EPS nPDFs & heavy boson production at the LHC

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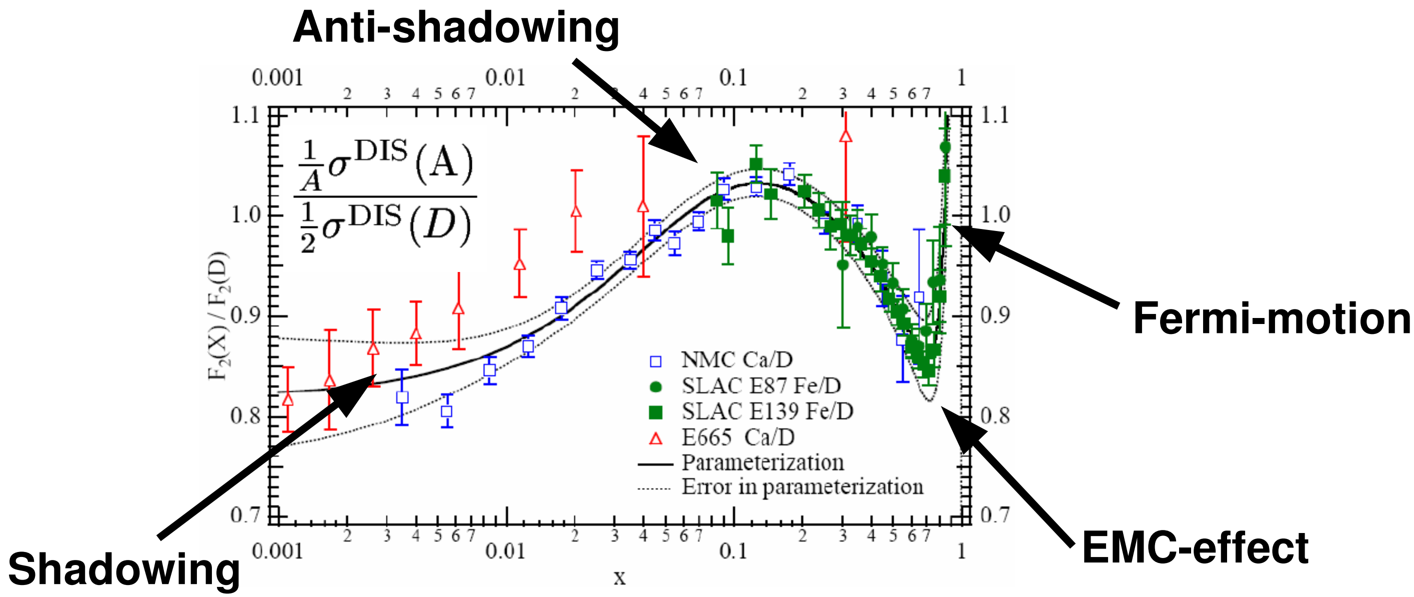
nPDFs: Testing the factorization



- **Nuclear modifications in experimental cross-sections:**

  $\sigma_{\text{bound nucleon}} \neq \sigma_{\text{free nucleon}}$

- **Various analyses indicate that such effects can be factorized to the universal nuclear PDFs:** ***EPS09, HKN07, nDS, nCTEQ...***

$$\sigma_{AB\to h+X} = \sum_{ij} \underbrace{f_i^A(x_1,Q^2) \otimes f_j^B(x_2,Q^2)}_{\text{Nuclear PDFs, obeying DGLAP equations}} \otimes \underbrace{\sigma^{i+j\to h+X}}_{\text{Standard pQCD cross-sections}}$$

Nuclear PDFs, obeying DGLAP equations

Standard pQCD cross-sections

12 years of EPS-studies

- **1998: EKS98** (Eskola, Kolhinen, Ruuskanen, Salgado) **LO**

  The pioneering work – demonstrated that the factorization works for

  $e+A \rightarrow e + X$ *(DIS)*

  $p+A \rightarrow \mu^{+}+\mu^{-} + X$ *(Drell-Yan)*

  The "fit" was done by eye.

- **2007 : EKPS** (Eskola, Kolhinen, Paukkunen, Salgado) **LO**

  Reanalysis of EKS98 – automated minimization (MINUIT) and a first try to estimate the uncertainties.

- **2008 : EPS08** (Eskola, Paukkunen, Salgado) **LO**

  Motivated by small-pT suppression of BRAHMS pion data, the purpose was to study how strong gluon suppression at small-x would be possible.

- **2009 : EPS09** (Eskola, Paukkunen, Salgado) **LO & NLO**

  The analysis extended to NLO and an error analysis "a la CTEQ" was carried out.

Experimental constraints in EPS09

- Three types of data:

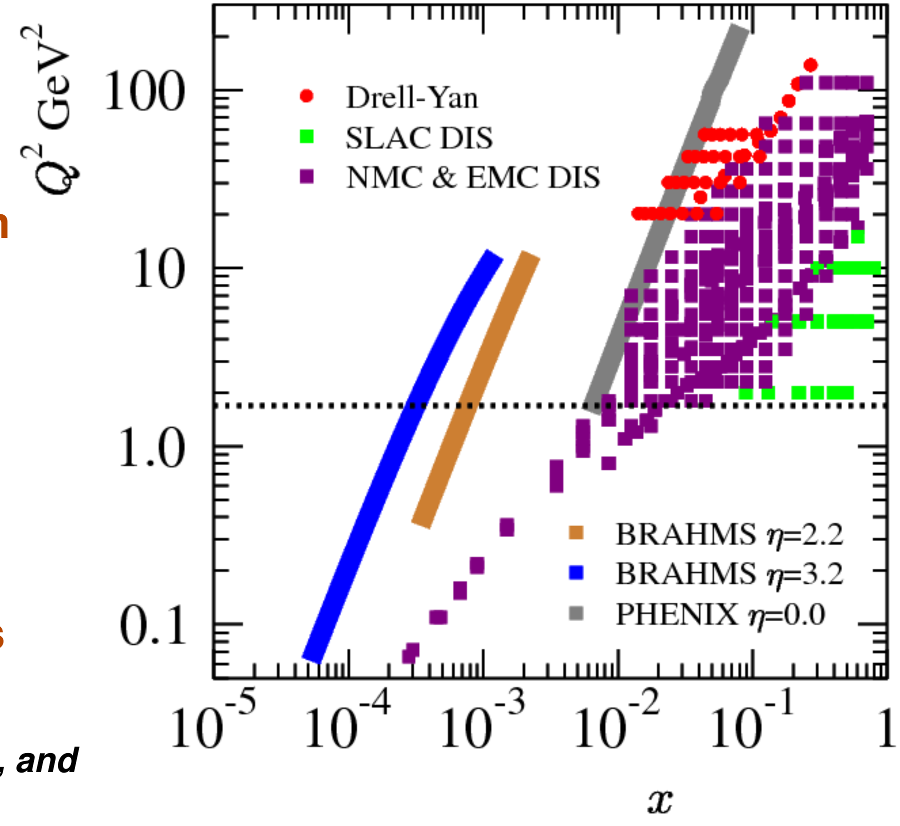
  Deeply inelastic scattering: $e + A \rightarrow e + X$
  Drell-Yan dilepton production: $p + A \rightarrow \mu^{+} + \mu^{-} + X$
  Inclusive pion production: $d + Au \rightarrow \pi + X$

- Mutual consistency between the data sets is necessary. For example:

  - HERMES DIS data display a Q^2-dependence not in agreement with other data. Not used.

  - The forward rapidity pions from BRAHMS display tension with other data. Not used.

  - Combatibility of the neutrino-nucleus DIS data with the rest is still under discussion. *See e.g. JHEP 1007 (2010) 032, and aXiv:1012.0286.*



The Framework of EPS09

- **The bound proton PDFs $f_i(x,Q)$ in a nucleus A are defined as**

$$f_i^A(x,Q^2) \equiv R_i^A(x,Q^2)\, f_i^{\text{CTEQ6.1M}}(x,Q^2)$$

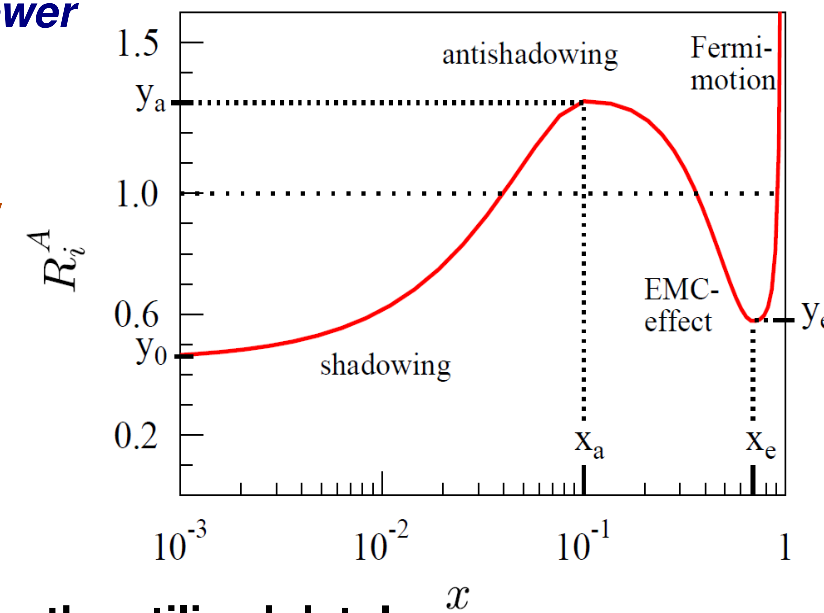
- **$\overline{\text{MS}}$, Zero-mass variable flavour number scheme**

  Our studies utilizing the SACOT-prescription (with e.g. CTEQ6.6) for the heavy quarks do not display large deviations from the zero-mass results in the regions constrained by the data.

→ ***One may safely use EPS09 also with newer sets of CTEQ6.6, CT10 , etc...***

- **The nuclear modifications are parametrized at initial scale Q_0=1.3 GeV**

$R_V^A(x,Q_0^2)$	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 flavor-separation not well constrained by the utilized data!**

The Framework of EPS09

- The optimal parameters are found by minimizing χ^2

$$\chi^2 \equiv \sum_N w_N \sum_{i\in N} \left(\frac{D_i - T_i}{\sigma_i} \right)^2$$

Some data sets are assigned an extra weight to improve the convergence of the fit. → Somewhat too optimistic nPDF errors?

- We apply the Hessian error analysis approximating the χ^2 close to the minumum by

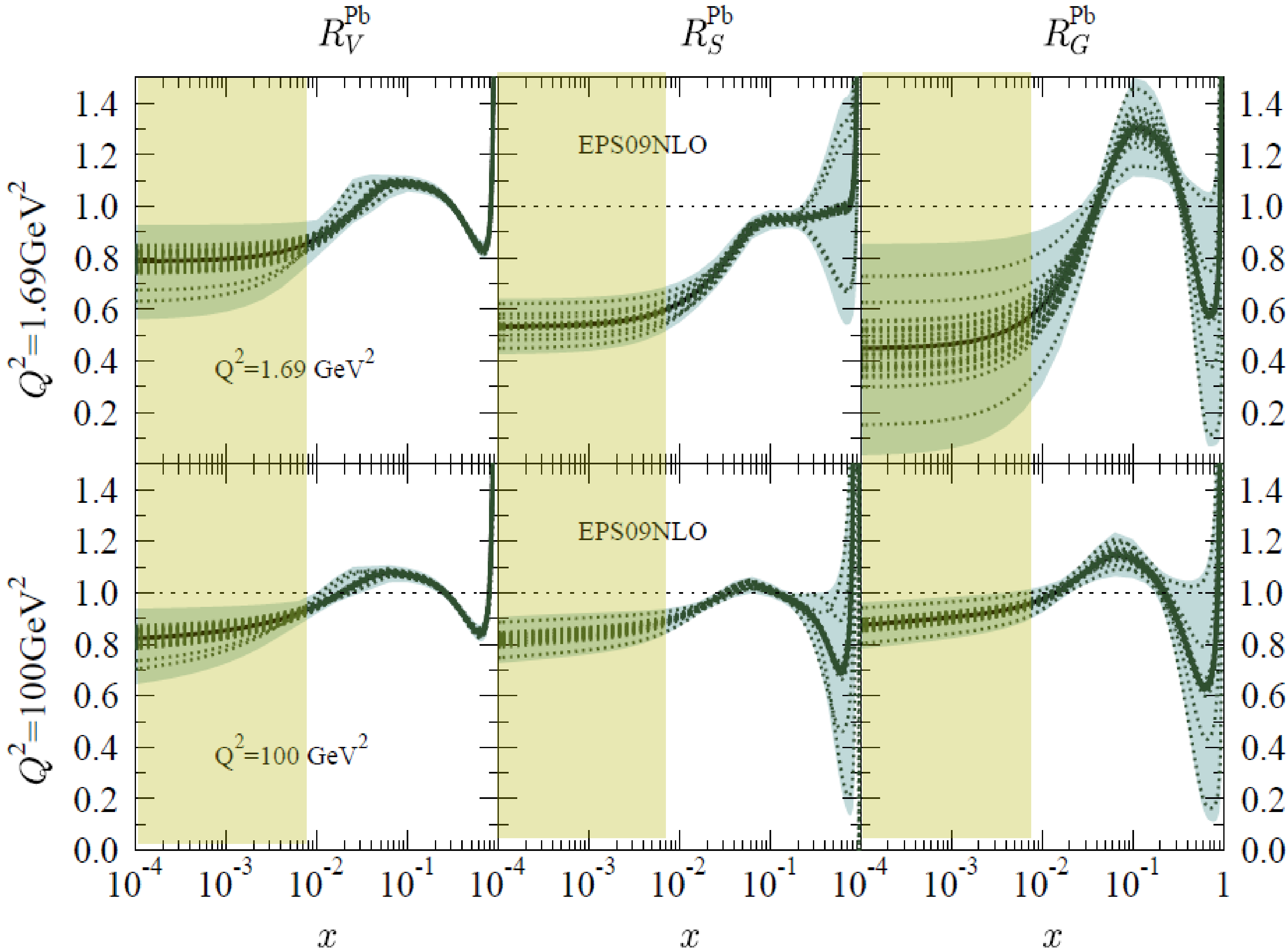
$$\chi^2(\{a_i\}) \approx \chi^2_0 + \sum_{ij} \delta a_i H_{ij} \delta a_j = \chi^2_0 + \sum_i z_i^2$$

- The uncertainty sets of nPDFs are constructed in z-space by requiring each data set to remain roughly within its ”90% confidence limits”.

- Uncertainty in any nPDF-dependend quantity X can be estimated by (S_0 is the central set and $S_i^{\pm}$ the error sets)

$$\Delta X^{+\backslash -} = \sqrt{\sum_i \max\backslash\min\left[X(S_i^+) - X(S_0), X(S_i^-) - X(S_0), 0\right]^2}$$

EPS09NLO for Lead



= No data in these x regions

Application of EPS09 to the heavy boson production at the LHC.

arXiv:1010.5392 [hep-ph]
(submitted to JHEP)

Framework: Z Production

- **We look at the leptonic channel:** $$\frac{d^2\sigma\left(\sqrt{s}, \mathrm{H}_1 + \mathrm{H}_2 \to \ell^+ + \ell^- + \mathrm{X}\right)}{dM^2 dy_R}$$

  y_R = rapidity of the lepton pair

  $M = M_Z$ = invariant mass of the lepton pair

- **Experimentally well measurable – already seen in PbPb at the LHC!**

- **In the leading order the cross-section reads (we do of course NLO)**

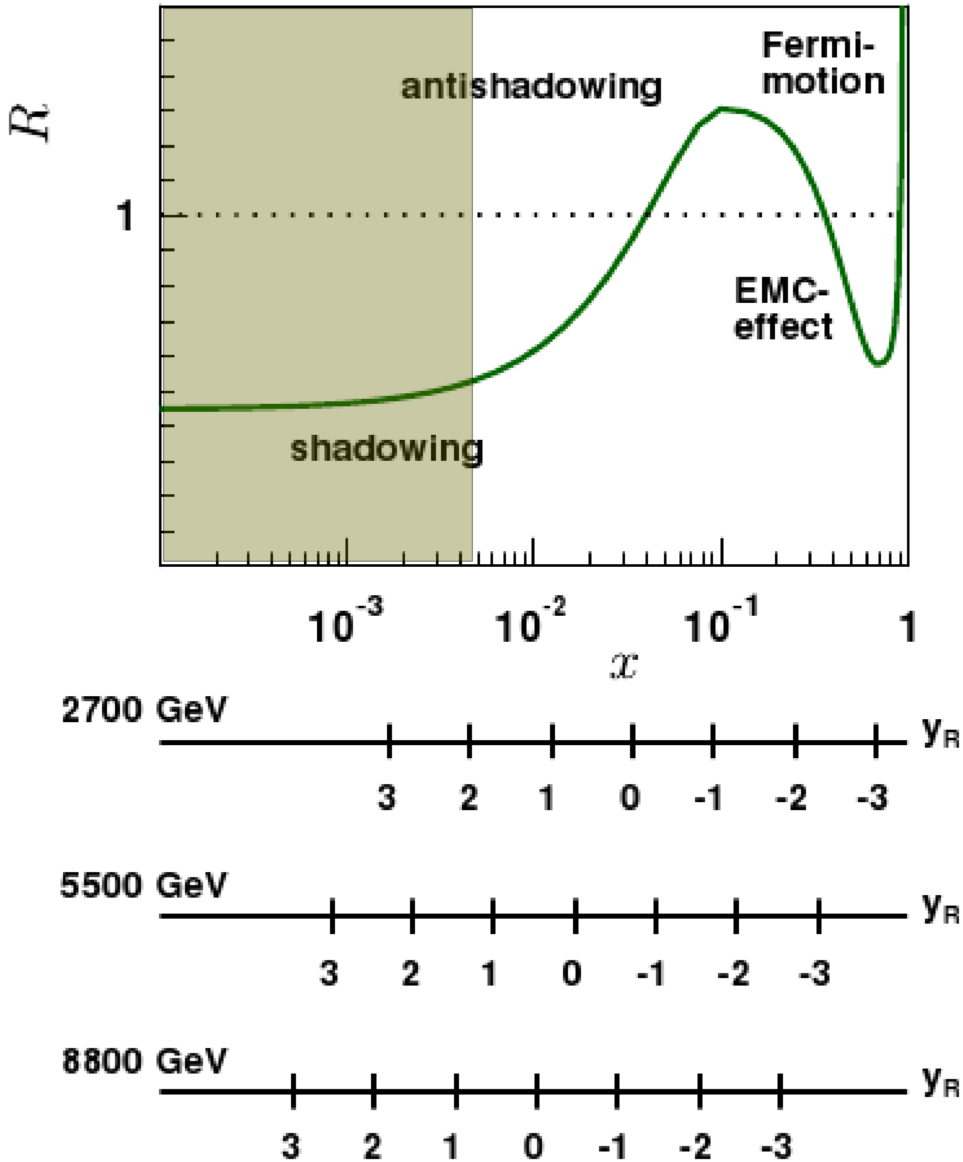
$$\frac{d^2\sigma}{dM^2 dy_R} = \frac{4\pi\alpha_{\mathrm{em}}^2}{9sM^2}\sum_q c_q^2\left[q^{(1)}(x_1, Q_f^2)\overline{q}^{(2)}(x_2, Q_f^2) + \overline{q}^{(1)}(x_1, Q_f^2)q^{(2)}(x_2, Q_f^2)\right]$$

$$x_{1,2} \equiv (M/\sqrt{s})e^{y_R, -y_R}$$

Framework: Z Production

- We look ... $+ \ell^- + X)$

  $y_R =$ ...
  $M =$ ...



- Experime ... e LHC!

- In the lea ... e NLO)

$\frac{d^2\sigma}{dM^2 dy_R} =$ ... $_f)q^{(2)}(x_2, Q_f^2)]$

$x_{1,2} \equiv$ ...

Framework: W Production

- We look at the leptonic channel: $$\frac{d^2\sigma\left(\sqrt{s}, \mathrm{H}_1 + \mathrm{H}_2 \to \begin{cases} \ell^+ + \nu \\ \ell^- + \overline{\nu} \end{cases} + \mathrm{X}\right)}{dM^2 dy_R}$$

$$\frac{d^2\sigma^{W^\pm}}{dM^2 dy_R} = \frac{\pi\alpha_{\rm em}^2}{36 s M^2 \sin^4\theta_{\rm W}} \frac{M^4}{\left(M^2 - M_W^2\right)^2 + M_W^2\Gamma_W^2} \times \sum |V_{ij}|^2 \left[q_i^{(1)}(x_1, Q_f^2)\overline{q}_j^{(2)}(x_2, Q_f^2) + \overline{q}_j^{(1)}(x_1, Q_f^2) q_i^{(2)}(x_2, Q_f^2)\right]$$

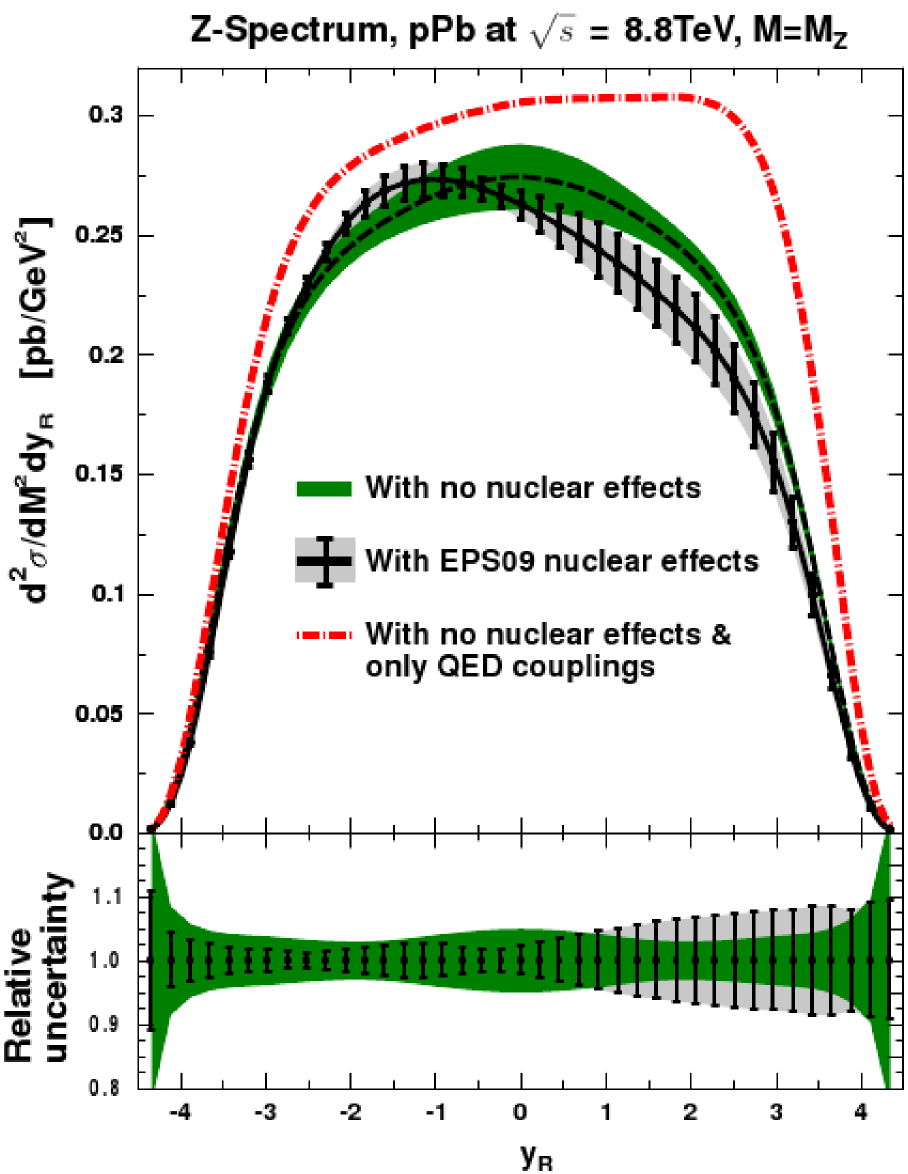
$$x_{1,2} \equiv (M/\sqrt{s})e^{y_R, -y_R}$$

- The missing neutrino momentum cannot be fully reconstructed, so this is not directly observable. However, one can show that in leading order

$$E\frac{d^3\sigma^{h_1 h_2 \to \ell^\pm + X}}{d^3p}\Bigg|_{p_T = \frac{M_W}{2}} \propto \frac{d^2\sigma^{W^\pm}}{dM^2 dy_R}\Bigg|_{M = M_W}$$

→ The results I present roughly apply also to charged lepton production.

Z Production in p+Pb Collisions

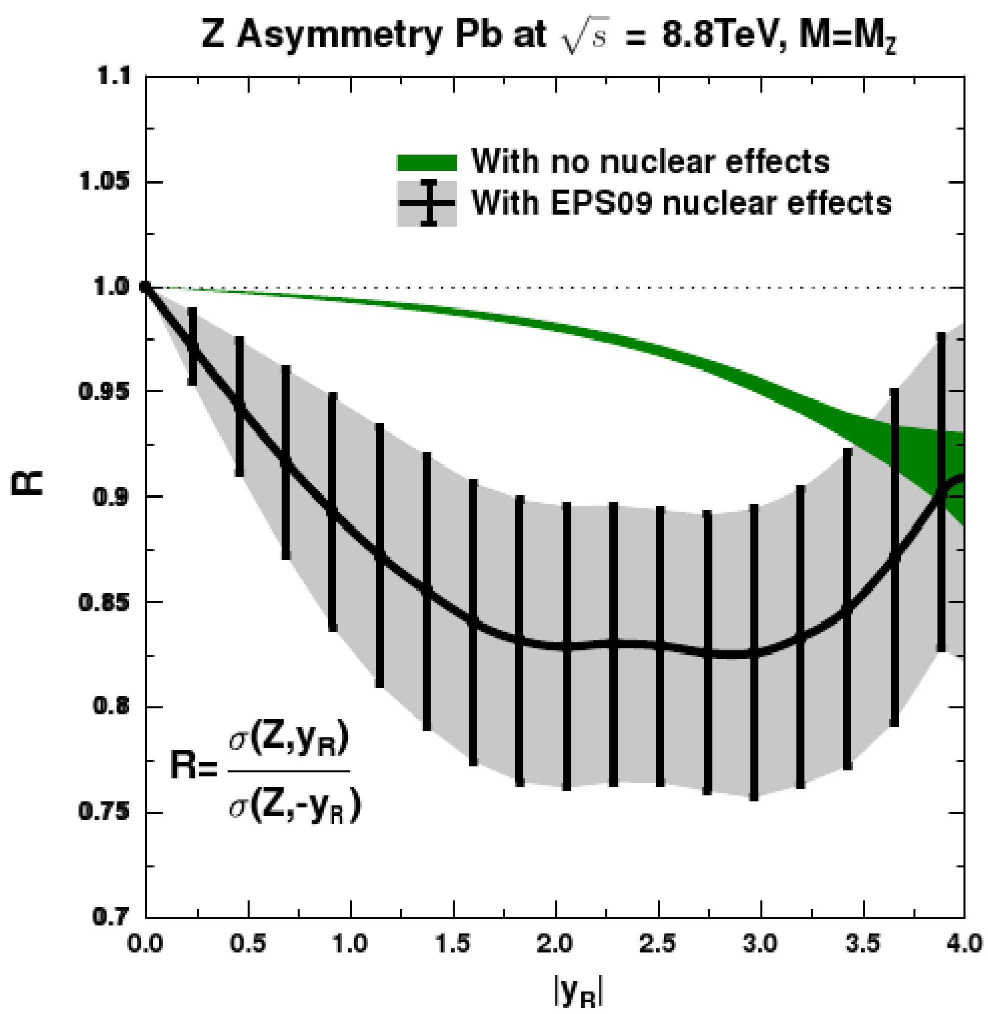


Z Production in p+Pb Collisions

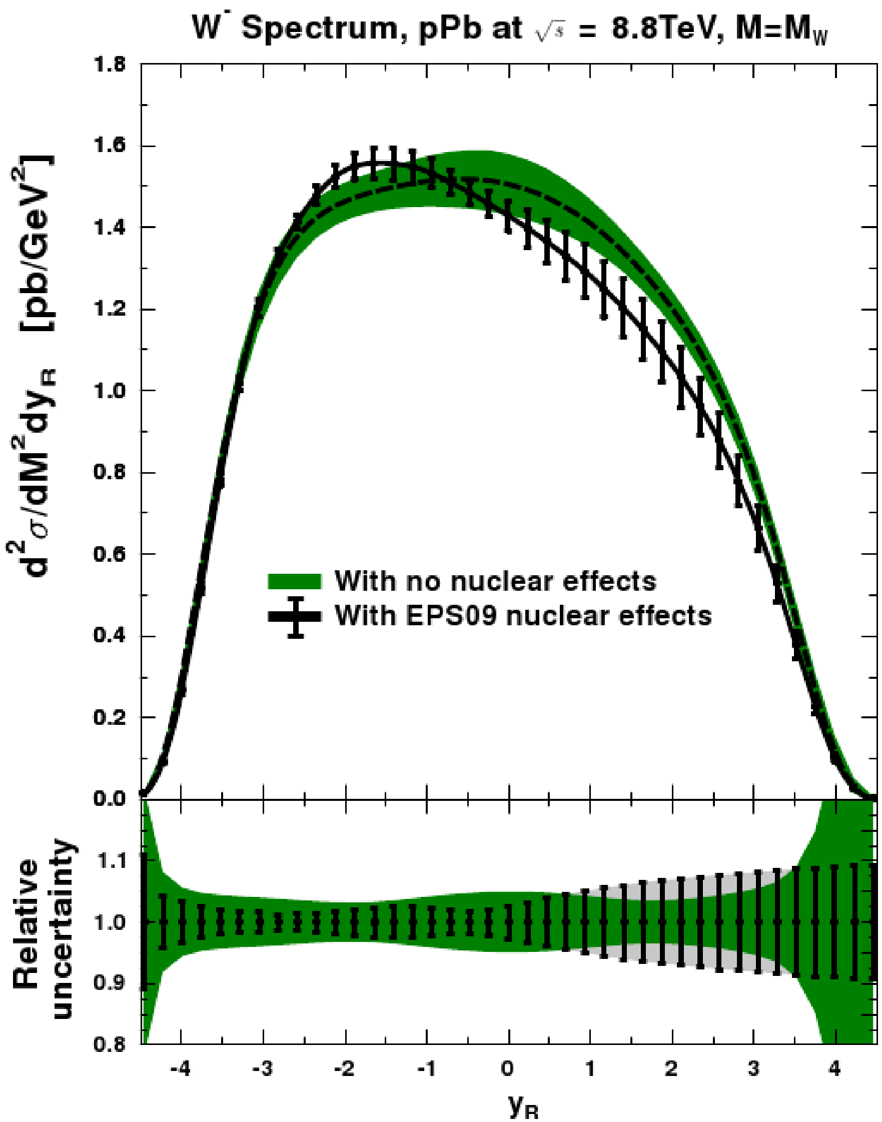
- Look at the ratio

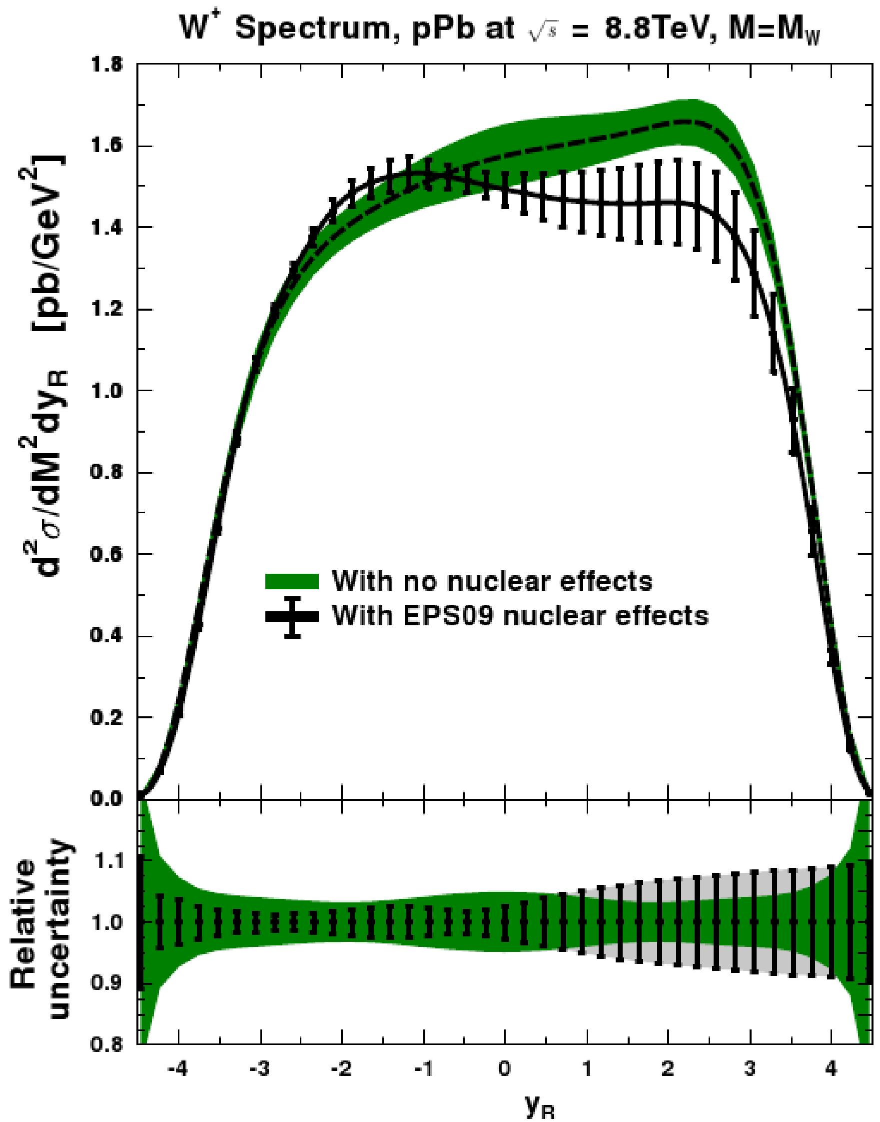
$$\frac{d^2\sigma^{Z,y_R}}{dM^2dy_R} \Big/ \frac{d^2\sigma^{Z,-y_R}}{dM^2dy_R}$$

- Sizable effect from nuclear Modifications to the PDFs!
- The free proton uncertainties cancel to large extent!
- No normalization problems (e.g. luminosity)



W Production in p+Pb Collisions

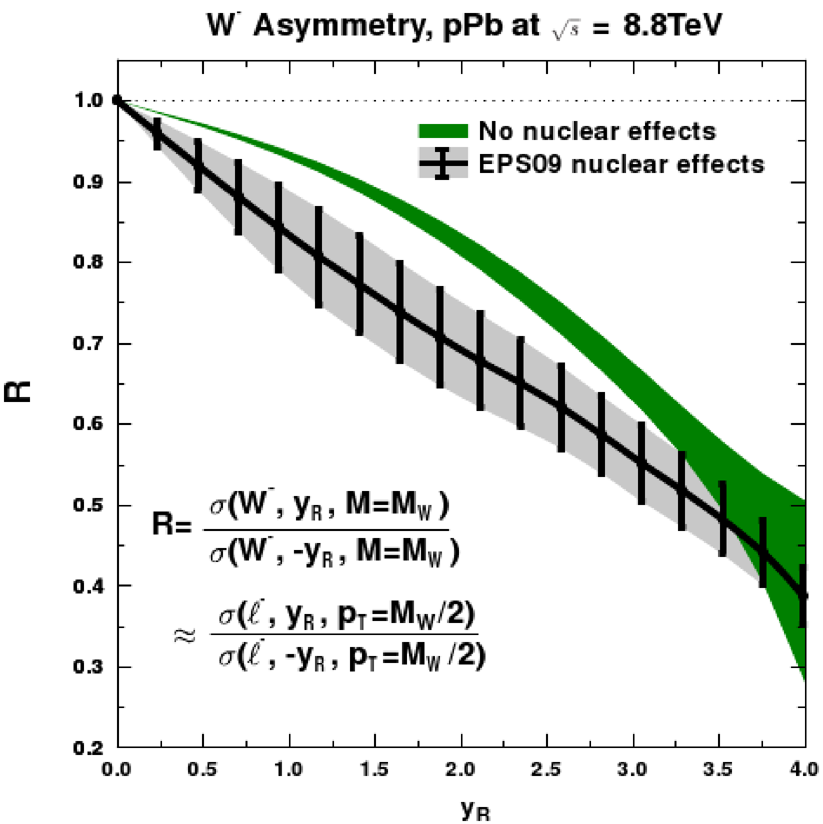


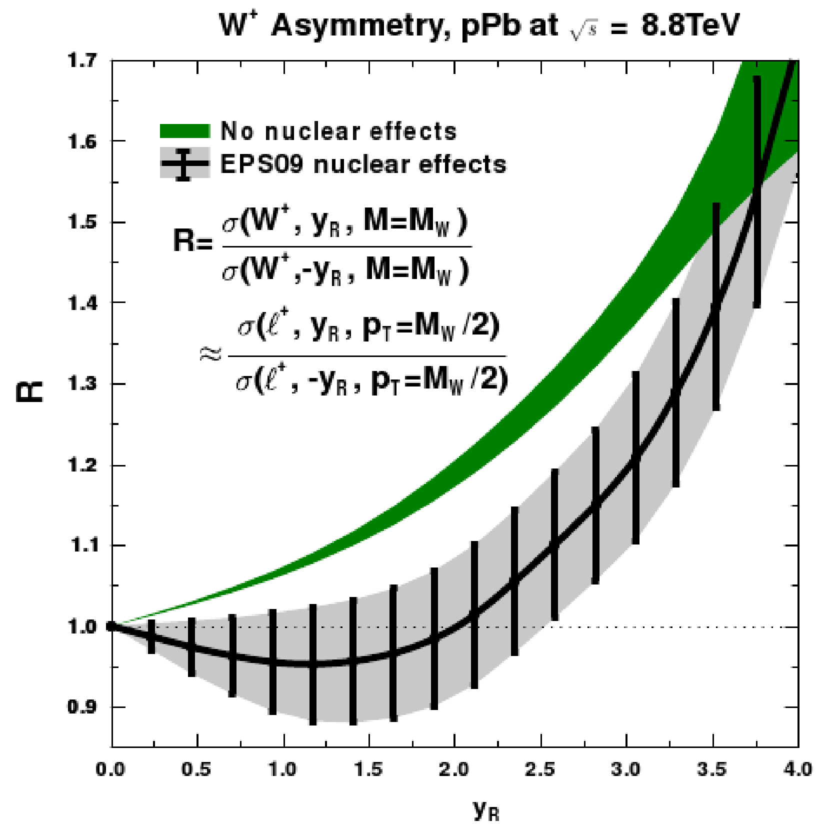


W Production in p+Pb Collisions

- The nuclear effect in rapidity asymmetry ratio is much smaller than in Z production.

$$\frac{d^2\sigma^{W^\pm,y_R}}{dM^2dy_R} \Big/ \frac{d^2\sigma^{W^\pm,-y_R}}{dM^2dy_R}$$





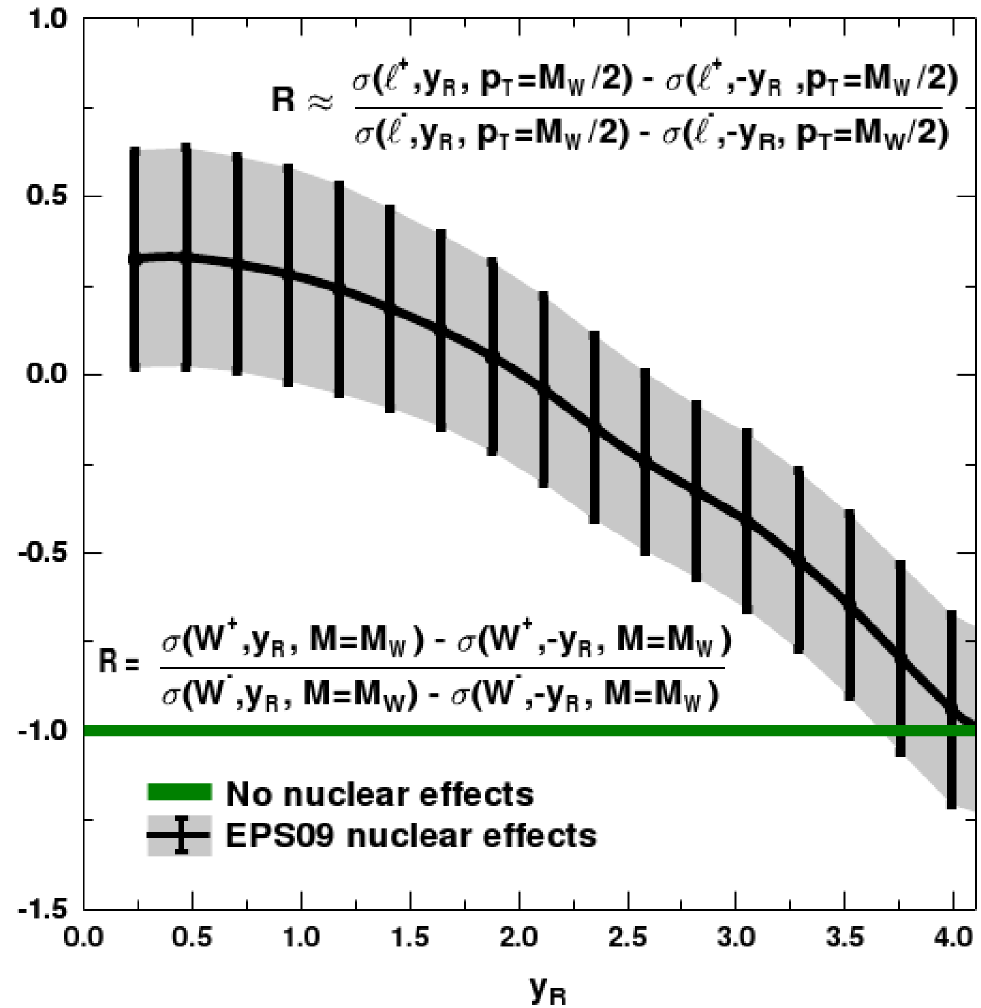
W Production in p+Pb Collisions

- Look at the combination $$\left[\frac{d^2\sigma^{W^+,y_R}}{dM^2dy_R} - \frac{d^2\sigma^{W^+,-y_R}}{dM^2dy_R}\right] \Big/ \left[\frac{d^2\sigma^{W^-,y_R}}{dM^2dy_R} - \frac{d^2\sigma^{W^-,-y_R}}{dM^2dy_R}\right]$$

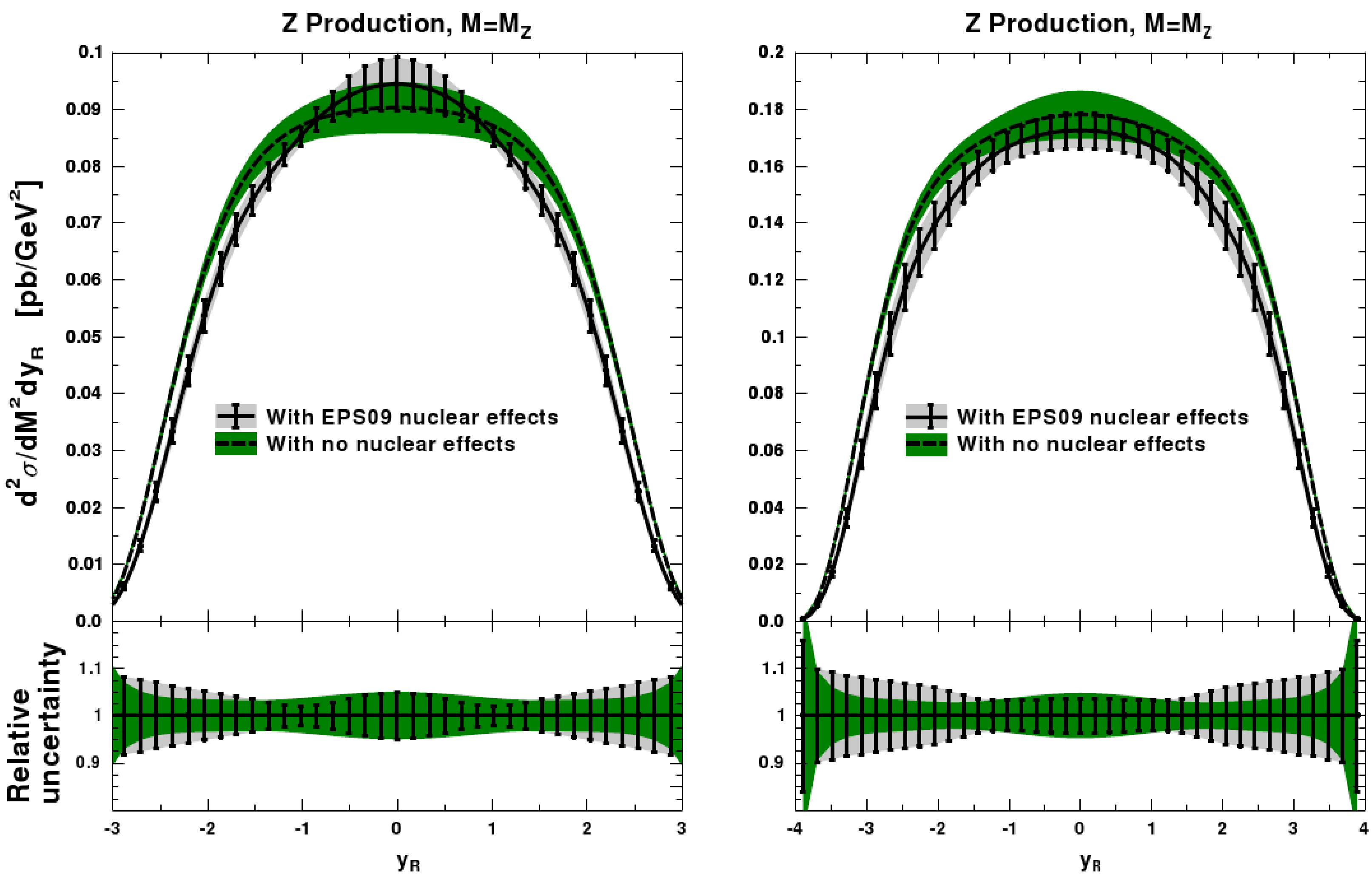
- Large nuclear effect with a large uncertainty already at the midrapidity.

- Due to the “flavor-blind” parametrization of the nuclear modifications in EPS09, these uncertainties are, however, only lower limits.

Another Asymmetry, pPb at $\sqrt{s}$ = 8.8TeV

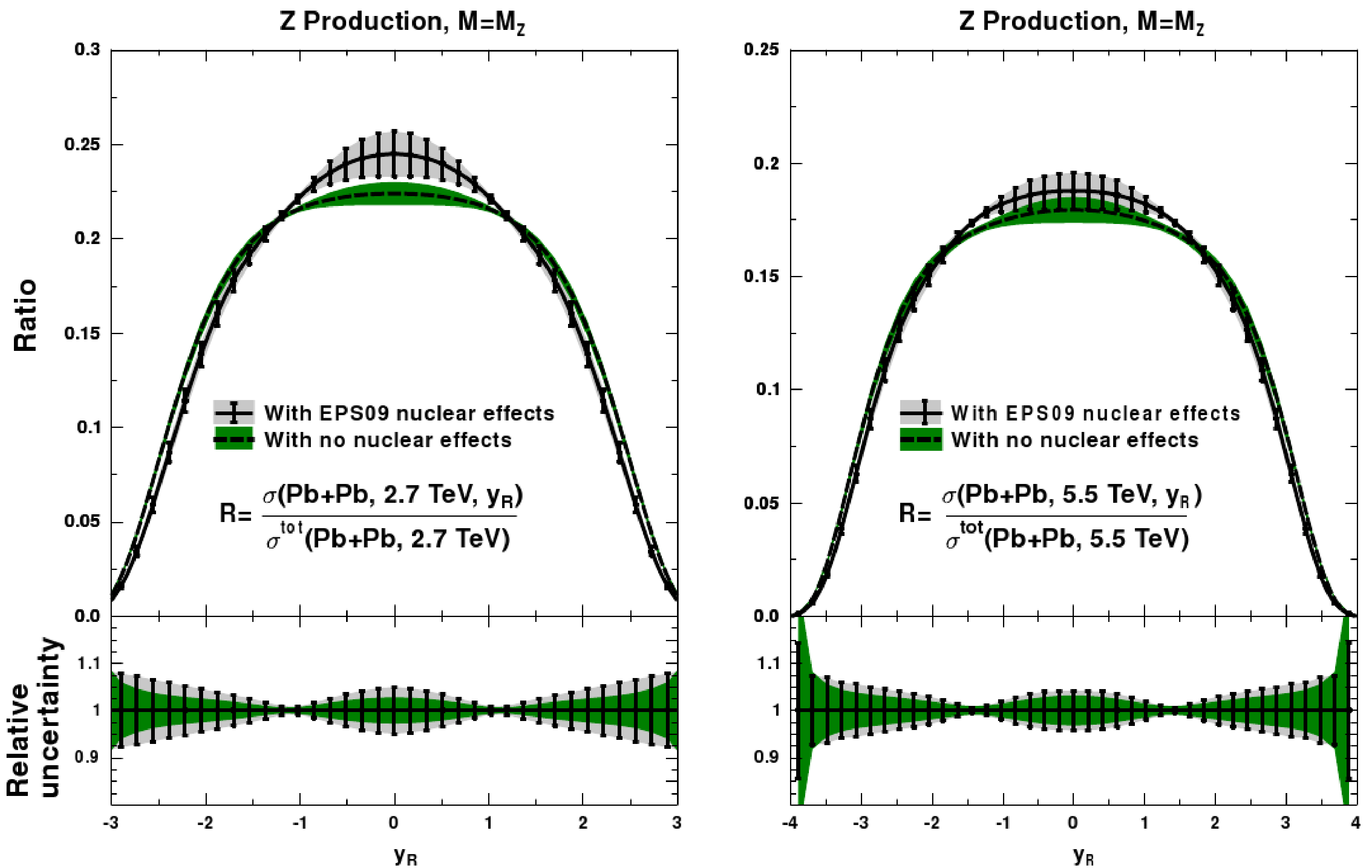


Z Production in Pb+Pb Collisions



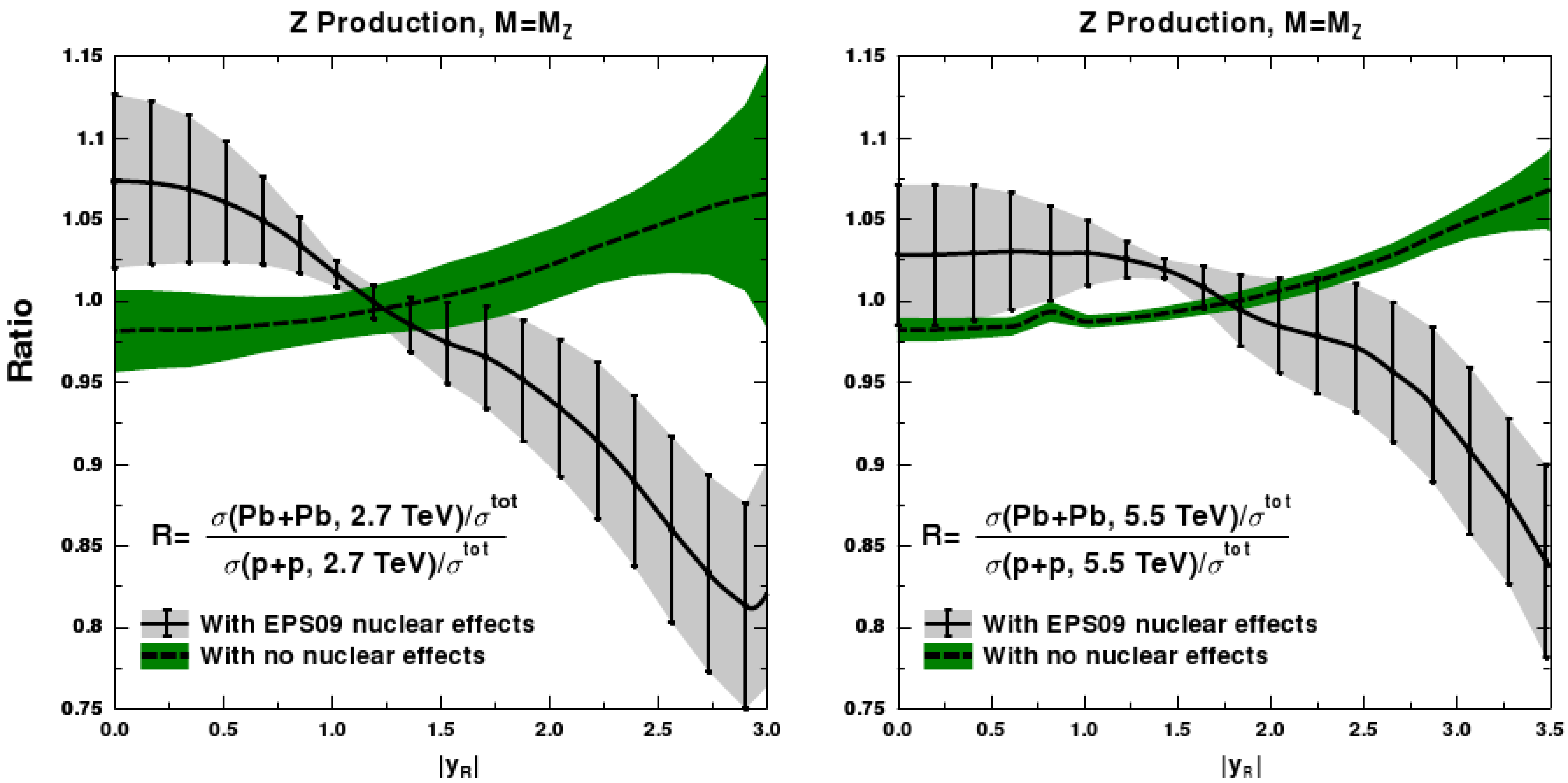
- Unlike in p+Pb, in Pb+Pb the spectra are symmetric in rapidity.

Z Production in Pb+Pb Collisions



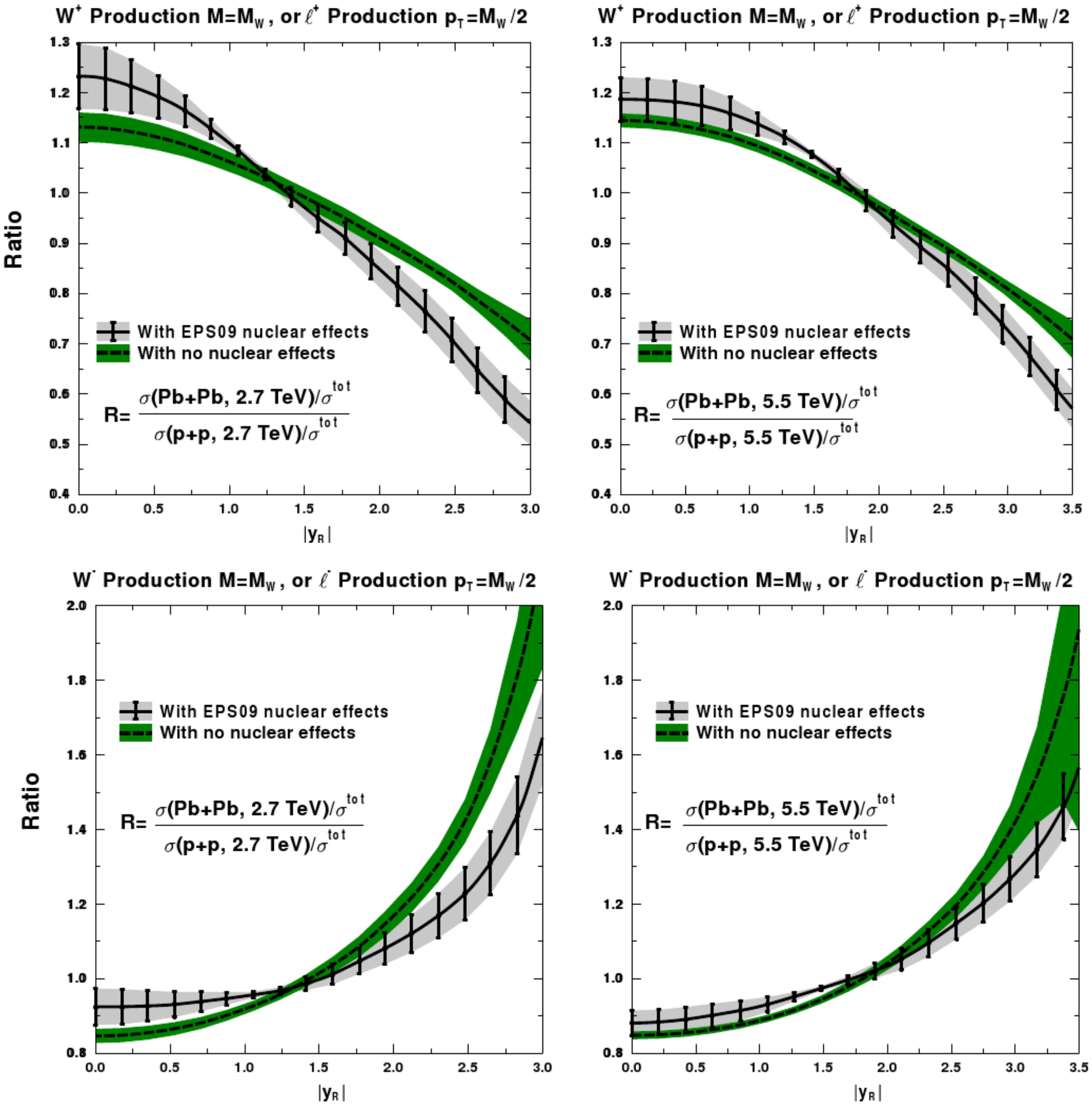
- Normalizing by the rapidity-integrated cross-section reduces especially the free proton uncertainties.

Z Production in Pb+Pb Collisions



- Normalizing by a reference cross-section from p+p collisions brings up the nuclear effects. The free proton uncertainties estimated from a interpolation 7 Tev → 2.7 & 5.5 TeV.

W Production in Pb+Pb Collisions



Conclusions

- The p+Pb collisions at the LHC would be extremely useful to study the nuclear effects in PDFs. Large effects expected in quantities:

$$\frac{d^2\sigma^{Z,y_R}_{\rm pPb}}{dM^2dy_R} \Big/ \frac{d^2\sigma^{Z,-y_R}_{\rm pPb}}{dM^2dy_R}$$

$$\left[\frac{d^2\sigma^{W^+,y_R}}{dM^2dy_R} - \frac{d^2\sigma^{W^+,-y_R}}{dM^2dy_R}\right] \Big/ \left[\frac{d^2\sigma^{W^-,y_R}}{dM^2dy_R} - \frac{d^2\sigma^{W^-,-y_R}}{dM^2dy_R}\right]$$

- Nuclear effects in Pb+Pb are more difficult to extract. A baseline from p+p collisions would be needed to better see the nuclear effects in PDFs. The Z production probably more useful than the W production.