Impact of LHCb η_c Measurements on Theory

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LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

LHCb MiniWorkshop
CERN
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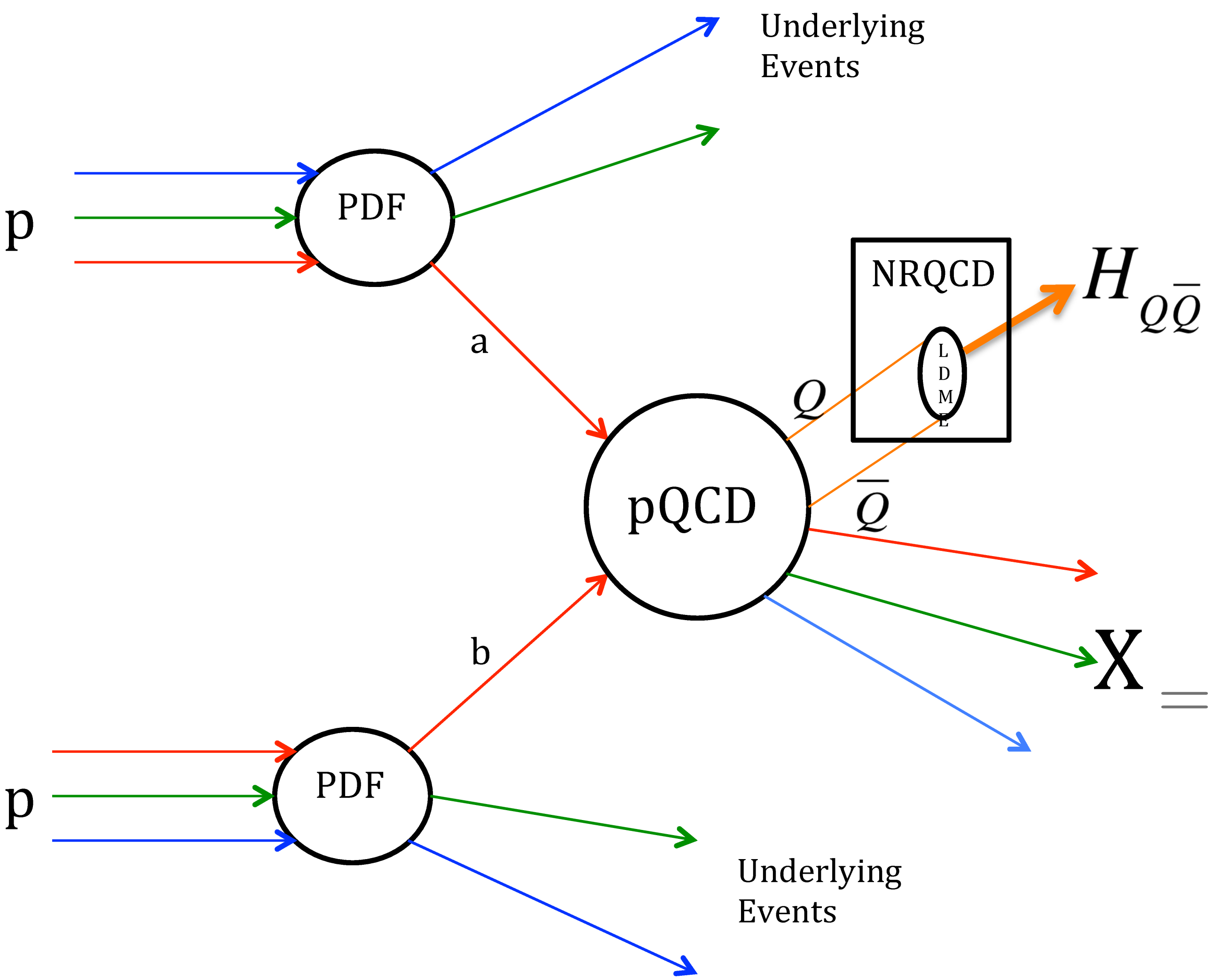
INCLUSIVE QUARKONIUM PRODUCTION
NRQCD FACTORIZATION



NRQCD factorization

$$d\sigma(pp \to H_{Q\bar{Q}} + X)$$
$$= \sum_n d\sigma(pp \to Q\bar{Q}[n] + X) \times \langle \mathcal{O}^{H_{Q\bar{Q}}}(n) \rangle$$

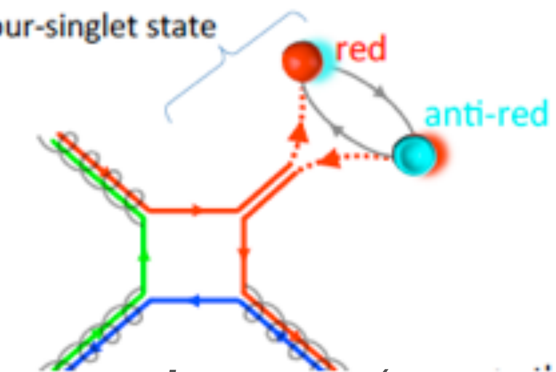
pQCD factorization

$$d\sigma(pp \to Q\bar{Q}[n] + X)$$
$$= \sum_{a,b} f_{a/p}(x_1) f_{b/p}(x_2) |\mathcal{A}(ab \to Q\bar{Q}[n] + X)|^2$$

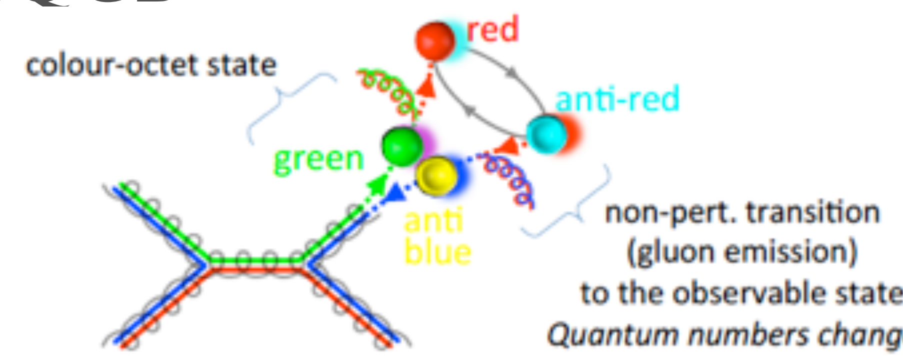
LDME $\langle \mathcal{O}^{H_{Q\bar{Q}}}(n) \rangle$ and PDF $f_{i/p}(x)$ are non-perturbative and (should be) universal.

QUARKONIUM PRODUCTION: INTRODUCTION

- **Experiment:** **easy to measure and many precise data are available**
- **Theory:** **various production models**
  - Color-Singlet Model (CSM) back in the game
    - *Pro: good performance; In the game for the total yields*
    - *Con: large QCD corrections; Insufficient to explain inclusive onium production (=onium+jet)*



  - Color-Octet Mechanism (COM) predicted by (NR)QCD
    - *Pro: helps to describe the P_T spectrum of inclusive onium*
    - *Con: debates on its magnitude; only partially works*



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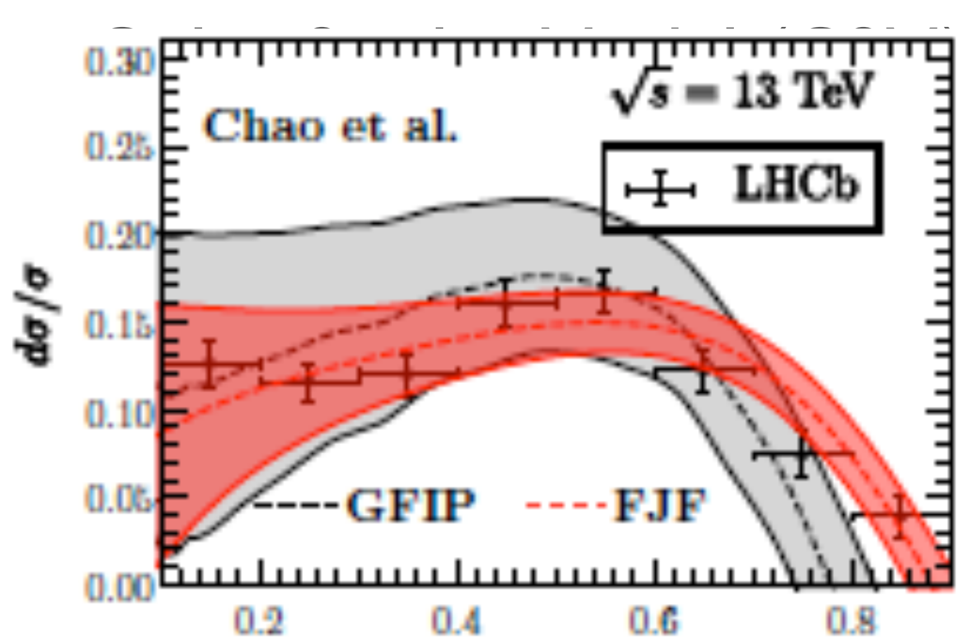

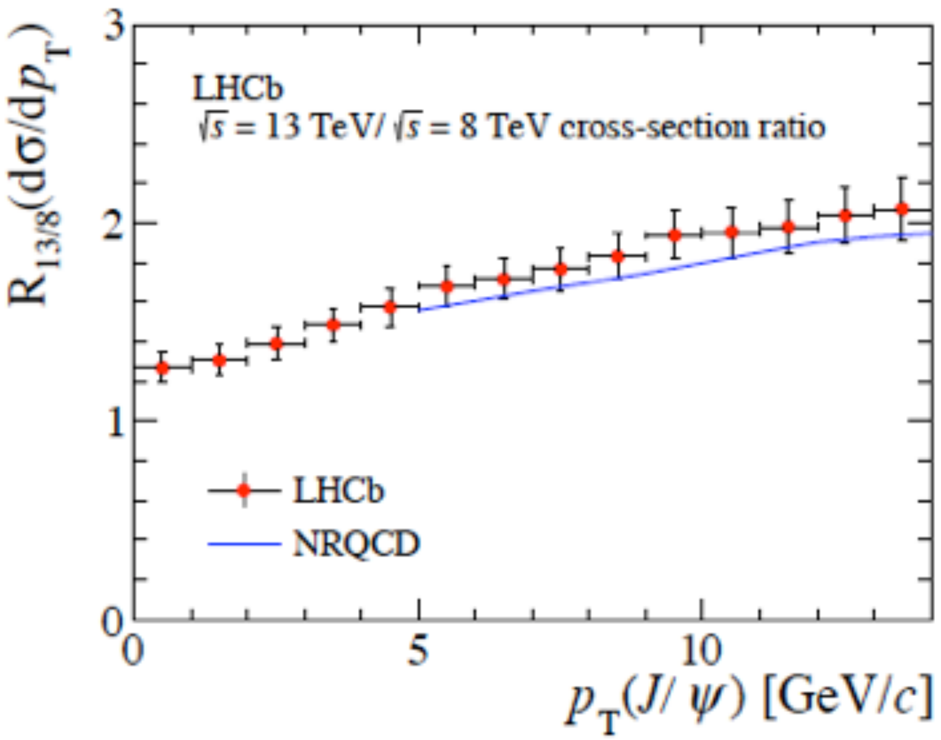

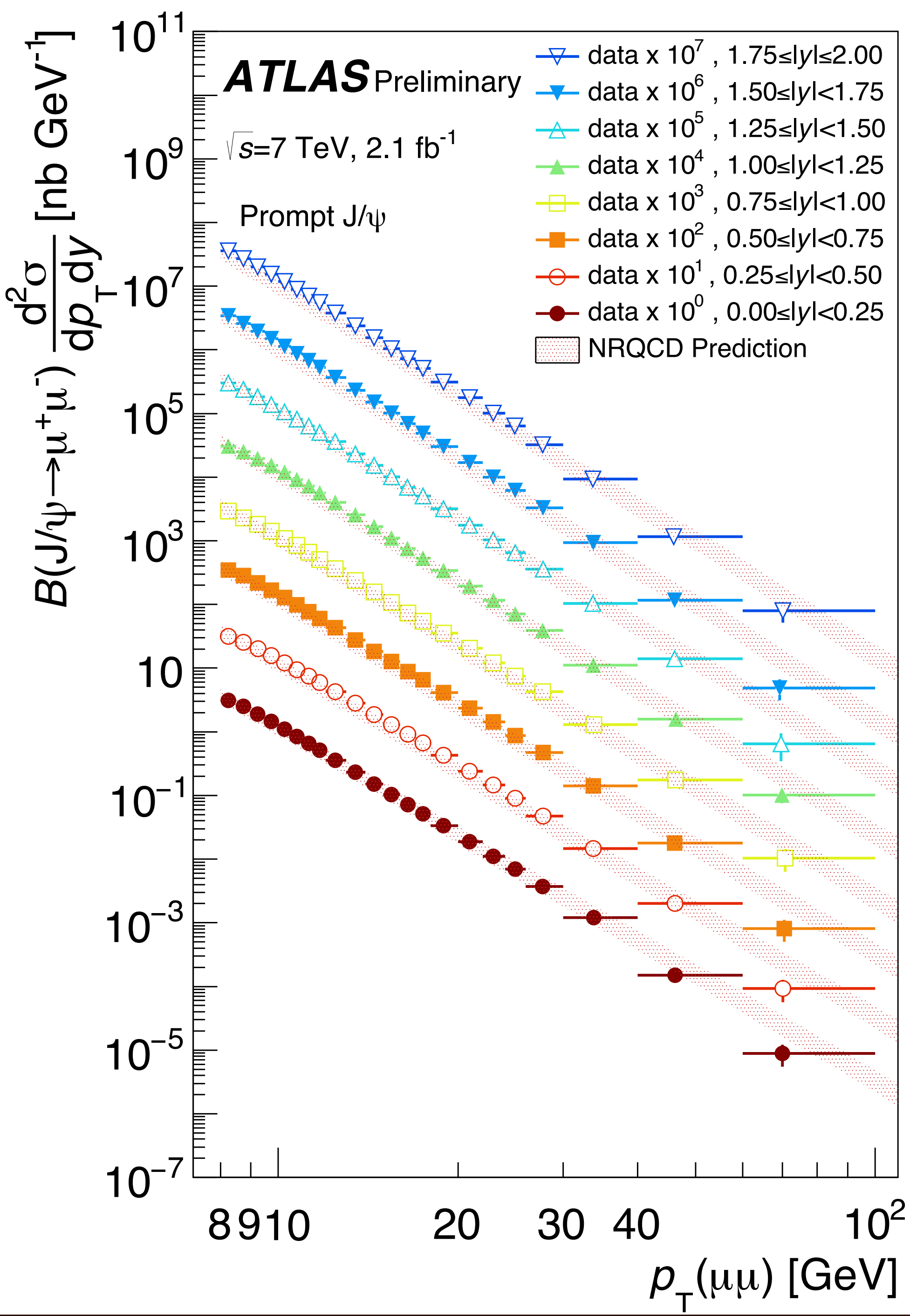

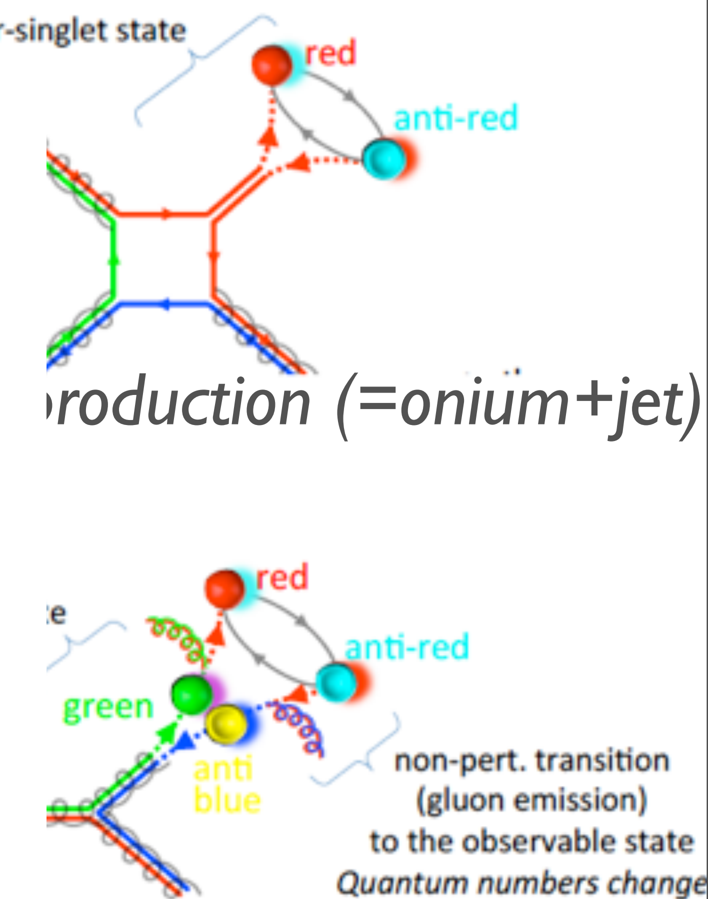

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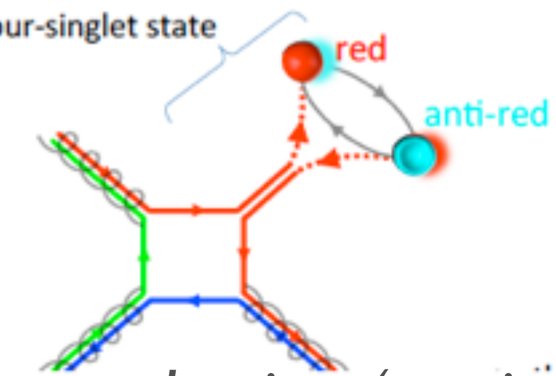

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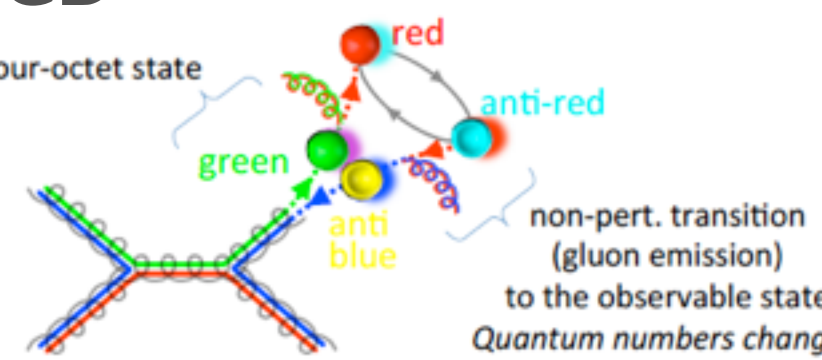

- All approaches have troubles in describing the onium inclusive production data
- This motivates the study of new observables which can be more discriminant for specific effects
- Quarkonium production at the LHC remains a very sensitive probe of the gluon density in the proton.

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

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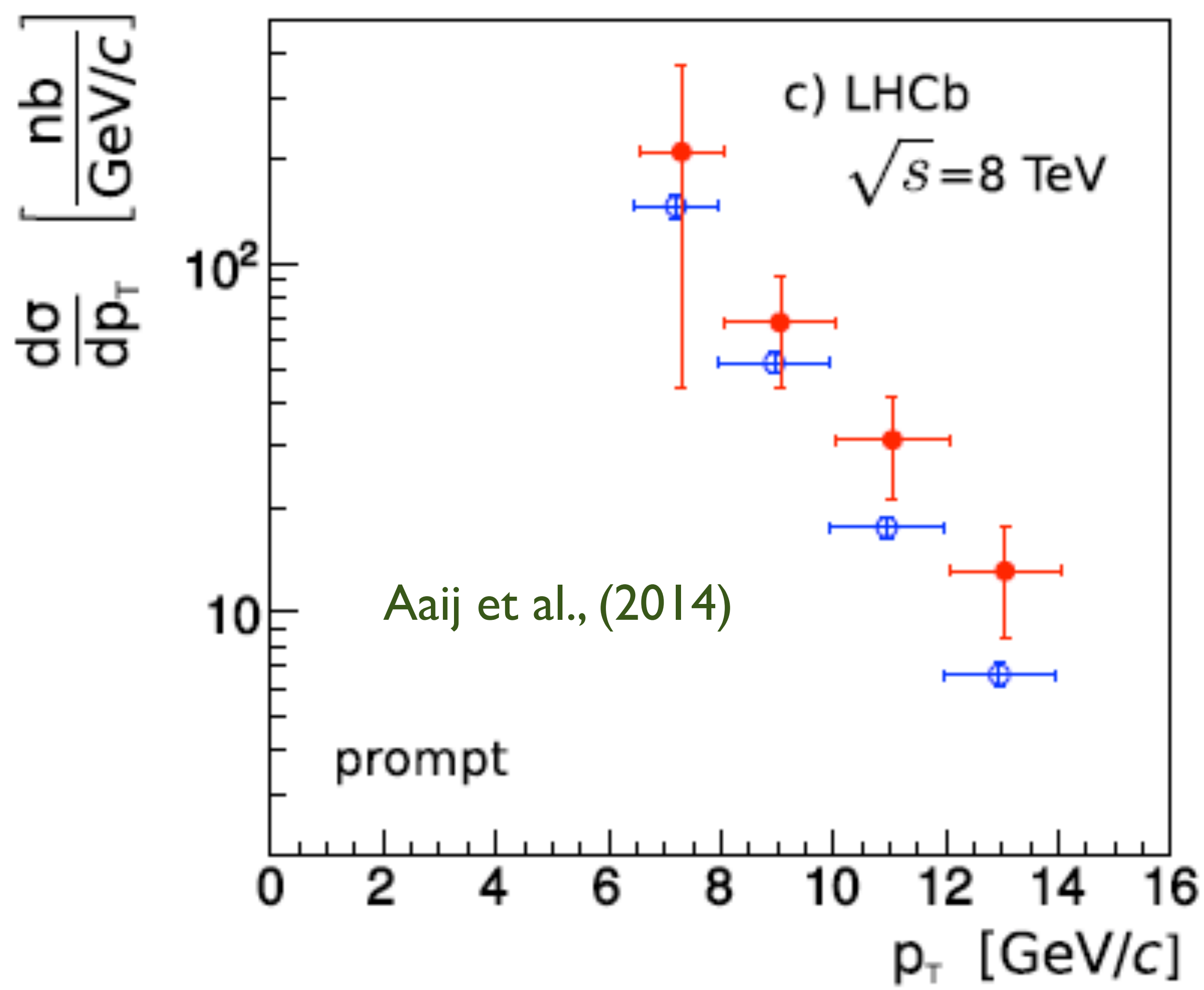
- LHCb has measured $\eta_c \to p\bar{p}$ Aaij et al., (2014)



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- No promising channel for searching η_b at the LHC ?
  - Looking at it decaying into $D^* D^{(*)}$? Maltoni, Polosa, (2004)

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  - Looking at it decaying into $D^* D^{(*)}$? Maltoni, Polosa, (2004)
- h_b is more challenging

HEAVY-QUARK SPIN SYMMETRY

- HQSS provides approximate relations between matrix elements for the various spin states
- HQSS is a symmetry in the nonrelativistic limit
- The leading violations of HQSS come from spin-flip terms at the relative order v^2

Charmonium: $v^2 \approx 0.3$ Bottomonium: $v^2 \approx 0.1$

- HQSS helps to reduce the number of nonpert. LDMEs: predictive power of NRQCD Bodwin, Braaten, Lepage, (1995)
- HQSS implies the wavefunction of η_c and ψ up to corrections of v^2

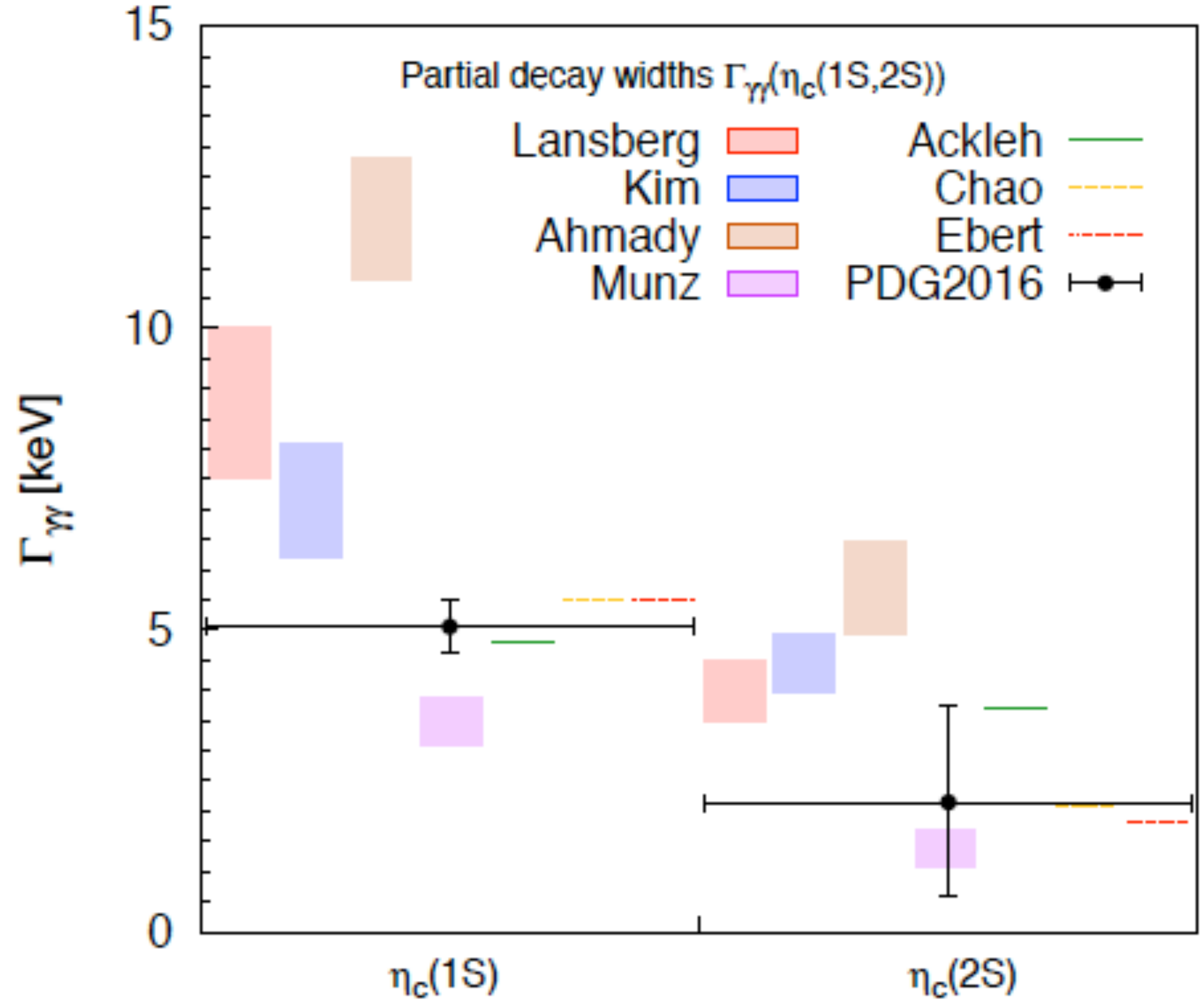
$$R_\psi(r) = R_{\eta_c}(r)\left(1 + O(v^2)\right)$$

- HQSS implies the simple spin counting of P-waves

$$\langle \mathcal{O}^{\psi}({}^3P_J^{[8]})\rangle = (2J+1)\langle \mathcal{O}^{\psi}({}^3P_0^{[8]})\rangle \qquad \langle \mathcal{O}^{\chi_J}({}^3P_J^{[1]})\rangle = (2J+1)\langle \mathcal{O}^{\chi_0}({}^3P_0^{[1]})\rangle$$

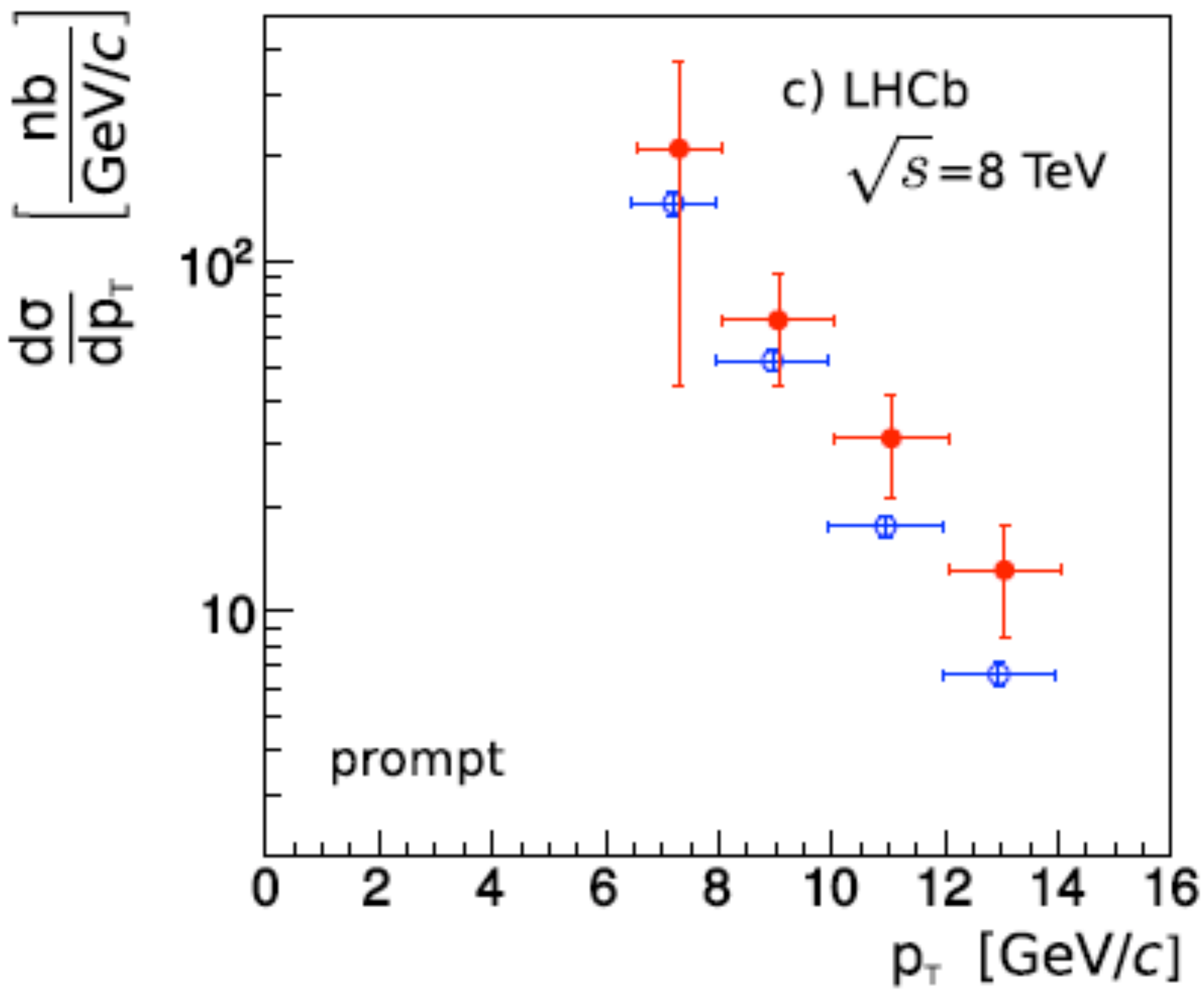
HEAVY-QUARK SPIN SYMMETRY

- HQSS implies the spin-flip is suppressed in polarization observables
- The experimental test of HQSS is mainly in the color-singlet part (and in decay) so far



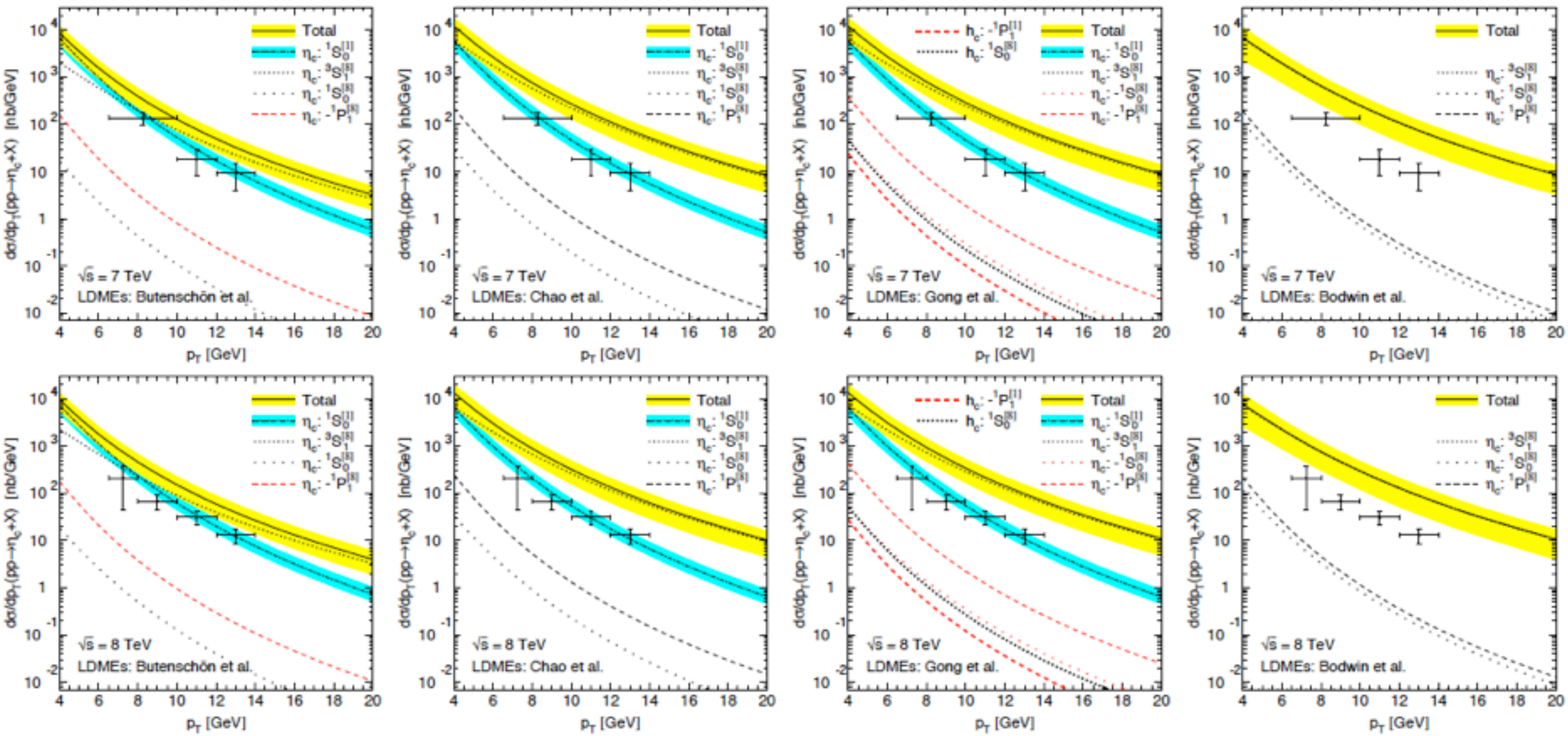
INCLUSIVE ETA_C PRODUCTION

- LHCb has measured η_c production Aaij et al., (2014)



INCLUSIVE ETA_C PRODUCTION

- **LHCb has measured η_c production** Aaij et al., (2014)
- **It triggers several theoretical calculations**
  - Hamburg group Butenschoen, He and Kniehl '15 : claim nothing work !



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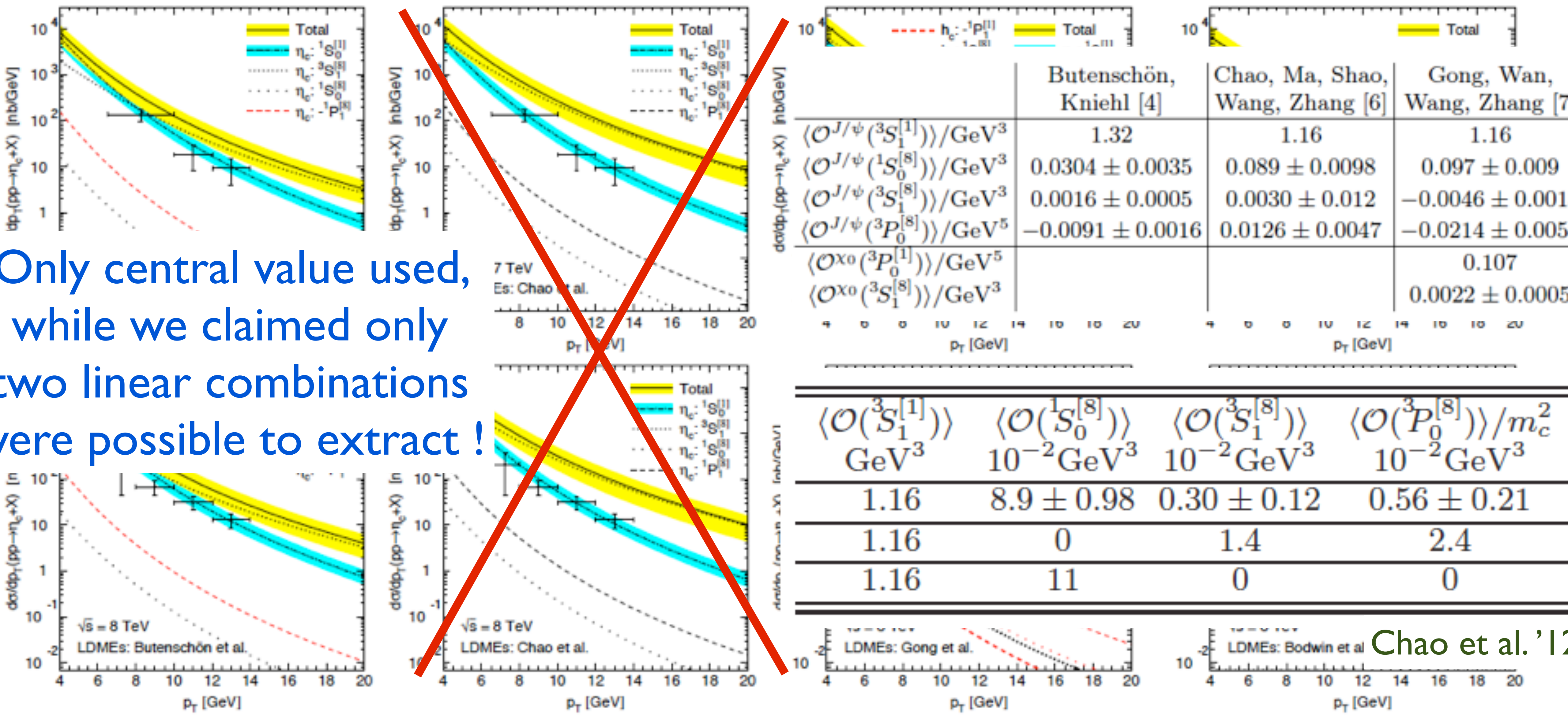


Only central value used, while we claimed only two linear combinations were possible to extract !

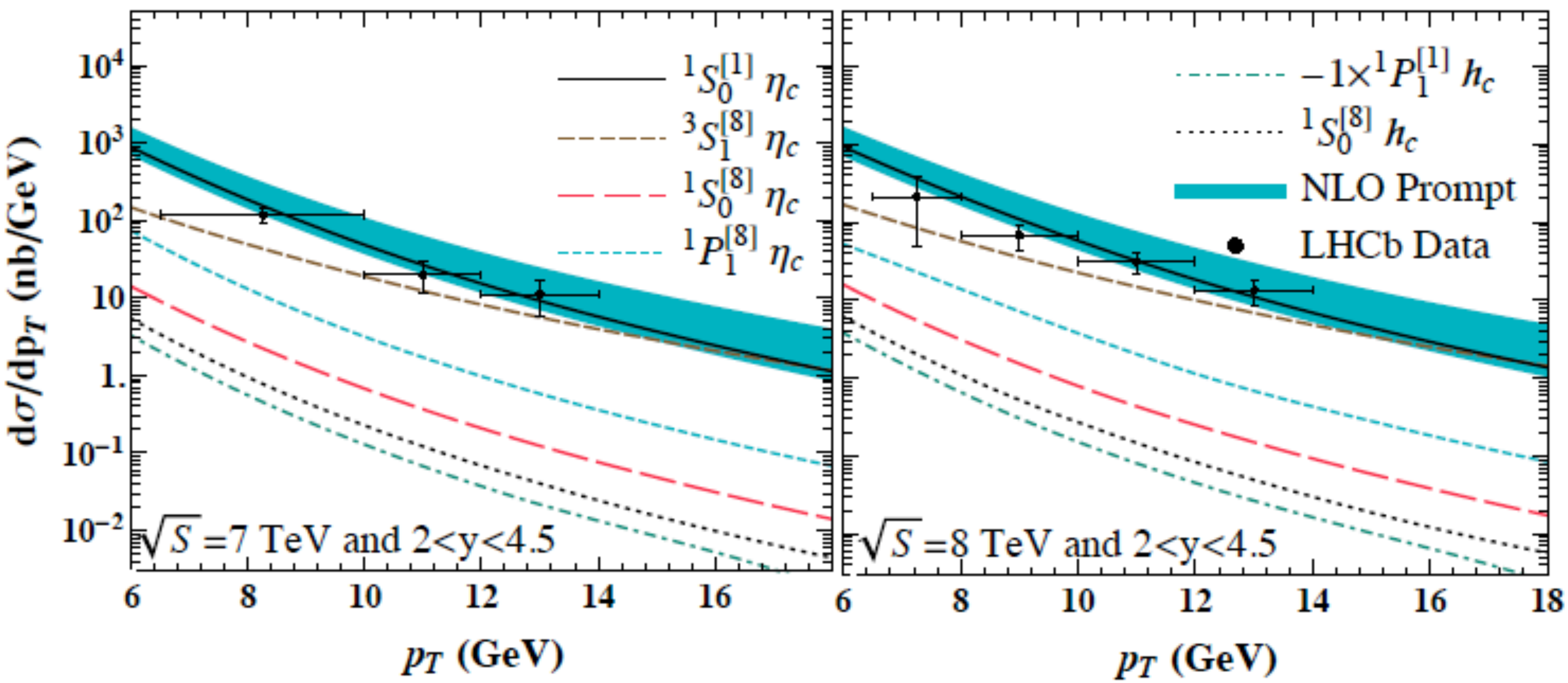
	Butenschön, Kniehl [4]	Chao, Ma, Shao, Wang, Zhang [6]	Gong, Wan, Wang, Zhang [7]	Bod… Ki…
$\langle\mathcal{O}^{J/\psi}(^3S_1^{[1]})\rangle/\mathrm{GeV}^3$	1.32	1.16	1.16	
$\langle\mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle/\mathrm{GeV}^3$	0.0304 ± 0.0035	0.089 ± 0.0098	0.097 ± 0.009	0.0
$\langle\mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle/\mathrm{GeV}^3$	0.0016 ± 0.0005	0.0030 ± 0.012	-0.0046 ± 0.0013	0.0
$\langle\mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle/\mathrm{GeV}^5$	-0.0091 ± 0.0016	0.0126 ± 0.0047	-0.0214 ± 0.0056	0.0
$\langle\mathcal{O}^{\chi_0}(^3P_0^{[1]})\rangle/\mathrm{GeV}^5$			0.107	
$\langle\mathcal{O}^{\chi_0}(^3S_1^{[8]})\rangle/\mathrm{GeV}^3$			0.0022 ± 0.0005	

$\langle\mathcal{O}(^3S_1^{[1]})\rangle$ GeV^3	$\langle\mathcal{O}(^1S_0^{[8]})\rangle$ $10^{-2}\mathrm{GeV}^3$	$\langle\mathcal{O}(^3S_1^{[8]})\rangle$ $10^{-2}\mathrm{GeV}^3$	$\langle\mathcal{O}(^3P_0^{[8]})\rangle/m_c^2$ $10^{-2}\mathrm{GeV}^3$
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

Chao et al. '12

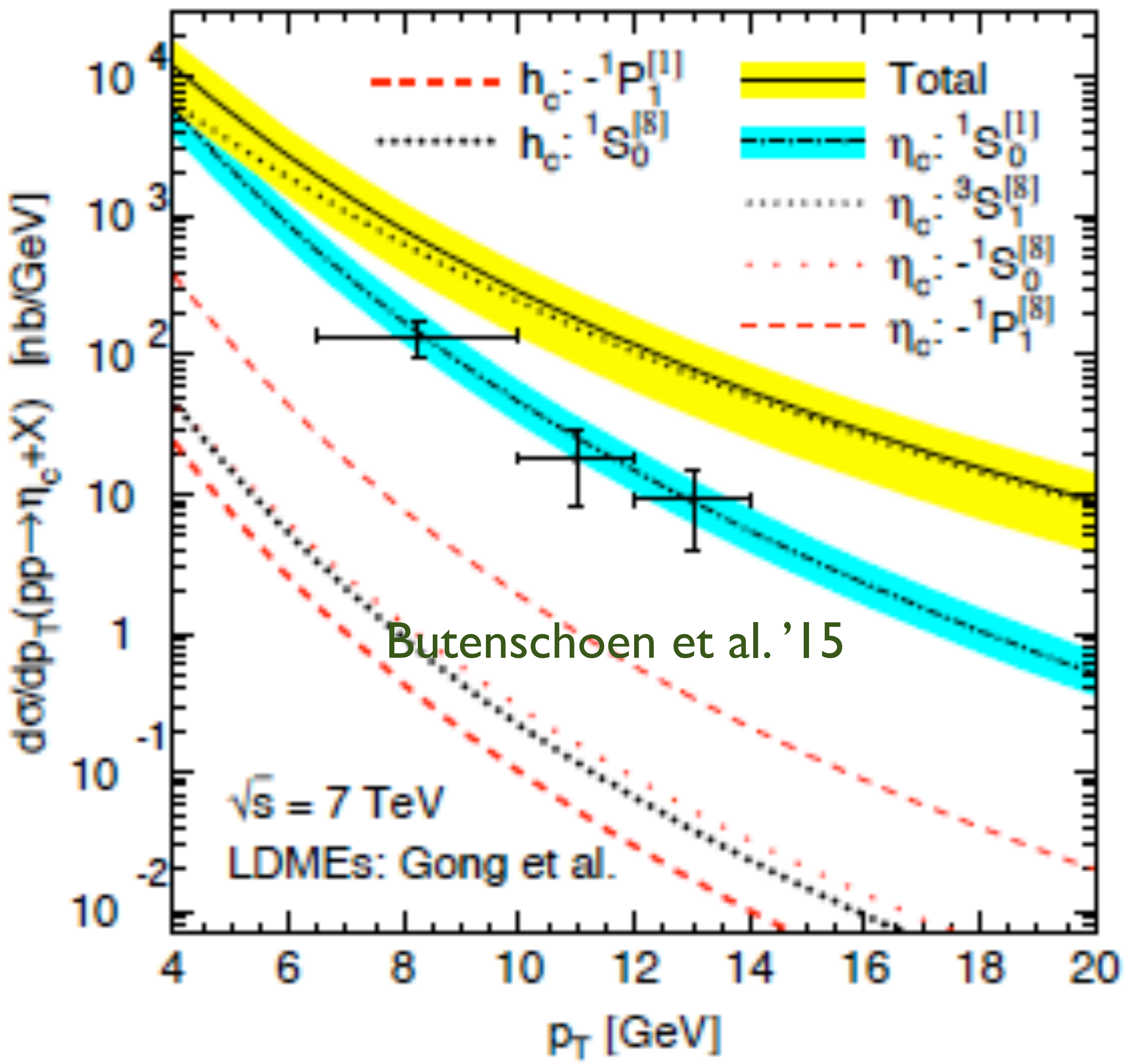
INCLUSIVE ETA_C PRODUCTION

- **LHCb has measured η_c production** Aaij et al., (2014)
- **It triggers several theoretical calculations**
  - Hamburg group Butenschoen, He and Kniehl '15 : claim nothing work !
  - Other groups Han et al. '15; Zhang et al. '15 NRQCD still works with another tunning !



INCLUSIVE ETA_C PRODUCTION

- **Messages from η_c production:**
  - CS contribution already saturates the yields
  - In CO contributions, the only possible relevant one is ${}^3S_1^{[8]}$
  - Feeddown from h_c is quite irrelevant



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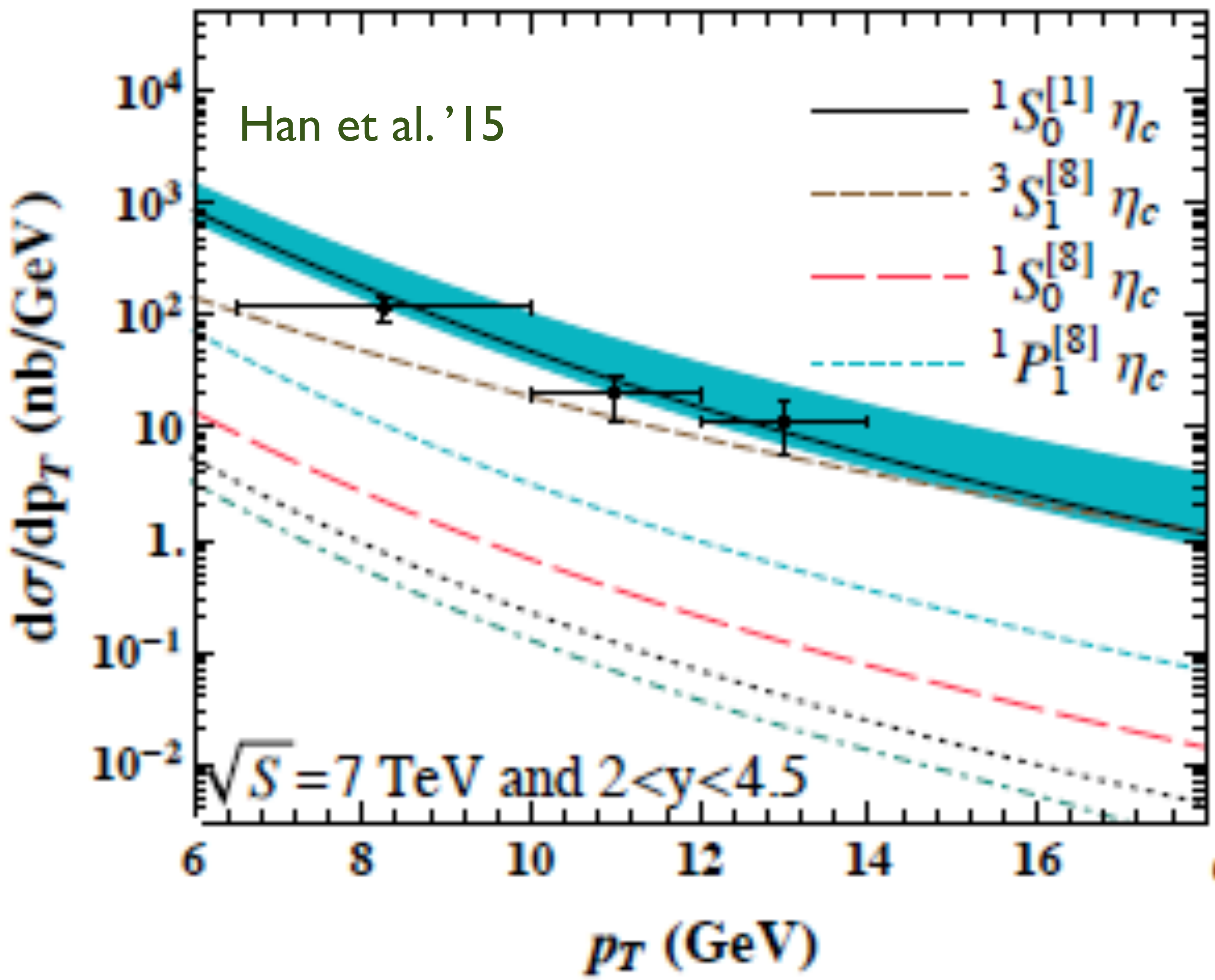


HQSS:

$$\langle \mathcal{O}^{\eta_c}(^3S_1^{[8]})\rangle = \langle \mathcal{O}^{\psi}(^1S_0^{[8]})\rangle(1+\mathcal{O}(v^2))$$

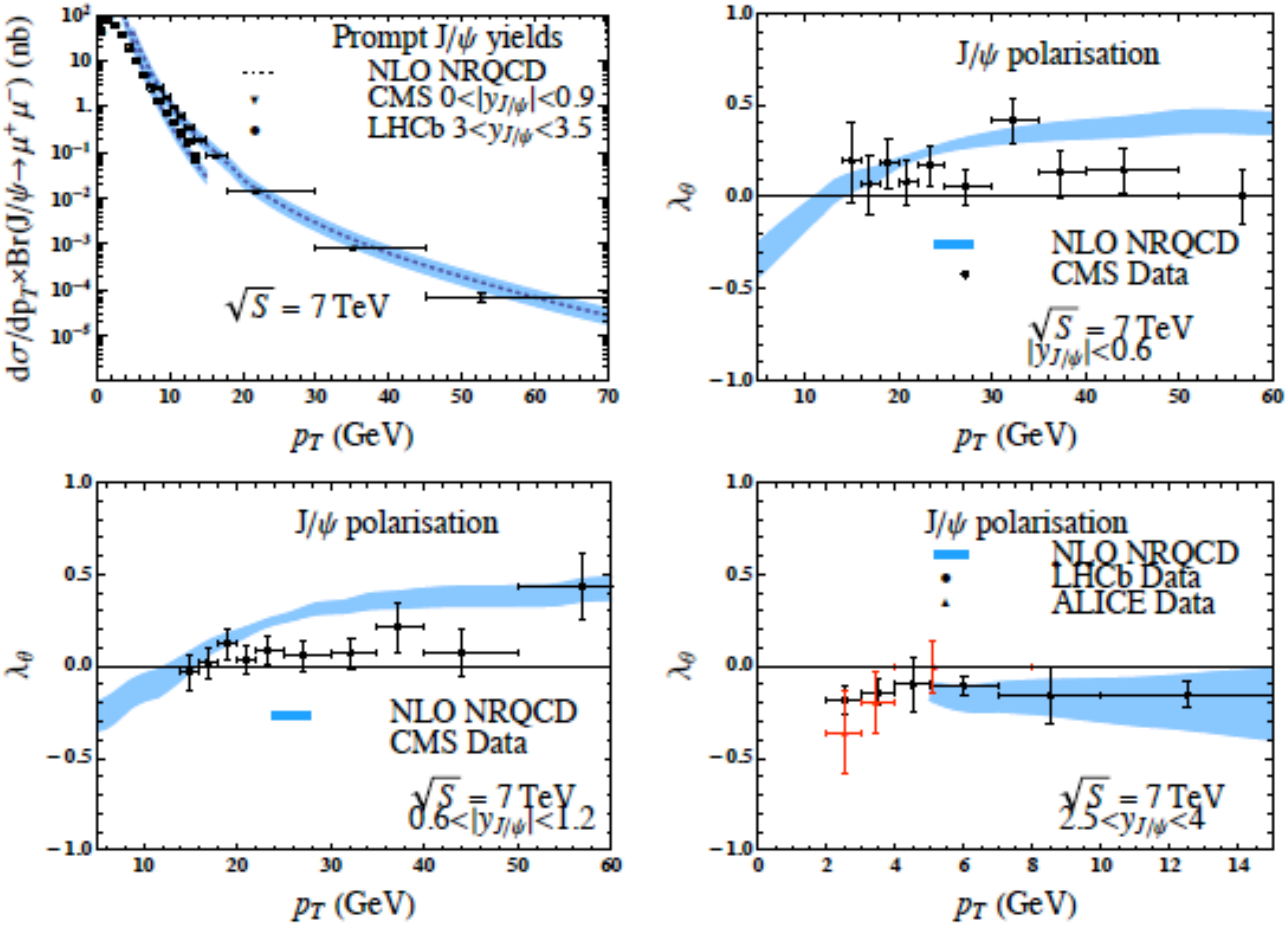
Constrain CO LDME:

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

$$0 \leq \langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle \leq 1.46\times 10^{-2}\ \mathrm{GeV}^3$$

INCLUSIVE CHARMONIUM PRODUCTION

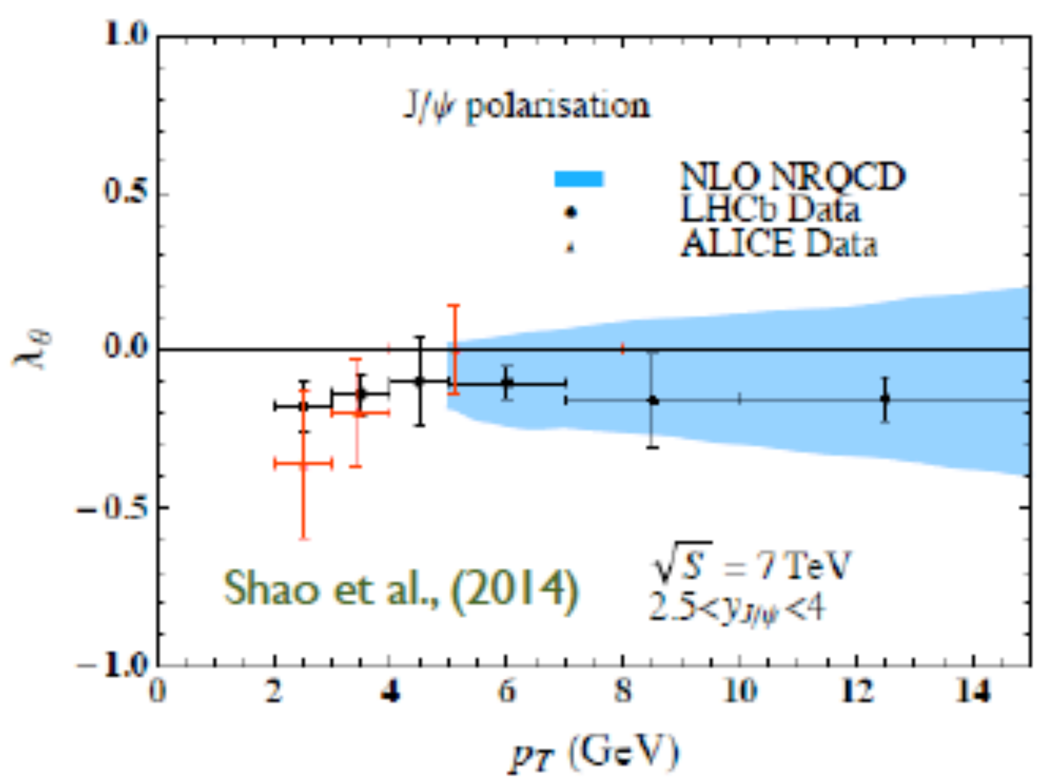
- Test the consistence in J/ψ production



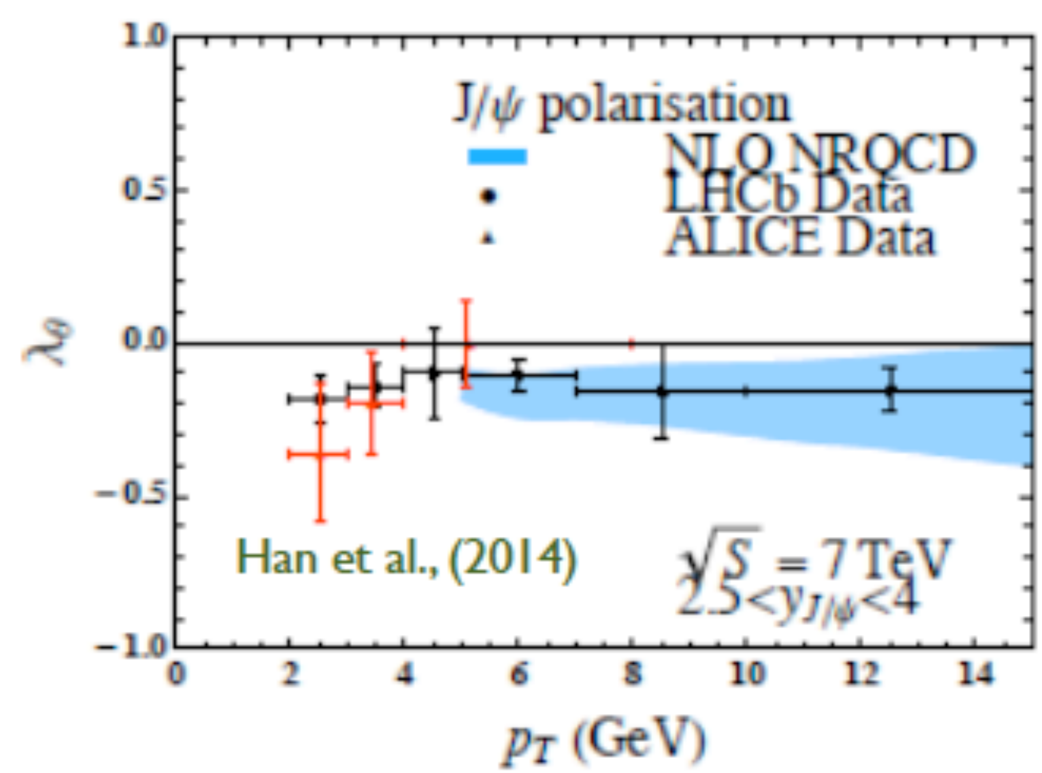
INCLUSIVE CHARMONIUM PRODUCTION

- Test the consistence in J/ψ production
- Reduce the uncertainty from CO LDMEs

Before



After



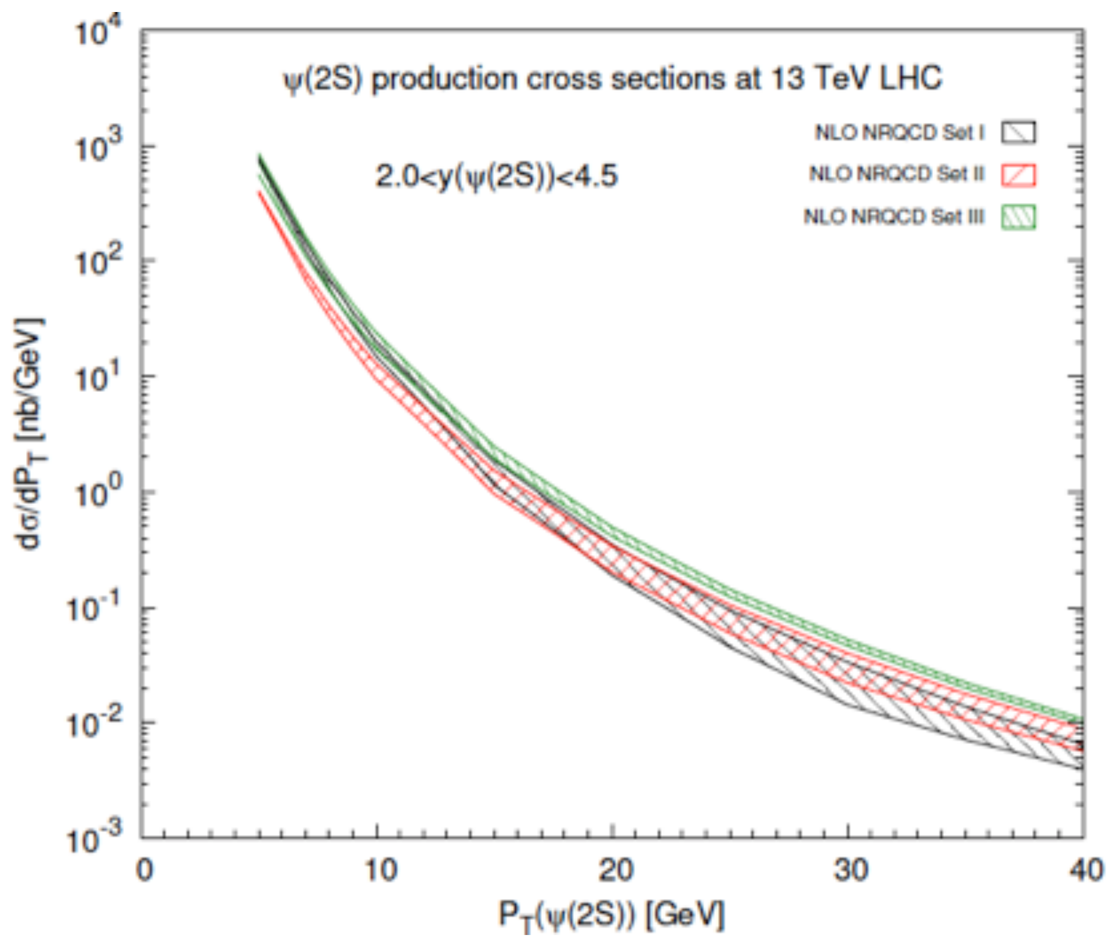
THE SAME GAME FOR 2S STATES ?

- **What about $\eta_c(2S)$?**
- **The question is: which decay mode can be measured ?**

HQSS: $\langle \mathcal{O}^{\eta_c(2S)}({}^3S_1^{[8]}) \rangle = \langle \mathcal{O}^{\psi(2S)}({}^1S_0^{[8]}) \rangle$

Disparate extractions:

	Set I: *Shao et.al* [11]	Set II: *Gong et.al* [7]	Set III: *Bodwin et.al* [16]
$\langle \mathcal{O}^{\eta_c(2S)}({}^3S_1^{[8]}) \rangle$ [GeV^3]	$[0, 3.82] \times 10^{-2}$	$[-0.881, 0.857] \times 10^{-2}$	$[2.35, 3.93] \times 10^{-2}$



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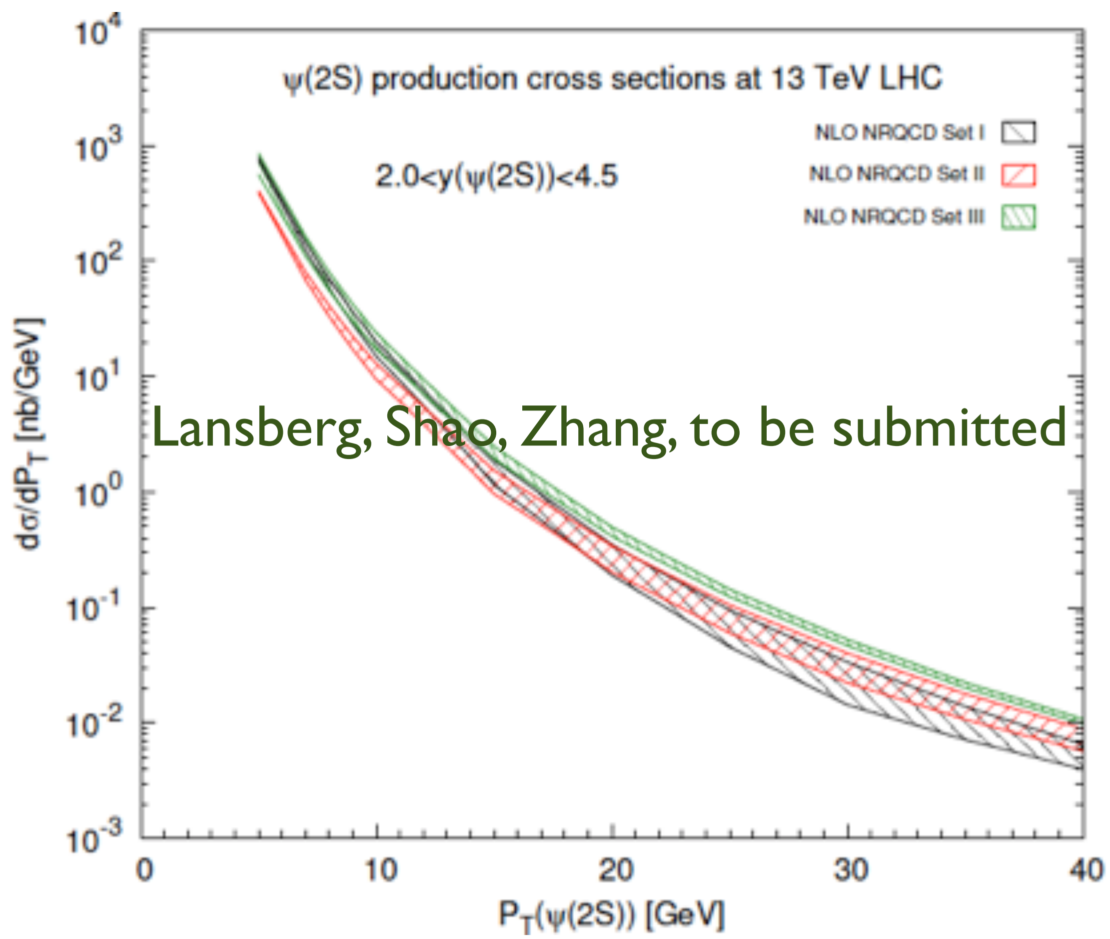

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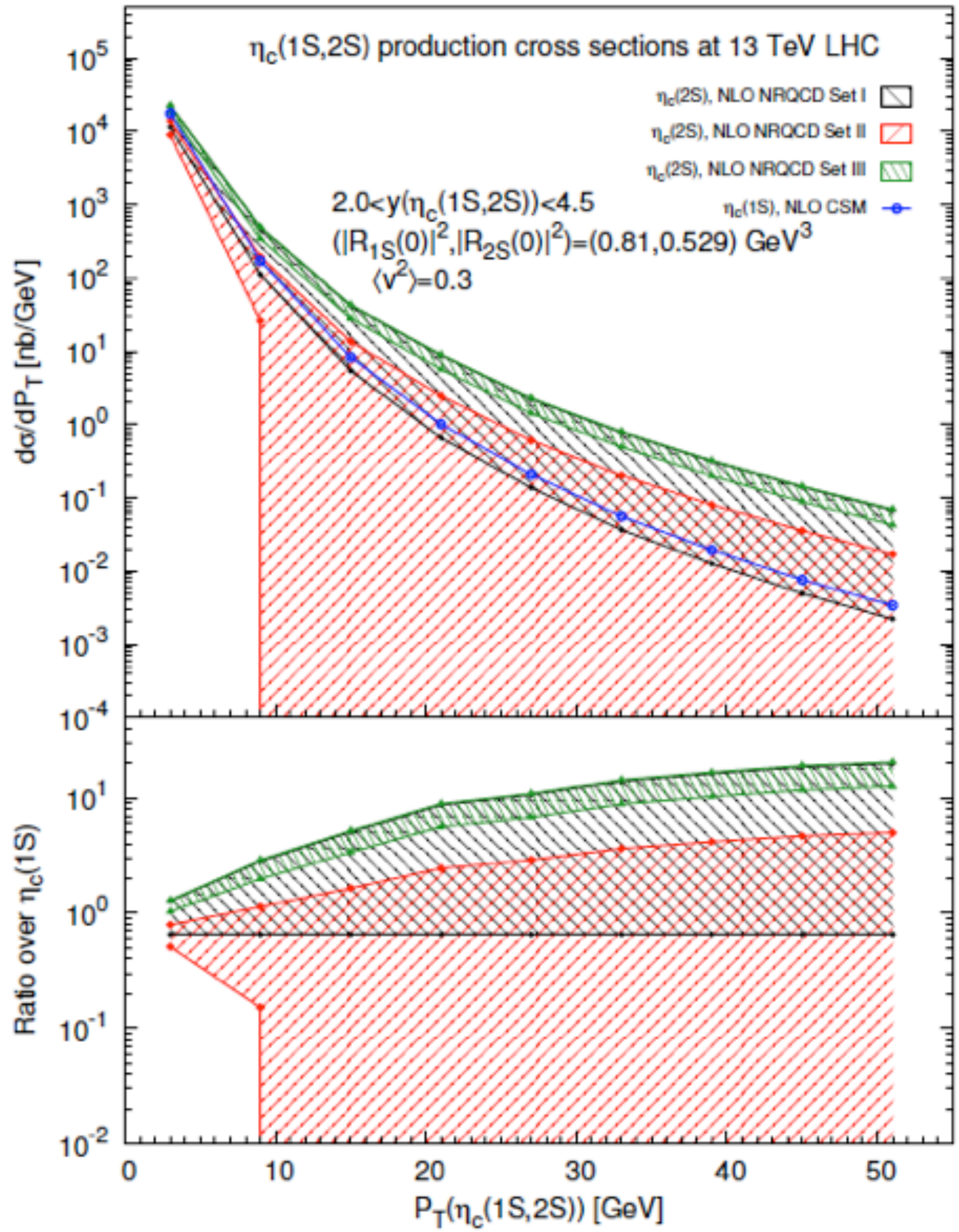
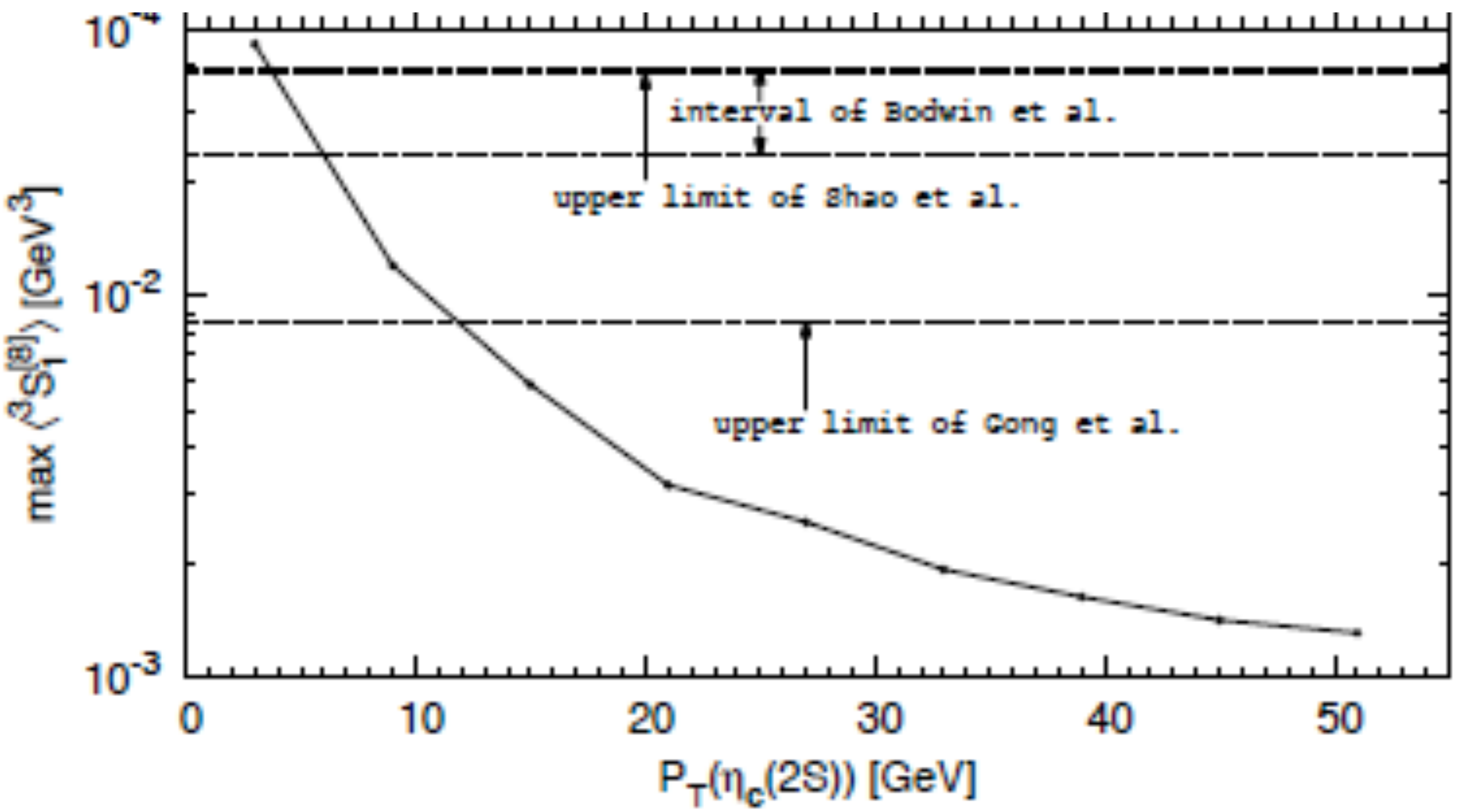
THE SAME GAME FOR 2S STATES ?

- **Different predictions for $\eta_c(2S)$** Lansberg, Shao, Zhang, to be submitted



THE SAME GAME FOR 2S STATES ?

- **Different predictions for $\eta_c(2S)$** Lansberg, Shao, Zhang, to be submitted
- **A possibly reasonable assumption:**
  Similar as 1S, 2S is also saturated by CS contribution
- **The potential to constrain** $\langle \mathcal{O}^{\eta_c(2S)}(^3S_1^{[8]})\rangle \simeq \langle \mathcal{O}^{\psi(2S)}(^1S_0^{[8]})\rangle$



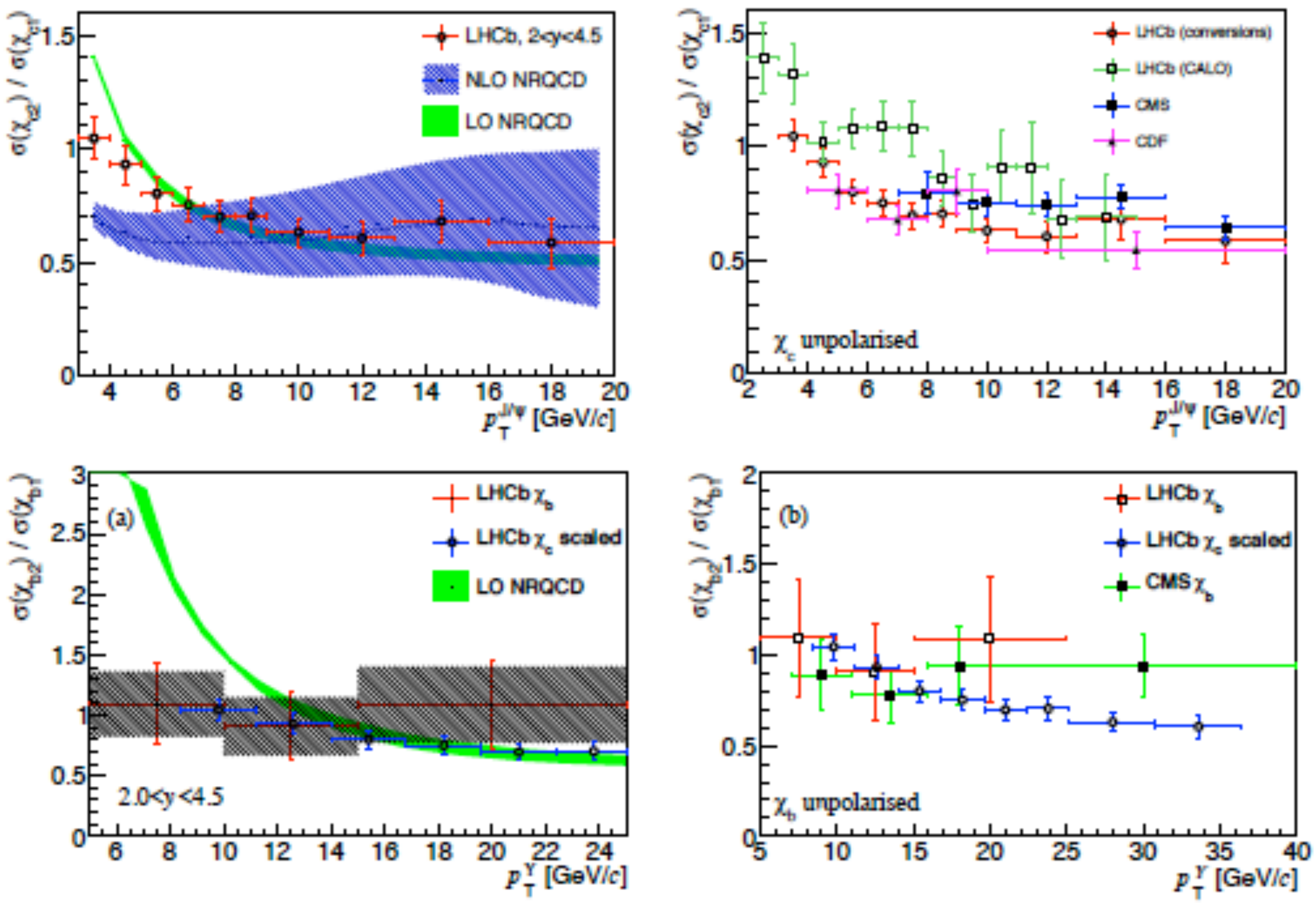
On the importance of Low P_T χ_{Q1}/χ_{Q2} measurements

LHCb, JHEP 10(2013)115 & JHEP 1410 (2014) 88 ; CMS, EPJC, 72, 2257 (2012); ATLAS, JHEP 07(2014)154

- At low P_T, test of χ_{Q1} suppression following the Landau-Yang theorem
- At larger P_T, test of production mechanism of χ_{QJ} (not of J/ψ or Υ)

χ_c

χ_b



- The Landau-Yang suppression shows up for χ_c in the Low P_T/m_Q region; signs that the quantum # still matter
- Testable with χ_{c0} and h_c using the hadronic decays

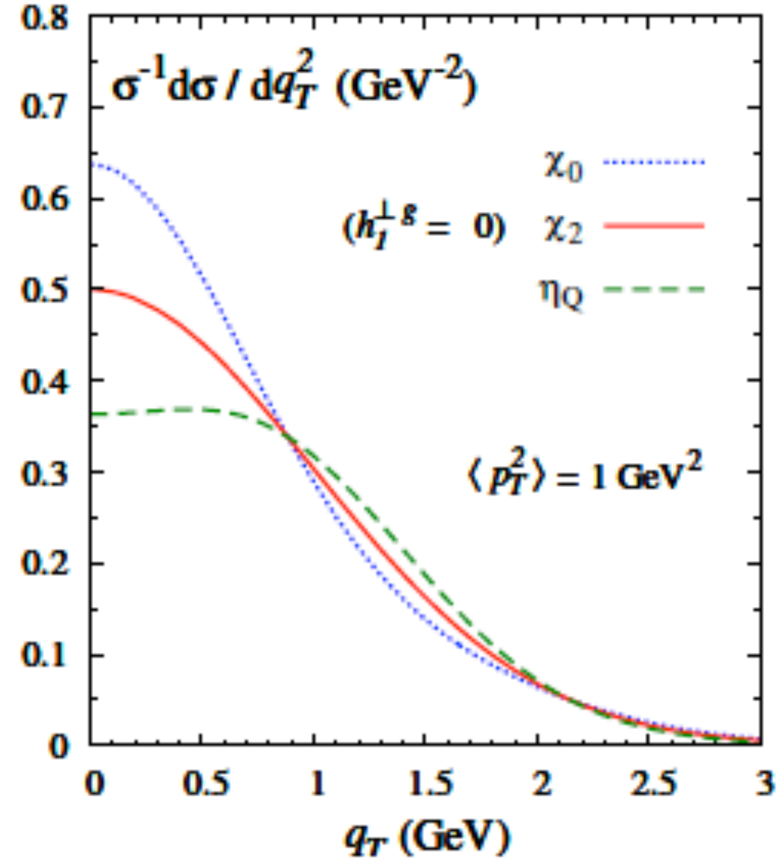
Jean-Philippe's slide

Low P_T quarkonia and Transverse Momentum Dependent distributions

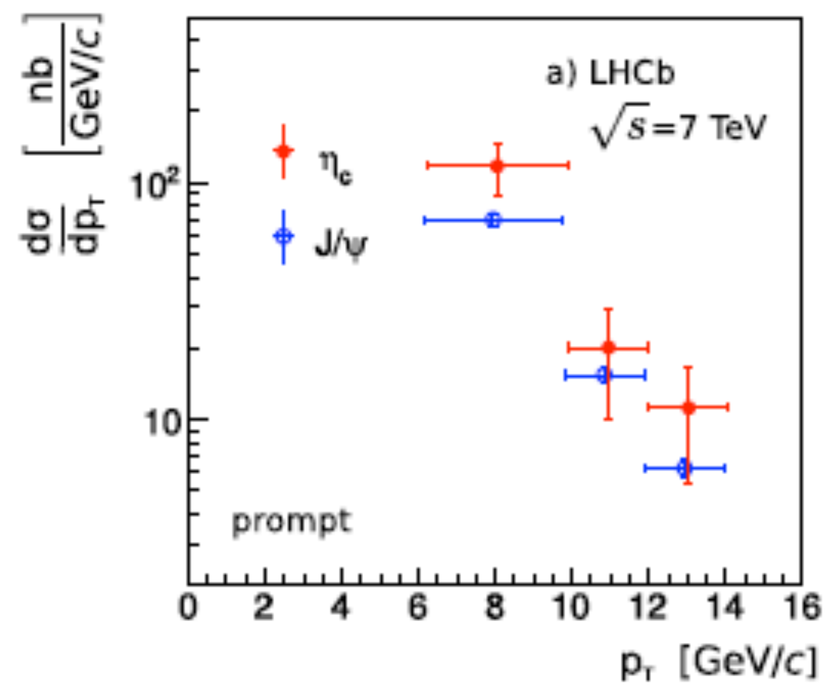
PHYSICAL REVIEW D **86**, 094007 (2012)

Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

Daniël Boer*
Theory Group, KVI, University of Groningen, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands
Cristian Pisano†
Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, C.P. 170, I-09042 Monserrato (CA), Italy



- Low P_T C-even quarkonium production is a good probe of $h_1^{\perp g}$ [distribution of linearly polarised gluons]
- In general, heavy-flavor prod. selects out gg channels
- Affect the low P_T spectra:
$$\frac{1}{\sigma}\frac{d\sigma(\eta_Q)}{d\mathbf{q}_T^2} \propto 1 - R(\mathbf{q}_T^2) \;\&\; \frac{1}{\sigma}\frac{d\sigma(\chi_{Q,0})}{d\mathbf{q}_T^2} \propto 1 + R(\mathbf{q}_T^2)$$
$$\left(R = \frac{\mathcal{C}[w_0^{hh}\, h_1^{\perp g} h_1^{\perp g}]}{\mathcal{C}[f_1^g f_1^g]}\right)$$
- Low P_T: Experimentally very challeging



Being able to look at all the states in the same hadronic decay channel and at lower P_T would be very useful

Jean-Philippe's slide

Back Up Slides

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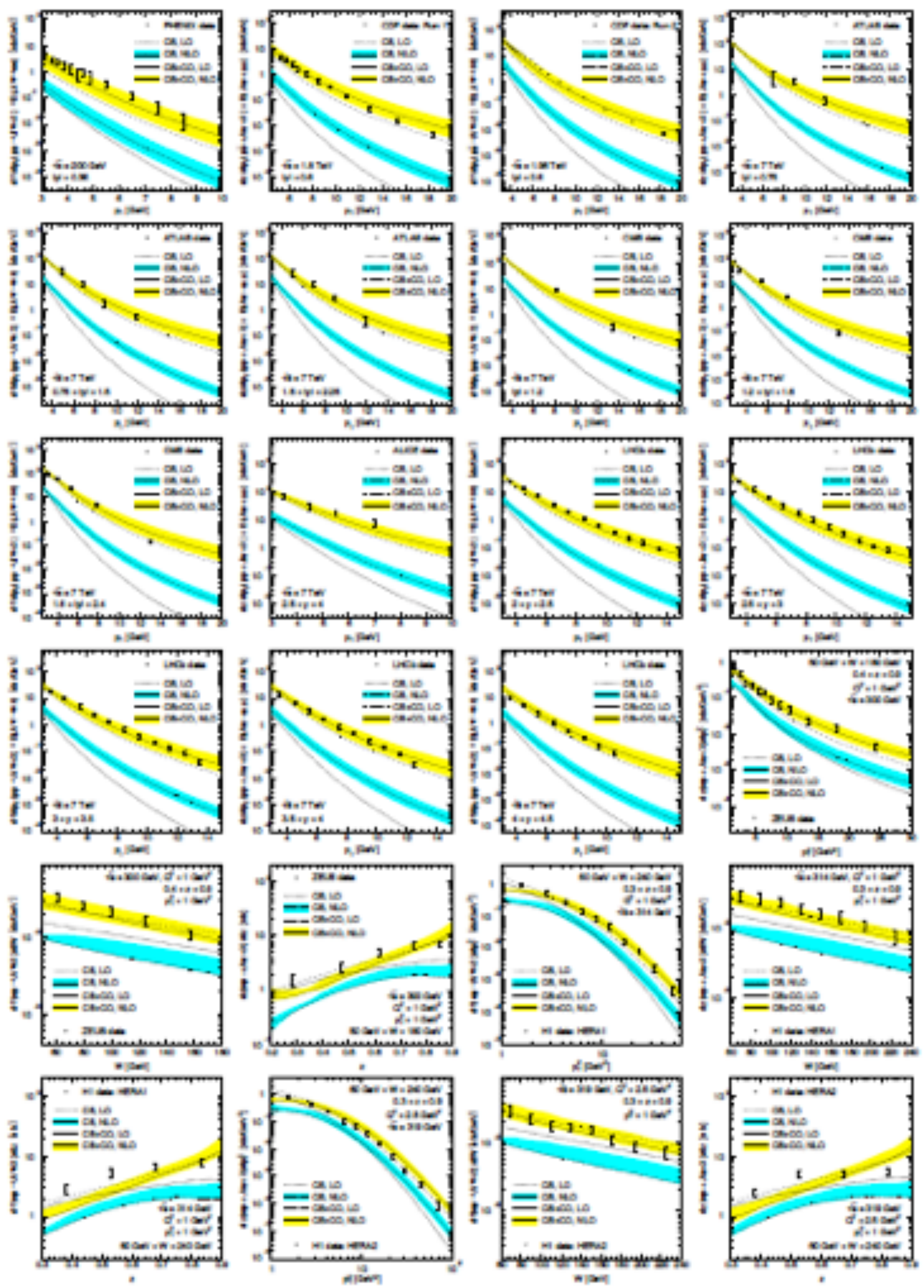
WHERE WE STAND ?

- **CO LDME fit philosophy: pick your favorite data**
  - World yield data before 2011 Butenschon and Kniehl '11



√ • Driven by low- and medium-pt data

3 GeV<pt<20 GeV @ pp

1 GeV<pt<10 GeV @$\gamma p, \gamma\gamma$

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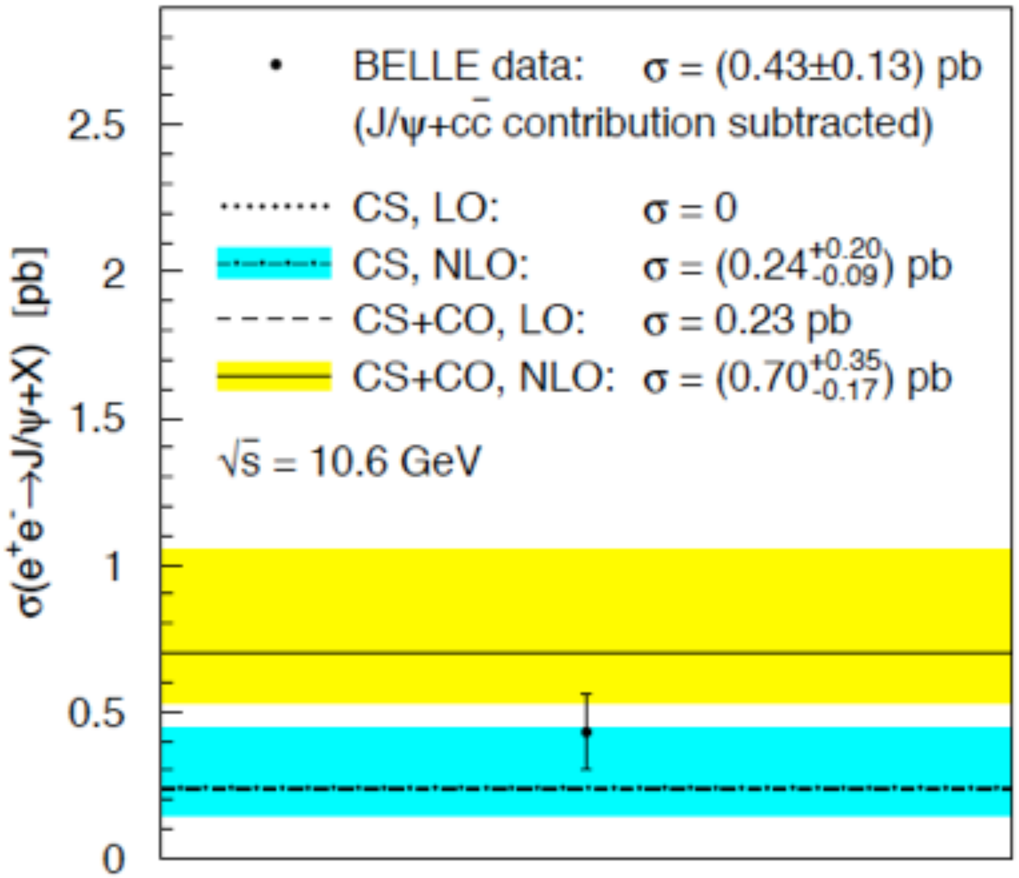

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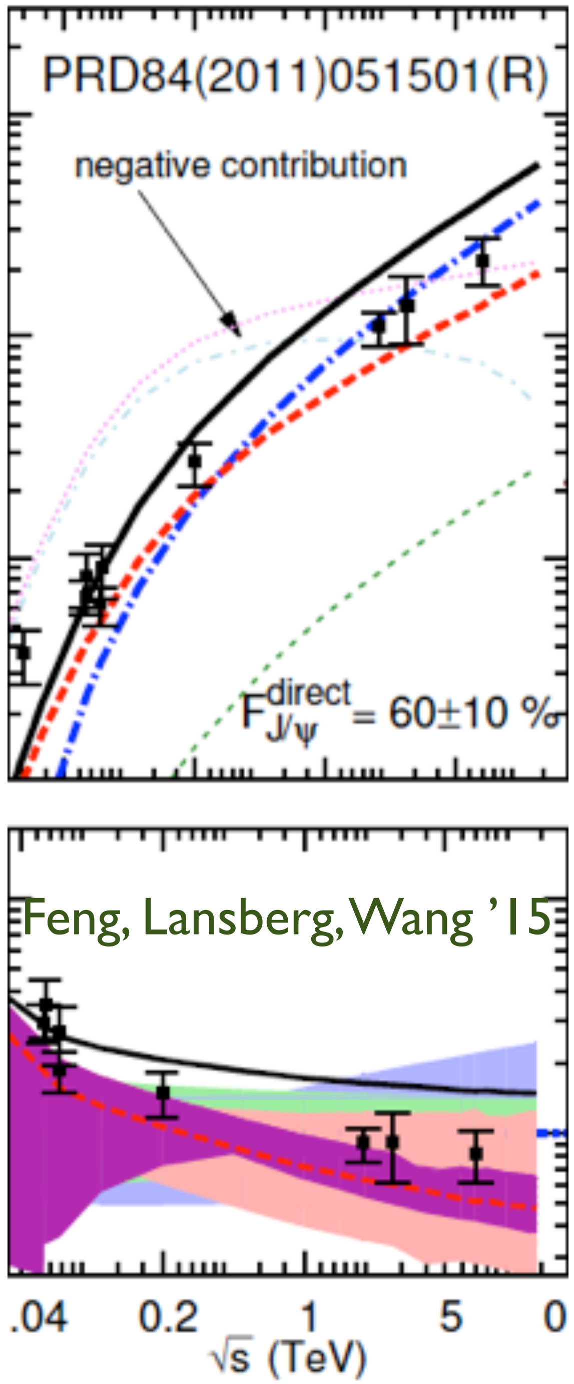

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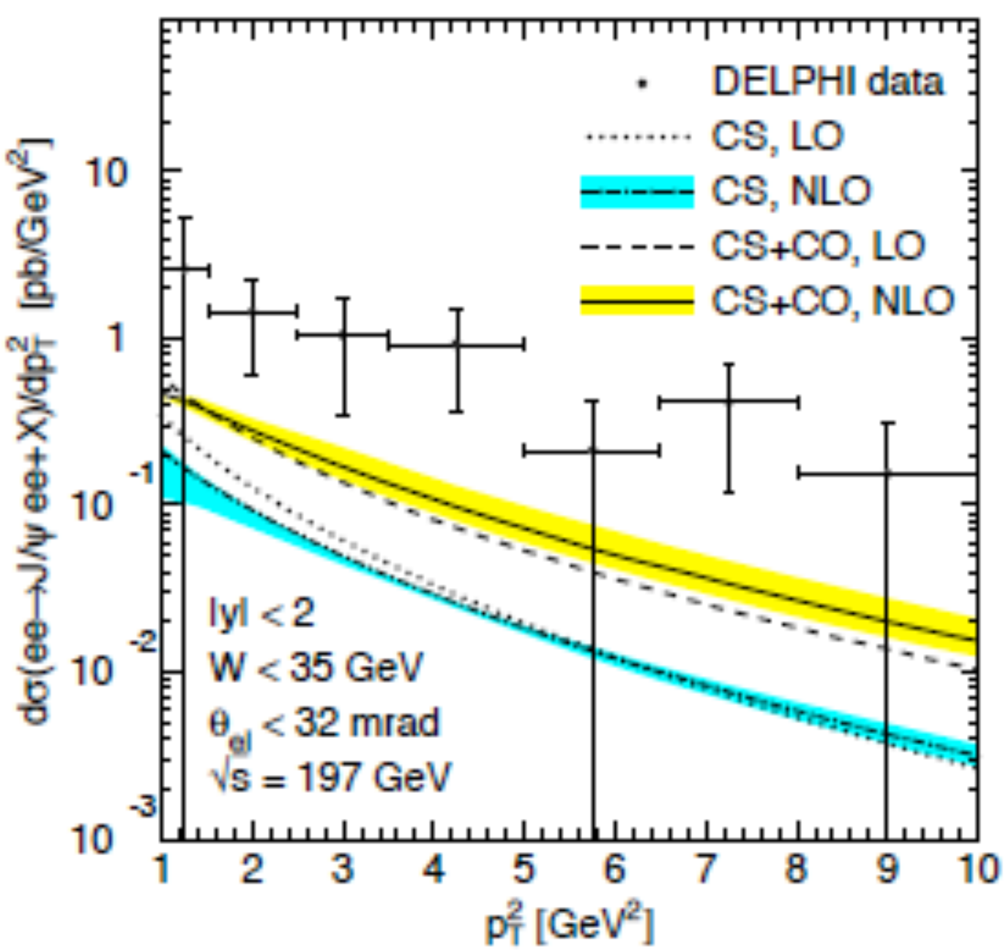

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1 GeV<pt<10 GeV @$\gamma p,\gamma\gamma$

√ • Agreement with e+e- and pt-integrated

✗ • Tension with $\gamma\gamma$ data

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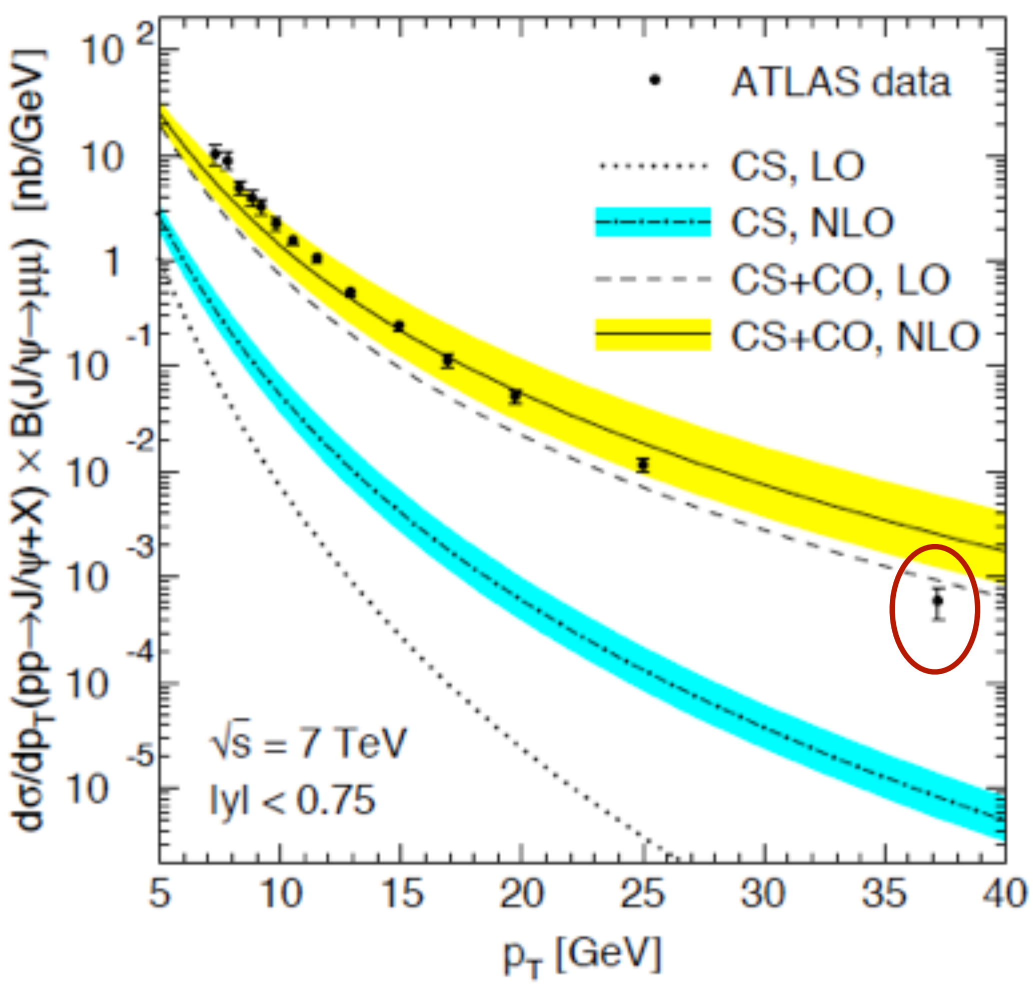
  - World yield data before 2011 Butenschon and Kniehl '11



√ • Driven by low- and medium-pt data
  3 GeV<pt<20 GeV @ pp
  1 GeV<pt<10 GeV @$\gamma p, \gamma\gamma$

√ • Agreement with e+e- and pt-integrated

× • Tension with $\gamma\gamma$ data

× • Deviation with larger-pt data
  Argument: need to resume $\log \frac{p_T^2}{M^2}$

INCLUSIVE CHARMONIUM PRODUCTION WHERE WE STAND ?

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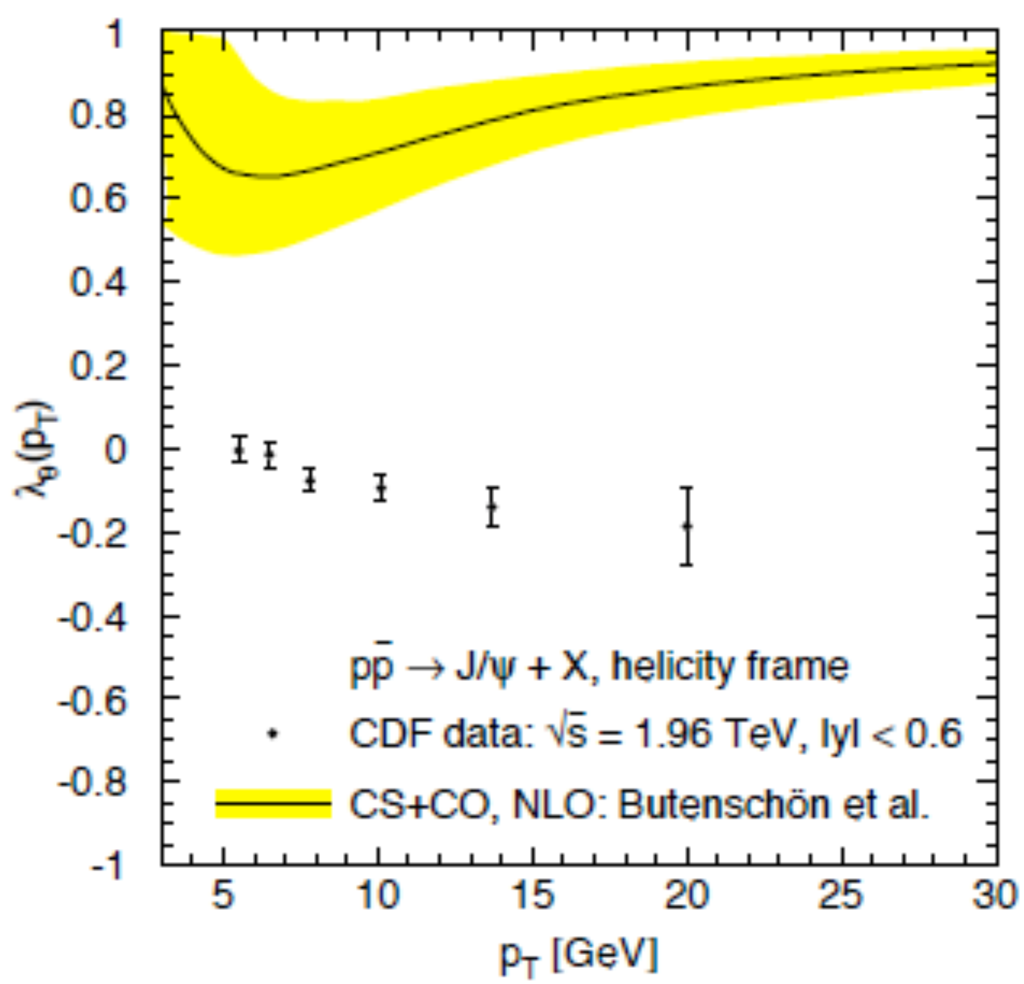

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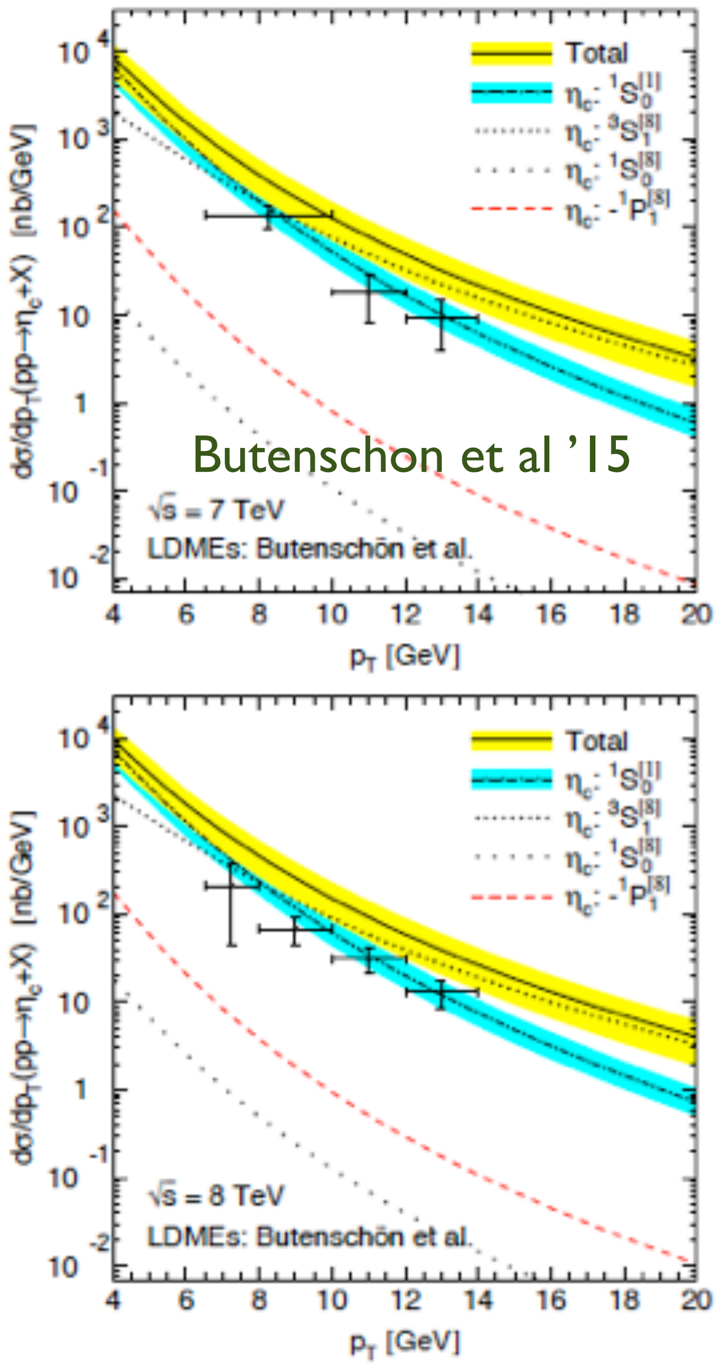

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Assumption: heavy-quark spin symmetry

INCLUSIVE CHARMONIUM PRODUCTION
WHERE WE STAND ?

- **CO LDME fit philosophy:** **pick your favorite data**
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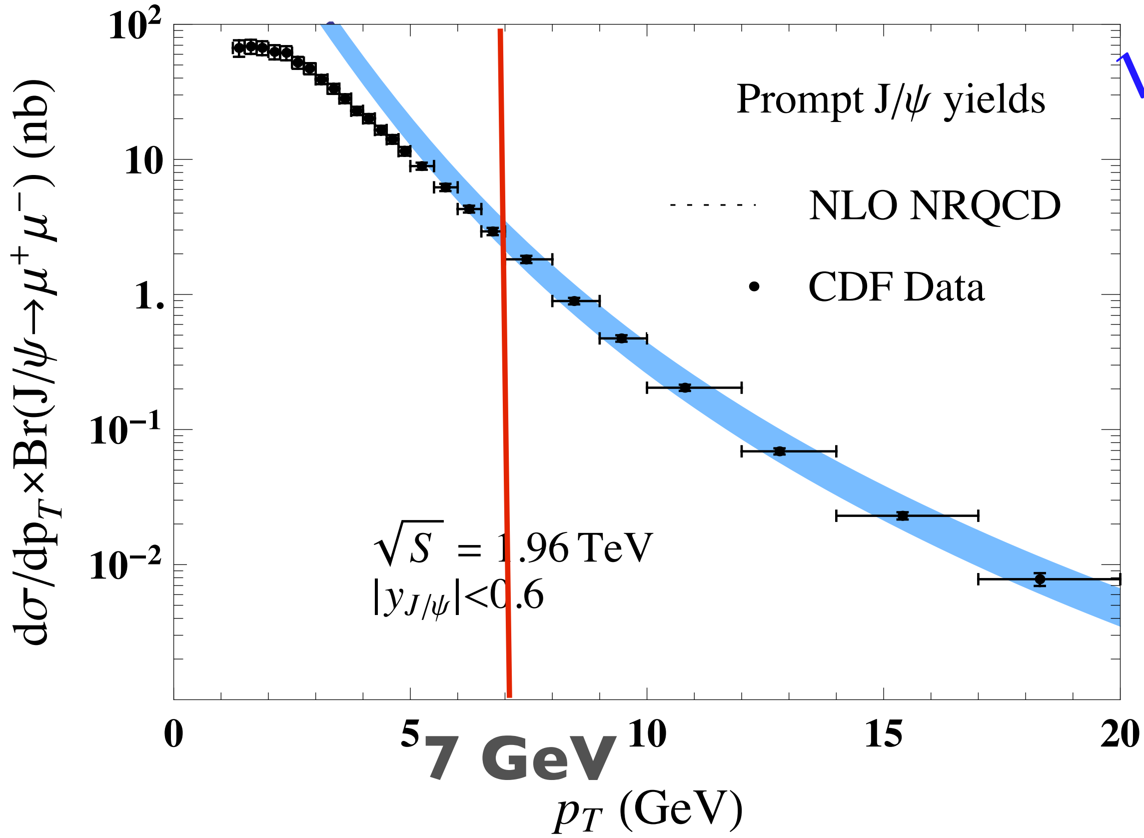
Chao et al. '11-15; Gong et al. '13; Bodwin et al. '14-16

Argument: reduce the nonperturbative effects and/or factorization breaking effects



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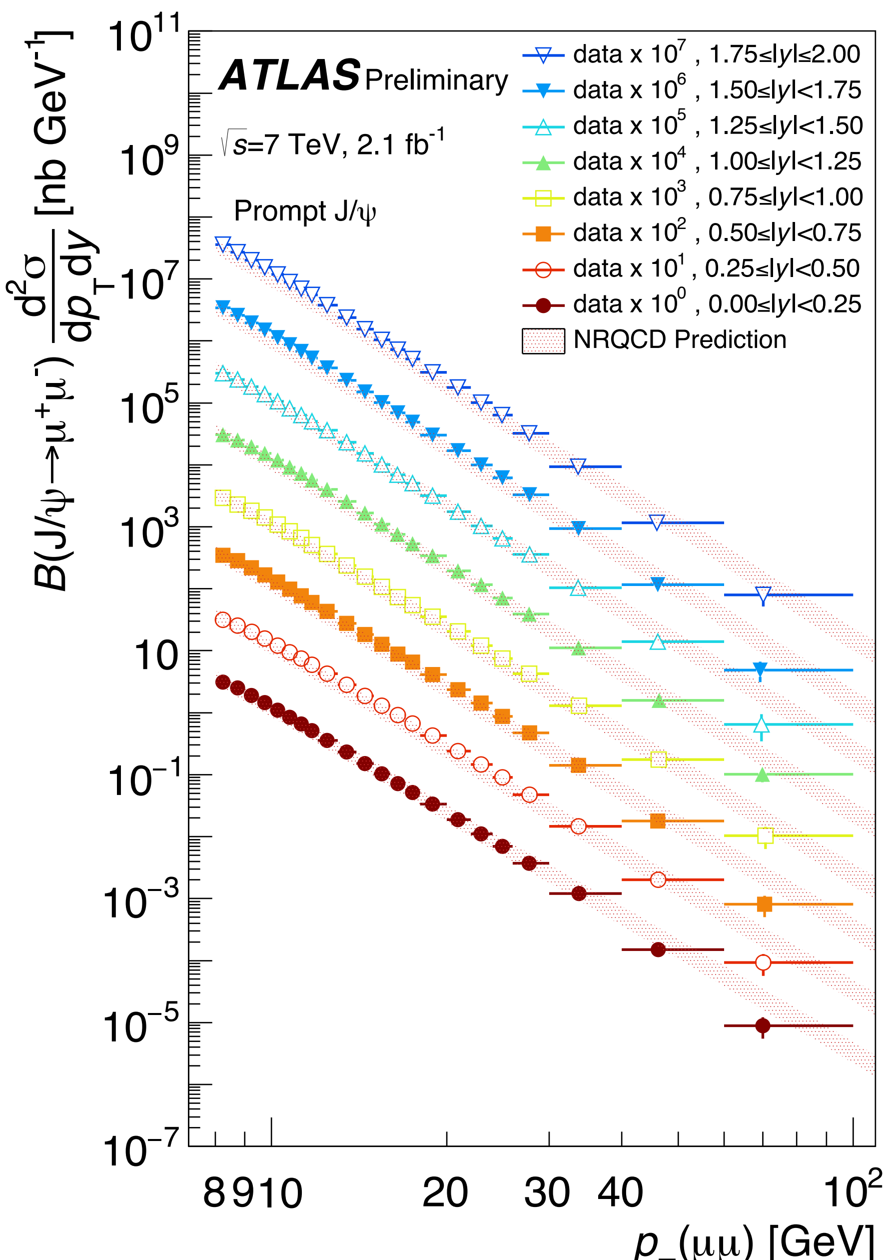

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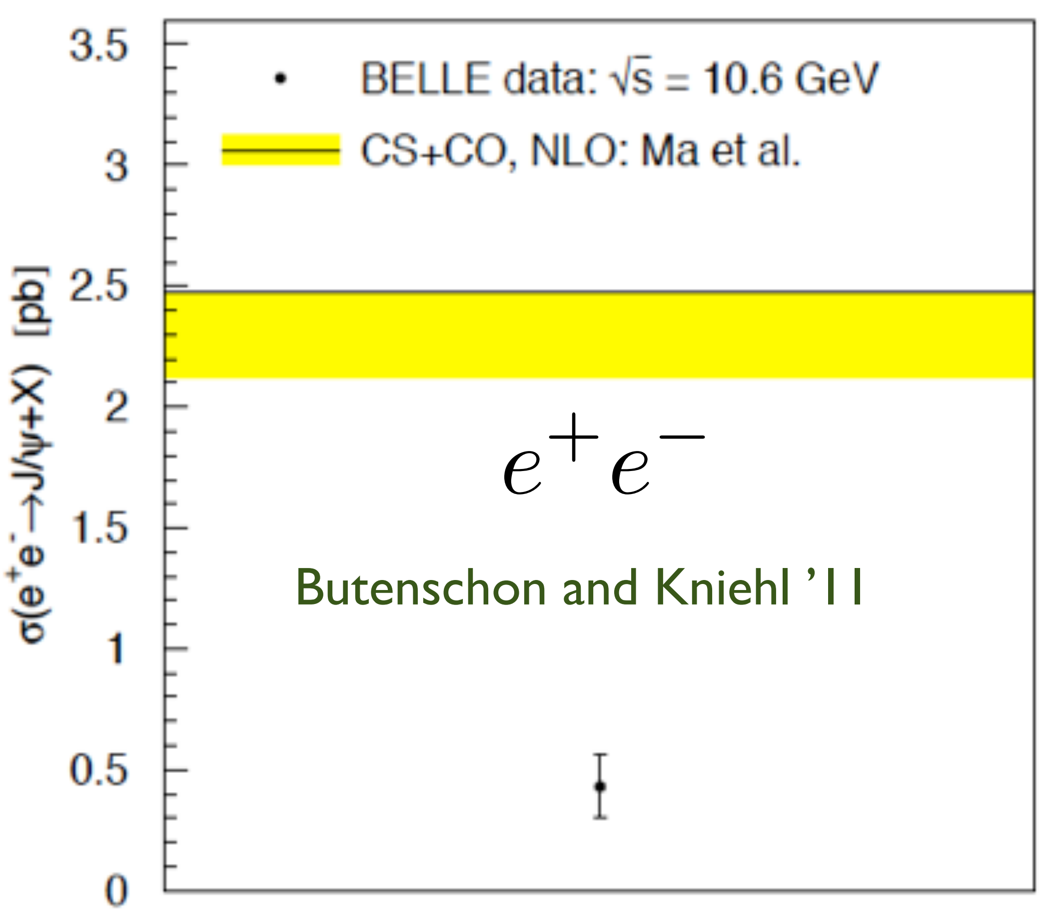

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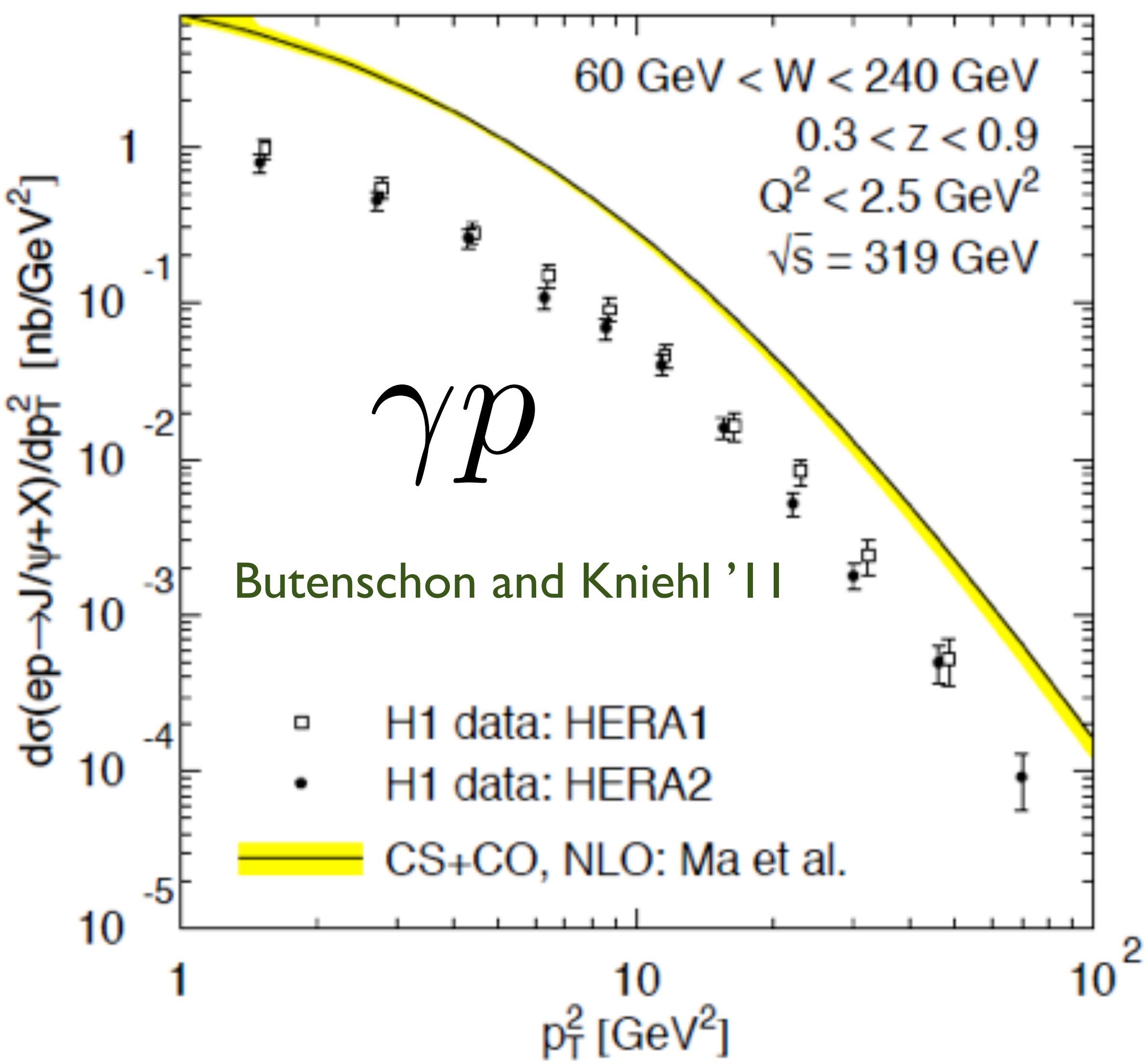

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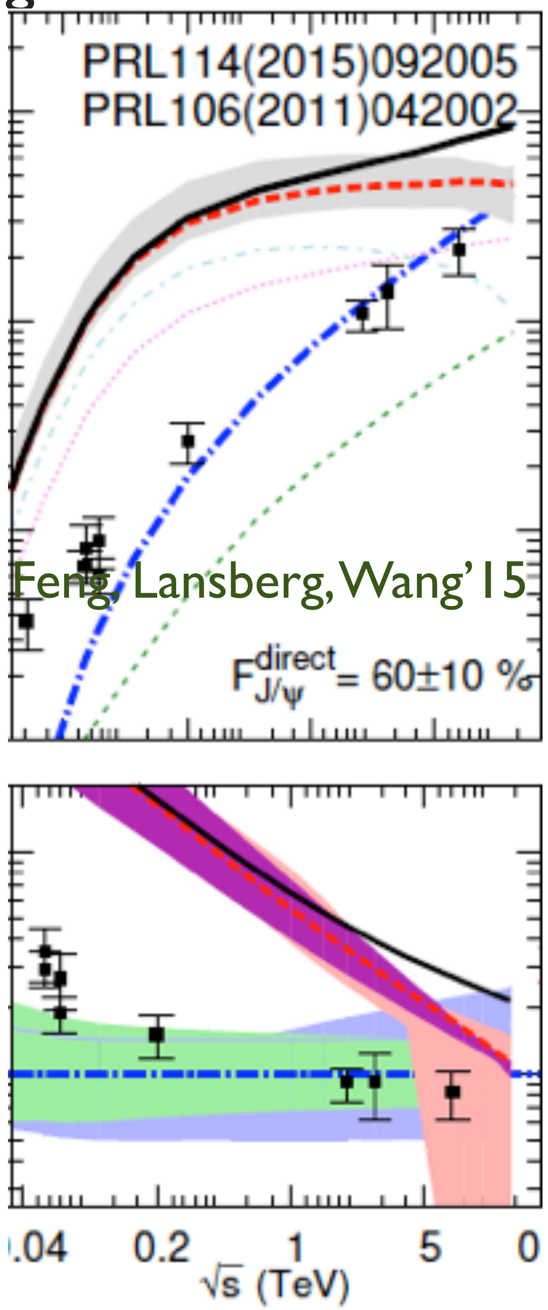

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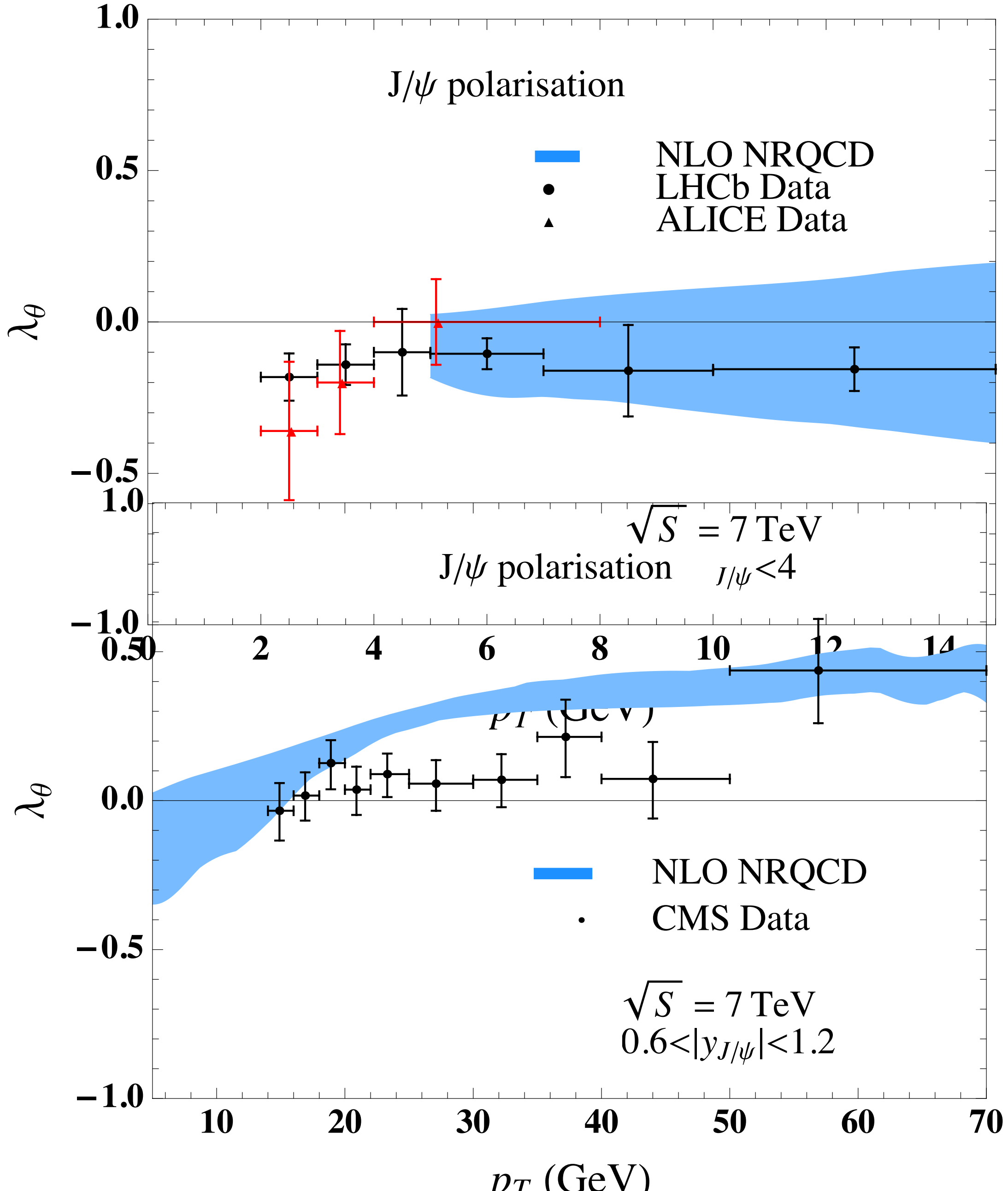

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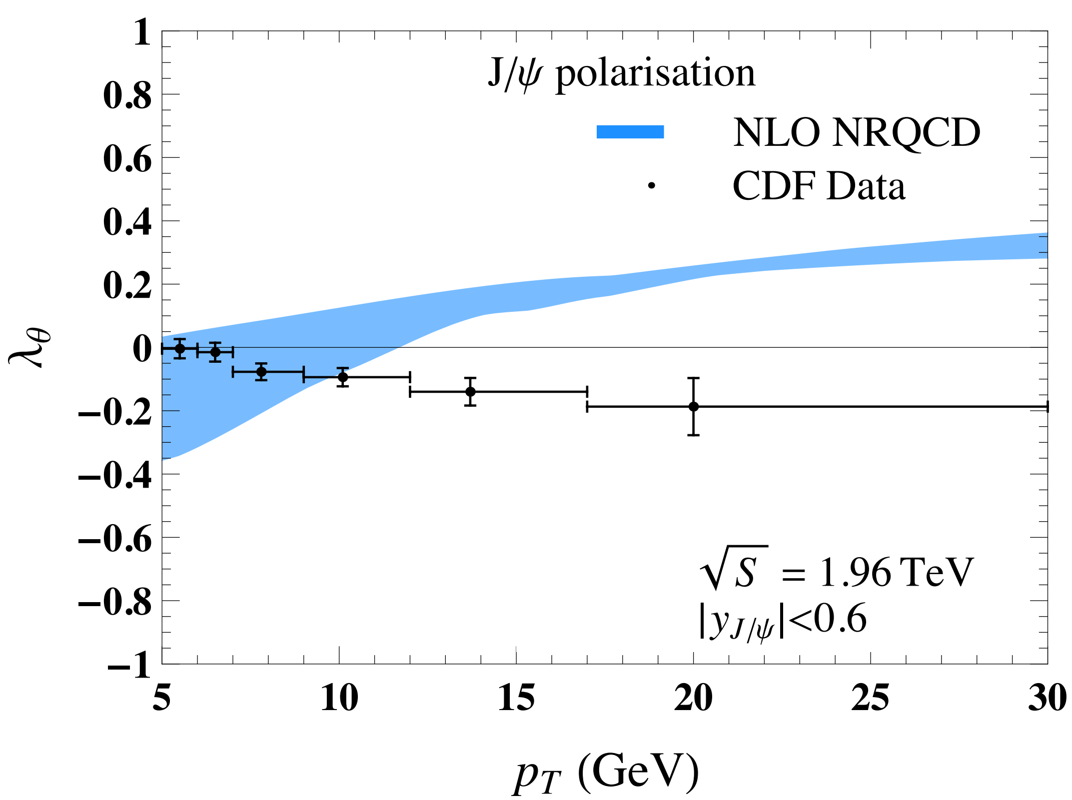

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Argument: doubt on CDF measurement

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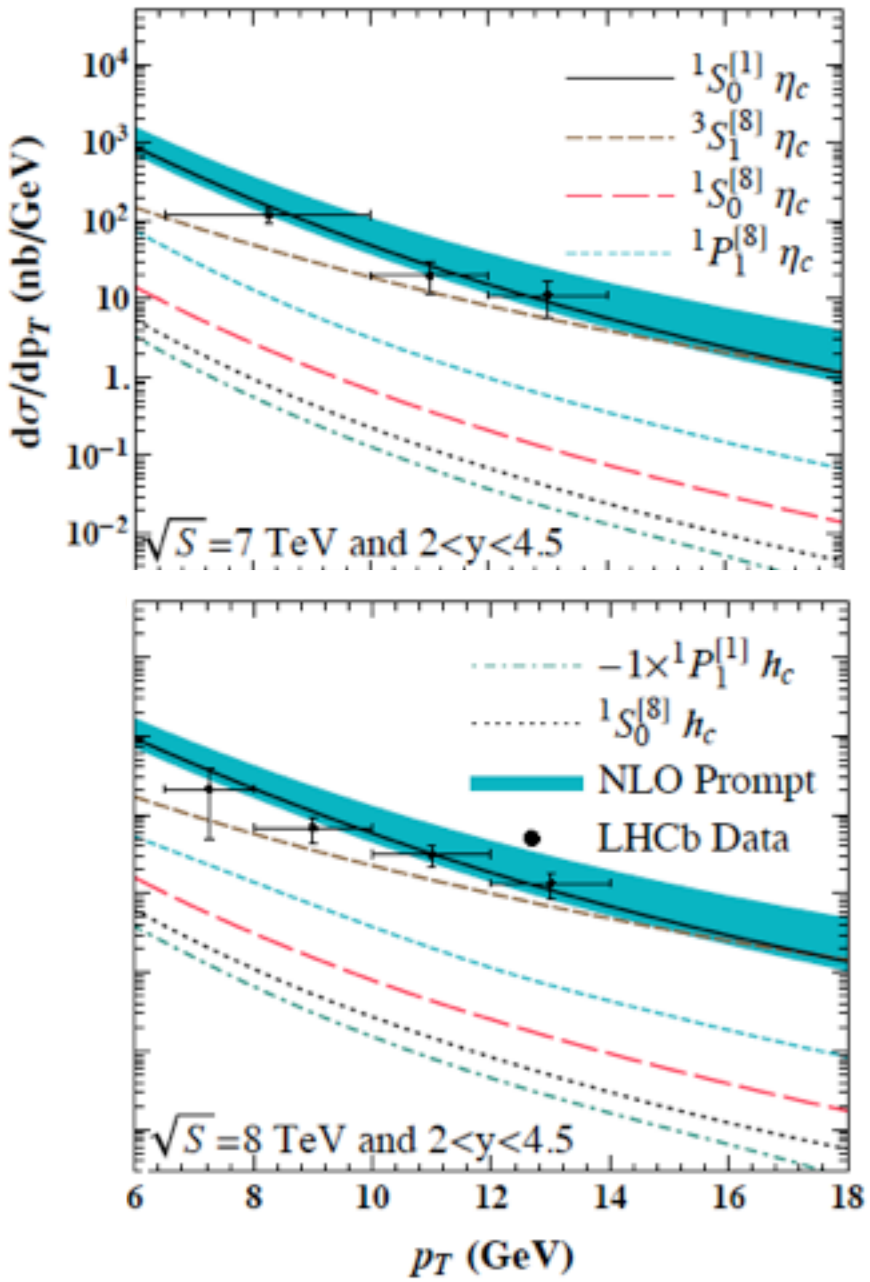

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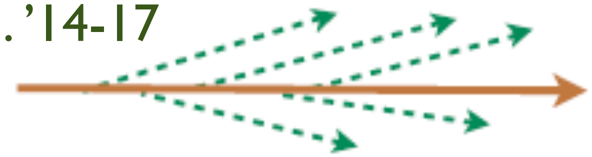
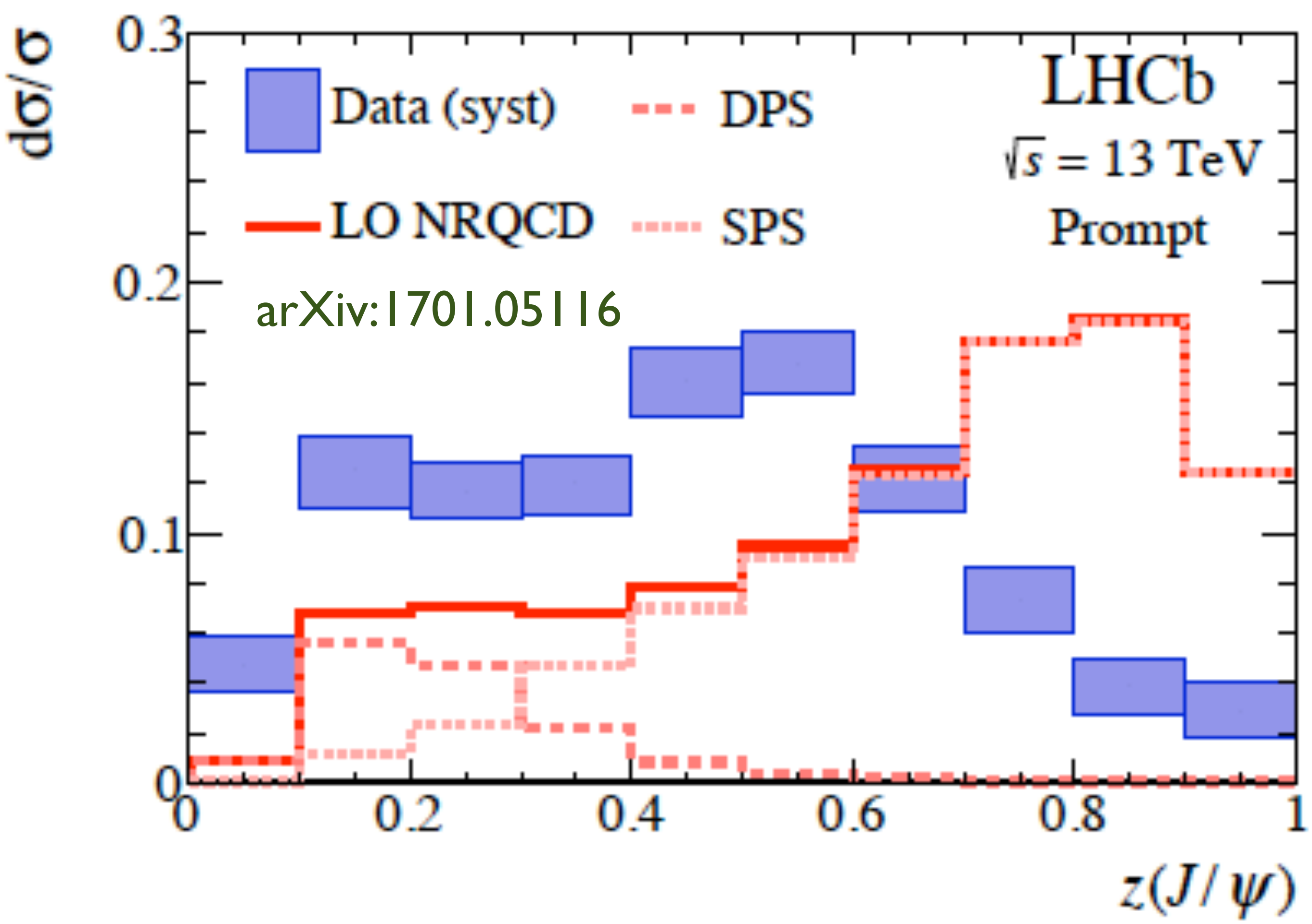
√ Agreement with η_c data
  Assumption: heavy-quark spin symmetry
  Note: only one survives Chao et al. '11-15

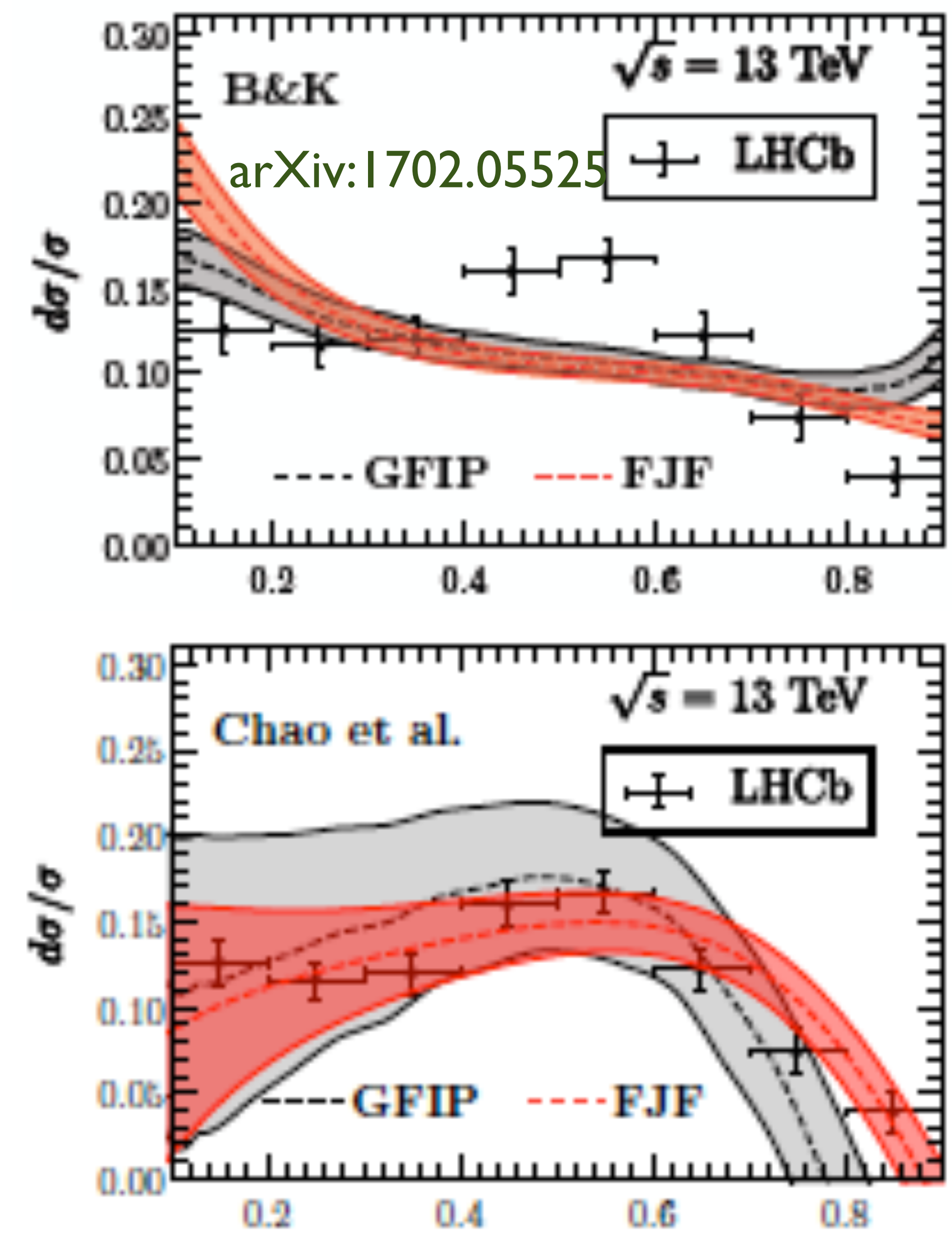
INCLUSIVE CHARMONIUM PRODUCTION NEW HANDLES

- **Quarkonium in the jet:** new handles with jet substructure

Mehen et al. '14-17





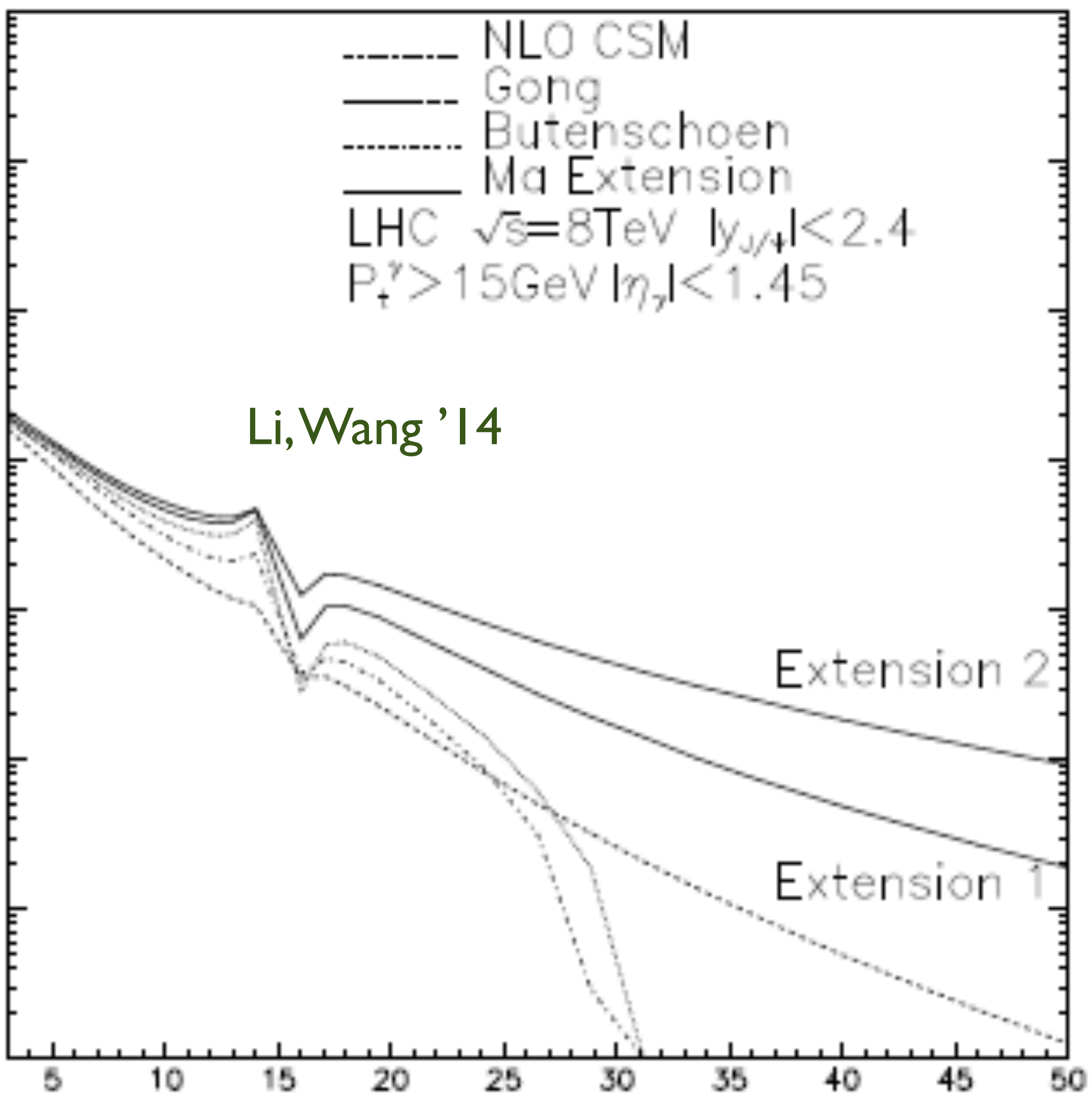


- Pythia8 is not able to capture all the important radiations
- NLL' FJF favors Chao et al. '11-15

INCLUSIVE CHARMONIUM PRODUCTION
NEW HANDLES

- **Associated quarkonium production**

$J/\psi + \gamma$



Li, Wang '14

- Only one fit results in positive cross section Chao et al. '11-15

$J/\psi + \Upsilon$

Shao, Zhang '16

Experiment	CSM			
	DR	LI	EW	INTER
D0: $27 \pm 42.2\%$	$0.0146^{+233\%}_{-66.6\%}$	$0.229^{+264\%}_{-70.4\%}$	$0.065^{+75.5\%}_{-46.6\%}$	$-0.068^{+162\%}_{-62.2\%}$
LHCb	$0.255^{+391\%}_{-79.7\%}$	$6.05^{+436\%}_{-82.2\%}$	$1.71^{+135\%}_{-65.2\%}$	$-3.23^{+262\%}_{-75.9\%}$

COM			
Set I	Set II	Set III	Set IV
$2.96^{+135\%}_{-56.2\%}$	$1.41^{+160\%}_{-77.6\%}$	$1.80^{+143\%}_{-58.0\%}$	$0.418^{+144\%}_{-58.3\%}$
$38.8^{+238\%}_{-73.0\%}$	$21.2^{+243\%}_{-73.6\%}$	$28.1^{+243\%}_{-73.8\%}$	$6.57^{+243\%}_{-73.9\%}$

- CO > CS in SPS
- Larger disparate CO SPS
- Need to suppress DPS first

Thursday, June 15, 17