Probing Quarkonium Production Mechanisms with Jet Substructure

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Review of Quarkonium Production Theory

Heavy Quarkonium Fragmenting Jet Functions

New Tests of NRQCD Using Jet Observables

Non-Relativistic QCD (NRQCD) Factorization Formalism

(Bodwin, Braaten, Lepage)

$$\sigma(gg \to J/\psi + X) = \sum_n \sigma(gg \to c\bar{c}(n) + X)\langle \mathcal{O}^{J/\psi}(n)\rangle$$

$$n - {}^{2S+1}L_J^{(1,8)}$$

double expansion in α_s, v

NRQCD long-distance matrix element (LDME)

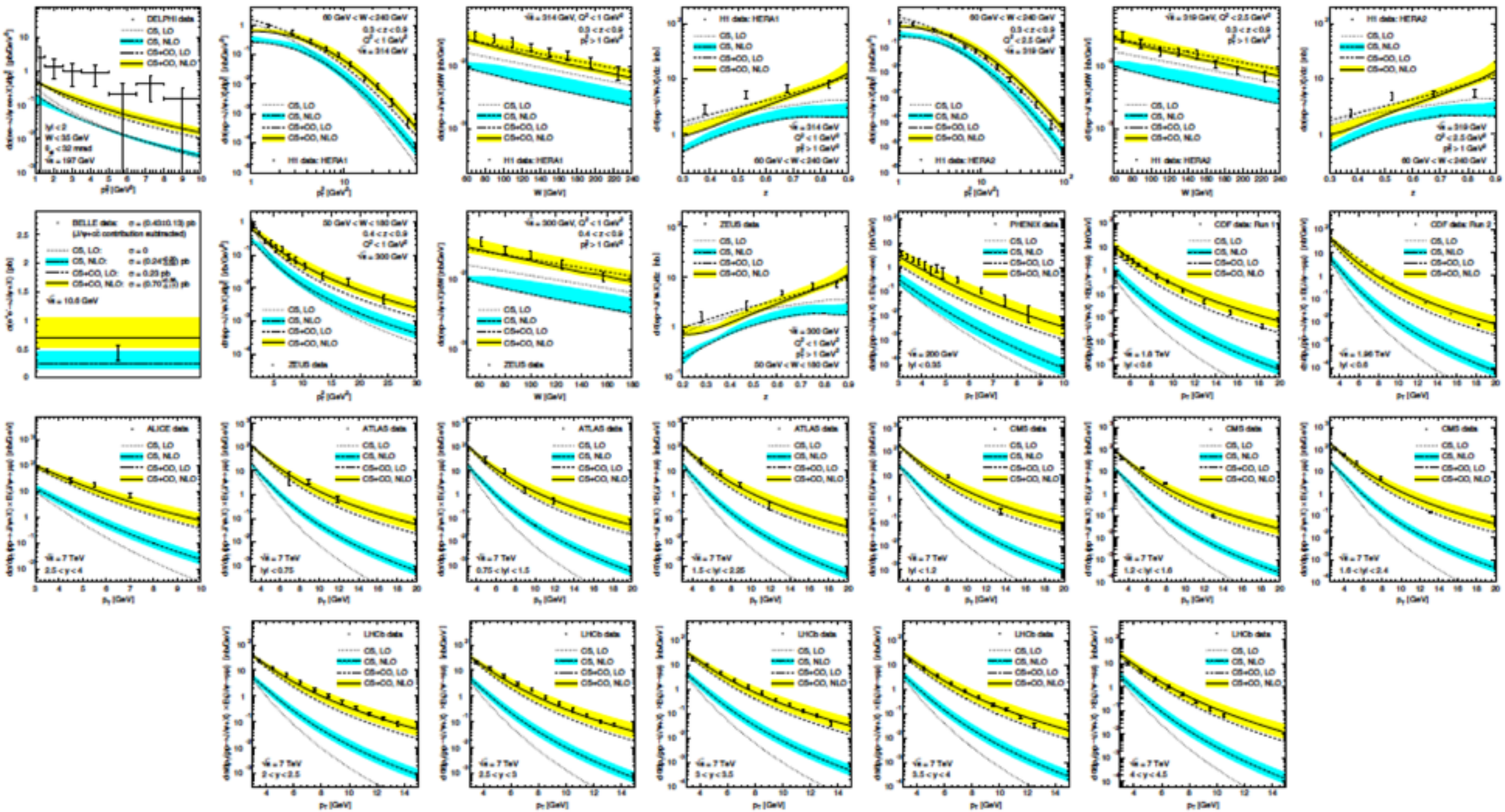
$$\langle \mathcal{O}^{J/\psi}({}^3S_1^{[1]})\rangle \sim v^3$$

CSM - lowest order in v

$$\langle \mathcal{O}^{J/\psi}({}^3S_1^{[8]})\rangle, \langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]})\rangle, \langle \mathcal{O}^{J/\psi}({}^3P_J^{[8]})\rangle \sim v^7$$

color-octet mechanisms

Global Fits with NLO CSM + COM

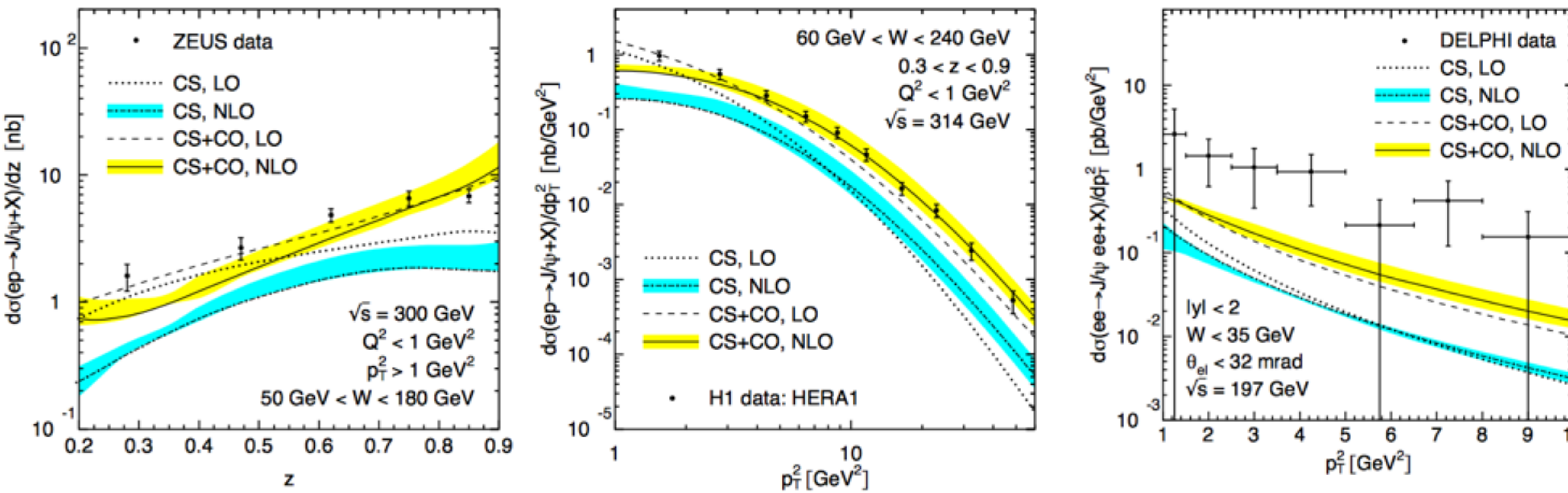


$$e^+e^-, \gamma\gamma, \gamma p, p\bar{p}, pp \rightarrow J/\psi + X$$

fit to 194 data points, 26 data sets,

Butenschoen and Kniehl, PRD 84 (2011) 051501

NLO: CSM + COM Required to Fit Data



$$ep \to J/\psi + X$$

$$\gamma^*\gamma^* \to J/\psi + X$$

Status of NRQCD approach to J/ψ Production

NLO: COM + CSM required for most processes

extracted LDME satisfy NRQCD v-scaling

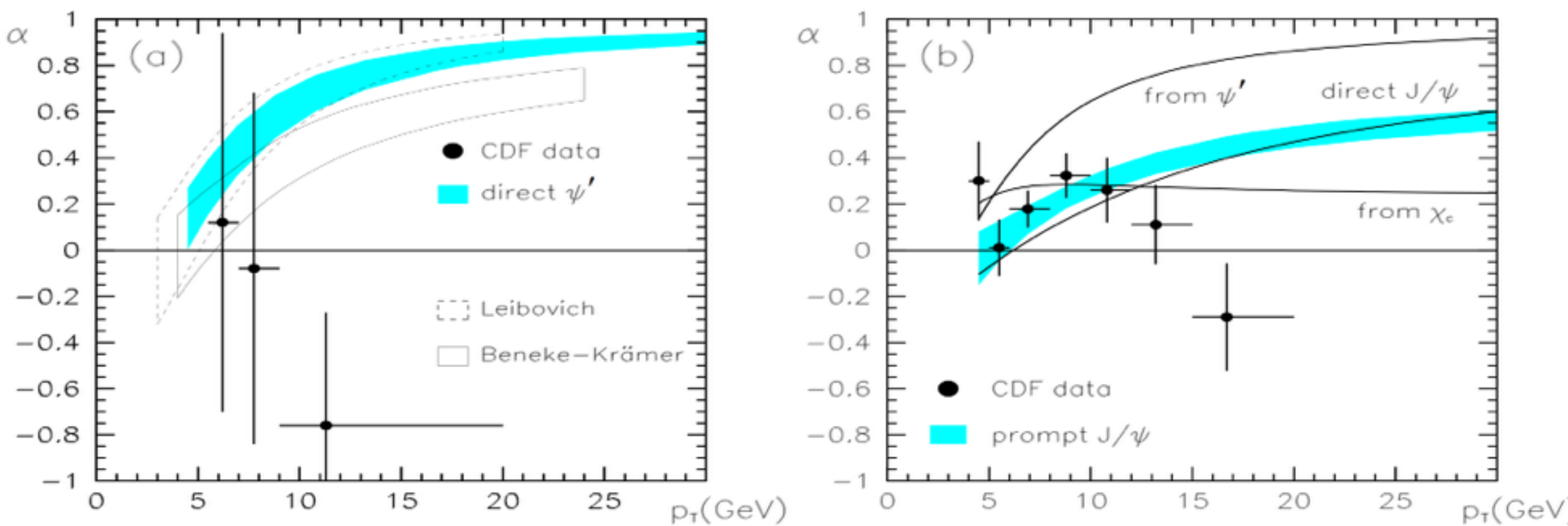
$$\langle \mathcal{O}^{J/\psi}(^3S_1^{[1]}) \rangle = 1.32 \text{ GeV}^3$$

$\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]}) \rangle$	$(4.97 \pm 0.44) \times 10^{-2}$ GeV^3
$\langle \mathcal{O}^{J/\psi}(^3S_1^{[8]}) \rangle$	$(2.24 \pm 0.59) \times 10^{-3}$ GeV^3
$\langle \mathcal{O}^{J/\psi}(^3P_0^{[8]}) \rangle$	$(-1.61 \pm 0.20) \times 10^{-2}$ GeV^5

$$\chi^2_{\text{d.o.f.}} = 857/194 = 4.42$$

Polarization Puzzle

$^3S_1^{[8]}$ fragmentation at large p_T predicts transversely polarized J/ψ, ψ'

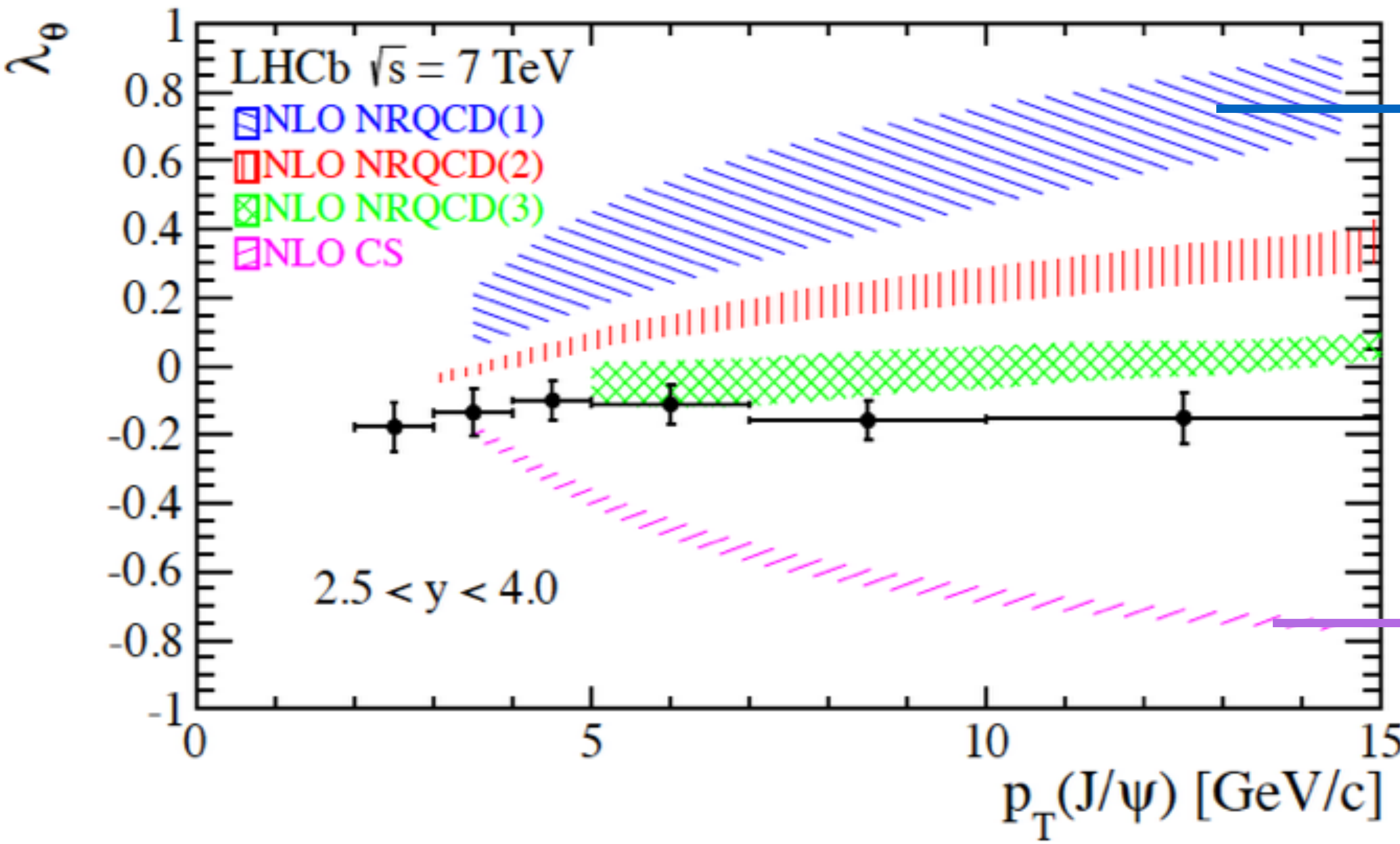


ψ ′

J/ψ

Braaten, Kniehl, Lee, 1999

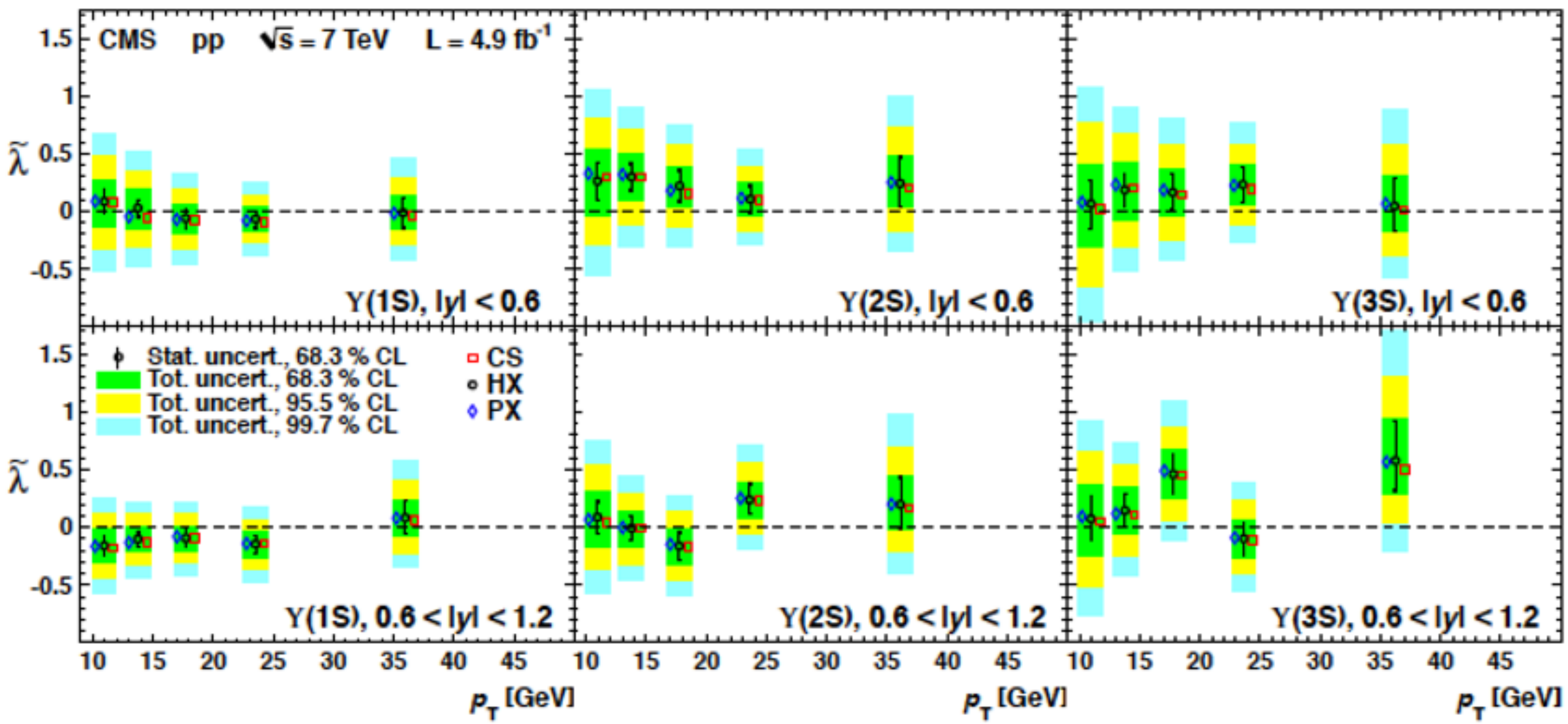
Polarization of J/ψ at LHCb



LDME from Global fits

CSM

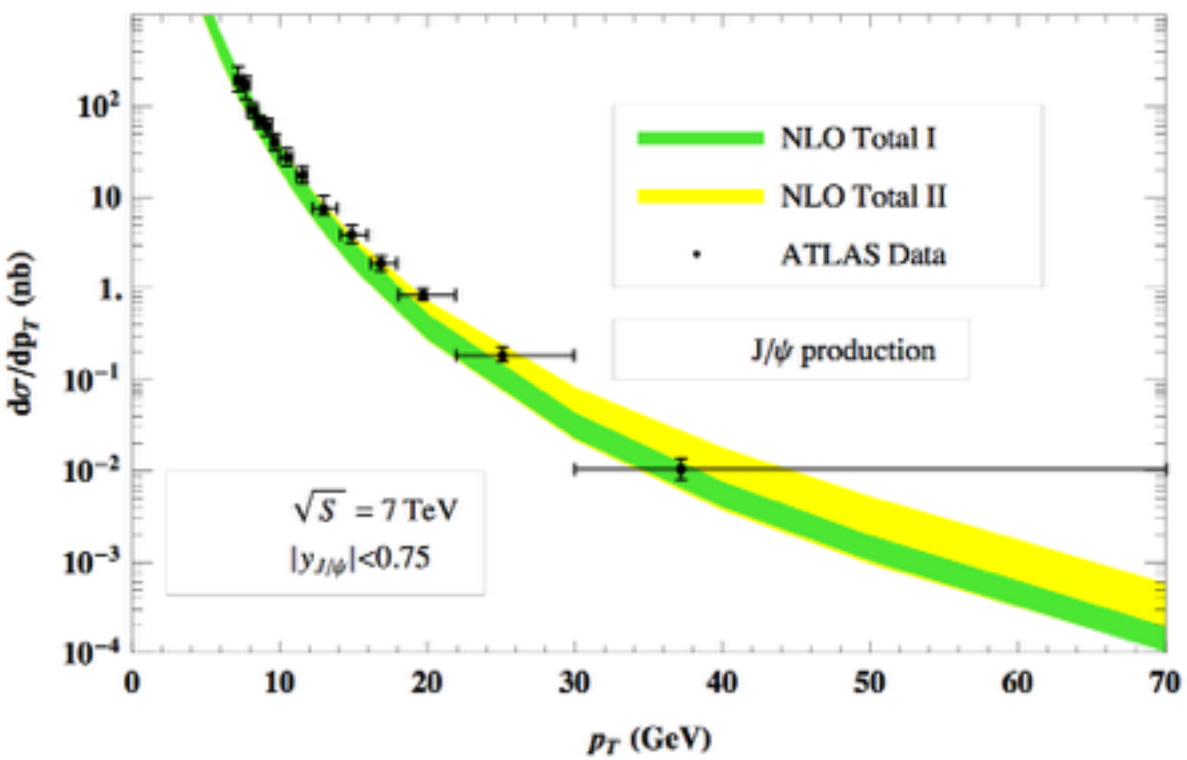
Polarization of Υ(nS) at CMS

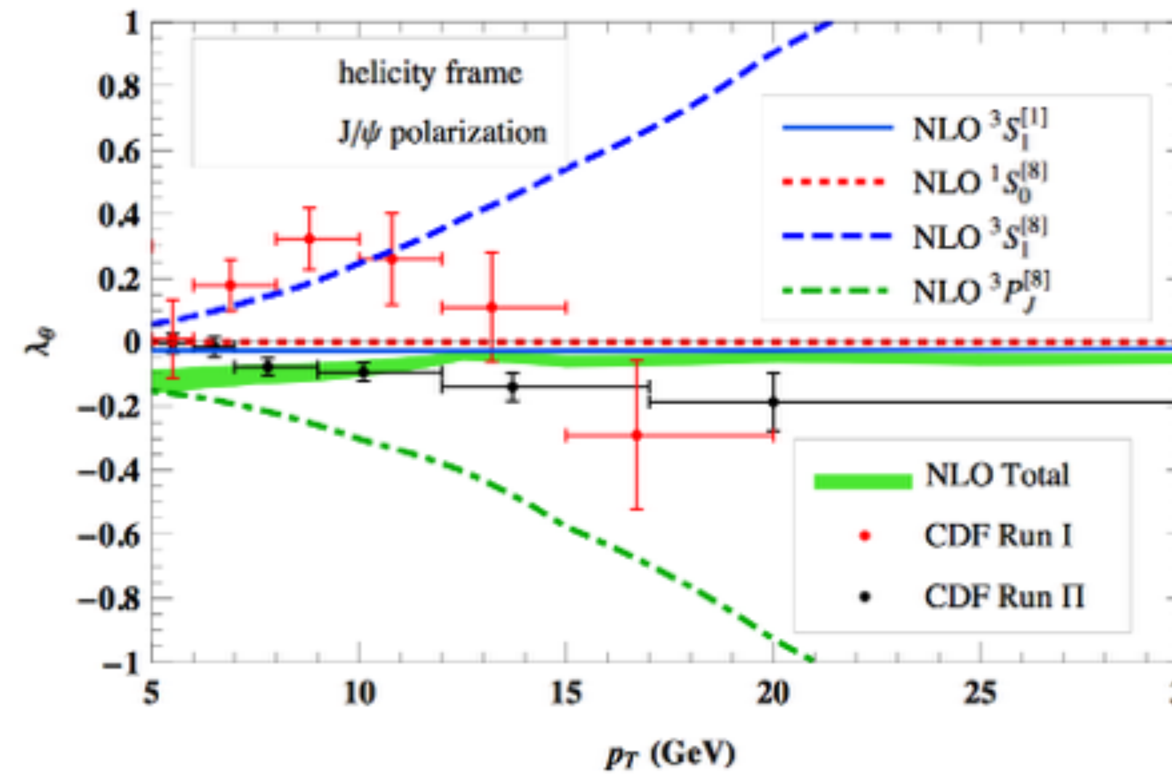


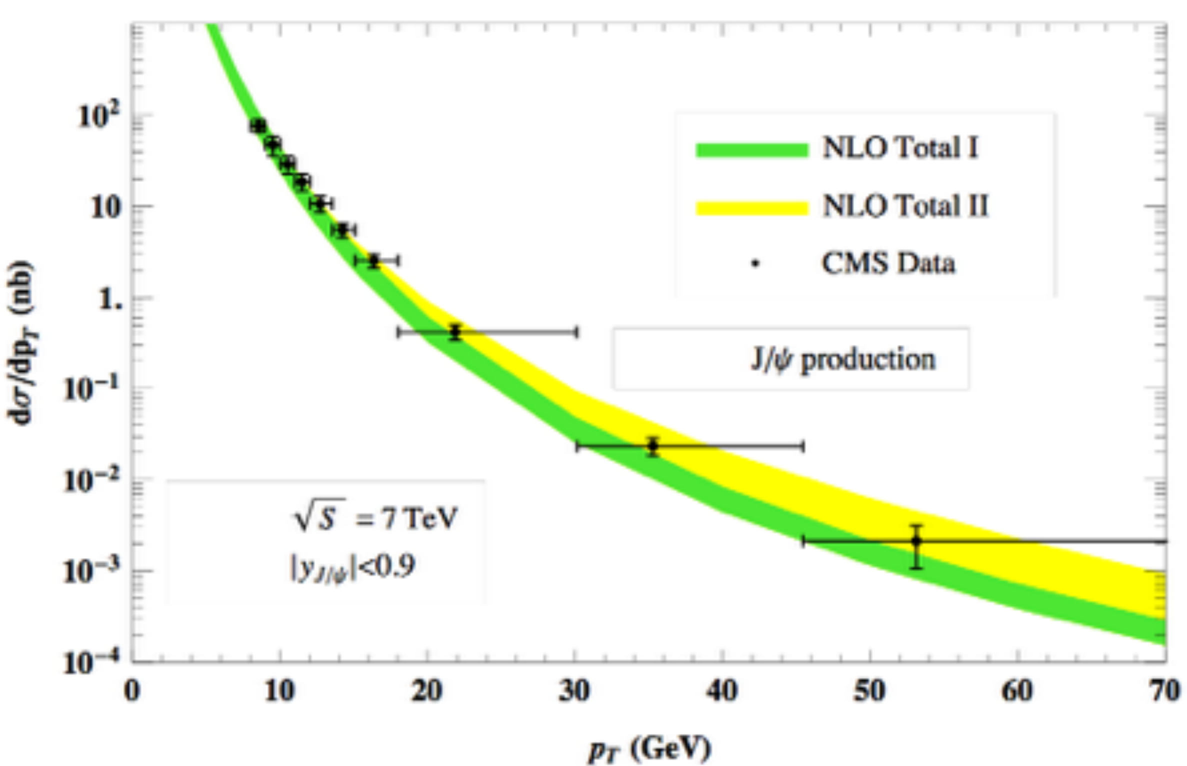
Recent Attempts to Resolve J/ψ Polarization Puzzle

simultaneous NLO fit to CMS, ATLAS high p_t production, polarization

Chao, et. al. PRL 108, 242004 (2012)







$\langle\mathcal{O}(^3S_1^{[1]})\rangle$ 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
1.16	8.9 ± 0.98	0.30 ± 0.12	0.56 ± 0.21
1.16	0	1.4	2.4
1.16	11	0	0

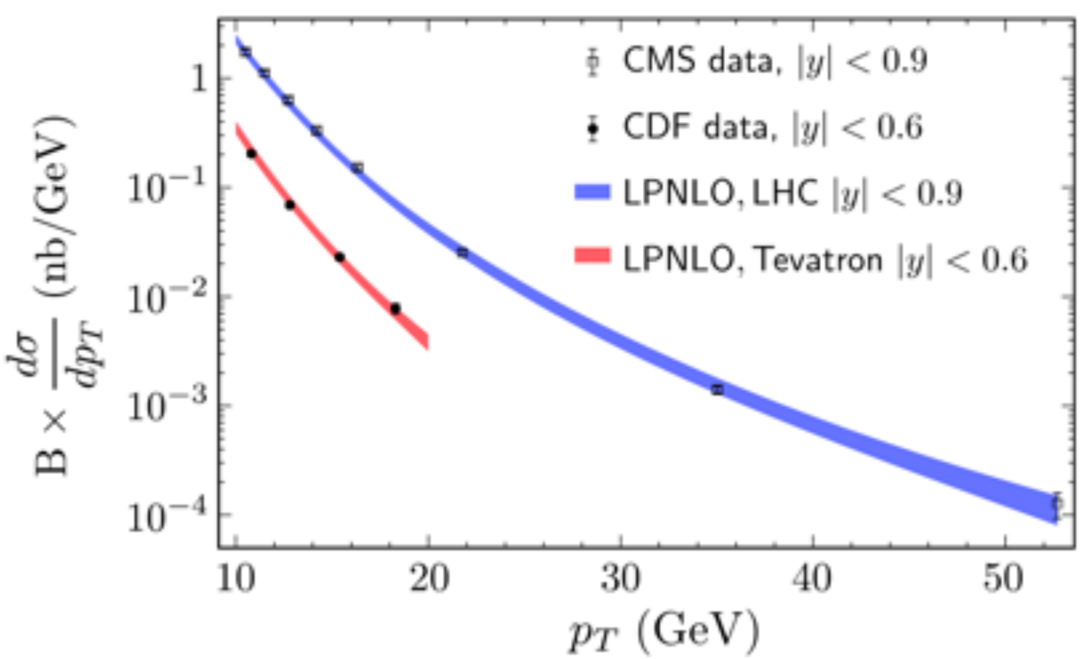
Recent Attempts to Resolve J/ψ Polarization Puzzle

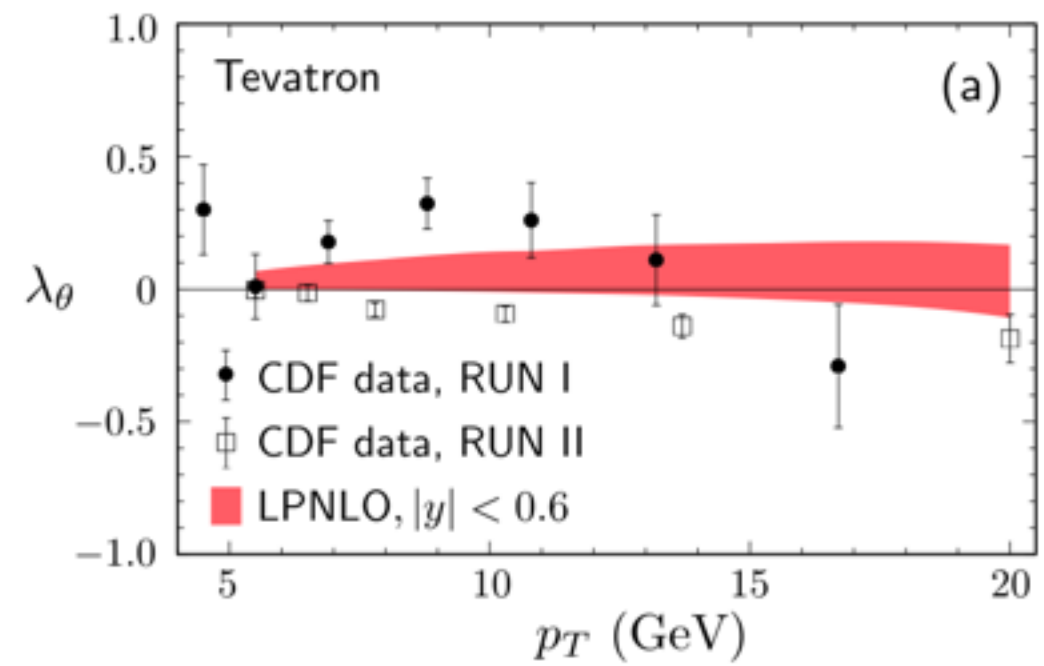
i) large p_t production at CDF

Bodwin, et. al., PRL 113, 022001(2014)

ii) resum logs of p_t/m_c using AP evolution

iii) fit COME to p_t spectrum, predict basically no polarization





Extracted COME **inconsistent** with global fits

$$\langle \mathcal{O}^{J/\psi}(^1S_0^{(8)}) \rangle = 0.099 \pm 0.022 \, \mathrm{GeV}^3$$

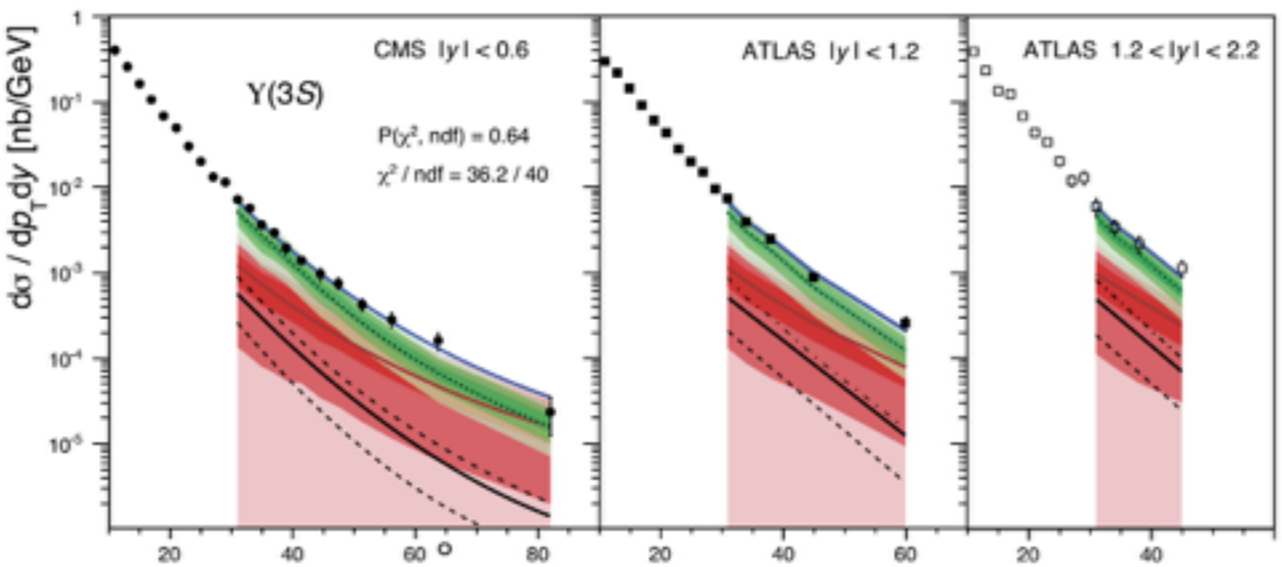
$$\langle \mathcal{O}^{J/\psi}(^3S_1^{(8)}) \rangle = 0.011 \pm 0.010 \, \mathrm{GeV}^3$$

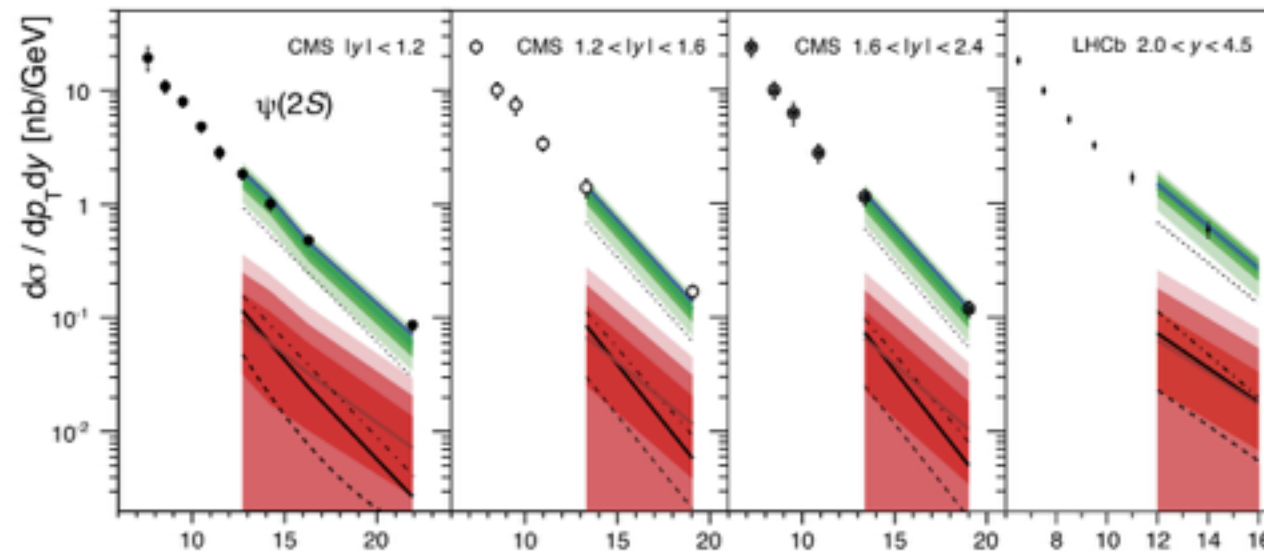
$$\langle \mathcal{O}^{J/\psi}(^3P_0^{(8)}) \rangle = 0.011 \pm 0.010 \, \mathrm{GeV}^5$$

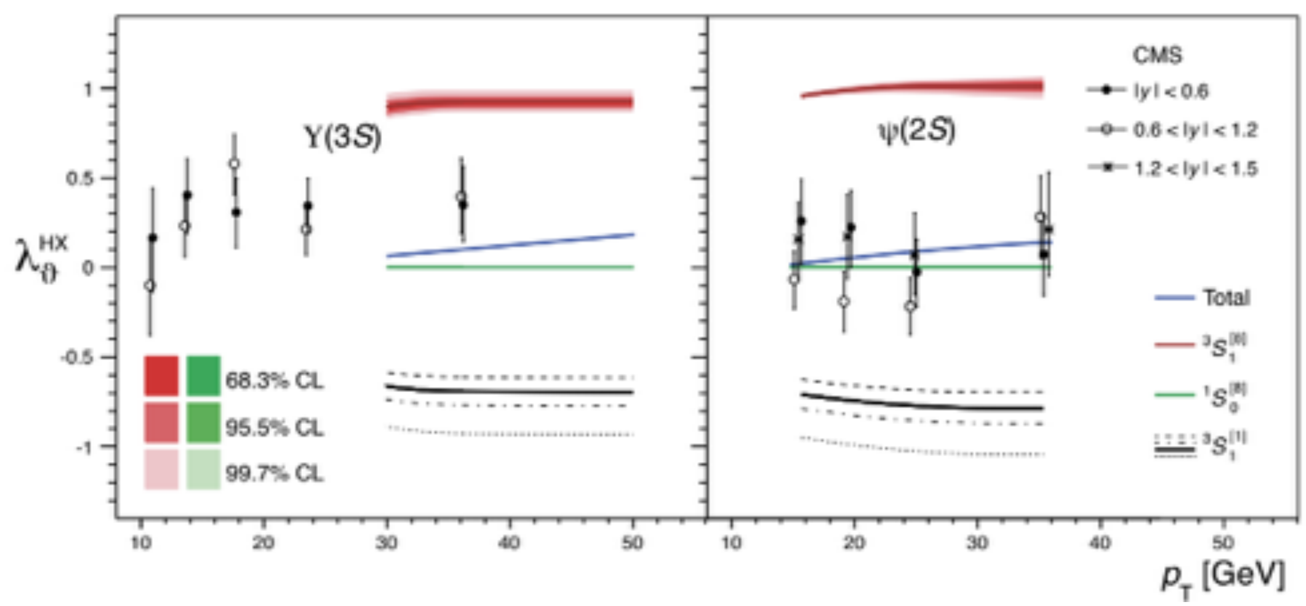
Recent Attempts to Resolve J/ψ Polarization Puzzle

Faccioli, et. al. PLB736 (2014) 98

Lourenco, et. al., NPA, in press





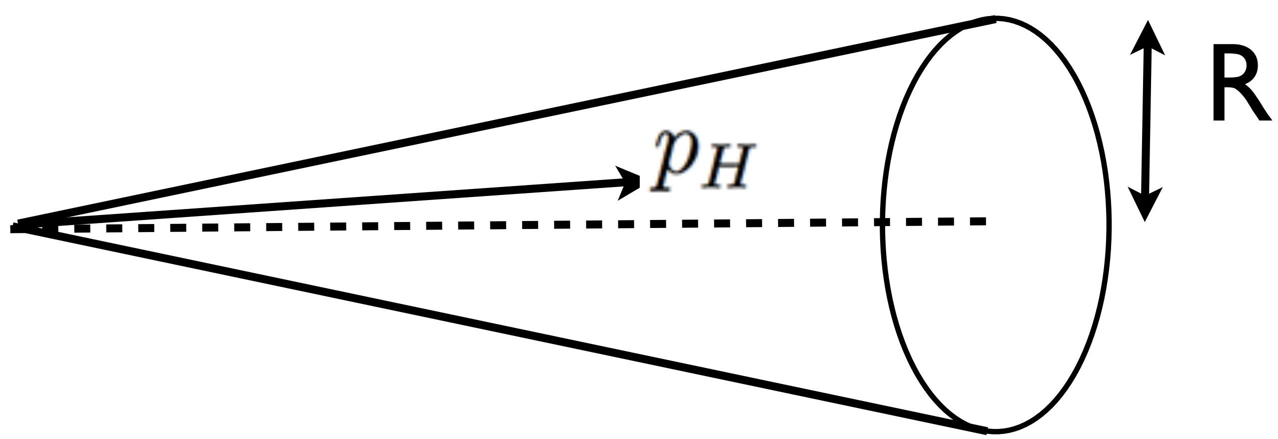


argue for $^{1}S_0^{(8)}$ dominance in both ψ(2S) & ϒ(3S) production

Fragmenting Jet Functions

Procura, Stewart, arXiv:0911.4980
Jain, Procura, Waalewijn, arXiv:1101.4953
Procura, Waalewijn, arXiv:1111.6605

jets with identified hadrons



Jet Energy: E

$$p_H^+ = z p_{\rm jet}^+$$

cross sections determined by **fragmenting jet function (FJF):**

$$\mathcal{G}_g^h(E, R, \mu, z)$$

inclusive hadron production: **fragmentation functions**

$$\frac{1}{\sigma_0}\frac{d\sigma^h}{dz}(e^+e^- \to h\,X) = \sum_i \int_z^1 \frac{dx}{x}\, C_i(E_{\rm cm}, x, \mu)\, D_i^h(z/x, \mu)$$

jet cross sections: **jet functions**

$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}z}(E, R) = \int \mathrm{d}\Phi_N \mathrm{tr}[H_N S_N] \prod_\ell J_\ell$$

$$\boxed{\mathcal{G}_g^h(E, R, \mu, z) \longrightarrow D_i^h(z/x, \mu)\ ,\ J_\ell}$$

relationship to jet function:

$$\sum_h \int_0^1 \mathrm{d}z\, z\, D_j^h(z, \mu) = 1$$

$$J_i(E, R, z, \mu) = \frac{1}{2} \sum_h \int \frac{dz}{(2\pi)^3}\, z\, \mathcal{G}_i^h(E, R, z, \mu)$$

cross section for jet w/ identified hadron from jet cross section

$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}z}(E, R) = \int \mathrm{d}\Phi_N \mathrm{tr}[H_N S_N] \prod_\ell J_\ell\; J_i(E, R, z, \mu)$$

$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}z}(E, R) = \int \mathrm{d}\Phi_N \mathrm{tr}[H_N S_N]\, \mathcal{G}_i^h(E, R, z, \mu) \prod_\ell J_\ell$$

relationship to fragmentation functions

$$\mathcal{G}_i^h(E,R,z,\mu) = \sum_i \int_z^1 \frac{dz'}{z'} \mathcal{J}_{ij}(E,R,z',\mu) D_j^h\left(\frac{z}{z'},\mu\right)\left[1+\mathcal{O}\left(\frac{\Lambda_{\rm QCD}^2}{4E^2\tan^2(R/2)}\right)\right]$$

matching coefficients calculable in perturbation theory

$$\frac{\mathcal{J}_{gg}(E,R,z,\mu)}{2(2\pi)^3} = \delta(1-z) + \frac{\alpha_s(\mu)C_A}{\pi}\left[\left(L^2-\frac{\pi^2}{24}\right)\delta(1-z) + \hat{P}_{gg}(z)L + \hat{\mathcal{J}}_{gg}(z)\right]$$

$$\hat{\mathcal{J}}_{gg}(z) = \begin{cases} \hat{P}_{gg}(z)\ln z & z \le 1/2 \\ \frac{2(1-z+z^2)^2}{z}\left(\frac{\ln(1-z)}{1-z}\right)_+ & z \ge 1/2. \end{cases}$$

$$L = \ln[2E\tan(R/2)/\mu],$$

scale for $\mathcal{J}_{ij}(E,R,z,\mu)$

sum rule for matching coefficients

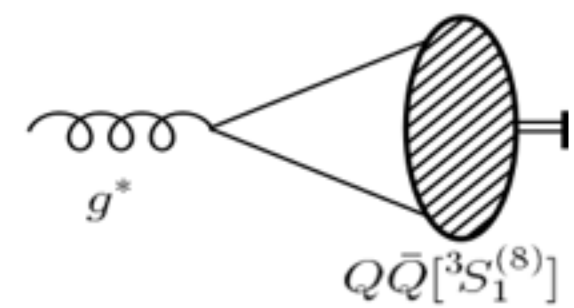
$$\sum_j \int_0^1 dz\, z\, \mathcal{J}_{ij}(R,z,\mu) = 2(2\pi)^3 J_i(R,\mu)$$

NRQCD fragmentation functions

Braaten, Yuan, hep-ph/9302307
Braaten, Chen, hep-ph/9604237
Braaten, Fleming, hep-ph/9411365

Perturbatively calculable **at the scale 2m$_c$**

$$D_g^{\psi(8)}(z, 2m_c) = \frac{\pi\alpha_s(2m_c)}{3M_\psi^3}\langle O^\psi(^3S_1^{(8)})\rangle\delta(1-z)$$



$$D_g^{\psi(1)}(z, 2m_c) = \frac{5\alpha_s^3(2m_c)}{648\pi^2}\frac{\langle O^\psi(^3S_1^{(1)})\rangle}{M_\psi^3}\int_0^z dr\int_{(r+z^2)/2z}^{(1+r)/2} dy \frac{1}{(1-y)^2(y-r)^2(y^2-r)^2}$$
$$\sum_{i=0}^{2} z^i\left(f_i(r,y) + g_i(r,y)\frac{1+r-2y}{2(y-r)\sqrt{y^2-r}}\ln\frac{y-r+\sqrt{y^2-r}}{y-r-\sqrt{y^2-r}}\right),$$

Altarelli-Parisi evolution: 2m$_c$ to 2E tan(R/2)

FJF in terms of fragmentation function

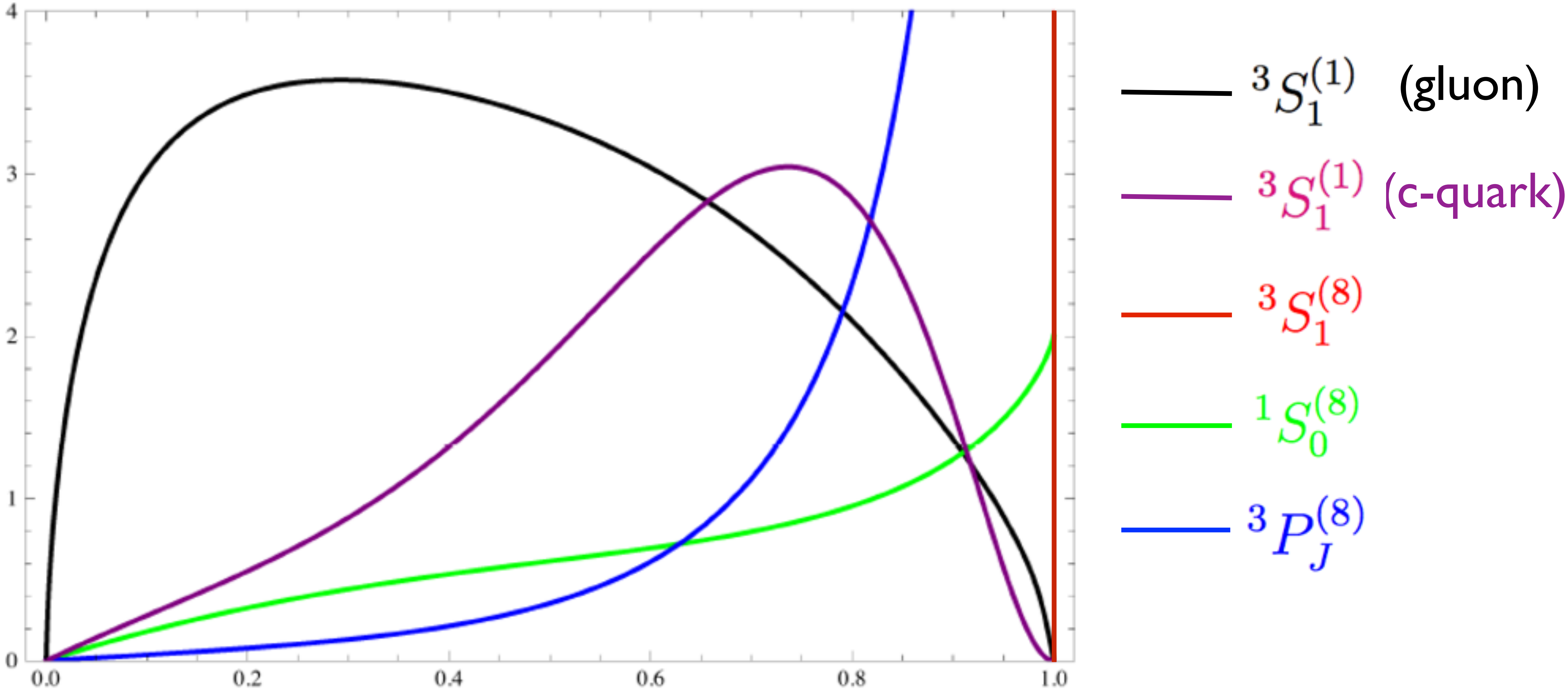
$$\mathcal{G}_g^{\psi}(E,R,z,\mu) = D_{g\to\psi}(z,\mu)\left(1+\frac{C_A\alpha_s}{\pi}\left(L_{1-z}^2-\frac{\pi^2}{24}\right)\right)$$
$$+\frac{C_A\alpha_s}{\pi}\left[\int_z^1 \frac{dy}{y}\tilde{P}_{gg}(y)L_{1-y}D_{g\to\psi}\left(\frac{z}{y},\mu\right)\right.$$
$$+2\int_z^1 dy\frac{D_{g\to\psi}(z/y,\mu)-D_{g\to\psi}(z,\mu)}{1-y}L_{1-y}$$
$$\left.+\theta\left(\frac{1}{2}-z\right)\int_z^{1/2}\frac{dy}{y}\hat{P}_{gg}(y)\ln\left(\frac{y}{1-y}\right)D_{g\to\psi}\left(\frac{z}{y},\mu\right)\right]$$

$$L_{1-z} = \ln\left(\frac{2E\tan(R/2)(1-z)}{\mu}\right)$$

For large E, FJF ~ NRQCD frag. function (at scale 2E tan(R/2))

$$\mathcal{G}_g^{h}(E,R,\mu=2E\tan(R/2),z) \to D_g^{\psi}(z,2E\tan(R/2))+O(\alpha_s)$$

NRQCD FF's (at scale $2m_c$)

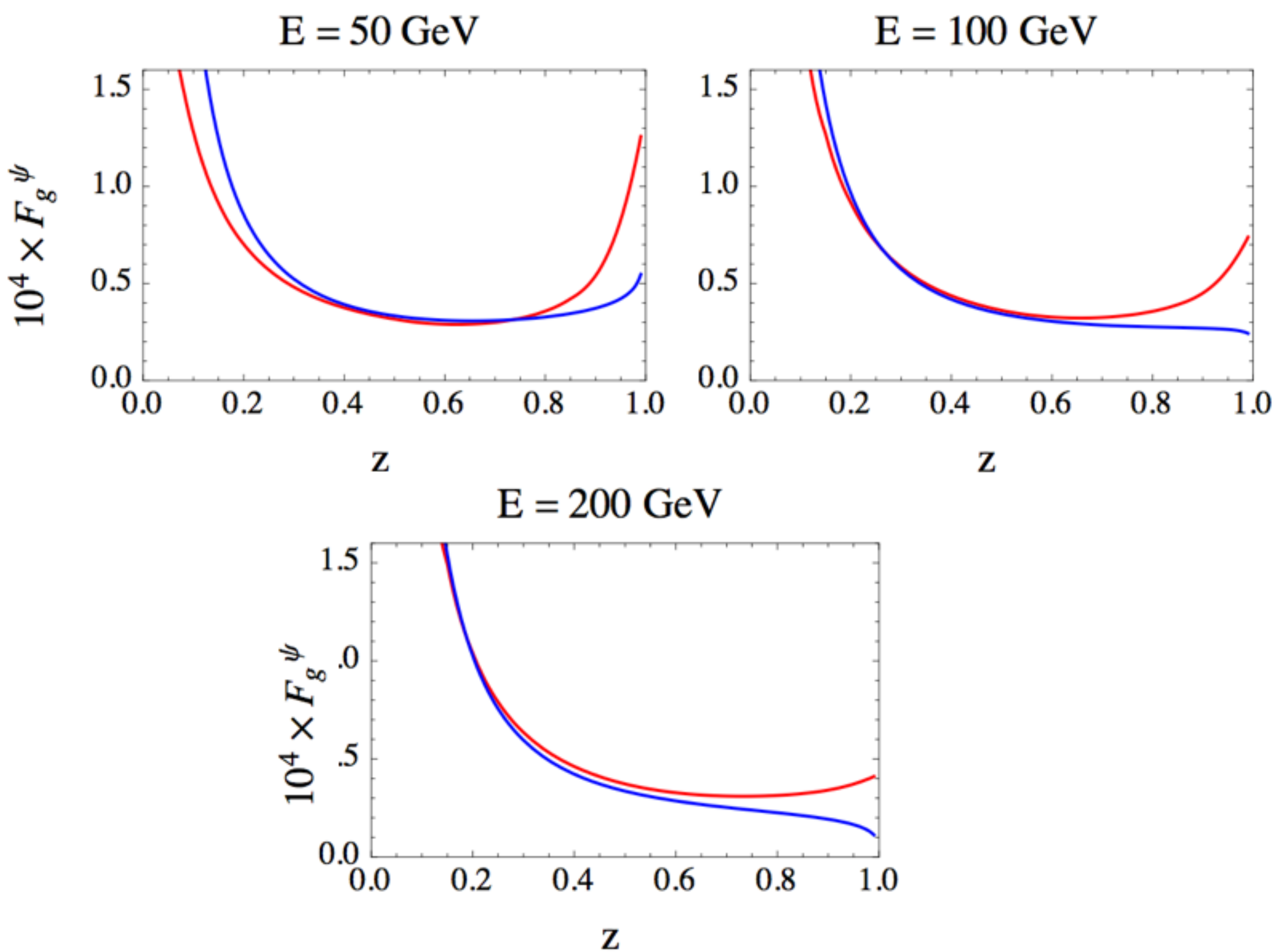


(normalization arbitrary)

Evolution to 2E tan(R/2) will soften discrepancies

Color-Octet $^3S_1$ fragmentation function, FJF

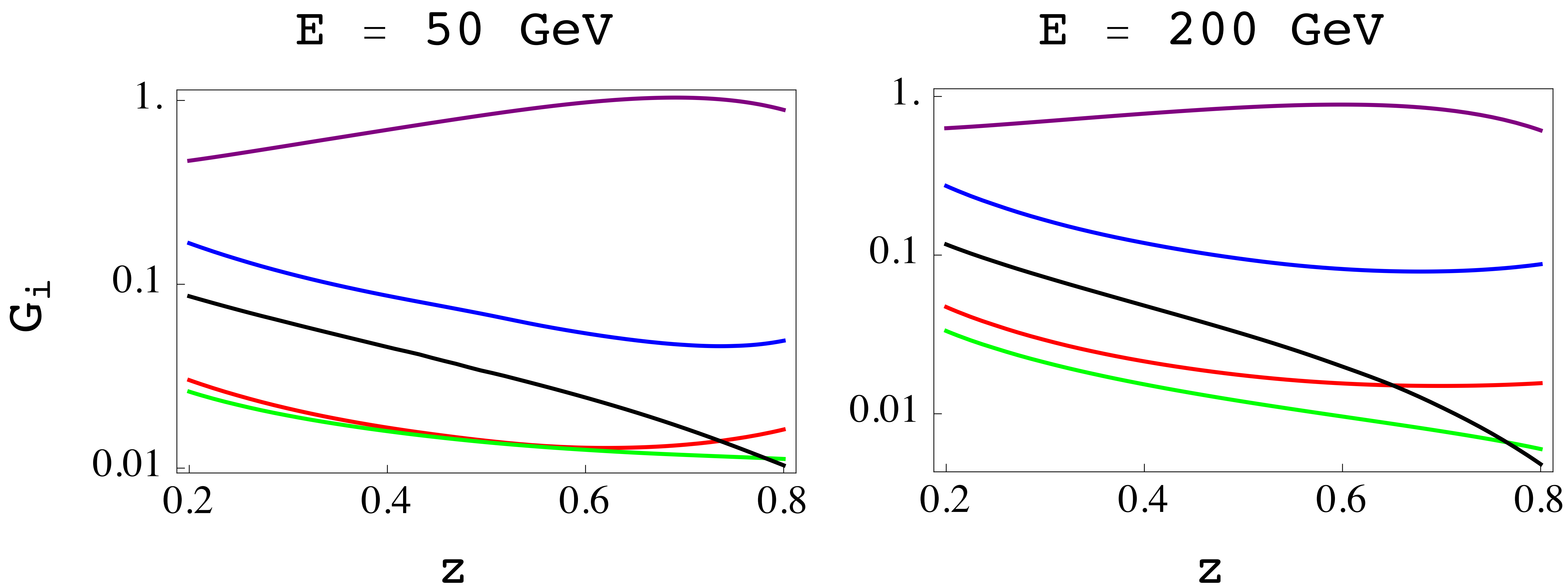
M. Baumgart, A. Leibovich, T.M., I. Z. Rothstein, arXiv:1406.2295



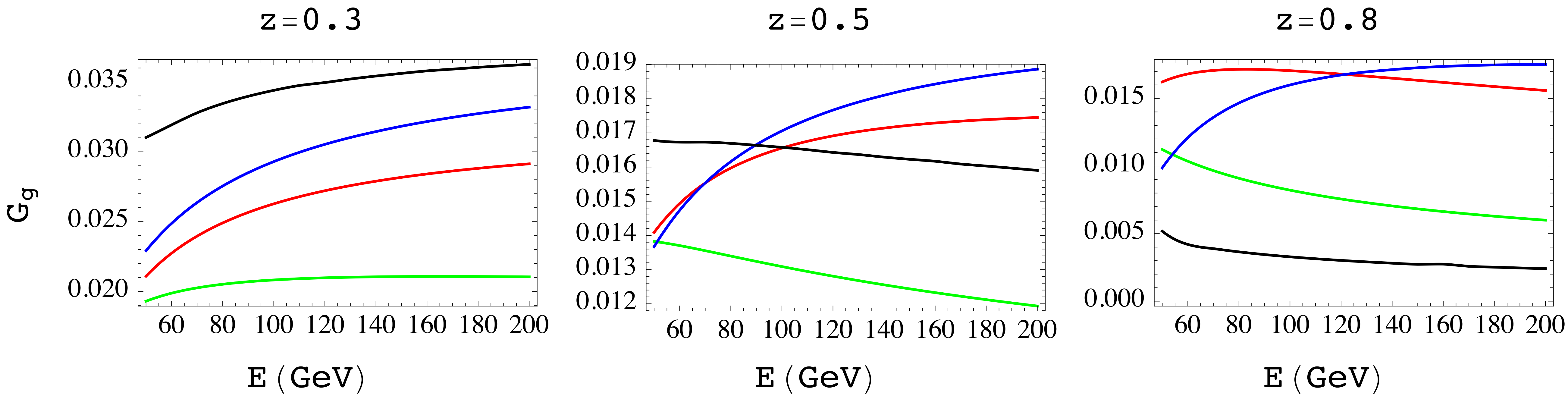
fragmentation function

fragmenting jet function

FJF's at Fixed Energy vs. z



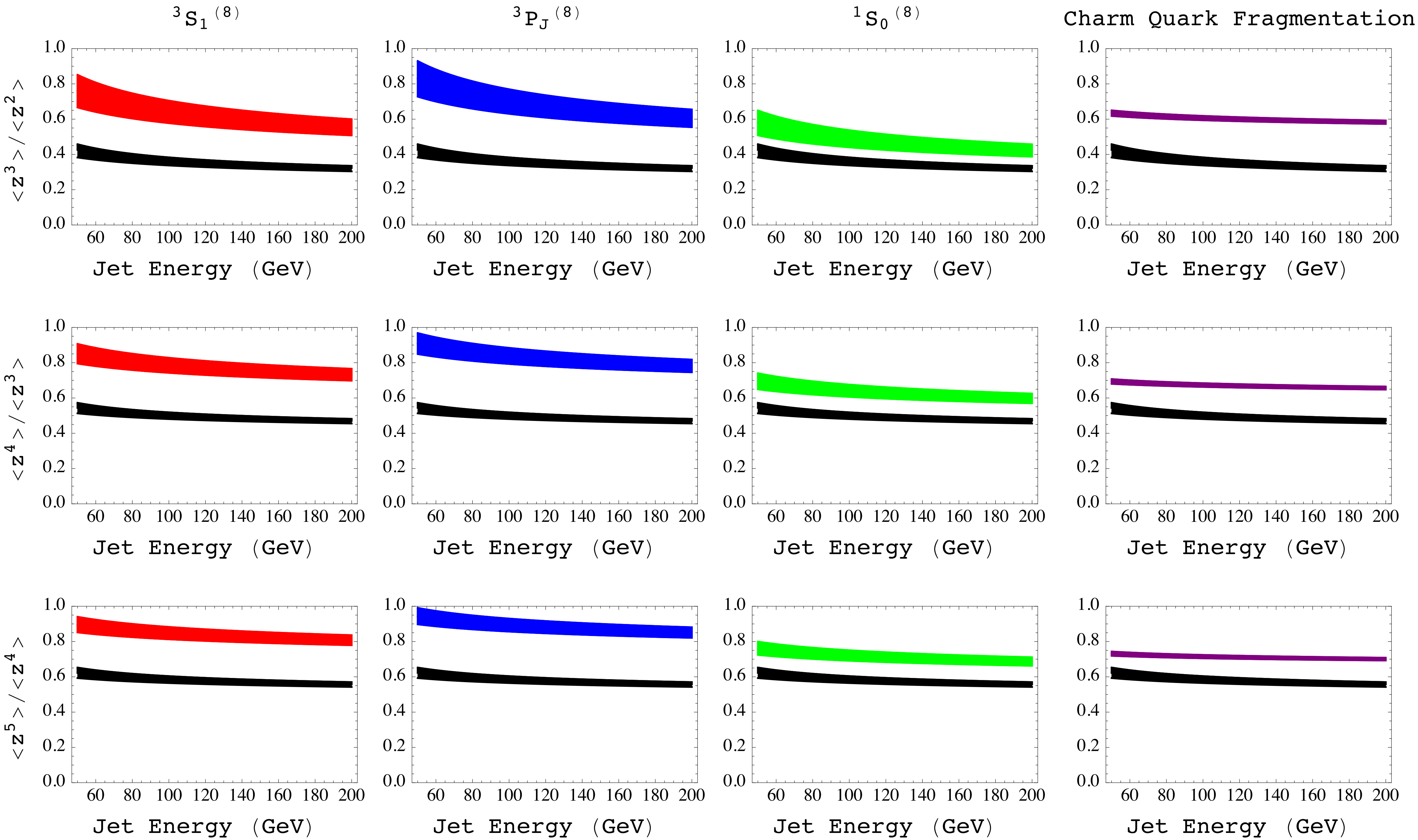
FJF's at Fixed z vs. Energy



$^{1}S_0^{(8)}$ dominance predicts negative slope for z vs. E if z > 0.5

Ratios of Moments

$$E \tan(R/2) < \mu < 4E \tan(R/2)$$

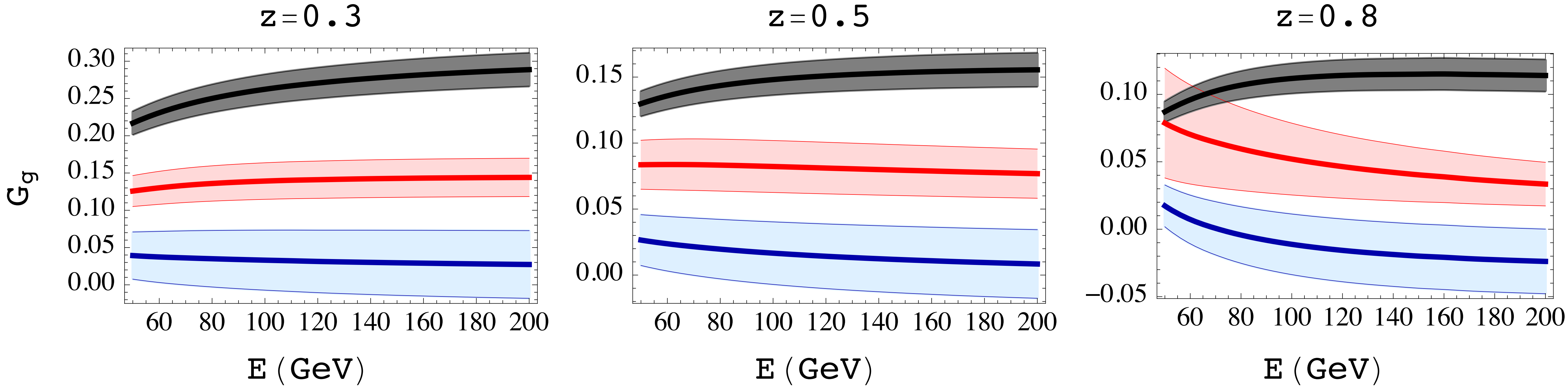


Ratios of Moments

$$\left.\frac{\langle z^{n+1}\rangle}{\langle z^n\rangle}\right|_{{}^3P_J^{(8)}} \approx \left.\frac{\langle z^{n+1}\rangle}{\langle z^n\rangle}\right|_{{}^3S_1^{(8)}} > \left.\frac{\langle z^{n+1}\rangle}{\langle z^n\rangle}\right|_{{}^1S_0^{(8)}} \approx \left.\frac{\langle z^{n+1}\rangle}{\langle z^n\rangle}\right|_{\mathrm{c-quark}} > \left.\frac{\langle z^{n+1}\rangle}{\langle z^n\rangle}\right|_{{}^3S_1^{(1)}}$$

Gluon FJF for different extractions of LDME

fix z, vary energy



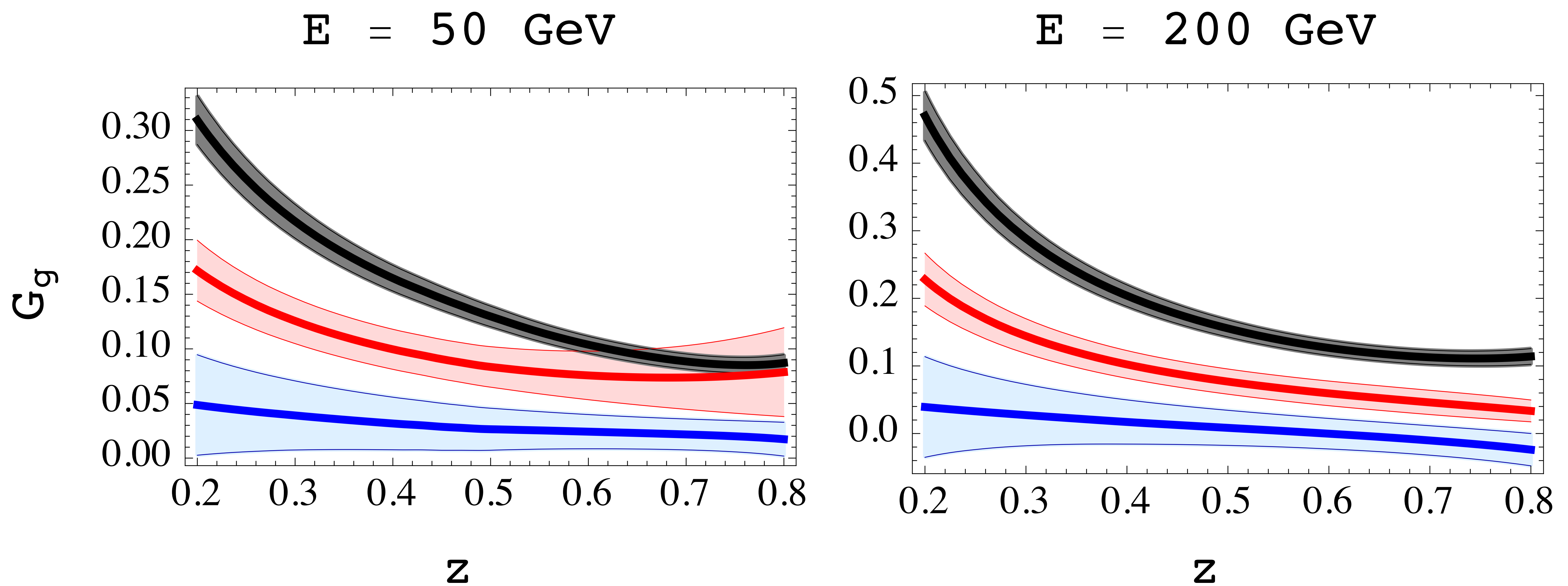
Butenschoen and Kniehl, PRD 84 (2011) 051501, arXiv:1105.0822

Bodwin, et. al. arXiv:1403.3612

Chao, et. al. PRL 108, 242004 (2012)

Gluon FJF for different extractions of LDME

fix energy, vary z



Conclusions

NRQCD describes much world data on quarkonium data but puzzles, esp. polarization, remain

existing analyses focus on inclusive p_t spectra, polarization can we find other observables distinguish various production mechanisms at high p_T?

measuring $Q\bar{Q}$ within jets, and using jet observables should provide insights into $Q\bar{Q}$ production

quarkonium fragmenting jet functions (FJFs)

If $^1S_0^{(8)}$ mechanism dominates high p_T production FJF should have negative slope for z(E), for z>0.5

Backup

fragmentation function (QCD)

$$D_q^h(z) = z \int \frac{\mathrm{d}x^+}{4\pi}\, e^{ik^- x^+/2}\, \frac{1}{4N_c}\, \mathrm{Tr} \sum_X \langle 0 | \bar{\not{n}}\, \Psi(x^+, 0, 0_\perp) | Xh \rangle \langle Xh | \bar{\Psi}(0) | 0 \rangle \Big|_{p_h^\perp = 0}$$

fragmentation function (SCET)

$$D_q^h\Big(\frac{p_h^-}{\omega}, \mu\Big) = \pi\omega \int dp_h^+\, \frac{1}{4N_c}\, \mathrm{Tr} \sum_X \bar{\not{n}}\, \langle 0 | [\delta_{\omega,\bar{\mathcal{P}}}\, \delta_{0,\mathcal{P}_\perp}\, \chi_n(0)] | Xh \rangle \langle Xh | \bar{\chi}_n(0) | 0 \rangle$$

Jet function (SCET)

$$J_u(k^+\omega) = -\frac{1}{\pi\,\omega}\, \mathrm{Im} \int d^4x\, e^{ik\cdot x}\, i\, \langle 0 | \, \mathrm{T}\, \bar{\chi}_{n,\omega,0_\perp}(0)\, \frac{\bar{\not{n}}}{4N_c}\, \chi_n(x) | 0 \rangle$$

fragmentation jet function (SCET)

$$\mathcal{G}_{q,\mathrm{bare}}^h(s, z) = \int \mathrm{d}^4y\, e^{ik^+y^-/2} \int \mathrm{d}p_h^+ \sum_X \frac{1}{4N_c}\, \mathrm{tr}\Big[\frac{\bar{\not{n}}}{2} \langle 0 | [\delta_{\omega,\overline{\mathcal{P}}}\, \delta_{0,\mathcal{P}_\perp}\, \chi_n(y)] | Xh \rangle \langle Xh | \bar{\chi}_n(0) | 0 \rangle\Big]$$

$$\delta(p^+/z - P_H^+) \rightarrow \delta(p^+/z - P_H^+)\,\delta(p^- - s/p^+)$$

FF FJF