

Nuclear pQCD at the FCC energies

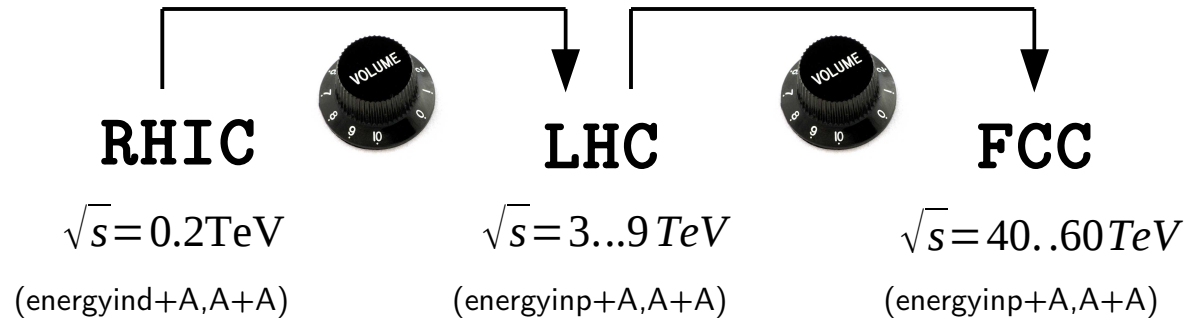
Hannu Paukkunen

University of Jyväskylä & Helsinki Institute of Physics, Finland



**Hard processes in nuclear collisions – what
have we learned from the LHC?**

Nuclear machines – today vs. FCC

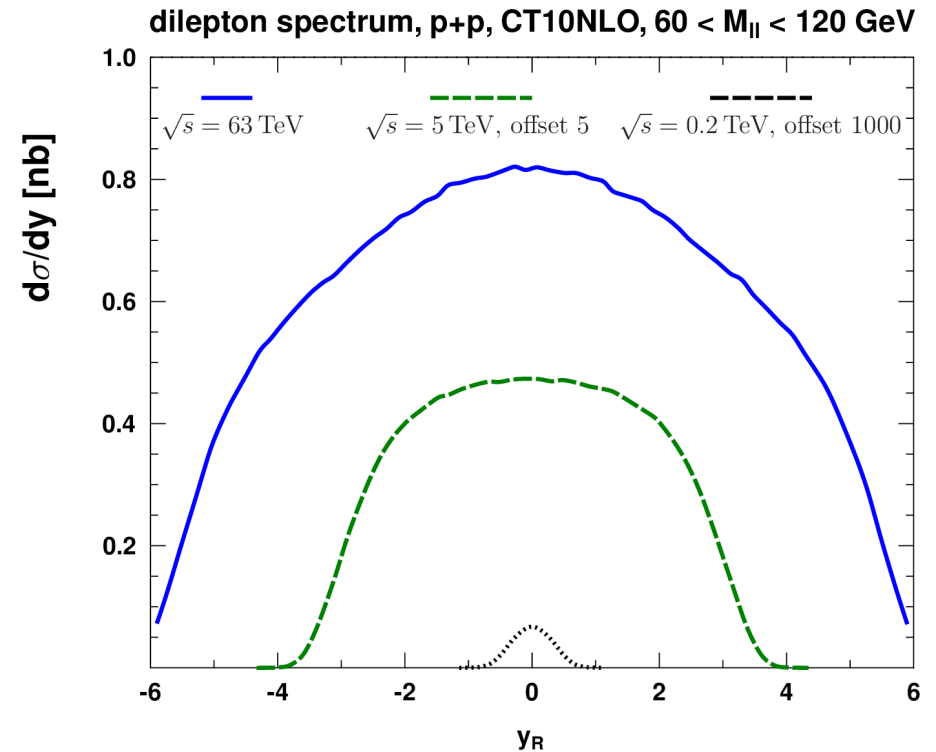


- Naively, for fixed invariant mass M and rapidity y of the final state

$$x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y}$$

➔ Order of magnitude increase in \sqrt{s} ,
order of magnitude more reach in x

- However, also larger cross sections and broader rapidity distributions.
Example: Z boson production



Nuclear machines – today vs. FCC

- Any projections of p+Pb and Pb+Pb to FCC realm call for justifications from the LHC
- Relevant for this talk, do we (or do we not) have evidence for factorization in p(Pb)+Pb ?

$$\sigma^{A+B \rightarrow \mathcal{O}} = \sum_{i,j} \underbrace{f_i^A(\mu_{\text{fact}}^2)}_{\text{nuclear PDFs, obey the usual DGLAP}} \otimes \underbrace{\hat{\sigma}^{i+j \rightarrow \mathcal{O}}(\mu_{\text{fact}}^2, \mu_{\text{ren}}^2)}_{\text{usual pQCD coefficient functions}} \otimes \underbrace{f_j^B(\mu_{\text{fact}}^2)}_{\text{nuclear PDFs, obey the usual DGLAP}}$$

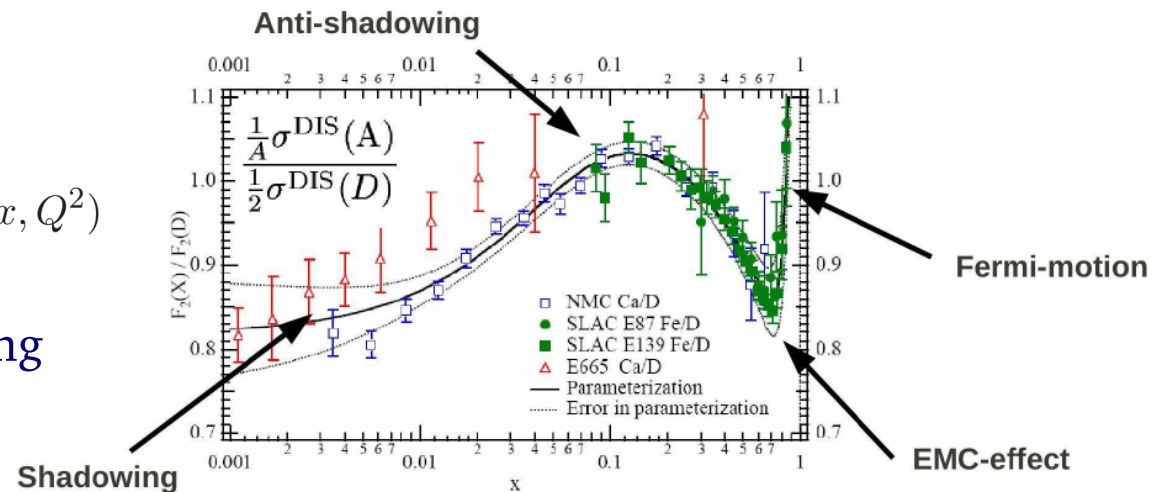
- Two kinds of effects expected:

a trivial isospin effect:

$$f_i^A(x, Q^2) = \left(\frac{Z}{A}\right) f_i^{\text{p},A}(x, Q^2) + \left(\frac{N}{A}\right) f_i^{\text{n},A}(x, Q^2)$$

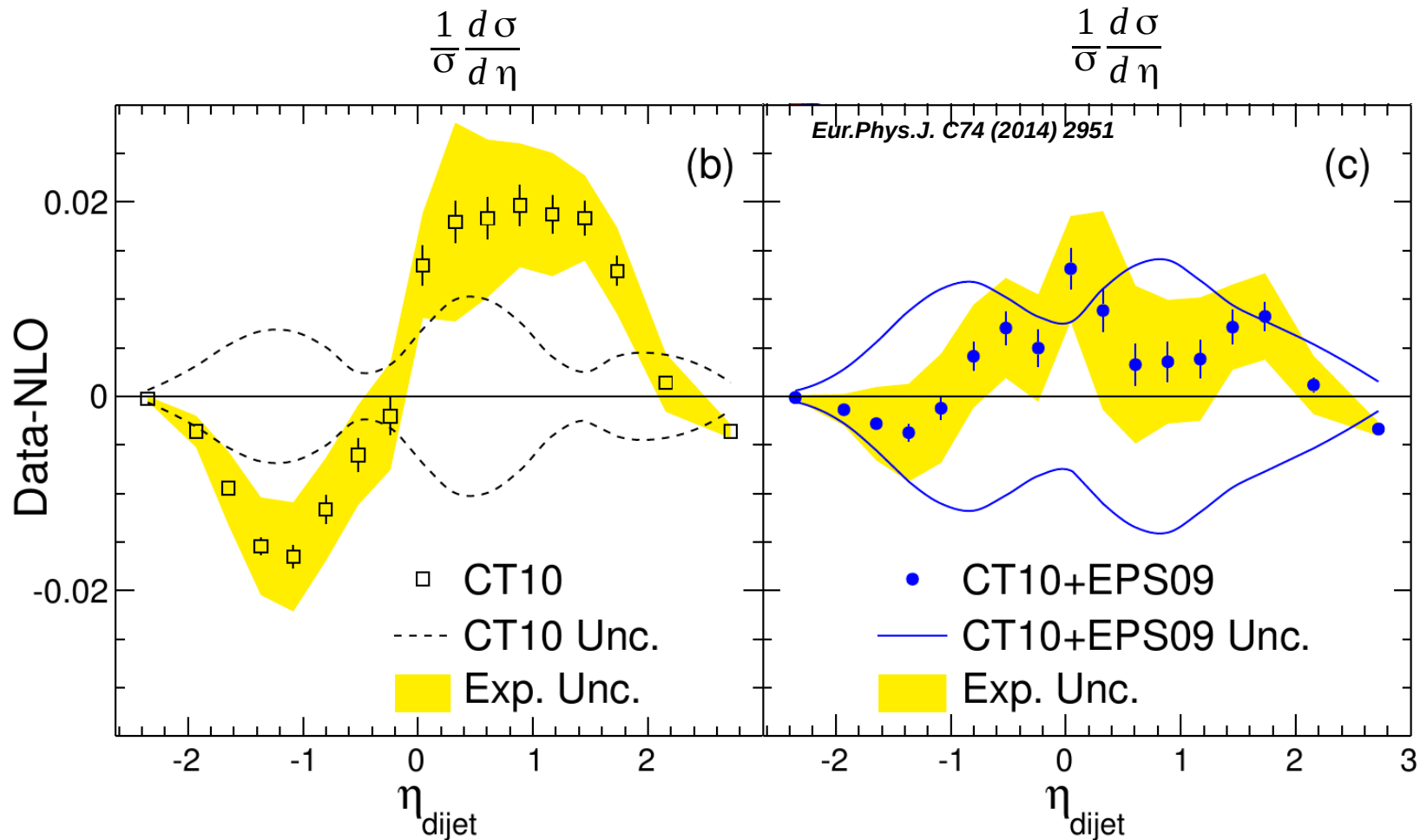
non-trivial shadowing/antishadowing
(EPS09, DSSZ, HKN07, nCTEQ)

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



Hard processes – lessons from the LHC?

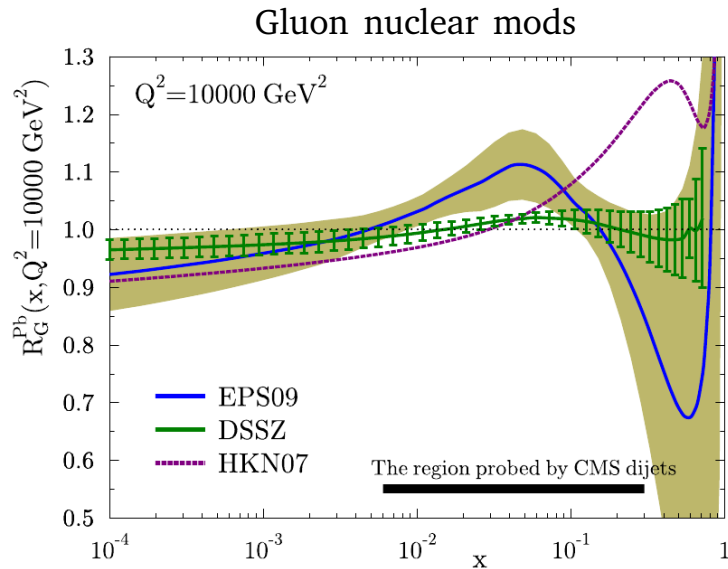
- The most compelling evidence to date for the need of nuclear PDFs at the LHC are the CMS dijets in p+Pb...



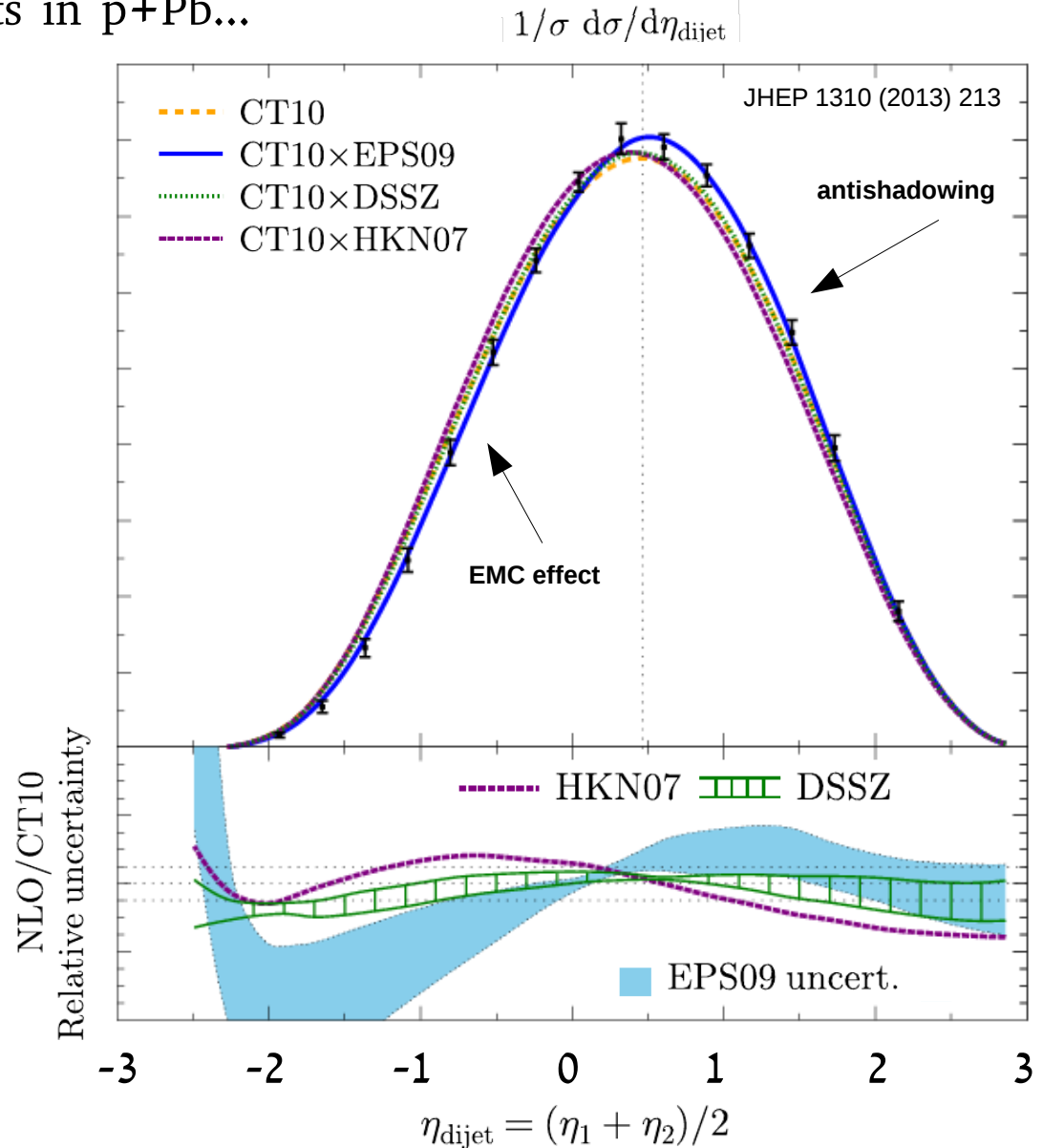
- Not very sensitive to free proton PDF uncertainties nor to the NNLO corrections at central region $-2 \lesssim \eta_{\text{dijet}}^{\text{cms}} \lesssim 2$ [JHEP 1310 (2013) 213]

Hard processes – lessons from the LHC?

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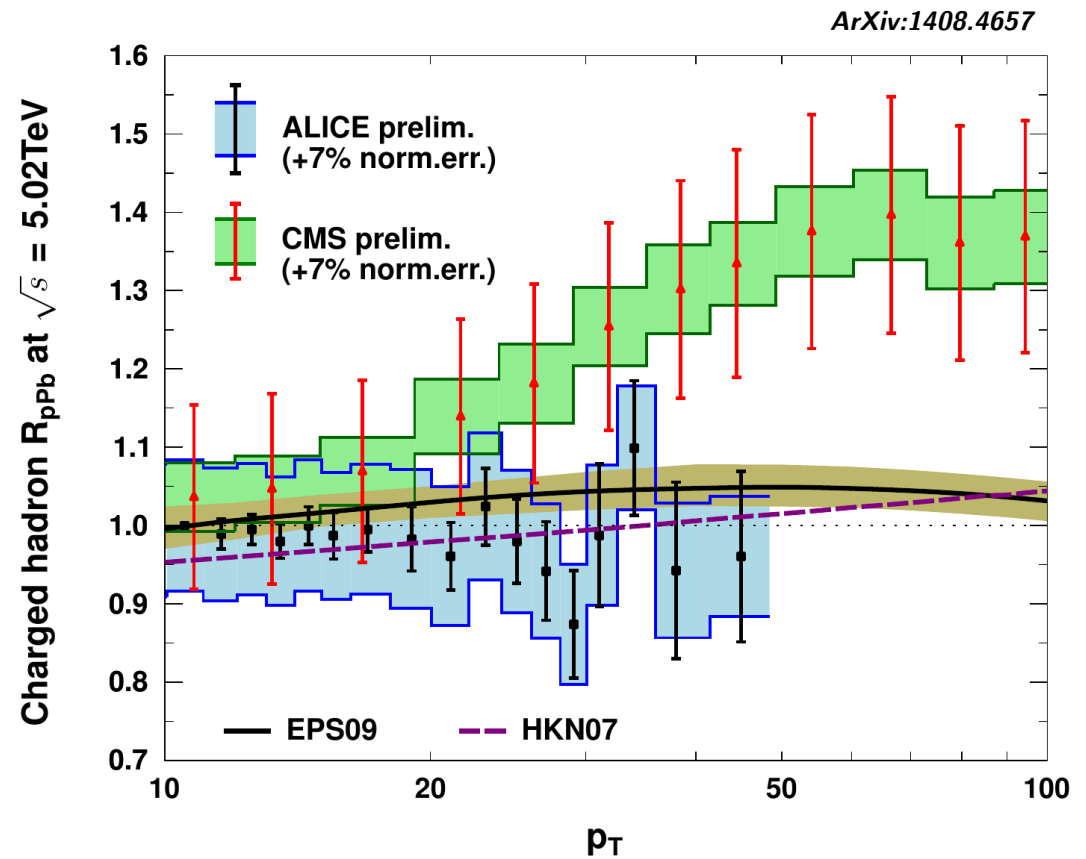


The data supports the gluon antishadowing



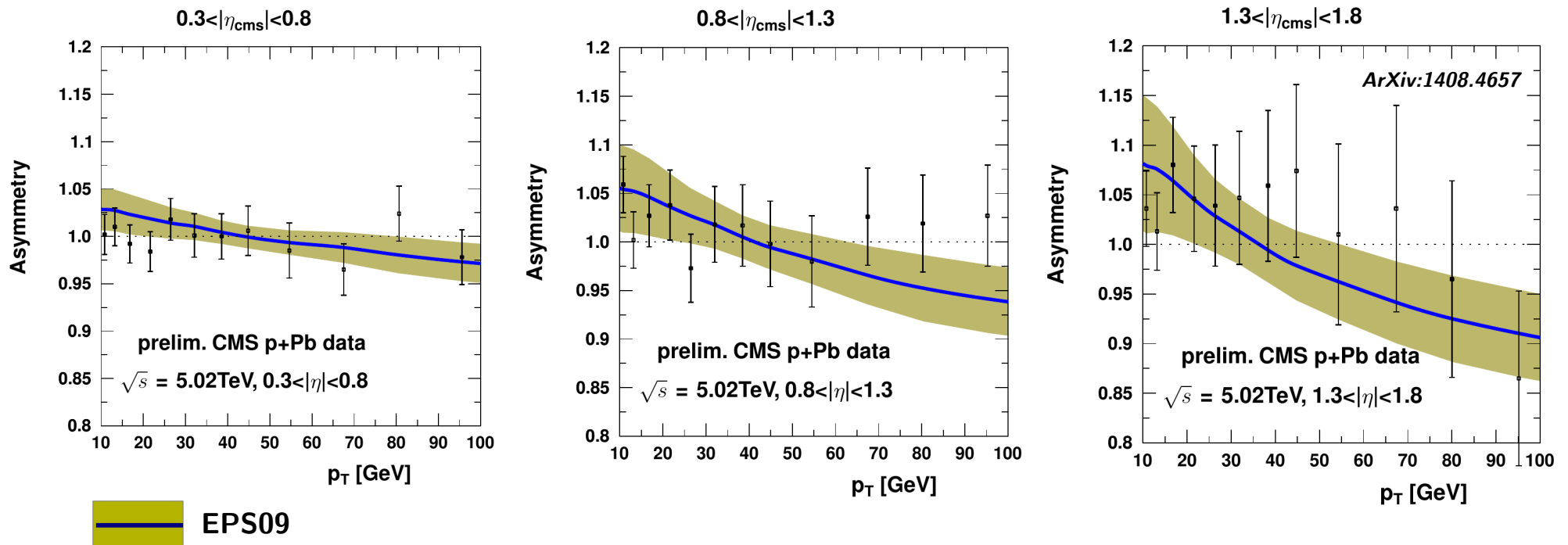
Hard processes – lessons from the LHC?

- The biggest surprise comes from the CMS as well



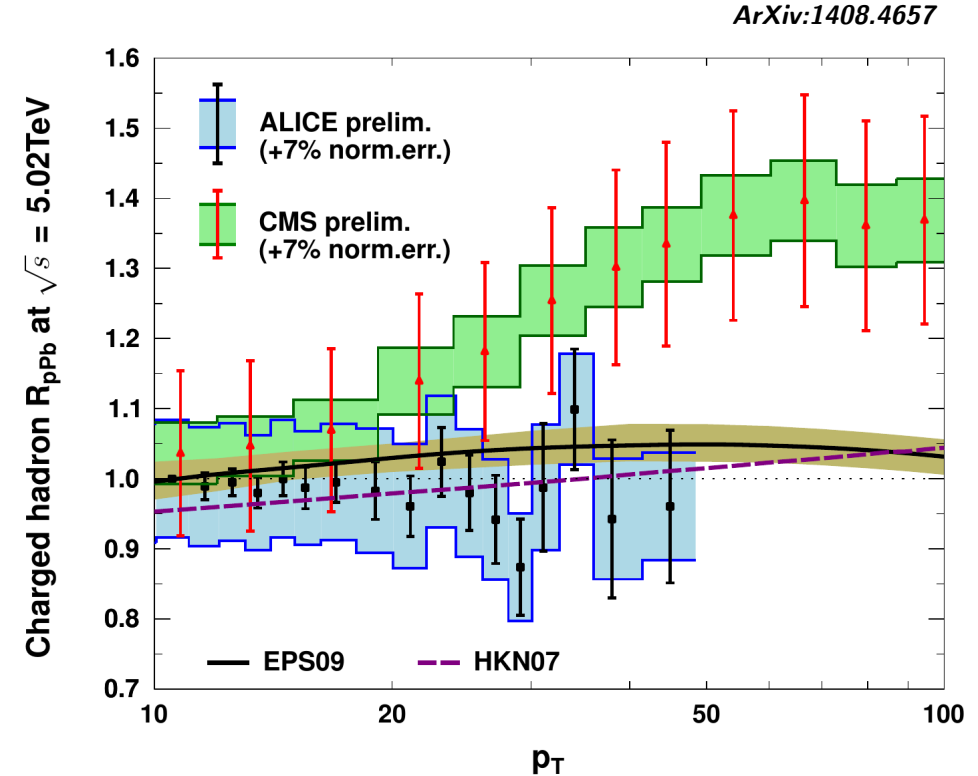
Hard processes – lessons from the LHC?

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- The enhancement at large p_T seems to be the same for p- and Pb-going directions



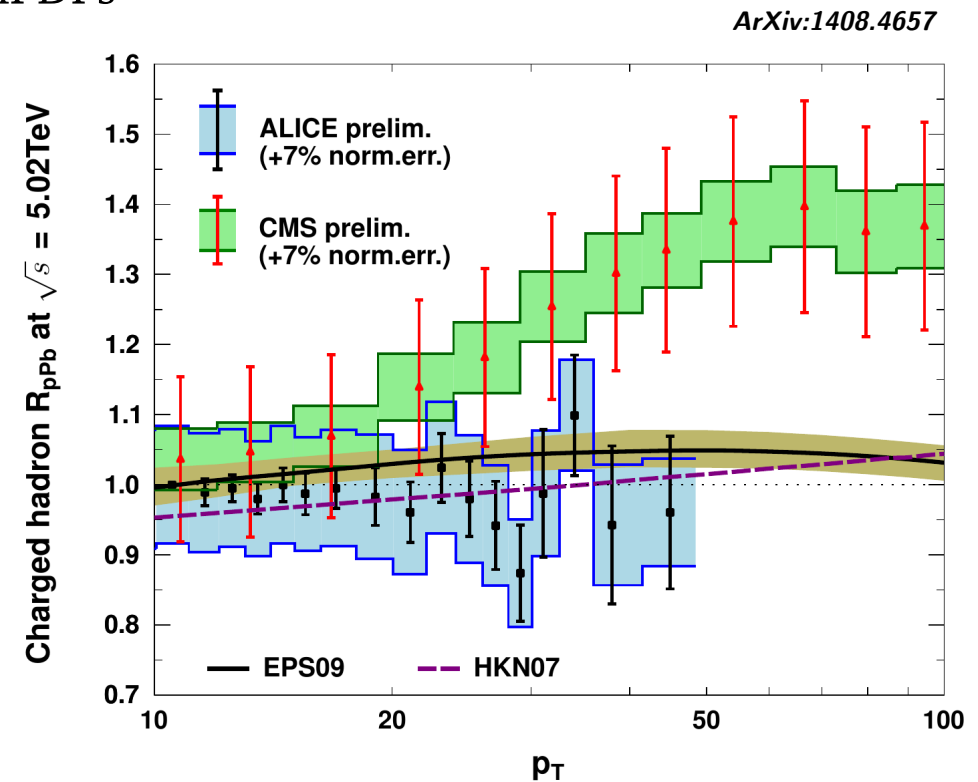
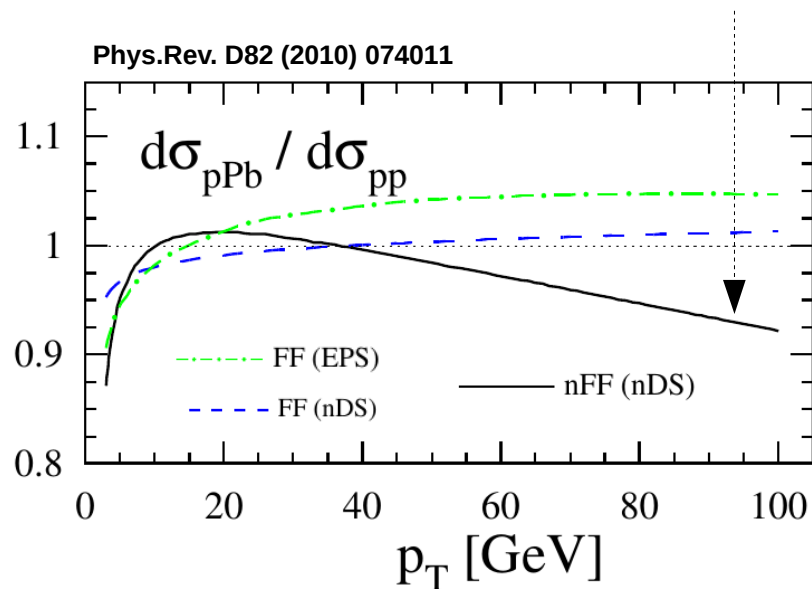
Hard processes – lessons from the LHC?

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- The CMS “anomaly” not explainable by nPDFs



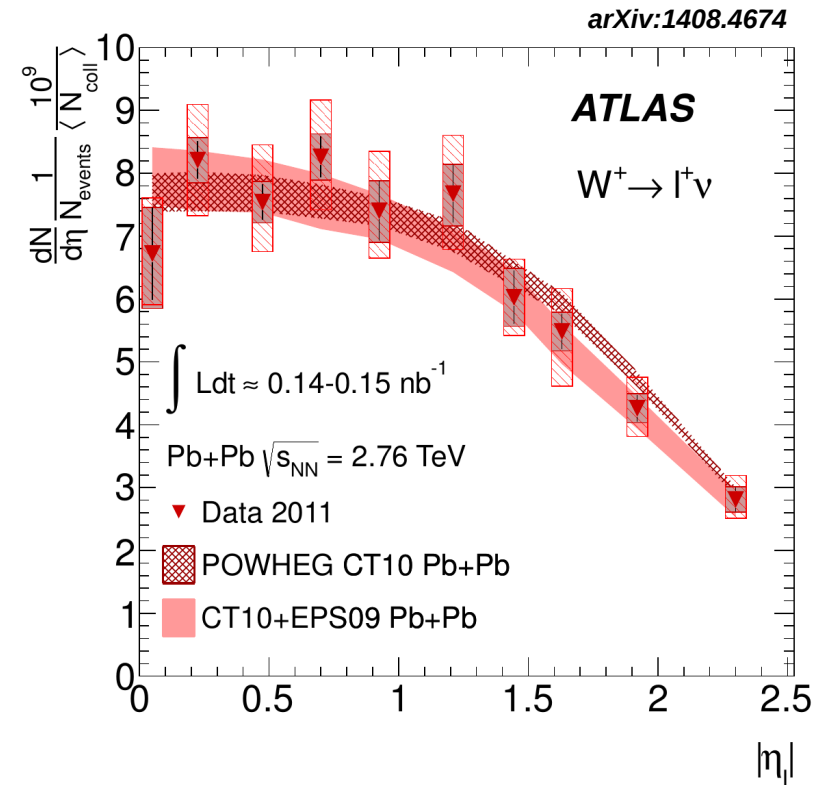
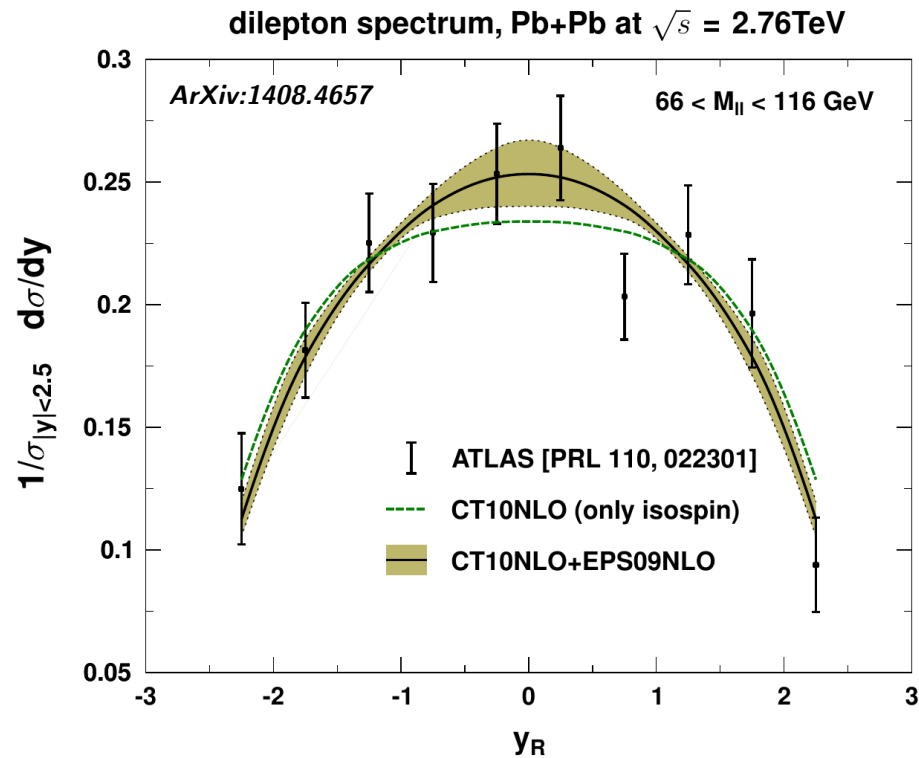
Hard processes – lessons from the LHC?

- The biggest surprise comes from the CMS as well
- The enhancement at large p_T seems to be the same for p- and Pb-going directions
- The CMS “anomaly” not explainable by nPDFs
- The nuclear effects in fragmentation functions suggested in [Phys.Rev. D81 (2010) 054001] seem to cause suppression rather than an enhancement



Hard processes – lessons from the LHC?

- The electroweak “standard candles” (=Z and W): Pb+Pb in line with factorization

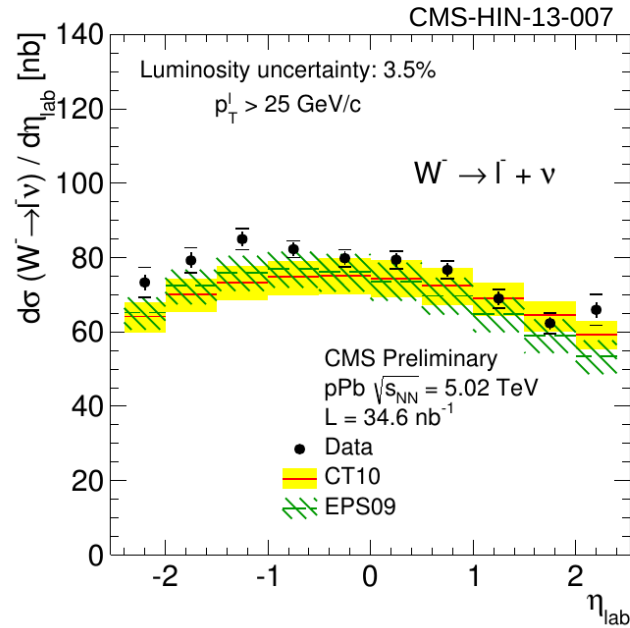
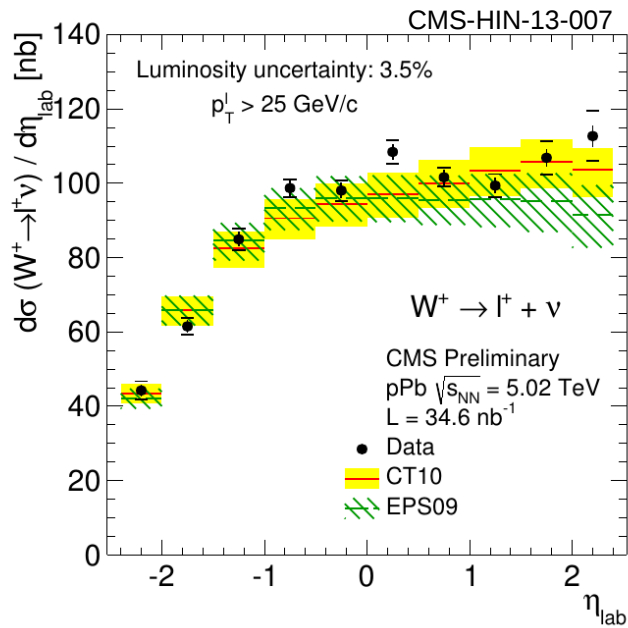


- Somewhat more statistics (but not enormously more!) needed to make detailed conclusions

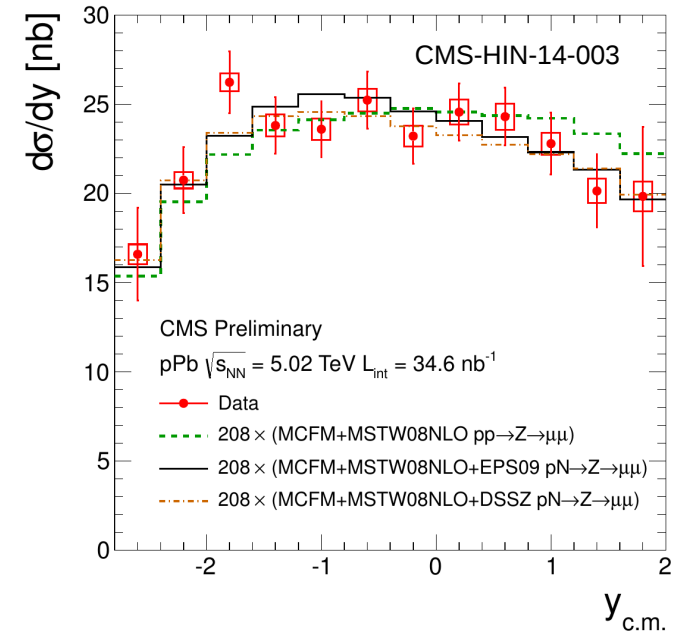
Hard processes – lessons from the LHC?

- The electroweak “standard candles” (=Z and W): pPb data more precise than PbPb

The production cross sections for $W^+ \rightarrow l^+ \nu$ (left) and $W^- \rightarrow l^- \nu$ (right).



Z bosons in pPb collisions



- Some deviations from the predictions in W production – qualitative agreement in Z distribution

Hard processes – lessons from the LHC?

- My opinion: the current LHC p+Pb and Pb+Pb data roughly in line with

$$\sigma^{A+B \rightarrow \mathcal{O}} = \sum_{i,j} \underbrace{f_i^A(\mu_{\text{fact}}^2)}_{\text{nuclear PDFs, obey the usual DGLAP}} \otimes \underbrace{\hat{\sigma}^{i+j \rightarrow \mathcal{O}}(\mu_{\text{fact}}^2, \mu_{\text{ren}}^2)}_{\text{usual pQCD coefficient functions}} \otimes \underbrace{f_j^B(\mu_{\text{fact}}^2)}_{\text{nuclear PDFs, obey the usual DGLAP}}$$

but inconclusive, for the moment. More data will come and will eventually tell.

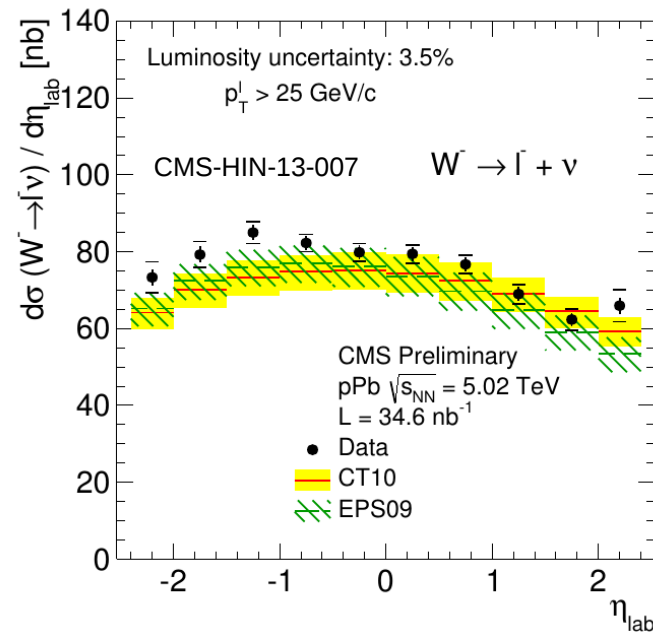
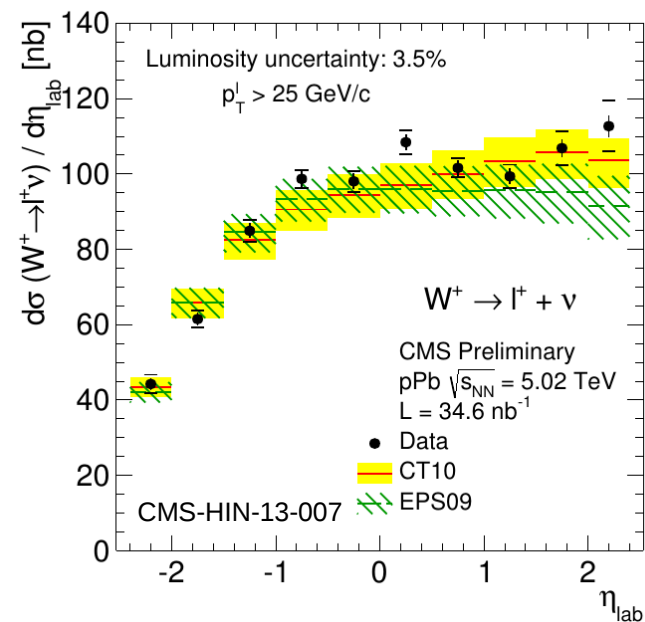
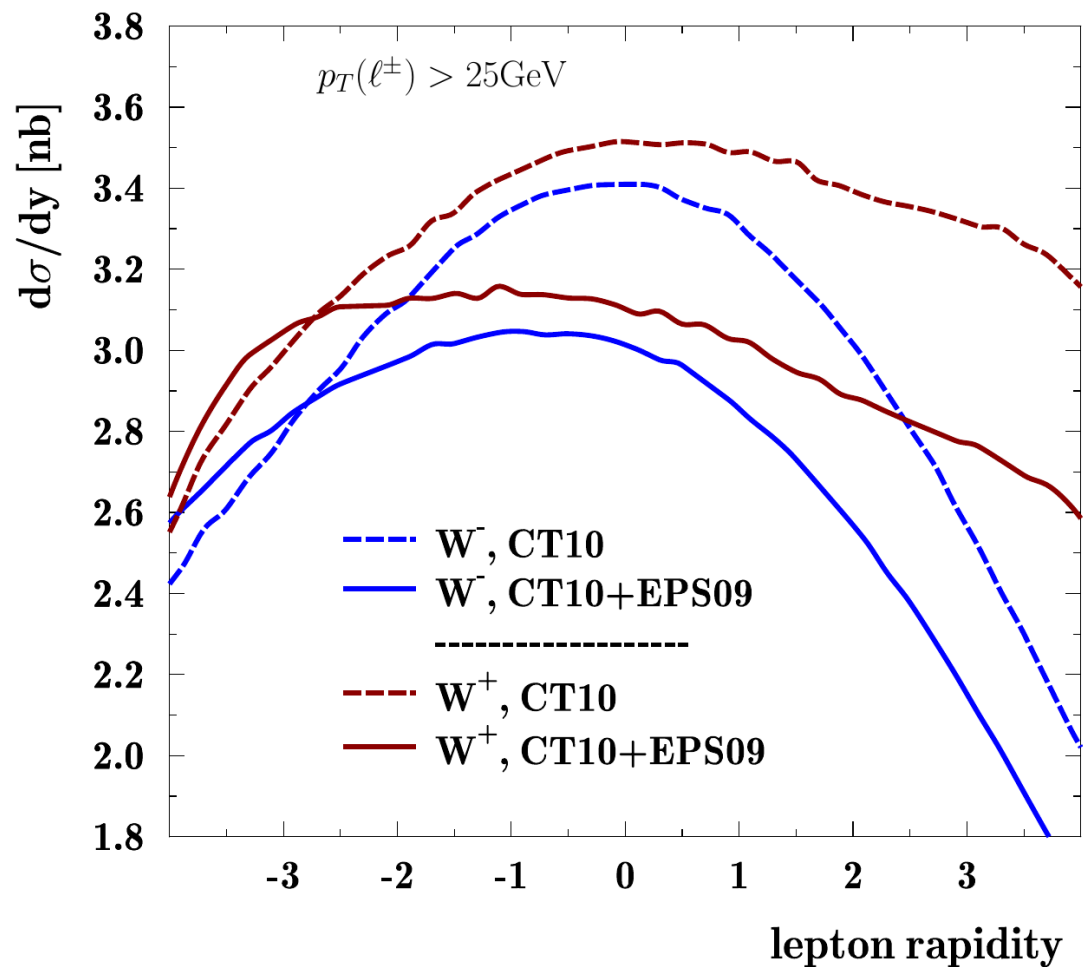
- Many theoretical improvements to make and to be considered utilizing the LHC data
 - GM-VFN scheme (already included in DSSZ, EPS to follow in next update)
 - NNLO corrections to nPDFs (will be done, sooner or later)
 - Photon nPDFs (currently cannot be constrained by other than sum rules)
 - LHC data may allow much more reliable flavor decomposition (e.g. $R_{u_{\text{valence}}} \neq R_{d_{\text{valence}}}$)
 - Region with $x > 1$ (momentum sum rule not as strict as for free proton)
 - etc...

Projections to FCC (in pPb and ePb)

Projections: From LHC to FCC

- Inclusive charged lepton spectrum from W decays

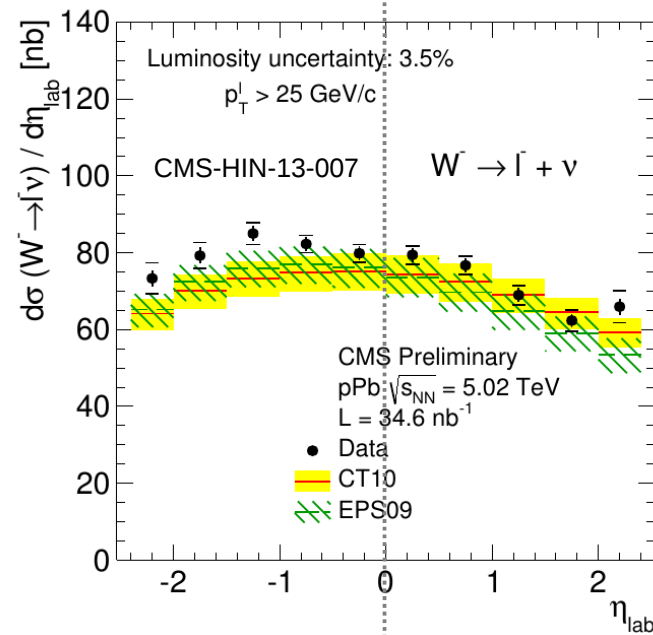
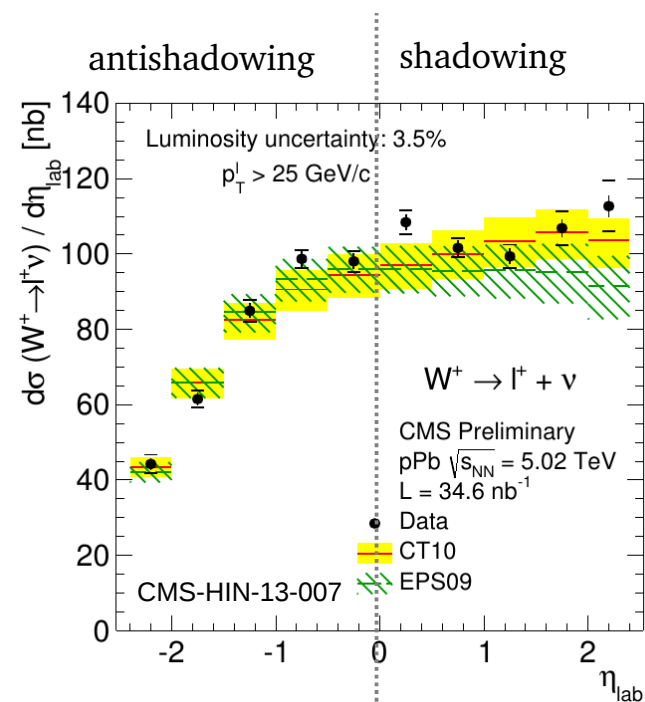
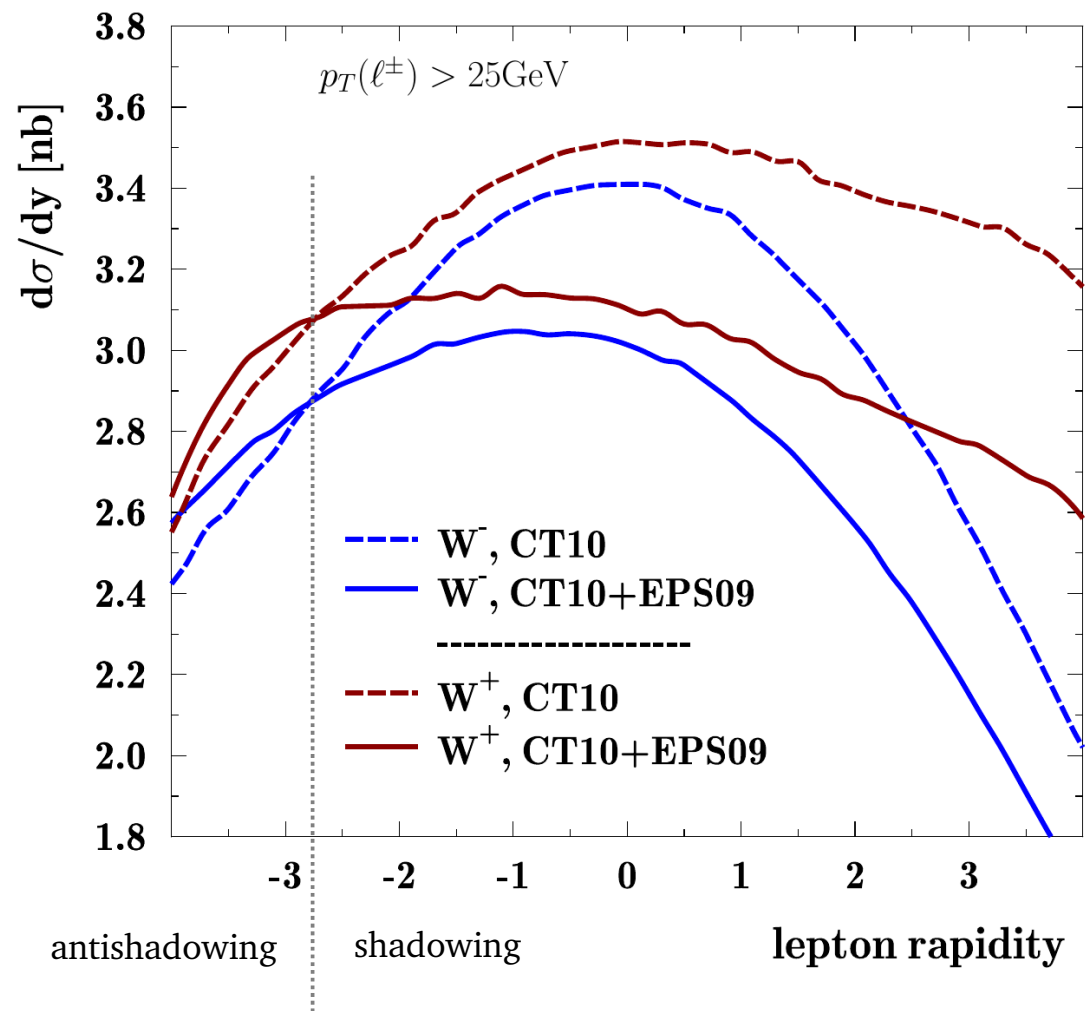
ℓ^\pm production, p+Pb, $\sqrt{s} = 63\text{TeV}$



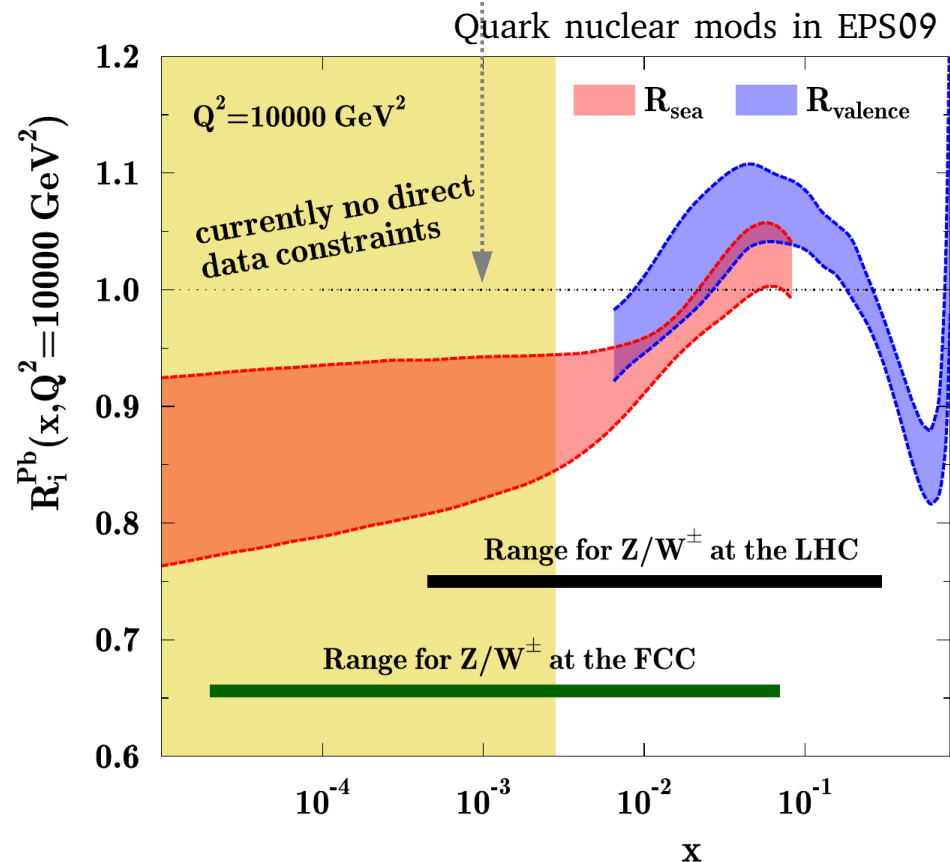
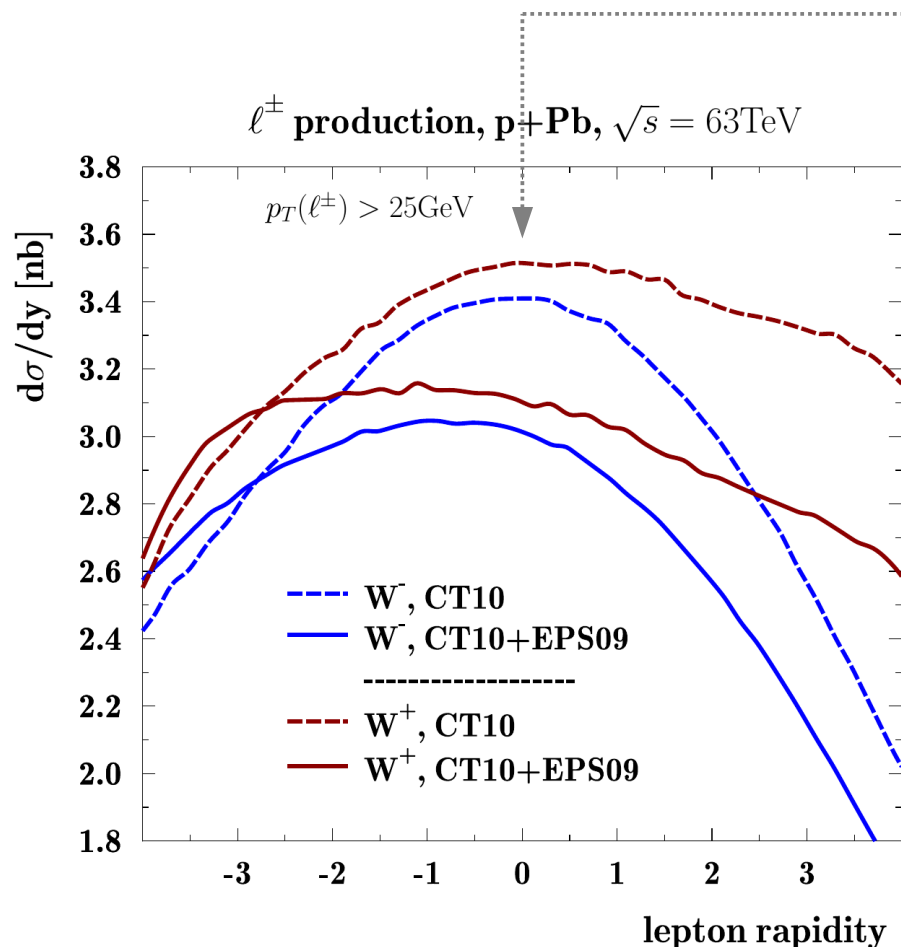
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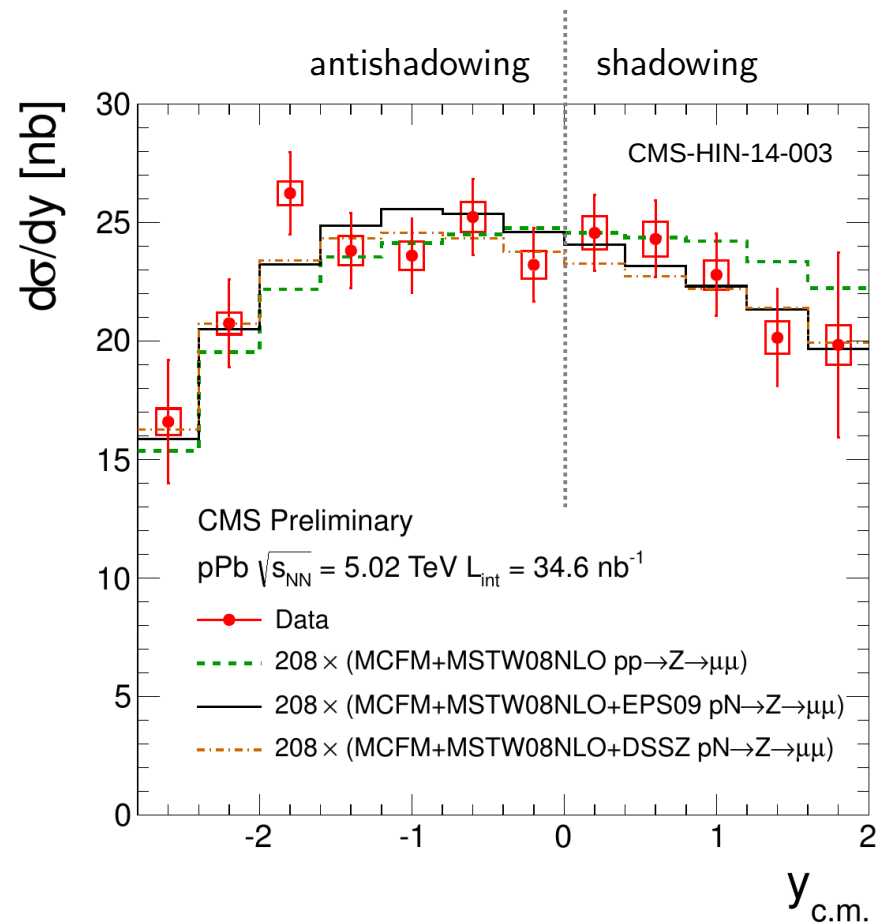
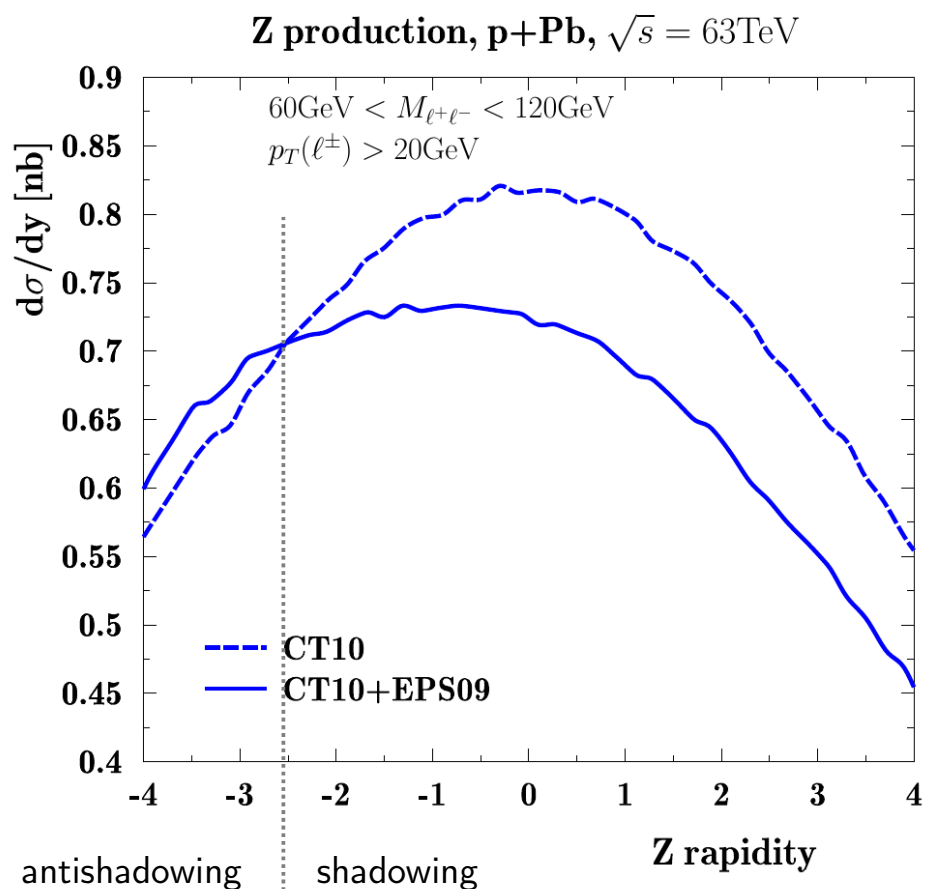
Projections: From LHC to FCC



- The FCC kinematics would probe now directly unconstrained region already at midrapidity
- Significant contribution from $c\bar{s}$ and $s\bar{c}$ partonic channels at midrapidity (at the LHC the lighter u and d quarks still largely dominate)
- The present nPDF predictions underestimate the uncertainties

Projections: From LHC to FCC

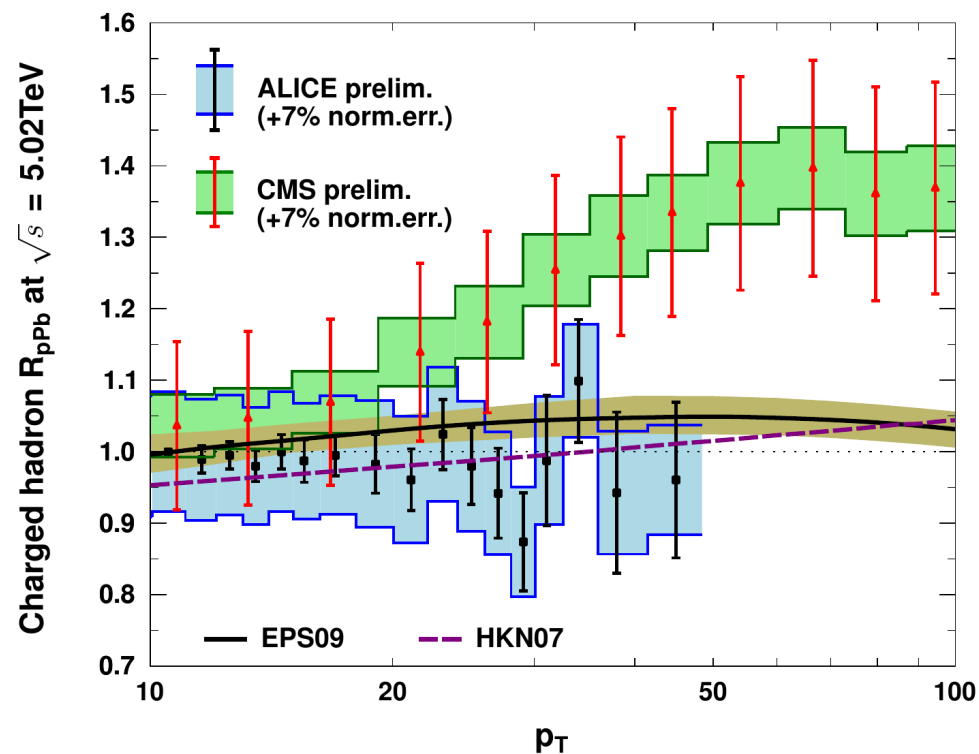
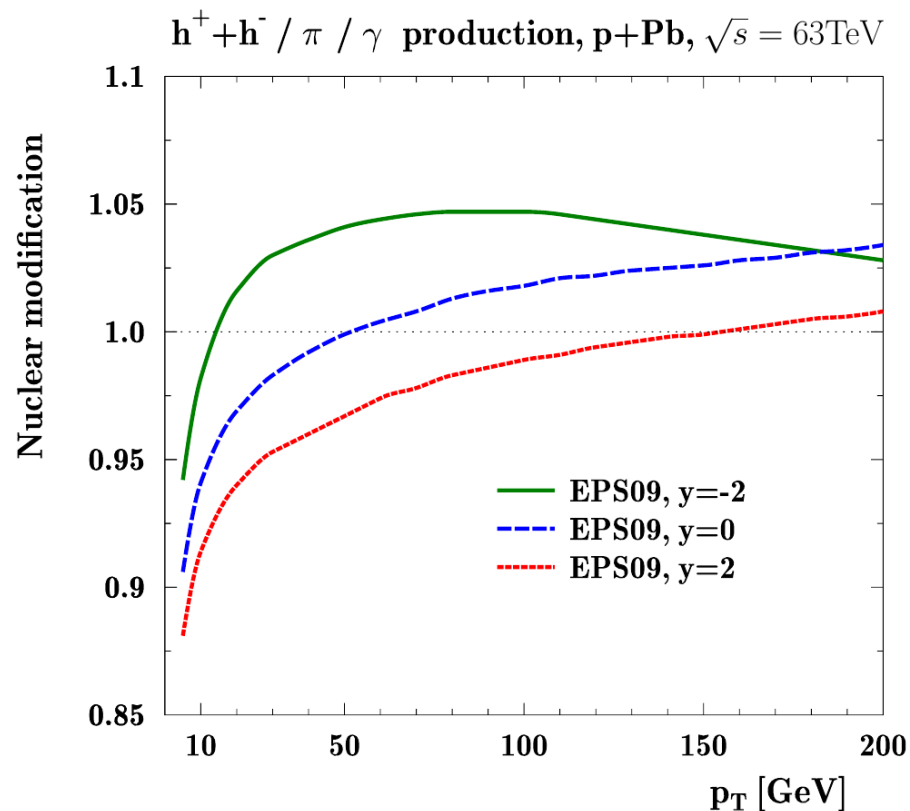
- Dilepton spectrum from Z decays



- All light-quark channels $u\bar{u}, d\bar{d}, s\bar{s}$ at midrapidity important, in FCC even the charm
- The present nPDF predictions underestimate the uncertainties

Projections: From LHC to FCC

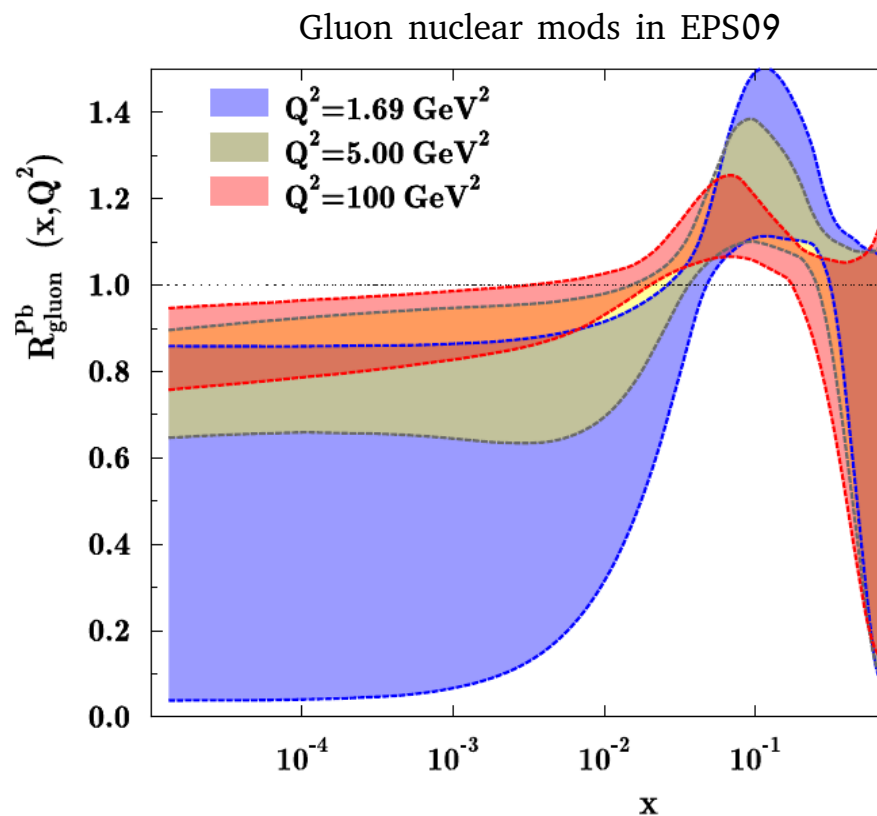
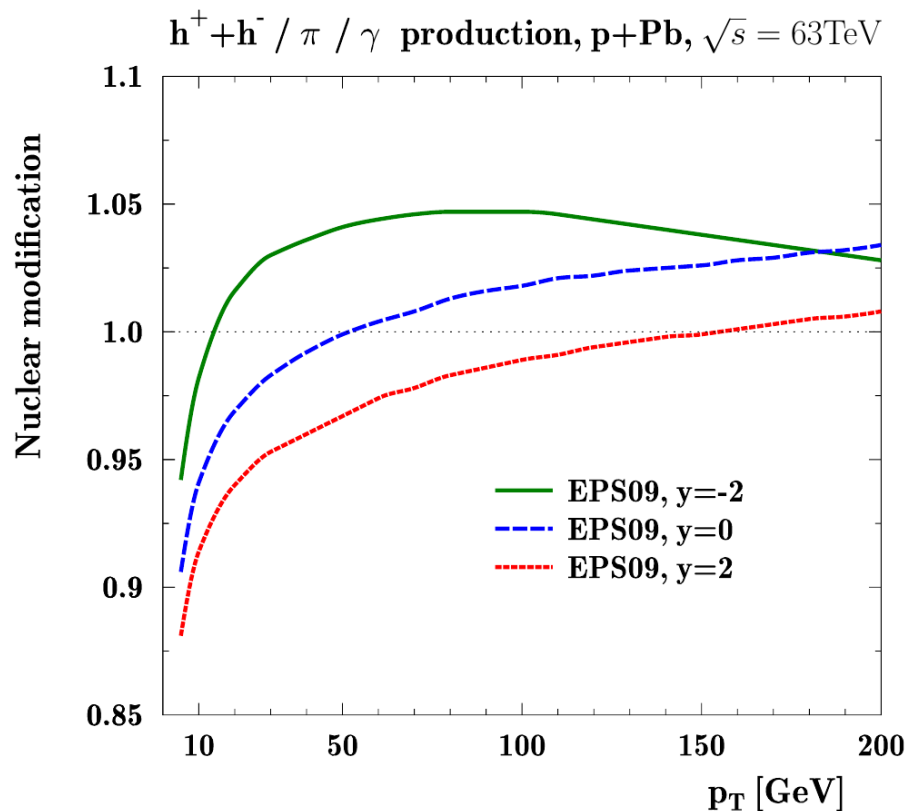
- Inclusive charged-hadron/pion production:



- Access the small-x gluons. The shadowing lasts until $p_T=50\text{GeV}$ at midrapidity (until $p_T=10\text{GeV}$ at the LHC)
- Only mild nuclear effects expected from EPS09 (DSSZ and HNK07 give even less)

Projections: From LHC to FCC

- Inclusive charged-hadron/pion production:



- Even at large center-of-mass energy or forward direction, nPDF approach cannot yield dramatic suppression (unlike CGC...) at small p_T
- This is partly for the functional form at small- x parametrization in EPS09, broad x distributions, but mostly due to rapid DGLAP evolution of gluons.

Projections: From LHC to FCC

- The reliability of collinear factorization in inclusive hadron production could be jeopardized by the unstable DGLAP evolution of FFs below $z=0.1$...

$$\lim_{z \rightarrow 0} P_{gg}^{(T)}(z) = \frac{\alpha_s}{2\pi} \left(\frac{2C_A}{z} - \frac{\alpha_s}{2\pi} \frac{4C_A^2}{z} \ln^2 z \right) \quad (\text{no } \log^2 z \text{ for PDF splitting functions})$$

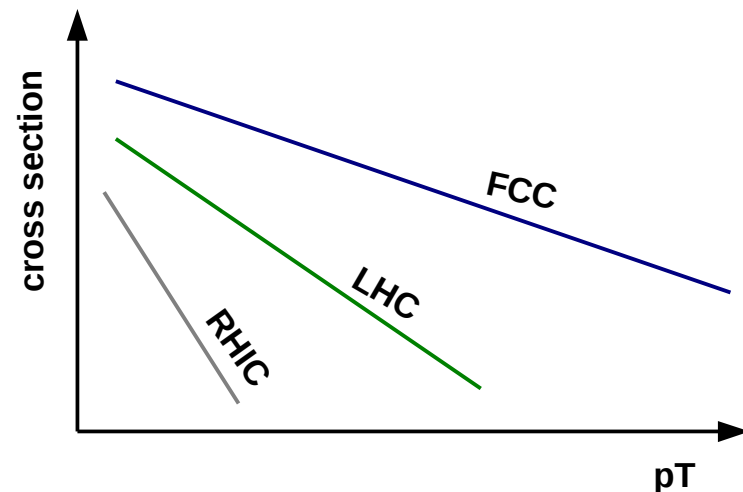
..which can lead to negative cross sections

- Approximate the convolution of PDFs and the partonic matrix elements by

$$\sum_{ij} \int dx_1 dx_2 f_i^{h_1}(x_1, \mu_{\text{fact}}^2) f_j^{h_2}(x_2, \mu_{\text{fact}}^2) \frac{d\hat{\sigma}(\hat{p}_1^i + \hat{p}_2^j \rightarrow \hat{p}_3^\ell, \mu_{\text{ren}}^2, \mu_{\text{fact}}^2, \mu_{\text{frag}}^2)}{d\hat{p}_{3T} d\eta} \approx C_\ell \hat{p}_{3T}^{-n}$$

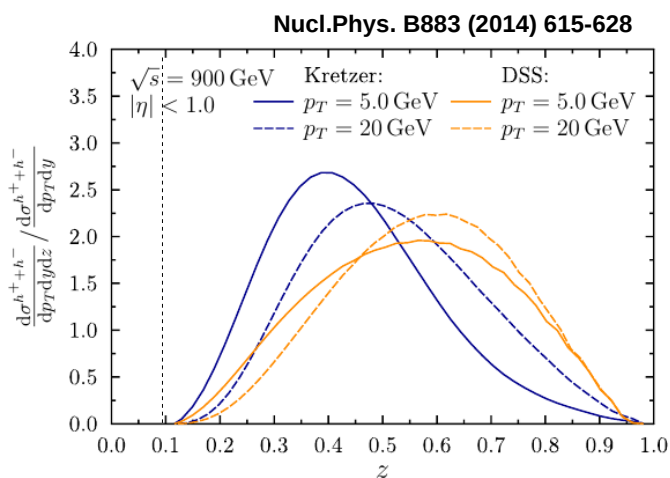
$$\begin{array}{c} p_{3T} = z \hat{p}_{3T} \\ \longrightarrow \end{array} \frac{d\sigma(h_1 + h_2 \rightarrow h_3 + X)}{dp_T d\eta dz} \approx \sum_\ell \frac{C_\ell}{z} \hat{p}_{3T}^{-n} D_{\ell \rightarrow h_3}(z, \mu_{\text{frag}}^2) = p_T^{-n} \sum_\ell \underline{\underline{C_\ell z^{n-1} D_{\ell \rightarrow h_3}(z, \mu_{\text{frag}}^2)}}$$

- Larger \sqrt{s} sensitive to smaller z

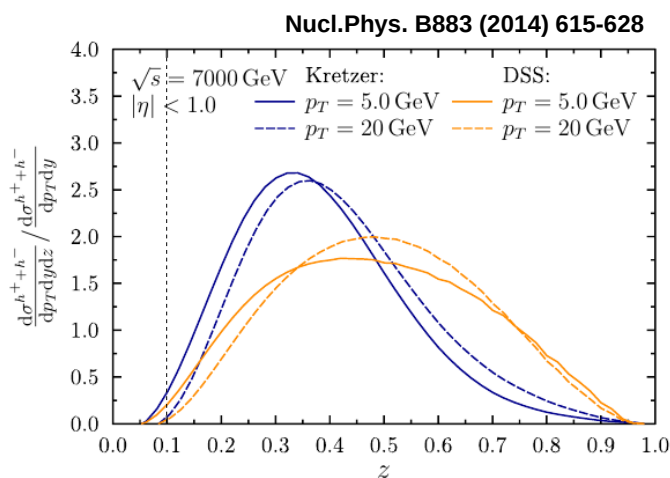


Projections: From LHC to FCC

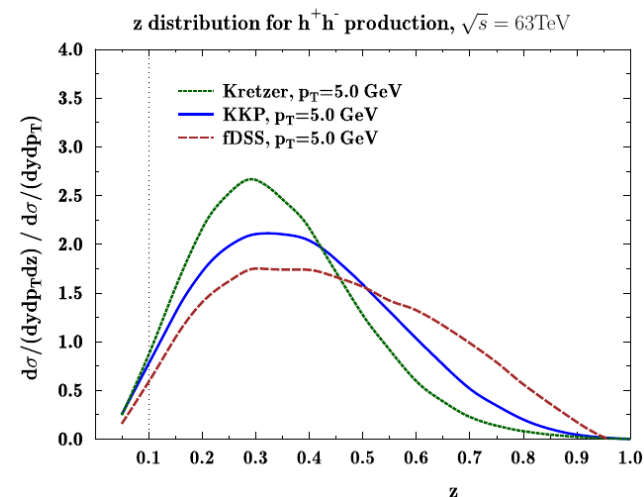
- Evolution of the z distributions from LHC to FCC



LHC



LHC

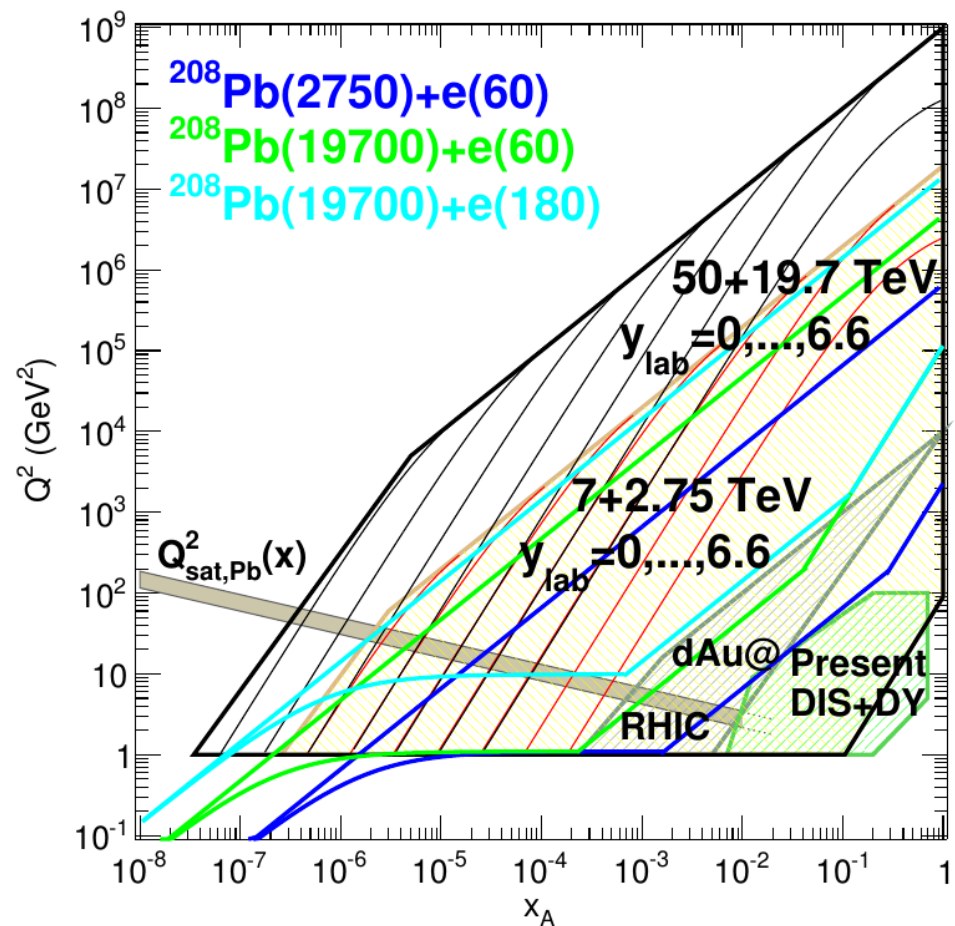
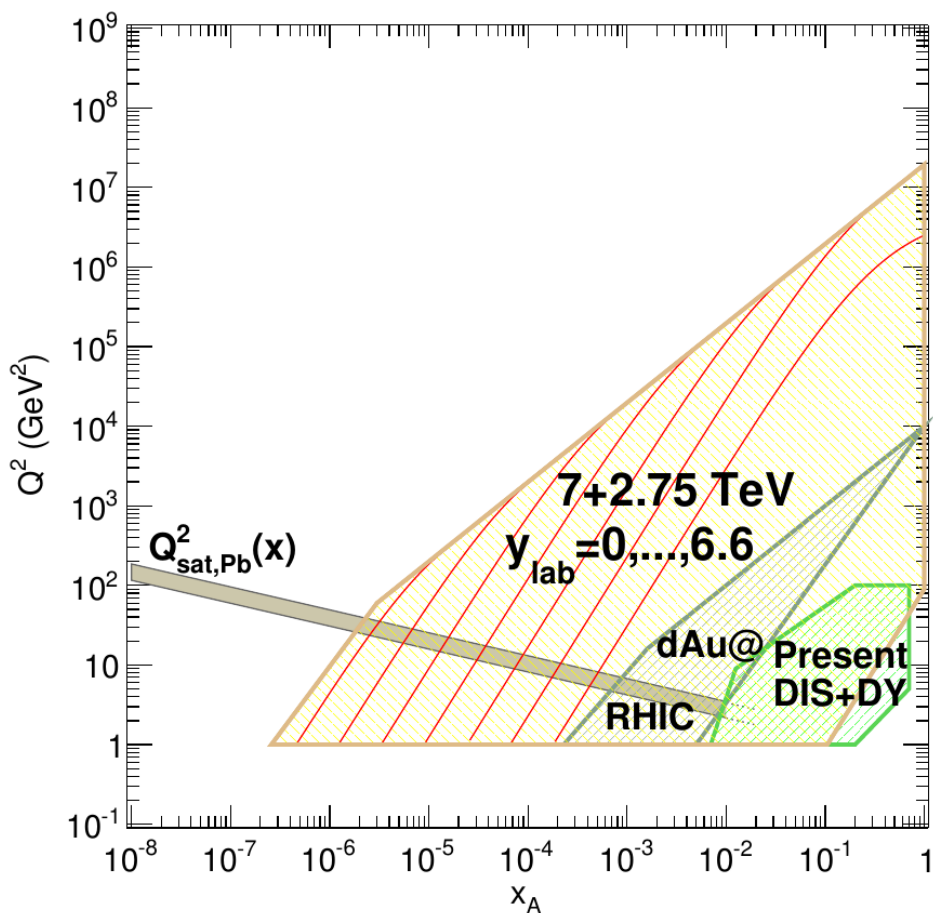


FCC

- As expected, the z distributions shift to smaller z . However, not dramatically so and not more than few-percent contributions expected from $z < 0.1$ even at the FCC (in inclusive yields).
- The standard picture of collinear fragmentation should hold even at the FCC energies

FCC as an ion-electron collider

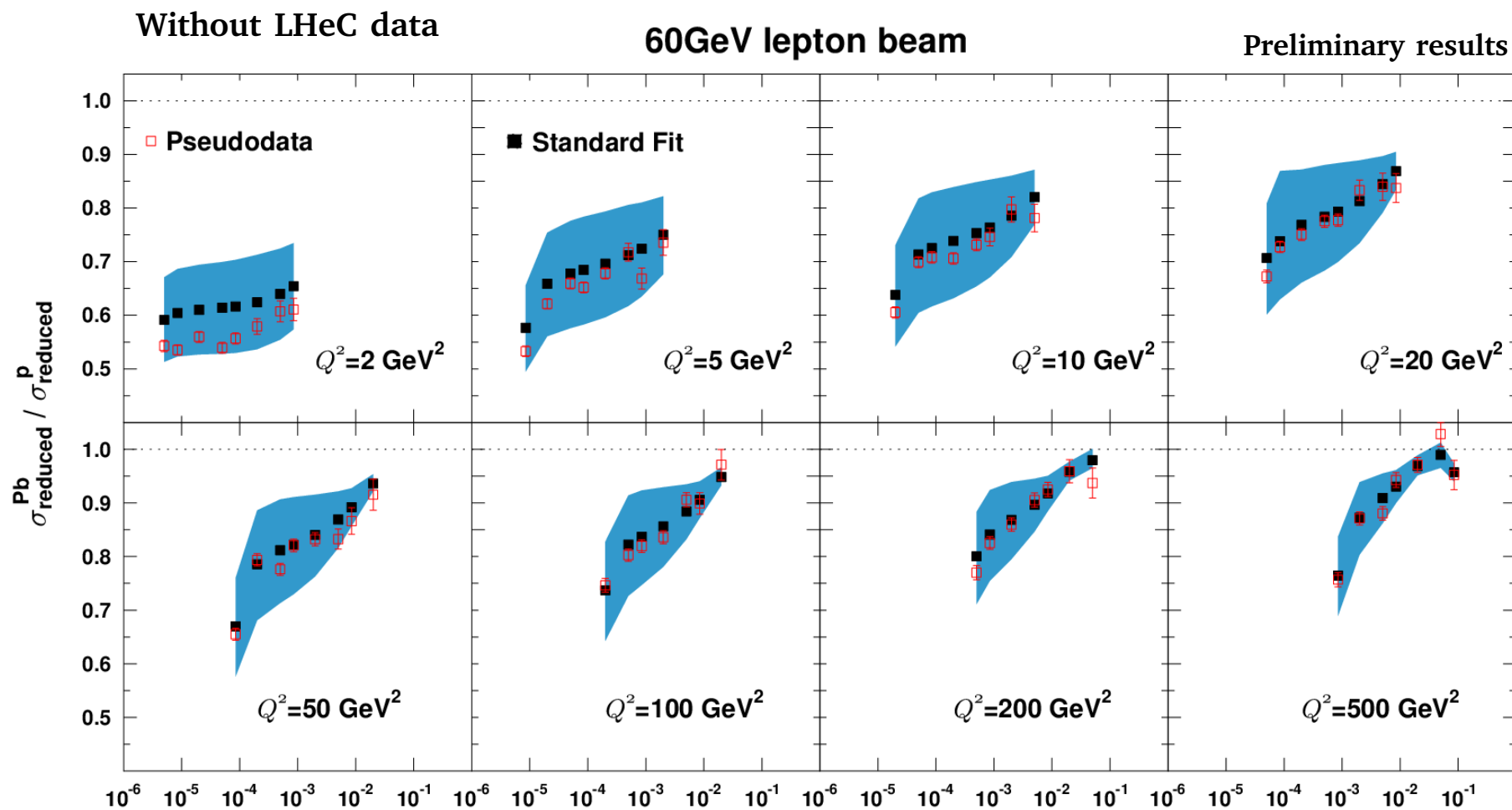
- FCC as an ion-electron collider would enlarge the kinematic reach in DIS by a tremendous amount



- Multitude of different physics possibilities: nPDFs, nGPDs, diffractive physics,...

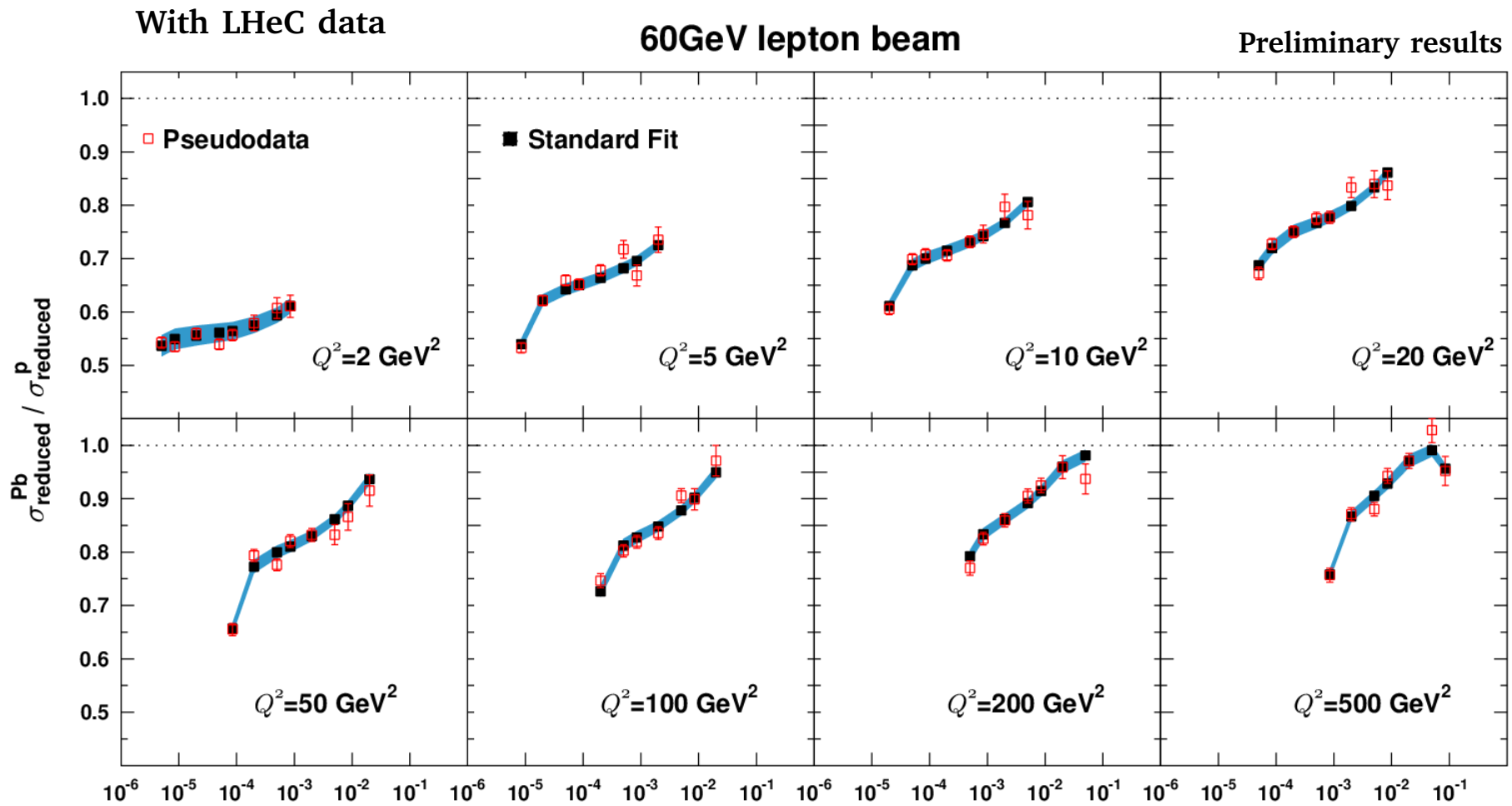
FCC as an ion-electron collider

- A concrete example: the nPDF determination at the LHeC
- Pseudodata for reduced DIS cross sections in e-Pb and e-p with $E_{\text{Pb}} = 2750\text{GeV}$, $E_{\text{p}} = 7000\text{GeV}$



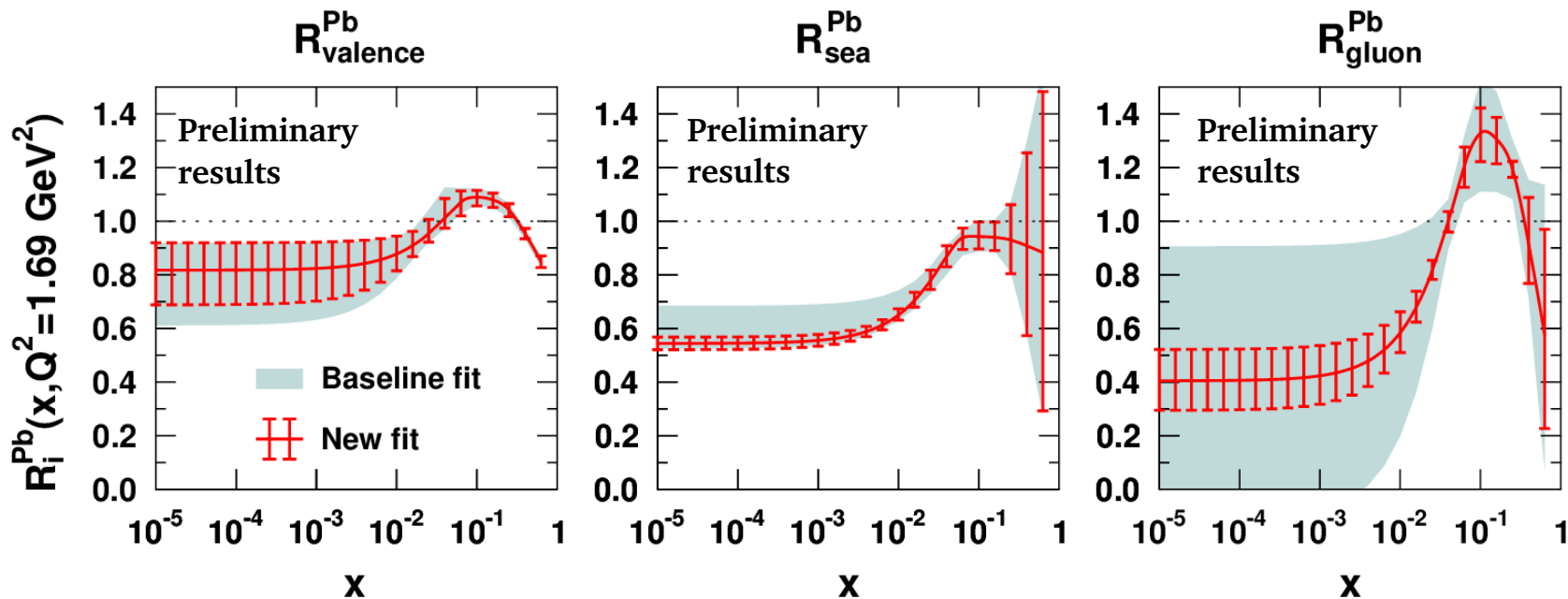
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- The nuclear mods in PDFs would undergo a dramatic improvement



- Studies like this can be easily done also via PDF reweighting for usual χ^2 fits [arXiv:1402.6623] and for NNPDF fits [Nucl.Phys. B849 (2011) 112-143]

Summary

- The LHC p+Pb and Pb+Pb results give qualitative confidence for the adequacy of collinear factorization in hard particle production

Some data set in excellent agreement – other ones less so

- Thus, it makes sense to extrapolate up to the FCC energies

The uncertainties in the predictions are currently underestimated as the limited amount of data that goes into the nPDF fits has forced to make many simplifying assumptions

- The nPDF determination with LHeC pseudodata

A concrete example (direct fit) of how the current state of affairs would improve.

PDF reweighting (applies to any χ^2 analyses) is the general method to do such predictions for FCC