Quarkonium-in-Jet Production at the LHC and the EIC

Taewook Ha
Fudan University

with Yunlu Wang, Hee Sok Chung, Daekyoung Kang, U-Rae Kim

(arXiv:2601.05530, arXiv:26**.ongoing)

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Challenges in Heavy Quarkonium Production

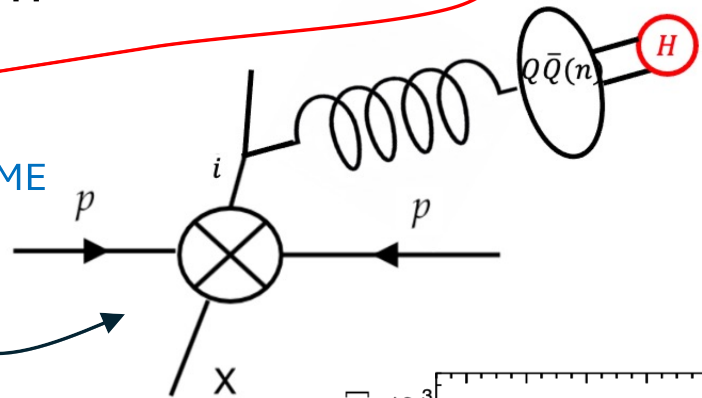
- Non-Relativistic QCD Factorization

Long-Distance

$$\sigma \sim \sum_n \sigma_n^{\mathrm{SDC}} \times \langle \mathcal{O}^H(n) \rangle$$

LDME

Short-Distance

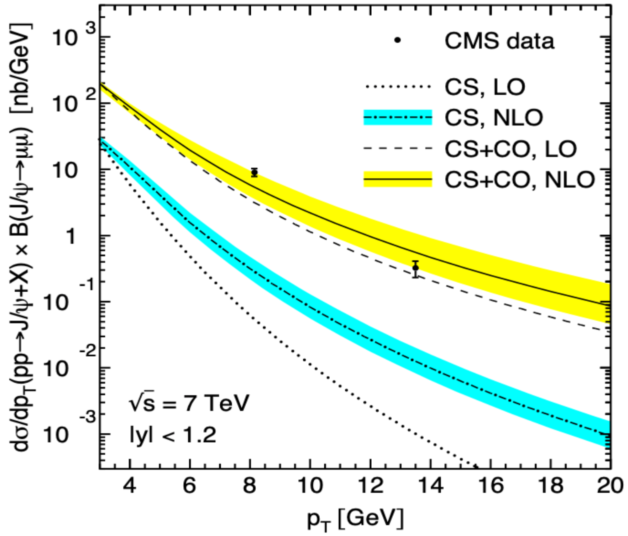


- Our Primary Focus

- LDME universality: Theory vs. Reality

- Inability to distinguish LDMEs via p_T spectra

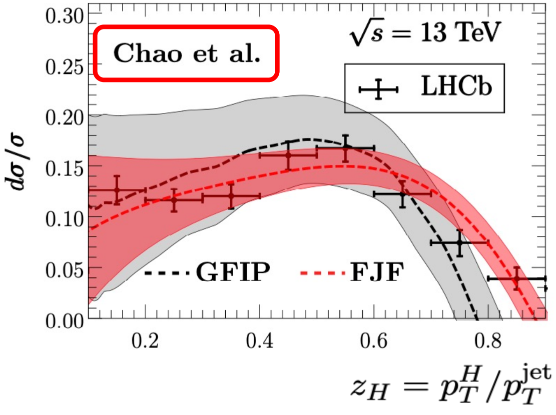
⇒ Need for complementary probes!

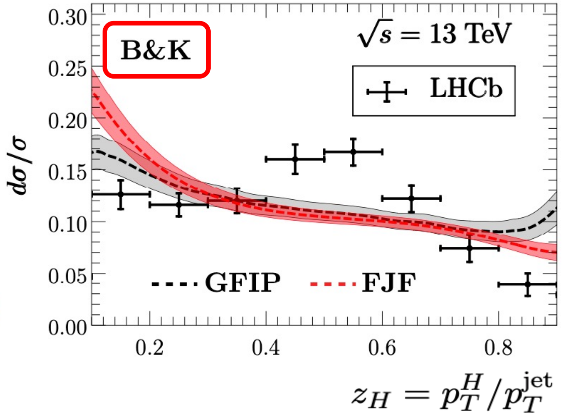


M. Butenschoen, B. Kniehl (2011)

Quarkonium-in-Jet as a Solution

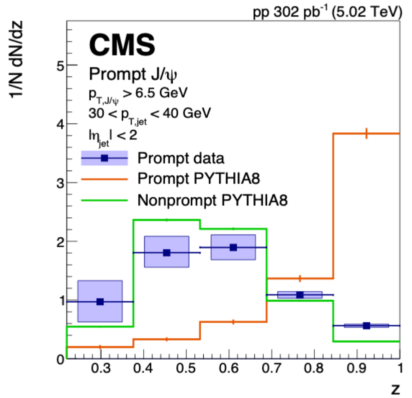
- Why Jets? $z_H = p_T^H / p_T^{\text{jet}}$
- Beyond the p_T spectrum
- Breaking the degeneracy
- Testing universality of LDMEs



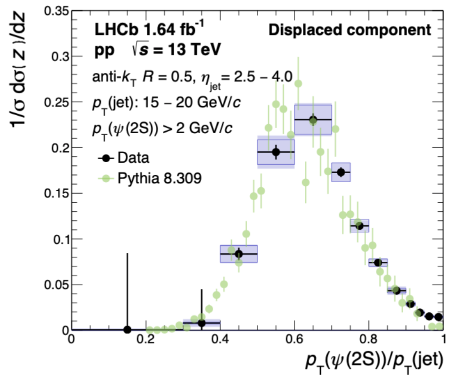


T. Mehen, R. Bain, Y. Makris, L. Dai, A. Leibovich (2017)

- Expanding experimental measurements



J/ψ, CMS, arXiv:2106.13235



ψ(2S), LHCb, arXiv: 2410.18018

and more!

NRQCD: Effective Theory for Heavy Quarkonium

- Scale Hierarchy

- Hard (m_Q) >> Soft ($m_Q v$) >> Ultrasoft ($m_Q v^2$)

- Factorization Theorem

$$\sigma \sim \sum_n \sigma_n^{\mathrm{SDC}} \times \langle \mathcal{O}^H(n) \rangle \left(1 + \mathcal{O}(v^2)\right)$$

- Velocity Scaling

- Expansion in v ($v^2 \sim 0.3\ for\ J/\psi$, $v^2 \sim 0.1\ for\ \Upsilon$)

- Hierarchy of LDMEs

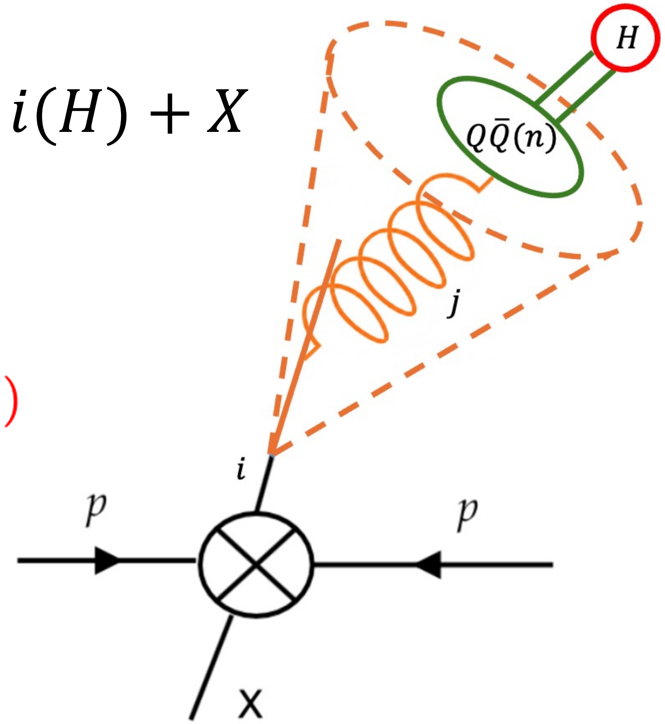
$${}^3S_1^{[1]}(\sim v^3)\ ,\quad {}^3S_1^{[8]}, {}^3P_J^{[8]}, {}^1S_0^{[8]}\ (\sim v^7)\quad ,\qquad \cdots$$

Factorization Theorem

- Single heavy quarkonium production: $pp(ep) \to i(H) + X$

$$\sigma \sim \hat{\sigma}^i(z) \otimes \mathcal{G}_i^H(z, z_H)(1 + \mathcal{O}(m_Q^2/p_T^2))$$
$$\sim \hat{\sigma}^i(z) \otimes \mathcal{J}_{ij}(z, z_H) \otimes D_j^H(z_H)$$
$$\sim \hat{\sigma}^i(z) \otimes \mathcal{J}_{ij}(z, z_H) \otimes \sum_n d_{j\to n}^H(z_H) \times \langle \mathcal{O}^H(n) \rangle (1 + \mathcal{O}(v^2))$$

where $z = p_T^{jet}/p_T^i$, $z_H = p_T^H/p_T^{jet}$



$\hat{\sigma}^i(z)$: Hard scattering process

$\mathcal{J}_{ij}(z, z_H)$: Perturbative jet evolution and collinear radiation

$d_{j\to n}^H(z_H)$: Short-distance matching of parton j onto $Q\bar{Q}(n)$

$\langle \mathcal{O}^H(n) \rangle$: Non-perturbative transition from $Q\bar{Q}(n)$ to H

Fragmenting Jet Functions (FJFs)

$\mathcal{G}_i^h(s,z)$: constraints on jet invariant mass s with light hadron h

M. Procura, I. Stewart (2009), A. Jain, M. Procura, W. Waalewijn (2011)

$\mathcal{G}_i^h(E,R,z)$: jet algorithm with R and resum threshold log

M. Procura, W. Waalewijn (2011)

$\mathcal{G}_i^H(E,R,z)$: application to heavy quarkonium H

$z = p_T^H / p_T^i$

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

$\mathcal{G}_i^h(z, z_H, E_J, R)$: semi-inclusive FJF! where $z = p_T^{jet}/p_T^i$, $z_H = p_T^H/p_T^{jet}$

T. Kaufmann, A. Mukherjee, W. Vogelsang (2015), Z. Kang, F. Ringer, I. Vitev (2016)

Generalize with z and z_H dependence

$$\mathcal{G}_i^H(z, z_H, p_T R, \mu) = \sum_j \int \frac{dz'_H}{z'_H} \mathcal{J}_{ij}(z, z'_H, p_T R, \mu)\, D_j^H\left(\frac{z_H}{z'_H}, \mu\right)$$

Scale hierarchy and Resummation

- DGLAP evolution

Hard scale ($\mu_H \sim p_T$) $\hat{\sigma}^i(z, p_T) \otimes \mathcal{G}_i^H(z, z_H, p_T)$

Jet scale ($\mu_J \sim p_T R$) $\hat{\sigma}^i(z, p_T) \otimes \mathcal{J}_{ij}(z, z_H, p_T R) \otimes D_j^H(z_H, p_T R)$

Fragmentation scale ($\mu_0 \sim 2m_Q$) $\hat{\sigma}^i(z, p_T) \otimes \mathcal{J}_{ij}(z, z_H, p_T R) \otimes \sum_n d_{j \to n}^H(z_H, 2m_Q) \times \langle \mathcal{O}^H(n) \rangle$

- Threshold Resummation for the quarkonium FF

H. Chung, U. Kim, J. Lee (2024, 2026)

NRQCD Hard scale ($\mu_{NR,H} \sim m_Q$) Working at fixed hard scale $(\mu_{NR,H} \sim m_Q)$, no evolution!

Threshold Resummation for the Quarkonium FF

H. Chung, U. Kim, J. Lee (2024, 2026)

- Singular behavior of Fixed-order FFs at NLO

$$\left(\frac{\alpha_s}{\pi}\right)^n \left[\frac{\log^{2n-1}(1-z)}{1-z}\right]_+ \otimes D^{\mathrm{LO}}(z)$$

- Target Channels (Gluon FFs) – ${}^3S_1^{[8]}, {}^3P_J^{[8]}$
- Resummation Framework in Mellin space

$$\tilde{D}^{\mathrm{resum}}_{g\to Q\bar{Q}(\mathcal{N})}(N) = \exp\left[J^N_{\mathcal{N}}\right] \tilde{D}^{\mathrm{LO}}_{g\to Q\bar{Q}(\mathcal{N})}(N)$$ where $$J^N_{{}^3S_1^{[8]}} = \frac{\alpha_s C_A}{\pi}\int_0^1 dz\, z^{N-1}\left[\frac{-2\log(1-z)}{1-z}\right]_+$$

$$J^N_{{}^3P^{[8]}} = J^N_{{}^3P^{[1]}} = \frac{4}{3} J^N_{{}^3S_1^{[8]}}$$

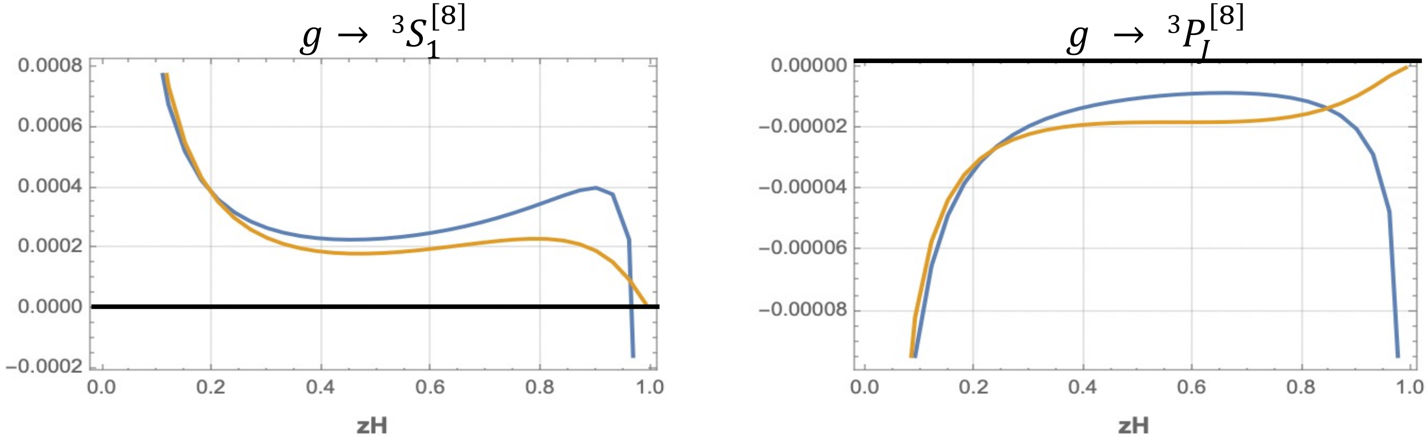
- Advantage of Threshold Resummation

- Restoring convergence
- Positivity of cross section
- Phenomenological accuracy (Fixes $\chi_{c1}(3872)$ overestimation)

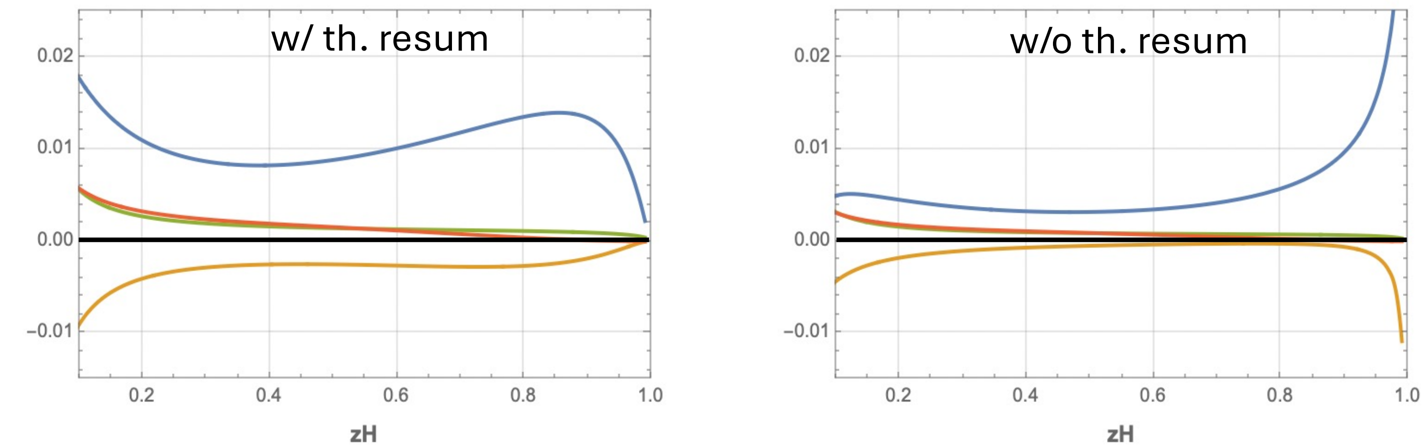
W. Lai, H. Chung (2025)

With vs. Without Threshold Resummation

- $d_{g\to n}^{H}(60\ \text{GeV})$



- $\sigma_n^{SDC}(60\ \text{GeV})$



⇒ Threshold resummation restores the physical distribution

Classification of LDME Sets for J/ψ

- Same signs for $\langle \mathcal{O}(^3S_1^{[8]})\rangle$ and $\langle \mathcal{O}(^3P_J^{[8]})\rangle$

- Category 1 → (Small $\langle \mathcal{O}(^1S_0^{[8]})\rangle$) Han '14, Zhang '14, Shao '14, Brambilla '21, Chung '24

- Category 2 → (Large $\langle \mathcal{O}(^1S_0^{[8]})\rangle$) Gong '12, Shao '14, Bodwin '15, Feng '18, Butenschoen '22

- Opposite signs for $\langle \mathcal{O}(^3S_1^{[8]})\rangle$ and $\langle \mathcal{O}(^3P_J^{[8]})\rangle$

- Category 3 Butenschoen '11, Bodwin '15

		$\langle \mathcal{O}(^3S_1^{[1]})\rangle$ $\times$ GeV^3	$\langle \mathcal{O}(^3S_1^{[8]})\rangle$ $\times 10^{-2}$ GeV^3	$\langle \mathcal{O}(^1S_0^{[8]})\rangle$ $\times 10^{-2}$GeV^3	$\langle \mathcal{O}(^3P_0^{[8]})\rangle/m_c^2$ $\times 10^{-2}$ GeV^3
Cat.1	Brambilla et al.[15, 72]	1.18 ± 0.35	1.40 ± 0.42	-0.63 ± 3.22	2.33 ± 0.83
Cat.2	Bodwin et al. [11]	1.32 ± 0.20	-0.71 ± 0.36	11.0 ± 1.4	-0.31 ± 0.15
Cat.3	B&K [6]	1.32 ± 0.20	0.22 ± 0.06	4.97 ± 0.44	-0.72 ± 0.09

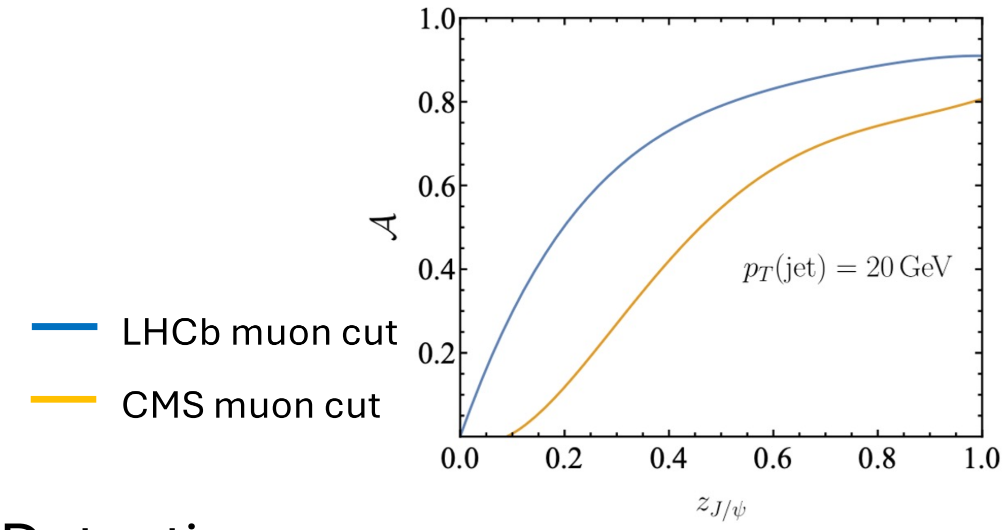
Muon acceptance $\mathcal{A}$

- Why Muon Channel ($H \rightarrow \mu^+\mu^-$)?

- Superior Signal Purity

- High Trigger Efficiency

- Excellent Mass Resolution



- Kinematic Requirements for Muon Detection

LHCb [19]: Both muons satisfy $2.0 < \eta(\mu) < 4.5$ and $p_T(\mu) > 0.5$ GeV, with the additional requirement that $p(\mu) > 5$ GeV, and $\sqrt{p_T(\mu^+)p_T(\mu^-)} > 1.5$ GeV. LHCb (2017)

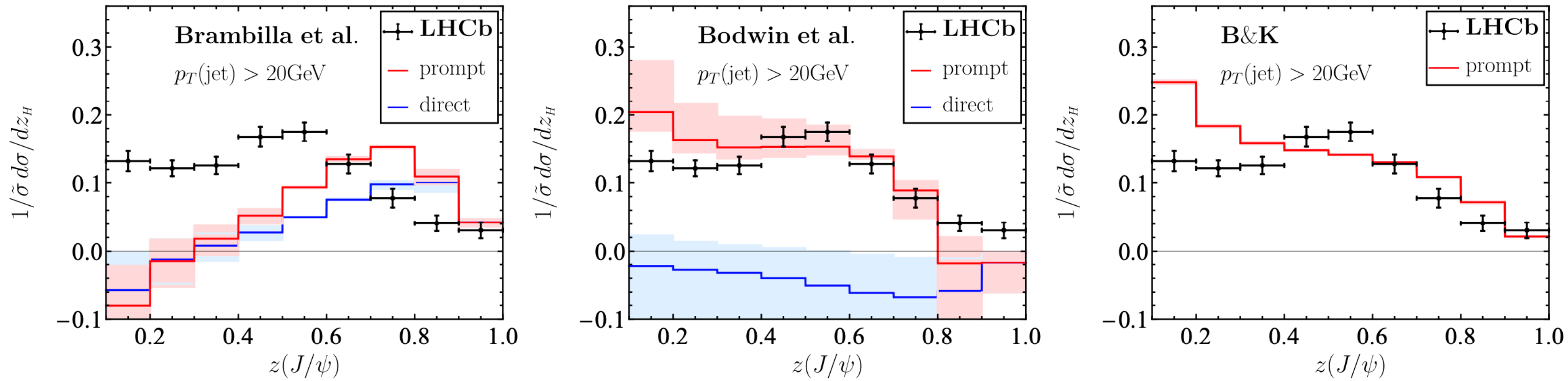
CMS [73, 74]: Each muon satisfies one of the following kinematic domains, depending on its pseudorapidity: $p_T(\mu) > 3.5$ GeV for $|\eta(\mu)| < 1.2$; $p_T(\mu) > (5.47 - 1.89|\eta(\mu)|)$ GeV for $1.2 < |\eta(\mu)| < 2.1$; and $p_T(\mu) > 1.5$ GeV for $2.1 < |\eta(\mu)| < 2.4$. CMS (2021)

CMS example ($\mathcal{A}$ corrected): $\mathcal{B}(\mathcal{Q} \rightarrow \mu^+\mu^-)\,\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_\mathrm{T}\,\mathrm{d}y} = \frac{N(p_\mathrm{T},y)}{\mathcal{L}\Delta y \Delta p_\mathrm{T}} \left\langle \frac{1}{\epsilon(p_\mathrm{T},y)\mathcal{A}(p_\mathrm{T},y)} \right\rangle$

Application 1: J/ψ at the LHCb

Y. Wang, D. Kang, H. Chung (2025)

Cat. 1: Brambilla | Cat. 2: Bodwin | Cat. 3: B&K



direct : J/ψ from hard scattering — prompt : direct + feeddown from $\chi_c, \psi(2S)$

Cat. 1: Discrepancy at low z_H

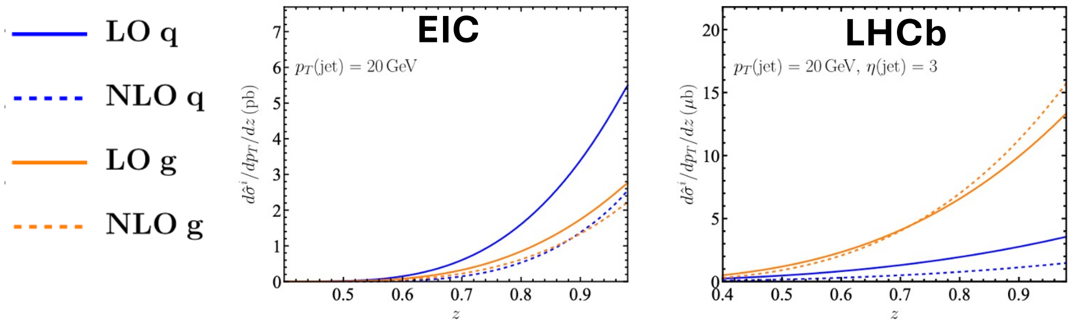
Cat. 2: Better agreement with data

Cat. 3: Similar to Cat. 2 result

⇒ Allows us to discriminate between different LDME sets

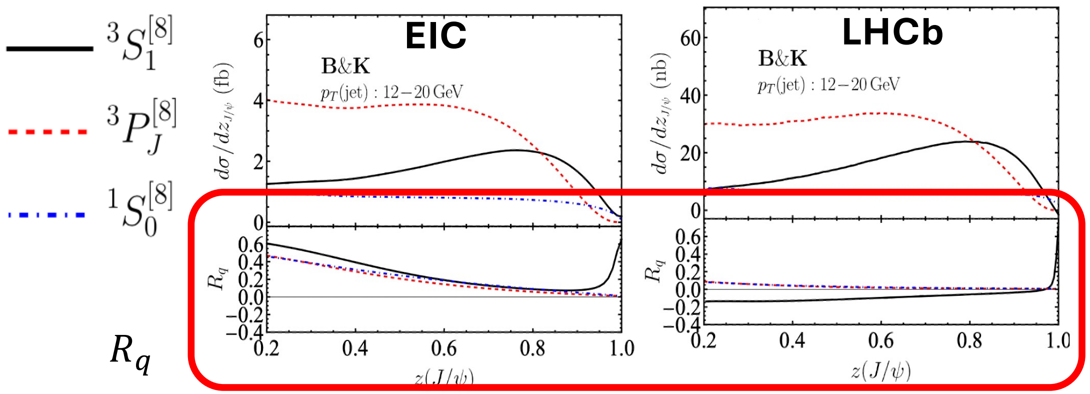
Application 2: J/ψ at the EIC: A New Frontier

- EIC Photoproduction ($q^2 \approx 0$) Partonic Cross Section



Enhancement of quark-initiated process at EIC

- R_q Comparison in Cross section



where $R_q = \dfrac{\sum_{j\in\{q\}} \hat{\sigma}_{ep\to jX} \otimes \mathcal{G}_j^{J/\psi}}{\sum_{j\in\{q,g\}} \hat{\sigma}_{ep\to jX} \otimes \mathcal{G}_j^{J/\psi}}$

R_q is higher at the EIC across all octet channel

$\Rightarrow$ EIC: a complementary facilitiy to test LDMEs

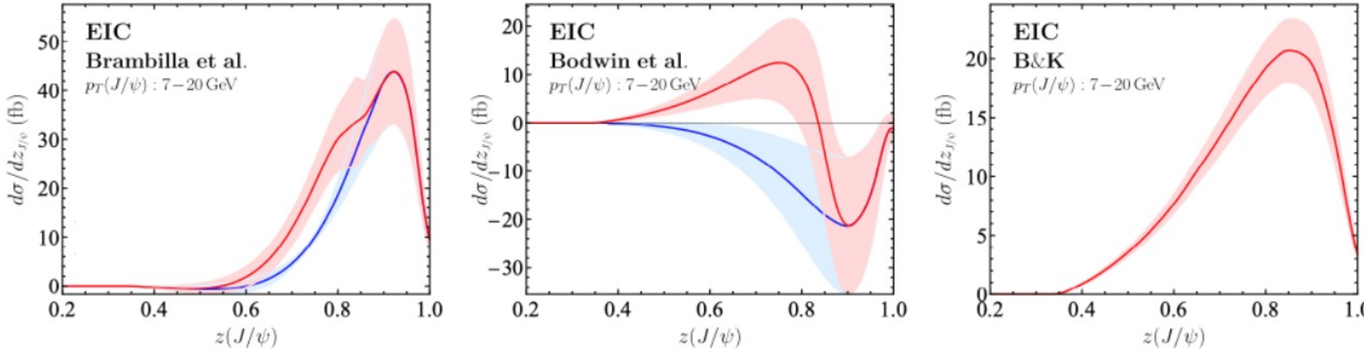
Application 2: J/ψ at the EIC: A New Frontier

- LDME Sensitivity

direct

prompt

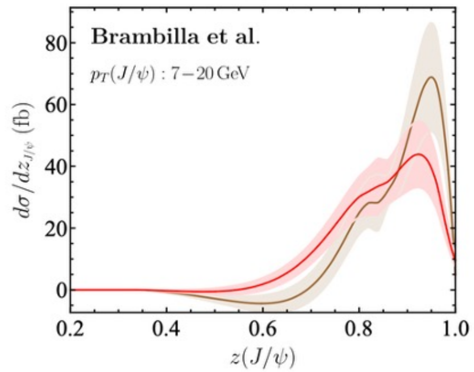
Cat. 1 Cat. 2 Cat. 3

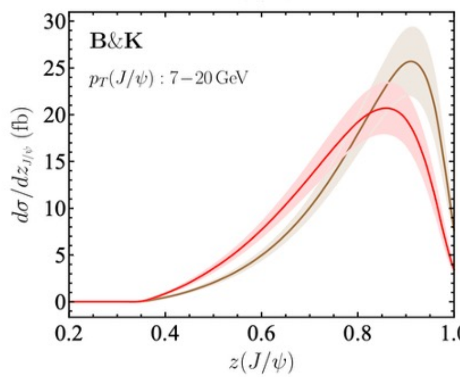


- Jet Radius (R) Dependence

$R = 0.4$

$R = 0.8$





$\Rightarrow$ Changing R provides enhanced discriminating power to the LDME

Bottomonium vs. Charmonium - preliminary

- Key Physical Parameters

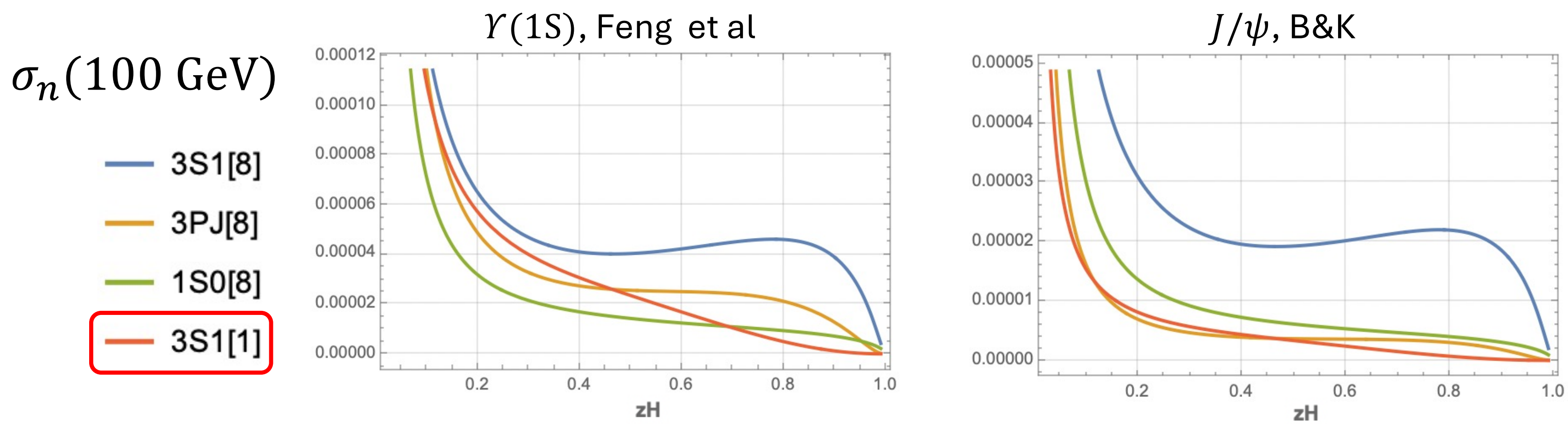
	Charmonium (J/ψ)	Bottomonium ($\Upsilon(1S)$)
Quark Pole Mass (m_Q)	~ 1.5 GeV	~ 4.8 GeV
Velocity (v^2)	~ 0.3	~ 0.1
NRQCD Expansion (v^2)	Good	Excellent
SCET Expansion (m_Q^2/p_T^2)	Typical	Enhanced

$\Rightarrow \Upsilon(1S)$ has smaller v^2 for NRQCD, it requires higher p_T

Bottomonium vs. Charmonium - preliminary

- LDME Comparison : $\Upsilon(1S)$ vs. J/ψ

Channel	${}^3S_1^{[1]}$	${}^3S_1^{[8]}$	${}^3P_J^{[8]}$	${}^1S_0^{[8]}$
Velocity scaling	$\sim m_Q^3 v^3$	$\sim m_Q^3 v^7$	$\sim m_Q^3 v^7$	$\sim m_Q^3 v^7$
$J/\psi\ (GeV^3)$	0.55	0.050	0.050	0.050
$\Upsilon(1S)\ (GeV^3)$	3.49	0.035	0.035	0.035
Ratio (B/C)	6.31 $(\gg \mathbf{1})$	0.70 (< 1)	0.70 (< 1)	0.70 (< 1)



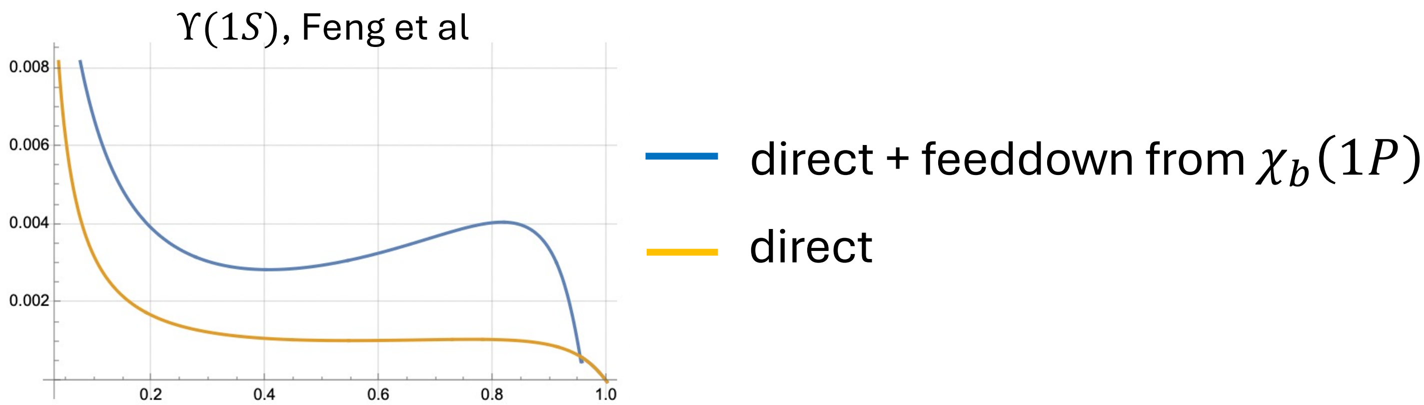
⇒ Enhanced Color-Singlet sensitivity in Bottomonium

Feeddown Components: χ_b vs. χ_c - preliminary

- LDME Comparison: $\chi_b(1P)$

Channel	$^3P_J^{[1]}$	$^3S_1^{[8]}$
Velocity scaling	$\sim m_Q^3 v^5$	$\sim m_Q^3 v^5$
χ_c (GeV^3)	0.17	0.17
χ_b (GeV^3)	0.35	0.35
Ratio (B/C)	2.1 ($\gg$ 1)	2.1 ($\gg$ 1)

σ (60 GeV)



$\Rightarrow$ Prompt $\Upsilon(1S)$ is highly sensitive to the P-wave feeddown

Conclusion

- z_H distribution (siFJF) breaks LDME degeneracy
- Threshold resummation for quarkonium FF restores convergence and ensures positivity in cross section
- EIC provides complementary sensitivity to quark FFs
- Bottomonium provides a testbed for the consistency of SCET + NRQCD factorization across different mass scales

Backup

Factorization Theorem

$$\frac{d\sigma_{pp\to(\text{jet}H)+X}}{dp_T d\eta dz_H} = \sum_{a,b,i} \int dx_a dx_b f_{a/p}(x_a,\mu) f_{b/p}(x_b,\mu) \int dz \frac{d\hat{\sigma}_{ab\to i+X}}{dp_T d\eta}\left(\frac{p_T}{z},\eta,\mu\right) \mathcal{G}_i^H(z, z_H, p_T R, \mu),$$

Backup

Grammer-Yennie approximation

$$D_{g\to H}(z) = \frac{-g^{\mu\nu} z^{d-3}}{2\pi K^+(N_c^2-1)(d-2)} \int_{-\infty}^{+\infty} dx^- e^{-iK^+x^-}$$
$$\times \langle 0|G^c_{+\mu}(0)\Phi_n^{\dagger bc}(\infty,0)a^\dagger_{H(P)}a_{H(P)}\Phi_n^{ba}(\infty,x^-)G^a_{+\nu}(nx^-)|0\rangle$$ where $\Phi_k(y,x) = \mathcal{P}\exp\left[-ig\int_x^y d\lambda\, k\cdot A^{\rm adj}(k\lambda)\right]$

$$W_{p_1}(t',t) = \mathcal{P}\exp\left[-ig\int_t^{t'} d\lambda\, p_1\cdot A(p_1\lambda)\right] \qquad \mathcal{A}^{\mu,a}_{\rm soft} = T\left[\bar{u}(p_1)W_{p_1}(\infty,0)(-ig\gamma^\mu T^a)W^\dagger_{p_2}(\infty,0)v(p_2)\right]$$

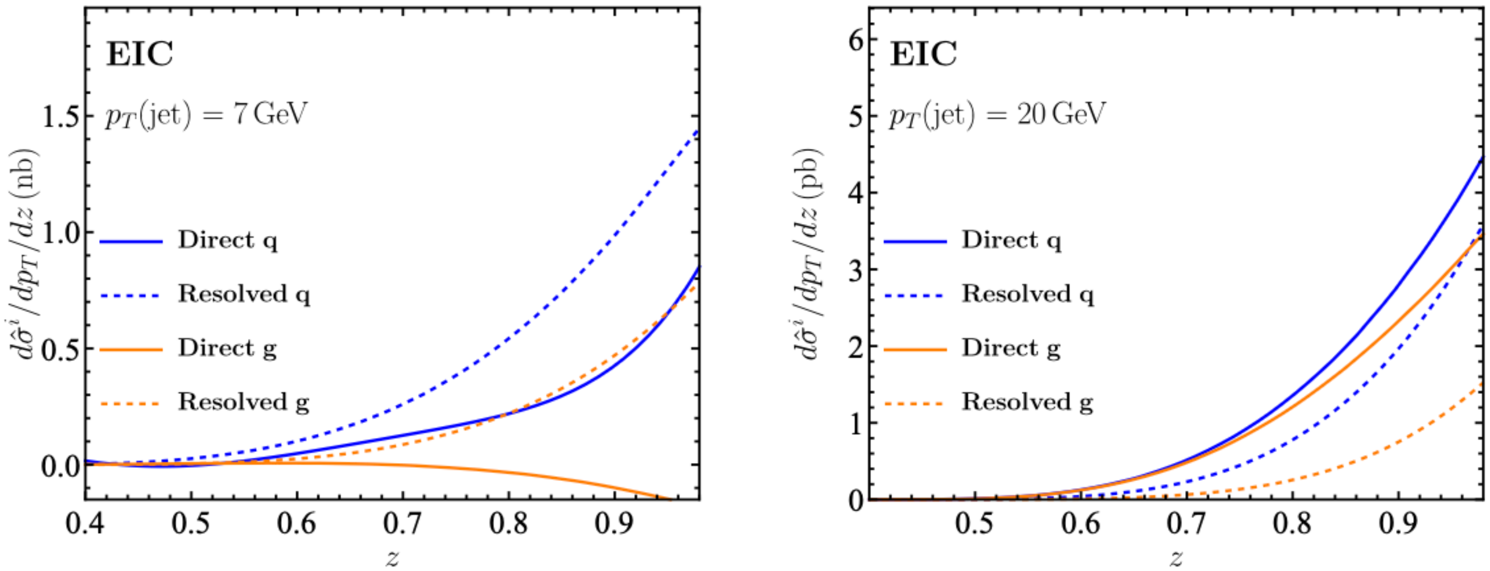
$$D^{\rm soft}_{g\to Q\bar{Q}}(z) = 2MC_{\rm frag}\left|\frac{-i}{K^2+i\varepsilon}\right|^2 I_T^{\alpha\beta}S_{\alpha\beta}(z),$$

where $S_{\alpha\beta}(z)$ is the soft function defined by

$$S^{\alpha\beta}(z) \equiv \langle 0|\bar{T}\left[\mathcal{A}^{\beta,c}_{\rm soft}\Phi_n^{bc}(\infty,0)\right]^\dagger 2\pi\delta(n\cdot\hat{p}-P^+(1-z))T\left[\mathcal{A}^{\alpha,a}_{\rm soft}\Phi_n^{ba}(\infty,0)\right]|0\rangle$$

Backup

Partonic cross section at the EIC (direct vs. resolved)



Backup

Velocity Scaling 1

TABLES

Operator	Estimate	Description
α_s	v	effective quark-gluon coupling constant
ψ	$(Mv)^{3/2}$	heavy-quark (annihilation) field
χ	$(Mv)^{3/2}$	heavy-antiquark (creation) field
D_t (acting on ψ or χ)	Mv^2	gauge-covariant time derivative
$\mathbf{D}$ (acting on ψ or χ)	Mv	gauge-covariant spatial derivative
$g\mathbf{E}$	M^2v^3	chromoelectric field
$g\mathbf{B}$	M^2v^4	chromomagnetic field
$g\phi$ (in Coulomb gauge)	Mv^2	scalar potential
$g\mathbf{A}$ (in Coulomb gauge)	Mv^3	vector potential

TABLE I. Estimates of the magnitudes of NRQCD operators for matrix elements between heavy-quarkonium states in terms of the heavy-quark mass M and the typical heavy-quark velocity v. The estimates shown apply to matrix elements in a quarkonium state $|H\rangle$ whose position is localized to a region of size $1/Mv$ or less. If the states are normalized to $\langle H|H\rangle = 1$, then the product of the magnitudes of the operators gives the magnitude of the matrix element. (In order to obtain estimates for matrix elements between momentum eigenstates that are normalized to $\langle H|H\rangle = V$, where V is the volume of space, one should multiply the estimates for localized states of unit norm by $(Mv)^{-3}$.)

Backup

Velocity Scaling 2

$$\mathcal{O}_1(^1S_0) = \psi^\dagger \chi \, \chi^\dagger \psi, \tag{2.10a}$$

$$\mathcal{O}_1(^3S_1) = \psi^\dagger \boldsymbol{\sigma} \chi \cdot \chi^\dagger \boldsymbol{\sigma} \psi, \tag{2.10b}$$

$$\mathcal{O}_8(^1S_0) = \psi^\dagger T^a \chi \, \chi^\dagger T^a \psi, \tag{2.10c}$$

$$\mathcal{O}_8(^3S_1) = \psi^\dagger \boldsymbol{\sigma} T^a \chi \cdot \chi^\dagger \boldsymbol{\sigma} T^a \psi. \tag{2.10d}$$

Color-Singlet Matrix Element	Numerical Value	NRQCD Scaling Order
$\langle 0 \vert O_1^{J/\psi}(^3S_1) \vert 0 \rangle$	3.9×10^{-1} GeV^3	$M_c^3 v_c^3$
$\langle 0 \vert O_1^{\chi_{c1}}(^3P_1) \vert 0 \rangle$	3.2×10^{-1} GeV^5	$M_c^5 v_c^5$
$\langle 0 \vert O_1^{\psi'}(^3S_1) \vert 0 \rangle$	2.5×10^{-1} GeV^3	$M_c^3 v_c^3$
$\langle 0 \vert O_1^{\Upsilon(1S)}(^3S_1) \vert 0 \rangle$	3.1 GeV^3	$M_b^3 v_b^3$
$\langle 0 \vert O_1^{\chi_{b1}(1P)}(^3P_1) \vert 0 \rangle$	6.1 GeV^5	$M_b^5 v_b^5$
$\langle 0 \vert O_1^{\Upsilon(2S)}(^3S_1) \vert 0 \rangle$	1.5 GeV^3	$M_b^3 v_b^3$
$\langle 0 \vert O_1^{\chi_{b1}(2P)}(^3P_1) \vert 0 \rangle$	7.1 GeV^5	$M_b^5 v_b^5$
$\langle 0 \vert O_1^{\Upsilon(3S)}(^3S_1) \vert 0 \rangle$	1.2 GeV^3	$M_b^3 v_b^3$
$\langle 0 \vert O_1^{\chi_{b1}(3P)}(^3P_1) \vert 0 \rangle$	7.7 GeV^5	$M_b^5 v_b^5$

Table I