ACCESSING SATURATION AND SUBNUCLEAR STRUCTURE WITH MULTIPICITY DEPENDENT J/Ψ PRODUCTION IN p+p AND p+Pb COLLISIONS

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29TH INTERNATIONAL CONFERENCE ON ULTRA-RELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS

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Study production of $J/\psi$ at different rapidities relative to charged hadrons at midrapidity.

Expect varying sensitivity to saturation, depending on probed $Q_s$ and mass:

$m_{J/\psi} = 3.1\,\text{GeV}$

$m_{h_c} \approx 0.5\,\text{GeV}$

Most important physics in $Q_s^2(x, R_\perp) = T_A(R_\perp) S_\perp Q_s^2(x)$. Depends on rapidity ($x$) and transverse space.

Spatial dependence in $T_A(R_\perp)$ includes fluctuations of nucleon positions and nucleon substructure:

3 hot spots locations per nucleon sampled from

$P(R_{\perp,i}) = \frac{1}{2\pi B_{qc}} e^{-R_{\perp,i}/(2B_{qc})}$

and hot spot density distribution

$T_q(R_\perp - R_{\perp,i}) = \xi Q_s^2 e^{-(R_\perp - R_{\perp,i})^2/(2(\xi B_q)B_q)}$
**CHARGED HADRON AND J/Ψ PRODUCTION**

Use $k_T$-factorization for gluon production

$$\frac{dN_g(b_\perp)}{d^2p_g \, db_g} = \frac{\alpha_s}{(\sqrt{2})^6 C_F} \int \frac{\phi^p(x_p; k_\perp; R_\perp) \phi^A(x_A; p_g - k_\perp; R_\perp - b_\perp)}{k_{1\perp} R_\perp}$$

Unintegrated gluon distributions $\phi^p$ and $\phi^A$ (with $A = p, Pb$) from BK evolution with McLerran-Venugopalan initial conditions + spatial dependence

Hadronize using KKP fragmentation function

**c\bar{c}-pair production in NRQCD**

$$\frac{dN_{c\bar{c}}(b_\perp)}{d^2P_\perp \, dY} = \frac{\alpha_s}{(2\pi)^9 (N_c^2 - 1)} \int \frac{\mathcal{H}^\kappa(P_\perp - k_\perp, k_\perp)}{k_{1\perp}^2} \frac{\phi^p(x_p; k_\perp; R_\perp)}{k_{1\perp} R_\perp} \tilde{\mathcal{E}}^\kappa(x_A; P_\perp - k_\perp, k_\perp, k_\perp') R_\perp - b_\perp$$

for quantum state $\kappa$. The pair momentum is $P_\perp = p_\perp + q_\perp$, $\mathcal{H}^\kappa$ are the hard factors, and the $\tilde{\mathcal{E}}^\kappa$ contain dipole amplitudes (related to $\phi^A$)

$$\frac{dN_{J/Ψ}(b_\perp)}{d^2P_\perp \, dY} = \sum_{\kappa} \frac{dN_{c\bar{c}}(b_\perp)}{d^2P_\perp \, dY} \langle \mathcal{O}_\kappa^{J/Ψ} \rangle \text{ with non-perturbative long distance matrix elements } \langle \mathcal{O}_\kappa^{J/Ψ} \rangle$$

RESULTS: FLUCTUATIONS

Charged hadron multiplicity distribution


\[ k_T\text{-fact. + KKP} \]
\[ \text{CMS } N_{\text{track}} \]

\[ p+\text{Pb} \text{ 5.02 TeV} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_q )</td>
<td>3</td>
<td>( \alpha_s )</td>
<td>0.16</td>
</tr>
<tr>
<td>( B_{q_c} )</td>
<td>3 GeV(^{-2})</td>
<td>( m_{\text{IR}} )</td>
<td>0.2 GeV</td>
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<tr>
<td>( B_q )</td>
<td>1 GeV(^{-2})</td>
<td>( m_{J/\psi} )</td>
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<tr>
<td>( \sigma_{B_q} )</td>
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<td>( m_c )</td>
<td>( m_{J/\psi}/2 )</td>
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<td>( \sigma_{Q_s^2} )</td>
<td>0.1</td>
<td>( m_D )</td>
<td>1.87 GeV</td>
</tr>
<tr>
<td>( S_\perp )</td>
<td>13 mb</td>
<td>( \sigma_{B_q} ) and ( \sigma_{Q_s} ): width parameters in log-normal fluctuations ( \xi )</td>
<td></td>
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<td></td>
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<td>( m_{\text{IR}} ): infrared regulator in the charged hadron calculation</td>
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</tbody>
</table>
Saturation drives the correlation between $J/\psi$ and charged hadrons


\[ dN_{ch}/d\eta = 4\langle dN_{ch}/d\eta \rangle \]
More normalization fluctuations (less size fluctuations) lead to stronger saturation effects on the J/ψ in the Pb-going direction.

- Mean $p_T$ driven by mass and $Q_s$
- $Q_s$ fluctuations and hot spot size matter

Experimental data: ALICE Collaboration, JHEP 09, 162 (2020)
$(\phi(x; k) \perp R) \rightarrow k^2 \perp C F^2 \alpha s \mathcal{S}_{\text{Adj}}(x; k \perp R) \perp R^\perp$
**MODEL: CHARGED HADRON PRODUCTION**

Use $k_T$-factorization for gluon production

\[
\frac{dN_g(b_\perp)}{d^2p_{g\perp}dy_g} = \frac{\alpha_s}{(\sqrt{2}\pi)^6} C_F p_{g\perp}^2 \int \phi^p(x_p; k_1; R) \phi^A(x_A; p_{g\perp} - k_1; R - b_\perp)
\]

Unintegrated gluon distributions $\phi^p$ and $\phi^A$ (with $A = p, Pb$) from Balitsky-Kovchegov evolution with McLerran-Venugopalan initial conditions

Modified to include spatial dependence with nucleon substructure. 3 hot spots locations sampled from

\[
P(R_{\perp,i}) = \frac{1}{2\pi B_{q{i}}} e^{-R_{\perp,i}^2/(2B_{q{i}})}
\]

and hot spot density distribution

\[
T_q(R_\perp - R_{\perp,i}) = \frac{\xi Q^2}{2(\xi B_q) B_q} e^{-(R_\perp - R_{\perp,i})^2/(2(\xi B_q) B_q)}
\]

$B_q$ is given an $x$ dependence motivated by JIMWLK evolution of proton size

Hadronize using KKP fragmentation function

\[
\frac{dN_{ch}(b_\perp)}{d\eta} = \int_{p_{\perp}}^1 \frac{dN_g(b_\perp)}{d^2p_{g\perp}dy_g} \left| \frac{dN_{ch}(b_\perp)}{d\eta} \right| p_{g\perp} = p_{\perp}/z
\]


**MODEL: J/ψ PRODUCTION (NRQCD)**

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**c¯c-pair production in NRQCD**

Z.-B. Kang, Y.-Q. Ma, and R. Venugopalan, JHEP 01, 056 (2014)

\[
\frac{dN_{c\bar{c}}^\kappa(b_\perp)}{d^2P_\perp dY} = \frac{\alpha_s}{(2\pi)^9(N_c^2 - 1)} \int_{k_{1\perp},k_{1\perp}'} \mathcal{H}^\kappa(P_\perp - k_{1\perp}, k_{1\perp}, k_{1\perp}') \frac{\phi^p(x_p, k_{1\perp}, R_\perp)}{k_{1\perp}^2} \tilde{\Xi}^\kappa(x_A; P_\perp - k_{1\perp}, k_{1\perp}, k_{1\perp}' R_\perp - b_\perp)
\]

for quantum state \(\kappa\). The pair momentum is \(P_\perp = p_\perp + q_\perp\), \(\mathcal{H}^\kappa\) are the hard factors, and \(\tilde{\Xi}^\kappa\) the Wilson line correlators:

\[
\tilde{\Xi}^{[8]}(x; l_\perp, k_\perp, k_\perp'; R_\perp) = (2\pi)^2 \delta^{(2)}(k_\perp - k_\perp') \tilde{S}_F^A(x; k_\perp R_\perp) \tilde{S}_F^A(x; l_\perp - k_\perp; R_\perp) + \mathcal{O}(1/N_c) \quad \text{(octet)}
\]

\[
\tilde{\Xi}^{[1]}(x; l_\perp, k_\perp, k_\perp'; R_\perp) = \tilde{S}_F^A(x; k_\perp R_\perp) \tilde{S}_F^A(x; k_\perp' R_\perp) \tilde{S}_F^A(x; l_\perp - k_\perp - k_\perp'; R_\perp) + \mathcal{O}(1/N_c) \quad \text{(singlet)}
\]

\[
\frac{dN_{J/\psi}(b_\perp)}{d^2P_\perp dY} = \sum_\kappa \frac{dN_{c\bar{c}}^\kappa(b_\perp)}{d^2P_\perp dY} \langle \Theta_{J/\psi}^\kappa \rangle \quad \text{with non-perturbative long distance matrix elements } \langle \Theta_{J/\psi}^\kappa \rangle
\]

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Again, spatial dependence in \(\phi^p\) and \(\tilde{S}_F^A\)
\( \bar{c} c \)-pair production in the Improved Color Evaporation Model (ICEM):


\[
\frac{dN_{\bar{c}c}(b_{\perp})}{d^2p_{\perp}d^2q_{\perp}dy_{c}dy_{\bar{c}}} = \frac{\alpha_s N_c^2}{2(2\pi)^{10}(N_c^2 - 1)} \int_{k_{\perp1};k_{\perp1};R_1} \phi^p(x_\chi,k_{\perp1};R_1) \tilde{\delta}_F^A(x_\chi;k_{\perp1};R_1 - b_1) \tilde{\delta}_F^A(x_\chi;p_{\perp} + q_{\perp} - k_{\perp1} - k_{\perp1};R_1 - b_1) \mathcal{H}(p_{\perp},q_{\perp},k_{\perp1},p_{\perp} + q_{\perp} - k_{\perp1} - k_{\perp1}) + \mathcal{O}(1/N_c)
\]

with the Wilson line correlator \( \tilde{\delta}_F^A \) in the fundamental representation (with \( A = p, Pb \))

Production of \( J/\psi \) is then given by

\[
\frac{dN_{J/\psi}(b_{\perp})}{d^2P_{\perp}dY} = F \int_{m_{J/\psi}^2}^{4m_{J/\psi}^2} dM^2 \frac{M^2}{m_{J/\psi}^2} \frac{dN_{\bar{c}c}(b_{\perp})}{dM^2d^2P_{\perp}dY}, \quad \text{where} \quad \frac{dN_{\bar{c}c}(b_{\perp})}{dM^2d^2P_{\perp}dY} = \int_{0}^{\sqrt{M^2 - m_c^2}} d\bar{q} \int_{0}^{2\pi} d\phi \mathcal{J} \frac{dN_{\bar{c}c}(b_{\perp})}{d^2P_{\perp}d^2q_{\perp}dy_{p}dy_{\bar{q}}}
\]

where \( \bar{q} \) and \( \phi \) are the relative transverse momentum and angle between the \( c \) and the \( \bar{c} \) in the rest frame of the pair.
NRQCD VS ICEM

\[ \phi(x; k_\perp; R_\perp) = k_\perp^2 C_F^2 \alpha_s \mathcal{S}_{\text{Adj}}(x; k_\perp; R_\perp) \]

**J/ψ SPECTRA AND $R_{pPb}$**

**Experimental data:** ALICE Collaboration, JHEP 07 (2018) 160
$Q_s$ VS. MULTIPLICITY

\[ \varphi \left( \mathbf{x} ; \mathbf{k} \perp ; \mathbf{R} \perp \right) = k^2 \perp \mathcal{C}_F \perp \alpha_s \mathcal{S}_{\text{Adj}} \left( \mathbf{x} ; \mathbf{k} \perp ; \mathbf{R} \perp \right) \]