

J/ψ PRODUCTION AT HADRON COLLIDERS

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Geoffrey T. Bodwin, **HSC**, U-Rae Kim, Jungil Lee, **PRL** 113, 022001 (2014)
Geoffrey T. Bodwin, **HSC**, U-Rae Kim, Jungil Lee, Yan-Qing Ma, Kuang-Ta Chao,
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OUTLINE

- Leading-power fragmentation in quarkonium production
- Cross section and polarization of J/ψ
- Summary

HEAVY QUARKONIUM

- A heavy quarkonium is a bound state of a heavy quark and a heavy antiquark.
- J/ψ is a charmonium with $J^{PC} = 1^{--}$, provides clean signal through decay into lepton pair
- Typical energy scales : $m > mv > mv^2 \approx \Lambda_{\text{QCD}}$
 $v^2 \approx 0.3$ for charmonia, $v^2 \approx 0.1$ for bottomonia
- Nonrelativistic description is possible :
use a nonrelativistic effective theory of QCD

INCLUSIVE J/ψ PRODUCTION

- Inclusive quarkonium production cross section at large p_T provides tests of QCD through
 - perturbative calculation of hard processes involving quarks and gluons
 - evolution of hadronic matrix elements such as PDFs and fragmentation functions
- Furthermore, long-distance nature of quarkonia can be investigated using NRQCD

INCLUSIVE J/ψ PRODUCTION

- NRQCD factorization conjecture

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

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

- Short-distance cross sections contain physics above the scale of the heavy-quark mass m , perturbatively calculable
- Nonperturbative long-distance matrix elements contain physics below m , scale with powers of v
- Sum is organized in powers of v

INCLUSIVE J/ψ PRODUCTION

- NRQCD factorization conjecture

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

- At LO in v , the $c\bar{c}$ are produced with same color and angular momentum as the J/ψ : color-singlet channel
- At higher orders in v , the $c\bar{c}$ in color-octet states can evolve into a J/ψ through soft gluon emission

INCLUSIVE J/ψ PRODUCTION

- NRQCD factorization conjecture

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

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

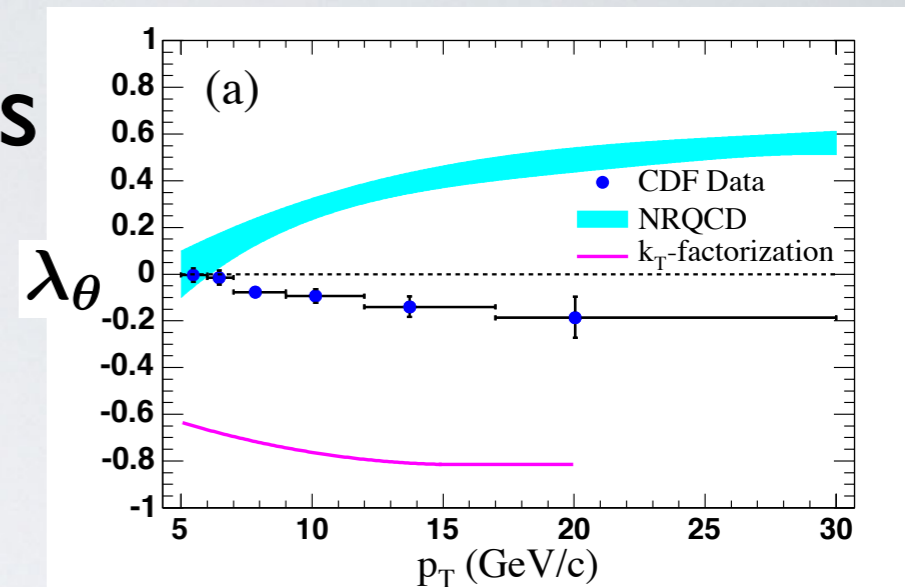
- Usually truncated at relative order v^4 :
 $^1S_0^{[8]}$, $^3S_1^{[8]}$, $^3P_J^{[8]}$, $^3S_1^{[1]}$ channels for J/ψ
- Color-singlet LDMEs can be determined from lattice NRQCD, potential models, or from decay rates
- Not known how to calculate color-octet LDMEs, usually extracted from fits to measurements at large p_T

J/ψ POLARIZATION PUZZLE

- Polarization of J/ψ was suggested as a test of the color-octet mechanism

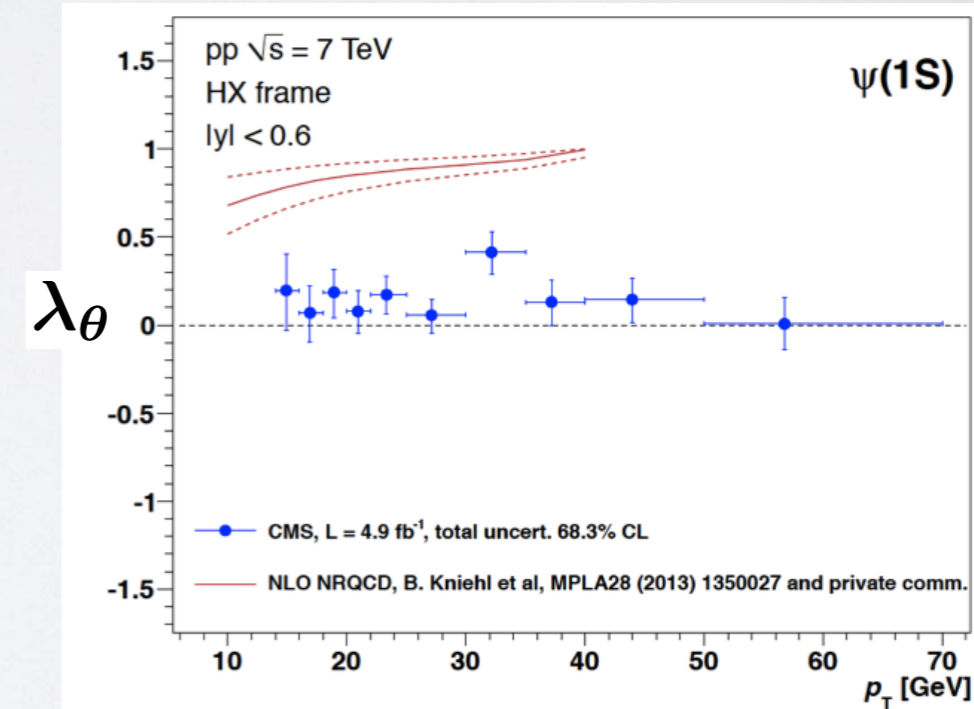
$$\lambda_\theta = \begin{cases} +1 & : \text{Transverse} \\ 0 & : \text{Unpolarized} \\ -1 & : \text{Longitudinal} \end{cases}$$

- 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
- NRQCD at NLO still predicts transverse polarization



CDF, PRL99, 132001 (2007)

Braaten, Kniehl, and Lee, PRD62, 094005 (2000)



CMS, PLB727, 381 (2013)

Butenschoen and Kniehl, PRL108, 172002 (2012)

LP FRAGMENTATION

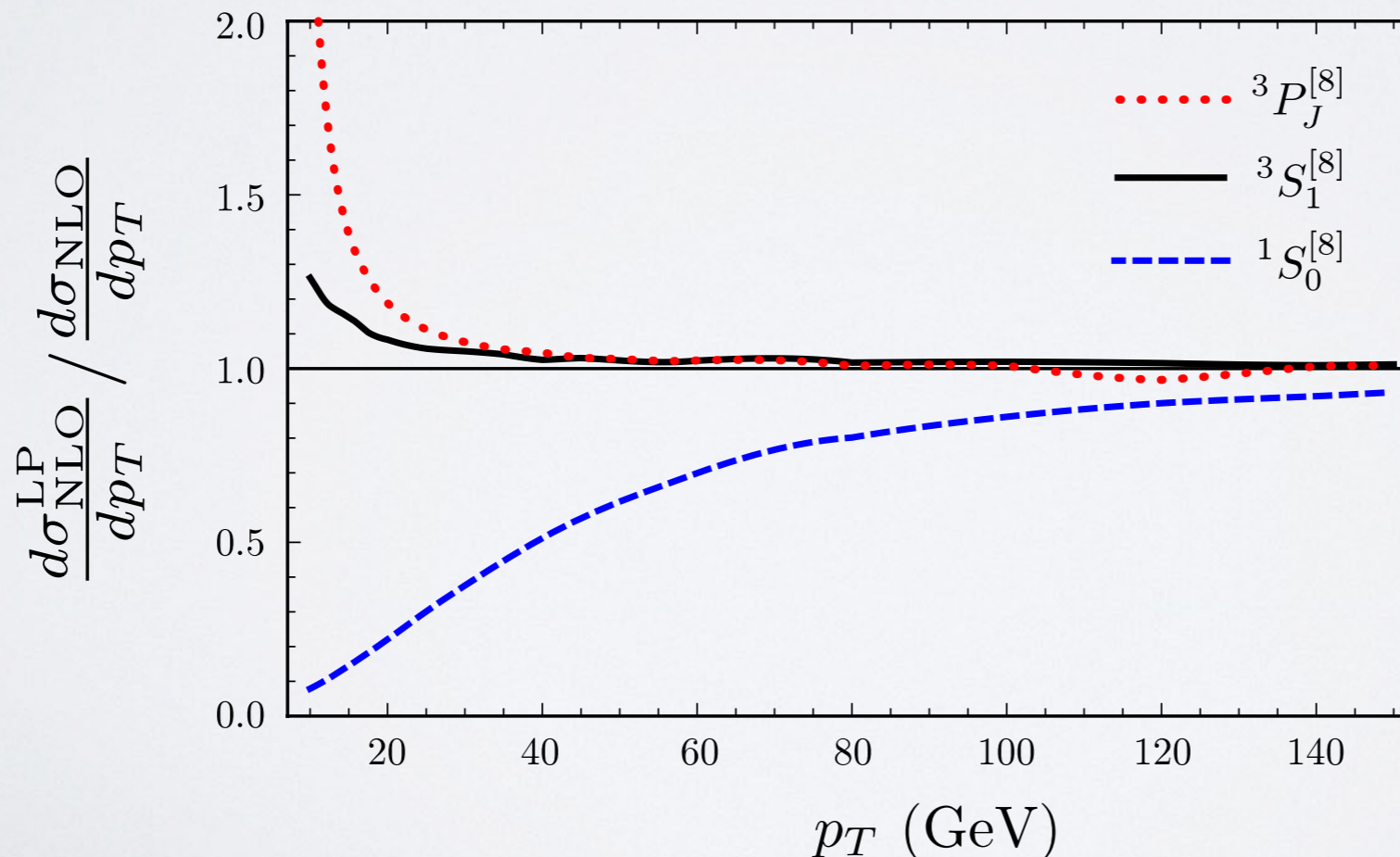
- Shape of the p_T -differential cross section is important for extraction of color-octet LDMEs.
- Short-distance cross sections depend on scales of both m and p_T
- Corrections of higher orders in α_s can be enhanced by powers of p_T/m
- Large NLO corrections arise because new channels that fall off more slowly with p_T open up at NLO

LP FRAGMENTATION

- 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 contribution is given by convolution of the 1-parton cross section and the fragmentation function for the parton to evolve into a $c\bar{c}$
- LP fragmentation reproduces the fixed-order calculation at NLO accuracy at large p_T



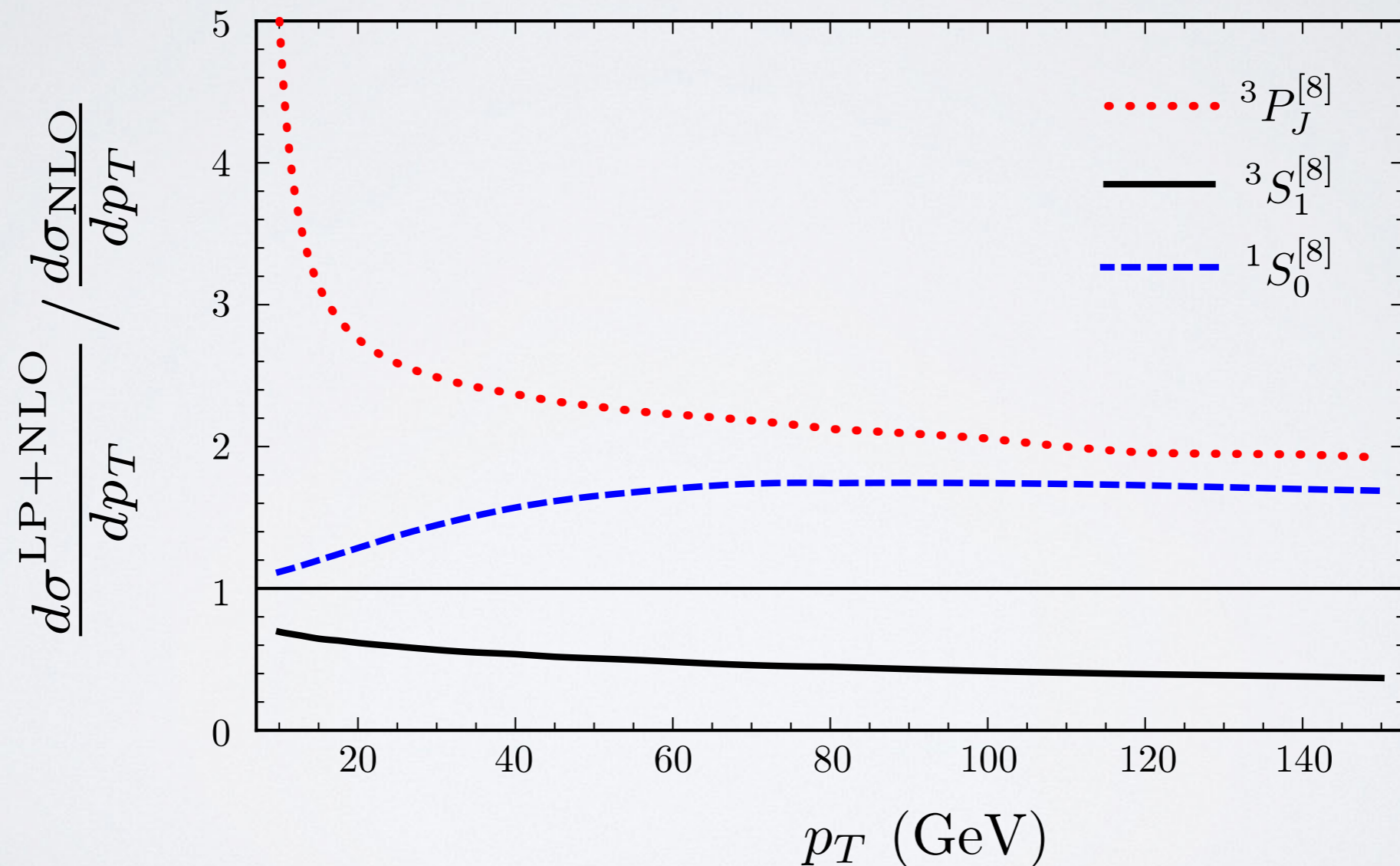
LP FRAGMENTATION

- Corrections beyond NLO accuracy can be obtained by including perturbative corrections to the parton cross sections and the fragmentation functions.
- Leading logarithms of all orders in α_s can be included by evolving the fragmentation functions.
- These additional contributions can be combined with the fixed-order calculation as

$$\begin{aligned}
 & \text{LP fragmentation resummed leading logs} \quad \text{LP fragmentation to NLO accuracy} \\
 & \frac{d\sigma^{\text{LP+NLO}}}{dp_T} = \underbrace{\frac{d\sigma^{\text{LP}}}{dp_T} - \frac{d\sigma_{\text{NLO}}^{\text{LP}}}{dp_T}}_{\text{Additional fragmentation contributions}} + \frac{d\sigma_{\text{NLO}}}{dp_T} \\
 & \text{fixed-order calculation to NLO}
 \end{aligned}$$

LP+NLO

- The additional fragmentation contributions have important effects on the shapes in CO channels



J/ψ PRODUCTION

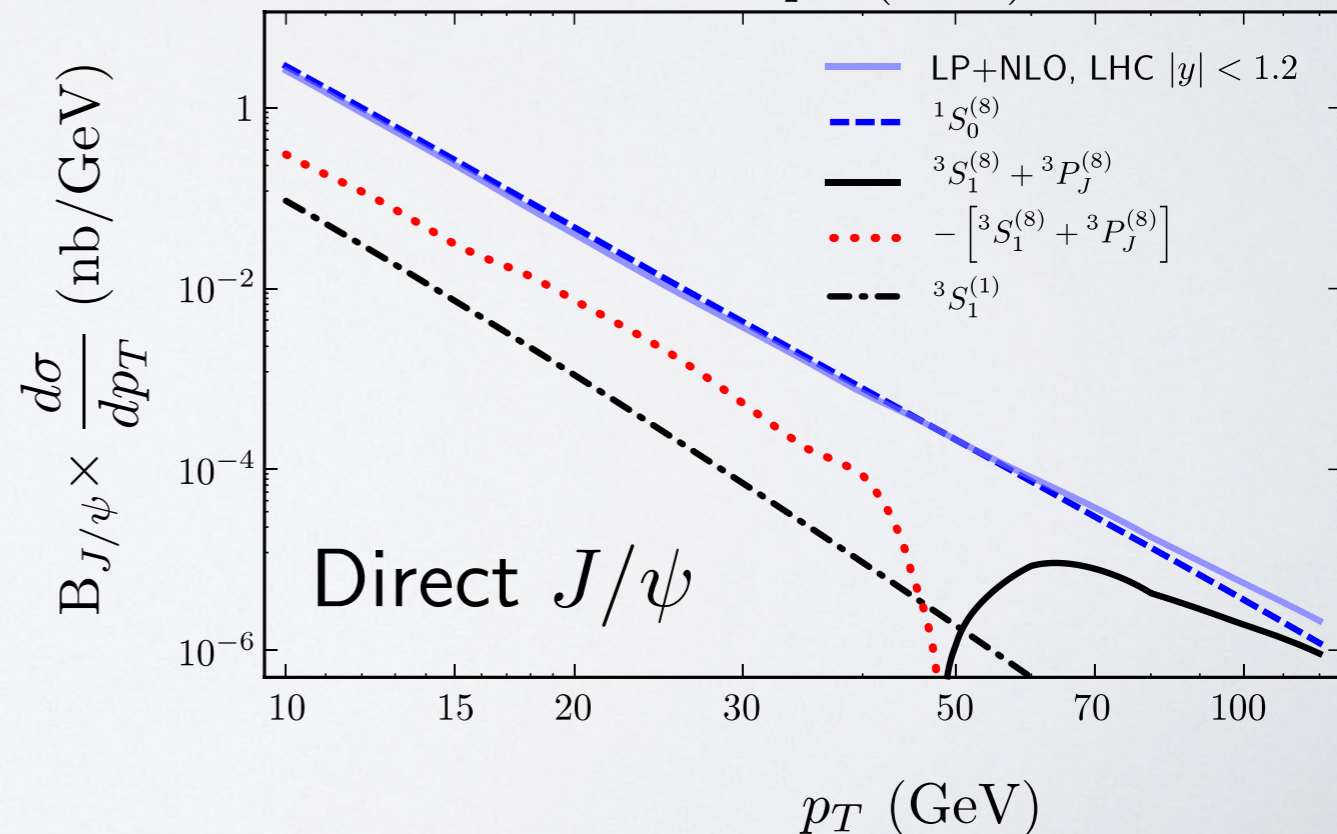
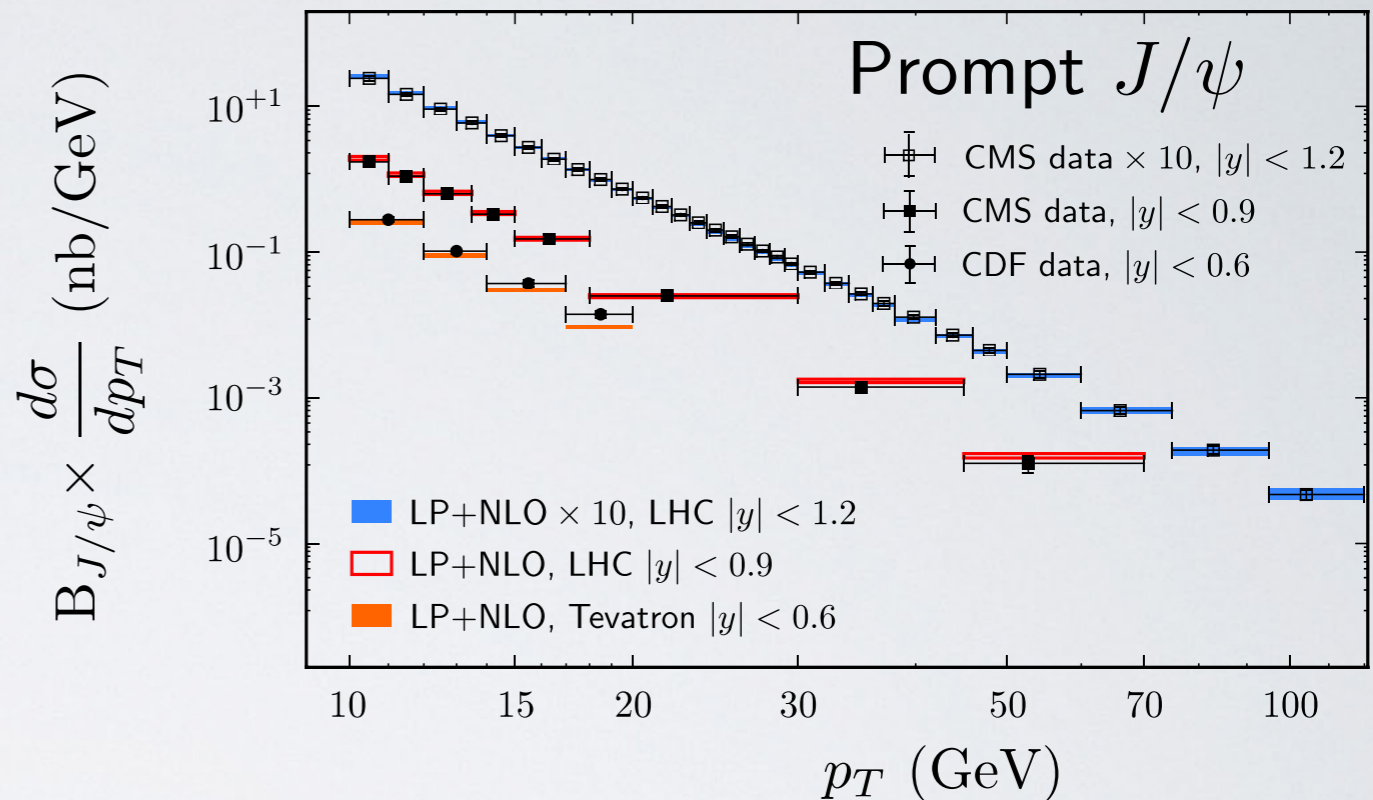
- We obtain good fits to data for $p_T > 10$ GeV ($\approx 3 \times m_{J/\psi}$)

CDF, PRD71, 032001 (2005)

CMS, JHEP02, 011 (2012)

CMS, PRL114, 191802 (2015)

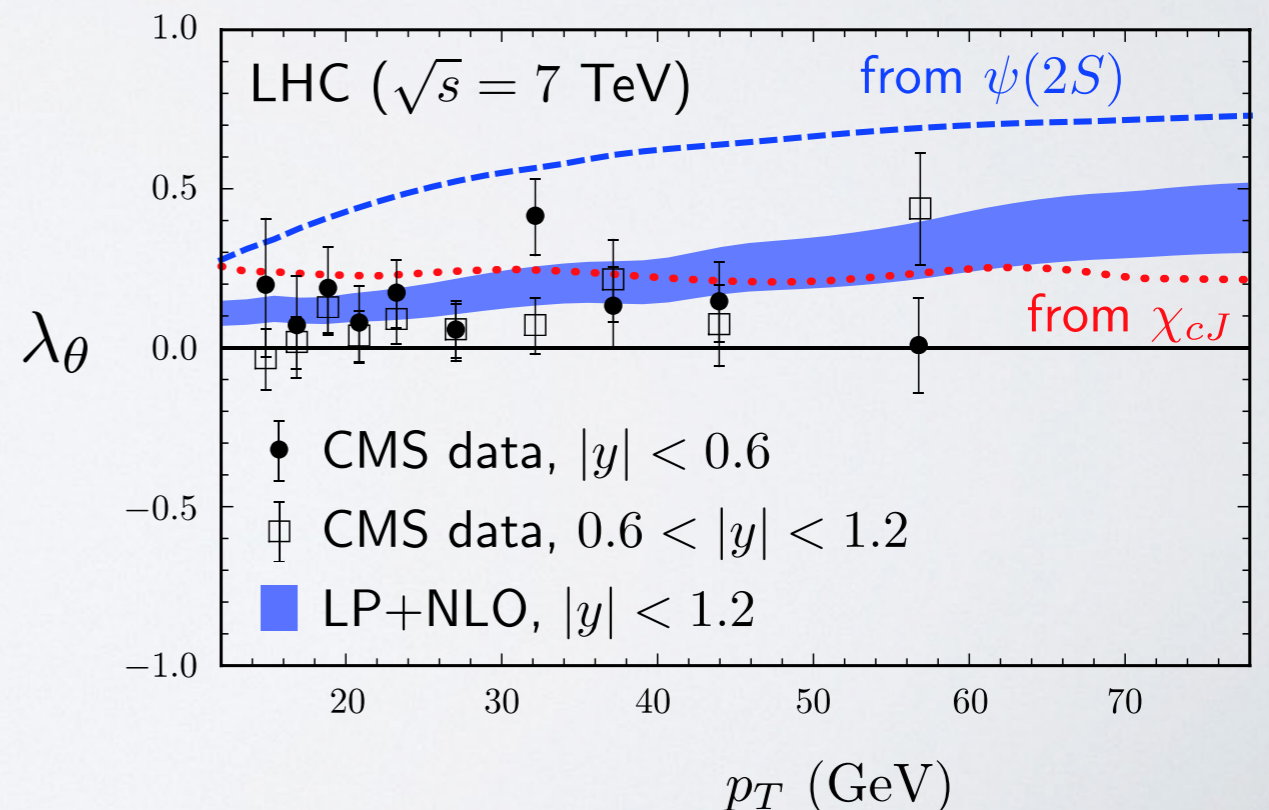
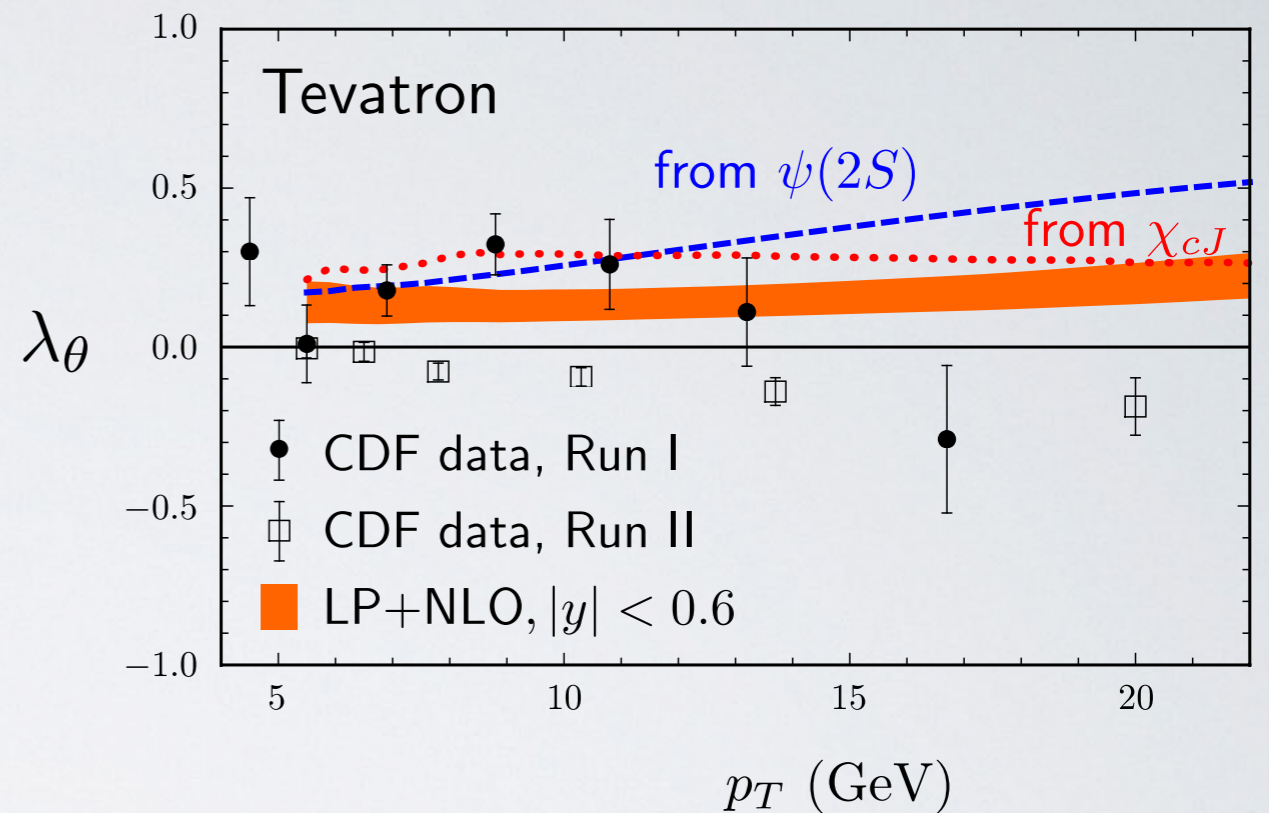
- Cross section is dominated by the $^1S_0^{[8]}$ channel



J/ψ POLARIZATION

- **PROMPT J/ψ HAS SMALL POLARIZATION**
- This is in *reasonably good agreement with CMS* data

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



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 at hadron colliders*
- *This is the first prediction of small J/ψ polarization at high p_T in NRQCD*
- Work on higher-order corrections is in progress

SUPPLEMENTARY

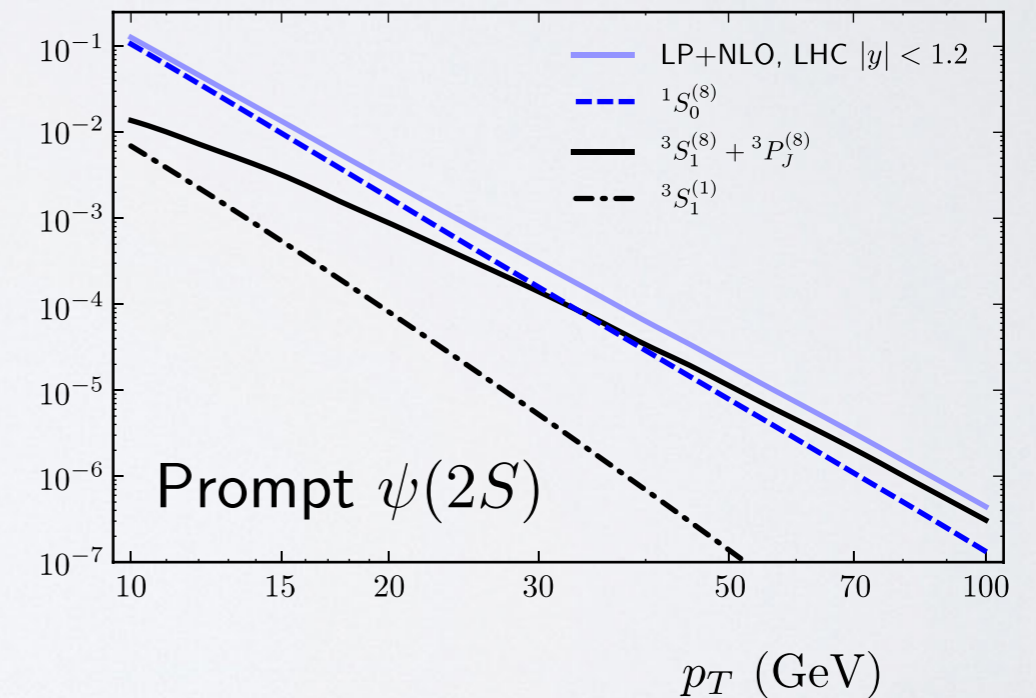
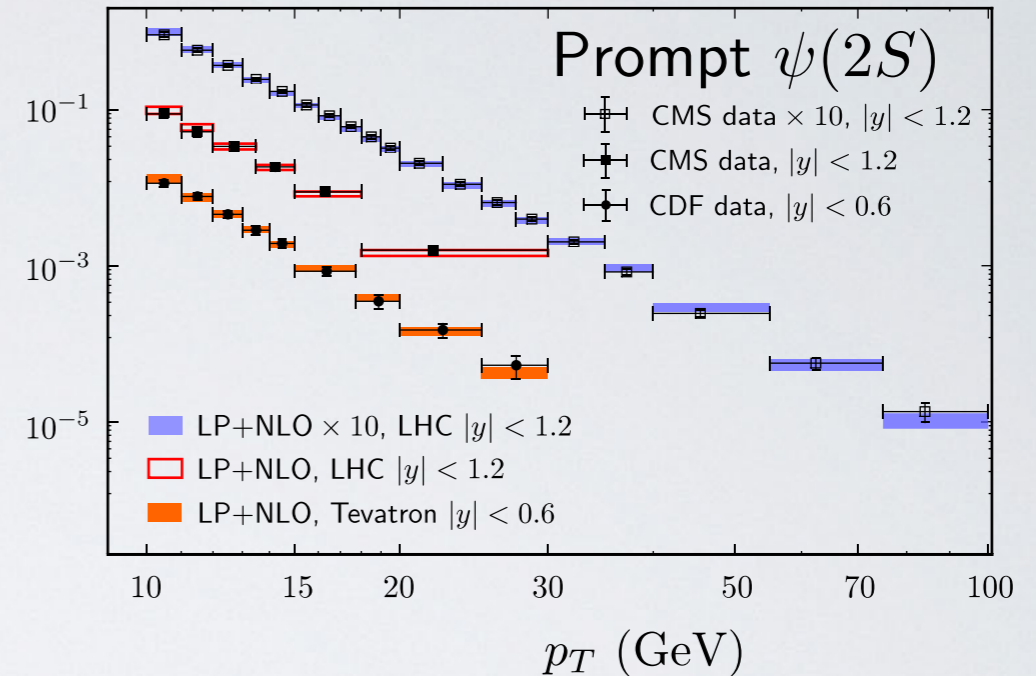
$\psi(2S)$ PRODUCTION

- $\psi(2S)$ LDMEs from fit to CMS and CDF cross section data for $p_T > 11\text{GeV}$ ($\approx 3 \times m_{\psi(2S)}$)

CDF, PRD80, 031103 (2009)
 CMS, JHEP02, 011 (2012)
 CMS, PRL114, 191802 (2015)

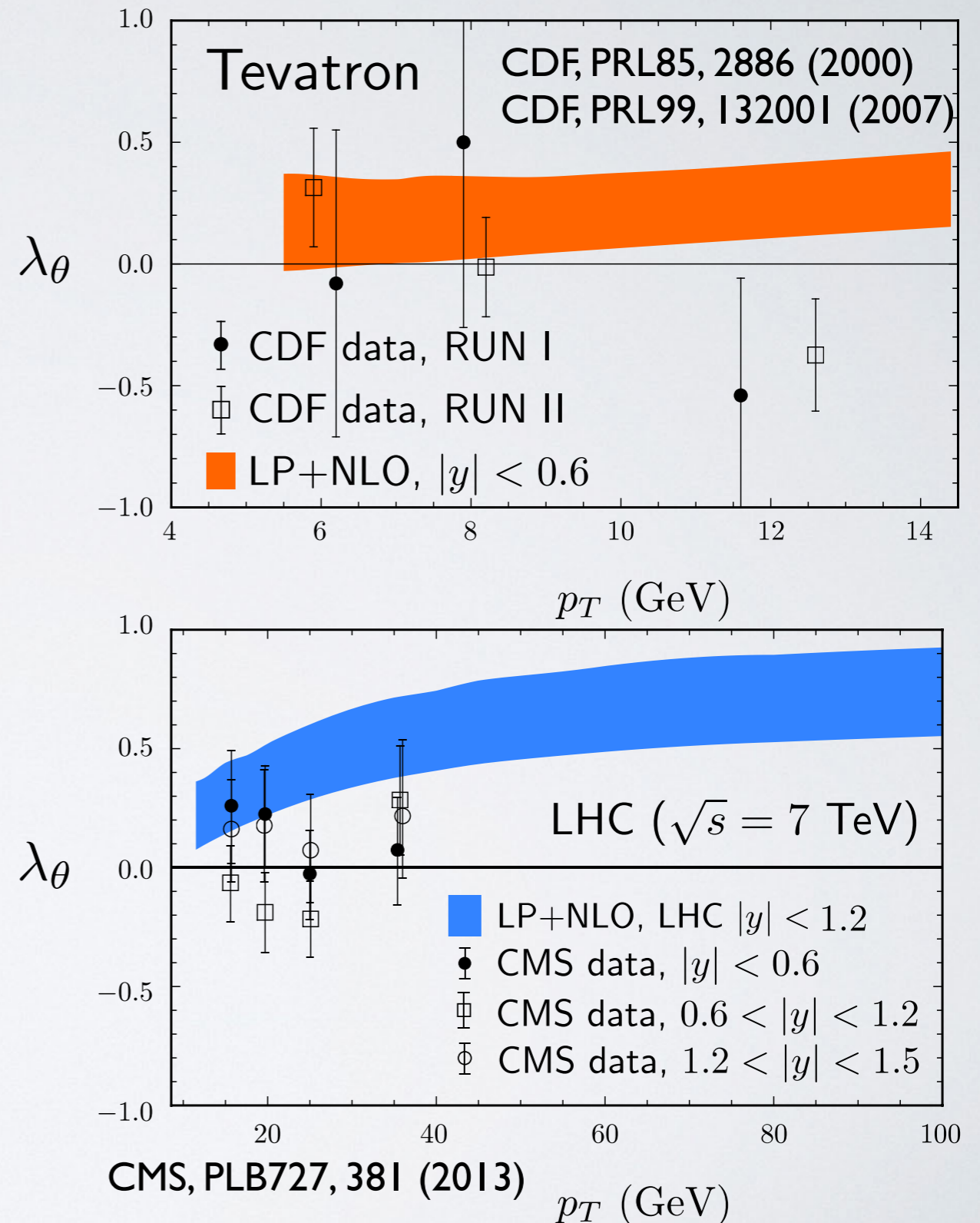
$$B_{\psi(2S)} \times \frac{d\sigma}{dp_T} \text{ (nb/GeV)}$$

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$\psi(2S)$ POLARIZATION

- Slightly transverse at the Tevatron and the LHC
- Agrees with CMS data within errors



χ_{cJ} PRODUCTION

- $^3S_1^{[8]}$ and $^3P_J^{[1]}$ channels contribute at leading order in v
- We obtain good fits to ATLAS data ATLAS, JHEP1407, 154 (2014)
- The $^3P_J^{[1]}$ matrix element obtained from fit agrees with the potential model calculation

Potential model

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

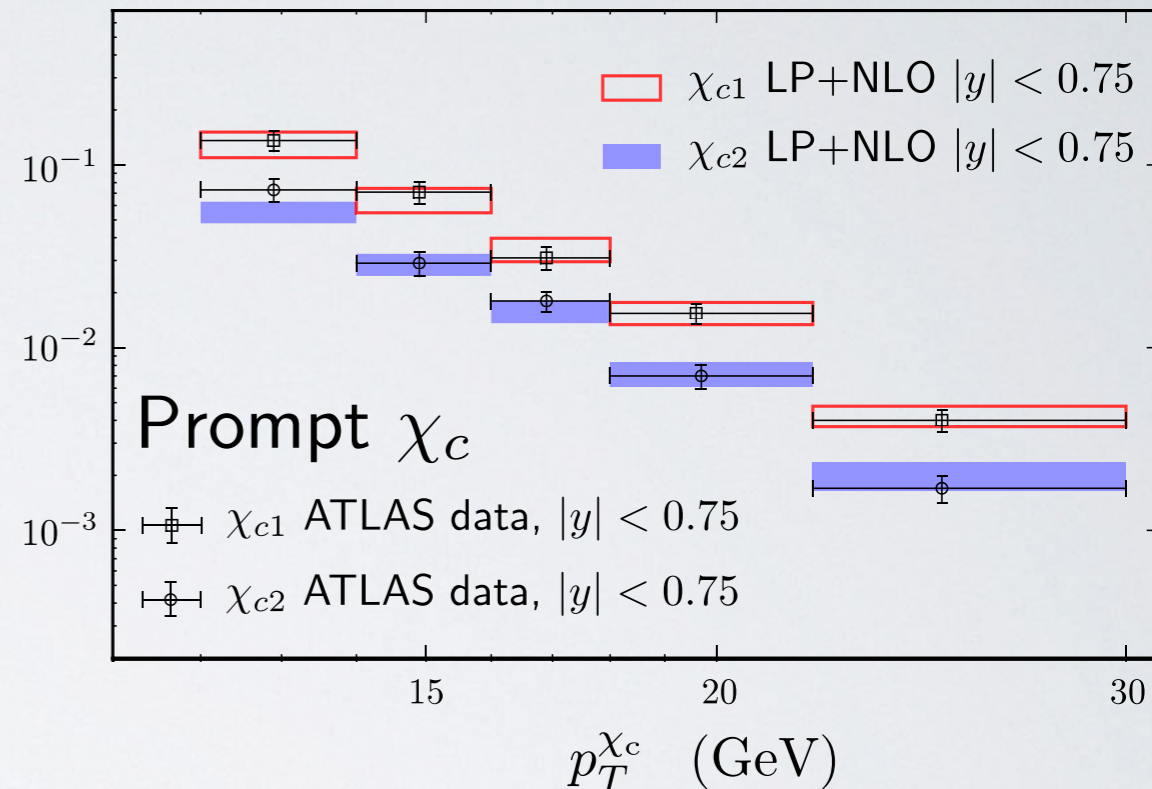
Eichten and Quigg, PRD 52, 1726 (1995)

Our fit

$$|R'(0)|^2 = 0.055 \pm 0.025 \text{ GeV}^5$$

→ Suggests that NRQCD factorization works

$\frac{d\sigma}{dp_T} \times B_{\chi_c}$ (nb/GeV)



χ_{cJ} POLARIZATION

- Polarization of J/ψ from $\chi_{cJ} \rightarrow J/\psi + \gamma$
- No measurement available

