Update on $\Upsilon(nS)$ Production and Polarization

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Outline

I. Introduction

II. J/ψ production and polarization

III. $\Upsilon(\mathrm{nS})$ production and polarization

IV. Summary and Outlook

Theories for quarkonium production

1. 1974 - Discovery of J/ψ, CSM and CEM

CSM: IR divergence, ψ' surplus — Einhorn, Ellis (1975), Chang (1980), Berger, Jone (1981), …

CEM: wrong for ratio — Fritzsch (1977), Halzen (1977), …

2. 1994 - NRQCD

Bodwin, Braaten, Lepage, 9407339, …

No divergence up to now, solving many puzzles

Plain NRQCD fails when $p_T \gg M$ or $p_T \ll M$, leak all order proof

See George Sterman's talk

3. 2014 -

High p_T: collinear factorization — Kang, Qiu, Sterman, 1109.1520; Fleming, Leibovich, Mehen, Rothstein 1207.2578; Kang, YQM, Qiu, Sterman, 1401.0923, …

Low p_T: CGC+NRQCD — Kang, YQM, Venugopalan, 1309.7337; Qiu, Sun, Xiao, Yuan, 1310.2230, …

……: ?????

NRQCD Factorization

➢ Factorization formula

Bodwin, Braaten, Lepage, 9407339

$$d\sigma_\psi = \sum_{i,j,n} \int \underbrace{dx_1 dx_2 \boxed{G_{i/A} G_{j/B}}}_{\Lambda_{QCD}} \times \underbrace{\boxed{\hat{\sigma}[ij \to c\bar{c}[n] + X]}}_{m_c} \times \underbrace{\boxed{\langle O_n^\psi \rangle}}_{m_c v}$$

- n: quantum numbers of the pair, spectroscopic notation ${}^{2S+1}L_J^{[c]}$.

➢ Dominate channels

- For $\psi(nS)$ and $\Upsilon(nS)$ production: ${}^3\boldsymbol{S}_1^{[1]}$, ${}^1\boldsymbol{S}_0^{[8]}$, ${}^3\boldsymbol{S}_1^{[8]}$, ${}^3P_J^{[8]}$
- For $\chi_{cJ}(nP)$ and $\chi_{bJ}(nP)$ production: ${}^3P_J^{[1]}$, ${}^3\boldsymbol{S}_1^{[8]}$
- For $\eta_c(nS)$ and $\eta_b(nS)$ production: ${}^1S_0^{[1]}$, ${}^3\boldsymbol{S}_1^{[8]}$

➢ LO NRQCD: polarization puzzle

- Fitting yield data implies $^3S_1^{[8]}$ dominance, predicts transversely polarized J/ψ, contradicts with CDF data

CDF, 0704.0638

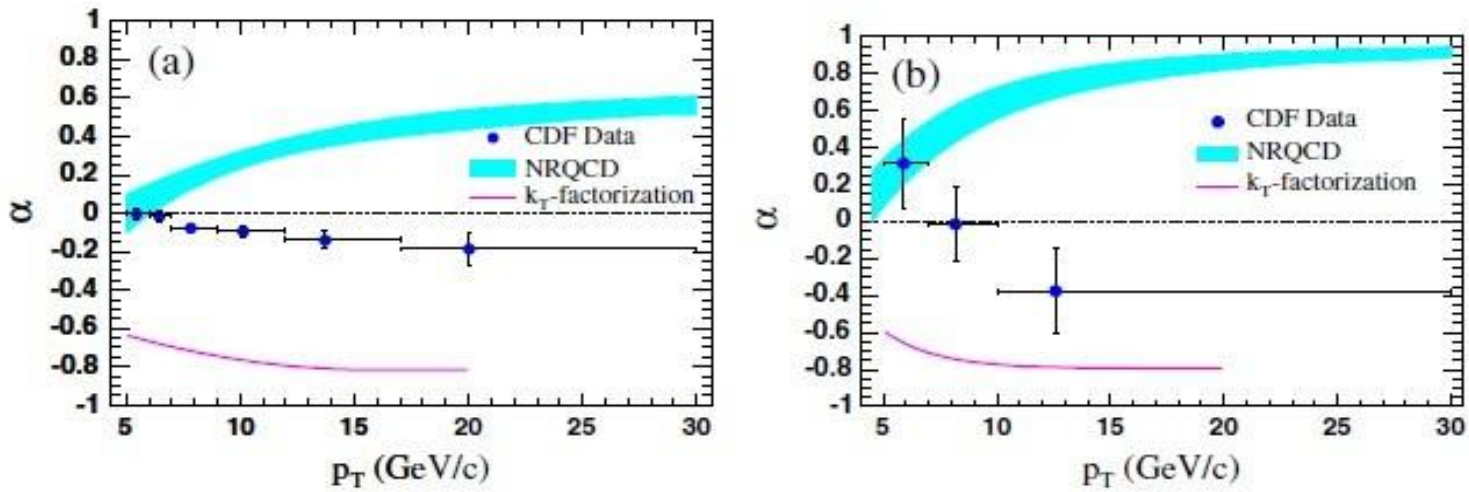


FIG. 4 (color online). Prompt polarizations as functions of p_T: (a) J/ψ and (b) $\psi(2S)$. The band (line) is the prediction from NRQCD [4] (the k_T-factorization model [9]).

High order calculation for J/ψ production in pp

- 0703113: Campbell, Maltoni, Tramontano

NLO, cross section, S-wave

- 0802.3727: Gong, Wang

NLO, polarization, S-wave

- 0806.3282: Artoisenet, Campbell, Lansberg, Maltoni, Tramontano

NNLO*, S-wave

- 1002.3987: YQM, Wang, Chao
- 1009.3655: YQM, Wang, Chao
- 1009.5662: Butenschöen, Kniehl

Complete NLO (S- and P-wave), cross section

- 1201.1872: Butenschöen, Kniehl
- 1201.2675: Chao,YQM,Shao,Wang,Zhang
- 1205.6682: Gong,Wan,Wang,Zhang

Complete NLO (S- and P-wave), with polarization

- 1403.3612: Bodwin, Chung, Kim, Lee
- 1509.07904: Bodwin, Chao, Chung, Kim, Lee, YQM

Resummation of leading power

NOT fully comprehensive!!!

What we learn?

- Transverse polarization proportional to

$$\mathrm{M}'_1 = \langle O\left({}^3\mathrm{S}_1^{[8]}\right)\rangle - 0.52\,\langle O\left({}^3\boldsymbol{P}_0^{[8]}\right)\rangle/m_c^2$$

Chao,YQM,Shao,Wang,Zhang,1201.2675

- Fit to J/ψ cross section requires a very small

$$\mathrm{M}_1 = \langle O\left({}^3\mathrm{S}_1^{[8]}\right)\rangle - 0.56\,\langle O\left({}^3\boldsymbol{P}_0^{[8]}\right)\rangle/m_c^2$$

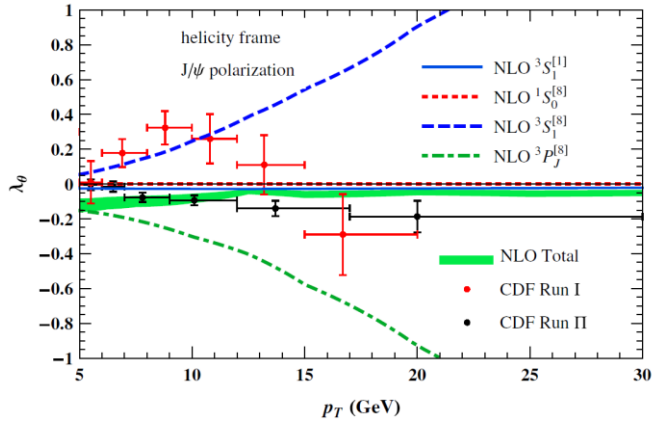
YQM, Wang, Chao, 1009.3655

➢ **Cross section requires small transverse polarization—consistent with data!!!**

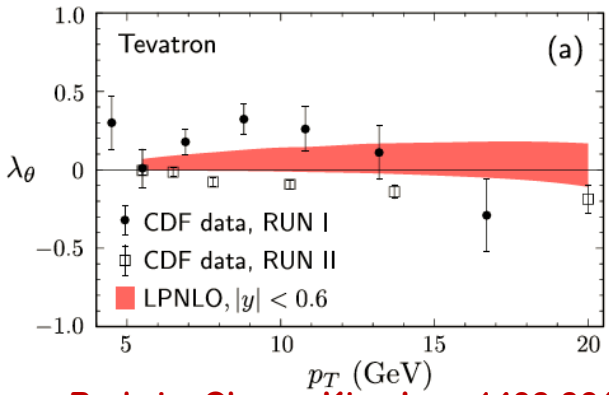
- Quantitatively modified by LP corrections, picture not changed

Explain J/ψ polarization

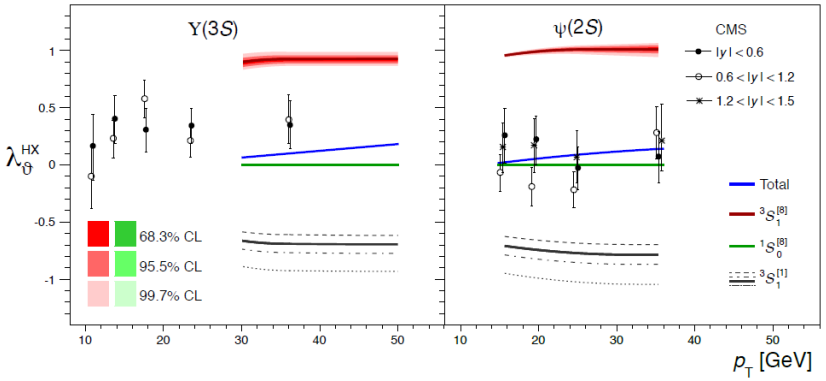
- Transverse polarization cancelled between ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ channel, ${}^1S_0^{[8]}$ may dominate



Chao,YQM,Shao,Wang,Zhang,1201.2675



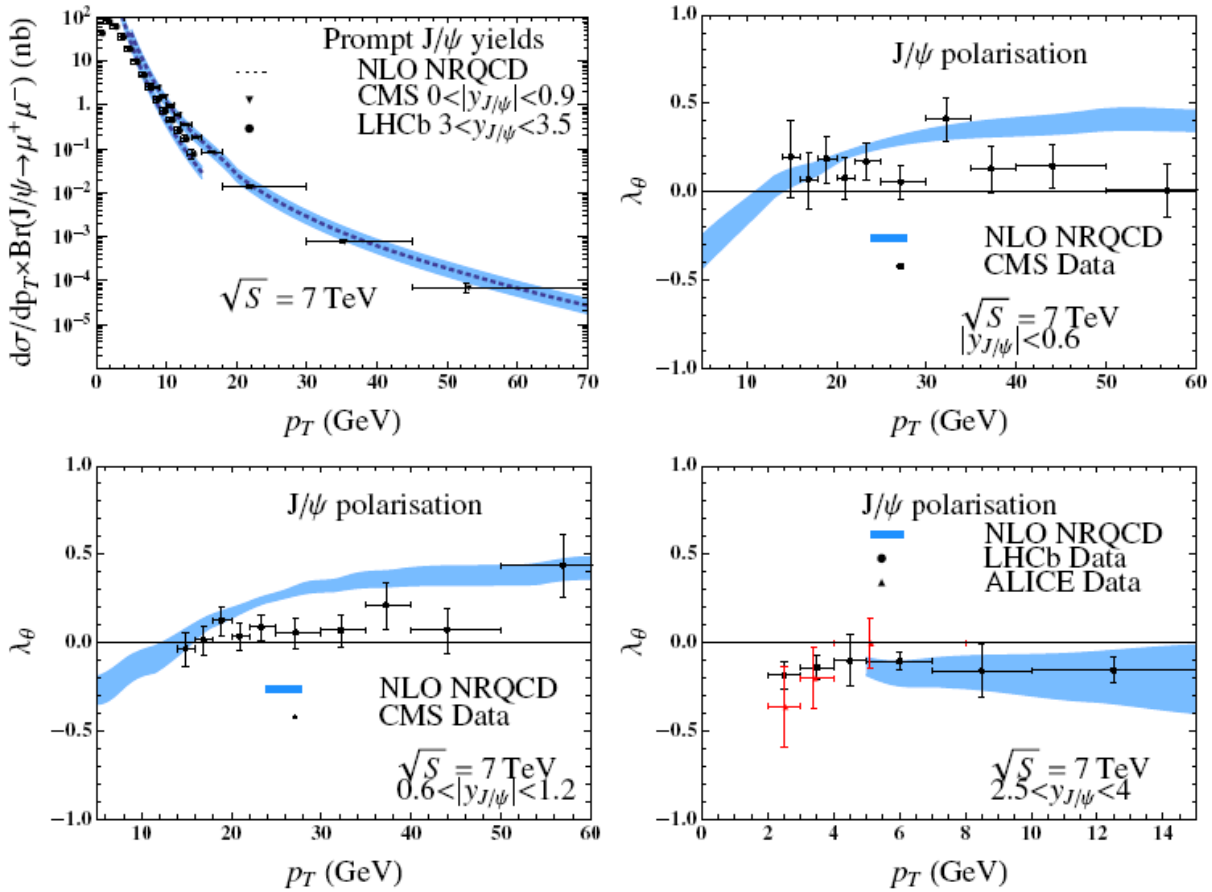
Bodwin, Chung, Kim, Lee, 1403.3612



Faccioli,Knunz,Lourenco,Seixas,Wohri,1403.3970

J/ψ theory V.S. data

- **Roughly consistent with data**



Han,YQM, Meng, Shao, Chao,1411.7350

Why $\Upsilon(\mathrm{nS})$ production?

- m_b **much larger than** m_c
  - Smaller α_s and v, better convergence on the double expansion

- **A similar system with** J/ψ
  - Test the theory that explains J/ψ production

High order calculation for Υ production in pp

- 1202.6012: Wang, YQM, Chao

  Complete NLO, no polarization

- 1305.0748: Gong, Wan, Wang, Zhang

  Complete NLO, fit polarization, no $\chi_b(3P)$

- 1410.8537: Han, YQM, Meng, Shao, Zhang, Chao (arXiv version not updated yet)

  Complete NLO, predict polarization, $\chi_b(3P)$

- 1503.08439: Feng, Gong, Wan, Wang

  Complete NLO, fit polarization, $\chi_b(3P)$

In the following talk

Parameters

- $\Upsilon(\mathrm{nS})$ **LDMEs**

$$\cancel{\langle \mathcal{O}^{\Upsilon(nS)}(\,^3\boldsymbol{S}_1^{[1]})\rangle}$$
$$\langle \mathcal{O}^{\Upsilon(nS)}(\,^1\boldsymbol{S}_0^{[\mathbf{8}]})\rangle$$
$$\langle \mathcal{O}^{\Upsilon(nS)}(\,^3\boldsymbol{S}_1^{[\mathbf{8}]})\rangle$$
$$\langle \mathcal{O}^{\Upsilon(nS)}(\,^3P_0^{[\mathbf{8}]})\rangle$$

- $\chi_{bJ}(\mathrm{nP})$ **LDMEs**

$$\cancel{\langle \mathcal{O}^{\chi_b(n\mathrm{P})}(\,^3\mathrm{P}_\mathrm{J}^{[1]})\rangle}$$
$$\langle \mathcal{O}^{\chi_b(n\mathrm{P})}(\,^3\boldsymbol{S}_1^{[\mathbf{8}]})\rangle$$

- **CS LDMEs fixed by potential model**

- **Unknown branch ratios**

$$Br\big(\chi_{b\mathrm{J}}(3P) \to \Upsilon(mS)\gamma\big); \qquad \mathrm{J} = 0,1,2; \mathrm{m} = 1,2,3$$

Fix $\chi_{bJ}(3P)$ decay branch ratios

1. Assuming total decay widths of χ_{bJ} equal

$$\Gamma_{tot}(\chi_{bJ}(3P)) \approx \Gamma_{tot}(\chi_{bJ}(2P)) \approx \Gamma_{tot}(\chi_{bJ}(1P))$$

Inspired by $|R'_{3P}(0)|^2 \approx |R'_{2P}(0)|^2 \approx |R'_{1P}(0)|^2$

2. Taking $\Gamma(\chi_{bJ}(3P) \to \Upsilon(mS)\gamma)$ from potential model

Kwong, Rosner, (1988)

3. Unknown branch ratios

Br	$theory$	$Experiment[25]$
$\chi_{b1}(2P) \to \Upsilon(2S)$	15.6%	$19.9 \pm 1.9\%$
$\chi_{b1}(2P) \to \Upsilon(1S)$	9.7%	$9.2 \pm 0.8\%$
$\chi_{b2}(2P) \to \Upsilon(2S)$	8.3%	$10.6 \pm 2.6\%$
$\chi_{b2}(2P) \to \Upsilon(1S)$	7.3%	$7.0 \pm 0.7\%$

Br	$n=1$	$n=2$	$n=3$
$\chi_{b0}(3P) \to \Upsilon(nS)$	0.24%	0.22%	0.50%
$\chi_{b1}(3P) \to \Upsilon(nS)$	3.81%	3.68%	10.44%
$\chi_{b2}(3P) \to \Upsilon(nS)$	1.92%	1.91%	6.11%

Fit LDMEs

➢ Using data

1. $\Upsilon(nS)$ yield data by CMS and ATLAS
2. Diagonal yield ratio $R^{\chi_b(nP)}_{\Upsilon(\mathrm{nS})}$ and $R^{\chi_{b2}(1P)}_{\chi_{b1}(1P)}$ by LHCb and CMS, respectively

◆ To avoid possible nonperturbative effects, using only data with $p_T > 15GeV$

Fit LDMEs (con.)

- χ_{bJ}(nP) **LDMEs**

$$r(nP) \equiv \frac{\langle \mathcal{O}^{\chi_b(nP)}\left({}^3S_1^{[8]}\right)\rangle}{\langle \mathcal{O}^{\chi_b(nP)}\left({}^3P_J^{[1]}\right)\rangle / m_b^2}$$

$r(nP)$	$n=1$	$n=2$	$n=3$
This work	0.42 ± 0.05	0.62 ± 0.08	0.83 ± 0.22

- Υ(nS) **LDMEs**

$$\mathrm{M}_{0,r_0} \equiv \langle O\left({}^1\mathrm{S}_0^{[8]}\right)\rangle + r_0 \langle O\left({}^3\boldsymbol{P}_0^{[8]}\right)\rangle / m_b^2$$

$$\mathrm{M}_{1,r_1} \equiv \langle O\left({}^3\mathrm{S}_1^{[8]}\right)\rangle + r_1 \langle O\left({}^3\boldsymbol{P}_0^{[8]}\right)\rangle / m_b^2$$

	$\langle \mathcal{O}({}^3S_1^{[1]})\rangle$ GeV^3	M_{0,r_0} 10^{-2}GeV^3	M_{1,r_1} 10^{-2}GeV^3
$\Upsilon(1S)$	9.28	13.70 ± 1.11	1.17 ± 0.02
$\Upsilon(2S)$	4.63	6.07 ± 1.08	1.08 ± 0.20
$\Upsilon(3S)$	3.54	2.83 ± 0.07	0.83 ± 0.02

$\mathrm{M}_1/\mathrm{M}_0$ **increases with** n**, large than that of** J/ψ

Predictive power

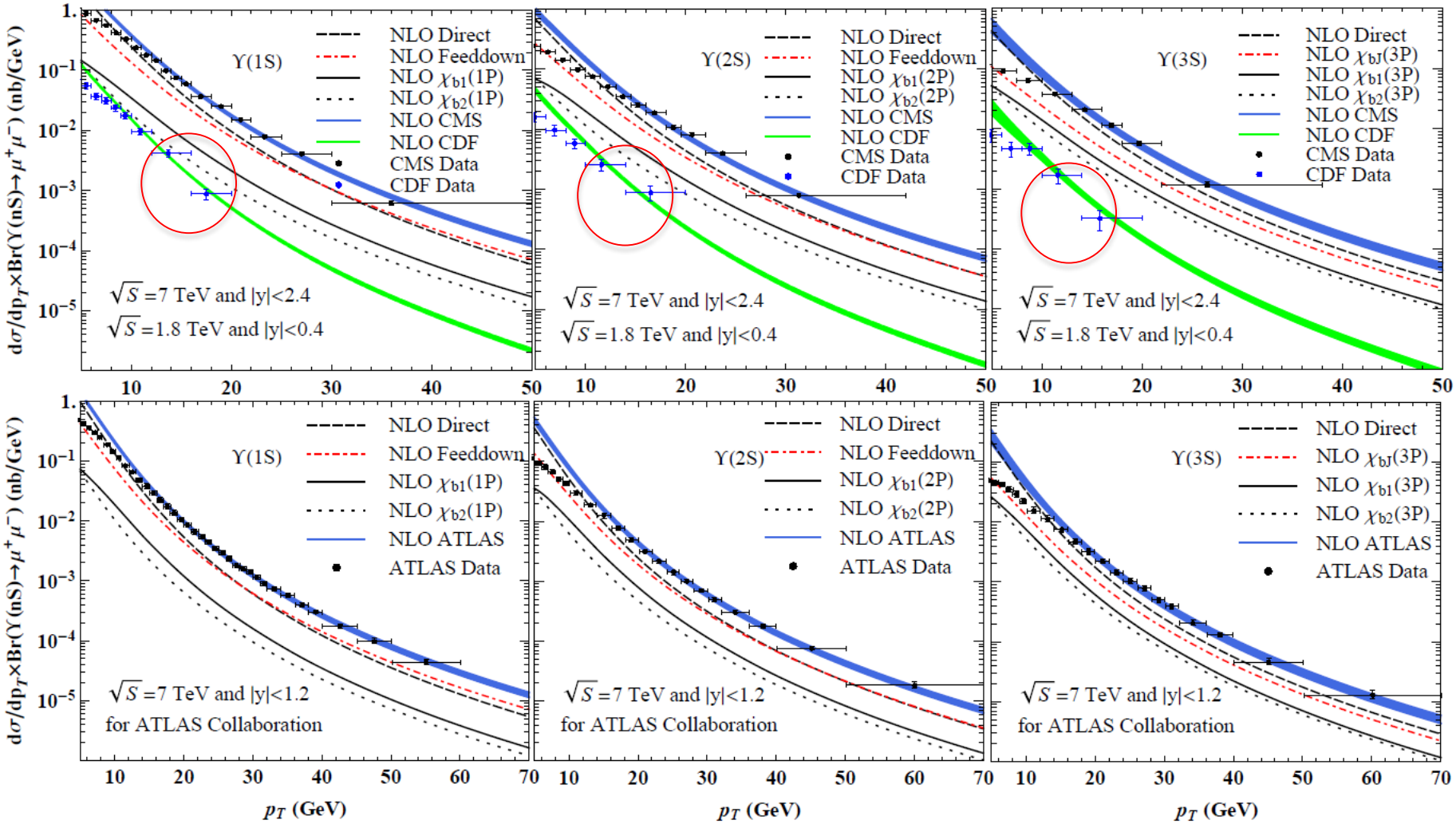
1. Yield of $\Upsilon(nS)$ by CDF

2. Off-diagonal yield ratio $R^{\chi_b(nP)}_{\Upsilon(\mathrm{mS})}$

3. Polarizations

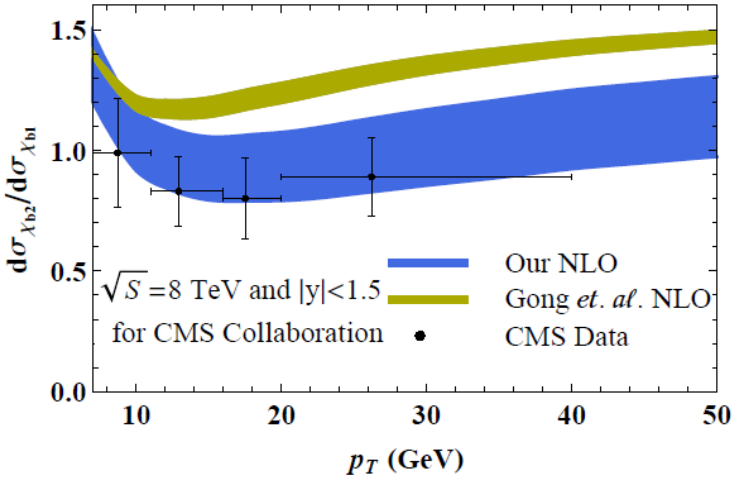
Yield of $\Upsilon(nS)$

Postdiction: with red circles



Ratios

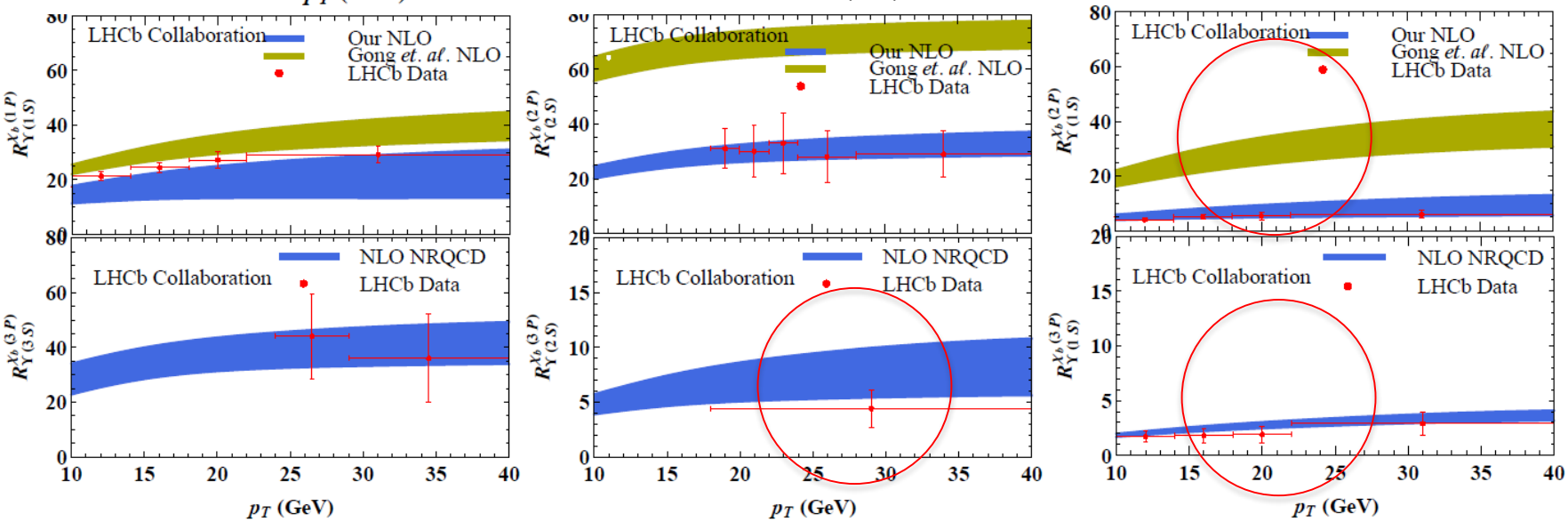
CMS $\sigma(\chi_{b2}(1P))/\sigma(\chi_{b1}(1P))$



Agreement of off-diagonal yield ratio

$R^{\chi_b(nP)}_{\Upsilon(mS)}$**: confirm our** $Br\left(\chi_{bJ}(3P) \to \Upsilon(mS)\gamma\right)$

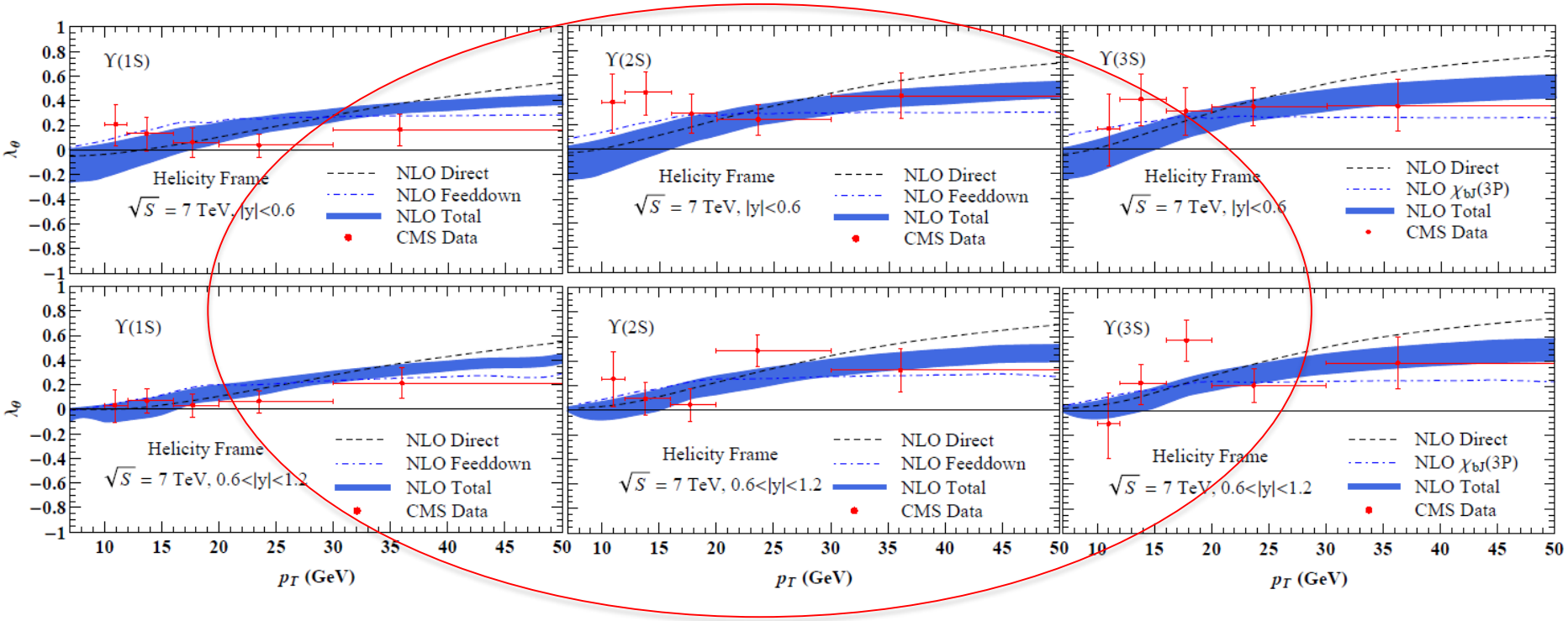
LHCb $R^{\chi_b(nP)}_{\Upsilon(mS)}$



ϒ polarization

➢ Good agreement

Big feeddown contribution help to reduce transverse polarization



Summary

- J/ψ: very small M_1/M_0 requires small transverse polarized contribution

- $\Upsilon(\mathrm{nS})$: M_1/M_0 larger, predict large transverse polarization at very high p_T in direct production

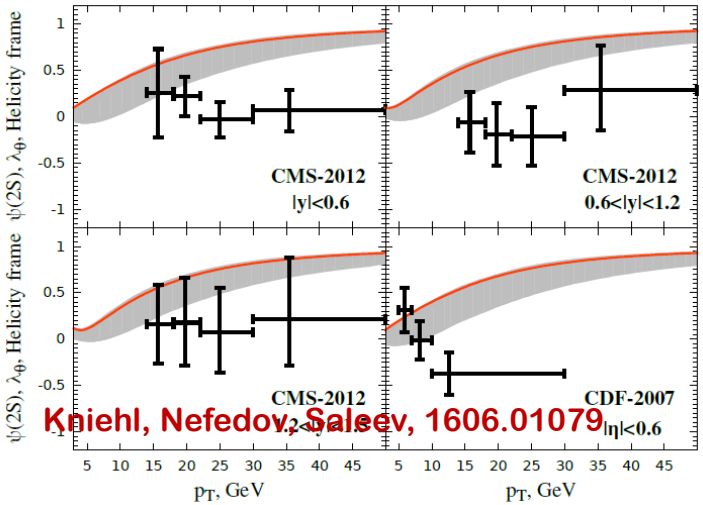
  p_T of data is not large enough right now

- Feeddown reduces transverse polarization

Fit yield data, give correct polarization predictions

Outlook

- Polarization of $\psi(2S)$ is still a puzzle, M_1/M_0 large, p_T large, no feeddown contribution



Kniehl, Nefedov, Saleev, 1606.01079

- Interpretation of η_c production still under debate

See Bernd Kniehl's talk and Round Table

- High p_T resummation maybe important to understand these puzzles

See Hee-Sok Chung's talk and Hong Zhang's talk

Thank you!