Heavy Flavor and Quarkonium Production in the Color Glass Condensate framework: From p+p to p+A collisions

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PRC**97** (2018) 014909 with Y.-Q. Ma, R. Venugopalan, H. F. Zhang
arXiv:1803.11093 with Y.-Q. Ma, P. Tribedy, R. Venugopalan

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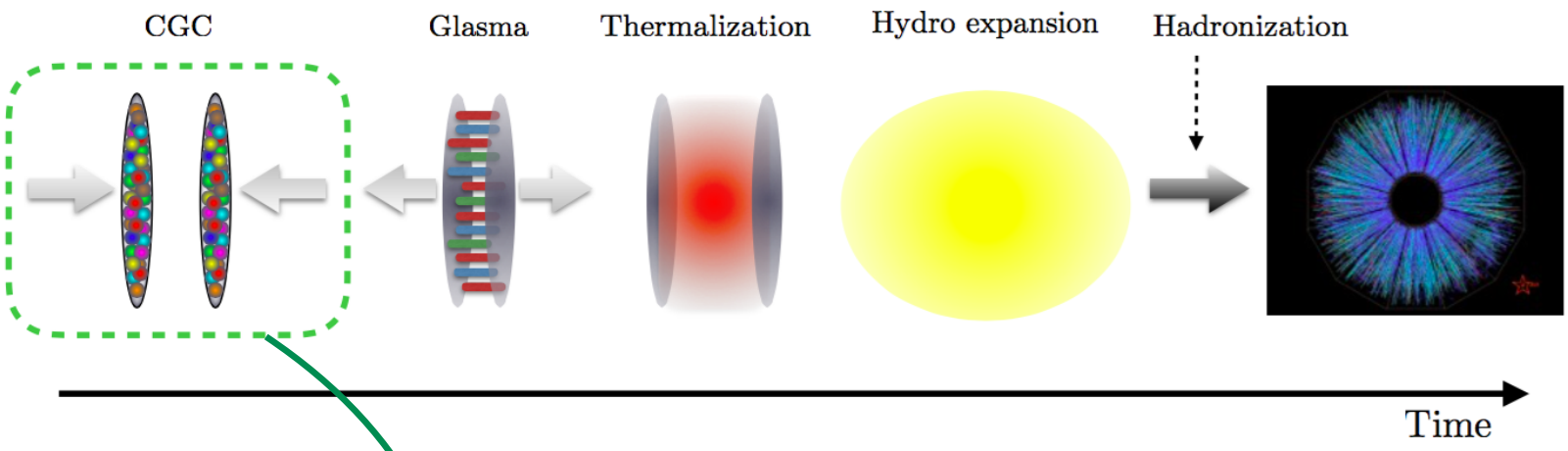
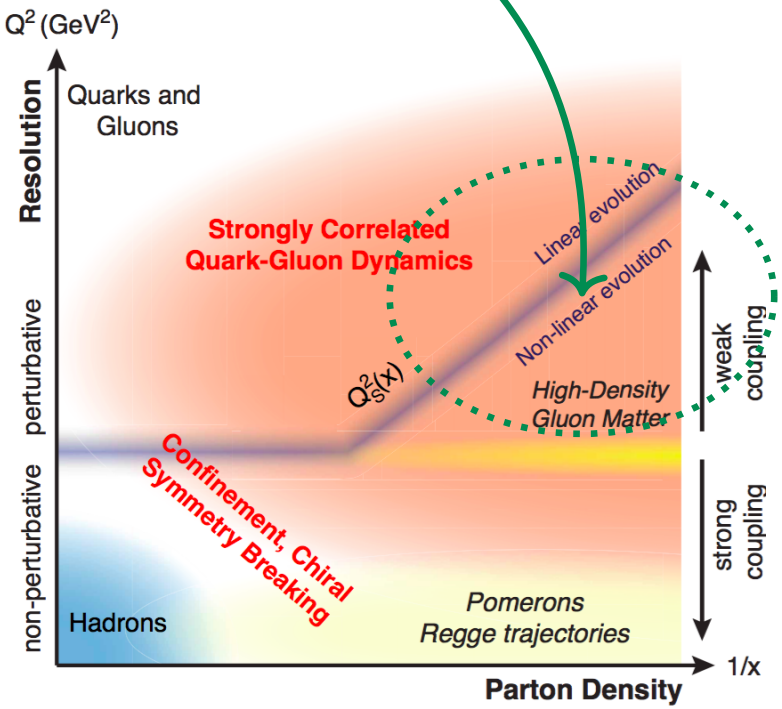
A QCD Landscape at High Energy





1708.01527

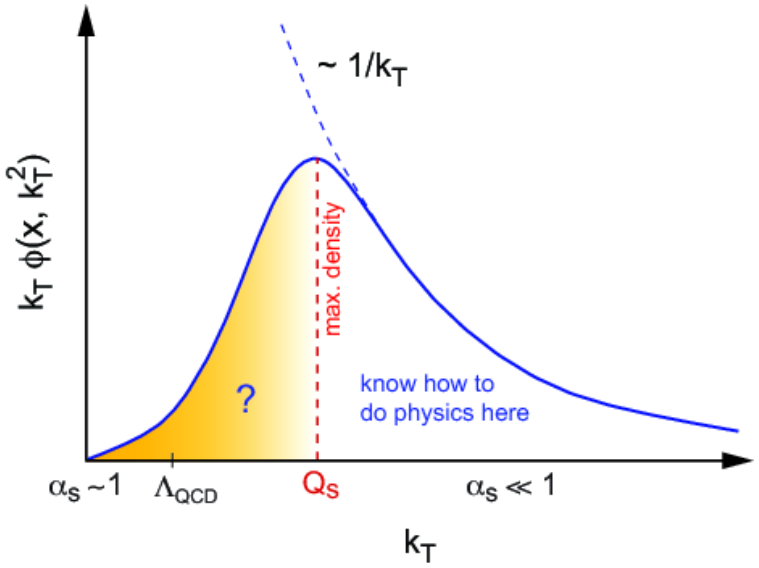
- Highly occupied small-x gluons are at the core in the Color-Glass-Condensate (CGC).
- Nonlinear gluon recombination leads to "Gluon Saturation".
- Semihard saturation scale in nucleus:

$$Q_{sA}^2(x) \sim A^{1/3}\left(\frac{1}{x}\right)^{0.3} \gg \Lambda_{\rm QCD}^2$$

- How to probe into the CGC in HICs? What are we able to expect from the CGC in HICs? $\Rightarrow$ Heavy quarks in p+p and p+A collisions.

Why Heavy quarks?

- Heavy quark pair ($Q\bar{Q}$) is mainly produced in a hard gluon scattering at high energy. $Q\bar{Q}$ probes into gluons inside hadron or nucleus.
- $m \gg \Lambda_{\rm QCD}$ allows weak coupling calculations. If $m \lesssim Q_s$, heavy quark pair can probe a dense gluon regime inside hadron/nucleus even at low-$p_\perp$ of order $\mathcal{O}(\Lambda_{\rm QCD})$.



The role of p+p collision

- Elementary process for understanding HF and Onium production mechanisms at low $p_\perp$. The CGC framework is complementary to pQCD approach which works well at high Q^2.
- p+p is an important reference against p+A and A+A collisions.

The role of p+A collision

- Large Q_s should modify $p_\perp$ distribution of $Q\bar{Q}$ production compared to p+p collisions. $\Rightarrow$ This is a Cold Nuclear Matter (CNM) effect which must be distinguished from hot medium effect in A+A collisions.

1 Framework

2 Minimum Bias events

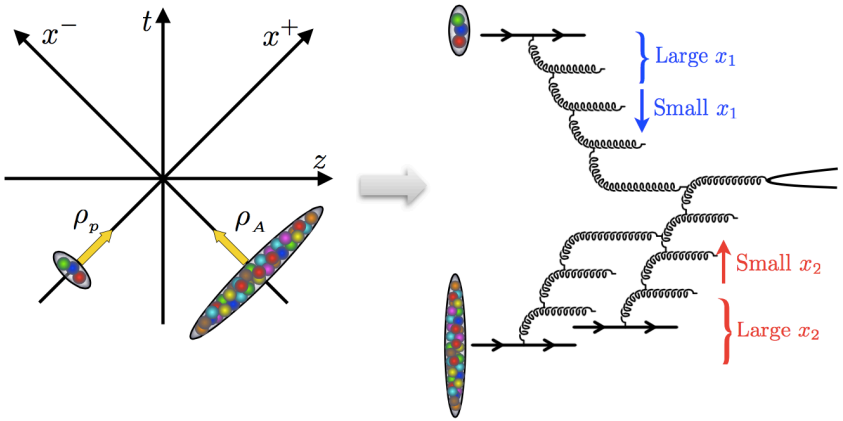
3 High Multiplicity events

4 Summary

$Q\bar{Q}$ production in the CGC framework

[Blaizot, Gelis and Venugopalan, NPA**743**, 57 (2004)]

- Large-x:
  $J^\nu = g\delta^{\nu+}\delta(x^-)\rho_p(x_\perp) + g\delta^{\nu-}\delta(x^+)\rho_A(x_\perp)$.
- Small-x: Classical fields satisfy CYM equation, $[D_\mu, F^{\mu\nu}] = J^\nu$.
- $Q\bar{Q}$ is produced coherently as a whole in the background fields.



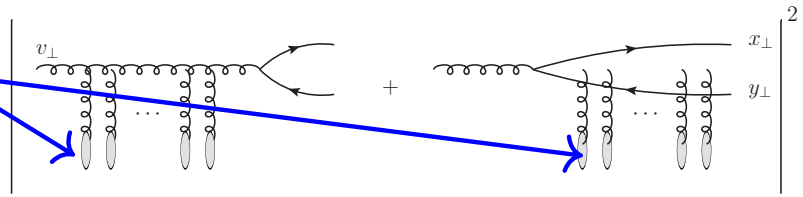
- In Large-N_c limit,

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

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

✓ Wilson lines represents Multiple scattering of fast partons in background fields (Higher twist).

✓ Energy/Rapidity dependence: Running coupling BK equation. [Balitsky, PRD**75**, 014001 (2007)]



- Caveat: The CGC framework is essentially applicable to a dilute-dense system at forward rapidity. Backward rapidity is unfavorable.

(∗Suppose charm production)

Single Open Heavy Flavor production:

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

- Heavy quark fragmentation function $D_{c\to D}(z)$ modifies $p_\perp$ spectrum of charm: $\langle p_\perp^D \rangle < \langle p_\perp^c \rangle$.
- Large theoretical uncertainties may be indispensable at $p_\perp \lesssim m$.
  cf. [Cacciari, Frixione, Houdeau, Mangano, Nason and Ridolfi, JHEP**1210**, 137 (2012)]

Heavy Flavor Decay Lepton production:

$$\frac{d\sigma_l}{d^2p_{l\perp}dy} = \int dp_{D\perp}p_{D\perp}dy_D \; \mathcal{F}(p_l, p_D) \; \frac{d\sigma_D}{d^2p_{D\perp}dy}$$

- Decay distribution function involved.
- $\mathcal{F}$ is calculable analytically or obtained by fitting CLEO data.
- Decay from heavy flavor meson at high $p_\perp$ into low $p_\perp$ lepton is actually unfavorable in the CGC framework.

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

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

Soft gluons emission takes some momentum away from $c\bar{c}$ in final state: $\langle p_\perp^\psi \rangle > \langle p_\perp^{c\bar{c}} \rangle$.

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

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

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

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

- CS channel probes the quadrupole amplitude $Q_Y \to$ 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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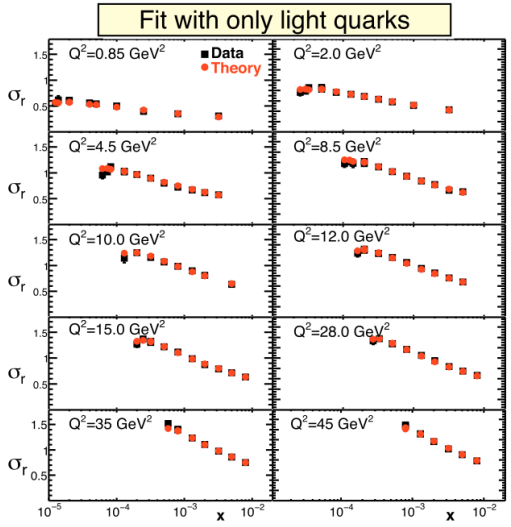
1. Proton

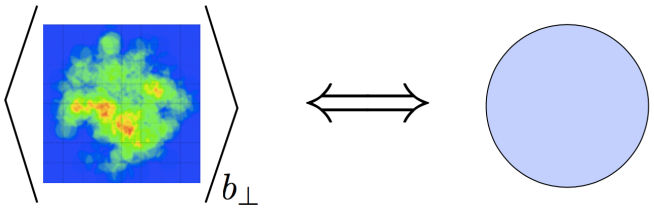
- Saturation scale is embedded in the initial condition:

$$S_Y(r_\perp) = \exp\left[-\frac{\left(x_\perp^2 Q_{s,0}^2\right)^\gamma}{4}\ln\left(\frac{1}{|r_\perp|\Lambda}+e\right)\right]$$

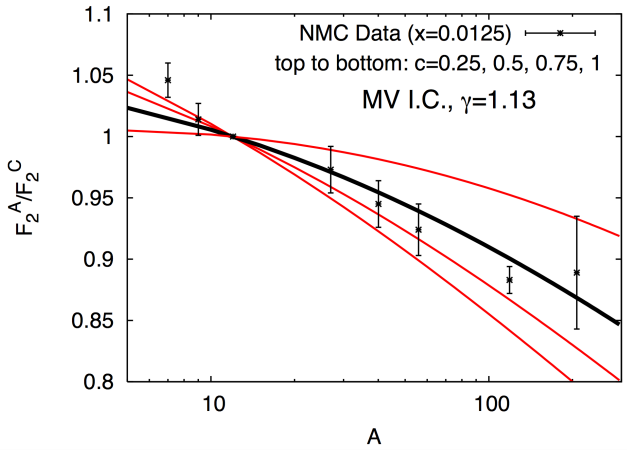
- $Q_{sp,0}^2 = Q_0^2 \sim 0.168$ GeV^2 with $\gamma \sim 1.1$ at $x = 0.01$ by DIS global data fitting for total cross section at HERA.
[Albacete, Armesto, Milhano, Quiroga-Arias and Salgado, EPJC**71**, 1705 (2011)]



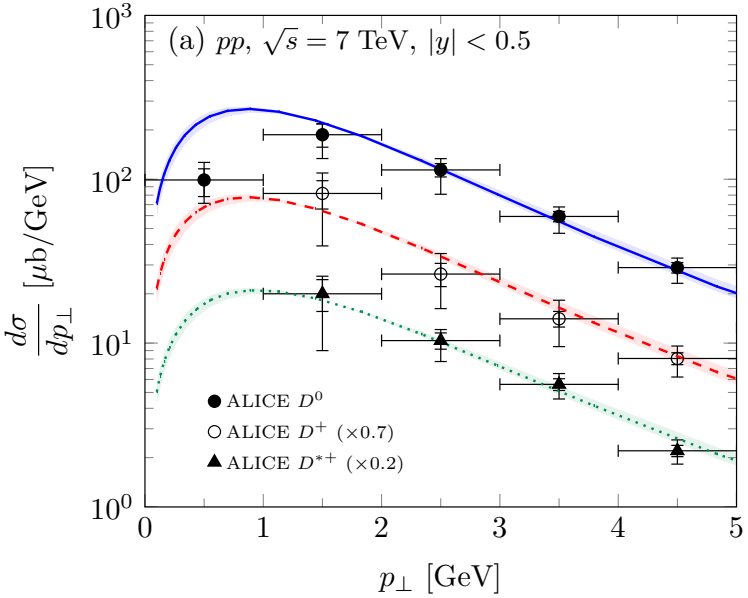
2. Nucleus

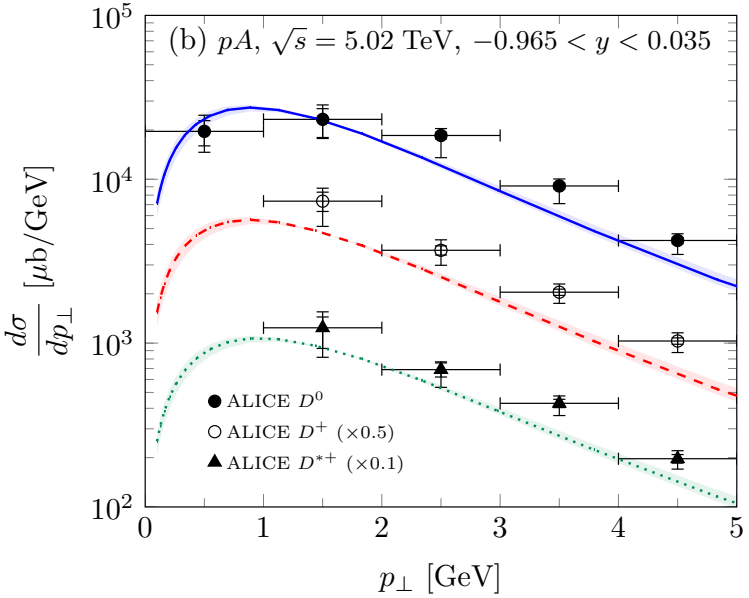


- $Q_{sA,0}^2(b_\perp) \propto A\hat{T}_A(b_\perp)S_\perp Q_{sp,0}^2$.
- $Q_{sA,0}^2 \sim (0.25-0.5)A^{1/3}Q_{sp,0} \sim 2Q_0^2$ at $x \sim 0.01$ for heavy nuclei by fitting the New Muon Collaboration data on $F_{2,A}$.
[Dusling, Gelis, Lappi and Venugopalan, NPA**836**, 159 (2010)]

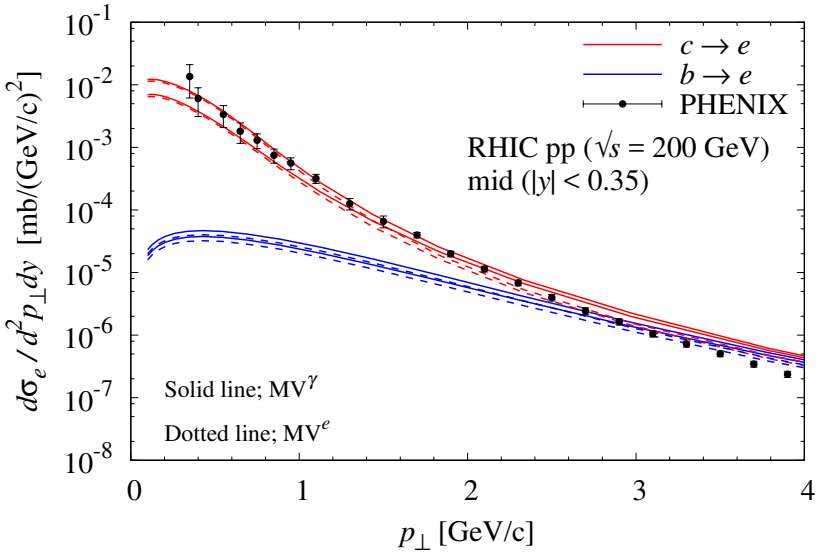


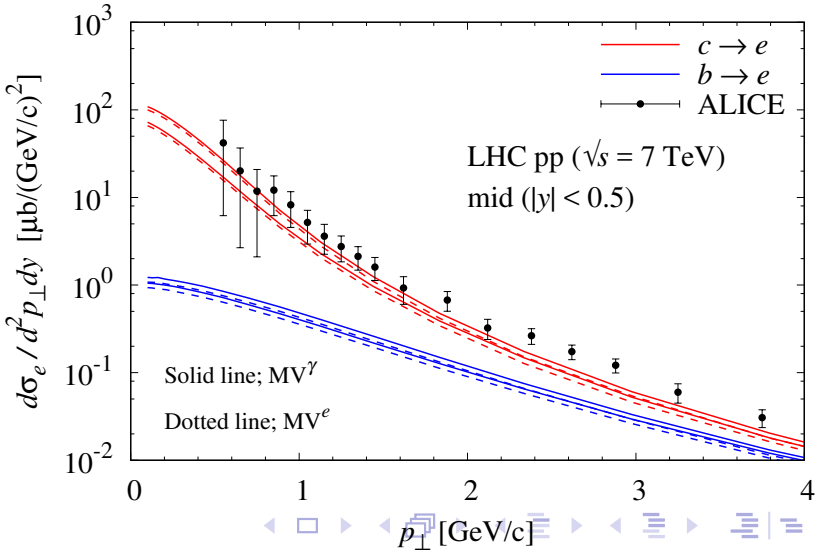
D mesons [Ma, Tribedy, Venugopalan, KW, 1803.11093]



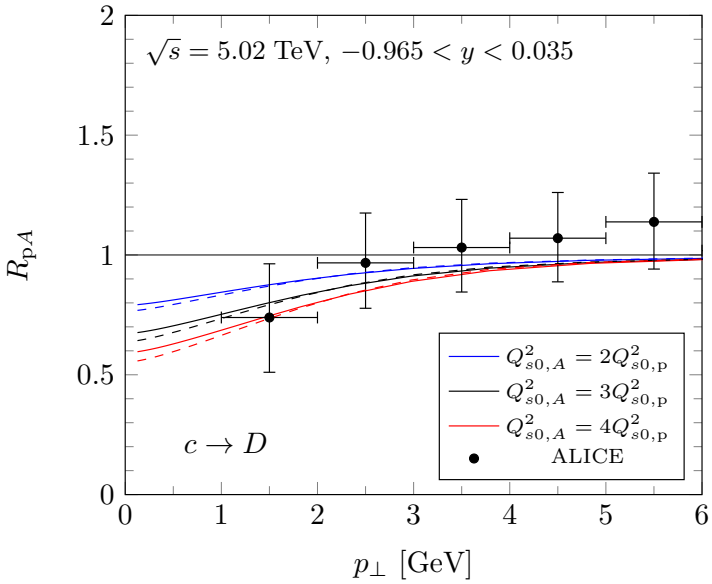


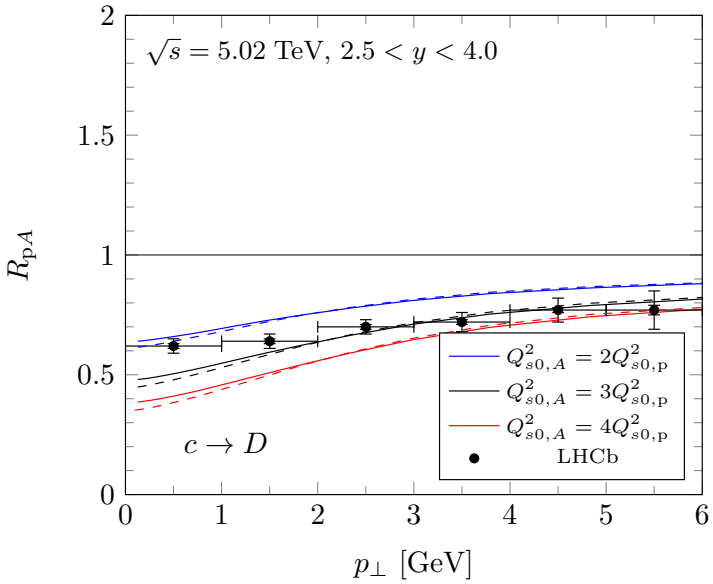
Charm decay leptons [Fujii, KW, NPA**951** (2016) 45]



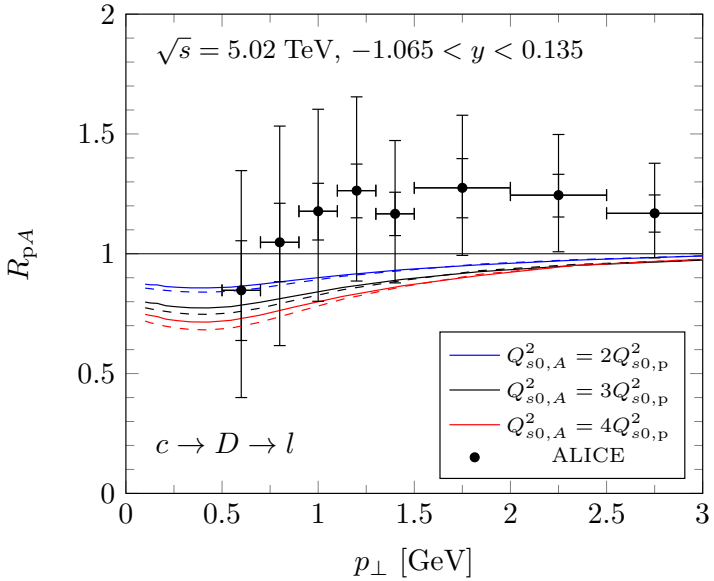


D meson [Fujii, KW, 1706.06728]





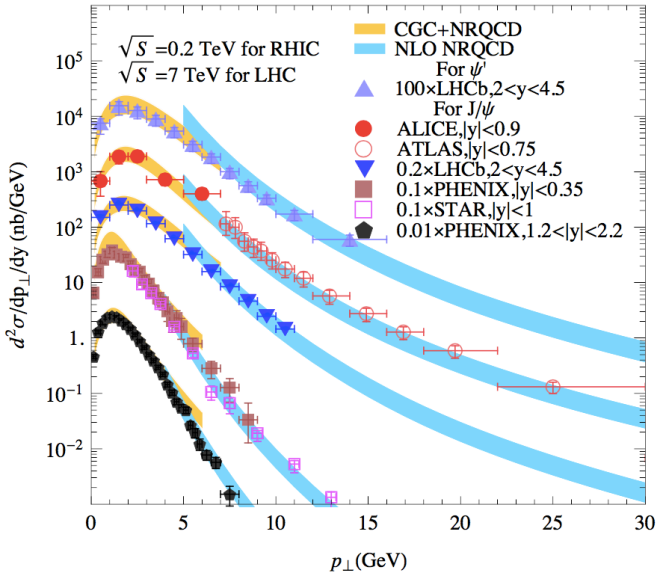
Charm decay electron



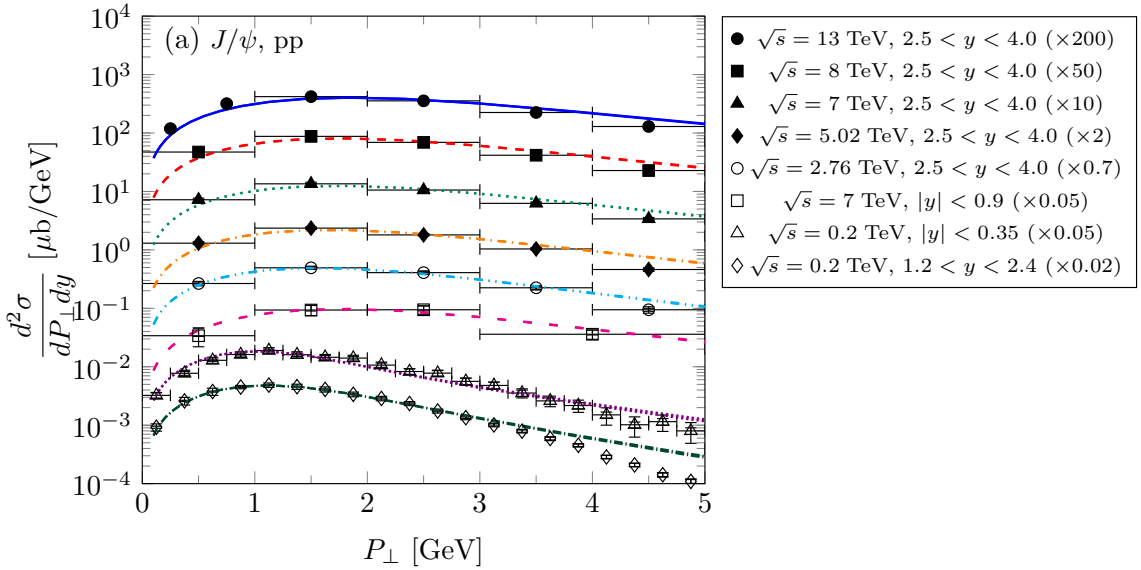
- Nice agreement between the CGC calculation and D mesons' data.
- The choice of $Q^2_{sA,0} = 2Q^2_{sp,0}$ (blue curves) works.
- Charm decay lepton is less suppressed: $R^l_{pA} > R^D_{pA}$.

[Ma, Venugopalan, PRL**113**,192301(2014)] [Ma, Venugopalan, Zhang, KW, PRC**97**,014909(2018)]

NRQCD



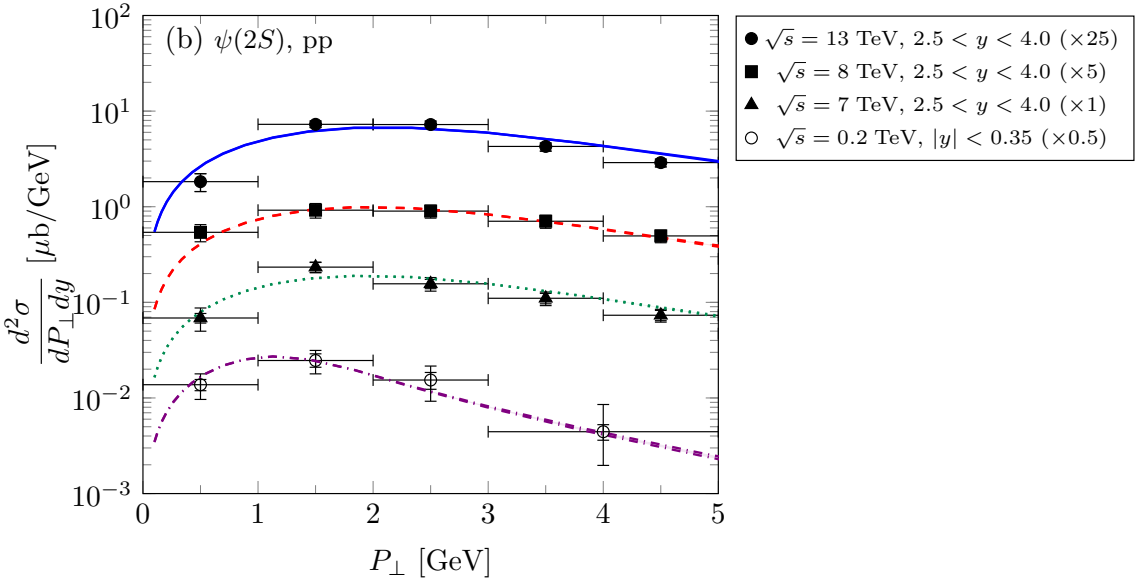
ICEM



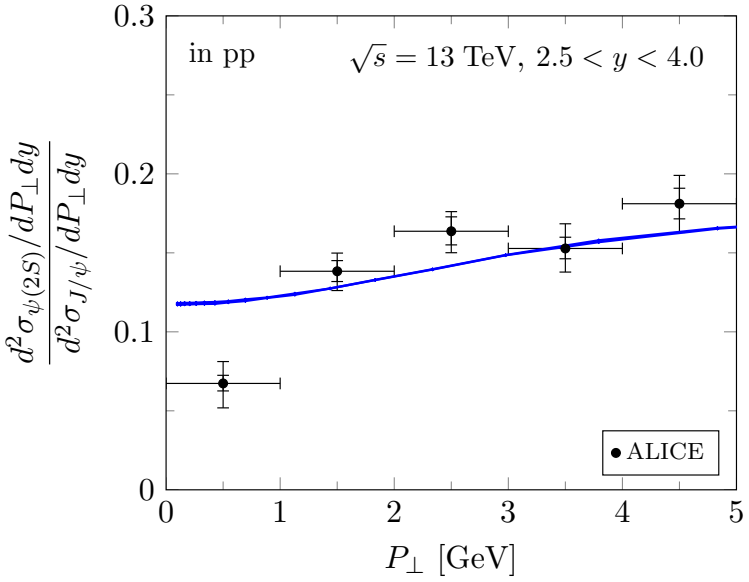
- Both the NRQCD and ICEM reproduce nicely J/ψ data.
- The LDMEs are extracted from high $p_\perp$ data fitting at Tevatron. [Chao, Ma, Shao, Wang and Zhang, PRL**108**,242004(2012)]
  $\langle \mathcal{O}^{J/\psi}[^1S_0^{[8]}]\rangle = 0.089 \pm 0.0098\text{GeV}^3$, $\langle \mathcal{O}^{J/\psi}[^3S_1^{[8]}]\rangle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

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

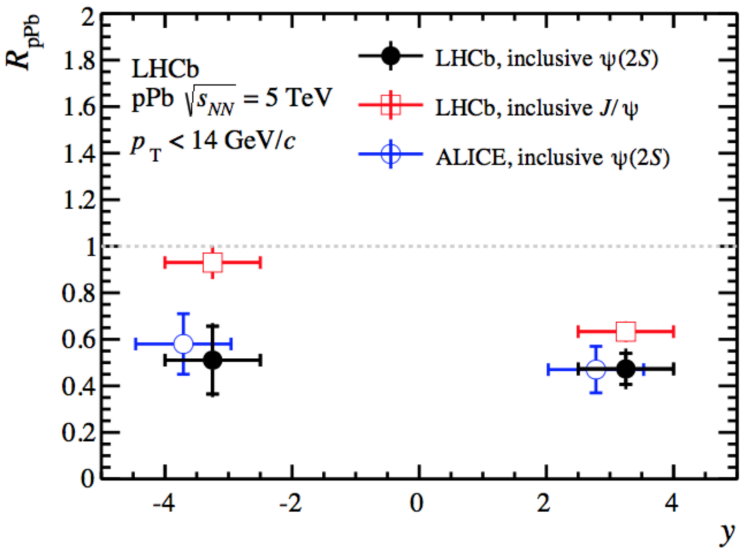
ICEM



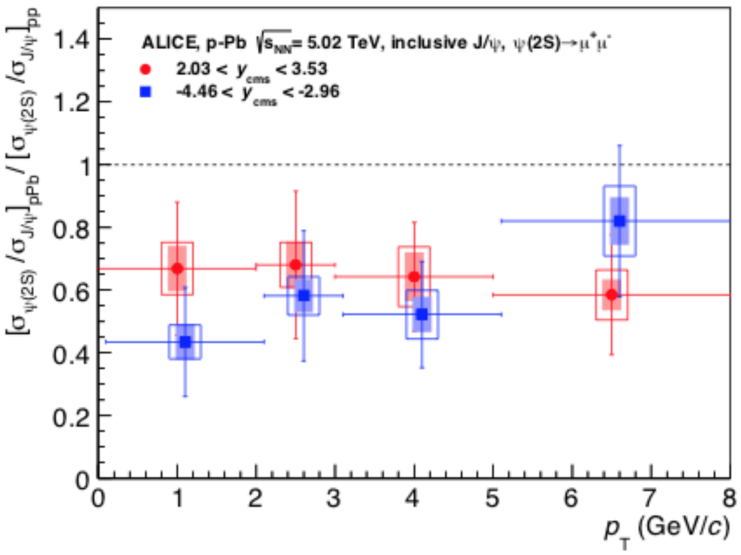
ICEM



- Description of $\psi(2S)$ in the CGC+NRQCD is unclear: Large systematic uncertainties w.r.t quark mass and LDMEs.
- The ICEM explains the $p_\perp$ dependence of data on the ratio of the $\psi(2S)$ to J/ψ yields. In CEM, the ratio of the $\psi(2S)$ to J/ψ yields is always constant.



[LHCb, JHEP **1603**, 133 (2016)]



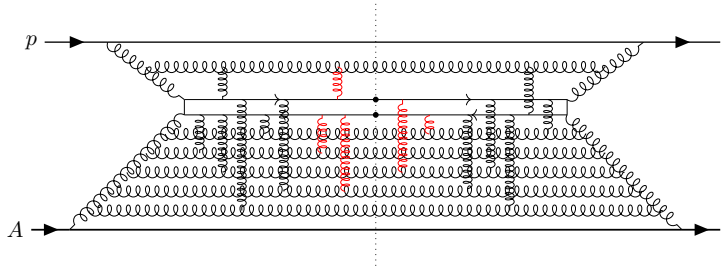
[ALICE, JHEP **1412**, 073 (2014)]

- $c\bar{c}$ 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 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 comovers.

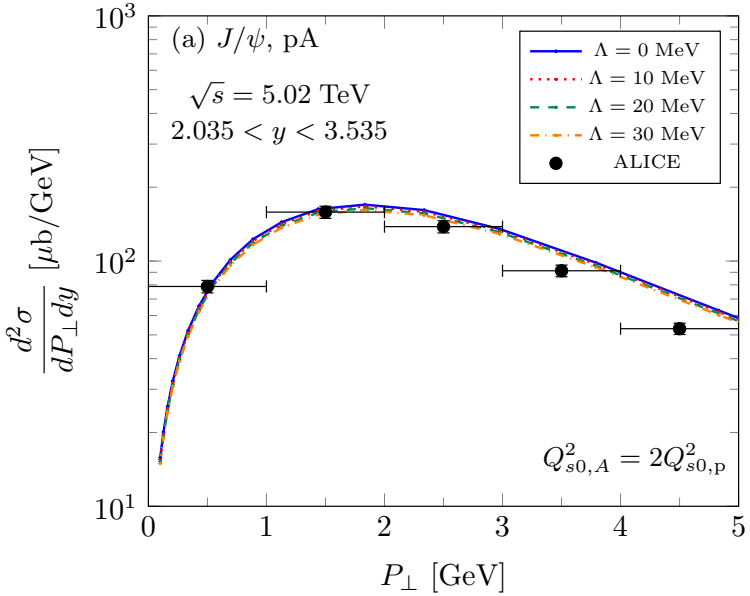
  cf. [Ferreiro, PLB**749**, 98 (2015)]

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

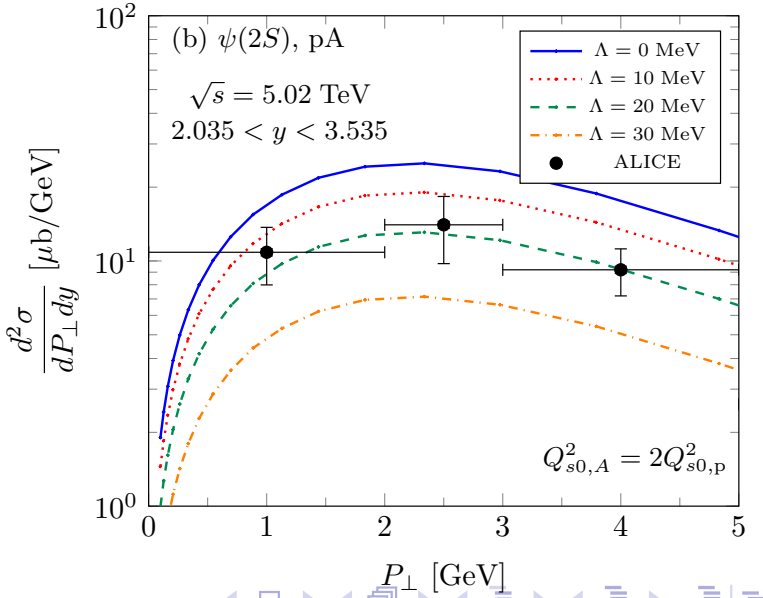
- Soft color exchange (SCE) between $c\bar{c}$ and comover spectators can happen at later stage.
- The role of SCEs should be enhanced in p+A collisions so that momentum kick given by additional nuclear parton comovers breaks bound state: $2m_\psi \leq M_{c\bar{c}} \leq 2m_D - \Lambda$.
- Λ: the average momentum kick given by additional nuclear parton comovers. $\Lambda = 0$ in p+p collisions.



J/ψ



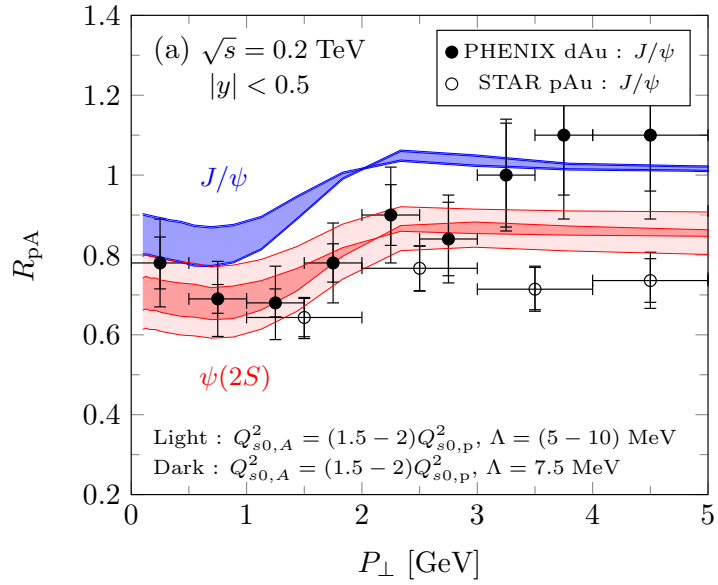
$\psi(2S)$

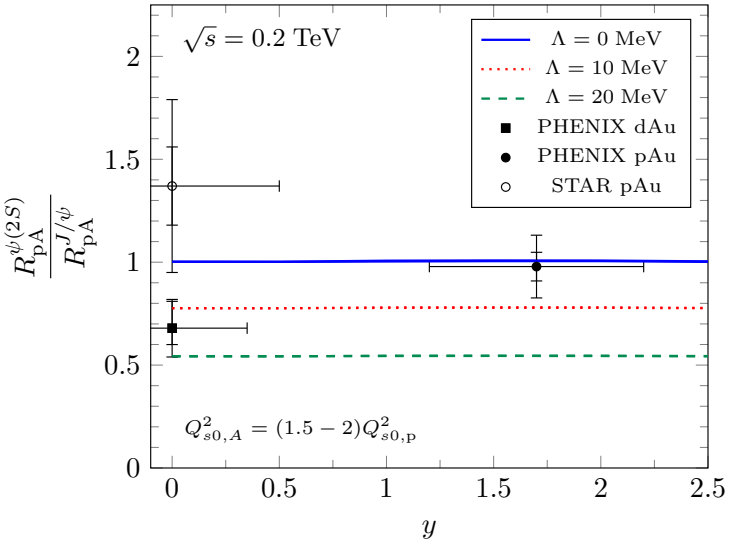


Nuclear suppression: J/ψ vs $\psi(2S)$

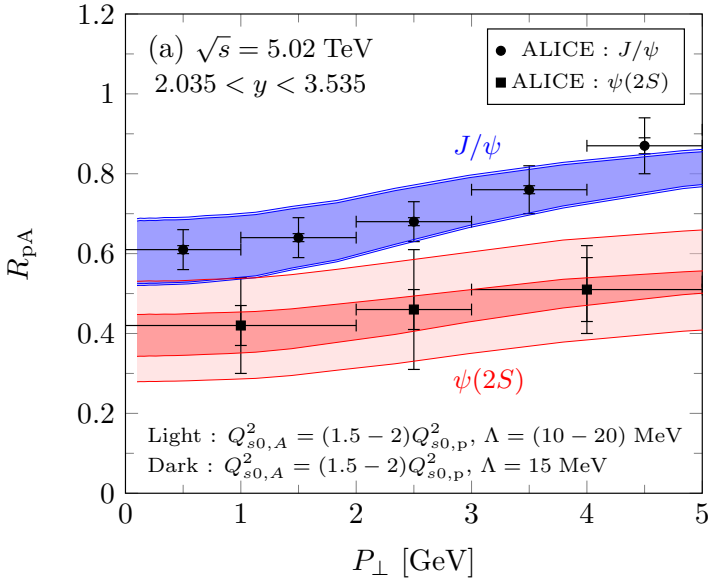
[Ma, Venugopalan, Zhang, KW, PRC**97**,014909(2018)]

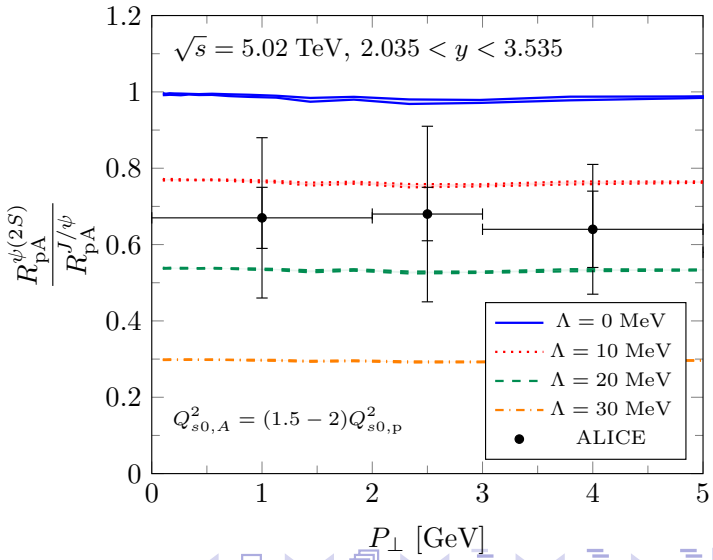
RHIC



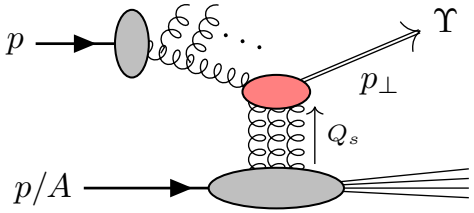


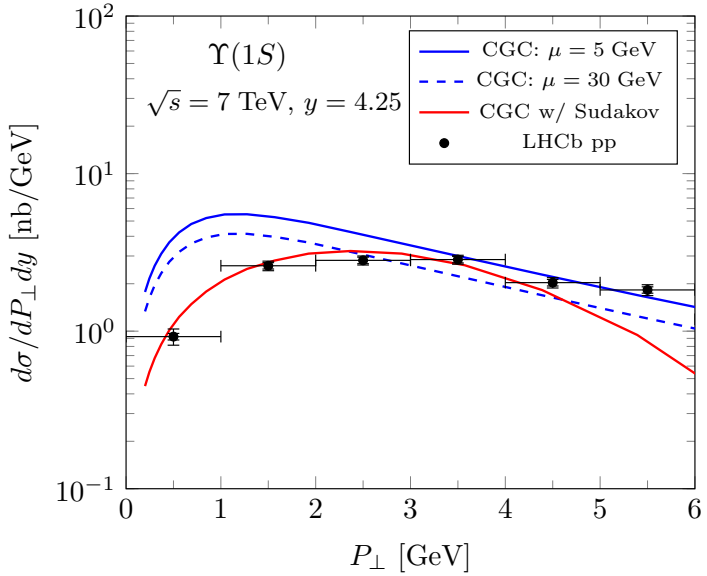
LHC

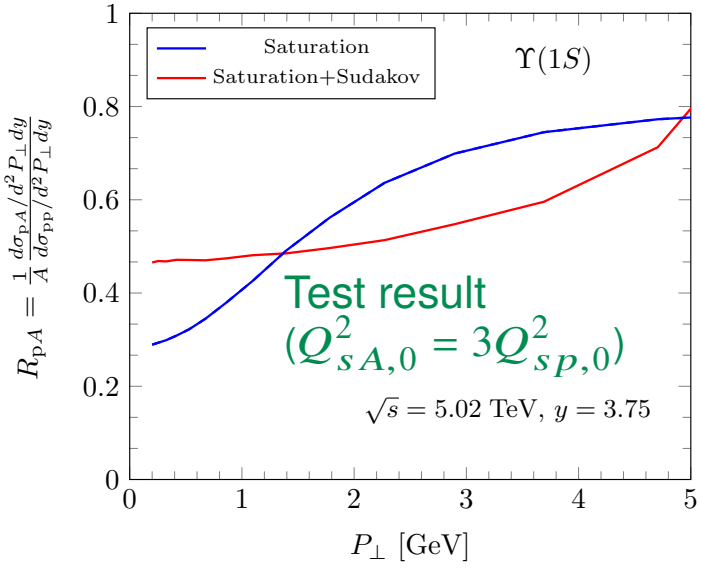




[KW, Xiao, PRD**92**,111502(2015)]







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

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

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.

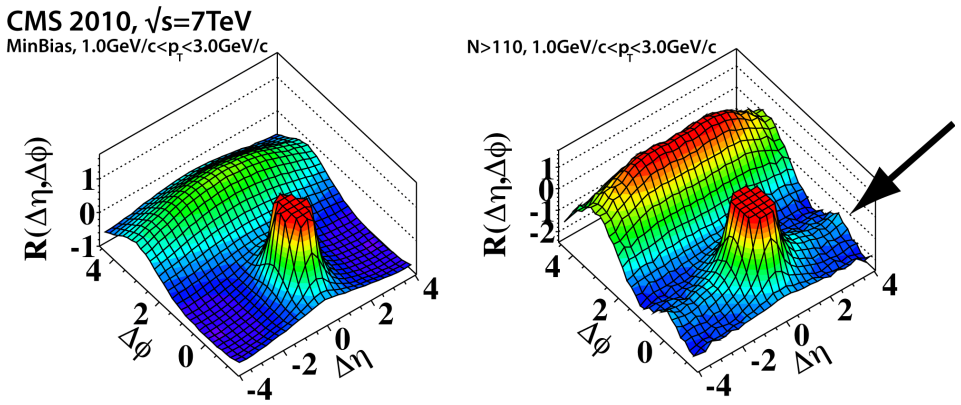
1 Framework

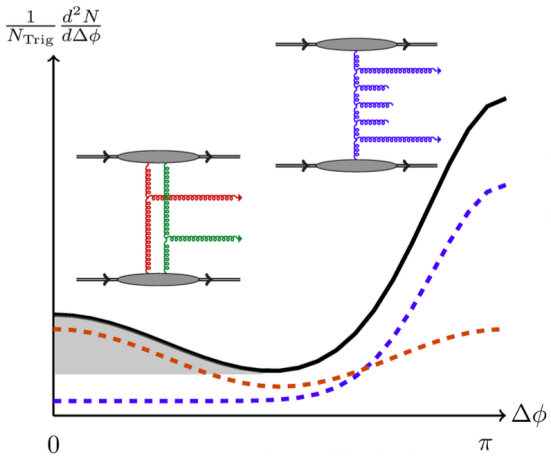
2 Minimum Bias events

3 High Multiplicity events

4 Summary

- Discovery of ridge like structure: The starting point.
- p+p vs p+A vs A+A: Initial state (fluctuation) or Final state (hydro) origins?

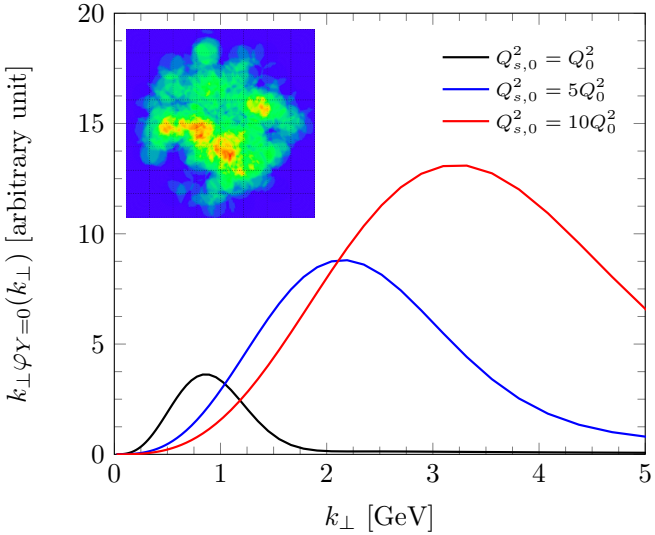




- Gluon saturation/CGC is a natural way to explain this phenomenon.
- Classical gluon fields have $A \sim 1/g$:

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

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

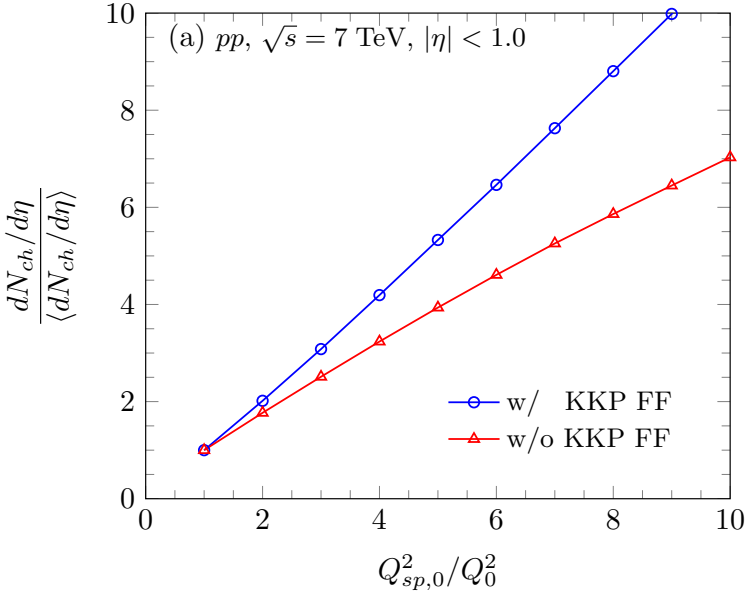


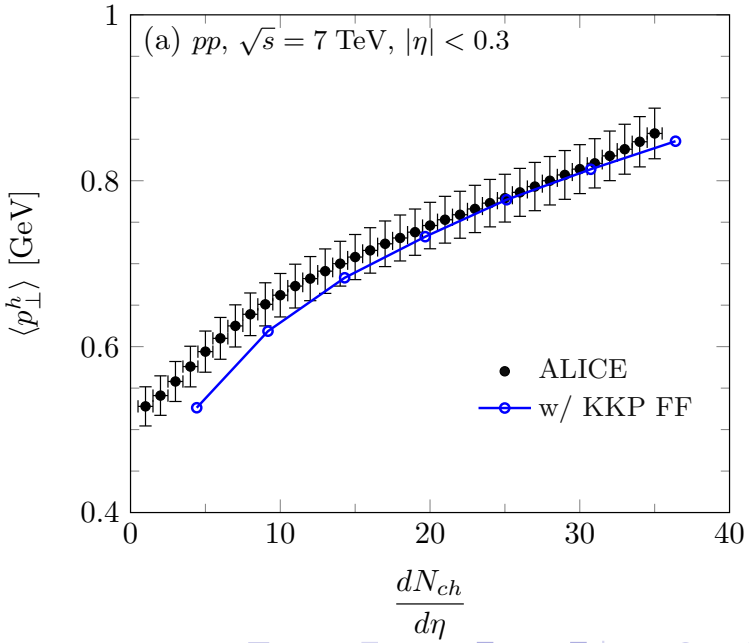
[Ma, Tribedy, Venugopalan, KW, 1803.11093]

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

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

- $b_\perp$ dependence $\leftrightarrow$ $Q^2_{s,0}$ dependence with $S_\perp$ fixed.
- MB: $dN_{ch}/\langle dN_{ch}\rangle = 1$ at $Q^2_{s,0} = Q^2_0$ in p+p and $2Q^2_0$ in p+A.
- Large $Q^2_{s,0}$ gives High Multiplicity events: $dN_{ch}/\langle dN_{ch}\rangle \gg 1$.
- W/o the FF, larger $Q^2_{s,0}$ is required to obtain large event activity. Use of the FF mitigates this.

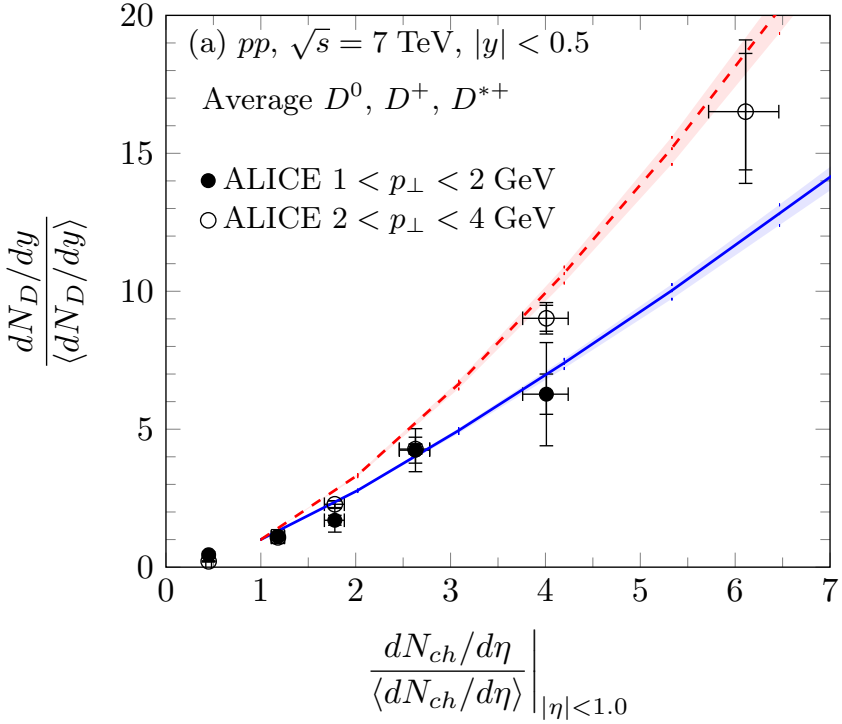




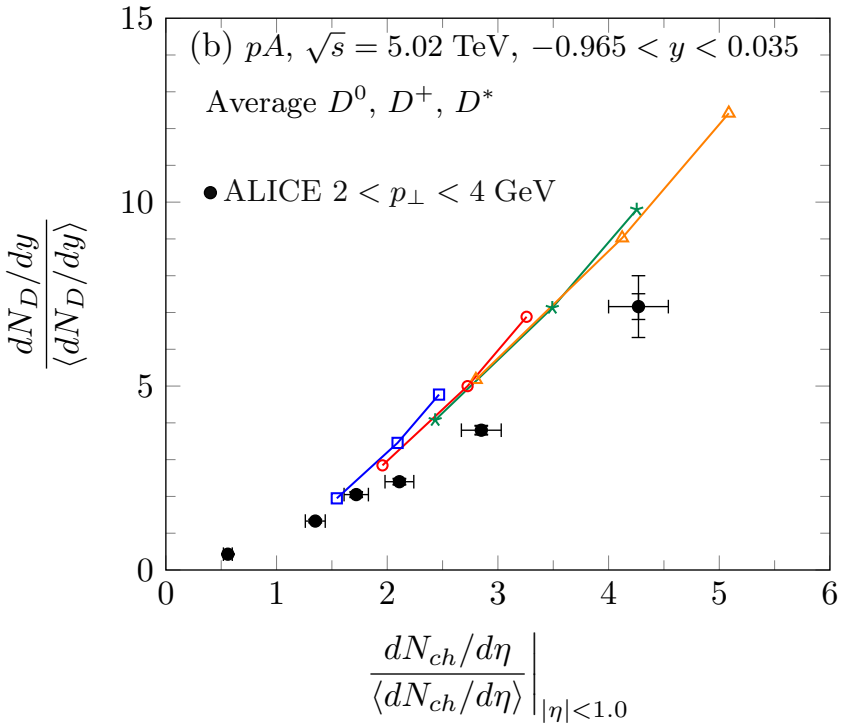
N_{ch} DEPENDENCE OF D PRODUCTION USING THE BCFY FF

[Ma, Tribedy, Venugopalan, KW, 1803.11093]

p+p



p+A



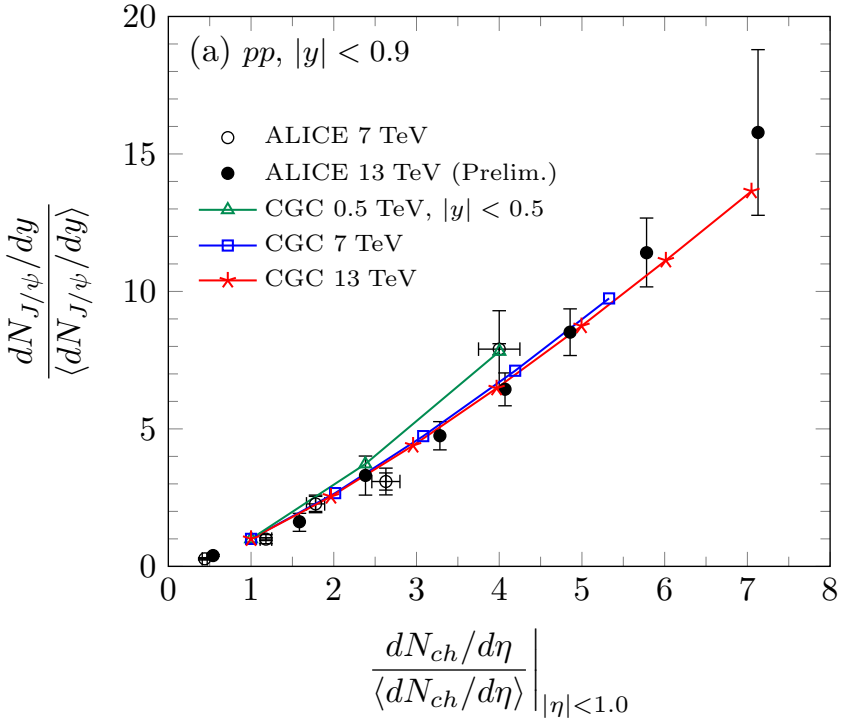
- $Q^2_{sp_1} \sim Q^2_{sp_2} > Q^2_0$ is required. $\rightarrow$ $\phi_p \times \phi_A$ has a large probability at $Q^2_{sp_1} \sim Q^2_{sp_2}$.

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

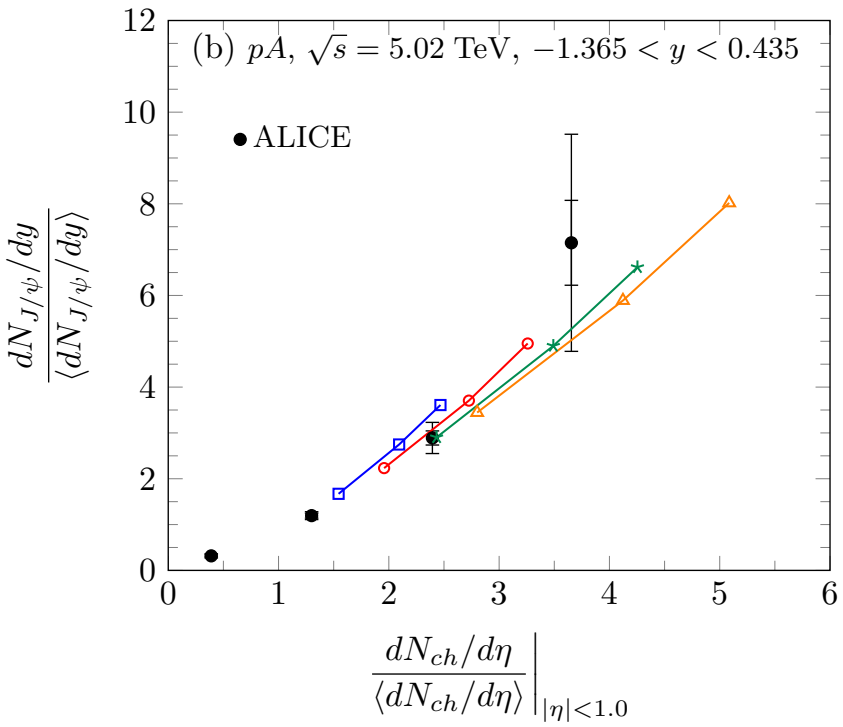
N_{ch} DEPENDENCE OF J/ψ PRODUCTION IN THE CGC + ICEM

[Ma, Tribedy, Venugopalan, KW, 1803.11093]

p+p



p+A

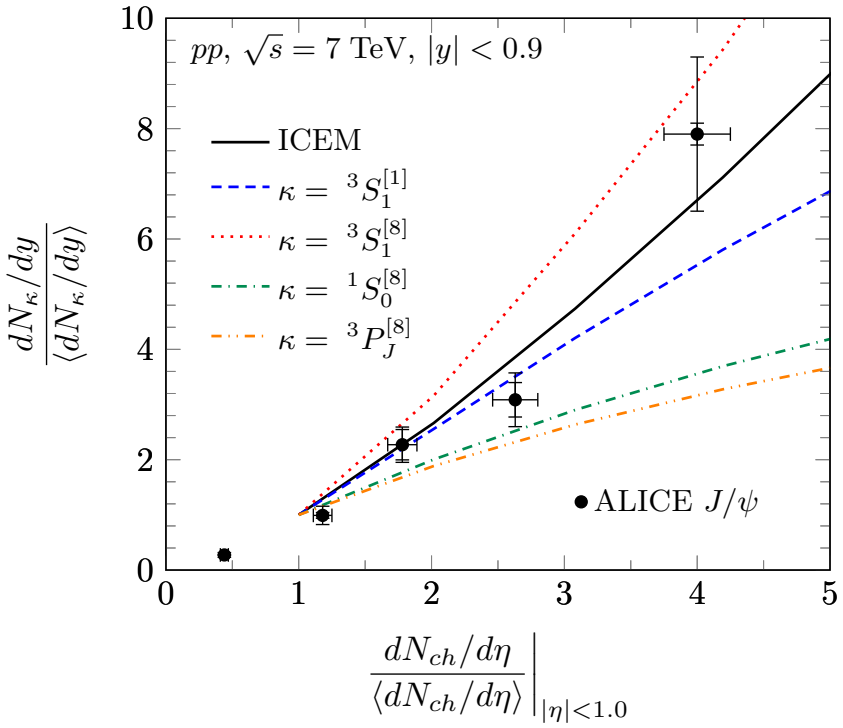


- $\sqrt{s}$-dependence of the ratios are weak.

- $Q^2_{sp,0} = (1-3)Q^2_0$
- 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.

[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:

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

[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.

1 Framework

2 Minimum Bias events

3 High Multiplicity events

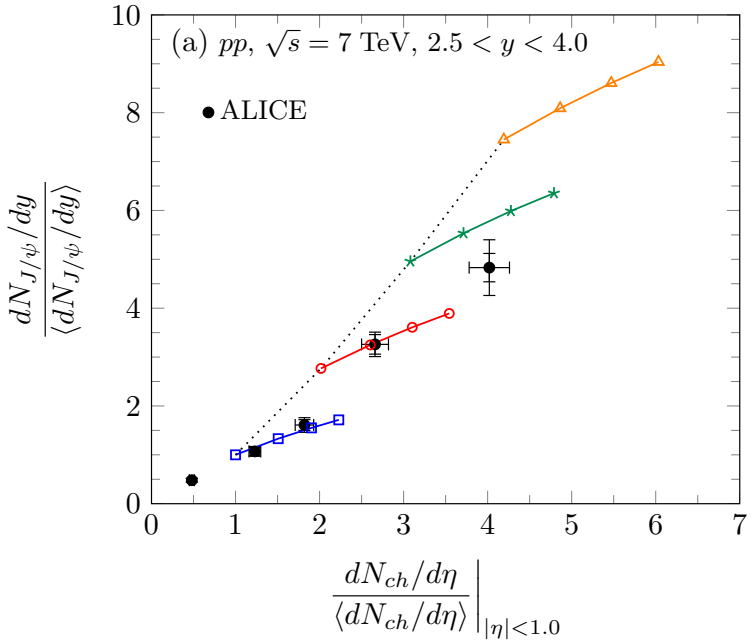
4 Summary

Summary

- "Event engineered" Heavy Flavor mesons and Quarkonia production in p+p and p+A collisions have been studied extensively 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.
- The factorization breaking effect at last stage causes strong $\psi(2S)$ nuclear suppression.
- Quantitative evaluation of R_{pA} of Υ in the CGC + Parton Shower effect is needed.
- ${}^1S_0^{[8]}$ vs ${}^3S_1^{[8]}$: New constrains on the NRQCD LDMEs for J/ψ production are found.
- N_{ch} dependence of $\psi(2S)$, Υ, and Heavy flavor decay lepton are in progress.

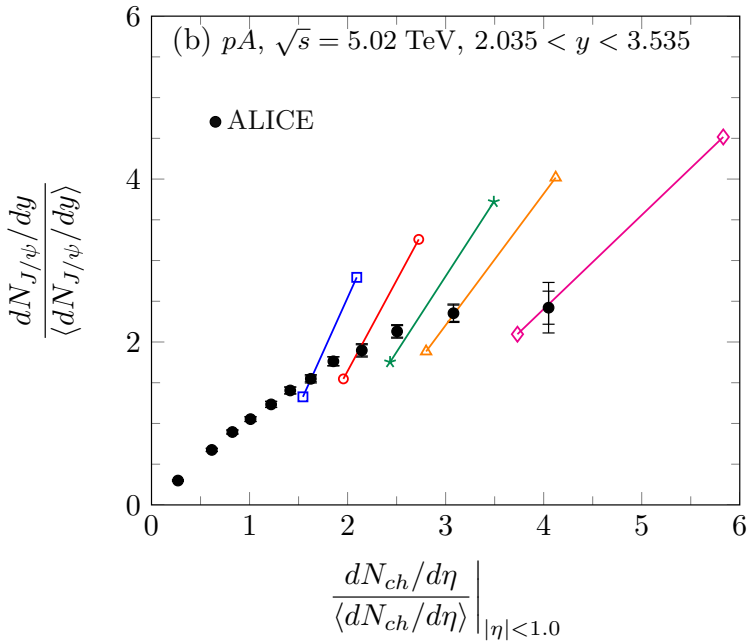
5 Backup

J/ψ vs N_{ch} at Forward Rapidity



← 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; $Q^2_{sp_1,0} = Q^2_{sp_2,0}$ 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; $Q^2_{sp_1,0} < Q^2_{sp_2,0}$.



← p+A collisions

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