η_c' Hadroproduction at NLO and Its Relevant to ψ' Production

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MOTIVATION

- Why we are interested in $\eta_{c,b}$ and $h_{c,b}$?

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- Test heavy quark spin symmetry Bodwin, Braaten, Lepage (1995)

$$\eta_c \leftrightarrow J/\psi \qquad\qquad h_c \leftrightarrow \chi_c$$

$$\langle \mathcal{O}^{\eta_c}({}^1S_0^{[1,8]})\rangle = \langle \mathcal{O}^{J/\psi}({}^3S_1^{[1,8]})\rangle/3 \qquad \langle \mathcal{O}^{h_c}({}^1S_0^{[8]})\rangle = 3\langle \mathcal{O}^{\chi_{c0}}({}^3S_1^{[8]})\rangle$$

$$\langle \mathcal{O}^{\eta_c}({}^1P_1^{[8]})\rangle = 3\langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]})\rangle \qquad \langle \mathcal{O}^{h_c}({}^1P_1^{[1]})\rangle = 3\langle \mathcal{O}^{\chi_{c0}}({}^3P_0^{[1]})\rangle$$

$$\langle \mathcal{O}^{\eta_c}({}^3S_1^{[8]})\rangle = \langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]})\rangle$$

Power counting	η_c, η_b	$J/\psi, \psi(2S), \Upsilon$	h_c, h_b	χ_{cJ}, χ_{bJ}
v^3	${}^1S_0^{[1]}$	${}^3S_1^{[1]}$	–	–
v^5	–	–	${}^1P_1^{[1]}, {}^1S_0^{[8]}$	${}^3P_J^{[1]}, {}^3S_1^{[8]}$
v^7	${}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^1P_1^{[8]}$	${}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_J^{[8]}$	–	–

MOTIVATION

- HQSS basically plays a central role in quarkonium physics
- In quarkonium production, we always assumed

$$\langle \mathcal{O}^{\chi_{QJ}}({}^3P_J^{[1]})\rangle = (2J+1)\langle \mathcal{O}^{\chi_{Q0}}({}^3P_0^{[1]})\rangle$$
$$\langle \mathcal{O}^{\chi_{QJ}}({}^3S_1^{[8]})\rangle = (2J+1)\langle \mathcal{O}^{\chi_{Q0}}({}^3S_1^{[8]})\rangle$$
$$\langle \mathcal{O}^{\psi}({}^3P_J^{[8]})\rangle = (2J+1)\langle \mathcal{O}^{\psi}({}^3P_0^{[8]})\rangle$$

- In quarkonium polarisation, it is assumed no spin-flip for electric (like) dipole transitions

$$\hat{S}_z \left| c\bar{c}({}^3S_1^{[8]}) \right\rangle = \hat{S}_z \left| \psi \right\rangle$$ two E1 transitions

$$\hat{S}_z \left| c\bar{c}({}^3P_J^{[8]}) \right\rangle = \hat{S}_z \left| \psi \right\rangle$$ an E1 transition

- NRQCD velocity scaling rule tells us the above equations are violated only by higher-order in v^2

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HEAVY QUARKONIUM PHYSICS

hep-ph/0412158

QWG

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- It was suggested to look at η_c in 2004
- It was overlooked since then because of "difficult to measure"

$$\eta_c \to \gamma\gamma$$

overwhelmed by background

variation has also been observed in a ratio of production rates of P-wave states, namely the χ_{c1} to χ_{c2} ratio. More precise measurements of these and other ratios would be valuable. Of particular importance would be measurements of ratios of production rates of spin-singlet and spin-triplet quarkonium states, such as the η_c to J/ψ ratio. The absence of clean signatures for spin-singlet quarkonium states makes such measurements difficult.

LHC MEASUREMENTS ON 1S

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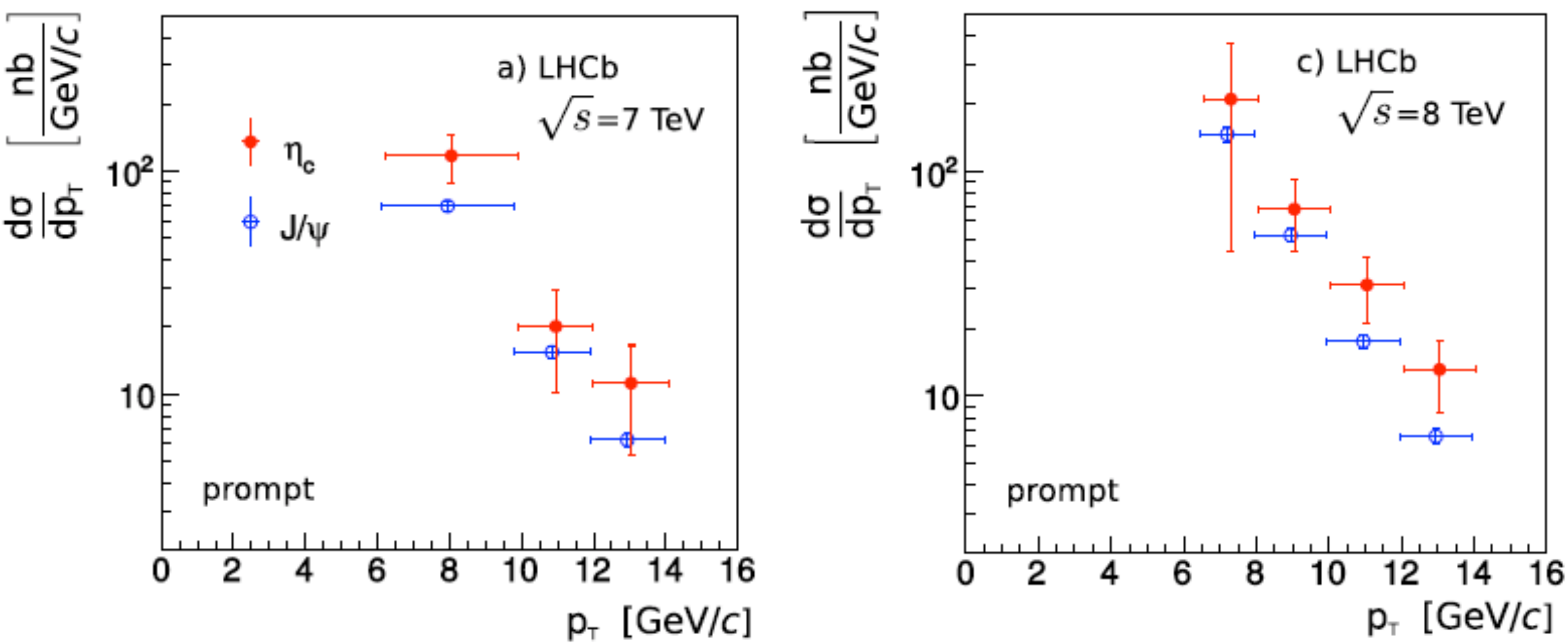
- It was proposed to use $\eta_c \to p\bar{p}$ in 2012

  Barsuk, He, Kou, Viaud (2012)

- In 2014, LHCb released a first measurement

  Aaij et al., (2014)



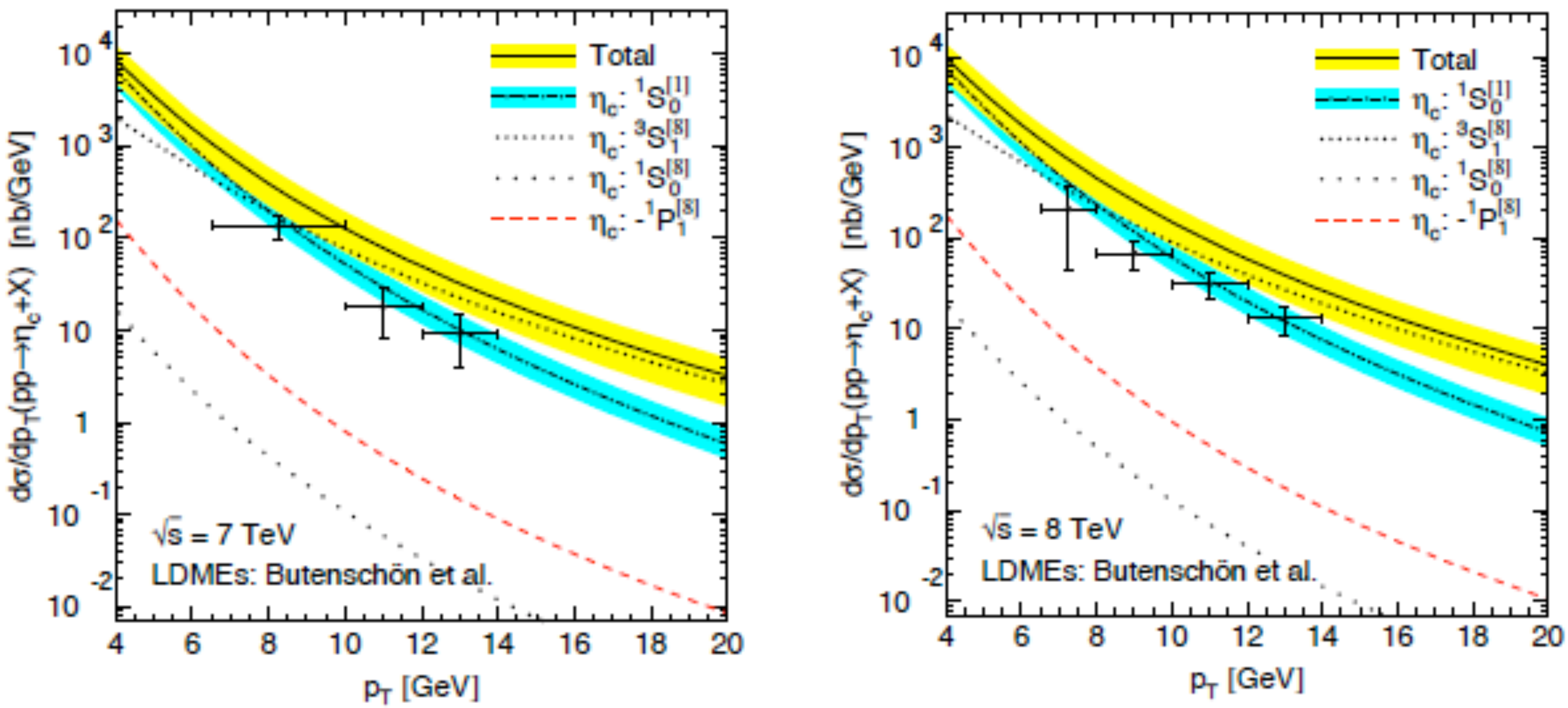
LHC MEASUREMENTS ON 1S

- The LHCb measurement inspires theoretical studies

Butenschoen, He, Kniehl, (2014); Han et al., (2014); Zhang et al., (2014)

- Global fit + HQSS greatly overshoot the LHCb data

Butenschoen, He, Kniehl, (2014)



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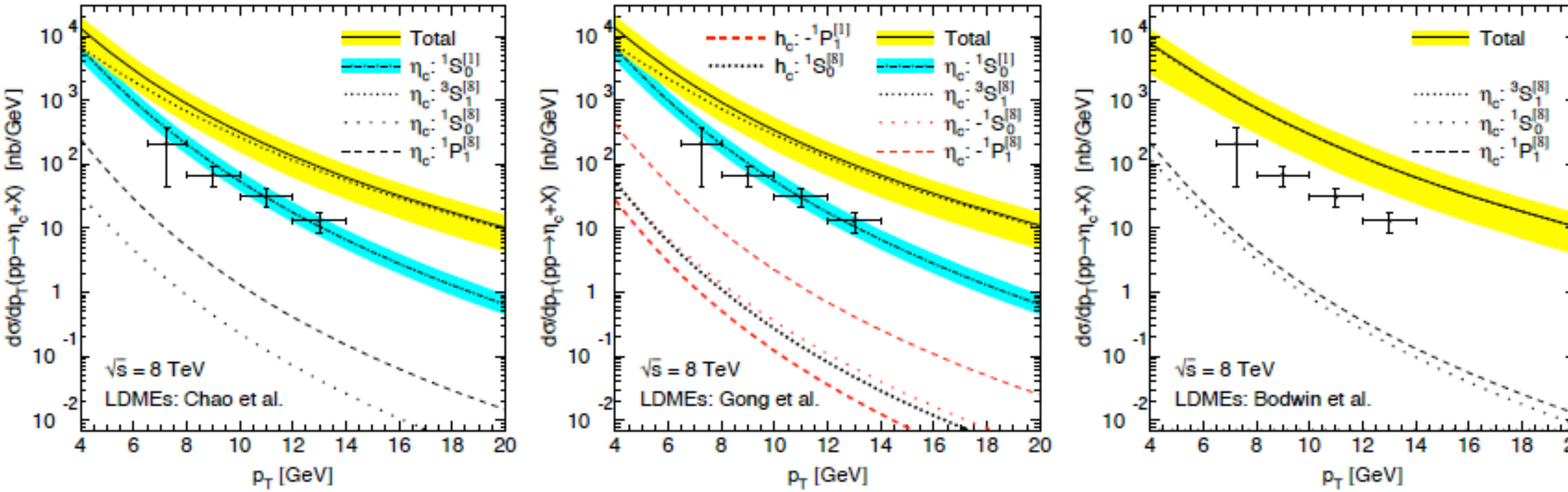
LHC MEASUREMENTS ON 1S

- Actually, the constrain is more powerful under HQSS

Butenschoen, He, Kniehl, (2014)



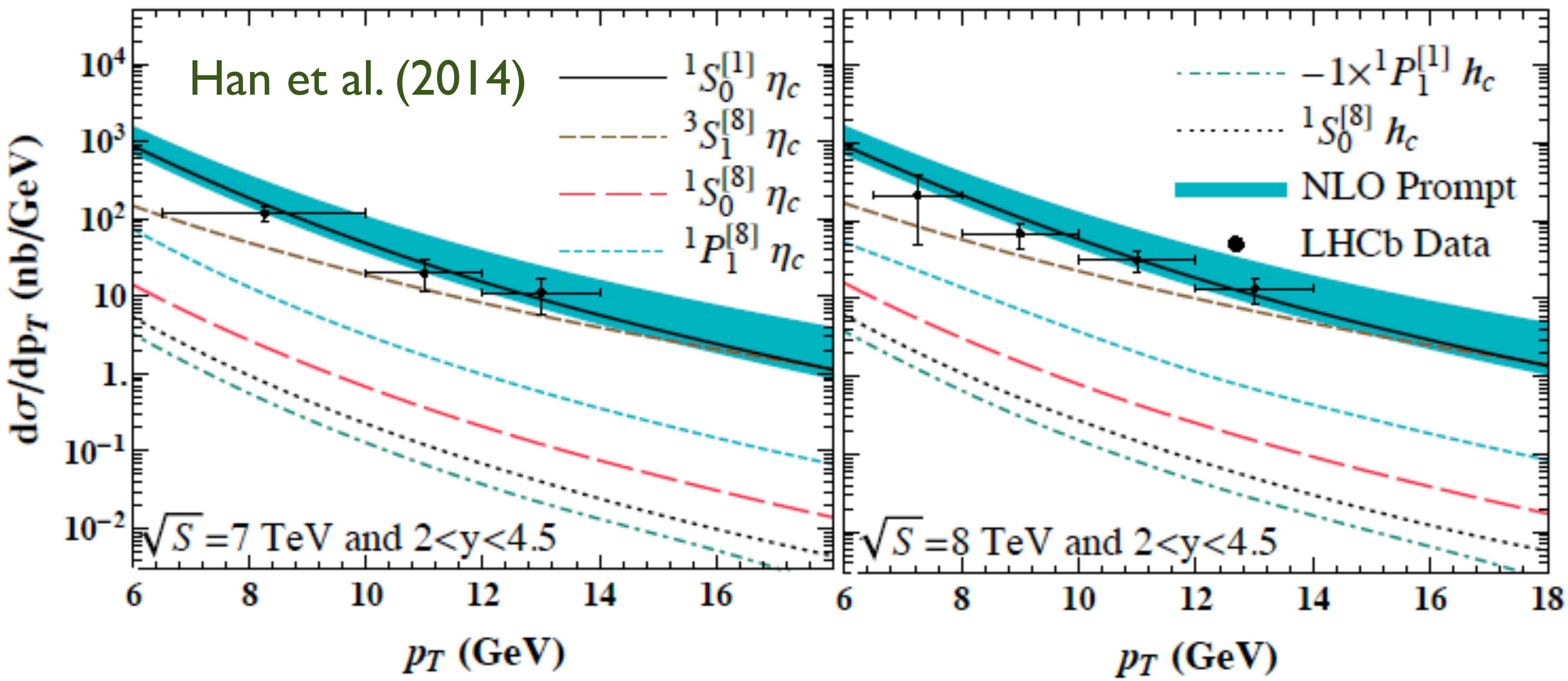
$\langle\mathcal{O}({}^3S_1^{[1]})\rangle$ GeV^3	$\langle\mathcal{O}({}^1S_0^{[8]})\rangle$ 10^{-2}GeV^3	$\langle\mathcal{O}({}^3S_1^{[8]})\rangle$ 10^{-2}GeV^3	$\langle\mathcal{O}({}^3P_0^{[8]})\rangle/m_c^2$ 10^{-2}GeV^3
1.16	8.9 ± 0.98	0.30 ± 0.12	0.56 ± 0.21
1.16	0	1.4	2.4
1.16	11	0	0

1. It excludes our central fit without FD
   Chao et al. (2012)
2. and other two fits based on large pT
   Gong et al. (2013); Bodwin et al. (2014)

LHC MEASUREMENTS ON 1S

- The measurement provides additional constraint on the LDME of J/psi based on HQSS
- Interestingly, the only relevant channels are

$$^1S_0^{[1]} \quad \text{and} \quad ^3S_1^{[8]}$$



- Colour-singlet alone works pretty well

LHC MEASUREMENTS ON 1S

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- LHCb data + HQSS helps to constrain $\langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]}) \rangle$

$$\langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]}) \rangle = \langle \mathcal{O}^{\eta_c}({}^3S_1^{[8]}) \rangle$$

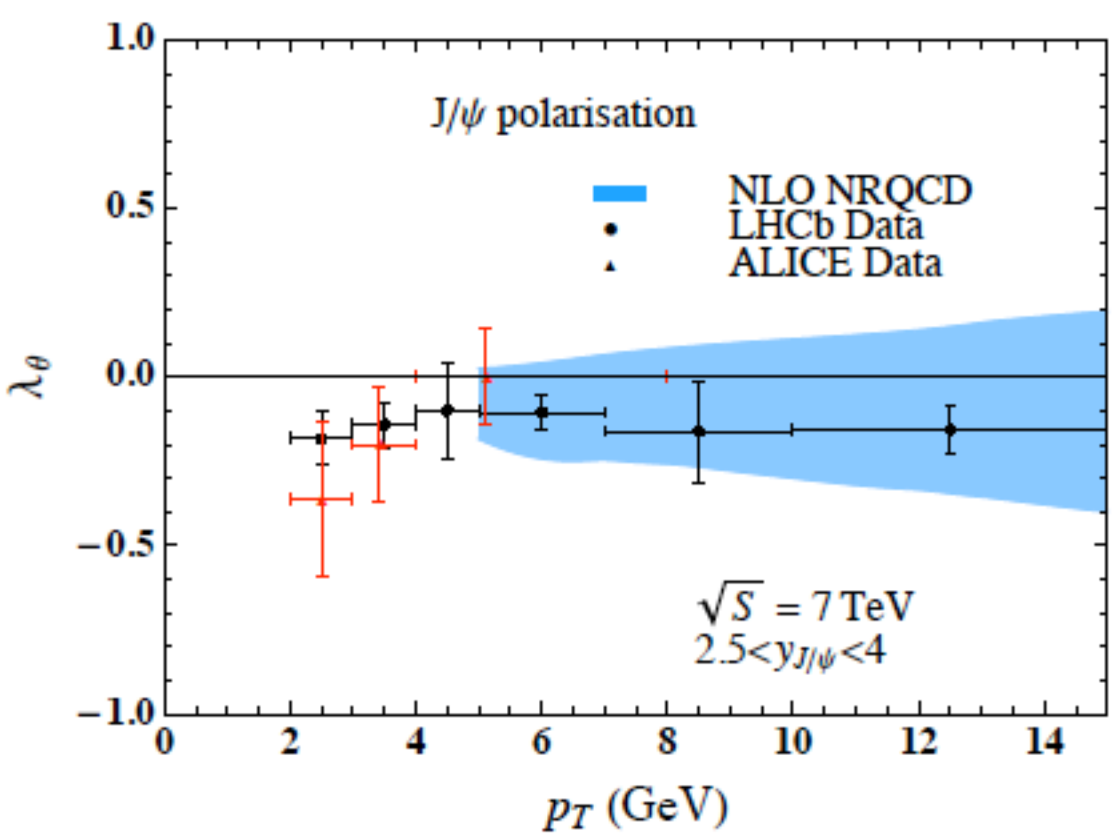
- A conservative upper limit was set via

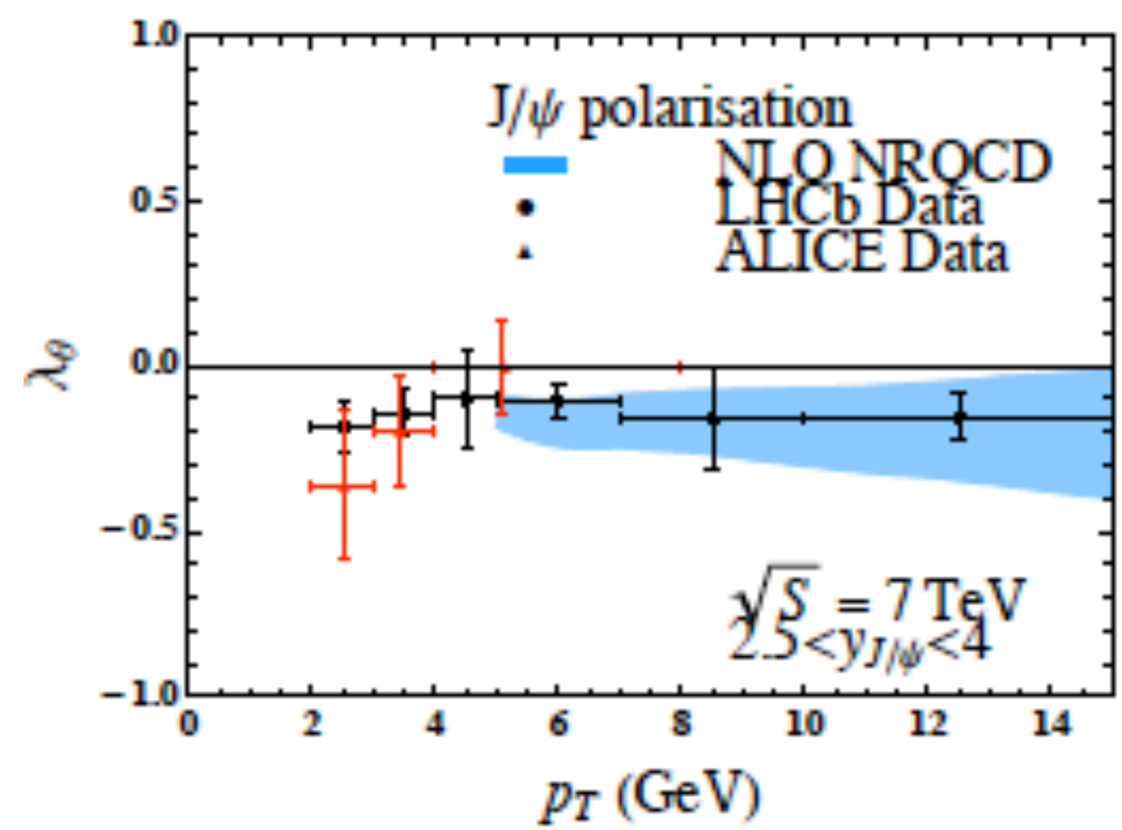
$$\langle \mathcal{O}^{\eta_c}({}^3S_1^{[8]}) \rangle \hat{\sigma}(c\bar{c}\left[{}^3S_1^{[8]}\right]) = \sigma_{\mathrm{LHCb\ data}}$$

Before

After Han et al. (2014)

$$0 < \langle \mathcal{O}^{\eta_c}({}^3S_1^{[8]}) \rangle < 1.46 \times 10^{-2}\ \mathrm{GeV}^3$$





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- Another upper limit without ignoring colour-singlet

$$\langle \mathcal{O}^{\eta_c}({}^3S_1^{[8]})\rangle \lesssim 5\times 10^{-3}\ \mathrm{GeV}^3$$

Lansberg (1903.09185)

- It challenges the simple interpretation of "$\langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]})\rangle$ dominance" in order to explain the unpolarised data

- How about the excited state η_c' ?
  - Is $\eta_c' \to p\bar{p}$ still feasible ? The channel is just seen !

$\Gamma(\eta_c(2S) \to p\bar{p})/\Gamma_{\text{total}}$ Γ_{14}/Γ

PDG 2018

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	106	[1] AAIJ	2017AD	LHCB	$p\,p \to B^+X \to p\bar{p}K^+X$

[1] AAIJ 2017AD report a 6.4 standard deviation signal, with B($B^+ \to \eta_c(2S)K^+ \to p\bar{p}K^+$)/B($B^+ \to J/\psi K^+ \to p\bar{p}K^+$) = 0.0158 ±0.0033 ±0.0009.

References:

AAIJ 2017AD PL B769 305 Observation of $\eta_c(2S) \to p\bar{p}$ and Search for $X(3872) \to p\bar{p}$ Decays

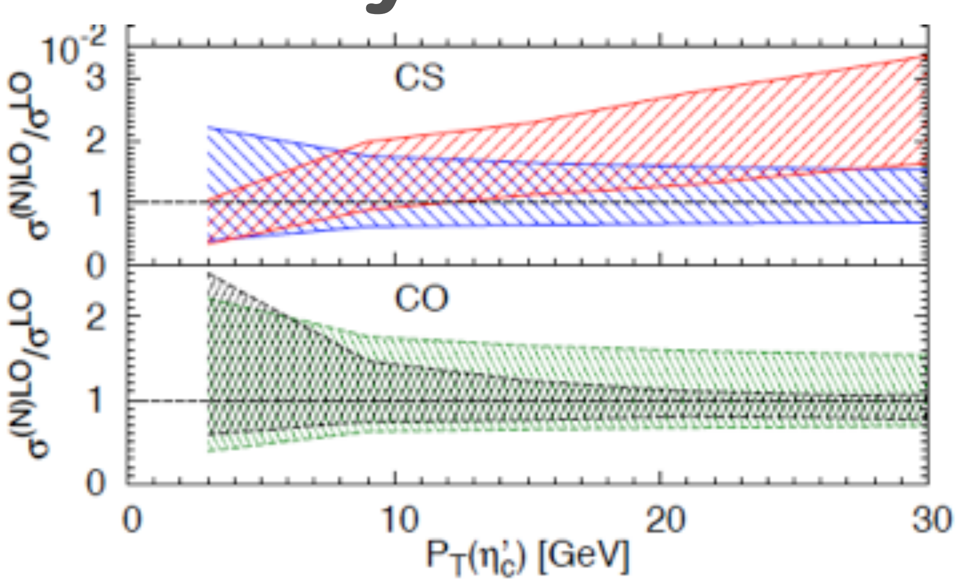
LHC FUTURE MEASUREMENTS ON 2S

- The possible decay channels at the LHCb

Lansberg, HSS, Zhang (2017)

Channel	η_c' ~~partial width~~ branching ratio	status
$p\bar{p}$	$(1.0 \pm 0.5) \times 10^{-4}$	measured
$\gamma\gamma$	$(1.9 \pm 1.2) \times 10^{-4}$	measured
$K\bar{K}\pi$	$(1.9 \pm 1.2) \times 10^{-2}$	measured
$\phi\phi$	$(1 \div 4) \times 10^{-4}$	extrapolated
$\Lambda\bar{\Lambda}$	$O(10^{-4})$	estimated
$\Xi\bar{\Xi}$	$O(10^{-4})$	estimated

- Like other (inclusive) quarkonium states, it is necessary to include NLO QCD at large pT



$^1S_0^{[1]}$ Giant K factor

$^3S_1^{[8]}$ Reduce scale uncertainty

LHC FUTURE MEASUREMENTS ON 2S

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- **Using different $\langle \mathcal{O}^{\psi'}(^1S_0^{[8]})\rangle$ extractions**

Reminding HQSS: $\langle \mathcal{O}^{\psi'}(^1S_0^{[8]})\rangle = \langle \mathcal{O}^{\eta_c'}(^3S_1^{[8]})\rangle$

Shao et al. (2014) Gong et al. (2013) Bodwin et al. (2015)

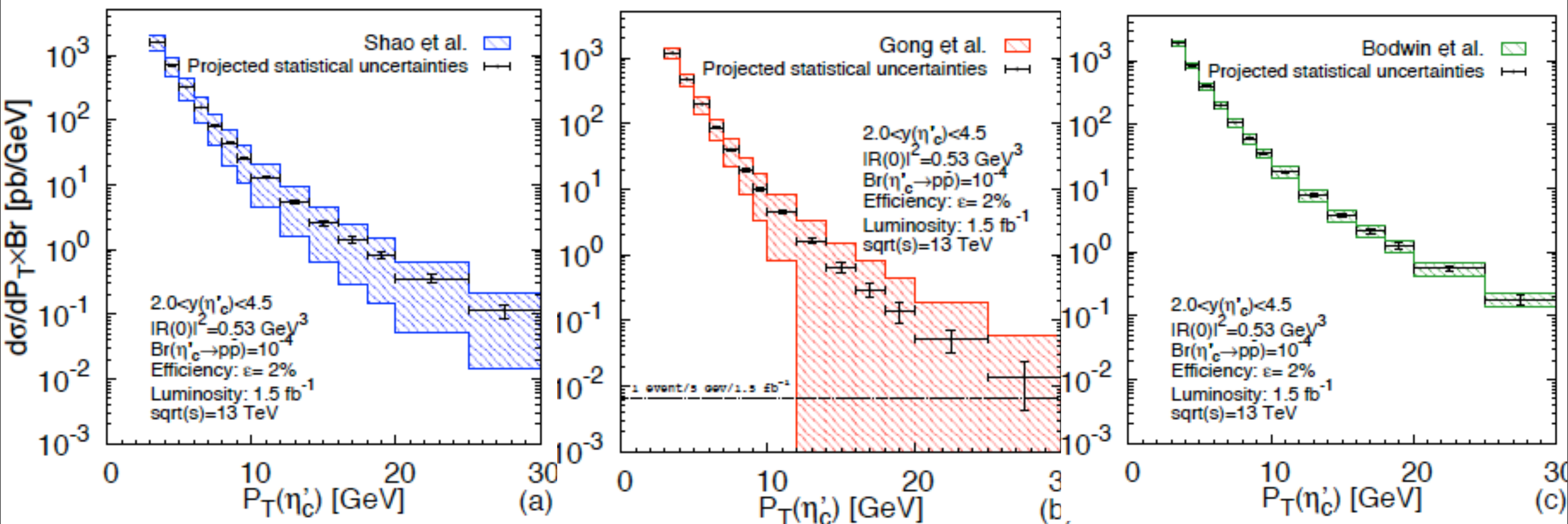
	Shao *et al.* [21]	Gong *et al.* [22]	Bodwin *et al.* [23]
$\langle \mathcal{O}^{\eta_c'}(^3S_1^{[8]})\rangle$ $[10^{-2}\ \mathrm{GeV}^3]$	$[0, 3.82]$	$[-0.881, 0.857]$	$[2.35, 3.93]$

LHC FUTURE MEASUREMENTS ON 2S

- As anticipated, the predicted yields strongly depend on $\langle \mathcal{O}^{\eta_c'}({}^3S_1^{[8]}) \rangle$

➡ Potential power to differentiate different extractions

Lansberg, HSS, Zhang (2017)



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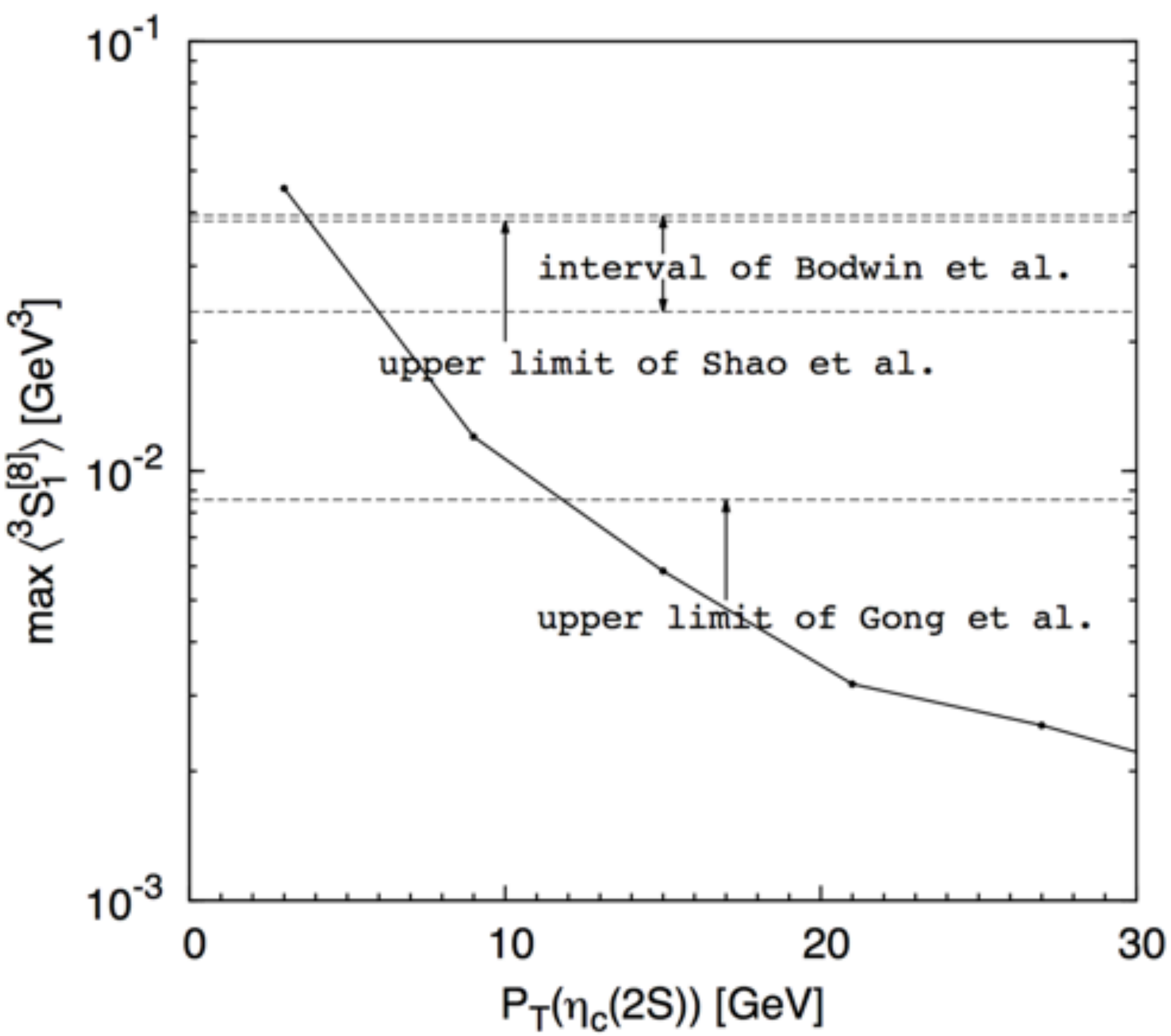
LHC FUTURE MEASUREMENTS ON 2S

- As anticipated, the predicted yields strongly depend on $\langle \mathcal{O}^{\eta_c'}({}^3S_1^{[8]}) \rangle$

➡ I would favor a larger p_T but less precise measurement than a smaller p_T and precise one



1. Like 1S state, by assuming the observed data described by CS alone

2. Use CO to saturate the data to draw a conservative upper limit

FINAL WORDS

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- NRQCD predicts HQSS should be hold also in the colour-octet sector, which definitely should be tested by experiments.
- η_c and η_c' provide very useful information of CO LDMEs of J/ψ and ψ', while the measurement of the former by the LHCb already gives us many surprises.
- Our study shows that there are already enough statistics to measure η_c' at the LHCb.
- To our LHCb colleagues, please also open a specific trigger window for η_c', like what you did for η_c in run I and run II.

I now welcome your comments