Decays of mesons at LHCb

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Decays of mesons at LHCb

Selected measurements:

- Amplitude analysis of $B^+ \to J/\psi\phi K^+$ decays **[PRD 95, 012002; PRL 118, 02200]**
- Observation of $\eta_c(2S) \to p\bar{p}$ and search for $X(3872) \to p\bar{p}$ **[PLB 769, 305]**
- Study of charmonium production in b-hadron decays and first evidence for the decay $B_s^0 \to \phi\phi\phi$ **[EPJC 77, 609]**

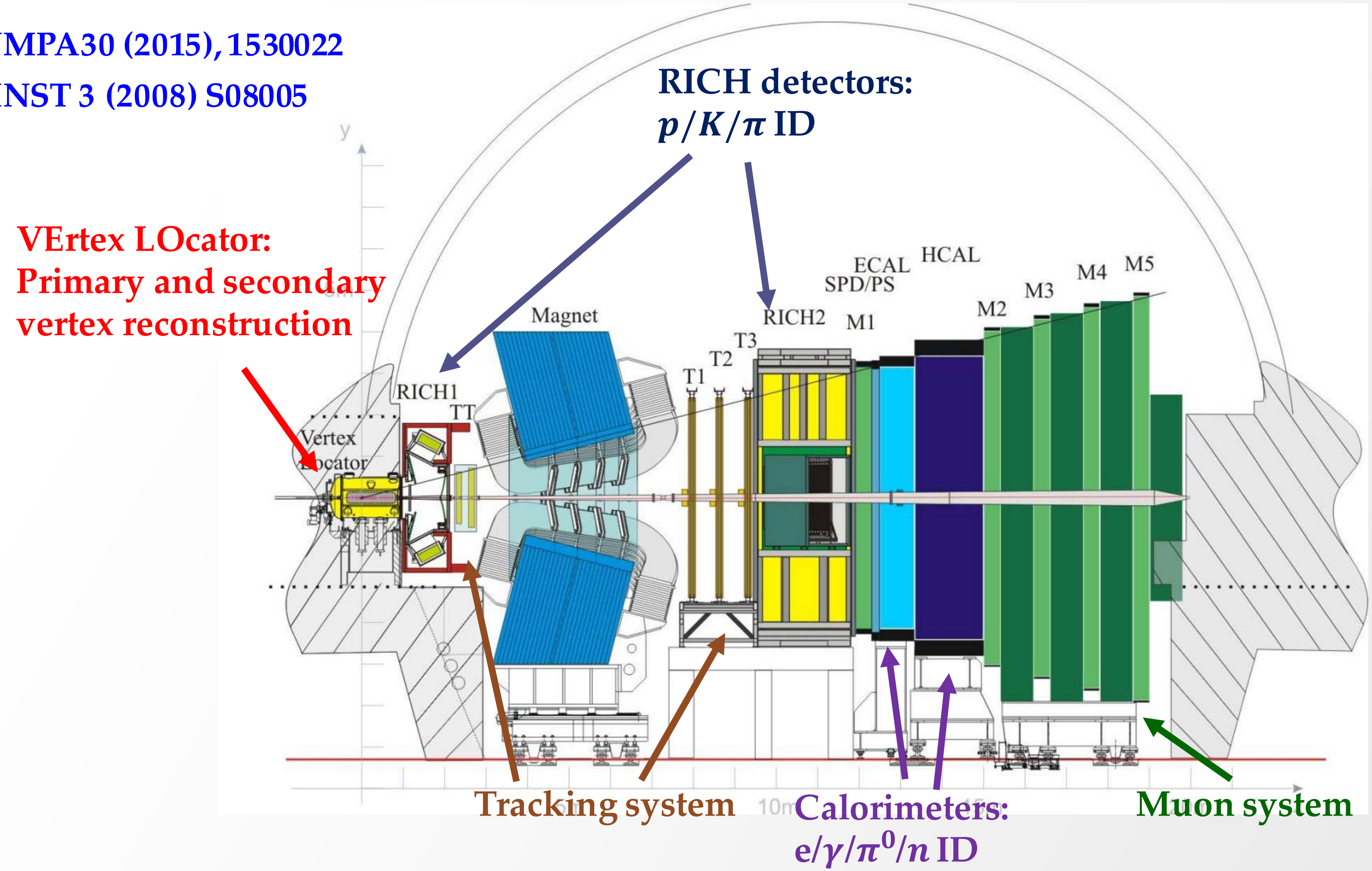
See other talks:

Observation of the doubly charmed baryon by Daniel Vieira *(06/11)*
Results on charmed baryons from LHCb by Daniel Vieira *(06/11)*
Spectroscopy results from LHCb by Lucio Anderlini *(06/11)*
LHCb Quarkonium results in p-Pb and Pb-Pb by Jiayin Sun *(08/11)*
Study of B_c decays at LHCb by Jiesheng Yu *(08/11)*
Decays of baryons with heavy quark at LHCb by Mengzhen Wang *(08/11)*
Study of J/ψ production in jets (LHCb) by Jia-Jia Qin *(09/11)*
Measurement of the J/ψ pair production cross-section at $\sqrt{s} = 13$ TeV by Liupan An *(09/11)*
CEP of J/ψ and $\psi(2S)$ mesons in pp collisions at $\sqrt{s} = 13$ TeV by Liupan An *(09/11)*
Measurement of Upsilon polarizations in pp collisions at $\sqrt{s}$= 7 and 8 TeV by Lucio Anderlini *(09/11)*

Complete set of the LHCb results in https://cds.cern.ch/collection/LHCb%20Papers?ln=en

LHCb detector

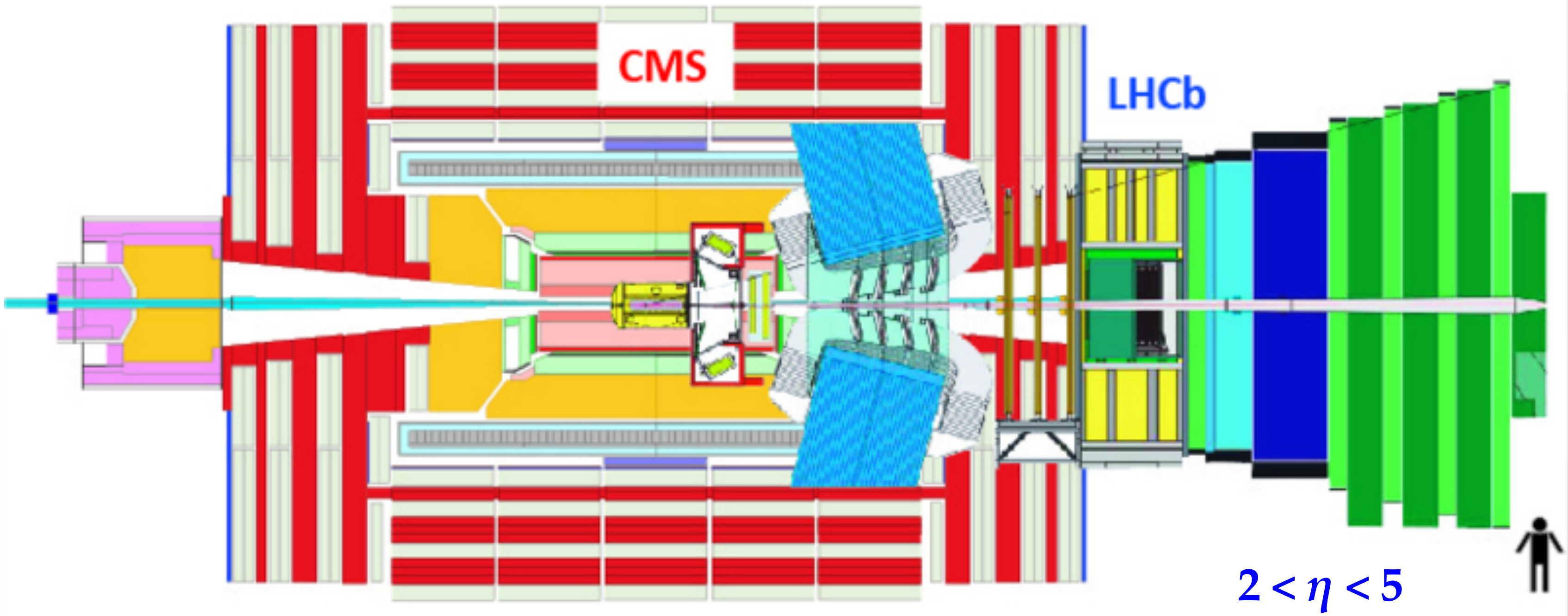
IJMPA30 (2015), 1530022
JINST 3 (2008) S08005



- Precise vertex reconstruction with VELO
- Powerful charge particle ID by RICH detectors
- Robust trigger

LHCb detector

IJMPA30 (2015), 1530022
JINST 3 (2008) S08005



- Precise vertex reconstruction with VELO
- Powerful charge particle ID by RICH detectors
- Robust trigger
    - **Coverage complementary to ATLAS and CMS in p_T and η**

Amplitude analysis of $B^+ \to J/\psi\phi K^+$ decays

PRD 95, 012002
PRL 118, 022003

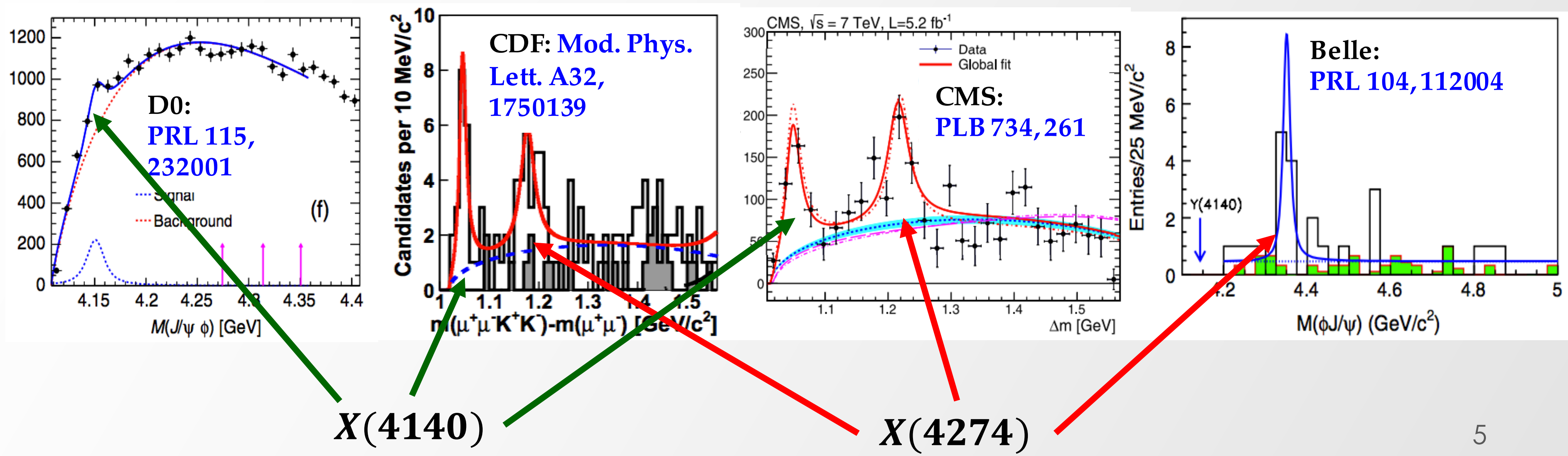
$X(4140) \to J/\psi\phi$ historical overview:

- First evidence by CDF with later observation by CMS
- **Narrow** resonance (world average for width: $\Gamma(X(4140)) = 15.7 \pm 6.3$ **MeV**
  - charmonium resonances expected to be much broader at this mass region
  - exotic candidate containing no u- or d-quarks

  ➞ possible interpretations:
  - **molecular state**
  - **tetraquark**
  - **hybrid state**
  - **rescattering effect**

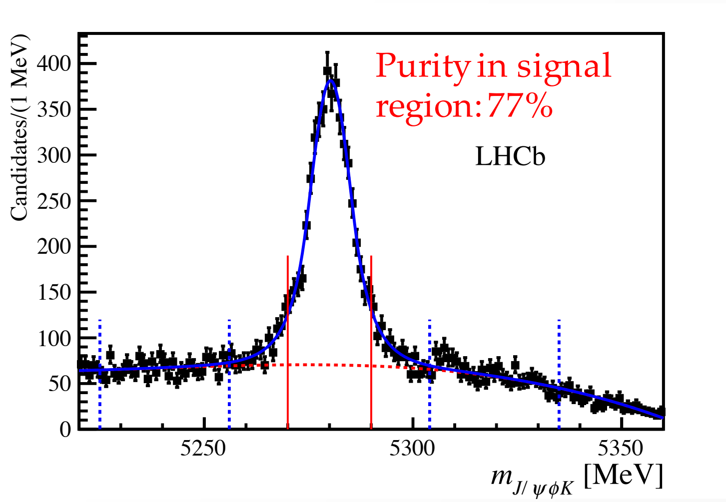
$X(4274)$:

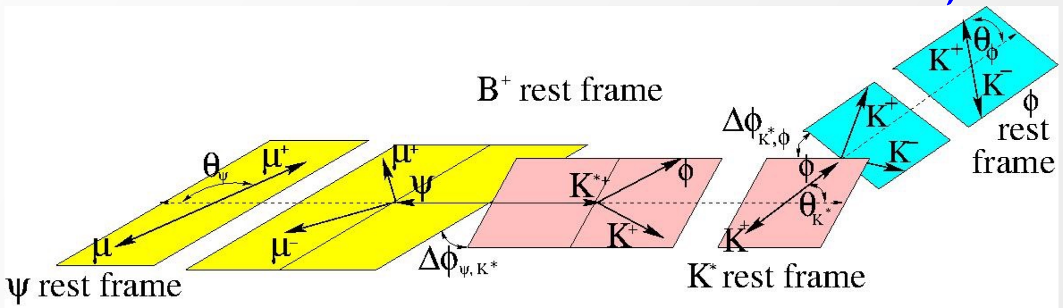
- Seen by CDF, CMS and Belle
- No strong observation



Amplitude analysis of $B^+ \to J/\psi \phi K^+$ decays

PRD 95, 012002
PRL 118, 022003

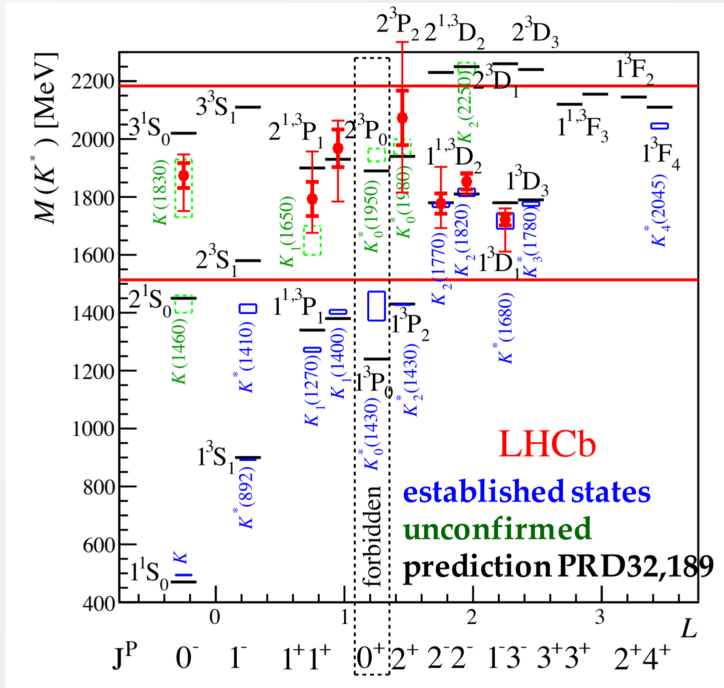




<u>First</u> 6D full amplitute analysis:

- mass $M_{\phi K}$
- helicity angles θ_{ψ}, θ_{K^*}, θ_{ϕ}
- angles between decay planes $\Delta\phi_{\psi,K^*}$, $\Delta\phi_{K^*,\phi}$

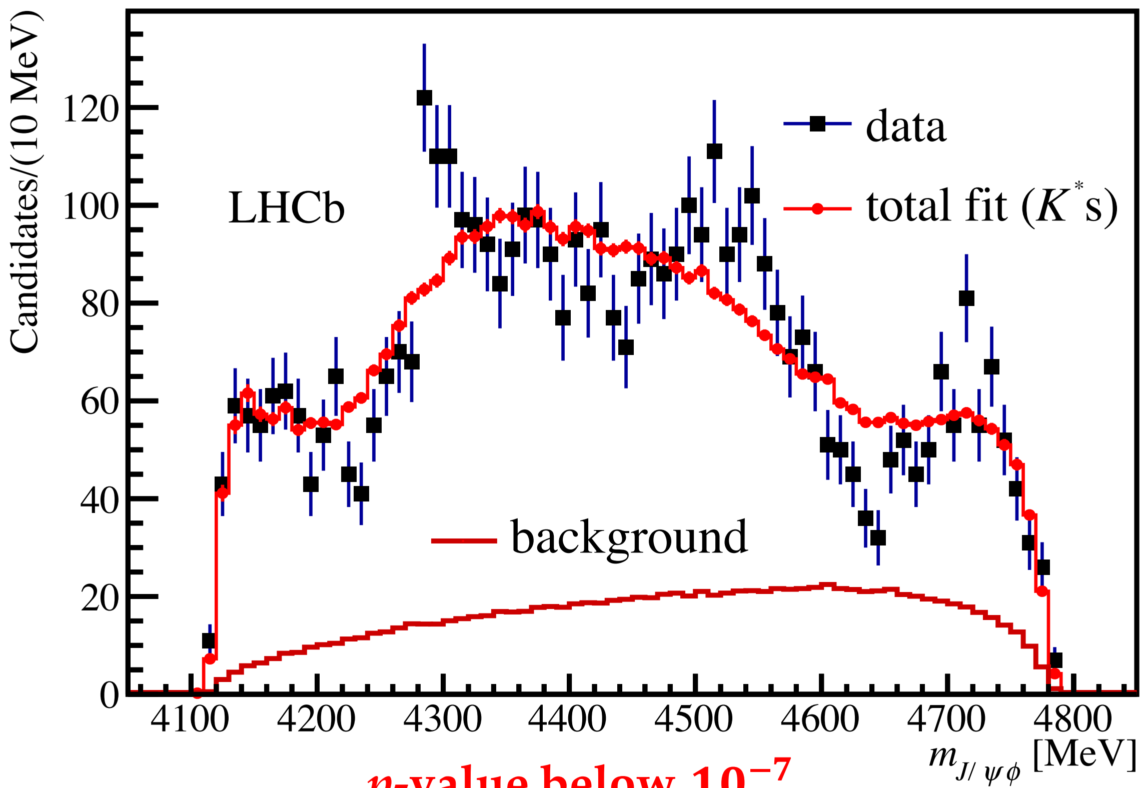
- Contributions from all possible $\boldsymbol{B^+ \to J/\psi K^{*+}}$
- Not many $K^{*+} \to \phi K^+$ **well established**
- Using **Godfrey-Isgur** model to define **quantum numbers of not established** K^{*+} states
- Masses and widths of all K^{*+} states **are free fit parameters**



PRD 95, 012002
PRL 118, 022003

K^*'s-only hypothesis fit:

- $M_{\phi K}$ and $M_{J/\psi K}$ can be described by model
- $M_{J/\psi\phi}$ is not described by fit



***p*-value below 10^{-7}**

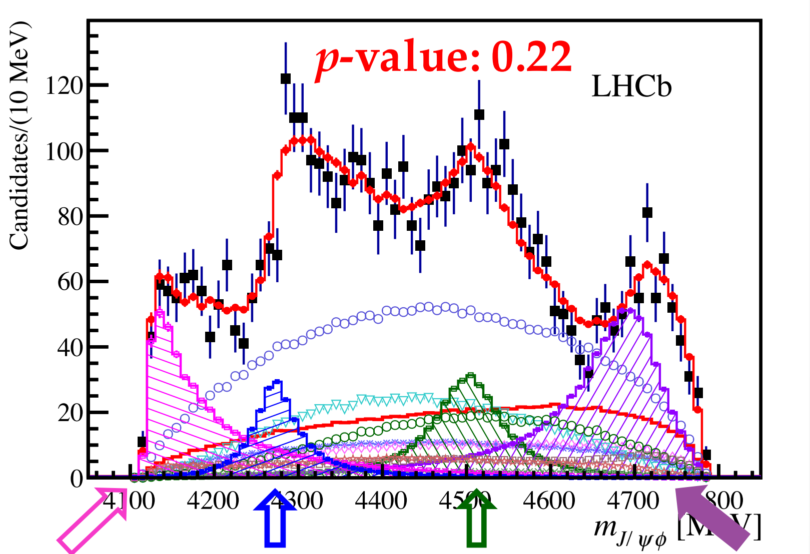
→ **non-K^* resonances needed:**

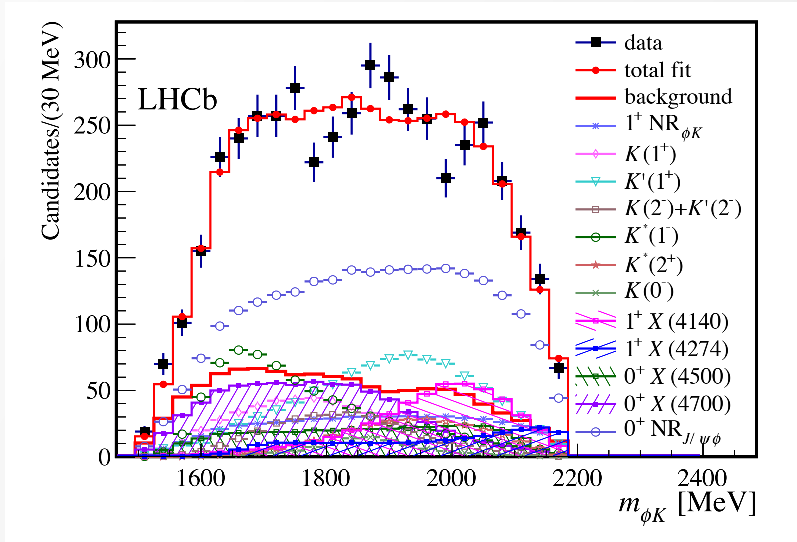
- $Z^+ \to J/\psi K^+$ - does not lead to significant improvements
- $X \to J/\psi\phi$

Amplitude analysis of $B^+ \to J/\psi\phi K^+$ decays

PRD 95, 012002
PRL 118, 022003

After including contributions from four X-states:





$X(4140)$ 8.4σ | $X(4274)$ 6.0σ | $X(4500)$ 6.1σ | $X(4700)$ 5.6σ

Most significant ϕK^+ resonance - $K^*(1680)^+$
$\to$ first observation of $\boldsymbol{K^*(1680)^+ \to \phi K^+}$ **(8.5σ)**

	M(MeV)	Γ(MeV)	J^{PC}	
$X(4140)$	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$ (first measurement from amplitude analysis) ⇒ **wider than world average (15.7±6.3)**	1^{++} (5.7σ)	⇒ **rule out $D_s^{*+}D_s^{*-}$ molecular model. Cusp model?**
$X(4274)$	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	1^{++} (5.8σ)	⇒ **not molecule or cusp, not a hybrid charmonium. Tetraquark?**
$X(4500)$	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	0^{++} (4.0σ)	⇒ **$D_s^{*+}D_s^{*-}$ state? EPJC 64, 373**
$X(4700)$	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	0^{++} (4.5σ)	

Tetraquark models:

- Lebed-Polosa: 1^{++} *X(4140)*, but 0^{-+} *X(4274)* **(Phys. Rev. D93 (2016) 094024)**
- Anisovich et al: only one 1^{++} state **(Int. J. Mod. Phys. A30 (2015) 1550186)**
- Stancu model: 1^{++} *X(4140)* and 1^{++} state a bit higher than *X(4274)* **(J. Phys.G37 075017)**

Observation of $\eta_c(2S) \to p\bar{p}$ and search for $X(3872) \to p\bar{p}$

PLB 769, 305

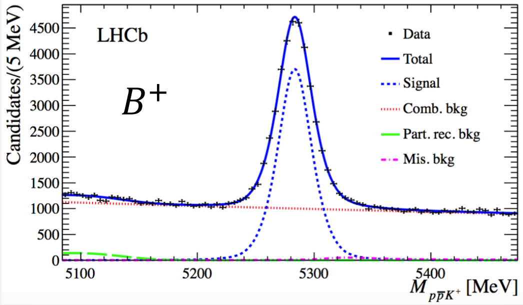
- Only few decay modes of $\eta_c(2S)$ were observed
- $BR(\eta_c(2S) \to p\bar{p})$ – important knowledge for **further prompt production** studies

J.-P. Lansberg, H.-S. Shao, H.-F. Zhang arXiv:1711.00265

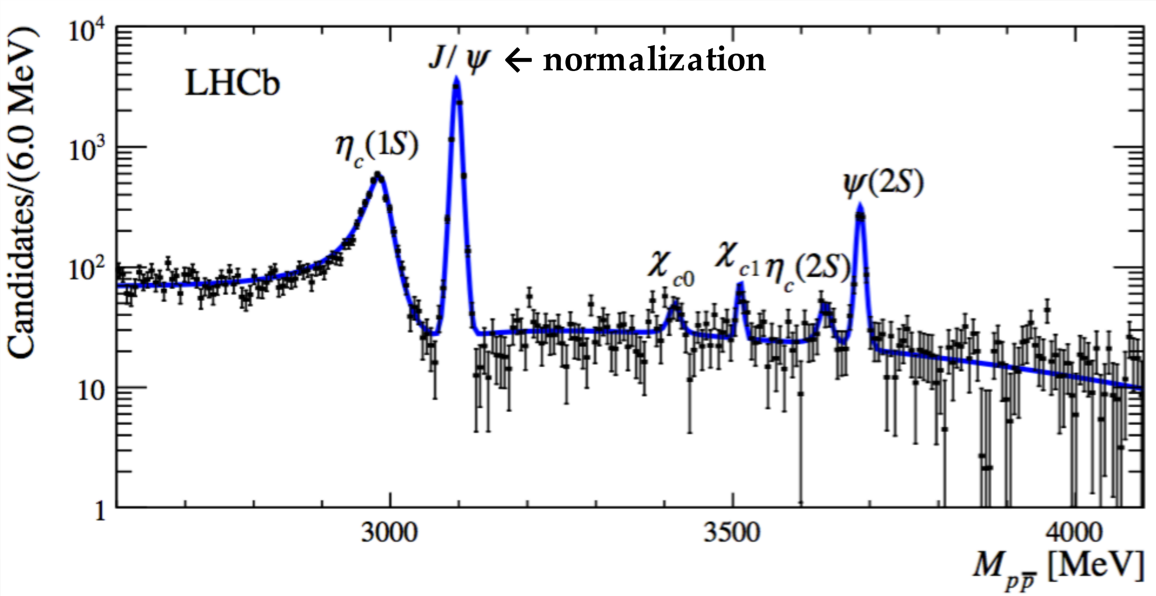
→ only upper limit on $\boldsymbol{BR(\psi(2S) \to \eta_c(2S)\gamma) \times BR(\eta_c(2S) \to p\bar{p})}$ by BESIII
- Spectroscopy studies for $\eta_c(1S)$

→ tensions in mass and width measurements performed using different $\eta_c(1S)$ production processes

→ *complications in line shape when using* $\boldsymbol{\eta_c(1S)\gamma}$ *radiative decays*
- Spectroscopy studies for $\eta_c(2S)$: lack of measurements
- Search for $X(3872) \to p\bar{p}$ and $\psi(3770) \to p\bar{p}$
  - $\boldsymbol{B^+ \to p\bar{p}K^+}$: clean environment to study $(c\bar{c}) \to p\bar{p}$



- **Background subtracted $\boldsymbol{M(p\bar{p})}$ distribution:**



State	Signal Yield
$\eta_c(1S)$+non res.	11246 ± 119
J/ψ	6721 ± 93
χ_{c0}	84 ± 22
χ_{c1}	95 ± 16
$\eta_c(2S)$	106 ± 22
$\psi(2S)$	588 ± 30
$\psi(3770)$	-6 ± 9
$X(3872)$	-14 ± 8

Observation of $\eta_c(2S) \to p\bar{p}$ and search for $X(3872) \to p\bar{p}$

PLB 769, 305

- First observation of $\eta_c(2S) \to p\bar{p}$ **(6.0σ significance)**

$$\frac{\mathcal{B}(B^+ \to \eta_c(2S)K^+) \times \mathcal{B}(\eta_c(2S) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} = (1.58 \pm 0.33 \pm 0.09) \times 10^{-2}$$

using $BR(B^+ \to J/\psi K^+) \times BR(J/\psi \to p\bar{p})$ from PDG:

$$\mathcal{B}(B^+ \to \eta_c(2S)K^+) \times \mathcal{B}(\eta_c(2S) \to p\bar{p}) = (3.47 \pm 0.72 \pm 0.20 \pm \underbrace{0.16}_{\text{BR uncertainty}}) \times 10^{-8}$$

- Spectroscopy of $\eta_c(1S)$ and $\eta_c(2S)$:

$$M_{J/\psi} - M_{\eta_c(1S)} = 110.2 \pm 0.5 \pm 0.9\,\text{MeV}$$
$$M_{\psi(2S)} - M_{\eta_c(2S)} = 52.5 \pm 1.7 \pm 0.6\,\text{MeV}$$

→ **tensions with world averages**

$$\Gamma_{\eta_c(1S)} = 34.0 \pm 1.9 \pm 1.3\,\text{MeV}$$

→ **in agreement with world average**

- Search for $X(3872)$ and $\psi(3770)$:

$$\frac{\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} < 0.20\,(0.25) \times 10^{-2}$$

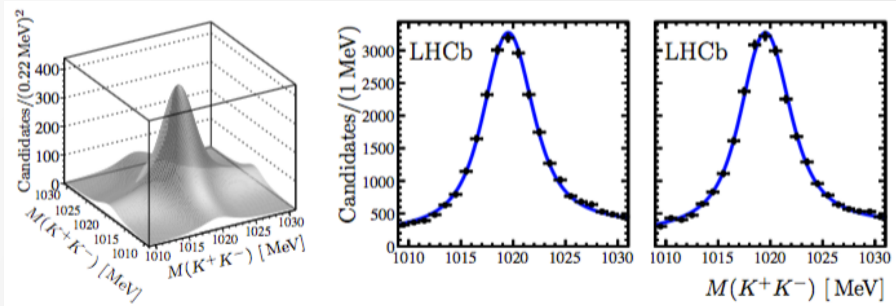
$$\frac{\mathcal{B}(B^+ \to \psi(3770)K^+) \times \mathcal{B}(\psi(3770) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} < 9\,(10) \times 10^{-2}$$

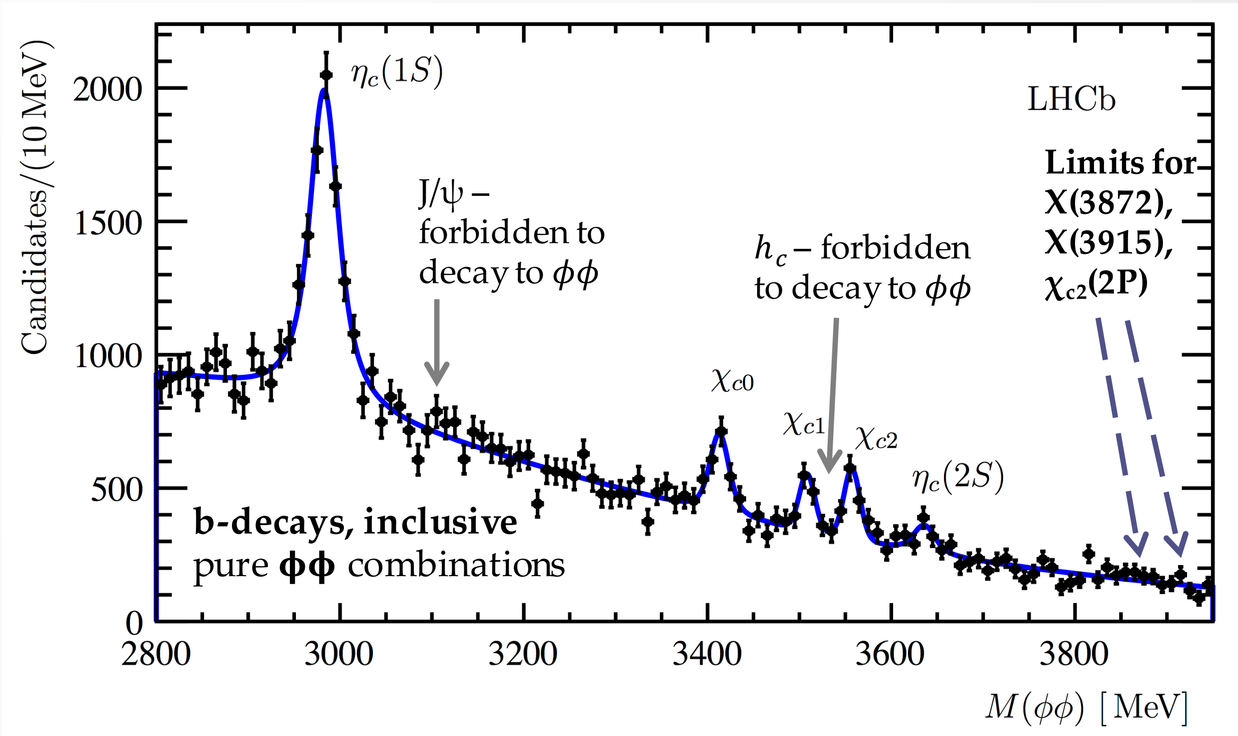
χ_c and $\eta_c(2S)$ production in inclusive b-decays using $\phi\phi$ at $\sqrt{s} = 7{,}8$ TeV

EPJC 77 (2017), 609

- Powerful test of NRQCD factorization, universality of LDME and heavy quark spin symmetry assumptions
- Aiming at constraining LDMEs simultaneously by prompt and b-decays measurements

- 2D fit of $M(K^+K^-{}_1)\times M(K^+K^-{}_2)$ in bins of $M(KKKK)$ to select true $\phi\phi$ combinations



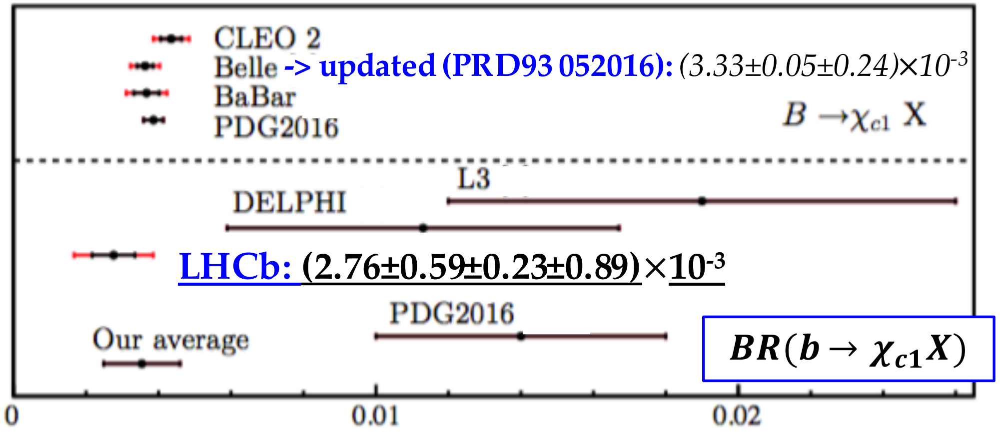


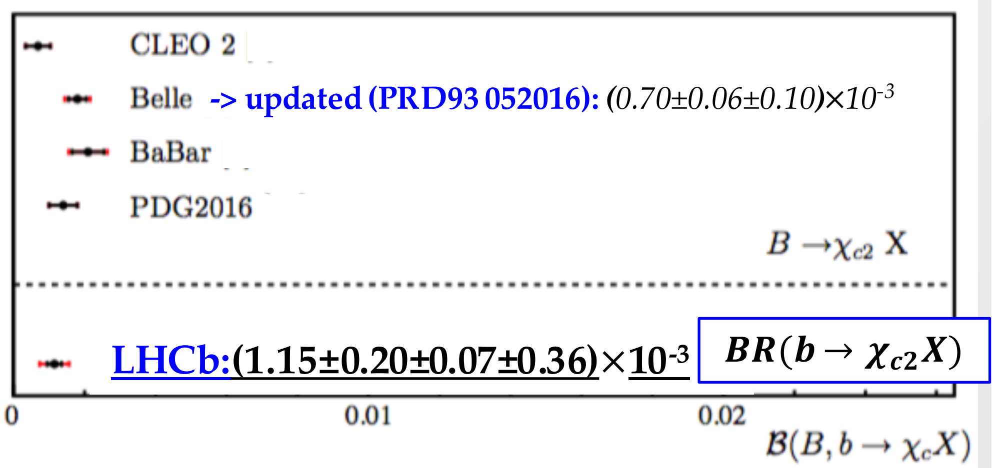
- χ_c and $\eta_c(2S)$ production rates measured using measurement of $BR(b \to \eta_c(1S)X)$ **EPJC 75, 311**

χ_c and $\eta_c(2S)$ production in inclusive b-decays using $\phi\phi$ at $\sqrt{s}$ = 7,8 TeV

EPJC 77 (2017), 609

- First measurement of χ_{c0} production in inclusive b-decays
  $\boldsymbol{BR(b \to \chi_{c0}X)}$ = **(3.02±0.47±0.23±0.94)×10⁻³**
- The most precise measurements of $\boldsymbol{BR(b \to \chi_{c1}X)}$ and $\boldsymbol{BR(b \to \chi_{c2}X)}$
- $\boldsymbol{BR(b \to \chi_{c1}X)}$ and $\boldsymbol{BR(b \to \chi_{c2}X)}$ are in agreement with measurements at B-factories

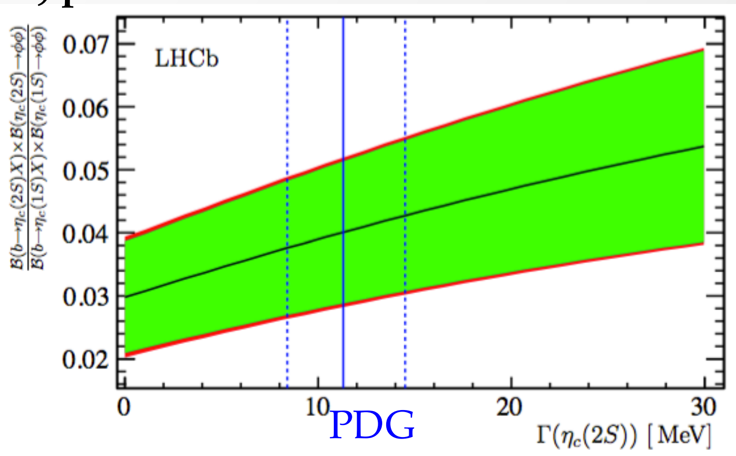




- First measurement of $\eta_c(2S)$ production in inclusive b-decays; first evidence of $\eta_c(2S) \longrightarrow \phi\phi$

$$\frac{BR(b \to \eta_c(2S)X)}{BR(b \to \eta_c(1S)X)} \frac{BR(\eta_c(2S) \to \phi\phi)}{BR(\eta_c(1S) \to \phi\phi)} = 0.040 \pm 0.011 \pm 0.004$$ **(3.7σ significance)**

$\eta_c(2S)$ production as a function of assumed $\Gamma[\eta_c(2S)]$



➔ ***first step to measure $\eta_c(2S)$ hadroproduction***

χ_c and $\eta_c(2S)$ production in inclusive b-decays using $\phi\phi$ at $\sqrt{s} = 7{,}8$ TeV

Barsuk, Kou, Usachov LAL-17-051

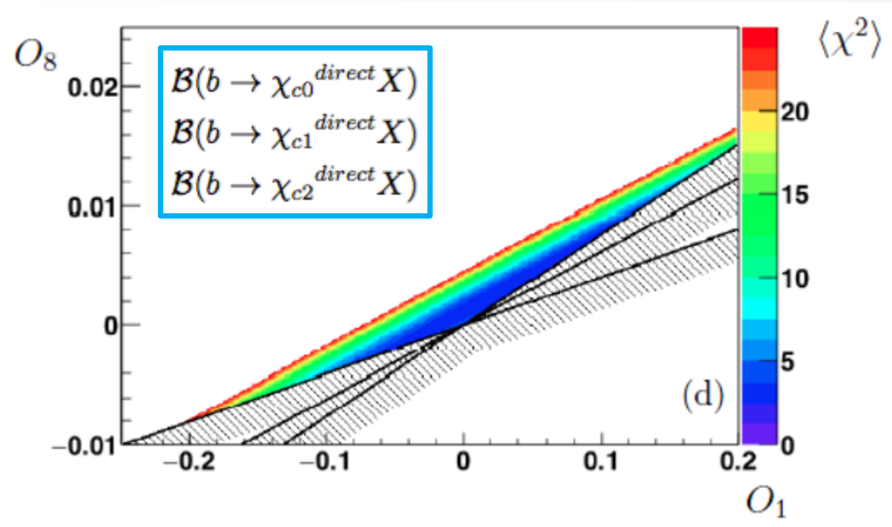
- From **EPJC 77 (2017), 609** and **PDG:**

$$\mathcal{B}(b \to \chi_{c0}{}^{direct} X) = (2.74 \pm 0.47 \pm 0.23 \pm 0.94_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c1}{}^{direct} X) = (2.49 \pm 0.59 \pm 0.23 \pm 0.89_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c2}{}^{direct} X) = (0.89 \pm 0.20 \pm 0.07 \pm 0.36_{\mathcal{B}}) \times 10^{-3}$$

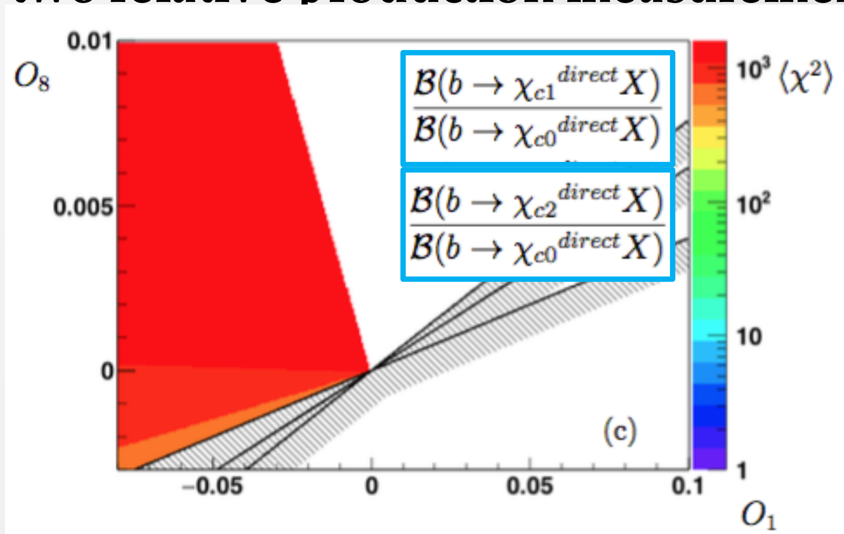
- Relation between LDME from HQSS:
- Short-distance coefficients calculated within NRQCD NLO
Beneke, Maltoni, Rothstein, PRD 59, 054003

$$O_1 \equiv \langle O_1^{\chi_{c0}}(^3P_0)\rangle / m_c^2,$$
$$O_8 \equiv \langle O_8^{\chi_{c0}}(^3S_1)\rangle,$$
$$\langle O_1^{\chi_{cJ}}(^3P_J)\rangle / m_c^2 = (2J+1) O_1,$$
$$\langle O_8^{\chi_{cJ}}(^3S_1)\rangle = (2J+1) O_8.$$

1. Fit two LDMEs to three measurements:



2. Discrepancy when fitting two LDMEs to two relative production measurements:

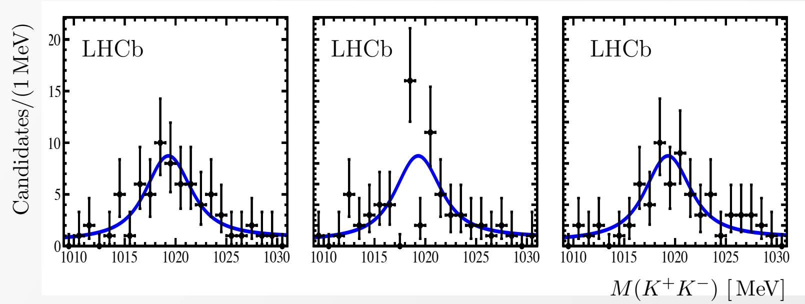


- *to constrain theory using* ***simultaneously*** *results on* ***charmonia hadroproduction and*** *on* ***charmonia from b-inclusive decays***

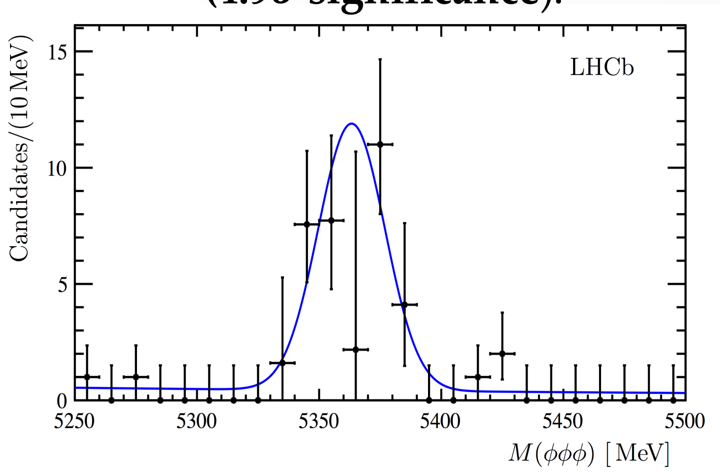
First evidence of $B_s^0 \to \phi\phi\phi$

EPJC 77 (2017), 609

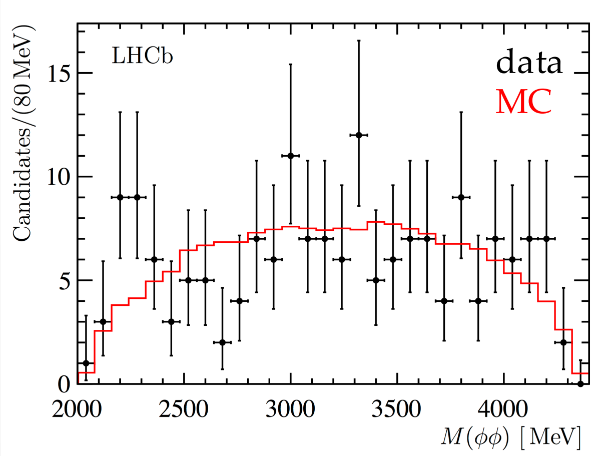
- 3D fit of $M(K^+K^-{}_1) \times M(K^+K^-{}_2) \times M(K^+K^-{}_3)$ in bins of $M(KKKKKK)$ to select true $\phi\phi\phi$ combinations



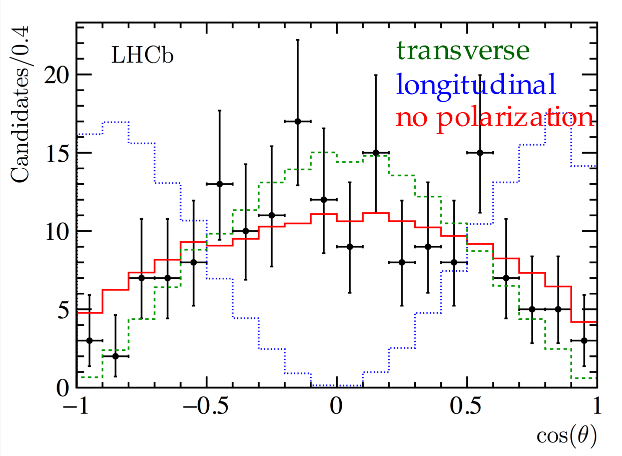
First evidence of $B_s^0 \to \phi\phi\phi$ **(4.9σ significance)**:



No indication of significant resonant contributions



Longitudinal polarization of ϕ does not describe the data:



- $B_s^0 \to \phi\phi$ used as a reference:

$$\frac{BR(B_s^0 \to \phi\phi\phi)}{BR(B_s^0 \to \phi\phi)} = 0.117 \pm 0.030 \pm 0.015$$

using $BR(B_s^0 \to \phi\phi)$ from ***JHEP 10, 053***:

$$\boldsymbol{BR(B_s^0 \to \phi\phi\phi) = (2.15 \pm 0.54 \pm 0.28 \pm 0.21_{BR}) \times 10^{-6}}$$

In agreement with measured $\boldsymbol{BR(B_s^0 \to \eta_c \phi)}$ **JHEP 1707 (2017) 021**

Ratio of the branching fractions for the η_c decays to $\phi\phi$ and to $p\bar{p}$

EPJC 77 (2017), 609

- $\boldsymbol{BR(\eta_c \to \phi\phi)}$: PDG fit and PDG average values differs
- Tension between measurements at B-factories and measurements performed using radiative decays to η_c
- Branching fractions ratio $\frac{BR(\eta_c \to \phi\phi)}{BR(\eta_c \to p\bar{p})}$ extracted using $B_s^0 \to \phi\phi$ as a reference:

$$\frac{BR(\eta_c \to \phi\phi)}{BR(\eta_c \to p\bar{p})} = \underbrace{\frac{N(\eta_c \to \phi\phi)}{N(B_s^0 \to \phi\phi)}}_{\text{from data}} \underbrace{\frac{\epsilon(B_s^0)}{\epsilon(\eta_c)}}_{\text{from MC}} \times \underbrace{BR(B_s^0 \to \phi\phi)}_{\text{JHEP 10, 053 (LHCb)}} \times \underbrace{BR(\bar{b} \to B_s^0)}_{\text{JHEP 04, 001 (LHCb)}} \times$$

$$\times \underbrace{\left[\frac{BR(b \to \eta_c X) \cdot BR(\eta_c \to p\bar{p})}{BR(b \to J/\psi X) \cdot BR(J/\psi \to p\bar{p})}\right]^{-1}}_{\text{EPJC 75, 311 (LHCb)}} \times [\underbrace{BR(b \to J/\psi X)}_{\text{PDG}} \cdot \underbrace{BR(J/\psi \to p\bar{p})}_{\text{PDG}}]^{-1}$$

$$\boldsymbol{\frac{BR(\eta_c \to \phi\phi)}{BR(\eta_c \to p\bar{p})} = 1.79 \pm 0.14 \pm 0.09 \pm 0.31_{BR}}$$

value extracted using PDG fit: ***1.17 ± 0.18***

Summary

- **First** full 6D amplitude analysis of $\boldsymbol{B^+ \to J/\psi\phi K^+}$
  → other than $\boldsymbol{K^*}$ resonances needed to describe data
  → observation of four $J/\psi\phi$ structures $\boldsymbol{X(4140)}$, $\boldsymbol{X(4274)}$, $\boldsymbol{X(4500)}$ and $\boldsymbol{X(4700)}$
  → **quantum numbers determined with significance better than 4 std. deviations**
  → width of $X(4140)$ measured to be larger than world average
  → first observation of $K^*(1680)^+ \to \phi K^+$

- The decay $\eta_c(2S) \to p\bar{p}$ was observed for the first time using $\boldsymbol{B^+ \to p\bar{p}K^+}$
  → important knowledge for **further prompt production** studies
  → search for $X(3872) \to p\bar{p}$ and $\psi(3770) \to p\bar{p}$

- $\boldsymbol{\chi_{c0,1,2}}$ and $\boldsymbol{\eta_c(2S)}$ production in inclusive *b*-decays measured using decays to $\boldsymbol{\phi\phi}$.
  → relative $\boldsymbol{\chi_c}$ production differs from theoretical prediction
  → approach *to constrain theory using* ***simultaneously*** *results on* ***charmonia hadroproduction and*** *on* ***charmonia from b-inclusive decays***
  → first or most precise measurements
- First evidence of $B_s^0 \to \phi\phi\phi$ decay
- $\frac{BR(\eta_c \to \phi\phi)}{BR(\eta_c \to p\bar{p})}$ extracted using $B_s^0 \to \phi\phi$ as a reference

Search for $X(3872)$, $X(3915)$ and $\chi_{c2}(2P)$ decays to $\phi\phi$

EPJC 77 (2017), 609

Limits with respect to states with similar quantum numbers:

$$\frac{BR(b \to X(3872)X) \times BR(X(3872) \to \phi\phi)}{BR(b \to \chi_{c1}X) \times BR(\chi_{c1} \to \phi\phi)} < 0.39\ (0.34)$$

$$\frac{BR(b \to X(3915)X) \times BR(X(3915) \to \phi\phi)}{BR(b \to \chi_{c0}X) \times BR(\chi_{c0} \to \phi\phi)} < 0.14\ (0.12)$$

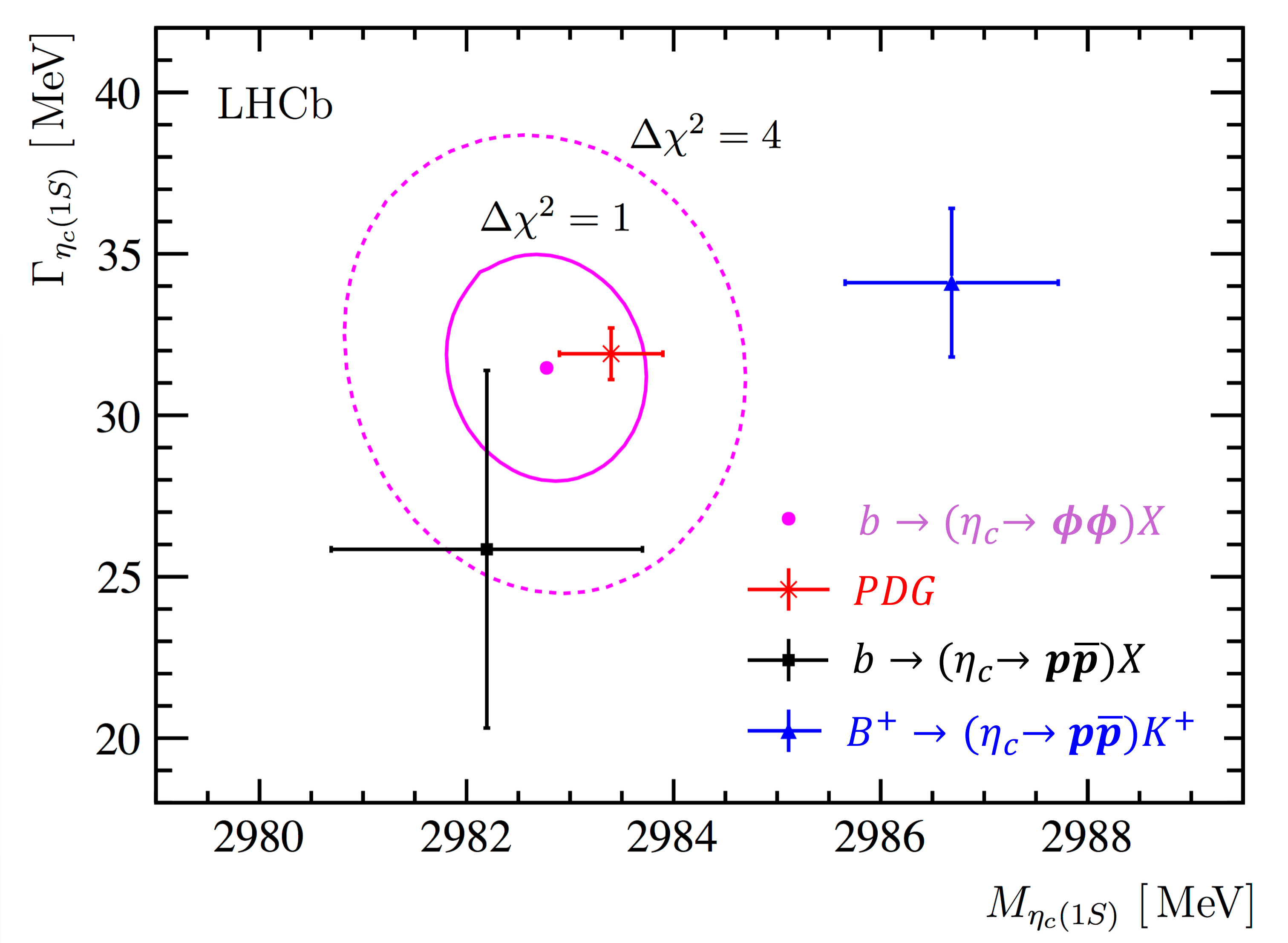
$$\frac{BR(b \to \chi_{c2}(2P)X) \times BR(\chi_{c2}(2P) \to \phi\phi)}{BR(b \to \chi_{c2}X) \times BR(\chi_{c2} \to \phi\phi)} < 0.20\ (0.16)$$

$$BR(b \to X(3872)X) \times BR(X(3872) \to \phi\phi) < 4.5\ (3.9) \times 10^{-7}$$

$$BR(b \to X(3915)X) \times BR(X(3915) \to \phi\phi) < 3.1\ (2.7) \times 10^{-7}$$

$$BR(b \to \chi_{c2}(2P)X) \times BR(\chi_{c2}(2P) \to \phi\phi) < 2.8\ (2.3) \times 10^{-7}$$

Spectroscopy with η_c decays to hadrons

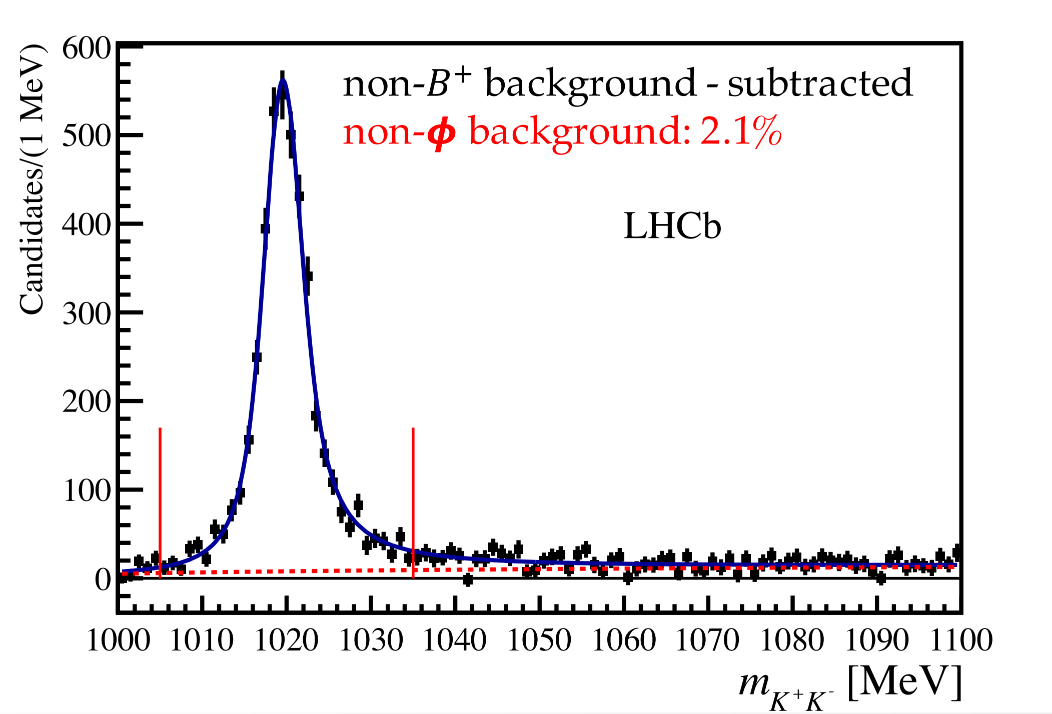


EPJC 77, 609
EPJC 75, 311
PLB 769, 305

- General agreement with world average
- Similar to PDG precision expected for η_c mass with Run II data

Amplitude analysis of $B^+ \to J/\psi\phi K^+$ decays

PRD 95, 012002
PRL 118, 022003



$BR(b \to (c\bar{c})X)$ from theory including HQSS relations

$$\mathcal{B}(B \to J/\psi X) = 7.54 \cdot 10^{-4} \langle O_1^{J/\psi}(^3S_1)\rangle + 0.195 \langle O_8^{J/\psi}(^3S_1)\rangle + 0.342 \left[\langle O_8^{J/\psi}(^1S_0)\rangle + \frac{3.10}{m_c^2} \langle O_8^{J/\psi}(^3P_0)\rangle \right],$$

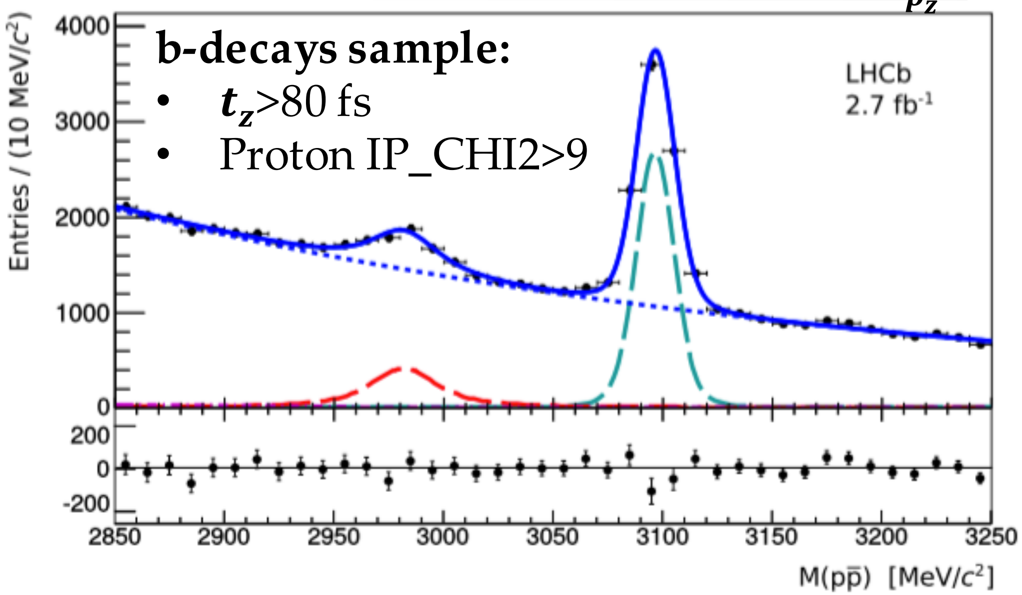
$$\mathcal{B}(B \to \eta_c(1S)X) = 8.33 \cdot 10^{-4} \langle O_1^{J/\psi}(^3S_1)\rangle + 0.114 \langle O_8^{J/\psi}(^3S_1)\rangle + 0.195 \left[\langle O_8^{J/\psi}(^1S_0)\rangle - \frac{0.720}{m_c^2} \langle O_8^{J/\psi}(^3P_0)\rangle \right].$$

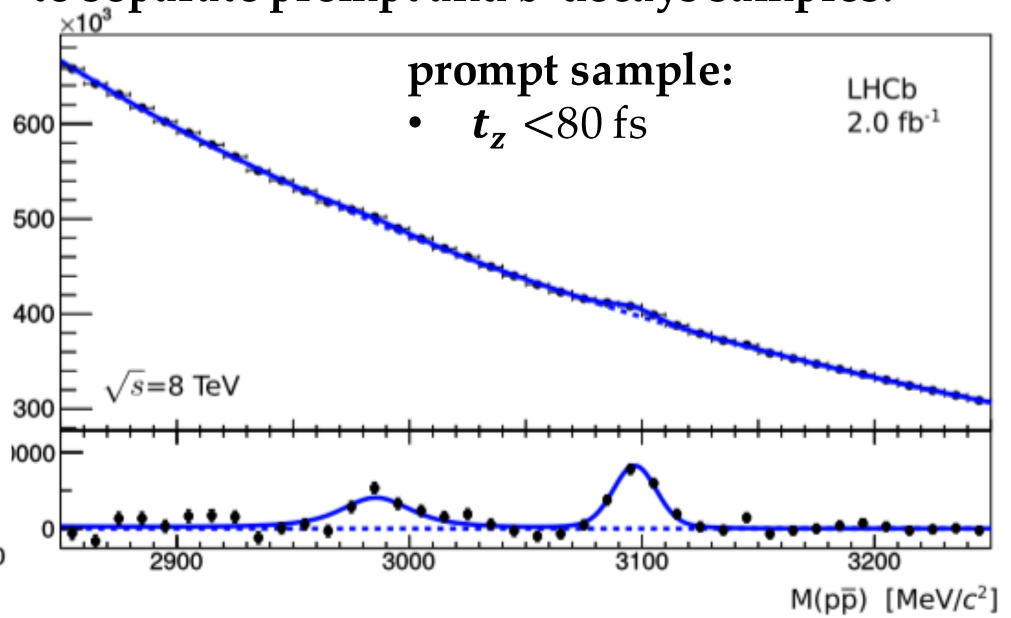
$$\mathcal{B}(B \to \chi_{c0}X) = -0.0148\ O_1 + 0.195\ O_8,$$
$$\mathcal{B}(B \to \chi_{c1}X) = -0.0234\ O_1 + 0.585\ O_8,$$
$$\mathcal{B}(B \to \chi_{c2}X) = -0.0600\ O_1 + 0.975\ O_8.$$

η_c production measurement via $\eta_c \to p\bar{p}$ at $\sqrt{s} = 7{,}8$ TeV

EPJC 75 (2015) 311

- **Most of the selection performed at trigger level**
- **Use pseudo-proper decay time $t_z = \frac{(z_{SV}-z_{PV})M_{c\bar{c}}}{p_z}$ to separate prompt and b-decays samples:**





- Measurement of $M(\eta_c)$, $\Gamma(\eta_c)$
- **First measurement of $BR(b \to \eta_c X)$**

- Challenging background conditions
- Use masses, $\Gamma(\eta_c)$ and resolution from b-decays sample
- **First measurement of η_c hadroproduction**

	$\sqrt{s} = 7$TeV	$\sqrt{s} = 8$TeV
$\sigma_{\eta_c}/\sigma_{J/\psi}$ (prompt, PT>6.5 GeV)	$1.74 \pm 0.29_{stat} \pm 0.28_{syst} \pm 0.18$	$1.60 \pm 0.29_{stat} \pm 0.25_{syst} \pm 0.17$
$\frac{BR(b \to \eta_c X)}{BR(b \to J/\psi X)}$	$0.421 \pm 0.055 \pm 0.022 \pm 0.045$	

J/ψ and η_c production in inclusive b-decays

Barsuk, Kou, Usachov LAL-17-051

- From **EPJC 75 (2015) 311** and **PDG:**

$$\frac{\mathcal{B}(b \to \eta_c(1S)^{direct} X)}{\mathcal{B}(b \to J/\psi^{direct} X)} = 0.691 \pm 0.090 \pm 0.024 \pm 0.103.$$

- Relation between LDME from HQSS:

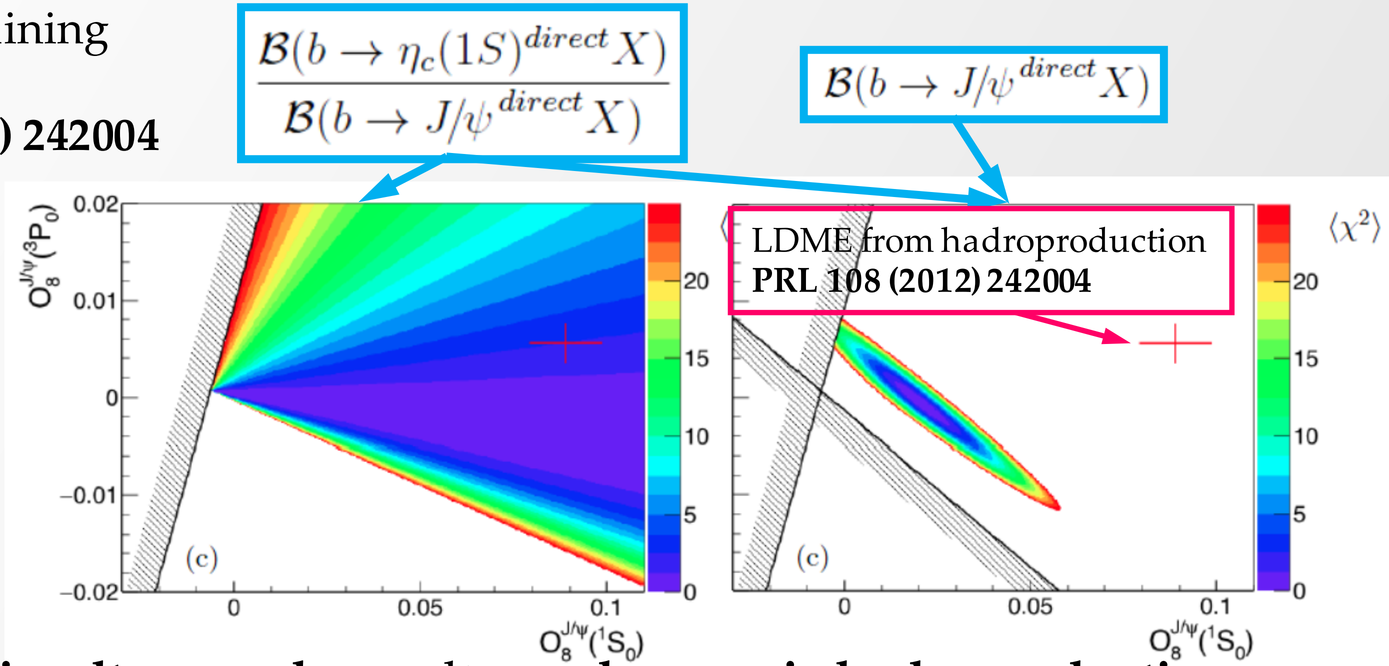
$$\langle O_1^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_1^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_8^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^3S_1)\rangle = \langle O_8^{J/\psi}(^1S_0)\rangle,$$
$$\langle O_8^{\eta_c}(^1P_1)\rangle = 3\langle O_8^{J/\psi}(^3P_0)\rangle.$$

- Branching fractions calculated in **Beneke, Maltoni, Rothstein, PRD 59 (1999) 054003**

- **Fit two LDMEs to measurements**

- Consecutively fix two remaining LDME from **Chao et al., PRL 108 (2012) 242004**

$$\langle O_8^{J/\psi}(^3S_1)\rangle = 0.003\ \mathrm{GeV}^3$$
$$\langle O_8^{J/\psi}(^3S_1)\rangle = 1.16\ \mathrm{GeV}^3$$



- Constrain theory using **simultaneously** results on **charmonia hadroproduction and** on **charmonia from b-inclusive decays**