Quarkonium production in high multiplicity p+p and p+A collisions

- A new test of the universality of the NRQCD LDMEs -

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Ma, Tribedy, Venugopalan, KW, PRD**98**, 074025 (2018).
Ma, Tribedy, Venugopalan, KW, NPA**982**, 747 (2019).

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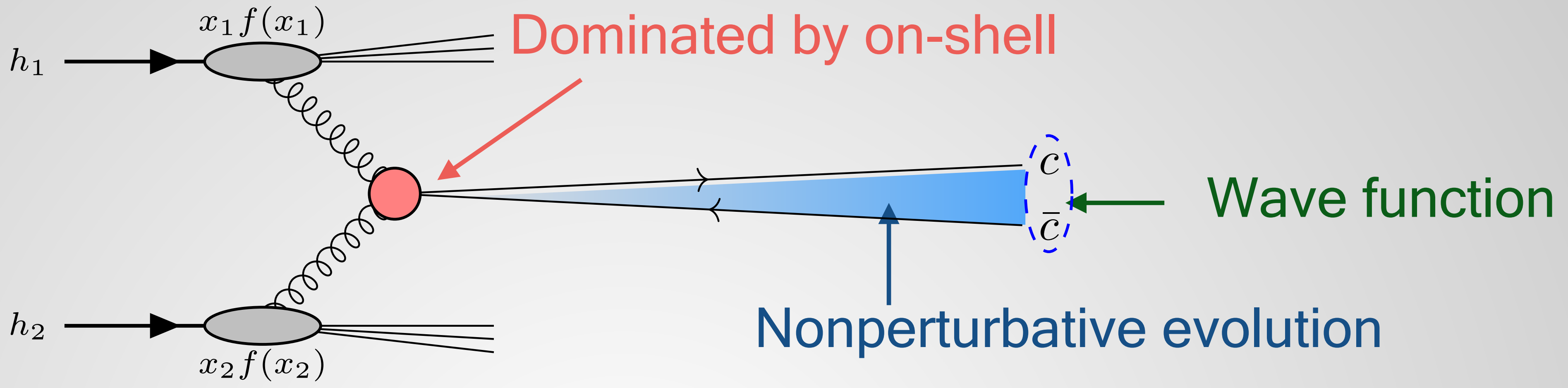
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Hadronic Quarkonium production: $h+h\rightarrow\psi+X$



Dominated by on-shell

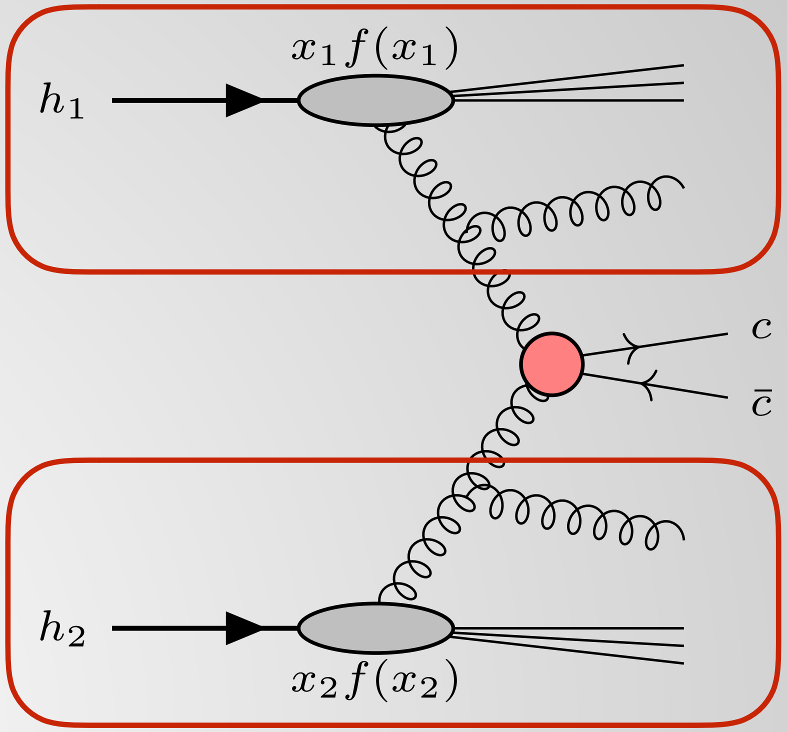
Wave function

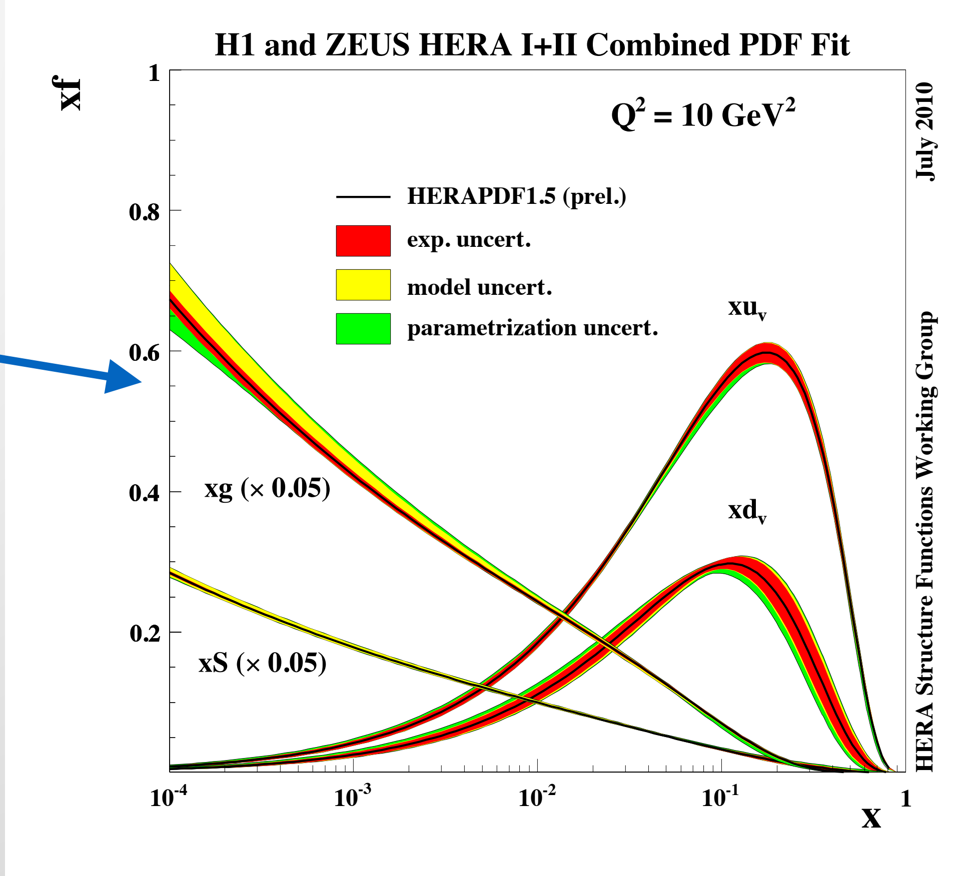
Nonperturbative evolution

- Two steps to formulate x-section of quarkonium production.
- (i) Quarkonium production of high pt: Collinear factorization since one scale problem (pt>>m).
- (ii) A bound quarkonium formation: Model dependent approach. CEM vs CSM vs COM (NRQCD)…
- NRQCD factorization approach has been successful in describing the pt-spectra.
- Issue: the relative weight of the LDMEs is unclear.

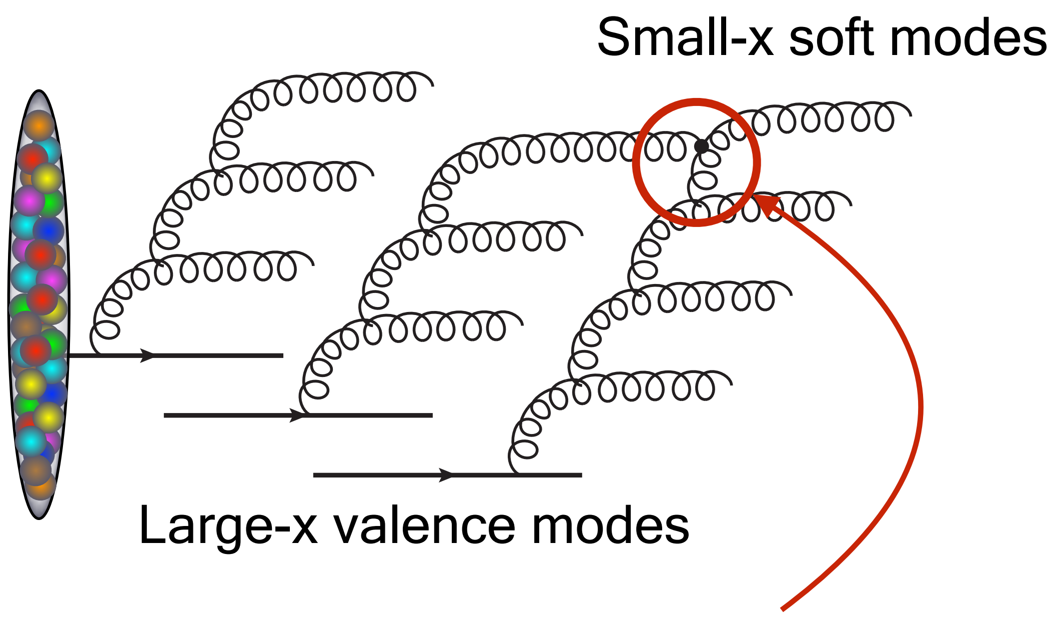
Hadronic Quarkonium production of low pt

- If pt<<M, large Sudakov logs $\alpha_s \ln^2(M^2/p_t^2)$ come in psi’s x-section: gluon shower effect.
- For J/psi of 2m∼3GeV, non-perturbative shower effect should be more essential.
- At collider energies, gluon’s density in a hadron at Small Bjorken-x grows rapidly. $x_2 = Me^{-Y}/\sqrt{s} \sim 10^{-5}$@LHC
- Hadrons are over occupied by soft gluons at small-x limit. Nonlinear gluon recombination can happen, and twist-2 contributions are not sufficient.

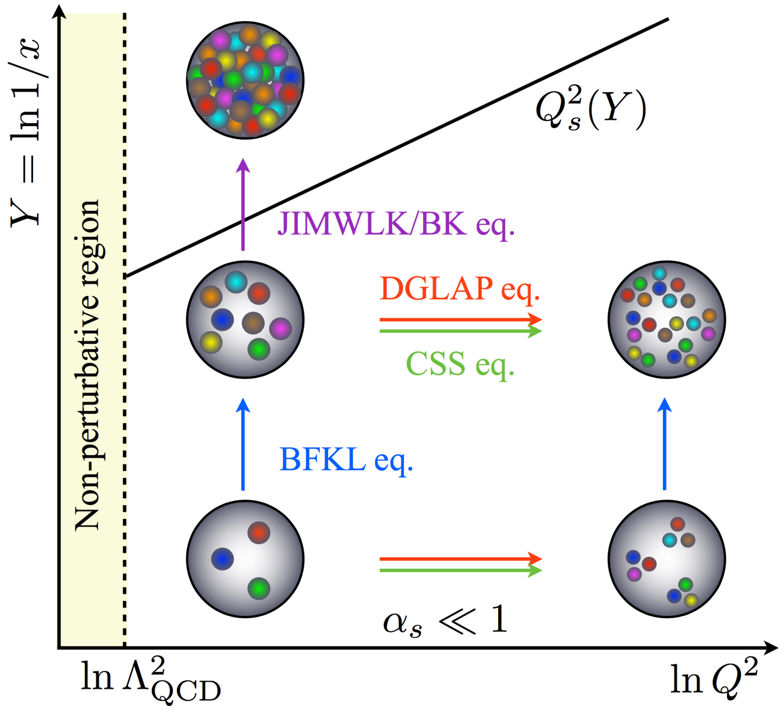




Color-Glass-Condensate (CGC) EFT



BFKL+Recombination = BK-JIMWLK



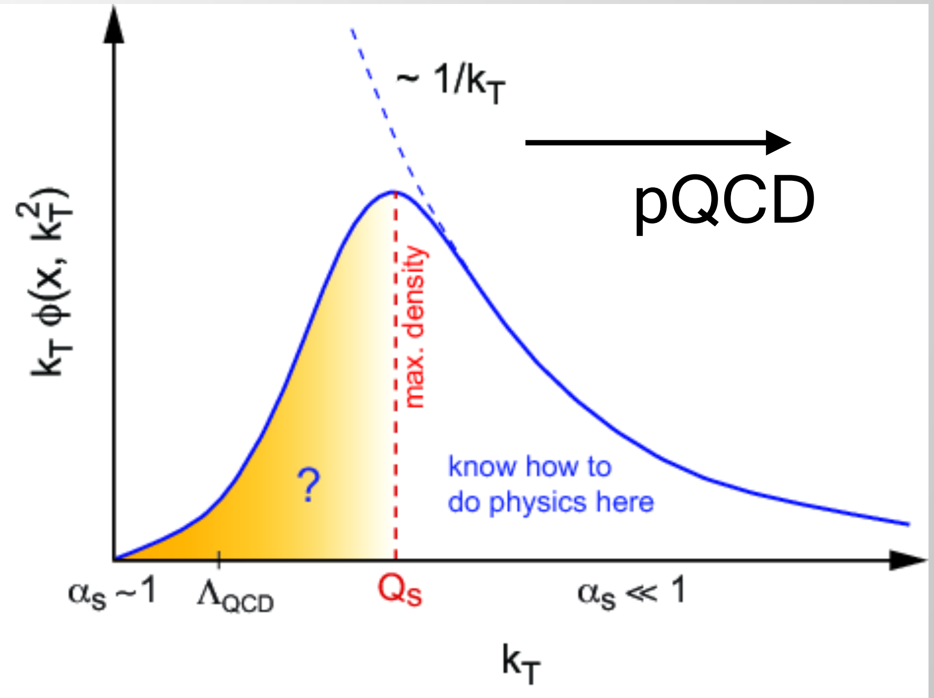
Saturation scale

Gribov, Levin, Ryskin (1983)
See also, Mueller, Qiu (1986)

$$Q_s^2 = \frac{\alpha_s N_c}{S_\perp} x f_g(x) \propto A^{1/3} \frac{1}{x^\lambda} \gg \Lambda^2_{\rm QCD}$$

Charm can be softer than Qs:

$$m_c \lesssim Q_s \sim p_\perp$$



- Assumption: BFKL evolution >> DGLAP evolution when μ~2m.

Quarkonium production in the CGC framework

NRQCD factorization

Fujii, Gelis, Venugopalan (2006)
Kang, Ma, Venugopalan (2013), …

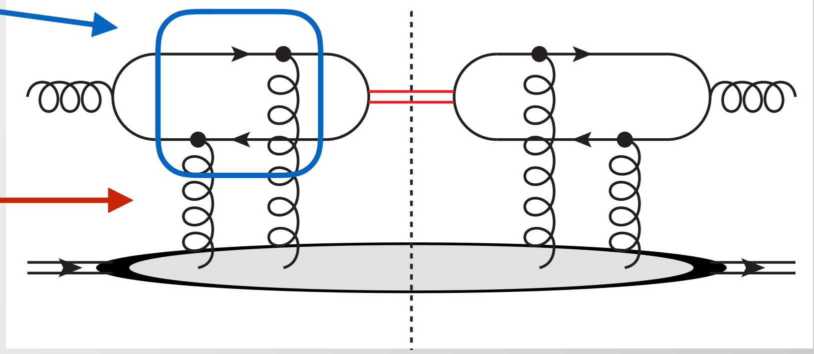
$$\frac{d\sigma^{\psi}}{dy\,dp_\perp^2} = \sum_{\kappa} \frac{d\hat{\sigma}^{\kappa}_{c\bar{c}}}{dy\,dp_\perp^2} \times \boxed{\langle \mathcal{O}^{\psi}_{\kappa} \rangle}$$

LDMEs fitted by data on high-pt quarkonium in the collinearly NRQCD factorization.

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

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

Color&Spin projection



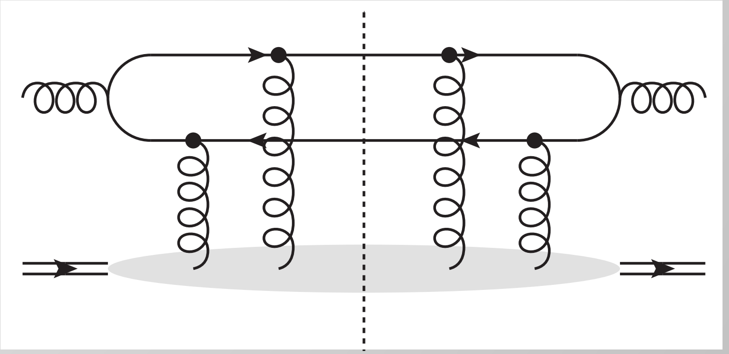
Wilson line with Eikonal approximation

$$U(x_\perp) \equiv \mathcal{P}_+ \exp\left[ig\int dx^+ t^a A_a^-(x^+,x_\perp)\right] = 1 + ig\int dx^+ t^a A_a^-(x^+,x_\perp) + \cdots$$

Color Evaporation Model

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

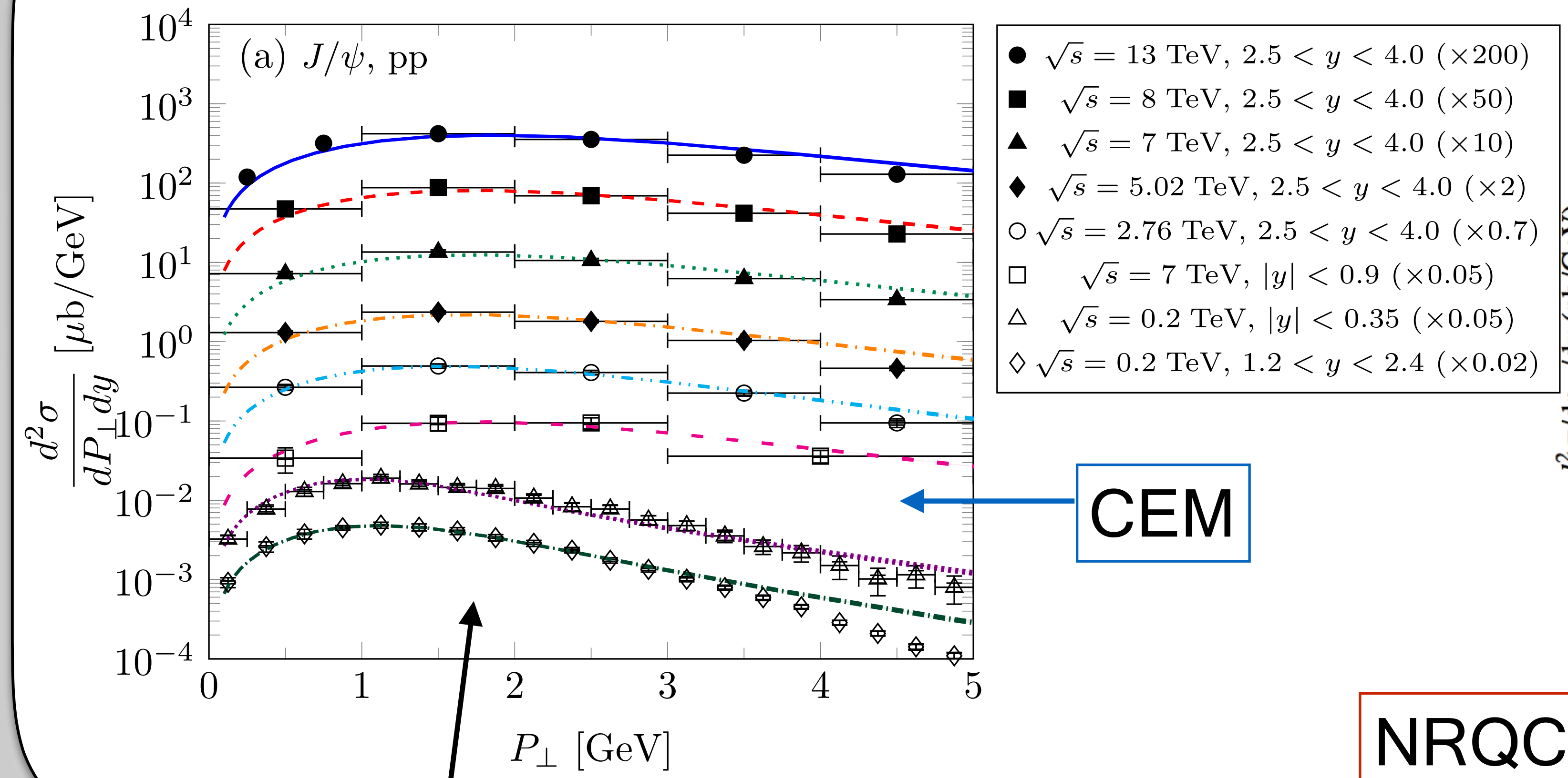
Color&Spin Sum



- The CGC should reproduce kt-factorization with the BFKL in the dilute limit.
- Nuclear dependence is universal in the large-Nc limit: Two dipoles for the target nucleus.

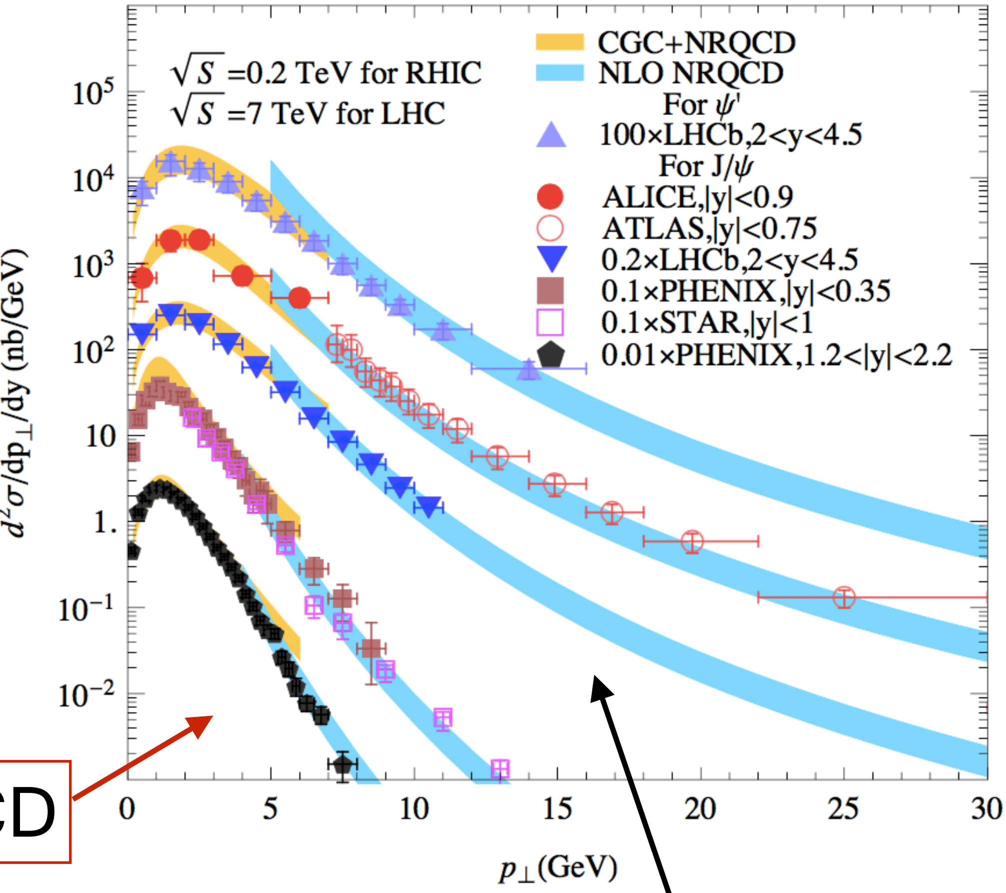
J/psi in MB events

Ma, Venugopalan, KW, Zhang (2017)



CEM

Ma, Venugopalan (2014)



NRQCD

Point-by-point fit with $F_{c\bar{c}\to J/\psi}$

The CGC gives a good parametrization of the transverse momentum dependent (TMD) gluon distribution function at small-x.

$$\langle \mathcal{O}^{J/\psi}[^1S_0^{[8]}]\rangle = 0.089 \pm 0.0098\,\mathrm{GeV}^3$$

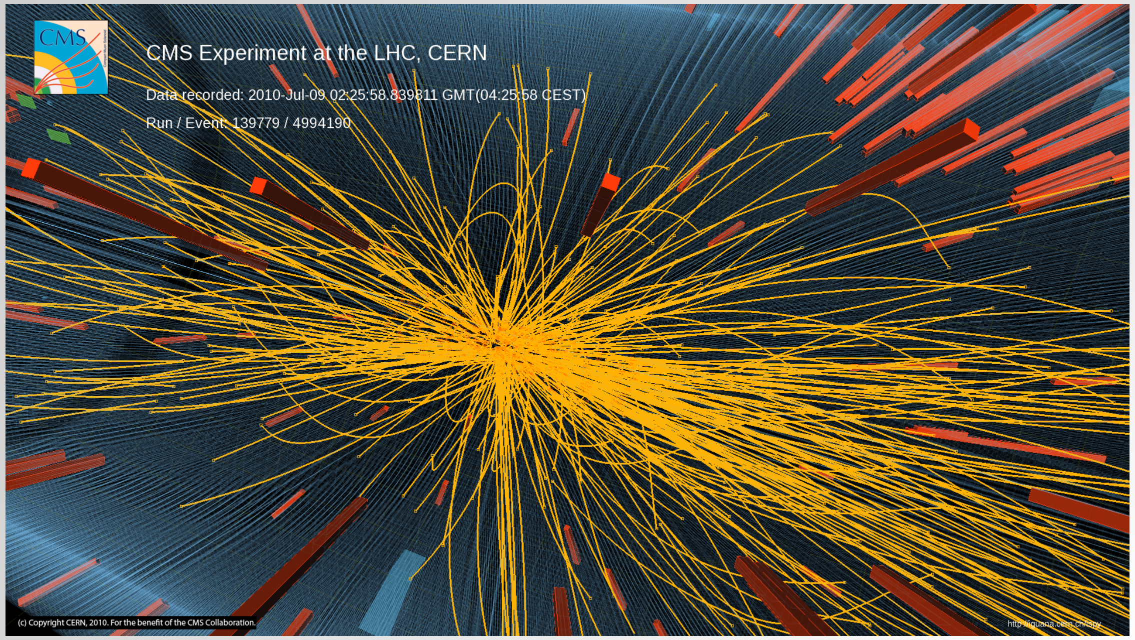
$$\langle \mathcal{O}^{J/\psi}[^3S_1^{[8]}]\rangle = 0.0030 \pm 0.0012\,\mathrm{GeV}^3$$

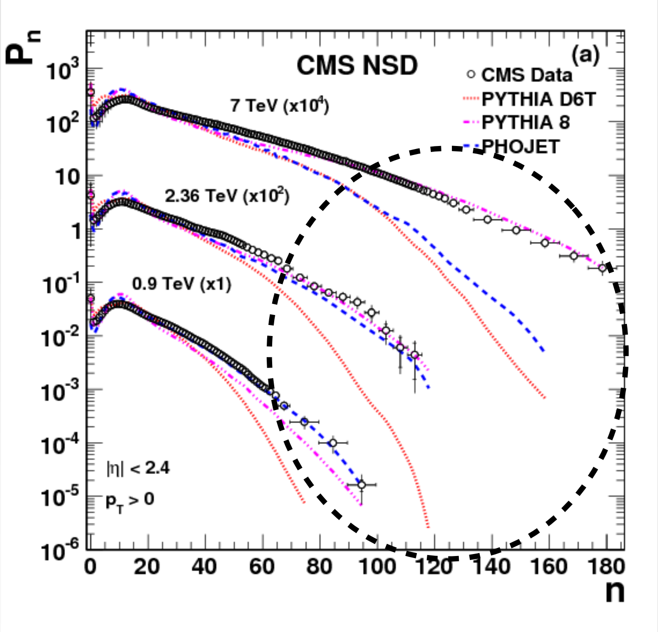
$$\langle \mathcal{O}^{J/\psi}[^3P_0^{[8]}]\rangle/m_c^2 = 0.0056 \pm 0.0021\,\mathrm{GeV}^3$$

Fitted by high pt prompt J/psi data at Tevatron

Chao, Ma, Shao, Wang, Zhang (2012).

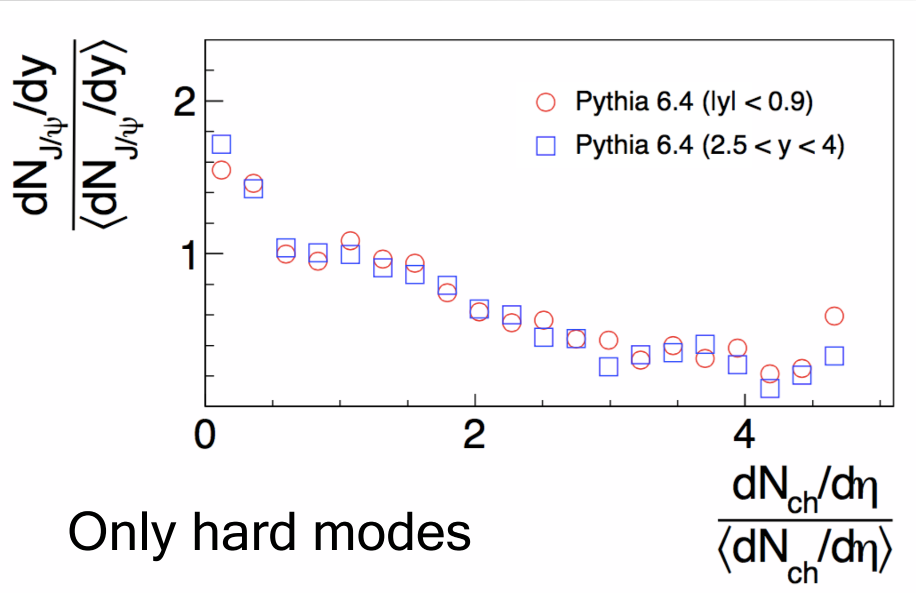
High multiplicity events





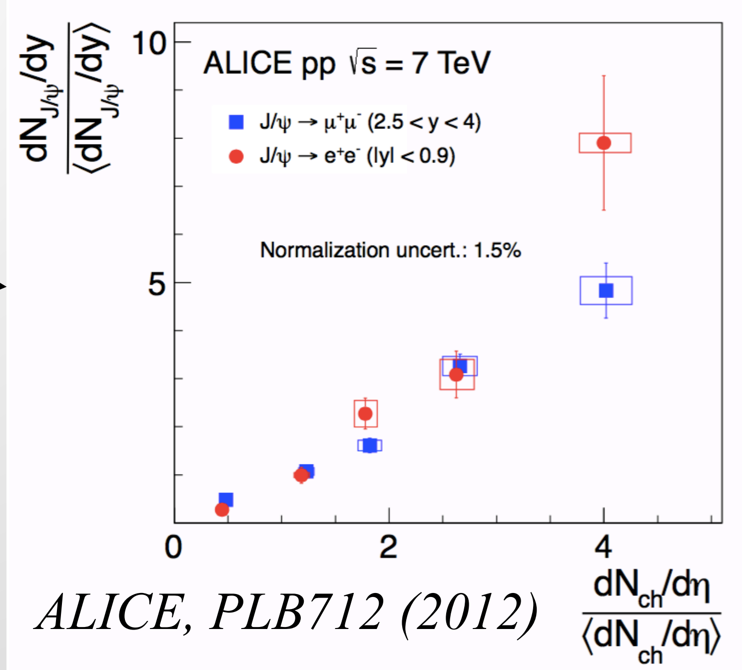
$$P_{\mathrm{MB}} \gg P_{\mathrm{HM}}$$

Extreme rare phenomena: New test grounds for Quarkonium production.



Only hard modes

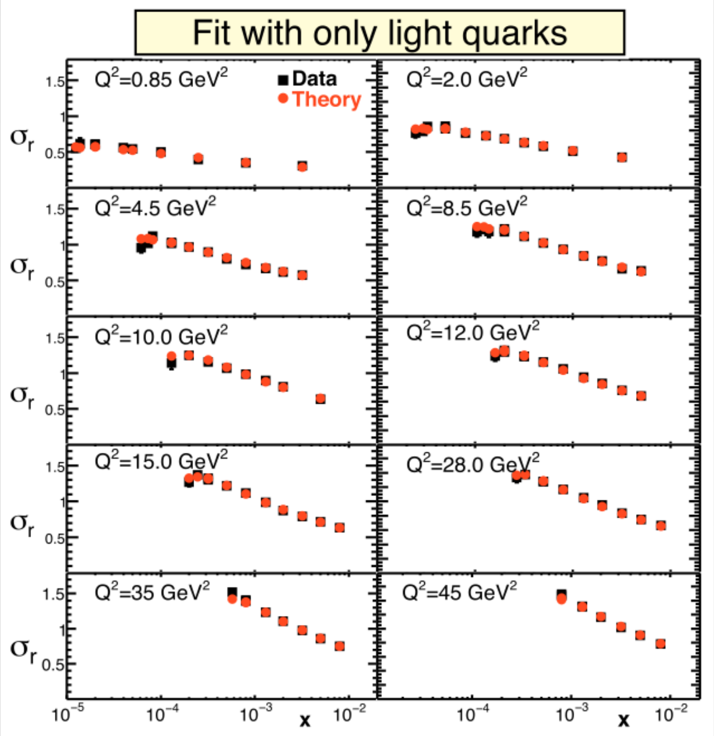
Soft modes?



ALICE, PLB712 (2012)

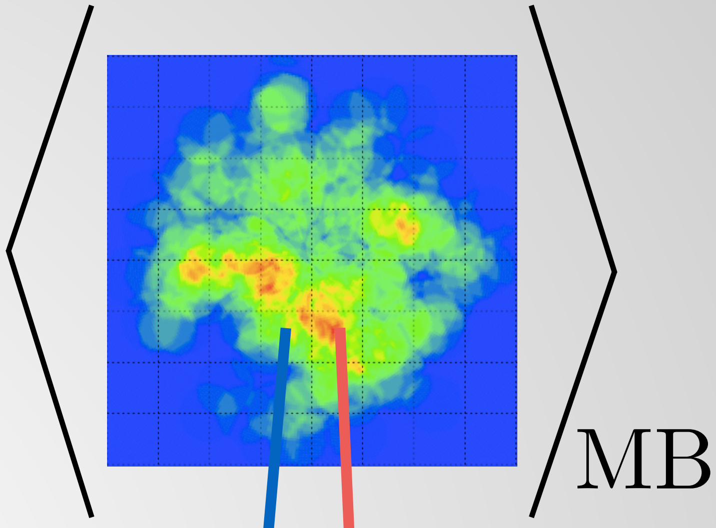
What is the dynamics of soft gluon modes in high multiplicity events?

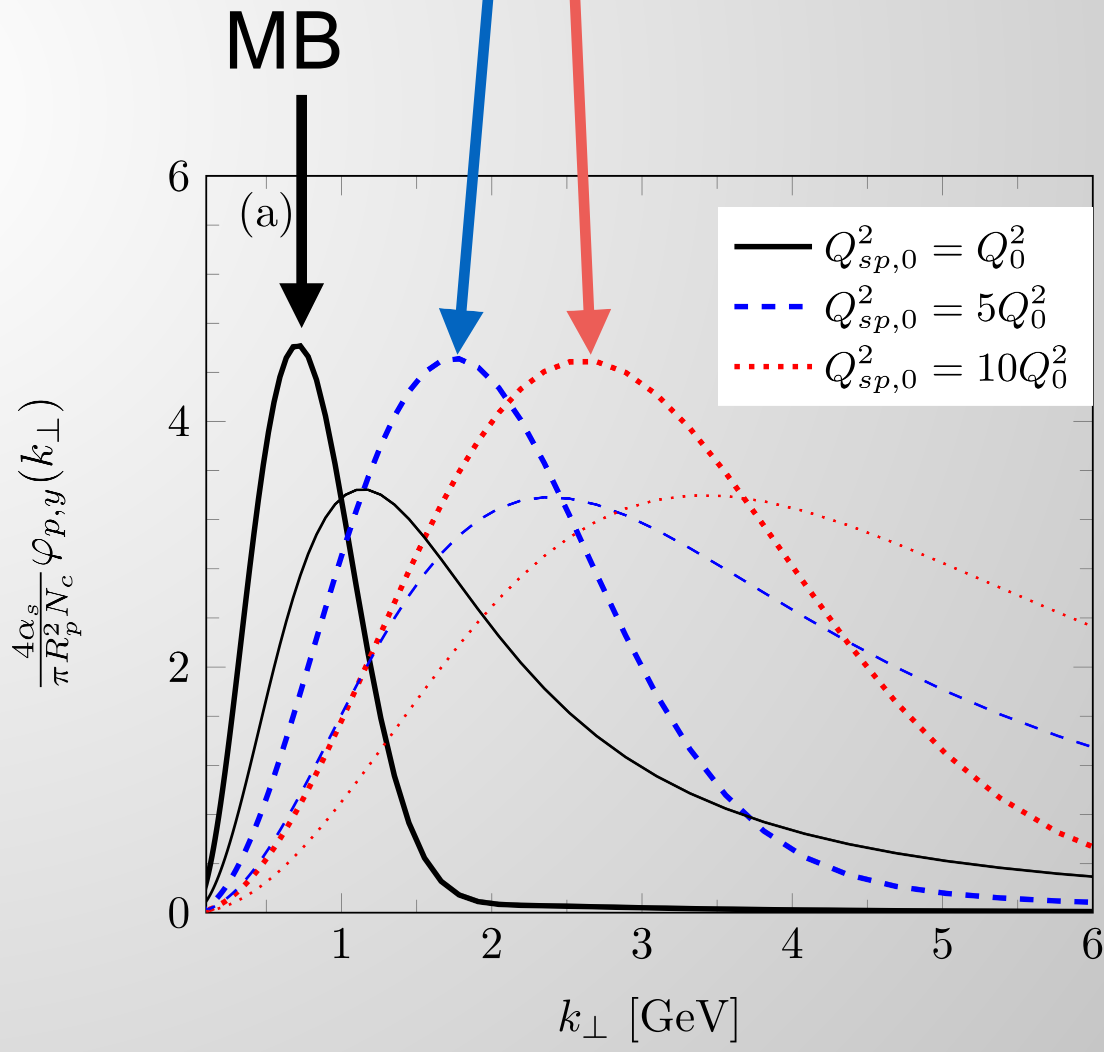
Event-by-Event parton configurations



DIS global data fitting
below x=0.01

*Albacete et al., EPJC**71** (2011)*





Gluon fields behave like classical: $A \sim 1/g$

$$\frac{dN_{ch}}{dy} \sim \int d^2b_\perp d^2k_\perp \langle AA\rangle \sim \frac{S_\perp Q_s^2}{\alpha_s}$$

Rare lumpy partons configuration
↔ large Qs ↔ High multiplicity

The CGC EFT gives a natural way
to achieve HM phenomena.

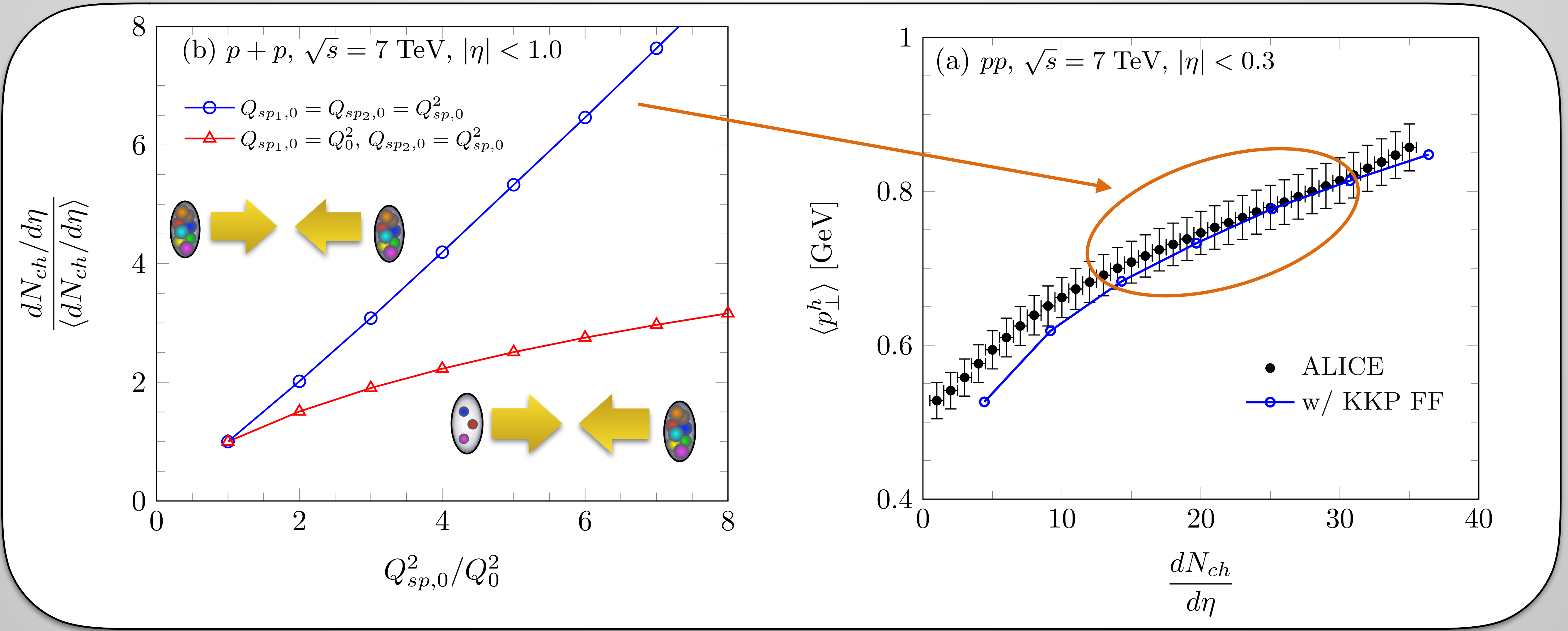
Charged hadron multiplicity in kt-factorization

Ma, Venugopalan, Tribedy, KW (2018)

Normalization factors

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

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

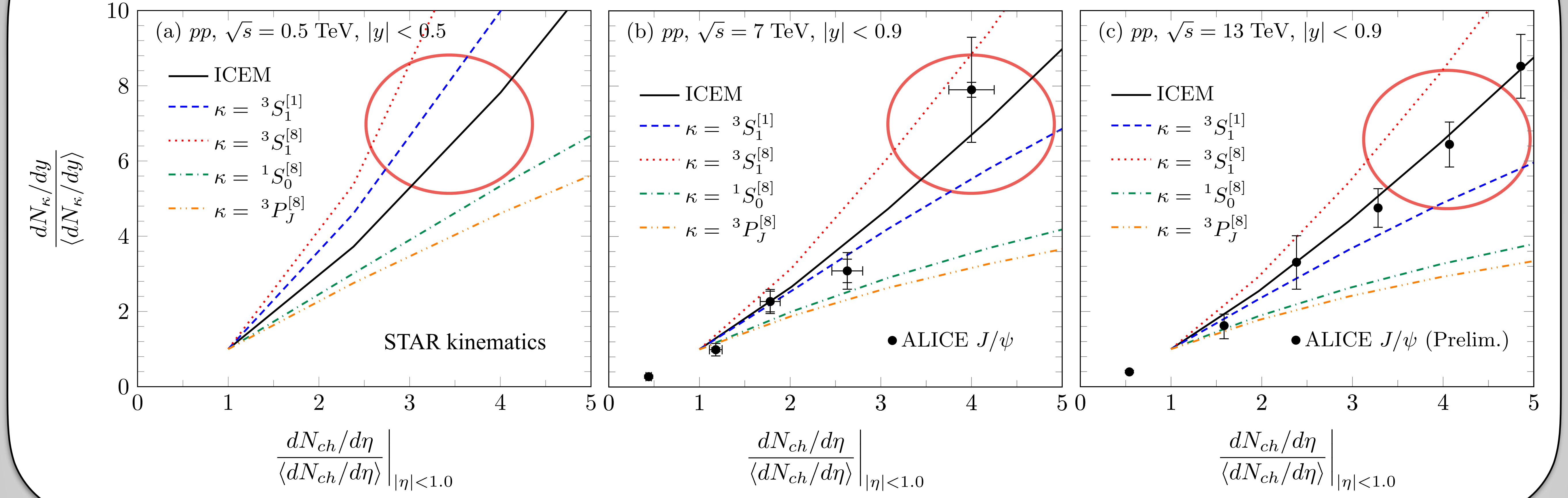


Similar pt-broadening is seen in high multiplicity p+A collisions.

Channel-by-Channel: New insight into the LDMEs

CGC+NRQCD

Ma, Tribedy, Venugopalan, KW (2018) (2019)



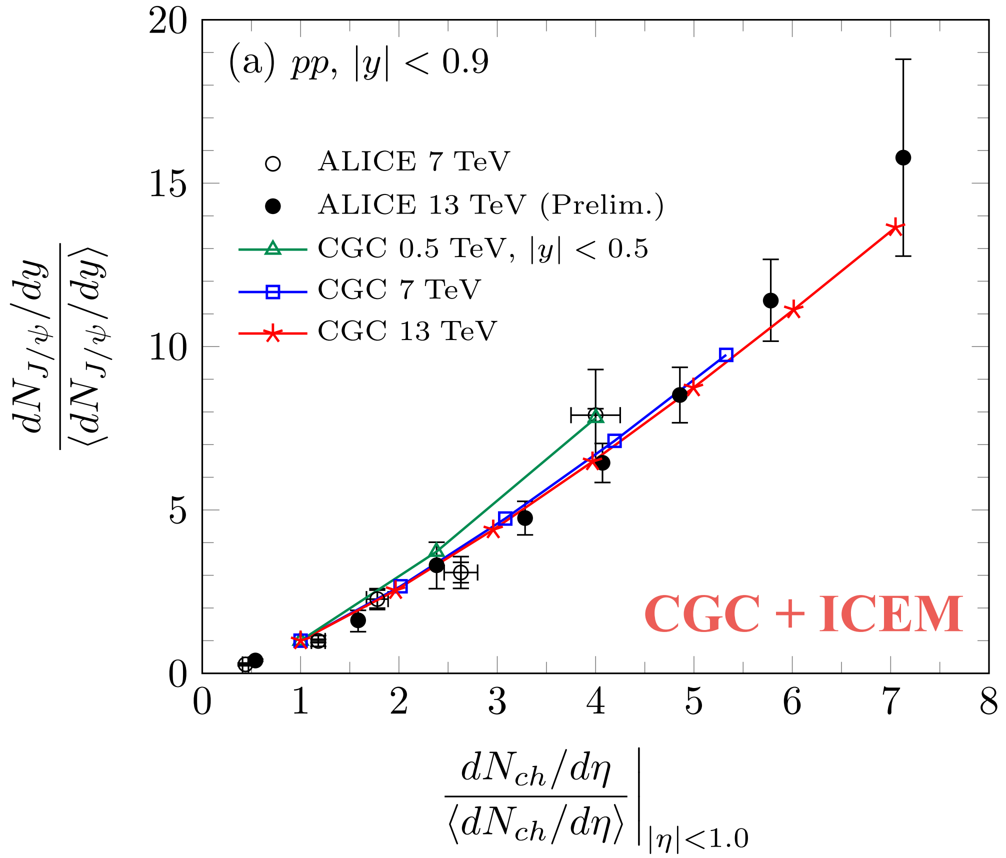
- ${}^3S_1$ octet channel might have a large relative weight in HM events compared to MB → <u>CEM may work from MB to HM.</u>
- Consistent with the universality requirement from BELLE e^+e^- data:

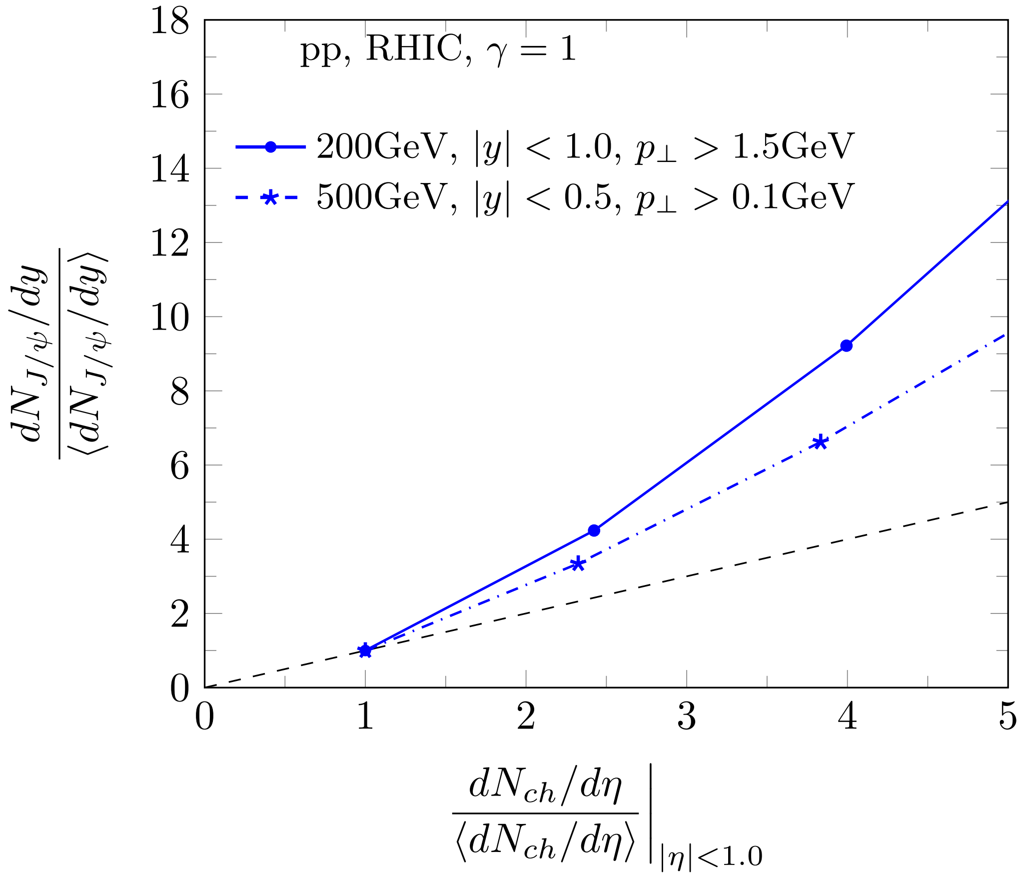
$$\langle \mathcal{O}^{J/\psi}[{}^1S_0^{[8]}]\rangle + 4.0\langle \mathcal{O}^{J/\psi}[{}^3P_0^{[8]}]\rangle/m^2 < 2.0 \pm 0.6 \times 10^{-2}\mathrm{GeV}^3$$

NLO NRQCD calculations by
*Zhang, Ma, Wang, Chao, PRD**81** (2010)*

Predictions in the CGC+CEM

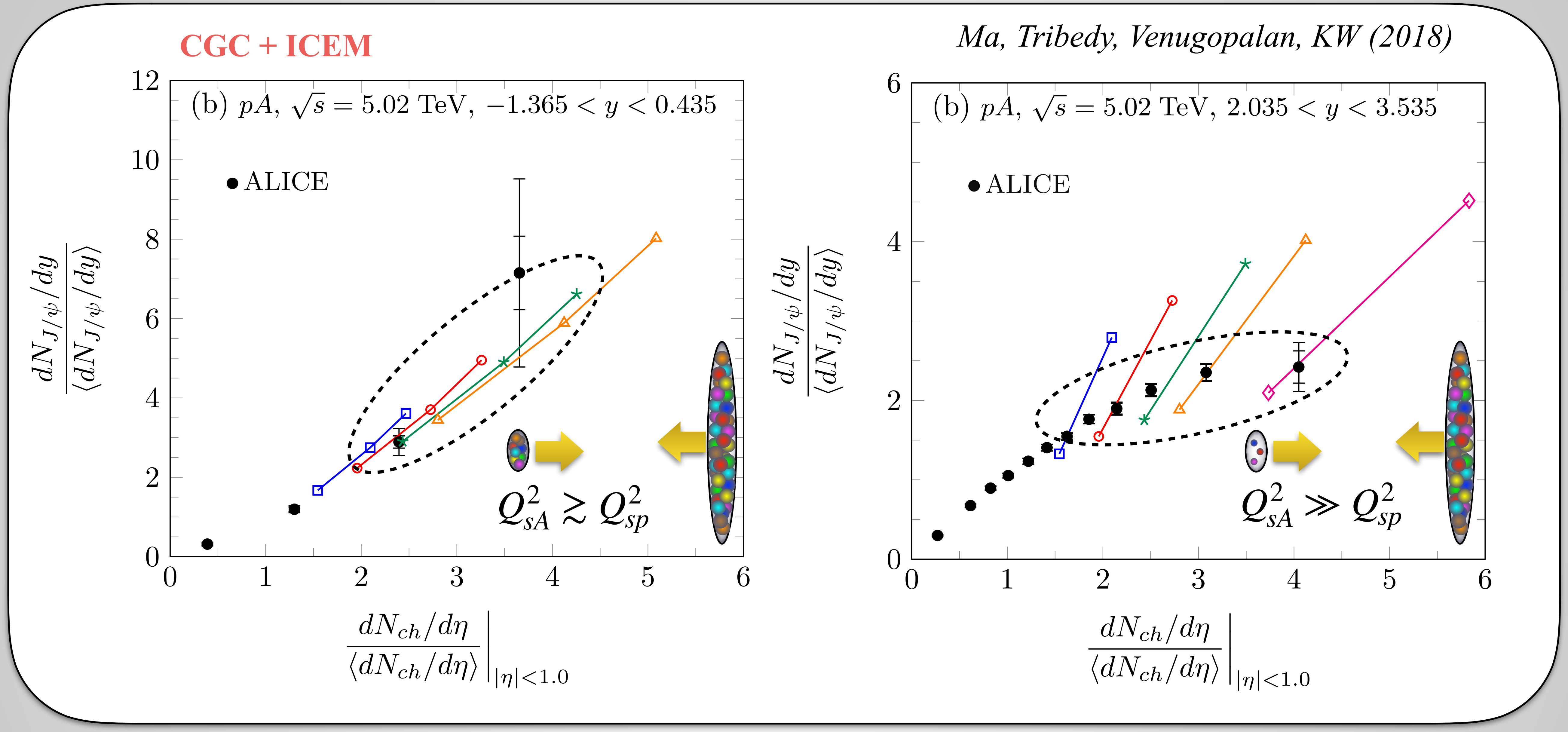
Ma, Tribedy, Venugopalan, KW (2018)





- The saturation effect at short distance plays a key role in describing data.
- Final state effect, e.g. Hydro, should be negligible in p+p collisions.
- Weak energy dependence, but pt-cut dependence is noticeable.

High multiplicity p+A collisions



Ma, Tribedy, Venugopalan, KW (2018)

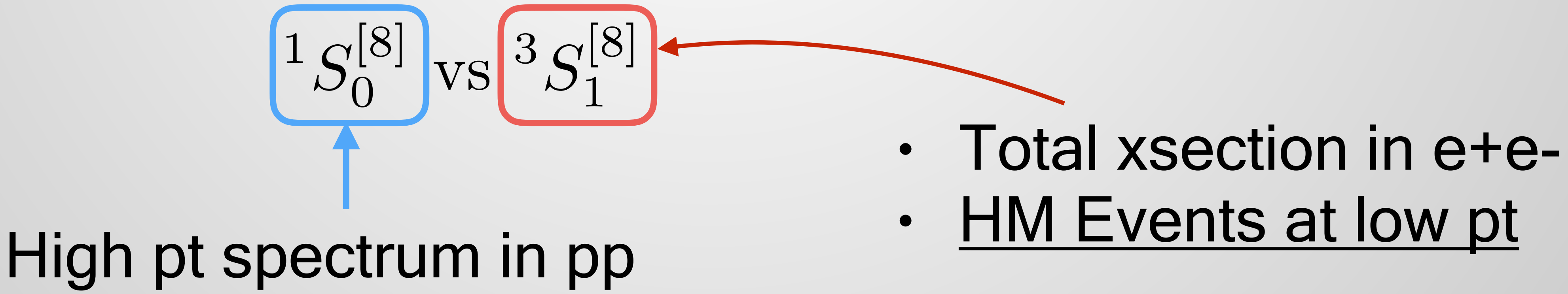
- The CGC framework is more robust at forward rapidity where J/psi probes the large fluctuation effect for the target nucleus.
- It just seems “p+p $\sim$ p+A” in high multiplicity events at mid rapidity.

Summary

- The CGC EFT can give a good parametrization of the gluon TMD at small-x because μ∼2m∼pt.

- The CGC+NRQCD describes pt-distribution of J/psi production in MB events. ${}^1S_0$ octet channel is likely to have a large relative weight.

- HM events provide a new test for the LDMEs: ${}^3S_1$ octet channel might have a large relative weight compared to MB events.



$\boxed{{}^1S_0^{[8]}}$ vs $\boxed{{}^3S_1^{[8]}}$

High pt spectrum in pp

- Total xsection in e+e-
- HM Events at low pt

Outlook

Issue to be solved

- b-quark decay contribution (non-prompt production) can be an important contaminant for inclusive J/psi production in HM.

Other observables

✅ D-meson: Results are similar to J/psi. *See Ma, Tribedy, Venugopalan, KW (2018).*

🔄 Psi(2S): Final state effect, e.g. Comover effect, should be important. *Work in progress and See also Ma, Venugopalan, KW, Zhang (2017).*

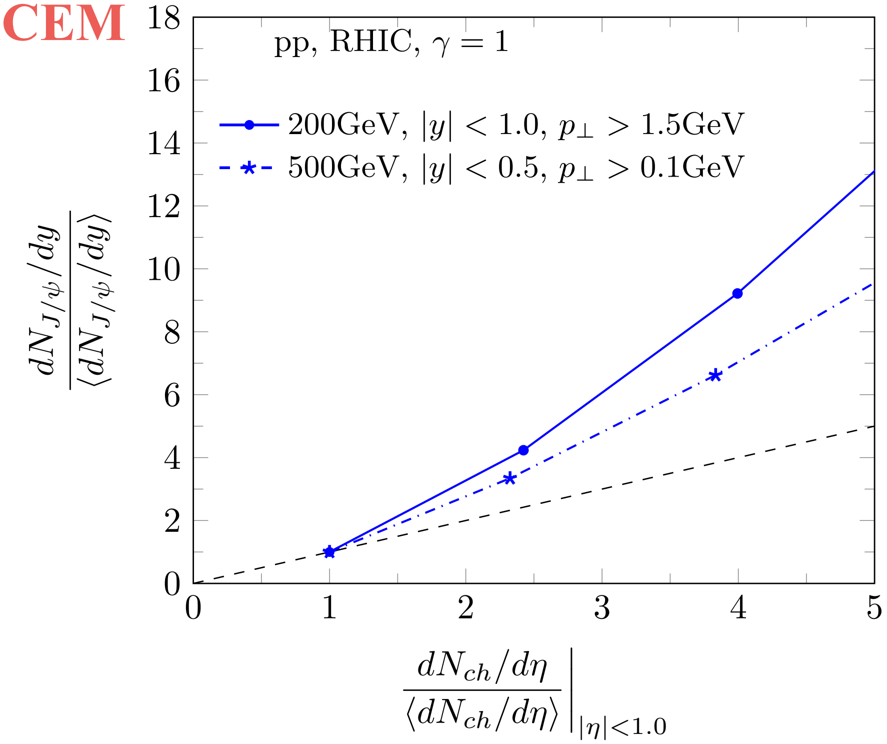
🔄 Upsilon(nS): Complicated than J/psi because two scale problem. *Work in progress and See also Watanabe, Xiao (2015).*

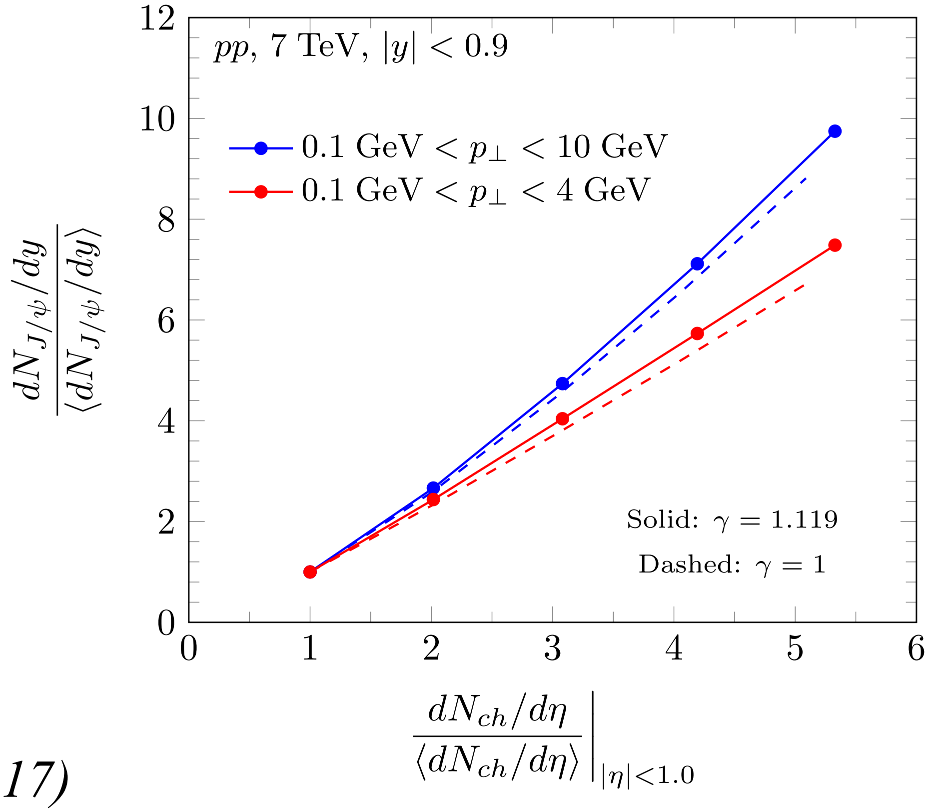
Thank you!

Backup

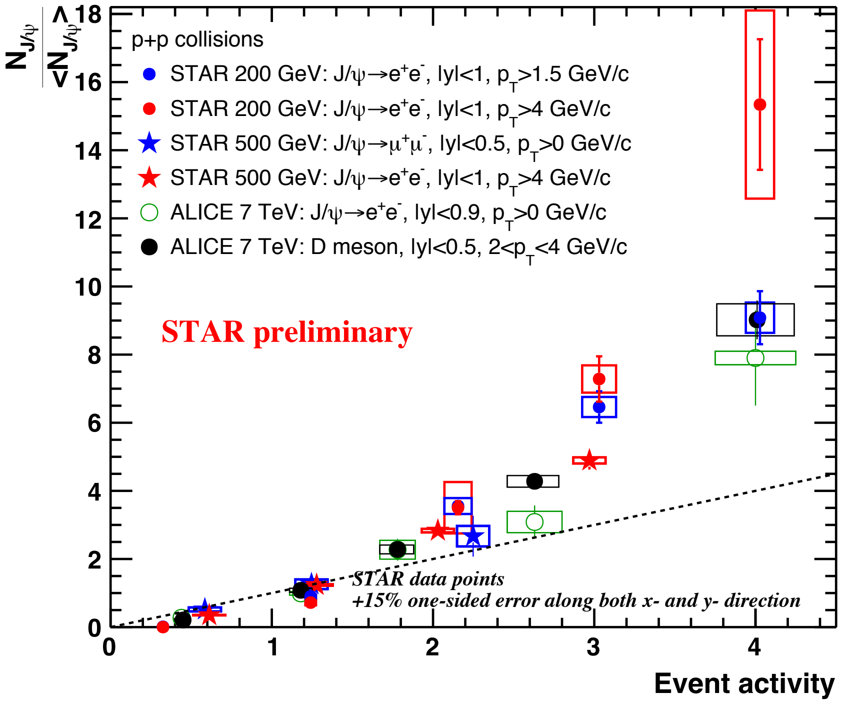
pt-cut dependence

CGC + ICEM





*STAR Collaboration, EPJ**138**, 01017 (2017)*



CEM vs ICEM vs NRQCD

CEM

Fujii, Gelis, Venugopalan, (2006)

$$\frac{d\sigma_{Q\bar{Q}}}{d^2p_{Q\perp}d^2q_{\bar{Q}\perp}dy_Q dy_{\bar{Q}}} = \frac{\alpha_s N_c^2 S_\perp}{2(2\pi)^{10} d_A}\int_{k_{2\perp},k_\perp}\frac{\varphi_{p,y_p}(k_{1\perp})}{k_{1\perp}^2}\mathcal{N}_Y(k_\perp)\mathcal{N}_Y(k_{2\perp}-k_\perp)\;\Xi$$

$$\frac{d\sigma_\psi}{d^2p_\perp dy} = F_{c\bar{c}\to\psi}\int_{2m_c}^{2m_D} dM\,\frac{d\sigma_{c\bar{c}}}{dM\,d^2p_\perp dy}$$

Improved CEM

Ma, Vogt, PRD94 (2016)

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

Gluon radiation during hadronization

NRQCD

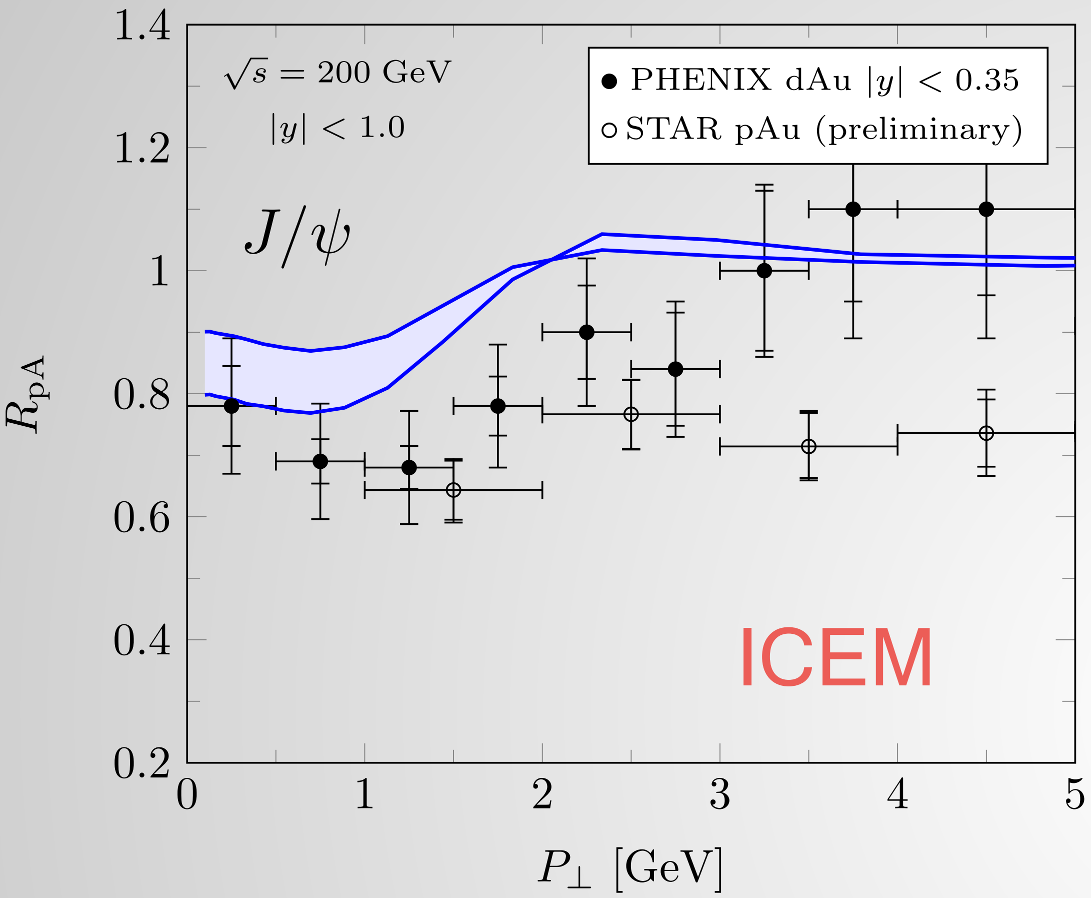
Kang, Ma, Venugopalan, (2013)

$$\frac{d\sigma^\psi}{dy dp_\perp^2} = \sum_\kappa \frac{d\hat{\sigma}^\kappa_{c\bar{c}}}{dy dp_\perp^2}\times\langle\mathcal{O}^\psi_\kappa\rangle$$

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

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

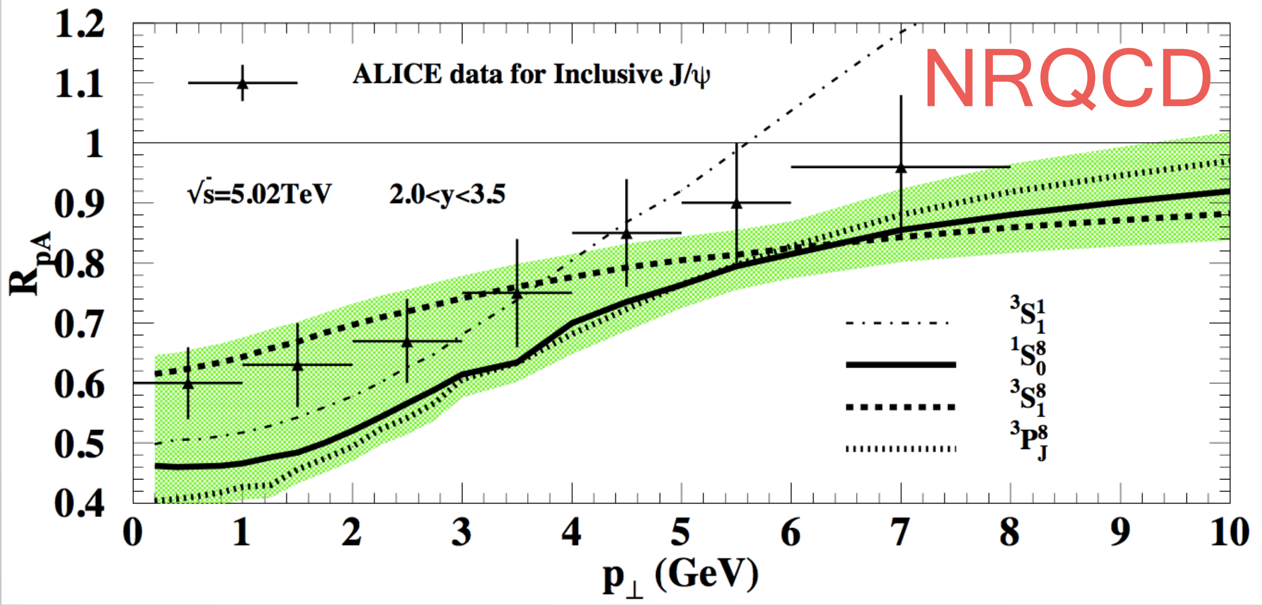
RpA in the NRQCD, ICEM

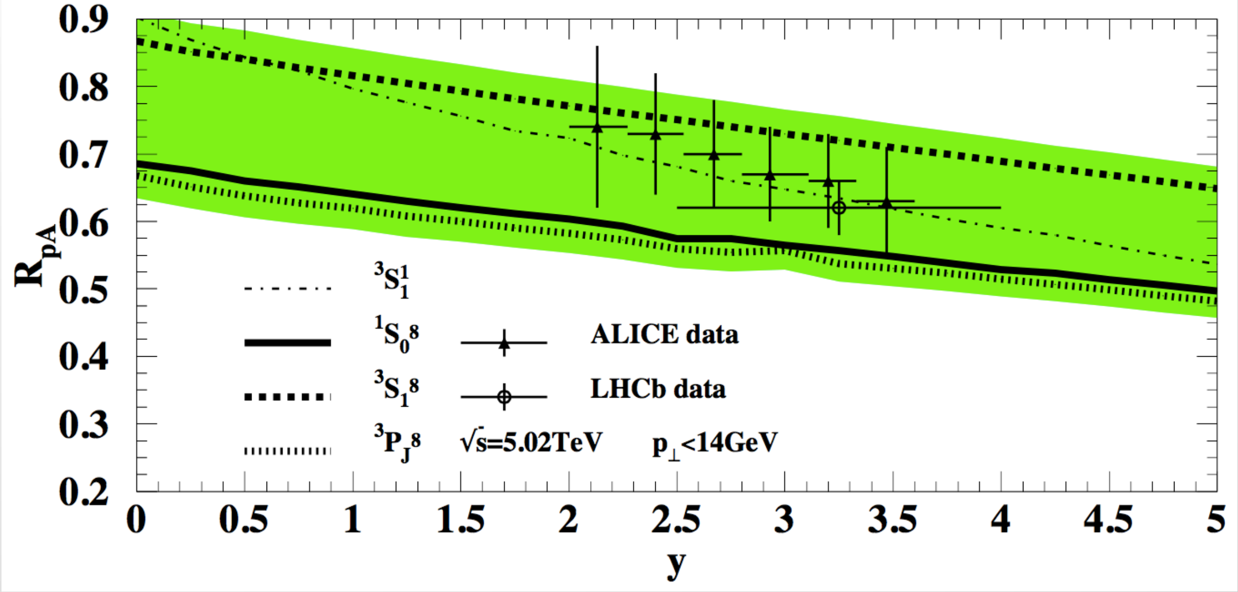


Fujii, KW (2013)
Ma, Venugopalan, KW, Zhang (2017)

Cronin like peak disappears due to the running coupling BK evolution effect.

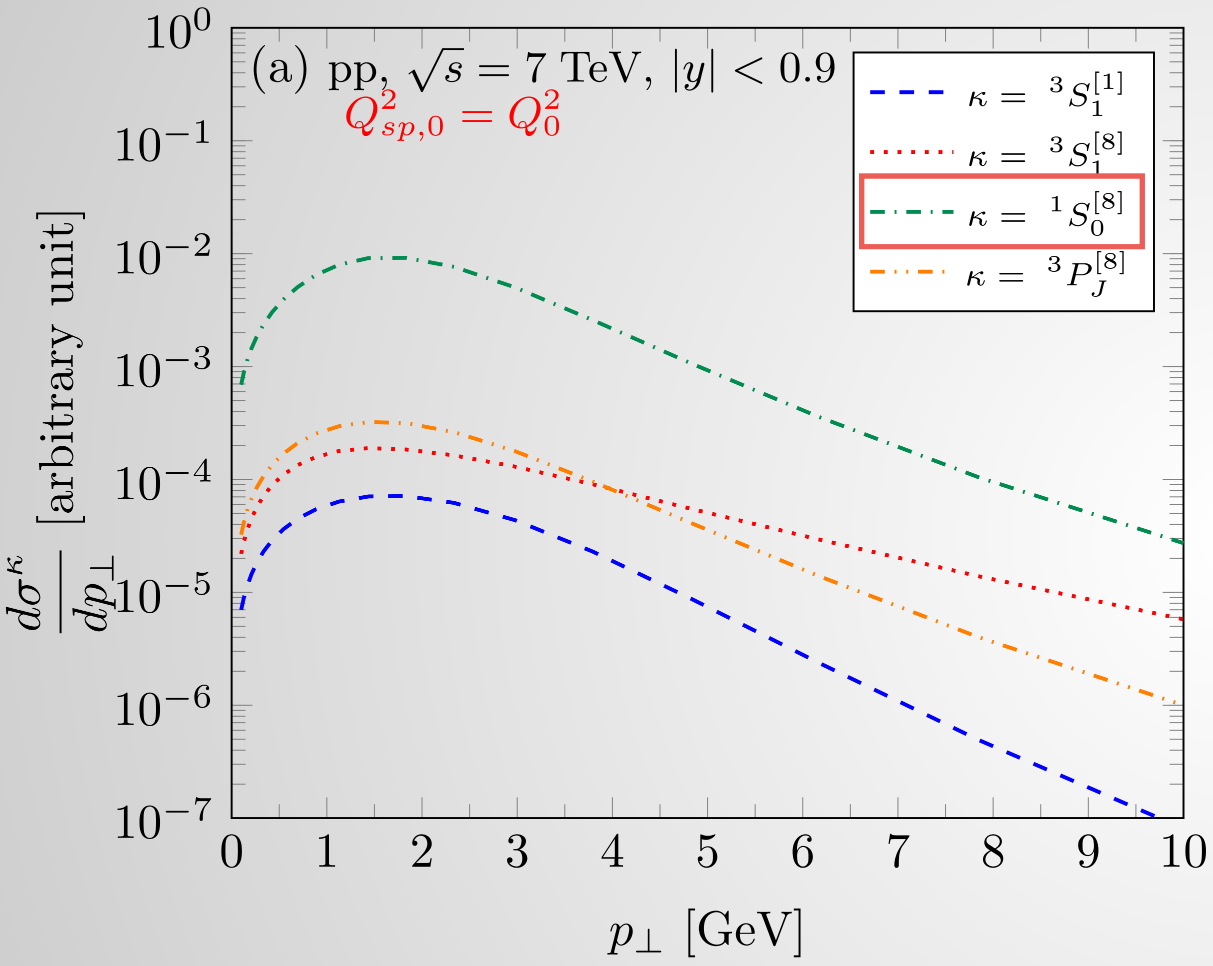
Ma, Venugopalan, Zhang (2015)



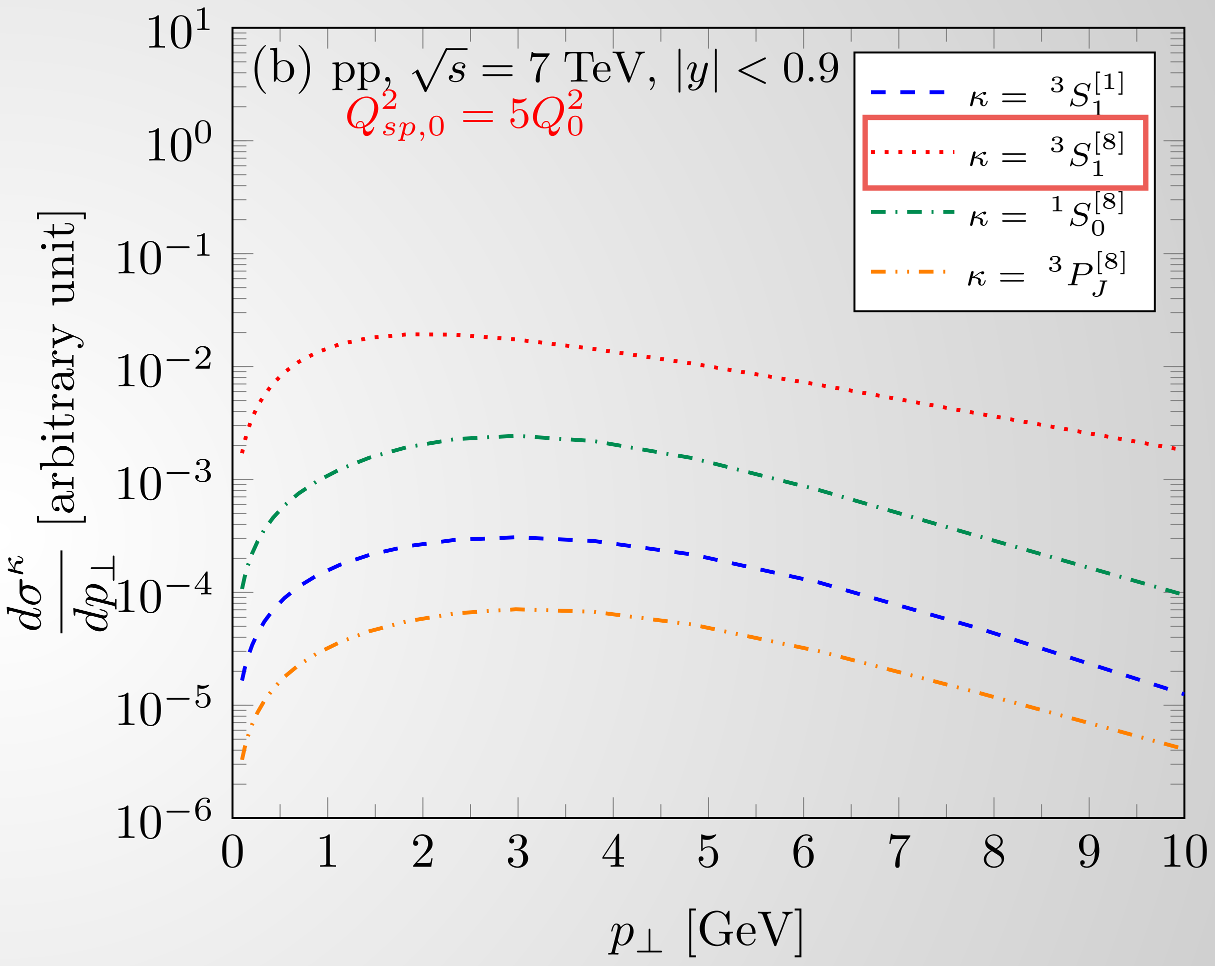


MB vs High Multiplicity events

Ma, Tribedy, Venugopalan, KW (2018)



MB events



HM events

NRQCD LDMEs

Fits from Tevatron, LHC, HERA, LEP:

	$\langle \mathcal{O}(^3S_1^{[1]}) \rangle$ GeV^3	$\langle \mathcal{O}(^1S_0^{[8]}) \rangle$ 10^{-2} GeV^3	$\langle \mathcal{O}(^3S_1^{[8]}) \rangle$ 10^{-2} GeV^3	$\langle \mathcal{O}(^3P_0^{[8]}) \rangle / m_c^2$ 10^{-2} GeV^3
Bodwin et al	-	9.9	1.1	0.49
Butenschoen et al	1.32	3.04	0.16	-0.30
Chao et al	1.16	8.9	0.30	0.56
Gong et al	1.16	9.7	-0.46	-0.95

Bodwin, Chung, Kim, Lee, PRL113, 022001 (2014).
Butenschoen, Kniehl, PRD84, 051501 (2011).
Chao, Ma, Shao, Wang, Zhang, PRL108, 242004 (2012).
Gong, Wan, Wang, Zhang, PRL110, 042002 (2013).

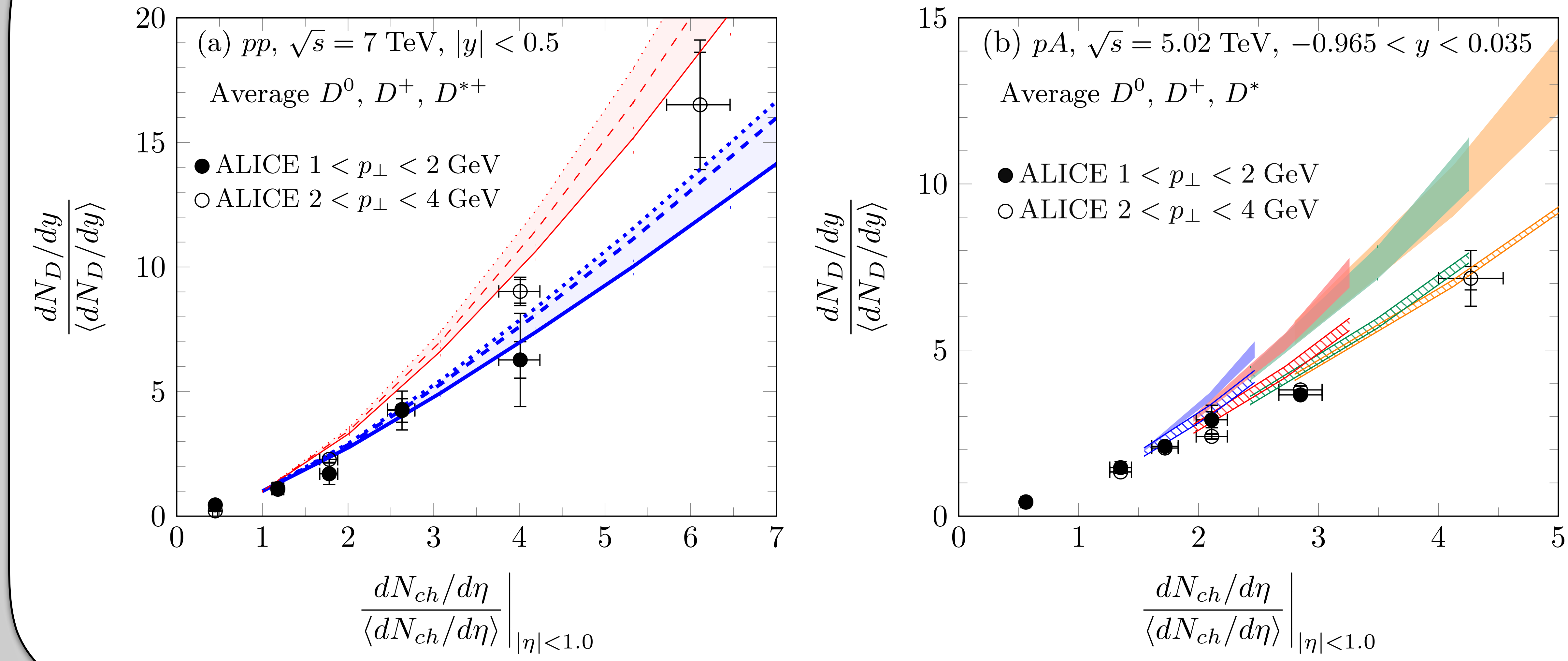
In e+e- scattering:

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

*Zhang, Ma, Wang, Chao, PRD**81** (2010)*

D mesons vs Nch

Ma, Venugopalan, Tribedy, KW (2018)



- Systematic uncertainty w.r.t. HF FF increases at large event activity but very nice agreements are found.

- The results in p+p and p+A collisions show the similar trend.