PRODUCTION OF HEAVY HADRON AND QUARKONIA

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OUTLINE

- Heavy hadron production cross sections in QCD
- Inclusive quarkonium production
- Exclusive quarkonium production
- Summary

PRODUCTION CROSS SECTIONS IN QCD

- QCD provides factorization formulae that separates long-distance physics from short-distance processes.

- Inclusive production cross section at large p_T can be described by fragmentation

Fragmentation function (FF)

$$\frac{d\sigma_{h+X}}{dp_T^2} = \sum_{i=g,q,\bar{q}} \frac{d\sigma_{i+X}}{dp_T^2} \otimes D_{i\to h}(z,\mu)$$

J.C.Collins and D.E.Soper, NPB194, 445 (1982)

- Exclusive production amplitude at large energies are factorized as

Light-cone distribution amplitude (LCDA)

$$\mathcal{M}(h+\gamma) = T_{Q\bar{Q}+\gamma}(s,\mu,z) \otimes \phi(\mu,z)$$

G.P. Lepage, S.J. Brodsky, PRD22, 2157 (1980)
V.L. Chernyak, A.R. Zhitnitsky, Phys. Rept. 112, 173 (1984)

PRODUCTION CROSS SECTIONS IN QCD

- The heavy quark mass allows use of effective field theories with expansion in $1/m$
- Heavy flavored mesons can be described by HQET
- Heavy quarkonia can be investigated using NRQCD
- Both EFTs imply heavy quark spin symmetry from suppression of spin-flip operators
- In NRQCD, nonperturbative functions are reduced to a few universal constants (NRQCD long-distance matrix elements)

W.E. Caswell, G.P. Lepage, PLB167, 437 (1986)
G.T. Bodwin, E. Braaten, G.P. Lepage, PRD51, 1125 (1995)

INCLUSIVE PRODUCTION CROSS SECTION

- p_T-differential cross section at leading power in $1/p_T$ is given by leading-power (LP) fragmentation

Fragmentation function (FF)

$$\frac{d\sigma_{h+X}}{dp_T^2} = \sum_{i=g,q,\bar{q}} \frac{d\sigma_{i+X}}{dp_T^2} \otimes D_{i\to h}(z,\mu)$$

J.C.Collins and D.E.Soper, NPB194, 445 (1982)

- FFs are usually extracted from data as function of z
- Fragmentation approximation has been successfully applied for inclusive 1-hadron cross sections of light hadrons and heavy flavored mesons

INCLUSIVE QUARKONIUM CROSS SECTION

- In NRQCD, quarkonium cross sections are factorized into perturbative $Q\bar{Q}$ cross sections times corresponding NRQCD LDMEs. $\sigma_h = \sum_n \sigma_{Q\bar{Q}(n)} \times \langle \mathcal{O}_h(n) \rangle$
- FFs are factorized similarly as perturbative FFs and LDMEs: $D_{i\to h}(z,\mu) = \sum D_{i\to Q\bar{Q}(n)}(z,\mu) \langle O_h(n) \rangle$
- Fragmentation approximation had limited success for heavy quarkonia for a number of reasons :
    - Large power corrections in m/p_T
    - Competing effects of α_s, v and m/p_T

LARGE POWER CORRECTIONS IN m/p_T

- In heavy flavored meson production, power corrections to fragmentation go like ~Λ/p_T
- On the other hand, in production of heavy quarkonium, power corrections go like ~m/p_T, which can be significant.
- Next-to-leading power (NLP) contributions are given by double parton fragmentation

$$\sigma_{h+X} = \sum_{i=g,q,\bar{q}} \sigma_{i+X} \otimes D_{i\to h}(z,\mu) + \sum_n \sigma_{Q\bar{Q}(n)+X} \otimes D_{Q\bar{Q}(n)\to h}(z,\zeta_1,\zeta_2,\mu)$$

Z.-B. Kang, J.-W. Qiu, G. Sterman, PRL108, 102002 (2012)
S. Fleming, A. K. Leibovich, T. Mehen, I. Z. Rothstein, PRD86, 094012 (2012)
Y.-Q. Ma, J.-W. Qiu, G. Sterman, H. Zhang, PRL113, 142002 (2014)

COMPETING EFFECTS OF α_s, v AND m/p_T

- Production of $Q\bar{Q}$ at different powers of v occurs at different orders in α_s. For J/ψ or Υ production,

	${}^3S_1^{[1]}$	${}^3S_1^{[8]}$	${}^1S_0^{[8]}$	${}^3P_J^{[8]}$
LP ($\sim 1/p_T^4$)	order α_s^5 (gluon)	order $\alpha_s^3 v^4$	order $\alpha_s^4 v^3$	order $\alpha_s^4 v^4$
NLP ($\sim m^2/p_T^6$)	order α_s^4	order $\alpha_s^3 v^4$	order $\alpha_s^3 v^3$	order $\alpha_s^3 v^4$

- LDMEs are suppressed by different powers of v; however the contribution to cross sections from channels suppressed by powers of v can be significant.

CURRENT STATE OF PHENOMENOLOGY

- Usually truncated at relative order v^4, which involve 4 channels for J/ψ or Υ production.
- A common approach is to compute $Q\bar{Q}$ cross sections in a fixed-order calculation. Short-distance cross sections are available through $\mathrm{O}(\alpha_s{}^4)$ (NLO).

$$\sigma_h = \sum_n \sigma_{Q\bar{Q}(n)} \times \langle \mathcal{O}_h(n) \rangle$$

- Large K-factors occur from enhancements of powers and logarithms of p_T/m.

Ma, Wang, and Chao, PRL106, 042002 (2011)
Butenschoen and Kniehl, PRL108, 172002 (2012)
Gong, Wan, Wang, and Zhang, PRL110, 042002 (2013)

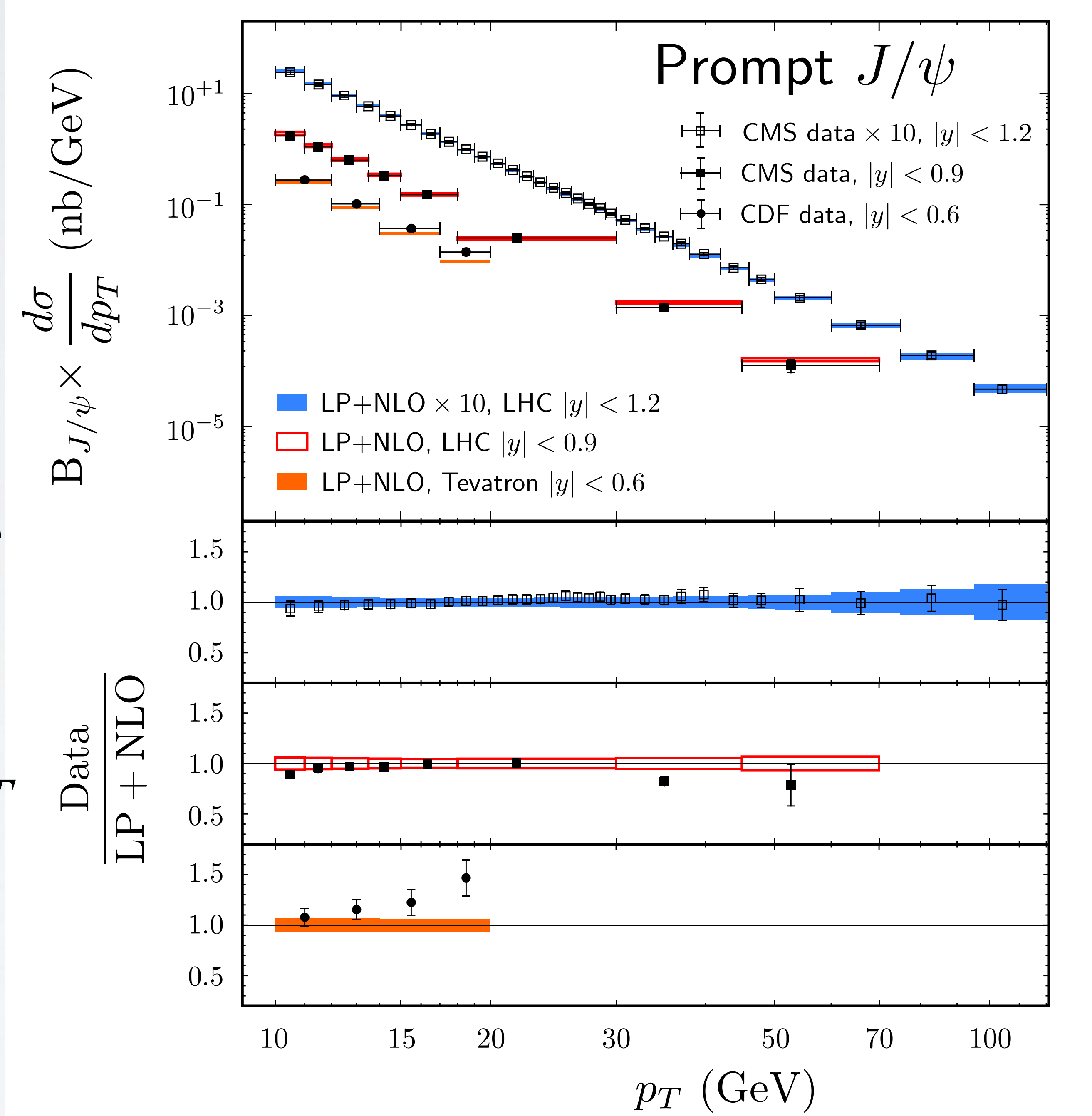
CURRENT STATE OF PHENOMENOLOGY

- An alternative approach is to compute $Q\bar{Q}$ FFs in perturbative QCD, which give LP contributions.
- NLP contributions can be supplied by double parton fragmentation, or by comparing fixed-order calculations with LP contributions.
- Logarithms of p_T/m can be resummed for LP contribution by solving DGLAP evolution equations.
- Consistent with fixed-order calculations if computed to same accuracy

G. T. Bodwin, **HSC**, U-R. Kim, J. Lee, PRL113, 022001 (2014)

INCLUSIVE J/ψ PRODUCTION

- Parton cross sections available through $O(\alpha_s^3)$ (NLO).
- FFs computed through $O(\alpha_s^2)$.
- Leading logarithms of p_T/m are resummed at LP in p_T.
- LDMEs extracted from high-p_T data.



G.T. Bodwin, **HSC**, U-R. Kim, J. Lee, PRL113, 022001 (2014)
G.T. Bodwin, **HSC**, U-R. Kim, J. Lee, PRD93, 034041 (2016)

CURRENT STATE OF PHENOMENOLOGY

- LDMEs are poorly determined. Only the leading-order matrix element can be obtained from decay rates; not known how to compute the higher order color octet matrix elements from first principles.
- When evolution is ignored, cross section at large p_T is a combination of $1/p_T{}^4$ (LP) and $m^2/p_T{}^6$ (NLP) : impossible to fix all 3 unknowns, and can have different sets of matrix elements giving similar predictions.
- Resummation of logarithms of p_T/m helps reduce the degeneracy a bit.

CURRENT STATE OF PHENOMENOLOGY

- LDMEs need to be constrained to make definite predictions.
- Degeneracy in LDME determination can be removed by considering other inclusive production processes, but most of the data are in low p_T
- Measurements of other heavy quarkonium states at large p_T would be valuable. Large-p_T data of η_c production or associated production (J/ψ+γ or Z) is highly anticipated.
- Careful analysis of nonrelativistic effective field theories may also help constrain nonperturbative matrix elements.

EXCLUSIVE QUARKONIUM PRODUCTION

- LHC can probe rare exclusive decays of heavy particles.
- Especially, exclusive decays into heavy quarkonium are sensitive to interactions with heavy quarks.
- Higgs decay into vector quarkonium (J/ψ, Υ) + γ is sensitive to both size and phase of the Higgs-heavy quark coupling.
- Z decay into vector quarkonium (J/ψ, Υ) + γ occurs through a similar process, and together with Higgs decays the processes can serve as probes of the standard model and the quarkonium production mechanism.

EXCLUSIVE QUARKONIUM PRODUCTION

- Exclusive hadron production amplitude at large s is factorized into light-cone distribution amplitude (LCDA) and hard part at leading power in $1/s$.

Light-cone distribution amplitude (LCDA)

$$\mathcal{M}(h+\gamma) = T_{Q\bar{Q}+\gamma}(s,\mu,z) \otimes \phi(\mu,z)$$

G.P. Lepage, S.J. Brodsky, PRD22, 2157 (1980)

V.L. Chernyak, A.R. Zhitnitsky, Phys. Rept. 112, 173 (1984)

- The hard part T can be computed in perturbative QCD.
- LCDAs are nonperturbative, renormalized hadronic matrix elements.
- z : collinear momentum fraction of quark in meson. Convolution is an integral over z.

EXCLUSIVE QUARKONIUM PRODUCTION

- LCDAs of heavy quarkonia can be computed in NRQCD; corrections in higher orders in α_s and v can be computed systematically.

Y. Jia, D. Yang, NPB814 217 (2009),
Y. Jia, J.-X. Wang D. Yang, JHEP 1110 (2011)
X.-P. Wang, D. Yang, JHEP 1406 (2014)

- Solving the Efremov-Radyushkin-Brodsky-Lepage evolution equation resums logarithms of s/m^2

G.P. Lepage, S.J. Brodsky, PRD22, 2157 (1980)
A.V. Efremov, A.V. Radyushkin, PLB94, 245 (1980)

- Evolving from scale m to s, the LCDA approaches an asymptotic form that depends only on the decay constant. Hence, exclusive processes are not very sensitive to relativistic corrections.

CURRENT STATE OF PHENOMENOLOGY

- LCDA of J/ψ or Υ are calculated to NLO accuracy through relative order v^2.

Y. Jia, D. Yang, NPB814 217 (2009),
Y. Jia, J.-X. Wang D. Yang, JHEP 1110 (2011)
X.-P. Wang, D. Yang, JHEP 1406 (2014)

- Hard parts are available to NLO accuracy.

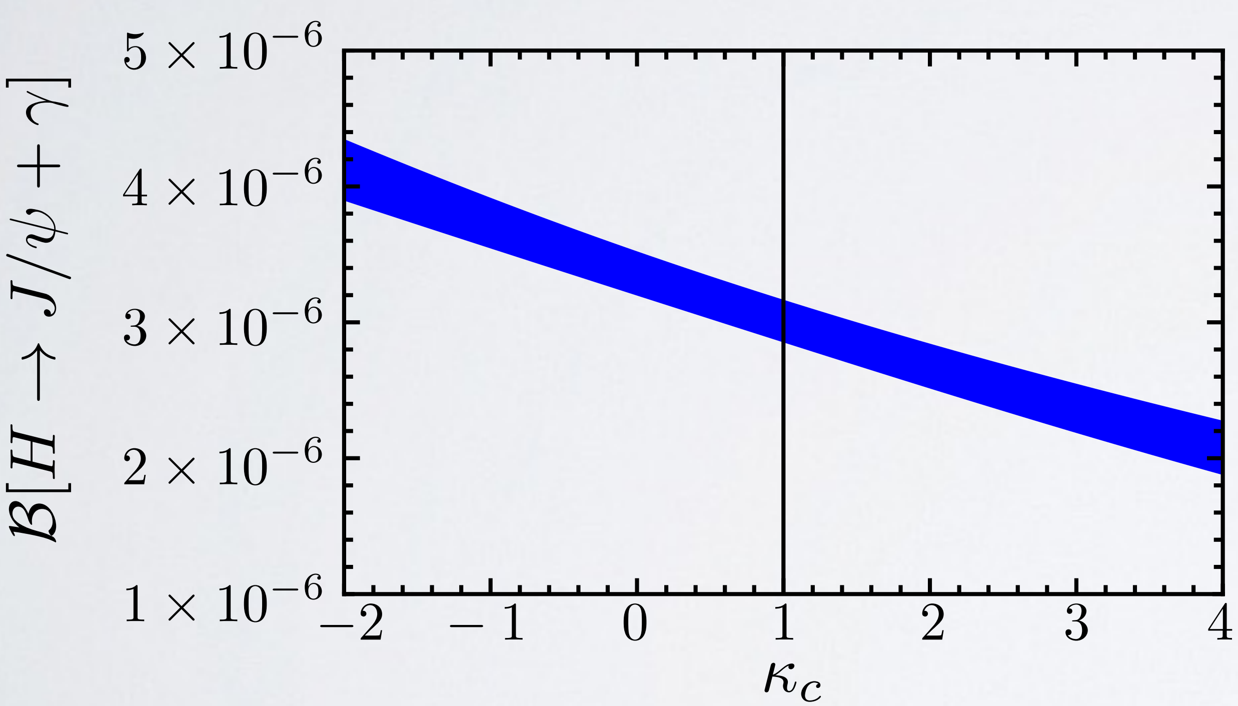
Shifman and Vysotsky, NPB 186, 475 (1981)
X.-P. Wang, D. Yang, JHEP 1406 (2014)

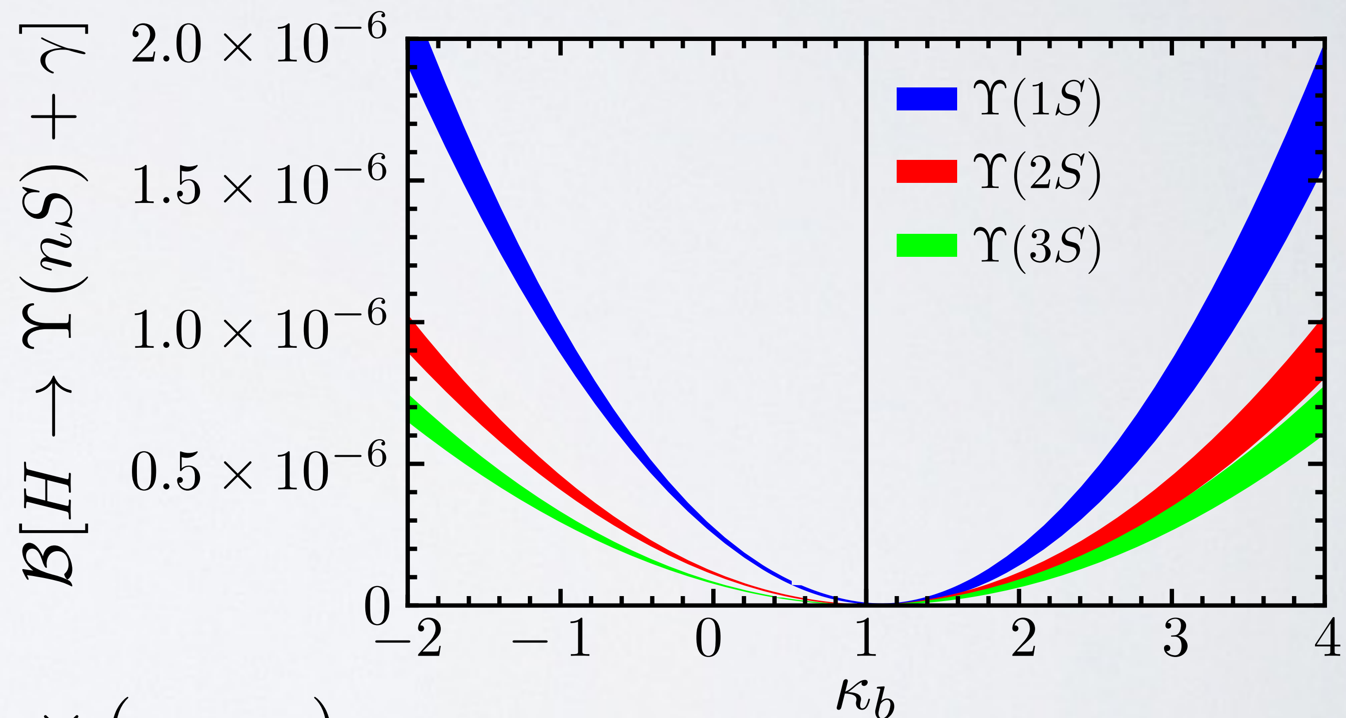
- Evolution equation can be solved at NLL accuracy.

D. Müller, PRD 49, 2525 (1994), PRD 51, 3855 (1995)

QUARKONIUM + PHOTON PRODUCTION IN HIGGS DECAYS

- Higgs decay into J/ψ+γ is sensitive to the size and phase of the Hcc coupling.





$$g_{HQQ} = \kappa_Q \times (g_{HQQ})_{\rm SM}$$

G.T.Bodwin, **HSC**, J.-H. Ee, J. Lee, PRD95, 054018 (2017)
Numerical results in agreement with model LCDA calculation in M.König, M.Neubert, JHEP 1508, 012 (2015)

QUARKONIUM + PHOTON PRODUCTION IN Z DECAYS

- Z boson decays into $J/\psi+\gamma$ can be computed in the same way. Logarithms in $m_{J/\psi}/m_Z$ can be resummed by using the factorization formula.

V	$\text{Br}(Z \to V + \gamma)$
J/ψ	$8.96^{+1.51}_{-1.38} \times 10^{-8}$
$\Upsilon(1S)$	$4.80^{+0.26}_{-0.25} \times 10^{-8}$
$\Upsilon(2S)$	$2.44^{+0.14}_{-0.13} \times 10^{-8}$
$\Upsilon(3S)$	$1.88^{+0.11}_{-0.10} \times 10^{-8}$

G.T.Bodwin, **HSC**, J.-H. Ee, J. Lee, arXiv:1709.09320

Numerical results in agreement with previous works in T.C. Huang, F.Petriello, PRD92, 014007 (2015) and Y.Grossman, M.König, M.Neubert, JHEP1504 (2015) 101

CURRENT STATE OF PHENOMENOLOGY

- J/ψ can be measured from its leptonic decay (Br[$J/\psi \to \mu^+\mu^-$]=5.961%).
- Upper limits have been studied by ATLAS

  ATLAS, PRL114, 121801 (2015)

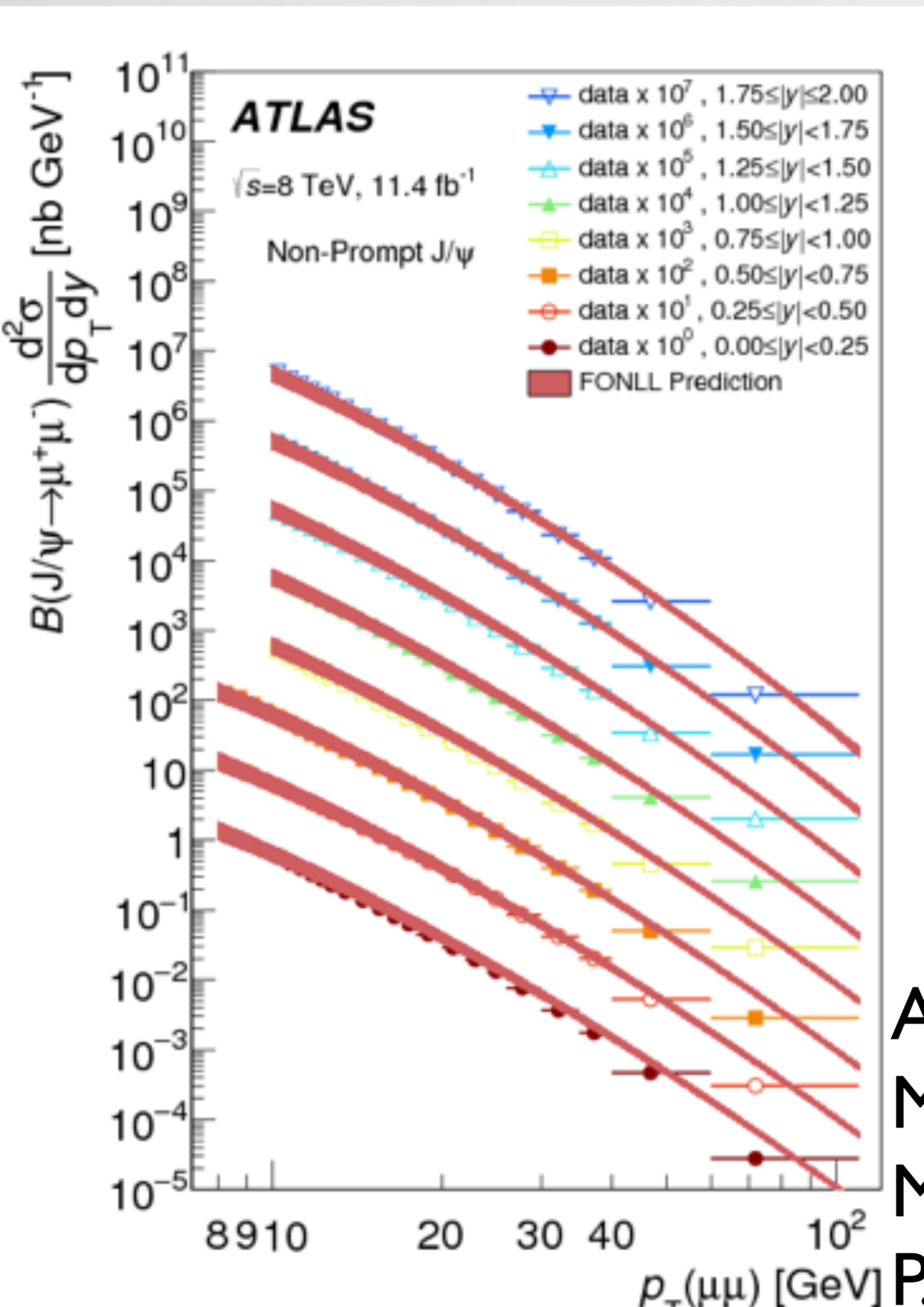
- $Z \to J/\psi + \gamma$ should be accessible with LHC Run 2.
- Higgs$\to J/\psi + \gamma$ would require a 3000fb^{-1} high-luminosity LHC

SUMMARY

- Heavy quarkonium production processes can be described with only a few nonperturbative unknowns thanks to nonrelativistic effective field theory methods.
- Inclusive quarkonium production has the potential to probe perturbative QCD at high energies, but involves poorly constrained nonperturbative unknowns; more experimental and theoretical effort is necessary for proper understanding.
- Exclusive quarkonium production from Higgs decays may allow measurement of Higgs-charm coupling.

BACKUP

B MESON CROSS SECTION



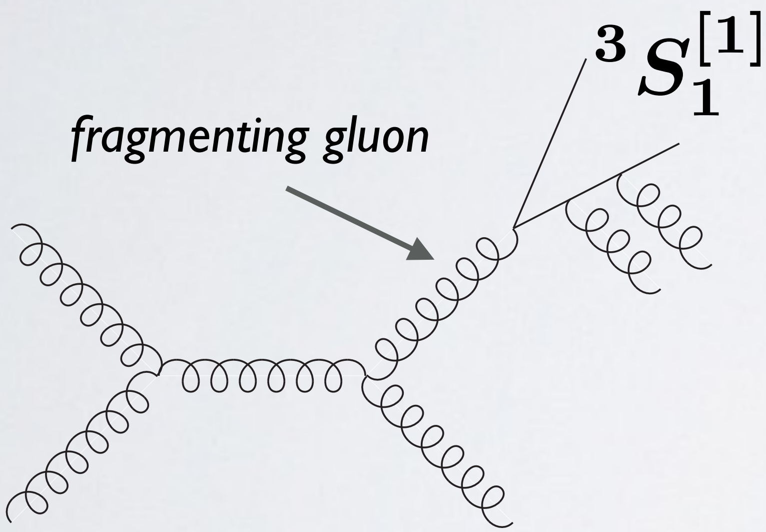
- Fragmentation approximation works well for B mesons.

J/ψ from in B decays at LHC compared with LP fragmentation prediction (FONLL).
FFs extracted from LEP data, parton cross sections computed to NLO accuracies

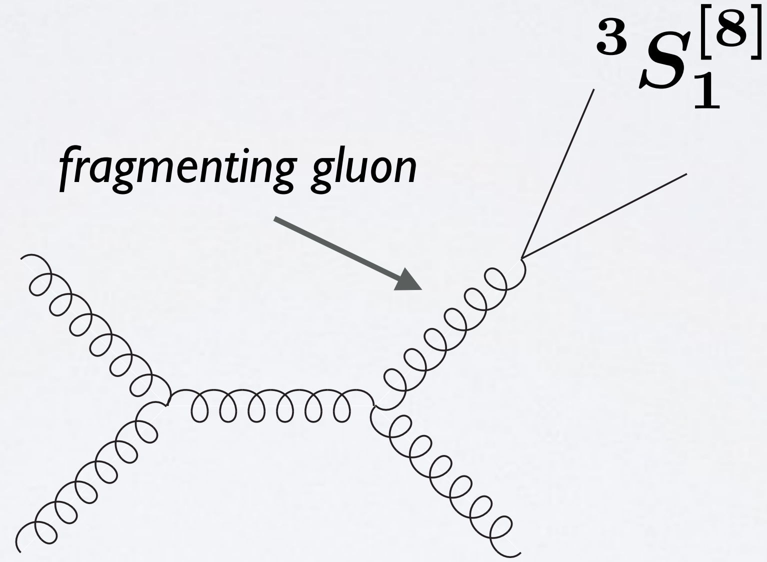
ATLAS, EPJC76, 283 (2016)
M. Cacciari, S. Frixione, P. Nason, JHEP 0103 (2001) 006
M. Cacciari, S. Frixione, N. Houdeau, M. L. Mangano, P. Nason, G. Ridolfi, JHEP 1210 (2012) 137

INCLUSIVE J/ψ PRODUCTION

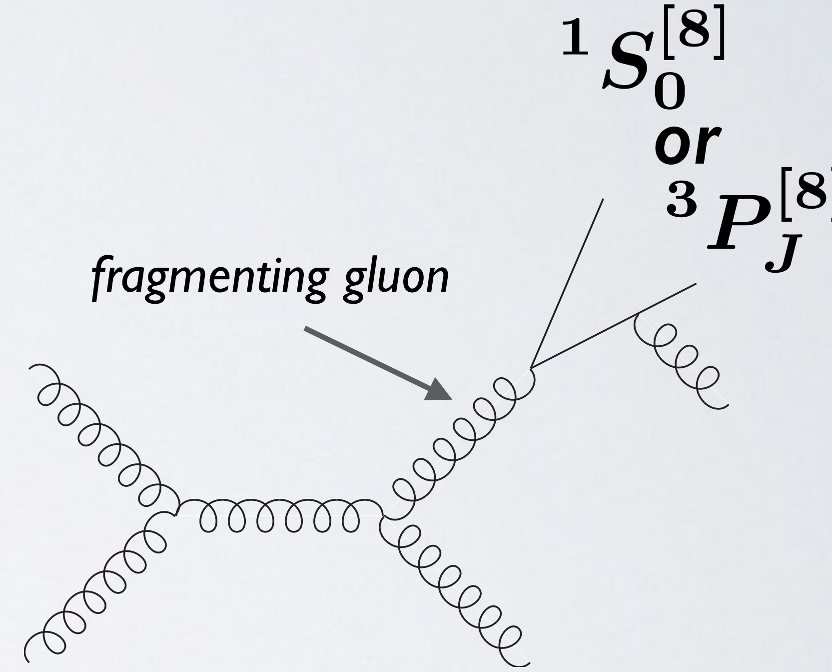
- Gluon fragmentation processes at lowest orders in α_s



order **α_s^5 (color singlet)**



order **α_s^3 (color octet)**



order **α_s^4 (color octet)**

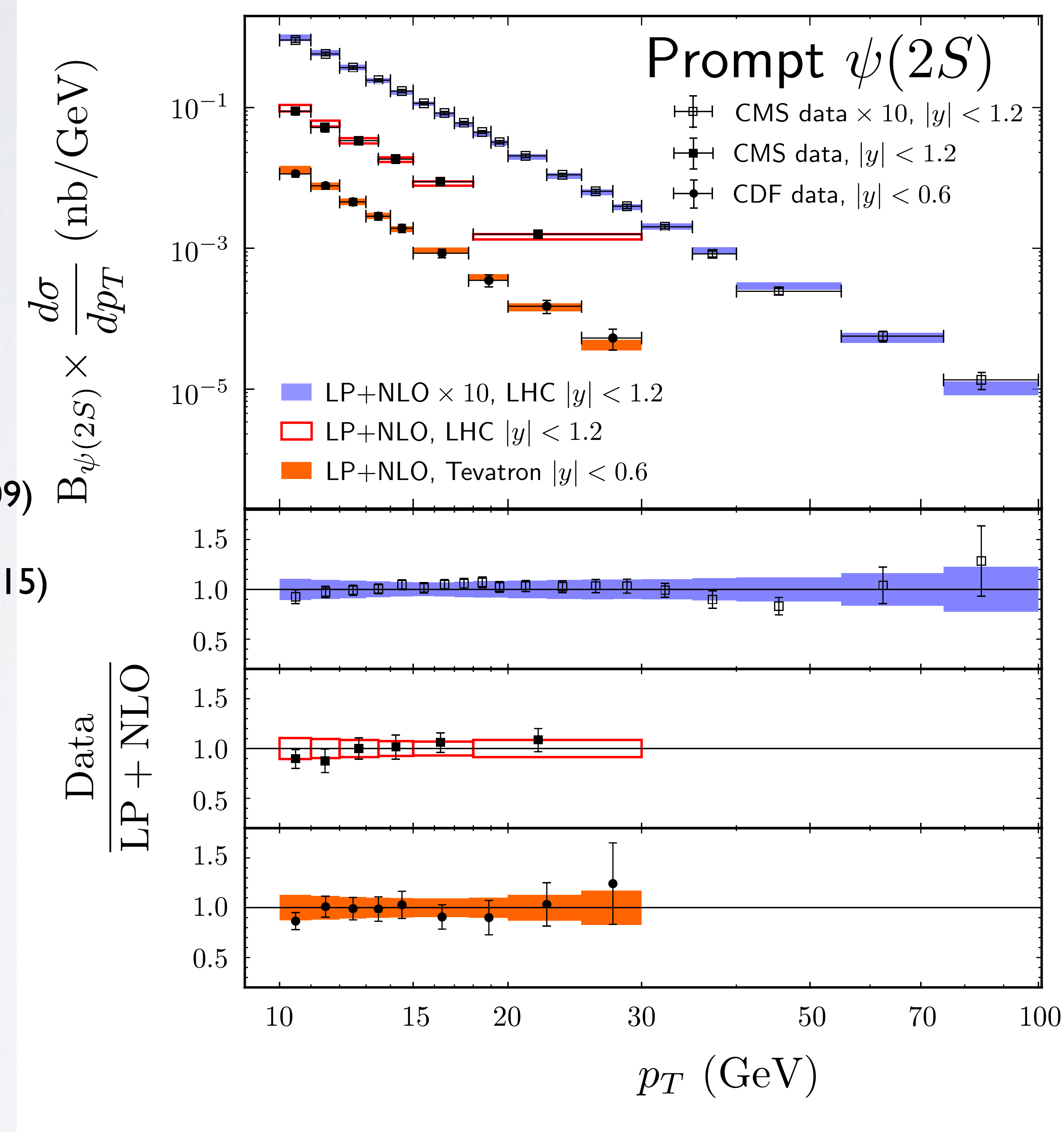
$\psi(2S)$ HADROPRODUCTION

- 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)

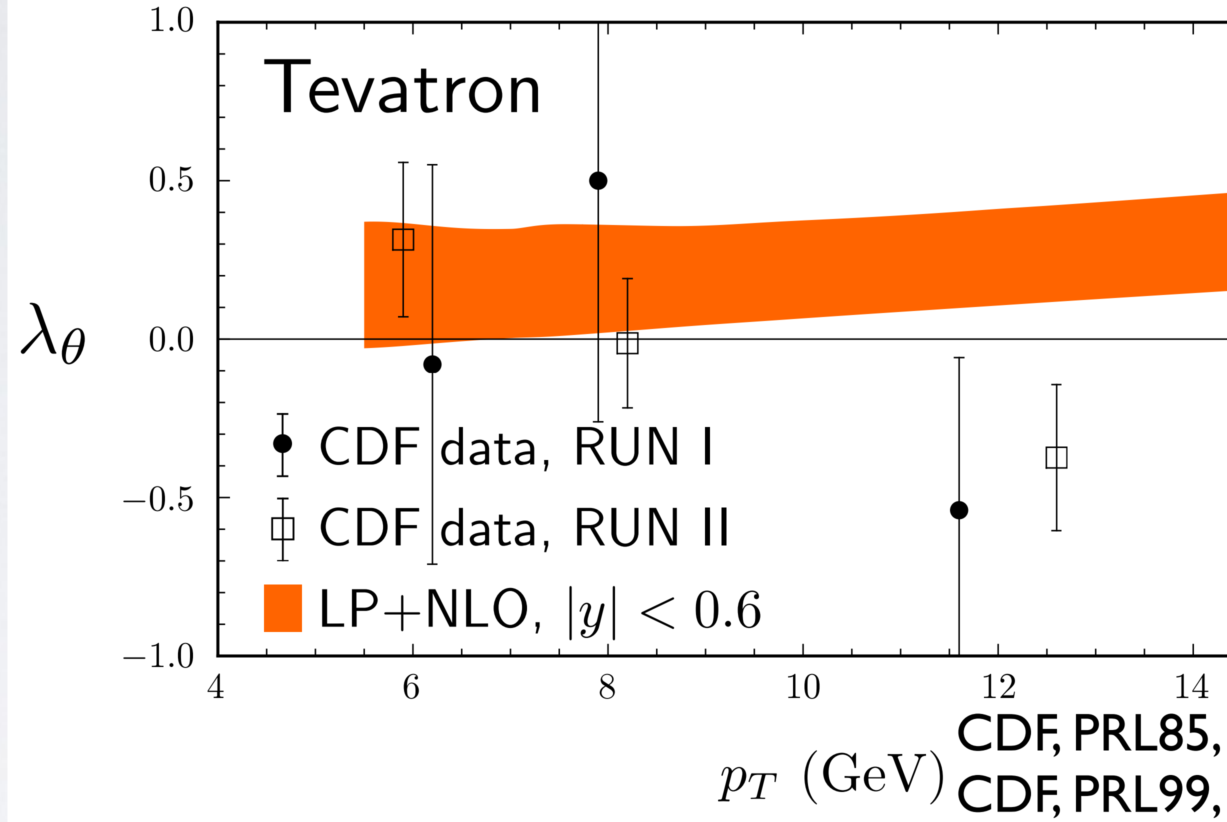
- 30% theoretical uncertainty from scale variation

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

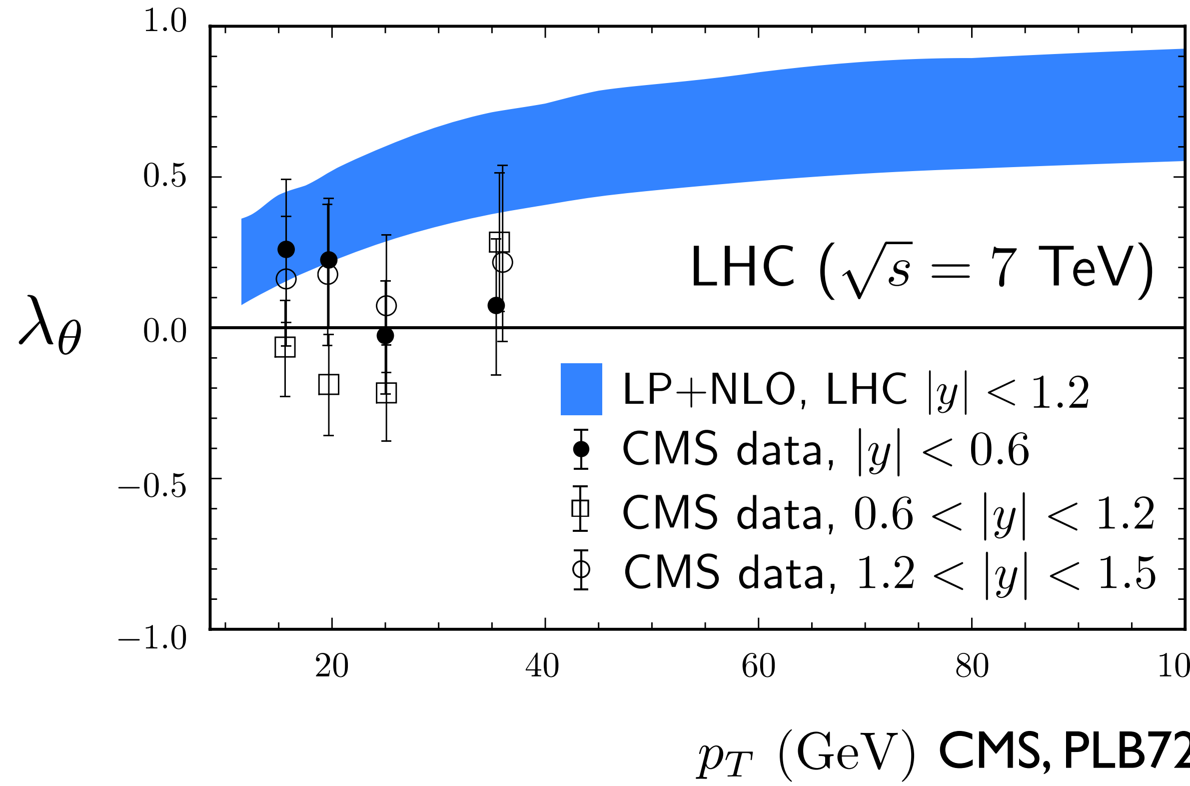


$\psi(2S)$ POLARIZATION

- 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



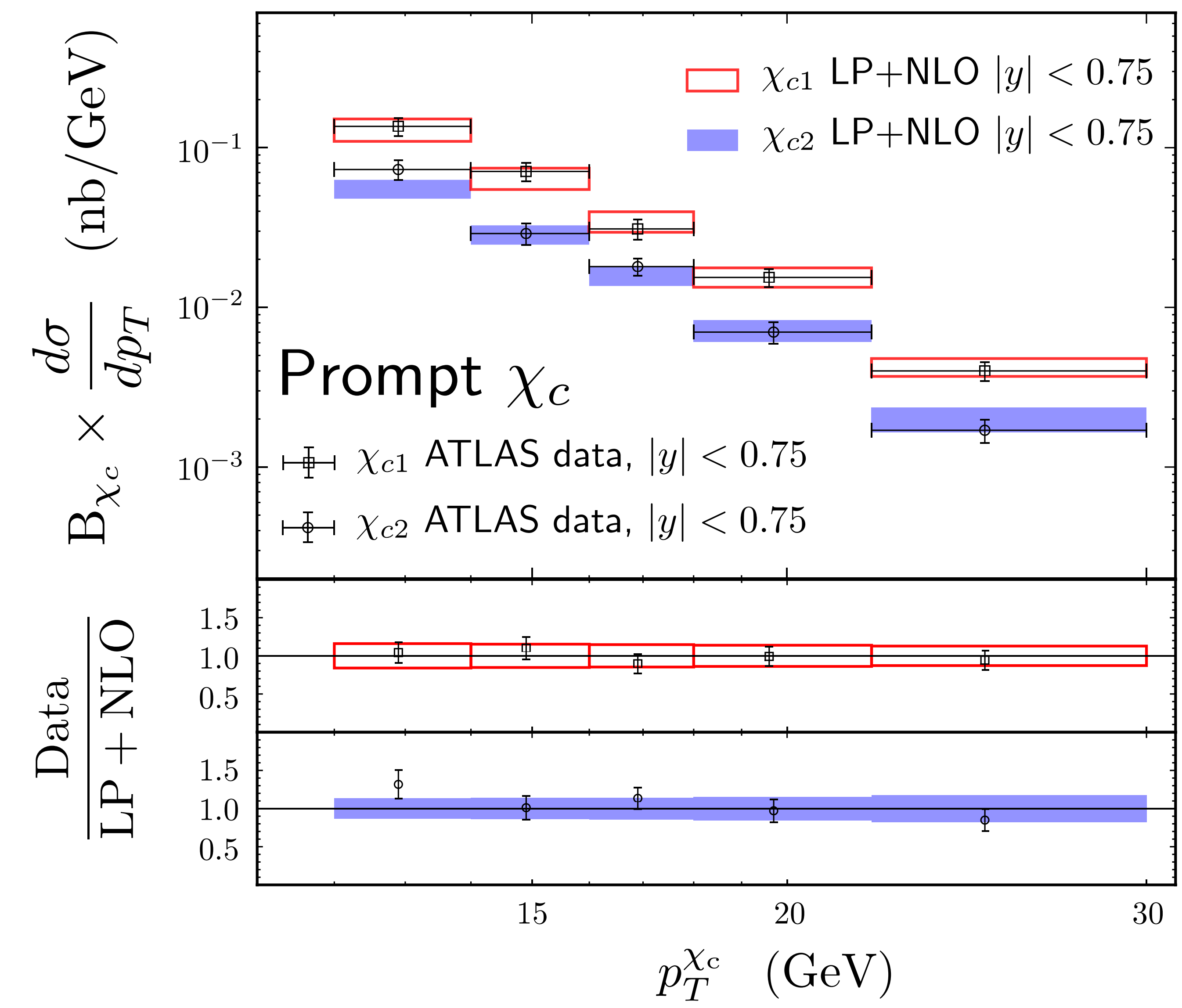
CDF, PRL85, 2886 (2000)
CDF, PRL99, 132001 (2007)



CMS, PLB727, 381 (2013)

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)

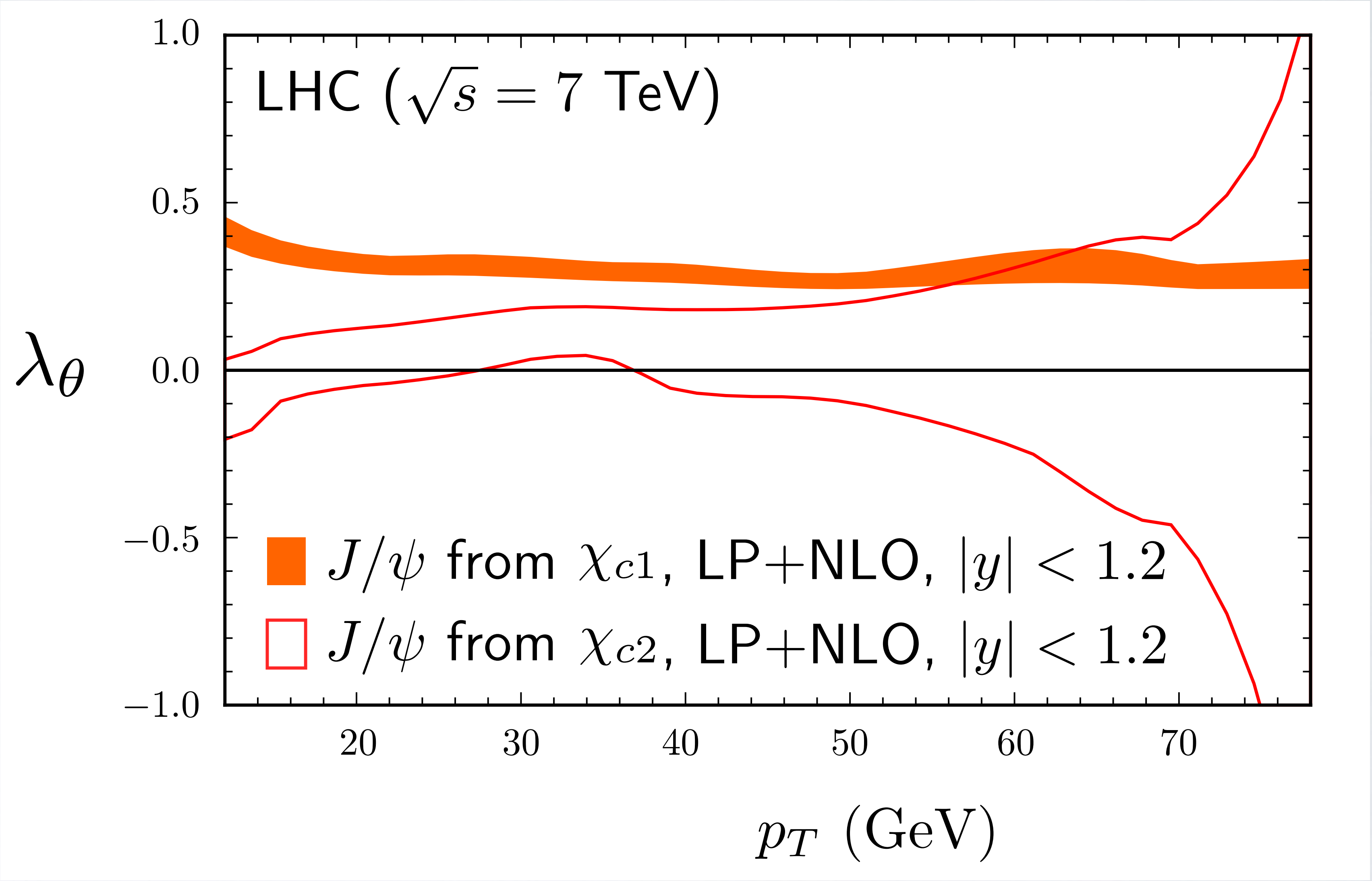
Our fit

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

→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

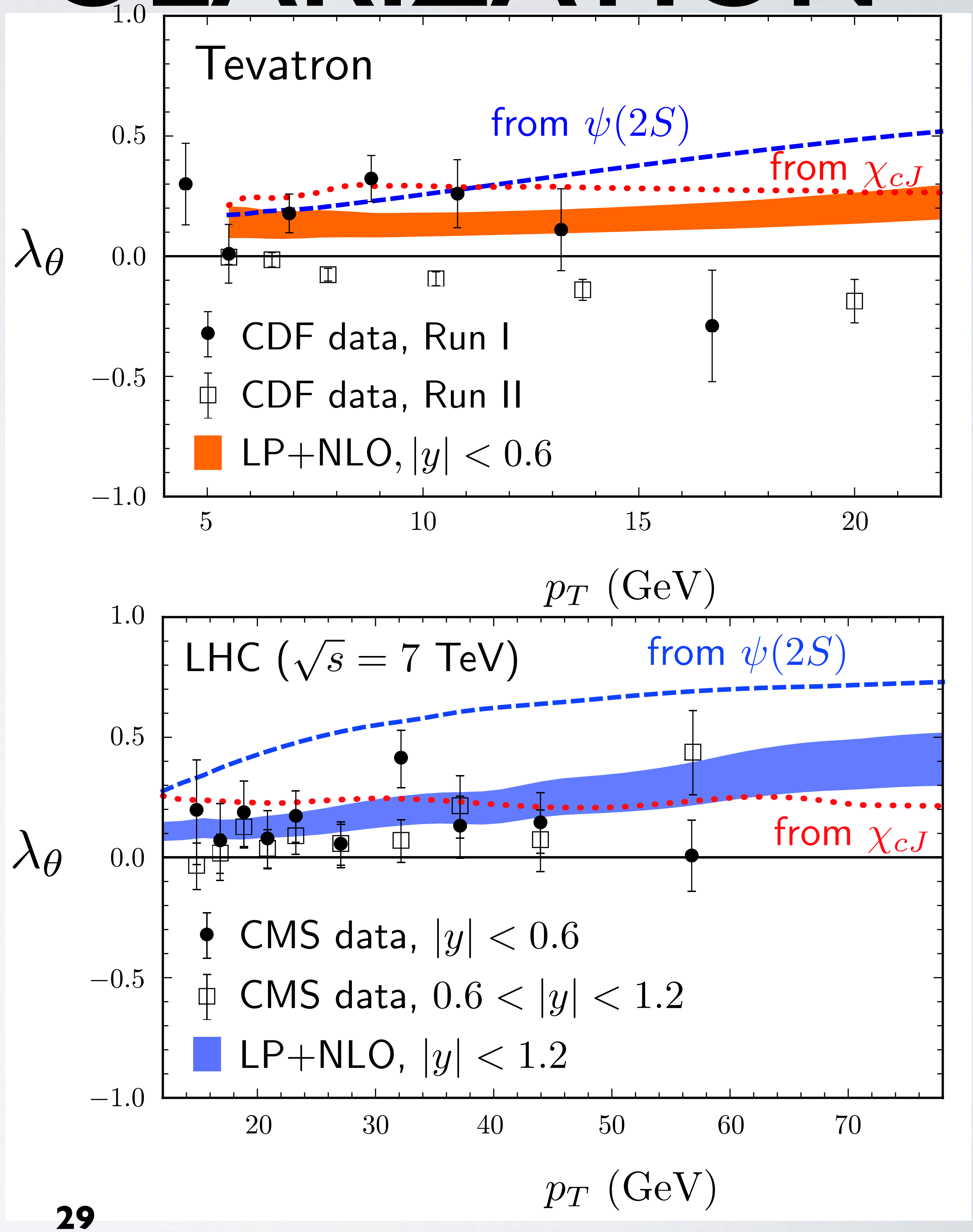


- We assume $\mathbf{E1}$ transition in $\chi_{cJ} \to J/\psi + \gamma$ (higher-order transitions have little effect)

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

PROMPT J/ψ POLARIZATION

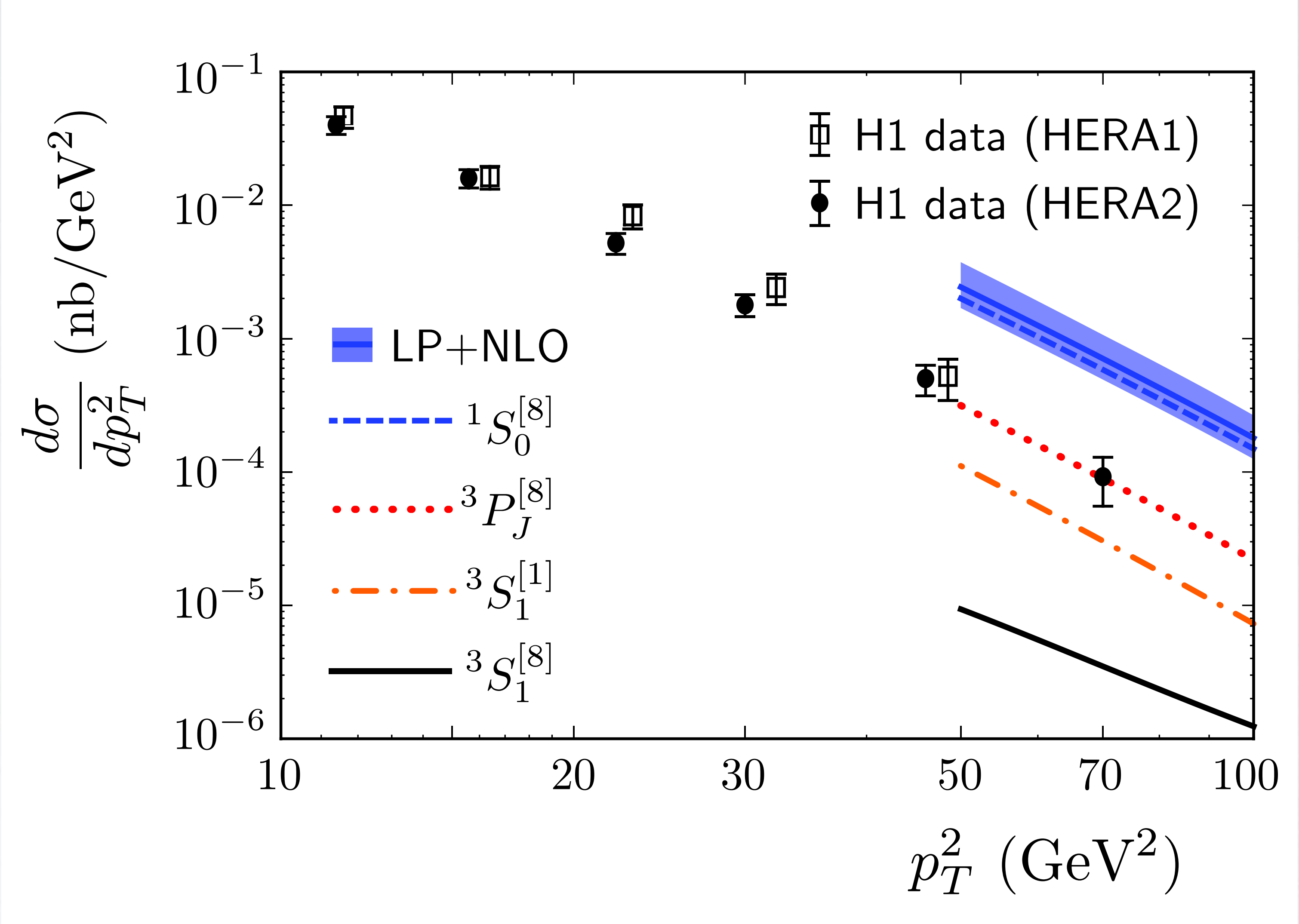
- Direct J/ψ and J/ψ from feeddown is slightly transverse
- **PROMPT J/ψ HAS SMALL POLARIZATION**
- This is in *reasonably good agreement with CMS* data, but disagrees with CDF Run II data



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

J/ψ PHOTOPRODUCTION

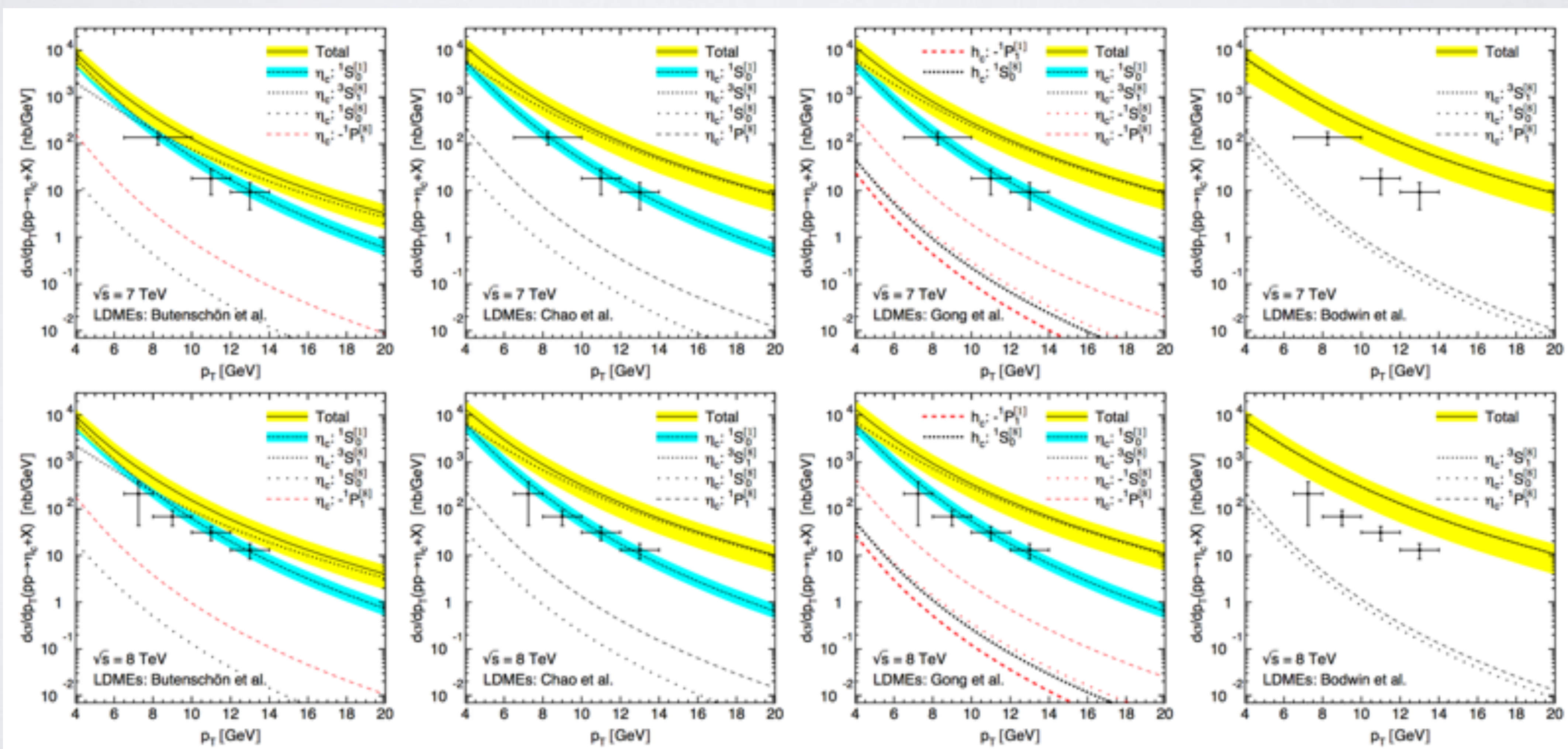
- The LDMEs obtained from fit to hadroproduction cross section lead to predictions for the photoproduction cross section that overshoot the data by a factor of 8 at the highest p_T
- Feeddown contributions are negligible



- p_T is rather small to expect factorization to work

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)