Linearly Polarized Gluons in J/ψ and Υ Production

Sangem Rajesh

IIT Bombay

HUGS-2016

Jefferson Lab

Thomas Jefferson National Accelerator Facility

Outline

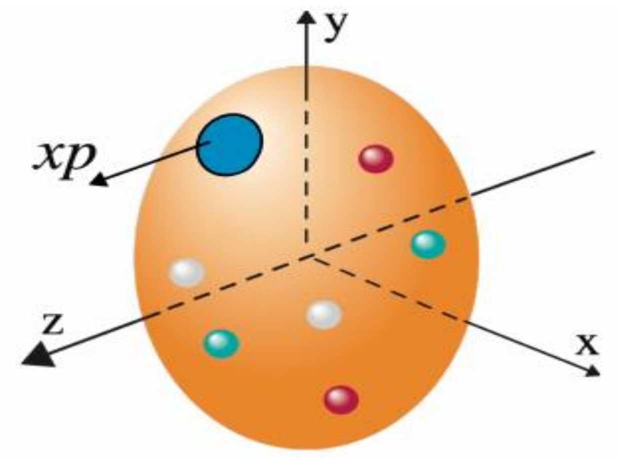
Gluon TMDs

Quarkonium Models

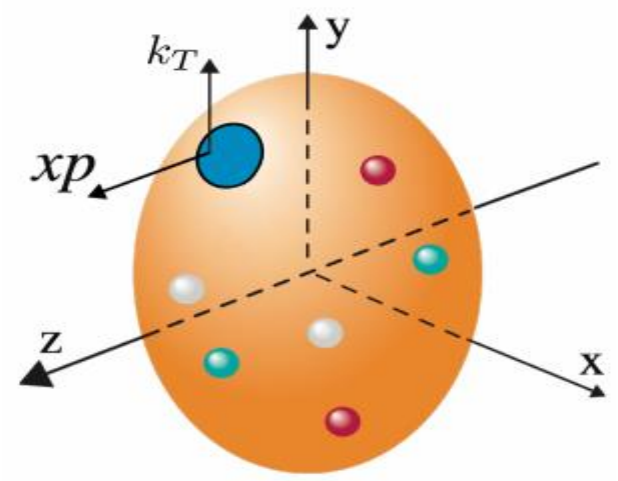
J/ψ **and** Υ **production**

Conclusion

Transverse Momentum Dependent (TMD) Distributions



1D



3D

Collinear pdf $f(x)$

TMD pdf $f(x, k_\perp)$

Universality

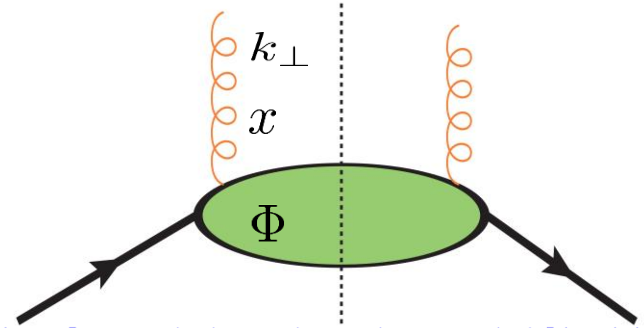
Non-trivial Universality

$$lp \to lX$$

$$lp \to lhX$$

$$pp \to hX$$

Gluon Correlator



$$\Phi_g^{\mu\nu}(x, \mathbf{k}_\perp) = \frac{n_\rho n_\sigma}{(k.n)^2} \int \frac{d(\lambda.\ P) d^2\lambda_T}{(2\pi)^3} e^{ik.\lambda} \langle P| \mathrm{Tr}[F^{\mu\rho}(\lambda) W(\lambda, 0) F^{\nu\sigma}(0)]|P\rangle|_{LF}$$

P. J. Mulders and J. Rodrigues PRD 63 094021(2001)

Parameterization of gluon correlator at "Leading Twist " is

$$= -\frac{1}{2x}\left\{ g_T^{\mu\nu} f_1^g(x, \mathbf{k}_\perp^2) - \left(\frac{k_\perp^\mu k_\perp^\nu}{M_h^2} + g_T^{\mu\nu} \frac{\mathbf{k}_\perp^2}{2M_h^2} \right) h_1^{\perp g}(x, \mathbf{k}_\perp^2) \right\}$$

Gluons / Target	Unpolarized	Circularly	Linearly
Unpolarized	f_1^g		$h_1^{\perp g}$
Longitudinal		g_{1L}^g	
Transverse	$f_{1T}^{\perp g}$	g_{1T}^g	$h_{1T}^g, h_{1T}^{\perp g}$

D. Boer et al. arXive 1507.05267

Linearly Polarized Gluons

No experimental investigation has been carried out to extract the $h_1^{\perp g}$ until now .

★ Theoretical upper bound of $h_1^{\perp g}$ is only known.

D. Boer et al. PRL 106 132001 (2011)

In proton-proton collision

★ $pp \to \gamma\gamma X$ at RHIC — Qiu, Schlegel, Vogelsang, PRL 107, 062001 (2011)

★ $pp \to \Upsilon\gamma X$ at LHC — Dunnen, Lansberg, Pisano, Schlegel, PRL 112, 212001 (2014)

★ $pp \to HX$ — D. Boer et al. PRL 108, 032002 (2012)

★ $pp \to \eta_{c,b}$ or $\chi_{c,b} + X$ at LHCb and AFTER — D. Boer, C. Pisano, PRD 86, 094007 (2012)

In electron-proton scattering

★ $ep \to eQ\bar{Q}X$ *or* $e + jet + jet + X$ — C. Pisano et al. JHEP 10 (2013) 024

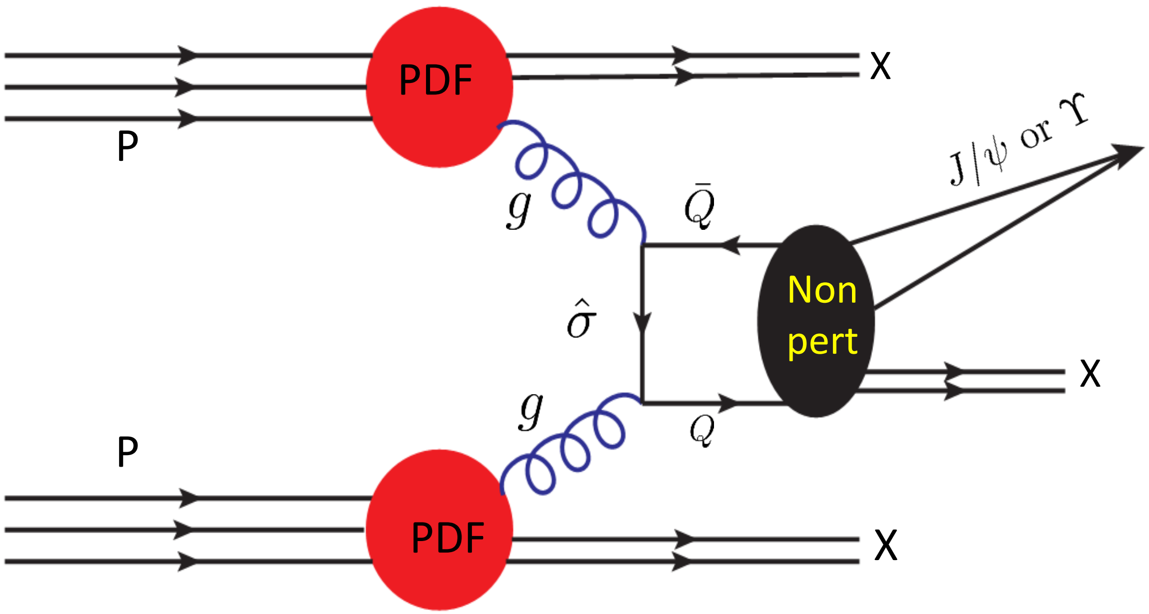
Quarkonium Models

Color Singlet Model (CSM)

Color Octet Model (COM)

Color Evaporation Model (CEM)

$$\sigma_{J/\psi,\Upsilon} = \hat{\sigma} \times \text{Nonperturbative term}$$

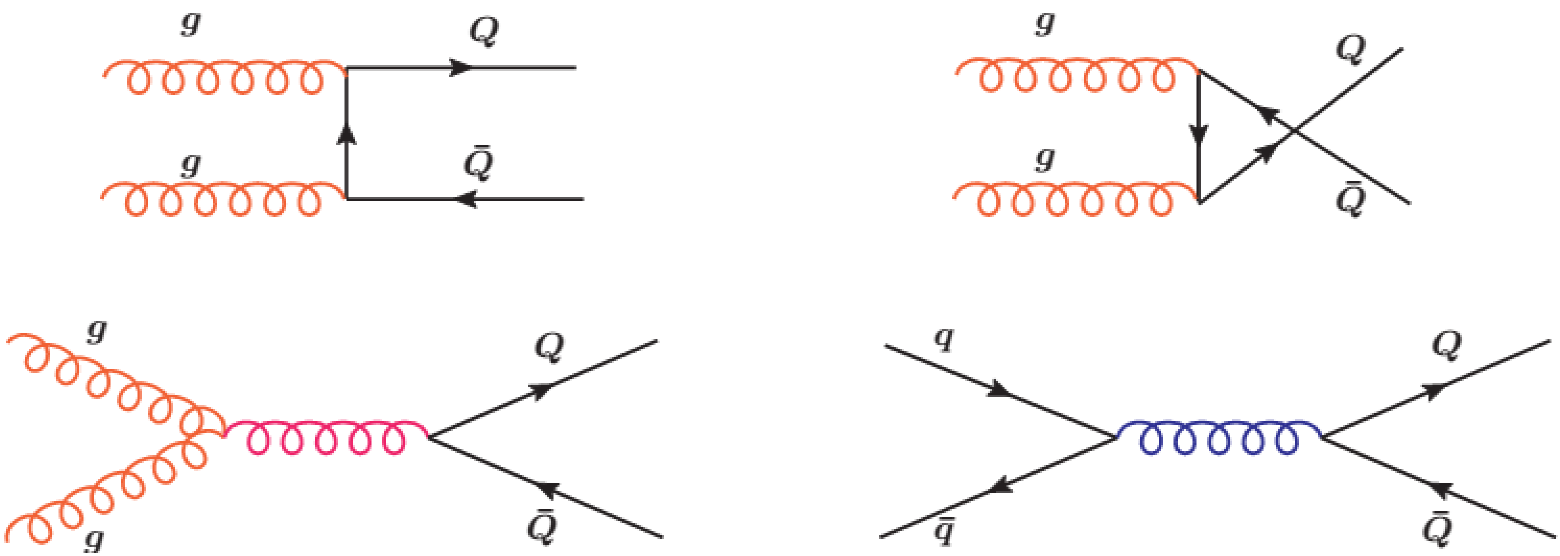


$pp \to J/\psi \ or \ \Upsilon + X$

The cross section for Quarkonium production in CEM is

$$\sigma = \frac{\rho}{9}\int_{2m_Q}^{2m_{Q\bar{q}}} dM \frac{d\hat{\sigma}_{Q\overline{Q}}}{dM}$$

Where $m_Q = m_c(m_b)$ and $m_{Q\bar{q}} = m_D\ (m_B)$ for charmonium (bottomonium)



$pp \to J/\psi \ or \ \Upsilon + X$

Using QCD factorization theorem

$$d\sigma = \frac{\rho}{9}\int dx_a dx_b d^2\mathbf{k}_{\perp a} d^2\mathbf{k}_{\perp b}\left\{\Phi_g^{\mu\nu}(x_a,\mathbf{k}_{\perp a})\Phi_{g\mu\nu}(x_b,\mathbf{k}_{\perp b})d\hat{\sigma}^{gg\to Q\overline{Q}} + \left[\Phi^q(x_a,\mathbf{k}^2_{\perp a})\Phi^{\bar{q}}(x_b,\mathbf{k}^2_{\perp b}) + \Phi^{\bar{q}}(x_a,\mathbf{k}^2_{\perp a})\Phi^q(x_b,\mathbf{k}^2_{\perp b})\right]d\hat{\sigma}^{q\bar{q}\to Q\overline{Q}}\right\}$$

TMDs Parameterization

TMDs exhibit Gaussian distribution

$$f_1^g(x,\mathbf{k}^2_\perp,Q^2) = f_1^g(x,Q^2)\frac{1}{\pi\langle k^2_\perp\rangle}e^{-\mathbf{k}^2_\perp/\langle k^2_\perp\rangle}$$

Evolution in collinear PDFs

No Evolution in $k_\perp$

DGLAP Evolution

$pp \to J/\psi \; or \; \Upsilon + X$

Model independent theoretical upper bound

$$\frac{\mathbf{k}_\perp^2}{2M_h^2} |h_1^{\perp g}(x, \mathbf{k}_\perp^2)| \leq f_1^g(x, \mathbf{k}_\perp^2)$$

D. Boer et al. PRL 106 132001 (2011)

Assuming linearly polarized gluons also exhibit Gaussian form

$$h_1^{\perp g}(x, \mathbf{k}_\perp^2) = \frac{M_h^2 f_1^g(x, Q^2)}{\pi \langle k_\perp^2 \rangle^2} \frac{2(1-r)}{r} e^{1 - \mathbf{k}_\perp^2 \frac{1}{r \langle k_\perp^2 \rangle}}$$

$$0 < r < 1$$

D. Boer, C. Pisano, PRD 86, 094007 (2012)

Differential Cross Section in DGLAP approach

$$\frac{d^2\sigma^{ff}}{dy dq_T^2} = \frac{\beta^2\rho}{36 s\pi^2}\int_{4m_Q^2}^{4m_{Q\bar{q}}^2} dM^2 \int d\phi_{q_T} \int dk_{\perp a} k_{\perp a} \int d\phi_{k_{\perp a}} e^{-\Delta\beta}$$

$$\times \Big\{ f_1^g(x_a) f_1^g(x_b) \hat{\sigma}^{gg\to Q\overline{Q}}(M^2) + \frac{1}{2}\sum_q \left[f_1^q(x_a) f_1^{\bar{q}}(x_b) + f_1^{\bar{q}}(x_a) f_1^q(x_b)\right]$$

$$\times\, \hat{\sigma}^{q\bar{q}\to Q\overline{Q}}(M^2) \Big\}$$

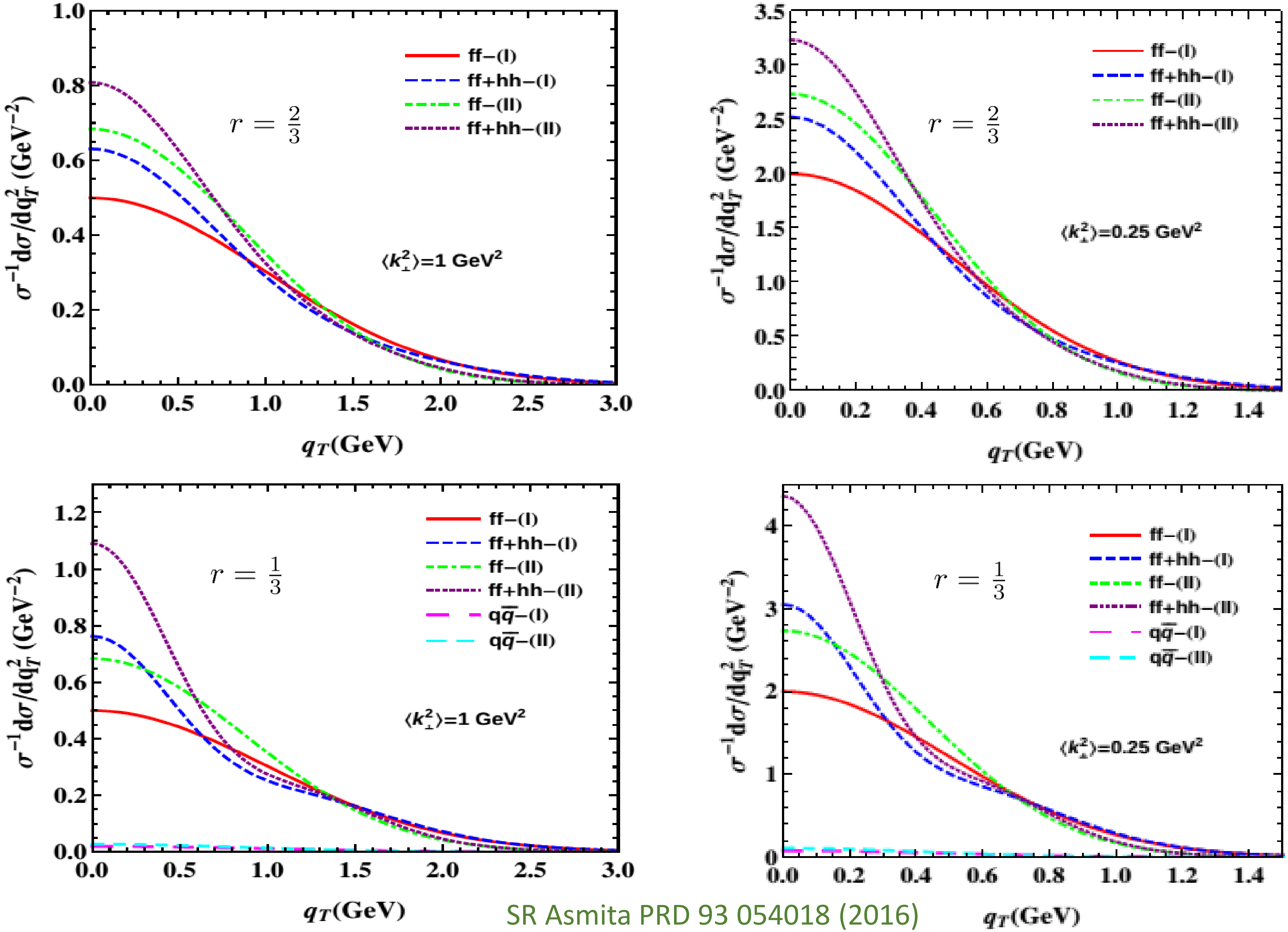
$$\frac{d^2\sigma^{hh}}{dy dq_T^2} = \frac{\beta^4\rho(1-r)^2}{18 s r^2\pi^2}\int_{4m_Q^2}^{4m_{Q\bar{q}}^2} dM^2 \int d\phi_{q_T} \int dk_{\perp a} k_{\perp a} \int d\phi_{k_{\perp a}}$$

$$\times \left[\frac{1}{2}k_{\perp a}^4 - \frac{1}{2}k_{\perp a}^2 q_T^2 - q_T k_{\perp a}^3 \cos(\phi_{k_{\perp a}} - \phi_{q_T}) + q_T^2 k_{\perp a}^2 \cos^2(\phi_{k_{\perp a}} - \phi_{q_T})\right]$$

$$\times\, e^{[2-\frac{\beta}{r}\Delta]} f_1^g(x_a) f_1^g(x_b) \hat{\sigma}^{gg\to Q\overline{Q}}(M^2)$$

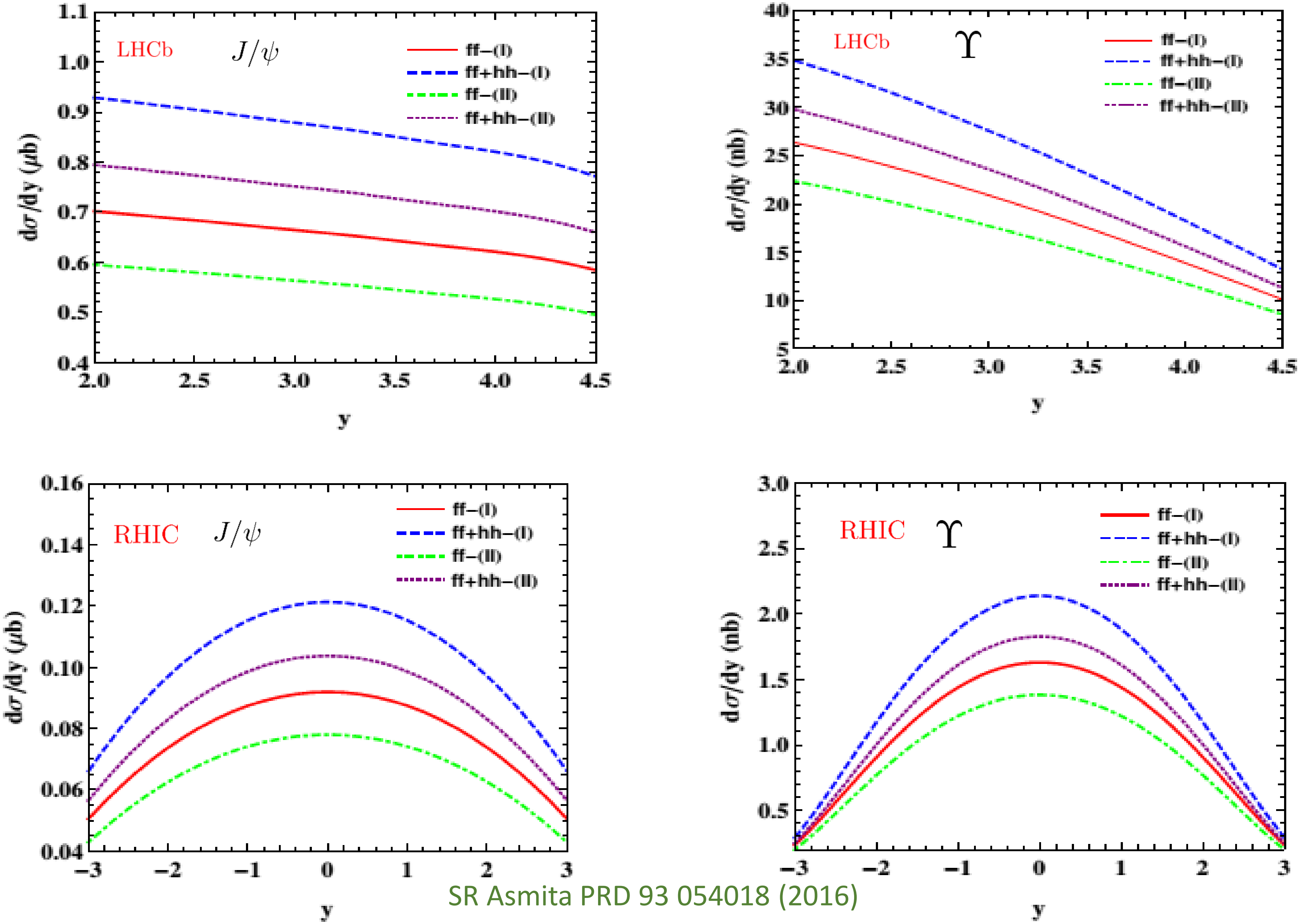
where $\Delta = 2k_{\perp a}^2 + q_T^2 - 2q_T k_{\perp a}\cos(\phi_{k_{\perp a}} - \phi_{q_T})$ and $\beta = \frac{1}{\langle k_\perp^2\rangle}$

q_T Spectrum in DGLAP Evolution



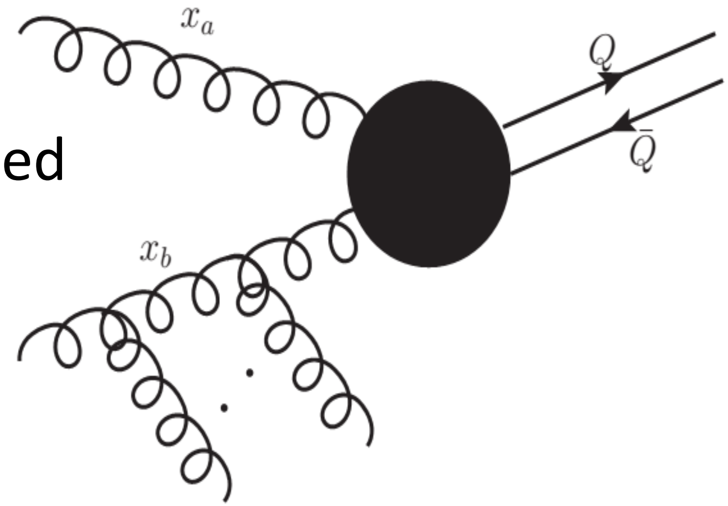
SR Asmita PRD 93 054018 (2016)

Rapidity Spectrum in DGLAP Evolution



SR Asmita PRD 93 054018 (2016)

Resummation of Sudakov logarithms



The region of low q_T is strongly influenced by initial state gluon radiation showers

These additional gluon radiation from initial state partons leads to logarithmic corrections for each gluon radiation of the form

$$\alpha_s \log(\frac{Q^2}{q_T^2})$$

Collins Soper Sterman (CSS) resummation formalism has been used to resum the large logarithmic terms to all order in α_s

TMD Evolution

CSS TMD Evolution

J. Collins, Foundations of Perturbative QCD, 2011

$$f(x,b_\perp,Q_f,\zeta) = f(x,b_\perp,Q_i,\zeta)R_{pert}\left(Q_f,Q_i,b_*\right)R_{NP}\left(Q_f,Q_i,b_\perp\right)$$

$$R_{pert}\left(Q_f,Q_i,b_*\right) = \exp\left\{-\int_{Q_i}^{Q_f}\frac{d\mu}{\mu}\left(A\log\left(\frac{Q_f^2}{\mu^2}\right)+B\right)\right\}$$

$$R_{NP} = \exp\left\{-\left[\frac{g_2}{2}\log\frac{Q_f}{2Q_0}+\frac{g_1}{2}\left(1+2g_3\log\frac{10xx_0}{x_0+x}\right)\right]b_\perp^2\right\}$$

D. Boer, W. J. den Dunnen, Nucl. Phys. B **886** (2014) 421

$$\text{where } Q_i = \frac{2e^{-0.577}}{b_*},\; Q_f = Q \text{ and } \zeta = Q_f^2$$

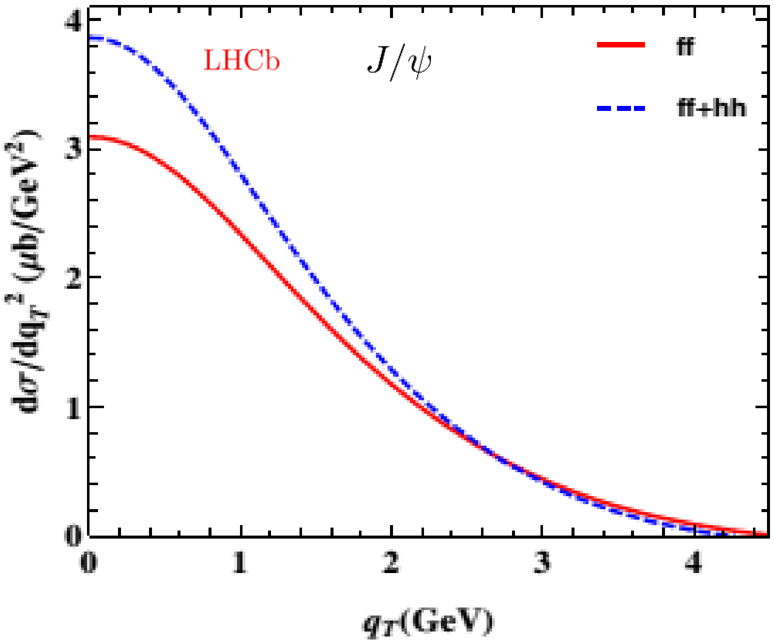
$$b_* = \frac{b_\perp}{\sqrt{1+(\frac{b_\perp}{b_{\max}})^2}} \quad,\quad A = \sum_{n=1}^{\infty}\left(\frac{\alpha_s(\mu)}{\pi}\right)^n A_n\,,\; B = \sum_{n=1}^{\infty}\left(\frac{\alpha_s(\mu)}{\pi}\right)^n B_n$$

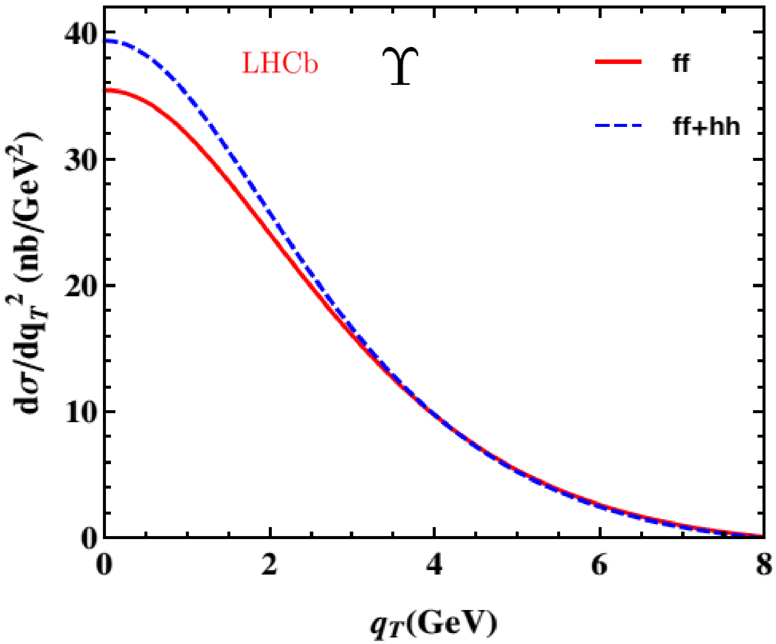
Differential Cross Section in TMD Evolution approach

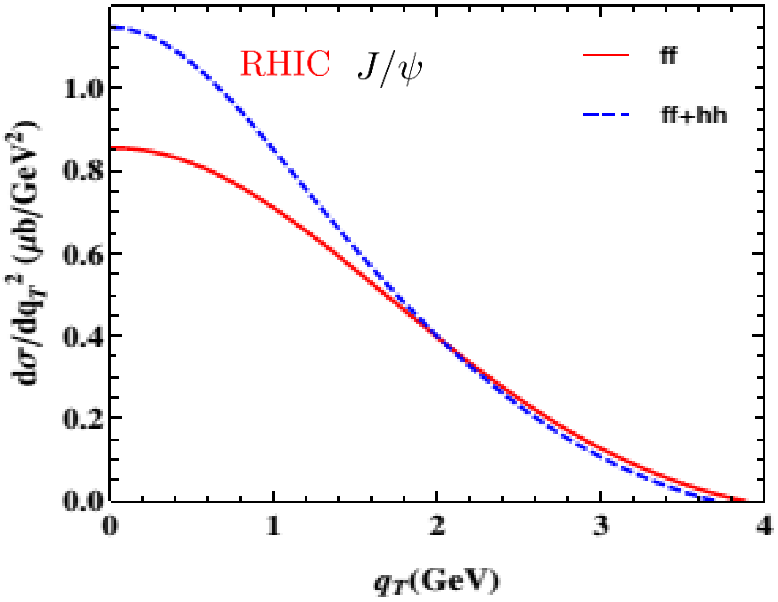
$$\frac{d^2\sigma^{ff}}{dydq_T^2} = \frac{\rho}{36s}\int_{4m_Q^2}^{4m_{Q\bar{q}}^2} dM^2 \int_0^\infty b_\perp db_\perp J_0(q_T b_\perp) f_1^g(x_a, c/b_*) f_1^g(x_b, c/b_*) \hat{\sigma}^{gg\to Q\overline{Q}}(M^2)$$
$$\exp\left\{-2\int_{c/b_*}^{Q}\frac{d\mu}{\mu}\left(A\log\left(\frac{Q^2}{\mu^2}\right)+B\right)\right\}\exp\left\{-\left[0.184\log\frac{Q}{2Q_0}+0.332\right]b_\perp^2\right\}$$

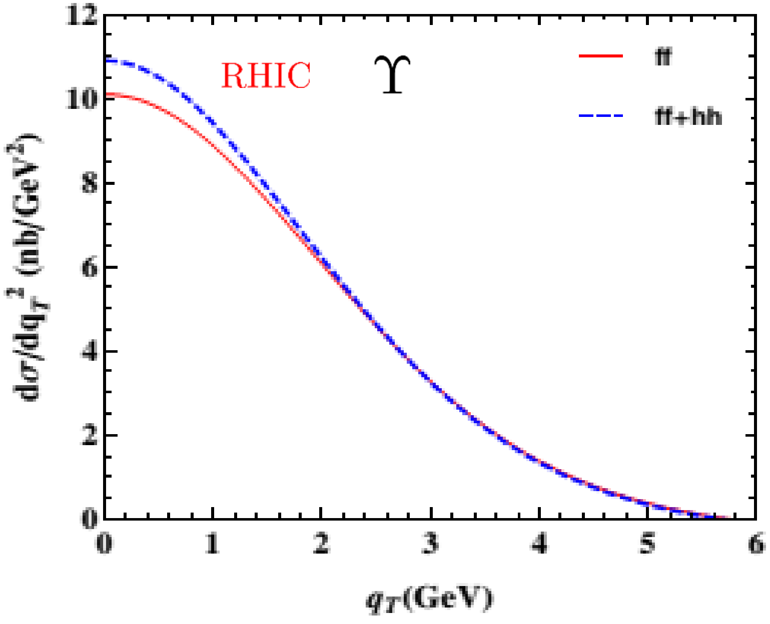
$$\frac{d^2\sigma^{hh}}{dydq_T^2} = \frac{\rho C_A^2}{36s\pi^2}\int_{4m_Q^2}^{4m_{Q\bar{q}}^2} dM^2 \int_0^\infty b_\perp db_\perp J_0(q_T b_\perp)\alpha_s^2(c/b_*)\hat{\sigma}^{gg\to Q\overline{Q}}(M^2)$$
$$\int_{x_a}^{1}\frac{dx_1}{x_1}\left(\frac{x_1}{x_a}-1\right) f_1^g(x_1, c/b_*)\int_{x_b}^{1}\frac{dx_2}{x_2}\left(\frac{x_2}{x_b}-1\right) f_1^g(x_2, c/b_*)$$
$$\exp\left\{-2\int_{c/b_*}^{Q}\frac{d\mu}{\mu}\left(A\log\left(\frac{Q^2}{\mu^2}\right)+B\right)\right\}\exp\left\{-\left[0.184\log\frac{Q}{2Q_0}+0.332\right]b_\perp^2\right\}$$

q_T Spectrum in TMD Evolution

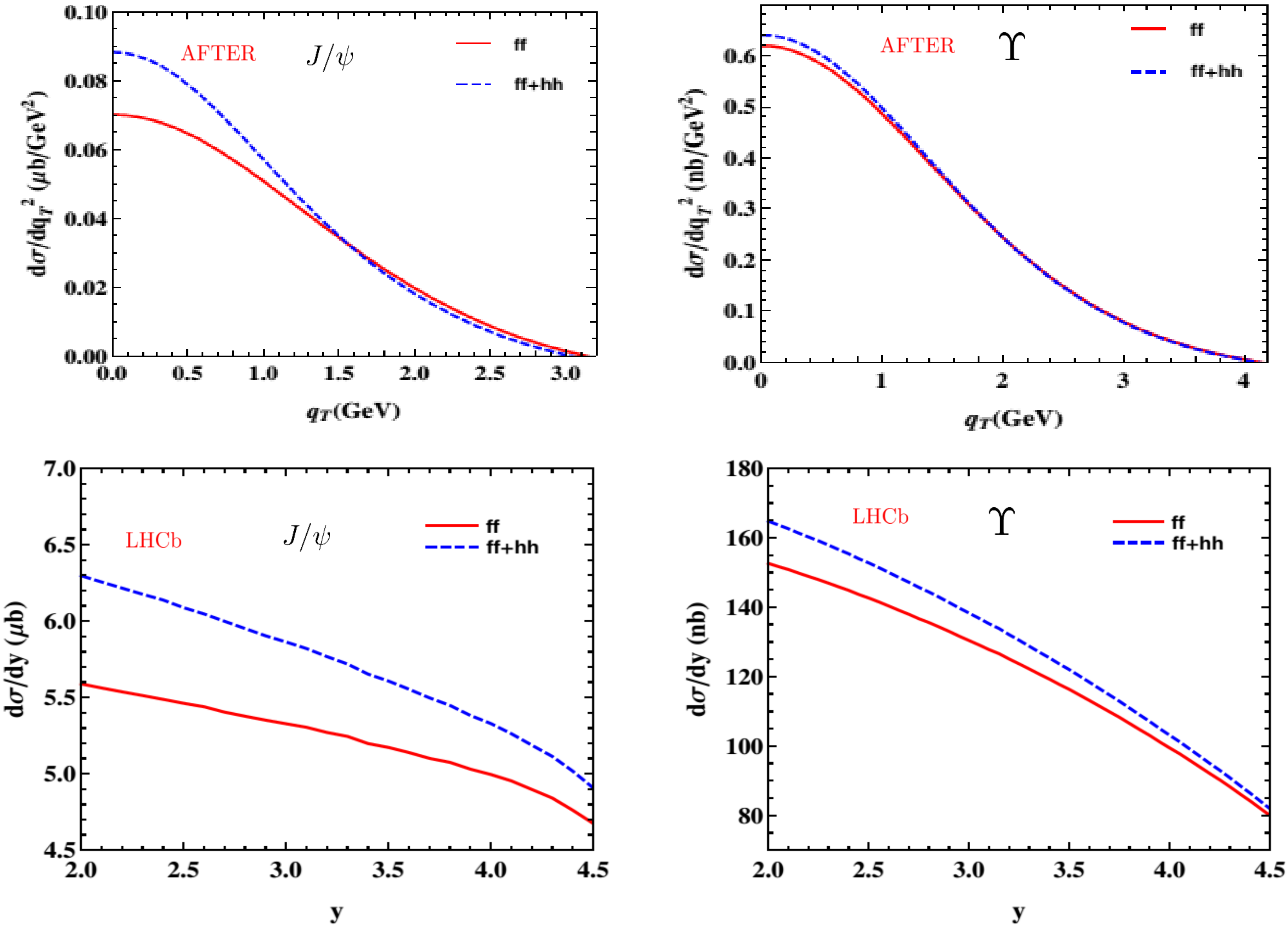








Results in TMD Evolution



Conclusion

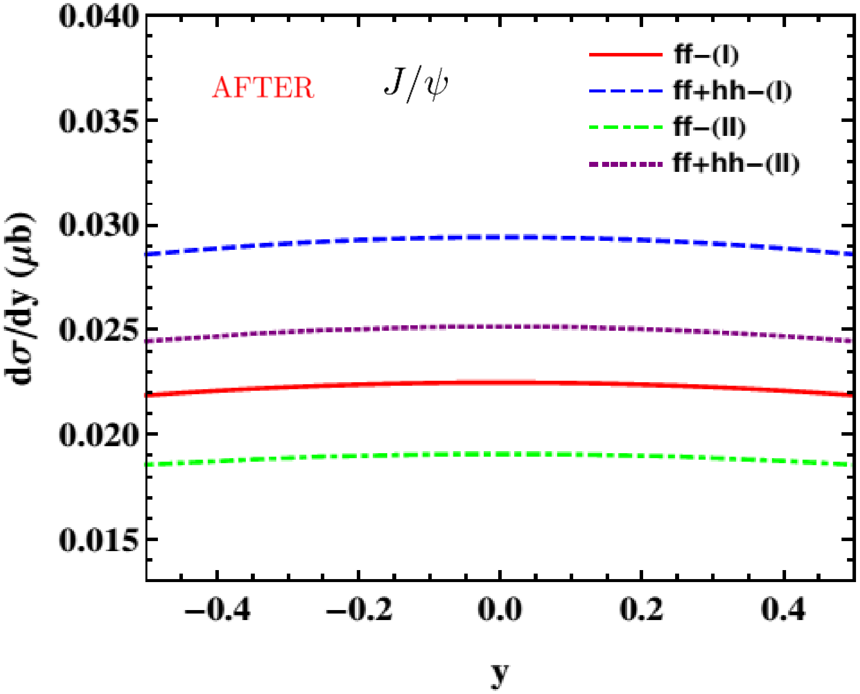
- The q_T and y distributions of quarkonium can been modulated by the presence of linearly polarized gluons in unpolarized proton proton collision.

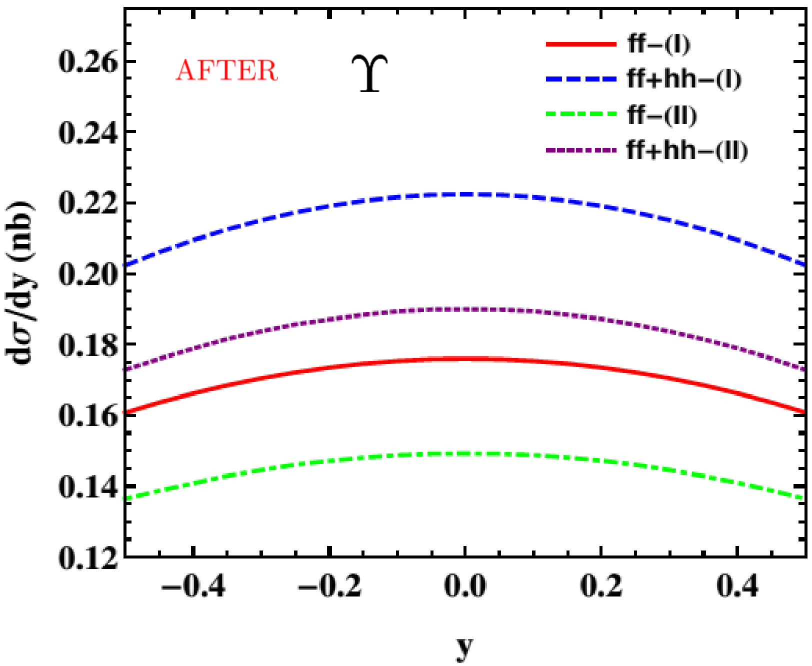
- Hence, the production of quarkonium is a promising process to probe not only the $h_1^{\perp g}$ but also unpolarized TMD pdf f_1^g.

- It would be interesting to include the linearly polarized gluon contribution in the cross section to fit the experimental data to the extent of reasonable accuracy.

Thank you

Rapidity Spectrum in DGLAP Evolution

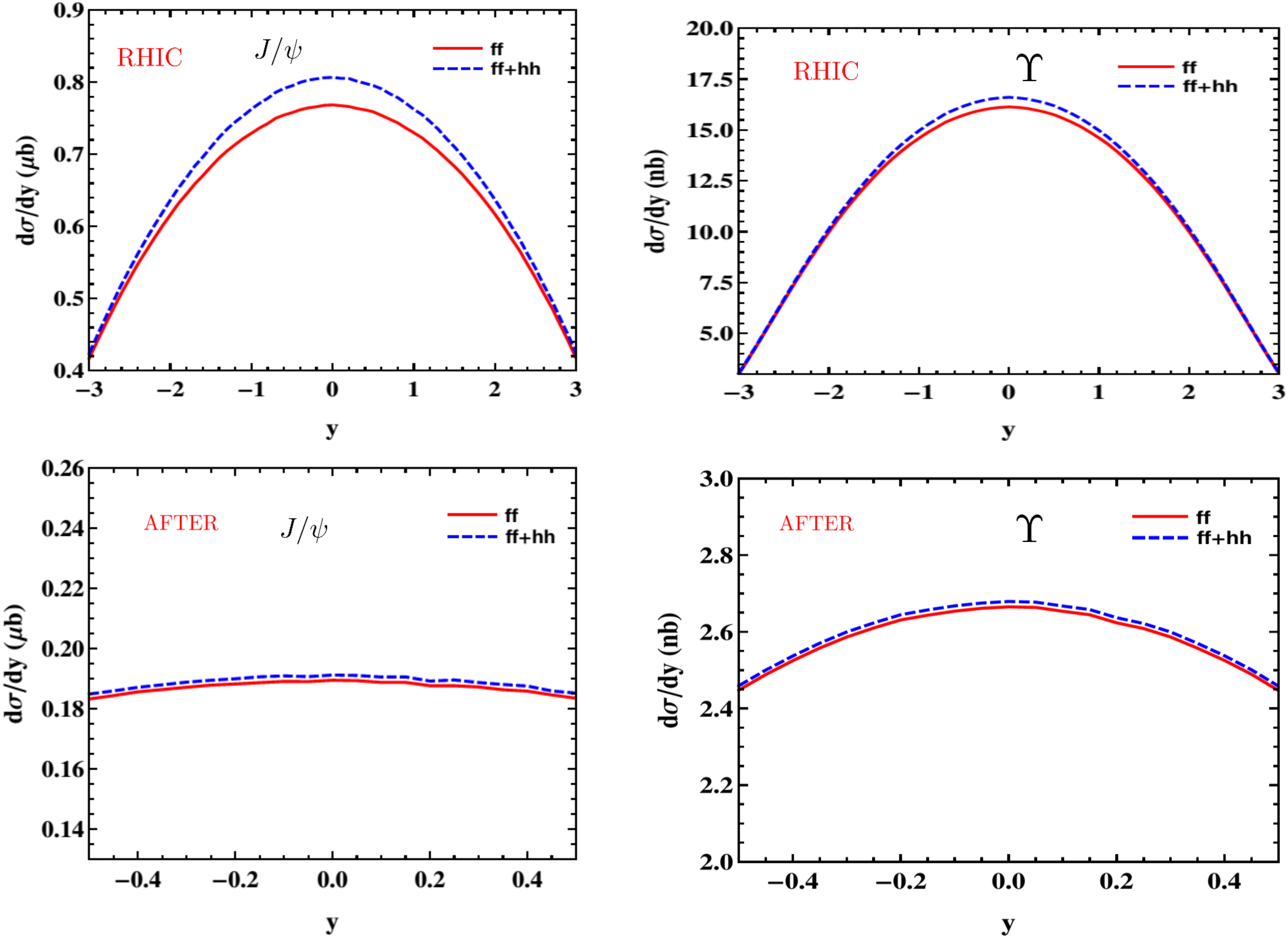




$$r = \frac{1}{3}$$

$$\langle k_\perp^2 \rangle = 1 \text{ GeV}^2$$

Backup Rapidity Spectrum in TMD Evolution



Backup DGLAP and TMD Comparison