Charmonia production in pp collisions @ LHCb
Decays to hadronic final states

Sergey Barsuk, LAL Orsay
sergey.barsuk@lal.in2p3.fr

Core part of the talk: Recent LHCb results by Andrii, Jibo, Valeriia et al.
Recent theory input by Hua-Sheng, Jean-Philippe, Hong-Fei and Yu-Feng

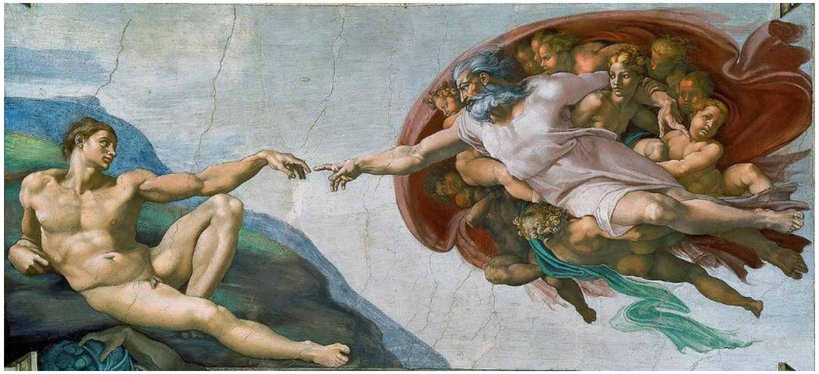
FCPPL QUARKONIUM
PRODUCTION WORKSHOP

- (Short) Introduction
- Production of η_c using decays to $p\bar{p}$
- Production of χ_c and $\eta_c(2S)$ using decays to $\phi\phi$
- Other examples
- (No) Summary

A (very short) introduction: generic

- 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 ;
  - Simultaneous description of different charmonia ;
  - Simultaneous description of production and polarization in the entire pT range.
- Extract **LDMEs from pT dependence** of x-sections

Charmonium production

- ❑ Two scales of production:

  hard process of **$Q\bar{Q}$ formation** and **hadronization of $Q\bar{Q}$** 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

❑ <u>Colour-singlet model</u>: intermediate $Q\bar{Q}$ state is colourless and has the same J^{PC} quantum numbers as the final-state quarkonium

❑ <u>NRQCD</u>: 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

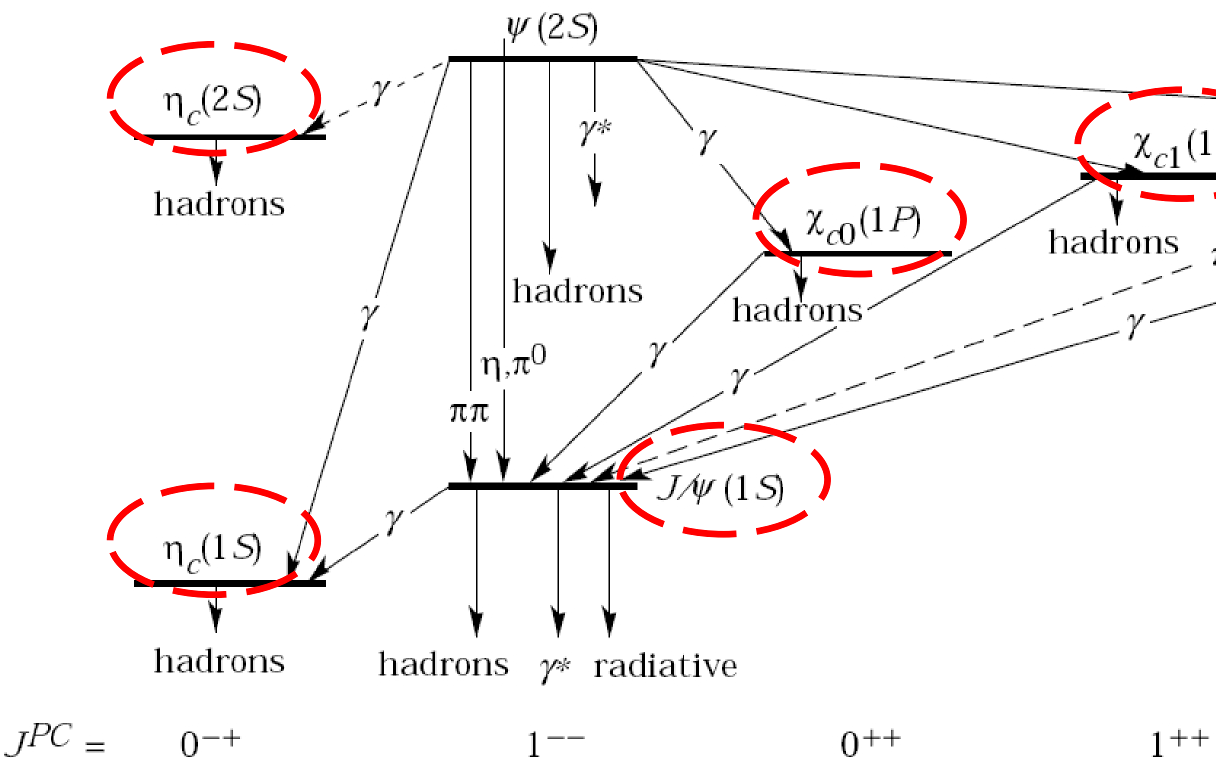
❑ **Universality**: *same LDME for prompt production and production in b-decays*

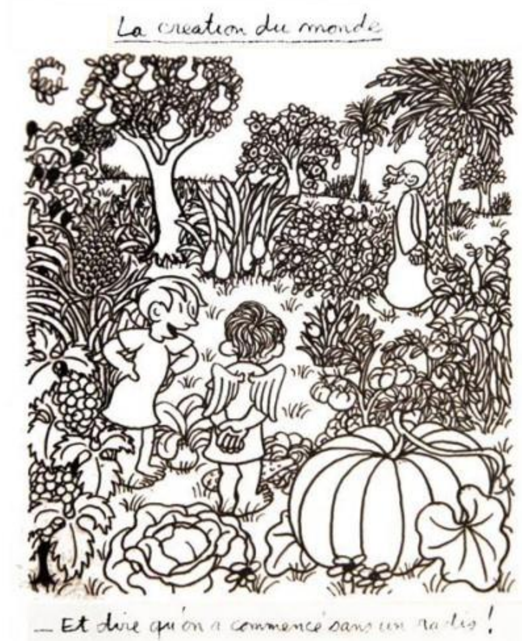
❑ Heavy-Quark **Spin-Symmetry** (HQSS): links between colour-singlet (CS) and colour-octet (CO) LDME of different quarkonium states

Charmonia production

- **Over-constrain** to test universality, factorization and HQ spin symmetry
- Impressive effort and progress in theory
- **Joint theory and experimental effort**

Very bad charmonia | **Good charmonia** | **Bad (or not so bad) charmonia**



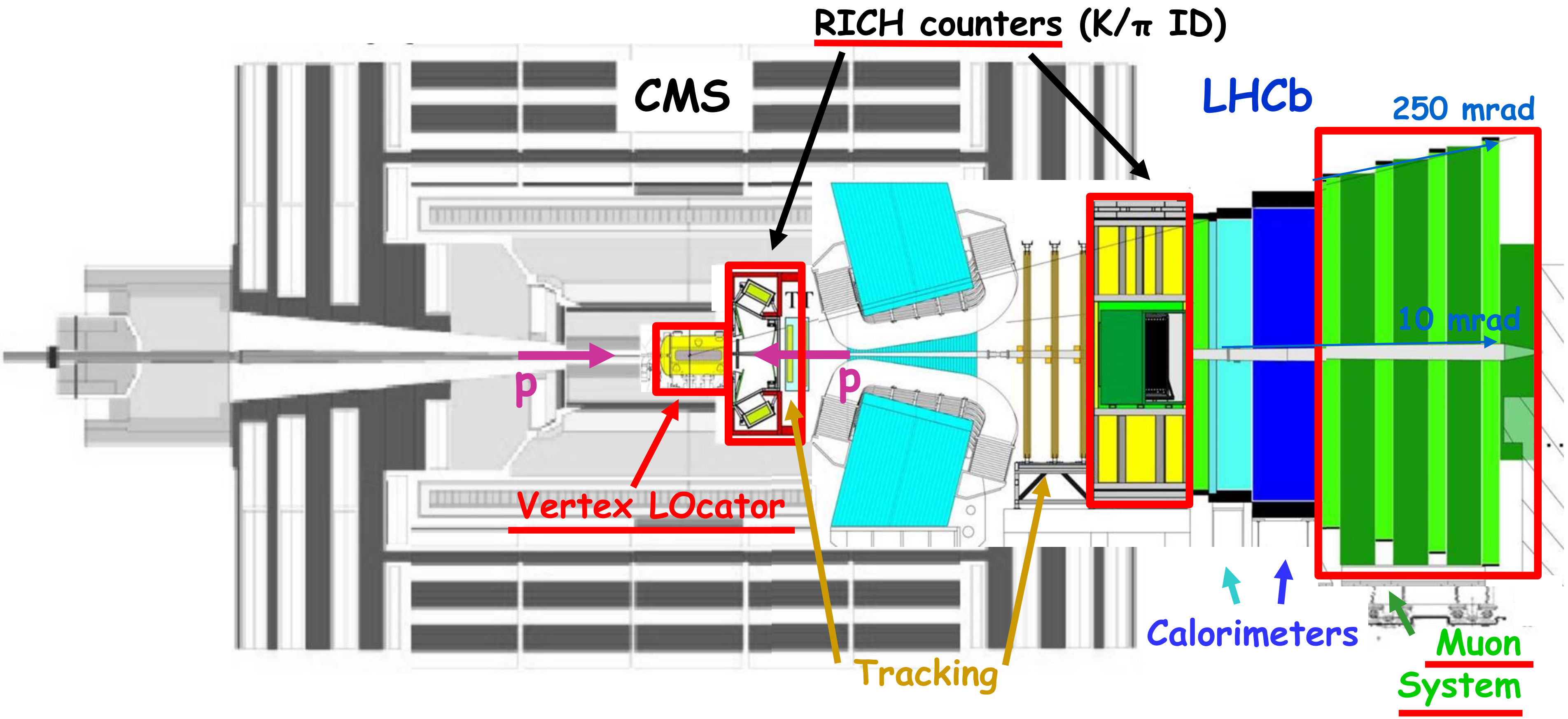


- **Hadronic decays** to access "all" charmonium states

LHCb detector – single-arm forward spectrometer 10-250 mrad (V), 10-300 mrad (H)

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

- **Forward peaked HQ production** at the LHC, second b in acceptance once the first b is in
- Forward region 1.9 < η < 4.9, **~4% of solid angle**, but **~40% of HQ production x-section**

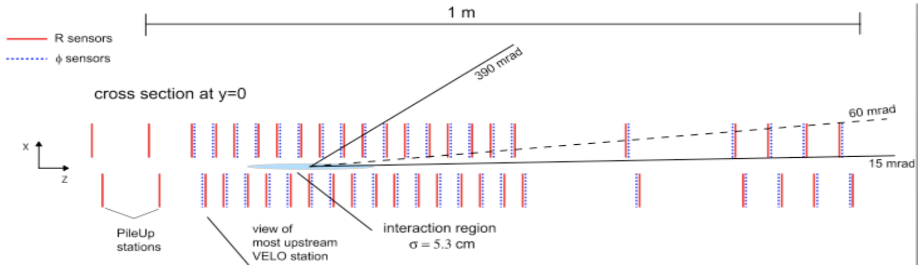


- **Complementary cross-section measurements** and overlap in terms of rapidity
- Key detector systems for production measurements: **vertex reconstruction (VELO), particle identification (Muon detector, RICHs), Trigger**

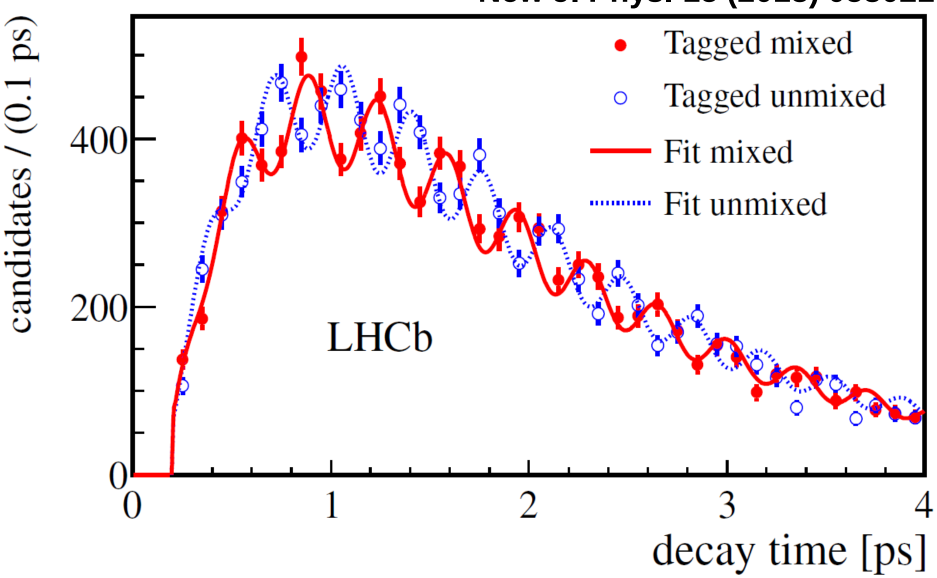
VELO: Vertex LOcator

JINST 8 (2013) P08002, arXiv:1405.7808

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



New J. Phys. 15 (2013) 053021



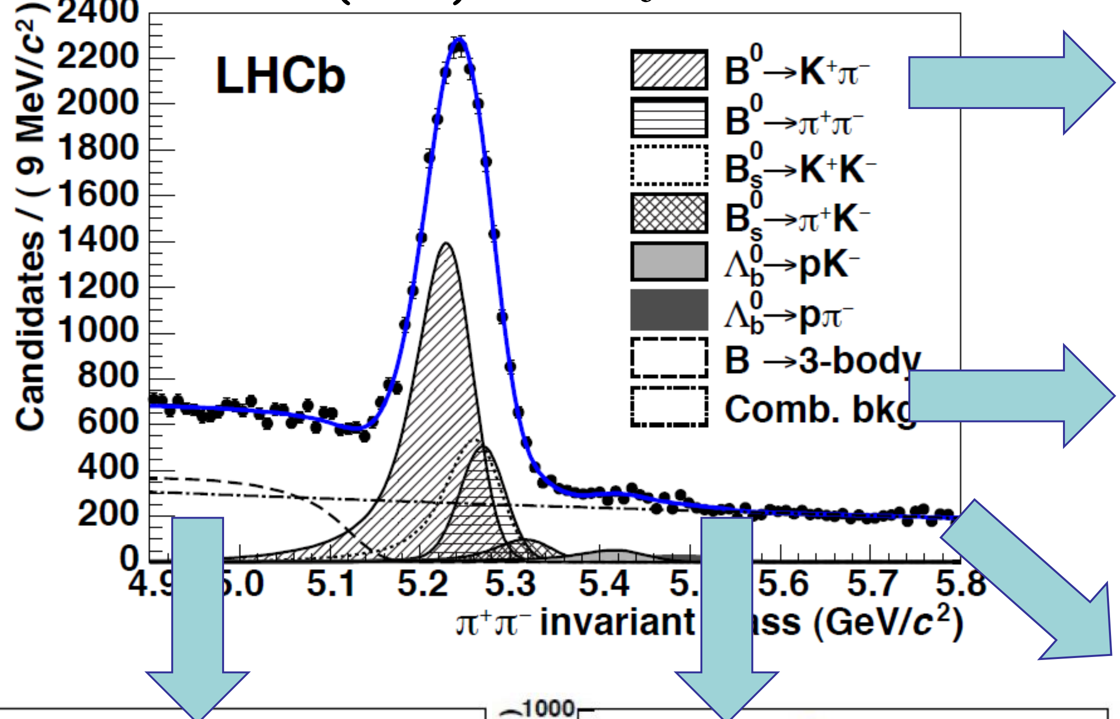
- **First active strip at 8.2mm from the beam axis**
- Moves away every fill and centers around the beam with self measured vertices

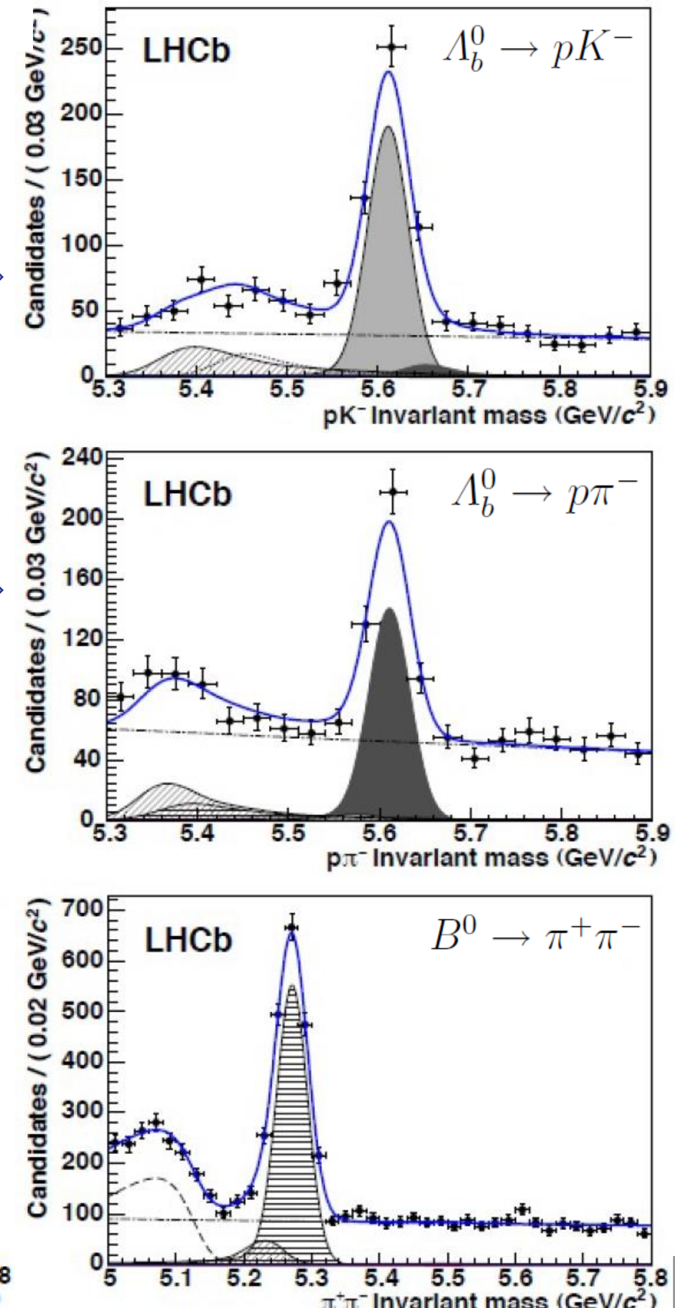
- ***Vertex resolution*** allows to resolve fast (x~27) $B_s\overline{B}_s$ oscillations

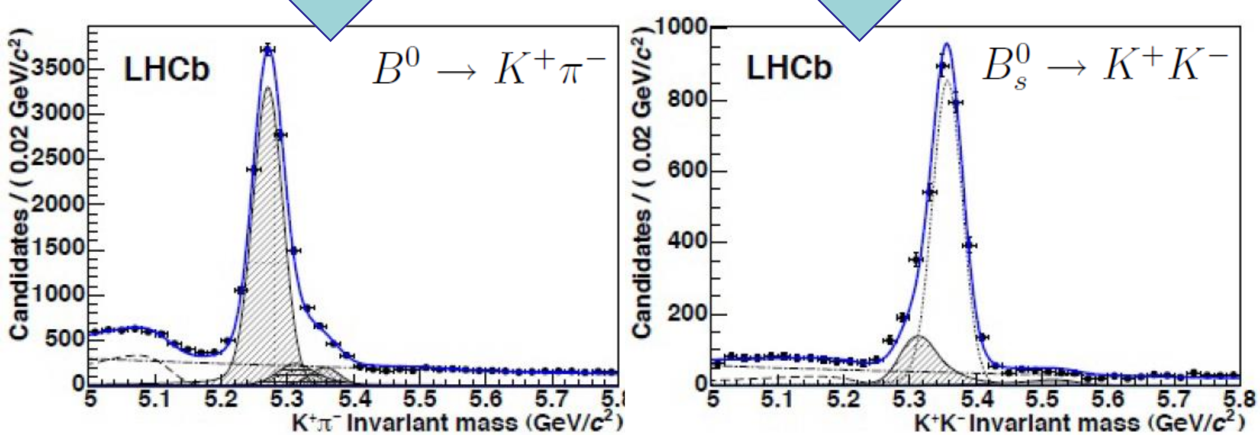
LHCb: charged hadron ID with RICH

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

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







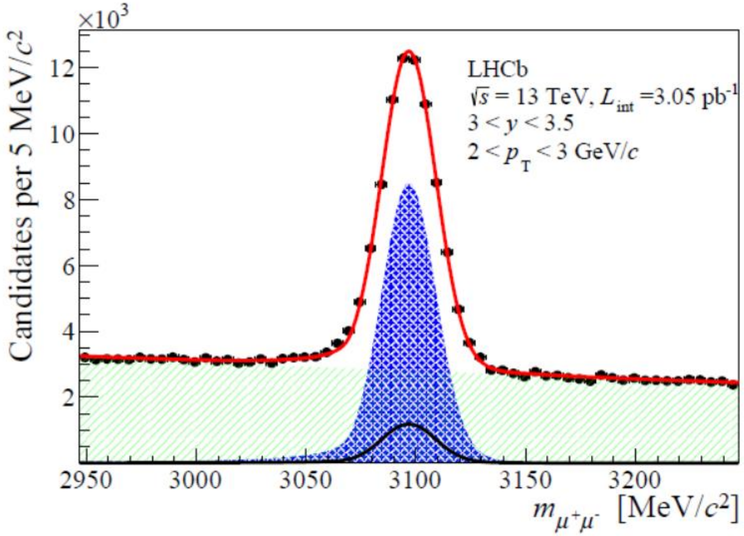
A (very short) introduction: *good* charmonia

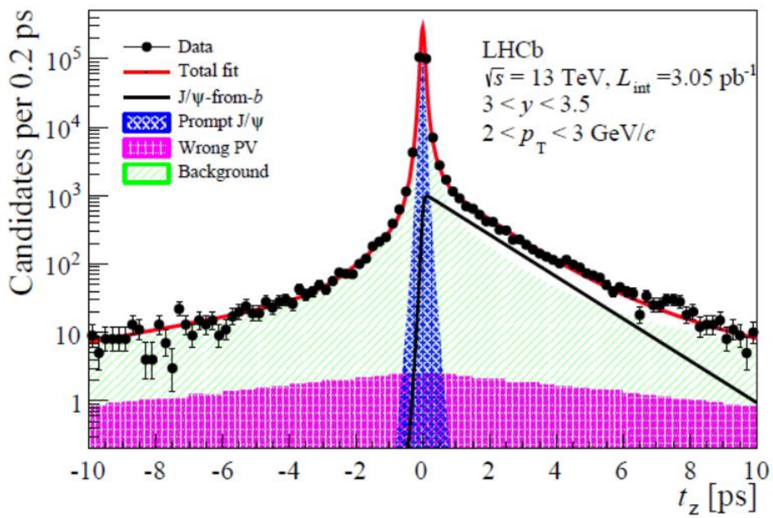
- Example of J/ψ production
- ψ(2S) production discussed yesterday by Miroslav

- **Prompt J/ψ production** and **production in b-hadron decays**
- Double differential cross-sections from two-dimensional fit in bins of p_T and y
- Prompt and b-decay components are extracted from the fit to pseudo-lifetime distribution

JHEP 1510 (2015) 172
JHEP 1705 (2017) 063
$\sqrt{s}$ = 13 TeV, $\int L dt \sim 3\ pb^{-1}$

$$t_z = \frac{(z_{J/\psi} - z_{PV}) \times M_{J/\psi}}{p_z}$$





- Production **cross-section, integrated over acceptance** :

$$\sigma(\text{prompt } J/\psi, p_T < 14\,\text{GeV}/c, 2.0 < y < 4.5) = 15.03 \pm 0.03 \pm 0.94\,\mu\text{b}$$
$$\sigma(J/\psi\text{-from-}b, p_T < 14\,\text{GeV}/c, 2.0 < y < 4.5) = 2.25 \pm 0.01 \pm 0.14\,\mu\text{b}$$

- **$b\bar{b}$ cross-section**, integrated over 4π :

$$\sigma(pp \to b\bar{b}X) = 495 \pm 2 \pm 52\,\mu\text{b}$$

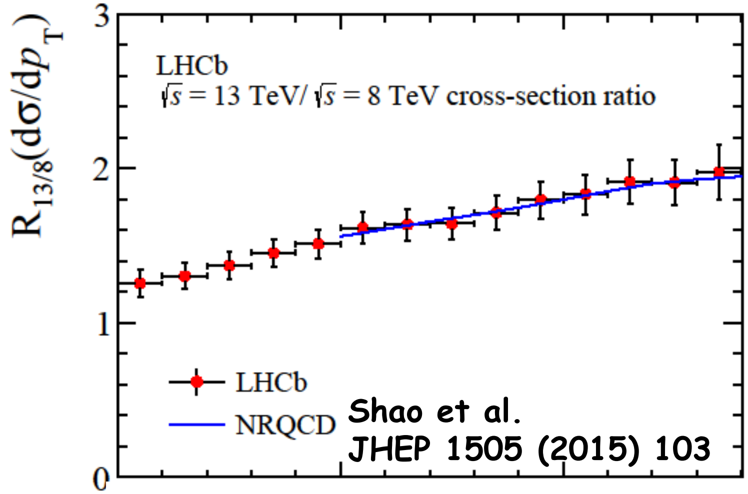
using extrapolation factor $\alpha_{4\pi}$ = 5.2 from the LHCb tuning of PYTHIA 6

JHEP 0605 (2006) 026

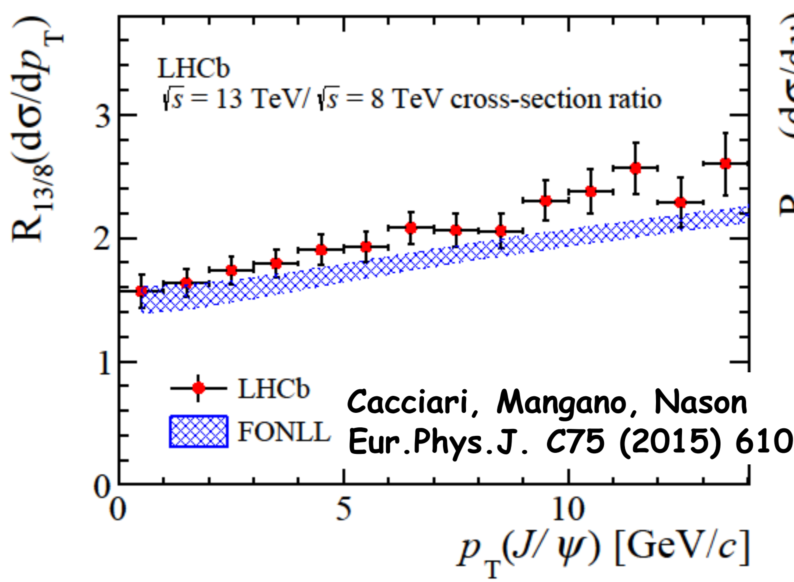
- The **J/ψ production** measured **at √s = 13 TeV** and compared to that **at √s = 8 TeV** and **theory**

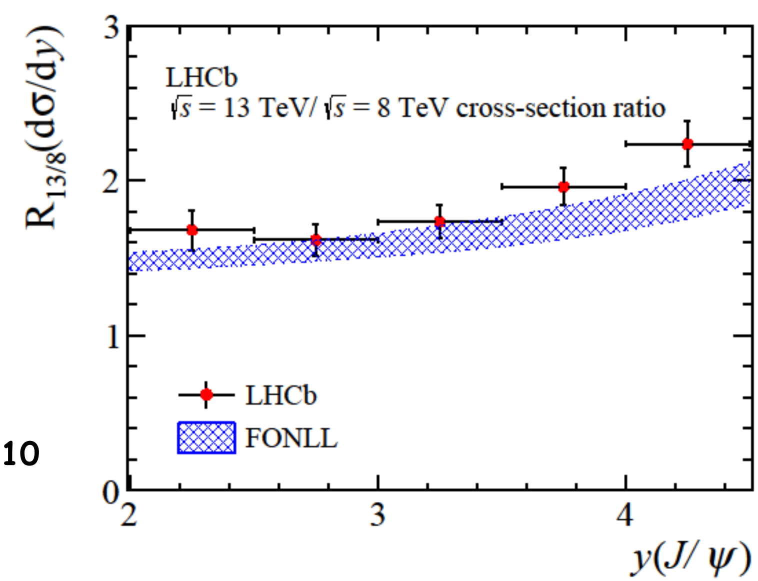
JHEP 1510 (2015) 172
JHEP 1705 (2017) 063
√s = 13 TeV, ∫Ldt ~ 3 pb^{-1}

- **Prompt production**



- **Production in b-decays**





- Perfect (good) **theory-experiment agreement** for prompt (b-decay) production

- Being not able to show you very preliminary results, I will often suggest questions, then either nothing or hints for solutions …
- **Concept of leaves: grape vs. fig**

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

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

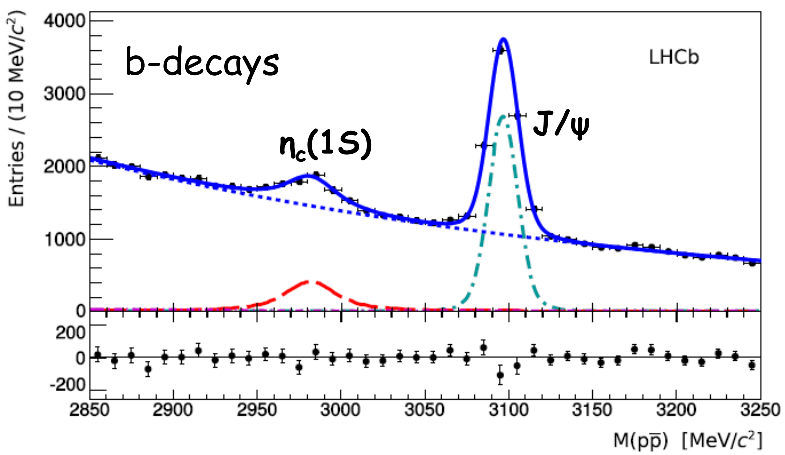
$$\frac{\mathcal{B}_{b\to\eta_c(1S)X}}{\mathcal{B}_{b\to J/\psi X}} = \frac{N^b_{\eta_c(1S)}}{N^b_{J/\psi}} \times \frac{\mathcal{B}_{J/\psi\to p\bar{p}}}{\mathcal{B}_{\eta_c(1S)\to p\bar{p}}} \times \frac{\epsilon_{J/\psi\to p\bar{p}}}{\epsilon_{\eta_c(1S)\to p\bar{p}}}$$

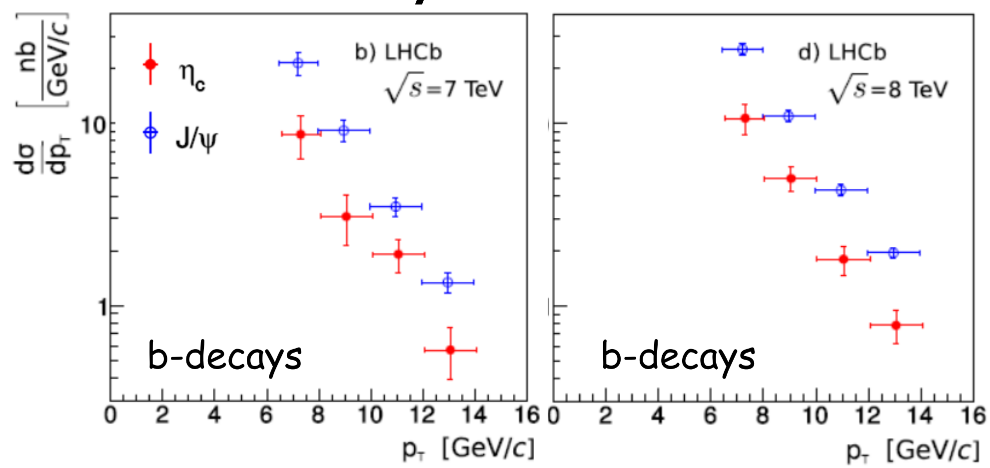
From data | From PDG | From MC

- 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
- X-feed between samples subtracted

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

Production **in b-hadron decays**





- First measurement

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

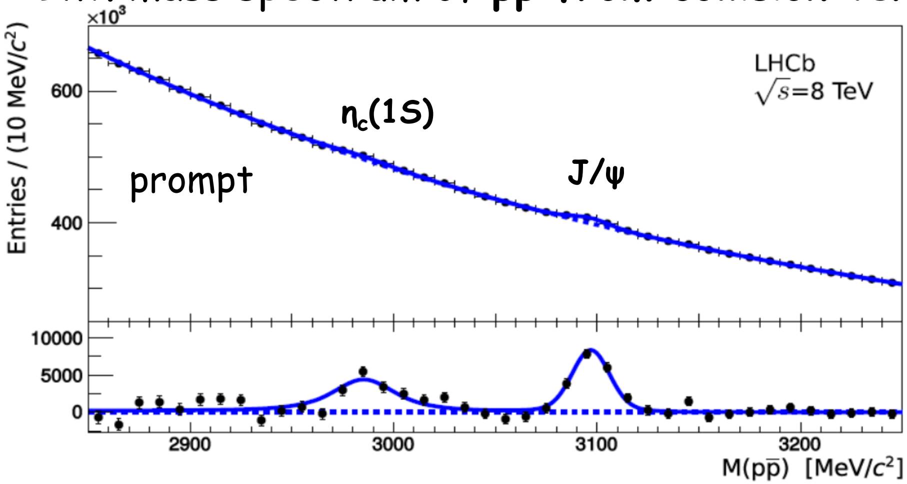
Next:

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

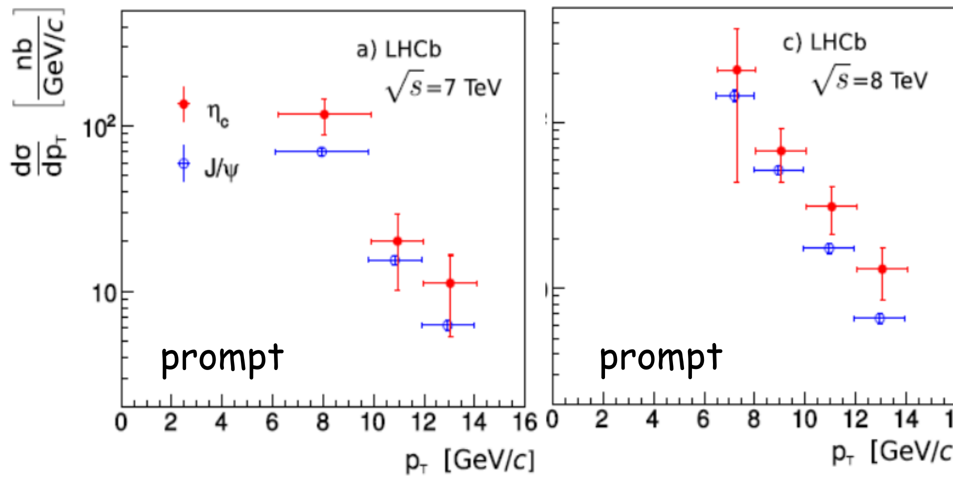
Maltoni, Polosa, **PRD 70 (2004) 054014**
Petrelli et al., **Nucl. Phys. B514 (1998) 245**
Kuhn, Mirkes, **PRD 48 (1993) 179**

HISTORICAL: The $\eta_c(1S)$ prompt production EPJC 75 (2015) 311

Inv. mass spectrum of **$p\bar{p}$ from collision vertex**



Diff. cross-section of the **$\eta_c(1S)$ production**



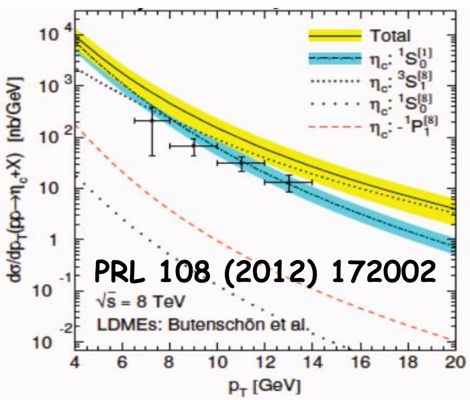
❑ First measurement of **$\eta_c(1S)$ prompt production**

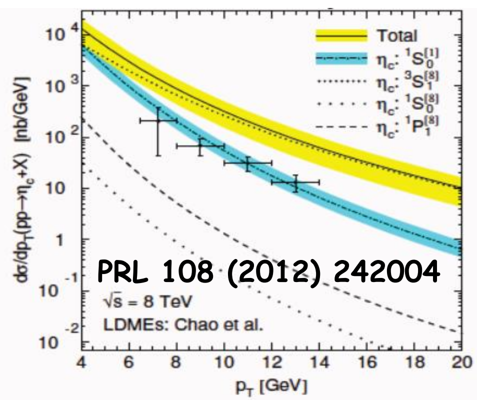
$$\sigma_{\eta_c(1S)} = 0.52 \pm 0.09 \pm 0.08 \pm 0.06\ \mu\text{b} \quad \sqrt{s} = 7\,\text{TeV}$$
$$0.59 \pm 0.11 \pm 0.09 \pm 0.08\ \mu\text{b} \quad \sqrt{s} = 8\,\text{TeV}$$

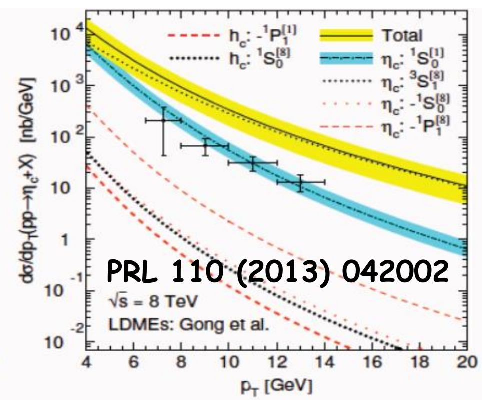
❑ **Different p_T spectra for J/ψ and $\eta_c(1S)$ not observed** on data

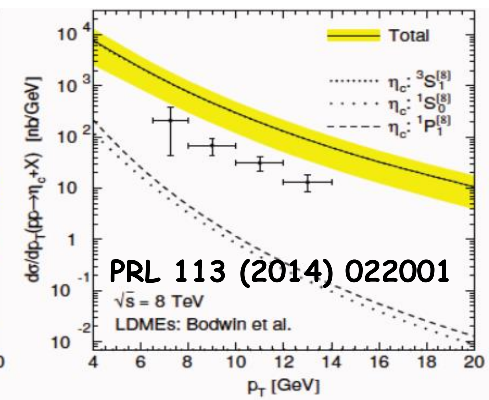
❑ Using J/ψ production and relation between matrix elements, « immediate » reaction

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





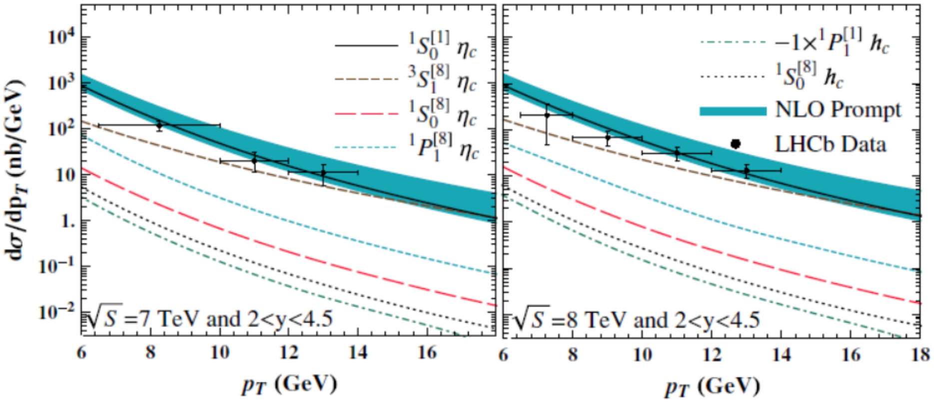




❑ Results are described by **CS NLO**, below expected CO contribution

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

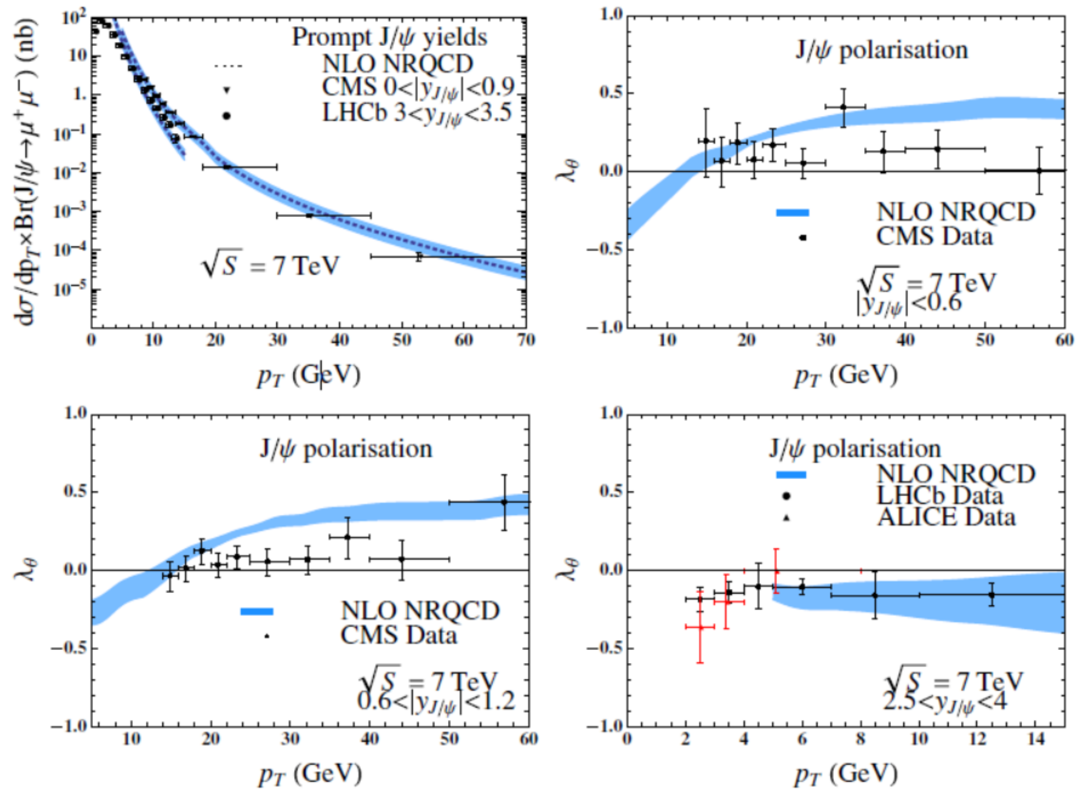
Han, Ma, Meng, Shao, Chao
PRL 114 (2015) 092005



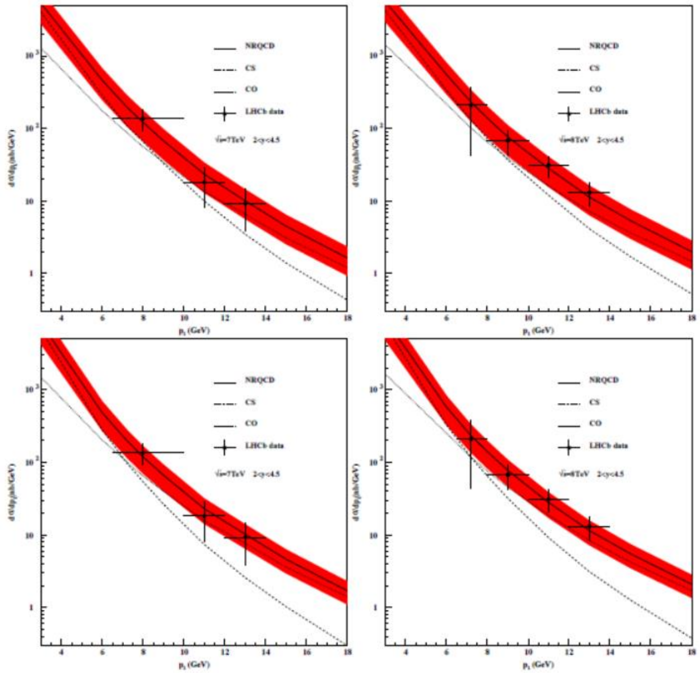
- Constrain CO LDME $^3S_1^{[8]}$ for η_c, and thus $^1S_0^{[8]}$ for J/ψ by the HQSS relation

- **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



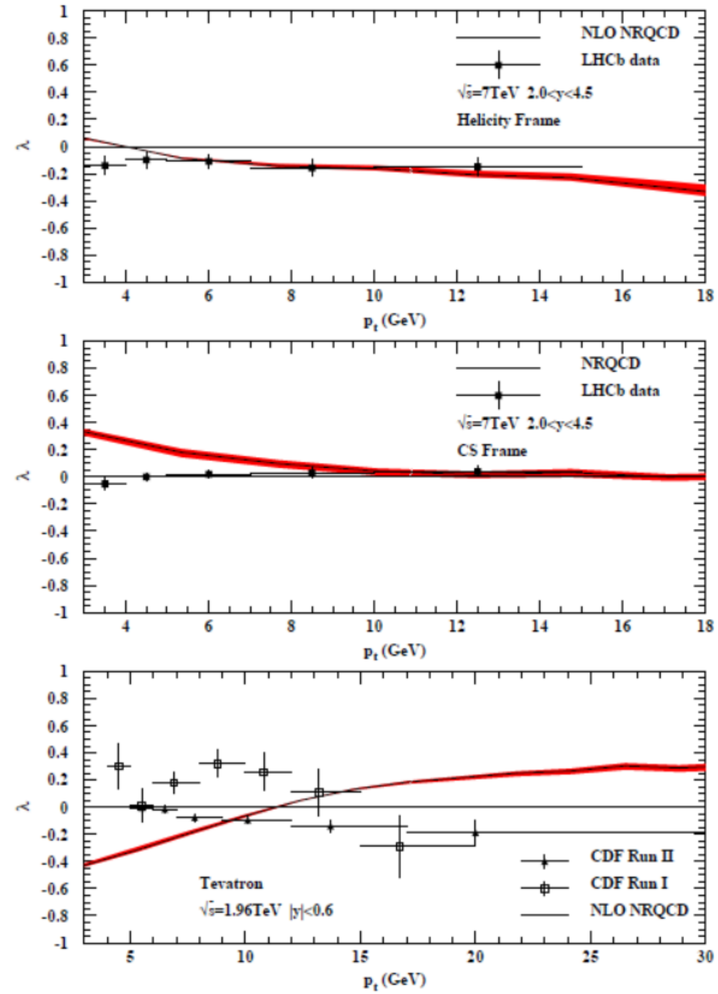
THEORY: The $\eta_c(1S)$ AND J/ψ prompt production



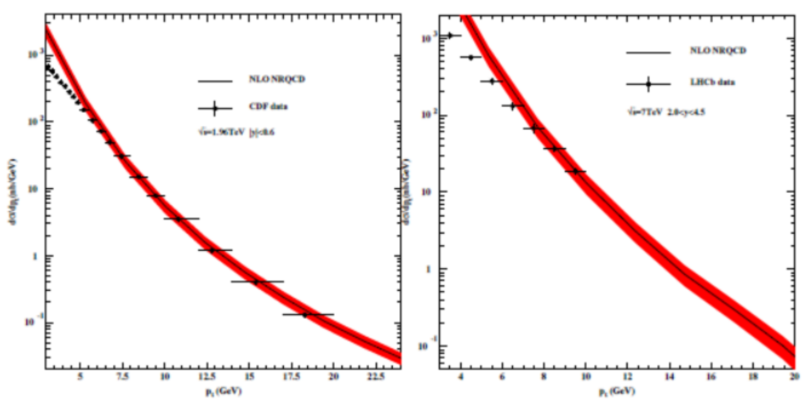
Zhang, Sun, Sang, Li
PRL 114 (2015) 092006

- ❑ 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**



- Two techniques

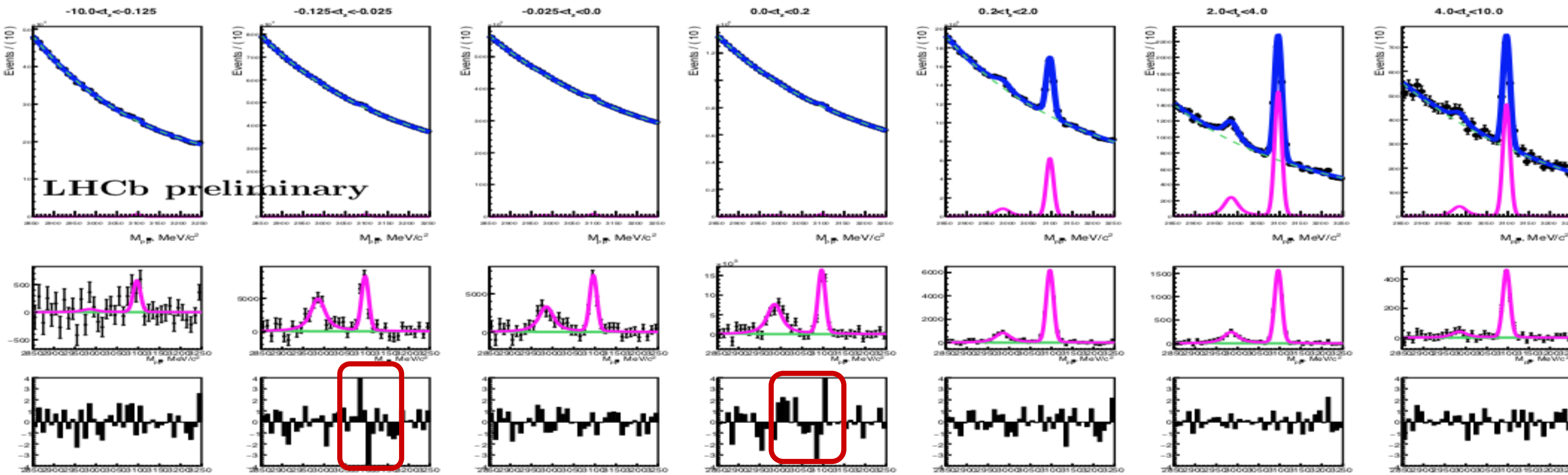
- **Distinguish prompt and b-decay charmonium**

1. **t_z distribution fit** (J/ψ analysis - like) : separate prompt and from b-decays charmonia: simultaneous integral χ^2 t_z fit in pT bins

2. **t_z and proton IP based selection requirements** (run I $\eta_c(1S)$ analysis - like) : simultaneous fits in pT bins

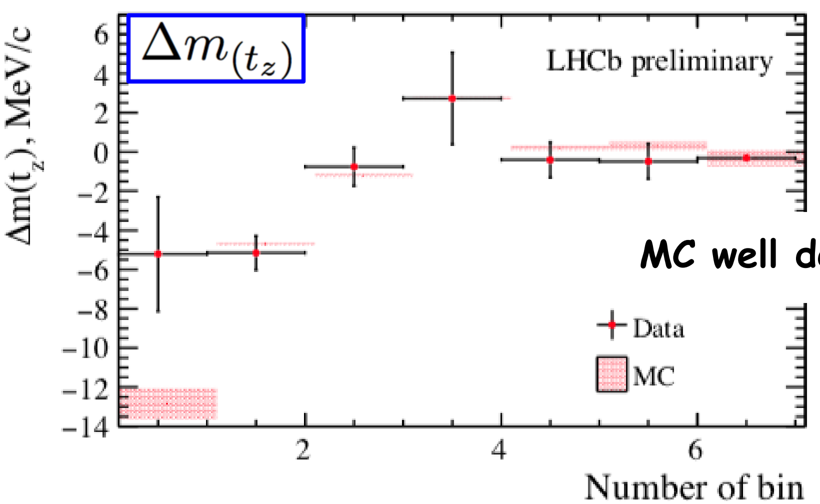
ALMOST PUBLIC: $\eta_c(1S)$ ($\to p\bar{p}$) prompt production at $\sqrt{s}$=13 TeV

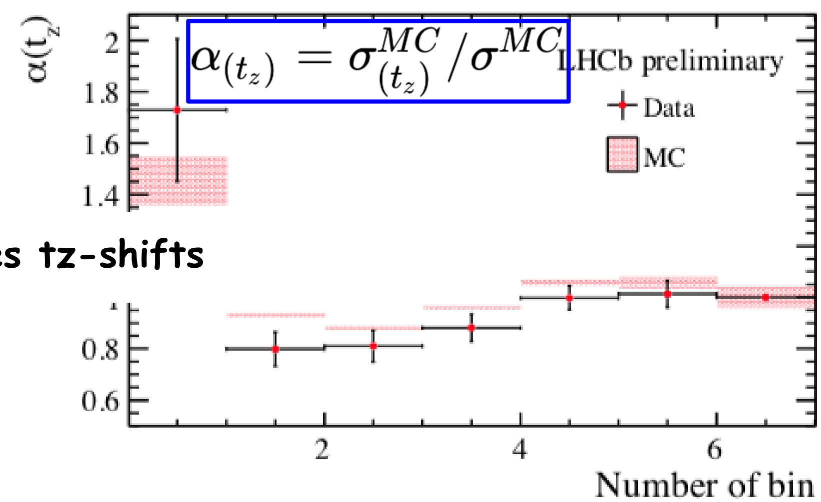
- Careful study of systematic effects
- Simultaneous fit to inv. mass fit in t_z bins, **no peaks shifts positions assumed**



Mass shift in t_z bins

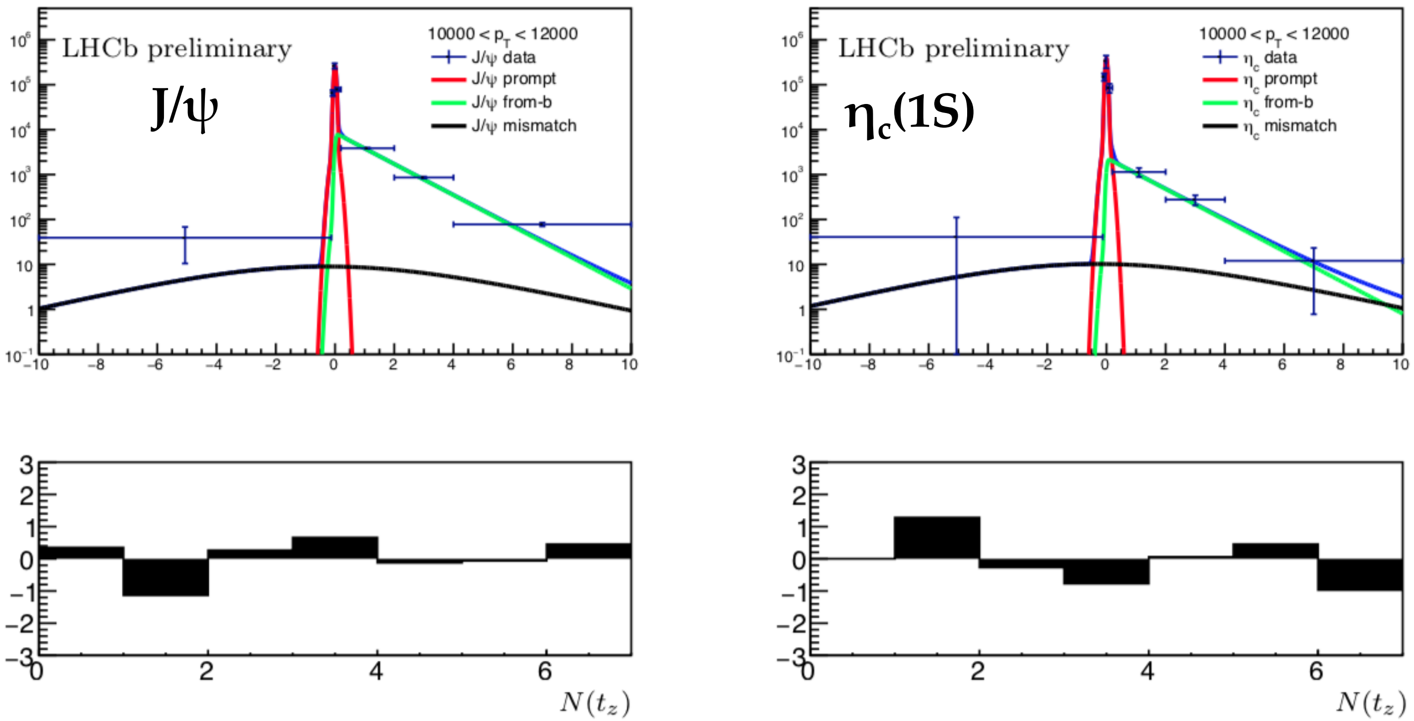
Corrections extracted using simultaneous MC fits for η_c and J/ψ, same mass shifts assumed





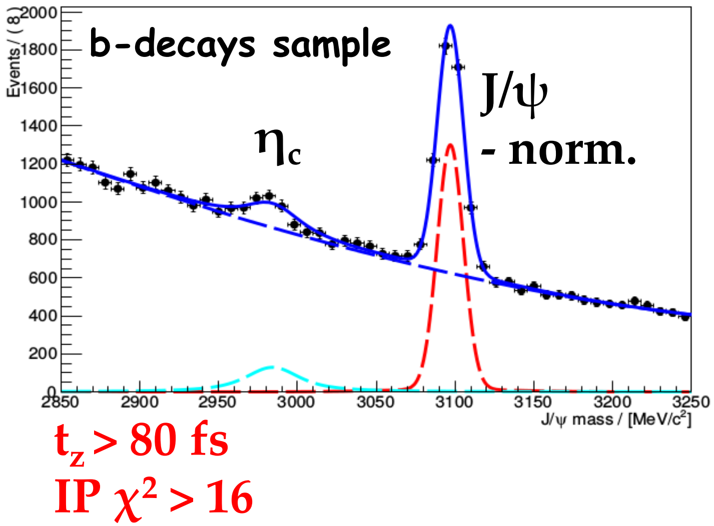
MC well describes tz-shifts

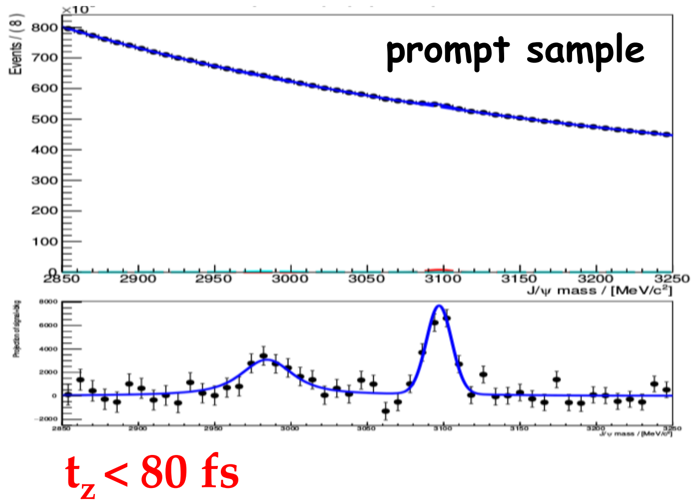
- Simultaneous t_z χ^2 fit to η_c and J/ψ yields from mass fit in pT bins



$$\mu = (-1.3 \pm 1.8) \times 10^{-3}\,\mathrm{ps},$$
$$S_n = (4.28 \pm 0.28) \times 10^{-2}\,\mathrm{ps},$$
$$\langle \tau_b \rangle = 1.28 \pm 0.02\,\mathrm{ps}.$$

- Distinguish prompt and b-decay charmonium using **selection** and fit them simultaneously in pT bins (Run I - like)





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

$$\begin{cases} n^p_{\eta_c} &= \epsilon^{P\to P}\boldsymbol{N^P_{\eta_c}} + \epsilon^{b\to P}\boldsymbol{N^b_{\eta_c}} \\ n^b_{\eta_c} &= \epsilon^{b\to b}\boldsymbol{N^b_{\eta_c}} + \epsilon^{P\to b}\boldsymbol{N^P_{\eta_c}}, \end{cases}$$

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

LHCb:

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

6.5 GeV/c < PT < 14.0 GeV/c

2.0 < y < 4.5

Yu-Feng, Hua-Sheng & Co:

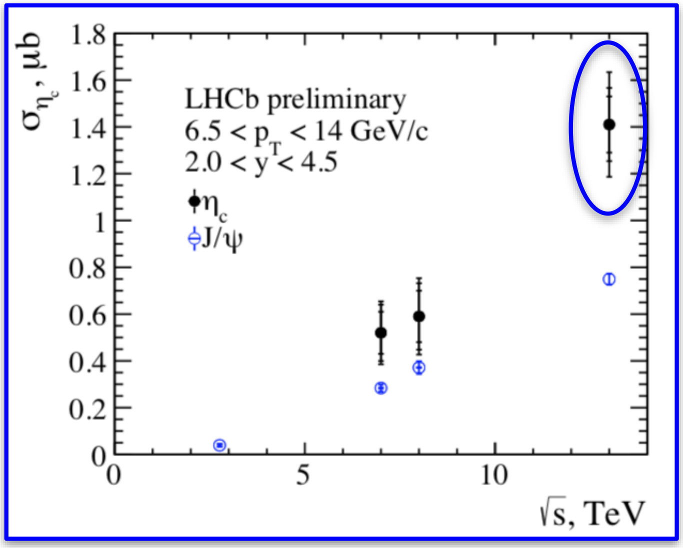
$\sigma_{\eta c}= 1.56\,^{+0.83}_{-0.49}\,{}_{scale}\,^{+0.38}_{-0.17}\,{}_{CT14NLO}$

6.5 GeV/c < PT < 14.0 GeV/c

2.0 < y < 4.5

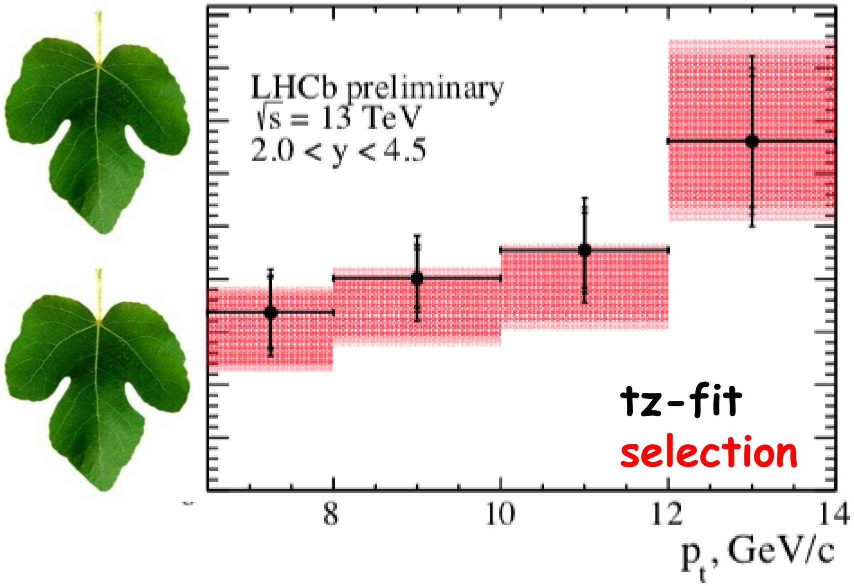
- Excellent agreement !
  Absolute x-section nicely reproduced.
  (Keeping in mind that 7 and 8 TeV data used to educate predictions)

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

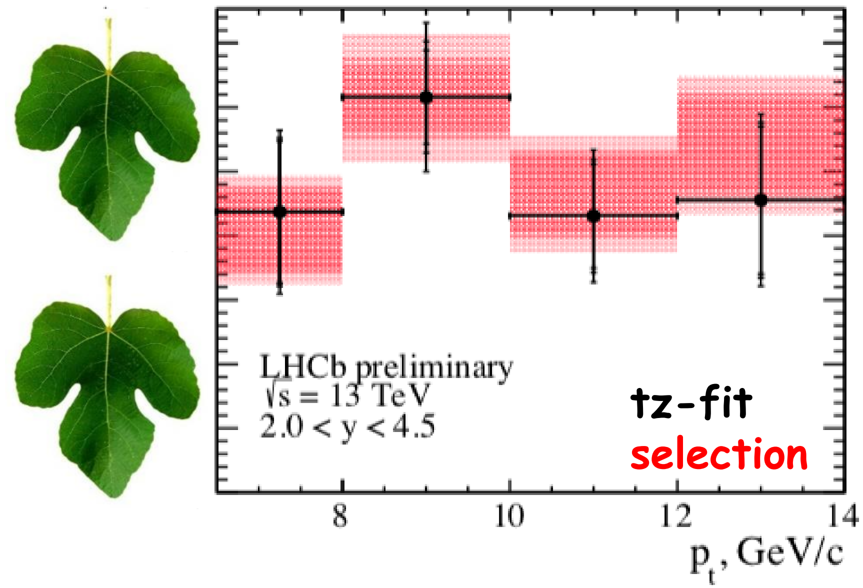


- **pT-differential** prompt production, ratio:

prompt

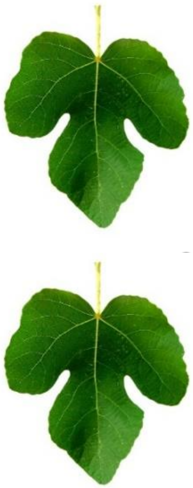


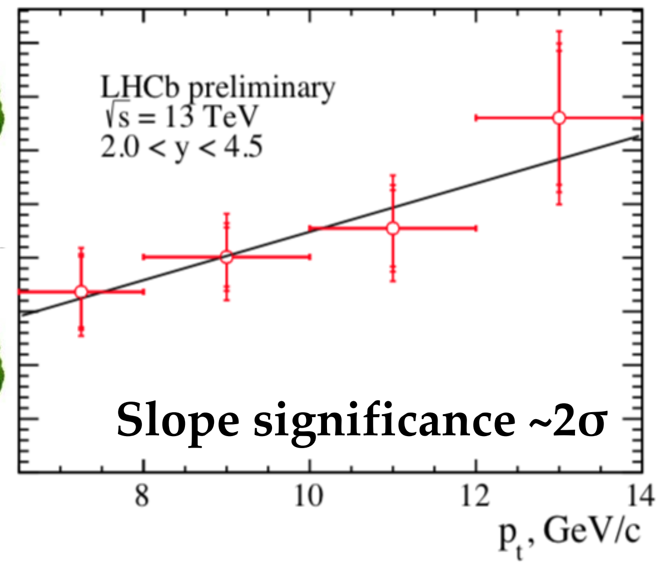
from b



- Two techniques consistent and yield similar precision

- **pT-differential** prompt production, ratio:

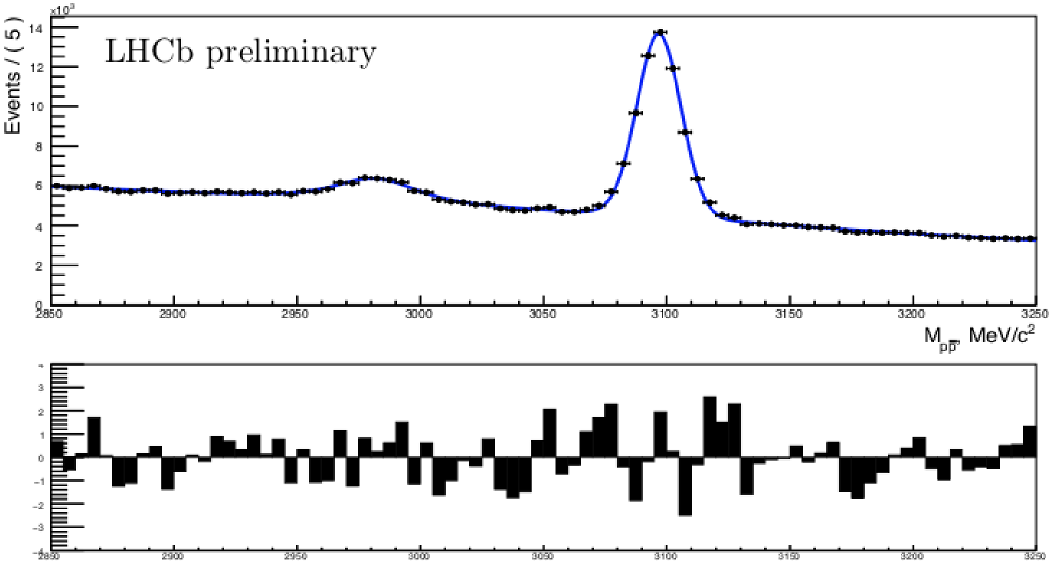




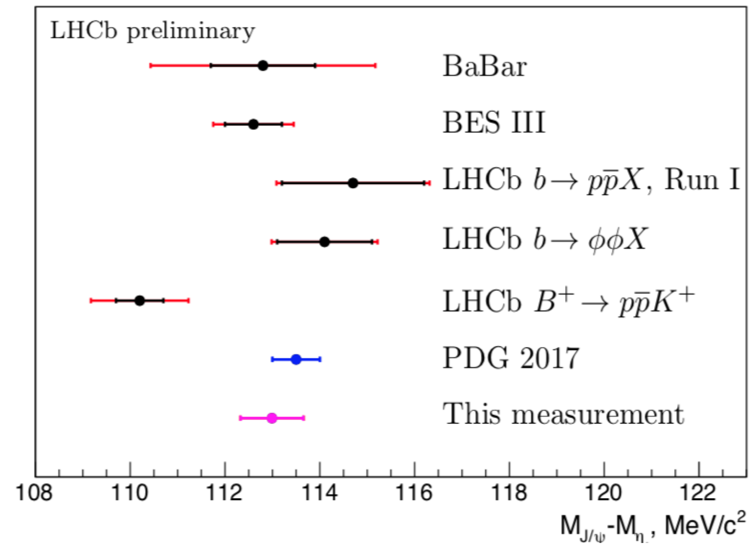
- Finally, a hint of different pT behavior for $\eta_c(1S)$ and J/ψ … who is steeper ?

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

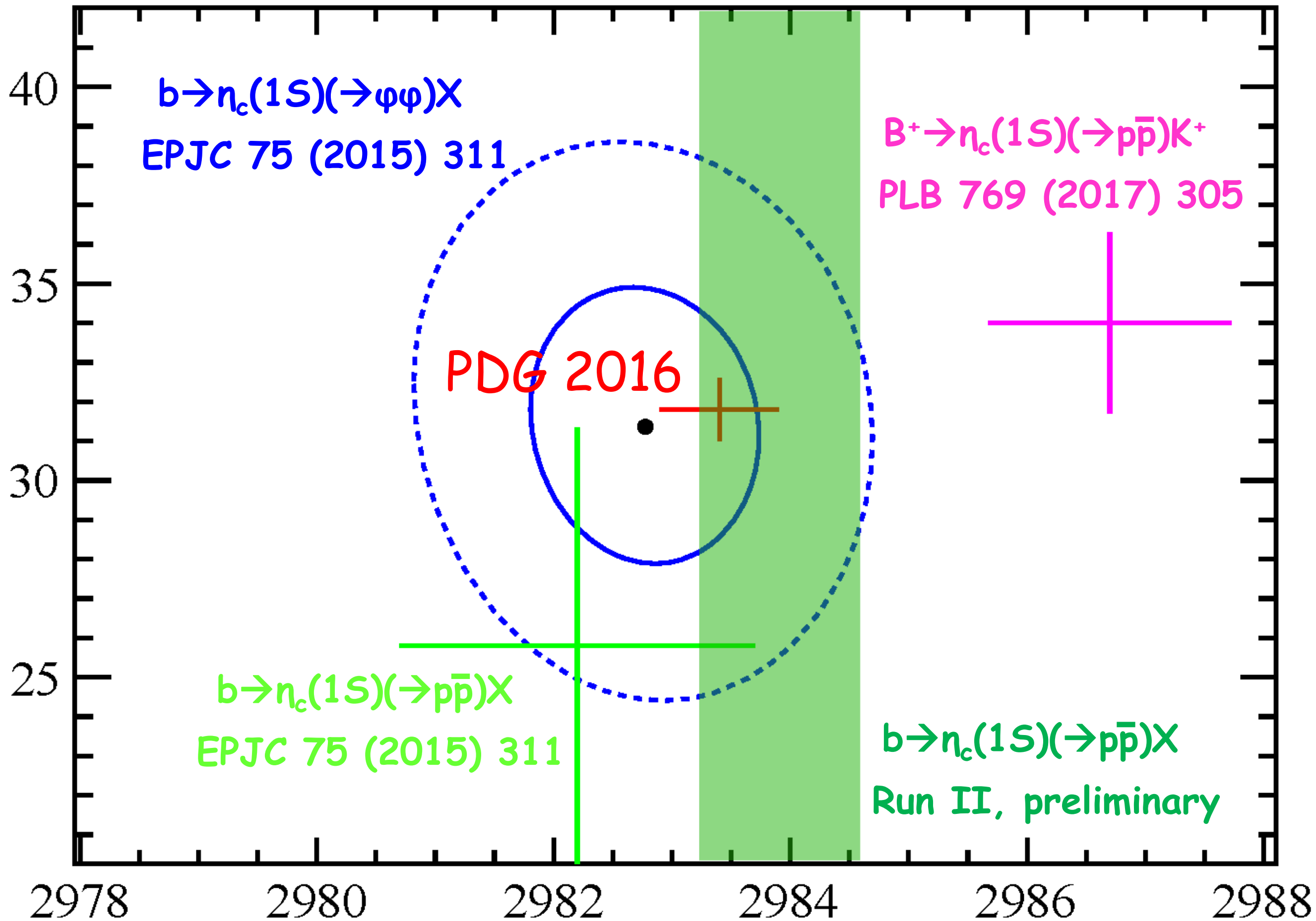
- **Mass measurement** using topological triggers



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



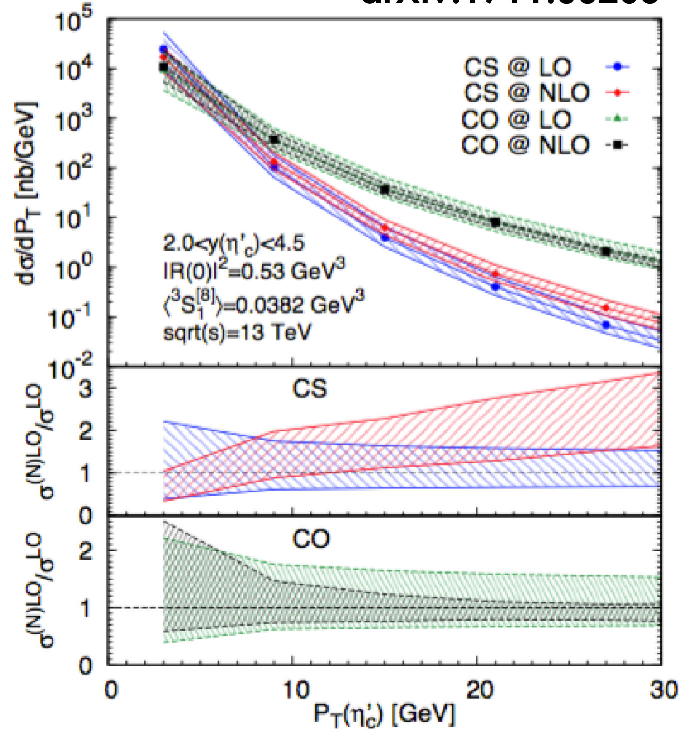
- Contour plot for $\eta_c(1S)$

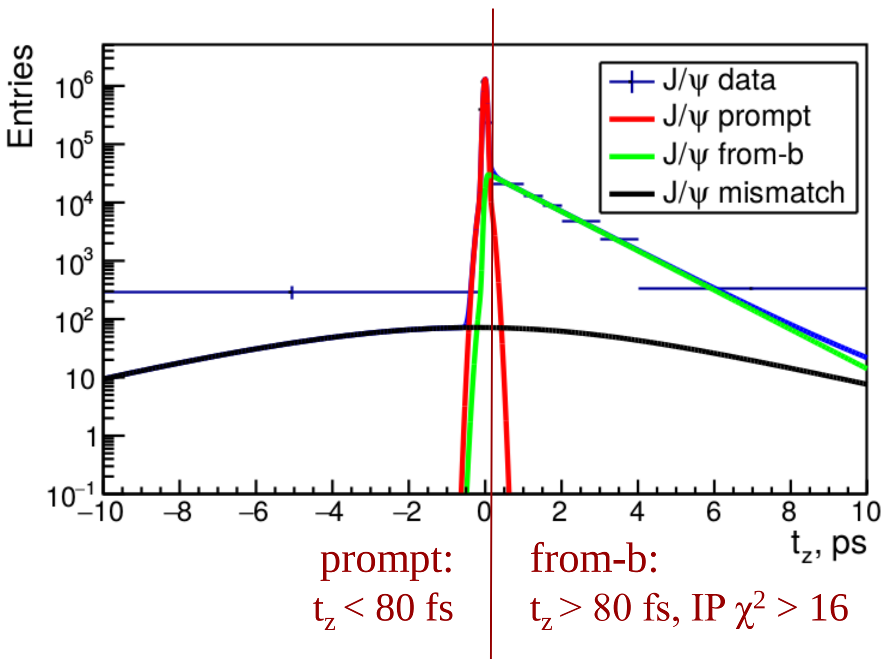


- Motivated by theory calculations
- **Dedicated LHCb trigger in 2018**

- Prompt and b-decay production distinguished via selection cuts

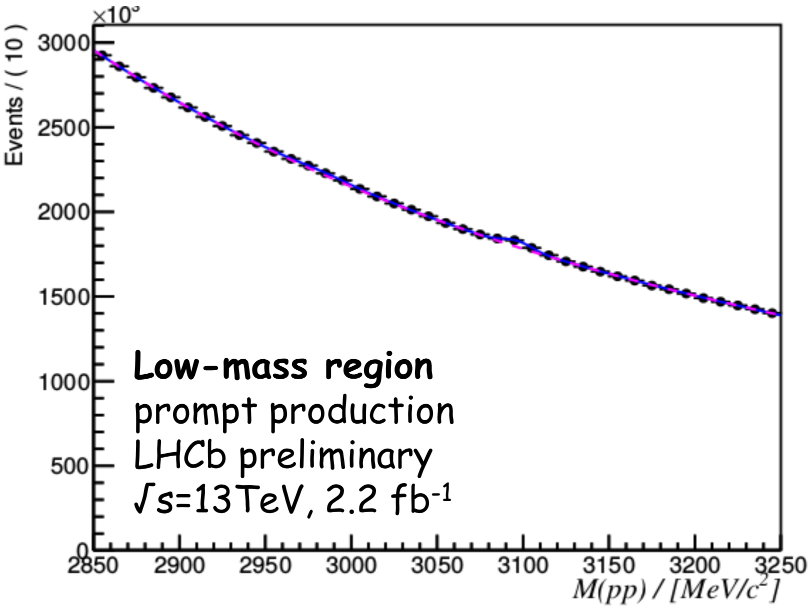
Lansberg, Shao, Zhang
arXiv:1711.00265

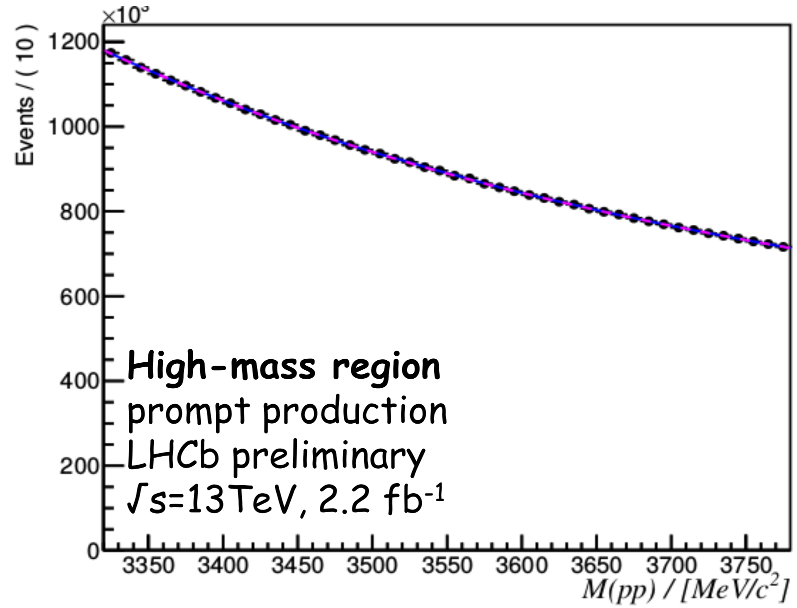


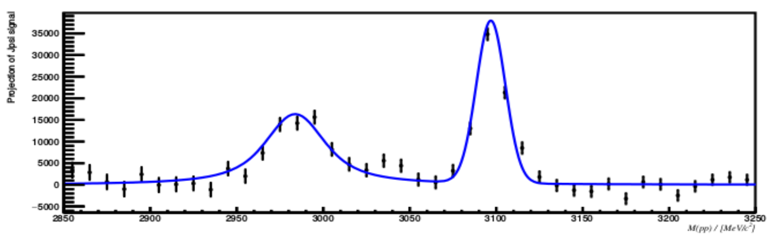


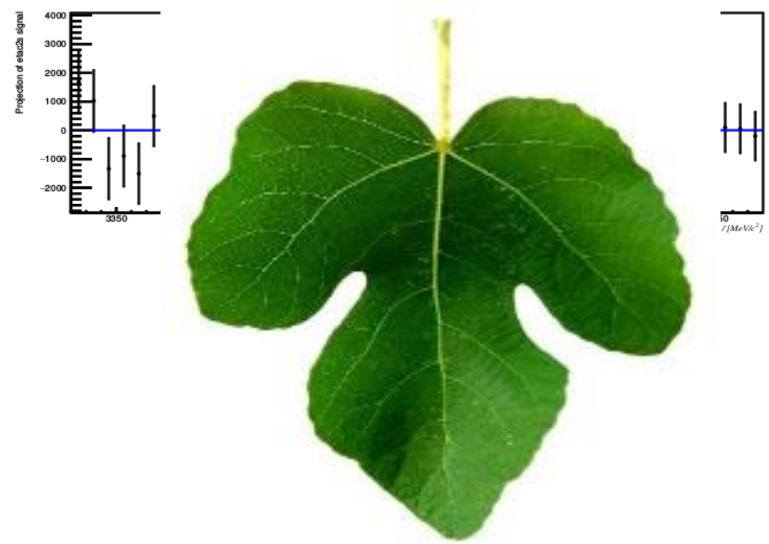
- Efficiencies and x-feeds from MC

- Simultaneous fit in two regions



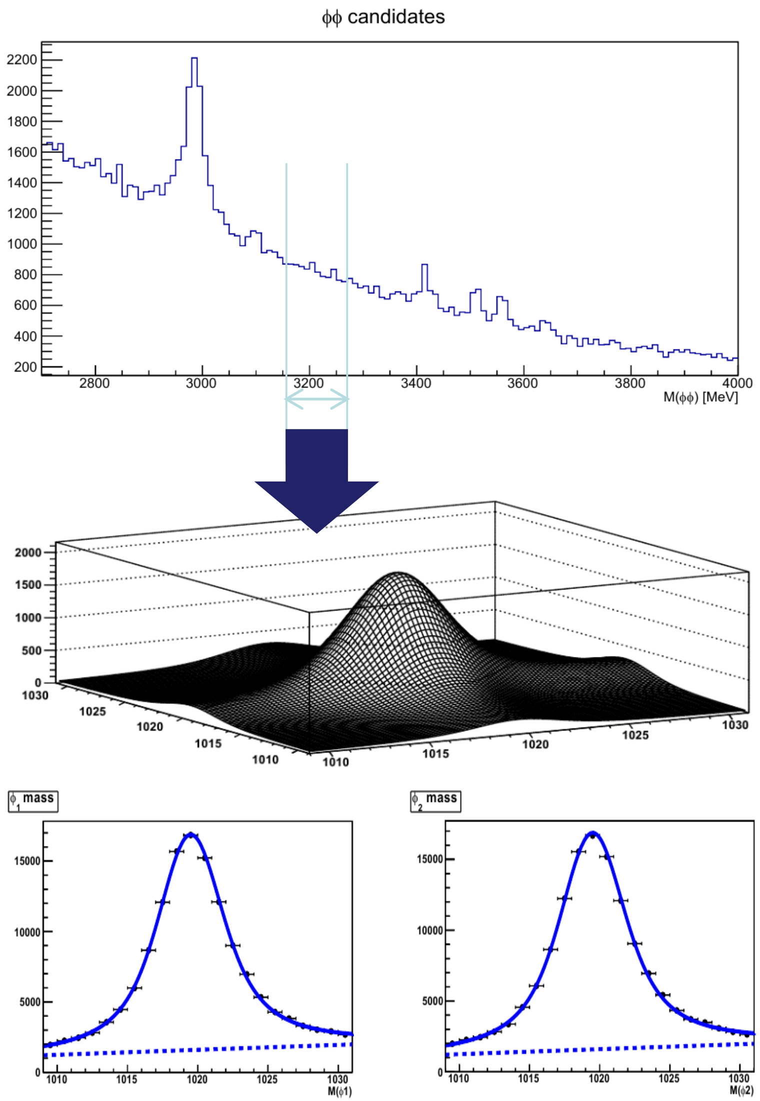






- Simultaneous fit in two regions

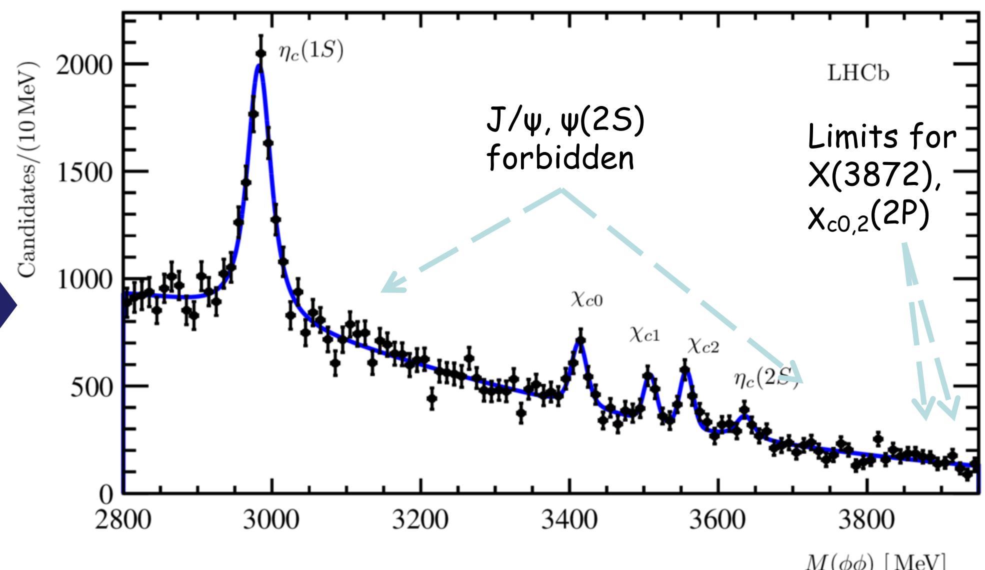
Production of χ_c and $\eta_c(2S)$ in b-decays, $\phi\phi$ final state



Excludes φKK, 4K, etc.

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

- **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 double ratios:

$$\frac{\mathcal{B}(b \to \chi_{c0}X) \times \mathcal{B}(\chi_{c0} \to \phi\phi)}{\mathcal{B}(b \to \eta_c(1S)X) \times \mathcal{B}(\eta_c(1S) \to \phi\phi)} = 0.147 \pm 0.023 \pm 0.011,$$

$$\frac{\mathcal{B}(b \to \chi_{c1}X) \times \mathcal{B}(\chi_{c1} \to \phi\phi)}{\mathcal{B}(b \to \eta_c(1S)X) \times \mathcal{B}(\eta_c(1S) \to \phi\phi)} = 0.073 \pm 0.016 \pm 0.006,$$

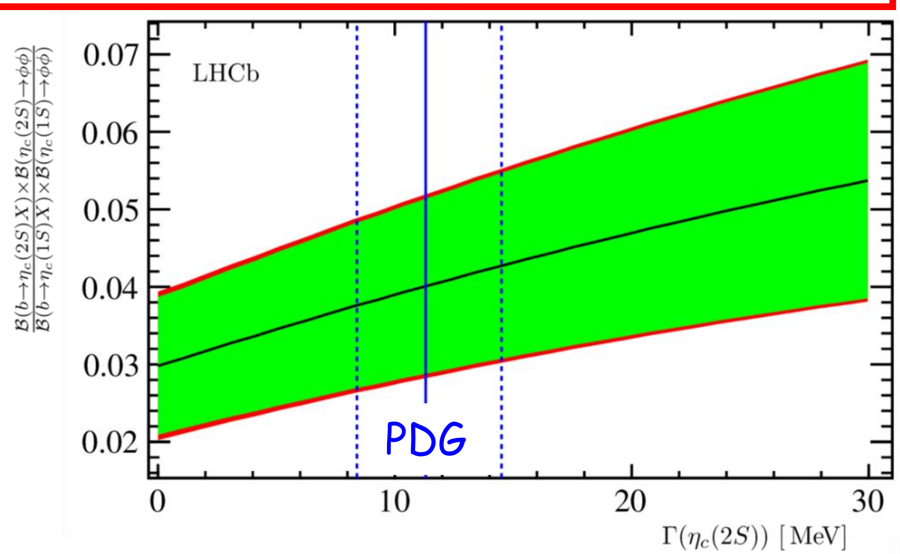
$$\frac{\mathcal{B}(b \to \chi_{c2}X) \times \mathcal{B}(\chi_{c2} \to \phi\phi)}{\mathcal{B}(b \to \eta_c(1S)X) \times \mathcal{B}(\eta_c(1S) \to \phi\phi)} = 0.081 \pm 0.013 \pm 0.005,$$

$$\frac{\mathcal{B}(b \to \chi_{c1}X) \times \mathcal{B}(\chi_{c1} \to \phi\phi)}{\mathcal{B}(b \to \chi_{c0}X) \times \mathcal{B}(\chi_{c0} \to \phi\phi)} = 0.50 \pm 0.11 \pm 0.01,$$

$$\frac{\mathcal{B}(b \to \chi_{c2}X) \times \mathcal{B}(\chi_{c2} \to \phi\phi)}{\mathcal{B}(b \to \chi_{c0}X) \times \mathcal{B}(\chi_{c0} \to \phi\phi)} = 0.56 \pm 0.10 \pm 0.01,$$

$$\frac{\mathcal{B}(b \to \eta_c(2S)X) \times \mathcal{B}(\eta_c(2S) \to \phi\phi)}{\mathcal{B}(b \to \eta_c(1S)X) \times \mathcal{B}(\eta_c(1S) \to \phi\phi)} = 0.040 \pm 0.011 \pm 0.004,$$

- Dependence on $\Gamma(\eta_c(2S))$:



$BR(\eta_c(1S) \to \phi\phi)$, a hint of the problem

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

$\Gamma(\phi\phi)/\Gamma(K\overline{K}\pi)$ Γ_7/Γ_{28}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0240±0.0026 OUR FIT					
0.044 $^{+0.012}_{-0.010}$ OUR AVERAGE					
0.055 ±0.014 ±0.005		AUBERT,B	04B	BABR	$B^{\pm} \to K^{\pm}\eta_c$
0.032 $^{+0.014}_{-0.010}$ ±0.009	7	[1] HUANG	03	BELL	$B^{\pm} \to K^{\pm}\phi\phi$

Almost 2 times difference

Use B-factories measurements performed (not radiative decays), cf. Claudia Patrignani

$$BR(\eta_c(1S) \to \phi\phi) = 3.21 \pm 0.72$$

$$\frac{\mathcal{B}(b \to \chi_{c0}X)}{\mathcal{B}(b \to \eta_c(1S)X)} = 0.615 \pm 0.095 \pm 0.047 \pm 0.149,$$

$$\frac{\mathcal{B}(b \to \chi_{c1}X)}{\mathcal{B}(b \to \eta_c(1S)X)} = 0.562 \pm 0.119 \pm 0.047 \pm 0.131,$$

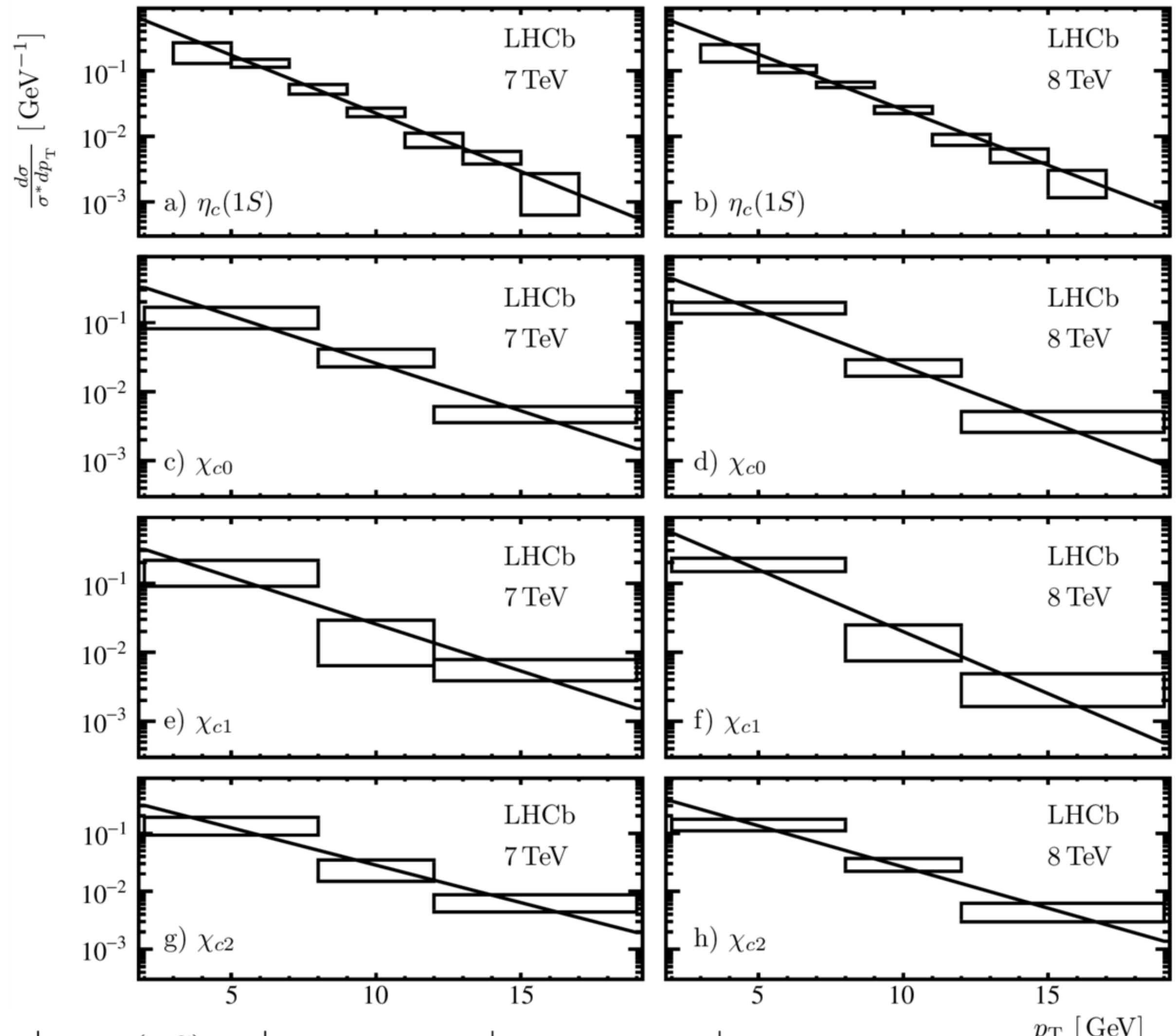
$$\frac{\mathcal{B}(b \to \chi_{c2}X)}{\mathcal{B}(b \to \eta_c(1S)X)} = 0.234 \pm 0.038 \pm 0.015 \pm 0.057,$$

	PDG $(B^{\pm}/B_0)$:	PDG $(B^{\pm}/B_0/B_{s}/\,b-baryons)$:
$\mathcal{B}(b \to \chi_{c0}X) = (3.02 \pm 0.47 \pm 0.23 \pm 0.94) \times 10^{-3}$,		-
$\mathcal{B}(b \to \chi_{c1}X) = (2.76 \pm 0.59 \pm 0.23 \pm 0.89) \times 10^{-3}$,	$(3.86 \pm 0.27) \times 10^{-3}$	$(1.4 \pm 0.4) \times 10^{-2}$
$\mathcal{B}(b \to \chi_{c2}X) = (1.15 \pm 0.20 \pm 0.07 \pm 0.36) \times 10^{-3}$,	$(1.4 \pm 0.4) \times 10^{-3}$	-

EPJC 77 (2017) 609

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

- **pT differential production in b-decays** measured for $\eta_c(1S)$ and χ_c states
- Statistical and uncorr. systematic uncertainties shown in quadrature



	$\eta_c(1S)$	χ_{c0}	χ_{c1}	χ_{c2}
$\sqrt{s} = 7$ TeV	0.41 ± 0.02	0.32 ± 0.04	0.31 ± 0.06	0.30 ± 0.05
$\sqrt{s} = 8$ TeV	0.39 ± 0.02	0.37 ± 0.04	0.41 ± 0.06	0.33 ± 0.04

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

- **Relative yields with respect to resonances with similar quantum numbers**
- Proposed by Valery 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
√s = 7 and 8 TeV, ∫Ldt ~ 3 fb⁻¹

$$BR\left(B_s^0 \to \phi\phi\right) = \frac{N_{B_s^0}}{N_{\eta_c}} \times \frac{\varepsilon_{\eta_c}}{\varepsilon_{B_S^0}} \times$$

$$\times \frac{BR(b \to \eta_c X) \cdot BR(\eta_c \to p\bar{p})}{BR(b \to J/\psi\, X) \cdot BR(J/\psi \to p\bar{p})} \times$$

$$\times \frac{BR(\eta_c \to \phi\phi)}{BR(\eta_c \to p\bar{p})} \times BR(b \to J/\psi\, X) \times BR(J/\psi \to p\bar{p}) \,/ BR(\bar{b} \to B_s^0)$$

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

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

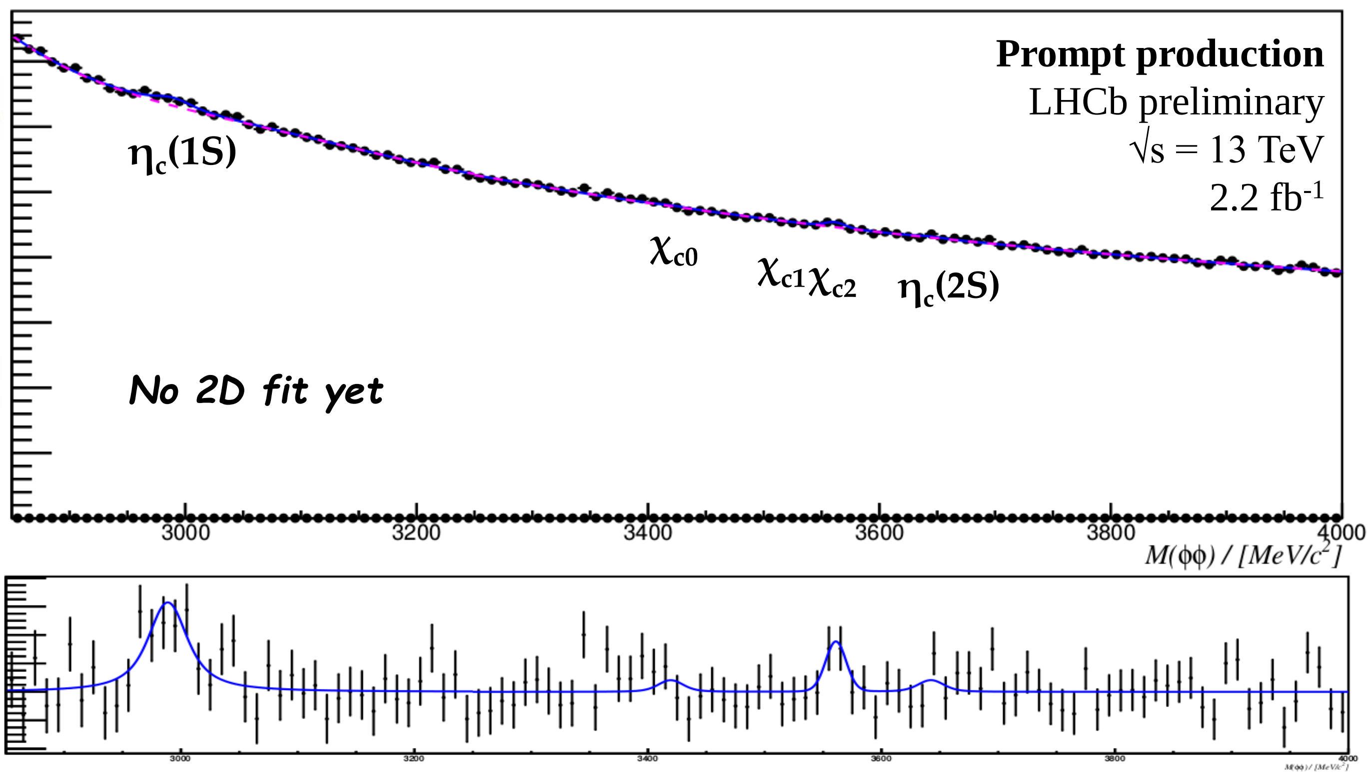
$$\frac{\mathcal{B}(\eta_c(1S) \to \phi\phi)}{\mathcal{B}(\eta_c(1S) \to p\bar{p})} = 1.79 \pm 0.14 \pm 0.09 \pm 0.10 \pm 0.03 \pm 0.29$$

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**

- What is next ?

- Update the analysis using 13 TeV data (Run II) → improved precision
- Use charmonia decays to φφ for studying of hadroproduction



(Over-) 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:

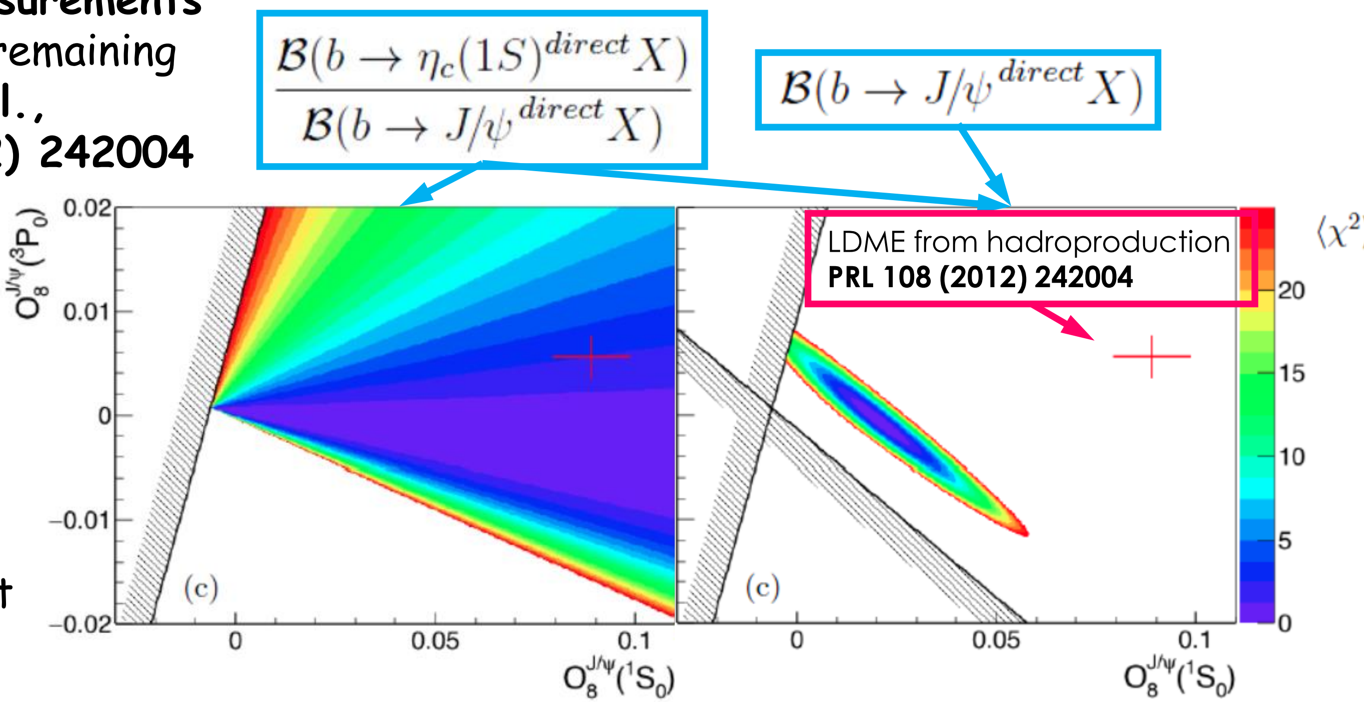
$$\langle O_1^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_1^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_8^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^3S_1)\rangle = \langle O_8^{J/\psi}(^1S_0)\rangle,$$
$$\langle O_8^{\eta_c}(^1P_1)\rangle = 3\langle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

- 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**

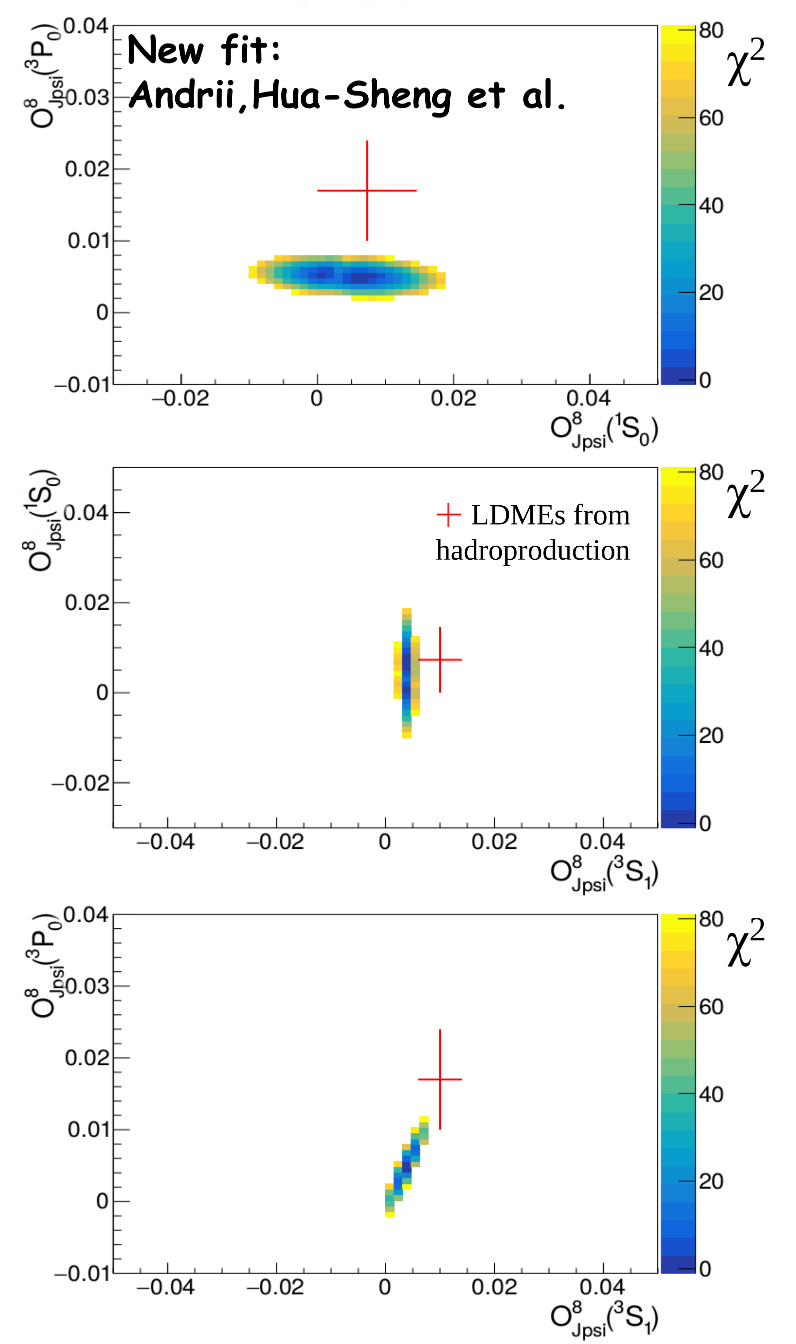
$$\langle O_8^{J/\psi}(^3S_1)\rangle = 0.003\,\mathrm{GeV}^3$$
$$\langle O_8^{J/\psi}(^3S_1)\rangle = 1.16\,\mathrm{GeV}^3$$

- Two independent measurements (constraints) important



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**
- $\langle O(^1S_0)\rangle$ is fixed at 1.16 GeV^3
- Sequentially fix other LDMEs according to theoretical prediction
- **Red points** from **PRL 114 (2015) 092005**
- Understanding of theoretical uncertainties crucial to make a comparison, plots with included theory uncertainties →



Simultaneous study of χ_c production in inclusive b-decays

Usachov, Kou, SB, LAL-17-051

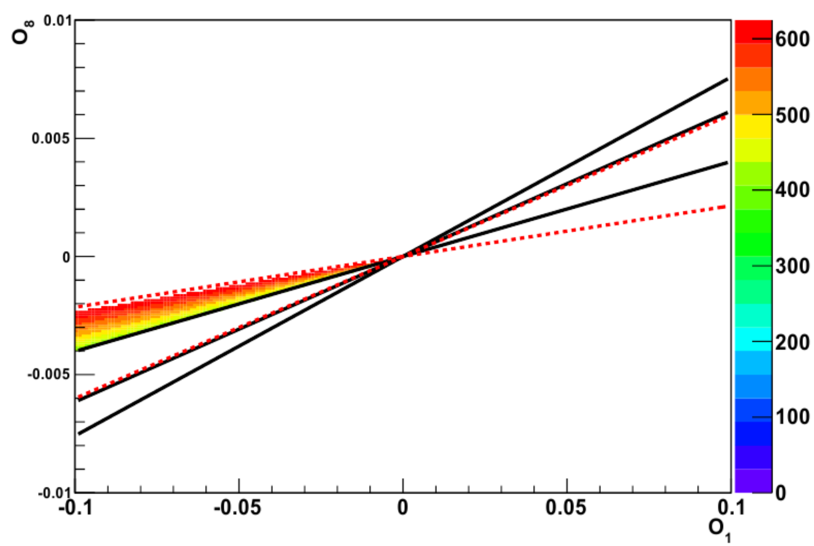
- From **EPJC 77 (2017) 609** and **Chin. Phys. C40 (2016) 100001**:

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

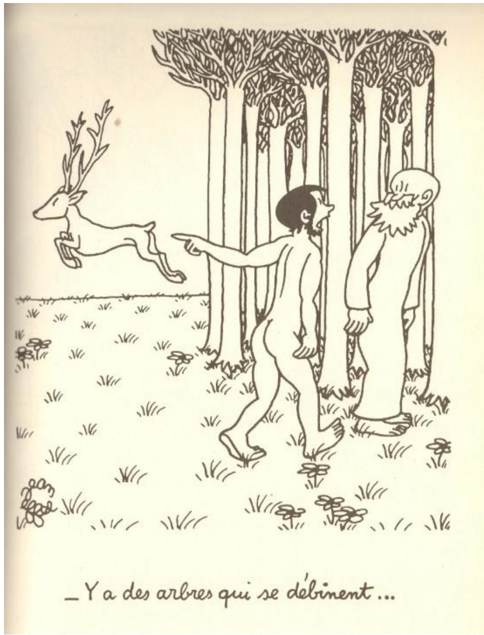
- Relation between LDME from HQSS:

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

- Branching fractions calculated in **Beneke, Maltoni, Rothstein, PRD 59 (1999) 054003**
- **Fit two LDME to three measurements**
- Important to revisit theory calculations



- More precision, further calculations and new ideas are needed.



- 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**.

Other studies of charmonia production

In case I have time … otherwise goto slide 55.

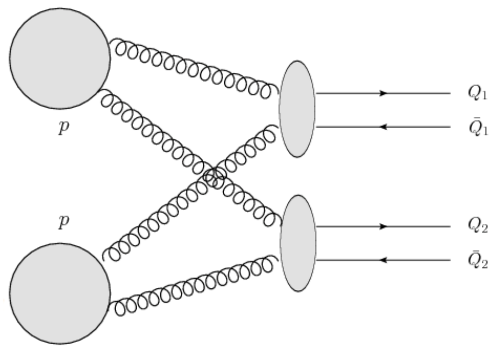
Associated production

Double J/ψ production at $\sqrt{s}$=13 TeV

JHEP 1706 (2017) 047
$\sqrt{s}$ = 13 TeV, $\int Ldt \sim 279\ pb^{-1}$

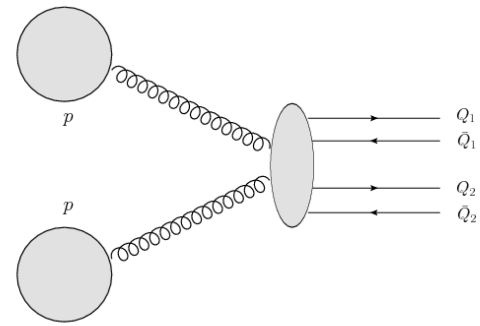
- Production via **Double Parton Scattering** (DPS) or **Single Parton Scattering** (SPS)
- **DPS**: two independent hard scatters that are assumed to factorize
- **SPS**: gluon splitting expected to dominate $c\bar{c}$ production

DPS

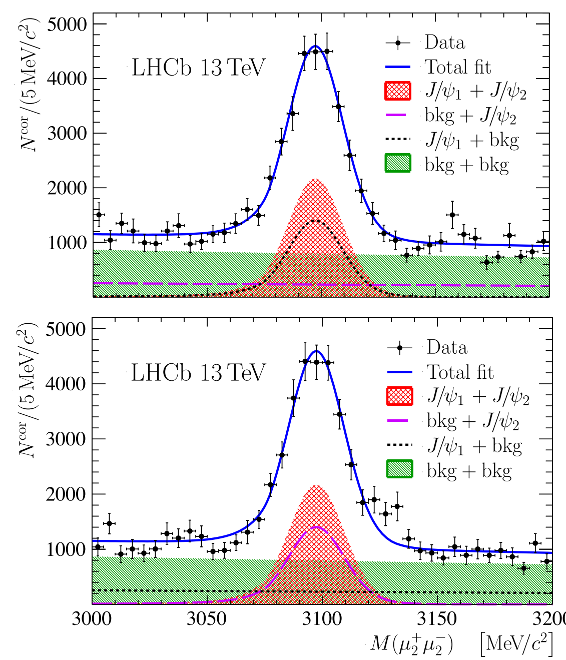


$$\sigma_{\mathrm{DPS}}\left(J/\psi\, J/\psi\right) = \frac{1}{2}\frac{\sigma\left(J/\psi\right)^2}{\sigma_{\mathrm{eff}}}$$

SPS



- DPS provides important information on gluon correlations and parton p_T-distribution

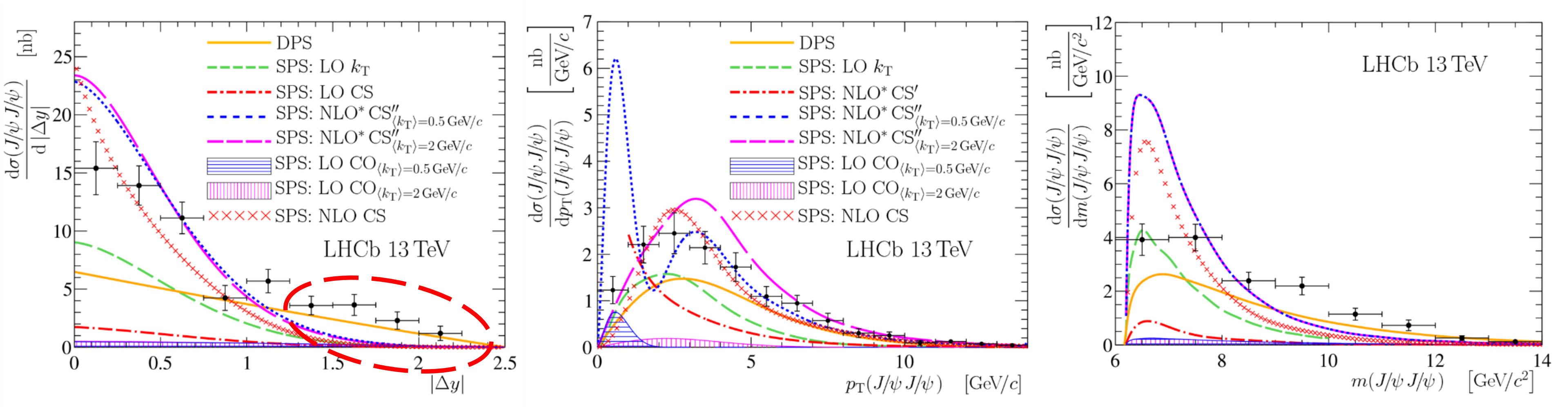


- Each J/ψ in the fiducial volume: $p_T < 10$ GeV/c, $2.0 < y < 4.5$
- Assumed no J/ψ polarization
- **The J/ψ pair production cross-section**

$$\sigma(J/\psi\, J/\psi) = 15.2 \pm 1.0\,(\mathrm{stat}) \pm 0.9\,(\mathrm{syst})\ \mathrm{nb}$$

JHEP 1706 (2017) 047
$\sqrt{s}$ = 13 TeV, $\int$Ldt ~ 279 pb^{-1}

- **Differential production cross-section** in bins of kinematical variables



- **Evidence for DPS at high |Δy| region** — **Kom, Kulesza, Stirling, PRL 107 (2011) 082002**
- Fit of kinematical distributions to extract DPS fraction and σ_{eff}
- Agreement between fits of |Δy|, $p_T(J/\psi J/\psi)$, $y(J/\psi J/\psi)$, $m(J/\psi J/\psi)$
- Using various SPS descriptions, σ_{eff} ~ 10-12 mb

- σ_{eff} is often compared across different energies, different particles, different rapidities …

PRL 118 (2017) 192001
$\sqrt{s}$ = 13 TeV, $\int Ldt \sim 1.4\ fb^{-1}$

- J/ψ produced in direct **parton scattering** or through **parton showering**
- Significant J/ψ production in showers can explain lack of observed polarization

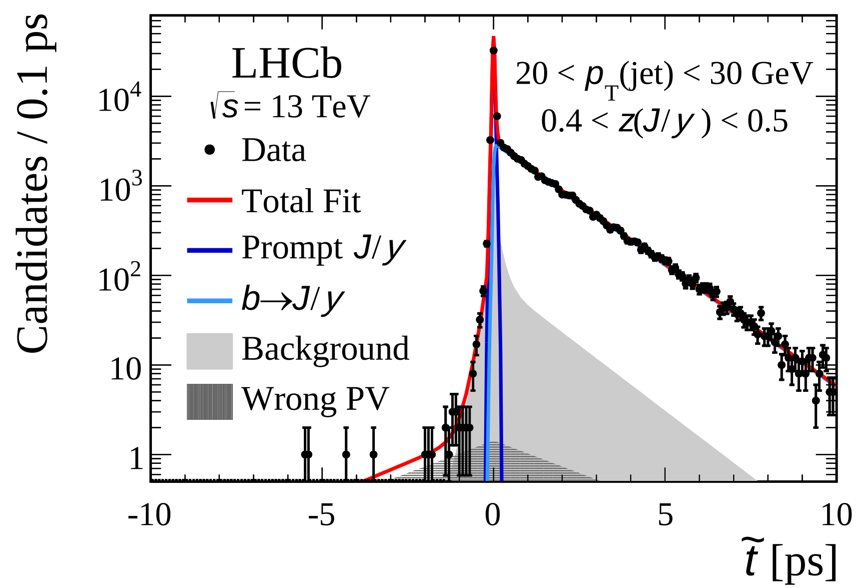
- Anti-k_T algorithm
- **Fiducial region**
  - Jets: p_T > 20 GeV/c, 2.5 < η < 4.0
  - J/ψ: 2.0 < η < 4.5

- Fraction of the jet transverse momentum carried by J/ψ:

$$z(J/\psi) = p_T\,(J/\psi)\ /\ p_T\,(\text{jet})$$

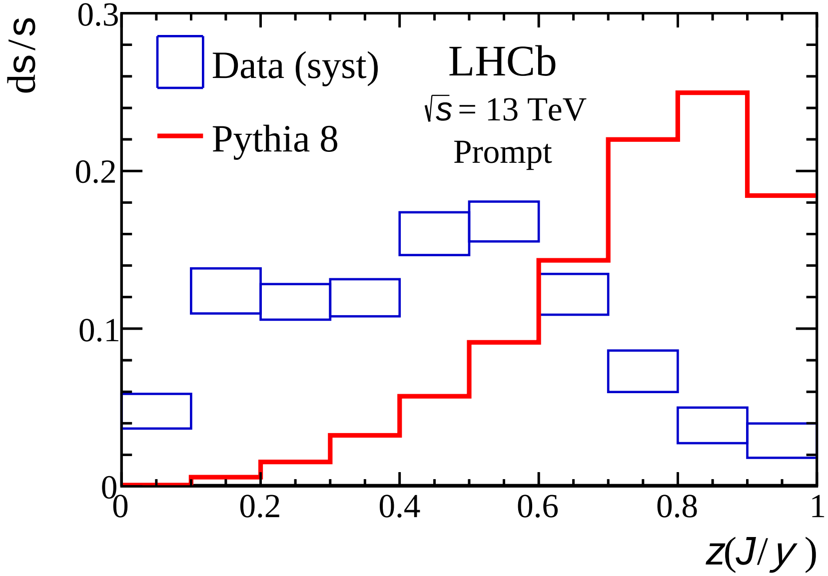
- Separate prompt J/ψ and J/ψ from b-decays using pseuso-lifetime:

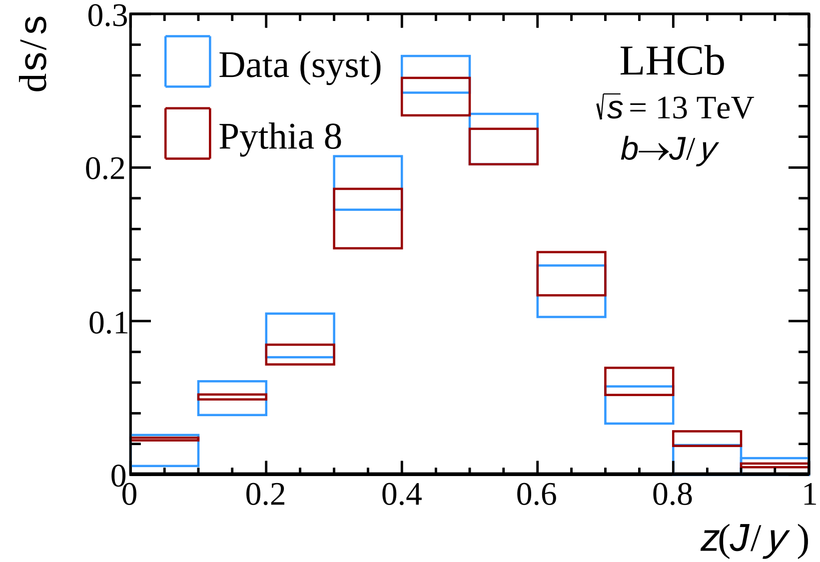
$$\tilde{t} \equiv \lambda\, m(J/\psi)/p_{\rm L}(J/\psi)$$



- Fit in bins of $z(J/\psi)$
- J/ψ yields corrected for detection efficiency by applying per-candidate weights (no knowledge of J/ψ polarization required)

PRL 118 (2017) 192001
$\sqrt{s}$ = 13 TeV, $\int Ldt$ ~ 1.4 fb^{-1}

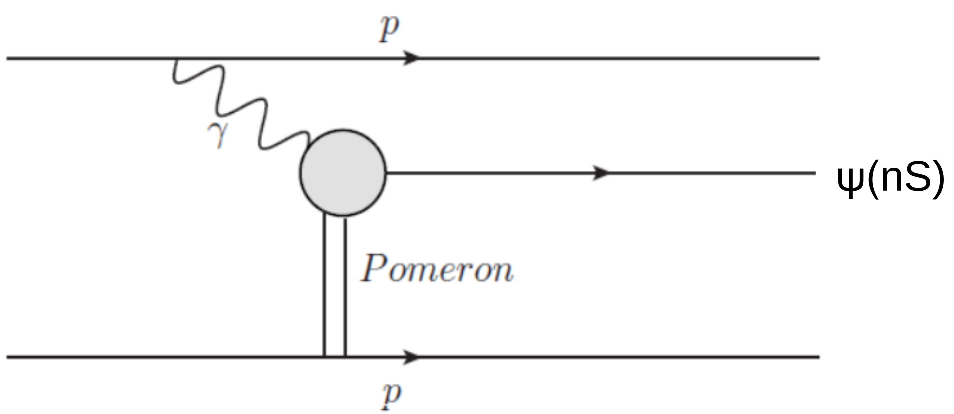




- $z(J/\psi)$ distribution for J/ψ produced in b-decays is consistent with the Pythia 8 prediction
- **Prompt J/ψ are less isolated than the prediction of Pythia based on fixed-order NRQCD**
- Indication for significant contribution from parton showering

Bain et al., JHEP 1606 (2016) 121
Bain et al., arXiv:1702.02947

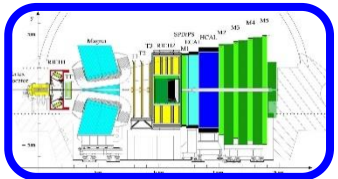
- CEP: **QCD tests with clean theoretical interpretation**
- Only **CS production**
- Sensitivity with cross-sections in the LHCb coverage down to x ~ 1.5 x 10^{-5}

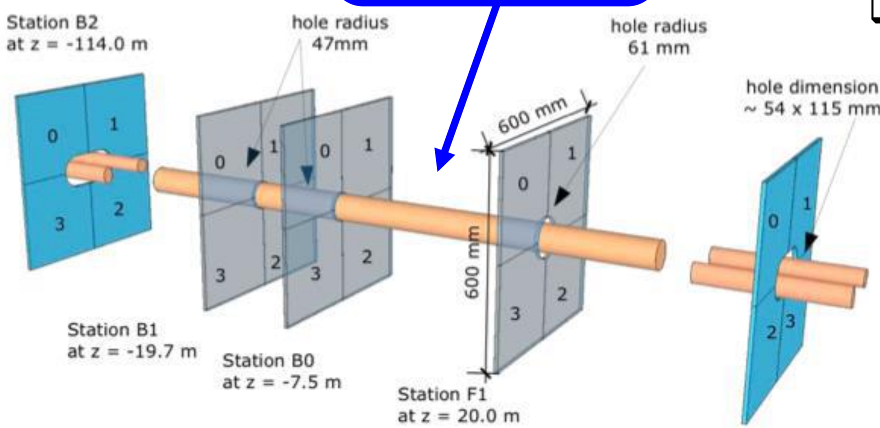


Central Exclusive Production of J/ψ and ψ(2S)

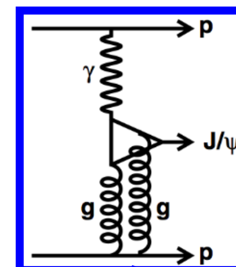
- **Herschel detector** increases rapidity gap in forward region $-8.0 < \eta < -1.5$, $5.0 < \eta < 8.0$

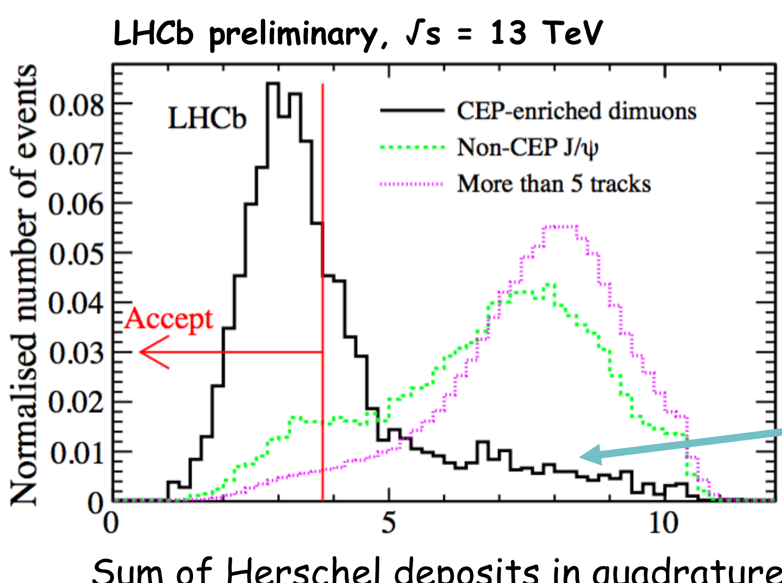
LHCb-CONF-2016-007
$\sqrt{s}$=13 TeV, $\int Ldt \sim 0.2\ fb^{-1}$

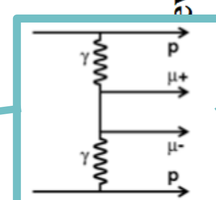


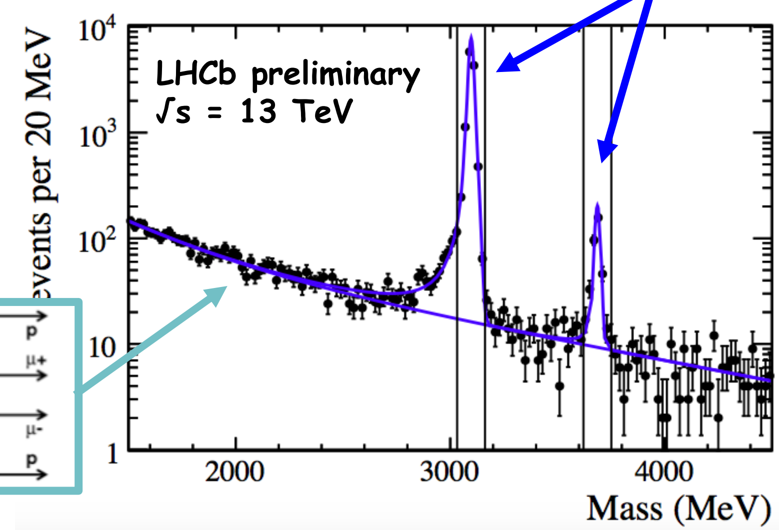


- Dedicated CEP trigger
- **Exclusivity**: precisely two forward muons; no backward tracks; no activity in SPD (< 10 hits). Quantify with p_T spectrum.









LHCb-CONF-2016-007

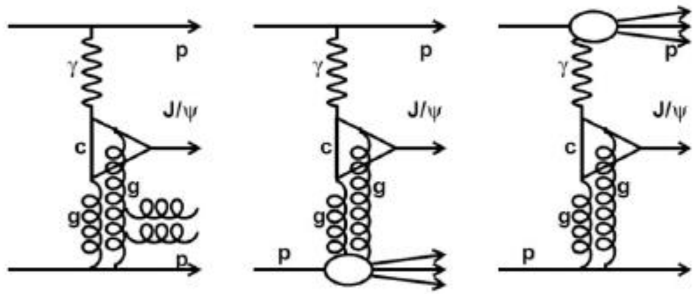
$\sqrt{s}$=13 TeV, $\int$Ldt ~0.2 fb^{-1}

Signal shape

- Estimated from Superchic using exp(- b p_T^2)
- Slope b estimated from HERA data.
  Agreement to the fit of LHCb data

Inelastic backgrounds

- One/two protons dissociate(s) or additional gluon radiations.
  Extra particles are undetected.
- P_T shape estimated from data, cross checked with PYTHIA, LPAIR

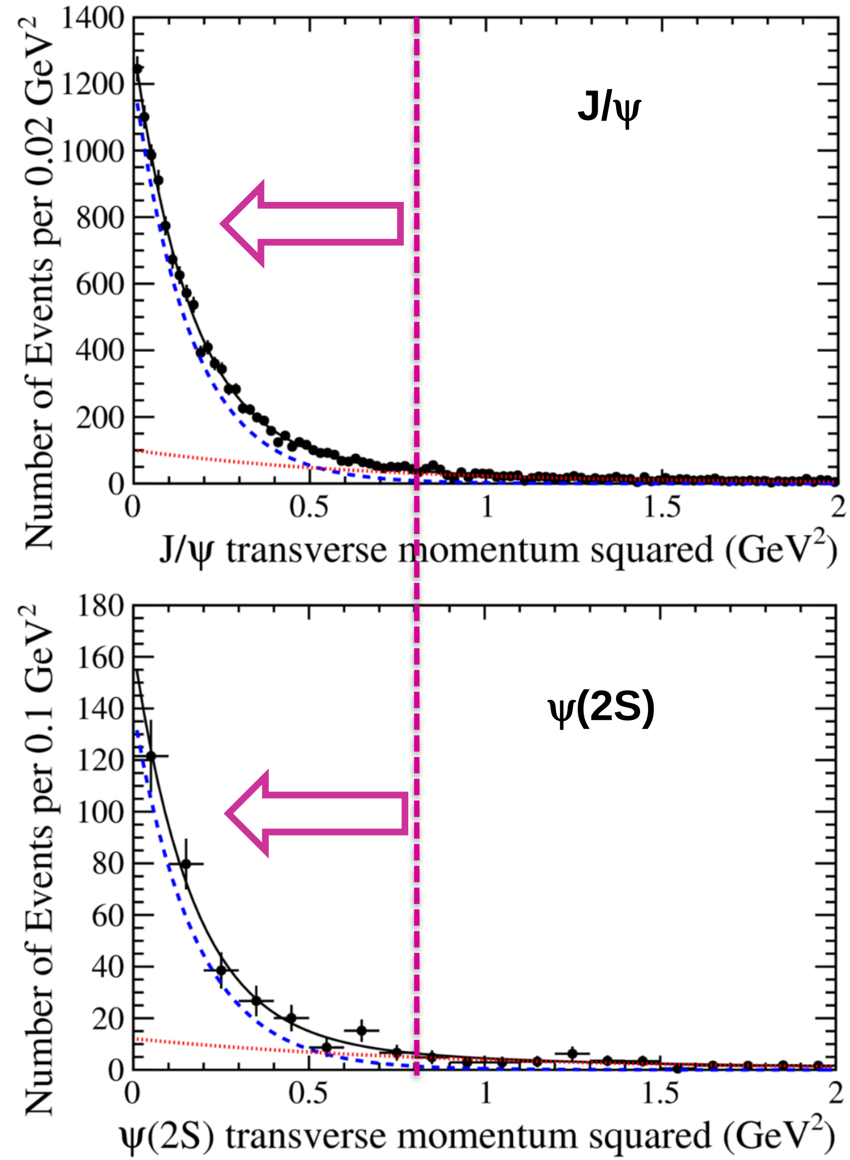


Feed-down

$\psi(2S) \rightarrow J/\psi\pi\pi$: $2.5 \pm 0.2\%$

$\chi_c \rightarrow J/\psi\gamma$ $7.6 \pm 0.9\%$

$X(3872) \rightarrow \psi(2S)\gamma$ $2.0 \pm 2.0\%$

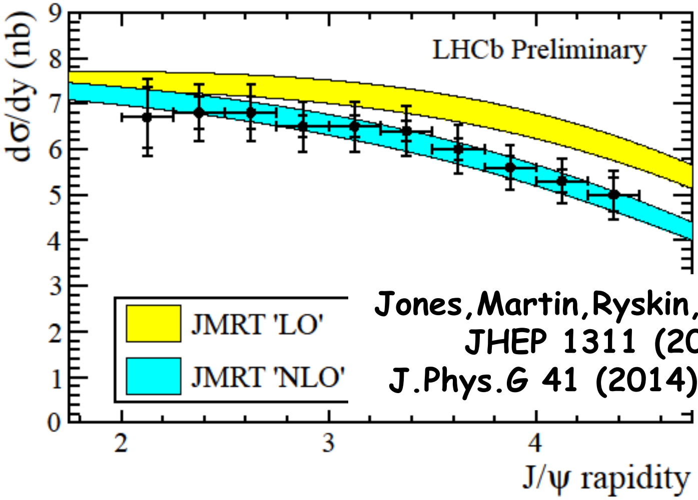


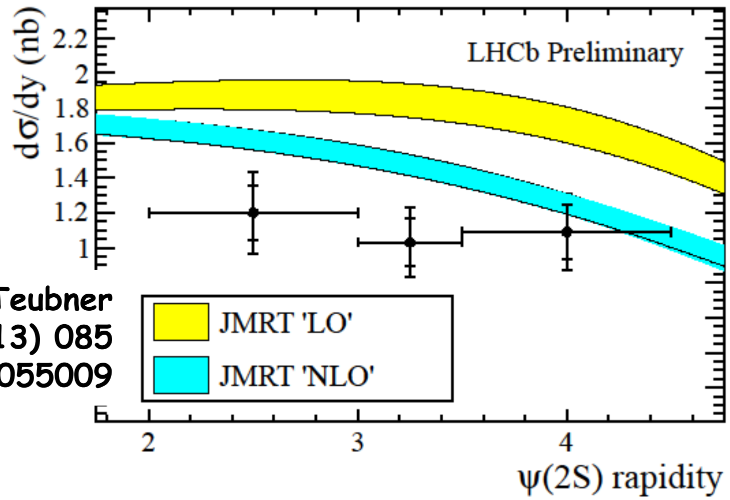
J/ψ and ψ(2S) differential cross-sections

- Differential cross-section compared to theory predictions

LHCb-CONF-2016-007

$\sqrt{s}$=13 TeV, $\int L dt$ ~0.2 fb^{-1}





Jones, Martin, Ryskin, Teubner
JHEP 1311 (2013) 085
J.Phys.G 41 (2014) 055009

- Integrated cross-sections times branching fractions

$$\sigma_{J/\psi\to\mu^+\mu^-}(2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5) = 407 \pm 8 \pm 24 \pm 16 \text{ pb}$$
$$\sigma_{\psi(2S)\to\mu^+\mu^-}(2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5) = 9.4 \pm 0.9 \pm 0.6 \pm 0.4 \text{ pb}$$

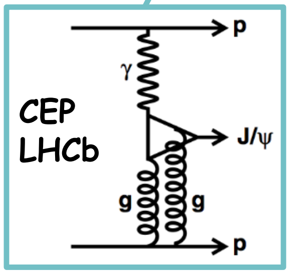
- **Good agreement with NLO predictions**
- Confirms a hint of NLO importance from the analysis at 7 TeV

Photo-production cross-section

- The cross-section for the CEP of vector mesons in pp collisions is related to the **photo-production cross-section**:

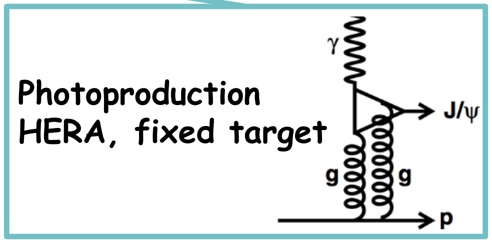
LHCb-CONF-2016-007
$\sqrt{s}$=13 TeV, $\int Ldt$ ~0.2 fb^{-1}

$$\sigma_{pp\to p\psi p} = r(W_+)k_+\frac{dn}{dk_+}\sigma_{\gamma p\to\psi p}(W_+) + r(W_-)k_-\frac{dn}{dk_-}\sigma_{\gamma p\to\psi p}(W_-)$$



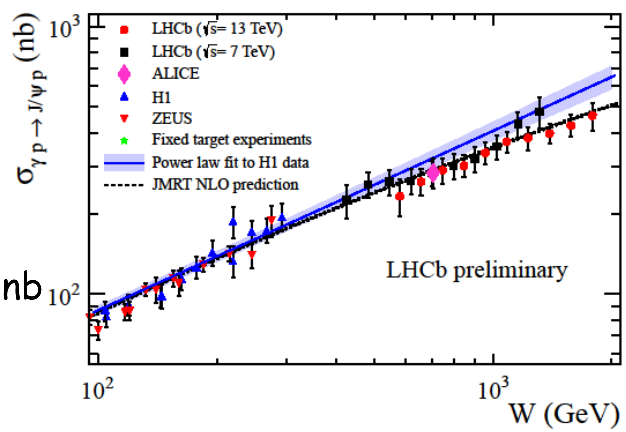
Gap survival

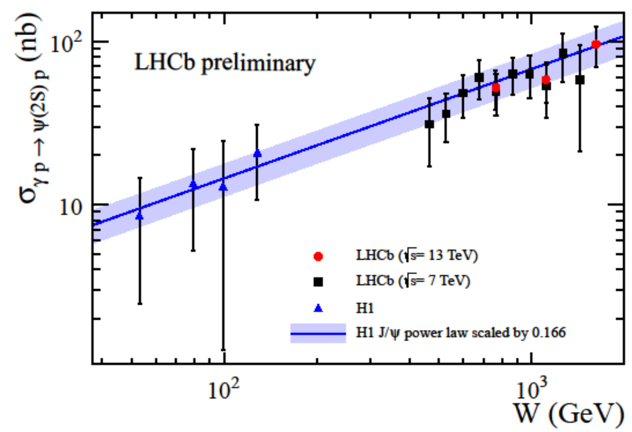
Photon flux



Jones, Martin, Ryskin, Teubner, JHEP 1311 (2013) 085, J.Phys.G 41 (2014) 055009, and update

- Compilation of photo-production cross-section measurements
- H1 measured power-law: $\sigma_{\gamma p\to J/\psi p}(W) = 81(W/90\ \text{GeV})^{0.67}$ nb





- J/ψ photo-production cross-section: **deviation from a pure power-law extrapolation of HERA data; agreement to theory prediction**

- **Impressive progress** in both theory and experiment … and **great ambitions**, which are far from being achieved.
- **Comprehensive model** describing charmonium hadroproduction and production in b-decays, in the entire pT and rapidity ranges, at all available energies, still to be developed and tested on variety of available charmonia.

- This requires
  - From **theory**: calculations to higher orders – both for hadroproduction and for b-decays, and new bright ideas, …
  - From **experiment**: more dedication to key measurements (e.g. trigger, but also MC), precision measurements of « service » branching fractions, …

- **Do we want to know the entire answer now ?**