Heavy flavour production measurements at LHCb

Sergey Barsuk, LAL Orsay
on behalf of the LHCb collaboration

Selected recent LHCb results on

- ❑ **Quarkonia and open flavour production**
- ❑ **Associated production**
- ❑ **Production in jets**
- ❑ **Central Exclusive Production**

❑ Other LHCb results presented here:

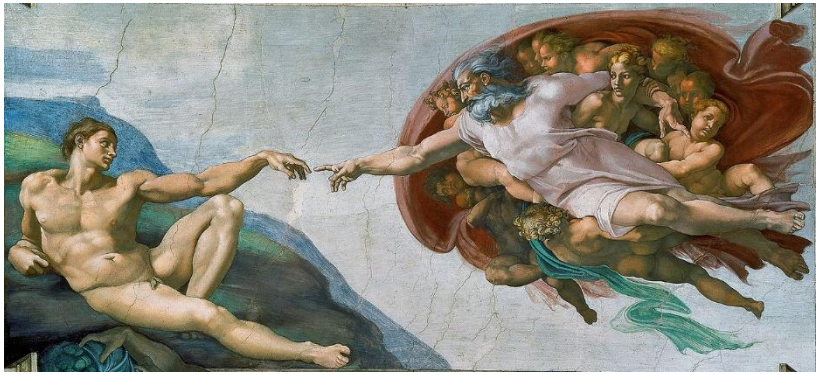
✓*Experimental review of rare B decays, Lars Eklund*
✓*CP violation in b hadrons (LHCb), Adlène Hicheur*
✓*Lepton-flavour universality tests (LHCb), Anna Lupato*
✓*Mixing and CPV in charm hadrons (LHCb), Wojciech Krzemien*
✓*Heavy ion physics (LHCb), Jiayin Sun*
✓*Heavy flavour spectroscopy (LHCb), Ao Xu*
✓*EW production (LHCb), Hang Yin*

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

Heavy flavour production

❑ **Powerful QCD tests**, instead of using QCD to estimate observables, use production measurements to qualify QCD

Michelangelo: 创建



Botticelli: 分娩

❑ New theory developments confronted to new experimental results. Impressive progress in both domains

❑ First clash to describe **« J/ψ production puzzle »**

❑ **« J/ψ production AND polarization puzzle »** boosted the progress

❑ Recently with the $\eta_c(1S)$ production measurement by LHCb more challenging
« J/ψ production AND polarization AND $\eta_c(1S)$ production puzzle »

❑ **More precision** in conventional studies and **new sources of input**: associated production, isolation, production in pPb and PbPb collisions, …

❑ Comprehensive model of **HF production** still missing

Heavy flavour production

- Two scales of production:

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

- **Factorization**:

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

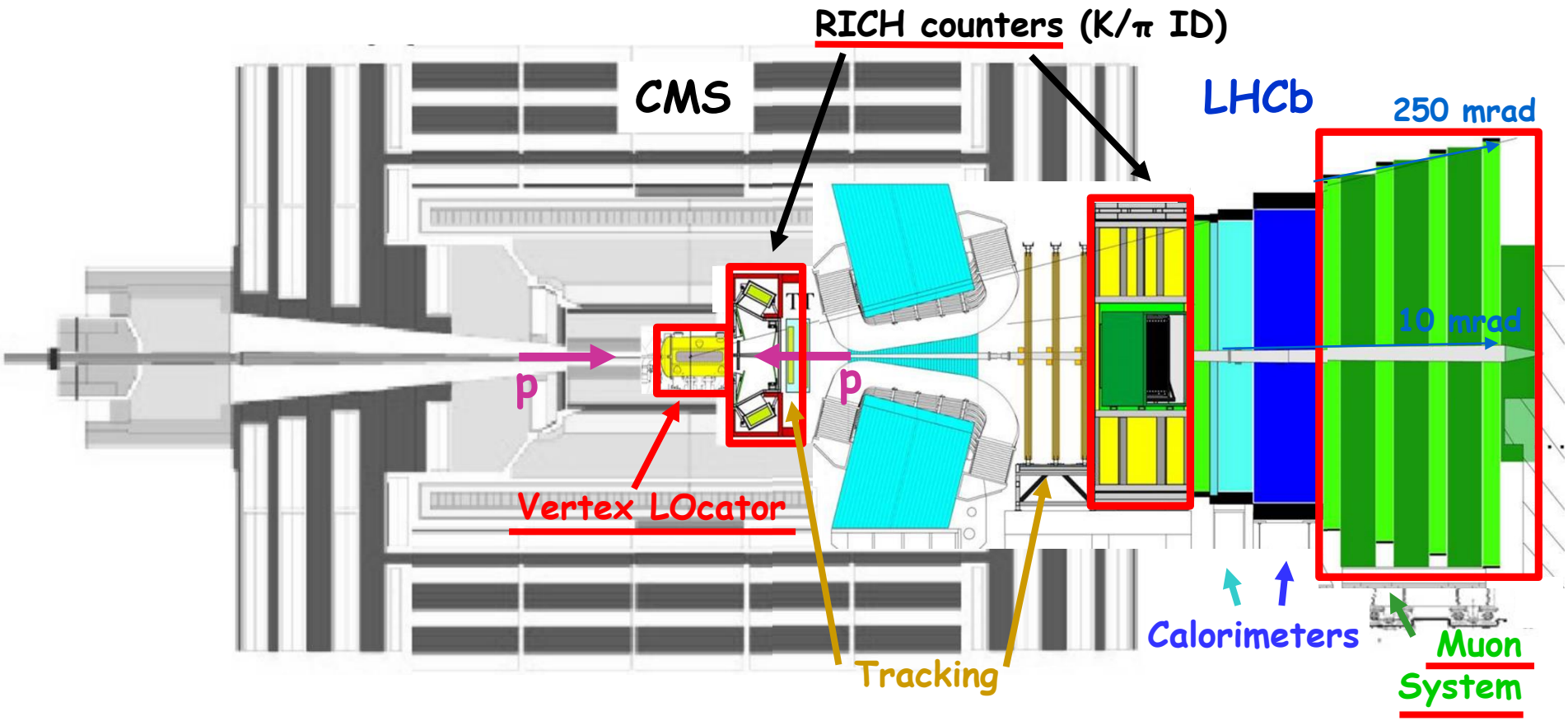
Short distance: perturbative cross-sections + pdf for the production of a $Q\bar{Q}$ pair

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

- 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. LDME from experimental data
- **Universality**: *same LDME for prompt production and production in b-decays*
- Heavy-Quark **Spin-Symmetry**: links between colour-singlet and colour-octet LDME of different quarkonium states

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 $1.9 < \eta < 4.9$, **~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**

LHCb integrated luminosity
$\sqrt{s}$ = 7 TeV, $\int Ldt \sim 1.2$ fb^{-1}
$\sqrt{s}$ = 8 TeV, $\int Ldt \sim 2.1$ fb^{-1}
$\sqrt{s}$ = 13 TeV, $\int Ldt \sim 2.5$ fb^{-1}

- **Quarkonia production**
  - J/ψ production ($\sqrt{s}$ = 13 TeV) *****
- **Open charm and beauty production**
  - Open charm production ($\sqrt{s}$ = 5 and 13 TeV) *****
  - b-hadron production asymmetries ($\sqrt{s}$ = 7 and 8 TeV)
- **Associated production** : Double J/ψ production ($\sqrt{s}$ = 13 TeV)
- **Production in jets** : J/ψ production ($\sqrt{s}$ = 13 TeV)
- **Central Exclusive Production** of J/ψ and ψ(2S) ($\sqrt{s}$ = 13 TeV)

(*****) *An issue was identified in the simulated samples used to calculate **track reconstruction efficiencies for some LHCb Run II production papers → UPDATES.***

Reason: VELO simulation updated prior to Run II to account for radiation damage, but error in the parametric correction for the effect. Track efficiency calibration in data was unable to correct mis-modeling; track reconstruction efficiency underestimated in simulation; most affected: low pseudorapidity and low p_T.

- Tests of **perturbative and non-perturbative regimes of QCD**
- **No consistent model describing simultaneously J/ψ and η_c production and J/ψ polarization in the whole p_T range**

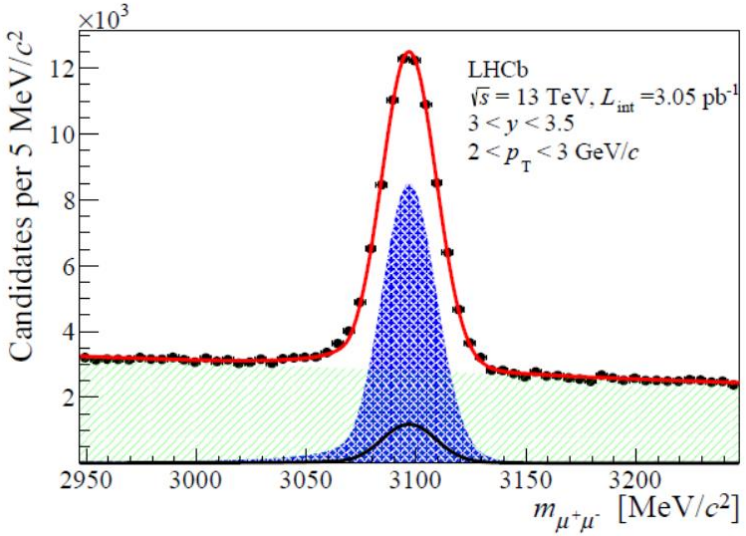
- J/ψ production at 2.76 TeV — JHEP 1302 (2013) 041
- J/ψ production at 7 TeV — EPJC 71 (2011) 1645
- J/ψ production at 8 TeV — JHEP 1306 (2013) 064
- J/ψ production at 13 TeV — JHEP 1510 (2015) 172
  Err.: JHEP 1705 (2017) 063

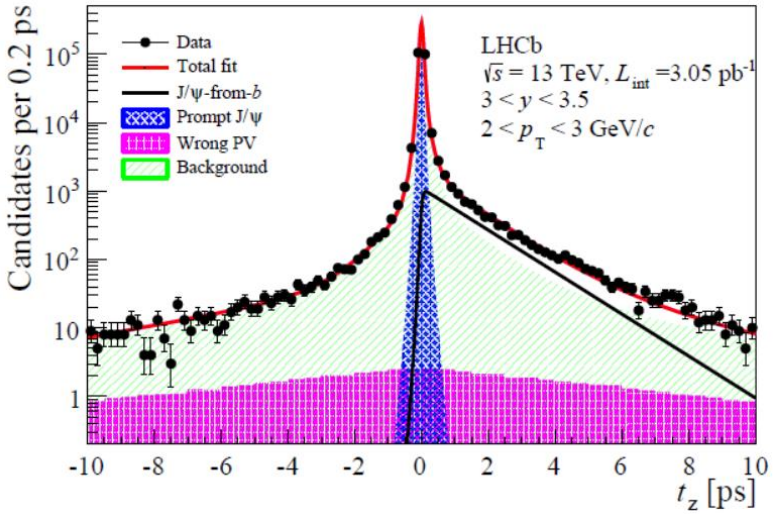
J/ψ production at √s = 13 TeV — update !

- **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
√s = 13 TeV, ∫Ldt ~ 3 pb^{-1}

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





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

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

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

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

using extrapolation factor $a_{4\pi}$ = 5.2 from the LHCb tuning of PYTHIA 6
JHEP 0605 (2006) 026

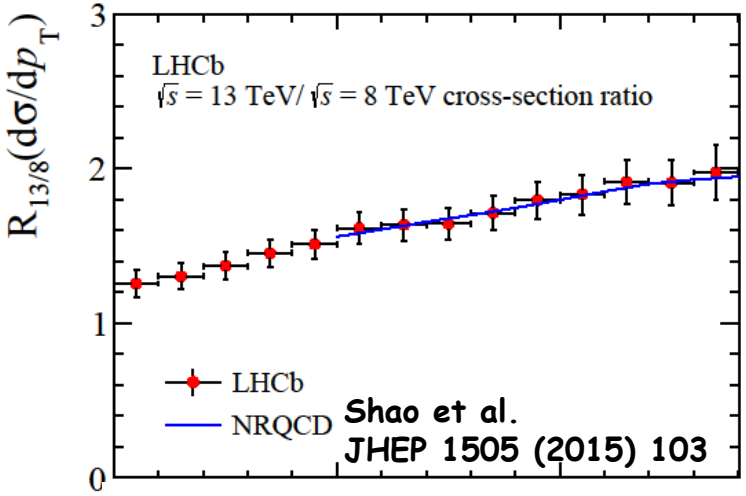
J/ψ production at √s = 13 TeV update !

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

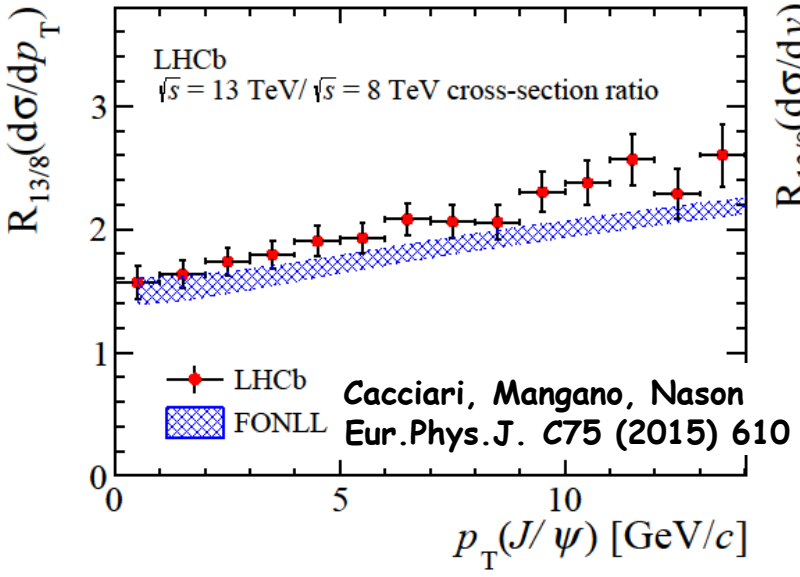
JHEP 1510 (2015) 172
JHEP 1705 (2017) 063

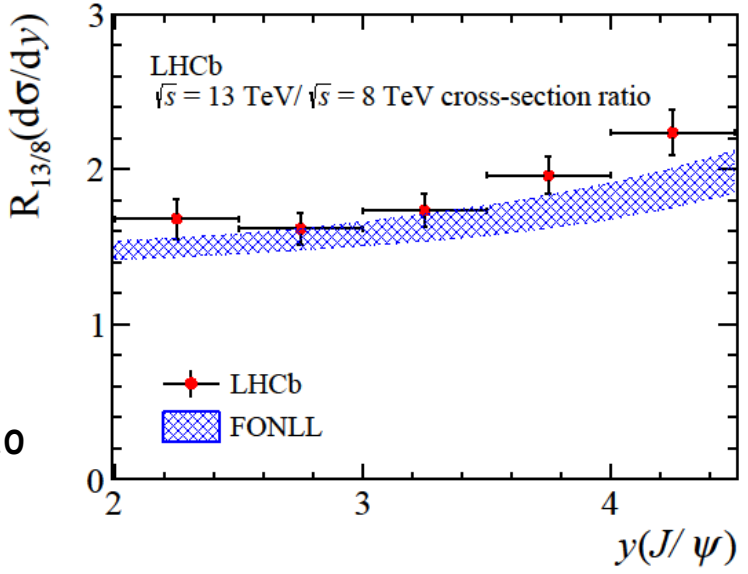
√s = 13 TeV, ∫Ldt ~ 3 pb^{-1}

- **Prompt production**



- **Production in b-decays**





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

J/ψ and $\eta_c(1S)$ production in inclusive 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:

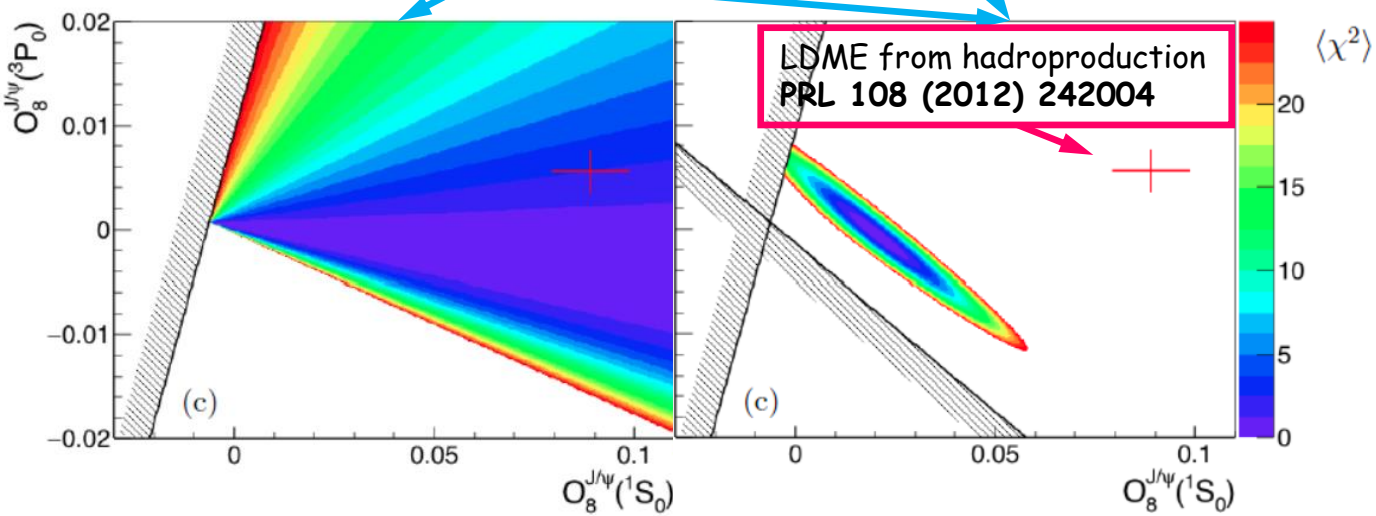
$$\langle O_1^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_1^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_8^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^3S_1)\rangle = \langle O_8^{J/\psi}(^1S_0)\rangle,$$
$$\langle O_8^{\eta_c}(^1P_1)\rangle = 3\langle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

- 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**

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

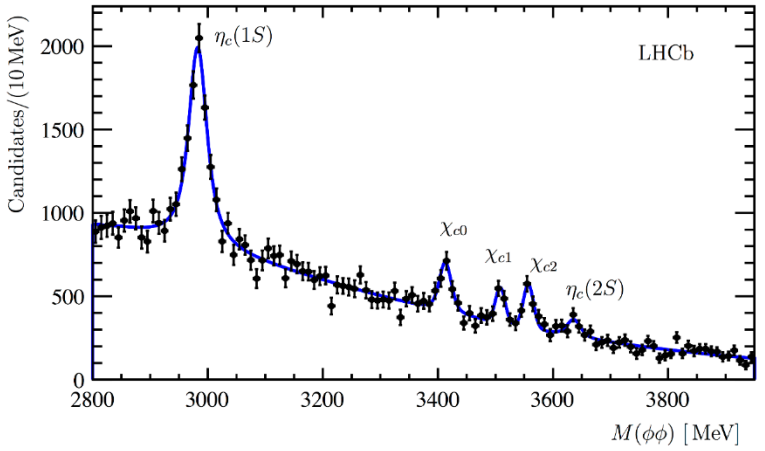
$\frac{\mathcal{B}(b \to \eta_c(1S)^{direct} X)}{\mathcal{B}(b \to J/\psi^{direct} X)}$ $\mathcal{B}(b \to J/\psi^{direct} X)$

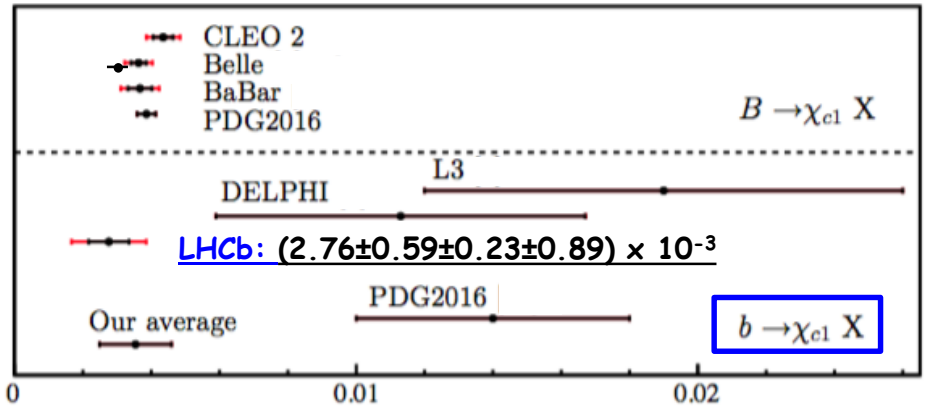


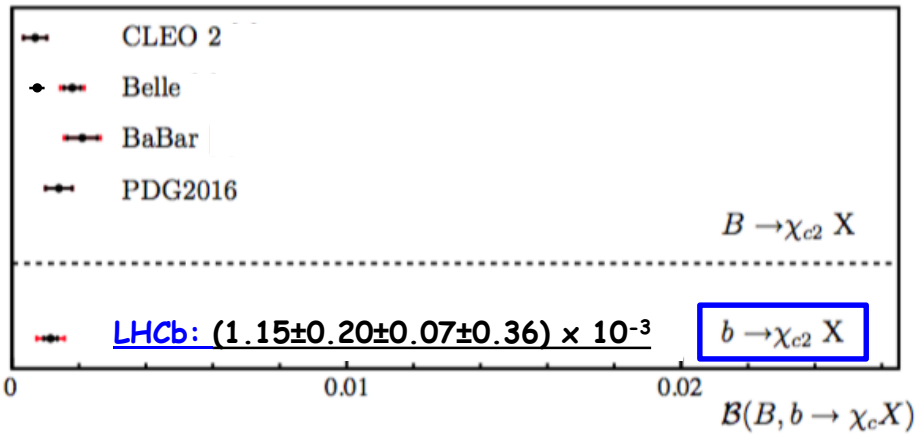
χ_c and $\eta_c(2S)$ production in inclusive b-decays

arXiv:1706.07013

- Charmonium reconstructed via **decays to φφ**; true φφ combinations using 2D fit technique
- First measurement of χ_{c0} production in b-hadron decays: **BR(b→χ_{c0}X)=(3.02±0.47±0.23±0.94)x10^{-3}**
- Most precise measurements of χ_{c1} and χ_{c2} production in b-decays, consistent with B-factories







- First measurement of $\eta_c(2S)$ production in b-decays; first evidence for $\eta_c(2S)$→φφ
- Important to measure hadroproduction

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

χ_c and $\eta_c(2S)$ production in inclusive b-decays

Usachov,Kou,SB, LAL-17-051

- From **arXiv:1706.07013** and **Chin. Phys. C40 (2016) 100001:**

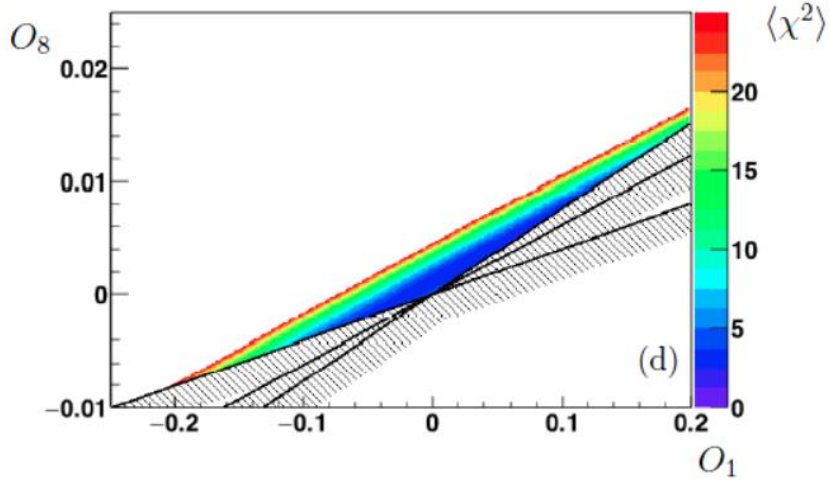
$$\mathcal{B}(b \to \chi_{c0}{}^{direct} X) = (2.74 \pm 0.47 \pm 0.23 \pm 0.94_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c1}{}^{direct} X) = (2.49 \pm 0.59 \pm 0.23 \pm 0.89_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c2}{}^{direct} X) = (0.89 \pm 0.20 \pm 0.07 \pm 0.36_{\mathcal{B}})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

- 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**



- 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**.

Open charm and open beauty production

- Test of **pQCD and QCD-based models**
- **Sensitivity of precision SM tests** with CPV and rare decays
- **Normalization of backgrounds** for precision studies

Open charm prompt production at 7 TeV	Nucl.Phys.B 871 (2013) 1
Open charm prompt production at 13 TeV	JHEP 1603 (2016) 159 Err.: JHEP 1609 (2016) 013 Err.: JHEP 1705 (2017) 074
Open charm prompt production at 5 TeV	JHEP 1706 (2017) 147
b-quark production using decays to $D^0\mu^-X$ at 7 TeV	PLB 694 (2010) 209
b-quark production using decays $b \rightarrow J/\psi X$ at 7 TeV	EPJC 71 (2011) 1645
b-quark production cross-section at 7 and 13 TeV	PRL 118 (2017) 052002

Open charm production at √s = 5 and 13 TeV

JHEP 1706 (2017) 147 $\sqrt{s}$ = 5 TeV, $\int L dt \sim 8.6$ pb^{-1}

JHEP 1705 (2017) 074 $\sqrt{s}$ = 13 TeV, $\int L dt \sim 5.0$ pb^{-1}

JHEP 1609 (2016) 013

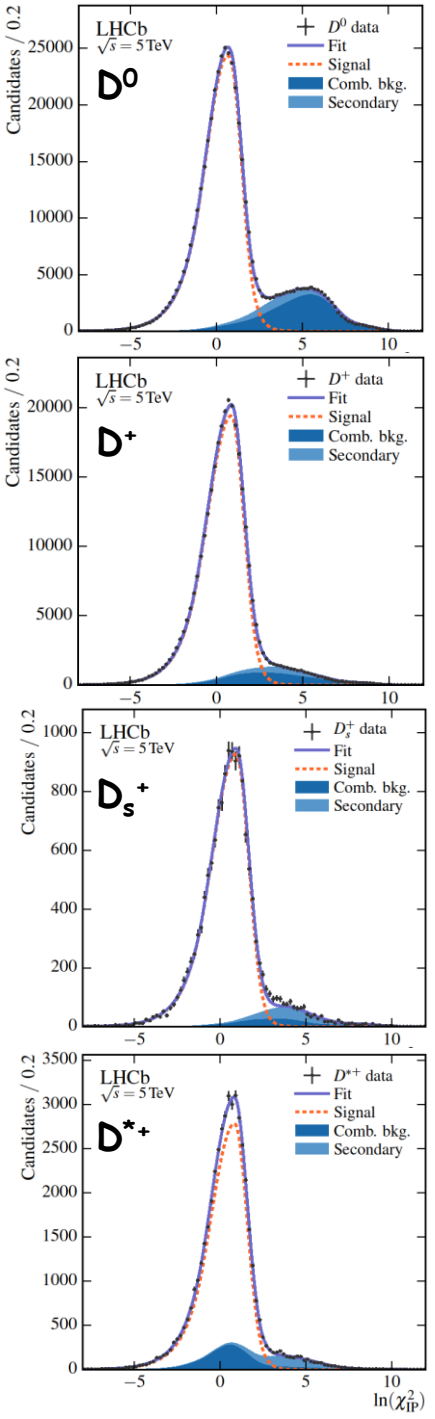
JHEP 1603 (2016) 159

update !

- Measurement of **integrated** and **differential production cross-sections** of charmed mesons
- Fits to the ln χ^2 of the impact parameter with respect to the *pp* interaction vertex
- **Integrated inclusive cross-sections**

($1 < p_T < 8$ GeV/c, $2.0 < y < 4.5$) :

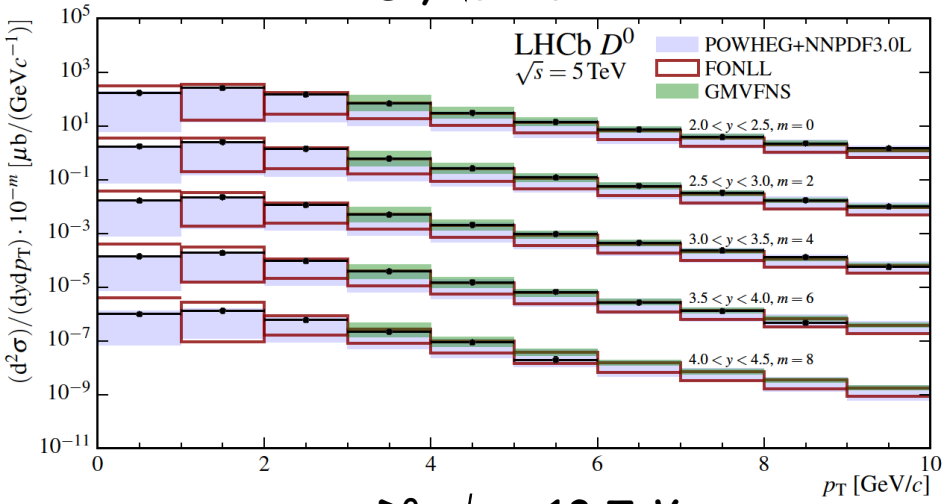
	$\sqrt{s}$ = 5 TeV	**$\sqrt{s}$ = 13 TeV**
$\sigma(pp \to D^0 X)$	1004 ± 3 ± 54 μb	2072 ± 2 ± 124 μb
$\sigma(pp \to D^+ X)$	402 ± 2 ± 30 μb	834 ± 2 ± 78 μb
$\sigma(pp \to D_s^+ X)$	170 ± 4 ± 16 μb	353 ± 9 ± 76 μb
$\sigma(pp \to D^{*+} X)$	421 ± 5 ± 36 μb	784 ± 4 ± 87 μb



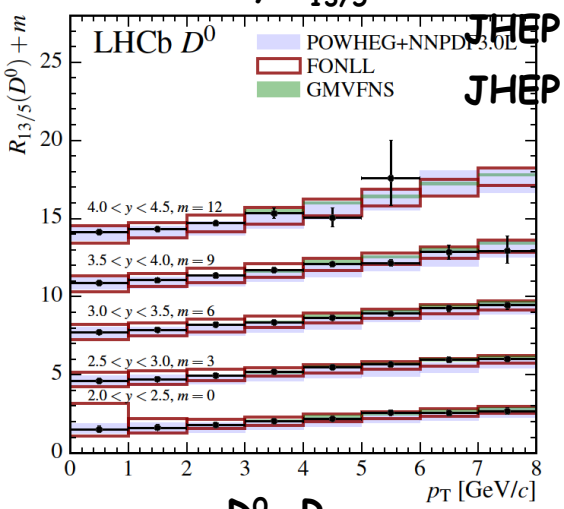
- Differential production cross-sections, *2.0 < y < 4.5*

JHEP 1706 (2017) 147
JHEP 1705 (2017) 074
JHEP 1609 (2016) 013
JHEP 1603 (2016) 159

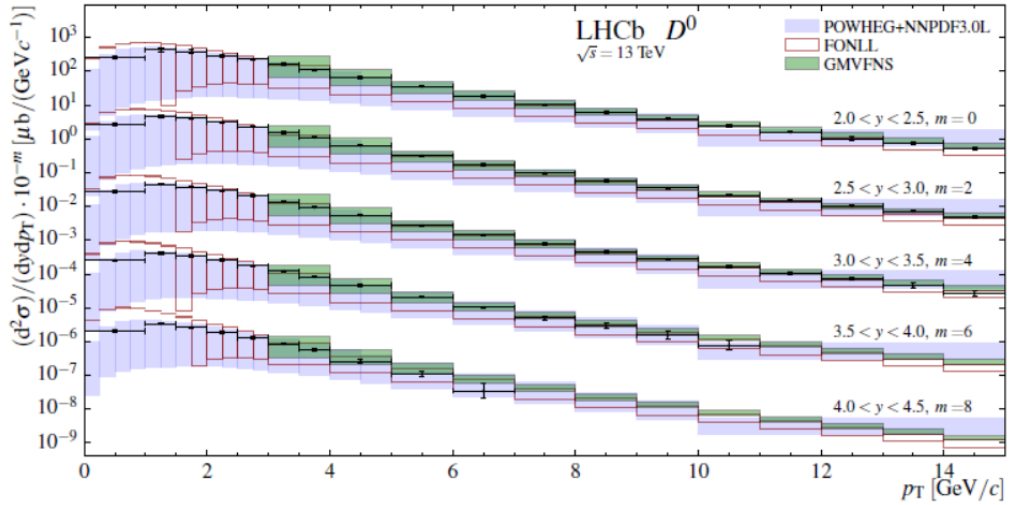
D⁰, √s = 5 TeV



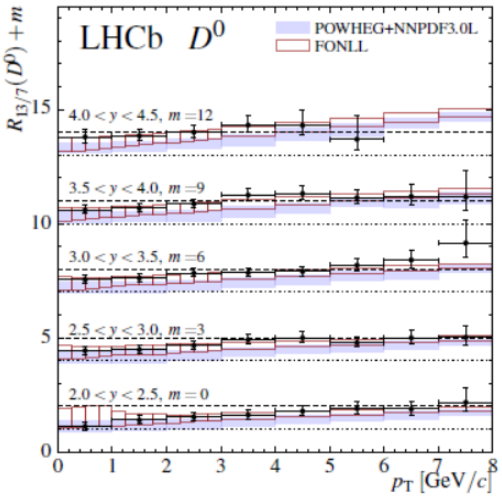
D⁰, $R_{13/5}$



D⁰, √s = 13 TeV



D⁰, $R_{13/7}$



- Reduced uncertainties in ratios
- General agreement with theory predictions

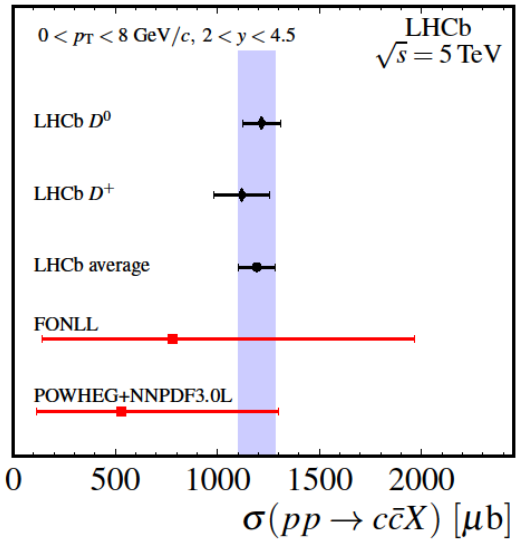
- **Cross-sections pp → $c\bar{c}$ X from meson measurements**

($0 < p_T < 8$ GeV/c, $2.0 < y < 4.5$)

Lyons,Gibaut,Clifford, NIM A270 (1988) 110

JHEP 1706 (2017) 147
JHEP 1705 (2017) 074
JHEP 1609 (2016) 013
JHEP 1603 (2016) 159

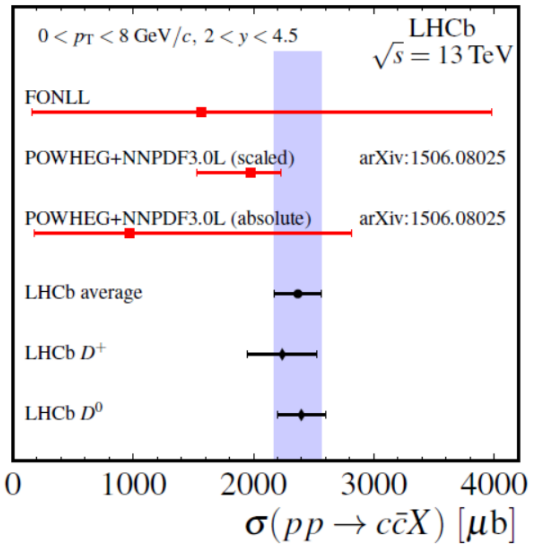
$$\sigma(pp \to c\bar{c}X) = 1193 \pm 3 \pm 67 \pm 58\,\mu\text{b}$$



Cacciari, Mangano, Nason, Eur.Phys.J. C75 (2015) 610

Gauld et al., JHEP 1511 (2015) 009

$$\sigma(pp \to c\bar{c}X) = 2369 \pm 3 \pm 152 \pm 118\,\mu\text{b}$$



Cacciari, Mangano, Nason, Eur.Phys.J. C75 (2015) 610

Gauld et al., JHEP 1511 (2015) 009

b-hadron production asymmetries at $\sqrt{s}$=7 and 8 TeV

Measurement of **hadron production asymmetries:**

- Understanding of **production mechanisms**
- **Input for CP-violation studies**

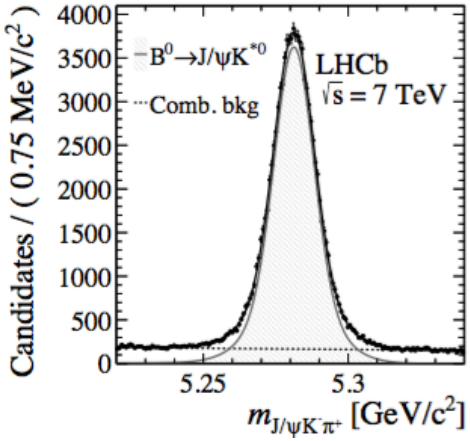
Production asymmetries of B^0 and B^0_s at 7 TeV	**PLB 739 (2014) 218**
Production asymmetries of D^+ and D^+_s at 7 TeV	**PLB 718 (2013) 902** **PLB 713 (2012) 186**
Sum of Λ^0_b production asymmetry and CP asymmetry in $\Lambda^0_b \rightarrow J/\psi\, pK^-$ decay at 7 TeV	**Chin.Phys.C 40 (2016) 011001**
Production asymmetries of B^0, B^0_s, B^+ and Λ^0_b at 7, 8 TeV	**arXiv:1703.08464**

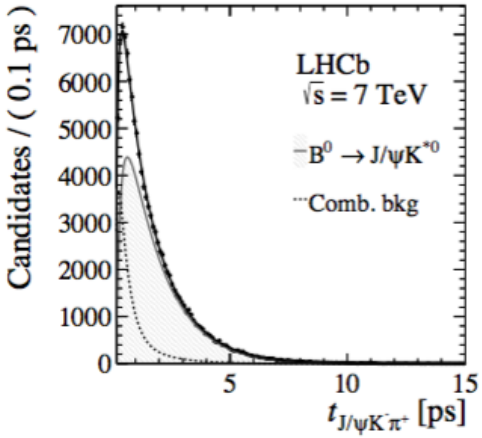
b-hadron production asymmetries at $\sqrt{s}$=7 and 8 TeV

arXiv:1703.08464

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

- **Production asymmetry** $A_P = \dfrac{\sigma(B^-)-\sigma(B^+)}{\sigma(B^-)+\sigma(B^+)}$
- Measurements using $B^+ \to J/\psi\, K^+$, $B^0 \to J/\psi\, K^{*0}$, $B^0_s \to D^-_s\, \pi^+$
- Time-dependent analysis for A_P (B^0), A_P (B^0_s) to tag the initial state



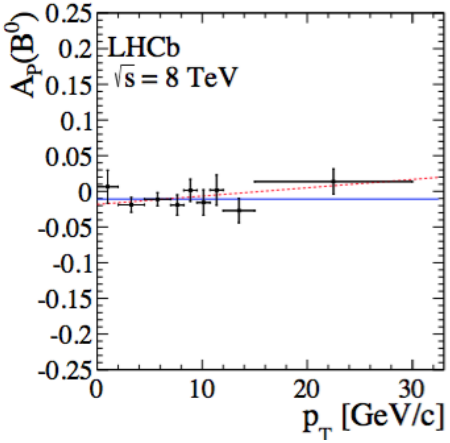


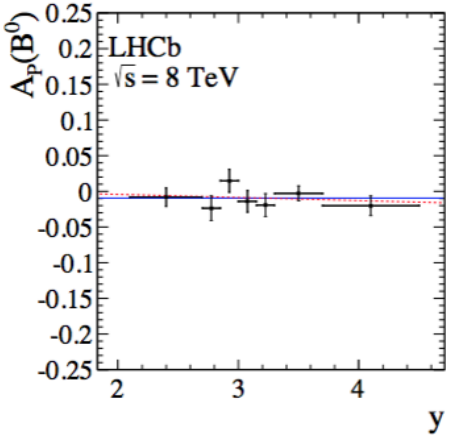
- **Raw asymmetry:**

$$A_{raw} = A_P + A_{CP} + A_{det}$$

  - A_{CP} - external information, theory or measurement
  - A_{det} – detection asymmetry, determined from control samples

- Production asymmetries of B^0, B^0_s, B^+ determined in bins (p_T,y)
- No evidence for any dependence is observed





arXiv:1703.08464

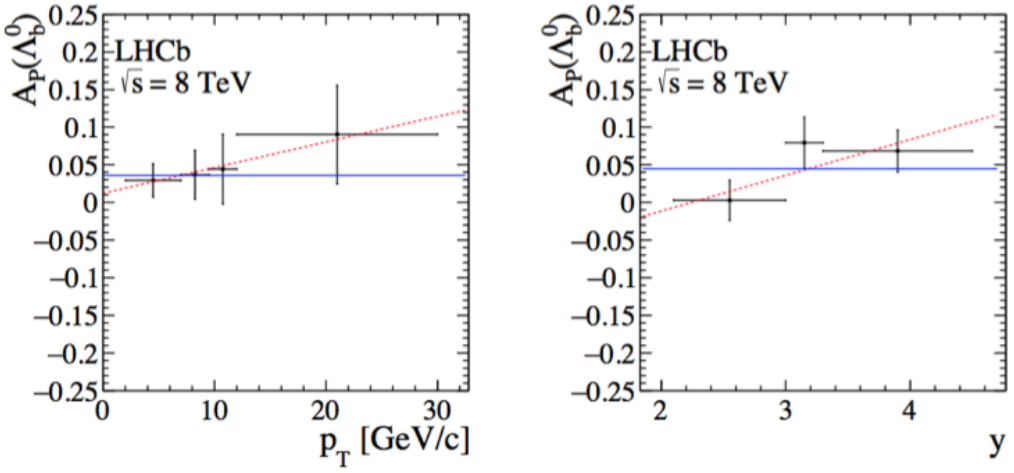
$\sqrt{s}$=7, 8 TeV, $\int$Ldt ~3 fb^{-1}

❑ **Production asymmetry of Λ^0_b** determined indirectly

$$A_P(\Lambda_b^0) = -\left[\frac{f_u}{f_{\Lambda_b^0}} A_P(B^+) + \frac{f_d}{f_{\Lambda_b^0}} A_P(B^0) + \frac{f_s}{f_{\Lambda_b^0}} A_P(B_s^0) + \frac{f_c}{f_{\Lambda_b^0}} A_P(B_c^+) + \frac{f_{\text{other}}}{f_{\Lambda_b^0}} A_P(\text{other})\right]$$

from JHEP 1304 (2013) 001
JHEP 1408 (2014) 143

estimated as 2 x 10^{-3}



❑ Slight increase of A_P (Λ^0_b) with p_T and y was already seen in the direct study.

Chin.Phys.C 40 (2016) 011001

$$\begin{aligned}
A_P(B^+)_{\sqrt{s}=7\,\text{TeV}} &= -0.0023 \pm 0.0024\ (\text{stat}) \pm 0.0037\ (\text{syst}),\\
A_P(B^+)_{\sqrt{s}=8\,\text{TeV}} &= -0.0074 \pm 0.0015\ (\text{stat}) \pm 0.0032\ (\text{syst}),\\
A_P(B^0)_{\sqrt{s}=7\,\text{TeV}} &= 0.0044 \pm 0.0088\ (\text{stat}) \pm 0.0011\ (\text{syst}),\\
A_P(B^0)_{\sqrt{s}=8\,\text{TeV}} &= -0.0140 \pm 0.0055\ (\text{stat}) \pm 0.0010\ (\text{syst}),\\
A_P(B_s^0)_{\sqrt{s}=7\,\text{TeV}} &= -0.0065 \pm 0.0288\ (\text{stat}) \pm 0.0059\ (\text{syst}),\\
A_P(B_s^0)_{\sqrt{s}=8\,\text{TeV}} &= 0.0198 \pm 0.0190\ (\text{stat}) \pm 0.0059\ (\text{syst}),\\
A_P(\Lambda_b^0)_{\sqrt{s}=7\,\text{TeV}} &= -0.0011 \pm 0.0253\ (\text{stat}) \pm 0.0108\ (\text{syst}),\\
A_P(\Lambda_b^0)_{\sqrt{s}=8\,\text{TeV}} &= 0.0344 \pm 0.0161\ (\text{stat}) \pm 0.0076\ (\text{syst}).
\end{aligned}$$

❑ **All results consistent with zero within 2.5 standard deviations.**

Associated production

- Tests of **production mechanisms**
- In CS NRQCD LO no feed-down from cascade decays of excited C-even states.

- Double J/ψ production was observed by LHCb with 36 pb^{-1} **PLB 707 (2012) 052**
  In agreement with SPS and also DPS.
- Double charm production cross-section involving open charm **JHEP 1206 (2012) 141**
  Exceeds SPS predictions.
- Associated (bb)(cc) production via B_c^+ production **PRL 114 (2014) 132001**
  In agreement with SPS predictions.
- Associated (bb)(cc) production via Y(nS) and open charm **JHEP 1607 (2016) 052**
  In agreement with DPS, exceeds SPS predictions.
- Double J/ψ production at 13 TeV **JHEP 1706 (2017) 047**

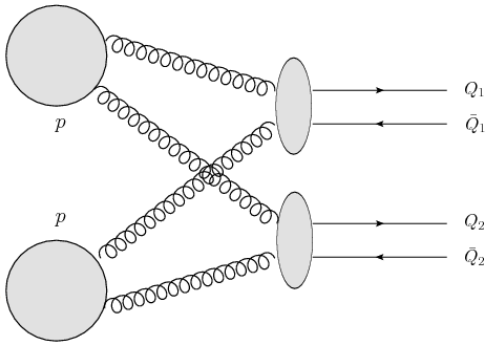
Double J/ψ production at $\sqrt{s}$=13 TeV

- Production via **Double Parton Scattering** (DPS) or **Single Parton Scattering** (SPS)

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

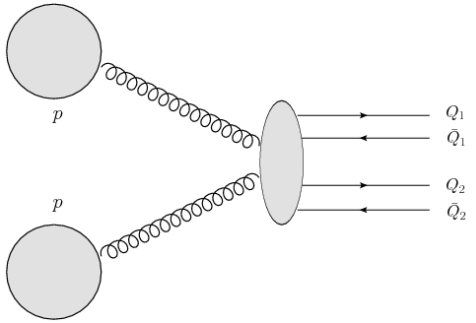
- **DPS**: two independent hard scatters that are assumed to factorize
- **SPS**: gluon splitting expected to dominate $c\bar{c}$ production

DPS

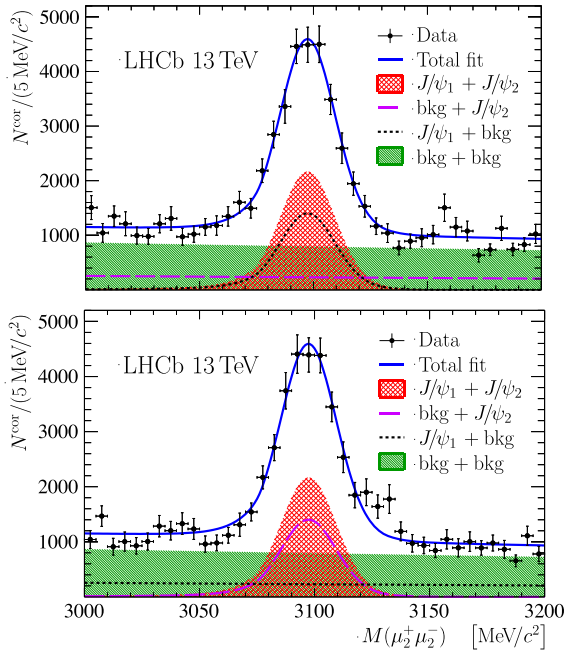


$$\sigma_{\mathrm{DPS}}\left(J/\psi\, J/\psi\right) = \frac{1}{2}\frac{\sigma\left(J/\psi\right)^2}{\sigma_{\mathrm{eff}}}$$

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**

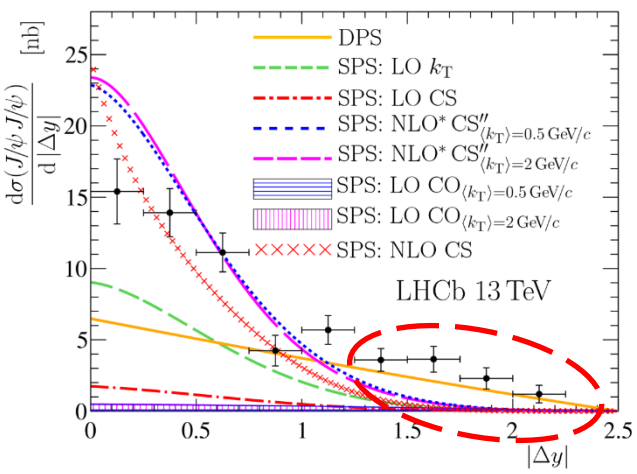
$$\sigma(J/\psi\, J/\psi) = 15.2 \pm 1.0\,(\mathrm{stat}) \pm 0.9\,(\mathrm{syst})\ \mathrm{nb}$$

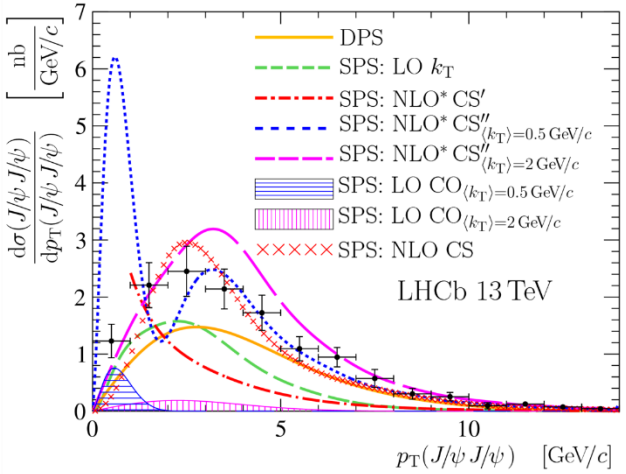
Double J/ψ production at $\sqrt{s}$=13 TeV

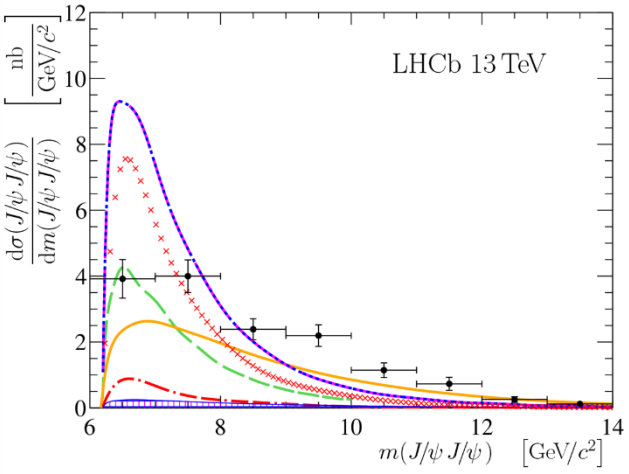
JHEP 1706 (2017) 047

$\sqrt{s}$ = 13 TeV, $\int$Ldt ~ 279 pb^{-1}

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





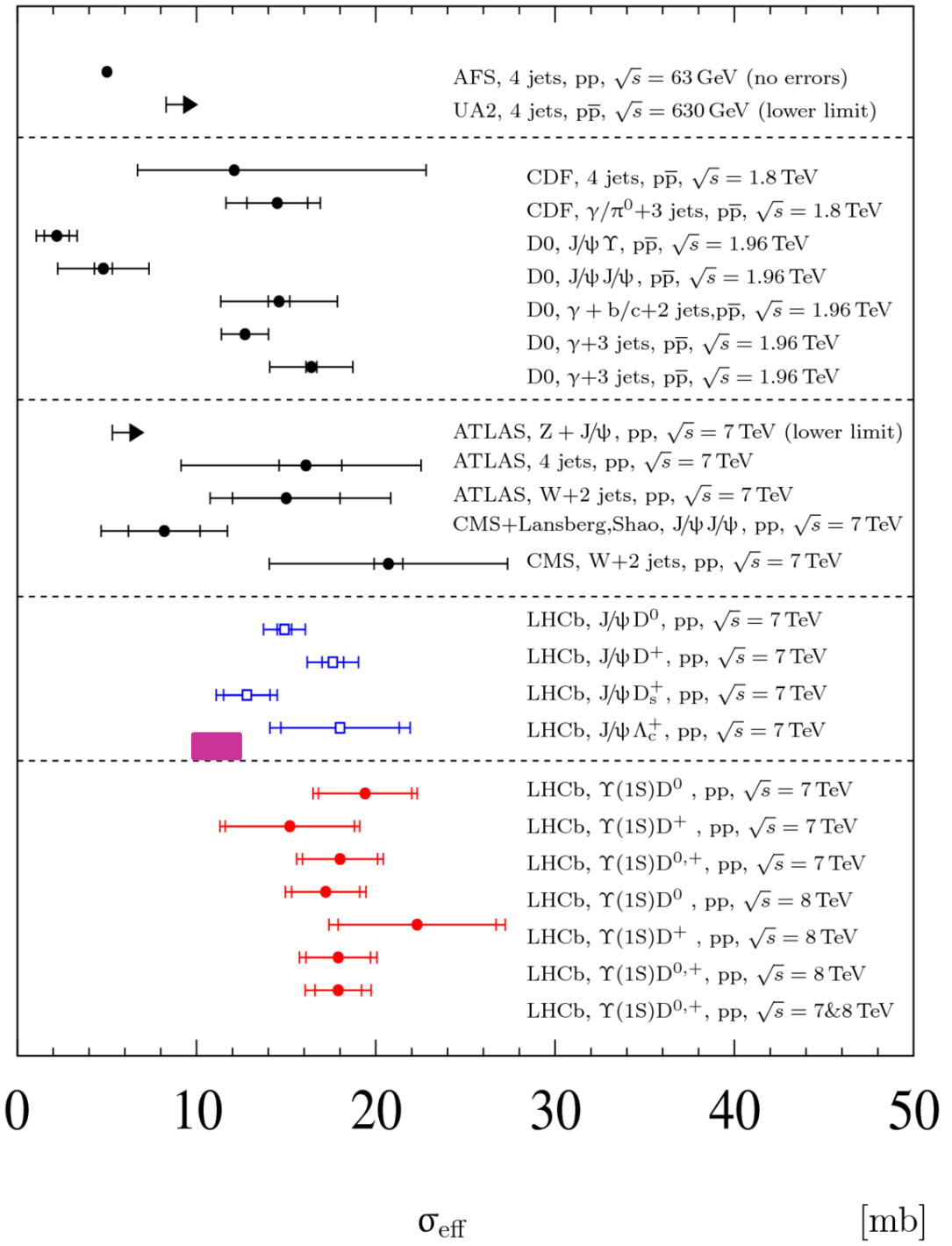


- **Evidence for DPS at high |Δy| region** — Kom, Kulesza, Stirling, PRL 107 (2011) 082002
- Fit of kinematical distributions to extract DPS fraction and σ_{eff}
- Agreement between fits of $|\Delta y|$, $p_T(J/\psi J/\psi)$, $y(J/\psi J/\psi)$, $m(J/\psi J/\psi)$
- Using various SPS descriptions, σ_{eff}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

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

- Compilation of results on σ_{eff}

LHCb, $J/\psi J/\psi$, pp, $\sqrt{s}$=13 TeV
JHEP 1706 (2017) 047



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

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

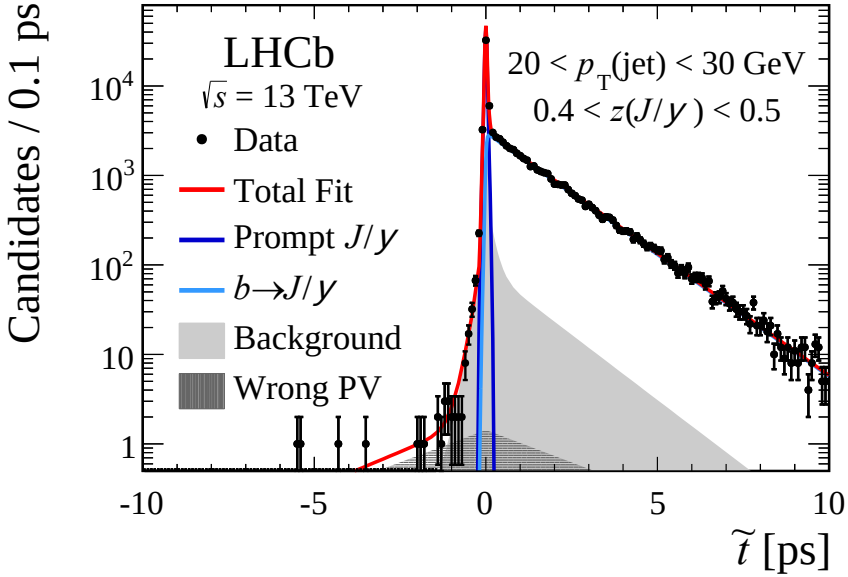
- J/ψ produced in direct **parton scattering** or through **parton showering**
- Significant J/ψ production in showers can explain lack of observed polarization
- Anti-k_T algorithm
- **Fiducial region**
  - Jets: p_T > 20 GeV/c, 2.5 < η < 4.0
  - J/ψ: 2.0 < η < 4.5

- 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:

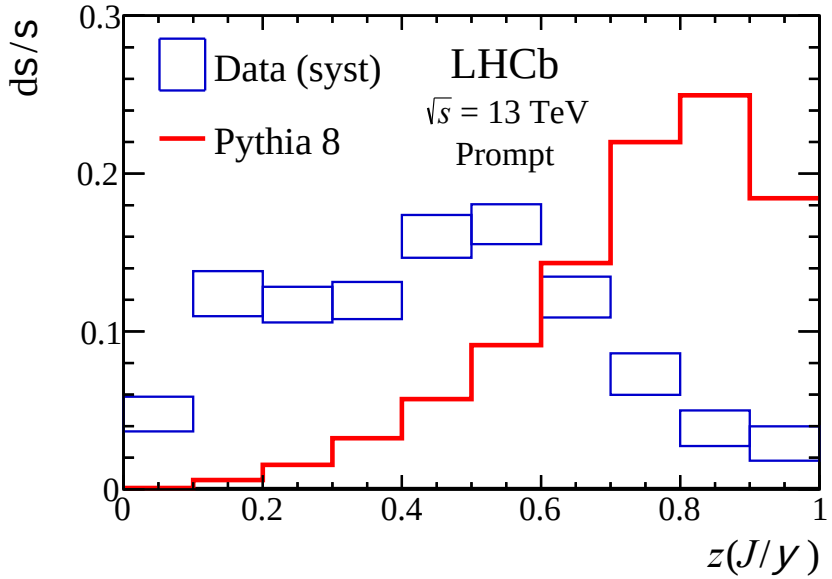
$$\tilde{t} \equiv \lambda\, m(J/\psi)/p_L(J/\psi)$$

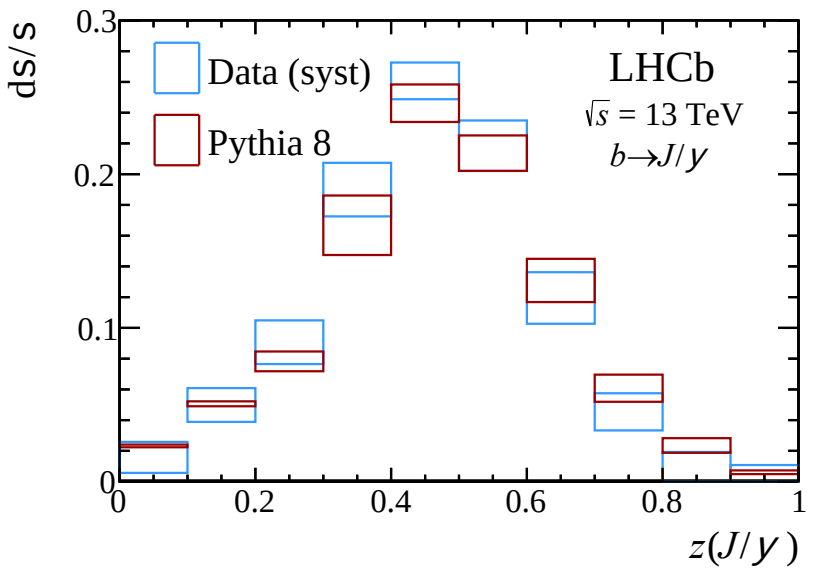


J/ψ production in jets at $\sqrt{s}$=13 TeV

- Fit in bins of z(J/ψ)
- 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}

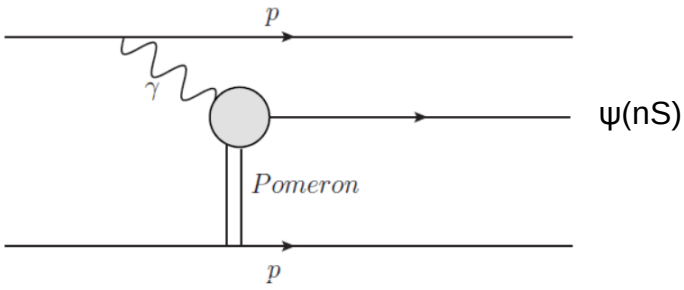




- z(J/ψ) distribution for J/ψ produced in b-decays is consistent with the Pythia 8 prediction
- **Prompt J/ψ are less isolated than the prediction of Pythia based on fixed-order NRQCD**
- Indication for significant contribution from parton showering

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 $x \sim 1.5 \times 10^{-5}$



Results at 7 and 8 TeV

- Exclusive J/ψ and ψ(2S) production at 7 TeV — **JPG 41 (2014) 055002**
- Exclusive ϒ production at 7 and 8 TeV — **JHEP 1509 (2015) 084**
- Double charmonia production at 7 and 8 TeV — **JPG 40 (2013) 045001**
- Exclusive χ_c and $\mu^+\mu^-$ production (preliminary) — **LHCb-CONF-2011-022**

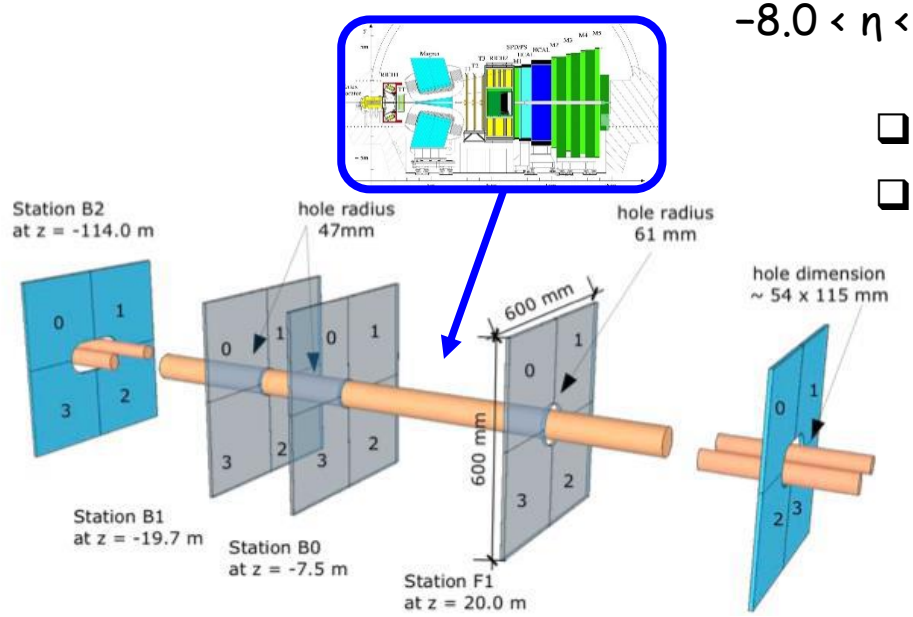
Results at 13 TeV (new Herschel detector)

- Exclusive J/ψ and ψ(2S) production at 13 TeV — **LHCb-CONF-2016-007**

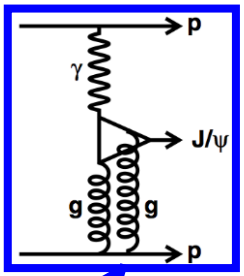
Central Exclusive Production of J/ψ and ψ(2S)

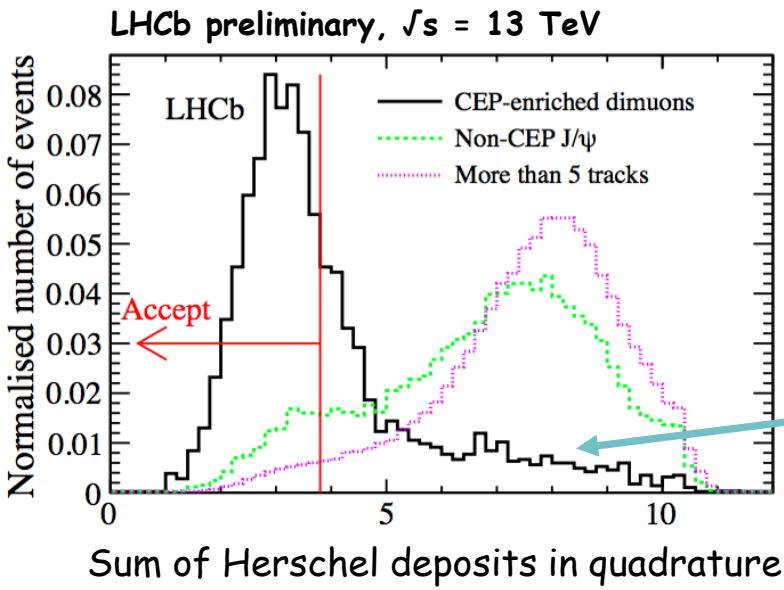
- New **Herschel detector** increases rapidity gap in forward region
  $-8.0 < \eta < -1.5$, $5.0 < \eta < 8.0$

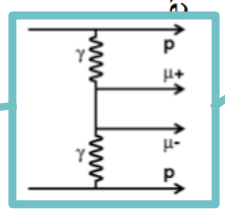
LHCb-CONF-2016-007
$\sqrt{s}$=13 TeV, $\int$Ldt ~0.2 fb^{-1}

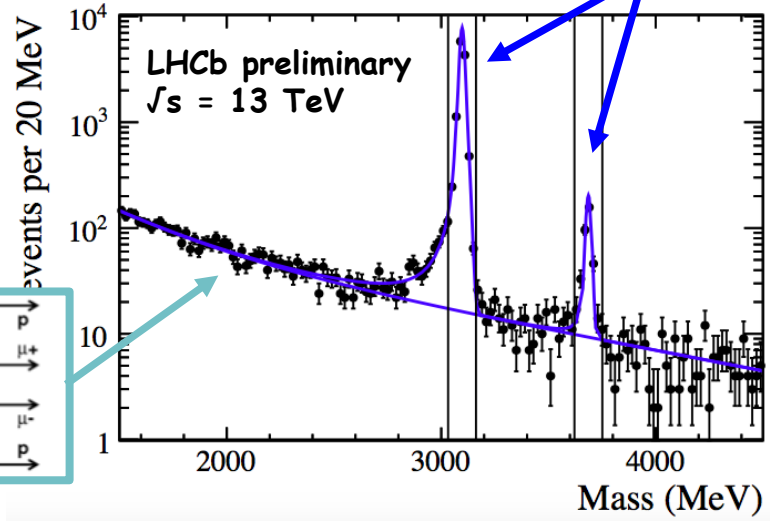


- Dedicated CEP trigger
- **Exclusivity**: precisely two forward muons; no backward tracks; no activity in SPD (< 10 hits). Quantify with p_T spectrum.









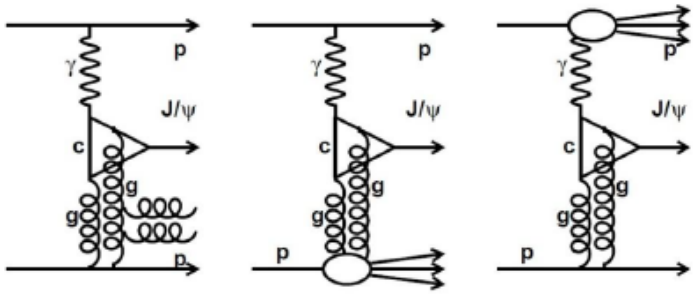
Central Exclusive Production of J/ψ and ψ(2S)

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

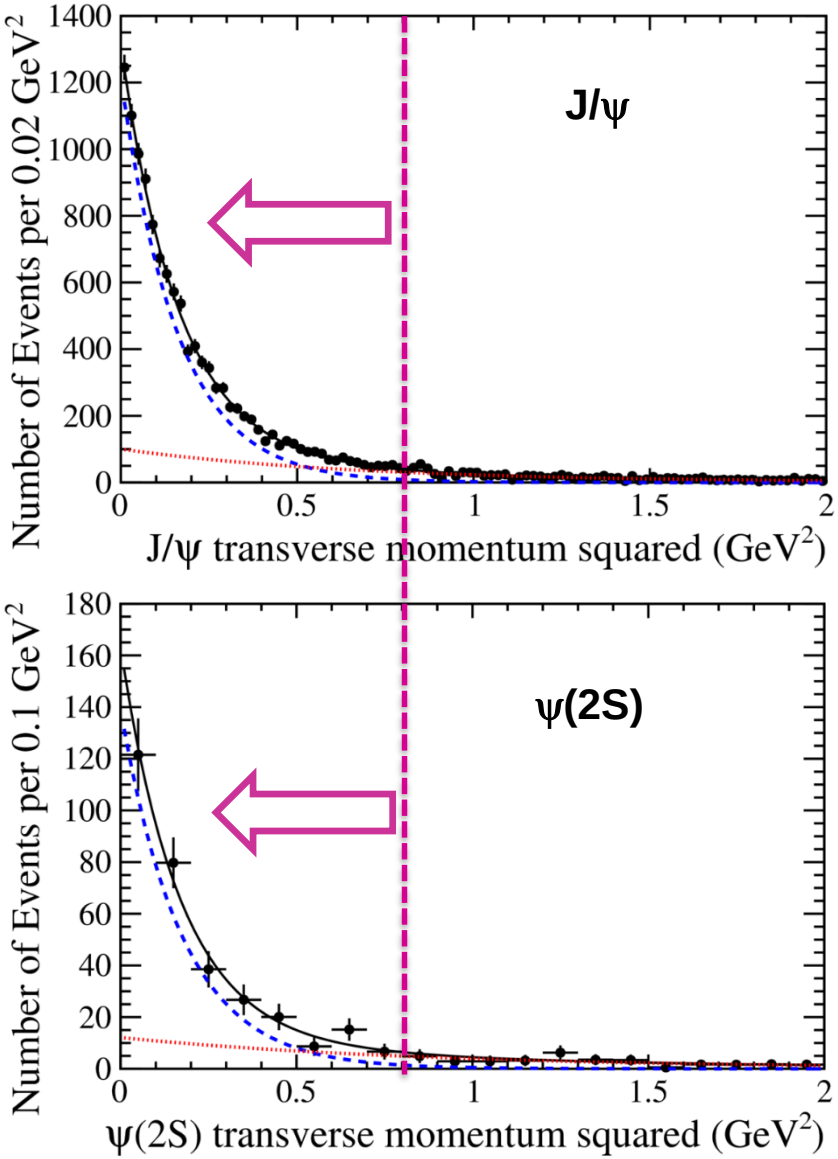
$\psi(2S) \to J/\psi\pi\pi$: $2.5 \pm 0.2\%$

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

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

LHCb-CONF-2016-007

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

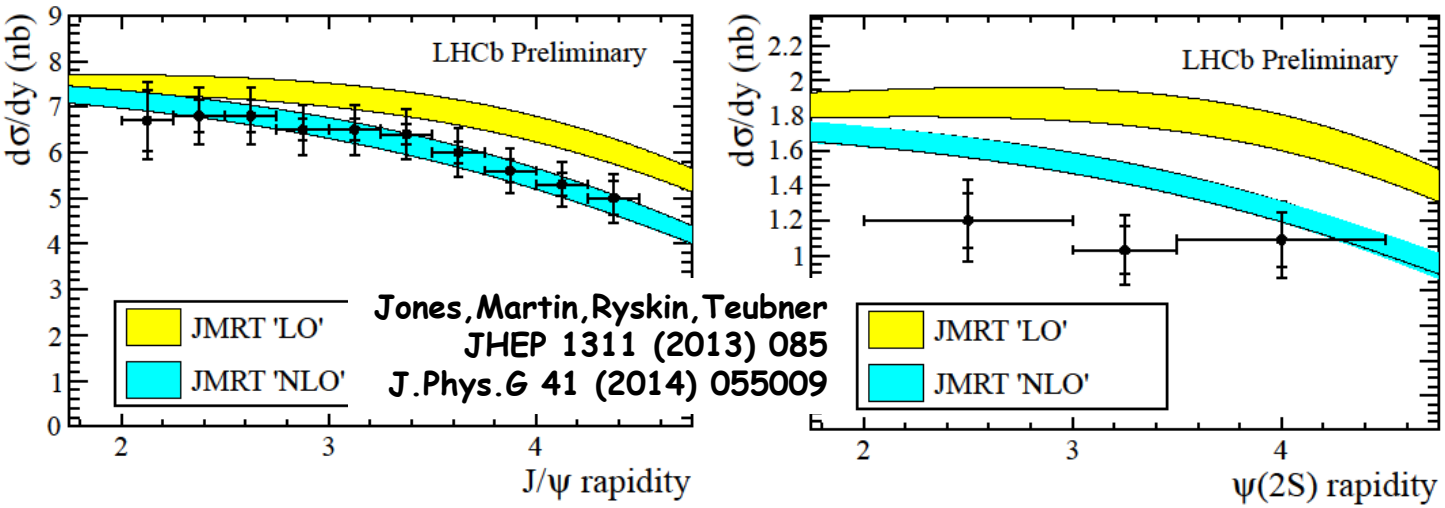


J/ψ and ψ(2S) differential cross-sections

❑ Differential cross-section compared to theory predictions

LHCb-CONF-2016-007

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



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

❑ Integrated cross-sections times branching fractions

$$\sigma_{J/\psi\to\mu^+\mu^-}(2.0<\eta_{\mu^+},\eta_{\mu^-}<4.5) = 407\pm8\pm24\pm16\ \text{pb}$$
$$\sigma_{\psi(2S)\to\mu^+\mu^-}(2.0<\eta_{\mu^+},\eta_{\mu^-}<4.5) = 9.4\pm0.9\pm0.6\pm0.4\ \text{pb}$$

❑ **Good agreement with NLO predictions**

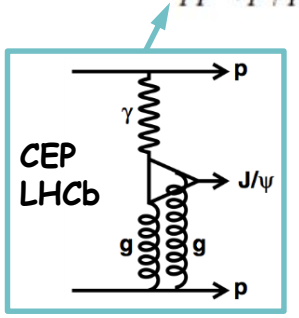
❑ Confirms a hint of NLO importance from the analysis at 7 TeV

Photo-production cross-section

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

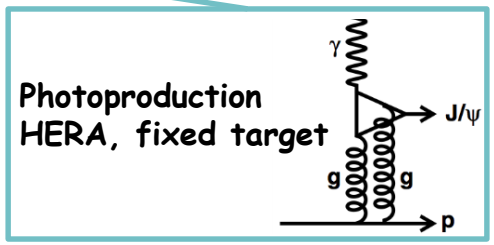
LHCb-CONF-2016-007
$\sqrt{s}$=13 TeV, $\int$Ldt ~0.2 fb^{-1}

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



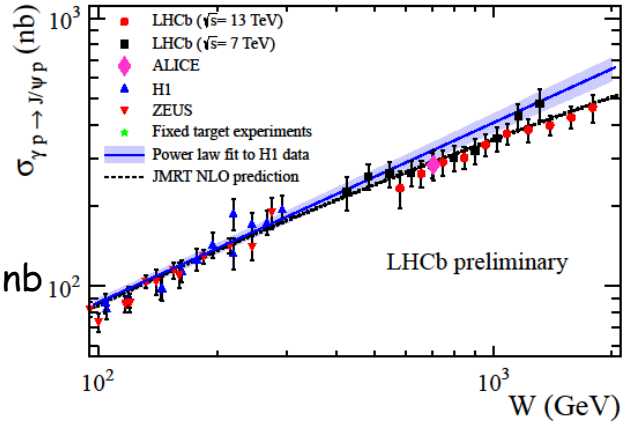
Gap survival

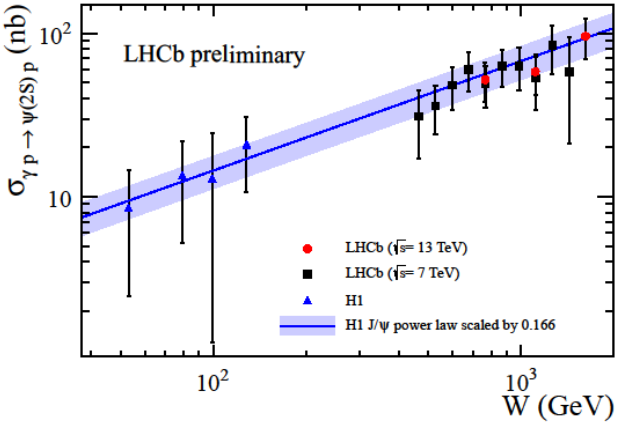
Photon flux



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:
  $\sigma_{\gamma p\to J/\psi p}(W) = 81(W/90\ GeV)^{0.67}$ nb

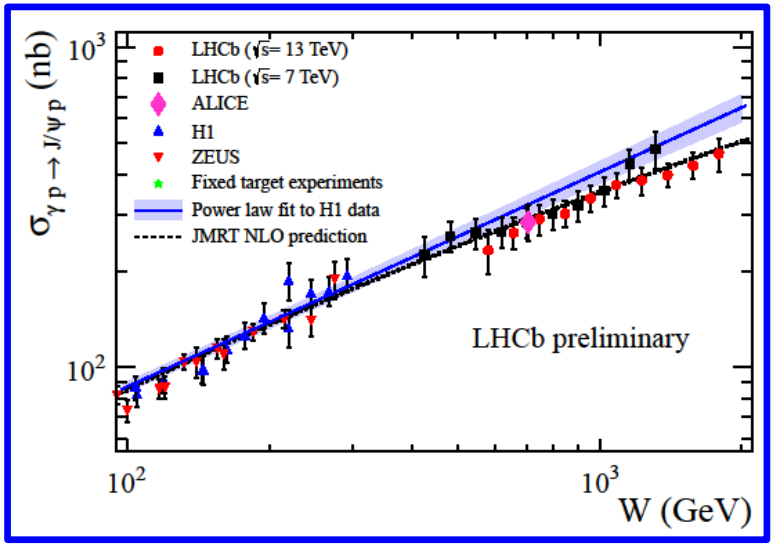


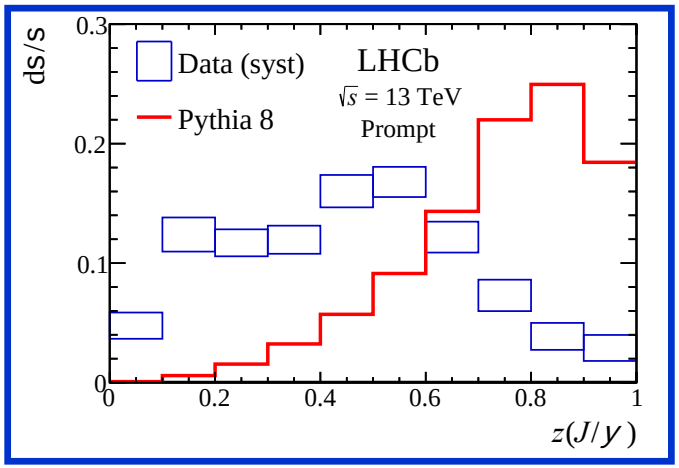


- Good agreement between LHCb results at 7 and 13 TeV
- J/ψ photo-production cross-section: **deviation from a pure power-law extrapolation of HERA data; agreement to theory prediction**

Summary

- Thanks to excellent LHC and LHCb operation, LHCb performs **new precision tests** of our QCD comprehension to systematically qualify/constrain theory
- **Run I** until 2012: $\sqrt{s}$ = 7 and 8 TeV, new results on HF production
- More precision tests with **Run II** data, 2015-2018 at $\sqrt{s}$ = 13 TeV, bigger datasets, better sensitivities and new measurements, access to larger p_T range





- Theory/experiment agreement made great progress since Tevatron days
- FONLL describes b-hadron production reasonably well, with caveats; prompt charmonia still puzzle

- New complementary probes from associated production, production in jets, CEP, …
- Yet another **effort needed in both theory and experiment to establish a consistent picture of HF production**