Factorization for quarkonium production in p+p and p+A collisions

Kazuhiro Watanabe

Theory Center, Jefferson Lab

11/15/2018 @ INT

U.S. DEPARTMENT OF ENERGY | Office of Science

Jefferson Lab

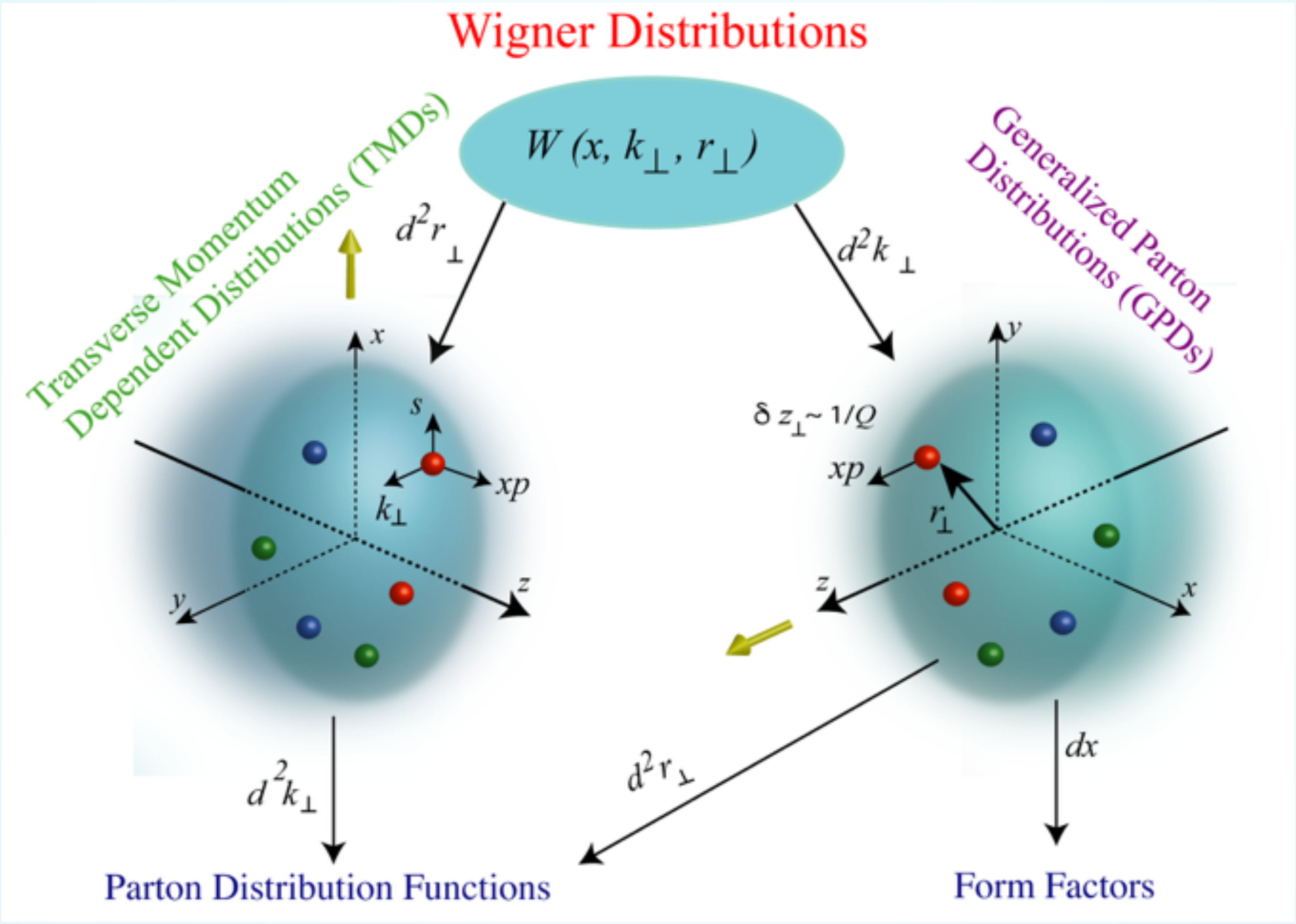
Thomas Jefferson National Accelerator Facility

3D Tomography: Key physics

4+1D

2+1D

1D

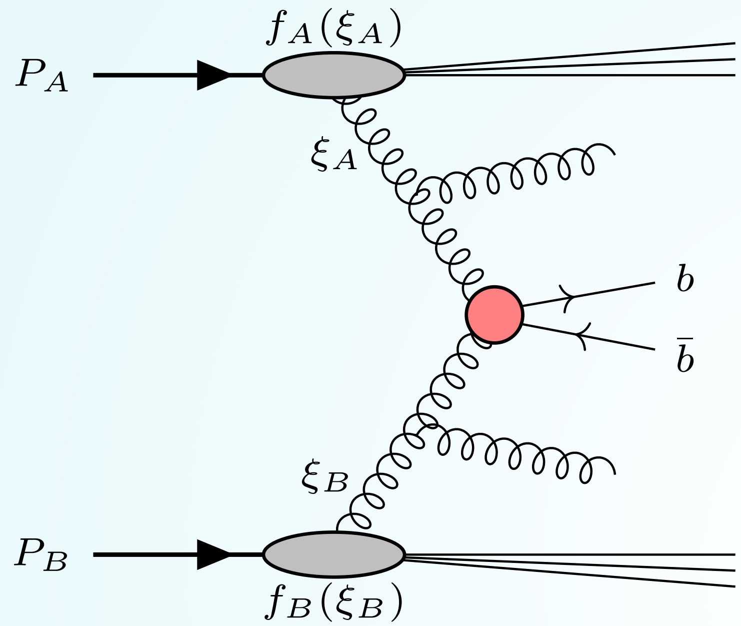


TMDs: 3D parton’s confined motion.

GPDs: 3D parton’s spatial distribution.

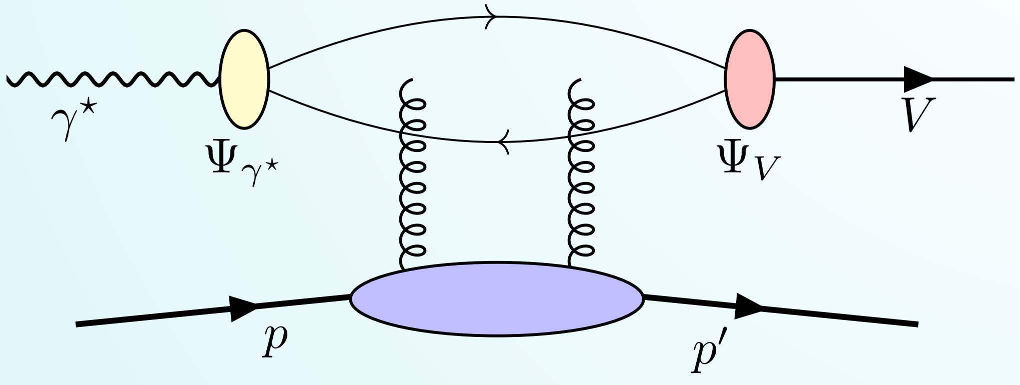
Access to 3D structures

TMD: Two hard scales required. $\Lambda_{\rm QCD} \ll p_\perp \ll Q$



- Semi-Inclusive DIS
- Drell-Yan process
- Higgs, Z/W, and Quarkonium production

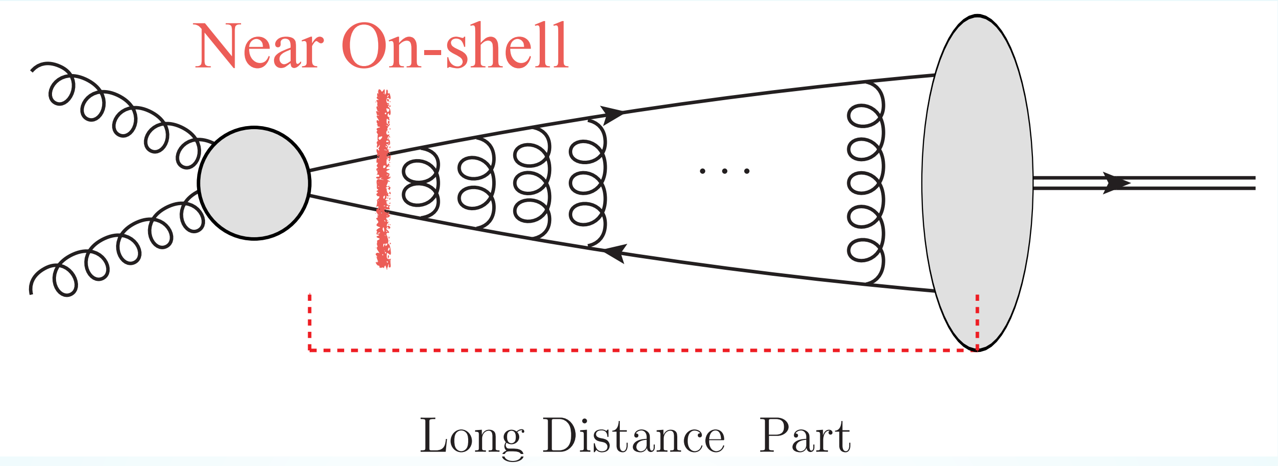
GPD: Non-forward Exclusive process



- Deeply Virtual Compton Scattering
- Exclusive Vector Meson Production

Quarkonium is a very interesting probe.

Modern approaches for quarkonium production



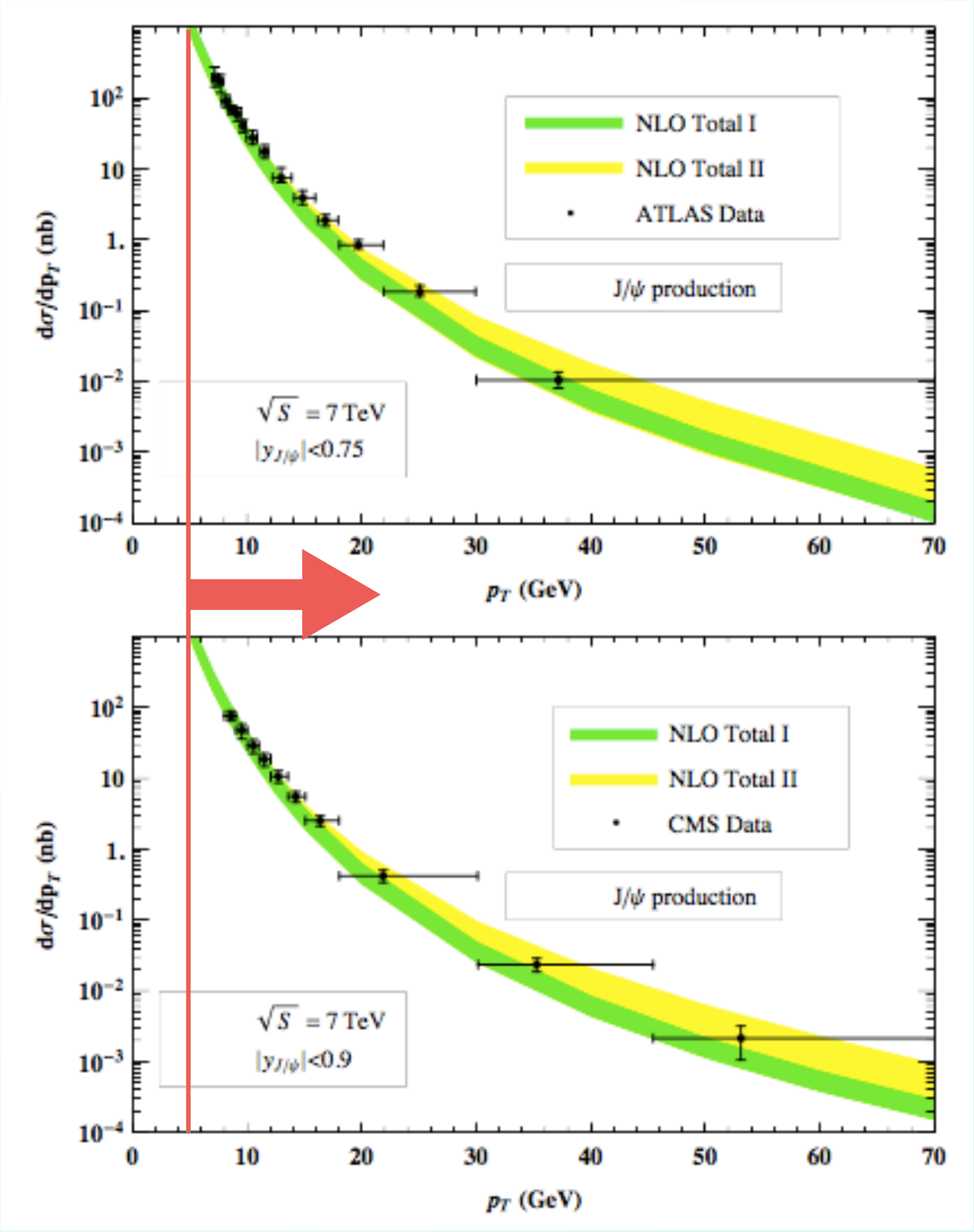
- QQbar production
  - Initial parton distribution functions
  - Hard scattering part
- Onium production
  - Color Singlet Model (CSM): Produced QQbar is in Color singlet state.
  - Color Evaporation Model (CEM): All color and spin states are summed up.
  - Non-Relativistic QCD (NRQCD): Color octet contribution, heavy quark velocity expansion.

Success in NRQCD

$$\frac{d\sigma^{\psi}}{dyd^2p_\perp} = \sum_\kappa \frac{d\hat{\sigma}^\kappa}{dyd^2p_\perp} \langle \mathcal{O}_\kappa^\psi \rangle$$

- Long Distance Matrix Elements (LDMEs) are fitted by Tevatron data at large $p_\perp$.
- NLO, Collinear factorization.
- Fixed order calculation works down to $p_\perp \sim 5\mathrm{GeV}$ (pt ~ M).

Chao, Ma, Shao, Wang and Zhang, PRL **108** (2012)



Issues from 1st week

THEORY DEVELOPMENTS NEEDED OR PLANNED:

-- Explore applicability of NRQCD methods to exclusive heavy quarkonium photo/electroproduction at EIC. Possible points of interest are (i) tests of universality of the NRQCD matrix elements, (ii) better insight into bound-state structure and production mechanism through Q2-dependence.

CONNECTIONS WITH OTHER FIELDS:

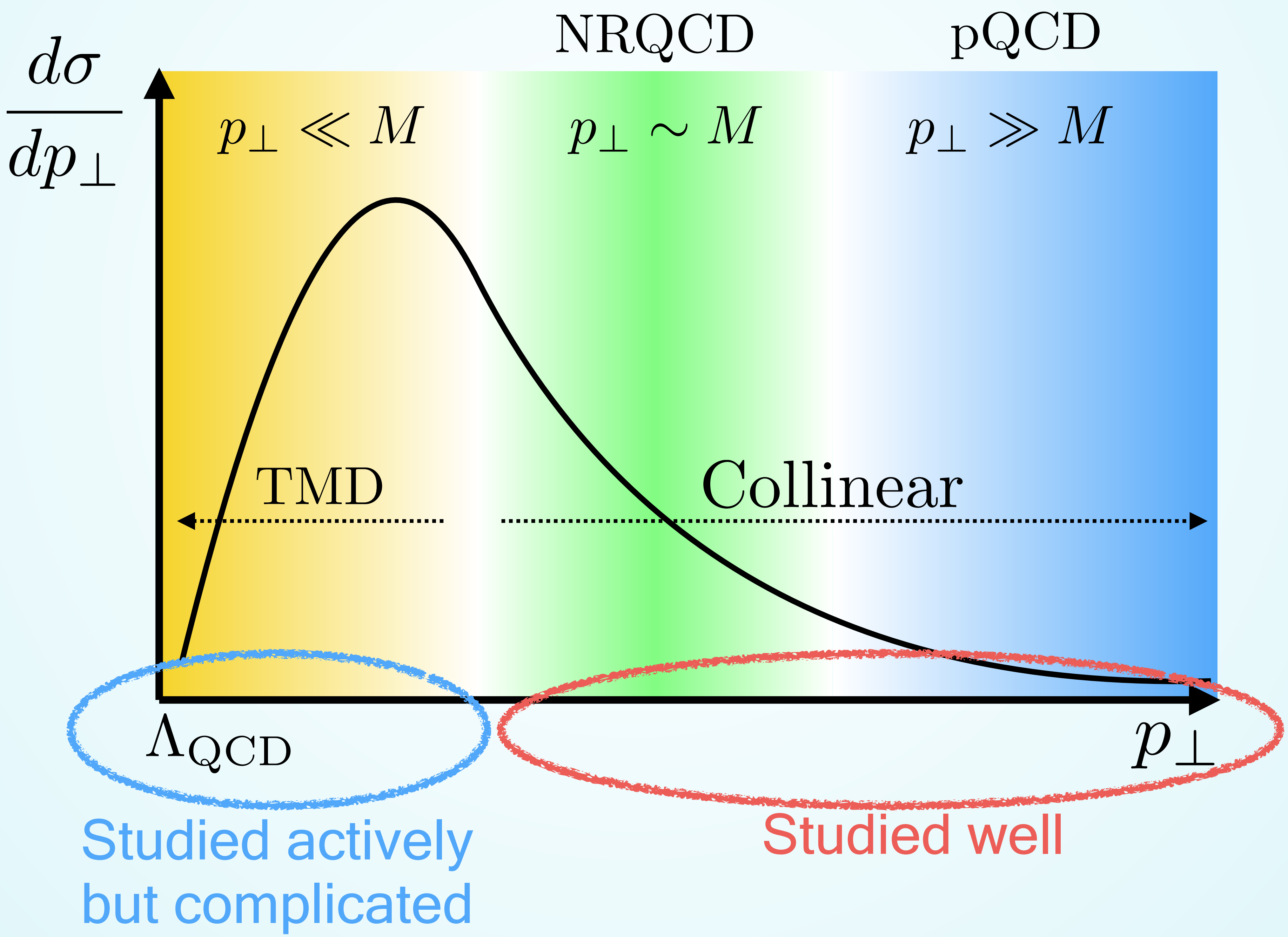
NONRELATIVISTIC QCD (NRQCD):

-- NRQCD matrix elements used in inclusive heavy quarkonium production in pp/pA may be used/tested/measured in exclusive production in ep/gamma-p.

Consider carefully factorization for quarkonium production in p+p/p+A collisions.

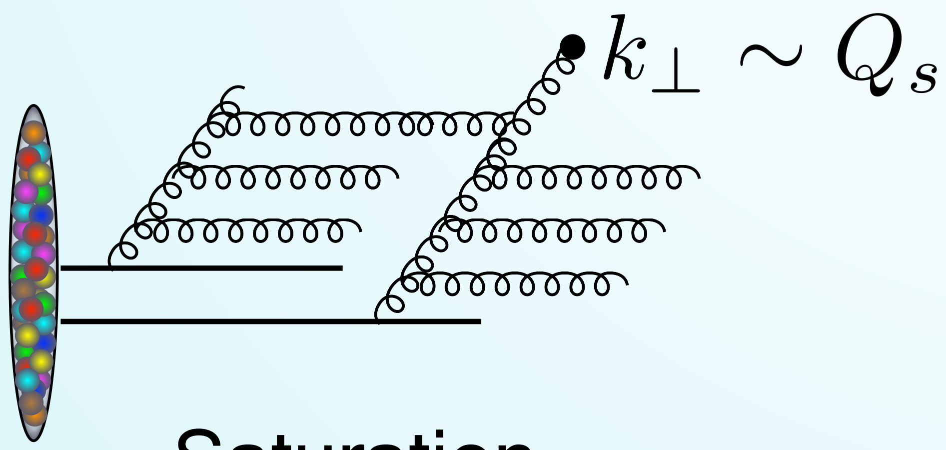
From TMD to Collinear

TMD: Transverse Momentum Dependent Framework
(kt-factorization)



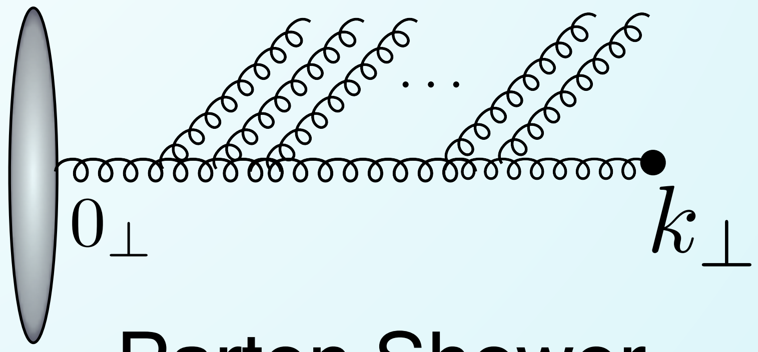
TMD approach

- <u>CGC framework</u>
  - Transverse Momentum Dependent PDF w/ Qs
  - Single logs
  - JIMWLK or BK eq. (Nonlinear evolution)
  - Applicable to only small-x



Saturation

- <u>CSS formalism</u>
  - Transverse Momentum Dependent PDF
  - Single logs + Double logs
  - DGLAP and Collins-Soper eqs. (Linear evolution)
  - Applicable to the whole x



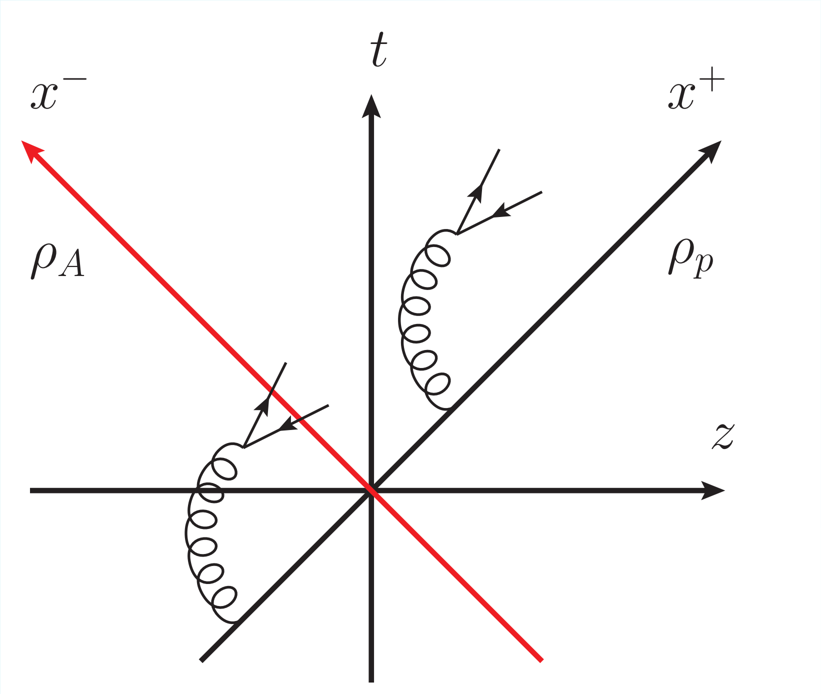
Parton Shower

Outline

1. Quarkonium production in the CGC framework
2. Quarkonium production in the TMD framework
3. Factorization breaking in p+A collisions

Quarkonium production in the CGC framework

QQbar production in dilute-dense system



Blaizot, Gelis, Venugopalan (2004)
Kovchegov, Tuchin (2006)
See also, Kharzeev, Tuchin (2005)

- Proton side: Leading twist
- Nucleus side: All orders resummation
- $\alpha_s^2 A^{1/3} \sim \mathcal{O}(1)$ → Multiple scattering

$$M_{s_1 s_2;ij}(p,q) = \frac{g^2}{(2\pi)^4}\int d^2k_\perp d^2k_{1\perp}\frac{\rho_p(x_p,k_{1\perp})}{k_{1\perp}^2}\int d^2x_\perp d^2y_\perp e^{ik_\perp\cdot x_\perp}e^{i(p_\perp-k_\perp-k_{1\perp})\cdot y_\perp}$$
$$\times\bar{u}_{s_1,i}\left(\frac{p}{2}+q\right)\left[T_g(p,k_{1\perp})t^b W^{ba}(x_\perp)+T_{q\bar{q}}(p,q,k_{1\perp},k_\perp)U(x_\perp)t^a U^\dagger(y_\perp)\right]v_{s_2,j}\left(\frac{p}{2}-q\right)$$

$\mathcal{O}(\rho_p^1\rho_A^\infty)$

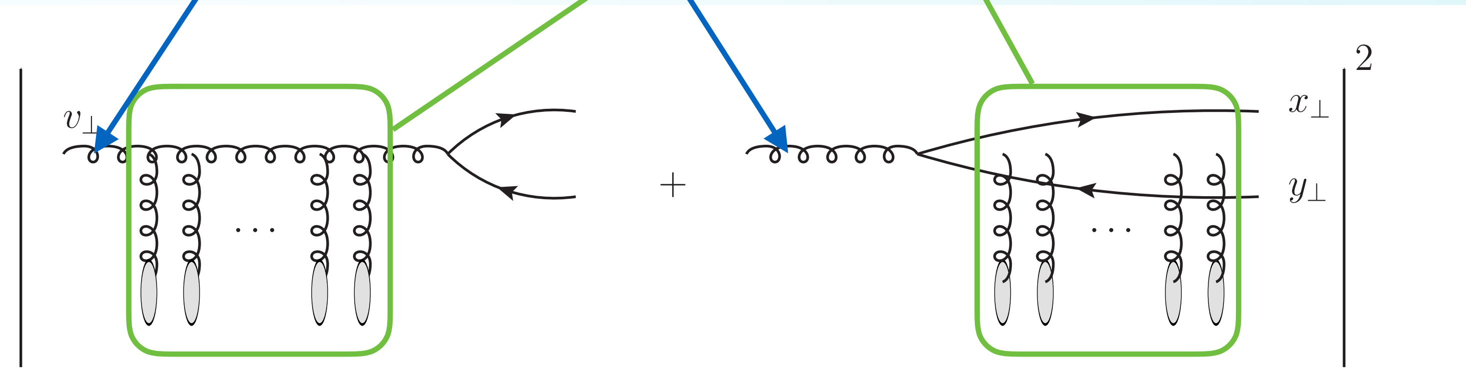
$$U(x_\perp) = \mathcal{P}_+\exp\left[ig\int_{-\infty}^{+\infty}dz^+A_A^-(z^+,x_\perp)\cdot t\right]$$
$$W(x_\perp) = \mathcal{P}_+\exp\left[ig\int_{-\infty}^{+\infty}dz^+A_A^-(z^+,x_\perp)\cdot T\right]$$

Wilson lines in the Eikonal approximation

Onium in the CGC+CEM

UGDF

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



CEM

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

Improved CEM   Ma, Vogt, PRD94 (2016)

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

Gluon radiation during hadronization

Onium in the CGC+NRQCD

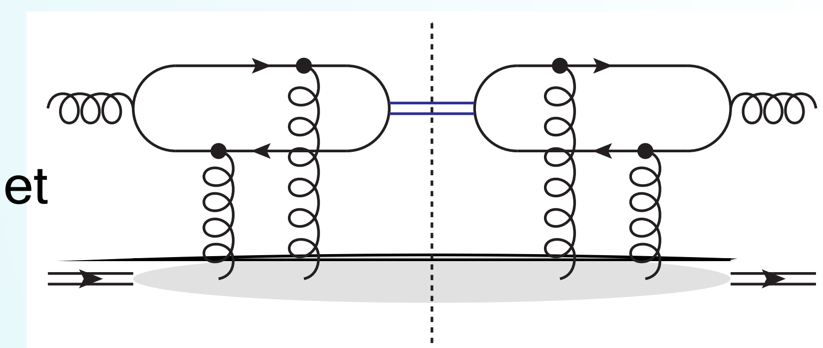
Kang, Ma, Venugopalan, (2013)

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

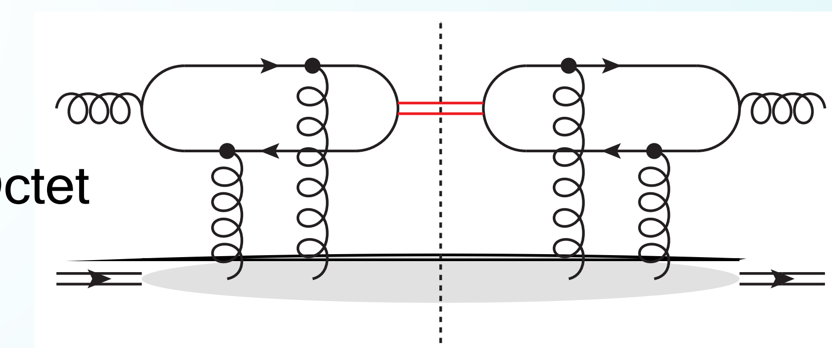
$$\frac{d\sigma^{\kappa}_{c\bar{c},\mathrm{CS}}}{d^2p_\perp dy} = \frac{\alpha_s \pi R_A^2}{(2\pi)^9 d_A} \int_{k_{2\perp}, k_\perp, k'_\perp} \frac{\varphi_{p,y_p}(k_{1\perp})}{k_{1\perp}^2} \mathcal{N}_Y(k_\perp) \mathcal{N}_Y(k'_\perp) \mathcal{N}_Y(k_{2\perp} - k_\perp - k'_\perp)\, \mathcal{G}_1^{\kappa}$$

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

Color Singlet



Color Octet

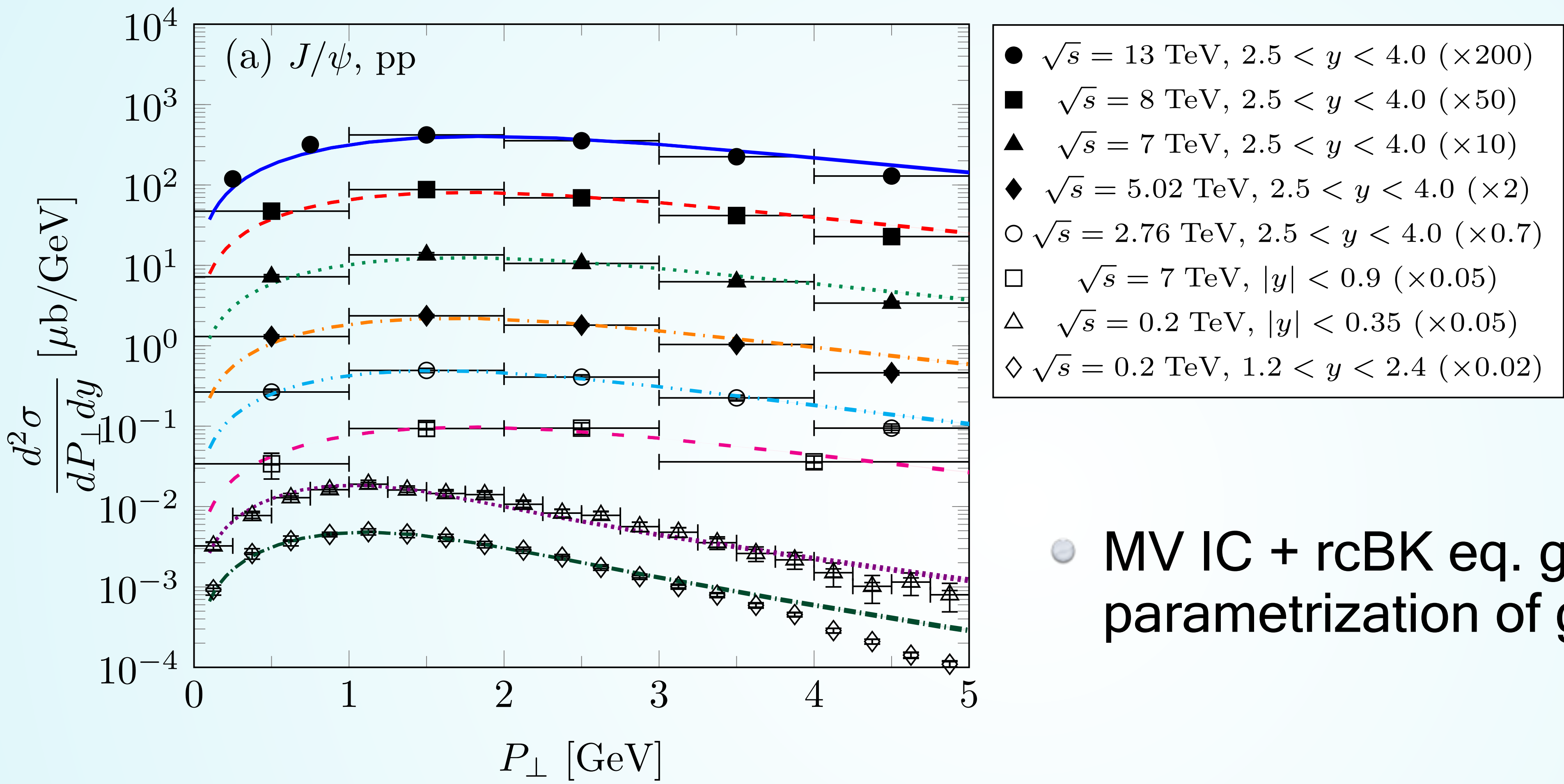


CS channel probes the quadrupole amplitude. However, thanks to large-Nc approximation and quasi-classical approximation, the quadrupole amplitude is simply cubic in N_Y.

Dominguez, Kharzeev, Levin, Mueller, Tuchin, PLB710, (2012)

J/psi in the CGC+ICEM

Ma, Venugopalan, KW, Zhang (2018)

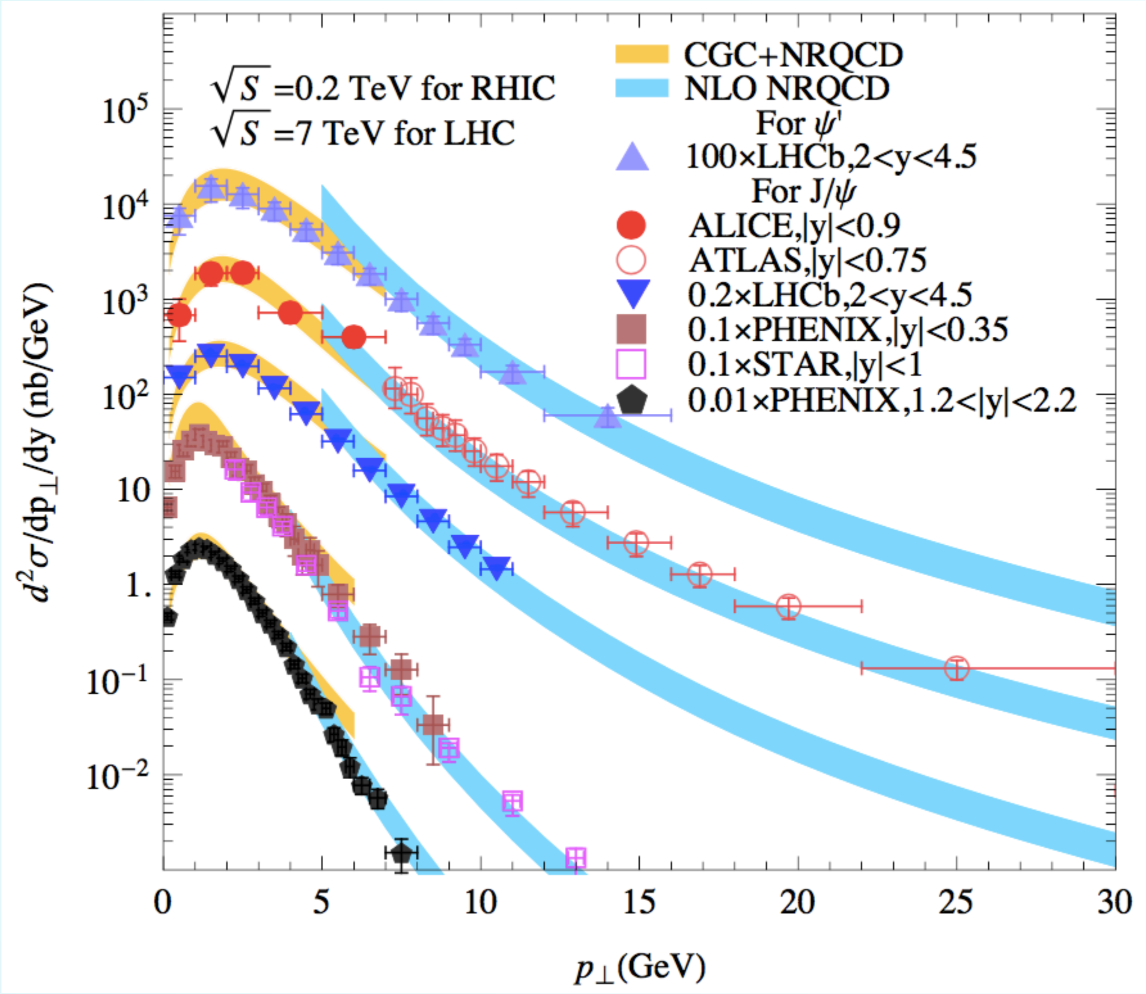


- MV IC + rcBK eq. gives a good parametrization of gluon TMD at small-x.

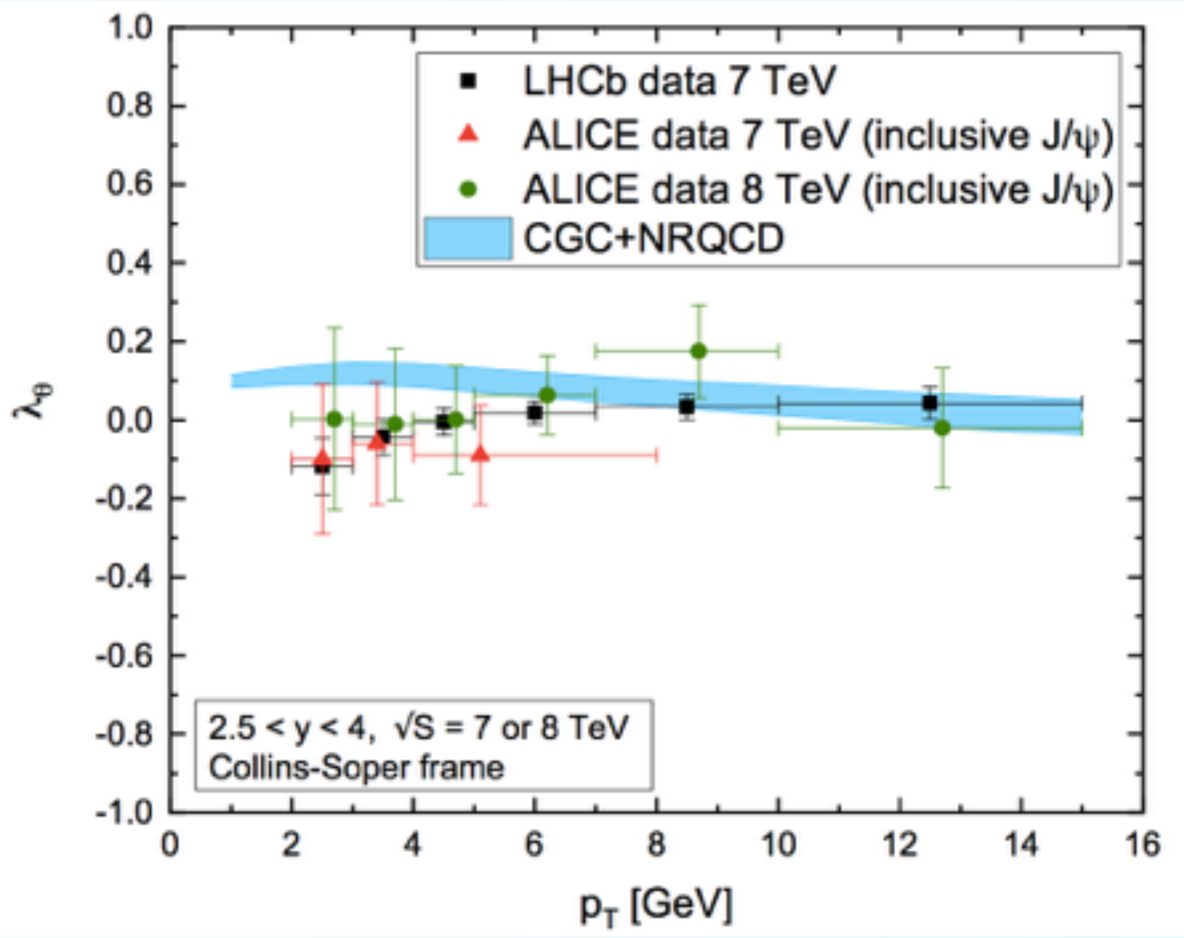
$\sqrt{s}$ [TeV]	y bin	Data points	$F_{J/\psi}$ (1.3)	$\chi^2/d.o.f.$
13	$2.5 < y < 4.0$	7	$5.63\times10^{-3} \pm 3.56\times10^{-4}$	8.7
8	$2.5 < y < 4.0$	6	$5.84\times10^{-3} \pm 3.79\times10^{-4}$	4.3
7	$\|y\| < 0.9$	5	$4.52\times10^{-3} \pm 2.33\times10^{-4}$	0.33
7	$2.5 < y < 4.0$	6	$4.86\times10^{-3} \pm 3.01\times10^{-4}$	5.3
5.02	$2.5 < y < 4.0$	6	$5.26\times10^{-3} \pm 3.35\times10^{-4}$	7.0
2.76	$2.5 < y < 4.0$	6	$5.27\times10^{-3} \pm 1.84\times10^{-4}$	0.88
0.2	$\|y\| < 0.35$	21	$6.36\times10^{-3} \pm 1.94\times10^{-4}$	0.93
0.2	$1.2 < y < 2.4$	24	$1.06\times10^{-2} \pm 1.30\times10^{-4}$	0.35

J/psi in the CGC+NRQCD

Ma, Venugopalan (2014)



Ma, Stebel, Venugopalan (2018)



Prompt J/psi data at high pt at Tevatron;

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

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

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

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

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).

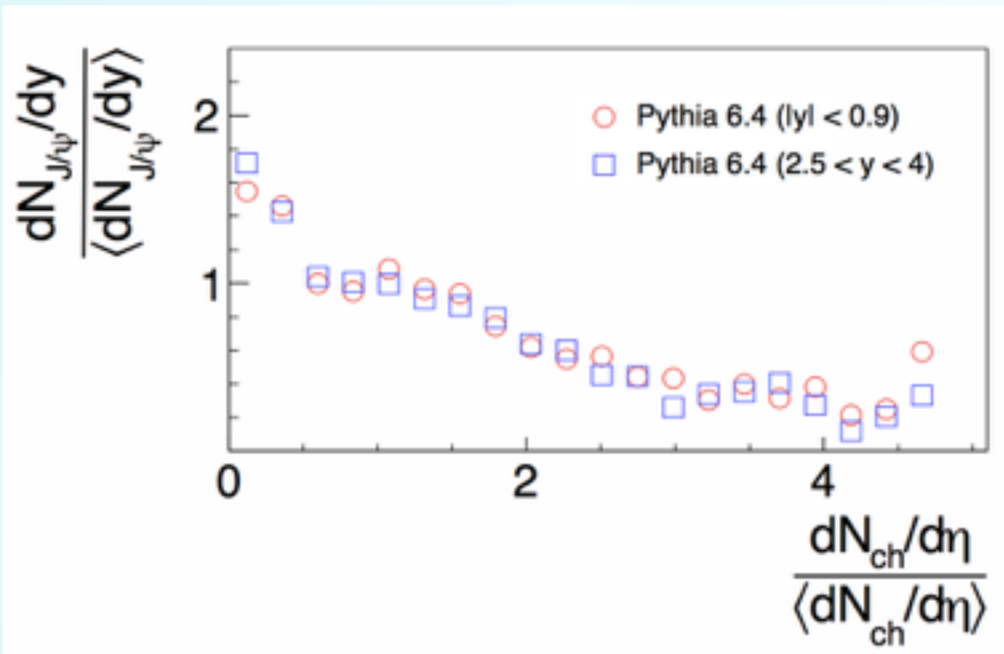
In e+e- scattering:

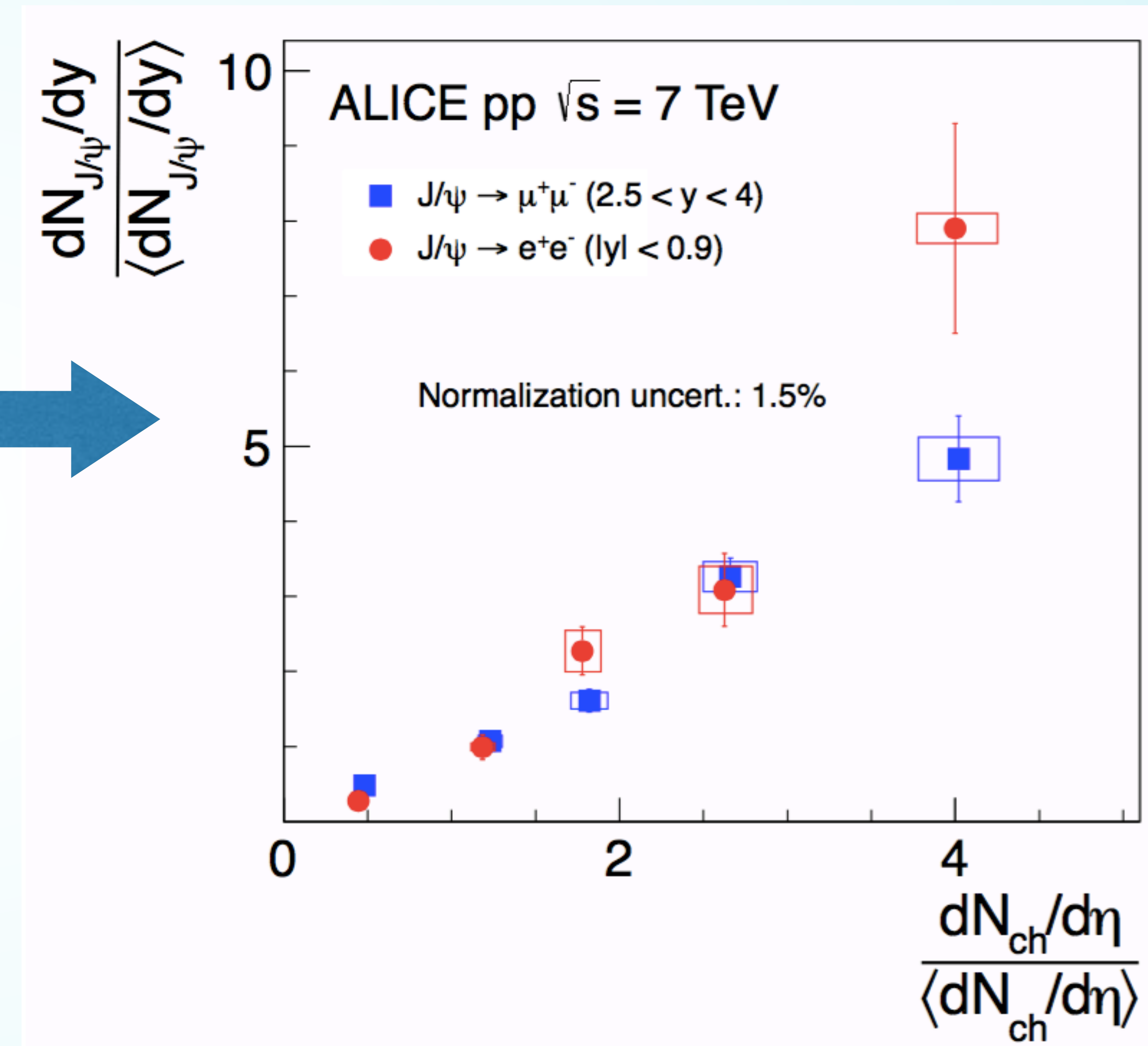
$$\langle\mathcal{O}^{J/\psi}[^1S_0^{[8]}]\rangle + 4.0\langle\mathcal{O}^{J/\psi}[^3P_0^{[8]}]\rangle/m^2 < 2.0 \pm 0.6 \times 10^{-2}\mathrm{GeV}^3$$

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

J/psi vs Nch

ALICE Collaboration,
PLB712 (2012)





Soft mode vs Hard mode

Can we test universality of LDMEs?

Quantum Fluctuation

At extreme high energy, gluon field behaves like classical: Small coupling constant and gluon nonlinear interaction. ↔ $A \sim 1/g$

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

- If S_perp is fixed, Qs can controls Nch.
- Qs depends on impact parameter (b).

Tribedy, Venugopalan (2011)
Schenke, Tribedy, Venugopalan (2012)

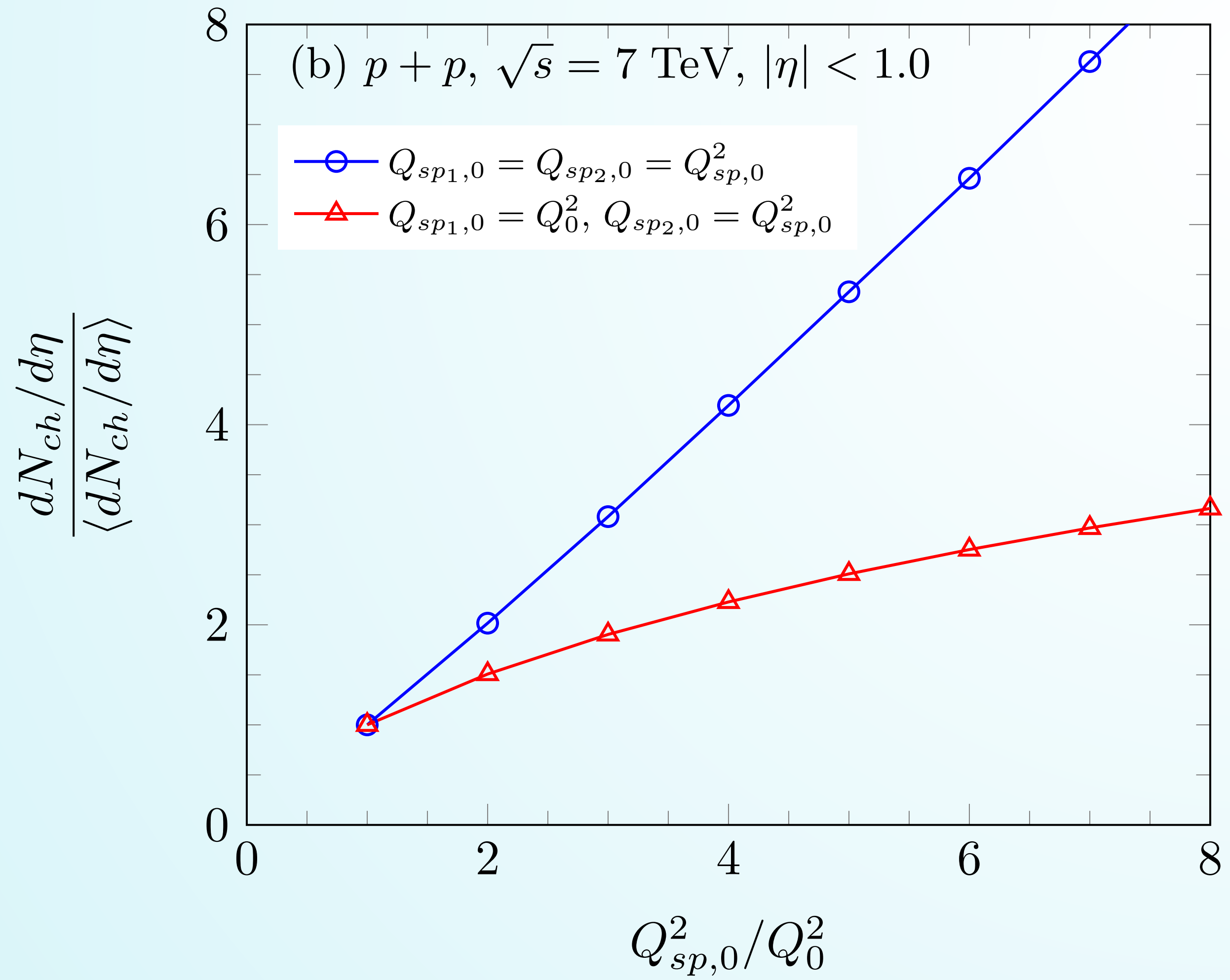
- IP-Sat Model deals with b-dependent Qs and can model NBD of Nch.
- Spatial configurations of color charge density of parton inside hadron are nonperturbative and complicated…

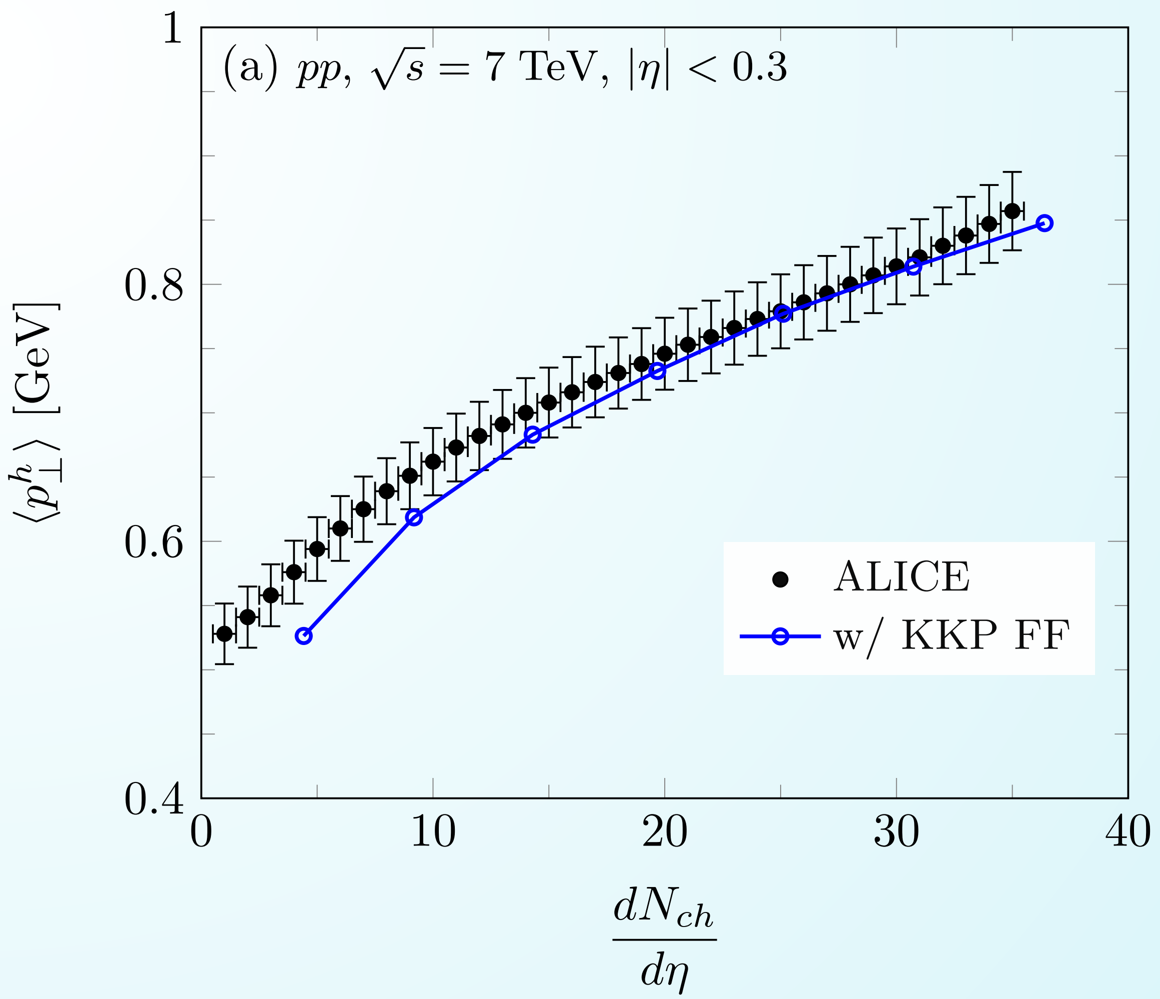
See talk by Mace (11/13)

Nch in p+p collisions

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

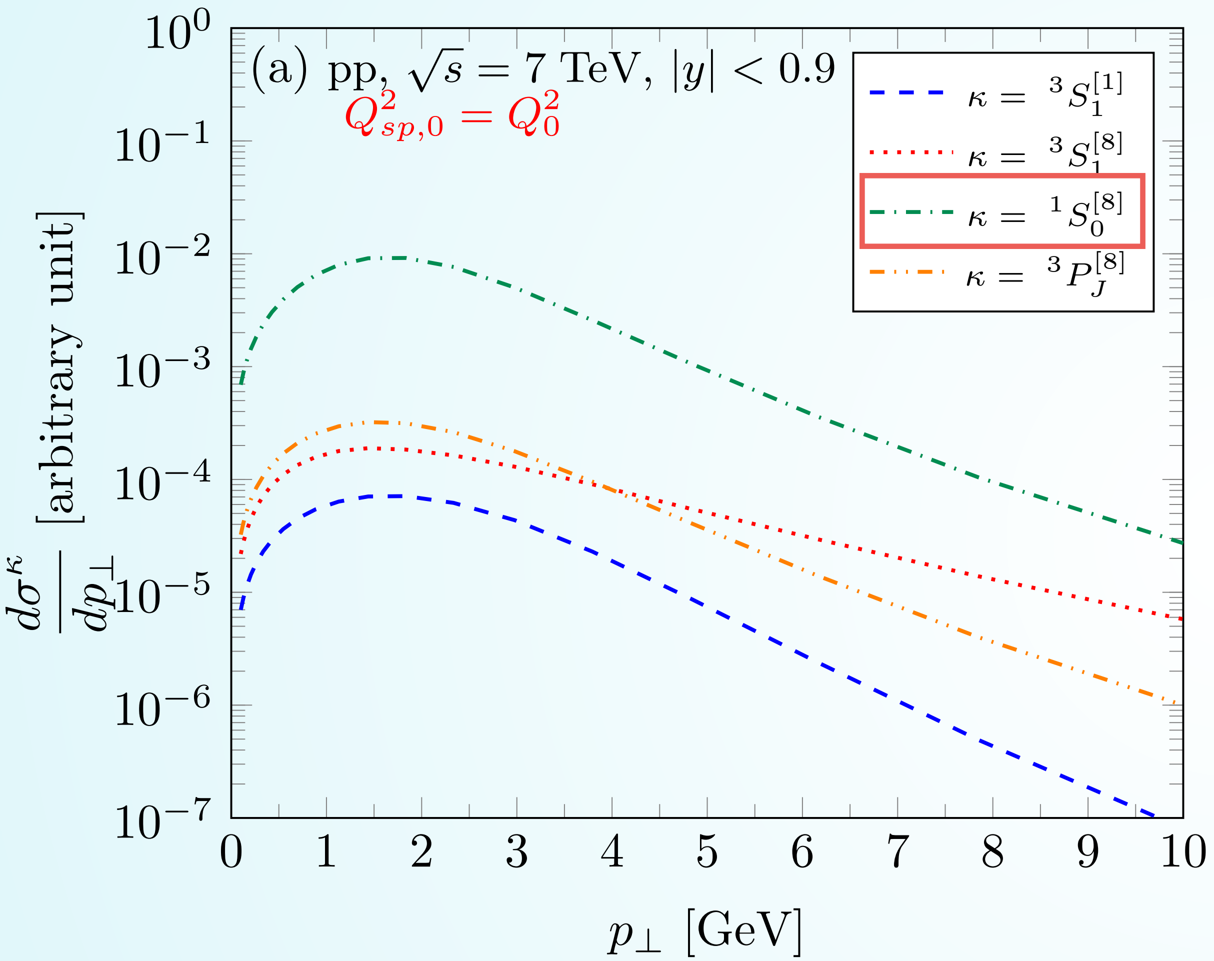
$$\frac{dN_{ch}}{d\eta} = \frac{\hat{K}_{ch}}{\sigma_{\mathrm{inel}}}\int d^2p_\perp \int_{z_{\min}}^{1} dz \frac{D_h(z)}{z^2} J_{y\to\eta}\frac{d\sigma_g}{d^2p_{g\perp}dy}$$



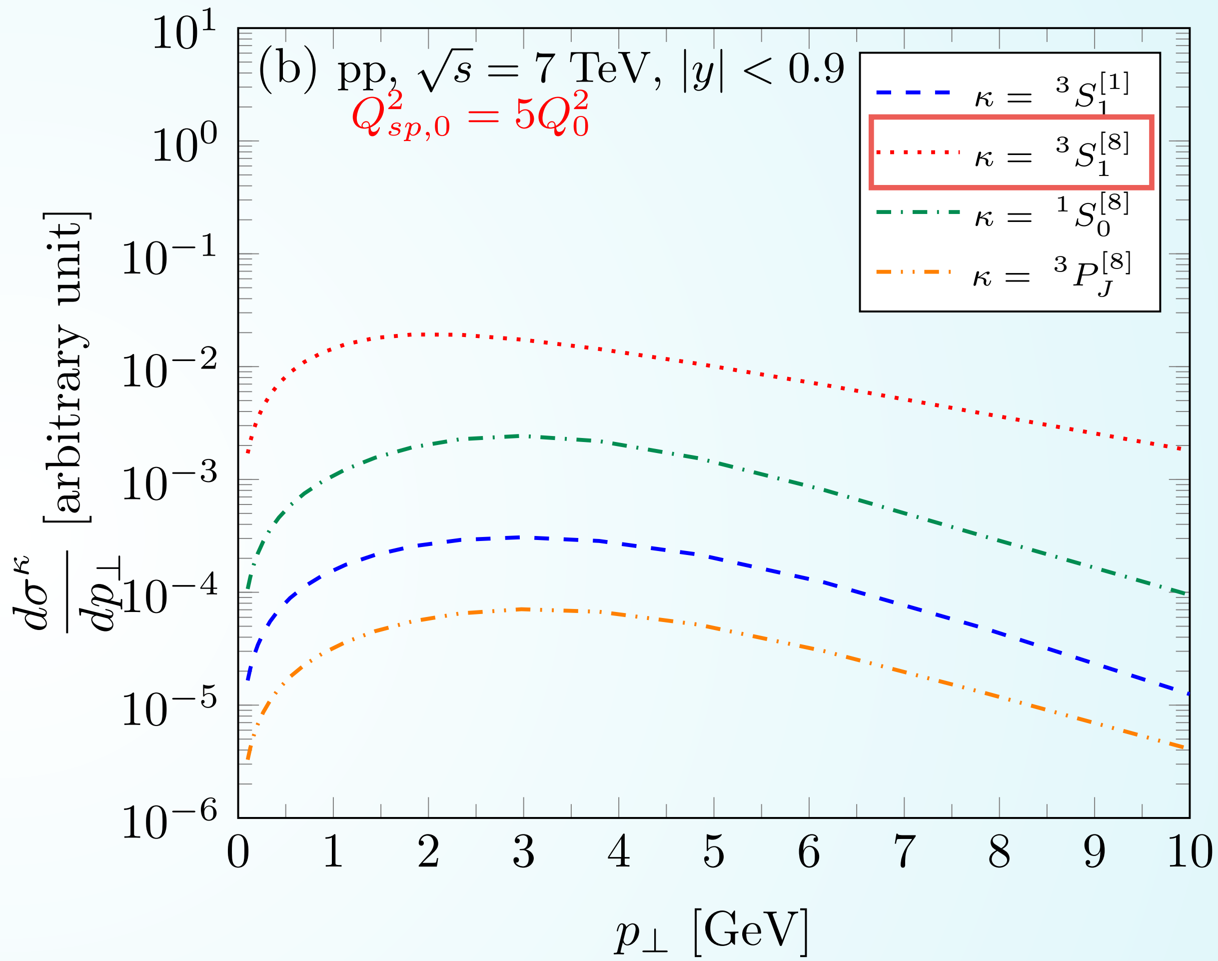


MB vs High Multiplicity events

Ma, Venugopalan, Tribedy, KW (2018)

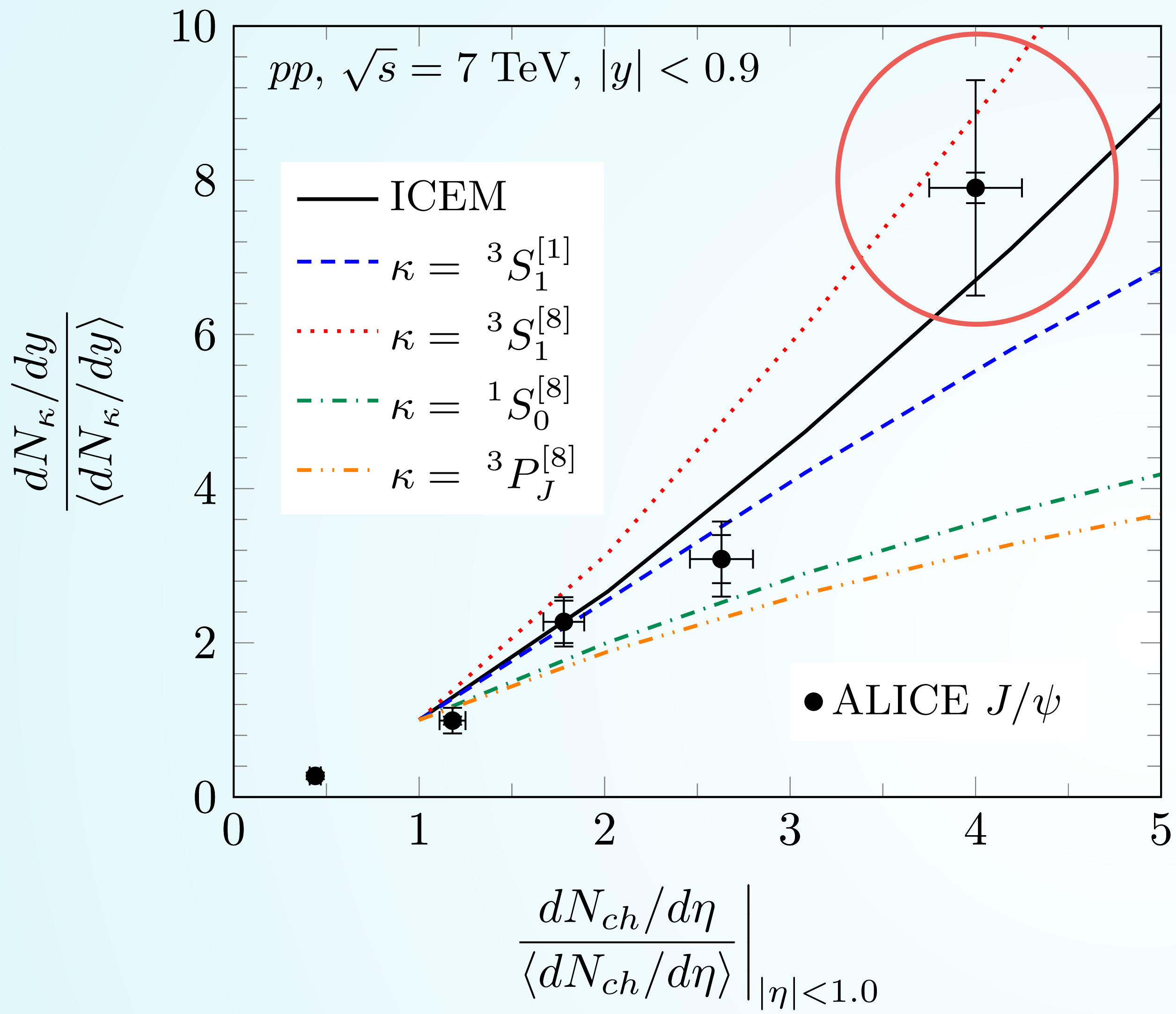


MB events



HM events

New constraints on the LDMEs



1S0 octet channel should have a larger weight compared to MB.

- Consistent with the universality requirement from BELLE e^+e^- data:

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

- b-quark decay contribution is not included.

Short Summary I

- Nice agreement between the CGC expectation and experimental data about pt distribution of J/psi production.

- J/psi production in high multiplicity events provides an interesting universality test of LDMEs.

- Other observables: J/psi production within jets.

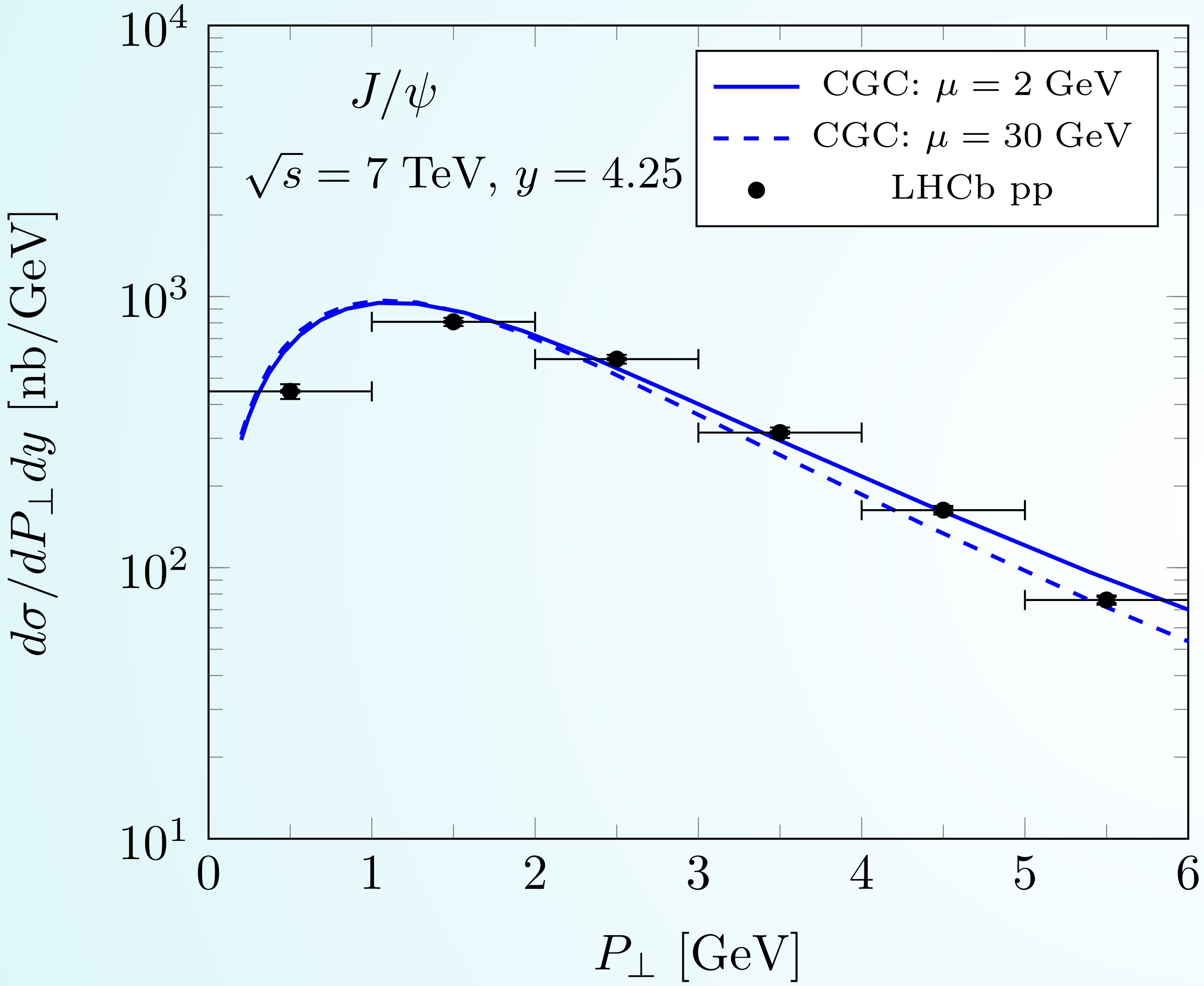
Bain, Makris, Mehen, Dai, Leibovich, PRL119, 032002 (2017)

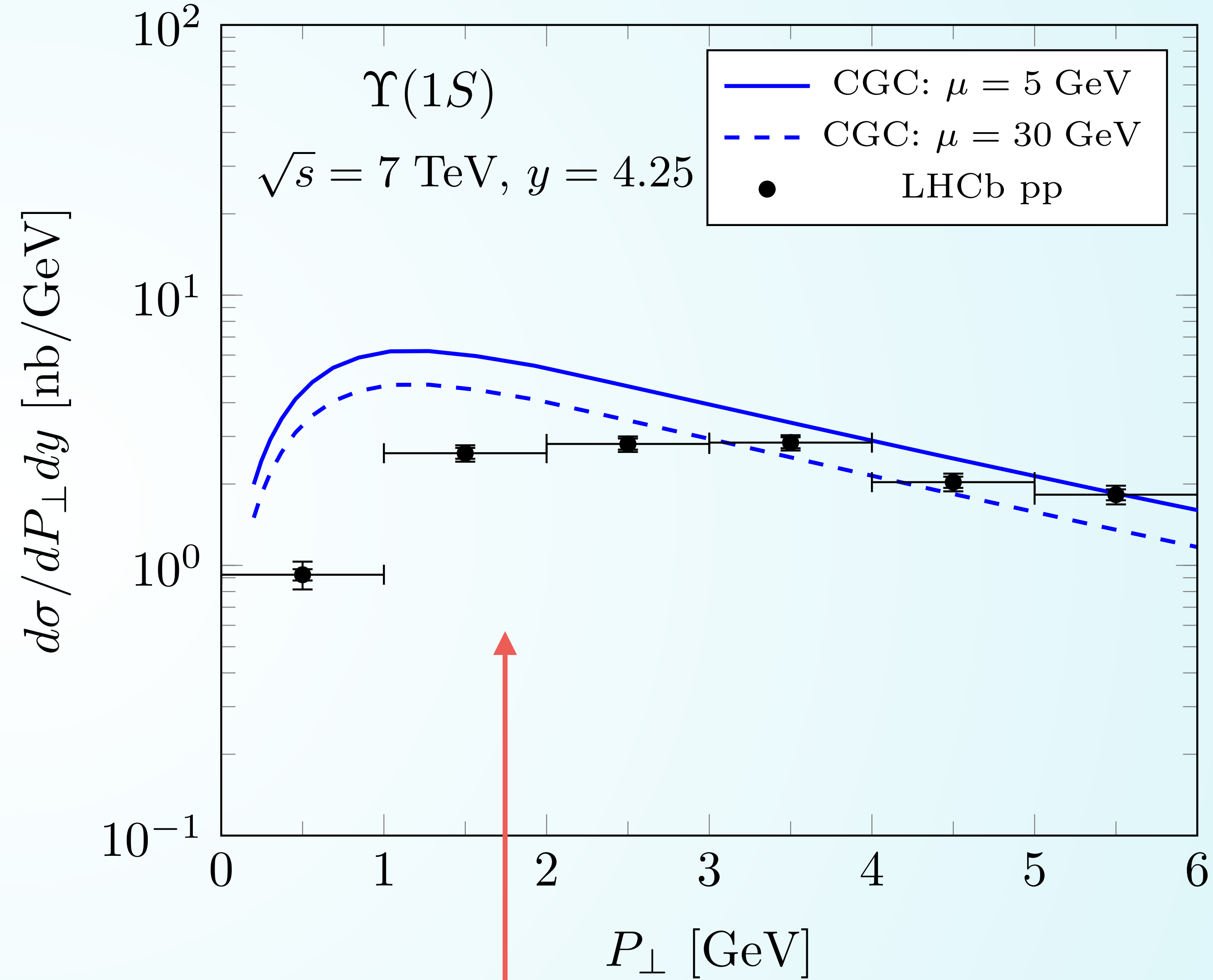
Kang, Qiu, Ringer, Xing, Zhang, PRL119, 032001 (2017)

Quarkonium production in the TMD framework

J/psi vs Upsilon in the CGC

Fujii, KW (2013)
KW, Xiao (2015)



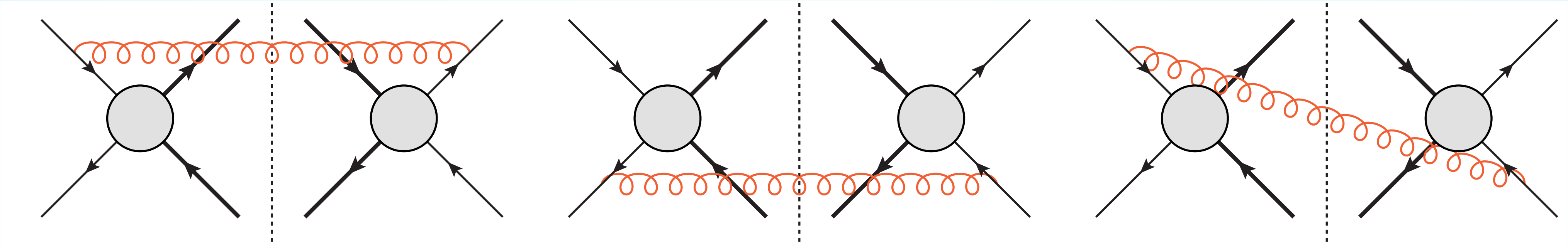


Sudakov resummation effect is important for Upsilon production.

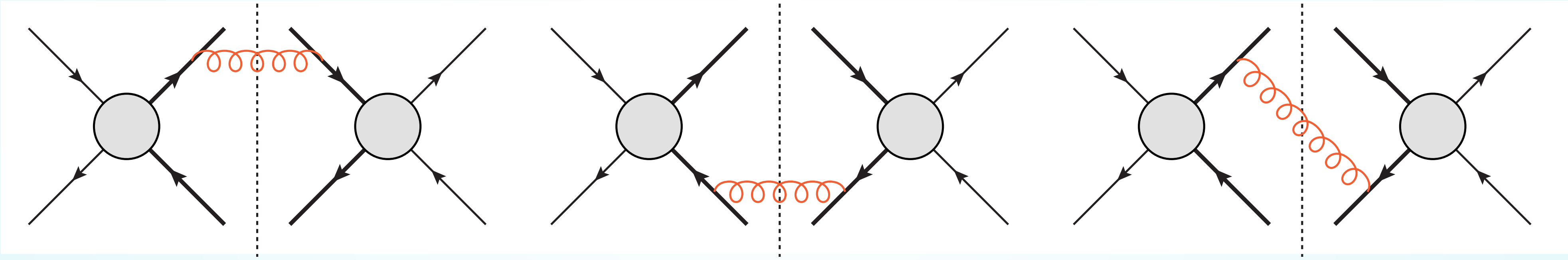
$$\alpha_s \ln^2 \frac{M^2}{p_\perp^2} \sim \mathcal{O}(1)$$

Soft gluon radiation

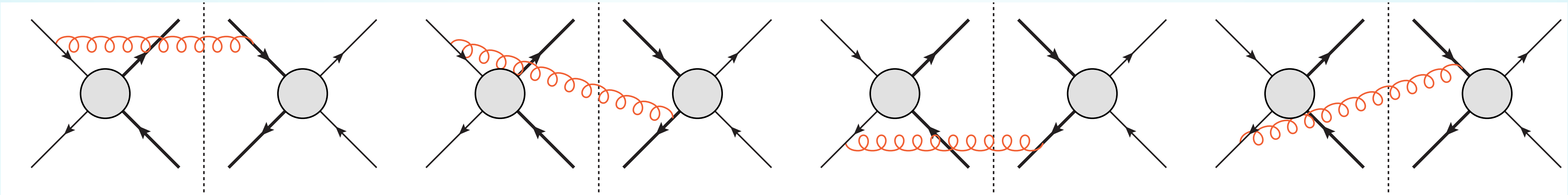
Initial state interaction: Soft and collinear singularities



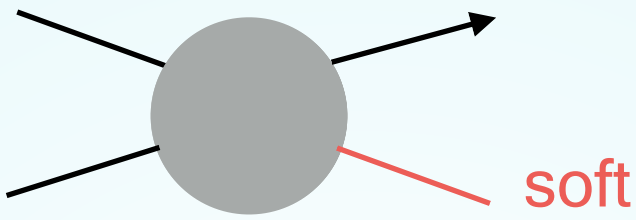
Final state interaction: Soft singularity



Interference: Soft and collinear singularities



Soft momentum limit: g+g channel



Qiu, KW in progress

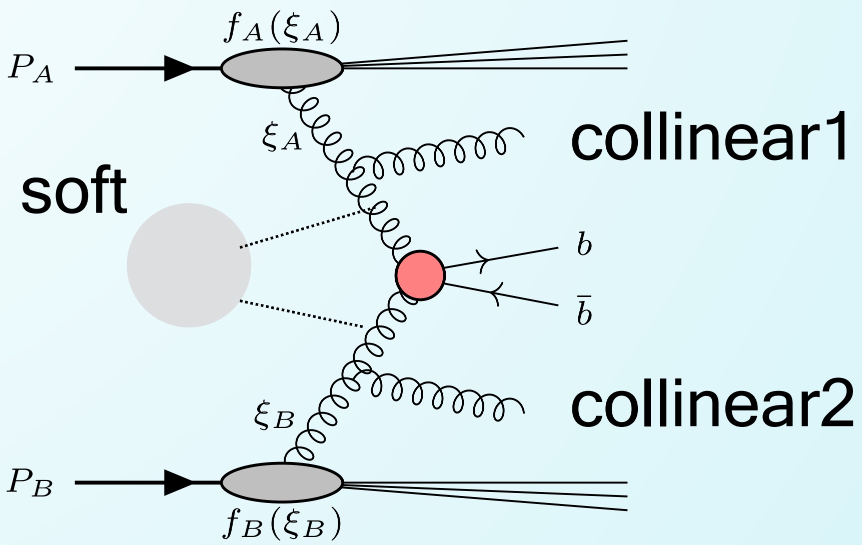
$$\frac{\hat{s}}{\pi}\frac{d\hat{\sigma}_\kappa}{d\hat{t}}\delta(\hat{s}+\hat{t}+\hat{u}-M^2)$$

$$\overset{p_\perp^2 \ll M^2}{=\!=\!=} \hat{\sigma}_0^\kappa \frac{1}{p_\perp^2}\left[\frac{3(z_B^2-z_B+1)^2\alpha_s}{\pi^2}\frac{\delta(1-z_A)}{[1-z_B]_+}+\frac{3(z_A^2-z_A+1)^2\alpha_s}{\pi^2}\frac{\delta(1-z_B)}{[1-z_A]_+}+\frac{3\alpha_s}{\pi^2}\delta(1-z_A)\delta(1-z_B)\ln\frac{M^2}{p_\perp^2}\right]$$

$$=\hat{\sigma}_0^\kappa \frac{C_A\alpha_s}{2\pi^2}\frac{1}{p_\perp^2}\left[z_B\hat{P}_{gg}^R(z_B)\delta(1-z_A)+z_A\hat{P}_{gg}^R(z_A)\delta(1-z_B)+2\delta(1-z_A)\delta(1-z_B)\ln\frac{M^2}{p_\perp^2}\right]$$

$$\frac{d\hat{\sigma}_{gg}^\kappa}{d^2p_\perp dy}=\hat{\sigma}_{0,gg}^\kappa\frac{C_A\alpha_s}{2\pi^2}\int_{x_A}^1 d\xi_A\int_{x_B}^1 d\xi_B f_A(\xi_A)f_B(\xi_B)\frac{1}{p_\perp^2}$$
$$\times\left[z_B\hat{P}_{gg}^R(z_B)\delta(1-z_A)+z_A\hat{P}_{gg}^R(z_A)\delta(1-z_B)+2\ln\frac{M^2}{p_\perp^2}\delta(1-z_A)\delta(1-z_B)\right]$$

The same form as Higgs production



Initial state interaction should be important.

Collins-Soper-Sterman formalism

Collins, Soper, Sterman (1985)

$$\frac{d\sigma^{Q\bar{Q}}}{d^2p_\perp dy} = \int \frac{d^2b_\perp}{(2\pi)^2} e^{ip_\perp \cdot b_\perp} W(M, b_\perp, x_1, x_2) + (d\sigma_{\text{perp}} - d\sigma_{\text{asy}})$$

Resummation — important at high pt

$$W(M, b_\perp, x_1, x_2) = \sum_{ij} d\hat{\sigma}_{\text{LO}}^{ij\to Q\bar{Q}} W_{ij}(M, b_\perp) e^{-S_{ij}(M, b_\perp)}$$

$$W_{ij}(M, b_\perp) = \sum_{a,b} \int \frac{d\xi}{\xi} \frac{d\xi'}{\xi'} C_{a\to i}\left(\frac{x_A}{\xi}\right) C_{b\to j}\left(\frac{x_B}{\xi'}\right) f_{a/A}(\xi, \mu) f_{b/B}(\xi', \mu)$$

collinear pdfs

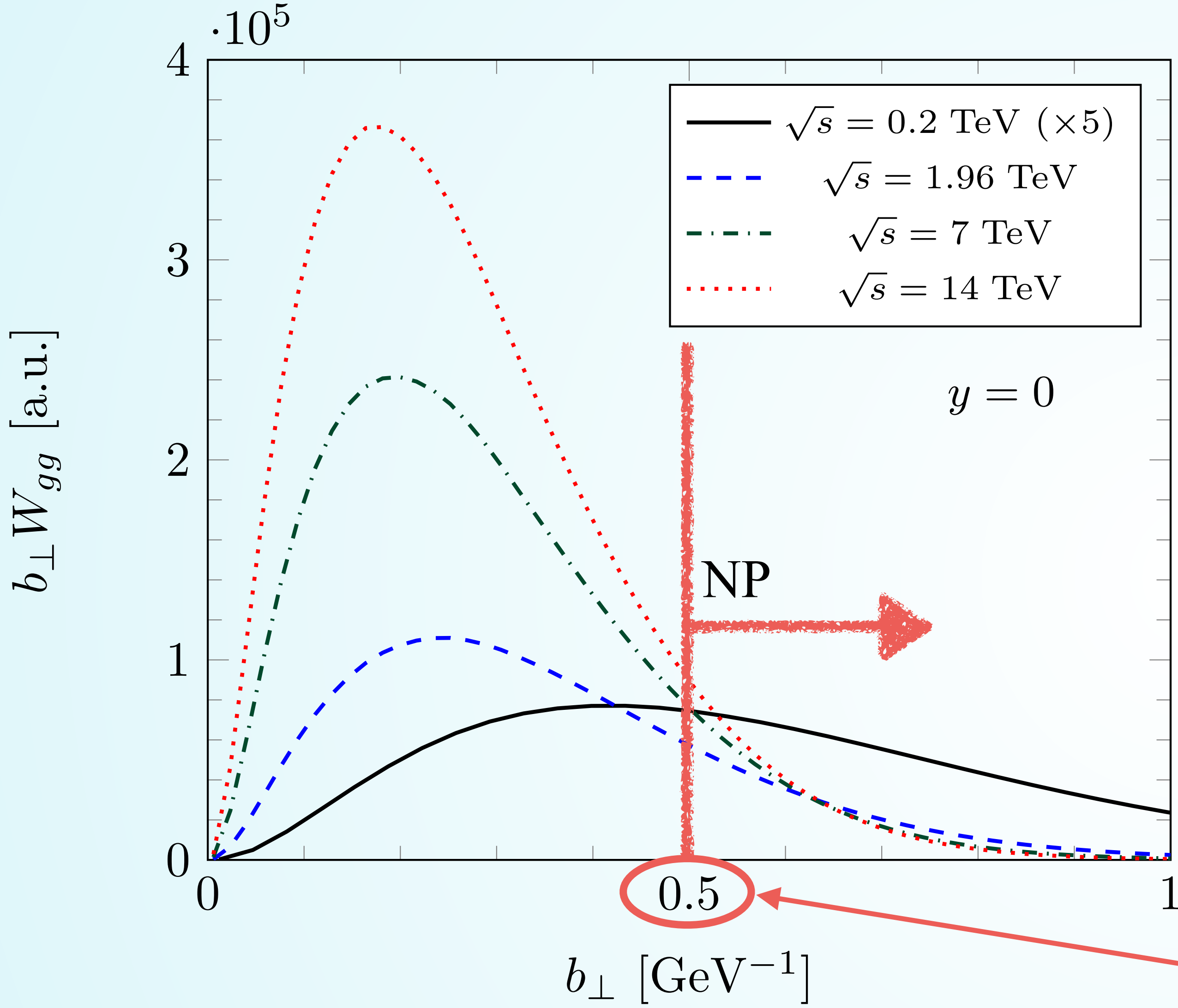
$$S_{ij}(M, b) = \int_{c_0/b^2}^{M^2} \frac{d\mu^2}{\mu^2} \left[A_{ij} \ln\left(\frac{M^2}{\mu^2}\right) + B_{ij} \right]$$

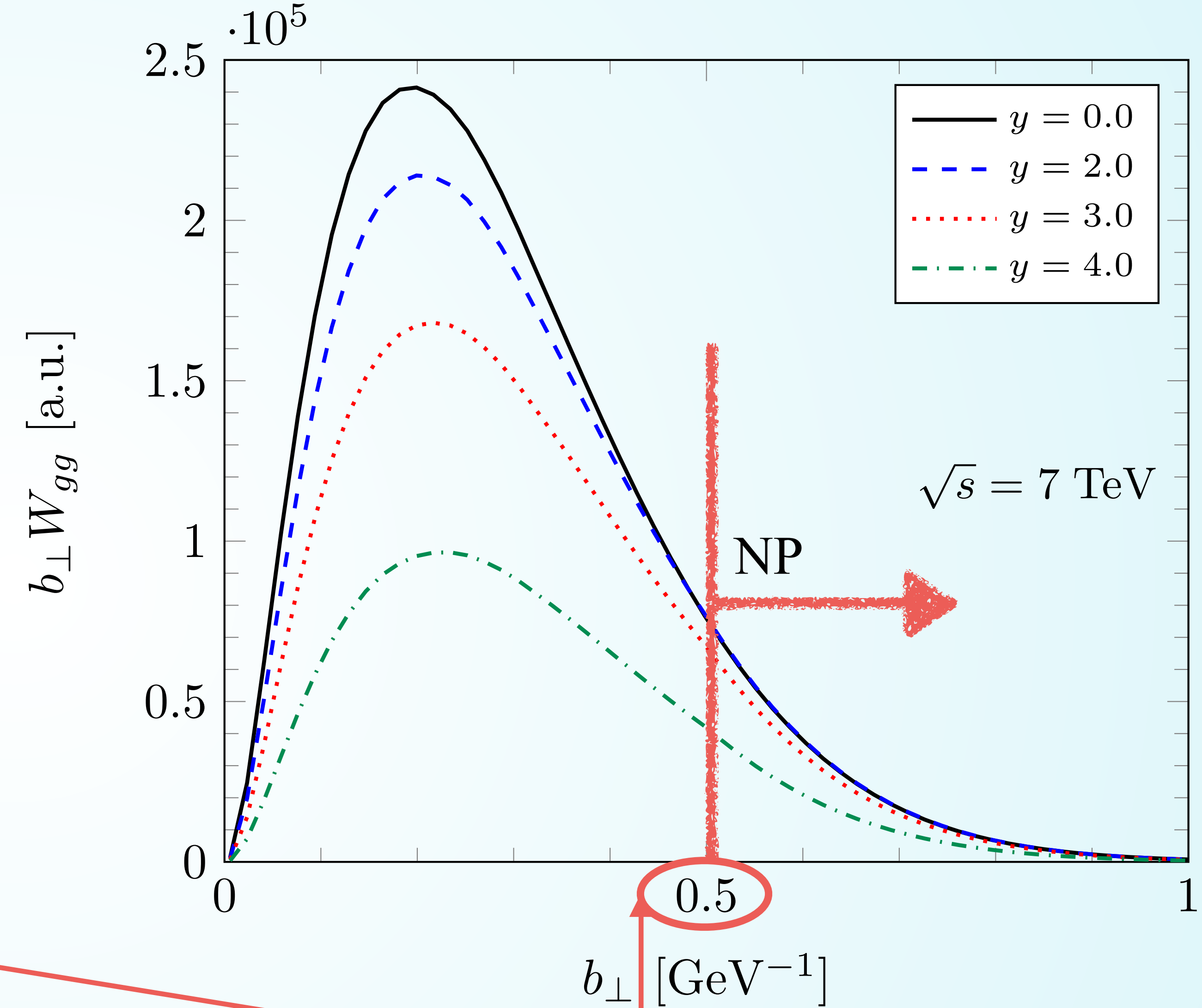
universal in gg-channel

A, B, C are calculated perturbatively.

b-space distribution for Upsilon

Qiu, KW (2017)



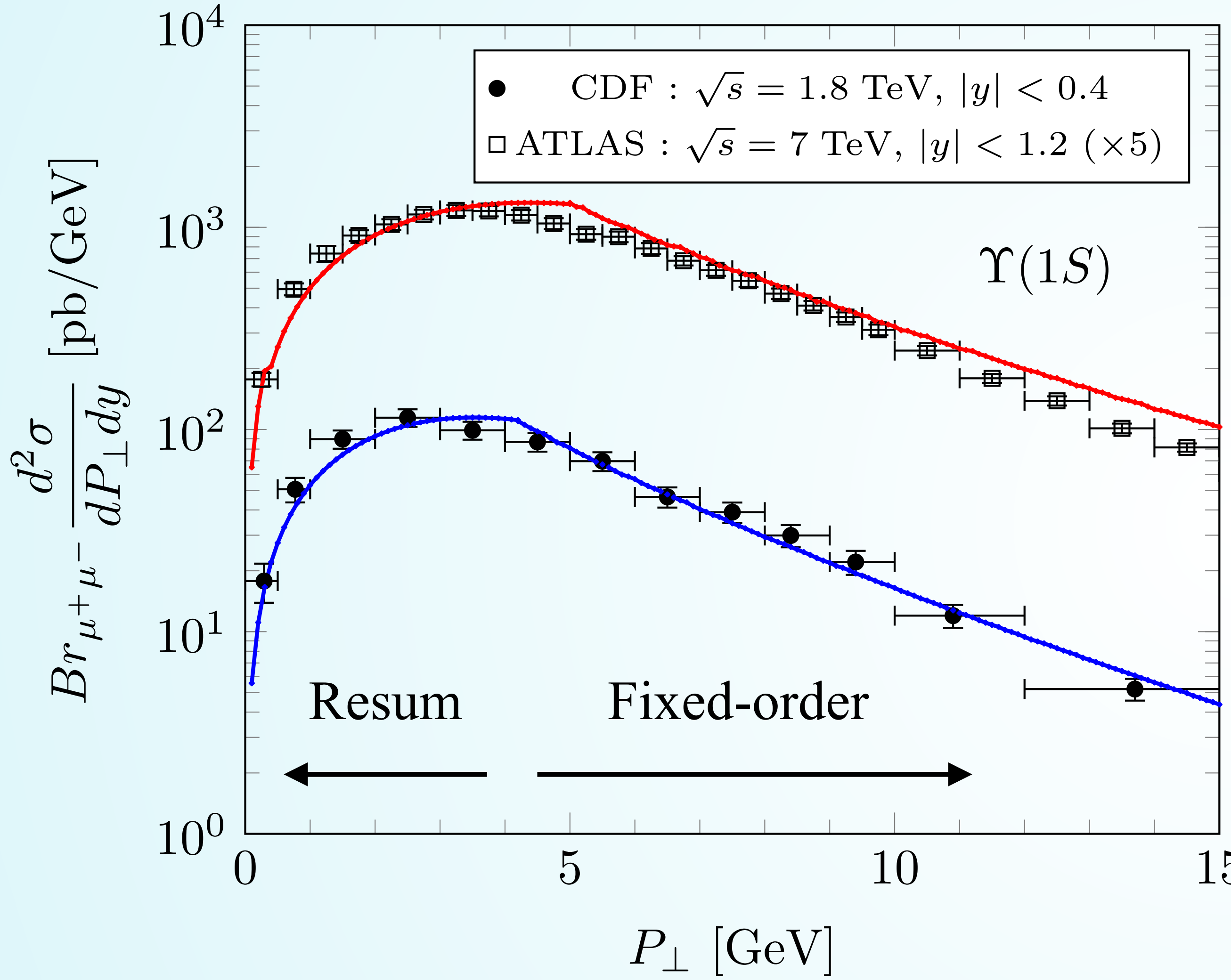


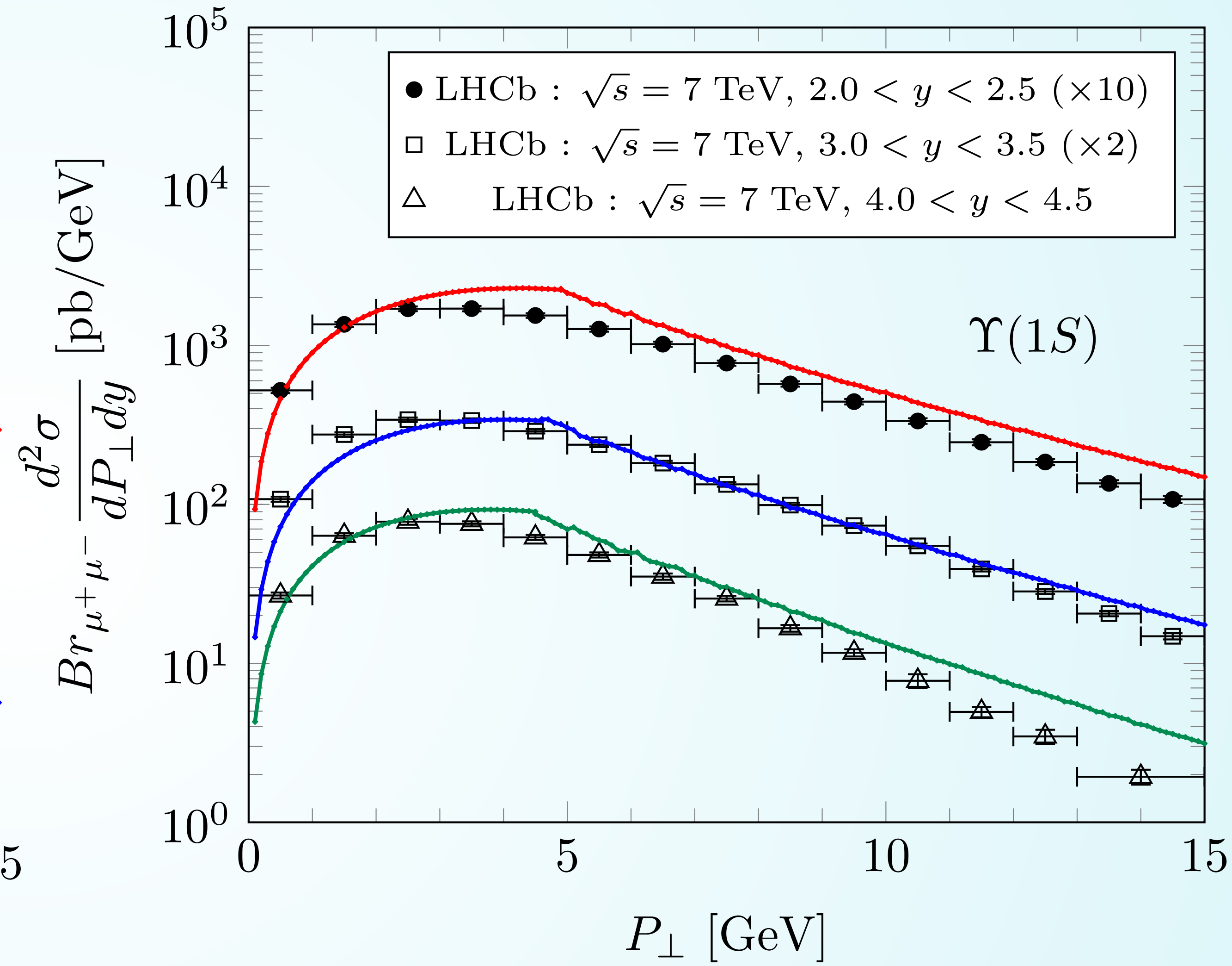
$$W(M, b_\perp) = \begin{cases} W^{\text{perp}}(M, b_\perp) & b_\perp \leq b_{\max} \\ W^{\text{perp}}(M, b_{\max}) F^{\text{NP}}(M, b_\perp; b_{\max}) & b_\perp > b_{\max} \end{cases}$$

Upsilon: Perturbative shower, J/psi: Nonperturbative shower

Results in the CSS formalism

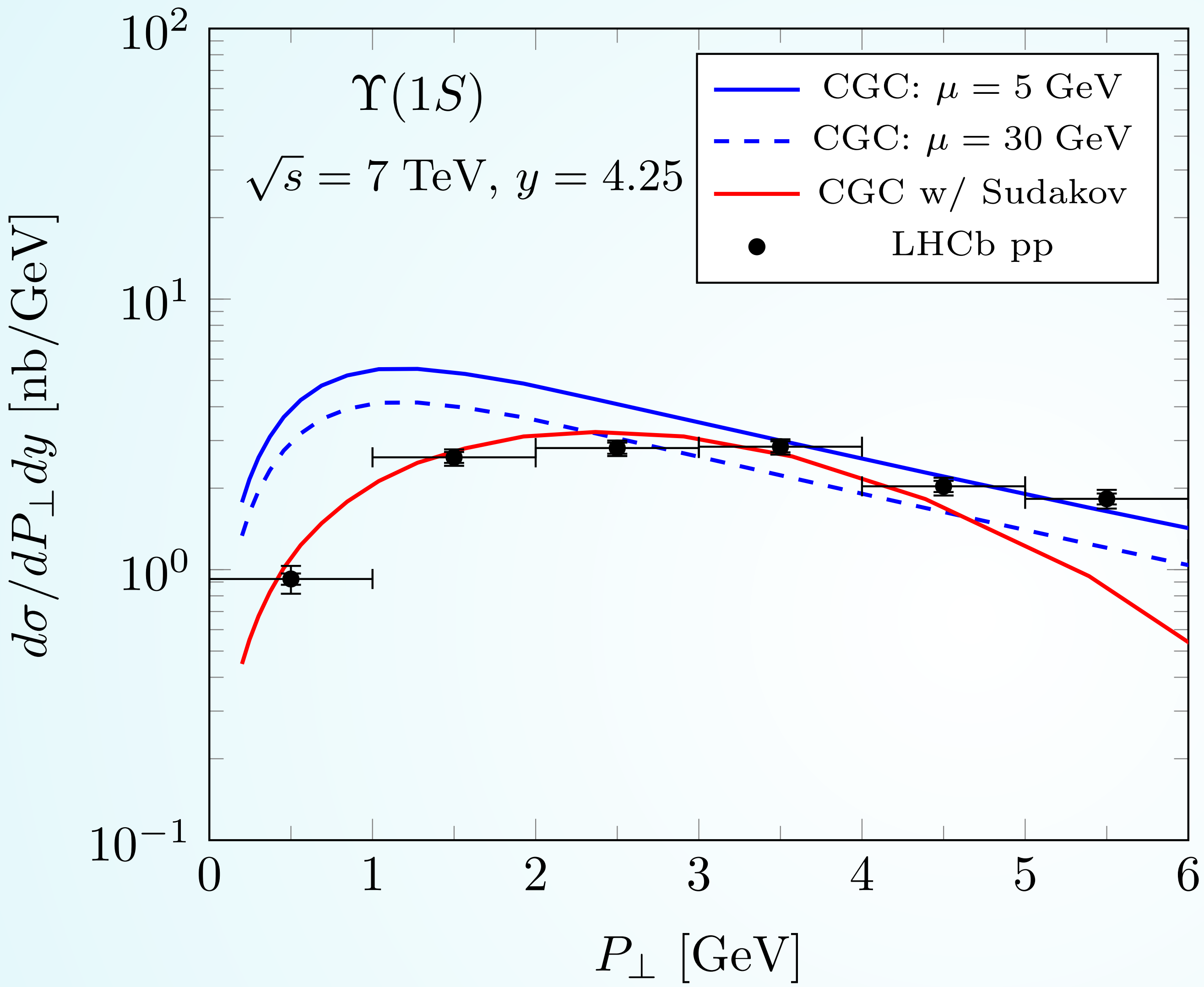
Qiu, KW (2017)





Initial state hard person shower describes data of J/psi production from Tevatron to LHC.

CGC + Sudakov factor



KW, Xiao (2015)

See also, Mueller, Xiao, Yuan (2013)

$$\frac{d\sigma_{Q\bar{Q}}}{d^2q_{Q\perp}d^2q_{\bar{Q}\perp}dy_Q dy_{\bar{Q}}} = \frac{\alpha_s^2 \overline{S}_\perp}{16\pi^2 C_F}\int d^2l_\perp d^2k_\perp \frac{\Xi_{\text{coll}}(k_{2\perp}, k_\perp - zl_\perp)}{k_{2\perp}^2} F_{\text{TMD}}(l_\perp)\mathcal{N}_{Y_g}(k_\perp)\mathcal{N}_{Y_g}(k_{2\perp} - k_\perp + l_\perp)$$

$$F_{\text{TMD}}(M, l_\perp) = \int \frac{d^2b_\perp}{(2\pi)^2} e^{-ib_\perp \cdot l_\perp} e^{-S_{\text{Sud}}(M, b_\perp)} x_1 G\left(x_1, \mu = \frac{c_0}{b_\perp}\right).$$

Short Summary ||

- Large double logs are essential for Upsilon production.
- Initial state soft gluon radiation can provide double logs. Parton shower > Saturation effect in p+p collisions.
- Rigorous calculation of TMD factorization for quarkonium production in the NRQCD is underway.

Factorization breaking in p+A collisions

Reminder: Effective factorization

Qiu, Sun, Xiao, Yuan (2013)

Consider

$$\Lambda_{\rm QCD} \ll p_\perp \sim Q_s \ll M$$

If $Q_s \sim mv \sim Mv/2$ $\longrightarrow$ v-expansion is unclear

However, at very forward rapidity, Lorentz time dilation gives

$$\frac{1}{mv}\frac{p_\parallel}{M} \gg \frac{1}{p_\perp} \sim \frac{1}{Q_{sA}} \quad \text{or} \quad y \gg \ln\frac{2mv}{p_\perp} \sim \ln\frac{Mv}{Q_{sA}}$$

The QQbar pair's hadronization is effectively frozen when the pair passes through a target.

So, if v is small

$$\frac{1}{mv^2}\frac{p_\parallel}{M} \gg \frac{1}{mv}\frac{p_\parallel}{M} \gg \frac{1}{p_\perp}$$

The effective factorization between the coherent interaction and the hadronization is justified at forward rapidity in CEM and NRQCD.

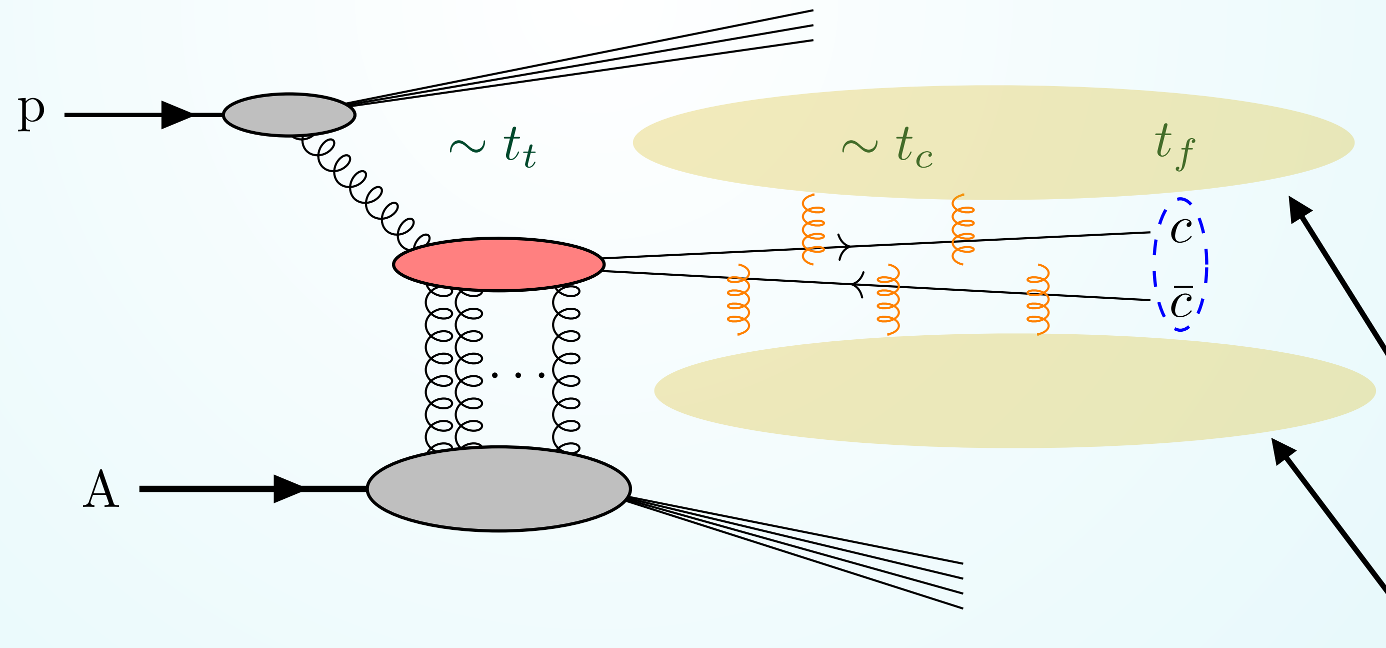
Spectators interaction

We have assumed that the same statement applies to charmonium.

$$\Lambda_{\rm QCD} \ll p_\perp \sim Q_s \sim M$$

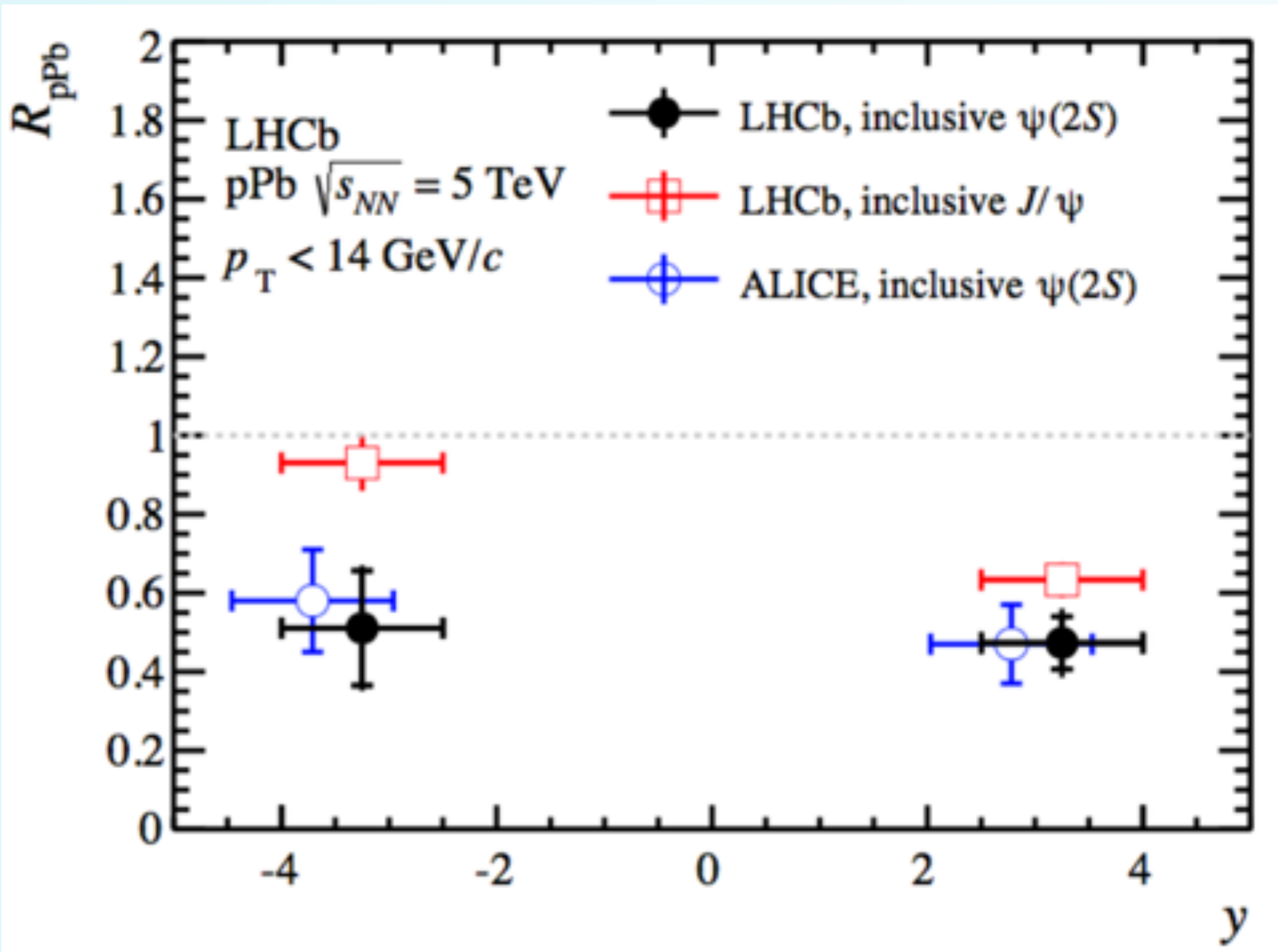
However, we must be careful at low pt because soft color exchanges between spectators and ccbar pair is indispensable.

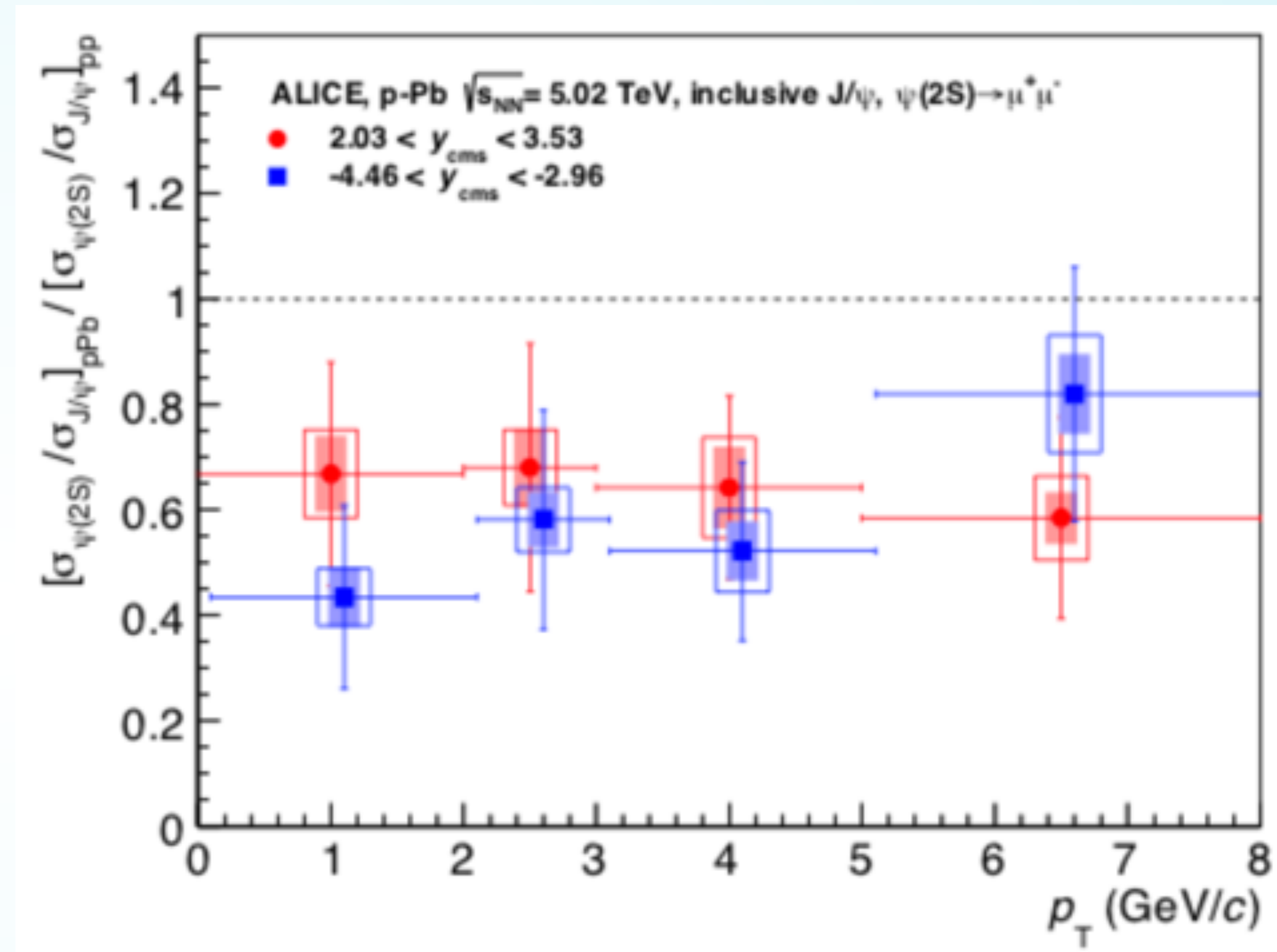
→ Factorization breaking Brodsky, Mueller (1988)



Comover partons emitted at forward rapidity

Psi(2S) anomalous suppression





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.

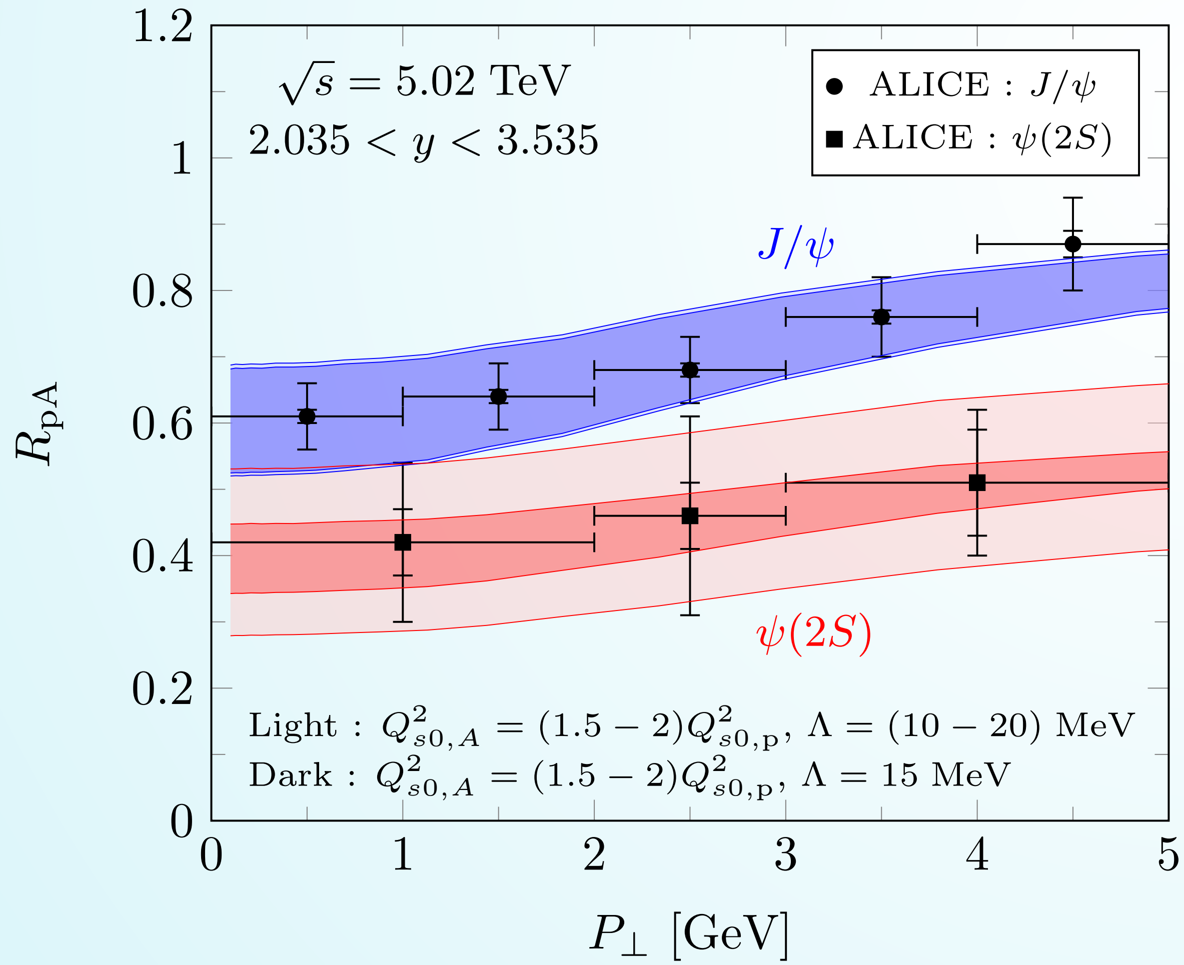
FSI in the CGC+ICEM

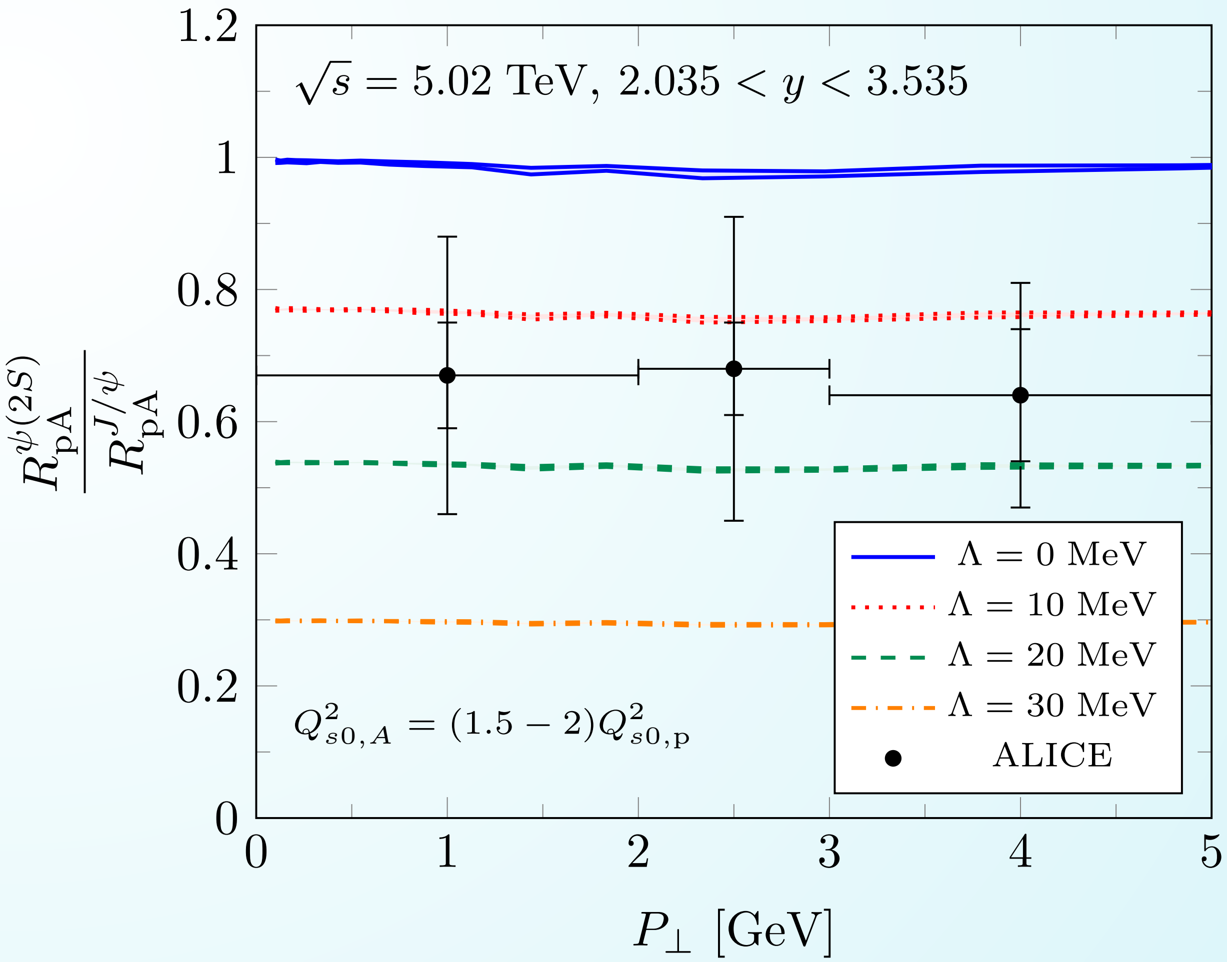
Ma, Venugopalan, KW, Zhang (2017)

Fitted in p+p

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

Assumption: the role of soft color exchanges should be enhanced in p+A collisions.





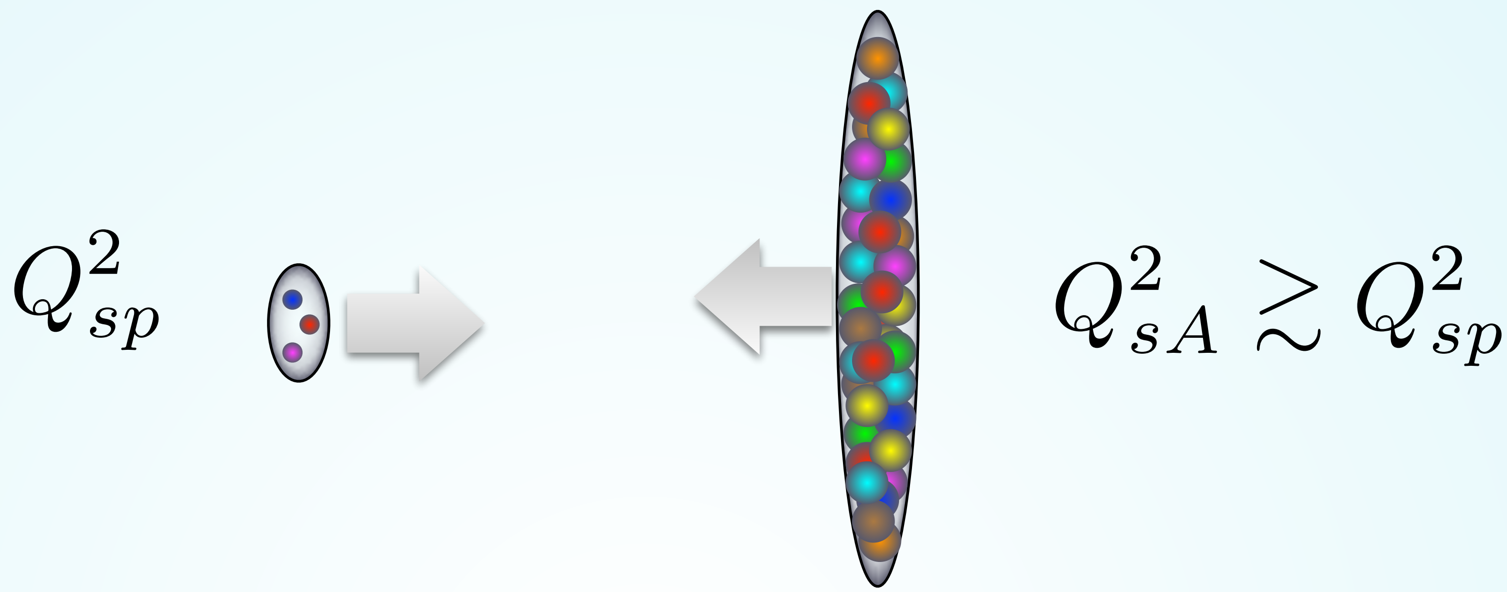
Short Summary III

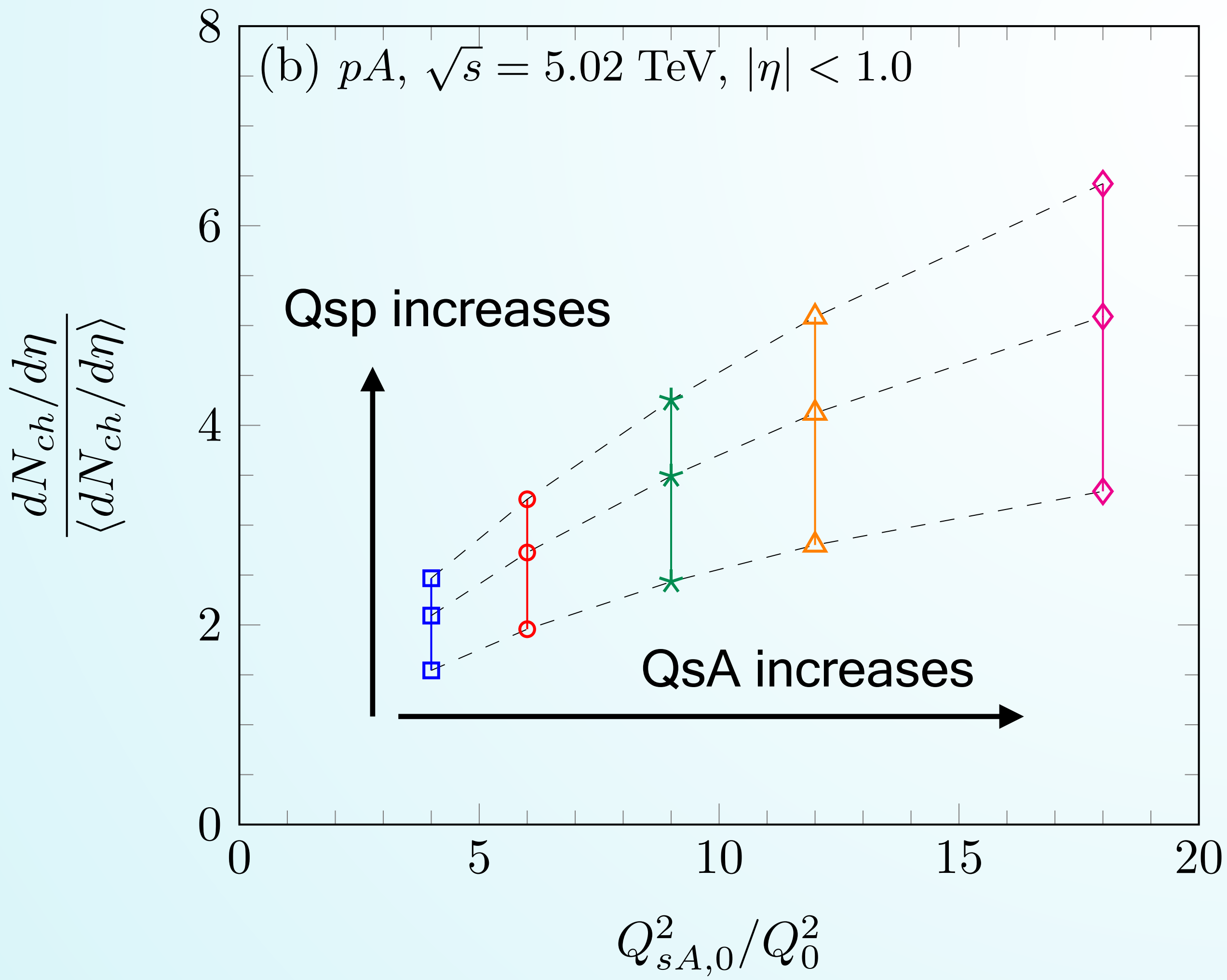
- Spectator interaction breaks strongly factorization for Psi(2S) production. → Color Entanglement between the QQbar pair and spectator partons.
- Need more careful analysis on spectators interaction: higher twist in final state.
- Similar factorization breaking effect could happen in e+A collisions?

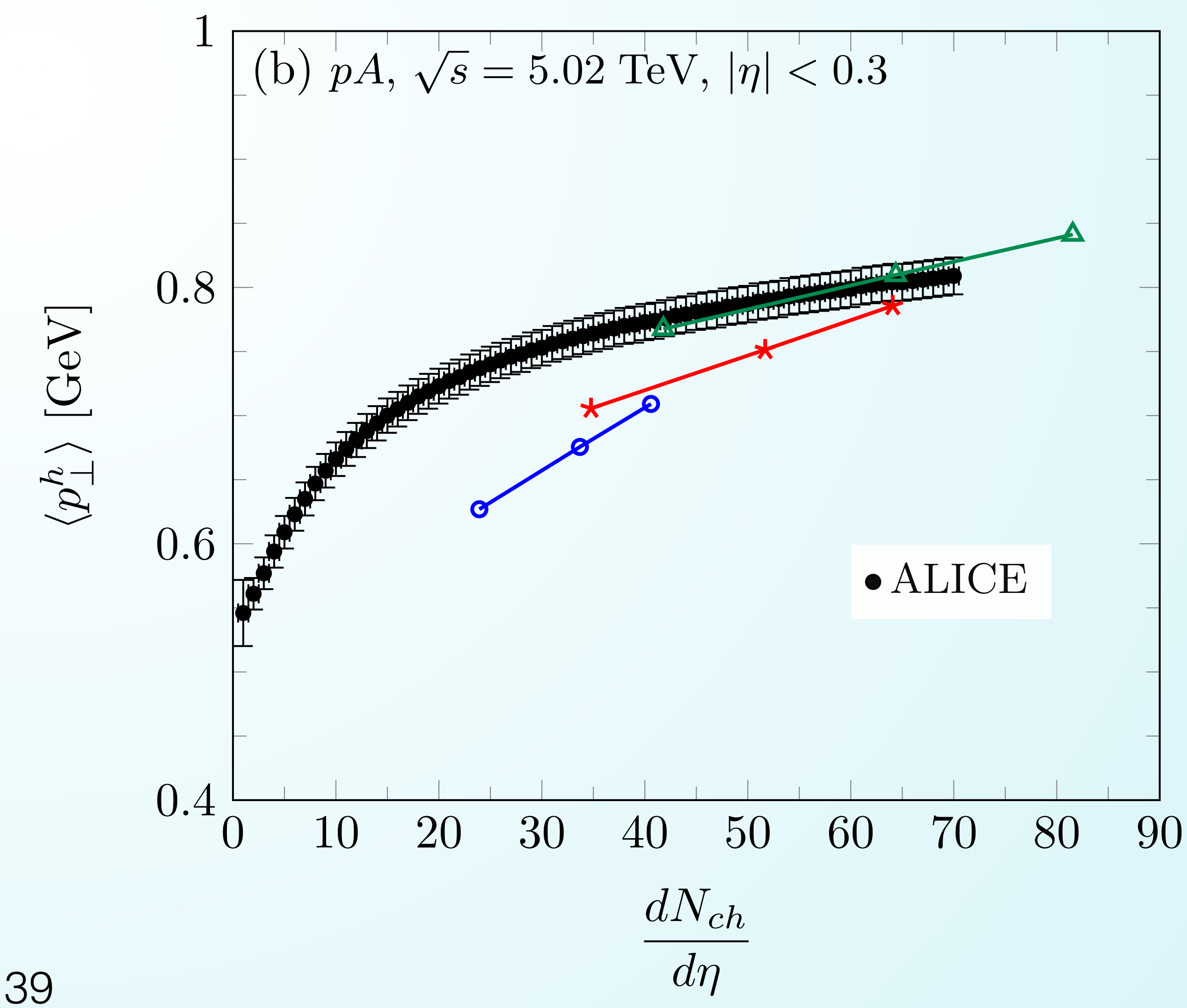
Thank you!

Backup

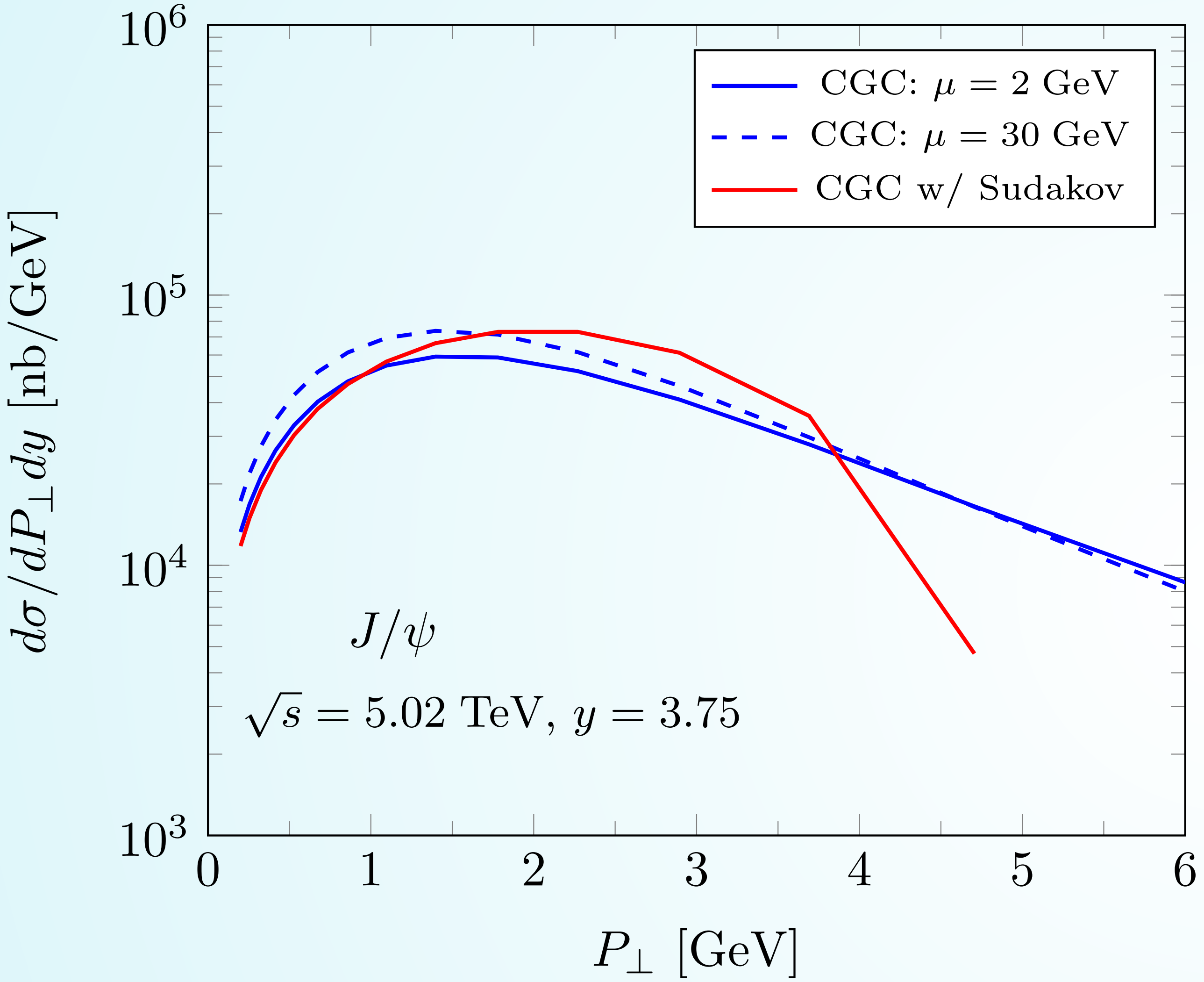
Nch in p+A collisions

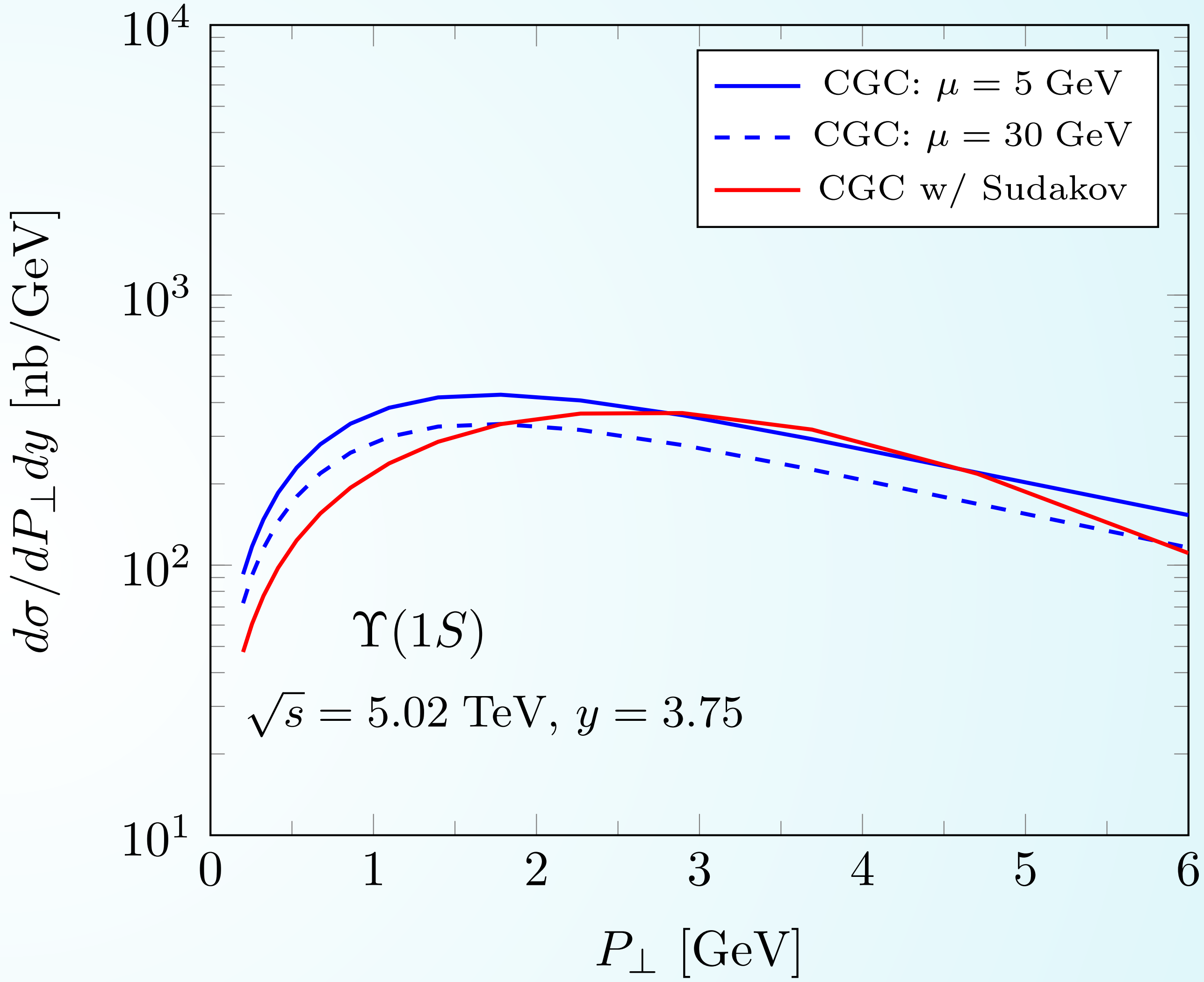






Results in p+A collisions





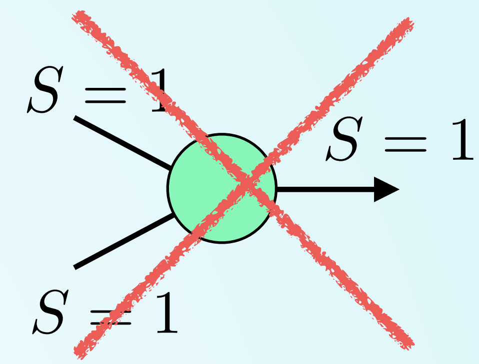
Saturation effect and parton shower effect are comparable in p+A collisions.

Singular spike at low pt

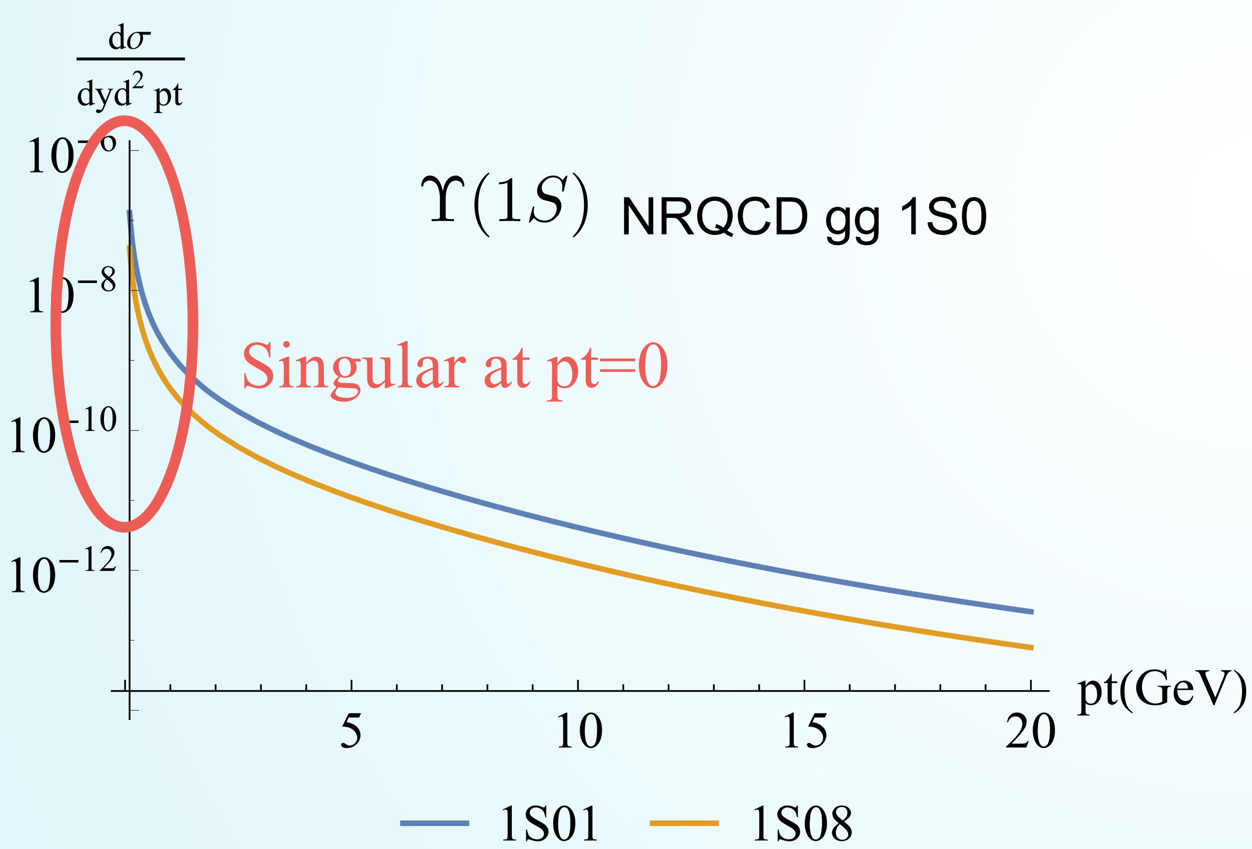
$$\hat{\sigma}_{0,gg}^{{}^1S_0^{[1]}} = \frac{\pi}{M^4}\frac{4}{3}\frac{\pi^2\alpha_s^2}{M}$$

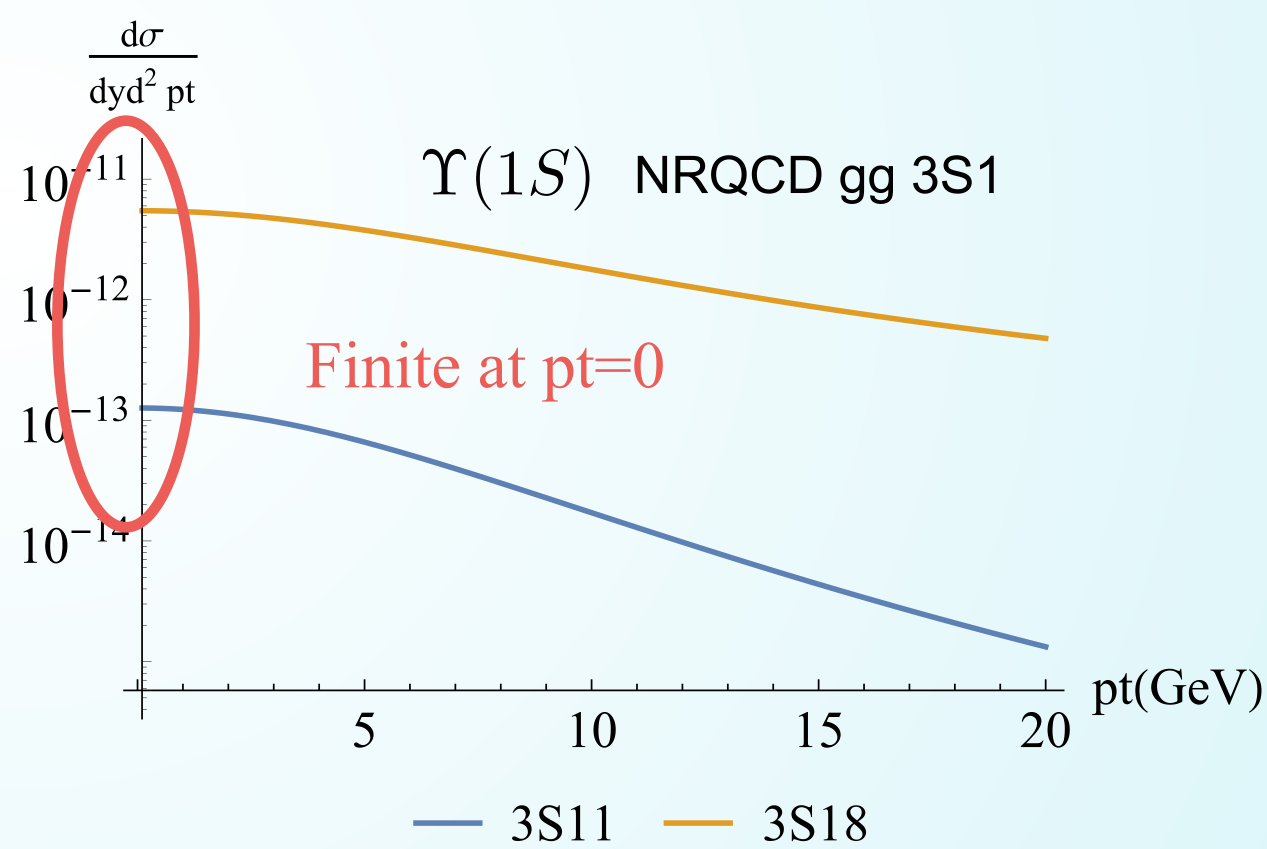
$$\hat{\sigma}_{0,gg}^{{}^1S_0^{[8]}} = \frac{\pi}{M^4}\frac{5}{12}\frac{\pi^2\alpha_s^2}{M}$$

$$\hat{\sigma}_{0,gg}^{{}^3S_1^{[1,8]}} = 0$$



Landau-Yang's theorem





✔Go to resummation

Go to higher order calculations