Recent results on Dalitz-plot analyses of D mesons decays at LHCb

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On behalf of the LHCb collaboration

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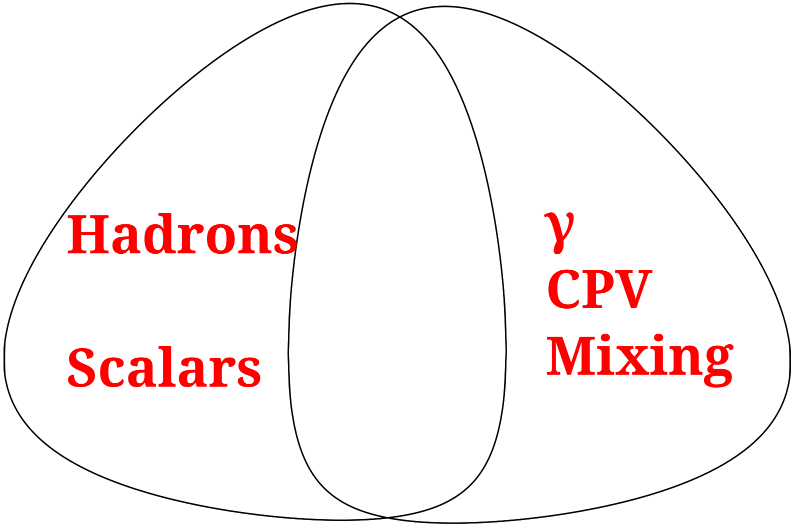
Why do we do amplitude analysis ?



Amplitude analysis at LHCb.

- Very large datasets $> 100,000$ events at $> 95\%$ purity in many channels.
- Introduces several technical and physics challenges.
- Analyses to be discussed :
  - $D^0 \to K_S^0 K^\mp \pi^\pm$ [1]
  - $D^+ \to K^- K^+ K^-$ LHCb-CONF-2016-008.

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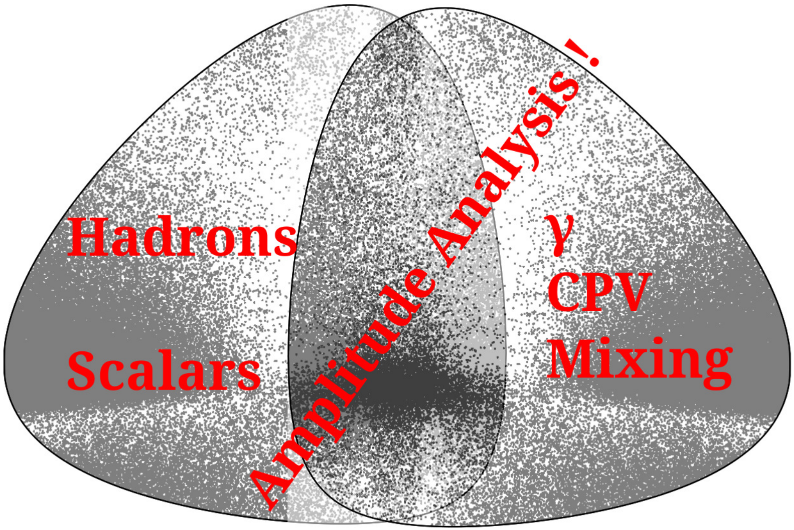

Amplitude analysis at LHCb.

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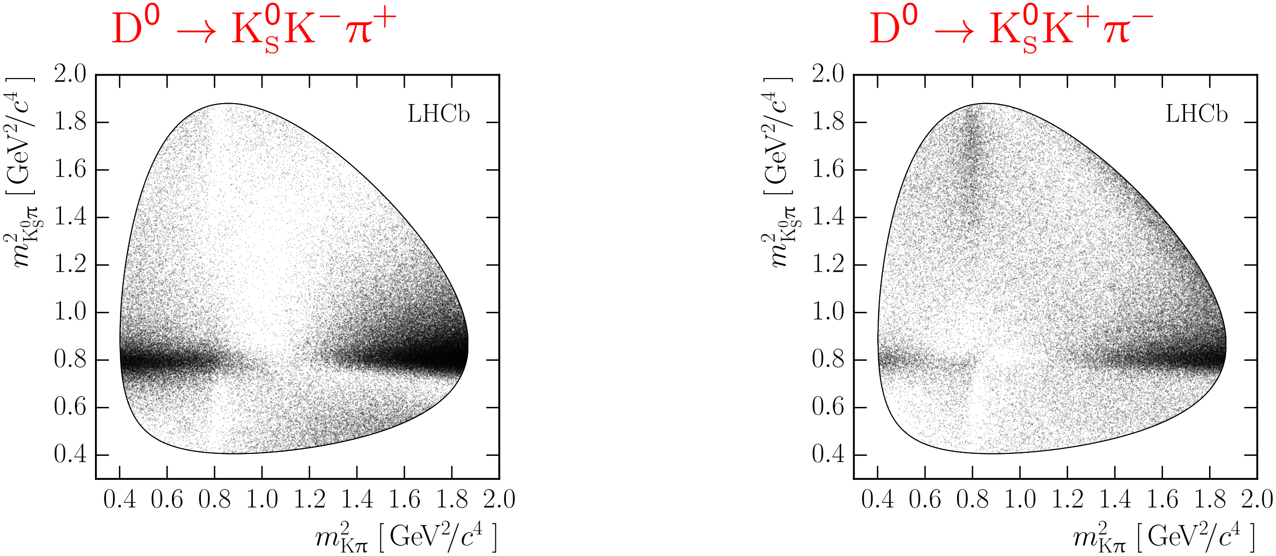
  - $\mathrm{D}^+ \to \mathrm{K}^-\mathrm{K}^+\mathrm{K}^-$ LHCb-CONF-2016-008.

$D^0 \to K^0_S K^\mp \pi^\pm$

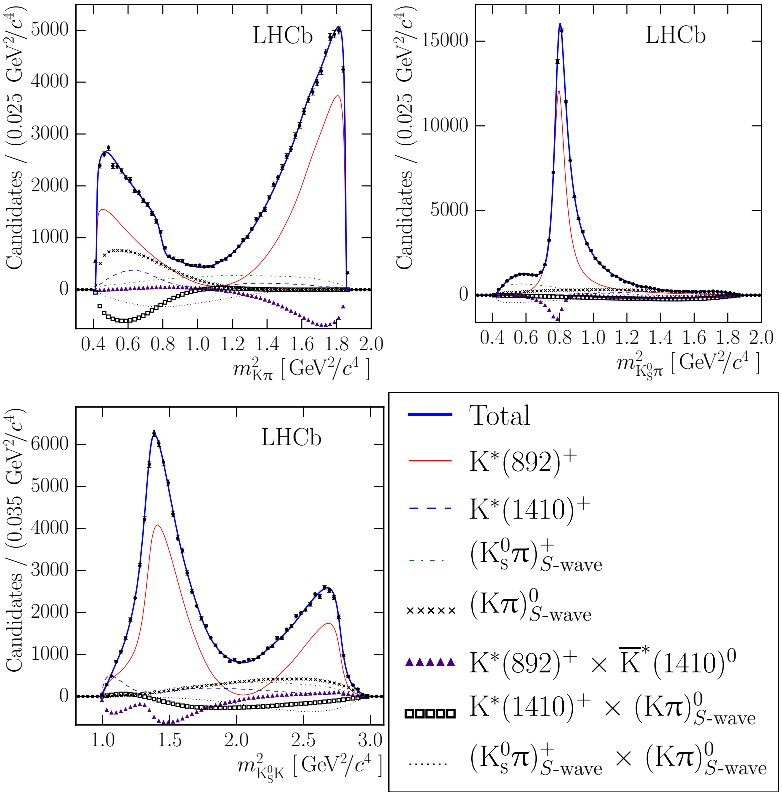


113290 ± 130 signal events @ 96% purity.

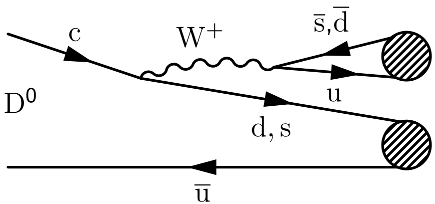
76380 ± 120 signal events @ 96% purity.

- Time integrated amplitude analysis of 'favoured' $D^0 \to K^0_S K^- \pi^+$ and 'suppressed' $D^0 \to K^0_S K^+ \pi^-$.
- $\approx 170\times$ the number of signal candidates as the CLEO amplitude analysis for these channels.
- Uses full $3\,fb^{-1}$ Run 1 dataset, prompt D^0 tags.
- Fitting performed using GPUs (GooFit).

$D^0 \to K^0_S K^- \pi^+$ Projections (LASS)



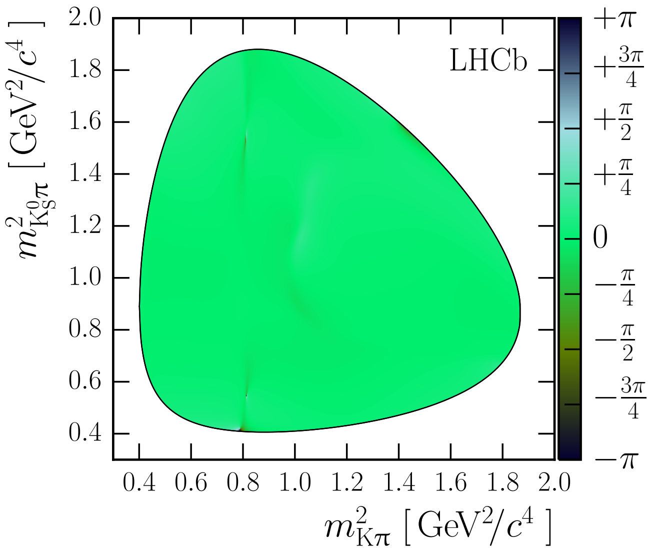
- Isobar model used throughout.
- Amplitude dominated by $D^0 \to K^*(892)^+ \left[K^0_S\pi^+\right] K^-$.
- Dominant diagram :



- Colour favoured tree-diagram produces $K^*(892)^+$ from external W^+ emission.

$D^0 \to K^0_S K^- \pi^+$ Fit Fractions

Resonance	Fit fraction [%] GLASS	Fit fraction [%] LASS
$K^*(892)^+$	$57.0 \pm 0.8 \pm 2.6$	$56.9 \pm 0.6 \pm 1.1$
$K^*(1410)^+$	$5 \pm 1 \pm 4$	$9.6 \pm 1.1 \pm 2.9$
$(K^0_S\pi)^+_{S\text{-wave}}$	$12 \pm 2 \pm 9$	$11.7 \pm 1.0 \pm 2.3$
$\bar{K}^*(892)^0$	$2.5 \pm 0.2 \pm 0.4$	$2.47 \pm 0.15 \pm 0.23$
$\bar{K}^*(1410)^0$	$9 \pm 1 \pm 4$	$3.8 \pm 0.5 \pm 2.0$
$\bar{K}^*_2(1430)^0$	$3.4 \pm 0.6 \pm 2.7$	—
$(K\pi)^0_{S\text{-wave}}$	$11 \pm 2 \pm 10$	$18 \pm 2 \pm 4$
$a_0(980)^-$	—	$4.0 \pm 0.7 \pm 1.1$
$a_2(1320)^-$	$0.20 \pm 0.06 \pm 0.21$	$0.15 \pm 0.06 \pm 0.13$
$a_0(1450)^-$	$1.2 \pm 0.2 \pm 0.6$	$0.74 \pm 0.15 \pm 0.34$
$\rho(1450)^-$	$1.3 \pm 0.3 \pm 0.7$	$1.4 \pm 0.2 \pm 0.7$
$\rho(1700)^-$	$0.12 \pm 0.05 \pm 0.14$	—



- Two different models, with different parameterisations of $K\pi$ S-wave components.
- Amplitude dominated by $K^*(892)^+$ and $K\pi$ S-waves ($K^*(1430)^+$ and $K^*(1430)^0$)
- Figure: Phase difference between GLASS and LASS models.
- Enough flexibility to reproduce roughly the same phase with either $K\pi$ S-wave hypothesis.

More about Kπ S-waves

- LASS parametrisation :

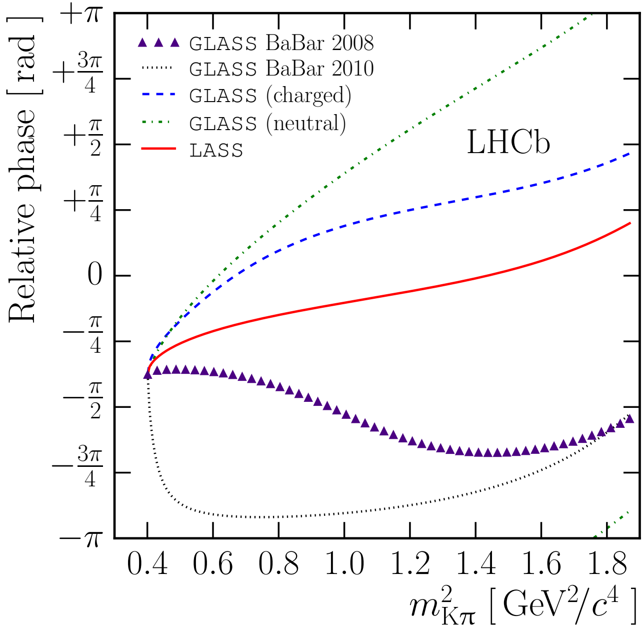
$$T_R = \sin(\delta_S + \delta_F)e^{i(\delta_S+\delta_F)},$$

where δ_S is the Breit-Wigner phase, δ_F the phase of the 'non-resonant' component.

- Generalises to GLASS formalism :

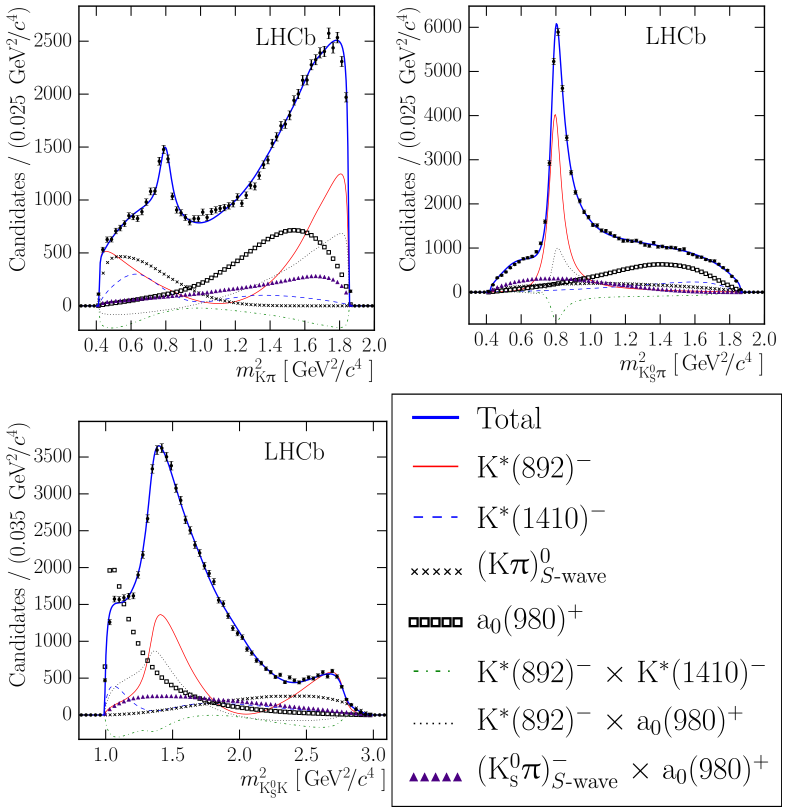
$$T_R = F\sin(\phi_S + \delta_F)e^{i(\delta_F+\phi_F)} + \sin(\delta_S)e^{i(\delta_S+\phi_S)}e^{2i(\delta_F+\phi_F)}$$

- Introduces free phase(s) and an amplitude between the 'resonant' and 'non-resonant' components of the S-wave.
- But, not guaranteed to reproduce the same phase behaviour as the original scattering data - tension with Watson's theorem.
- Alternative is to introduce an empirical (scalar) form factor to the original LASS formula.
- Gives similar fit qualities $\chi^2/dof = 1.12$ (GLASS) vs 1.10 (LASS).

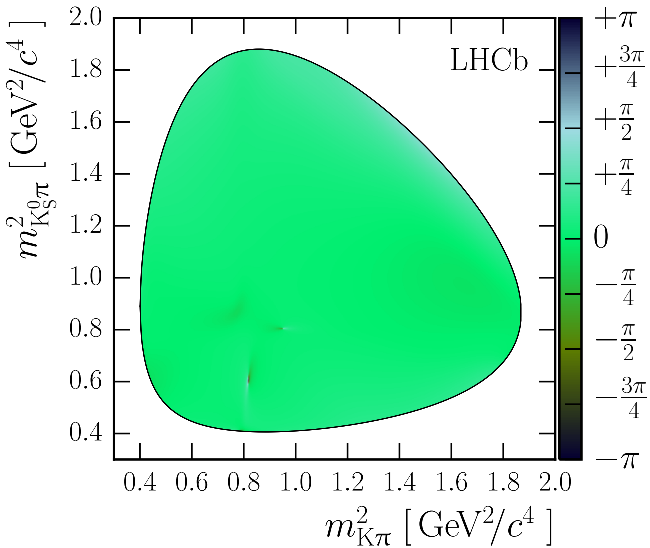


- Comparison of phases with GLASS parametrisation, the original LASS paper, and the findings in $D^0 \to K^0_S\pi^+\pi^-$ from BaBar [2].

$D^0 \to K^0_S K^+ \pi^-$ Projections (LASS)



$D^0 \to K_S^0 K^+ \pi^-$ Fit Fractions



Resonance	Fit fraction [%] GLASS	Fit fraction [%] LASS
$K^*(892)^-$	$29.5 \pm 0.6 \pm 1.6$	$28.8 \pm 0.4 \pm 1.3$
$K^*(1410)^-$	$3.1 \pm 0.6 \pm 1.6$	$11.9 \pm 1.5 \pm 2.2$
$(K^0_S\pi)^-_{S\text{-wave}}$	$5.4 \pm 0.9 \pm 1.7$	$6.3 \pm 0.9 \pm 2.1$
$K^*(892)^0$	$4.82 \pm 0.23 \pm 0.35$	$5.17 \pm 0.21 \pm 0.32$
$K^*(1410)^0$	$5.2 \pm 0.7 \pm 1.6$	$2.2 \pm 0.6 \pm 2.1$
$K^*_2(1430)^0$	$7 \pm 1 \pm 4$	—
$(K\pi)^0_{S\text{-wave}}$	$12 \pm 1 \pm 8$	$17 \pm 2 \pm 6$
$a_0(980)^+$	$11 \pm 1 \pm 6$	$26 \pm 2 \pm 10$
$a_0(1450)^+$	$0.45 \pm 0.09 \pm 0.34$	$1.5 \pm 0.3 \pm 0.4$
$\rho(1450)^+$	$1.5 \pm 0.5 \pm 0.9$	—
$\rho(1700)^+$	$0.5 \pm 0.1 \pm 0.5$	$0.53 \pm 0.11 \pm 0.23$

- Able to reproduce the same phase motion with either $K\pi$ S-wave parametrisation.

Search for time integrated CPV

- Amplitude and phase parameters replaced with :

$$a_R \rightarrow a_R(1 \pm \Delta a_R)$$
$$\phi_R \rightarrow \phi_R(1 \pm \Delta \phi_R) \quad (1)$$

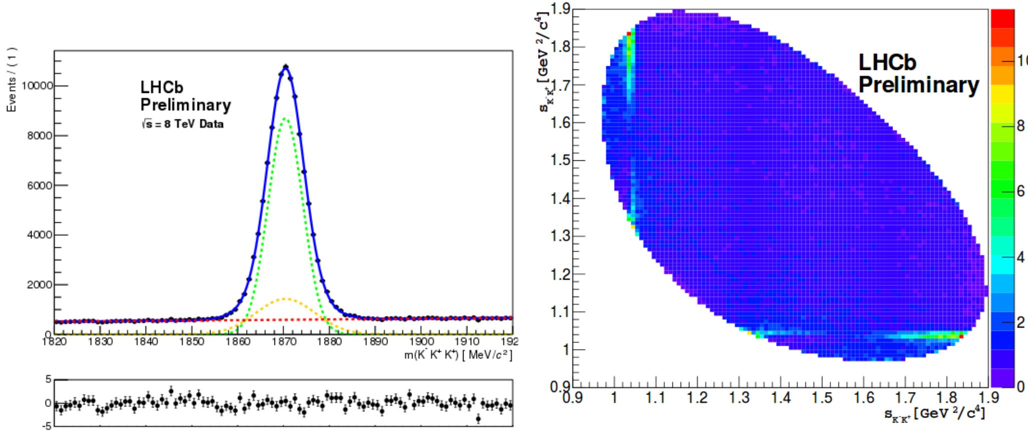
where $-$ sign is for D^0, $+$ for $\overline{\mathrm{D}}^0$.

- Difference between S-wave parameterisations taken as the model systematic.
- $\chi^2/ndf = 30.5/32 = 0.95$ for GLASS model(s) - corresponding to p-value of 0.54 - compatible with no CPV hypothesis.
- But, model uncertainty is comparable to stat. uncertainty. Improved understanding of $\mathrm{K}\pi$ S-wave is needed to benefit from higher statistics.

Resonance	Δa_{R} $\mathrm{K^0_S K^- \pi^+}$ (GLASS)	$\Delta \phi_{\mathrm{R}}$ ($^\circ$)
$\mathrm{K}^*(892)^+$	0.0 (fixed)	0.0 (fixed)
$\mathrm{K}^*(1410)^+$	$0.07 \pm 0.06 \pm 0.04$	$3.9 \pm 3.5 \pm 1.9$
$(\mathrm{K^0_S}\pi)^+_{S\text{-wave}}$	$0.02 \pm 0.08 \pm 0.07$	$2.0 \pm 1.7 \pm 0.0$
$\overline{\mathrm{K}}^*(892)^0$	$-0.046 \pm 0.031 \pm 0.005$	$1.2 \pm 1.6 \pm 0.3$
$\overline{\mathrm{K}}^*(1410)^0$	$0.006 \pm 0.034 \pm 0.017$	$2 \pm 5 \pm 5$
$(\mathrm{K}\pi)^0_{S\text{-wave}}$	$0.05 \pm 0.04 \pm 0.02$	$0.4 \pm 1.6 \pm 0.6$
$\mathrm{a}_2(1320)^-$	$-0.25 \pm 0.14 \pm 0.01$	$2 \pm 9 \pm 3$
$\mathrm{a}_0(1450)^-$	$-0.01 \pm 0.14 \pm 0.12$	$0 \pm 5 \pm 4$
$\rho(1450)^-$	$0.06 \pm 0.13 \pm 0.11$	$-13 \pm 10 \pm 9$

First uncertainty statistical, second systematic.

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



100930 signal candidates @ 90.6% purity.

- Amplitude analysis of doubly Cabbibo suppressed decay $D^+ \to K^+K^-K^+$ using the isobar model.
- Branching ratio of $D^+ \to K^+K^-K^+$ measured to be (8.7×10^{-5}).
- Analysis based on $2\,\text{fb}^{-1}$ of data taken in 2012.
- Emphasis on understanding the K^+K^- S-wave component.

K^+K^- S-wave parametrisation

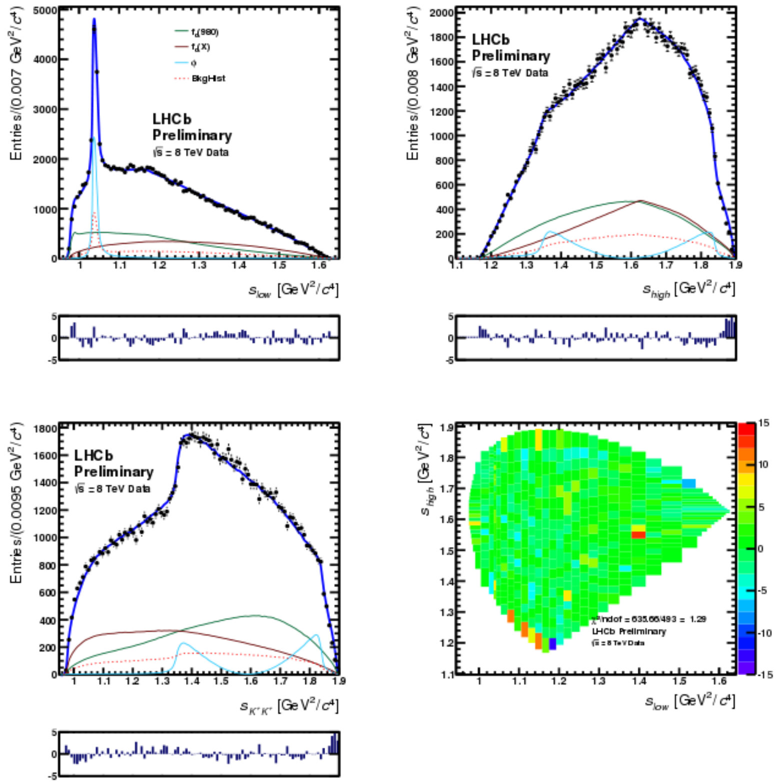
Three different S-wave parameterisations :

1. Non-resonant (i.e. flat) + $f_0(980)$.
2. $f_0(X)$ (single Breit-Wigner with floating mass and width) + $f_0(980)$.
3. $a_0(1450)$ + $f_0(980)$.

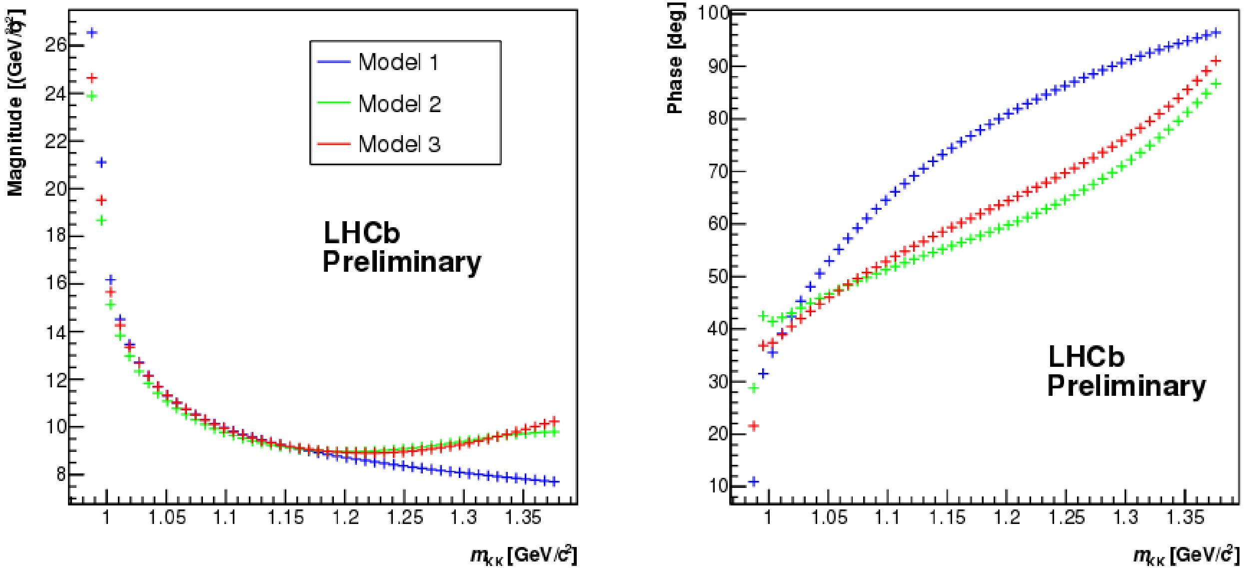
All models additionally include a $\phi(1020)$ component.

For $f_0(x)$:
$m_0 = 1430 \pm 19\,\mathrm{MeV}/c^2$,
$\Gamma_0 = 348 \pm 49\,\mathrm{MeV}/c^2$.

Model	χ^2/dof	$\sum$ FF [%]
1	$844.49/495 = 1.71$	93.6 ± 8.0
2	$635.66/493 = 1.29$	55 ± 13
3	$652.15/495 = 1.32$	55.9 ± 2.2



Comparing S-wave models



Comparison of prediction of $\mathrm{K}^+\mathrm{K}^-$ S-wave amplitude in the the three different models.

- Models 2 and 3 predict similar phase and amplitude for S wave - $f_0(X)$ has similar mass and width to the $a_0(1450)$.
- Improvement in χ^2 with models 2 and 3 indicate S wave is not completely flat / non-resonant.
- More theoretically motivated analysis using multi-meson model ongoing (complimented by MIPWA) [3].

Conclusions

- Challenging but interesting environment - very high statistics.
- Can we fit a million events sensibly with the isobar model?
- Models inform model independent strategies for measuring γ, mixing.
- Searches for CPV ongoing - better understanding of S-waves necessary to exploit higher statistics.

- LHCb, R. Aaij *et al.*, *Studies of the resonance structure in $D^0 \to K^0_S K^{\pm}\pi^{\mp}$ decays*, Phys. Rev. **D93** (2016), no. 5 052018, arXiv:1509.06628.
- BABAR Collaboration, B. Aubert, *Improved measurement of the ckm angle γ in $B^{\mp} \to D^{(*)}K^{(*)\mp}$ decays with a dalitz plot analysis of d decays to $K^0_S\pi^+\pi^-$ and $K^0_S K^+ K^-$*, Phys. Rev. D **78** (2008) 034023.
- R. T. Aoude, P. C. Magalhães, A. C. dos Reis, and M. R. Robilotta, *Multi-Meson Model applied to $D^+ \to K^+K^-K^+$*, arXiv:1604.02904.