Charmonia in b decays

S. Barsuk, E. Kou, A. Usachov
LAL-IN2P3, Orsay

Mini-Workshop on charmonium production at LHCb
The 16th June 2017 at CERN

Charmonium production at hadron machines

- The first measurement of direct J/ψ and ψ' production at CDF in '97: striking discrepancy from theoretical expectation

CDF, PRL79 ('97)

- NRQCD: double expansion in terms of α_s and v (velocity): an addition of "colour-octet" term was proposed.

Bodwin, Braaten, Lepage, PRD51 ('95)

- Tremendous efforts have been made to obtain more precise theoretical prediction for the charmonium production at hadron machines (computation of the higher order corrections, extracting the matrix element of NRQCD, Color-singlet approach etc). ➡ after many debates, still the situation is unclear!

More investigation is needed!

New observables to help the situation ???

Hadronic final state (pp, ΦΦ) to study, η_c, χ_{Jc}...

- LHCb succeeded η_c prompt/secondary production using pp final state! ---> very important information to determine matrix element. Now, new result of χ_{Jc} available (see talk Usachov)

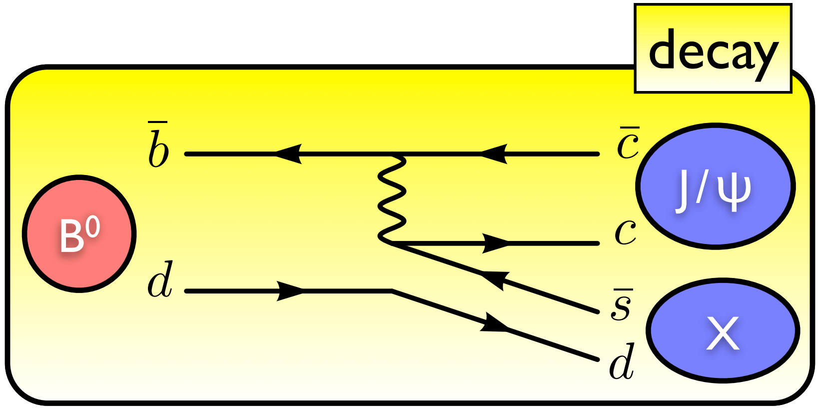
Charmonium from B decays to extract the matrix elements?

- Secondary charmonium production is experimentally cleaner than the prompt production. Theoretically, it is less clean (e.g. issues in the NLO estimate of the singlet contribution) but can't we still learn something?

<--- Universality of matrix elements!

Revisiting the NRQCD computation of inclusive B decaying into charmonium

Beneke, Maltoni, Rothstein PRD59 ('99)



$$H_{eff} = \frac{G_F}{\sqrt{2}} \sum_{q=s,d} \left\{ V_{cb}^* V_{cq} \left[\frac{1}{3} C_{[1]}(\mu) \mathcal{O}_1(\mu) + C_{[8]}(\mu) \mathcal{O}_8(\mu) \right] - V_{tb}^* V_{tq} \sum_{i=3}^{6} C_i(\mu) \mathcal{O}_i(\mu) \right\}$$

$$\mathcal{O}_1 = [\bar{c}\gamma_\mu(1-\gamma_5)c]\,[\bar{b}\gamma^\mu(1-\gamma_5)q]$$

$$\mathcal{O}_8 = [\bar{c}\,T^A\gamma_\mu(1-\gamma_5)c]\,[\bar{b}\,T^A\gamma^\mu(1-\gamma_5)q]$$

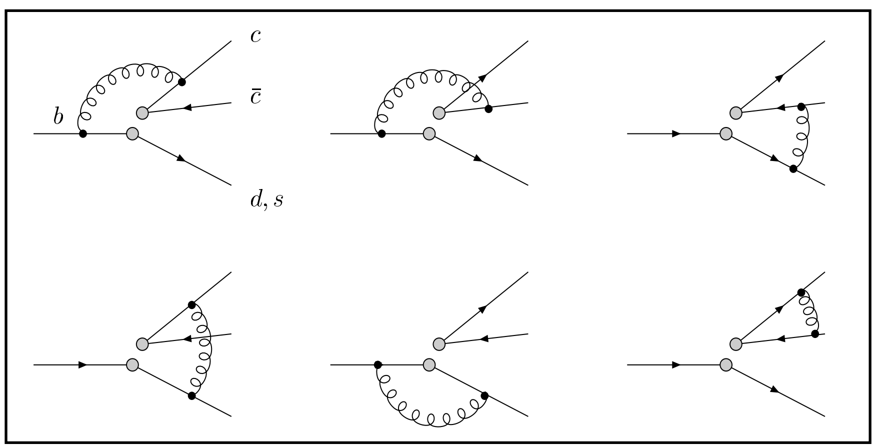
It has been pointed out by several authors that the singlet term is too small to explain the experimental data.

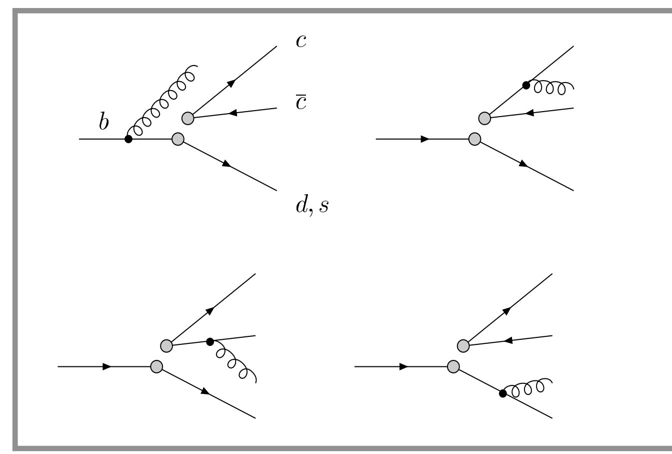
Revisiting the NRQCD computation of inclusive B decaying into charmonium

NLO computation

Beneke, Maltoni, Rothstein PRD59 ('99)

$$\Gamma[n] = \Gamma_0 \Big[C_{[1,8]}^2 f[n](\eta)\,(1+\delta_P[n]) + \frac{\alpha_s(\mu)}{4\pi}\Big(C_{[1]}^2 g_1[n](\eta) + 2C_{[1]}C_{[8]} g_2[n](\eta) + C_{[8]}^2 g_3[n](\eta)\Big)\Big] \langle \mathcal{O}^H[n]\rangle,$$





The singlet term has a large renormalization running effect which makes it large negative (unphysical) at mb scale.

The secondary J/ψ, η_c production from B decays

Beneke, Maltoni, Rothstein PRD59 ('99)

Improved NLO result

$$Br(B \to J/\psi X) = 0.0754 \times 10^{-2} \langle \mathcal{O}_1^{\psi}(^3S_1)\rangle + 0.195 \langle \mathcal{O}_8^{\psi}(^3S_1)\rangle + 0.342 \underbrace{\left[\langle \mathcal{O}_8^{\psi}(^1S_0)\rangle + 3.1/m_c^2 \langle \mathcal{O}_8^{\psi}(^3P_0)\rangle\right]}_{\mathcal{M}^{\psi}_{1,k}(^1S_0^{(8)},\,^3P_0^{(8)})}$$

$$Br(B \to \eta_c X) = 0.250 \times 10^{-2} \langle \mathcal{O}_1^{\eta_c}(^1S_0)\rangle + 0.342 \langle \mathcal{O}_8^{\eta_c}(^1S_0)\rangle + 0.195 \underbrace{\left[\langle \mathcal{O}_8^{\eta_c}(^3S_1)\rangle - 0.24/m_c^2 \langle \mathcal{O}_8^{\eta_c}(^1P_1)\rangle\right]}_{\mathcal{M}^{\eta_c}_{1,0.24}(^3S_1^{(8)},\,^1P_1^{(8)})}$$

Spin symmetry

$$\langle \mathcal{O}_8^{\eta_c}(^1S_0)\rangle = \frac{1}{3} \langle \mathcal{O}_8^{J/\psi}(^3S_1)\rangle,$$

$$\langle \mathcal{O}_8^{\eta_c}(^3S_1)\rangle = \langle \mathcal{O}_8^{J/\psi}(^1S_0)\rangle,$$

$$\langle \mathcal{O}_8^{\eta_c}(^1P_1)\rangle = 3 \langle \mathcal{O}_8^{J/\psi}(^3P_0)\rangle.$$

Caveat:
A large uncertainty
(factor two?)

The secondary J/ψ, η_c production from B decays

Momentum dependence of B-> J/psi X

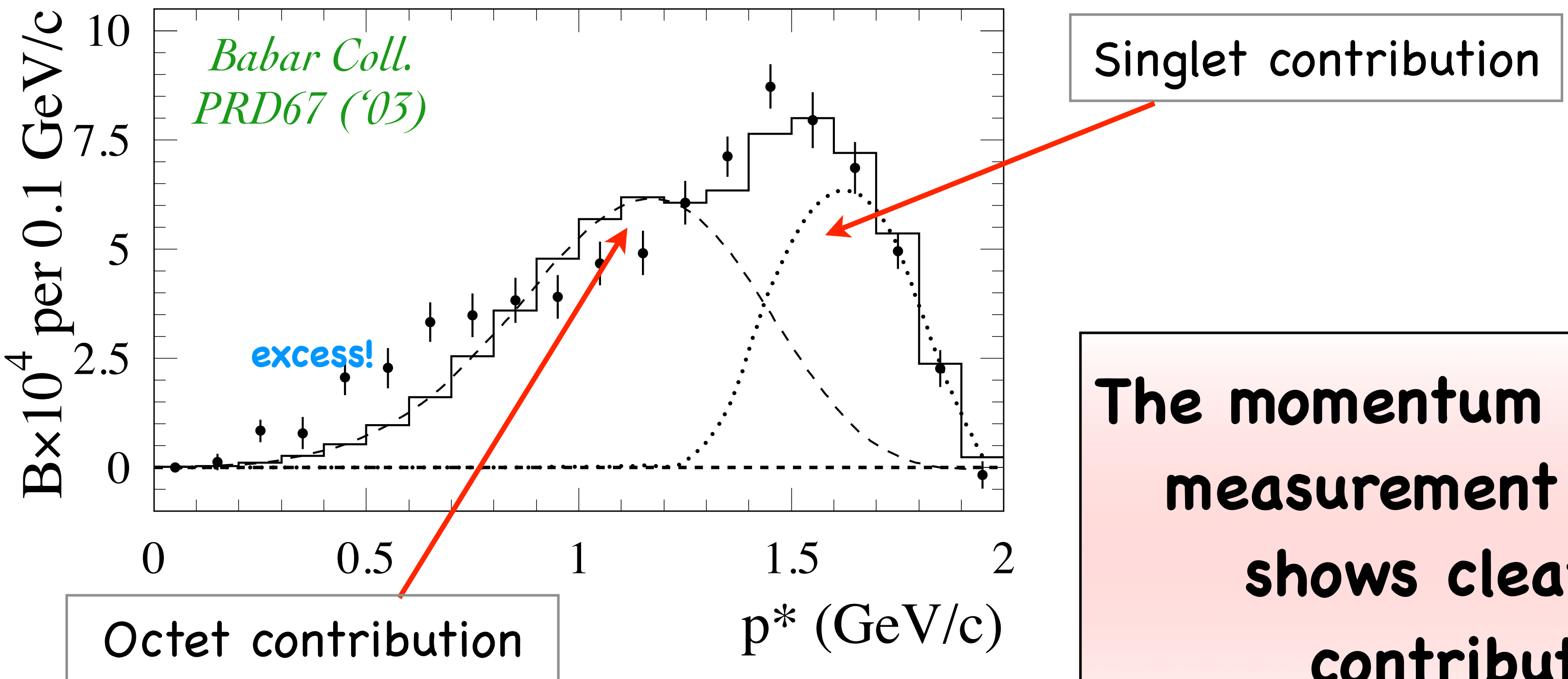
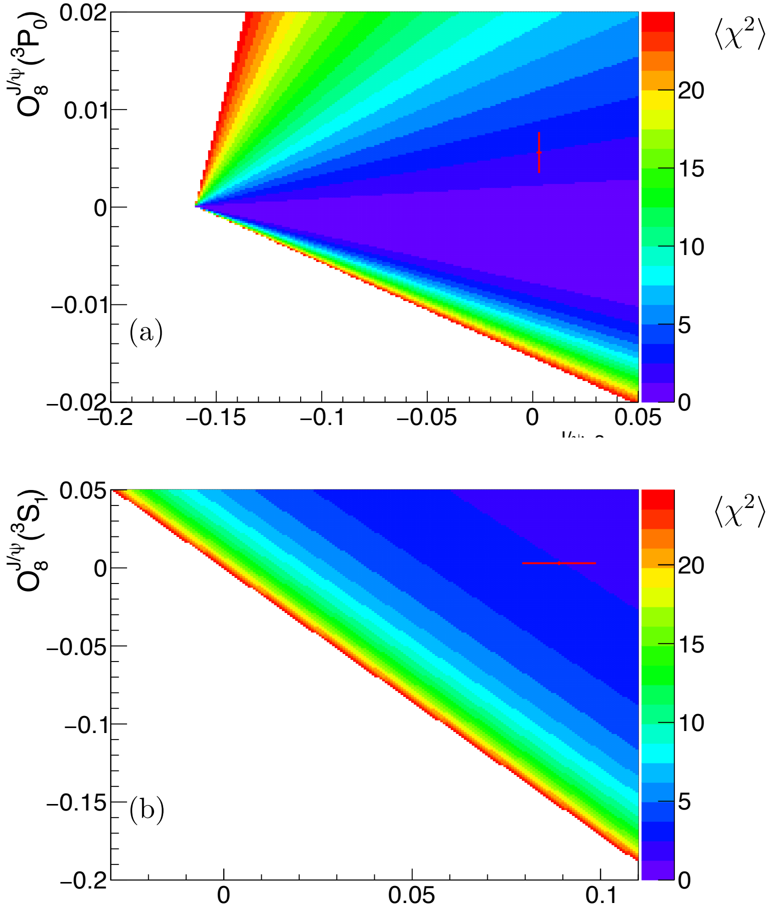


FIG. 10: p^* of J/ψ mesons produced directly in B decays (points). The histogram is the sum of the color-octet component from a recent NRQCD calculation [20] (dashed line) and the color-singlet $J/\psi\, K^{(*)}$ component from simulation (dotted line).

Beneke, Scgykerm Wolf, PRD62 ('00)

The momentum dependence measurement by Babar shows clear octet contributions.

The secondary J/ψ, η_c production from B decays



Fit of the matrix elements with secondary J/ψ, η_c production and comparison to the matrix element determined by the prompt production.

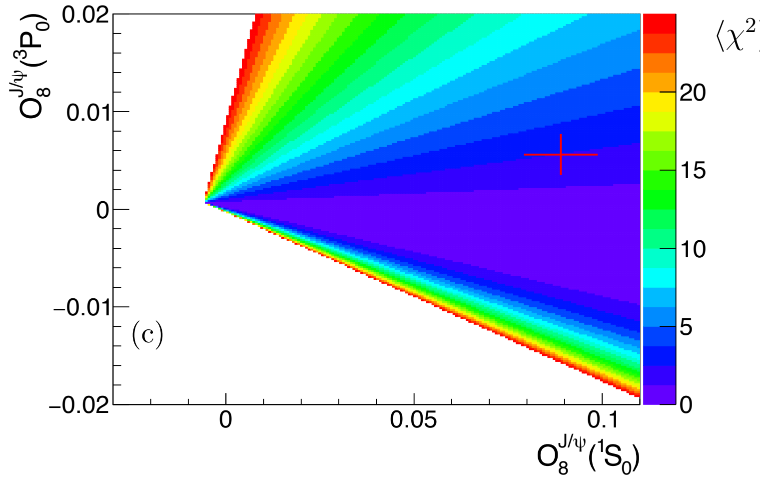
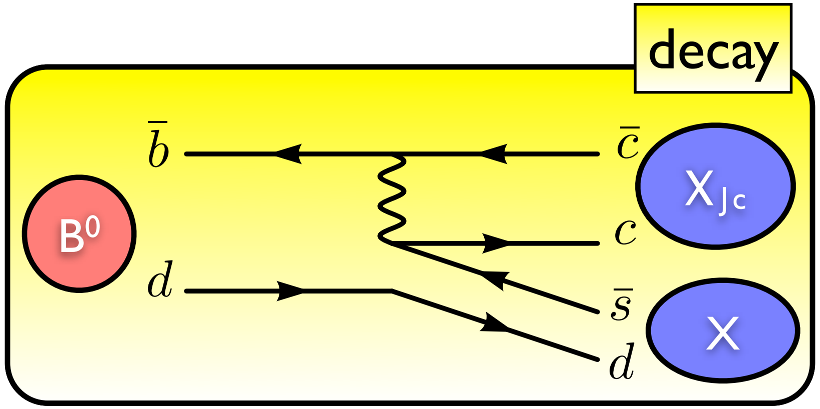


Figure 1: The $\langle\chi^2\rangle$ distribution for the (a) $\langle O_8^{J/\psi}(^3S_1)\rangle$ and $\langle O_8^{J/\psi}(^3P_0)\rangle/m_c^2$ matrix elements, where $\langle O_8^{J/\psi}(^1S_0)\rangle = 0.089\,\mathrm{GeV}^3$, (b) $\langle O_8^{J/\psi}(^3S_1)\rangle$ and $\langle O_8^{J/\psi}(^1S_0)\rangle/m_c^2$ matrix elements, where $\langle O_8^{J/\psi}(^3P_0)\rangle/m_c^2 = 0.0056\,\mathrm{GeV}^3$, (c) $\langle O_8^{J/\psi}(^1S_0)\rangle$ and $\langle O_8^{J/\psi}(^3P_0)\rangle/m_c^2$ matrix elements. where $\langle O_8^{J/\psi}(^3S_1)\rangle = 0.003\,\mathrm{GeV}^3$, from the measurement of $\frac{\mathcal{B}(b\to\eta_c(1S)X)}{\mathcal{B}(b\to J/\psi^{direct}X)}$. For all listed plots $\langle O_8^{J/\psi}(^3S_1) = 1.16\rangle\,\mathrm{GeV}^3$ was used. Only area with $\langle\chi^2\rangle < 25$ are shown with colour code. Red points represents values from Ref. [18]

The secondary χ_{Jc} production from B decays



Beneke, Maltoni, Rothstein PRD59 ('99)

$$H_{eff} = \frac{G_F}{\sqrt{2}} \sum_{q=s,d} \left\{ V_{cb}^* V_{cq} \left[\frac{1}{3} C_{[1]}(\mu) \mathcal{O}_1(\mu) + C_{[8]}(\mu) \mathcal{O}_8(\mu) \right] - V_{tb}^* V_{tq} \sum_{i=3}^{6} C_i(\mu) \mathcal{O}_i(\mu) \right\}$$

The V-A interaction does not allow χ_{c0} and χ_{c2} production at singlet model @ LO. Only χ_{c1} is allowed there.

The secondary χ_{Jc} production from B decays

Latest LHCb result

$$\mathcal{B}(b \to \chi_{c0} X) = (3.02 \pm 0.47 \pm 0.23 \pm 0.94_{\mathcal{B}}) \times 10^{-3},$$
$$\mathcal{B}(b \to \chi_{c1} X) = (2.76 \pm 0.59 \pm 0.23 \pm 0.89_{\mathcal{B}}) \times 10^{-3},$$
$$\mathcal{B}(b \to \chi_{c2} X) = (1.15 \pm 0.20 \pm 0.07 \pm 0.36_{\mathcal{B}}) \times 10^{-3},$$

$$\frac{\mathcal{B}(b \to \chi_{c1} X)}{\mathcal{B}(b \to \chi_{c0} X)} = 0.92 \pm 0.20 \pm 0.02 \pm 0.14_{\mathcal{B}}$$
$$\frac{\mathcal{B}(b \to \chi_{c2} X)}{\mathcal{B}(b \to \chi_{c0} X)} = 0.38 \pm 0.07 \pm 0.01 \pm 0.05_{\mathcal{B}}$$

No strong suppression of χ_{c0} and χ_{c2} production w.r.t. χ_{c1} observed. χ_{c2} is suppressed w.r.t. χ_{c0}.

The secondary J/ψ, η_c production from B decays

Beneke, Maltoni, Rothstein PRD59 ('99)

Improved NLO result

$$\mathcal{B}(B \to \chi_{c0} X) = \frac{-0.0148}{m_c^2}\langle O_1^{\chi_{c0}}(^3P_0)\rangle + 0.195\langle O_8^{\chi_{c0}}(^3S_1)\rangle,$$

$$\mathcal{B}(B \to \chi_{c1} X) = \frac{-0.00783}{m_c^2}\langle O_1^{\chi_{c1}}(^3P_1)\rangle + 0.195\langle O_8^{\chi_{c1}}(^3S_1)\rangle,$$

$$\mathcal{B}(B \to \chi_{c2} X) = \frac{-0.0120}{m_c^2}\langle O_1^{\chi_{c2}}(^3P_2)\rangle + 0.195\langle O_8^{\chi_{c2}}(^3S_1)\rangle,$$

Caveat:
A large uncertainty
(factor two-three?)

Spin symmetry

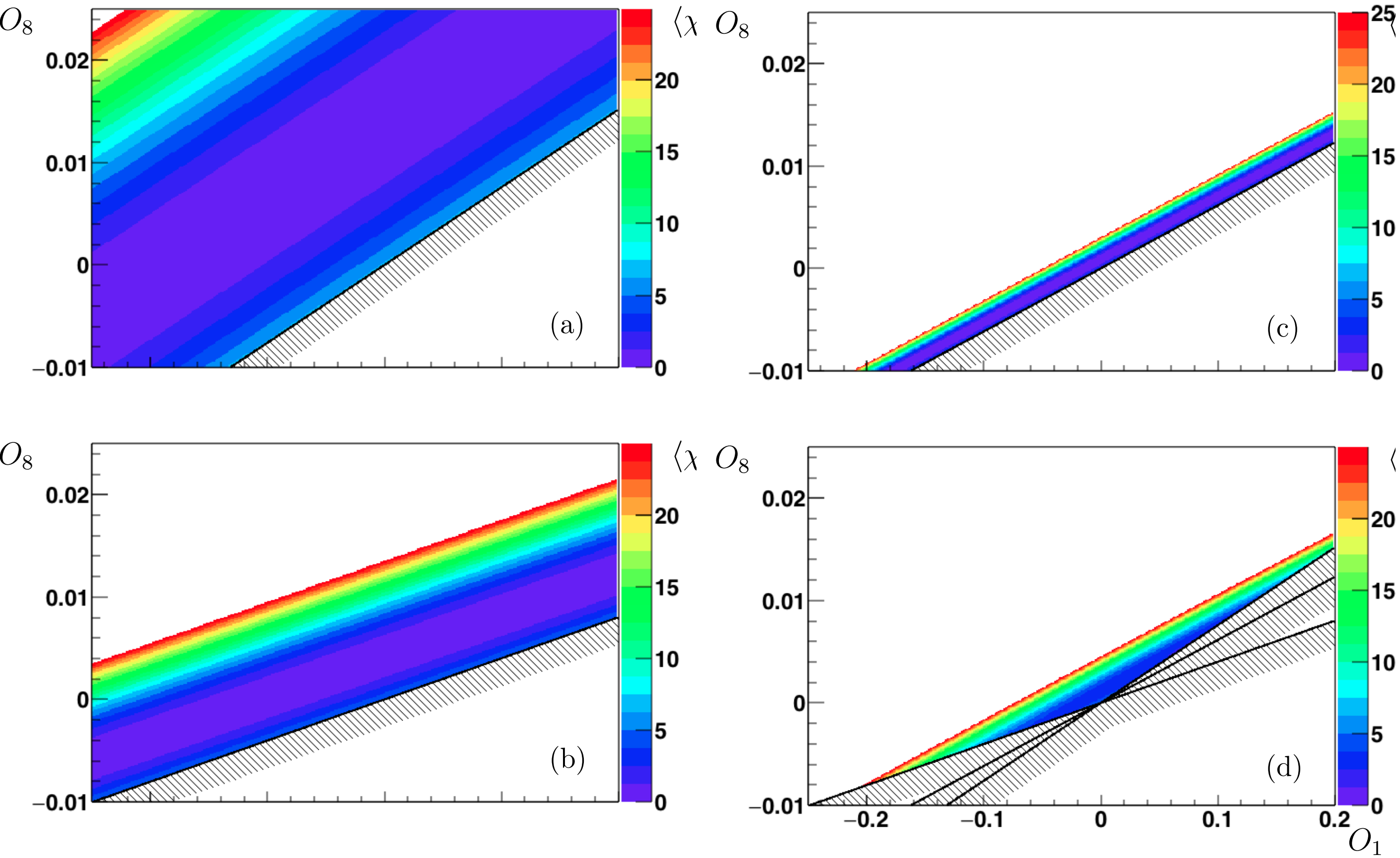
$$\langle \mathcal{O}_1^{\chi_{cJ}}(^3P_J)\rangle = (2J+1)\,\langle \mathcal{O}_1^{\chi_{c0}}(^3P_0)\rangle$$

$$\langle \mathcal{O}_8^{\chi_{cJ}}(^3S_1)\rangle = (2J+1)\,\langle \mathcal{O}_8^{\chi_{c0}}(^3S_1)\rangle$$

Implication of the LHCb data:

- **octet term is important**
- **spin relation X_{c0}: X_{c1}: X_{c2} = 1:3:5 is not visible**

The secondary χ_{Jc} production from B decays



$$O_1 \equiv \langle O_1^{\chi_{c0}}(^3P_0)\rangle / m_c^2,$$
$$O_8 \equiv \langle O_8^{\chi_{c0}}(^3S_1)\rangle,$$

Slight tension in χ_{2c} ???

Figure 4: The $\langle\chi^2\rangle$ distribution for the O_1 and O_8 matrix elements from the measurement of the (a) $\mathcal{B}(b \to \chi_{c0}X)$, (b) $\mathcal{B}(b \to \chi_{c1}X)$, (c) $\mathcal{B}(b \to \chi_{c2}X)$ and (d) using simultaneously all branching fractions $\mathcal{B}(b \to \chi_c X)$. Black lines indicate boundaries, where branching fractions become negative. Only area with $\langle\chi^2\rangle < 25$ are shown with colour code

The secondary χ_{Jc} production from B decays

Table 1: Measured of exclusive $\mathcal{B}(B \to \chi_c)$

	χ_{c0}	χ_{c1}	χ_{c2}
$\mathcal{B}(B^+ \to \chi_c K^+)$	$(1.50 \pm 0.15) \times 10^{-4}$	$(4.79 \pm 0.23) \times 10^{-4}$	$(1.1 \pm 0.4) \times 10^{-5}$
$\mathcal{B}(B^0 \to \chi_c K^0)$	$(1.47 \pm 0.27) \times 10^{-4}$	$(3.93 \pm 0.27) \times 10^{-4}$	$< 1.5 \times 10^{-5}$
$\mathcal{B}(B^+ \to \chi_c K^{*+})$	$< 2.1 \times 10^{-4}$	$(3.0 \pm 0.6) \times 10^{-4}$	$< 1.52 \times 10^{-4}$
$\mathcal{B}(B^0 \to \chi_c K^{*0})$	$(1.7 \pm 0.4) \times 10^{-4}$	$(2.39 \pm 0.19) \times 10^{-4}$	$(4.9 \pm 1.2) \times 10^{-5}$
$\mathcal{B}(B^+ \to \chi_c \pi^+)$	$< 1 \times 10^{-7}$	$(2.2 \pm 0.5) \times 10^{-5}$	$< 1 \times 10^{-7}$
$\mathcal{B}(B^0 \to \chi_c \pi^0)$	–	$(1.12 \pm 0.28) \times 10^{-5}$	–
$\mathcal{B}(B^0 \to \chi_c K^- \pi^+)$	–	$(3.8 \pm 0.4) \times 10^{-4}$	–
$\mathcal{B}(B_s^0 \to \chi_c \phi)$	–	$(2.03 \pm 0.29) \times 10^{-4}$	–

But suppression of χ_{c2} is observed also in the exclusive channels: the naive spin relation is not applicable!

Conclusions...

- The new LHCb result on the χ_{Jc} production from B decay is very interesting.
- The naive spin counting relation $\mathbf{X_{c0}: X_{c1}: X_{c2} = 1:3:5}$ is strongly violated.
- The branching fraction to the factorization forbidden channel χ_{0c}, χ_{2c} are not negligible.
- The NLO NRQCD computation leads to the naive spin counting relation e.g. to the color-octet contribution while the LHCb result implies such a simple relation is not visible.
- It seems that there are several missing pieces (c.f. exclusive NLO computation) and we need more theoretical investigations.