J/ψ PRODUCTION AT HADRON COLLIDERS

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Based on
Geoffrey T. Bodwin, **HSC**, U-Rae Kim, Jungil Lee, PRL113, 022001 (2014)
Geoffrey T. Bodwin, HSC, U-Rae Kim, Jungil Lee, Yan-Qing Ma, Kuang-Ta Chao, in preparation

OUTLINE

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

HEAVY QUARKONIUM

- Bound states of a heavy quark and a heavy antiquark :
  e.g. J/ψ, ψ', η_c, h_c, χ_{cJ}, $\Upsilon(nS)$, η_b, χ_{bJ} ...
- $2m_b > 2m_c \gg \Lambda_{\rm QCD}$
- $m_{J/\psi} \approx m_{\eta_c} \approx 2m_c,\ m_{\Upsilon(1S)} \approx m_{\eta_b} \approx 2m_b,$
  which allow nonrelativistic description :
  $v^2 \approx 0.3$ for charmonia, $v^2 \approx 0.1$ for bottomonia
- Typical energy scales $m > mv > mv^2 \approx \Lambda_{\rm QCD}$,
  Ideal for studying interplay between perturbative and nonperturbative physics

HEAVY QUARKONIUM

- Quark model assignments of some heavy quarkonia

	Spin Triplet	Spin Singlet
S-wave	$J/\psi\,,\psi'$	η_c
P-wave	χ_{cJ}	h_c

Charmonia

	Spin Triplet	Spin Singlet
S-wave	$\Upsilon(nS)$	η_b
P-wave	χ_{bJ}	h_b

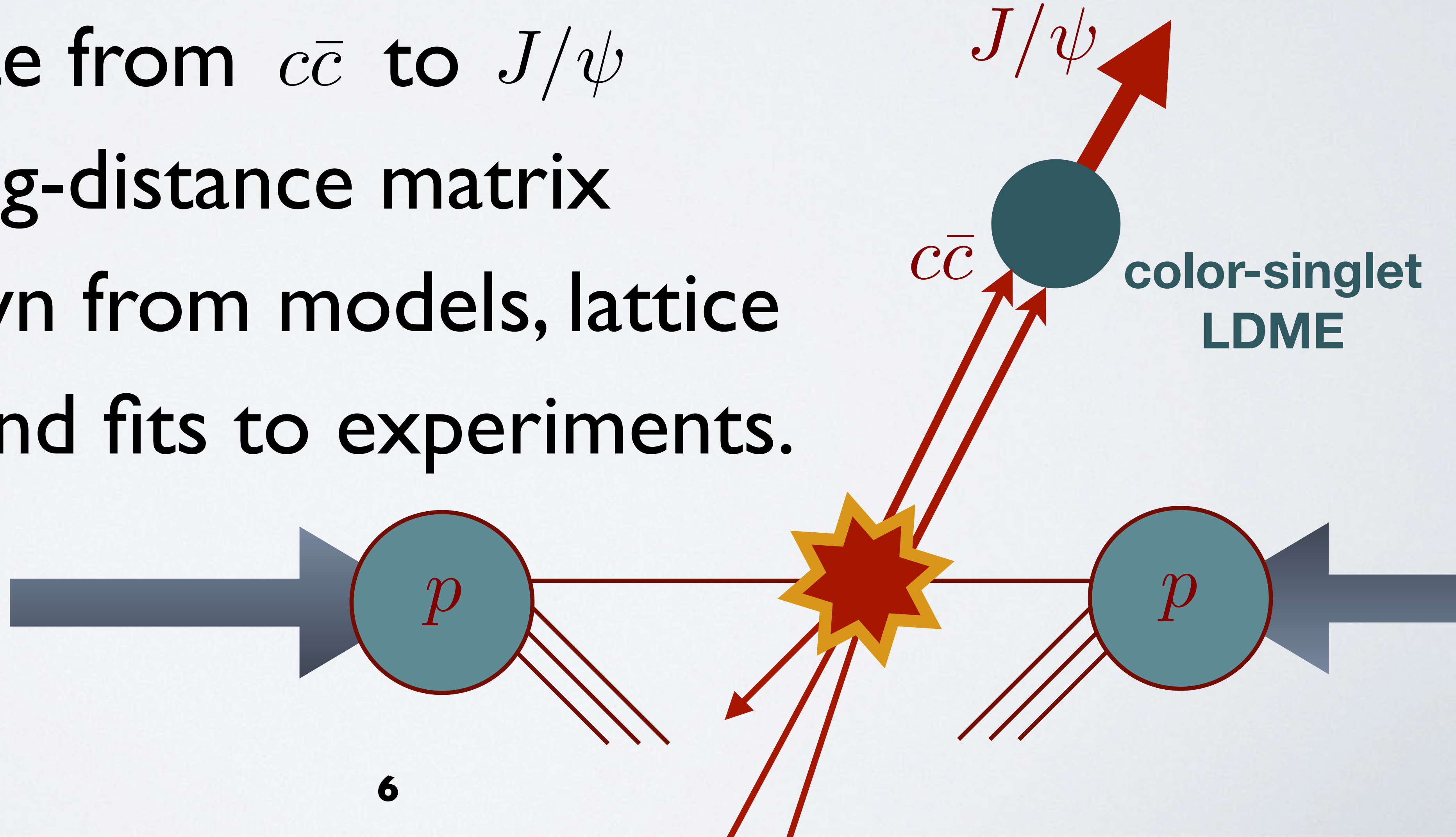
Bottomonia

INCLUSIVE J/ψ PRODUCTION

- The p_T-differential cross section has been measured at hadron colliders like RHIC, Tevatron and the LHC.
- J/ψ is usually identified from its leptonic decay.
- Large contributions from B hadron decays are subtracted to yield the "prompt" cross section, which includes contributions from direct production and from decays of heavier charmonia

INCLUSIVE J/ψ PRODUCTION

- Color-singlet model (CSM) :
  A $c\bar{c}$ pair with same spin, color and C P T is created in the hard process, which evolves in to the J/ψ.
  The universal rate from $c\bar{c}$ to J/ψ (color-singlet long-distance matrix element) is known from models, lattice measurements, and fits to experiments.

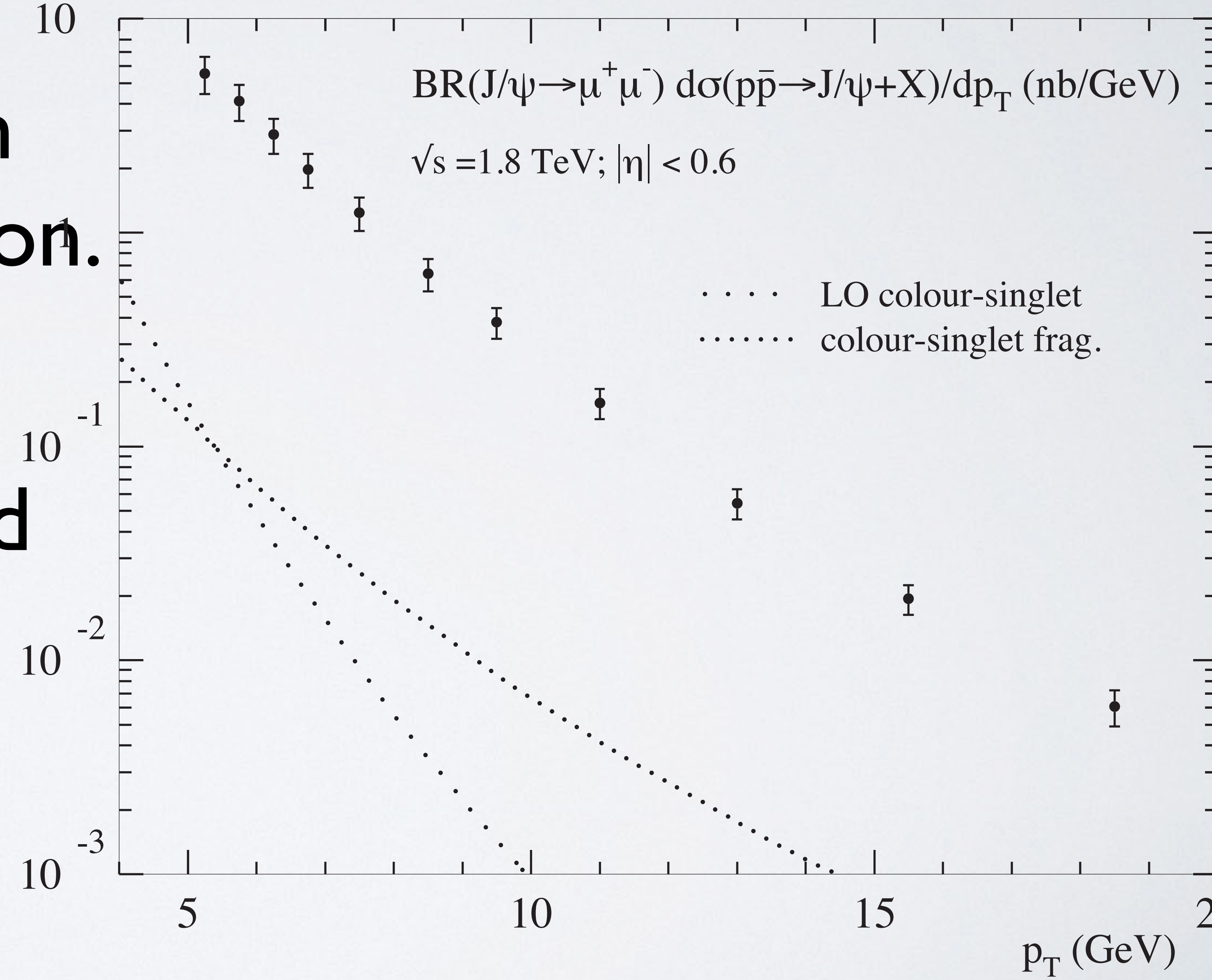


INCLUSIVE J/ψ PRODUCTION

- CSM is incomplete :
  - A color-octet (CO) $c\bar{c}$ pair can evolve into a color singlet meson by emitting soft gluons.
  - In the effective theory nonrelativistic QCD, CO LDMEs are suppressed by powers of v .
  - In many cases, color-octet channels are necessary :
  - For S-wave vector quarkonia ($J/\psi, \psi(2S), \Upsilon(nS)$), CSM severely underestimates the cross section.
  - For production or decay of P-wave quarkonia (χ_{cJ}, χ_{bJ}), CS channel contains IR divergences that can be cancelled only when the CO channels are included.

INCLUSIVE J/ψ PRODUCTION

- CSM prediction vs. measurement at Tevatron
- LO CSM ($\sim 1/p_T^8$) is inconsistent with both shape and normalization.
- Radiative corrections are larger than LO and has different shape ($\sim 1/p_T^4$), but still not large enough



INCLUSIVE J/ψ PRODUCTION

- NRQCD can be used to describe the physics of scales smaller than the quarkonium mass.
- NRQCD factorization conjecture for production of H

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

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

- Short-distance cross sections are essentially the production cross section of $Q\bar{Q}$ that can be computed using perturbative QCD
- The LDMEs are nonperturbative quantities that correspond to the rate for the $Q\bar{Q}$ to evolve into H
- LDMEs have known scaling with v

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

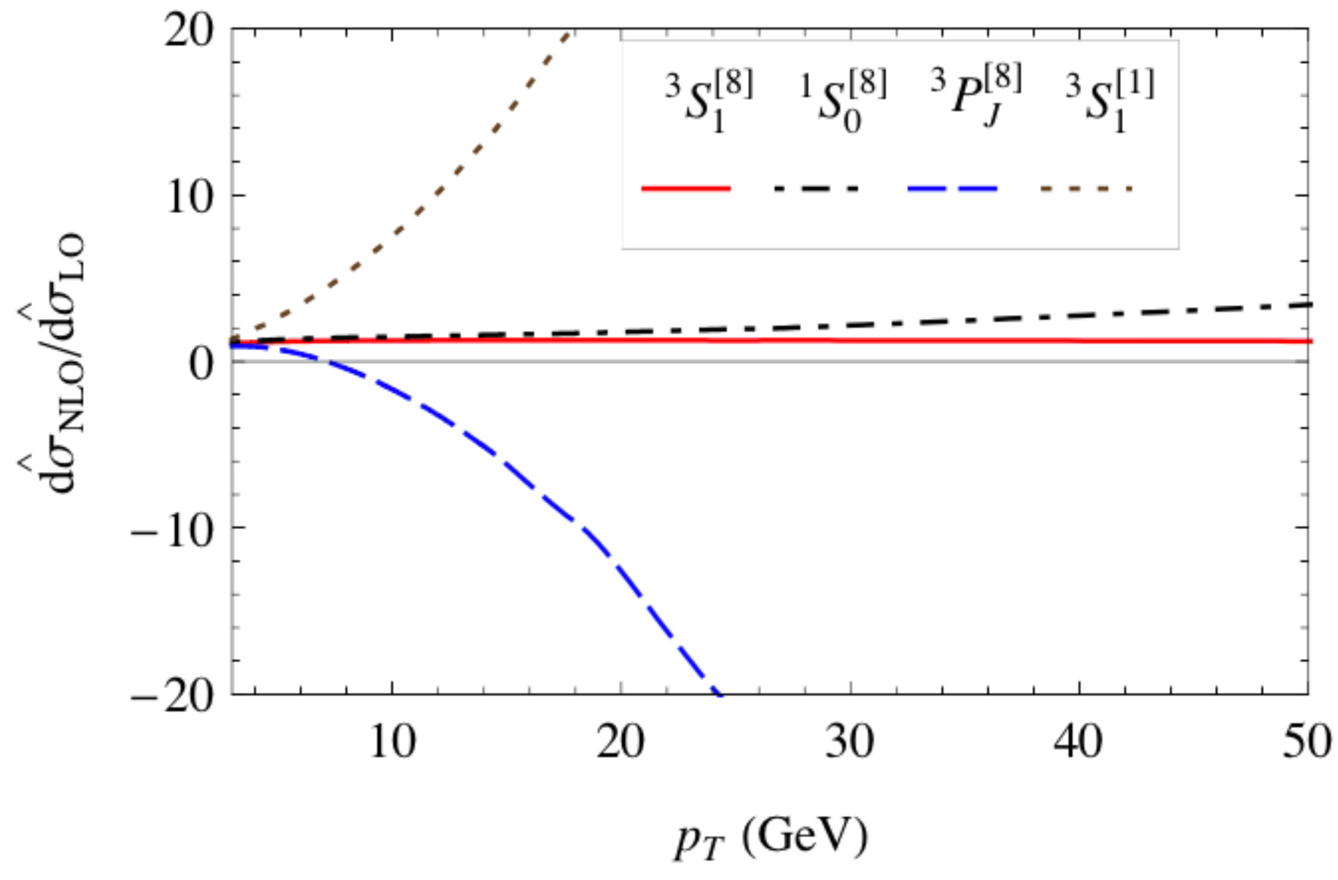
- The short-distance cross sections have been computed to NLO in α_s by three groups :

  Kuang-Ta Chao's group (PKU) : Ma, Wang, Chao, Shao, Wang, Zhang
  Bernd Kniehl's group (Hamburg) : Butenschön, Kniehl
  Jianxiong Wang's group (IHEP) : Gong, Wan, Wang, Zhang

- It is not known how to calculate color-octet LDMEs, and are usually extracted from measurements

INCLUSIVE J/ψ PRODUCTION

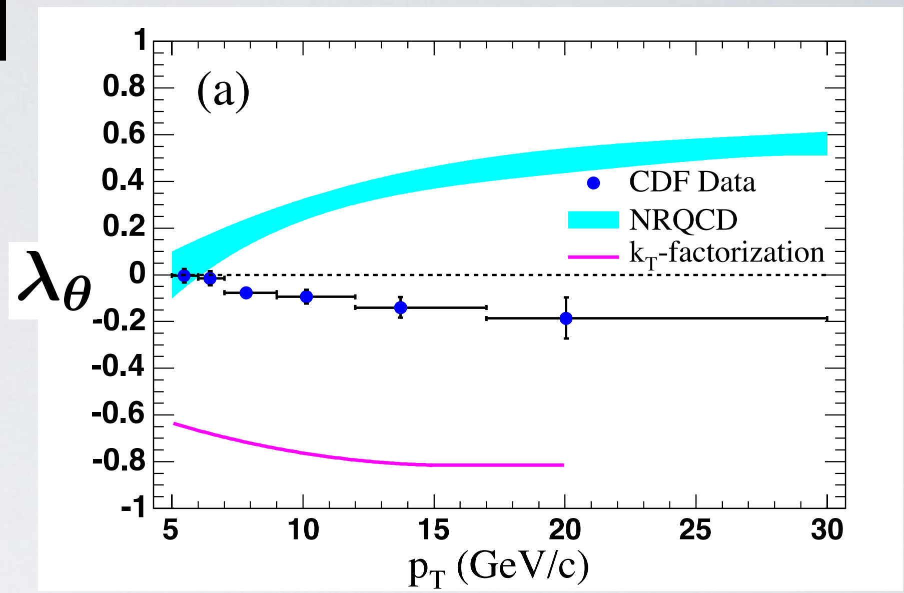
- In order to extract CO LDMEs from measured cross sections we need to determine the short-distance cross sections as functions of p_T
- NLO corrections give large K-factors that rise with p_T; this casts doubt on the reliability of perturbation theory



Ma, Wang, Chao, PRL106, 042002 (2011)

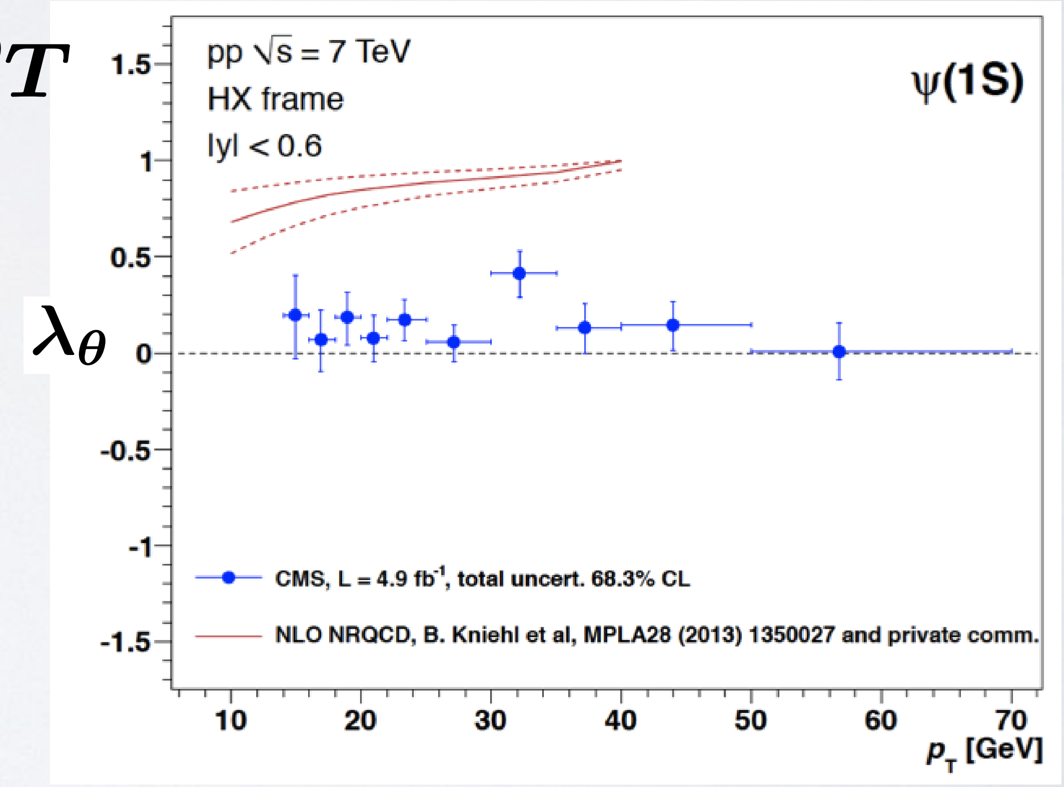
J/ψ POLARIZATION PUZZLE

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



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
- NRQCD at NLO still predicts transverse polarization



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)

Parton production cross sections

Fragmentation Functions

$$\frac{d\sigma}{dp_T^2}[ij \to c\bar{c} + X]$$
$$= \sum_k \int_0^1 dz \frac{d\sigma}{dp_T^2}[ij \to k + X] D[k \to c\bar{c} + X] + O(m_c^2/p_T^6)$$

z : **fraction of momentum transferred from parton k to hadron**

i, j, k **run over quarks, antiquarks, and gluon**

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

FRAGMENTATION FUNCTIONS

- Fragmentation functions (FFs) for production of $c\bar{c}$ can be computed using perturbative QCD

Collins and Soper, NPB194, 445 (1982)

- A gluon can produce a $c\bar{c}$ pair in ${}^3S_1^{[8]}$ state directly : gluon FF for this channel starts at order α_s, involves a delta function at $z = 1$

- A gluon can produce a $c\bar{c}$ in ${}^3P_J^{[8]}$ state by emitting a soft gluon : gluon FF for this channel starts at order α_s^2, involves distributions singular at $z = 1$

- A gluon can produce a $c\bar{c}$ in ${}^1S_0^{[8]}$ state by emitting a gluon : gluon FF for this channel starts at order α_s^2, does not involve divergence at order α_s^2

FRAGMENTATION FUNCTIONS

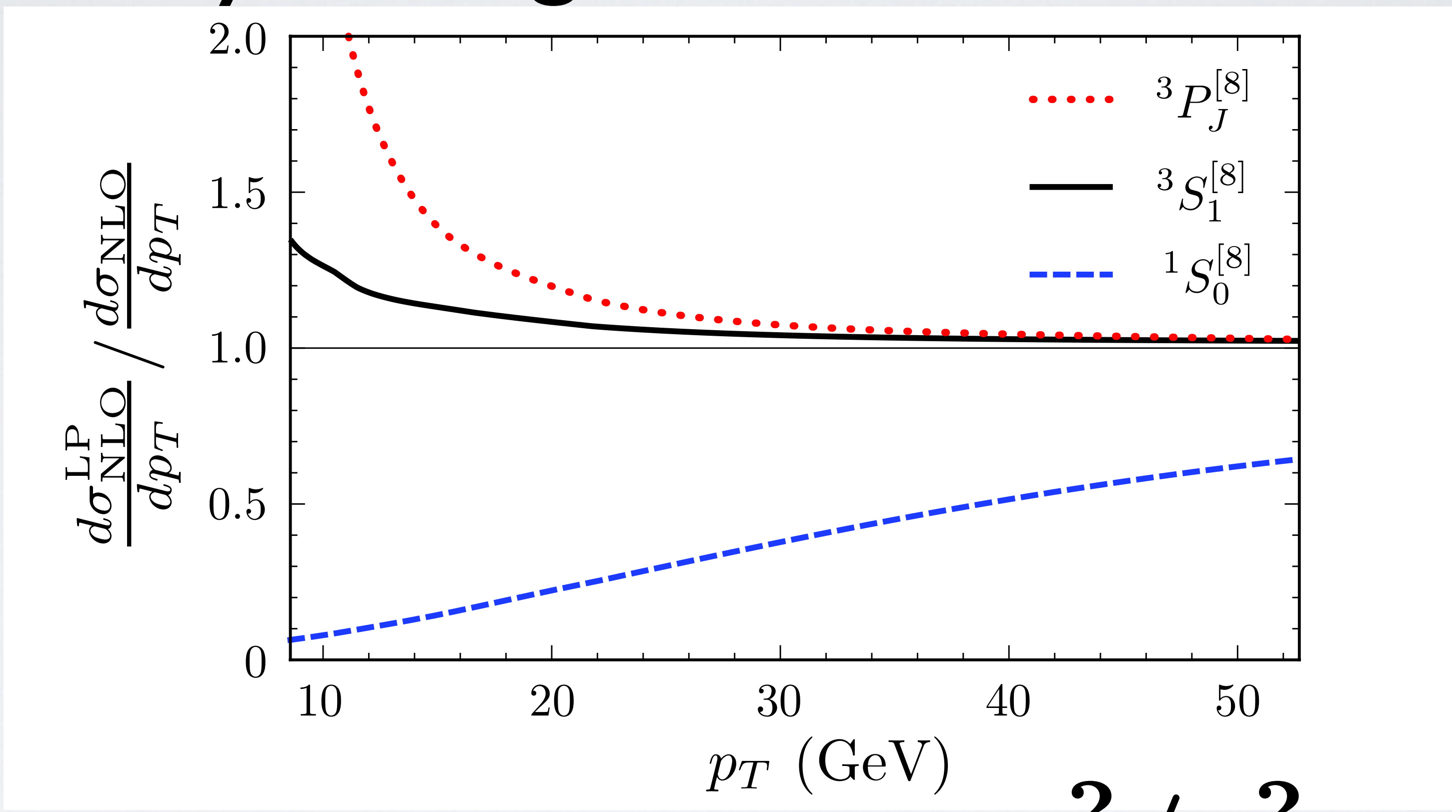
- For the $^{3}S_{1}^{[8]}$ and $^{3}P_{J}^{[8]}$ channels, gluon polarization is transferred to the $c\bar{c}$ pair, and therefore the $c\bar{c}$ is mostly transverse.
- For the $^{1}S_{0}^{[8]}$ channel, the $c\bar{c}$ is unpolarized because it is isotropic.

LP FRAGMENTATION

- LP fragmentation explains the large, p_T-dependent K-factors that appear in fixed-order calculations
- ${}^3S_1^{[8]}$ 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

- We combine the LP fragmentation contributions with fixed-order NLO calculations to include corrections of relative order m_c^2/p_T^2

fixed-order calculation to NLO

LP fragmentation to NLO accuracy

$$\frac{d\sigma^{\mathrm{LP+NLO}}}{dp_T} = \frac{d\sigma^{\mathrm{LP}}}{dp_T} + \frac{d\sigma_{\mathrm{NLO}}}{dp_T} - \frac{d\sigma^{\mathrm{LP}}_{\mathrm{NLO}}}{dp_T}$$

LP fragmentation resummed leading logs

corrections of relative order m_c^2/p_T^2

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

LP+NLO

- Alternatively, one can consider the LP fragmentation to supplement the fixed-order NLO calculation

LP fragmentation resummed leading logs

LP fragmentation to NLO accuracy

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

fixed-order calculation to NLO

Additional fragmentation contributions

LP CONTRIBUTIONS THAT WE COMPUTE

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

Fragmentation functions (columns) / **Parton production cross sections** (rows)

	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 (columns)

	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 resume 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)
- Corrections to LP contributions give "normal" K-factors ($\lesssim 2$)

RESUMMATION OF LEADING LOGARITHMS

- The leading logarithms can be resummed to all orders by solving the LO DGLAP equation

$$\frac{d}{d\log\mu_f^2}\begin{pmatrix}D_S\\ D_g\end{pmatrix}=\frac{\alpha_s(\mu_f)}{2\pi}\begin{pmatrix}P_{qq} & 2n_f P_{gq}\\ P_{qg} & P_{gg}\end{pmatrix}\otimes\begin{pmatrix}D_S\\ D_g\end{pmatrix}$$

$$D_S=\sum_q(D_q+D_{\bar{q}})$$

- This equation is diagonalized in Mellin space; the inverse transform can then be carried out numerically
- Because the FFs are singular at the endpoint, the inversion is divergent at $z=1$; special attention is needed for contribution at $z\approx 1$

RESUMMATION OF LEADING LOGARITHMS

- We split the z integral :

$$\int_0^1 dz\,\hat{\sigma}(z)D(z) = \int_0^{1-\epsilon} dz\,\hat{\sigma}(z)D(z) + \int_{1-\epsilon}^1 dz\,\hat{\sigma}(z)D(z)$$

$$\approx \int_0^{1-\epsilon} dz\,\hat{\sigma}(z)D(z) + \hat{\sigma}(z=1)\int_{1-\epsilon}^1 dz\,z^N D(z)$$

- N is chosen so that $\hat{\sigma}(z) \approx \hat{\sigma}(1)z^N$ near $z \approx 1$

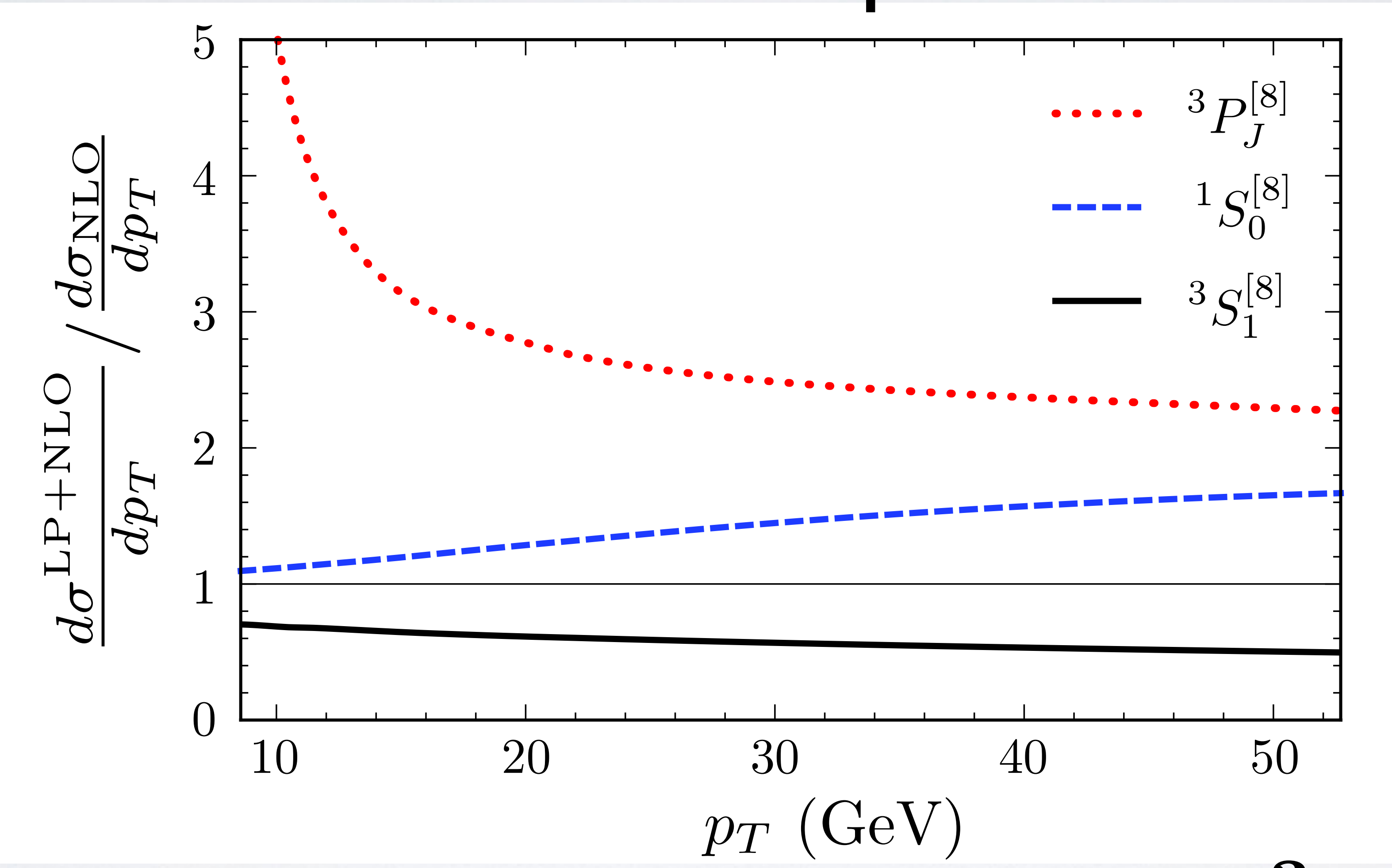
$$\int_{1-\epsilon}^1 dz\,z^N D(z) = \int_0^1 dz\,z^N D(z) - \int_0^{1-\epsilon} dz\,z^N D(z)$$

Well defined in Mellin space (Mellin transform of D(z))

Well behaved numerically

LP+NLO

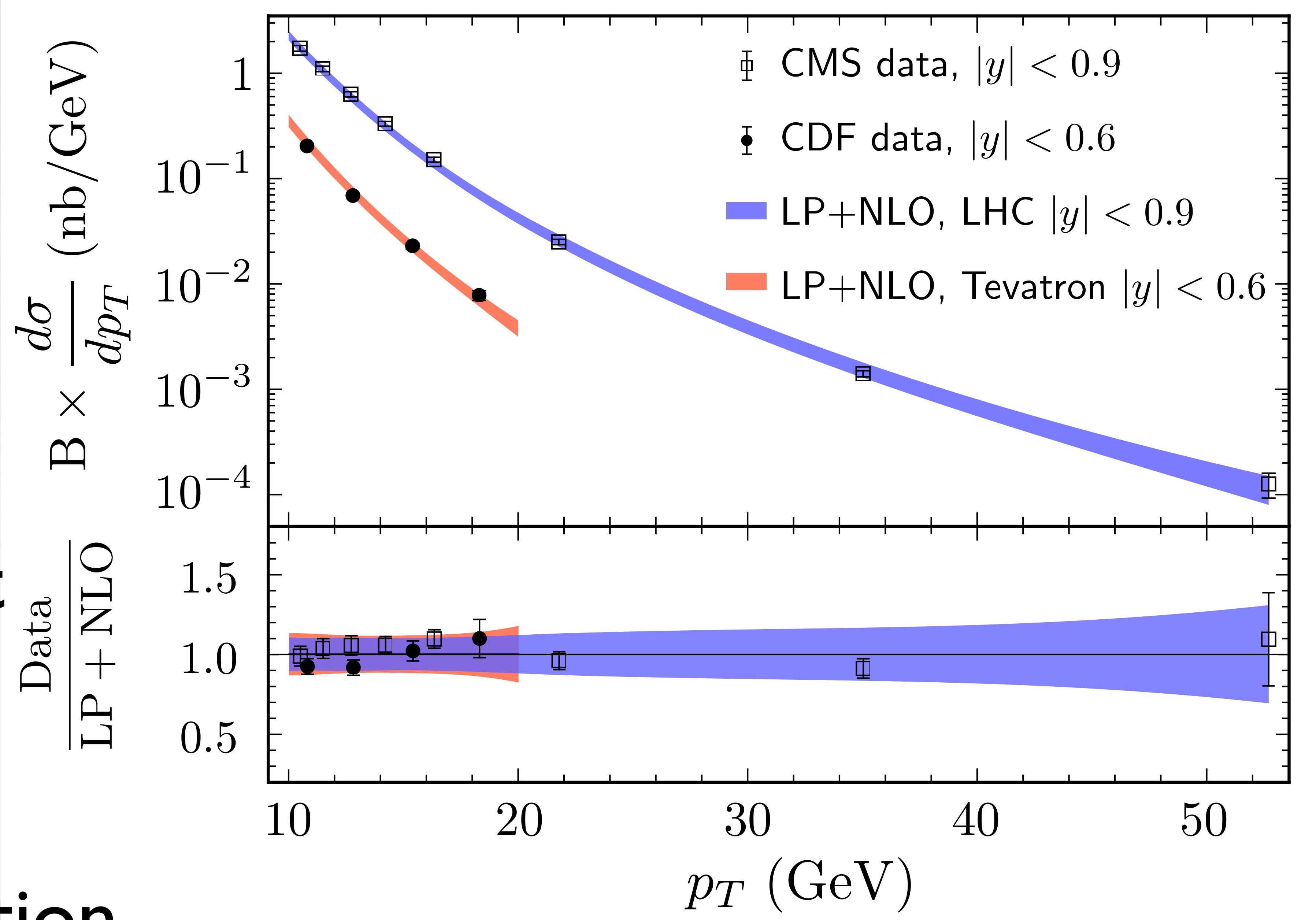
- The additional fragmentation contributions have important effects on the shapes in the ${}^3P_J^{[8]}$ channel



- 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



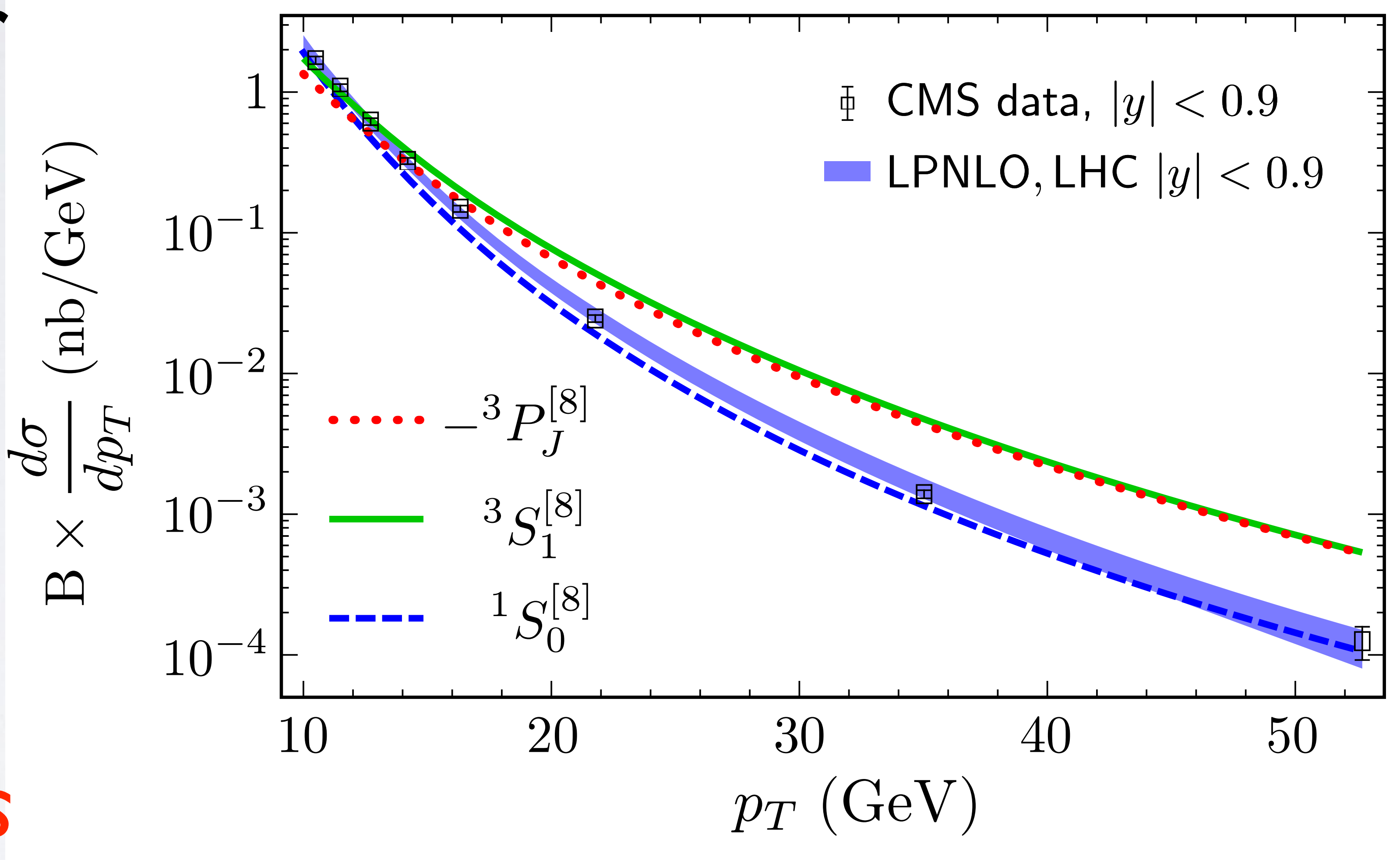
CDF, PRD71, 032001 (2005)
CMS, JHEP02, 011 (2012)
Bodwin, **HSC**, Kim, Lee, PRL113, 022001 (2014)

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

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)



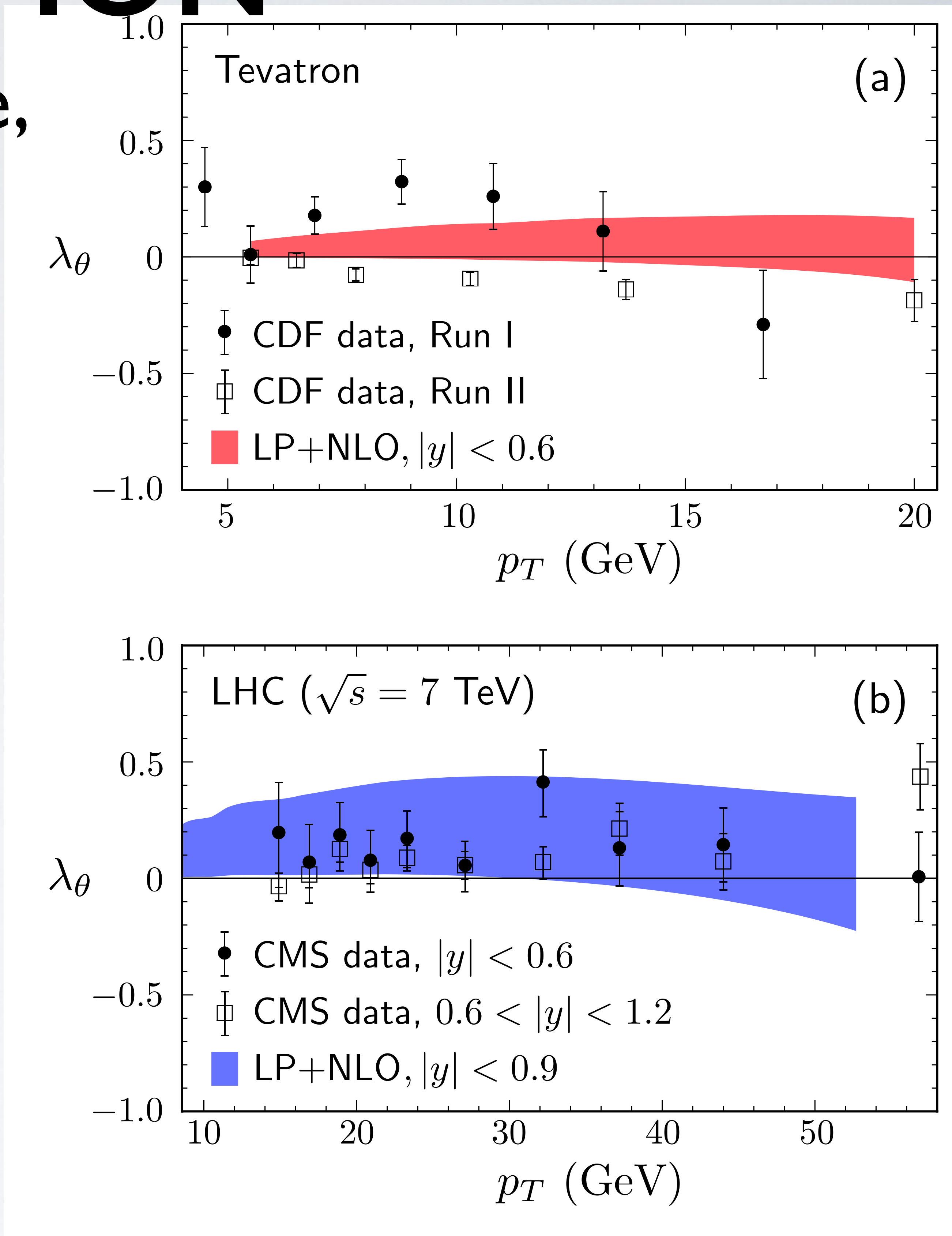
$$\langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]}) \rangle = 0.099 \pm 0.022 \text{ GeV}^3$$

$$\langle \mathcal{O}^{J/\psi}({}^3S_1^{[8]}) \rangle = 0.011 \pm 0.010 \text{ GeV}^3$$

$$\langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]}) \rangle = 0.011 \pm 0.010 \text{ GeV}^5$$

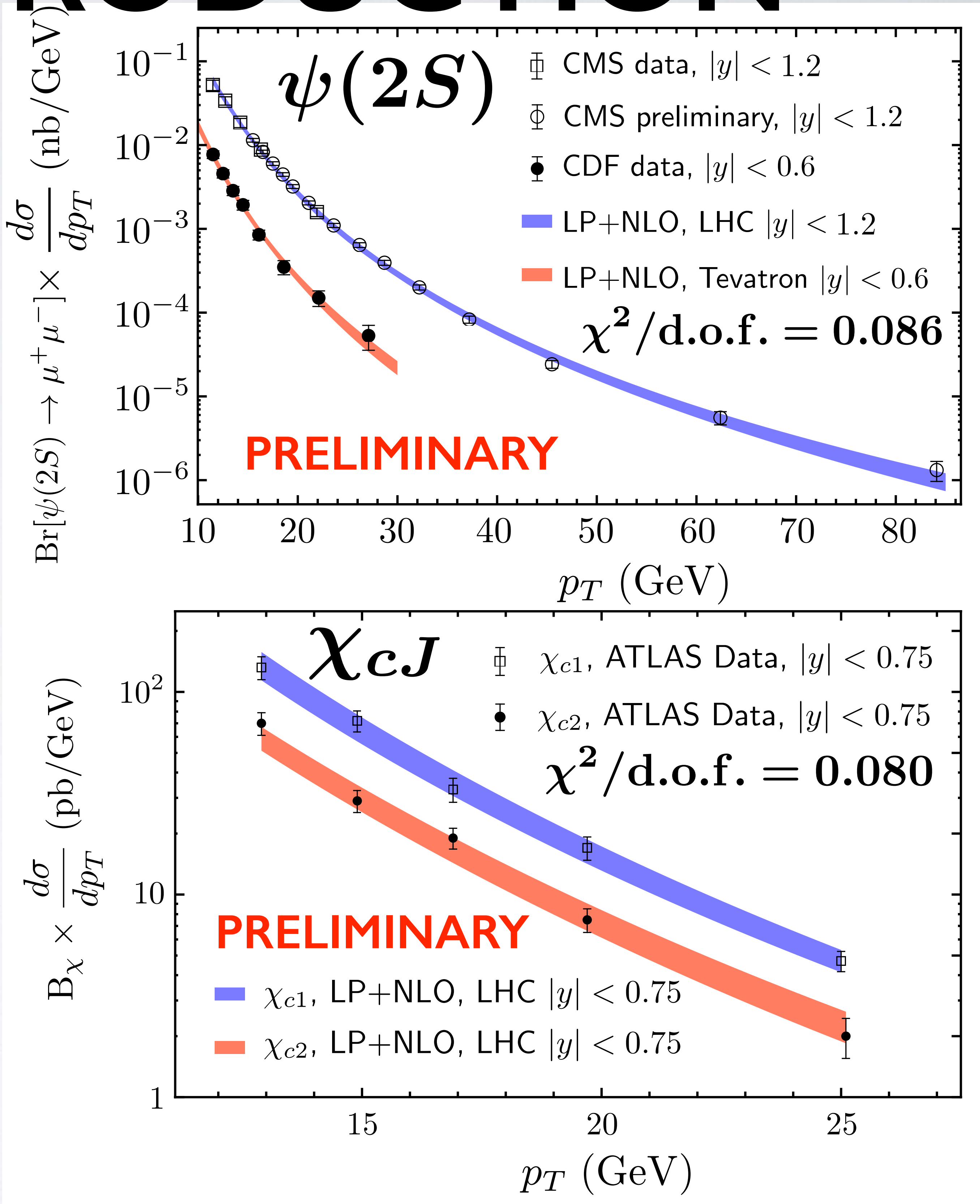
J/ψ POLARIZATION

- 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

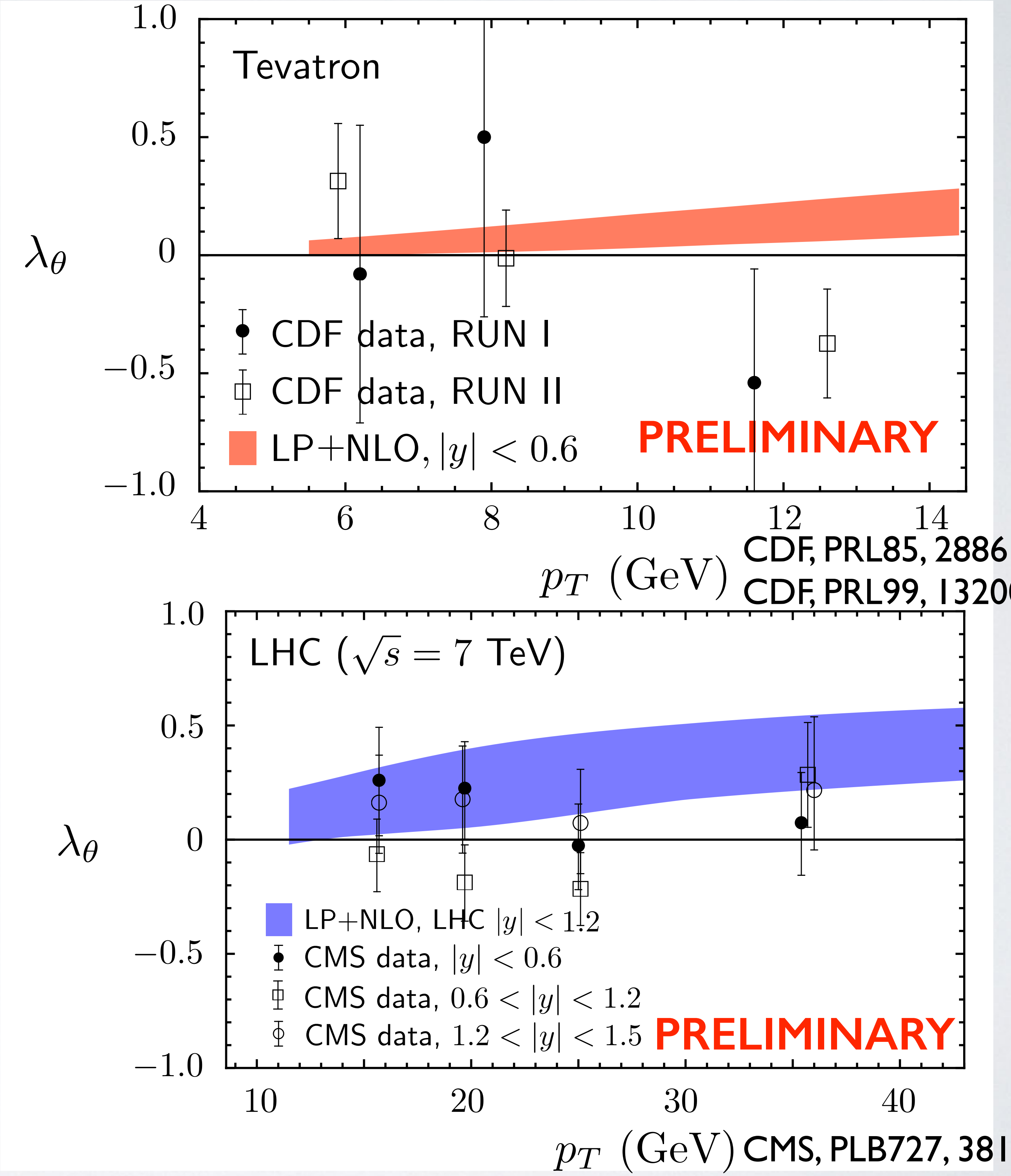
- J/ψ can also be produced from decays of $\psi(2S)$ and χ_{cJ}
- $\psi(2S)$ LDMEs from fit to CMS and CDF cross section data CDF, PRD80, 031103 (2009) CMS, JHEP02, 011 (2012) CMS-PAS-BPH-14-001
- χ_{cJ} LDMEs from fit to ATLAS cross section data ATLAS, JHEP1407, 154 (2014)
- 30% theoretical uncertainty from scale variation



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

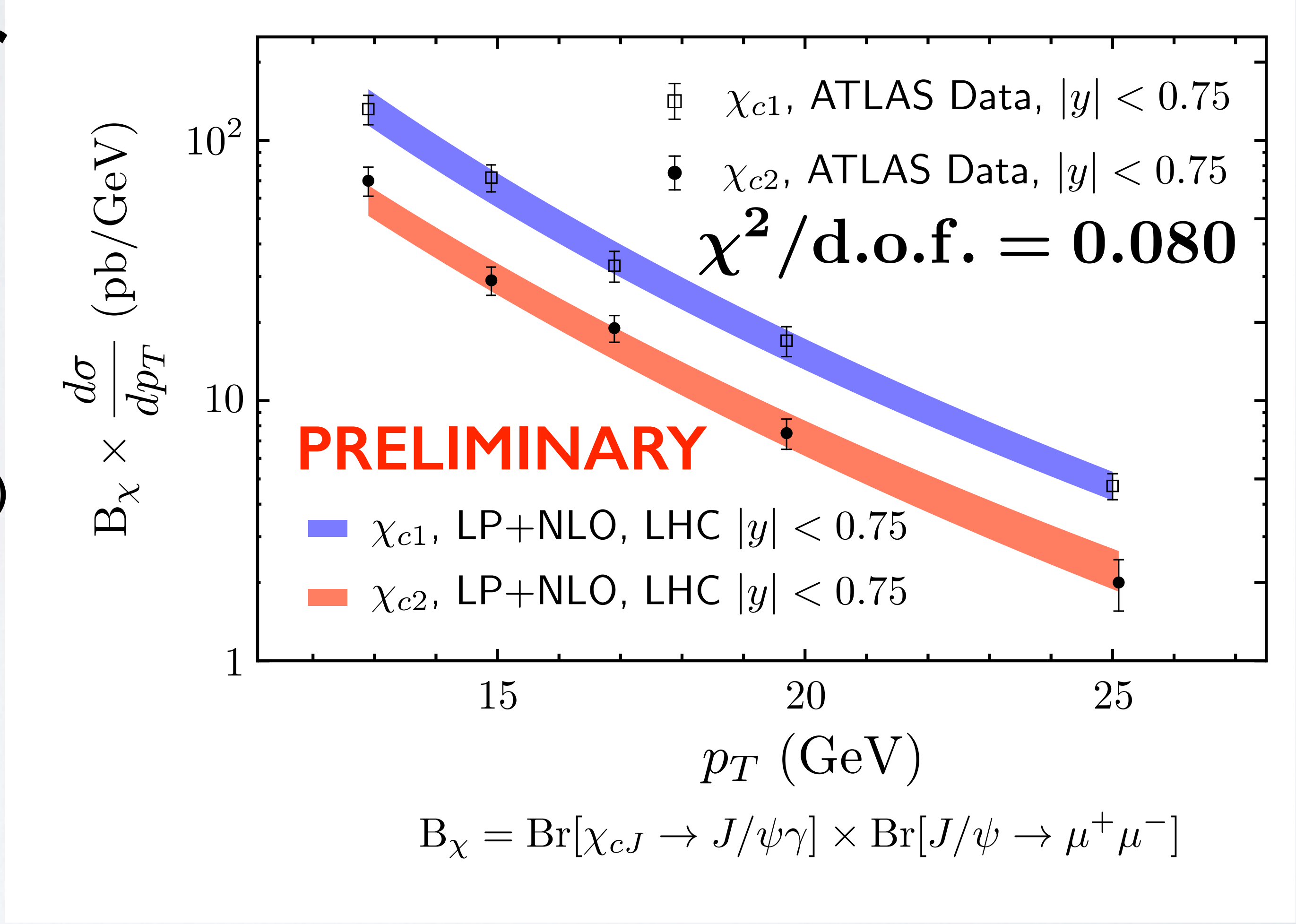
$\psi(2S)$ POLARIZATION

- 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



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

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

Eichten and Quigg, PRD 52, 1726 (1995)

Our fit

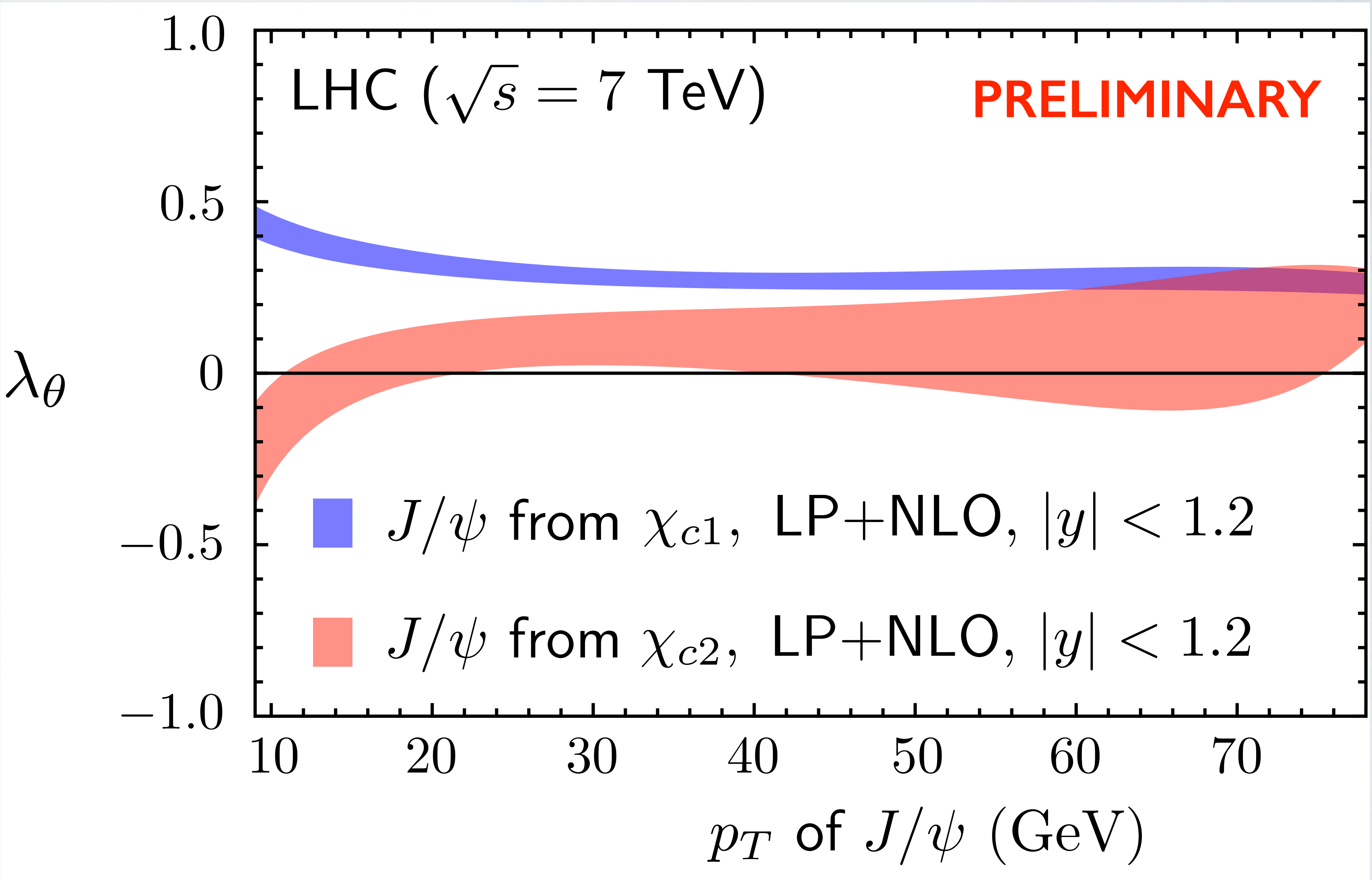
$$|R'(0)|^2 = 0.055 \pm 0.025\ \mathrm{GeV}^5$$

→*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)

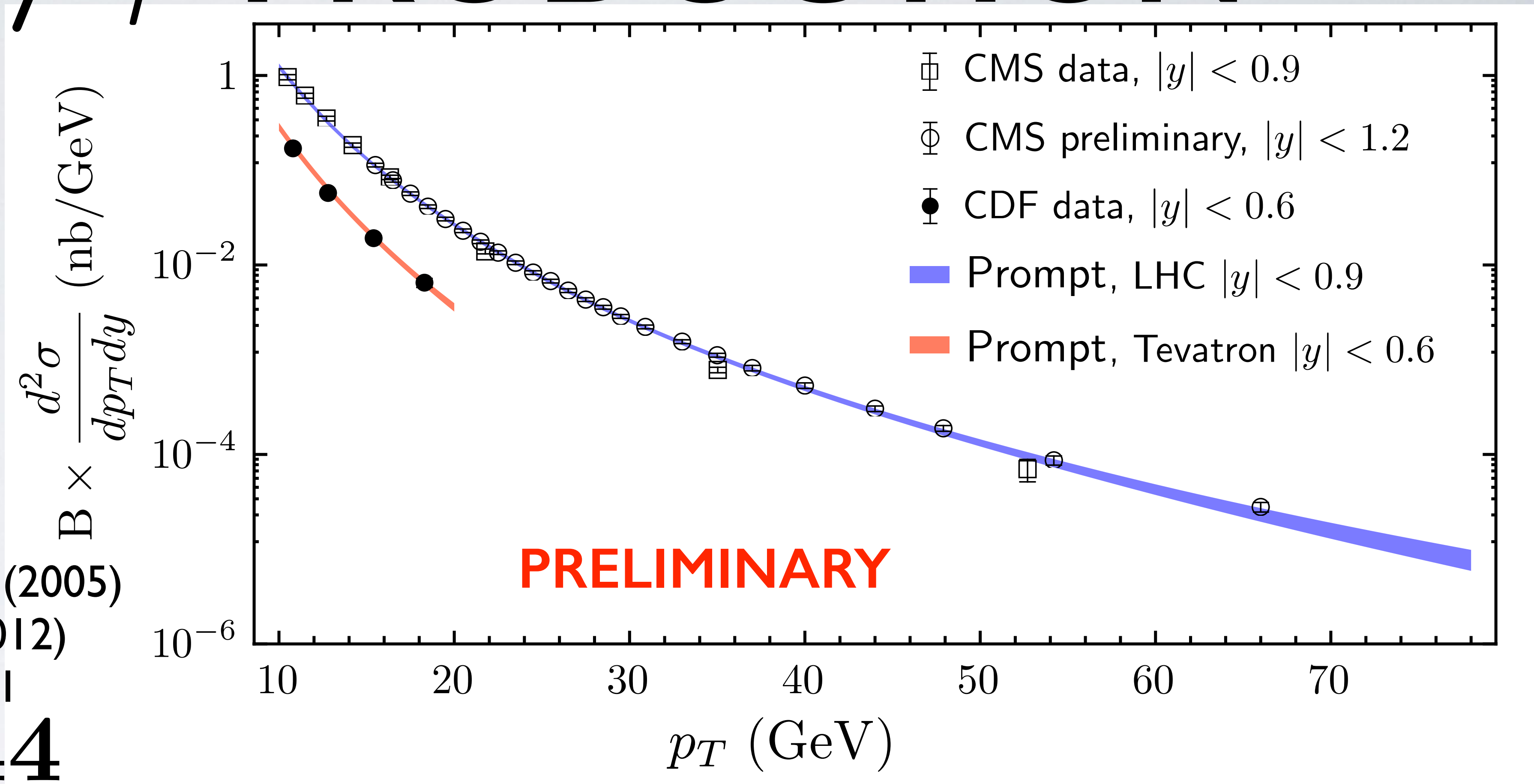
PROMPT J/ψ PRODUCTION

- After including feeddown contributions, we again obtain good fits

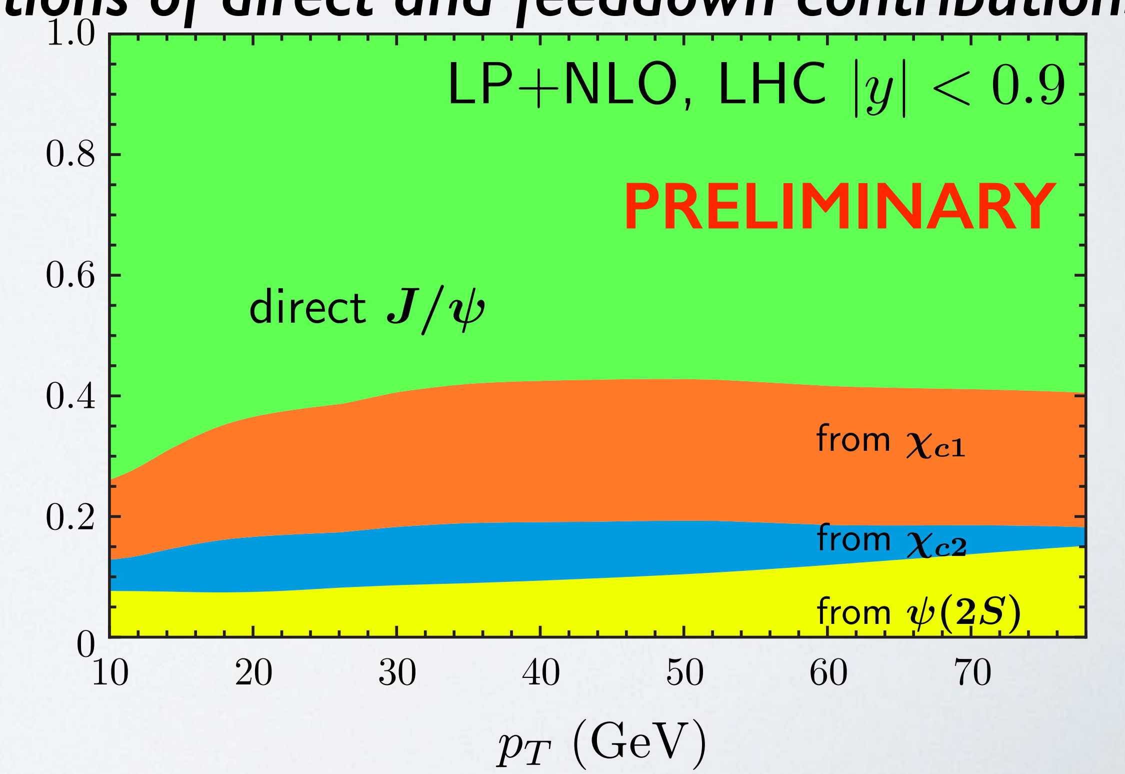
CDF, PRD71, 032001 (2005)
CMS, JHEP02, 011 (2012)
CMS-PAS-BPH-14-001

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

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

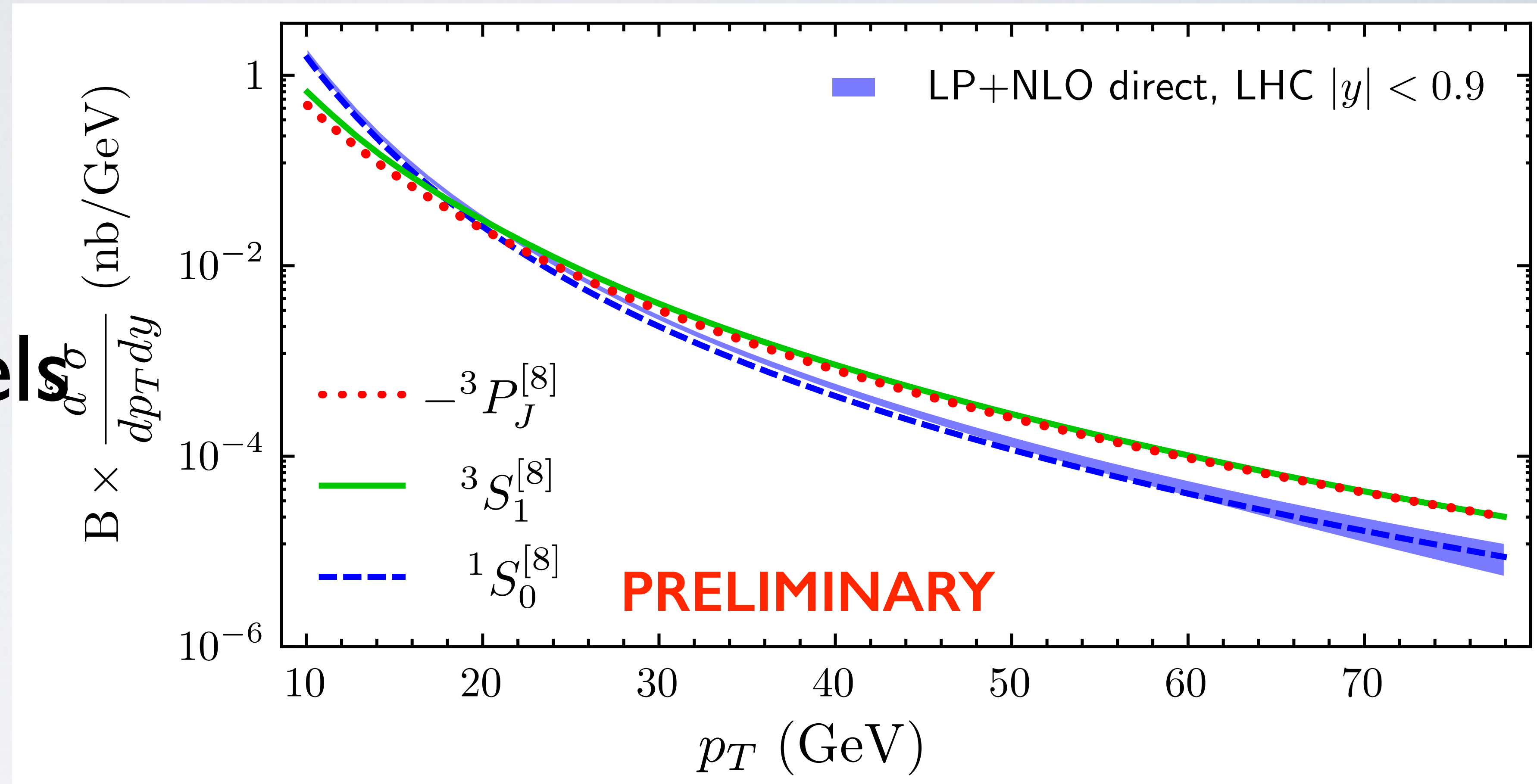


Fractions of direct and feeddown contributions



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*



$$\langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]}) = 0.094 \pm 0.016 \mathrm{GeV}^3$$

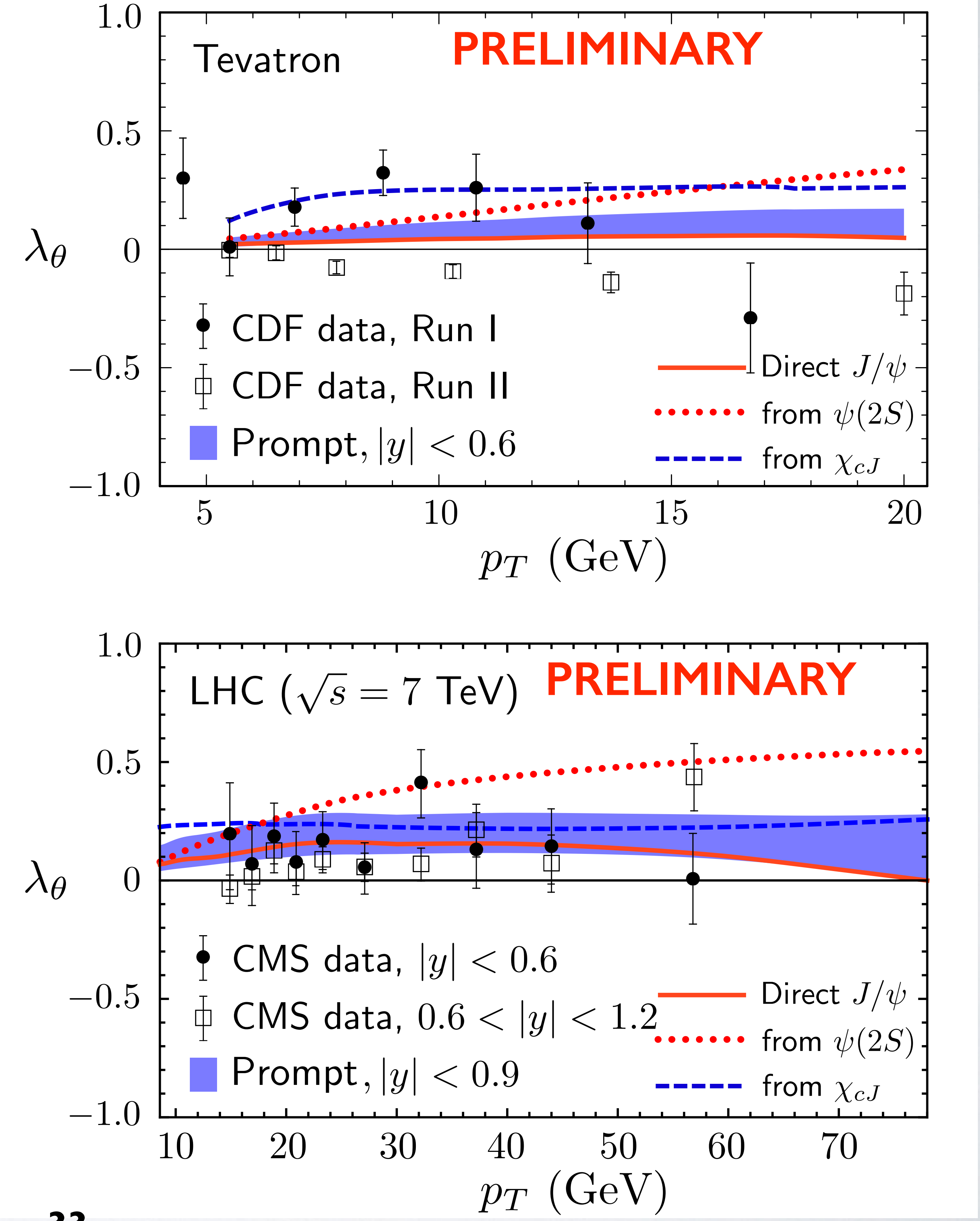
$$\langle \mathcal{O}^{J/\psi}({}^3S_1^{[8]}) = 0.004 \pm 0.008 \mathrm{GeV}^3$$

$$\langle \mathcal{O}^{J/\psi}({}^3P_J^{[8]}) = 0.005 \pm 0.007 \mathrm{GeV}^5$$

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*

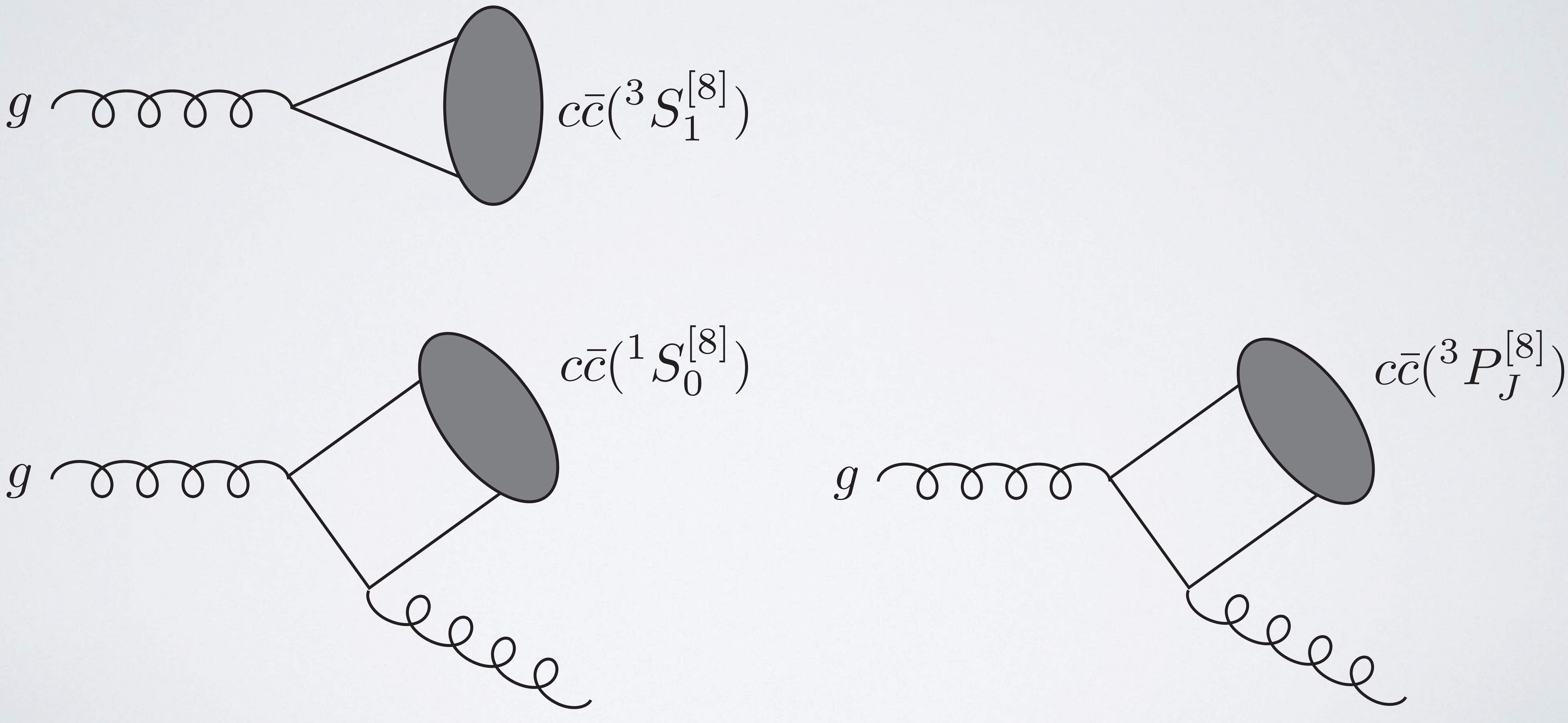
- *This is the **first prediction of small J/ψ polarization** at high p_T in NRQCD*

- Work on higher-order corrections, as well as other quarkonium states is in progress

BACKUP

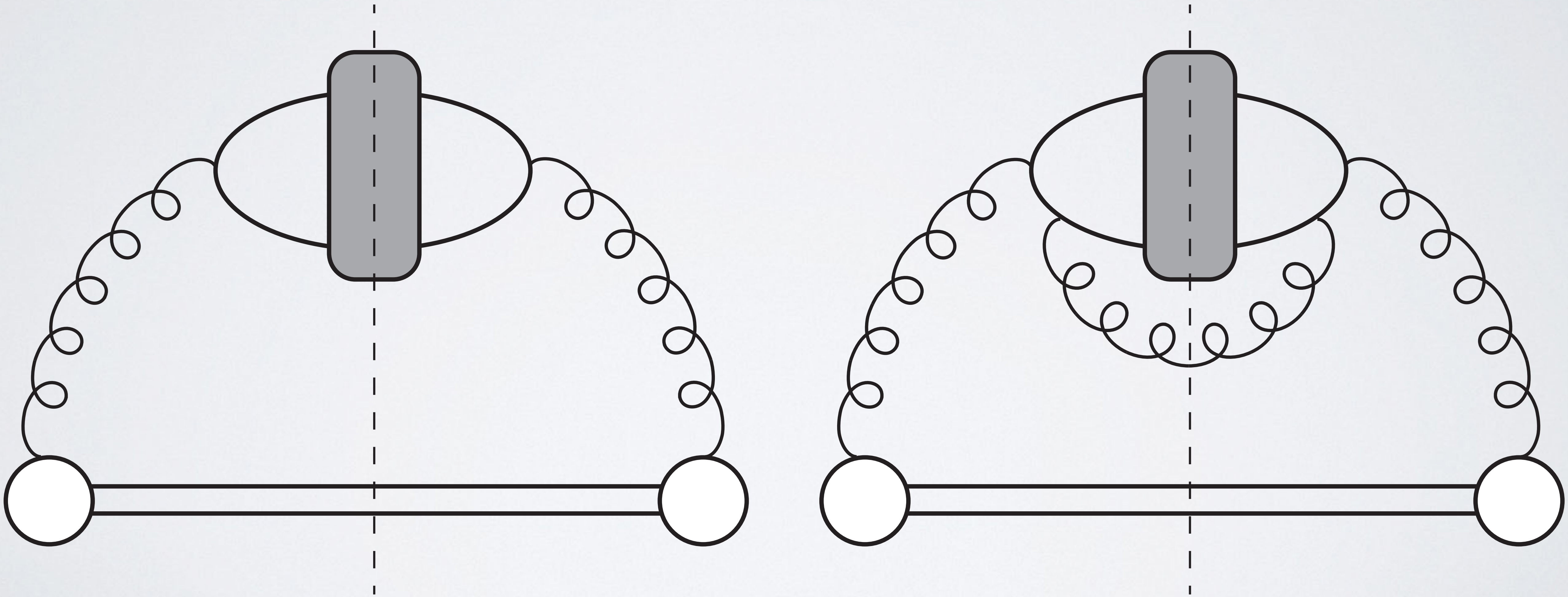
GLUON FRAGMENTATION INTO $c\bar{c}$

- Lowest-order diagrams of a gluon producing CO $c\bar{c}$



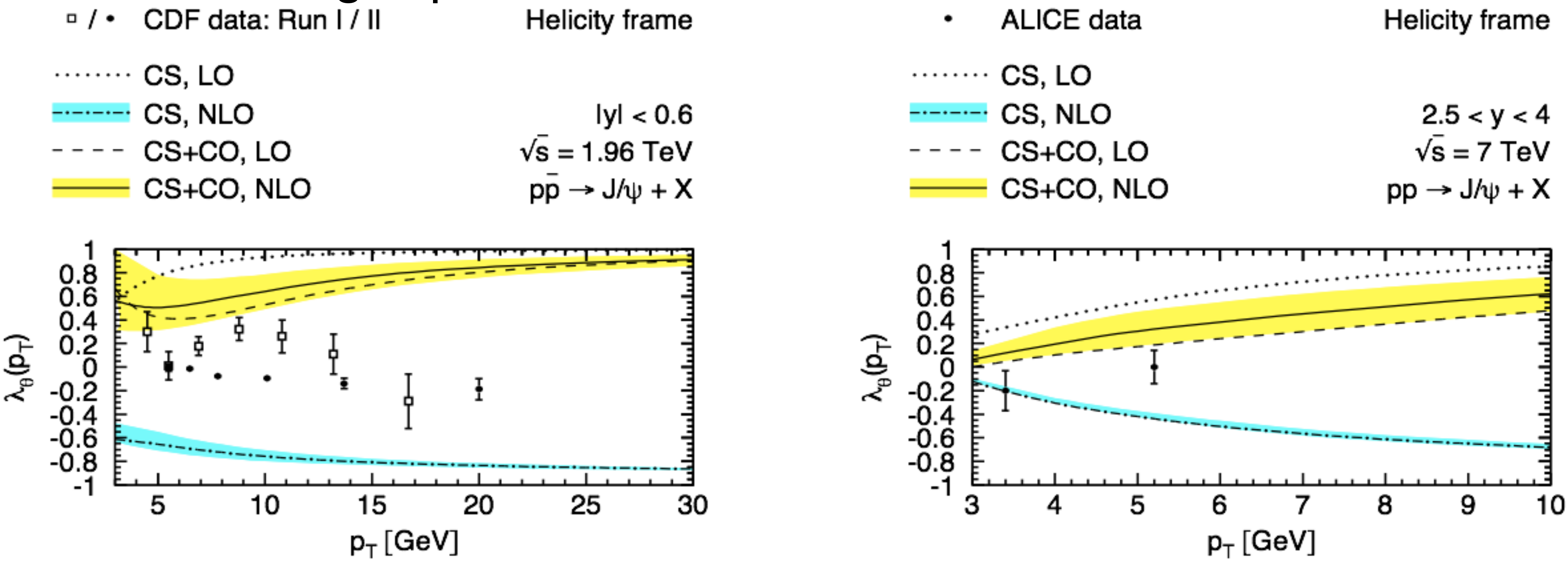
GLUON FRAGMENTATION INTO $c\bar{c}$

- Computation of fragmentation functions involve Eikonal lines, and their interaction with gluons



PREDICTIONS AT NLO

Bernd Kniehl's group



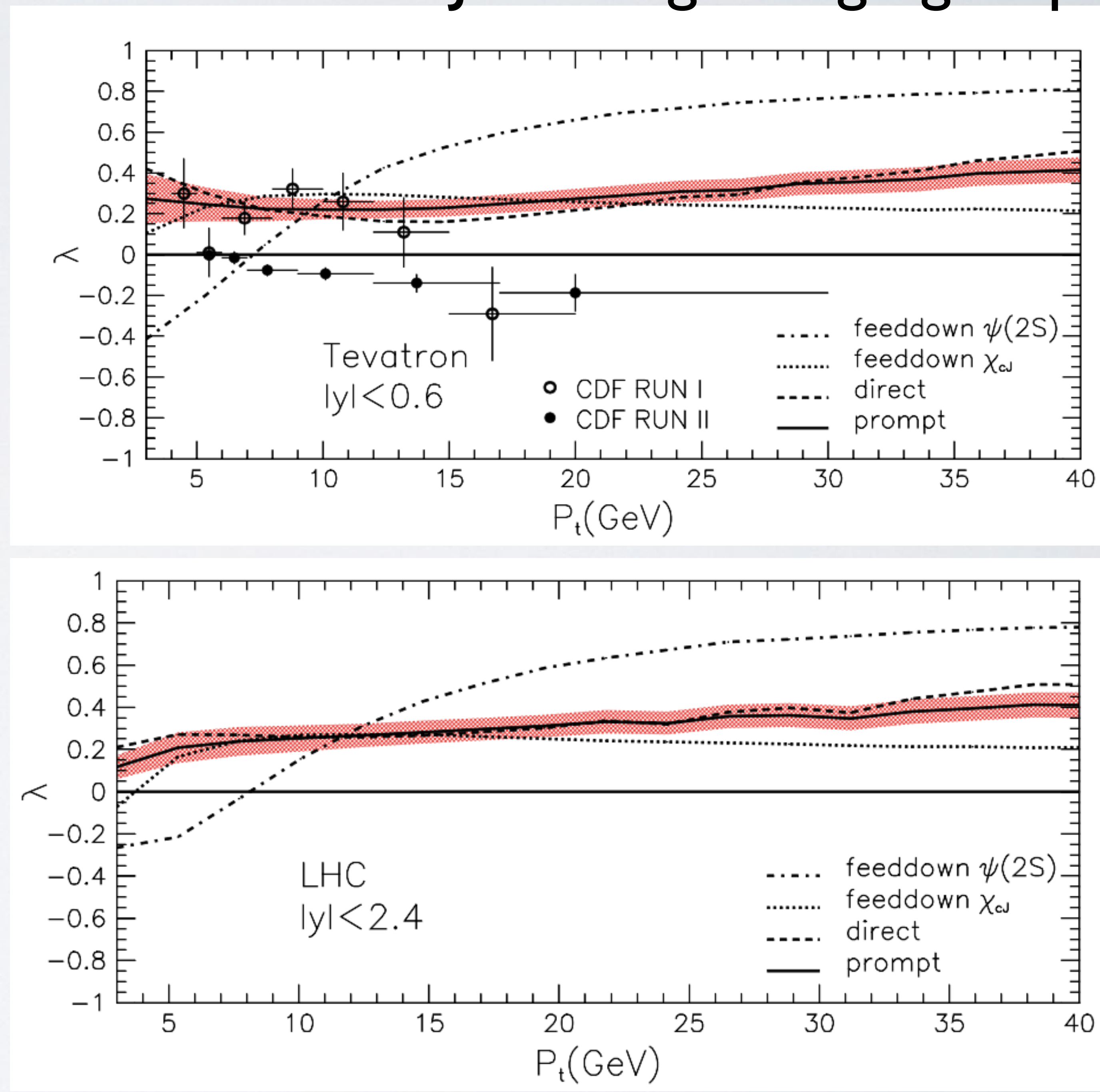
Butenschoen and Kniehl, Mod.Phys.Lett.A28, 1350027 (2013)

- Used cross section measurements at HERA and Tevatron to fix LDMEs, predicts transverse polarization at large p_T
- H1 and ZEUS data are at small p_T
- Does not include feeddown

PREDICTIONS AT NLO

- Used CDF and LHCb cross section data to fit LDMEs
- Includes feeddown
- Prediction still more transverse than measurement

Jianxiong Wang's group

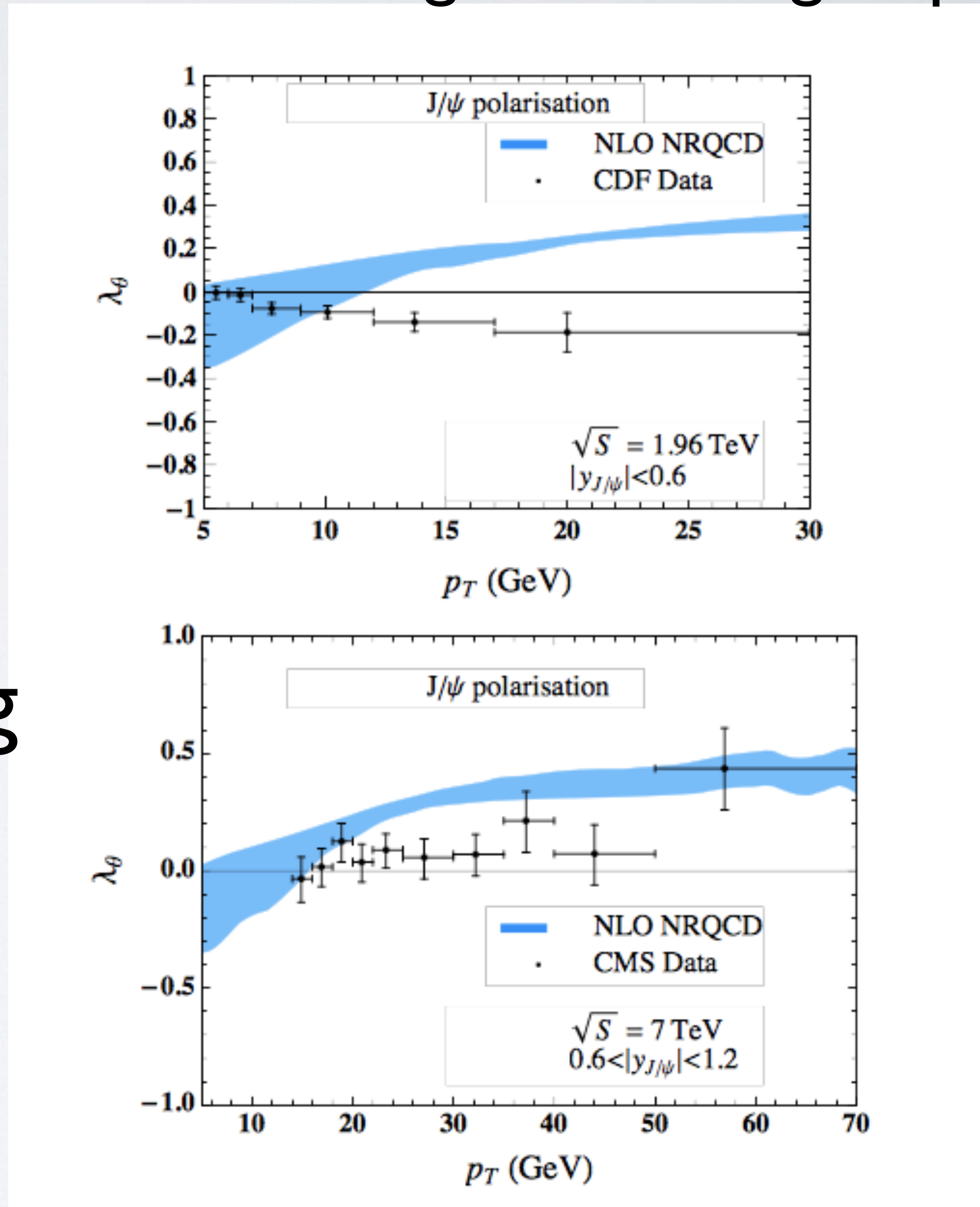


Gong, Wan, Wang, Zhang, PRL110, 042002 (2013)

PREDICTIONS AT NLO

- Used CDF, ATLAS, CMS, LHCb cross section data to fit LDMEs
- Included feeddown
- Assumed positivity of all LDMEs, although ${}^3P_J^{[8]}$ LDME has strong factorization scale dependence
- Prediction still more transverse than data

Kuang-Ta Chao's group



Shao, Han, Ma, Meng, Zhang, Chao, hep-ph/1411.3300 (2014)

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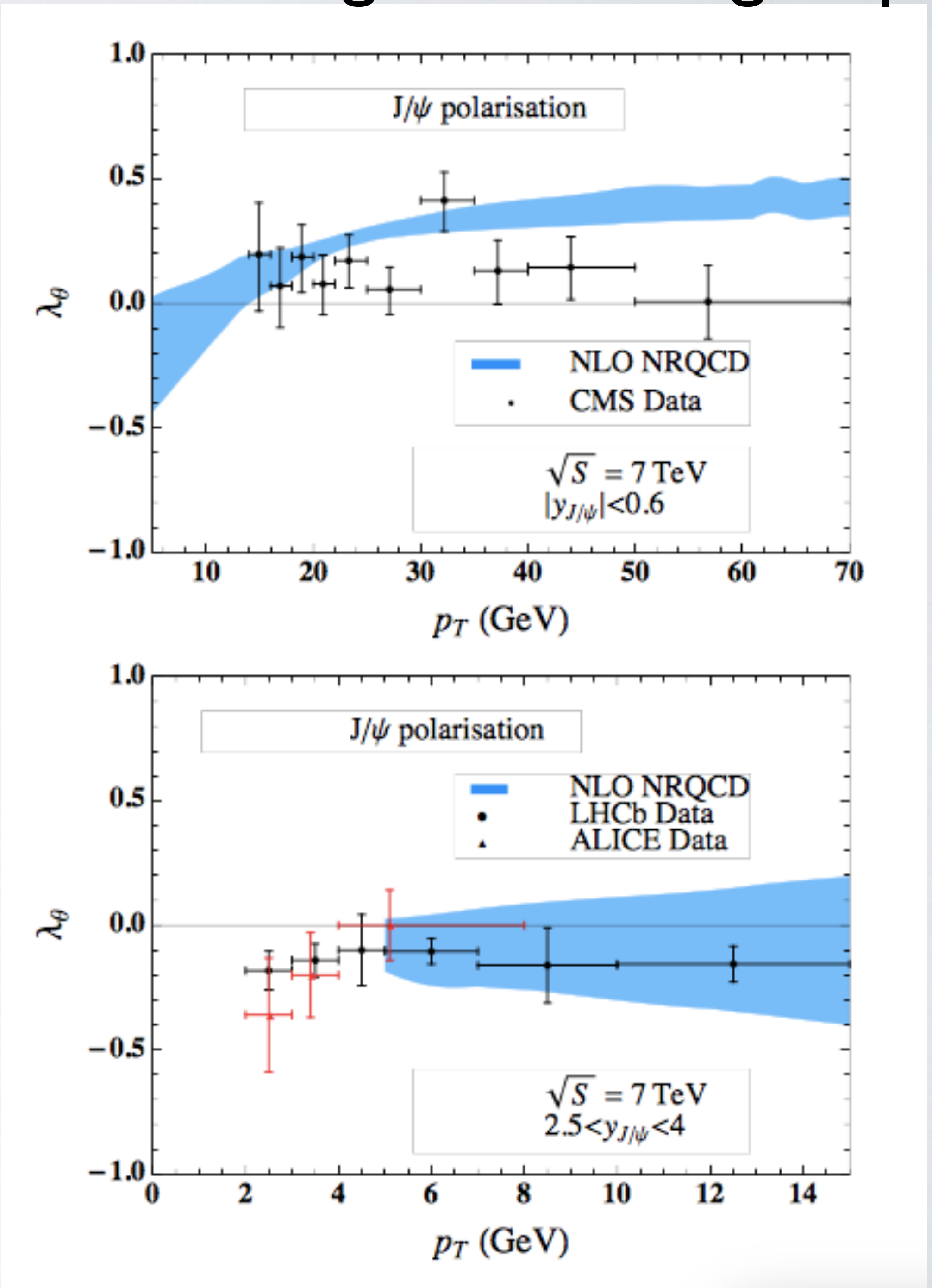
Kuang-Ta Chao's group



Shao, Han, Ma, Meng, Zhang, Chao, hep-ph/1411.3300 (2014)