Vector Boson production with Heavy Ions at the LHC

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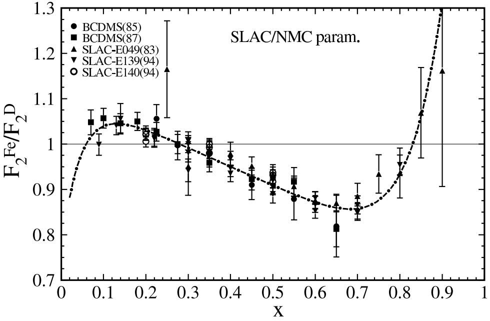
nPDFs and Nuclear Corrections

Nuclear Modifications to PDFs

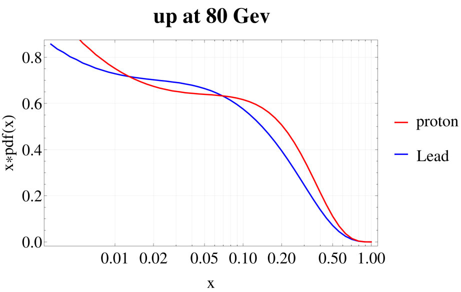
- Nuclear PDFs (nPDFs) can show significant modifications to free proton PDFs.

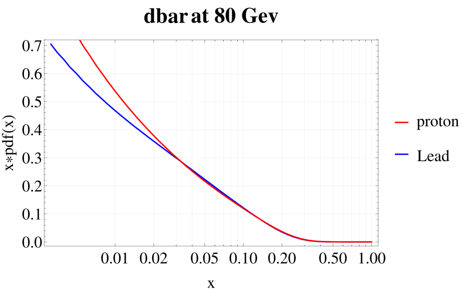
- DIS data suggest several types of corrections:
  - Shadowing
    $x < 0.05 - 0.1$
  - Anti-shadowing
    $0.1 \leq x \leq 0.3$
  - EMC effect
    $0.3 \leq x \leq 0.8$
  - Fermi motion
    $x > 0.8$



(Schienbein et. al. arXiv:0907.2357v2)

Nuclear Modifications





- The nuclear modifications are present in the PDFs, but appear in different regions of x than for the observables.
- We expect modifications to any hadronic observable involving heavy nuclei.

nCTEQ PDFs

- The nCTEQ proton PDFs are parameterized according to the following prescription;

$$\begin{aligned} x\,f_k(x,Q_0) &= c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5} \\ k &= u_v, d_v, g, \bar{u}+\bar{d}, s, \bar{s}\,, \\ \bar{d}(x,Q_0)/\bar{u}(x,Q_0) &= c_0 x^{c_1}(1-x)^{c_2} + (1+c_3 x)(1-x)^{c_4} \end{aligned}$$

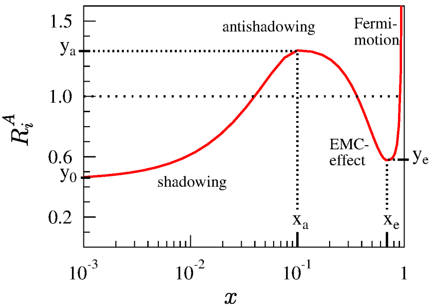
- The nuclear A-dependence is then applied to the coefficients in the parameterization.

$$c_k \to c_k(A) \equiv c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right), \quad k = \{1, \ldots, 5\}$$

(Schienbein et. al. arXiv:0907.2357v2)

EPS PDFs

- Another popular nPDF set is EPS09.



- In this analysis, an x-dependent nuclear correction is factorized from a fixed proton PDF.

$$f_i^A(x, Q) \equiv R_i^A(x, Q) f_i^{\mathrm{p}}(x, Q),$$

nCTEQ PDFs

- The nCTEQ group has produced a several sets of nuclear nPDFs at NLO for public distribution.

(Schienbein et. al. arXiv:0907.2357v2)

(Stavreva et. al. arXiv:1012.1178)

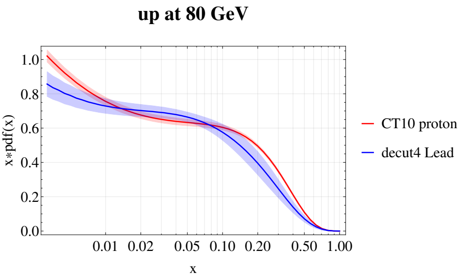
- The PDF for a general nucleus can be constructed as a linear combination of the PDFs using (approximate) isospin symmetry

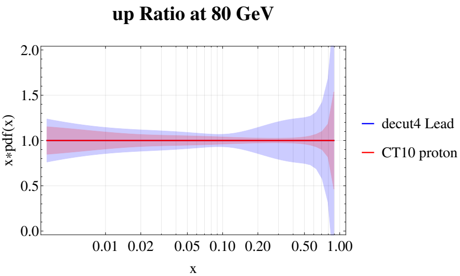
$$f_i^{(A,Z)}(x,Q) = \frac{Z}{A}\, f_i^{p/A}(x,Q) + \frac{(A-Z)}{A}\, f_i^{n/A}(x,Q)$$

(Schienbein et. al. arXiv:0907.2357v2)

- Hessian error sets for the nPDFs are provided for the parameters of the nuclear correction.

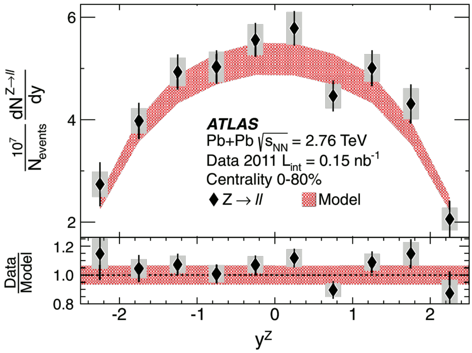
nCTEQ Errors vs CT10 Errors





- Error sets have been created for the nCTEQ PDFs by A. Kusina, K. Kovařík, and T. Ježo.
- The error sets are over 16 eigenvectors. Each family contains 34 PDF sets.

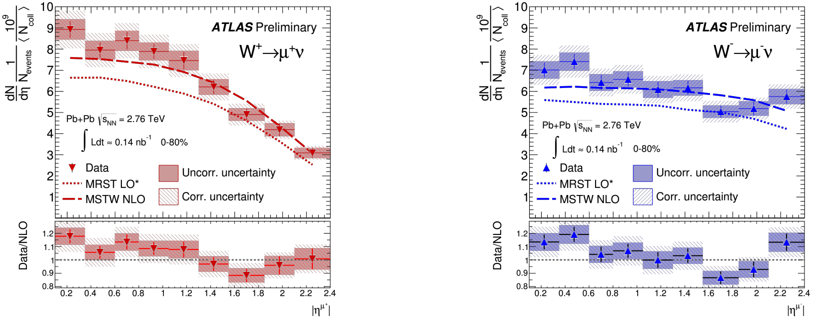
ATLAS measurement



(ATLAS Collaboration, PRL 110,022301 92013))

- In January of 2013, ATLAS released the results of their Z boson rapidity distribution for PbPb collisions at $2.76\mathrm{TeV}$.
- ATLAS observed 1995 candidate events corresponding to $0.15\mathrm{nb}^{-1}$ of integrated Luminosity.

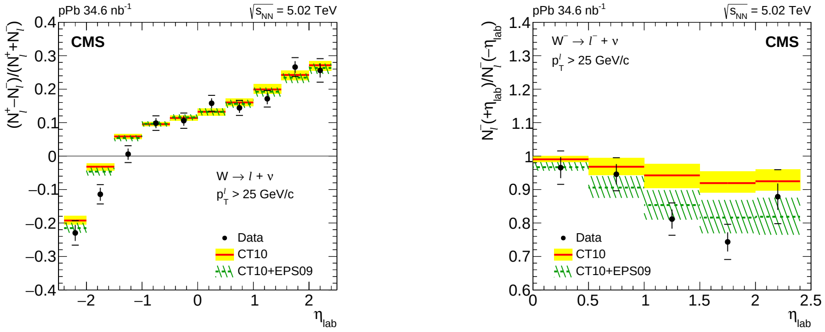
ATLAS measurement



(ATLAS Collaboration, ATLAS-CONF-2013-106)

- In November of 2013, ATLAS released the result of their μ^+ and μ^- rapidity measurements in PbPb.
- All of the heavy ion runs have been compared to predictions made with NLO PDFs.

CMS measurement



(CMS Collaboration, CMS-HIN-13-007, CERN-PH-EP-2015-054)

- In March of 2015, CMS released the result of their μ^+ and μ^- rapidity measurements in pPb collisions at $5.02\mathrm{TeV}$.
- LHC experiments have yet to detect any nuclear modifications to Vector Boson cross sections.

Heavy Ion Collisions

Vector Boson Production

- High Energy collisions at the LHC are capable of producing many electroweak bosons (W/Z) at high absolute rapidity.
- Properties of these bosons are well constrained making them ideal "standard candle" measurements for detector calibration.
- The hadronic cross section for Drell-Yan pair production is written

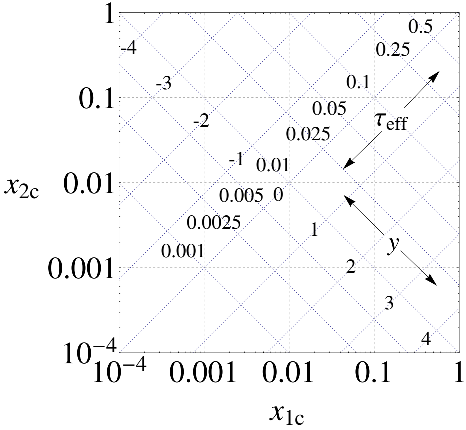
$$\frac{d\sigma}{dQ^2\, dy} = \sum_{a,b} \int_0^1 d\xi_1 \int_0^1 d\xi_2 \frac{d\hat{\sigma}}{dQ^2 dy} f_{a/A}(\xi_1) f_{b/B}(\xi_2)$$

- At LO we can make the approximation,

$$\xi_1 \approx x_1 \equiv \tau e^{y}, \quad \xi_2 \approx x_2 \equiv \tau e^{-y}, \quad \text{where} \quad \tau \equiv \frac{Q}{\sqrt{S}}.$$

Vector Boson Production

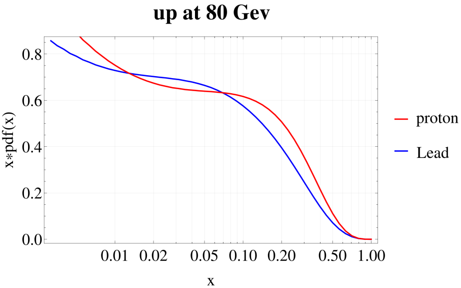
- This means that rapidity measurements for on-shell vector boson production provide a method for probing the x dependence of the PDFs.

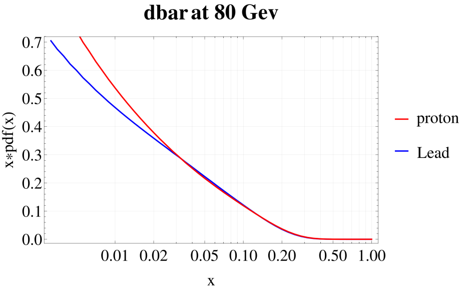


$$\tau \equiv \frac{Q}{\sqrt{S}}.$$

(Guzey,V. et al, arXiv:1212.5344v1)

PDF Contributions



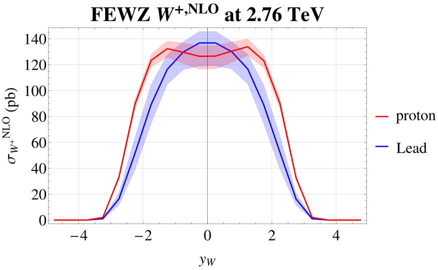


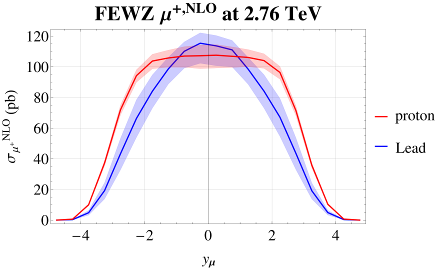
- For $W^{\pm}\,(Z)$ production at $2.76\mathrm{TeV}$, $\tau \approx 0.029\,(0.033)$
- For $W^{\pm}\,(Z)$ production at $5.02\mathrm{TeV}$, $\tau \approx 0.016\,(0.018)$

Results

PbPb vs. p-p Rapidity

- There is an observable shape change for on-shell W^+ production. The difference is up to 20 % in some regions of parameter space.





- These differences should be seen with a higher integrated luminosity for PbPb collisions.

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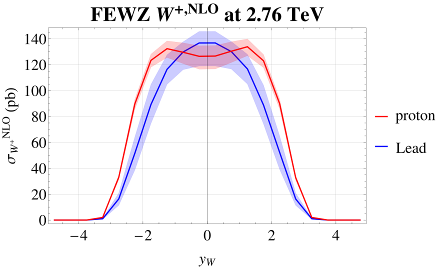

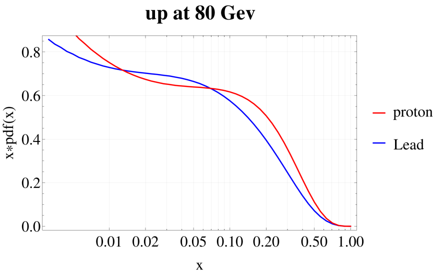

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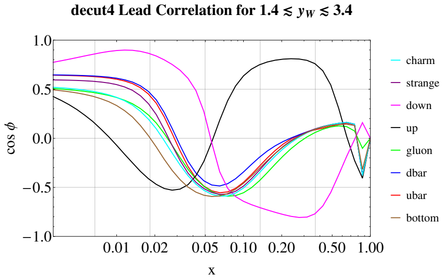
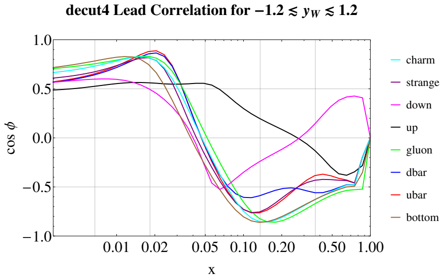
PDF Correlations

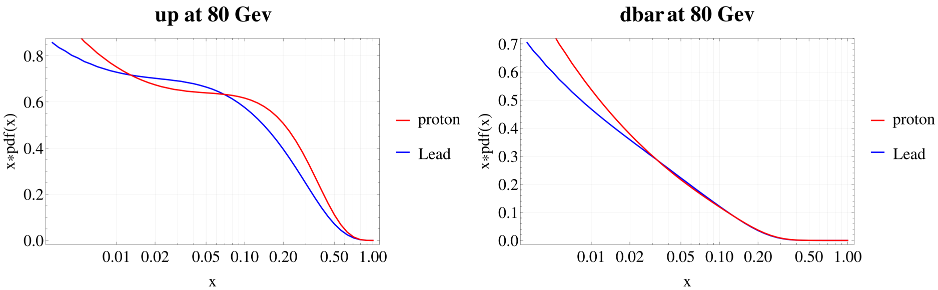




- In the high absolute rapidity region, the error is dominated by the uncertainty on the down PDF.
- The up and down distributions are anti-correlated in x allowing for flavor decomposition.
- In the central region, the $\bar{u}$ and $\bar{d}$ uncertainty provides the largest contribution

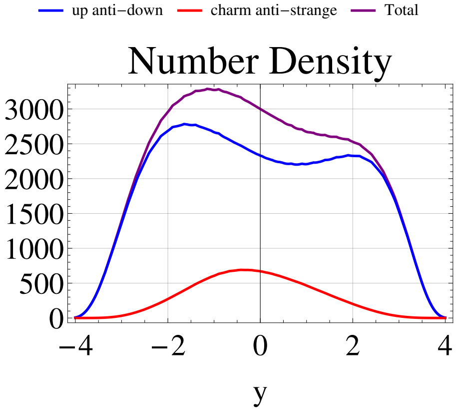
pPb Rapidity

- The shape of the pPb cross sections can be predicted by looking at the nuclear corrections to the PDFs.



- These predictions are presented in the Center of Momentum frame of the two nuclei. The experimental results include a 0.465 rapidity shift.

PDF Contributions

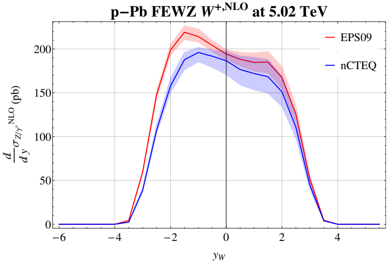


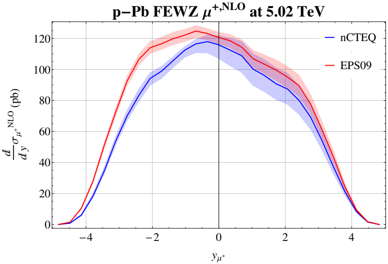
- Here we look at the $u - \bar{d}$ and $c - \bar{s}$ interactions for W^+ production.

$$\sigma_{DY} \sim f_{a/A}(\tau e^{y}, Q) * f_{b/B}(\tau e^{-y}, Q)$$

pPb W Rapidity

- The resulting W^+ predictions with nCTEQ15 show significant differences to the predictions using EPS09 nuclear corrections.

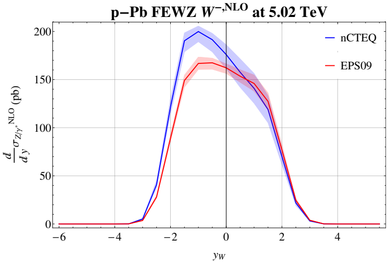


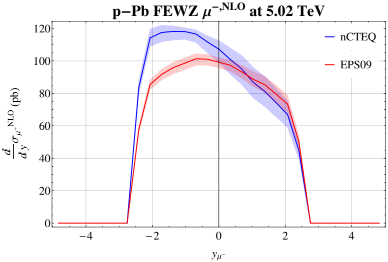


- Current CMS measurements show tension with the EPS09 predictions. A direct comparison to CMS data is underway to see if better agreement is possible with nCTEQ PDFs.

pPb W Rapidity

- The resulting W^- predictions with nCTEQ15 also show differences to the predictions using EPS09 nuclear corrections.





- Differences with EPS09 are visable for all Vector Bosons and for the resulting muon distributions.

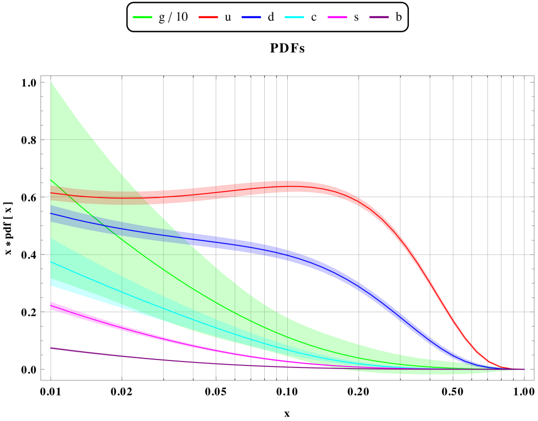
Conclusions and Future Work

- Nuclear modifications to PbPb cross sections are up to 20% and should be visible with a higher integrated luminosity.
- Work is underway to produce predictions at $8.16\mathrm{TeV}$ and $8.80\mathrm{TeV}$ for pPb cross sections.
- A comparison to AMC@NLO is in progress. AMC will be used in the next nCTEQ fit containing LHC data.
- Current results from CMS show tension with EPS09 predictions. A comparison of nCTEQ predictions to recent CMS results is underway.
- The nCTEQ predictions show significant differences to the EPS predictions at high negative rapidity where the ratio $d(x, Q_0)/u(x, Q_0)$ is important.

Backup Slides

Parton Distribution Functions

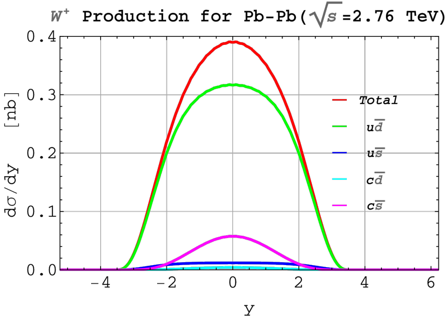
- Parton Distribution Functions (PDFs) describe the distribution of quarks and gluons within the Proton.
- Parton Distributions are given as functions of the Bjorken variable x and the hard momentum scale Q.



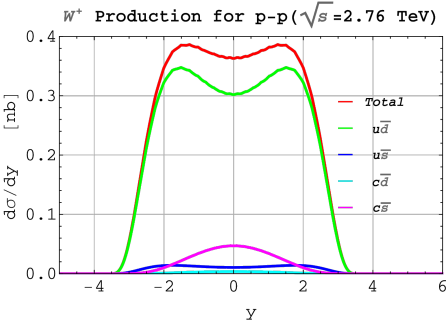
CTEQ 10

LO Rapidity Calculation

- A LO calculation of rapidity shows shape changes due to the softening of the $u\ (x, Q)$ and $\bar{d}\ (x, Q)$ PDFs.



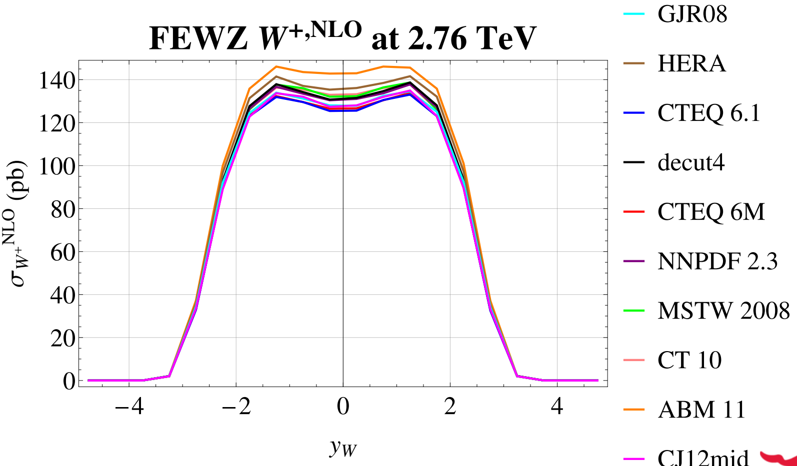
Pb-Pb



p-p

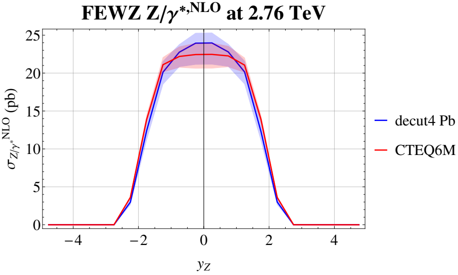
PDF Comparison

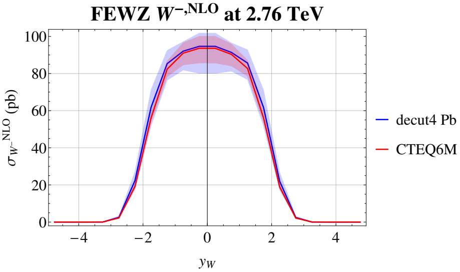
- The nCTEQ proton PDF set gives similar predictions to other commonly used sets.



Pb-Pb vs. p-p rapidity

- No shape change for on-shell Z and W^- rapidity is found as we move from the proton PDFs to Lead.





- The shapes of the lepton distributions for these bosons are also indistinguishable.

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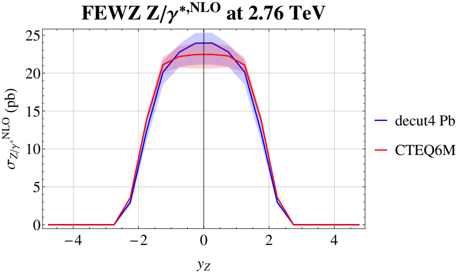

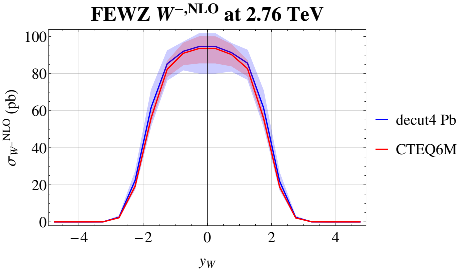

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