Heavy Flavor and Quarkonium production in p+p and p+A collisions

Kazuhiro Watanabe

Thomas Jefferson National Accelerator Facility

Probing QCD at the high energy frontier
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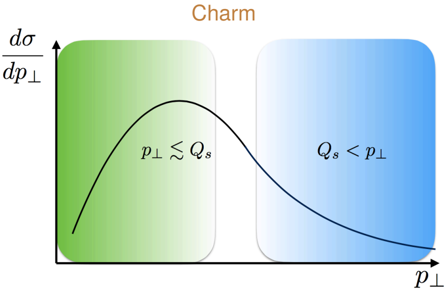
with Y.-Q. Ma, R. Venugopalan, H. F. Zhang
arXiv:1803.11093
with Y.-Q. Ma, P. Tribedy, R. Venugopalan

Jefferson Lab
Exploring the Nature of Matter

Introduction: Expectations



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- $p_\perp \lesssim Q_s$: Color-Glass-Condensate
- $p_\perp > Q_s$: Collinear factorization

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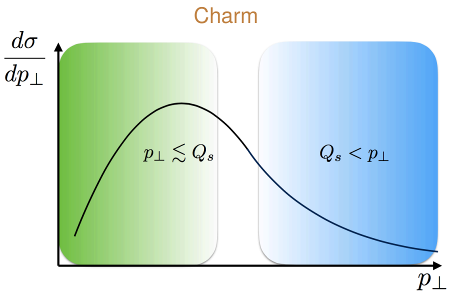

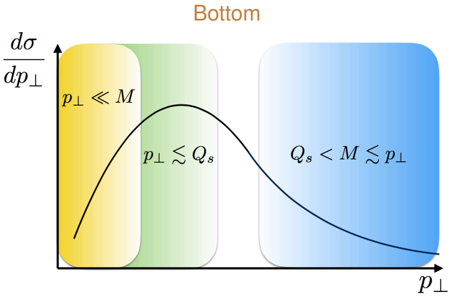

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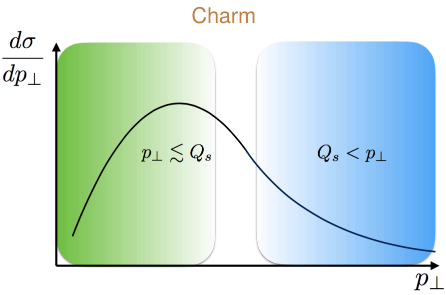
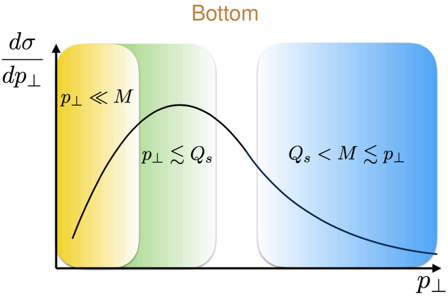
- $p_\perp \lesssim Q_s$: Color-Glass-Condensate
- $p_\perp \lesssim M > Q_s$: Collinear factorization
- $p_\perp \ll M$: Transverse momentum dependent framework





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Understanding of heavy quark production mechanism at low $p_\perp$ is not mature compared to high $p_\perp$ region where pQCD is robust.

We study HF and Onium production

1. in p+p collisions: Elementary process for understanding HF and Onium production mechanisms. Important reference against p+A and A+A collisions.

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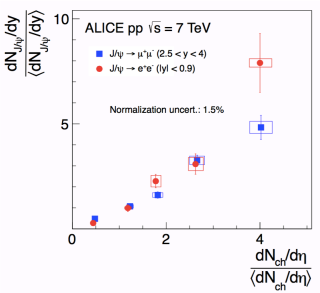

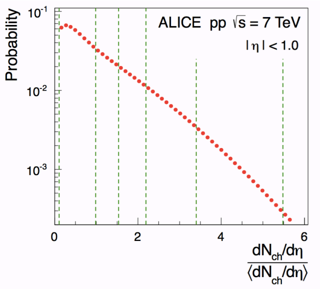

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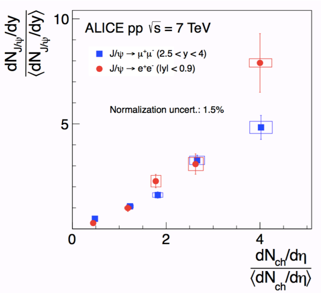
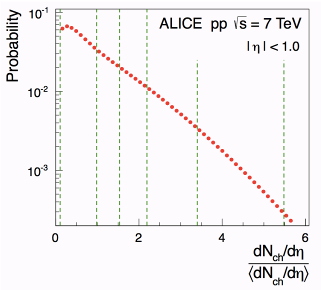




We consider Event Engineering HF and Quarkonium production in minimum bias and high multiplicity events in p+p and p+A collisions in the CGC framework.

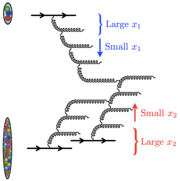
1 Framework

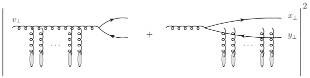
2 Minimum Bias events

3 High multiplicity events

4 Summary

- Large-x d.o.f: $\rho_p, \rho_A \to J$.
- Small-x d.o.f: Classical fields satisfy CYM equation, $[D^\mu, F_{\mu\nu}] = J_\nu$.
- Heavy quark pair is produced coherently as a whole in the background fields.
- Multiple scattering of quark/gluon in background fields is represented by Wilson lines.
- BK-JIMWLK equation takes Energy/Rapidity dependence of a pair production cross section.





[Blaizot, Gelis and Venugopalan, NPA**743**, 57 (2004)][Kovchegov and Tuchin, PRD**74**, 054014 (2006)][Fujii, Gelis and Venugopalan, NPA**780**, 146 (2006)]

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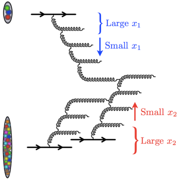

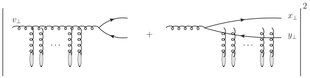

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- We use running coupling-BK equation. [Balitsky, PRD**75**, 014001 (2007)] $\to$ Saturation scale is embedded in the initial condition: MV model.
- MB, proton: $Q^2_{sp,0} = Q^2_0 = 0.168$ GeV^2 at $x = 0.01$ from DIS global data fitting for total cross section at HERA. [Albacete, Armesto, Milhano, Quiroga-Arias and Salgado, EPJC**71**, 1705 (2011)]
- MB, nucleus: $Q^2_{sA,0} \lesssim 0.5 A^{1/3} Q_{sp,0} \sim 2Q^2_0$ by fitting the New Muon Collaboration data on $F_{2,A}$. [Dusling, Gelis, Lappi and Venugopalan, NPA**836**, 159 (2010)]

- Heavy quark pair production xsection in Large-N_c:

$$\frac{d\sigma_{c\bar{c}}}{d^2\boldsymbol{p}_{c\perp}d^2\boldsymbol{q}_{\bar{c}\perp}dy_c dy_{\bar{c}}} = \frac{\alpha_s N_c^2 \pi R_A^2}{2(2\pi)^{10} d_A} \int_{\boldsymbol{k}_{2\perp},\boldsymbol{k}_\perp} \frac{\varphi_{p,y_p}(\boldsymbol{k}_{1\perp})}{k_{1\perp}^2} \mathcal{N}_Y(\boldsymbol{k}_\perp)\mathcal{N}_Y(\boldsymbol{k}_{2\perp} - \boldsymbol{k}_\perp)\ \Xi$$

φ_{p,y_p}: Unintegrated gluon distribution function. $\mathcal{N}_Y$: Dipole amplitude. Ξ: Hard part.

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- Open Heavy Flavor production xsection:

$$\frac{d\sigma_D}{d^2\boldsymbol{p}_{D\perp}dy} = \int_{z_{min}}^1 dz \frac{D_{c\to D}(z)}{z^2} \int dy_{\bar{c}} \int_{\boldsymbol{q}_{\bar{c}\perp}} \frac{d\sigma_{c\bar{c}}}{d^2\boldsymbol{p}_{c\perp}d^2\boldsymbol{q}_{\bar{c}\perp}dy dy_{\bar{c}}}$$

- Several functional forms for $D_{c\to D}(z)$ have been proposed: Peterson, Kartvilishvili, Braaten-Cheung-Fleming-Yuan, ...
- Quantitatively, these forms give similar $p_\perp$ spectrum of D meson if we choose appropriate nonperturbative input parameters.
- Large theoretical uncertainties may be indispensable at $p_\perp \lesssim m$. cf. [Cacciari, Frixione, Houdeau, Mangano, Nason and Ridolfi, JHEP**1210**, 137 (2012)]

Assume Factorization for Onia production at low $p_\perp$ but can be violated in p+A collisions.

1. CEM or Improved CEM (ICEM): See [Ma, Vogt, PRD**94**,114029(2016)]

$$\frac{d\sigma_\psi}{d^2p_\perp dy} = F_{c\bar{c}\to\psi}\int_{m_\psi}^{2m_D} dM \left(\frac{M}{m_\psi}\right)^2 \frac{d\sigma_{c\bar{c}}}{dM\,d^2p'_\perp}dy\Big|_{p'_\perp=\frac{M}{m_\psi}p_\perp}$$

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2. NRQCD: See [Kang, Ma, Venugopalan,JHEP**1401**,056(2014)]

$$\frac{d\sigma^\psi}{dydp_\perp^2} = \sum_\kappa \frac{d\hat{\sigma}^\kappa_{c\bar{c}}}{dydp_\perp^2}\times\underbrace{\left\langle O^\psi_\kappa\right\rangle}_{\text{LDMEs}} \qquad (\kappa = {}^{2S+1}L_J^{[c]})$$

$$\frac{d\sigma^\kappa_{c\bar{c},\mathrm{CS}}}{d^2\boldsymbol{p}_\perp dy} = \frac{\alpha_s\pi R_A^2}{(2\pi)^9 d_A}\int_{\boldsymbol{k}_{2\perp},\boldsymbol{k}_\perp,\boldsymbol{k}'_\perp}\frac{\varphi_{p,y_p}(\boldsymbol{k}_{1\perp})}{k_{1\perp}^2}\mathcal{N}_Y(\boldsymbol{k}_\perp)\mathcal{N}_Y(\boldsymbol{k}'_\perp)\mathcal{N}_Y(\boldsymbol{k}_{2\perp}-\boldsymbol{k}_\perp-\boldsymbol{k}'_\perp)\ \mathcal{G}_1^\kappa$$

$$\frac{d\sigma^\kappa_{c\bar{c},\mathrm{CO}}}{d^2\boldsymbol{p}_\perp dy} = \frac{\alpha_s\pi R_A^2}{(2\pi)^7 d_A}\int_{\boldsymbol{k}_{2\perp},\boldsymbol{k}_\perp}\frac{\varphi_{p,y_p}(\boldsymbol{k}_{1\perp})}{k_{1\perp}^2}\mathcal{N}_Y(\boldsymbol{k}_\perp)\mathcal{N}_Y(\boldsymbol{k}_{2\perp}-\boldsymbol{k}_\perp)\ \Gamma_8^\kappa$$

- CS channel probes the quadrupole amplitude $\mathcal{Q}_Y$ → Cubic in $\mathcal{N}_Y$ in a quasi-classical approximation in the large-N_c limit. cf. [Dominguez, Kharzeev, Levin, Mueller and Tuchin, PLB**710**, 182(2012)]

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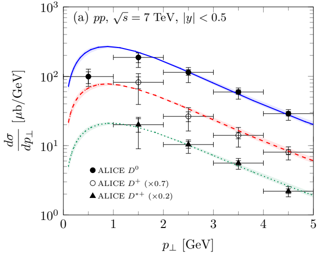
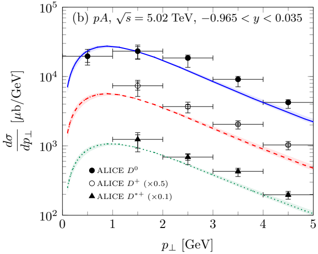
p+p



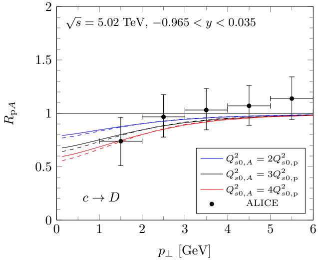
p+A



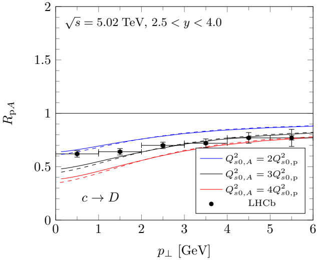
BCFY FF. The same K-factor in p+p and p+A.

[Ma, Tribedy, Venugopalan, KW, 1803.11093]

R_{pA} at mid



R_{pA} at forward

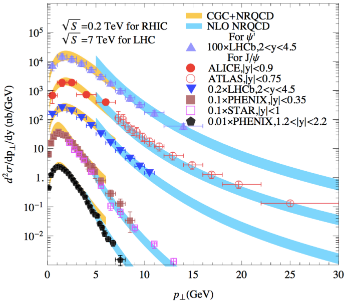


[Fujii, KW, NPA**920**,78(2013) and 1706.06728]

J/ψ production in the CGC + NRQCD

[Ma, Venugopalan, PRL**113**,192301(2014)][Ma, Venugopalan, Zhang, PRD**92**,071901(2015)]

p+p



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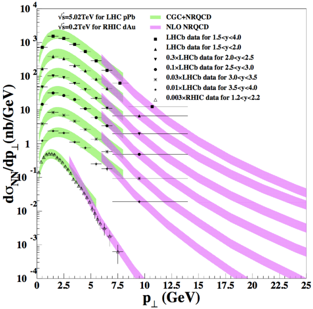
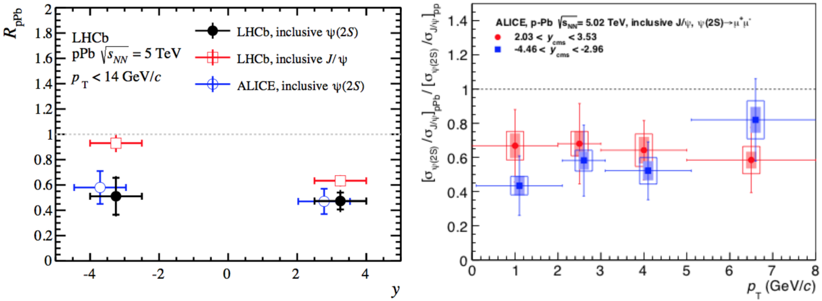


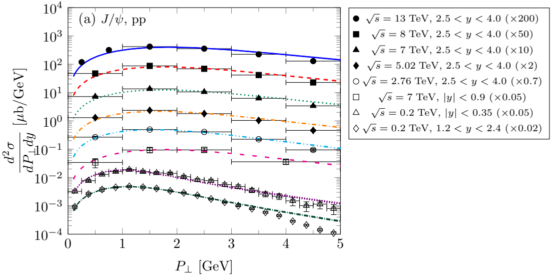
- The LDMEs are extracted from high $p_\perp$ data fitting at Tevatron. [Chao, Ma, Shao, Wang and Zhang, PRL**108**,242004(2012)]
  $\langle \mathcal{O}^{J/\psi}[{}^1S_0^{[8]}]\rangle = 0.089 \pm 0.0098\text{GeV}^3$, $\langle \mathcal{O}^{J/\psi}[{}^3S_1^{[8]}]\rangle = 0.0030 \pm 0.0012\text{GeV}^3$,
  $\langle \mathcal{O}^{J/\psi}[{}^3P_0^{[8]}]\rangle = 0.0056 \pm 0.0021\text{GeV}^3$
- ${}^1S_0^{[8]}$ has a large weight.
- The contribution of CS channel is relatively small. (10% in p+p, $15\% - 20\%$ in p+A at small-$p_\perp$)



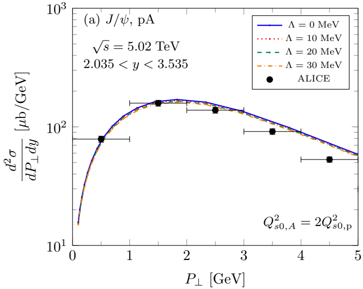
- $c\bar{c}$ produced at short distance $t_c \gtrsim 1/2m \sim 0.07$ fm does not know yet long distance information.
- The saturation effect is short distance physics at t_c and $M_{J/\psi} \sim M_{\psi(2S)} \Rightarrow$ The CGC frameowork predicts $R_{pA}^{J/\psi} \sim R_{pA}^{\psi(2S)}$.
- The large suppression of $\psi(2S)$ production in p+A at both RHIC and the LHC has widely been interpreted as arising from final state interactions with hadron comovers. cf. [Ferreiro, PLB**749**, 98 (2015)]
- We shall argue this from an aspect of factorization breaking effect in the Onium formation.

[Ma, Venugopalan, Zhang, KW, PRC**97**,014909(2018)]

p+p



p+A



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[Ma, Venugopalan, Zhang, KW, PRC**97**,014909(2018)]

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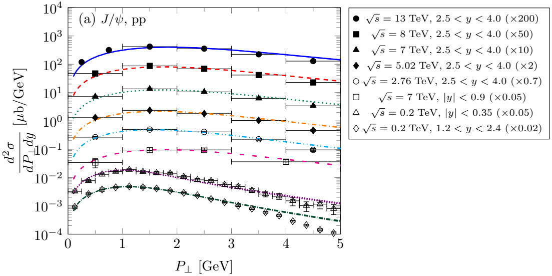

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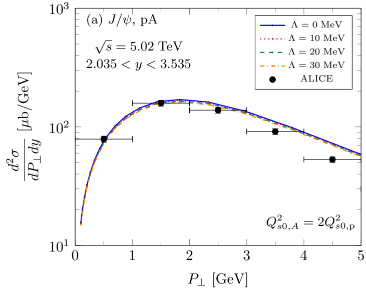

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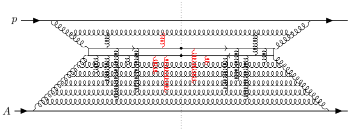
- Soft color exchange (SCE) between $c\bar{c}$ and comover spectators can happen at later stage.
- The role of SCEs should be enhanced in p+A collisions: $2m_\psi \leq M_{c\bar{c}} \leq 2m_D - \Lambda$.
- Λ: the average momentum kick given by additional nuclear parton comovers.
- Factorization breaking effect is small for J/ψ.



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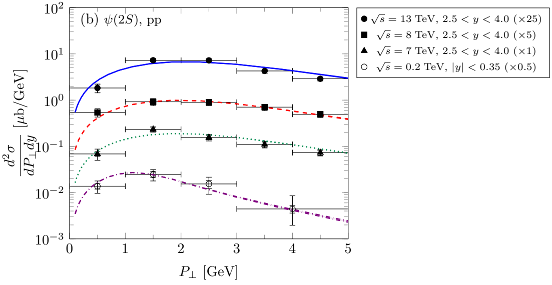

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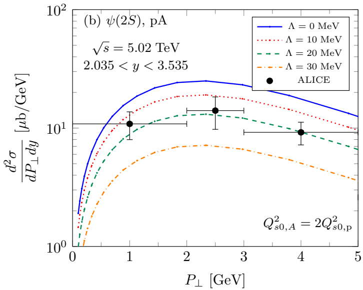
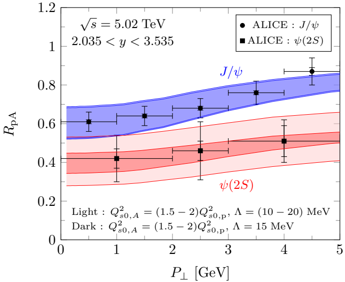


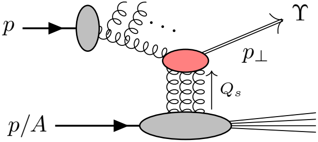
[Ma, Venugopalan, Zhang, KW, PRC**97**,014909(2018)]

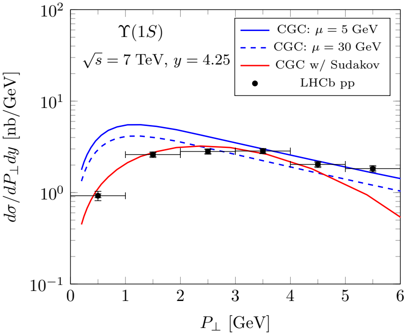
- SCEs between $c\bar{c}$ and partonic comovers can affect greatly $\psi(2S)$ production.
- Factorization breaking at $\Lambda = \mathcal{O}(\Delta E_{\psi(2S)})$ (Very Soft!). → Model dependent. cf. [Ferreiro, PLB**749**, 98 (2015)]
- The comover effect could bring complications for $\psi(2S)$ production in high multiplicity events.



Remarks on Υ production

[KW, Xiao, PRD**92**,111502(2015)]





- Two different scales in the problem: $m_\Upsilon \gg p_\perp \gg \Lambda_{\rm QCD}$ allows more phase space for gluons shower. $\Rightarrow$ Sudakov double logs:

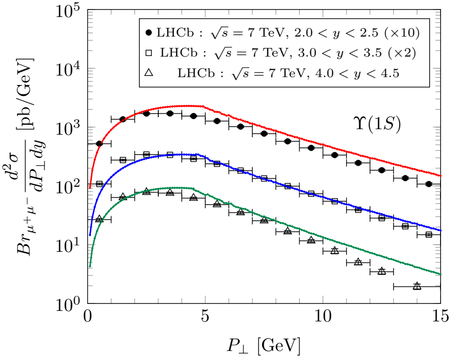
$$\frac{d\sigma^{c\bar{c}}}{d^2p_\perp dy} \propto F.T.\left[x_1 G\left(x_1, \frac{c_0}{v_\perp}\right) D_Y(x_\perp) D_Y(y_\perp)\, e^{-S_{\rm Sud}(M, v_\perp)} \hat{H}_{\rm LO}\right]$$

  where $v_\perp = zx_\perp + (1-z)y_\perp \sim (x_\perp + y_\perp)/2$.
- Parton shower effect is dominant for low-$p_\perp$ Υ production in p+p collisions, however, can be comparable to Saturation effect in p+A collisions.
- Υ (and B) production in high multiplicity events is not obvious.

See [Qiu, KW, arXiv:1710.06928]

$$\frac{d\sigma^{pp\to b\bar{b}+X}}{d^2P_\perp dy} = \int \frac{d^2b_\perp}{(2\pi)^2} e^{iP_\perp\cdot b_\perp} \underbrace{W(M,b_\perp,x_1,x_2)}_{\text{resum}} + \underbrace{(d\sigma_{\text{perp}} - d\sigma_{\text{asy}})}_{\text{Y-term}}$$

where
$W = \sum_{ij} d\hat{\sigma}_{\text{LO}}^{ij\to q\bar{q}} W_{ij}(M,b_\perp) e^{-S_{ij}(M,b_\perp)}$



$$\begin{cases} W_{ij}(M,b_\perp) = \sum_{a,b} \int \frac{d\xi}{\xi}\frac{d\xi'}{\xi'} C_{a\to i}\left(\frac{x_A}{\xi}\right) C_{b\to j}\left(\frac{x_B}{\xi'}\right) \underbrace{\phi_{a/A}(\xi,\mu)\phi_{b/B}(\xi',\mu)}_{\text{collinear-pdfs}} \\ S_{ij}(M,b) = \int_{c_0/b^2}^{M^2} \frac{d\mu^2}{\mu^2}\left[A_{ij}\ln\left(\frac{M^2}{\mu^2}\right) + B_{ij}\right] \end{cases}$$

A, B, C are calculated perturbatively.

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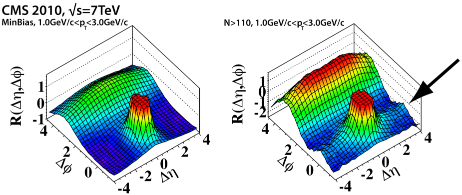
- p+p vs p+A vs A+A: Initial state (fluctuation) or Final state (hydro) origins?



High Multiplicity events and Gluon Saturation

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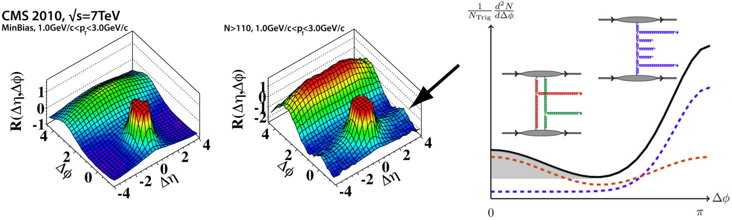

- Gluon saturation/CGC is a natural way to explain this phenomenon. cf. [Dumitru, Dusling, Gelis, Jalilian-Marian, Lappi and Venugopalan, PLB**697**, 21 (2011)][Dusling and Venugopalan, PRL**108**, 262001 (2012), PRD**87**, 051502, 054014, 094034 (2013)]

High Multiplicity events and Gluon Saturation

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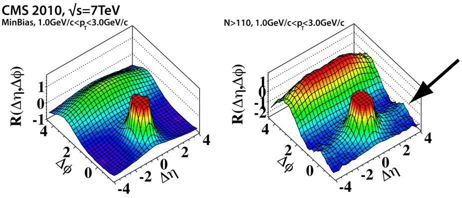
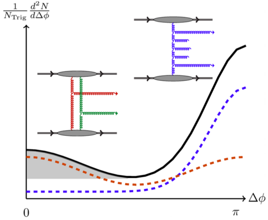
- p+p vs p+A vs A+A: Initial state (fluctuation) or Final state (hydro) origins?





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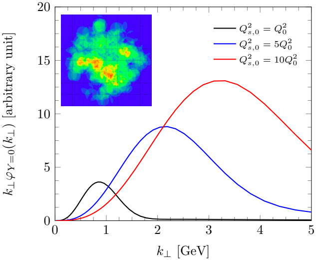
- Classical gluon fields have $A \sim 1/g$:

$$\frac{dN_{ch}}{d^2b_\perp d^2k_\perp dy} \sim \langle AA \rangle \sim \frac{f(k_\perp/Q_s)}{\alpha_s} \Rightarrow \frac{dN_{ch}}{dy} \sim \frac{S_\perp Q_s^2}{\alpha_s}$$

Large fluctuation in $Q_s(x) \leftrightarrow$ Rare partons configuration.

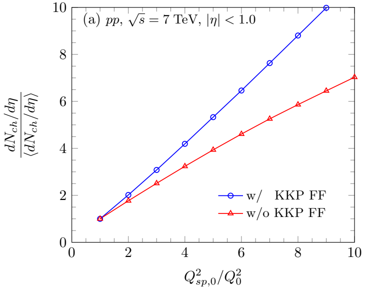


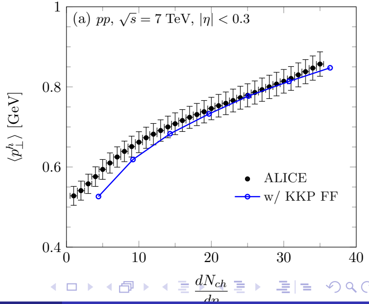
[Ma, Tribedy, Venugopalan, KW, 1803.11093]

$$\frac{d\sigma_g}{d^2\boldsymbol{p}_{g\perp}dy} = \frac{\alpha_s \hat{K}_b}{(2\pi)^3\pi^3 C_F}\int \frac{d^2\boldsymbol{k}_\perp}{p_{g\perp}^2}\varphi_{p,y_p}(\boldsymbol{k}_\perp)\,\varphi_{A,Y}(\boldsymbol{p}_{g\perp}-\boldsymbol{k}_\perp)$$

$$\frac{dN_{ch}}{d\eta} = \frac{\hat{K}_{ch}}{\sigma_{\text{inel}}}\int d^2\boldsymbol{p}_\perp \int_{z_{\text{min}}}^{1} dz \frac{D_h(z)}{z^2} J_{y\to\eta}\frac{d\sigma_g}{d^2\boldsymbol{p}_{g\perp}dy}$$

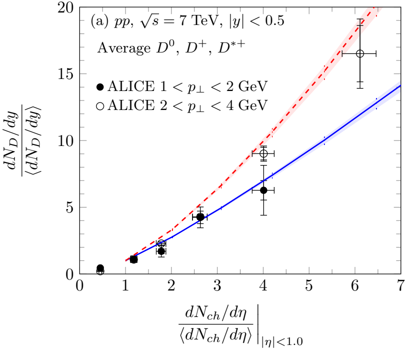
- $b_\perp$ dependence $\leftrightarrow$ $Q_{s,0}^2$ dependence with $S_\perp$ fixed.
- MB: $dN_{ch}/\langle dN_{ch}\rangle = 1$ at $Q_{s,0}^2 = Q_0^2$ in p+p and $2Q_0^2$ in p+A.
- Large $Q_{s,0}^2$ gives High Multiplicity events: $dN_{ch}/\langle dN_{ch}\rangle \gg 1$.
- W/o the FF, larger $Q_{s,0}^2$ is required to obtain large event activity. Use of the FF mitigates this.





[Ma, Tribedy, Venugopalan, KW, 1803.11093]

p+p



- $Q^2_{sp_1} \sim Q^2_{sp_2} > Q^2_0$ is required. $\rightarrow$ Quantum entanglement of the wave functions of gluons in both the projectile and the target.

[Ma, Tribedy, Venugopalan, KW, 1803.11093]

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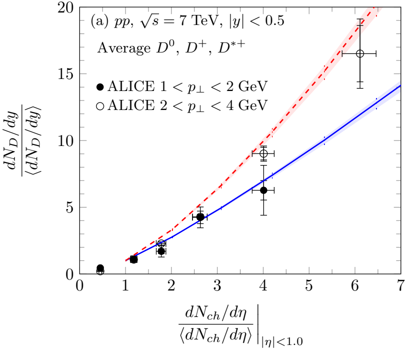
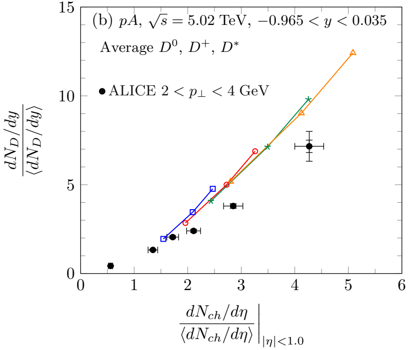


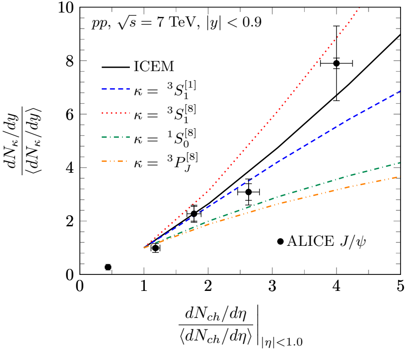
p+A



- $Q^2_{sp_1} \sim Q^2_{sp_2} > Q^2_0$ is required. $\rightarrow$ Quantum entanglement of the wave functions of gluons in both the projectile and the target.

- $Q^2_{sp,0} = (1-3)Q^2_0$
- Different colors: Different $Q^2_{sA,0}$

[Ma, Tribedy, Venugopalan, KW, 1803.11093]



- The ${}^3S_1^{[8]}$ state dominates J/ψ production with increasing event activity.
- Remarkably consistent with the universality requirement from BELLE e^+e^- data:

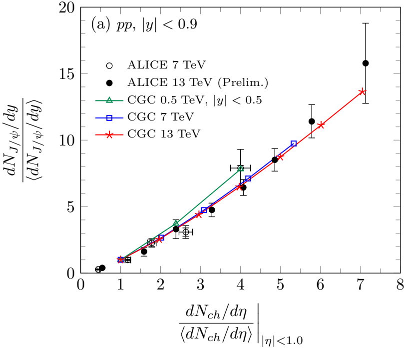
$$\langle O^{J/\psi}[{}^1S_0^{[8]}]\rangle + 4.0\langle O^{J/\psi}[{}^3P_0^{[8]}]\rangle/m^2 < 2.0 \pm 0.6 \times 10^{-2}\text{GeV}^3$$

[Zhang, Ma, Wang, Chao, PRD**81**,034015(2010)]

- Caveat: The ${}^1S_0^{[8]}$ is likely to be dominant by comparison with $p_\perp$ spectrum of J/ψ production in p+p and p+A collisions in the CGC+NRQCD.

[Ma, Tribedy, Venugopalan, KW, 1803.11093]

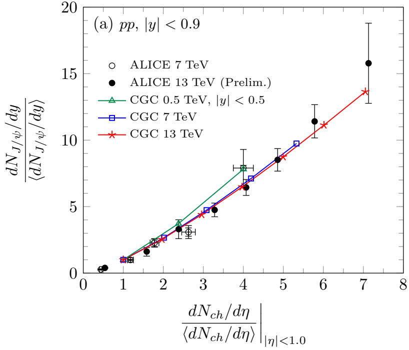
p+p



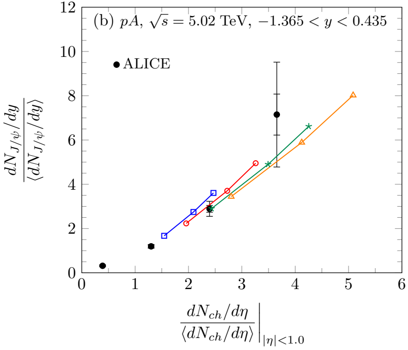
- $\sqrt{s}$-dependence of the ratios are weak! Events at different energies with the same Q_s are almost identical.

[Ma, Tribedy, Venugopalan, KW, 1803.11093]

p+p



p+A



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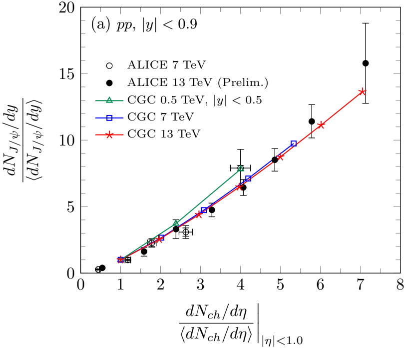
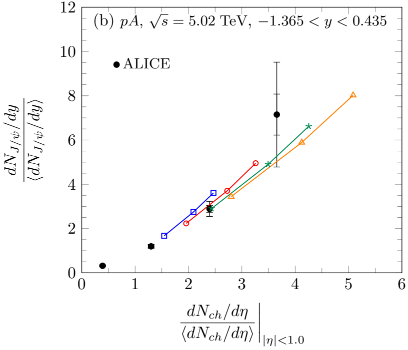


p+A



- $\sqrt{s}$-dependence of the ratios are weak! Events at different energies with the same Q_s are almost identical.
- $Q^2_{sp,0} = (1-3)Q^2_0$
- Different colors: Different $Q^2_{sA,0}$

The similar trends are seen for D and J/ψ production. → Hadronization dynamics is irrelevant, rather saturation effect at short distance plays a key role in describing data.

1 Framework

2 Minimum Bias events

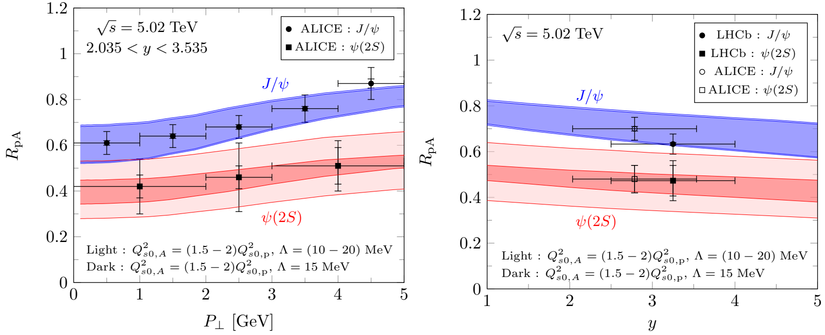
3 High multiplicity events

4 Summary

- We study event engineered HF and Onium production in p+p and p+A collisions in the CGC framework.
- Nice agreement is found between the CGC computations and the LHC data on D and J/ψ production in minimum bias and rare high multiplicity events in p+p and p+A collisions.
- Strong $\psi(2S)$ nuclear suppression is due to the factorization breaking effect at last stage.
- Saturation effect is not seen for Υ production in p+p but can be important in p+A.
- ${}^1S_0^{[8]}$ is likely to be dominant channel for J/ψ production by going through its $p_\perp$ distribution in minimum bias p+p and p+A collisions at RHIC and the LHC.
- Meanwhile, by considering J/ψ's total cross section, ${}^3S_1^{[8]}$ should be dominant in large event activity.
- N_{ch} dependence of $\psi(2S)$, Υ, and Heavy flavor decay lepton are also interesting and in progress.

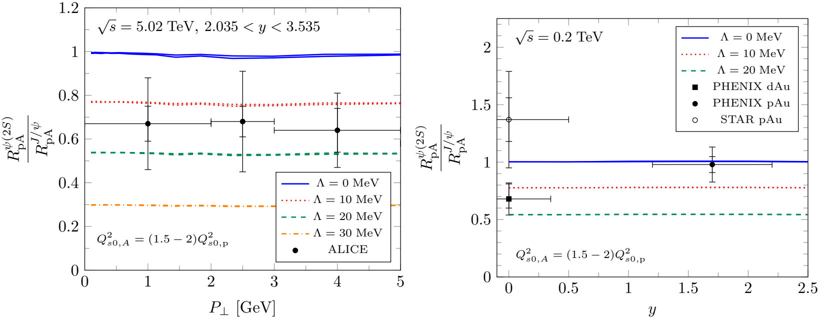
5 Backup

[Ma, Venugopalan, Zhang, KW, PRC**97**,014909(2018)]

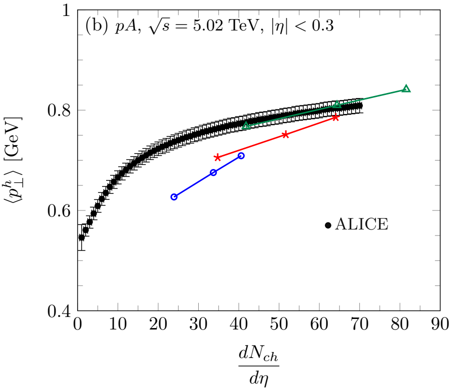


- The factorization breaking effect clearly leads to a stronger $\psi(2S)$ suppression while it is negligible for J/ψ.
- The enhanced soft color exchanges in p+A are sufficient to explain the data.

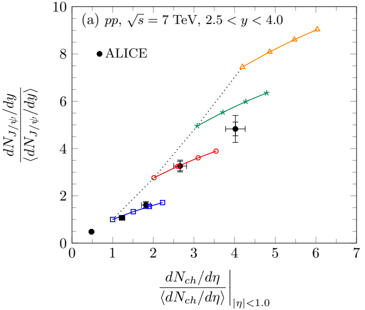
[Ma, Venugopalan, Zhang, KW, PRC**97**,014909(2018)]



- Advantage of the double ratio : many systematic uncertainties including Q^2_{sA} can cancel.
- The suppression of the double ratio can be controlled by Λ alone clearly.
- The relative factorization breaking effect is seen at the LHC but it is ambiguous at RHIC.

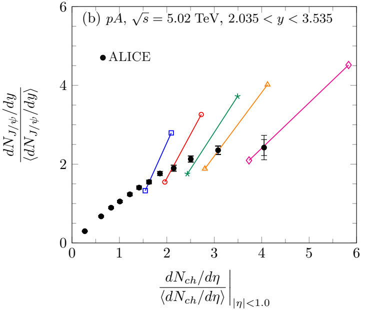


- $Q^2_{sp,0} = (1-3)Q^2_0$
- Different colors: Different $Q^2_{sA,0}$



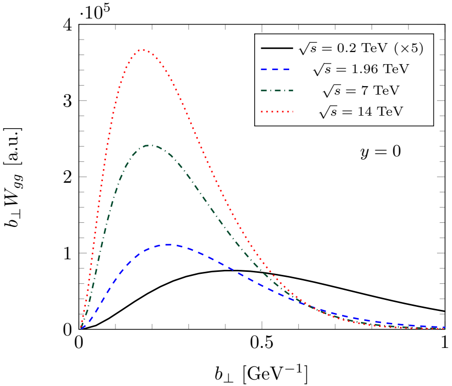
← p+p collisions

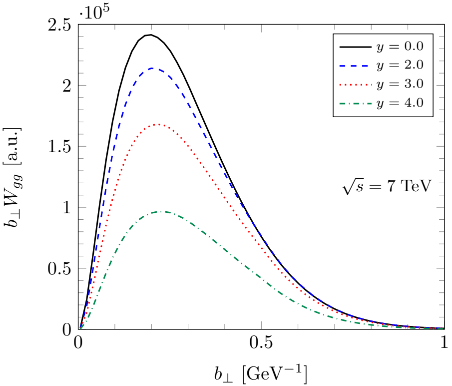
- Different colors: Different $Q^2_{sp1,0}$ and $Q^2_{sp2,0} \geq Q^2_{sp1,0}$.
- In contrast to mid rapidity, the symmetrical treatment; $Q^2_{sp1,0} = Q^2_{sp2,0}$ overshoots the data slightly in $p + p$ collisions (Dashed line). Data point at $dN_{ch}/\langle dN_{ch}\rangle \sim 4$ seems to favor the asymmetrical treatment; $Q^2_{sp1,0} < Q^2_{sp2,0}$.



← p+A collisions

- Different colors: Different $Q^2_{sA,0}$.
- Lower points: $Q^2_{sp,0} = Q^2_0$, Upper points: $Q^2_{sp,0} = 2Q^2_0$.





- $s \uparrow \Longrightarrow b_{sp}$ shifts toward small $b_\perp$: Perturbative domains ($b < b_{max} = 0.5[\text{GeV}^{-1}]$) are essential. F^{NP} is not crucial for $b\bar{b}$ production at Tevatron & LHC.
- $y \uparrow \Longrightarrow b_{sp}$ shifts toward large $b_\perp$ but $b_{sp} < b_{max}$.