LHCb results on rare Λ_b decays

Carla Marin Benito,
Michal Kreps

Why Λ_b baryons

- Compared to mesons, three differences
  - Different spectator system — diquark vs. single quark
  - If Λ_b produced polarised, access to more information than in meson case
  - Lowest strange baryon Λ decays weakly with asymmetry in decay amplitudes and retains non-trivial structure in angular distribution (unlike K_S)
    - Form factors for $\Lambda_b \rightarrow \Lambda$ known well from LQCD (Phys.Rev. D93 (2016), 074501)
- Potentially interesting system to complement knowledge gain from meson decays

Angular analysis of $\Lambda_b \to \Lambda\mu\mu$

- Latest analysis uses about 5 fb^{-1} of data (Run 1, 2015+2016)
- From 3 fb^{-1} analysis we knew only significant signal at high q^2
- Perform measurement only in $15<q^2<20$ GeV^2
- Get full angular information
  - Low statistics, use method of moments

q^2 interval [GeV^2/c^4]	Total signal yield	Significance
0.1 – 2.0	16.0 ± 5.3	4.4
2.0 – 4.0	4.8 ± 4.7	1.2
4.0 – 6.0	0.9 ± 2.3	0.5
6.0 – 8.0	11.4 ± 5.3	2.7
11.0 – 12.5	60 ± 12	6.5
15.0 – 16.0	57 ± 9	8.7
16.0 – 18.0	118 ± 13	13
18.0 – 20.0	100 ± 11	14
1.1 – 6.0	9.4 ± 6.3	1.7
15.0 – 20.0	276 ± 20	21

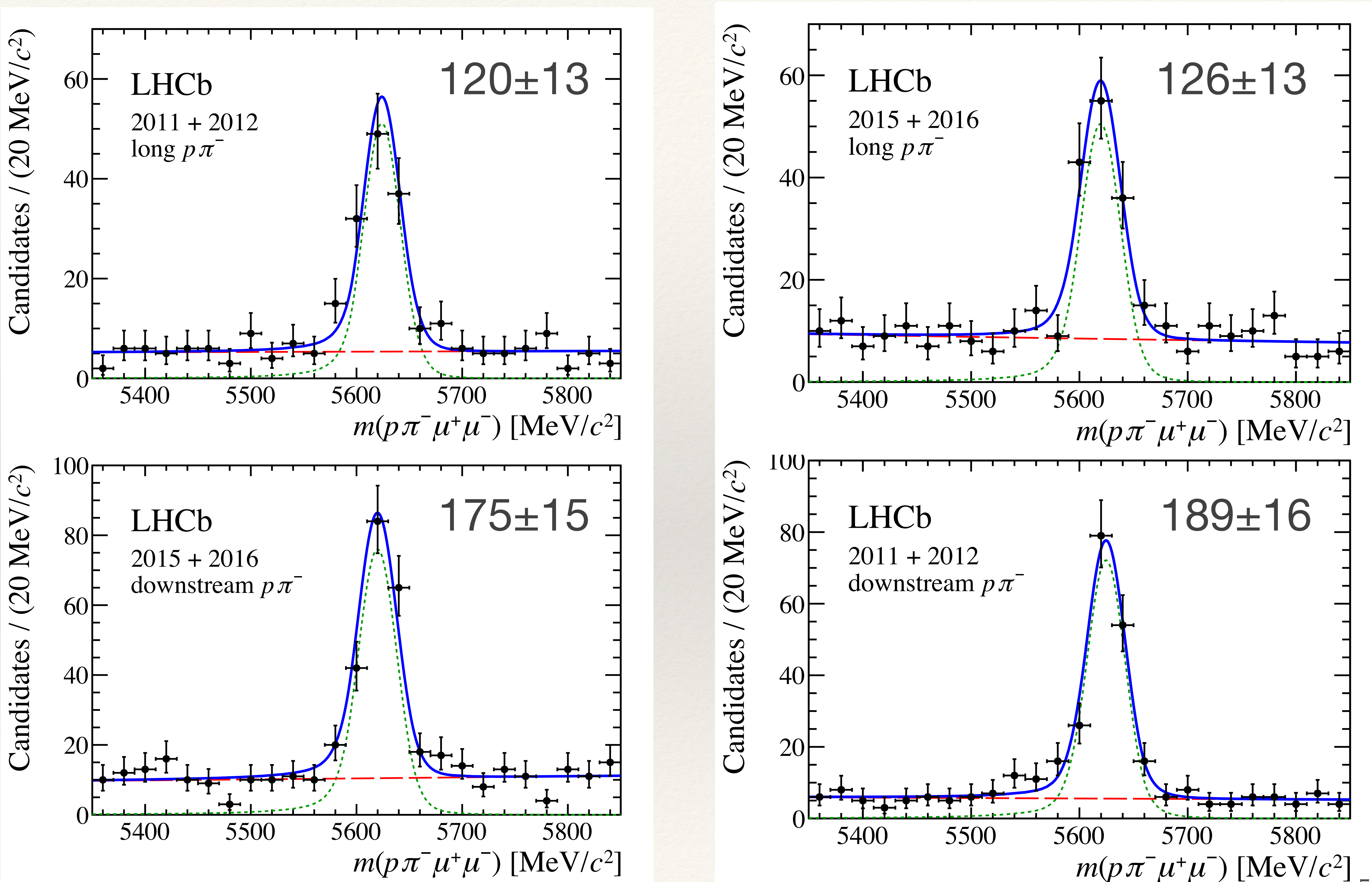
JHEP 06 (2015) 115

Angular distribution

- Full 5D angular distribution from JHEP 1711 (2017) 138
- Observables 1-10 do not depend on production polarisation
- Others proportional to production polarisation
  - Expect close to zero given small measured polarisation

$$
\begin{aligned}
\Big(& \left(K_1 \sin^2\theta_l + K_2 \cos^2\theta_l + K_3 \cos\theta_l\right) + \\
& \left(K_4 \sin^2\theta_l + K_5 \cos^2\theta_l + K_6 \cos\theta_l\right) \cos\theta_b + \\
& \left(K_7 \sin\theta_l \cos\theta_l + K_8 \sin\theta_l\right) \sin\theta_b \cos\left(\phi_b + \phi_l\right) + \\
& \left(K_9 \sin\theta_l \cos\theta_l + K_{10} \sin\theta_l\right) \sin\theta_b \sin\left(\phi_b + \phi_l\right) + \\
& \left(K_{11} \sin^2\theta_l + K_{12} \cos^2\theta_l + K_{13} \cos\theta_l\right) \cos\theta + \\
& \left(K_{14} \sin^2\theta_l + K_{15} \cos^2\theta_l + K_{16} \cos\theta_l\right) \cos\theta_b \cos\theta + \\
& \left(K_{17} \sin\theta_l \cos\theta_l + K_{18} \sin\theta_l\right) \sin\theta_b \cos\left(\phi_b + \phi_l\right) \cos\theta + \\
& \left(K_{19} \sin\theta_l \cos\theta_l + K_{20} \sin\theta_l\right) \sin\theta_b \sin\left(\phi_b + \phi_l\right) \cos\theta + \\
& \left(K_{21} \cos\theta_l \sin\theta_l + K_{22} \sin\theta_l\right) \sin\phi_l \sin\theta + \\
& \left(K_{23} \cos\theta_l \sin\theta_l + K_{24} \sin\theta_l\right) \cos\phi_l \sin\theta + \\
& \left(K_{25} \cos\theta_l \sin\theta_l + K_{26} \sin\theta_l\right) \sin\phi_l \cos\theta_b \sin\theta + \\
& \left(K_{27} \cos\theta_l \sin\theta_l + K_{28} \sin\theta_l\right) \cos\phi_l \cos\theta_b \sin\theta + \\
& \left(K_{29} \cos^2\theta_l + K_{30} \sin^2\theta_l\right) \sin\theta_b \sin\phi_b \sin\theta + \\
& \left(K_{31} \cos^2\theta_l + K_{32} \sin^2\theta_l\right) \sin\theta_b \cos\phi_b \sin\theta + \\
& \left(K_{33} \sin^2\theta_l\right) \sin\theta_b \cos\left(2\phi_l + \phi_b\right) \sin\theta + \\
& \left(K_{34} \sin^2\theta_l\right) \sin\theta_b \sin\left(2\phi_l + \phi_b\right) \sin\theta \Big) \,.
\end{aligned}
$$

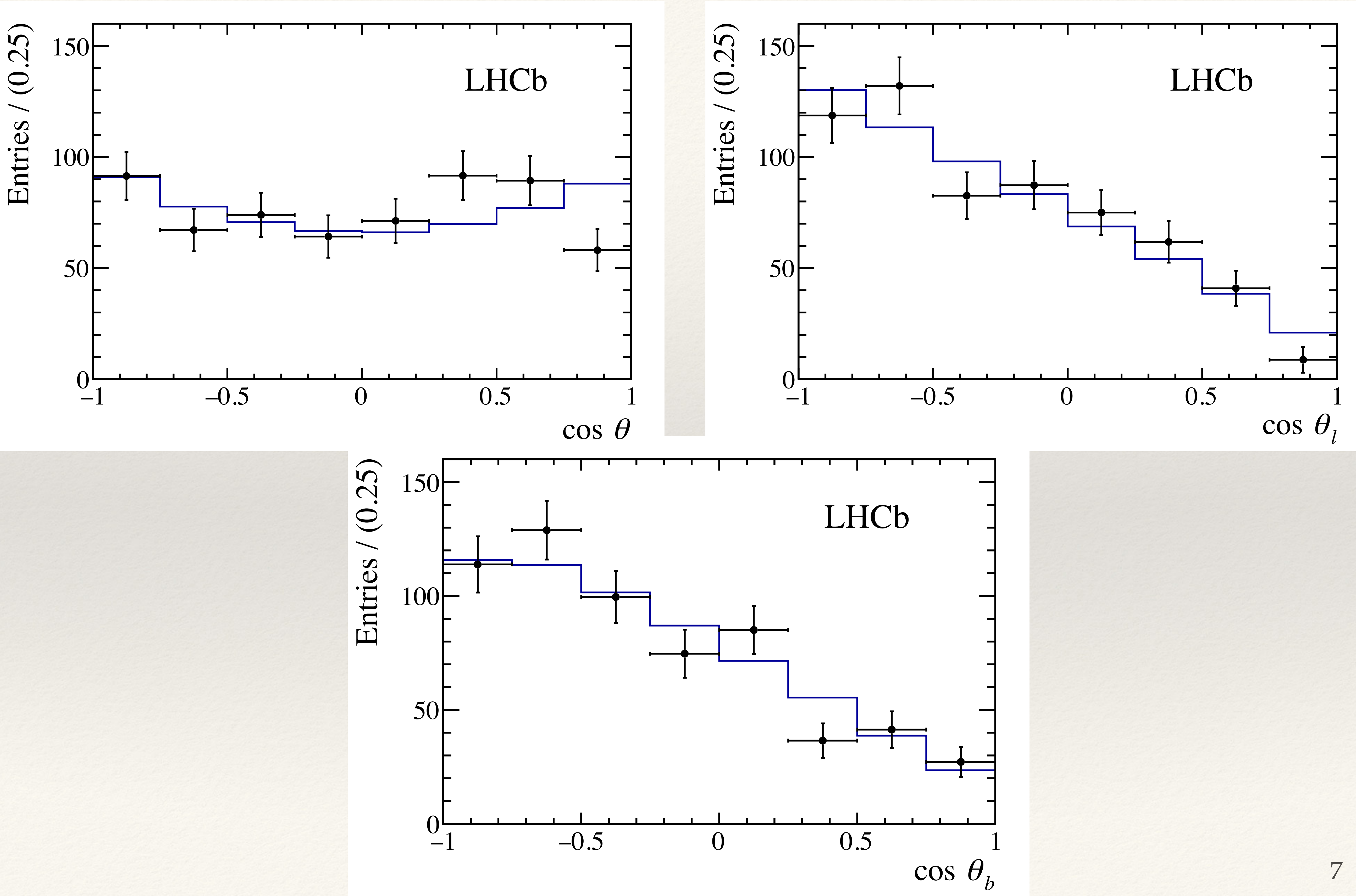
Signal yield



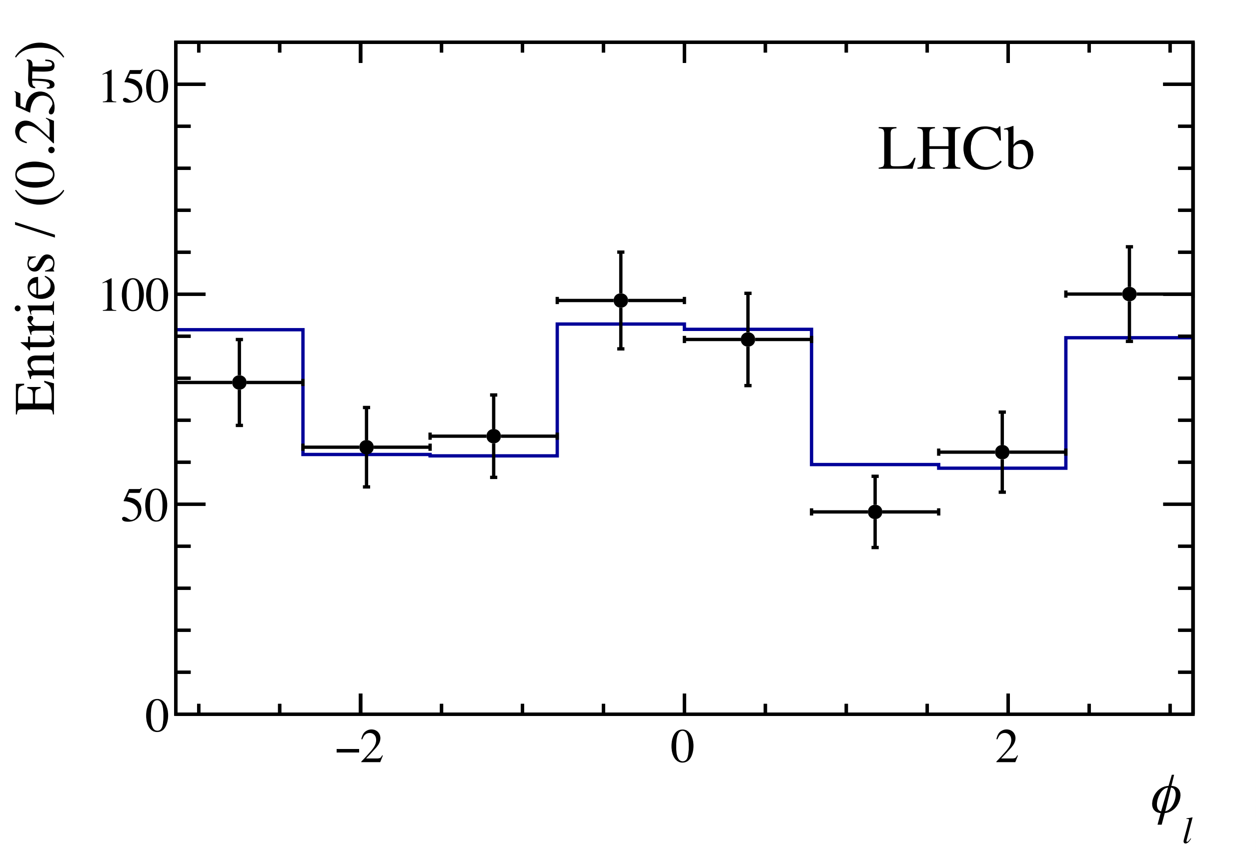
Background subtraction/Efficiency correction

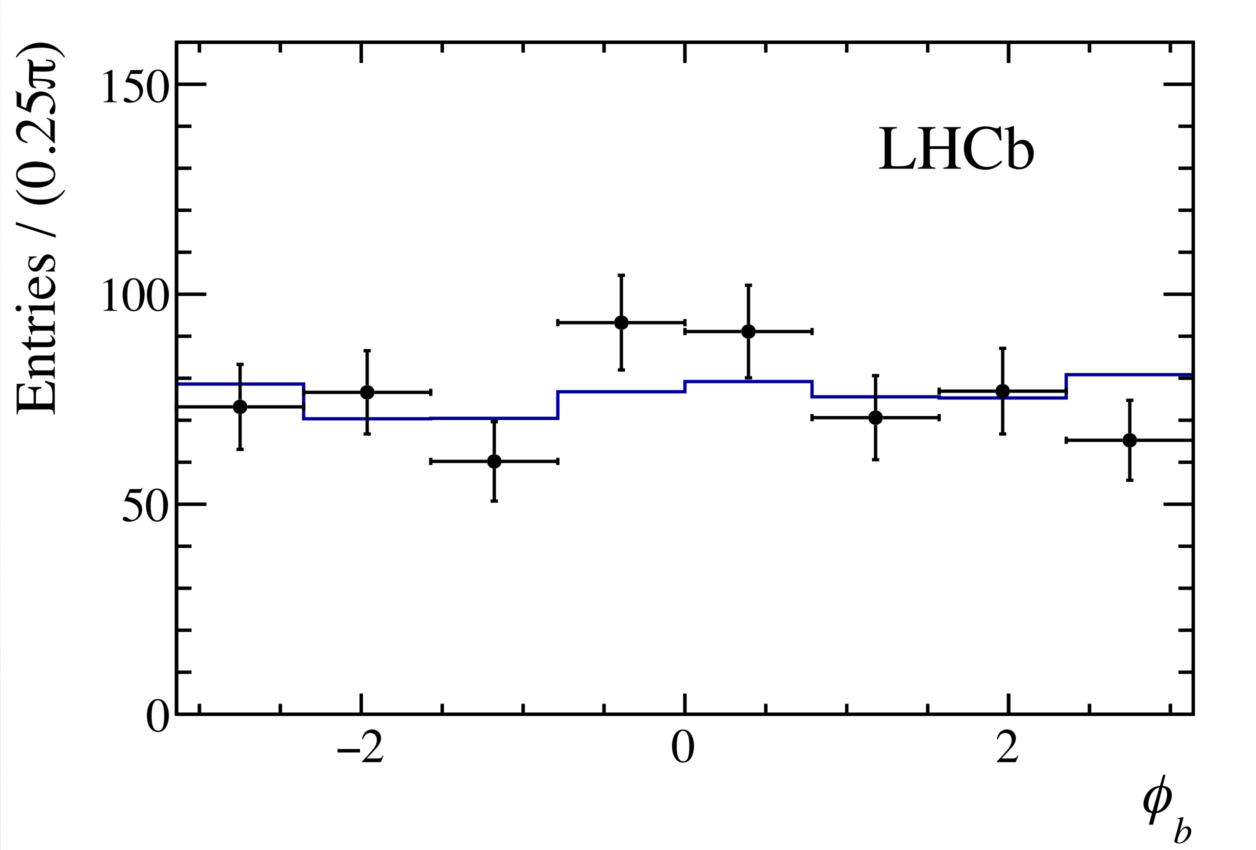
- Method of moments based on orthogonality of trigonometric functions
- Observables obtained by calculating weighted sum, need to subtract background and correct for efficiency
- Background subtracted using sWeights
- Efficiency corrected using sum of products of Legendre polynomials
  - Takes into account correlations
  - Can be bit tricky with large number of terms needed

Angular projections



Angular projections





- Good description of data
- Be aware that shape of $\cos(\theta_b)$ controlled by Λ decay asymmetry parameter
  - BESIII measurement in Nature Phys. 15 (2019) 631-634 much higher than PDG value

Systematic uncertainties

- Generally smaller than statistical uncertainties
- Many can be improved rather easily if they would start to be comparable to statistics
    - Some variations are unnecessary large but did not really matter

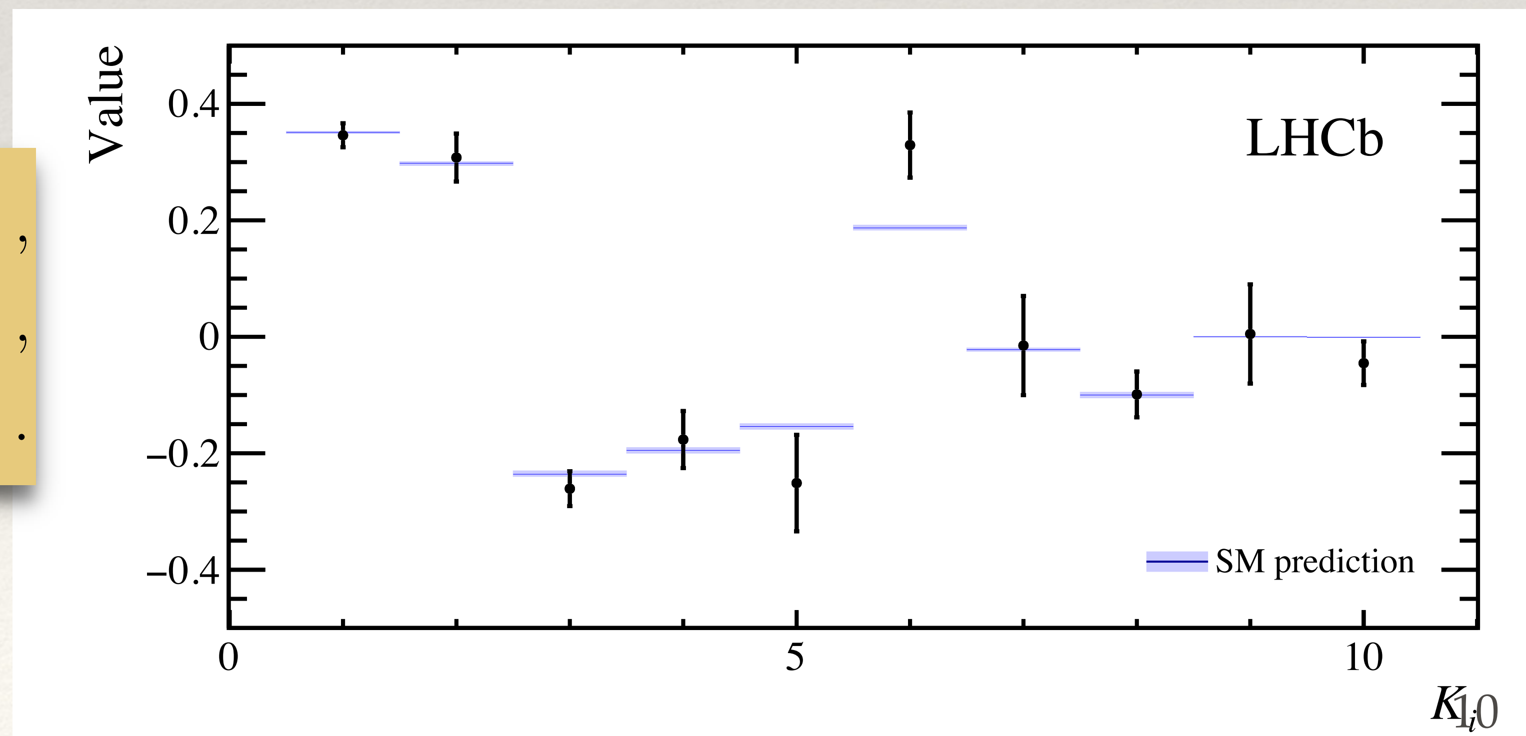
Source	Uncertainty $[10^{-3}]$	
	Range among K_i	Mean
Simulated sample size	3–22	9
Efficiency parameterisation	1–13	4
Data-simulation differences	2–16	6
Angular resolution	1–11	4
Beam crossing angle	1–8	4
Signal mass model	1–4	2

Results

- Consistent with SM but also with C^{NP}_9=-1
- Combines different CMS energies
  - Moments of $\Lambda_b \to J/\psi\Lambda$ consistent $\Longleftrightarrow$ no difference in polarisation
- Covariance matrix OK

Obs.	Value	Obs.	Value
K_1	$0.346 \pm 0.020 \pm 0.004$	K_{18}	$-0.108 \pm 0.058 \pm 0.008$
K_2	$0.308 \pm 0.040 \pm 0.008$	K_{19}	$-0.151 \pm 0.122 \pm 0.022$
K_3	$-0.261 \pm 0.029 \pm 0.006$	K_{20}	$-0.116 \pm 0.056 \pm 0.008$
K_4	$-0.176 \pm 0.046 \pm 0.016$	K_{21}	$-0.041 \pm 0.105 \pm 0.020$
K_5	$-0.251 \pm 0.081 \pm 0.016$	K_{22}	$-0.014 \pm 0.045 \pm 0.007$
K_6	$0.329 \pm 0.055 \pm 0.012$	K_{23}	$-0.024 \pm 0.077 \pm 0.012$
K_7	$-0.015 \pm 0.084 \pm 0.013$	K_{24}	$0.005 \pm 0.033 \pm 0.005$
K_8	$-0.099 \pm 0.037 \pm 0.012$	K_{25}	$-0.226 \pm 0.176 \pm 0.030$
K_9	$0.005 \pm 0.084 \pm 0.012$	K_{26}	$0.140 \pm 0.074 \pm 0.014$
K_{10}	$-0.045 \pm 0.037 \pm 0.006$	K_{27}	$0.016 \pm 0.140 \pm 0.025$
K_{11}	$-0.007 \pm 0.043 \pm 0.009$	K_{28}	$0.032 \pm 0.058 \pm 0.009$
K_{12}	$-0.009 \pm 0.063 \pm 0.014$	K_{29}	$-0.127 \pm 0.097 \pm 0.016$
K_{13}	$0.024 \pm 0.045 \pm 0.010$	K_{30}	$0.011 \pm 0.061 \pm 0.011$
K_{14}	$0.010 \pm 0.082 \pm 0.013$	K_{31}	$0.180 \pm 0.094 \pm 0.015$
K_{15}	$0.158 \pm 0.117 \pm 0.027$	K_{32}	$-0.009 \pm 0.055 \pm 0.008$
K_{16}	$0.050 \pm 0.084 \pm 0.023$	K_{33}	$0.022 \pm 0.060 \pm 0.009$
K_{17}	$-0.000 \pm 0.120 \pm 0.022$	K_{34}	$0.060 \pm 0.058 \pm 0.009$

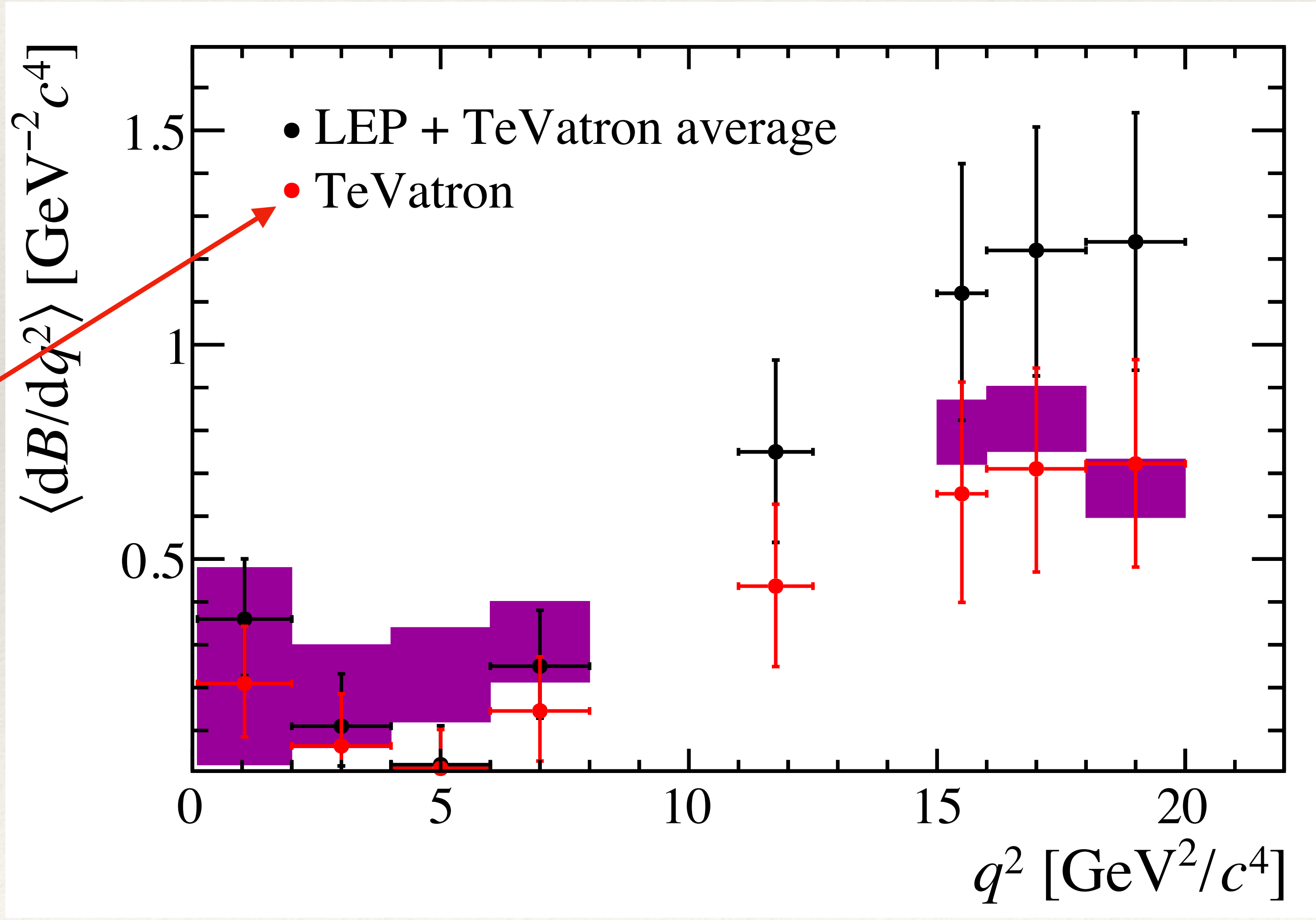
$$A^{\ell}_{\rm FB} = -0.39 \pm 0.04\,(\text{stat}) \pm 0.01\,(\text{syst}) ,$$
$$A^{h}_{\rm FB} = -0.30 \pm 0.05\,(\text{stat}) \pm 0.02\,(\text{syst}) ,$$
$$A^{\ell h}_{\rm FB} = +0.25 \pm 0.04\,(\text{stat}) \pm 0.01\,(\text{syst}) .$$



Note on $\Lambda_b \to \Lambda\mu\mu$ BF

- Measured relative to $\Lambda_b \to J/\psi\Lambda$ but its BF not well known
- $\Lambda_b \to J/\psi\Lambda$ BF based on $f_\Lambda/f_d \times B(\Lambda_b \to J/\psi\Lambda)/B(B^0 \to J/\psi K_S)$ dominated by D0 measurement
- Fragmentation fraction is p_T dependent, depends on experiment

b hadron	Fraction at Z[%]	Fraction at $\bar{p}p$ [%]
B^+, B^0	41.2 ± 0.8	34.0 ± 2.1
B_s^0	8.8 ± 1.3	10.1 ± 1.5
b baryons	8.9 ± 1.2	21.8 ± 4.7



- Will need new $\Lambda_b \to J/\psi\Lambda$ BF measurement to have solid number

Near term future

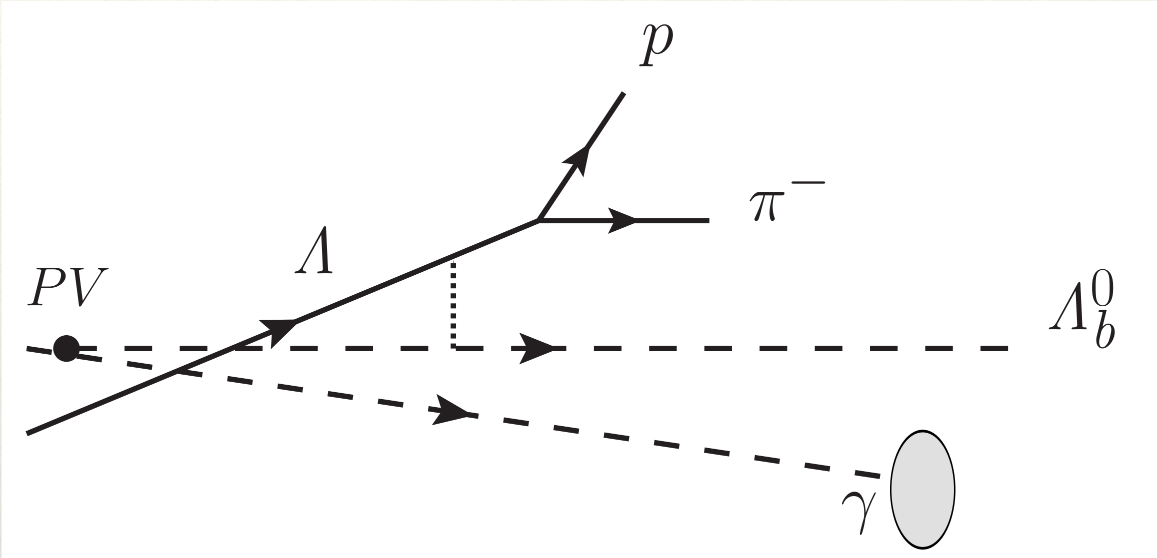
- Measure $\Lambda_b \to J/\psi \Lambda$ BF with LHCb data to have solid normalisation
- Look back to differential branching fraction of $\Lambda_b \to \Lambda\mu\mu$ with full LHCb dataset
  - Should be about 4× previous dataset
  - LQCD (Phys.Rev. D93 (2016), 074501) expects in 1.1-6 GeV^2 about 1/4 of signal in 15-20 GeV^2
  - It should be feasible to see some signal also at low q^2
- Add remaining data for angular analysis of $\Lambda_b \to \Lambda\mu\mu$
  - Should double dataset
  - Might be possible to do something at low q^2 but might be difficult to get fully correct correlations
- Measure $\Lambda_b \to pK\mu\mu$ differential branching fraction

Observation of $\Lambda_b \to \Lambda\gamma$

- No radiative b-baryon decay measured before
- In SM: BR = (10^{-7} — 10^{-5})
  - large form factor uncertainties at $q^2=0$
  - best limit: BR < 1.9×10^{-3} at 90% CL [CDF Phys.Rev.D66:112002]
- Gives access to the photon polarisation thanks to weak decay of Λ baryon
  - test of right-handed currents in C_7
- Analysis uses 1.7 fb^{-1} (2016)
- Dedicated trigger implemented in Run 2
  - Run 1 data has no sensitivity

Event reconstruction

- Very challenging decay topology:
  - Large Λ lifetime
  - No direction from the γ cluster
  - Cannot reconstruct decay vertex



- Dedicated reconstruction:
  - Λ_b momentum as direct sum of Λ and γ momenta (origin at PV)
  - Reconstructed Λ and Λ_b trajectories don't necessarily cross but distance should be small → exploit in selection
  - still, large combinatorial background expected

Multivariate selection

- Key analysis part: before this ~750 signal with ~150k background events expected!
- Exploit high performance BDT using XGBoost algorithm
  - Kinematic and isolation information as input
- Requirement on BDT output optimised with Punzi figure of merit:

$$FoM = \frac{\epsilon_S}{\sigma/2 + \sqrt{N_B}}, \sigma = 5$$

  - achieve 99.8% background rejection with 30% signal efficiency

Normalisation

- Use well-known $B^0 \to K^*\gamma$ decay to extract BR measurement:

$$\frac{N(\Lambda_b^0 \to \Lambda\gamma)}{N(B^0 \to K^{*0}\gamma)} = \frac{f_{\Lambda_b^0}}{f_{B^0}} \times \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma)}{\mathcal{B}(B^0 \to K^{*0}\gamma)} \times \frac{\mathcal{B}(\Lambda \to p\pi^-)}{\mathcal{B}(K^{*0} \to K^+\pi^-)} \times \frac{\epsilon(\Lambda_b^0 \to \Lambda\gamma)}{\epsilon(B^0 \to K^{*0}\gamma)}$$

  - Hadronisation fraction from LHCb [Phys. Rev. D 100, 031102(R)]
  - Input branching fractions from PDG
  - Efficiencies from simulation and calibration samples

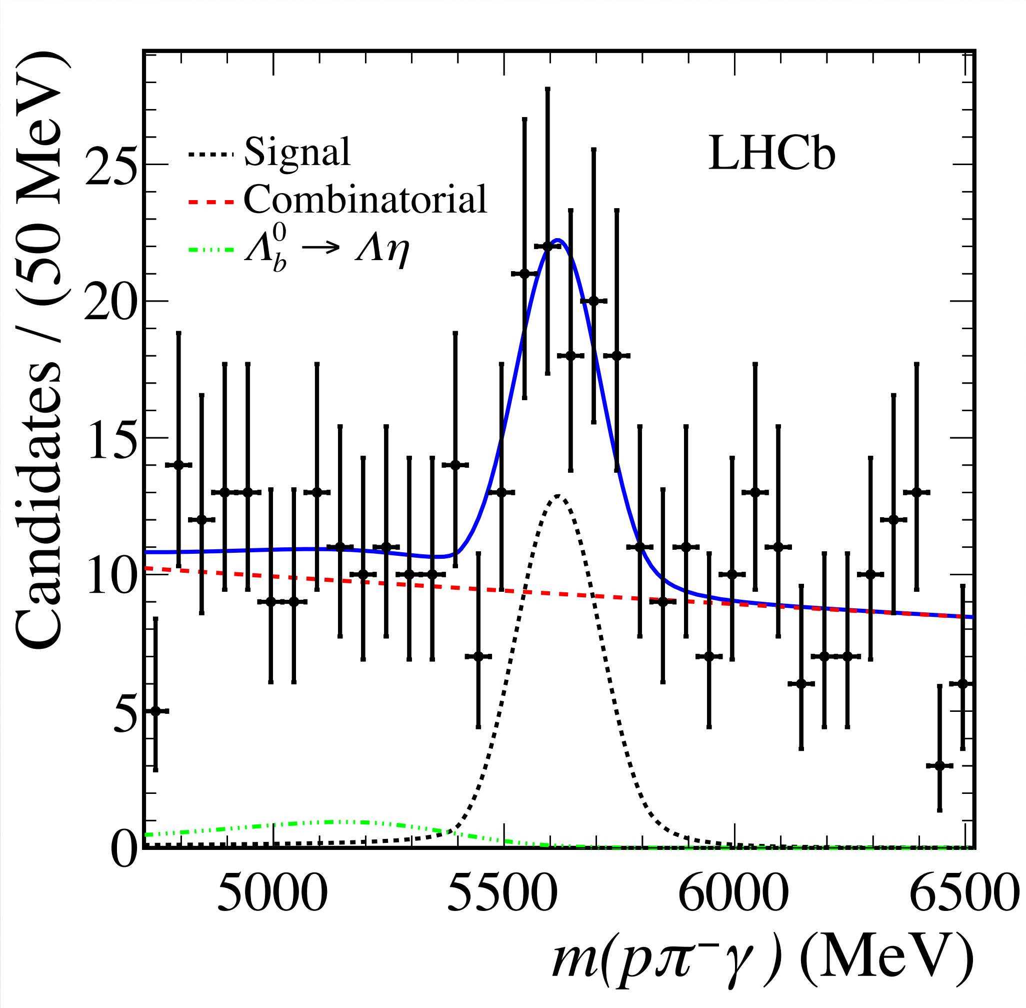
Systematic uncertainties

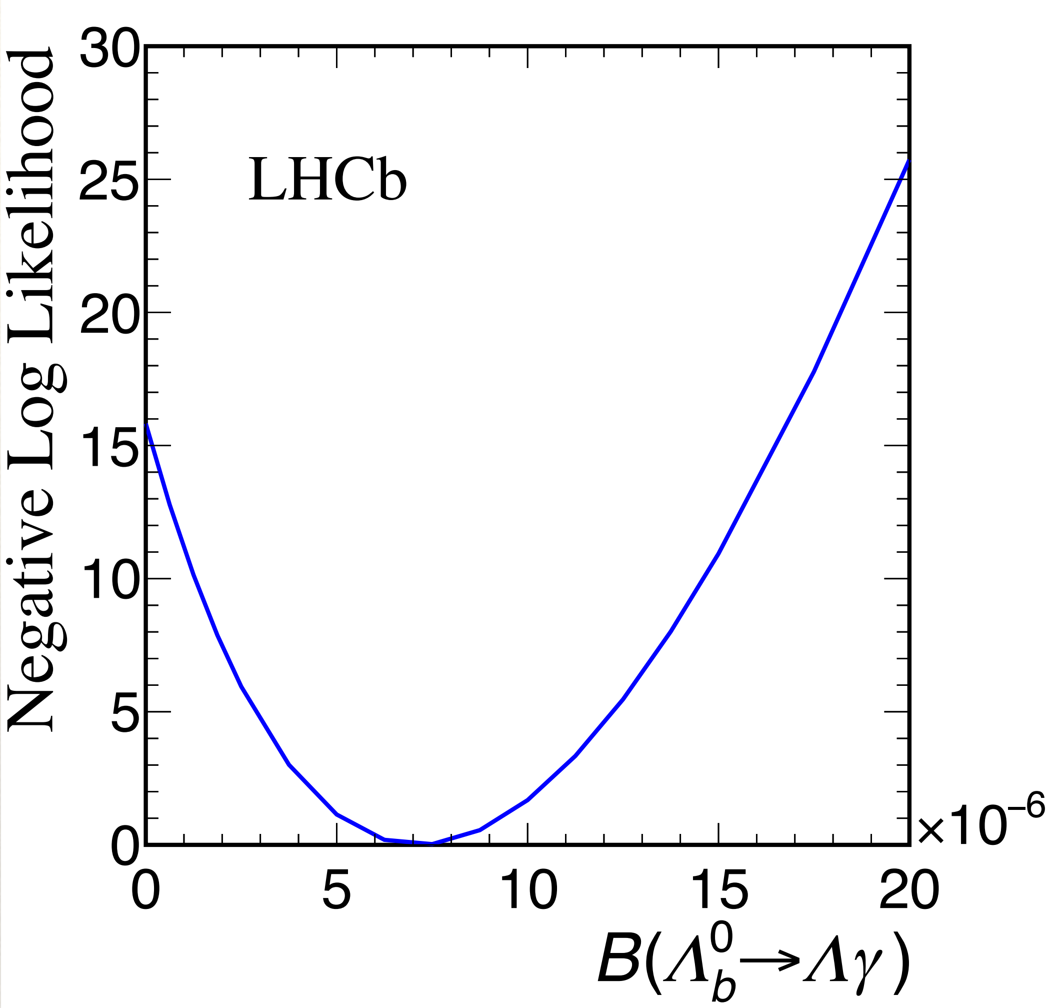
- Analysis statistically dominated, main uncertainties:

	Source	Uncertainty (%)
Internal	Data/simulation agreement	7.7
	Λ_b^0 fit model	3.0
	$B^0 \to K^{*0}\gamma$ backgrounds	2.7
	Size of simulated samples	1.7
	Efficiency ratio	1.4
	Sum in quadrature	9.0
External	$f_{\Lambda_b^0}/f_{B^0}$	8.7
	Input branching fractions	3.0
	Sum in quadrature	9.2

$\Lambda_b \to \Lambda\gamma$ observation

- Invariant mass fit yield with 65 ± 13 signal events

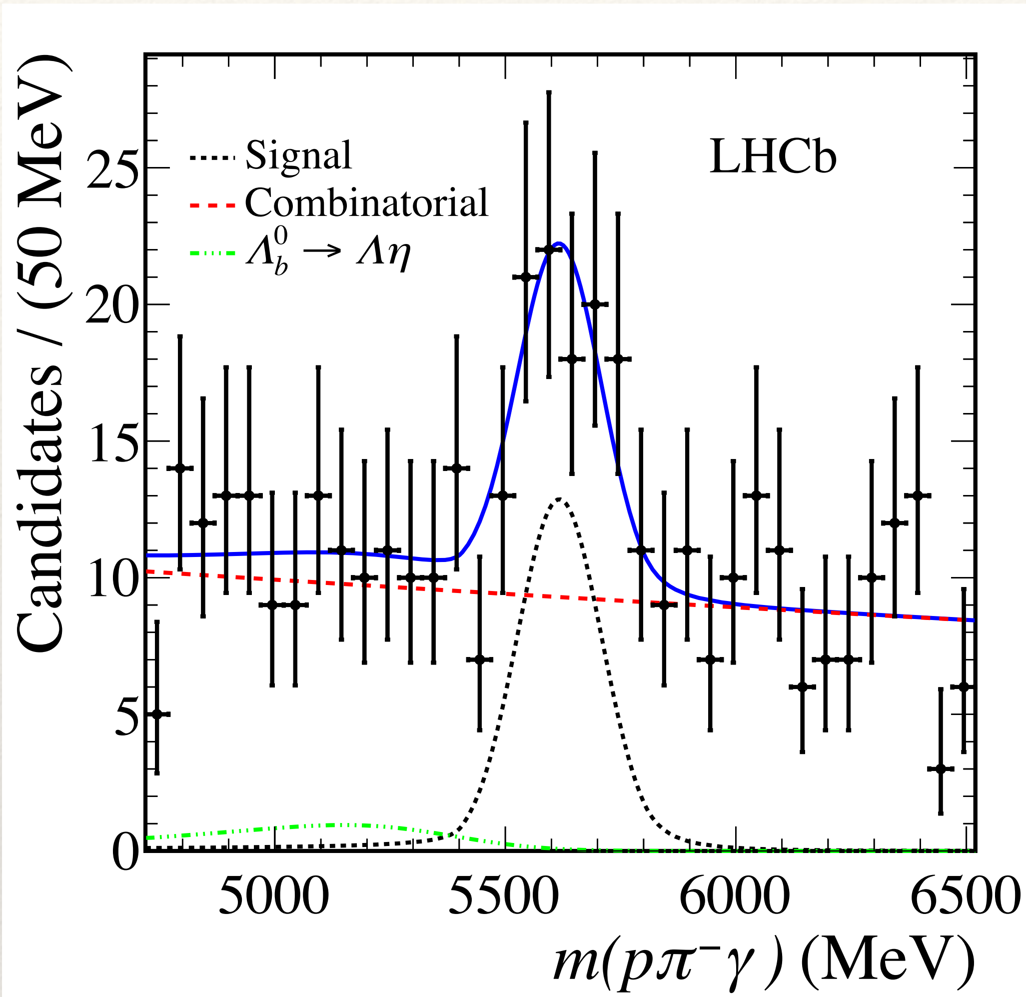


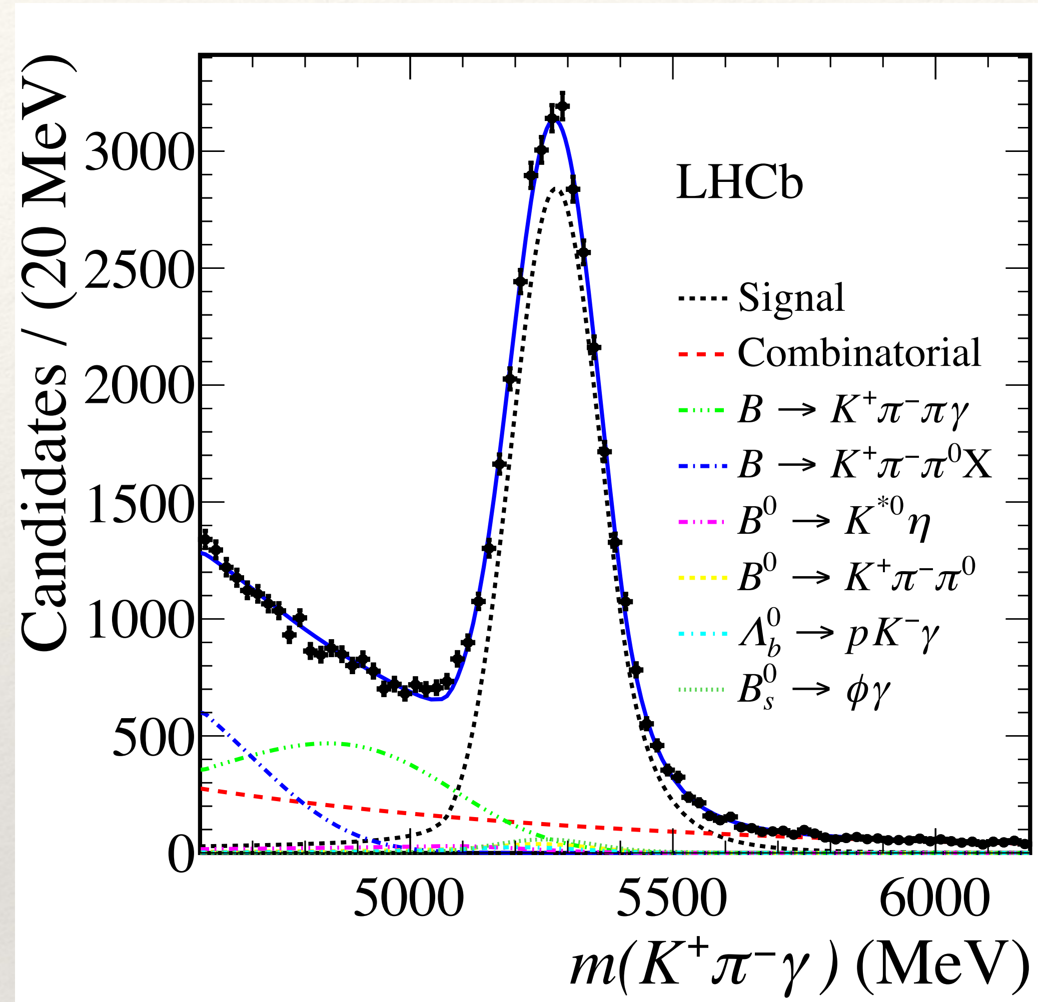


Signal excess has 5.6σ significance

BR measurement

- Simultaneous fit to signal and normalisation modes





$$\text{BR} = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \times 10^{-6}$$

- In agreement with SM predictions from LCSR, HQL and Covariant Constituent QM [Wang et al., Mannel et al., Gutsche et al.]

Near term prospects

- With full Run 2 data, expect ~250 signal events
- Perform angular analysis to extract photon polarisation → constrain C'_7

[Hiller & Kagan]

$$\frac{d\Gamma}{d\cos\theta_\gamma} \propto 1 - \alpha_\gamma P_{\Lambda_b} \cos\theta_\gamma$$

$$\frac{d\Gamma}{d\cos\theta_p} \propto 1 - \alpha_\gamma \alpha_{p,1/2} \cos\theta_p$$

$P_{\Lambda b}$ is initial Λ_b polarisation, small at LHC

$\alpha_{p,1/2}$ is Λ decay parameter, well known

$$\alpha_\gamma = \frac{P(\gamma_L)-P(\gamma_R)}{P(\gamma_L)+P(\gamma_R)} \qquad \alpha_\gamma^{LO} = \frac{|C_7|^2-|C'_7|^2}{|C_7|^2+|C'_7|^2}$$