J/Ψ Production and Polarization within a Jet

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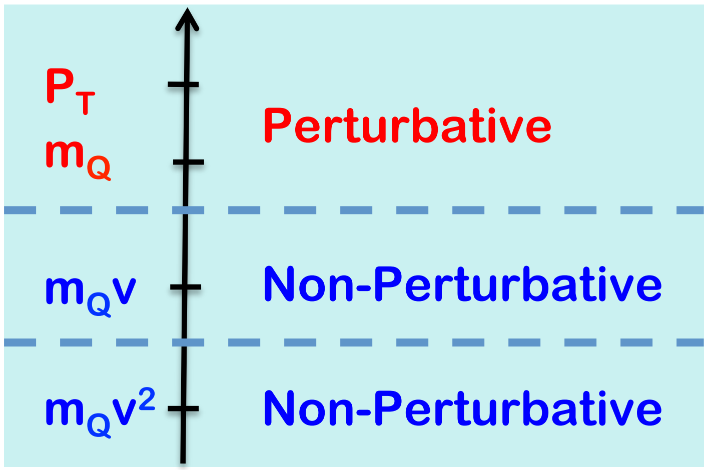
Heavy quarkonium

- **One of the simplest QCD bound states:**

  Localized color charges (heavy mass), non-relativistic relative motion

  Charmonium: $v^2 \approx 0.3$ **Bottomonium:** $v^2 \approx 0.1$

- **Well-separated momentum scales – effective theory:**



Hard — Production of $Q\bar{Q}$ [pQCD]

Soft — Relative Momentum [NRQCD]

$\Lambda_{\rm QCD}$

Ultrasoft — Binding Energy [pNRQCD]

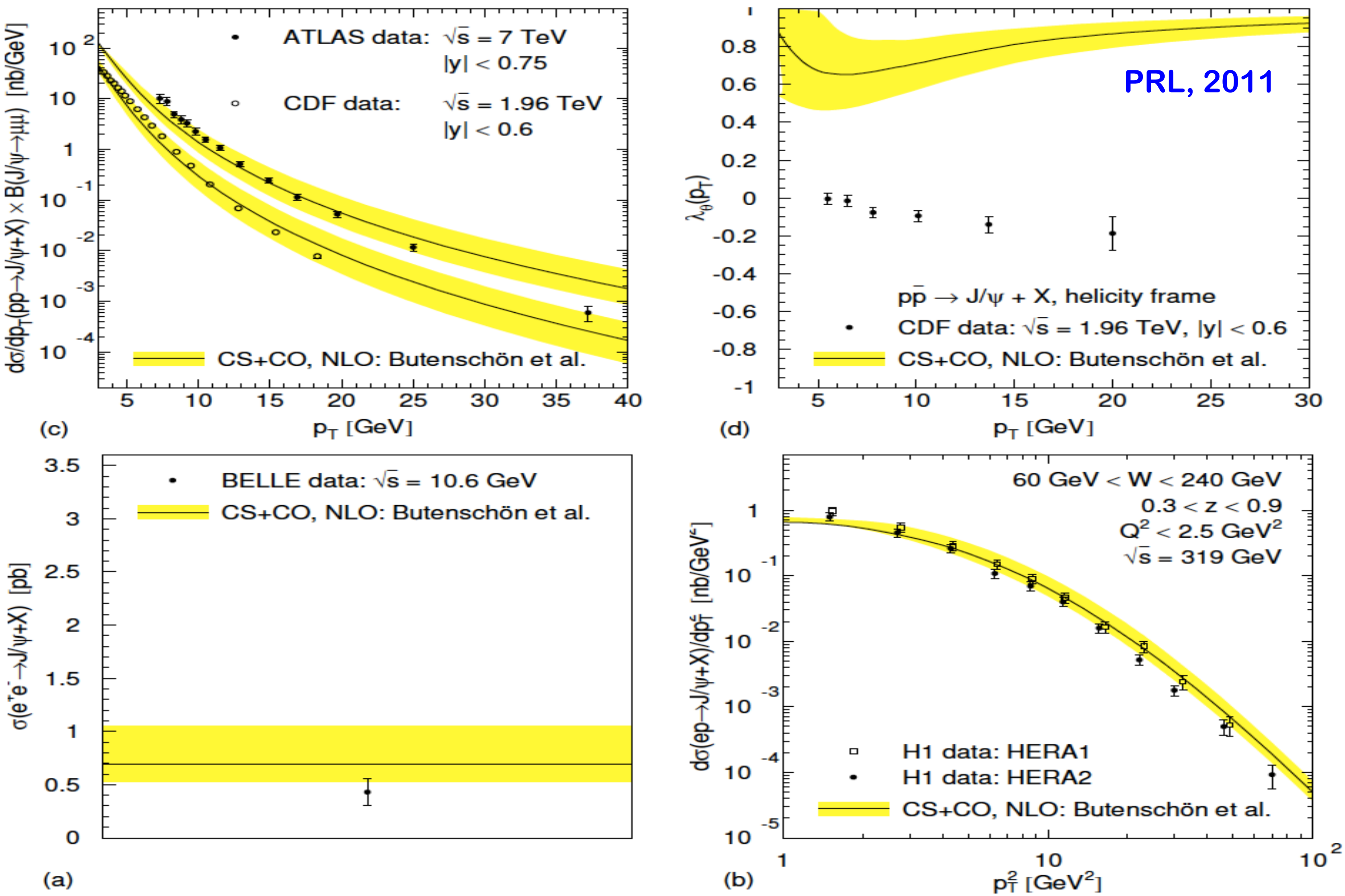
- **Cross sections and observed mass scales:**

$$\frac{d\sigma_{AB\to H(P)X}}{dy dP_T^2} \qquad \sqrt{S}, \qquad P_T, \qquad M_H,$$

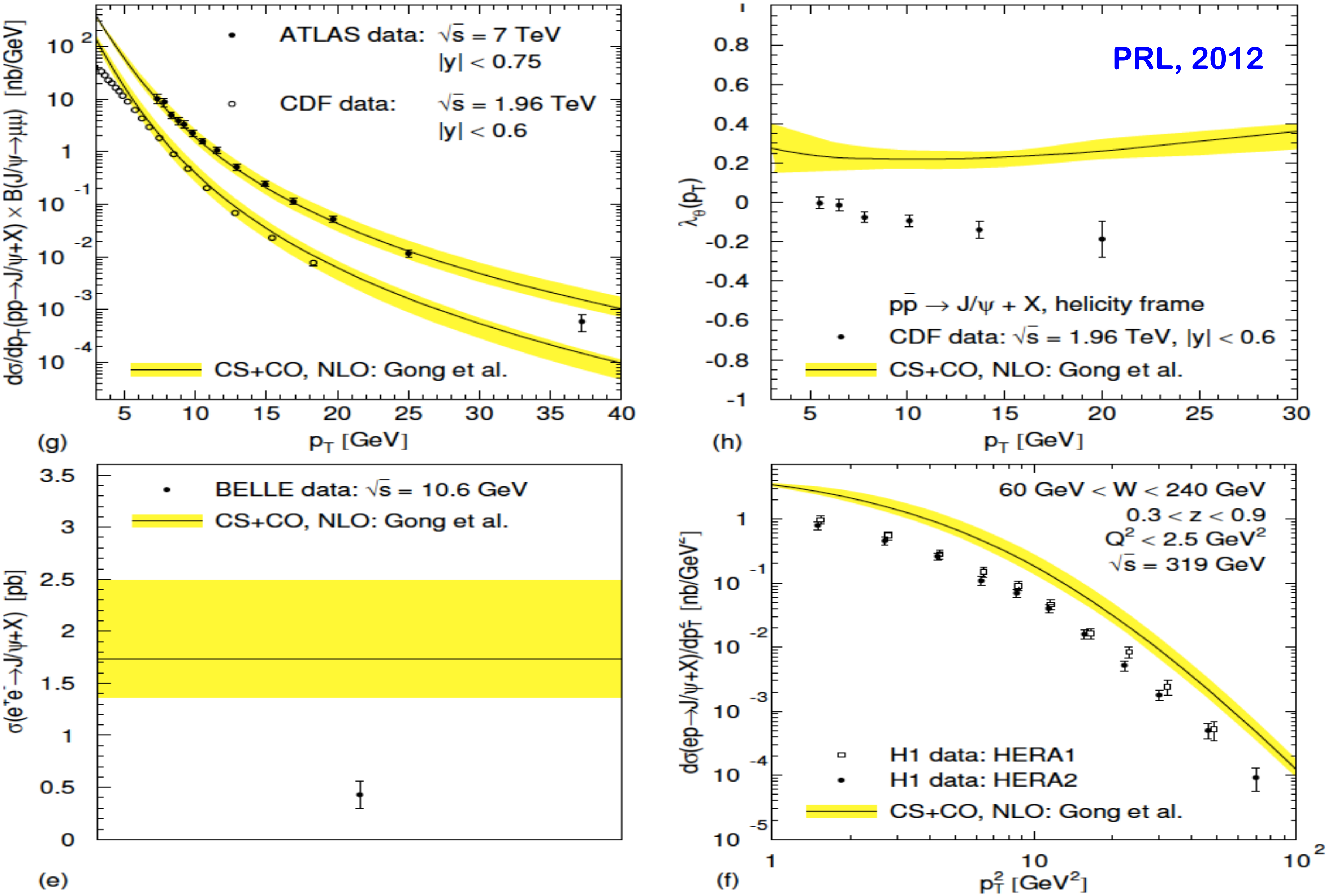
PQCD is "expected" to work for the production of heavy quarks

Emergence of a quarkonium from a heavy quark pair?

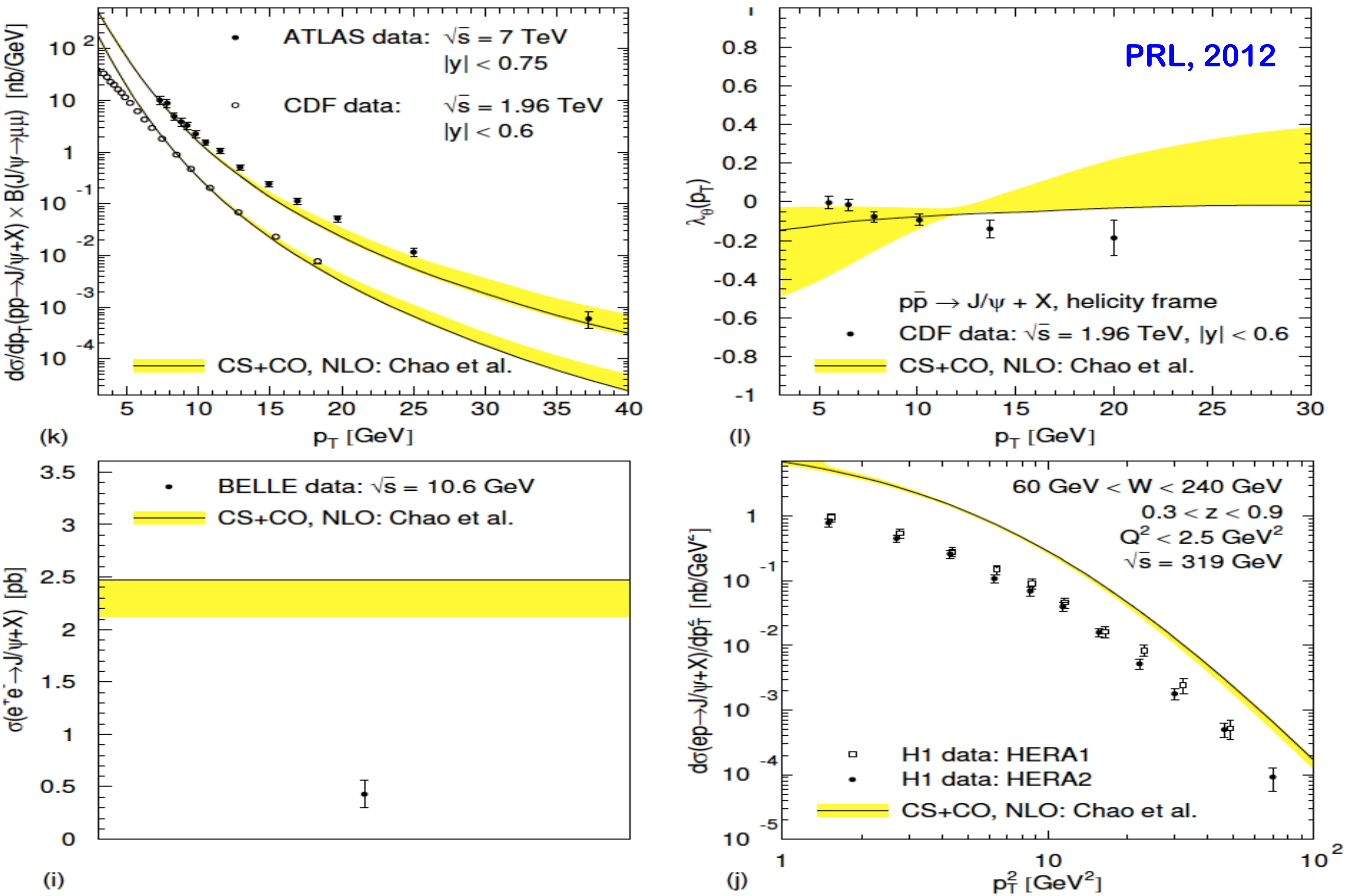
NLO theory fits – Butenschoen et al.



NLO theory fits – Gong et al.



NLO theory fits – Chao et al.



Production at collider energies

G.T. Bodwin, et al., PRD 1995

- **NRQCD factorization:**

Expansion in powers of both α_s and v!

$$d\sigma_{A+B\to H+X}(p_T) = \sum_n d\hat{\sigma}_{A+B\to[Q\bar{Q}(n)]+X}(p_T)\,\langle\mathcal{O}_n^H\rangle$$

Hadronization

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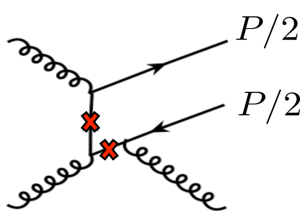
Hadronization

❑ Re-organization is needed when $p_T \gg m_Q$:

Z.B. Kang, et al., PRL 2011

CS channel as a case study

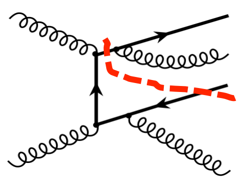
LO in α_s:

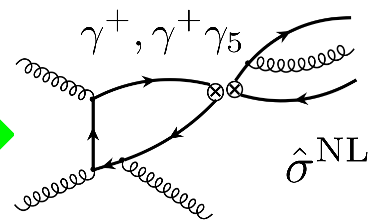


$$\hat{\sigma}^{\rm LO} \propto \frac{\alpha_s^3(p_T)}{p_T^8}$$

P$_T$ Power!

NLO in α_s:

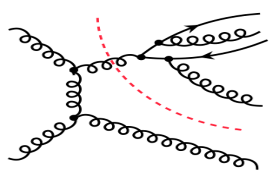




$$\hat{\sigma}^{\rm NLO} \to \frac{\alpha_s^3(p_T)}{p_T^6} \otimes \alpha_s(\mu)\log(\mu^2/\mu_0^2)$$

$$\mu_0 \gtrsim 2m_Q$$

NNLO in α_s:



$$\hat{\sigma}^{\rm NNLP} \to \frac{\alpha_s^2(p_T)}{p_T^4} \otimes \alpha_s^3(\mu)\log^m(\mu^2/\mu_0^2)$$

✧ When $p_T \gg m_Q$, the expansion in powers of α_s is not reliable!

✧ Leading order in α_s-expansion =\= leading power in $1/p_T$-expansion!

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- **PQCD factorization:**

G.T. Nayak, et al., PRD2005
Z.B. Kang, et al., PRD2014

$$d\sigma_{A+B\to H+X}(p_T) = \sum_i d\tilde{\sigma}_{A+B\to i+X}(p_T/z,\mu)\otimes D_{H/i}(z,\mu)$$

LP

NLP

$$+\sum_n d\tilde{\sigma}_{A+B\to[Q\bar{Q}(n)]+X}(p_T/z,\zeta_1,\zeta_2,\mu)\otimes\mathcal{D}_{H/[Q\bar{Q}(n)]}(z,\zeta_1,\zeta_2,\mu)$$

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Model: Using NRQCD factorization for the INPUT fragmentation functions

Y.Q. Ma, et al., PRD2014

$$D_{H/i}(z,\mu_0) = \sum_n d_{i\to[Q\bar{Q}(n)]}(z,\mu_0)\,\langle\mathcal{O}_n^H\rangle$$

$$\mathcal{D}_{H/[Q\bar{Q}(m)]}(z,\zeta_1,\zeta_2,\mu_0) = \sum_n d_{[Q\bar{Q}(m)]\to[Q\bar{Q}(n)]}(z,\zeta_1,\zeta_2,\mu_0)\,\langle\mathcal{O}_n^H\rangle$$

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❑ PQCD improved NRQCD factorization:

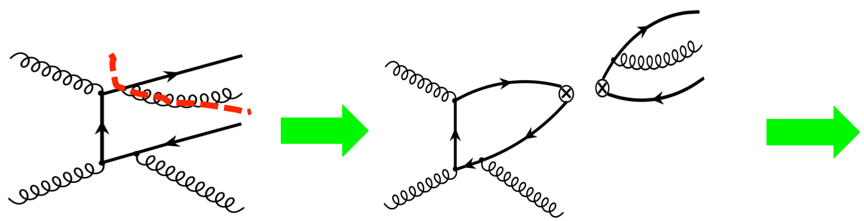
Evolution = resummation

$$d\hat{\sigma}_{A+B\to[Q\bar{Q}(n)]+X}(p_T) = \sum_i d\tilde{\sigma}_{A+B\to i+X}(p_T/z)\otimes d_{i\to[Q\bar{Q}(n)]}(z)$$

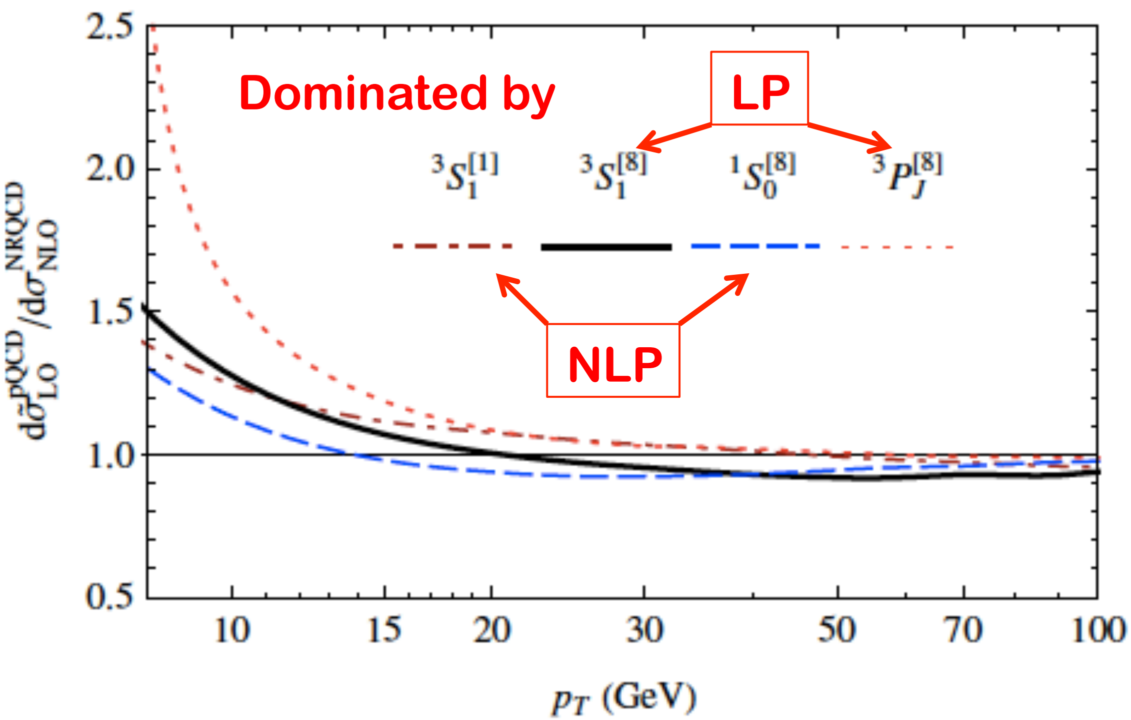
$$+\sum_m d\tilde{\sigma}_{A+B\to[Q\bar{Q}(m)]+X}(p_T/z,\zeta_1,\zeta_2)\otimes d_{[Q\bar{Q}(m)]\to[Q\bar{Q}(n)]}(z,\zeta_1,\zeta_2)$$

Channel-by-channel comparison

❑ NRQCD vs. PQCD improved NRQCD:



$$\sigma^{(\mathrm{NLO})}_{\mathrm{NRQCD}} \propto \left[d\hat{\sigma}^{A(\mathrm{LO})}_{ab\to[Q\bar{Q}(v8)]} \otimes \mathcal{D}^{(\mathrm{LO})}_{[Q\bar{Q}(v8)]\to J/\psi} + d\hat{\sigma}^{S(\mathrm{LO})}_{ab\to[Q\bar{Q}(a8)]} \otimes \mathcal{D}^{(\mathrm{LO})}_{[Q\bar{Q}(a8)]\to J/\psi} \right]$$

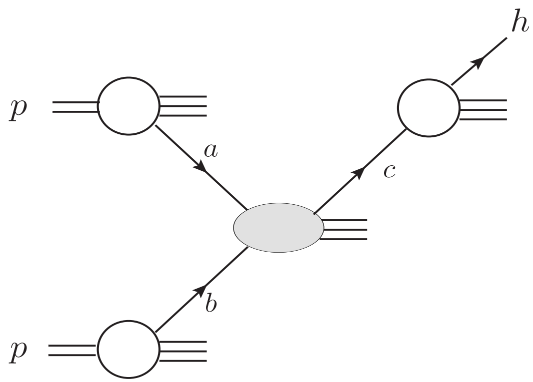


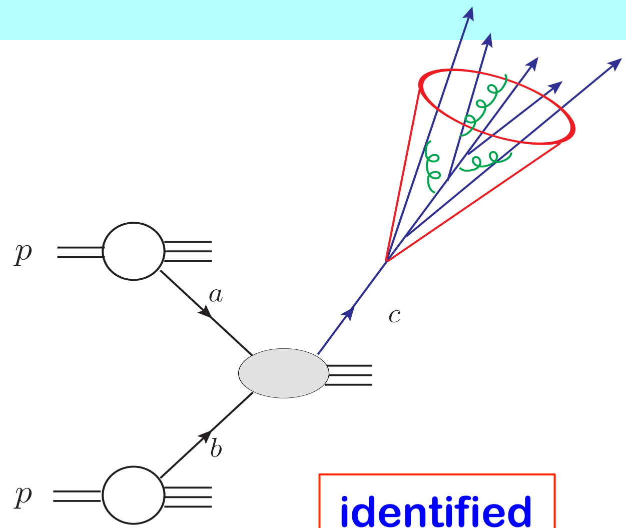
LO analytical results reproduce NLO NRQCD calculations (numerical)

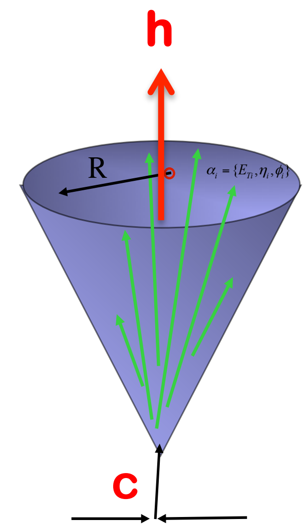
P_T – distribution is not sufficient for fixing all NRQCD matrix elements
Need more physical observables!

Hadron distributions at high P_T

❑ Factorization formulas:







$$z = p_T / p_T^c$$

$$z_h = p_T^h / p_T$$

$$\frac{d\sigma^{pp\to hX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes D_c^h$$

identified

Not identified

$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes J_c(\mu \sim p_T R)$$

Identified within a jet

$$\frac{d\sigma^h}{dy dp_T dz_h} \propto \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes \mathcal{G}_c^h(z, z_h, R, \mu)$$

Hadron distributions at high P_T

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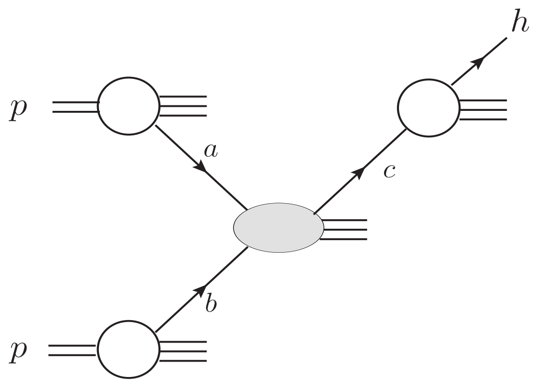

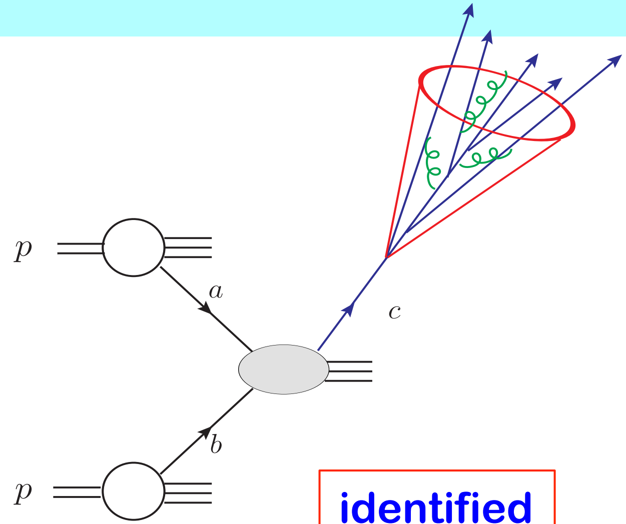

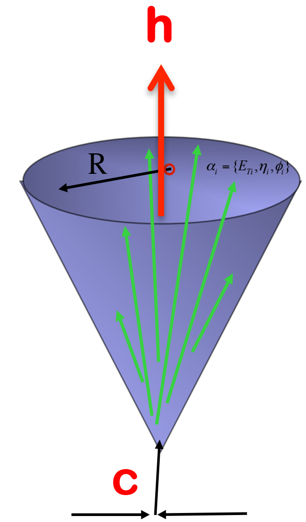

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Identified within a jet

$$z = p_T / p_T^c$$
$$z_h = p_T^h / p_T$$

❑ Scale dependence – (R << 1):

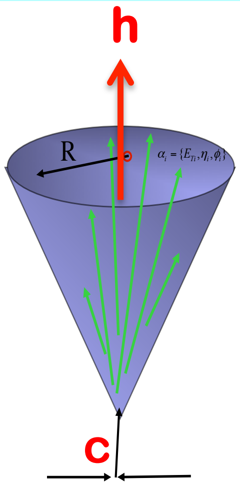
$$\mu \frac{\partial}{\partial \mu} \begin{Bmatrix} D_c^h \\ J_c \\ \mathcal{G}_c^h \end{Bmatrix} = \mathcal{P}_{c/d}^{\mathrm{DGLAP}} \otimes \begin{Bmatrix} D_d^h \\ J_d \\ \mathcal{G}_d^h \end{Bmatrix}$$

Calculable!

$$\mathcal{G}_c^h(z, z_h, R, \mu) = \sum_d \mathcal{J}_{cd}(z, z_h, R, z', \mu)\, D_d^h\left(\frac{z}{z'}, \mu\right) \times \left[1 + \mathcal{O}\left(\frac{\max(\Lambda_{\mathrm{QCD}}^2, m_h^2)}{(E_{\mathrm{jet}} R)^2}\right)\right]$$

Jet fragmentation function

- **Ratio of two physical observables:**



$$F(z_h, p_T) = \frac{d\sigma^h}{dy\,dp_T\,dz_h} \Big/ \frac{d\sigma}{dy\,dp_T}$$

$$z_h = p_T^h / p_T$$

$$z = p_T / p_T^c$$

First produce a jet, and then look further for a hadron inside the jet!

➡ *Favor the contribution initiated by a single energetic parton!*

$$F_{A+B\to H+X}(z_h, p_T) \propto \sum_n \tilde{\mathcal{F}}_{A+B\to[Q\bar{Q}(n)]+X}(z_h, p_T)\, \langle \mathcal{O}_n^H \rangle$$

Different relative size of the coefficients, and different weights of the matrix elements

Jet fragmentation function

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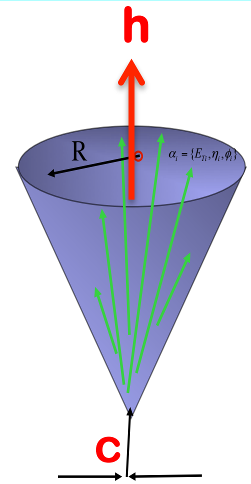
$$F(z_h, p_T) = \frac{d\sigma^h}{dy\,dp_T\,dz_h} \Big/ \frac{d\sigma}{dy\,dp_T} \qquad z_h = p_T^h / p_T \qquad z = p_T / p_T^c$$



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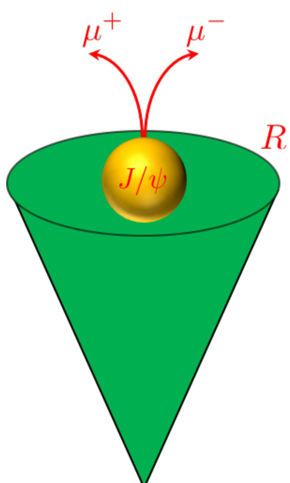
Different relative size of the coefficients, and different weights of the matrix elements

❑ Polarization:



In the helicity frame:

Kang, Qiu, Ringer, Xing, Zhang, PRL 2017

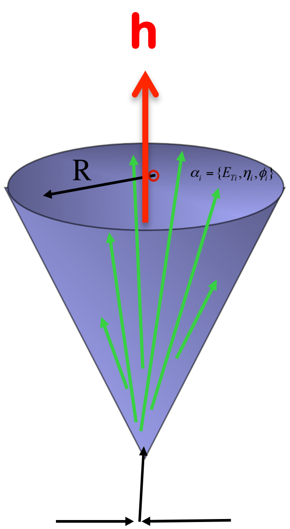
$$\frac{d\sigma^{J/\psi(\to\ell^+\ell^-)}}{d\cos\theta} \propto 1 + \lambda_F \cos^2\theta$$

with

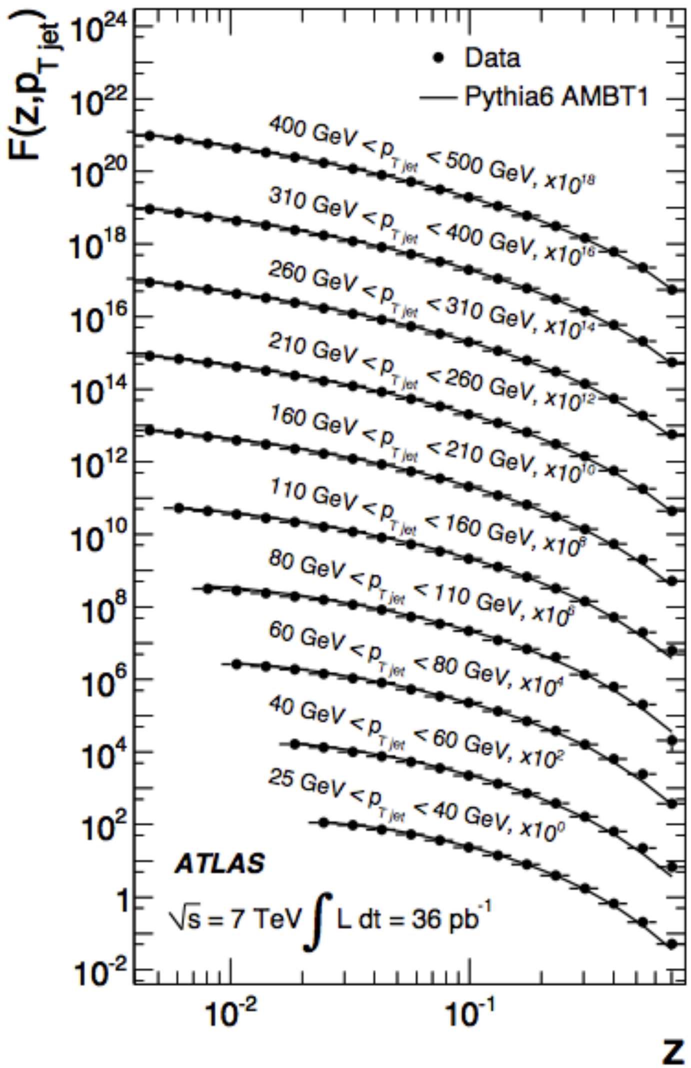
$$\lambda_F(z_h, p_T) = \frac{F_T^{J/\psi} - F_L^{J/\psi}}{F_T^{J/\psi} + F_L^{J/\psi}} = \begin{cases} +1, & \text{Transverse} \\ -1, & \text{Longitudinal} \end{cases}$$

Jet fragmentation function at the LHC

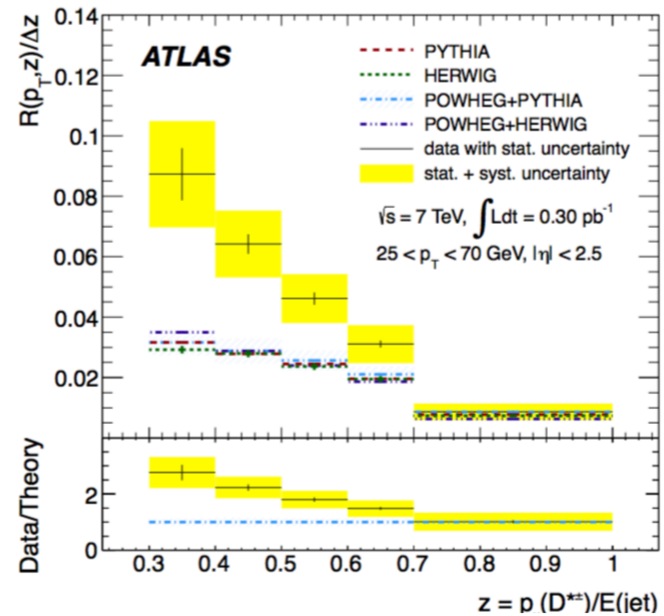
❑ A puzzle (or opportunity) for heavy flavor?

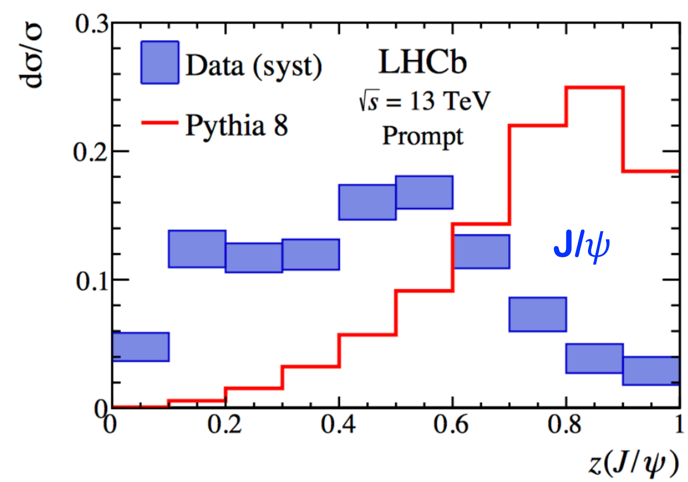


$$z_h = \frac{E_h}{E_{\mathrm{jet}}}$$



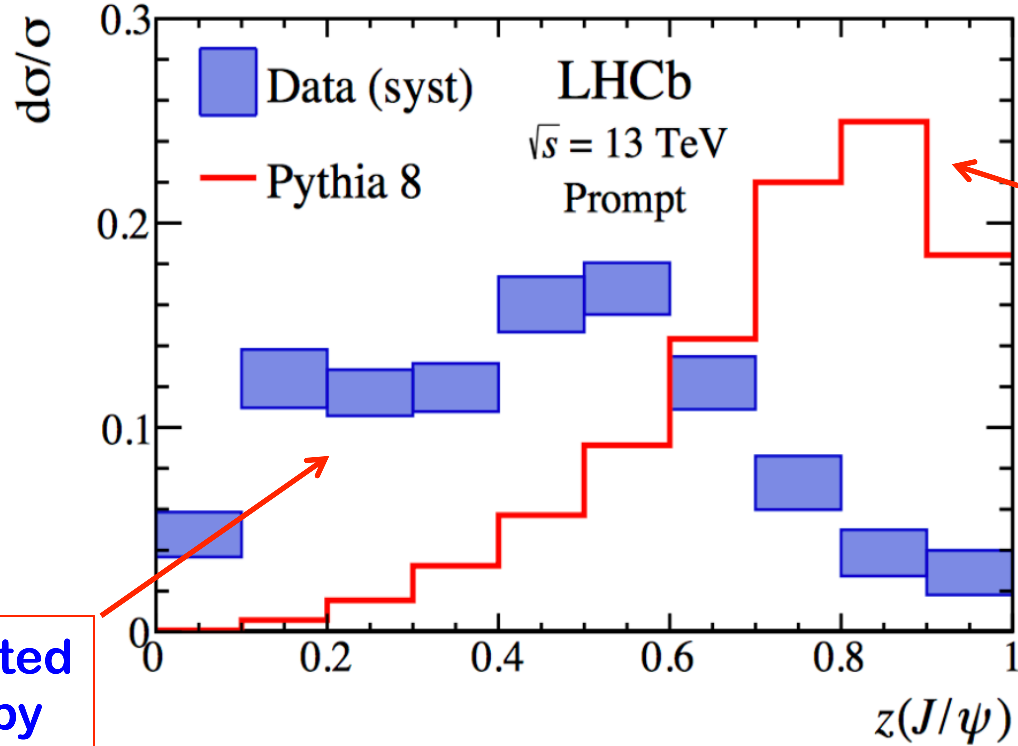
Light charged hadrons





Quarkonium production inside a jet

- J/ψ-in-jet measurement from LHCb:



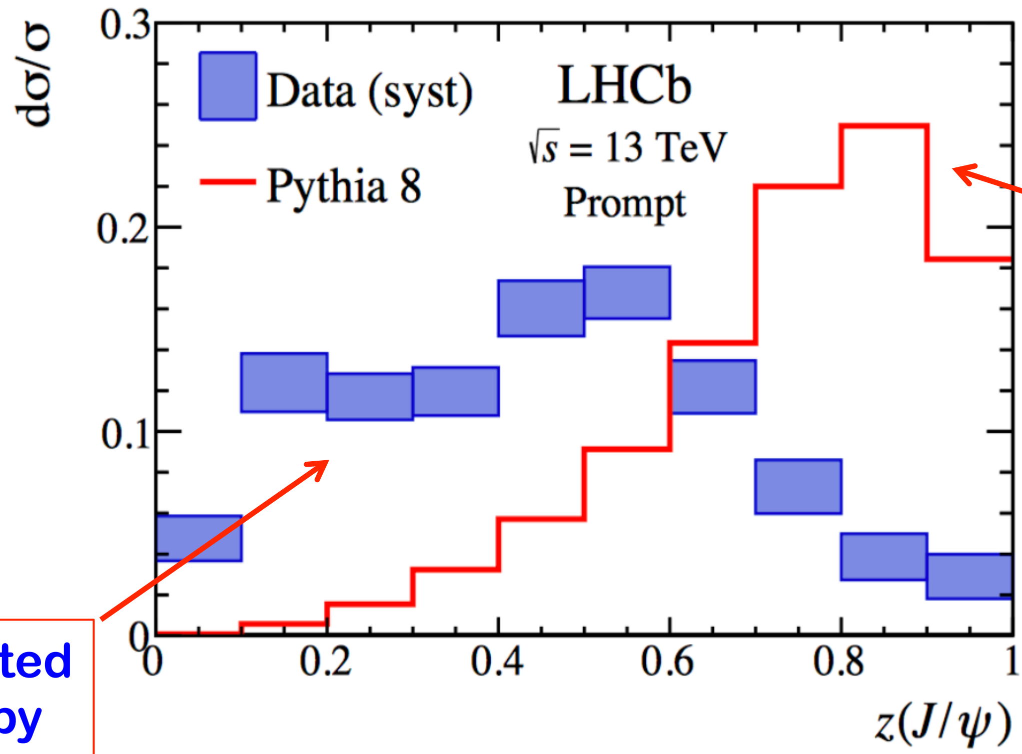
Jet was initiated likely by a produced heavy quark pair

Jet was initiated more likely by a produced SINGLE parton

Leading power contribution dominated!

Quarkonium production inside a jet

- **J/ψ-in-jet measurement from LHCb:**



Jet was initiated likely by a produced heavy quark pair

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Leading power contribution dominated!

Recall: A delicate cancelation was required between $^3S_1^{[8]}$ and $^3P_J^{[8]}$ channels was required for fitting the high p_T-distribution!

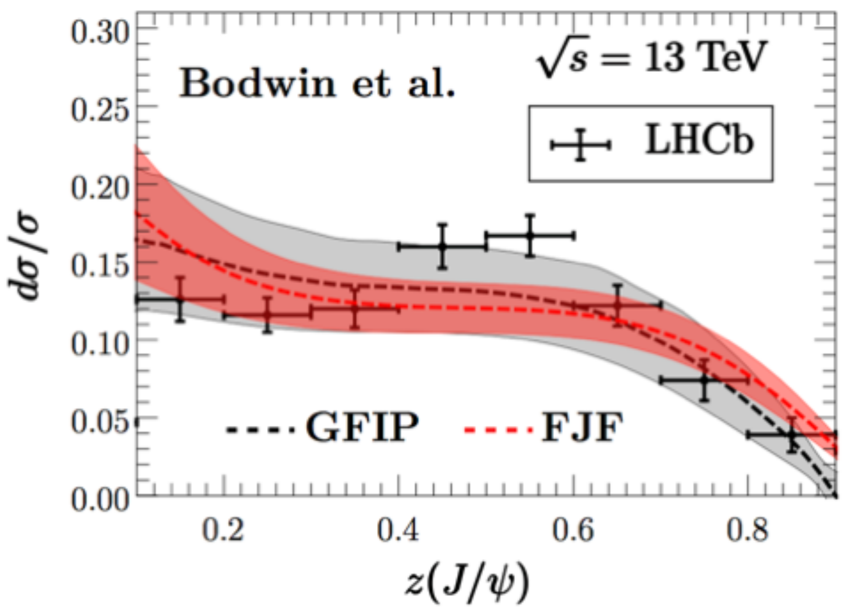
→ *Incomplete cancelation could lead to a "negative" $d\sigma$ or F, ...*

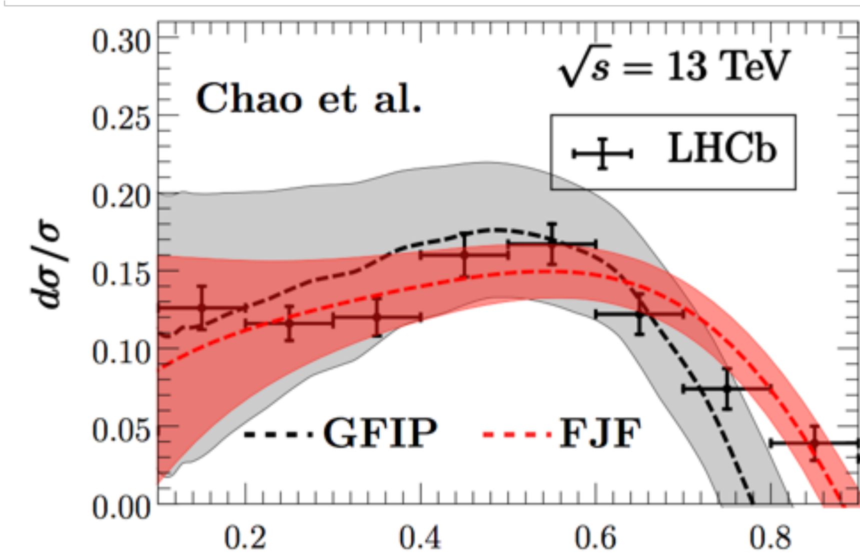
J/ψ production in jets

Baumgart et al., JHEP14
Bain et al. PRL17

- Fitted NRQCD matrix elements:

	$\langle \mathcal{O}^{J/\psi}(^3S_1^{[1]})\rangle$ $\times$ 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 [5, 6]	1.32 ± 0.20	0.224 ± 0.59	4.97 ± 0.44	-0.72 ± 0.88
Chao, et al. [12]	1.16 ± 0.20	0.30 ± 0.12	8.9 ± 0.98	0.56 ± 0.21
Bodwin et al. [13]	1.32 ± 0.20	1.1 ± 1.0	9.9 ± 2.2	0.49 ± 0.44





FJFs: fragmentation jet functions
GFIP: gluon fragmentation improved PYTHIA

Two are consistent

J/ψ production in jets

Baumgart et al., JHEP14
Bain et al. PRL17

- **Fitted NRQCD matrix elements:**

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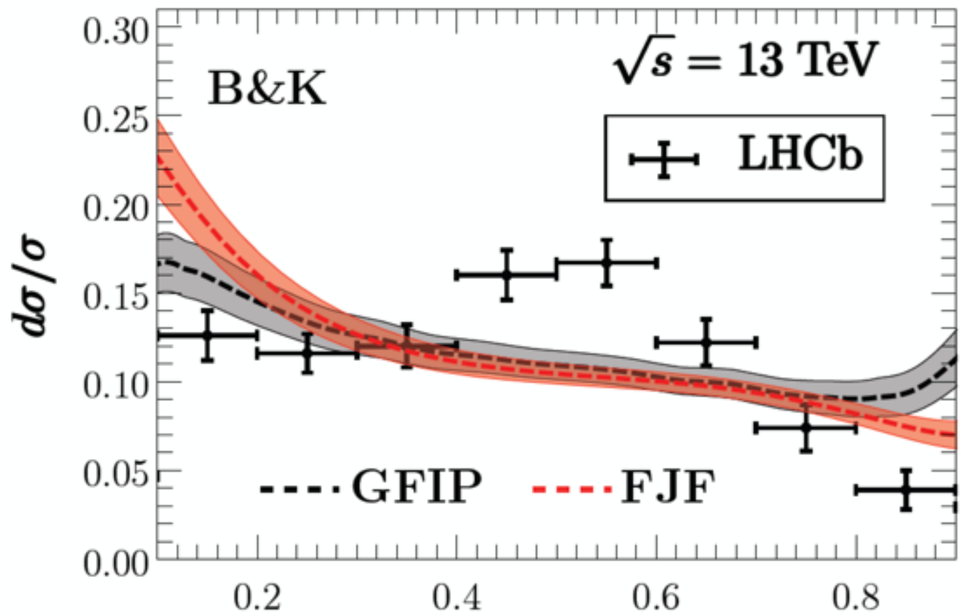


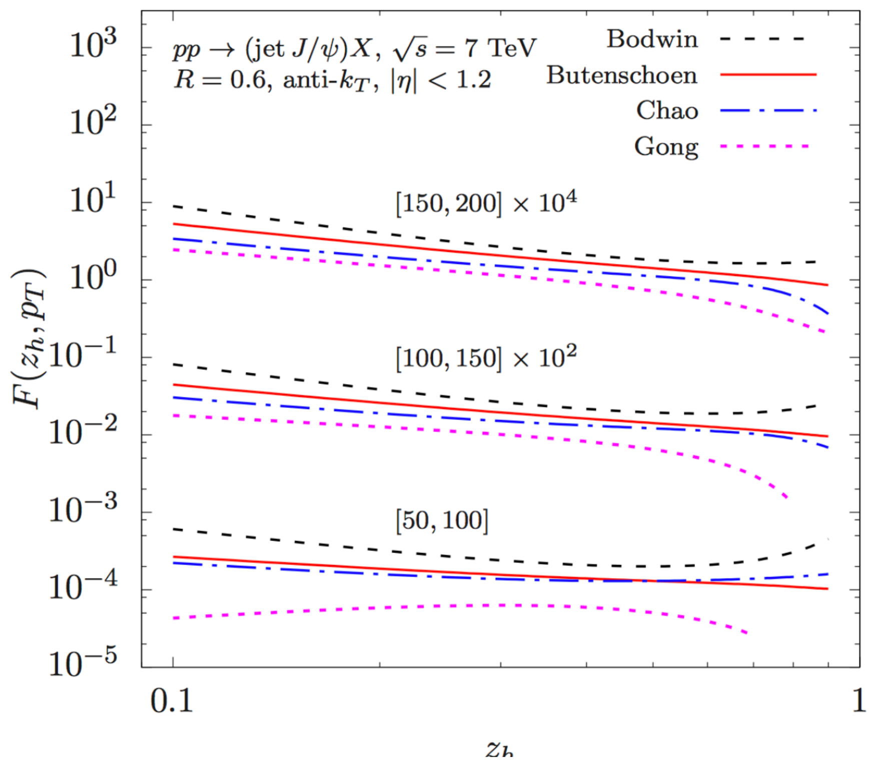
FJFs: fragmentation jet functions
GFIP: gluon fragmentation improved PYTHIA

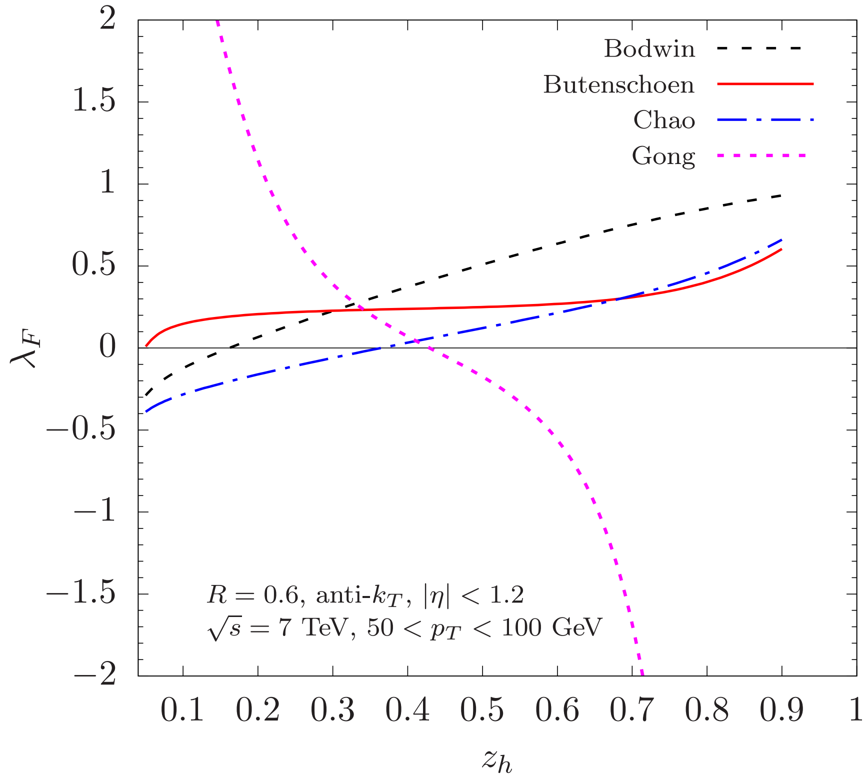
This fit has a poor agreement with jet data

J/ψ production and polarization in jets

❑ Polarization:

Kang, Qiu, Ringer, Xing, Zhang, PRL 2017
See also Bain, et al, PRL 2017





NOTE: $\lambda_F(z_h, p_T) = \dfrac{F_T^{J/\psi} - F_L^{J/\psi}}{F_T^{J/\psi} + F_L^{J/\psi}}$

$|\lambda_F| \leq 1!$

If $|\lambda_F| > 1$, the F_T or F_L is effectively negative!

➡ ***More differential than inclusive J/ψ p_T spectrum, and can better discriminate different NRQCD parameterizations!***

Summary and outlook

- It has been over 40 years since the discovery of J/Ψ, we still have a lot of questions about their production mechanism

- When p_T (E) >> m_Q at collider energies, earlier model calculations for the production of heavy quarkonia are not perturbatively stable

  LO in α_s-expansion may not be the LP term in m_Q/p_T(E)-expansion

- QCD factorization works for both LP and NLP (α_s for each power)

  Sub-leading power is very important for the p_T-shape and polarization

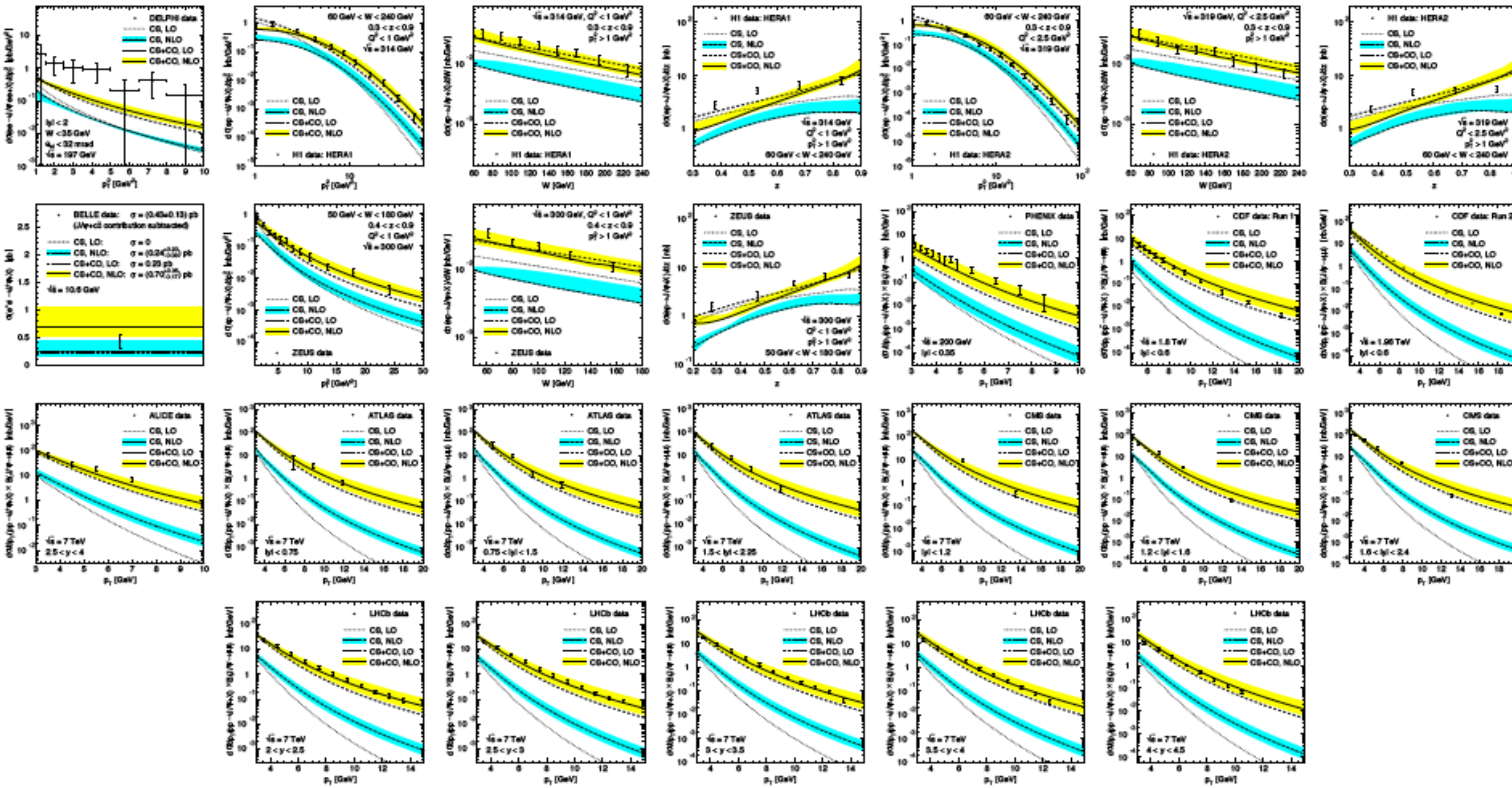
  There are still a lot of unanswered questions related to quarkonium!

- Quarkonium production and polarization in the jet could be very good observables to help pin down the production mechanism

Thank you!

Backup slides

Global analysis of heavy quarkonium production



194 data points from 10 experiments, fix singlet $\langle O[{}^3S_1{}^{[1]}] \rangle = 1.32\ \mathrm{GeV}^3$

→ $\langle O[{}^1S_0{}^{[8]}] \rangle = (4.97 \pm 0.44)\cdot 10^{-2}\ \mathrm{GeV}^3$ $\langle O[{}^3S_1{}^{[8]}] \rangle = (2.24 \pm 0.59)\cdot 10^{-3}\ \mathrm{GeV}^3$

$\langle O[{}^3P_0{}^{[8]}] \rangle = (-1.61 \pm 0.20)\cdot 10^{-2}\ \mathrm{GeV}^5$

$\chi^2/d.o.f. = 857/194 = 4.42$

Butenschoen and Kniehl, arXiv: 1105.0820