# Production of Heavy Mesons and Quarkonia within Jets

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Review of Quarkonium Production Theory

Heavy Quarkonium Fragmenting Jet Functions

New Tests of NRQCD Using Jet Observables

Cross sections for $e^+e^-$, pp collisions

## Color-Singlet Model (pre-1995)

$$\sigma(pp \to J/\psi + X) = f_{g/p} \otimes f_{g/p} \otimes \sigma[gg \to c\bar{c}(^3S_1^{(1)}) + X]\, |\psi_{c\bar{c}}(0)|^2$$

$c\bar{c}$ pair produced with same quantum numbers as J/ψ

## Predictive Formalism

$\sigma[gg \to c\bar{c}(^3S_1^{(1)}) + X]$ calculable in QCD perturbation theory

$|\psi_{c\bar{c}}(0)|^2$ fixed by $\Gamma[J/\psi \to \ell^+\ell^-]$

**Suffers from theoretical inconsistencies when applied to $\chi_{cJ}$**

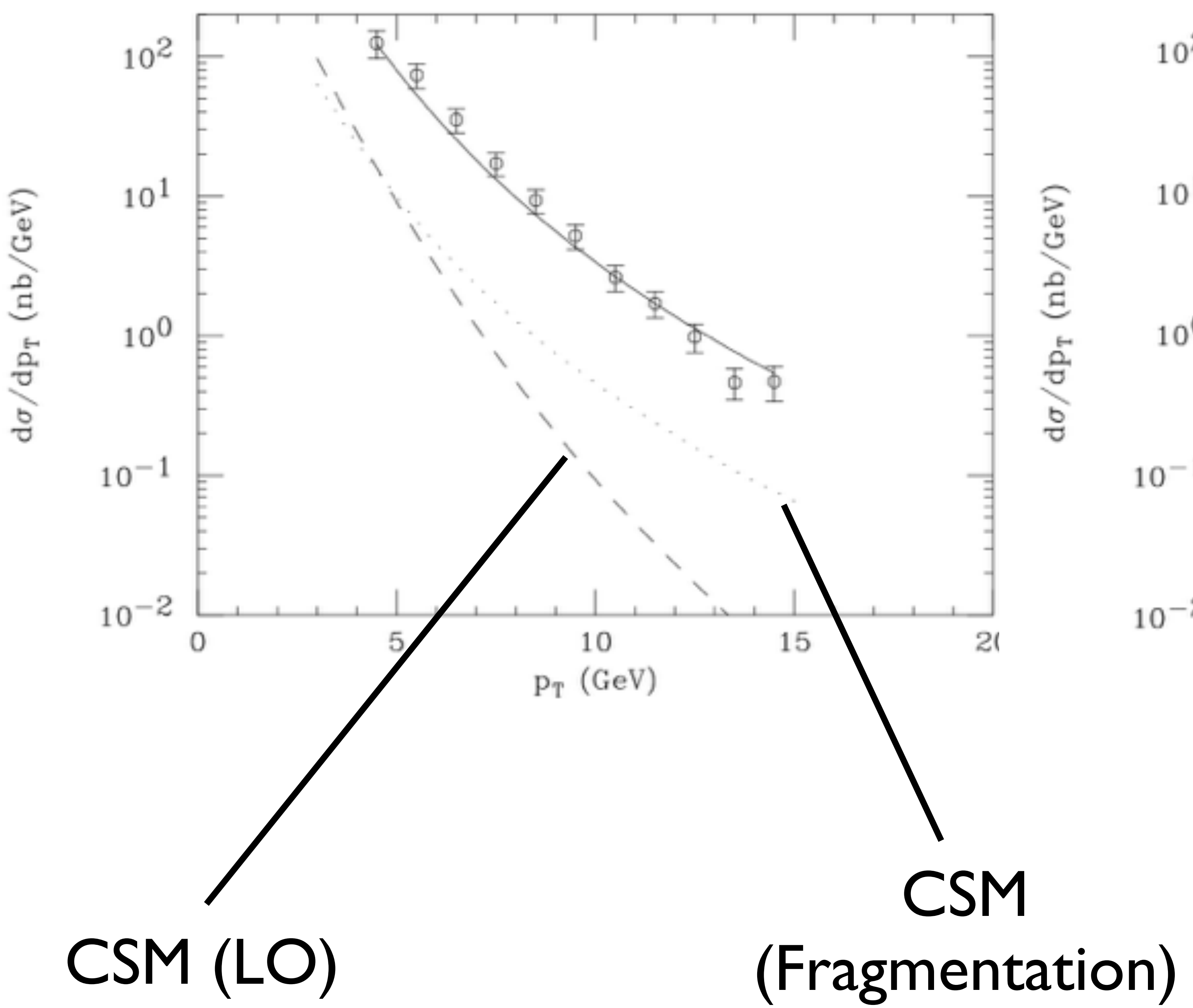
$$\Gamma[\chi_{cJ} \to \text{hadrons}] = |\psi'_{c\bar{c}}(0)|^2 \sigma(c\bar{c}(^3P_J^{(1)}) \to gg)$$

— **Not IR Safe**

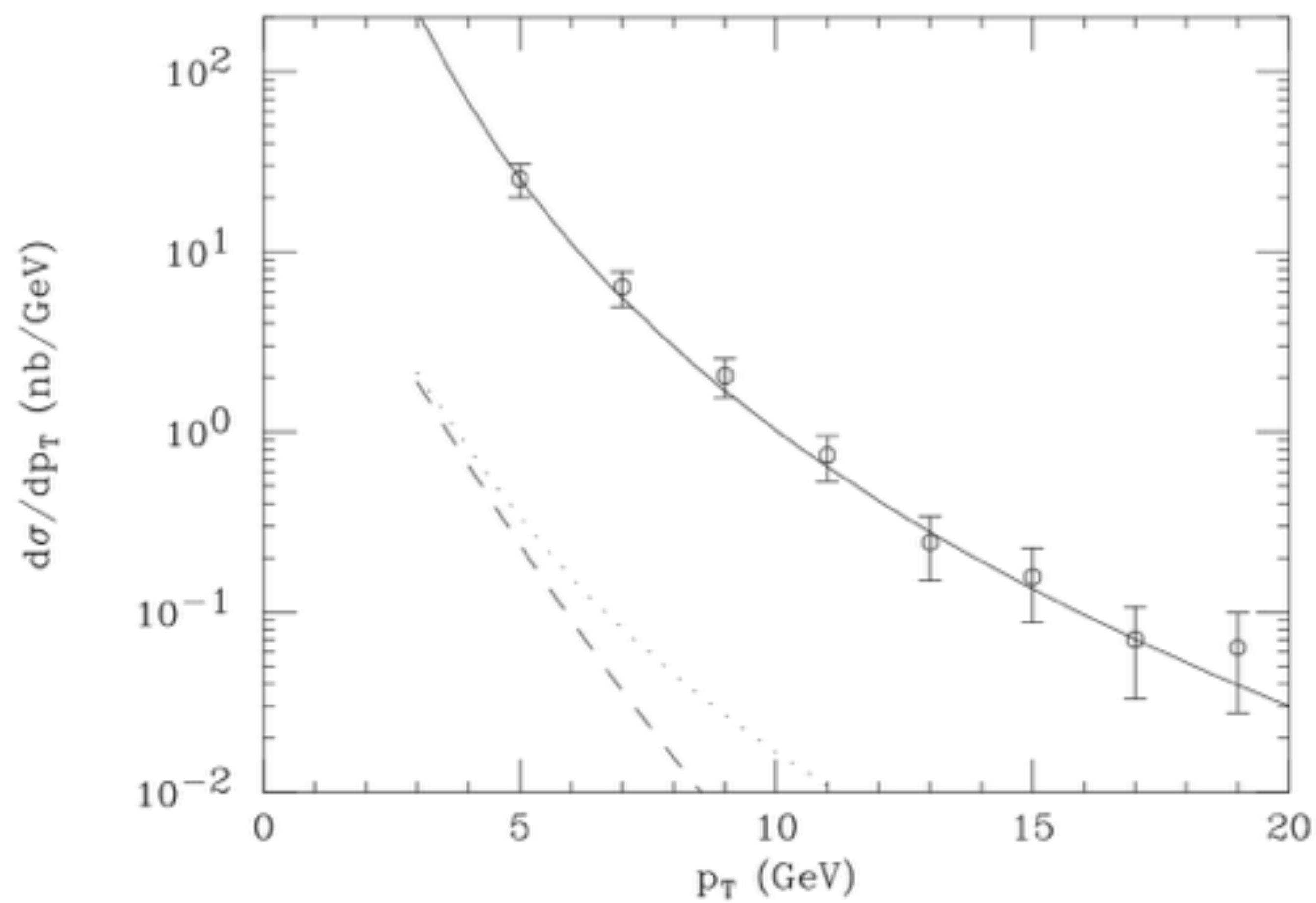
# J/ψ production at Tevatron (1996)

CSM badly underpredicts J/ψ and ψ' production at large $p_T$

J/ψ




ψ'



# 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 $\alpha_s, v$

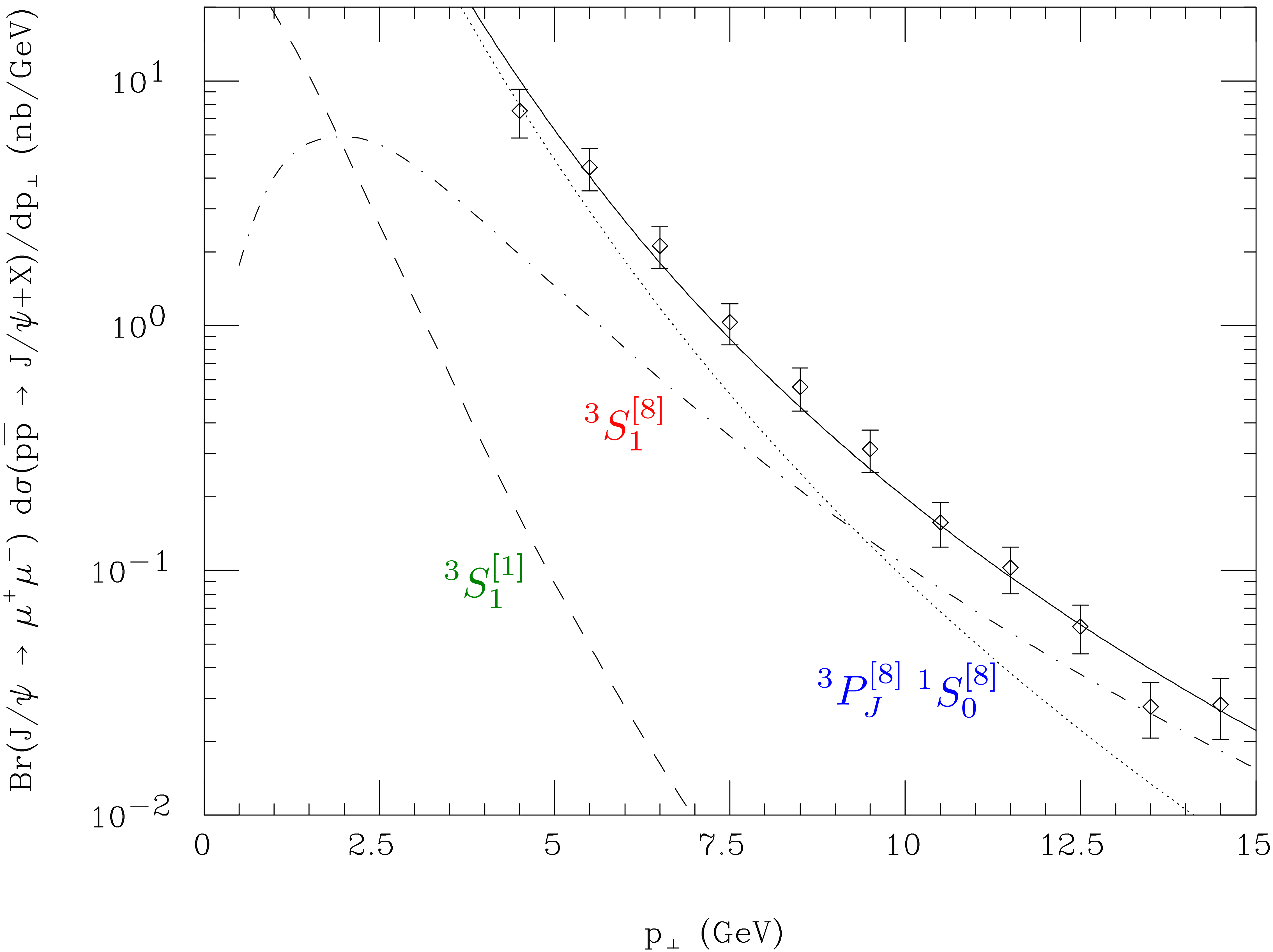
# NRQCD long-distance matrix element (LDME)

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

CSM - lowest order in $v$

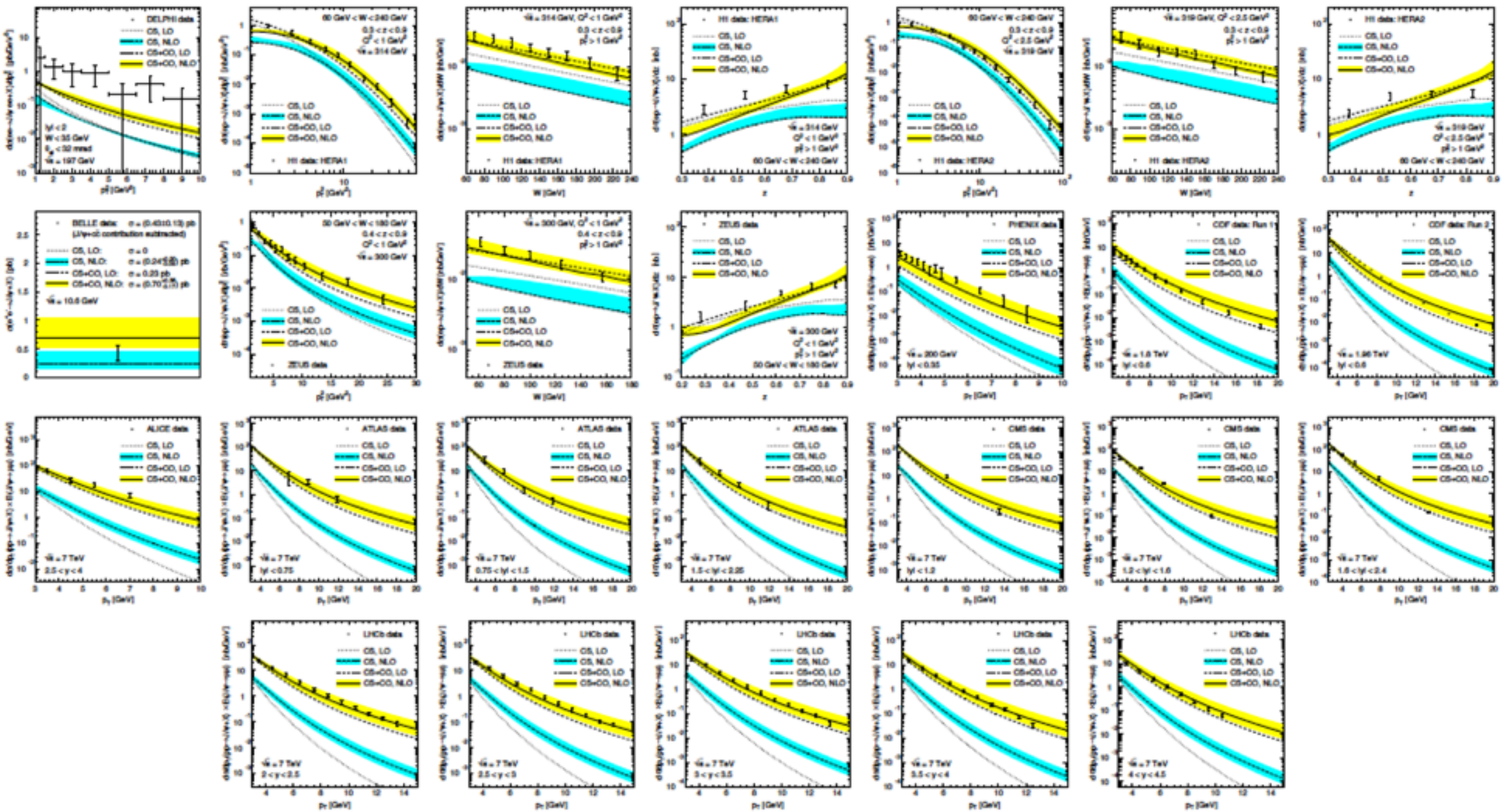
$$\langle \mathcal{O}^{J/\psi}({}^3S_1^{[8]})\rangle, \langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]})\rangle, \langle \mathcal{O}^{J/\psi}({}^3P_J^{[8]})\rangle \sim v^7$$

color-octet mechanisms



$\mathrm{Br}(J/\psi \to \mu^+\mu^-)\ d\sigma(p\bar{p} \to J/\psi + X)/dp_\perp$ (nb/GeV)
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
0
2.5
5
7.5
10
12.5
15
$p_\perp$ (GeV)
${}^3S_1^{[8]}$
${}^3S_1^{[1]}$
${}^3P_J^{[8]}\ {}^1S_0^{[8]}$

# Global Fits with NLO CSM + COM

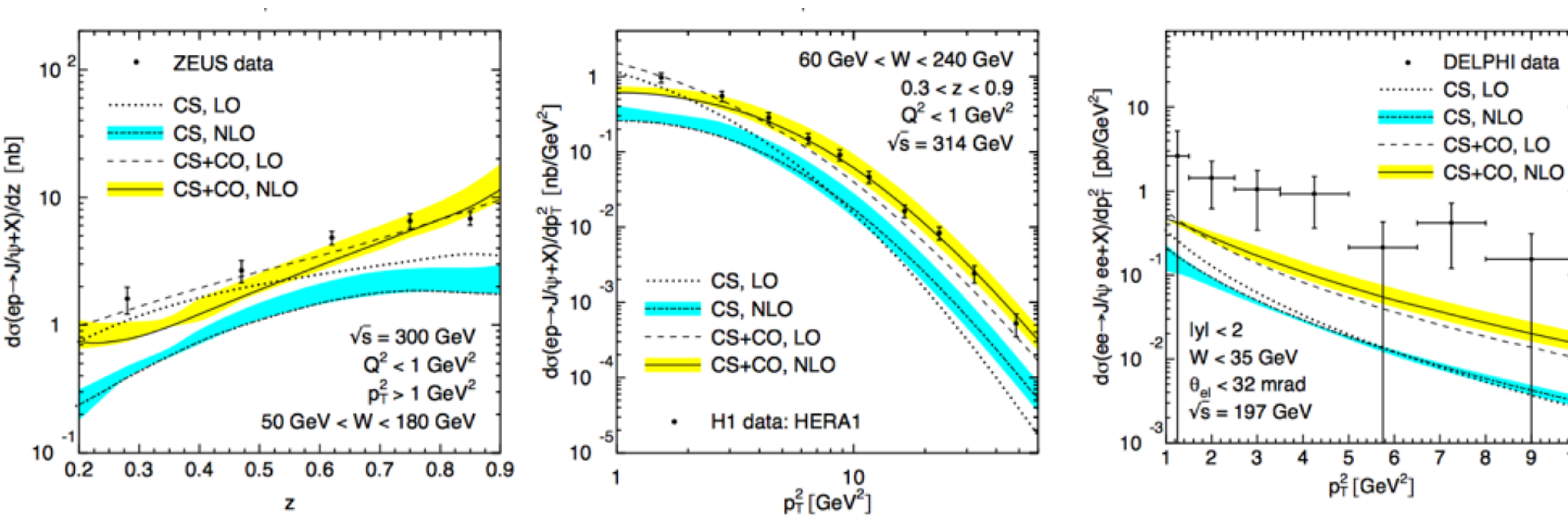


$$e^+e^-, \gamma\gamma, \gamma p, p\bar{p}, pp \to J/\psi + X$$

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**

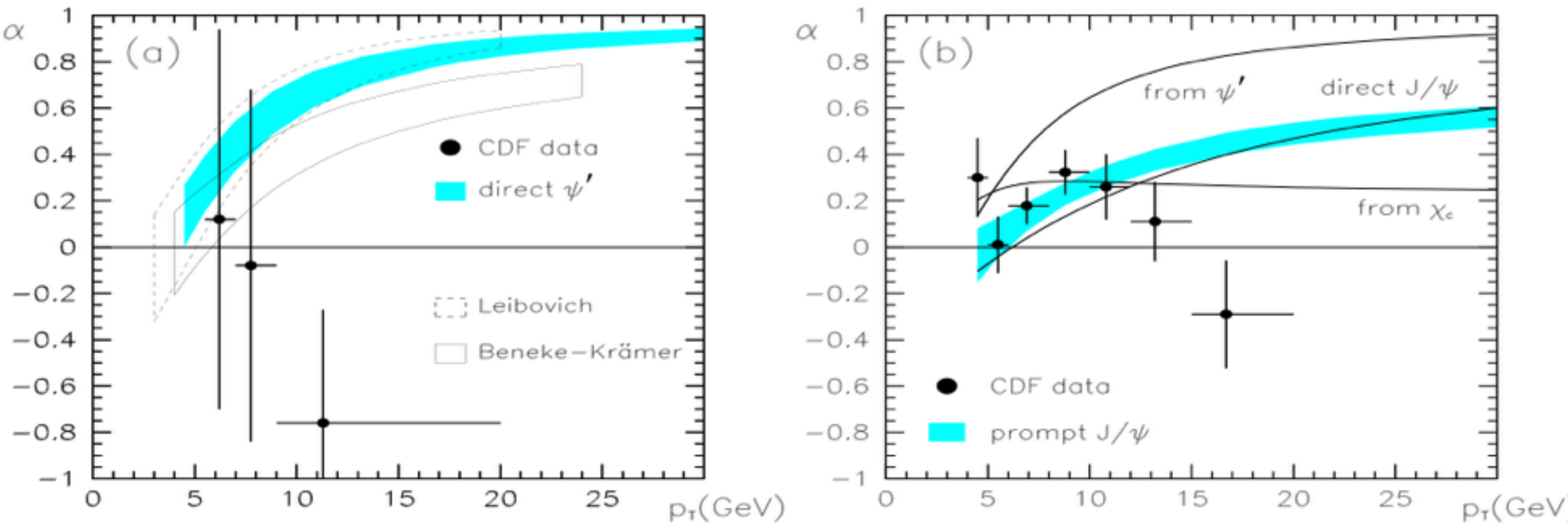
$$\langle \mathcal{O}^{J/\psi}(^3S_1^{[1]})\rangle = 1.32\ \text{GeV}^3$$

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

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

# Polarization Puzzle

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

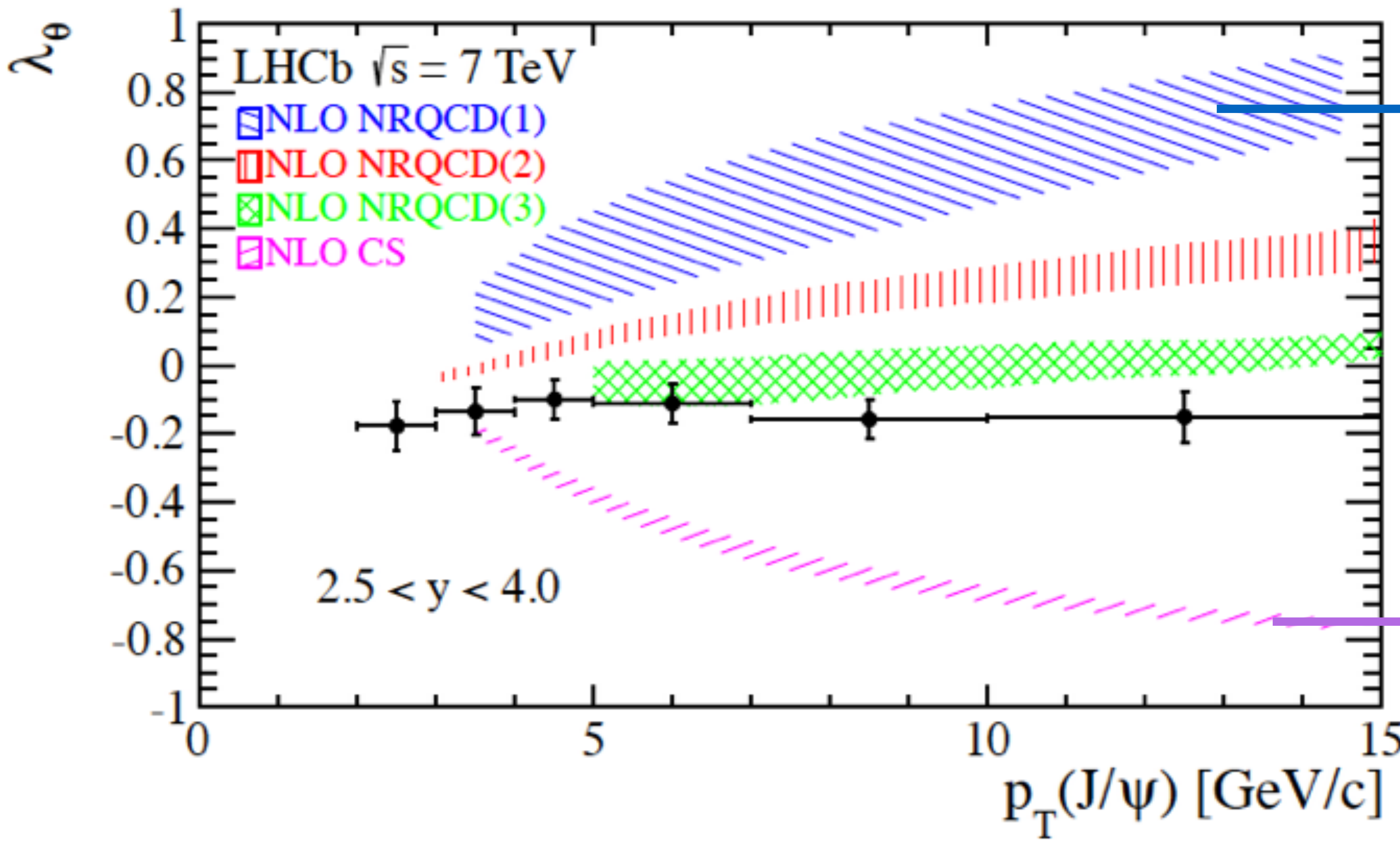



ψ '

J/ψ

Braaten, Kniehl, Lee, 1999

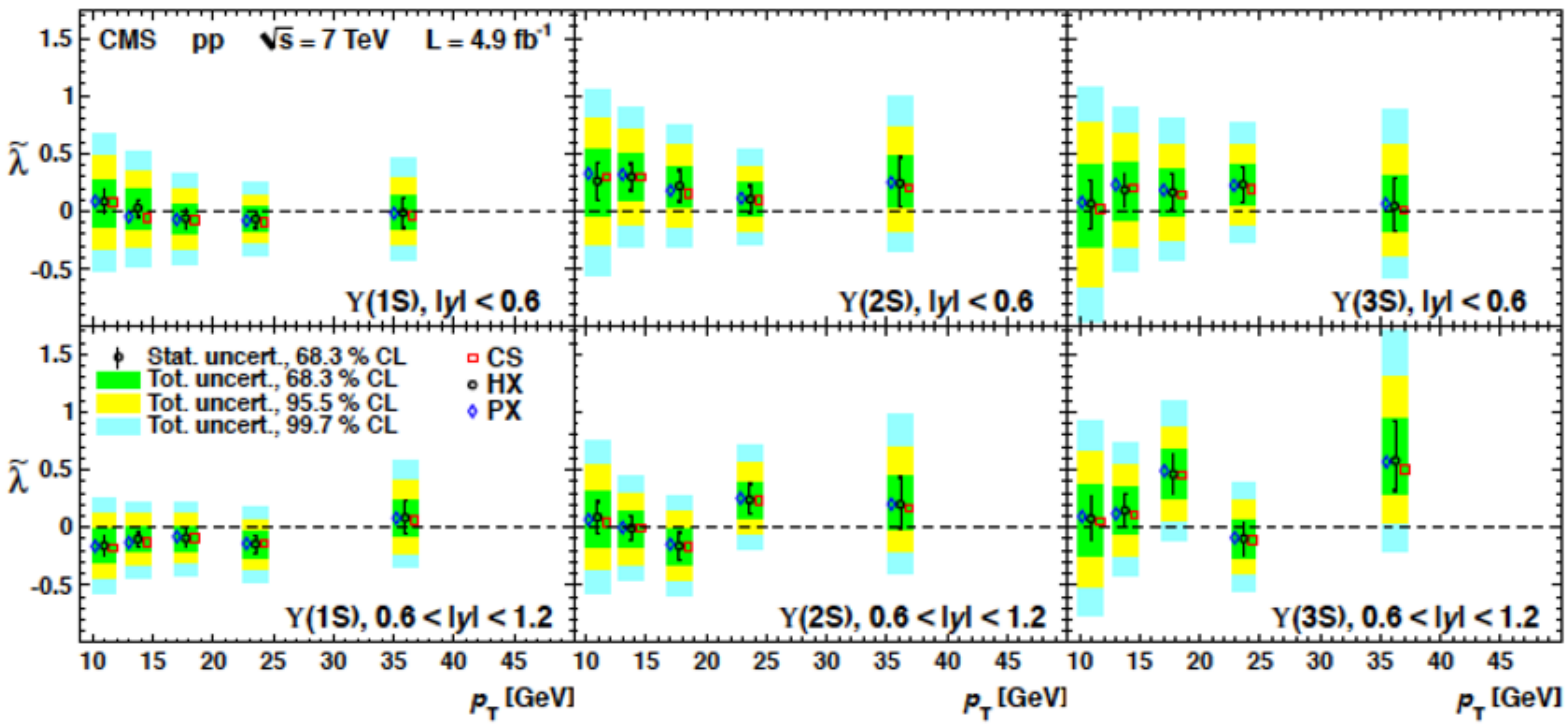
# Polarization of J/ψ at LHCb




LDME from Global fits

CSM

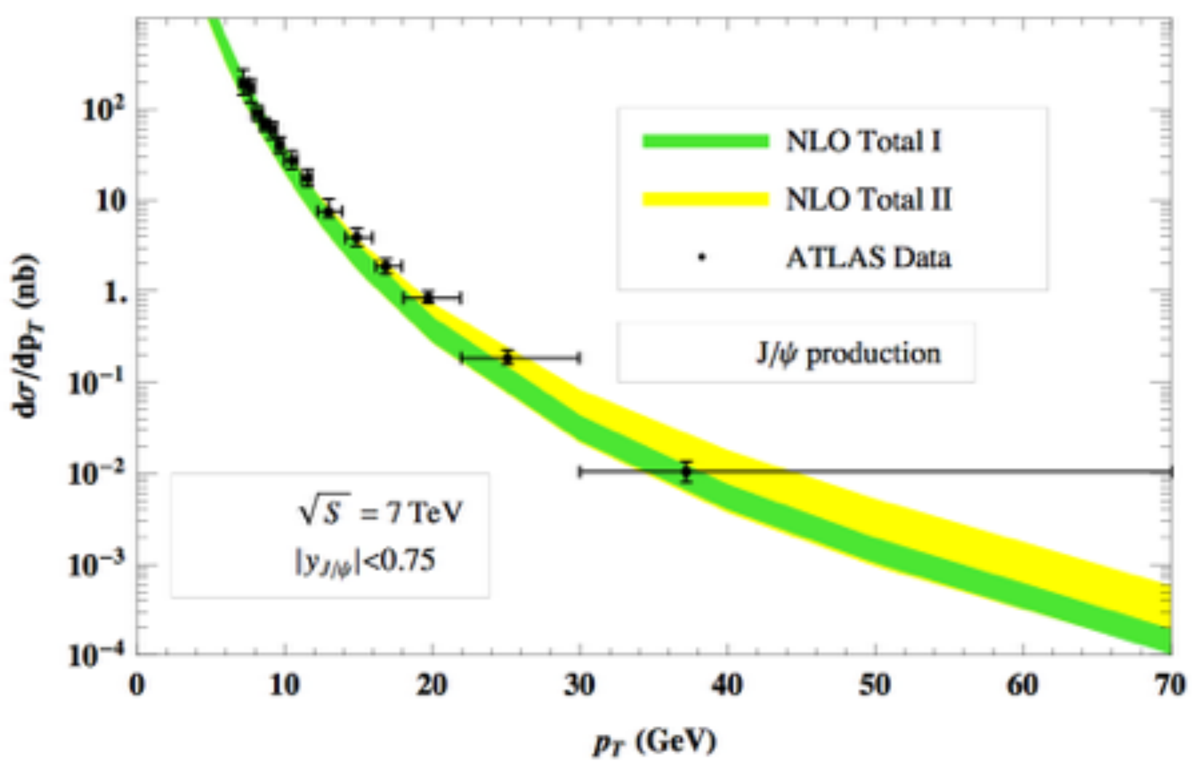
# Polarization of Υ(nS) at CMS

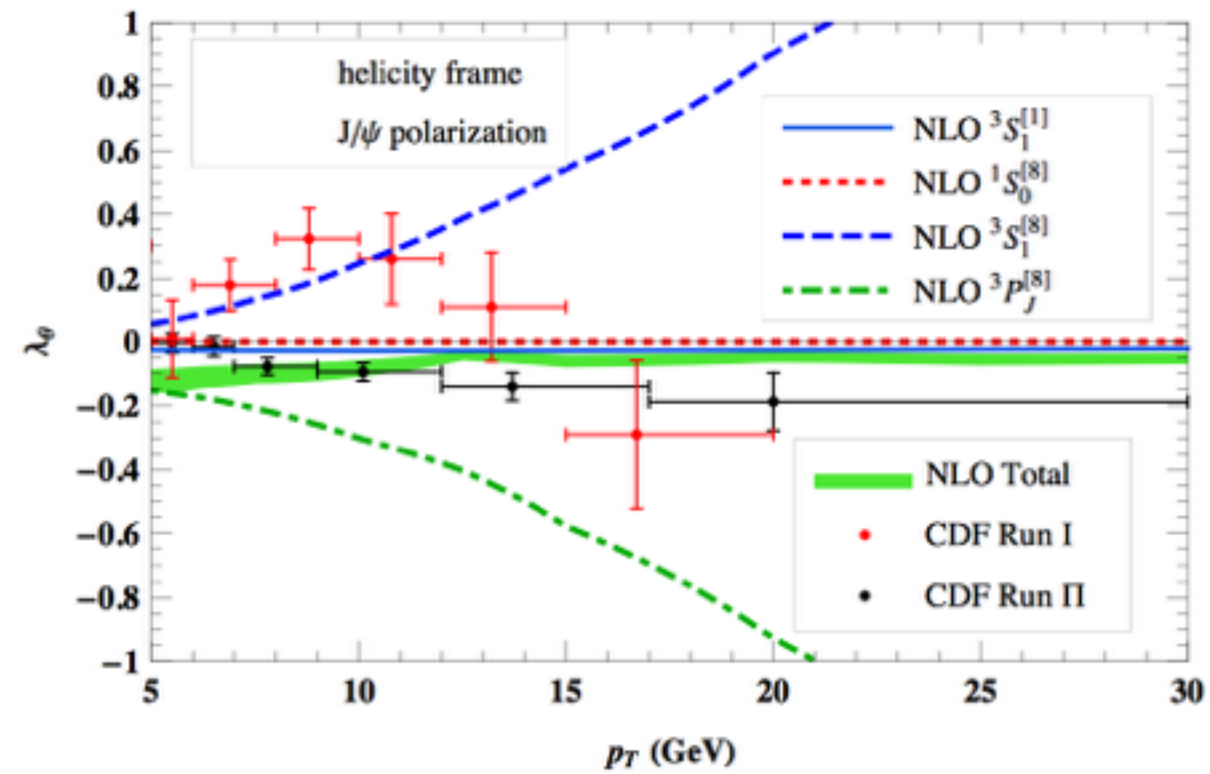


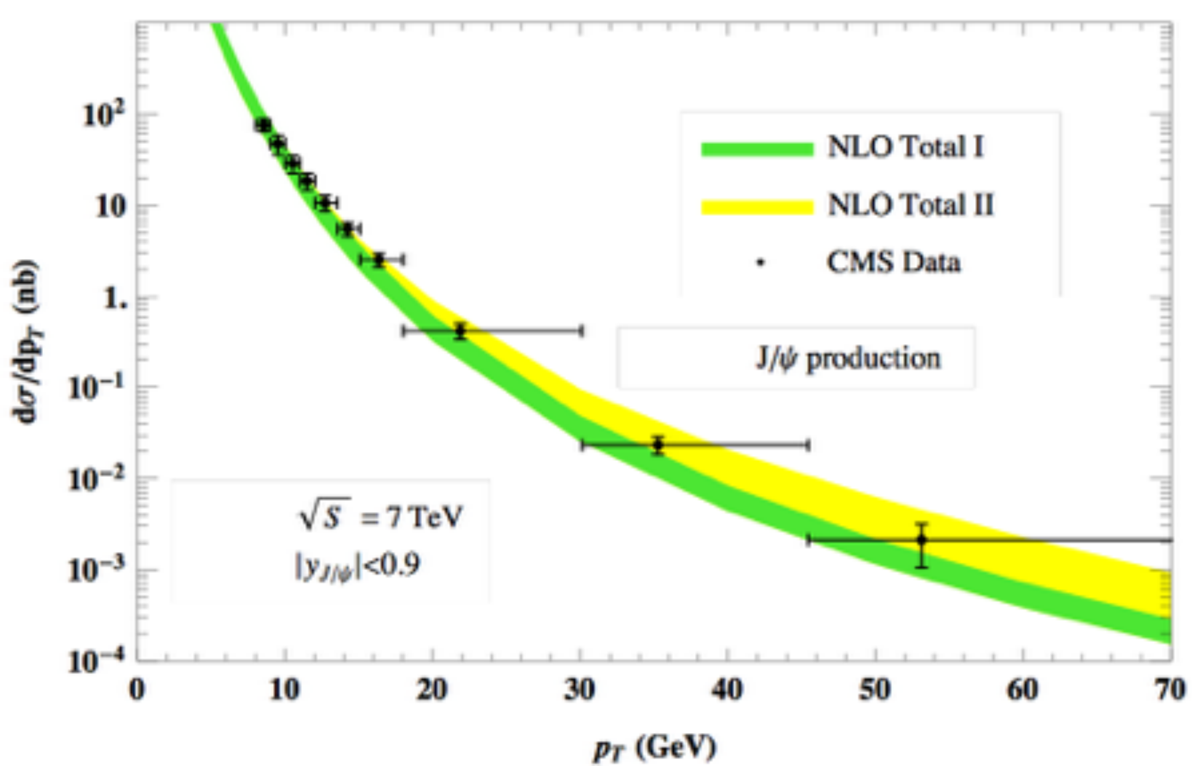
# Recent Attempts to Resolve J/ψ Polarization Puzzle

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 | $8.9 \pm 0.98$ | $0.30 \pm 0.12$ | $0.56 \pm 0.21$ |
| 1.16 | 0 | 1.4 | 2.4 |
| 1.16 | 11 | 0 | 0 |

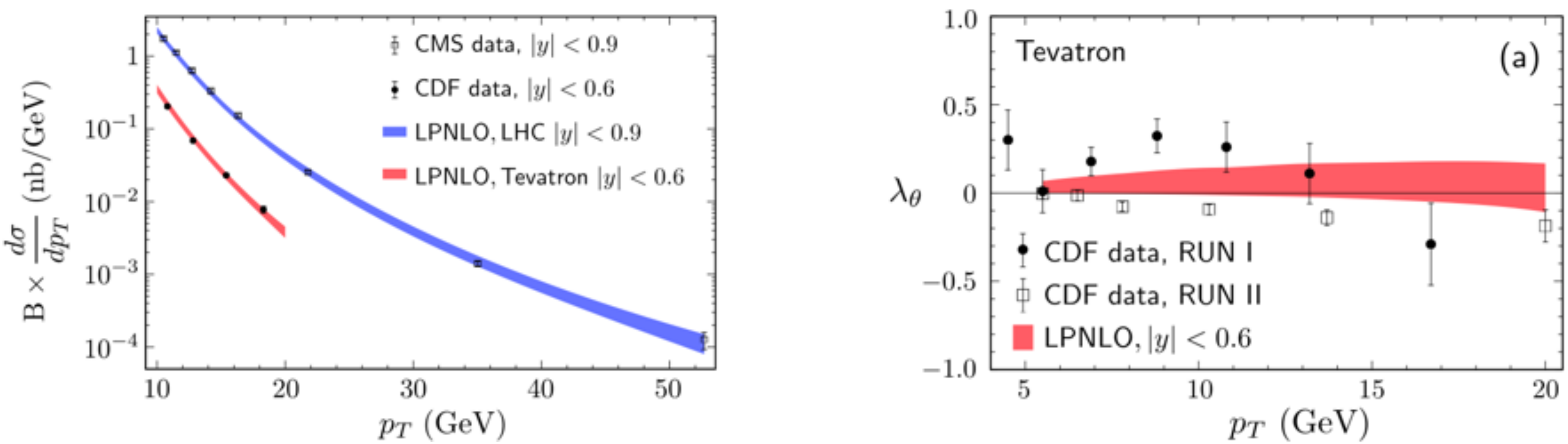
# Recent Attempts to Resolve J/ψ Polarization Puzzle

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

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

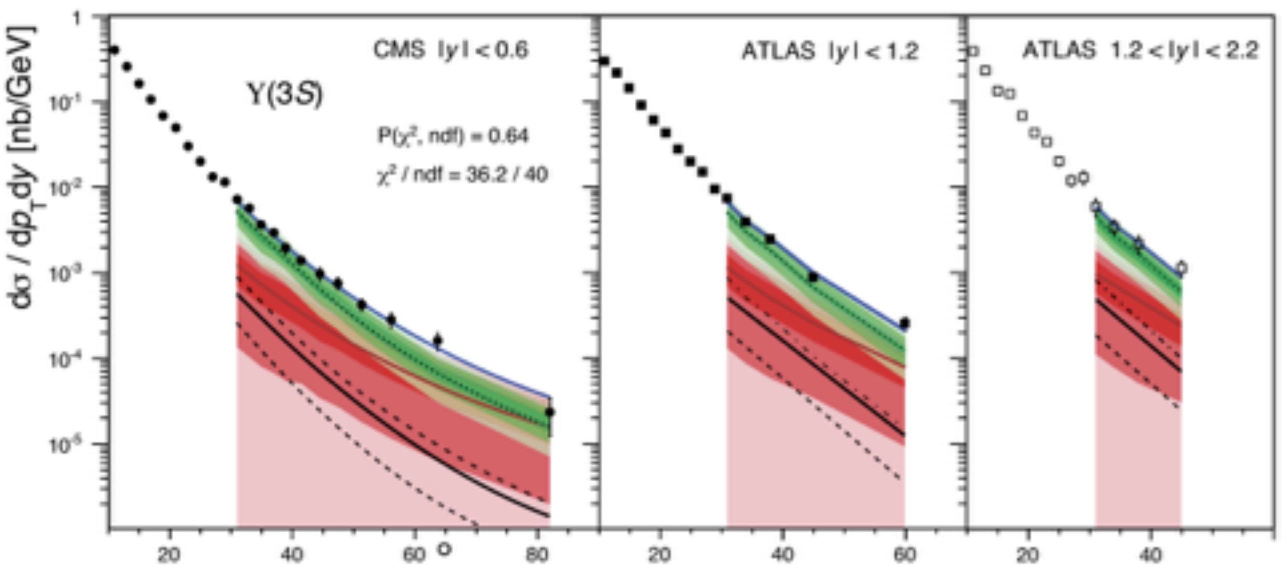
$$\langle \mathcal{O}^{J/\psi}(^3S_1^{(8)})\rangle = 0.011 \pm 0.010\,\mathrm{GeV}^3$$

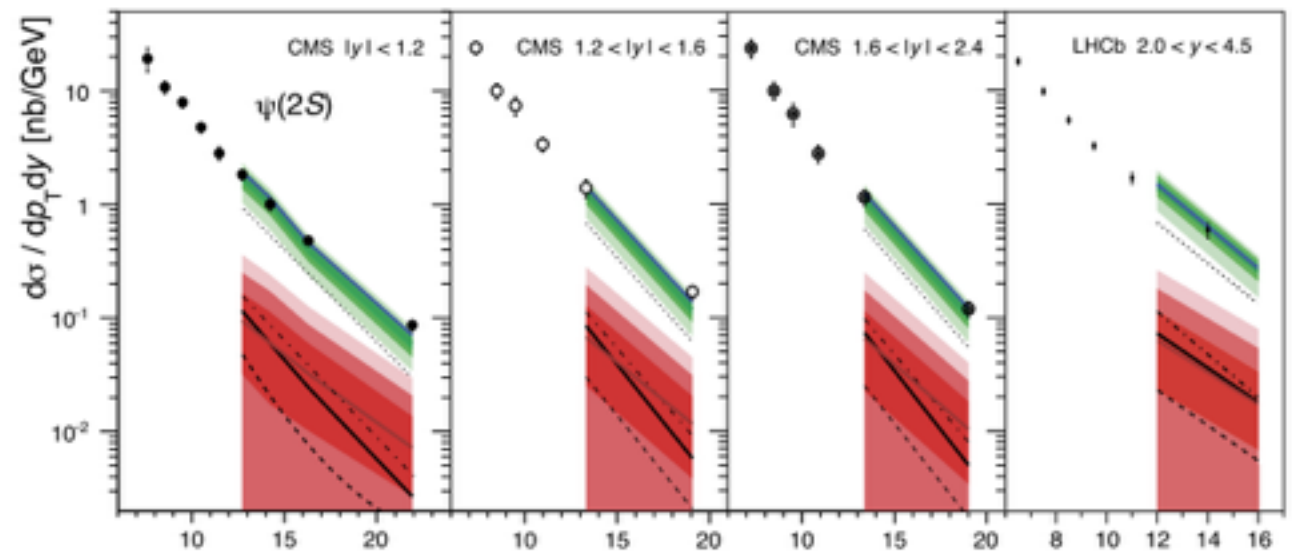
$$\langle \mathcal{O}^{J/\psi}(^3P_0^{(8)})\rangle = 0.011 \pm 0.010\,\mathrm{GeV}^5$$

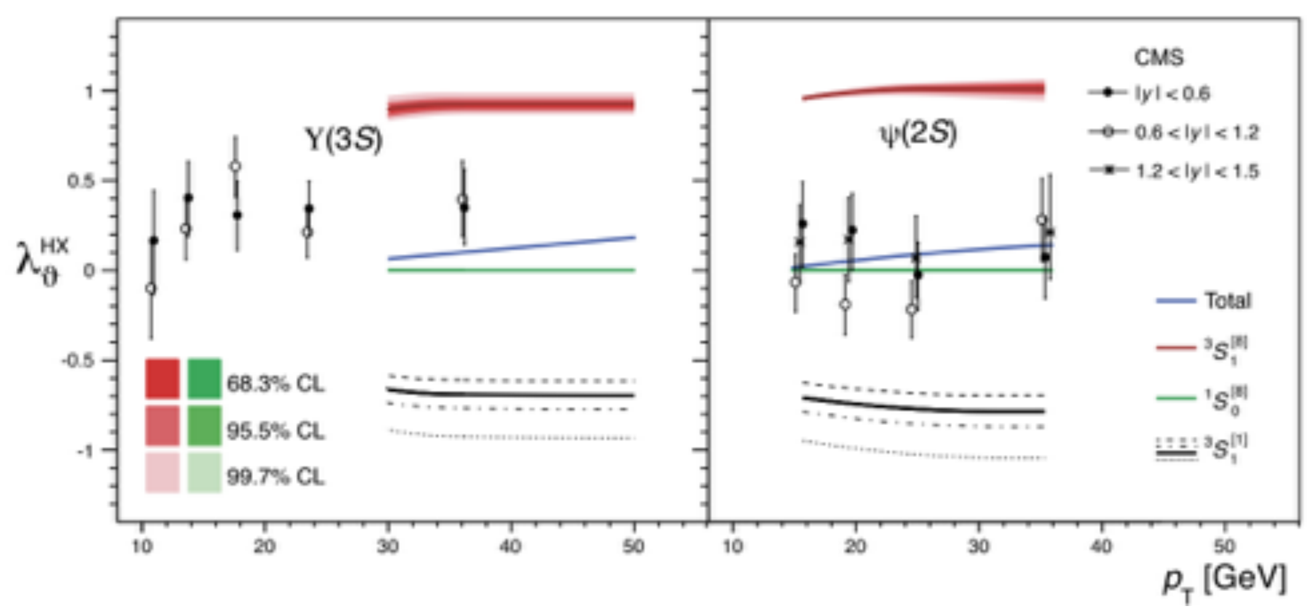
# Recent Attempts to Resolve J/ψ Polarization Puzzle

Faccioli, et. al. PLB736 (2014) 98

Lourenco, et. al., NPA, in press



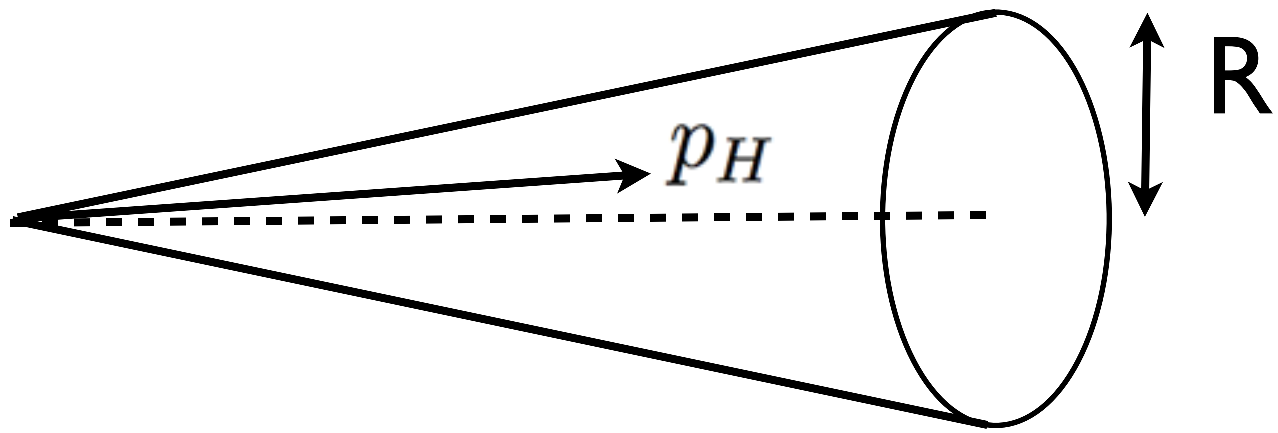




argue for $^1S_0^{(8)}$ dominance in both ψ(2S) & ϒ(3S) production

# 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:

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

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

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

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

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

## relationship to fragmentation functions

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

**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

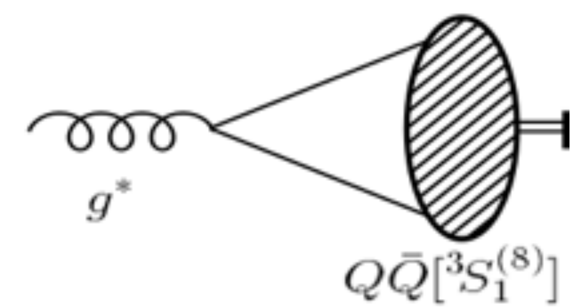
$$\sum_j \int_0^1 \mathrm{d}z\, z\, \mathcal{J}_{ij}(R,z,\mu) = 2(2\pi)^3\, J_i(R,\mu)$$

# 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

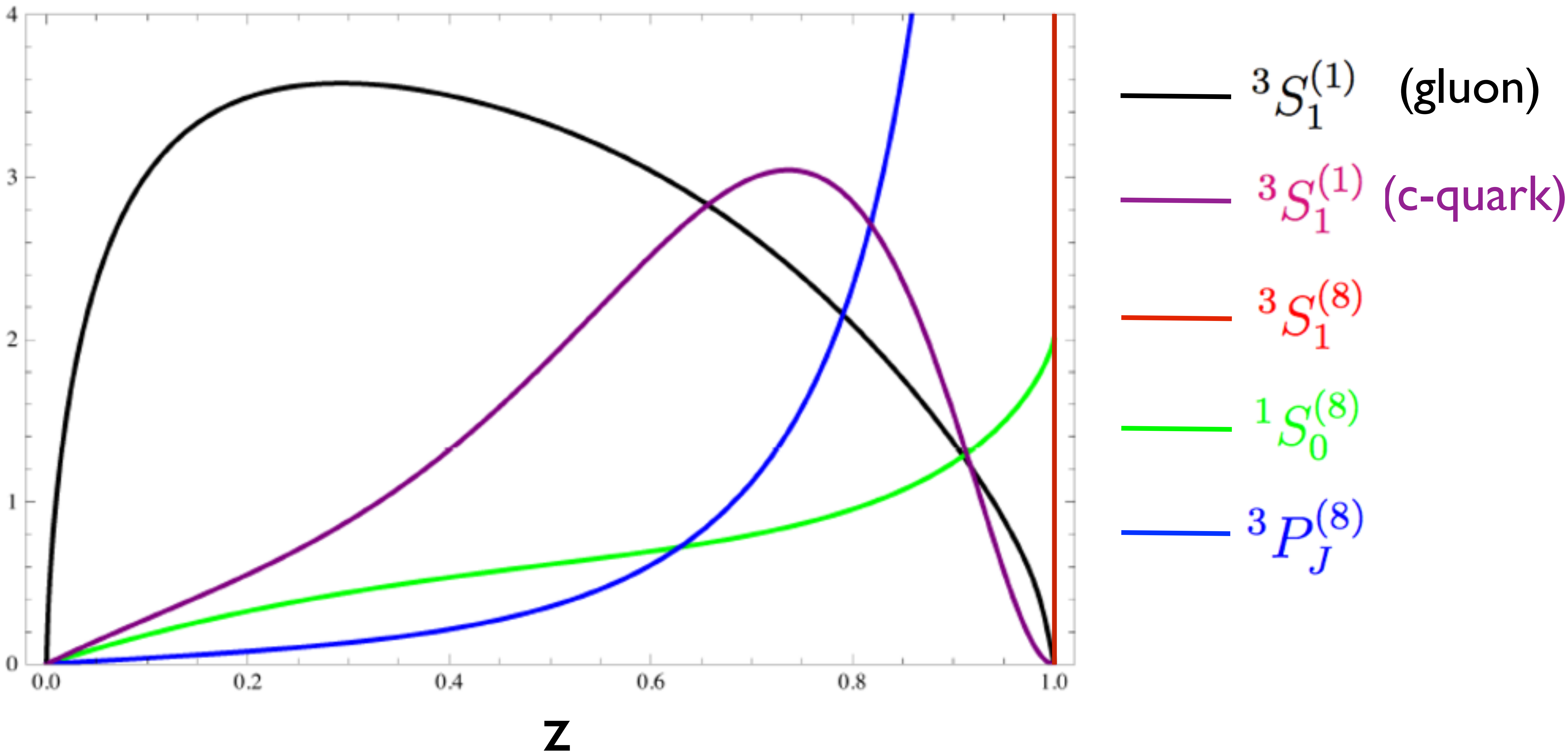
$$
\begin{aligned}
\mathcal{G}_g^{\psi}(E,R,z,\mu) \;=\; & D_{g\to\psi}(z,\mu)\left(1+\frac{C_A\alpha_s}{\pi}\left(L_{1-z}^2-\frac{\pi^2}{24}\right)\right) \\
& +\frac{C_A\alpha_s}{\pi}\left[\int_z^1 \frac{dy}{y}\tilde{P}_{gg}(y)L_{1-y}D_{g\to\psi}\left(\frac{z}{y},\mu\right)\right. \\
& +2\int_z^1 dy\frac{D_{g\to\psi}(z/y,\mu)-D_{g\to\psi}(z,\mu)}{1-y}L_{1-y}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

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

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

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

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

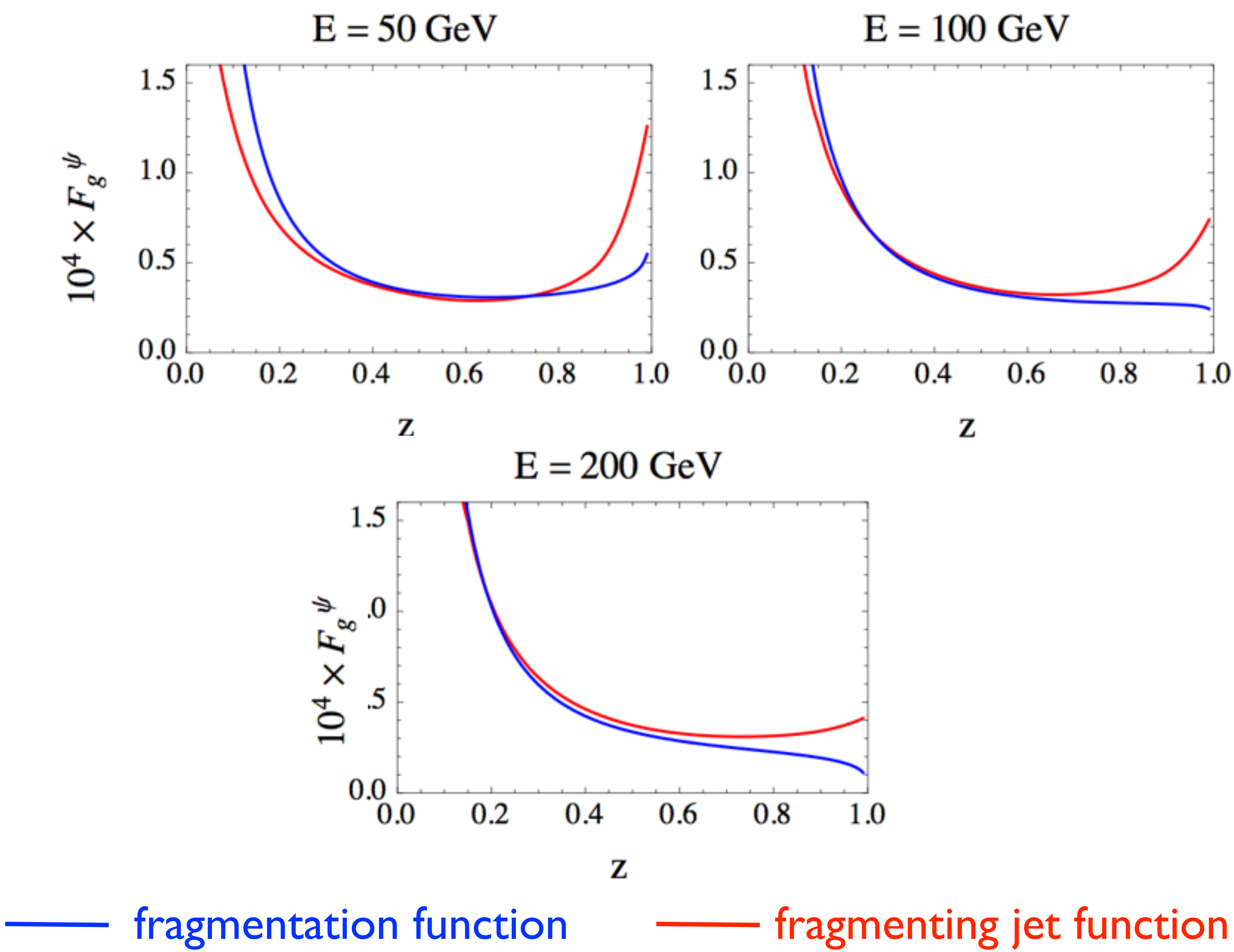



(normalization arbitrary)

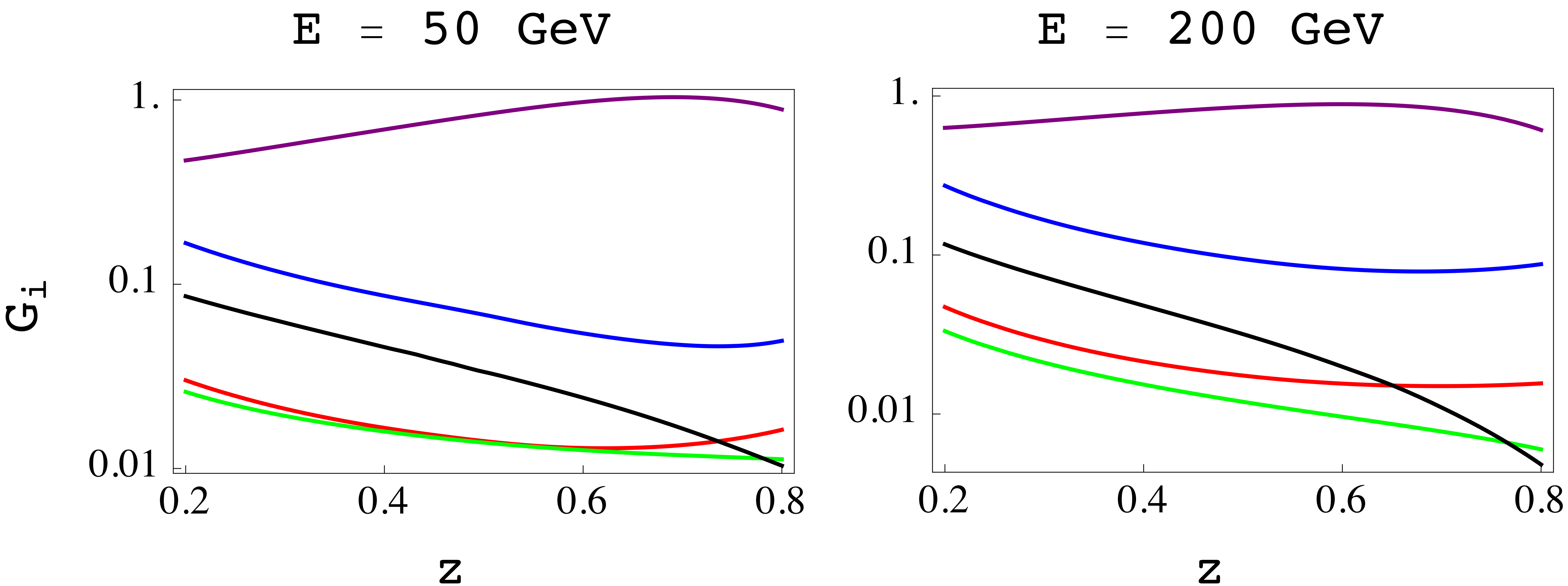
Evolution to 2E tan(R/2) will soften discrepancies

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

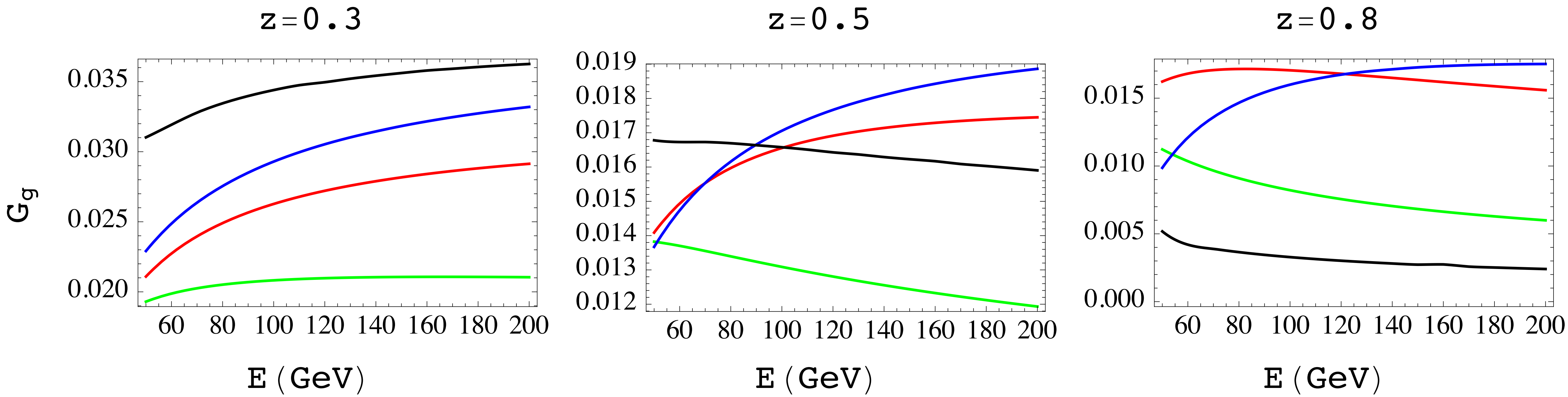
M. Baumgart, A. Leibovich, T.M., I. Z. Rothstein, JHEP 1411 (2014) 003



# FJF's at Fixed Energy vs. z



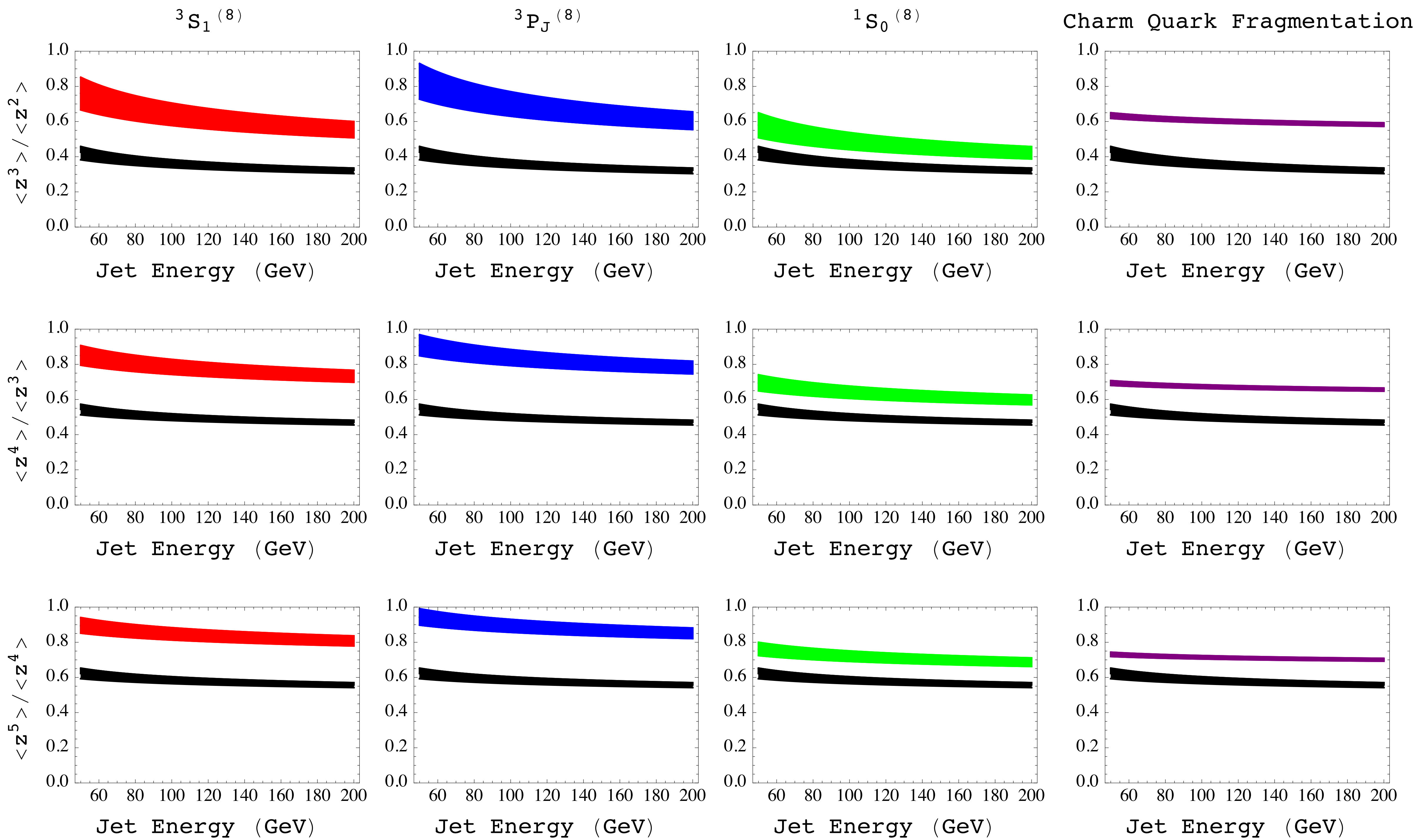
# FJF's at Fixed z vs. Energy




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

# Ratios of Moments

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

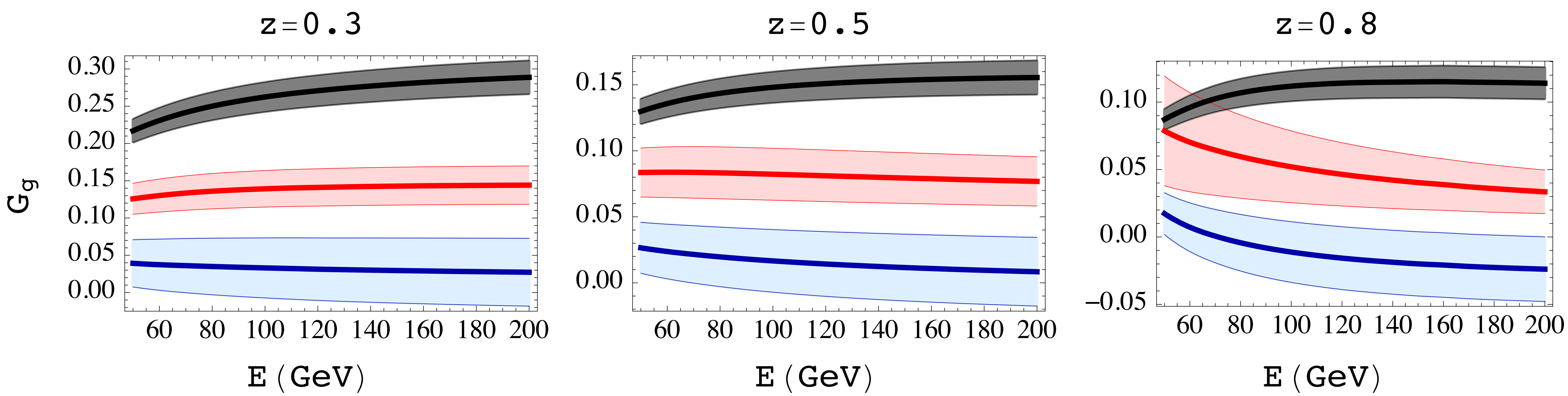


# Ratios of Moments

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

# Gluon FJF for different extractions of LDME

fix z, vary energy



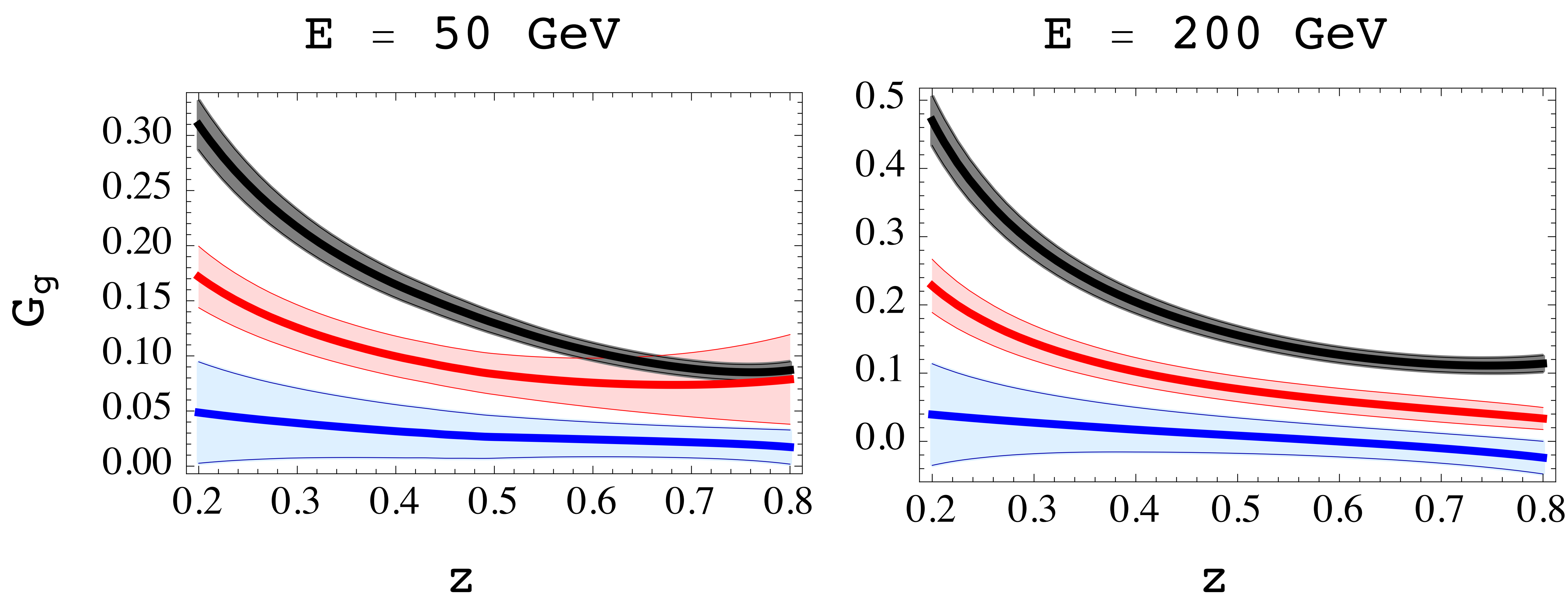

Butenschoen and Kniehl, PRD 84 (2011) 051501, arXiv:1105.0822

Bodwin, et. al. arXiv:1403.3612

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

# Gluon FJF for different extractions of LDME

fix energy, vary z



# Jets w/ Heavy Mesons: Analytic vs. Monte Carlo

(w/ R. Bain, L. Dai, A. Hornig, A.Leibovich, Y. Makris)

JHEP 1606 (2016) 121 (arXiv:1601.05815)

$$e^+e^- \to b\bar{b}$$
$$\hookrightarrow \text{B jet}$$

$$e^+e^- \to q\bar{q}g$$
$$\hookrightarrow J/\psi \text{ jet}$$

NLL vs. Monte Carlo

# $e^+e^- \rightarrow$ Jets in SCET

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

$$d\sigma = H \times J^q \otimes J^{\bar{q}} \otimes J^g \otimes S$$

unmeasured jets:

E, R

measured jets:

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

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

# $e^+e^- \to$ Jets Formula (NLL')

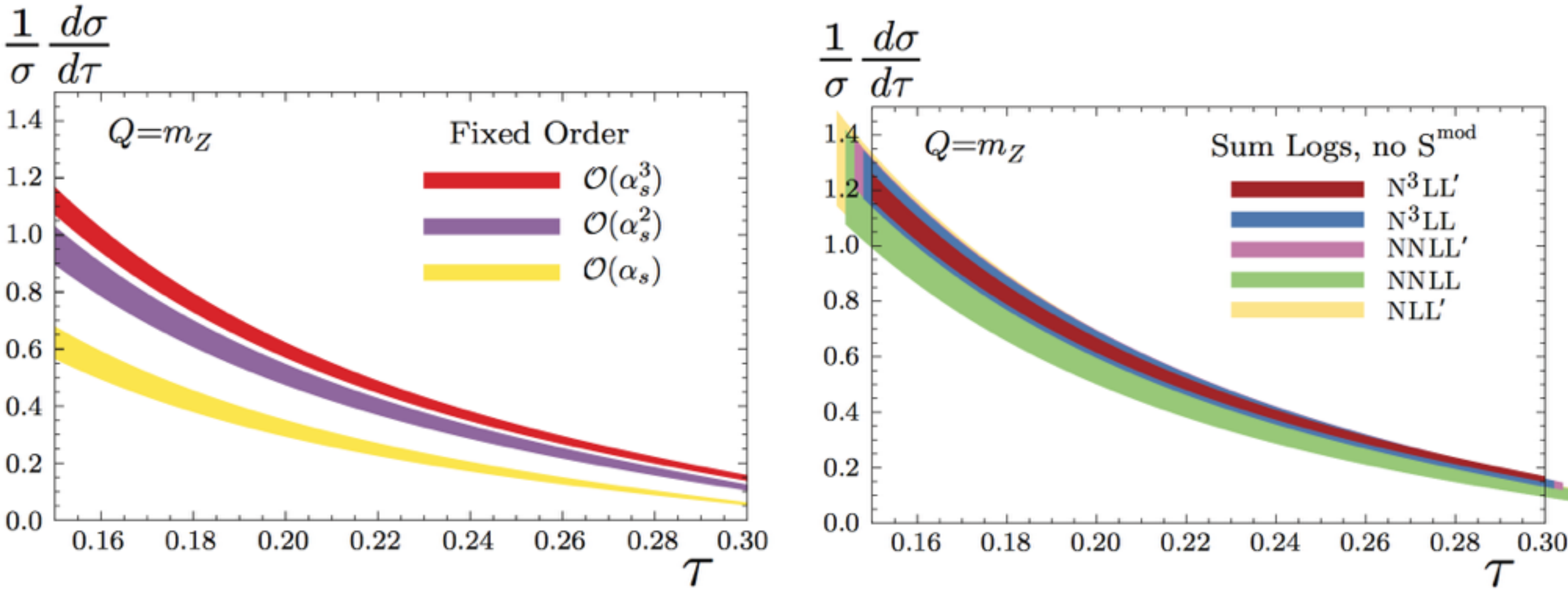
$$
\begin{aligned}
\frac{1}{\sigma^{(0)}}\frac{d\sigma^{(i)}}{dz\,d\tau_a} = \sum_j \int_z^1 \frac{dx}{x} D_j(x;\mu_J) H_2(\mu_H) \left(\frac{\mu_H}{\omega}\right)^{\omega_H(\mu,\mu_H)} S^{\text{unmeas}}(\mu_\Lambda) J_\omega(\mu_R) \left(\frac{\mu_R}{\omega \tan\frac{R}{2}}\right)^{\omega_R(\mu,\mu_R)} \\
\times \left\{ \left[\delta_{ij}\delta(1-z/x)(1+f_S(\tau_a,\mu_S)) + f_{\mathcal{J}}^{ij}(\tau_z, z/x;\mu_J)\right] \left(\frac{\mu_S \tan^{1-a}\frac{R}{2}}{\omega_1}\right)^{\omega_S(\mu,\mu_S)} \right. \\
\left. \times \left(\frac{\mu_J}{\omega}\right)^{(2-a)\omega_J(\mu,\mu_J)} \frac{1}{\Gamma[-\omega_J(\mu,\mu_J)-\omega_S(\mu,\mu_S)]} \frac{1}{\tau_a^{1+\omega_J(\mu,\mu_J)+\omega_S(\mu,\mu_S)}} \right\}_+ \\
\times \exp\left[\mathcal{K}(\mu;\mu_H,\mu_R,\mu_J,\mu_S,\mu_\Lambda) + \gamma_E \Omega(\mu;\mu_J,\mu_S)\right].
\end{aligned}
$$

# $e^+e^- \to$ Jets Formula (NLL')

$$
\begin{aligned}
\frac{1}{\sigma^{(0)}}\frac{d\sigma^{(i)}}{dz\,d\tau_a} = \sum_j \int_z^1 \frac{dx}{x} D_j(x;\mu_J) H_2(\mu_H) \left(\frac{\mu_H}{\omega}\right)^{\omega_H(\mu,\mu_H)} S^{\text{unmeas}}(\mu_\Lambda) J_\omega(\mu_R) \left(\frac{\mu_R}{\omega \tan\frac{R}{2}}\right)^{\omega_R(\mu,\mu_R)} \\
\times \Bigg\{ \Big[\delta_{ij}\delta(1-z/x)(1+f_S(\tau_a,\mu_S)) + f_{\mathcal{J}}^{ij}(\tau_z, z/x;\mu_J)\Big] \left(\frac{\mu_S \tan^{1-a}\frac{R}{2}}{\omega_1}\right)^{\omega_S(\mu,\mu_S)} \\
\times \left(\frac{\mu_J}{\omega}\right)^{(2-a)\omega_J(\mu,\mu_J)} \frac{1}{\Gamma[-\omega_J(\mu,\mu_J)-\omega_S(\mu,\mu_S)]} \frac{1}{\tau_a^{1+\omega_J(\mu,\mu_J)+\omega_S(\mu,\mu_S)}} \Bigg\}_+ \\
\times \exp\left[\mathcal{K}(\mu;\mu_H,\mu_R,\mu_J,\mu_S,\mu_\Lambda) + \gamma_E \Omega(\mu;\mu_J,\mu_S)\right].
\end{aligned}
$$

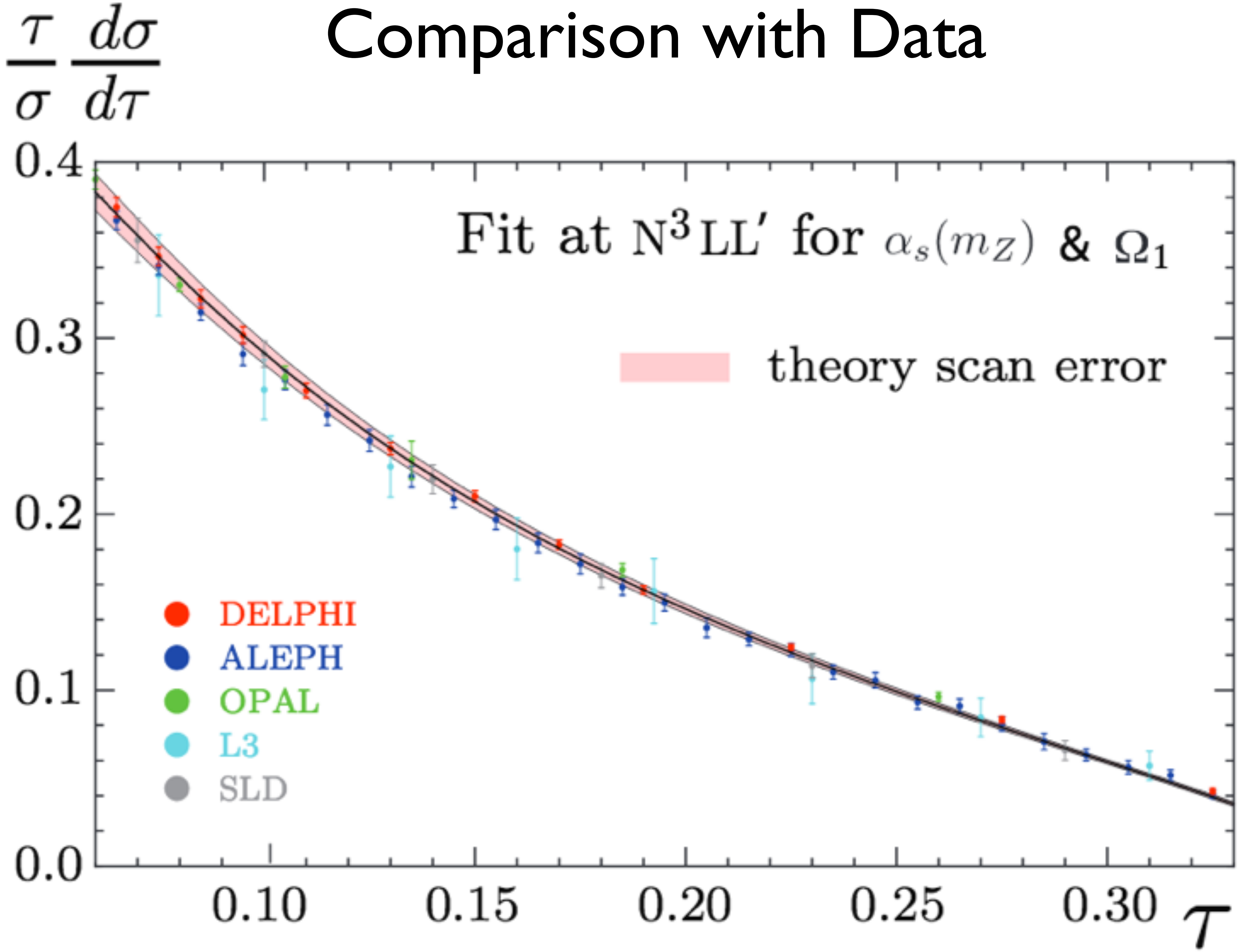
RGE evolution

# Importance of Resummation of Logarithms in Thrust




R. Abbate, et.al., Phys.Rev. D83 (2011) 074021

# Comparison with Data

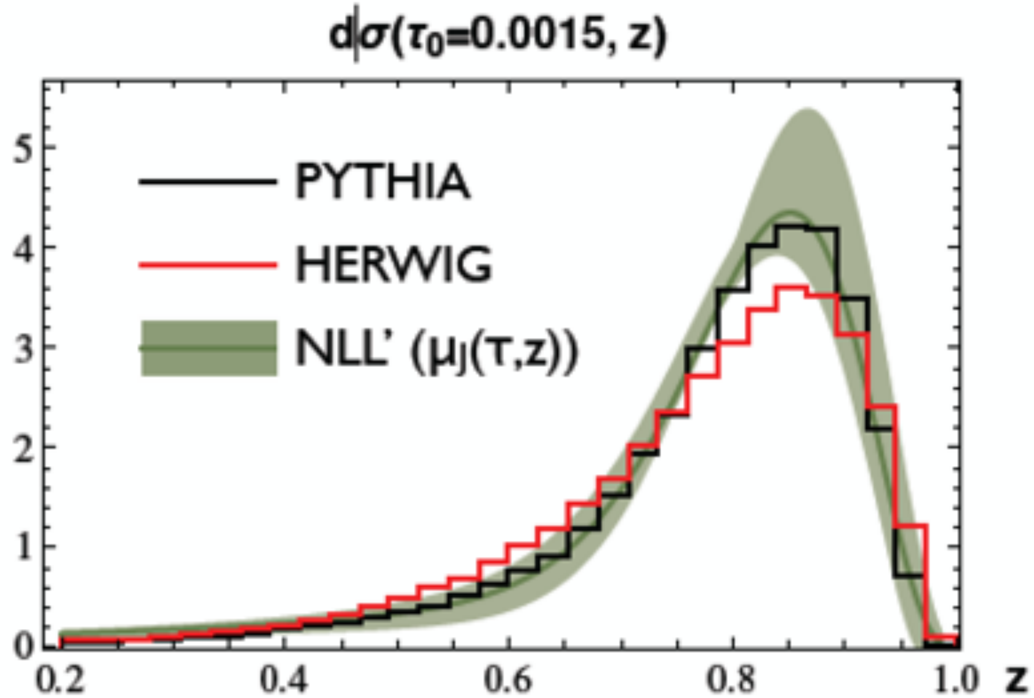


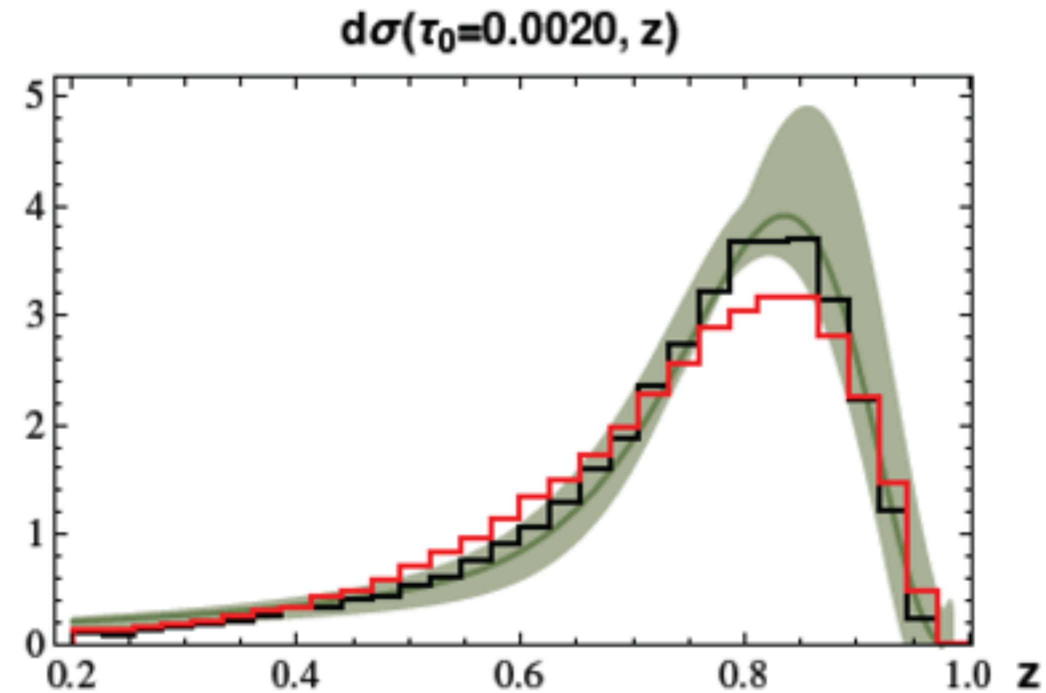

$$\alpha_s(M_Z) = 0.1135 \pm 0.0022$$

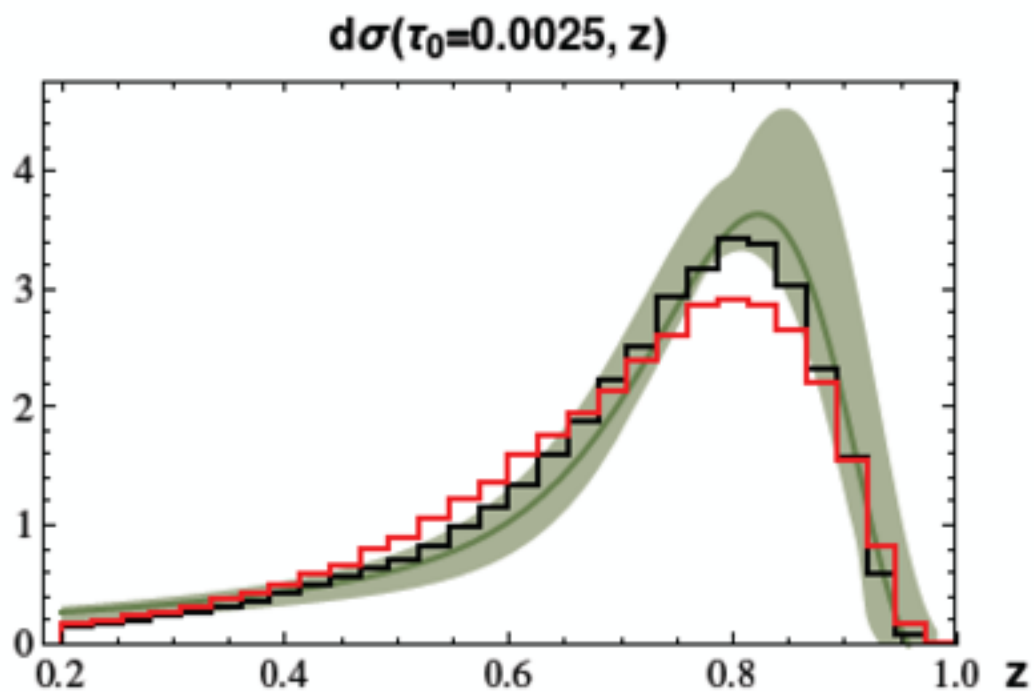
R. Abbate, et.al., Phys.Rev. D83 (2011) 074021

# NLL vs. Monte Carlo

fixed $\tau_0$, variable $z$




***Monte Carlo Details***

SISCone, $R = 0.6,\ N_{jets} = 2$

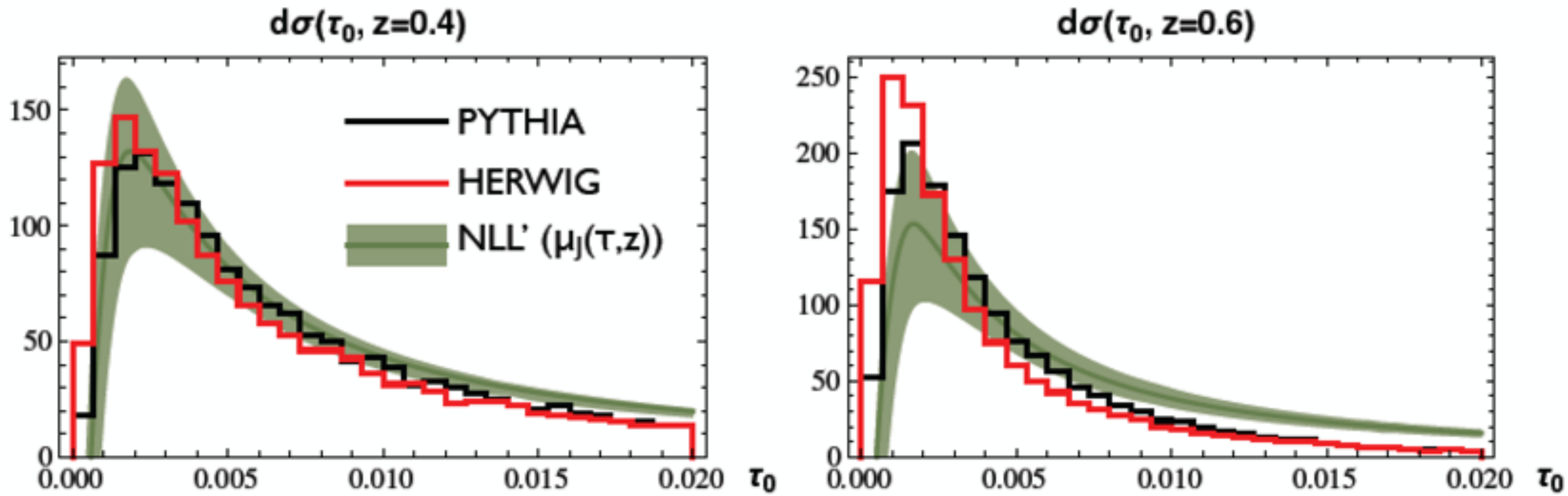
$E_{jet} > \dfrac{E_{cm} - \Lambda}{N_{jets}},\ E_{cm} = 250\text{GeV}$

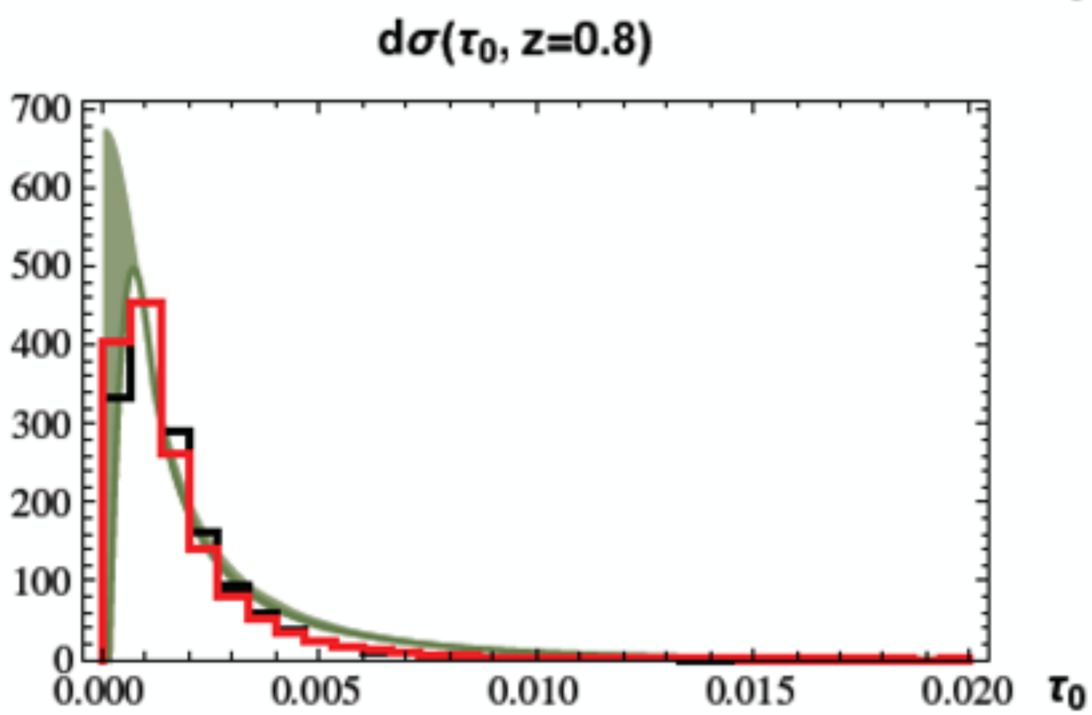
$\Lambda = 30\text{GeV}$

(HQ FF from LEP data) Kniehl, et. al. Phys.Rev. D77 (2008) 014011

# NLL vs. Monte Carlo

fixed $z$, variable $\tau_0$




***Monte Carlo Details***

SISCone, $R = 0.6$, $N_{jets} = 2$

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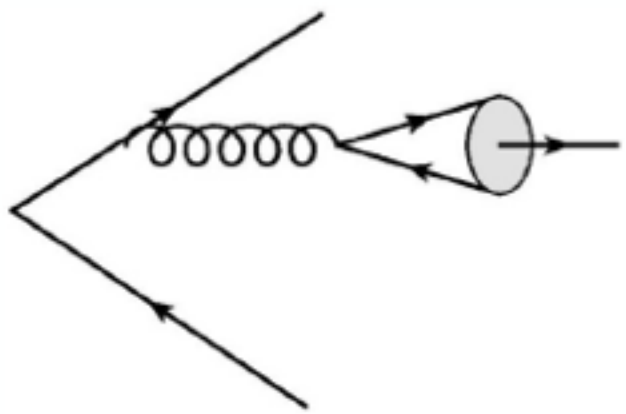
$\Lambda = 30\text{GeV}$

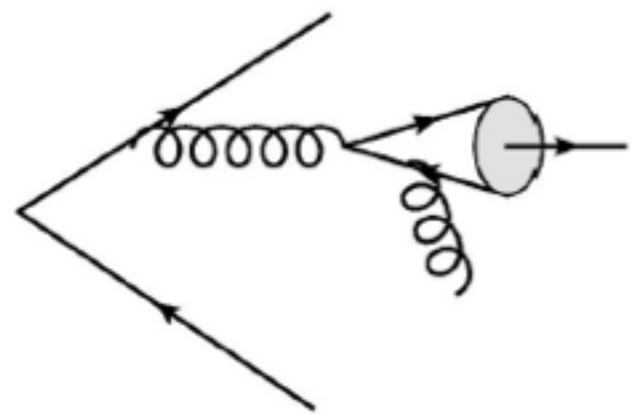
(HQ FF from LEP data) Kniehl, et. al. Phys.Rev. D77 (2008) 014011

# Madgraph + PYTHIA

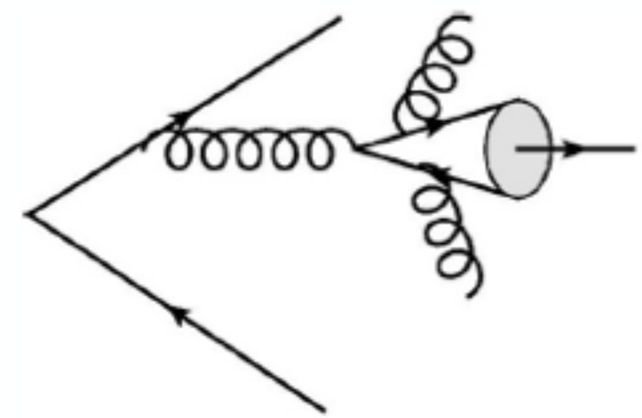
$e^+e^- \to b\,\bar{b}\,c\,\bar{c}\left[{}^3S_1^{(8)}\right]$



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



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

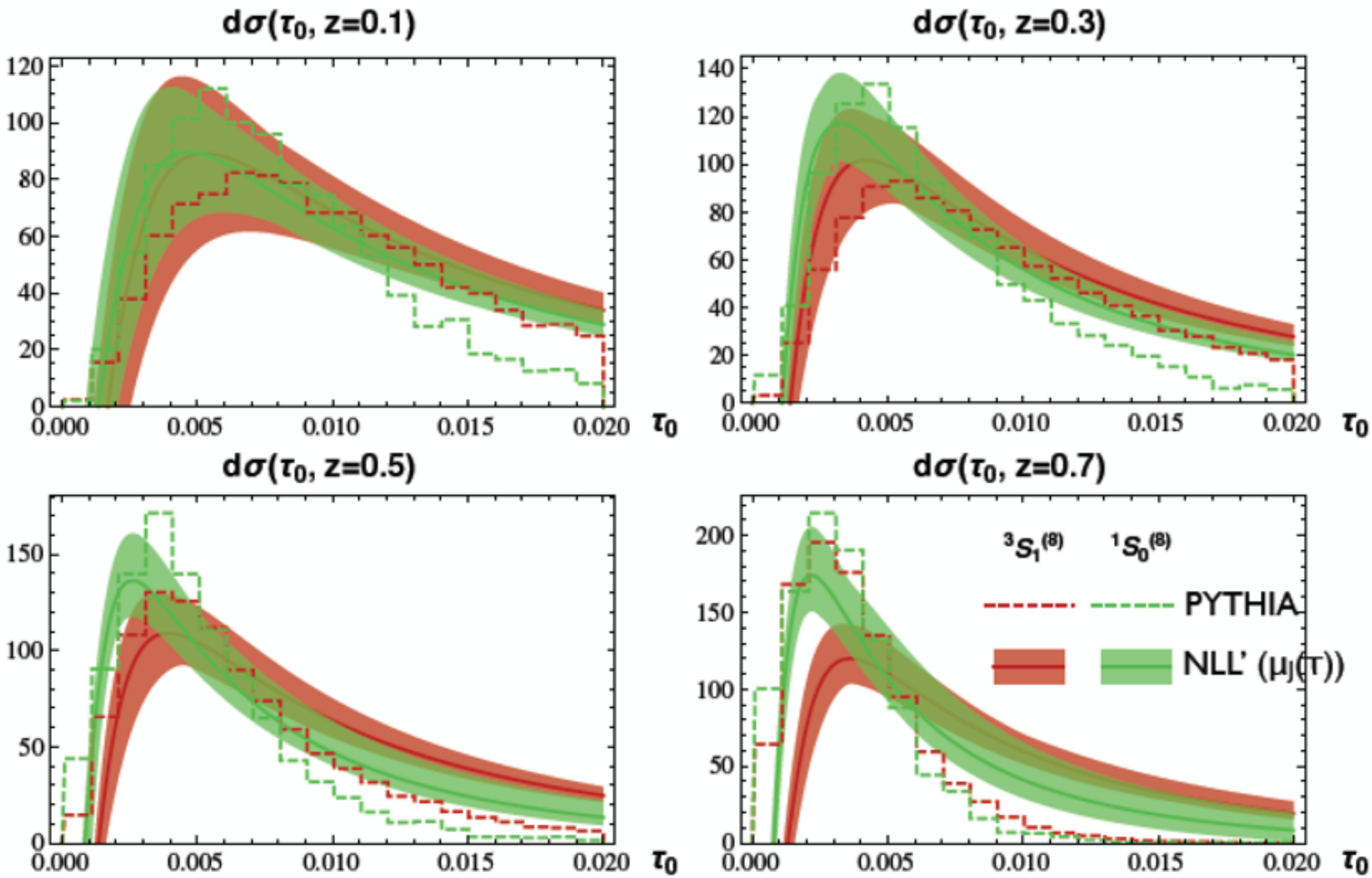


Force Madgraph to create $J/\psi$ from gluon initiated jet

PYTHIA: parton shower, hadronization

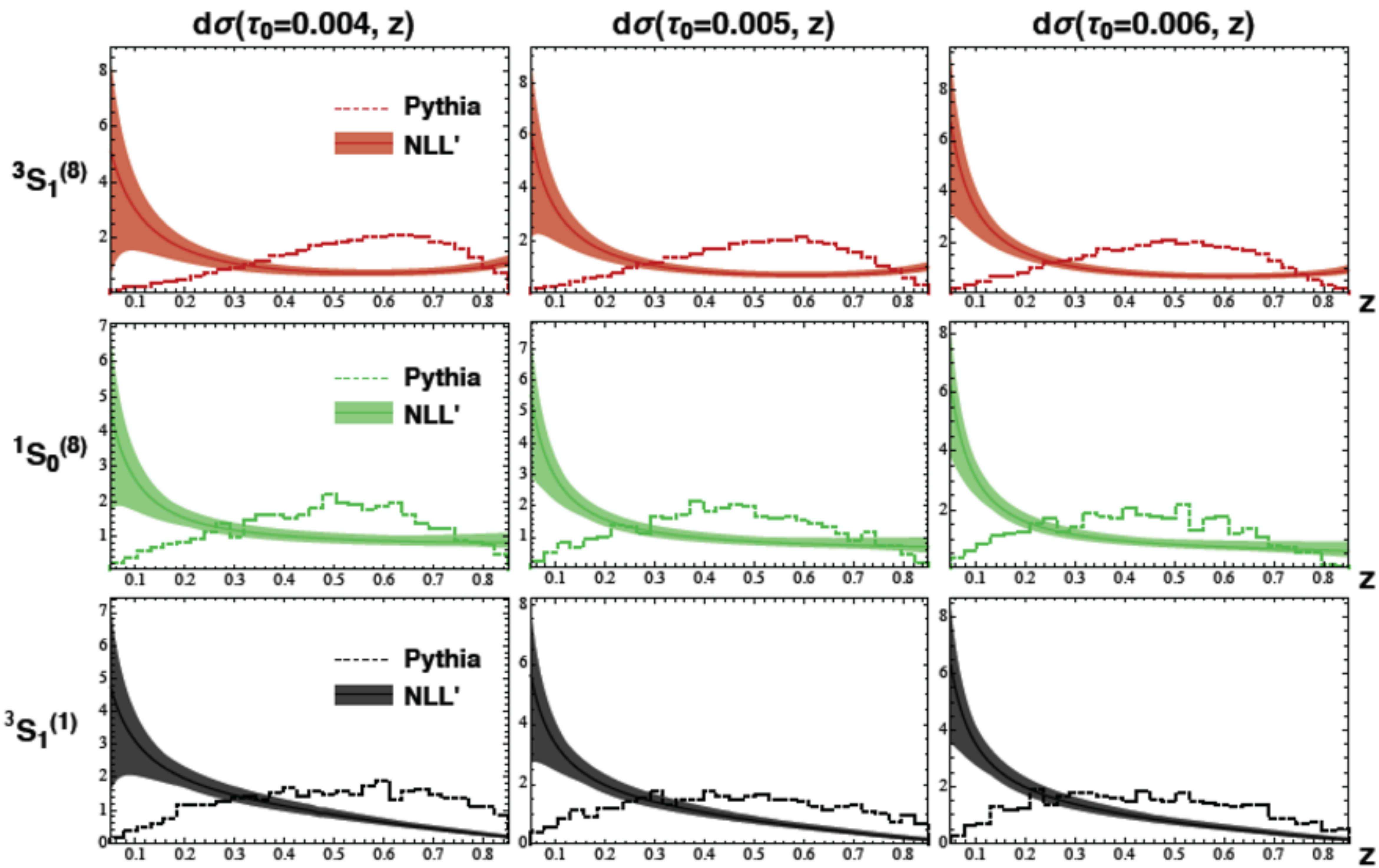
# NLL vs. Monte Carlo

fixed $z$, variable $\tau_0$




good agreement, some discrimination for large z

# NLL vs. Monte Carlo

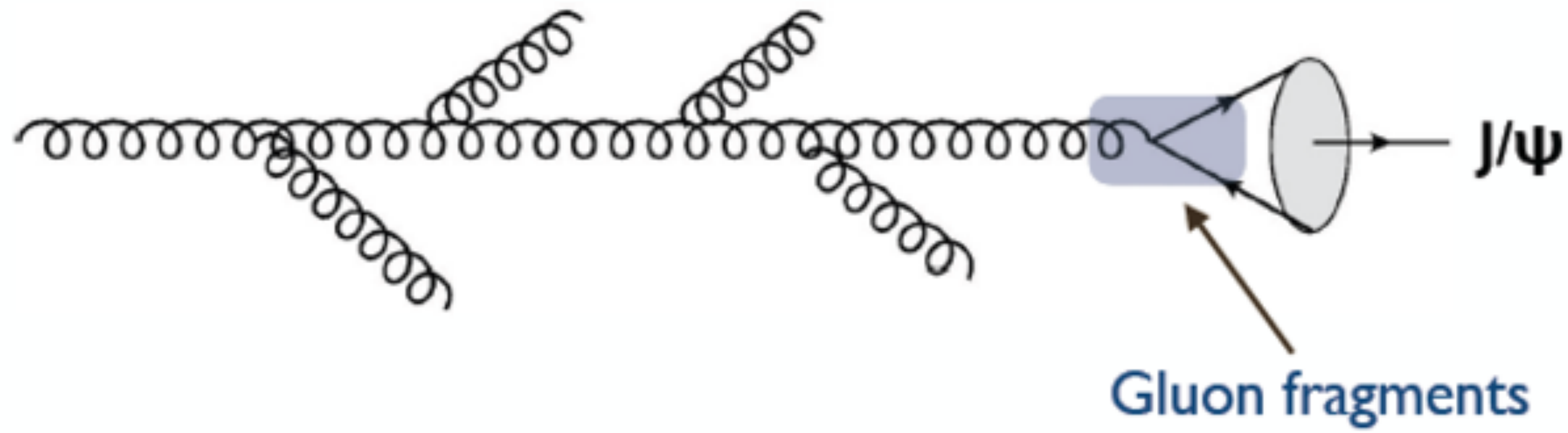



PYTHIA yields harder z distributions

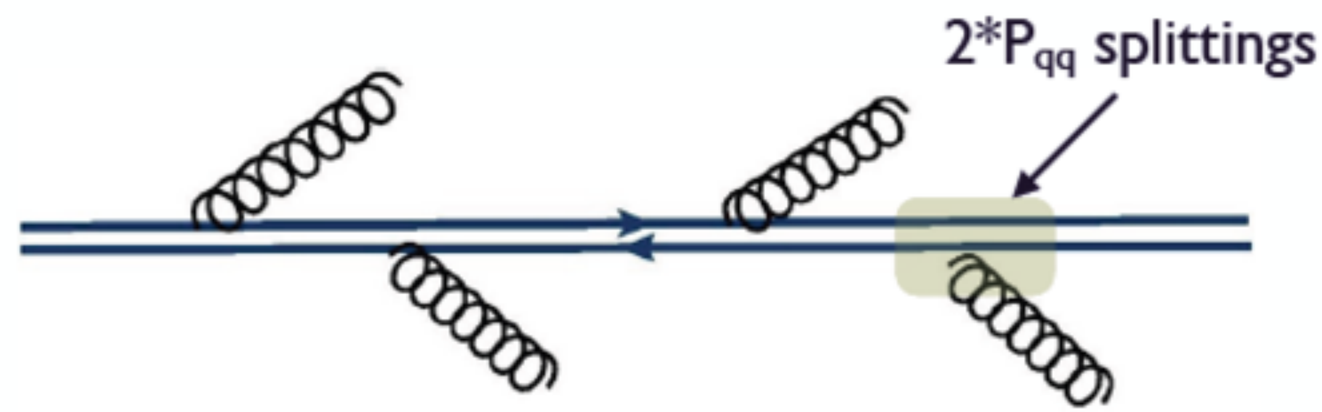
# Gluon Fragmentation and PYTHIA

PYTHIA's picture of showering off onia different from theory

*Analytic*




*PYTHIA*

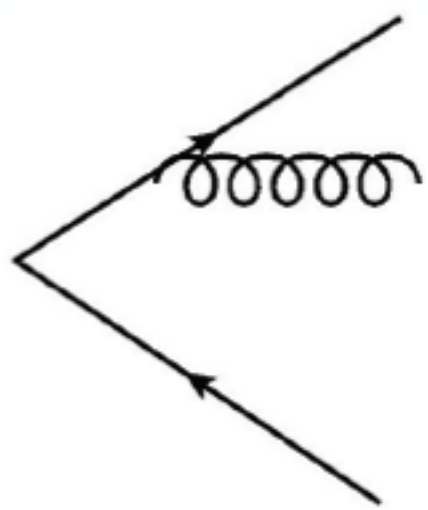



Monte carlo z distributions much harder than analytic

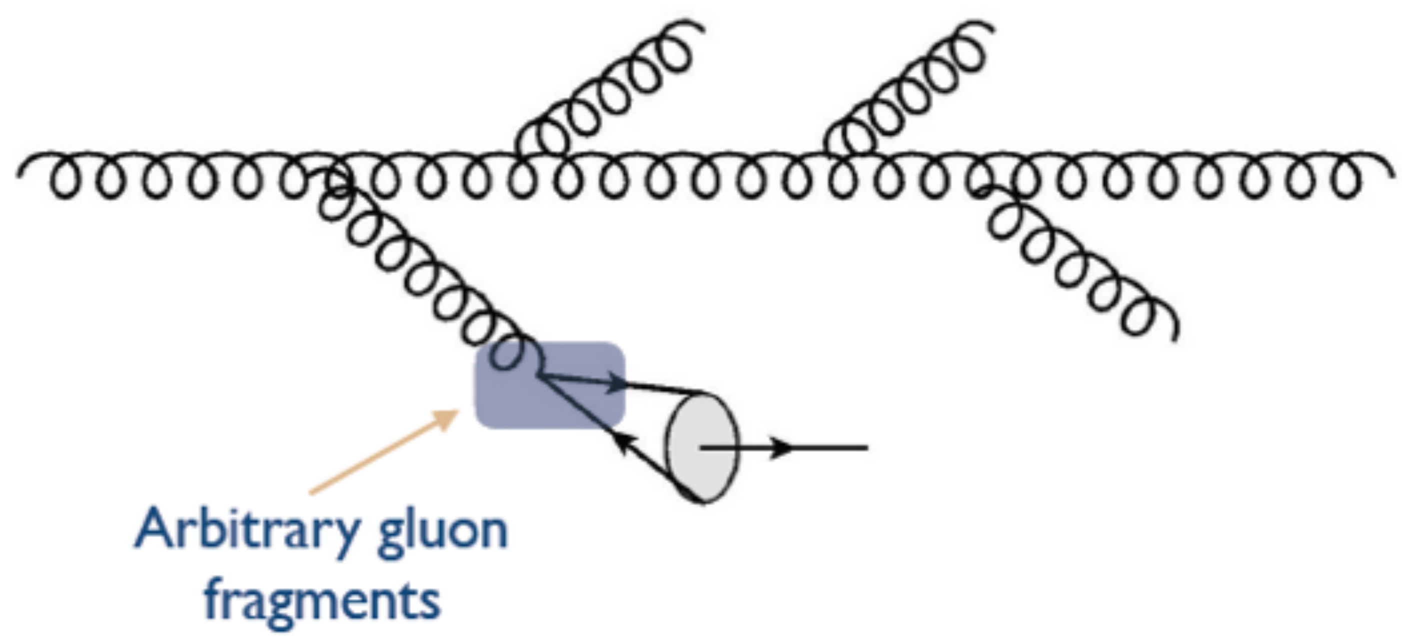
# Gluon Fragmentation Improved PYTHIA (GFIP)

## Madgraph 5

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



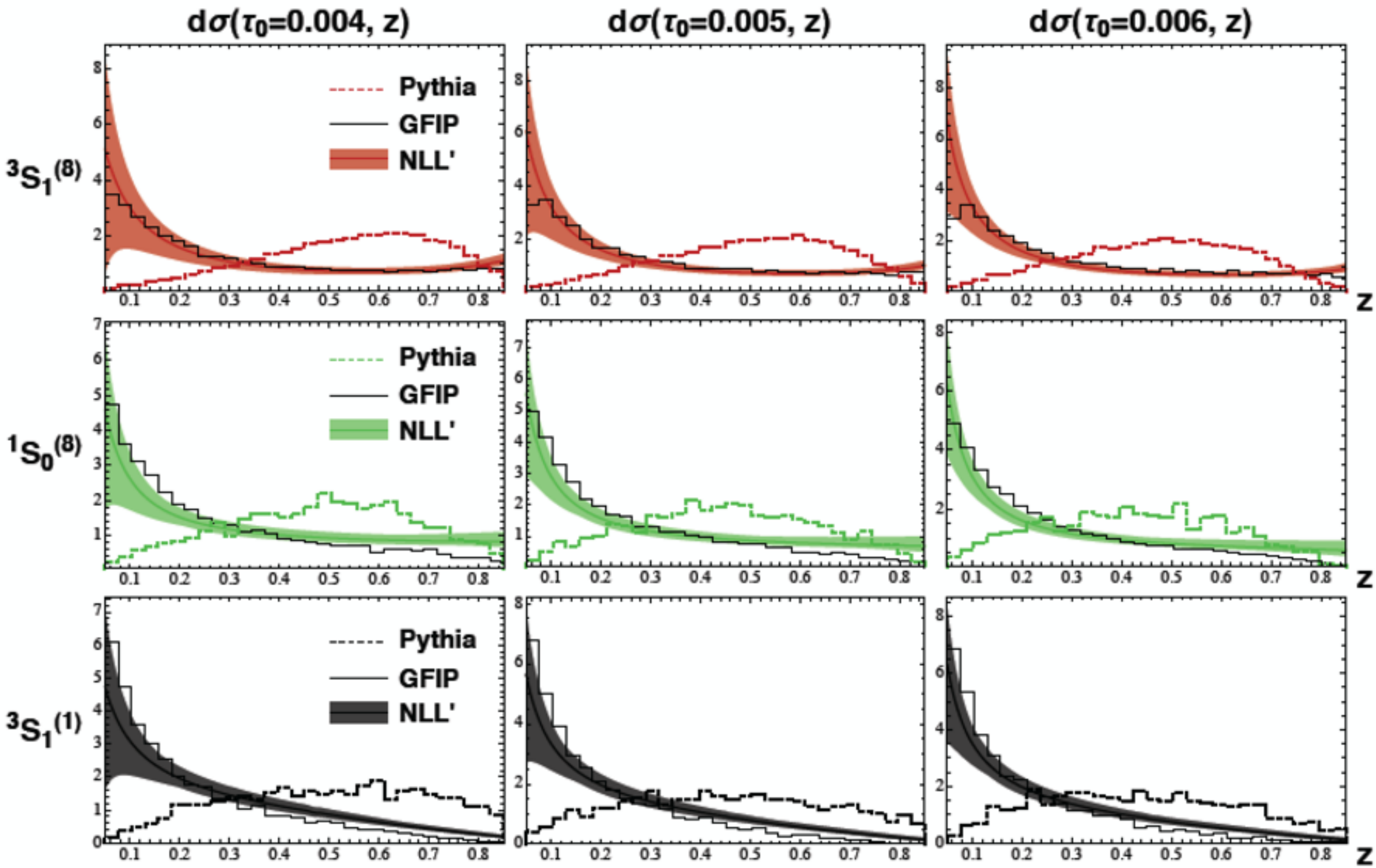
## PYTHIA + Convolution




2. PYTHIA ⟶ No hadronization, adjust shower pT cutoff

3. Convolve NRQCD FFs w/ random final state gluon

# NLL vs. Monte Carlo vs. GFIP




GFIP in much better agreeement with NLL

# Resummed Cross Section vs. Monte Carlo

**Agreement:** $\tau_a$ dependence

**Disagreement:** z dependence

PYTHIA model of evolution of color-octet $c\bar{c}$
disagrees with physical
interpretation of NLL calculation

# Jet Shapes in Dijet Events at the LHC

(w/ A. Hornig, Y. Makris)

JHEP 1604 (2016) 097 (arXiv:1601.01319)

## boost invariant angularity

$$\tau_a^{e^+e^-} = \frac{1}{2E_J}\sum_i |p_T^{iJ}| e^{-(1-a)|y_{iJ}|}$$

$$= (2E_J)^{-(2-a)}(p_T)^{1-a}\sum_i |p_T^i|\left(\frac{\theta_{iJ}}{\sin\theta_J}\right)^{2-a}(1+\mathcal{O}(\theta_{iJ}^2))$$

$$\tau_a^{pp} = \left(\frac{2E_J}{p_T}\right)^{2-a}\tau_a^{e^+e^-} + \mathcal{O}(\tau_a^2)$$

## modified jet function

$$J_i(\tau_a) = \left(\frac{p_T}{2E_J}\right)^{2-a} J_i^{e^+e^-}\left(\left(\frac{p_T}{2E_J}\right)^{2-a}\tau_a\right)$$

# Analogous Formulae for pp collisions

Soft Function in $e^+e^-$

rotationally invariant cuts: $E < E_{min}$

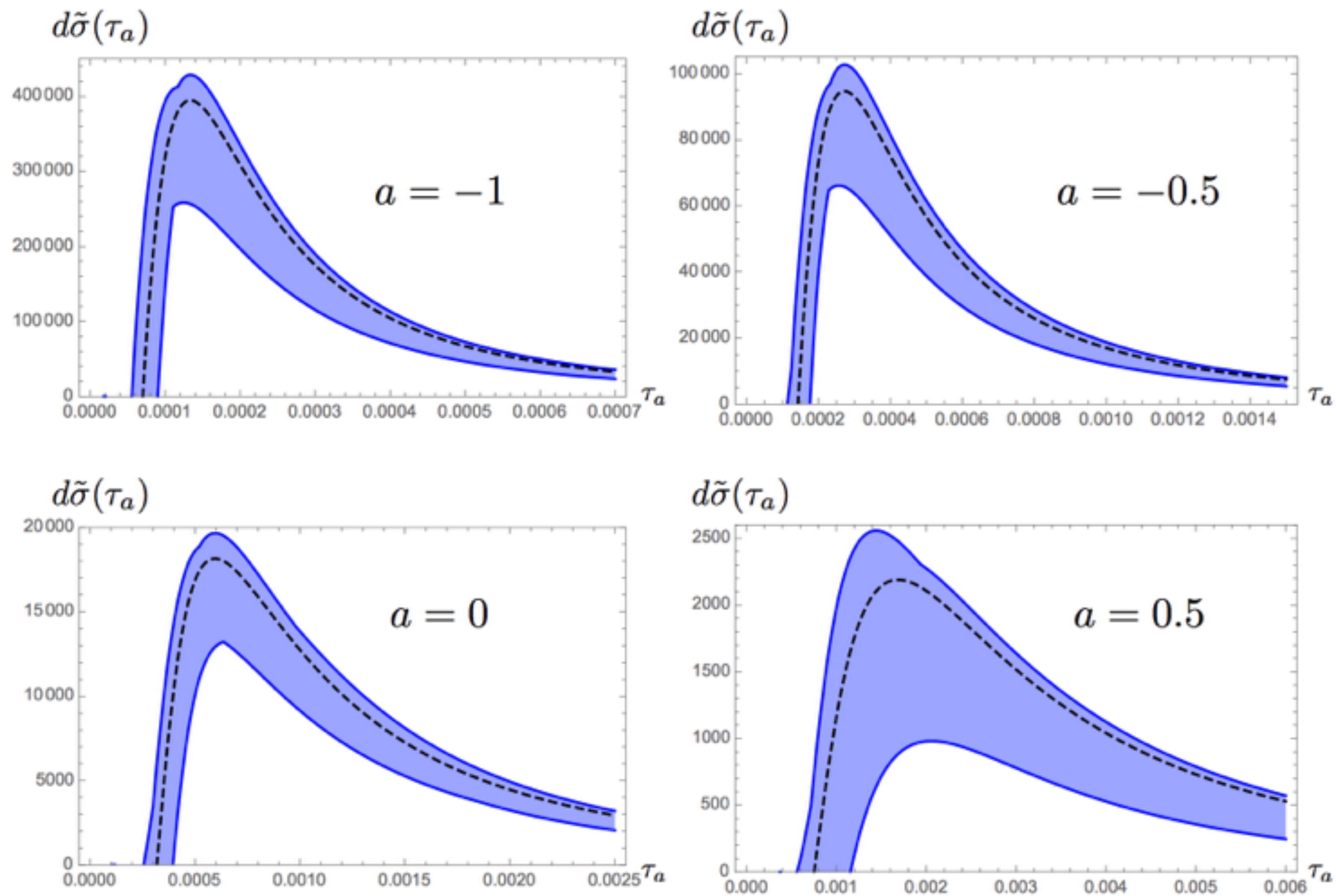
Soft Function in pp

boost invariant cuts, observables: $p_T$, rapidity

hard, soft functions are matrices in color space

$$d\sigma(\tau_a^1, \tau_a^2) = \frac{p_T x_1 x_2}{8\pi E_{\rm cm}^4} \frac{1}{N} B(x_1;\mu)\bar{B}(x_2;\mu)\,\mathrm{Tr}\{\mathbf{H}(\mu)\mathbf{S}(\tau_a^1, \tau_a^2;\mu)\} \otimes [J_1(\tau_a^1;\mu)J_2(\tau_a^2;\mu)]$$

# pp → 2 jets with boost invariant soft function




$q\bar{q}$ channel only

Study dependence on: a, R, $p_T$ cut, scale variation

# 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 QQ 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**

# Work in Progress

comparing SCET factorization theorems w/ Monte Carlo

developing analytic formulae for pp collisions

**comparison with experiment from ATLAS, CMS, LHCb**

# Backup

fragmentation function (QCD)

$$D_q^h(z) = z \int \frac{\mathrm{d}x^+}{4\pi}\, e^{ik^- x^+/2}\, \frac{1}{4N_c}\, \mathrm{Tr} \sum_X \, \langle 0| \bar{n}\!\!\!/\, \Psi(x^+, 0, 0_\perp)|Xh\rangle\langle Xh|\bar{\Psi}(0)|0\rangle\Big|_{p_h^\perp=0}$$

fragmentation function (SCET)

$$D_q^h\Big(\frac{p_h^-}{\omega}, \mu\Big) = \pi\omega \int dp_h^+ \, \frac{1}{4N_c}\, \mathrm{Tr} \sum_X \bar{n}\!\!\!/\, \langle 0|[\delta_{\omega,\bar{\mathcal{P}}}\, \delta_{0,\mathcal{P}_\perp}\, \chi_n(0)]|Xh\rangle\langle Xh|\bar{\chi}_n(0)|0\rangle$$

Jet function (SCET)

$$J_u(k^+\omega) = -\frac{1}{\pi\,\omega}\, \mathrm{Im} \int d^4x \, e^{ik\cdot x}\, i \, \big\langle 0\big|\, \mathrm{T}\, \bar{\chi}_{n,\omega,0_\perp}(0)\, \frac{\bar{n}\!\!\!/}{4N_c}\, \chi_n(x) \big|0\big\rangle$$

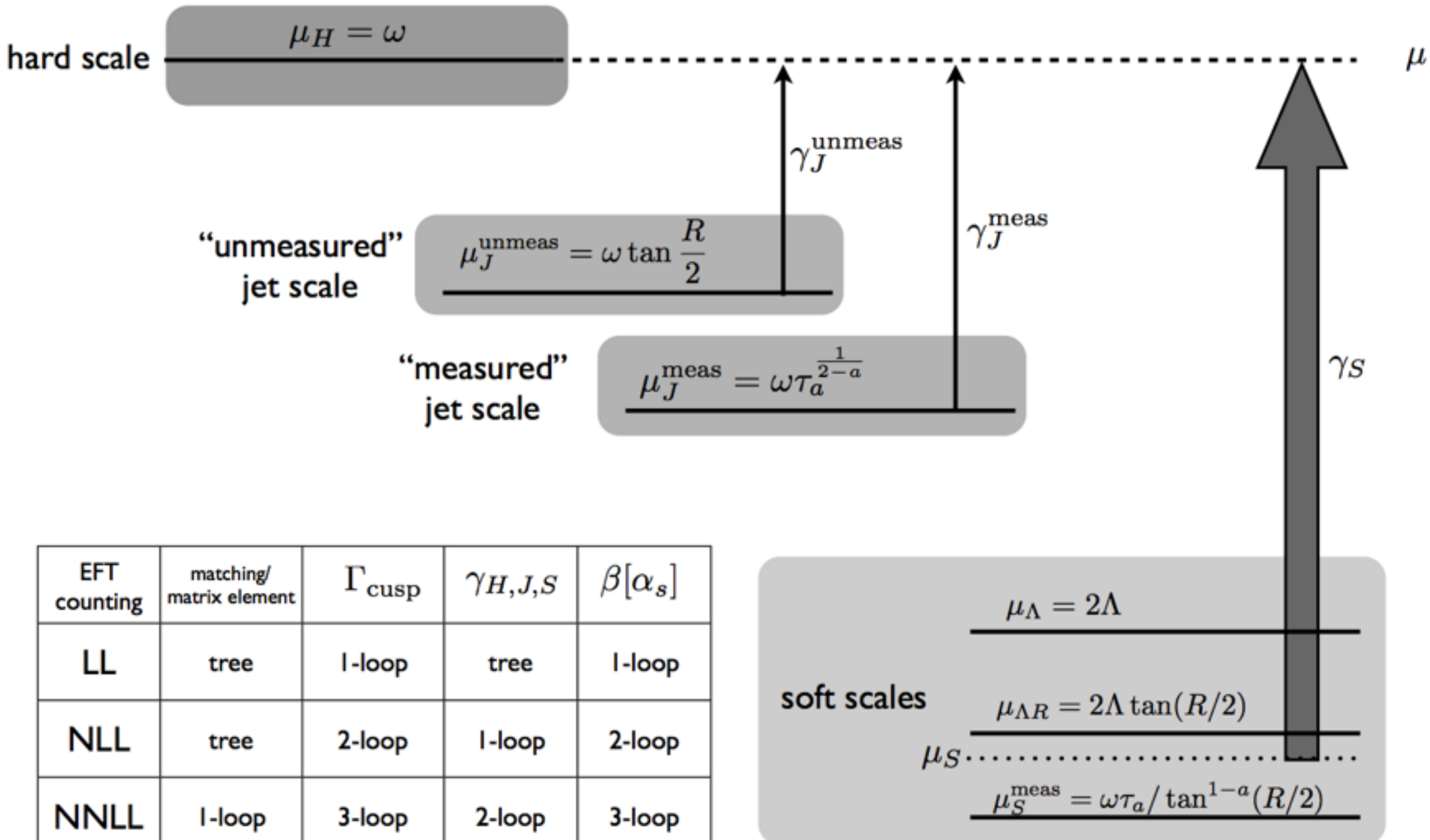
fragmentation jet function (SCET)

$$\mathcal{G}_{q,\mathrm{bare}}^h(s,z) = \int \mathrm{d}^4 y\, e^{\mathrm{i}k^+ y^-/2} \int \mathrm{d}p_h^+ \sum_X \frac{1}{4N_c}\, \mathrm{tr}\Big[\frac{\bar{n}\!\!\!/}{2} \langle 0|[\delta_{\omega,\overline{\mathcal{P}}}\,\delta_{0,\mathcal{P}_\perp}\, \chi_n(y)]\big|Xh\rangle\langle Xh|\bar{\chi}_n(0)|0\rangle\Big]$$

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

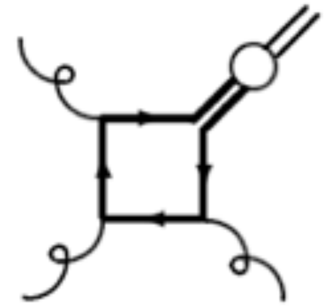
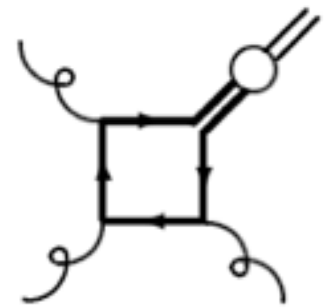
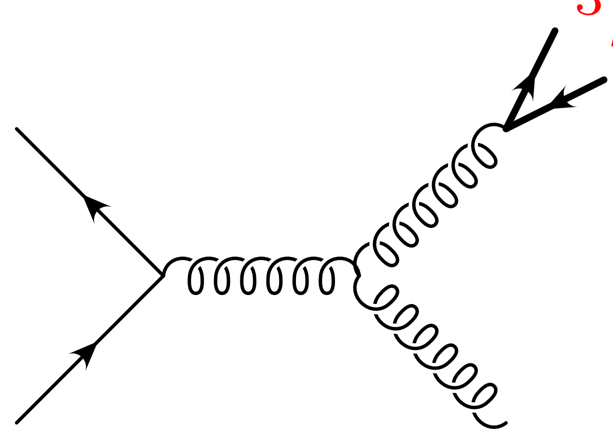
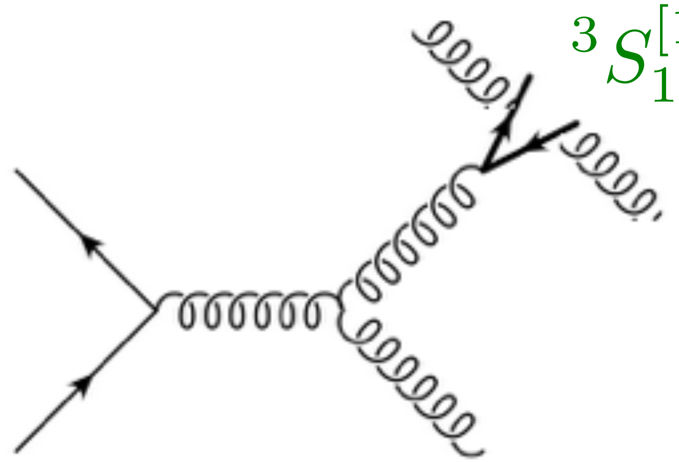
FF FJF

# Scales in Jet Cross section

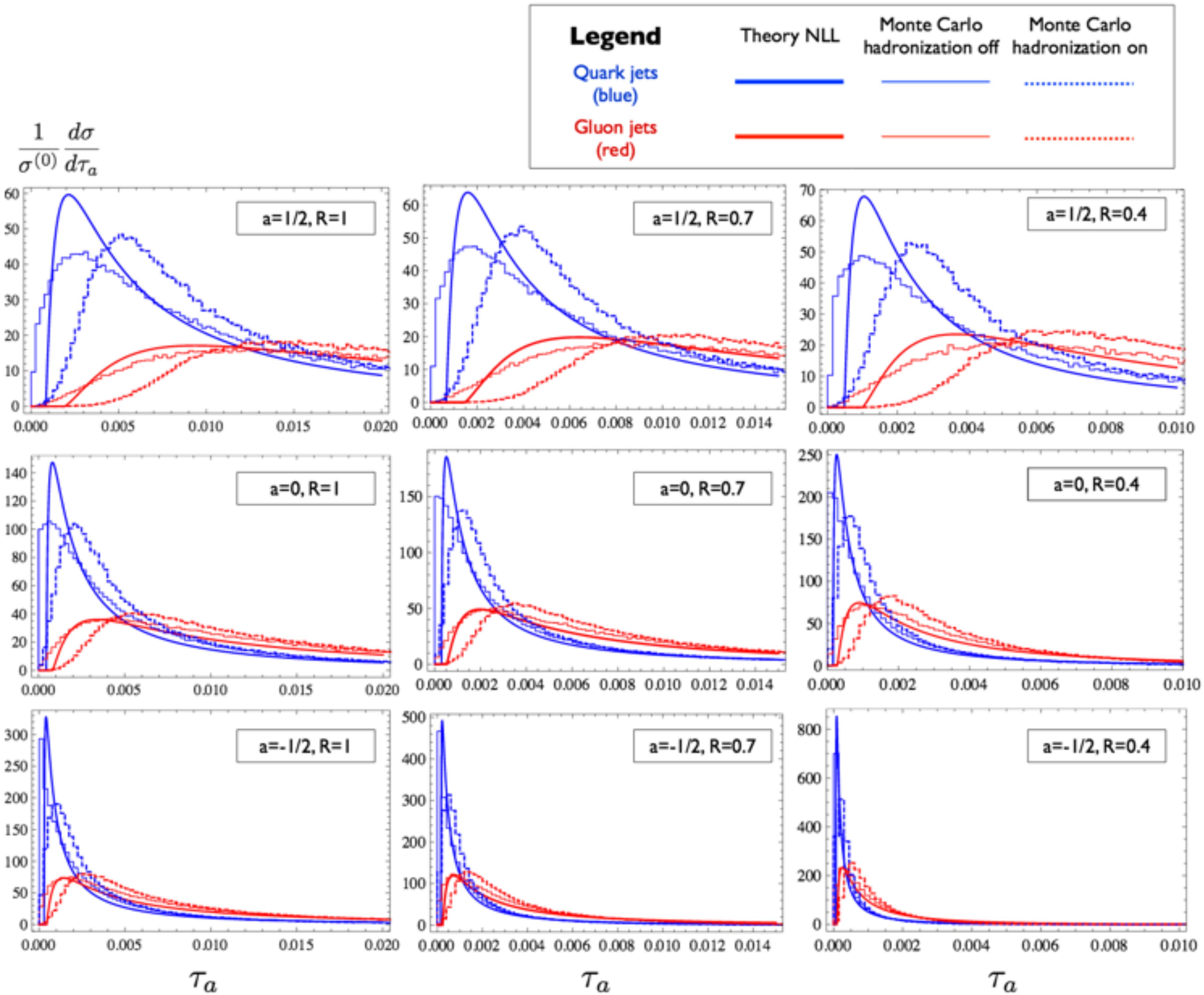



| EFT counting | matching/ matrix element | $\Gamma_{\mathrm{cusp}}$ | $\gamma_{H,J,S}$ | $\beta[\alpha_s]$ |
|---|---|---|---|---|
| LL | tree | 1-loop | tree | 1-loop |
| NLL | tree | 2-loop | 1-loop | 2-loop |
| NNLL | 1-loop | 3-loop | 2-loop | 3-loop |

mechanisms contributing to J/ψ production

| | | | $\frac{d\sigma}{dp_\perp^2}$ |
|---|---|---|---|
| CSM (LO) |  | ${}^3S_1^{[1]}$ | $\alpha_s^3 v^3 \frac{m_Q^4}{p_\perp^8}$ |
| COM (LO) |  | ${}^3P_J^{[8]}$ ${}^1S_0^{[8]}$ | $\alpha_s^3 v^7 \frac{m_Q^2}{p_\perp^6}$ |
| COM (Fragmentation) |  | ${}^3S_1^{[8]}$ | $\alpha_s^3 v^7 \frac{1}{p_\perp^4}$ |
| CSM (Fragmentation) |  | ${}^3S_1^{[1]}$ | $\alpha_s^5 v^3 \frac{1}{p_\perp^4}$ |

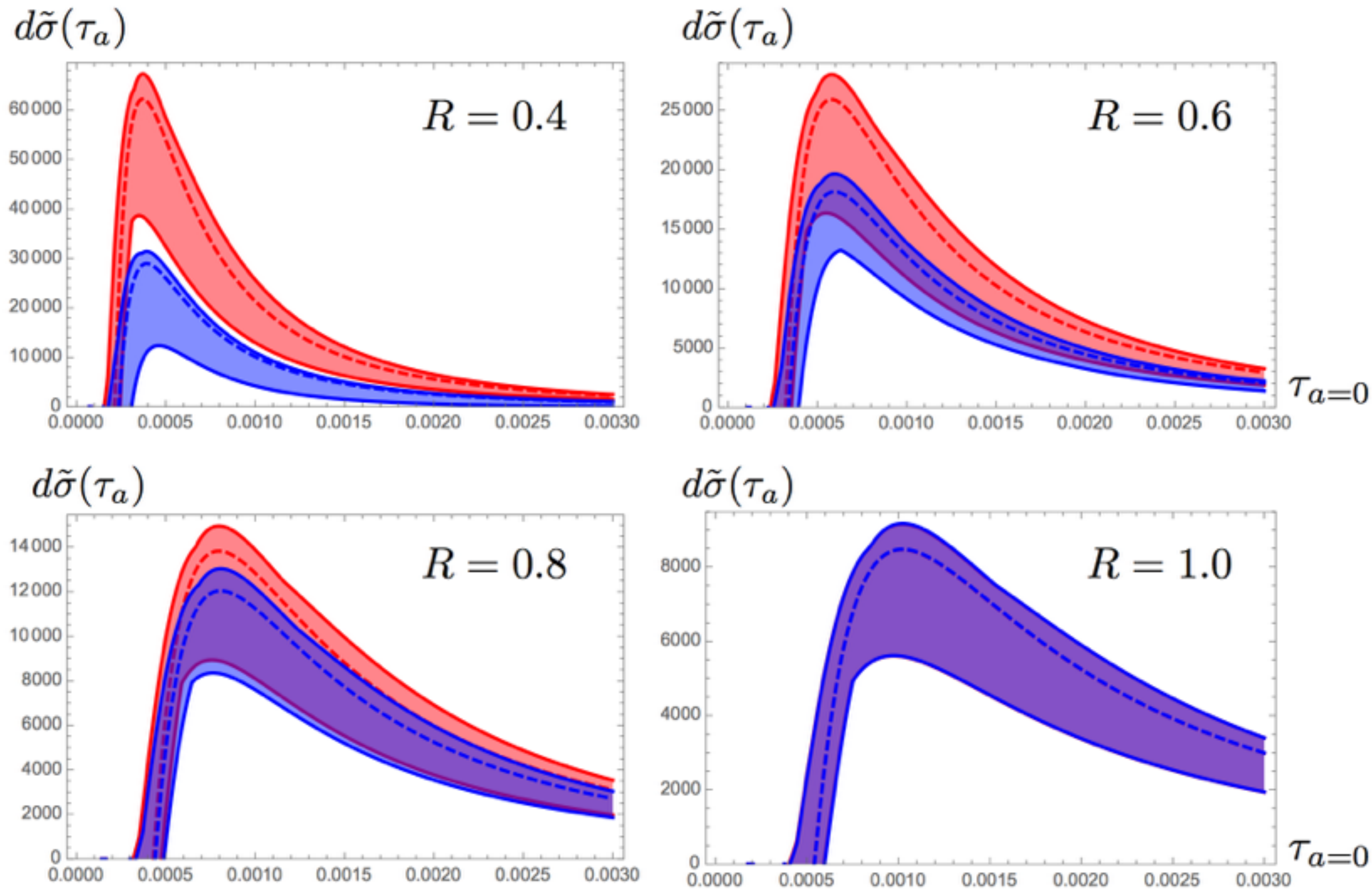
# Dependence on a,R vs. Monte Carlo



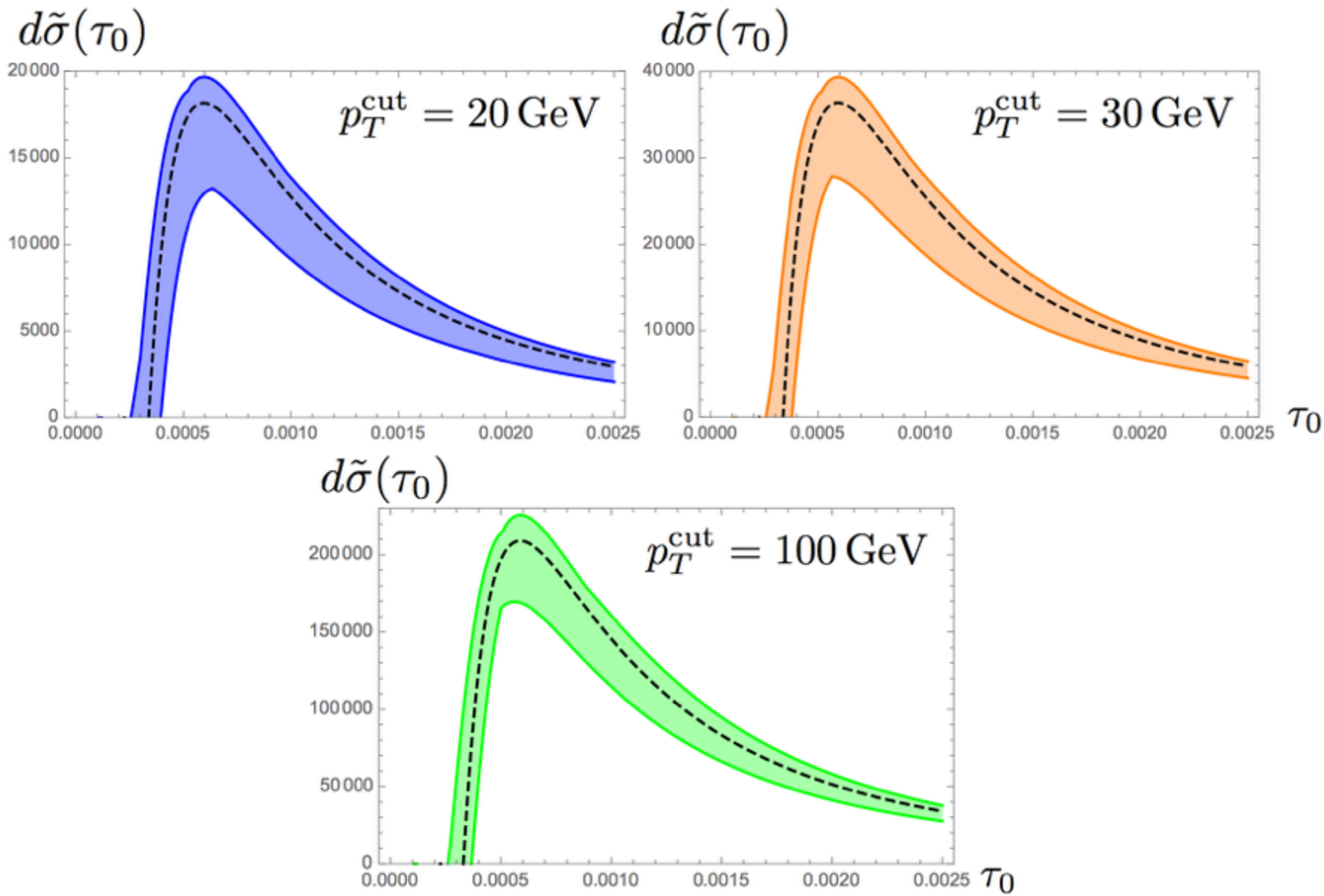

S.D. Ellis, et.al., JHEP1011(2010) 101

# Refactorizing the Soft function

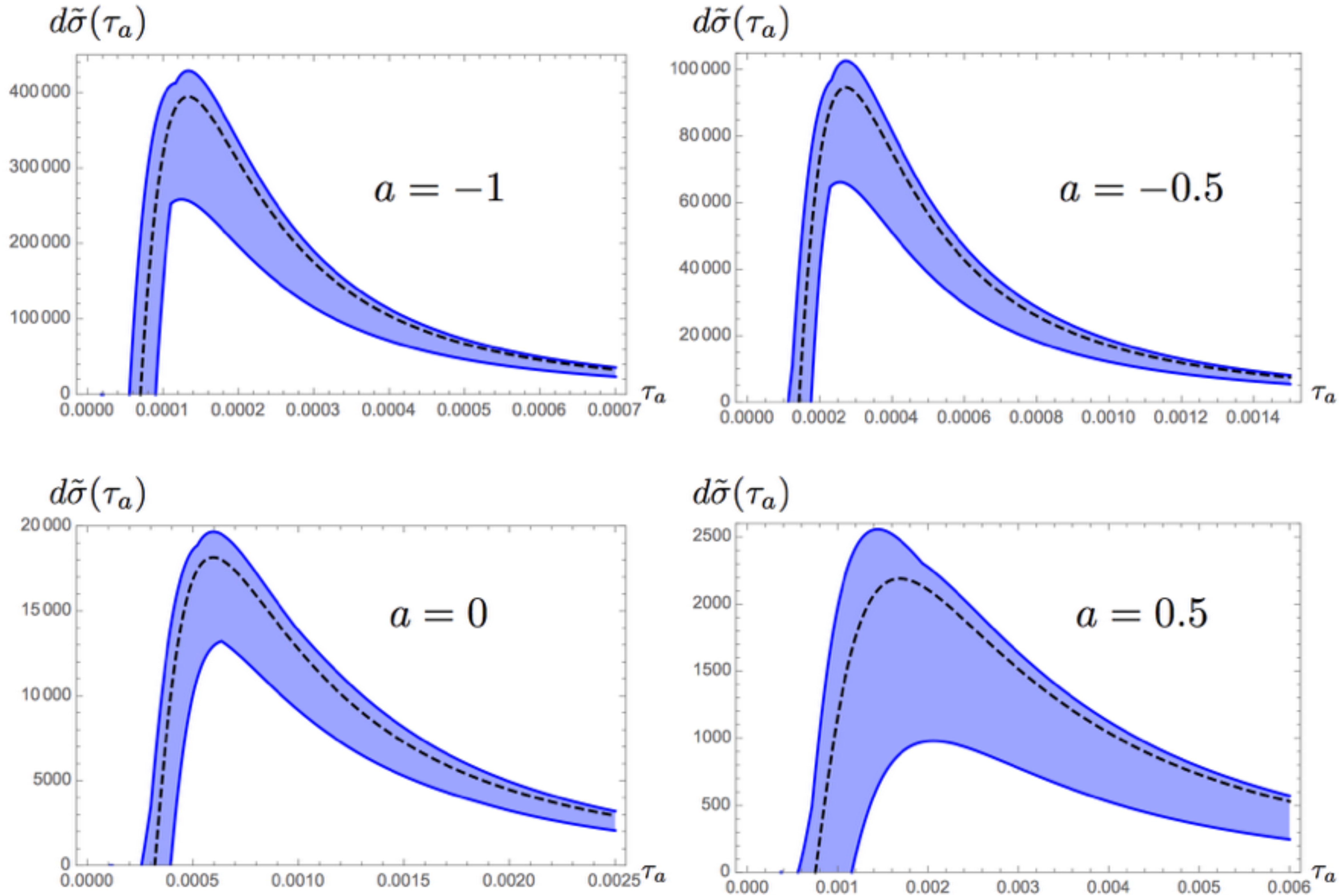
Y.T. Chien, A. Hornig, C. Lee, Phys.Rev. D93 (2016) 1, 014033




A. Hornig, Y. Makris, T.M., arXiv:1601.01319



$d\tilde{\sigma}(\tau_0)$
$p_T^{\mathrm{cut}} = 20\,\mathrm{GeV}$
20 000
15 000
10 000
5000
0
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
$d\tilde{\sigma}(\tau_0)$
$p_T^{\mathrm{cut}} = 30\,\mathrm{GeV}$
40 000
30 000
20 000
10 000
0
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
$\tau_0$
$d\tilde{\sigma}(\tau_0)$
$p_T^{\mathrm{cut}} = 100\,\mathrm{GeV}$
200 000
150 000
100 000
50 000
0
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
$\tau_0$


$d\tilde{\sigma}(\tau_a)$
$a = -1$
400 000
300 000
200 000
100 000
0
0.0000
0.0001
0.0002
0.0003
0.0004
0.0005
0.0006
0.0007
$\tau_a$
$d\tilde{\sigma}(\tau_a)$
$a = -0.5$
100 000
80 000
60 000
40 000
20 000
0
0.0000
0.0002
0.0004
0.0006
0.0008
0.0010
0.0012
0.0014
$\tau_a$
$d\tilde{\sigma}(\tau_a)$
$a = 0$
20 000
15 000
10 000
5000
0
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
$\tau_a$
$d\tilde{\sigma}(\tau_a)$
$a = 0.5$
2500
2000
1500
1000
500
0
0.000
0.001
0.002
0.003
0.004
0.005
0.006
$\tau_a$