In Medium Quarkonium Production from the SPS to the LHC

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Outline

• Quarkonium Production in the Color Evaporation Model
• Baseline Nuclear Effects on Quarkonium Production
  – Initial-State Shadowing
  – Final-State Absorption
• Shadowing and Absorption in $pA$ at the SPS
• Comparison to RHIC $pp$, $d+Au$ and $AA$ Data
• Predictions for $J/\psi$ and $\Upsilon$ at the LHC
Production: Color Evaporation Model (CEM)

Gavai et al., G. Schuler and R.V.

All quarkonium states are treated like $Q\bar{Q}$ below $H\bar{H}$ threshold
Distributions $(x_F, p_T, \sqrt{S}, A)$ for all quarkonium family members identical — leads to constant ratios
At LO, $gg \to Q\bar{Q}$ and $q\bar{q} \to Q\bar{Q}$; NLO add $gq \to Q\bar{Q}q$

$$\sigma_{CEM}^C = F_C \sum_{i,j} \int_{4m^2}^{4m^2_H} d\hat{s} \int dx_1 dx_2 f_{i/p}(x_1, \mu^2) f_{j/p}(x_2, \mu^2) \hat{\sigma}_{ij}(\hat{s}) \delta(\hat{s} - x_1 x_2)$$

$F_C$ fixed at NLO from total cross section data as a function of $\sqrt{S}$,
$\sigma(x_F > 0)$ for inclusive $J/\psi$ and $B_{\mu\mu} d\sigma(\gamma + \gamma' + \gamma'')_{y=0}/dy$

Values of $m$ and $\mu$ (here $\mu \propto \sqrt{(p_{T\bar{Q}}^2 + p_{TQ}^2)/2 + m_Q^2} = m_{T\bar{Q}Q} \equiv m_T$ in the exclusive $Q\bar{Q}$ code) for several parton densities fixed from $Q\bar{Q}$ production.
\( \chi_c/J/\psi \) Ratio Energy Independent

HERA-B comparison of \( R_{\chi_c} = \sigma(\chi_c)/\sigma(J/\psi) \) with \( \pi A \) and \( pA \) data

Result consistent with \( R_{\chi_c} \) independent of \( \sqrt{S} \), predicted by CEM

CDF result, \( R_{\chi_c} = 0.297 \pm 0.017 \pm 0.057 \), consistent with fixed-target

![Graph](image)

Figure 1: Ratio of \( \chi_c \) to \( J/\psi \) cross sections as a function of \( \sqrt{S} \) for \( \pi A \) and \( pA \) fixed-target measurements. The CSM and NRQCD curves are obtained from Monte Carlo while the ‘average’ is the average value of all measurements. From I. Abt et al. (HERA-B Collab.), Phys. Lett. 561 (2003) 61.
$\psi'/J/\psi$ Ratio Also Energy Independent

Data from $pp$ and $pA$ interactions
Horizontal line corresponds to CEM

Figure 2: Ratio of $\psi'$ to $J/\psi$ cross sections to lepton pairs as a function of $\sqrt{S}$ for $pp$ and $pA$ measurements. Adapted from R.V., Phys. Rept. 310 (1999) 197.
Inclusive $J/\psi$ Total Forward Cross Sections

Total forward $J/\psi$ cross sections as a function of energy
Agrees well with PHENIX $pp$ data at 200 GeV, a bit low for Run II
CDF inclusive cross section

Figure 3: NLO $J/\psi$ forward cross sections. The solid curve employs the MRST HO distributions with $m = 1.2$ GeV $\mu/m_T = 2$, the dashed, MRST HO with $m = 1.4$ GeV $\mu/m_T = 1$, the dot-dashed, CTEQ 5M with $m = 1.2$ GeV $\mu/m_T = 2$, and the dotted, GRV 98 HO with $m = 1.3$ GeV $\mu/m_T = 1$. 
Inclusive $\Upsilon$ Cross Sections at $y = 0$

Cross sections include all $\Upsilon(nS)$ states and their decays to muon pairs.

Data is from $pp$ interactions except for highest two points where only $p\bar{p}$ colliders available.

At high energies, $gg \rightarrow Q\bar{Q}$ dominates and differences between $p\bar{p} \rightarrow \Upsilon$ and $pp \rightarrow \Upsilon$ are negligible.

![Figure 4: Inclusive $\Upsilon$ production data, combined from all three $S$ states, and compared to NLO CEM calculations. The solid curve employs the MRST HO distributions with $m = 4.75$ GeV $\mu/m_T = 1$, the dashed, $m = 4.5$ GeV $\mu/m_T = 0.5$, the dot-dashed, $m = 5$ GeV $\mu/m_T = 2$, and the dotted, GRV 98 HO with $m = 4.75$ GeV $\mu/m_T = 1.$]
Prediction of $J/\psi$ Rapidity Distributions at RHIC

Agreement of CEM with overall normalization of Run 3 data good
Shape has right trend for d+Au with EKS98 shadowing

Figure 5: The inclusive $J/\psi y$ distributions in $\sqrt{s} = 200$ pp (left-hand side for $\psi 1$ (solid), $\psi 2$ (dashed), $\psi 3$ (dot-dashed) and $\psi 4$ (dotted)) and d+Au (right-hand side with $\psi 1$ and EKS98) interactions. Plots courtesy of Mike Leitch.
Medium Effects Important in $p\bar{d}A$ and $AA$ Interactions

Nuclear effects on charmonium important in fixed-target interactions

Parameterizing $\sigma_{pA} = \sigma_{pp} A^\alpha$, $\alpha(x_F, p_T)$

For $\sqrt{S_{NN}} \leq 40$ GeV and $x_F > 0.25$, $\alpha$ decreases strongly with $x_F$

Consider two low $x_F$ cold matter effects at colliders:

- Nuclear Shadowing — initial-state effect on the parton distributions affecting total rate, important as a function of $y/x_F$
- Absorption — final-state effect, after $c\bar{c}$ that forms the $J/\psi$ has been produced, pair breaks up in matter due to interactions with nucleons

At high $x_F$, other mechanisms (energy loss, intrinsic charm) may be important but $x_F > 0.25$ corresponds to $y > 2.8$ at 200 GeV (larger $y$ for higher $\sqrt{S}$) and do not appear in $p_T$-integrated $y$ distributions
Nuclear Parton Distributions

Nuclear parton densities

\[ F_i^A(x, Q^2, \vec{r}, z) = \rho_A(s) S_i^i(A, x, Q^2, \vec{r}, z) f_i^N(x, Q^2) \]

\[ s = \sqrt{r^2 + z^2} \]

\[ \rho_A(s) = \rho_0 \frac{1 + \omega(s/R_A)^2}{1 + \exp[(s - R_A)/d]} \]

We use EKS98, Frankfurt, Guzey and Strikman (FGSo, FGSh, and FGSl) and DeFlorian and Sassot (nDS and nDSg)

EKS98, FGSo, nDS and nDSg have no spatial dependence, FGSh and FGSl do

With no nuclear modifications, \( S_i^i(A, x, Q^2, \vec{r}, z) \equiv 1 \)

Assume spatial dependence proportional to nuclear path length:

\[ S_{\rho}^i(A, x, Q^2, \vec{r}, z) = 1 + N_\rho (S_i^i(A, x, Q^2) - 1) \frac{\int dz \rho_A(\vec{r}, z)}{\int dz \rho_A(0, z)} \]

Normalization: \((1/A) \int d^2r dz \rho_A(s) S_{\rho}^i \equiv S^i_i\). Larger than average modifications for \( s = 0 \). Nucleons like free protons when \( s \gg R_A \). Similar normalization for spatial dependence of FGS.
Comparing Shadowing Parameterizations: $x$ Dependence

EKS98, nDS and nDSg for all $A$, FGS for $A = 12, 40, 110$ and 197/206

Ratios shown for GRV98 scales, $\mu = 1.3$ and 4.75 GeV for charm and bottom but if $\mu < \mu_0$ for set, take $\mu = \mu_0$

EKS98 and nDSg similar for $A = 208$ but nDSg weaker for smaller $A$

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Figure 6: Shadowing parameterizations for $J/\psi$ (left) and $\Upsilon$ (right) scales for $A = 208$. The parameterizations are EKS98 (solid red), FGS0 (dashed blue), FGSh (dot-dashed magenta), FGSI (dotted red), nDS (dot-dot-dot-dashed blue) and nDSg (dash-dash-dash dotted magenta).
Average $x_2$ as a Function of Energy and Rapidity

$\langle x_2 \rangle$ as a function of rapidity (N.B. $\langle x_1 \rangle$ is mirror imagine of $\langle x_2 \rangle$)
Increasing $\sqrt{S}$ broadens $y$ range and decreases $x_2$

Figure 7: We give the average value of the nucleon momentum fraction, $x_2$, in $pp$ collisions as a function of rapidity for (a) the CERN SPS with $\sqrt{S} = 19.4$ GeV, (b) RHIC with $\sqrt{S} = 200$ GeV and (c) the LHC with $\sqrt{S} = 6.2$ TeV.
Quarkonium Absorption by Nucleons

Woods-Saxon nuclear density profiles typically used

\[
\sigma_{pA} = \sigma_{pN} \int d^2 b \int_\infty -\infty dz \, \rho_A(b, z) S_{A}^{abs}(b) \\
= \sigma_{pN} \int d^2 b \int_\infty -\infty dz \, \rho_A(b, z) \exp \left\{ - \int_z^\infty dz' \rho_A(b, z') \sigma_{abs}(z' - z) \right\}
\]

Note that if \( \rho_A = \rho_0 \), \( \alpha = 1 - 9\sigma_{abs}/(16\pi r_0^2) \)

The value of \( \sigma_{abs} \) depends on the parameterization of \( \sigma_{pA} \) – Glauber, hard sphere, \( A^\alpha \) etc. (shown by NA50)

Initial-state shadowing not taken into account at SPS energies, increasing \( \sqrt{S_{NN}} \) and rapidity range of measurement influences total shadowing effect: could make effective \( \sigma_{abs} \) without shadowing depend on \( y, \sqrt{S_{NN}} \)

Feed down to \( J/\psi \) from \( \chi_c \) and \( \psi' \) decays included

\[
\sigma_{pA} = \sigma_{pN} \int d^2 b \left[ 0.58 S_{\psi, \text{dir}}(b) + 0.3 S_{\chi_c J}(b) + 0.12 S_{\psi'}(b) \right]
\]
Comparing Absorption Calculations

$A^\alpha$ with $\alpha = 1 - 9\sigma_{\text{abs}}/(16\pi r_0^2)$, $\sigma_{\text{abs}} = 4.8$ mb is line on semi-log plot.

Exponential survival probability with $S \propto \exp(-\rho_0\sigma_{\text{abs}}L)$ has convex shape. Using $\rho_0 = 0.16$ fm$^{-3}$ and $L = (3/4)r_0A^{1/3}$ gives smooth curve.

Real nuclear shapes (points) show fluctuations due to different densities, sizes.

Figure 8: The $J/\psi$ $A$ dependence, all with $\sigma_{\text{abs}} = 4.8$ mb, normalized to typical SPS $J/\psi$ cross section. The red line is the result for $A^\alpha$, the dashed with $\exp(-\rho_0\sigma_{\text{abs}}L)$ and the points are numerical calculations of the survival probability with real nuclear shapes.
Absorption Models Influenced by Production Mechanism

singlet: Individual charmonium cross sections grow quadratically with proper time until formation time; only effective when state can form in target – no effect when formed outside

octet: \[ |(c\bar{c})_8g\rangle \] “pre-resonance” travels through nucleus, \((c\bar{c})_8\) can dissociate before final state forms; assume either “constant” (\(y\) independent) or “growing”, (octet to singlet conversion inside target for \(y < 0\)) – little difference at collider energy; \(A\) dependence same for all final states

NRQCD: Nonrelativistic QCD approach differs from CEM in that states are produced with fixed singlet and octet contributions (\(J/\psi\) and \(\psi'\) predominantly octet, \(\chi_c\) singlet so \(J/\psi\) and \(\chi_c\) \(A\) dependence should be different)

Simultaneous measurement of \(J/\psi\) and \(\chi_c\) \(A\) dependence would help determine the production mechanism (CEM vs. NRQCD)
Singlet Absorption Model

All $c\bar{c}$ pairs assumed to be produced in small color singlet states

Assume quadratic growth of cross section with proper time until formation time $\tau_F$ (Blaizot and Ollitrault)

Strongest at low to negative $x_F$ where $J/\psi$ can form in the target

Asymptotic $\psi'$ and $\chi_c$ cross sections proportional to the final state meson size, e.g. $\sigma^{s}_{\psi'N} = \sigma^{s}_{J/\psi N}(r_{\psi'}/r_{J/\psi})^2$ (Povh and Hübner)

Radii determined from potential model calculations, used mostly for cross section ratios

$$\sigma_{abs}(z' - z) = \begin{cases} \sigma^{s}_{CN}\left(\frac{\tau}{\tau_F^C}\right)^2 & \text{if } \tau < \tau_F^C \\ \sigma^{s}_{CN} & \text{otherwise} \end{cases}$$

$$\tau_F^{J/\psi} = 0.92 \text{ fm} \quad \sigma^{s}_{J/\psi N} \sim 2.5 \text{ mb}$$
$$\tau_F^{\psi'} = 1.5 \text{ fm} \quad \sigma^{s}_{\psi'N} = 3.7 \sigma^{s}_{J/\psi N}$$
$$\tau_F^{\chi_c} = 2 \text{ fm} \quad \sigma^{s}_{\chi_c N} = 2.4 \sigma^{s}_{J/\psi N}$$
A Dependence of ‘Color Transparency’

All states typically produced outside target for $x_F \geq 0$
Strong decrease at negative $x_F$ expected for all states

Figure 9: The $A$ dependence of singlet absorption is shown for 158 (a), 450 (b), and 920 (c) GeV interactions. The total $J/\psi$ (solid), direct $J/\psi$ (dashed), $\psi'$ (dot-dashed) and $\chi_c$ (dotted) dependencies are shown.
Octet Absorption Model

Pre-resonant $c\bar{c}$ pairs travel through the nucleus as $|(c\bar{c})_8g\rangle$ color octet states

Characteristic octet lifetime $\tau_8 \sim 0.25$ fm

For $x_F \geq -0.1$, path length of $|(c\bar{c})_8g\rangle$ through the target from its production point is greater than maximum path length

These fast states pass through nucleus in color octets so that the pre-resonant $A$ dependence is the same for $J/\psi$, $\psi'$ and $\chi_c$ (Kharzeev and Satz) — $\sigma_{abs}^o = 3$ mb agrees with E866 forward $A$ dependence

Universal constant absorption cross section usually assumed for all states at forward $x_F$

At negative $x_F$, path length is shorter and octet state can neutralize its color inside target and be absorbed as color singlet
A Dependence of Octet Absorption

Dependencies different at large negative $x_F$ due to neutralization
All values of $\alpha$ identical when state passes through target as octet

Figure 10: The $A$ dependence of octet absorption at 158 (a), 450 (b), and 920 (c) GeV interactions. The total $J/\psi$ (solid), direct $J/\psi$ (dashed), $\psi'$ (dot-dashed) and $\chi_c$ (dotted) dependencies are shown.
Singlet + Octet Absorption

Relative contributions of singlet and octet production to each state set by NRQCD

Equal absorption cross sections for all octet states

Singlet cross sections set by final state size

\[
\frac{d\sigma_{pA}^{\psi}}{dx_F} = \int d^2b \left[ \frac{d\sigma_{pp}^{\psi,\text{oct}}}{dx_F} S_A^{\psi,\text{oct}}(b) + \frac{d\sigma_{pp}^{\psi,\text{sing}}}{dx_F} S_A^{\psi,\text{sing}}(b) \right],
\]

\[
\frac{d\sigma_{pA}^{\chi_{cJ} \rightarrow J/\psi X}}{dx_F} = \int d^2b \sum_{J=0}^{2} B(\chi_{cJ} \rightarrow J/\psi X) \left[ \frac{d\sigma_{pp}^{\chi_{cJ},\text{oct}}}{dx_F} S_A^{\chi_{cJ},\text{oct}}(b) + \frac{d\sigma_{pp}^{\chi_{cJ},\text{sing}}}{dx_F} S_A^{\chi_{cJ},\text{sing}}(b) \right],
\]

\[
\frac{d\sigma_{pA}^{J/\psi,\text{tot}}}{dx_F} = \int d^2b \left\{ \left[ \frac{d\sigma_{pp}^{J/\psi,\text{dir,\ oct}}}{dx_F} S_A^{J/\psi,\text{oct}}(b) \right.ight.
\]
\[\left. + \sum_{J=0}^{2} B(\chi_{cJ} \rightarrow J/\psi X) \frac{d\sigma_{pp}^{\chi_{cJ},\text{oct}}}{dx_F} S_A^{\chi_{cJ},\text{oct}}(b) + B(\psi' \rightarrow \psi X) \frac{d\sigma_{pp}^{\psi',\text{oct}}}{dx_F} S_A^{\chi_{cJ},\text{oct}}(b) \right. \]
\[\left. + \left[ \frac{d\sigma_{pp}^{J/\psi,\text{dir,\ sing}}}{dx_F} S_A^{J/\psi,\text{dir,\ sing}}(b) + \sum_{J=0}^{2} B(\chi_{cJ} \rightarrow \psi X) \frac{d\sigma_{pp}^{\chi_{cJ},\text{sing}}}{dx_F} S_A^{\chi_{cJ},\text{sing}}(b) \right. \]
\[\left. + B(\psi' \rightarrow \psi X) \frac{d\sigma_{pp}^{\psi',\text{sing}}}{dx_F} S_A^{\psi',\text{sing}}(b) \right] \right\}.
\]
A Dependence of Combination Model

$\alpha(x_F)$ depends on relative octet/singlet contributions

Inclusive $J/\psi$ and $\psi'$ $\alpha$ similar for $0 < x_F < 0.5$ while for $\chi_c$ $\alpha \sim 1$

Figure 11: The $A$ dependence of singlet and octet absorption is shown at 158 (a), 450 (b), and 920 (c) GeV. The total $J/\psi$ (solid), direct $J/\psi$ (dashed), $\psi'$ (dot-dashed) and $\chi_c$ (dotted) dependencies are shown.
Rapidity Dependence of Absorption at RHIC

Results strong function of energy, formation effects negligible, little rapidity dependence observable, same for LHC

Figure 12: The $J/\psi$ dAu/pp ratio at 200 GeV as a function of rapidity for absorption alone. We show (a) constant octet with 3 mb, (b) growing octet with 3 mb asymptotic cross section for all states, (c) singlet with 2.5 mb $J/\psi$ absorption cross section, all calculated in the CEM and (d) NRQCD with a combination of octet and singlet matrix elements. The curves show total $J/\psi$ (solid), direct $J/\psi$ (dashed), $\psi'$ (dot-dashed) and $\chi_c$ (dotted).
Interplay of Shadowing and Absorption

Absorption alone always gives $\alpha < 1$

Depending on $x$ values probed, shadowing can enhance or reduce absorption cross section needed to describe data

For SPS energies $17.3 \leq \sqrt{S} \leq 29$ GeV, rapidity range covered is in EMC and antishadowing region, $\alpha > 1$ with no absorption

Adding shadowing to absorption calculations here means a larger absorption cross section is needed to maintain agreement with data

For $\sqrt{S} \geq 38$ GeV, $x$ in shadowing regime, thus $\alpha < 1$ with shadowing alone in forward region, reducing needed absorption cross section
Shadowing and Absorption Effects at the SPS: Rapidity

Predicted effects for 158 (upper) and 450 (lower) GeV

Ratio of \( p\text{Pb}/pp \) not symmetric around \( y = 0 \), antishadowing seen

Figure 13: The \( p\text{Pb}/pp \) ratio as a function of rapidity for shadowing alone (left) and with \( \sigma_{\text{abs}} = 4 \text{ mb} \) (right) for 158 (upper) and 450 (lower) GeV with EKS98 (solid blue), FGSh (dot-dashed red) and FGSl (dotted magenta).
Shadowing and Absorption Effects at the SPS: $A$

$A$ dependence with shadowing alone increases with $A$. Need 7 mb cross section to get the same effect as with 4.8 mb.

Figure 14: The $J/\psi$ $A$ dependence for octet cross sections of 0 (solid red), 4 (dashed blue) and 7 (dot-dashed magenta) mb calculated with the EKS98 parameterization. The points indicate the values of $A$ used in the calculations at $0 < y < 1$. The curves are to guide the eye. There is negligible energy dependence between 158 and 450 GeV.
Setting Baseline Cold Nuclear Matter Effects at RHIC: In Collaboration with Mike Leitch

Determine balance of shadowing and absorption from RHIC data

Compare combinations of shadowing parameterizations and absorption cross sections to RHIC d+Au data

Make $\chi^2$ fits to $R_{\text{dAu}}(y)$, $R_{\text{dAu}}(N_{\text{coll}})$ for all combinations – are some parameterizations more favored than others?

Take results with relative best agreement to determine the maximum range of cold nuclear matter effects in $AA$ collisions

This becomes baseline onto which hot matter effects of color screening and recombination can be added

Results shown here for EKS98 and nDSg shadowing since their shapes are most compatible with the data
Absorption and Shadowing at RHIC: $R_{dAu}(y)$

EKS98 and nDSg compared to d+Au data with $0 < \sigma_{abs} < 3$ mb and MRST parton densities with $m = 1.2$ GeV, $\mu = 2m_T$.

**Figure 15:** Octet absorption for $0 \leq \sigma_{abs} \leq 3$ mb calculated with EKS98 (left) and nDSg (right) using the MRST PDFs and $m = 1.2$ GeV, $\mu = 2m_T$ compared to PHENIX data. (An additional overall normalization error of 12% is not shown.) RV and Mike Leitch, in progress.
Absorption and Shadowing at RHIC: $R_{AA}(y)$

Larger difference between EKS98 and nDSg for Au+Au than Cu+Cu

General trends of cold matter effects similar to data

Figure 16: Octet absorption for $0 \leq \sigma_{\text{abs}} \leq 3$ mb (top to bottom) calculated with EKS98 (left) and nDSg (right) with the MRST PDFs and $m = 1.2$ GeV, $\mu = 2m_T$. PHENIX data (QM’05) are shown for Au+Au and Cu+Cu collisions at 200 GeV. The absolute normalization uncertainty is shown by the gray bands. RV and Mike Leitch, in progress.
Centrality Dependence of Shadowing and Absorption

PHENIX d+Au results presented as a function of the number of binary nucleon-nucleon collisions, $N_{\text{coll}}$, the convolution of the nuclear profile functions multiplied by the inelastic $NN$ cross section, 42 mb at RHIC

$$N_{\text{coll}}(b) = \sigma_{NN}^{\text{in}} \int d^2 s T_A(s) T_B(|\vec{b} - \vec{s}|)$$

AA results presented as a function of the number of nucleon participants, $N_{\text{part}}$,

$$N_{\text{part}}(b) = \int d^2 s [T_A(s)(1 - \exp(-\sigma_{NN}T_B(|\vec{b} - \vec{s}|))) + T_B(|\vec{b} - \vec{s}|)(1 - \exp(-\sigma_{NN}T_A(s)))]$$

Results with EKS98 and nDSg compared at $y = -1.7$ (antishadowing), 0 (transition region) 1.7 (shadowing)
Absorption and Shadowing at RHIC: $R_{dAu}(N_{coll})$

Centrality dependence of shadowing alone generally stronger for nDSg at $y = -1.7, 0$, similar for $y = 1.7$

Data do not help distinguish between different $\sigma_{abs}$

![Graphs showing absorption and shadowing at RHIC](image)

Figure 17: Octet absorption for $0 \leq \sigma_{abs} \leq 3\; \text{mb}$ (upper to lower) calculated with EKS98 (left) and nDSg (right) with the MRST PDFs and $m = 1.2\; \text{GeV}, \mu = 2m_T$. PHENIX data are shown for d+Au collisions at 200 GeV for $y = -1.7$ (top), 0 (middle) and 1.7 (bottom). (An additional 12% overall normalization error is not shown.) RV and Mike Leitch, in progress.
Absorption and Shadowing at RHIC: \( R_{AA}(N_{\text{part}}) \)

Cold matter effects with \( \sigma_{\text{abs}} \sim 2 - 3 \) mb in relatively good agreement with all but most central data

Room left for some dense matter effects

Figure 18: Octet absorption for \( 0 \leq \sigma_{\text{abs}} \leq 3 \) mb (top to bottom) calculated with EKS98 (left) and nDSg (right) with the MRST PDFs and \( m = 1.2 \) GeV, \( \mu = 2m_T \). PHENIX data are shown for Au+Au and Cu+Cu collisions at 200 GeV in the forward \( \mu\mu \) (upper) and central \( ee \) detectors. RV and Mike Leitch, in progress.
$J/\psi$ Absorption and Shadowing in $pPb$ at 8.8 TeV

Left: Effect of $\sigma_{abs}$ for EKS98

Right: Comparing shadowing parameterizations for $\sigma_{abs} = 2$ mb

Absorption small relative to shadowing

No rapidity shift included on $pPb$, assume $pPb$, $pp$ at same $\sqrt{S}$

Figure 19: Left-hand side: The $J/\psi$ $pPb/pp$ ratio at 8.8 TeV with the EKS98 shadowing parameterization for $\sigma_{abs} = 0$ (solid red), 1 (dashed blue), 2 (dot-dashed magenta) and 3 (dotted green) mb. Right-hand side: Comparison of shadowing results for a 2 mb octet cross section with EKS98 (solid red), FGSo (dashed blue), FGSh (dot-dashed magenta), FGSl (dotted red), nDS (dot-dot-dot-dashed blue) and nDSg (dash-dash-dash-dotted magenta).
**J/ψ Absorption and Shadowing in Pb+Pb at 5.5 TeV**

**Left:** Effect of $\sigma_{\text{abs}}$ for EKS98

**Right:** Comparing shadowing parameterizations for $\sigma_{\text{abs}} = 2$ mb

Two nuclei produces two antishadowing peaks with dip in between

Assume Pb+Pb and $pp$ at same $\sqrt{s}$

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**Figure 20:** Left-hand side: The $J/ψ$ Pb+Pb/$pp$ ratio at 5.5 TeV with the EKS98 shadowing parameterization for $\sigma_{\text{abs}} = 0$ (solid red), 1 (dashed blue), 2 (dot-dashed magenta) and 3 (dotted green) mb. Right-hand side: Comparison of shadowing results for a 2 mb octet cross section with EKS98 (solid red), FGSo (dashed blue), FGSh (dot-dashed magenta), FGSI (dotted red), nDS (dot-dot-dot-dashed blue) and nDSg (dash-dash-dash-dotted magenta).
\textbf{γ Absorption and Shadowing in }p\textbf{Pb at }8.8 \textbf{TeV}

\textbf{Left: Effect of }\sigma_{\text{abs}} \text{ for EKS98}

\textbf{Right: Different shadowing for }\sigma_{\text{abs}} = 1 \text{ mb (lower because }\gamma \text{ smaller)}

\textbf{Antishadowing at larger }y \text{ for }\gamma

Assume }p\text{Pb and }pp \text{ at same }\sqrt{S}, \text{ no }y \text{ shift}

Figure 21: Left-hand side: The }\gamma p\text{Pb/pp ratio at }8.8 \text{ TeV with the EKS98 shadowing parameterization for }\sigma_{\text{abs}} = 0 \text{ (solid red), }0.5 \text{ (dashed blue), }1 \text{ (dot-dashed magenta) and }1.5 \text{ (dotted green) mb. Right-hand side: Comparison of shadowing results for a }1 \text{ mb octet cross section with EKS98 (solid red), FGSo (dashed blue), FGSh (dot-dashed magenta), FGSl (dotted red), nDS (dot-dot-dot-dashed blue) and nDSg (dash-dash-dash-dotted magenta).}
γ Absorption and Shadowing in Pb+Pb at 5.5 TeV

Left: Effect of $\sigma_{\text{abs}}$ for EKS98

Right: Comparing shadowing parameterizations for $\sigma_{\text{abs}} = 1$ mb

Antishadowing peaks closer than for $J/\psi$

Assume Pb+Pb and $pp$ at same $\sqrt{S}$

Figure 22: Left-hand side: The $\gamma$ Pb+Pb/pp ratio at 5.5 TeV with the EKS98 shadowing parameterization for $\sigma_{\text{abs}} = 0$ (solid red), 0.5 (dashed blue), 1 (dot-dashed magenta) and 1.5 (dotted green) mb. Right-hand side: Comparison of shadowing results for a 1 mb octet cross section with EKS98 (solid red), FGSo (dashed blue), FGSh (dot-dashed magenta), FGSl (dotted red), nDS (dot-dot-dot-dashed blue) and nDSg (dash-dash-dash-dotted magenta).
Summary.

- CEM useful tool for studying cold nuclear matter effects
- Preliminary SPS shadowing and absorption calculations show larger absorption cross sections needed to counter antishadowing effects
- Measurement of $\chi_c A$ dependence would provide clear test of absorption mechanism
- Current d+Au $J/\psi$ data agree well with combination of initial state shadowing and final state absorption
- Need better statistics to distinguish between shadowing parameterizations and determine strength of absorption
- Cold matter effects need to be accounted for in AA collisions but room for dense matter effects
- $\gamma$ measurements at LHC should further probe $x$ and $Q^2$ dependence of initial state effects with less absorption
- LHC $pA$ program needed to fix level of cold matter effects on the TeV scale