FRAGMENTATION CONTRIBUTIONS TO J/ψ PRODUCTION AT THE TEVATRON AND THE LHC

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Geoffrey T. Bodwin, **HSC**, U-Rae Kim, Jungil Lee, **PRL**113, 022001 (2014)

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OUTLINE

- Leading-power fragmentation in quarkonium production
- Cross section and polarization of
    - direct J/ψ
    - $\psi(2S)$ and χ_{cJ}
    - prompt J/ψ
- Summary

INCLUSIVE J/ψ PRODUCTION

- NRQCD factorization conjecture for production of H

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

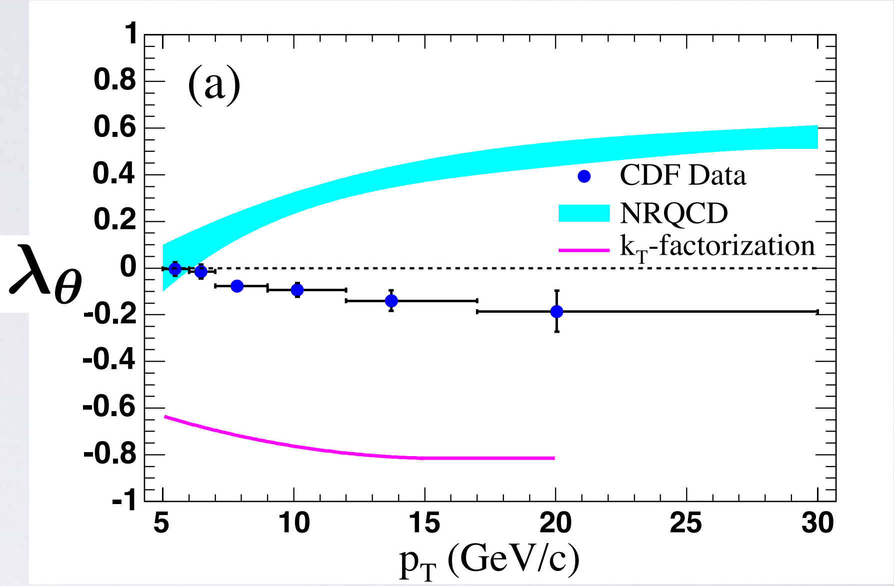
$$d\sigma_{A+B\to H+X} = \sum_n \underbrace{d\sigma_{A+B\to Q\bar{Q}(n)+X}}_{\text{Short-distance cross section}} \underbrace{\langle \mathcal{O}^H(n)\rangle}_{\text{LDME}}$$

- Usually truncated at relative order v^4: ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, ${}^3P_J^{[8]}$, ${}^3S_1^{[1]}$ channels for J/ψ
- We neglect the ${}^3S_1^{[1]}$ channel because its contribution is small at NLO
- Not known how to calculate nonperturbative color-octet LDMEs
- CO LDMEs extracted from fits to measured cross sections

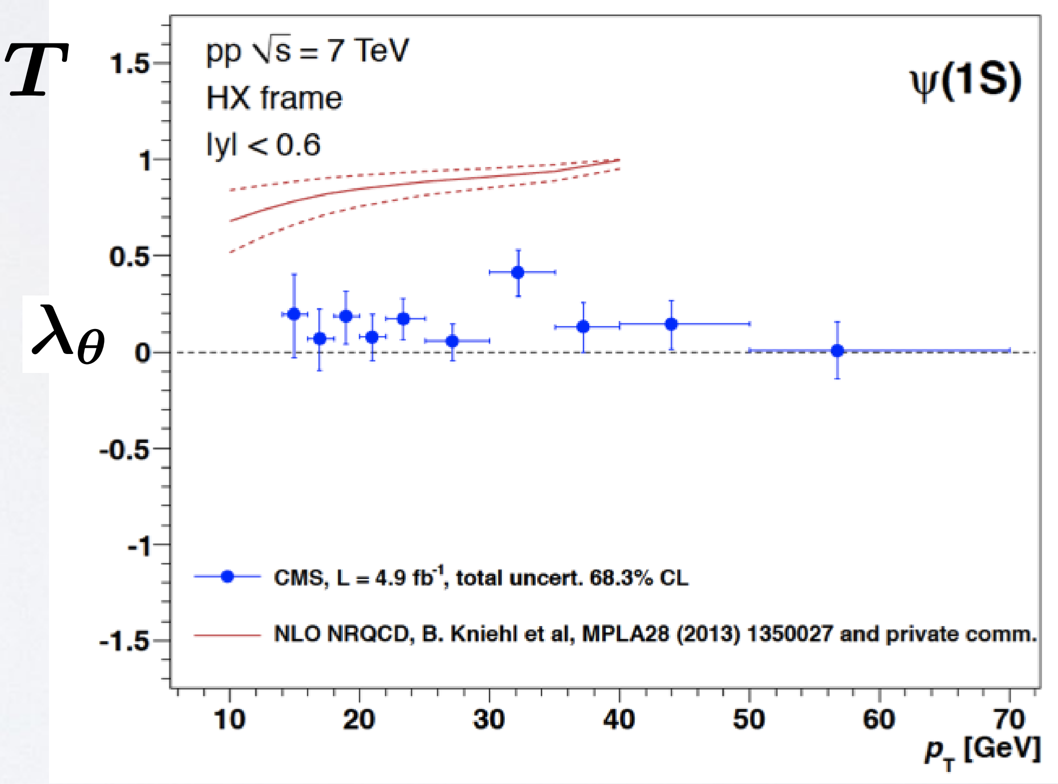
J/ψ POLARIZATION PUZZLE

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

- 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

- 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)

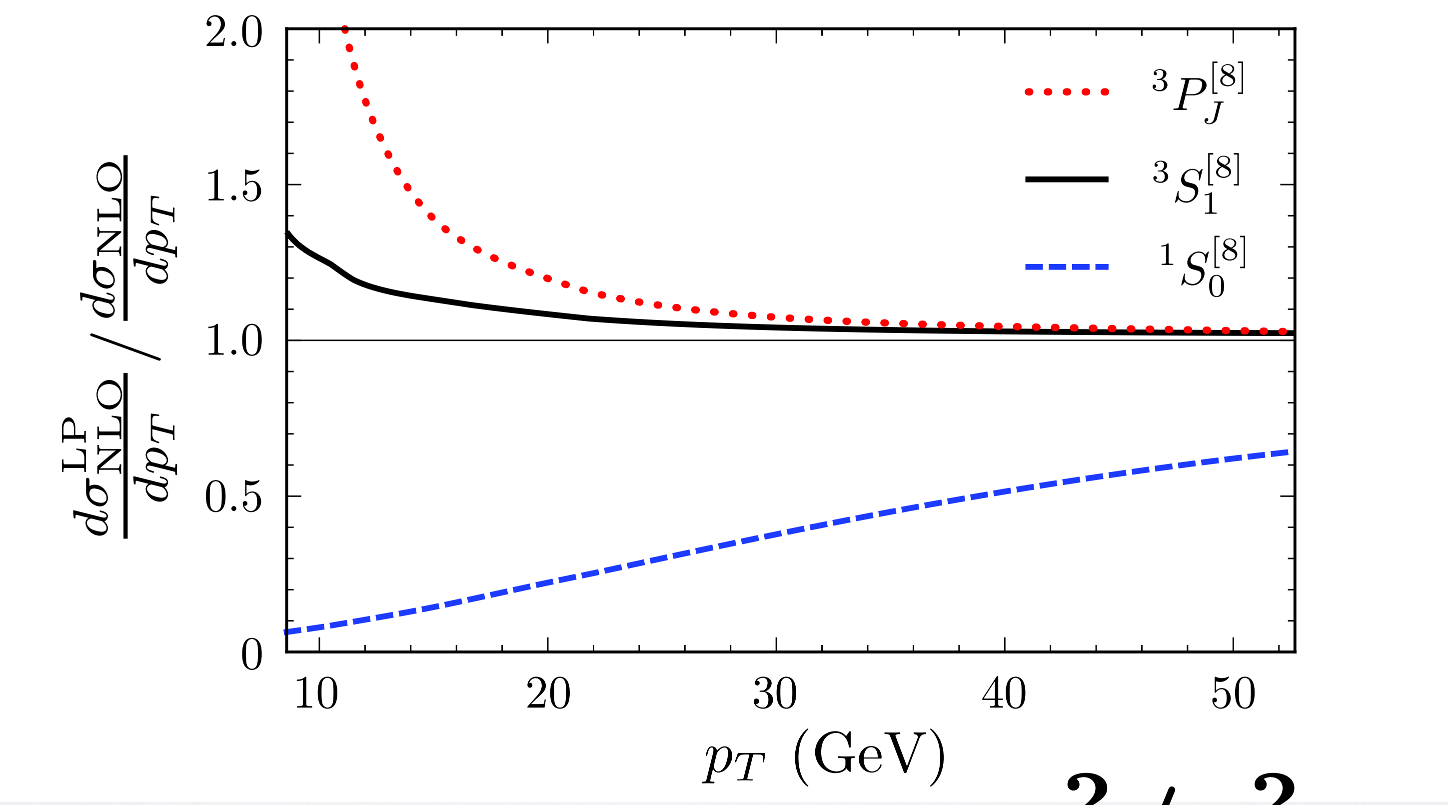
- Corrections to LP fragmentation go as m_c^2/p_T^2

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

$$\frac{d\sigma^{\mathrm{LP+NLO}}}{dp_T} = \underbrace{\overset{\textit{LP fragmentation resummed leading logs}}{\frac{d\sigma^{\mathrm{LP}}}{dp_T}} - \overset{\textit{LP fragmentation to NLO accuracy}}{\frac{d\sigma^{\mathrm{LP}}_{\mathrm{NLO}}}{dp_T}}}_{\textit{Additional fragmentation contributions}} + \underset{\textit{fixed-order calculation to NLO}}{\frac{d\sigma_{\mathrm{NLO}}}{dp_T}}$$

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

LP+NLO

- Alternatively, one can consider the NLO calculations to supply the corrections of relative order m_c^2/p_T^2

fixed-order calculation to NLO

LP fragmentation to NLO accuracy

$$\frac{d\sigma^{\mathrm{LP+NLO}}}{dp_T} = \frac{d\sigma^{\mathrm{LP}}}{dp_T} + \underbrace{\frac{d\sigma_{\mathrm{NLO}}}{dp_T} - \frac{d\sigma^{\mathrm{LP}}_{\mathrm{NLO}}}{dp_T}}_{\text{corrections of relative order } m_c^2/p_T^2}$$

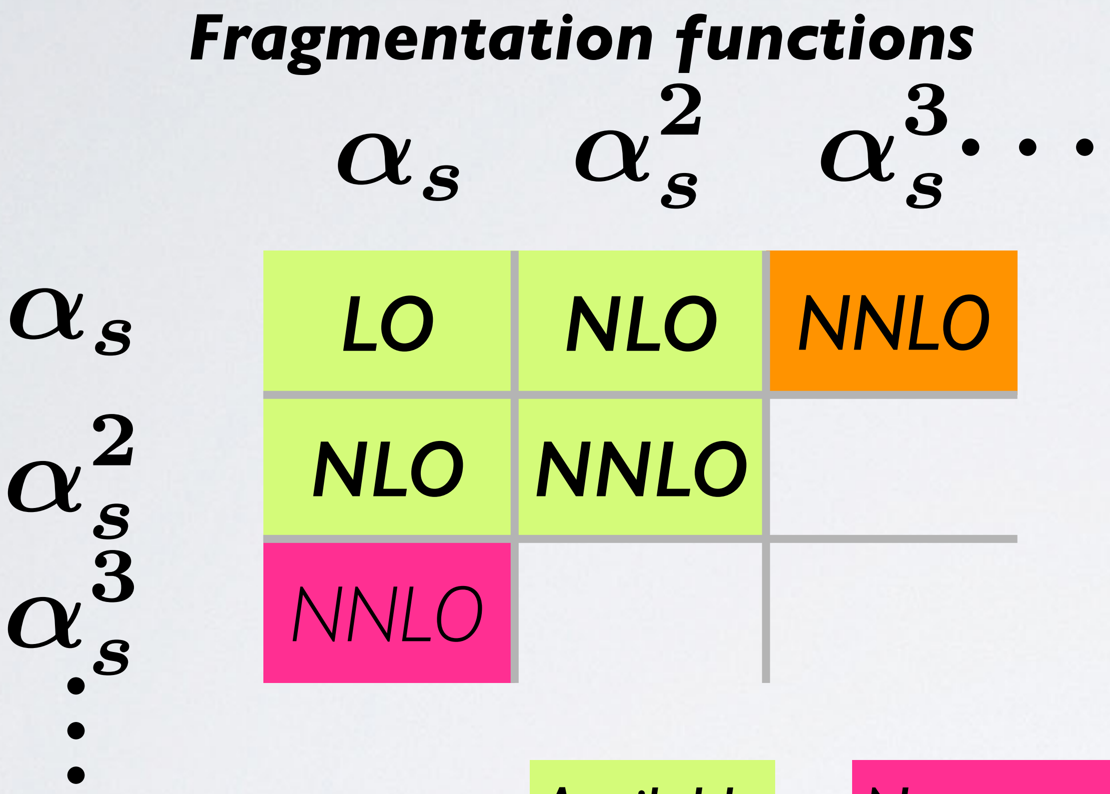
LP fragmentation resumed leading logs

- The m_c^2/p_T^2 corrections can also be obtained from NLP factorization contributions (double-parton fragmentation)

Kang, Qiu, and Sterman, NPB, Proc. Suppl. 214, 39 (2011)
Kang, Qiu, and Sterman, PRL108, 102002 (2012)
Ma, Qui, Sterman, and Zhang, PRL113, 142002 (2014)

LP CONTRIBUTIONS THAT WE COMPUTE

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

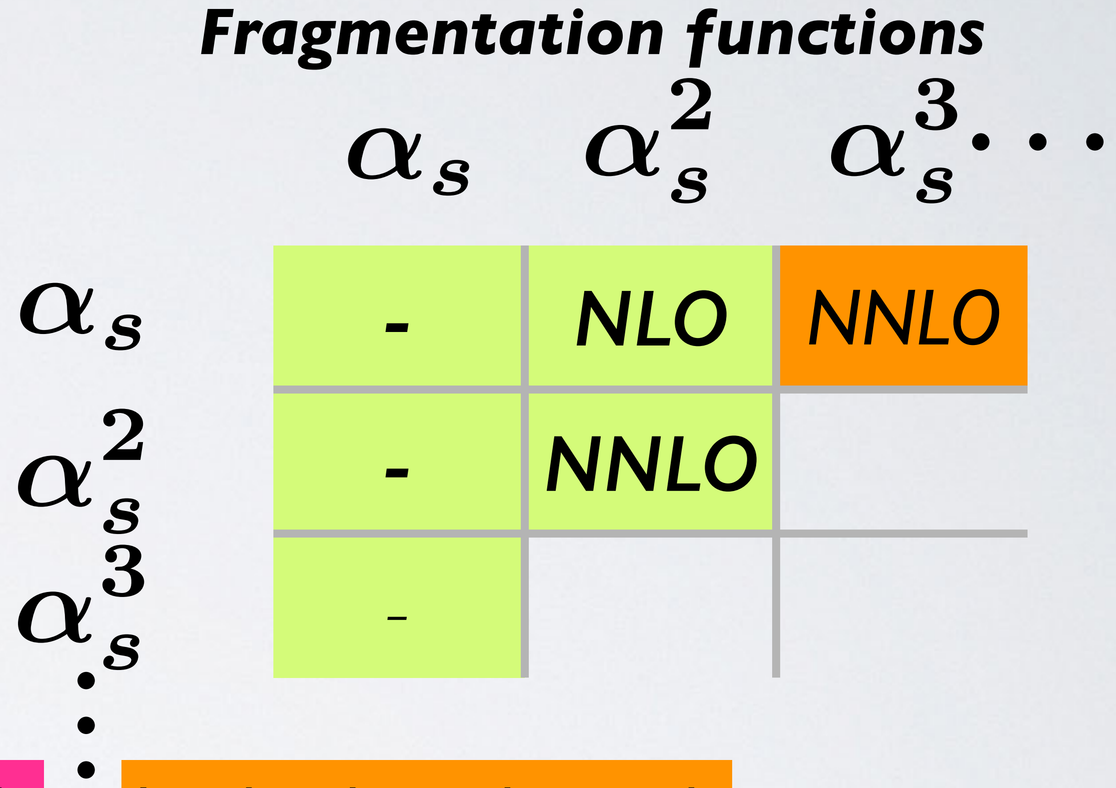


Fragmentation functions

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

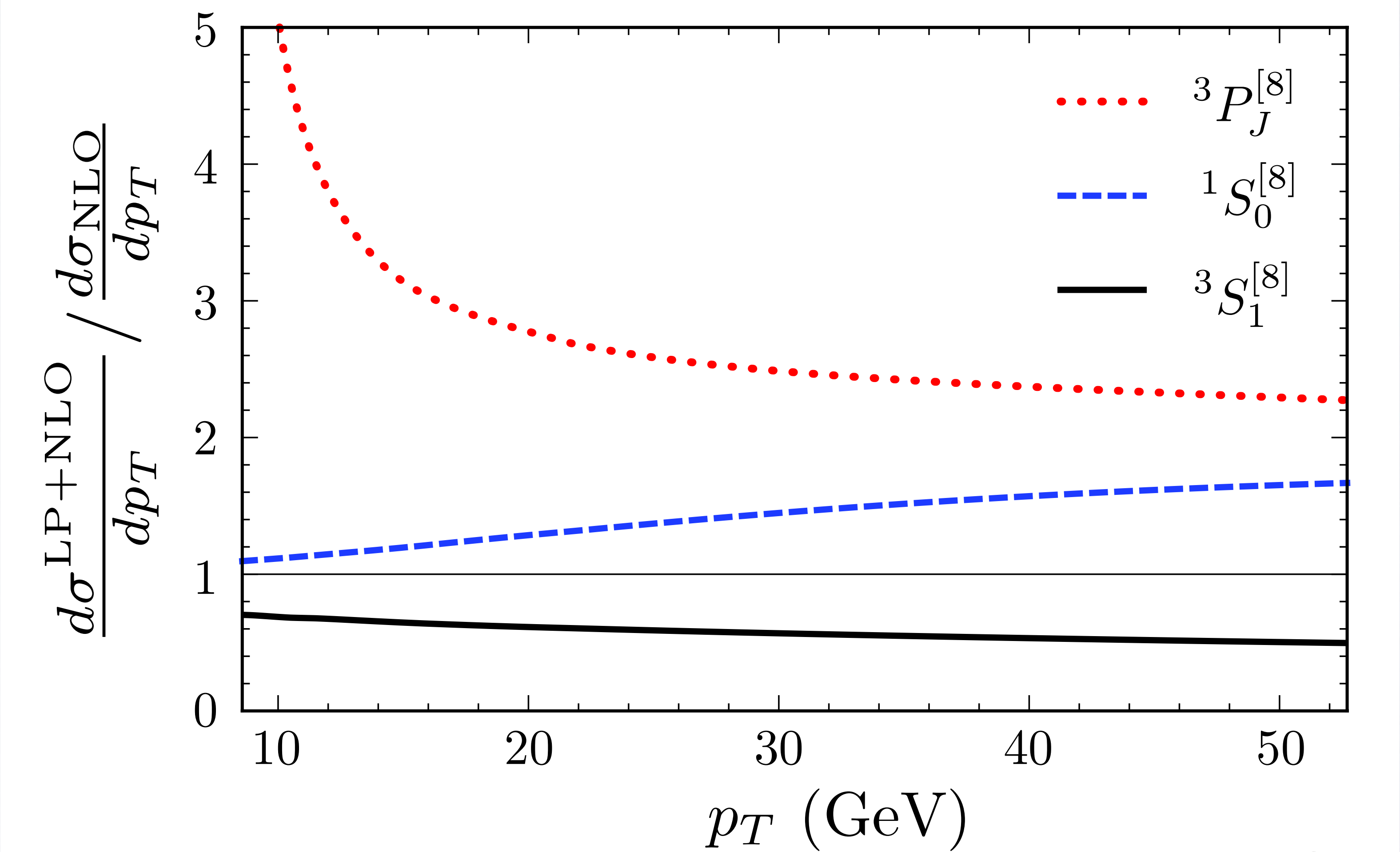
	α_s	α_s^2	$\alpha_s^3 \cdots$
α_s	-	*NLO*	*NNLO*
α_s^2	-	*NNLO*	
α_s^3	-		
$\vdots$			

🟩 *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

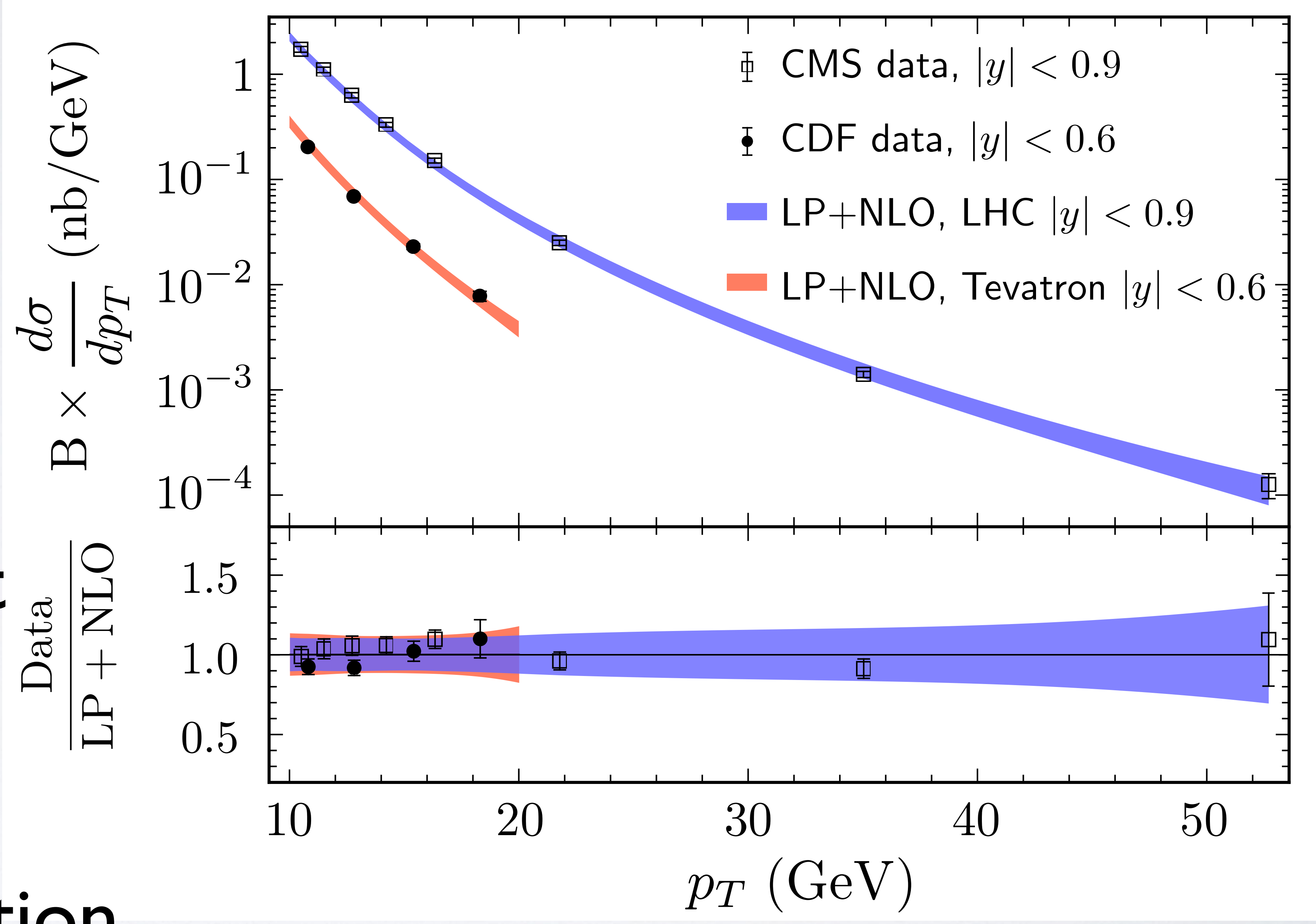
- The additional fragmentation contributions have important effects on the shapes in the $^3P_J^{[8]}$ channel



- 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

J/ψ PRODUCTION

- We obtain good fits to the cross section measurements by CDF and CMS
- $p_T > 10$ GeV ($\approx 3 \times m_{J/\psi}$) was used in the fit
- 25% theoretical uncertainty from varying fragmentation, factorization and renormalization scales



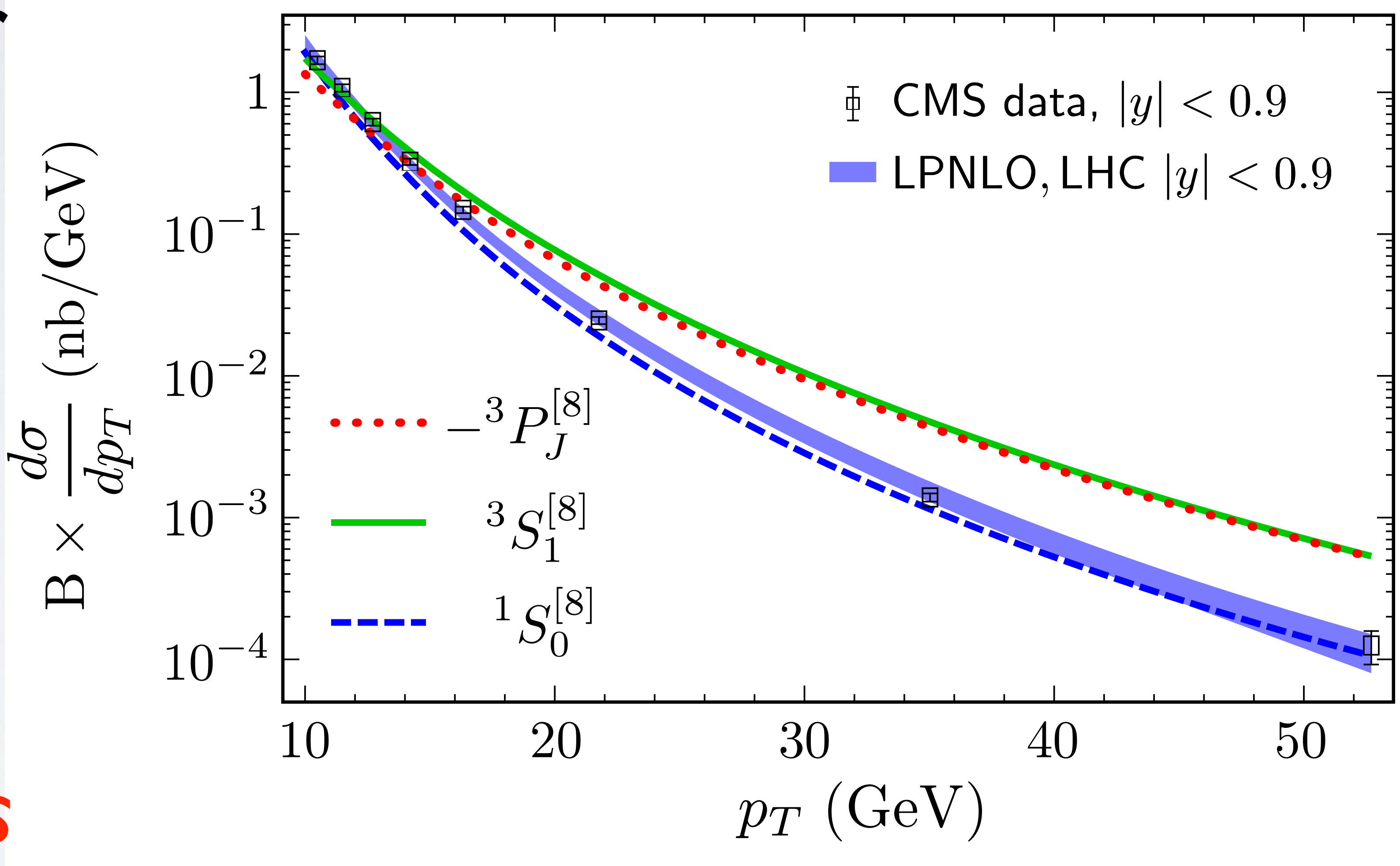
CDF, PRD71, 032001 (2005)
CMS, JHEP02, 011 (2012)
Bodwin, **HSC**, Kim, Lee, PRL113, 022001 (2014)

$\mathrm{B} = \mathrm{Br}[J/\psi \to \mu^+\mu^-]$ $\boldsymbol{\chi^2/\mathrm{d.o.f.} = 0.085}$

J/ψ PRODUCTION

- The data 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 cross section*
- This possibility was first suggested by Chao et al.

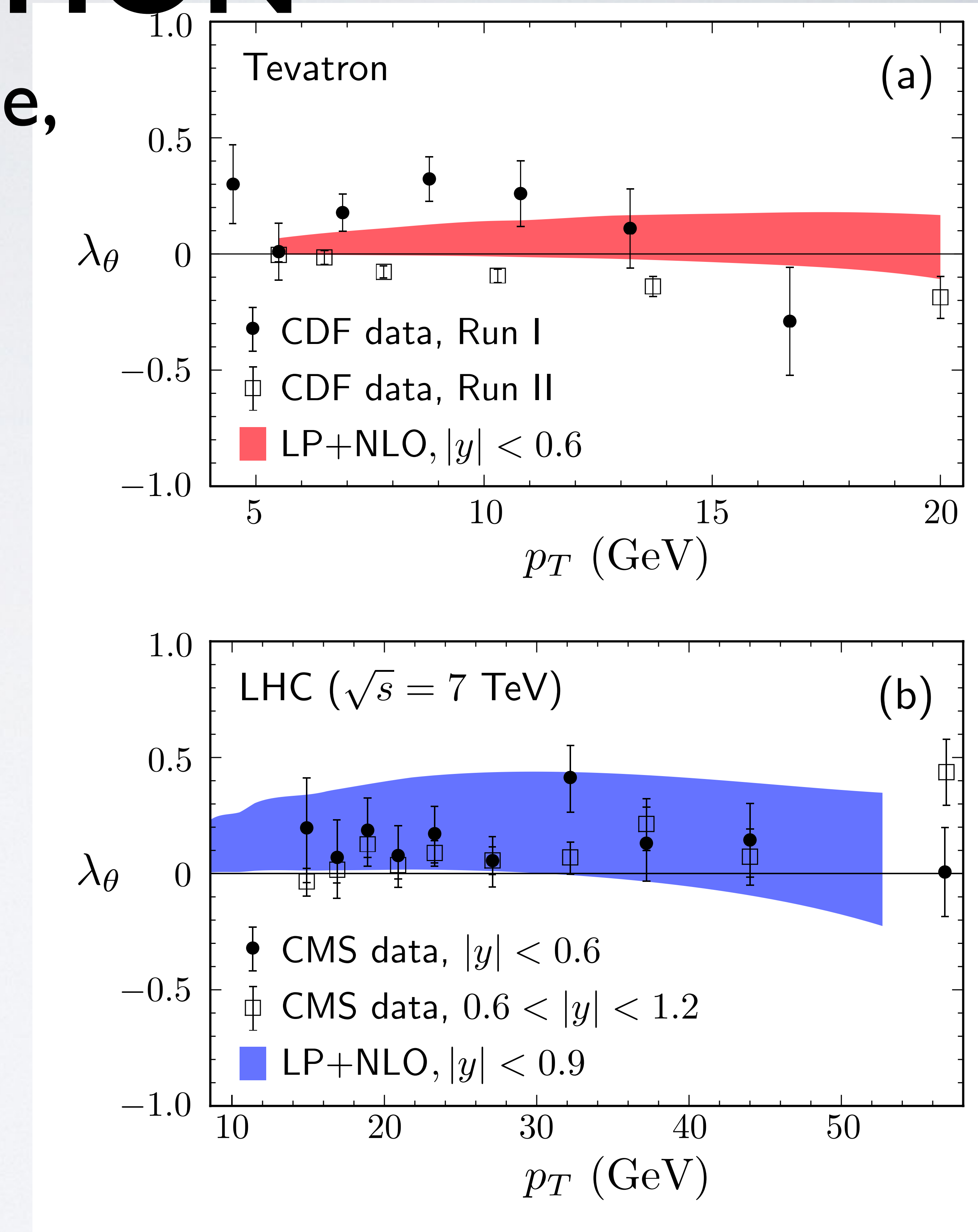
Chao, Ma, Shao, Wang, Zhang, PRL108, 242004 (2012)



- They were able to fit the cross section and polarization simultaneously but could not predict the polarization

J/ψ POLARIZATION

- Because of ${}^1S_0^{[8]}$dominance, J/ψ is almost unpolarized
- **FIRST PREDICTION OF UNPOLARIZED J/ψ IN NRQCD**
  Bodwin, **HSC**, Kim, Lee, PRL113, 022001 (2014)
- This is in *good agreement with CMS* data and much *improved agreement with CDF Run II* data
  CDF, PRL 85, 2886 (2000), PRL99, 132001 (2007)
  CMS, PLB727, 381 (2013)
- *Caveat : feeddown ignored*



PROMPT J/ψ PRODUCTION

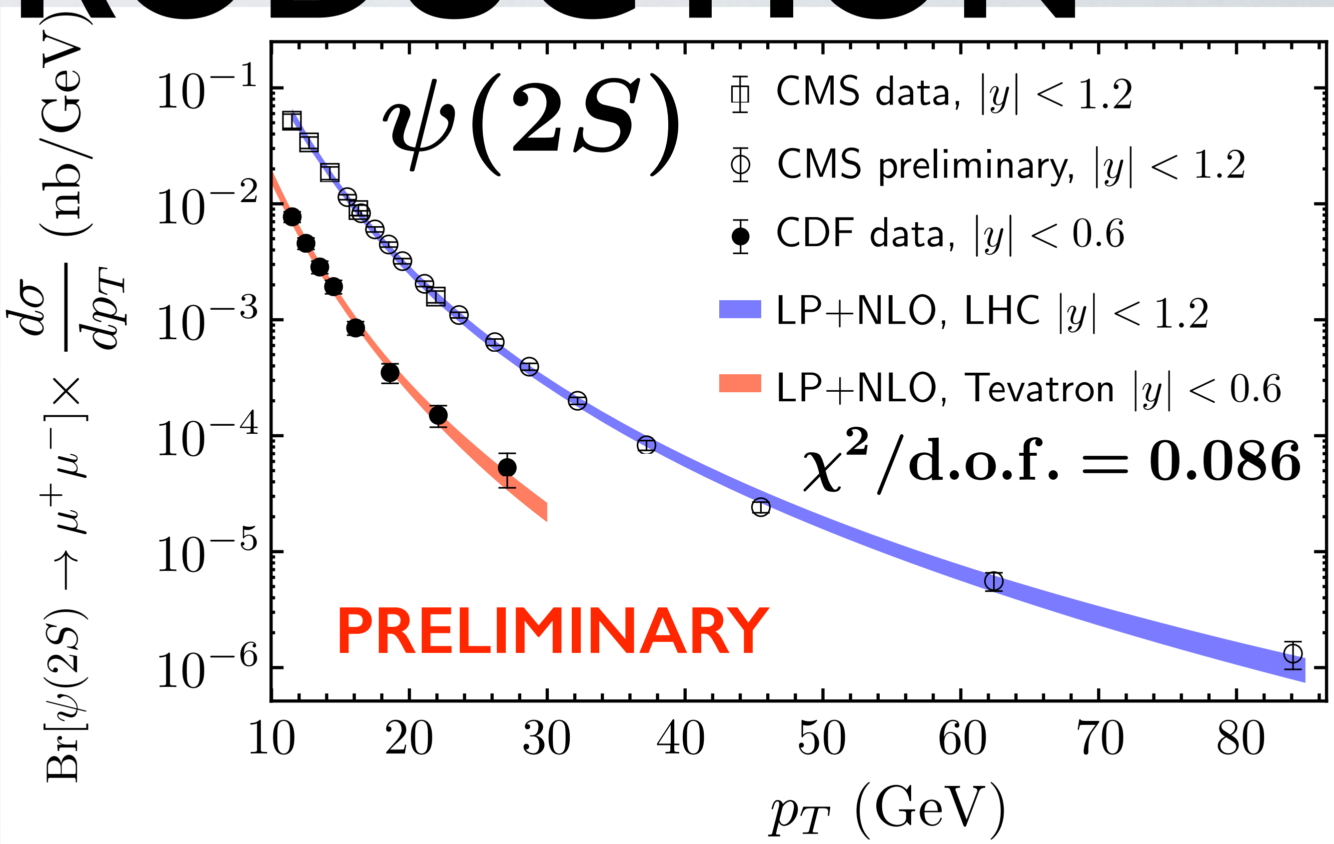
- J/ψ can also be produced from decays of $\psi(2S)$ and χ_{cJ}
- $\psi(2S)$ LDMEs from fit to CMS and CDF cross section data

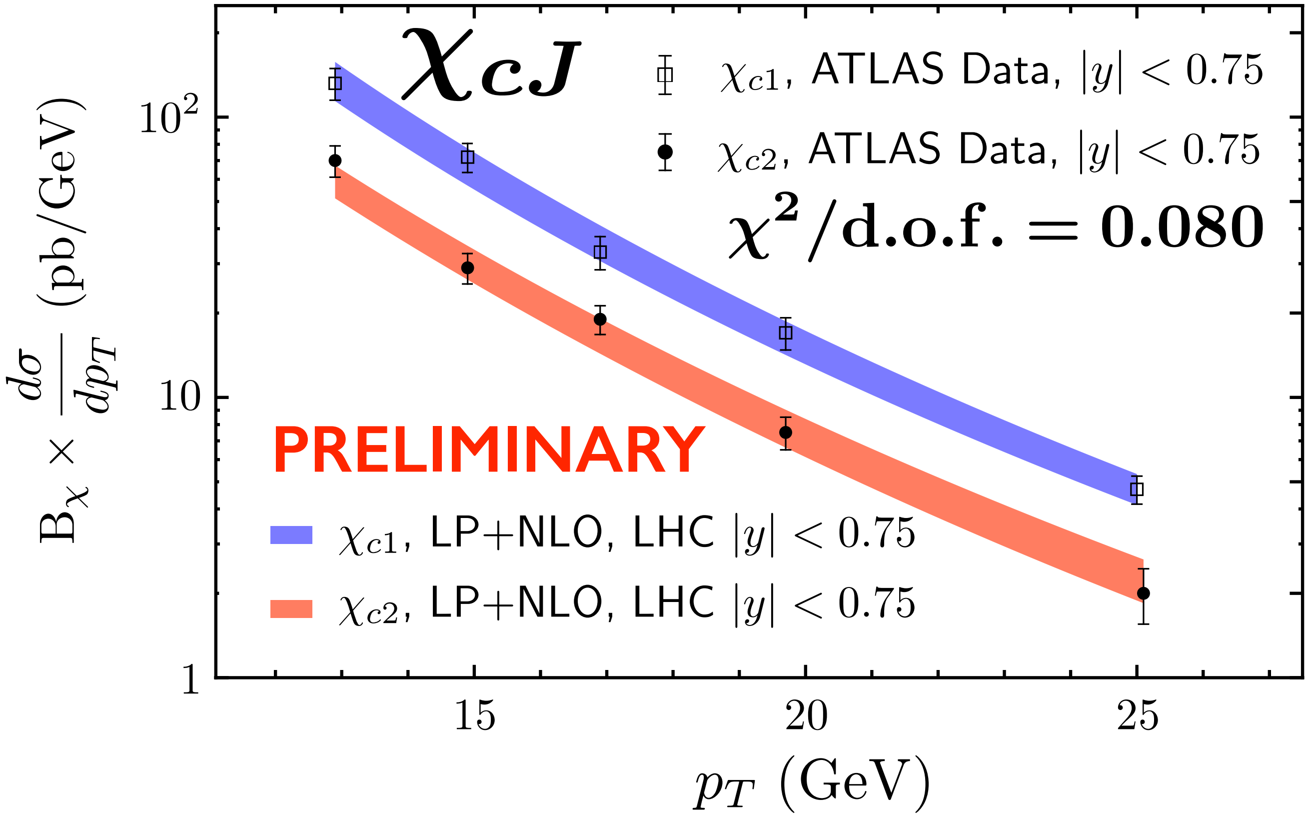
CDF, PRD80, 031103 (2009)
CMS, JHEP02, 011 (2012)
CMS-PAS-BPH-14-001

- χ_{cJ} LDMEs from fit to ATLAS cross section data

ATLAS, JHEP1407, 154 (2014)

- 30% theoretical uncertainty from scale variation

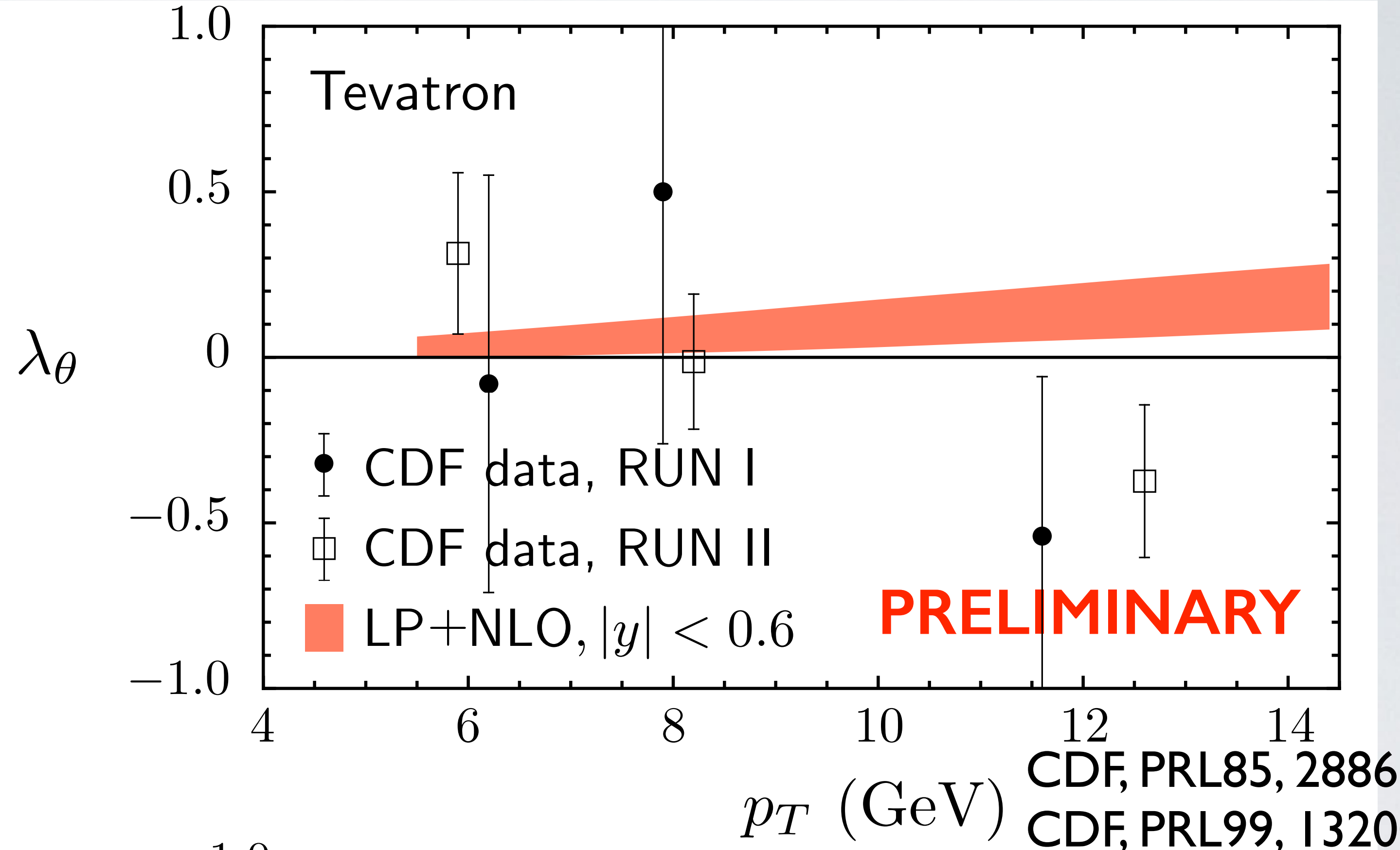




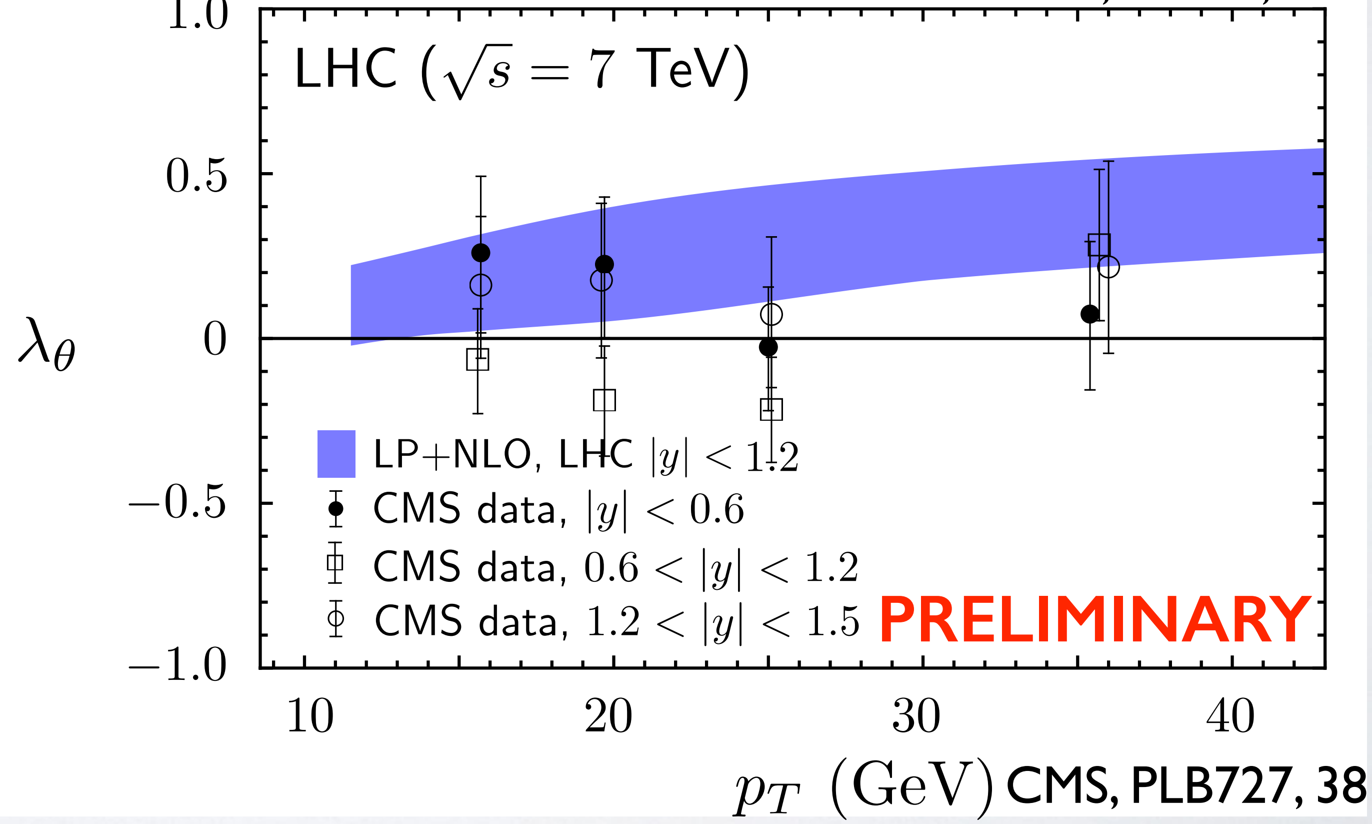
$\text{B}_\chi = \text{Br}[\chi_{cJ} \to J/\psi\gamma] \times \text{Br}[J/\psi \to \mu^+\mu^-]$

$\psi(2S)$ 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



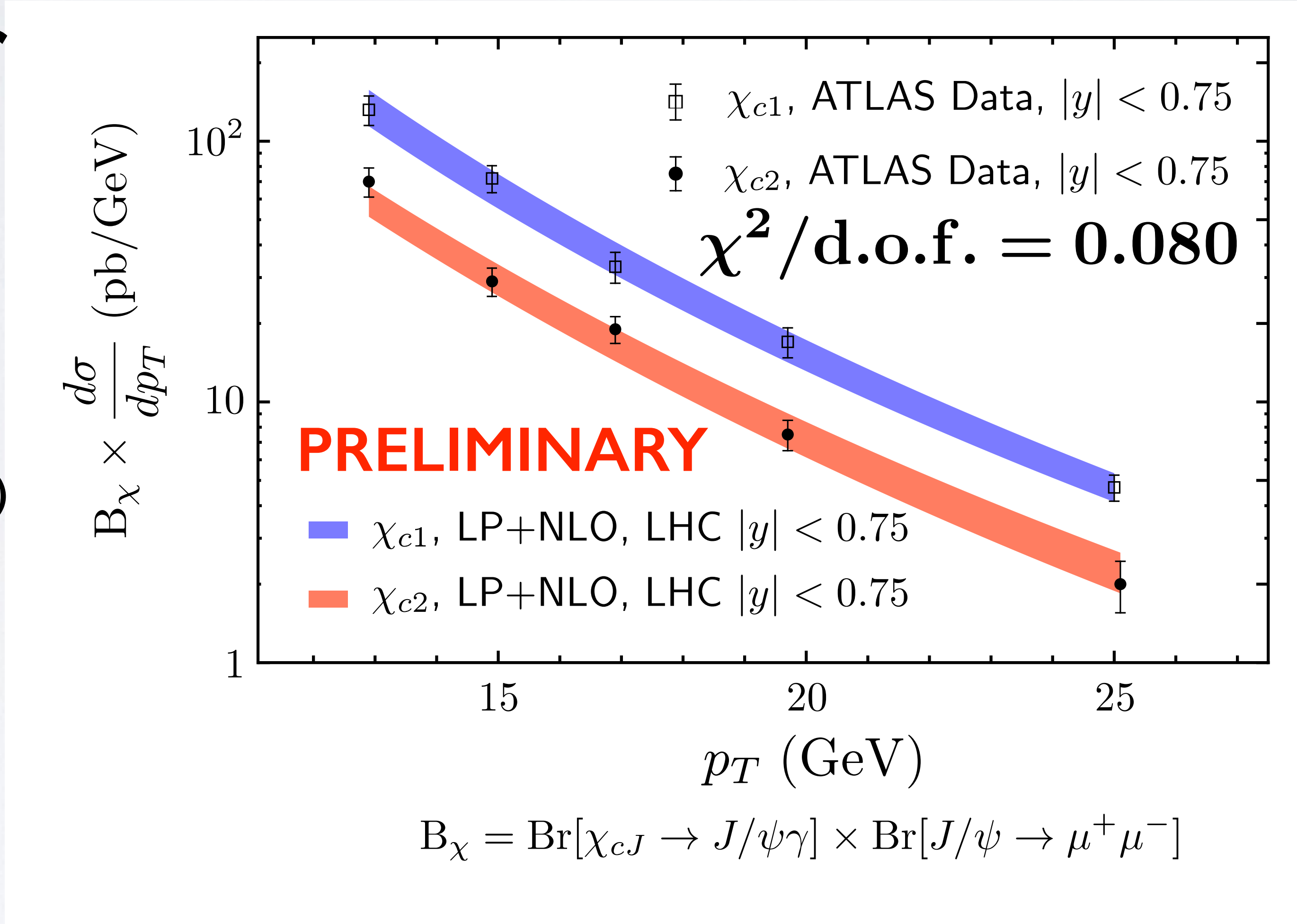
CDF, PRL85, 2886 (2000)
CDF, PRL99, 132001 (2007)



CMS, PLB727, 381 (2013)

χ_{cJ} 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



$\mathrm{B}_\chi = \mathrm{Br}[\chi_{cJ} \to J/\psi\gamma] \times \mathrm{Br}[J/\psi \to \mu^+\mu^-]$

Potential model

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

Eichten and Quigg, PRD 52, 1726 (1995)

Our fit

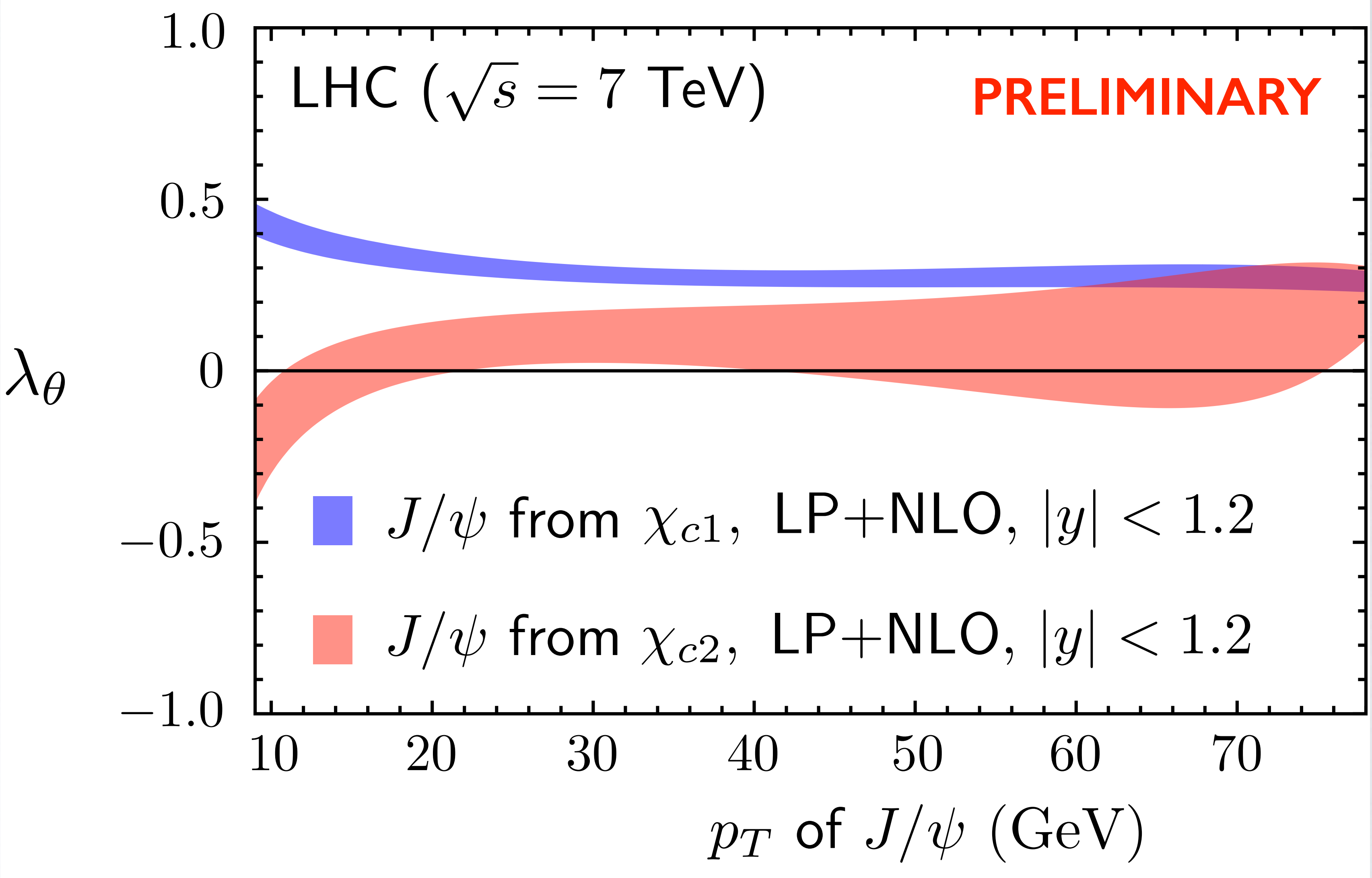
$$|R'(0)|^2 = 0.055 \pm 0.025 \text{ GeV}^5$$

→***Suggests that NRQCD factorization works***

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)



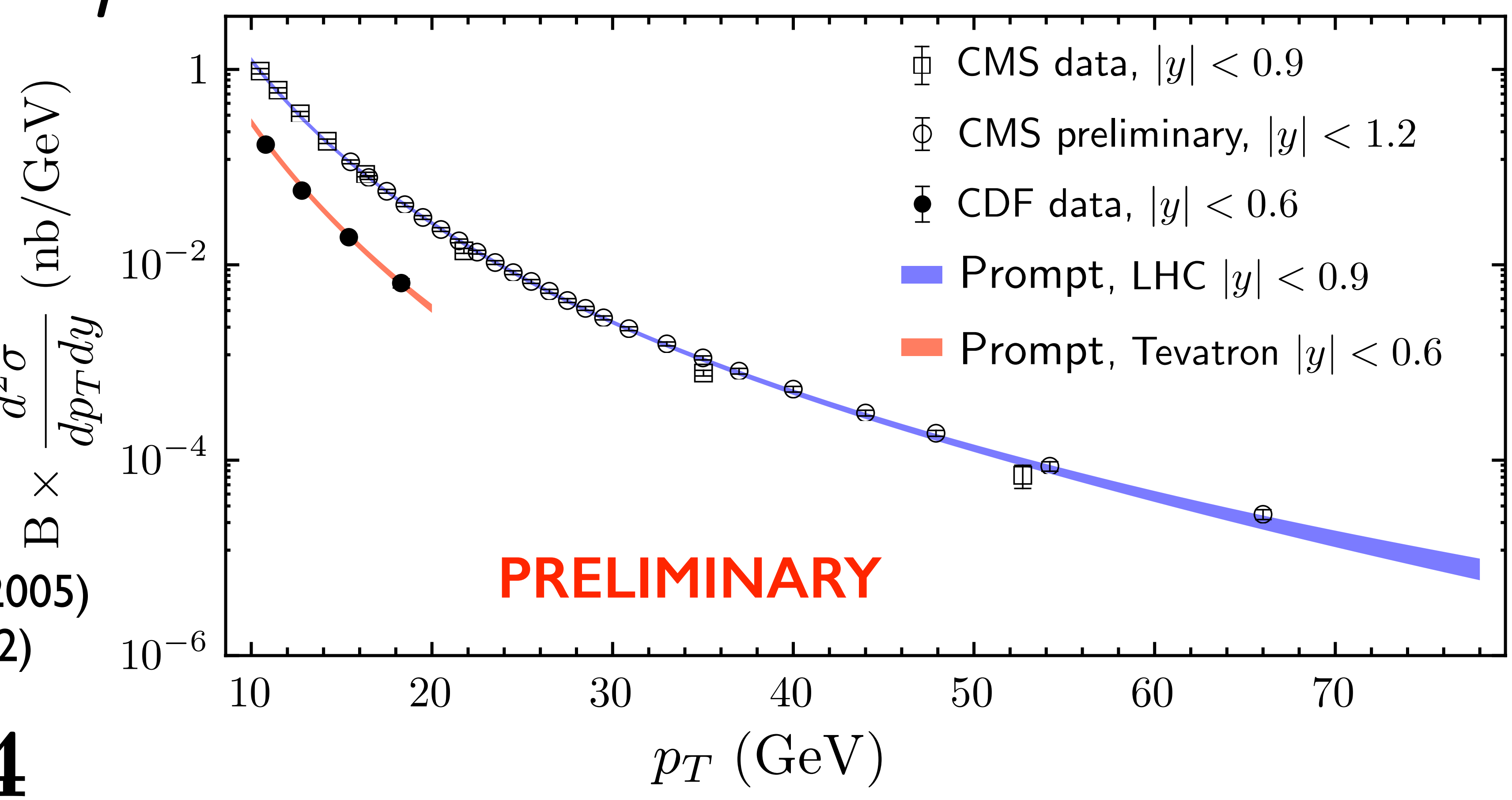
Faccioli, Lourenco, Seixas, and Wohri, PRD83, 096001 (2011)

PROMPT J/ψ PRODUCTION

- After including feeddown contributions, we again obtain good fits

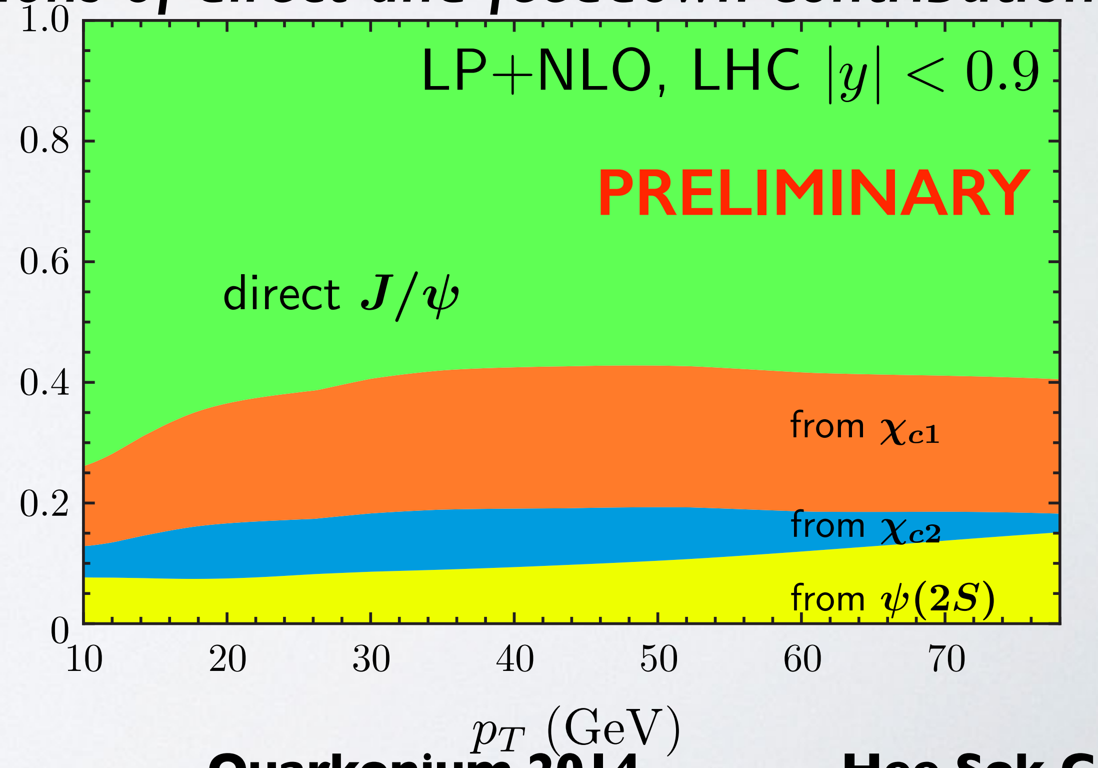
$$\chi^2/\mathrm{d.o.f.} = 0.44$$

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



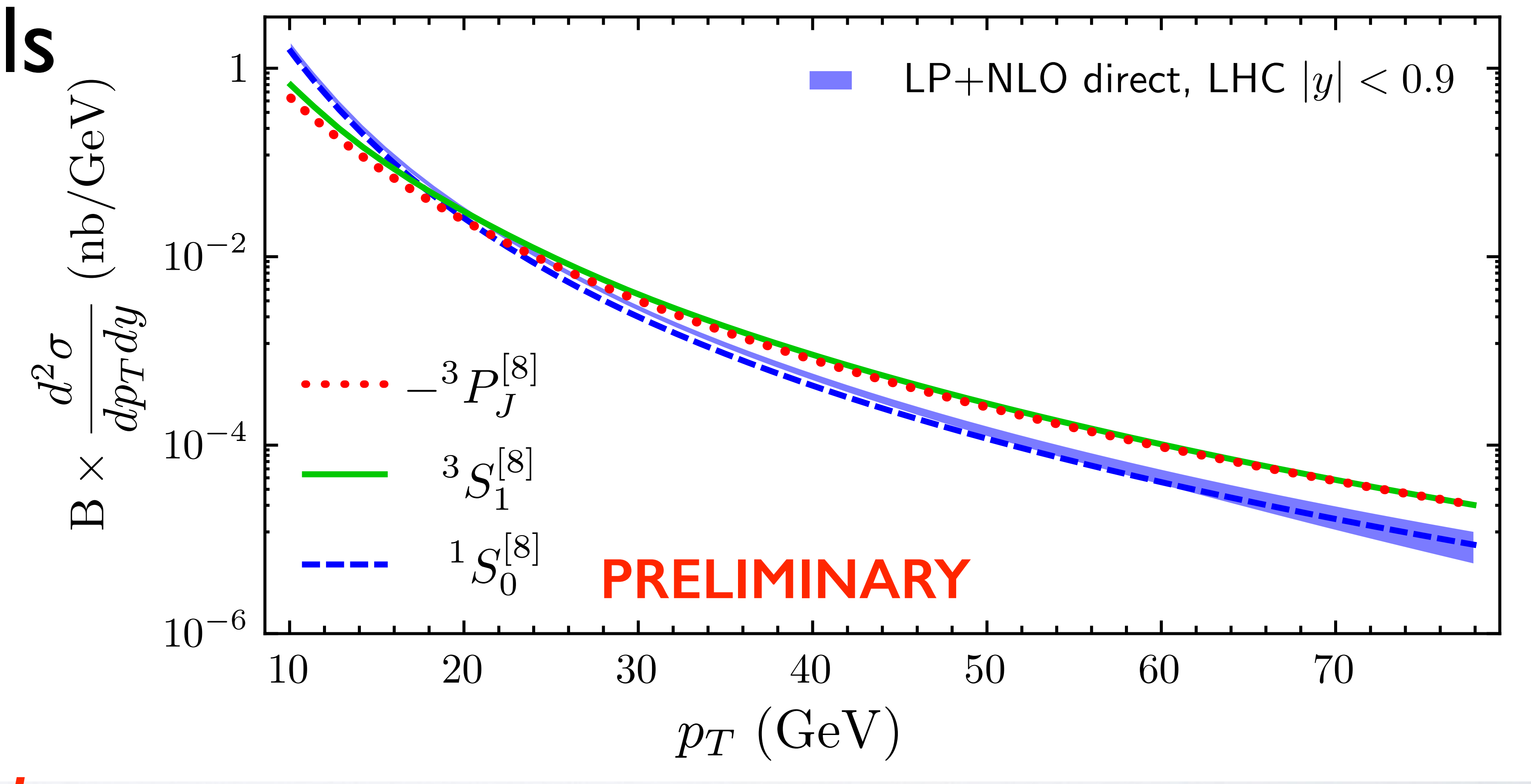
CDF, PRD71, 032001 (2005)
CMS, JHEP02, 011 (2012)
CMS-PAS-BPH-14-001

Fractions of direct and feeddown contributions



PROMPT J/ψ PRODUCTION

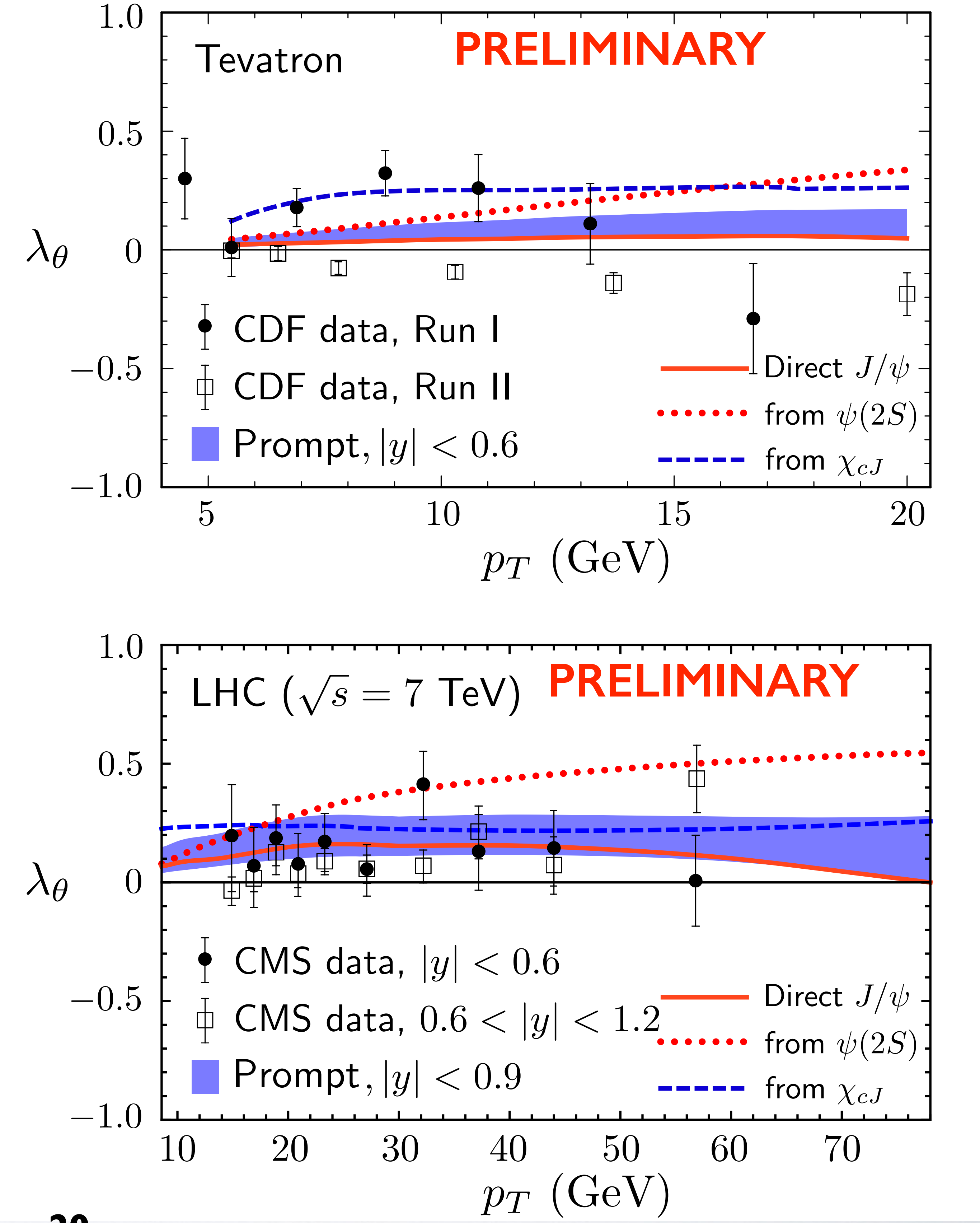
- The direct cross section falls off faster than $^3S_1^{[8]}$ and $^3P_J^{[8]}$ channels
- The fit constrains the $^3S_1^{[8]}$ and $^3P_J^{[8]}$ channels to cancel
- *$^1S_0^{[8]}$ channel dominates the direct cross section*



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

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, as well as other quarkonium states is in progress