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Experimental results from *b*-hadron decays to three-body final states

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Mini-workshop: multi-particle final states in B decays

Overview of recents 3-body decays results

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This talk covers some recent publications from hadronic three-body decays

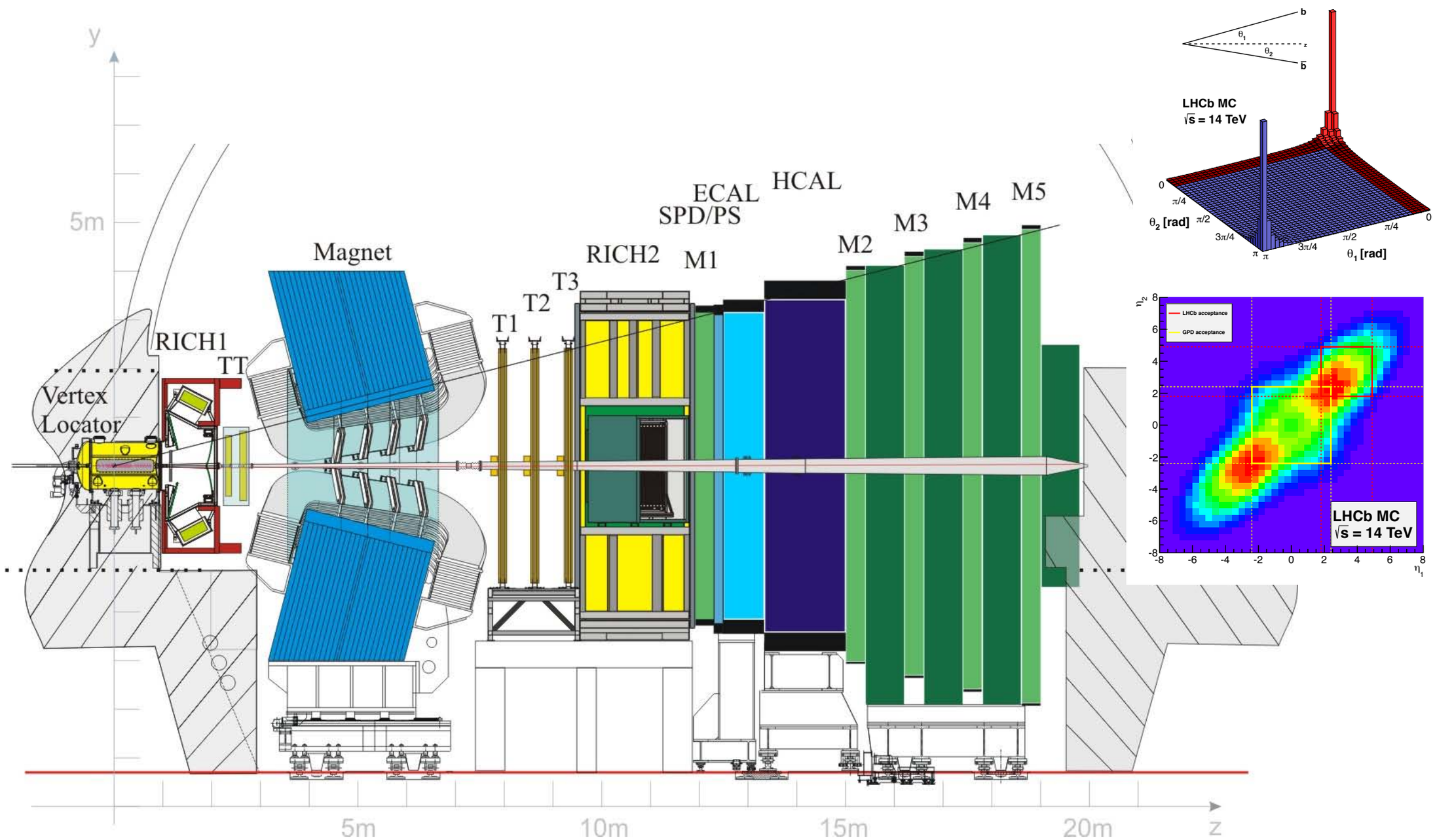
- Introduction to three-body decays analyses
- B decays to open charm, *i.e.* Dalitz plot analyses of $B \to Dhh'$ channels

  [Spectroscopy, CKM phase]

- Status and plans for CPV measurements in charmless three-body charged decays

  [Large CP violation seen in $B^{\pm} \to h^{\pm}h^{+}h^{-}$ decays]

The LHCb experiment



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

Dalitz plot analysis

Technique named after Richard Dalitz (1925-2006)

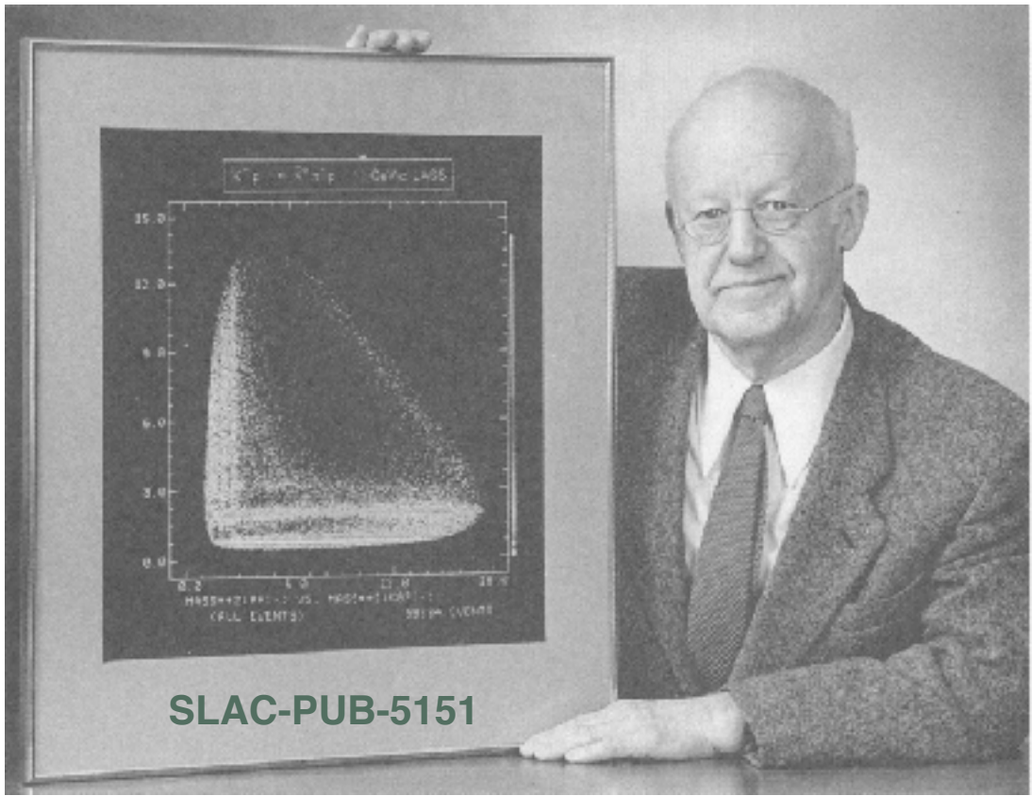
Spin/parity determination of the known τ/θ particles in its decay products

"On the analysis of tau-meson data and the nature of the tau-meson."
R. H. Dalitz, Phil. Mag. 44 (1953) 1068

"I visualise geometry better than numbers"
Richard Dalitz

Scatter-plot visualisation can be interpreted as:

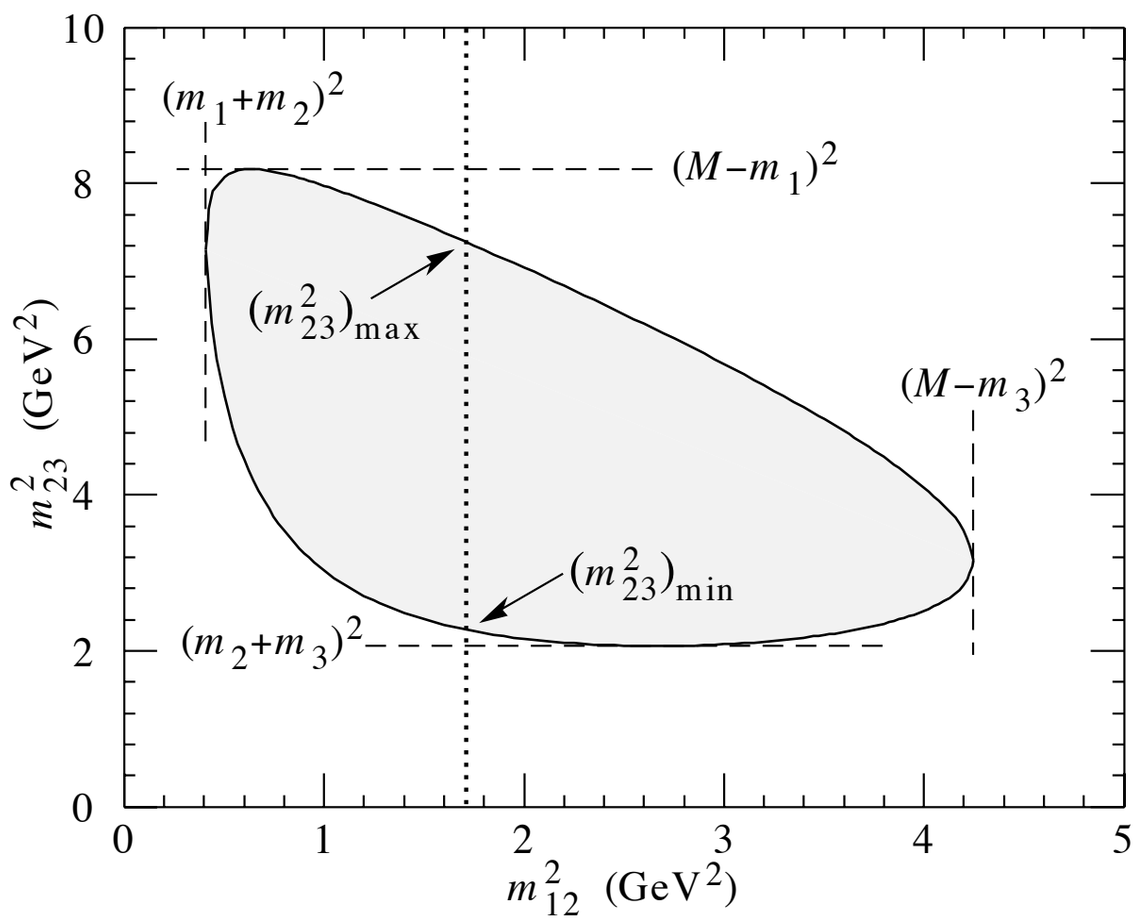
- Matrix element is constant, *i.e.* DP uniformly populated with events
- Non-uniform distributions gives information about the dynamics
- Interference patterns between intermediate states can be studied and parametrised



"A work of art" - gift from B. Richter, W. Panofsky, S. Drell, D. Leith, D. Aston, W. Dunwoodie and B. Ratcliff

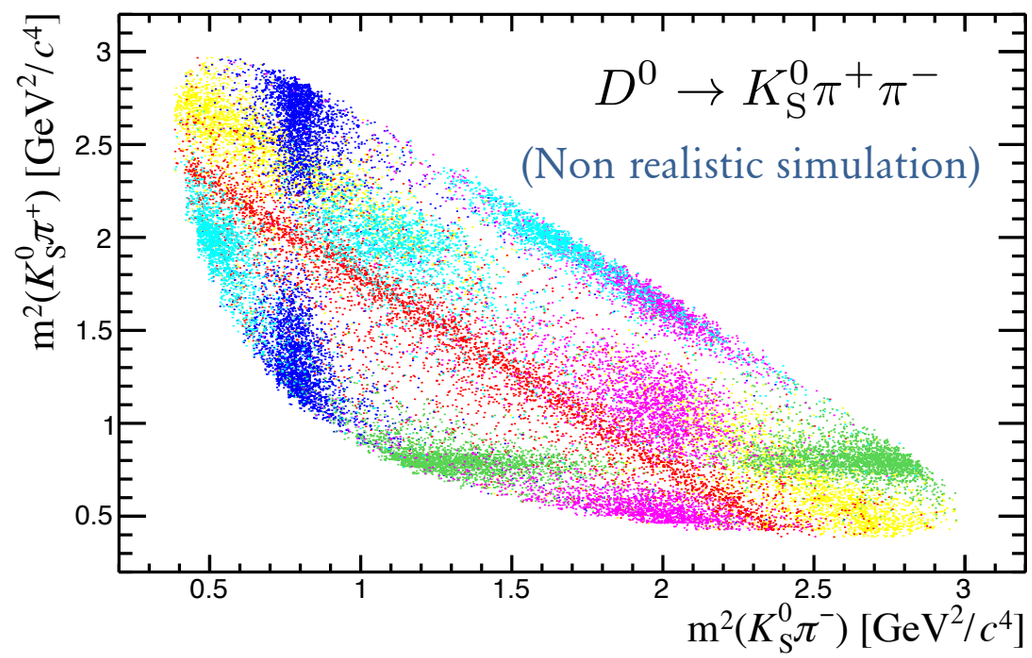
Dalitz plot analysis

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:
https://laura.hepforge.org



Amplitude analysis can access:

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

Dalitz plot analysis - Isobar Model

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A possibility is to perform an "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}

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B decays to open charm, *i.e.* B → Dhh' channels

Dalitz-plot analyses (*e.g.* spectroscopy and CKM angle measurements)

Charm and charm-strange spectroscopy

[PRL 113, 162001 (2014), PRD 90, 072003 (2014)]
[PRD 91, 092002 (2015)]
[PRD 92, 032002 (2015)]

$D_s^{(**)}$ spectroscopy - $B^0_s \to \bar{D}^0 K^- \pi^+$

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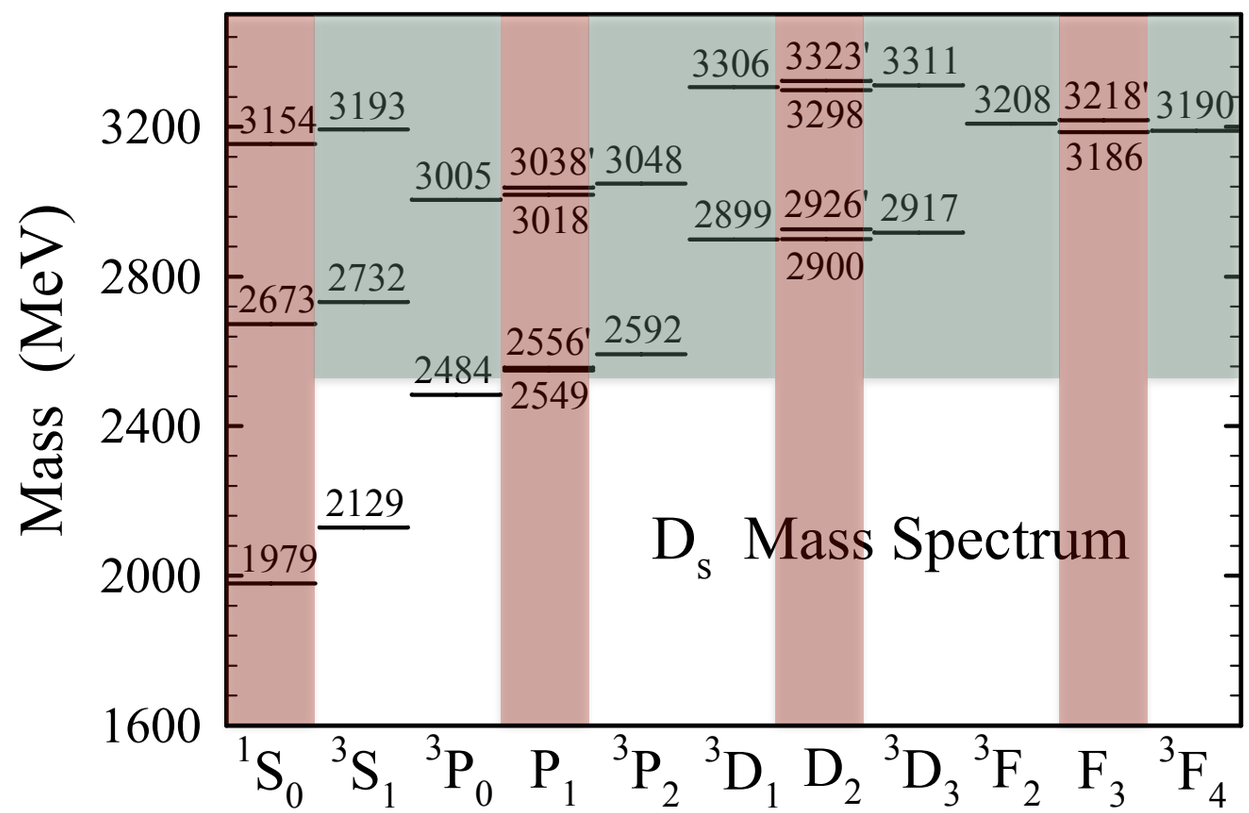
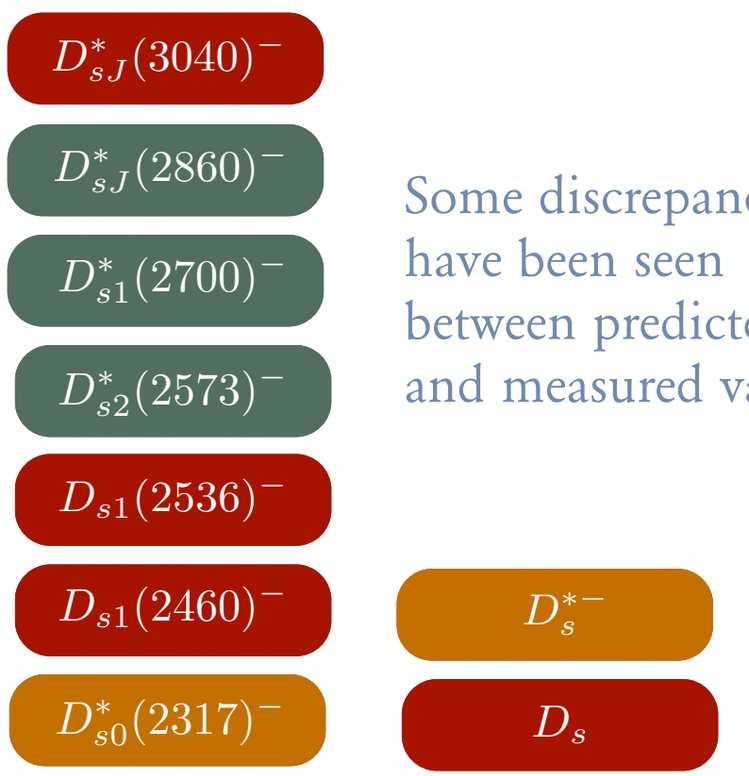
PRD 89, 074023 (2014)
Stephen Godfrey, Ian T. Jardine

Spectroscopy of strange-charm states has been reinvigorated due to recent observations of $D_{s0}^*(2317)$ and $D_{s1}(2460)$

DP analysis of $B^0_s \to D_s^{**-}(\bar{D}^0 K^-)\pi^+$





Some discrepancies have been seen between predicted and measured values

- D_s^* and $D_{s0}^*(2317)$ are too light to decay to D^0K^-
- Neither can states with unnatural spin-parity ($J^P = 0^-, 1^+, 2^-$, etc)
- $D_{s2}^*(2573)$, $D_{s1}^*(2700)$ and $D_{sJ}^*(2860)$ are possible

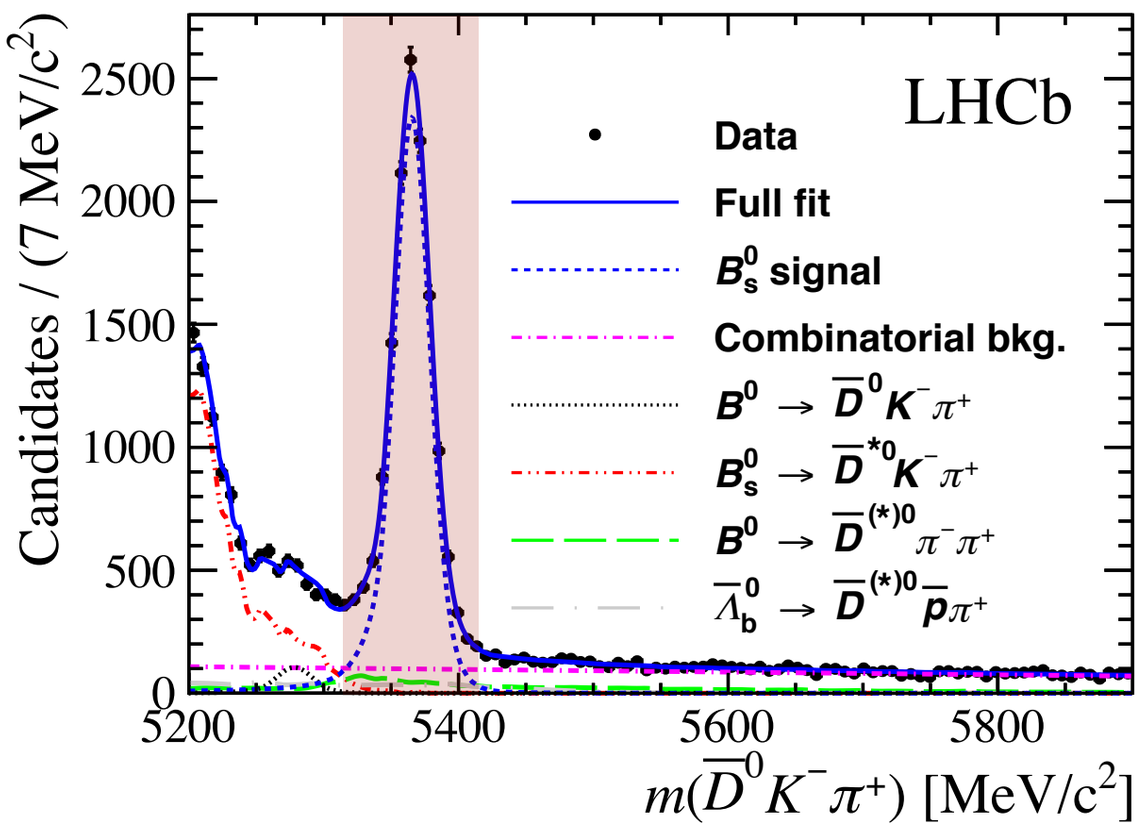
Dalitz plot analysis of $B^0_s \to \bar{D}^0 K^- \pi^+$

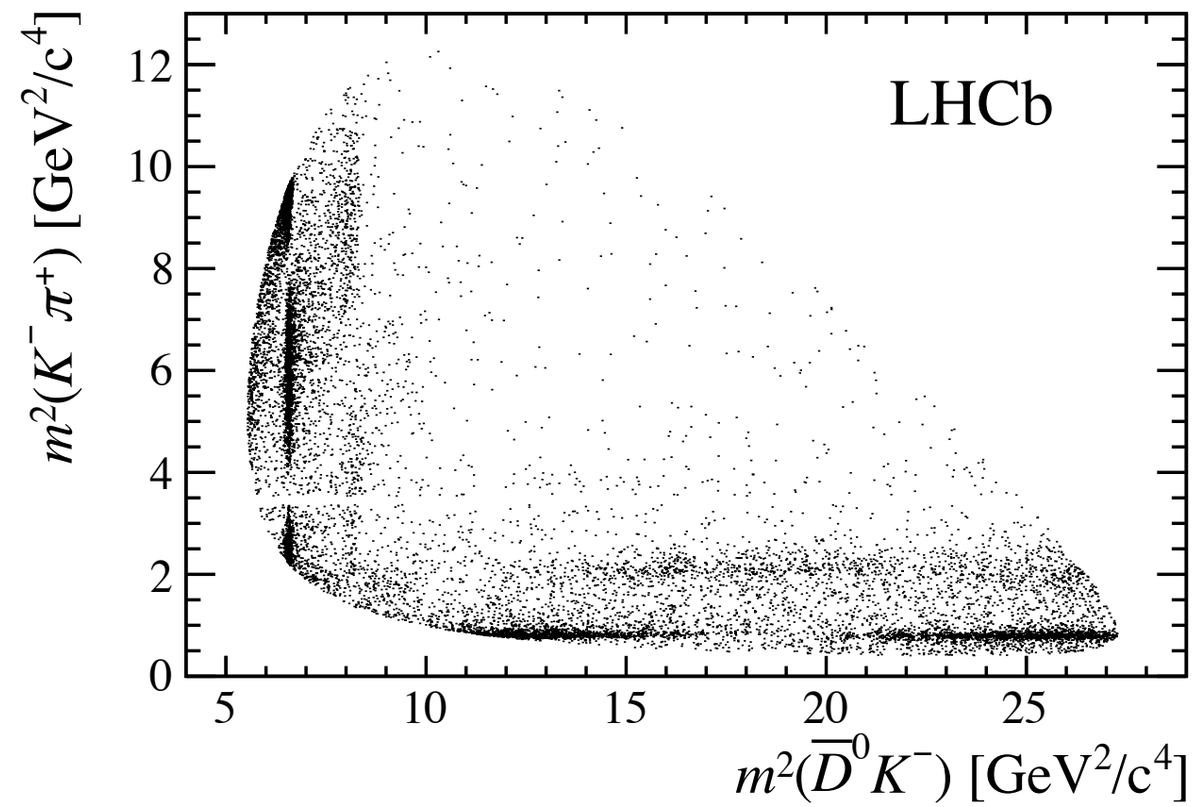
PRL 113, 162001 (2014) PRD 90, 072003 (2014)

Analysis performed with ~11K signal events and purity of 87%

Backgrounds due to Combinatorial (7.3%), $B^0 \to D^{(*)0}\pi\pi$ (2.8%) and $\Lambda^0_b \to D^{(*)0}p\pi$ (2.3%)

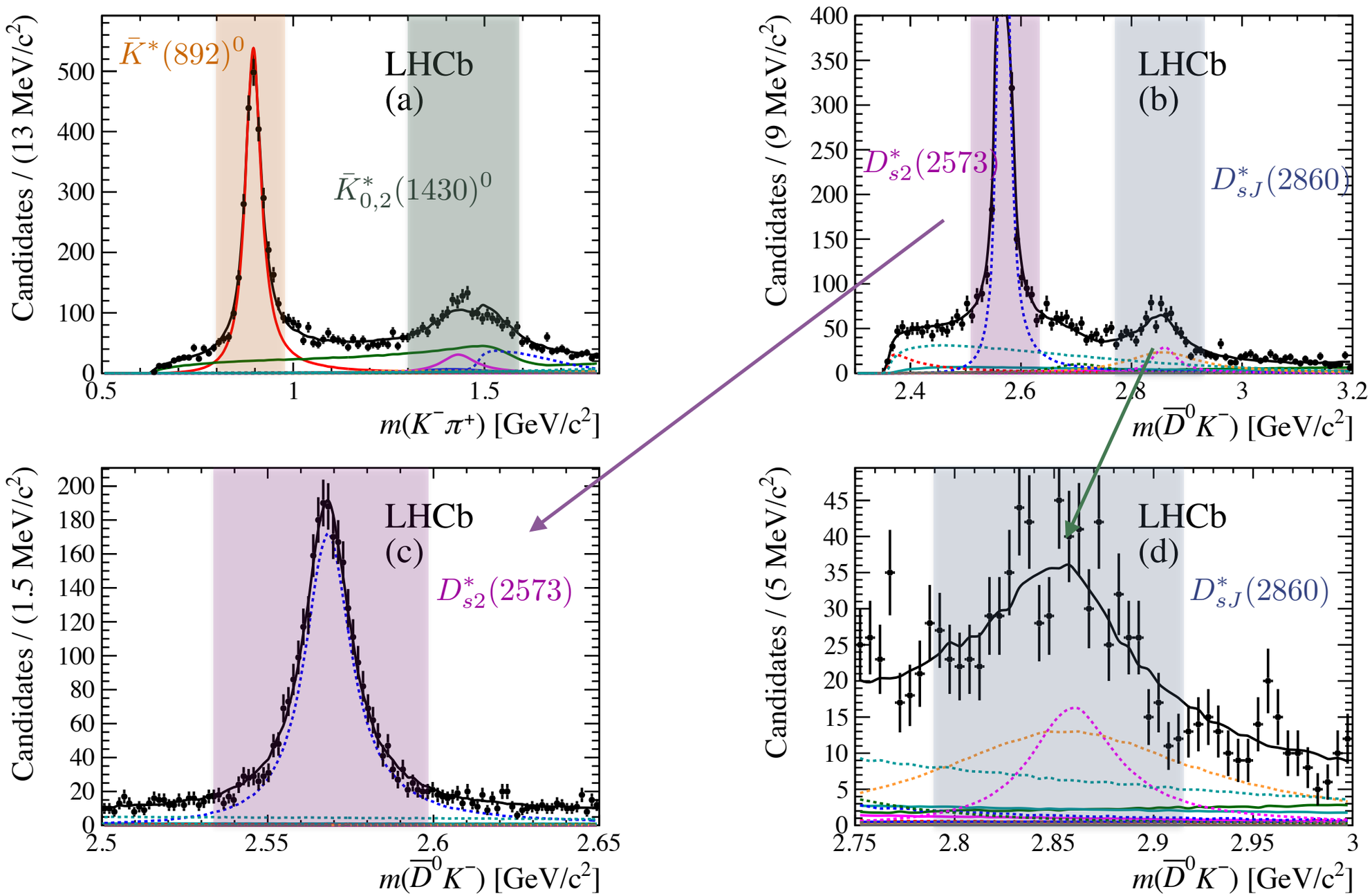
Signal region: $\pm 2.5\sigma$ around nominal mass is considered for the Dalitz plot fit





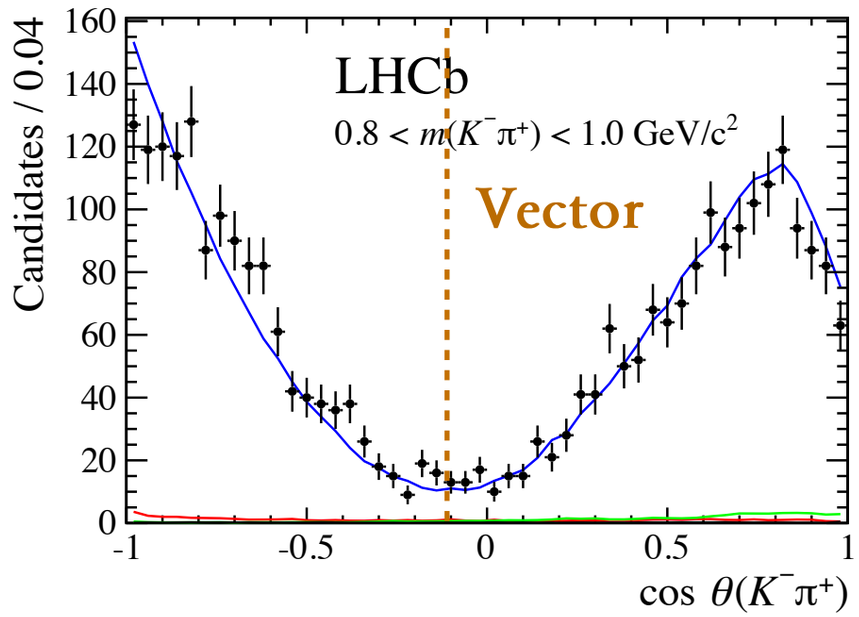
Dalitz plot fit results

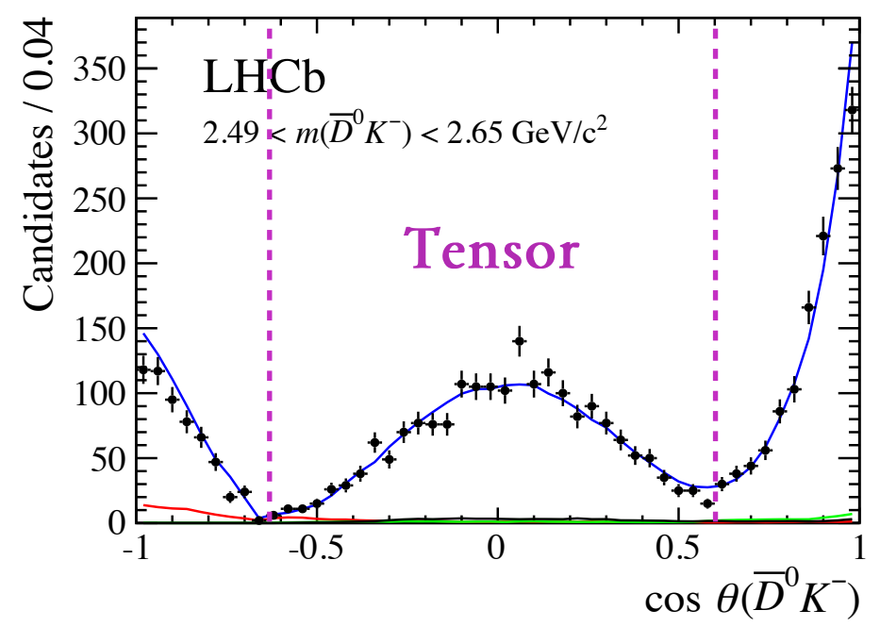
PRL 113, 162001 (2014) PRD 90, 072003 (2014)

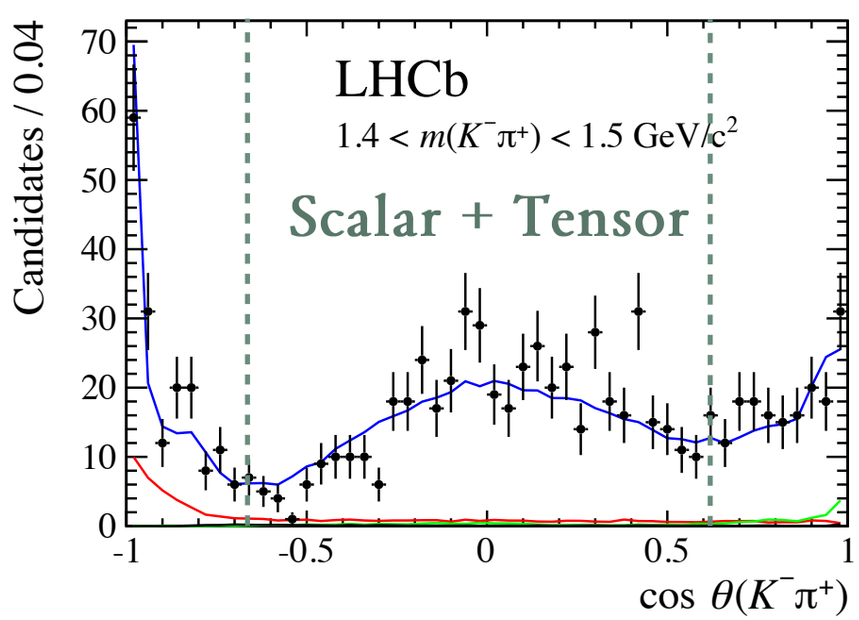


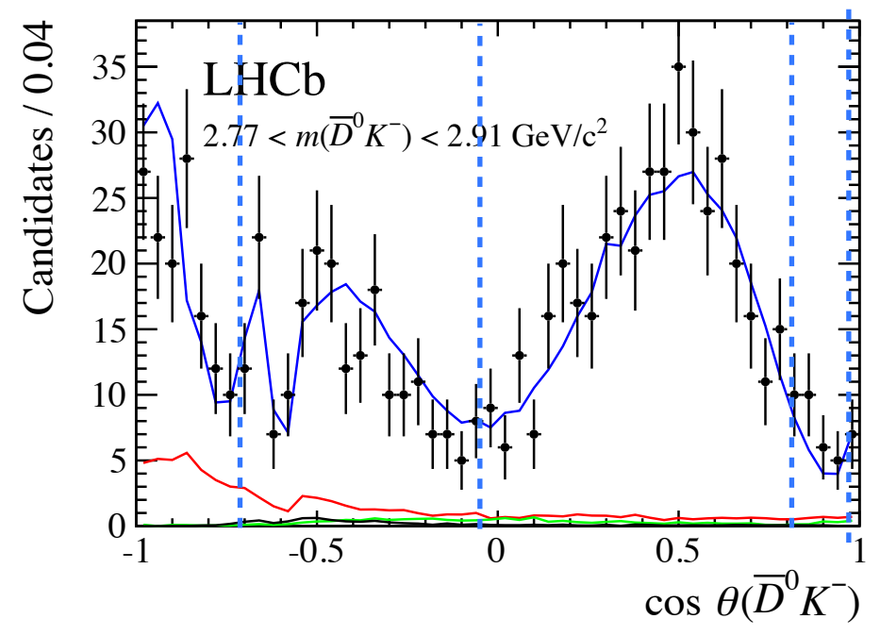
Dalitz plot fit results - helicity projections

PRL 113, 162001 (2014) PRD 90, 072003 (2014)









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$D_{sJ}^*(2860)^-$ state

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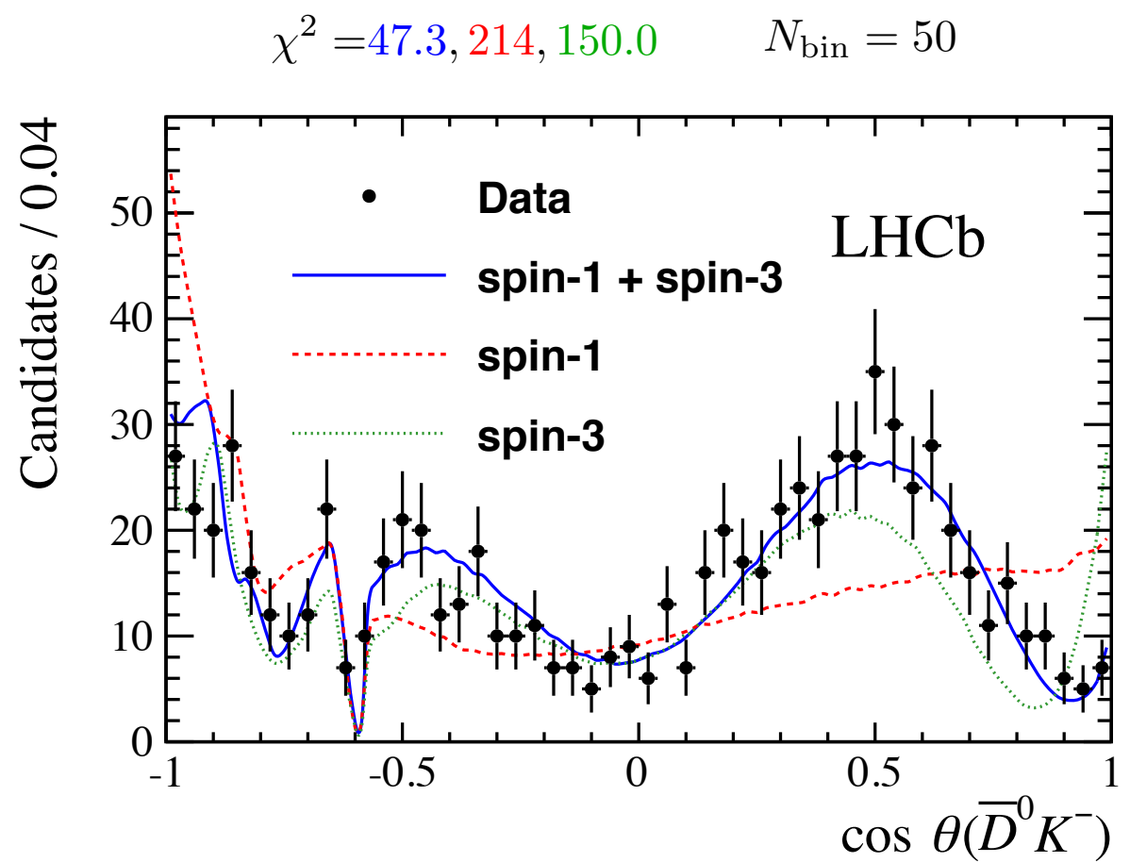
PRL 113, 162001 (2014) PRD 90, 072003 (2014)

Several spin hypotheses have been investigated for the $D_{sJ}^*(2860)^-$

Two states [**$D_{s1}^*(2860)^-$, $D_{s3}^*(2860)^-$**] are required in the region 2.86 GeV/c^2 (each with a significance of 10σ)

1st observation of a heavy flavoured spin-3 resonance and 1st time a spin-3 state seen to be produced in B decay

Spin hypothesis	ΔNLL	$\sqrt{2\Delta NLL}$	Masses and widths			
1+3	0	—				
0	141.0	16.8	2862	57		
0+1	113.2	15.0	2446	250	2855	96
0+2	155.1	17.6	2870	61	2569	17
0+3	105.1	14.5	2415	188	2860	52
1	156.8	17.7	2866	92		
1+2	138.6	16.6	2851	99	3134	174
2	287.9	24.0	3243	81		
2	365.5	27.0	2569	17		
2+3	131.2	16.2	2878	12	2860	56
3	136.5	16.5	2860	57		



The presence of the state $D_{s3}^*(2860)$ has been independently confirmed in studies of pp → $D^{*(+,0)}K^{0,+}X$ (LHCb)

[JHEP 02 (2016) 133]

DP analysis of $B^- \to D^+K^-\pi^-$, $B^0 \to \bar{D}^0\pi^+\pi^-$

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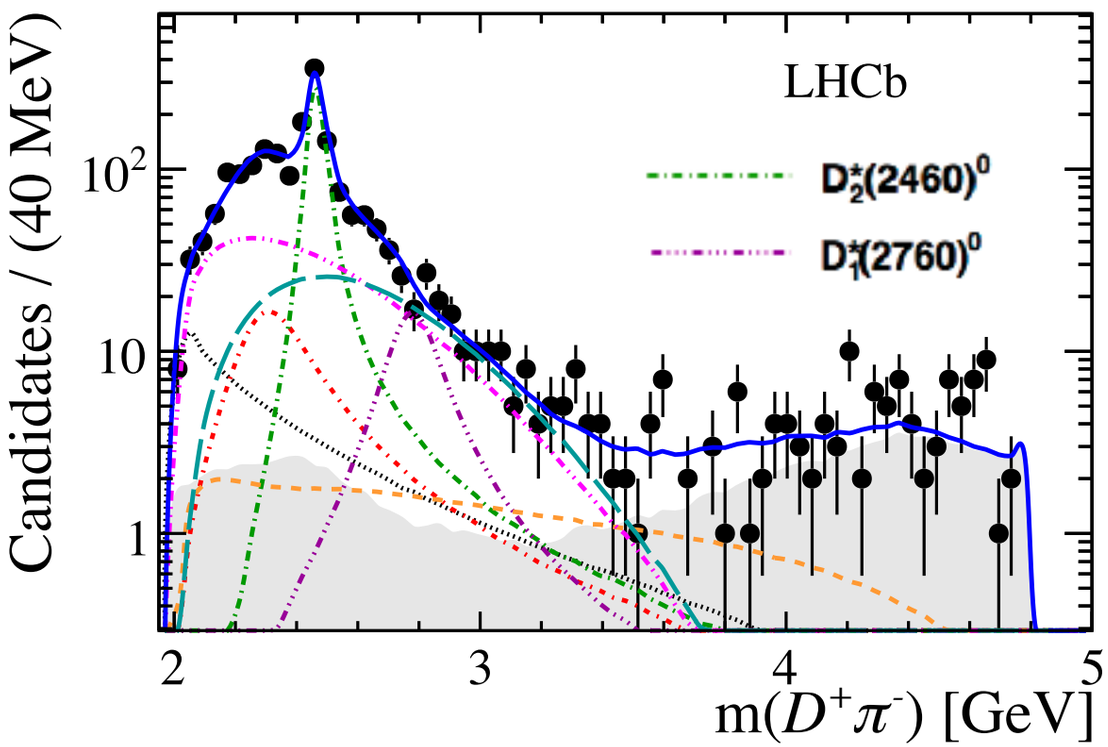
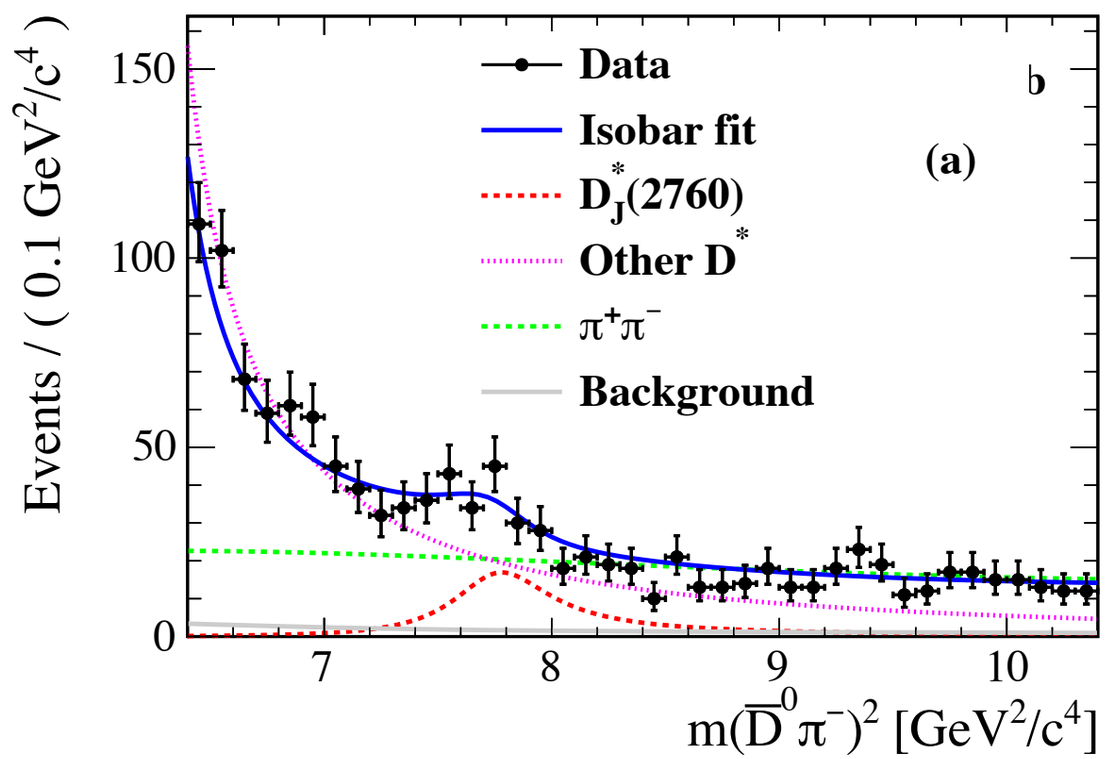
PRD 92, 032002 (2015) PRD 91, 092002 (2015)

$B^- \to D^+K^-\pi^-$



$B^0 \to \bar{D}^0\pi^+\pi^-$



Data favours spin-1 hypothesis for the state $D^*_J(2760)^0$ (other assignments are rejected with > 6σ)

Data strongly (10 σ) favours spin-3 assignment to the state $D^*_J(2760)^-$

No evidence for an additional spin-1

Dalitz plot analysis of $\Lambda^0_b \to D^0 p \pi^-$ decays

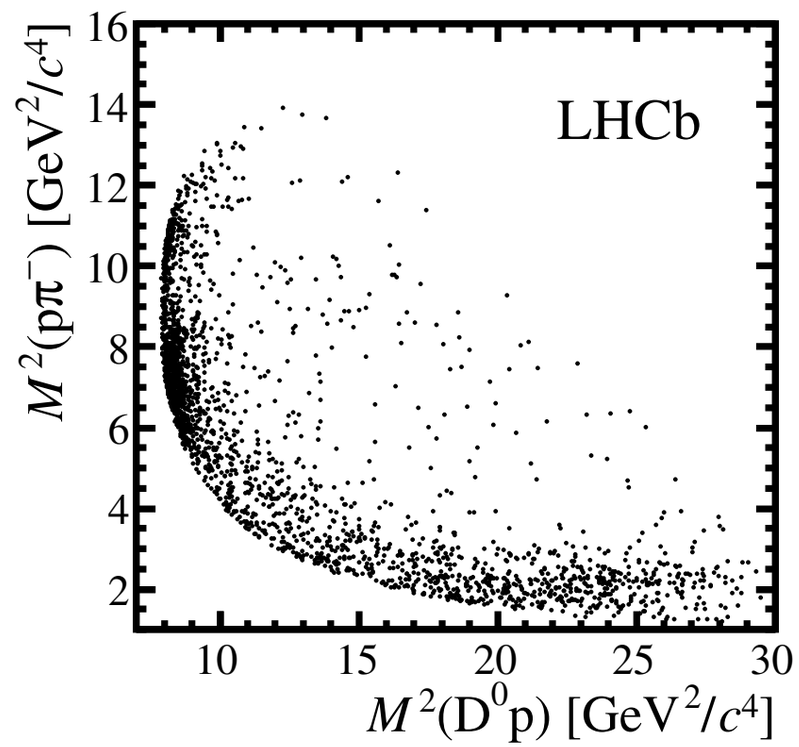
Analogous to the $B \to D\pi h$ family, there are many interesting aspects:

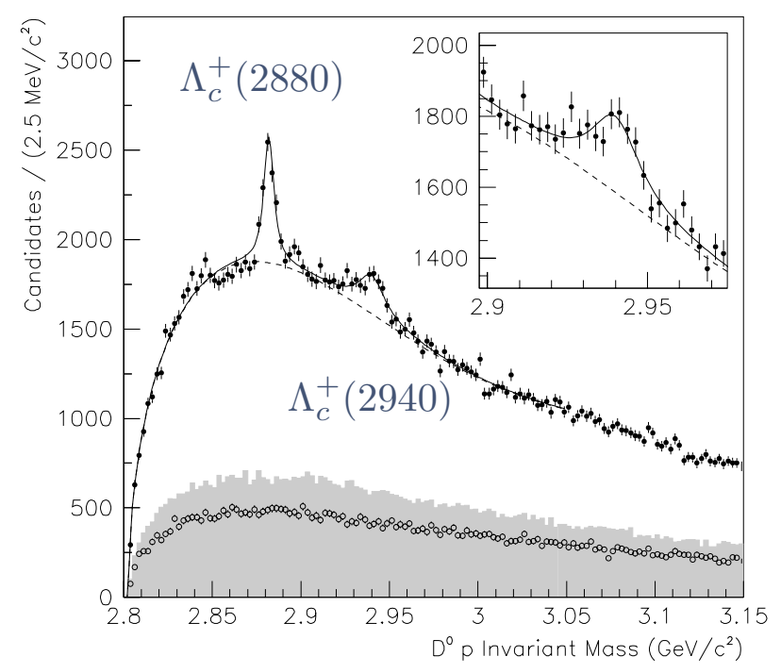
- Spectroscopy of the $Dp/p\pi$ resonances
- $\Lambda^0_b \to D^0 p K^-$ decay should be sensitive to CKM angle γ
- Final state also accessible to Ξ^0_b's

First observations of Λ^0_b and Ξ^0_b decaying to $D^0 ph$ and $\Lambda_c h$ final states with 1 fb^{-1}

[BR and Ξ^0_b mass measurement]

[NEW] Amplitude analysis (DP + 3 angles) of $\Lambda^0_b \to D^0 p \pi^-$ decays





Dalitz plot analysis of $\Lambda^0_b \to D^0 p \pi^-$ decays

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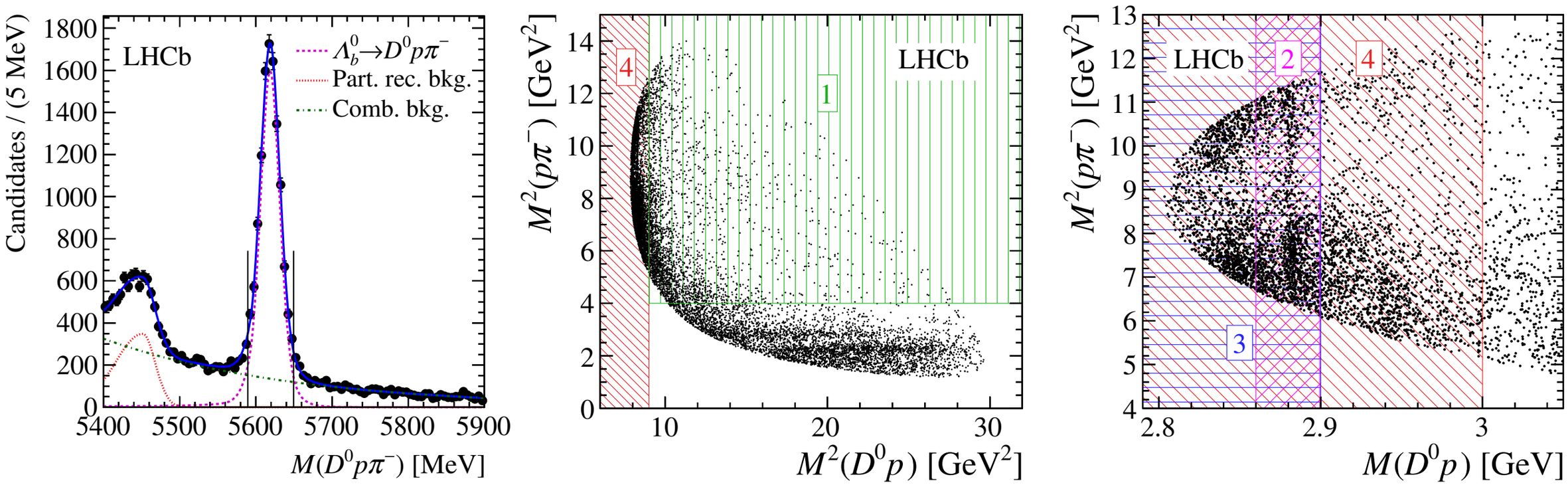
arXiv:1701.07873v2



[1] Resonance-free region: constrain reflections between Dp and pπ channels

[2] Vicinity of $\Lambda_c(2880)$: model-independent determination of amplitude

[3] $\Lambda_c(2880)$ down to threshold: understand near-threshold structure

[4] Threshold to $\Lambda_c(2940)$: J^P, mass and width for $\Lambda_c(2940)$

[5] pπ amplitude: N^* states (interplay with $\Lambda^0_b \to J/\psi p \pi^-$) [Next time]

[1] Resonance free region

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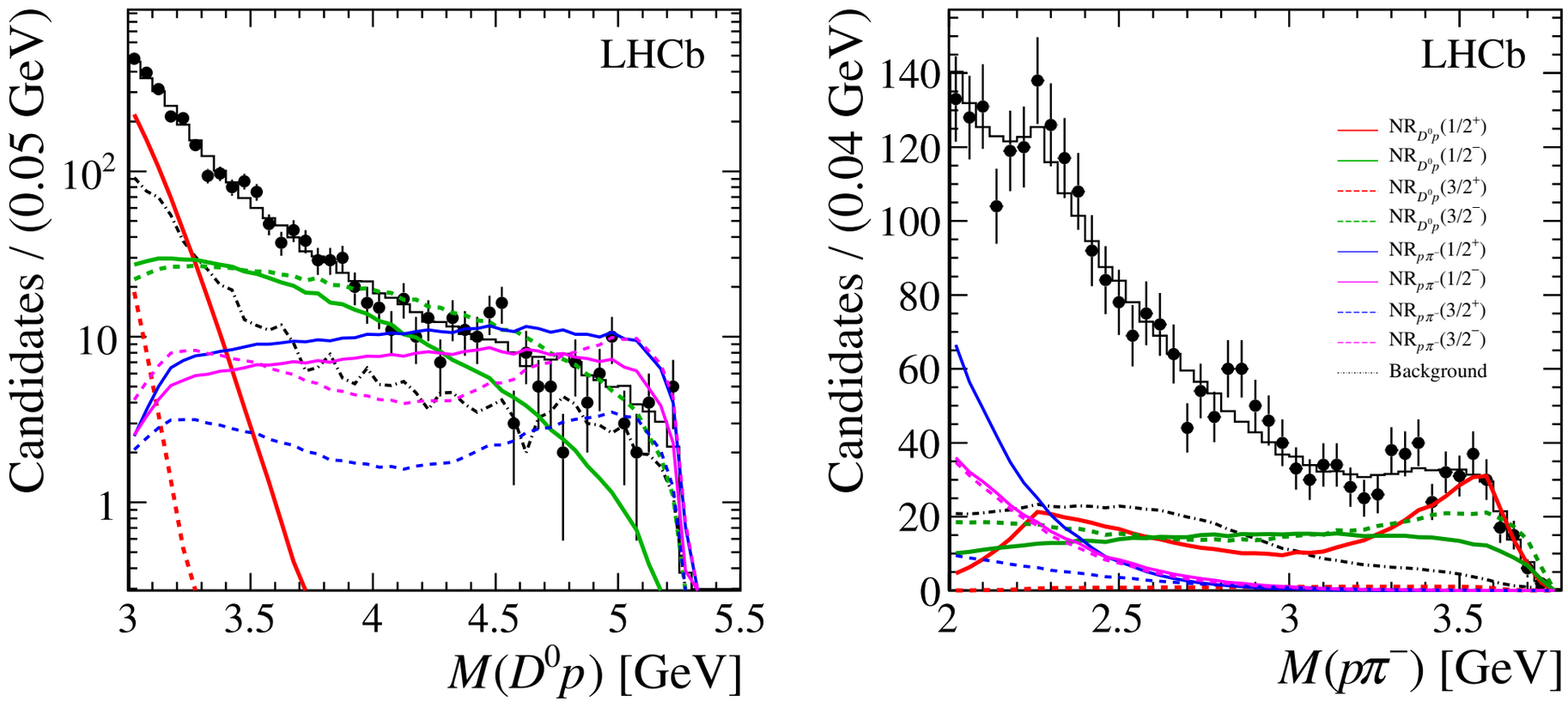
arXiv:1701.07873v2

The effect of pπ reflections in Dp decays can be examined in region [1]



	Region	Phase space selections	N_{exp}	$N_{reflected}$
2	$\Lambda_c(2880)$	$2.86 < M(Dp) < 2.9\,\mathrm{MeV}/c^2$	1499.6	9.4
3	low-Dp	$M(Dp) < 2.9\,\mathrm{MeV}/c^2$	2802.8	15.8
4	Dp	$M(Dp) < 3.0\,\mathrm{MeV}/c^2$	4261.2	60.9

Add single $1/2^+$ amplitude with floating magnitude in region [4]

[2] D^0p in the $\Lambda^+_c(2880)$ region

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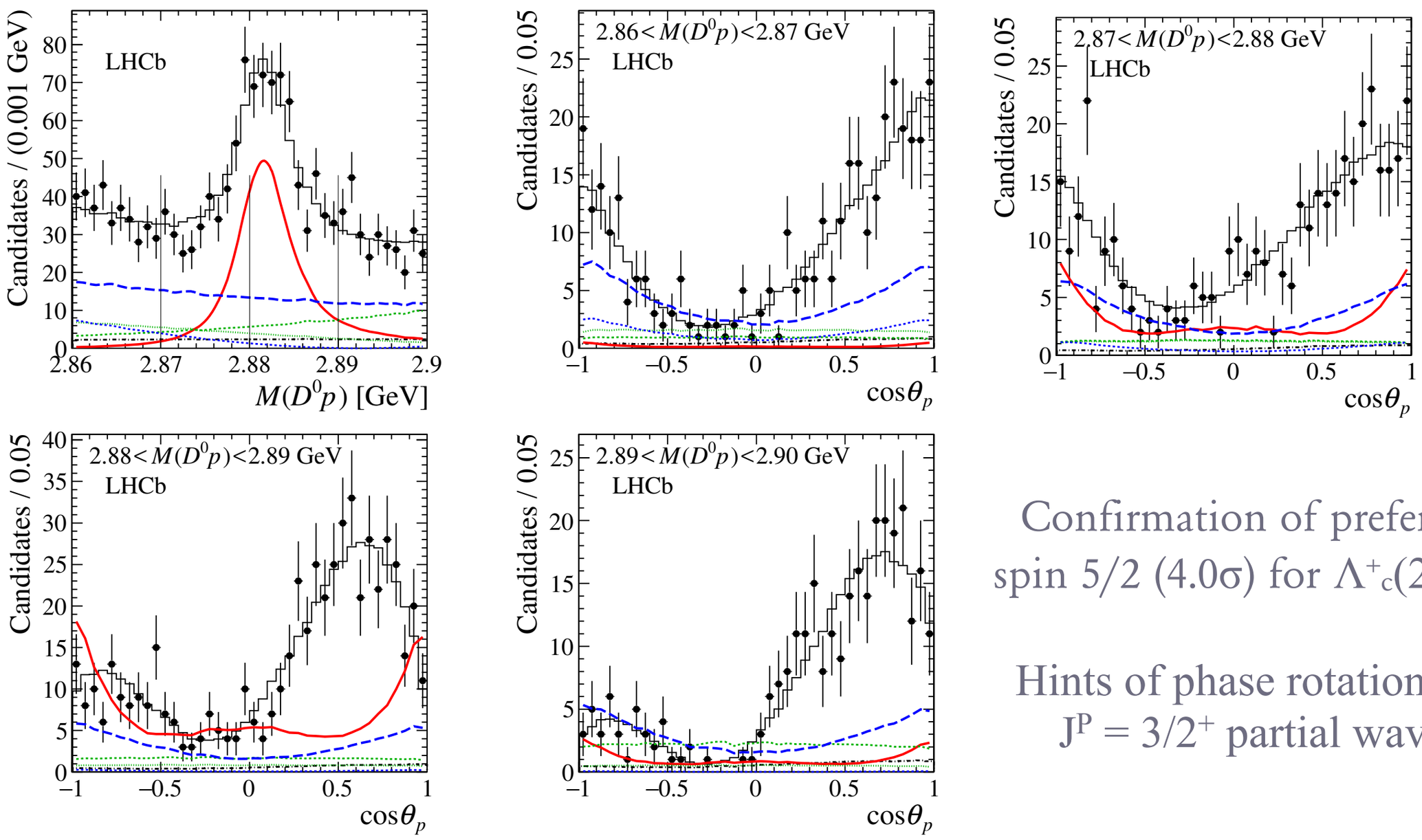
arXiv:1701.07873v2

Using $\Lambda^+_c(2880)$ as a reference amplitude allows us to constrain "NR" amplitude



Confirmation of preferred spin 5/2 (4.0σ) for $\Lambda^+_c(2880)$

Hints of phase rotation for $J^P = 3/2^+$ partial wave

[3] Near-threshold and $\Lambda^+_c(2880)$ regions

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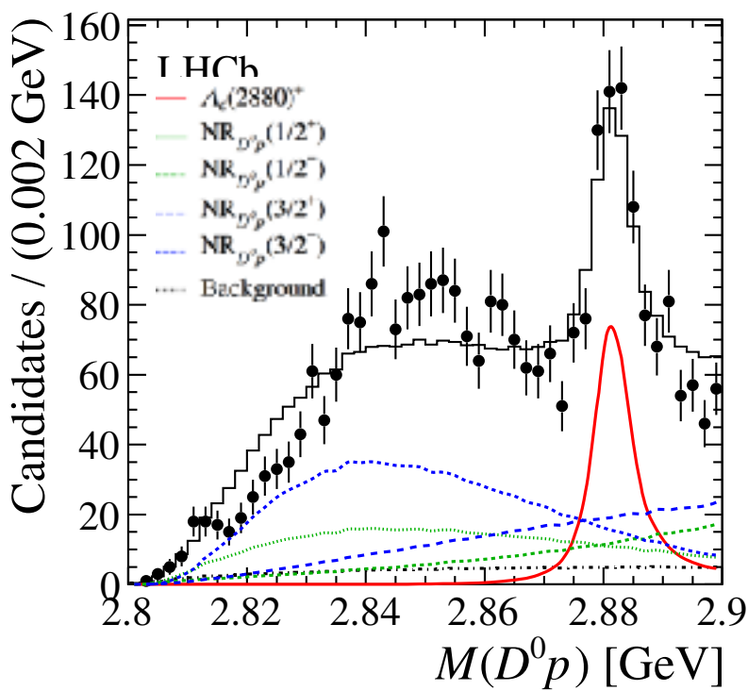
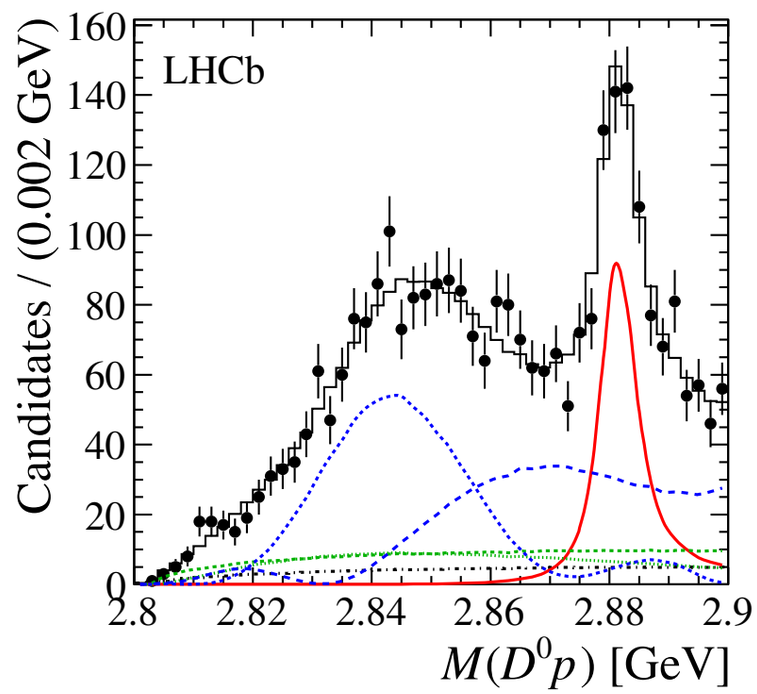
arXiv:1701.07873v2

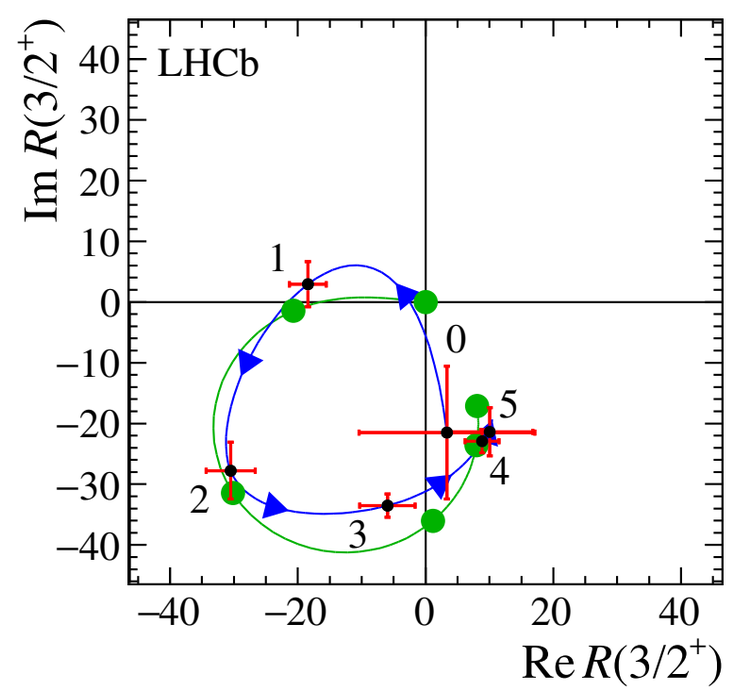
$\Lambda^+_c(2880)$ plus 4 exponential NR components ($1/2^\pm$, $3/2^\pm$)



BW in $J^P = 3/2^+$ and Exp. in $1/2^\pm$, $3/2^-$



Argand diagrams for the $J^P = 3/2^+$ partial wave



Existence of $3/2^+$ (1D in heavy quark-light diquark model) is suggested by many theorists (see, e.g. [arXiv:1609.07967]), mostly in the region of 2850 MeV/c^2

[4] Fit including Λ^+_c (2940)

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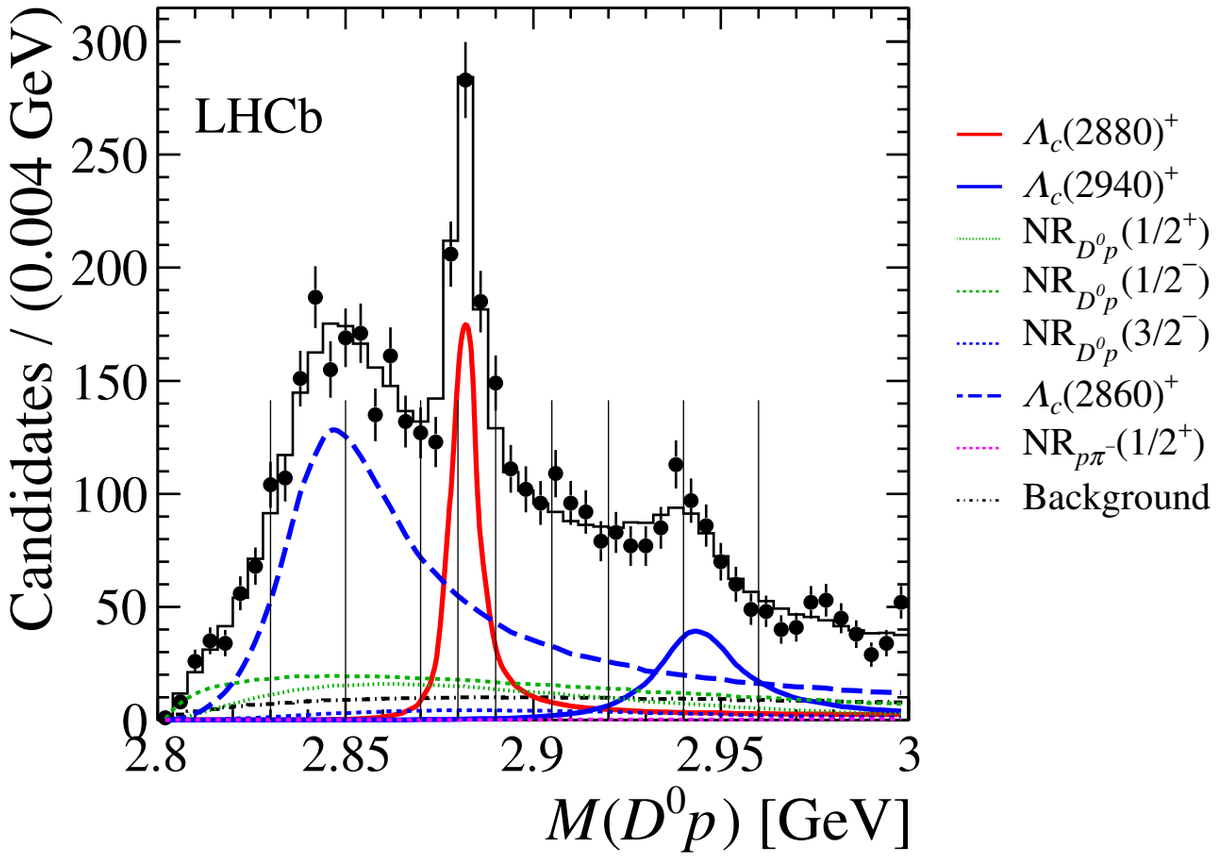
arXiv:1701.07873v2

First constraints on quantum numbers of Λ^+_c (2940) are obtained.

Fits favour JP = 3/2 , but other solutions cannot yet be excluded, depending on the non-resonant model

Mass and width of the Λ^+_c (2940) are consistent with and have comparable precision to the current world average



Λ^+_c (2940)+ has different explanations depending on J^P , 3/2 is a typical molecular assignment (D^*N) (e.g. [arXiv:1212.5325])

Prospects/status for $B \to Dhh'$ channels

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Spectroscopy studies have received a great attention from the community with numerous recent results

- Additional insights can be obtained in near future through from $B \to D^*hh'$ channels, where unnatural spin-parity states can appear

- Similar modes, *e.g.* $B \to D^{(*)}D^{(*)}h$ are of great interest (*e.g.* for leptonic decays) - recently performed by BaBar [Phys. Rev. D 91, 052002 (2015)]

Measurements of CKM weak phases (*i.e.* γ, β and β_s) are being gradually performed

- LHCb performed a simultaneous analysis of $B^0 \to \bar{D}^0 K^+\pi^-$, with $\bar{D}^0 \to K^+\pi^-$ and of $B^0 \to D_{CP}K^+\pi^-$ (+cc) with $D_{CP} \to \pi^+\pi^-$ or K^+K^- [Phys.Rev. D93 (2016) 112018]

- Similar approach can be applied to other final states. Moreover, time-dependent amplitude analysis can provide clean measurements of mixing phases

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Dalitz-plot analysis of $B^{\pm} \to h^{\pm}h^{\mp}h'^{\pm}$ decays, where $h^{(\prime)} \in \{\pi^{\pm}, K^{\pm}\}$

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

Large local phase-space asymmetries observed in charmless charged B decays

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

Conditions for *CP* violation in decay

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The presence of multiple amplitudes leads can be modelled as

$$A(B \to f) = \sum_i |A_i| e^{i(\delta_i + \phi_i)} \qquad \bar{A}(\bar{B} \to \bar{f}) = \sum_i |A_i| e^{i(\delta_i - \phi_i)}$$

Strong phase (δ) invariant under *CP*, while weak phase (φ) changes sign under *CP*

$$\mathcal{A}_{CP}(B \to f) \equiv \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} \propto \sum_{i,j} |A_i||A_j| \sin(\delta_i - \delta_j) \sin(\phi_i - \phi_j)$$

Conditions for *CP* violation in decay

- At least two amplitudes
- Non-zero strong phase difference
- Non-zero weak phase difference

Source of weak phase differences come from different CKM phases of each amplitude

Dalitz plot strong phase manifestation

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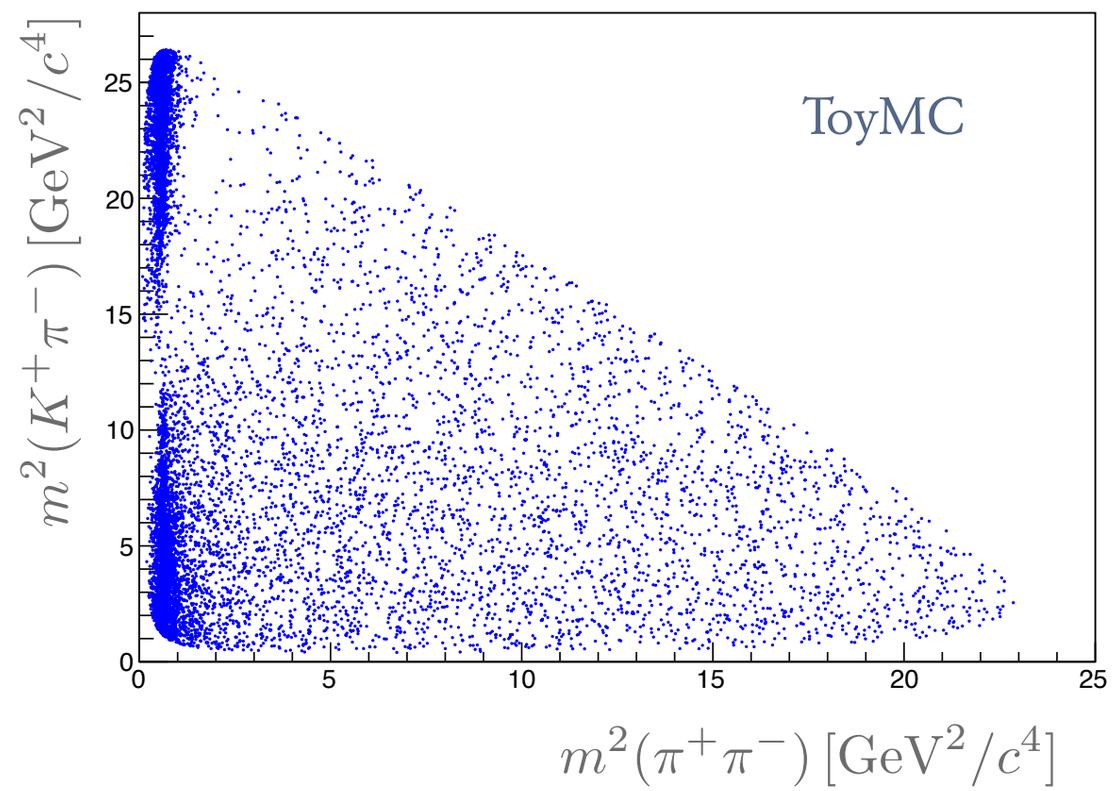
Each source of strong phase leaves a unique signature in the Dalitz plot

[Illustrative example] Consider $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ with only two isobars, *i.e.* $B^{\pm} \to \rho^{0}K^{\pm}$ and a flat non-resonant (NR) component

$$A_+ = |a_+^\rho| e^{i\delta_+^\rho} F_\rho^{\mathrm{BW}} \cos\theta + |a_+^{\mathrm{NR}}| e^{i\delta_+^{\mathrm{NR}}}$$

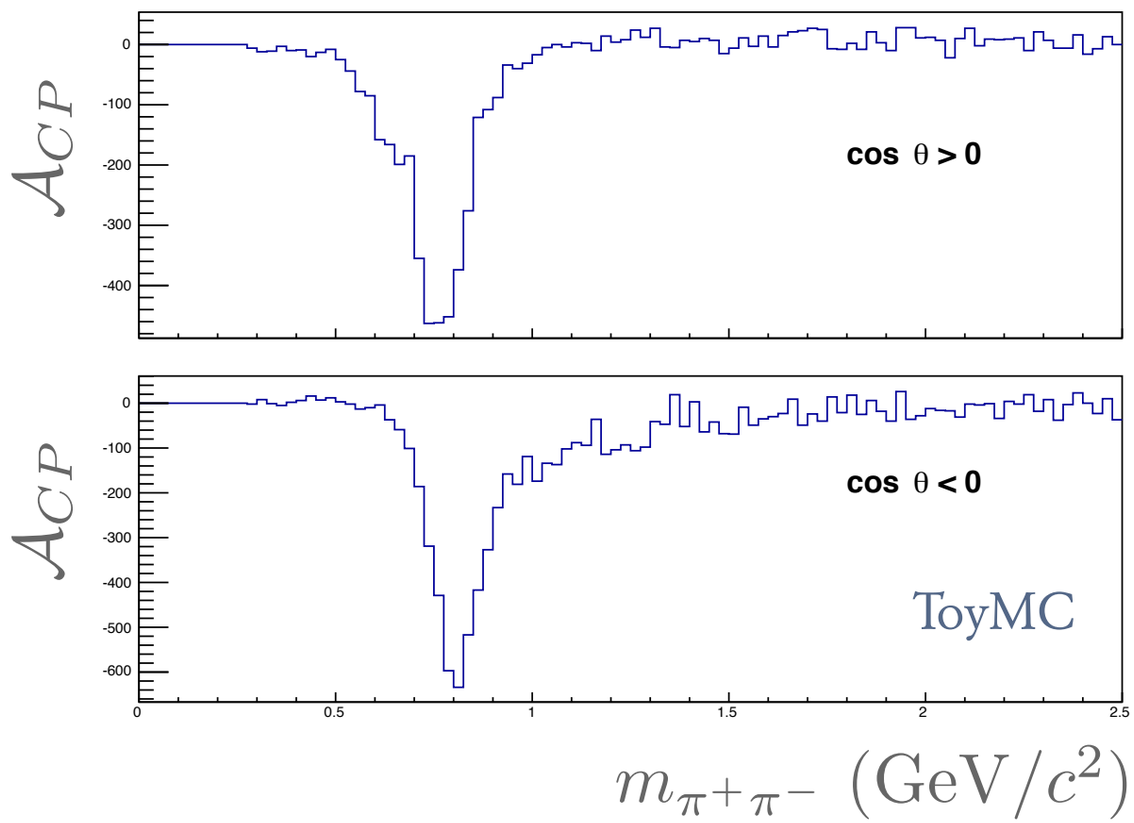
$$A_- = |a_-^\rho| e^{i\delta_-^\rho} F_\rho^{\mathrm{BW}} \cos\theta + |a_-^{\mathrm{NR}}| e^{i\delta_-^{\mathrm{NR}}}$$

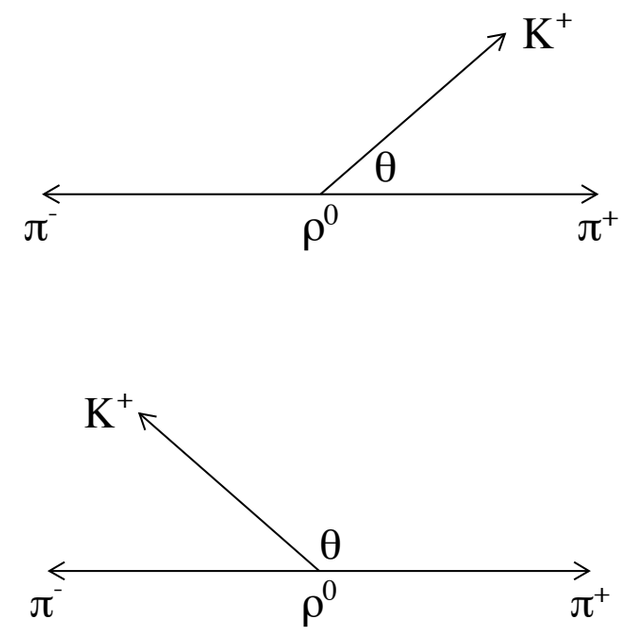
$$\begin{aligned} \mathcal{A}_{CP} &\propto |A_-|^2 - |A_+|^2 \\ &\propto (|a_-^\rho|^2 - |a_+^\rho|^2)|F_\rho^{\mathrm{BW}}|^2 \cos^2\theta \\ &\quad -2(m_\rho^2 - s)|F_\rho^{\mathrm{BW}}|^2 \cos\theta \ldots \\ &\quad +2m_\rho\Gamma_\rho|F_\rho^{\mathrm{BW}}|^2 \cos\theta \ldots \end{aligned}$$



Dalitz plot strong phase manifestation

[1] Short distance effects, i.e. only responsible for



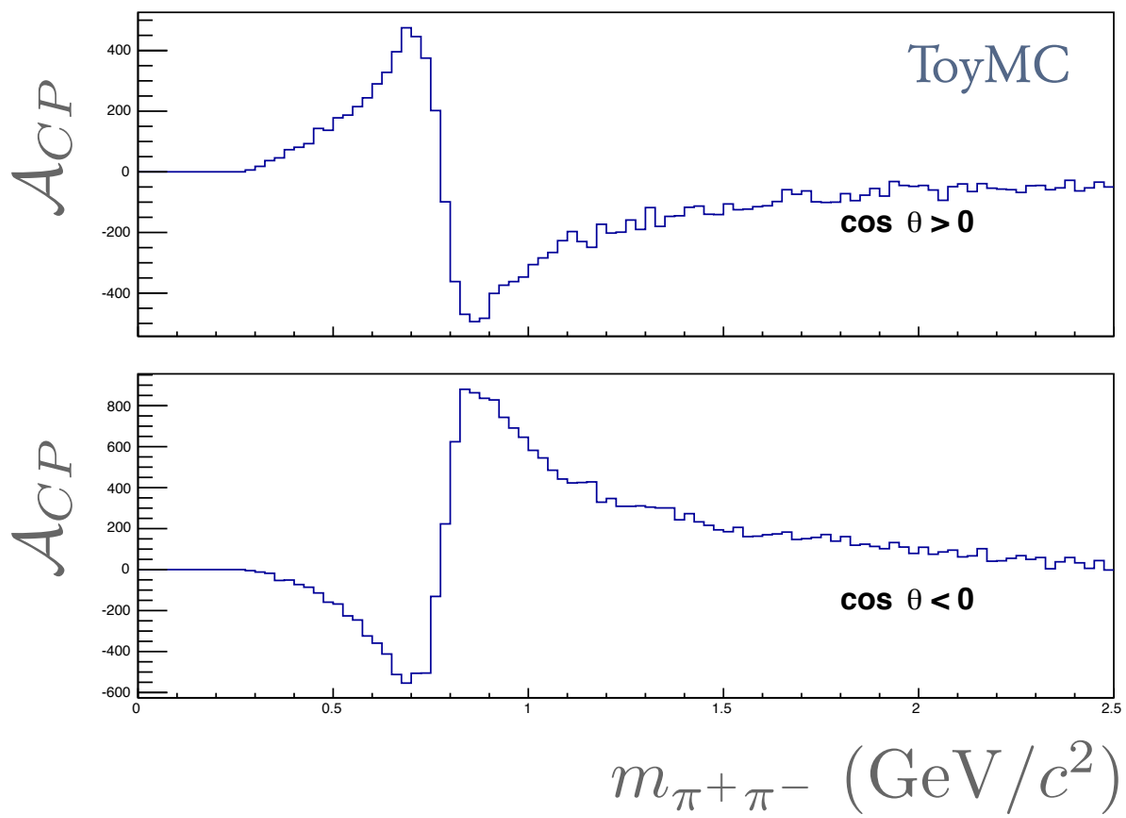


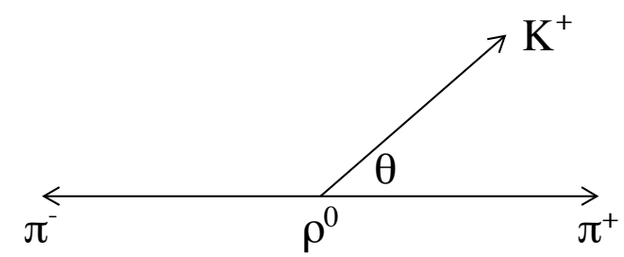
$$\mathcal{A}_{CP} \propto (|a_-^\rho|^2 - |a_+^\rho|^2)|F_\rho^{\mathrm{BW}}|^2 \cos^2\theta \ldots$$
$$-2(m_\rho^2 - s)|F_\rho^{\mathrm{BW}}|^2 \cos\theta \ldots$$
$$+2m_\rho\Gamma_\rho|F_\rho^{\mathrm{BW}}|^2 \cos\theta \ldots$$

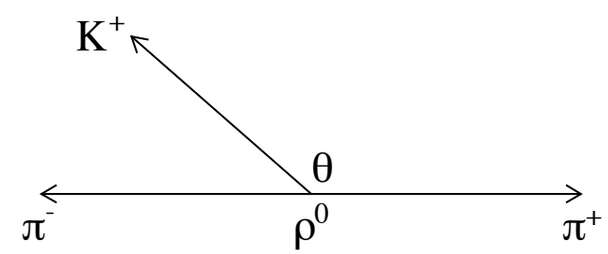
Only depends on ρ resonance, maximum difference at ρ pole, quadratic in helicity

Dalitz plot strong phase manifestation

[2] Long-distance effects (Real term) from final state interactions







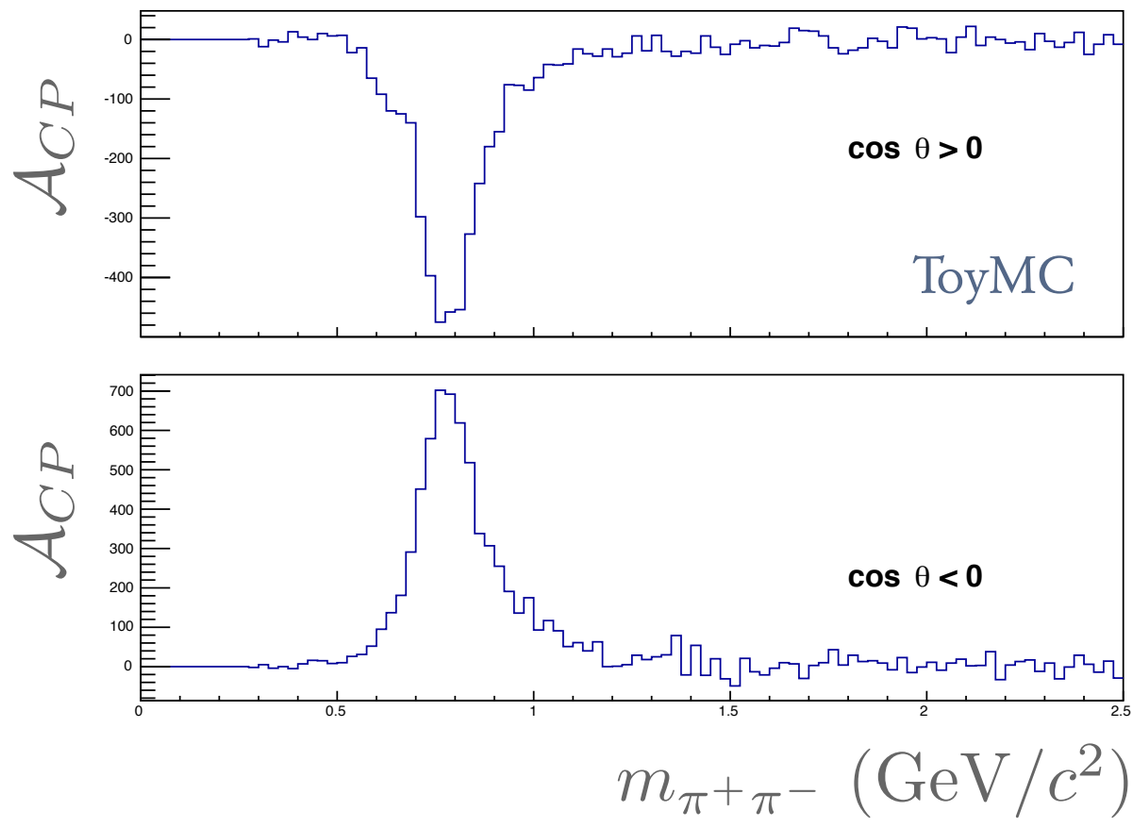
$$\mathcal{A}_{CP} \propto (|a_-^\rho|^2 - |a_+^\rho|^2)|F_\rho^{\mathrm{BW}}|^2 \cos^2\theta \ldots$$
$$-2(m_\rho^2 - s)|F_\rho^{\mathrm{BW}}|^2 \cos\theta \ldots$$
$$+2m_\rho\Gamma_\rho|F_\rho^{\mathrm{BW}}|^2 \cos\theta \ldots$$

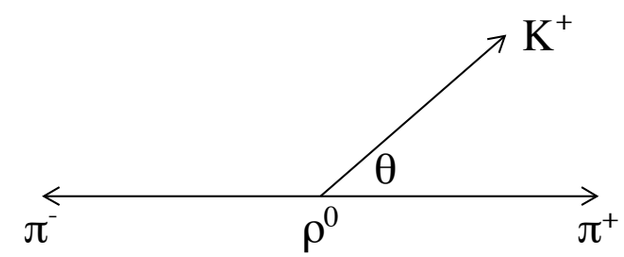
Interference term from real part of Breit-Wigner, zero at ρ pole, linear in helicity

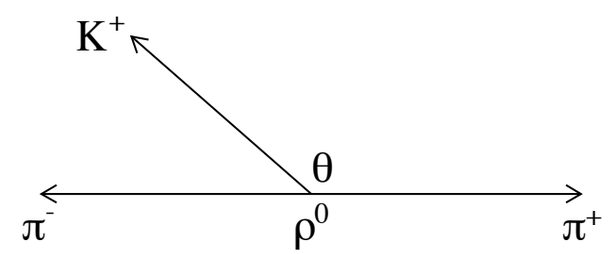
Dalitz plot strong phase manifestation

Universität Zürich[UZH]

[3] Long-distance effects from Breit-Wigner phase and final state interactions







$$\mathcal{A}_{CP} \propto (|a_-^\rho|^2 - |a_+^\rho|^2)|F_\rho^{\rm BW}|^2\cos^2\theta \ldots$$
$$-2(m_\rho^2 - s)|F_\rho^{\rm BW}|^2\cos\theta \ldots$$
$$+2m_\rho\Gamma_\rho|F_\rho^{\rm BW}|^2\cos\theta \ldots$$

Interference term from imaginary part of Breit-Wigner, maximum at ρ pole, linear in helicity

Dalitz plot strong phase manifestation

Universität Zürich[UZH]

[4] Final state re-scattering contributions (e.g $KK \leftrightarrow \pi\pi$)

Can occur between decay channels with the same flavour quantum numbers:

e.g. $B^{\pm} \to K^{\pm}K^{+}K^{-}$ and $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$

CPT conservation constrains hadron re-scattering:

- For given quantum numbers, sum of partial widths equal for charge-conjugate decays
- $KK \leftrightarrow \pi\pi$ re-scattering generates a strong phase

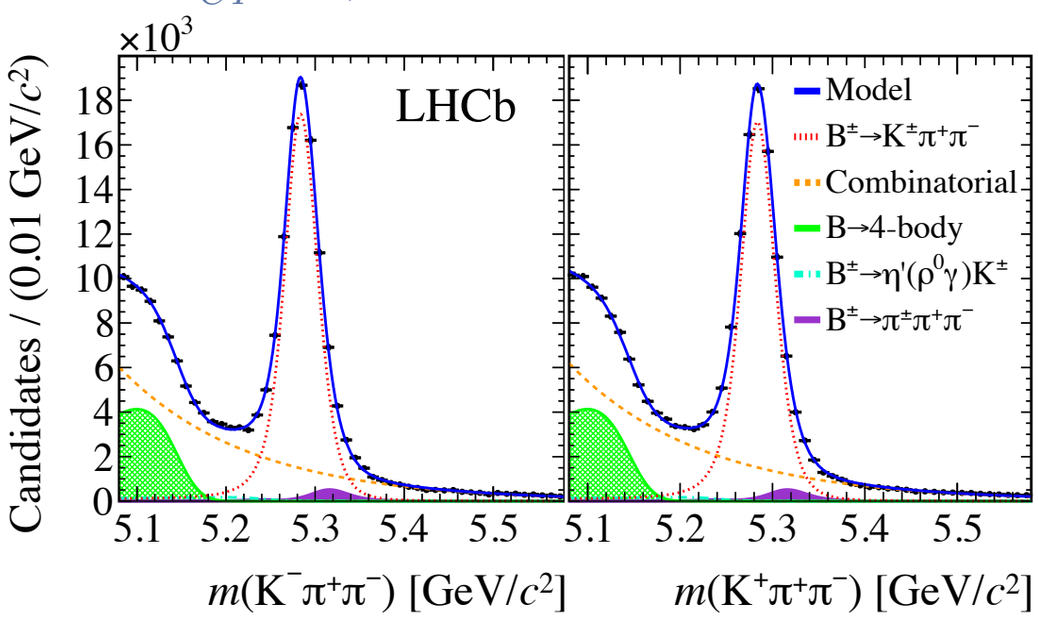
- If re-scattering phase in one decay channel generates direct *CP* violation in this region
- Re-scattering phase should generate opposite sign direct *CP* violation in partner decay channel

CP violation LHCb inclusive results

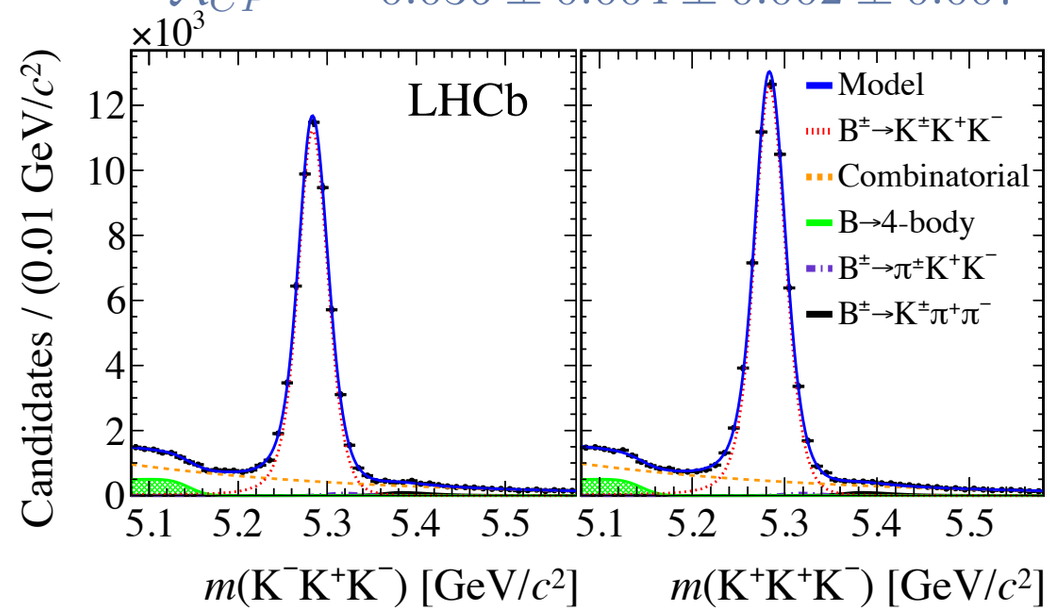
Universität Zürich[UZH]

PRD 90, 112004 (2014)

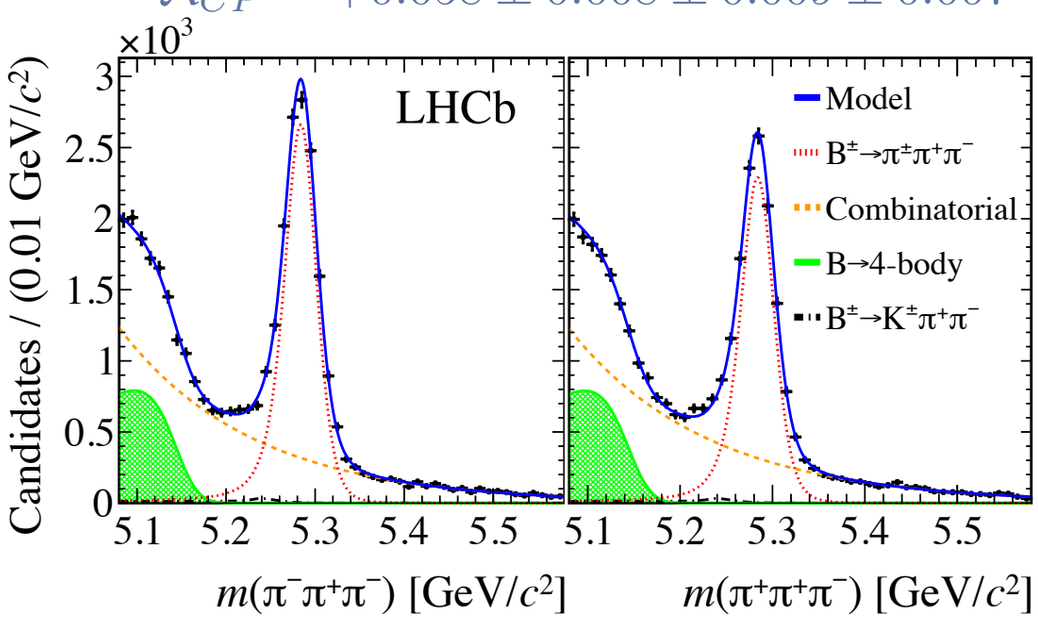
$\mathcal{A}_{CP} = +0.025 \pm 0.004 \pm 0.004 \pm 0.007$



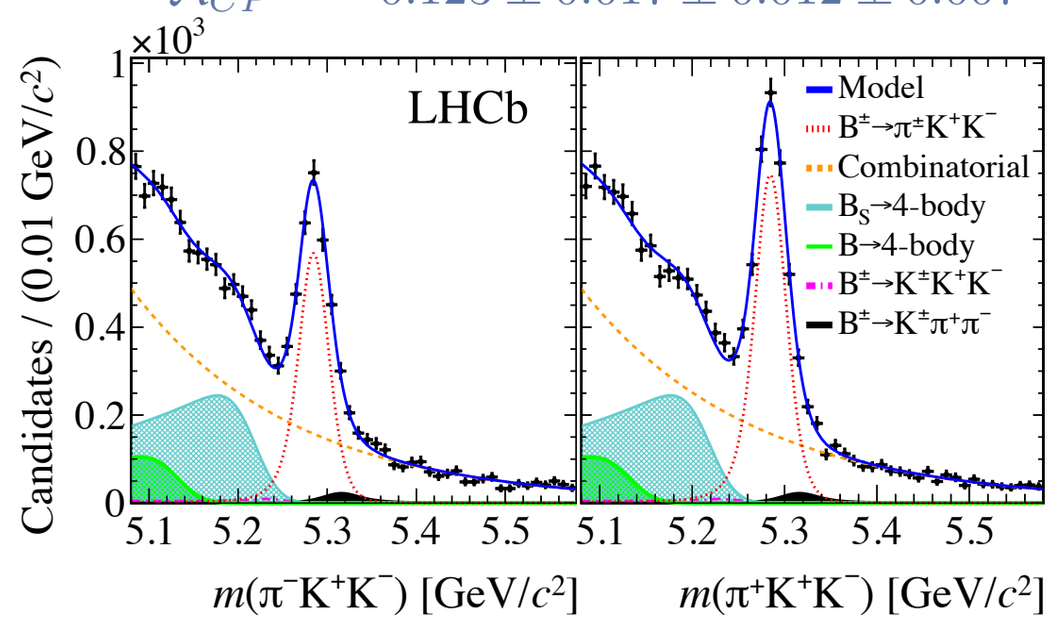
$\mathcal{A}_{CP} = -0.036 \pm 0.004 \pm 0.002 \pm 0.007$



$\mathcal{A}_{CP} = +0.058 \pm 0.008 \pm 0.009 \pm 0.007$

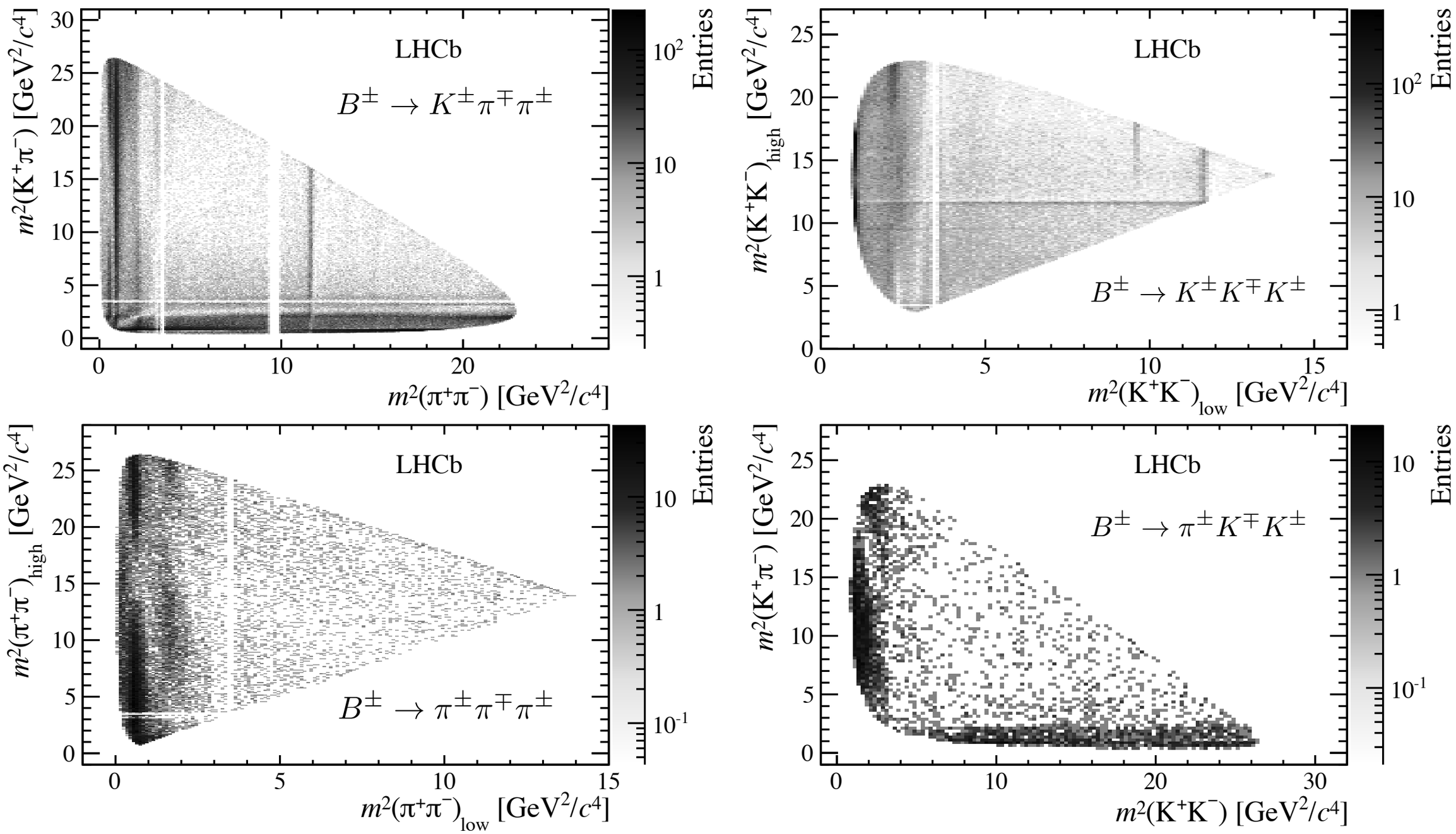


$\mathcal{A}_{CP} = -0.123 \pm 0.017 \pm 0.012 \pm 0.007$



Dalitz plot distributions - LHCb results

PRD 90, 112004 (2014)

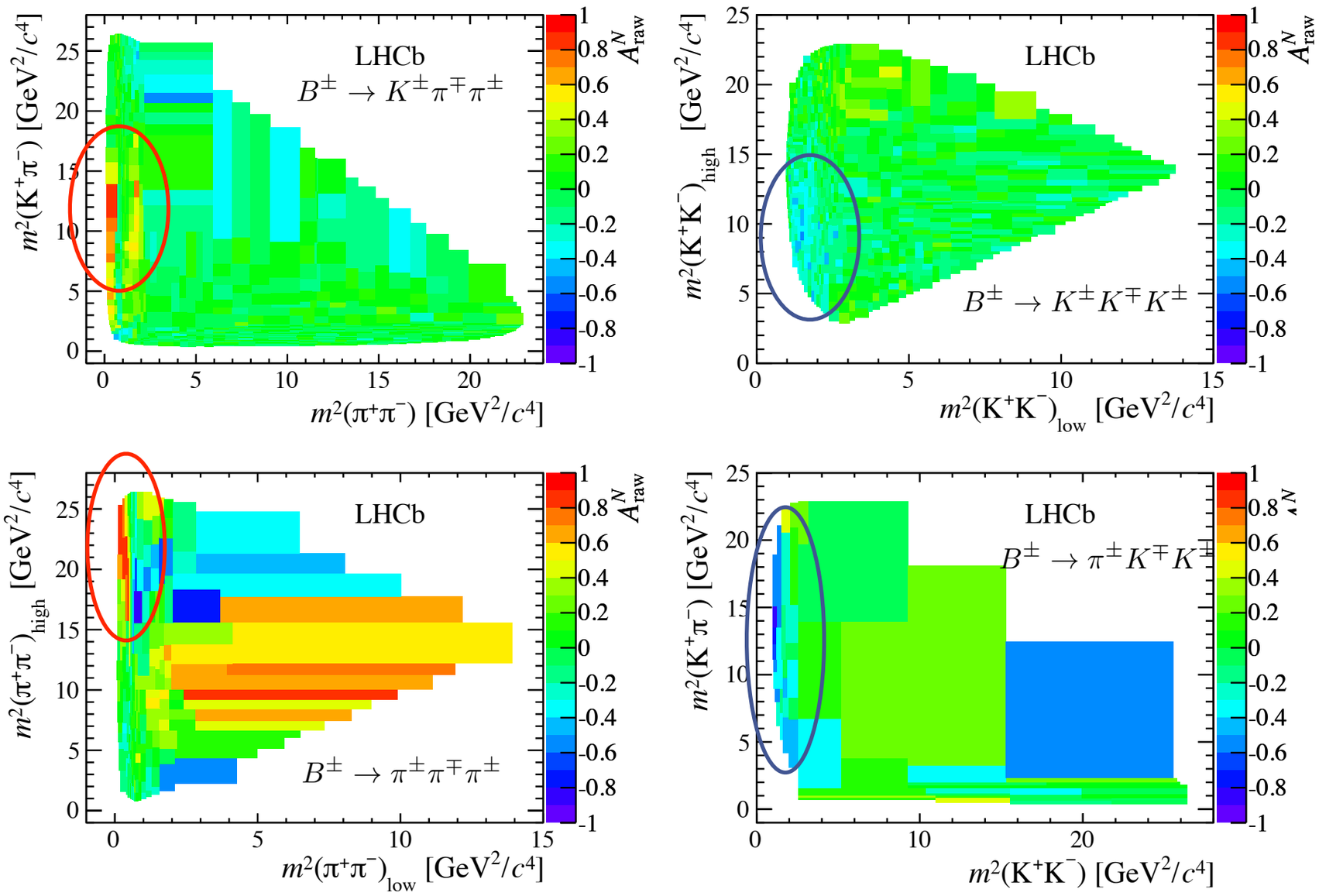


Local asymmetries - LHCb results

Universität Zürich[UZH]

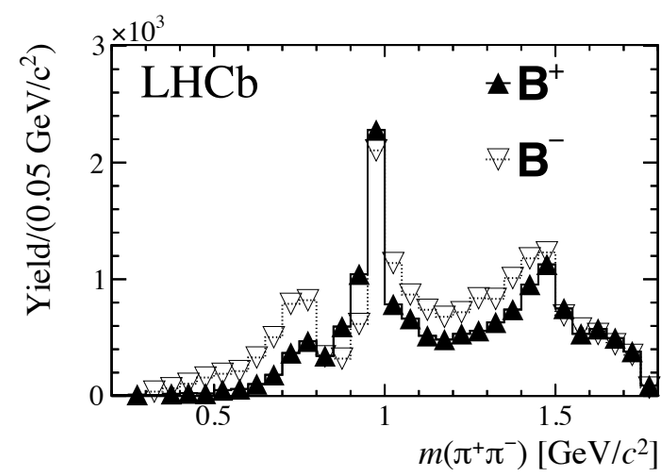
PRD 90, 112004 (2014)

Large local asymmetries observed in $B^{\pm} \to h^{\pm}h^{+}h^{-}$ with $h^{\pm} \in \{\pi^{\pm}, K^{\pm}\}$



Opposite sign asymmetry observed at low $m^2_{\pi\pi}$ and m^2_{KK}

Asymmetries as large as 60% in some regions!!

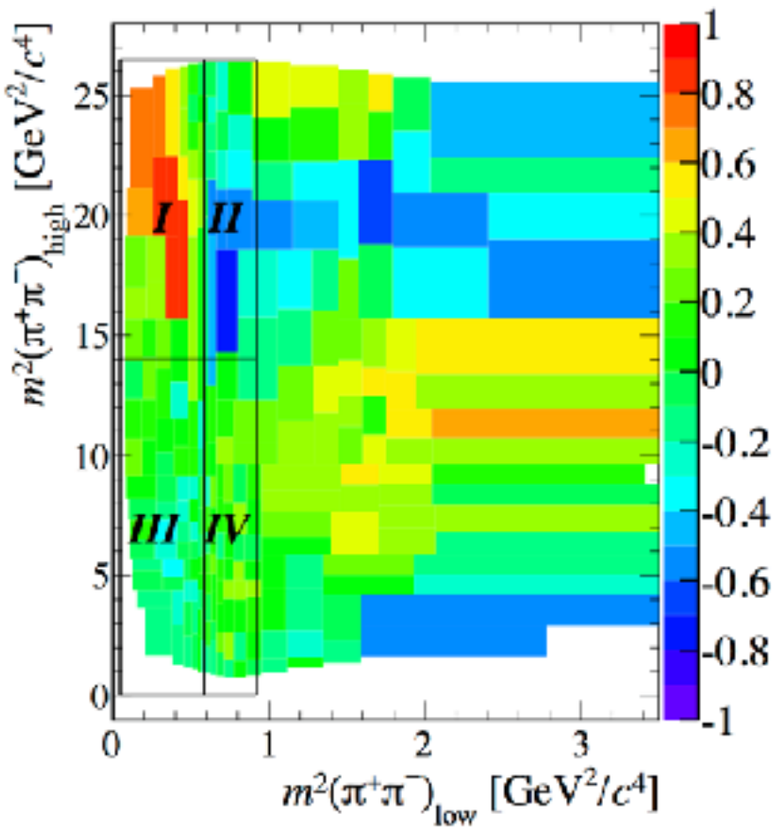


Confirmed CP violation around the rho(770)^{0}K$^+$ as seen by Babar and Belle

Local asymmetries - LHCb results

PRD 90, 112004 (2014)

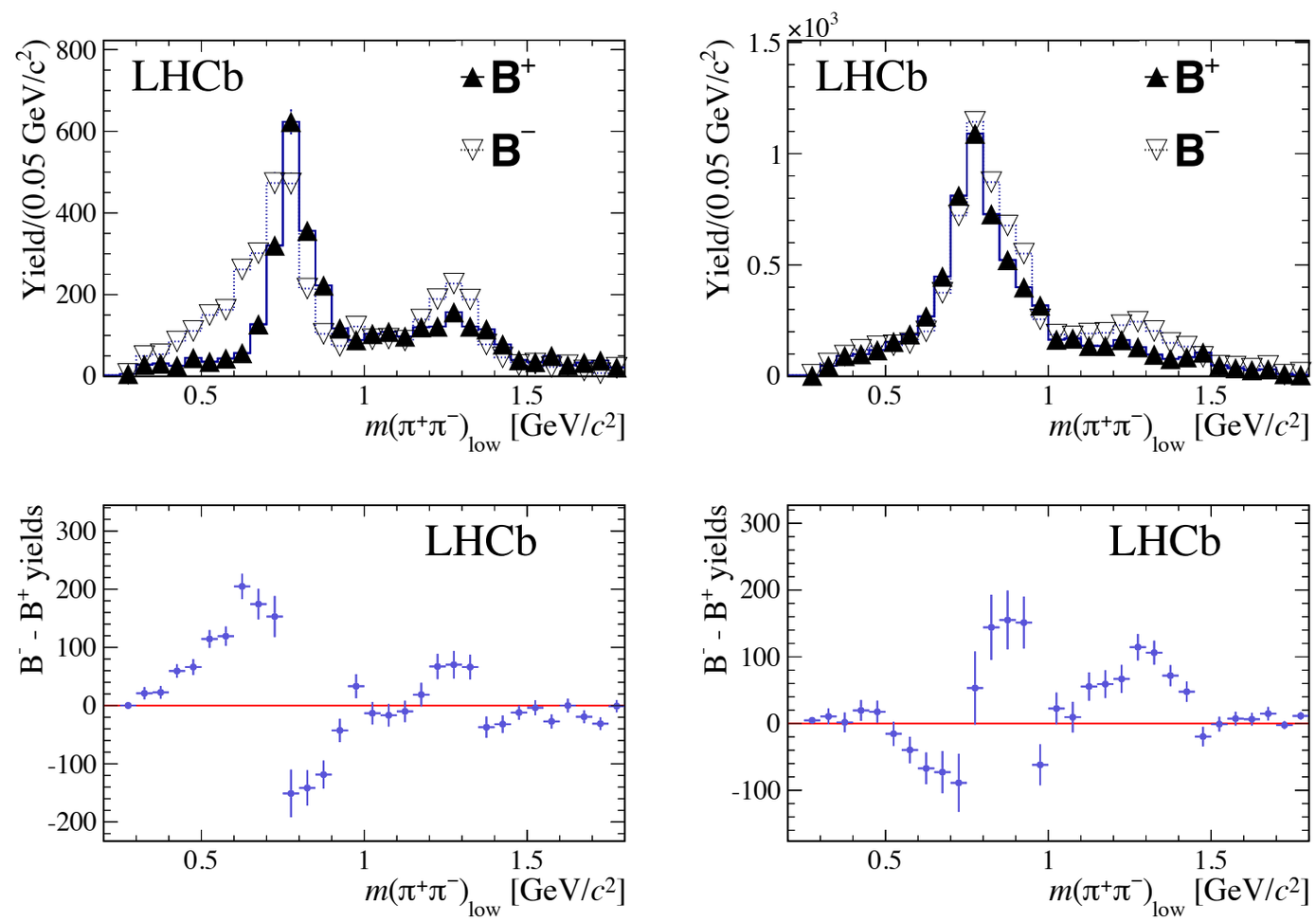
$B^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm}$



Sign-flip and zero around ρ^0 pole, *CP* asymmetry may be dominated by real part of Breit-Wigner

Dependence of asymmetry as function of invariant mass and helicity angle in regions around resonances

$\cos\theta < 0$ $\cos\theta > 0$



Large A_{CP} in charmless B^+ decays

Universität Zürich[UZH]

Full amplitude analysis is clearly the next step, in particular to understand the origin of the strong phase difference

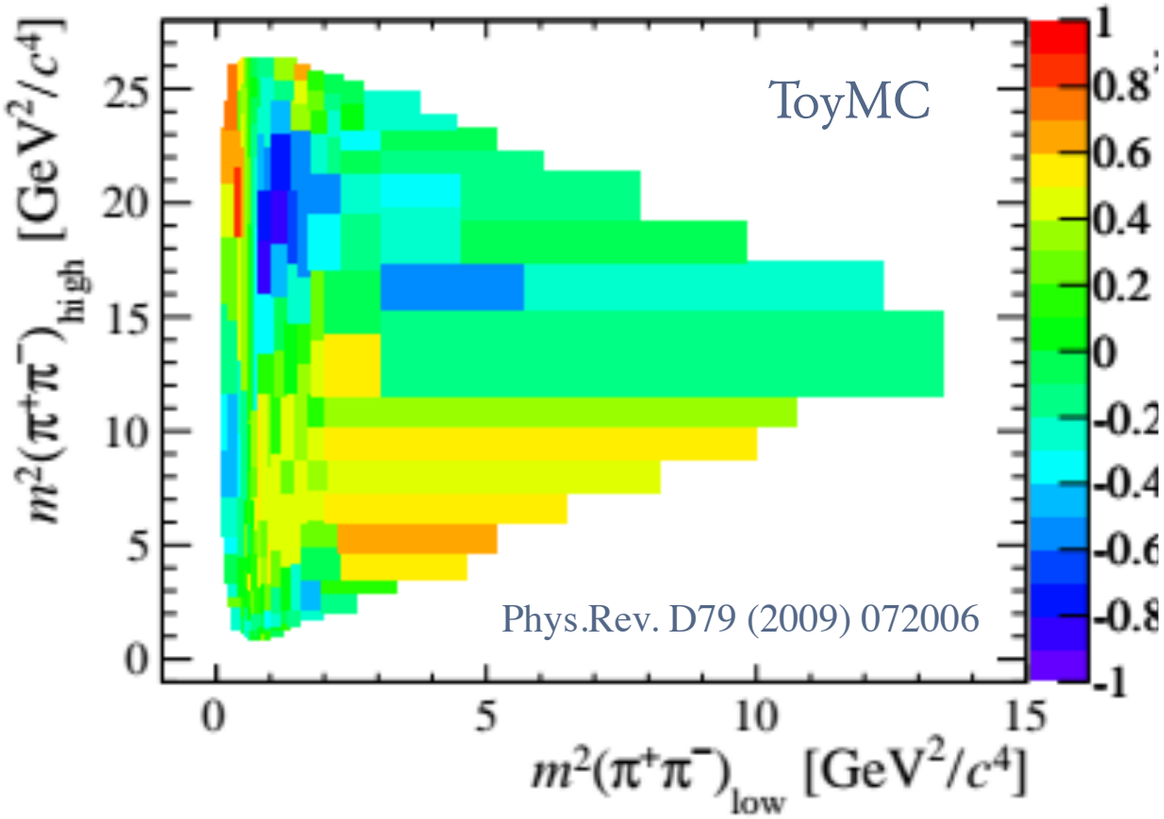
Such analyses are currently ongoing at LHCb!

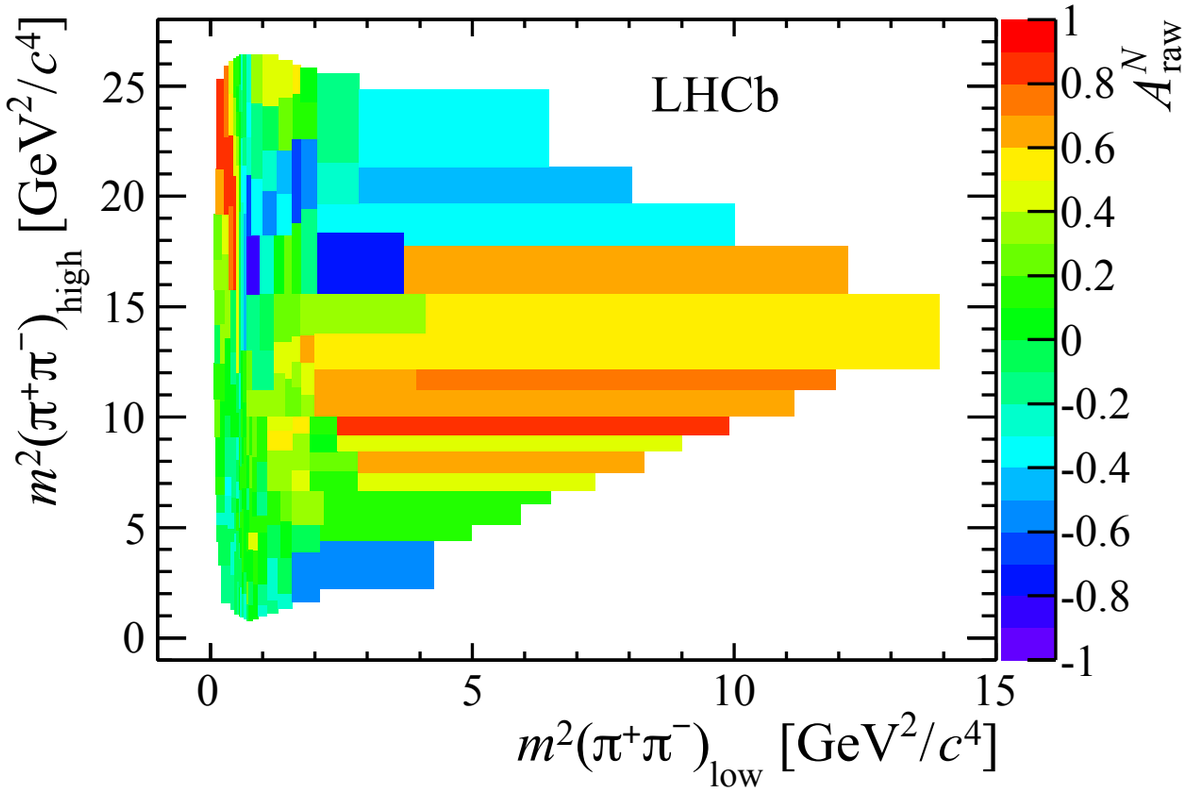
However, building models for these decays is challenging:

- Unprecedented statistics (e.g. 180K events for $B^\pm \to K^\pm\pi^\mp\pi^\pm$): simplified theoretical descriptions **are not sufficient** to accommodate the data
- How to model the large non-resonant components?
- How to describe re-scattering effects? Connect two (or all) different final states?
- How to include thee-body final state interaction (FSI)?

"Guinea pig": $B^\pm \to \pi^\pm\pi^+\pi^-$ decays with Run-I

Towards the $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ Dalitz plot fit





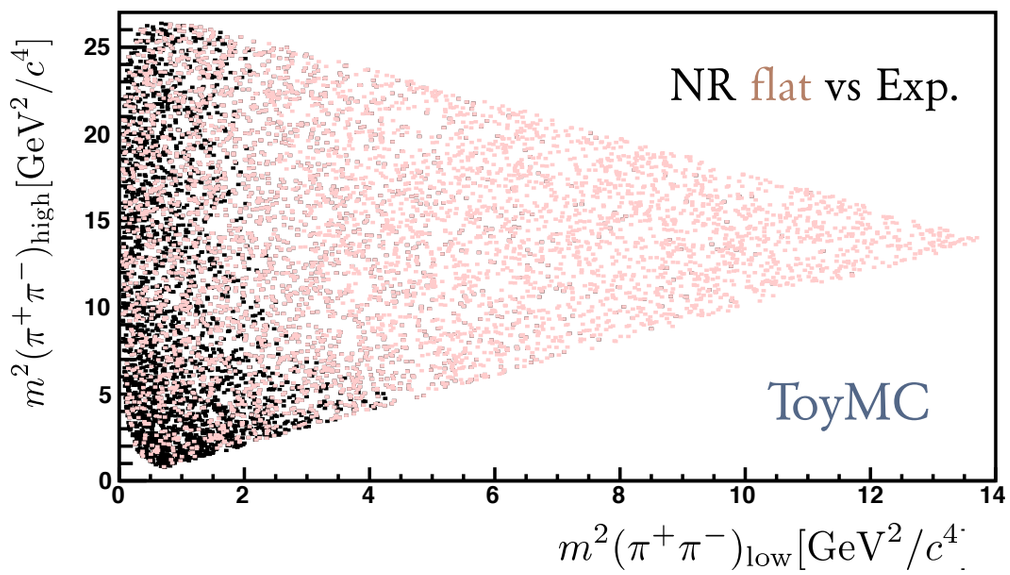
Main A_{CP} features of LHCb data Run-I are present in a simple simulation of the previous **BaBar** model

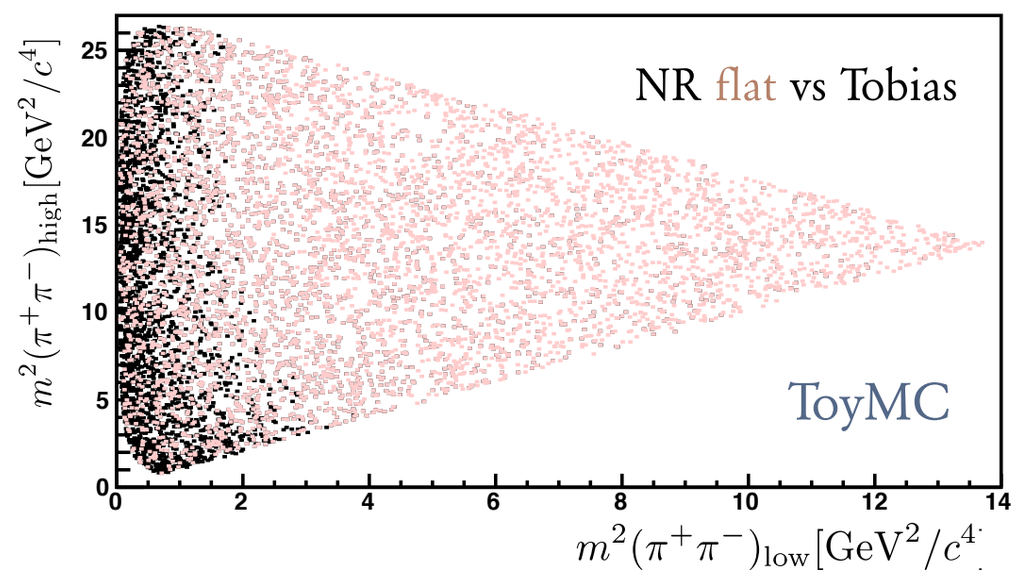
More work clearly required to fully reproduce all features seen in data

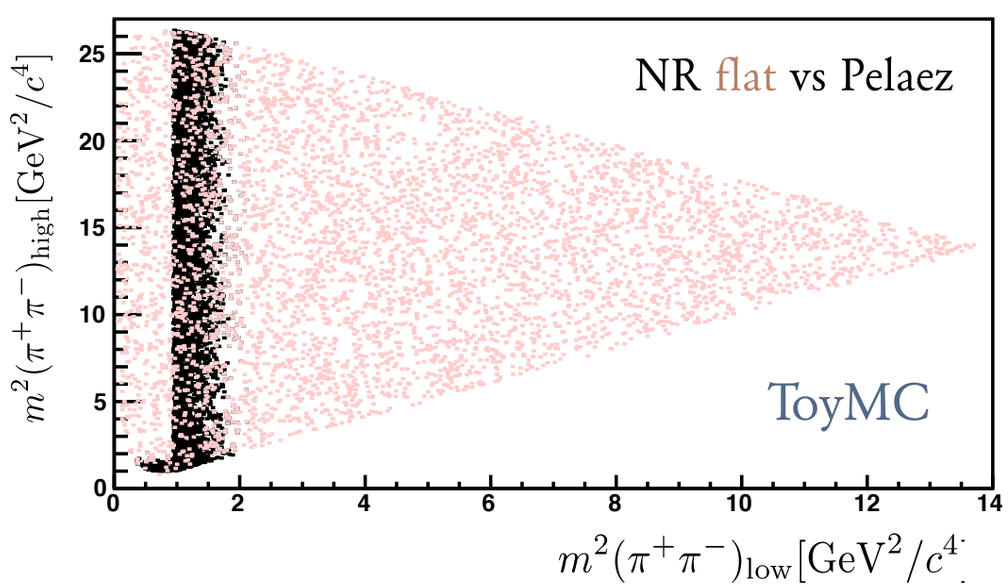
Towards the $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ Dalitz plot fit

Universität Zürich[UZH]

Several models are being investigated using the standard Isobar Model







[Tobias] Non-resonant parametrisation

[arXiv:hep-ph/1506.08332]

$$T_{nr}(m_{13}) = \frac{a^{nr}}{1 + \frac{m_{13}^2}{\Lambda^2}} e^{i\delta^{nr}}$$

[Pelaez] KK ↔ ππ re-scattering

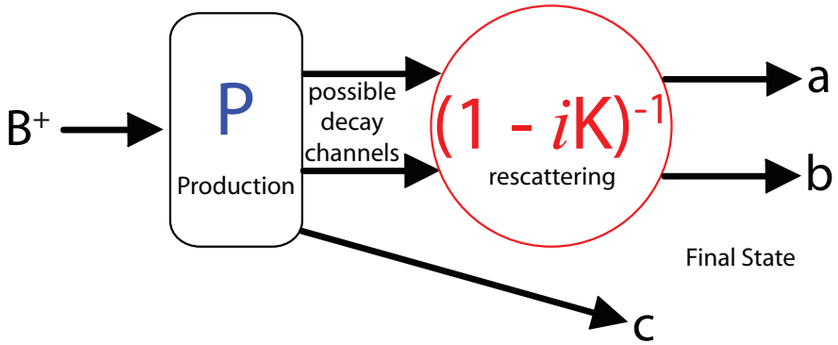
[Phys. Rev. D **71**, 074016 (2005)]

Towards the $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ Dalitz plot fit

Two alternative fits are also investigated

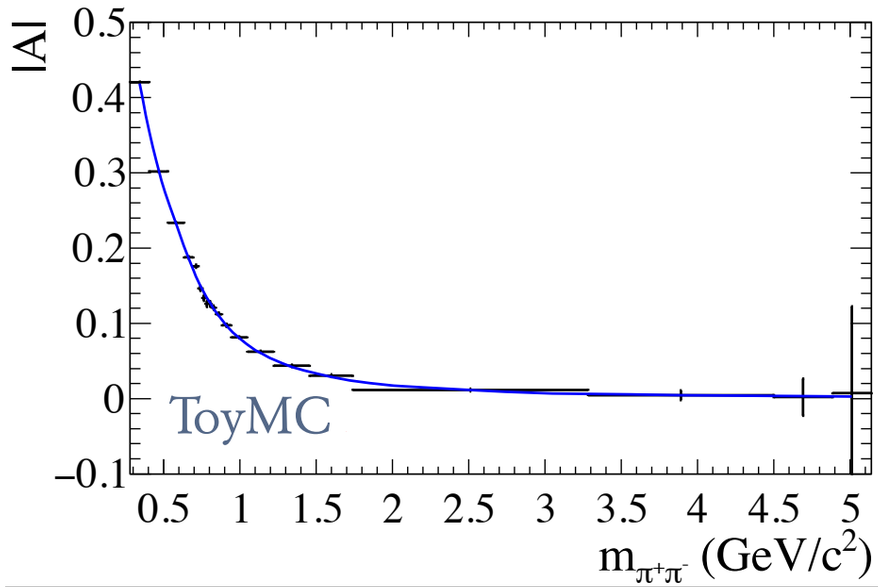
- K-matrix approach

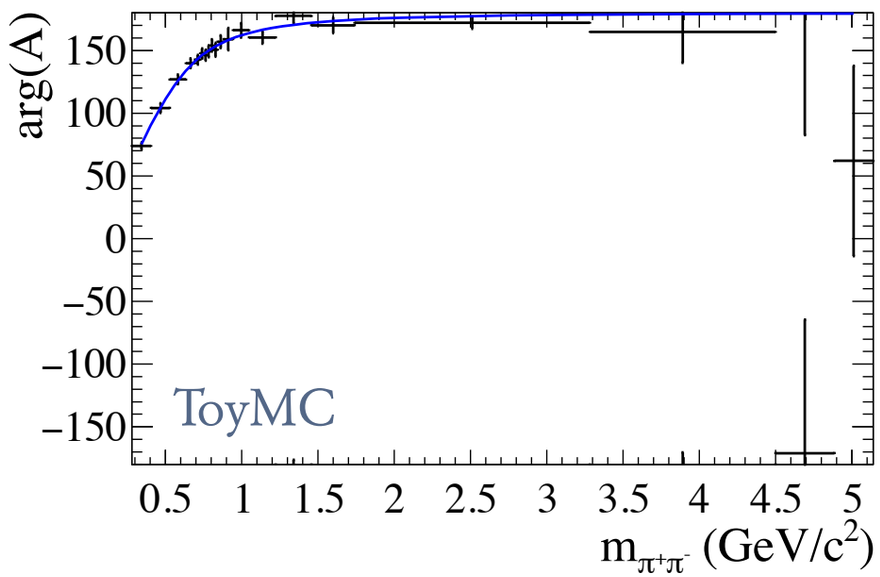
Resonances don't necessarily manifest as Breit-Wigner structures



- Quasi-model independent method (data driven)

Bin the phase space and determine the magnitude and phase in each bin





General conclusions

- Enormous wealth of physics to be found in three-body hadronic decays of b-hadrons (*e.g.* CKM phase measurements, CP violation)
- Some very interesting and intriguing results obtained recently
  - Latest results in multi-body charmless hadronic decays are using increasingly sophisticated amplitude analysis techniques
- Still many interesting results are foreseen with LHCb Run-I dataset (*e.g.* charmless DP analyses, *b*-baryon and B^+_c decays)
  - Potential for improving the spectroscopy and CKM measurements from $B \to Dhh$ using Run 1 + Run 2.
  - Larger datasets from the LHCb upgrade and Belle II will provide in the future the possibility to fully explore the potential of the field

Dalitz plot fit results

PRL 113, 162001 (2014) PRD 90, 072003 (2014)

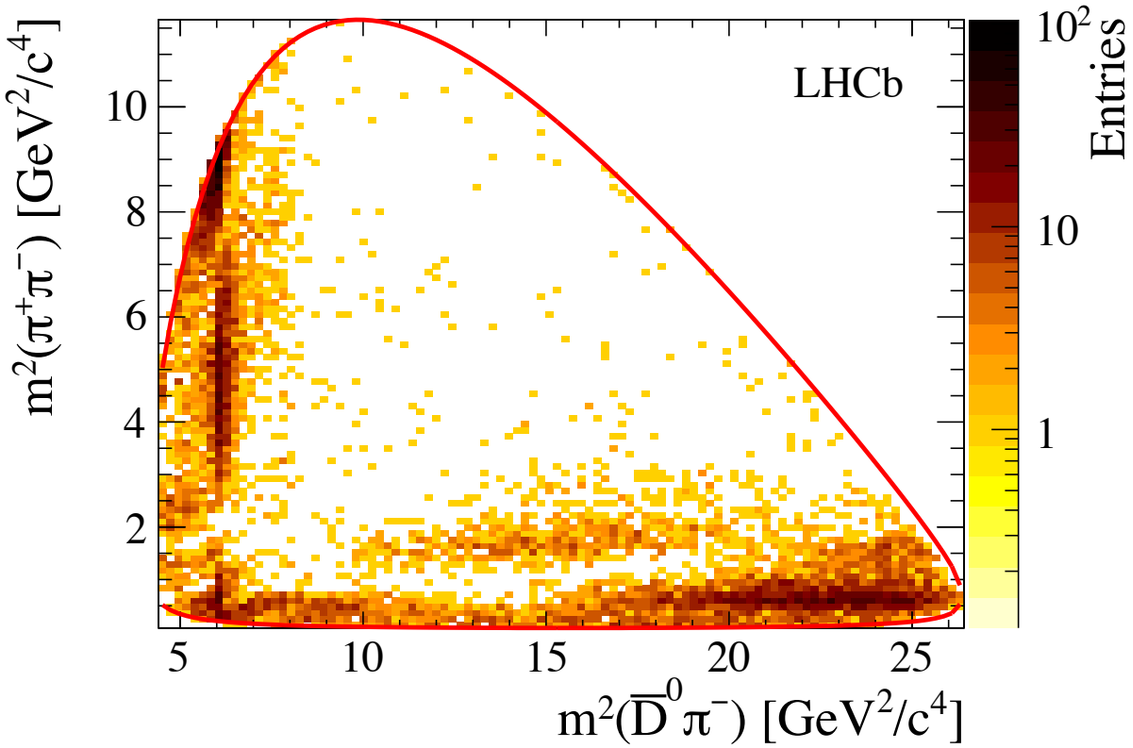
Contributions to the amplitude fit model (resonances labelled with subscript v are virtual)

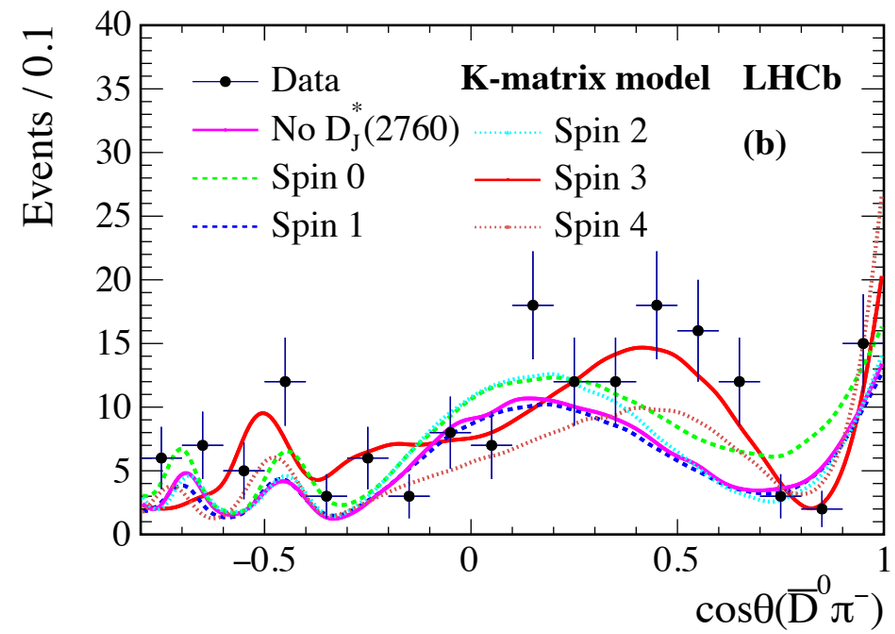
Resonance	Spin	Dalitz plot axis	Model	Parameters (MeV/c^2)
$\overline{K}^*(892)^0$	1	$m^2(K^-\pi^+)$	RBW	$m_0 = 895.81 \pm 0.19$, $\Gamma_0 = 47.4 \pm 0.6$
$\overline{K}^*(1410)^0$	1	$m^2(K^-\pi^+)$	RBW	$m_0 = 1414 \pm 15$, $\Gamma_0 = 232 \pm 21$
$\overline{K}_0^*(1430)^0$	0	$m^2(K^-\pi^+)$	LASS	Floating parameters
$\overline{K}_2^*(1430)^0$	2	$m^2(K^-\pi^+)$	RBW	$m_0 = 1432.4 \pm 1.3$, $\Gamma_0 = 109 \pm 5$
$\overline{K}^*(1680)^0$	1	$m^2(K^-\pi^+)$	RBW	$m_0 = 1717 \pm 27$, $\Gamma_0 = 322 \pm 110$
$\overline{K}_0^*(1950)^0$	0	$m^2(K^-\pi^+)$	RBW	$m_0 = 1945 \pm 22$, $\Gamma_0 = 201 \pm 90$
$D_{s2}^*(2573)^-$	2	$m^2(\overline{D}^0K^-)$	RBW	Floating parameters
$D_{s1}^*(2700)^-$	1	$m^2(\overline{D}^0K^-)$	RBW	$m_0 = 2709 \pm 4$, $\Gamma_0 = 117 \pm 13$
$D_{sJ}^*(2860)^-$	1	$m^2(\overline{D}^0K^-)$	RBW	Floating parameters + Multiple spin hypotheses
$D_{sJ}^*(2860)^-$	3	$m^2(\overline{D}^0K^-)$	RBW	
Nonresonant		$m^2(\overline{D}^0K^-)$	EFF	Floating parameters
D_{sv}^{*-}	1	$m^2(\overline{D}^0K^-)$	RBW	$m_0 = 2112.3 \pm 0.5$, $\Gamma_0 = 1.9$
$D_{s0v}^*(2317)^-$	0	$m^2(\overline{D}^0K^-)$	RBW	$m_0 = 2317.8 \pm 0.6$, $\Gamma_0 = 3.8$
B_v^{*+}	1	$m^2(\overline{D}^0\pi^+)$	RBW	$m_0 = 5325.2 \pm 0.4$, $\Gamma_0 = 0$

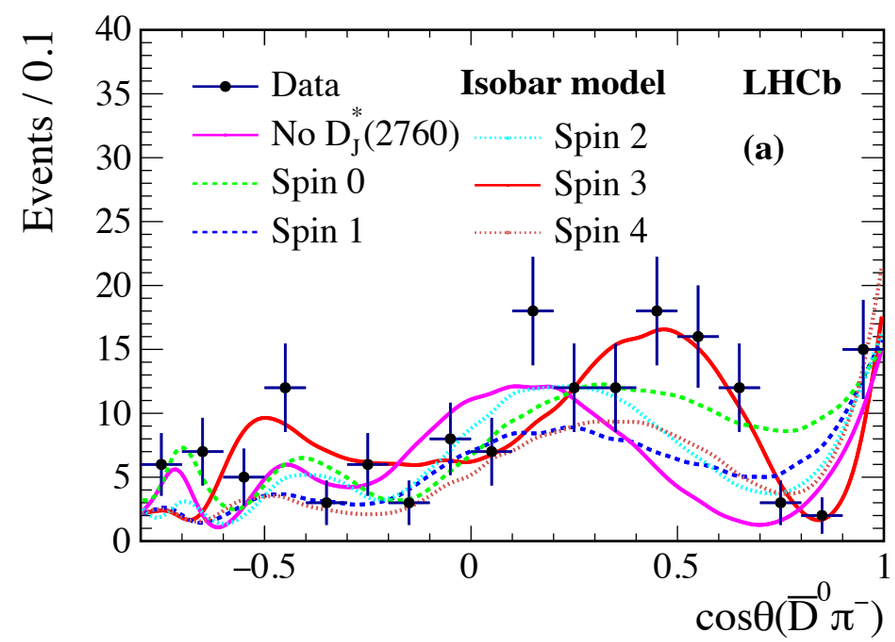
RBW = Relativistic Breit-Wigner, LASS = K S-wave parameter from LASS experiment and EFF = exponential form factor

DP analysis of $B^0 \to \overline{D}^0\pi^+\pi^-$

PRD 92, 032002 (2015)



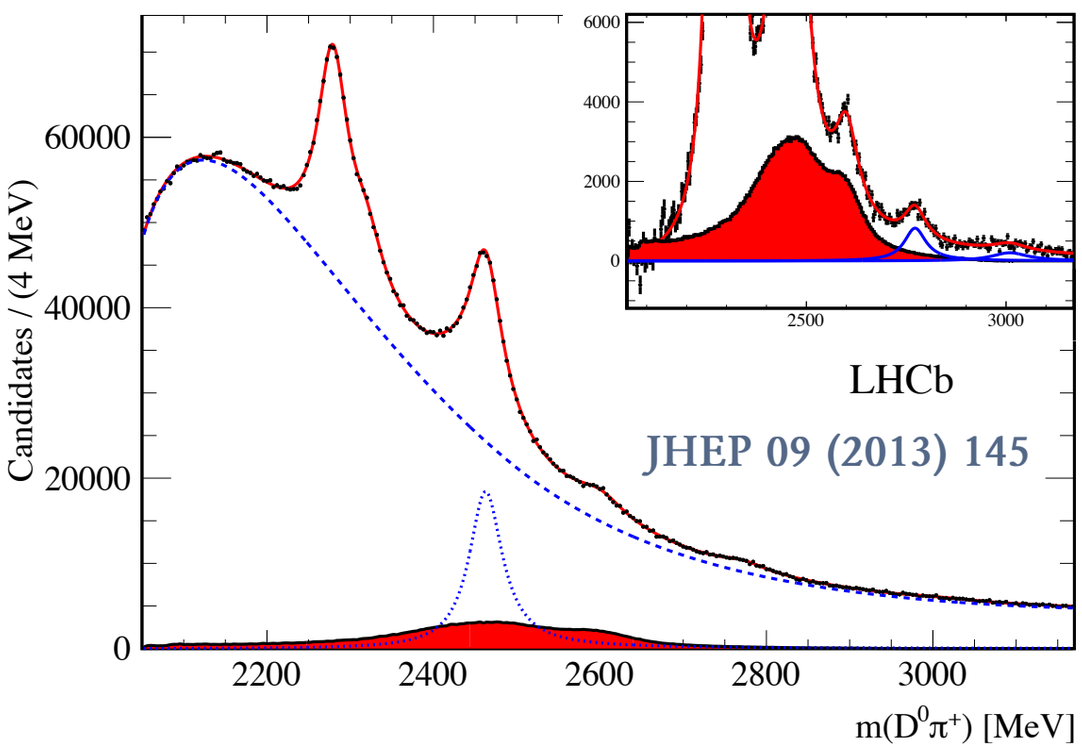




		Isobar	K-matrix
$D_0^*(2400)$	m	$2349 \pm 6 \pm 1 \pm 4$	$2354 \pm 7 \pm 11 \pm 2$
	Γ	$217 \pm 13 \pm 5 \pm 12$	$230 \pm 15 \pm 18 \pm 11$
$D_2^*(2460)$	m	$2468.6 \pm 0.6 \pm 0.0 \pm 0.3$	$2468.1 \pm 0.6 \pm 0.4 \pm 0.3$
	Γ	$47.3 \pm 1.5 \pm 0.3 \pm 0.6$	$46.0 \pm 1.4 \pm 1.7 \pm 0.4$
$D_3^*(2760)$	m	$2798 \pm 7 \pm 1 \pm 7$	$2802 \pm 11 \pm 10 \pm 3$
	Γ	$105 \pm 18 \pm 6 \pm 23$	$154 \pm 27 \pm 13 \pm 9$

Charm spectroscopy at LHCb

Recent measurements of e^+e^-/pp indicated the presence of higher excited states (both BaBar and LHCb)



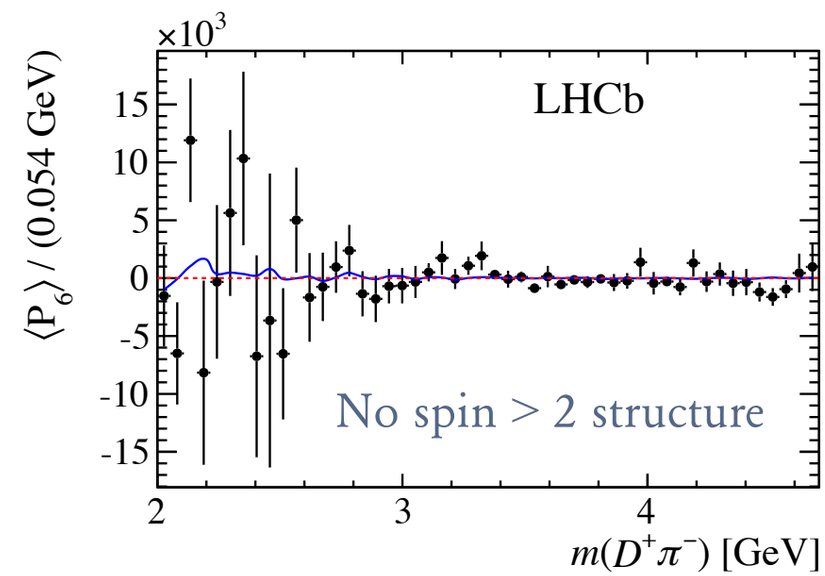
States $D^*_J(2650)$ and $D^*_J(2760)$ seen to decay to $D\pi$

PRD 92, 032002 (2015)

PRD 91, 092002 (2015)

$B^- \to D^+ K^- \pi^-$

Initial investigation of angular moments to guide the modelling



$B^0 \to \bar{D}^0 \pi^+ \pi^-$

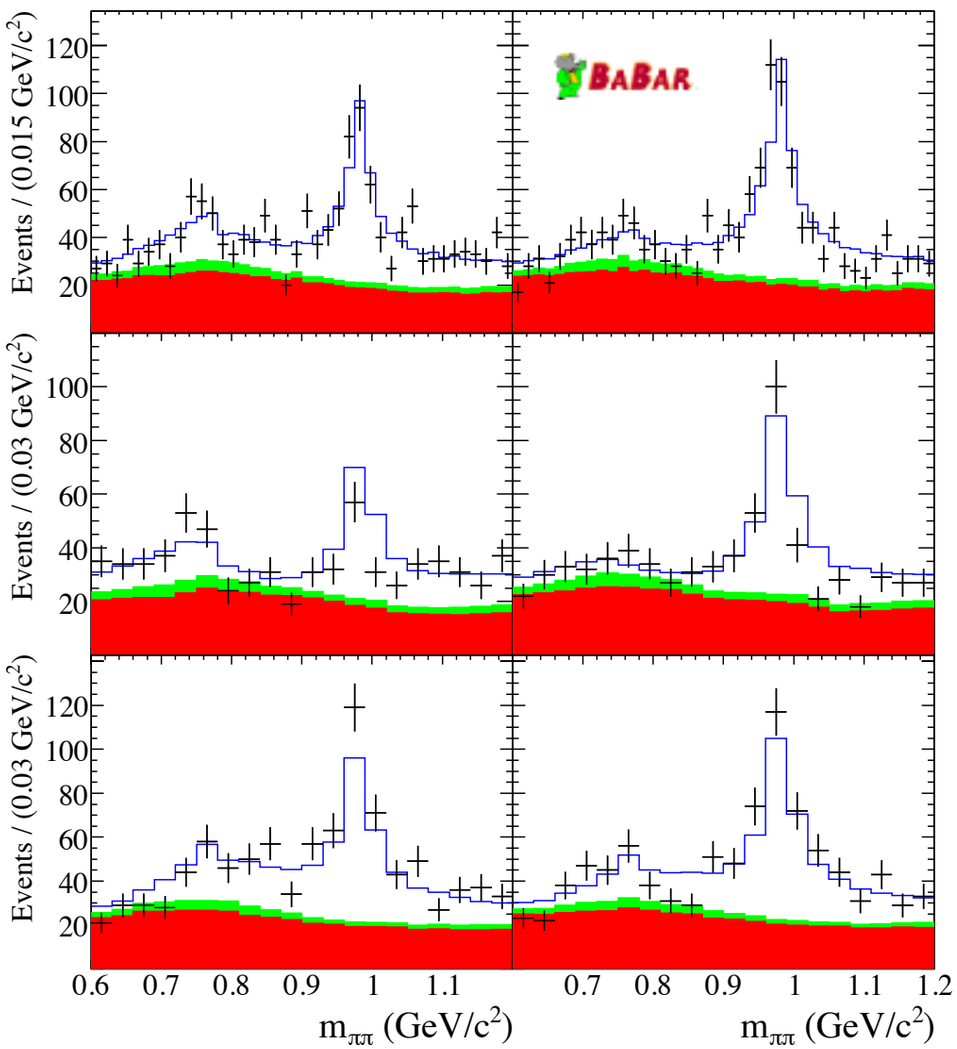
Two different DP fit framework: Isobar model and K-matrix parametrisation of the S-wave

Large A_{CP} in charmless B^+ decays

Many DP analyses of these modes have been performed by both Belle and Babar, *e.g.*

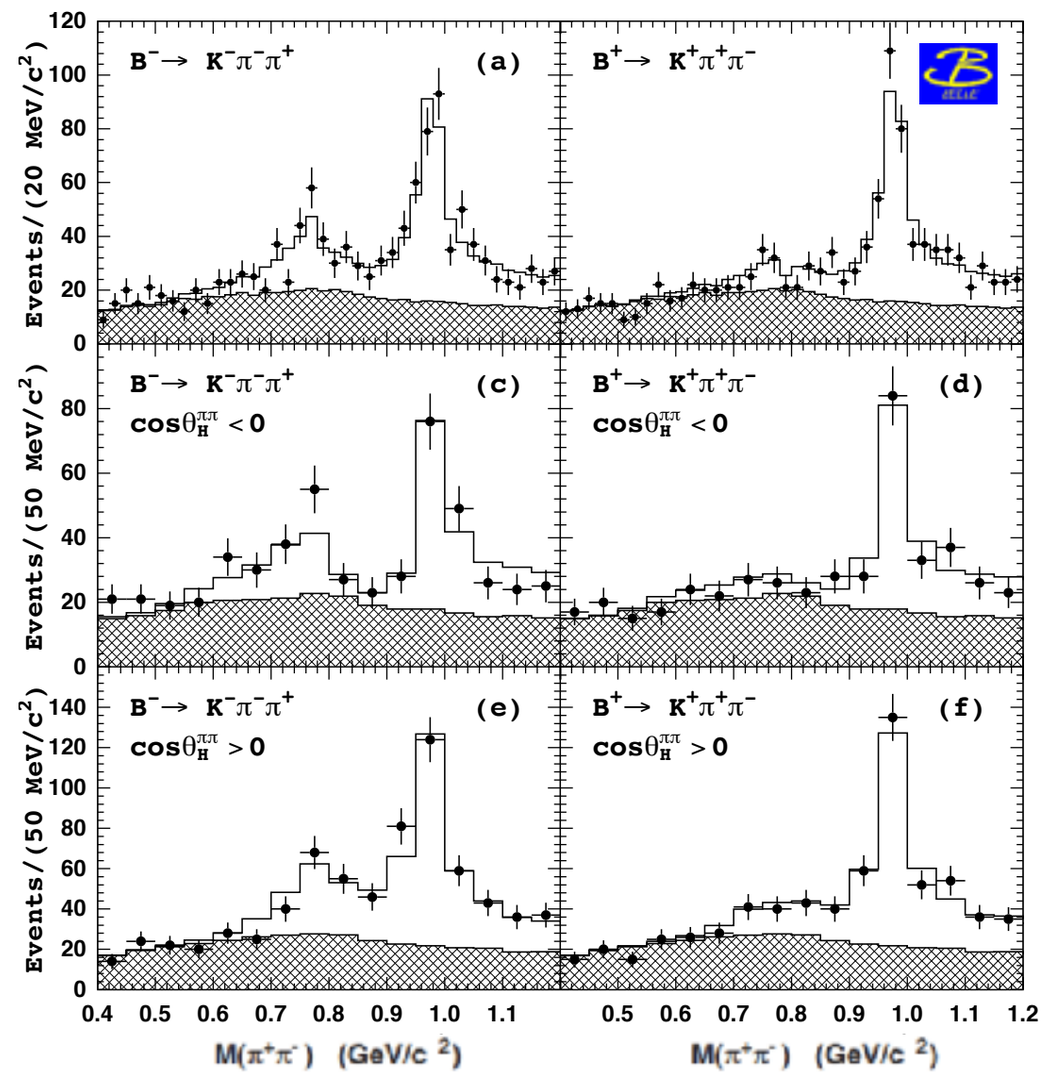
$$\mathcal{A}_{CP}(B^+ \to \rho(770)^0 K^+) = (44 \pm 10 \pm 4\,^{+5}_{-13})\%$$

[Phys. Rev. D 78, 012004 (2008)]



$$\mathcal{A}_{CP}(B^+ \to \rho(770)^0 K^+) = (30 \pm 11 \pm 2\,^{+11}_{-4})\%$$

[Phys. Rev. Lett. 96, 251803 (2006)]

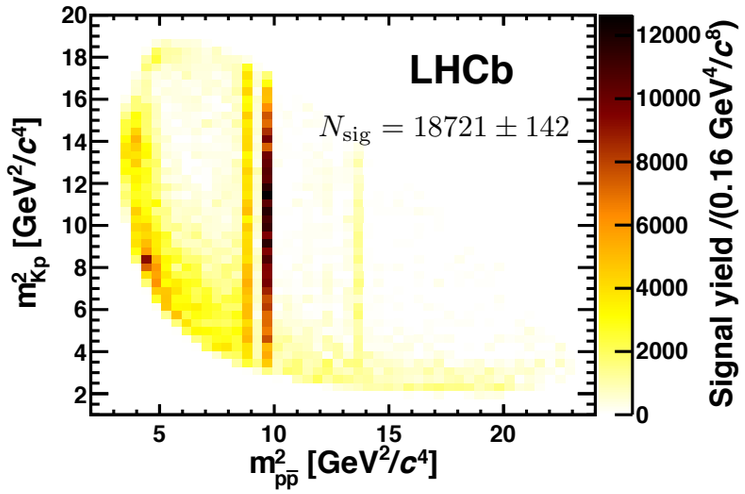


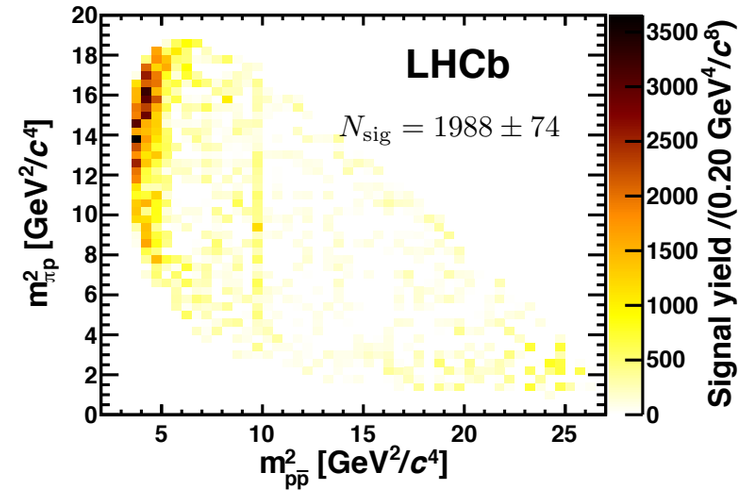
Baryonic final states

Channels with baryons in the final state are also of interest

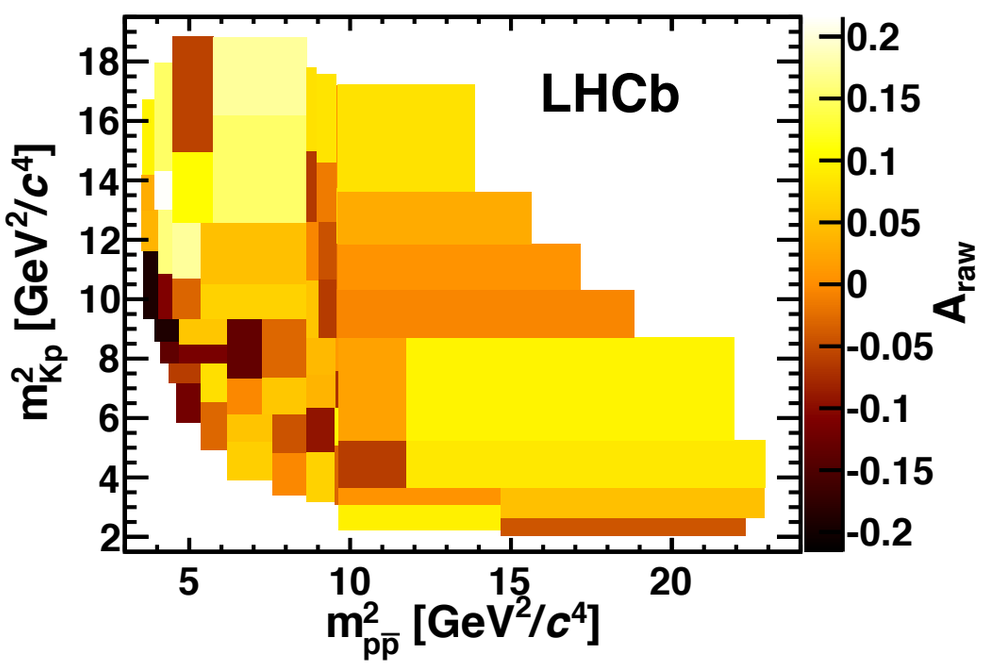
- Pronounced enhancement in the near-threshold region
- Inclusive global A^{CP} consistent with zero

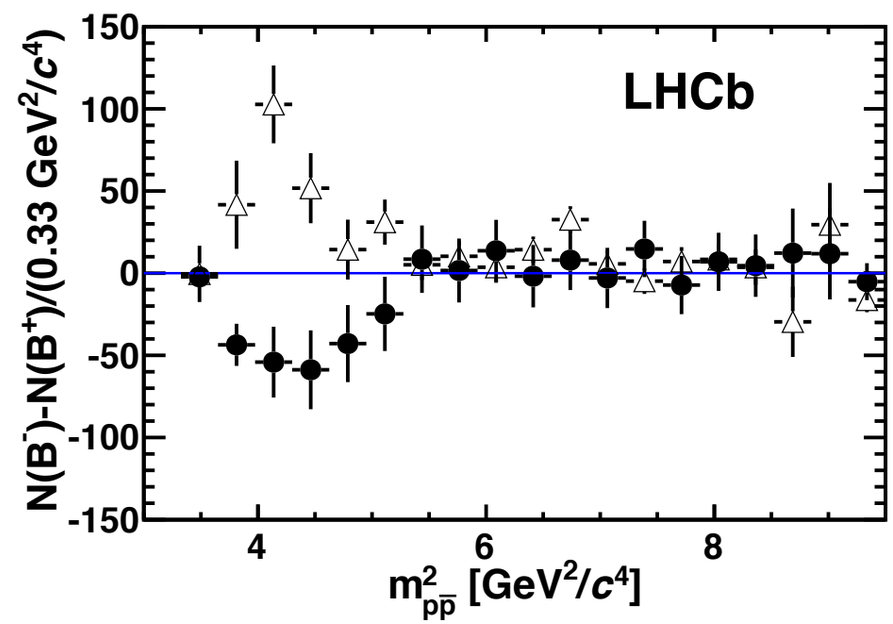
PRL 113 141801 (2014)
LHCb Collaboration





Local A^{CP} observed

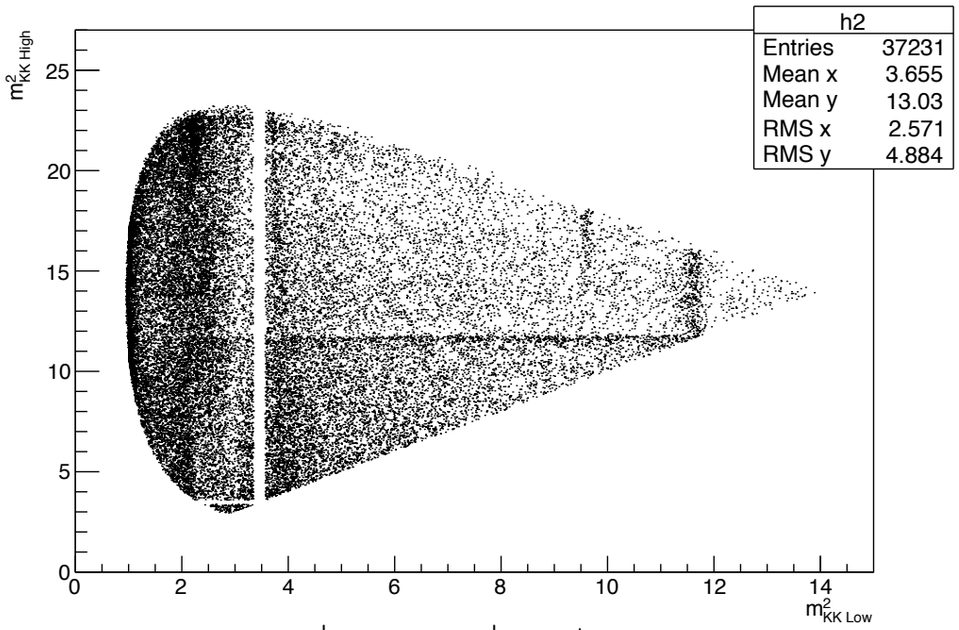




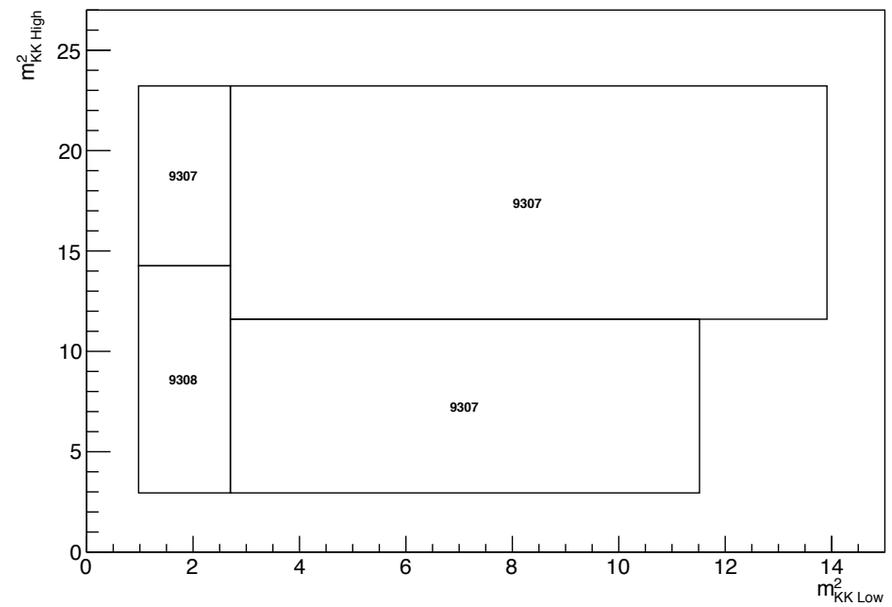
$$\mathcal{A}^{CP}(m_{p\bar{p}} < 2.85\,\mathrm{GeV}^2/c^4) = -0.036 \pm 0.023 \pm 0.004 \qquad m^2_{Kp} < 10\,\mathrm{GeV}^2/c^4$$

$$\mathcal{A}^{CP}(m_{p\bar{p}} < 2.85\,\mathrm{GeV}^2/c^4) = 0.096 \pm 0.024 \pm 0.004 \qquad m^2_{Kp} > 10\,\mathrm{GeV}^2/c^4$$

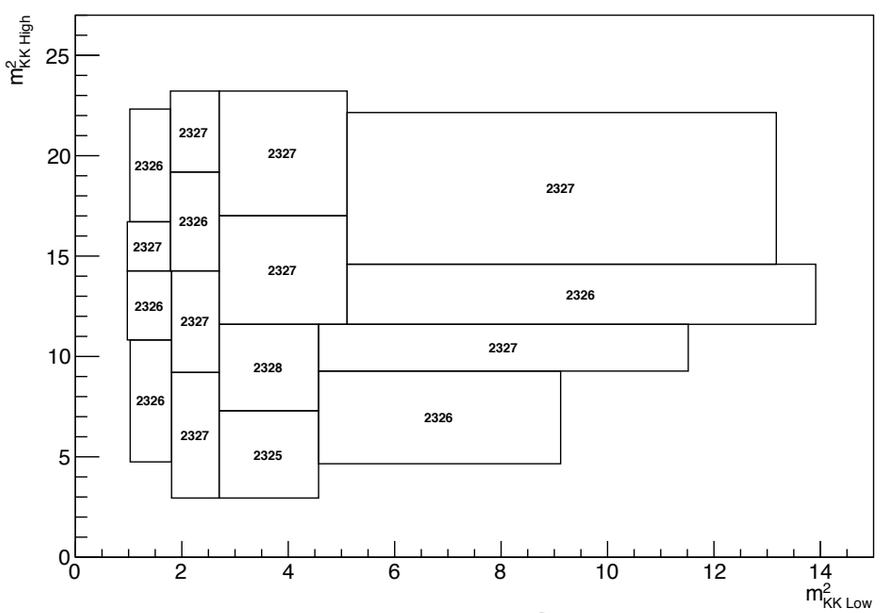
Adaptive binning algorithm



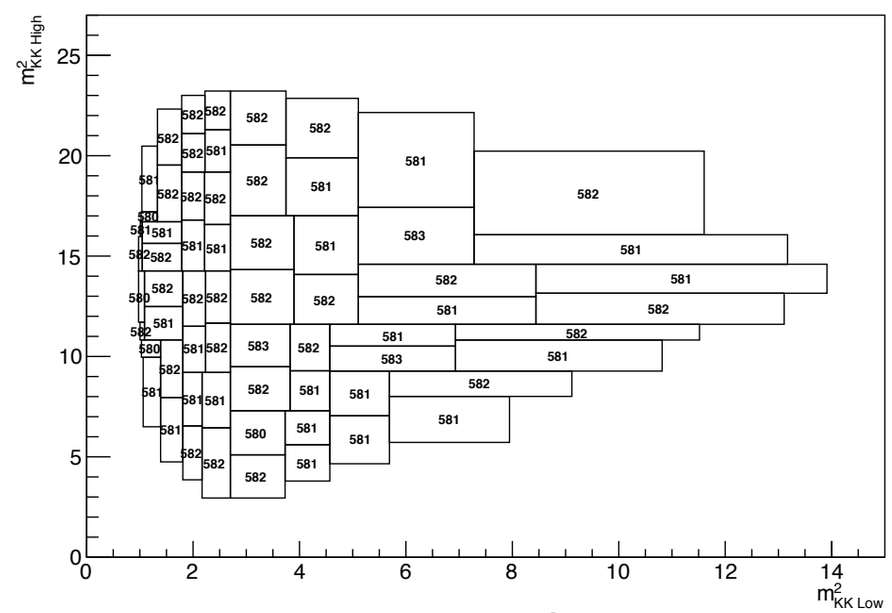
$B^{\pm} \to K^{\pm}K^{+}K^{-}$



1 iteration $\to 4^1 = 4$ bins

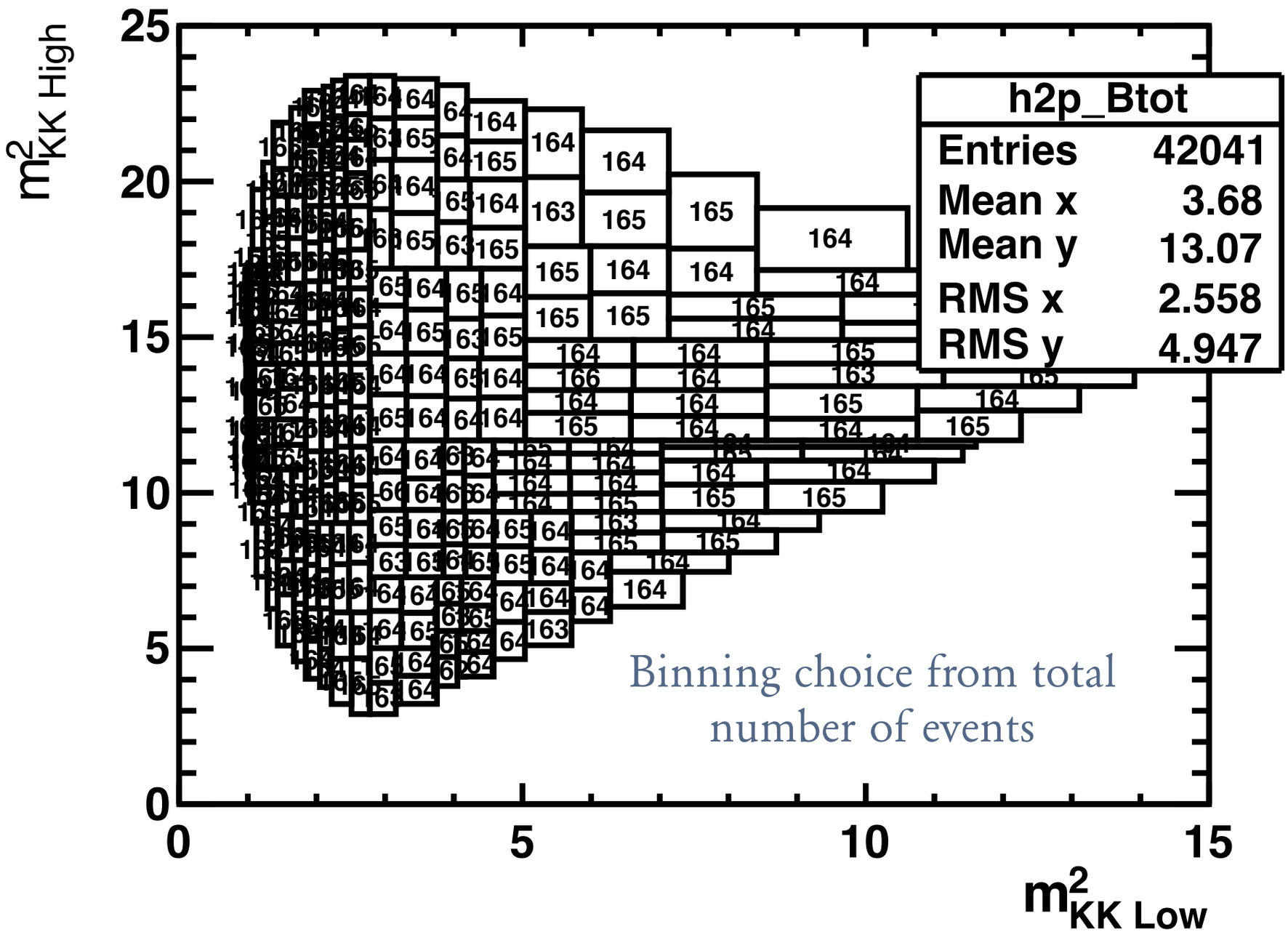


2 iterations $\to 4^2 = 16$ bins

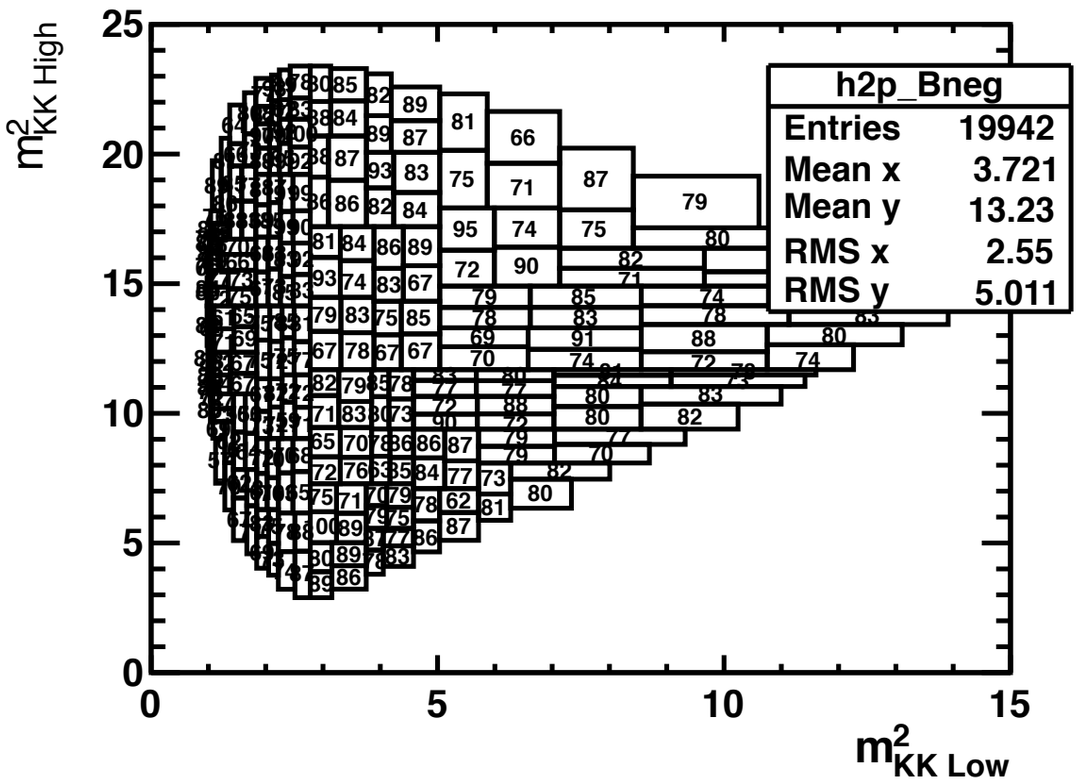


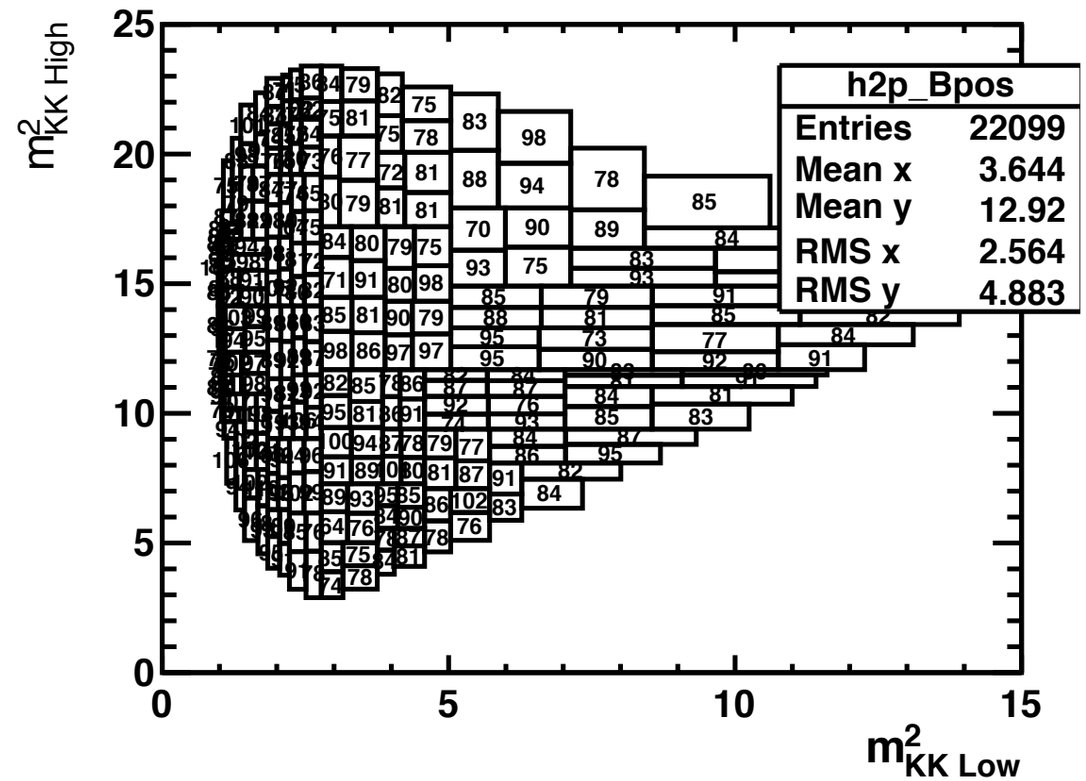
3 iterations $\to 4^3 = 64$ bins

Adaptive binning algorithm



Adaptive binning algorithm





$$acp_i = \frac{N_i^- - N_i^+}{N}$$

Example: for the biggest bin in figure we calculate the acp_i :

$$acp_i = \frac{79 - 85}{164} = -0.037$$

Further details on the re-scattering approach

Universität Zürich[UZH]

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$$S = \begin{bmatrix} \eta e^{2i\delta_{\pi\pi}} & i\sqrt{1-\eta^2}e^{i(\delta_{\pi\pi}+\delta_{KK})} \\ i\sqrt{1-\eta^2}e^{i(\delta_{\pi\pi}+\delta_{KK})} & \eta e^{2i\delta_{KK}} \end{bmatrix}$$

Only off-diagonal elements are relevant for amplitude analysis

Use models for the phase shifts $\delta_{\pi\pi}(s)$, $\delta_{KK}(s)$ and inelasticity $\eta(s)$

Phys. Rev. D **71**, 074016 (2005);

Phys. Rev. D **83**, 094011 (2011)