Charmless multi-body *b* decays at LHCb

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On behalf of the LHCb experiment

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Outline

This talk covers some recent highlights in this sector from LHCb

[$3\,\mathrm{fb}^{-1}$ Run-I (2011/12) at 7/8 TeV]

- CPV measurements in charmless three-body decays involving K^0_S

  [JHEP 11 (2017) 027, LHCb-PAPER-2017-033]

- Searches for *CP* violation in *b*-baryon multi-body decays and 4-body decays BR

  [i.e. $\Lambda^0_b \to p\{K,\pi\}$, $\Lambda^0_b \to \{\Lambda,K^0\}hh$, $\Lambda^0_b \to p3h$]
  [JHEP **098** (2018) 2018]

- Searches for *CP* violation in the baryonic sector

  [Preliminary: LHCb-PAPER-2018-001]

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Charmless three-body decays to final states containing a long-lived particle

LHCb results : $\mathcal{L} = 3\,\mathrm{fb}^{-1} - 2011 + 2012$ dataset

Updated branching fraction of $B^0_{(s)} \rightarrow K^0 h^+ h'^-$ decays

[JHEP 11 (2017) 027]

Dalitz plot analysis of $B^0 \rightarrow K^0 \pi^+ \pi^-$ decays

[arXiv:1712.09320, LHCb-PAPER-2017-033]

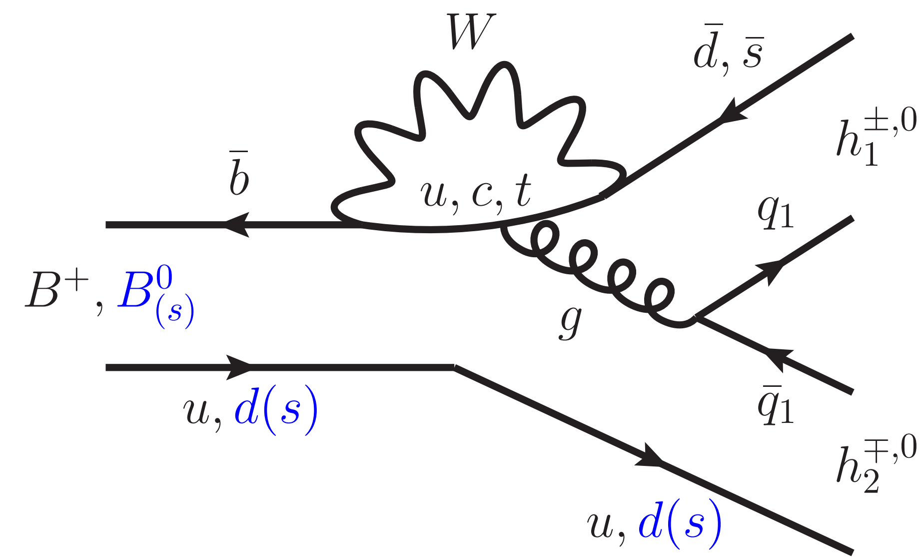
Three-body decays containing K^0_S

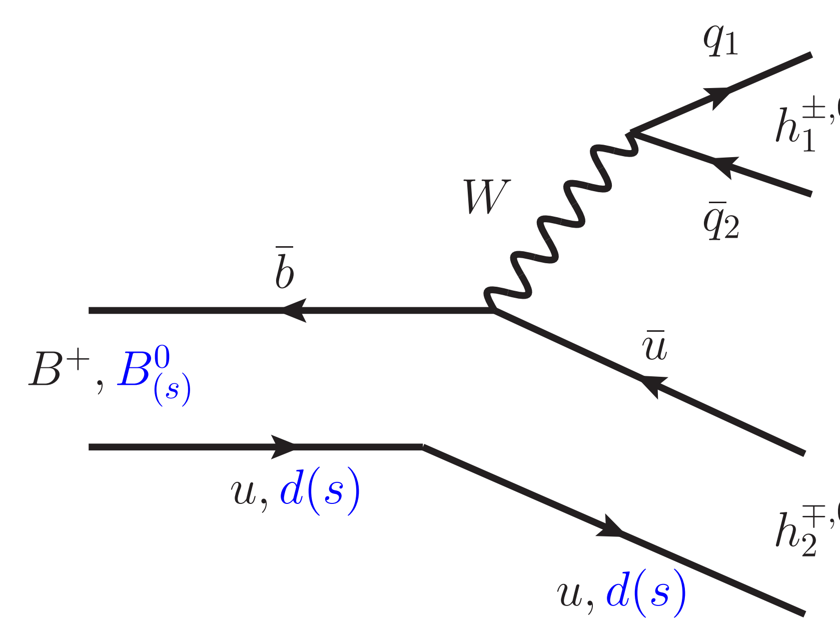
Many channels have been already explored in the B-factories which has a great range of interesting features

- Transitions mediated by $b \to u$ (tree) and/or $b \to d,s$ (penguin) diagrams
- Several comparable amplitudes can give rise to (via interference) large *CP* violation
- Deviations of observables from their expected values in the SM could indicate NP contributions
- Potential to measure all three UT angles

  [*e.g.* β-angle $B^0 \to K^0_S \pi^+\pi^-$, $B^0 \to K^0_S K^+K^-$]

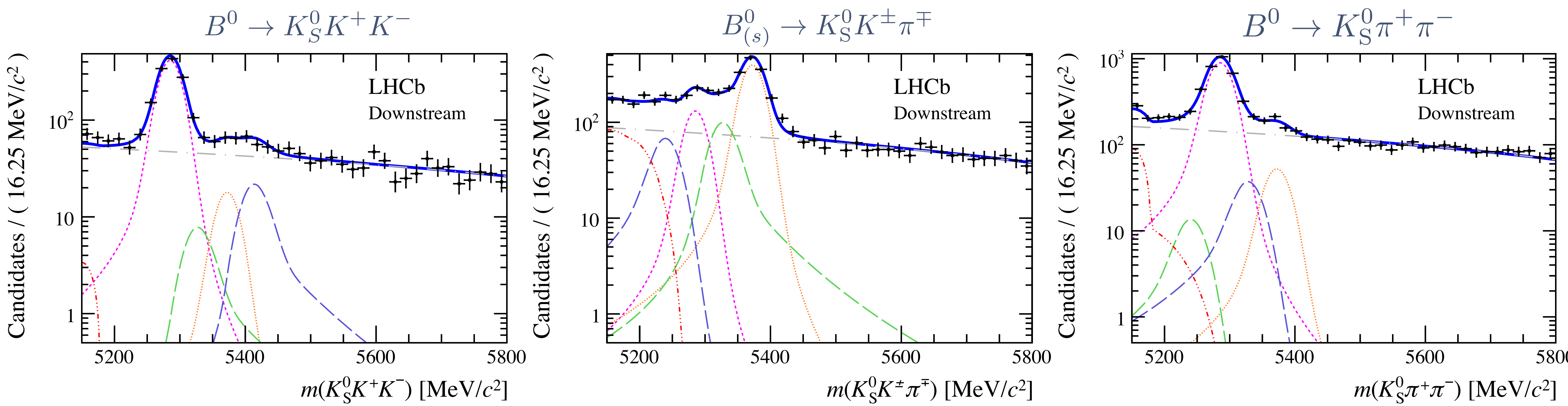
- Rich spectrum of final/resonant states can be further disentangled via amplitude analysis





Recent results from $B^0_{(s)} \rightarrow K^0 h^+ h'^-$ decays

LHCb JHEP 11 (2017) 027

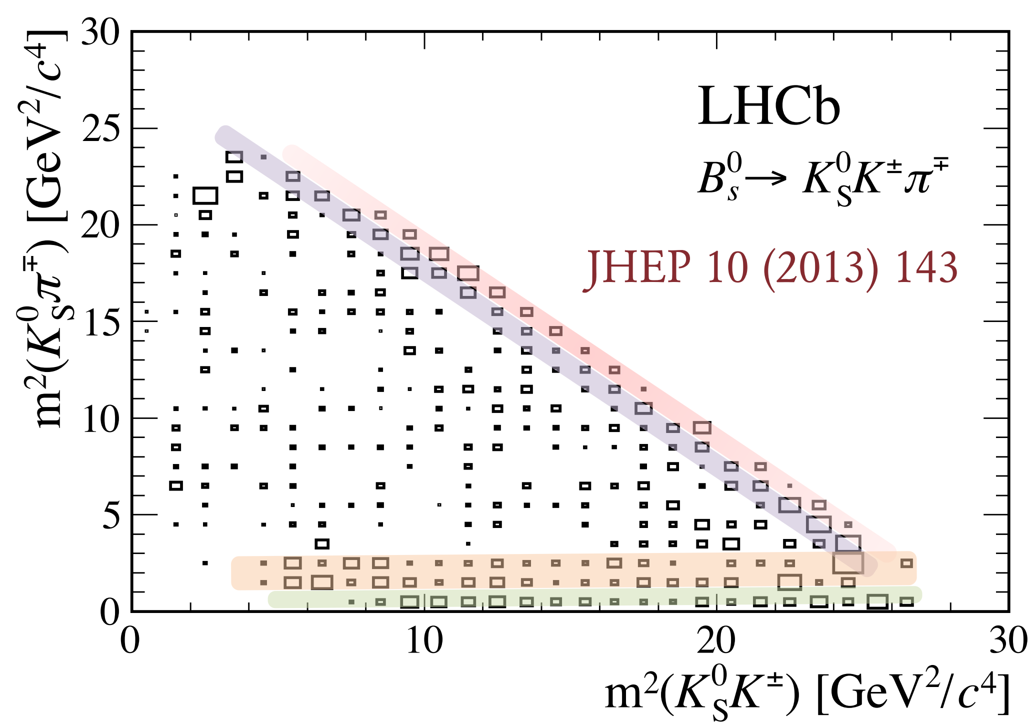


- BF measurements updated with 3 fb^{-1}

$$\mathcal{B}(B^0_s \to K^0 K^+ K^-) \in [0.4 - 2.5] \times 10^{-6} \text{ at } 90\% \text{ C.L.}$$

- Long term: time-dependent amplitude analysis for CKM-phases measurement
- Short term: time-integrated analysis

[sensitive to ~~CP~~ in flavour-specific contributions]



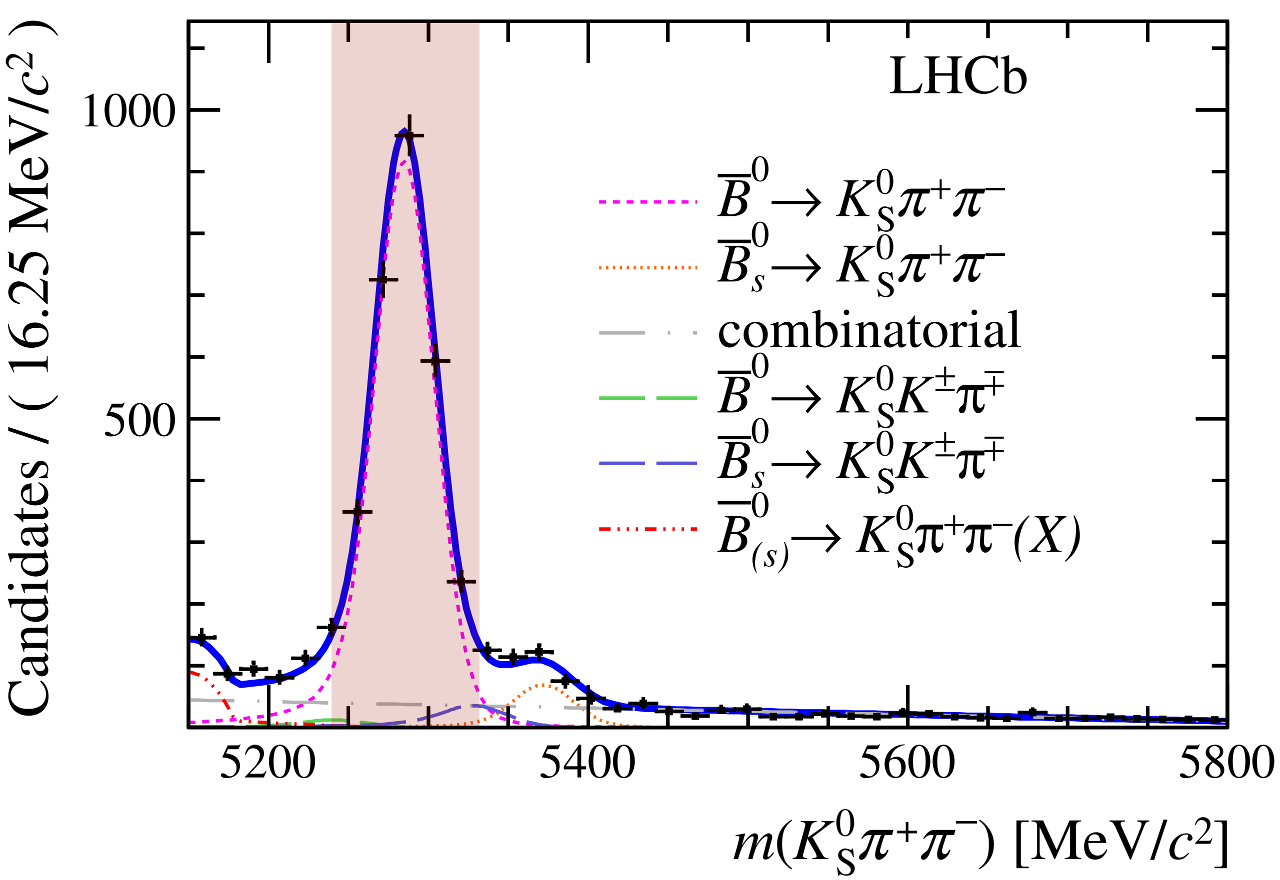
Dalitz plot analysis of $B^0 \to K^0\pi^+\pi^-$

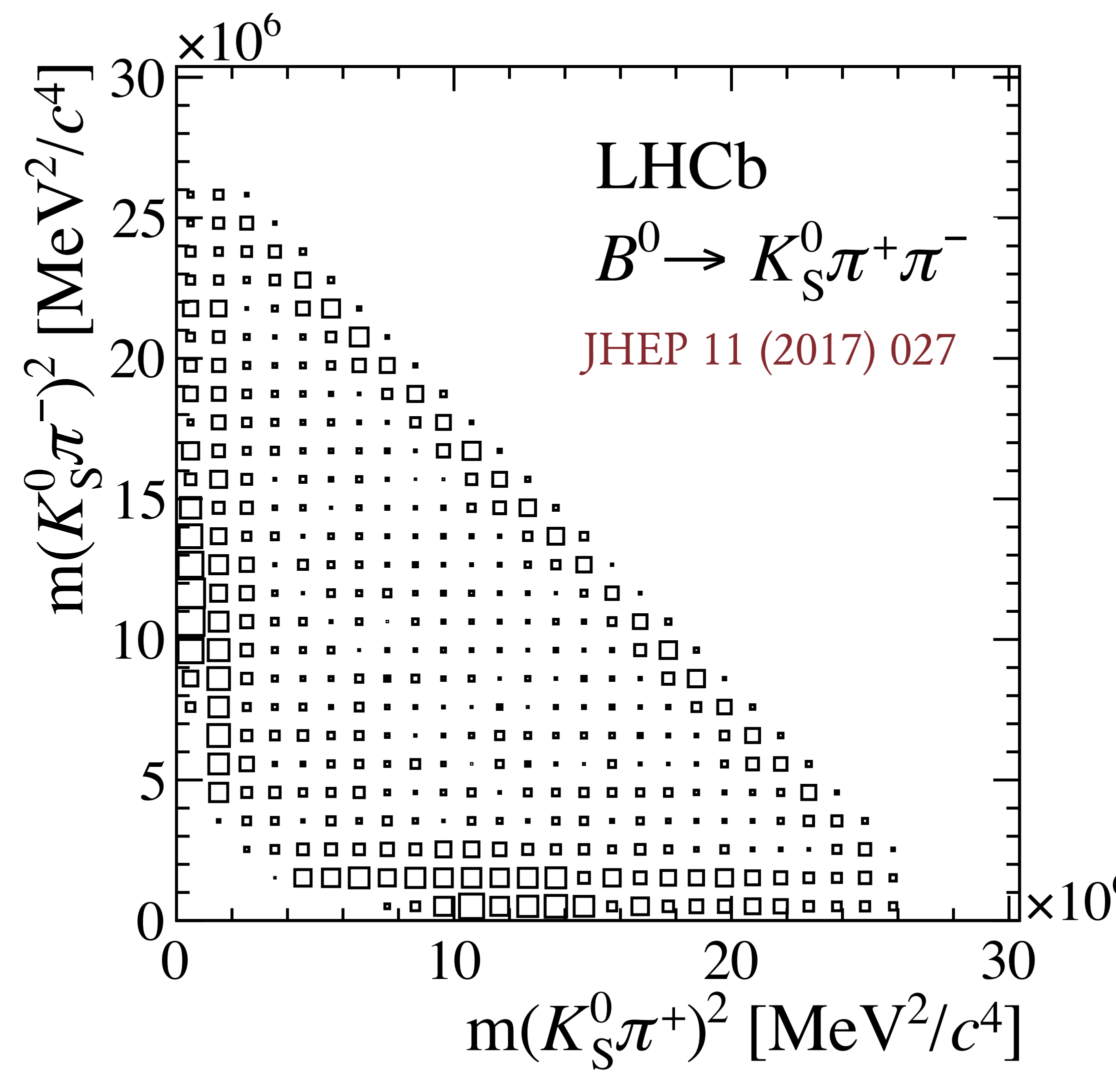
arXiv:1712.09320, LHCb-PAPER-2017-033, submitted to PRL

Analysis performed with ~3.2k signal events and purity of 85-95%

Signal region: $\pm3\sigma$ around nominal mass is considered for the Dalitz plot fit

Backgrounds due to Combinatorial (3-13%) and cross-feed (2-3%)





Quasi-flavour-specific final state

Dalitz plot analysis - Isobar Model

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Amplitude analysis most commonly performed in the "Isobar Model", in which the total amplitude is approximated as coherent sum of quasi-two-body contributions:

CP violating

Strong dynamics
CP conserving

$$\mathcal{A}(m_{ij}^2, m_{jk}^2) = \sum_{l=1}^{N} \boxed{c_l} \boxed{F_l(m_{ij}^2, m_{jk}^2)}$$

c_l : complex coefficients describing the relative magnitude and phase of the different isobars

F_l: dynamical amplitudes that contain the lineshape and spin-dependence of the hadronic part

$$F_l(L, m_{ij}^2, m_{jk}^2) = \boxed{R_l(m_{ij}^2)} \times \boxed{X_L(|\vec{p}|r)} \times \boxed{X_L(|\vec{q}|r)} \times \boxed{T_l(L, \vec{p}, \vec{q})}$$

Resonance mass term (e.g. Breit-Wigner)

Barrier factors - *p*, *q*: momenta of bachelor and resonance

Angular probability distribution

Many observables can be accessed: $\mathrm{Re}(c_i)$ and $\mathrm{Im}(c_i)$ or $|c_i|$ and $\arg(c_i)$; or derived quantities such as BF and A_{CP}

Dalitz plot analysis of $B^0 \to K^0\pi^+\pi^-$

Universität Zürich[UZH]

arXiv:1712.09320, LHCb-PAPER-2017-033, submitted to PRL

Resonance	Parameters	Lineshape
$K^*(892)^-$	$m_0 = 891.66 \pm 0.26$ $\Gamma_0 = 50.8 \pm 0.9$	RBW
$(K\pi)_0^-$	$\mathcal{R}e(\lambda_0) = 0.204 \pm 0.103$ $\mathcal{I}m(\lambda_0) = 0$ $\mathcal{R}e(\lambda_1) = 1$ $\mathcal{I}m(\lambda_1) = 0$	EFKLLM
$K_2^*(1430)^-$	$m_0 = 1425.6 \pm 1.5$ $\Gamma_0 = 98.5 \pm 2.7$	RBW
$K^*(1680)^-$	$m_0 = 1717 \pm 27$ $\Gamma_0 = 332 \pm 110$	Flatté
$f_0(500)$	$\mathrm{m}_0 = 513 \pm 32$ $\Gamma_0 = 335 \pm 67$	RBW
$\rho(770)^0$	$m_0 = 775.26 \pm 0.25$ $\Gamma_0 = 149.8 \pm 0.8$	GS
$f_0(980)$	$m_0 = 965 \pm 10$ $g_\pi = 0.165 \pm 0.025$ GeV $g_K = 0.695 \pm 0.119$ GeV	Flatté
$f_0(1500)$	$m_0 = 1505 \pm 6$ $\Gamma_0 = 109 \pm 7$	RBW
χ_{c0}	$m_0 = 3414.75 \pm 0.31$ $\Gamma_0 = 10.5 \pm 0.6$	RBW
Nonresonant (NR)		Phase space

EFKLLM: $R_j(m) = F(m)\left(\frac{\lambda_0}{m^2} + \lambda_1\right)$

Asymmetry observable derived from usual isobar parameters

$$\mathcal{A}_{\rm raw} = \frac{|\bar{c}_j|^2 - |c_j|^2}{|\bar{c}_j|^2 + |c_j|^2}$$

The *CP* asymmetry is related to the raw asymmetry by $\mathcal{A}_{CP} = \mathcal{A}_{\rm raw} - \mathcal{A}_\Delta$

PRL 110 (2013) 221601, PLB 713 (2012) 186

$$\mathcal{A}_\Delta = A_P(B^0) + A_D(\pi)$$

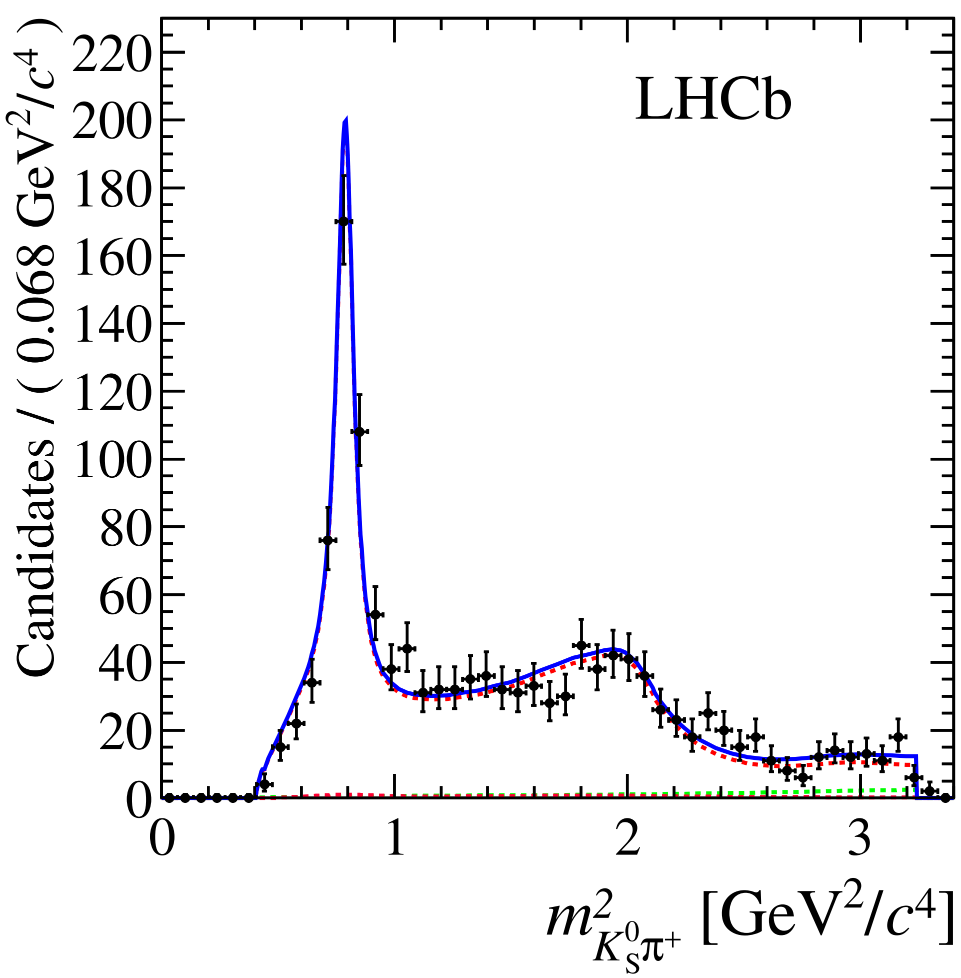
(-0.35 ± 0.81)%   0.25%

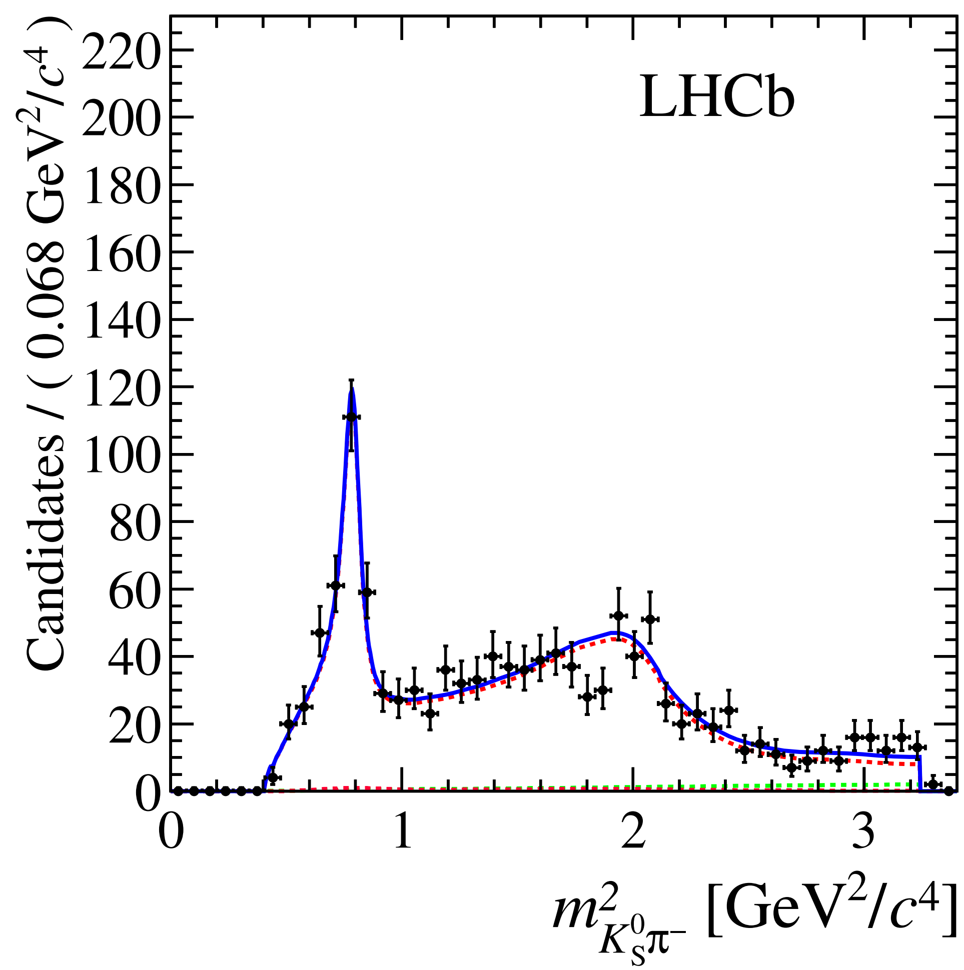
Fit fractions:

$$\mathcal{F}_i = \frac{\iint_{\rm DP} |c_i F_i(s_+, s_-)|^2 \, ds_+ ds_-}{\iint_{\rm DP} \left|\sum_j c_j F_j(s_+, s_-)\right|^2 ds_+ ds_-}$$

Dalitz plot fit results

arXiv:1712.09320, LHCb-PAPER-2017-033, submitted to PRL





$\mathcal{A}_{CP}(K^*(892)^-\pi^+)$	$= -0.308 \pm 0.060 \pm 0.011 \pm 0.012$
$\mathcal{A}_{CP}((K\pi)^-_0\pi^+)$	$= -0.032 \pm 0.047 \pm 0.016 \pm 0.027$
$\mathcal{A}_{CP}(K^*_2(1430)^-\pi^+)$	$= -0.29 \pm 0.22 \pm 0.09 \pm 0.03$
$\mathcal{A}_{CP}(K^*(1680)^-\pi^+)$	$= -0.07 \pm 0.13 \pm 0.02 \pm 0.03$
$\mathcal{A}_{CP}(f_0(980)K^0_S)$	$= 0.28 \pm 0.27 \pm 0.05 \pm 0.14$

First observation of *CP* violation in $B^0 \rightarrow K^*(892)\pi$ with ~ 6 sigma

Previous world average

$\mathcal{A}(K^*(892)\pi) = -0.23 \pm 0.06$

Dalitz plot fit results

arXiv:1712.09320, LHCb-PAPER-2017-033, submitted to PRL

Fit fractions:

$$
\begin{aligned}
\mathcal{F}(K^*(892)^-\pi^+) &= 9.43 \pm 0.40 \pm 0.33 \pm 0.34\ \% \\
\mathcal{F}((K\pi)_0^-\pi^+) &= 32.7 \pm 1.4 \pm 1.5 \pm 1.1\ \% \\
\mathcal{F}(K_2^*(1430)^-\pi^+) &= 2.45\ {}^{+\ 0.10}_{-\ 0.08} \pm 0.14 \pm 0.12\ \% \\
\mathcal{F}(K^*(1680)^-\pi^+) &= 7.34 \pm 0.30 \pm 0.31 \pm 0.06\ \% \\
\mathcal{F}(f_0(980)K^0_\mathrm{S}) &= 18.6 \pm 0.8 \pm 0.7 \pm 1.2\ \% \\
\mathcal{F}(\rho(770)^0K^0_\mathrm{S}) &= 3.8\ {}^{+\ 1.1}_{-\ 1.6} \pm 0.7 \pm 0.4\ \% \\
\mathcal{F}(f_0(500)K^0_\mathrm{S}) &= 0.32\ {}^{+\ 0.40}_{-\ 0.08} \pm 0.19 \pm 0.23\ \% \\
\mathcal{F}(f_0(1500)K^0_\mathrm{S}) &= 2.60 \pm 0.54 \pm 1.28 \pm 0.60\ \% \\
\mathcal{F}(\chi_{c0}K^0_\mathrm{S}) &= 2.23\ {}^{+\ 0.40}_{-\ 0.32} \pm 0.22 \pm 0.13\ \% \\
\mathcal{F}(K^0_\mathrm{S}\pi^+\pi^-)^{\mathrm{NR}} &= 24.3 \pm 1.3 \pm 3.7 \pm 4.5\ \%
\end{aligned}
$$

- The resonance state $K^*(1680)$ has been included in the model
  (not seen in previous analyses)
- No signature of $f_2(1270)$

Belle PRD 79 (2009) 072004, BaBar PRD 80 (2009) 112001

- Alternative LASS modelling for the S-wave has been examined:

$$-2\Delta \ln \mathcal{L} = 85$$

No systematic is assigned to the choice of the model, but only uncertainties associated to fixed parameters

Searches for *CP* violation in *b*-baryon decays

LHCb results : $\mathcal{L} = 3\,\mathrm{fb}^{-1} - 2011 + 2012$ dataset

Searches for CP in multi-body decays

[JHEP 04 (2014) **087**, JHEP 05 (2016) **08**]

BR measurements of Λ^0_b and Ξ^0_b decays

[LHCb, JHEP 1802 (2018) 098]

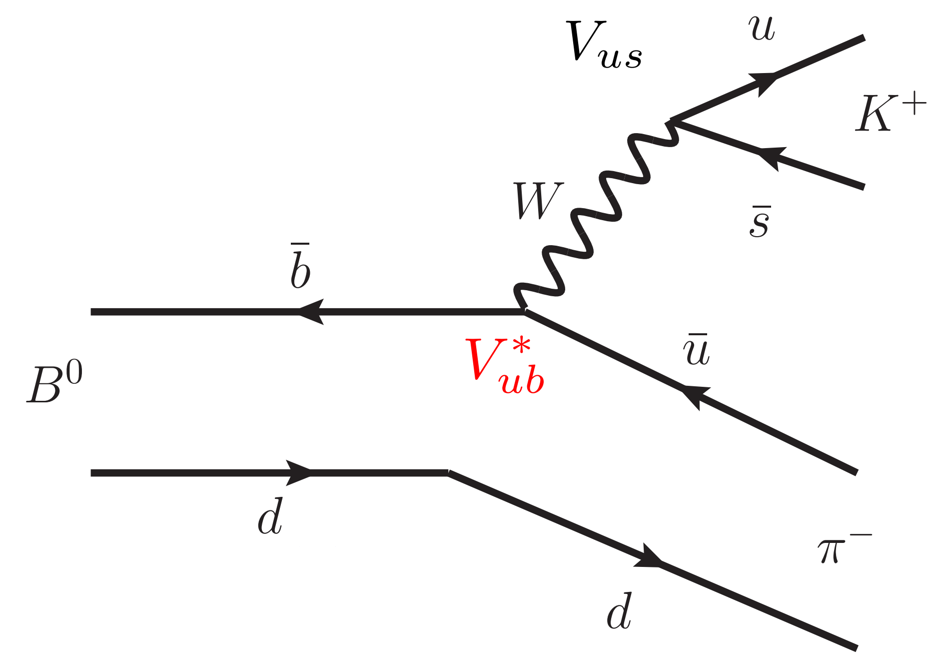
CP violation in the baryonic sector

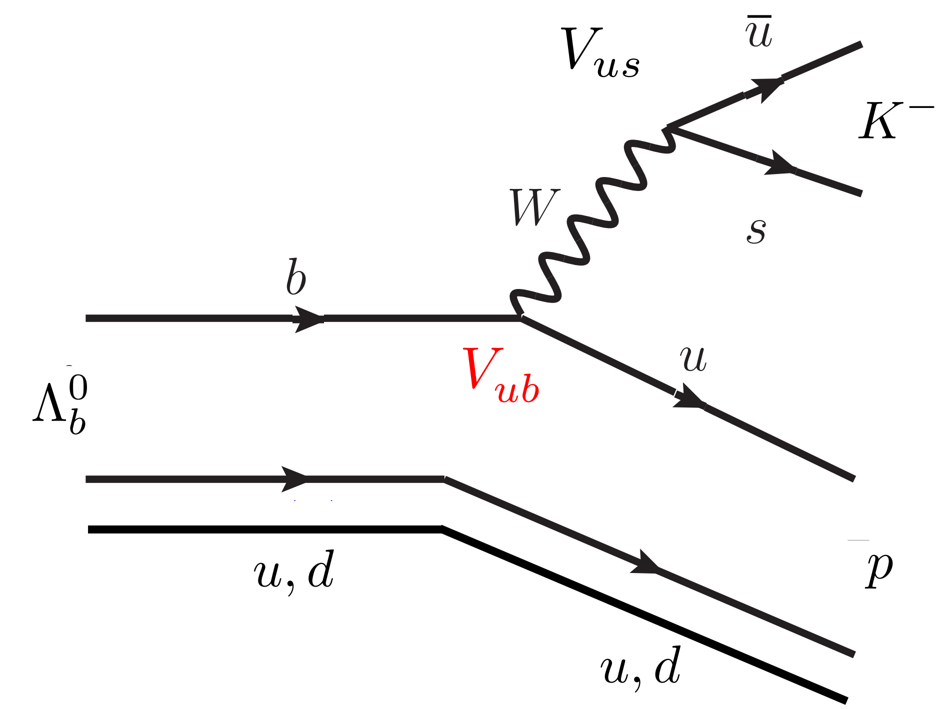
Phenomenon well stablished in the meson sector, *i.e.* Kaon and $B^{\pm,0}_{(s)}$ decays: no deviation from the SM has been seen

As-of-yet no *CP* violation in *b*-baryons has been observed, though the CKM mechanism predicts sizeable amount of violation

At LHCb *b*-baryons are collected in unprecedented quantities → opens a new field in flavour physics for precision measurements

Same underlying short distance physics for *b*-baryons and *B* mesons but with different spin and QCD structure





CP violation in the baryonic sector

CP violation **in decay**: only type available in the baryonic sector (no mixing due to baryon number conservation)

This observable can be measured by comparing yields between baryon/anti-baryon:

$$A_{CP} = \frac{N(A \to f) - N(\overline{A} \to \overline{f})}{N(A \to f) + N(\overline{A} \to \overline{f})} \propto \sin(\delta_1 - \delta_2) \sin(\varphi_1 - \varphi_2)$$

strong phase
CP conserving

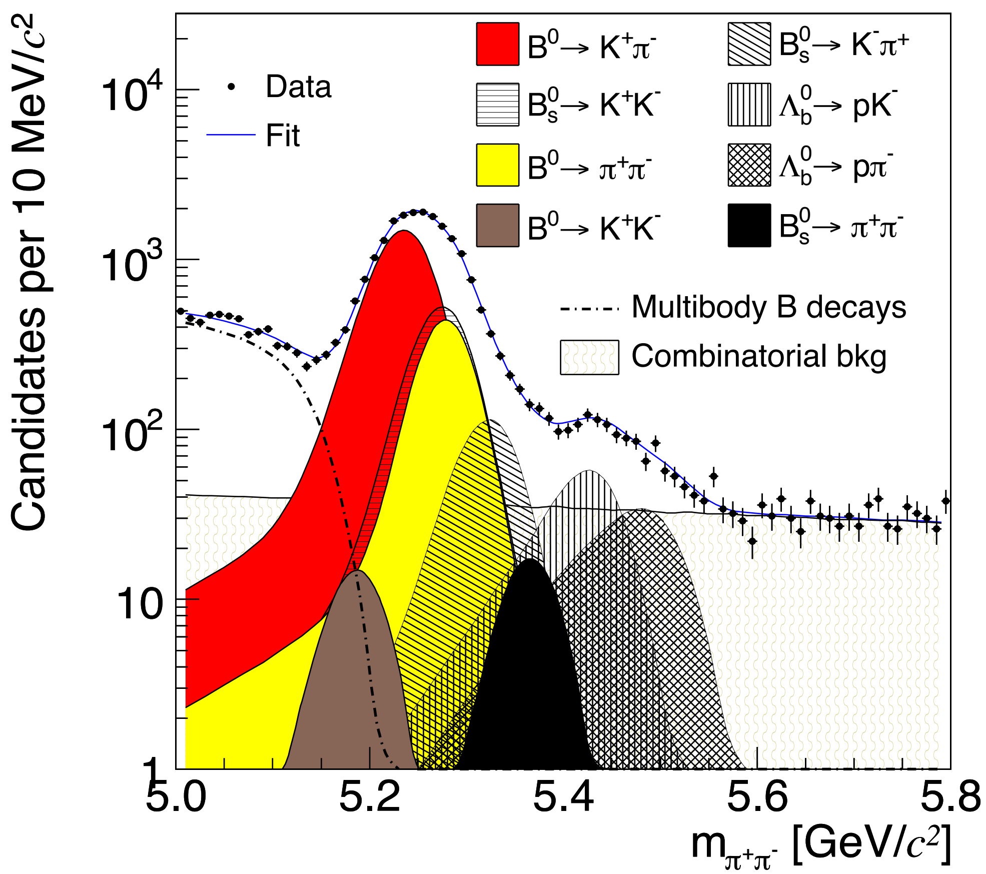
weak phase
CP violating

- Contributions from at least two amplitudes: *e.g.* $A_1 e^{i\delta_1} e^{i\phi_1}, A_2 e^{i\delta_2} e^{i\phi_2}$
- Need non-vanishing strong and weak phase difference
- Sensitive to baryon-antibaryon production asymmetries
- Sensitive to charged particle reconstruction asymmetries

Beauty baryon: two-body case

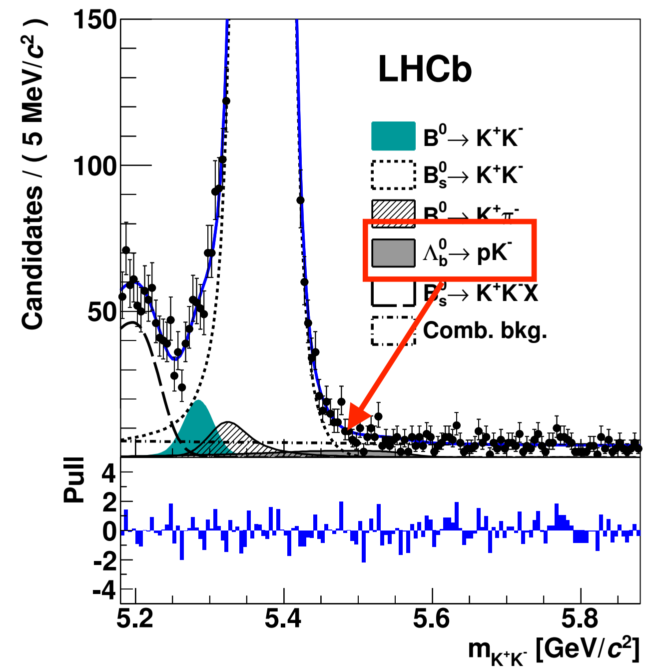
Simplest decay modes: $\Lambda^0_b \rightarrow pK^-, p\pi^-$

[CDF, PRL 113, 242001 (2014)]



Decay	$\mathcal{A}(b \rightarrow f)$
$\Lambda_b^0 \rightarrow p\pi^-$	$+0.06 \pm 0.07 \pm 0.03$
$\Lambda_b^0 \rightarrow pK^-$	$-0.10 \pm 0.08 \pm 0.04$

[LHCb, PRL 118, 081801 (2017)]



Ongoing analysis - expected approximately 10x CDF statistics

Potentially large CPV effects in charmless decays

[Phys. Rev. D 91, 116007 (2015)]

	our result	pQCD [5]	data
$10^2\mathcal{A}_{CP}(\Lambda_b \to pK^-)$	$5.8 \pm 0.2 \pm 0.1$	-5^{+26}_{-5}	$-10 \pm 8 \pm 4$ [8]
$10^2\mathcal{A}_{CP}(\Lambda_b \to p\pi^-)$	$-3.9 \pm 0.2 \pm 0.0$	-31^{+43}_{-1}	$6 \pm 7 \pm 3$ [8]
$10^2\mathcal{A}_{CP}(\Lambda_b \to pK^{*-})$	$19.6 \pm 1.3 \pm 1.0$	—	—
$10^2\mathcal{A}_{CP}(\Lambda_b \to p\rho^-)$	$-3.7 \pm 0.3 \pm 0.0$	—	—

Beauty baryon: multi-body decays

Limited information available in two-body decays: i.e. BF and A_{CP}

Additional information can be obtained via multi-body decays (n >2)

- CPV in $\Lambda^0_b \rightarrow pK^0\pi^-$ decays [LHCb, JHEP **04** (2014) 087]

  [Note that amplitude analysis (Dalitz plot) of this mode can access the intermediate channel pK* - SM *CP* violation expected to be ~20%]

- CPV in $\Lambda^0_b \rightarrow \Lambda h^+h^-$ decays [LHCb, JHEP **05** (2016) 08]
- Triple-product asymmetry in $\Lambda^0_b \rightarrow \Lambda\varphi$ decays [LHCb, PLB 759 (2016) 282]
- CPV in $\Lambda^0_b \rightarrow J/\psi p\pi^-$ and $J/\psi pK^-$ decays [LHCb, JHEP **07** (2014) 103]
- CPV in $\Lambda^0_b \rightarrow pK^-\mu^+\mu^-$ decays [LHCb, JHEP **06** (2017) 108]

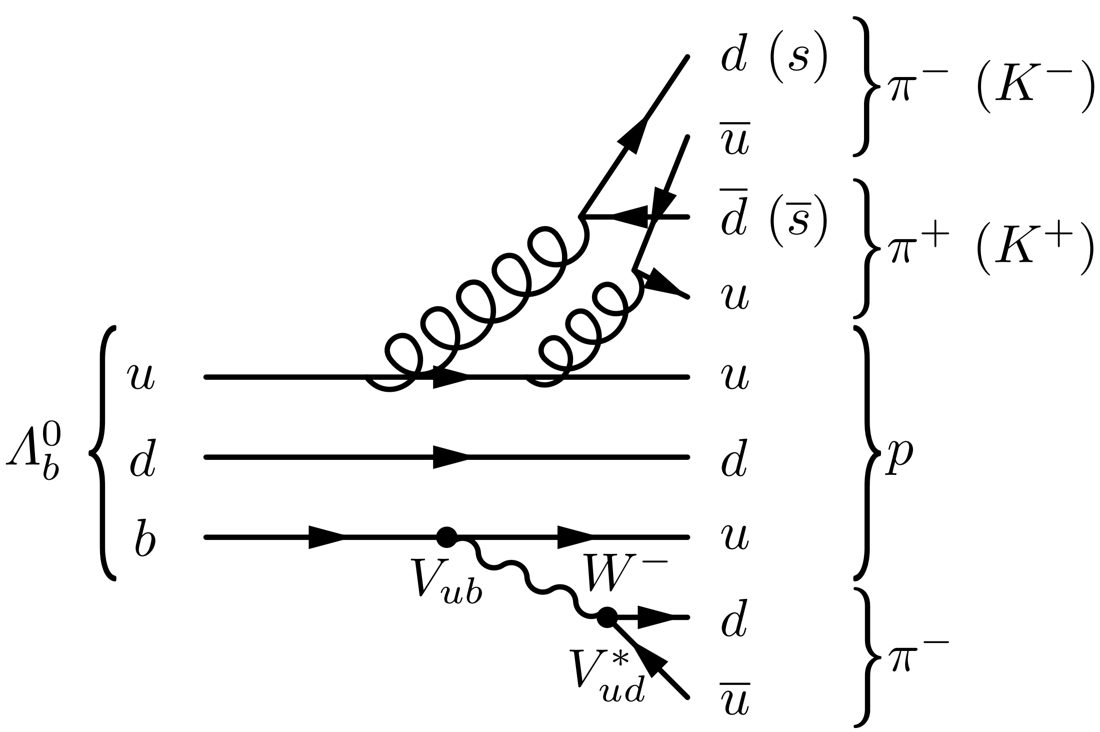
All measurements consistent with CP symmetry!

Search for *CP* violation in 4-body decays

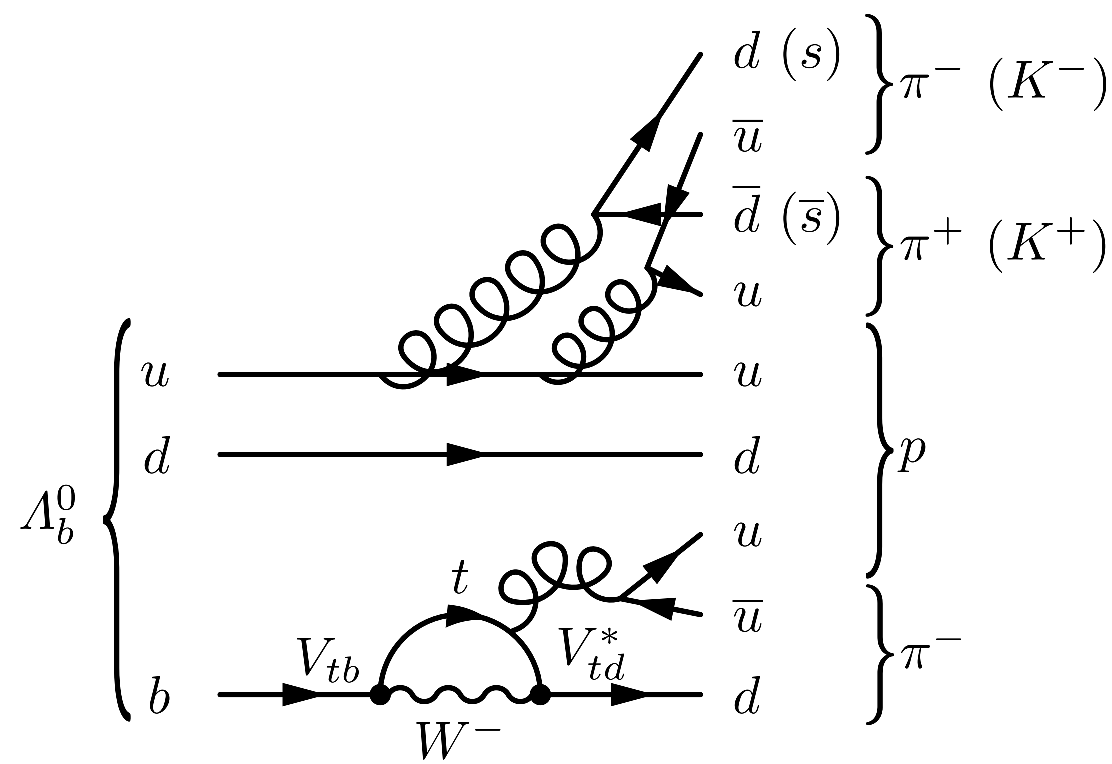
[LHCb, Nature Physics **13** (2017) 391, JHEP 1802 (2018) 098]

Integrated and triple-product asymmetry measurements in $\Lambda^0_b(\Xi^0_b) \rightarrow p\pi[\pi\pi, KK, K\pi]$

Transitions with both tree and penguin amplitudes at comparable magnitude



Tree diagram $\propto V_{ub} \sim \lambda^3$



Penguin diagram $\propto \sum_{x=u,c,t} V_{bx} V_{xd} \sim \lambda^3$

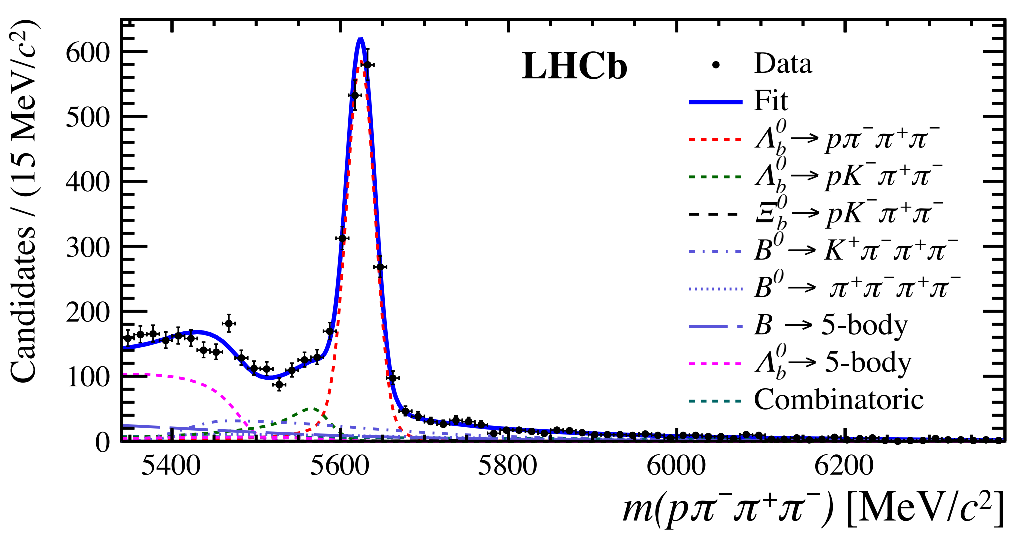
First step: determine the signal yields for these channels

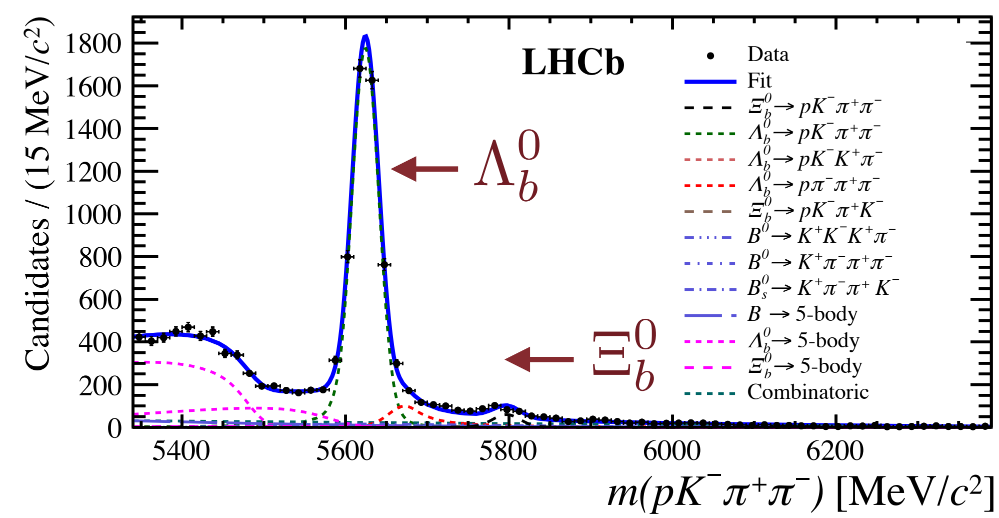
BR measurements of Λ^0_b, $\Xi^0_b \longrightarrow p3h$

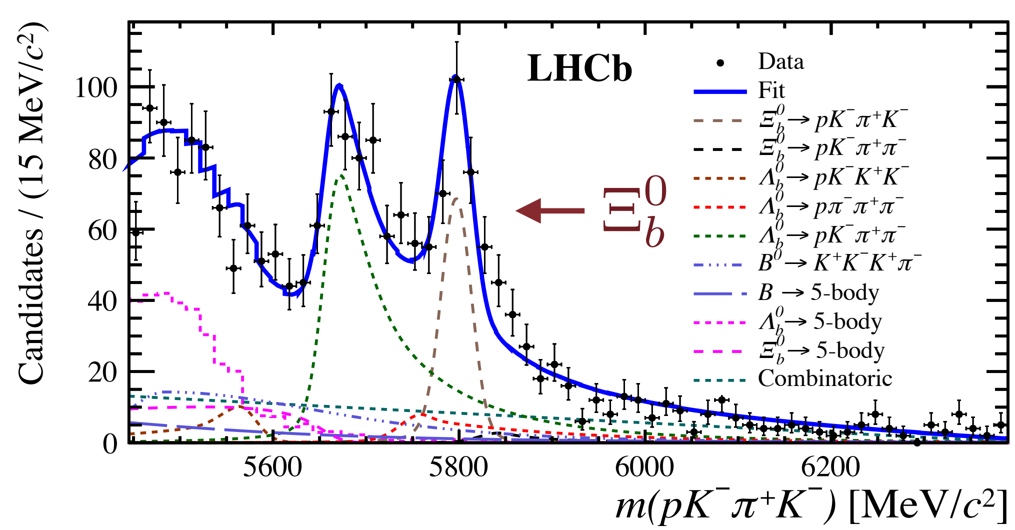
[LHCb, JHEP 1802 (2018) 098]

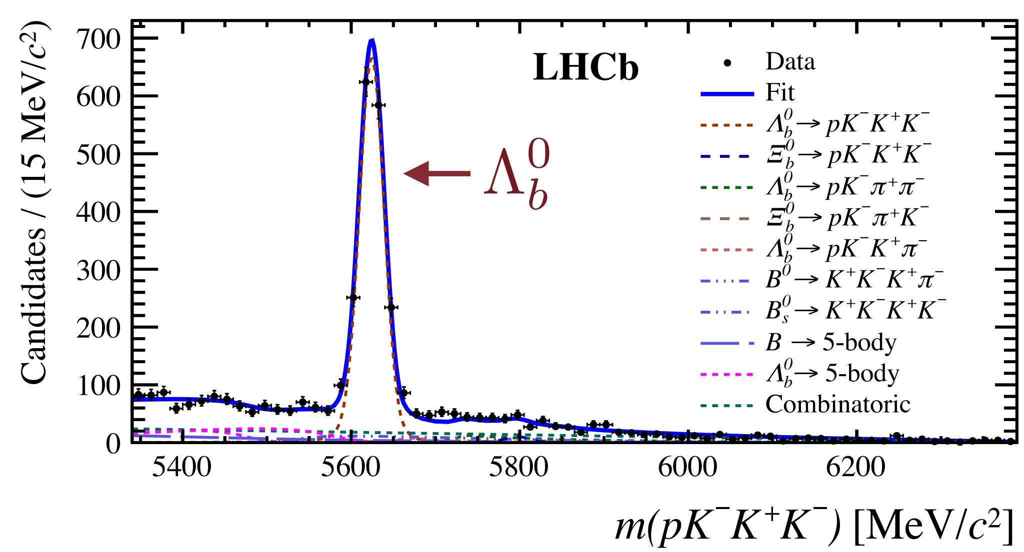
BR wrt the $\Lambda^0_b \longrightarrow \Lambda^+_c\pi$ channel [First observations]

$$\frac{\mathcal{B}(X_b \to phh'h'')}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)} \cdot \frac{f_{X_b}}{f_{\Lambda_b^0}} = \frac{\epsilon^{\rm geo.}_{\Lambda_b^0\to\Lambda_c^+\pi^-}}{\epsilon^{\rm geo.}_{X_b\to phh'h''}} \cdot \frac{\epsilon^{\rm sel.}_{\Lambda_b^0\to\Lambda_c^+\pi^-}}{\epsilon^{\rm sel.}_{X_b\to phh'h''}} \cdot \frac{\epsilon^{\rm PID}_{\Lambda_b^0\to\Lambda_c^+\pi^-}}{\epsilon^{\rm PID}_{X_b\to phh'h''}} \cdot \frac{1}{\epsilon^{\rm veto}_{X_b\to phh'h''}} \cdot \frac{\mathcal{N}_{X_b\to phh'h''}}{\mathcal{N}_{\Lambda_b^0\to\Lambda_c^+\pi^-}}$$









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Searches for *CP* violation in four body *b*-baryon decays

LHCb results : $\mathcal{L} = 3\,\mathrm{fb}^{-1}$ – 2011 + 2012 dataset

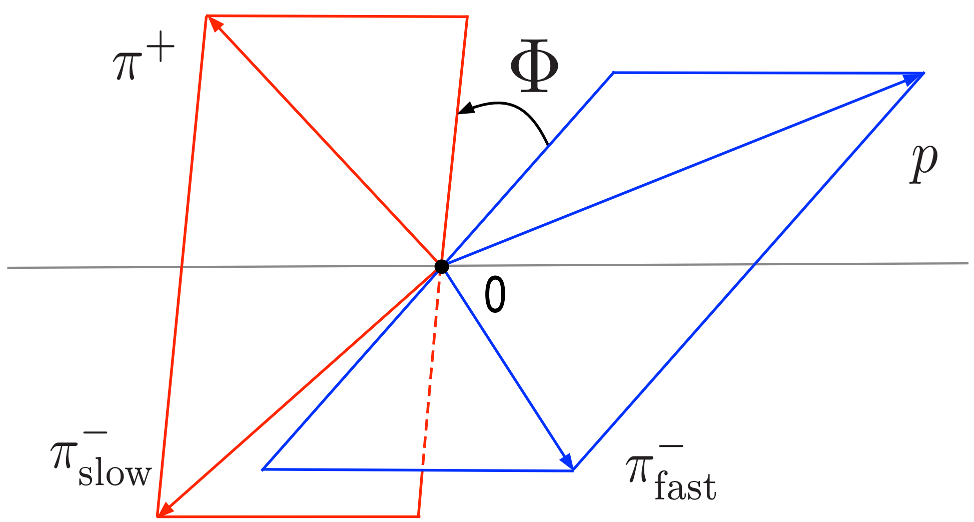
Searches for CPV in Λ^0_b (Ξ^0_b) $\rightarrow ph^+h'^-h''^-$ decays

[Nature Physics **13** (2017) 391, LHCb-PAPER-2018-001]

CP violation in the baryonic sector

Triple product asymmetry: use momenta of any 3 final particles in 4-body decays

$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}) \propto \sin\Phi \text{ , for } \Lambda_b^0$$
$$\overline{C}_{\hat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-}) \propto \sin\overline{\Phi} \text{ , for } \overline{\Lambda}_b^0$$



$$h_1 = \pi, h_2 = K \text{ for } \Lambda_b^0 \to p\pi^- K^+ K^-$$
$$h_1 = \pi_{\rm fast}, h_2 = \pi_{\rm slow} \text{ for } \Lambda_b^0 \to p\pi^-\pi^+\pi^-$$

P-odd asymmetries:

$$A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}}>0) - N(C_{\hat{T}}<0)}{N(C_{\hat{T}}>0) + N(C_{\hat{T}}<0)} \text{ , for } \Lambda_b^0$$

$$\overline{A}_{\hat{T}}(\overline{C}_{\hat{T}}) = \frac{\overline{N}(-\overline{C}_{\hat{T}}>0) - \overline{N}(-\overline{C}_{\hat{T}}<0)}{\overline{N}(-\overline{C}_{\hat{T}}>0) + \overline{N}(-\overline{C}_{\hat{T}}<0)} \text{ , for } \overline{\Lambda}_b^0$$

CP violation observable

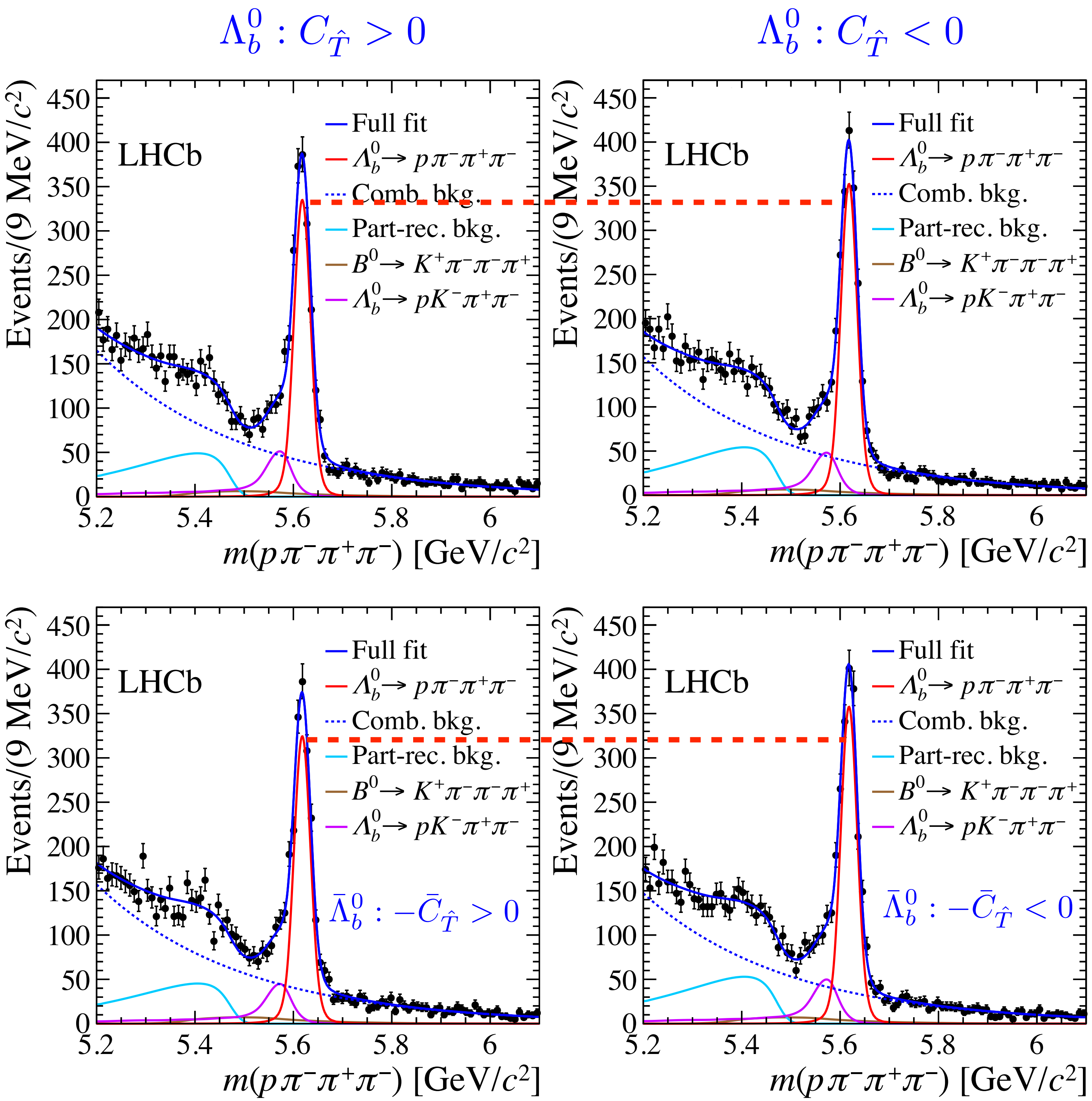
$$\boxed{a_{CP}^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} - \overline{A}_{\hat{T}}\right)}$$

P-violating observable

$$\boxed{a_{P}^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} + \bar{A}_{\hat{T}}\right)}$$

The $A_{\hat{T}}, \bar{A}_{\hat{T}}, a_P^{\hat{T}-\text{odd}}$ and $a_{CP}^{\hat{T}-\text{odd}}$ observables are largely unaffected by A_D and A_P

CP violation measurements in $\Lambda^0_b \to p\pi^-[\pi^+\pi^-, K^+K^-]$



[LHCb, Nature Physics **13** (2017) 391]

$$A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}}>0) - N(C_{\hat{T}}<0)}{N(C_{\hat{T}}>0) + N(C_{\hat{T}}<0)} \quad \text{, for } \Lambda_b^0$$

$$\overline{A}_{\hat{T}}(\overline{C}_{\hat{T}}) = \frac{\overline{N}(-\overline{C}_{\hat{T}}>0) - \overline{N}(-\overline{C}_{\hat{T}}<0)}{\overline{N}(-\overline{C}_{\hat{T}}>0) + \overline{N}(-\overline{C}_{\hat{T}}<0)} \text{, for } \overline{\Lambda}_b^0$$

Phase space integrated asymmetries for $\Lambda^0_b \to p\pi^-\pi^+\pi^-$

$$a_P^{\hat{T}-\mathrm{odd}} = (-3.71 \pm 1.45 \pm 0.32)\%$$

$$a_{CP}^{\hat{T}-\mathrm{odd}} = (1.15 \pm 1.45 \pm 0.32)\%$$

Consistent with hypothesis of P and CP symmetry

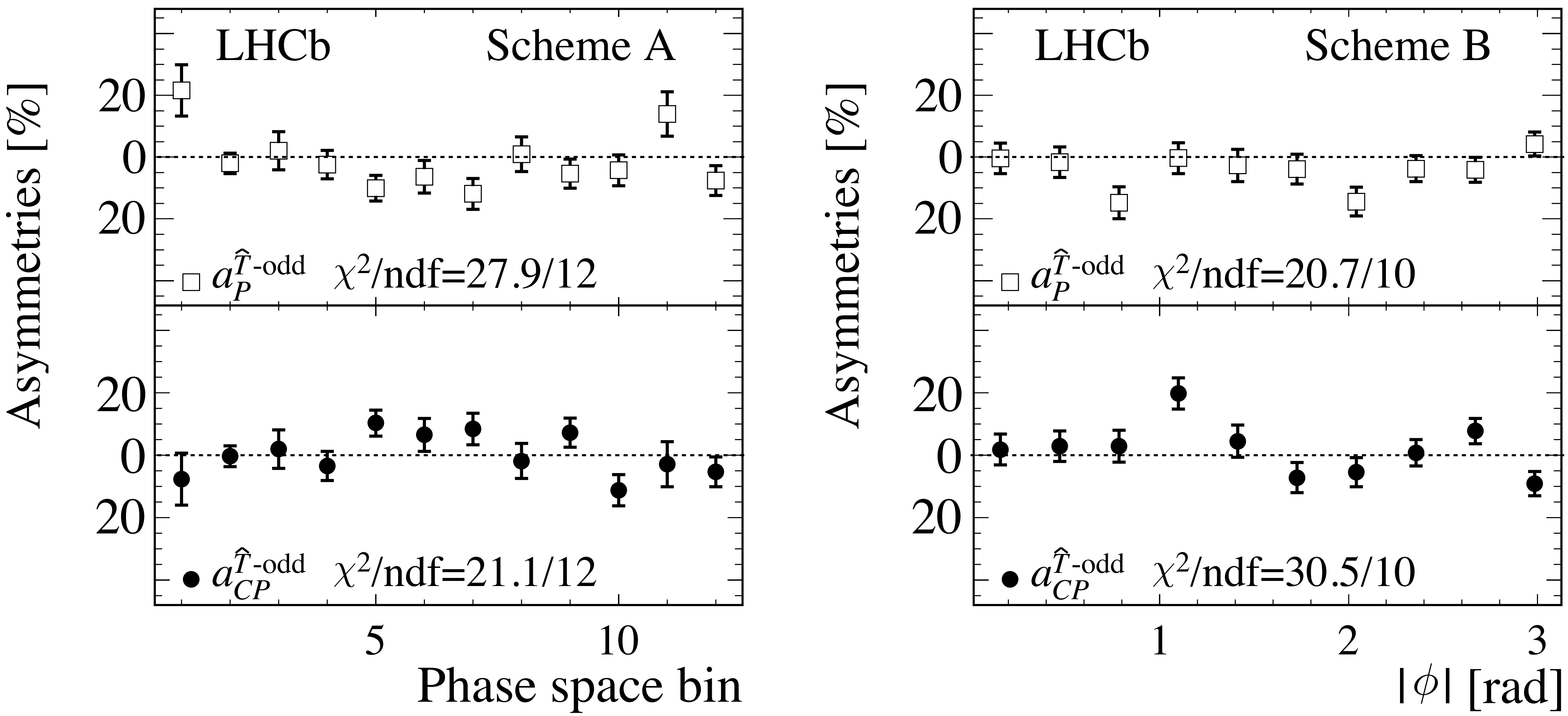
Similar results are found for the less sensitive mode $p\pi^-K^+K^-$

Phase-space *CP* violation in $\Lambda^0_b \to p\pi^-\pi^+\pi^-$

[LHCb, Nature Physics **13** (2017) 391]

Binning A: based on dominant resonant structures, *e.g.* Δ^{++}, N* and ρ(770)

Binning B: function of the angle between the decay planes $\pi^+\pi^-_{slow}$ and $p\pi^-_{fast}$

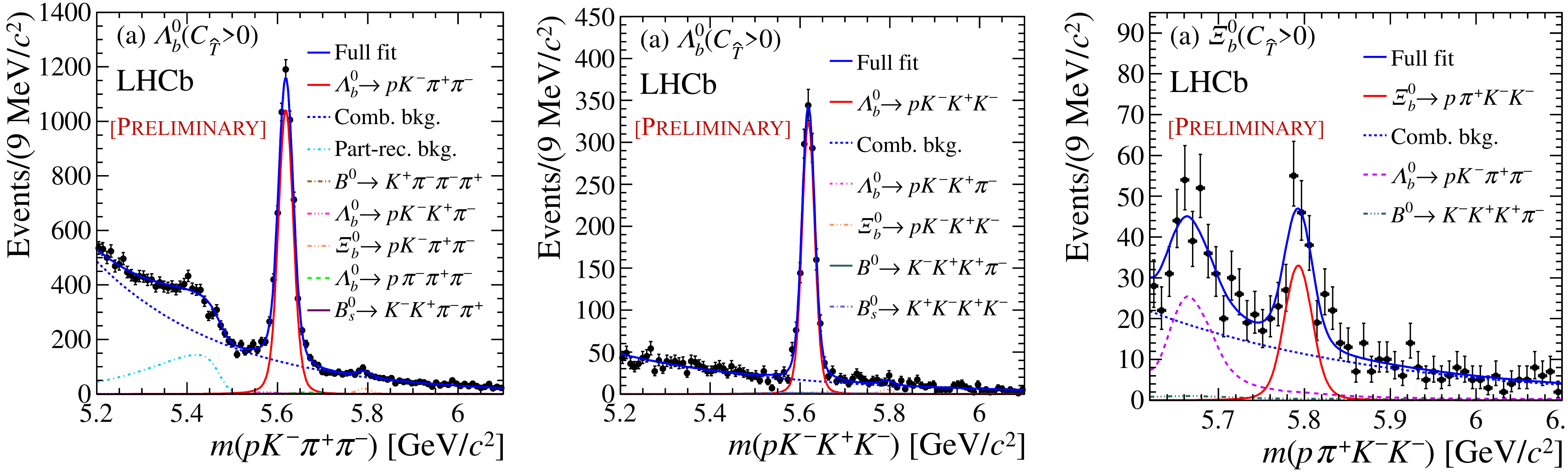


First evidence for *CP* violation with 3.3 standard deviations!

Measurements in $\Lambda^0_b \to pK[\pi\pi, KK]$, $\Xi^0_b \to pK\pi K$

[PRELIMINARY, LHCb-PAPER-2018-001]

Integrated and triple-product asymmetry measurements in dominant modes



	$\Lambda_b^0 \to pK^-\pi^+\pi^-$	$\Lambda_b^0 \to pK^-K^+K^-$	$\Xi_b^0 \to pK^-K^-\pi^+$
$a_P^{\widehat{T}\text{-odd}}$ (%)	$-0.60 \pm 0.84 \pm 0.31$	$-1.56 \pm 1.51 \pm 0.32$	$-3.04 \pm 5.19 \pm 0.36$
$a_{CP}^{\widehat{T}\text{-odd}}$ (%)	$-0.81 \pm 0.84 \pm 0.31$	$1.12 \pm 1.51 \pm 0.32$	$-3.58 \pm 5.19 \pm 0.36$

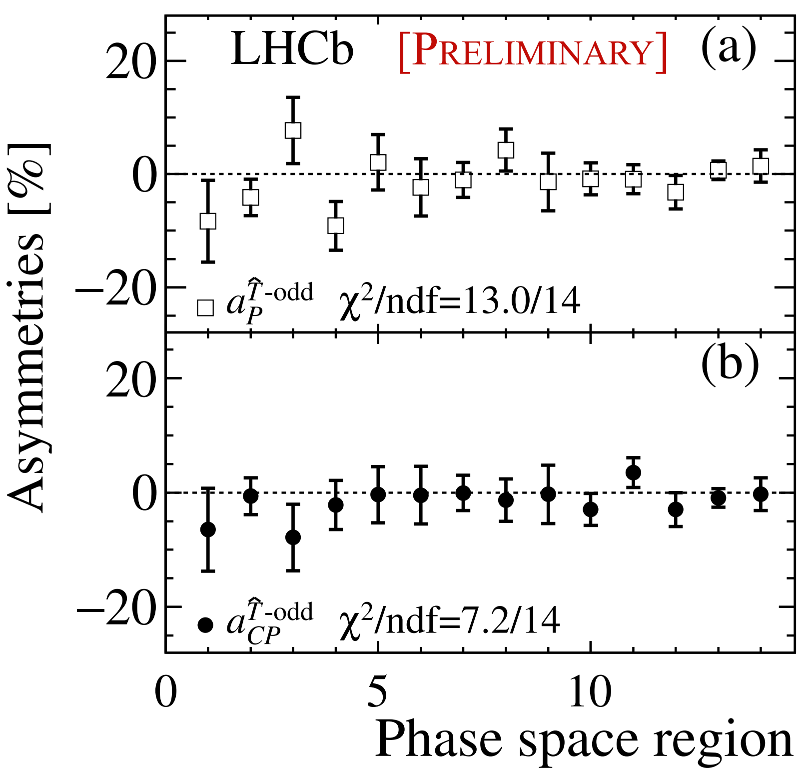
Results are found to be compatible with P and *CP* symmetries

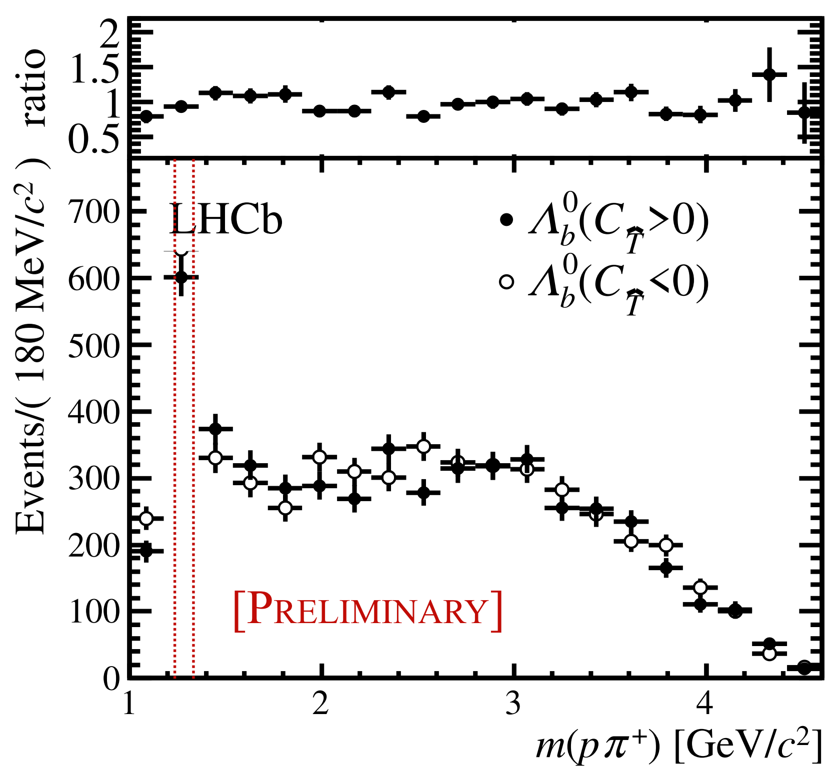
Measurements in $\Lambda^0_b \to pK[\pi\pi,KK]$

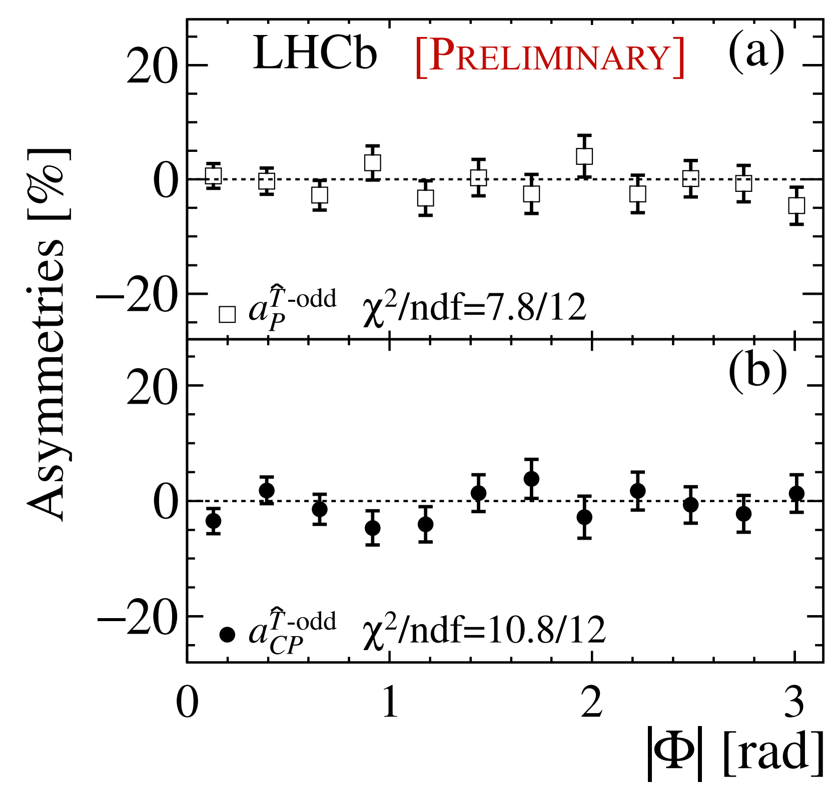
[PRELIMINARY, LHCb-PAPER-2018-001]

Binning A: dominant resonances,
e.g. Δ^{++}, $K^*(892)$ and $f_0(980)$

Binning B: angle between the decay planes pK and $\pi\pi$







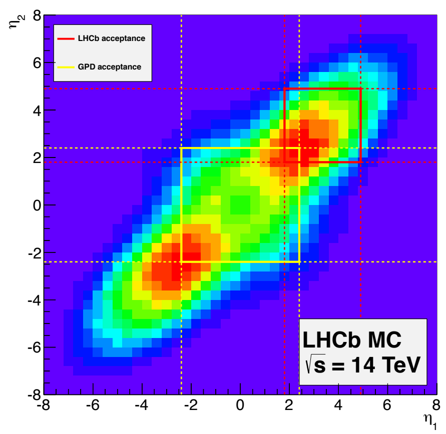
Measurements in regions of the phase space are also found to be consistent with the conservation of both P and CP symmetries

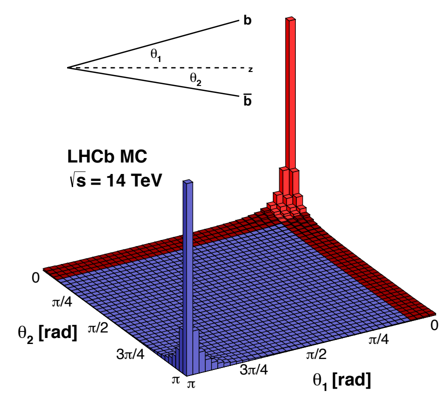
General conclusions

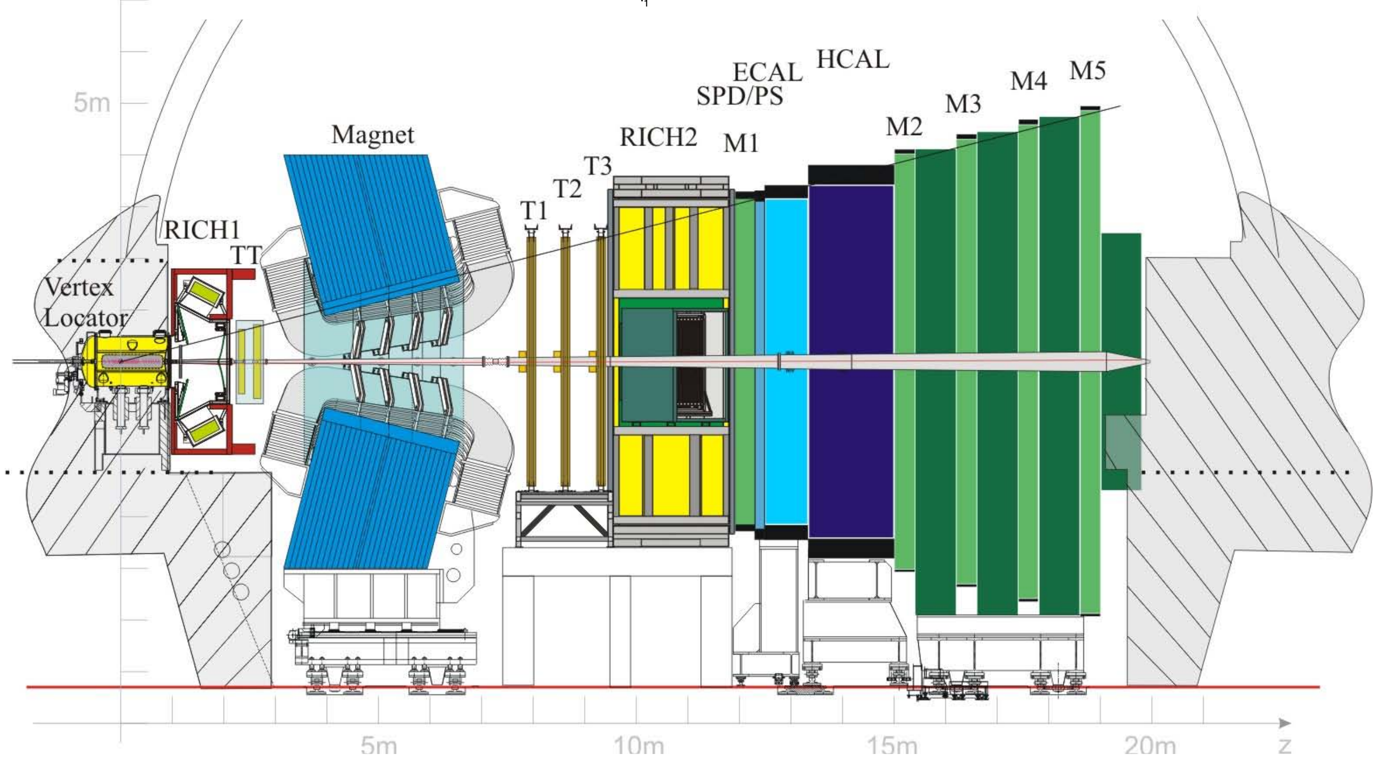
- Enormous wealth of physics to be found in multi-body hadronic decays (*e.g.* CKM phase measurements, *CP* violation)
- First observation of *CP* violation in $B^0 \to K^*(892)\pi$ decays
- Searches for CPV *b*-baryons are still in the early stages but with increased data from the LHC this area is becoming more of interest
- *CP* violation is expected in the baryon sector and first evidence in $\Lambda^0_b \to p\pi^-\pi^+\pi^-$ decays has been seen by LHCb
  - Still many interesting results are foreseen with LHCb Run-I dataset (*e.g.* B^0_s and *b*-baryon DP analyses, B^+_c decays)
  - Run-II dataset will provide unprecedented insights in this field

LHCb detector status

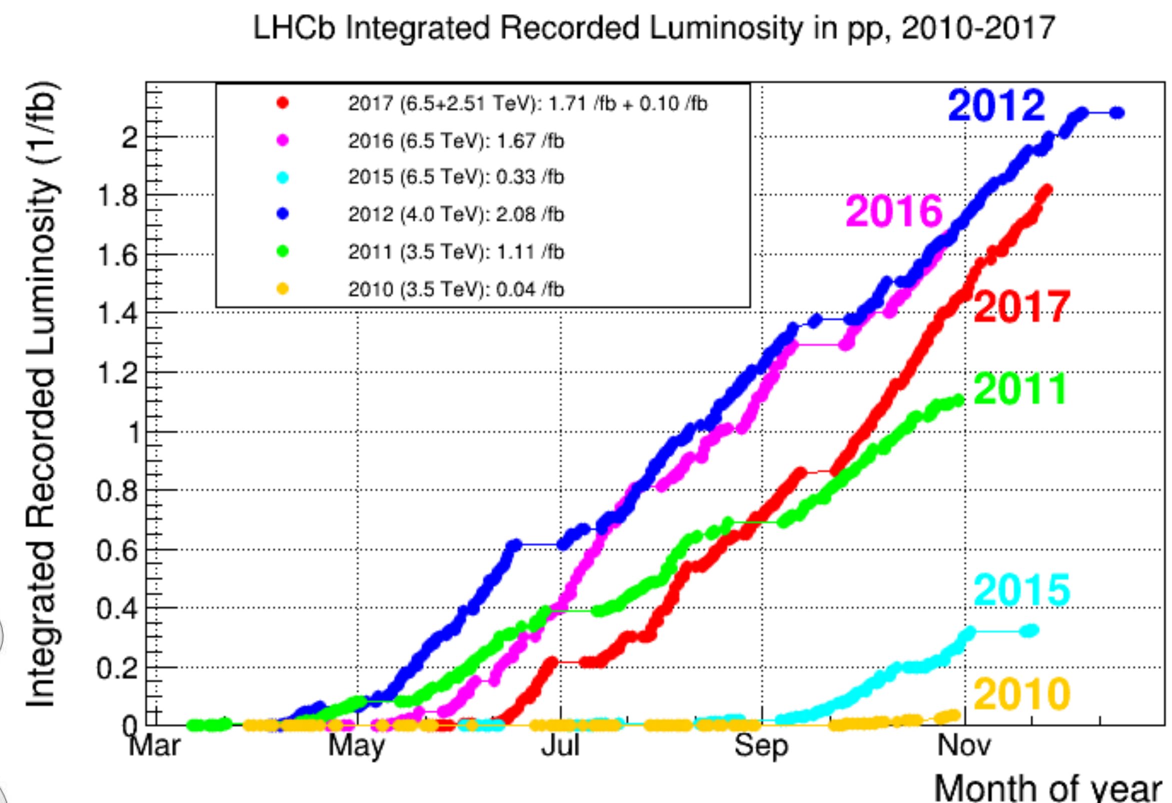
Spectrometer mainly dedicated to heavy flavour physics







[Int. J. Mod. Phys. A 30 (2015) 1530022]

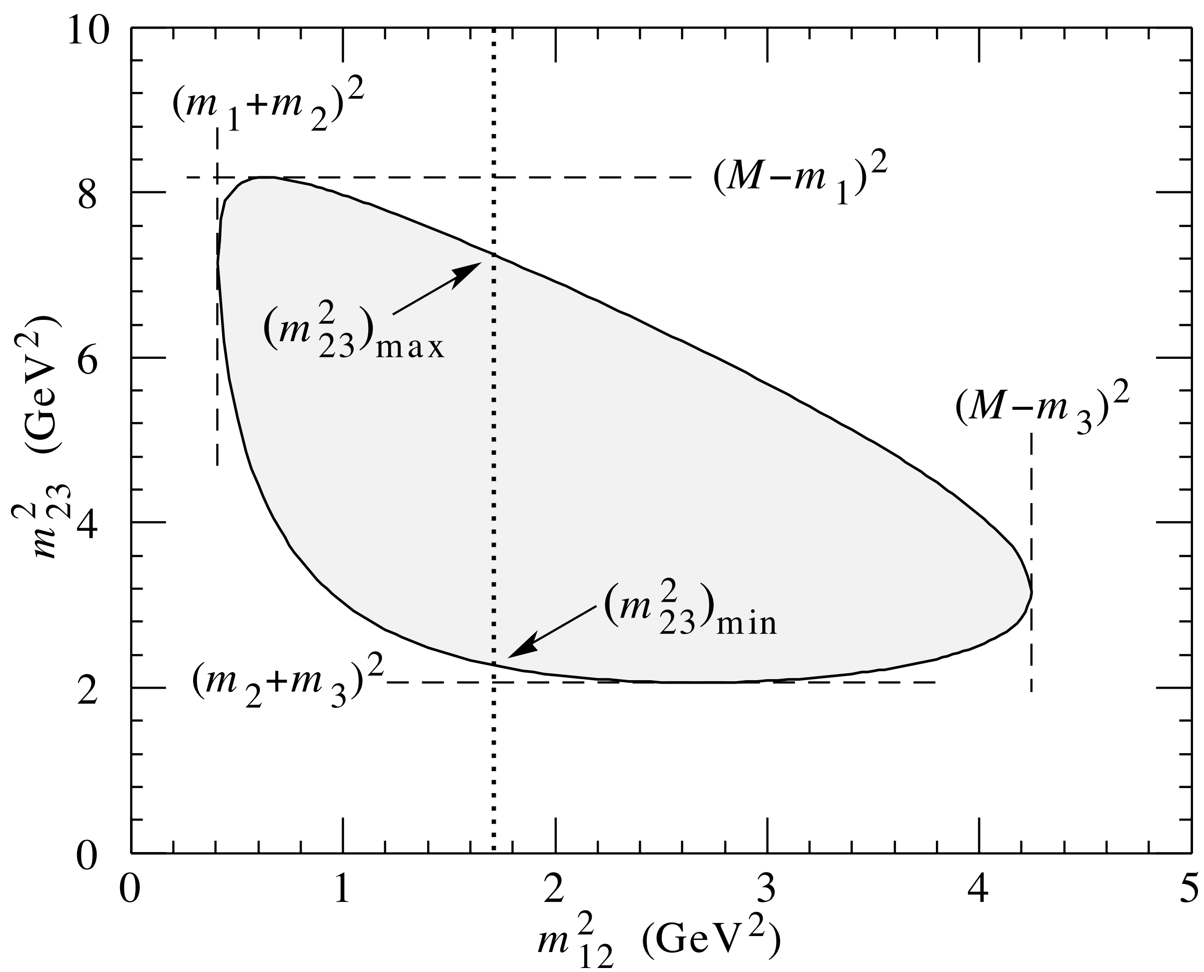


[$3\,\mathrm{fb}^{-1}$ Run-I (2011/12) at 7/8 TeV]

[$3.7\,\mathrm{fb}^{-1}$ Run-II (2015-17) at 13 TeV]

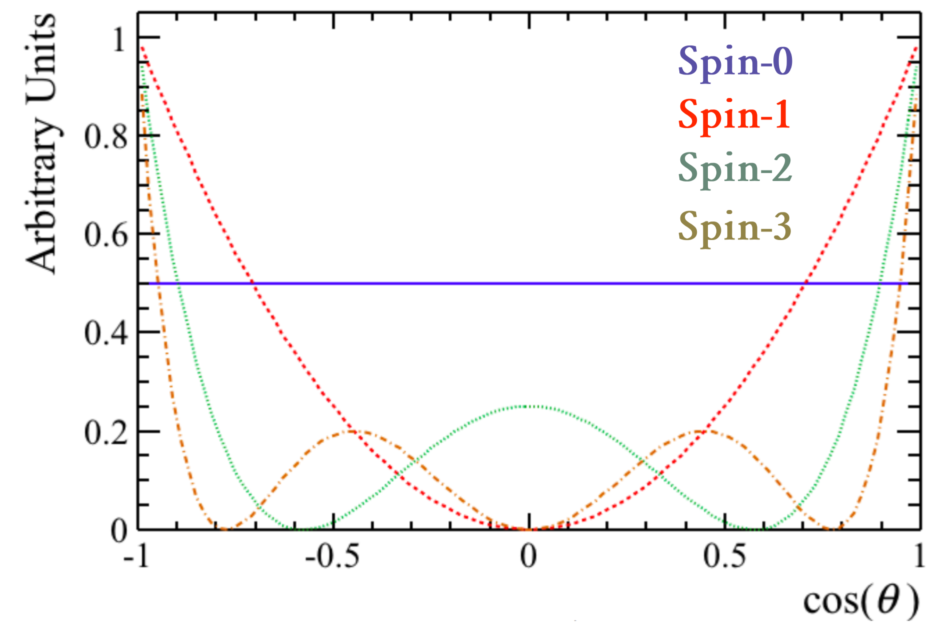
Dalitz plot analysis features

Intensity along bands indicates magnitude and the spin of the given resonance



Particle Data Group Collaboration
PRD 86 (2012) 010001

Angular distribution of resonance related to Legendre Polynomials

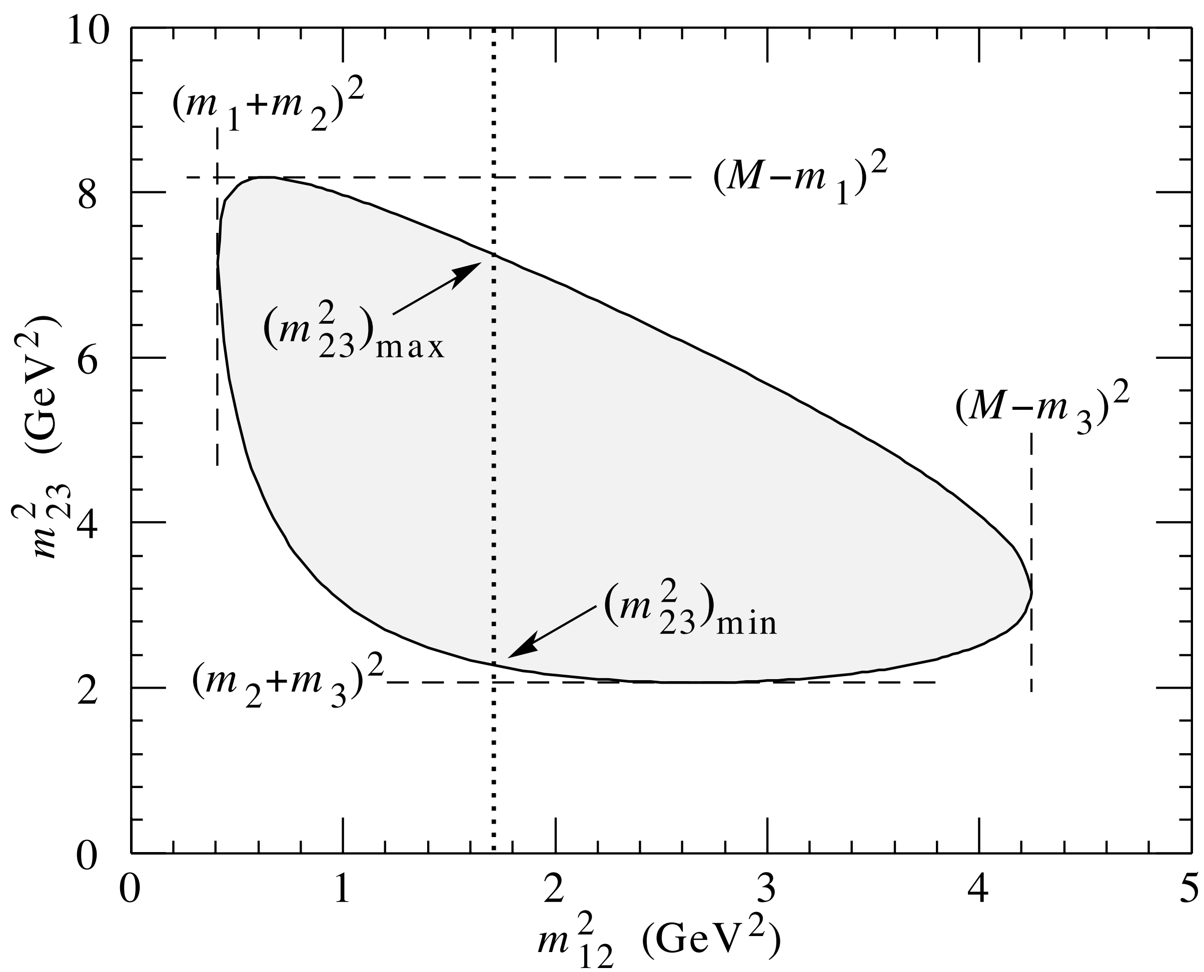


Amplitude analysis can access:

- Relative phases between states
- Sensitivity to CP violating effects
- Resolve ambiguities in weak phases
- Hadron spectroscopy

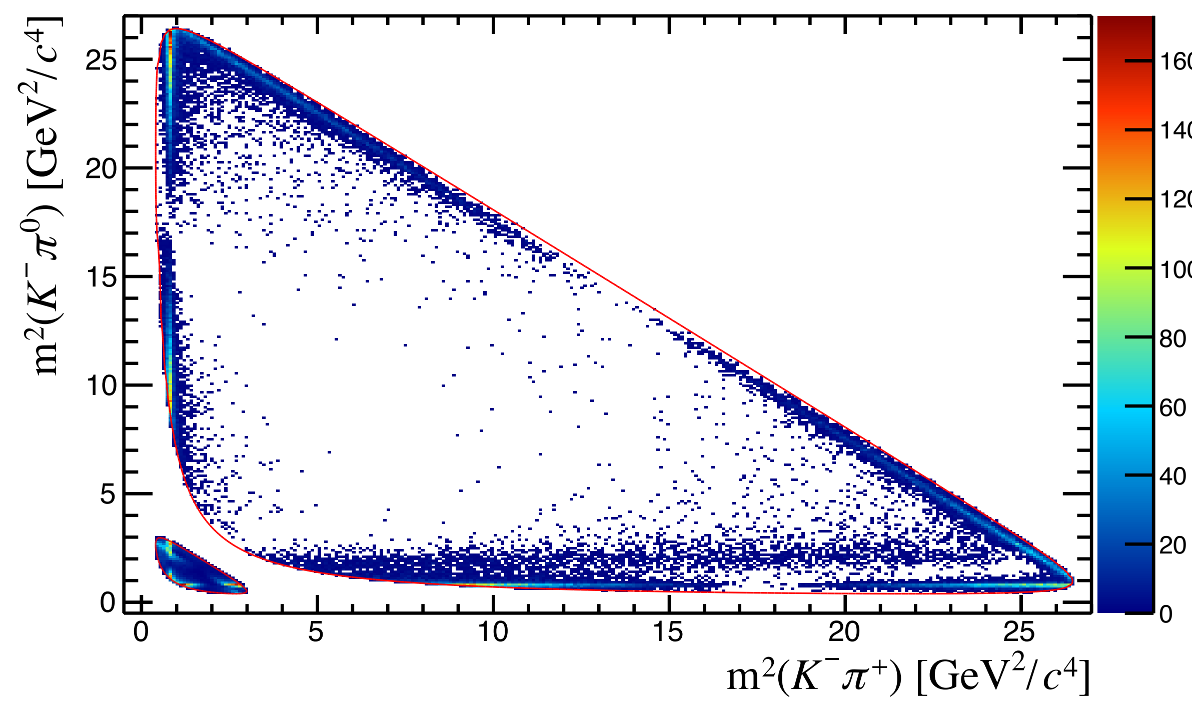
Dalitz plot analysis features

Intensity along bands indicates magnitude and the spin of the given resonance



Particle Data Group Collaboration
PRD 86 (2012) 010001

Toy simulation using Laura++ package:
arXiv:1711.09854, https://laura.hepforge.org



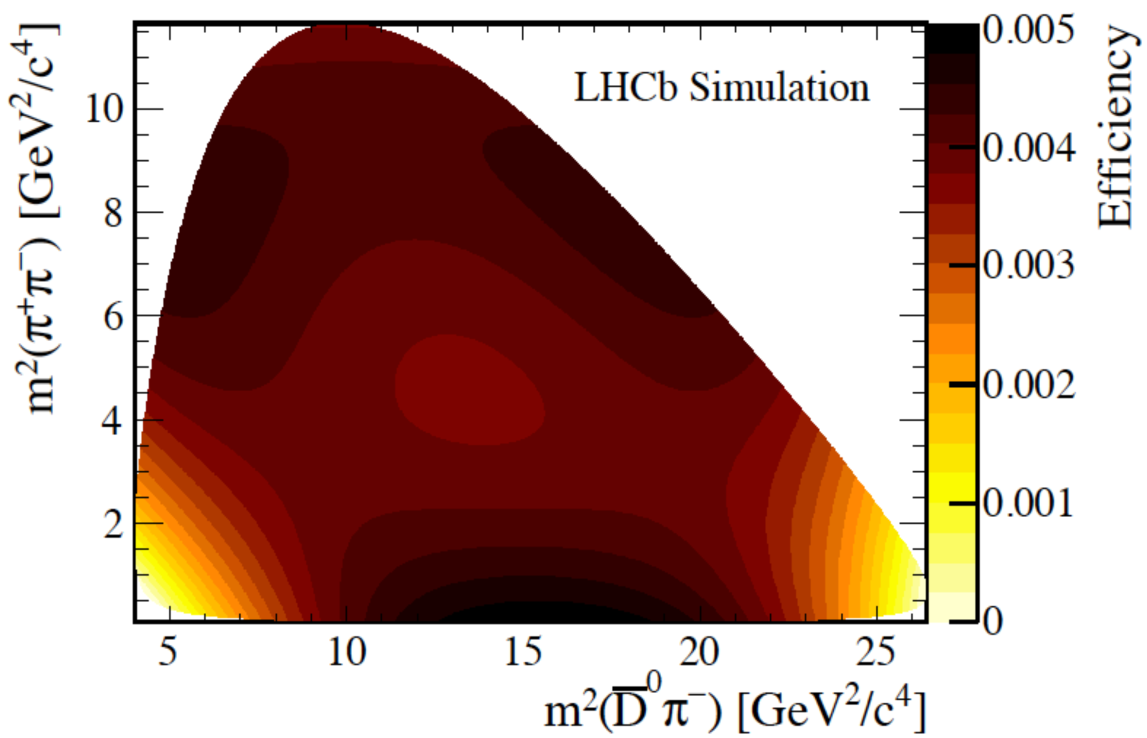
Amplitude analysis can access:

- Relative phases between states
- Sensitivity to CP violating effects
- Resolve ambiguities in weak phases
- Hadron spectroscopy

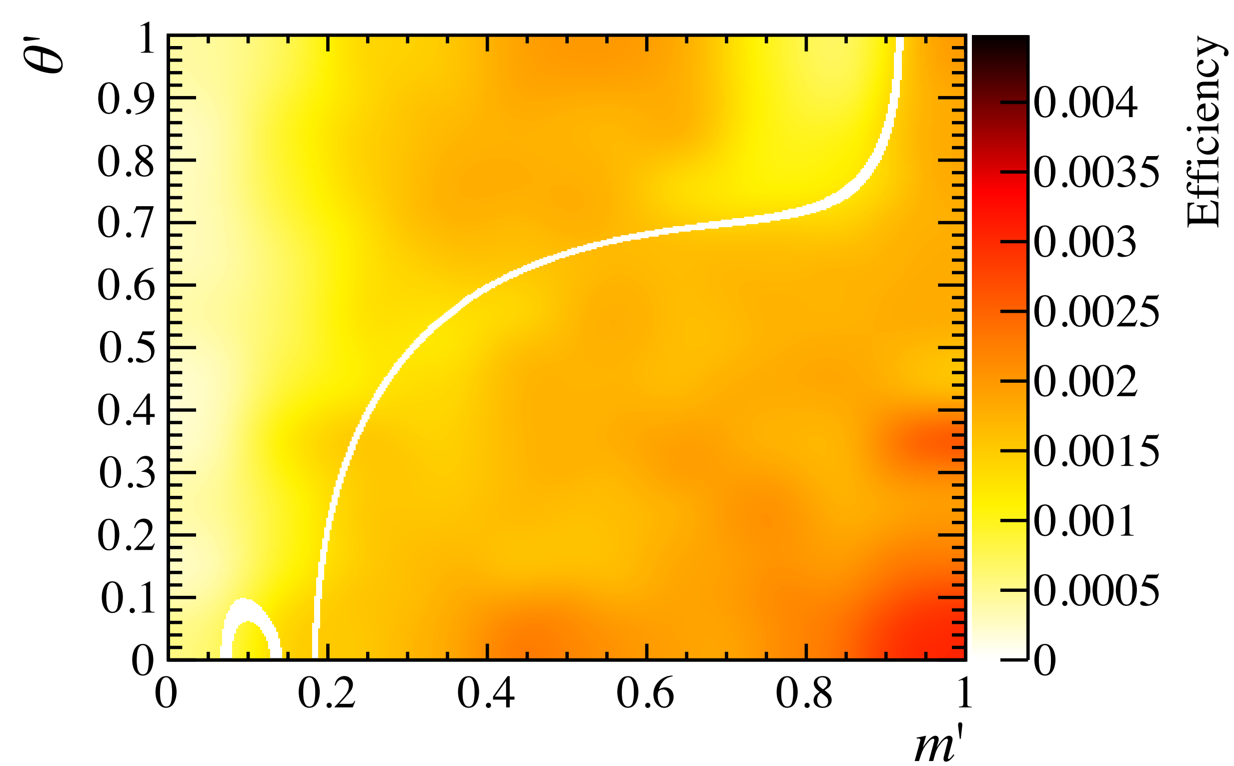
Detector acceptance modelling

Since each detector has its own acceptance, such effects need to be properly accommodated when performing a Dalitz plot fit

- Two general approaches: 2-D polynomial (or similar) function or a 2-D histogram



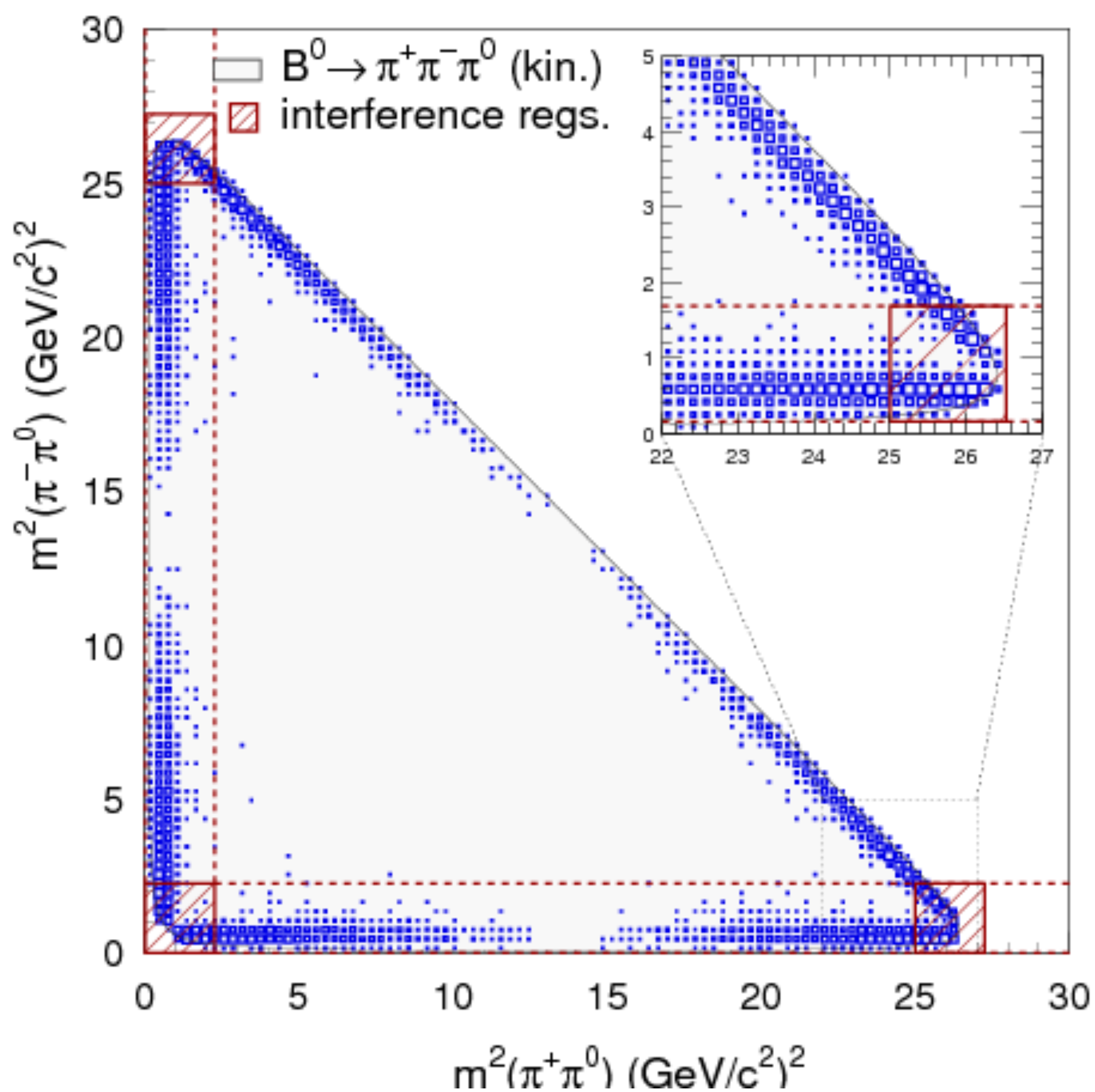
$$\mathcal{L} = \prod_{l=1}^{N_{evts}} \frac{\epsilon(m_{ij}^2, m_{jk}^2)\left|\sum_{m=1}^{N_R} c_m F_m(m_{ij}^2, m_{jk}^2)\right|^2}{\int_{DP} \epsilon(m_{ij}^2, m_{jk}^2)\left|\sum_{m=1}^{N_R} c_m F_m(m_{ij}^2, m_{jk}^2)\right|^2 dDP}$$

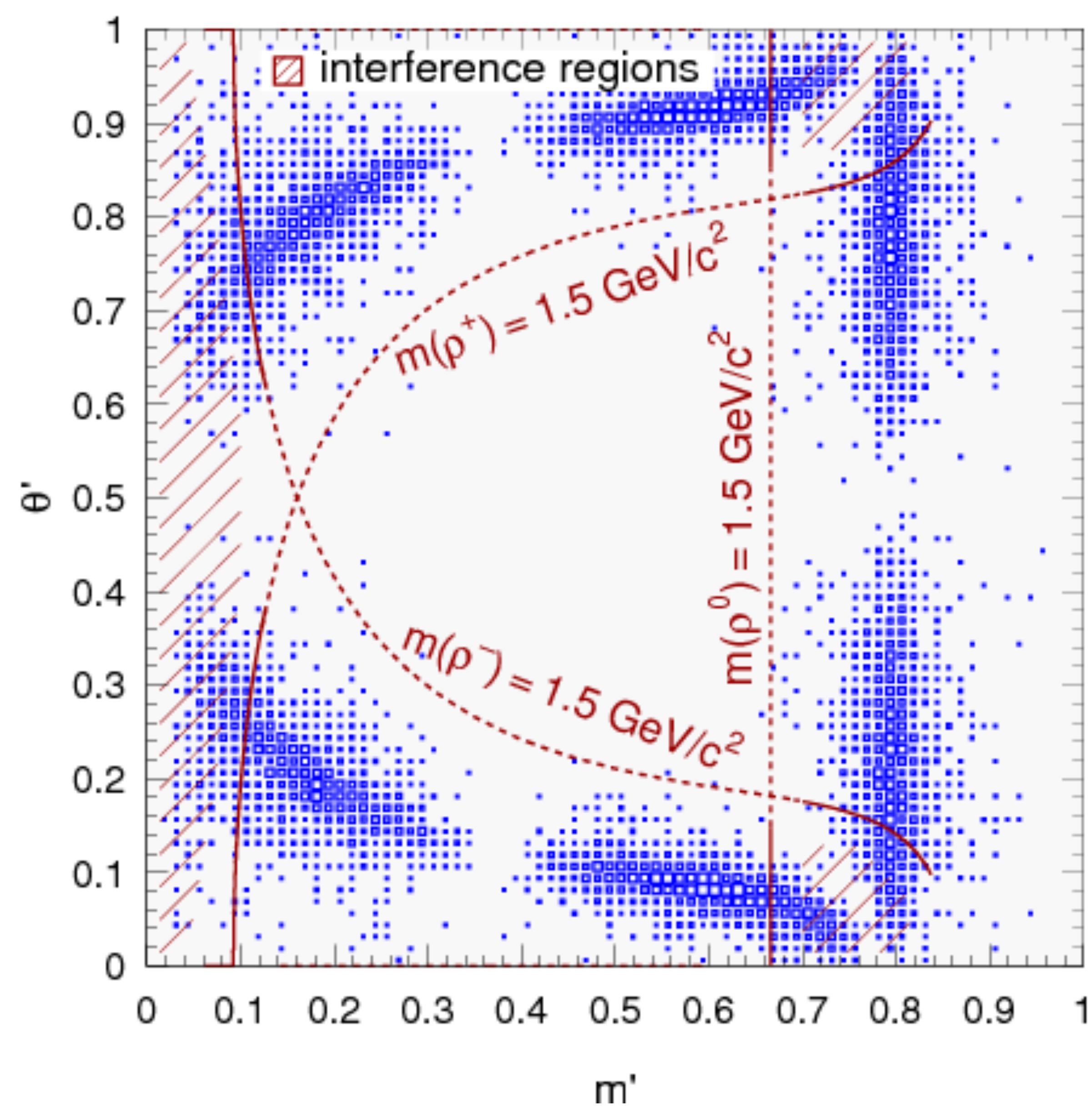


LHCb general strategy has been based on Spline these distributions in the squared DP

Detector acceptance modelling

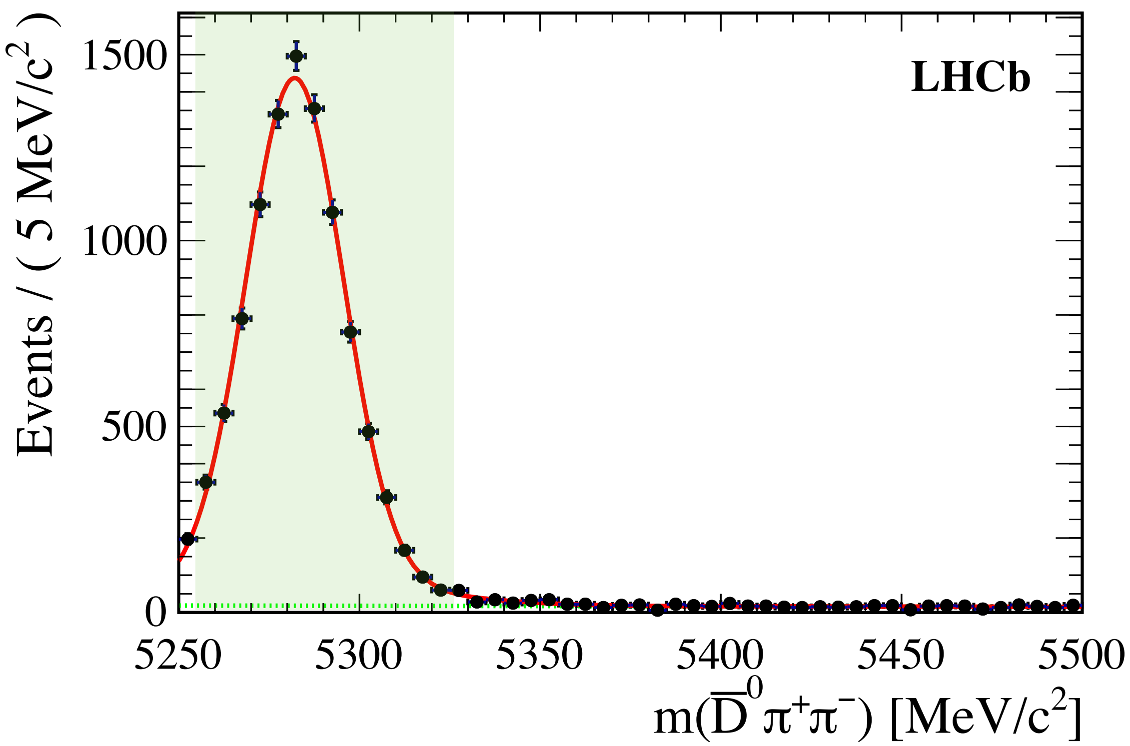
Preferential co-ordinate transformation to improve sensitivity modelling in the DP borders

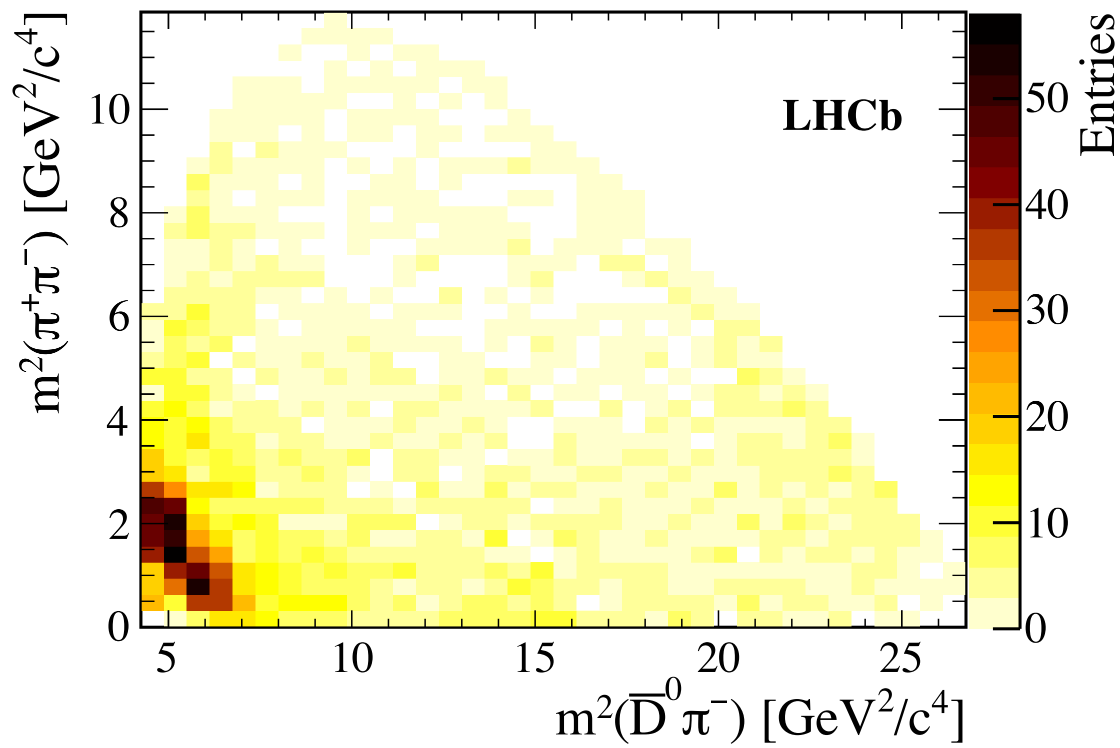




Background contributions

Contributions from different backgrounds can be presented and need to be modelled





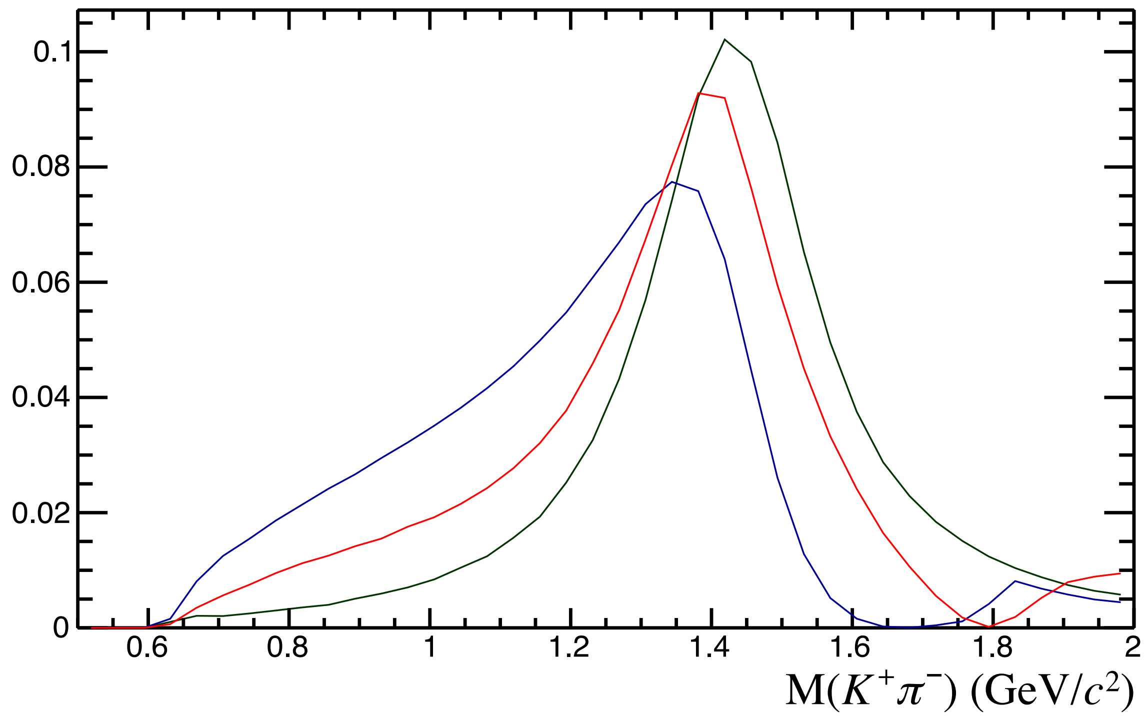
$$\mathcal{L} = \prod_{l=1}^{N_{evts}} \left[\frac{\epsilon(m_{ij}^2, m_{jk}^2) \left| \sum_{m=1}^{N_R} c_m F_m(m_{ij}^2, m_{jk}^2) \right|^2}{\int_{DP} \epsilon(m_{ij}^2, m_{jk}^2) \left| \sum_{m=1}^{N_R} c_m F_m(m_{ij}^2, m_{jk}^2) \right|^2 dDP} + \frac{\sum_{m=1}^{N_B} |k_m|^2 |B_m(m_{ij}^2, m_{jk}^2)|^2}{\int_{DP} \sum_{m=1}^{N_B} |k_m|^2 |B_m(m_{ij}^2, m_{jk}^2)|^2 dDP} \right]$$

Signal (Coherent) **Background (Incoherent)**

$K\pi$ invariant mass modelling

- **K*(892)** resonance - Relativistic Breit-Wigner
- **$K\pi$ S-wave** contribution

Toy simulation using Laura++ package
arXiv:1711.09854



— LASS lineshape [Nucl. Phys. B296 (1988) 493]

$$R_j(s) = \frac{\sqrt{s}}{q\cot\delta_B - iq} + e^{2i\delta_B}\frac{m_0\Gamma_0\frac{m_0}{q_0}}{(m_0^2 - s) - im_0\Gamma_0\frac{q}{\sqrt{s}}\frac{m_0}{q_0}}$$

— EFKLLM lineshape [PRD 79 (2009) 094005]

$$R_j(m) = F(m)\left(\frac{c_0}{m^2} + c_1\right)$$

— κ + K^*_0(1430) resonance [Flatté]

NR parametrisation [PRD 92 (2015) 054010]

$$R_j(s) = \frac{1}{1 + \frac{s}{\Lambda^2}}$$

Single model κ + K^*_0(1430) + K^*_0(1950)

[arXiv:1701.04881]

Others (non DP), polynomial expansion

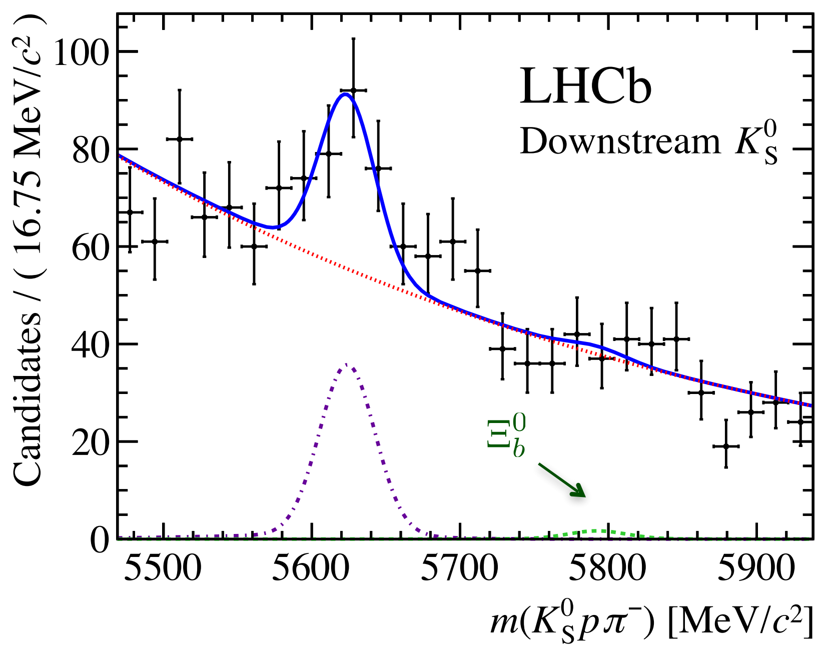
[PRD 93 (2016) 074025]

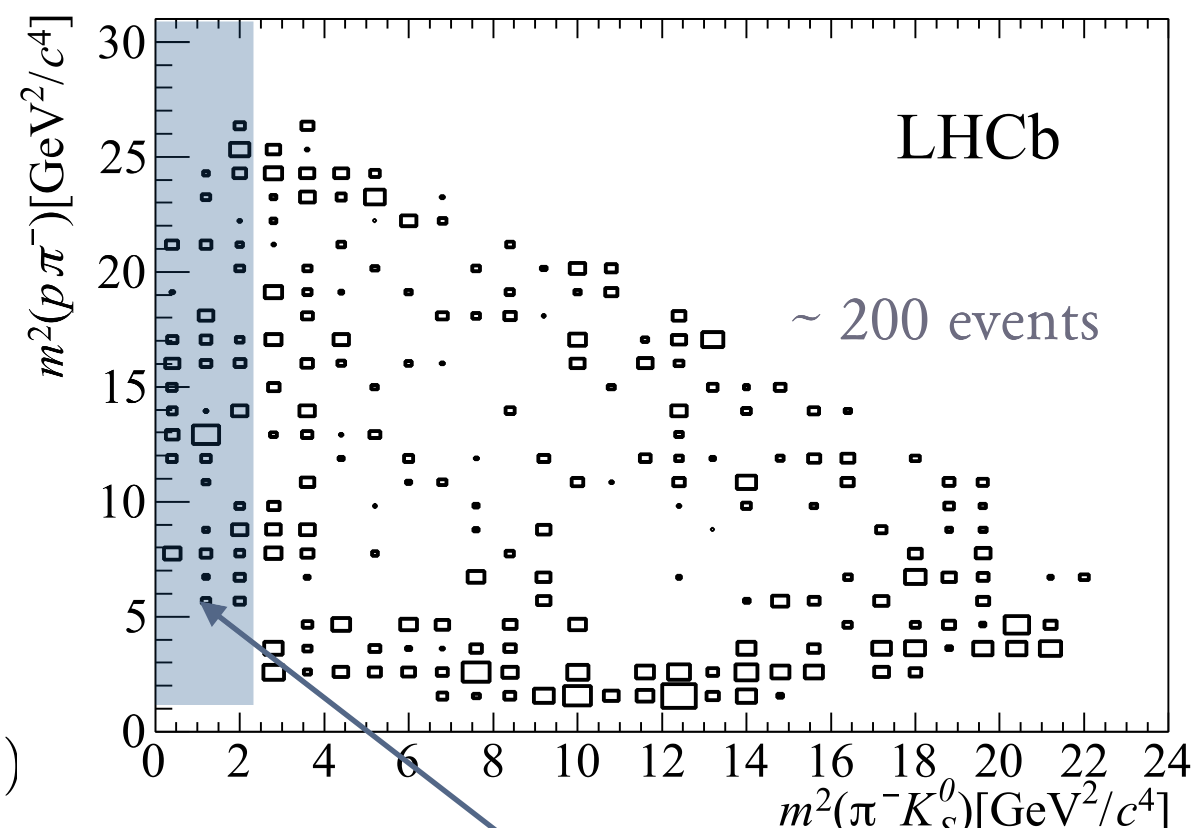
Search for *CP* violation in $\Lambda^0_b \to \{\Lambda, K^0\}hh$

[LHCb, JHEP 04 (2014) **087**]

Studies of *b*-baryon decays is still at an early stage, although LHCb interesting has been significantly increasing

First observation (8.6 σ) of the $\Lambda^0_b \to K^0 p\pi^-$ decay has been obtained with 1 fb^{-1}





- Phase space integrated asymmetry:

$$\mathcal{A}^{CP}(\Lambda^0_b \to K^0_S p\pi^-) = 0.22 \pm 0.13(\text{stat.}) \pm 0.03(\text{syst.})$$

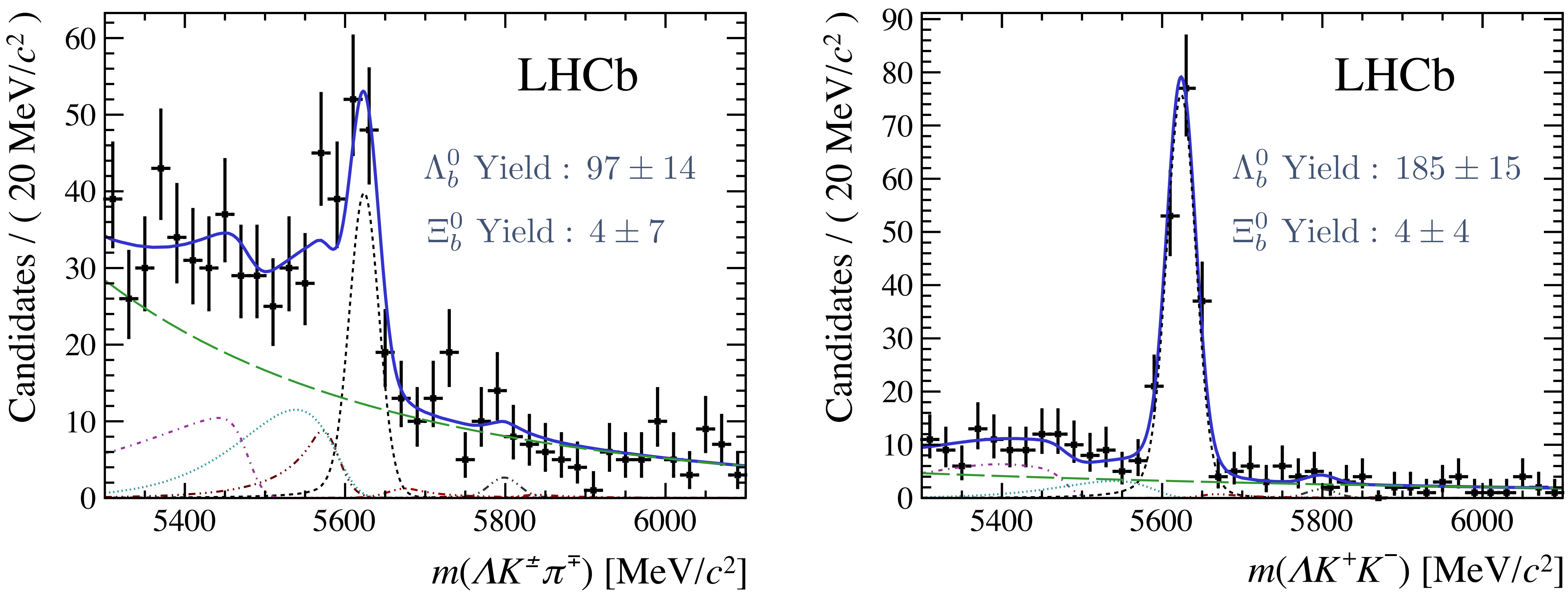
- Search for **local (binned) asymmetries**, *i.e.* similar to the $B^\pm \to h^\pm h^+ h^-$

Possible contribution from $\Lambda^0_b \to pK^{*-}$

Results for $\Lambda^0_b(\Xi^0_b) \rightarrow \Lambda h^+ h^-$ decays

[LHCb, JHEP 05 (2016) **08**]

First observation of the decays $\Lambda^0_b \rightarrow \Lambda K^+\pi^-$ (8.1σ) and $\Lambda^0_b \rightarrow \Lambda K^+K^-$ (15.8σ) with 3 fb^{-1}



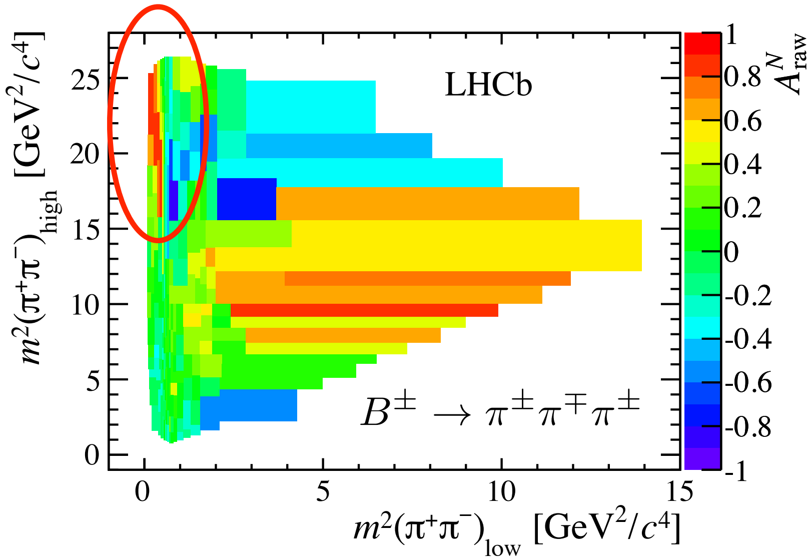
$$\mathcal{A}_{CP}(\Lambda_b^0 \rightarrow \Lambda K^+\pi^-) = -0.53 \pm 0.23\,(\text{stat}) \pm 0.11\,(\text{syst})$$

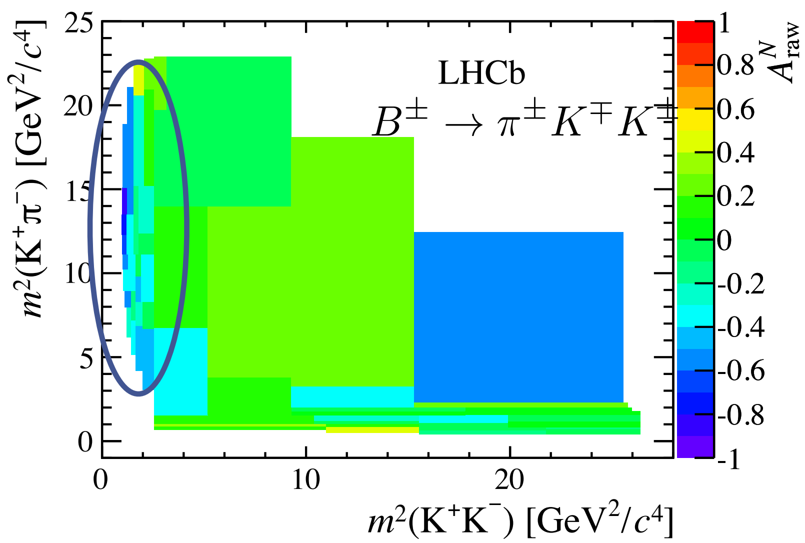
$$\mathcal{A}_{CP}(\Lambda_b^0 \rightarrow \Lambda K^+K^-) = -0.28 \pm 0.10\,(\text{stat}) \pm 0.07\,(\text{syst})$$

Towards [more] charmless DP analyses

LHCb PRD 90, 112004 (2014), PRL 112 (2014) 011801, PRL 111 (2013) 101801

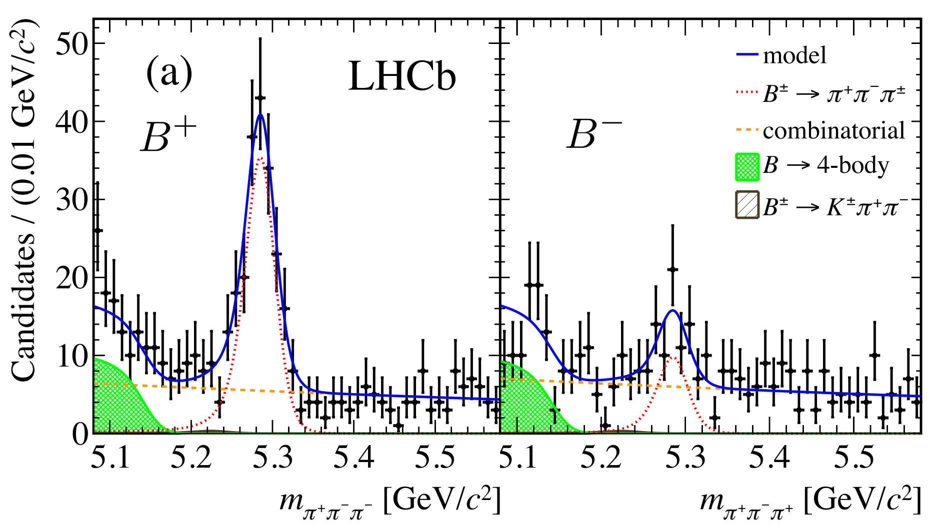
Efforts on understanding the large asymmetries seen in $B^+ \to h^+h^-h^+$ decays

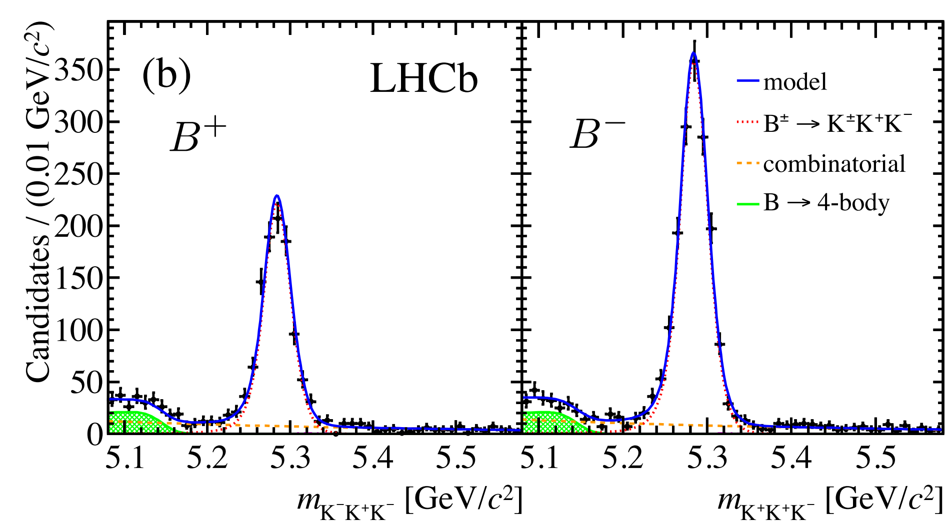




$m^2_{\pi^+\pi^-\ \text{low}} < 0.4\,\text{GeV}^2/c^4$ and $m^2_{\pi^+\pi^-\ \text{high}} > 15\,\text{GeV}^2/c^4$

$m^2_{K^+K^-} < 1.5\,\text{GeV}^2/c^4$



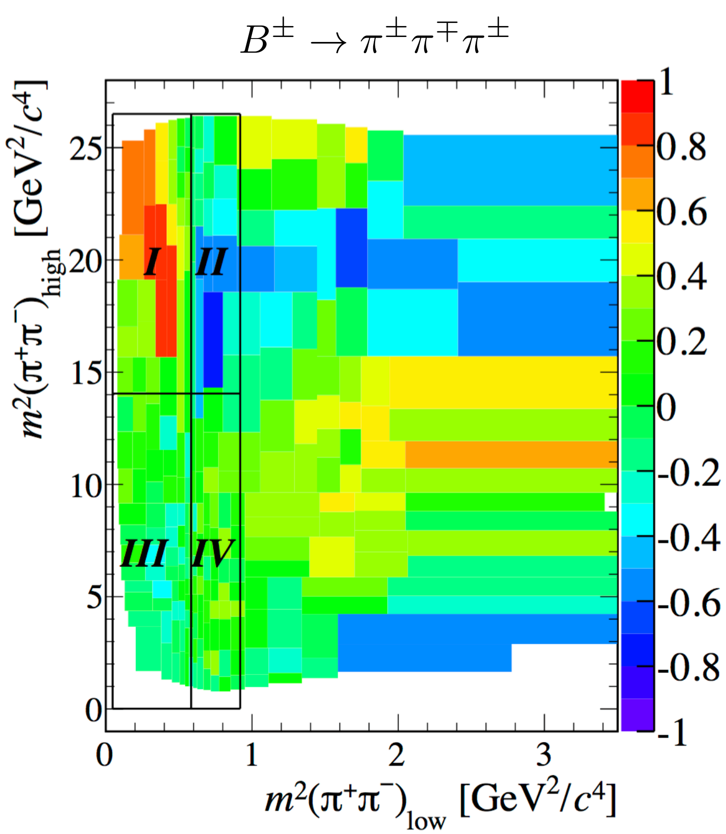


$$\mathcal{A}^{CP}_{\text{reg}}(B^\pm \to \pi^\pm\pi^+\pi^-) = 0.584 \pm 0.082 \pm 0.027 \pm 0.007$$

$$\mathcal{A}^{CP}_{\text{reg}}(B^\pm \to \pi^\pm K^+K^-) = -0.648 \pm 0.070 \pm 0.013 \pm 0.007$$

Towards [more] charmless DP analyses

LHCb PRD 90, 112004 (2014)



Sign of A^{CP} (e.g. regions I-II) indicate interference between S- and P-wave importance

Re-scattering may also play a role in the region between 1 and 1.5 GeV

- DP analysis is clearly required, in particular to understand the origin of the strong phase difference
- **Such analyses are currently ongoing at LHCb!**

  [*i.e.* (1) $B^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm}$, (2) $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ ...]

- Unprecedented statistics (*e.g.* 5-200 K events for $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$, $K^{\pm}\pi^{+}\pi^{-}$): simplified theoretical descriptions are no longer sufficient
  - How to model non-resonant contributions, final state interaction, re-scattering effects? Connect two (or all) different final states?
  - How to obtain an accurate description of the S-wave?

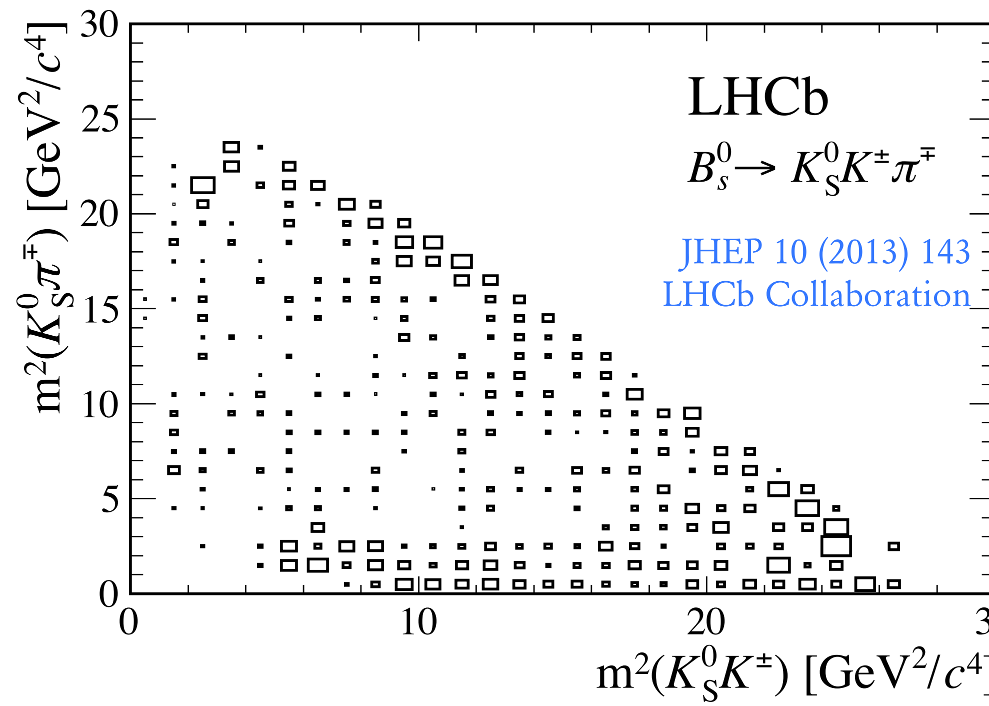
    [*e.g.* for $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ already limited, NR+ $K^{*}_{0}(1430)$ or κ + $K^{*}_{0}(1430)$?]

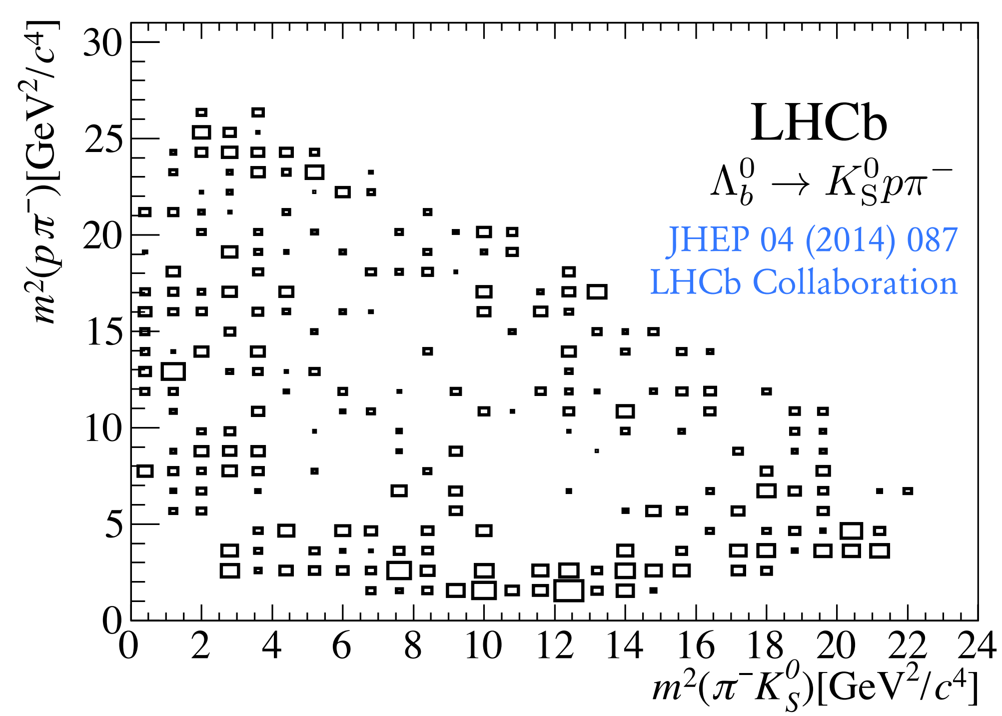
Towards [more] charmless DP analyses

Many other channels that have never been explored in the B-factories are gradually being investigated

- Untagged time-integrated analysis of $B^0_s \to K^0_S K\pi$ decays
  - Only flavour averaged fit fractions
  - Modelling of S-wave of crucial relevance, *i.e.* LASS/EFKLLM
- Amplitude analysis of $\Lambda_b \to K^0_S p\pi^-$
  - Large $A_{CP}(pK^*)$ ~ 20% predicted

[PRD 91 (2015) 11, 116007]





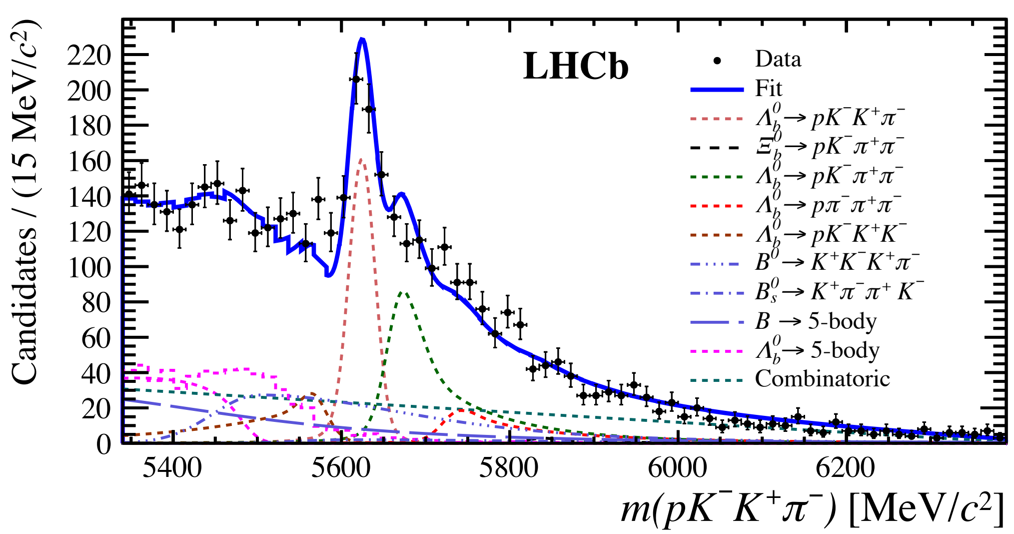
Universität Zürich[UZH]

BR measurements of Λ^0_b, $\Xi^0_b \rightarrow$ p3h

[LHCb, JHEP 1802 (2018) 098]

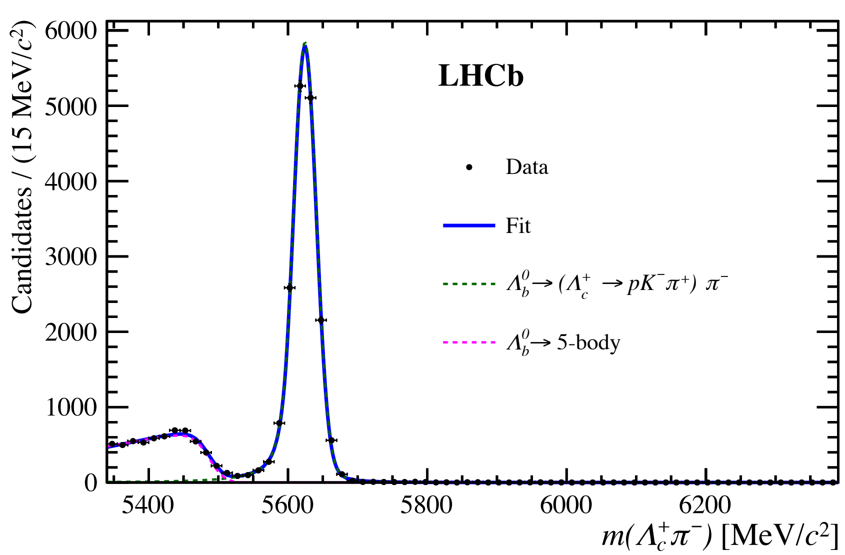
BR wrt the $\Lambda^0_b \rightarrow \Lambda^+_c\pi$ channel [First observations]

$$\frac{\mathcal{B}(X_b \to phh'h'')}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)} \cdot \frac{f_{X_b}}{f_{\Lambda_b^0}} = \frac{\epsilon^{\text{geo.}}_{\Lambda_b^0\to\Lambda_c^+\pi^-}}{\epsilon^{\text{geo.}}_{X_b\to phh'h''}} \cdot \frac{\epsilon^{\text{sel.}}_{\Lambda_b^0\to\Lambda_c^+\pi^-}}{\epsilon^{\text{sel.}}_{X_b\to phh'h''}} \cdot \frac{\epsilon^{\text{PID}}_{\Lambda_b^0\to\Lambda_c^+\pi^-}}{\epsilon^{\text{PID}}_{X_b\to phh'h''}} \cdot \frac{1}{\epsilon^{\text{veto}}_{X_b\to phh'h''}} \cdot \frac{\mathcal{N}_{X_b\to phh'h''}}{\mathcal{N}_{\Lambda_b^0\to\Lambda_c^+\pi^-}}$$



Using the world average BR($\Lambda^0_b \rightarrow \Lambda^+_c\pi$) and BR($\Lambda^+_c \rightarrow pK\pi$)

$$\mathcal{B}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (1.90 \pm 0.06 \pm 0.10 \pm 0.16 \pm 0.07) \cdot 10^{-5}$$
$$\mathcal{B}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (4.55 \pm 0.08 \pm 0.20 \pm 0.39 \pm 0.17) \cdot 10^{-5}$$
$$\mathcal{B}(\Lambda_b^0 \to pK^-K^+\pi^-) = (0.37 \pm 0.03 \pm 0.04 \pm 0.03 \pm 0.01) \cdot 10^{-5}$$
$$\mathcal{B}(\Lambda_b^0 \to pK^-K^+K^-) = (1.14 \pm 0.03 \pm 0.07 \pm 0.10 \pm 0.05) \cdot 10^{-5}$$



$$\mathcal{B}(\Xi_b^0 \to pK^-\pi^+\pi^-) \cdot f_{\Xi_b^0}/f_{\Lambda_b^0} = (1.72 \pm 0.21 \pm 0.25 \pm 0.15 \pm 0.07) \cdot 10^{-6}$$
$$\mathcal{B}(\Xi_b^0 \to pK^-\pi^+K^-) \cdot f_{\Xi_b^0}/f_{\Lambda_b^0} = (1.56 \pm 0.16 \pm 0.19 \pm 0.13 \pm 0.06) \cdot 10^{-6}$$
$$\mathcal{B}(\Xi_b^0 \to pK^-K^+K^-) \cdot f_{\Xi_b^0}/f_{\Lambda_b^0} \in [0.11\text{--}0.25] \cdot 10^{-6} \text{ at } 90\% \text{ C.L.}$$