Test of NRQCD with Quarkonium Production in Jets at the LHC

Lin Dai (代林)
(University of PITTsburgh)

with
Reggie Bain, Yiannis Makris, Thomas Mehen (DUKE)
Andrew Hornig (LANL)
Adam Leibovich (PITT)
Prashant Shrivastava (CMU)

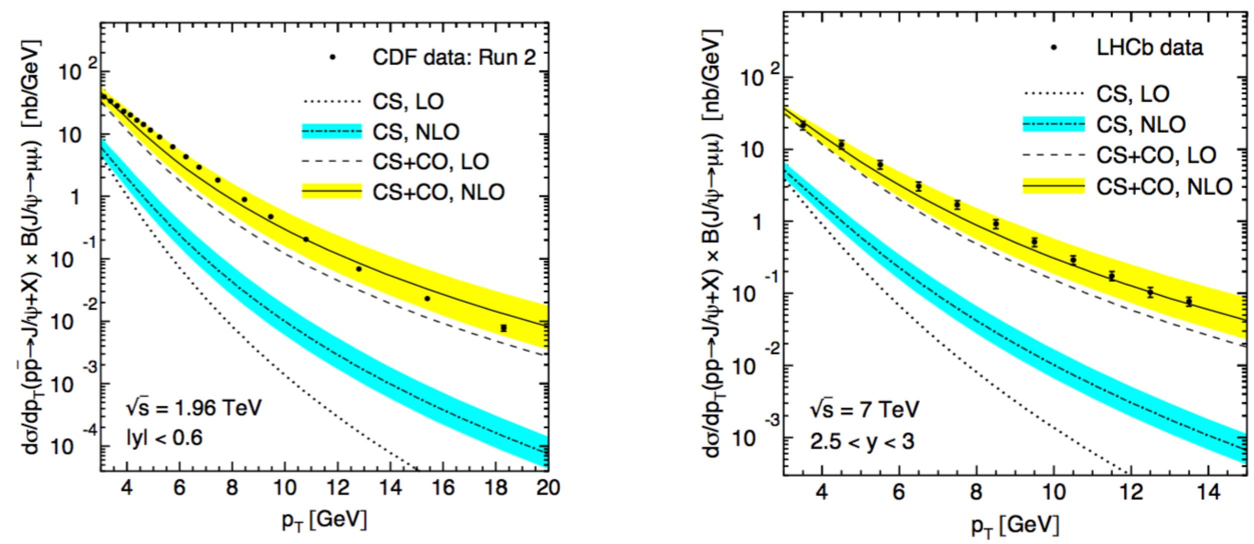
[arXiv:1603.06981, 1702.05525, 1707.08629]
(QWG2017, Beijing, Nov 9, 17)

Outline

- Motivations
- NRQCD factorization formalism (extraction LDMEs)
- Fragmenting Jet Functions (analytic tool)
- e^+e^- collisions: B, J/ψ production in jets (test framework)
- pp collisions: J/ψ production in jets, compare with LHCb data
- Summary

Some Motivations

- Much of quarkonium production pheno. based on NRQCD factorization formalism



[Butenschon, Kniehl, 1105.0820]

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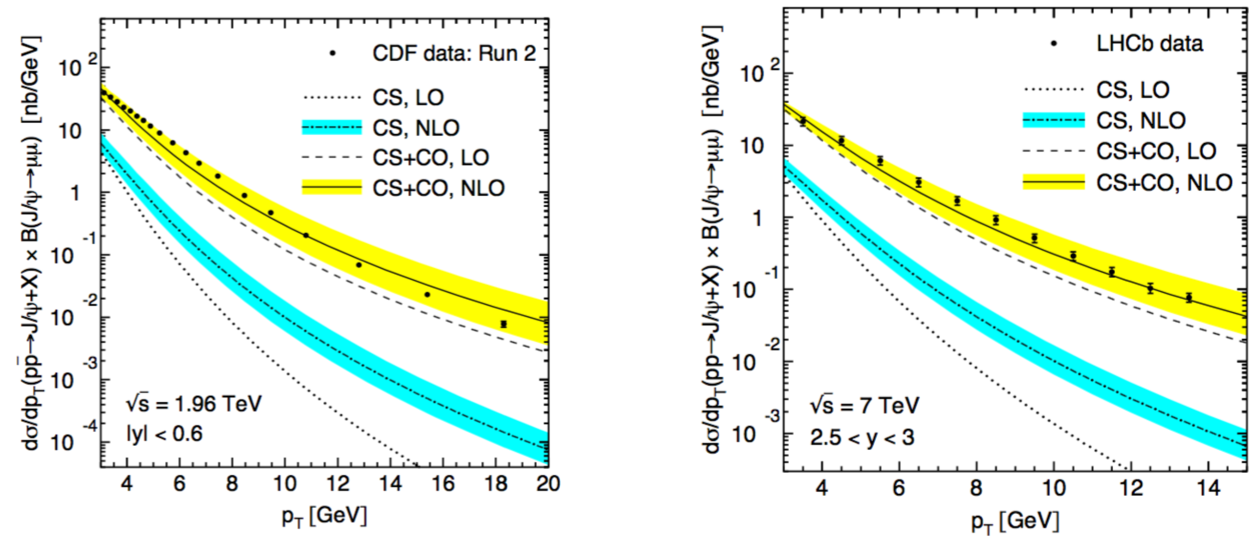

[Butenschon, Kniehl, 1105.0820]

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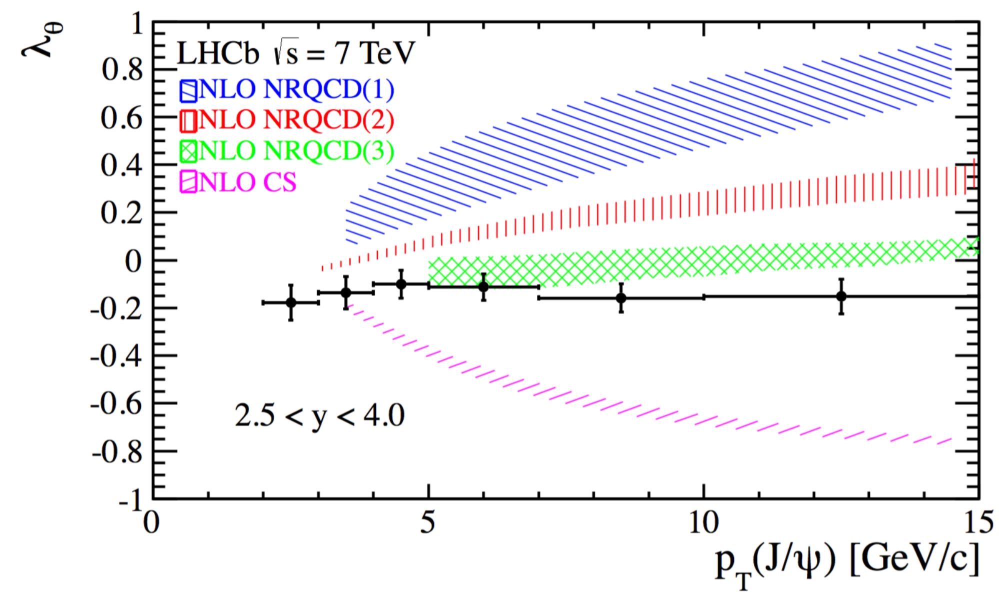

[LHCb, 1307.6379]

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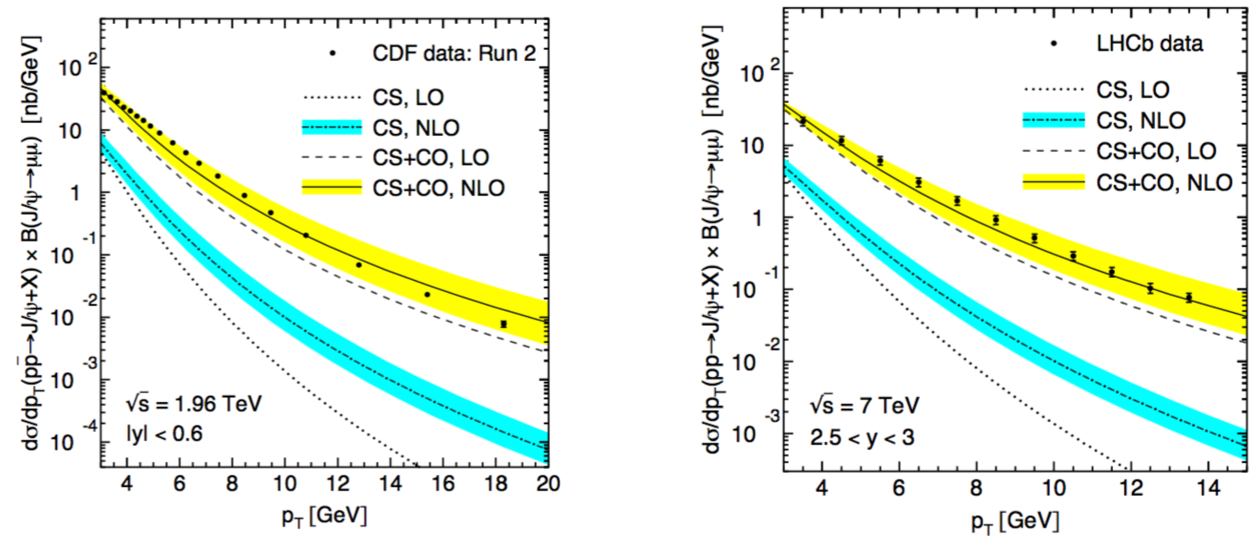

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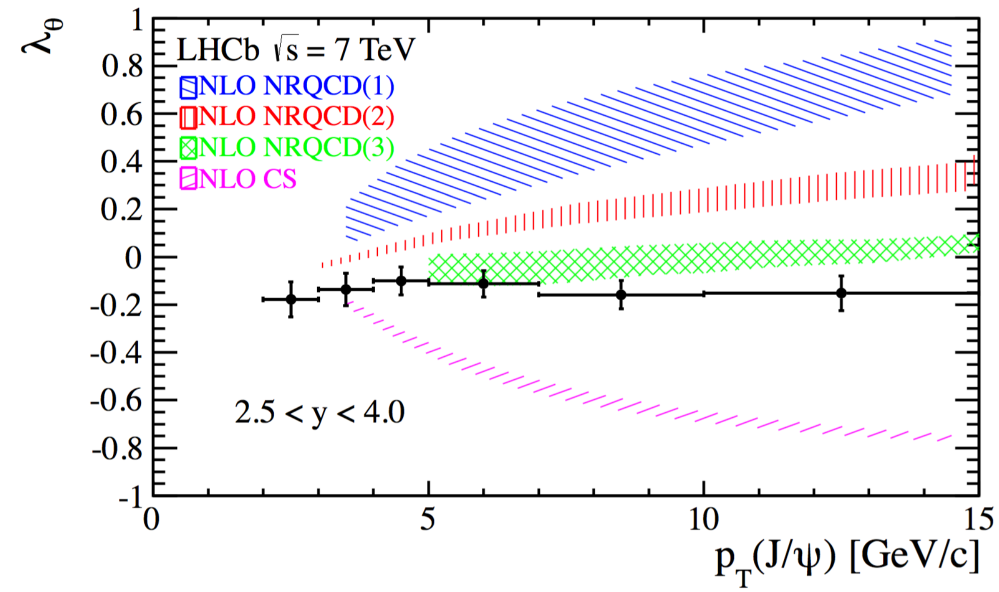
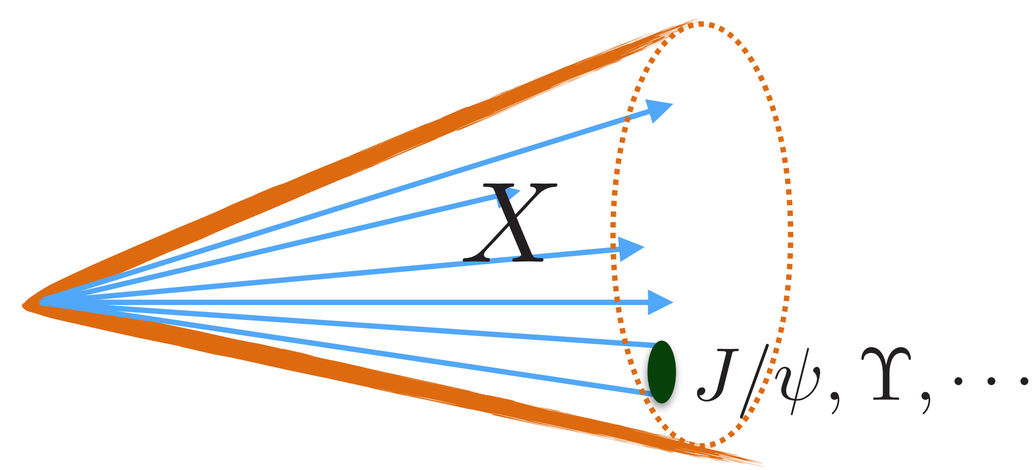


[LHCb, 1307.6379]

- ✦ Quarkonium production in jets provides us new way of studying these issues



NRQCD Factorization

Cross section:

SDCs (perturbative, scale>=m_H)

$$\sigma(H) = \sum_n d_n \langle 0|\mathcal{O}_n^H|0\rangle$$

LDMEs (nonperturbative, scale<m_H)

$$n: \ {}^1S_0^{[8]},\ {}^3S_1^{[1,8]},\ {}^3P_J^{[8]}, \ldots$$

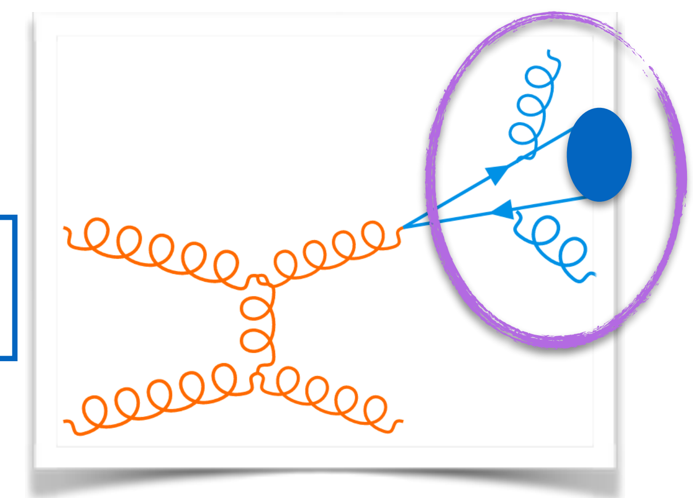
e.g.

$$\langle 0|\mathcal{O}^H_{{}^3S_1^{[8]}}|0\rangle = \sum_X \langle 0|\chi^\dagger \sigma^i T^a \psi|HX\rangle\langle HX|\psi^\dagger \sigma^i T^a \chi|0\rangle$$

[Bodwin, Braaten, Lepage, hep-ph/9407339]

NRQCD Factorization

Factorized form of FF:



SDCs (perturbative, ~m_H)

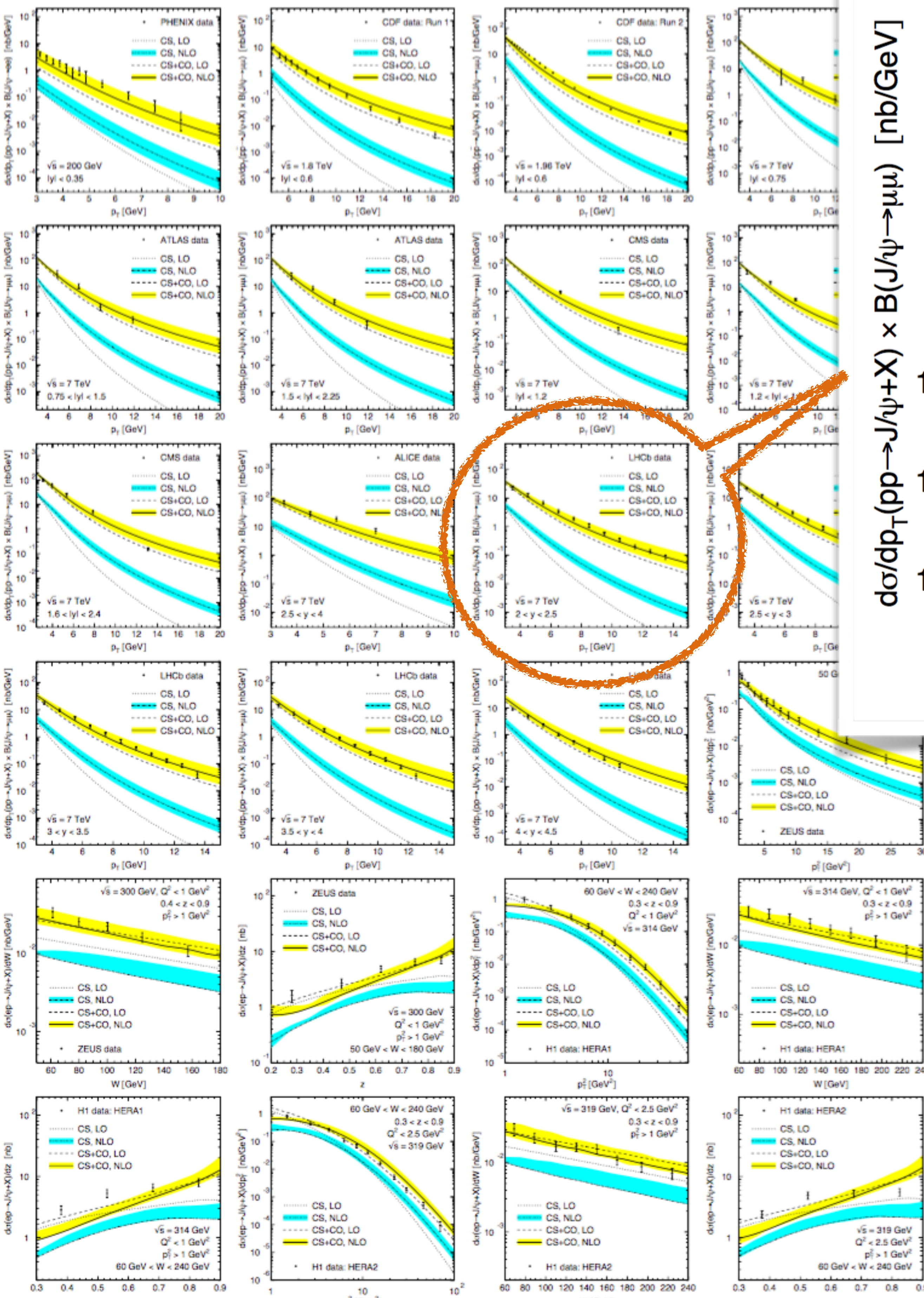
$$D^H_{q/g} = \sum_n d_{q/g,n} \langle 0|\mathcal{O}^H_n|0\rangle$$

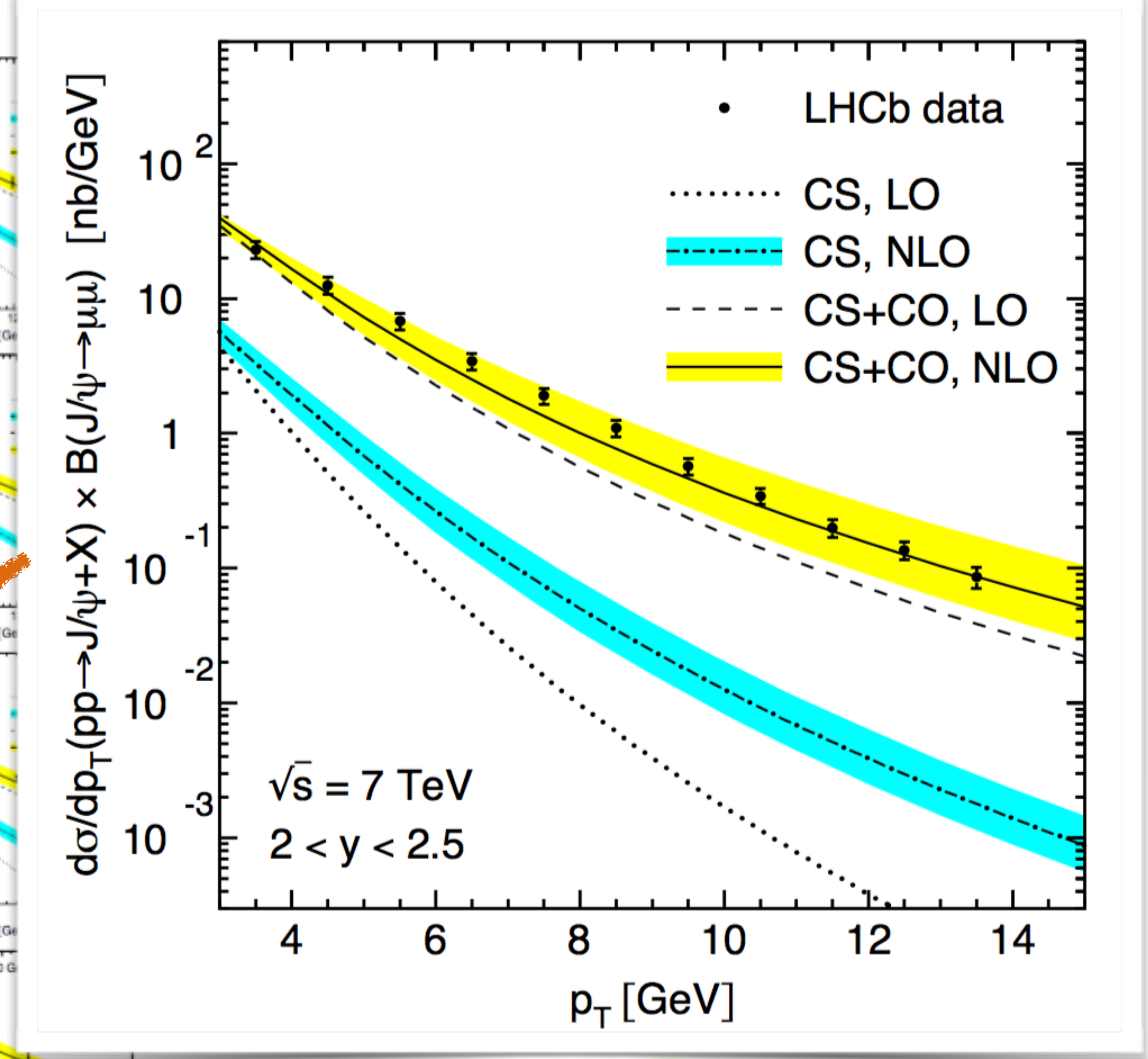
LDMEs (nonperturbative, <m_H)
The same as those in X-section

e.g. $D^{^1S_0^{(8)}}_{g\to\psi}(z, 2m_c) = \dfrac{5\alpha_s^2(2m_c)}{96m_c^3}\langle\mathcal{O}^\psi(^1S_0^{(8)})\rangle\left(3z - 2z^2 + 2(1-z)\log(1-z)\right)$

The channels we need: $^1S_0^{[8]},\ ^3S_1^{[1,8]},\ ^3P_J^{[8]}$
(power counting up to v^4)

[Bodwin, Braaten, Lepage, hep-ph/9407339]





NLO Global Fit:

26 sets, 196 data points

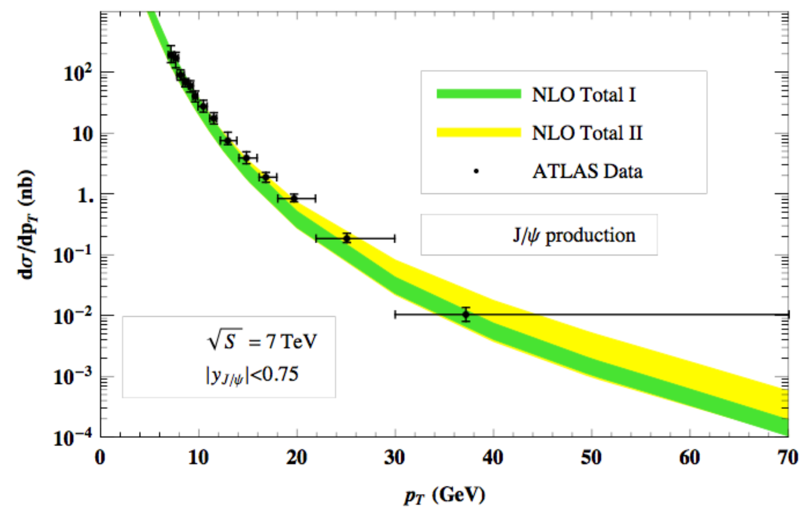
$$\chi^2_{\rm d.o.f.} = 4.42$$

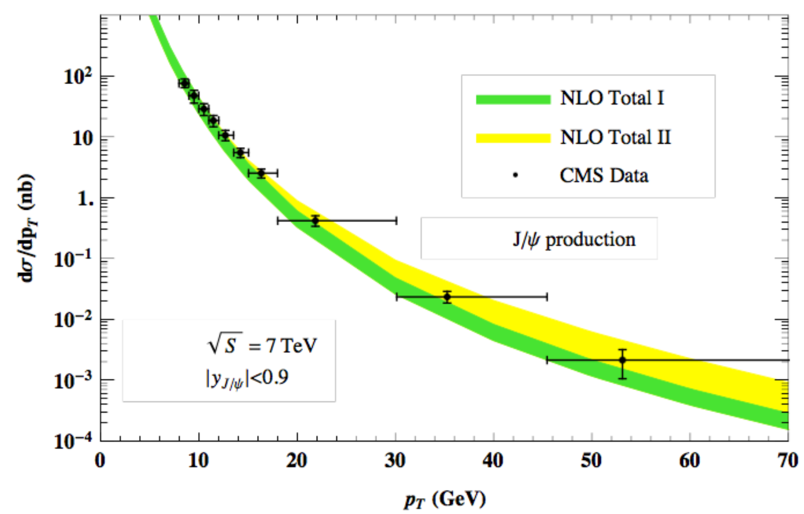
$$p_T,\ p_T^2,\ w, z \cdots$$

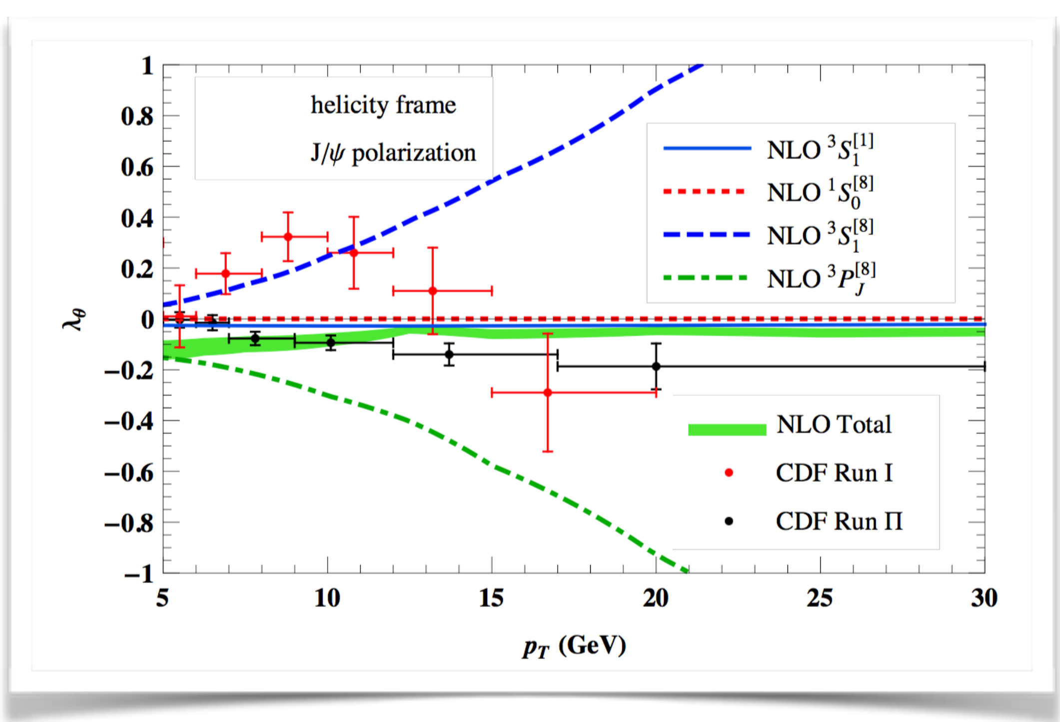
Includes low p_T region

[Butenschon, Kniehl, 1105.0820]

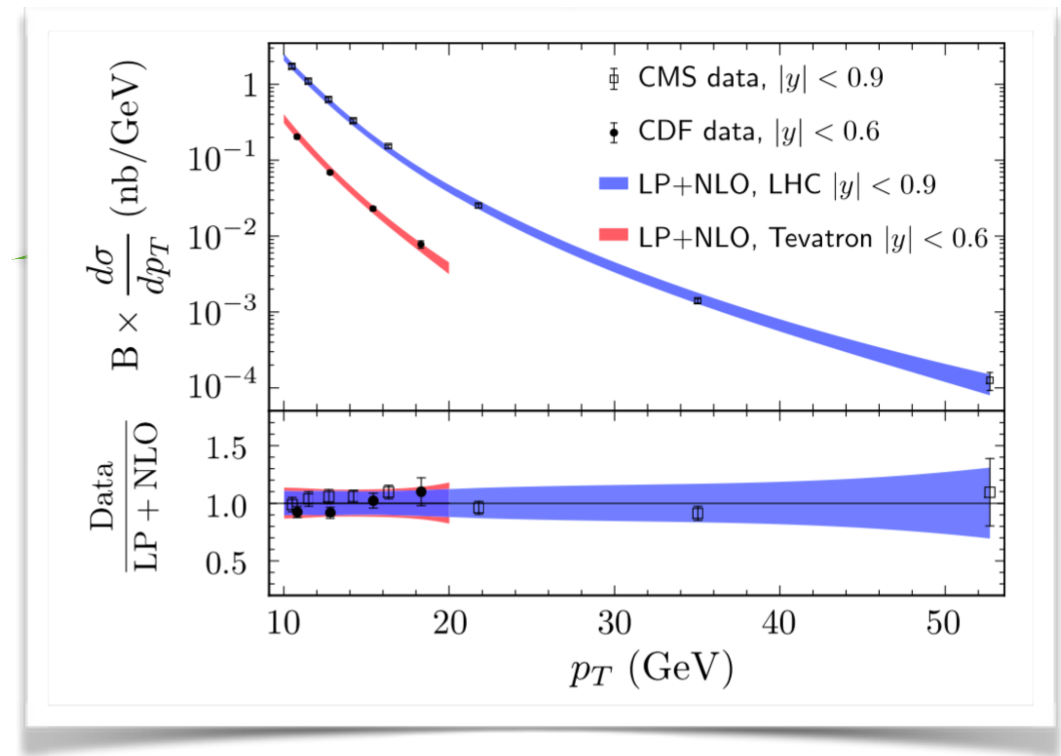
[Chao et al., 1201.2675]

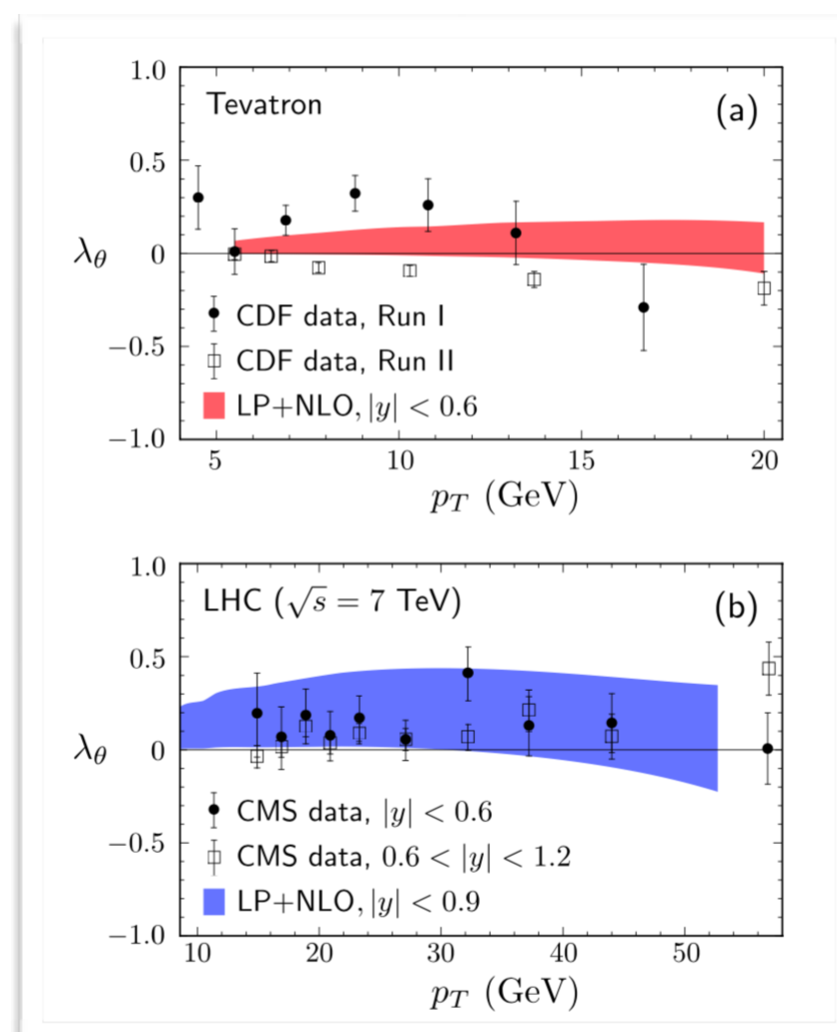






[Bodwin et al., 1403.3612]





Fragmenting Jet Function (FJF)

$$\mathcal{G}_i^H(s, z, \mu) = \sum_j \int_z^1 \frac{dz'}{z'} \mathcal{J}_{ij}(s, z', \mu) D_j^H(z/z', m_H, \mu)$$

Jet scale

Hadron scale

[M. Procura, I. Stewart, PRD, 81, 074009]

[M. Baumgart, A. Leibovich, T. Mehen, I. Rothstein, JHEP, 11, 003 (2014)]

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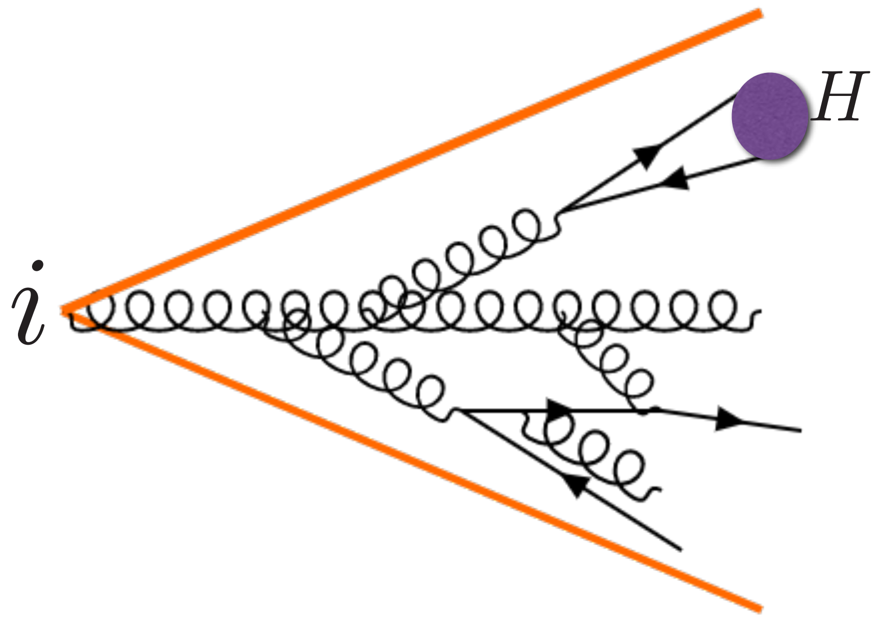

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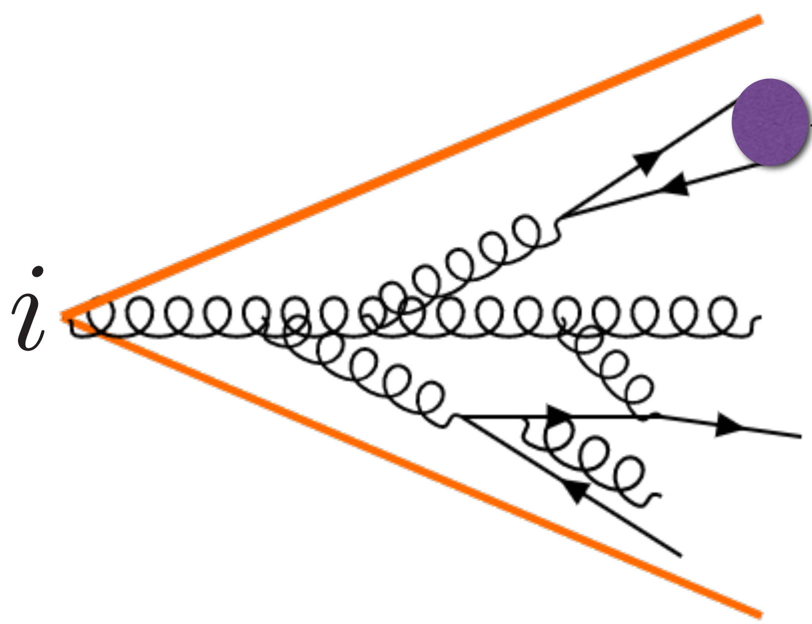

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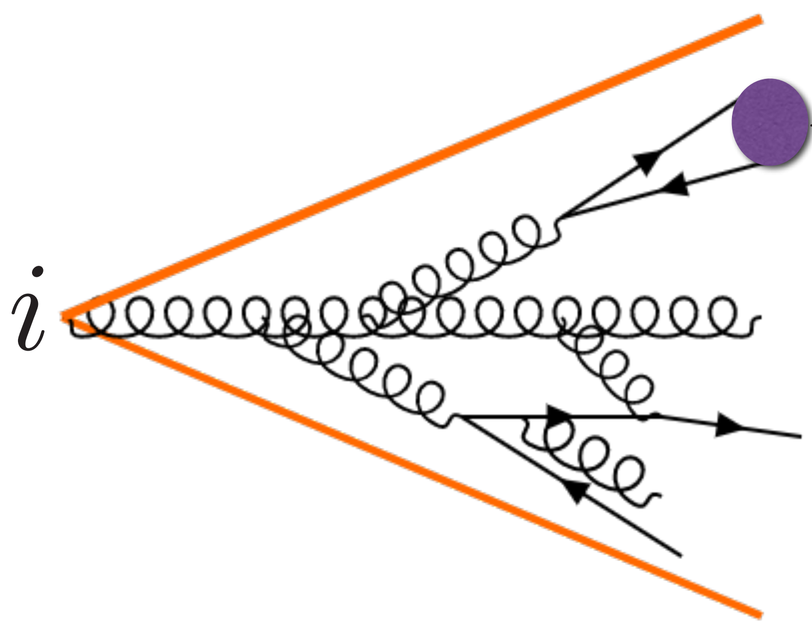

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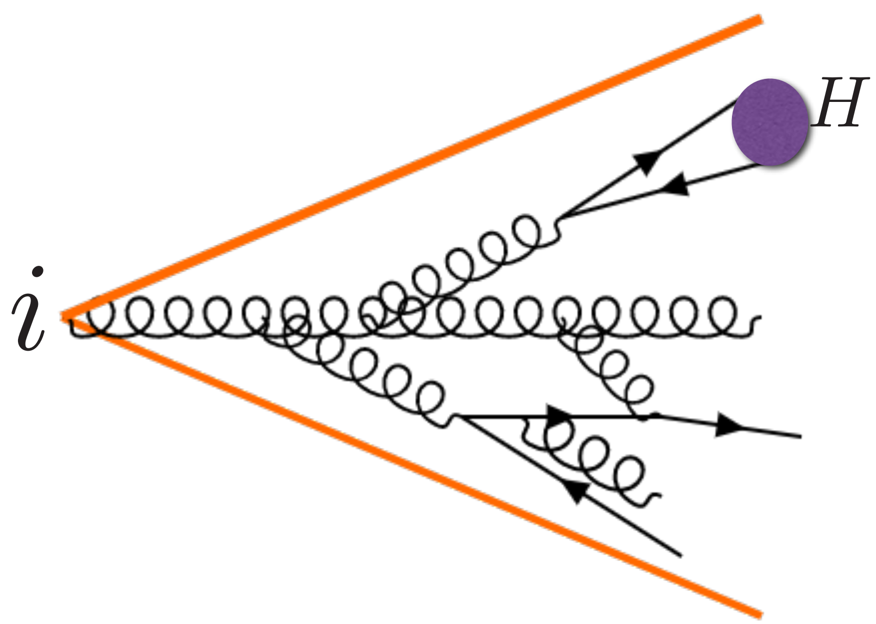

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Insert meas. Op. $\delta(s-\mathcal{S})$ for FFJ

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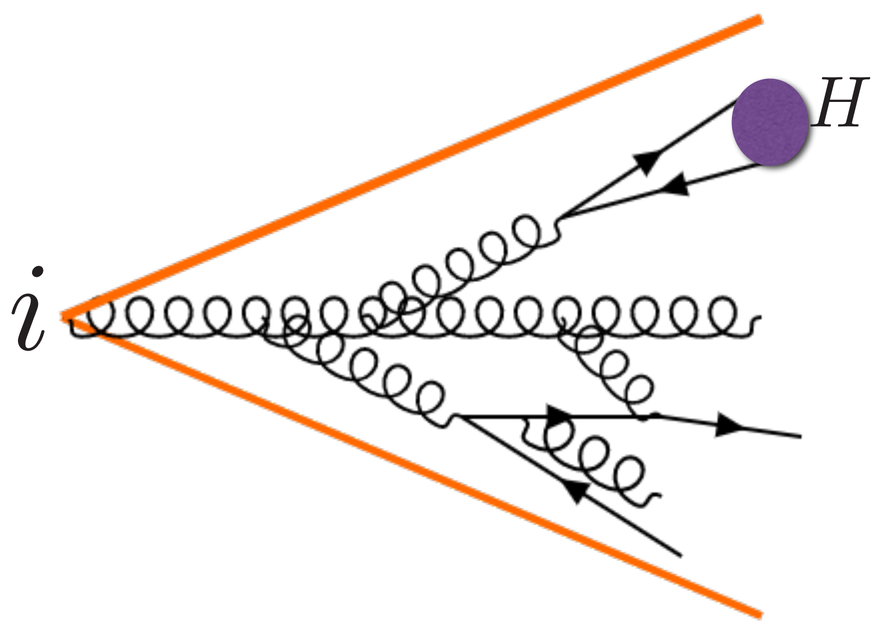

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Insert meas. Op. $\delta(s-\mathcal{S})$ for FFJ

Practical: resum $\log(\frac{m_H}{s})$

Factorize Everything

$$\sigma(H) = \sum_i \mathcal{H} \otimes \mathcal{S} \otimes \mathcal{G}_i^H \otimes \mathcal{J}_1 \otimes \mathcal{J}_2 \otimes \cdots$$

$$\mathcal{G}_i^H(s, z, \mu) = \sum_j \int_z^1 \frac{dz'}{z'} \mathcal{J}_{ij}(s, z', \mu) D_j^H(z/z', m_H, \mu)$$

B meson, or J/ψ FF.

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

$$B$$

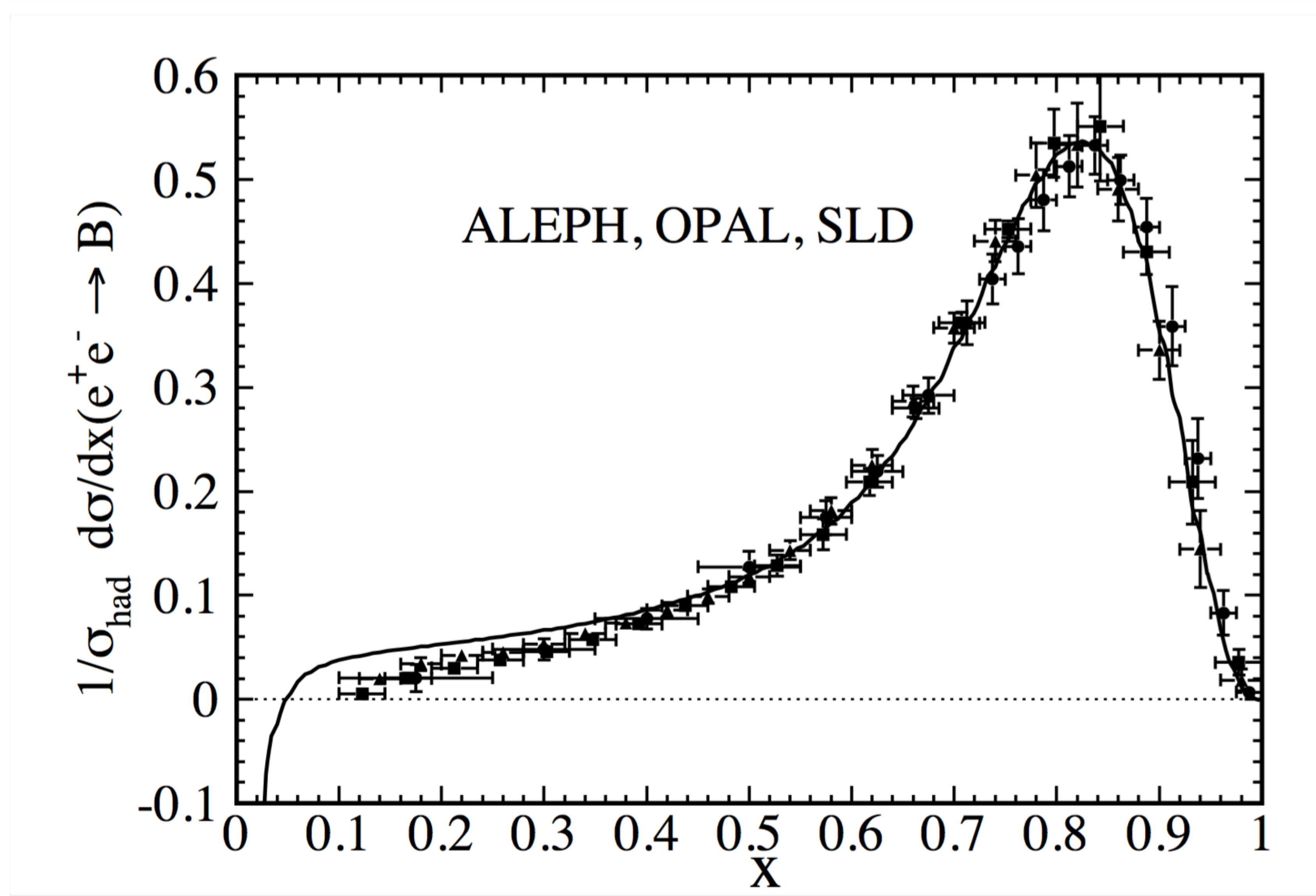
B Fragmentation Function

Power Model FF $D_b^B(z) = N z^\alpha (1-z)^\beta$

- $\alpha = 16.87, \beta = 2.02$

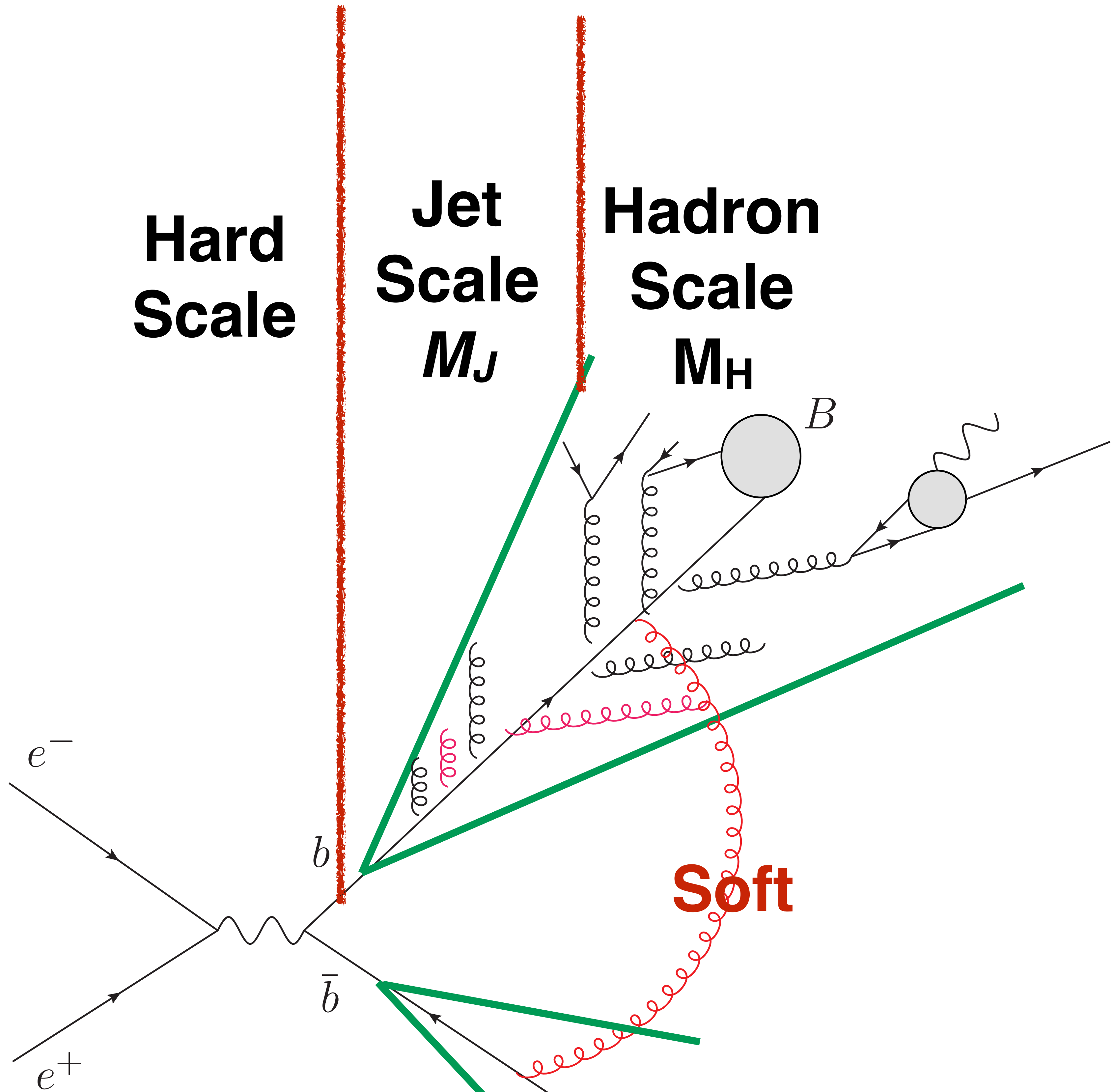
  2 parameters,
  N fixed by:
  $$\int_0^1 dz z D(z) = 1$$

- Fit at m_B scale



[Kniehl and Kramer, 0705.4392]

Monte Carlo & Analytic (B in jet)



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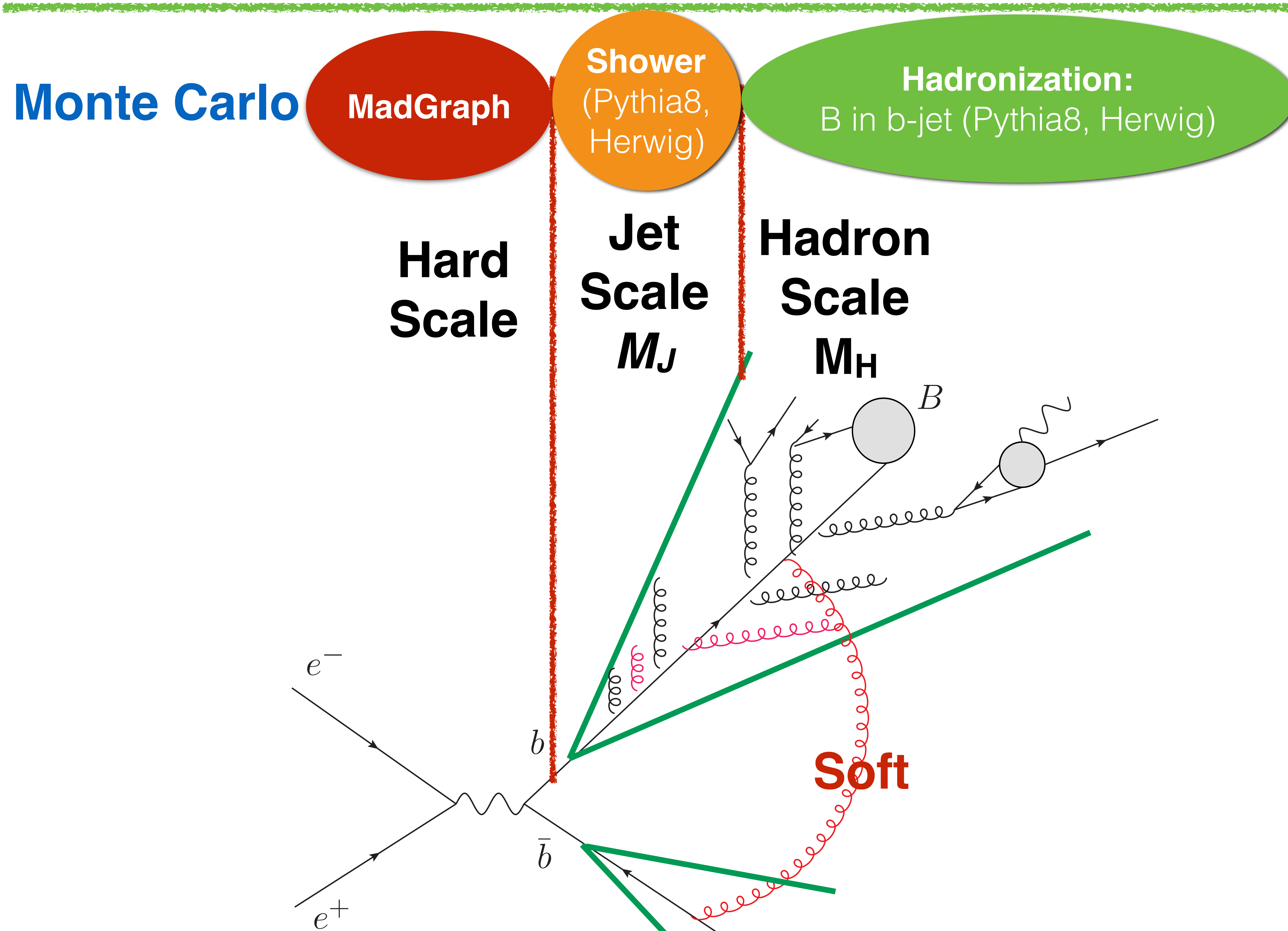

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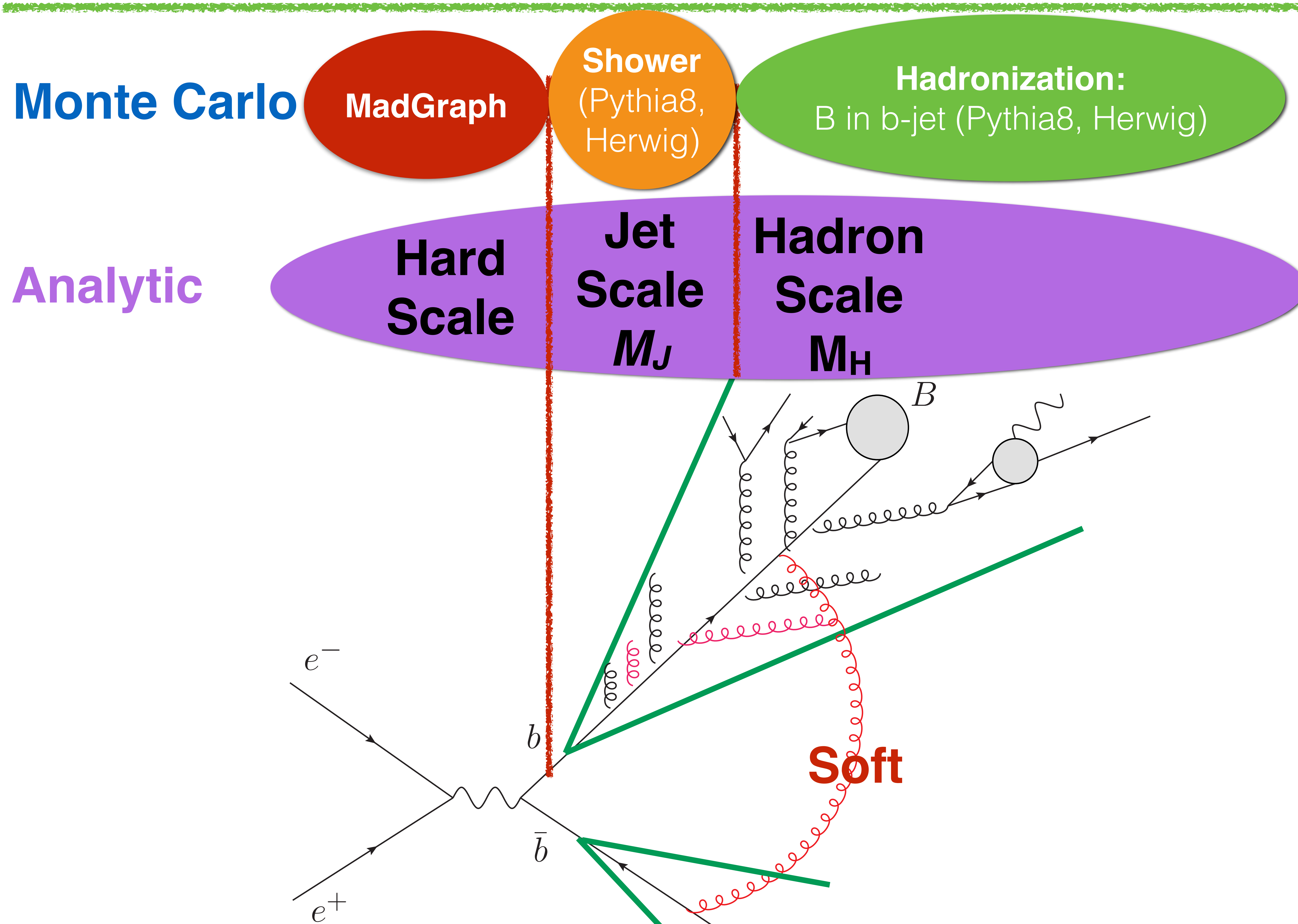
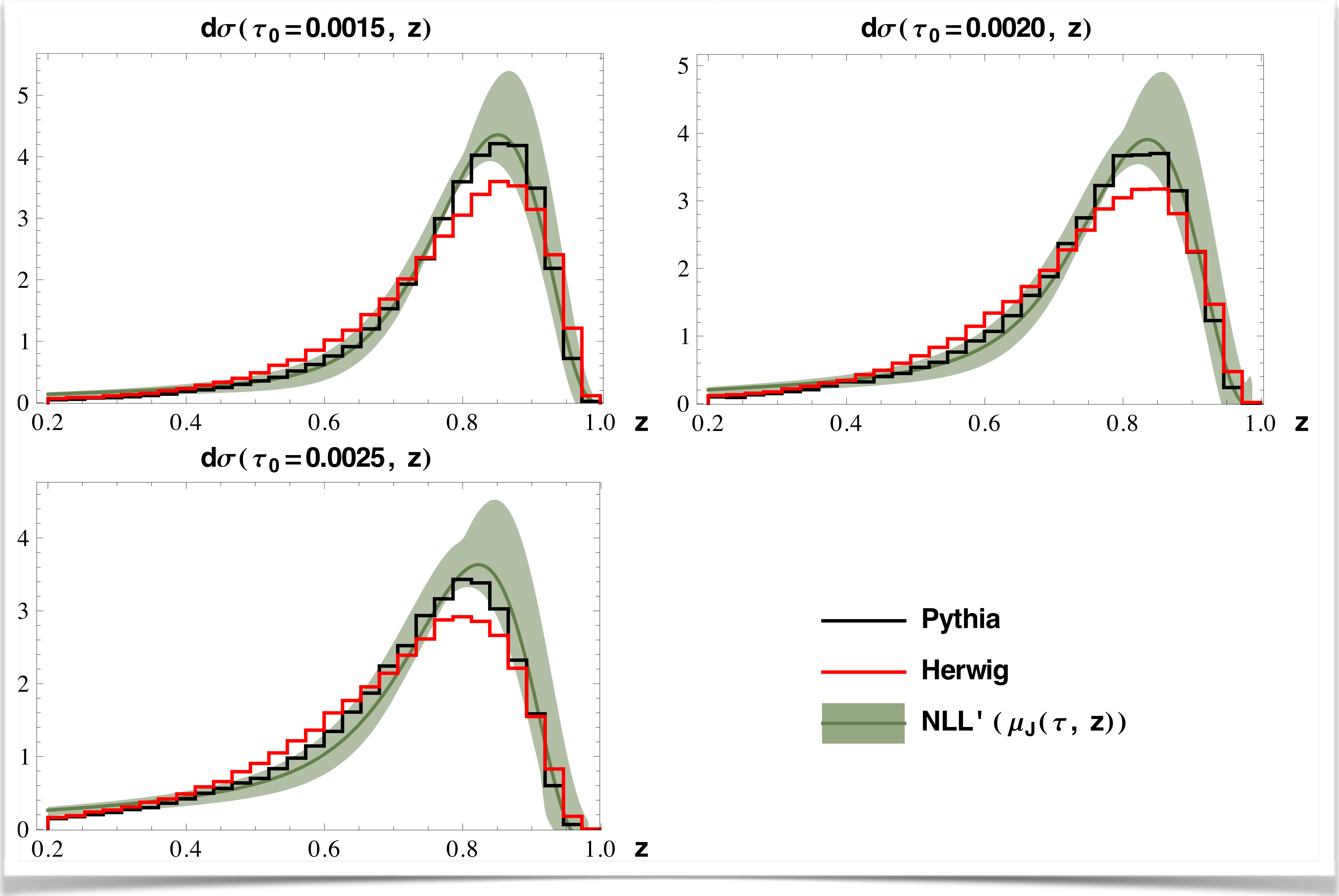




$$z \equiv \frac{E_B}{E_J} \qquad \tau_0 \propto m_J$$

FF: Pythia8 & Analytic: Power Model
Herwig: Cluster hadronization

[R. Bain, L. Dai, A. Hornig, A. Leibovich, Y. Makris, T. Mehen, JHEP, 06, 121 (2016)]

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

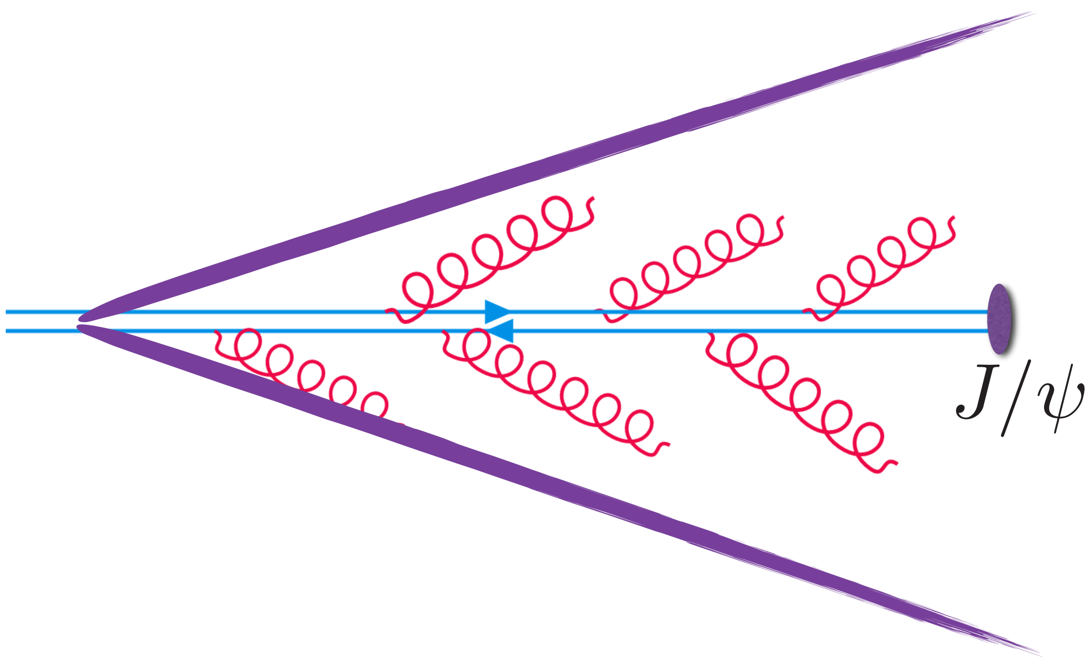
$\rightarrow \mathrm{J}/\psi$

J/ψ Production with Pythia

Pythia default:

$Q\bar{Q}(^3S_1^{[8]},\cdots)$ Produced in hard process

Pythia Shower with $2P_{qq}$



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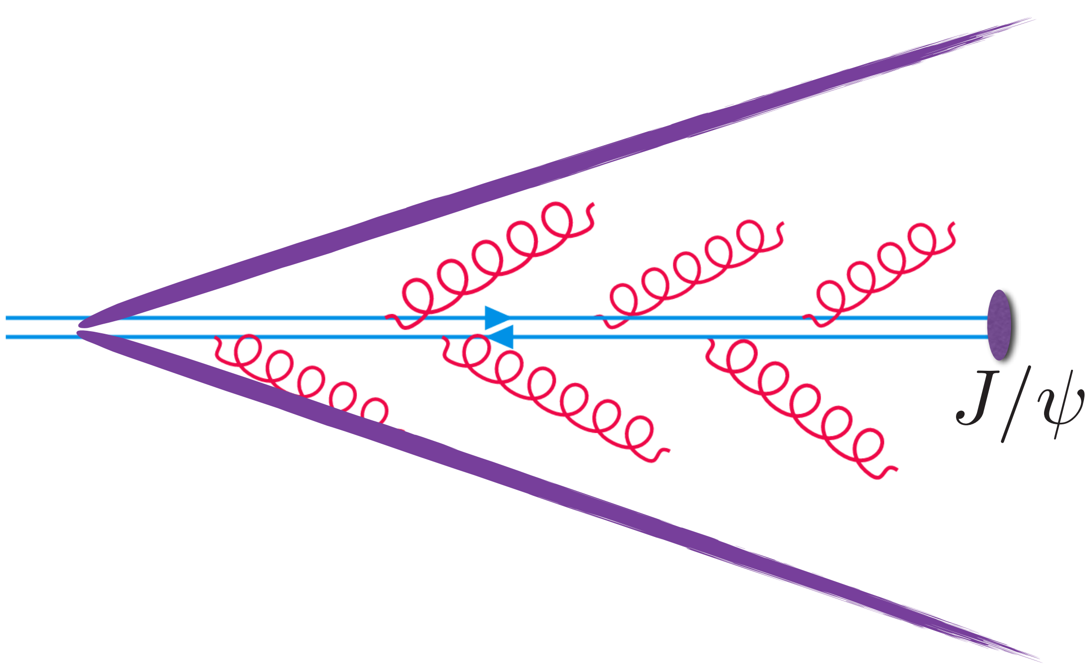
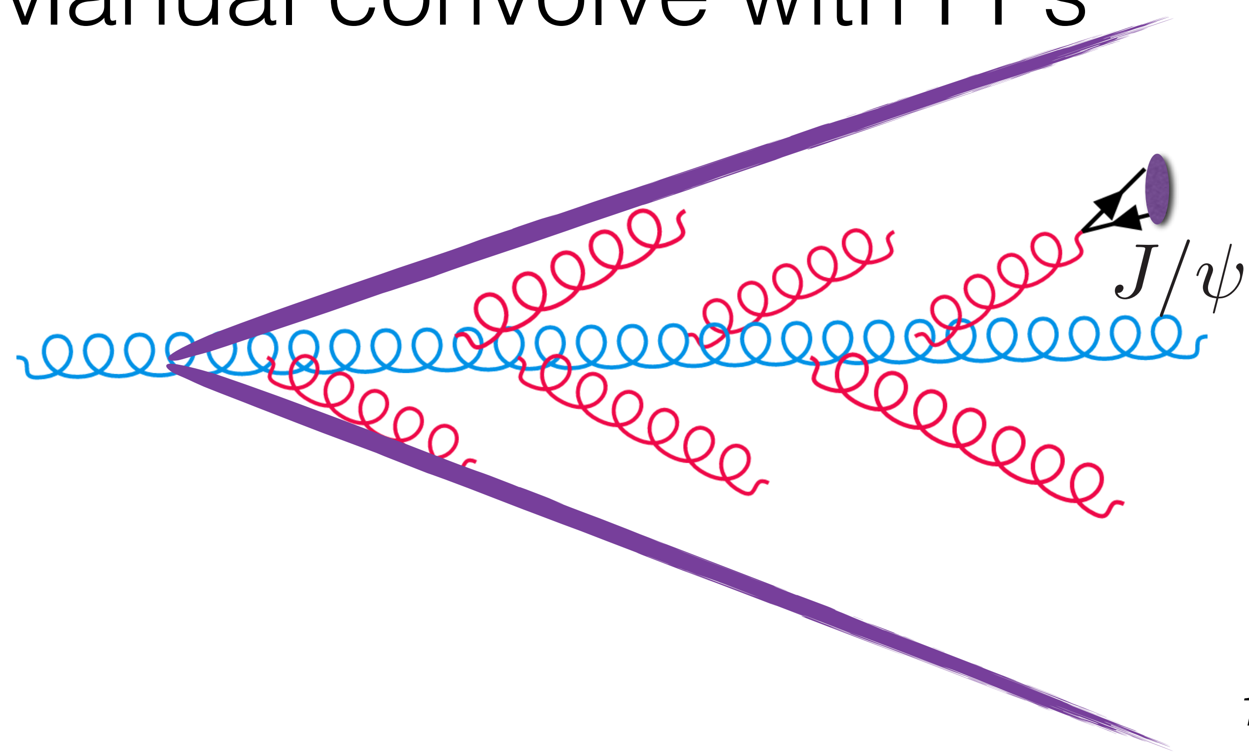


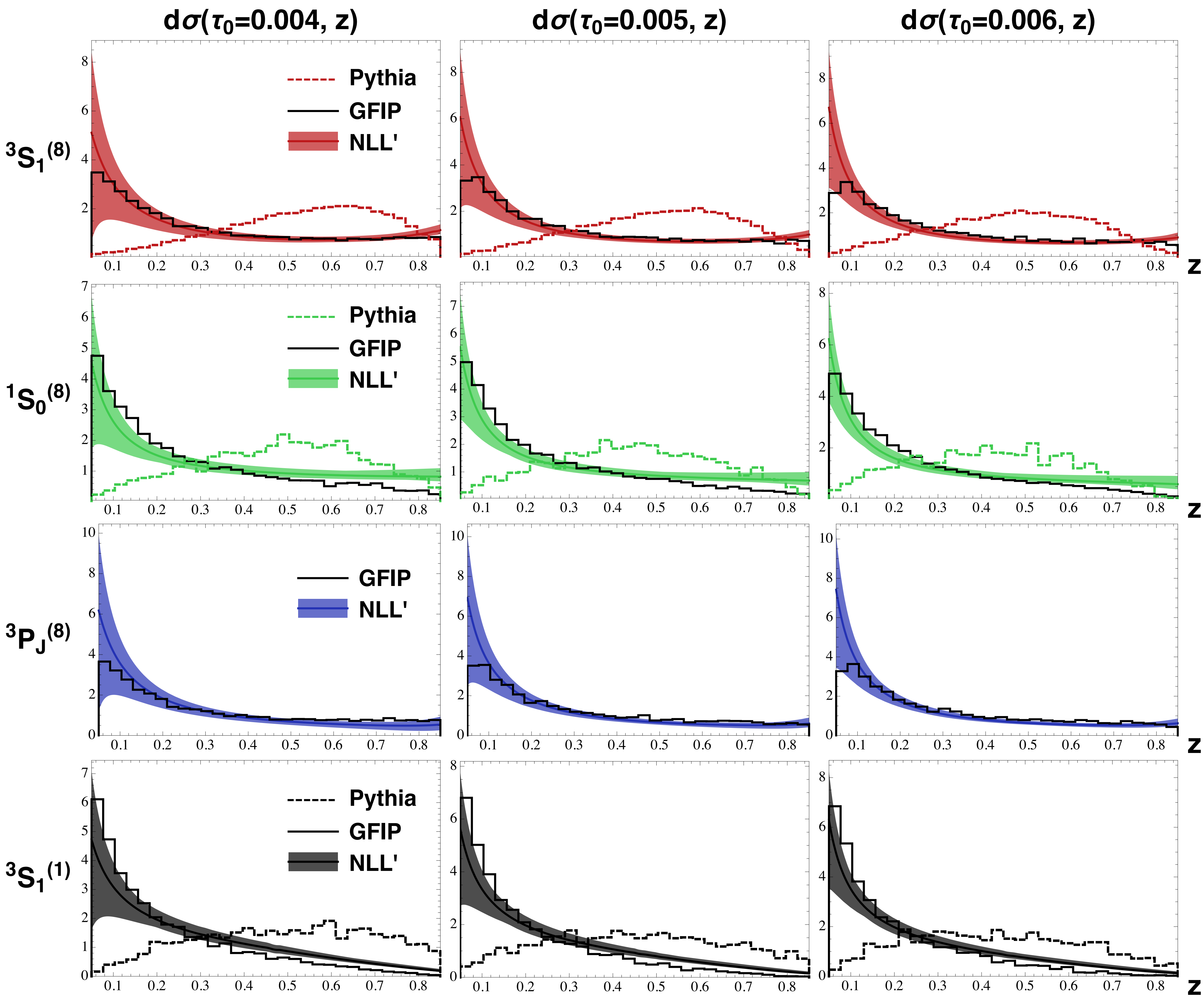
Gluon Fragmentation Improved Pythia (GFIP):

Initiating gluon produced in hard process

Pythia Shower
(to *2m*$_c$, Hadronization off)

Manual convolve with FFs





[R. Bain, L. Dai, A. Hornig, A. Leibovich, Y. Makris, T. Mehen, JHEP, 06, 121 (2016)]

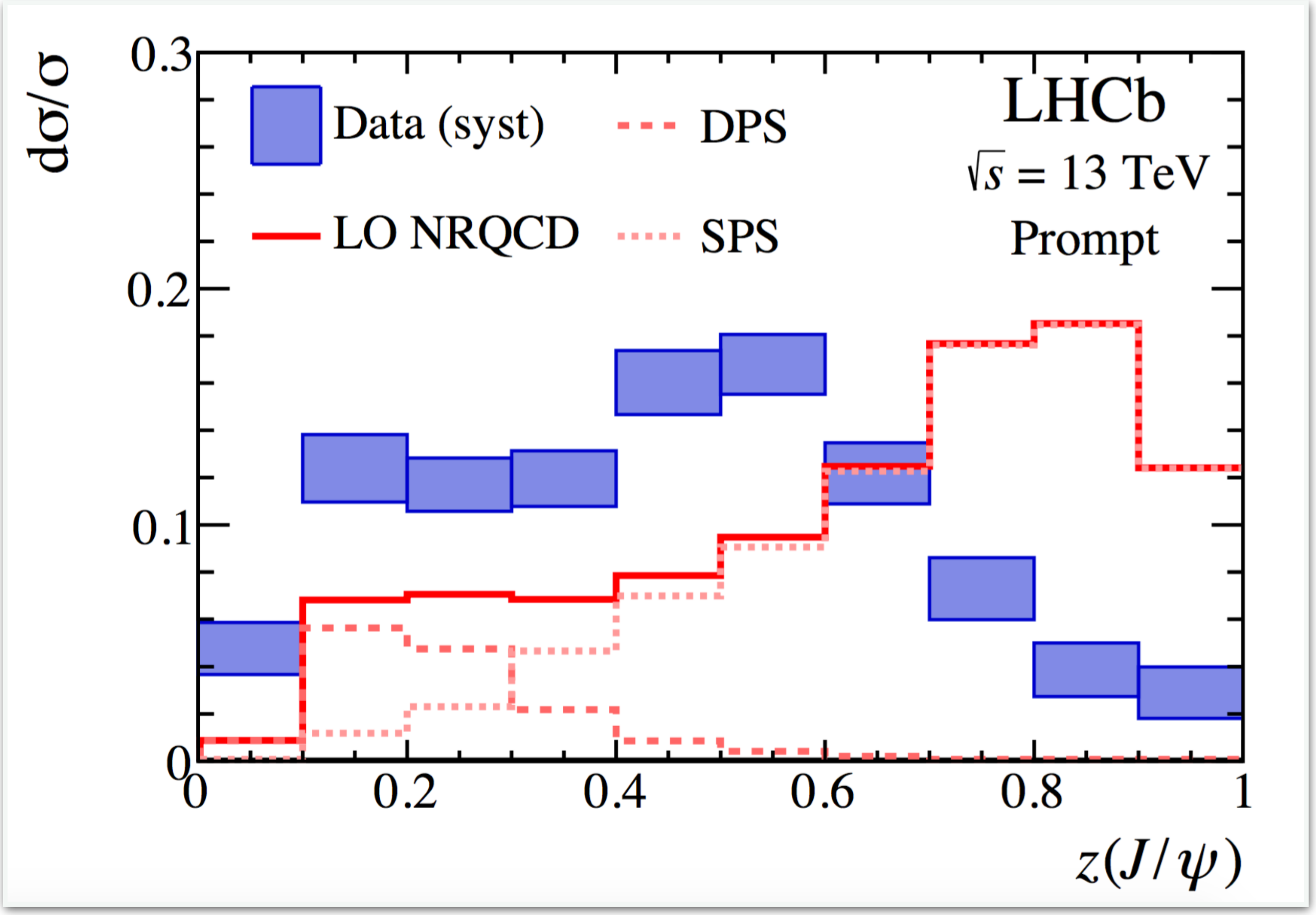
$$pp \rightarrow \text{jet} + X$$

$$\text{J}/\psi$$

J/psi in jets @ LHCb

Cuts:

$$p_T(\text{jet}) > 20 \text{ GeV}$$
$$2 > \eta(\text{jet}) > 2.5$$
$$p_T(\mu) > 0.5 \text{ GeV}$$
$$p(\mu) > 5 \text{ GeV}$$
$$4.5 > \eta(\mu) > 2$$

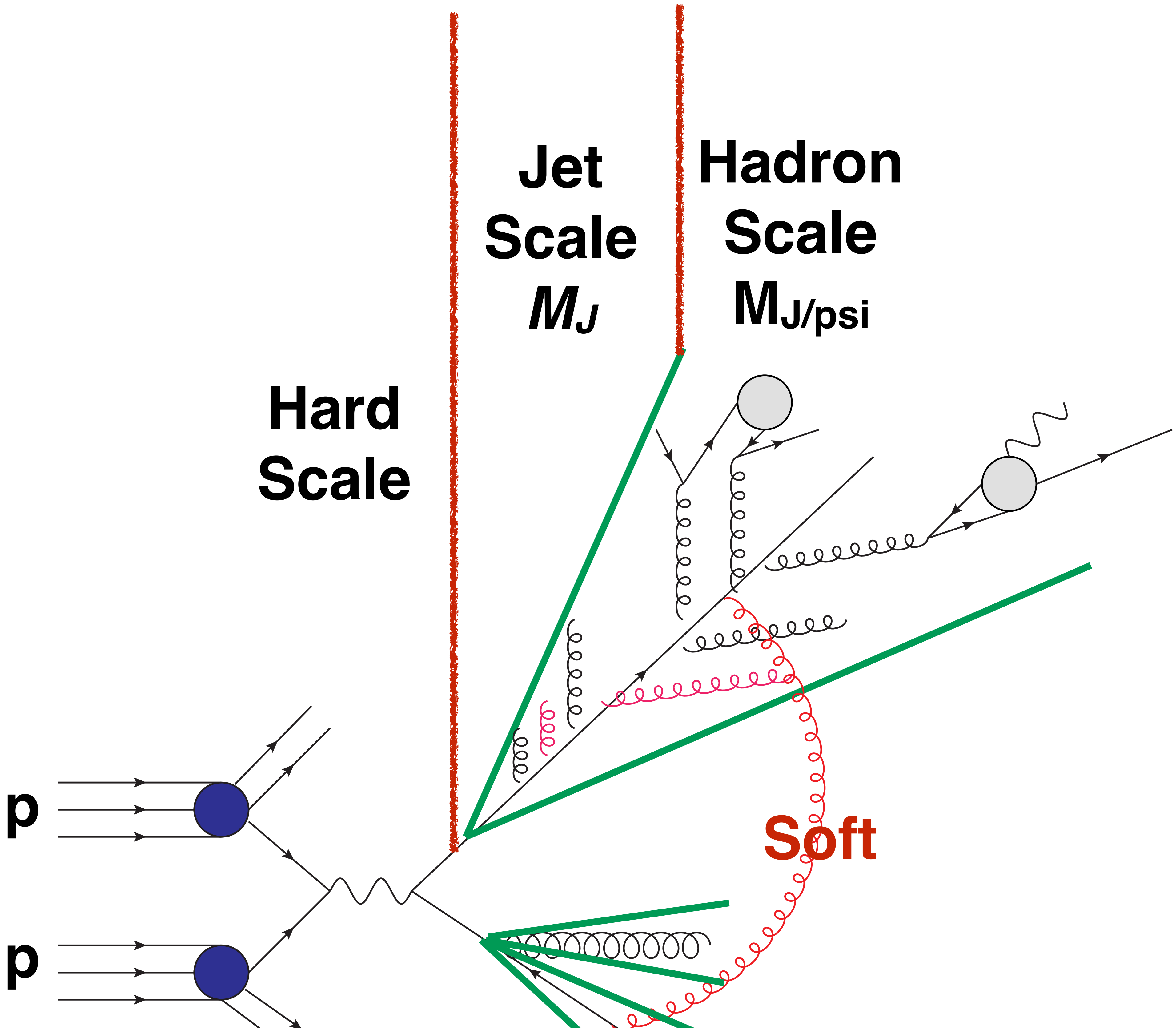


Similar to ee>J/psi:

J/psi too hard in jets

[LHCb, Phys. Rev. Lett. 118, 192001 (2017)]

Analytic & GFIP (J/psi in jets @ LHCb)



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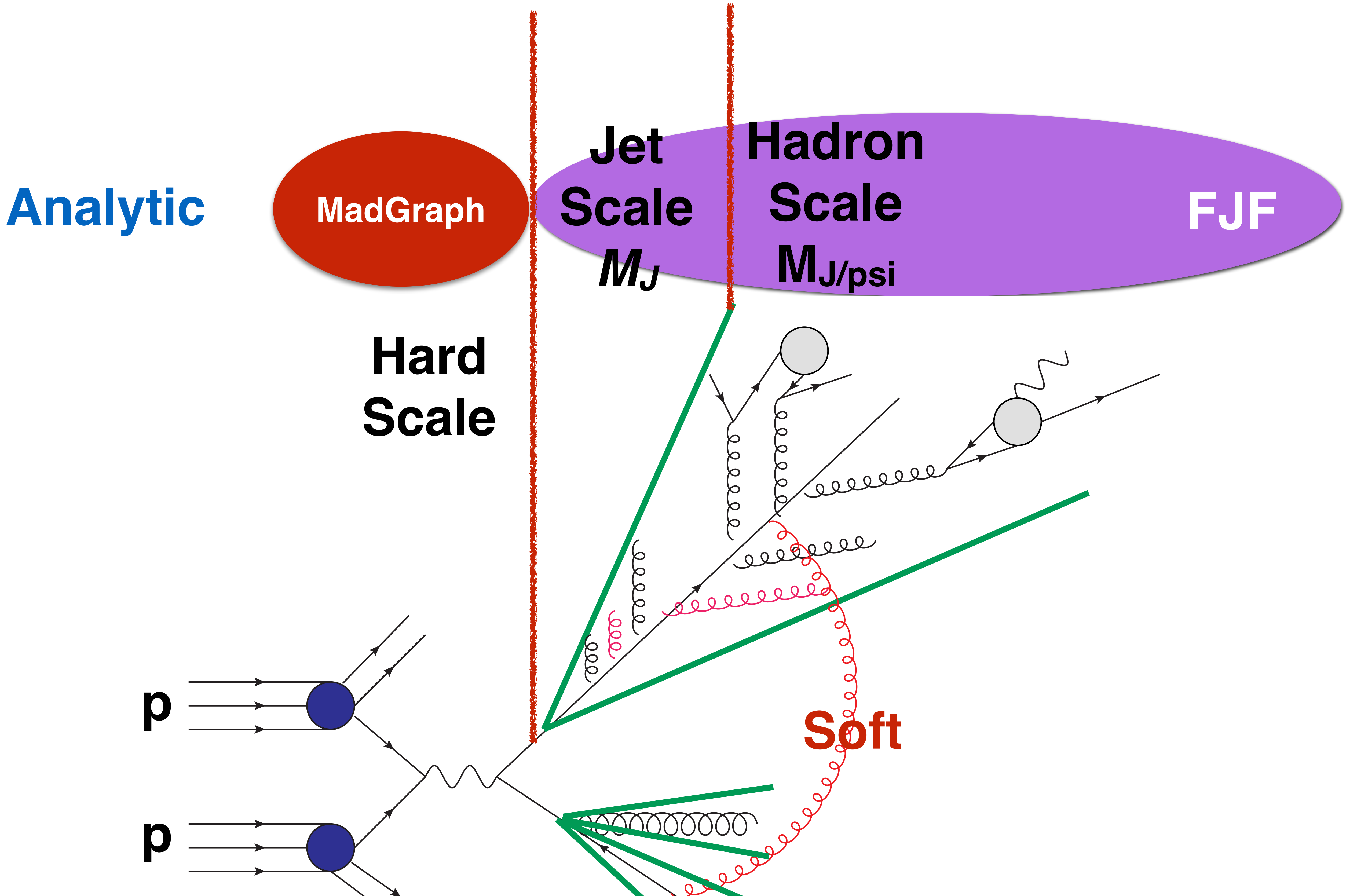

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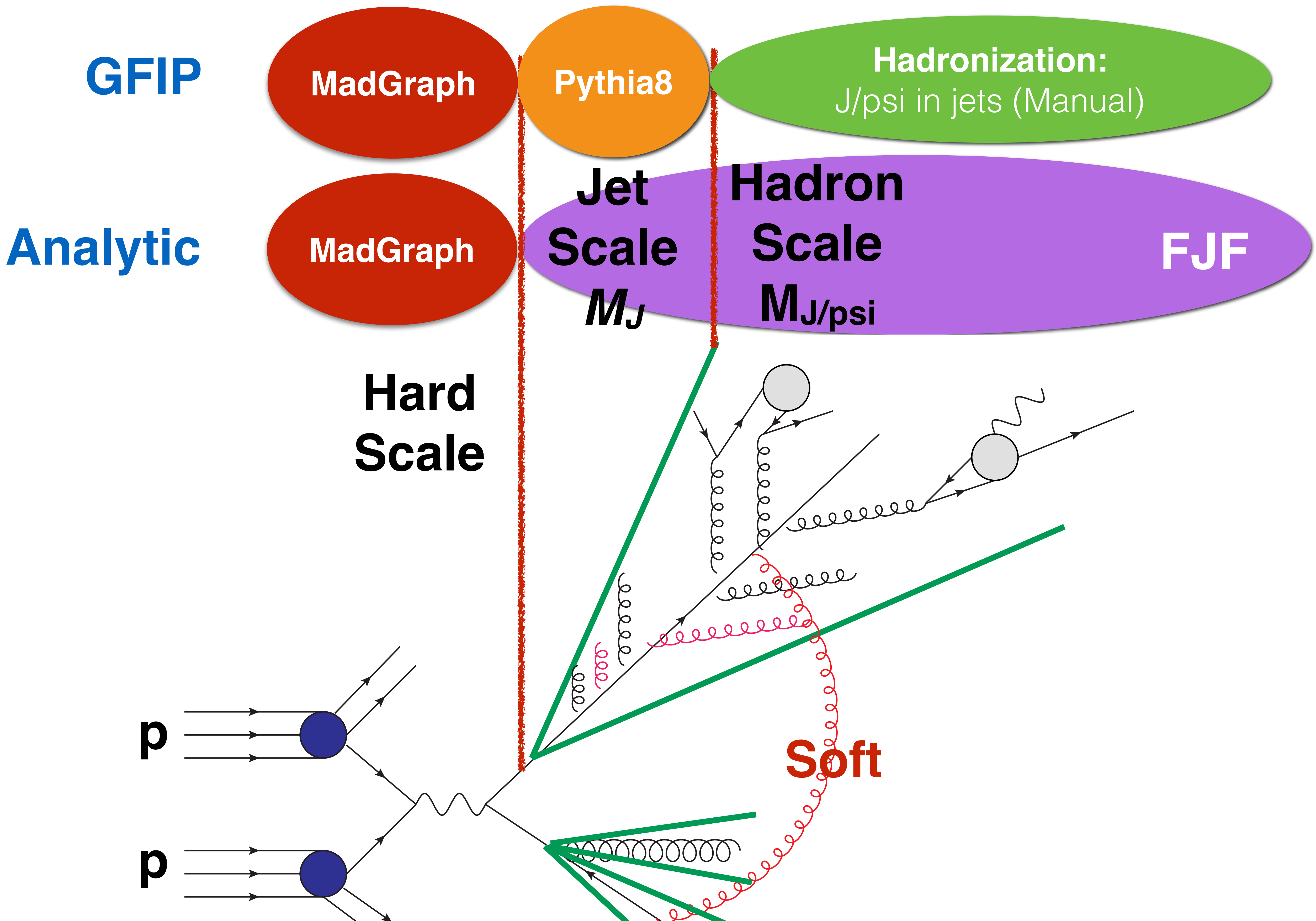
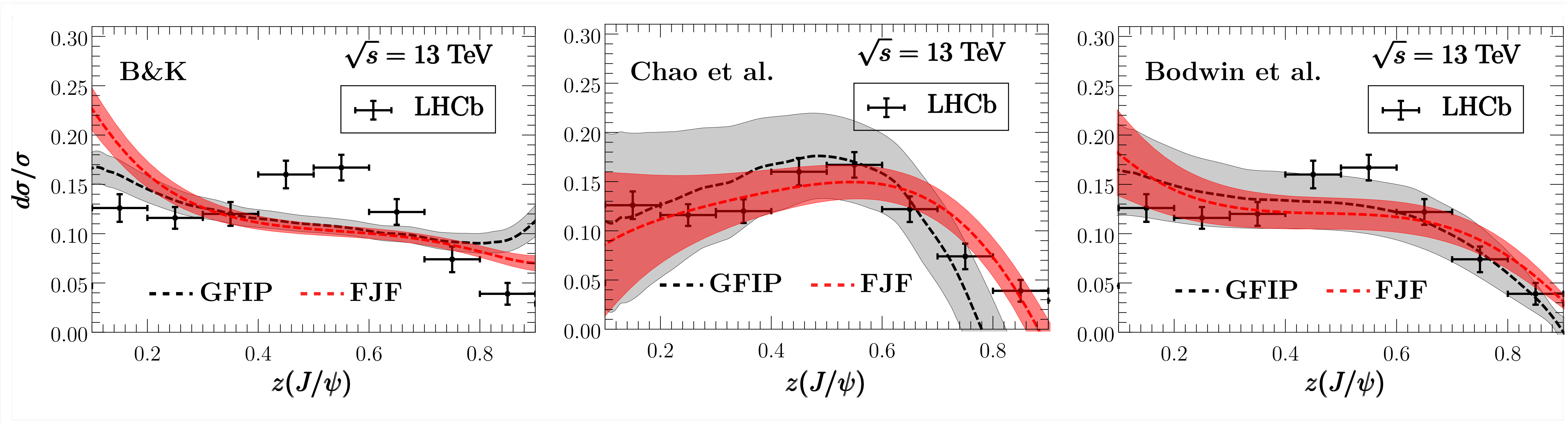


Comparison with LHCb Data



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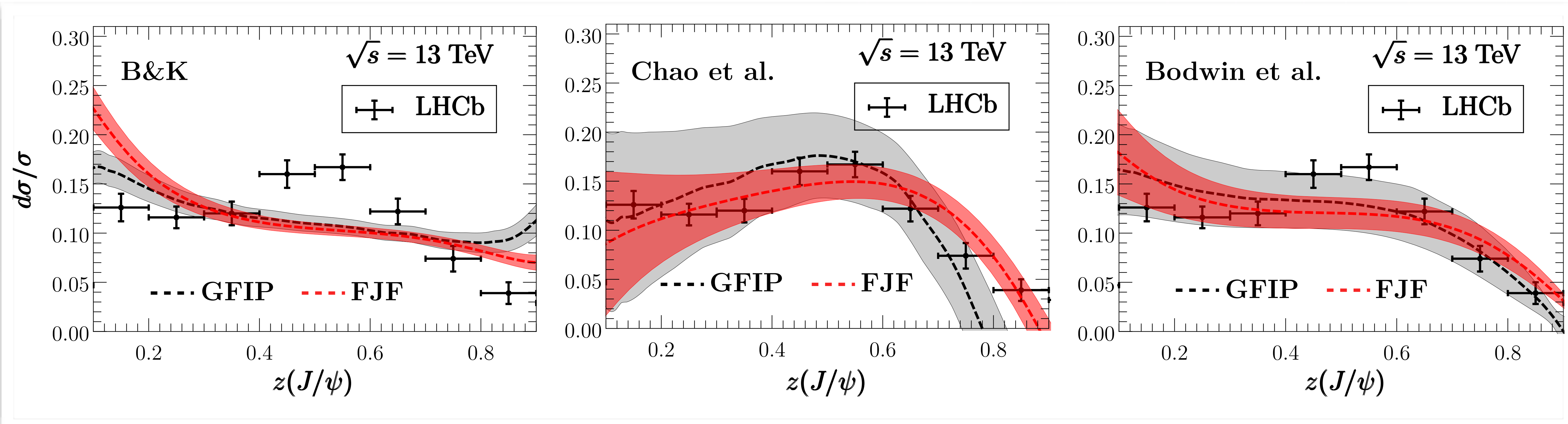

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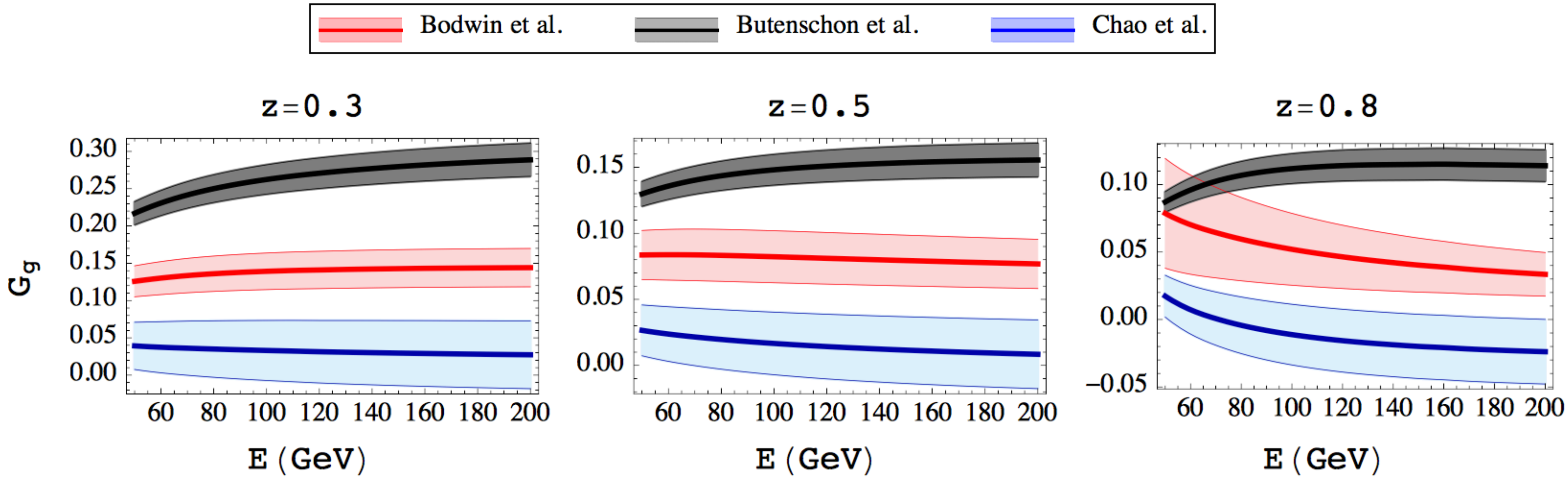
- Both FJF & GFIP work better than default Pythia;

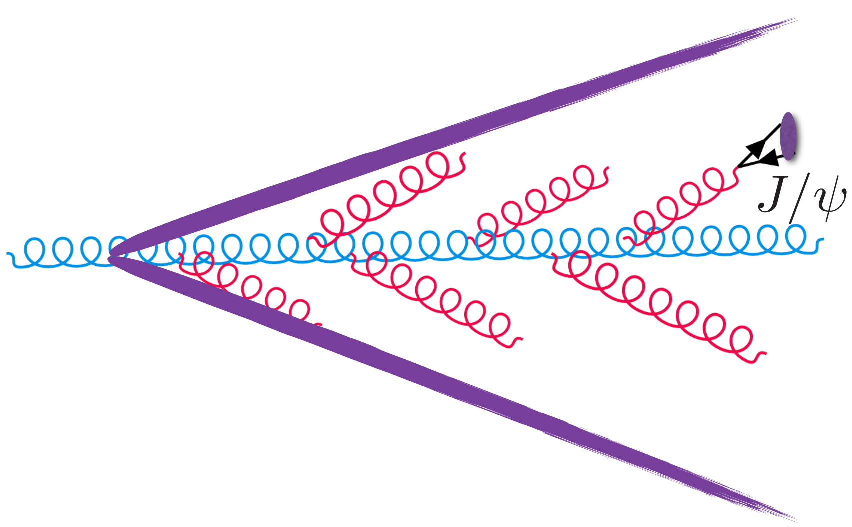
- High pT LDMEs give better description of data than the global fit ones

- Error band only from LDMEs (B&K narrower, used more data)

E(jet) distribution



[M. Baumgart, A. Leibovich, T. Mehen, I. Rothstein, JHEP, 11, 003 (2014)]



- ✦ E is jet energy
- ✦ LDME from Global and high-pt extractions different
- ✦ G_g is not observable…
- ✦ Evaluate at the cross section level (similar feature)

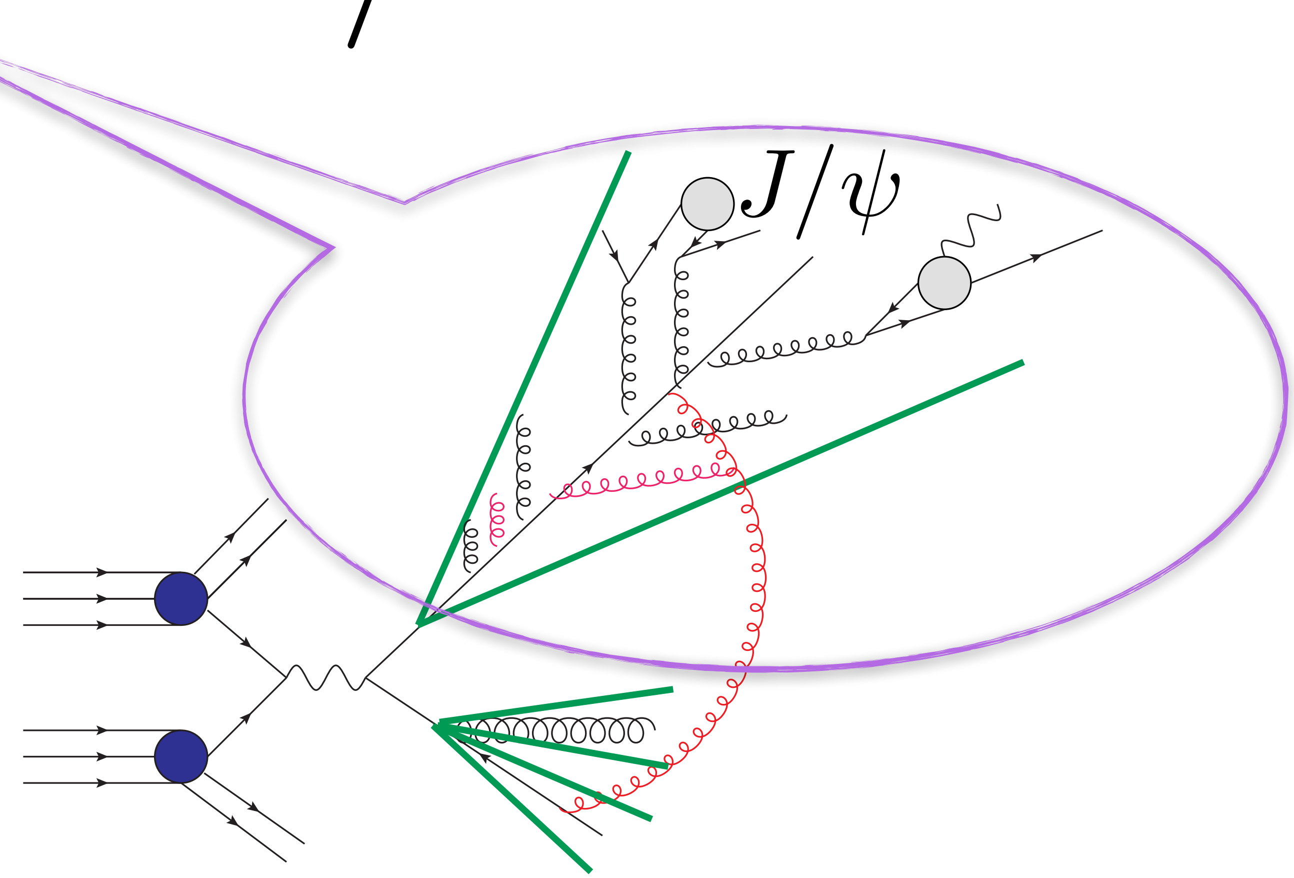
E(jet) distribution

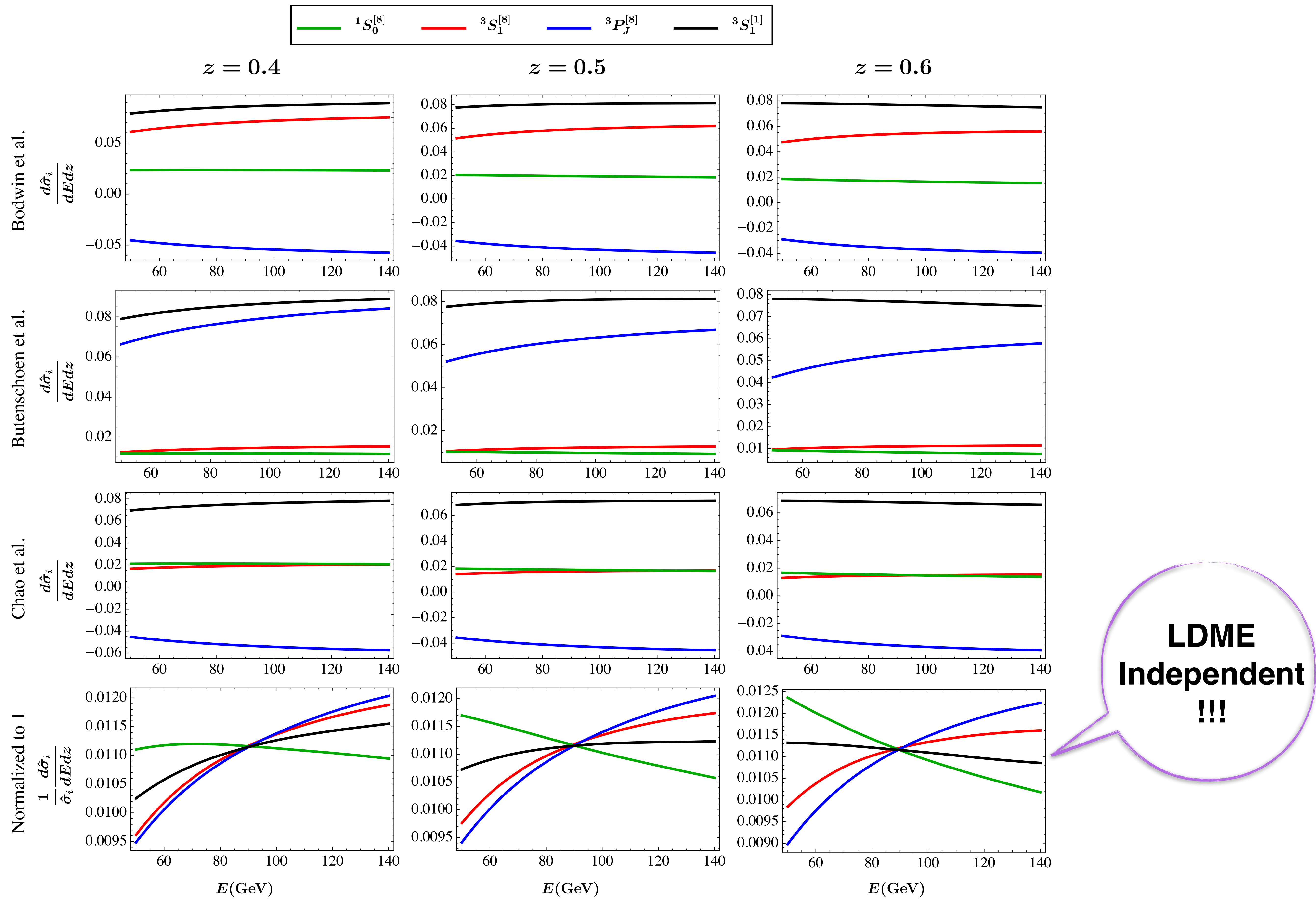
- Normalized cross sections for the LHC (i denote production channels):

$$\frac{d\sigma_i}{dEdz} = \sum_{a,b,l,m} H_{ab\to lm} \otimes f_{a/p} \otimes f_{b/p} \otimes J_m \otimes S \otimes \mathcal{G}_l^{\psi(i)}(E,R,z,\mu),$$

$$\frac{d\hat{\sigma}_i}{dEdz} \equiv \frac{d\sigma_i}{dEdz} \Bigg/ \frac{d\sigma_J}{dE}$$

- Normalized by inclusive 1-jet cross section (σ_J)



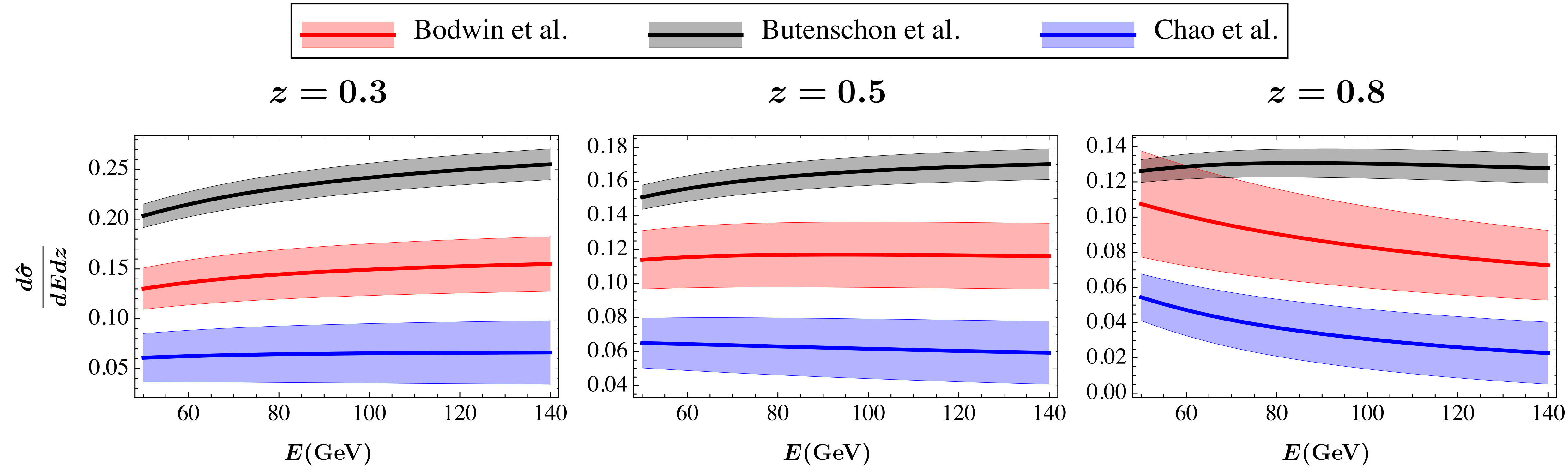


[L. Dai, P. Shrivastava, PRD 96, 036020 (2017)]

E(jet) distribution

- Total Cross Section:

$$\frac{d\hat{\sigma}}{dEdz} \equiv \sum_i \frac{d\hat{\sigma}_i}{dEdz}$$



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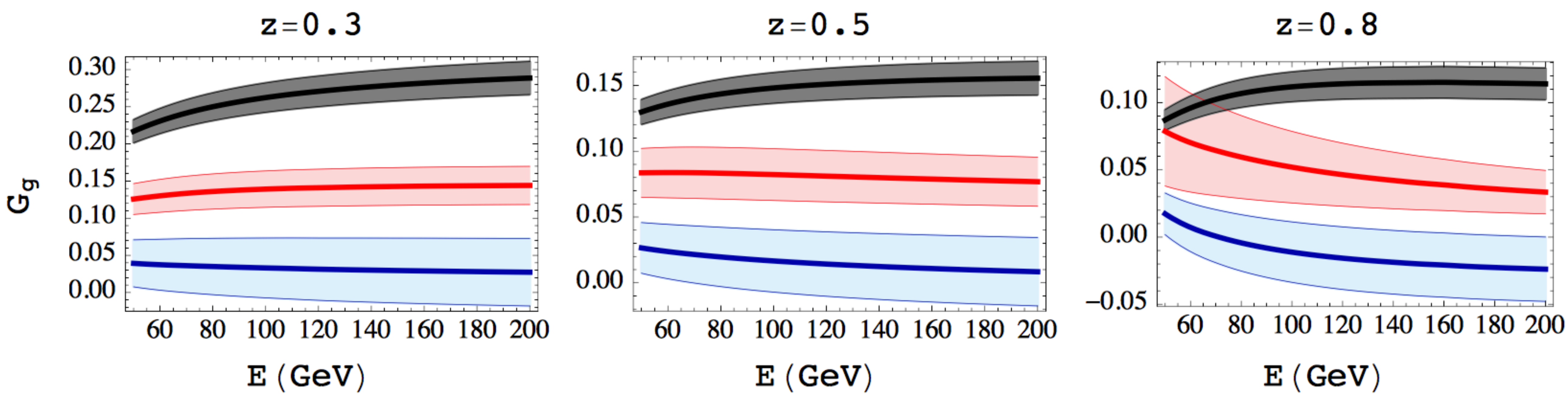

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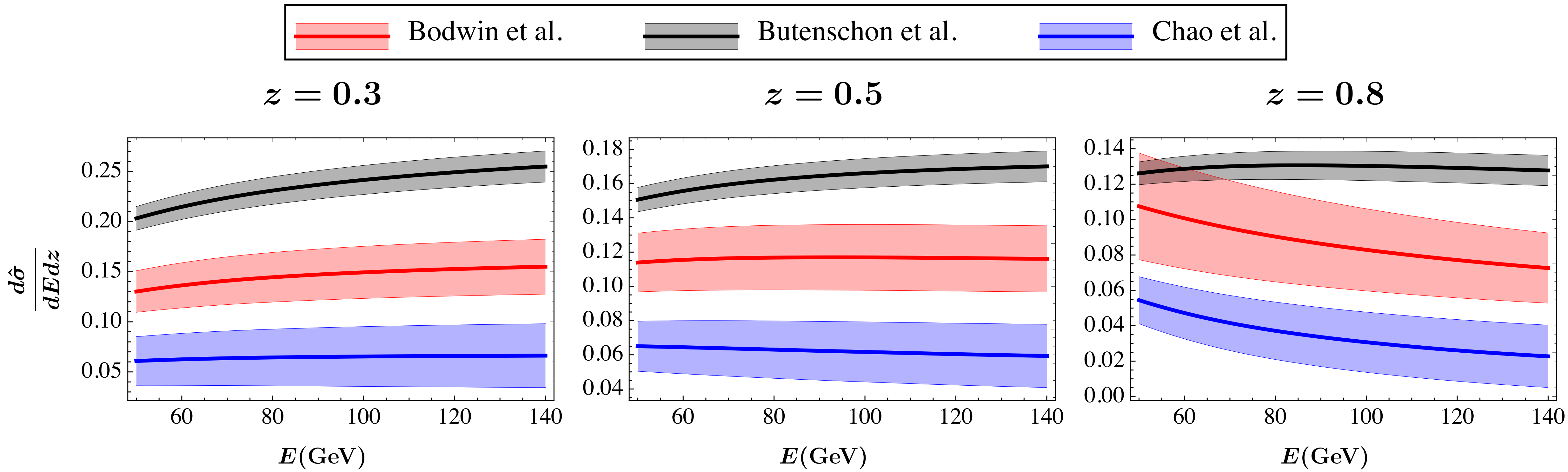
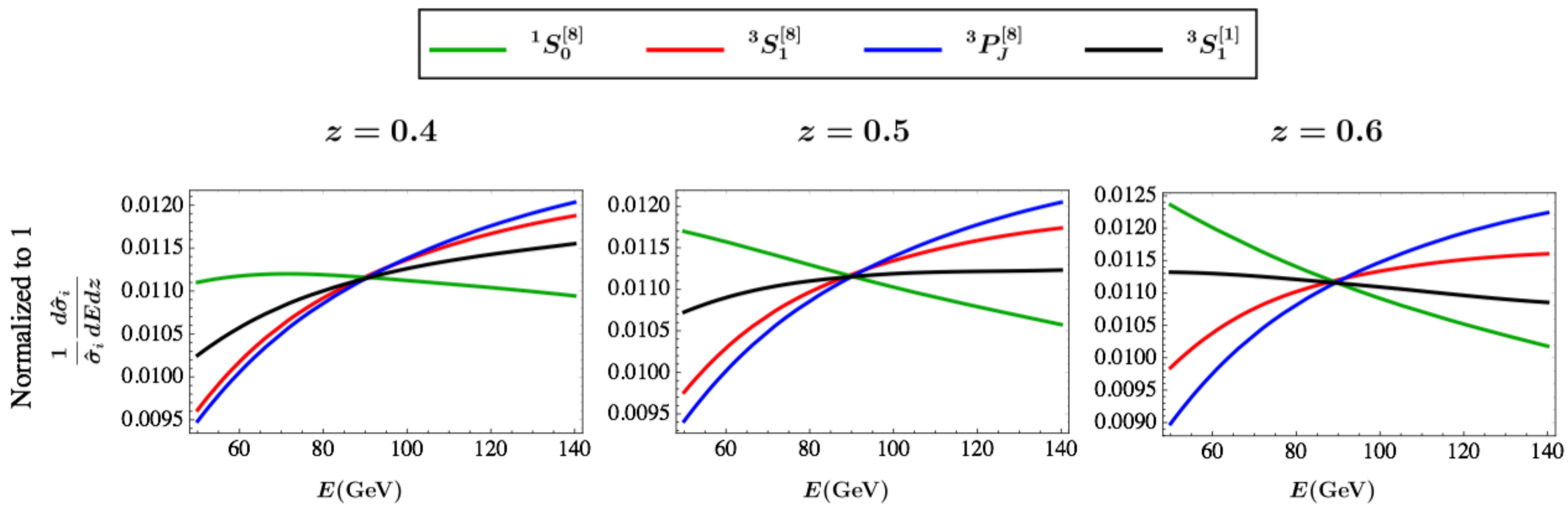


Decreasing at z > 0.5 (high pT), consistent with the dominance of $^1S_0^{[8]}$ at high pT



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Summary

- We study quarkonium production in jets using FJFs
- Use e^+e^- collisions to test our calculations:
  - B meson production agrees well with Pythia
  - J/ψ production, Pythia is not sufficient for our purpose
- Generalize to pp collision
  - Compare with LHCb data, high pT extractions give better description of data,
  - Study E(jet) distributions (the potential to distinguish production mechanisms and LDME extractions)

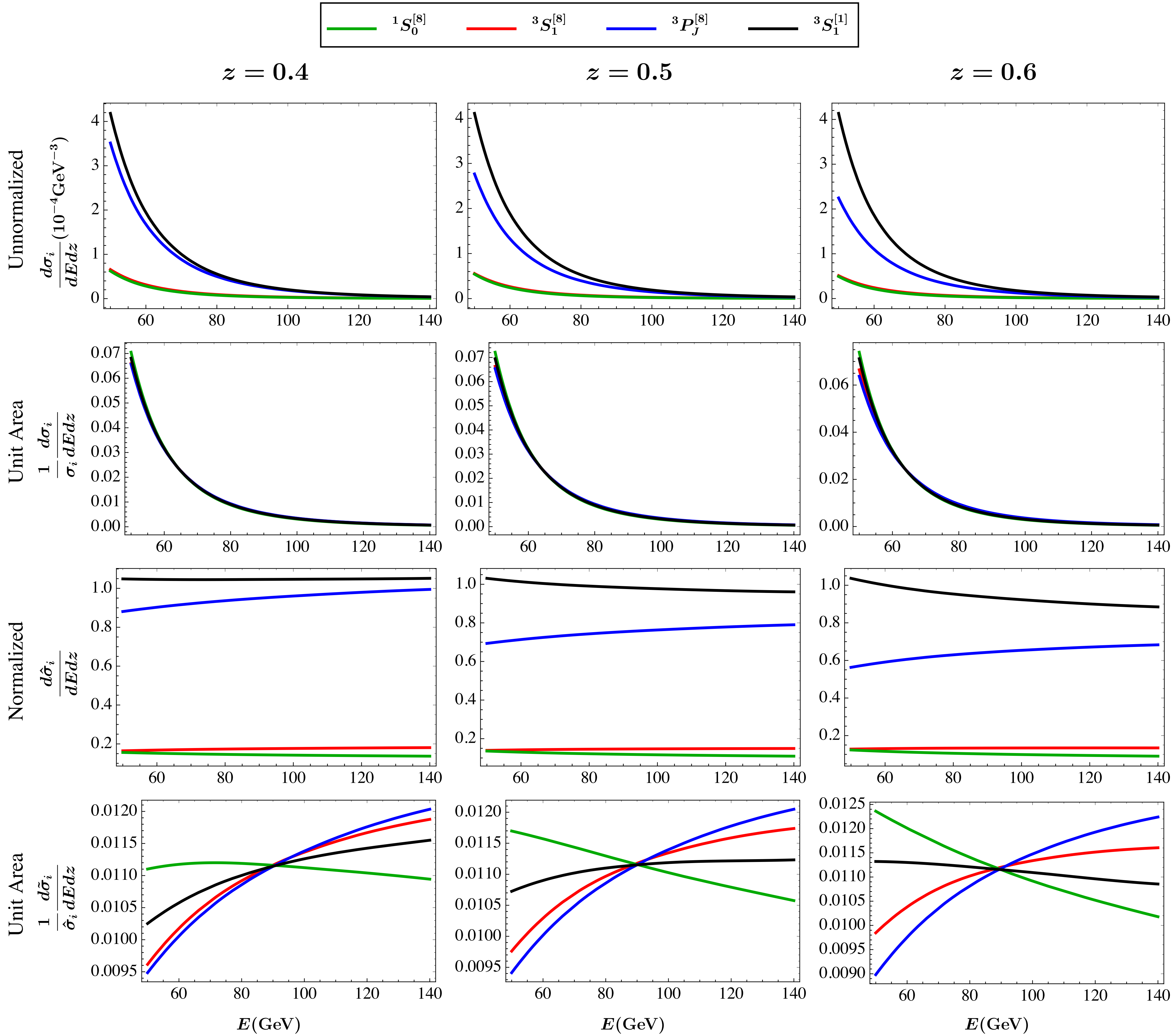
Summary

- We study quarkonium production in jets using FJFs
- Use e^+e^- collisions to test our calculations:
  - B meson production agrees well with Pythia
  - J/ψ production, Pythia is not sufficient for our purpose
- Generalize to pp collision
  - Compare with LHCb data, high pT extractions give better description of data,
  - Study E(jet) distributions (the potential to distinguish production mechanisms and LDME extractions)

Thank You!

Back Up

Butenschoen et al.



[L. Dai, P. Shrivastava, PRD 96, 036020 (2017)]

	$\langle \mathcal{O}^{J/\psi}(^3S_1^{[1]}) \rangle$ $\times$ 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	1.32 ± 0.20	0.224 ± 0.59	4.97 ± 0.44	-0.72 ± 0.88
Chao et al.	1.16 ± 0.20	0.30 ± 0.12	8.9 ± 0.98	0.56 ± 0.21
Bodwin et al.	1.32 ± 0.20	1.1 ± 1.0	9.9 ± 2.2	0.49 ± 0.44