W/Z Boson Production at the LHC with the nCTEQ Nuclear PDFs

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We compare predictions for vector boson rapidity for p p and Pb Pb collisions at $\sqrt{s} = 2.76\,\text{TeV}$ at the LHC. The calculations are performed using the nCTEQ parton distribution functions. Errors are estimated and presented for the rapidity of the W/Z bosons as well as the reconstructed $\mu^{\pm}$distribution. We compare these predictions to recent heavy ion collisions at the LHC.

CONTENTS


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The story:
question: can w/z help with nPDFs
W+ looks interesting:   - 2-hump structure for all proton pdf groups  - flat distribution persisits to muon
W+ lead  - contrast W+ lead and proton  - differences persist also for muon decay
w+: break-down in flavors
Root of cause:   - diff in u,d, for lead/proton
correlations ...
is this just an isospin issue?  i.e., just because lead is approx isoscalar and p is not???
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I. INTRODUCTION

A. Motivation

The mass and width of the electro-weak bosons is know to high precision. Electroweak and QCD corrections to cross sections for these bosons are well understood. At the Large Hadron Collider (LHC), many electroweak bosons are created through Drell-Yan scattering producing a large cross section even at high rapidities. For these reasons, the production of $W^{\pm}$ and Z^0 bosons make for ideal "standard candle" measurements used for partonic and collider luminosity calibration as well as precision measurements of electroweak paramaters both in proton-proton and Pb-Pb collisions. Additionally, the Standard Model (SM) relates the mass of the W boson, M_W, the square of the top quark mas, m_t^2, and the mass of the recently discoverd Higgs particle, M_H. For these reasons, measurements of electroweak boson observables are an important test of the consistancy of the SM.

Measurements of electroweak boson rapidities in PbPb and pPb collisions provide a unique opportunity to probe Nuclear Parton Distribution functions (nPDFs). This is particularly true in the high-rapidity regions where the ratio of up to down and ubar to dbar are significant. These measurements

Recent measurements from ATLAS and CMS of rapidity in Pb-Pb collisions at 2.76 GeV have been consistent with predictions made with proton PDF sets both for the vector boson rapidity and the resulting charged lepton rapidity. (Ref?) These measurements were compared to predictions from FEWZ and VRAP generated with MSTW NLO and MRST LO proton PDFs. (REF)

Heavy nuclei can show significant modifications to free proton PDFs. That is to say, the cross section for an interaction between heavy nuclei cannot be found by simply adding the cross-sections for the individual nucleons. This nuclear binding effect is well known in the literature. (REF)

The nCTEQ group has produced sets of nuclear PDFs for various heavy nuclei. The use of these PDFs provides advantages over previous analyses because they do not assume a form of the nuclear correction. The nCTEQ PDFs are extracted from 708 data points after cuts. These data come from different processes which include Deeply Inelastic Scattering (DIS), Drell-Yan (DY) and jet production for various HI targets.

Analysis of vector boson production in Pb-Pb collisions with the nCTEQ PDFs reveals subtle differences in cross-section shapes. These differences in shape from the p-p predictions are not due to iso-spin effects as the Pb PDF used is scaled back to the proton with all iso-spin effects removed. Understanding this data can help to constrain uncertainties on future nuclear PDF fits.

B. Outline

In Section 2 we will discuss the nCTEQ nuclear parameterization and show how it's use provides advantages over previous analyses. In section 3 we will present analysis with several different groups PDFs and discuss potential known effects that can mimic the nuclear modifications we see. In section 4 we will present the results of this analysis along with an estimation of theoretical errors. In setion 5 we present our conclusions.

II. NUCLEAR PARTON DISTRIBUTION FUNCTIONS

A. nCTEQ Parameterization

The predictions presented in this paper are made with nuclear PDFs published by the nCTEQ collaboration. These NPDFs are created using charged-lepton DIS and Drell-Yan data for a variety of nuclear targets. The resulting PDFs are scaled by the atomic mass number and iso-spin symmetric effects are accounted for. This prduces a PDF that represents the proton bound within a nucluon of mass nuber A. The modifications to this NPDF versus the proton PDF at the same value of x and Q are then atributable to the nuclear corrections, e.g. shadowing, the EMC effect, anti-shadowning. (REF) The cross-sections as a fuction of rapidity presented in (FIG 3 & 4) are calculated for proton-proton collisions with FEWZ 2.0 (REF). We compare the calculation performed with the CTEQ6M (REF) proton PDF to the calculation performed with the nCTEQ Lead PDF. The shape differences between the two curves are correlated with the nuclear modifications to the PDFs seen in (FIG 5&6).

(FIGS 5&6) show $x * pdf(x, Q)$ and are presented at $Q^2 = M_W^2$ and plotted as a function of Bjorken x. For central rapidity at LO we have a Bjorken $x = M_W/\sqrt{s} \approx .03$. Production of heavy W^+bosons is primarily due to $u - \bar{d}$ interactions for proton-proton collisions at the LHC as can be seen in the leading order calculation of (FIG 7). At $x \approx .03$ we see that the up quark PDF is firmly in the anti-shadowing region. The anti-down quark is at the threshold between behavior in the shadowing and anti-shadowing regions. The result on the cross-section is shown in (FIG 8). In this LO calculation we see that there is an enhancement in the region of central rapidity. This is due to the anti-shadowing enhancement seen in the up-quark PDF. Additionally, the overall softening of the valance PDF reduces the characteristic 2-hump (REF) structure $p - p$ W^+ production at the LHC. The shape of the cross section is most heavily modified in the high rapidity region.

The nCTEQ PDFs are given with Hessian error estimation sets for the 17 nuclear paramaters in the fit according to (REF). In (FIG 1&2) we see a comparison of predictions for W^+cross-sections for the nCTEQ proton central value to the central value from various popular proton PDF fits. These predictions show that the overall normalization of the cross-section can vary between the releases, but the shape remains more-or-less consistant. This plot was produced with FEWZ 2.0. (REF) We expect that the predictions with nCTEQ sets are compatible with other sets.

Furthermore, the nCTEQ PDFs for various nuclear targets are corrected for known iso-spin effects. So predictions made with these PDFs represent the

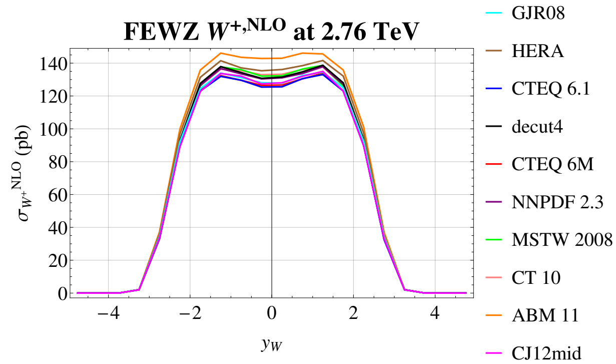

Figure 1: The W^+cross-section as a function of rapidity for various popular PDF releases.

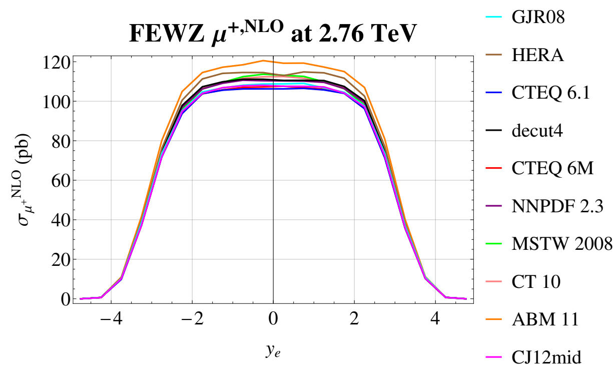

Figure 2: The μ^+cross-section as a function of rapidity for various popular PDF releases.

B. Previous Analysis

Analysis of vector boson product ion at the LHC has been preformed before with various forms for the nuclear correction, most notably by Guzey,et. al. (REF) In this analysis, a particular function was assumed for the nuclear correction based general features of the nuclear correction measured in the F_2 nuclear structure function at SLAC.(REF) This Z-dependent nuclear modification funciton was then multiplied by the free-proton PDF to produce a reasonable approximation of the bound nuclean distribution. These predictions were limited by the assumptions made in constructing the nuclear modification function.

This analysis produced some general effects that should be visible in the vector boson production measurements. The authors demonstrated the effect of the know nuclear modifications on the cross-section and allowed for a heuristic argument promoting the study of these nuclear effects. (REF) showed that scanning rapidity is equivalent to scanning in momentum fraction for each of the beams. This allows study of the nuclear modifications as a function of x at the fixed hard-scattering scale of the process Q. This modivated the authors of this paper to do a more comprehensive analysis of vector boson production by using the recent nCTEQ nuclear PDF fits.

C. nCTEQ Analysis

This paper presents an study of vector boson production at the LHC using the nCTEQ NPDF fits. These NPDFS are a global fit to data, mostly DIS and DY. To fit the data, the proton fit is assumed and set equal to the CTEQ6M proton fit. The Z-dependence is then assumed to modify the paramaters of the CTEQ6M paramaterization. This modified paramaterization is then fit to the data for each of the 20 nuclear targets provided. A least χ^2fit is used to minimize the parameters and Hessian error sets for each of the 17 nuclear parameters are presented. The 34 error sets can be combined in quadriture according to the usual presecption (REF) to produce an estimation of the error on some obervable.

This has the advantage that the PDFs used for the analysis are a global fit to data. We expect that predictions made with these PDFs will be more reliable than previous studies.

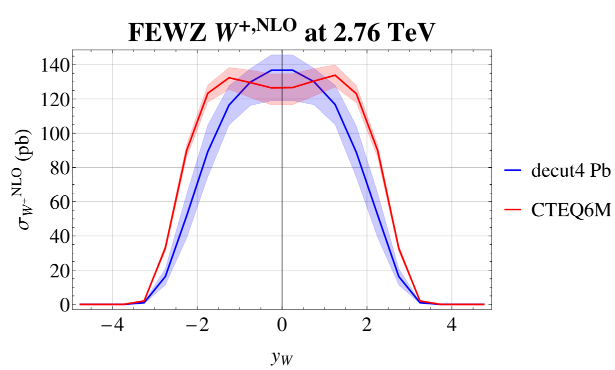

Figure 3: Here we see a comparison of the nCTEQ Pb PDF to the CTEQ 6M proton PDF for the rapidity of the W^+boson. Theoretical errors are represented by the shaded regions for each set.

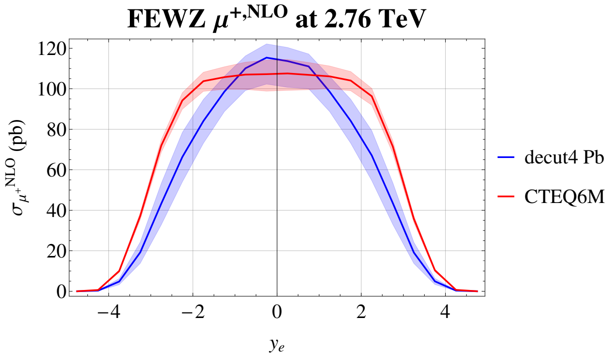

Figure 4: Here we see a comparison of the nCTEQ Pb PDF to the CTEQ 6M proton PDF for the rapidity of the reconstructed μ^+. Theoretical errors are represented by the shaded regions for each set.

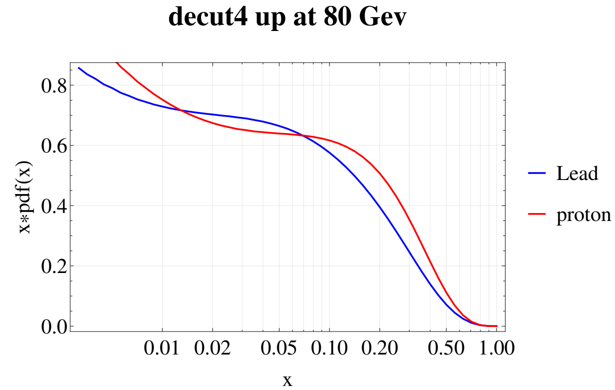

Figure 5: Here we see the free-proton verses the Pb PDF for the up quark. Notice the nuclear modifications: Shadowing, Anti-Shadowing, EMC, and Fermi motion of the nucleus.

III. SETUP

Predictions for rapidity distributions in this study were produced with FEWZ 2.0(REF). The fully-exclusive cross-sections are shown for both the vector boson and the reconstructed lepton. Plots were produced in Mathematica 9 (REF).

In (fig) we see the W^+rapidity for various popular PDF sets. (REF) The nCTEQ proton PDF is seen in black in the middle of the range of different central value predictions. We expect that the predictions made with the nCTEQ PDFs will provide a reliable prediction for vector boson production. Moreover, we can see that the nCTEQ prediction is very similar to the prediction with MSTW 2008. In (fig) we see the rapidity of the reconstructed $\mu^+$and, again we see very good agreement with the nCTEQ proton central value sitting right in the middle of the predictions made with the other PDF sets. As stated in (sec 2??), the central value is fit to DIS, DY, and jet production data so we expect reliable results from the nCTEQ PDFs for all of the available heavy ions.

These predictions are compared to calculations made with CTEQ6M proton PDFs. These PDFs ware chosen to produce accurate representations of their asymmetric errors. The proton from the nCTEQ fit does not have corresponding error sets. The errors displayed for the Pb-Pb prediction are for the nuclear parameters only as there currently exists no way to combine the errors for the free-proton parameters with the errors for the A-dependent nuclear parameters. This is not expected to be a problem as the the nuclear parameters are significantly less well constrained and represent the major contribution to the errors on these predictions.

All calculations are preformed in FEWZ 2.0 (REF) and plotted in Mathematica 9.0 (REF). The rapidity distributions for $W^-$and Z^0show a shape difference as we move from p-p to Pb-Pb collisions but this difference is within the error bands for the two calculations. The shape change for the $W^+$and μ^+distributions is much more dramatic.

A. Iso-spin Effects

It has been suggested that noticeable shape differences in the measurements for electroweak boson production will occur due to iso-spin effects. This is because the lead nucleus is closer to an iso-scalar than the free proton. Our predictions are presented with all know iso-scalar effects removed. As stated in (section 2), the nCTEQ PDFs are scaled to the free proton with all of the know iso-spin effects removed. We expect that the shape changes shown in this study are due to nuclear binding modifications themselves.

If (fig) we see a comparison between an iso-scalar proton and the full lead nucleus constructed according to reference (REF). We see that there is a distinct flattening of the distribution for both nuclei. This shape change is visible in the measurement from ATLAS in (REF) and is mentioned by the authors. We can see that this shape change is small compared to the shape change due solely to nuclear modifications.

The current analysis compares the free proton to the proton in the Pb nucleus to highlight the nuclear modifications. As we scan over the rapidity range we select different regions of phase space for the PDFs. As stated in reference (REF), at central rapidity, both PDFs have a momentum fraction of $x \approx M_W/\sqrt{s} = 0.03$ and as we move in rapidity we probe regions of the PDFs with $x \approx (M_W/\sqrt{s})\exp(\pm y)$.

A value of $x \approx 0.03$ is in the range where the nuclear modification is crossing over from shadowing to anti-shadowing in the anti-down PDF as seen in (FIG). For the up quark, however, the momentum fraction at central rapidity is in the range of anti-shadowing for the central value. The major contribution to W^+production comes from the $u-\bar{d}$ interaction. We expect that the preditction

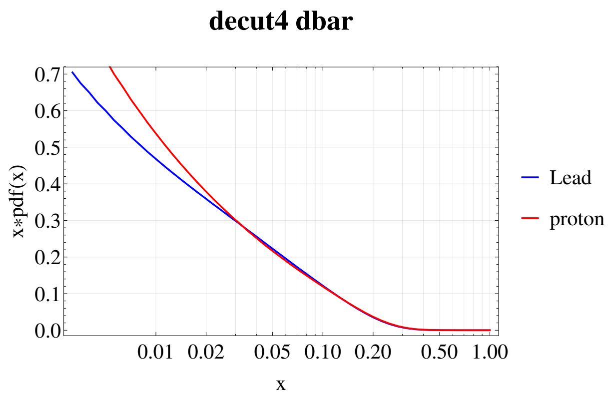

Figure 6: Here we see the free-proton verses the Pb PDF for the anti-down quark. Notice the nuclear modifications: Shadowing, Anti-Shadowing, EMC, and Fermi motion of the nucleus.

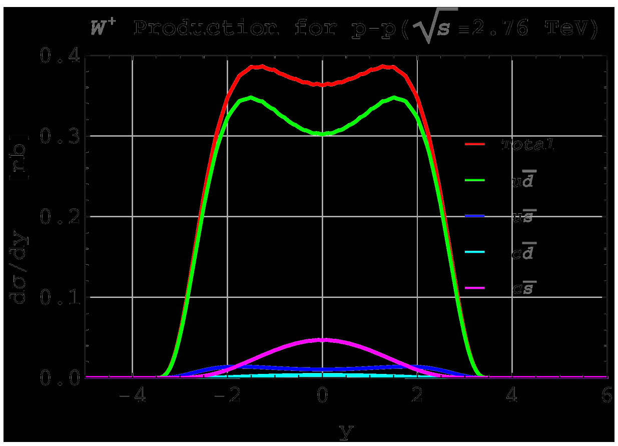

Figure 7: Here we see a LO calculation of the W^+rapidity in p-p collisions for each of the $q - \bar{q}$ interactions.

for the Pb-Pb cross-section should be slightly enhanced at central rapidity and supressed away from this value as compared to the p-p prediction.

A Leading Order (LO) calculation shows that this is indeed the case for the $u - \bar{d}$ interaction. We lose the characteristic 2-hump shape for the W^+rapidity distribution due to the $u - \bar{d}$ interaction. We also notice that we have a slight enhancement in the $c - \bar{s}$ and $u - \bar{s}$ interactions at central rapidity. These effects persist through the NLO calculation and produce the results seen in (FIG).

IV. RESULTS

Our analysis shows a distinct shape difference in the Pb-Pb prediction for μ^+production due to nuclear modifications of the PDF. We find that the differences are present at LO and persist through NLO. We find a narrowing of the rapidity distribution with a shift toward central rapidities. In addition, we find that the caracteristic "2-hump" structure of the cross-section disappears. This is due to an enhancement of the PDF at central rapidity and a suppression of the PDF at high rapidity.

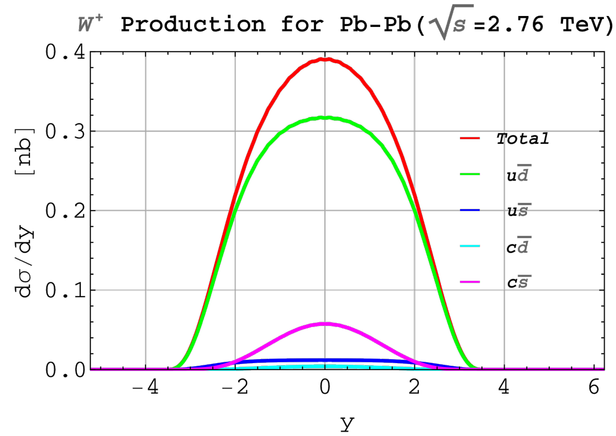

Figure 8: Here we see a LO calculation of the W^+rapidity in Pb-Pb collisions for each of the $q - \bar{q}$ interactions.

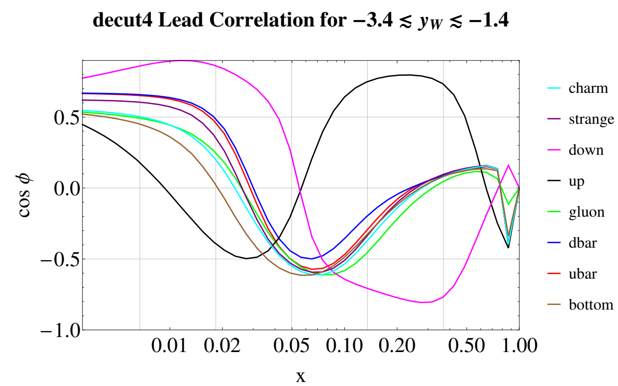

Figure 9: Here we see the PDF correlation for the high rapidity region of the W^+ cross section.

A slight shape difference is observed in the $\mu^-$and Z predictions but this difference is within the prediction of the PDF error on these measurements. This shape difference will not be visible regardless of the amount of data taken.

We have also examined the PDF correlations to the W^+prediction. The correlation angle $\cos(\phi)$ gives the angle between the gradient of the prediction with the gradient of the PDF error at that point in phase space. A correlation angle of $\cos(\phi) \approx 1$means that the error on that PDF is the major contributer to the error on the measurement at that point in phase space. To look at these correlations we used a proprietary Mathematica package developed by the authors for the use and analysis of CTEQ PDFs. The correlations show that, in the central rapidity region, The error on the cross section is driven by the error on the$\bar{u}$ and $\bar{d}$quark PDFs but is followed closely by the gluon. The anti-up and anti-down quark PDFs are already well constrained. Reduction of the error on the gluon distribution in future nCTEQ re-

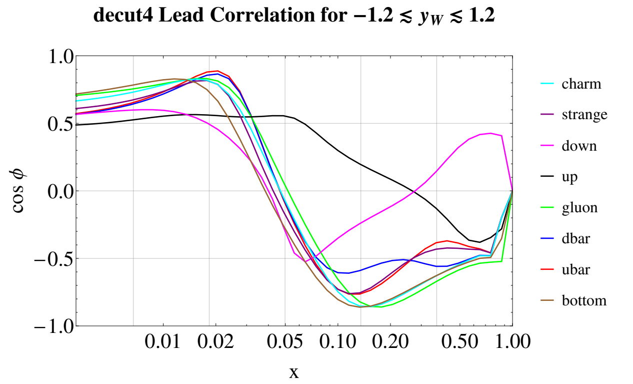

Figure 10: Here we see the PDF correlation for the central rapidity region of the W^+ cross section.

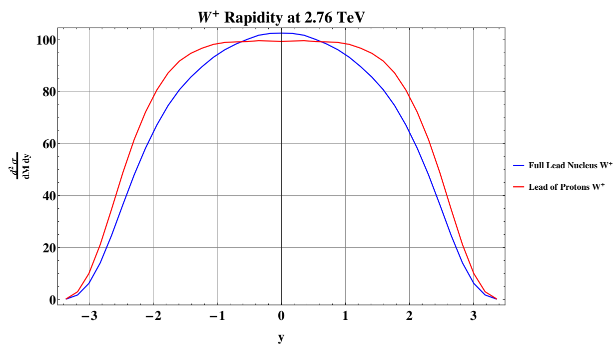

Figure 11: In this figure, we see the W^+cross section as a function of rapidity for a full lead nucleus with 82 protons and 125 neutrons. The blue curve is calculated with the nCTEQ lead PDF while the red curve is calculated with the nucleus constructed from the proton PDF. Here we are incorporating the iso-scalar effects of the heavy nucleus.

leases will help to reduce the theoretical uncertainties on the W^+prediction.

Furthermore, we see that in the high rapidity regions the correlation between the theoretical uncertainty on the down quark and the error on the W^+cross section is above 0.7. The error on this PDF is very well constrained, even for the nuclear parameterization. The prediction for the cross-section in this region is well outside of the proton prediction. Here we see the largest deviations do to the nuclear modifications.

SHOW RATIOS:

$$p->n$$

$$\{u,d\} \to d,u\}$$

$$Green = \frac{1}{2}\,p(x,Q) + \frac{1}{2}\,n(x,Q)$$
$$red = \frac{Z}{A}\,p(x,Q) + \frac{N}{A}\,n(x,Q)$$

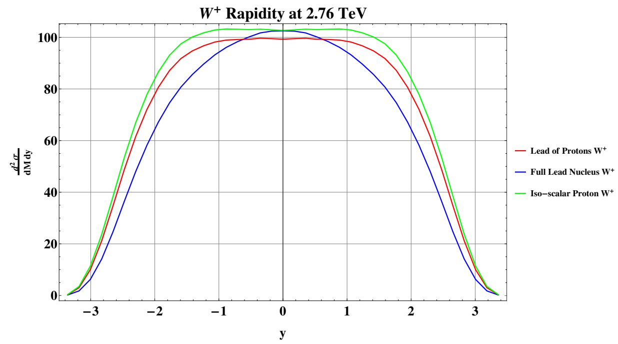

Figure 12: In this figure, we see the W^+cross section as a function of rapidity for a full lead nucleus with 82 protons and 125 neutrons constructed with the Lead PDF and proton PDF. We also see an artificial iso-scalar proton constructed with 1 proton and 1 neutron. The blue curve is calculated with the nCTEQ lead PDF while the red and green curves are calculated with the nucleus constructed from the proton PDF. Here the modification of the cross section with an approximate iso-scalar target are clearly visable. Comparison to the prediction made with the iso-scalar effects removed reveals the nuclear modifications.

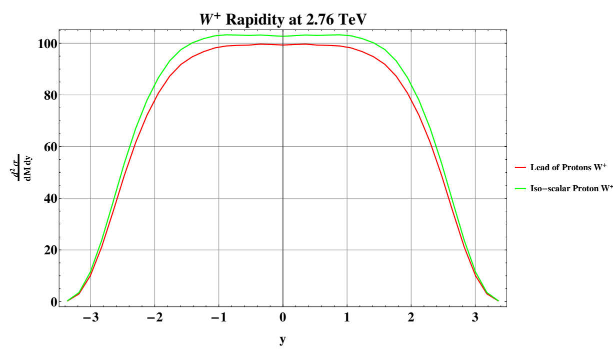

Figure 13: In this figure, we see the W^+cross section as a function of rapidity for a full lead nucleus with 82 protons and 125 neutrons, constructed with a proton PDF, as well as an artificial iso-scalar proton constructed with 1 proton and 1 neutron. We see that the two curves have approximately the same shape. This is because the iso-scalar effects dominate the behavior of this cross-section and must be removed so that the nuclear modifications are visible.

$$blue = \frac{Z}{A}\,Pb_p(x,Q) + \frac{N}{A}\,Pb_n(x,Q)$$

V. DISCUSSION NOTES

motivation:
fig: lead atlas or cms
fig: proton atlas + cms + lhc-b: cern courier???

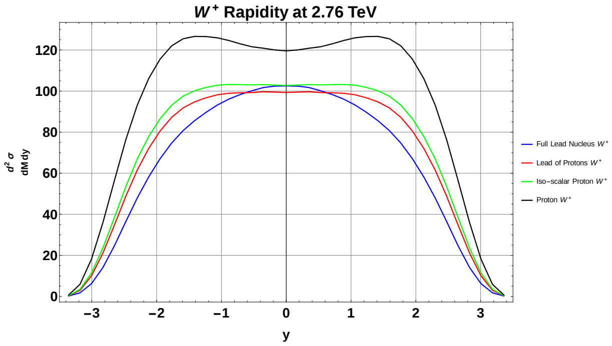

Figure 14: In this figure, we see the W^+cross section as a function of rapidity for a full lead nucleus with 82 protons and 125 neutrons constructed with the Lead PDF and proton PDF. We also see an artificial iso-scalar proton constructed with 1 proton and 1 neutron and the free proton PDF (black). The blue curve is calculated with the nCTEQ lead PDF while the red and green curves are calculated with the nucleus constructed from the proton PDF. Here the modification of the cross section with an approximate iso-scalar target are clearly visable. Comparison to the prediction made with the iso-scalar effects removed reveals the nuclear modifications.

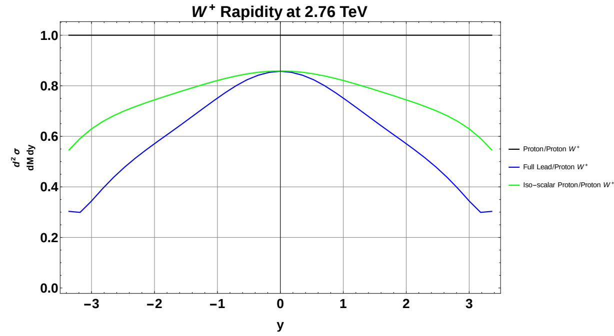

Figure 15: Here we see the iso-spin effects ploted as a ratio compared to the free proton PDF. The ratio of iso-scalar proton/proton is seen in Green and the Full Lead nucleus/proton is in Blue.

discu: LO fig: u softens, but integral is a bit larger; compesating d-bar: see figs

also runn 5.02 TEV

compare to hkn

eps: comment and recognize the work

pt distribution:

cursory comment

error pdf: compare proton and nuc