Quarkonium Production in Jets at the LHC

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TMD Collaboration

U.S. DEPARTMENT OF ENERGY

Outline

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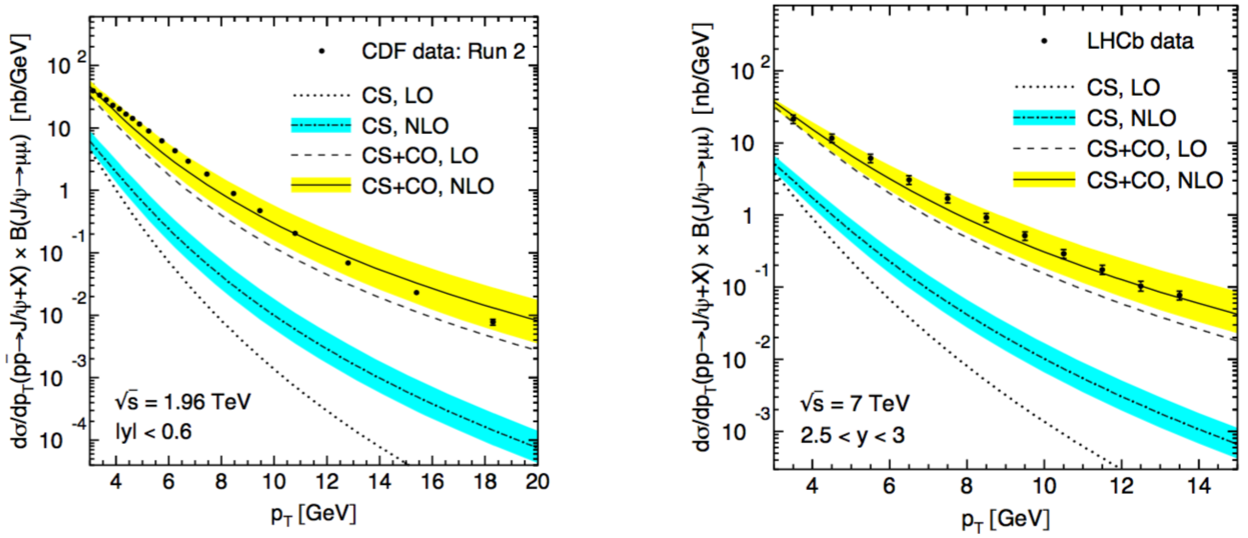
- pp collisions: J/ψ production in jets, compare with LHC data
- Summary

Some Motivations

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



[Butenschon, Kniehl, 1105.0820]

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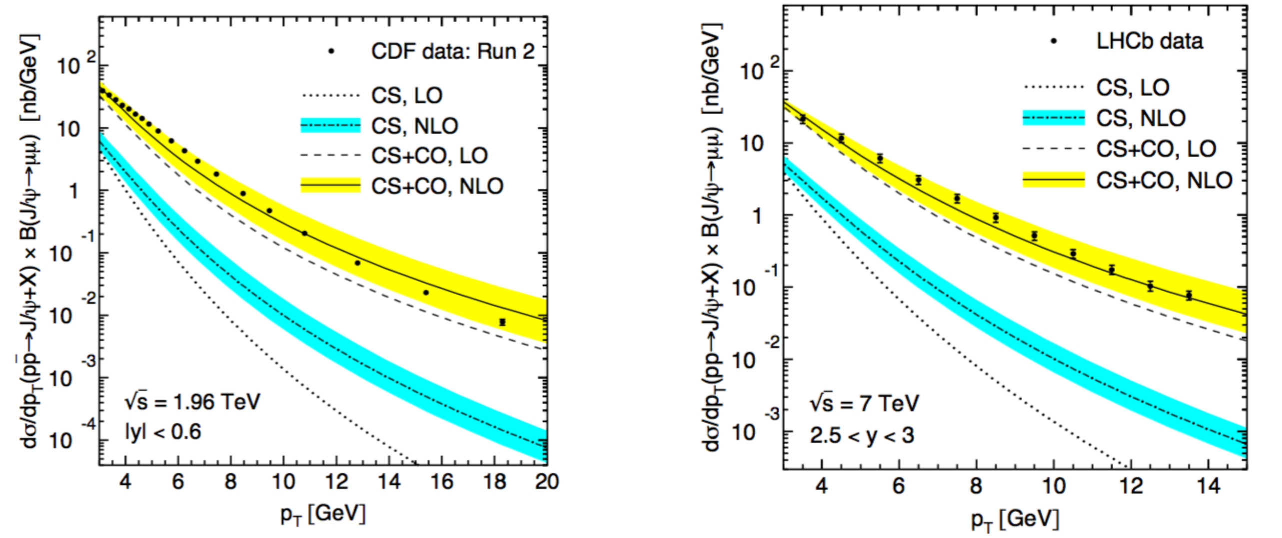

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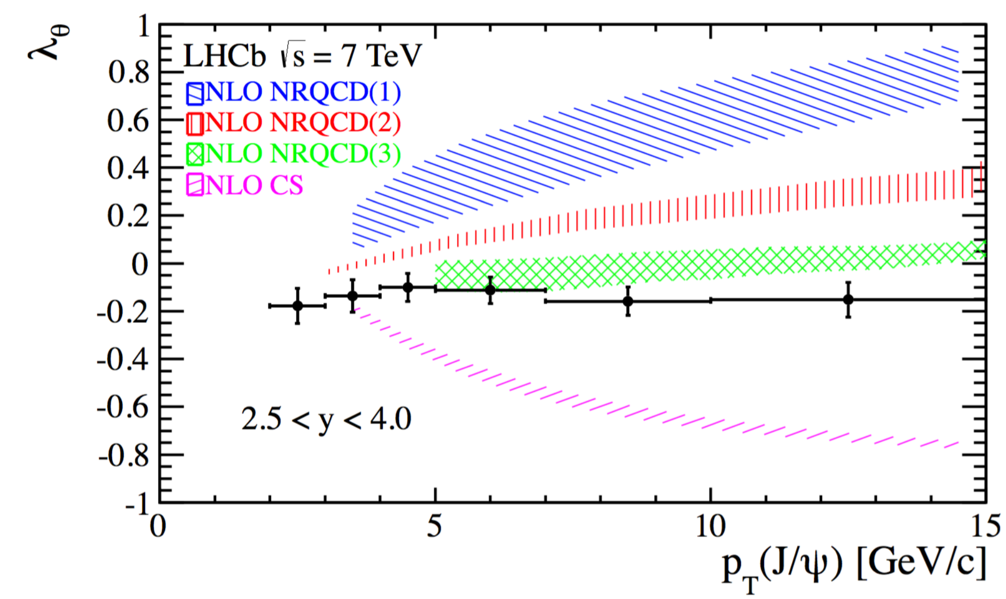
- In NRQCD, LDMEs supposed to be universal (however…)



[LHCb, 1307.6379]

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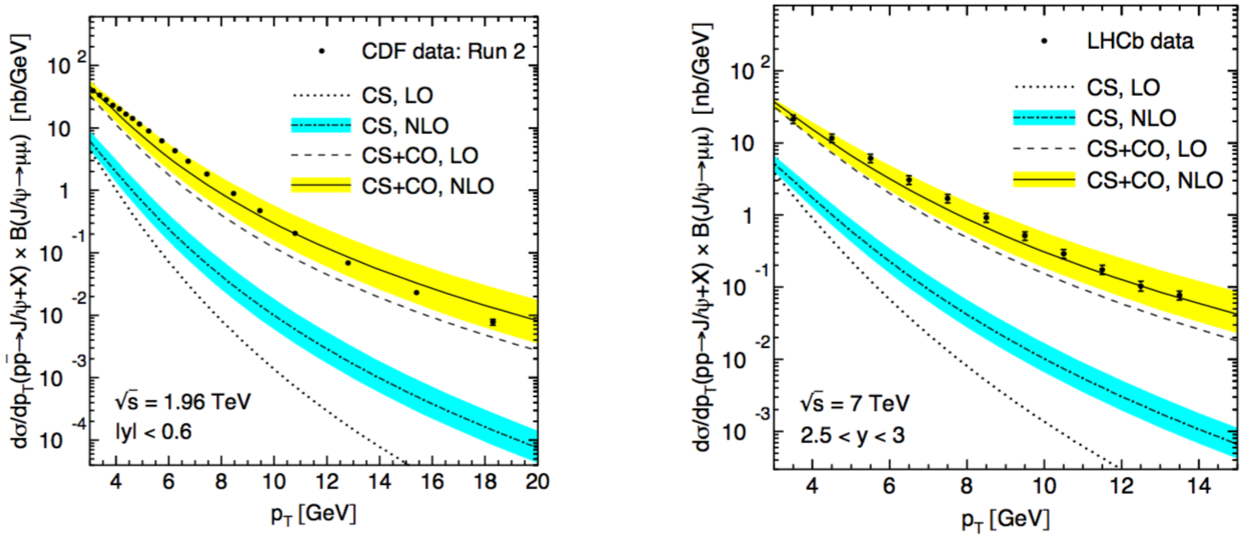

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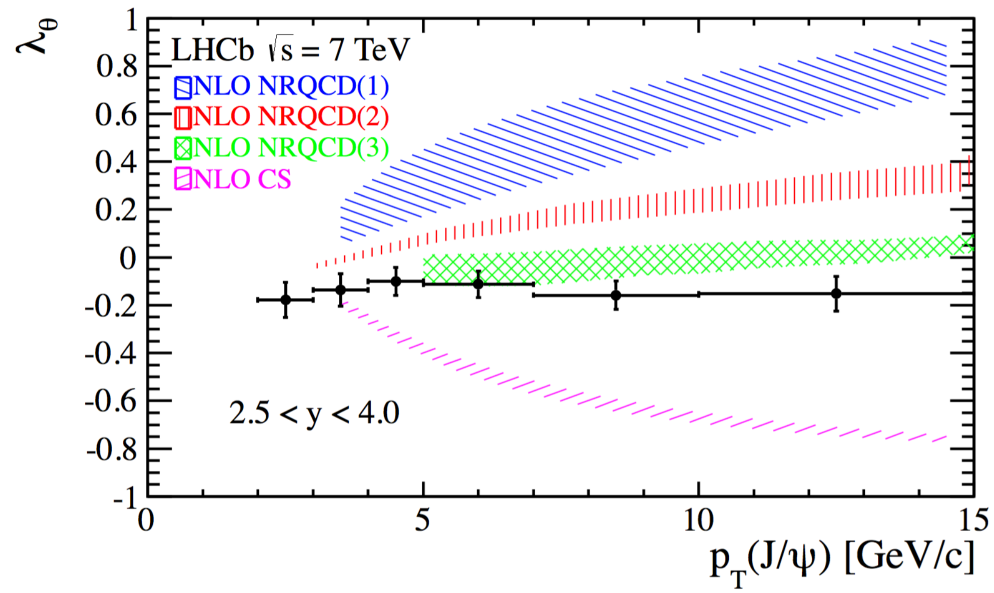
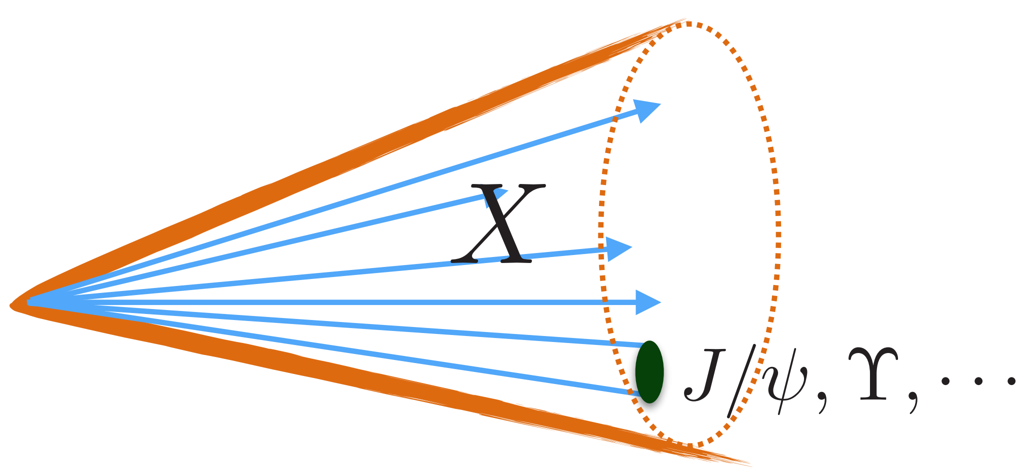


[LHCb, 1307.6379]

- Quarkonium production in jets provides us new way of studying these issues (cleaner)



NRQCD Power Counting

Estimate *v* : $mv^2 \sim \alpha_s/r \sim \alpha_s mv \;\Rightarrow\; v \sim \alpha_s$

NRQCD Power Counting

Charmonium: $v^2 \sim 0.3$

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Power count fields:

$$\langle H| \int d^3x \psi^\dagger \psi |H\rangle \sim 1$$

$$\int d^3x \sim 1/(mv)^3$$

$$\psi \sim (mv)^{3/2}$$

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Construct NRQCD Lagrangian (and other composite operators) order by order:

Operator	Estimate
ψ	$(Mv)^{3/2}$
χ	$(Mv)^{3/2}$
D_0 (acting on ψ or χ)	Mv^2
$\mathbf{D}$	Mv
$g\mathbf{E}$	M^2v^3
$g\mathbf{B}$	M^2v^4
gA_0 (in Coulomb gauge)	Mv^2
$g\mathbf{A}$ (in Coulomb gauge)	Mv^3

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

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.

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

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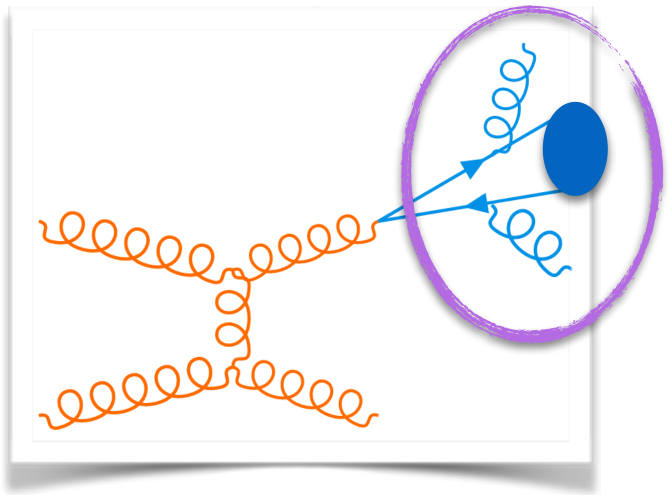
NRQCD Factorization

Factorized form of FF:



SDCs (perturbative)

$$D_{q/g}^{H} = \sum_{n} d_{q/g,n} \langle 0|\mathcal{O}_n^H|0\rangle$$

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The same as those in X-section

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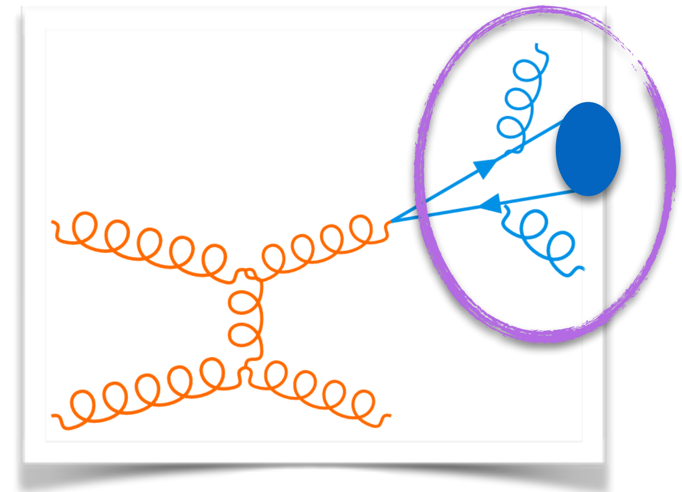

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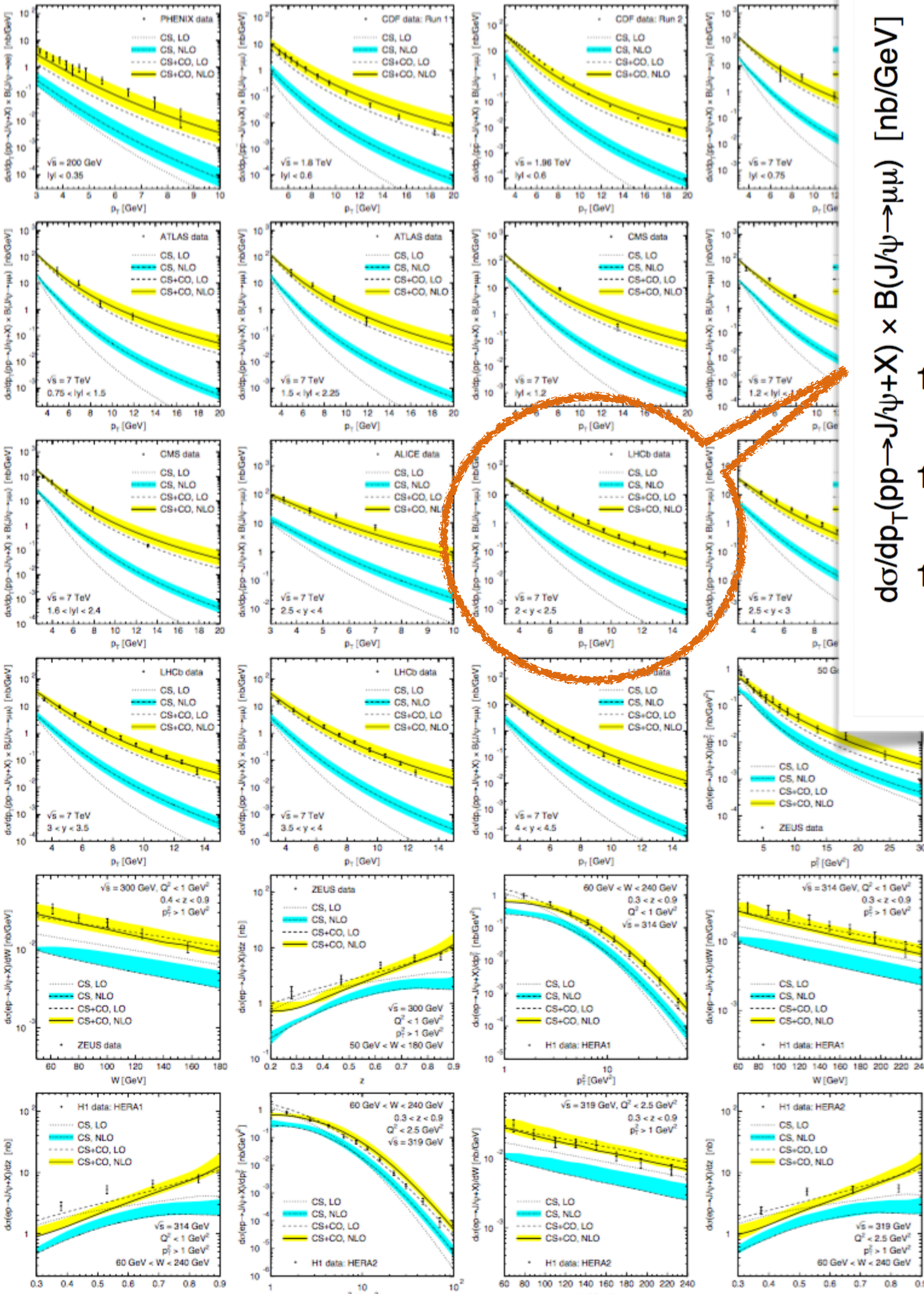
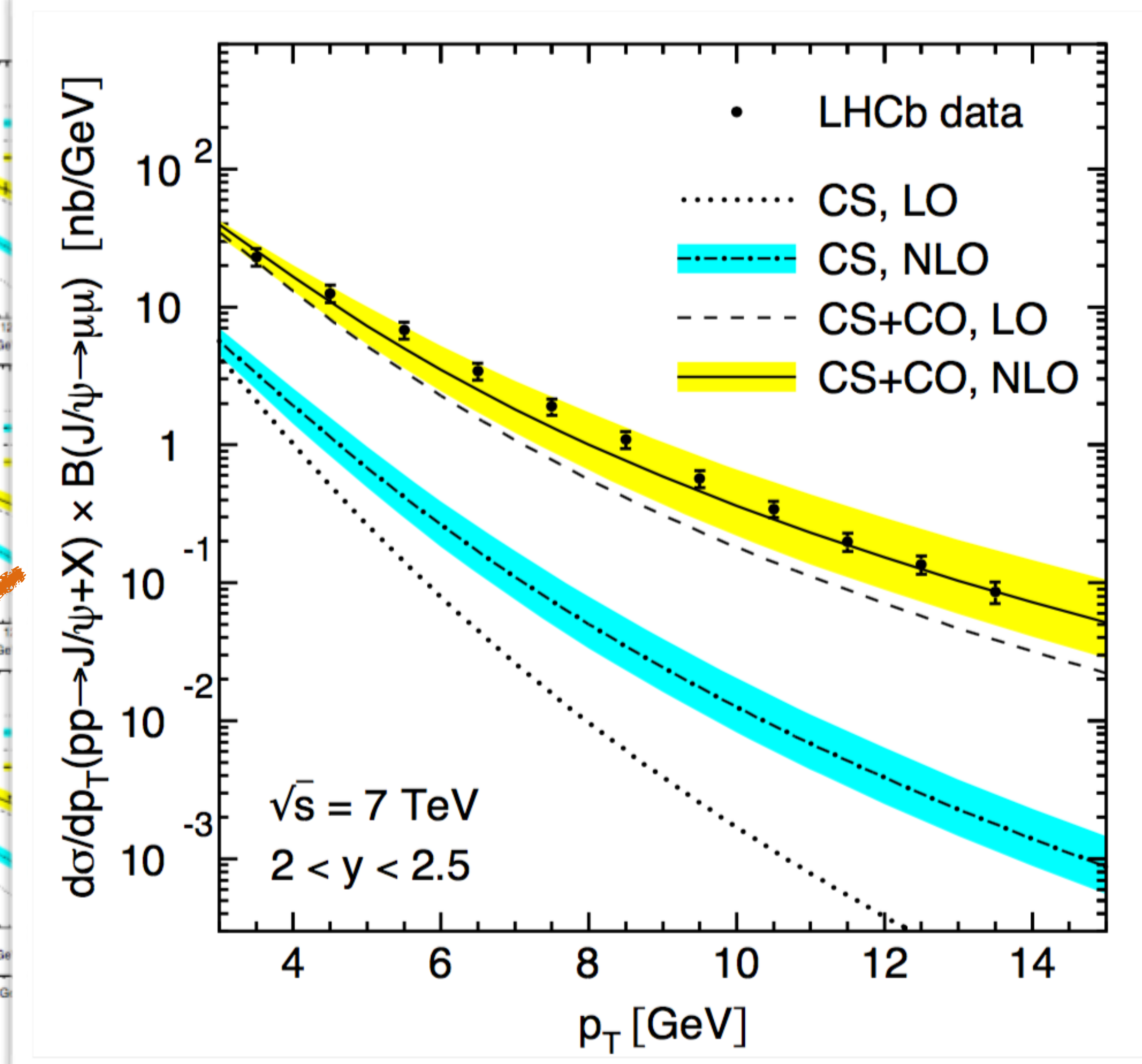
e.g. $D_{g\to\psi}^{^1S_0^{(8)}}(z, 2m_c) = \frac{5\alpha_s^2(2m_c)}{96m_c^3}\langle \mathcal{O}^\psi(^1S_0^{(8)})\rangle \left(3z - 2z^2 + 2(1-z)\log(1-z)\right)$

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

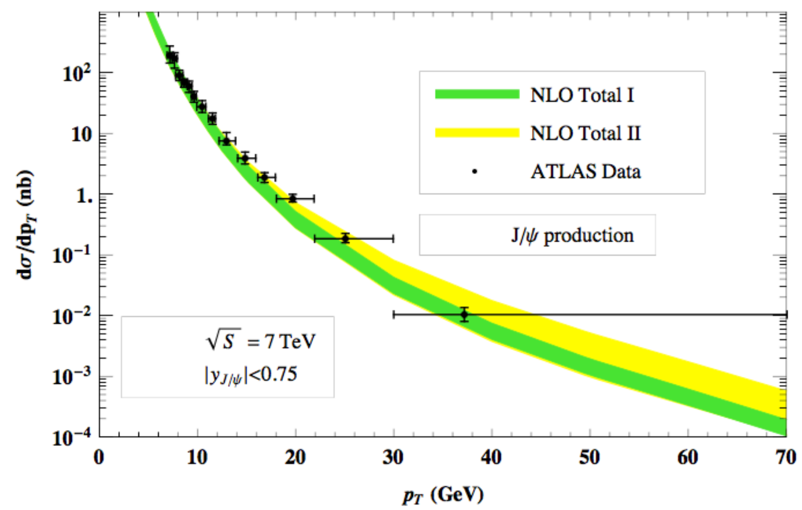
$$\chi^2_{\mathrm{d.o.f.}} = 4.42$$

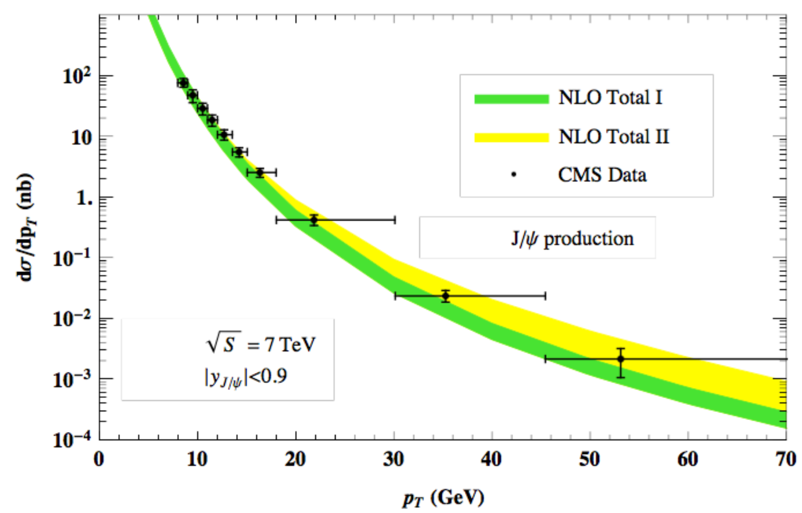
$$p_T,\ p_T^2,\ w, z \cdots$$

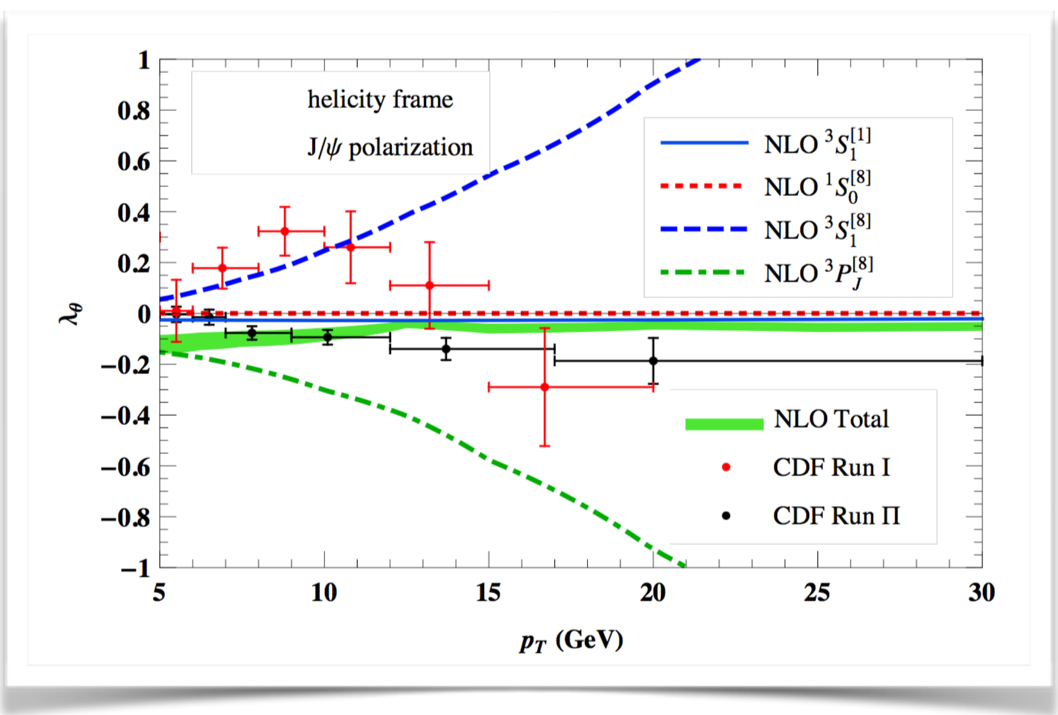
Includes low p_T region

[Butenschon, Kniehl, 1105.0820]

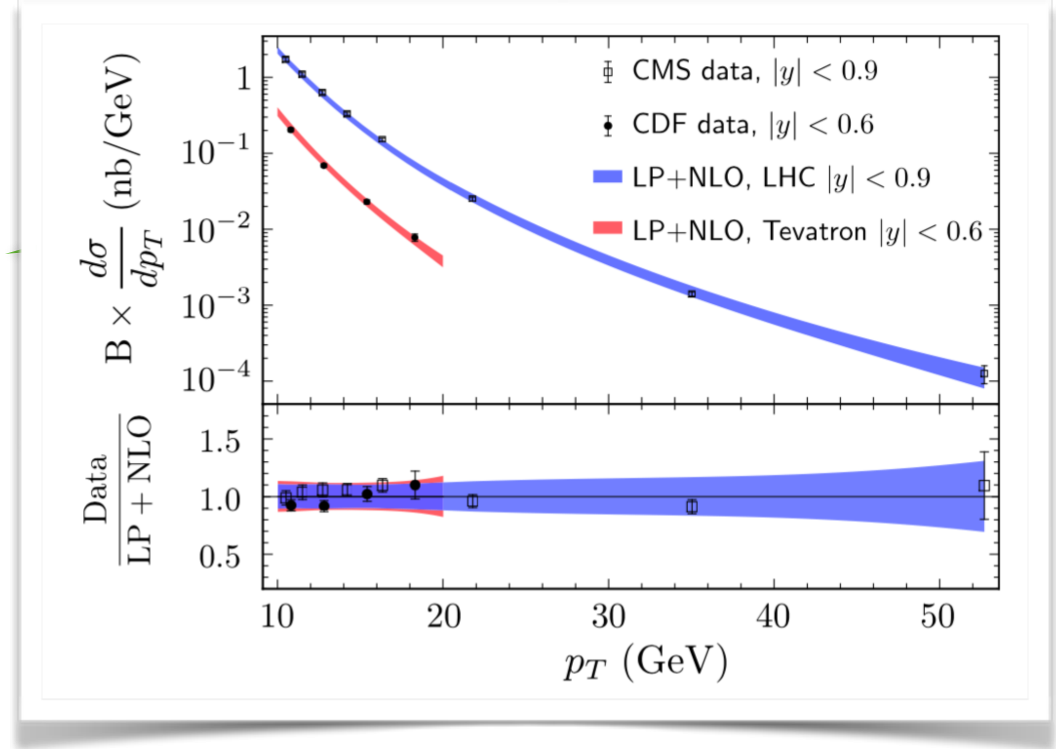
[Chao et al., 1201.2675]

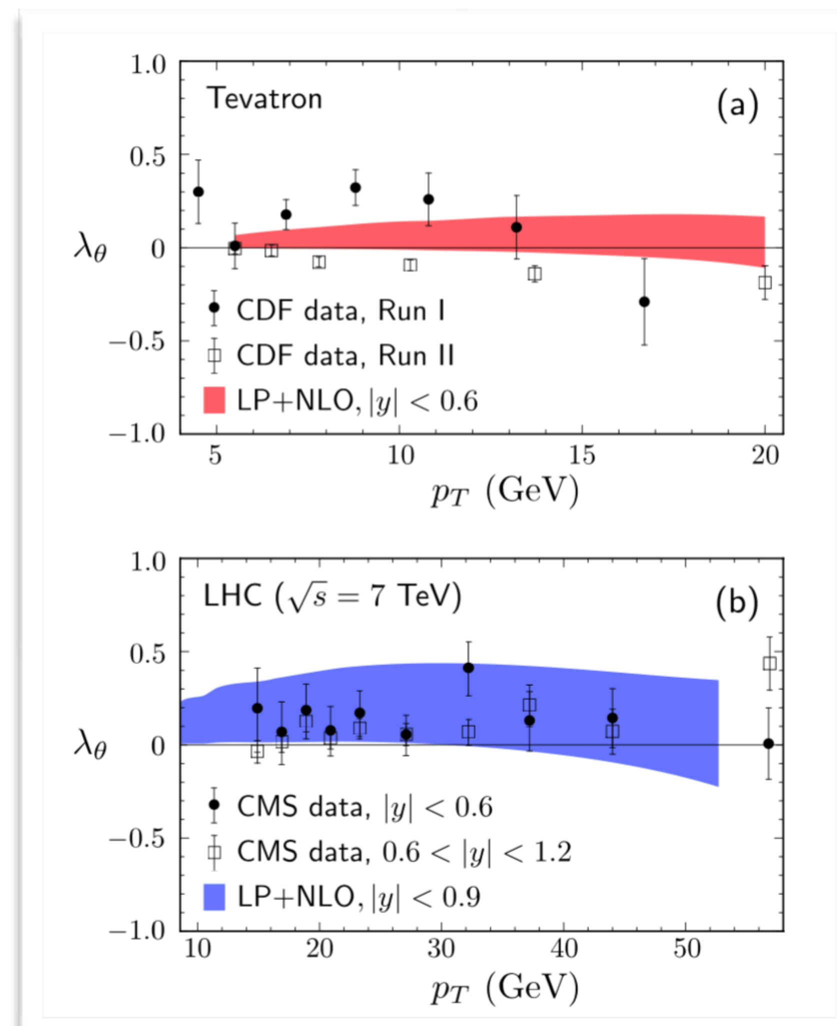




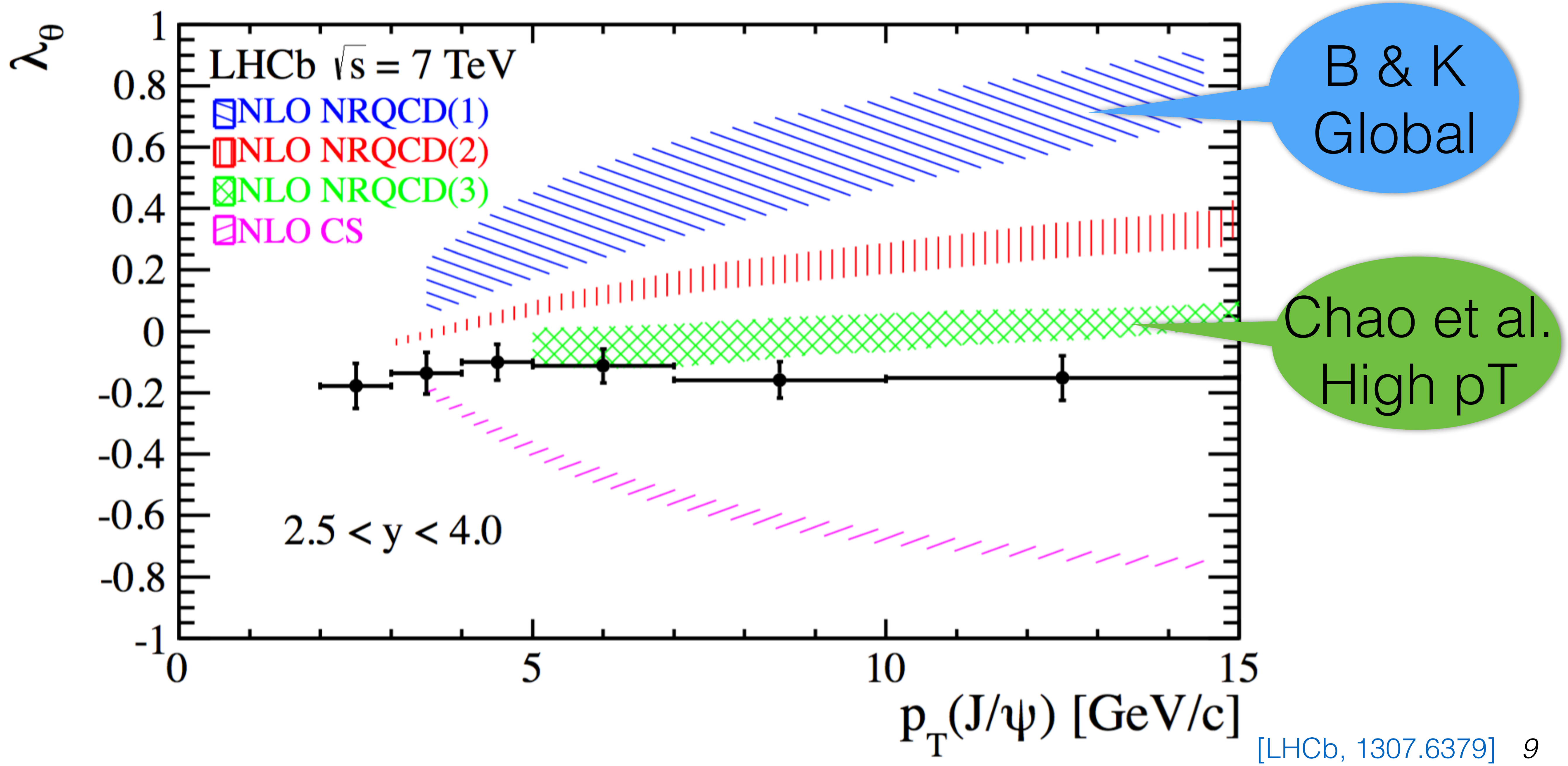


[Bodwin et al., 1403.3612]





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



[LHCb, 1307.6379]

Fragmenting Jet Function (FJF)

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

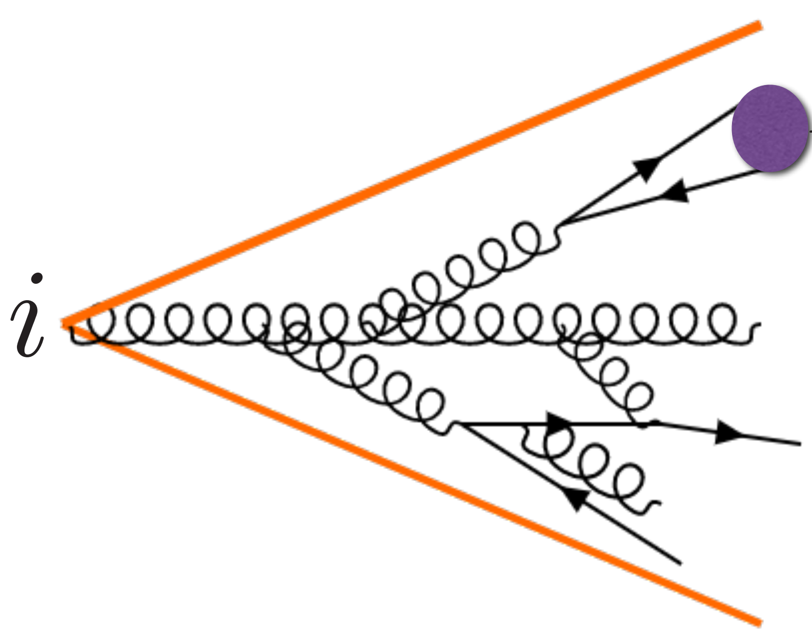
Jet scale

Hadron scale

[M. Procura, I. Stewart, PRD, 81, 074009 (2010)]

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

Physical meaning:



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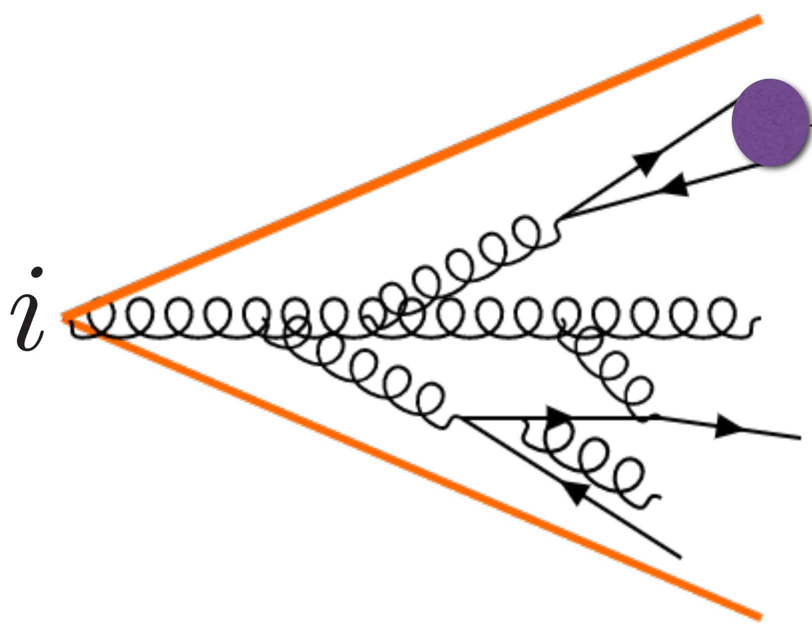

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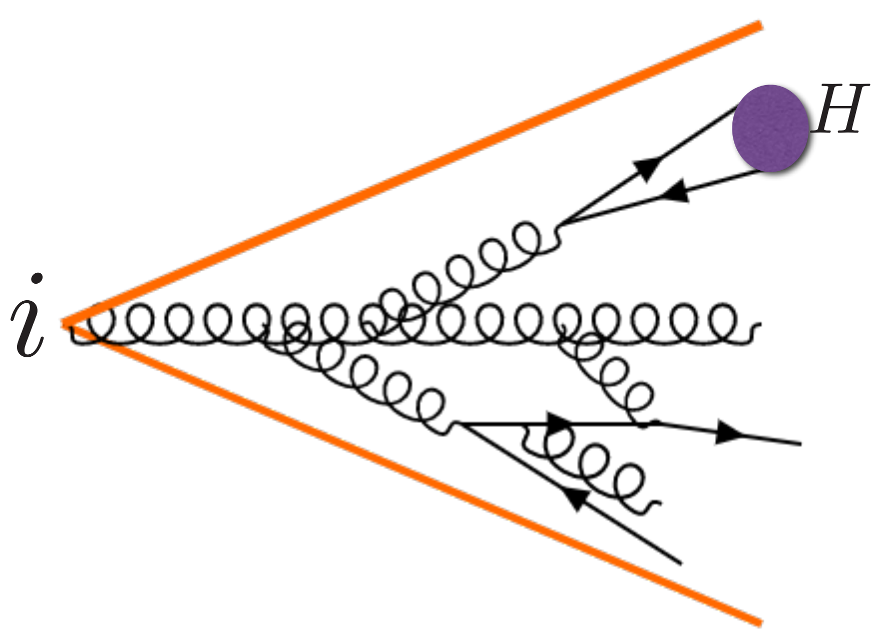

Frag. at jet scale:

$$D_q^H(z) \equiv \mathrm{Tr}\langle 0|\frac{\not{\bar{n}}}{2}\delta(\frac{p_-}{z} - \mathcal{P}_-)\psi|HX\rangle\langle HX|\psi|0\rangle$$

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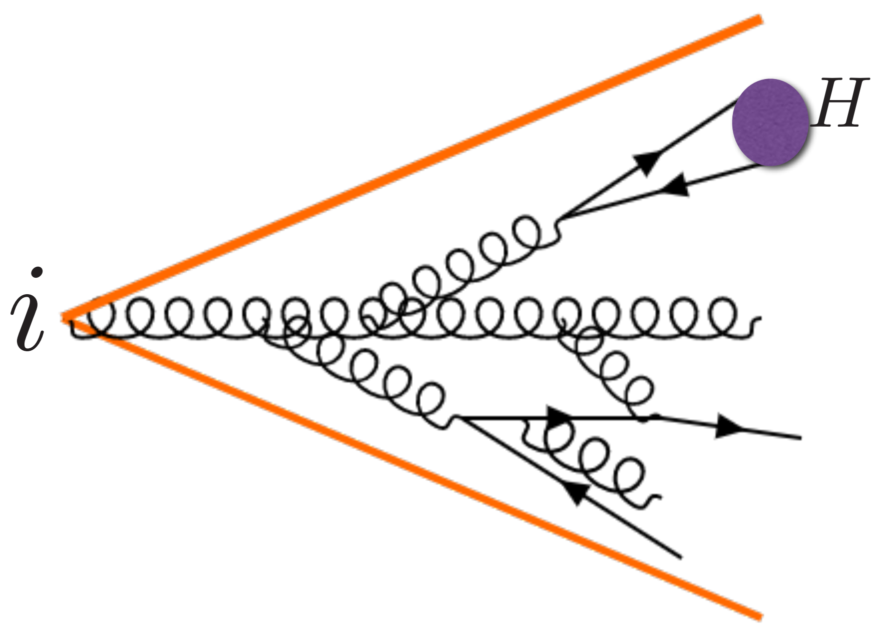

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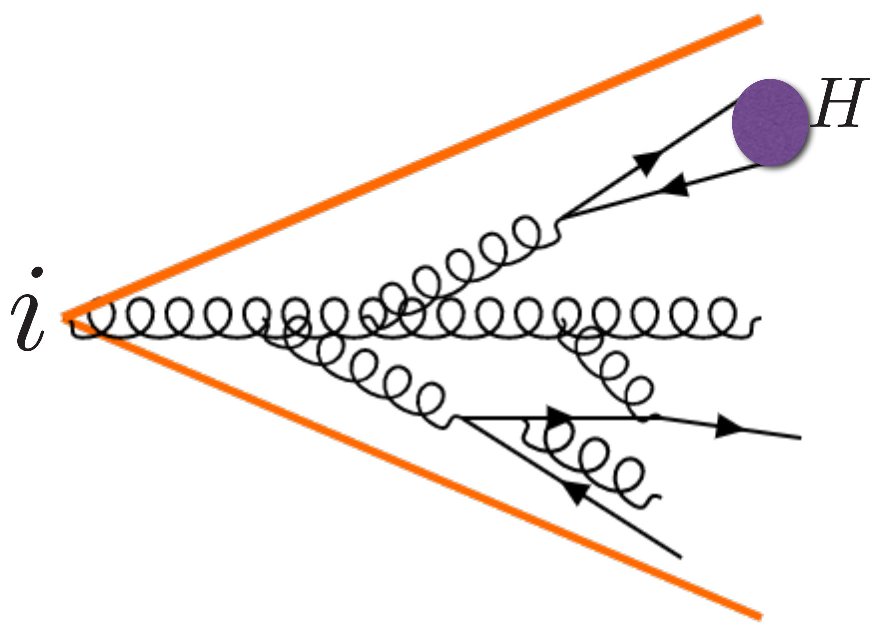

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Practical: resum $\log(\frac{m_H}{s})$

Factorize Everything

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

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B meson, or J/ψ FF.

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

$$B$$

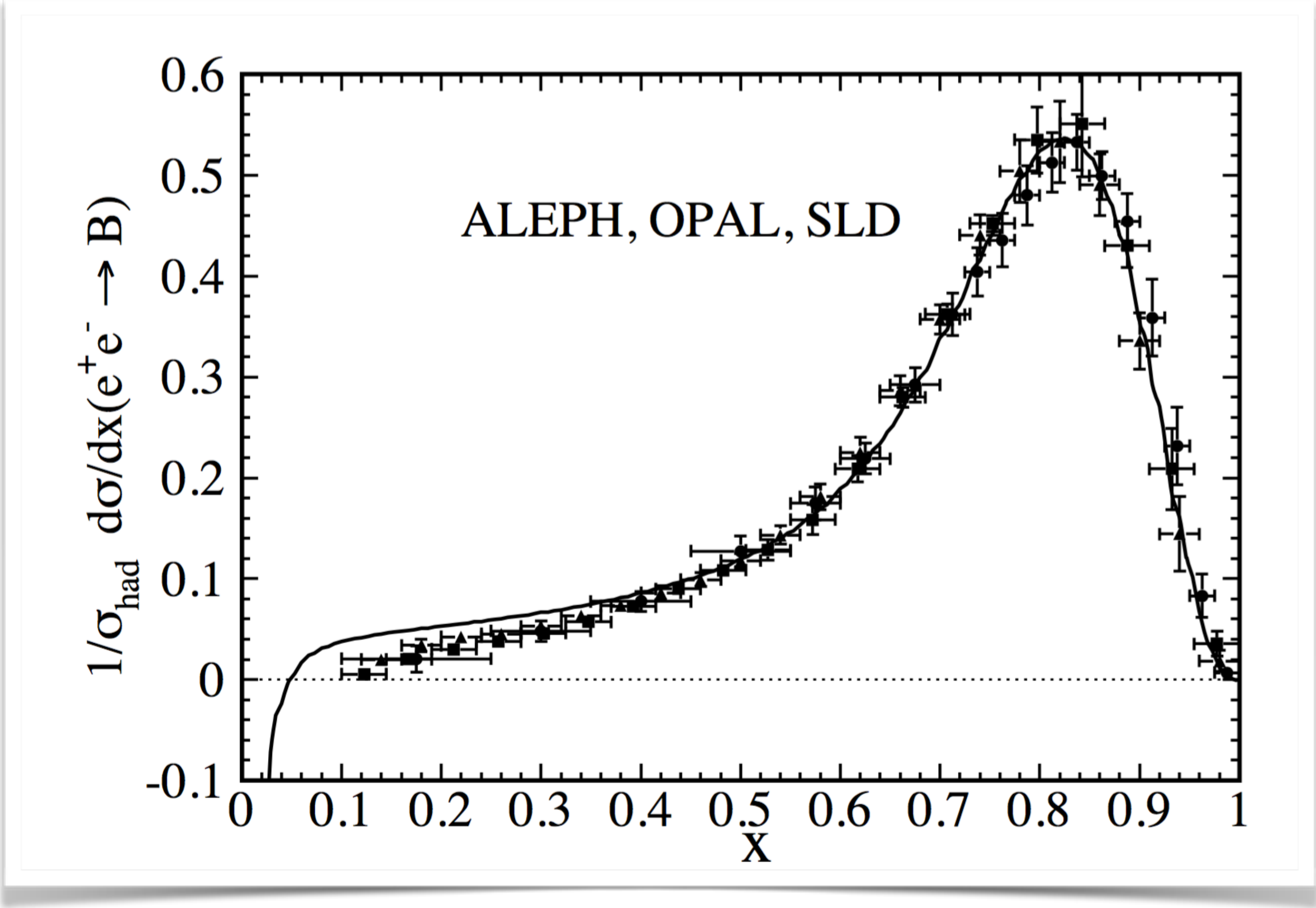
B Fragmentation Function

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

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

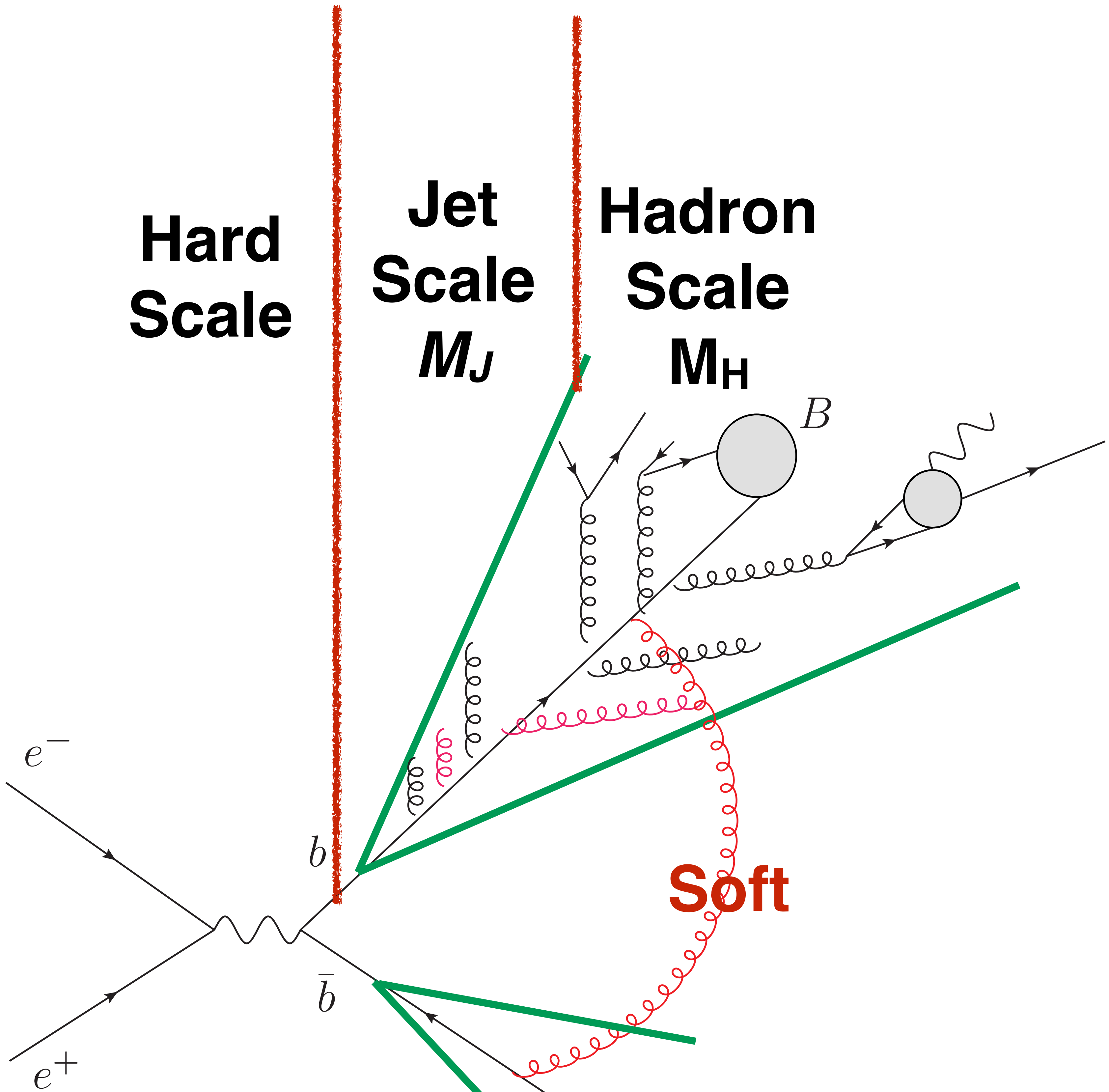
  2 parameters,
  N fixed by:
  $$\int_0^1 dz z D(z) = 1$$

- Fit at m_B scale



[Kniehl and Kramer, 0705.4392]

Analytic & Monte Carlo (B in jet)



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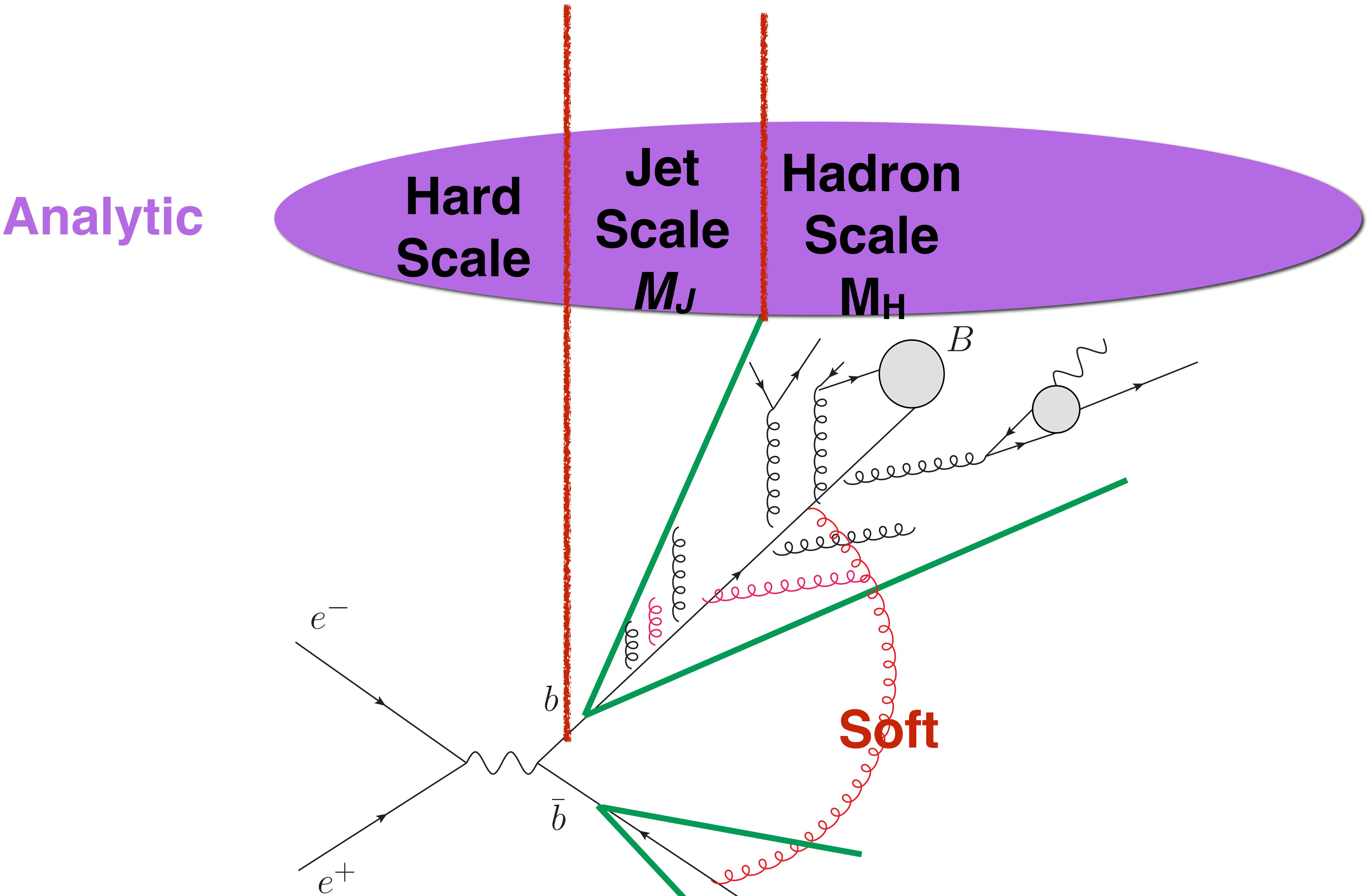

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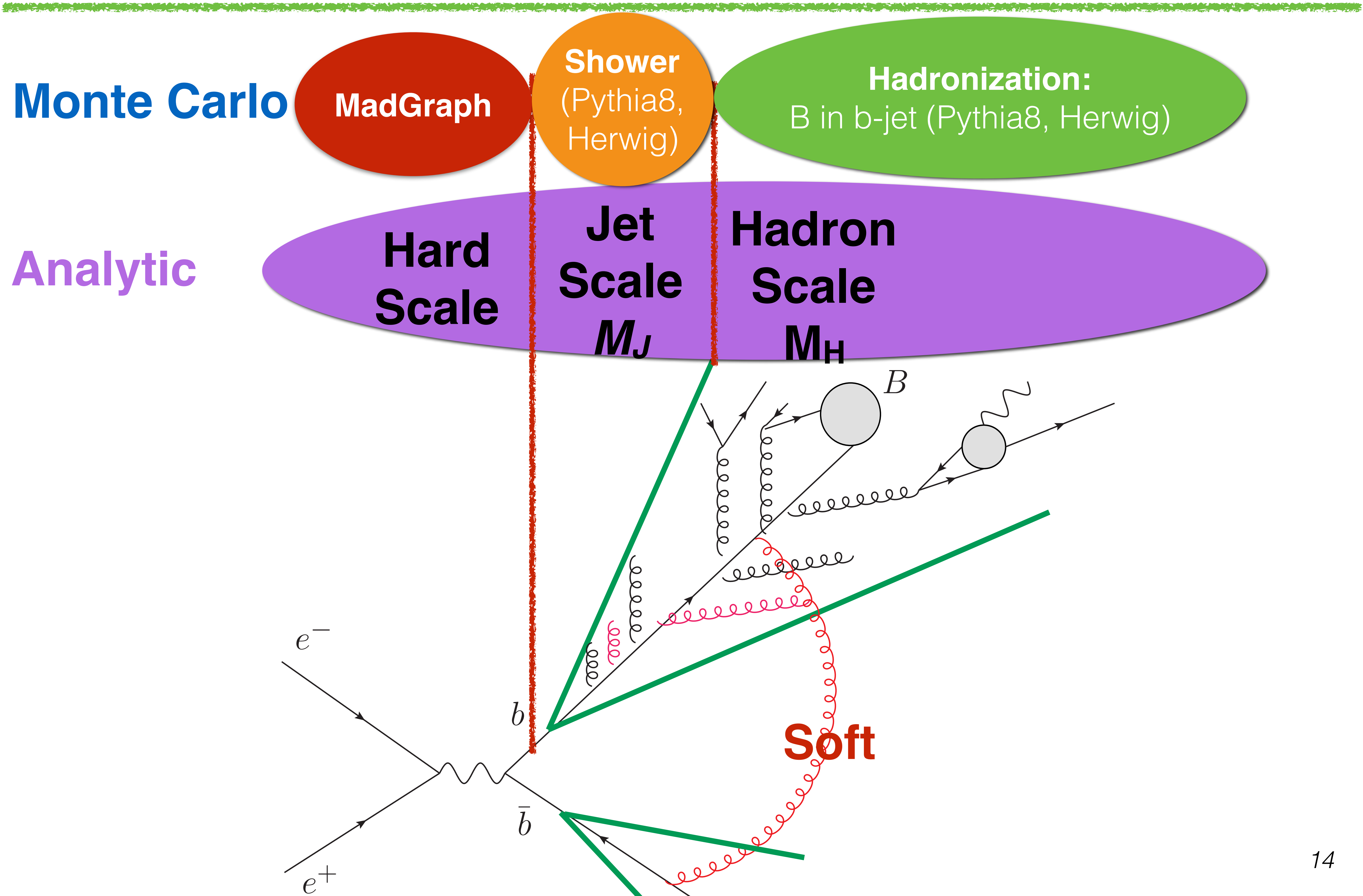

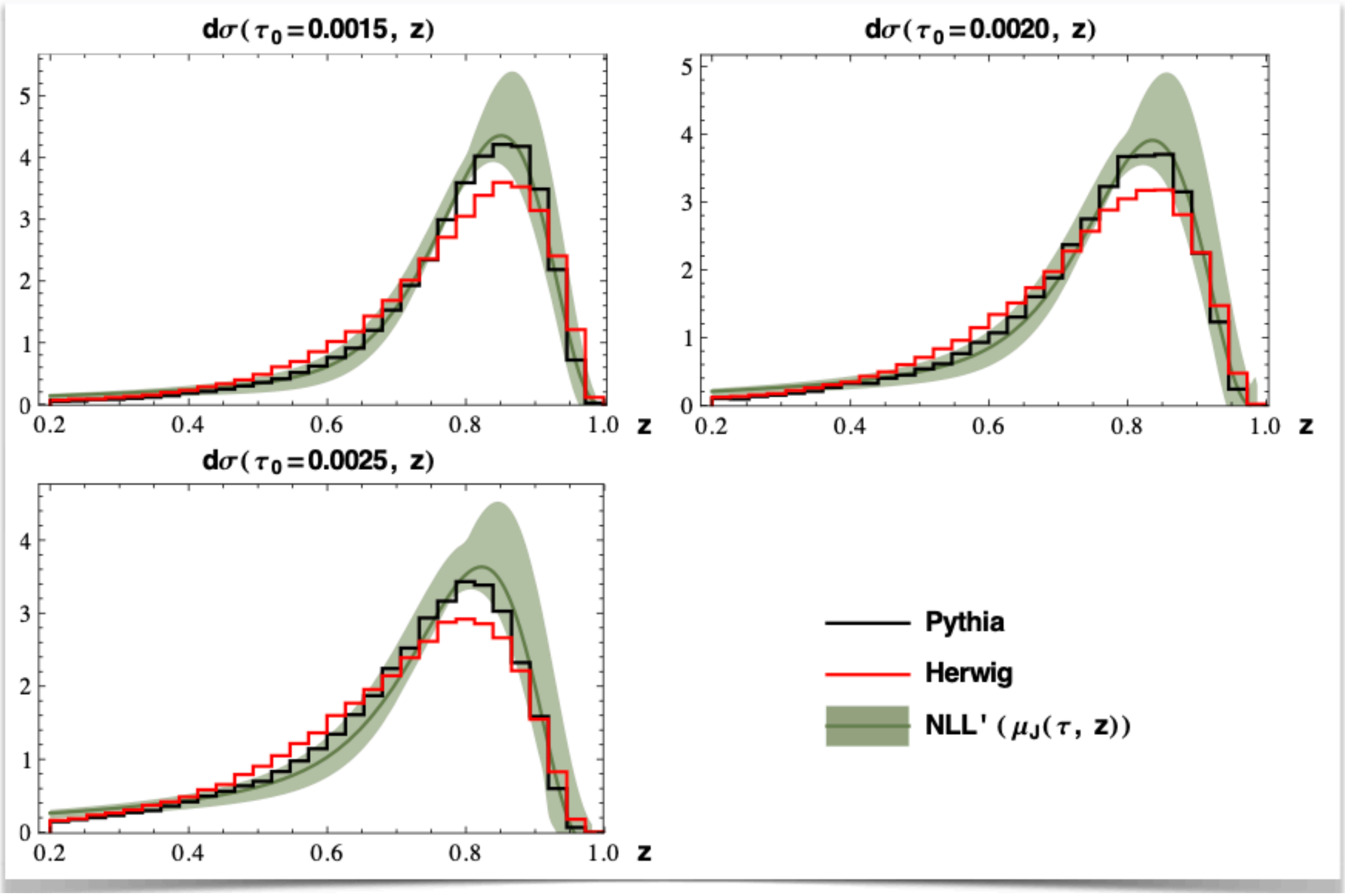

$$z \equiv \frac{E_B}{E_J} \qquad \tau_0 \propto m_J$$

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

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

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

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

J/psi Fragmentation Functions

NRQCD FF: $D_n(z) = d_n(z)\langle\mathcal{O}_n\rangle$

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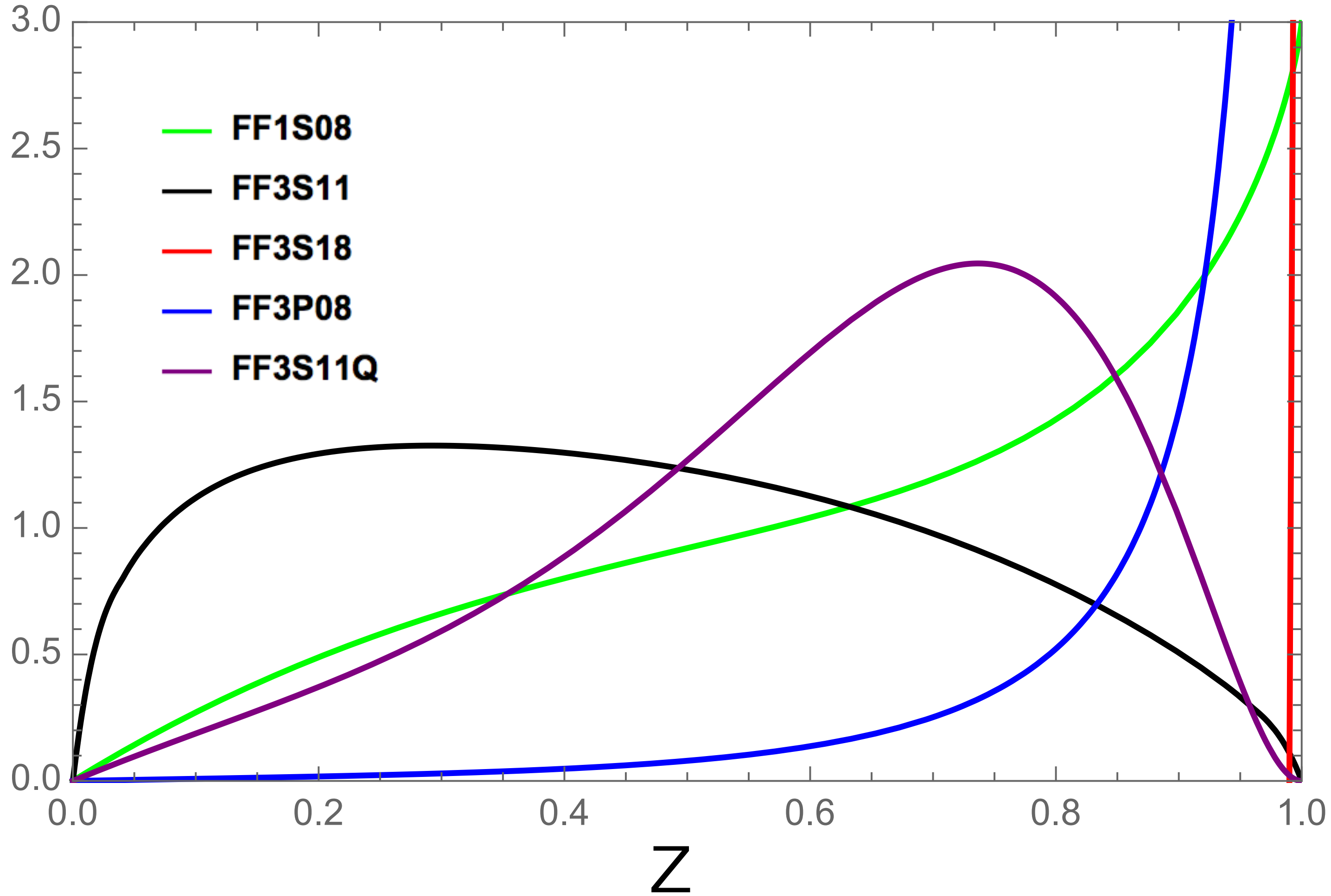


Unlike B FFs,
Not built in Pythia

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

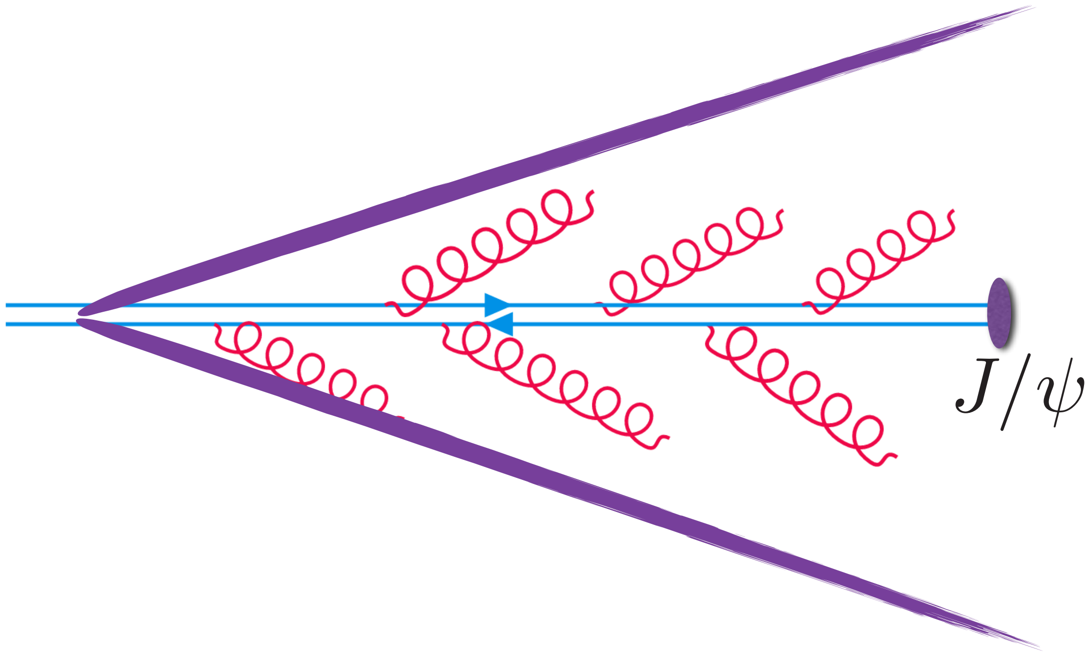
[Bodwin, Braaten, Lepage, hep-ph/9407339]

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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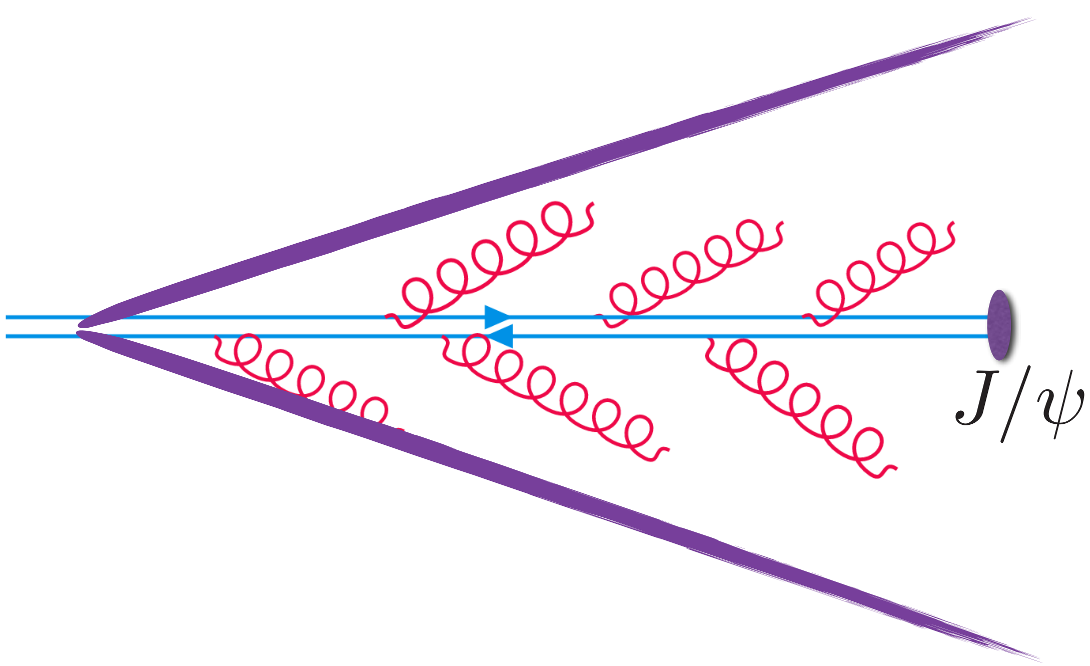
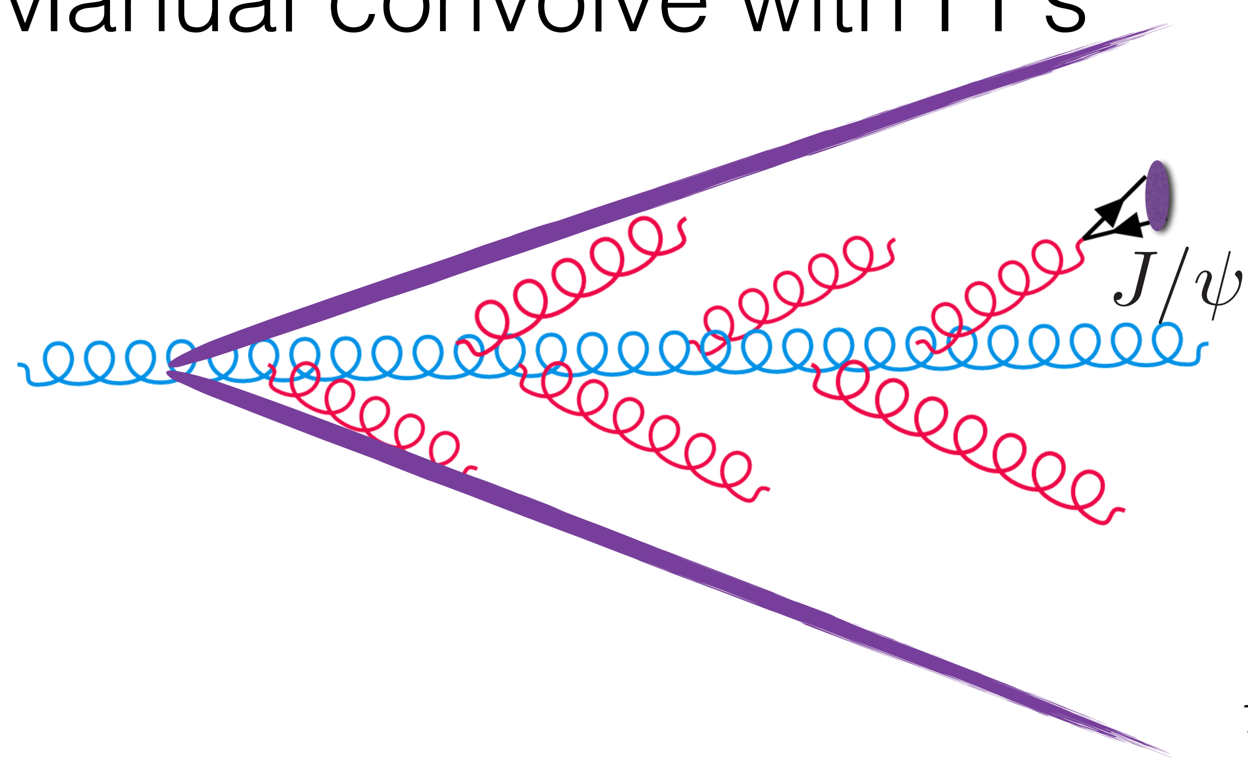


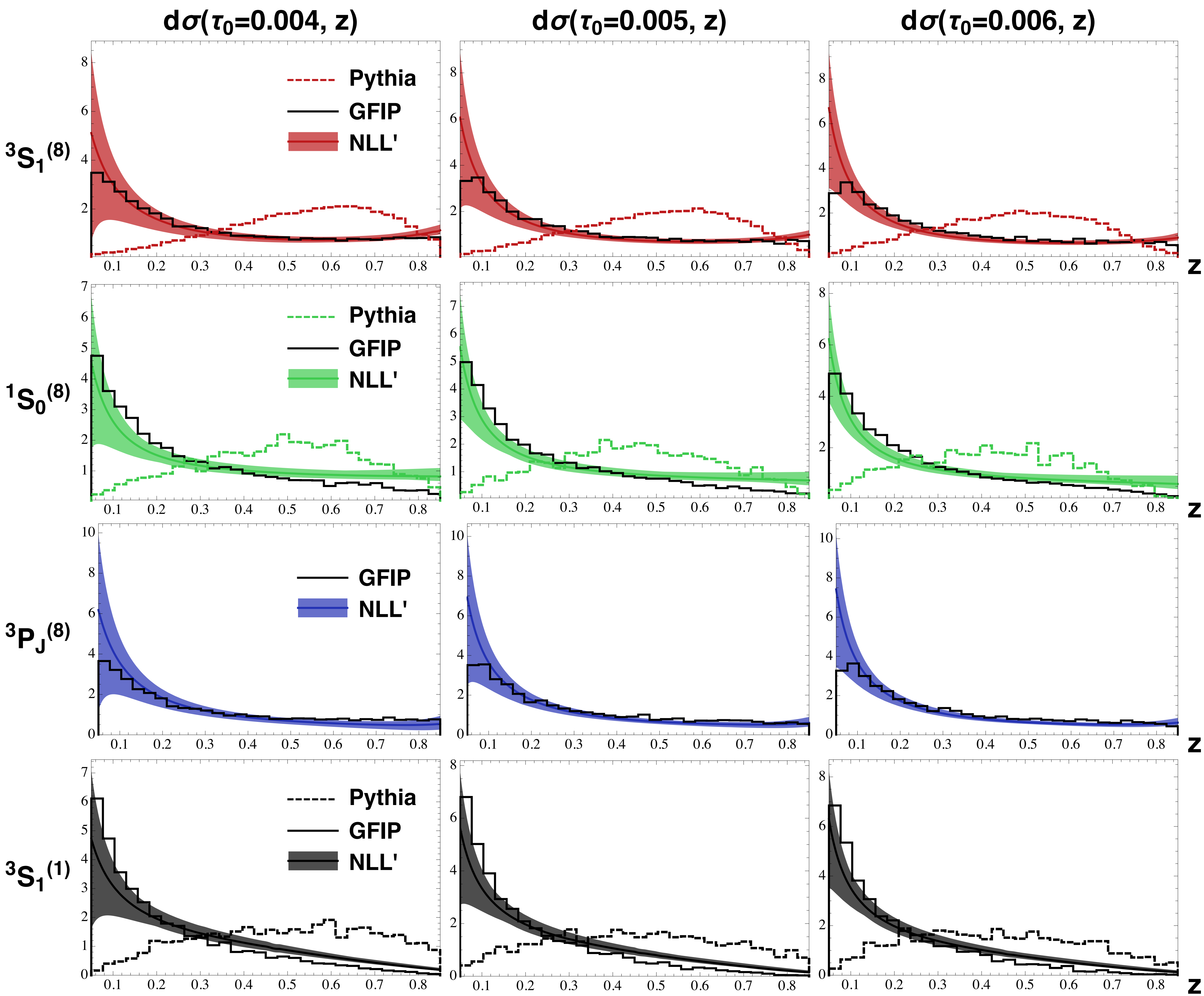
Gluon Fragmentation Improved Pythia (GFIP):

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)]

Analytic is Eqiv. to GFIP

FJF:
(Fragmenting Jet Function)

$$G_g^{J/\psi} = \sum_i \mathcal{J}_{gi} \otimes D_i^{J/\psi}$$

$$\frac{d\mathcal{J}(\mu, m_J)}{d\log\mu} = \gamma_J \otimes \mathcal{J}(\mu, m_J)$$

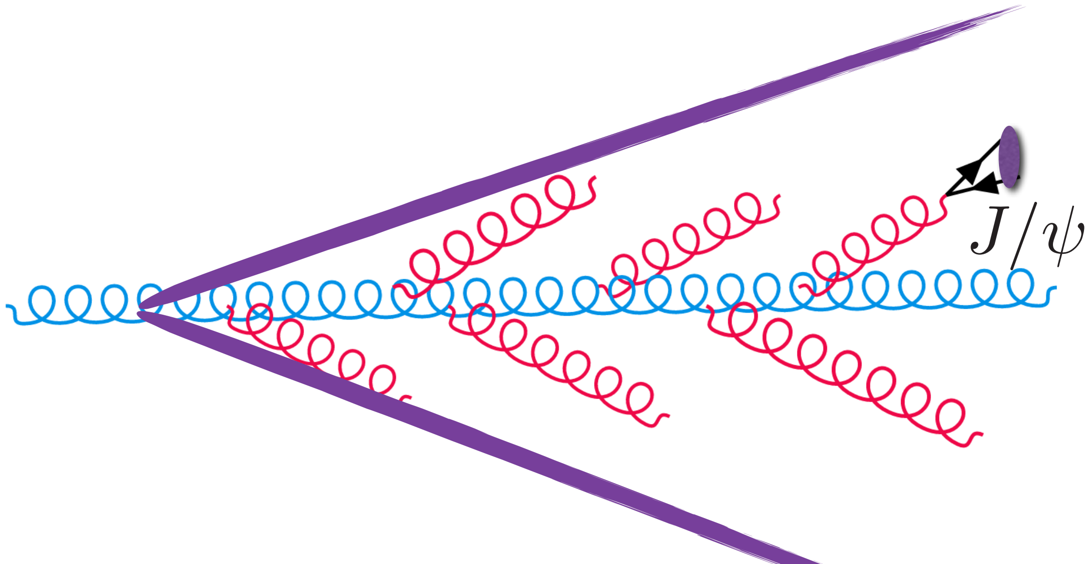
$$\frac{dD_i(\mu, m_{J/\psi})}{d\log\mu} = P_{ij} \otimes D_j(\mu, m_{J/\psi})$$

GFIP:
(Gluon FF Improve Pythis)

Pythia Shower

(to $2m_c$, Hadronization off)

Manual convolve with FFs



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Pythia Shower
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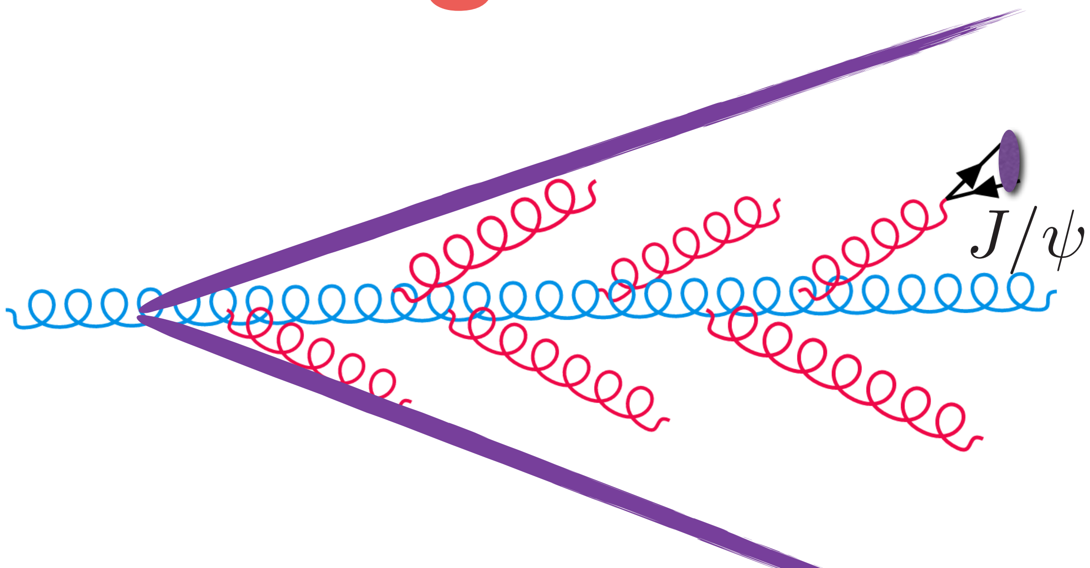
Manual convolve with FFs

RG Running = SHOWER



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

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

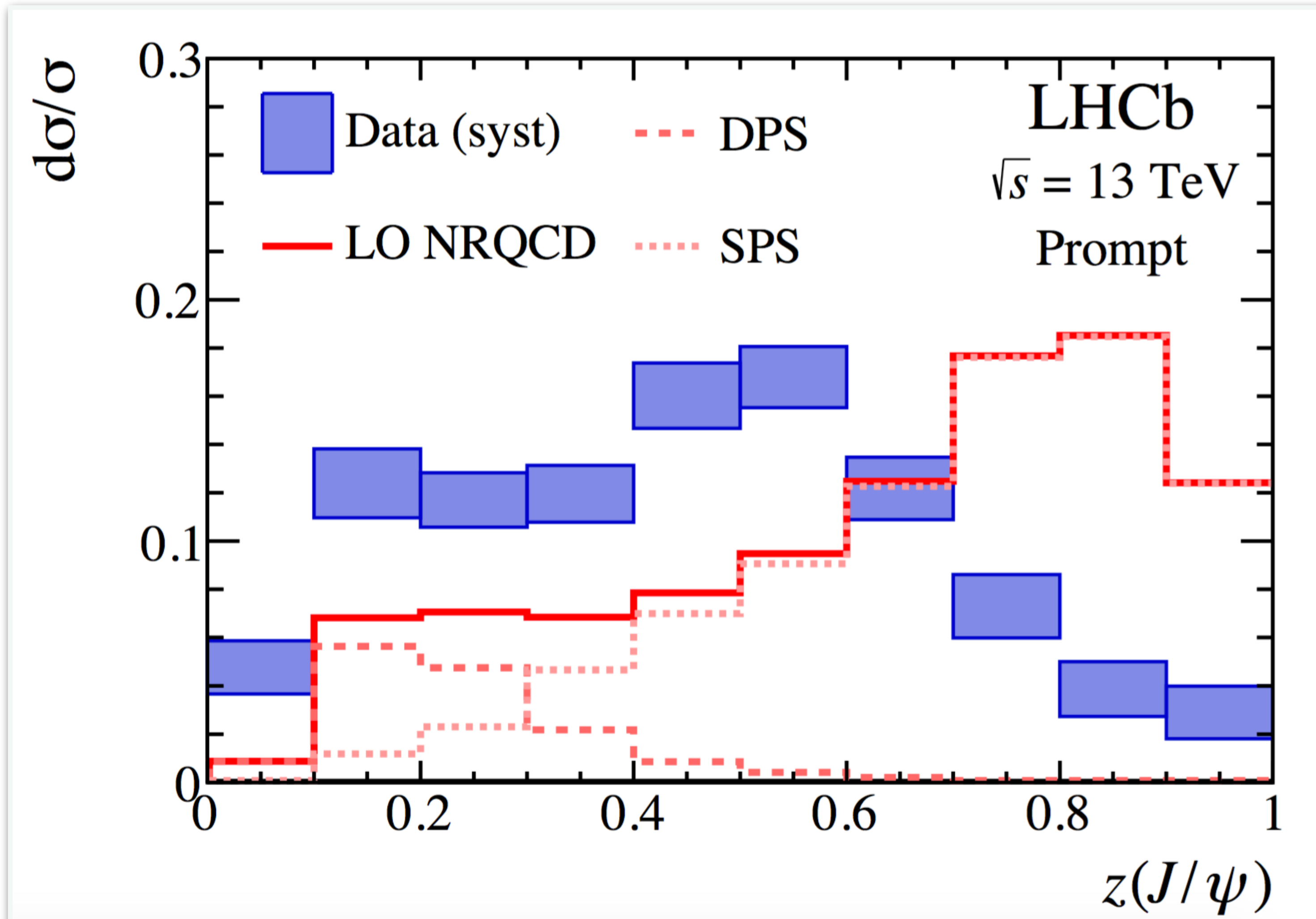
J/ψ in jets @ LHCb

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 $e^-e^+ \rightarrow J/\psi$:

J/ψ too hard in jets



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

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

Analytic

MadGraph

FJF

$$\frac{d\sigma}{dz} = \frac{d\sigma}{dE_i} \times \mathcal{G}_i^{J/\psi}(\mu_J, m_{J/\psi}, z)$$

GFIP

MadGraph

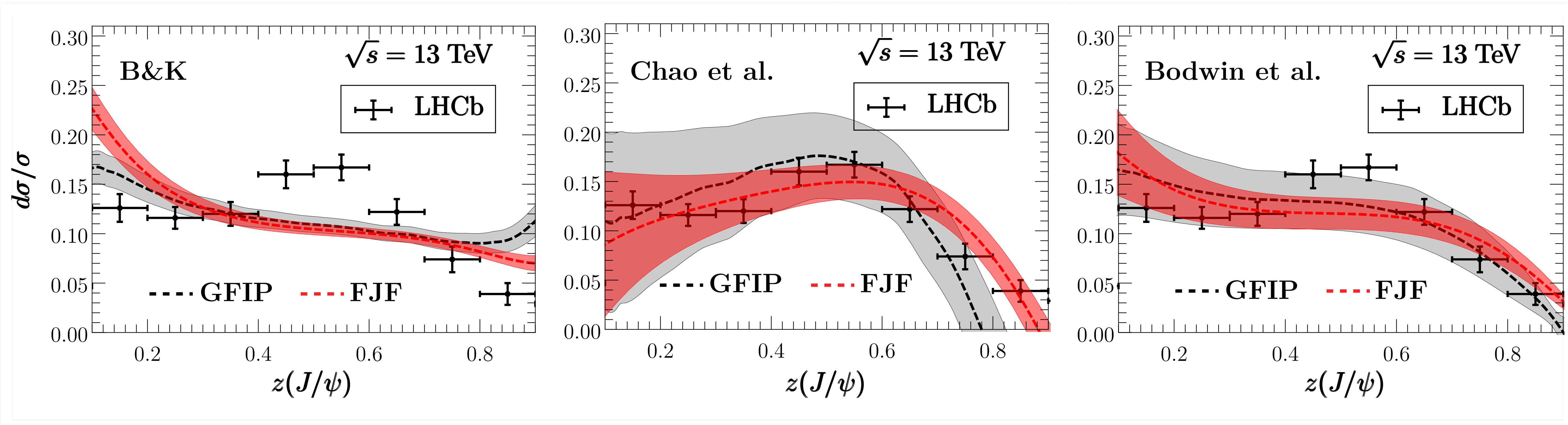
Pythia8

Hadronization:
J/psi in jets (Manual)

$$\frac{d\sigma}{dz} = \frac{d\sigma}{dz_i} \otimes D_i^{J/\psi}(m_{J/\psi}, z)$$

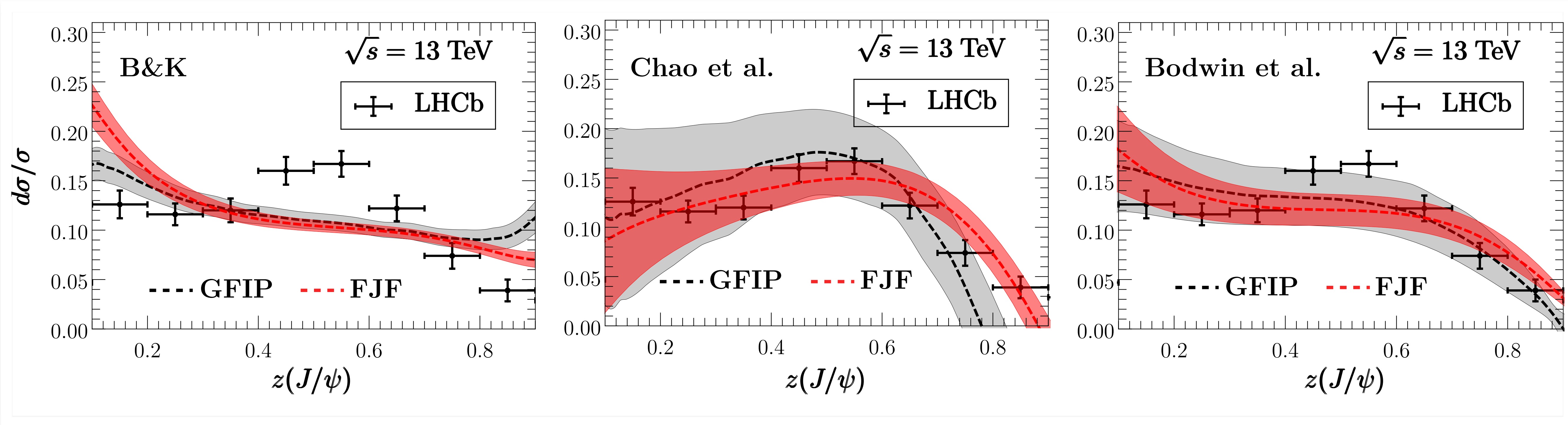
NRQCD FF

Comparison with LHCb Data



[R. Bain, L. Dai, A. Leibovich, Y. Makris, T. Mehen, Phys. Rev. Lett.119, 032002 (2017)]

Comparison with LHCb Data



[R. Bain, L. Dai, A. Leibovich, Y. Makris, T. Mehen, Phys. Rev. Lett.119, 032002 (2017)]

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

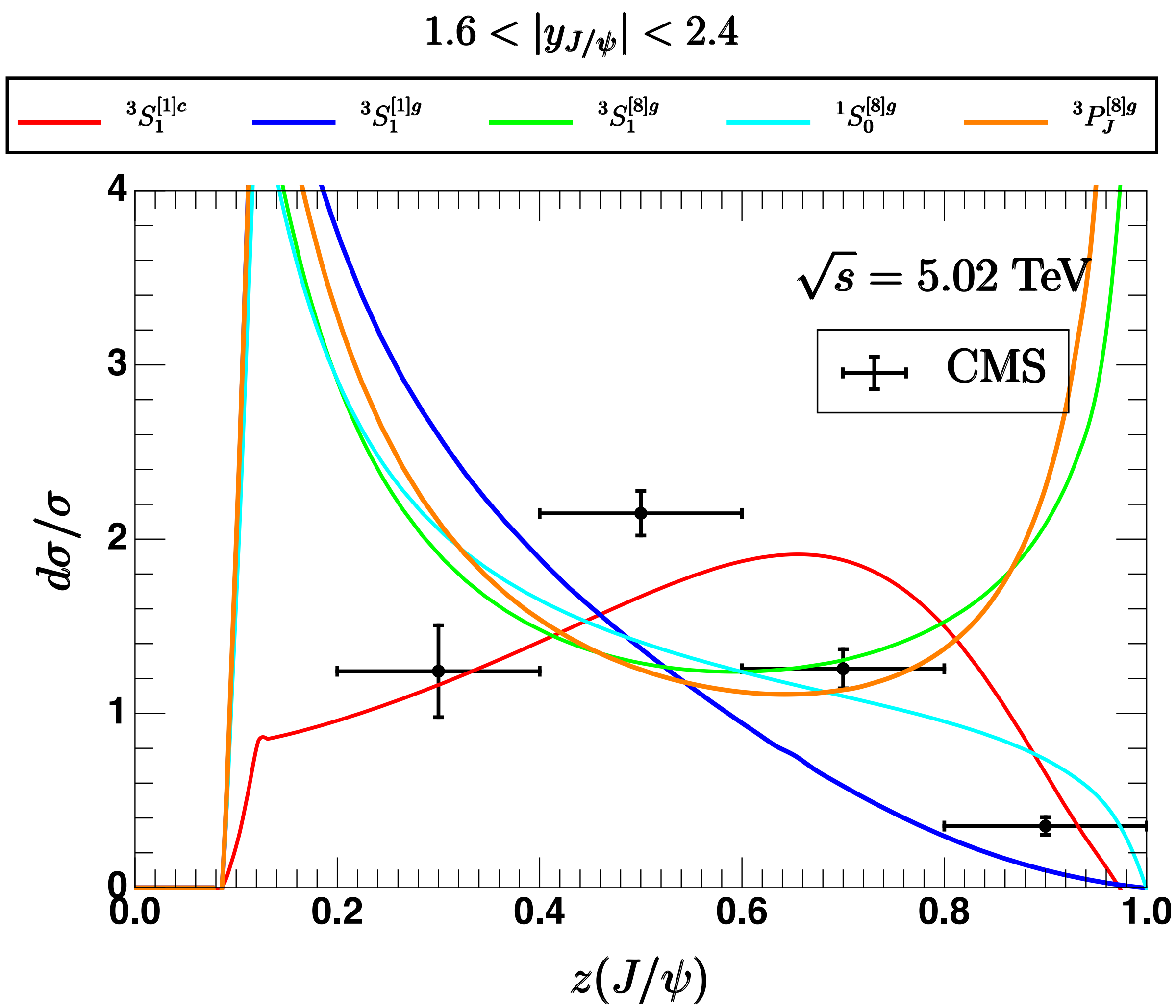
- Both FJF & GFIP work better than default Pythia;

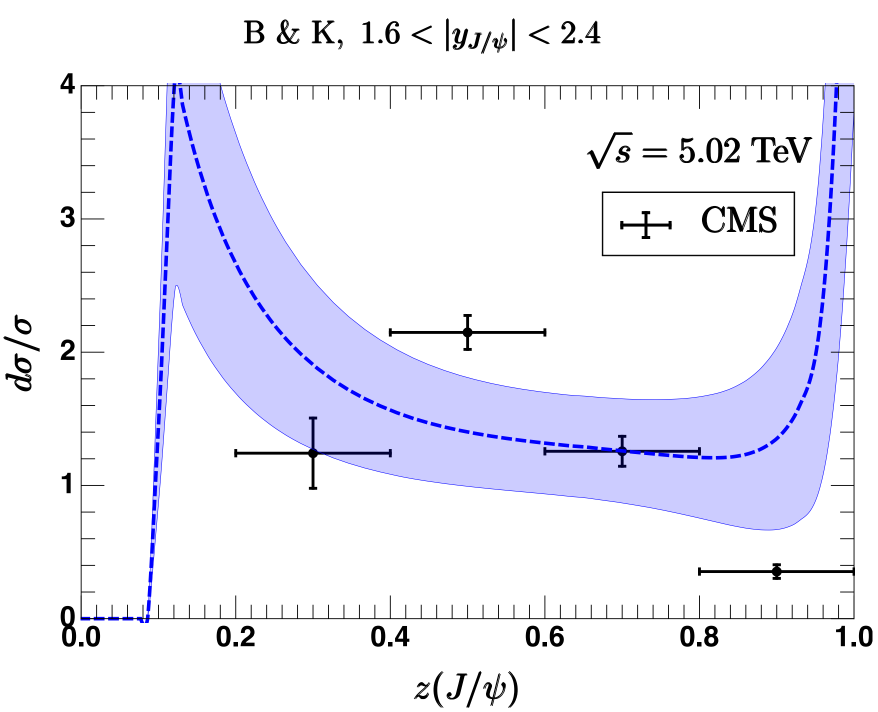
- High pT LDMEs give better description of data than the global fit ones

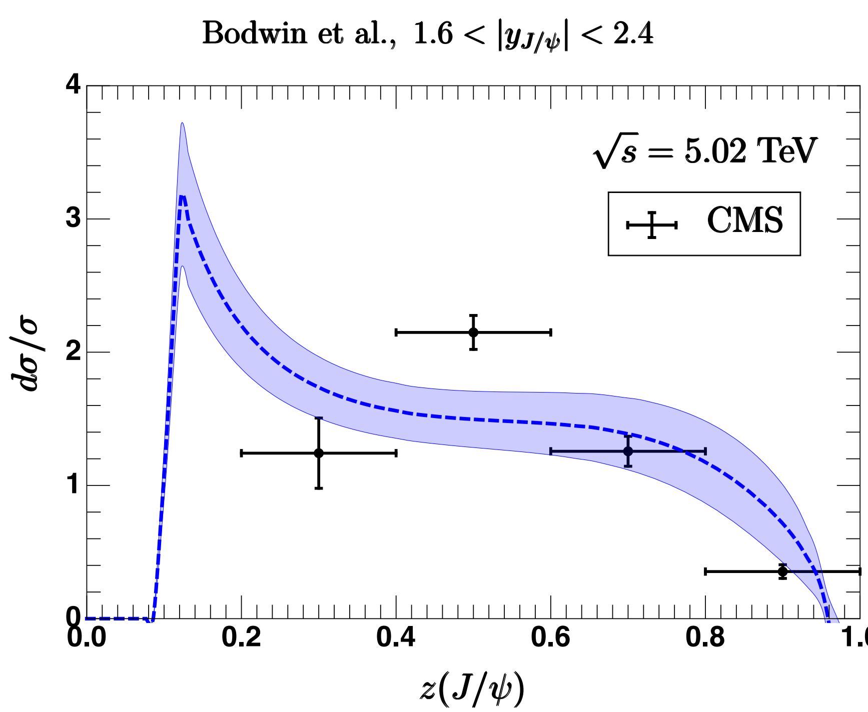
Preliminary

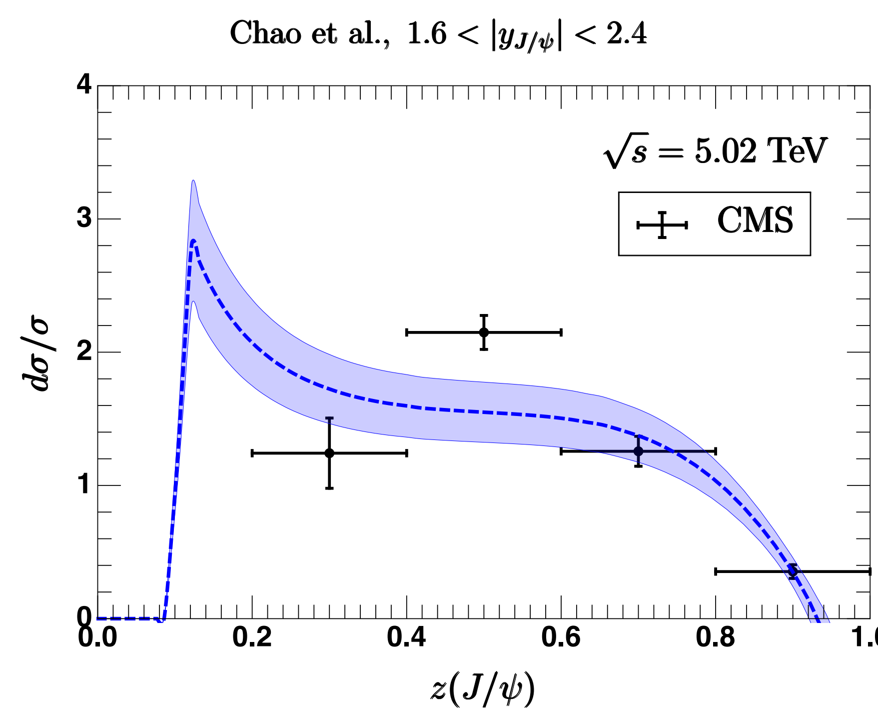
$$25\text{GeV} < p_{T,\text{jet}} < 35\text{GeV}$$

$$3\text{GeV} < p_{T,J/\psi} < 35\text{GeV}$$









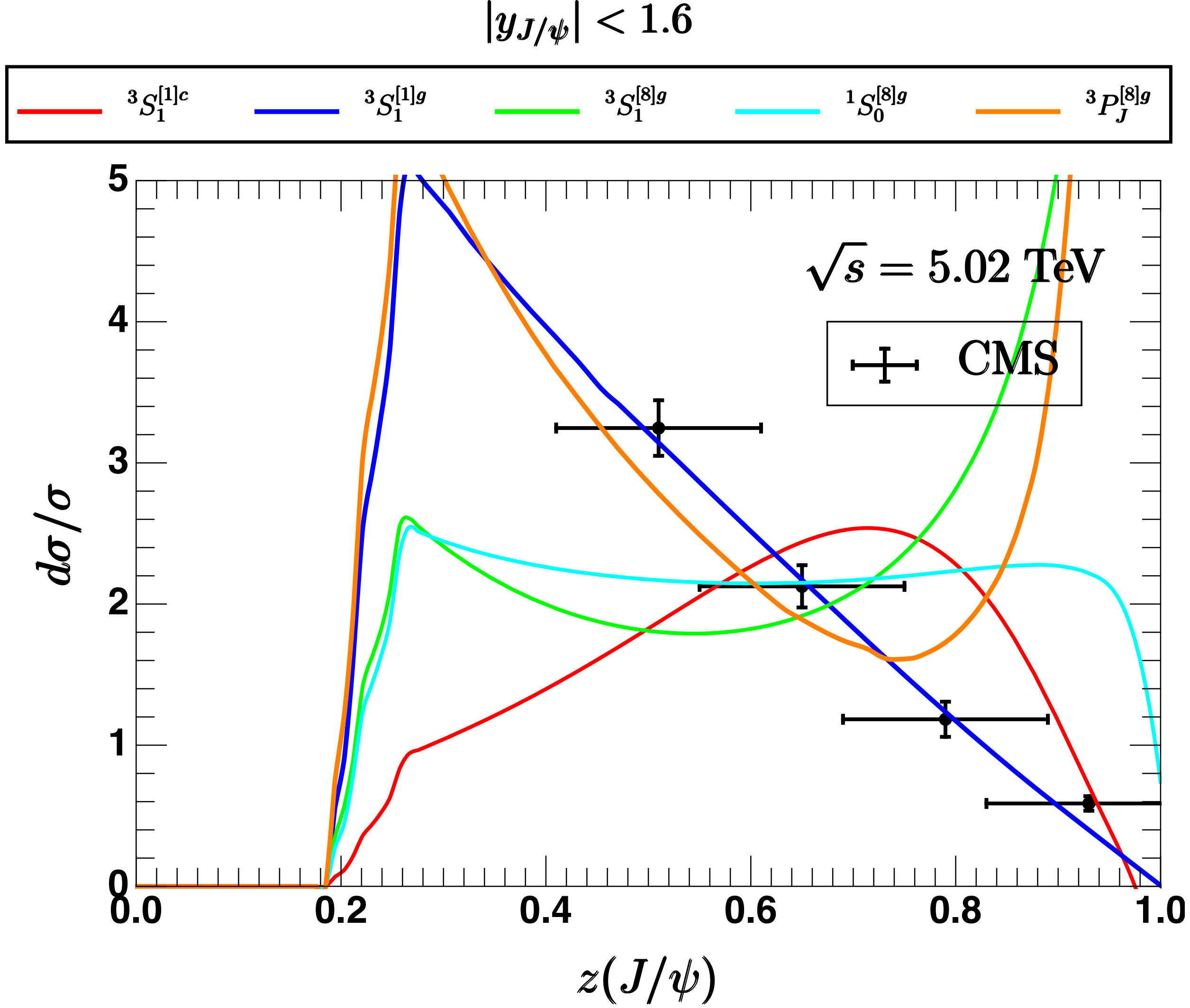
[L. Dai, A. Leibovich, Y. Makris, T. Mehen, work in progress]

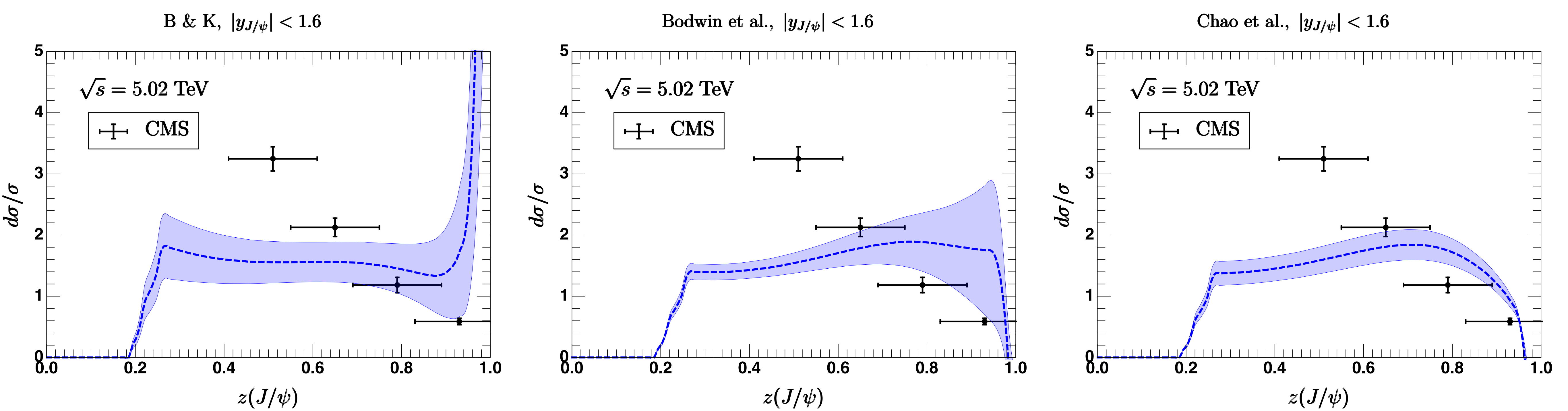
CMS-PAS-HIN-18-012

Preliminary

$$25\text{GeV} < p_{T,\text{jet}} < 35\text{GeV}$$

$$6.5\text{GeV} < p_{T,J/\psi} < 35\text{GeV}$$





[L. Dai, A. Leibovich, Y. Makris, T. Mehen, work in progress]

CMS-PAS-HIN-18-012

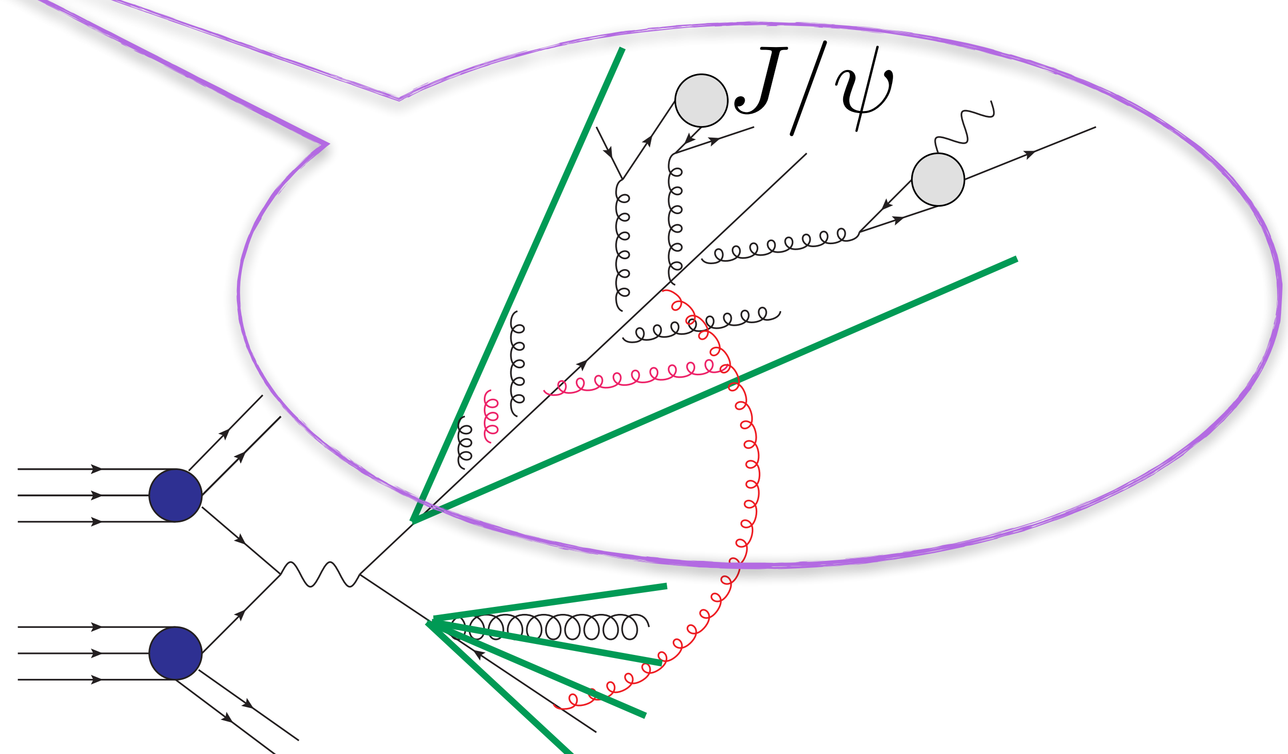
E(jet) distribution

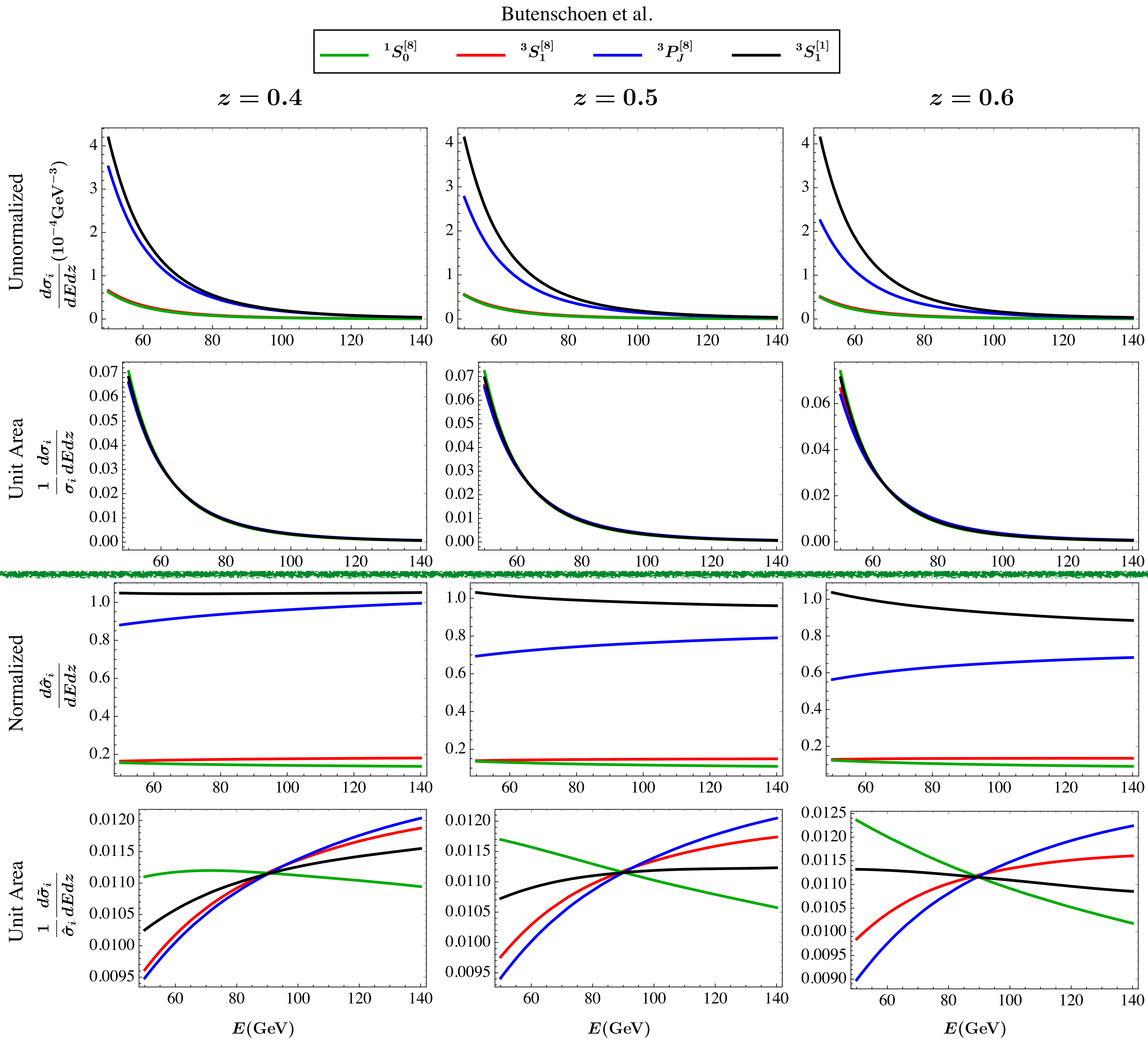
- Normalized cross sections for the LHC (*i* denotes production channels):

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

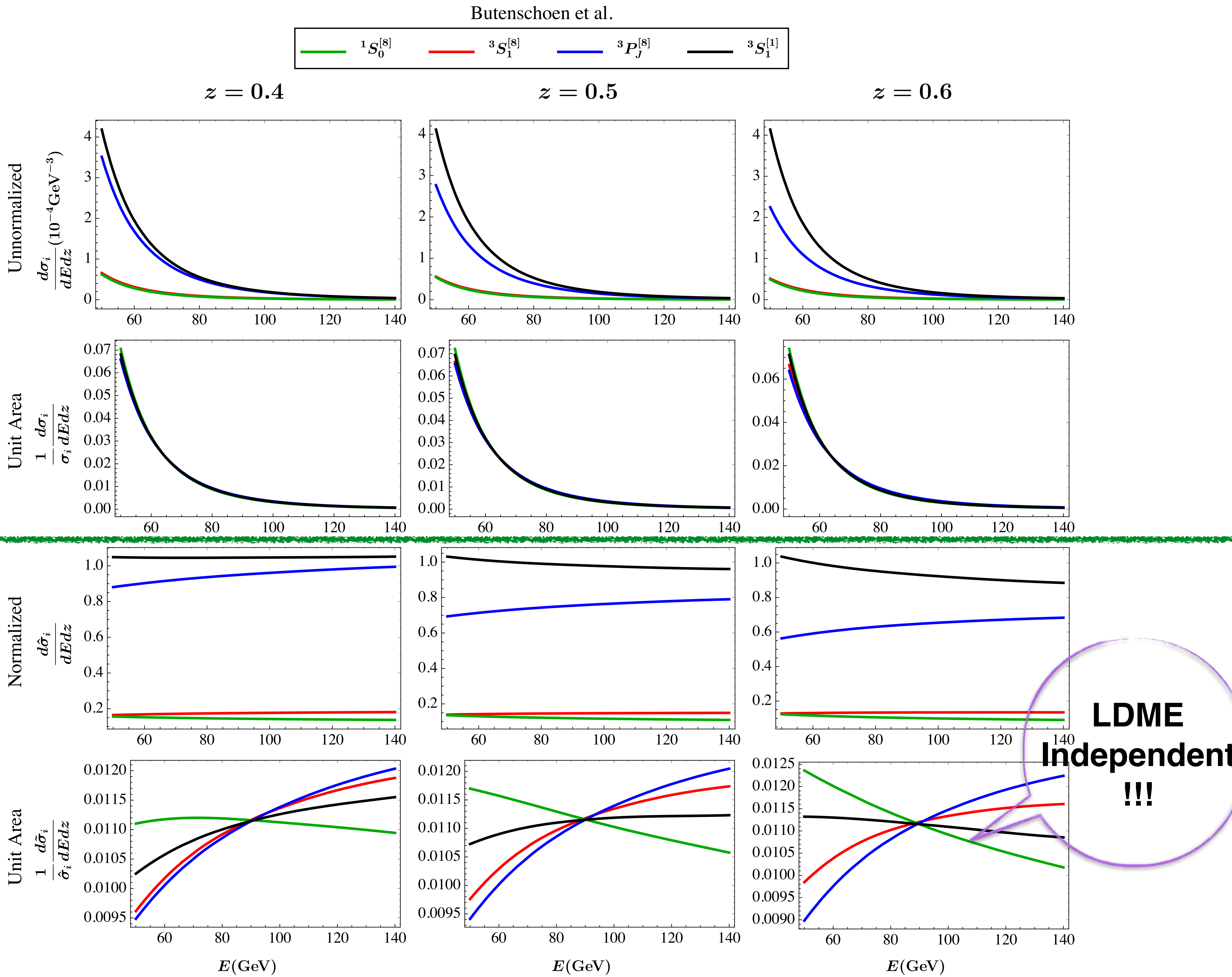
$$\frac{d\hat{\sigma}_i}{dEdz} \equiv \frac{d\sigma_i}{dEdz} \Bigg/ \frac{d\sigma_J}{dE}$$

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





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



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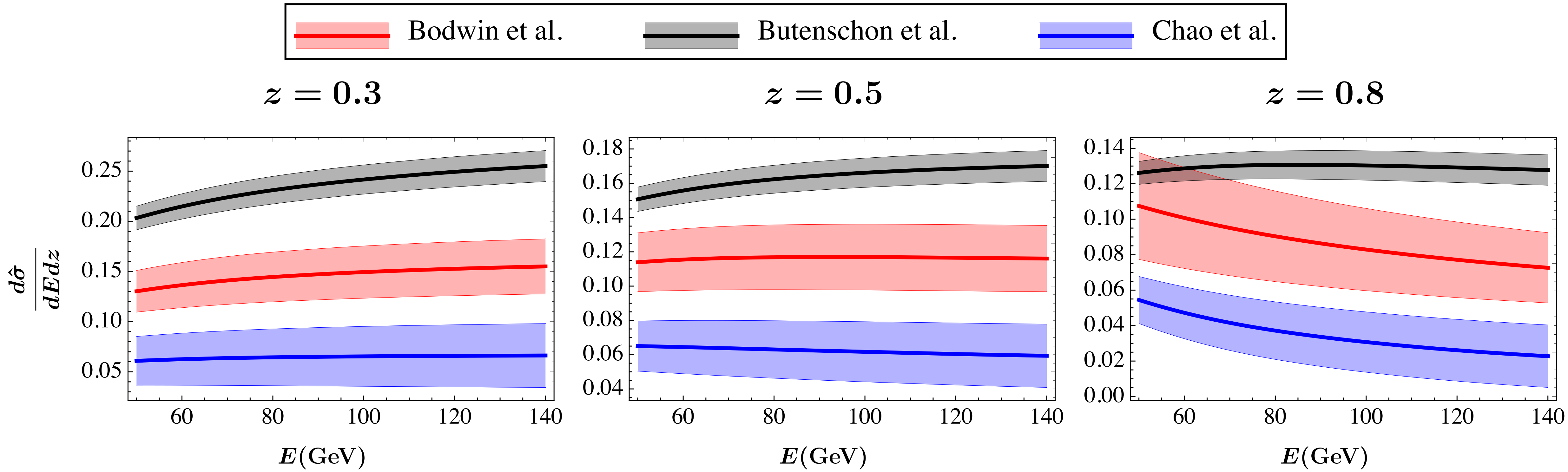
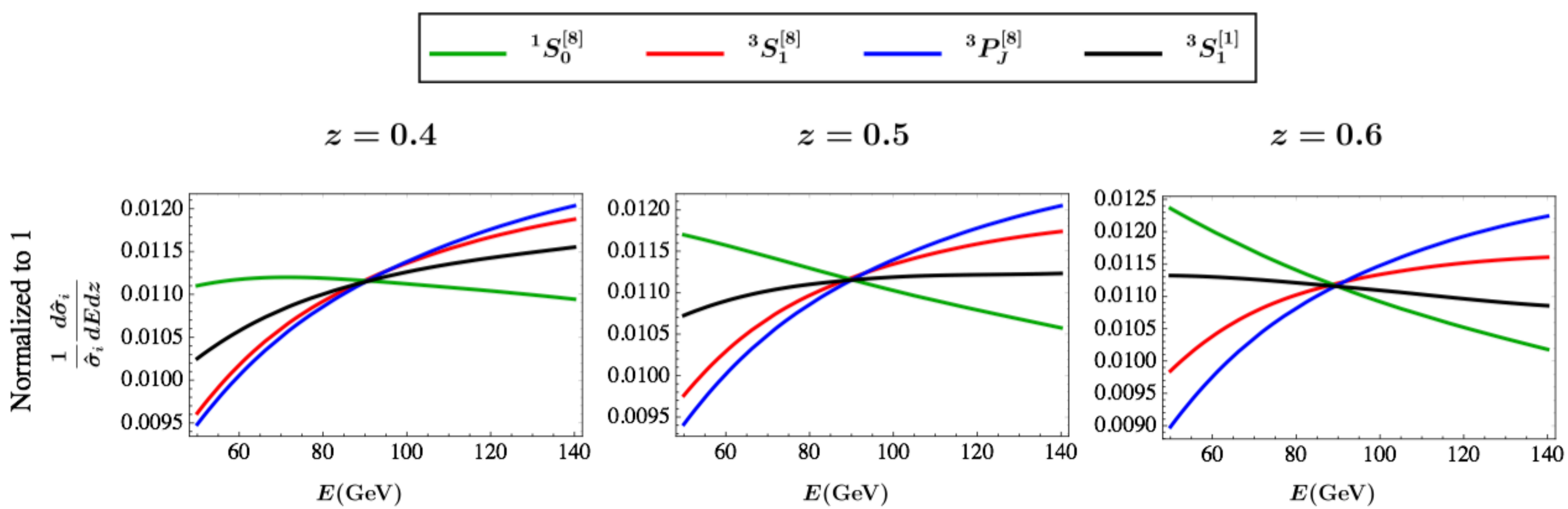
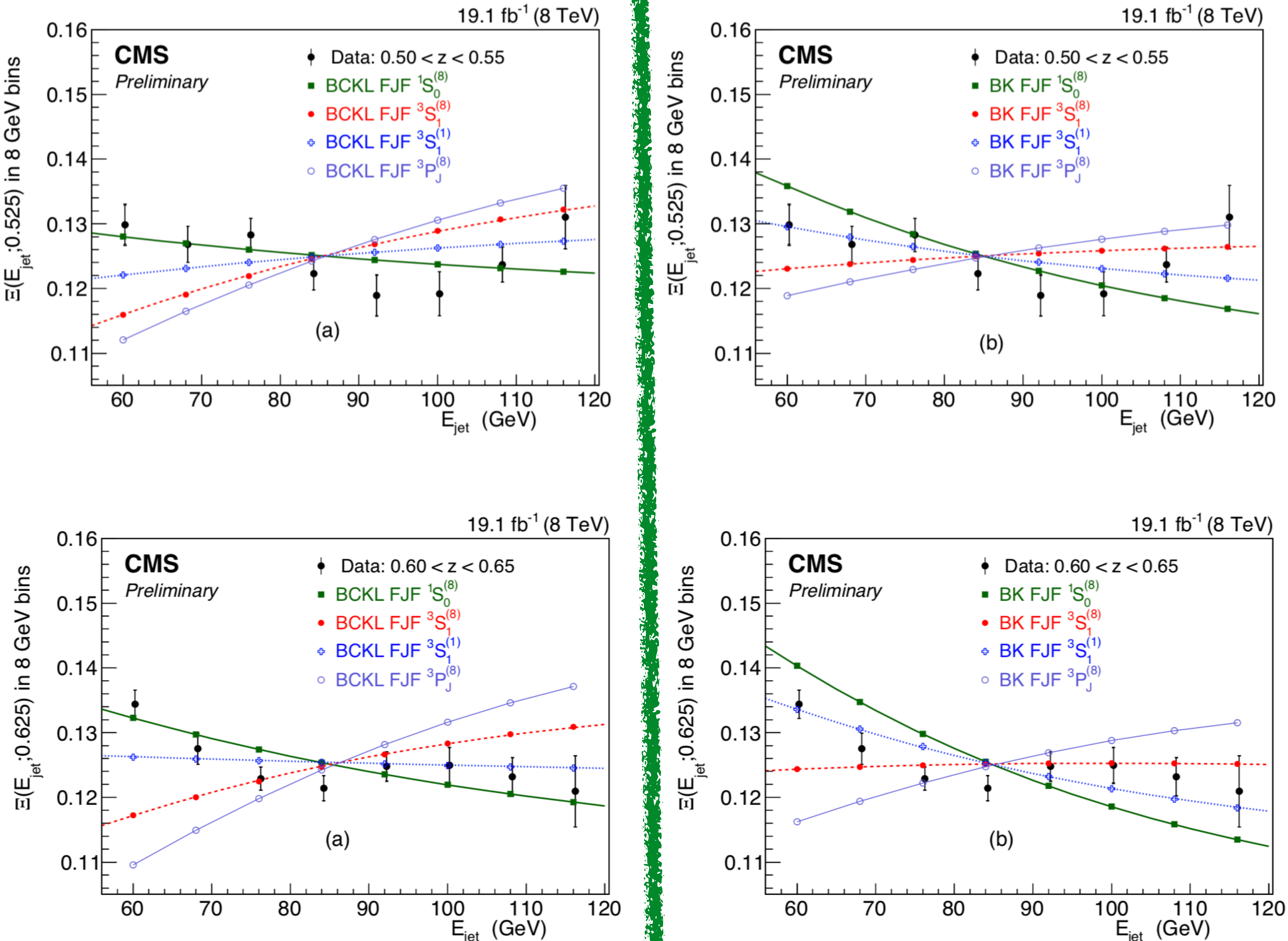


Decreasing at z > 0.5 (high pT), consistent with the dominance of $^1S_0^{[8]}$ at high pT



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


19.1 fb^{-1} (8 TeV)
CMS
Preliminary
Data: 0.50 < z < 0.55
BCKL FJF $^1S_0^{(8)}$
BCKL FJF $^3S_1^{(8)}$
BCKL FJF $^3S_1^{(1)}$
BCKL FJF $^3P_J^{(8)}$
(a)
$\Xi(E_{jet};0.525)$ in 8 GeV bins
E_{jet} (GeV)
19.1 fb^{-1} (8 TeV)
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Preliminary
Data: 0.50 < z < 0.55
BK FJF $^1S_0^{(8)}$
BK FJF $^3S_1^{(8)}$
BK FJF $^3S_1^{(1)}$
BK FJF $^3P_J^{(8)}$
(b)
$\Xi(E_{jet};0.525)$ in 8 GeV bins
E_{jet} (GeV)
19.1 fb^{-1} (8 TeV)
CMS
Preliminary
Data: 0.60 < z < 0.65
BCKL FJF $^1S_0^{(8)}$
BCKL FJF $^3S_1^{(8)}$
BCKL FJF $^3S_1^{(1)}$
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Thank You!

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