Impact of η_c Hadroproduction Data on Charmonium Production and Polarization within the Nonrelativistic QCD Framework [1]

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[1] Based on Phys. Rev. Lett. 116, 092006 (2015), HFZ, Zhan Sun, Wen-Long Sang and Rong Li

QCD Effective Theory

- QCD involve partons (quarks and gluons)
- Experiment measures hadrons
- The hadronization of partons usually can not be calculated perturbatively
- partons $\leftarrow$ effective theory $\rightarrow$ hadrons

Nonrelativistic QCD (NRQCD)[5]

- An effective theory to describe quarkonium productions and decays

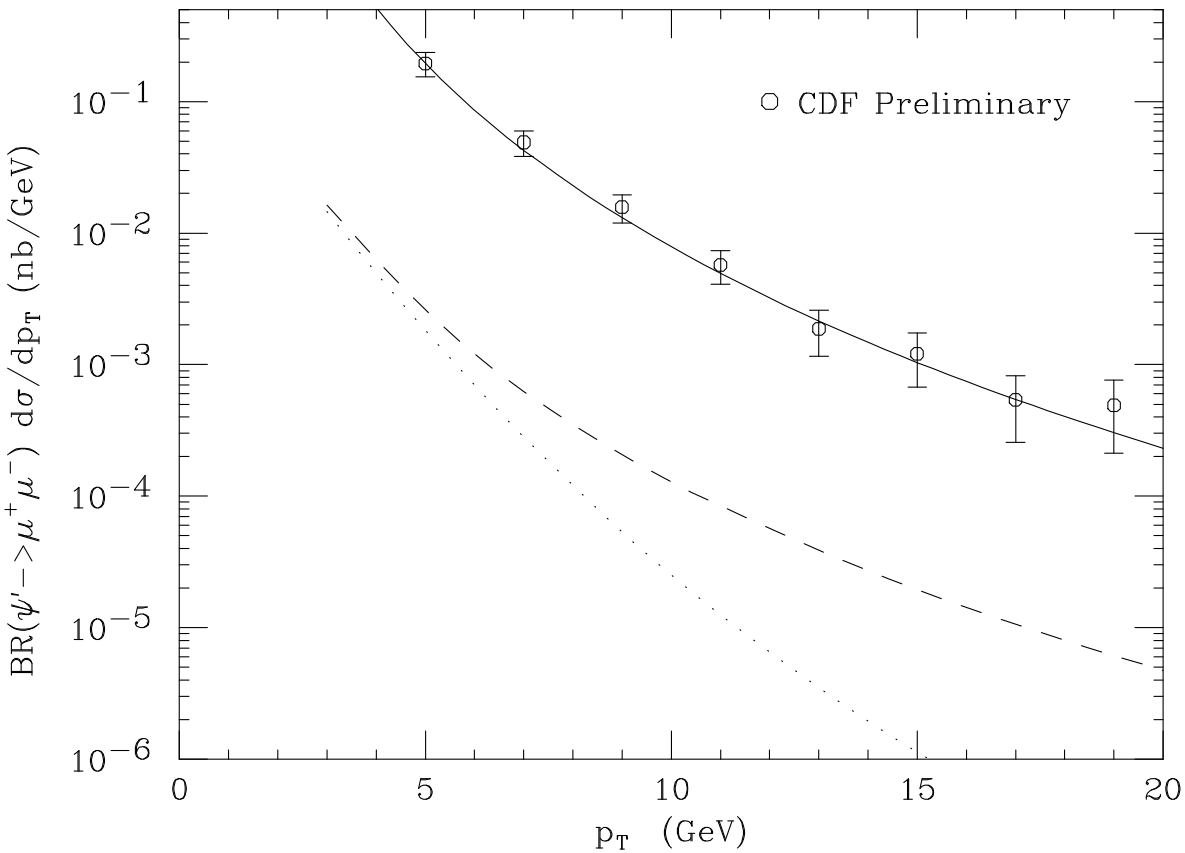
$$d\sigma(H) = \sum_n df_n \langle \mathcal{O}^H(n) \rangle$$

- f_n: Short-distance coefficient (SDC): production of a heavy quark pair with specific quantum numbers, to be calculated perturbatively
- $\langle \mathcal{O}^H(n) \rangle$: Long-distance matrix element (LDME): hadronization, to be extracted from experiment

[5] Bodwin, Braaten and Lepage, PRD 51, 1125 (1995)

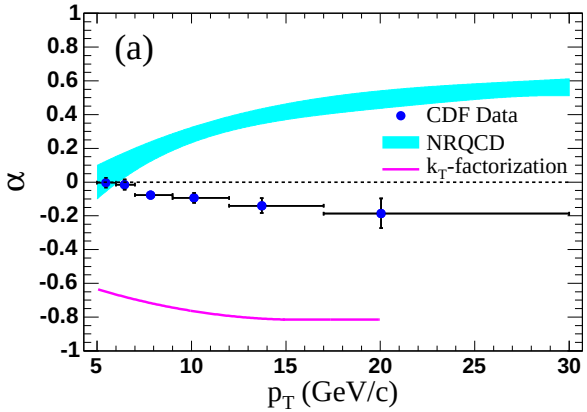
Successes of NRQCD

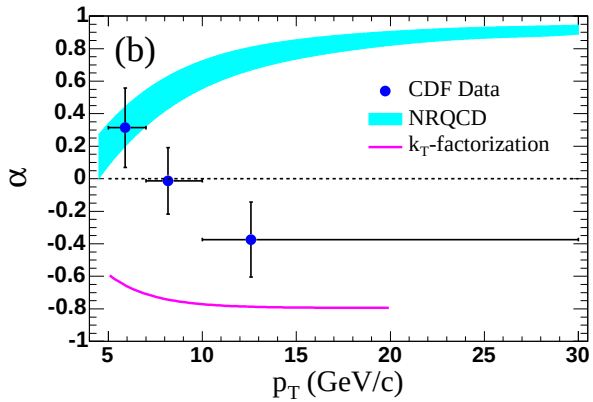
- ${}^3S_1^{[1]}$, ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ channels involved in ψ production up to $O(v^4)$
- NRQCD prediction for ψ' hadroproduction



J/ψ polarization puzzle

- LO NRQCD failed in the description of ψ polarization[8]
- $\alpha = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}$





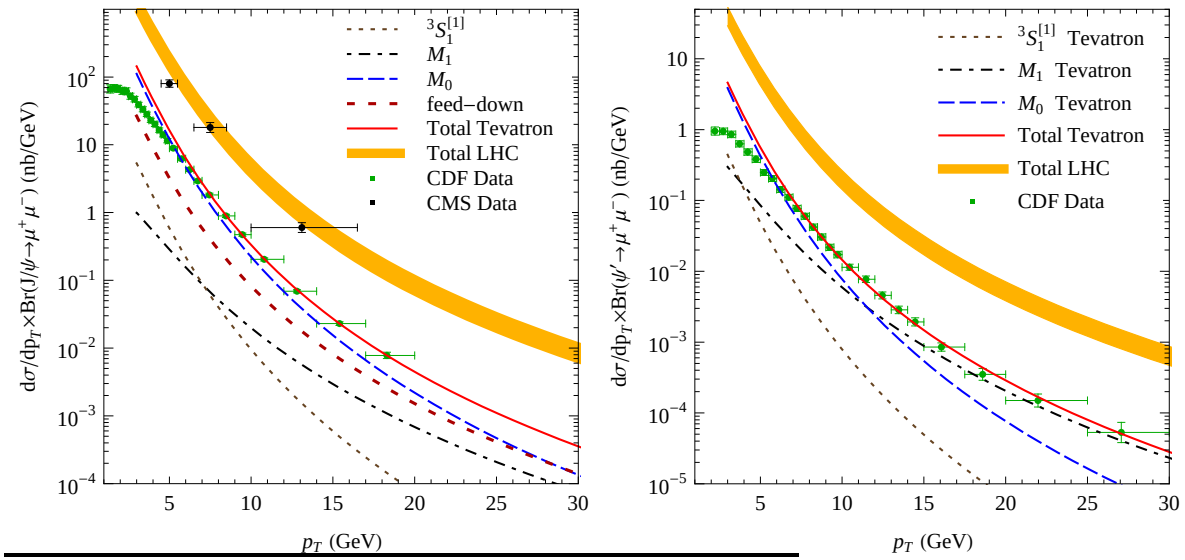
- Analysis
  - Dominant Mechanism: gluon fragmentation $\rightarrow$ $c\bar{c}(^3S_1^{[8]})$
  - Gluon is transversely polarized

[8] Braaten, Kniehl and Lee, PRD 62, 094005 (2000); CDF Collaboration, PRL 99, 132001 (2007)

Color-octet at NLO

NLO for CO[10]

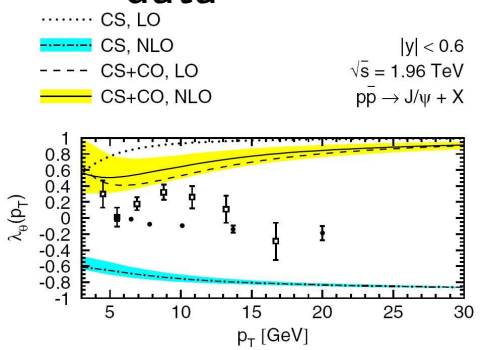
- ${}^3S_1^{[1]}$: $p_t^{-8} \to p_t^{-6}$, still very small
- ${}^1S_0^{[8]}$: $p_t^{-6} \to$additional small p_t^{-4} part emerges
- ${}^3S_1^{[8]}$: almost unchanged
- ${}^3P_J^{[8]}$: positive$\to$minus, $p_t^{-6} \to p_t^{-4}$
- $df({}^3P_J^{[8]}) = r_0 df({}^1S_0^{[8]}) + r_1 df({}^3S_1^{[8]})$ (medium and high p_t, roughly)

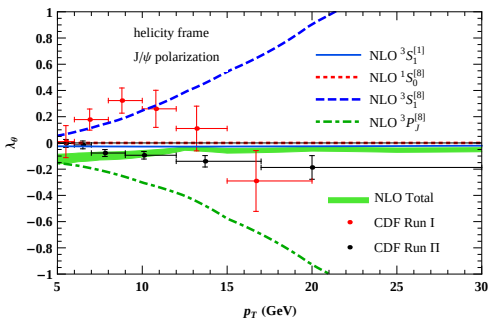


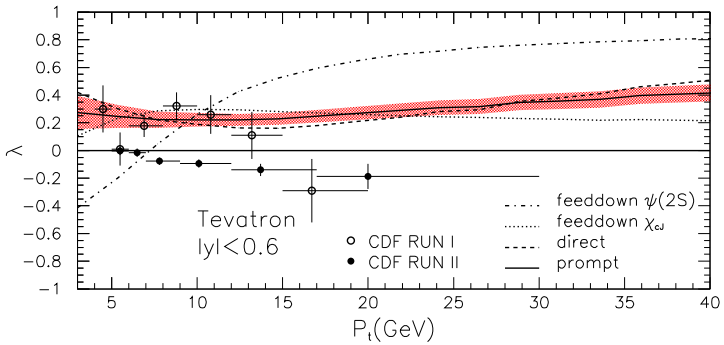
[10] Ma, Wang and Chao, PRL 106, 042002 (2011); Butenschon and Kniehl, PRL 106, 022003 (2011)

Polarization at NLO

- Left[12](missing feeddown): Global fit, transversely polarized, bad agreement
- Middle[13](missing feeddown): ${}^1S_0^{[8]}$ dominance, agree with CDF Run II data
- Right[14](complete): agree with CDF Run I data, contradict CDF Run II data







- Different fitting strategy→different LDMEs→different phenomenology
- Three LDMEs to be determined, too many!

[12] Butenschoen and Kniehl, PRL 108, 172002 (2012)
[13] Chao, Ma, Shao, Wang and Zhang, PRL 108, 242004 (2012)
[14] Gong, Wan, Wang and HFZ, PRL 110, 042002 (2013)

${}^1S_0^{[8]}$ Dominance

- ${}^1S_0^{[8]}$ dominance picture suggetsted to solve the J/ψ polarization puzzle
- Reason:
  - p_t spectrum: NLO ${}^1S_0^{[8]}$ similar to prompt J/ψ
  - Polarization: ${}^1S_0^{[8]}$ unpolarized
- Other groups came to similar conclusions

$(\times 10^{-2}\ \mathrm{GeV}^3)$	Kniehl[16]	Chao[17]	Wang[18]	Bodwin[19]
$\langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]}) \rangle$	3.04	8.9	9.7	9.9
$\langle \mathcal{O}^{J/\psi}({}^3S_1^{[8]}) \rangle$	0.168	0.3	-0.46	1.1
$\langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]}) \rangle / m_c^2$	-0.403	0.56	-0.95	0.49

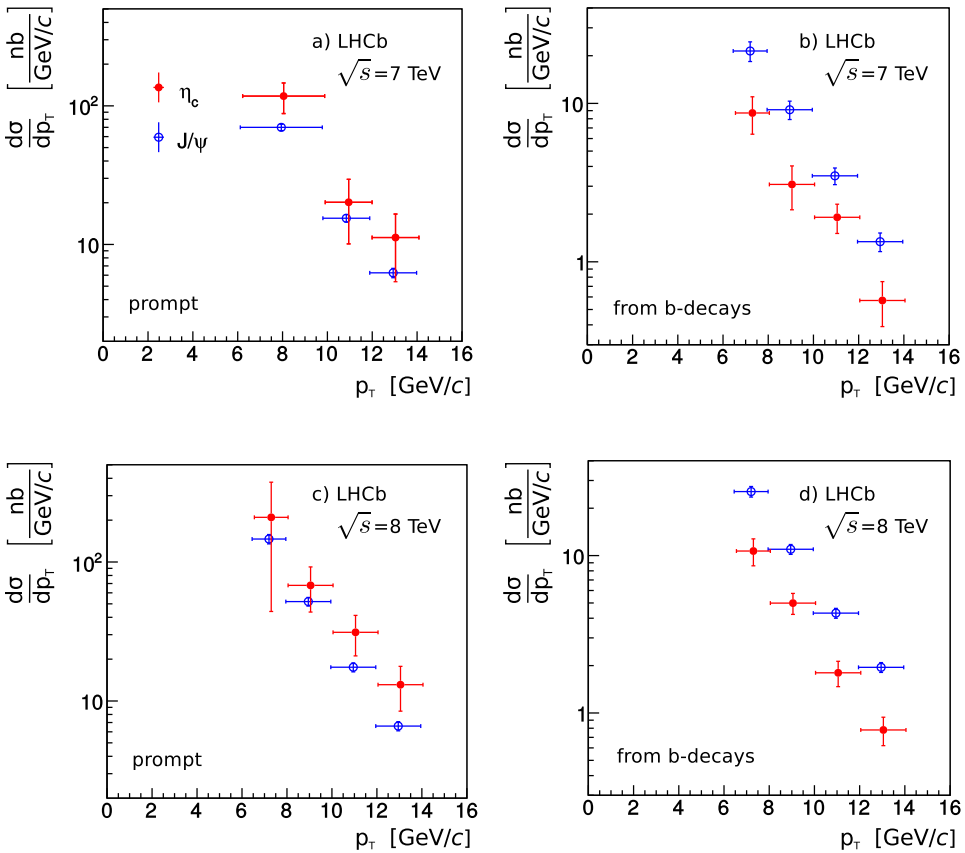
[16] Butenschoen and Kniehl, PRD 84, 051501 (2011)
[17] Chao, Ma, Shao, Wang and Zhang, PRL 108, 242004 (2012)
[18] Gong, Wan, Wang and HFZ, PRL 110, 042002 (2013)
[19] Bodwin, Chung, Kim and Lee, PRL 113, 022001 (2014)

η_c hadroproduction and its relation with J/ψ hadroproduction

- Heavy quark spin symmetry (HQSS)
  - $\langle O^{J/\psi}({}^3S_1^{[n]})\rangle \approx 3\langle O^{\eta_c}({}^1S_0^{[n]})\rangle$
  - $\langle O^{J/\psi}({}^1S_0^{[8]})\rangle \approx \langle O^{\eta_c}({}^3S_1^{[n]})\rangle$
  - $\langle O^{J/\psi}({}^3P_0^{[8]})\rangle \approx \frac{1}{3}\langle O^{\eta_c}({}^1P_1^{[8]})\rangle$
- SDCs for ${}^1S_0^{[8]}$ and ${}^1P_1^{[8]}$ are small relative to ${}^3S_1^{[8]}$

LHCb Data[22]

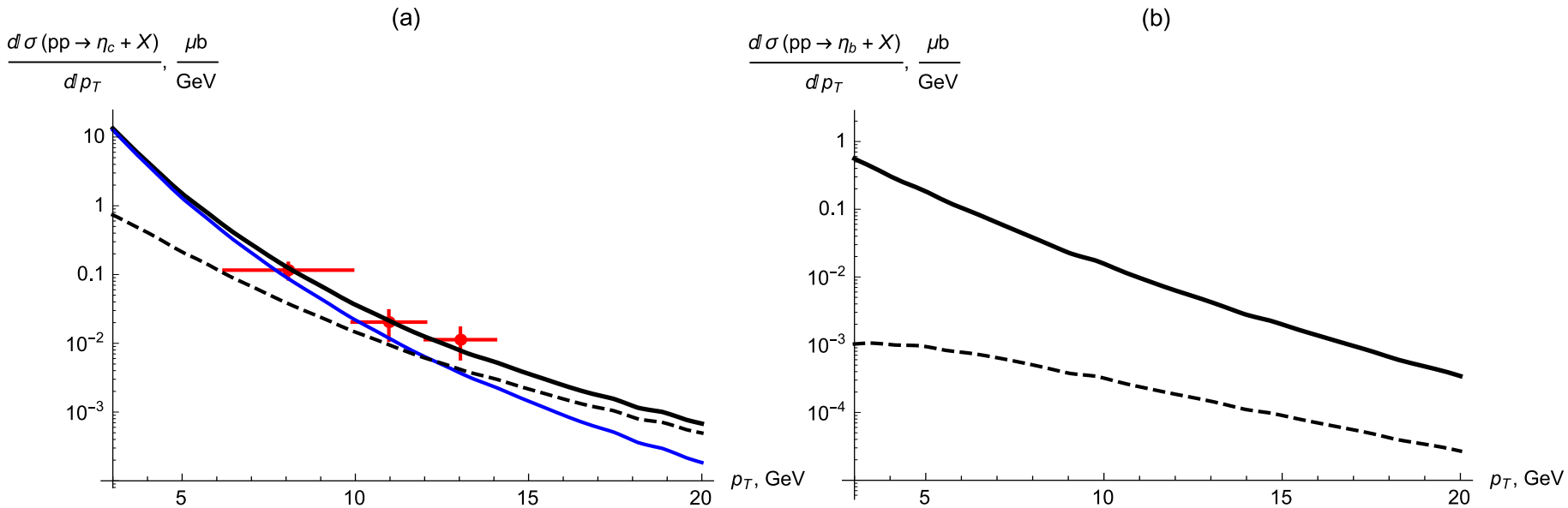
- Prompt η_c cross section larger than prompt J/ψ



[22]LHCb Collaboration, EPJC 75, 311

LO Study

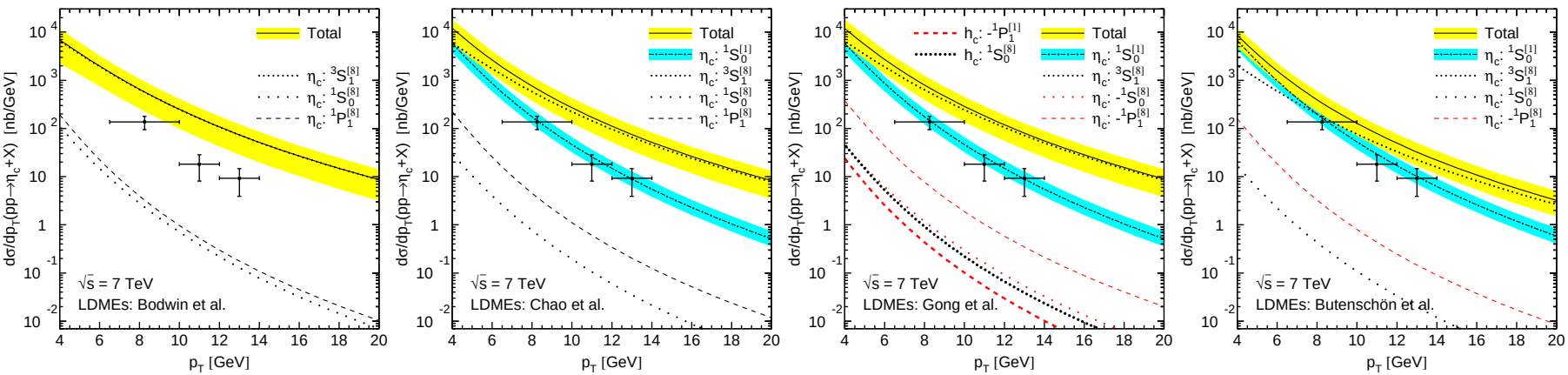
- LO colour-siglet contribution almost saturate data[24]



[24] Likhoded, Luchinsky and Poslavsky, MPL A30, 1550032

NRQCD Faces Challenge

- Challenges
  - Four sets of the LDMEs violate η_c hadroproduction data[26]



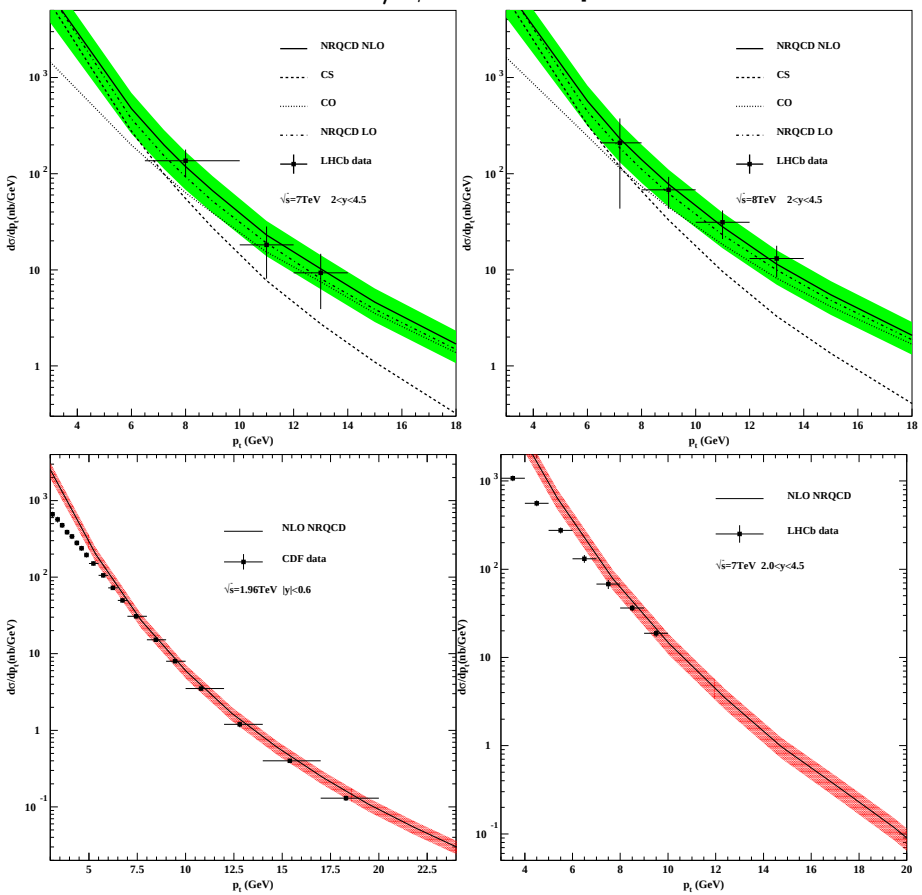
[26] Butenschoen, He and Kniehl, PRL 114, 092004 (2015)

NRQCD Wrong?

- Colour-siglet LDME?
  - potential model $\rightarrow \langle O^{\eta_c}({}^1S_0^{[1]})\rangle \approx 0.39\ \mathrm{GeV}^3$
  - η_c decay $\rightarrow \langle O^{\eta_c}({}^1S_0^{[1]})\rangle = 0.437^{+0.111}_{-0.105}\ \mathrm{GeV}^3$
- ${}^1S_0^{[8]}$ dominance picture?

η_c and J/ψ hadroproduction data reconciled

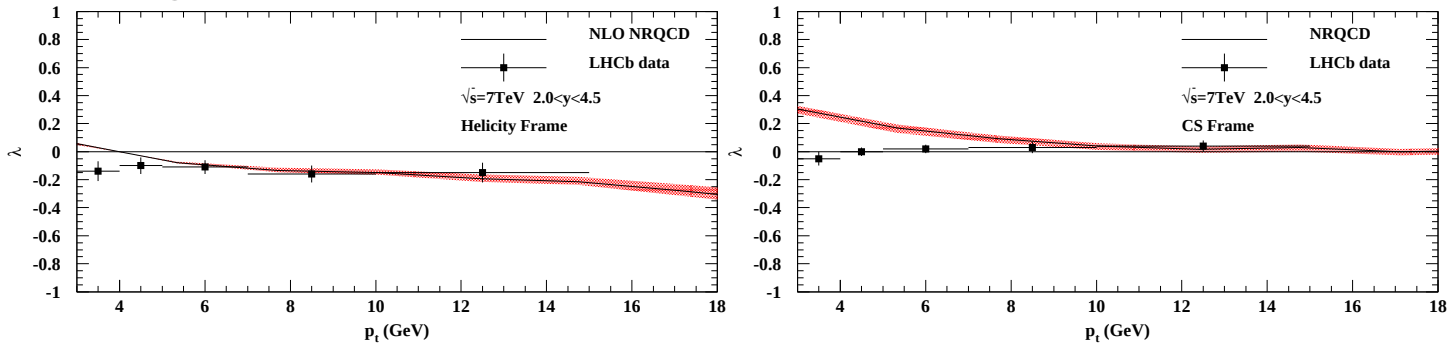
- η_c data help to determine LDMEs
- Consistent with J/ψ hadroproduction data[29]



[29] HFZ, Sun, Sang and Li, PRL 114, 092006 (2015)

Surprising Results for J/ψ Polarization

- J/ψ polarization at LHCb
- Good agreement



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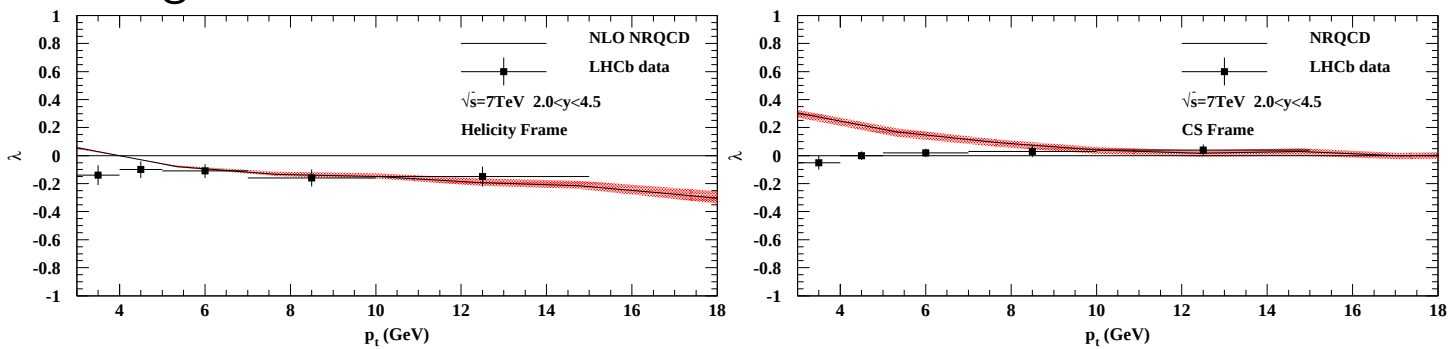
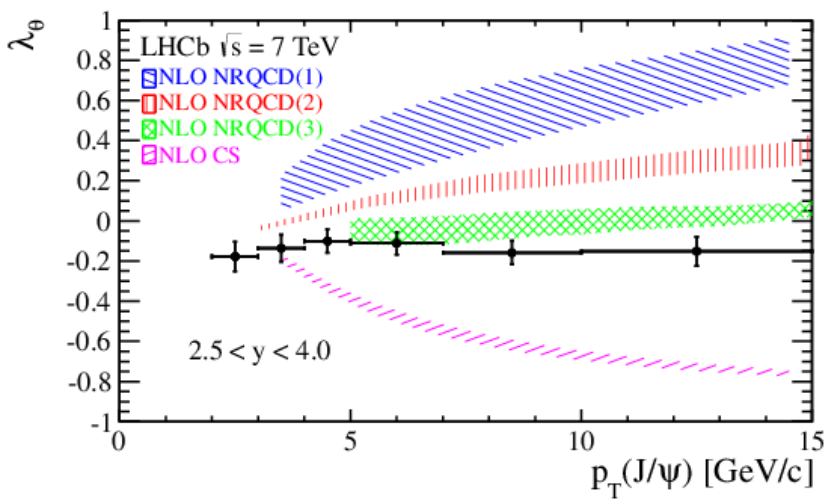




[31] Based on Phys. Rev. Lett. 116, 092006 (2015), HFZ, Zhan Sun, Wen-Long Sang and Rong Li

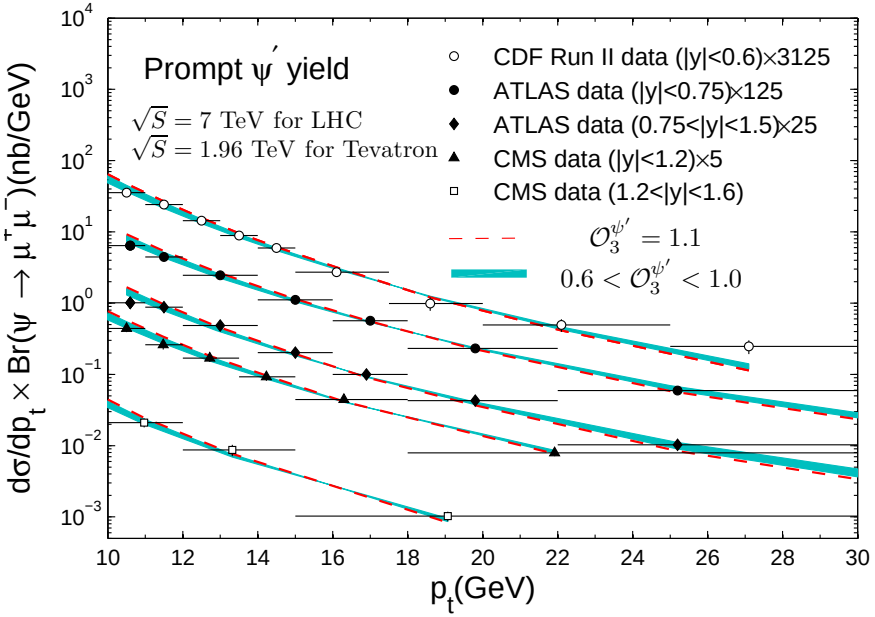
New Features for ψ Polarization[33]

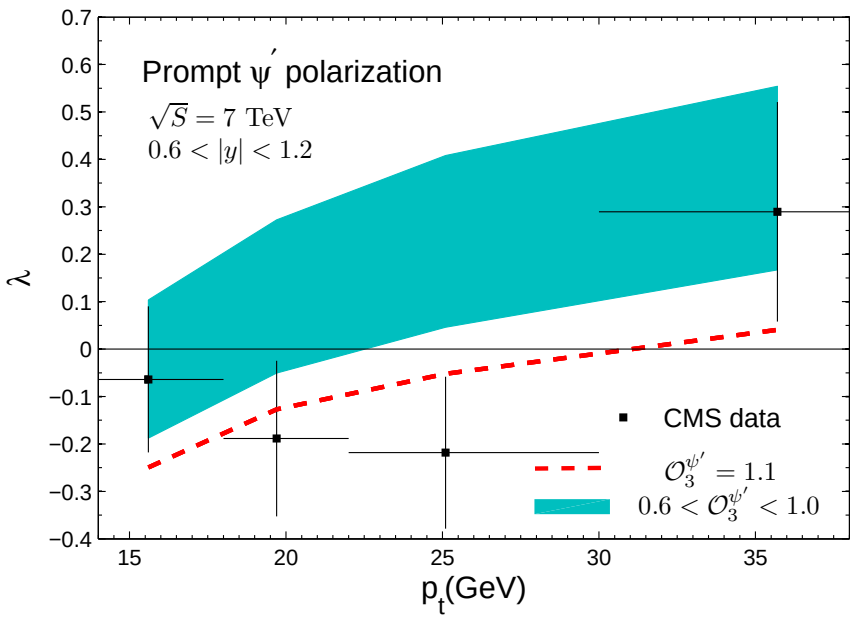
- New discovery in phenomenology
  - The unique key parameter to govern the polarization: $R_{J/\psi} \equiv \langle O^{J/\psi}(^3S_1^{[8]})\rangle / \langle O^{J/\psi}(^3P_0^{[8]})\rangle$
  - Equation to govern the yield: $\langle \mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle = k_{J/\psi}\langle \mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle + b_{J/\psi}$
  - $k_{J/\psi} = 0.367$, $b_{J/\psi} = 0.00348 \pm 0.00011\text{GeV}^3$, $R_{J/\psi} = 0.546 \pm 0.006$
  - The polarization is extremely sensitive to $R_{J/\psi}$
- Conclusion
  - Minimizing χ^2 in the fit to yield data does not apply
  - Yield data does not provide information for polarization!

[33] Sun and HFZ, 1505.02675

$\psi(2s)$ Hadroproduction as an Example

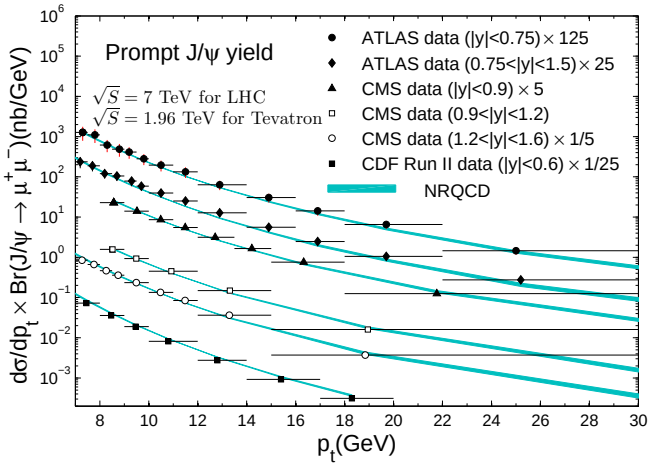
- narrow yield band→huge polarization band

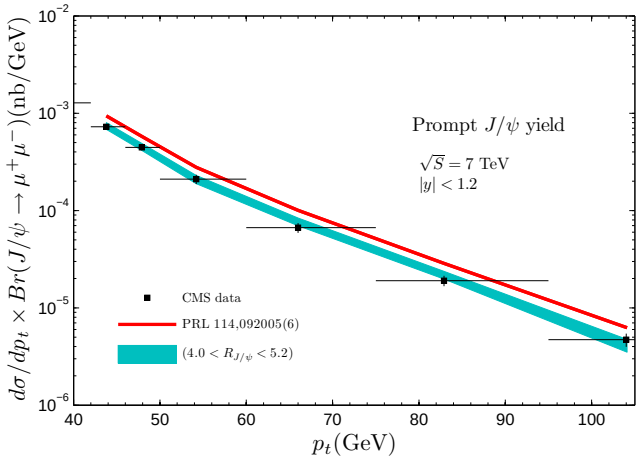


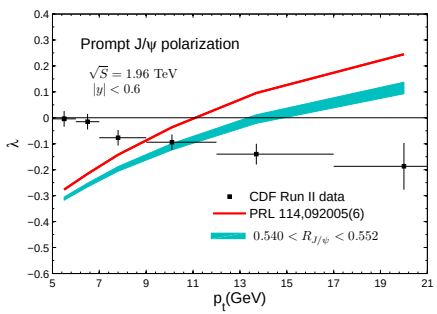


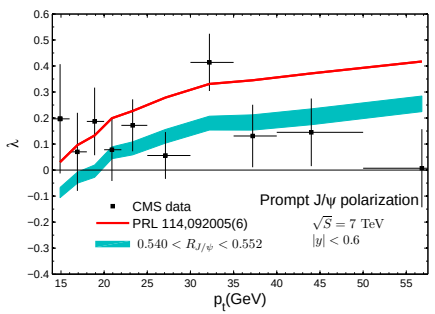
J/ψ yield and polarization reconciled

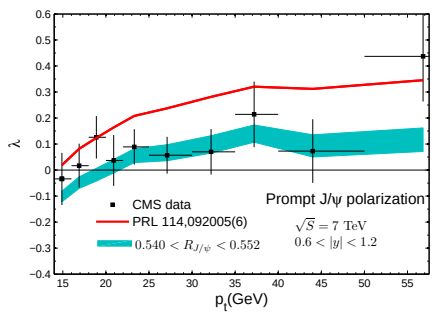
- Relativistic corrections will improve CDF predictions





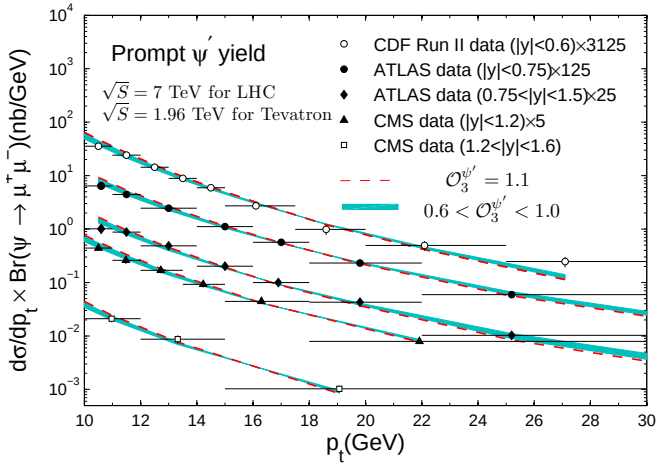


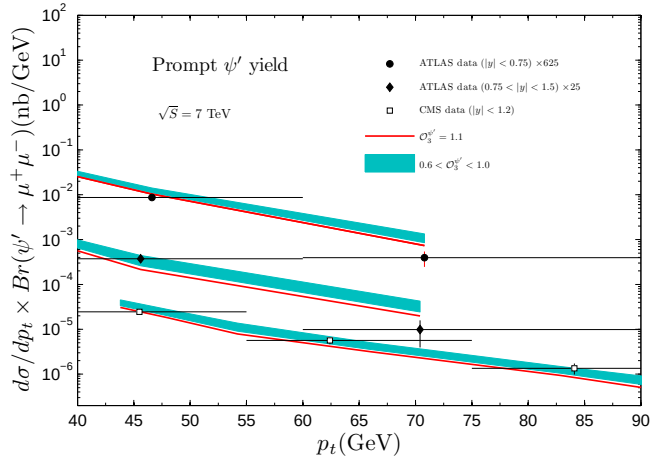


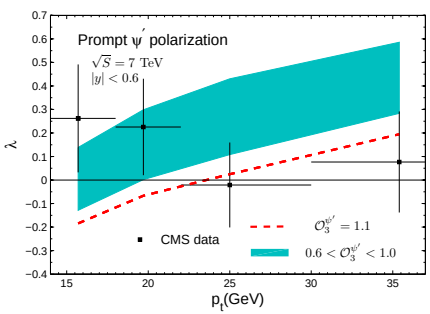


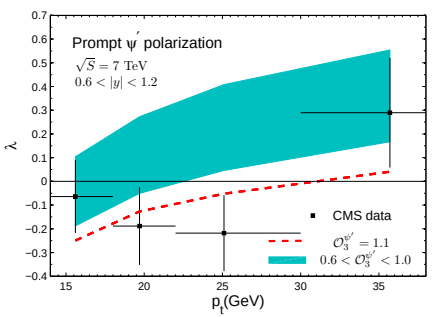
$\psi(2s)$—Theory Consistent with Experiment

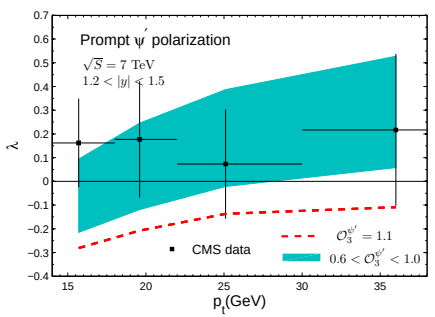
- The uncertainty for $\psi(2s)$ polarization measurement is too large
- The theoretical band covers the data











Conclusion and Future Opportunity

- η_c hadroproduction data help to determine the LDMEs (both CS and CO)
- ${}^1S_0^{[8]}$ dominance v.s. ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ cancellation (WIN!!)
- New features for ψ polarization
  - Minimizing χ^2 in the fit to yield data does not apply
  - Yield data does not provide information for polarization
- Future opportunity: Relativistic corrections might be important

Thanks!