Recent results on heavy flavour production at LHCb

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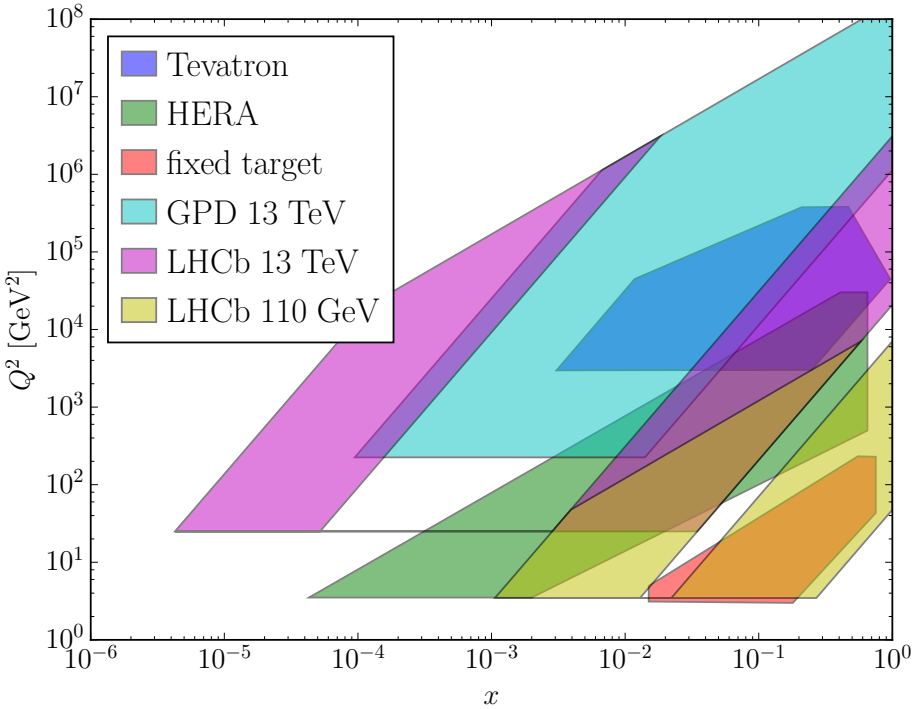
on behalf of the LHCb Collaboration

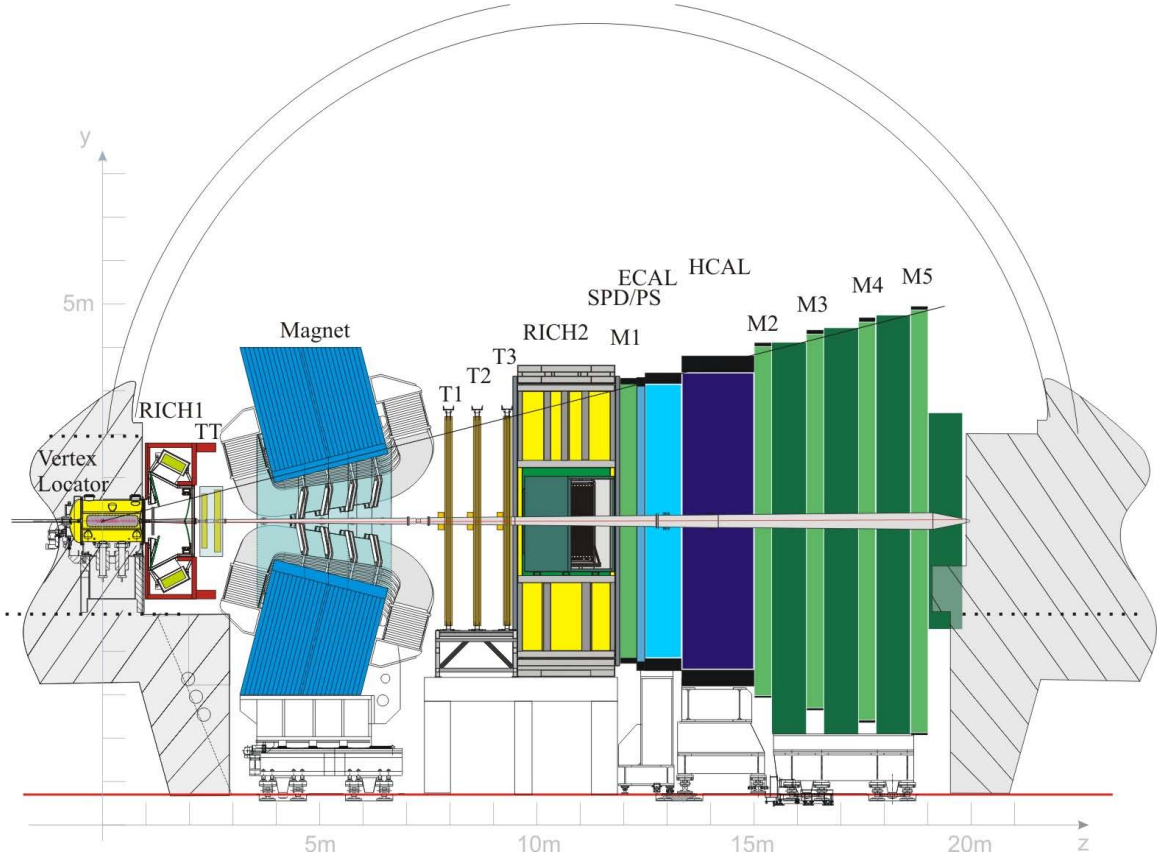
Overview

- LHCb provides a unique coverage for production studies
- Complementary to other experiments
- Results cover top, beauty and charm production
- Only covering analyses of *pp* datasets
- See Matt's talk tomorrow for heavy ion results



The LHCb Detector

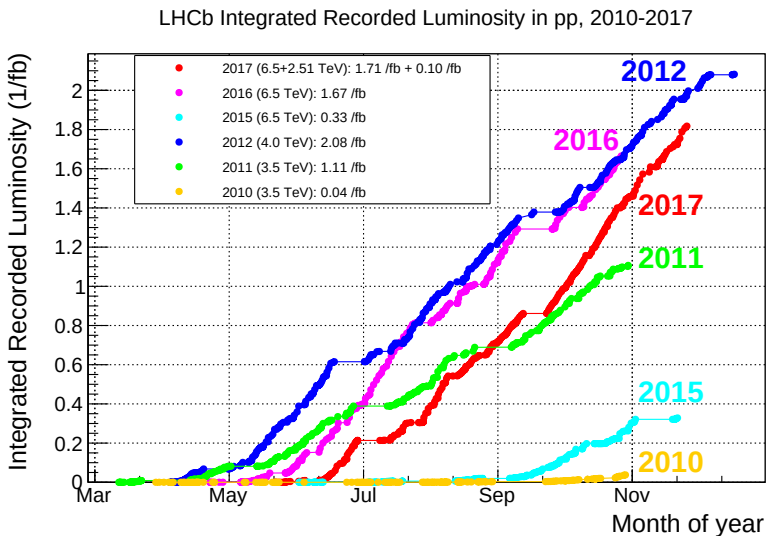
JINST **3** (2008) S08005



- Instrumentation in the forward region ($2 < \eta < 5$)
- Excellent secondary vertex reconstruction
- Precise tracking before and after magnet

LHCb *pp* datasets

Run	Year	$\sqrt{s}$	$\mathcal{L}$
Run 1	2010	7 TeV	$0.04\,\text{fb}^{-1}$
	2011	7 TeV	$1.11\,\text{fb}^{-1}$
	2012	8 TeV	$2.08\,\text{fb}^{-1}$
Run 2	2015	13 TeV	$0.33\,\text{fb}^{-1}$
	2016	13 TeV	$1.67\,\text{fb}^{-1}$
	2017	13 TeV	$1.71\,\text{fb}^{-1}$
	2015	5 TeV	$0.01\,\text{fb}^{-1}$
	2017	5 TeV	$0.10\,\text{fb}^{-1}$



Production in pp @ LHCb

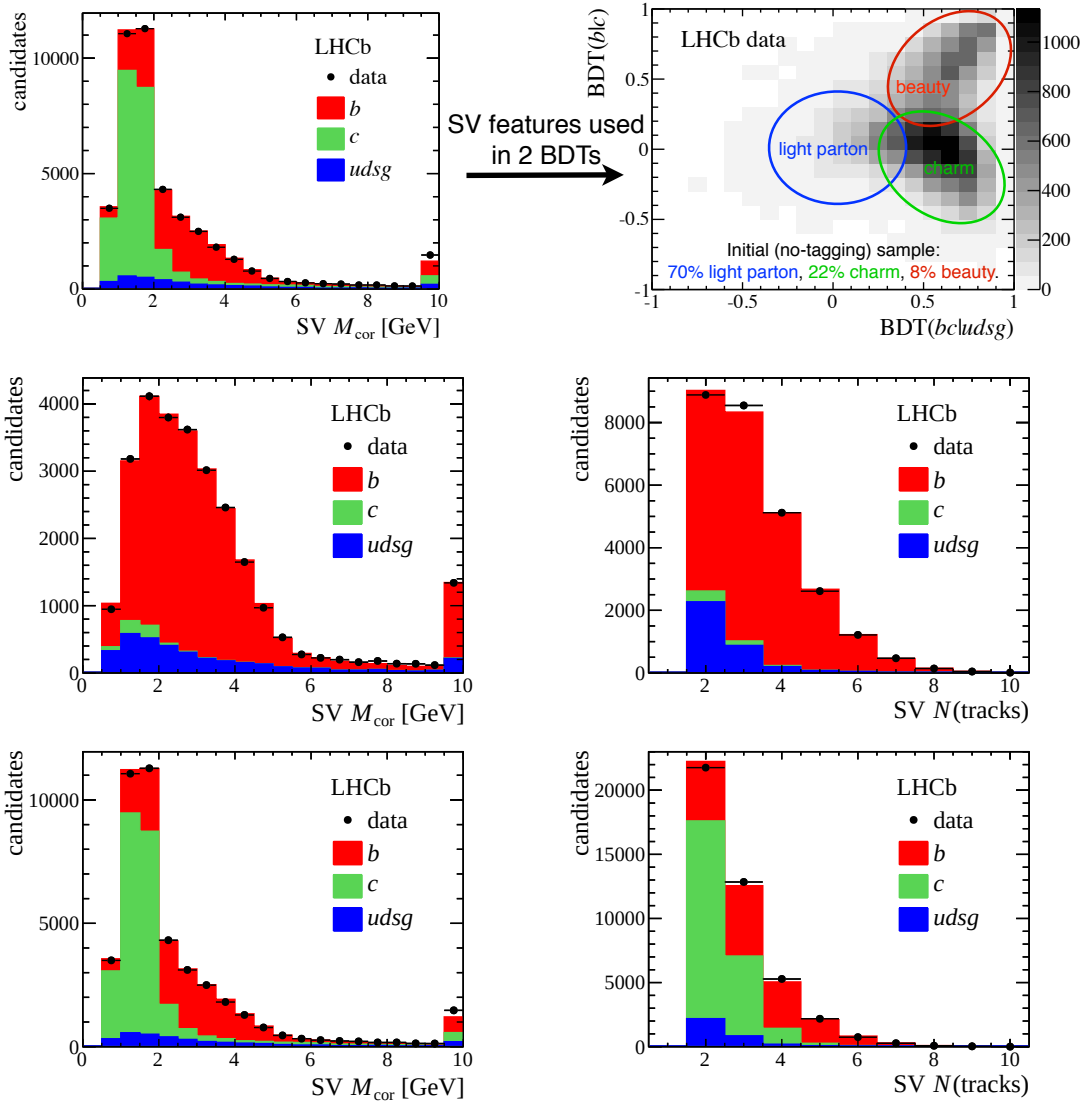
- Wide range of heavy flavour production results
  - Table not exhaustive
- Impossible to cover everything
- Will focus on **some new results** from the last year

Measurement	$\sqrt{s}$ (TeV)				
	2.76	5	7	8	13
D production		✓	✓		✓
D^+ prod. asym.			✓		
D_s^+ prod. asym.			✓		
J/ψ production	✓		✓	✓	✓
$J/\psi + J/\psi$ prod.			✓		✓
$J/\psi + D$ prod.			✓		
J/ψ in jets					✓
$W + c$			✓	✓	
$W + c\bar{c}$				✓	
B production			✓		✓
B prod. asym.			✓	✓	
$B\bar{B}$ prod. corr.			✓	✓	
Υ production	✓		✓	✓	
Υ polarisation			✓	✓	
$\Upsilon + D$ prod.			✓	✓	
$W + b$			✓	✓	
$Z + b$			✓		
$W + b\bar{b}$				✓	
t production			✓	✓	
$t\bar{t}$ prod.				✓	
...			...		

Jet flavour tagging @ LHCb

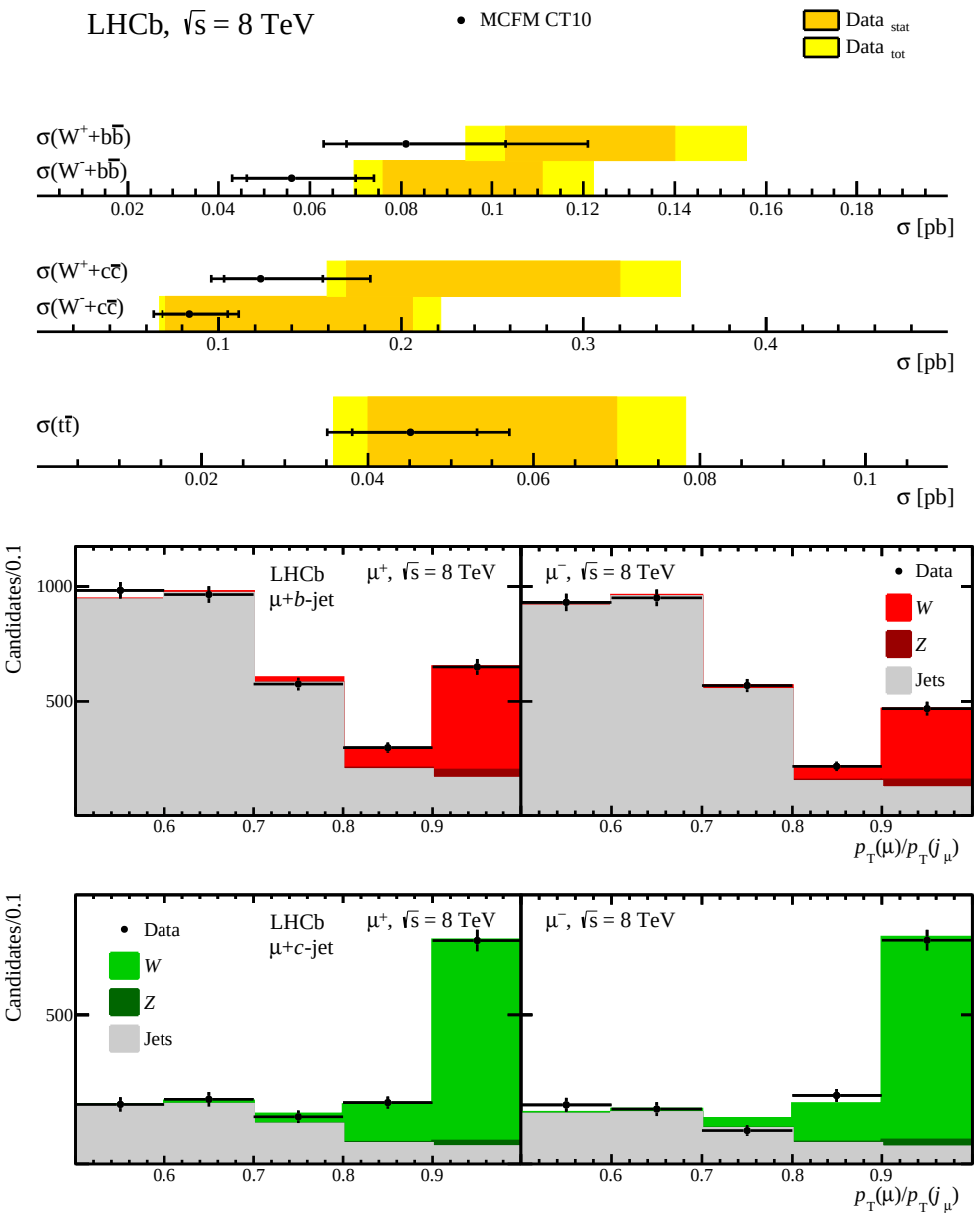
JINST **10** (2015) P06013

- BDTs developed to tag jets in Run 1 data
- Efficiency determined on flavour-enriched samples
  - *e.g.* tagged by fully reconstructed (middle) B or (bottom) D decays on "other" jet
- 2D fit to corrected mass and track multiplicity of reconstructed secondary vertices also gives good separation of jet flavours



Jet studies @ LHCb

PLB **767** (2017) 110 PR**D92** (2015) 052001

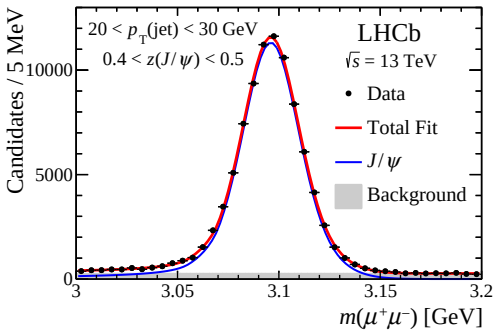


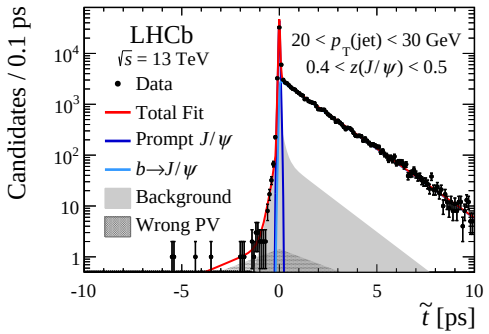
- Too many jet production studies to cover everything
- Run 1 studies of heavy jet and dijet production in association with W/Z bosons
  - Cross sections in good agreement with calculations

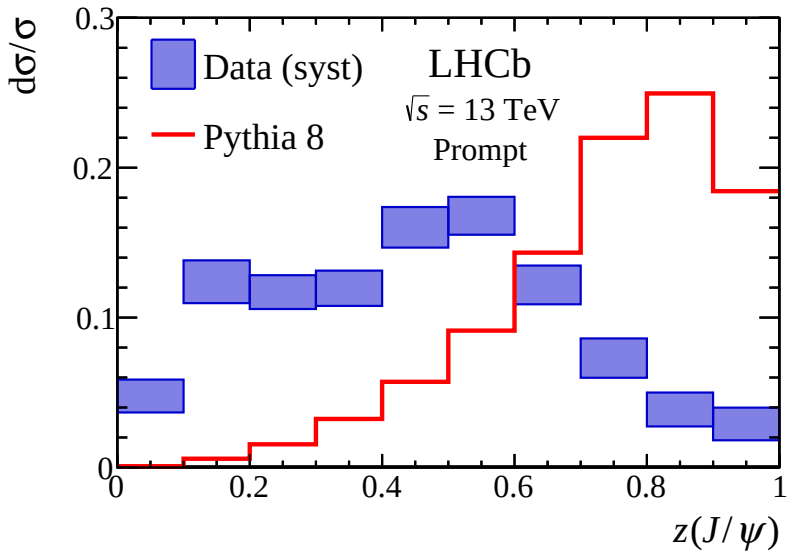
J/ψ in jets

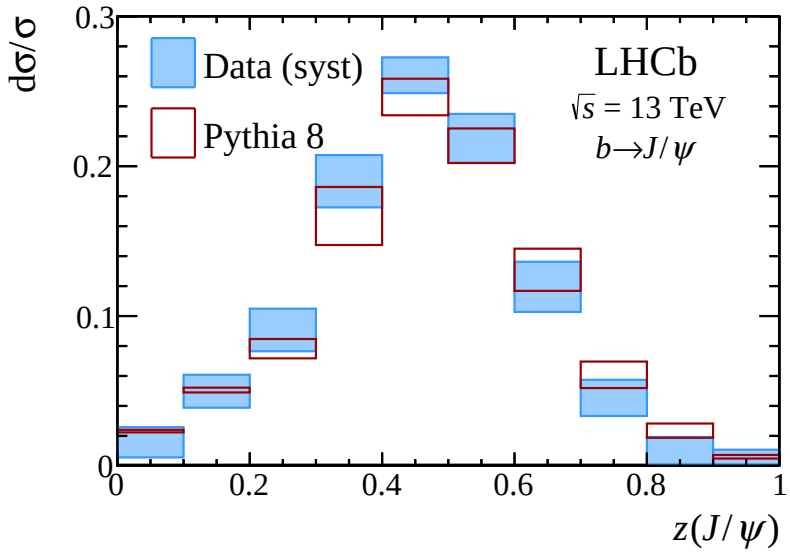
PRL **118** (2017) 192001

- Run 2 study of prompt and displaced J/ψ candidates in jets
  - Good mass and pseudo-decay-time resolution
  - p_{T} fraction carried by the J/ψ meson consistent with expectations for b jets
  - p_{T} fraction of prompt J/ψ mesons do not agree with expectations
  - First experimental measurement of p_{T} fraction for prompt J/ψ mesons in jets



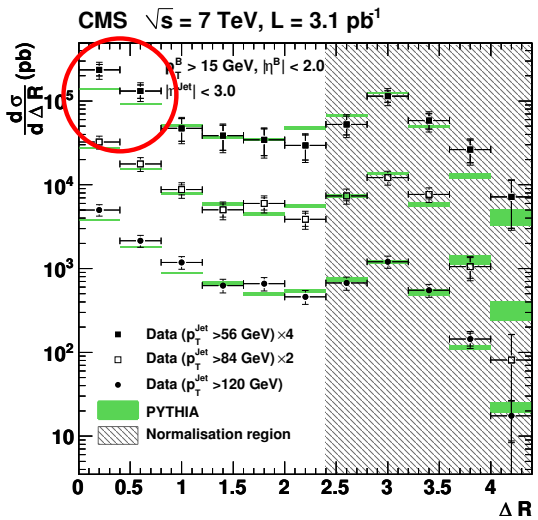


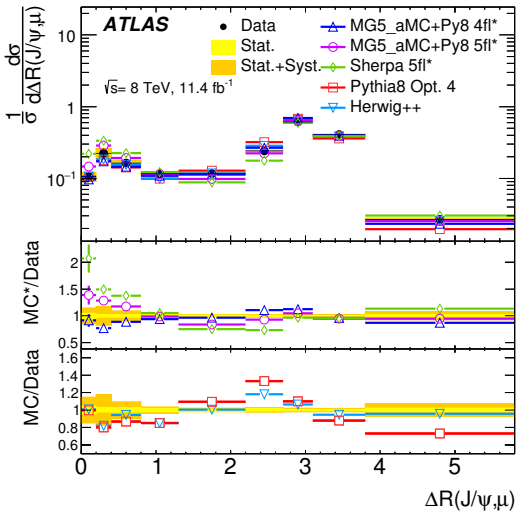




$b\bar{b}$ correlations

- Kinematic correlations between a heavy quark–antiquark pair can improve understanding of production mechanisms
- CDF, D0 and LHCb studies of $c\bar{c}$ correlations have identified gluon splitting, flavour-creation and flavour-excitation contributions
- $b\bar{b}$ correlations studied in $p\bar{p}$ by UA1, D0 and CDF and pp by CMS and Atlas





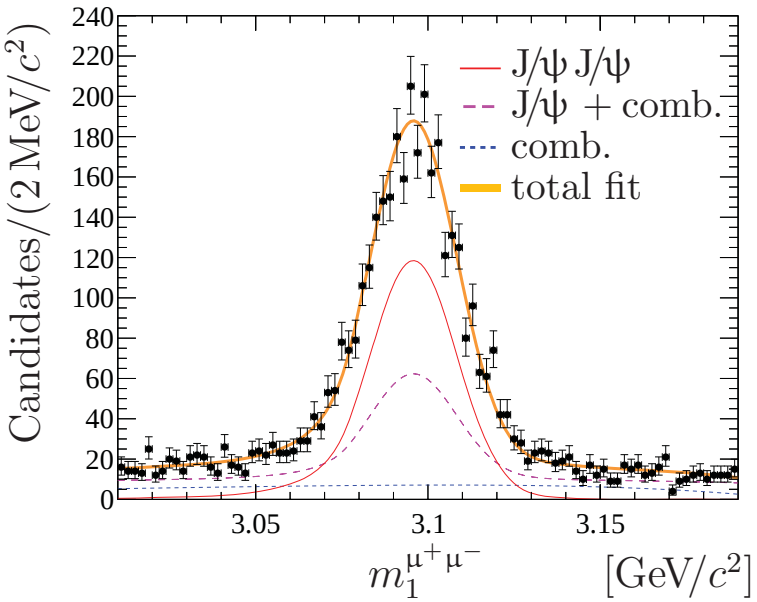
Plots reproduced from

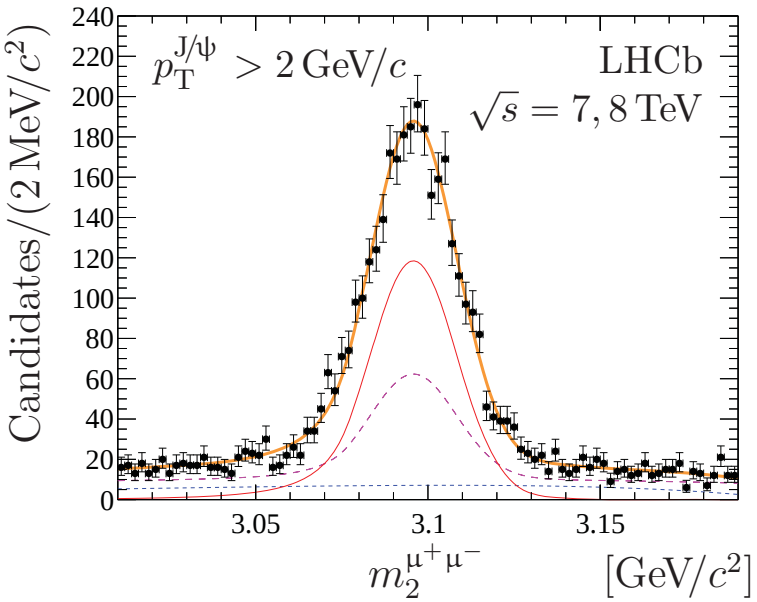
JHEP **03** (2011) 136 and

JHEP **11** (2017) 062

Nucl. Phys.Proc. Suppl. **170** (2007) 243
DIS (2007) 829
JHEP **06** (2012) 141
Z. Phys. **C61** (1994) 41
Phys. Lett. **B487** (2000) 264
Phys. Rev. **D55** (1997) 2546
Phys. Rev. **D61** (2000) 032001
Phys. Rev. **D71** (2005) 092001
Phys. Rev. **D77** (2008) 072004
JHEP **03** (2011) 136
JHEP **11** (2017) 062

$b\bar{b}$ correlations

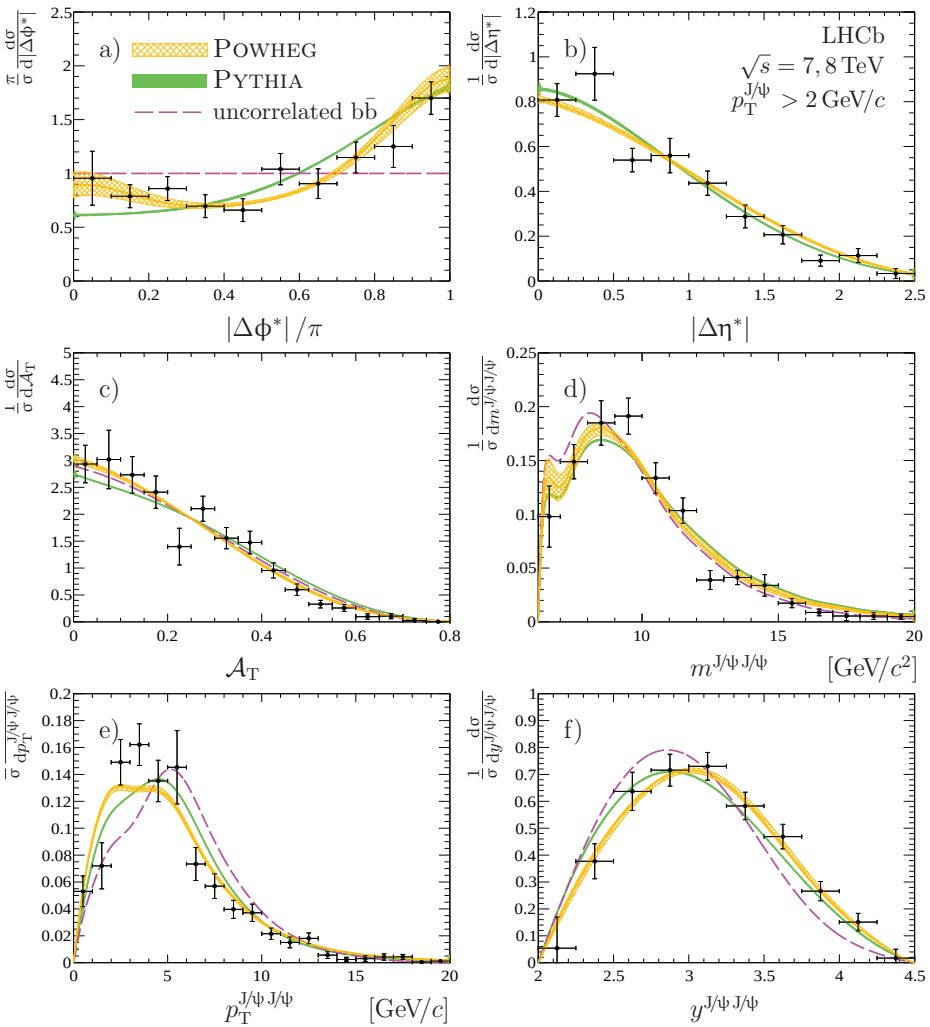




- *b* candidates reconstructed in $J/\psi(\rightarrow \mu^+\mu^-)X$ final state
- J/ψ candidates from both *b* candidates required to be associated with the same primary vertex have significantly displaced decay vertices
- 2D fit performed to the two dimuon invariant masses
- *sPlot* technique used to isolate signal component
- Normalised differential cross section determined as a function kinematic variables using efficiency-corrected yields

$b\bar{b}$ correlations

JHEP **11** (2017) 030



Cross section as a function of:

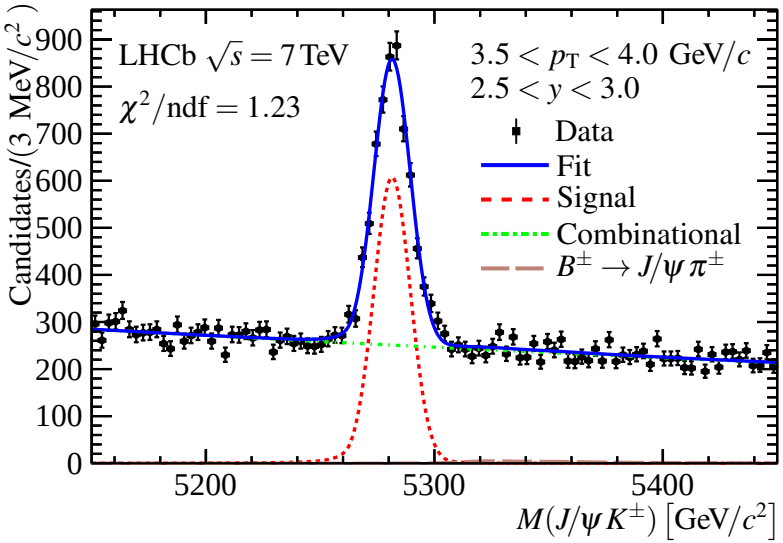
- relative azimuthal angle and pseudorapidity of beauty hadrons
- $p_{\rm T}$ asymmetry between J/ψ
- mass, $p_{\rm T}$ and rapidity of J/ψ pair

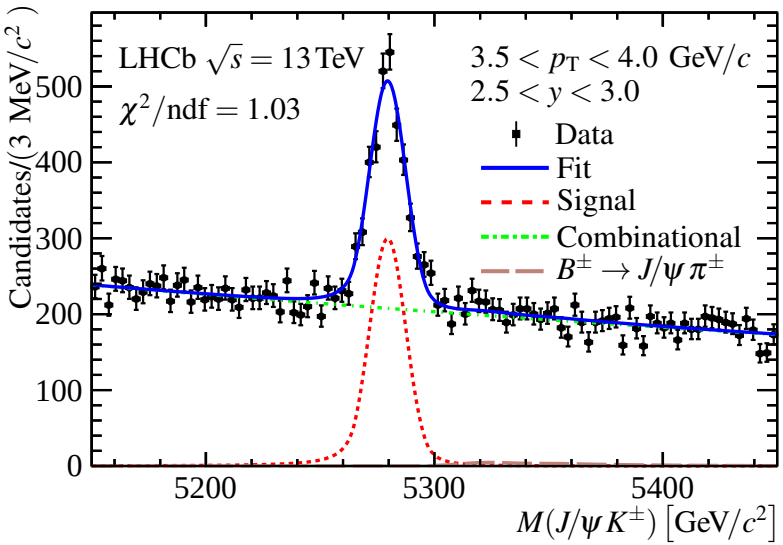
Good agreement with calculations

- NLO effects are small in this region *cf.* experimental precision
- no significant gluon splitting at small $|\Delta\phi^*|$

B^+ production @ 7 and 13 TeV

JHEP **12** (2017) 026





- Previous LHCb studies of $B^\pm$ production at 7 TeV performed in 2010 and 2011
- Recent analysis updates these results and adds measurements for 13 TeV
- Based on 1.0 fb^{-1} of data at 7 TeV and 362 pb^{-1} at 13 TeV
- $B^\pm$ reconstructed from the $J/\psi\,K^\pm$ final state
- cross sections measured in range $0 < p_T < 40$ GeV/c and $2.0 < y < 4.5$.

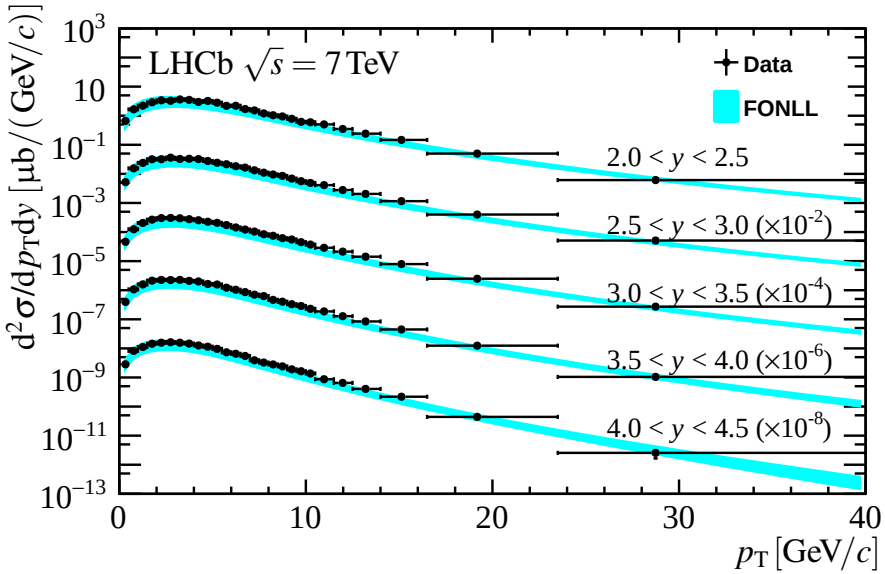
B^+ production @ 7 and 13 TeV

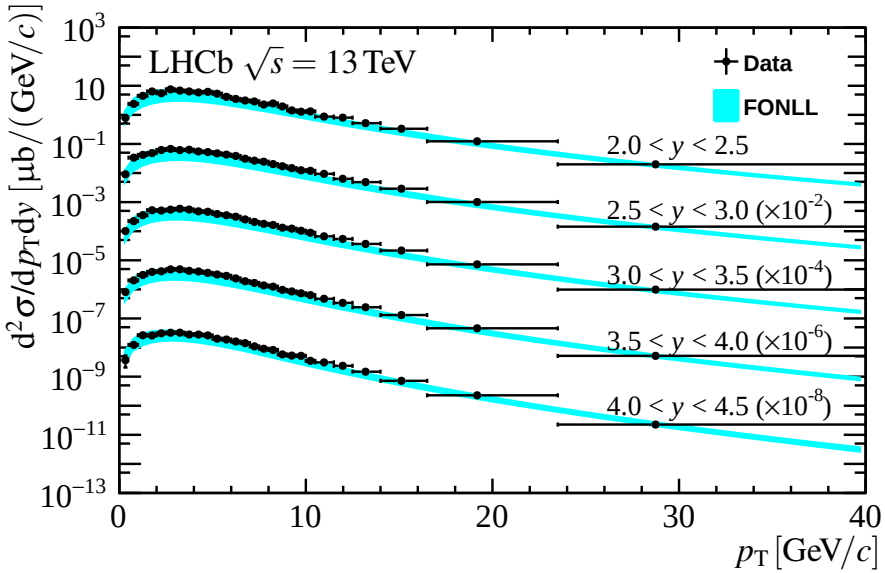
JHEP **12** (2017) 026

- Double differential cross sections determined as a function of p_{T} and rapidity at both energies
- Results are in good agreement with FONLL predictions
- Integrated cross sections in $p_{\mathrm{T}} < 40\,\mathrm{GeV}/c$, $2.0 < y < 4.5$

$$\sigma(pp \to B^{\pm}X) = 43.0 \pm 0.2\,(\mathrm{stat})$$
$$\pm 2.5\,(\mathrm{syst}) \pm 1.7\,(B^+)\ \mu\mathrm{b}\ @7\,\mathrm{TeV}$$

$$\sigma(pp \to B^{\pm}X) = 86.6 \pm 0.5\,(\mathrm{stat})$$
$$\pm 5.4\,(\mathrm{syst}) \pm 3.4\,(B^+)\ \mu\mathrm{b}\ @13\,\mathrm{TeV}$$





B^+ production @ 7 and 13 TeV

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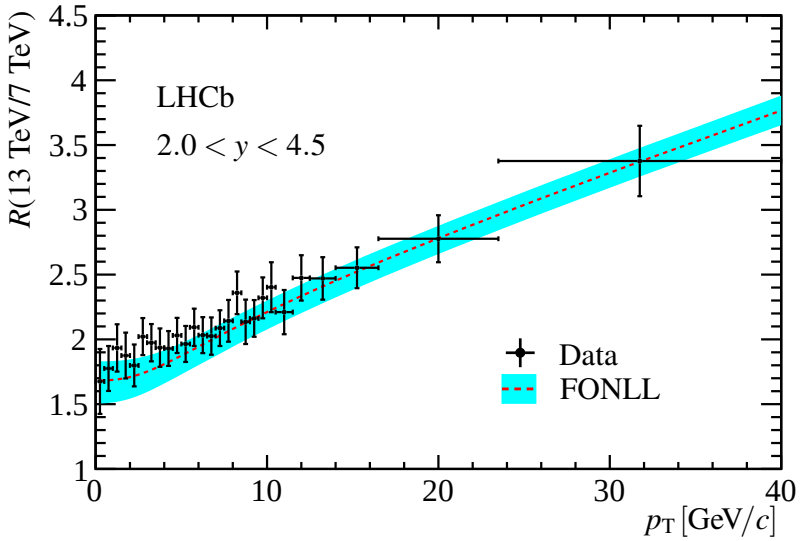
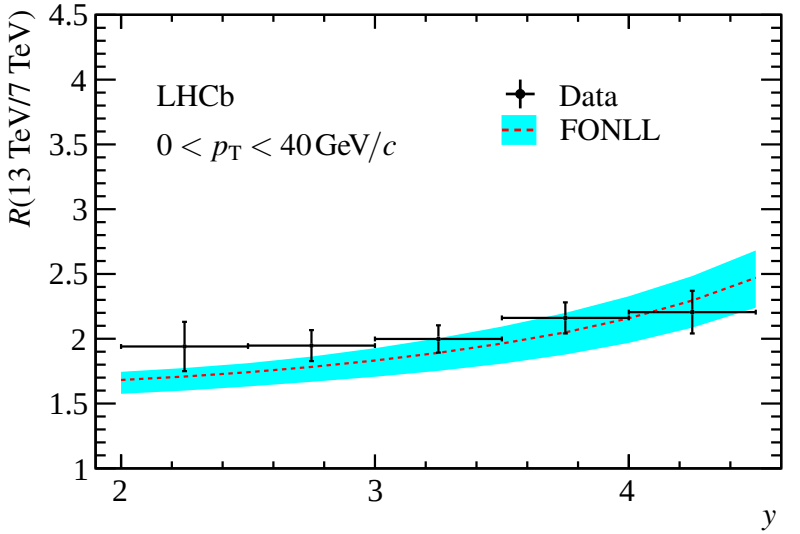


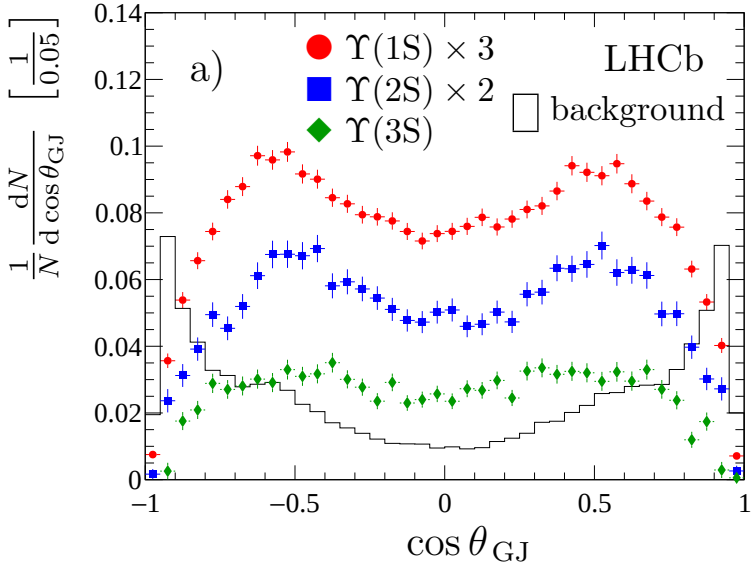


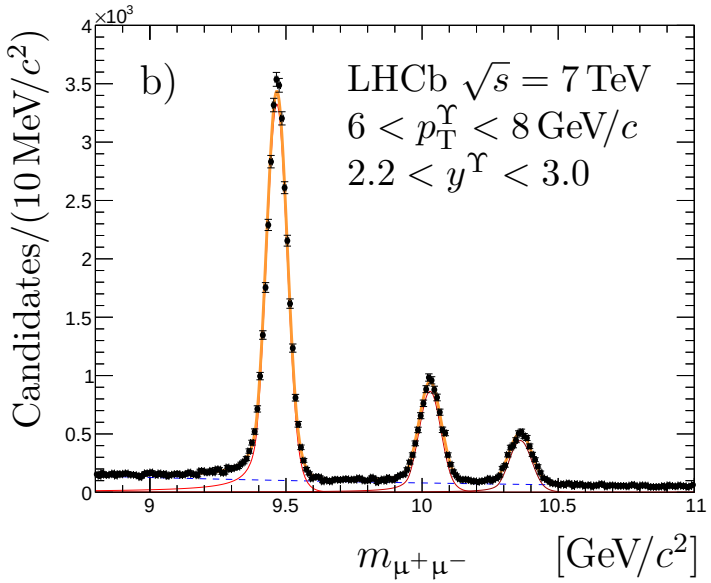
- Ratio of differential cross sections between 13 and 7 TeV also in good agreement with FONLL predictions
- Integrated ratio:
  $2.02 \pm 0.02\,(\text{stat}) \pm 0.12\,(\text{syst})$

Υ polarisation

JHEP **12** (2017) 110

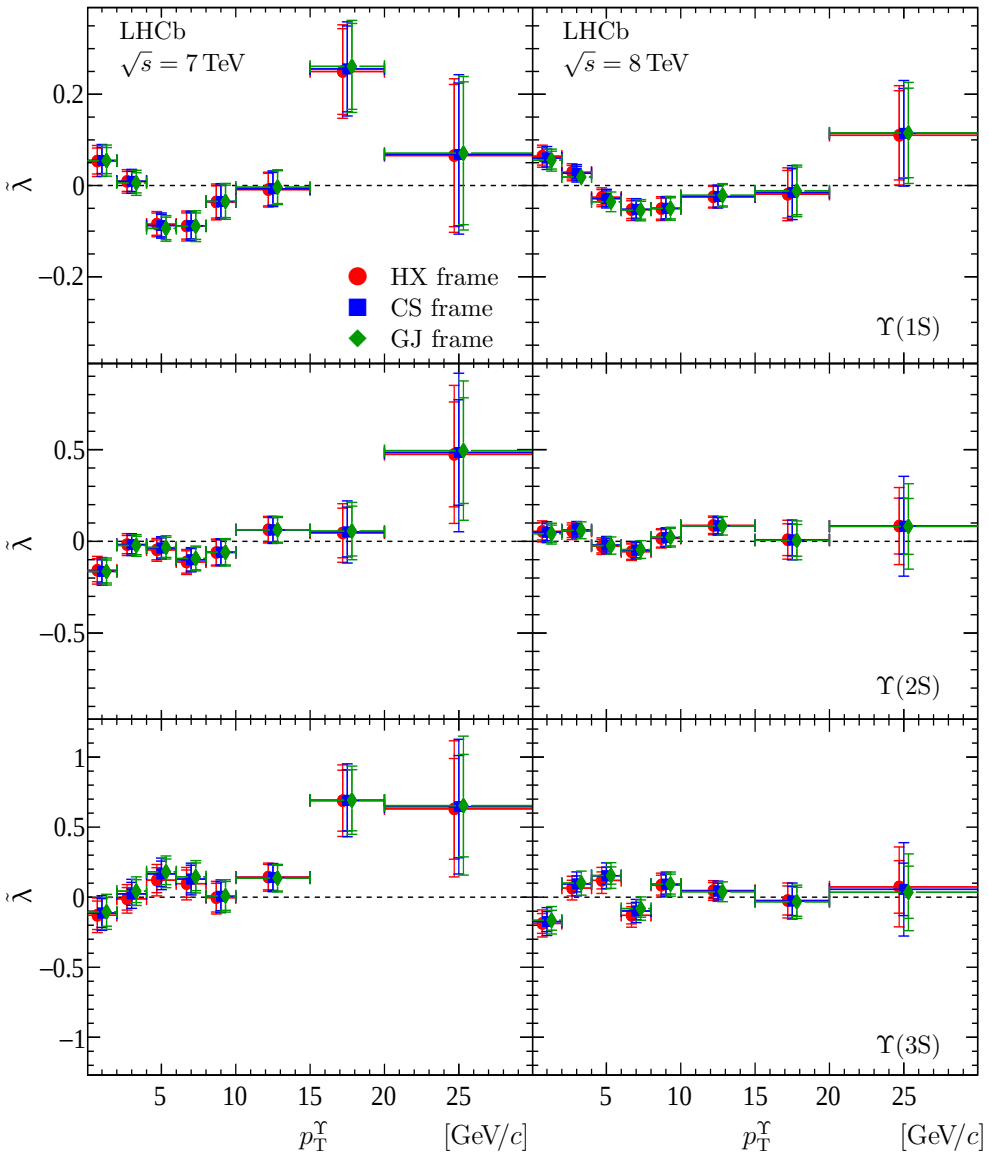
- Study of Υ(nS) polarisations in 7 and 8 TeV data
- Dimuon mass spectrum fitted in bins of $p_{\mathrm{T}\mu^+\mu^-}$
- Angular distributions of Υ candidates extracted using *sPlot* technique





ϒ polarisation

JHEP **12** (2017) 110



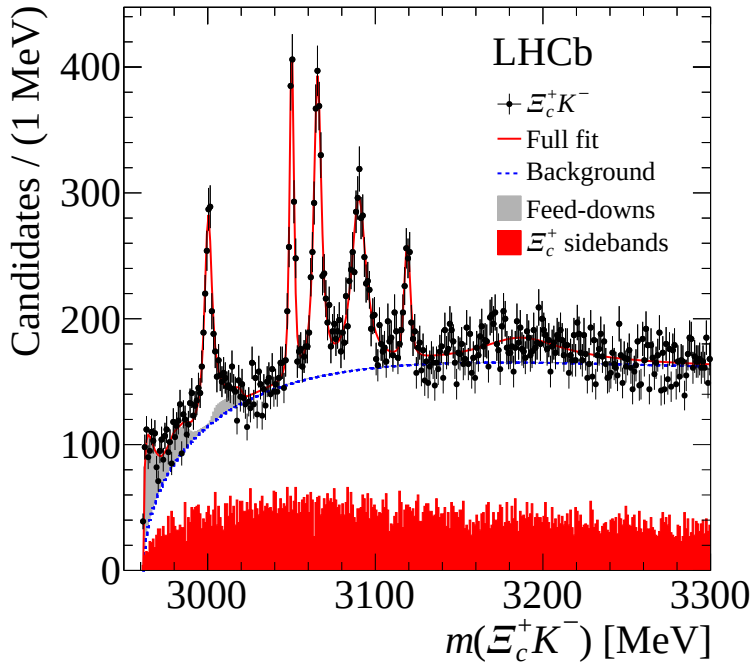
- Angular distributions extracted as function of p_T in helicity, Collins–Soper and Gottfried–Jackson reference frames.
- All can be converted into frame-invariant polarisation $\bar{\lambda}$ to cross-check systematics
- No large polarisation is observed
  - Consistent with CMS results

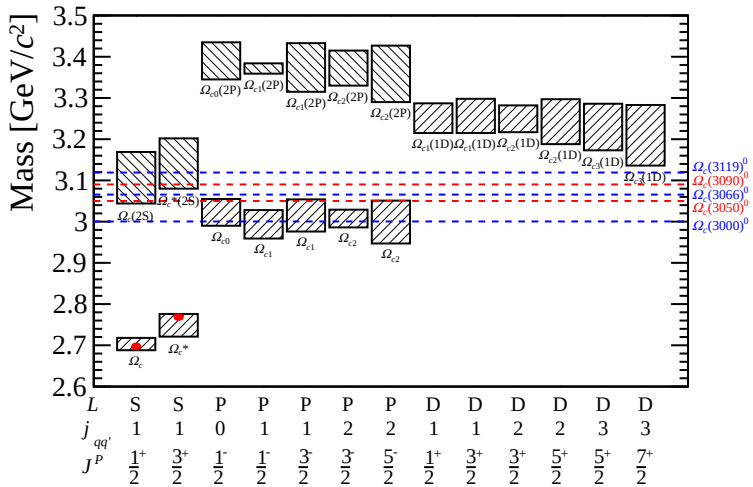
Phys. Rev. Lett. **110** (2013) 081802

Observation of Ω_c states

PRL **118** (2017) 182001

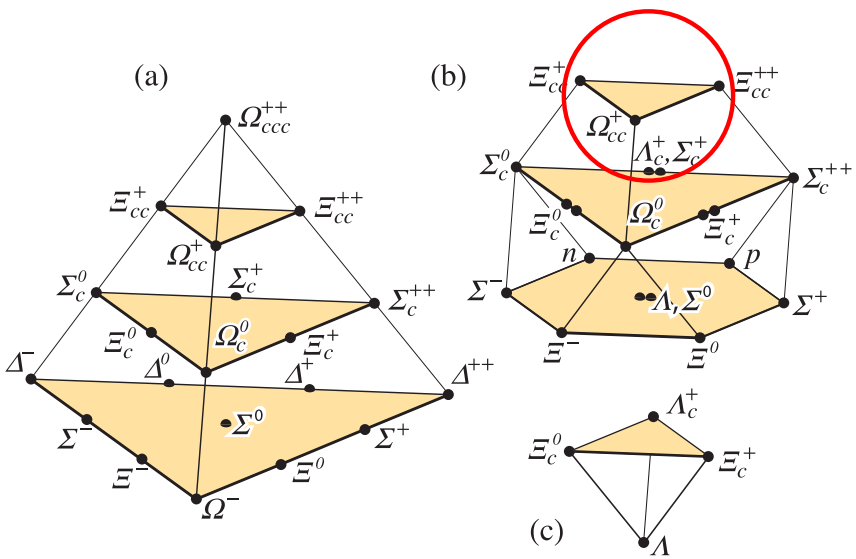
- Pure sample of $\Xi_c^+ \to pK^-\pi^+$ candidates combined with charged kaons
- Five narrow peaks observed
  - correspond to excited Ω_c states
- Masses consistent with predicted masses for 1P and 2S states
- Further studies required to assign quantum numbers





Searches for $\Xi_{cc}^{+(+)}$ states

PRL **119** (2017) 112001



SU(4) flavour multiplets of baryons containing *d*, *u*, *s* and *c* quarks, reproduced from Chin. Phys. **C40** (2016) 100001.

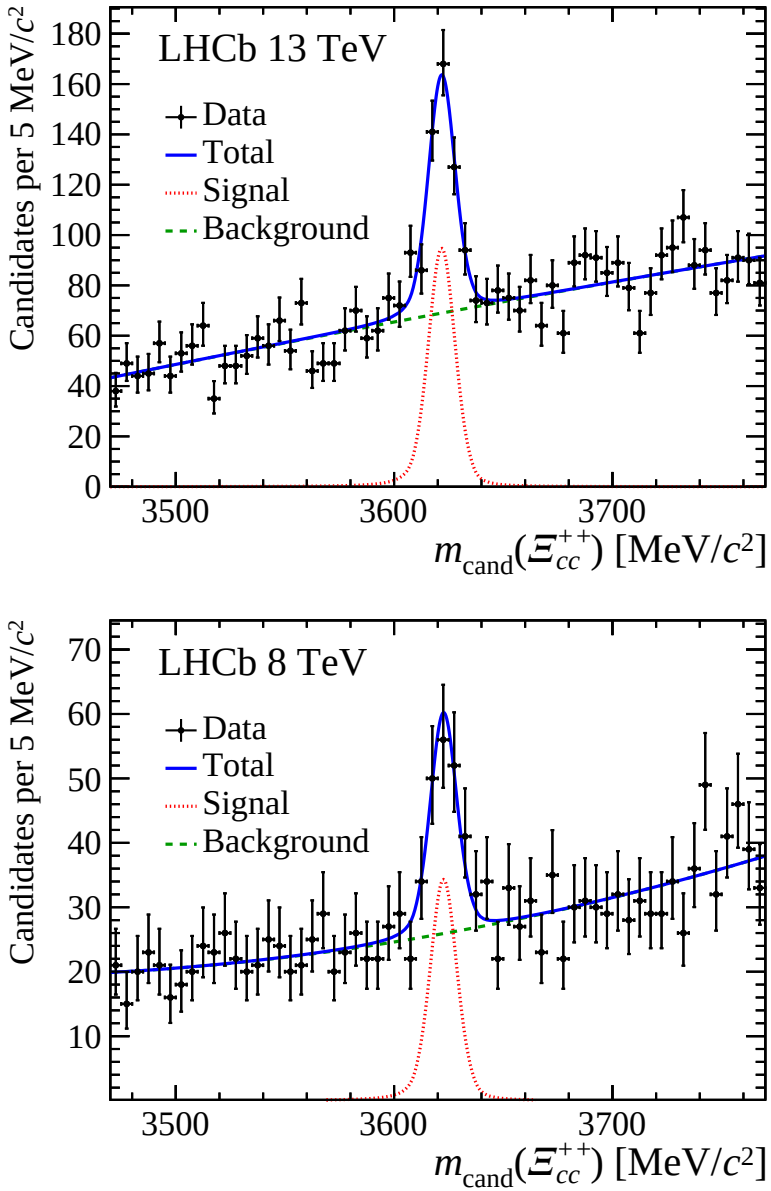
Phys. Rev. Lett. **89** (2002) 112001
Phys. Lett. **B628** (2005) 18
Nucl. Phys.Proc. Suppl. **115** (2003) 33
Phys. Rev. **D74** (2006) 011103
Phys. Rev. Lett. **97** (2006) 162001
JHEP **12** (2013) 090

- Quark model gives **three** weakly-decaying doubly-charmed $J^P = \frac{1}{2}^+$ Baryons: Ξ_{cc}^+ $(c\,c\,d)$, Ξ_{cc}^{++} $(c\,c\,u)$ and Ω_{cc}^+ $(c\,c\,s)$
- SELEX reported observations of the **singly-charged** Ξ_{cc}^+ state in $\Lambda_c^+ K^- \pi^+$ and $D^+ p K^-$
  - Unexpected short lifetime and high production rate
- Subsequent searches by FOCUS, BaBar and Belle found no evidence of doubly-charmed baryons
- Initial search by LHCb set upper limit on long-lived states but not inconsistent with SELEX claim

Observation of Ξ_{cc}^{++}

PRL **119** (2017) 112001

- New LHCb search for the **doubly-charged** state in $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ performed using data collected at $\sqrt{s} = 13\,\text{TeV}$
- Highly significant state found at $m = 3621.40 \pm 0.72\,(\text{stat}) \pm 0.27\,(\text{syst}) \pm 0.14(\Lambda_c^+)\,\text{MeV}/c^2$
  - Local statistical significance in excess of 12σ
- Verified in 8 TeV dataset
- Large mass difference from SELEX claim ($103\,\text{MeV}/c^2$)
  - Inconsistent with being isospin partners



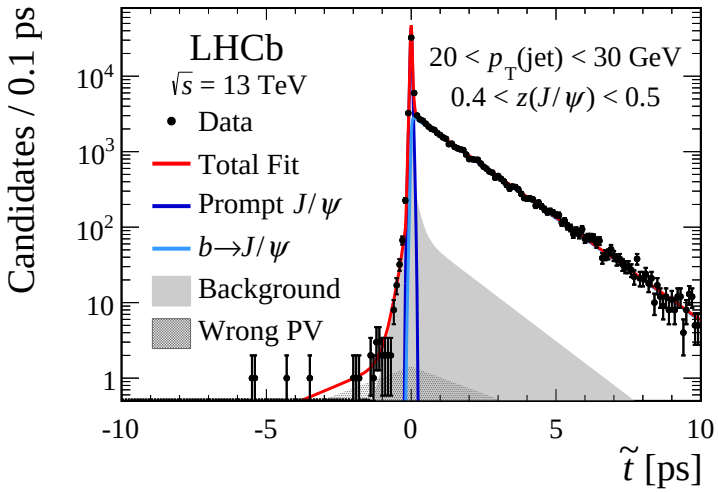
Summary and outlook

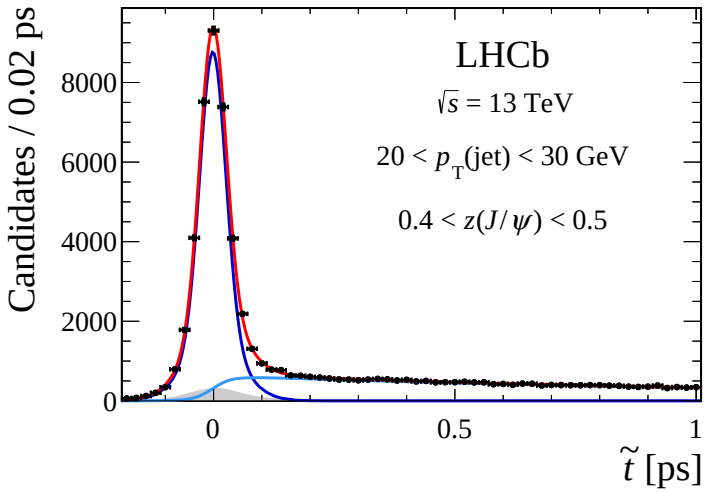
- LHCb tests cross section calculations in unique kinematic region
- Many new production results
  - but plenty more still to come
  - including results from the new larger 5 TeV dataset
- Jet tagging efficiency studies underway on 13 TeV dataset
  - Unlike in Run 1, these benefit from dedicated calibration samples
  - New 13 TeV jet studies to follow

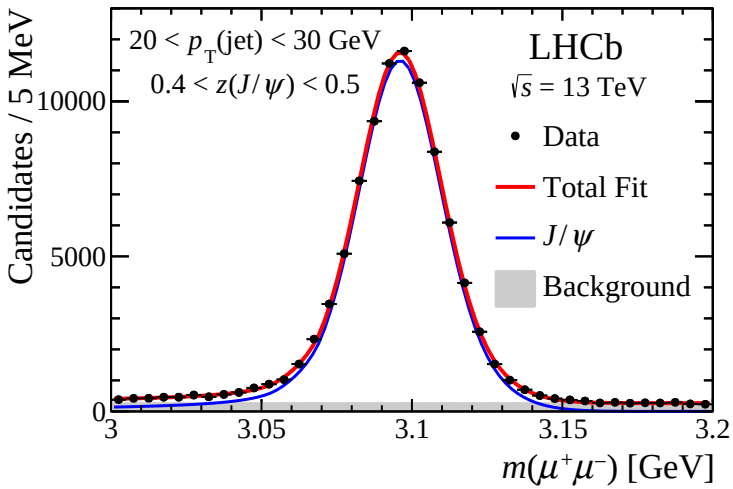
Backup

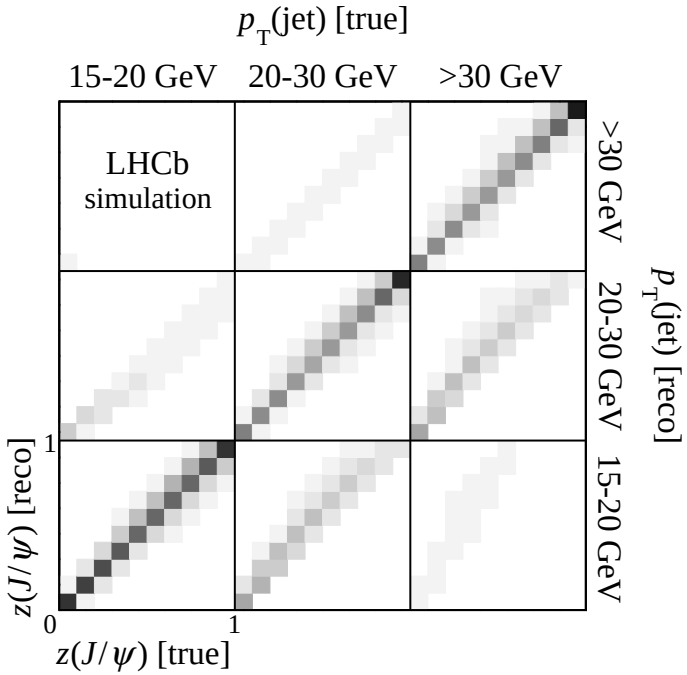
J/ψ in jets

PRL **118** (2017) 192001



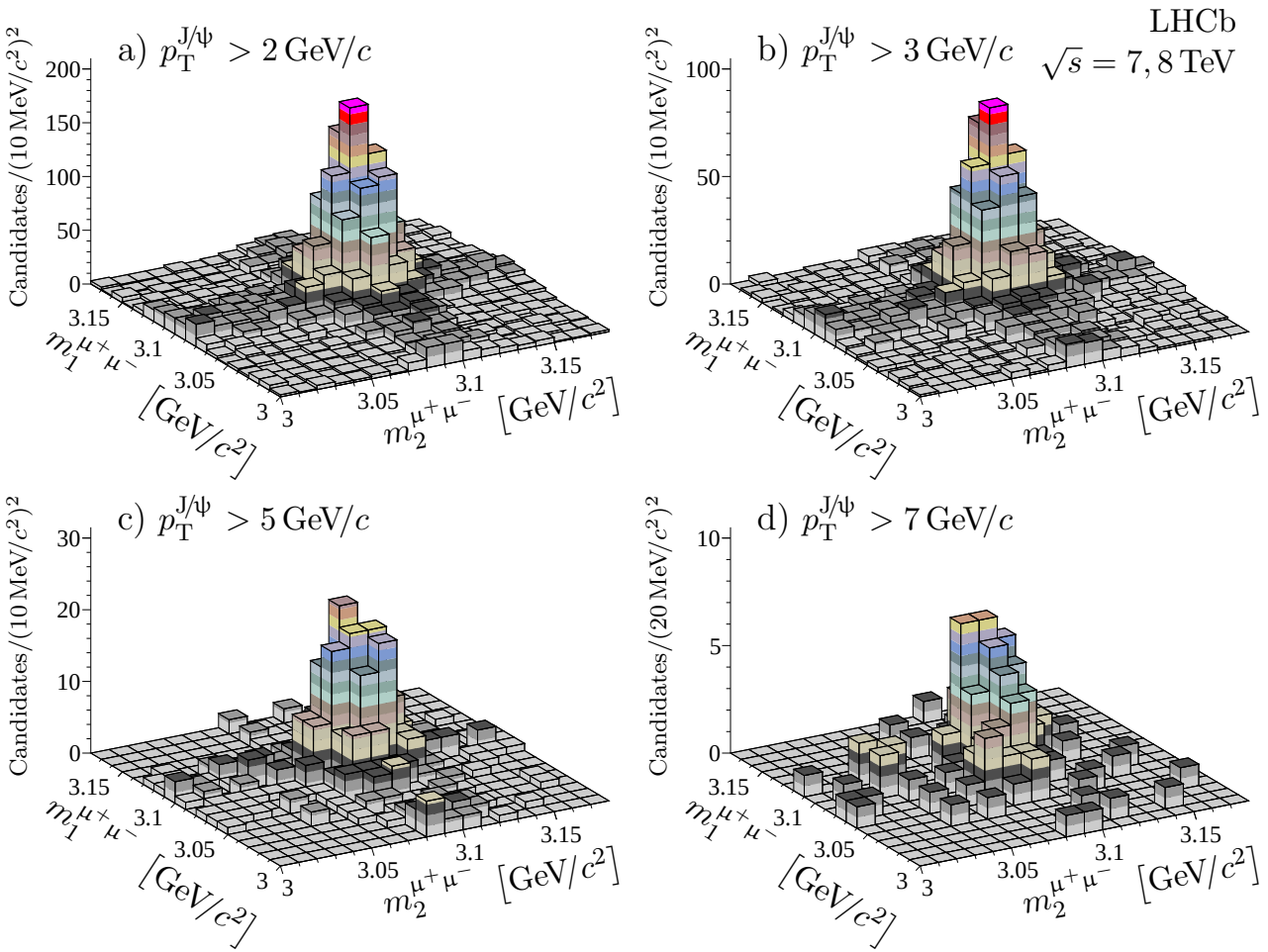






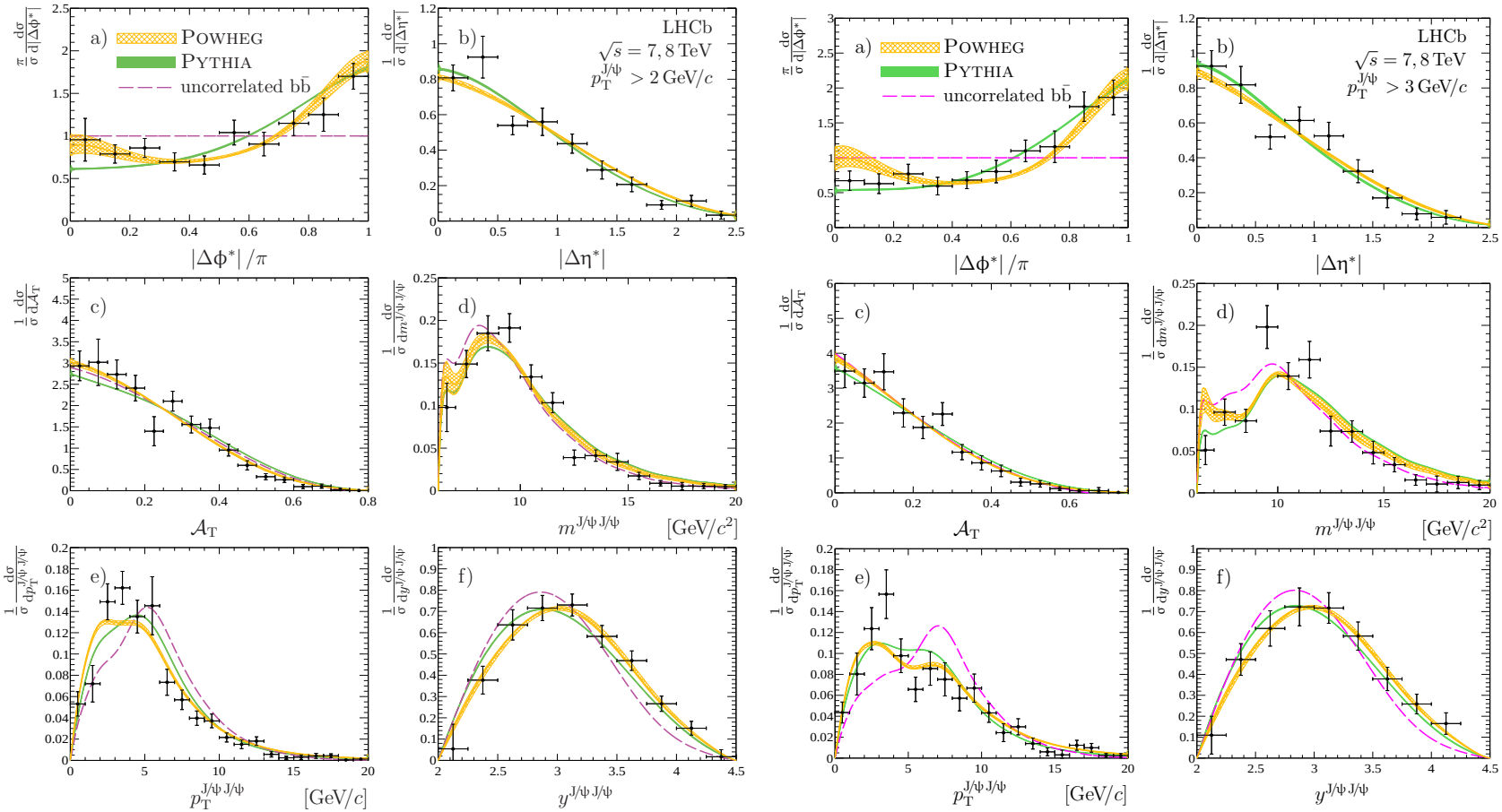
$b\bar{b}$ correlations

JHEP **11** (2017) 030



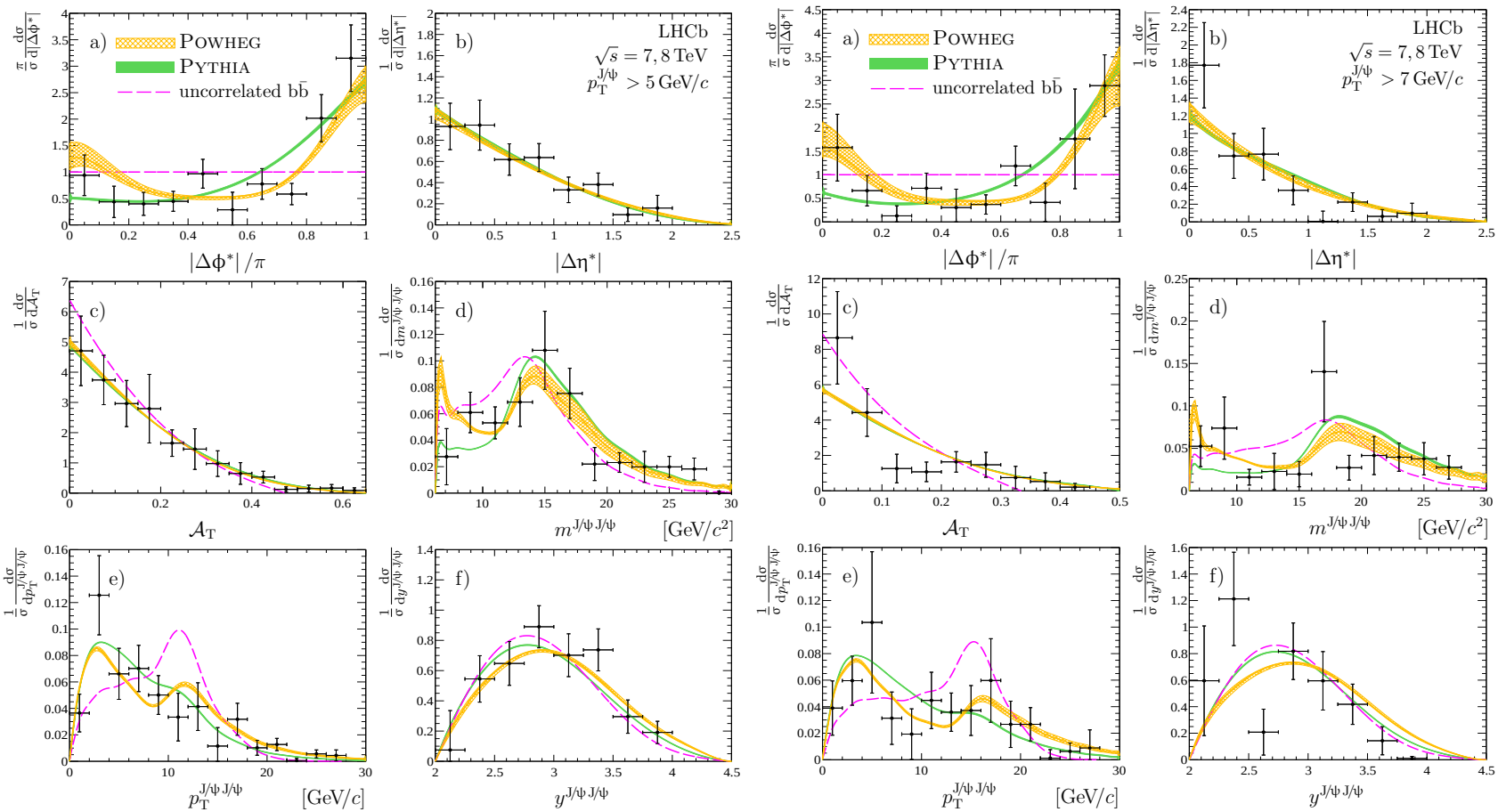
$b\bar{b}$ correlations

JHEP **11** (2017) 030



$b\bar{b}$ correlations

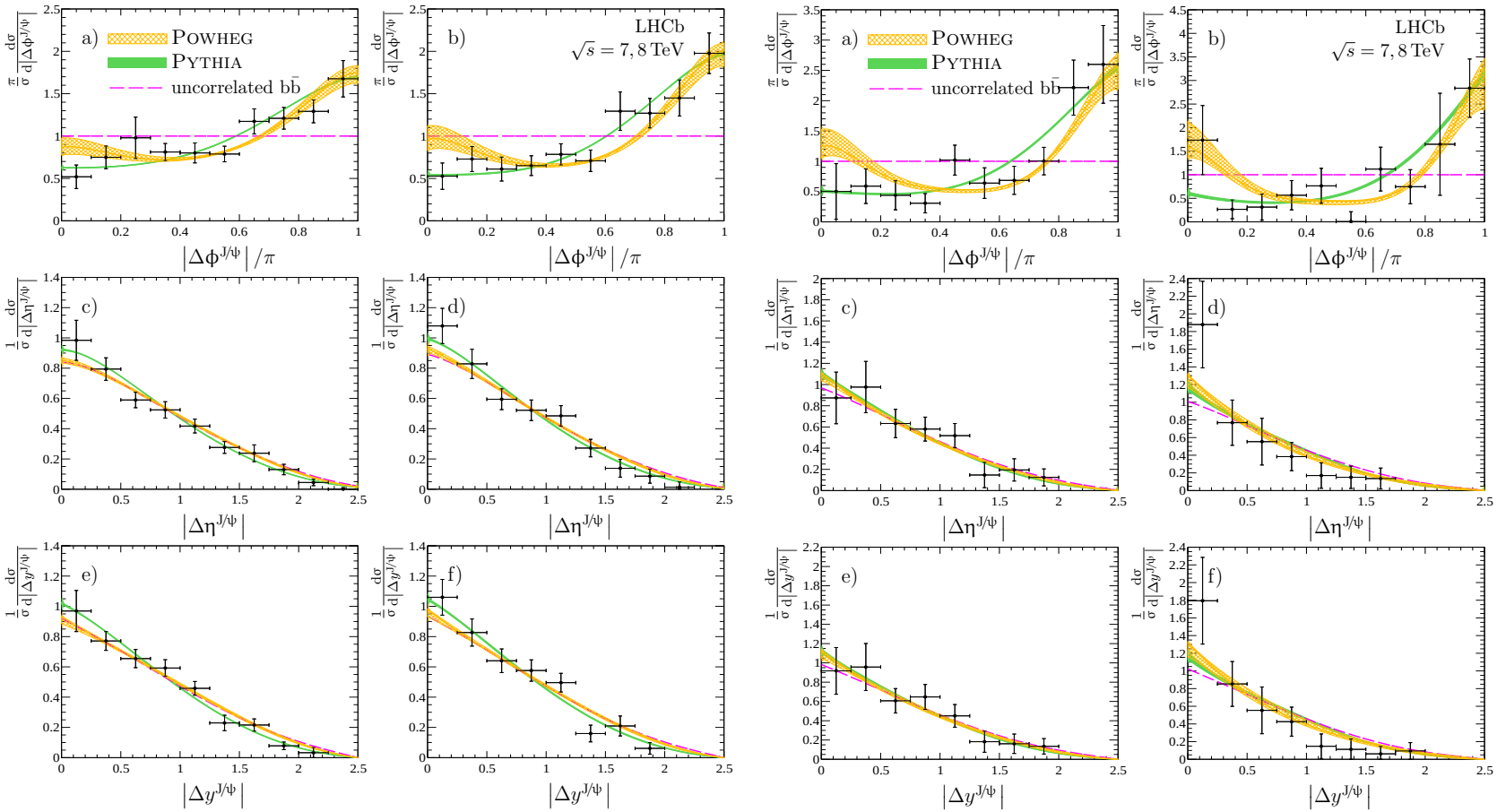
JHEP **11** (2017) 030



$b\bar{b}$ correlations

JHEP **11** (2017) 030

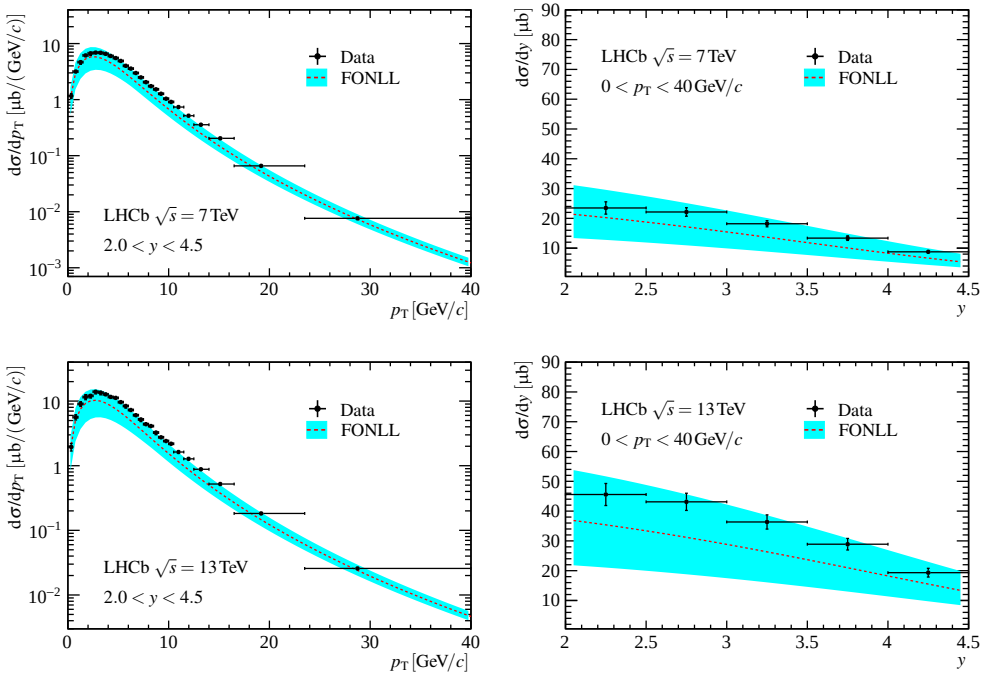
$p_T^{J/\psi} > 2\,\text{GeV}/c$ $p_T^{J/\psi} > 3\,\text{GeV}/c$ $p_T^{J/\psi} > 5\,\text{GeV}/c$ $p_T^{J/\psi} > 7\,\text{GeV}/c$



B^+ production @ 7 and 13 TeV

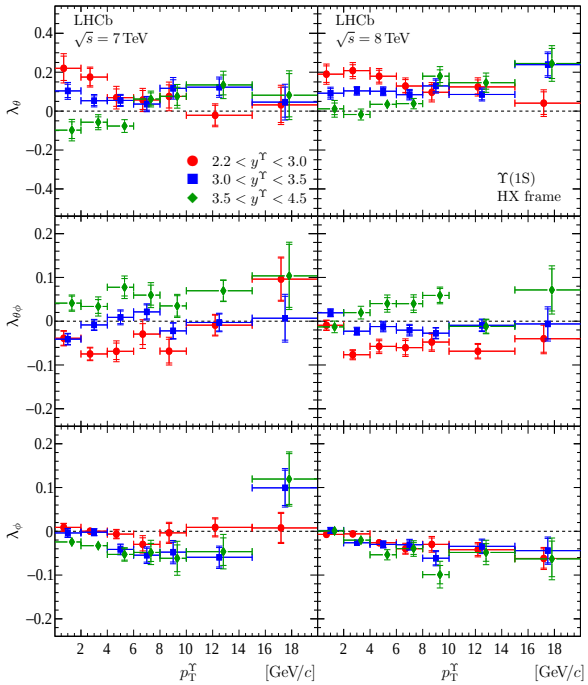
JHEP **12** (2017) 026

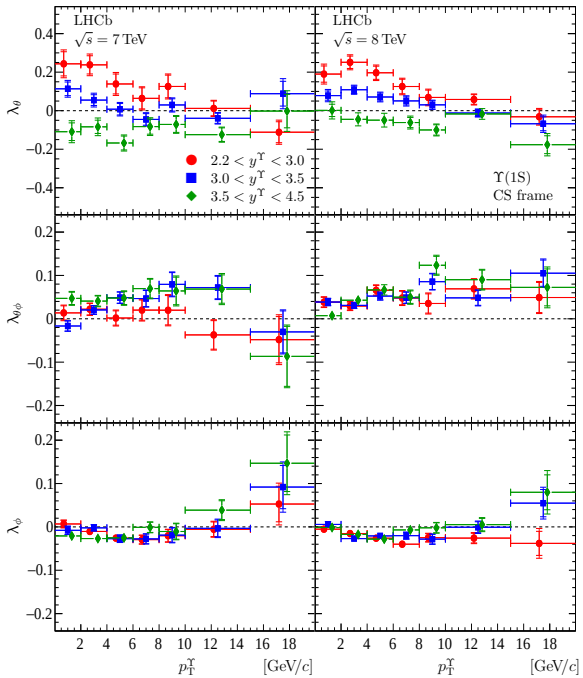
Sources	Uncertainty (%)		
	7 TeV	13 TeV	R(13 TeV/7 TeV)
Luminosity	1.7	3.9	3.4
Branching fractions	3.9	3.9	0.0
Binning	2.6	2.7	0.0
Mass fits	2.7	1.3	1.5
Acceptance	0.2	0.1	0.2
Reconstruction	0.1	0.1	0.2
Track	1.6	2.6	1.0
PID	0.4	0.1	0.4
Trigger	3.5	2.6	4.4
GEC	0.7	0.7	1.0
Selection	1.0	1.1	0.1
Weighting	0.2	0.2	0.3
Total	7.0	7.4	5.9

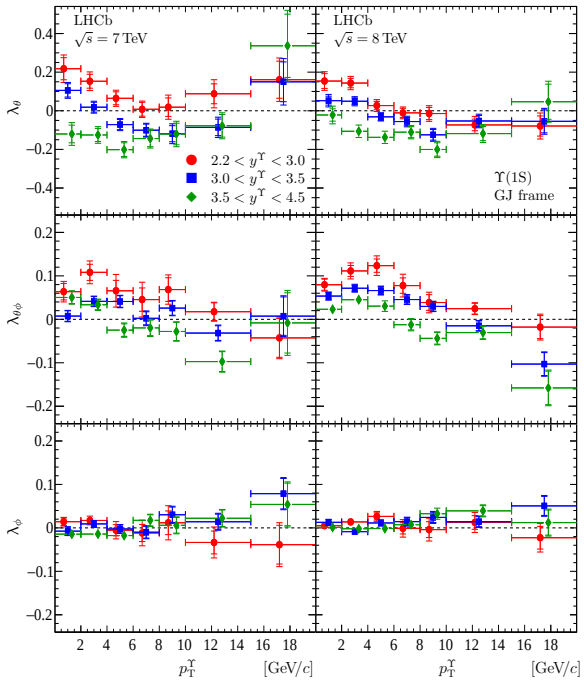


ϒ polarisation

JHEP **12** (2017) 110







ϒ polarisation

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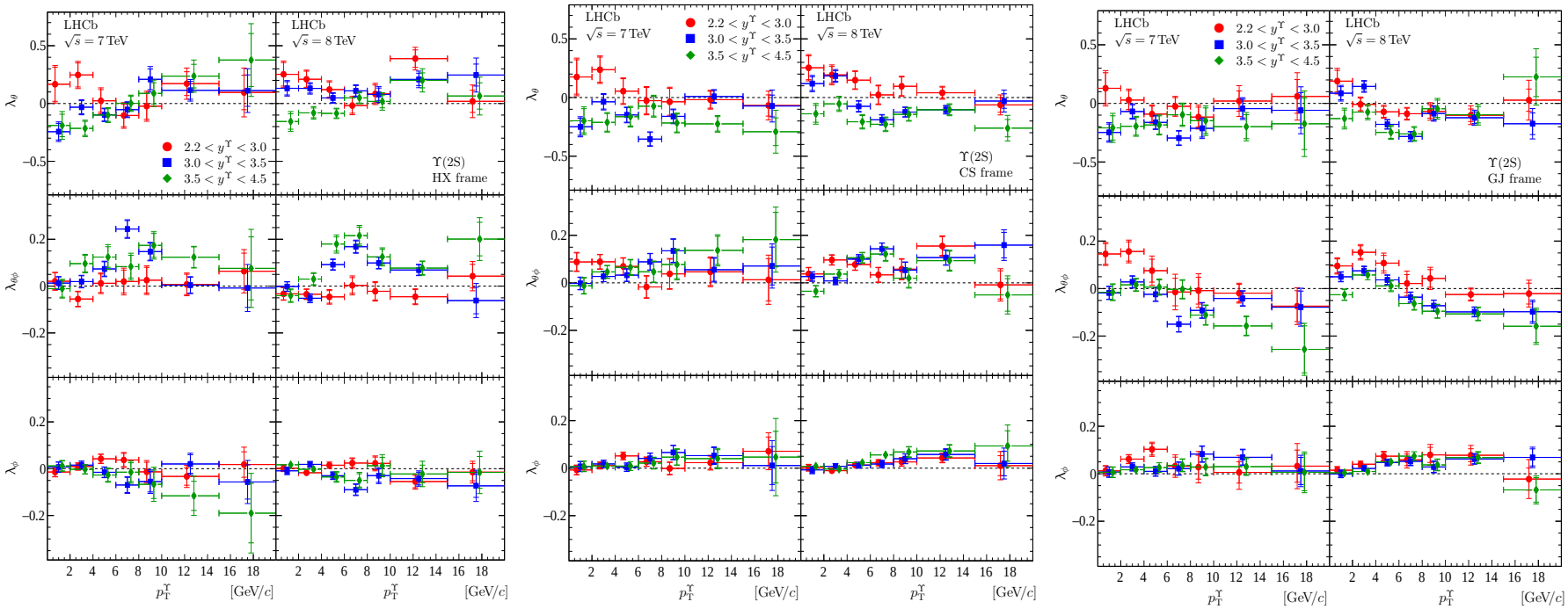

ϒ polarisation

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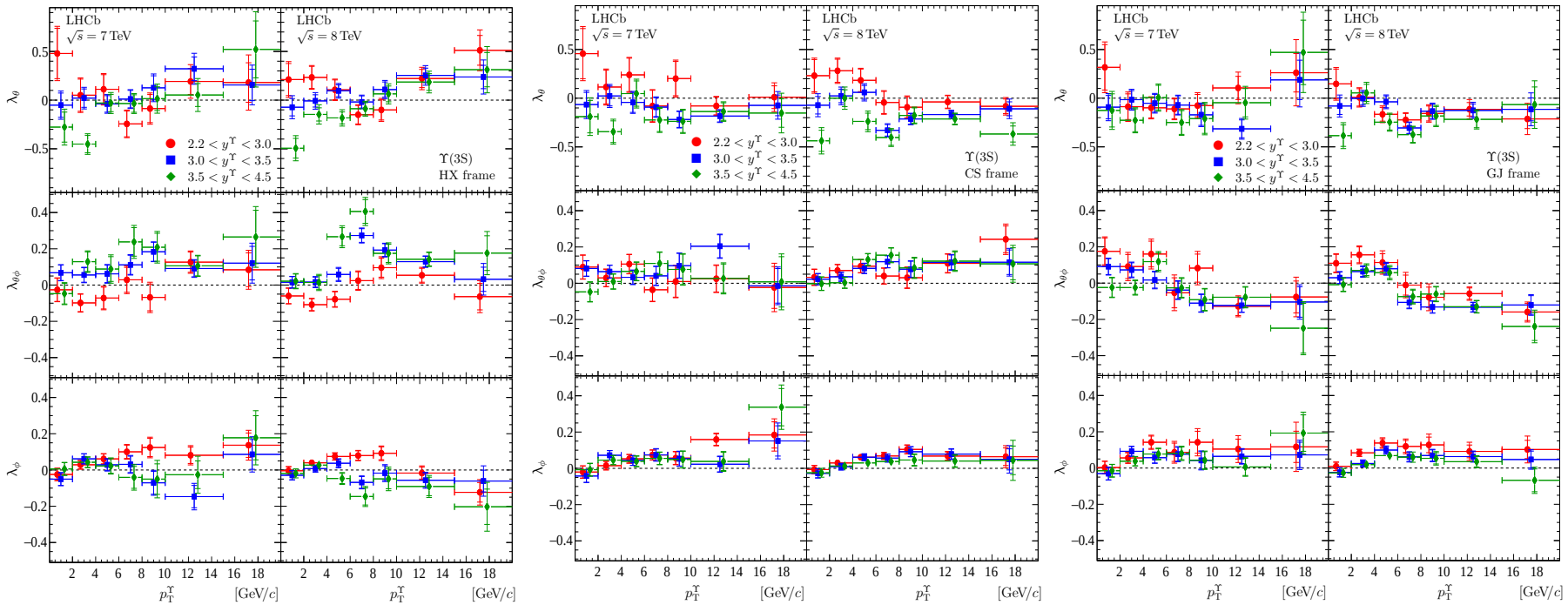

ϒ polarisation

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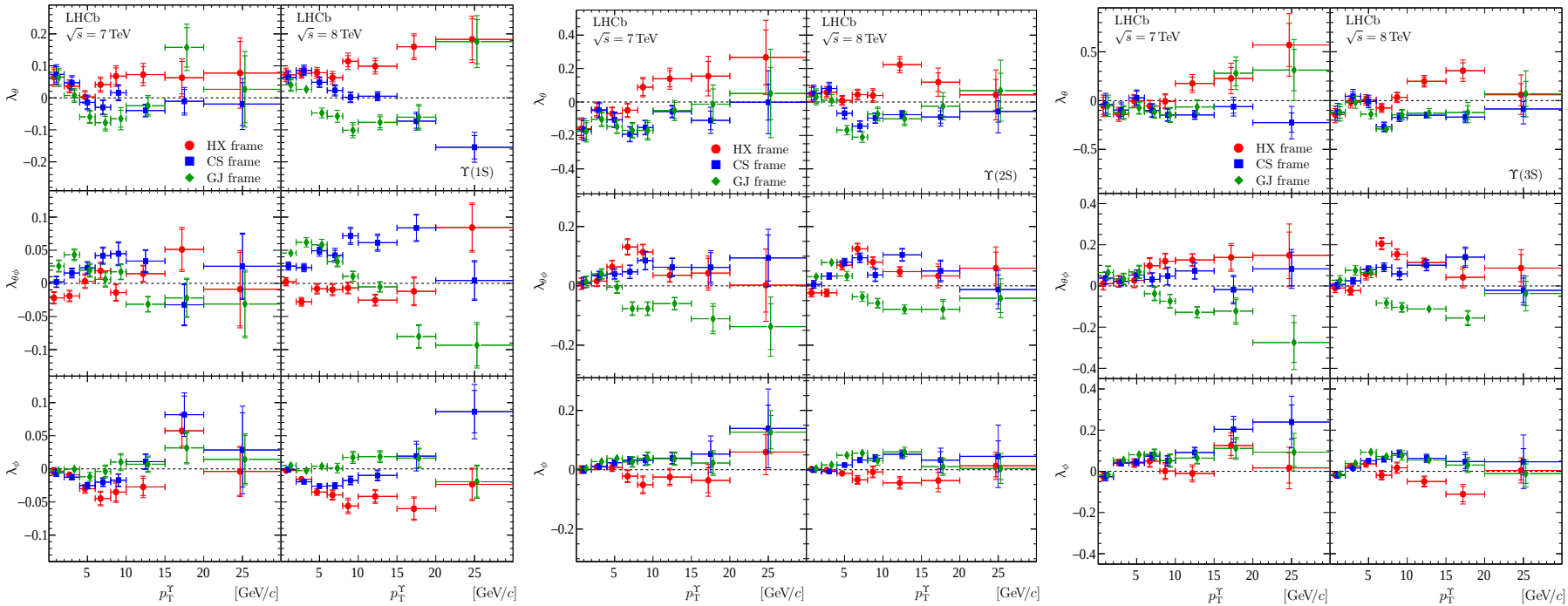

Observation of Ω_c states

PRL **118** (2017) 182001

TABLE I. Results of the fit to $m(\Xi_c^+ K^-)$ for the mass, width, yield, and significance for each resonance. The subscript fd indicates the feed-down contributions described in the text. For each fitted parameter, the first uncertainty is statistical and the second systematic. The asymmetric uncertainty on the $\Omega_c(X)^0$ arising from the Ξ_c^+ mass is given separately. Upper limits are also given for the resonances $\Omega_c(3050)^0$ and $\Omega_c(3119)^0$ for which the width is not significant.

Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		<1.2 MeV, 95% C.L.		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		<2.6 MeV, 95% C.L.		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{\rm fd}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{\rm fd}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{\rm fd}$			$190 \pm 70 \pm 20$	

Observation of Ξ_{cc}^{++}

PRL **119** (2017) 112001

Table 1: Systematic uncertainties on the Ξ_{cc}^{++} mass measurement.

Source	Value [MeV/c^2]
Momentum-scale calibration	0.22
Selection bias correction	0.14
Unknown Ξ_{cc}^{++} lifetime	0.06
Mass fit model	0.07
Sum of above in quadrature	0.27
Λ_c^+ mass uncertainty	0.14