Tests of NRQCD with Quarkonium Production in Jets at the LHC

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XIIIth Quark Confinement and the Hadron Spectrum
Maynooth U., Dublin, Ireland
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Fragmenting Jet Functions (FJFs)

NRQCD and Quarkonium Production

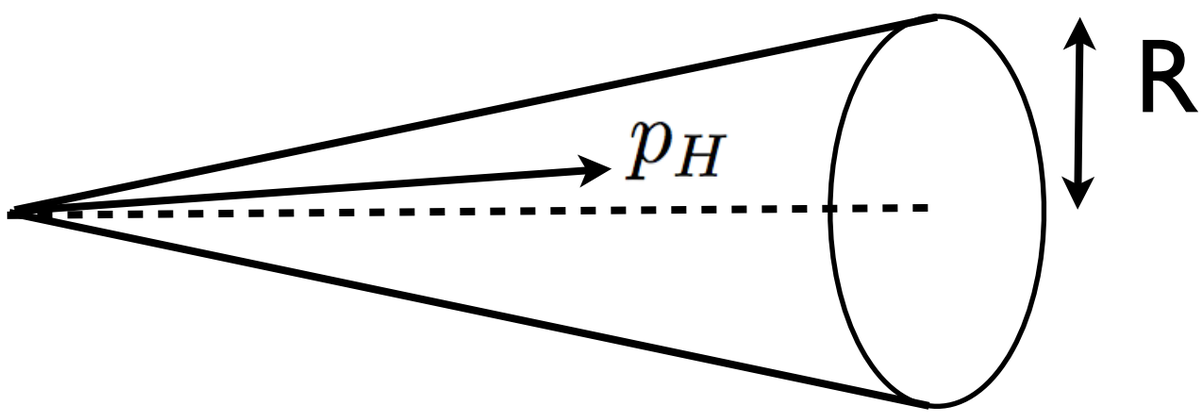
Heavy Quarkonium FJFs

Recent Data on Quarkonia in Jets (LHCb)

Fragmenting Jet Functions

M. Procura, I. Stewart, PRD 81 (2010) 074009
A. Jain, M. Procura, W. Waalewijn, JHEP 1105 (2011) 035
A. Procura, W. Waalewijn, PRD 85 (2012) 114041

jets with identified hadrons



Jet Energy: E

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

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

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

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

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

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

FJF in terms of fragmentation function

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

$$\mathcal{G}_i^h(E, R, z, \mu_J) = D_i^h(z, \mu_J) + O(\alpha_s) \qquad \mu_J = 2E \tan(R/2)$$

Non-Relativistic QCD (NRQCD) Factorization Formalism

Bodwin, Braaten, Lepage, PRD 51 (1995) 1125

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

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

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

Extractions of LDME in J/ψ Production

Global Fits

Butenschoen and Kniehl, PRD 84 (2011) 051501

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

fit to 194 data points, 26 data sets

decent fit to world's data

incorrectly predict transverse polarization at high p_T

Fits to high p_T collider data

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

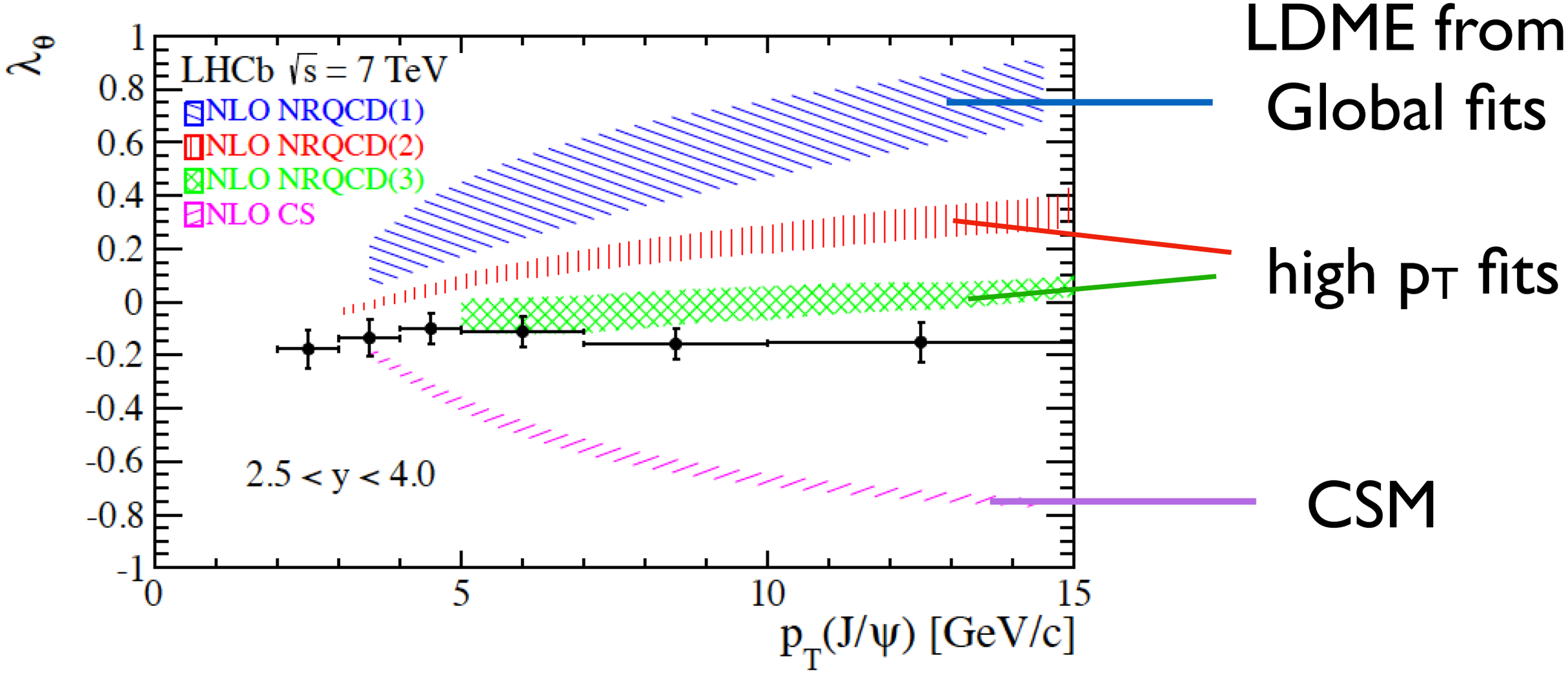
Chao, et. al. PRL 108, 242004 (2012)

can explain high p_T spectra, polarization

ignore most of data

larger statistical uncertainties

Polarization of J/ψ at LHCb

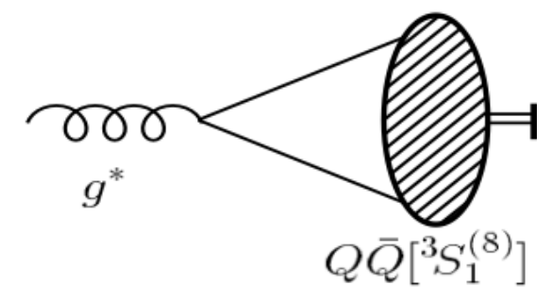


NRQCD fragmentation functions

Braaten, Yuan, PRD 48 (1993) 4230
Braaten, Chen, PRD 54 (1996) 3216
Braaten, Fleming, PRL 74 (1995) 3327

Perturbatively calculable **at the scale $2m_c$**

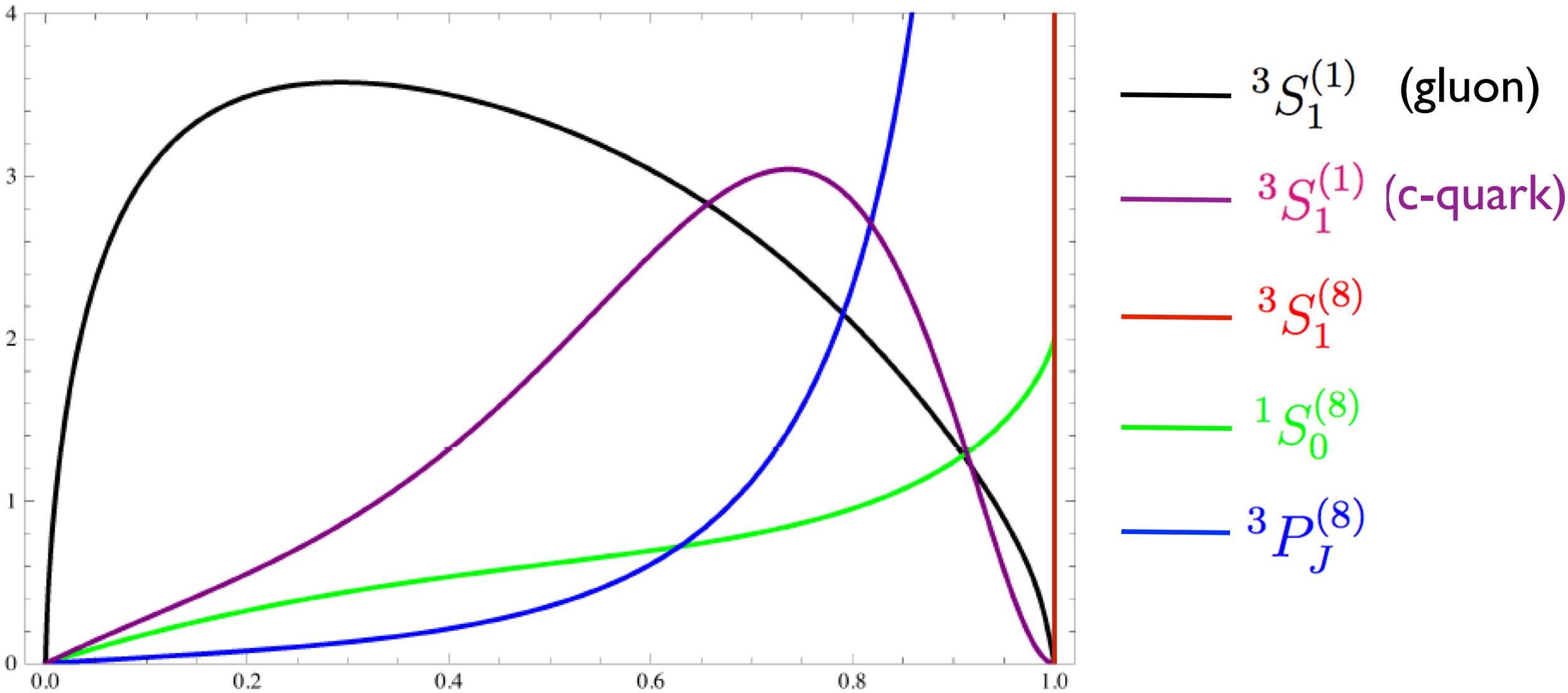
$$D_g^{\psi(8)}(z, 2m_c) = \frac{\pi\alpha_s(2m_c)}{3M_\psi^3}\langle O^\psi(^3S_1^{(8)})\rangle\delta(1-z)$$



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

DGLAP evolution: $2m_c$ to 2E tan(R/2)

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

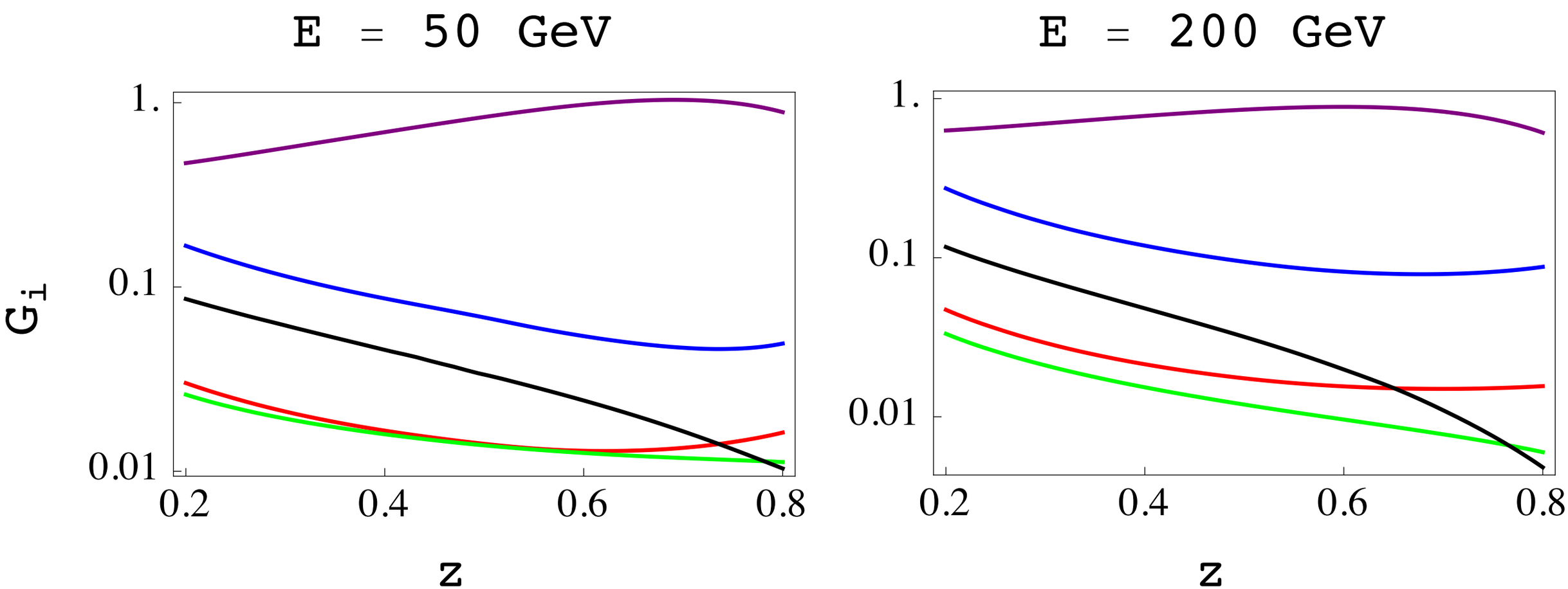


(normalization arbitrary)

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

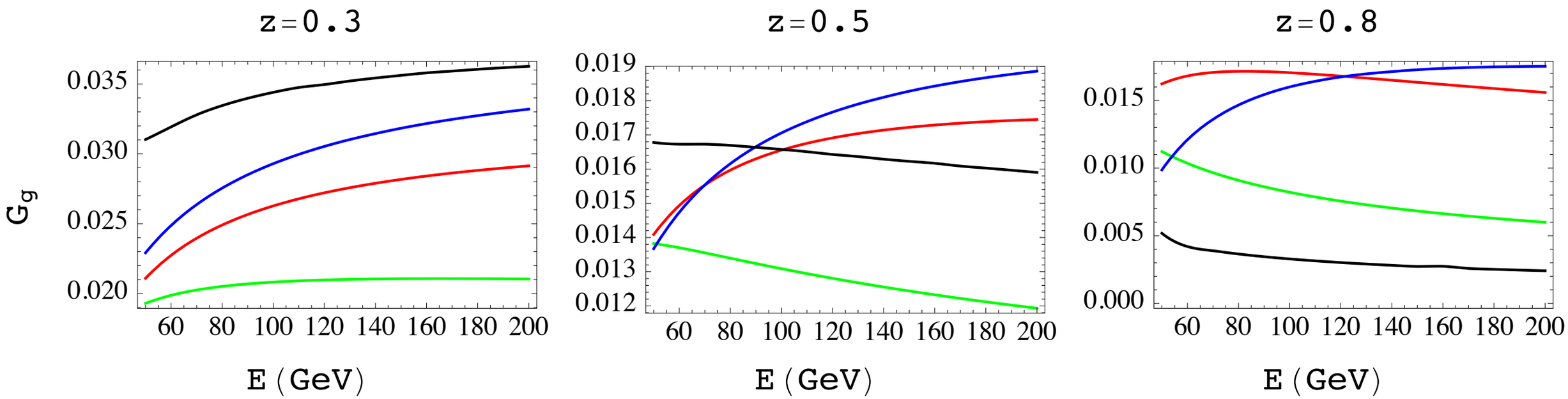
FJF's at Fixed Energy vs. z

M. Baumgart, A. Leibovich, T.M., I. Z. Rothstein, JHEP 1411 (2014) 003



FJF's at Fixed z vs. Energy

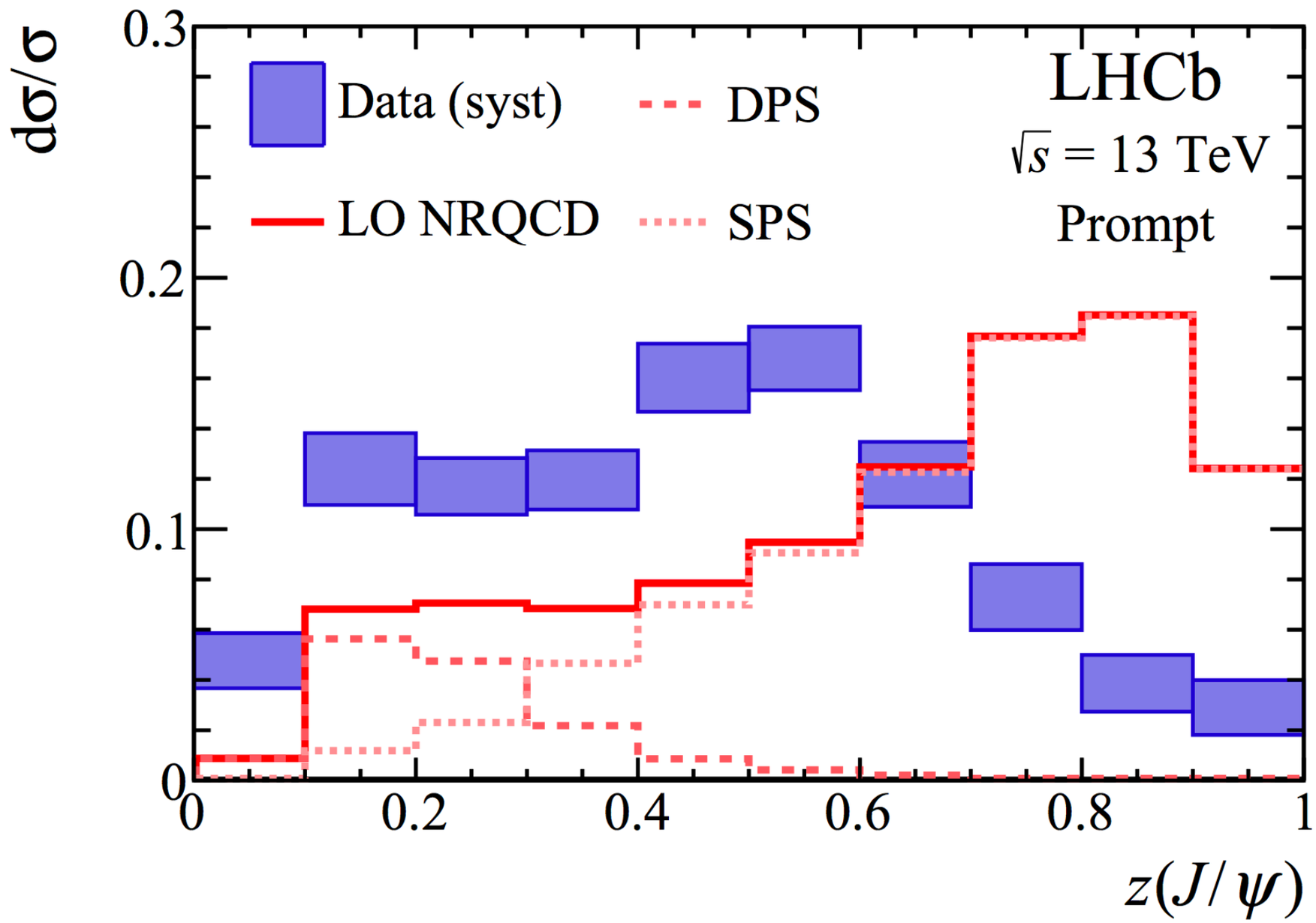
M. Baumgart, A. Leibovich, T.M., I. Z. Rothstein, JHEP 1411 (2014) 003



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

Recent Observations of Quarkonia within Jets

LHCb collaboration, Phys. Rev. Lett. 118 (2017) no.19, 192001



cuts: $2.5 < \eta_{\rm jet} < 4.0 \quad p_{T,jet} > 20\,\mathrm{GeV} \quad p(\mu) > 5\,\mathrm{GeV}$

This result was anticipated in:

R. Bain, L. Dai, A. Hornig, A. K. Leibovich, Y. Makris, T. Mehen JHEP 1606 (2016) 121

Jets w/ Heavy Mesons: NLL' vs. Monte Carlo

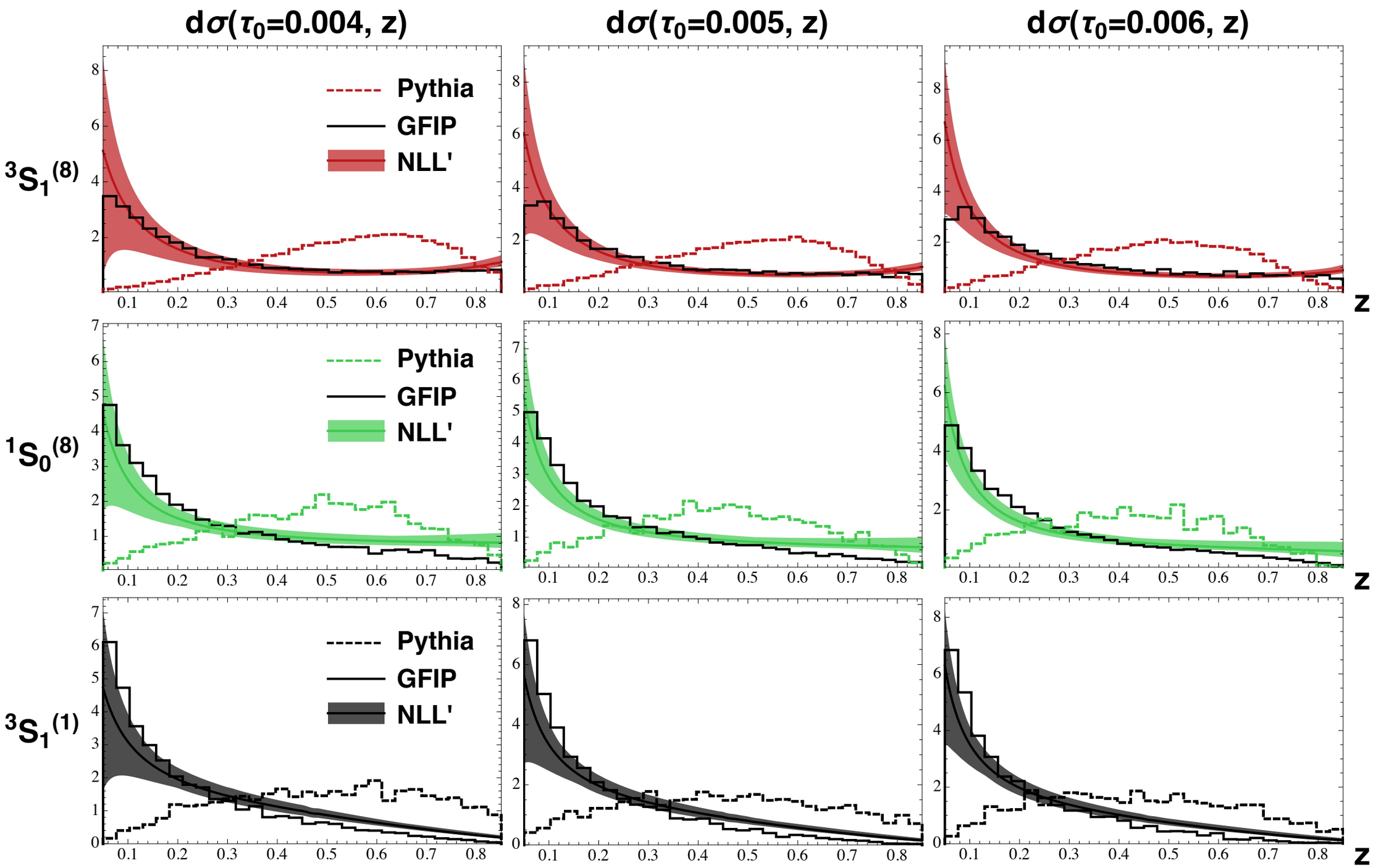
$$e^+e^- \to b\bar{b}$$

$\hookrightarrow$ B jet

$$e^+e^- \to q\bar{q}g$$

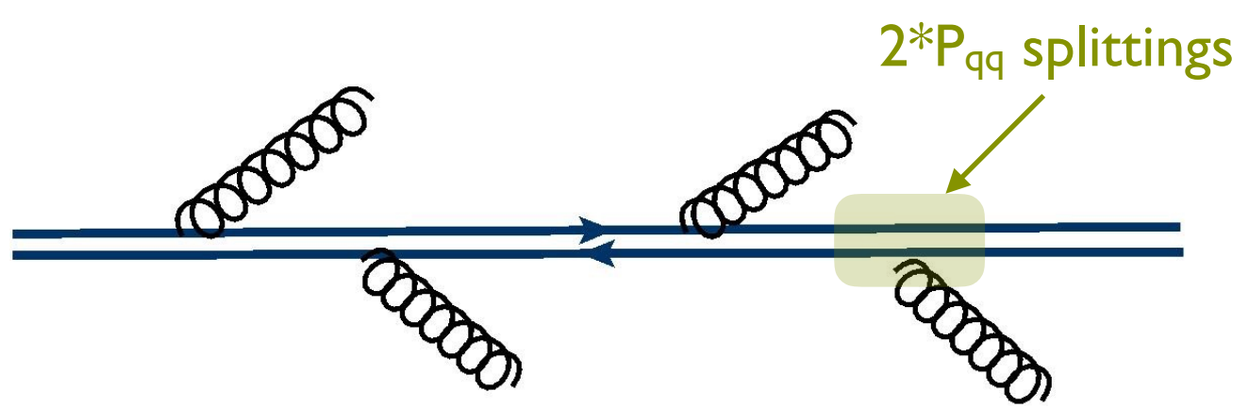
$\hookrightarrow$ J/ψ jet

NLL', PYTHIA, and GFIP

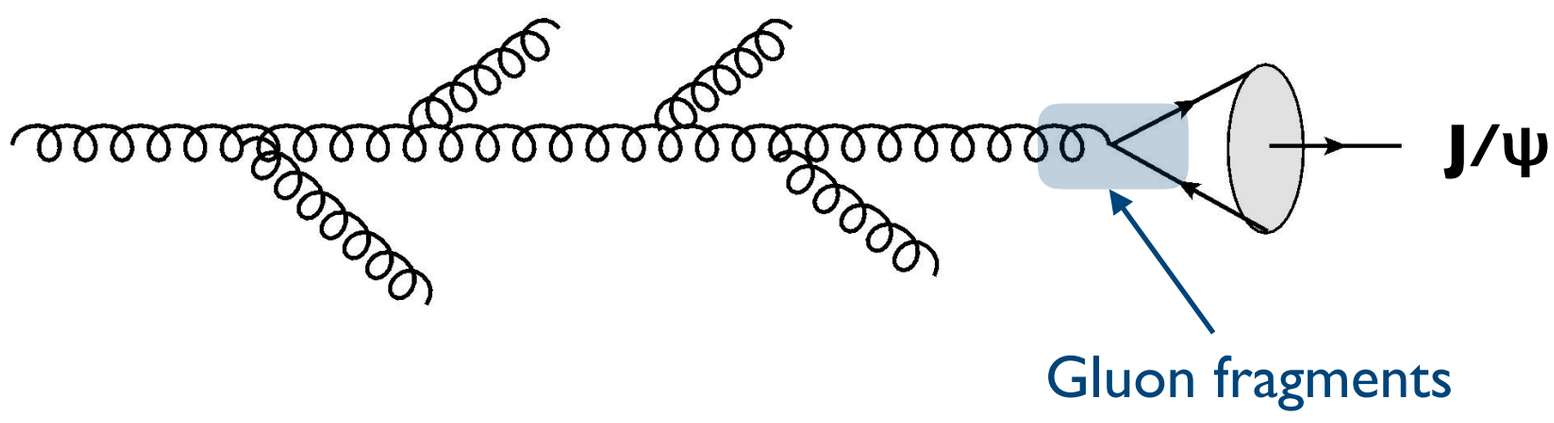


Explaining difference between NLL' vs Pythia

PYTHIA's model for showering color-octet $c\bar{c}$ pairs:



Physical picture of analytical calculation

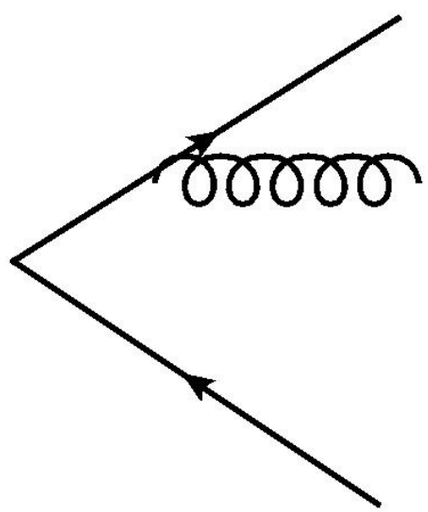


Pythia z distributions much harder than NLL' calculations

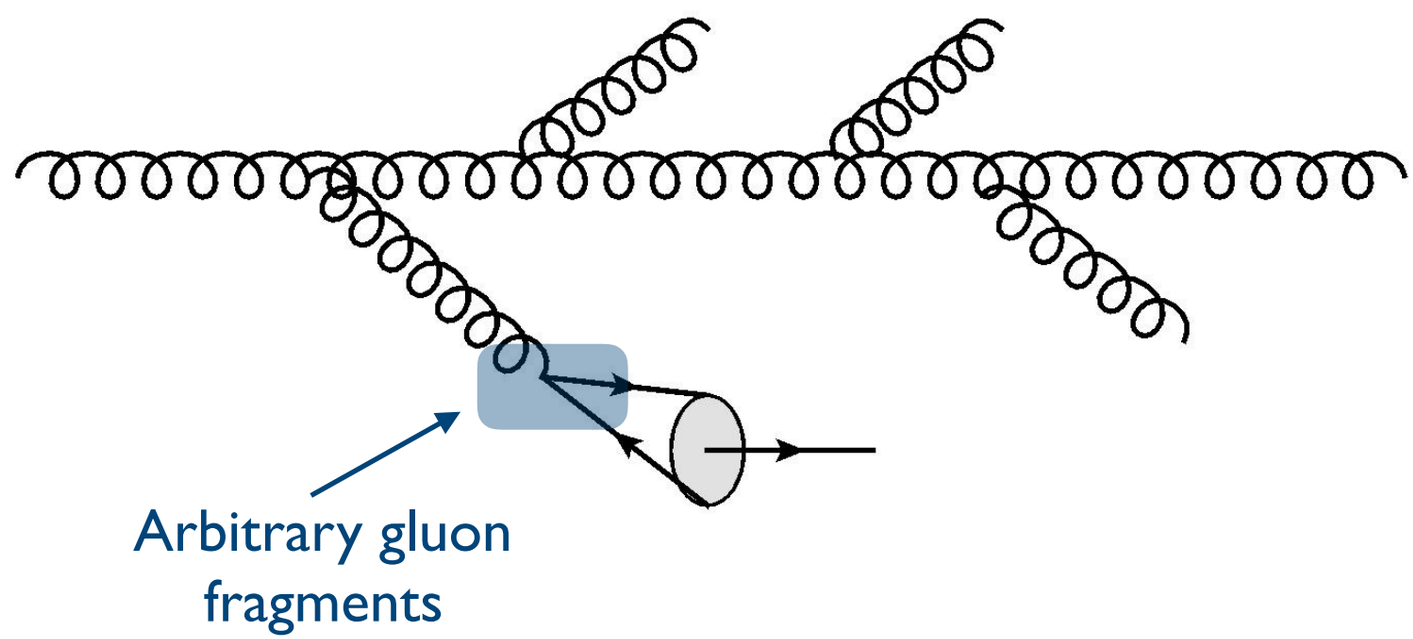
Gluon Fragmentation Improved PYTHIA (GFIP)

Madgraph 5

$e^+e^- \to b\bar{b}g$



PYTHIA + Convolution



shower gluon with PYTHIA down to scale ~$2m_c$, no hadronization

convolve final state gluon distribution w/ NRQCD FFs

Two Calculations for LHCb data

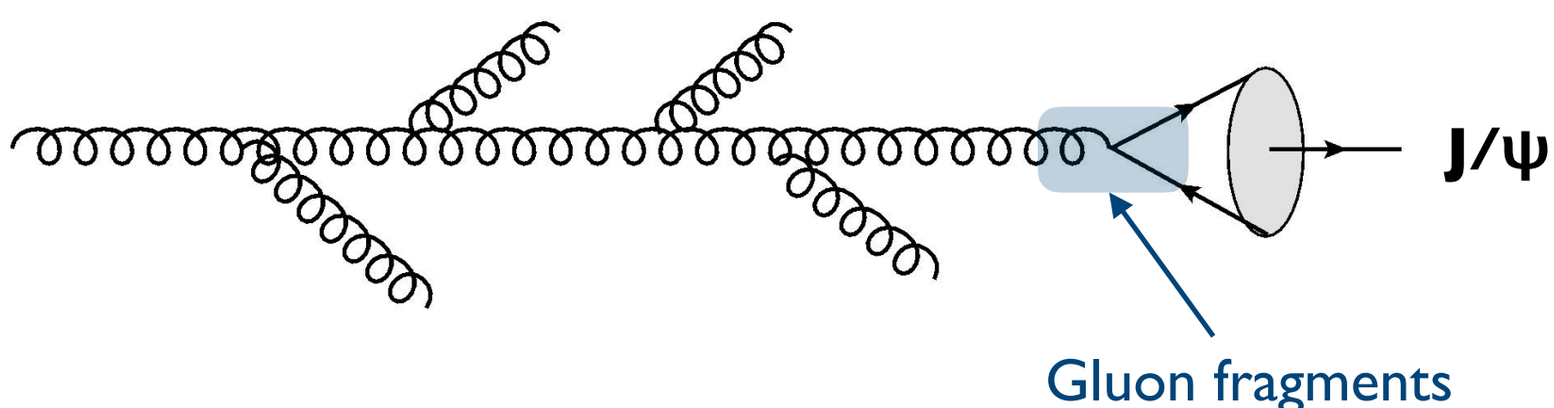
Fragmenting Jet Function (FJF)

convolve LO partonic cross sections w/ FJF's at jet scale

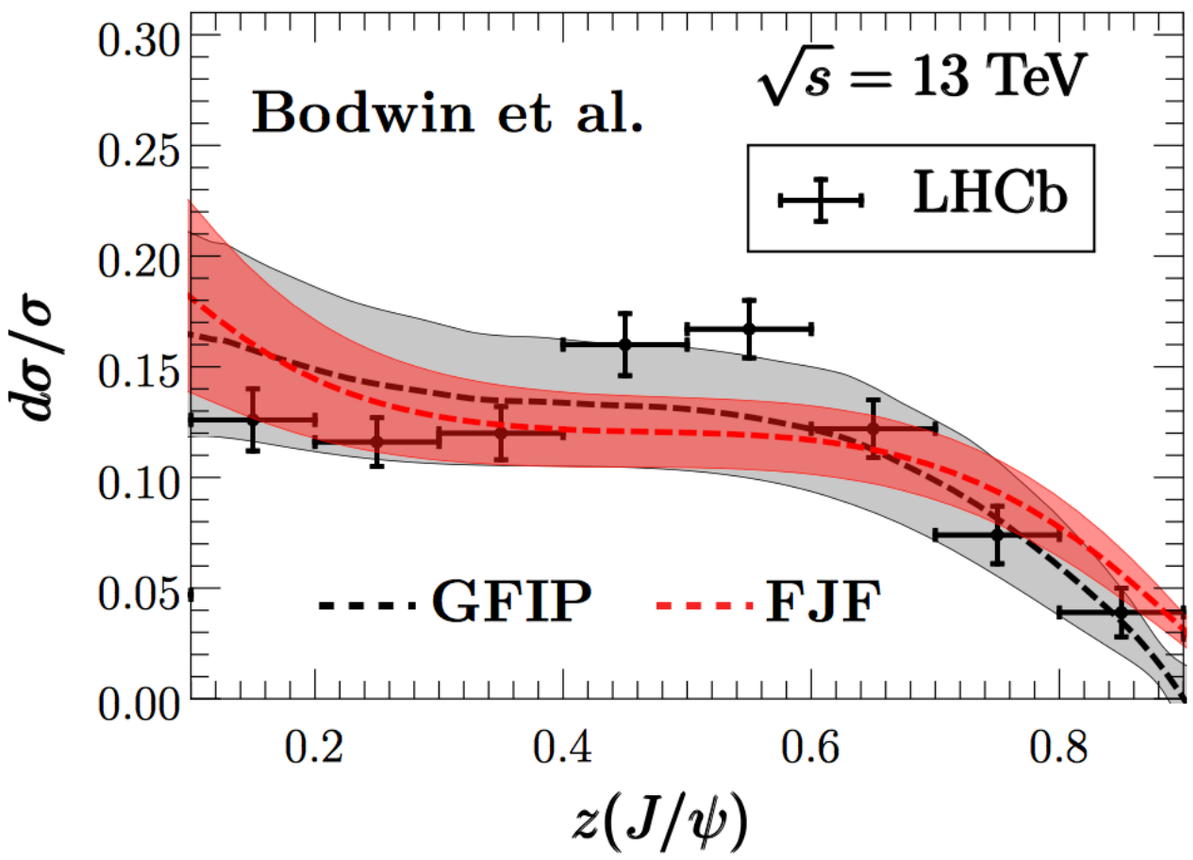
Gluon Fragmentation Improved PYTHIA (GFIP)

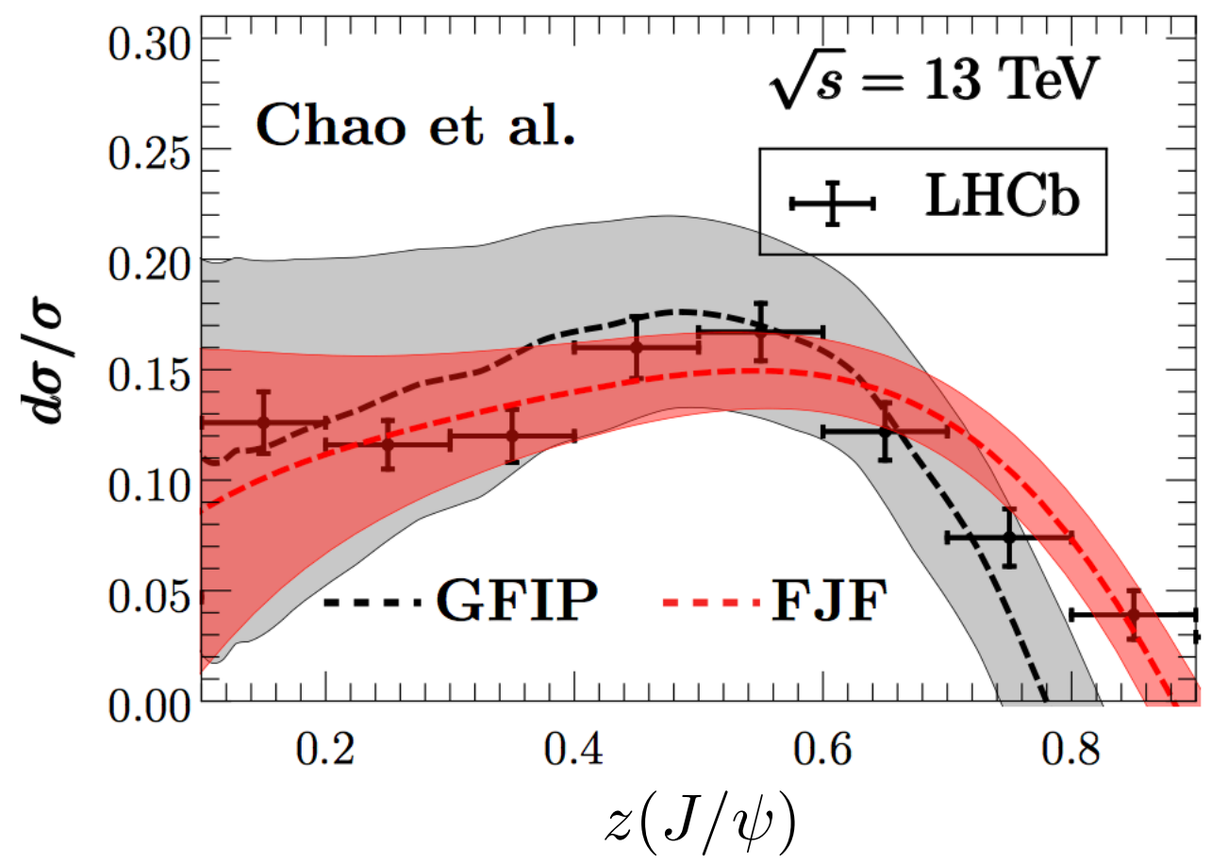
shower LO partonic cross sections
w/PYTHIA perturbatively down to scale $2m_c$

convolve resulting g,c distributions with
LO NRQCD fragmentation functions



Comparison with LHCb, FJF & GFIP

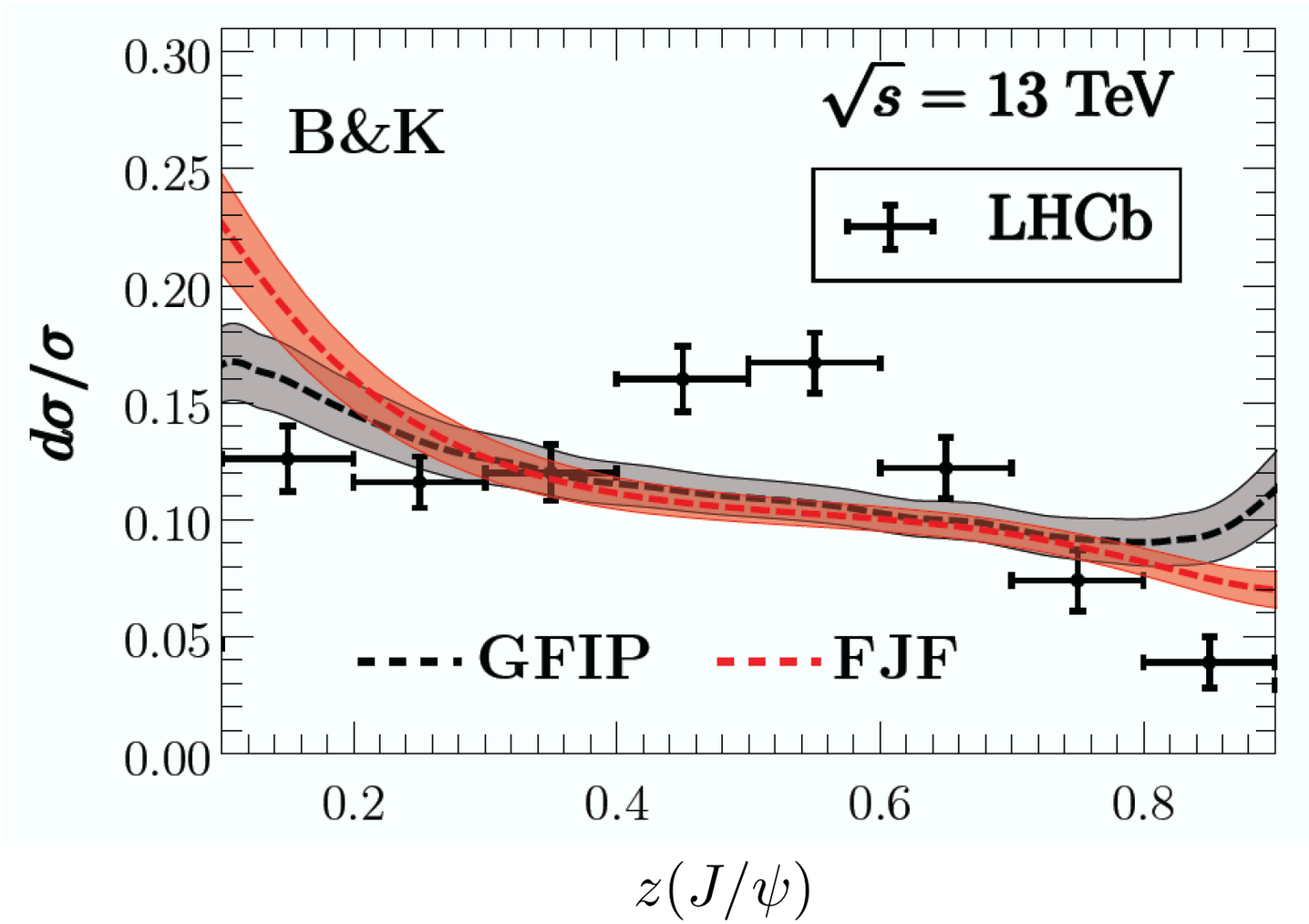




FJFs, GFIP consistent

LDME from fits high p_T agree with LHCb

Comparison with LHCb, FJF & GFIP



LDME from global fits:
poorer agreement with LHCb, better than PYTHIA

Future Measurements

polarization of J/ψ in jets

Z.-B. Kang, .J.-W. Qiu, F. Ringer, H. Xing, H. Zhang, PRL 119 (2017) 032001

absolute cross sections

alternative jet definitions, e.g., soft drop

p_T dependent FJFs

R. Bain, Y. Makris, TM, JHEP 1611 (2016) 144

Conclusions

measuring quarkonia within jets and using jet observables should provide insights into quarkonia production

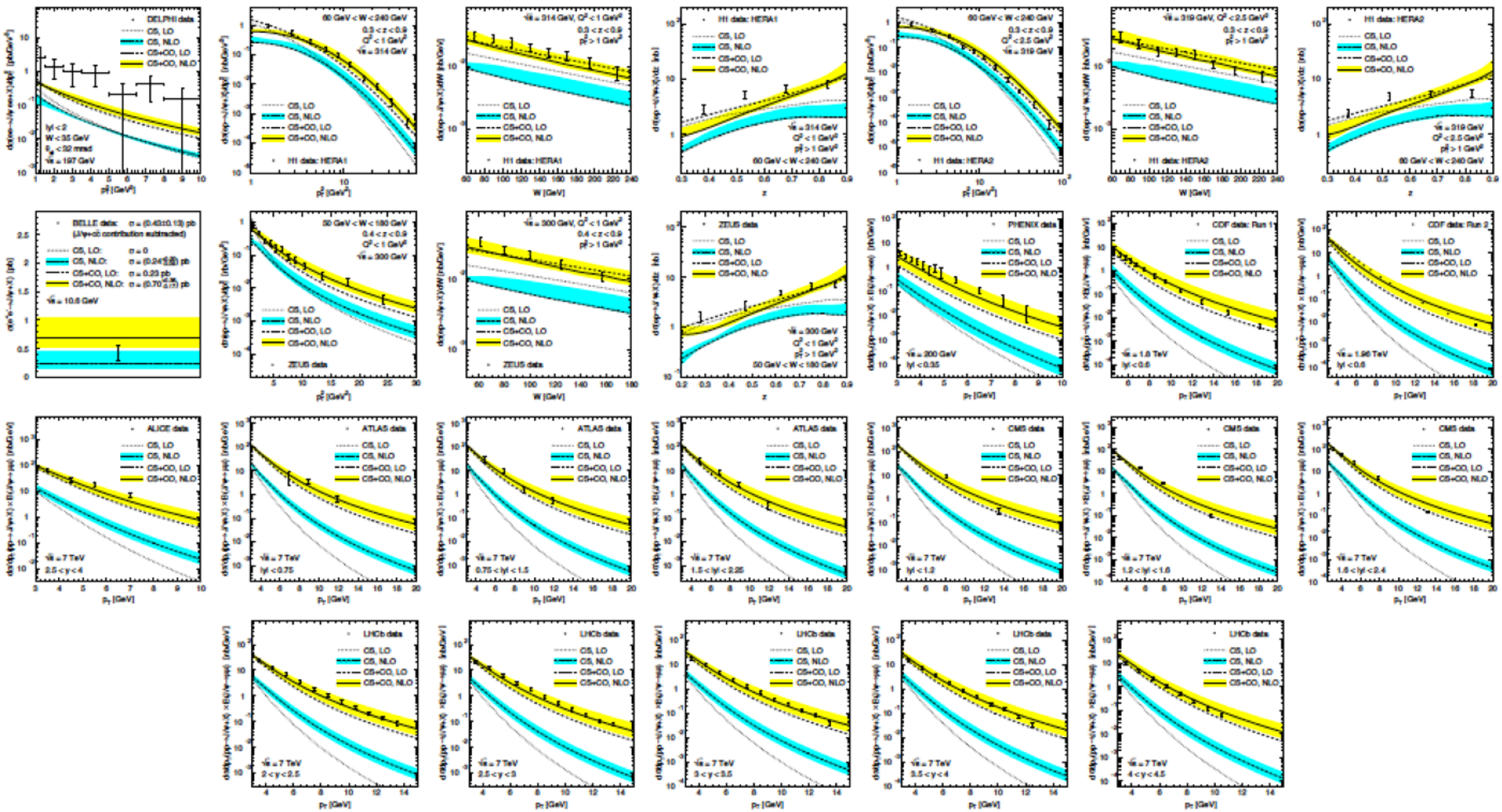
If $^1S_0^{(8)}$ mechanism dominates high p_T production
FJF should have negative slope for z(E), for z > 0.5

LHCb data on $z(J/\psi)$ well-described by FJF, GFIP
improvement over default PYTHIA, consistent w/ NLL' calculations
LDME extracted from high p_T slightly preferred

Back up Slides

Global Fits with NLO CSM + COM

Butenschoen and Kniehl, PRD 84 (2011) 051501



$e^+e^-, \gamma\gamma, \gamma p, p\bar{p}, pp \to J/\psi + X$ fit to 194 data points, 26 data sets

Status of NRQCD approach to J/ψ Production

NLO: COM + CSM required for most processes

extracted LDME satisfy NRQCD v-scaling

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

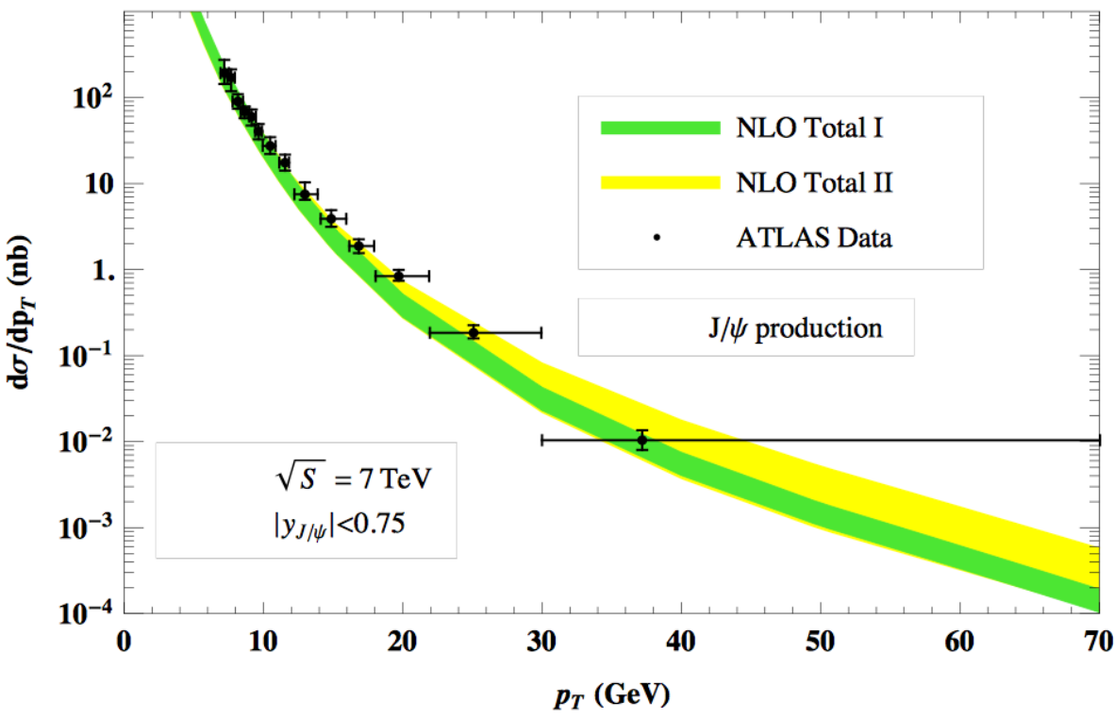
$\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$	$(4.97 \pm 0.44) \times 10^{-2}$ GeV^3
$\langle \mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle$	$(2.24 \pm 0.59) \times 10^{-3}$ GeV^3
$\langle \mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle$	$(-1.61 \pm 0.20) \times 10^{-2}$ GeV^5

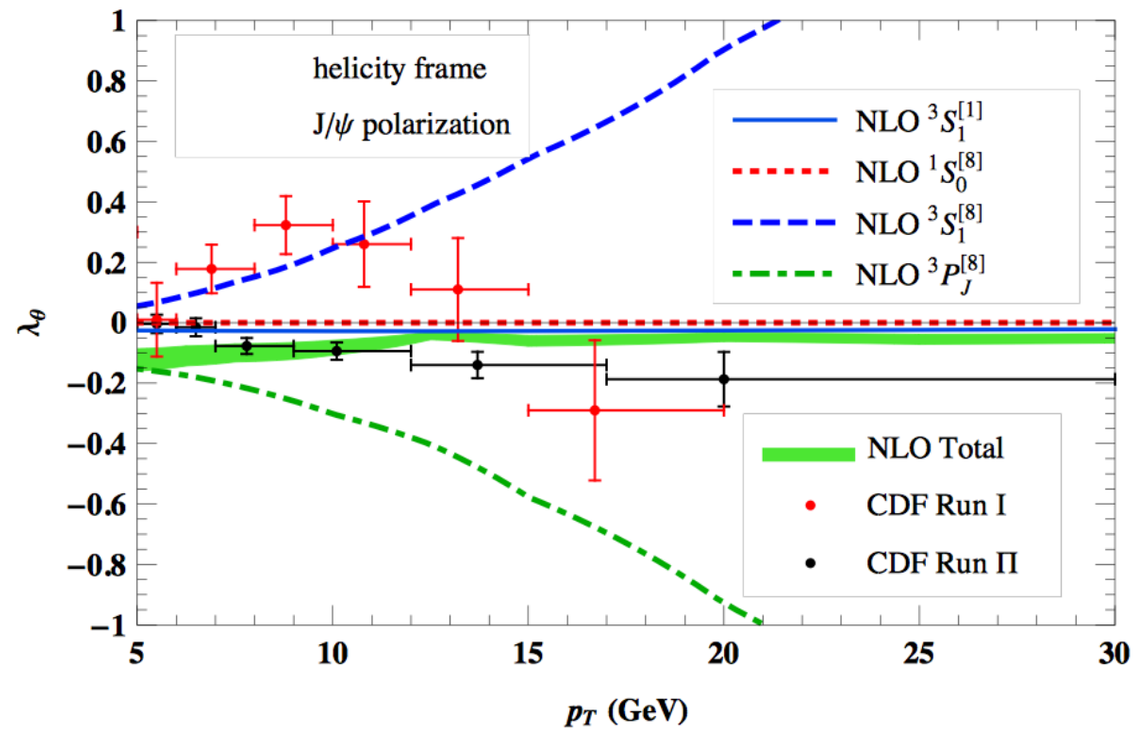
$$\chi^2_{\text{d.o.f.}} = 857/194 = 4.42$$

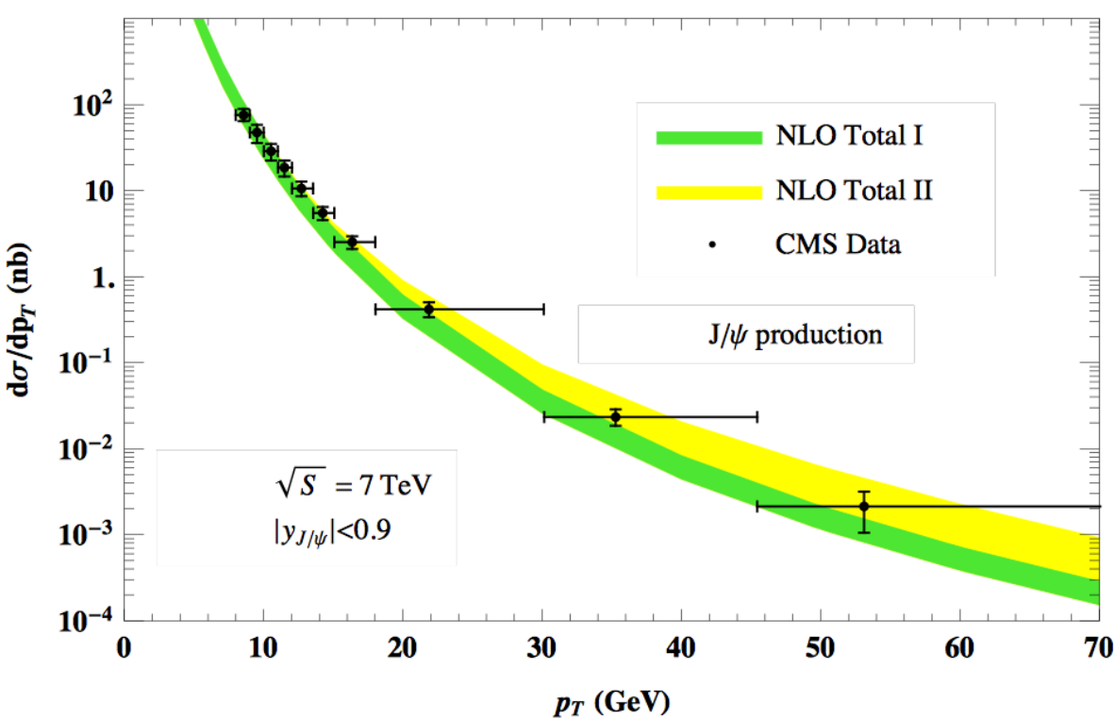
Recent Attempts to Resolve J/ψ Polarization Puzzle

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

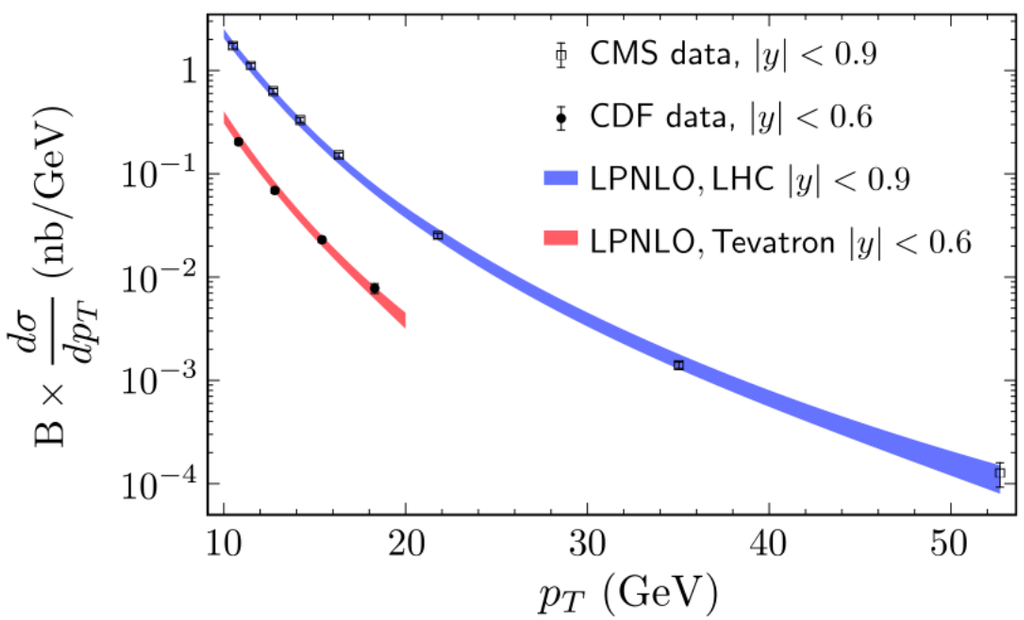
Recent Attempts to Resolve J/ψ Polarization Puzzle

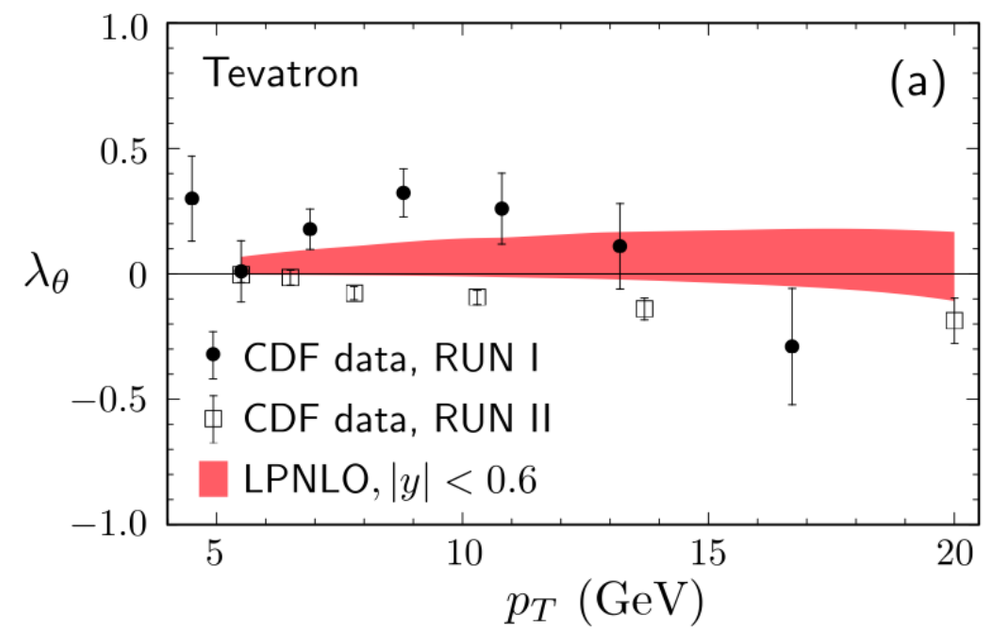
i) large p_t production at CDF

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

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

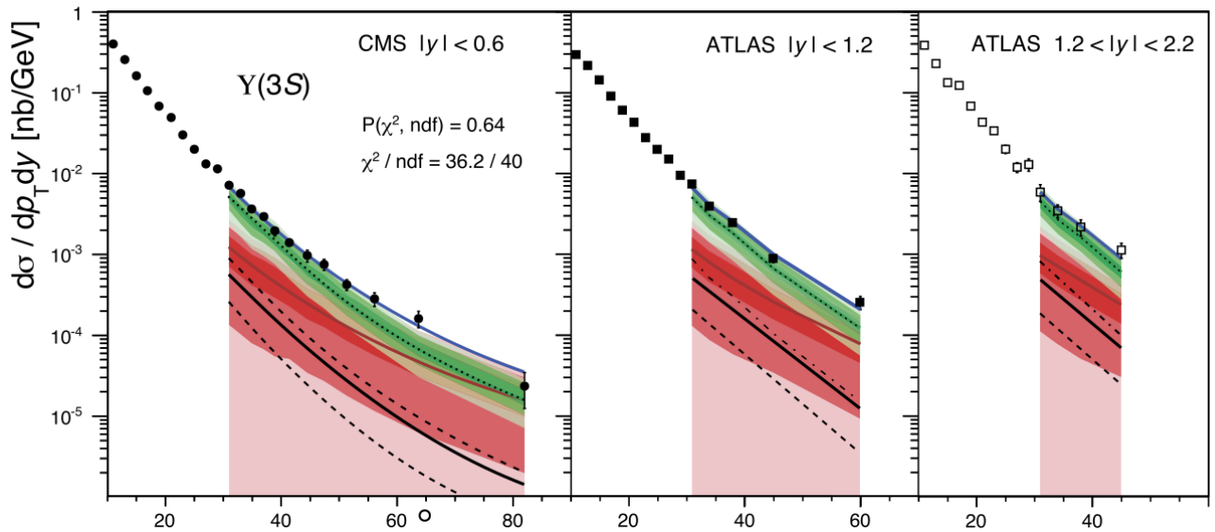
$$\langle \mathcal{O}^{J/\psi}(^3S_1^{(8)})\rangle = 0.011 \pm 0.010\,\mathrm{GeV}^3$$

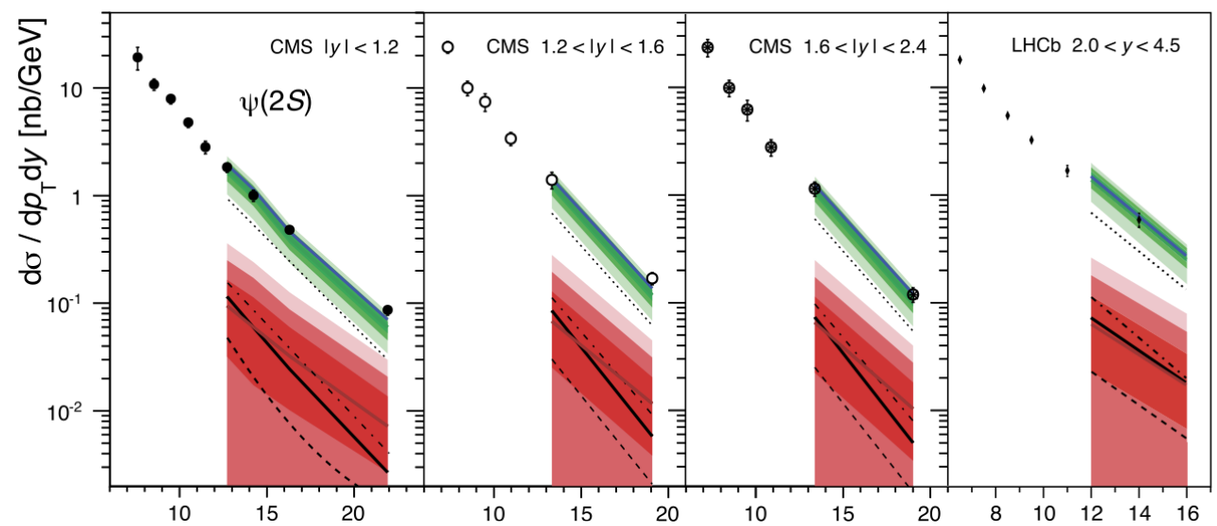
$$\langle \mathcal{O}^{J/\psi}(^3P_0^{(8)})\rangle = 0.011 \pm 0.010\,\mathrm{GeV}^5$$

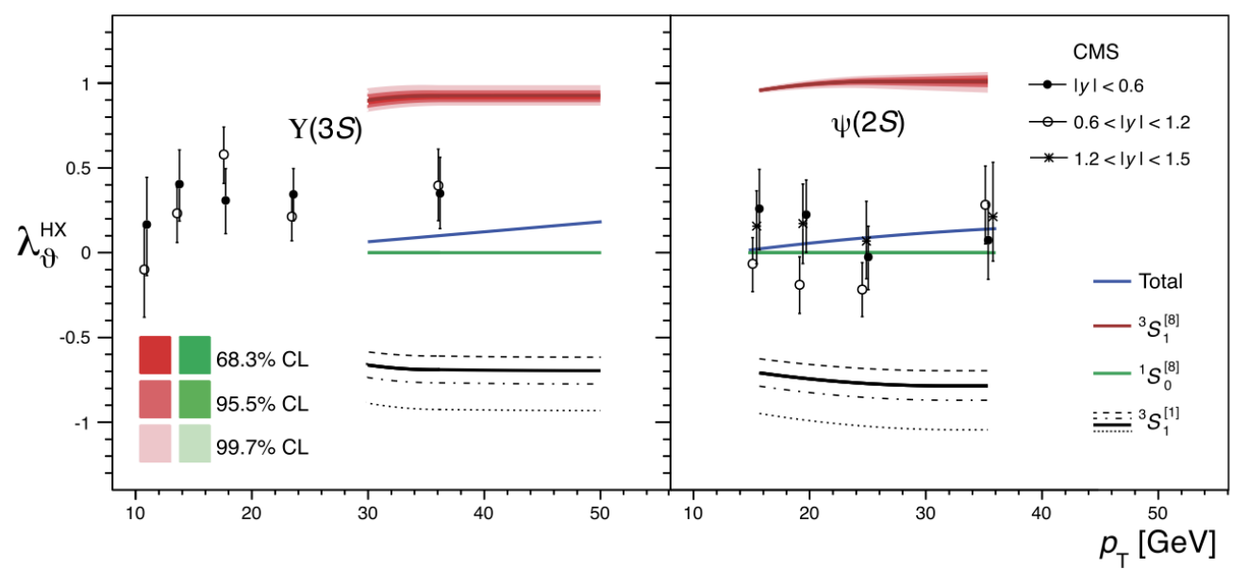
Recent Attempts to Resolve J/ψ Polarization Puzzle

Faccioli, et. al. PLB736 (2014) 98

Lourenco, et. al., NPA, in press

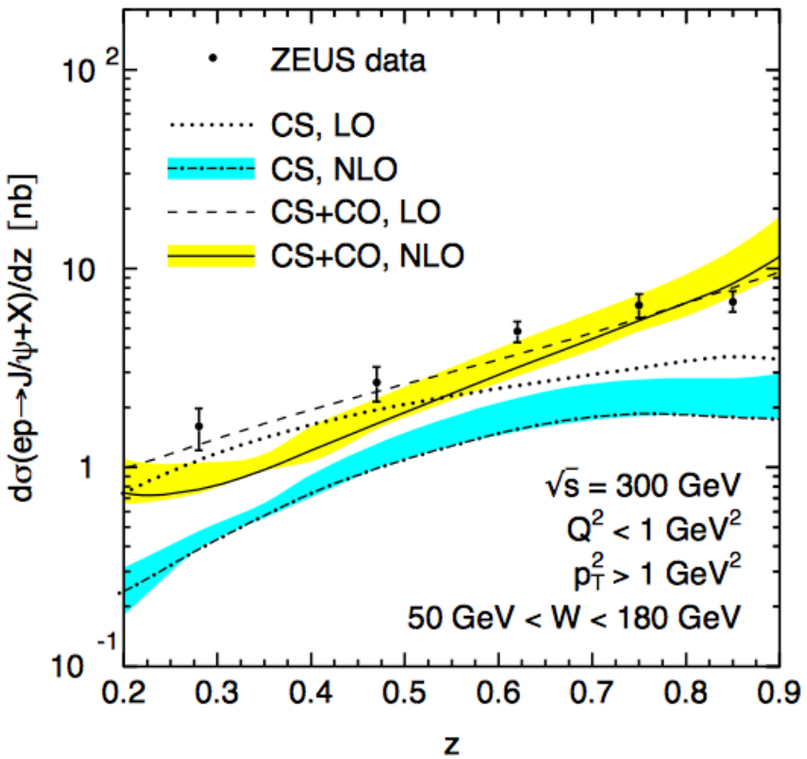


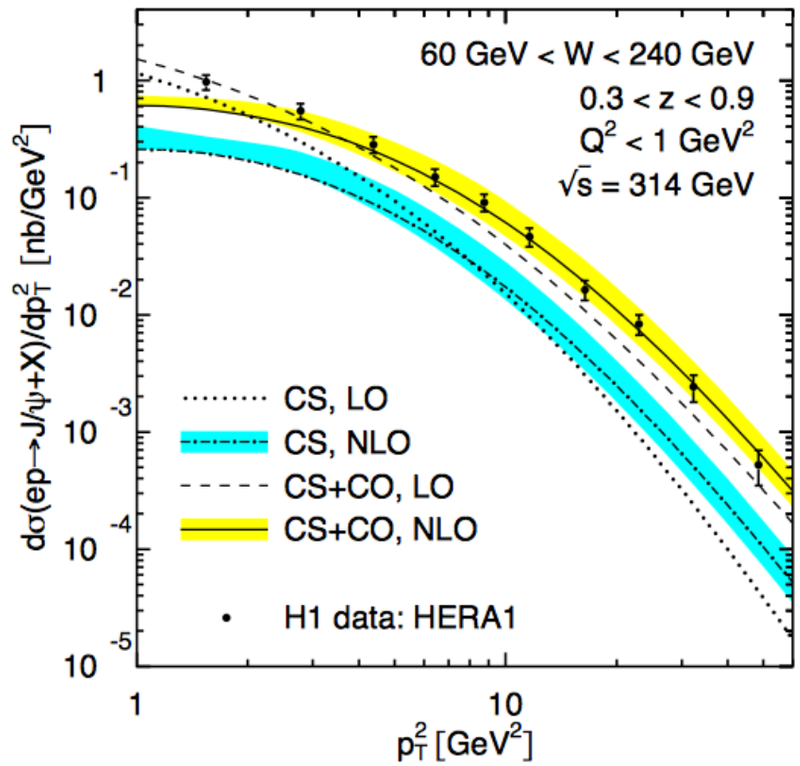


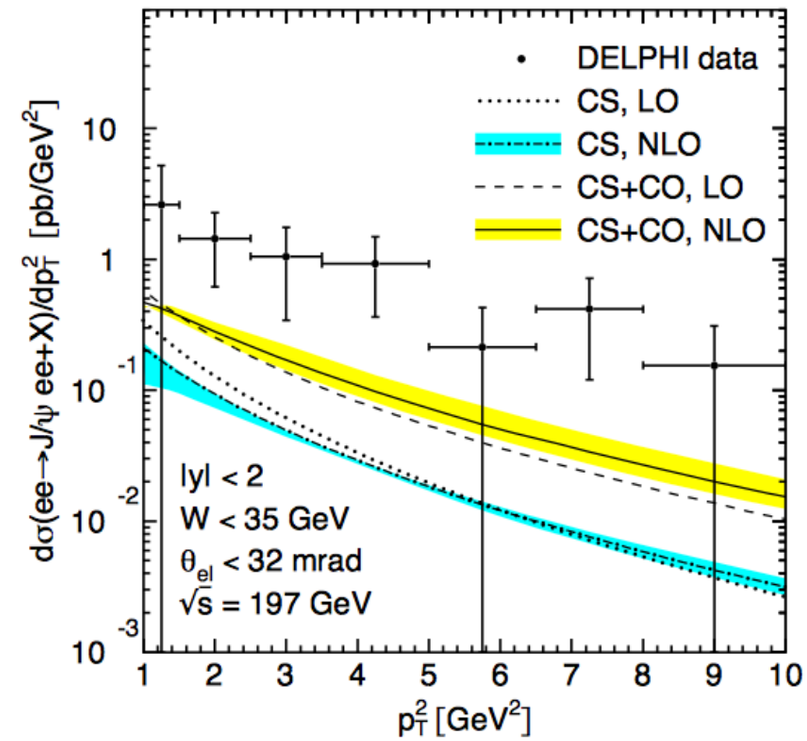


argue for $^1S_0^{(8)}$ dominance in both ψ(2S) & Υ(3S) production

NLO: CSM + COM Required to Fit Data







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

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

$e^+e^- \to$ Jets in SCET

S.D. Ellis, et.al., JHEP1011(2010) 101

$$d\sigma = H \times J_q \otimes J_{\bar{q}} \otimes J_g \otimes S$$

$$\longrightarrow \quad d\sigma = H \times J_q \otimes J_{\bar{q}} \otimes \mathcal{G}_g^{J/\psi} \otimes S$$

unmeasured jets:

E, R

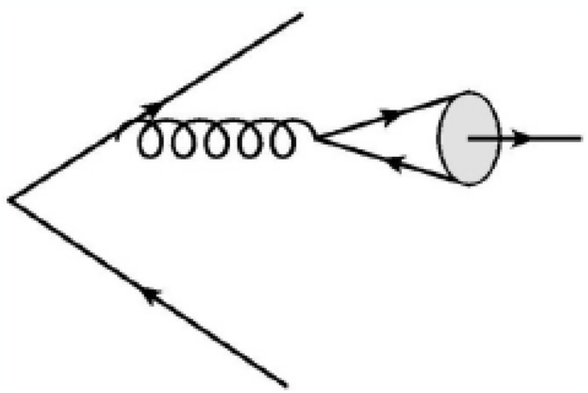
measured jets:

angularity: $\tau_a = \frac{1}{\omega} \sum_i (p_i^+)^{1-a/2} (p_i^-)^{a/2}$

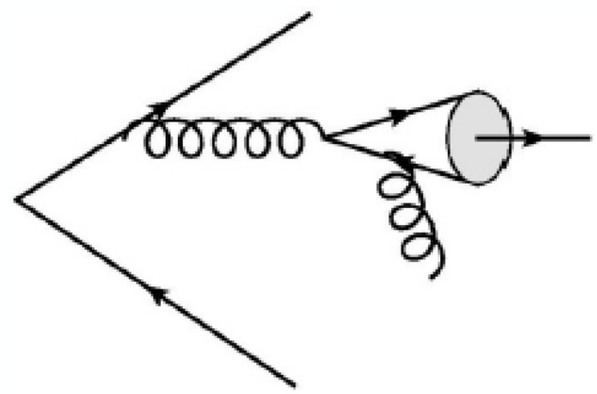
$$\omega = \sum_i p_i^- \qquad s = \omega^2 \tau_0$$

Madgraph + PYTHIA

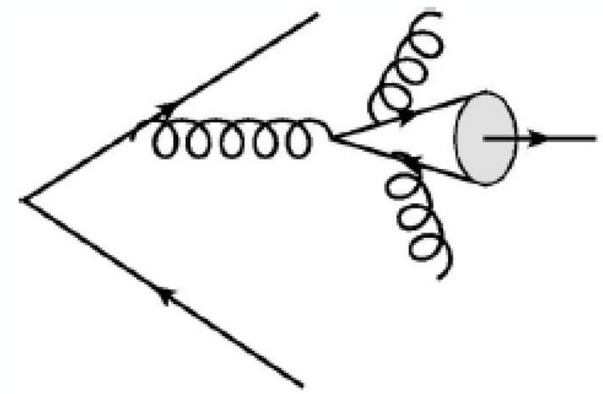
$e^+e^- \to b\bar{b}\,c\bar{c}\left[{}^3S_1^{(8)}\right]$



$e^+e^- \to b\bar{b}\,g\,c\bar{c}\left[{}^1S_0^{(8)}\right]$



$e^+e^- \to b\bar{b}\,g\,g\,c\bar{c}\left[{}^3S_1^{(1)}\right]$

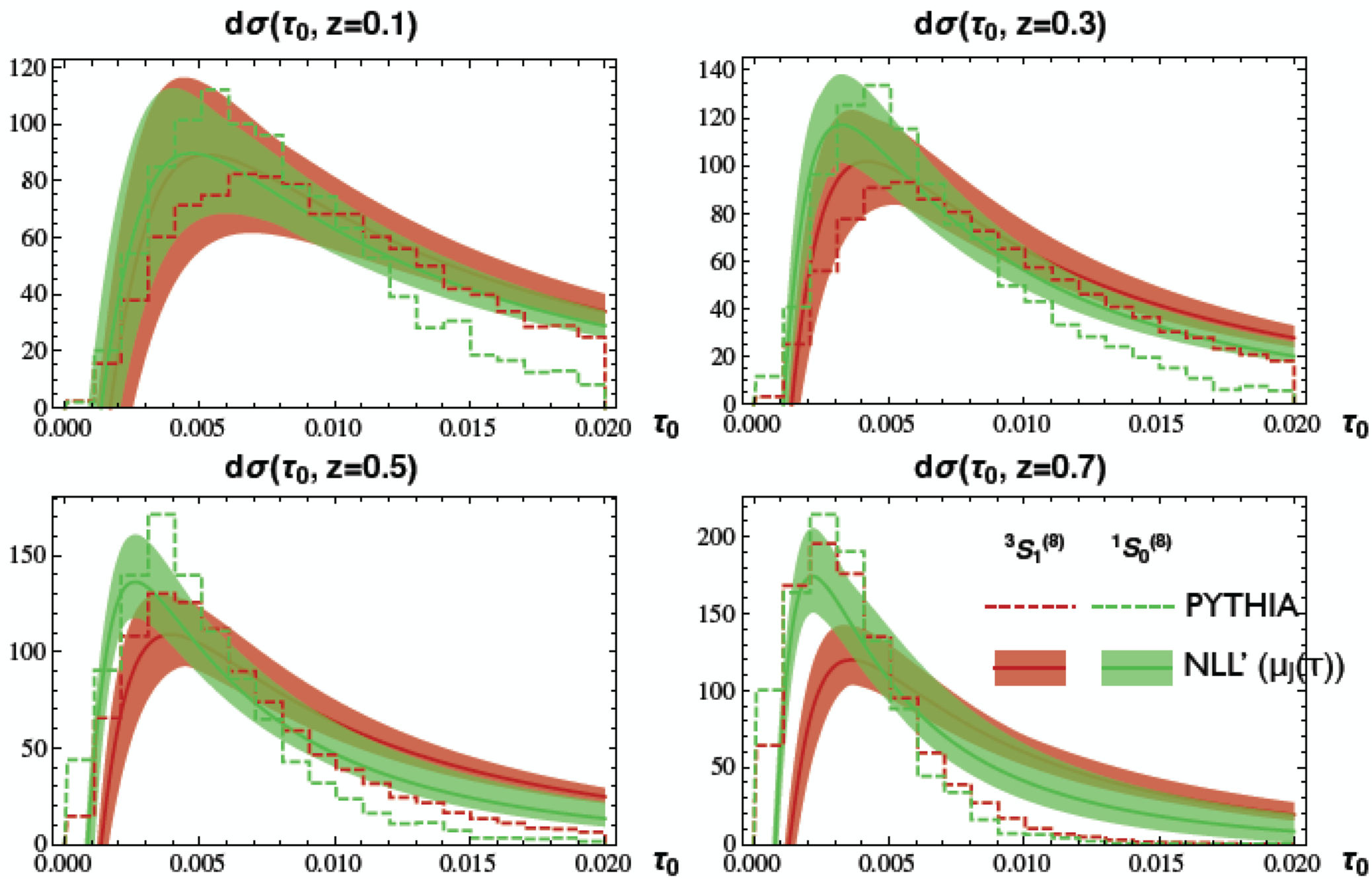


Force Madgraph to create J/ψ from gluon initiated jet

PYTHIA: parton shower, hadronization

NLL' vs. Monte Carlo

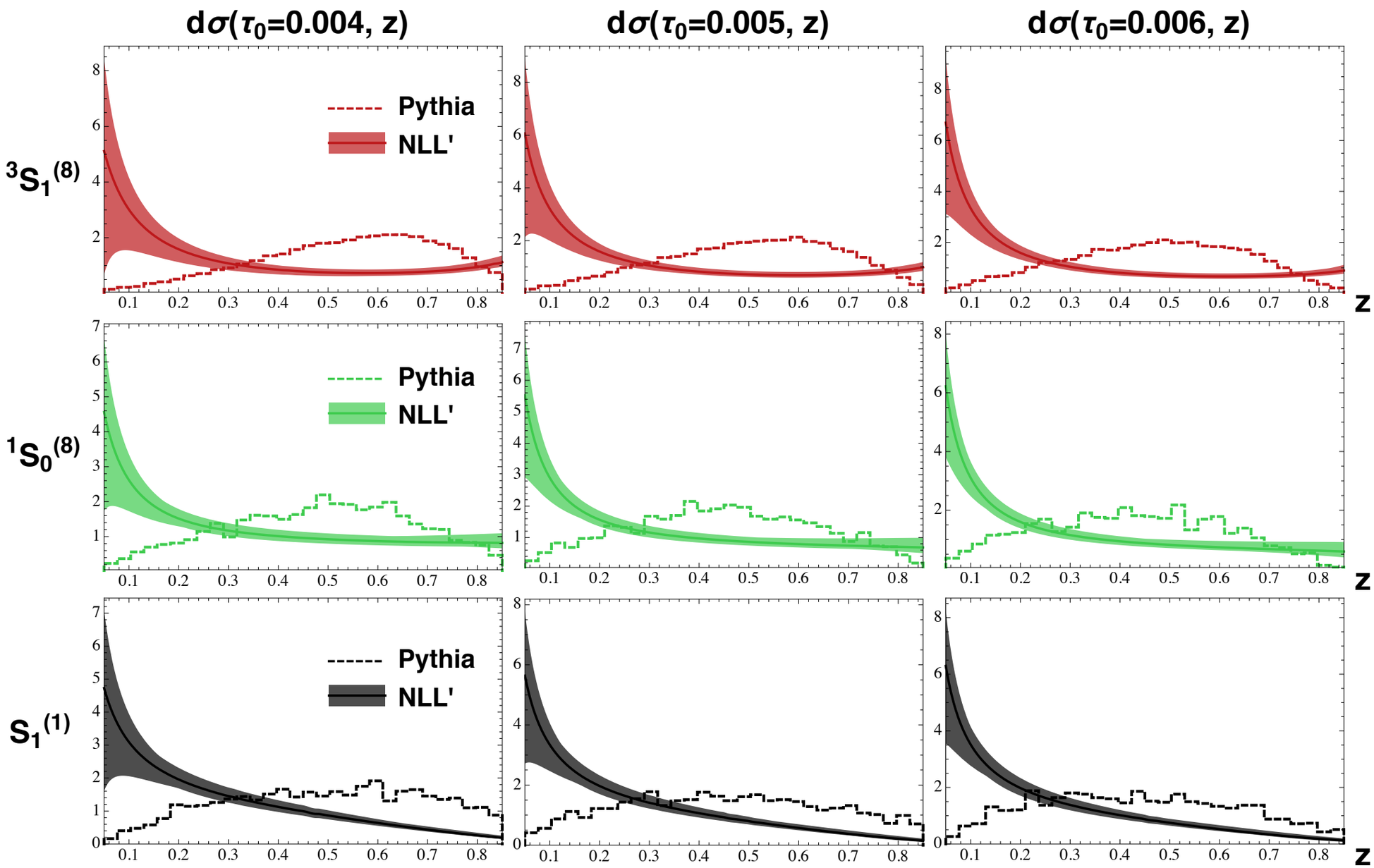
fixed z, variable τ_0



good agreement, some discrimination for large z

NLL' FJF vs. Pythia

R. Bain, L. Dai, A. Hornig, A. K. Leibovich, Y. Makris, T. Mehen JHEP 1606 (2016) 121



$e^+e^- \to \bar{q}qg$ $\quad E_{CM} = 250\,\mathrm{GeV} \quad \tau_0 = s/\omega^2$

↳ jet w/ J/ψ

GFIP and Recent LHCb Observations

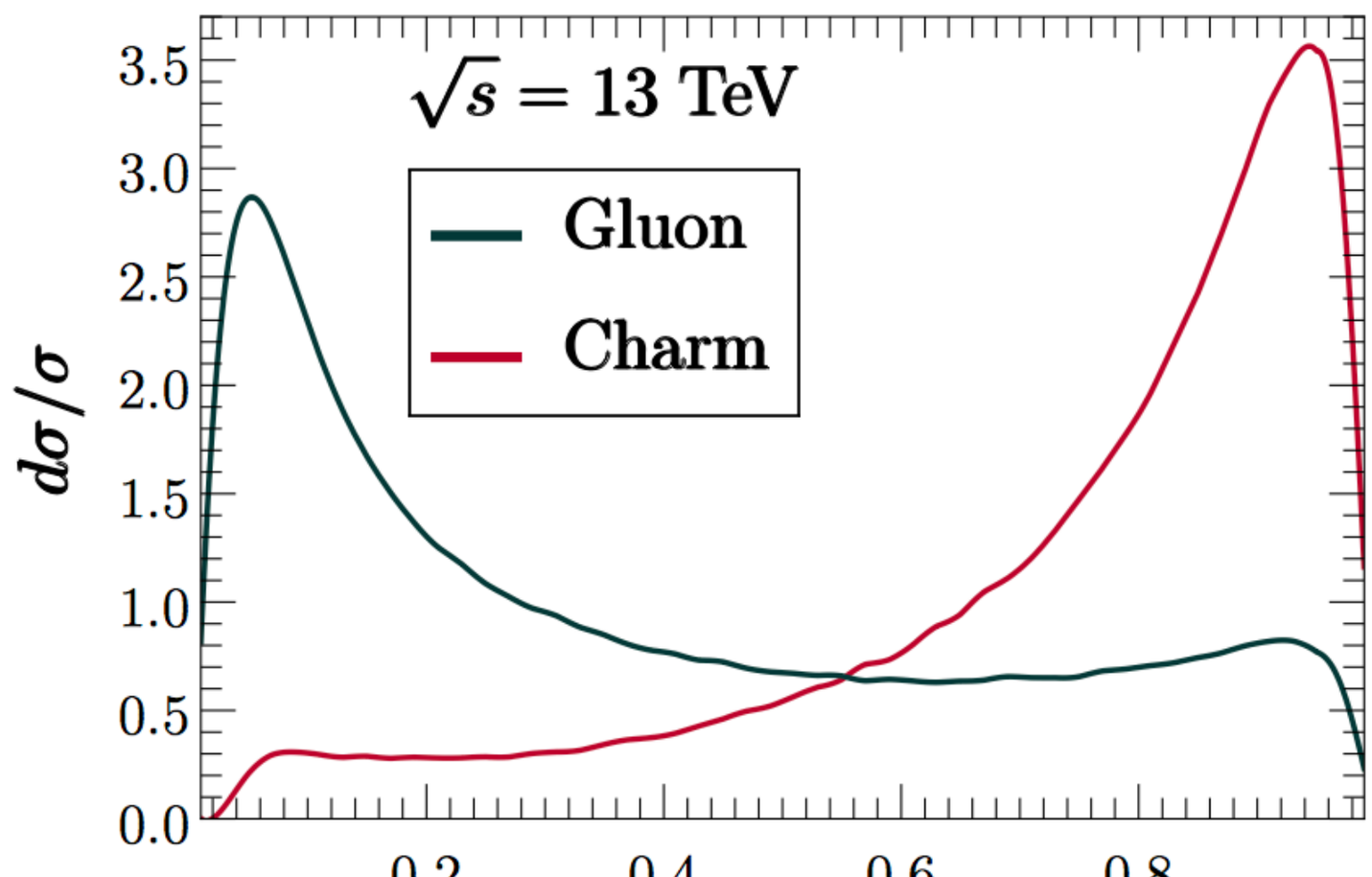
R. Bain, L. Dai, A. K. Leibovich, Y. Makris, T. Mehen, accepted in PRL

generate events with hard c-quark , gluons

LHCb: pp collisions $\sqrt{s} = 13\,\mathrm{TeV}$ cuts:

$2<\eta<4.5$
$R=0.5$
$p_{T,JET} < 20$ GeV
$p_\mu < 5$ GeV

evolve shower to scale ~$2m_c$



convolve w/ NRQCD FF for c quarks, gluons ~$2m_c$

LHCb data is normalized so $\sum_i \Delta z \left(\frac{d\sigma}{\sigma}\right)_i = \Delta z$

compare $0.1 < z < 0.9$

Use following three sets of LDMEs

	$\langle \mathcal{O}^{J/\psi}(^3S_1^{[1]})\rangle$ $\times$ GeV^3	$\langle \mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle$ $\times 10^{-2}$ GeV^3	$\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$ $\times 10^{-2}$GeV^3	$\langle \mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle/m_c^2$ $\times 10^{-2}$GeV^3
B & K [5, 6]	1.32 ± 0.20	0.224 ± 0.59	4.97 ± 0.44	-0.72 ± 0.88
Chao, et al. [12]	1.16 ± 0.20	0.30 ± 0.12	8.9 ± 0.98	0.56 ± 0.21
Bodwin et al. [13]	1.32 ± 0.20	1.1 ± 1.0	9.9 ± 2.2	0.49 ± 0.44

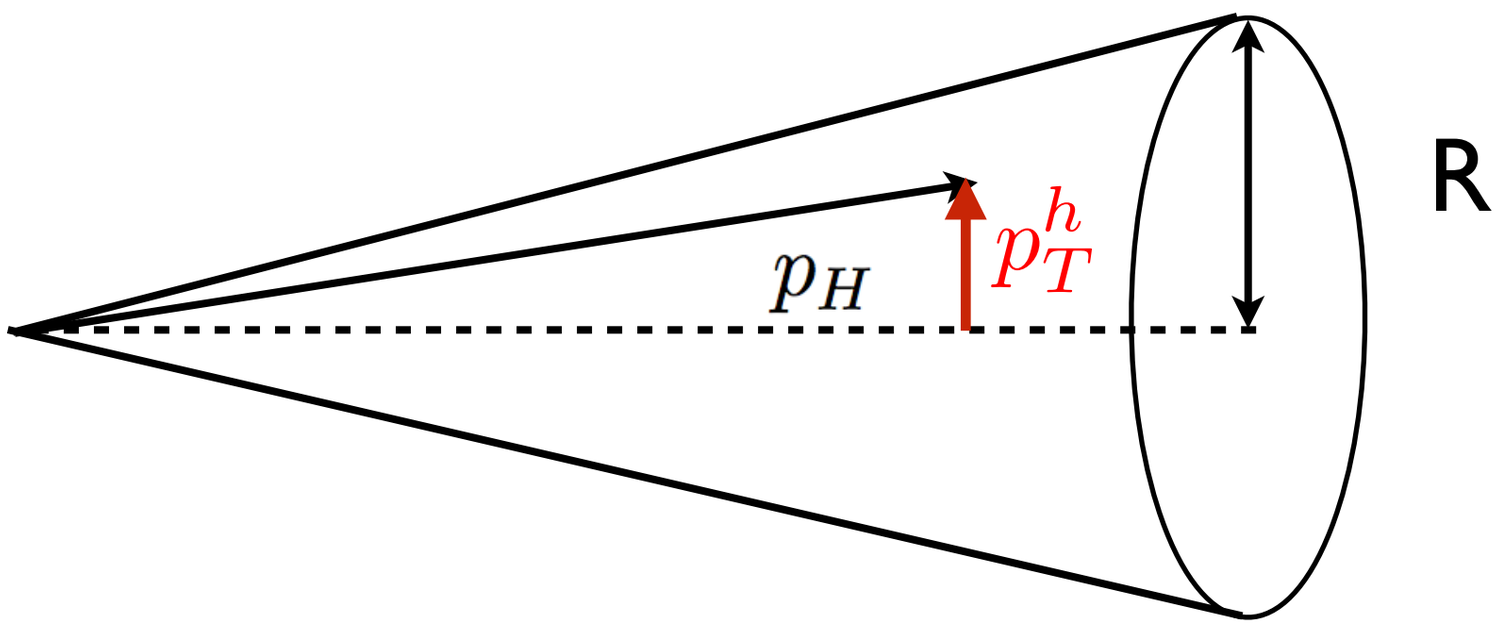
Butenschoen and Kniehl, PRD 84 (2011) 051501 **global fits to world's data**

Chao, et. al. PRL 108, 242004 (2012)
Bodwin, et. al., PRL 113, 022001(2014) **fits to high p_T hadron collider data**

Transverse Momentum Dependent FJFs

R. Bain, Y. Makris, TM, JHEP 1611 (2016) 144

jets with identified hadron: hadron z, p_T are both measured



Jet Energy: E

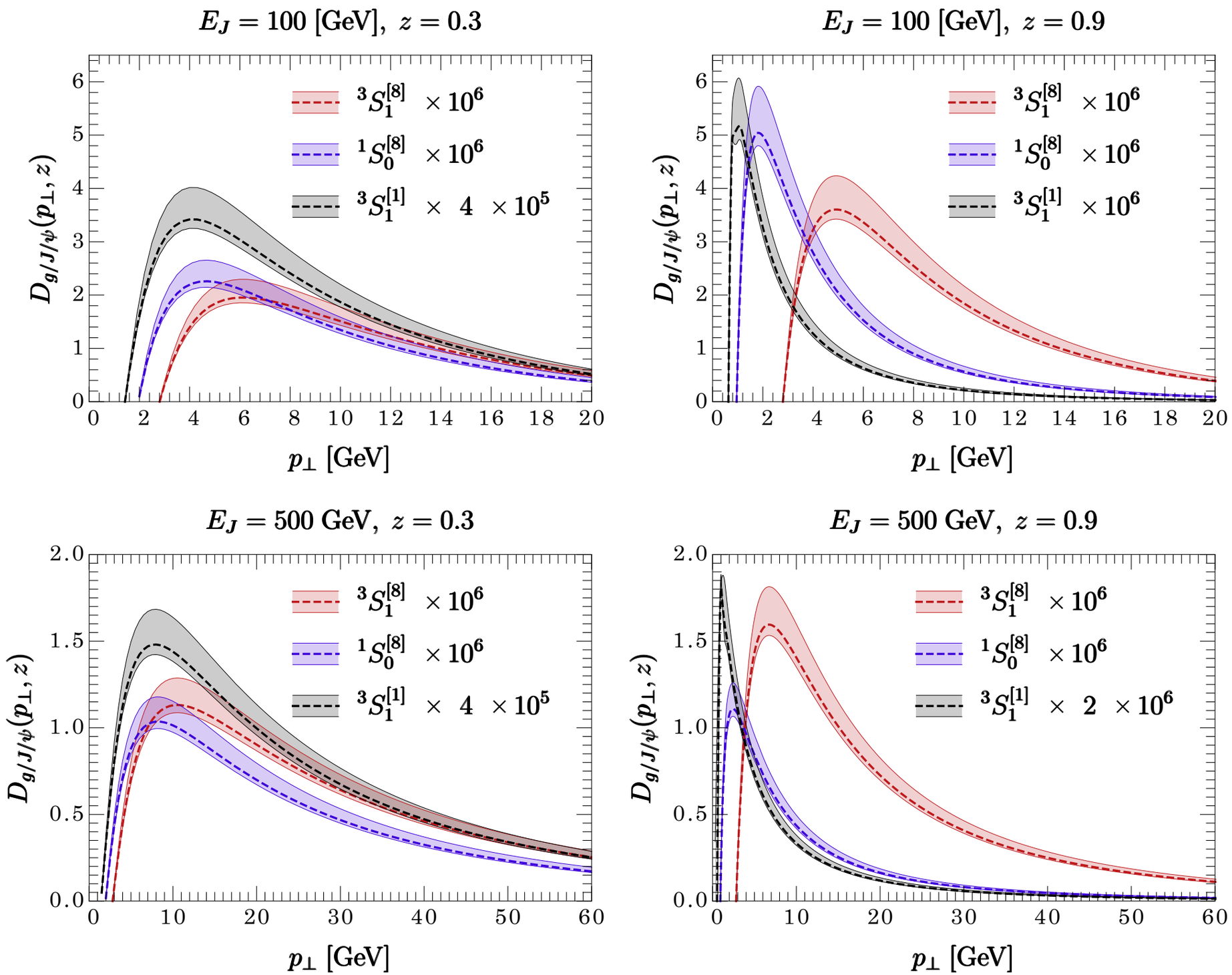
$$p_H^+ = z p_{\rm jet}^+$$

transverse momentum measured w/ rspt. to jet axis

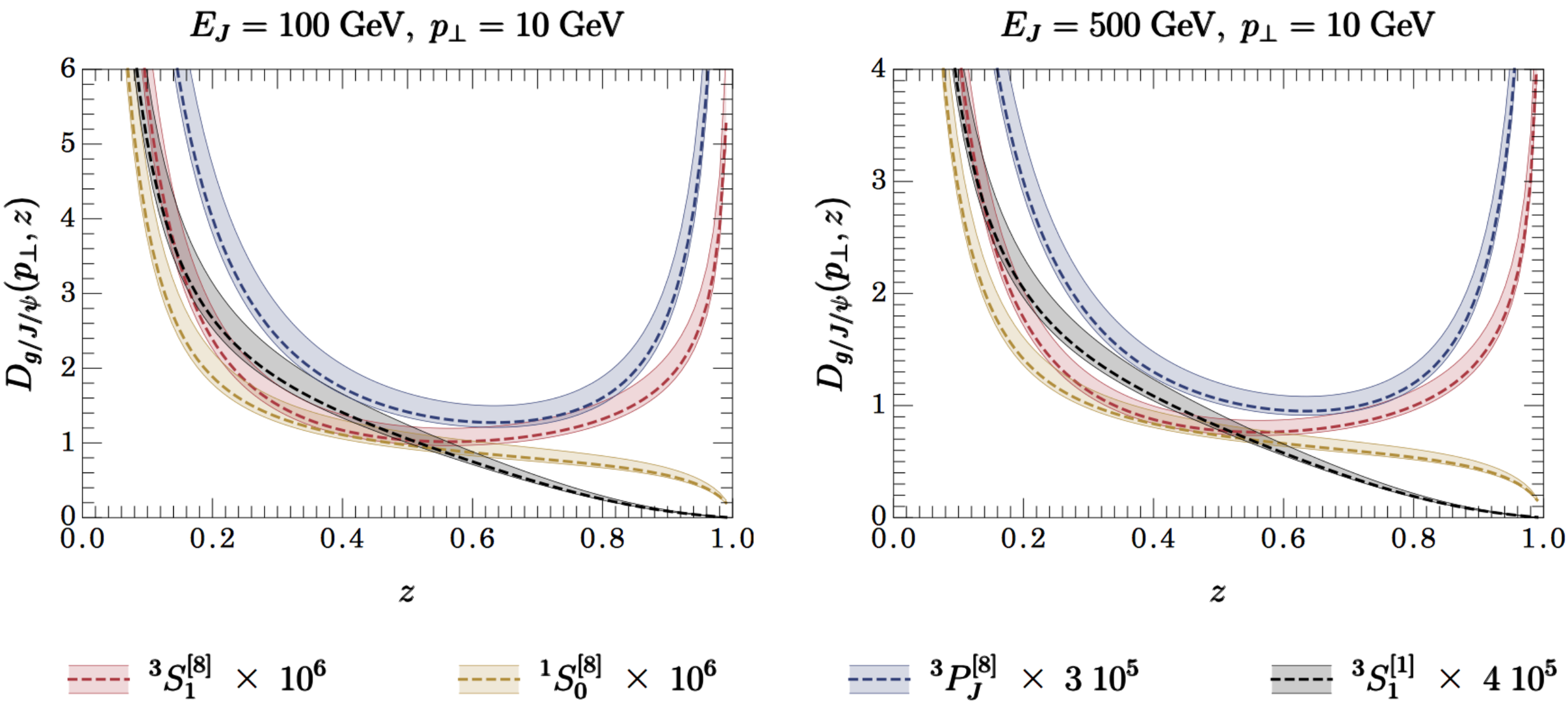
jet axis ~ parton initiating jet if out of jet radiation is ultrasoft

$$\omega \gg p_T^h \gg \Lambda \gg \Lambda_{\rm QCD}$$

Application to Quarkonium Production

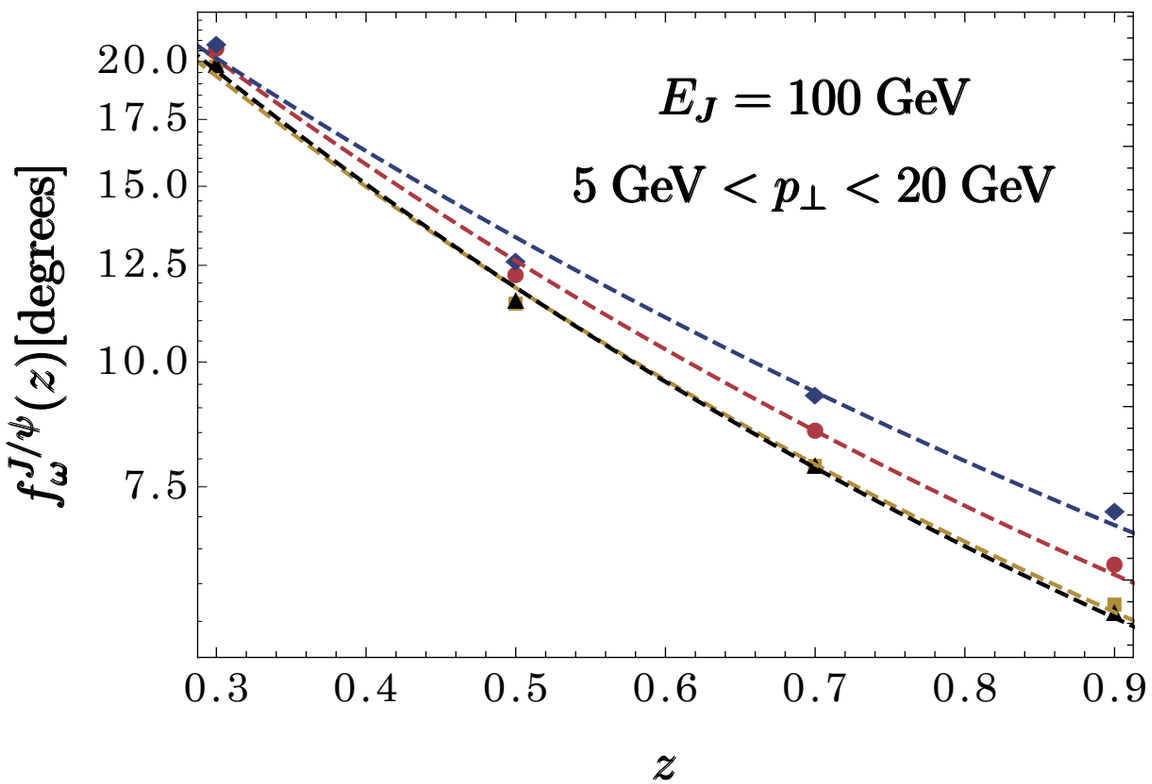


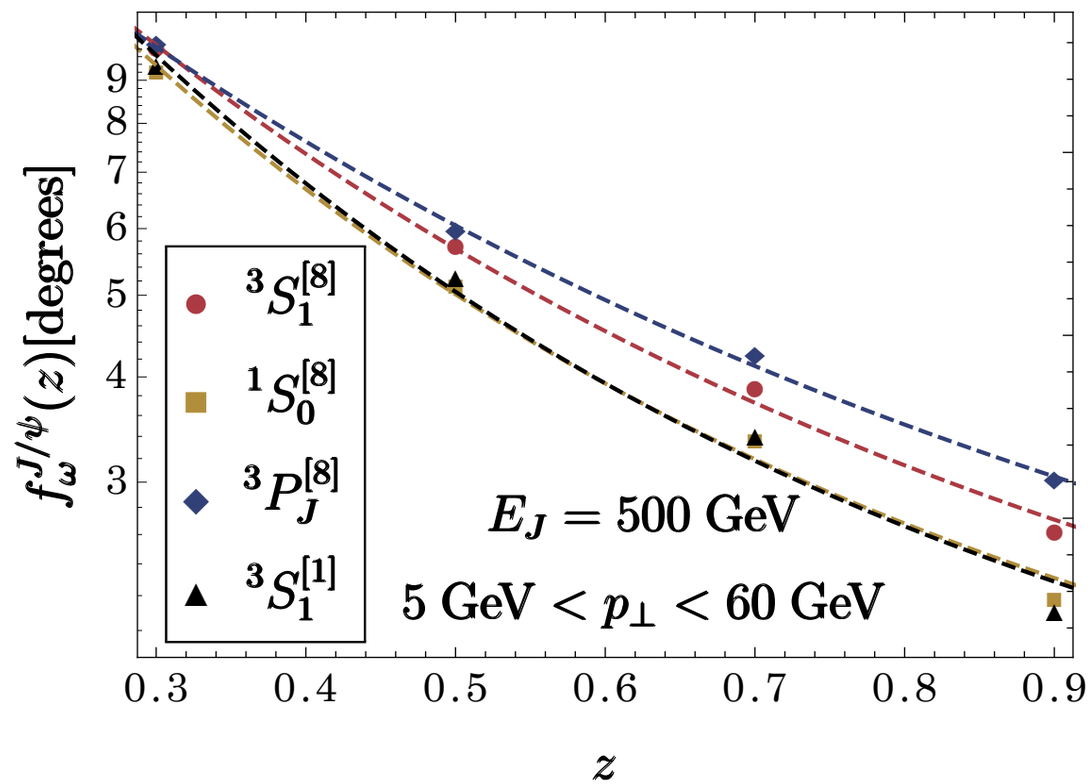
Application to Quarkonium Production



Application to Quarkonium Production

$$\langle\theta\rangle(z) \sim \frac{2\int dp_\perp\, p_\perp D_{g/h}(p_\perp, z, \mu)}{z\omega \int dp_\perp\, D_{g/h}(p_\perp, z, \mu)} \equiv f_\omega^h(z)$$





$E_J = 100$ GeV		
$^{2S+1}L_J^{[1,8]}$	C_0	C_1
$^3S_1^{[1]}$	3.92	0.92
$^3S_1^{[8]}$	3.86	0.84
$^1S_0^{[8]}$	3.88	0.90
$^3P_J^{[8]}$	3.75	0.74

$E_J = 500$ GeV		
$^{2S+1}L_J^{[1,8]}$	C_0	C_1
$^3S_1^{[1]}$	3.75	1.68
$^3S_1^{[8]}$	3.48	1.39
$^1S_0^{[8]}$	3.66	1.64
$^3P_J^{[8]}$	3.28	1.20

$$\ln(f(x)) = g(x; C_0, C_1) \text{ s.t. } g(x=0) = C_0$$

$$g_2(x) = C_0 \exp(-C_1 x)$$