Cold Nuclear Matter Effects on Open and Hidden Heavy Flavor Production

R. Vogt

Lawrence Livermore National Laboratory, Livermore, CA 94551, USA
Physics Department, University of California, Davis, CA 95616, USA

- $pp$ Collisions
- $pA$ Collisions
- Factorization of shadowing in $AA$ collisions into $pA \times Ap$
$pp$ Production: Open Heavy Flavor
Uncertainties on the $Q\bar{Q}$ Total Cross Section Are Large

Standard procedure of assuming uncertainties on the renormalization and factorization scales for heavy flavor as $0.5 \leq \mu_{R,F}/m(T) \leq 2$ gives large uncertainties on charm production (and on quarkonium in general)

Philosophy of FONLL approach is that the true cross section lies within uncertainty band but calculations are limited by scale choice and these $pp$-level uncertainties are typically larger than those due to the choice of nuclear parton densities, making it hard to reach conclusions, particularly at low $p_T$

Taking the total cross section direct from FONLL gives artificially low uncertainty because the heavy flavor is still ‘light’ in the fixed-order calculation

Instead, we use data to drive a fit of the heavy flavor scale parameters to reduce these uncertainties

We find that the resulting revised uncertainty bands are smaller than those for nuclear parton densities
Calculating the Uncertainty on the $Q\bar{Q}$ Cross Section

The one standard deviation uncertainties on the quark mass and scale parameters in the $c\bar{c}$ and $J/\psi$ $pp$ fits were calculated using the CT10 parton densities. If the central, upper and lower limits of $\mu_{R,F}/m$ are denoted as $C$, $H$, and $L$ respectively, then the seven sets corresponding to the scale uncertainty are

$$(\mu_F/m, \mu_R/m) = (C,C), (H,H), (L,L), (C,L), (L,C), (C,H), (H,C)$$

The upper and lower limits of the charm quark mass are used with the central values of $\mu_F/m$ and $\mu_R/m$

The uncertainty band comes from the upper and lower limits of mass and scale uncertainties added in quadrature:

$$\sigma_{\text{max}} = \sigma_{\text{cent}} + \sqrt{(\sigma_{\mu,\text{max}} - \sigma_{\text{cent}})^2 + (\sigma_{m,\text{max}} - \sigma_{\text{cent}})^2}$$

$$\sigma_{\text{min}} = \sigma_{\text{cent}} - \sqrt{(\sigma_{\mu,\text{min}} - \sigma_{\text{cent}})^2 + (\sigma_{m,\text{min}} - \sigma_{\text{cent}})^2}$$
Large Uncertainties with FONLL Fiducial Parameters

With a given PDF set define a fiducial region of mass and scale that should encompass the true value – central mass and scale \( (m, \mu_F/m, \mu_R/m) = (1.5 \text{ GeV}, 1, 1) \):

- For \( \mu_F = \mu_R = m \), vary mass, \( 1.3 < m < 1.7 \);
- For \( m = 1.5 \text{ GeV} \), vary scales independently within a factor of two: \( (\mu_F/m, \mu_R/m) = (1, 1), (2,2), (0.5,0.5), (0.5,1), (1,0.5), (1,2), (2,1) \).

Low scales set limits on uncertainty \( (\mu_R/m = 0.5 \text{ upper limit, } \mu_F/m = 0.5 \text{ lower limit}) \)

Figure 1: Uncertainty band on \( \sigma_{\text{total}} \) total cross section formed from adding mass and scale uncertainties in quadrature.
Fixing Scale Parameters by Fitting $\sigma_{\bar{c}c}$

Fit the NLO total $\bar{c}c$ cross section to open charm total cross section data – caveat: full NNLO cross section unknown, could still be large correction

Employ $m = 1.27$ GeV, value of charm quark mass from lattice calculations at $m(3 \text{ GeV})$

Use subset of $\bar{c}c$ total cross section data to fix best fit values of $\mu_F/m$ and $\mu_R/m$

Result with $\Delta \chi^2 = 1$ gives uncertainty on scale parameters; $\Delta \chi^2 = 2.3$ gives one standard deviation on total cross section

Range of $\mu_R$ for given $m$ is very narrow; range of $\mu_F$ is rather broad, especially when RHIC cross sections are included

Figure 2: The $\chi^2$/dof contours for (left) fixed target data only, (center) including the PHENIX 200 GeV cross section, and (right) including the STAR 2011 cross section but excluding the STAR 2004 cross section. The best fit values are given for the furthest extent of the $\Delta \chi^2 = 1$ contours.
Energy Dependence of Fit Results

Fixed-target only fit (left) gives worst agreement with RHIC data and largest spread in total cross section (due to low factorization scales in fit region).

Including most recent STAR analysis with PHENIX data at $\sqrt{s} = 200$ GeV gives strongest energy dependence and narrowest uncertainty region (right) than with PHENIX alone (center).

Only the last analysis gives good agreement with the ALICE data (not included in the fits).

Figure 3: The energy dependence of the charm total cross section compared to data for (left) fixed target data only, (center) including the PHENIX 200 GeV cross section, and (right) including the STAR 2011 cross section but excluding the STAR 2004 cross section. The best fit values are given for the furthest extent of the $\Delta \chi^2 = 1$ contours. The central value of the fit in each case is given by the solid red curve while the dashed magenta curves and dot-dashed cyan curves show the extent of the corresponding uncertainty bands. The dashed curves outline the most extreme limits of the band. On the bottom right, the solid blue curves in the range $19.4 \leq \sqrt{s} \leq 200$ GeV represent the uncertainty obtained from the extent of the $\Delta \chi^2 = 2.4$ contour of fit including STAR 2011 data.
Same Fit Procedure Can be Done for $b\bar{b}$ Cross Section

Fiducial parameter set gives good agreement with the data, fitting narrows the result still further. Data fluctuate more than the width of the uncertainty band, thus some calculations will agree with data better than others since data at similar energies are discrepant with each other.

Figure 4: The energy dependence of the bottom total cross section compared to data. The calculations are with the fiducial parameter set (left) and the fitted values (right).
$p_T$ Distributions Calculated with FONLL

Designed to cure large logs of $p_T/m$ for $p_T \gg m$ in fixed order calculation (FO) where mass is no longer only relevant scale.

Includes resummed terms (RS) of order $\alpha_s^2(\alpha_s\log(p_T/m))^k$ (leading log – LL) and $\alpha_s^3(\alpha_s\log(p_T/m))^k$ (NLL) while subtracting off fixed order terms retaining only the logarithmic mass dependence (the “massless” limit of fixed order (FOM0)), both calculated in the same renormalization scheme.

Scheme change needed in the FO calculation since heavy flavor is ‘heavy’ while in the RS approach the heavy flavor is an active light degree of freedom.

Schematically (Cacciari and Nason):

$$FONLL = FO + (RS - FOM0) \ G(m, p_T)$$

$G(m, p_T) \to 1$ as $m/p_T \to 0$ up to terms suppressed by powers of $m/p_T$.

Total cross section similar to NLO, differences due to the fact that FONLL employs $n_{lf} + 1$ in e.g. $\alpha_s$ while $n_{lf}$ employed in NLO, same in FO and FONLL for matching to work.

FONLL does not include $k_T$ broadening, not needed due to different fragmentation scheme, to include it, need to go back to full FO calculation.
Results on LHC Heavy Flavor Distributions

Excellent agreement with $\sqrt{s} = 7$ TeV ALICE $pp$ data on muons in the forward region $(2.5 < y < 4)$

Leptons from semi-leptonic heavy flavor decays include contributions from $D \to \mu X$, $B \to \mu X$, $B \to D \to \mu X$, all with $\sim 10\%$ decay branching ratios

Fit results gives narrower uncertainty without reducing agreement with data than fiducial results based on $m = 1.5$ GeV

Figure 5: (Left) Comparison of the single lepton $p_T$ distributions in the rapidity interval $2.5 < y < 4$ at $\sqrt{s} = 7$ TeV calculated with the FONLL set for charm (solid red) and the fitted set with $m = 1.27$ GeV (dashed black). (Center) Our calculations are compared with the reconstructed ALICE $D^0$ data in $|y| \leq 0.5$. The FONLL uncertainty bands with the fiducial charm parameter set are shown by the red solid curves while the blue dashed curves are calculated with the charm fit parameters. (Right) Our calculations are compared with the reconstructed LHCb $D^0$ data in the rapidity intervals: $2 < y < 2.5$ (solid red); $2.5 < y < 3$ (solid blue); $3 < y < 3.5$ (dashed red); $3.5 < y < 4$ (dashed blue); and $4 < y < 4.5$ (dot-dashed red). The rapidity intervals are separated by a factor of 10 to facilitate comparison. The lowest rapidity interval, $2 < y < 2.5$, is not scaled.
Results for Bottom Distributions

Both $B$ hadron (left) and muons from $b$ decays (right) show agreement with the $p_T$ distributions.

Figure 6: (Left) The $B$ hadron $p_T$ distribution measured by ATLAS. (Center) The muon $p_T$ distribution from $b$ decays measured by CMS. The calculations are with the central fit set and the one standard deviation in mass and scale values.
$pp$ Production: Quarkonium Color Evaporation Model
Color Evaporation Model

All quarkonium states are treated like $Q\bar{Q} \ (Q = c, b)$ below $HH \ (H = D, B)$ threshold; mass and scale parameters fixed from open $Q\bar{Q}$ calculation.

Distributions for all quarkonium family members similar, modulo decay feed down, production ratios should be independent of $\sqrt{s}$.

Gavai et al. calculated complete $J/\psi$ $p_T$ distribution starting from exclusive NLO $Q\bar{Q}$ production code by Mangano et al.

At LO, $gg \to Q\bar{Q}$ and $q\bar{q} \to Q\bar{Q}$; NLO add $gq \to Q\bar{Q}q$

$$\sigma_Q^{\text{CEM}} = F_Q \sum_{i,j} \int_{4m_Q^2}^{4m_H^2} d\hat{s} \int dx_1 dx_2 \ f_{i/p}(x_1, \mu^2) \ f_{j/p}(x_2, \mu^2) \ \hat{s}_{ij}(\hat{s}) \ \delta(\hat{s} - x_1 x_2 s)$$

Main uncertainties arise from choice of PDFs, heavy quark mass, renormalization ($\alpha_s$) and factorization (evolution of PDFs) scales.

Inclusive $F_Q$ fixed by comparison of NLO calculation of $\sigma_Q^{\text{CEM}}$ to $\sqrt{s}$ dependence of $J/\psi$ and $\Upsilon$ cross sections, $\sigma(x_F > 0)$ and $B d\sigma/dy|_{y=0}$ for $J/\psi$, $B d\sigma/dy|_{y=0}$ for $\Upsilon$

Data and branching ratios used to separate the $F_Q$'s for each quarkonium state

<table>
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<tr>
<th>Resonance</th>
<th>$J/\psi$</th>
<th>$\psi'$</th>
<th>$\chi_{c1}$</th>
<th>$\chi_{c2}$</th>
<th>$\Upsilon$</th>
<th>$\Upsilon'$</th>
<th>$\Upsilon''$</th>
<th>$\chi_{b}(1P)$</th>
<th>$\chi_{b}(2P)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_i^{\text{dir}}/\sigma_H$</td>
<td>0.62</td>
<td>0.14</td>
<td>0.6</td>
<td>0.99</td>
<td>0.52</td>
<td>0.33</td>
<td>0.20</td>
<td>1.08</td>
<td>0.84</td>
</tr>
<tr>
<td>$f_i$</td>
<td>0.62</td>
<td>0.08</td>
<td>0.16</td>
<td>0.14</td>
<td>0.52</td>
<td>0.10</td>
<td>0.02</td>
<td>0.26</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Table 1: The ratios of the direct quarkonium production cross sections, $\sigma_i^{\text{dir}}$, to the inclusive $J/\psi$ and $\Upsilon$ cross sections, denoted $\sigma_H$, and the feed down contributions of all states to the $J/\psi$ and $\Upsilon$ cross sections, $f_i$, Digal et al.
CEM $p_T$ Distributions

Without intrinsic $k_T$ smearing (or resummation) the $Q\overline{Q}$ $p_T$ distribution (LO at $\mathcal{O}(\alpha_s^3)$ while total cross section is NLO at this order) is too peaked at $p_T \to 0$, needs broadening at low $p_T$

Implemented by Gaussian $k_T$ smearing, $\langle k_T^2 \rangle_p = 1$ GeV$^2$ for fixed target $pp$ and $\pi p$, broadened for $pA$ and $AA$, NLO code adds in final state:

$$g_p(k_T) = \frac{1}{\pi \langle k_T^2 \rangle_p} \exp\left(-\frac{k_T^2}{\langle k_T^2 \rangle_p}\right)$$

Broadening should increase with energy we make a simple linear extrapolation to obtain

$$\langle k_T^2 \rangle_p = 1 + \frac{1}{n} \ln \left(\sqrt{s}/\sqrt{s_0}\right)\text{GeV}^2$$

We find $n \sim 12$ agrees best with RHIC $J/\psi$ data while $n \sim 3$ agrees with the Tevatron $\Upsilon$ data

Note that unlike FONLL-like calculation of single inclusive heavy flavor with resummed logs of $p_T/m$, at large $p_T$ distribution may be harder than it should be.
**J/ψ Cross Sections from $c\bar{c}$ Fits**

Take results of $c\bar{c}$ fits, calculate NLO $J/\psi$ cross section in CEM, fit scale factor $F_C$ (needed to match the $c\bar{c}$ cross section below the $D\bar{D}$ threshold to the inclusive $J/\psi$ cross section) with central value of parameter sets – tighter uncertainty band

CEM calculation reproduces shape of $J/\psi$ $p_T$ and $y$ distributions rather well with single parameter

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**Figure 7:** (Left) The uncertainty band on the forward $J/\psi$ cross section. The dashed magenta curves and dot-dashed cyan curves show the extent of the corresponding uncertainty bands. The dashed curves outline the most extreme limits of the band. The $J/\psi$ rapidity distribution (center) and the midrapidity $p_T$ distributions (right) and their uncertainties. The results are compared to PHENIX $pp$ measurements at $\sqrt{s} = 200$ GeV. The solid red curve shows the central value while the dashed magenta curves outline the uncertainty band. A $\langle k_T^2 \rangle$ kick of 1.19 GeV$^2$ is applied to the $p_T$ distributions.
Comparison to ALICE $pp$ Distributions

Figure 8: The $J/\psi$ rapidity distribution (a) and the midrapidity, $|y| < 0.9$ (b), and forward rapidity, $2.5 < y < 4$ (c) $p_T$ distributions at $\sqrt{s} = 7$ TeV (top) and 2.76 TeV (bottom) and their uncertainties. The results are compared to the ALICE rapidity distribution as well as the $p_T$ distributions. The solid red curve shows the central value while the dashed magenta curves outline the uncertainty band. A $\langle k_T^2 \rangle$ kick of 1.49 GeV$^2$ is applied to the $p_T$ distributions, as discussed in the text.
Cross Sections from $b\bar{b}$ Fits

Take results of $b\bar{b}$ fits, calculate NLO $\Upsilon$ cross section in CEM, fit scale factor $F_C$ (needed to match the $b\bar{b}$ cross section below the $B\bar{B}$ threshold to the summed inclusive $\Upsilon$ cross sections at $y = 0$) with central value of parameter sets – tighter uncertainty band

Agreement of CEM calculation with energy dependence is very good

Figure 9: The uncertainty band on the total inclusive $\Upsilon(1S) + \Upsilon(2S) + \Upsilon(3S)$ at midrapidity.
Comparison to $pp$ and $p\bar{p}$ $\Upsilon$ Data

Need a larger broadening for the higher mass $b$ quarks

Good agreement with Tevatron Run II data, both in the full rapidity range and separated into different rapidity regions

Agreement with CMS $\Upsilon$ data for $p_T < 30$ GeV, very high $p_T$ hard to reproduce, requires high $p_T$ resummation for logs of large $p_T/m$

Figure 10: (Left) $\Upsilon(1S)$ $p_T$ distribution in the full measured rapidity range, $|y| < 1.8$ (black), and different rapidity bins: $|y| < 0.8$ (red); $0.8 < |y| < 1.2$ (blue); and $1.2 < |y| < 1.8$ (magenta). The data are from the D0 collaboration with $\sqrt{s} = 1.96$ TeV in $p\bar{p}$ collisions at the Tevatron. (Right) Calculation of the $\Upsilon(1S)$ $p_T$ distribution in $pp$ collisions at $\sqrt{s} = 7$ TeV. The data are from the CMS collaboration and are from the rapidity range $|y| < 2.4$. 
\( pA \) Production
Cold Nuclear Matter Effects in Hadroproduction

In heavy-ion collisions, one has to fold in cold matter effects, typically studied in $pA$ or $dA$ interactions from fixed-target energies to colliders.

Hard probes, where production is calculable in QCD, are best to study differences between initial and final state effects.

Important cold nuclear matter effects in hadroproduction include:

- Initial-state nuclear effects on the parton densities (nPDFs)
- Initial- (or final-) state energy loss
- $k_T$ broadening from multiple scattering
- Final-state absorption on nucleons
- Final-state break up by comovers (hadrons or partons)
- Intrinsic $Q\bar{Q}$ pairs

I will concentrate on nuclear parton densities.

For direct $J/\psi$ and $\Upsilon$ production at LHC energies, extrapolated absorption cross section is $\sim 0$.

Higher quarkonium states more likely to be affected by absorption (larger radii = larger cross sections) as well as comover breakup (same reason).
Nuclear PDFs at NLO

EPS09 NLO (black) and EKS98 LO (magenta) very similar for $x > 0.002$, significant antishadowing, nDS NLO (blue) and nDSg NLO (red) have almost no antishadowing, nDSg and EKS98 have stronger shadowing than central EPS09 at low $x$ FGS-H and FGS-L have a minimum $x$ of $10^{-5}$, hence the drop

Figure 11: Gluon shadowing ratios calculated for Pb nuclei ($A = 208$) calculated at the central value of the fitted factorization scales for $J/\psi$ (left) and $\Upsilon$ (right). EPS09 NLO is shown by the black solid curve while the uncertainty band is outlined by the black dotted curves. The NLO nDS and nDSg parameterizations are given in the blue dashed and blue dot dashed curves. The LO EKS98 parameterization is in magenta (dot-dot-dot-dash-dashed). The red dot-dot-dot-dashed and dot-dash-dash-dashed curves are the FGS-L and FGS-H parameterizations respectively.
Calculating nPDF Uncertainties in $pA$

EPS09 LO and EPS09 NLO based on CTEQ61L and CTEQ6M respectively

The gluon densities in these two sets differ significantly at low $x$, hence the low $x$ modifications of EPS09 LO and NLO are quite different

nPDF uncertainties calculated with the 30+1 sets of EPS09: one central set and 30 sets obtained by varying each of the 15 parameters, i.e. sets 2 and 3 were obtained by changing parameter 1 by $\pm 1\sigma_1$ etc. where $\sigma_i$ is the standard deviation of parameter $i$

Uncertainties due to shadowing calculated using 30+1 error sets of EPS09 NLO added in quadrature so the uncertainty is cumulative
Open Heavy Flavor
Treating Open Heavy Flavor in $pp \rightarrow pA$

To investigate some nuclear effects, such as $k_T$ broadening, fixed-order scheme required sincd FONLL only includes fragmentation

Fixed-order MNR code uses Peterson function, $\propto z(1-z)^2/((1-z)^2 + \epsilon_Q z)^2$ with $\epsilon_c = 0.06, \epsilon_b = 0.006$, much stronger than the FONLL result derived from moments of the fragmentation function.

Fixed-order calculation can include bare quark only; fragmentation only; or broadening with fragmentation – compare to heavy flavor $D^0$ and $D^*$ meson data from STAR $pp$ collisions at $\sqrt{s} = 200$ GeV

We’ll try various combinations of fragmentation parameters $\epsilon_Q$ to match FONLL $D$ and $B$ meson results and compare/contrast the results of adding an additional $k_T$ kick – the $k_T$ kick was added to the MNR fixed-target calculations because the Peterson fragmentation function was too strong on its own to describe low $p_T$ fixed-target data

Single inclusive charm cross section is finite at $p_T = 0$ so the kick isn’t required as it is for quarkonium/heavy flavor pairs – however, it is the only thing that makes the azimuthal distribution between $Q$ and $\overline{Q}$ pair peak away from $\Delta \phi \sim \pi$
Heavy Quark $p_T$ Distributions at $\sqrt{s} = 200$ GeV

First we need to compare the heavy quark distributions in both approaches – the charm quark distributions alone give a rather good agreement with the data, $p_T$ distributions calculated both ways are compatible, differ by a few percent, mostly at low $p_T$

Figure 12: The charm (left) and bottom (right) FONLL uncertainty bands based on our fit parameters (red curves, solid is the central value, dashed curves outline the band) are compared to the MNR central result (no mass and scale uncertainties included).
Fragmentation Effects Alone

Including the Peterson function fragmentation scheme, a la MNR, destroys the agreement with the STAR $D$ meson data (even though it should agree better) as long as the standard Peterson function parameter is used, taking a smaller value of $\epsilon$ can restore the agreement but $\epsilon$ has to be decreased from 0.06 to 0.008 for charm.

Figure 13: The charm (left) and bottom (right) distributions with the Peterson function used for fragmentation. For charm the curves correspond to the standard $\epsilon_c = 0.06$ (black) and the reduced values of 0.04 (red dashed), 0.02 (blue dot-dashed), 0.01 (magenta dotted) and 0.008 (cyan dot-dash-dash-dashed). For bottom the curves correspond to the standard $\epsilon_c = 0.006$ (black) and the reduced values of 0.004 (red dashed), 0.002 (blue dot-dashed), 0.001 (magenta dotted) and 0.0008 (cyan dot-dash-dash-dashed).
Adding only a $k_T$ kick to the already finite $p_T$ distribution for charm and bottom, without fragmentation, changes the slope so that the calculated distribution now lies above the STAR data for $p_T > 2$ GeV. Any $k_T$ kick causes the effect.

For bottom, even though the level of assumed broadening is bigger, based on what was required for the $\Upsilon p_T$ distributions, the effect relative to the $b$ quark distribution is very small.

Figure 14: The charm (left) and bottom (right) $p_T$ distributions with only $k_T$ broadening included. The black curve is the quark distribution while the dashed red curves are $\langle k_T^2 \rangle = 1$ GeV$^2$. The remaining curve are $\langle k_T^2 \rangle = 1 + (a/n) \log(\sqrt{s}/20)$ with $a = 1, 0.5$ and 2 for the blue dashed, magenta dotted and cyan dot-dash-dash-dashed curves respectively. Here $n = 12$ for charm and 3 for bottom.
Combined Fragmentation and $k_T$ Broadening Effects

When broadening is included after the Peterson function fragmentation is applied, the agreement becomes somewhat better but to make it significantly better with fragmentation, a smaller value of $\epsilon$ need to be employed, \textit{i.e.} $\epsilon_c = 0.008$

Figure 15: The charm (left) and bottom (right) $p_T$ distributions with only $k_T$ broadening and Peterson fragmentation included. The black curve is the quark distribution while the dashed red curve includes the Peterson function only. The blue dashed curve employs $\langle k_T^2 \rangle = 1$ GeV$^2$. The remaining curves are $\langle k_T^2 \rangle = 1 + (a/n) \log(\sqrt{s}/20)$ with $a = 1$, 0.5 and 2 for the magenta dotted, cyan dot-dot-dash-dashed, and black dot-dot-dot-dashed curves respectively. Here $n = 12$ for charm and 3 for bottom.
Heavy Meson $p_T$ Distributions at $\sqrt{s} = 200$ GeV

Finally, we compare the heavy flavor meson distributions in both approaches – without any $k_T$ broadening and a weaker fragmentation function, $\epsilon_c = 0.008$ and $\epsilon_b = 0.0008$, the MNR result gives a good match to the FONLL result.

Figure 16: The $D$ (left) and $B$ (right) meson $p_T$ distributions based on our fit parameters (black curve, central value only). The blue curve shows the MNR result with standard Peterson function fragmentation while the red curve gives the result for MNR with a weaker fragmentation function.
Calculations for LHC at Midrapidity

Test the sensitivity of $R_{pPb}$ at midrapidity to the choice of the fragmentation function and amount of $k_T$ broadening

Use standard and reduced values of $\epsilon_Q$, both without and with $k_T$ broadening and calculate $R_{pPb}(p_T)$ at midrapidity, including EPS09 NLO parameterization

The $R_{pPb}(p_T)$ is only different if we assume higher $\langle k_T^2 \rangle$ in $p+Pb$ than $pp$.

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Figure 17: (Left) The $p_T$ distributions for $pp$ collisions (solid red) and $p+Pb$ interactions at $\sqrt{s_{NN}} = 5$ TeV with EPS09 NLO shadowing only (black), $k_T^2 = 0$ and $\epsilon_c = 0.06$ (blue), $k_T^2 = 0$ and $\epsilon_c = 0.008$ (red), $k_T^2 = 1.46 \text{ GeV}^2$ and $\epsilon_c = 0.008$ (magenta) and $k_T^2 = 1.92$ and $\epsilon_c = 0.008$ (cyan). The last result is assuming a larger intrinsic $k_T$ kick in $p+Pb$ than in $pp$. (Right) The ratios relative to $pp$, assuming the same $k_T$ kick and fragmentation value of $\epsilon_c$ in $p+Pb$ and $pp$ except for the last calculation where the $k_T$ kick is assumed to be larger in $p+Pb$. 

$-1.37 < y < 0.43$
Quarkonium
$R_{pPb}$ Independent of Proton PDF

Even though global fit for EPS09 is based on a specific proton PDF set, the calculated shadowing ratios are basically unchanged by the choice of proton PDF, similar for other nPDFs.

Figure 18: The ratio $R_{pPb}(p_T)$ for ALICE at forward rapidity (left) and $p_T$-integrated as a function of rapidity. The ratios are for CT10 (black), CTEQ5M (red), CTEQ6M (blue) and MSTW (magenta).
Data typically show stronger effect than central EPS09 result alone but the data
tend to fall within the uncertainty band.

These calculations (also for the rapidity dependence, next slide) differ somewhat
from previous results shown – the wrong scale was being passed to the nPDFs.

The ratio $R_{p\text{B}}(p_T)$ for ALICE at forward rapidity (left) and backward (middle) and central (right) rapidity. The EPS09 uncertainty band is shown.
EPS09 Uncertainty Bands II: \( R_{pPb}(y) \)

Backward rapidity data agree with the rise at \( y < -2.5 \) from antishadowing onset.

Preliminary midrapidity point is on the lower edge of the uncertainty band.

Forward rapidity data are underestimated, only the lower edge of the uncertainty band (strongest shadowing) is consistent with data.

For \( y > -2.5 \), the band is relatively wide, about \( \pm 12\% \), and \( R_{pPb} \) decreases by less than 10% in this region.

Figure 20: The EPS09 NLO uncertainty band, \( R_{pPb}(y) \).
EPS09 Uncertainty Bands III: $R_{FB}$

Reduced uncertainties in the forward/backward ratio because we take the ratio before adding differences in quadrature.

The $p_T$ ratio almost flat and above the data for $p_T < 6$ GeV.

Curvature of rapidity ratio at $y > 2.5$ reflects the antishadowing rise at backward rapidity and the narrower uncertainty band in this region relative to the forward region.

Figure 21: The ratio $R_{FB}(p_T)$ for ALICE at forward rapidity (left) and $R_{FB}(y)$ (right). The EPS09 uncertainty band is shown.
EPS09 Uncertainty Bands IV: $\Upsilon \, R_{pPb}(y), \, R_{FB}(y)$

Apparent discrepancy between the ALICE and LHCb values of $R_{pPb}$, forward ALICE ratio is similar to that of $J/\psi$

results with shadowing alone are in good agreement with LHCb

Figure 22: The ratio $R_{pPb}(y)$ (left) and $R_{FB}(y)$ (right) for $\Upsilon$ production. The EPS09 uncertainty band is shown.
NLO vs LO EPS09

The nPDF set should be appropriate to the order of the calculation: if using the LO set in a NLO calculation agrees better with the data, it isn’t really better

NLO calculation required for CEM to obtain $p_T$ distribution and is, anyway, more appropriate

LO CEM uncertainty band is broader, with stronger shadowing, to counterbalance the flatter low $x$ behavior of CTEQ61L while CTEQ6M is valence-like: different behavior of proton PDFs makes good order-by-order agreement of $R_{pPb}$ difficult

Figure 23: (Left) The EPS09 LO (blue) and NLO (red) uncertainty bands for gluon shadowing. The corresponding uncertainty bands for $R_{pPb}(y)$ at $\sqrt{s_{NN}} = 5$ TeV for $J/\psi$ (center) and $\Upsilon$ (right).
NLO vs LO nDS

While there are some differences between the LO and NLO nDS and nDSg ratios, especially for nDSg at $x \sim 0.01$, the LO and NLO ratios are much closer than those of the EPS09 central sets, here order of calculation is not an issue.

nDS(g) employs GRV98 LO and NLO proton PDFs, the $Q^2$ range of the nPDF, $1 < Q^2 < 10^6$ GeV$^2$, is above the minimum scale of GRV98, unlike EPS09 and CTEQ6.

Figure 24: (Left) The nDS and nDSg LO (blue) and NLO (red) gluon shadowing ratios. The corresponding results for $R_{pPb}(y)$ at $\sqrt{s_{NN}} = 5$ TeV are shown for $J/\psi$ (center) and $\Upsilon$ (right).
EPS09 vs Other nPDFs I: $R_{pPb}(p_T)$

Central EPS09 NLO set compared to nDS NLO, nDSg NLO and EKS98 (LO)
nDS effect is weakest of all while nDSg is weak at backward rapidity but stronger
than EPS09 at mid- and forward rapidity
EKS98 and EPS09 NLO are very similar for $x > 0.01$ so they agree well at backward
and mid-rapidity while EKS98 is stronger at forward rapidity

Figure 25: The ratio $R_{pPb}(p_T)$ for ALICE at forward (left), backward (center) and mid- (right) rapidity. The ratios are for central EPS09
NLO (black), nDS NLO (blue dashed), nDSg NLO (blue dot dashed), EKS98 LO (magenta), FGS-H NLO (red dot-dash-dash-dashed) and
FGS-L NLO (red dot-dot-dot-dashed).
EPS09 vs Other nPDFs II: $R_{pPb}(y)$

EKS98 LO follows EPS09 NLO central set until $y > -2$ where it decreases linearly while EPS09 becomes flatter

nDS and nDSg, with no antishadowing, have a weaker $y$ dependence overall

FGS-H and FGS-L are strongest function of rapidity, strong drop at $y > 3.7$ occurs where $x_2 \leq 10^{-5}$

![Figure 26](image_url)

Figure 26: The calculated $R_{pPb}(y)$ for central EPS09 NLO (black), nDS NLO (blue dashed), nDSg NLO (blue dot dashed), EKS98 LO (magenta), FGS-H NLO (red dot-dash-dash-dashed) and FGS-L NLO (red dot-dot-dot-dashed).
EPS09 vs Other nPDFs III: $R_{FB}$

nDS has strongest $p_T$ dependence of $R_{FB}(p_T)$, EKS98 comes closest to agreement with low $p_T$ data due to the stronger effect at low $x$ than EPS09

Only EPS09 shows curvature in $R_{FB}(y)$, the others show an almost linear $y$ dependence (aside from far forward ‘feature’ of FGS)

Figure 27: The ratio $R_{FB}(p_T)$ for ALICE at forward rapidity (left) and $R_{FB}(y)$ (right). The ratios are for central EPS09 NLO (black), nDS NLO (blue dashed), nDSg NLO (blue dot dashed), EKS98 LO (magenta), FGS-H NLO (red dot-dash-dash-dashed) and FGS-L NLO (red dot-dot-dot-dashed).
EPS09 vs Other nPDFs IV: $\Upsilon R_{pPb}(y), R_{FB}(y)$

Generally relatively good agreement with $R_{pPb}$

Rather narrow antishadowing band for FGS sets

Figure 28: The ratio $R_{pPb}(y)$ for ALICE at forward rapidity (left) and $p_T$-integrated as a function of rapidity. The ratios are for central EPS09 NLO (black), nDS NLO (blue dashed), nDSg NLO (blue dot dashed), EKS98 LO (magenta), FGS-H NLO (red dot-dash-dash-dashed) and FGS-L NLO (red dot-dot-dot-dashed).
Factorization of $R_{AA}$ into $R_{pA}(+y) \times R_{pA}(-y)$? $J/\psi$

The factorization is exact for the CEM at LO because the process is $2 \to 1$ and the scale is fixed ($p_T = 0$) so $x_1$ and $x_2$ are known at each $y$ – compare red line with circles on the left.

Factorization is not automatic at NLO because process is $2 \to 2 [c\bar{c} + g/q/\bar{q}]$ and the additional parton makes the correspondence between $x_1, x_2$ and $y$ inexact, even at fixed rapidity – agreement is good, nevertheless.

Figure 29: The $R_{AA}$ (red) ratio is compared to the product $R_{pA}(+y) \times R_{pA}(-y)$ (points) along with the individual $pA$ ratios at forward (dashed) and backward (dot-dashed) rapidity. Results are compared for the rapidity distributions at LO (left) and NLO (middle) as well as for the $p_T$ dependence at NLO (right).
Factorization of $R_{AA}$ into $R_{pA}(+y) \times R_{pA}(-y)$? 

Agreement also good for $\gamma$ production even though there is somewhat more scatter at high $p_T$.

Figure 30: The $R_{AA}$ (red) ratio is compared to the product $R_{pA}(+y) \times R_{pA}(-y)$ (points) along with the individual $pA$ ratios at forward (dashed) and backward (dot-dashed) rapidity. Results are compared for the rapidity distributions at LO (left) and NLO (middle) as well as for the $p_T$ dependence at NLO (right).
Summary

• Fitting the scale parameters to the total $Q\bar{Q}$ cross section data significantly reduces the uncertainties on open heavy flavor and quarkonium production.

• Differences in LO and NLO results for EPS09 on $J/\psi$ production illustrates the fact that gluon nPDF is still not very well constrained, although, given the approximate concordance of the nDS results, the EPS09 discrepancy may be due to the choice of CTEQ6 proton PDFs.

• LHC $p+Pb$ hadroproduction data could be taken into global analyses in the future but many caveats on medium effects, e.g. initial and/or final state energy loss, production mechanism, saturation effects – while the $R_{pPb}$ results, both as a function of $p_T$ and $y$, look good, the $R_{FB}$ results are not as good: $pp$ data at 5 TeV are required.
Backup
Three Methods Checked

We calculate the mass and scale uncertainties in 3 ways:

The first two follow Cacciari, Nason and RV where the cross section extremes with mass and scale are used to calculate the uncertainty

\[
\sigma_{\text{max}} = \sigma_{\text{cent}} + \sqrt{(\sigma_{\mu,\text{max}} - \sigma_{\text{cent}})^2 + (\sigma_{m,\text{max}} - \sigma_{\text{cent}})^2},
\]
\[
\sigma_{\text{min}} = \sigma_{\text{cent}} - \sqrt{(\sigma_{\mu,\text{min}} - \sigma_{\text{cent}})^2 + (\sigma_{m,\text{min}} - \sigma_{\text{cent}})^2},
\]

\[m/\mu_F/\mu_R \text{ v1} \]
We initially take the ratios of \(p+\text{Pb}\) to \(pp\) for each mass and scale combination and then locate the extrema in each case – this gives the uncertainty on \(R_{p\text{Pb}}\) of each set, can appear odd if ratios are not very different but the extrema changes between sets

\[m/\mu_F/\mu_R \text{ v2} \]
We locate the mass and scale extrema and calculate the uncertainty as above and then form \(R_{p\text{Pb}}\) by dividing by the \(pp\) cross section calculated with the central parameter set – this forms global \(R_{p\text{Pb}}\) based on the cross sections rather than the shadowing ratios and is thus significantly larger, especially at low \(p_T\), becoming smaller at high \(p_T\) (Does not apply to \(R_{FB}\))

\[m/\mu_F/\mu_R \text{ v3} \]
We add the mass and scale uncertainties in quadrature, a la EPS09, and then form \(R_{p\text{Pb}}\) by dividing by the central \(pp\) cross section – since this is a cumulative uncertainty rather than based on the greatest excursion from the mean, it is the largest uncertainty at low \(p_T\). This was calculated assuming that the appropriate \(\mu_F/m\) and \(\mu_R/m\) pairs are \([(H,H),(L,L)], [(H,C),(L,C)]\) and \([(C,H),(C,L)]\), other choices could lead to different results
Mass and Scale Uncertainty Bands I: $R_{pPb}(p_T)$

Uncertainties based on the differences due to EPS09 NLO alone, i.e. taking the extrema based on the ratios, gives very small uncertainty, smaller than EPS09 NLO Uncertainties based on cross sections are much larger with v3 bigger than v2 at low $p_T$, expected since ratio is cumulative

Ratios decrease at high $p_T$ where the scale choices are less important since $p_T \gg m$

The order switches for the lower limit at high $p_T$, possibly because of our pairing choices

Figure 31: The mass and scale uncertainties in the ratio $R_{pPb}(p_T)$ are compared to those for EPS09 NLO alone for ALICE at forward (left), backward (middle) and mid- (right) rapidity. The EPS09 uncertainty band is shown in red while the uncertainties calculated with method v1 in blue, v2 in magenta and v3 in black.
Mand Scale Uncertainty Bands II: $R_{pPb}(y)$

Rapidity dependence with v1 exhibits the perils (?) of basing extrema on individual $R_{pPb}$ ratios – when one ratio is larger at high $|y|$ but not at midrapidity, the calculated v1 changes slope at the switching point.

Right-hand plot indicates how this happens, the ratio with $(H, H)$ is larger than that of the next highest ratio, that with $(C, L)$ except for $|y| < 2$.

Figure 32: (Left) The mass and scale uncertainties in the ratio $R_{pPb}(y)$ are compared to those for EPS09 NLO alone. The EPS09 uncertainty band is shown in red while the uncertainties calculated with method v1 in blue, v2 in magenta and v3 in black. (Right) The $pp$ and $p+Pb$ rapidity distributions for the $(H, H)$ $(C, L)$ sets showing the differences leading to the change in the upper limit of the mass and scale uncertainties of method v1 around midrapidity.
Mass and Scale Uncertainty Bands III: $R_{FB}$

Only v1 and v3 apply here (v2 is equivalent to v1 in this case)

Taking the forward to backward ratio before calculating the uncertainty band makes this ratio essentially insensitive to the mass and scale.

Figure 33: The mass and scale uncertainties in the ratios $R_{FB}(p_T)$ (left) and $R_{FB}(y)$ (right) are compared to those for EPS09 NLO alone for ALICE at forward (left), backward (middle) and mid- (right) rapidity. The EPS09 uncertainty band is shown in red while the uncertainties calculated with method v1 in blue, v2 in magenta and v3 in black.
Mass and Scale Uncertainty Bands IV: $\Upsilon R_{pPb}(y)$, $R_{FB}(y)$

Mass and scale uncertainty narrower on $R_{pPb}$ for $\Upsilon$ than for $J/\psi$

Figure 34: The mass and scale uncertainties in the ratios $R_{pPb}(y)$ (left) and $R_{FB}(y)$ (right) are compared to those for EPS09 NLO alone for ALICE at forward (left), backward (middle) and mid- (right) rapidity. The EPS09 uncertainty band is shown in red while the uncertainties calculated with method v1 in blue, v2 in magenta and v3 in black.