LEADING-POWER FRAGMENTATION CONTRIBUTIONS TO HEAVY-QUARKONIUM PRODUCTION

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We thank Bernd Kniehl and Mathias Butenschoen
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Geoffrey T. Bodwin, HSC, U-Rae Kim, Jungil Lee, PRL113, 022001 (2014)
Geoffrey T. Bodwin, HSC, U-Rae Kim, Jungil Lee, PRD92, 074042 (2015)
Geoffrey T. Bodwin, HSC, U-Rae Kim, Jungil Lee, Yan-Qing Ma, Kuang-Ta Chao, PRD93, 034041 (2016)

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OUTLINE

- Leading-power fragmentation in quarkonium production
- Hadroproduction of J/ψ
- Polarization of J/ψ
- Photoproduction of J/ψ
- Summary

INCLUSIVE J/ψ PRODUCTION

- NRQCD factorization conjecture for production of H

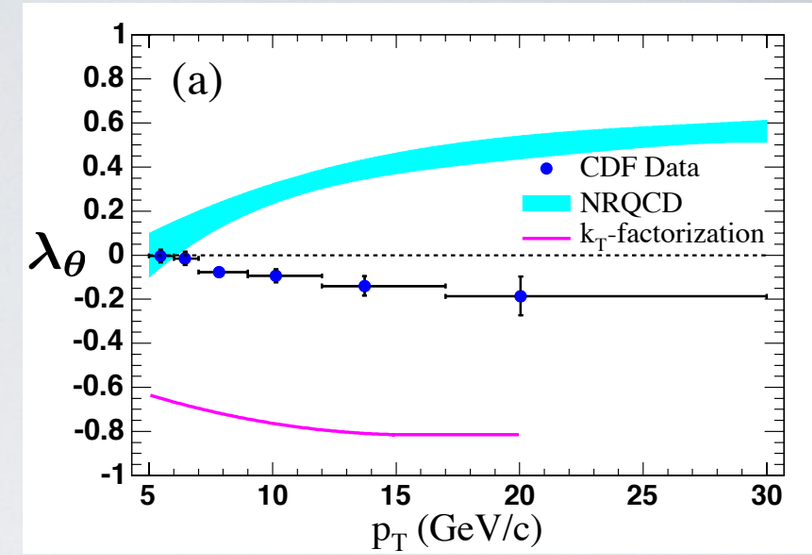
Bodwin, Braaten, and Lepage, PRD51, 1125 (1995)

$$d\sigma_{A+B\to H+X} = \sum_n \underbrace{d\sigma_{A+B\to Q\bar{Q}(n)+X}}_{\text{Short-distance cross section}} \underbrace{\langle \mathcal{O}^H(n)\rangle}_{\text{LDME}}$$

- Usually truncated at relative order v^4: ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, ${}^3P_J^{[8]}$, ${}^3S_1^{[1]}$ channels for J/ψ
- ${}^3S_1^{[1]}$ channel severely underestimates data at large p_T
- Not known how to calculate nonperturbative color-octet LDMEs
- CO LDMEs extracted from fits to measured cross sections

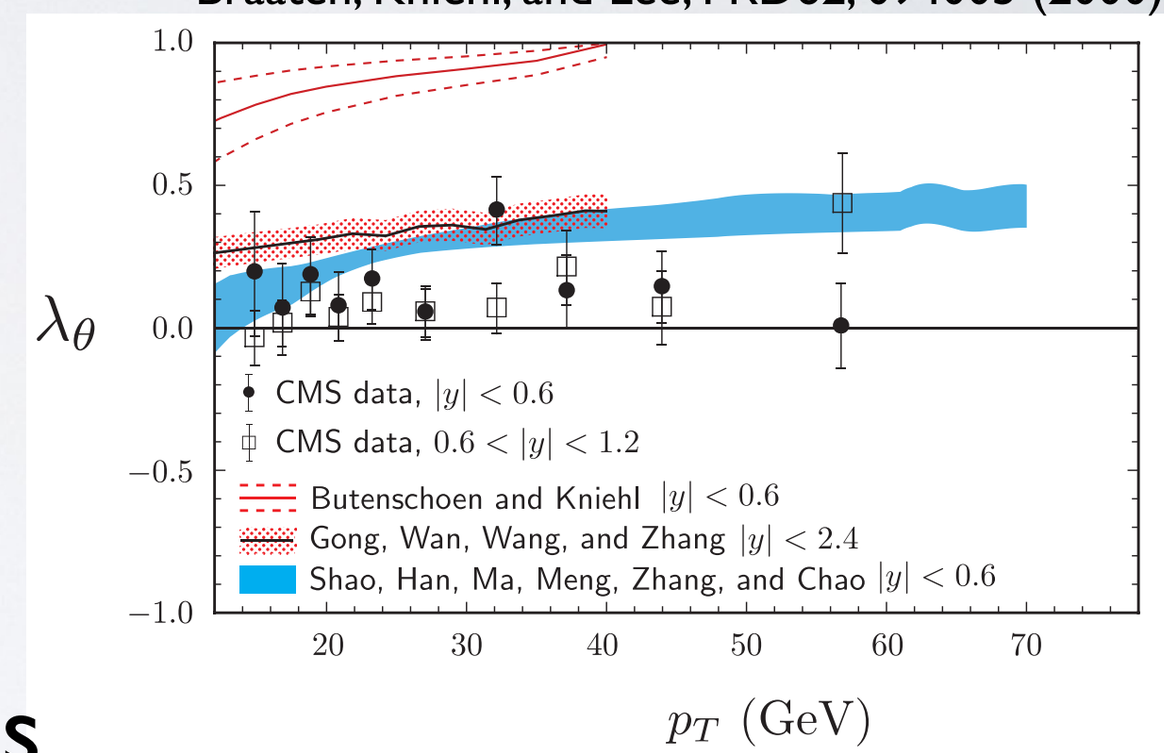
J/ψ POLARIZATION

$$\lambda_\theta = \begin{cases} +1 & : \textit{Transverse} \\ 0 & : \textit{Unpolarized} \\ -1 & : \textit{Longitudinal} \end{cases}$$



CDF, PRL99, 132001 (2007)
Braaten, Kniehl, and Lee, PRD62, 094005 (2000)

- NRQCD at LO in α_s predicts transverse polarization at large p_T
- Disagrees with measurement
- NLO corrections are large in the ${}^1S_0^{[8]}$ and ${}^3P_J^{[8]}$ channels
- NLO NRQCD predictions vary



CMS, PLB727, 381 (2013)
Butenschoen and Kniehl, PRL108, 172002 (2012), MPLA28, 1350027 (2013), plot taken from Pompili, CMS CR-2014/217
Gong, Wan, Wang, Zhang, PRL110, 042002 (2013)
Shao, Han, Ma, Meng, Zhang, Chao, JHEP05 (2015) 103

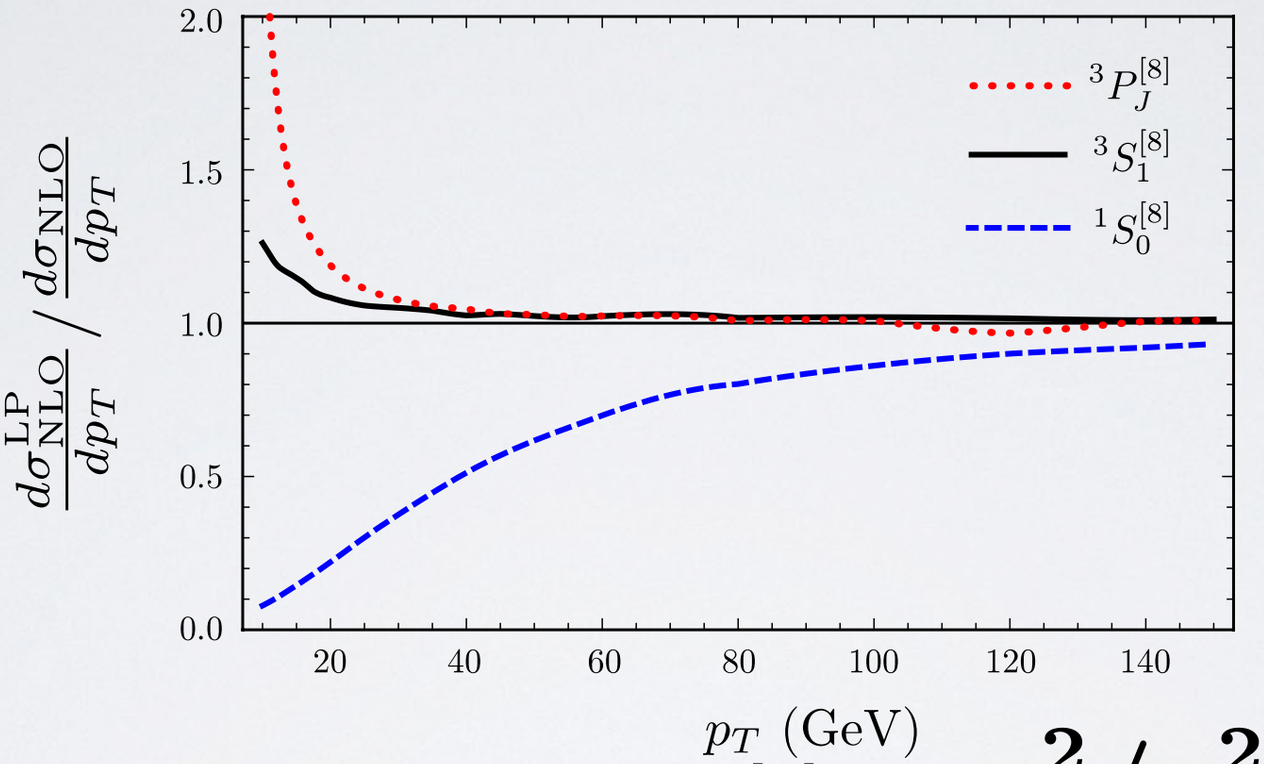
LP FRAGMENTATION

- Large NLO corrections arise because new channels that fall off more slowly with p_T open up at NLO
- The leading power (LP) in p_T $(1/p_T^4)$ is given by single-parton fragmentation

  Collins and Soper, NPB194, 445 (1982)
  Nayak, Qiu, and Sterman, PRD72, 114012 (2005)
- Corrections to LP fragmentation go as m_c^2/p_T^2
- ${}^3S_1^{[8]}$ channel is already at LP at LO : NLO correction is small
- ${}^1S_0^{[8]}$ and ${}^3P_J^{[8]}$ channels do not receive an LP contribution until NLO : NLO corrections are large

LP FRAGMENTATION

- LP fragmentation reproduces the fixed-order calculation at NLO accuracy at large p_T



The difference is suppressed by m_c^2/p_T^2

- The slow convergence in $^1S_0^{[8]}$ channel is because the fragmentation contribution is small
(no δ function or plus distribution from IR divergence)

LP+NLO

- Our strategy is to use LP fragmentation to supplement the fixed-order NLO calculation
- We calculate

LP fragmentation resummed leading logs

LP fragmentation to NLO accuracy

$$\frac{d\sigma^{\mathrm{LP+NLO}}}{dp_T} = \underbrace{\frac{d\sigma^{\mathrm{LP}}}{dp_T} - \frac{d\sigma^{\mathrm{LP}}_{\mathrm{NLO}}}{dp_T}}_{\text{Additional fragmentation contributions}} + \frac{d\sigma_{\mathrm{NLO}}}{dp_T}$$

fixed-order calculation to NLO

- We take $p_T > 3 \times m_{\mathrm{quarkonium}}$ in order to suppress possible non-factorizing contributions

LP CONTRIBUTIONS THAT WE COMPUTE

$^3S_1^{[8]}$ channel

Fragmentation functions

Parton production cross sections	α_s	α_s^2	$\alpha_s^3 \cdots$
α_s	*LO*	*NLO*	*NNLO*
α_s^2	*NLO*	*NNLO*	
α_s^3	*NNLO*		
$\vdots$			

$^1S_0^{[8]}$ and $^3P_J^{[8]}$ channels

Fragmentation functions

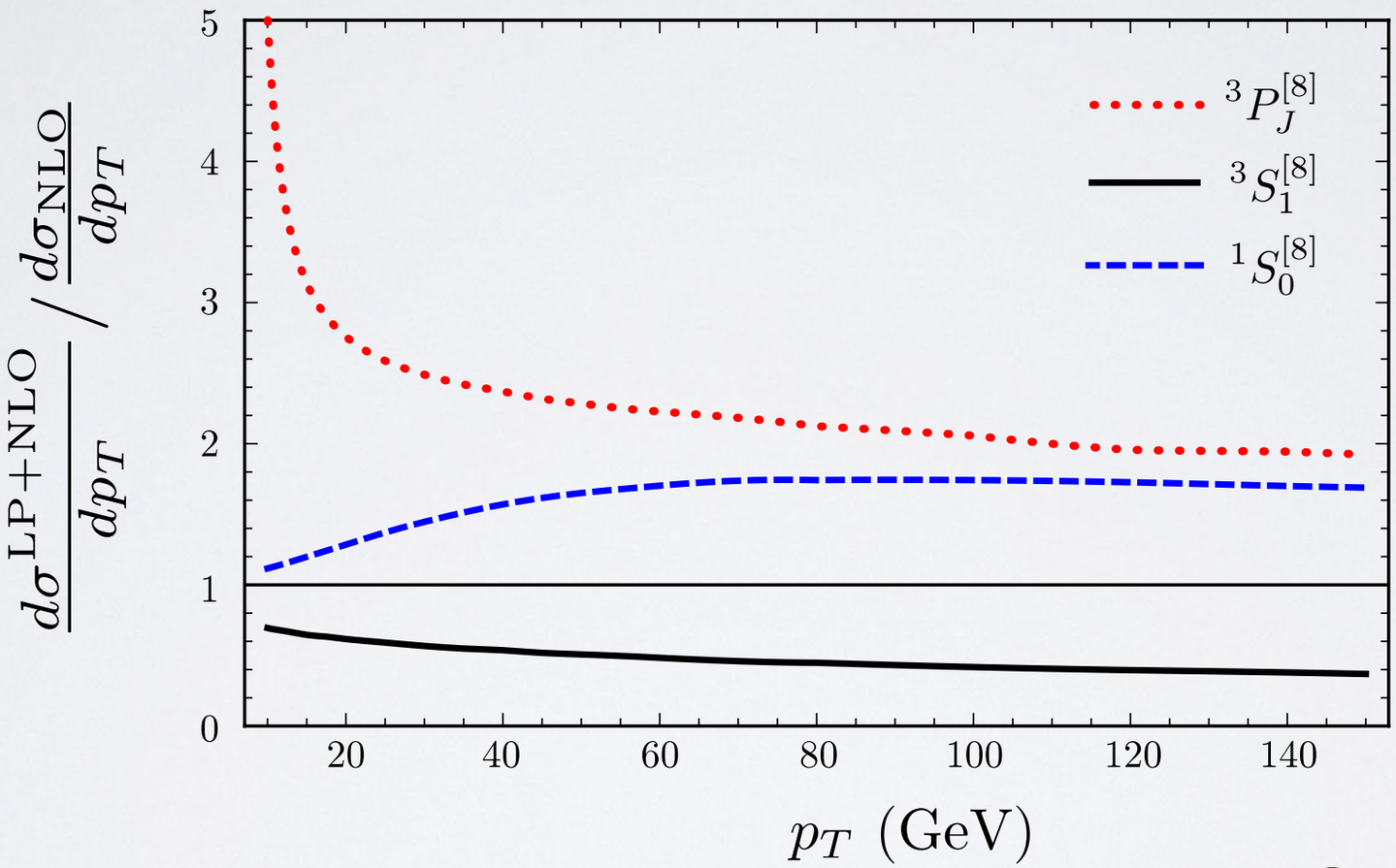
	α_s	α_s^2	$\alpha_s^3 \cdots$
α_s	-	*NLO*	*NNLO*
α_s^2	-	*NNLO*	
α_s^3	-		
$\vdots$			

Available *Not yet available* *Leading logarithms only*

- We resum the leading logarithms in p_T/m_c to all orders in α_s Gribov and Lipatov, Yad. Fiz. 15, 781 (1972) / Lipatov, Yad. Fiz. 20, 181 (1974) Dokshitzer, Zh. Eksp. Teor. Fiz. 73, 1216 (1977) / Altarelli and Parisi, NPB126, 298 (1977)
- Ultimately we would like to calculate all NNLO contributions to LP fragmentation

LP+NLO

- The additional fragmentation contributions have important effects on the shapes in the $^3P_J^{[8]}$ channel

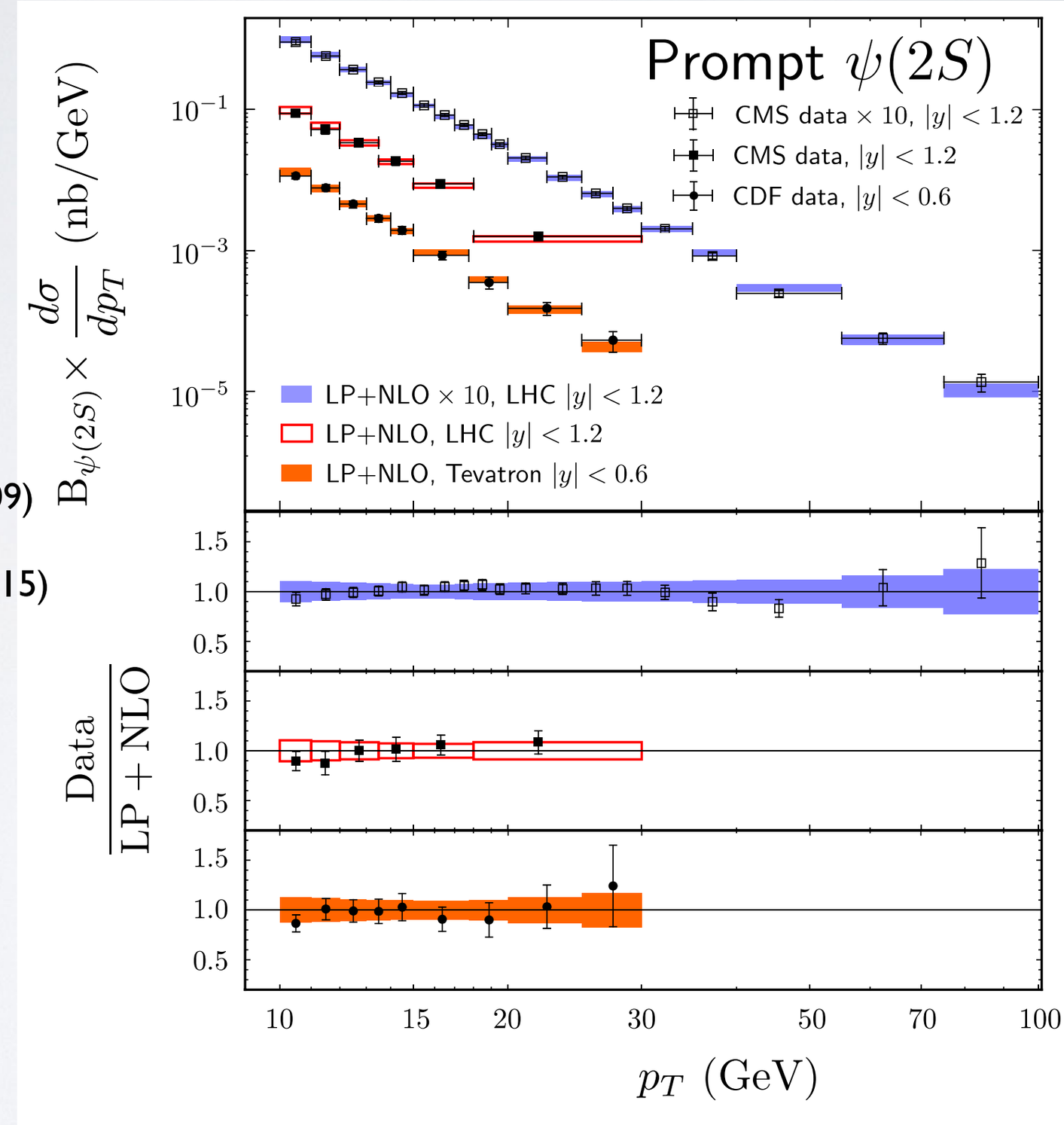


- Large corrections to the shape of the $^3P_J^{[8]}$ channel because the LO and NLO contributions cancel at about $p_T \approx 7.5$ GeV

$\psi(2S)$ HADROPRODUCTION

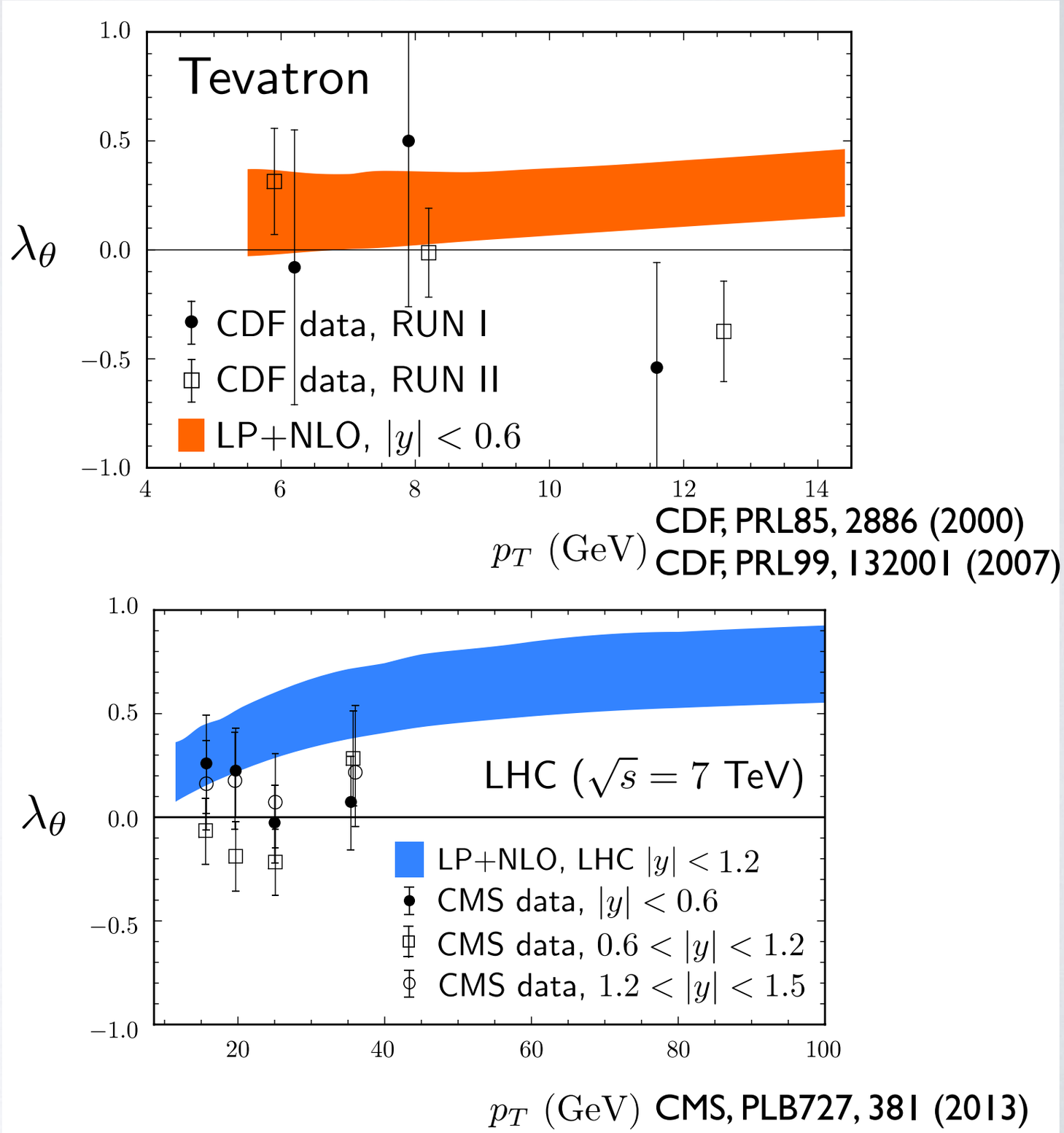
- J/ψ can be produced from decays of $\psi(2S)$ and χ_{cJ}
- $\psi(2S)$ LDMEs from fit to CMS and CDF cross section data CDF, PRD80, 031103 (2009) CMS, JHEP02, 011 (2012) CMS, PRL114, 191802 (2015)
- 30% theoretical uncertainty from scale variation

$$\chi^2/\mathrm{d.o.f} = 1.71/29$$



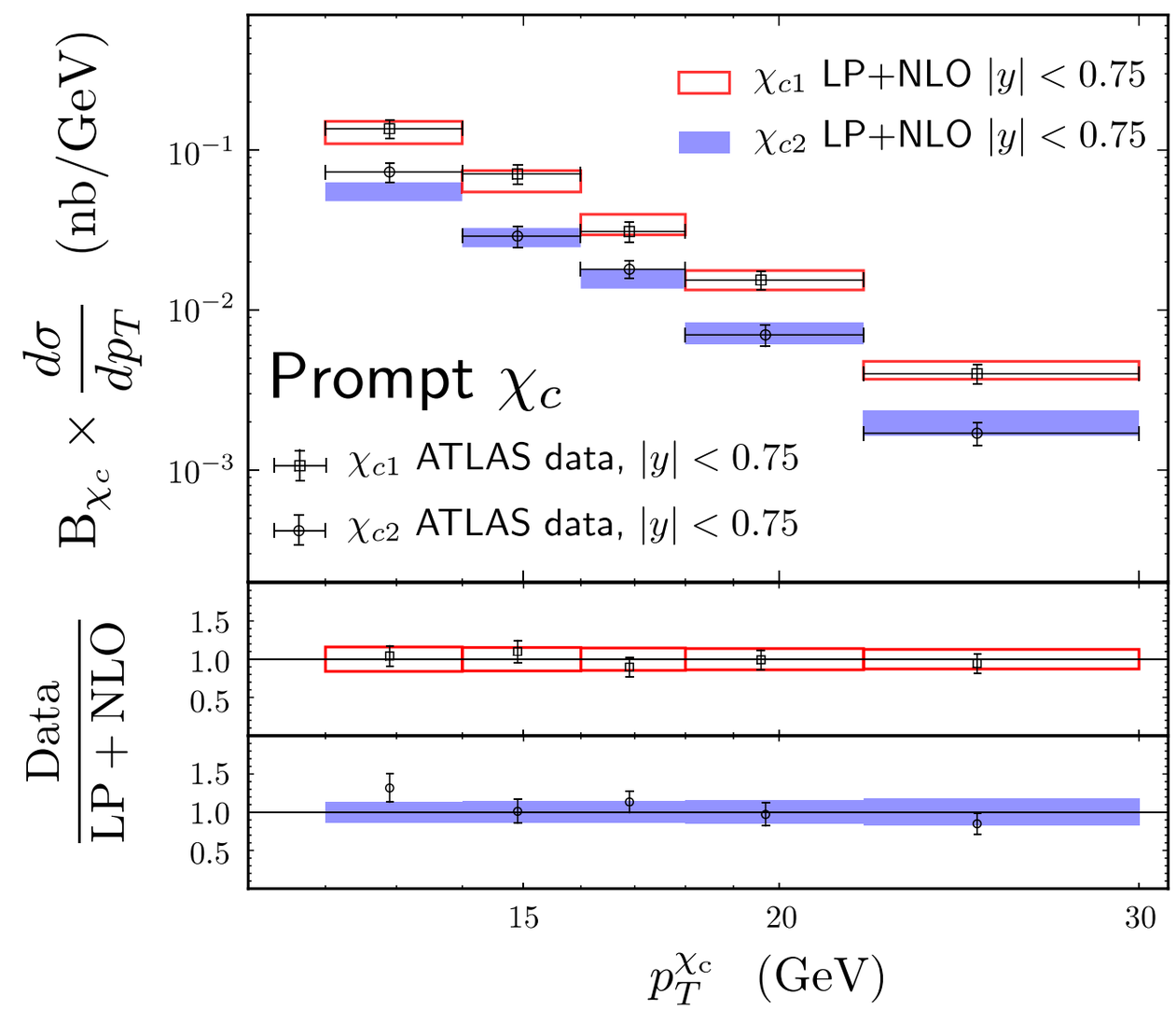
$\psi(2S)$ POLARIZATION

- We predict that the $\psi(2S)$ is slightly transverse at the Tevatron
- We predict that the $\psi(2S)$ is slightly transverse at the LHC Agrees with CMS data within errors



χ_{cJ} HADROPRODUCTION

- ${}^3S_1^{[8]}$ and ${}^3P_J^{[1]}$ channels contribute at LO in v
- We obtain good fits to ATLAS data ATLAS, JHEP1407, 154 (2014)
- The ${}^3P_J^{[1]}$ matrix element obtained from fit agrees with other independent determinations



$$\chi^2/\text{d.o.f} = 1.19/8$$

Potential model

$$|R'(0)|^2 = 0.075\ \text{GeV}^5$$

Eichten and Quigg, PRD 52, 1726 (1995)

Two-photon decays

$$|R'(0)|^2 = 0.042^{+0.030}_{-0.020}\ \text{GeV}^5$$

HSC, Lee, Yu, PRD78, 074022 (2008)

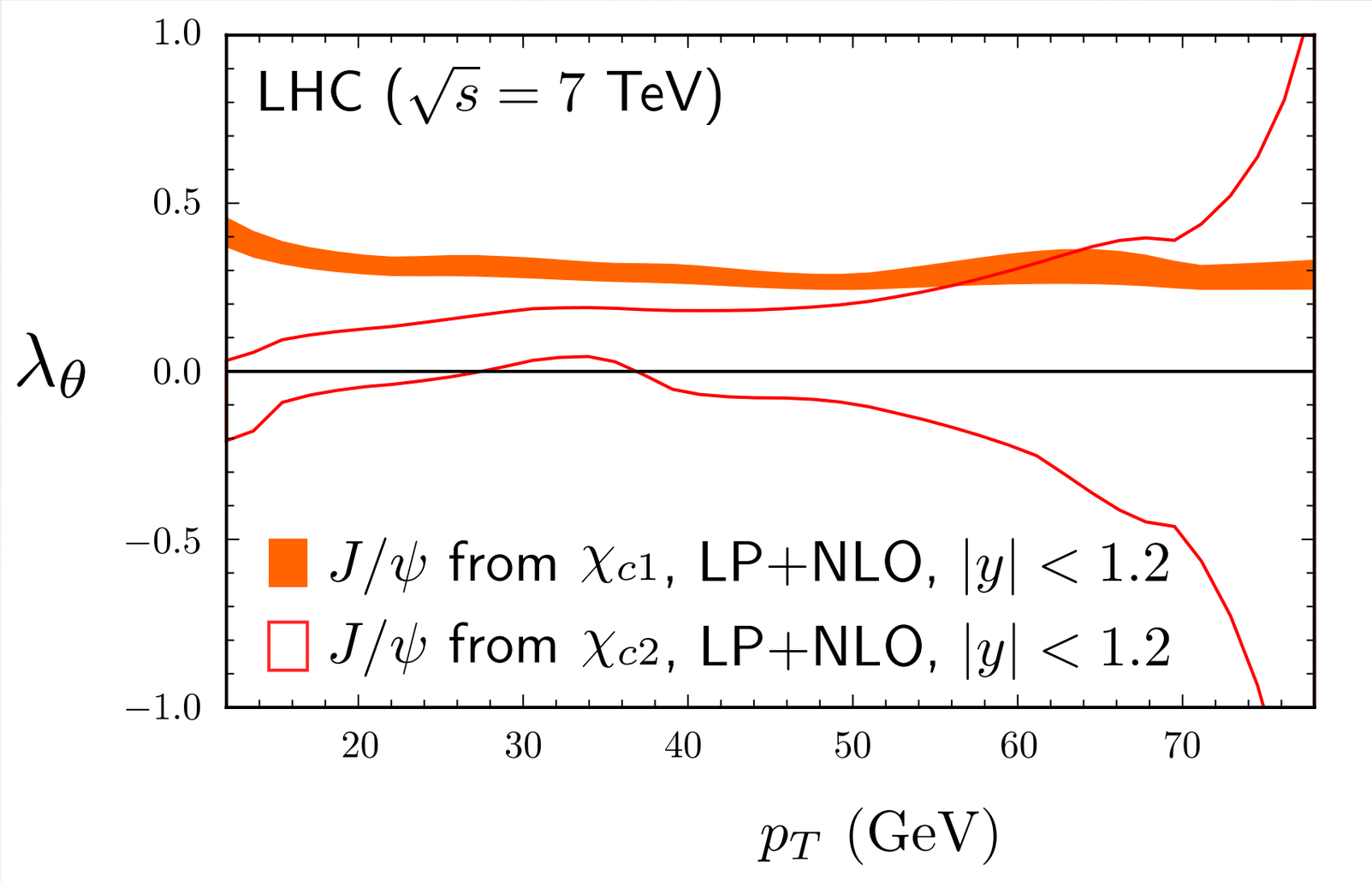
Our fit

$$|R'(0)|^2 = 0.055 \pm 0.017\ \text{GeV}^5$$

→Suggests that NRQCD factorization works

POLARIZATION OF J/ψ FROM χ_{cJ} DECAY

- We predict that the J/ψ from χ_{cJ} decay is slightly transverse at LHC
- We assume $\mathbf{E1}$ transition in $\chi_{cJ} \to J/\psi + \gamma$ (higher-order transitions have little effect)



Faccioli, Lourenco, Seixas, and Wohri, PRD83, 096001 (2011)

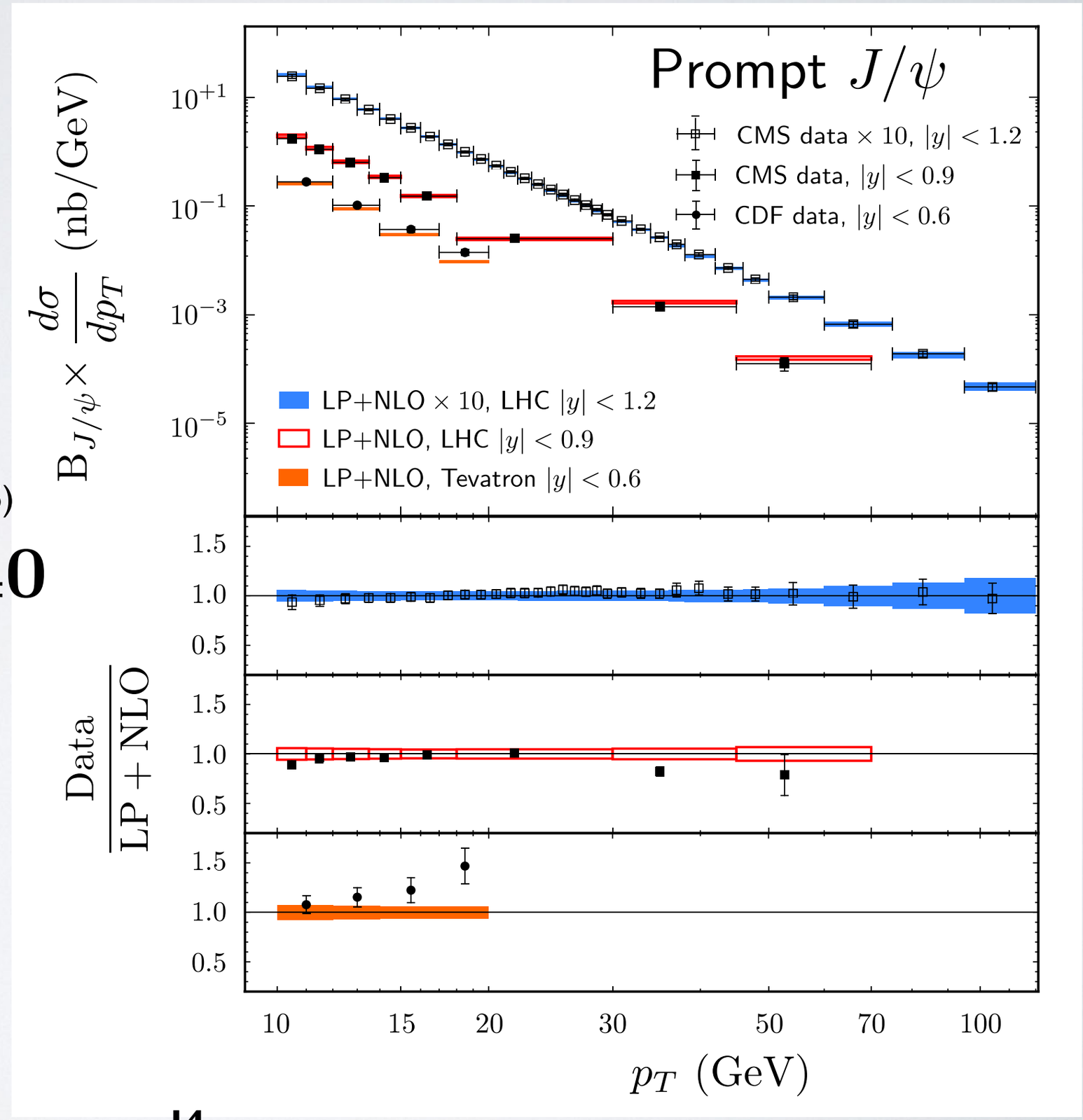
J/ψ HADROPRODUCTION

- Including feeddown contributions, we obtain good fits to J/ψ cross section

  CDF, PRD71, 032001 (2005)
  CMS, JHEP02, 011 (2012)
  CMS, PRL114, 191802 (2015)

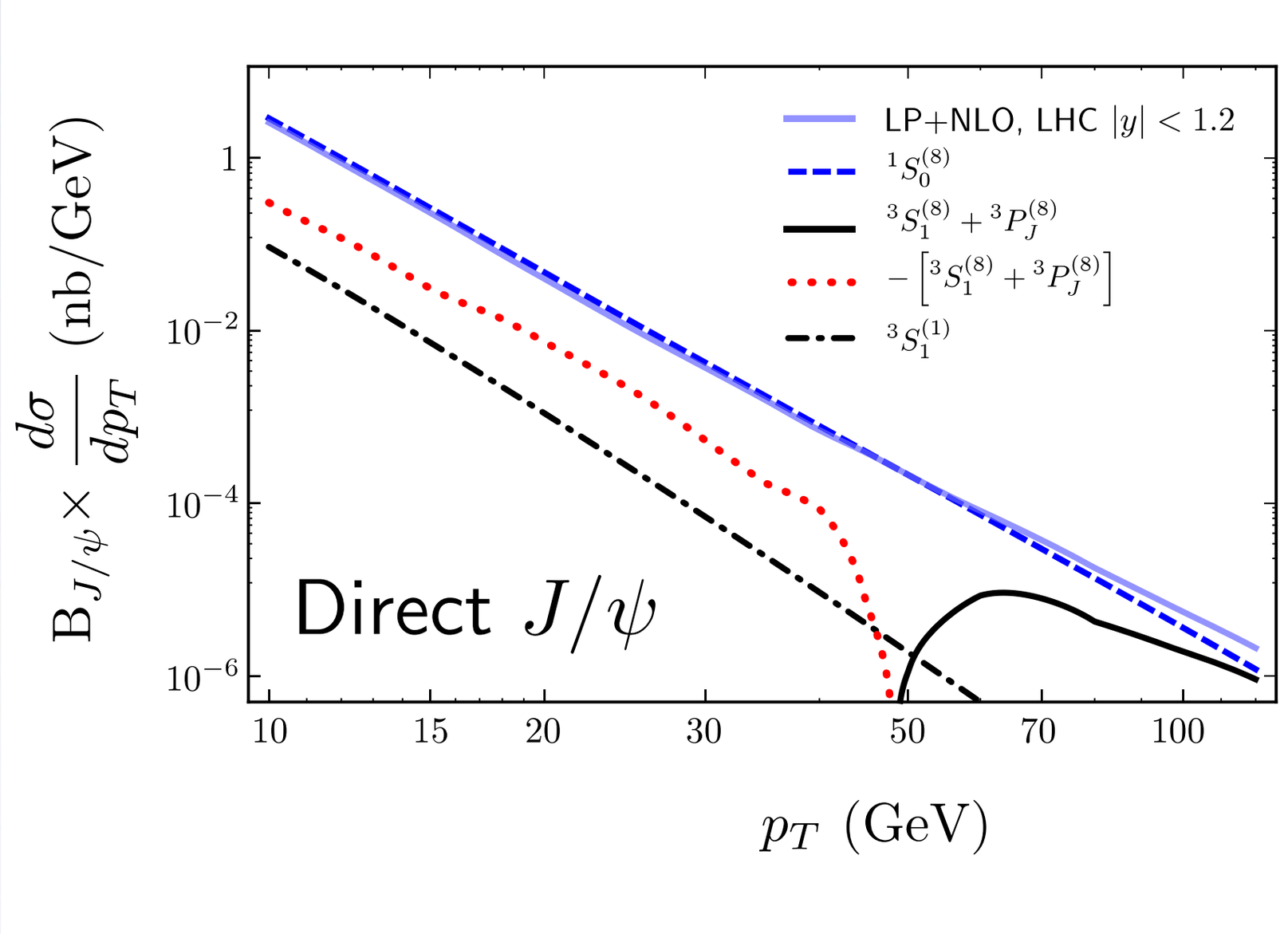
  $$\chi^2/\mathrm{d.o.f} = 8.20/40$$

- Again, $p_T > 10$ GeV ($\approx 3 \times m_{J/\psi}$) was used in the fit



J/ψ HADROPRODUCTION

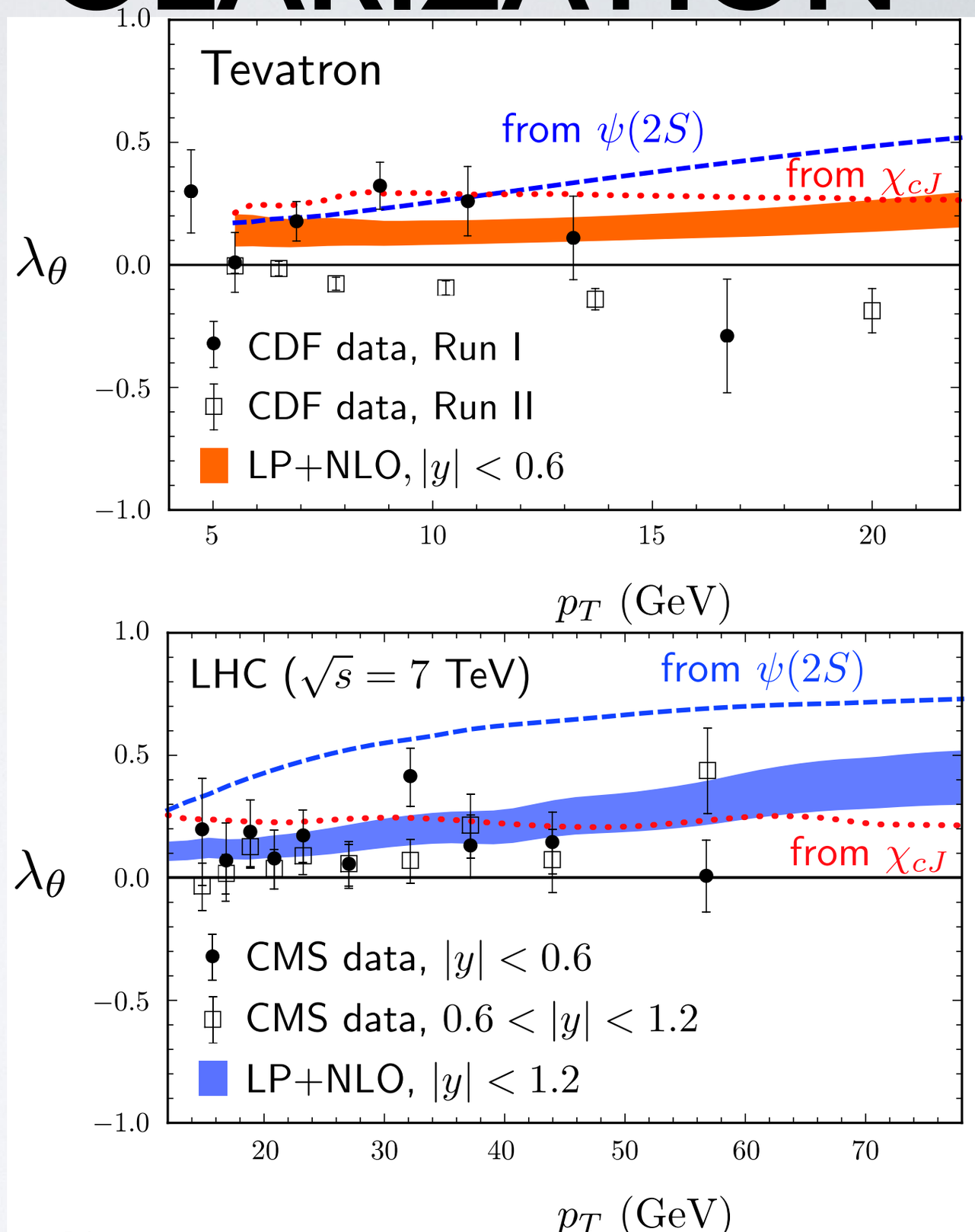
- The direct cross section falls off faster than $^3S_1^{[8]}$ and $^3P_J^{[8]}$ channels
- The fit constrains the $^3S_1^{[8]}$ and $^3P_J^{[8]}$ channels to cancel
- *$^1S_0^{[8]}$ channel dominates the direct cross section*



PROMPT J/ψ POLARIZATION

- Direct J/ψ and J/ψ from feeddown is slightly transverse
- **PROMPT J/ψ HAS SMALL POLARIZATION**
- This is in *reasonably good agreement with CMS* data, but disagrees with CDF Run II data

CDF, PRL85, 2886 (2000), PRL99, 132001 (2007)
CMS, PLB727, 381 (2013)



J/ψ PHOTOPRODUCTION

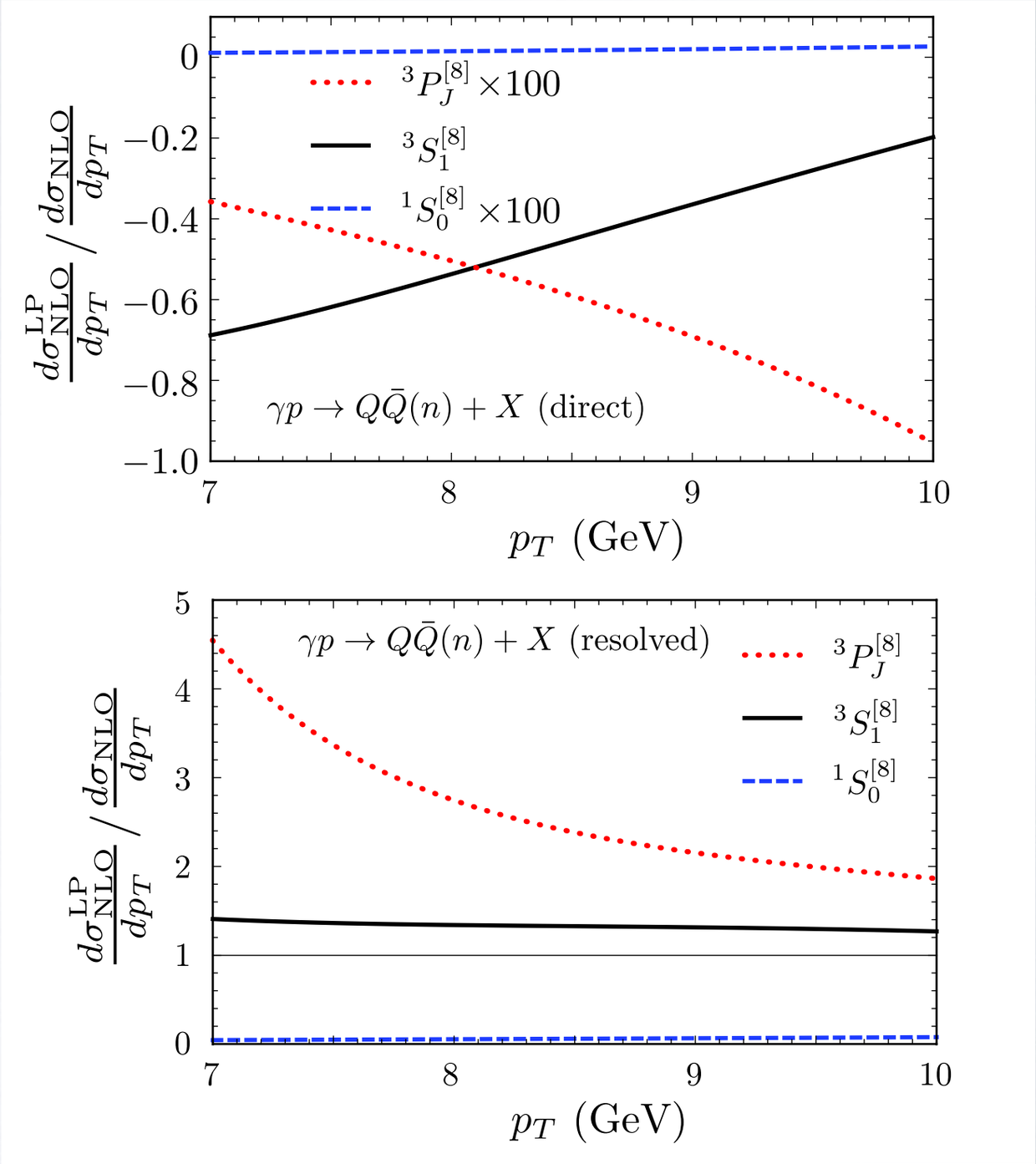
- The LDMEs can also be tested against the photoproduction cross section data $ep \to J/\psi + X$
- We calculate the LP fragmentation contributions using the kinematical cuts used by the H1 Collaboration

γp invariant mass	$60\ \mathrm{GeV} < W < 240\ \mathrm{GeV}$
elasticity (fraction of photon energy transferred to J/ψ)	$0.3 < z < 0.9$
virtual photon invariant mass	$Q^2 < 2.5\ \mathrm{GeV}^2$

- Caveat : data only available up to p_T less than $10\ \mathrm{GeV}$
- We consider both the direct and resolved cross sections

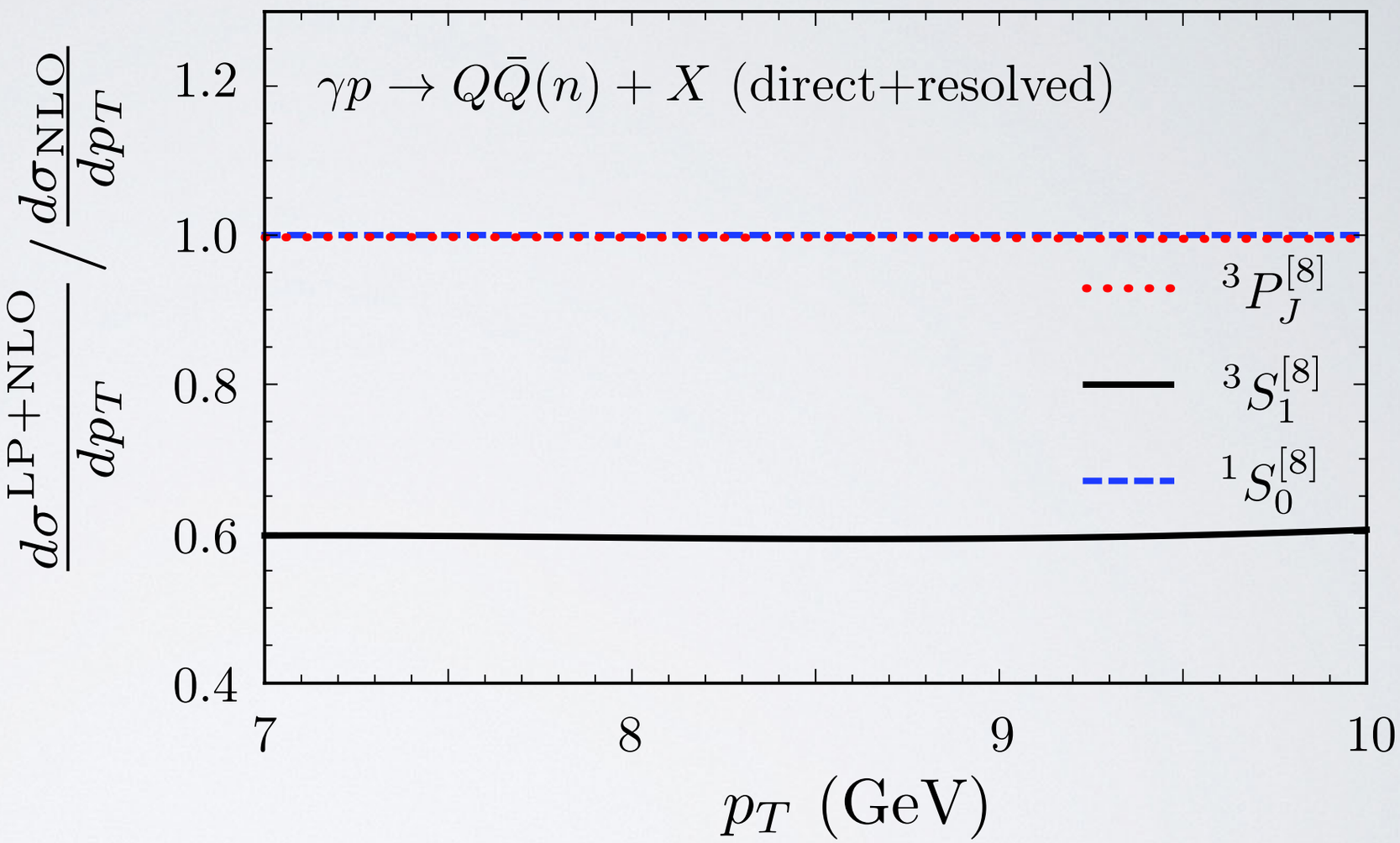
J/ψ PHOTOPRODUCTION

- LP fragmentation does not reproduce the fixed-order calculation at NLO accuracy.
- p_T may not be sufficiently large for fragmentation contributions to dominate cross section



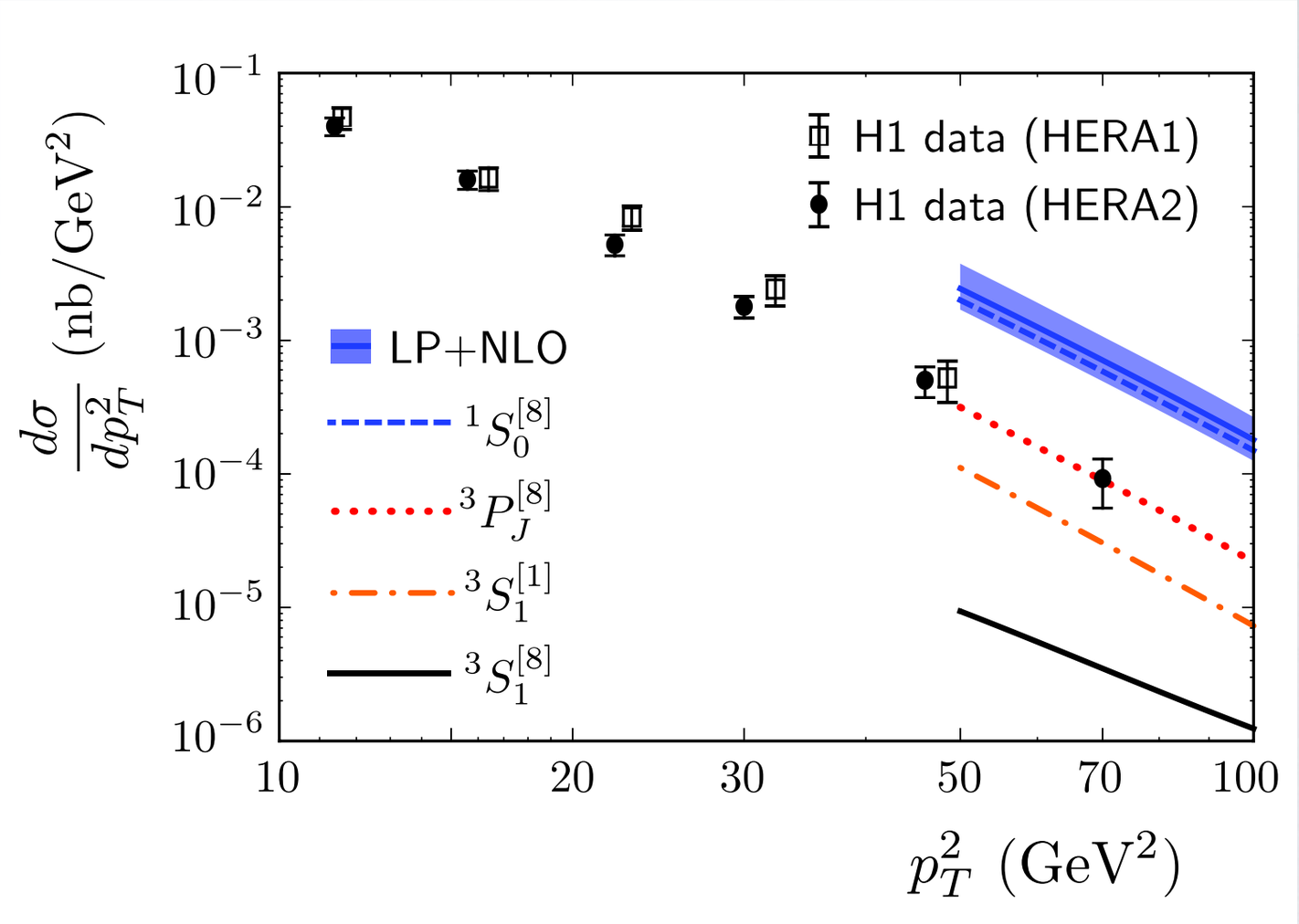
J/ψ PHOTOPRODUCTION

- The additional fragmentation contributions are only sizable in the $^3S_1^{[8]}$ channel



J/ψ PHOTOPRODUCTION

- The LDMEs obtained from fit to hadroproduction cross section lead to predictions for the photoproduction cross section that overshoot the data by a factor of 8 at the highest p_T
- Feeddown contributions are negligible



- p_T is rather small to expect factorization to work

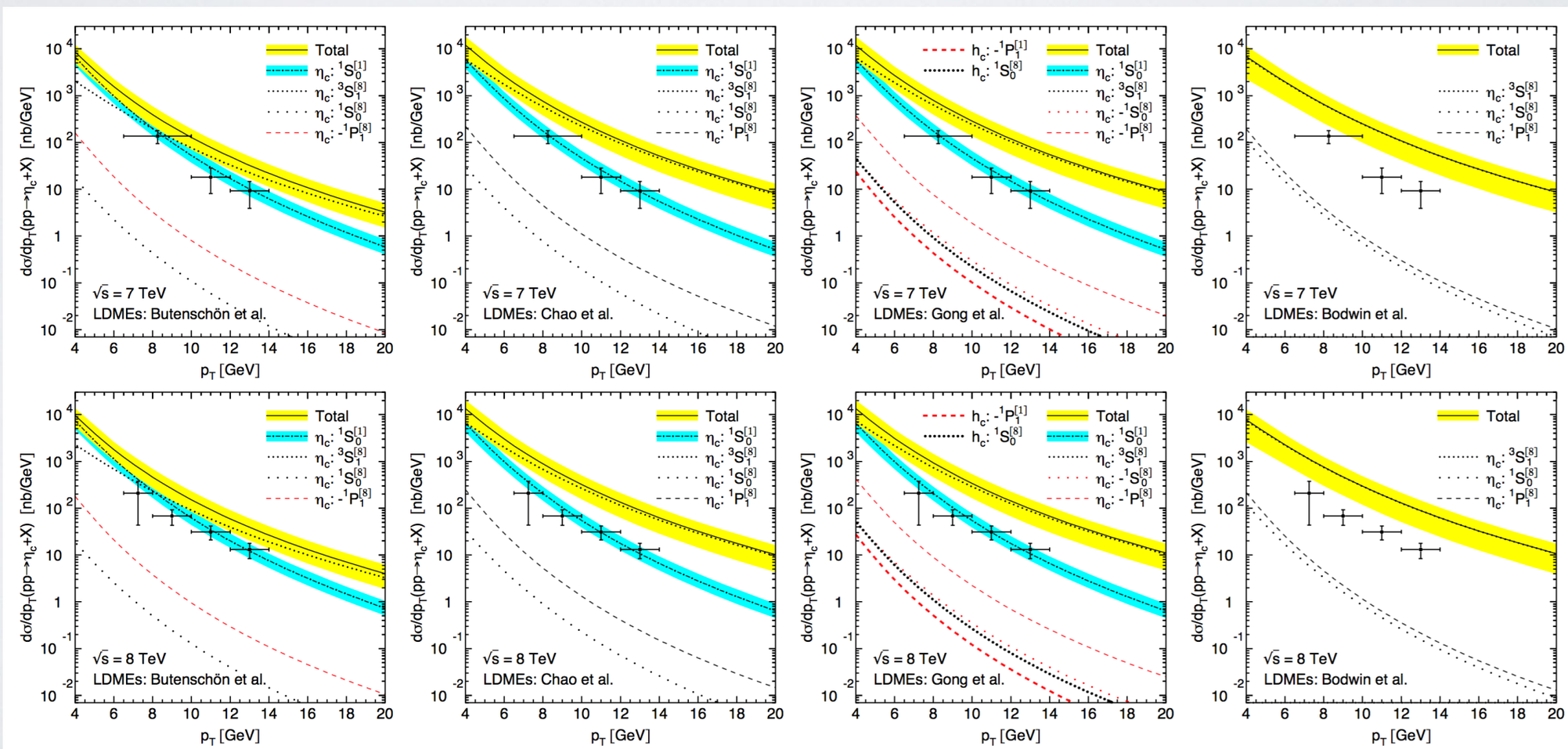
SUMMARY

- We present new LP fragmentation contributions that have a significant effect on calculations of J/ψ production in hadron colliders
- When we include LP fragmentation contributions, we predict the J/ψ to have *near-zero polarization at high p_T, which is in good agreement with LHC data*
- Predictions for the photoproduction cross section that are based on LDMEs from hadroproduction are at odds with the data.
- LP and NLP corrections at higher orders in α_s may help to bring theory into agreement with data.

SUPPLEMENTARY

η_c HADROPRODUCTION

- Heavy-quark spin symmetry can be used to predict the η_c LDMEs from the J/ψ LDMEs.
- Predictions that use these η_c LDMEs overestimate the cross section.



LHCb, EPJC75 (2015), 311

Butenschoen, He, Kniehl, PRL114, 092004 (2015)