a_e) \cdot F_2^Z$$

$$\mathbf{x} \mathbf{F}_3^\pm = \kappa_Z (\pm a_e + P v_e) \cdot x F_3^{\gamma Z} + \kappa_Z^2 (\mp 2v_e a_e - P(v_e^2 + a_e^2)) \cdot x F_3^Z$$

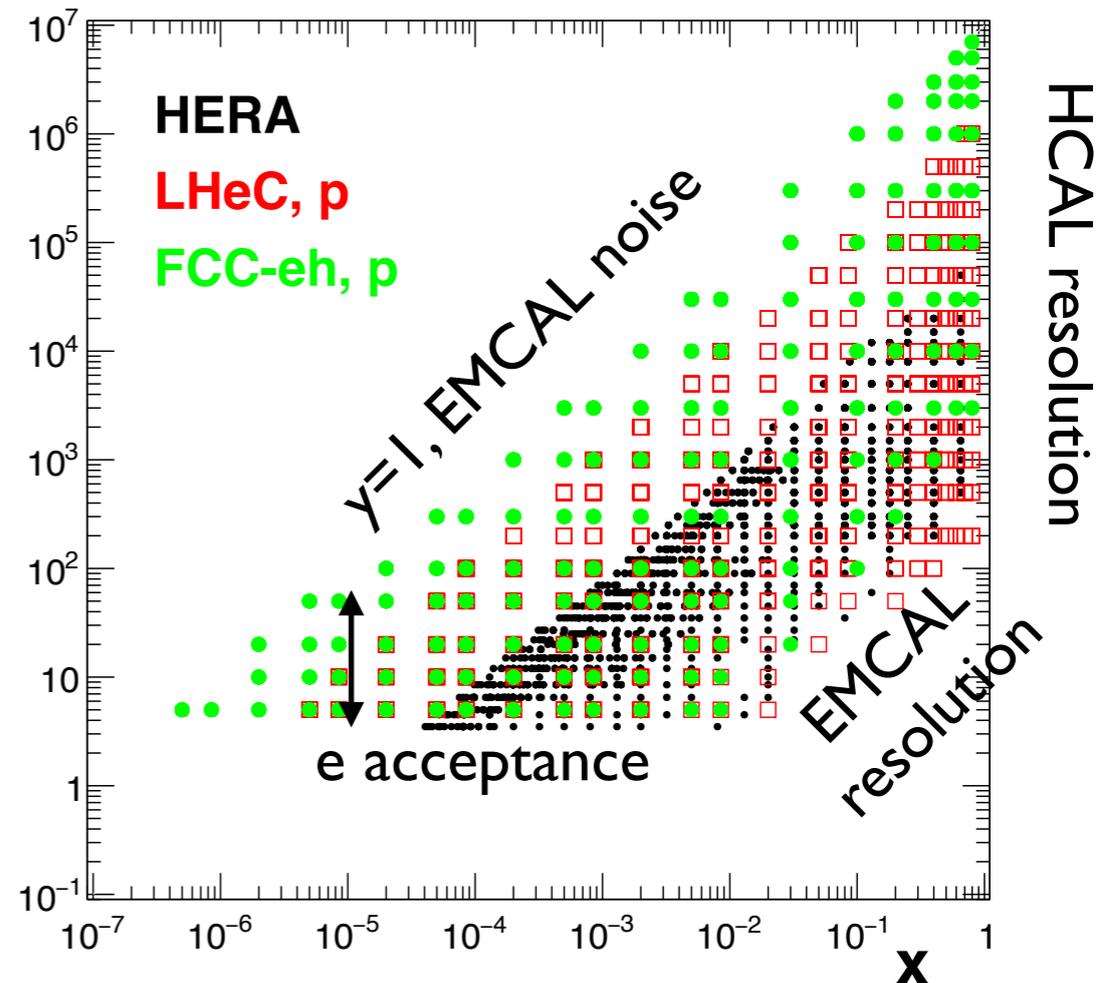
Extraction of PDFs:



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

$$\sigma_{r,NC} = F_2 + \frac{Y_-}{Y_+} x F_3 - \frac{y^2}{Y_+} F_L,$$

Q^2 (GeV²)



- Ignoring EW contributions:

$$F_2(x, Q^2) \propto \sum xq(x, Q^2) \quad \text{Sensitive to the sea.}$$

$$\frac{\partial F_2(x, Q^2)}{\partial \log Q^2} \propto xg(x, Q^2) \quad \text{Via DGLAP: requires lever arm in } Q^2.$$

$$F_L(x, Q^2) \propto xg(x, Q^2) - F_2(x, Q^2) \quad \text{Via DGLAP: requires lever arm in } s \text{ (different } y \text{ at fixed } x, Q^2\text{): better } \sigma_{\text{red}}.$$

EPPS16@LHeC (I):

The LHeC pseudodata

- Assume $\mathcal{L}_{ep} = 10 \text{ fb}$, $\mathcal{L}_{ePb} = 1 \text{ fb}$ (per nucleon)
- The assumed energy configs: $\sqrt{s_p} = 7 \text{ TeV}$, $\sqrt{s_{Pb}} = 2.75 \text{ TeV}$ (per nucleon) on $E_e = 60 \text{ GeV}$ electrons.
- The pseudodata are here obtained from ratios of reduced cross sections σ^i and relative point-to-point ($\delta_{\text{uncor.}}^i$) and normalization ($\delta_{\text{norm.}}^i$) uncertainties as

$$R_i = R_i(\text{EPS09}) \times \left[1 + \delta_{\text{uncor.}}^i r^i + \delta_{\text{norm.}}^i r^{\text{norm.}} \right]$$

where

$$R_i(\text{EPS09}) = \frac{\sigma_{ePb}^i(\text{CTEQ6.6} + \text{EPS09})}{\sigma_{ep}^i(\text{CTEQ6.6})},$$

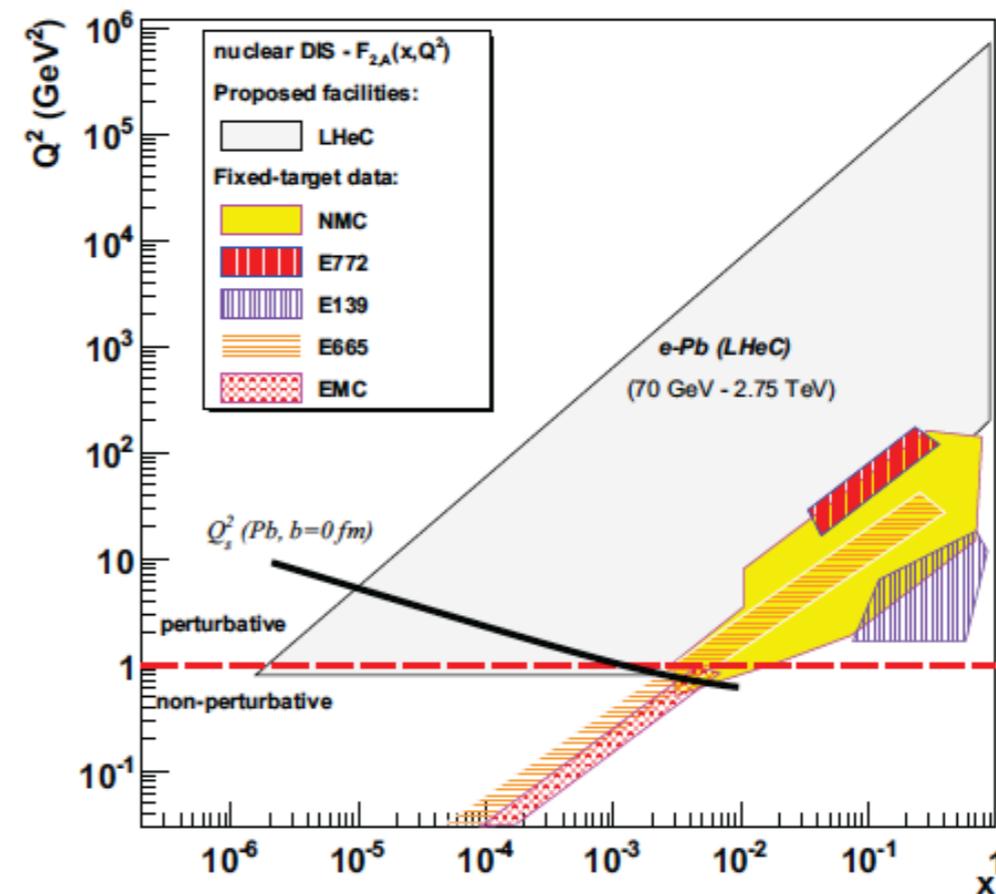
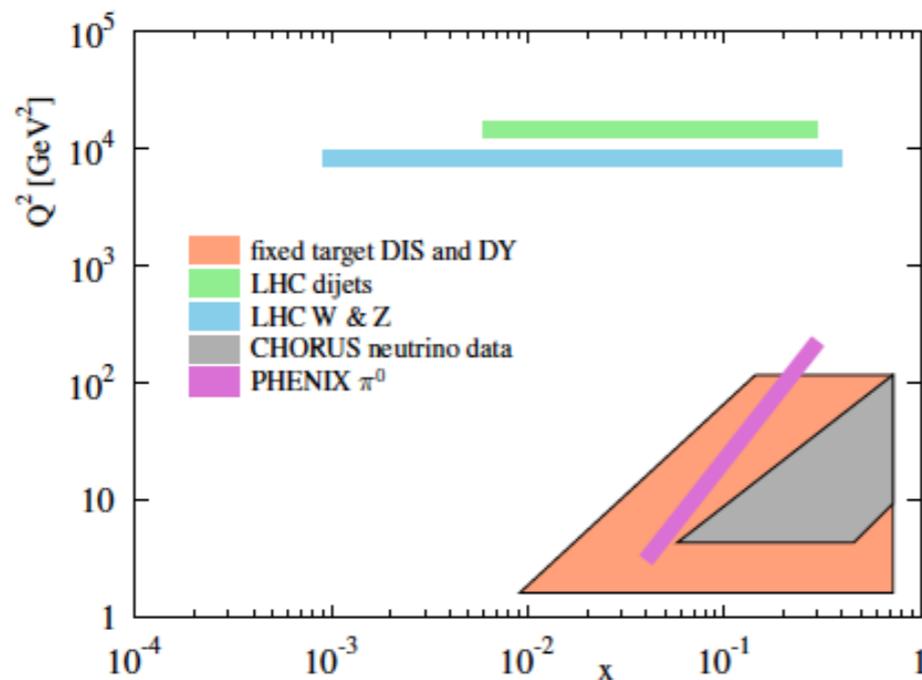
and r^i and $r^{\text{norm.}}$ are Gaussian random numbers.

- In EPS09 $R_{u_V} \approx R_{d_V}$, $R_{\bar{u}} \approx R_{\bar{d}} \approx R_{\bar{s}}$ (free in EPPS16, but would not expect large deviations from this)

EPPS16@LHeC (I):

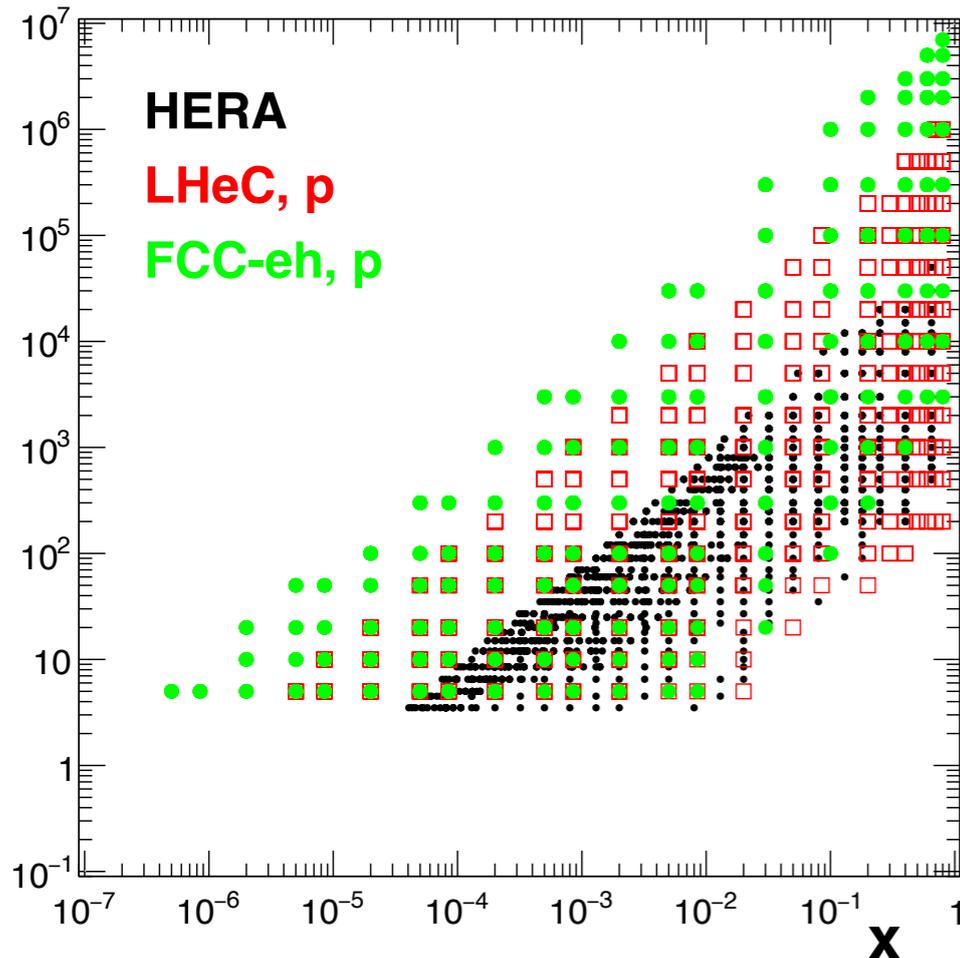
The analysis framework

- The fit framework same as in the EPPS16 analysis [EPJ C77, 163]
- Include the same data as in EPPS16 plus LHeC (NC and CC) pseudo data.
- Hessian uncertainty analysis with $\Delta\chi^2 = 52$ (as in EPPS16)

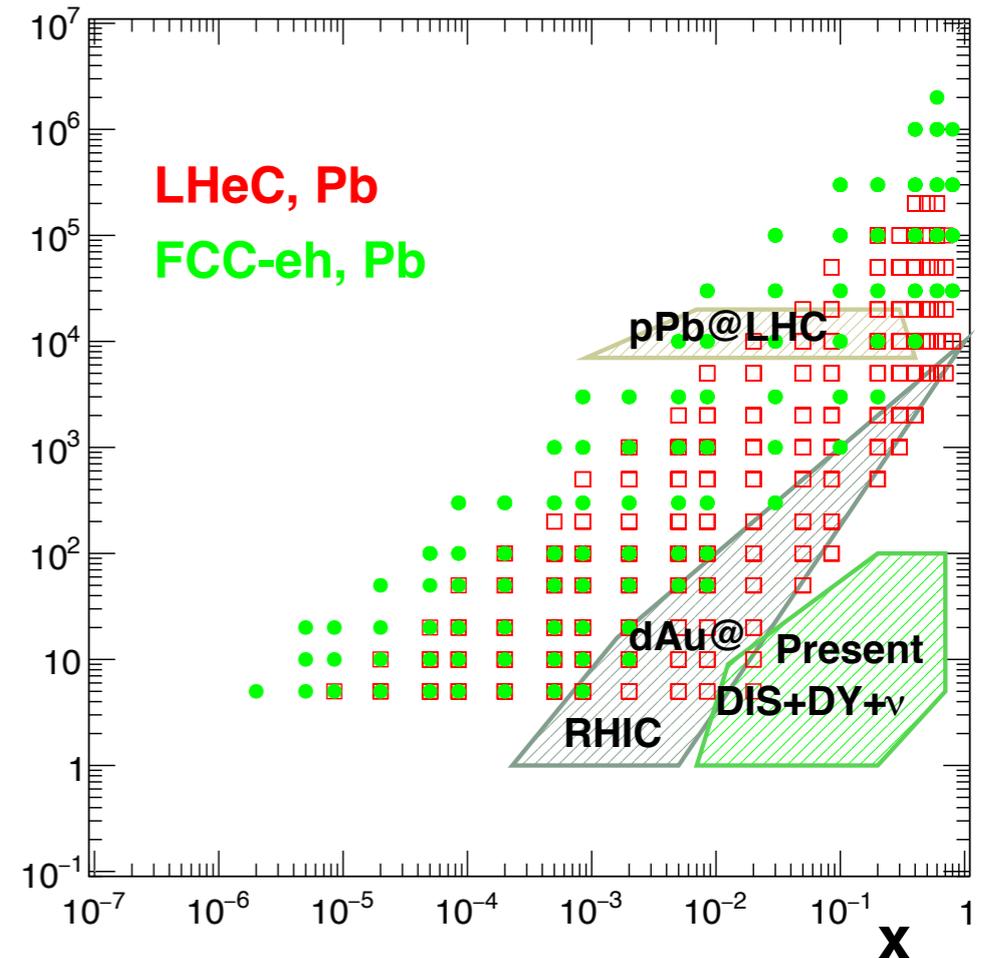


Pseudodata at LHeC/FCC-eh:

Q^2 (GeV²)



Q^2 (GeV²)



- Pseudodata generated using a code (Max Klein) validated with the HI MC.
- Cuts: $|\eta_{\max}|=5$, $0.95 < y < 0.001$.
- Error assumptions \sim factor 2 better than at HERA (luminosity uncertainty kept aside).
- Stat./syst. errors (ePb@FCC-eh) from 0.1/1.2% (small x , NC) to 37/6% (large x & Q^2 , CC).

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

Pseudodata:

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

xFitter:

- Extraction of Pb-only PDFs by fitting pseudodata, using xFitter (1410.4412) 1.2.2 to estimate the ‘ultimate’ precision that could be achieved (P.Agostini, NA):
 - HERAPDF2.0-type parametrisation (1506.06042, 14 parameters), NNLO evolution, RTOPT mass scheme, $\alpha_s=0.118$.

$$xg(x) = A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{C'_g},$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + E_{u_v} x^2),$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}},$$

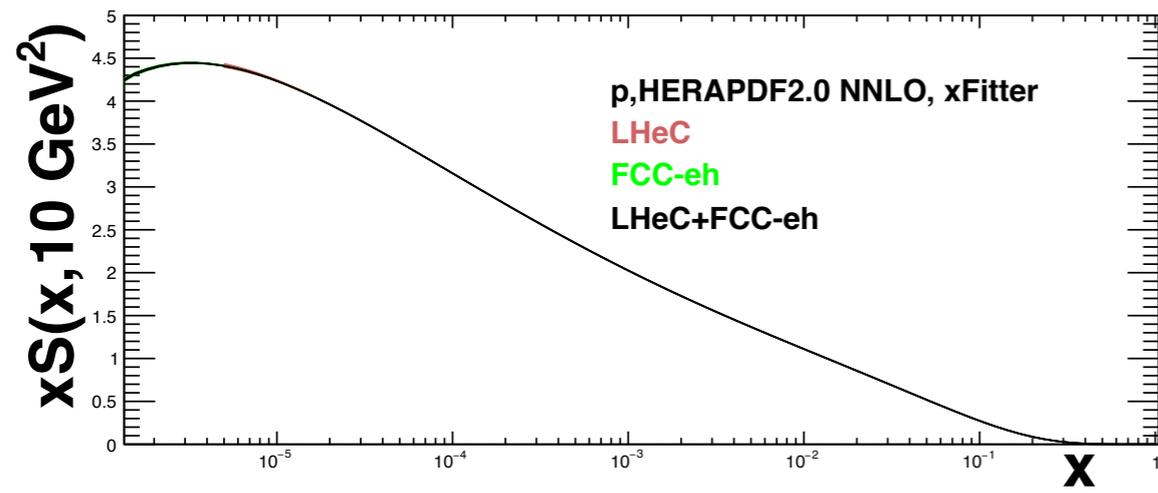
$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}} (1 + D_{\bar{U}} x),$$

$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}}.$$

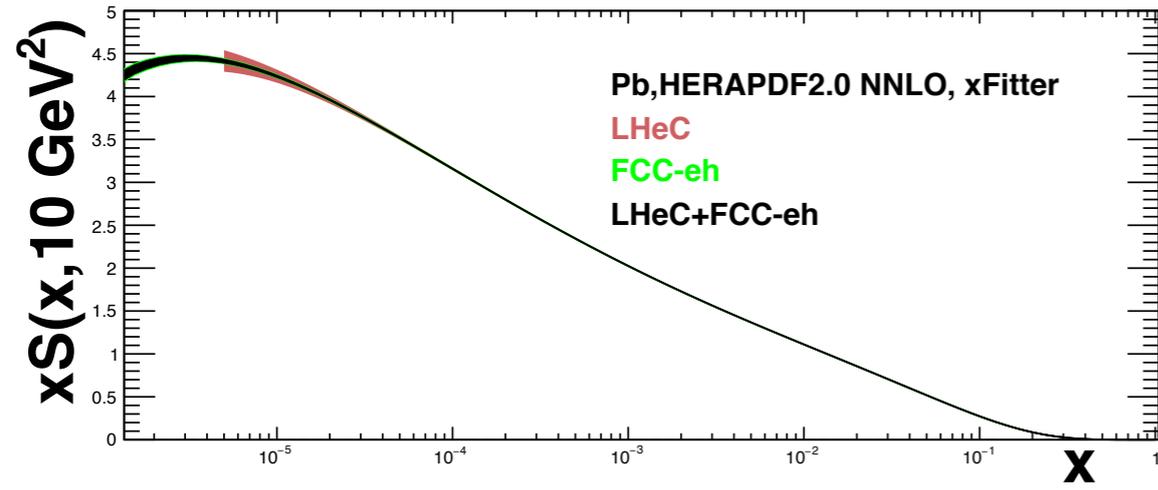
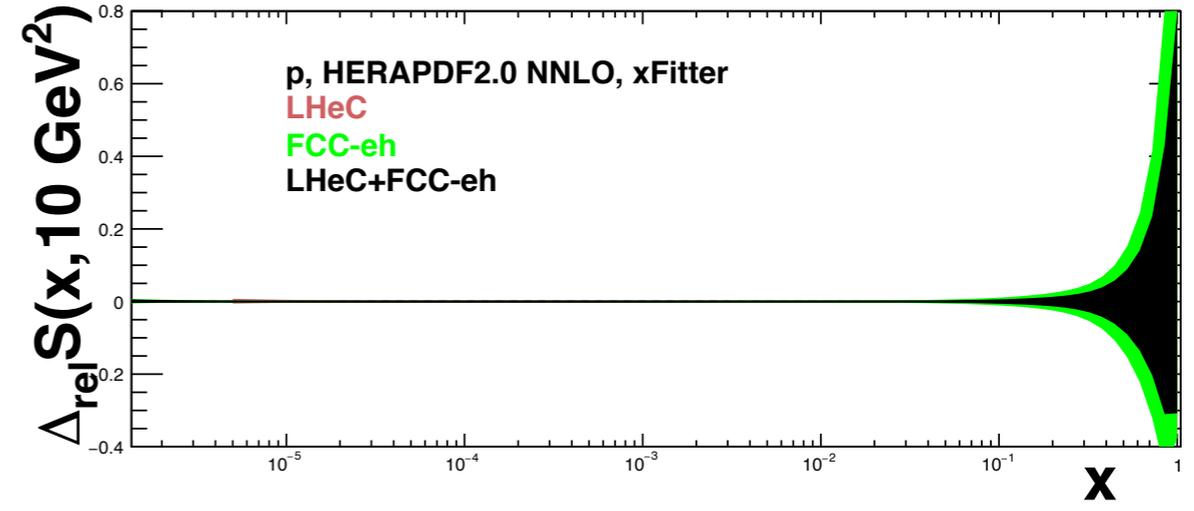
$$xU = xu + xc, \quad x\bar{U} = x\bar{u} + x\bar{c}, \quad xD = xd + xs, \quad x\bar{D} = x\bar{d} + x\bar{s}$$

- Central pseudodata values from HERAPDF2.0: no parametrisation bias.
- Standard xFitter/HERAPDF treatment of correlated/uncorrelated systematics.
- Only data with $Q^2 \geq 3.5 \text{ GeV}^2$, initial evolution scale 1.9 GeV^2 .
- Proton PDFs extracted in the same setup for consistency.

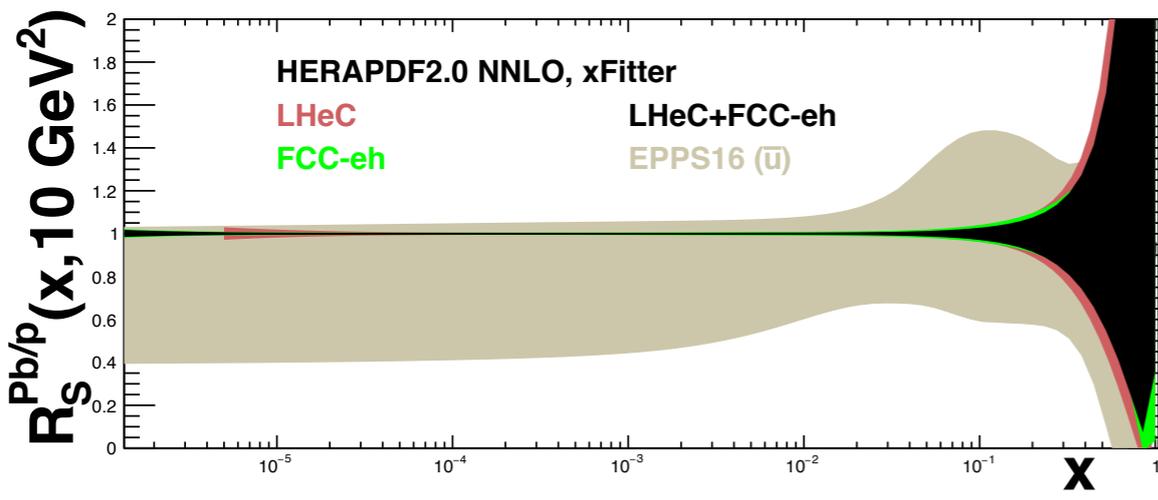
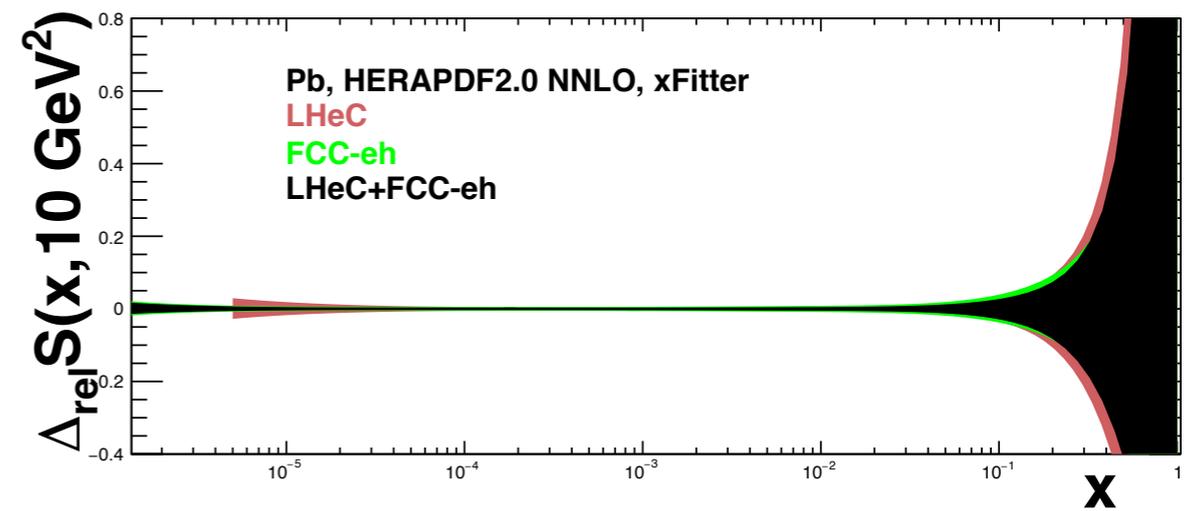
Results: sea



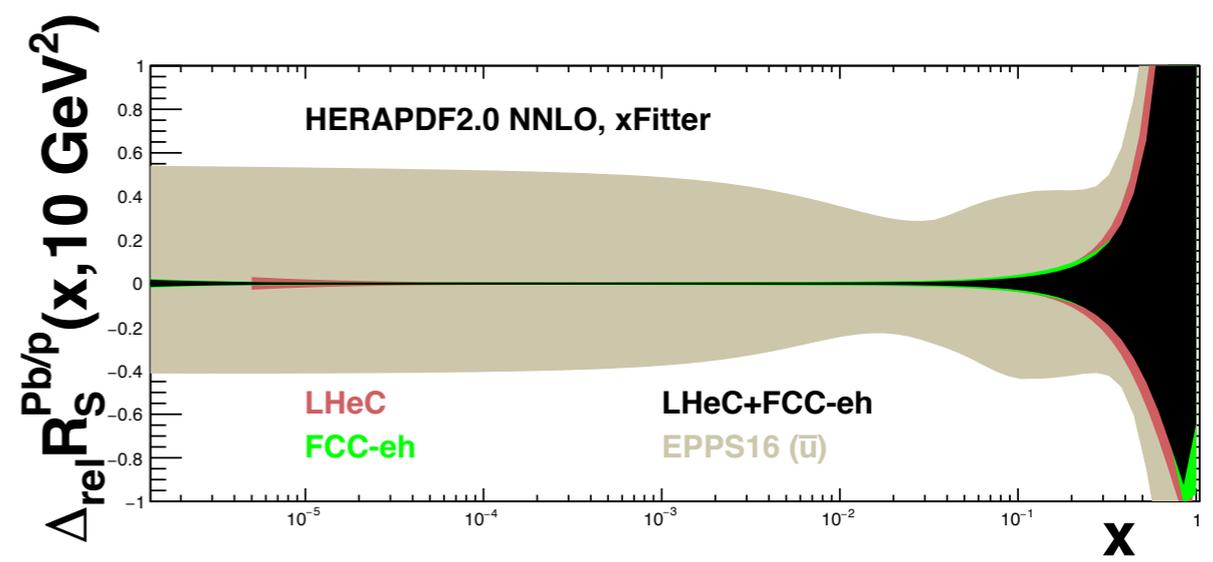
P



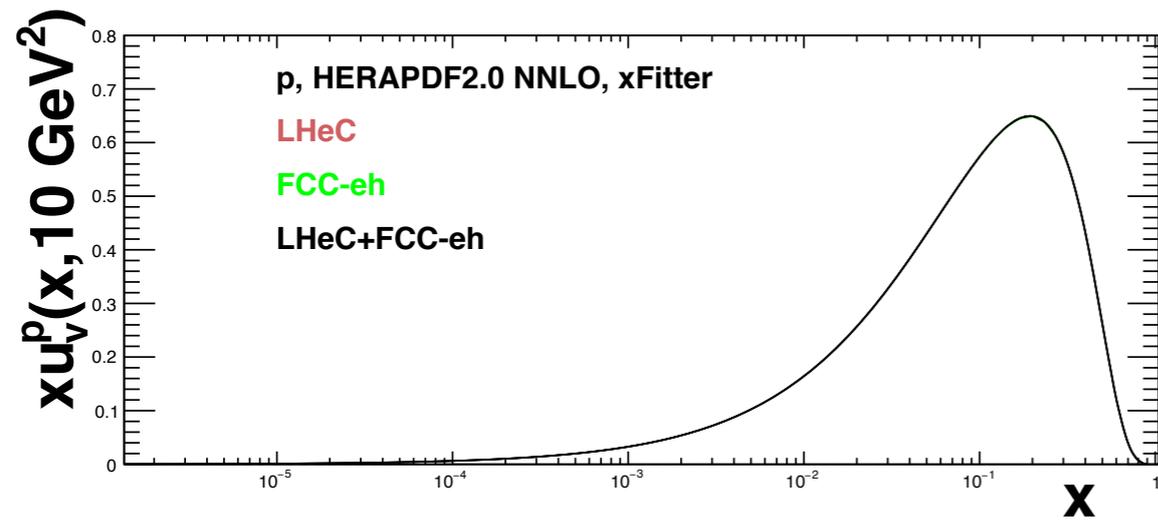
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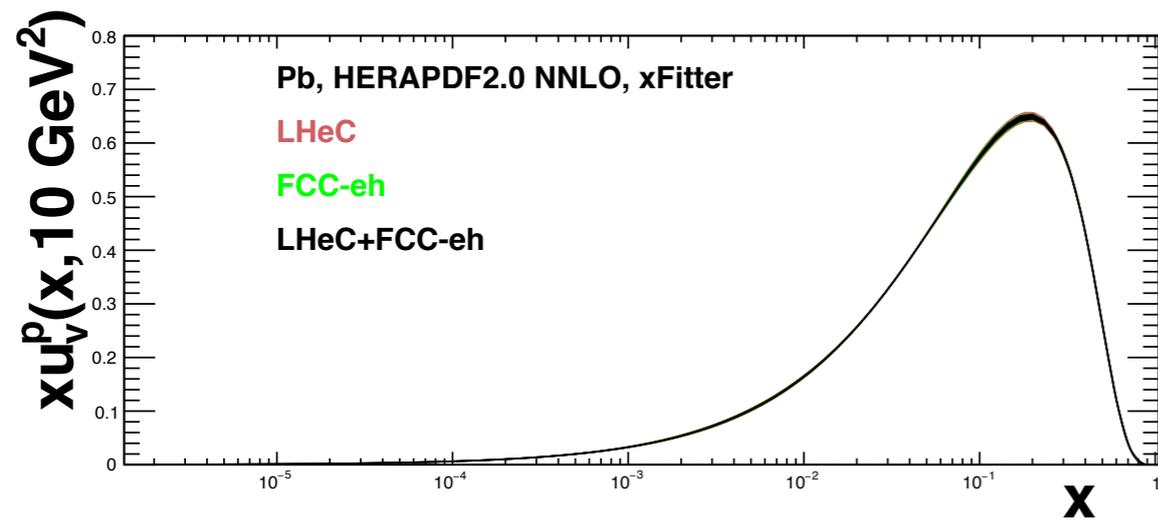
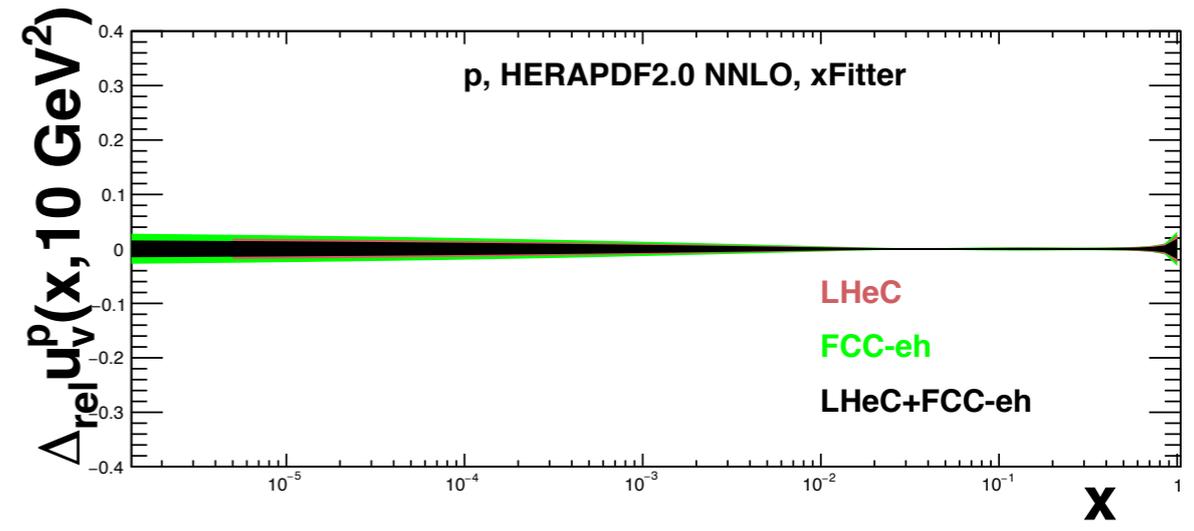
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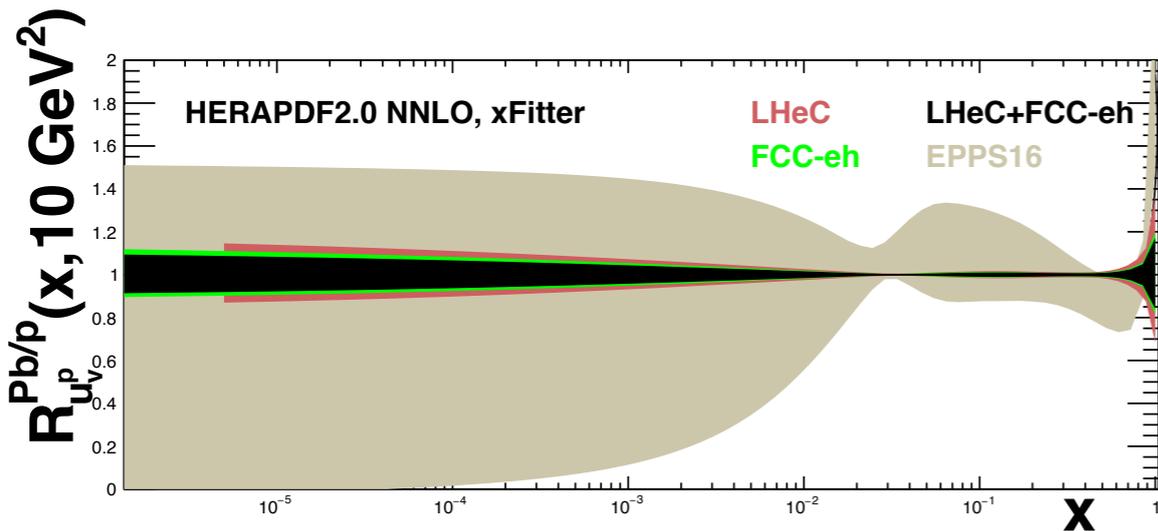
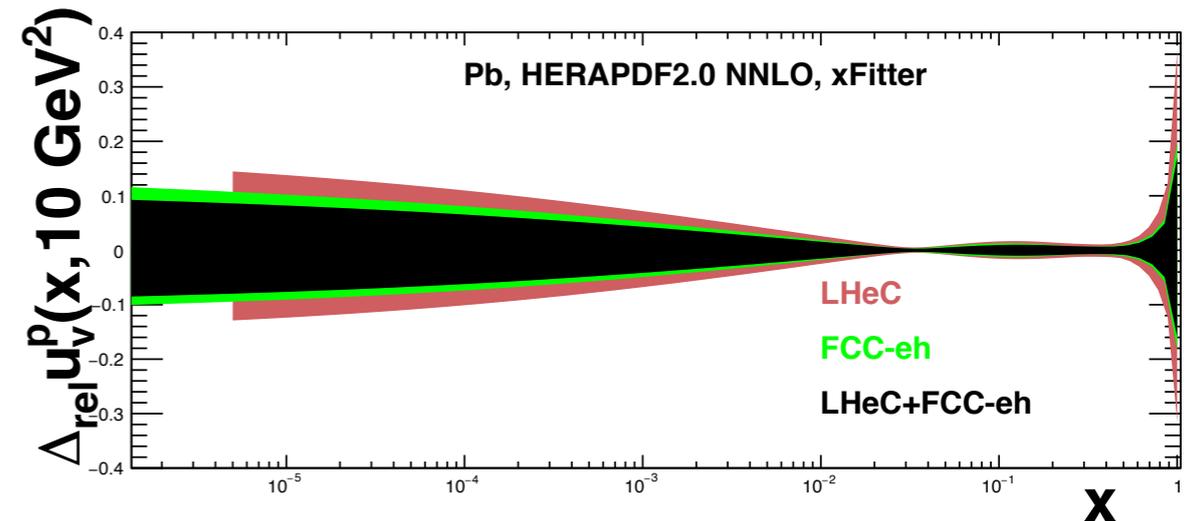
Results: valence



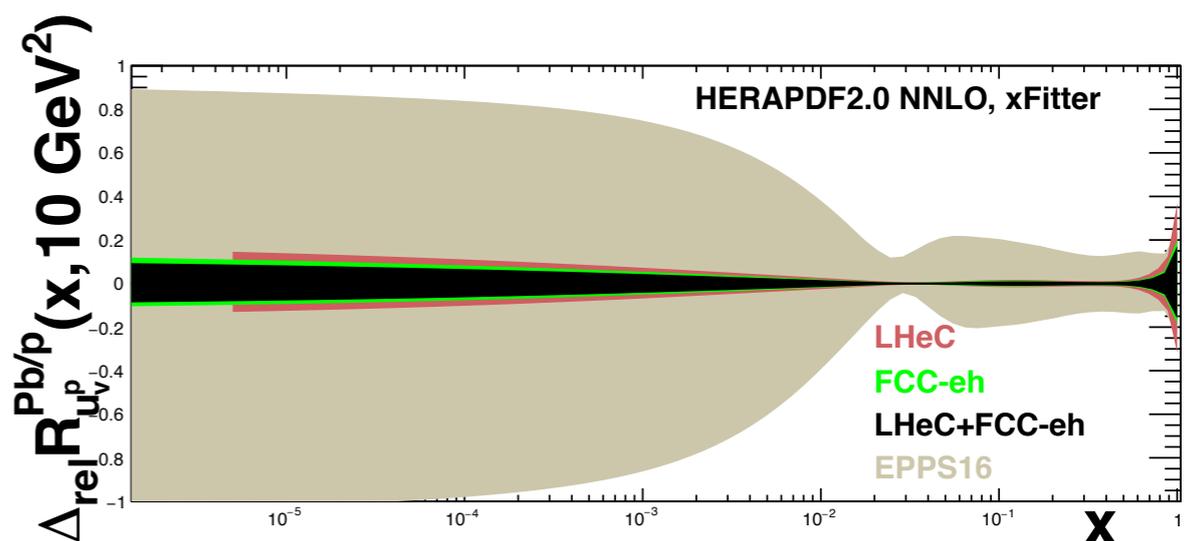
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P_b

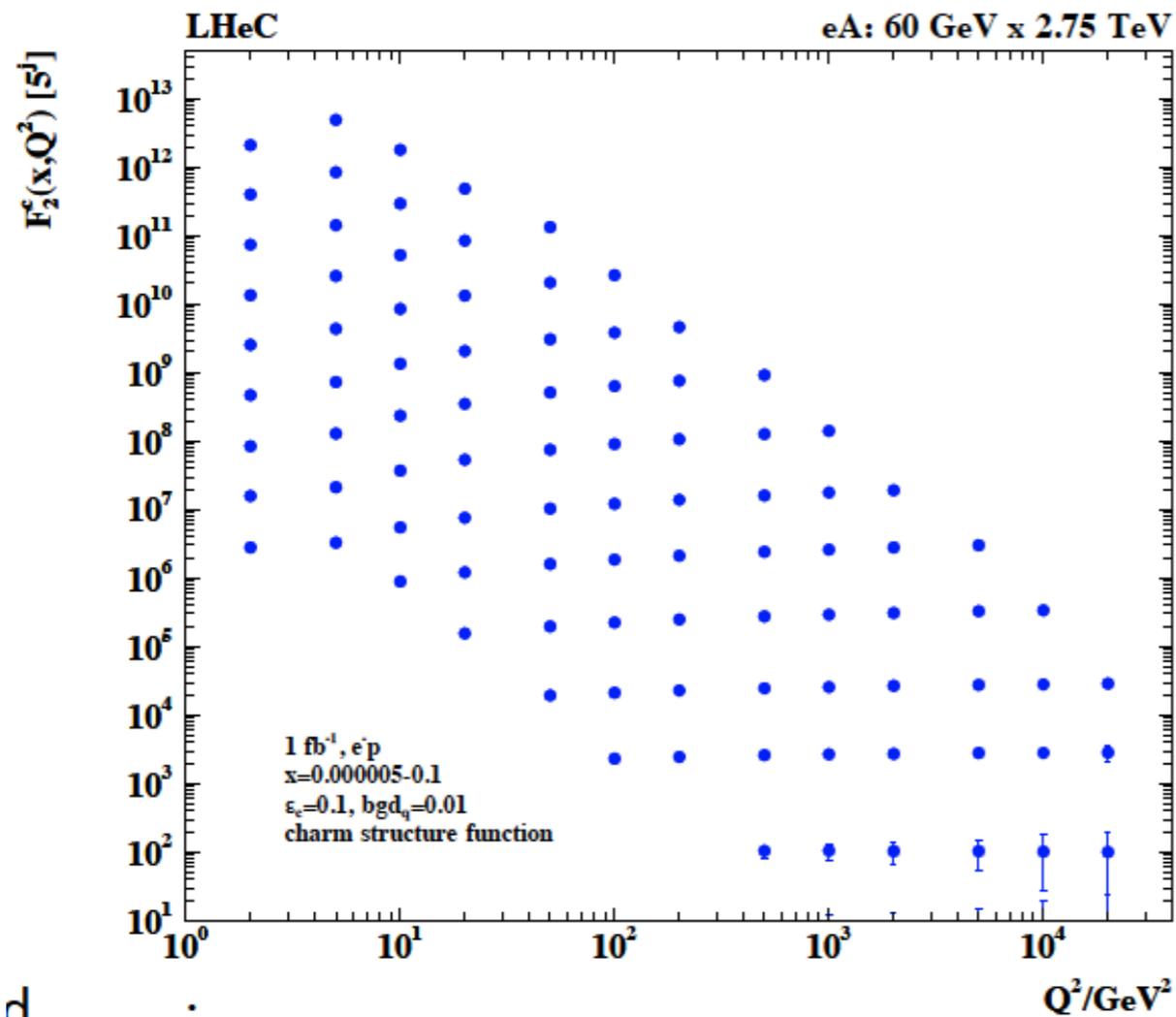


P_b/p

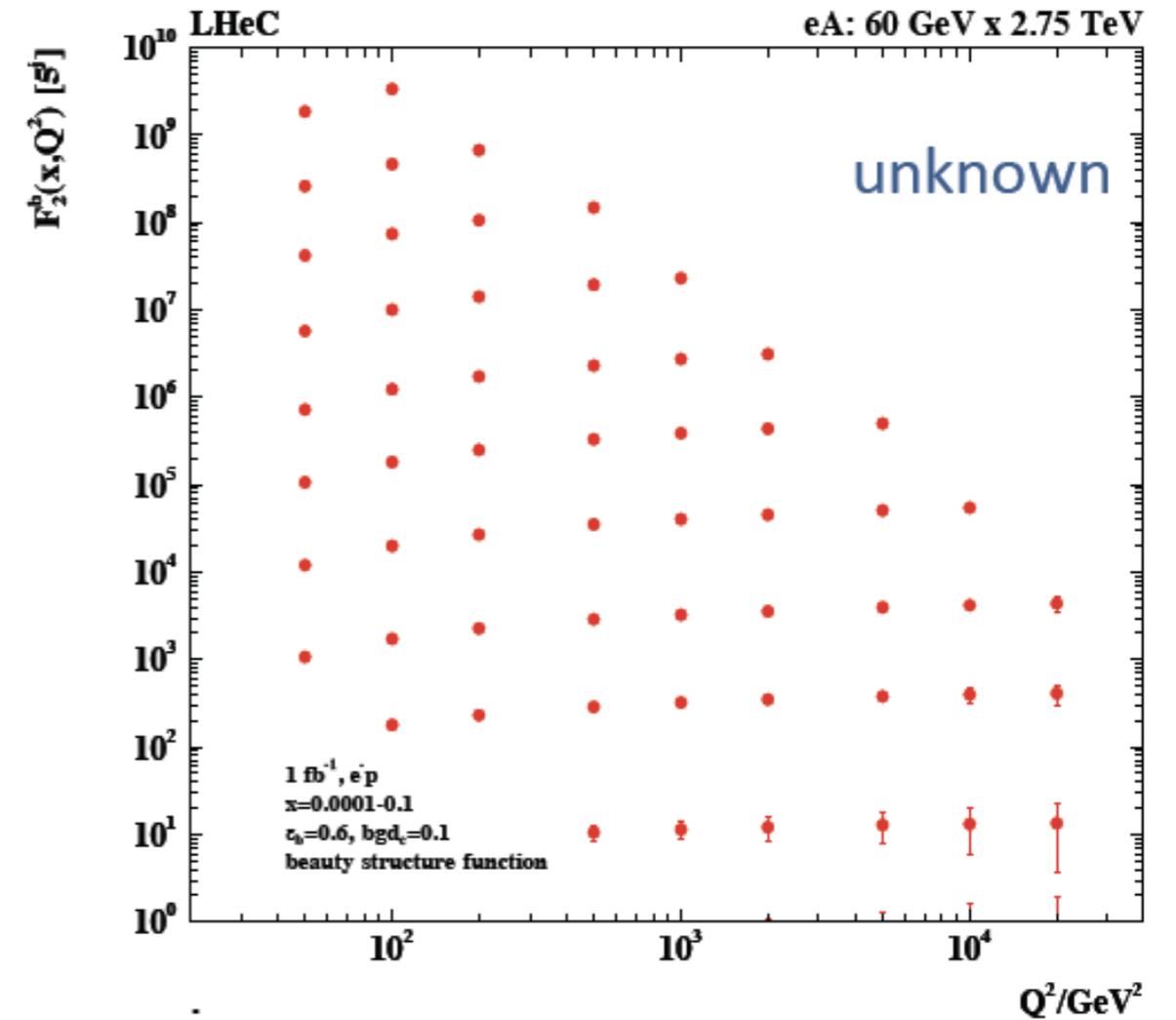


Heavy flavours at LHeC:

Charm density in nuclei

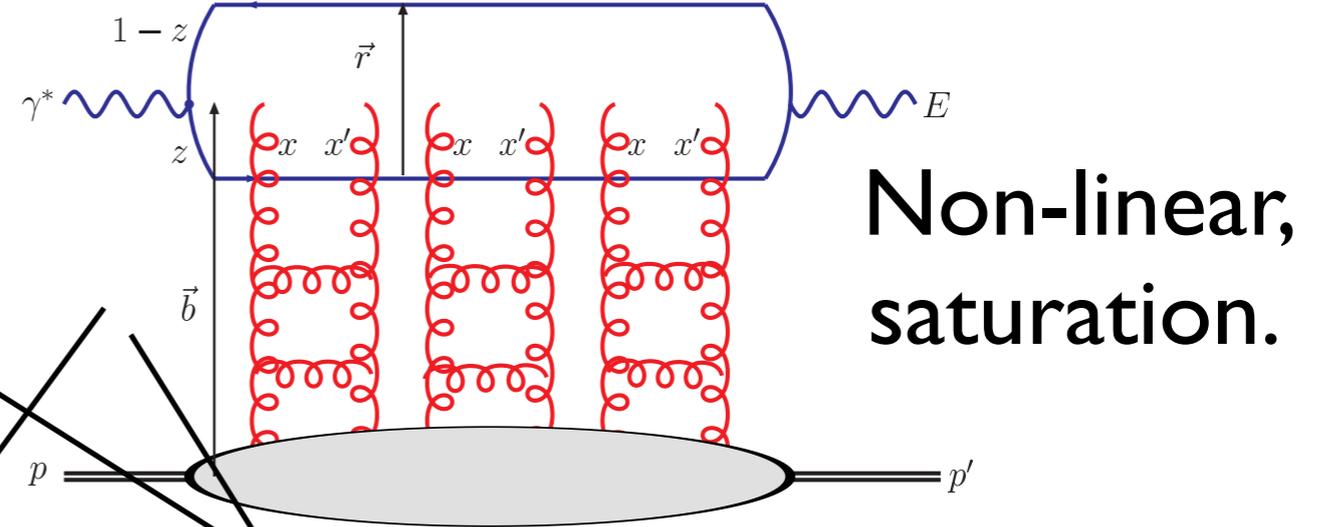
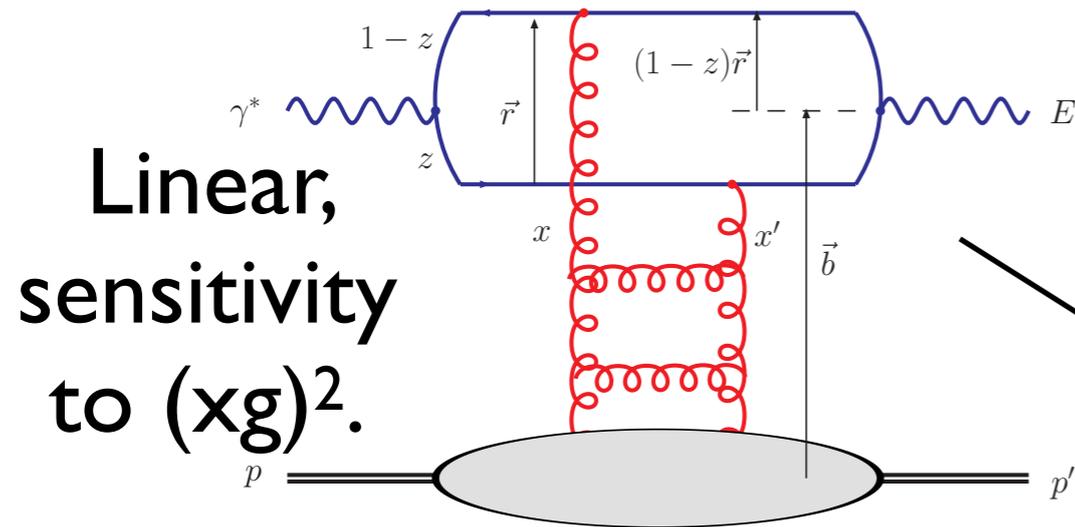


Beauty in Lead

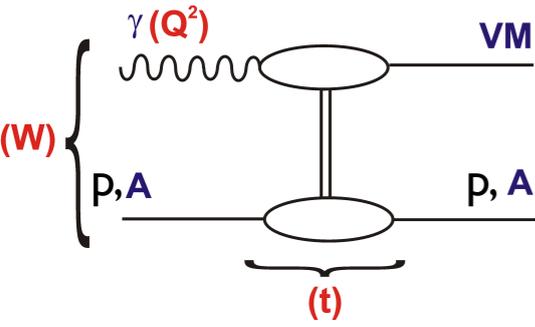


M. Klein, DOI: [10.1051/epjconf/201611203002](https://doi.org/10.1051/epjconf/201611203002)

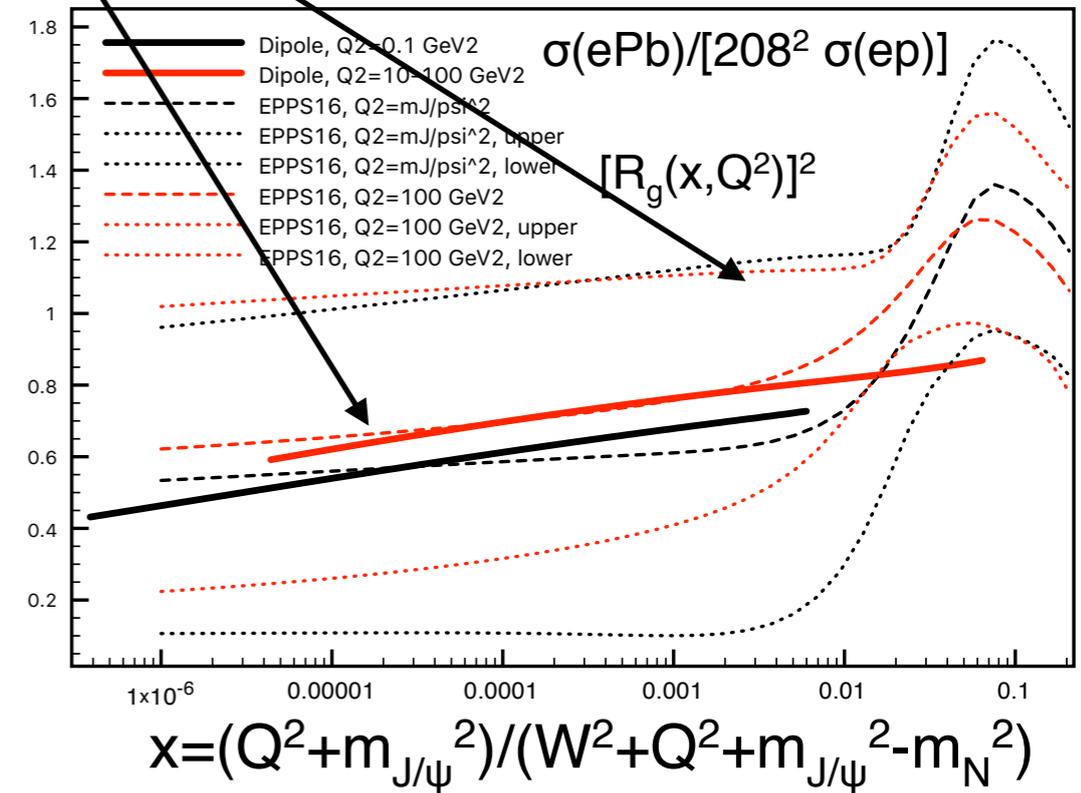
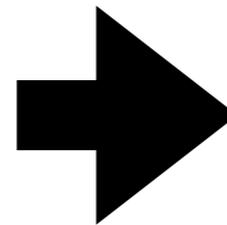
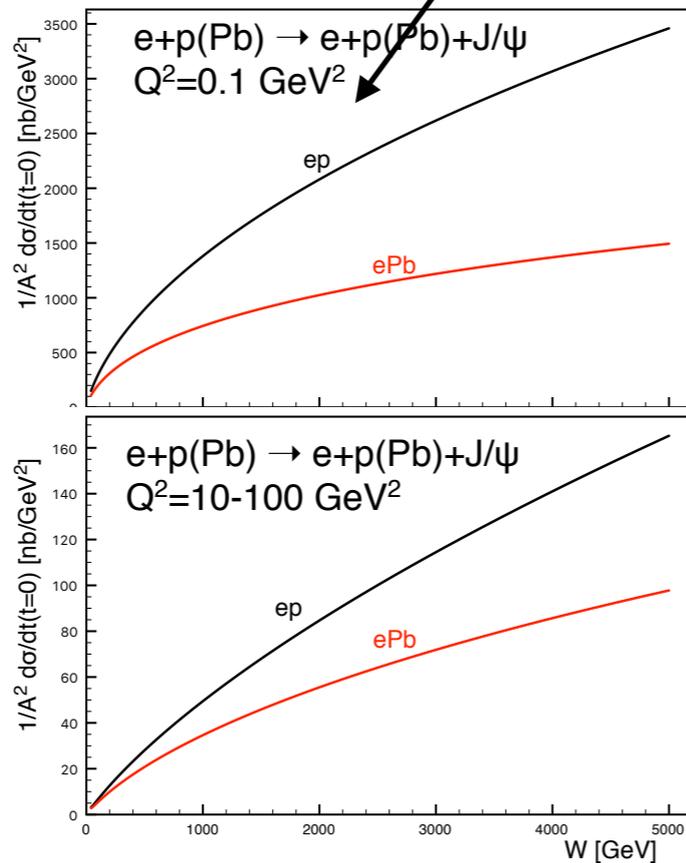
Exclusive VMs:



- The magnitude of nuclear shadowing needs not be different in collinear and non-collinear approaches.



Coherent diffractive VM production



Mantysaari, Paukkunen