2015 LHeC Workshop
Chavannes-de-Bogis, June 26th 2015

Nuclear PDFs at the LHeC

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for the LHeC Study group, http://cern.ch/lhec

Contents:

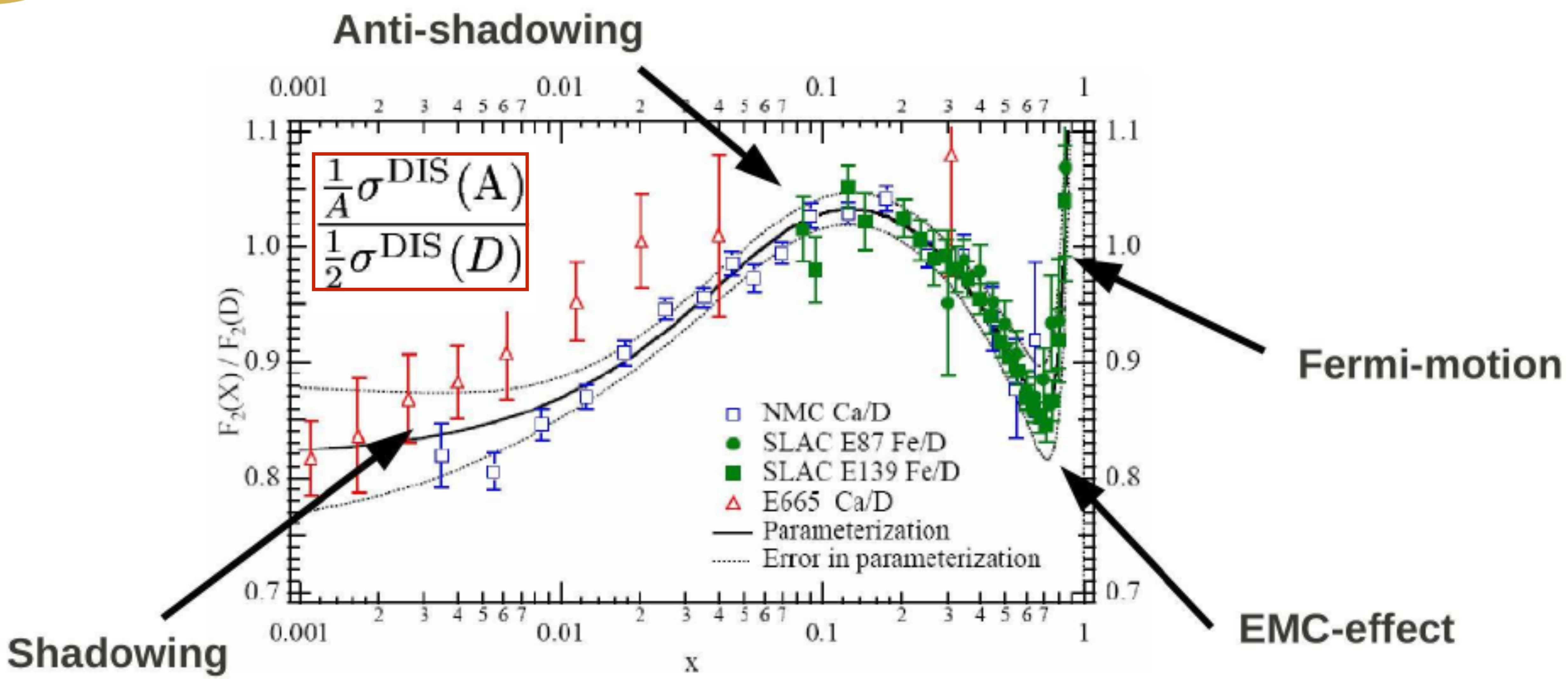
1. Present status.

2. The issue of the initial conditions.

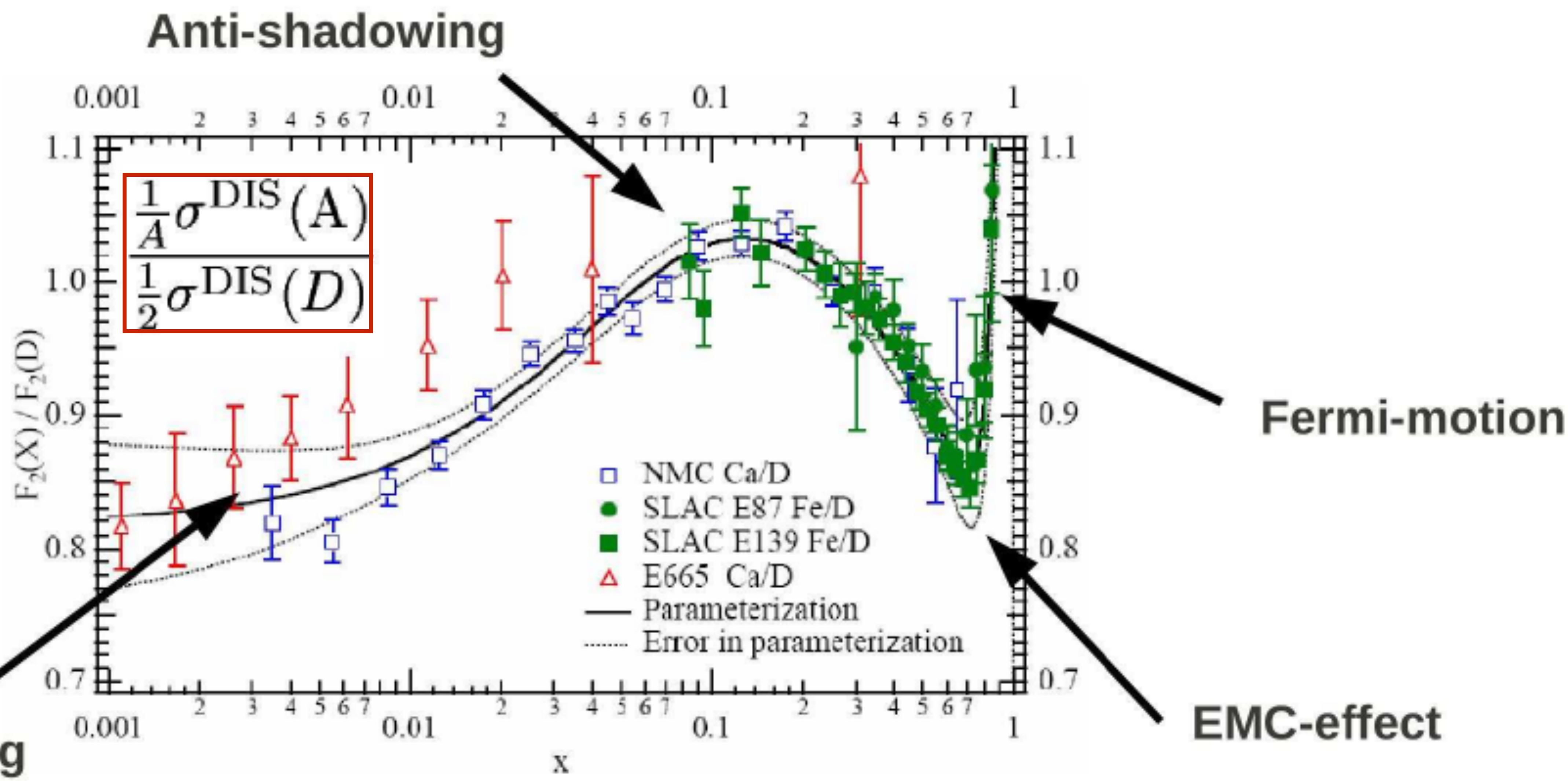
3. Results of the inclusion of LHeC pseudodata.

4. Conclusions and outlook.

Motivation:


Anti-shadowing
Fermi-motion
EMC-effect
Shadowing
$\frac{\frac{1}{A}\sigma^{\mathrm{DIS}}(A)}{\frac{1}{2}\sigma^{\mathrm{DIS}}(D)}$
NMC Ca/D
SLAC E87 Fe/D
SLAC E139 Fe/D
E665 Ca/D
Parameterization
Error in parameterization
F2(X) / F2(D)
x

Motivation:



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

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

Nuclear PDFs, obeying the standard DGLAP — **Usual perturbative coefficient functions**

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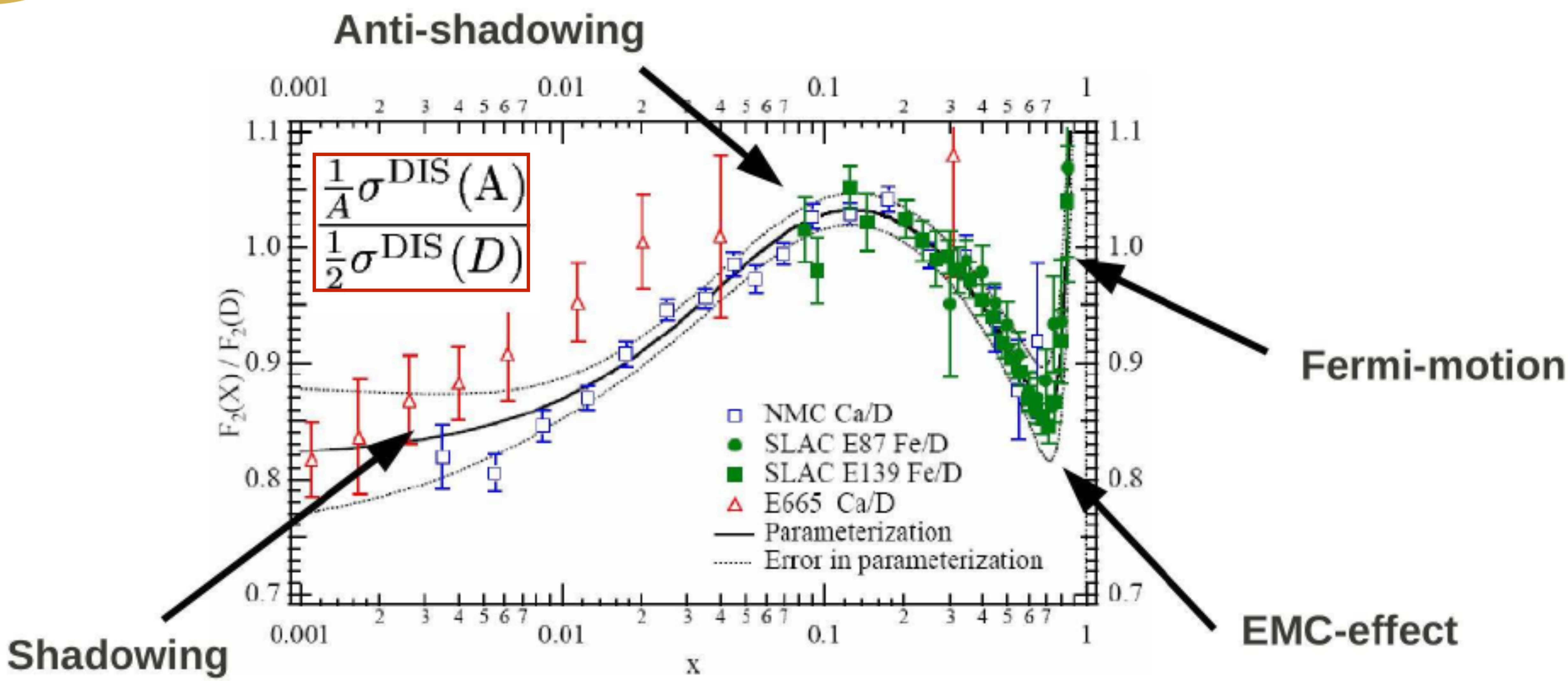

- Bound nucleon $\neq$ free nucleon: search for process independent nPDFs that realise this condition.

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

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

Contemporary sets:

- Most commonly used sets:

	HKN07	EPS09	DSSZ	nCTEQ prelim.
Ref.	Phys. Rev. C76 (2007) 065207	JHEP 0904 (2009) 065	Phys.Rev. D85 (2012) 074028	arXiv:1307.3454
Order	LO & NLO	LO & NLO	NLO	NLO
Neutral current e+A / e+d DIS	√	√	√	√
Drell-Yan dileptons in p+A / p+d	√	√	√	√
RHIC pions in d+Au / p+p		√	√	
Neutrino-nucleus DIS			√	
Q^2 cut in DIS	1GeV	1.3GeV	1GeV	2GeV
# of data points	1241	929	1579	708
Free parameters	12	15	25	17
Error sets available		√	√	√
Error tolerance $\Delta\chi^2$	13.7	50	30	35
Baseline	MRST98	CTEQ6.1	MSTW2008	CTEQ6M
Heavy quark treatment	ZM_VFNS	ZM_VFNS	GM_VFNS	GM_VFNS

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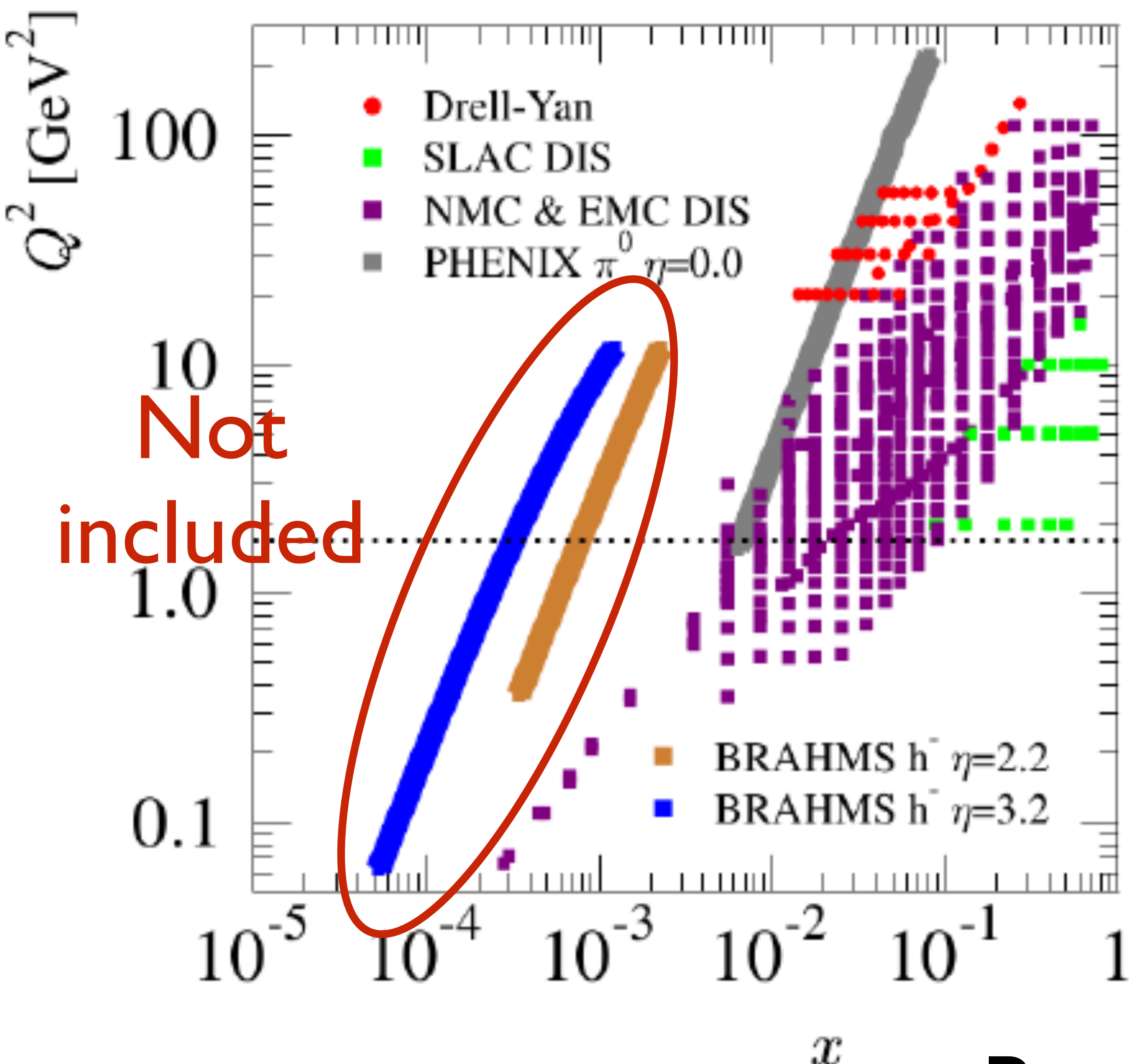
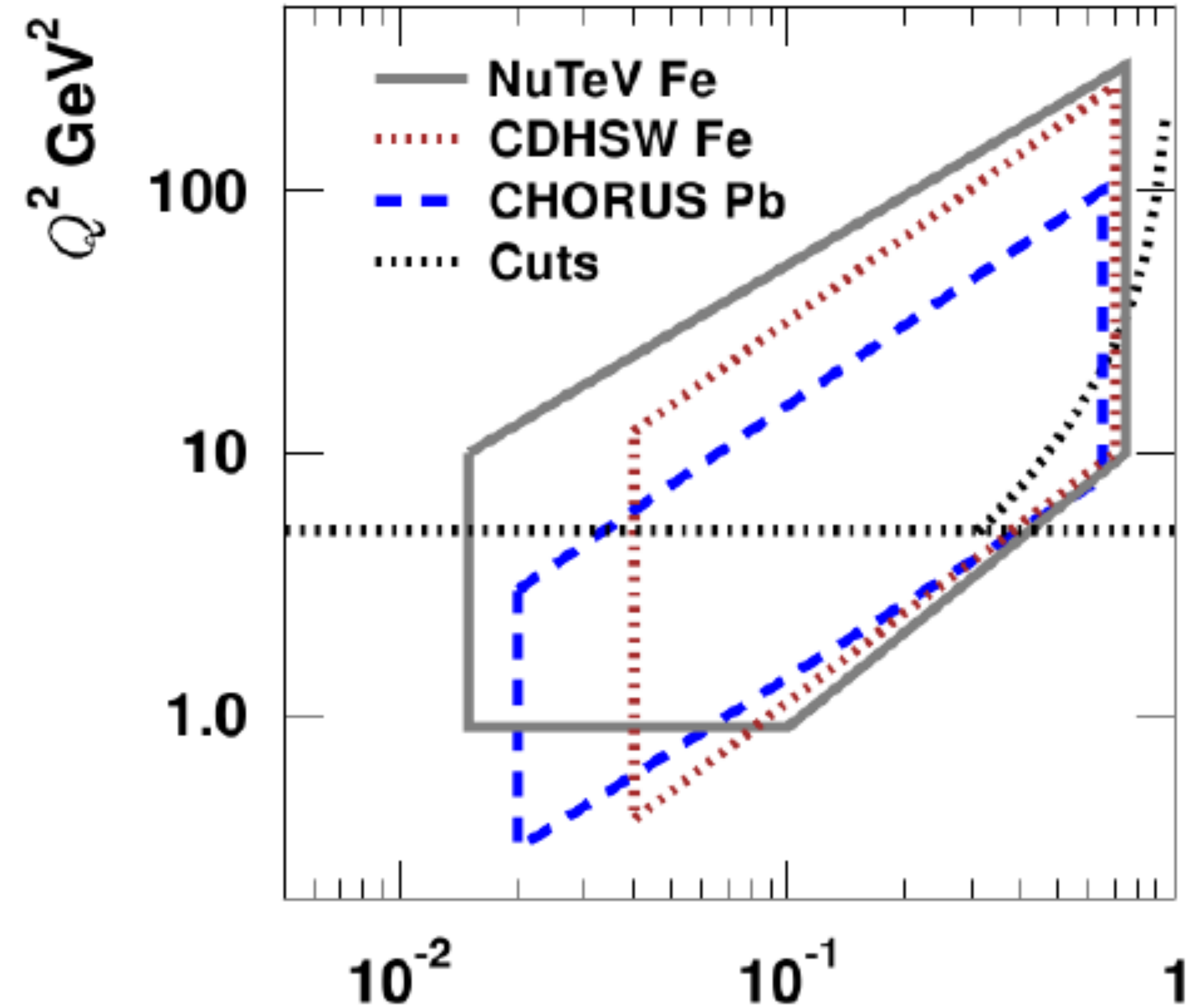
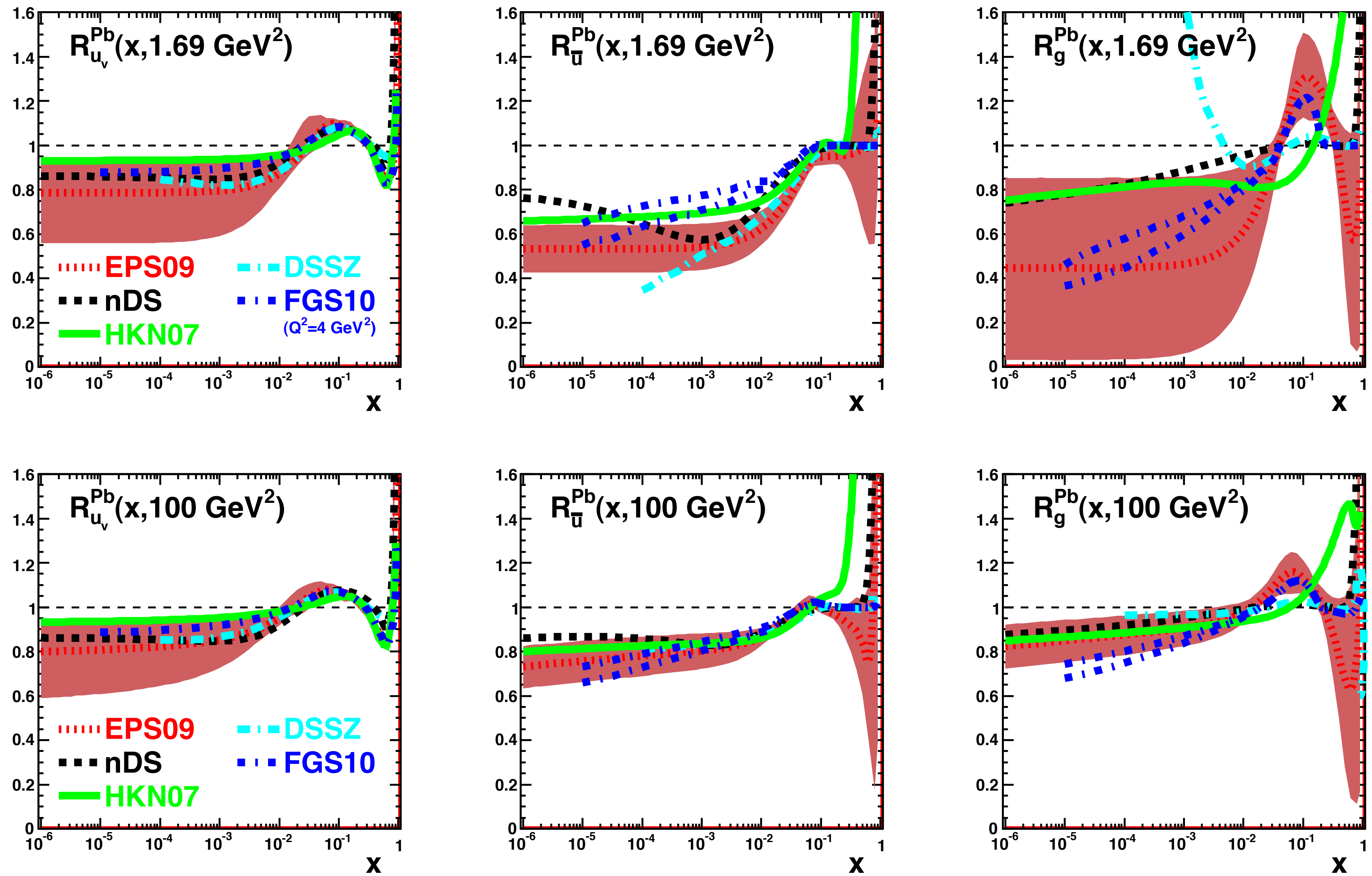


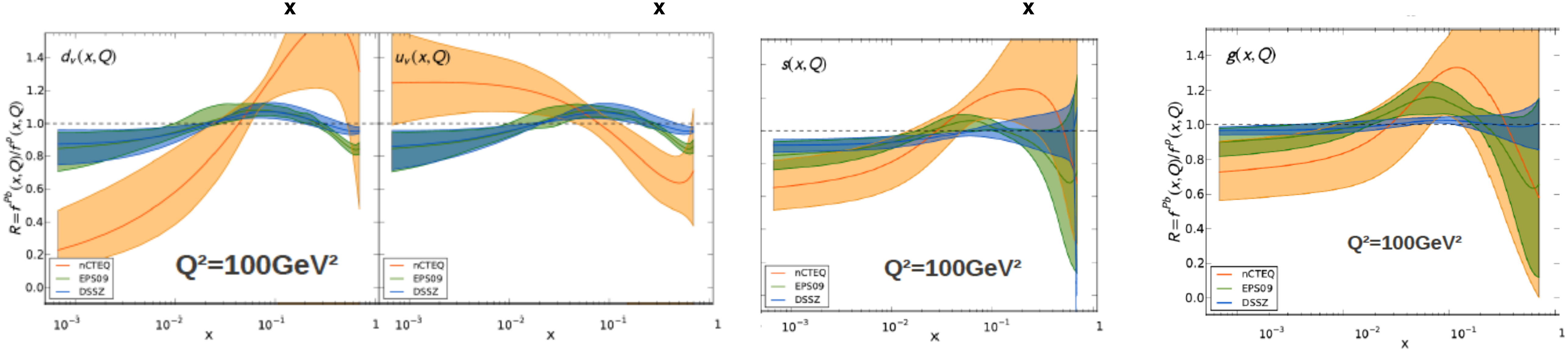


Presently included data

Contemporary sets:



- Uncertainties where there are no data.
- Differences (valence with nCTEQ: d_v, u_v) due to assumptions and data included.

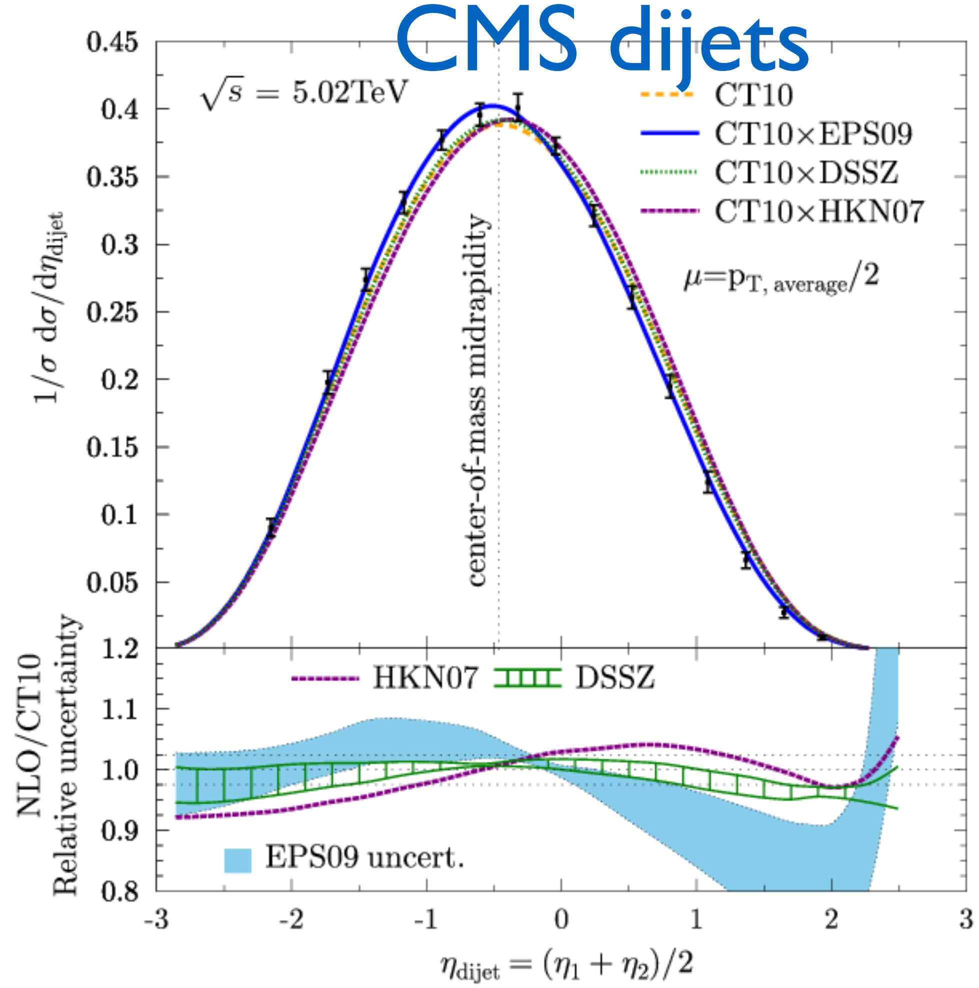


LHeC

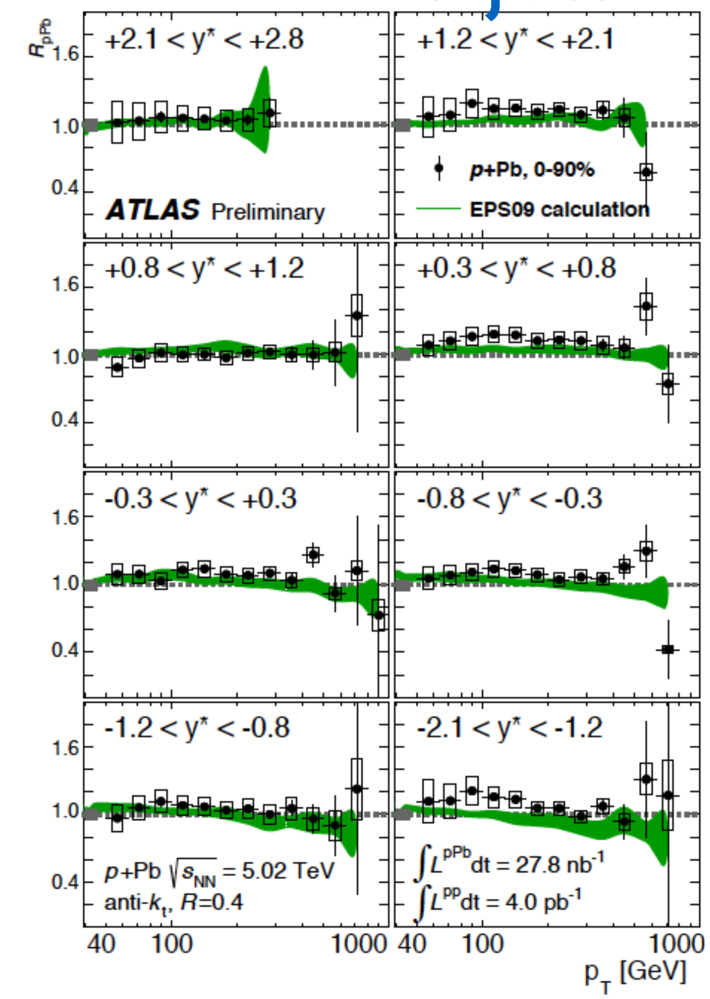
LHC?

- **Jets and EW bosons**: at present used to test factorisation in pA/AA, and they offer some constrains to nPDFs (pPb@5 TeV/n).
- No sizeable in-medium effects e.g. energy loss.
- Delicate centrality issues!!!

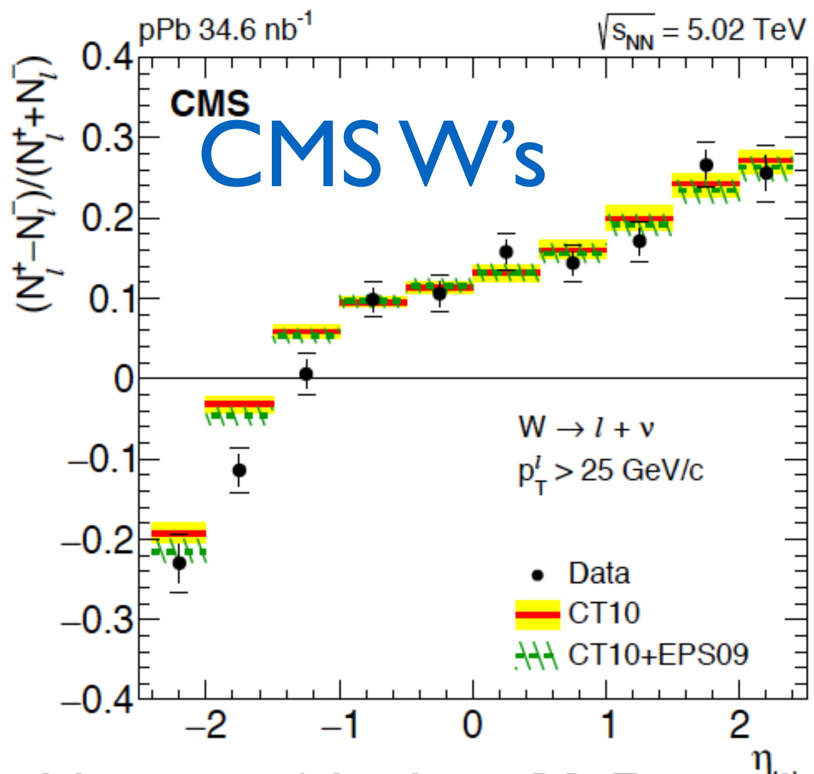
CMS dijets



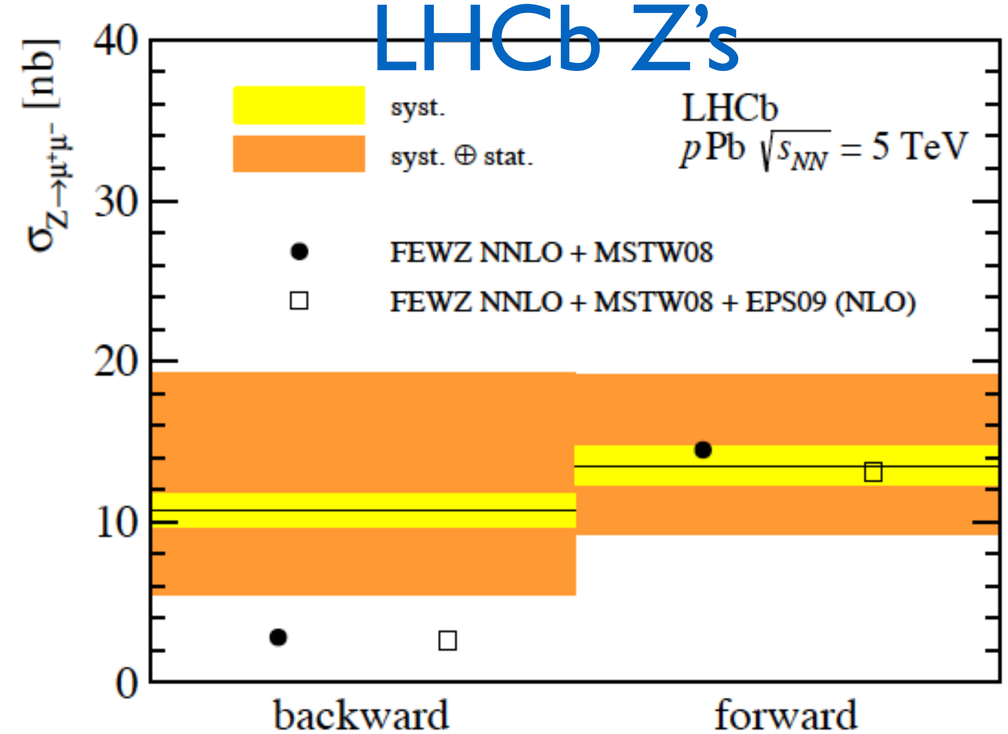
ATLAS jets



CMS W's



LHCb Z's



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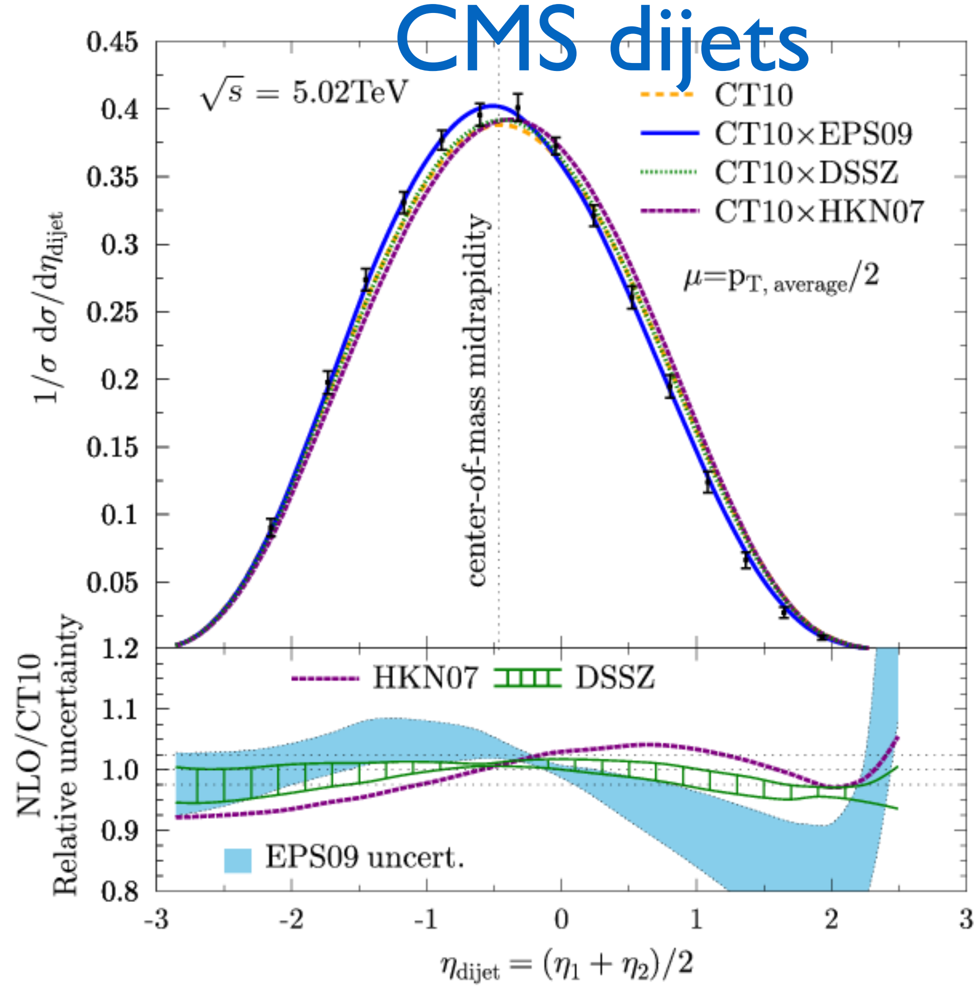
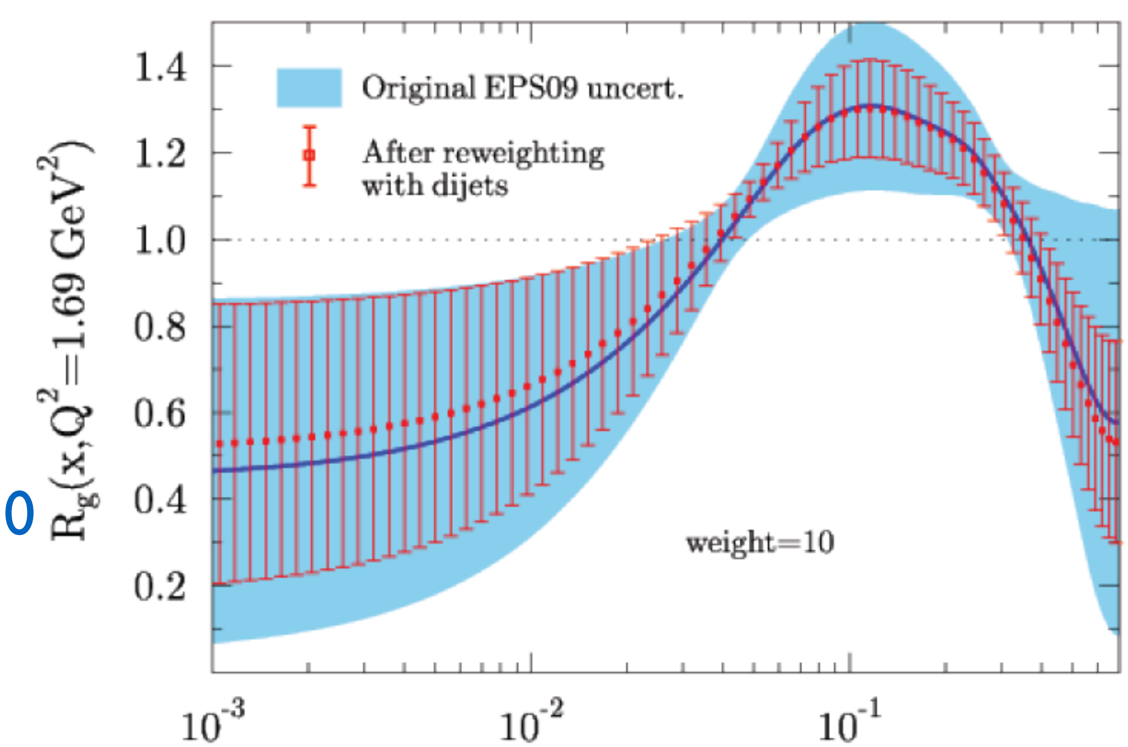


Hessian reweighting!!!

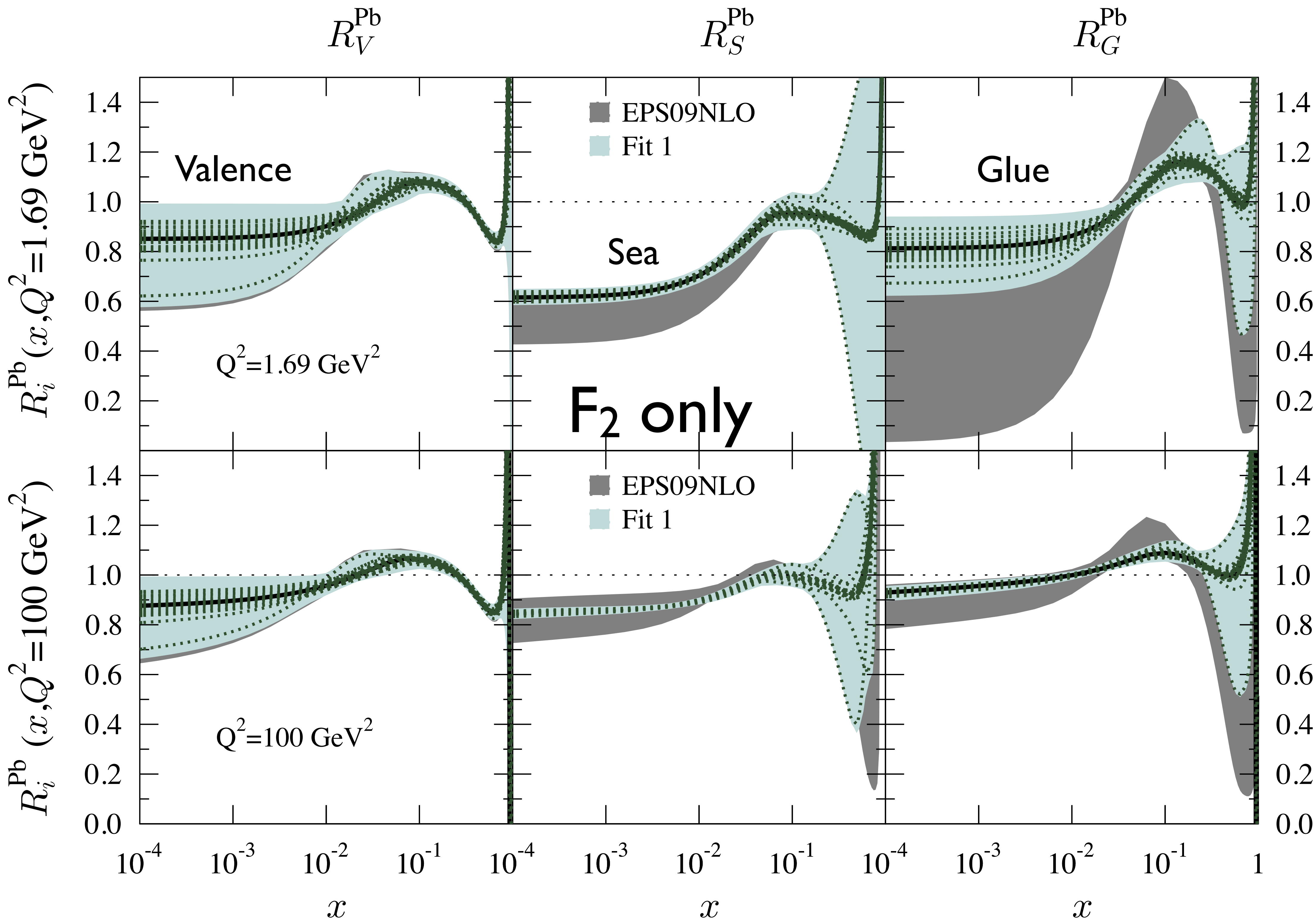
Note: W's, Z's demands modifying assumptions in ICs.

1408.4563, w=10 as RHIC π^0



Previous LHeC studies: CDR

- Original EPS09 fit with one additional free parameter, small-x pseudodata.



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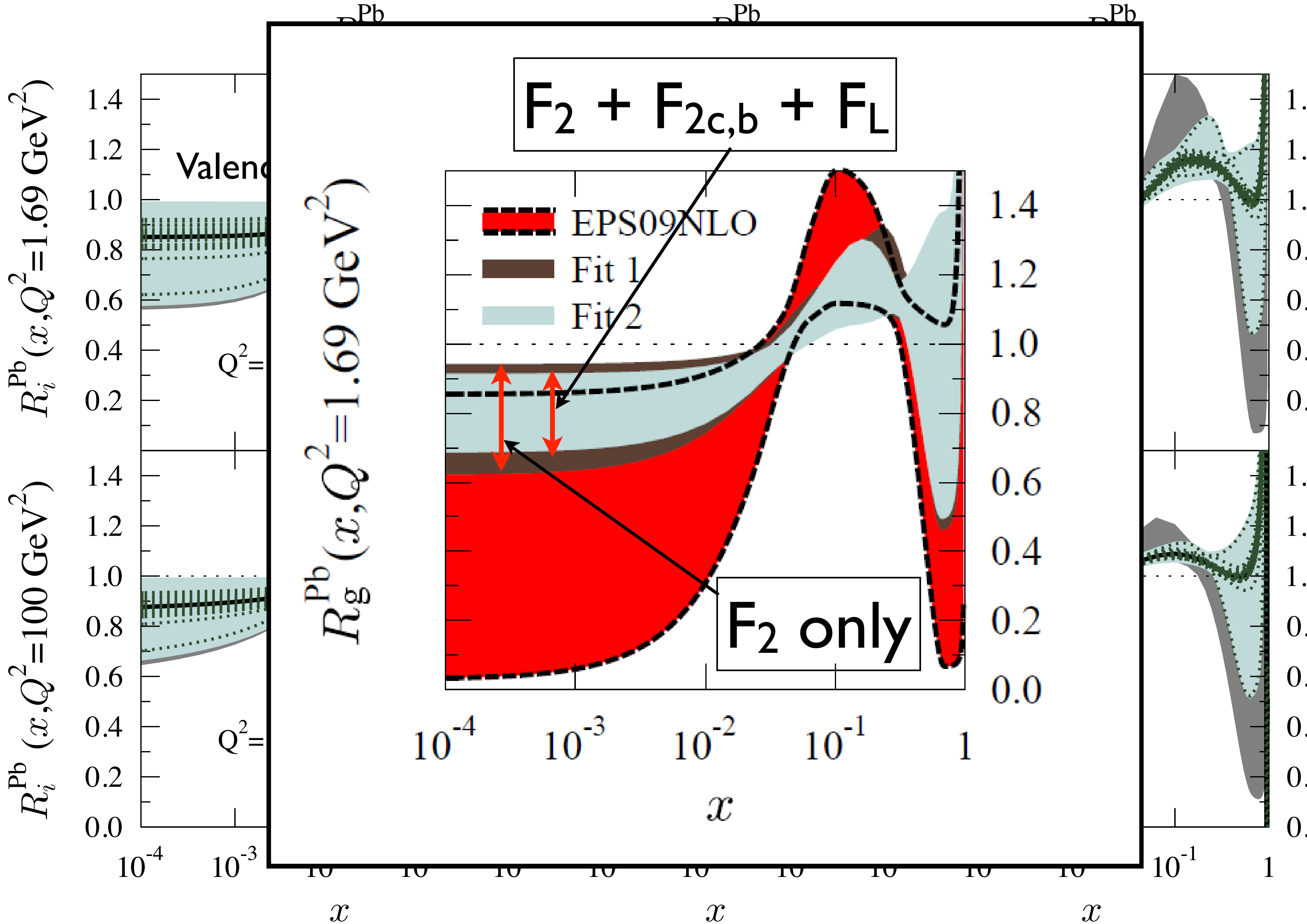
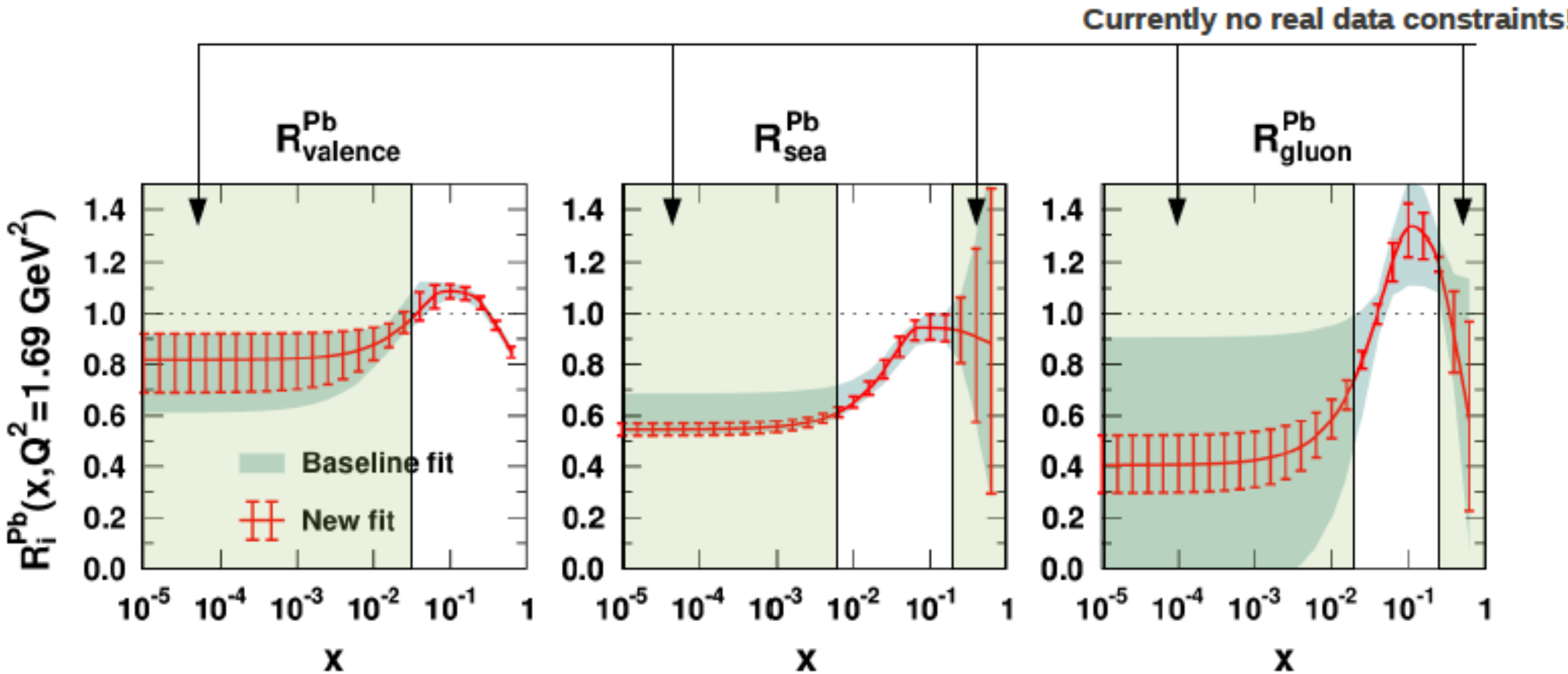


Previous LHeC studies: post-CDR

- Reduced cross sections only, different energies, all x.



Hannu Paukkunen, LHeC workshop 1401

- A drastic reduction in the small-x gluon and sea quark uncertainties
- More freedom in the fit function should be allowed – the baseline uncertainty probably underestimated
- Addition of charged-current data should give a handle on the flavor dependence, which is currently (practically) unconstrained

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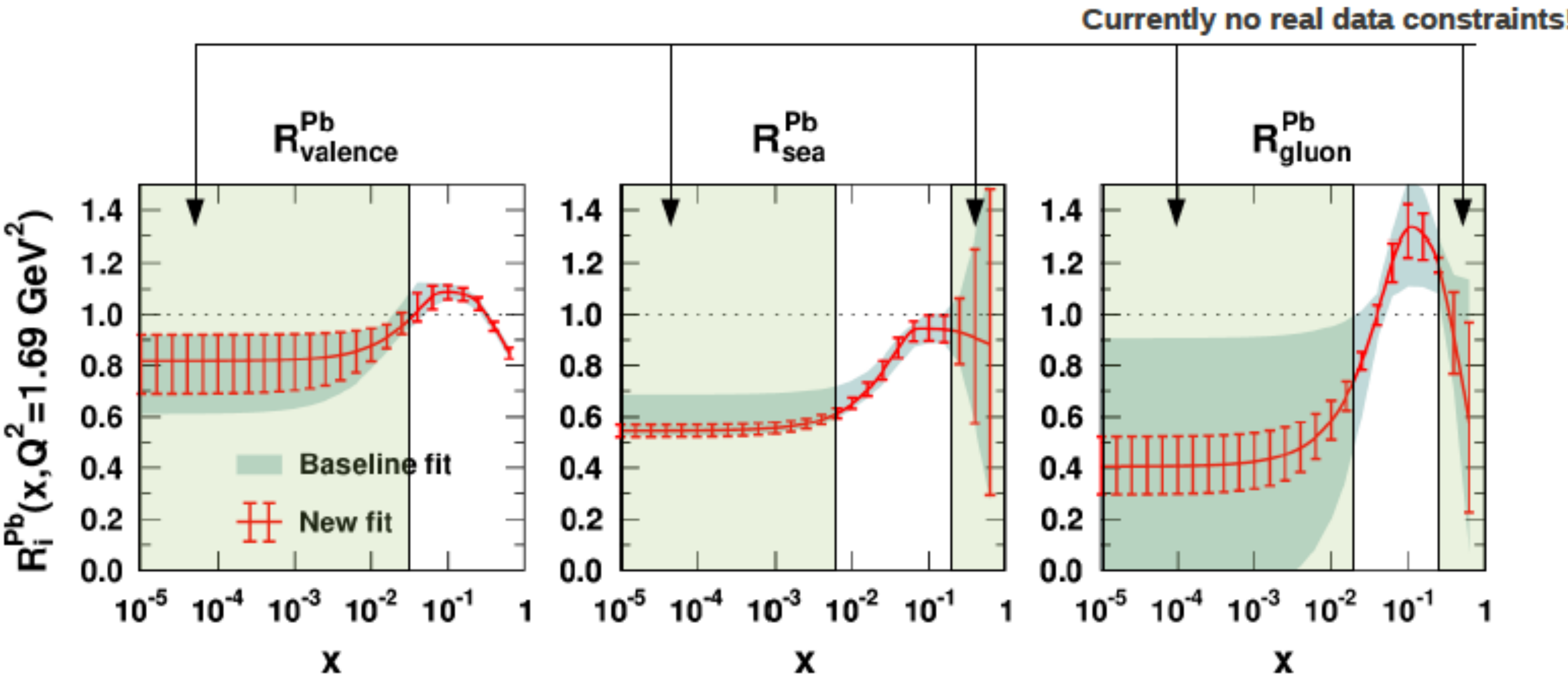

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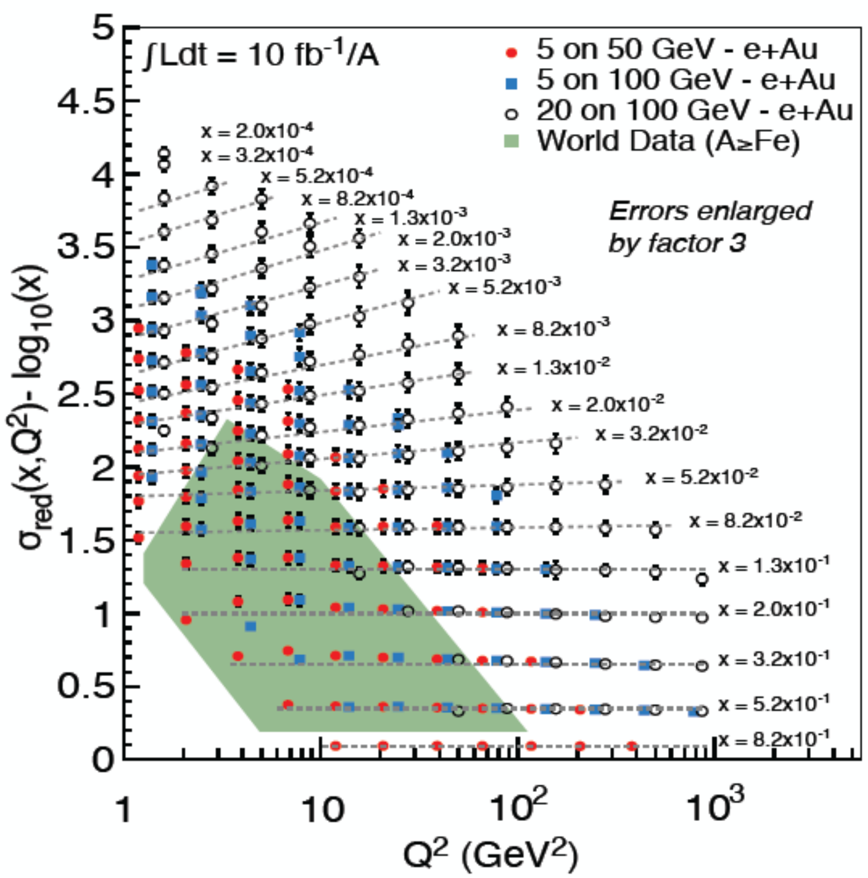
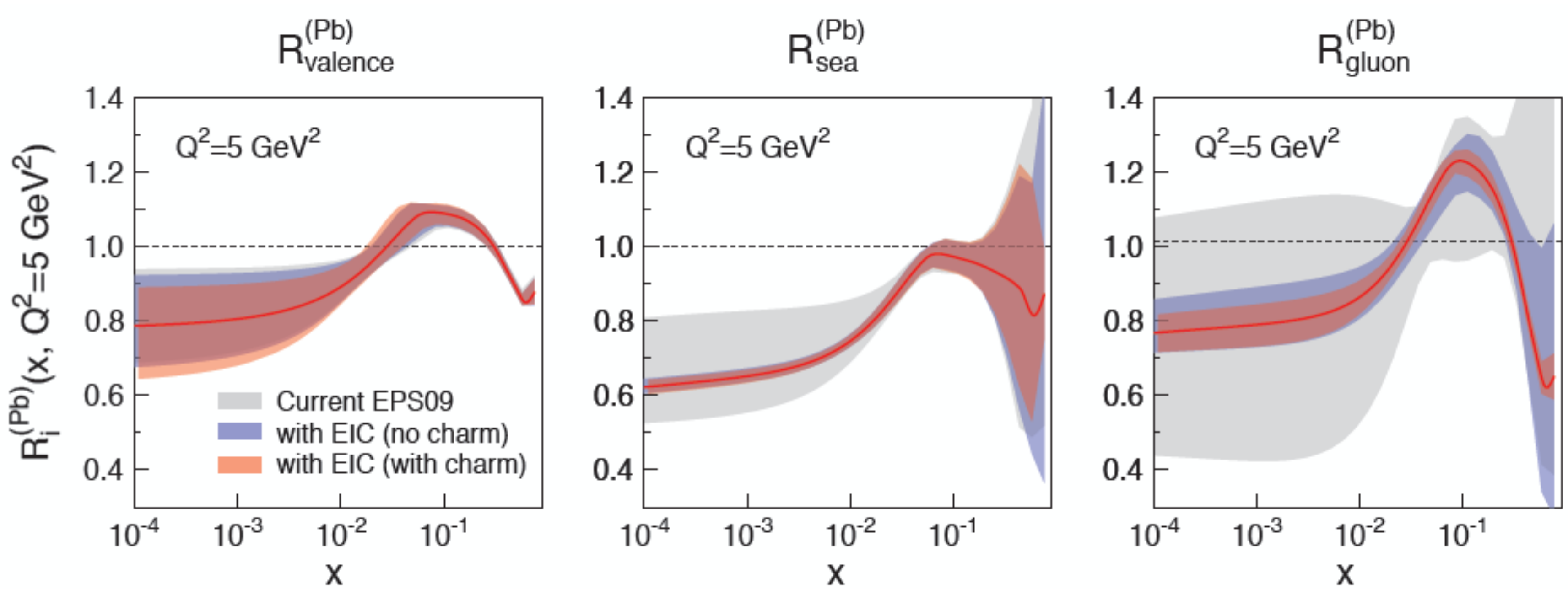
ICs and uncertainties:

- 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 data…





EIC example, Lamont at IS2014

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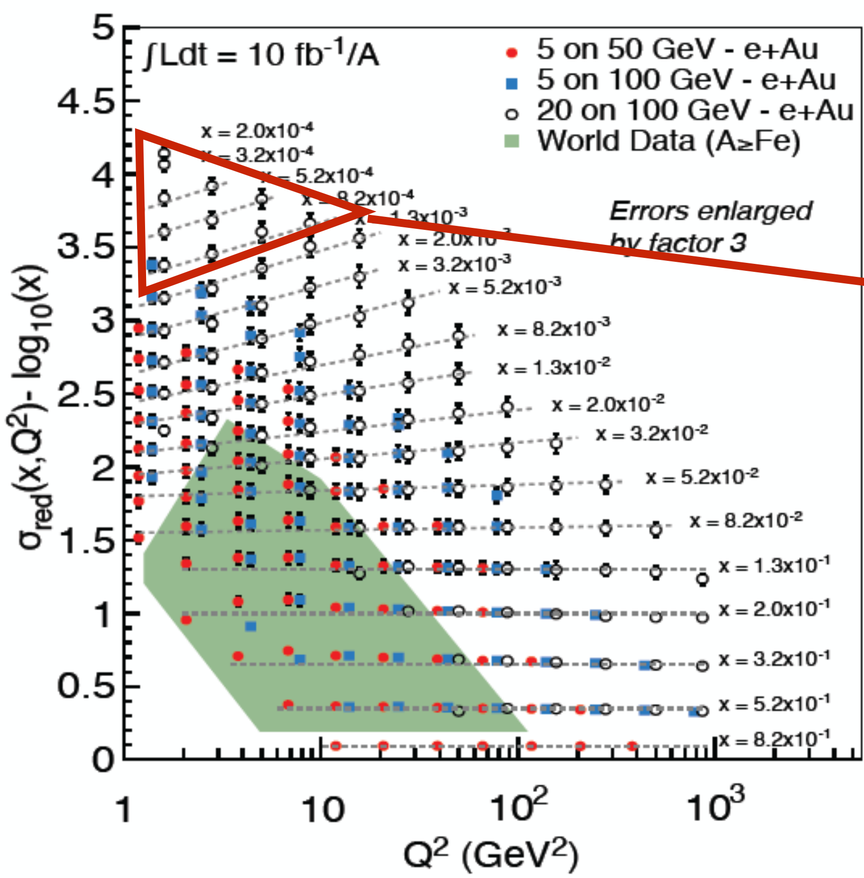
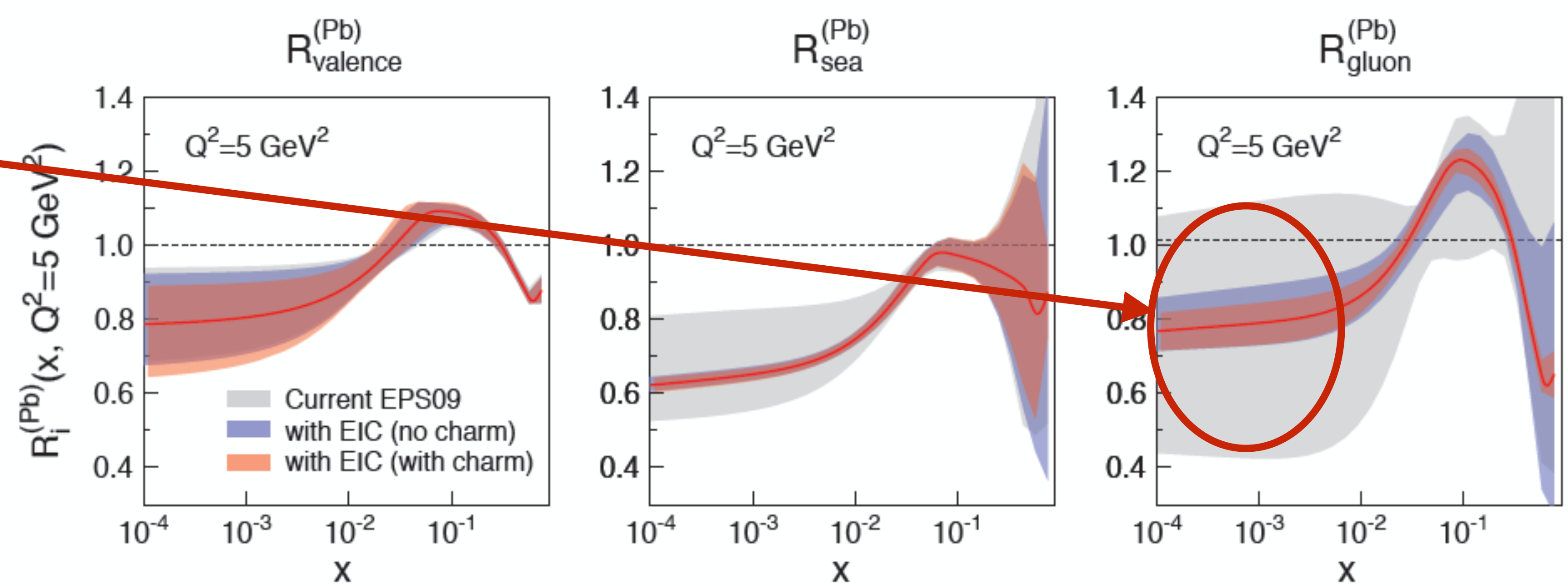


How?: mainly dictated by the shape of ICs



EIC example, Lamont at IS2014

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

hep-ph/0201256

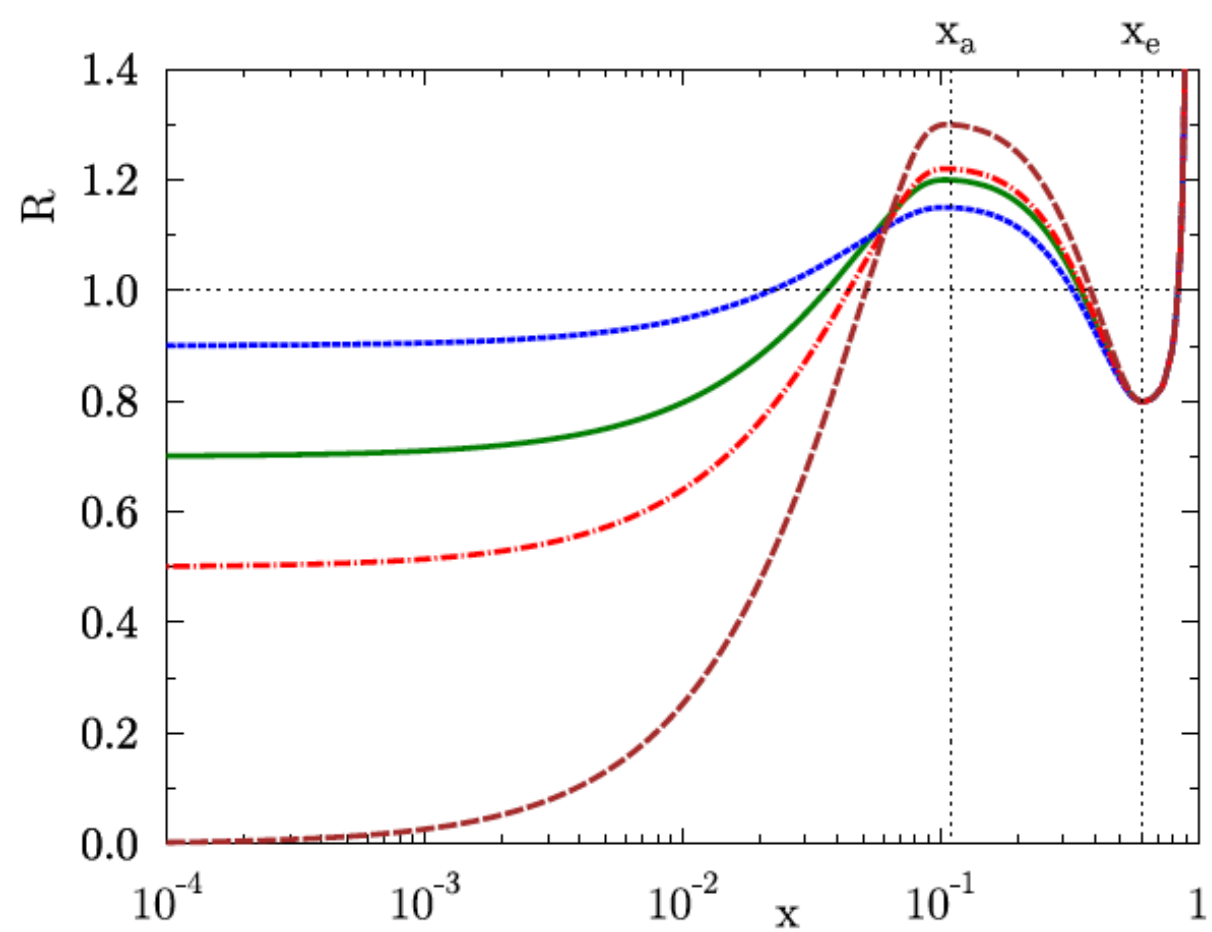
EPS09:

- Very little freedom at small x.

  The fit function in EPS09:

$$R^{\mathrm{EPS09}}(x) = \begin{cases} a_0 + (a_1 + a_2 x)\left(e^{-x} - e^{-x_a}\right) & x \le x_a \\ b_0 + b_1 x + b_2 x^2 + b_3 x^3 & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1 - x)^{-\beta} & x_e \le x \le 1 \end{cases}$$

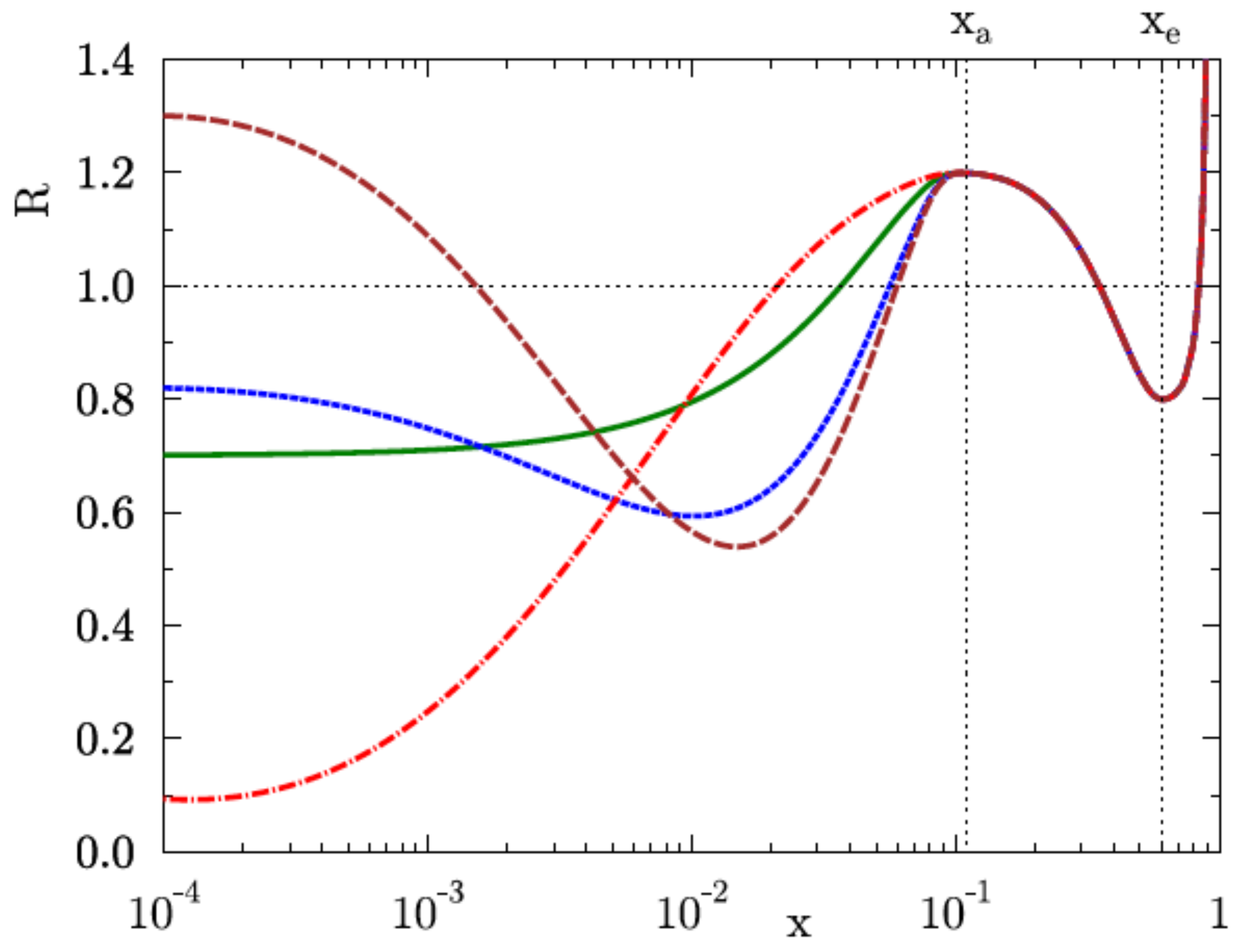
(power-law parametrization of A-dependence at x_a, x_e, and $x \to 0$)



New ICs:

- Use a far more flexible form to reduce the bias at small x:

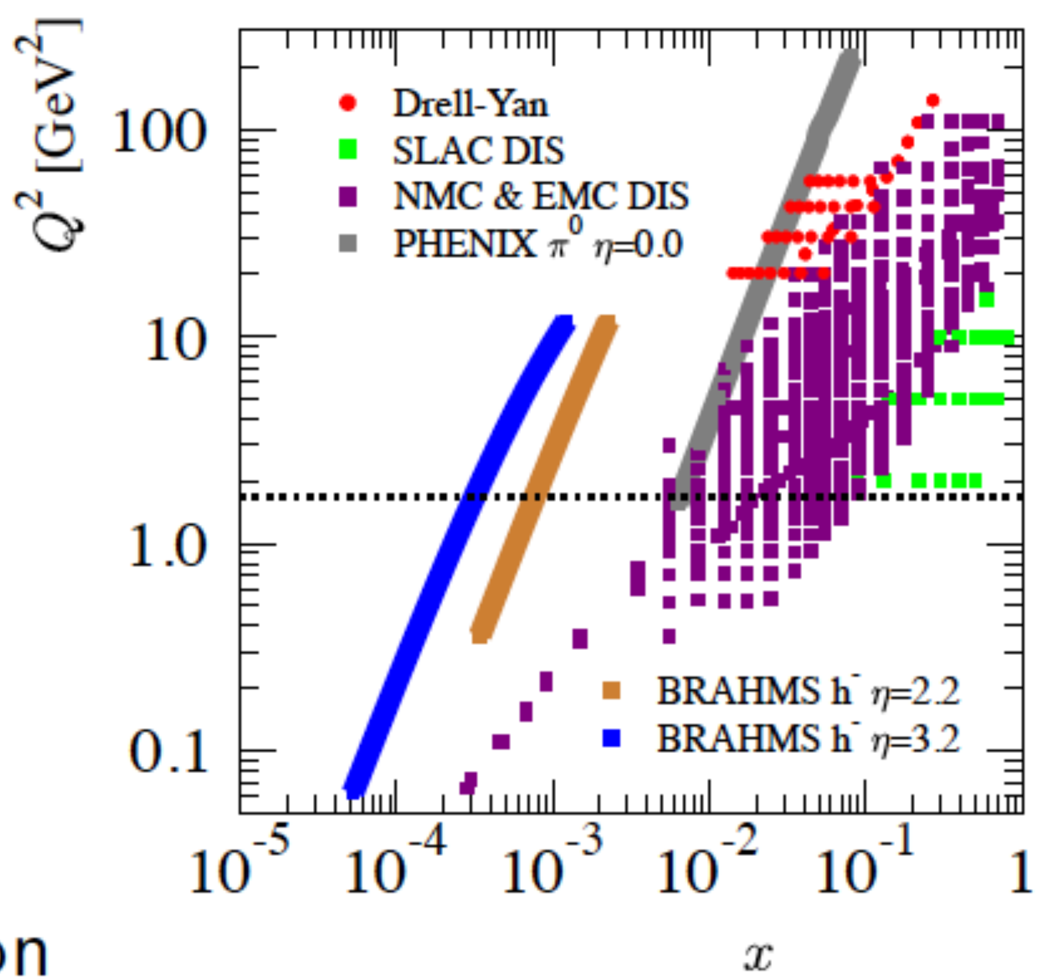
$$R(x \leq x_a) = a_0 + a_1(x - x_a)^2 + \sqrt{x}(x_a - x)\left[a_2 \log\left(\frac{x}{x_a}\right) + a_3 \log^2\left(\frac{x}{x_a}\right) + a_4 \log^3\left(\frac{x}{x_a}\right)\right]$$



New fit framework:

- 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 $Q_0 = 1.3\,\mathrm{GeV}$

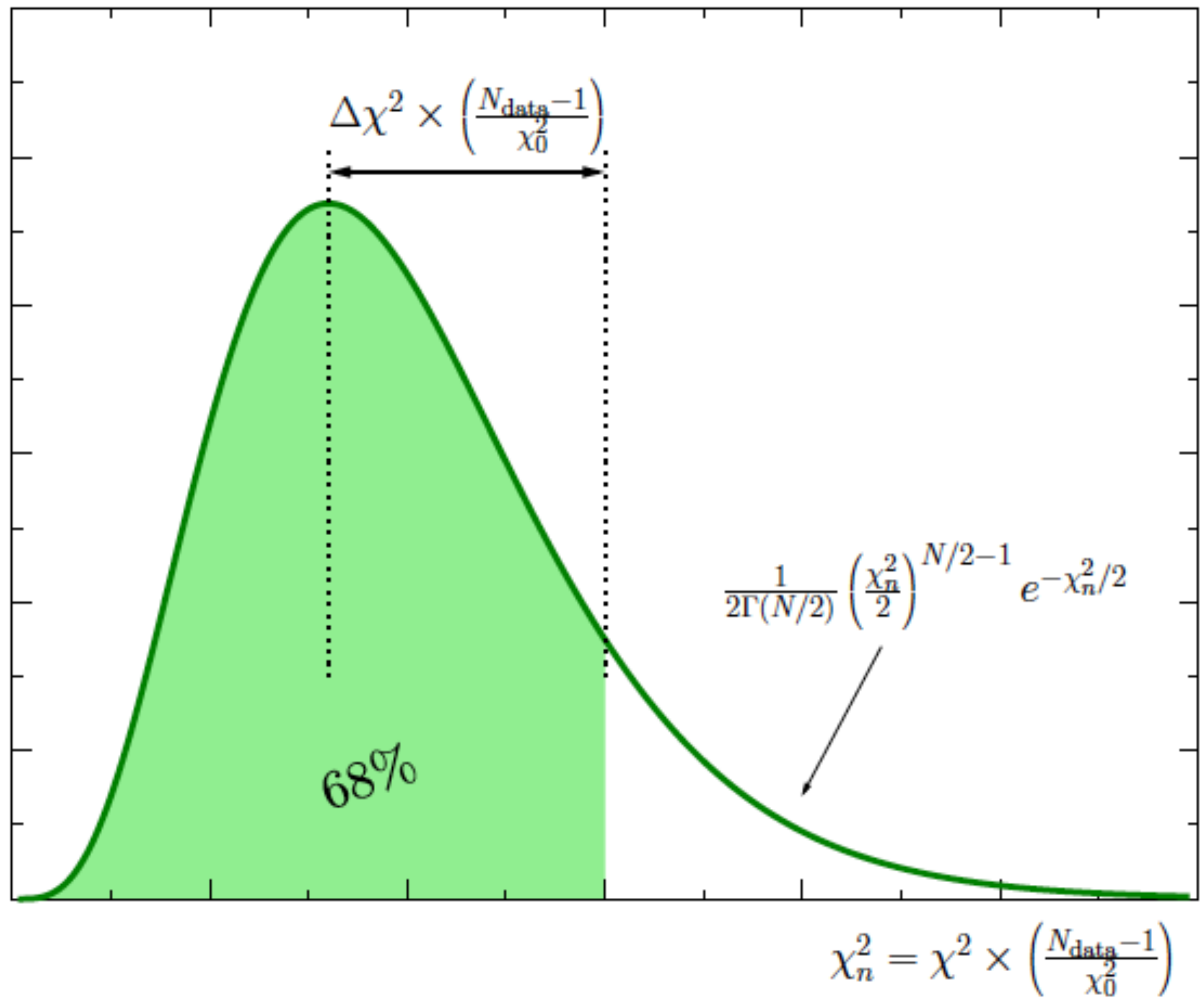
$$\begin{array}{ll} R_{\mathrm{V}}(x, Q_0) & \text{for both valence quarks} \\ R_{\mathrm{S}}(x, Q_0) & \text{for light sea quarks} \\ R_{\mathrm{G}}(x, Q_0) & \text{for gluons} \end{array}$$



- 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:

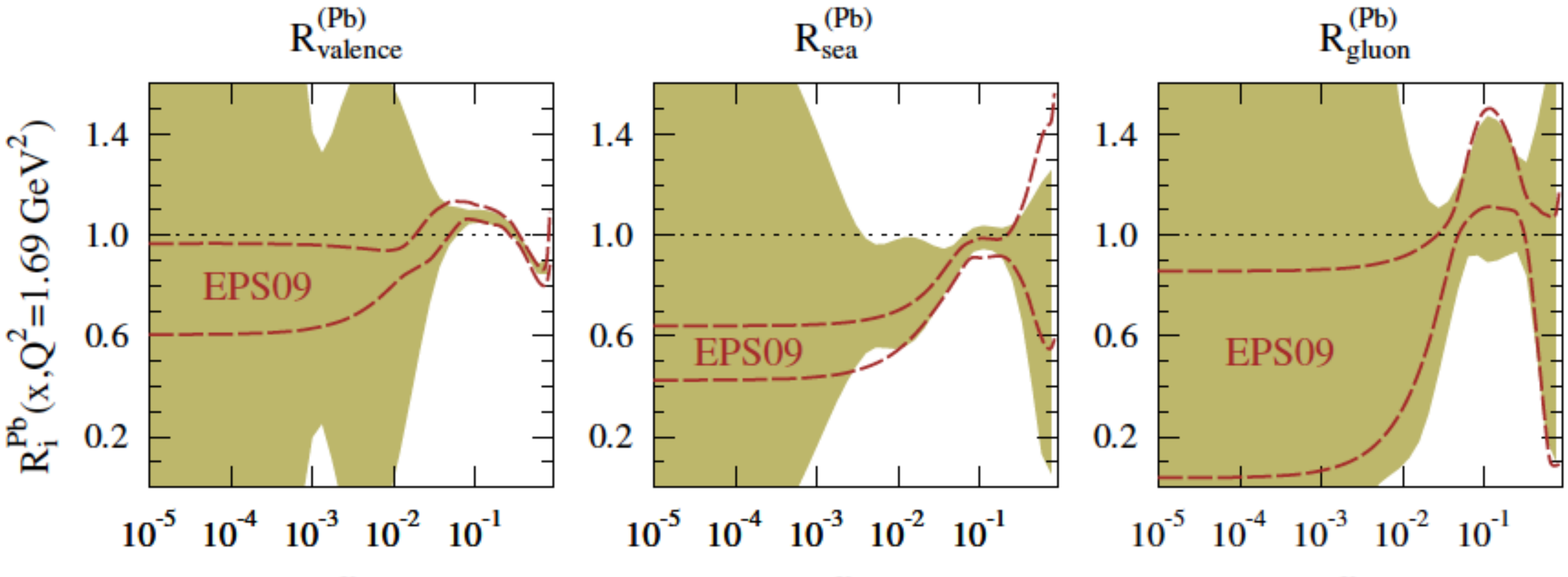
Standard Hessian uncertainty analysis (a la CTEQ, MSTW,...) with $\Delta\chi^2$ determined from the expected behaviour of probability distribution for the global χ^2



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

New fit framework:

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



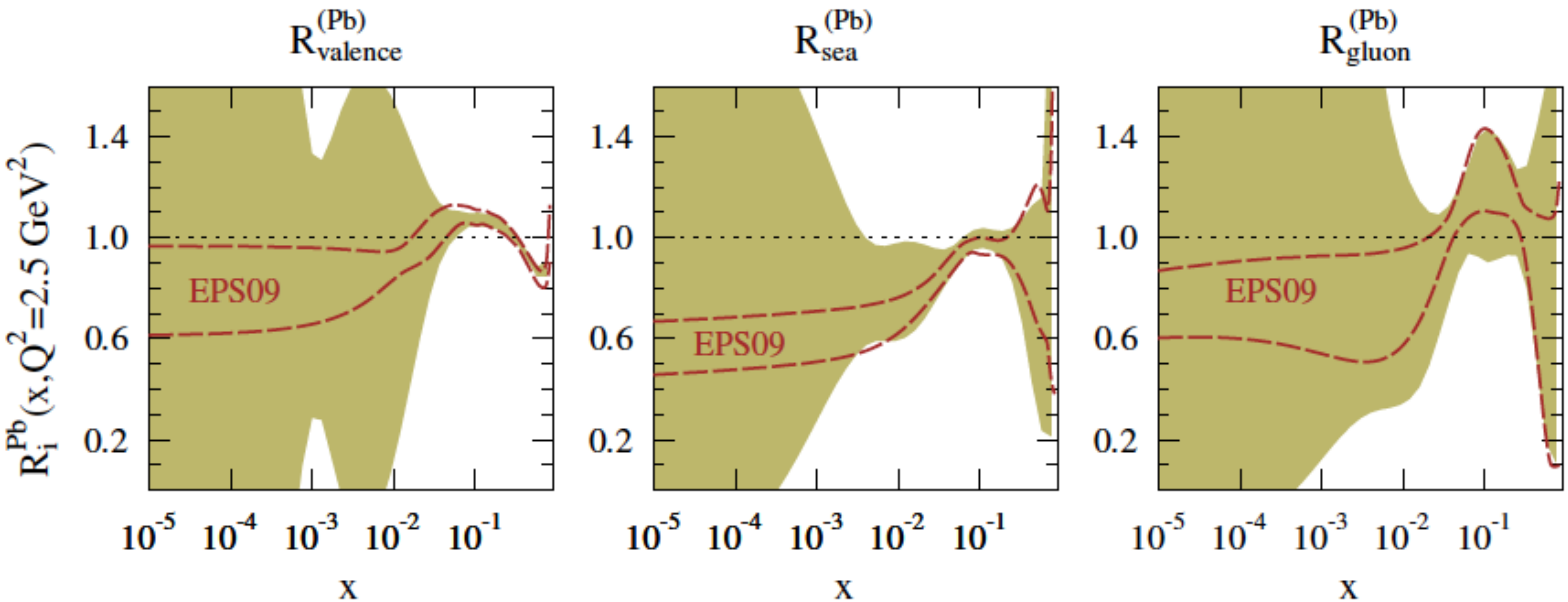
The lower bound restricted here by $F_L(Q^2 = 2\,\mathrm{GeV}^2, x > 10^{-5}) > 0$

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:

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



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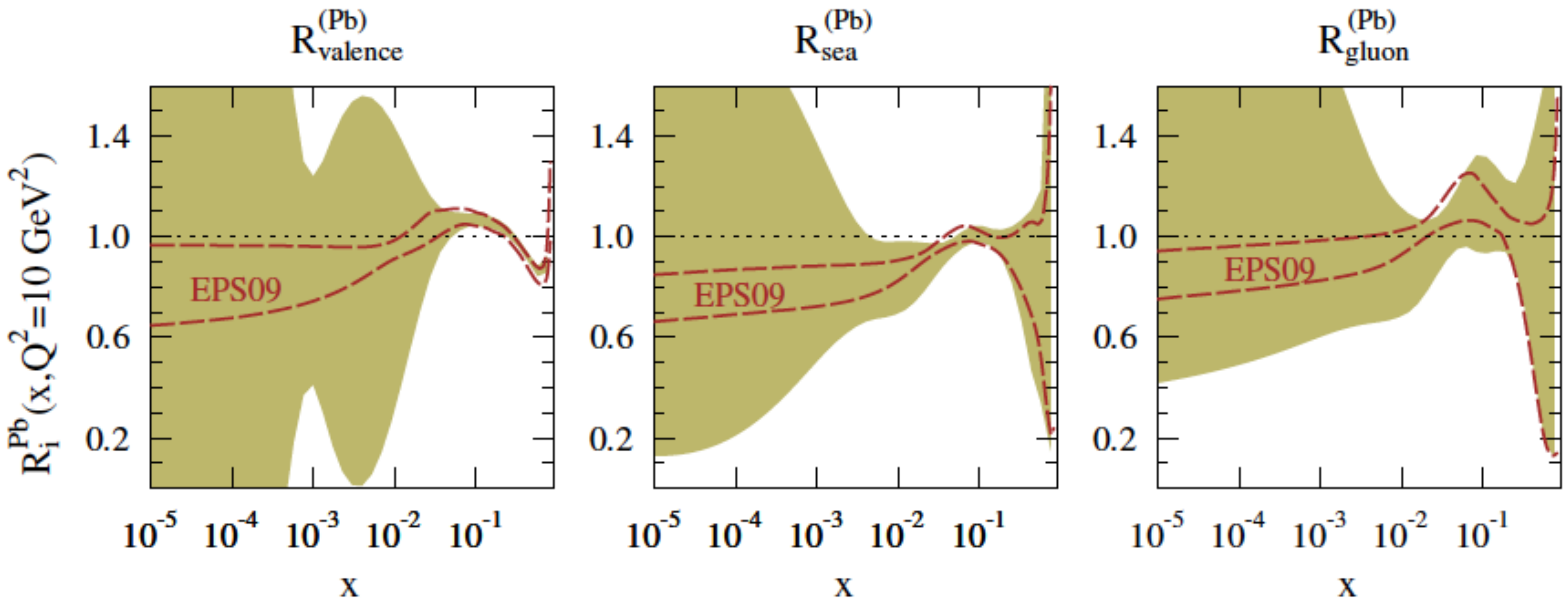

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Pseudodata:

- Assume $\mathcal{L}_{\mathrm{ep}} = 10\,\mathrm{fb}$, $\mathcal{L}_{\mathrm{ePb}} = 1\,\mathrm{fb}$ (per nucleon)
- Top LHC energies: 7/2.75 TeV/nucleon.
- The pseudodata are obtained from ratios of reduced cross sections σ^i and relative uncertainties $\delta^i_{\mathrm{uncor.}}$ and $\delta_{\mathrm{norm.}}$ by

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

where

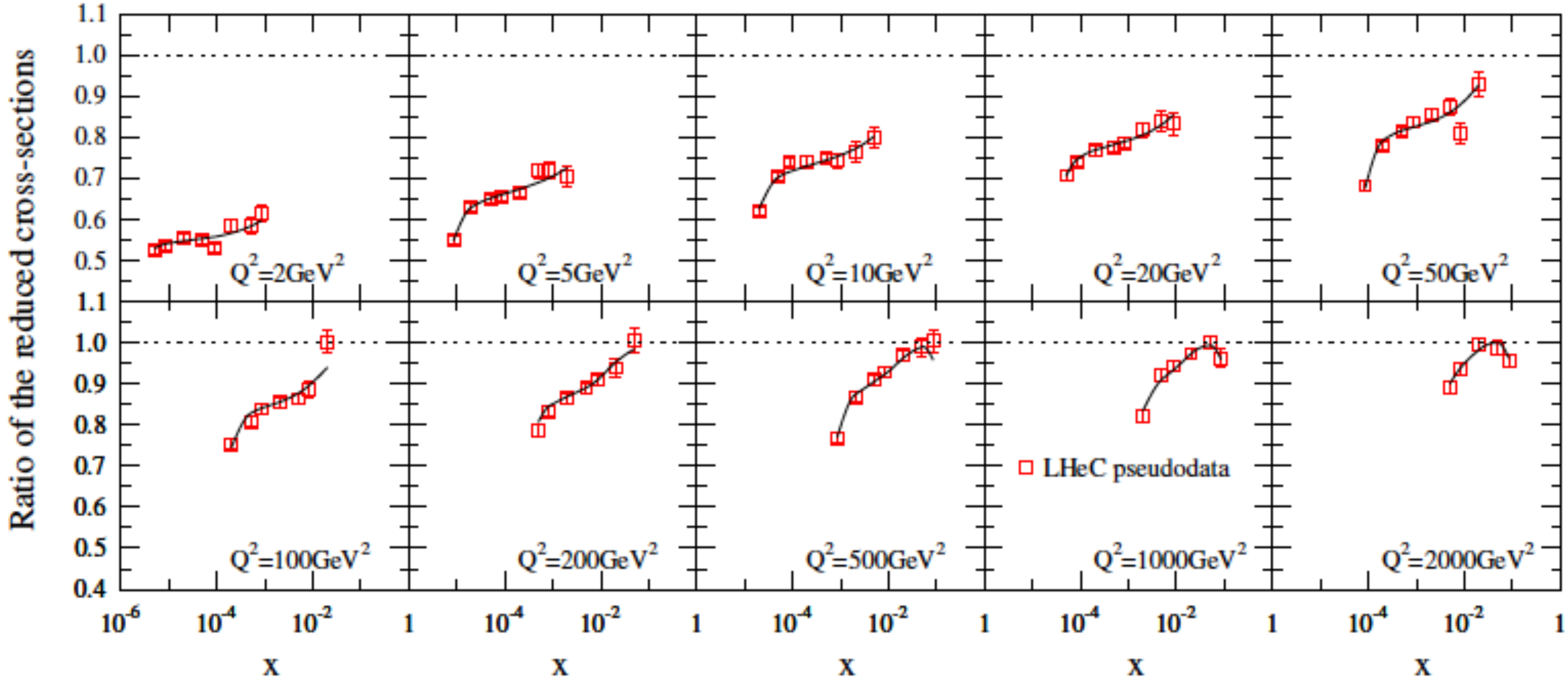
$$R_i(EPS09) = \frac{\sigma^i_{\mathrm{ePb}}(CTEQ6.6 + EPS09)}{\sigma^i_{\mathrm{ep}}(CTEQ6.6)},$$

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

- Typically $\delta^i_{\mathrm{uncor.}} < 2\%$ and $\delta_{\mathrm{norm.}} = 1.4\%$ (assuming that the uncertainties in e-p and e-Pb are uncorrelated)

Pseudodata:

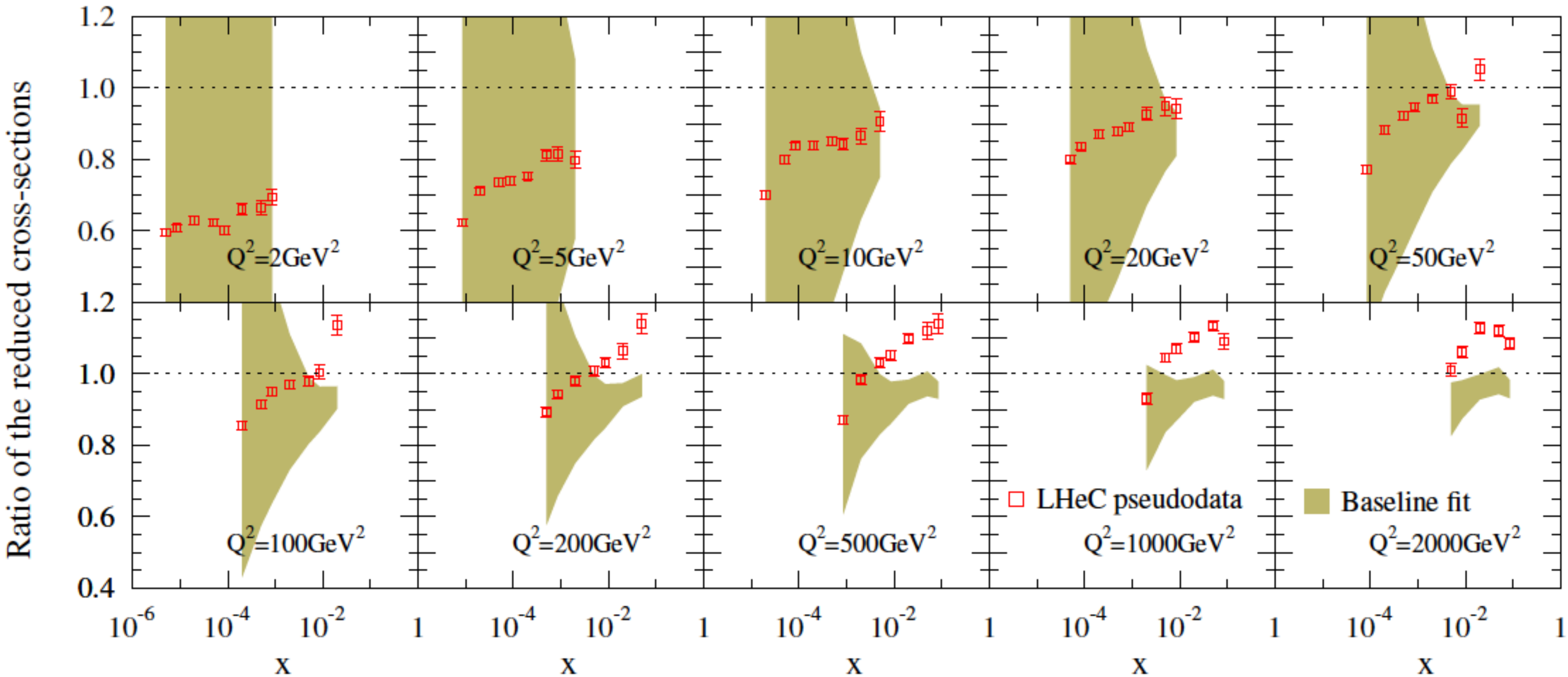
- Complete, new simulation: NC(+CC+c,b not yet used) with systematic uncertainties from a complete simulation.



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

Pseudodata:

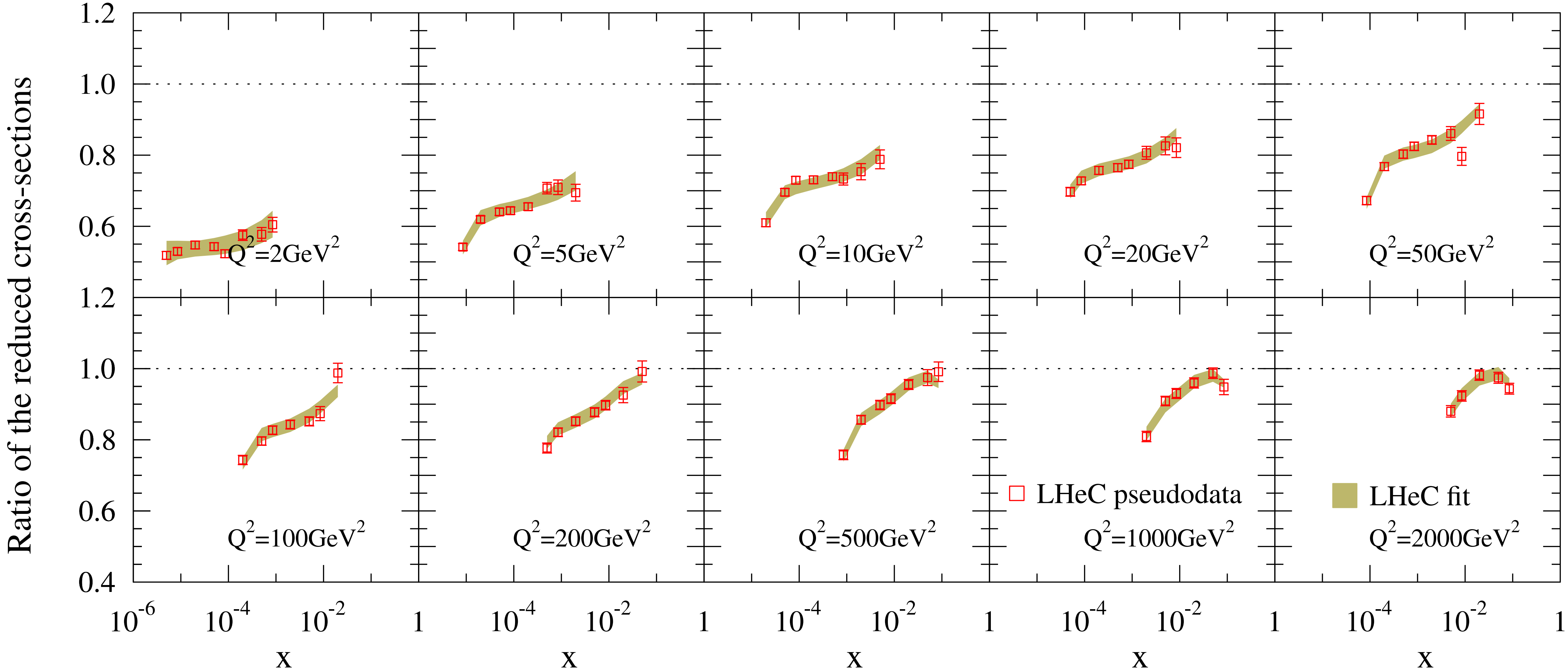
The error bands hugely exceed the data uncertainties



The "optimum" data normalization factor $f \sim 1.1$, hence the mismatch at large x

Results:

- Uncertainties shrink!!!



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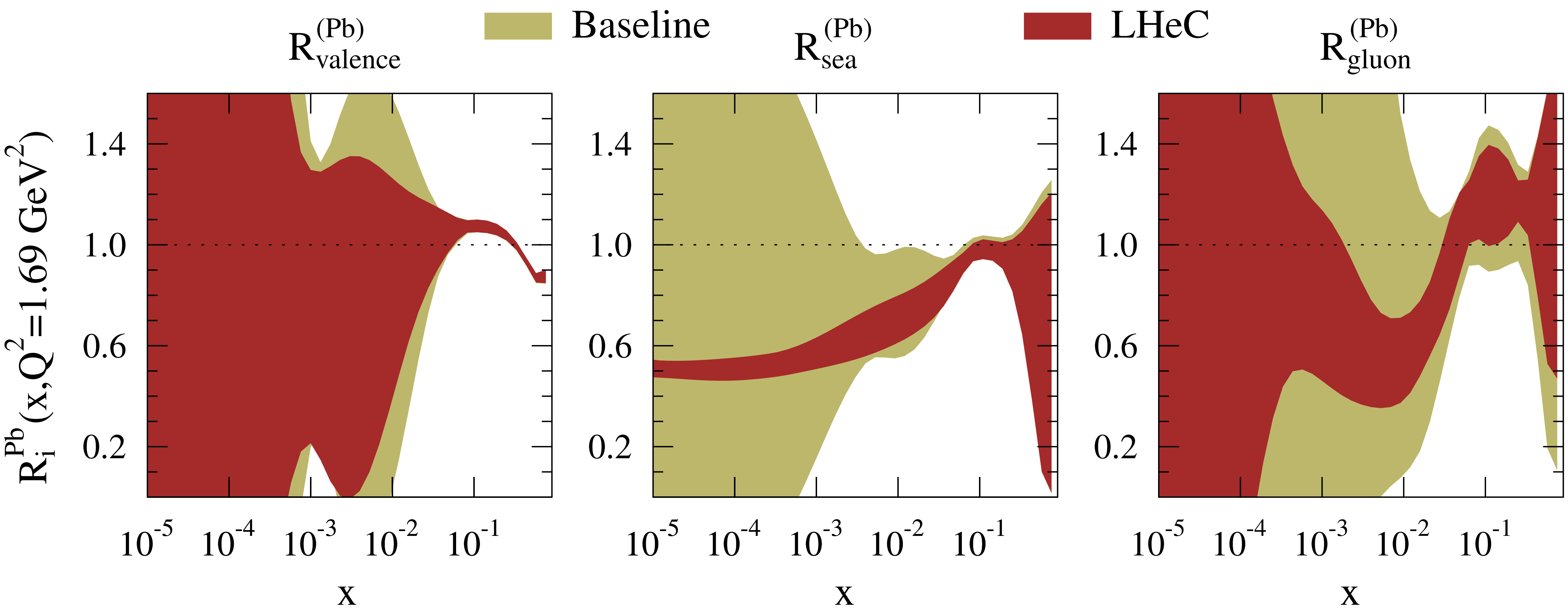

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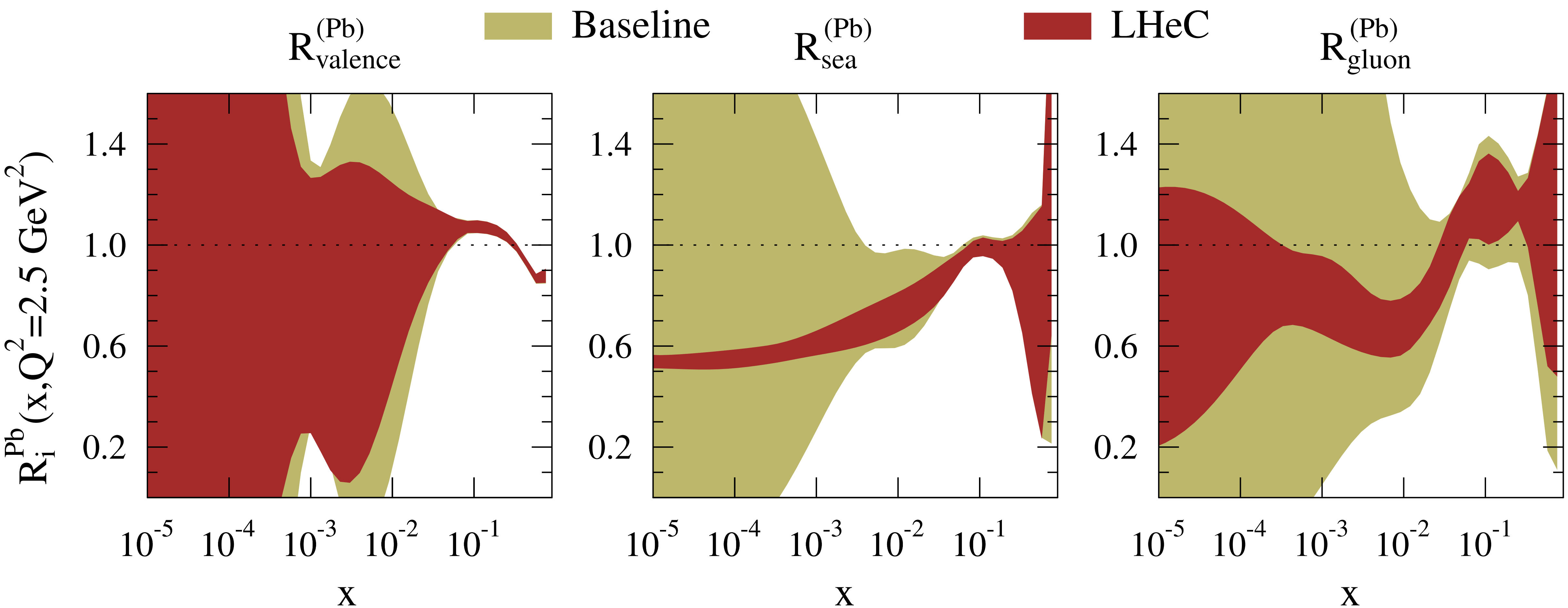

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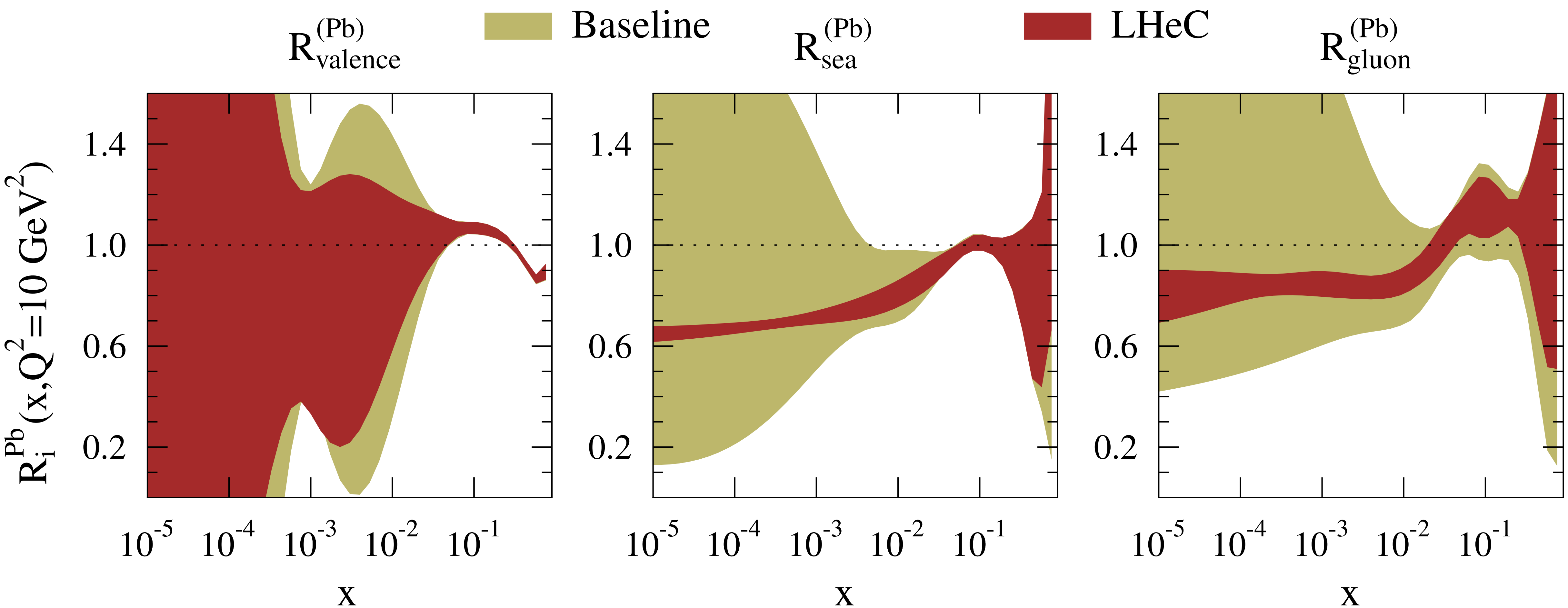

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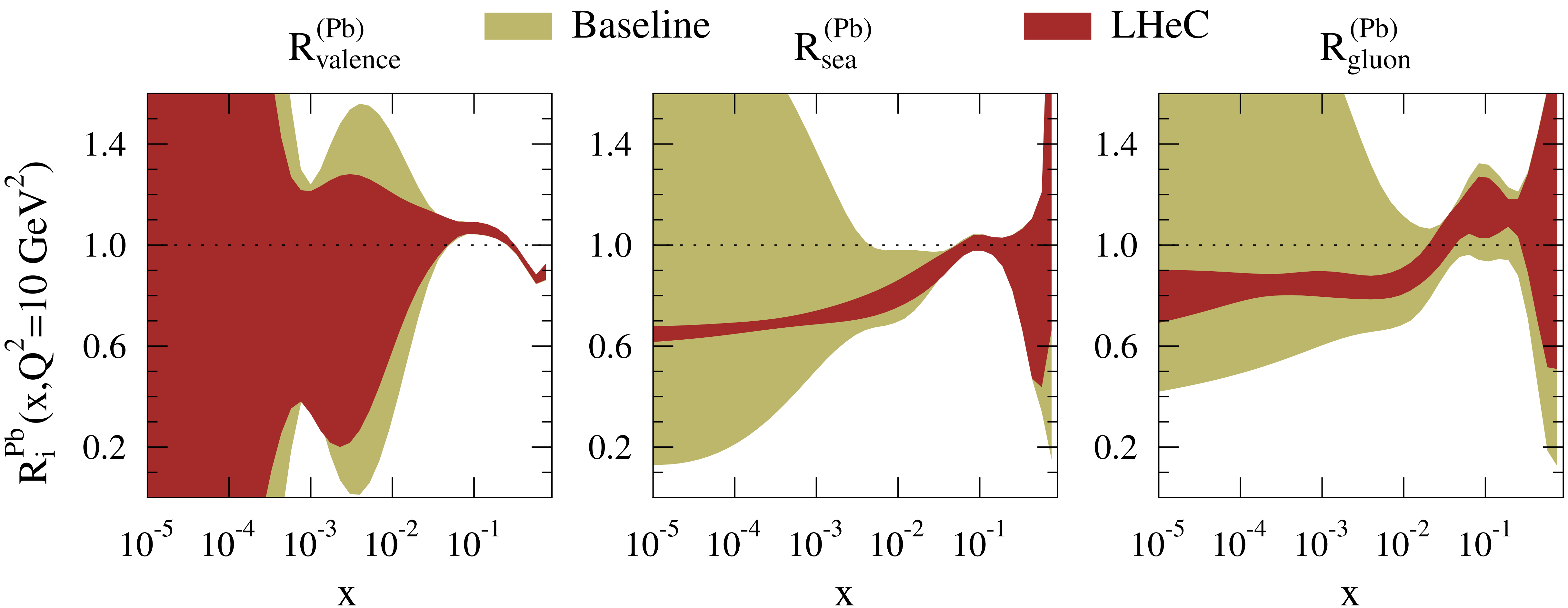
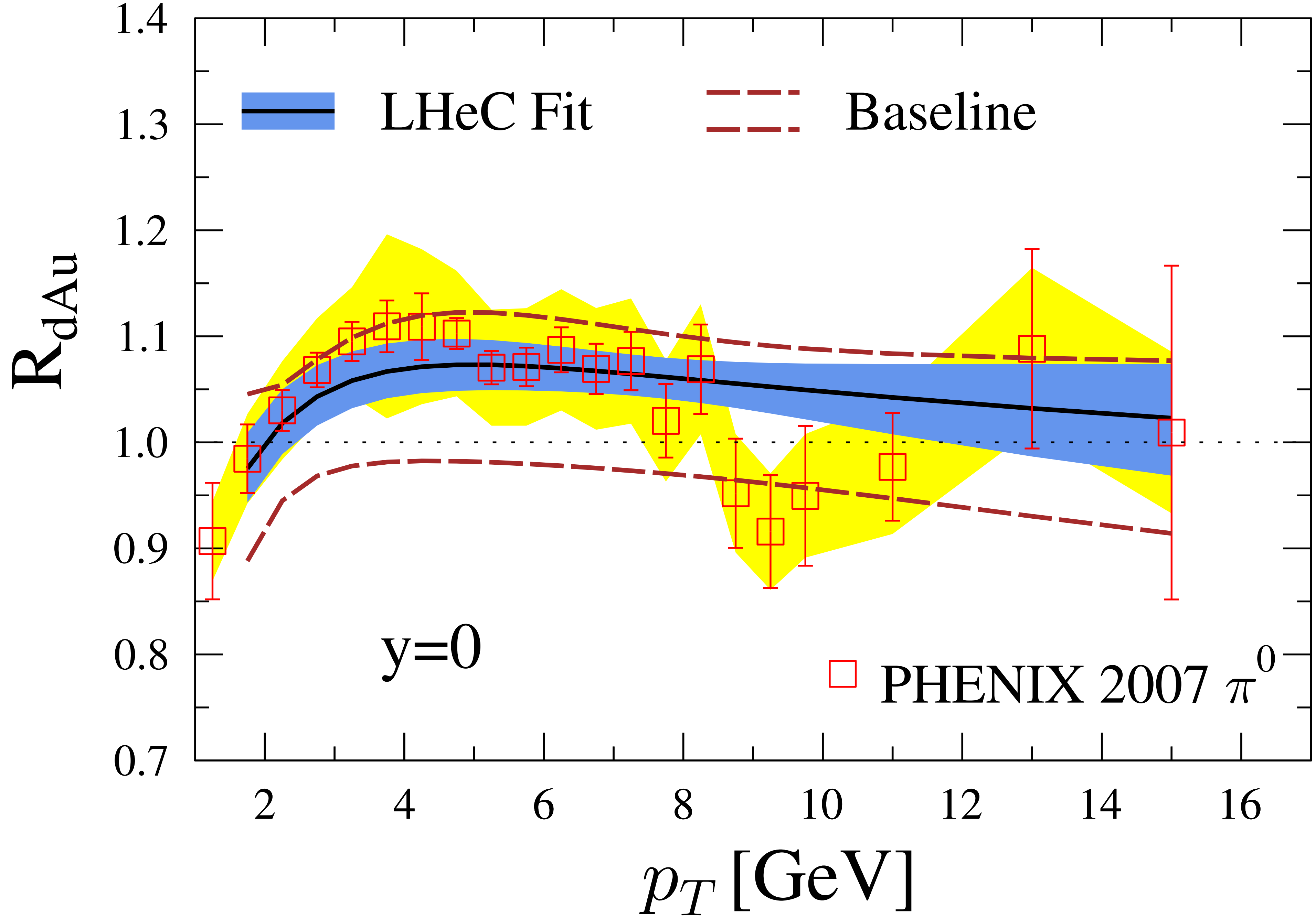


- Kind of precision required for better understanding of HI data on hard probes.

RHIC data:

- Looking back to RHIC π^0 data - only direct constrain on glue at present (hopefully to be substituted by LHC jets):



Summary and outlook:

- Limitations of the uncertainty analysis in existing nPDF datasets due to the form of initial conditions explored: uncertainties actually much larger in the regions where data are absent.

- Results may challenge physical intuition, but the aim of fitting is an extraction of the information in data…

- Potential of LHeC is huge in this respect.

- Outlook will (would) be: add CC, study flavour decomposition, check different mass schemes, check tension with saturation, use Pb data alone.

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Thanks to Hannu and Max for a most nice collaboration!!!

Thanks a lot to Hannu - this talk is his!!!

Thank you very much for your attention!!!