Charmonium production in pp collisions using decays to hadronic final states at LHCb

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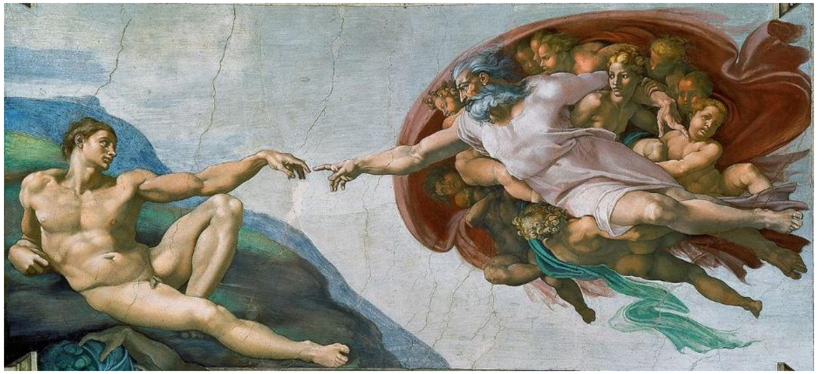
- ❑ Production of η_c using decays to $p\bar{p}$
- ❑ Production of χ_c and $\eta_c(2S)$ using decays to $\phi\phi$
- ❑ Phenomenological studies

Contacts: Jibo He and Sergey Barsuk

- Study of **charmonium production** provides powerful QCD tests

Michelangelo: 创建



Botticelli: 分娩

- Comprehension of **quarkonia production mechanism**, predictive model robust against experimental verifications wanted, yielding simultaneous description of
  - Hadroproduction and production in b-decays ;
  - Different charmonia ;
  - Production and polarization in the entire pT range.

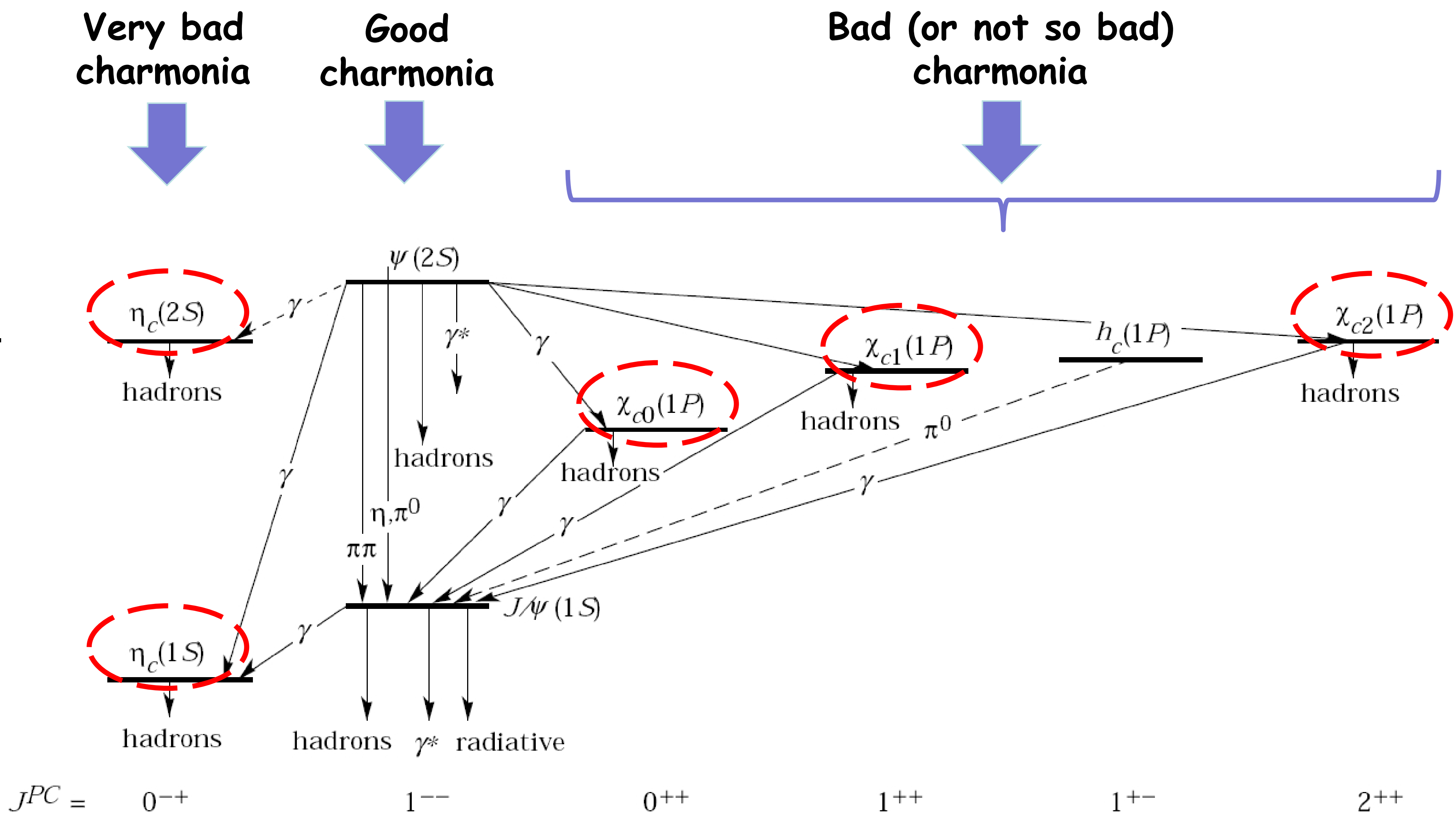
- Two scales of production:
  hard process of $\mathbf{Q\bar{Q}}$ **formation** and **hadronization of** $\mathbf{Q\bar{Q}}$ at softer scales
- **Factorization**:

$$d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X} \times \langle \mathcal{O}^H(n) \rangle$$

Short distance: perturbative cross-sections + pdf for the production of a $Q\bar{Q}$ pair

Long distance matrix elements (LDME), non-perturbative part

- Colour-singlet model: intermediate $Q\bar{Q}$ state is colourless and has the same J^{PC} quantum numbers as the final-state quarkonium
- NRQCD: all viable colours and J^{PC} allowed for the intermediate $Q\bar{Q}$ state, they are adjusted in the long-distance part with a given probability.
  Long-Distance Matrix Elements (LDME) from experimental data
- **Universality**: *same LDME for prompt production and production in b-decays*
- Heavy-Quark **Spin-Symmetry** (HQSS): links between colour-singlet (CS) and colour-octet (CO) LDME of different quarkonium states

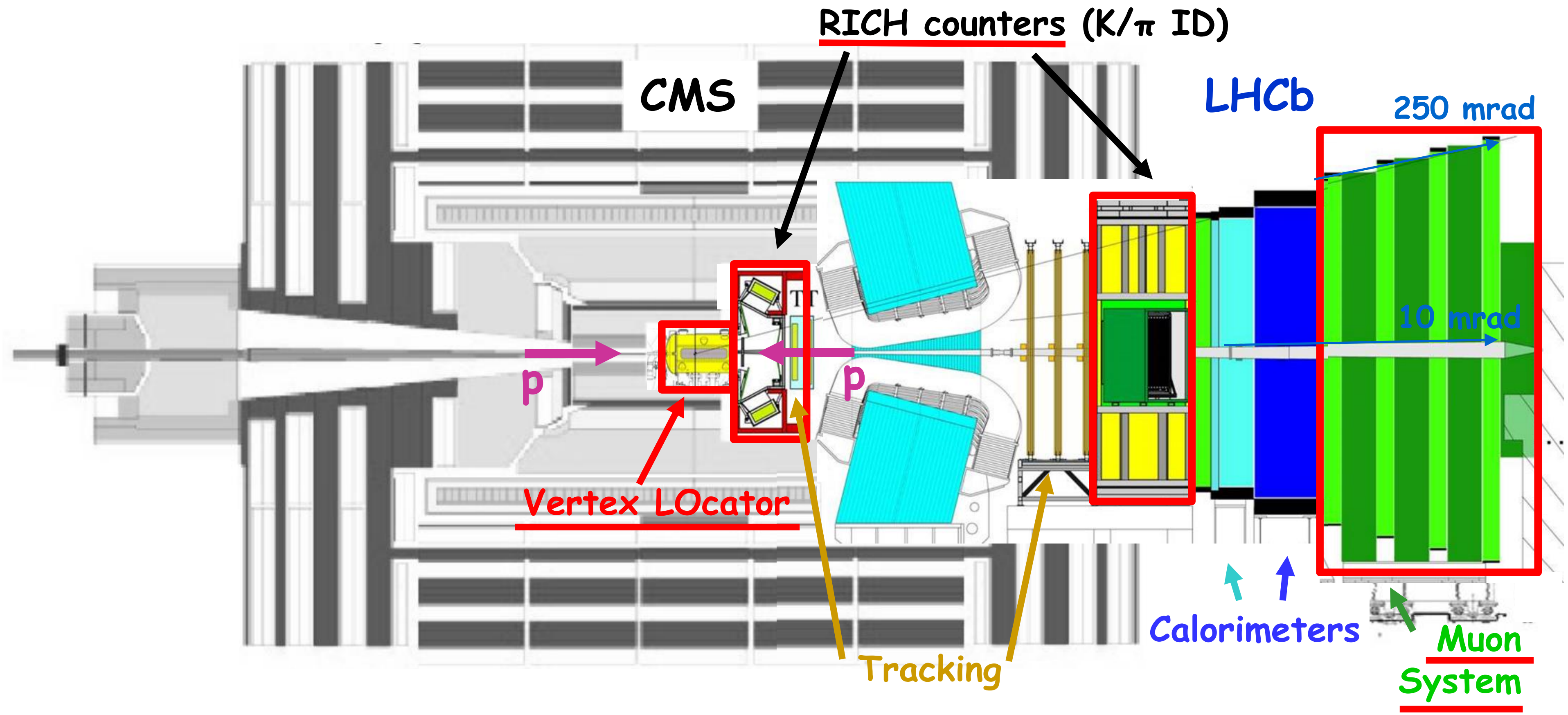


- **Hadronic decays** to access "all" charmonium states
- Extract LDMEs from pT dependence of cross-sections

LHCb detector: single-arm forward spectrometer

JINST 8 (2013) P08002, INT.J.MOD.PHYS.A30 (2015) 1530022

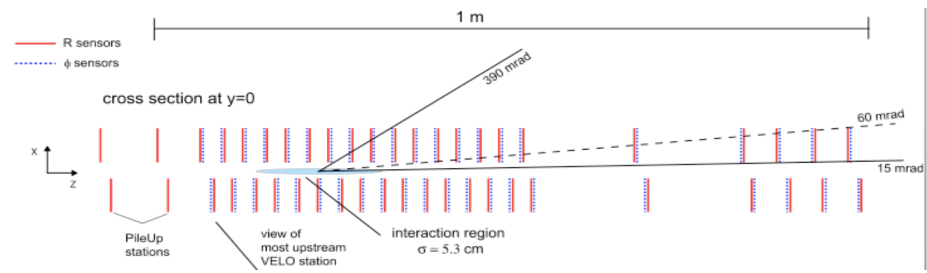
- **Forward peaked HQ production** at the LHC
- Forward region, **~4% of solid angle**, but **~40% of HQ production x-section**



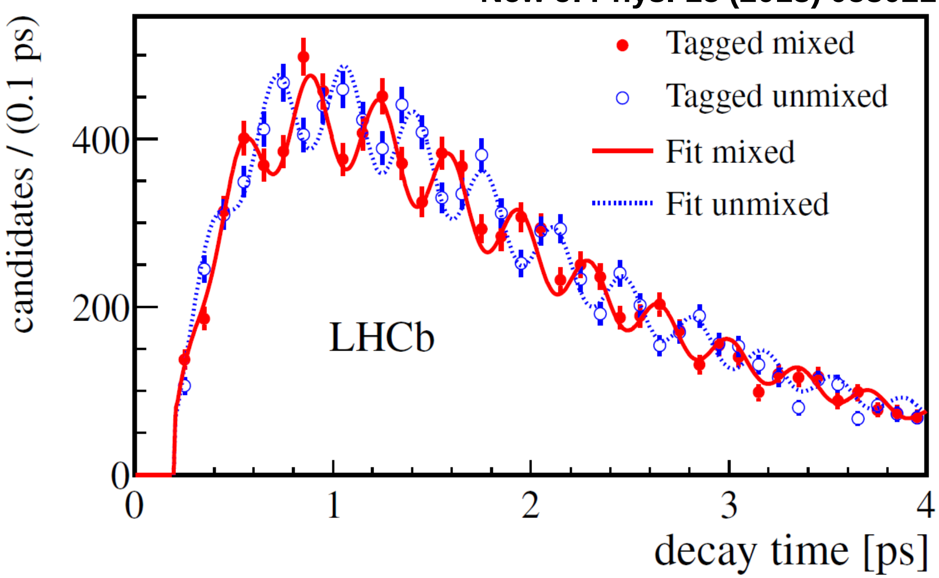
- **Complementary cross-section measurements** and overlap in rapidity
- Key detector systems for production measurements: **vertex reconstruction (VELO), particle identification (Muon detector, RICHs), Trigger**

JINST 8 (2013) P08002, arXiv:1405.7808

- 88 semi-circular **microstrip Si sensors**
- Double-sided, **R and φ** layout
- 300μ thick n-on-n sensors
- Strip pitches from 40 to 120μ



New J. Phys. 15 (2013) 053021

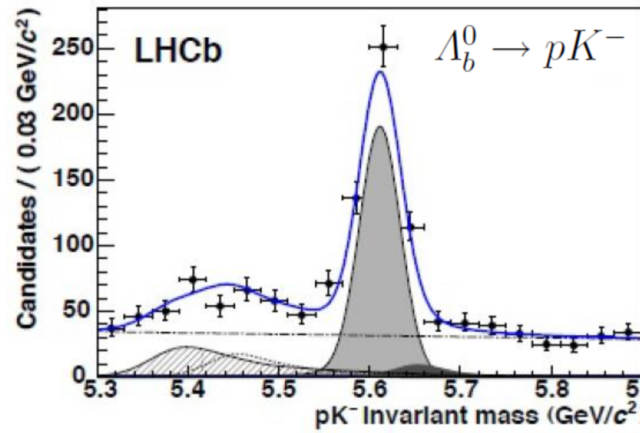


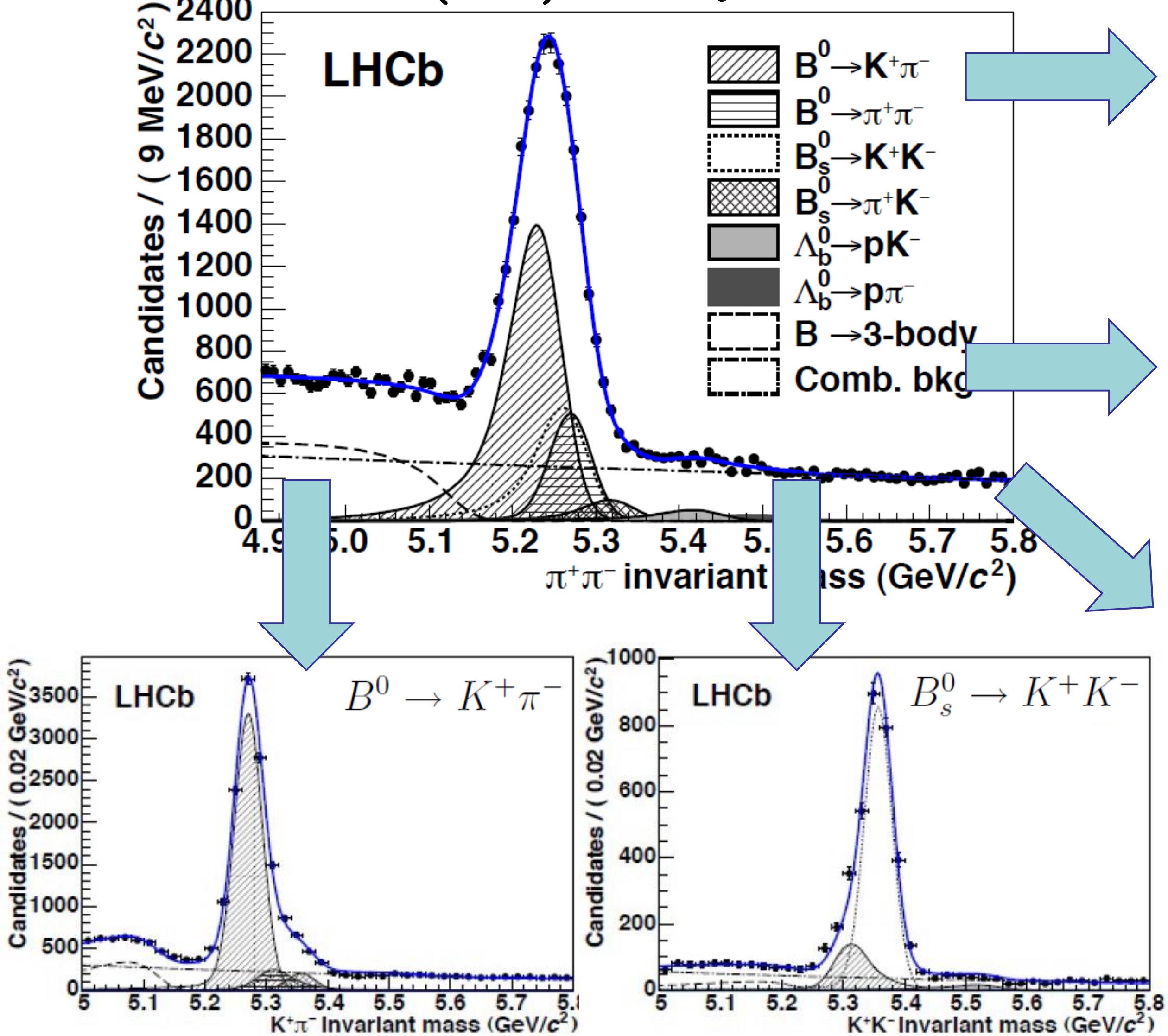
- **First active strip at 8.2mm from the beam axis**
- Moves away every fill and centers around the beam with self measured vertices
- ***Vertex resolution*** allows to resolve fast (x~27) $B_s\overline{B}_s$ oscillations

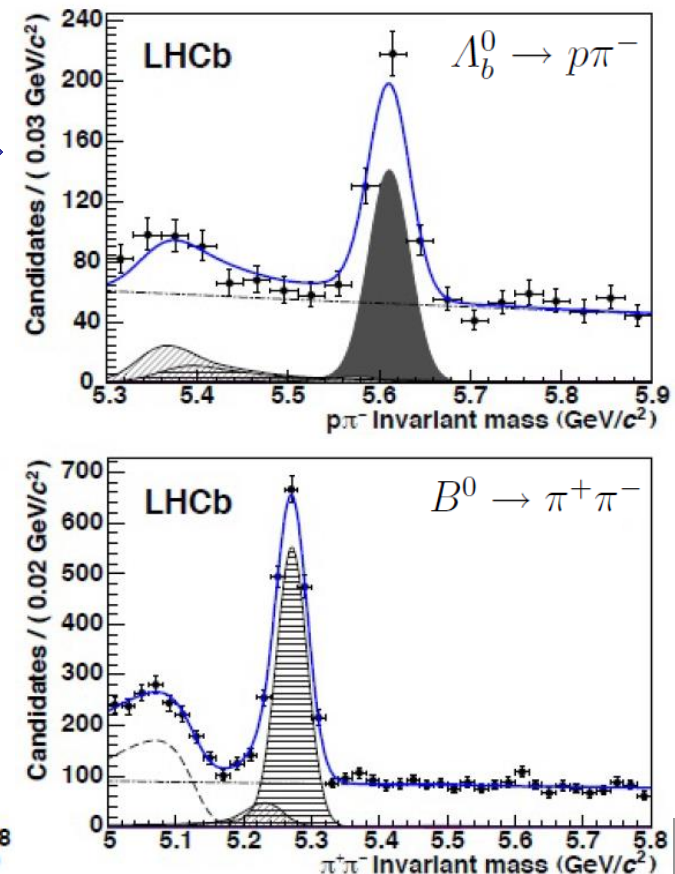
LHCb: charged hadron ID with RICH

- **2 RICH detectors: 3(2) Radiators**, light RO by **HPD**
- **Charmless two-body b-hadron decays**

JHEP 10 (2012) 037 $\int L dt \sim 0.37\ fb^{-1}$







Production of η_c, $p\bar{p}$ final state

$$\frac{\sigma(\eta_c(1S))}{\sigma(J/\psi)} = \frac{N^p_{\eta_c(1S)}}{N^p_{J/\psi}} \times \frac{\mathcal{B}_{J/\psi\to p\bar{p}}}{\mathcal{B}_{\eta_c(1S)\to p\bar{p}}} \times \frac{\epsilon_{J/\psi\to p\bar{p}}}{\epsilon_{\eta_c(1S)\to p\bar{p}}}$$

$$\frac{\mathcal{B}_{b\to\eta_c(1S)X}}{\mathcal{B}_{b\to J/\psi X}} = \frac{N^b_{\eta_c(1S)}}{N^b_{J/\psi}} \times \frac{\mathcal{B}_{J/\psi\to p\bar{p}}}{\mathcal{B}_{\eta_c(1S)\to p\bar{p}}} \times \frac{\epsilon_{J/\psi\to p\bar{p}}}{\epsilon_{\eta_c(1S)\to p\bar{p}}}$$

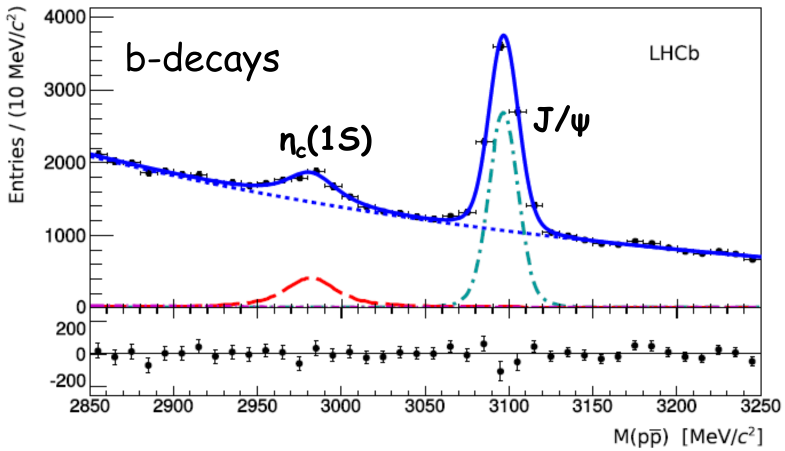
From data From PDG From MC

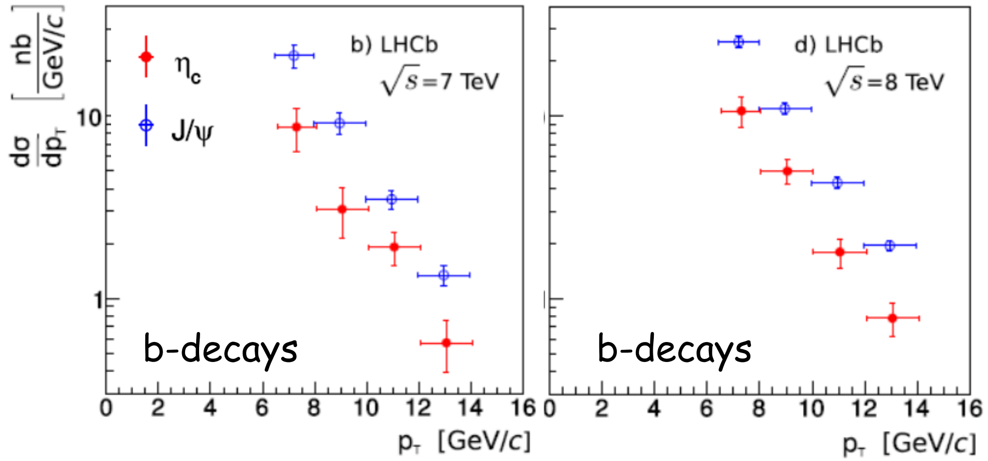
HISTORICAL: The $\eta_c(1S)$ production via decays to hadronic final states

- Two good-quality tracks identified as protons, forming a good-quality vertex
- Distinguish **prompt production** and **production in b-decays** using separation between pp-interaction vertex and charmonium decay vertex
- Subtract cross-feed

EPJC 75 (2015) 311
$\sqrt{s}$ = 7 TeV, $\int L dt$ ~ 1 fb^{-1}
$\sqrt{s}$ = 8 TeV, $\int L dt$ ~ 2 fb^{-1}

Production **in b-hadron decays**



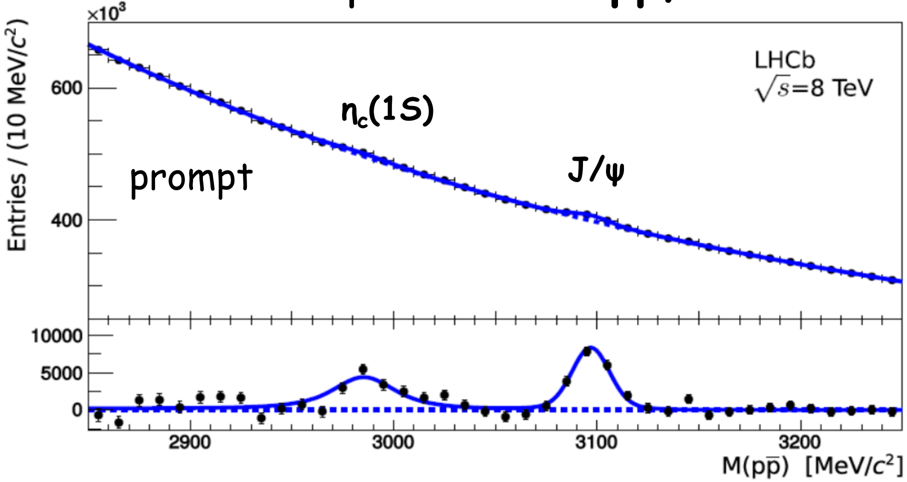


- First measurement $\mathcal{B}(b \to \eta_c(1S)X) = (4.88 \pm 0.64 \pm 0.29 \pm 0.67_{\mathcal{B}}) \times 10^{-3}$

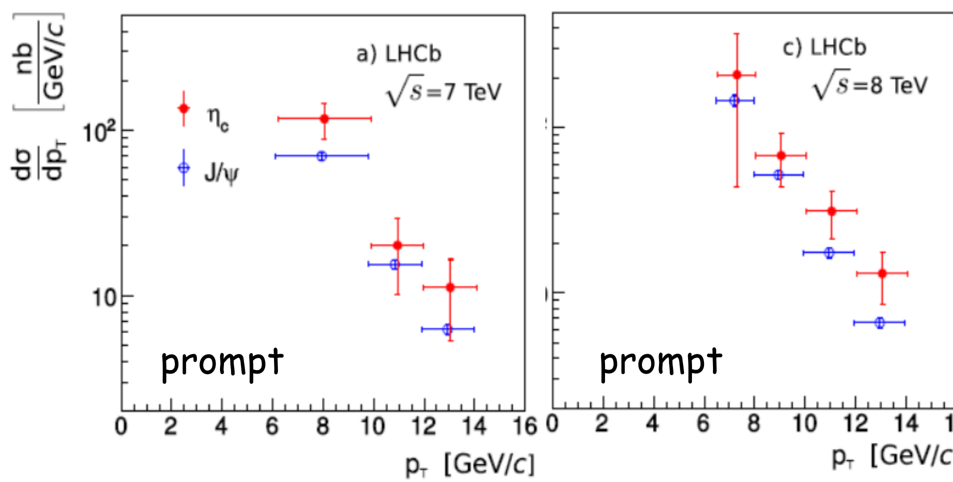
- Next: Measure $\eta_c(1S)$ **prompt production**
- Verify NRQCD prediction of **different p_T spectra for J/ψ and $\eta_c(1S)$**

Maltoni, Polosa, **PRD 70 (2004) 054014**
Petrelli et al., **Nucl. Phys. B514 (1998) 245**
Kuhn, Mirkes, **PRD 48 (1993) 179**

- Inv. mass spectrum of **pp**, **collision VX**



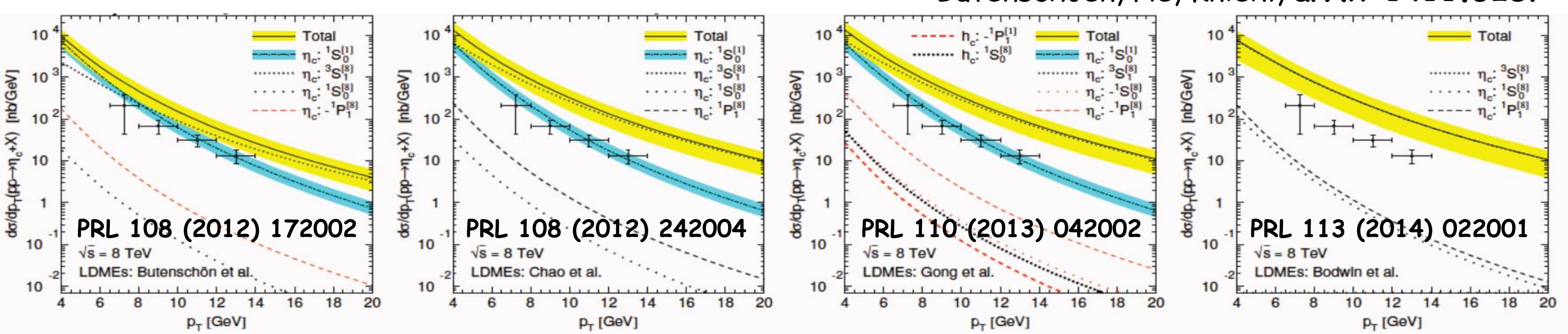
- **Different p_T spectra for J/ψ and $\eta_c(1S)$ not observed** on data



- First measurement of **$\eta_c(1S)$ prompt production**

$$\sigma_{\eta_c(1S)} = 0.52 \pm 0.09 \pm 0.08 \pm 0.06\ \mu b \quad \sqrt{s} = 7\,\mathrm{TeV}$$
$$0.59 \pm 0.11 \pm 0.09 \pm 0.08\ \mu b \quad \sqrt{s} = 8\,\mathrm{TeV}$$

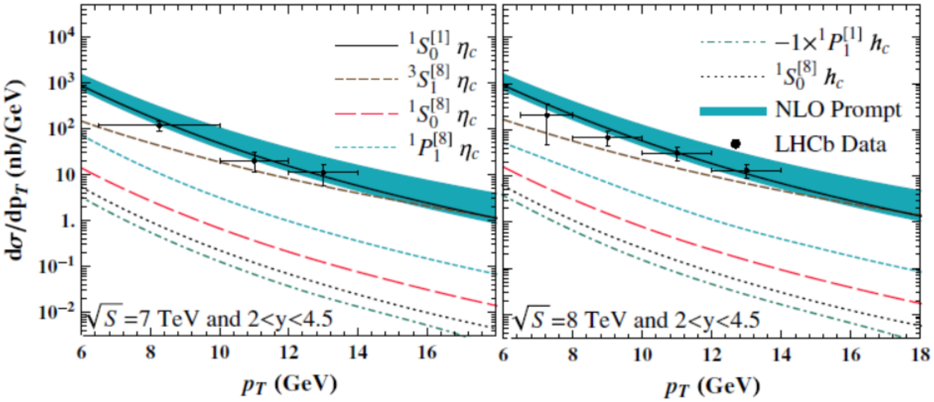
Butenschoen, He, Kniehl, **arXiv:1411.5287**



- Results are described by ***CS NLO***, below expected CO contribution

THEORY: The $\eta_c(1S)$ AND J/ψ prompt production

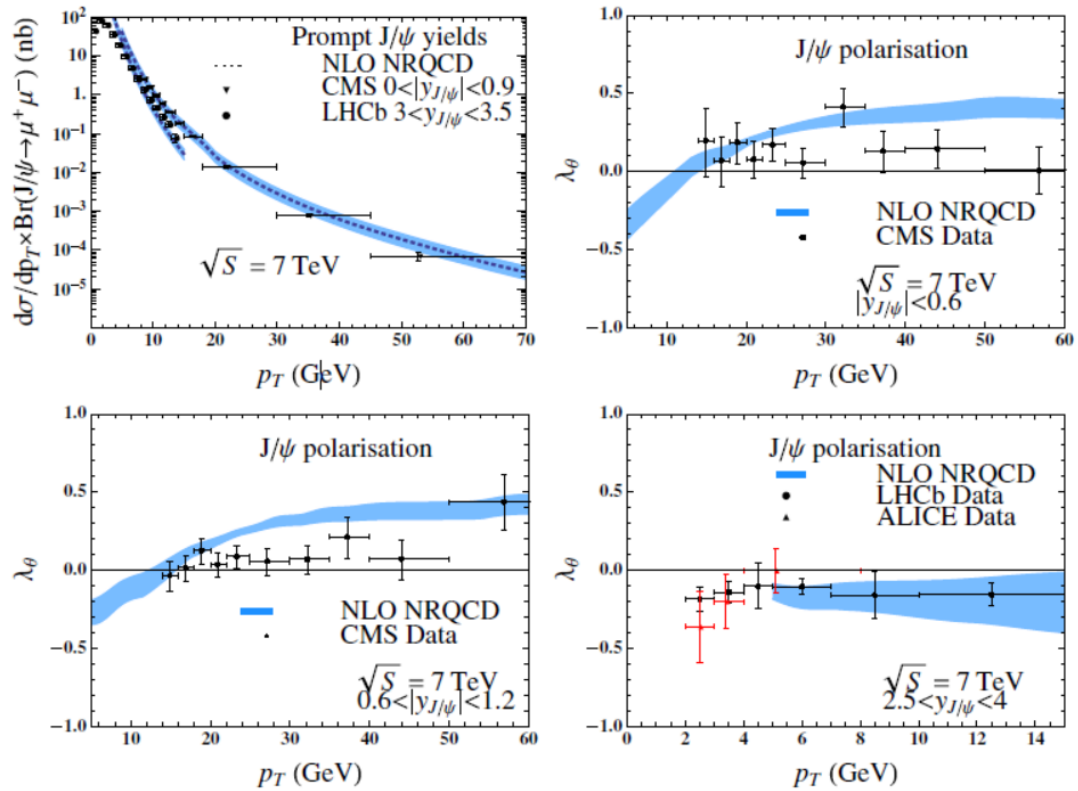
Han, Ma, Meng, Shao, Chao
PRL 114 (2015) 092005



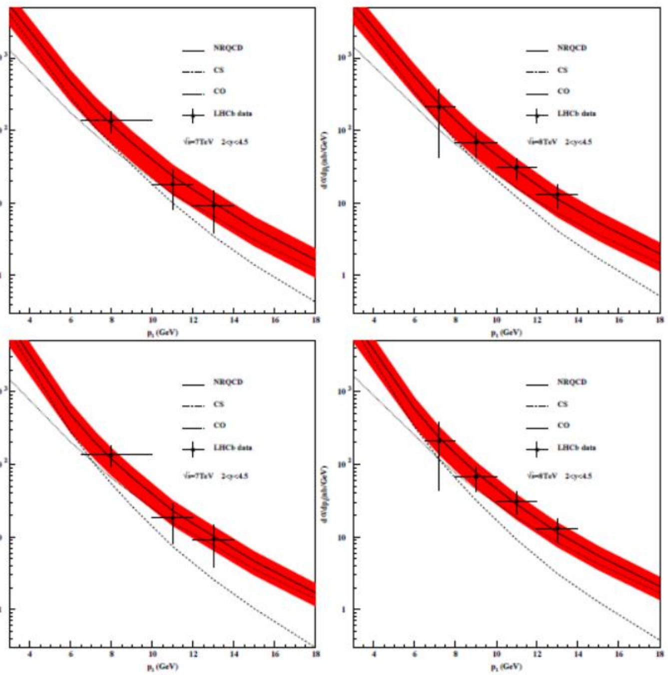
- Constrain CO LDME $^3S_1^{[8]}$ for η_c, and thus $^1S_0^{[8]}$ for J/ψ by HQSS

- **Predictions** for J/ψ production at 7 TeV

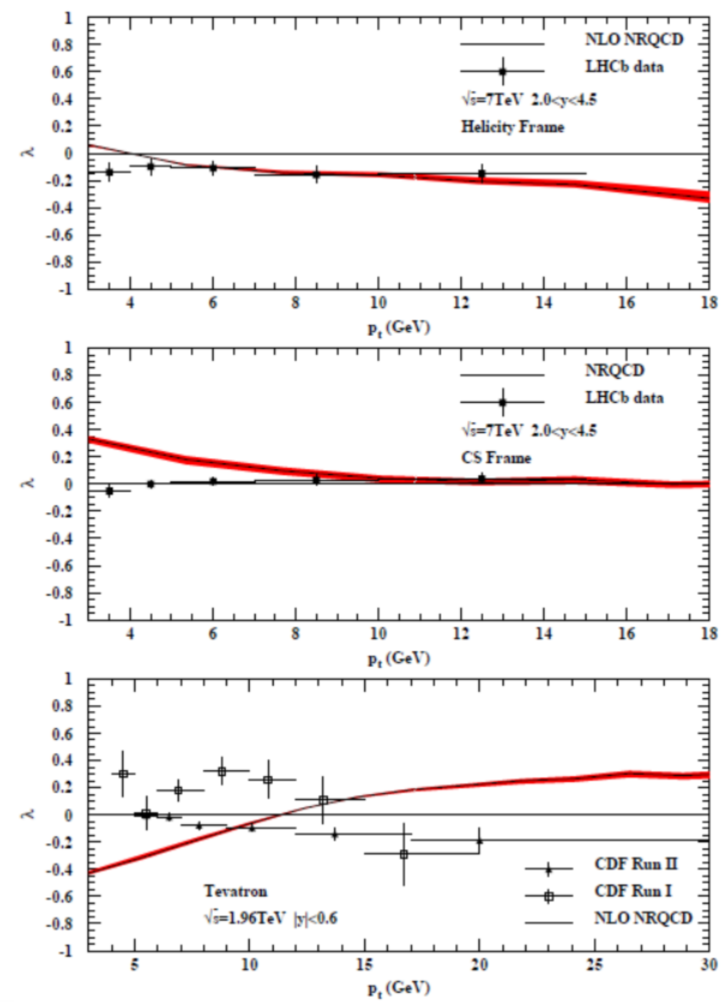
- **Constraints** from
  - CDF production measurements
    PRD 71 (2005) 032001
  - LHCb $\eta_c(1S)$ production
    EPJC 75 (2015) 311



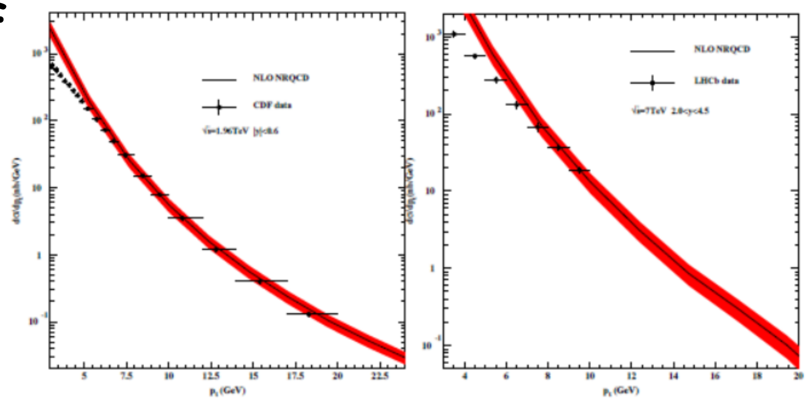
Zhang, Sun, Sang, Li
PRL 114 (2015) 092006



- LDMEs from the fit
- **Predictions** for J/ψ production



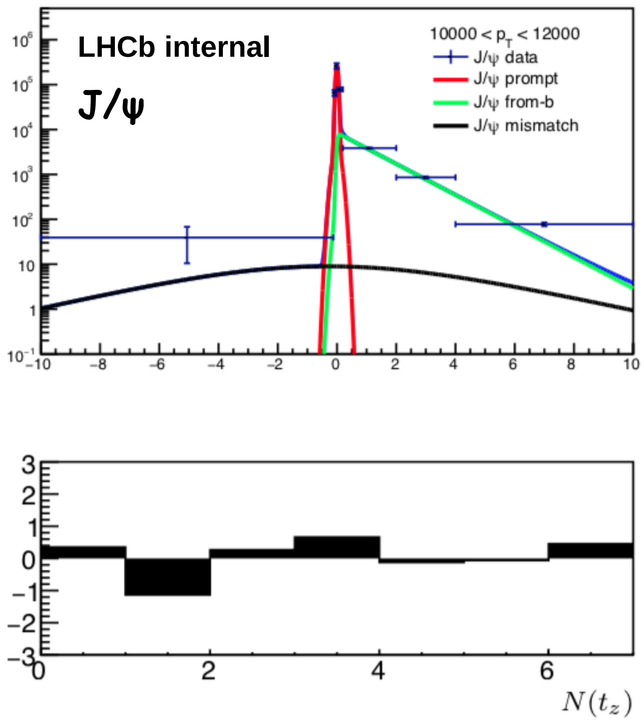
- Description of production and polarization at 7 TeV
- Problems: **production at low pT; J/ψ polarization at CDF**

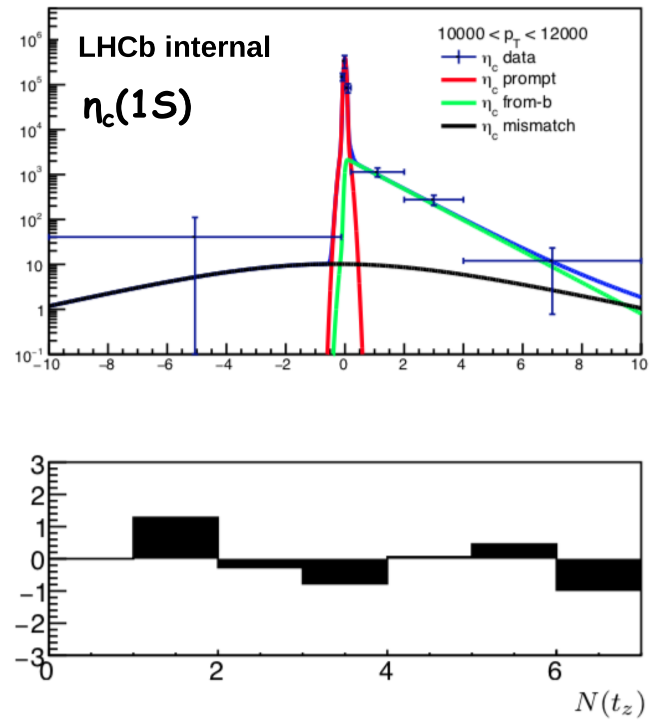


Technique 1: **Distinguish prompt and b-decay charmonium via t_z distribution fit** (J/ψ analysis - like).

$$t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{p\bar{p}}$$

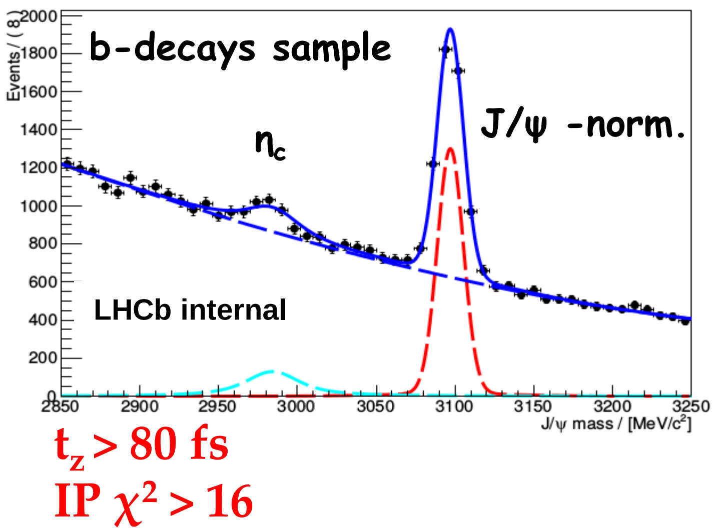
- Simultaneous integral χ^2 fit of t_z distributions constructed using η_c and J/ψ yields from mass fit in pT bins

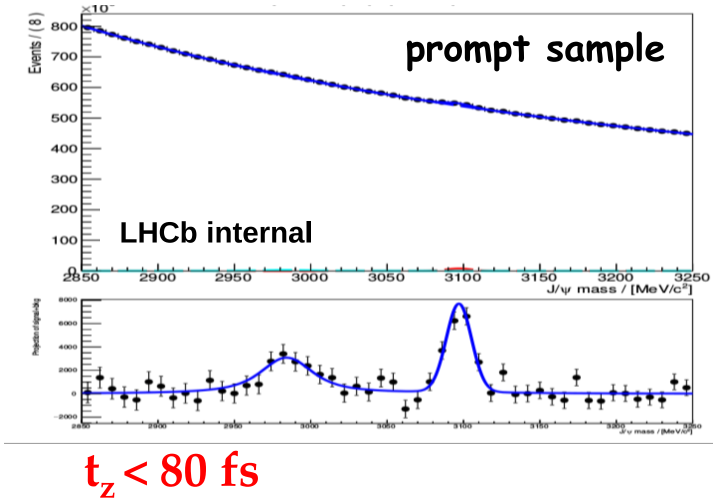




Technique 2: **Distinguish prompt and b-decay charmonium via** t_z and proton IP based **selection requirements** (run I $\eta_c(1S)$ analysis - like).

- Simultaneous fit in pT bins





- Extract **prompt** and **from b-decays** components from measured yields and determined efficiencies and cross-feeds

- Two techniques consistent and yield similar precision

ALMOST PUBLIC: $\eta_c(1S)$ ($\to p\bar{p}$) prompt production at $\sqrt{s}$=13 TeV

- Integral **x-section in LHCb fiducial region**:

LHCb:

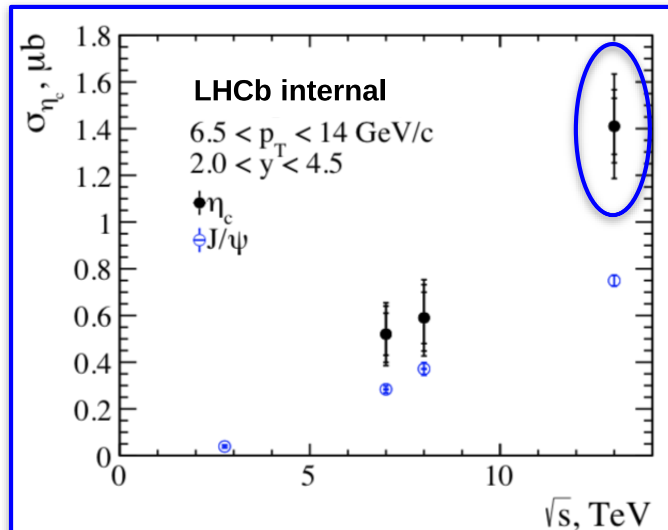
$\sigma_{\eta c}$= : .2$_{stat}$ ± 0.10$_{syst}$ ± 0.16$_{BR}$ μb

Yu-Feng, Hua-Sheng et al.:

$\sigma_{\eta c} = 1.56 \,^{+0.83}_{-0.49}\,_{scale}\,^{+0.38}_{-0.17}\,_{CT14NLO}$

LHCb fiducial region:
6.5 GeV/c < PT < 14.0 GeV/c
2.0 < y < 4.5

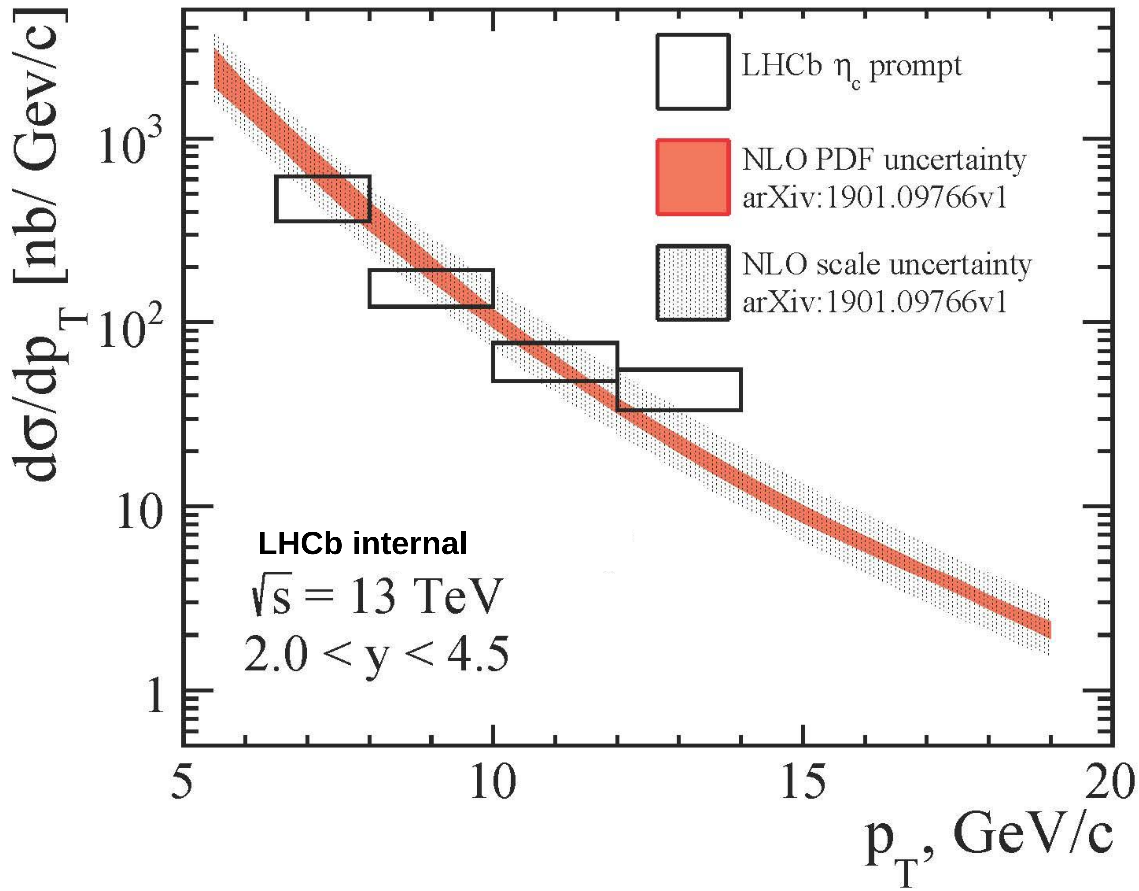
- Absolute x-section nicely reproduced.



- **Energy dependence of the $\eta_c(1S)$ production** with 2015-2016 data.

- **BR(b → $\eta_c(1S)$ X)** is consistent with the result at 7, 8 TeV and gives better stat. precision

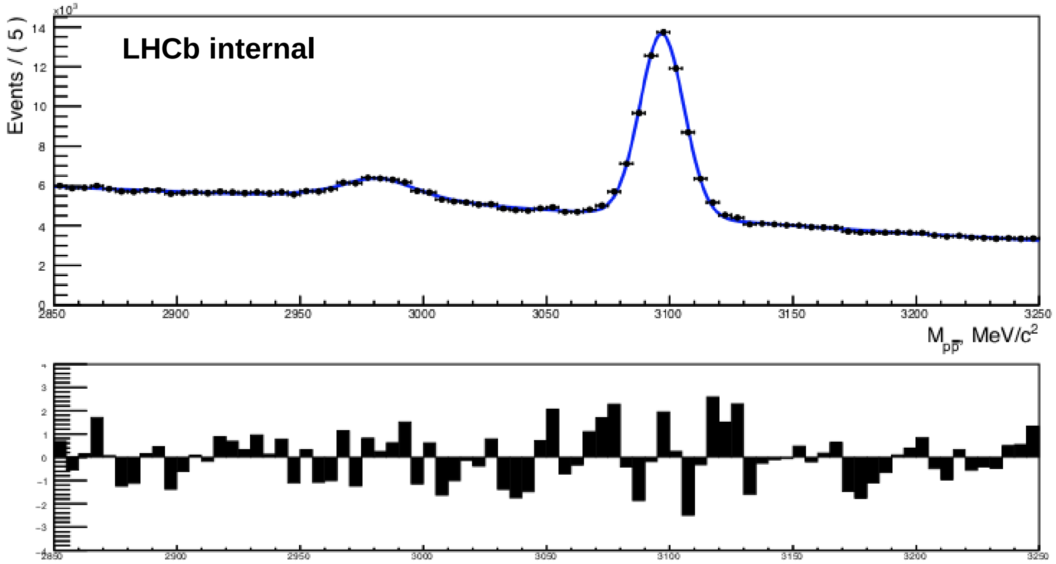
ALMOST PUBLIC: Also pT-differential production

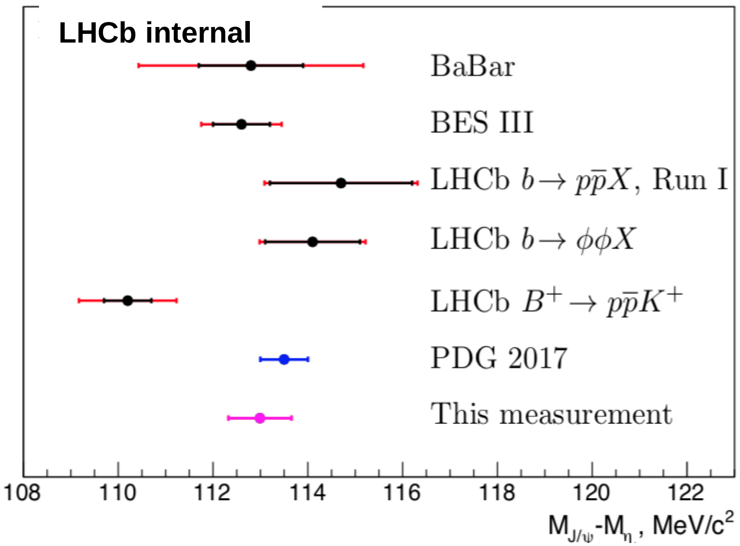


- Good **description of pT-differential x-section**
- Interesting to measure next pT bin when enough sensitivity

ALMOST PUBLIC: J/ψ and $\eta_c(1S)$ mass difference

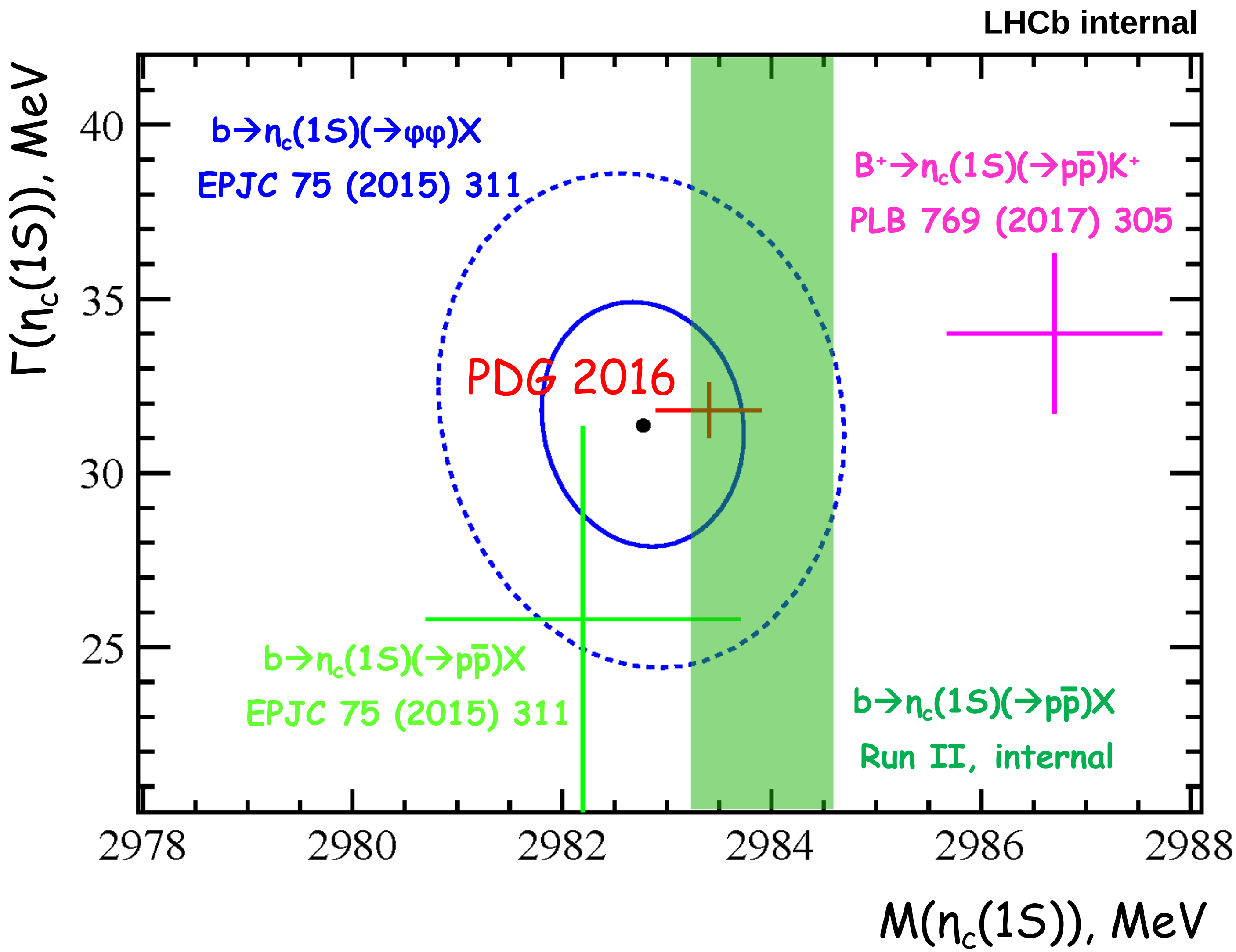
- **Mass measurement** using topological triggers





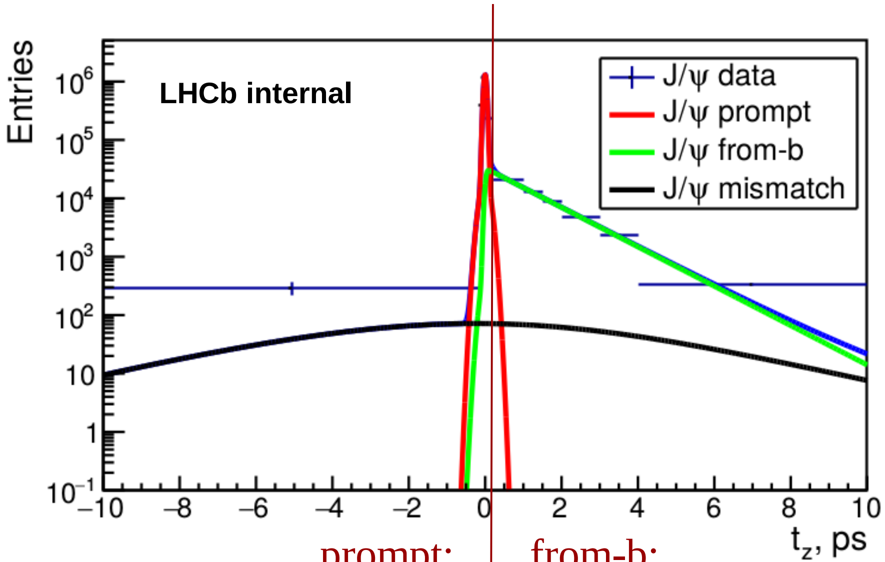
- Measurement dominated by stat. uncertainty
- Consistent with other measurements
- **Most precise single measurement to date**

ALMOST PUBLIC: $\eta_c(1S)$ resonance parameters



- Motivated by theory calculations
- **Dedicated LHCb trigger in 2018**

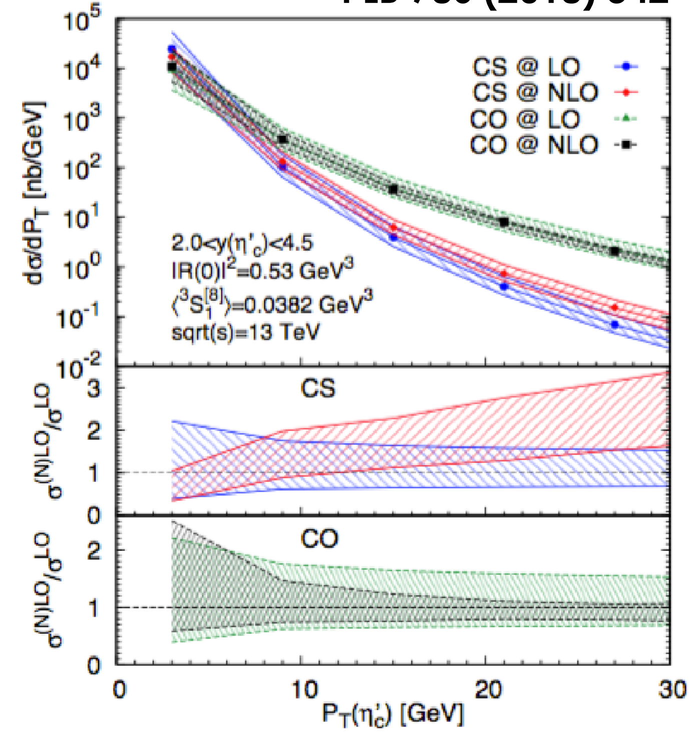
- Prompt and b-decay production distinguished via selection cuts



prompt: $t_z < 80$ fs

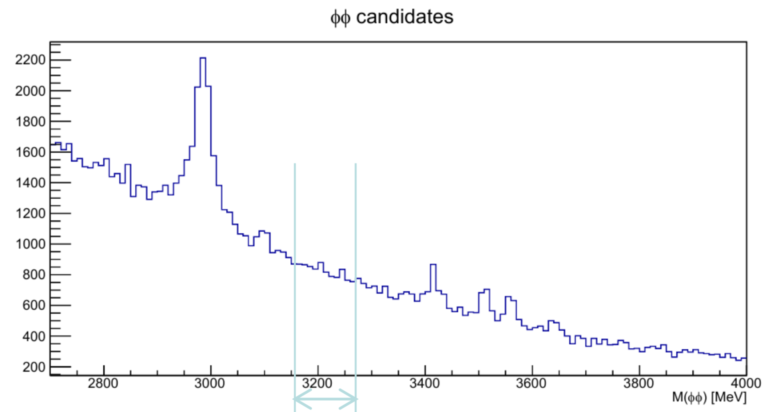
from-b: $t_z > 80$ fs, IP $\chi^2 > 16$

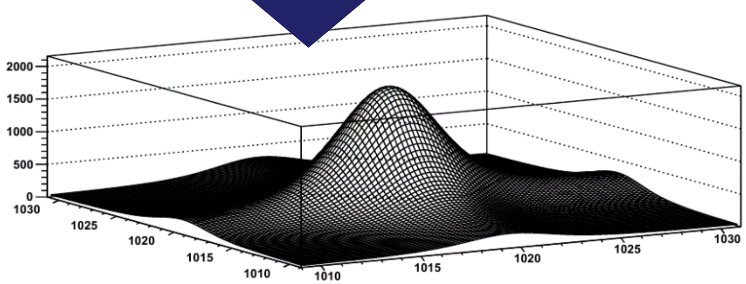
Lansberg, Shao, Zhang
PLB 786 (2018) 342

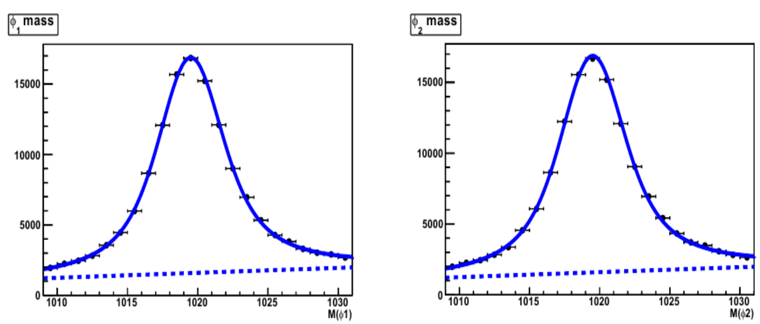


Production of χ_c and $\eta_c(2S)$ in b-decays, $\phi\phi$ final state

Charmonia production in b-decays study using decays to $\phi\phi$ at $\sqrt{s} = 7,8\,TeV$





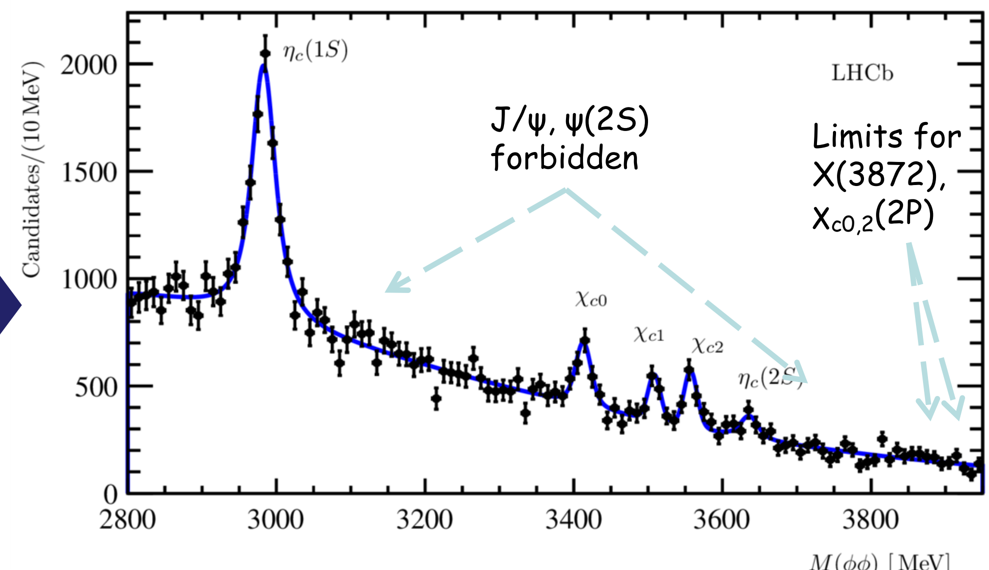


Excludes φKK, 4K, etc.

EPJC 77 (2017) 609

√s = 7 and 8 TeV, ∫Ldt ~ 3 fb^{-1}

- ❑ **Kaons**: good quality high-pT tracks, identified as Kaons, not consistent with coming from PV
- ❑ **ϕ mesons**: pairs of kaons with invariant mass around known mass
- ❑ **ϕϕ pairs**: good quality vertex well-separated from PV



True φφ pairs, coming from charmonium decays or random **φφ** combinations

EPJC 77 (2017) 609
$\sqrt{s}$ = 7 and 8 TeV, $\int Ldt \sim 3\ fb^{-1}$

- **First or most precise measurements:**

$$\frac{\mathcal{B}(b \to \chi_{c0}X)}{\mathcal{B}(b \to \eta_c(1S)X)} = 0.615 \pm 0.095 \pm 0.047 \pm 0.149,$$
$$\frac{\mathcal{B}(b \to \chi_{c1}X)}{\mathcal{B}(b \to \eta_c(1S)X)} = 0.562 \pm 0.119 \pm 0.047 \pm 0.131,$$
$$\frac{\mathcal{B}(b \to \chi_{c2}X)}{\mathcal{B}(b \to \eta_c(1S)X)} = 0.234 \pm 0.038 \pm 0.015 \pm 0.057,$$

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

Search for X(3872), $\chi_{c0,2}(2P)$

EPJC 77 (2017) 609
$\sqrt{s}$ = 7 and 8 TeV, $\int Ldt \sim 3\ fb^{-1}$

- **Relative yields with respect to resonances with similar quantum numbers**
- Proposed by V. Khoze

	90% CL	95% CL
$\frac{BR(b \to X(3872)X) \cdot BR(X(3872) \to \phi\phi)}{BR(b \to \chi_{c1}X) \cdot BR(\chi_{c1} \to \phi\phi)}$	<0.34	<0.39
$\frac{BR(b \to \chi_{c0}(2P)X) \cdot BR(\chi_{c0}(2P) \to \phi\phi)}{BR(b \to \chi_{c0}X) \cdot BR(\chi_{c0} \to \phi\phi)}$	<0.12	<0.14
$\frac{BR(b \to \chi_{c2}(2P)X) \cdot BR(\chi_{c2}(2P) \to \phi\phi)}{BR(b \to \chi_{c2}X) \cdot BR(\chi_{c2} \to \phi\phi)}$	<0.16	<0.20

	90% CL	95% CL
$BR(b \to X(3872)X) \cdot BR(X(3872) \to \phi\phi)$	$< 3.9 \times 10^{-7}$	$< 4.5 \times 10^{-7}$
$BR(b \to \chi_{c0}(2P)X) \cdot BR(\chi_{c0}(2P) \to \phi\phi)$	$< 2.7 \times 10^{-7}$	$< 3.1 \times 10^{-7}$
$BR(b \to \chi_{c2}(2P)X) \cdot BR(\chi_{c2}(2P) \to \phi\phi)$	$< 2.3 \times 10^{-7}$	$< 2.8 \times 10^{-7}$

Extraction of $\eta_c(1S)$ BRs using $B_s \to \phi\phi$

EPJC 77 (2017) 609

$\sqrt{s}$ = 7 and 8 TeV, $\int L dt \sim 3\ fb^{-1}$

$$BR(B_s^0 \to \phi\phi) = \frac{N_{B_s^0}}{N_{\eta_c}} \times \frac{\varepsilon_{\eta_c}}{\varepsilon_{B_S^0}} \times \frac{BR(b \to \eta_c X) \cdot BR(\eta_c \to p\bar{p})}{BR(b \to J/\psi X) \cdot BR(J/\psi \to p\bar{p})} \times \frac{BR(\eta_c \to \phi\phi)}{BR(\eta_c \to p\bar{p})} \times BR(b \to J/\psi X) \times BR(J/\psi \to p\bar{p}) / BR(\bar{b} \to B_s^0)$$

Using LHCb measurement (JHEP 10 (2015) 053):

$$\boldsymbol{BR(B_S \to \phi\phi) = ((1.84 \pm 0.05 stat \pm 0.07 sys \pm 0.12\ norm \pm 0.11\ (f_s/f_d)) \times 10^{-5}}$$

$$\frac{\mathcal{B}(\eta_c(1S) \to \phi\phi)}{\mathcal{B}(\eta_c(1S) \to p\bar{p})} = 1.79 \pm 0.14 \pm 0.09 \pm 0.10 \pm 0.03 \pm 0.29$$

Cf. PDG: $\frac{BR(\eta_c(1S) \to \phi\phi)}{BR(\eta_c(1S) \to p\bar{p})} = 1.17 \pm 0.18$

→ **New high-impact PDG entry**

Constraining LDMEs using different measurements

Simultaneous study of J/ψ and $\eta_c(1S)$ production in b-decays

Usachov, Kou, SB, LAL-17-051

- From **EPJC 75 (2015) 311** and **Chin. Phys. C40 (2016) 100001**:

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

- Relation between LDME from HQSS:

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

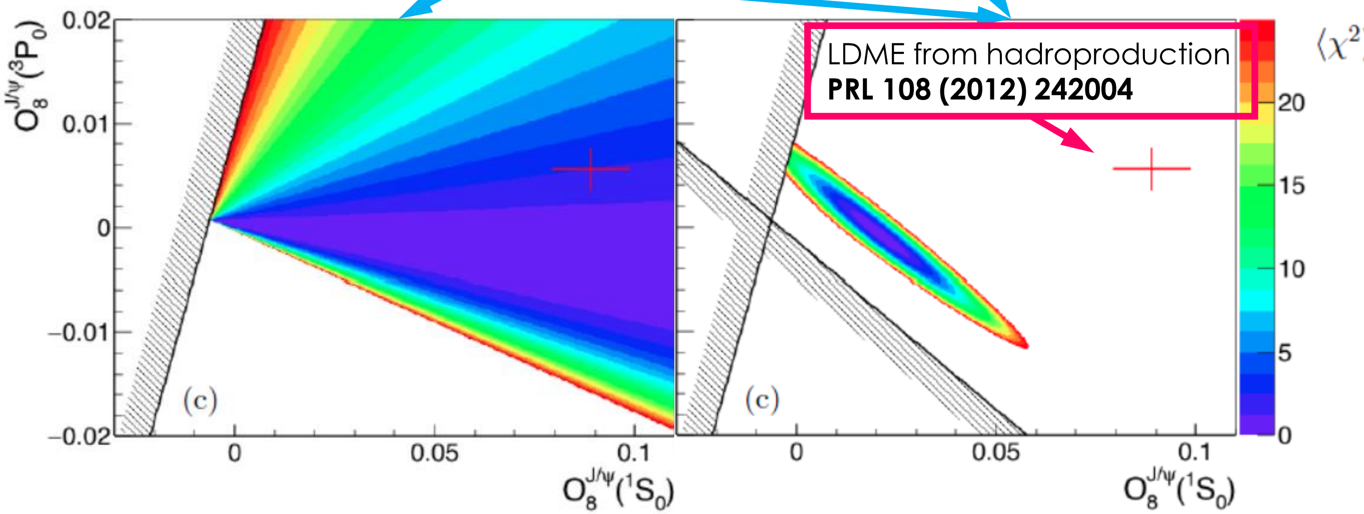
- Branching fractions calculated in **Beneke, Maltoni, Rothstein, PRD 59 (1999) 054003**

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

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

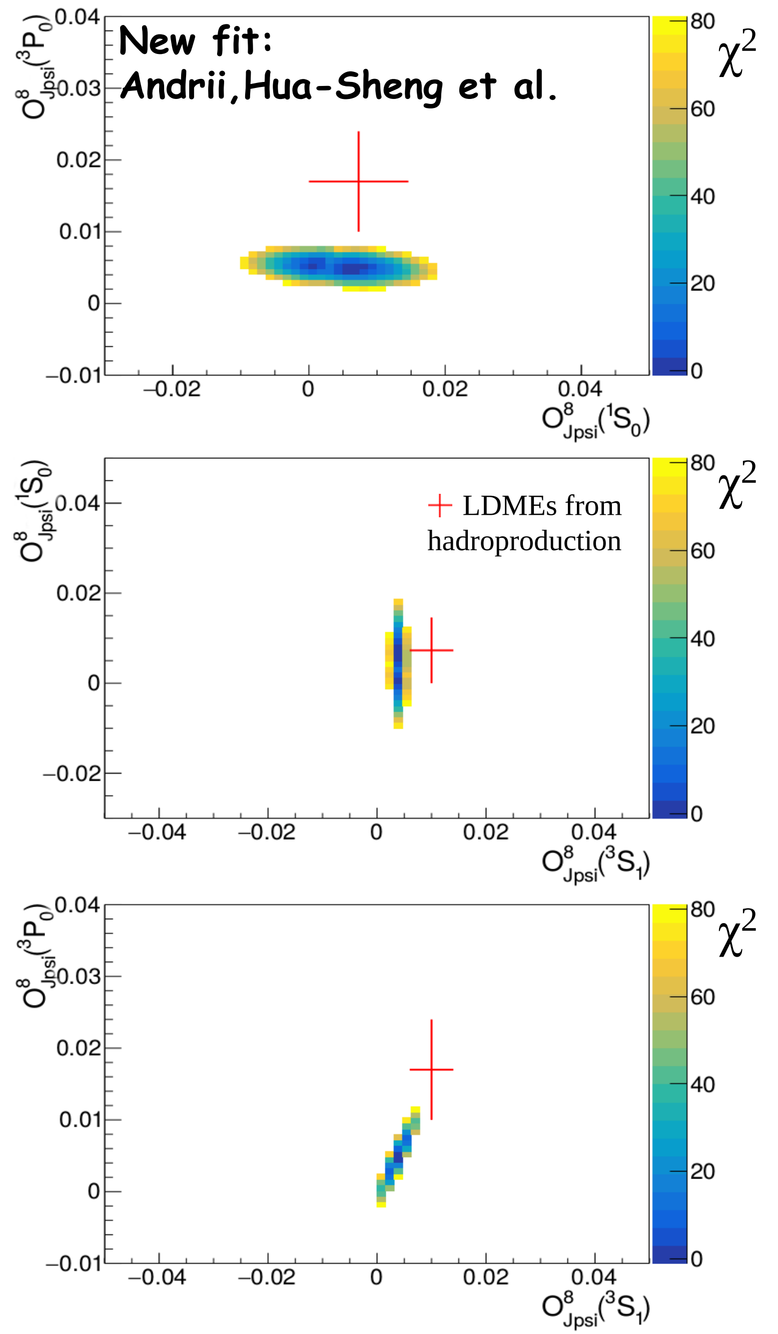
$$\frac{\mathcal{B}(b \to \eta_c(1S)^{direct} X)}{\mathcal{B}(b \to J/\psi^{direct} X)}$$

$$\mathcal{B}(b \to J/\psi^{direct} X)$$



Simultaneous study of J/ψ and $\eta_c(1S)$ production

- **Simultaneous fits to J/ψ and $\eta_c(1S)$ LDMEs, prompt and b-decay production**
- $\langle O(^1S_0)\rangle$ fixed at 1.16 GeV^3
- Sequentially fix other LDMEs according to theoretical prediction
- Red points: **PRL 114 (2015) 092005**
- Theoretical uncertainties crucial, plots including theory uncertainties



Simultaneous study of χ_c production in inclusive b-decays

Usachov, Kou, SB, LAL-17-051

- From **EPJC 77 (2017) 609** and **Chin. Phys. C40 (2016) 100001**:

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

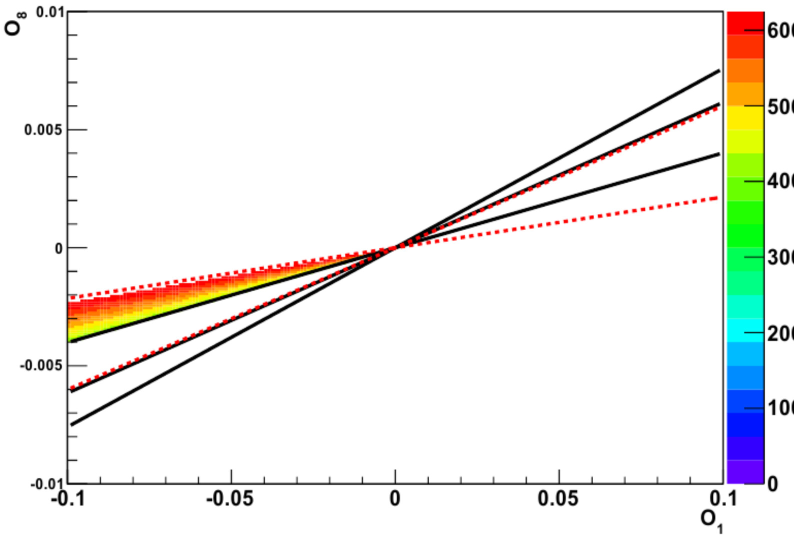
- Relation between LDME from HQSS:

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

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

- Fit **two LDME** to **three measurements**

- Important to revisit theory calculations



Simultaneous study of charmonia with linked LDMEs

- This technique constrains theory using **simultaneously** results on **charmonia hadroproduction and** on **charmonia from b-inclusive decays** under **assumptions of factorization, universality and HQSS**, with **different charmonium states.**

- Alternatively, once hadroproduction and production in b-decays measured for charmonium states with linked LDMEs, the above **assumptions can be tested quantitatively**.

- The FCPPL project pursues a series of **theoretical and phenomenological developments** and a series of **LHCb data analyses** to insight the **mechanism of quarkonia production.**
- The project challenges the mechanism of ground state charmonia production and its experimental verification using **charmonia decays to hadronic final states** (pp, φφ, …).

- Despite a newly created FCPPL project (2019) the **IPN – LAL – LPTHE – UCAS team** possesses a rich tradition of successful collaboration.