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Overview of $\eta_{c,b}, \chi_{c,b}, h_{c,b}$ and $X(3872)$ Production

Hua-Sheng Shao
Theoretical Physics Department, CERN

New Observables in Quarkonium Production

ECT*, Trento
29 February 2016

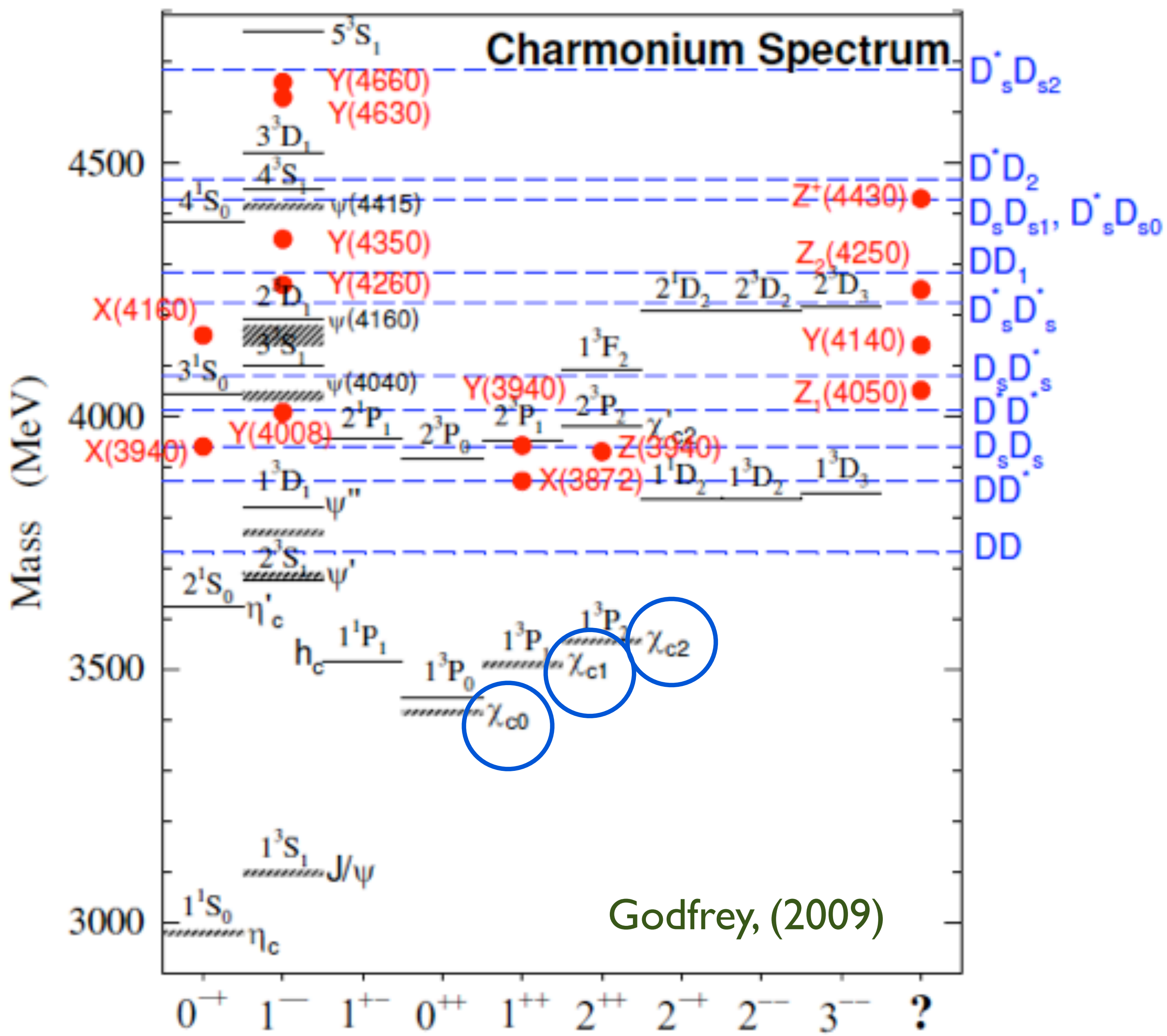
PLAN OF THE TALK

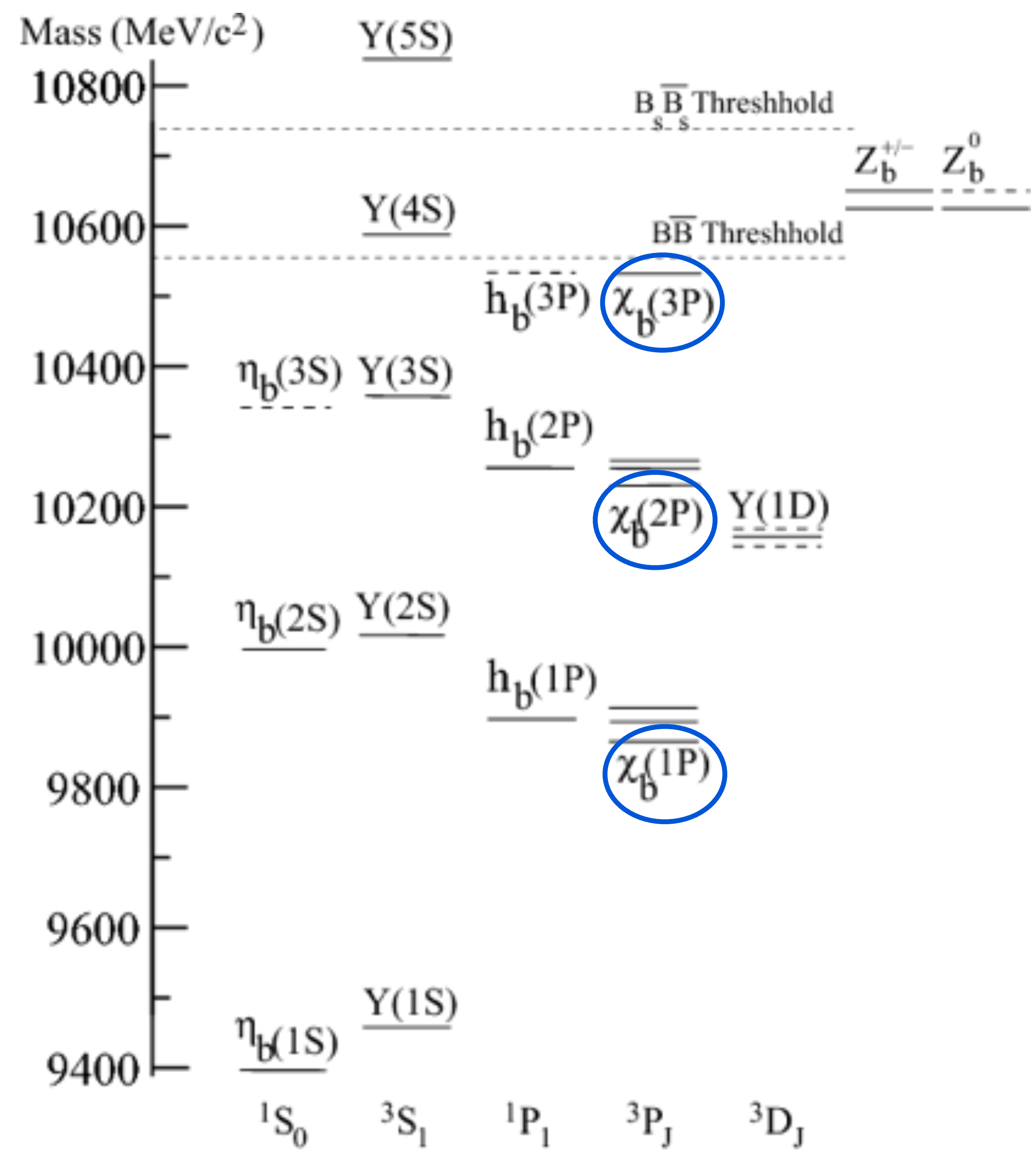
- **I will focus on the review of the following quarkonium production**

$$\chi_{c,b} \quad \eta_{c,b} \quad h_{c,b} \quad X(3872)$$

- **Disclaimer:**
  - by no means this talk is fully comprehensive
  - the choice of presented results is biased
  - apologies if I have left out some of your results
  - I will not talk on the theory development *(See Jian-Wei Qiu's first talk)*
  - I will only talk on proton-(anti-)proton collisions *(nucleus-nucleus or proton-nucleus collisions see the sessions this afternoon or on Tuesday)*
  - I will skip ψ and Υ production *(Covered by Jian-Wei Qiu's first talk)*

$\chi_{c,b}$





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WHY IT IS INTERESTING ?

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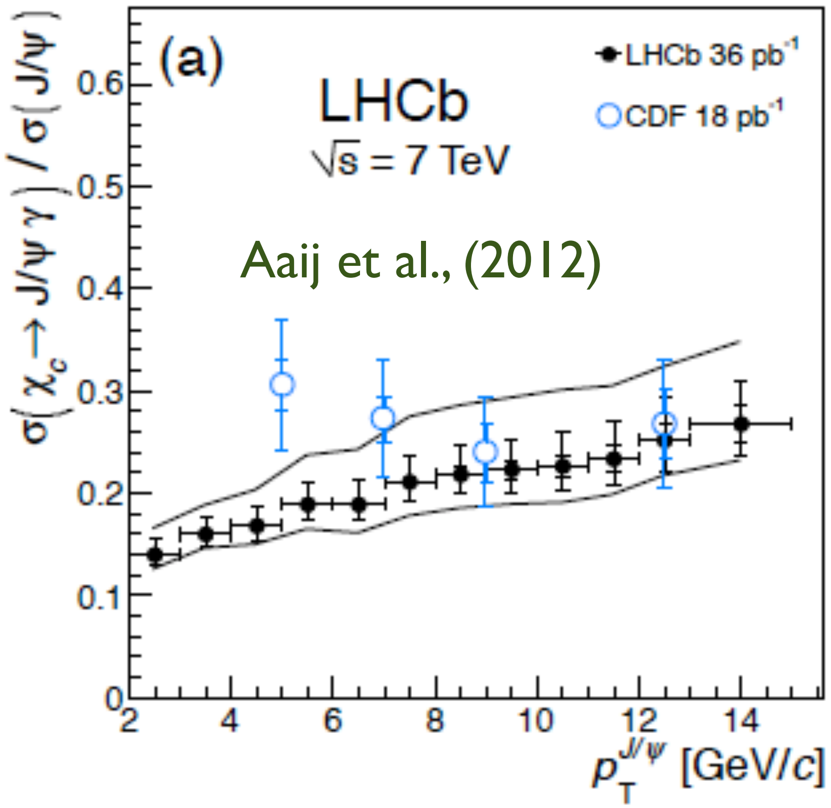
- Significant fraction of prompt J/ψ and Υ production

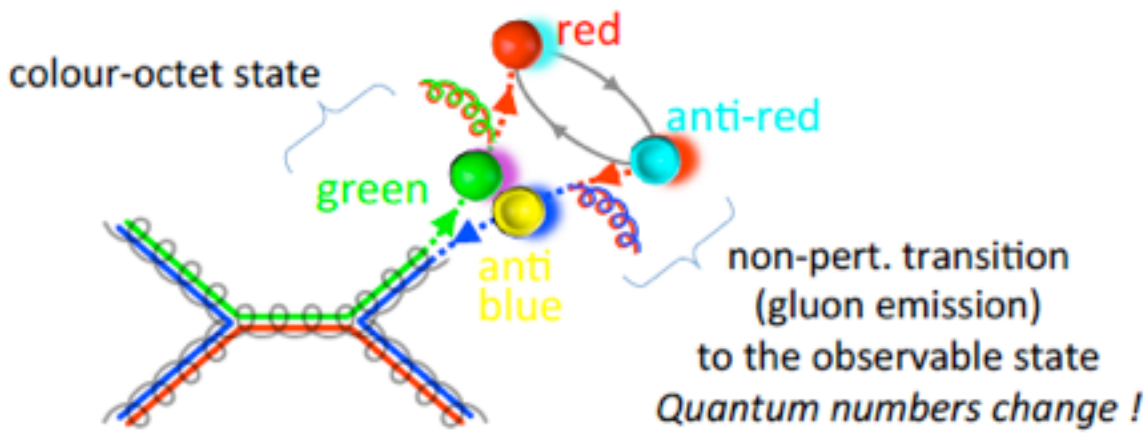


20%-30%

WHY IT IS INTERESTING ?

- Significant fraction of prompt J/ψ and Υ production
- Only one color-octet long distance matrix element

See Jian-Wei's talk for the theory development



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	${}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^1P_1^{[8]}$	${}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_J^{[8]}$	–	–

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  - No pain of suffering from too many freedom to be determined
  - A good candidate to test NRQCD velocity scaling rule

WHY IT IS INTERESTING ?

- Significant fraction of prompt J/ψ and Υ production
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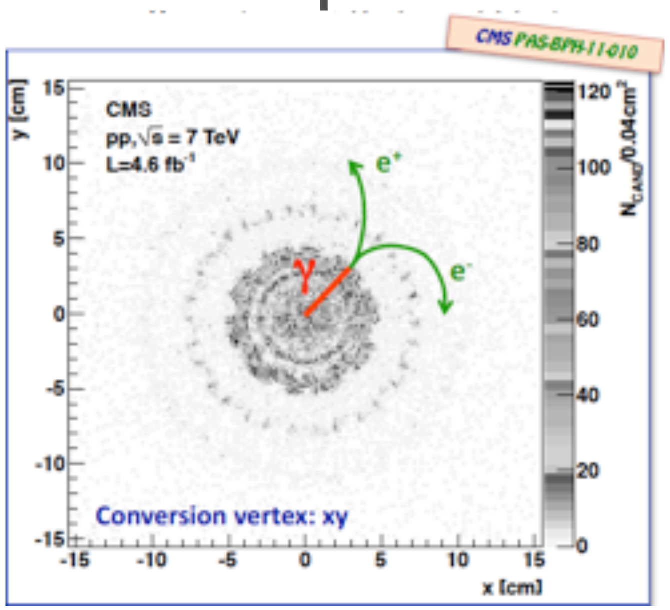
  See Jian-Wei's talk for the theory development

  - No pain of suffering from too many freedom to be determined
  - A good candidate to test NRQCD velocity scaling rule
- However, it is a little bit challenge to measure via

  $\chi_{cJ} \to J/\psi + \gamma$ and $\chi_{bJ}(nP) \to \Upsilon(mS) + \gamma$

  - The trigger of photon is high in order to suppress background
  - The photon is detected via photon conversion



THEORY VS EXPERIMENT

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- State of the art theoretical computation is NLO NRQCD

Ma, Wang, Chao, (2011)

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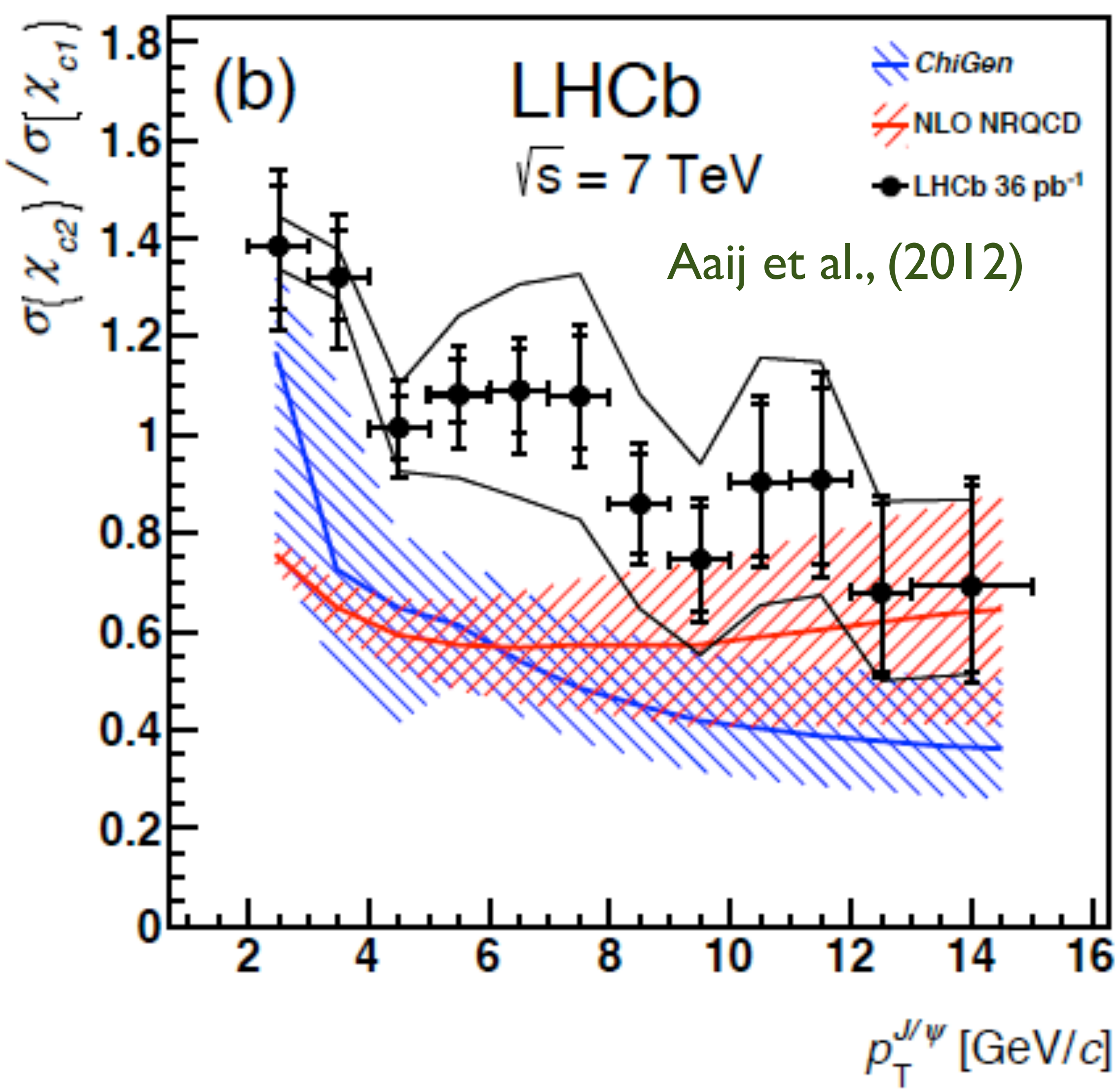
- Better agreement between theory and data



Naive spin counting:

$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} \sim \frac{5}{3}$$

Data:

$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} \sim 1$$

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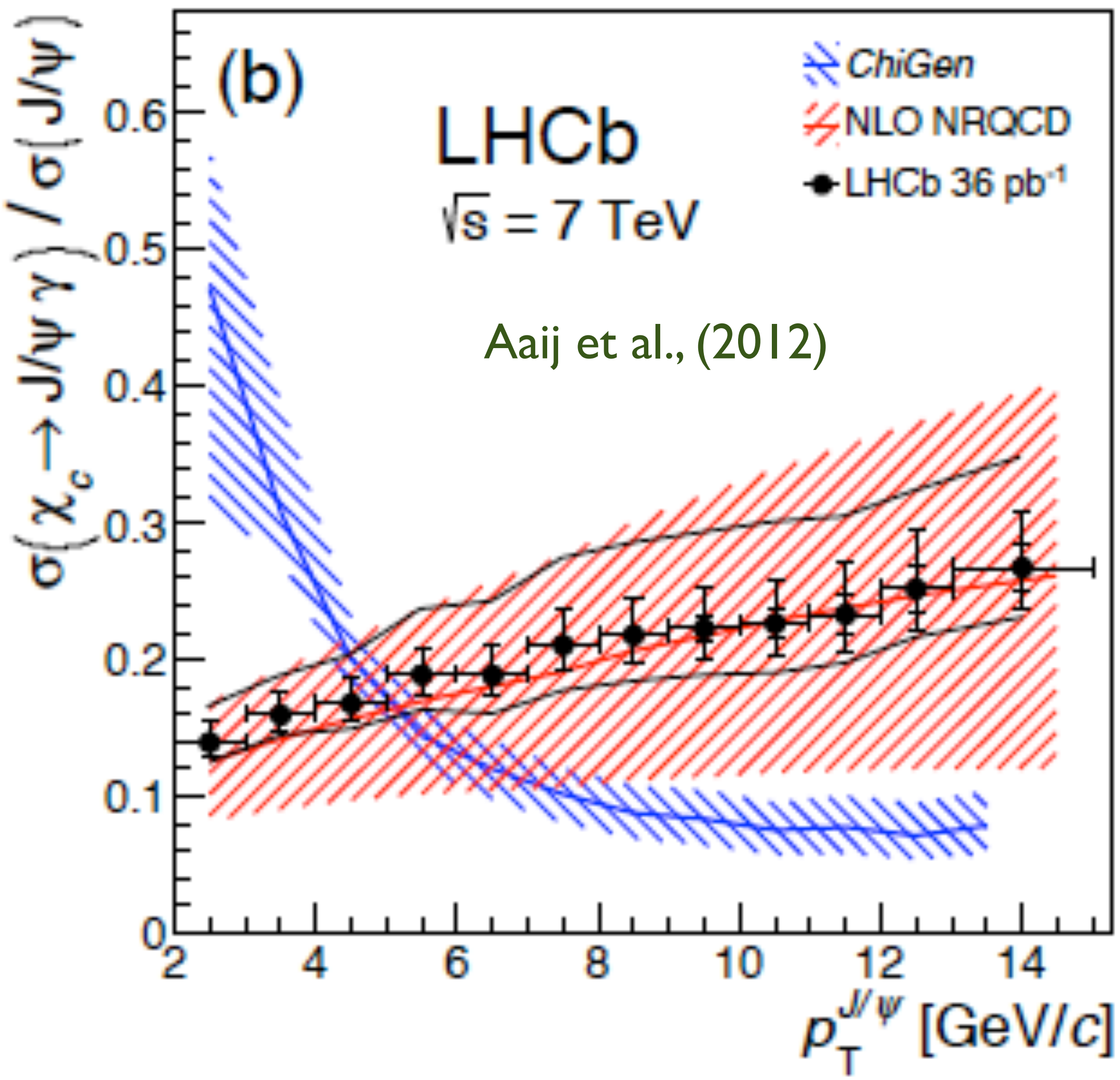

Correct fraction !
Correct trend !

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- Polarization observables are also available at NLO NRQCD

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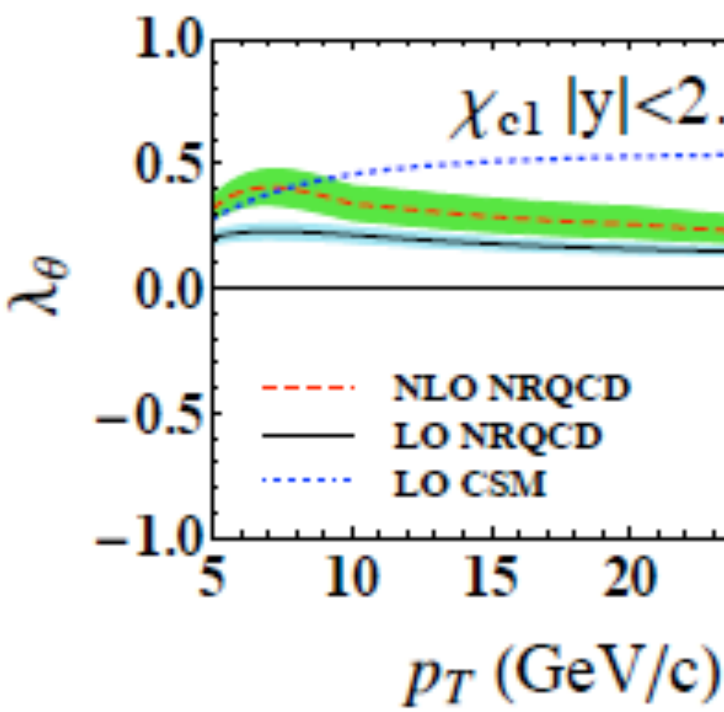

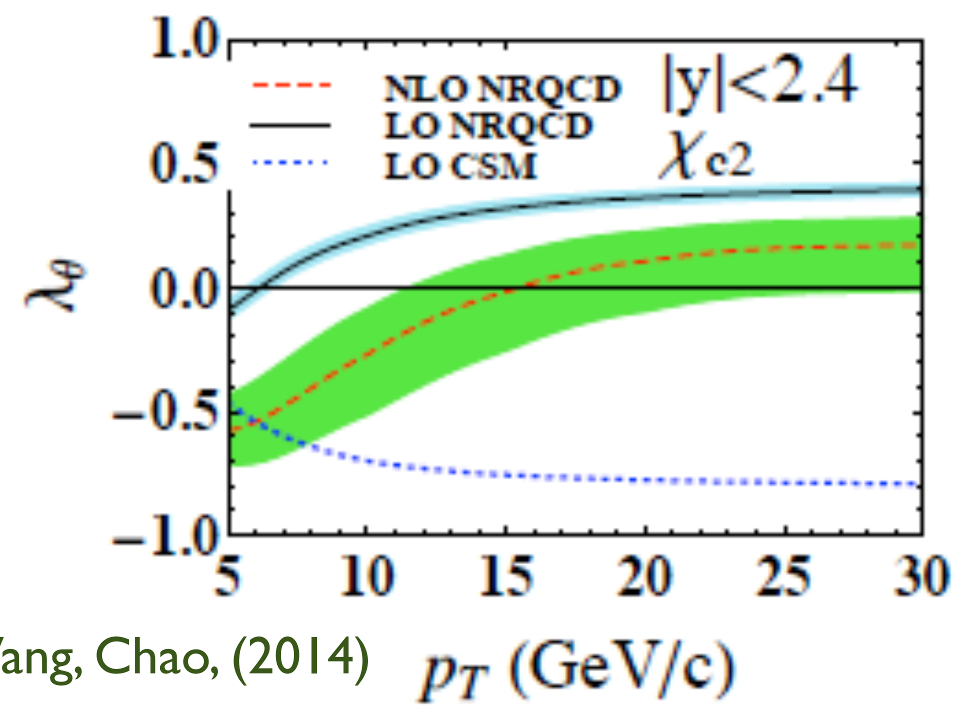

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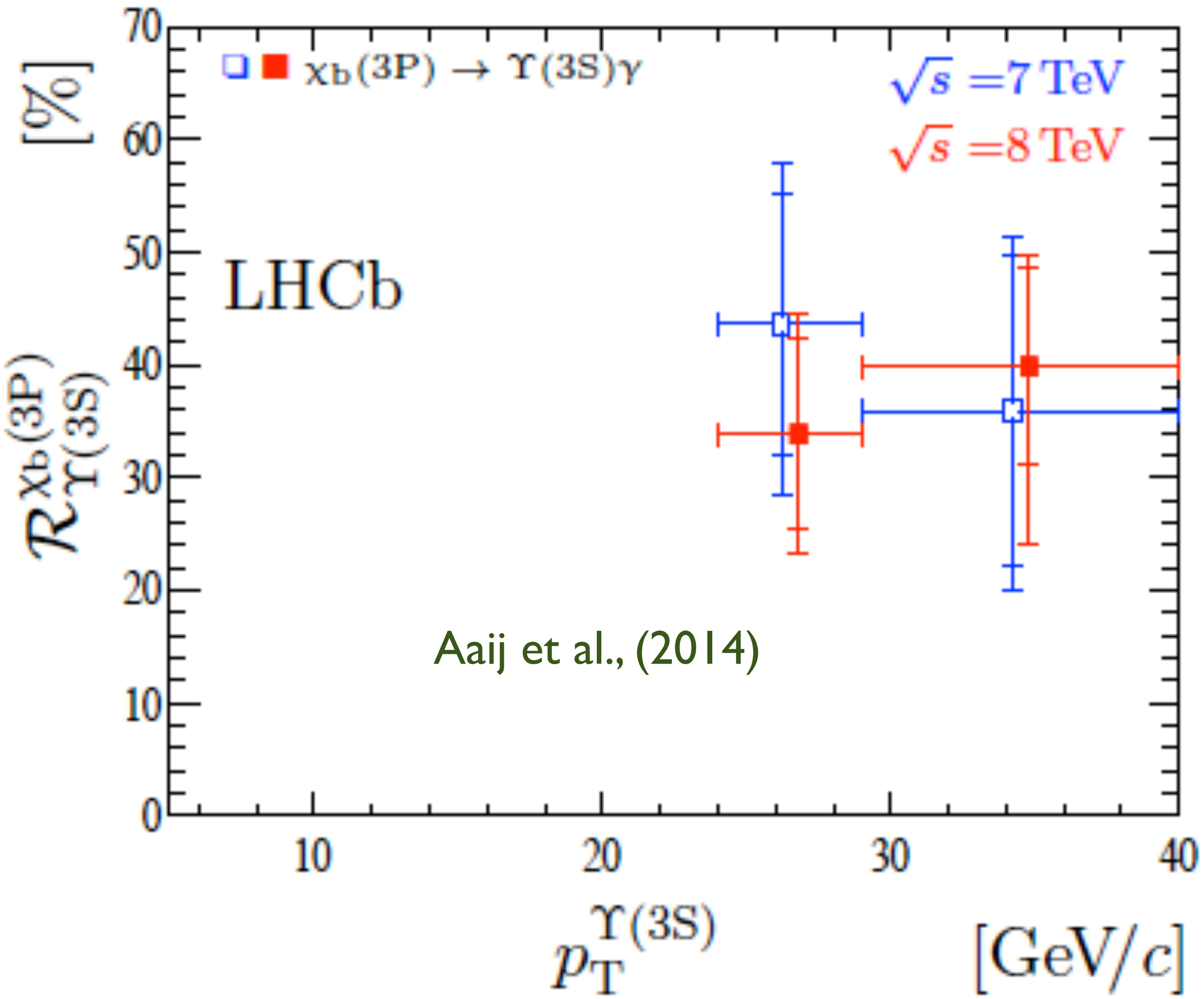
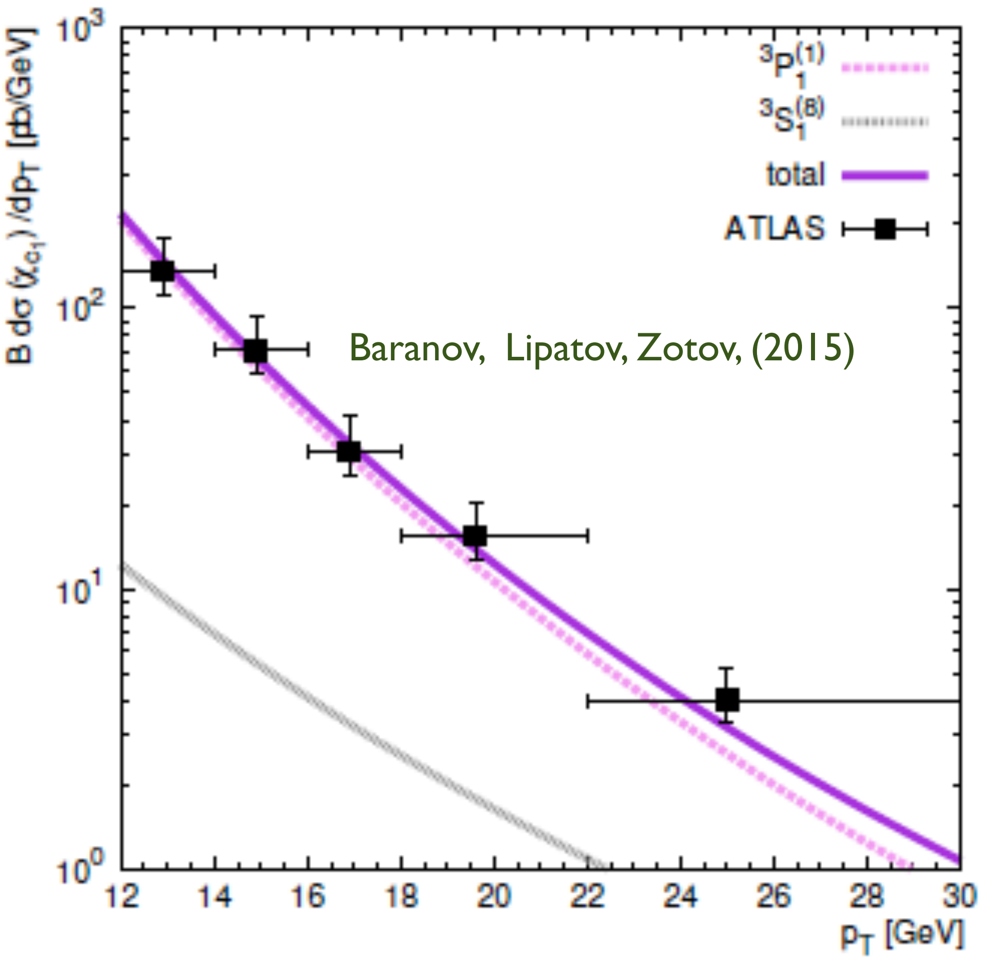
- However, r …

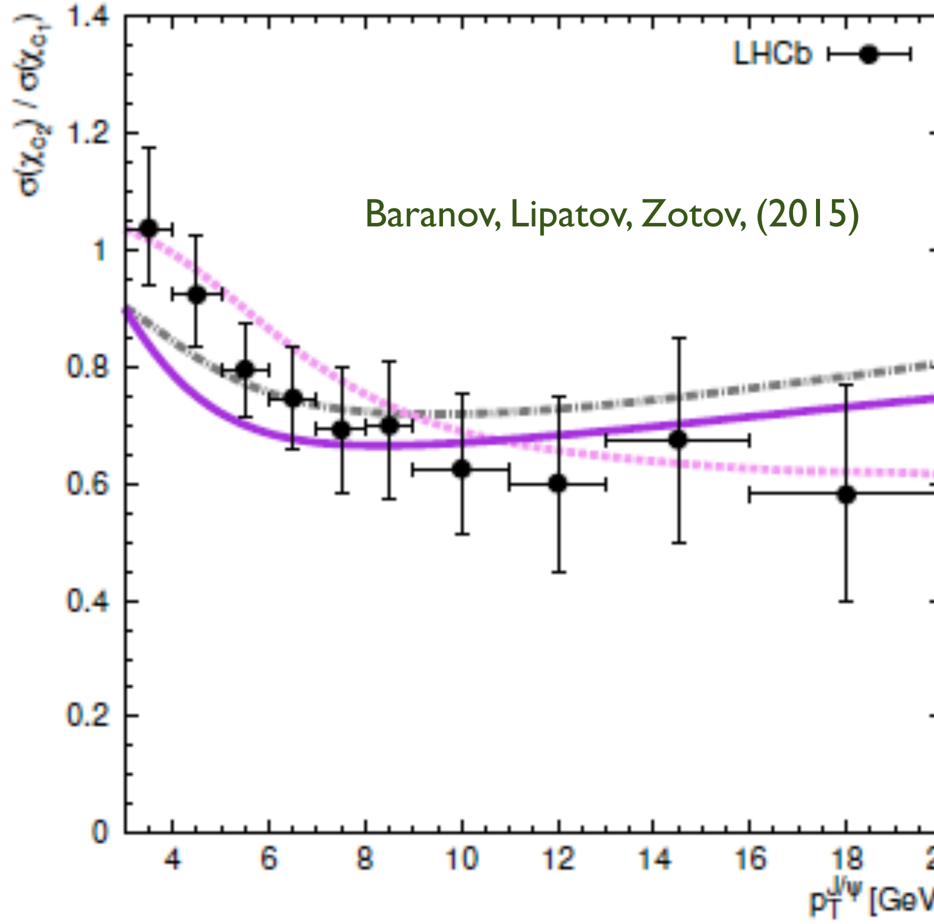
- Keep in mind: feeddown from $\chi_b(3P)$ is not negligible !



THEORY VS EXPERIMENT

- St… al cc … QCD
- Be… en th …)
- Cc… cted
- Po… mok
  See n…
- Po… are a … QCD … 4)





- However, no data to compare !
- Keep in mind: feeddown from $\chi_b(3P)$ is not negligible !
- Studies in kt-factorization also appear

Baranov, Lipatov, Zotov, (2015)

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- Comparis ... y
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- Polarizati ... LO NRQCD
  hao, (2014)

	$\vert\mathcal{R}'^{(1)}_{\chi_{c1}}(0)\vert^2/\text{GeV}^5$	$\vert\mathcal{R}'^{(1)}_{\chi_{c2}}(0)\vert^2/\text{GeV}^5$	$\langle\mathcal{O}^{\chi_{c0}}\left[{}^3S_1^{(8)}\right]\rangle/\text{GeV}^3$
A0	3.85×10^{-1}	6.18×10^{-2}	8.28×10^{-5}
JH	5.23×10^{-1}	9.05×10^{-2}	4.78×10^{-5}
KMR	3.07×10^{-1}	6.16×10^{-2}	1.40×10^{-4}
[9]	7.50×10^{-2}	7.50×10^{-2}	2.01×10^{-3}
[10]	3.50×10^{-1}	3.50×10^{-1}	4.40×10^{-4}

- However, n(

Non-identical WF@Orig
Big violation of HQSS ?

- Keep in mind: feeddown from $\chi_b(3P)$ is not negligible !
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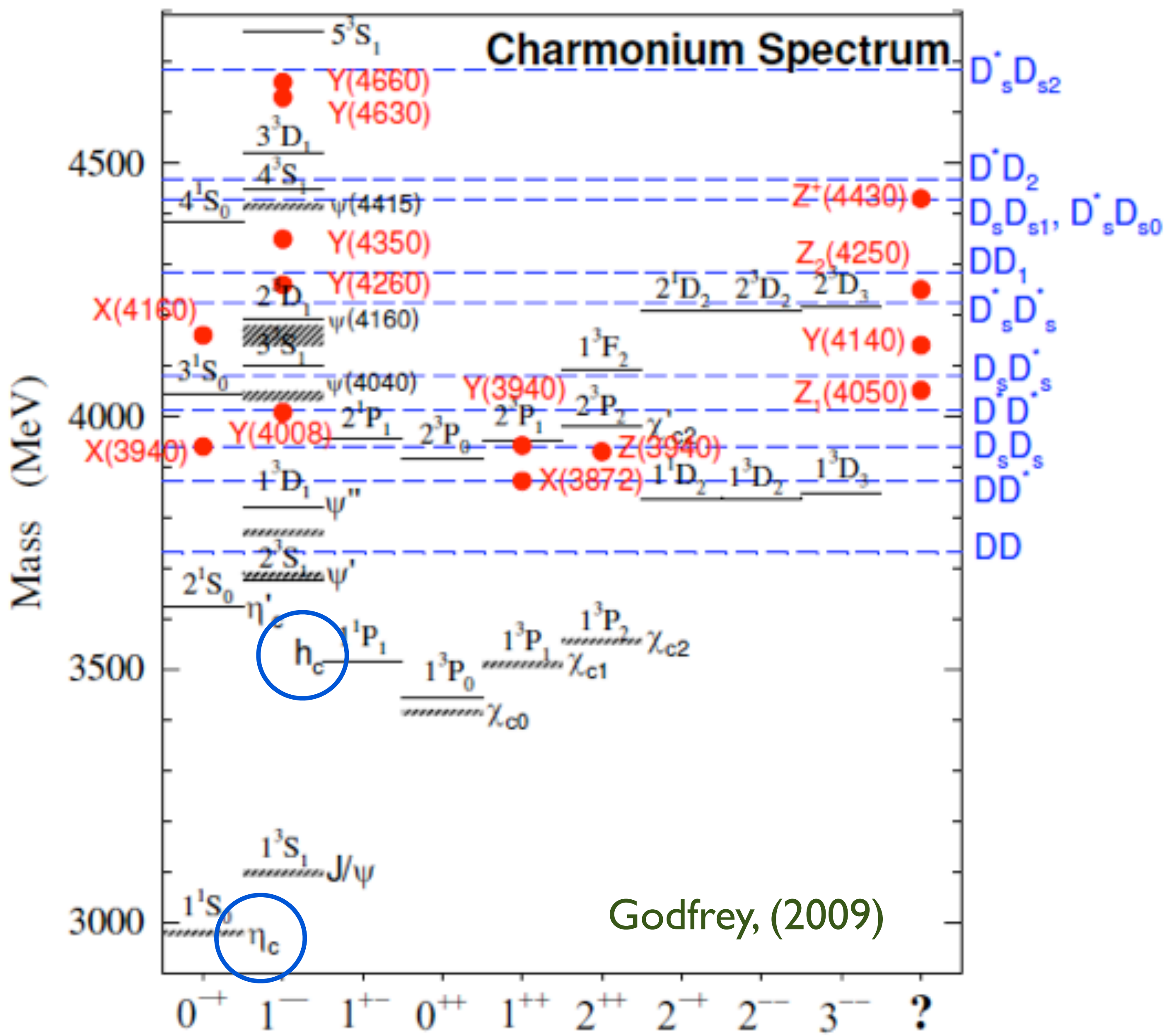
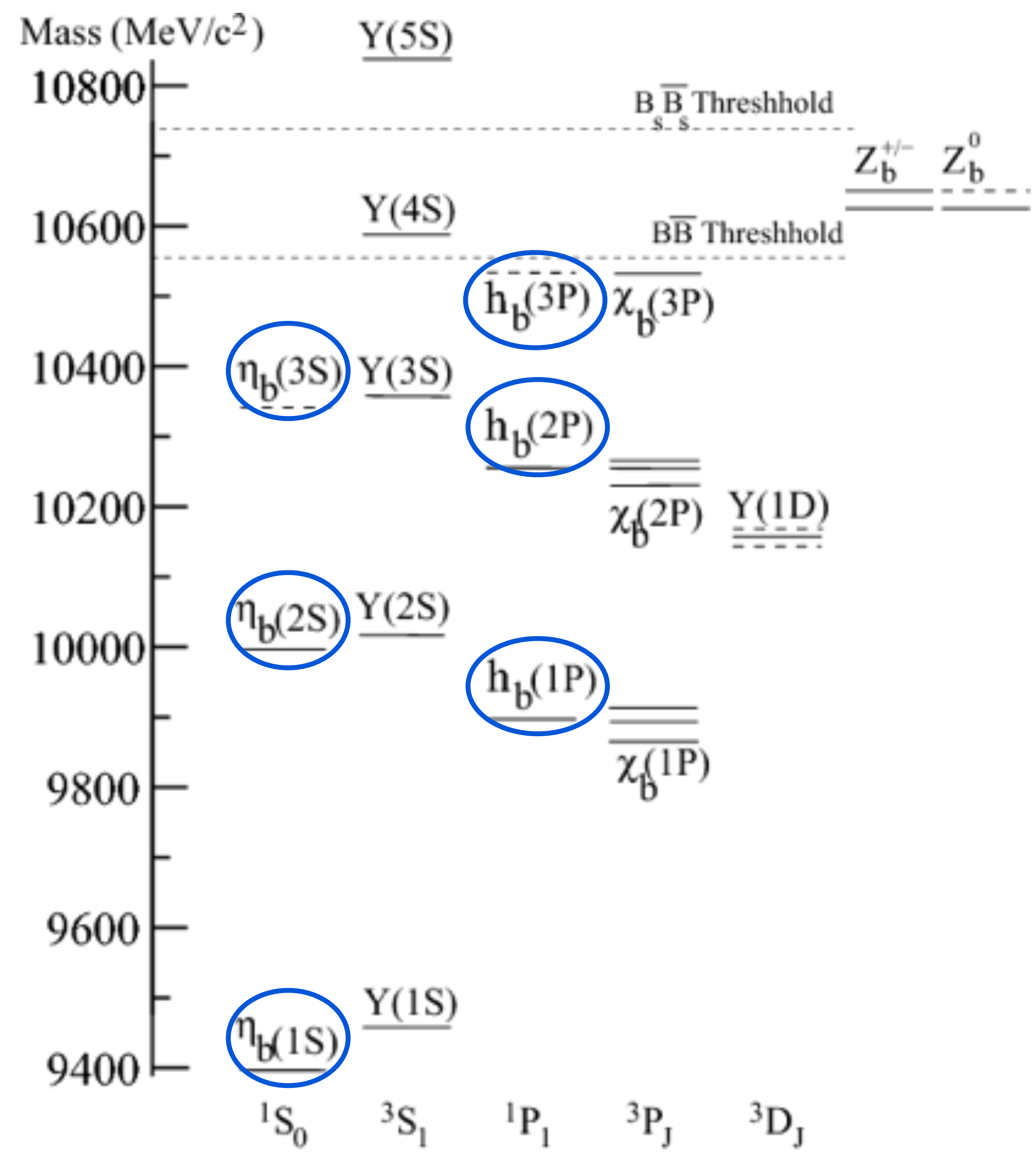
$\eta_{c,b}, h_{c,b}$





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MOTIVATION

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

MOTIVATION

- Why we are interested in $\eta_{c,b}$ and $h_{c,b}$?
- Test heavy quark spin symmetry Bodwin, Braaten, Lepage, (1995)

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

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

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

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

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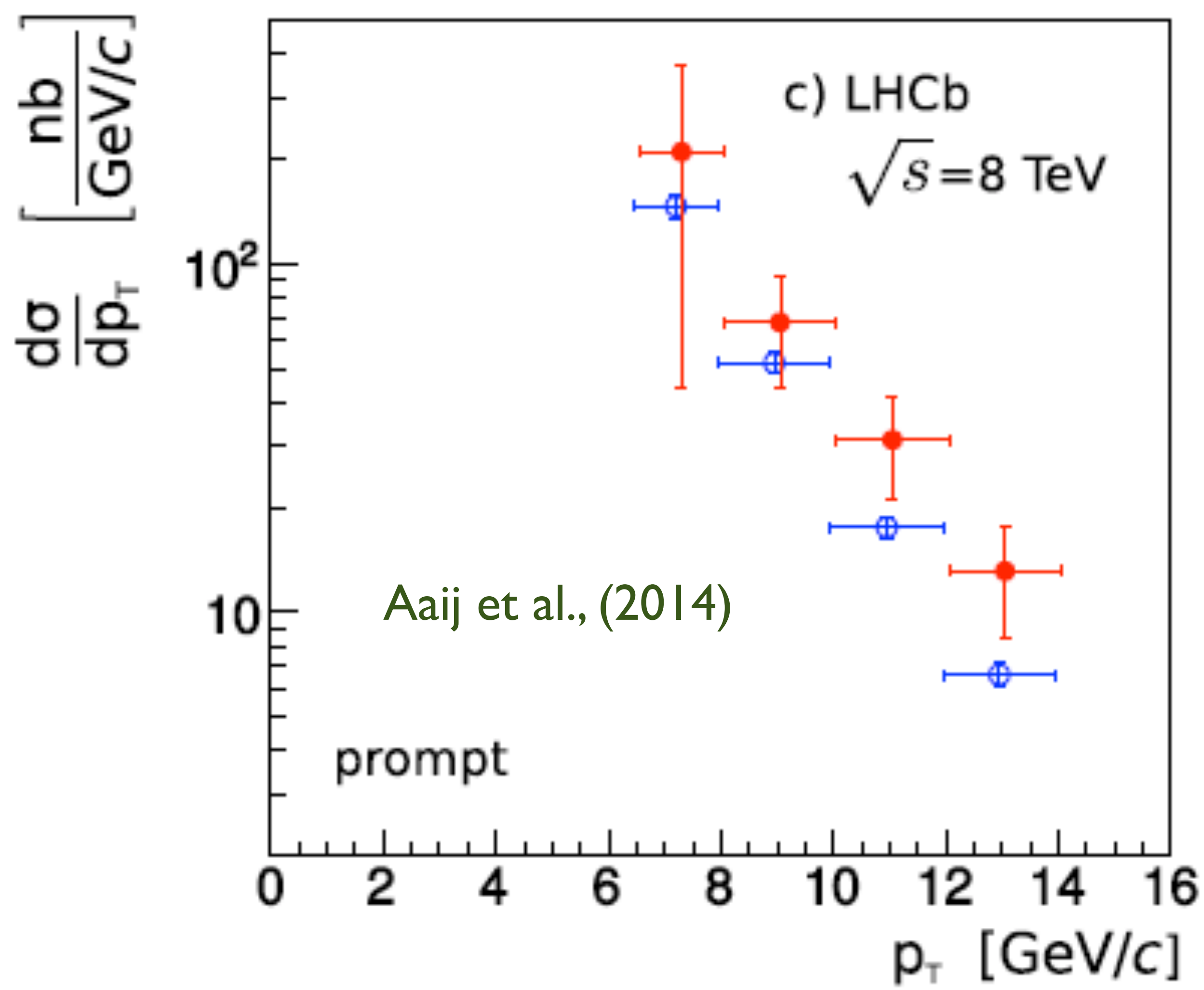

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- Would it be possible to measure

$$h_c \to \eta_c + \gamma$$

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  - 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

WHAT THE DATA TELL US ?

- The LHCb measurement inspires theoretical studies

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

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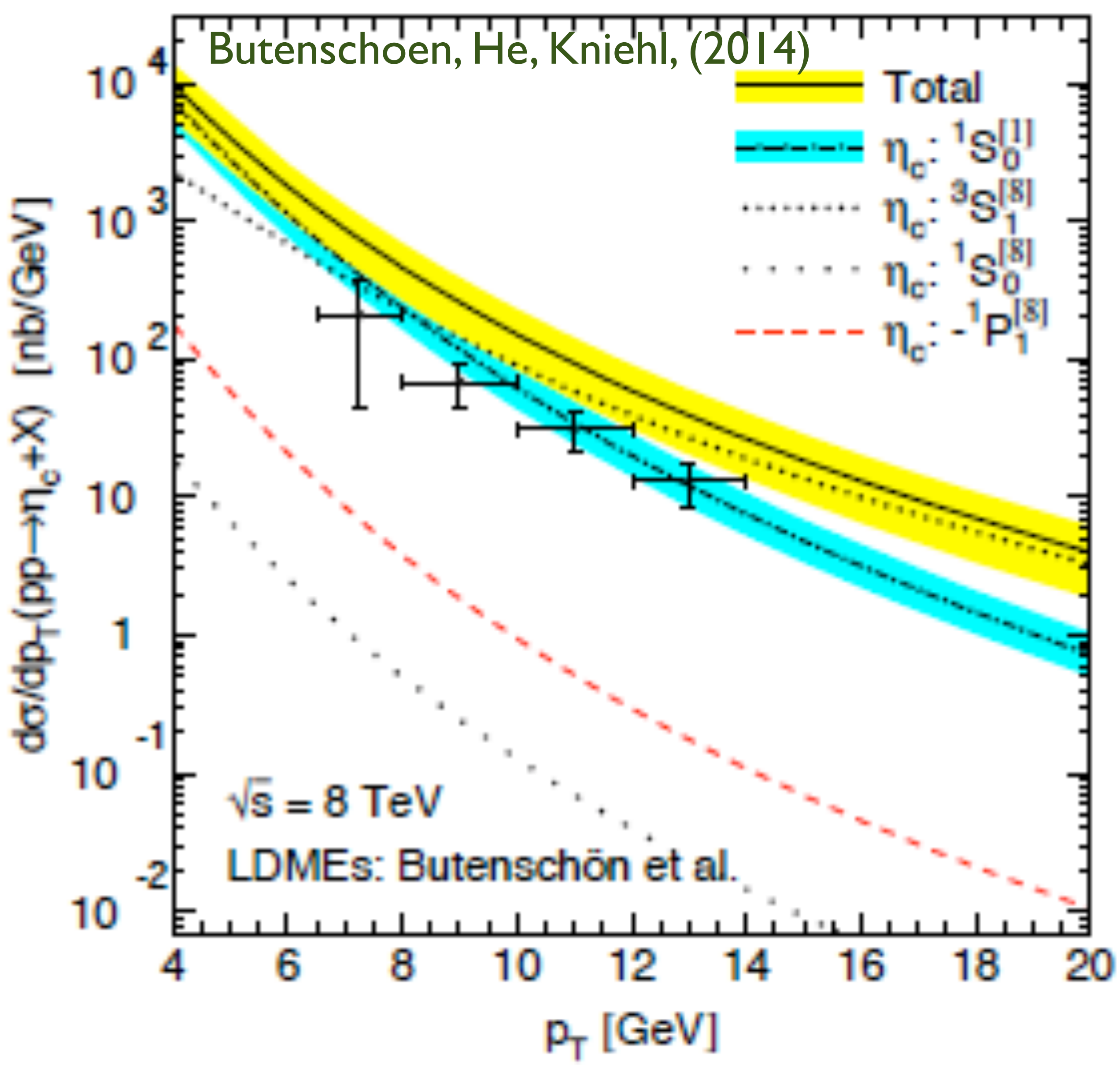

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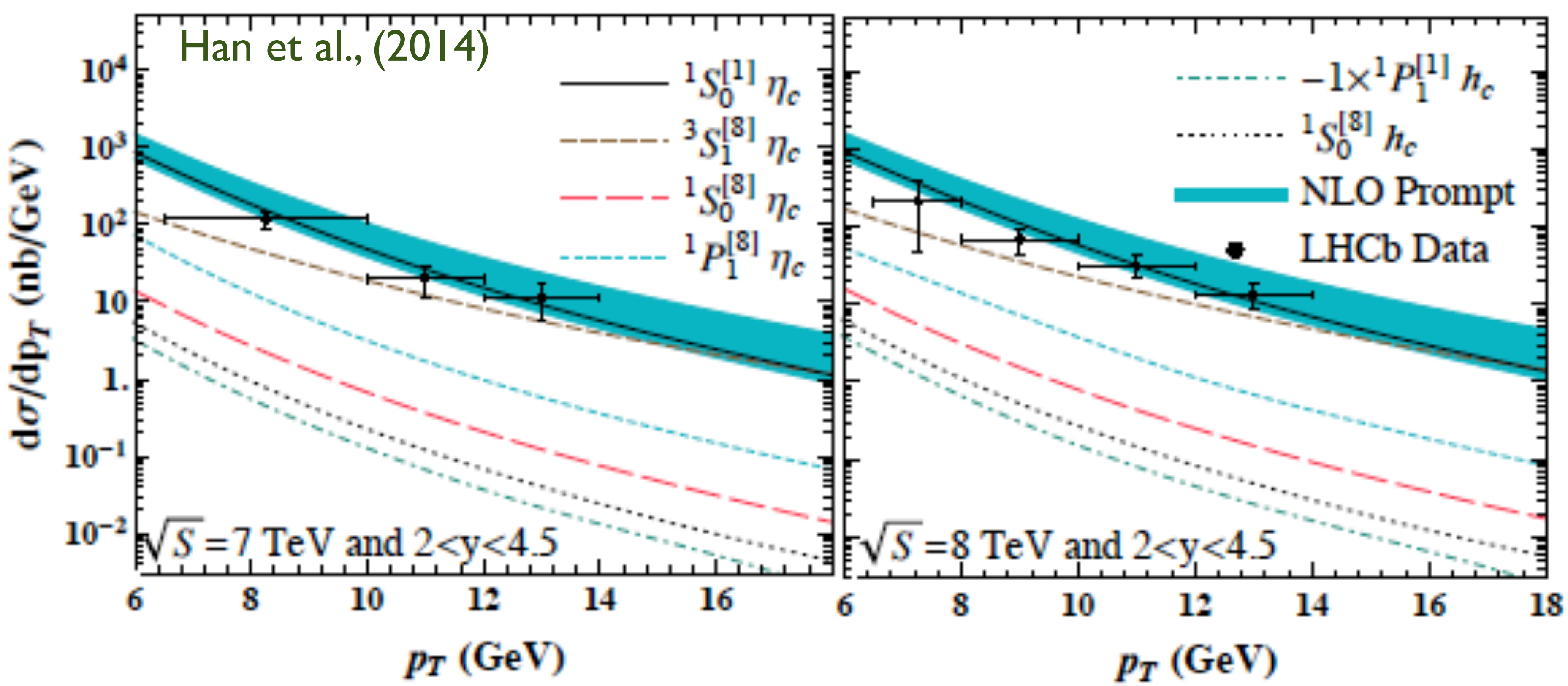
- LHCb data + HQSS helps to constrain $\langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]}) \rangle$

  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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Before

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After

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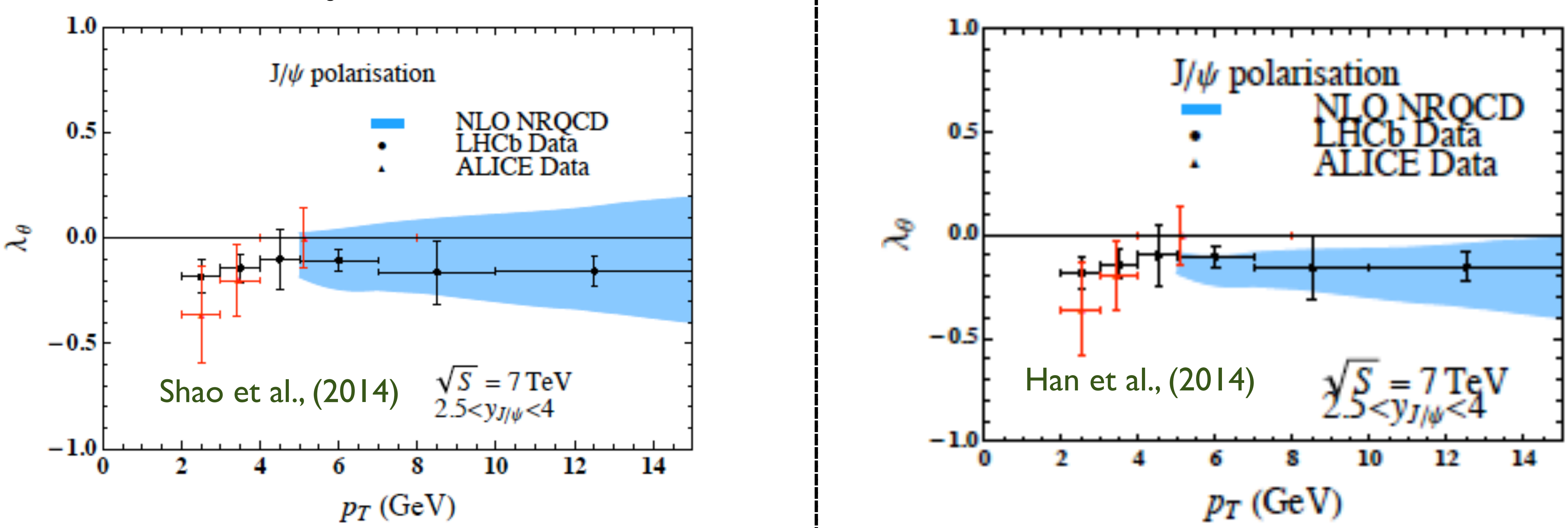

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CERN

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- **HQSS holds up to** $\mathcal{O}(v^2)$

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

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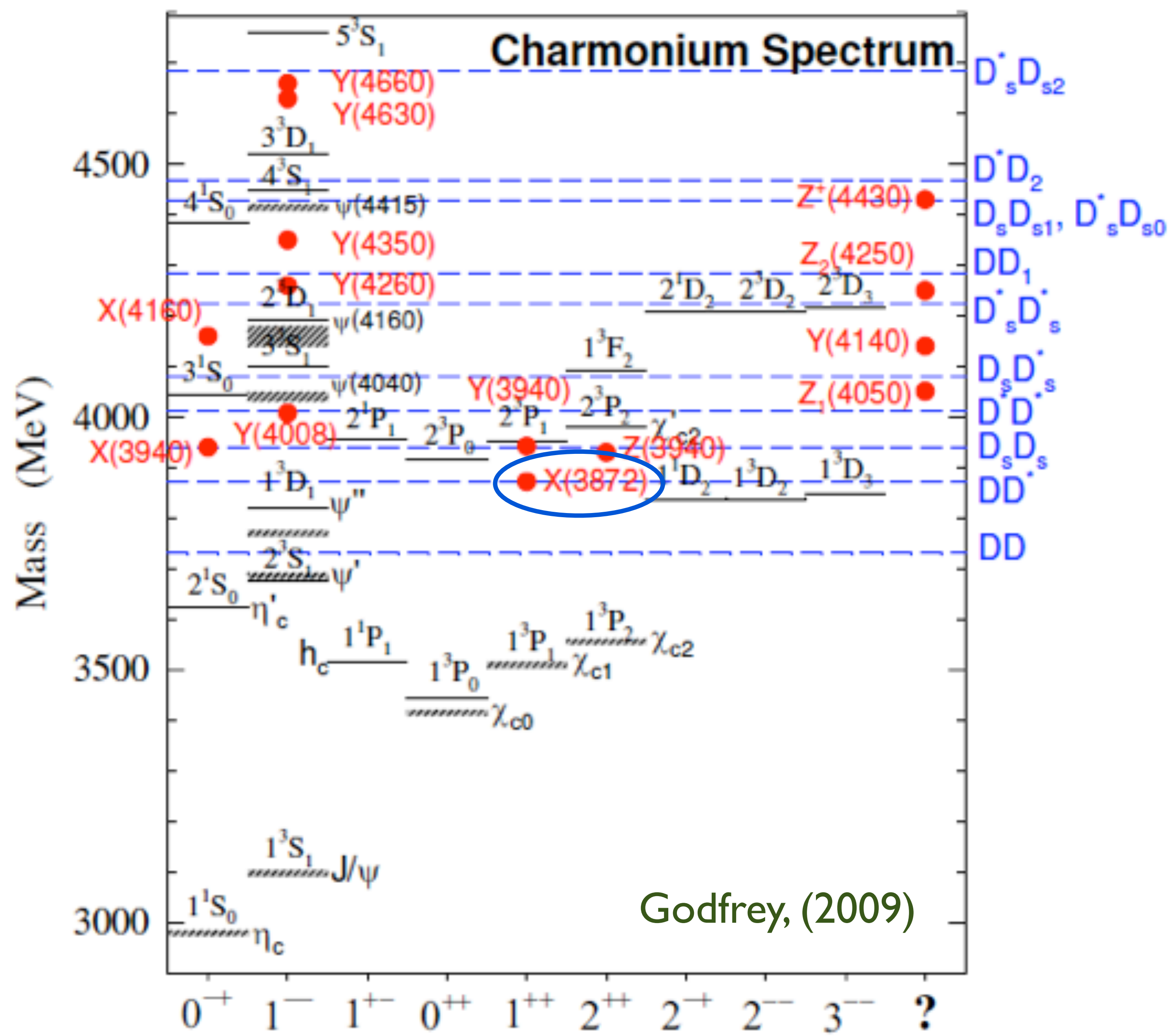
  Charmonium: $v^2 \approx 0.3$ Bottomonium: $v^2 \approx 0.1$

- Does HQSS hold also for P-wave: h_c ?

- NLO NRQCD result is available for h_c production

  Wang, Zhang, (2014)

$X(3872)$



Charmonium Spectrum
Mass (MeV)
4500
4000
3500
3000
Y(4660)
Y(4630)
Y(4350)
Y(4260)
X(4160)
X(3940)
Y(4008)
Y(3940)
Z(3940)
X(3872)
Z+(4430)
Z2(4250)
Y(4140)
Z1(4050)
ψ(4415)
ψ(4160)
ψ(4040)
ψ"
ψ'
J/ψ
ηc
η'c
hc
χc0
χc1
χc2
DD
DD*
DsDs
D*D*
DsD*s
D*sD*s
DD1
DsDs1, D*sDs0
D*D2
D*sDs2
0−+ 1−− 1+− 0++ 1++ 2++ 2−+ 2−− 3−− ?
Godfrey, (2009)

X(3872)

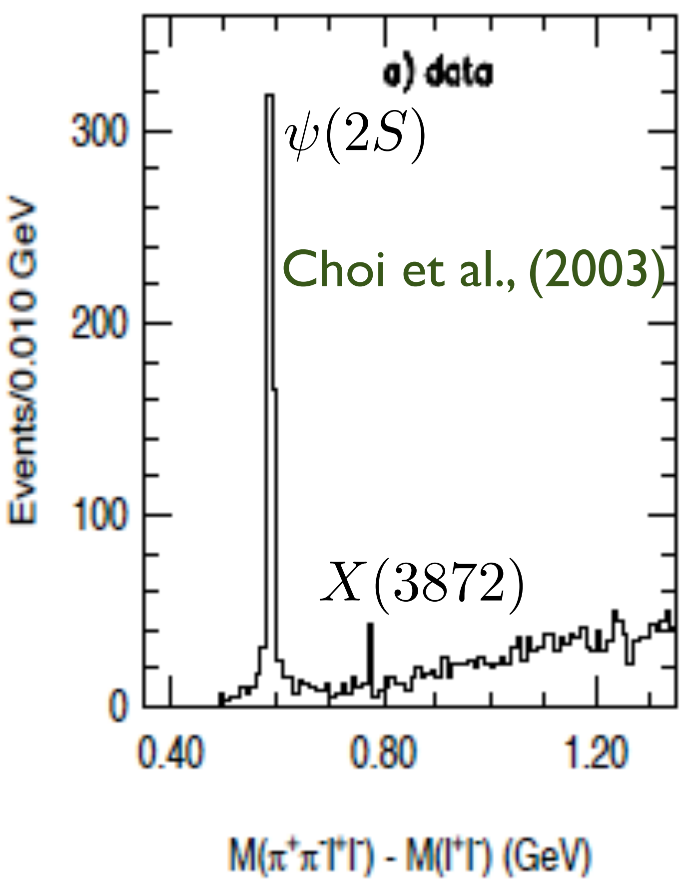
- First observed by the Belle Collaboration

Choi et al., (2003)

- A meson close to open charm pair threshold
- LHCb measurement determines its quantum numbers

$$J^{PC} = 1^{++}$$

Aaij et al., (2013)



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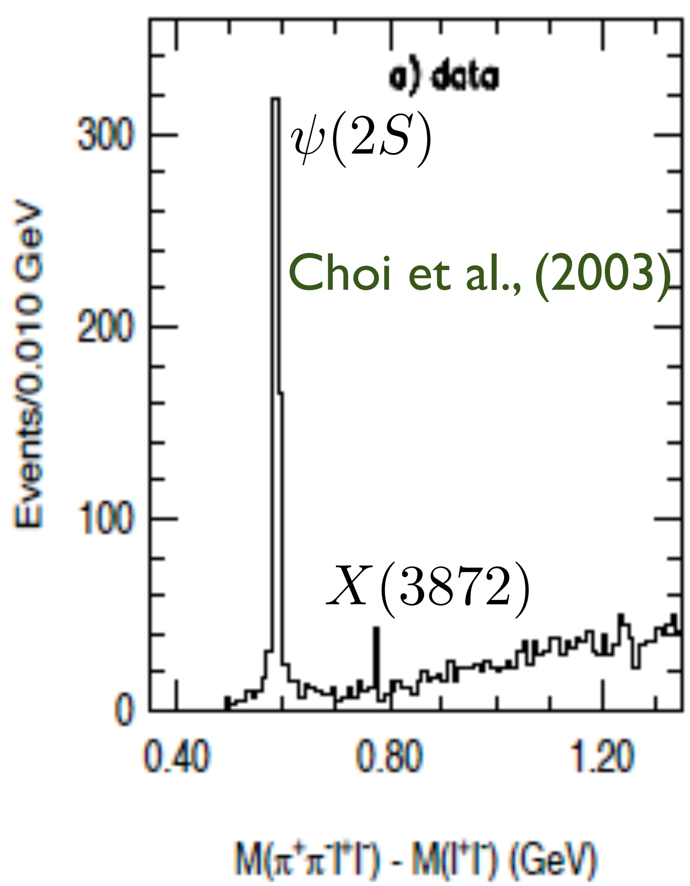
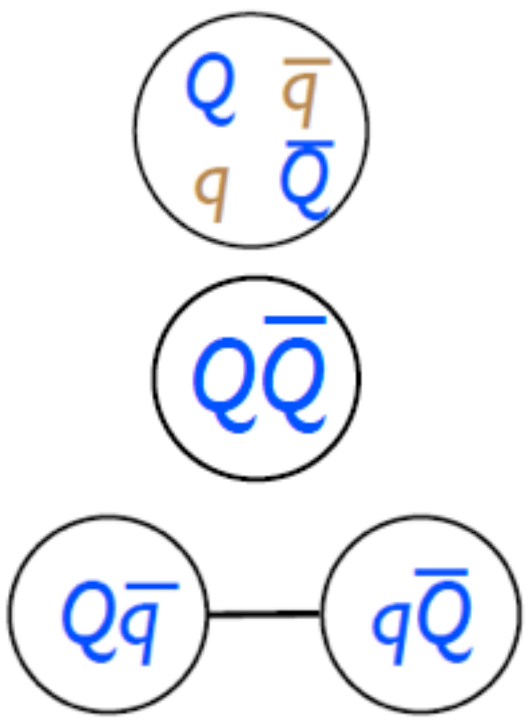


- How to interpret it ?
  - tetraquark ?
  - charmonium, $\chi_{c1}(2P)$?
  - hadronic molecule ?



X(3872)

- Understanding it from prompt yields at hadron colliders ?

X(3872)

- **Understanding it from prompt yields at hadron colliders ?**
  - hadronic molecule interpretation normally has lower yields than data

$\sigma(p\bar{p} \to X) \times \mathrm{Br}(X \to J/\psi\pi^+\pi^-)$

Suzuki, (2005); Bignamini et al., (2009)

theory	vs	CDF
0.085 nb		3.1 ± 0.7 nb

X(3872)

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  - hadronic molecule interpretation normally has lower yields than data

    Suzuki, (2005); Bignamini et al., (2009)
  - rescattering effects could enhance the molecule production rate

    Artoisenet, Braaten (2010)

X(3872)

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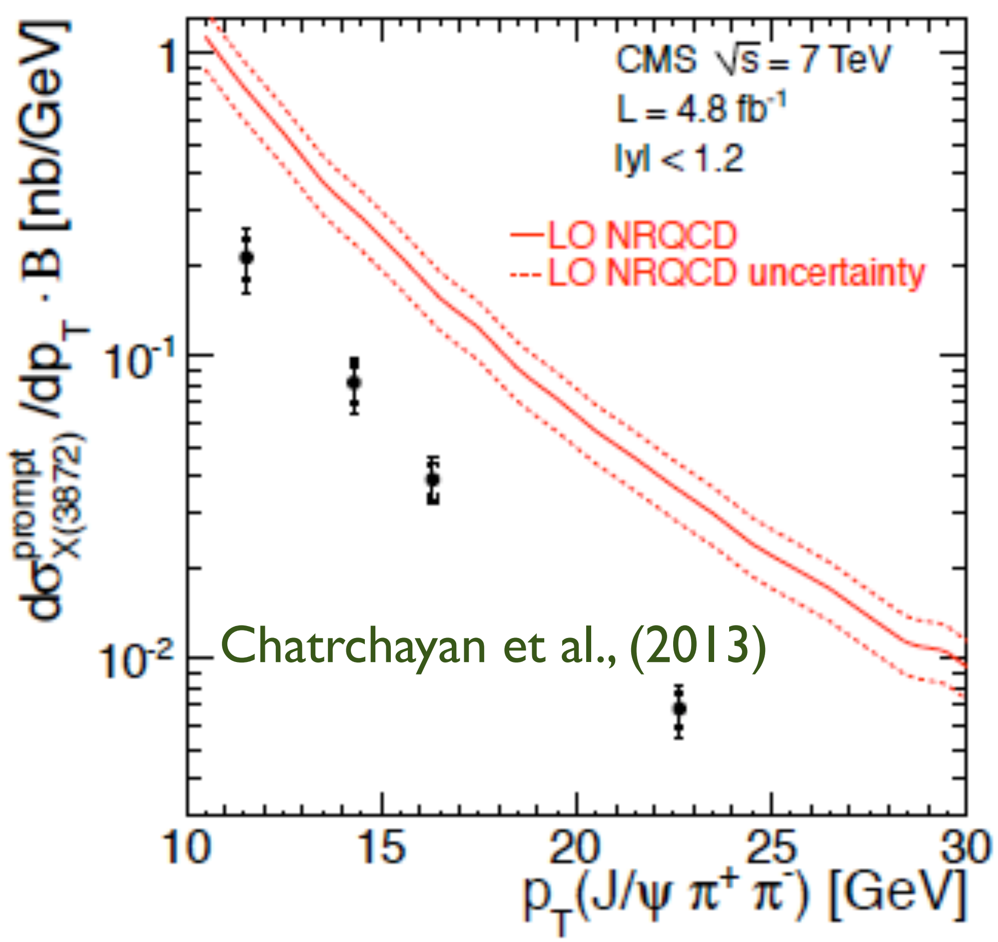
  - However, it overshots the LHCb and CMS data
    Aaij et al., (2012); Chatrchayan et al., (2013)



X(3872)

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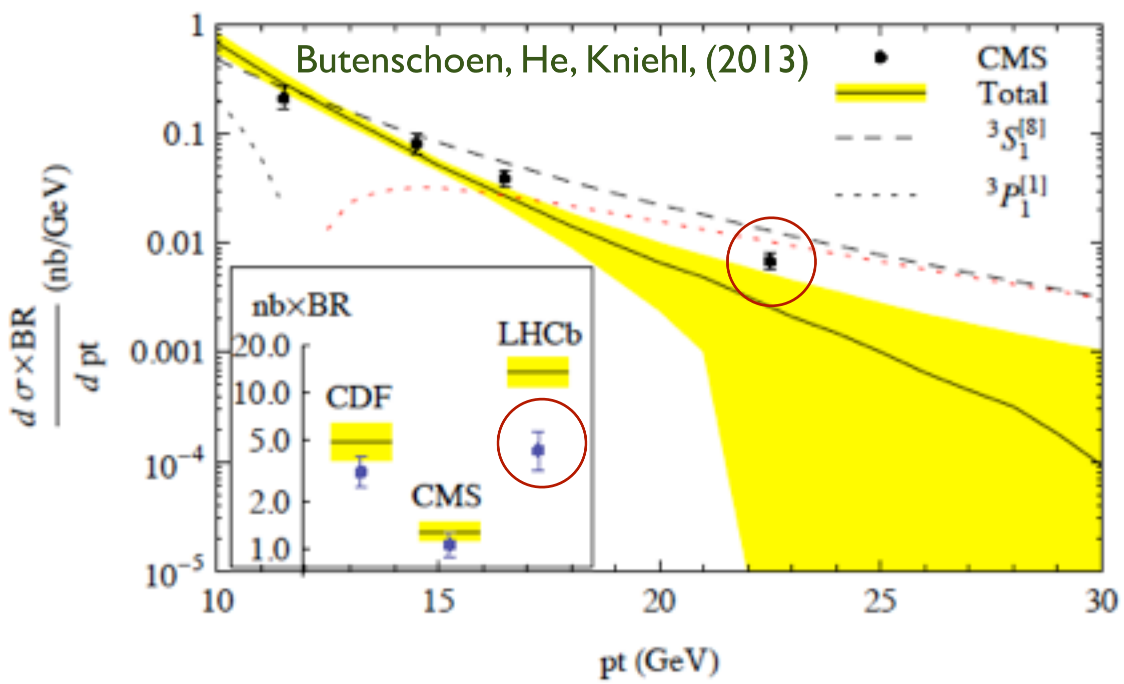
    Aaij et al., (2012); Chatrchayan et al., (2013)
  - Is it a charmonium ?
  - It disfavors a pure charmonium based on NLO NRQCD fit
    Butenschoen, He, Kniehl, (2013)



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X(3872)

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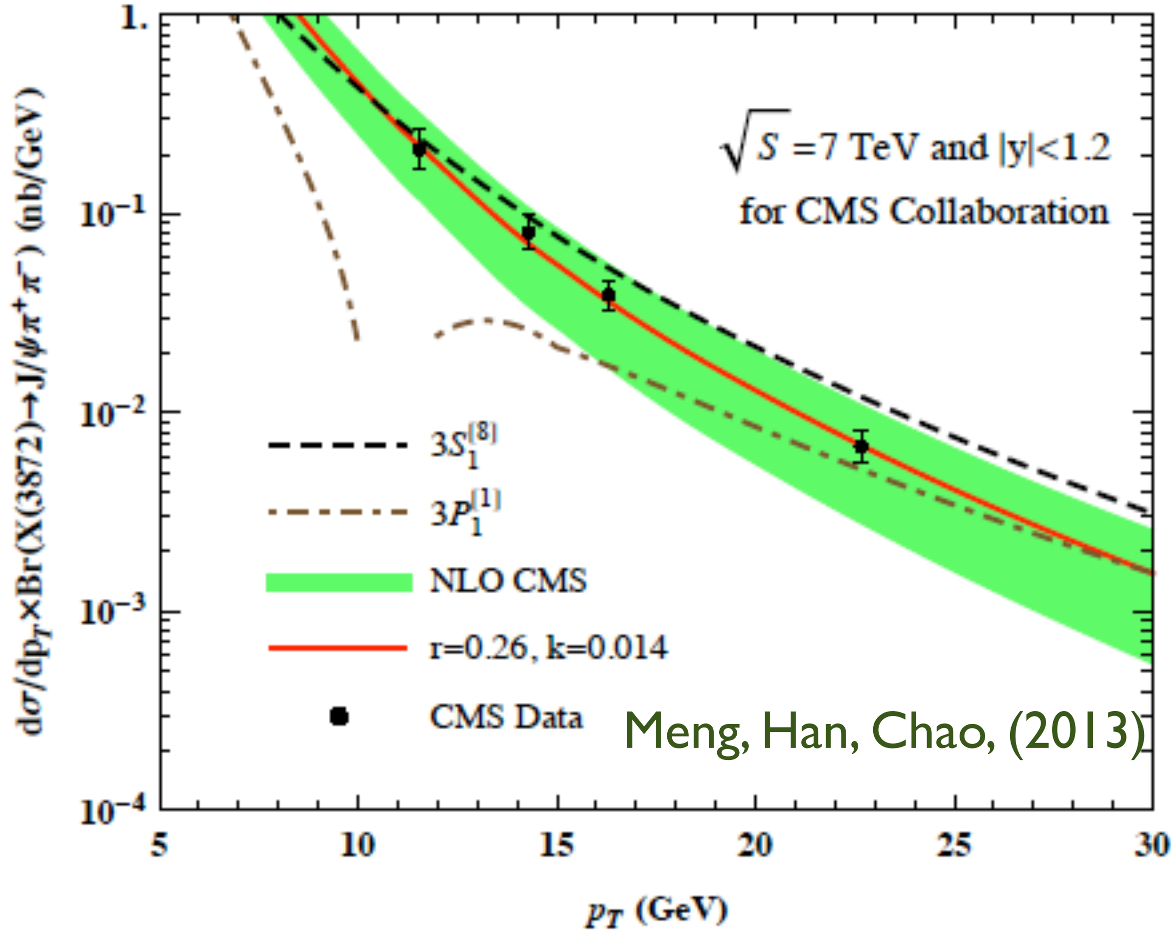

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X(3872)

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  - More comparisons are needed to confirm its ingredient

Conclusions

CONCLUSIONS

- We have a lot of quarkonium production data
  - *Most of them are for ψ and Υ production, because of easy reconstruction*
- We should not overlook other quarkonium
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Thank you for your attention !