Alternative Tests of Quarkonium Production Theory Using Jets

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(LANL)

Based on: arXiv:1702.05525
arXiv:1610.06508
arXiv:1603.06981
arXiv:1601.01319

In collaboration with: Reggie B., Lin D., Andrew H., Adam L., and Thomas M.

Los Alamos, NM, Nov 14, 2017

Introduction

- Formulation of the problem (The polarization puzzle of J/\psi)
  - Jets … ?

Quarkonium

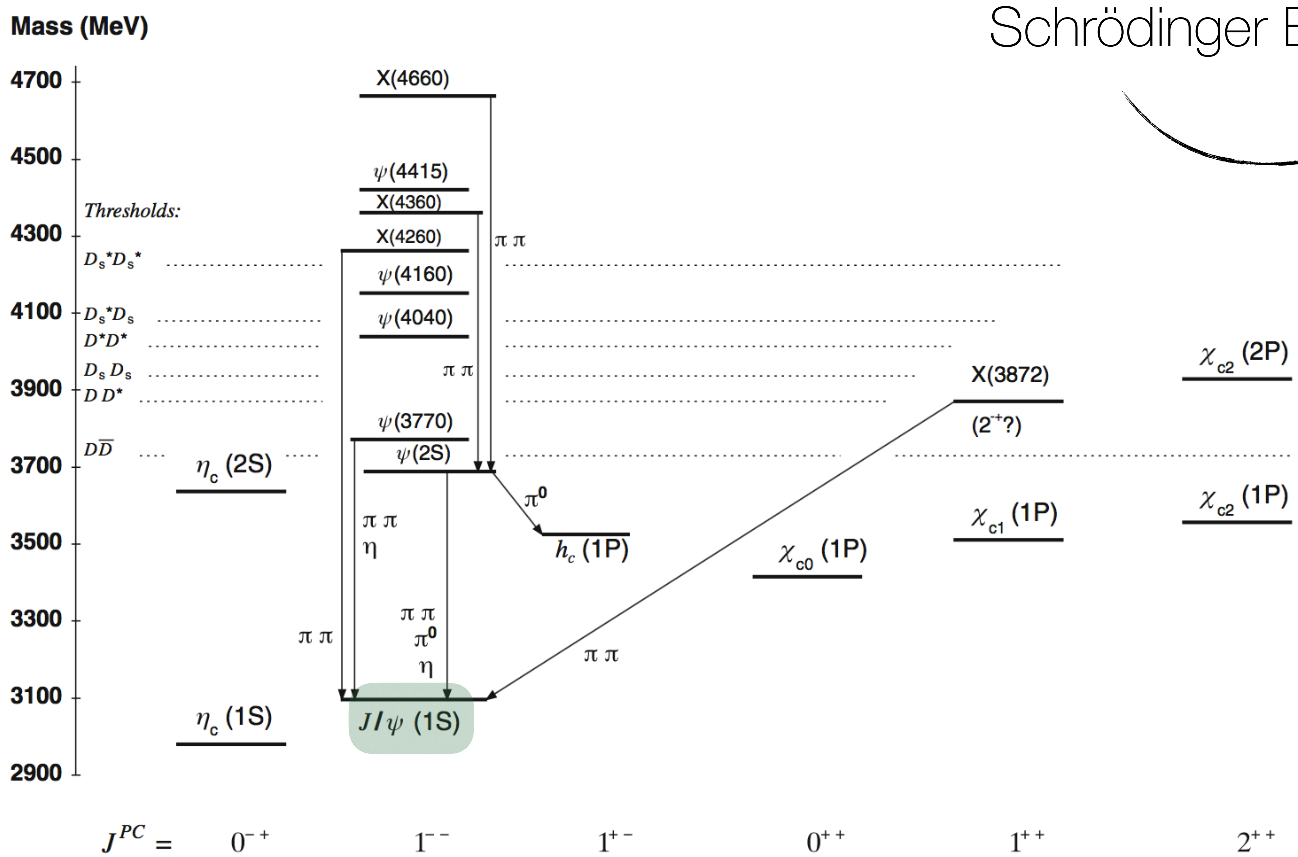
$b\bar{b}: \quad v^2 \sim 0.1$

$c\bar{c}: \quad v^2 \sim 0.3$

Quark potential model

Schrödinger Equation

Mass spectrum



Spectroscopic notation:

$n = {}^{2S+1} L_J$

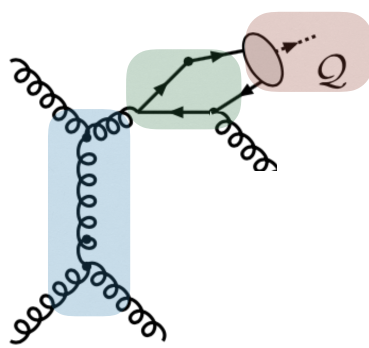
Quarkonium

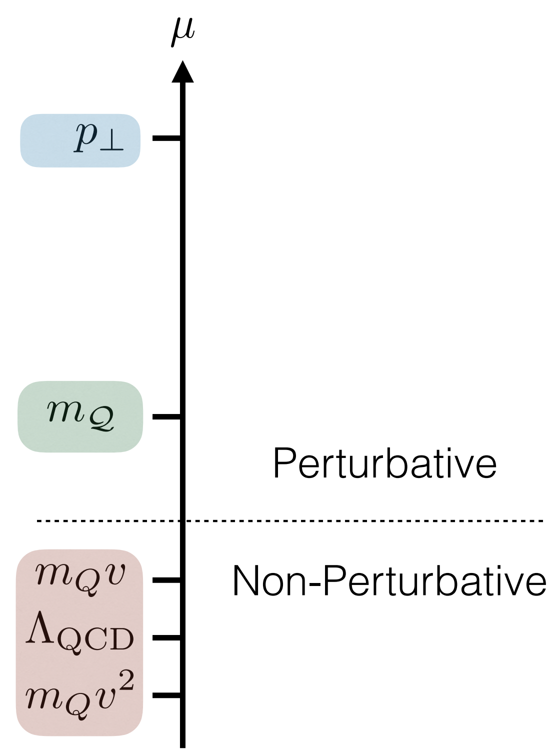
- Clean experimental signature (vector to di-lepton decays).
- Mutli-scale problem, provides non-trivial tests for QCD.
- Diagnostic tool for the formation of quark-gluon plasma.
- Precision determination of QCD parameters.
- No complete description of their production mechanisms.

How do we test it ?

Quarkonium production

Explores all regimes of QCD





Past Models

Color evaporation model (CEM) $Q\bar{Q} \xrightarrow{\mathcal{F}_{\mathcal{Q}}} \mathcal{Q}$

Does not predict the polarization.

No universal parameters.

Inconsistent with experiment regarding P-waves.

Color singlet model (CSM) $Q\bar{Q}(n) \xrightarrow{|\psi(0)|\delta_{n,\mathcal{Q}}} \mathcal{Q}$

Fail to predict the transverse momentum spectrum.

Uncanceled infrared divergences in P-waves.

NRQCD

NRQCD factorization

$$Q\bar{Q}(n) \xrightarrow{\langle \mathcal{O}_n^{\mathcal{Q}} \rangle} \mathcal{Q}$$

Polarization puzzle.

Spin symmetry predictions for charmonia (1S).

No complete proof of factorization theorem.

$$d\sigma(a+b \to \mathcal{Q}+X) = \sum_n d\sigma(a+b \to Q\overline{Q}(n)+X)\langle \mathcal{O}_n^{\mathcal{Q}} \rangle$$

Perturbative expansion in the strong coupling. → $d\sigma_0(1+\alpha_s C_1+\alpha_s^2 C_2+\dots)$

NRQCD Scaling Rules → $\langle \mathcal{O}(^{2S+1}L_J^{[1,8]})\rangle \sim v^{3+2L+2E+4M}$

NRQCD vs CSM

$$\langle \mathcal{O}(^{2S+1}L_J^{[1,8]}) \rangle \sim v^{3+2L+2E+4M}$$

S-waves: Leading order in the relative velocity gives CSM.

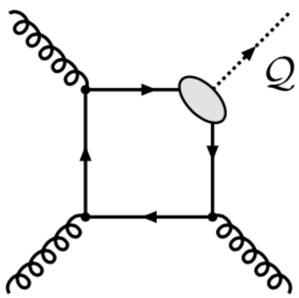
$$\langle \mathcal{O}(^3S_1^{[1]}) \rangle \sim v^3$$

P-waves: Leading order requires color-singlet and color-octet contributions.

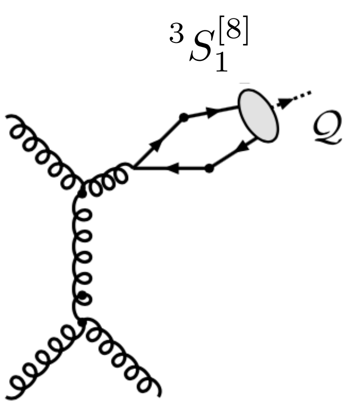
$$\langle \mathcal{O}(^3P_J^{[1]}) \rangle \sim \langle \mathcal{O}(^3S_1^{[8]}) \rangle \sim v^5$$

Cancelation of IR-divergences.

NRQCD vs CSM

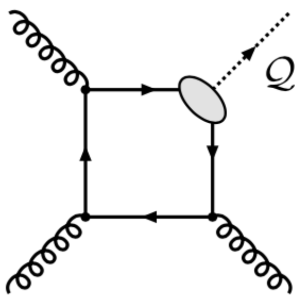


LO



LO

NRQCD vs CSM



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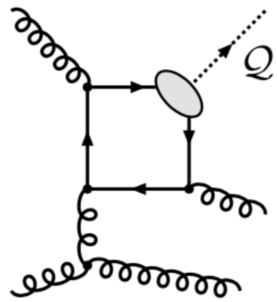
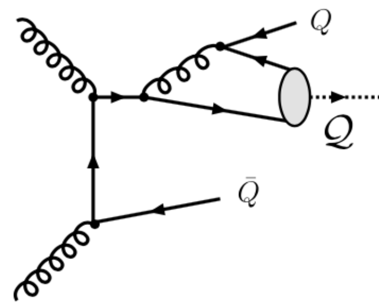
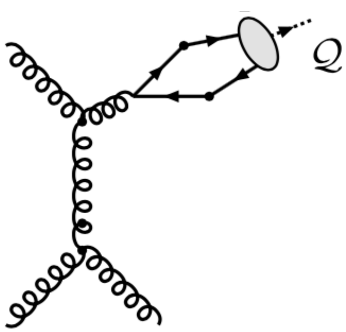


NLO



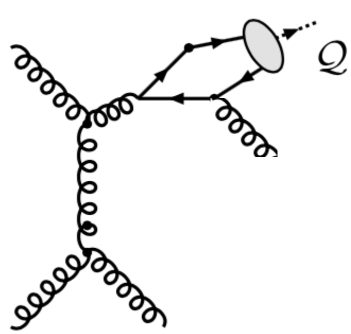
NLO

$^3S_1^{[8]}$



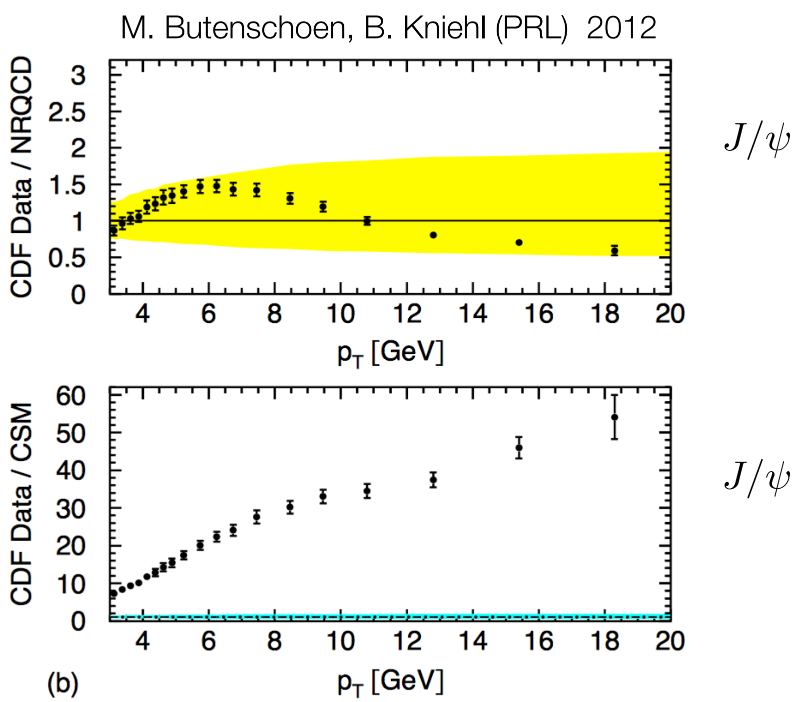
LO

$^1S_0^{[8]}$, $^3P_J^{[8]}$



NLO

NRQCD vs CSM



$$\langle \mathcal{O}(^{2S+1}L_J^{[1,8]}) \rangle \sim v^{3+2L+2E+4M}$$

S-waves: Leading order in the relative velocity gives CSM.

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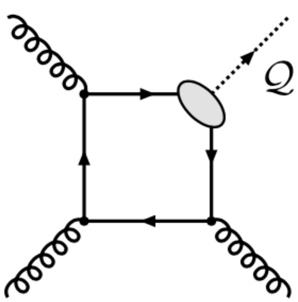
Cancelation of IR-divergences.

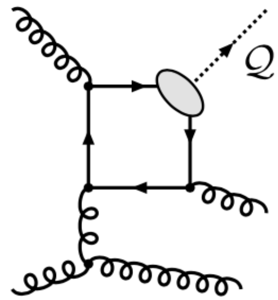
$\langle \mathcal{O}^{J/\psi}(^3S_1^{(1)}) \rangle$	$\langle \mathcal{O}^{J/\psi}(^3S_1^{(8)}) \rangle$	$\langle \mathcal{O}^{J/\psi}(^1S_0^{(8)}) \rangle$	$\langle \mathcal{O}^{J/\psi}(^3P_J^{(8)}) \rangle / m_c^2$
1.32 ± 0.2	$(2.24 \pm 0.59) \times 10^{-3}$	$(4.97 \pm 0.44) \times 10^{-2}$	$(-7.16 \pm 0.9) \times 10^{-3}$
$\sim v^3$	$\sim v^7$	$\sim v^7$	$\sim v^7$

The polarization puzzle



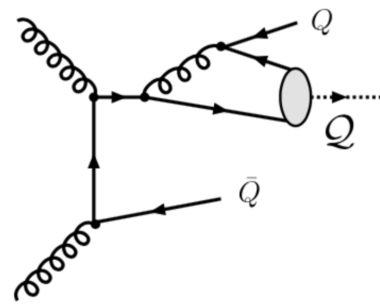
$\sim \frac{1}{p_\perp^8}$

LO



$\sim \frac{1}{p_\perp^6}$

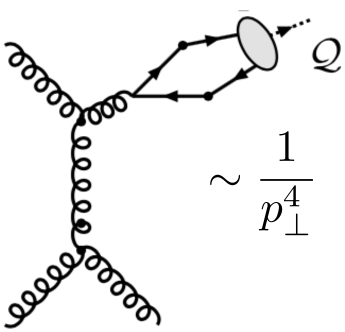
NLO



$\sim \frac{1}{p_\perp^4}$

NLO

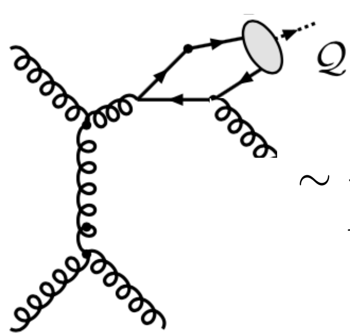
$^3S_1^{[8]}$



$\sim \frac{1}{p_\perp^4}$

LO

$^1S_0^{[8]}$, $^3P_J^{[8]}$

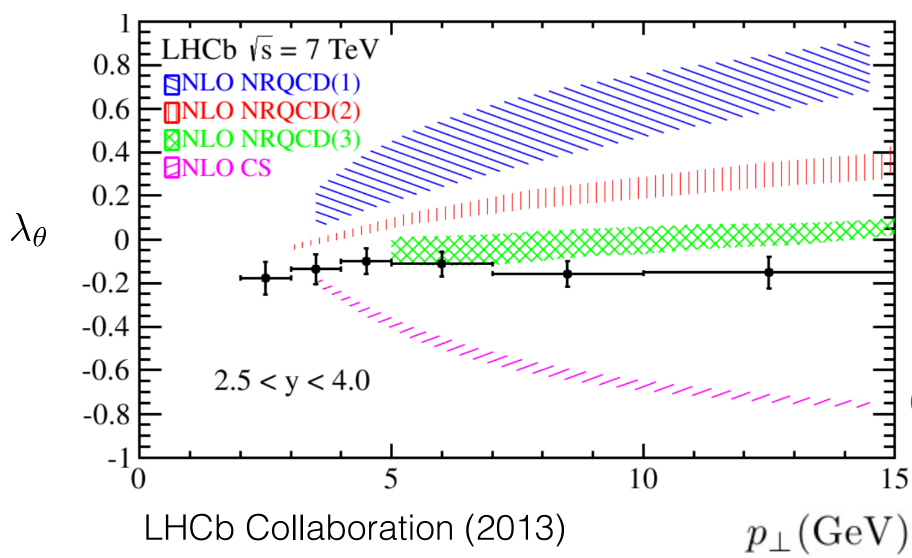


$\sim \frac{1}{p_\perp^4}$

NLO

The polarization puzzle

Transverse polarization: $\lambda_\theta = +1$ Longitudinal polarization: $\lambda_\theta = -1$



LHCb Collaboration (2013)

LDMES extracted from:

Global Fits to the wold's data

Feed-down contribution included

Simultaneous fit to pT and polarization

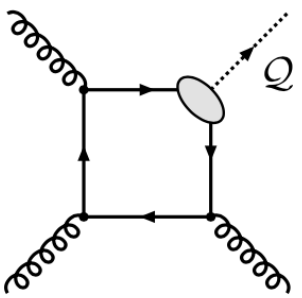
CSM@NLO

M. Butenschoen, B. Kniehl (PRL) 2012

B. Gong, L-P Wan, J-X Wang, H-F. Zhang (PRL) 2012

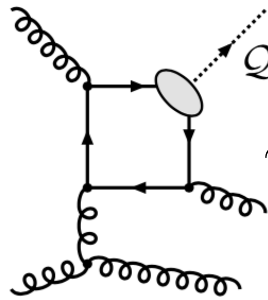
K-T. Chao, Y-Q. Ma,H-S. Shao, K. Wang, Y-J. Zhang (PRL) 2012

The polarization puzzle



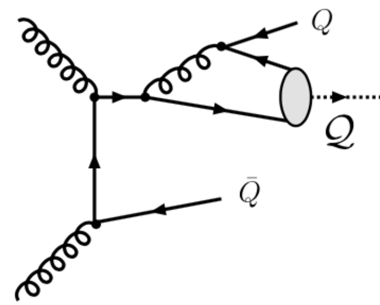
$\sim \frac{1}{p_\perp^8}$

LO



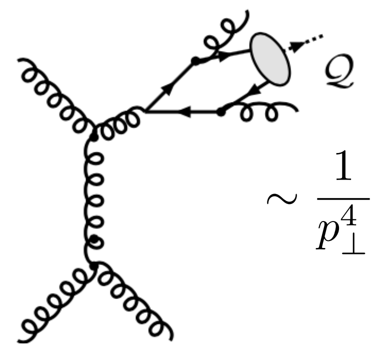
$\sim \frac{1}{p_\perp^6}$

NLO



$\sim \frac{1}{p_\perp^4}$

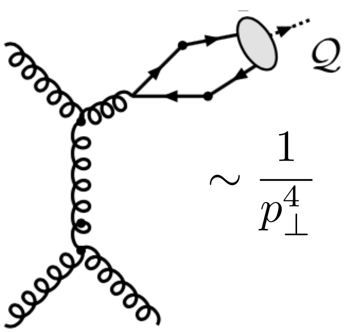
NLO



$\sim \frac{1}{p_\perp^4}$

NNLO

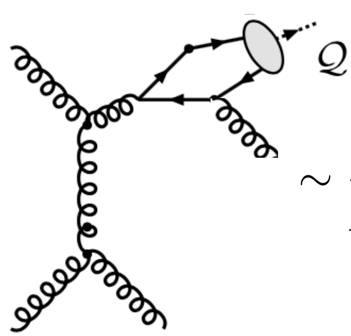
$^3S_1^{[8]}$



$\sim \frac{1}{p_\perp^4}$

LO

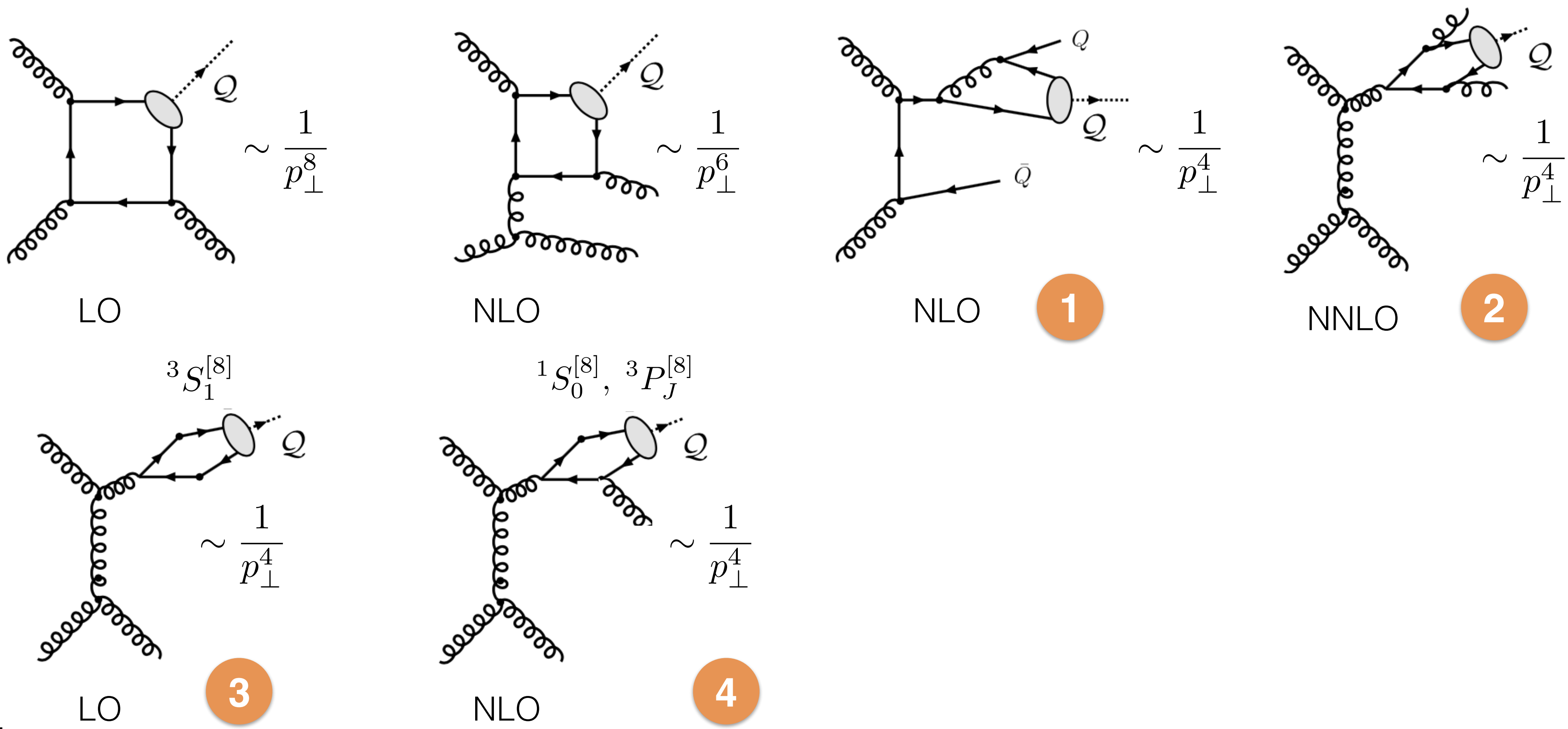
$^1S_0^{[8]}$, $^3P_J^{[8]}$



$\sim \frac{1}{p_\perp^4}$

NLO

The polarization puzzle



Leading Fragmentation

At sufficiently large pT the fragmentation processes will dominate the cross section:

For charmonium states: $\alpha_S(2m_c) \sim v^2 \sim 0.25$

Leading contributions from gluon fragmentation

2	$\langle\mathcal{O}(^3S_1^{(1)})\rangle \sim v^3,$	$d(^3S_1^{(1)}) \sim \alpha_s^3,$	$\longrightarrow$	$^3S_1^{(1)} :\sim \alpha_s^3 v^3$
3	$\langle\mathcal{O}(^3S_1^{(8)})\rangle \sim v^7,$	$d(^3S_1^{(8)}) \sim \alpha_s,$	$\longrightarrow$	$^3S_1^{(8)} :\sim \alpha_s v^7$
4	$\langle\mathcal{O}(^1S_0^{(8)})\rangle \sim v^7,$	$d(^1S_0^{(8)}) \sim \alpha_s^2,$	$\longrightarrow$	$^1S_0^{(8)} :\sim \alpha_s^2 v^7$
	$\langle\mathcal{O}(^3P_J^{(8)})\rangle \sim v^7,$	$d(^3P_J^{(8)}) \sim \alpha_s^2,$	$\longrightarrow$	$^3P_J^{(8)} :\sim \alpha_s^2 v^7$

Leading contributions from charm fragmentation

1	$\langle\mathcal{O}(^3S_1^{(1)})\rangle \sim v^3,$	$d(^3S_1^{(1)}) \sim \alpha_s^2,$	$\longrightarrow$	$^3S_1^{(1)} :\sim \alpha_s^2 v^3$

Fragmentation Functions

Leading Power (LP) Factorization

$$\frac{d\sigma_h}{dp_\perp}(p_\perp) = \sum_i \int_z^1 \frac{dx}{x} \frac{d\sigma_i}{dp_\perp}\left(\frac{p_\perp}{x}, \mu\right) D_{i/h}(x,\mu) + \mathcal{O}\left(\frac{m_h^2}{p_\perp^2}\right)$$

Expansion in: $\frac{m_Q}{p_\perp}$

DGLAP Evolution

$$\mu \frac{d}{d\mu} D_{i/h}(z,\mu) = \sum_i \int_z^1 \frac{dx}{x} P_{ij}(x) D_{i/h}\left(\frac{z}{x}, \mu\right)$$

Resummation: $\ln(p_T/m_h)$

Quarkonium production at LP

$$d\sigma(a+b\to \mathcal{Q}+X)=\sum_i d\sigma(a+b\to i+X)\otimes D_{i/\mathcal{Q}}(z)$$

$$D_{i/\mathcal{Q}}(z)=\sum_n d_n(z)\langle\mathcal{O}_n^{\mathcal{Q}}\rangle$$

E. Braaten, S.Fleming (PRL) 1994

E. Braaten, Y. Chen (PRD) 1996

G. Bodwin, E. Braaten, G. Lepage (PRD) 1997

Expansion in: $\alpha_s, \quad v, \quad \frac{m_{\mathcal{Q}}}{p_\perp}$

Quarkonium production at LP

$$d\sigma(a+b\to\mathcal{Q}+X)=\sum_i d\sigma(a+b\to i+X)\otimes D_{i/\mathcal{Q}}(z)$$

$$D_{i/\mathcal{Q}}(z)=\sum_n d_n(z)\langle\mathcal{O}_n^{\mathcal{Q}}\rangle$$

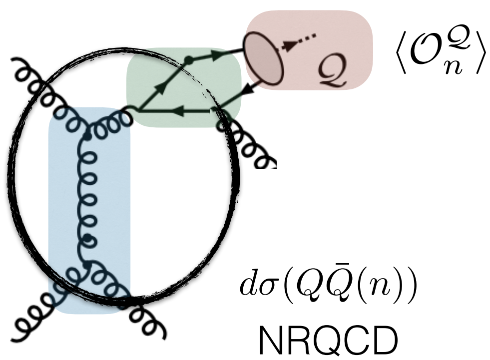
E. Braaten, S.Fleming (PRL) 1994

E. Braaten, Y. Chen (PRD) 1996

G. Bodwin, E. Braaten, G. Lepage (PRD) 1997

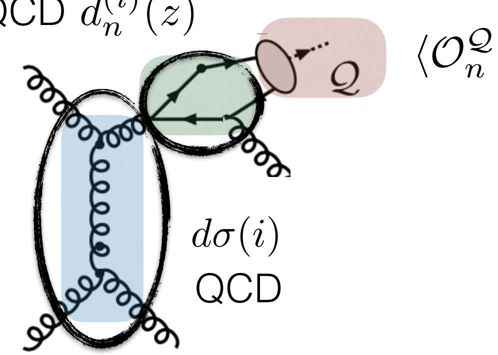
Fixed order NRQCD

$p_T \sim m_{\mathcal{Q}}$



Leading Power NRQCD

$p_T \gg m_{\mathcal{Q}}$



Quarkonium production at LP

$$D_{i/h}(z) = \sum_n d_n(z) \langle \mathcal{O}_n^h \rangle$$

Calculable in PT

Extracted from data.
Estimated size in the relative velocity scaling

For charmonium states: $\alpha_S(2m_c) \sim v^2 \sim 0.25$

Leading Order contributions from gluon fragmentation

J/ψ:

$\langle \mathcal{O}(^3S_1^{(1)}) \rangle \sim v^3,$	$d(^3S_1^{(1)}) \sim \alpha_s^3,$	$\longrightarrow$	$^3S_1^{(1)} :\sim \alpha_s^3 v^3$
$\langle \mathcal{O}(^3S_1^{(8)}) \rangle \sim v^7,$	$d(^3S_1^{(8)}) \sim \alpha_s,$	$\longrightarrow$	$^3S_1^{(8)} :\sim \alpha_s v^7$
$\langle \mathcal{O}(^1S_0^{(8)}) \rangle \sim v^7,$	$d(^1S_0^{(8)}) \sim \alpha_s^2,$	$\longrightarrow$	$^1S_0^{(8)} :\sim \alpha_s^2 v^7$
$\langle \mathcal{O}(^3P_J^{(8)}) \rangle \sim v^7,$	$d(^3P_J^{(8)}) \sim \alpha_s^2,$	$\longrightarrow$	$^3P_J^{(8)} :\sim \alpha_s^2 v^7$

Quarkonium production at LP

Fit to high transverse momenta data.

$10\ \mathrm{GeV} < p_\perp$

Use the LP factorization and DGLAP evolution to resum large logarithms.

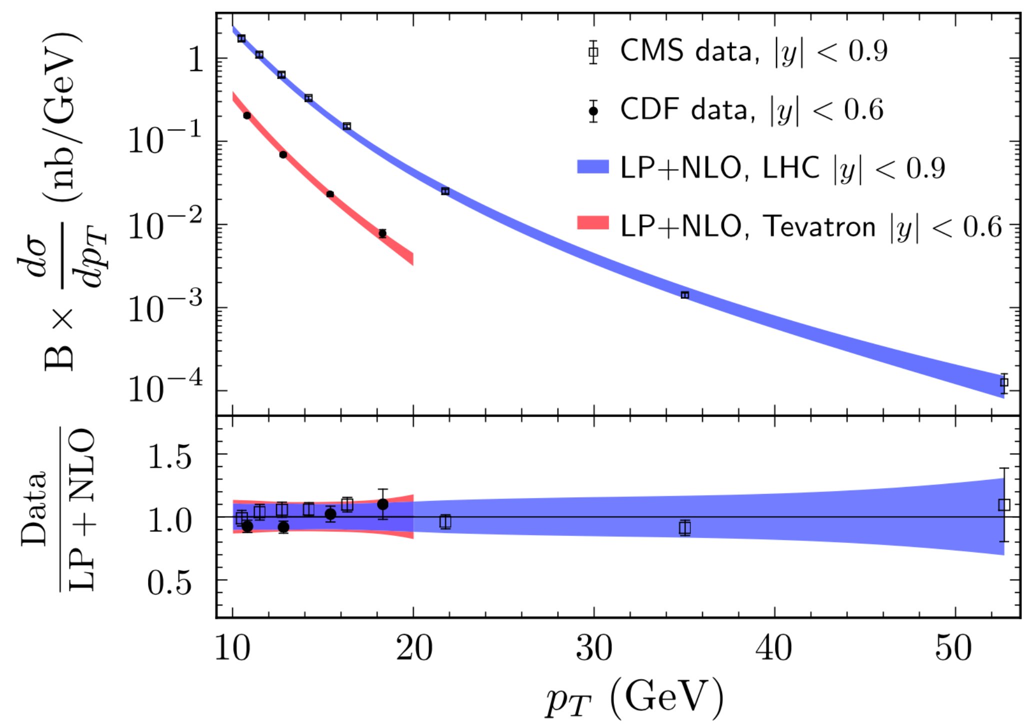
$\ln(2m_c/p_\perp)$

Includes only color-octet mechanisms.

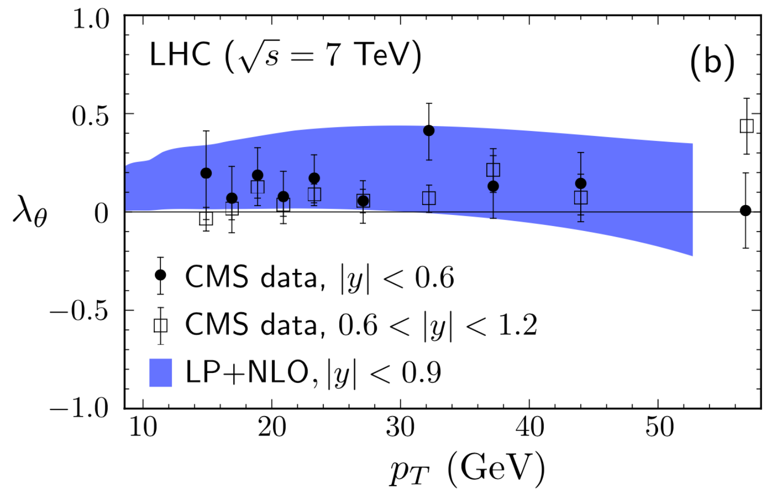
${}^3S_1^{(8)},\ {}^1S_0^{(8)},\ {}^3P_J^{(8)}$

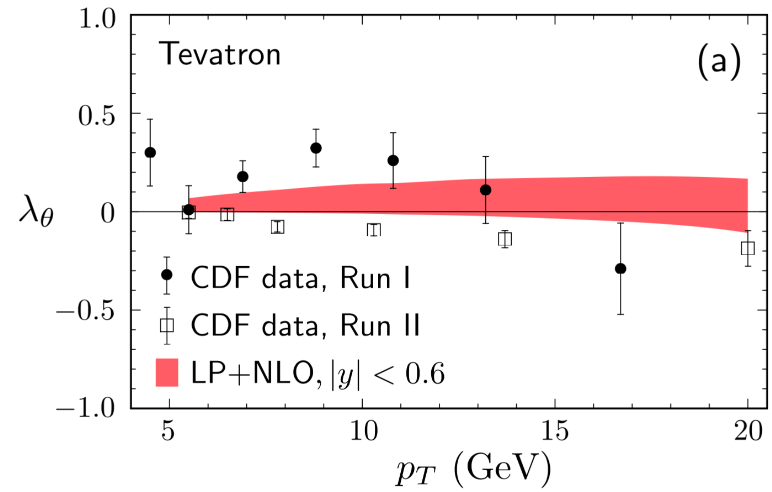
?

G. T. Bodwin, H. S. Chung, U-R. Kim, J. Lee: (PRL) 2014



Quarkonium production at LP





$\langle \mathcal{O}^{J/\psi}(^3S_1^{(1)}) \rangle$	$\langle \mathcal{O}^{J/\psi}(^3S_1^{(8)}) \rangle$	$\langle \mathcal{O}^{J/\psi}(^1S_0^{(8)}) \rangle$	$\langle \mathcal{O}^{J/\psi}(^3P_J^{(8)}) \rangle / m_c^2$
—	$(1.1 \pm 1.0) \times 10^{-2}$	$(9.9 \pm 2.2) \times 10^{-2}$	$(0.49 \pm 0.44) \times 10^{-2}$

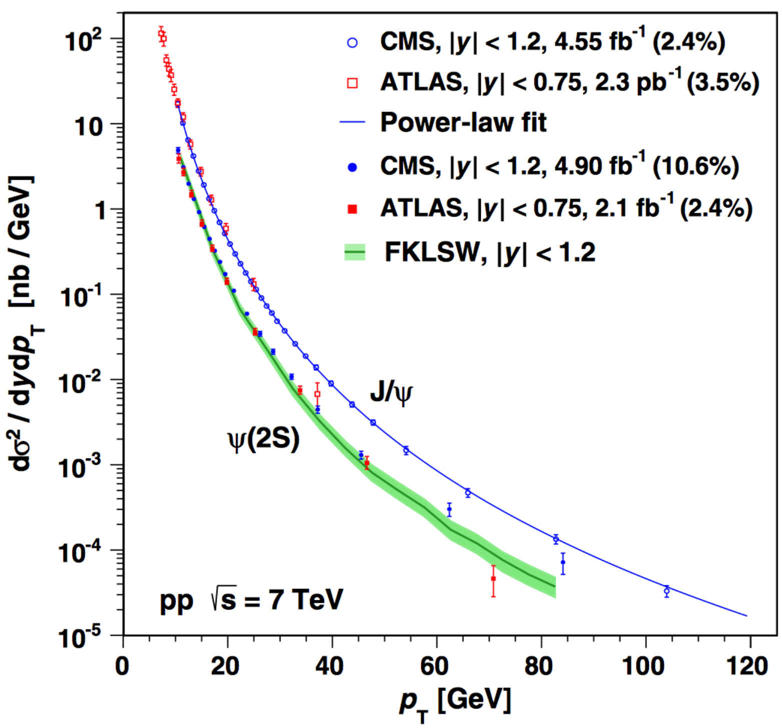
~100% uncertainty ?

~100% uncertainty ?

Geoffrey T. Bodwin, Hee Sok Chung, U-Rae Kim, Jungil Lee: (PRL) 2014

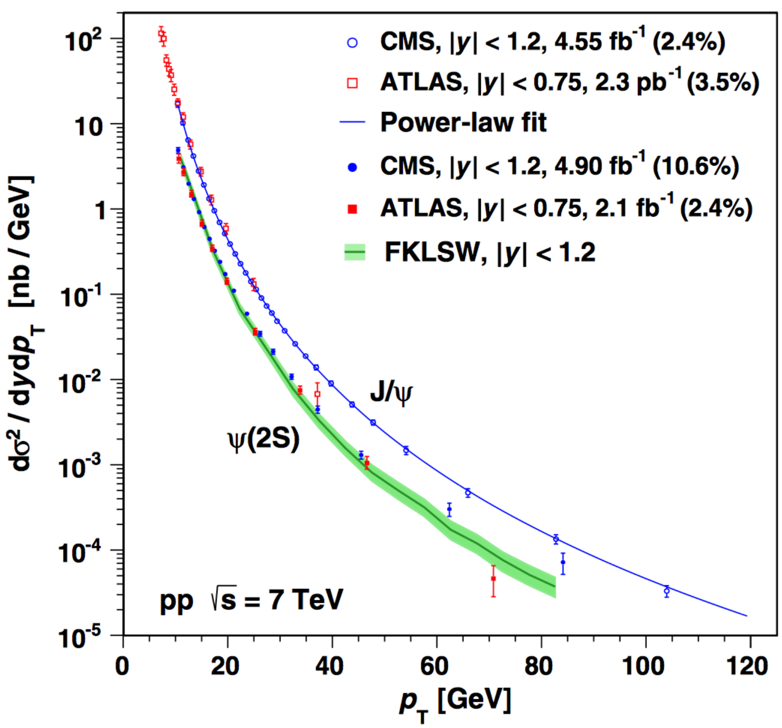
Quarkonium production at LP

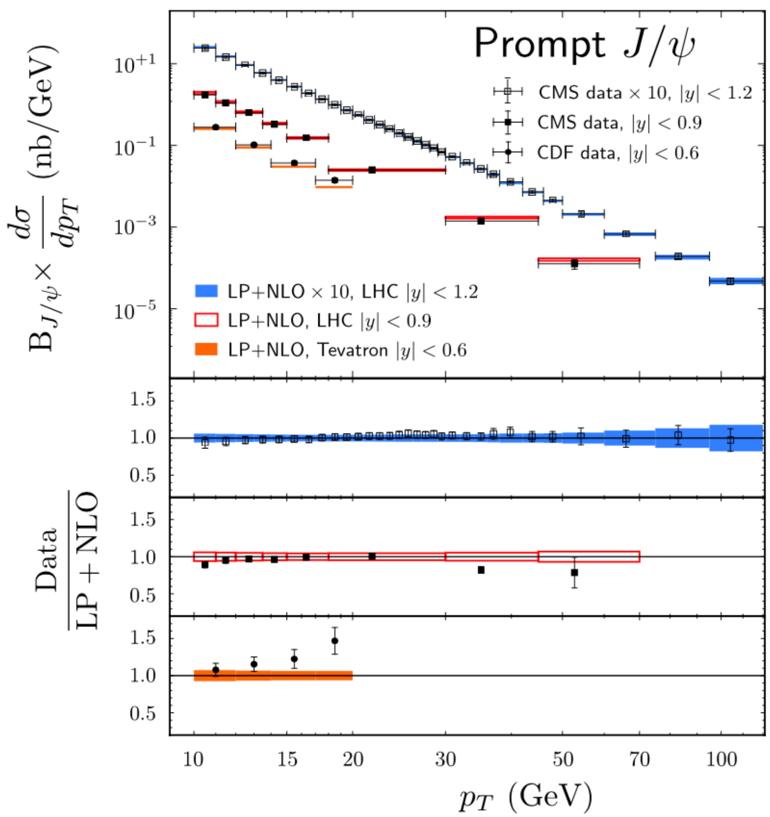
CMS Collaboration (PRL) 2016



Quarkonium production at LP

CMS Collaboration (PRL) 2015

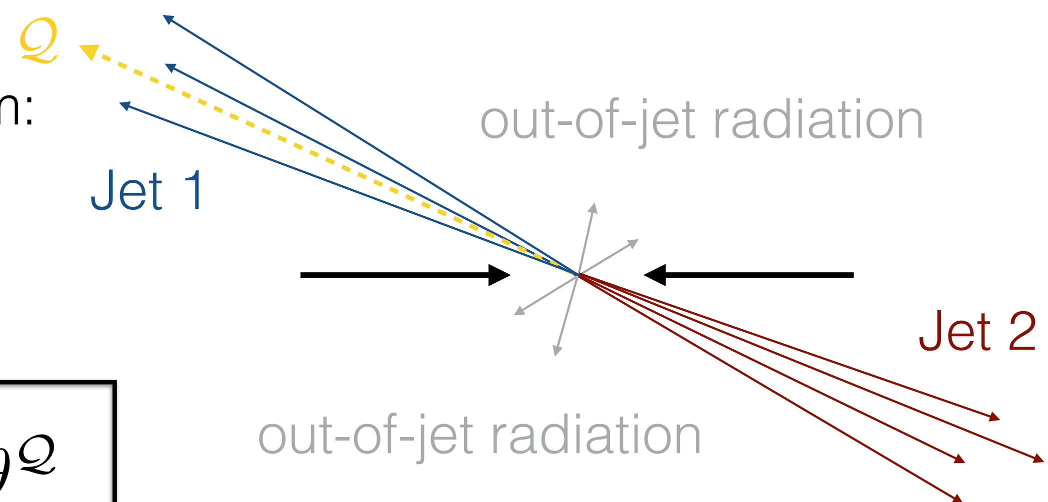




G. T. Bodwin, K-T. Chao, H. S. Chung, U-R. Kim,J. Lee, and Y-Q. Ma (PRD) 2016

Quarkonium production in jets

Jet algorithm:

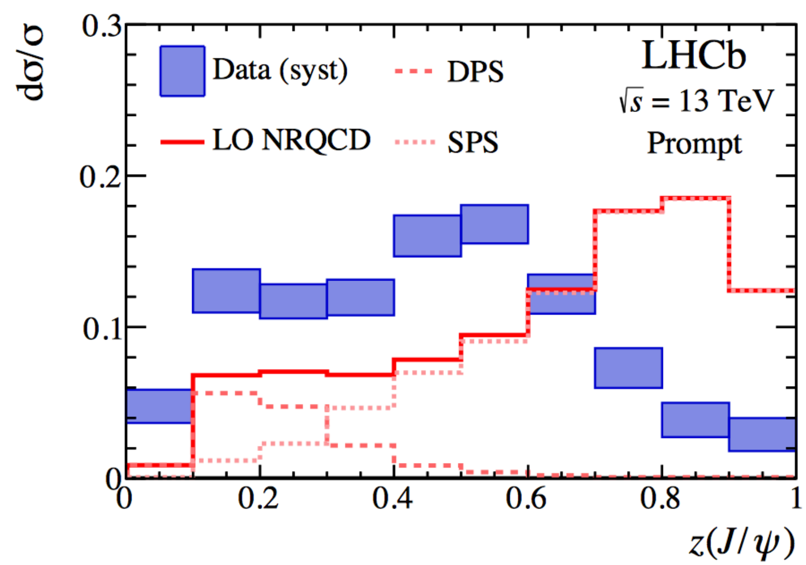


$$z = \frac{E_{\mathcal{Q}}}{E_J} \;/\; p_\perp^{\mathcal{Q}} \;/\; \theta^{\mathcal{Q}}$$

$$\tau = \sum_{i \in \mathrm{Jet}} f(p_i^\mu)$$

Quarkonium production in jets

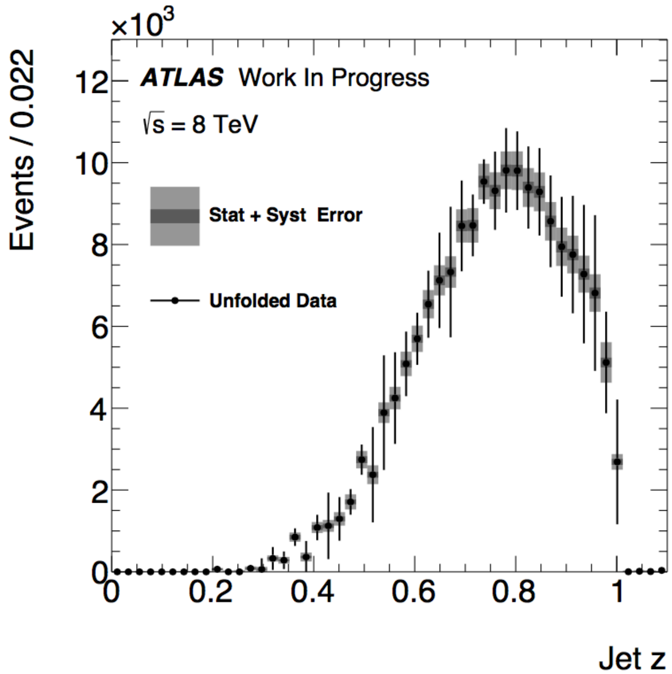
LHCb Collaboration (PRL) 2017

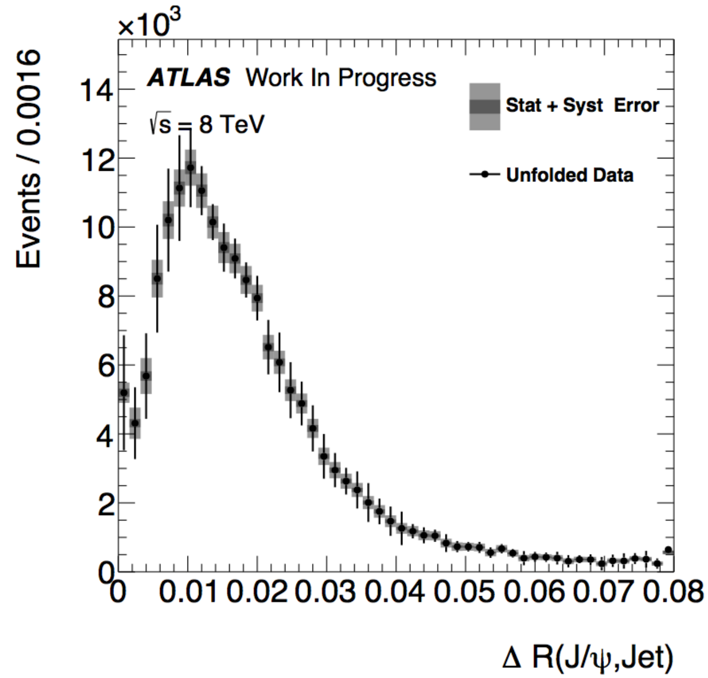


First experimental measurement of J/\psi within a jet

Quarkonium production in jets

Other experiments follow with more interesting observables

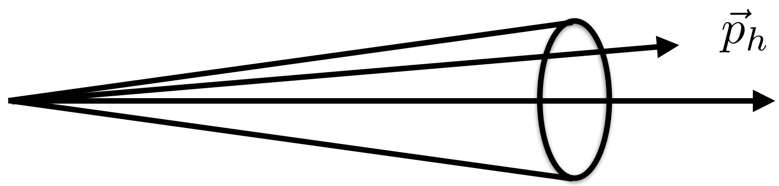




Outline

- Fragmenting Jet Functions (NLL’) vs MC
- TMD Fragmenting Jet Functions and applications (pT…)
- Compare FJF semi analytic prediction to LHCb data
- Summary

In-jet fragmentation



$\vec{k} = \frac{\omega}{2}\hat{n} \qquad s = \omega k^+$

Fragmenting Jet Function:

$$J_i(\tau,\mu) \to \mathcal{G}_{i/h}\left(z = \frac{p_h^-}{k^-}, s, \mu\right)$$

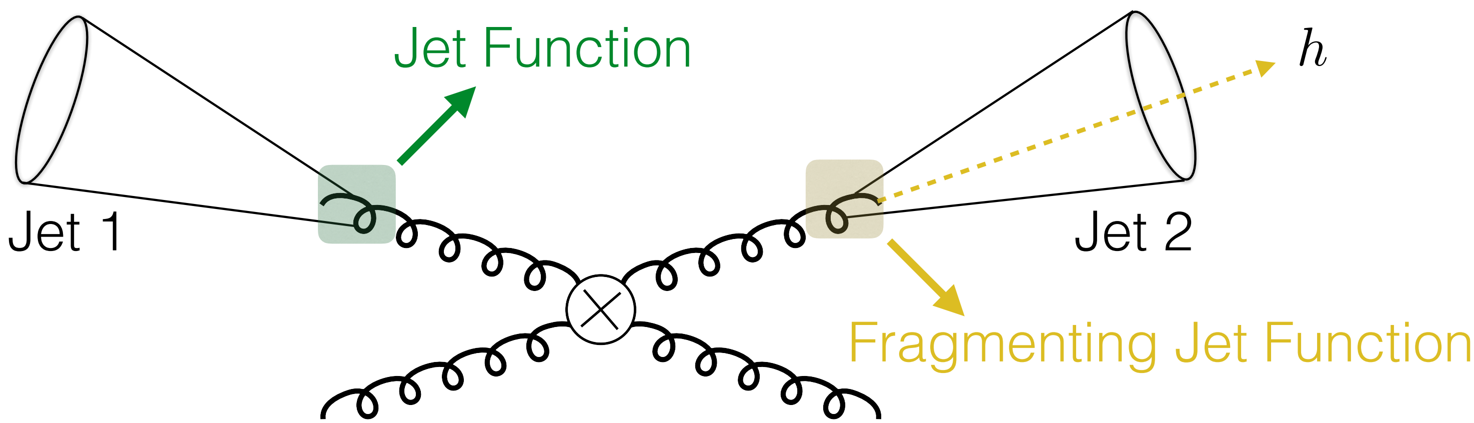
$D_{i/h}(z,\mu)$

DGLAP Evolution

$$\mathcal{G}_{i/h}\left(z,s,\mu\right) = [\mathcal{J}_{i/j}(s,\mu) \bullet D_{j/h}(\mu)](z) + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}^2}{s}\right)$$

Procura and Stewart (PRD) 2011
Procura and Waalewijn (PRD) 2012
Jain, Procura and Waalewijn (JHEP) 2011

Fragmenting Jet Functions



<u>Factorization in Soft-Collinear Effective Theory (SCET):</u>

$$d\sigma = \sum_{a,b,c,d} B_a \times B_b \times \mathrm{Tr}(\mathbf{H}_{ab}^{cd} \cdot \mathbf{S}) \times \mathcal{G}_c^{J/\psi} \times J_d$$

Angularities

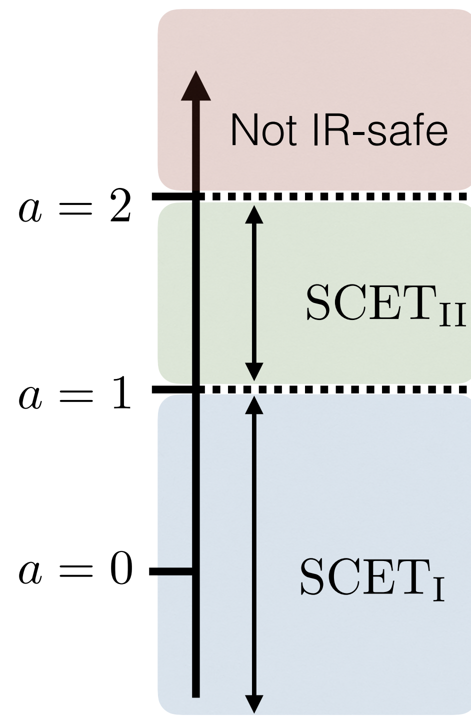
$$\tau_a = \frac{1}{\omega} \sum_{i\in \mathrm{Jet}} (p_i^+)^{1-a/2} (p_i^-)^{a/2}$$

$$\omega = \sum_{i\in \mathrm{Jet}} p_i^- \simeq 2E_{\mathrm{Jet}}$$

$\tau_2 = 1$

$\tau_1 = B = \frac{1}{\omega} \sum_{i\in \mathrm{Jet}} |\vec{p}_i^{\perp}|$ (Jet Broadening)

$\tau_0 = \tau = s/\omega^2 = m_J^2/\omega^2$ (Jet Mass)



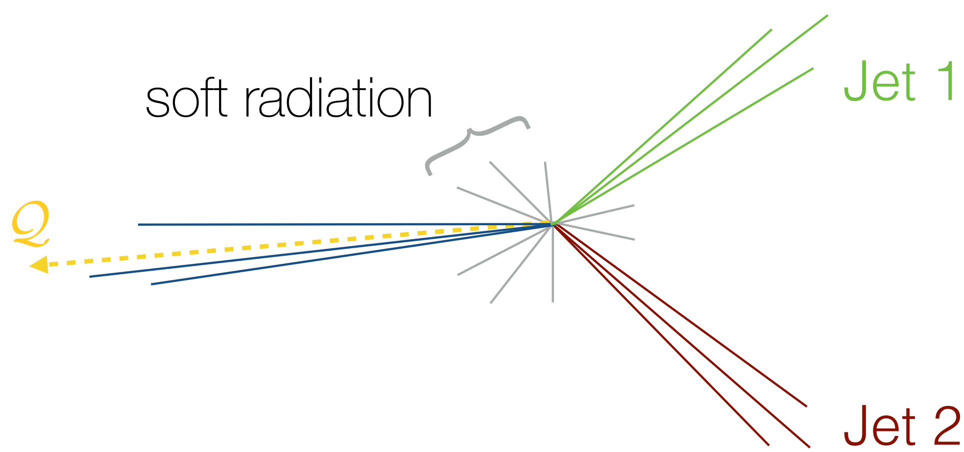
C. F. Berger, T. Kucs, and G. Sterman (PRD) 2003

Application to Quarkonium production

$$e^+ + e^- \to 3\,\text{jets}(g \to J/\psi)$$

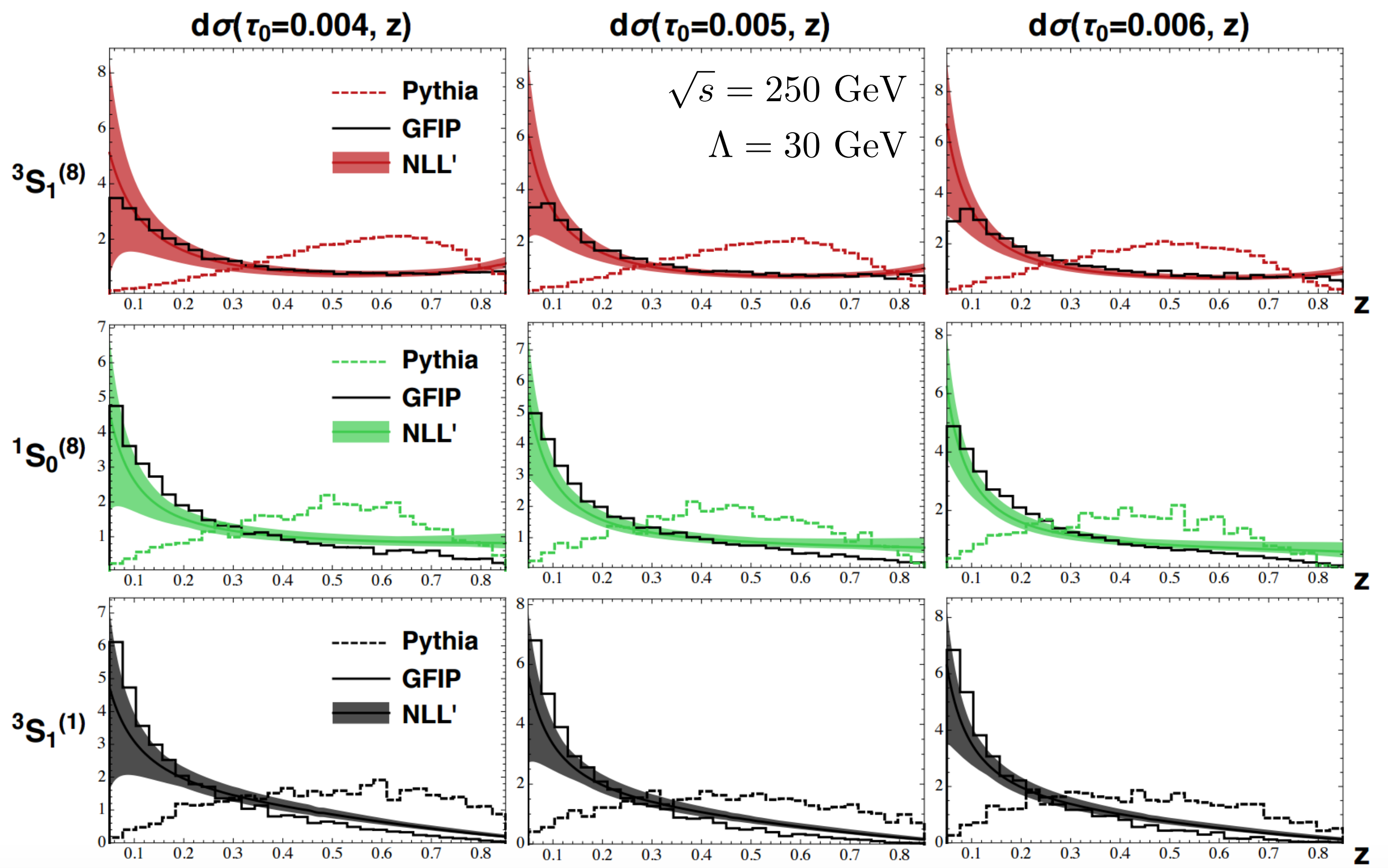
$$\frac{d\sigma^h}{dz\,d\tau_a} = \sum_n d_n(z,\tau_a)\langle \mathcal{O}_n^h \rangle$$

$$d_n(z,\tau_a) = \sigma_0 \times H_2(\mu) \times S^{\text{un}}(\mu) \times J_1(\omega_1,\mu) \times J_2(\omega_2,\mu)\left(S^{\text{ms}}(\mu) \otimes \frac{\mathcal{J}_{i/g}(z)}{2(2\pi)^3} \bullet d_n(z)\right)$$



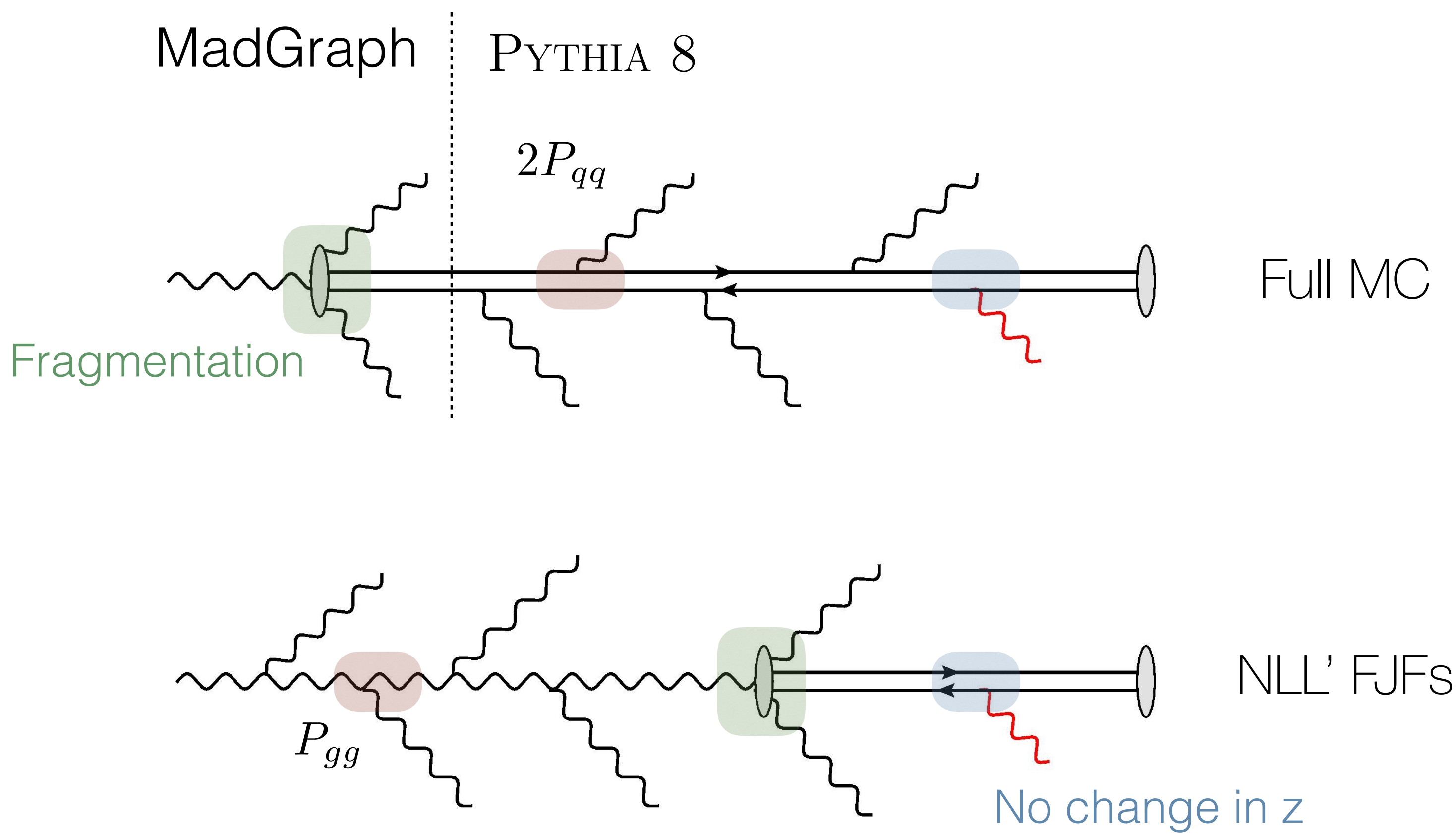
S. D. Ellis, C. K. Vermilion, J. R. Walsh, A. Hornig, and C. Lee (JHEP) 2011

Application to Quarkonium production

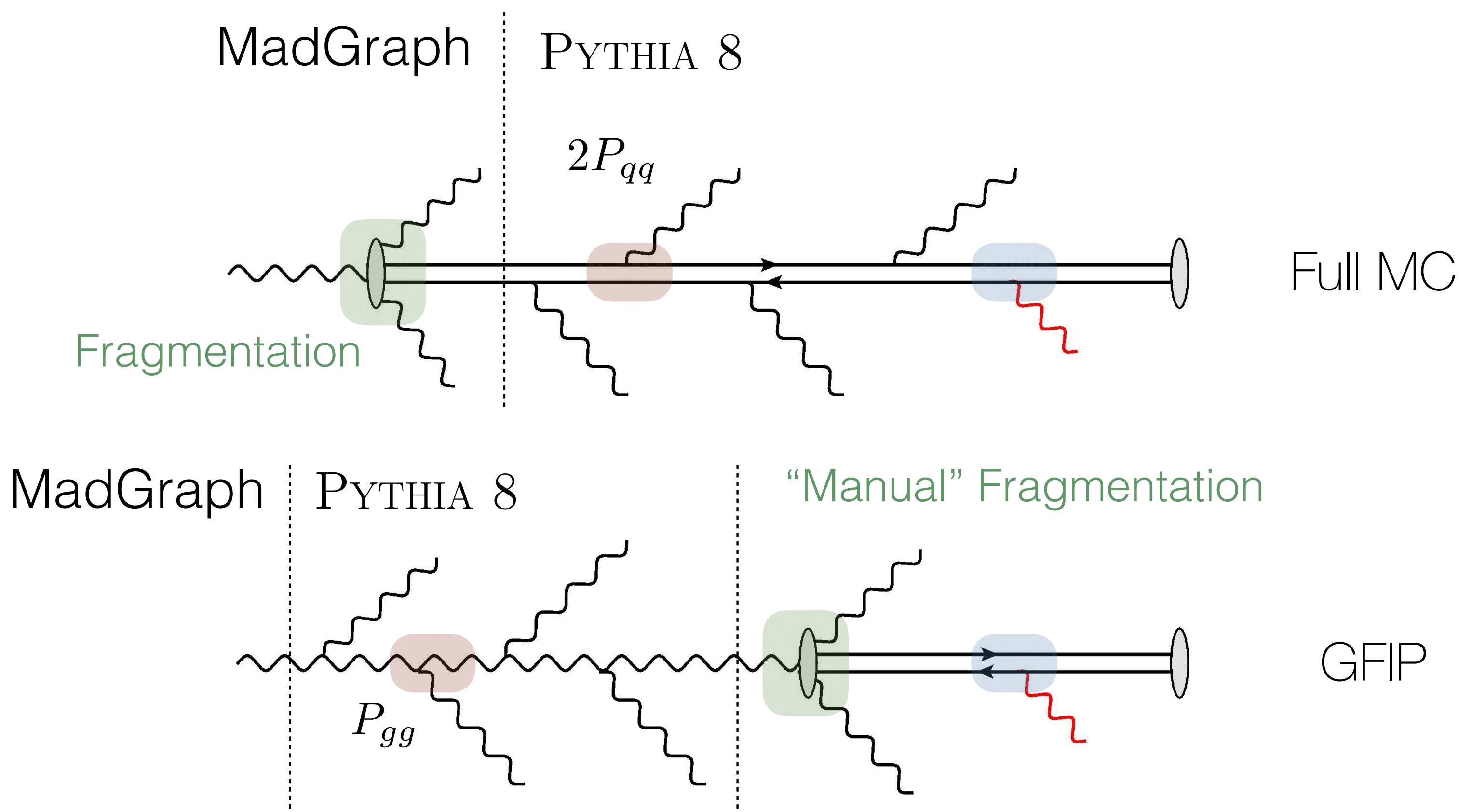


R. Bain, L. Dai, A. Hornig, A. K. Leibovich, YM, and T. Mehen (JHEP) 2016

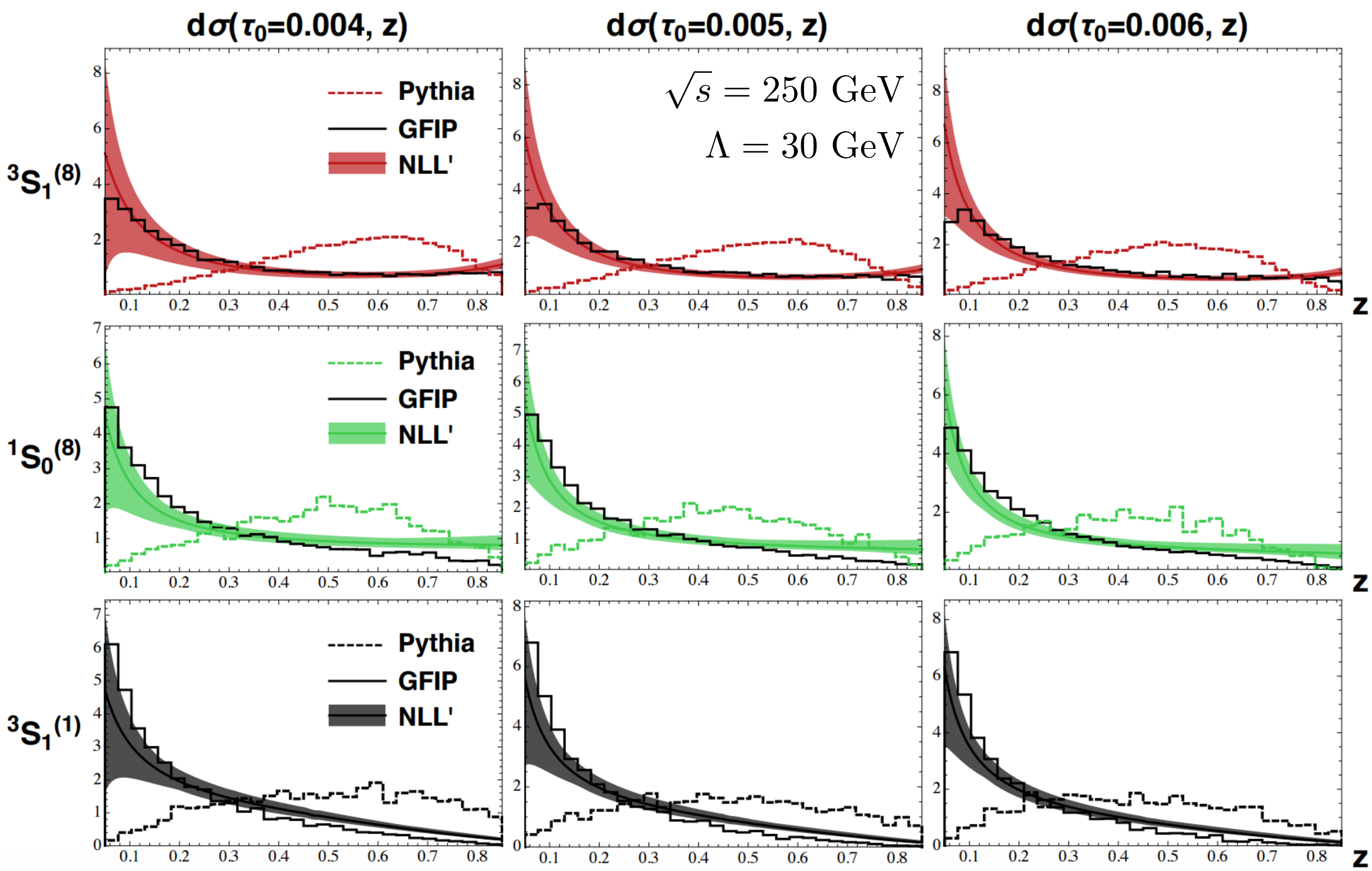
Application to Quarkonium production



Application to Quarkonium production

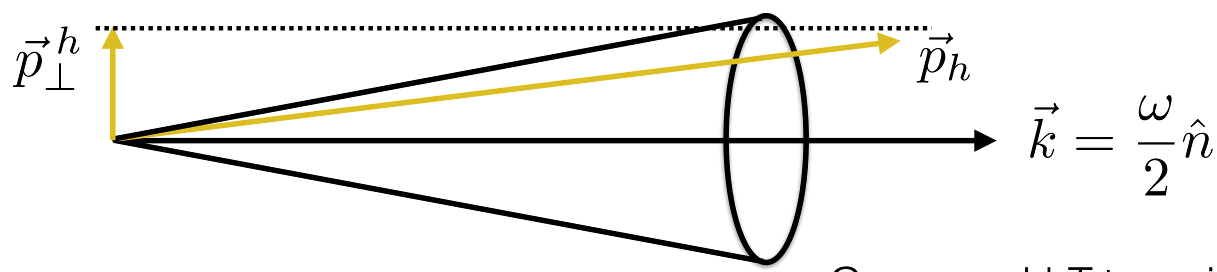


Application to Quarkonium production



R. Bain, L. Dai, A. Hornig, A. K. Leibovich, YM, and T. Mehen (JHEP) 2016

Transverse Momentum Dependent FJF



Cone and kT-type jet algorithms

$$J_i(\mu) \to D_{i/h}(\vec{p}_\perp^{\,h}, z, \mu)$$

$$D_{q/h}(\mathbf{p}_\perp, z, \mu) = \frac{1}{z}\sum_X \frac{1}{2N_c}\delta(p^-_{Xh;r})\delta^{(2)}(\mathbf{p}_\perp + \mathbf{p}_\perp^X)\,\mathrm{Tr}\left[\frac{\bar{n}\!\!\!/}{2}\langle 0|\delta_{\omega,\overline{\mathcal{P}}}\chi_n^{(0)}(0)|Xh\rangle \langle Xh|\bar{\chi}_n^{(0)}(0)|0\rangle\right]$$

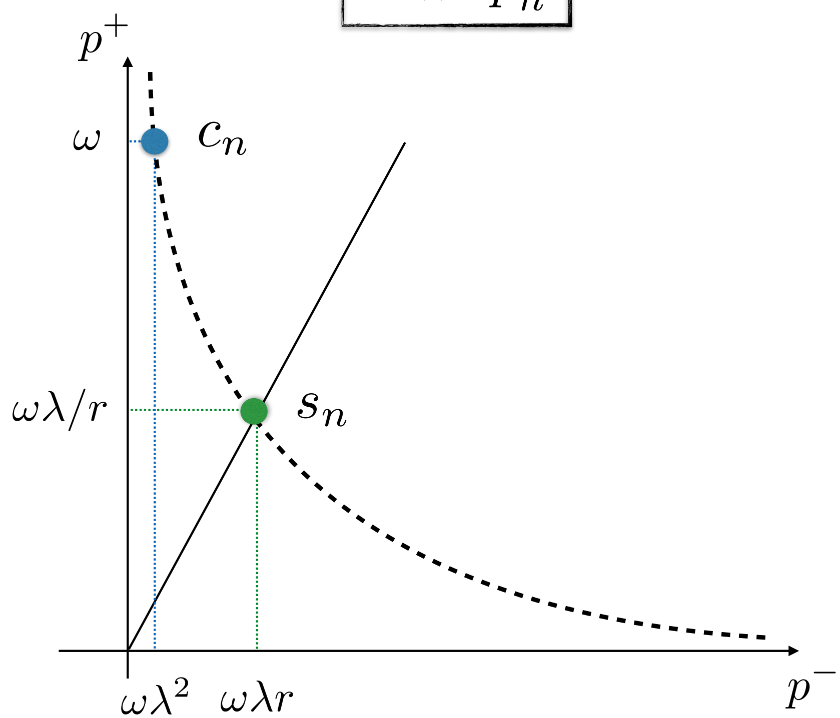
Transverse momentum measured with respect to the jet axis

Transverse momentum measured with respect to a recoil-free axis: D. Neill, I. Scimemi, and W. Waalewijn (JHEP) 2017

R. Bain, YM, and T. Mehen (JHEP) 2016

Transverse Momentum Dependent FJF

$\omega \gg p_h^\perp$



$D_{i/h}\left(z, p_h^\perp, \mu\right)$
$p_c \sim \omega(\lambda^2, 1, \lambda)$ $p_{cs} \sim p_h^\perp(r, 1/r, 1)$ $p_{us} \sim \Lambda(1, 1, 1)$
$\lambda = p_h^\perp/\omega$

Factorization

$$D_{q/h}(\mathbf{p}_\perp, z, \mu) = H_+(\mu) \times \left[\mathcal{D}_{q/h} \otimes_\perp S_C\right](\mathbf{p}_\perp, z, \mu)$$

Matching + Normalization

$$H_+(\mu) = (2\pi)^2 N_c\, C_+^\dagger(\mu) C_+(\mu)$$

Purely collinear + Fragmentation

$$\mathcal{D}_{i/h}(\mathbf{p}_\perp, z, \mu, \nu) = \int_z^1 \frac{dx}{x}\, \mathcal{J}_{i/j}(\mathbf{p}_\perp, x, \mu, \nu) D_{j/h}\left(\frac{z}{x}, \mu\right) \; + \; \mathcal{O}\left(\frac{\Lambda_{QCD}^2}{|\mathbf{p}_\perp|^2}\right)$$

Soft-Collinear radiation + Jet boundary sensitivity

$$S_C(\mathbf{p}_\perp^S) \equiv \frac{1}{N_c} \sum_{X_{cs}} \mathrm{Tr}\left[\langle 0|V_n^\dagger(0) U_n(0) \delta^{(2)}(\mathcal{P}_\perp + \mathbf{p}_\perp^S)|X_{cs}\rangle\langle X_{cs}|U_n^\dagger(0) V_n(0)|0\rangle\right]$$

Factorization

J.-Y. Chiu, A. Jain, D. Neill and I. Z. Rothstein (PRL) 2012

Rapidity Divergences:

$$V_n = \sum_{\text{perms}} \exp\left(-\frac{g\, w}{\bar{n}\cdot\mathcal{P}} \frac{|\bar{n}\cdot\mathcal{P}_g|^{-\eta/2}}{\nu^{-\eta/2}} \bar{n}\cdot A_{n,cs} \right)$$

$$S_C^R(\mathbf{p}_\perp, \mu, \nu_S) \qquad \mathcal{D}_{i/h}^R(\mathbf{p}_\perp, z, \mu, \nu_C)$$

$$W_n = \sum_{\text{perms}} \exp\left(-\frac{g\, w^2}{\bar{n}\cdot\mathcal{P}} \frac{|\bar{n}\cdot\mathcal{P}_g|^{-\eta}}{\nu^{-\eta}} \bar{n}\cdot A_{n} \right)$$

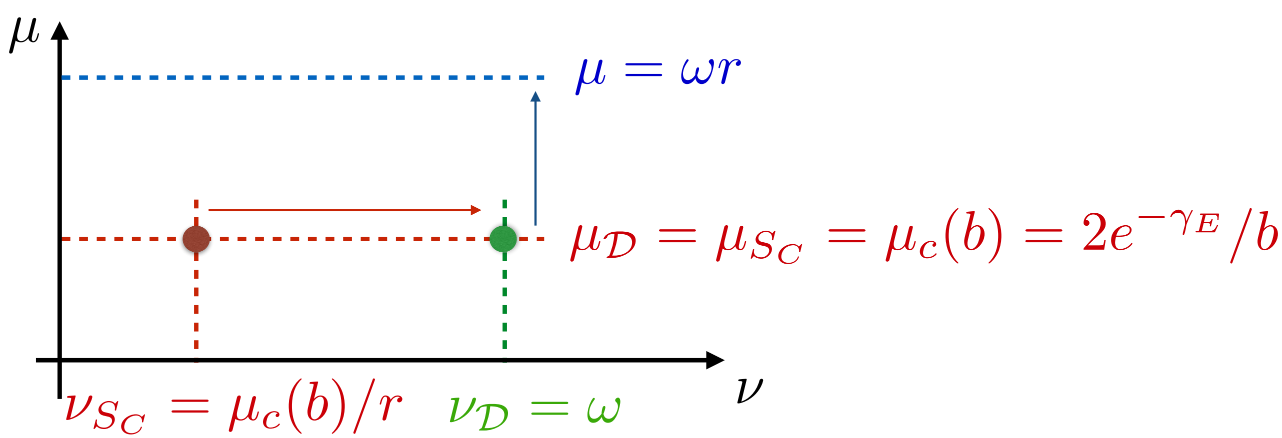
Fixed Order Result

$$\frac{\alpha_s T_{ii}}{\pi}\left[\ldots + \ln\left(\frac{\omega^2(1-z)^2}{\nu}\right) - \ln\left(\frac{\mu}{\nu r}\right) + \ldots \right]_{\nu_S=\nu_C=\nu}$$

$$\int d^{(2)}\mathbf{p}'_\perp \mathcal{D}_{i/h}^R(\mathbf{p}_\perp - \mathbf{p}'_\perp, z, \mu, \nu) S_C^R(\mathbf{p}'_\perp, \mu, \nu) = \delta^{(2)}(\mathbf{p}_\perp) D_{i/h}(z,\mu)$$
$$+ \frac{\alpha_s}{\pi}\Big\{ T_{ii} D_{i/h}(z,\mu)\Big[\ln\left(\frac{r^2\omega^2(1-z)^2}{\mu^2}\right) \mathcal{L}_0(\mathbf{p}_\perp^2, \mu^2) - \mathcal{L}_1(\mathbf{p}_\perp^2, \mu^2) - \frac{\pi^2}{24}\delta^{(2)}(\mathbf{p}_\perp)\Big]$$
$$+ f^{i/h}_{P\otimes D}(z,\mu)\mathcal{L}_0(\mathbf{p}_\perp^2, \mu^2) + f^{i/h}_{c\otimes D}(z,\mu)\delta^{(2)}(\mathbf{p}_\perp)\Big\}$$

Evolution in Fourier space

$$D_{i/h}(p_\perp, z, \mu) = (2\pi)^2\, p_\perp \int_0^\infty db\; b J_0(b p_\perp) \mathcal{U}_{S_C}(\mu, \mu_{S_C}, m_{S_C}) \mathcal{U}_{\mathcal{D}}(\mu, \mu_{\mathcal{D}}, 1)$$
$$\times\, \mathcal{V}_{S_C}(b, \mu_{S_C}, \nu_{\mathcal{D}}, \nu_{S_C}) \mathcal{FT}\Big[\mathcal{D}_{i/h}(\mathbf{p}_\perp, z, \mu_{\mathcal{D}}, \nu_{\mathcal{D}}) \otimes_\perp S_C^i(\mathbf{p}_\perp, \mu_{S_C}, \nu_{S_C})\Big]$$



Anomalous dimensions

Renormalization Group (RG)

$$\gamma_\mu^{S_C}(\nu) = \frac{\alpha_s C_i}{\pi} \ln\left(\frac{\mu^2}{r^2\nu^2}\right)$$

$$\gamma_\mu^{\mathcal{D}}(\nu) = \frac{\alpha_s C_i}{\pi}\left(\ln\left(\frac{\nu^2}{\omega^2}\right) + \bar{\gamma}_i\right)$$

$$\gamma_\mu^{\mathcal{D}}(\nu) + \gamma_\mu^{S_C}(\nu) = \gamma_\mu^J = \frac{\alpha_s C_i}{\pi}\left(\ln\left(\frac{\mu^2}{r^2\omega^2}\right) + \bar{\gamma}_i\right)$$

Rapidity Renormalization Group (RRG)

$$\gamma_\nu^{S_C}(p_\perp, \mu) = +(8\pi)\alpha_s C_i\, \mathcal{L}_0(\mathbf{p}_\perp, \mu^2)$$

$$\gamma_\nu^{\mathcal{D}}(p_\perp, \mu) = -(8\pi)\alpha_s C_i\, \mathcal{L}_0(\mathbf{p}_\perp, \mu^2)$$

$$\gamma_\nu^{\mathcal{D}}(\mathbf{p}_\perp, \mu) + \gamma_\nu^{S}(\mathbf{p}_\perp, \mu) = 0$$

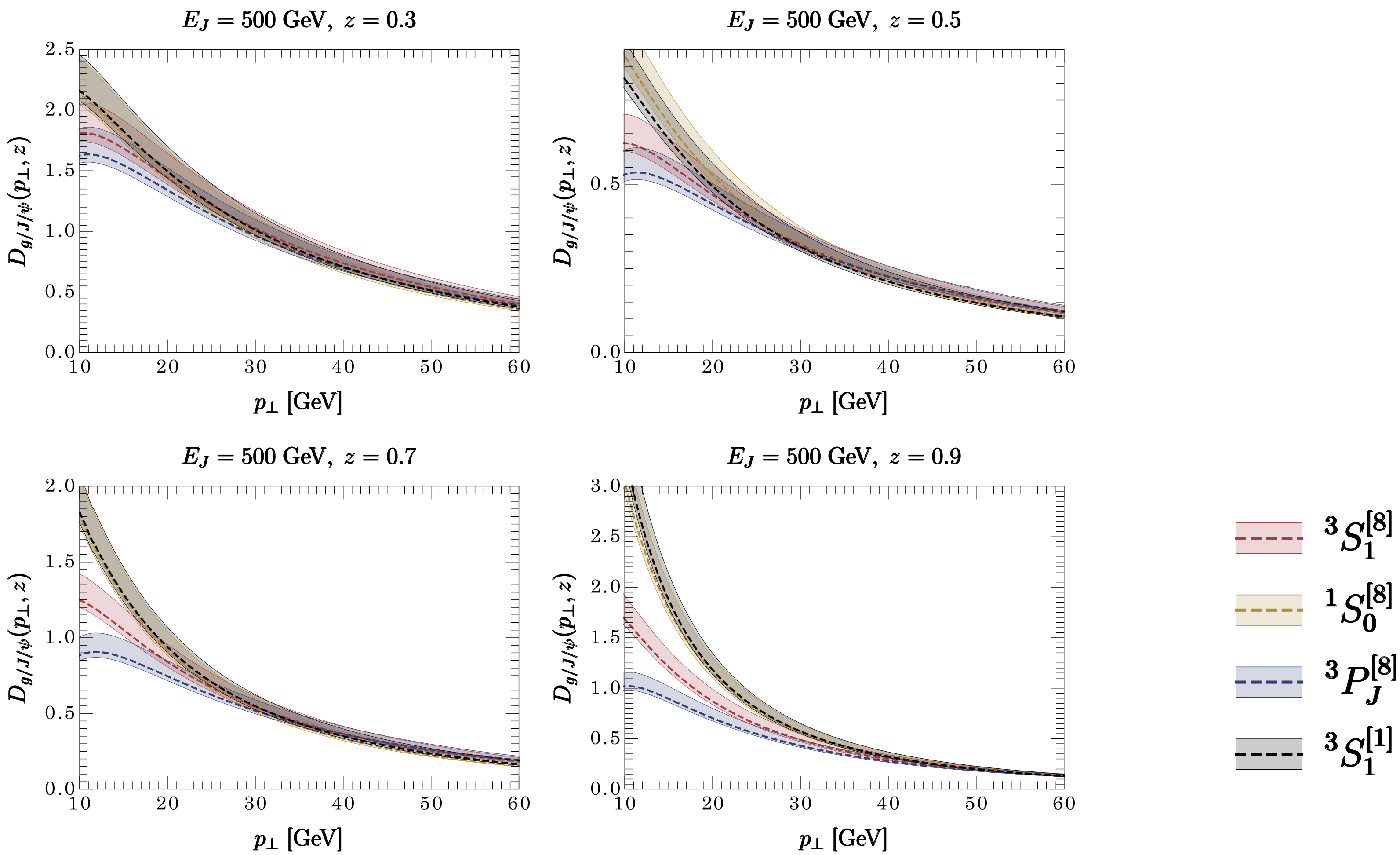
TMDFJF + NRQCD Fragmentation Functions

$$D_{i/h}(z) = \sum_n d_n(z)\langle \mathcal{O}_n^h \rangle$$

DGLAP evolution

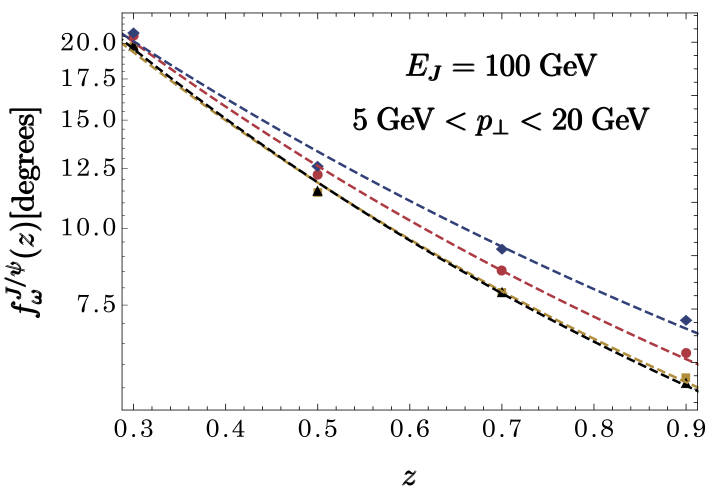
$$\mathcal{D}_{i/h}(\mathbf{p}_\perp, z, \mu, \nu) = \int_z^1 \frac{dx}{x}\, \mathcal{J}_{i/j}(\mathbf{p}_\perp, x, \mu, \nu) D_{j/h}\left(\frac{z}{x}, \mu\right) \; + \; \mathcal{O}\left(\frac{\Lambda_{QCD}^2}{|\mathbf{p}_\perp|^2}\right)$$

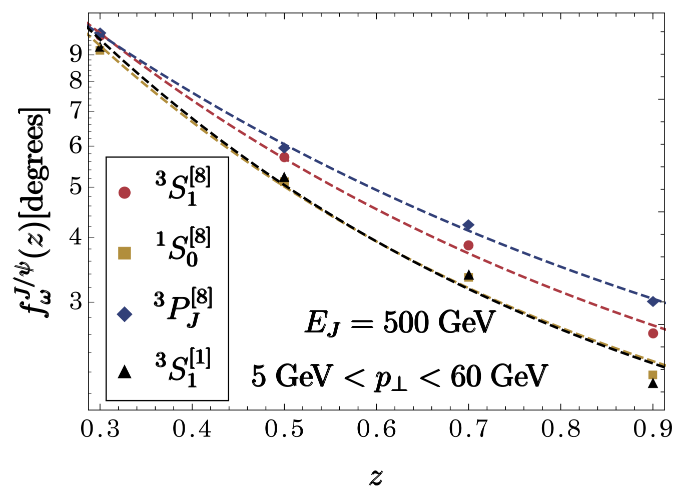
Application to Quarkonium production



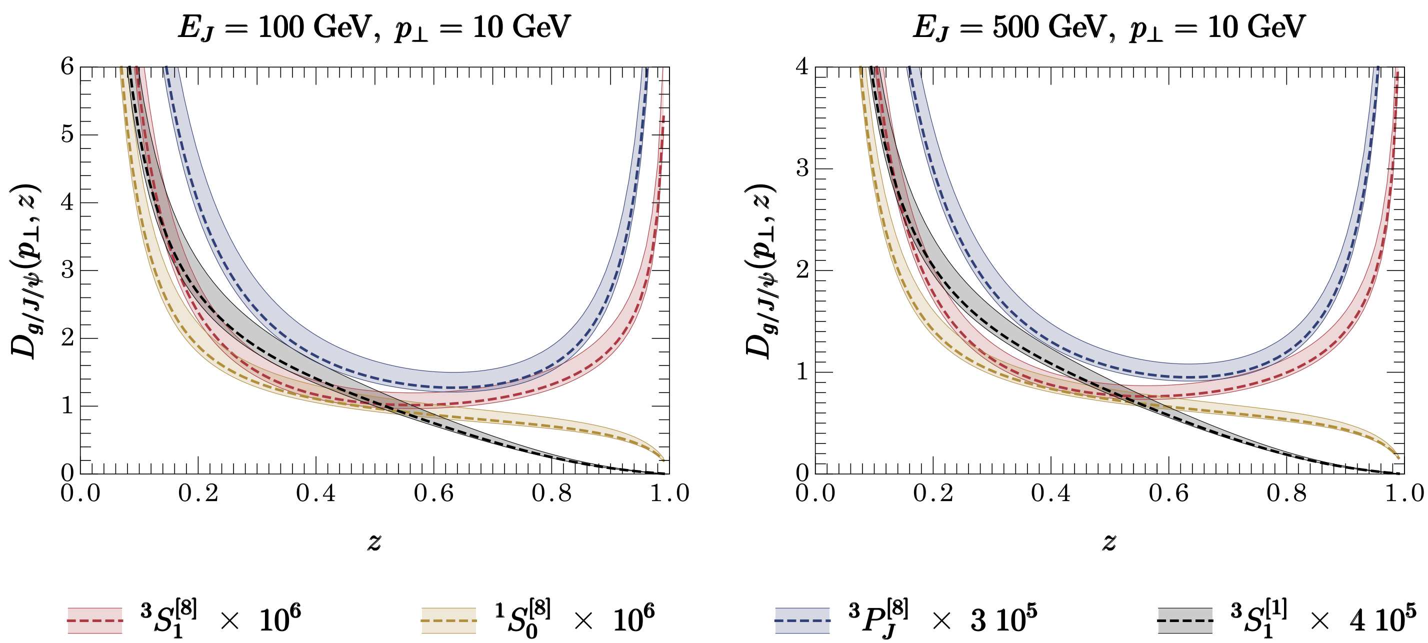
Application to Quarkonium production

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



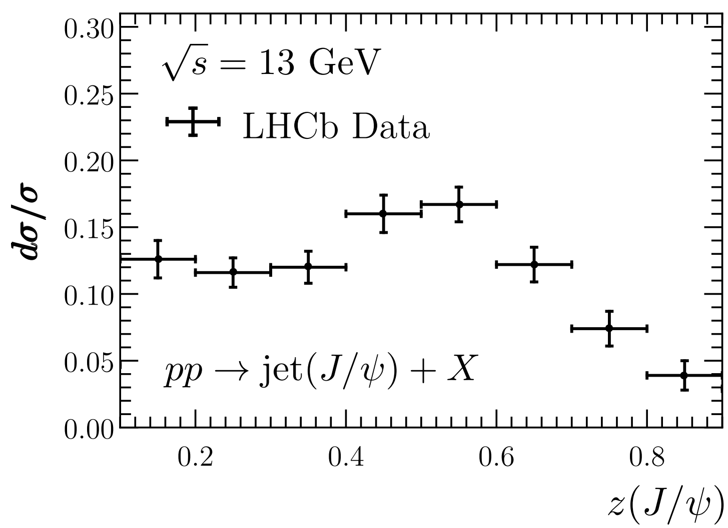


Application to Quarkonium production



Quarkonium production in jets at LHC

Quarkonium in jet (LHCb)



Experimental cuts:

$p_{\rm jet}^{\perp} > 20$ GeV

$E_\mu > 5$ GeV

$2.5 < \eta_{J\psi} < 4.5$

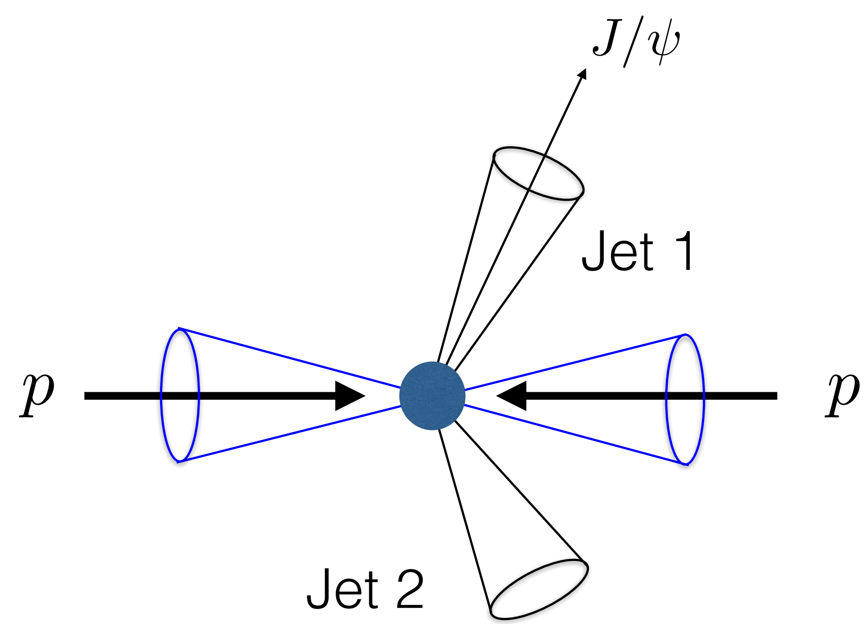
$2.0 < \eta_{jet} < 4.0$

$2.5 < \eta_\mu < 4.5$

Quarkonium production in jets at LHC

<u>Di-jet production</u>

$pp \to 2\ \text{jets}(J/\psi)$

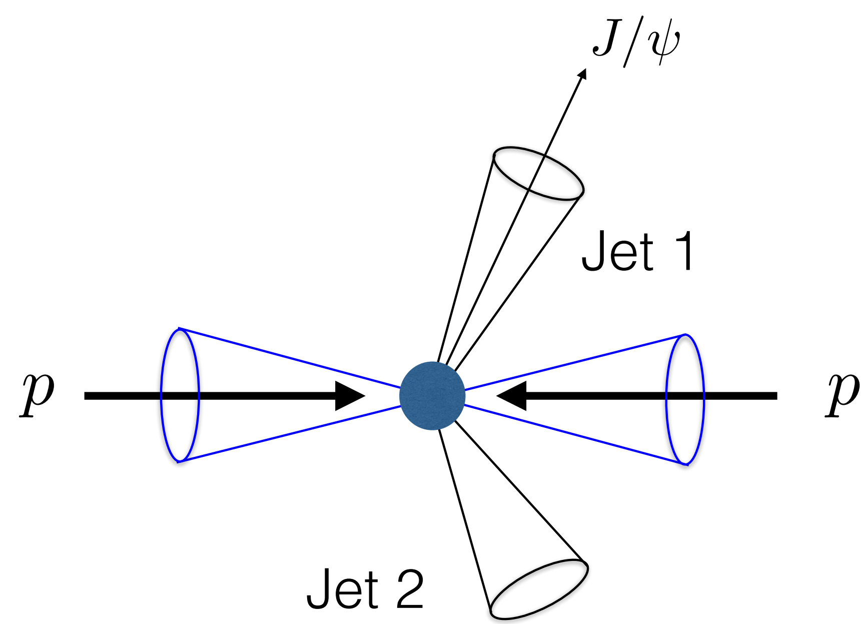


$$d\sigma = \sum_{a,b,c,d} B_a \times B_b \times \mathrm{Tr}(\mathbf{H}_{ab}^{cd} \cdot \mathbf{S}) \times \mathcal{G}_c^{J/\psi} \times J_d$$

Quarkonium production in jets at LHC

Di-jet production

$pp \to 2\ \mathrm{jets}(J/\psi)$

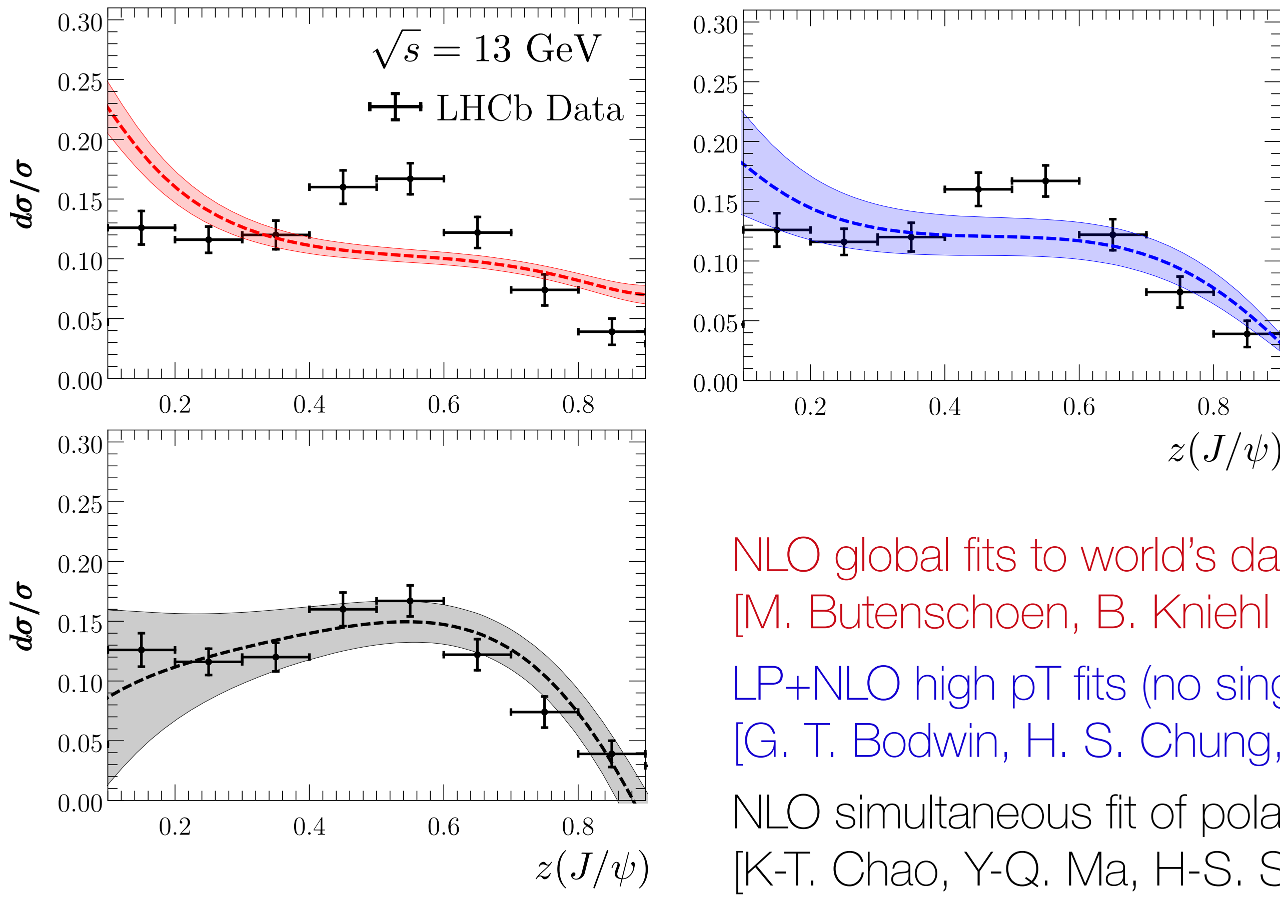


$$\frac{d\sigma}{dz}(pp \to \mathrm{jet}(J/\psi) + X) \sim \sum_i \int dE \frac{d\hat{\sigma}^{(i)\mathrm{LO}}}{dE}(E) \times \mathcal{G}_{i\to J/\psi}(z, \mu = 2E\tan(R/2))$$

Discretize and evaluate using monte-carlo integration methods (MadGraph package)

Quarkonium production in jets at LHC

R. Bain, L. Dai, A. K. Leibovich, YM, and T. Mehen (PRL) 2017



NLO global fits to world's data
[M. Butenschoen, B. Kniehl (PRL) 2012]

LP+NLO high pT fits (no singlet)
[G. T. Bodwin, H. S. Chung, U-R. Kim, J. Lee: (PRL) 2014]

NLO simultaneous fit of polarization and pT at high pT
[K-T. Chao, Y-Q. Ma, H-S. Shao, K. Wang, Y-J. Zhang (PRL) 2012]

Backup Slides

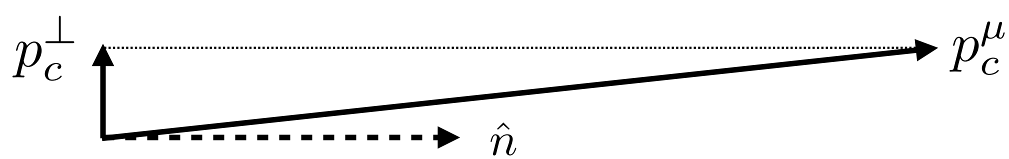
SCET Framework - Notation

$$n \cdot \bar{n} = 2, \quad p^- = \bar{n} \cdot p, \quad p^+ = n \cdot p$$

$$\bar{n}^\mu = (1, 0, 0, -1)$$

$$n^\mu = (1, 0, 0, +1)$$

$$p^\mu = p^- \frac{n^\mu}{2} + p^+ \frac{\bar{n}^\mu}{2} + p_\perp^\mu = (p^+, p^-, p_\perp)$$



$$p_c^- = 2E(1 + \mathcal{O}(\lambda^2)) \qquad \lambda = p_\perp / E \quad \rightarrow \quad p_c^\mu \sim \omega(\lambda^2, 1, \lambda)$$

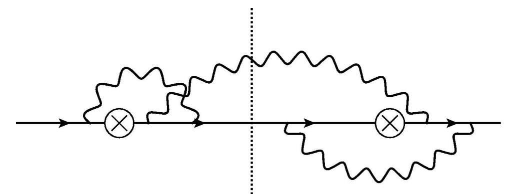
$$p_s^\mu \sim \omega(\lambda^\alpha, \lambda^\alpha, \lambda^\alpha)$$

$\alpha = 1$ soft

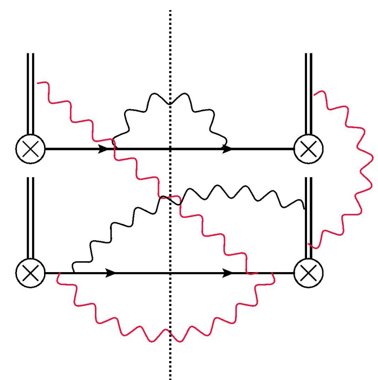
$\alpha = 2$ ultra-soft

SCET Framework - Notation

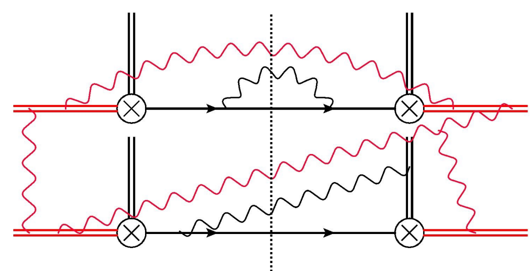
$$\frac{\mathcal{L}_{\rm QCD}(\psi, A^a_\mu)}{\bar\psi\gamma^\mu\psi}$$



$$\frac{\mathcal{L}_{\rm SCET}(\chi, A^a_{\mu,n}, A^a_{\mu,s})}{\bar\chi_{n_1}\gamma^\mu\chi_{n_2}}$$



$$\frac{\mathcal{L}_{us}(A^a_{\mu,s}) + \sum_n \mathcal{L}^{(0)}_n(\chi_n, A^a_{\mu,n})}{(\bar\chi^{(0)}_{n_1} Y^\dagger_{n_1})\gamma^\mu(Y_{n_2}\chi^{(0)}_{n_2})}$$



Scaling rules

$$\mathcal{O}_n^{\mathcal{Q}} = \mathcal{O}_2^{n\,\dagger} \left(\sum_X |X + \mathcal{Q}\rangle\langle X + \mathcal{Q}| \right) \mathcal{O}_2^n \qquad \mathcal{O}_2^n = \psi^\dagger \mathcal{K}^n \chi$$

P-waves involve: $\mathcal{K}^P \sim \mathbf{D} \sim v$

Leading chromo-electric transitions: $g\mathbf{A} \cdot \boldsymbol{\partial} \sim v$

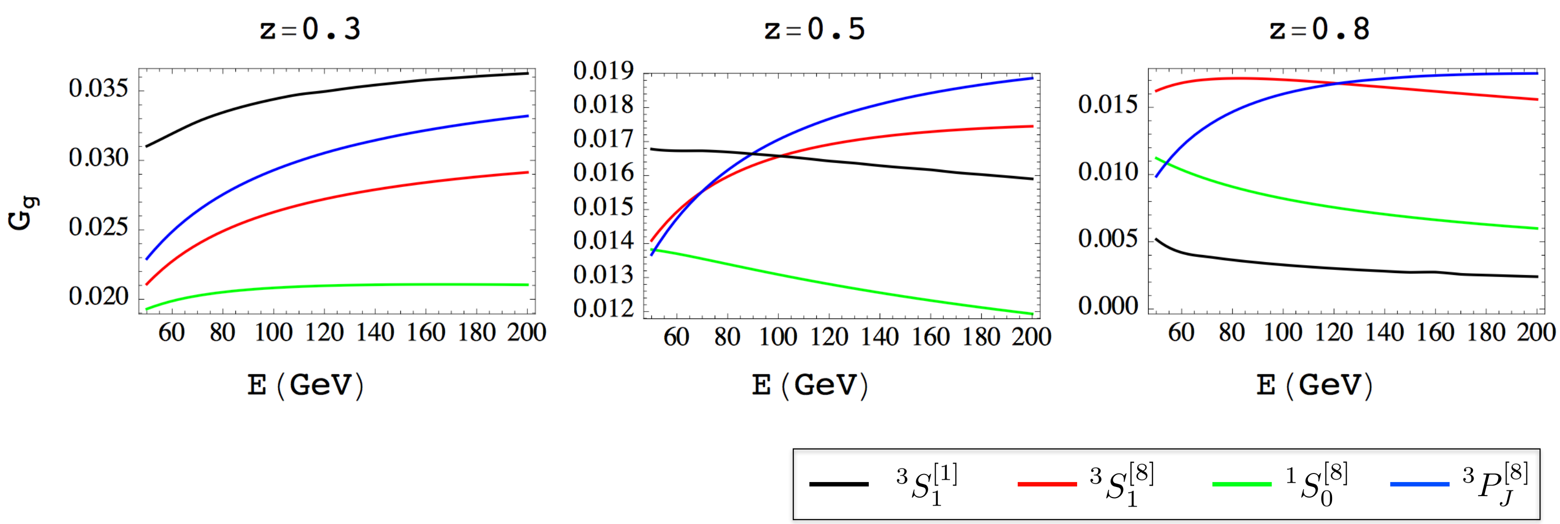
$(\Delta L = \pm 1,\ \Delta S = 0)$

Leading chromo-magnetic transitions: $g\mathbf{B} \cdot \boldsymbol{\sigma} \sim v^2$

$(\Delta L = 0,\ \Delta S = \pm 1)$

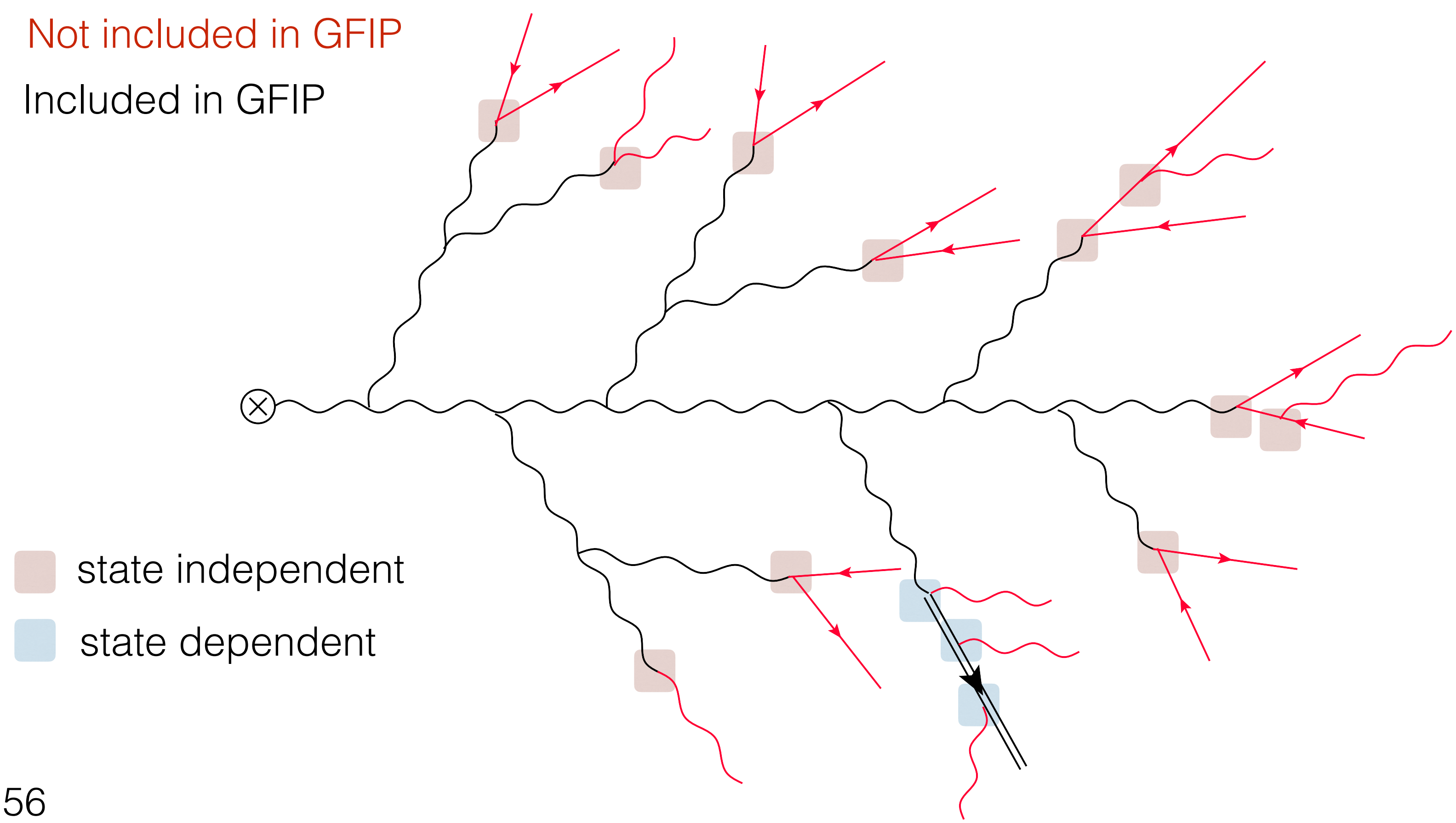
Fragmenting Jet Functions

Cone Jets: $R = 0.4$ Gluon fragmentation: $\mu = 2E\tan(R/2)$

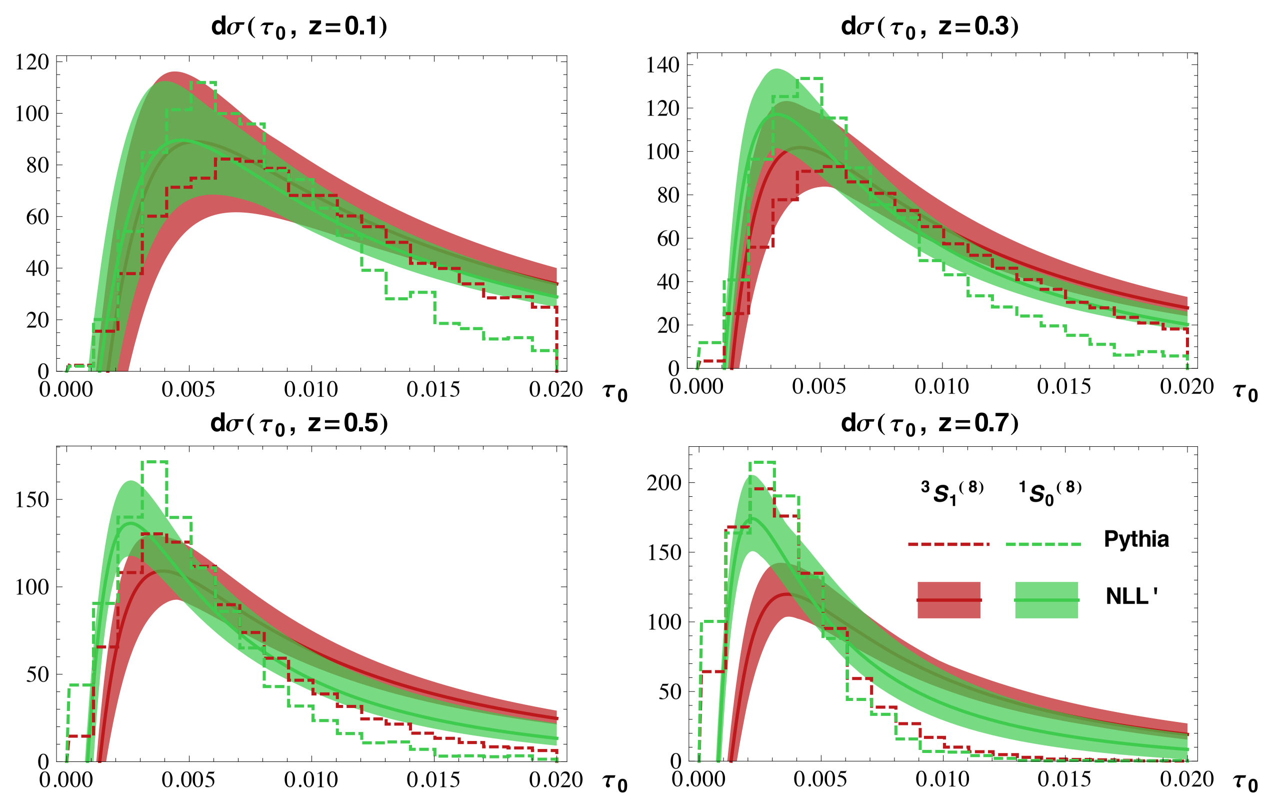


M. Baumgart, A. K. Leibovich, T. Mehen, I. Z. Rothstein (JHEP) 2014

GFIP - Improvements



Application to Quarkonium production



Profile Functions