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PDFs and Low x at LHeC
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Status of nPDF studies

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Unión Europea
Fondo Europeo
de Desarrollo Regional
"Una manera de hacer Europa"

CDR:

- F_2 data substantially reduce the uncertainties in DGLAP analysis;

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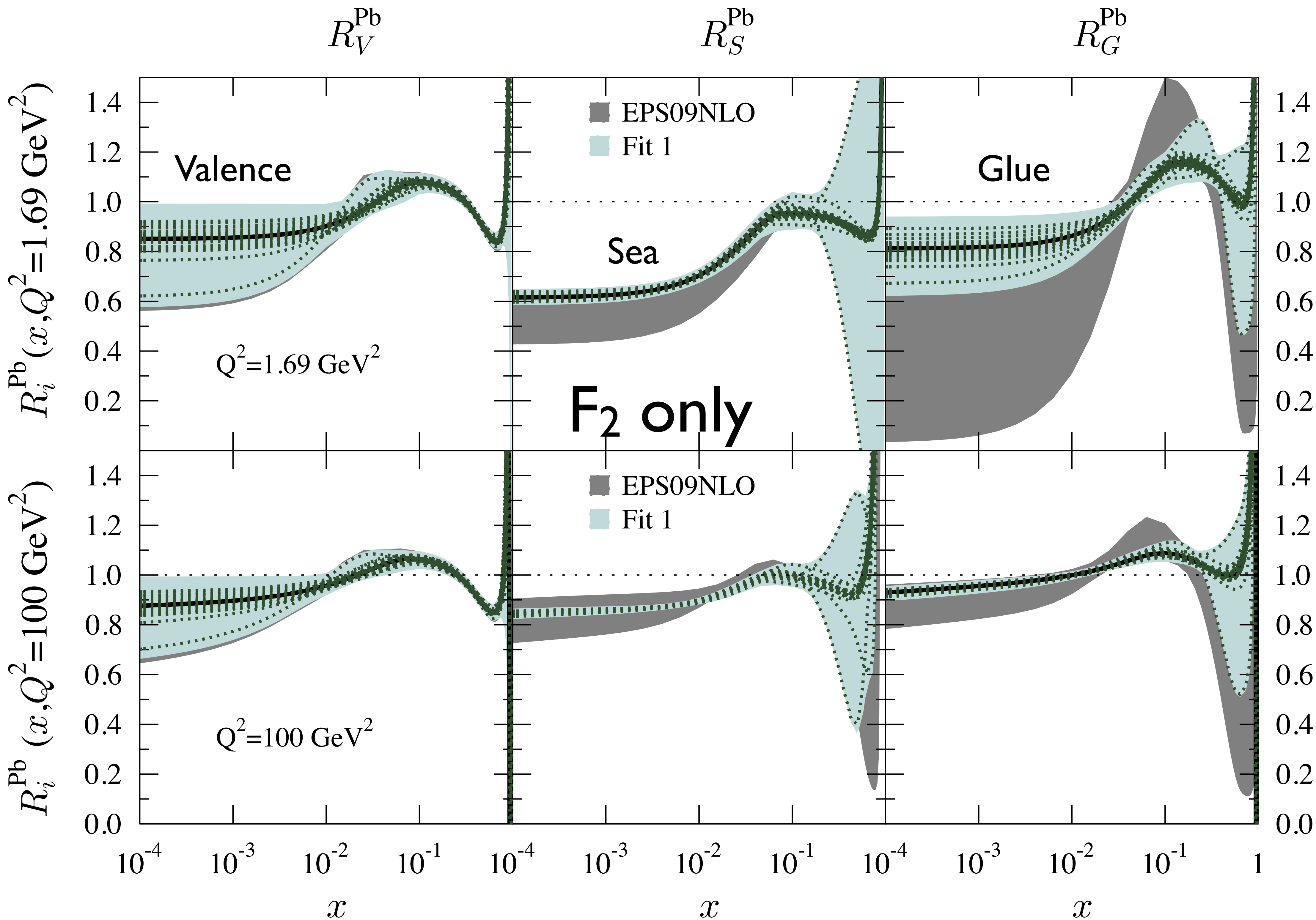

Electron-ion physics with the LHeC: 3. Physics case in eA.

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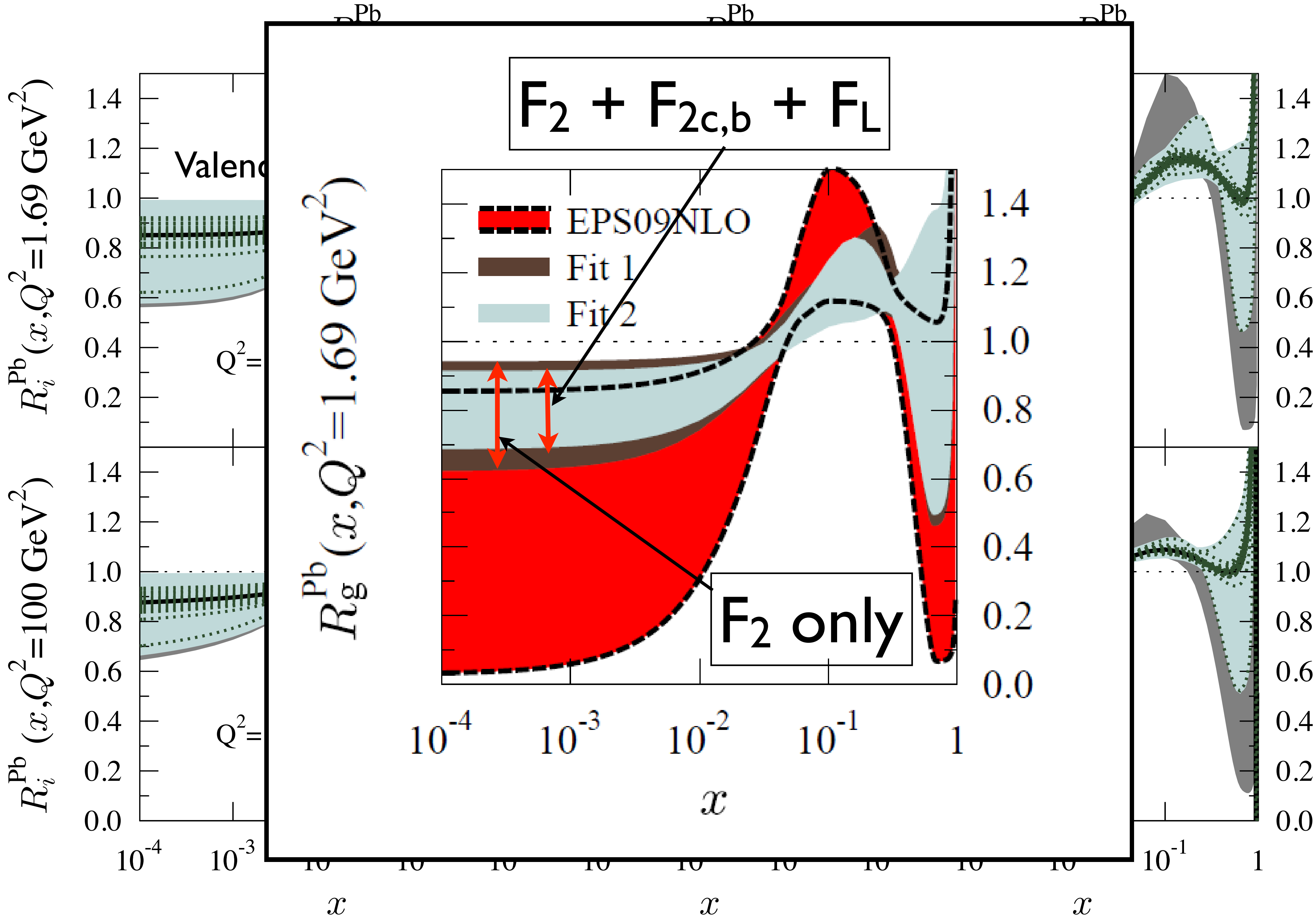


2014:

The LHeC & EIC pseudodata

- Samples of neutral-current DIS pseudodata for reduced cross-sections

$$\sigma_r = \frac{xQ^4}{2\pi\alpha_{\rm em}^2 Y_+}\frac{d^2\sigma}{dxdQ^2} \qquad Y_+ = 1 + (1-y)^2$$

$$\frac{d^2\sigma}{dxdQ^2} = \frac{4\pi\alpha_{\rm em}^2}{Q^4}\frac{1}{x}\left[xy^2F_1 + (1-y)F_2 \pm xy(1-\frac{y}{2})F_3\right]$$

was generated from using assuming:

E_{lepton} = 60 GeV, E_{proton} = 7000 GeV, E_{Pb} = 2750 GeV
E_{lepton} = 20 GeV, E_{proton} = 7000 GeV, E_{Pb} = 2750 GeV
E_{lepton} = 26.9 GeV, E_{proton} = 7000 GeV, E_{Pb} = 2750 GeV

in the kinematical window: $10^{-5} < x < 1$ & $2 < Q^2 < 10^5$ GeV^2

- For comparison, the foreseen EIC capabilities

E_{lepton} = 5 GeV, $E_{p,Au,Cu}$ = 50, 75, 100 GeV (Phase 1)
E_{lepton} = 20 GeV, $E_{p,Au,Cu}$ = 50, 75, 100 GeV (Phase 2)

in the kinematical window: $10^{-3} < x < 1$ & $Q^2 < 500$ GeV^2

- Nuclear effects in cross sections “EPS09 based”

2014:

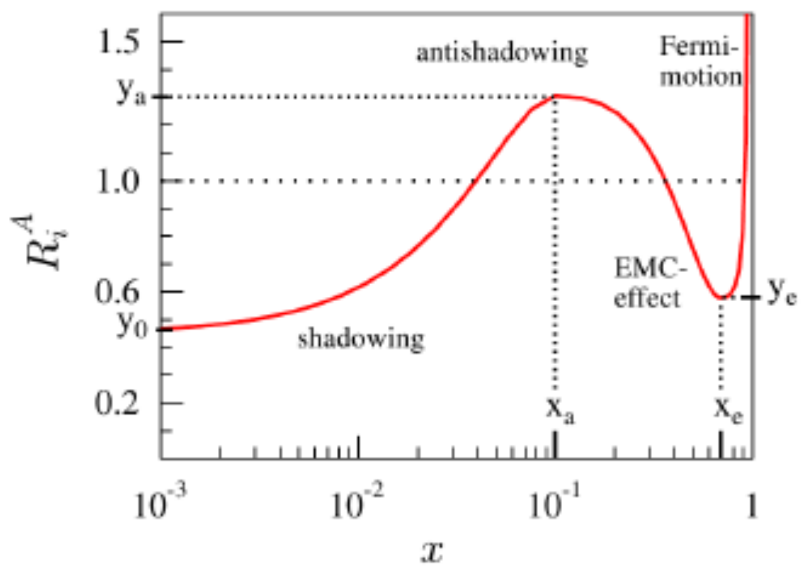
Framework of the pQCD analysis

- The cross-sections are computed at NLO with the SACOT prescription for the heavy quark treatment

- Parametrize the nuclear modifications at Q=1.3 GeV, CTEQ6.6 as the baseline

$$f_k^{\mathrm{proton},A}(x,Q^2) = R_k^A(x,Q^2)\, f_k^{\mathrm{proton}}(x,Q^2)$$

$R_V^A(x,Q_0^2)$	for all valence quarks
$R_S^A(x,Q_0^2)$	for all sea quarks
$R_G^A(x,Q_0^2)$	for gluons



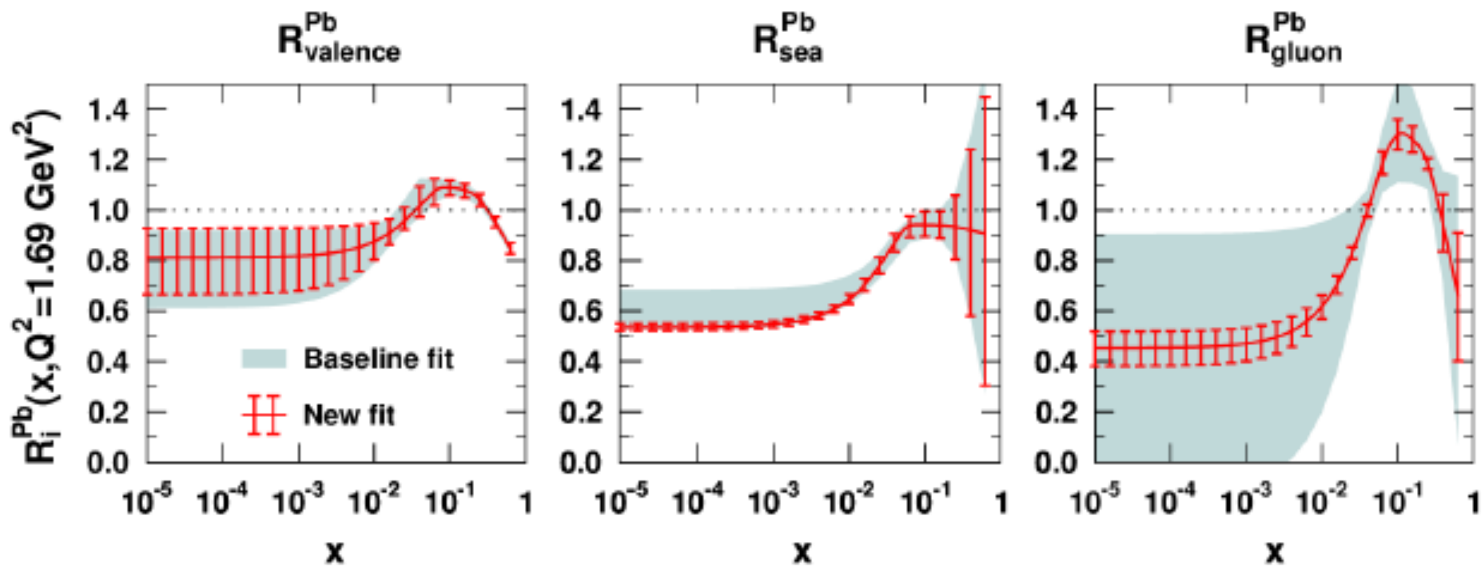
- The LHeC/EIC pseudodata are added on top of all other DIS, Drell-Yan, and inclusive pion data, that were included in EPS09.

- Standard χ^2-fit with Hessian error analysis with $\Delta\chi^2 = 25$

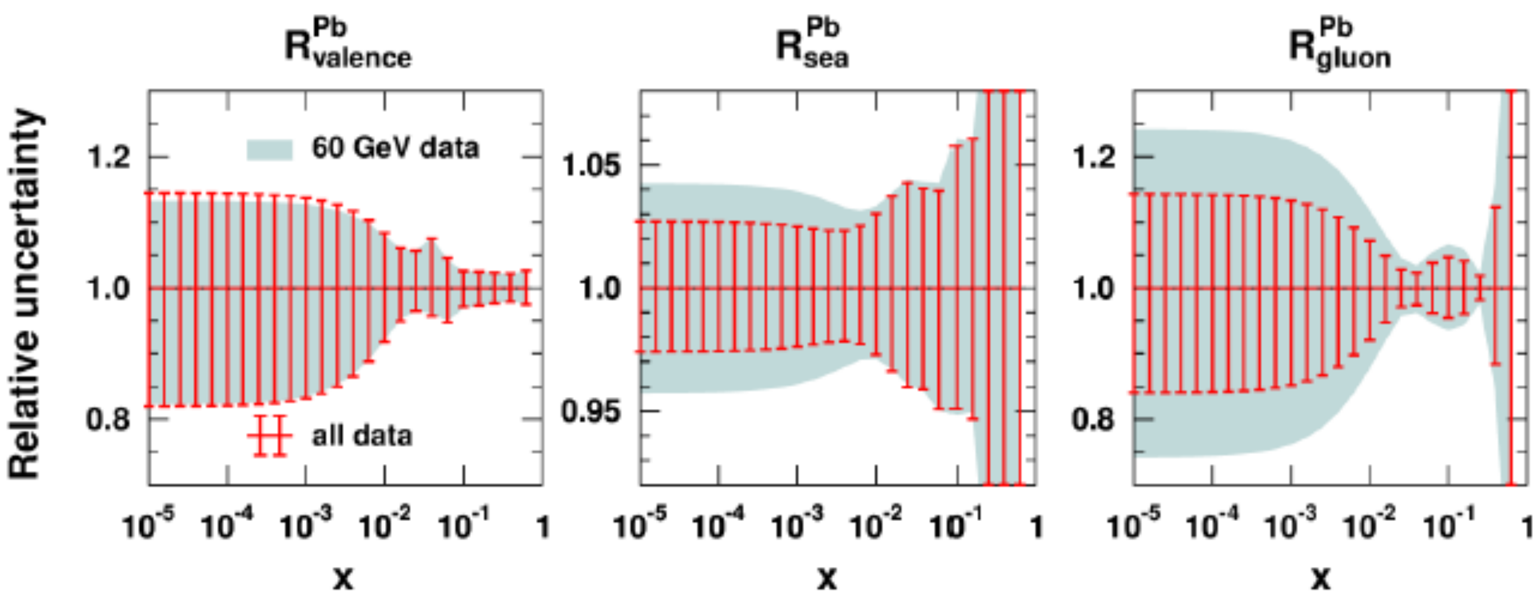
2014:

Inclusion of the low-energy data

- Include also the data from the E_{lepton} = 20GeV and E_{lepton} = 26.9GeV runs



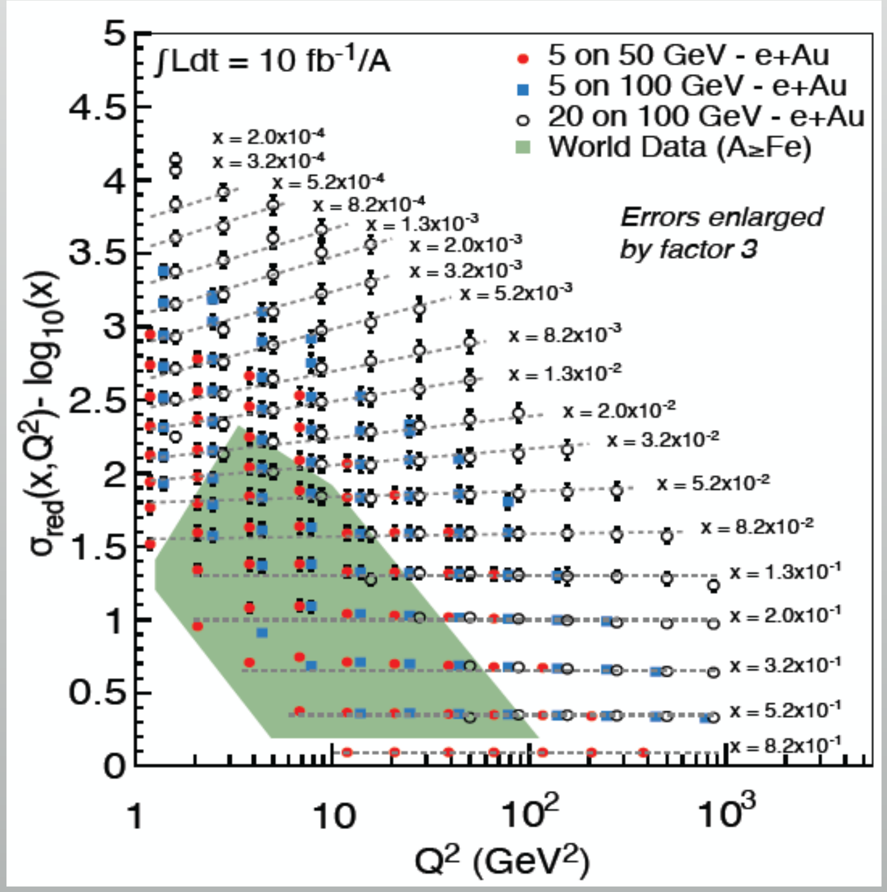
- Relative uncertainties compared to the case with E_{lepton} = 60GeV data only

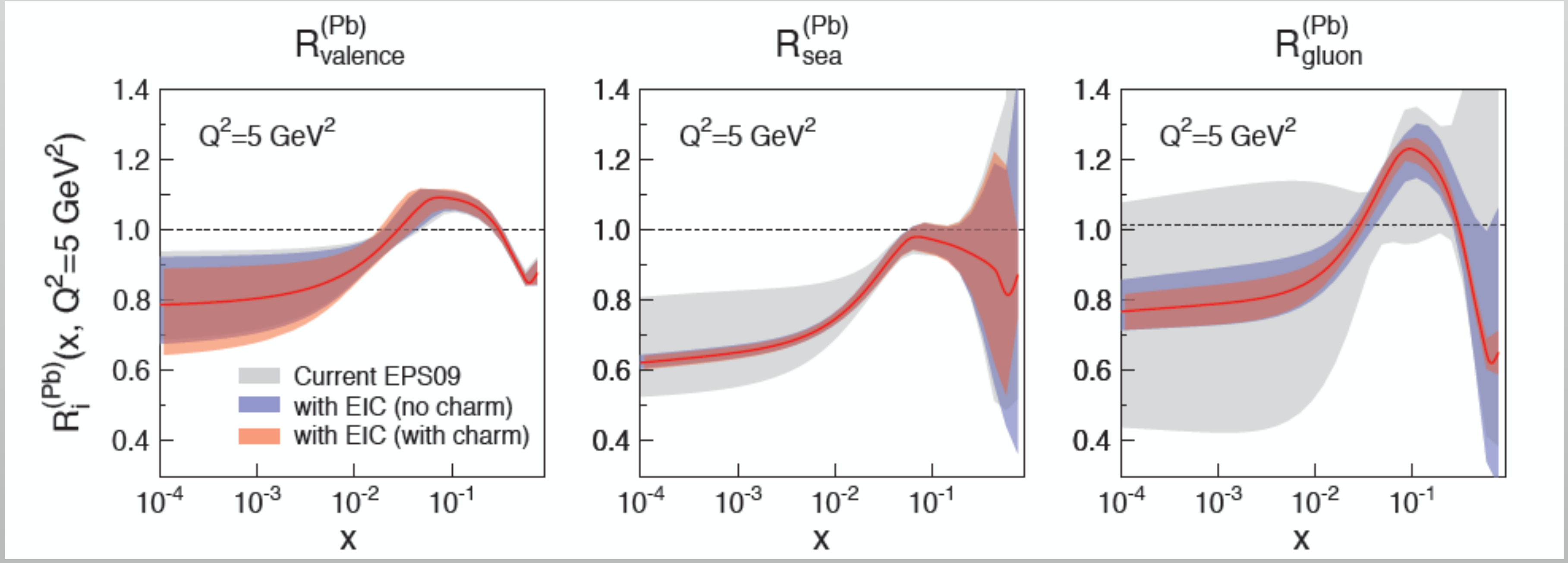


- Even larger reduction in the small-x uncertainties – though not dramatic

Parametrisation bias:

- Sensitivity to the mathematical form of the initial conditions is a well-known issue in proton PDFs: NNPDF, PDF4LHC recommendation of comparing different sets, HERAPDF2.0 studies, …
- In our case: determination of nPDFs beyond (pseudo)data…





EIC example

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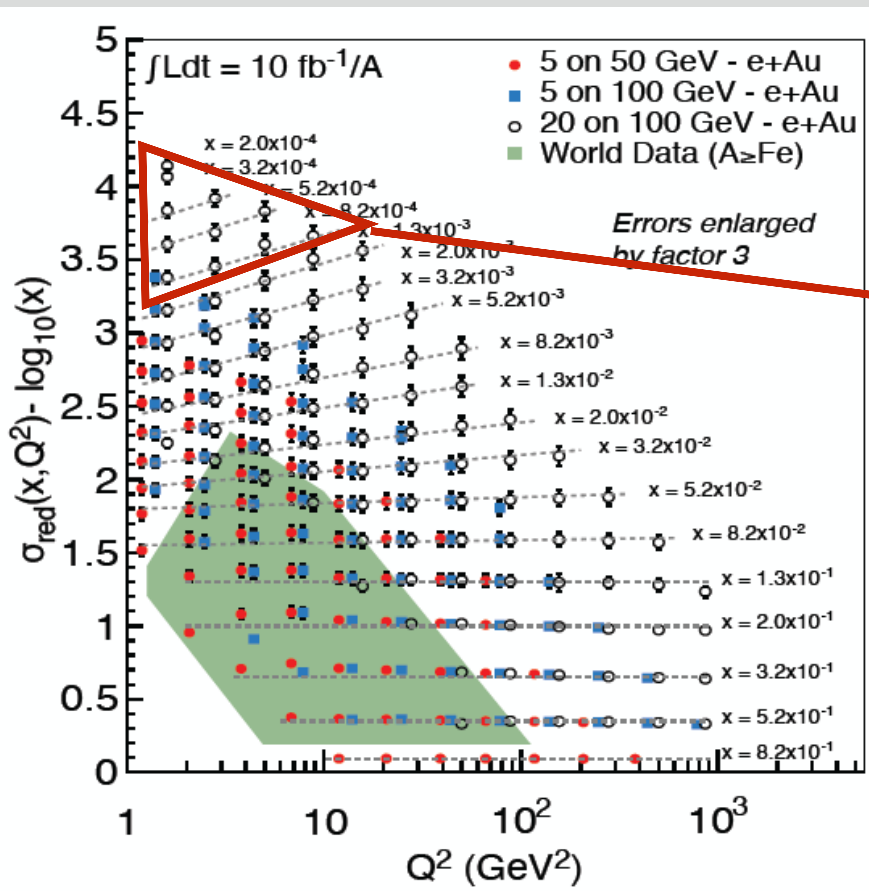
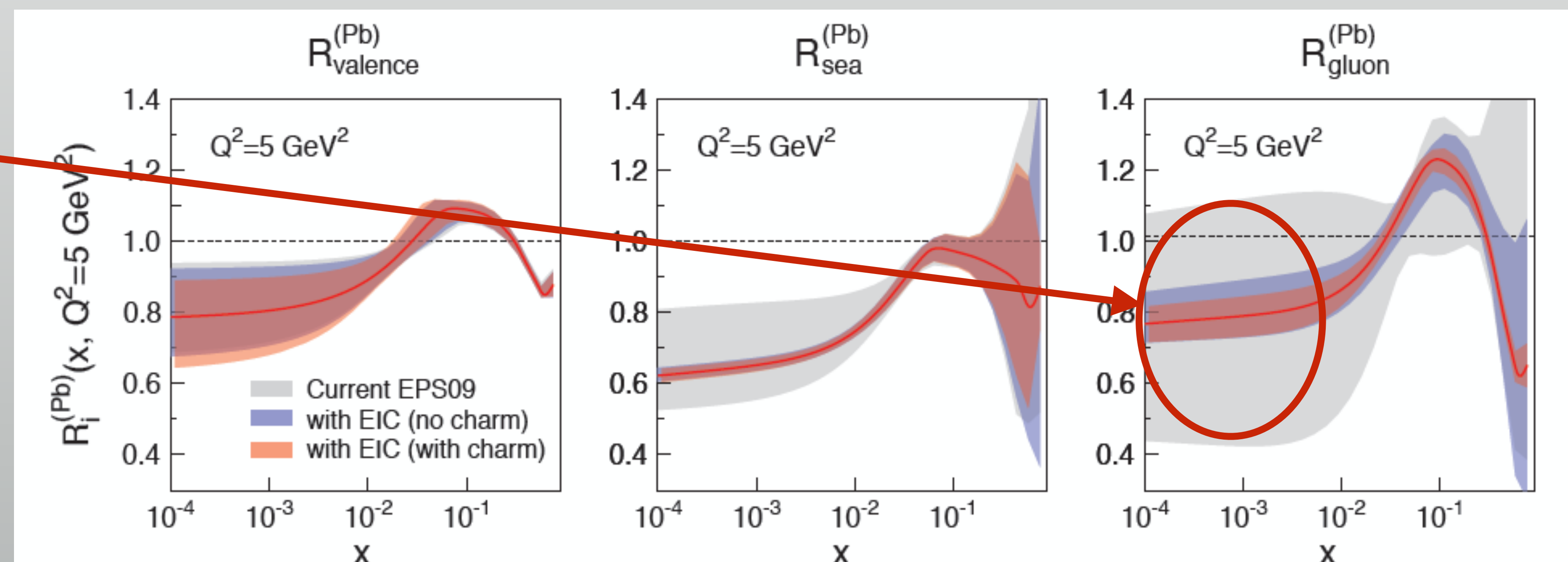


How?: mainly dictated by the shape of ICs



EIC example

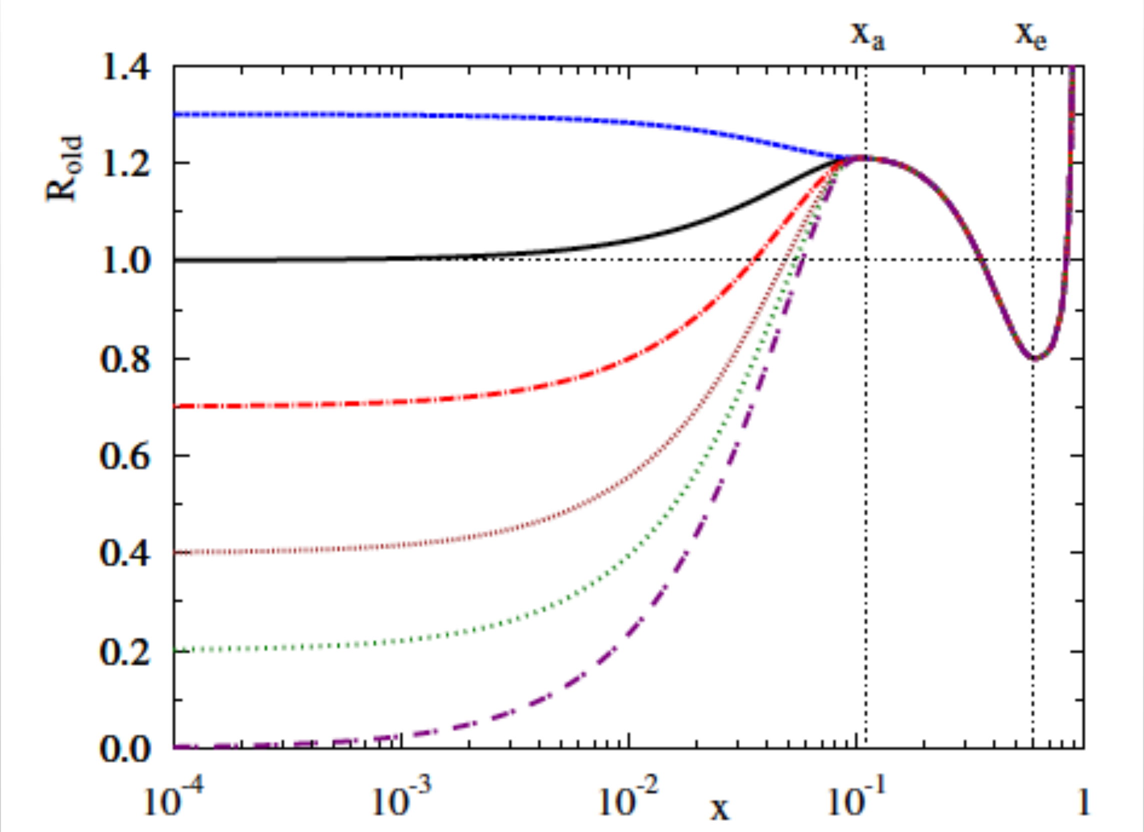
$$\frac{\partial R^A_{F_2}(x,Q^2)}{\partial \log Q^2} \approx \frac{10\alpha_s}{27\pi} \frac{xg(2x,Q^2)}{\frac{1}{2}F_2^{\rm D}(x,Q^2)} \left\{ R^A_g(2x,Q^2) - R^A_{F_2}(x,Q^2) \right\}$$

hep-ph/0201256

Parametrisation bias:

- An idea to deal with it in the EPS09 framework:

$$R_{\rm old}(x) = \begin{cases} a_0 + (a_1 + a_2 x)\left(e^{-x} - e^{-x_a}\right) & x \le x_a \\ b_0 + b_1 x + b_2 x^2 + b_3 x^3 & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \le x \le 1, \end{cases}$$



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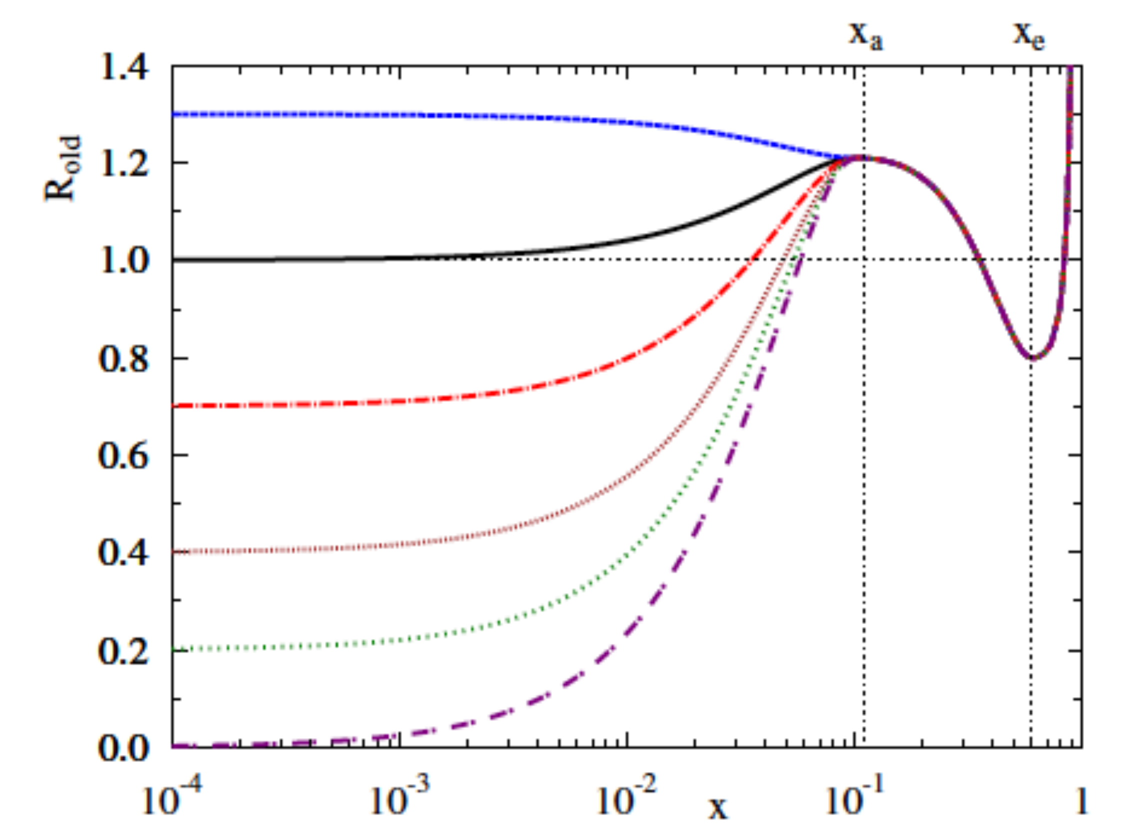
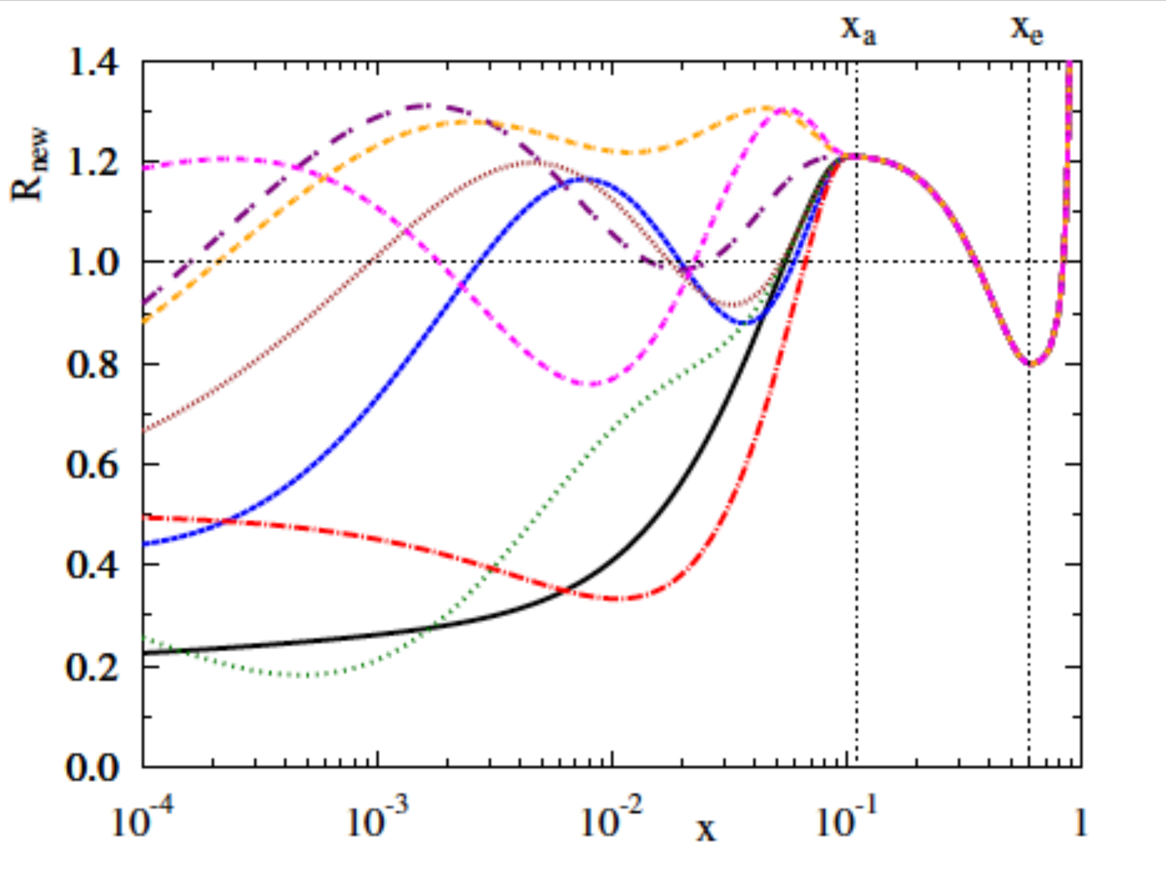
3 for LHeC

$$R(x \le x_a) = a_0 + a_1 (x - x_a)^2 + x(x_a - x)\left[\sum_{k=1}^{4} a_{k+2} \log\left(\frac{x}{x_a}\right)^k\right]$$

- 15 (orig.) → 19 (new) parameters.



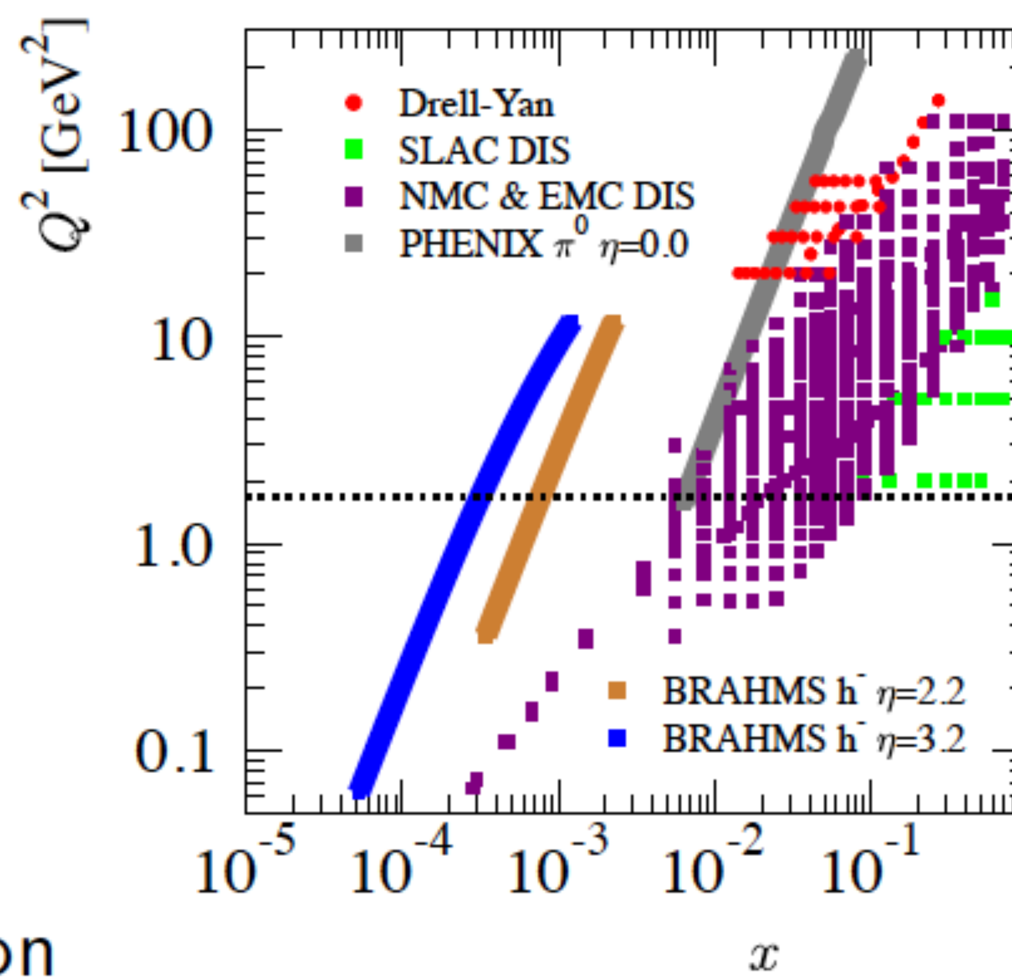


New fit framework:

Paukkunen

- Include the same data (DIS, Drell-Yan, inclusive π^0) as in EPS09 (no LHC data yet) plus LHeC (neutral current) pseudo data.
- CTEQ6.6 as baseline (doesn't really matter which one)
- Flavour-independent nuclear modifications at $Q_0 = 1.3\,\mathrm{GeV}$

$R_V(x, Q_0)$ for both valence quarks
$R_S(x, Q_0)$ for light sea quarks
$R_G(x, Q_0)$ for gluons

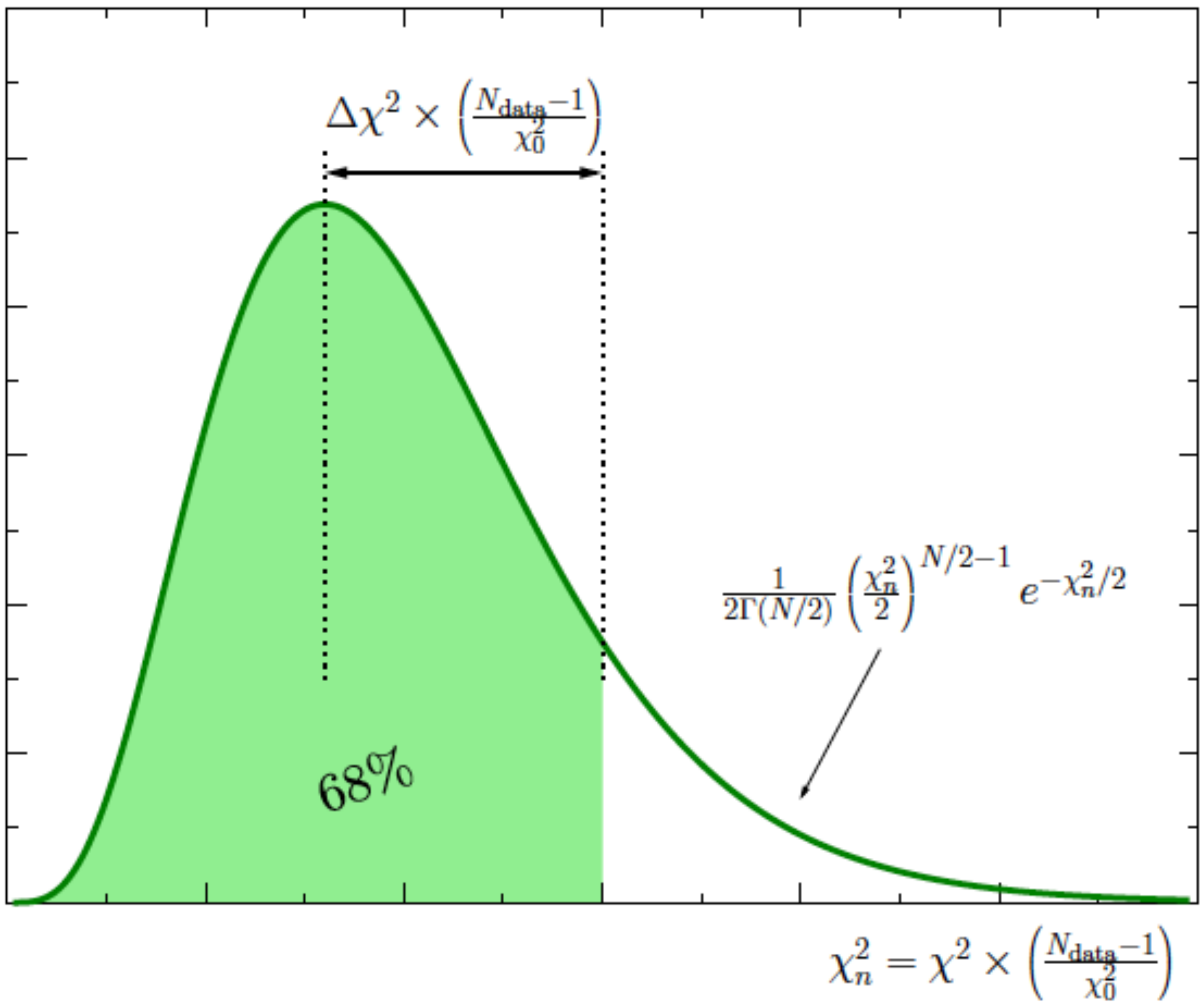


- Charged-current data will be added later on to study the flavour dependence
- Cross-sections at NLO in the SACOT heavy-quark scheme (as CTEQ6.6)
- Robust Levenberg-Marquardt minimization method

New fit framework:

Paukkunen

Standard Hessian uncertainty analysis (a la CTEQ, MSTW,...) with $\Delta\chi^2$ determined from the expected behaviour of probability distribution for the global χ^2

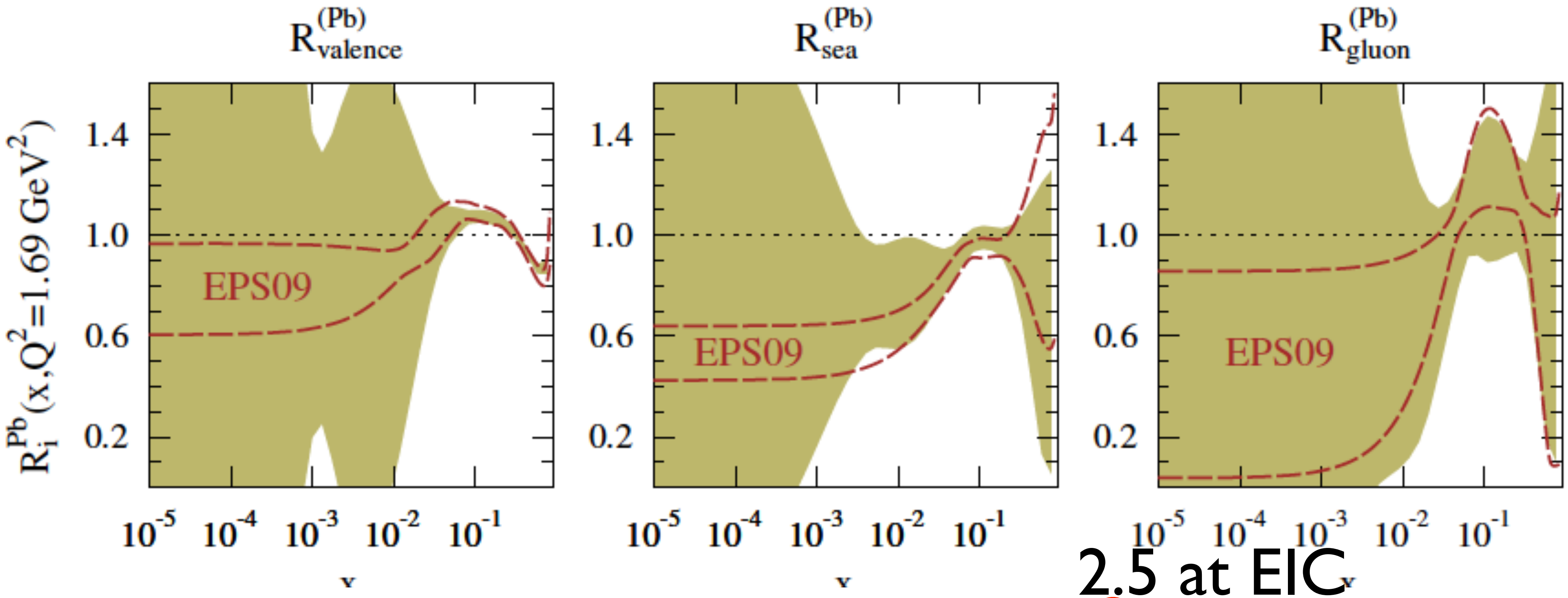


Gives $\Delta\chi^2 \approx 17$ (without or with the pseudodata)

New fit framework:

Paukkunen

The baseline fit using the new fit functions: no control over small x!



2.5 at EIC

The lower bound restricted here by $F_L(Q^2 = 2\,\mathrm{GeV}^2, x > 10^{-5}) > 0$

Maybe against "physical intuition" (small-x theory predicts shadowing, $R_i < 1$), but consistent with the data.

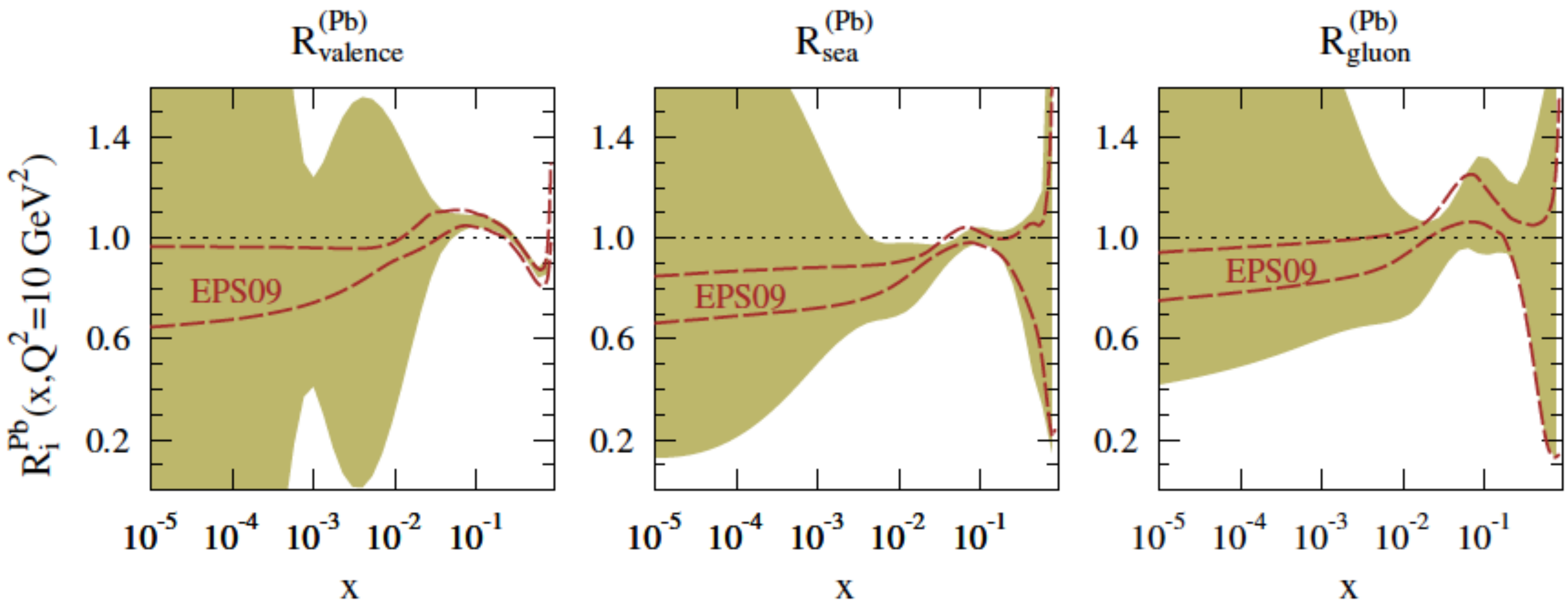
E.g. in EPS09, small-x shadowing was essentially built in

New fit framework:

Paukkunen

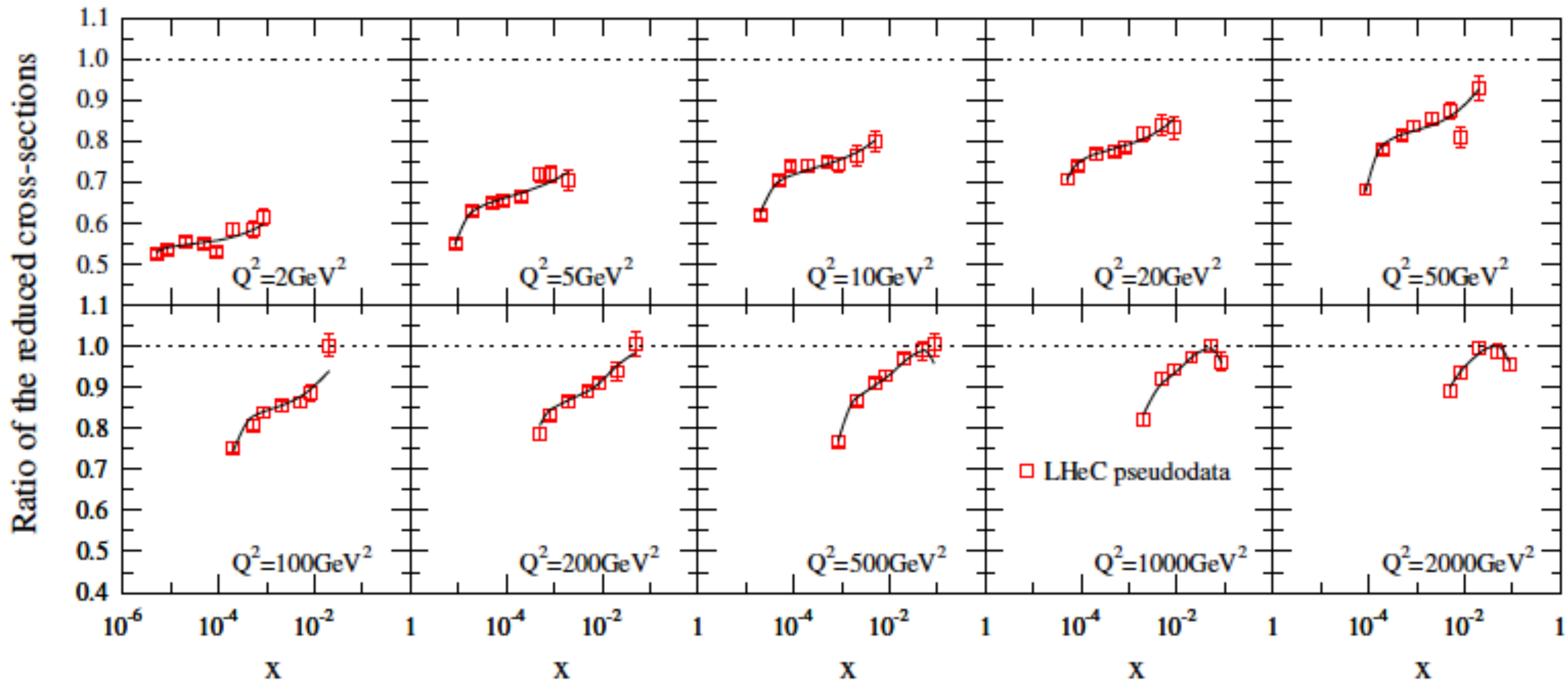
The baseline fit using the new fit functions: no control over small x!

The Q^2 dependence partly smooths out the differences in gluons



LHeC: pseudodata

• Simulation: NC(+CC+c,b not yet used) with systematic uncertainties from a complete simulation.



Checked that $\chi^2/N_{\rm data}$ to the underlying truth (=EPS09 ;)) fluctuates about unity depending on the random numbers that got chosen

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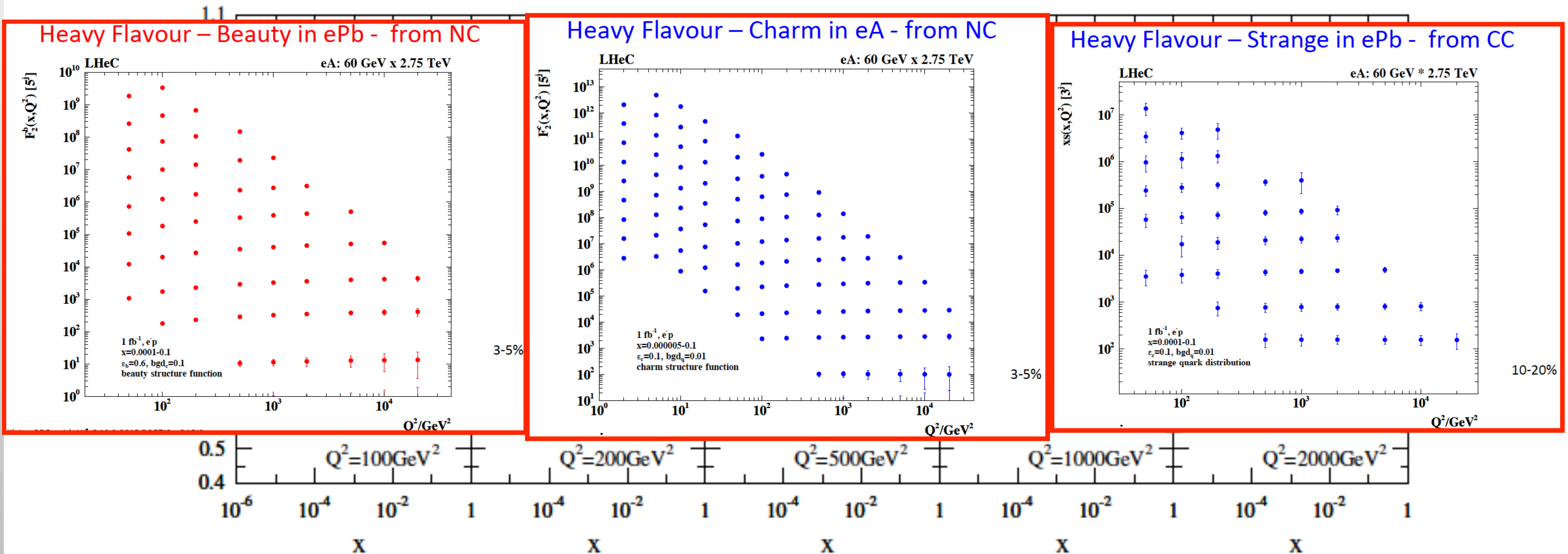

M. Klein at POETIC6

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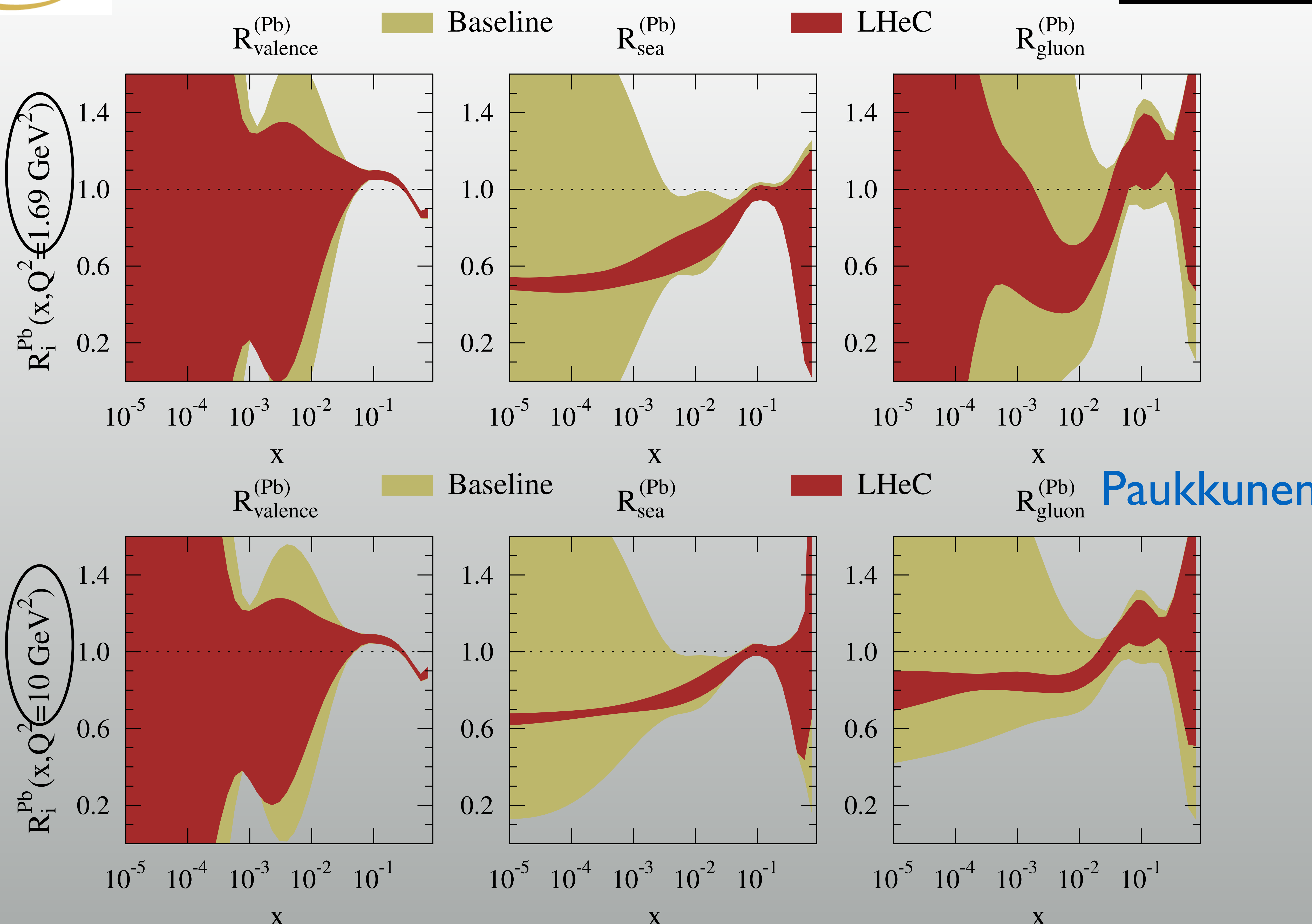
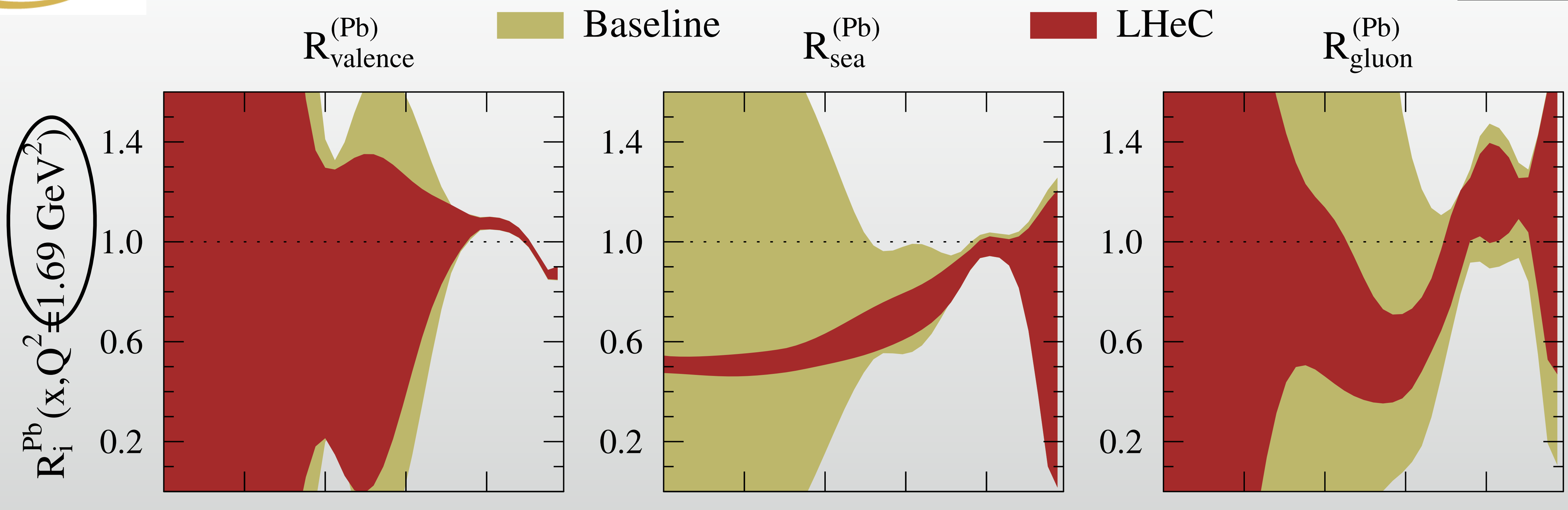
LHeC: nPDFs

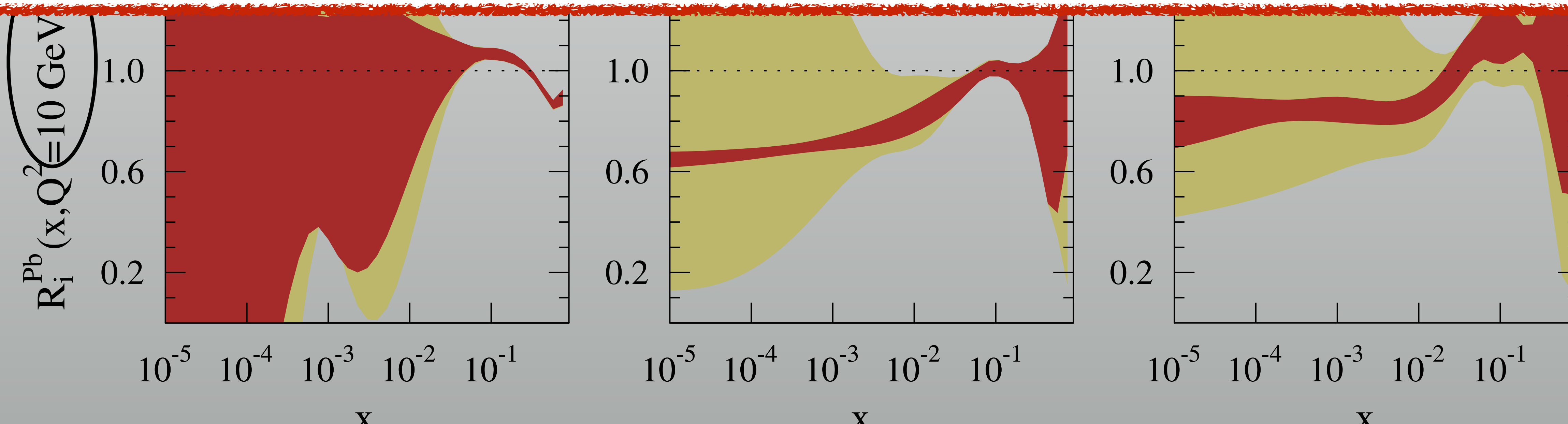


Baseline
LHeC
$R^{(Pb)}_{valence}$
$R^{(Pb)}_{sea}$
$R^{(Pb)}_{gluon}$
$R^{Pb}_{i}(x,Q^2=1.69\ GeV^2)$
$R^{Pb}_{i}(x,Q^2=10\ GeV^2)$
1.4
1.0
0.6
0.2
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}
x
Paukkunen

LHeC: nPDFs



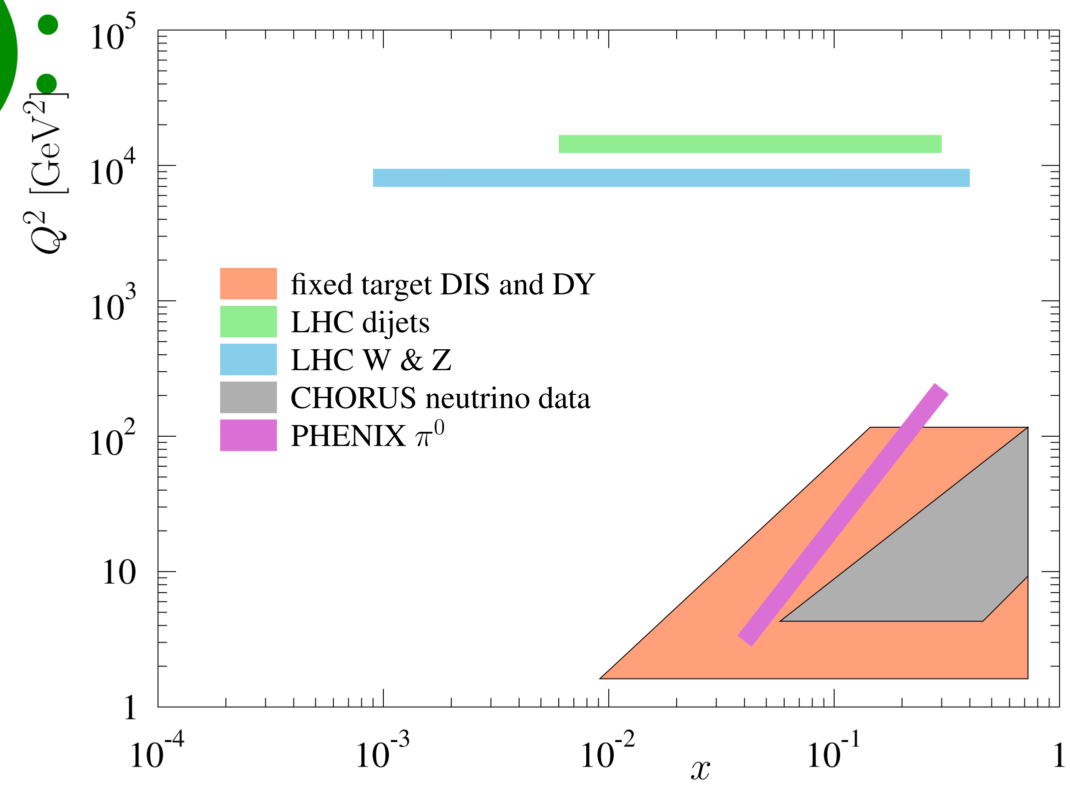
- Substantial reduction of uncertainties.
- EICs provide the nPDFs with the precision required for the heavy-ion programmes at RHIC, LHC and future colliders.

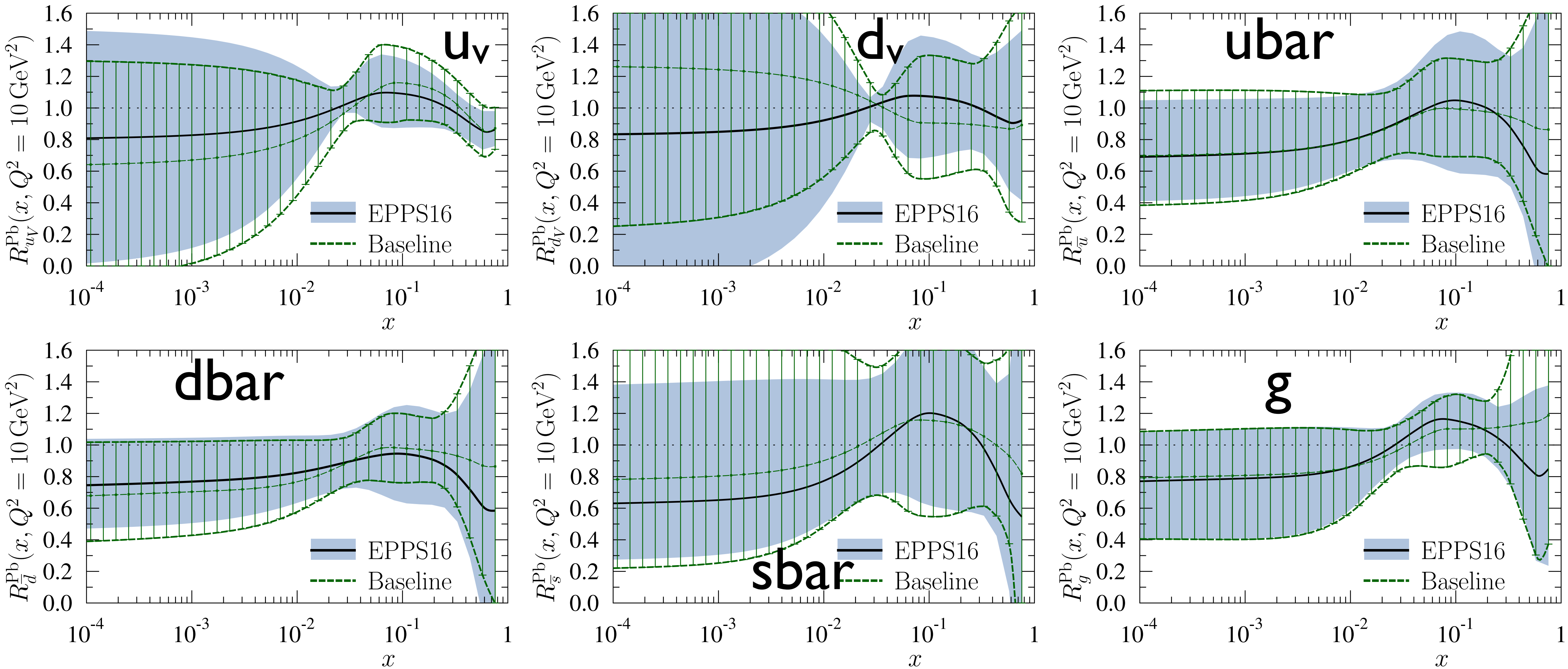


2017 (I):

- New setup EPPS16 [1612.05741] including baseline (fixed target DIS, DY, RHIC) plus neutrino and LHC (dijet, W, Z) pPb data. More flexible parametrisation, GM-VFNS, $R_u \neq R_d$.

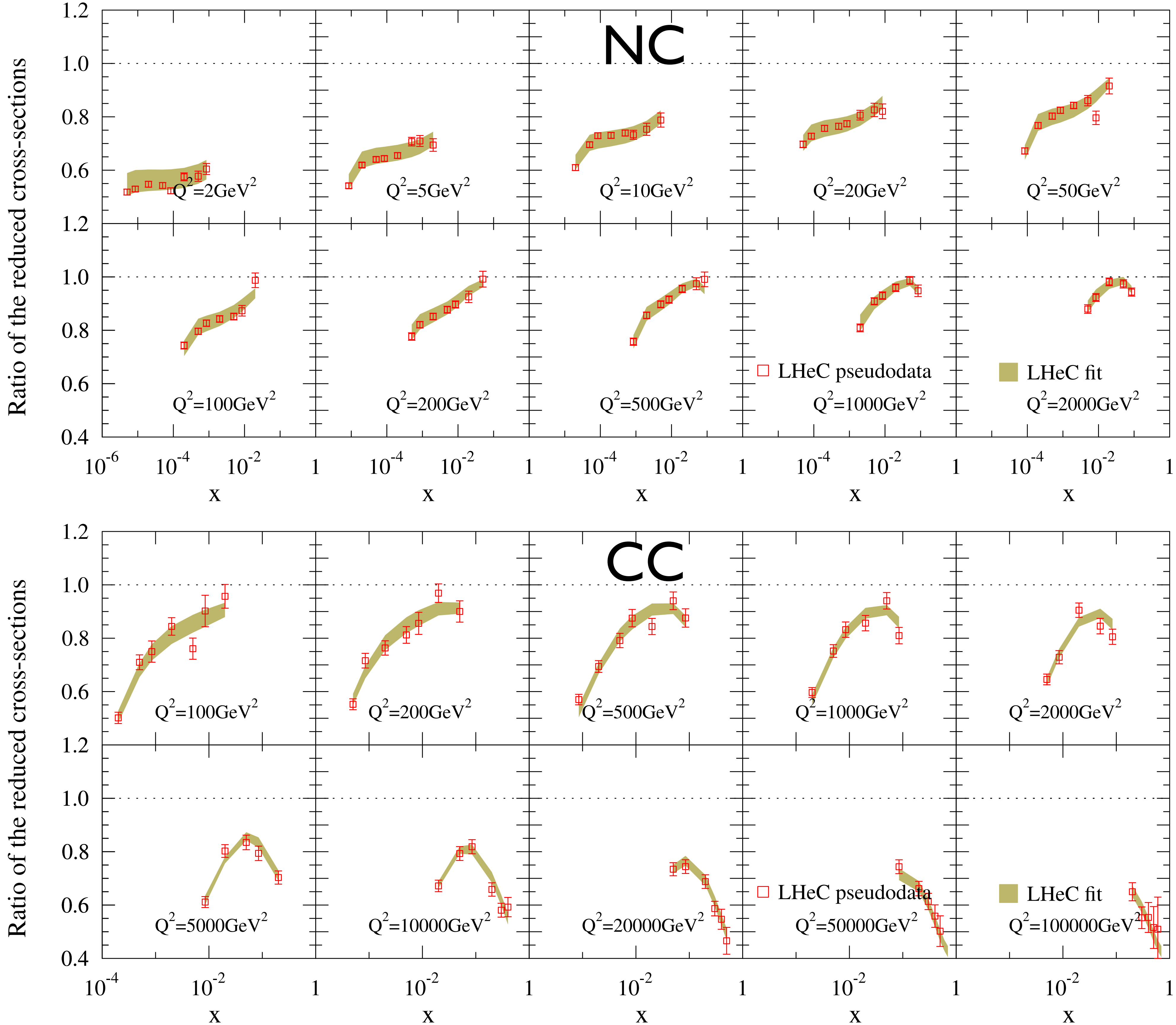
$$f_i^{p/A}(x,Q^2) = \boxed{R_i^A(x,Q^2)} f_i^p(x,Q^2)$$





2017 (II):

- Including eA (60+2760) NC and CC pseudodata reduces the uncertainties (notably on g), but u,d decomposition difficult (factor 2Z/A-1). [Paukkunen]



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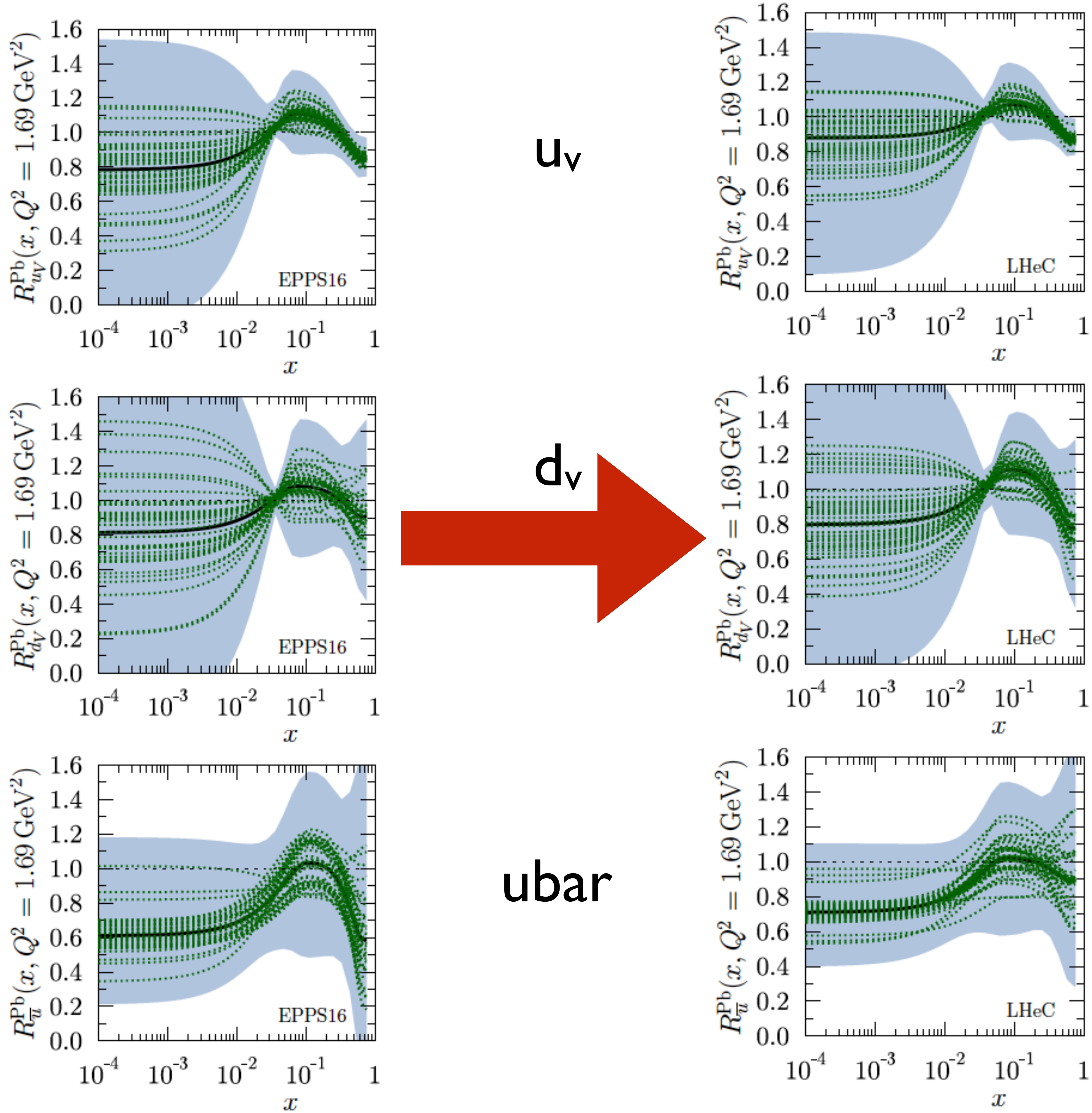

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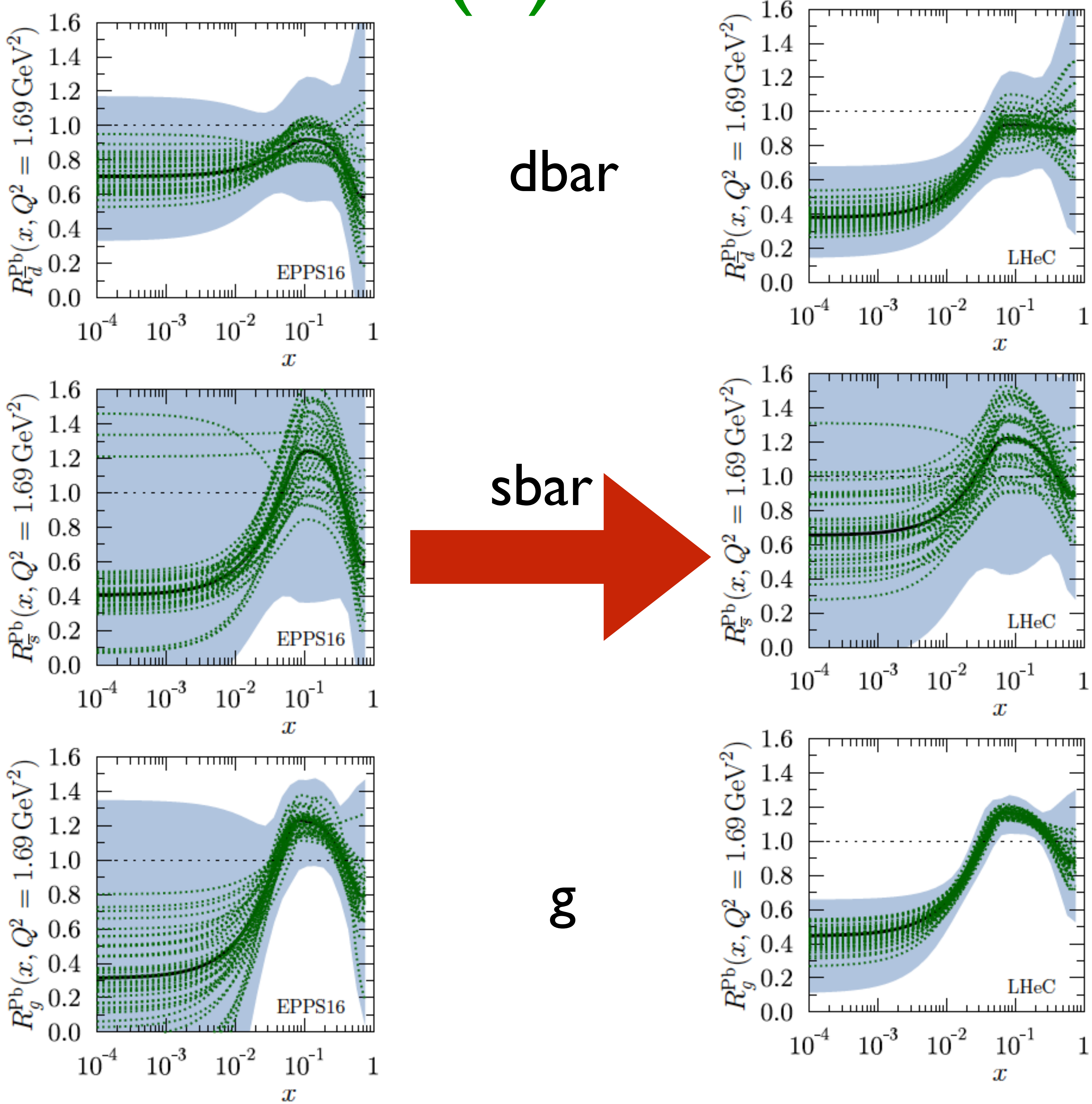


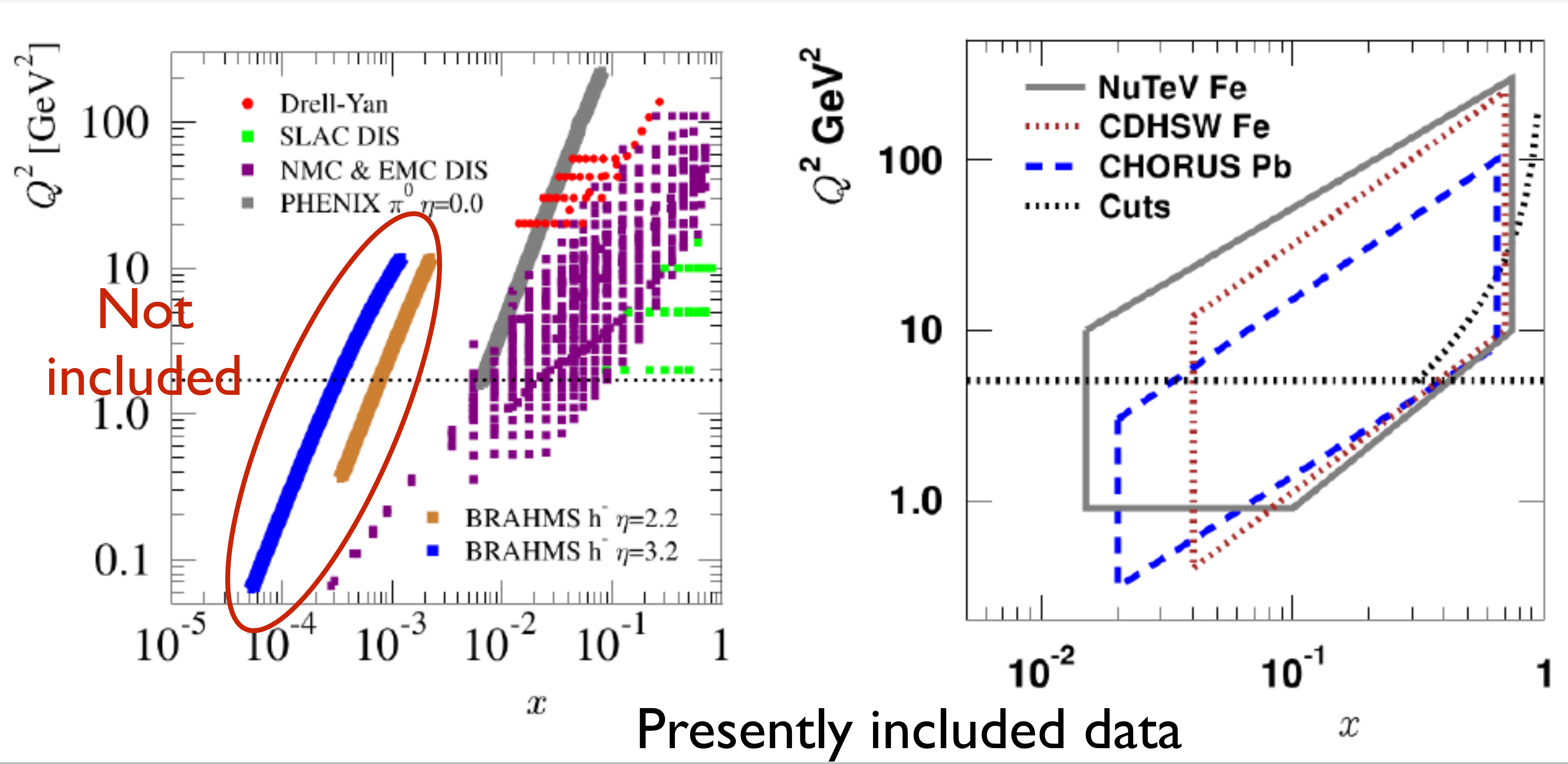
LHeC

Summary:

YEAR	BASELINE	SETS
CDR	EPS09 + 1 p., ZM-VFNS	NC F_2 + F_L + c,b
2014	EPS09 + 1 p., GM-VFNS (SACOT)	NC σ_{red}, three energies, not c,b
2015	EPS09 + more flexibility at small x, GM-VFNS (SACOT)	NC σ_{red}, top energy, not c,b
2017	EPPS16, GM-VFNS (SACOT)	NC + CC σ_{red}, top energy, not c,b

- Done by Max, **Hannu** and me.
- Additional possibilities: Pb fit e.g. using xFitter, use (NNLO) jets for the glue (see arXiv:1703.02864).

Available sets:



- Not enough data for any single nuclei: A-dependent parameters in either the ratios or the PDFs.
- Valence for $x>10^{-2}$ constrained by DIS, sea for $x>10^{-2}$ by DIS+DY, glue for x~0.1 by DIS Q^2-evolution and RHIC pions.

Available sets:

SET		HKN07 PRC76 (2007) 065207	EPS09 JHEP 0904 (2009) 065	DSSZ PRD85 (2012) 074028	nCTEQ15 PRD93 (2016) 085037	KA15 PRD93 (2016) 014036	EPPS16 EPJC C77 (2017)163
data	eDIS	✔	✔	✔	✔	✔	✔
	DY	✔	✔	✔	✔	✔	✔
	π^0	✘	✔	✔	✔	✘	✔
	νDIS	✘	✘	✔	✘	✘	✔
	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, no EMC for gluons	$\Delta\chi^2$=50, ratios, huge shadowing-antishadowing	$\Delta\chi^2$=30, ratios, medium-modified FFs for π^0	$\Delta\chi^2$=35, PDFs, flavour sep., not enough sensitivity	PDFs, deuteron data included	$\Delta\chi^2$=52, ratios, LHC pPb data

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data	eDIS	✔	✔	✔	✔	✔	✔
	DY	✔	✔	✔	✔	✔	✔
	π^0	✘	✔	✔	✔	✘	✔
	νDIS	✘	✘	✔	✘	✘	✔
	pPb	✘	✘	✘	✘	✘	✔
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• Centrality

LHeC scenarios:

For F_2

config.	E(e)	E(N)	N	∫L(e⁺)	∫L(e⁻)	|Pol|	$L/10^{32}$	P/MW	years	type
A	20	7	p	1	1	-	1	10	1	SPL
B	50	7	p	50	50	0.4	25	30	2	RR hiQ^2
C	50	7	p	1	1	0.4	1	30	1	RR lo x
D	100	7	p	5	10	0.9	2.5	40	2	LR
E	150	7	p	3	6	0.9	1.8	40	2	LR
F	50	3.5	D	1	1	--	0.5	30	1	eD
G	50	2.7	Pb	10^{-4}	10^{-4}	0.4	10^{-3}	30	1	ePb
H	50	1	p	--	1	--	25	30	1	lowEp
I	50	3.5	Ca	$5 \cdot 10^{-4}$		?	$5 \cdot 10^{-3}$	?	?	eCa

- For F_L: 10, 25, 50 + 2750 (7000); $Q^2 \leq sx$; Lumi=5,10,100 pb^{-1} respectively; charm and beauty: same efficiencies in ep and eA.