Andrii Usachov
on behalf of the LHCb Collaboration

LAL, Orsay

Hidden and open heavy flavour production at LHCb

Selected measurements:

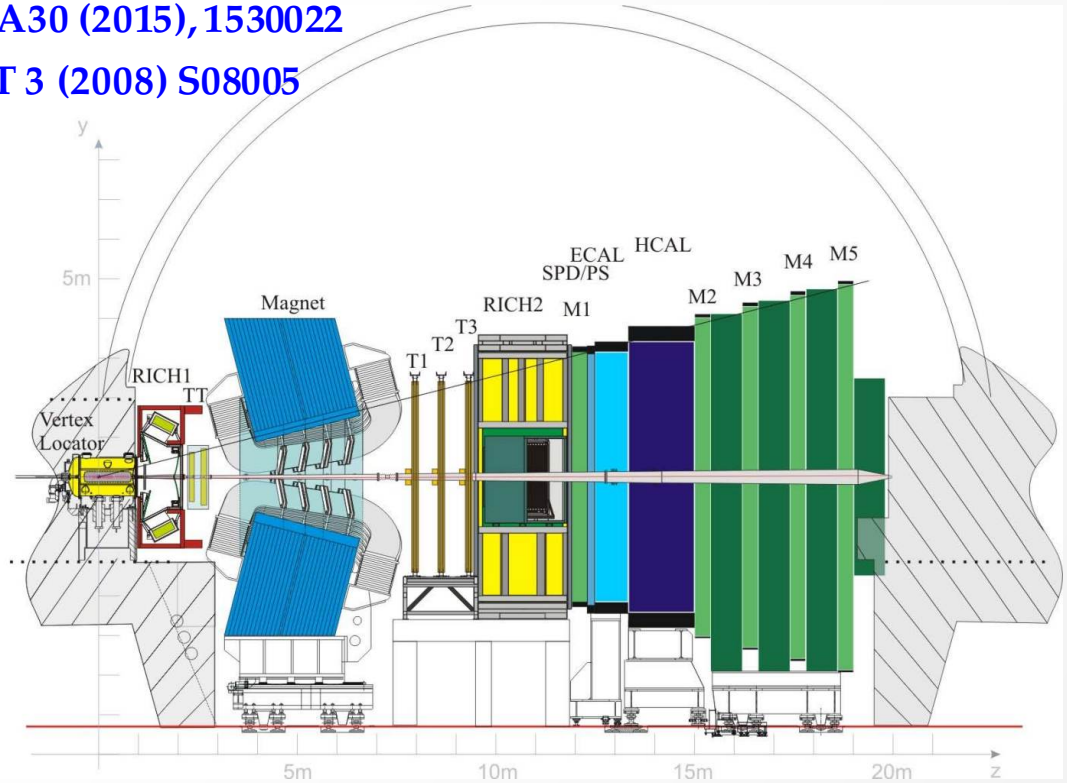
- Double J/ψ production at $\sqrt{s} = 13\ TeV$ **JHEP 1706 047**
- J/ψ production in jets at $\sqrt{s} = 13\ TeV$ **PRL 118 192001**
- Prompt charm production at $\sqrt{s} = 5\ TeV$ **arXiv:1610.02230**
- b −hadron production asymmetries $\sqrt{s} = 7{,}8\ TeV$ **arXiv:1703.08464**
- χ_c and $\eta_c(2S)$ production in inclusive b-decays at $\sqrt{s} = 7{,}8\ TeV$ **arXiv:1706.07013**
- J/ψ production at $\sqrt{s} = 13\ TeV$, updated **JHEP 1705 063**

See other talks:
"Spectroscopy with heavy flavours at LHCb" by Patrick Spradlin *(06/07, 12:45)*
"Measurement of Inelastic cross-section and CEP with the LHCb detector" by Michael Schmelling *(06/07, 09:30)*
"Quarkonium measurements in pPb and PbPb collisions at LHCb" by Francesco Bossu *(06/07, 10:15)*
"Open heavy flavour measurements in pPb collisions at LHCb" by Patrick Robbe *(06/07, 10:45)*
"Highlights from the LHCb Experiment" by Ulrik Egede *(11/07/2017, 09:00)*

LHCb detector

IJMPA30 (2015), 1530022

JINST 3 (2008) S08005



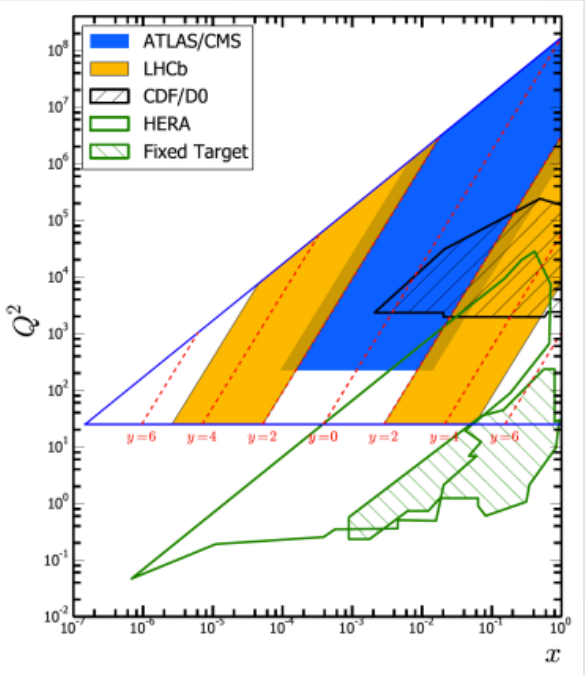
Important for heavy flavour production study :

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

- Covers complementary to ATLAS and CMS p_t and η range
- Access to the PDFs in high and low $\boldsymbol{x}$ regions

not studied by previous experiments

- LHCb can explore region down to $\boldsymbol{x < 10^{-4}}$ (below gluon density uncertainty becomes large)



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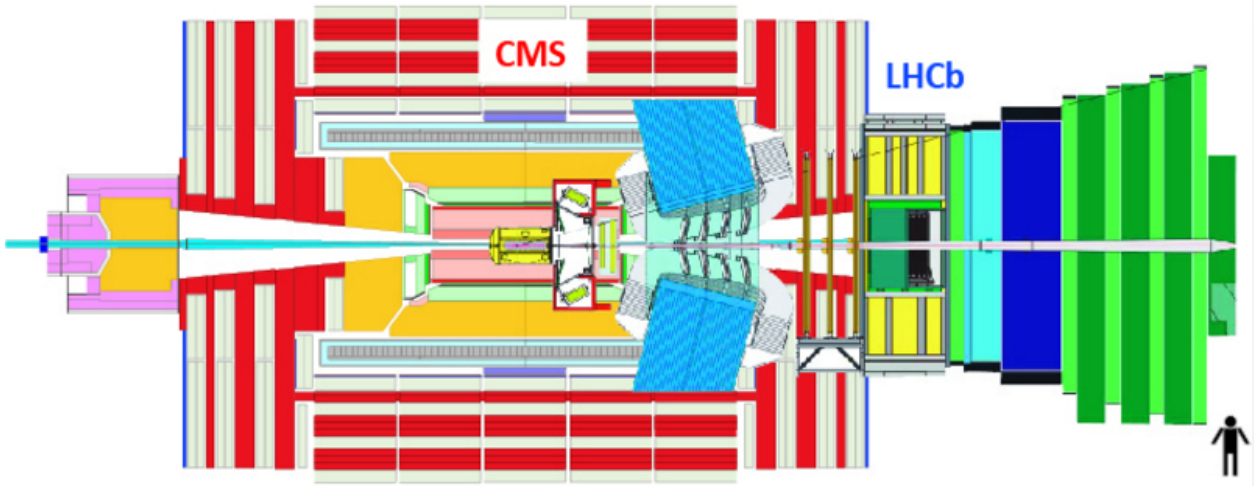

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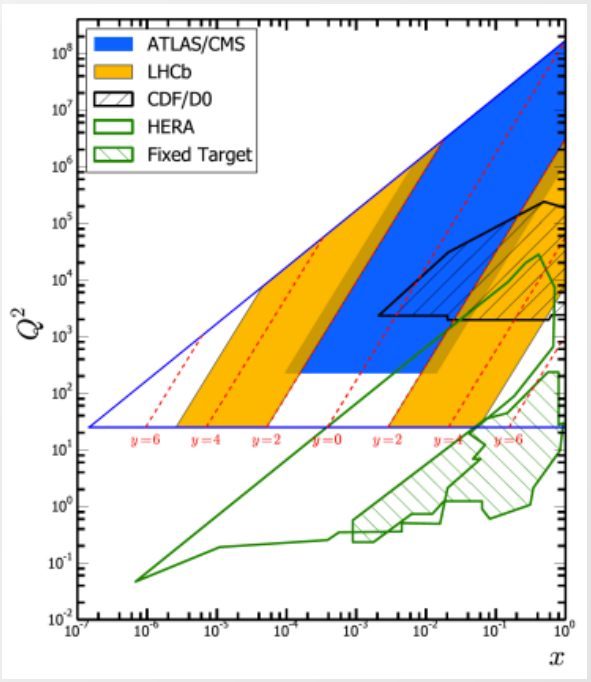


Heavy flavour production: motivation

- Variety of measurements
  - **Open heavy flavour** production and polarization
  - **Quarkonium** production and polarization
  - **Associative** and correlated production

- Important study for QCD, both perturbative and non-perturbative parts
  - **tests of QCD** predictions
  - determination of **non perturbative parameters**
  - probe of **proton structure**

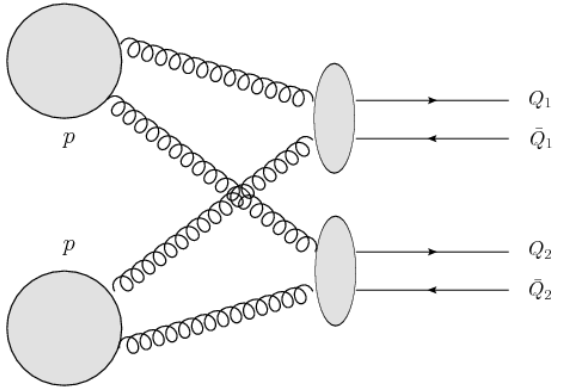
- Required for MC tuning ➜ inputs for precision flavor physics measurements

- Precise knowledge of SM background for New Physics searches

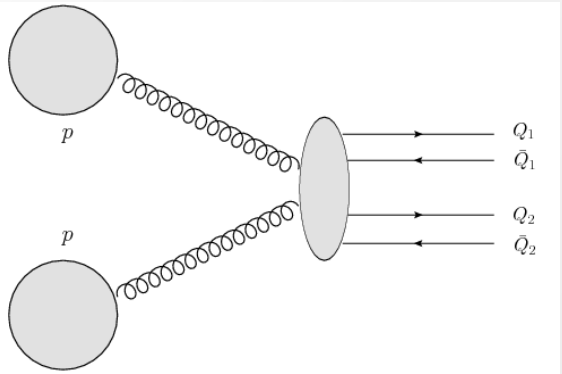
Double J/ψ production at $\sqrt{s} = 13\ TeV$ JHEP 1706 047

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

DPS



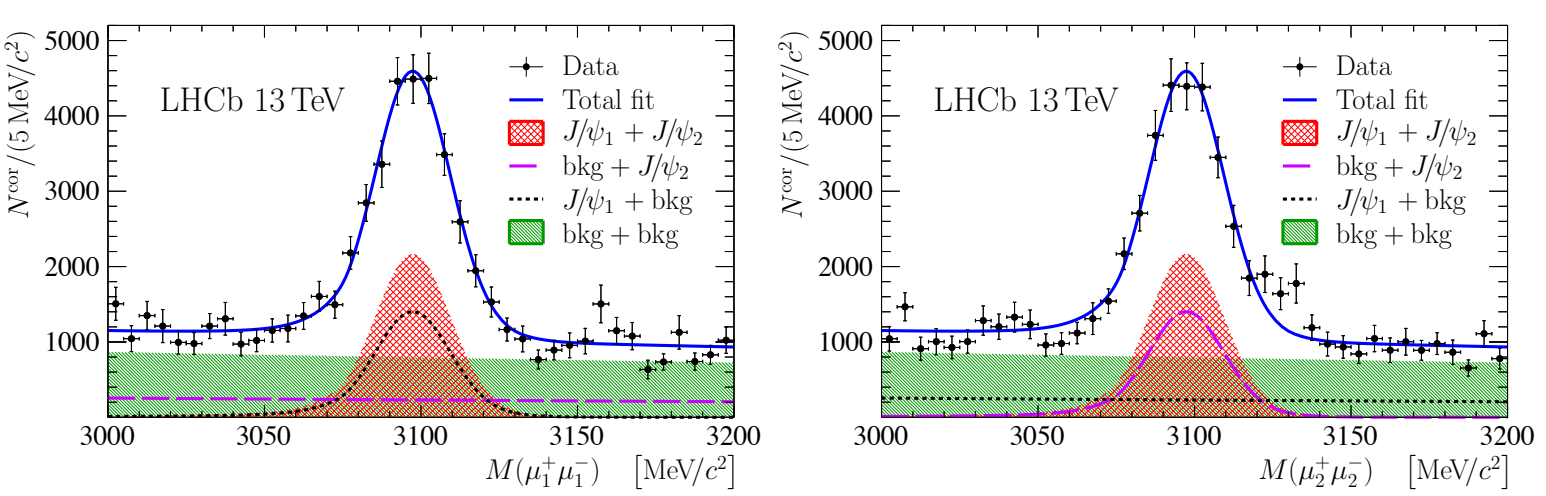
SPS



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

➜ DPS provides important information on gluon correlations and parton PT-distribution

- In LHCb studied using clean 4-muon signature:

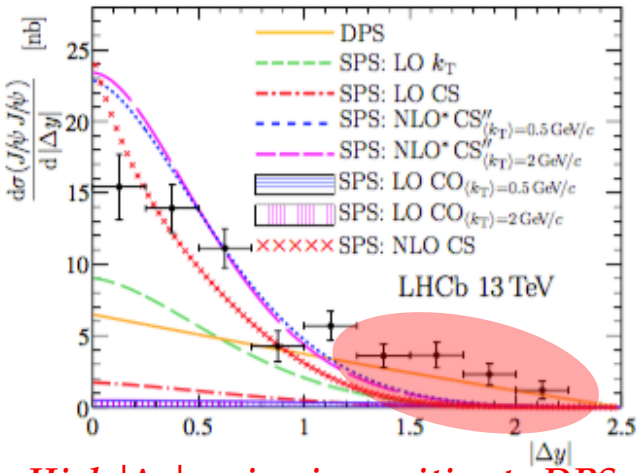


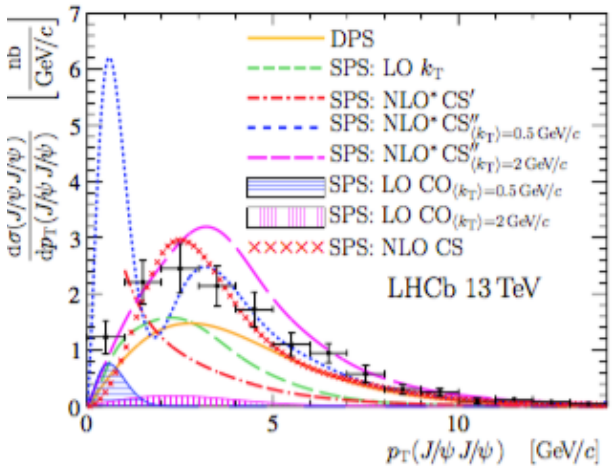
Double J/ψ production at $\sqrt{s} = 13\ TeV$

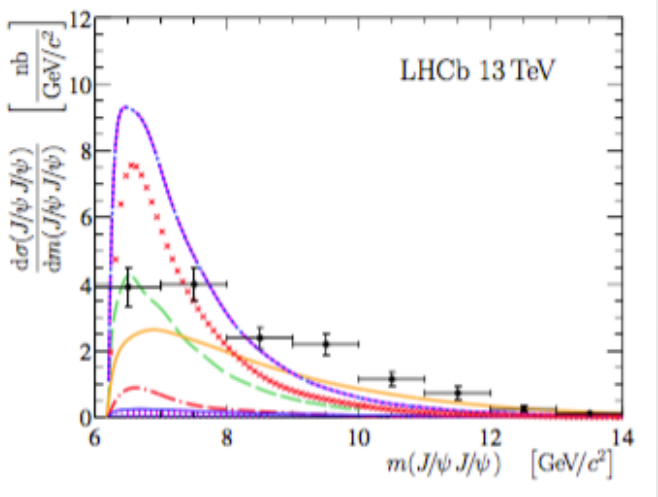
JHEP 1706 047

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

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







High $|\Delta y|$ region is sensitive to DPS

- Results show evidence of DPS contribution
- From fit of kinematical distributions **DPS fraction** and σ_{eff} are extracted

- **Values of σ_{eff} extracted from the fit of different kinematic variables using various SPS descriptions**

$$\sigma_{eff} = 10 - 12nb$$

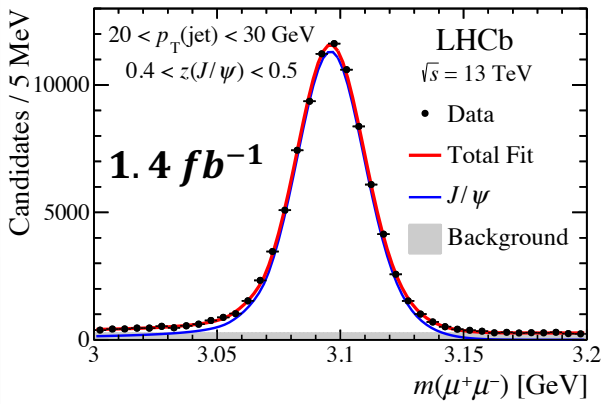
*agreement between fits of $|\Delta y|$, $p_T(J/\psi J/\psi)$, $y(J/\psi J/\psi)$, $m(J/\psi J/\psi)$

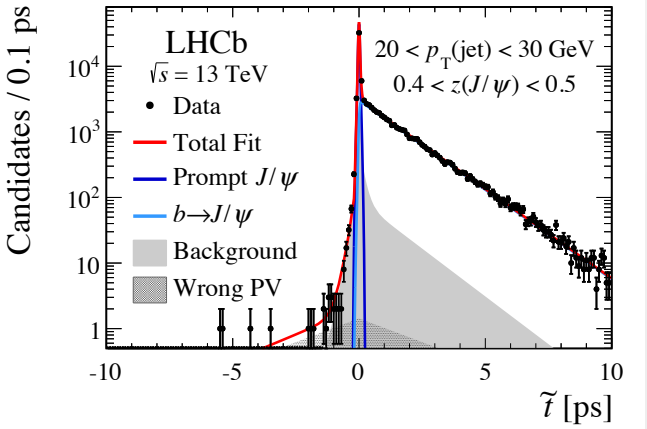
J/ψ production in jets at $\sqrt{s} = 13\ TeV$

PRL 118 192001

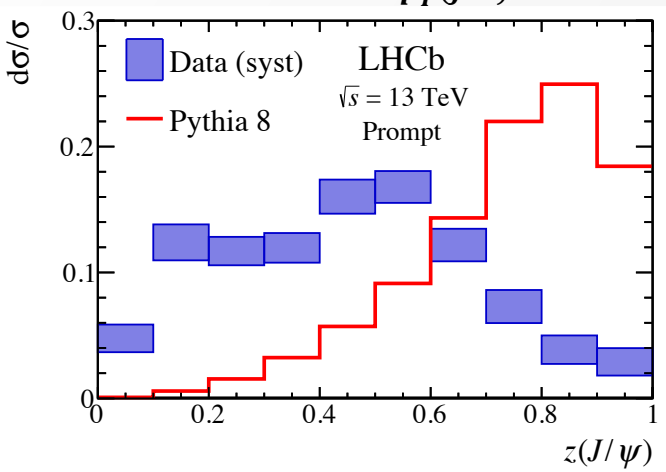
- J/ψ produced in **direct parton scattering** or **through parton showering**
- Additional flavor fixing constraints in hadronization
- Can explain the lack of observed polarization

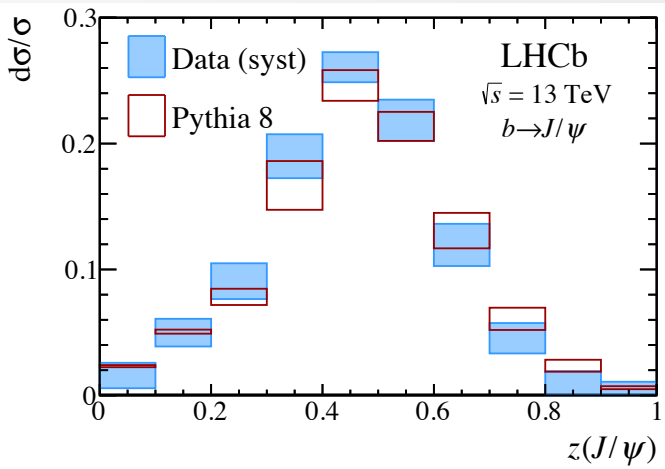
- Separate prompt and b-decays using fit of $\tilde{t}$ distribution $\quad \tilde{t} \equiv (z_{J/\psi} - z_{PV}) \frac{m\,(J/\psi)}{p_L(J/\psi)}$





- Perform fit in bins of $z(J/\psi) \equiv \frac{p_T\,(J/\psi)}{p_T(jet)}$





prompt J/ψ is observed to be
less isolated than in PYTHIA
➜ big contribution from parton showering

Prompt charm production at $\sqrt{s} = 5\ TeV$

arXiv:1610.02230

- Important test of perturbative QCD and factorization

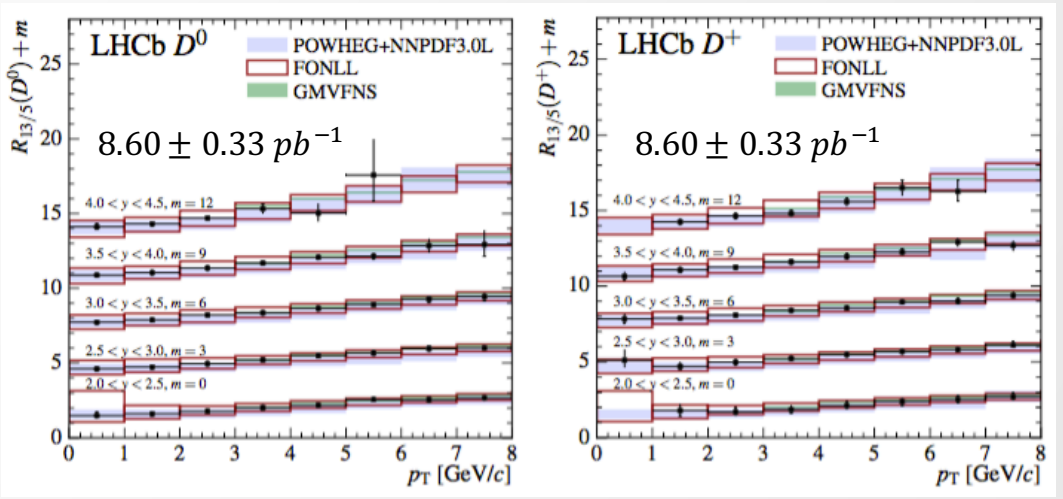
$$\begin{aligned}
\sigma(pp \to D^0 X) &= 1004 \pm 3 \pm 54\ \mu b, \\
\sigma(pp \to D^+ X) &= 402 \pm 2 \pm 30\ \mu b, \\
\sigma(pp \to D_s^+ X) &= 170 \pm 4 \pm 16\ \mu b, \\
\sigma(pp \to D^{*+} X) &= 421 \pm 5 \pm 36\ \mu b.
\end{aligned}$$

- Differential production cross sections
- Relative production cross-section ratios

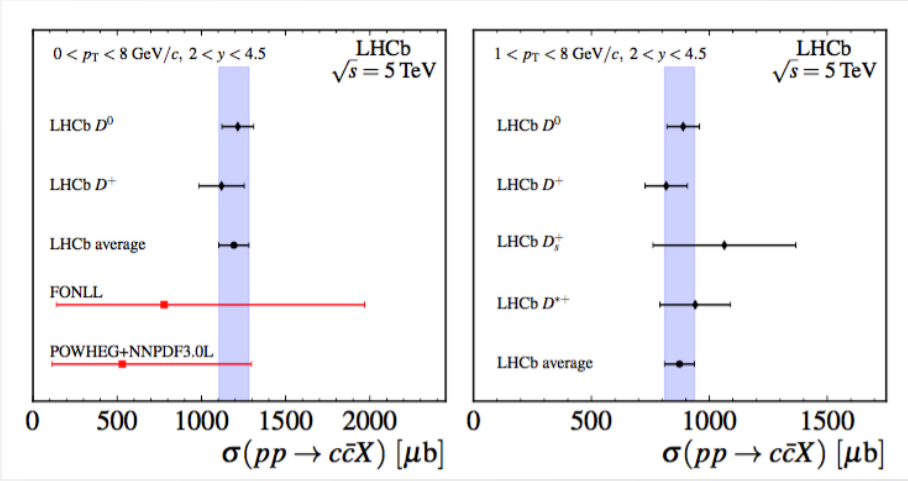
- **13/5 TeV production ratios :**

➜ more precise that previously presented for 13/7 TeV ratio

➜ general agreement with theoretical predictions



- $\sigma(b \to c\bar{c}X)$ extracted using known fragmentation f(c → D) PLB667 (2008) 1.



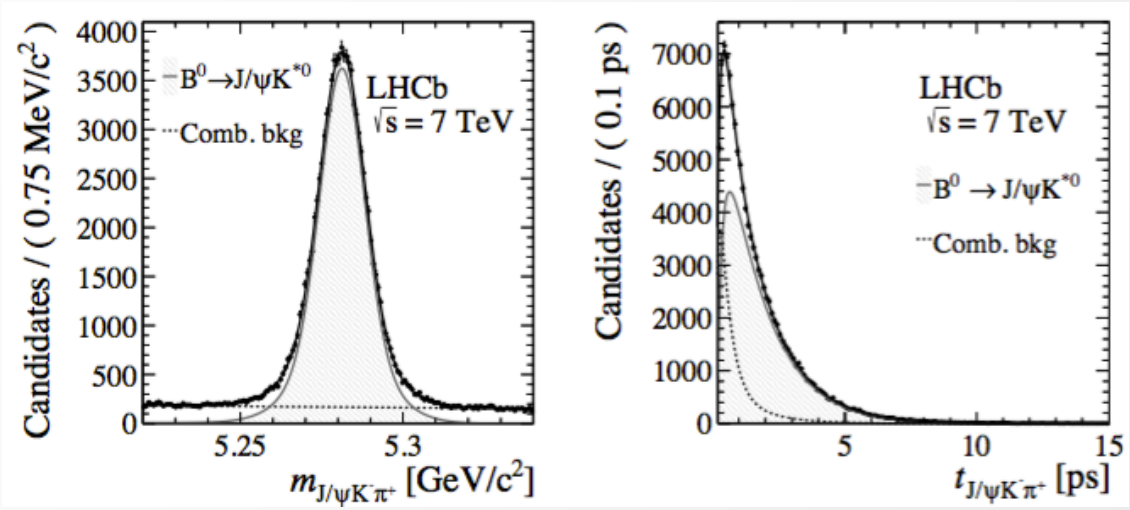
b –hadron production asymmetries at $\sqrt{s} = 7{,}8\ TeV$

arXiv:1703.08464

$$A_p = \frac{\sigma(\overline{H_b}) - \sigma(H_b)}{\sigma(\overline{H_b}) + \sigma(H_b)}$$

- Expected favoring H_b rather than $\overline{H_b}$ especially at high rapidity
- Inclusive b and $\bar{b}$ production are the same
- Key information for performing CP violation measurements

- $\boldsymbol{A_p(B^+)}$ accessed using final state charge of the decay $\boldsymbol{B^+ \longrightarrow J/\psi K^+}$
- $\boldsymbol{A_p(B^0)}$ and $\boldsymbol{A_p(B_s^0)}$ time dependent analysis performed to tag initial state using $\boldsymbol{B^0 \longrightarrow J/\psi K^*}$ and $\boldsymbol{B_s^0 \longrightarrow D_s^- \pi^+}$



$$\boldsymbol{A_{raw} = A_p + A_{CP} + A_{det}}$$

- $\boldsymbol{A_{CP}}$ - external information: theory or measurement
- $\boldsymbol{A_{det}}$ - determined from control samples

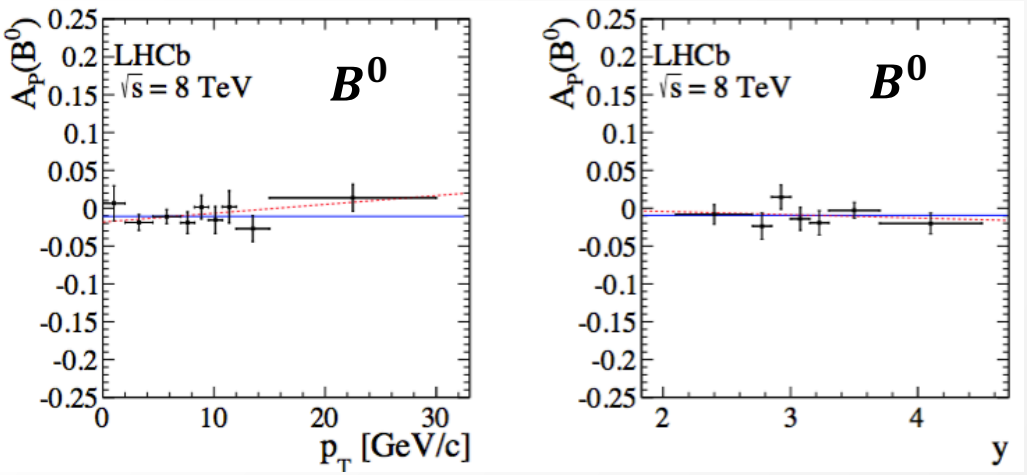
b –hadron production asymmetries at $\sqrt{s} = 7{,}8\ TeV$

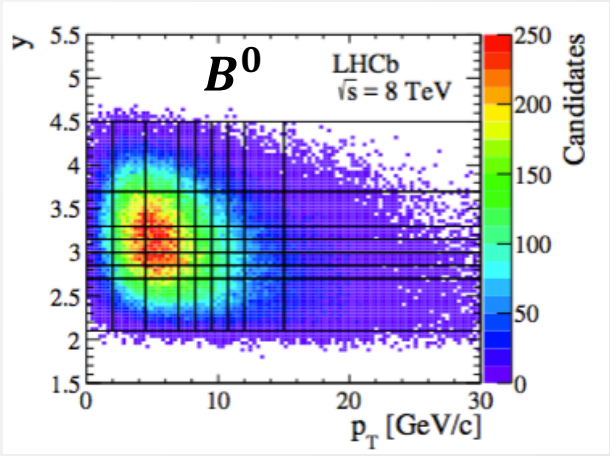
arXiv:1703.08464

- All results are consistent with zero:

$$
\begin{aligned}
A_{\rm P}(B^+)_{\sqrt{s}=7\,\rm TeV} &= -0.0023 \pm 0.0024\ (\rm stat) \pm 0.0037\ (\rm syst),\\
A_{\rm P}(B^+)_{\sqrt{s}=8\,\rm TeV} &= -0.0074 \pm 0.0015\ (\rm stat) \pm 0.0032\ (\rm syst),\\
A_{\rm P}(B^0)_{\sqrt{s}=7\,\rm TeV} &= 0.0044 \pm 0.0088\ (\rm stat) \pm 0.0011\ (\rm syst),\\
A_{\rm P}(B^0)_{\sqrt{s}=8\,\rm TeV} &= -0.0140 \pm 0.0055\ (\rm stat) \pm 0.0010\ (\rm syst),\\
A_{\rm P}(B^0_s)_{\sqrt{s}=7\,\rm TeV} &= -0.0065 \pm 0.0288\ (\rm stat) \pm 0.0059\ (\rm syst),\\
A_{\rm P}(B^0_s)_{\sqrt{s}=8\,\rm TeV} &= 0.0198 \pm 0.0190\ (\rm stat) \pm 0.0059\ (\rm syst),
\end{aligned}
$$

- Production asymmetries studied in bins of (p_T, η)





fitted by $A_p = ay + b$:

y	$\sqrt{s} = 8$ TeV		
	B^+	B^0	B^0_s
$a\,[10^{-4}]$	-86 ± 29	-44 ± 100	-217 ± 321
$b\,[10^{-3}]$	19 ± 9	-4 ± 32	85 ± 105
$\rho(m, q)$	-0.93	-0.99	-0.98

No evidence for any dependence is observed

b –hadron production asymmetries at $\sqrt{s} = 7{,}8\ TeV$

arXiv:1703.08464

- For Λ_b^0 determined indirectly

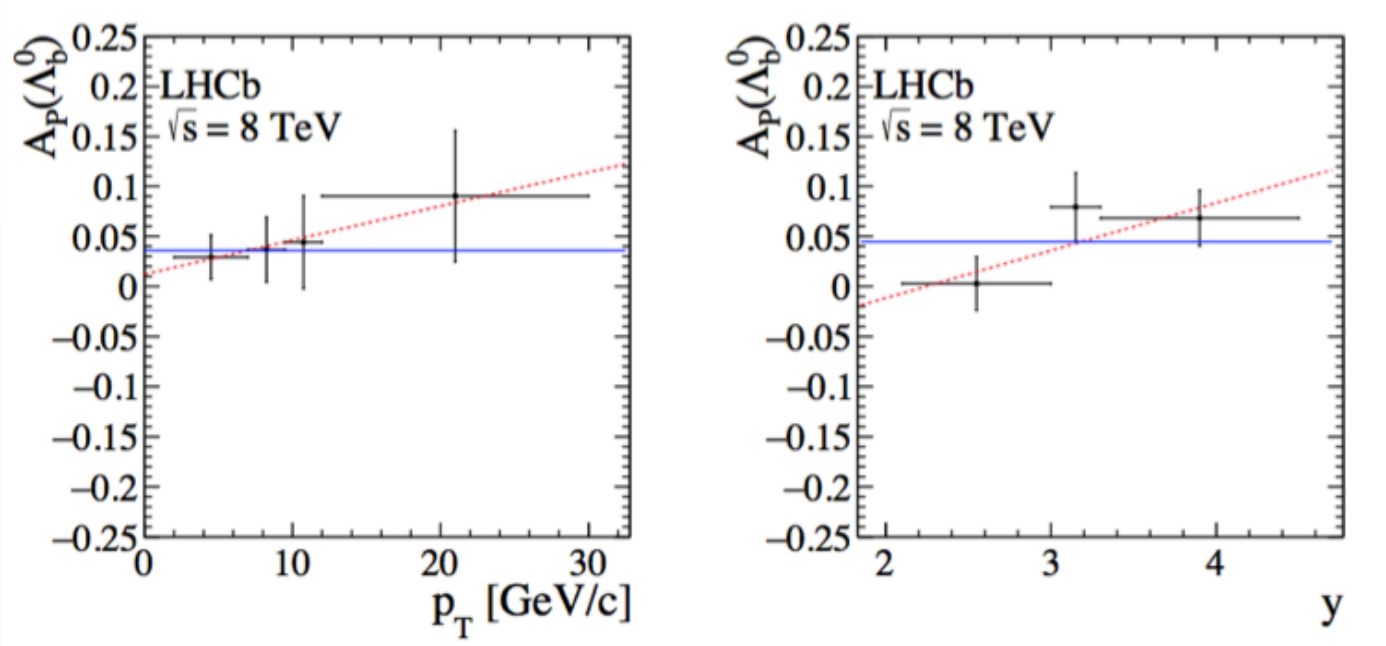
$$A_P(\Lambda_b^0) = -\left(\frac{f_u}{f_{\Lambda_b^0}} A_P(B^+) + \frac{f_d}{f_{\Lambda_b^0}} A_P(B^0) + \frac{f_s}{f_{\Lambda_b^0}} A_P(B_s^0) + \underbrace{\frac{f_c}{f_{\Lambda_b^0}} A_P(B_c^+) + \frac{f_{other}}{f_{\Lambda_b^0}} A_P(other)}_{estimated\ to\ be\ 2\times10^{-3}}\right)$$

*using previous measurement of $\frac{f_q}{f_{\Lambda_b^0}}$

- Results are consistent with zero:

$$A_P(\Lambda_b^0)_{\sqrt{s}=7\,\text{TeV}} = -0.0011 \pm 0.0253\ (\text{stat}) \pm 0.0108\ (\text{syst}),$$
$$A_P(\Lambda_b^0)_{\sqrt{s}=8\,\text{TeV}} = 0.0344 \pm 0.0161\ (\text{stat}) \pm 0.0076\ (\text{syst}).$$

- Slight increase with p_T and η (was seen by direct measurement **Chin.Phys. C40 011001**)

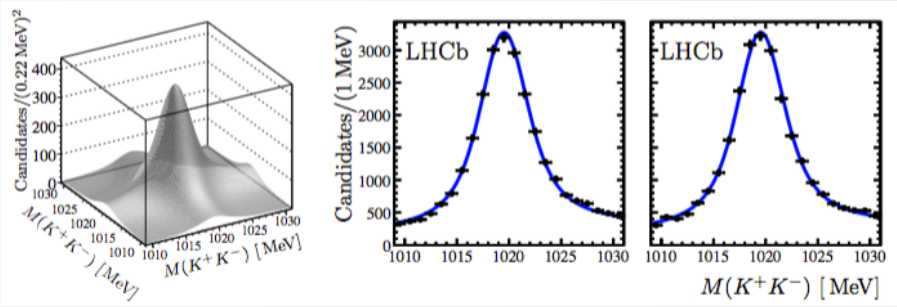


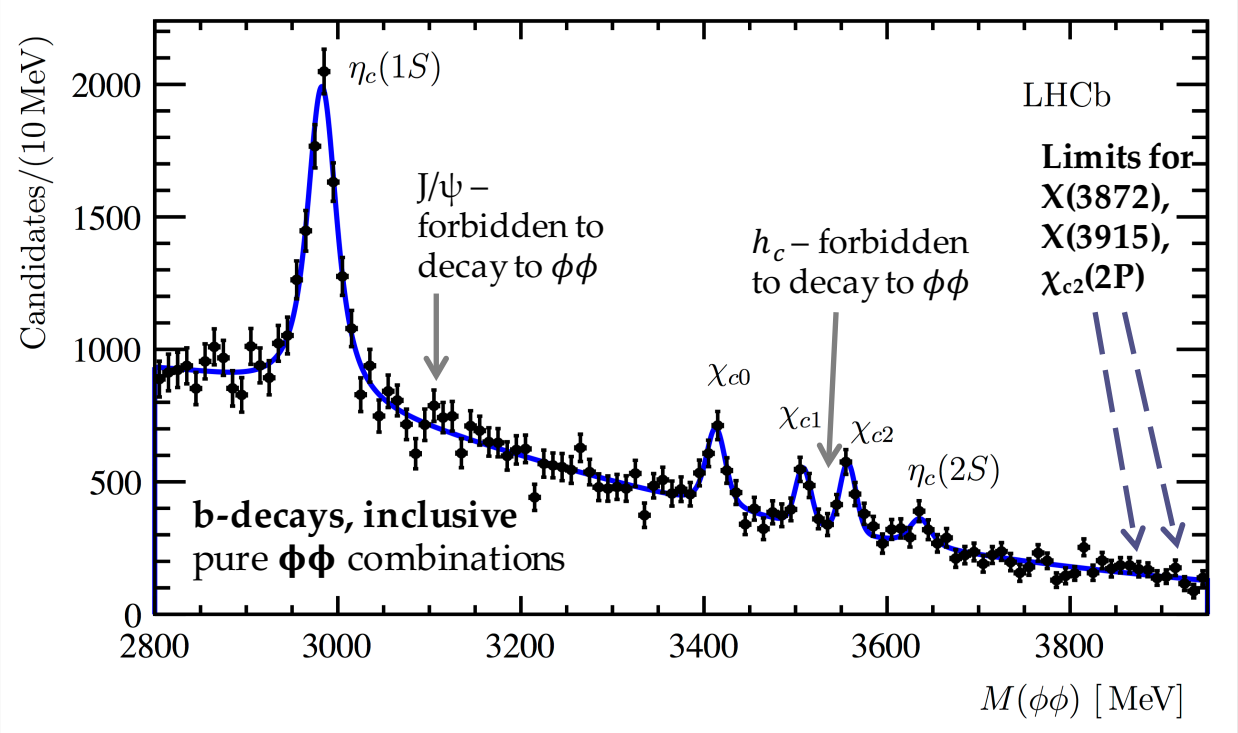
χ_c and $\eta_c(2S)$ production in inclusive b-decays using $\phi\phi$ at $\sqrt{s} = 7{,}8\ TeV$

arXiv:1706.07013

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

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

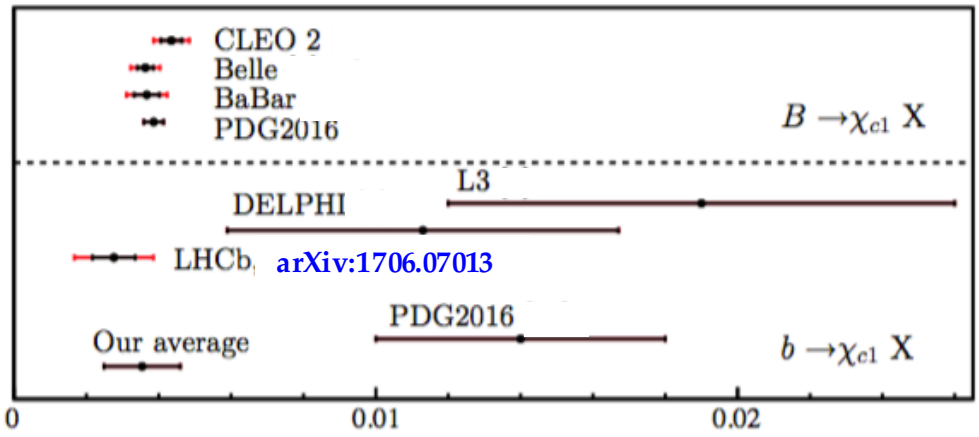


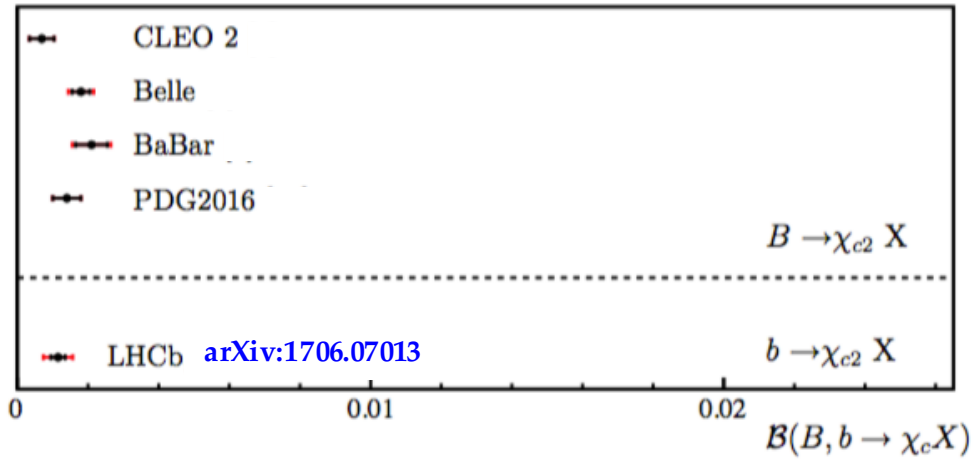


- χ_c and $\eta_c(2S)$ production rates measured using previously measured BR$(b \to \eta_c(1S)X)$

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

- First measurement of χ_{c0} production in inclusive b-decays **arXiv:1706.07013**
- The most precise measurements of $\boldsymbol{BR(b \to \chi_{c1} X)}$ and $\boldsymbol{BR(b \to \chi_{c2} X)}$
- $\boldsymbol{BR(b \to \chi_{c1} X)}$ and $\boldsymbol{BR(b \to \chi_{c2} X)}$ are in agreement with measurements at B-factories

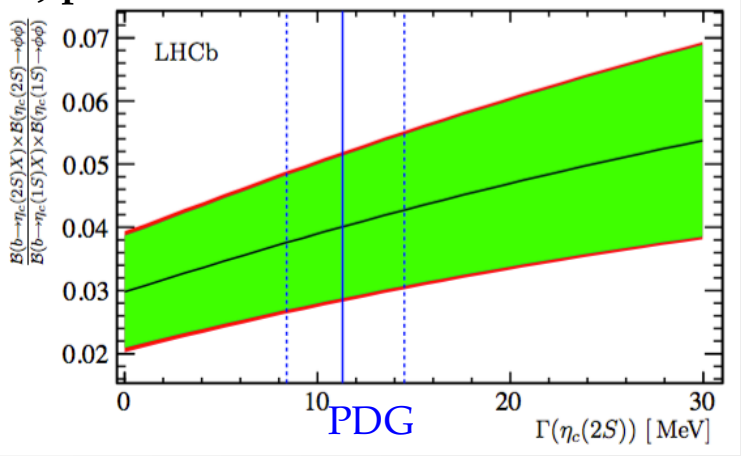




- First measurement of $\eta_c(2S)$ production in inclusive b-decays; first evidence of $\eta_c(2S) \longrightarrow \phi\phi$

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

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



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

Updated production measurements

- Several production measurements were performed very promptly
- Realized that was a problem in MC simulation efficiencies

- VELO simulation was updated (for Run II) to take into account **radiation damage**
  - One of the effect arises from charge induction on second metal layer routine lines
  - An error was made in parametric implementation of these effects

  ➜ **track reconstruction efficiency was underestimated** in simulation for tracks with **low η**

Updated measurements:

- Prompt charm production at $\sqrt{s} = 5\ TeV$ [updated, resubmitted arXiv:1610.02230]
- Prompt charm production at $\sqrt{s} = 13\ TeV$ [updated, published JHEP 09 (2016) 013]
- J/ψ production at $\sqrt{s} = 13\ TeV$ [updated, published JHEP 1705 063]
- Double J/ψ production at $\sqrt{s} = 13\ TeV$ [updated, published JHEP 1706 047]

J/ψ production at $\sqrt{s} = 13\ TeV$, updated JHEP 1705 063

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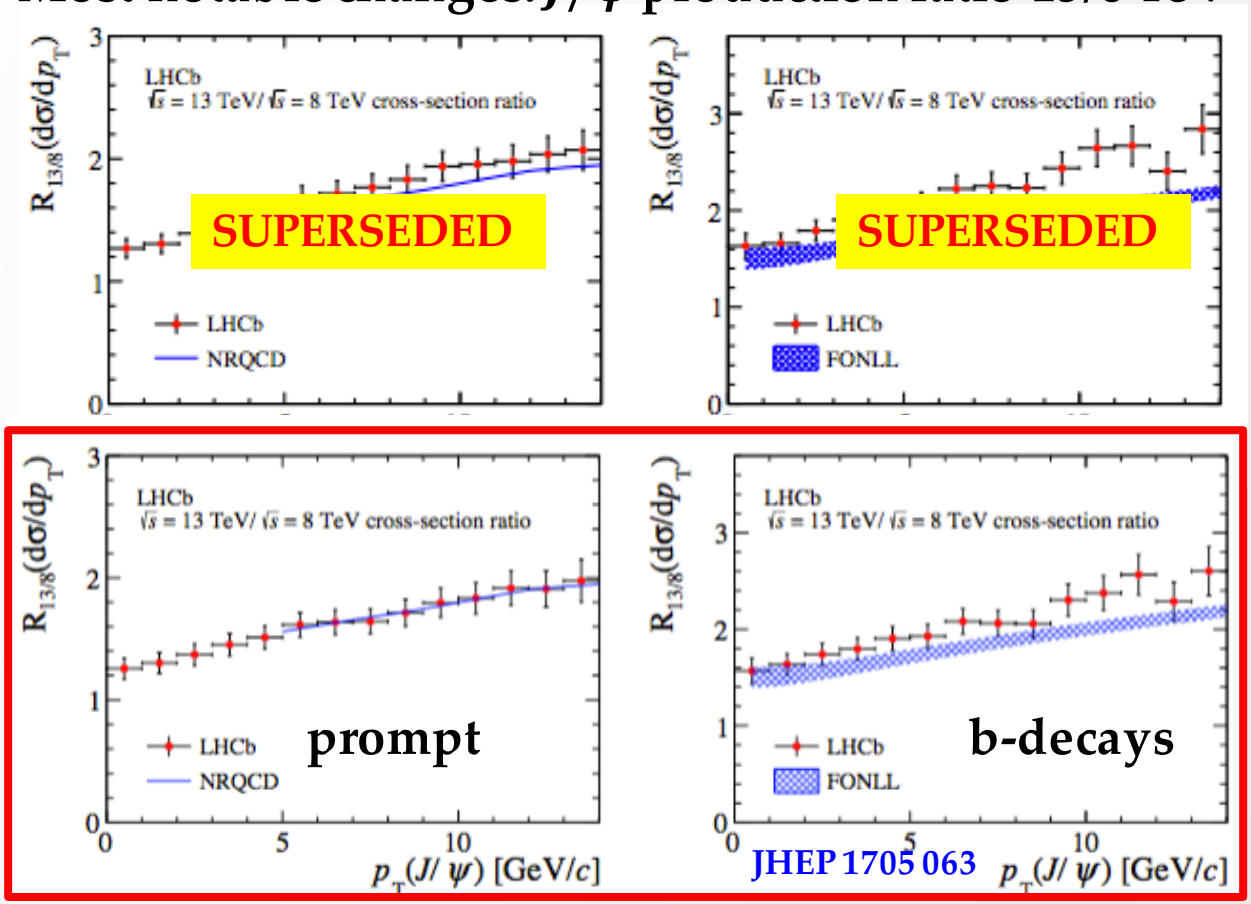
Most notable changes: J/ψ production ratio 13/8 TeV



Better agreement with theory for both prompt J/ψ and J/ψ from b-decays

Summary

Significant LHCb contribution to study of heavy flavour production mechanisms

- Double J/ψ production
  ➜ study of Double Parton Scattering
- J/ψ production in jets
  ➜ important to explain J/ψ polarization and for MC generators
- $b-$hadron production asymmetries
  ➜ key ingredient to perform CP violation measurements
- Prompt charm production
  ➜ test of perturbative QCD
- χ_c and $\eta_c(2S)$ production in inclusive b-decays
  ➜ aiming to test NRQCD together with prompt production measurements

More results in progress with Run II data

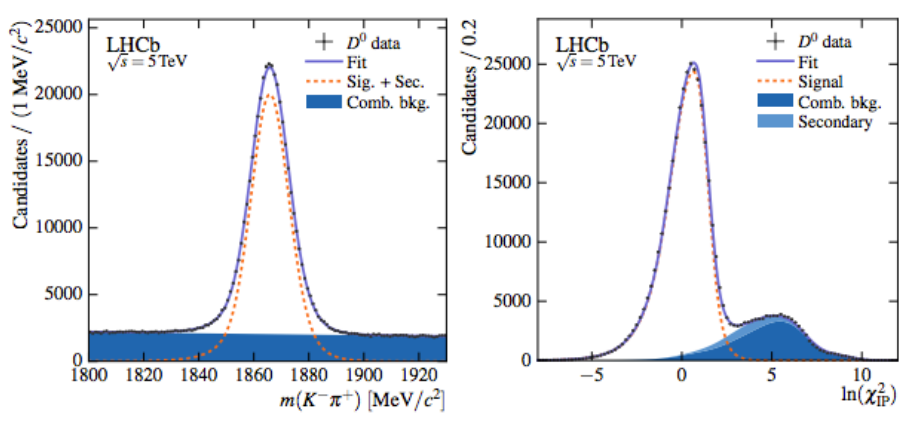
Prompt charm production at $\sqrt{s} = 5\ TeV$

Analysis

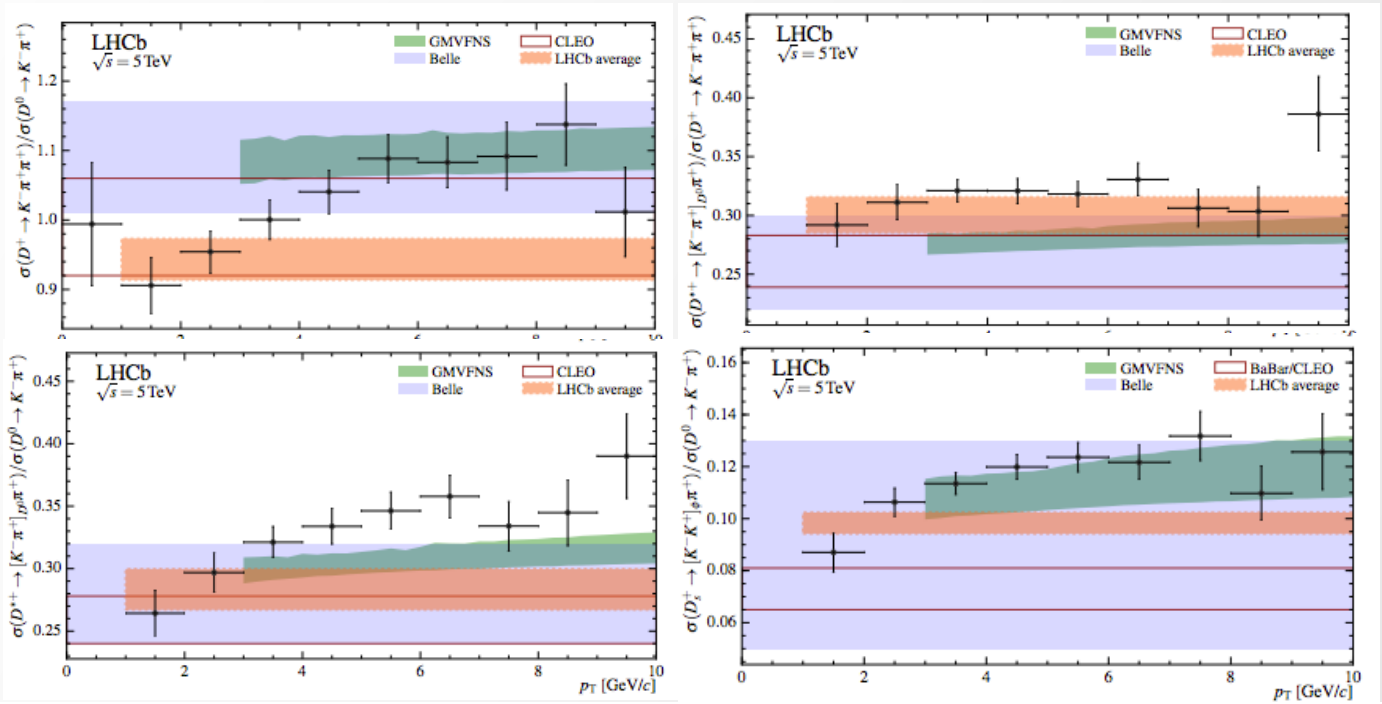
- Measured using decays:

$$D^0 \to K^-\pi^+$$
$$D^+ \to K^-\pi^+\pi^+$$
$$D_s^+ \to (K^-K^+)_\phi\pi^+$$
$$D^{*+} \to D^0\pi^+$$

- Invatiant mass and $\ln(\chi^2_{IP})$ fits in bins of (p_T, η) to extract signal yields



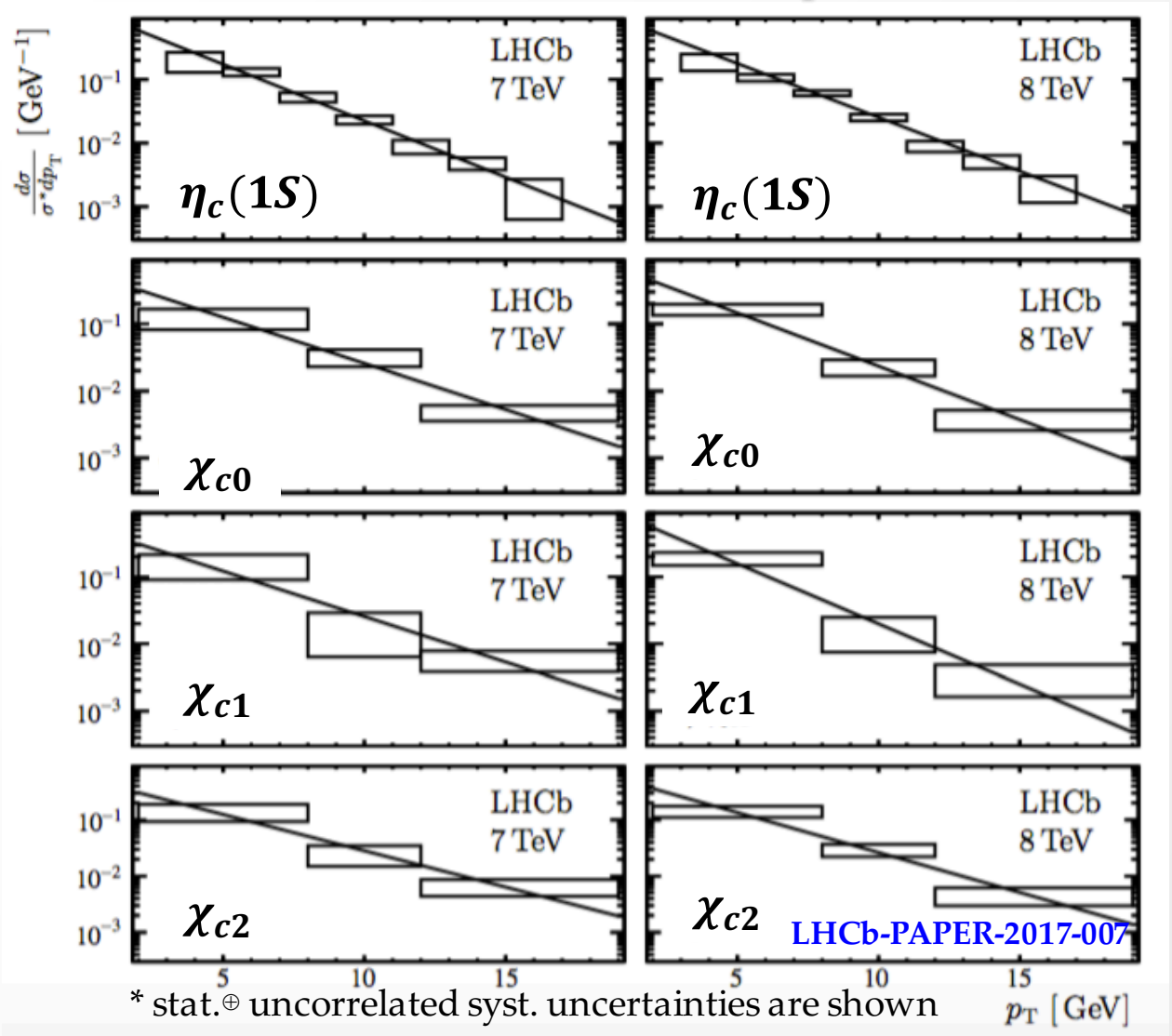
Results:



$$S(t,\psi) \propto [1-\psi(A_{CP}+A_D)] \left\{ e^{-\Gamma_{d(s)}t} \left[\Lambda_+ \cosh\left(\frac{\Delta\Gamma_{d(s)}t}{2}\right) + \psi\Lambda_- \cos\left(\Delta m_{d(s)}t\right) \right] \otimes R(t) \right\} \epsilon(t)$$

$$\Lambda_\pm \equiv (1-A_{\rm P}) \left|\frac{q}{p}\right|^{1-\psi} \pm (1+A_{\rm P}) \left|\frac{q}{p}\right|^{-1-\psi}$$

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



* stat.$\oplus$ uncorrelated syst. uncertainties are shown

Exponential slopes of normalized differential prodcution cross-section are extracted:

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