Linearly Polarized Gluons in J/ψ and Υ Production

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Outline

Gluon TMDs

Quarkonium Models

J/ψ **and** Υ **production**

Conclusion

Parton Distribution Functions (PDFs)

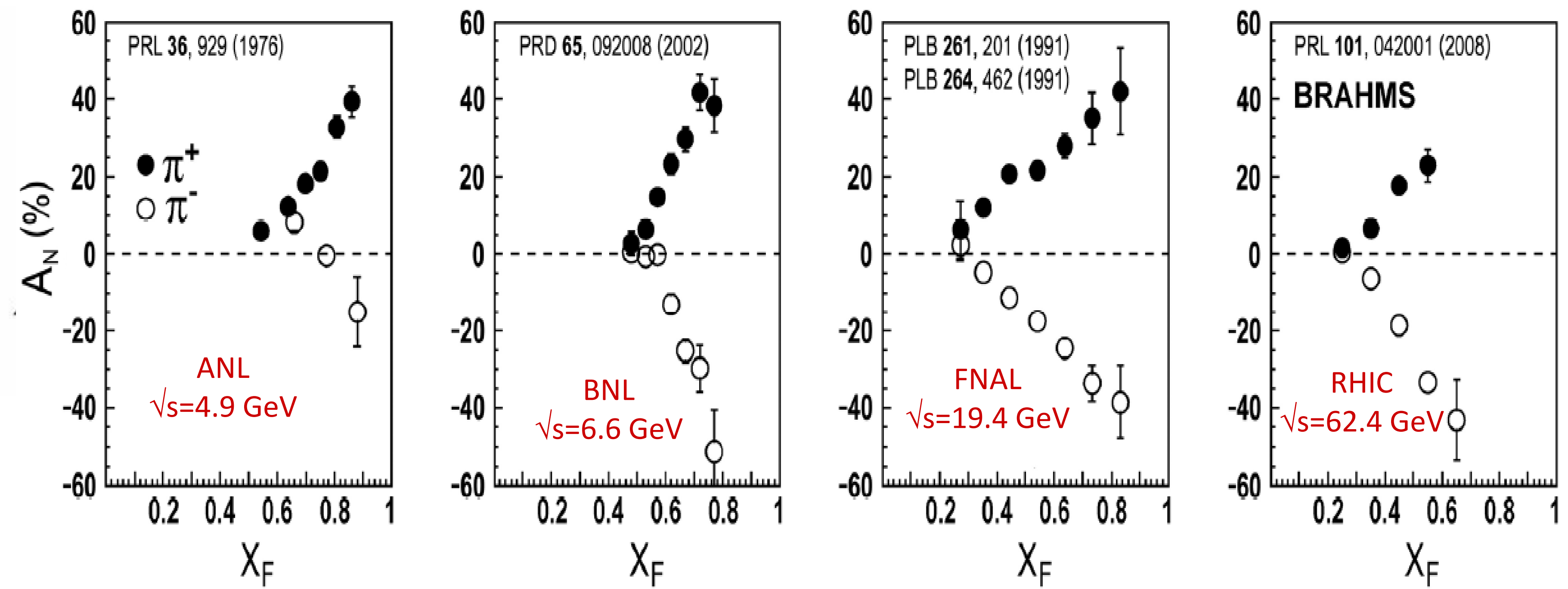


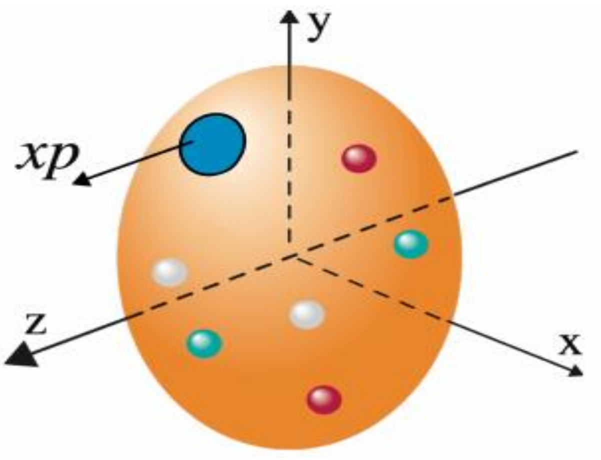
Figure by C. Aidala

- In 1990, D. Sivers proposed that SSA can be explained by considering correlation between transverse momentum of parton and polarization of hadron.

$$f(x) \rightarrow f(x, k_\perp)$$

$$f_{a/p^\uparrow}(x, \mathbf{k}_\perp) = f_{a/p}(x, \mathbf{k}_\perp) + \frac{1}{2}\Delta^N_{a/p}(x, \mathbf{k}_\perp)\hat{\mathbf{S}}.(\hat{\mathbf{P}} \times \hat{\mathbf{k}}_\perp)$$

Transverse Momentum Dependent (TMD) Distributions

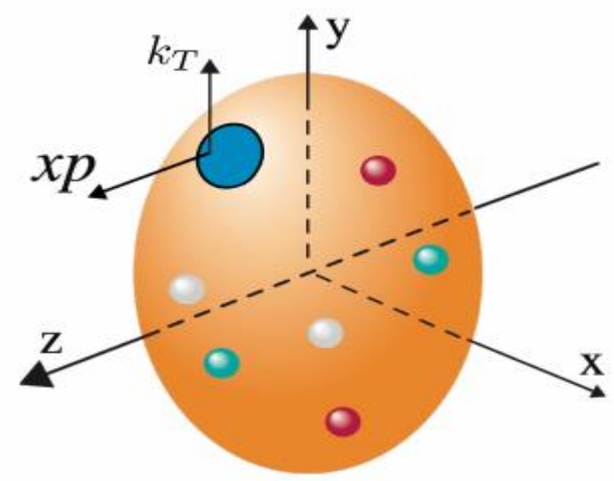


1D

Collinear pdf $f(x)$

Universality

$$lp \to lX$$



3D

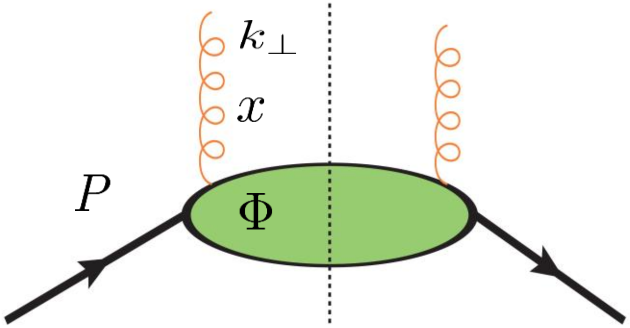
TMD pdf $f(x, k_\perp)$

Non-trivial Universality

$$lp \to lhX$$

$$pp \to hX$$

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

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

Unpolarized gluon TMD

Linearly polarized gluon TMD

Leading Twist Gluon TMDs

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

Boer-Mulders ($h_1^{\perp g}$)

Kotzinian-Mulders ($h_{1L}^{\perp g}$)

Sivers ($f_{1T}^{\perp g}$)

Pretzelosity ($h_{1T}^{\perp g}$)

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 $$\frac{\mathbf{k}_\perp^2}{2M_h^2}|h_1^{\perp g}(x,\mathbf{k}_\perp^2)| \leq f_1^g(x,\mathbf{k}_\perp^2)$$ D. Boer et al. PRL 106 132001 (2011)

In proton-proton collision

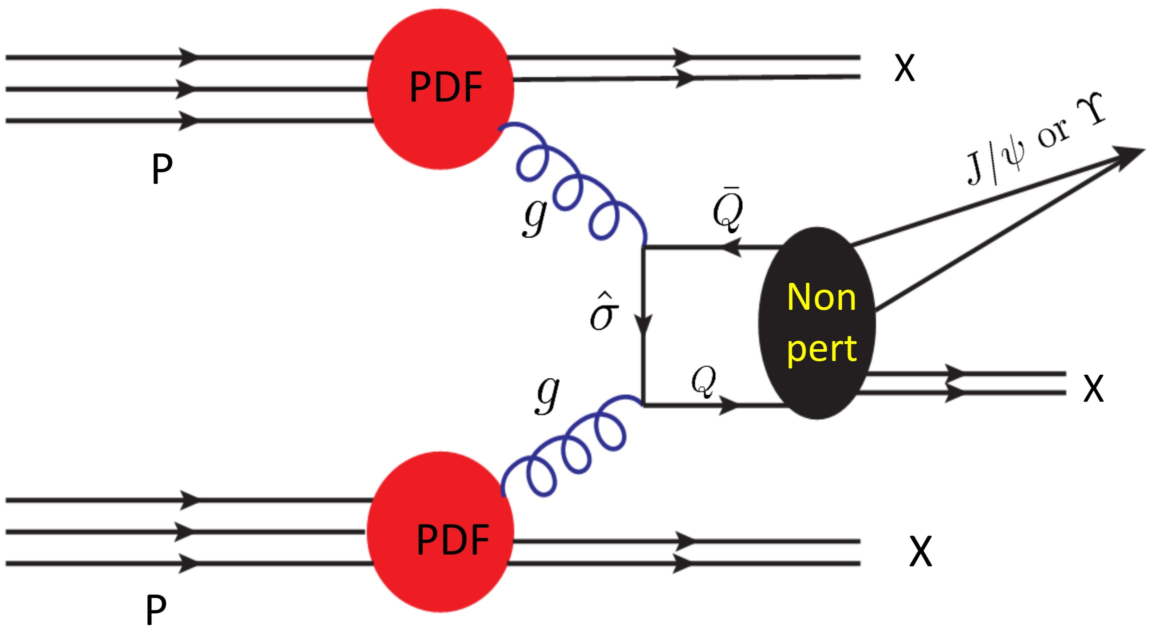
- $pp \to \gamma\gamma X$ at RHIC — Qiu, Schlegel, Vogelsang, PRL 107, 062001 (2011)
- $pp \to \Upsilon\gamma X$ at LHC — Dunnen, Lansberg, Pisano, Schlegel, PRL 112, 212001 (2014)
- $pp \to HX$ — D. Boer et al. PRL 108, 032002 (2012)
- $pp \to \eta_{c,b}$ or $\chi_{c,b} + X$ at LHCb and AFTER — D. Boer, 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

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

Quarkonium Models



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

Color Singlet Model (CSM)

Color Octet Model (COM)

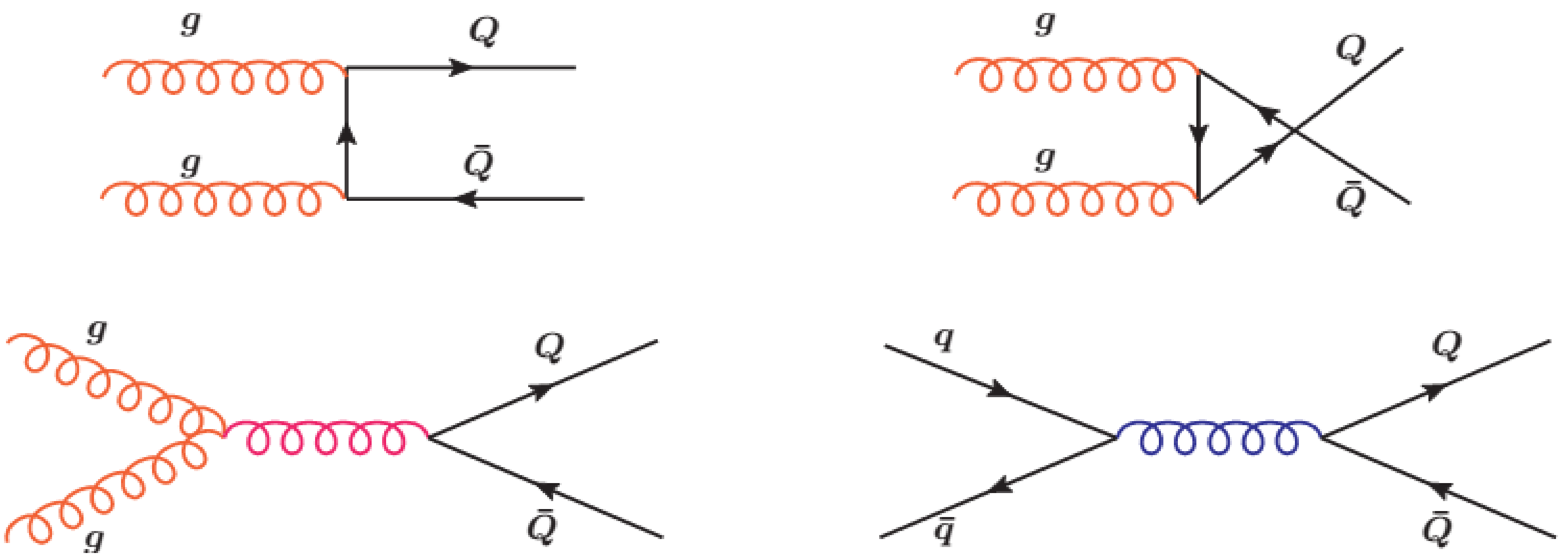
Color Evaporation Model (CEM)

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

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

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

$$\left[\Phi^q(x_a,\mathbf{k}^2_{\perp a})\Phi^{\bar{q}}(x_b,\mathbf{k}^2_{\perp b}) + \Phi^{\bar{q}}(x_a,\mathbf{k}^2_{\perp a})\Phi^q(x_b,\mathbf{k}^2_{\perp b})\right]d\hat{\sigma}^{q\bar{q}\to Q\overline{Q}}\Big\}$$

Convolution of TMDs is

$$C[wh_1^{\perp g}h_1^{\perp g}] = \int d^2\mathbf{k}_{\perp a}\int d^2\mathbf{k}_{\perp b}\delta^2(\mathbf{k}_{\perp a}+\mathbf{k}_{\perp b}-\mathbf{q}_T)wh_1^{\perp g}(x_a,\mathbf{k}^2_{\perp a})h_1^{\perp g}(x_b,\mathbf{k}^2_{\perp b})$$

$$\text{where } w = \frac{1}{2M^4}\left[(\mathbf{k}_{\perp a}.\mathbf{k}_{\perp b})^2 - \frac{1}{2}\mathbf{k}^2_{\perp a}\mathbf{k}^2_{\perp b}\right]$$

$$\int d^2\mathbf{q}_T(\mathbf{q}_T^2)^\alpha C[wh_1^{\perp g}h_1^{\perp g}] = 0 \qquad \alpha = 0,1$$

Model Independent property

$\alpha = 0 \implies$ Linearly polarized gluons do not affect the $\mathbf{q}_T$-integrated cross section

$\alpha = 1 \implies$ At least two nodes in $\mathbf{q}_T$

TMDs Parameterization

TMDs exhibit Gaussian distribution

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

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

$$0 < r < 1$$

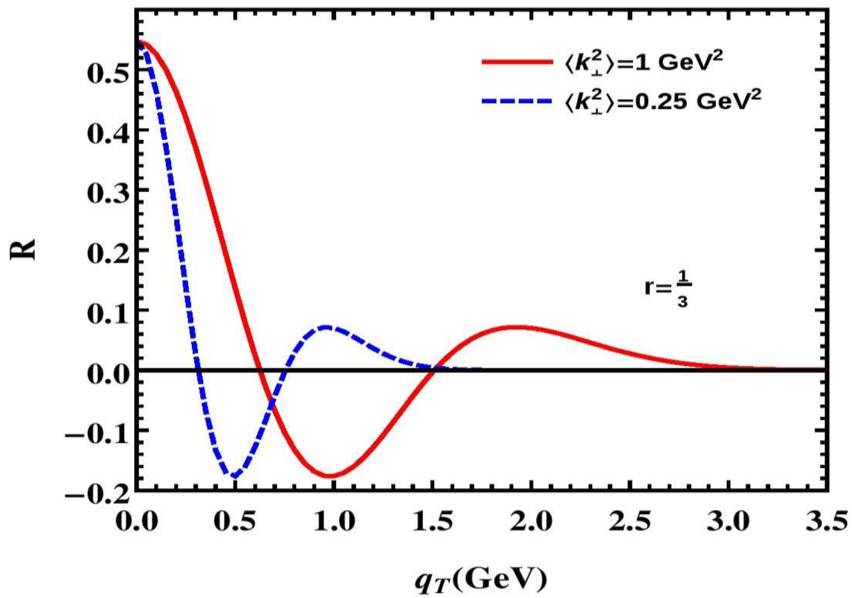
Evolution in collinear PDFs

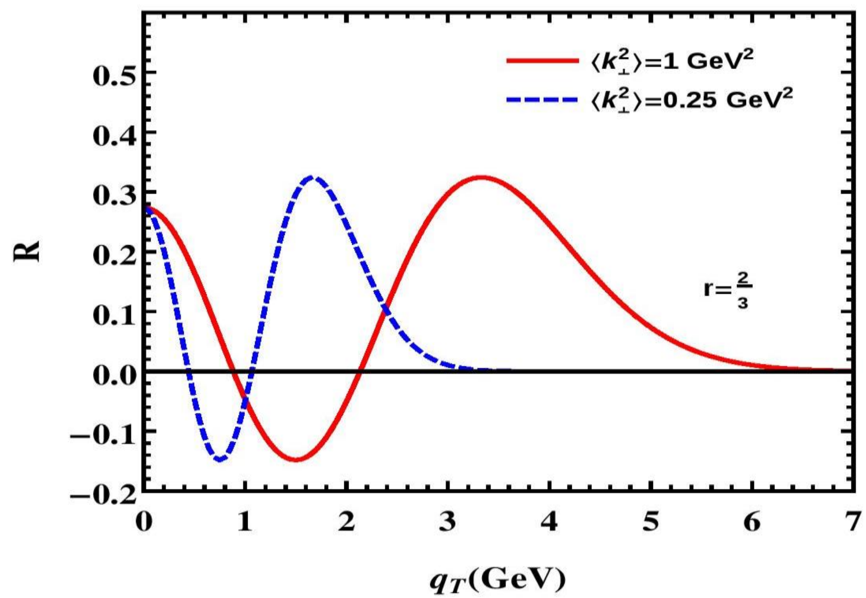
No Evolution in $k_\perp$

DGLAP Evolution

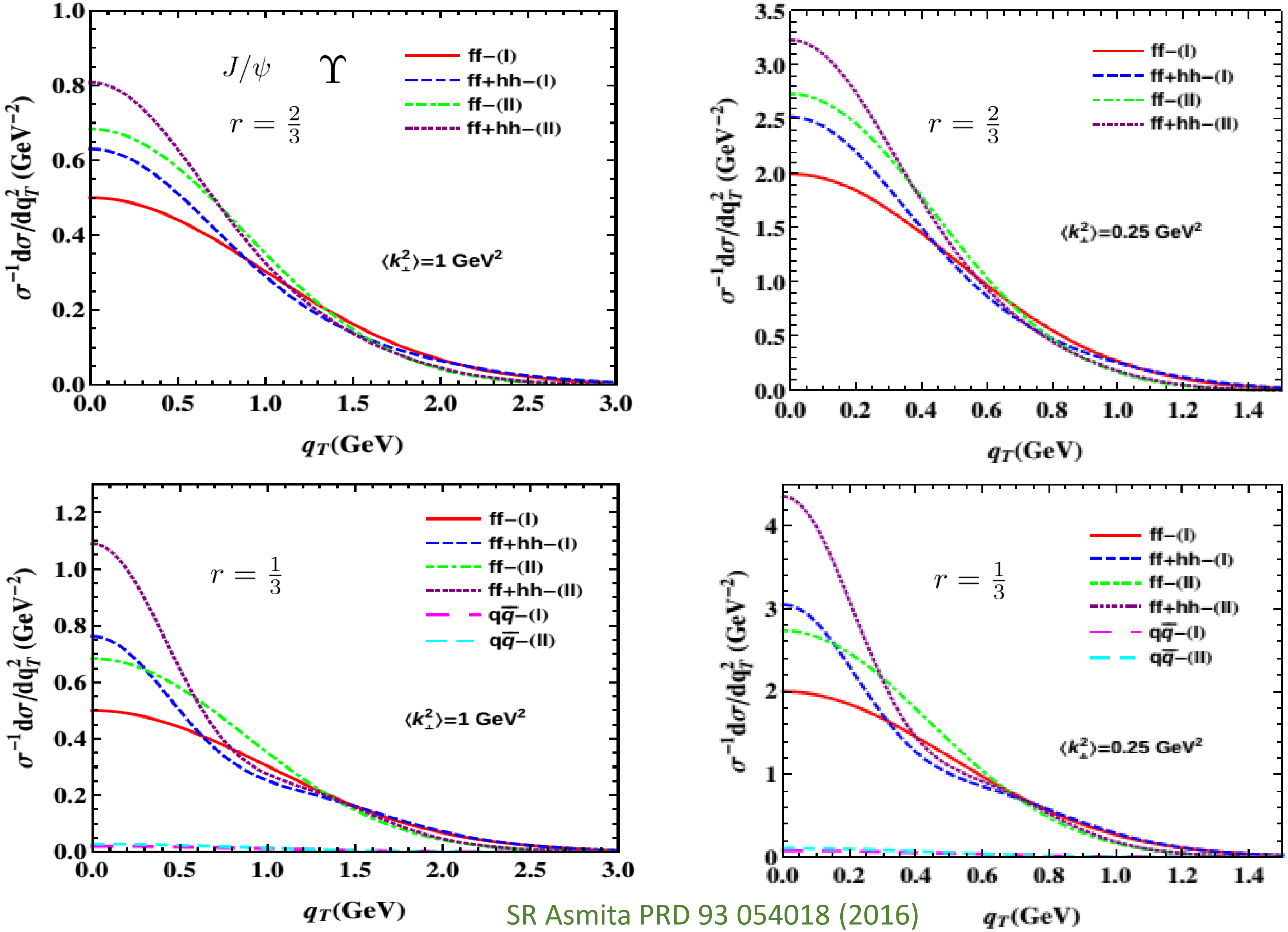
D. Boer, C. Pisano, PRD 86, 094007 (2012)

Define $$R(r, \mathbf{q}_T) = \frac{C[w h_1^{\perp g} h_1^{\perp g}]}{C[f_1 f_1]}$$



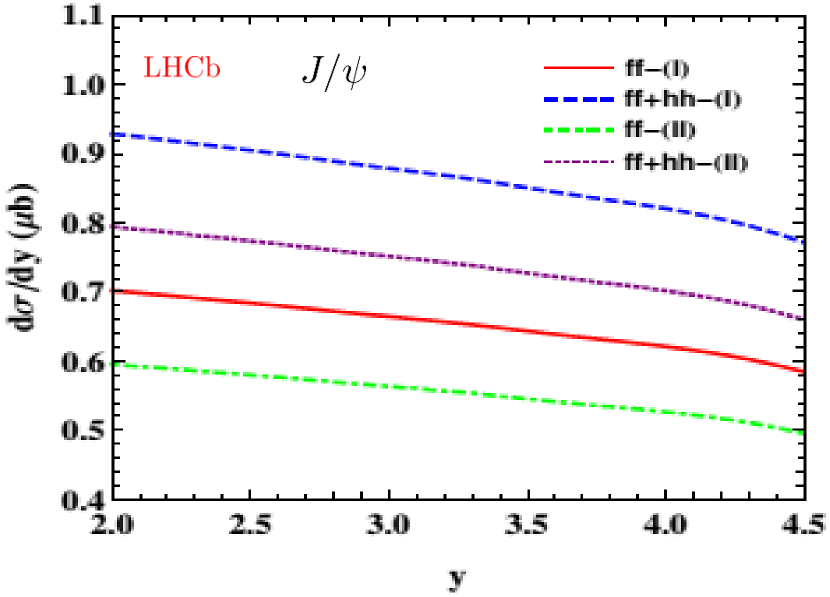


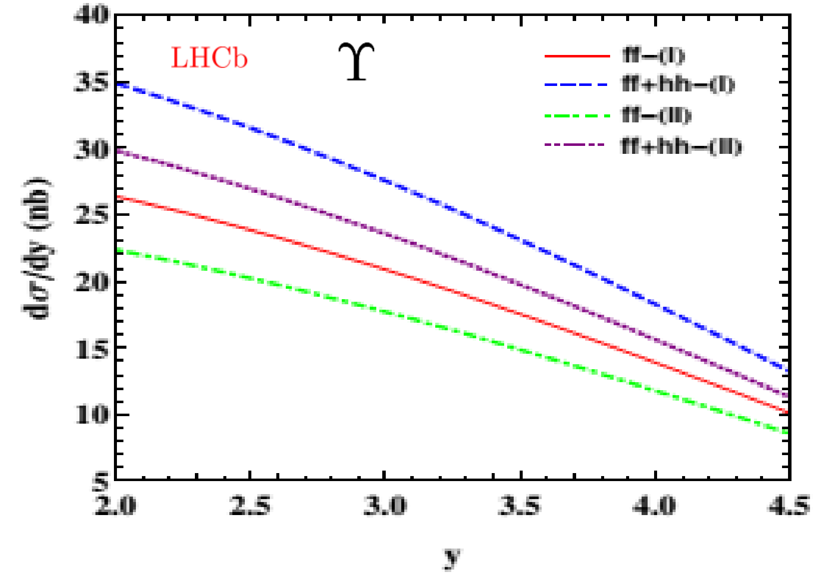
q_T Spectrum in DGLAP Evolution

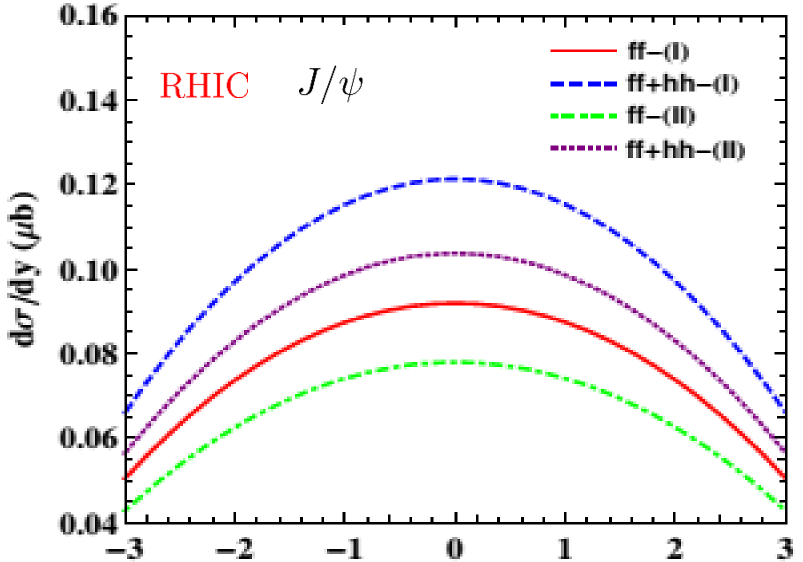


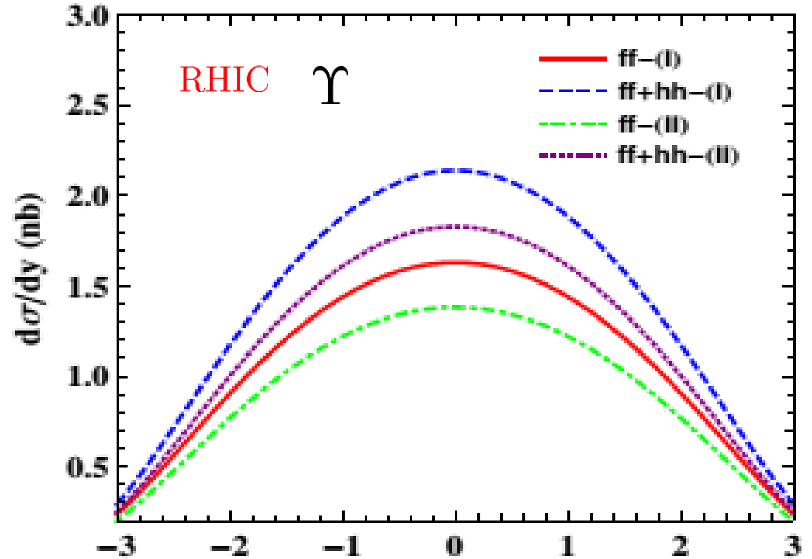
SR Asmita PRD 93 054018 (2016)

Rapidity Spectrum in DGLAP Evolution









SR Asmita PRD 93 054018 (2016)

TMD Evolution

- In Collins-Soper-Sterman (CSS) Evolution formalism, TMD pdfs depends on μ and ζ
- Collins-Soper equation and RGE for TMD

$$\frac{d}{d\ \ln\sqrt{\zeta}} \ln f(x, b_\perp, \mu, \zeta) = K(b_\perp, \mu)$$

$$\frac{d}{d\ \ln\mu} \ln f(x, b_\perp, \mu, \zeta) = \gamma_f(b_\perp, \zeta)$$

No x integral as in DGLAP

$$\frac{d\ K(b_\perp, \mu)}{d\ \ln\mu} = -\gamma_k(\mu)$$

J. Collins, Foundations of Perturbative QCD, 2011
S. M. Aybat et al. PRD 85 034043 (2012)

CSS TMD Evolution

J. Collins, Foundations of Perturbative QCD, 2011

$$f(x, b_\perp, Q_f, \zeta) = f(x, b_\perp, Q_i, \zeta_0) R_{pert}(Q_f, Q_i, b_*) R_{NP}(Q_f, Q_i, b_\perp)$$

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

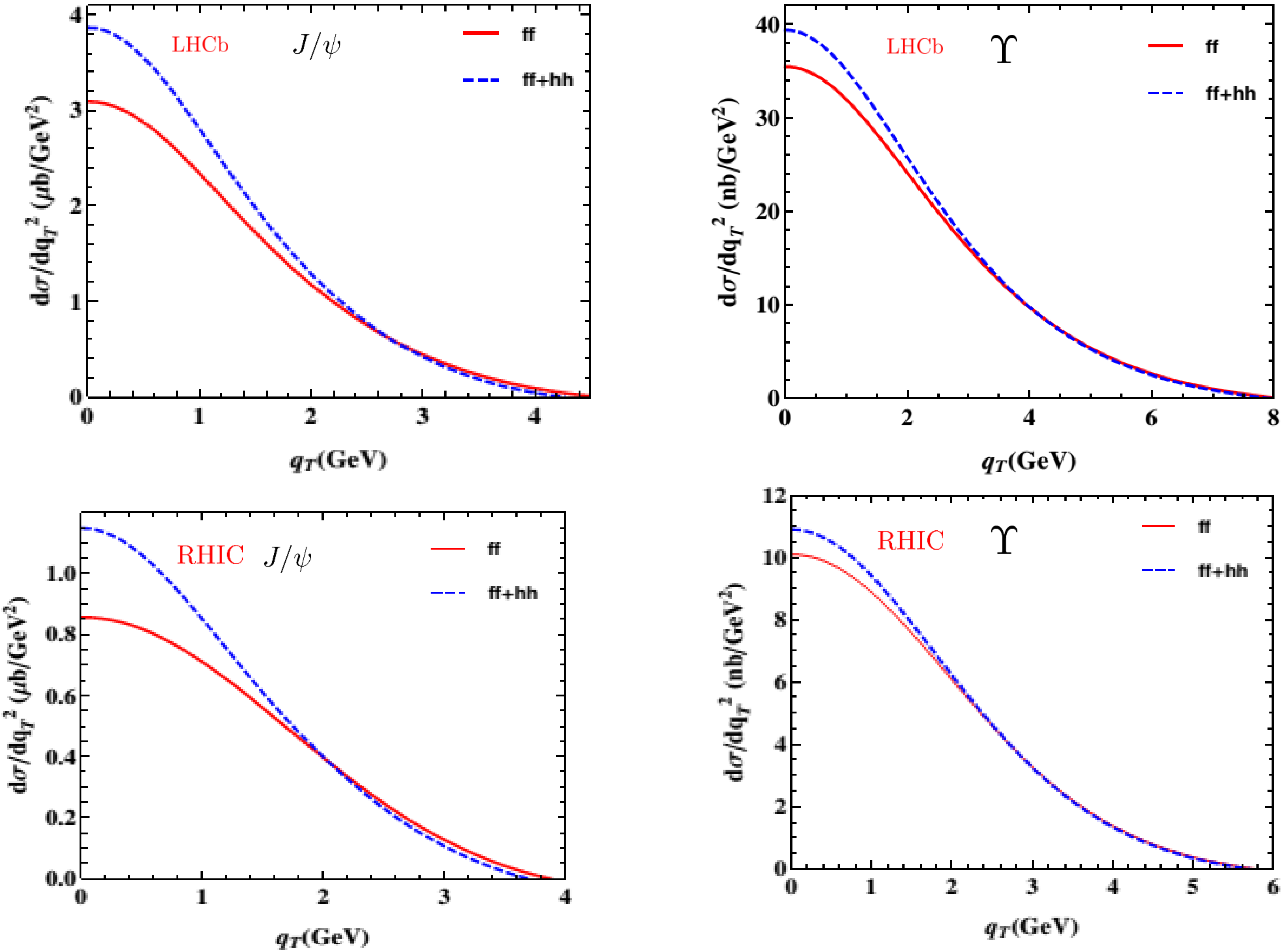
$$R_{NP} = \exp\left\{ -\left[\frac{g_2}{2} \log \frac{Q_f}{2Q_0} + \frac{g_1}{2} \left(1 + 2g_3 \log \frac{10 x x_0}{x_0 + x} \right) \right] b_\perp^2 \right\}$$

S. M. Ayabt et al. PRD 83 114042 (2011)

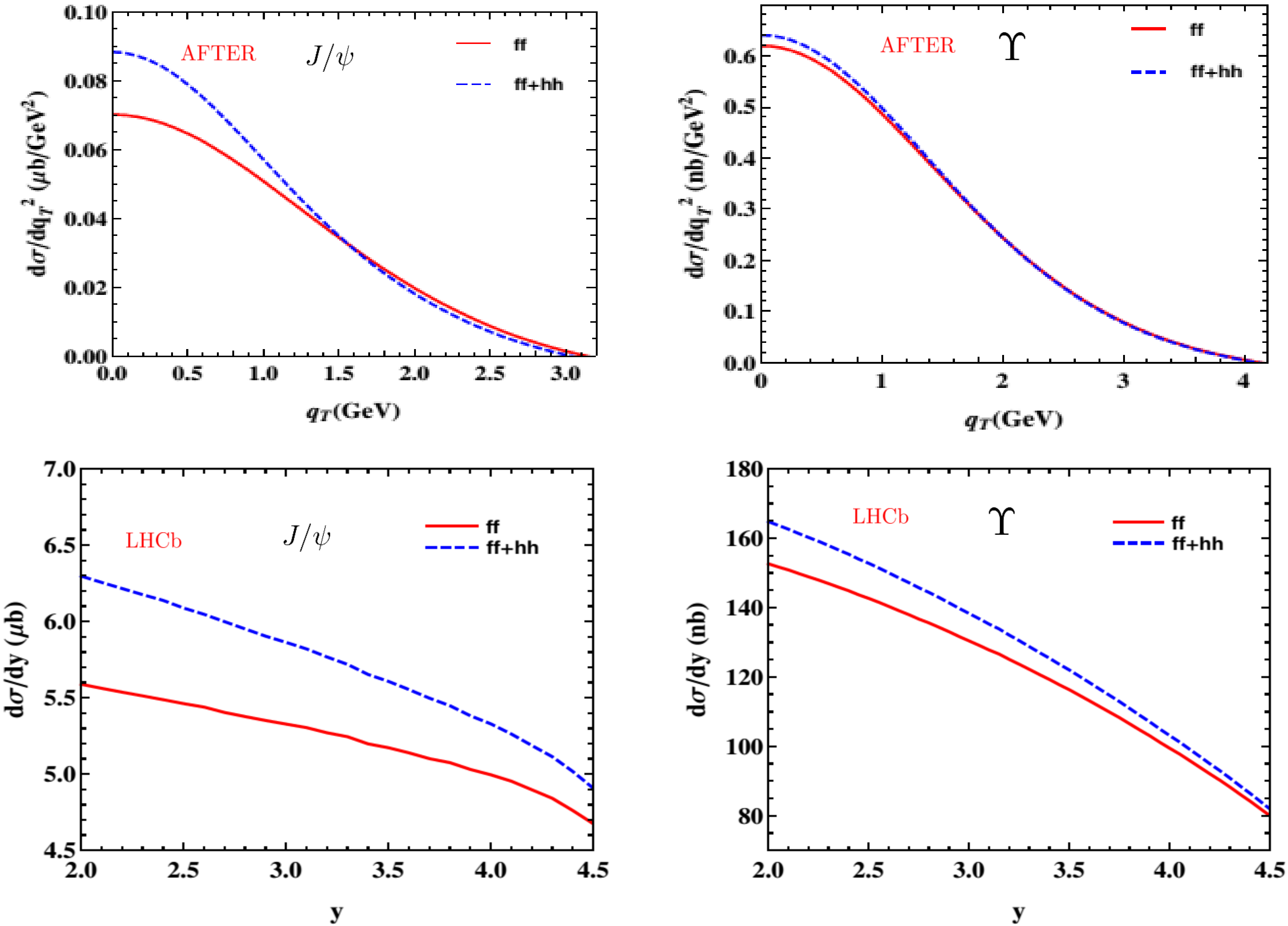
$$\text{where } Q_i = \frac{2e^{-0.577}}{b_*} = \sqrt{\zeta_0},\ Q_f = Q \text{ and } \zeta = Q_f^2$$

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

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.

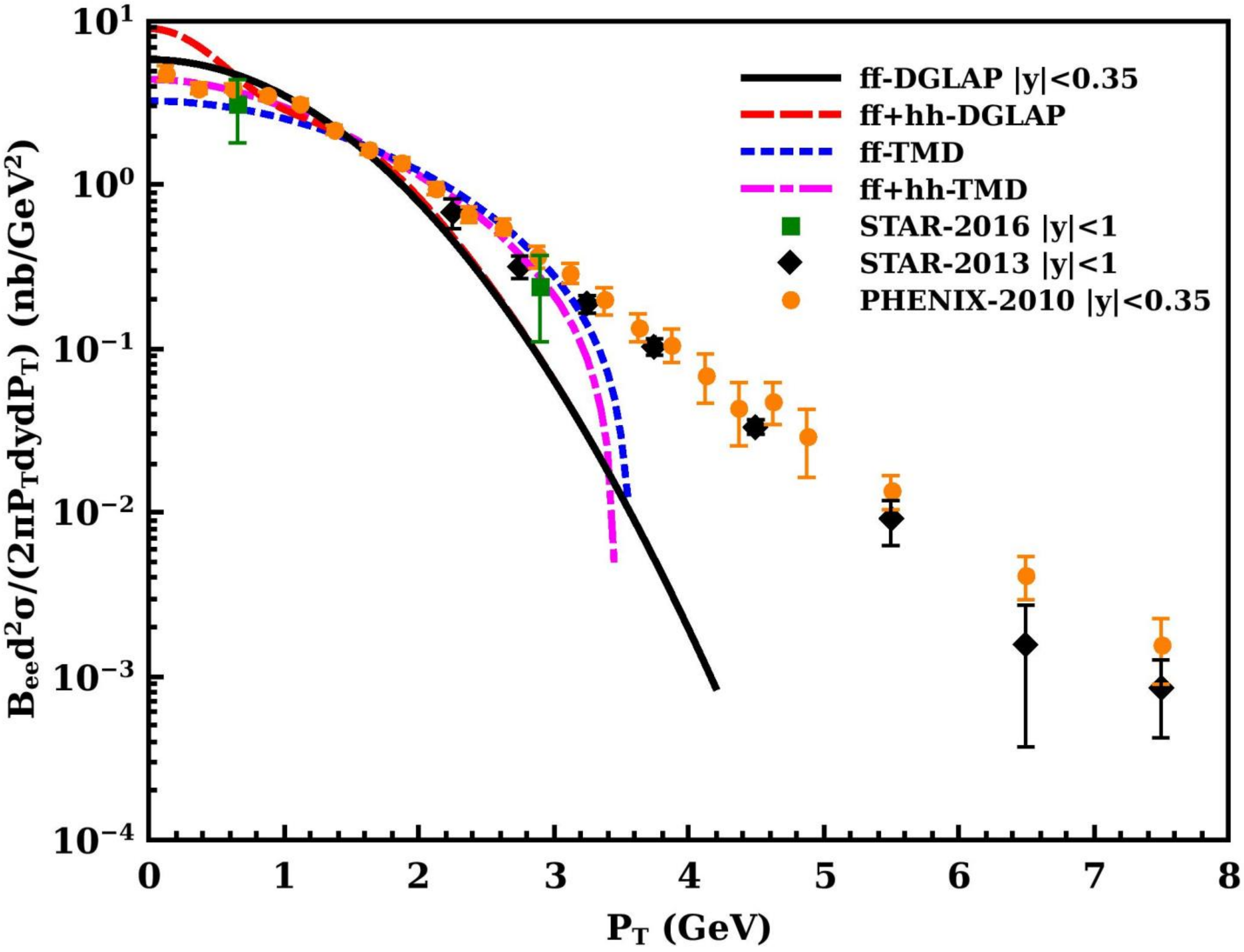
- Hence, the production of quarkonium is a promising process to probe the $h_1^{\perp g}$

- No angular analysis is needed to probe linearly polarized gluons

Comments & Suggestions

Thank You

Matching with Experimental data



Differential Cross Section in DGLAP approach

$$\frac{d^2\sigma^{ff}}{dydq_T^2} = \frac{\beta^2\rho}{36s\pi^2}\int_{4m_Q^2}^{4m_{Q\bar{q}}^2} dM^2 \int d\phi_{q_T} \int dk_{\perp a}k_{\perp a} \int d\phi_{k_{\perp a}} e^{-\Delta\beta}$$
$$\times \Big\{ f_1^g(x_a) f_1^g(x_b) \hat{\sigma}^{gg\to Q\overline{Q}}(M^2) + \frac{1}{2}\sum_q \Big[f_1^q(x_a) f_1^{\bar{q}}(x_b) + f_1^{\bar{q}}(x_a) f_1^q(x_b) \Big]$$
$$\times \hat{\sigma}^{q\bar{q}\to Q\overline{Q}}(M^2) \Big\}$$

$$\frac{d^2\sigma^{hh}}{dydq_T^2} = \frac{\beta^4\rho(1-r)^2}{18sr^2\pi^2}\int_{4m_Q^2}^{4m_{Q\bar{q}}^2} dM^2 \int d\phi_{q_T} \int dk_{\perp a}k_{\perp a} \int d\phi_{k_{\perp a}}$$
$$\times \Big[\frac{1}{2}k_{\perp a}^4 - \frac{1}{2}k_{\perp a}^2 q_T^2 - q_T k_{\perp a}^3 \cos(\phi_{k_{\perp a}} - \phi_{q_T}) + q_T^2 k_{\perp a}^2 \cos^2(\phi_{k_{\perp a}} - \phi_{q_T}) \Big]$$
$$\times e^{[2-\frac{\beta}{r}\Delta]} f_1^g(x_a) f_1^g(x_b) \hat{\sigma}^{gg\to Q\overline{Q}}(M^2)$$

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

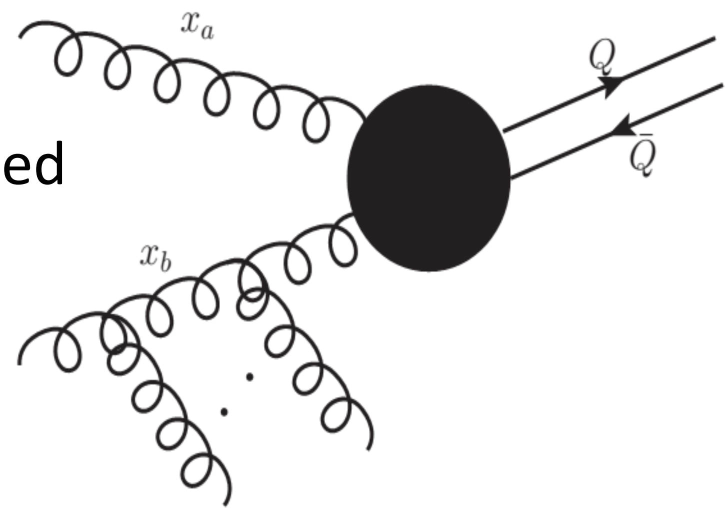
Differential Cross Section in TMD Evolution approach

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

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

Resummation of Sudakov logarithms

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



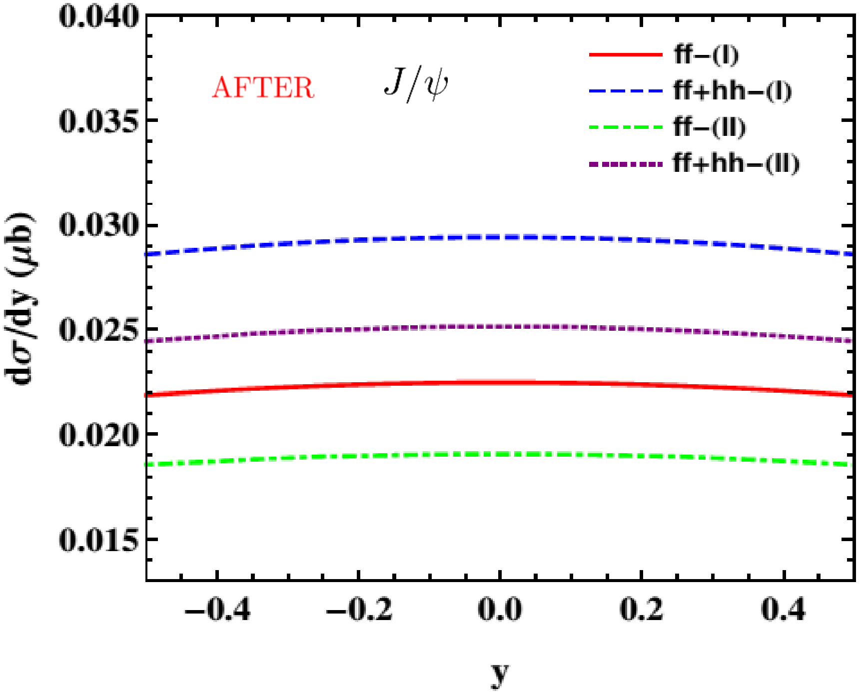
These additional gluon radiation from initial state partons leads to logarithmic corrections for each gluon radiation of the form

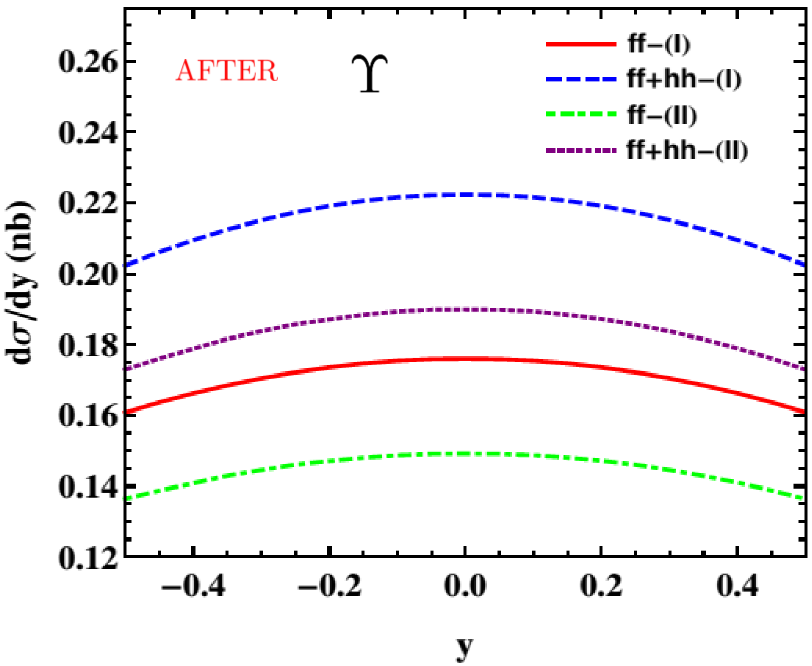
$$\alpha_s \log(\frac{Q^2}{q_T^2})$$

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

$f_1^g.$

Backup Rapidity Spectrum in DGLAP Evolution

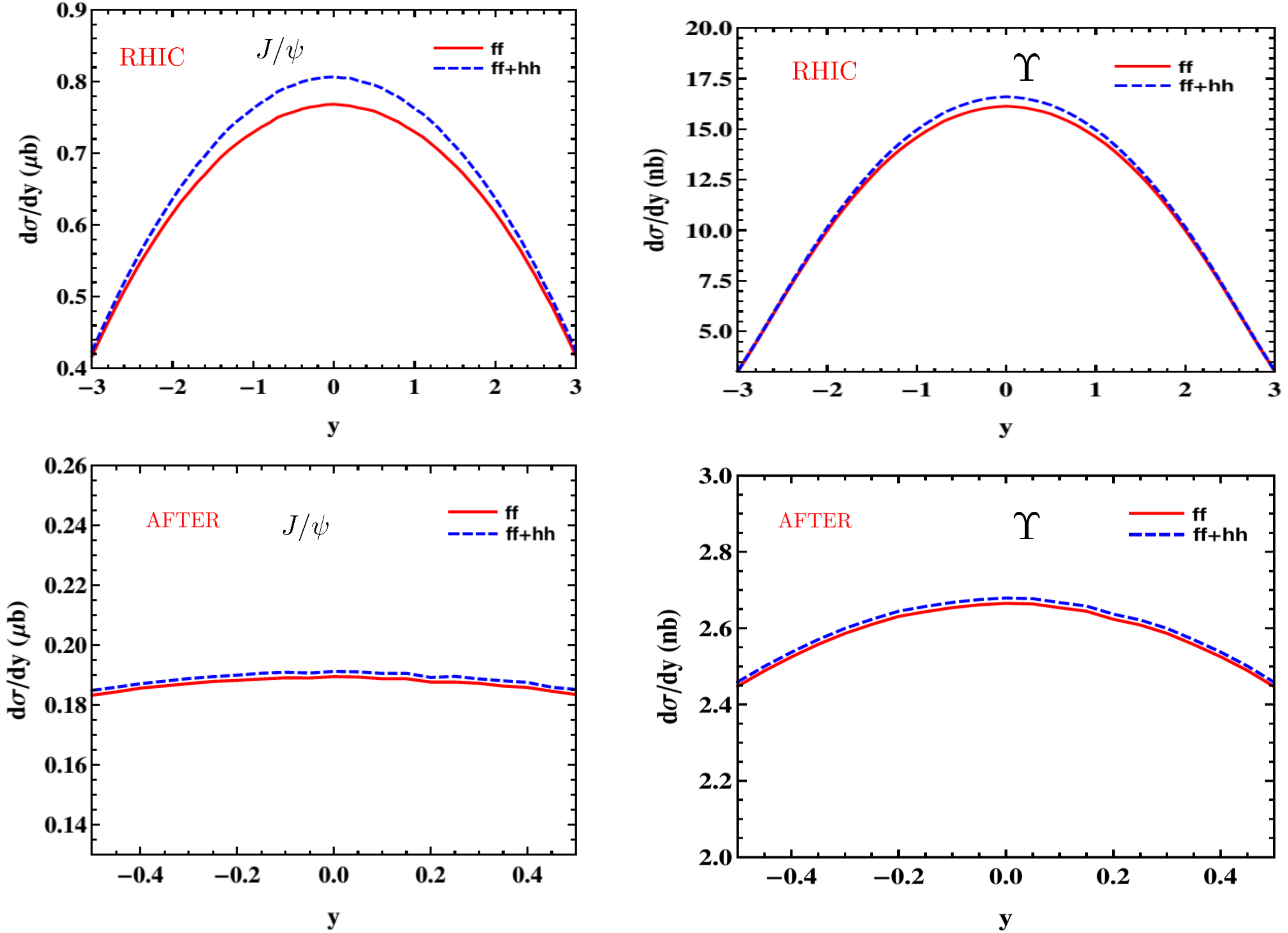




$$r = \frac{1}{3}$$

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

Backup Rapidity Spectrum in TMD Evolution



Backup DGLAP and TMD Comparison