



CP Violation in charm decays with LHCb

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Why Charm?

Charm is the only **up-type** quark allowing full range of probes for mixing and *CP* Violation:

- top quarks do not hadronize;
- no π^0 oscillations possible.

***CP* violation** is predicted to be small in charm sector, any nonzero measurement might give a significant hint towards New physics scenarios.

Unprecedented huge samples of D decays are necessary (much bigger amount than 1M events needed) in order to approach SM predictions.

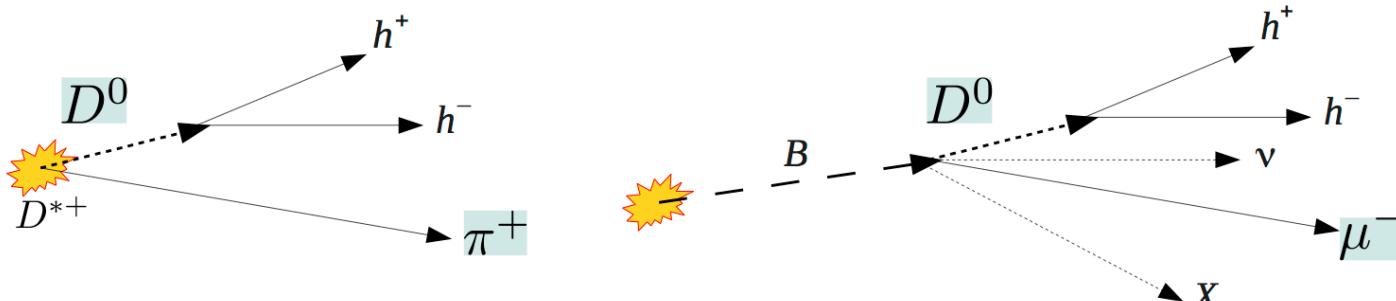
LHCb has got this statistics and sensitivity.

How we do it?

There are three ways of CPV:

- in mixing (**indirect**), $D^0 \rightarrow \text{anti-}D^0 \neq \text{anti-}D^0 \rightarrow D^0$
- in decay amplitudes (**direct**), $D \rightarrow f \neq \text{anti-}D \rightarrow \text{anti-}f$
- in interference (**indirect**) between direct decays and decays with mixing

We use two types of charm meson decays:



Prompt:

- coming from Collision Point
- tagged by soft pion
- numerous

Secondary:

- coming from semileptonic B-meson decay
- tagged by a lepton
- cover full decay time range

Time-integrated study

Direct CP violation in two-body decays

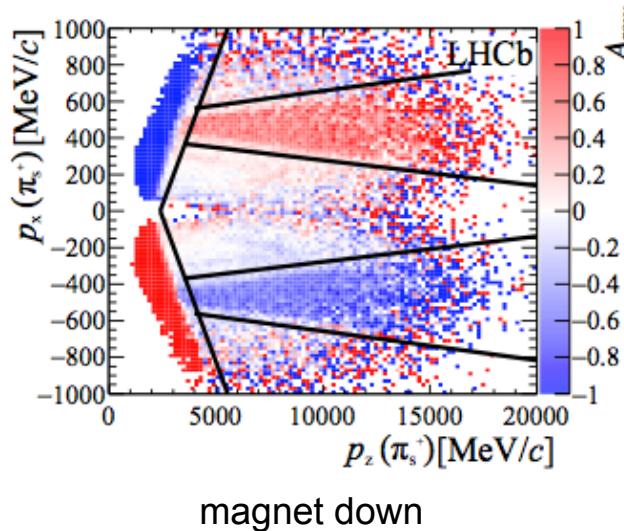
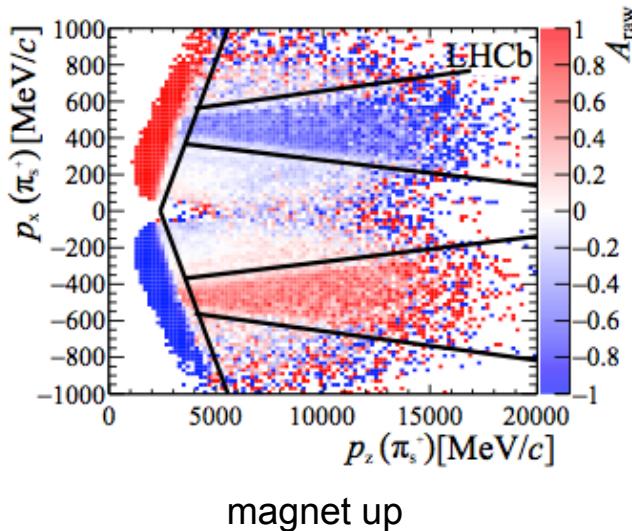
Experimentally yields are measured

$$A_{\text{raw}}(f) = \frac{N(D^{*+} \rightarrow D^0(\rightarrow f)\pi^+) - N(D^{*-} \rightarrow \bar{D}^0(\rightarrow f)\pi^-)}{N(D^{*+} \rightarrow D^0(\rightarrow f)\pi^+) + N(D^{*-} \rightarrow \bar{D}^0(\rightarrow f)\pi^-)}$$

$$\approx A_{CP}(f) + \color{blue}A_D(f)\color{black} + \color{green}A_D(\pi)\color{black} + \color{purple}A_P(D^*)\color{black}$$

$\color{blue}A_D(\pi)$ soft-pion (tag) detection asymmetry
 $\color{blue}A_D(f)$ final state detection asymmetry
 $\color{purple}A_P(D^*)$ production asymmetry

We also check that the instrumental asymmetry is healthy applying fiducial cuts:



Direct CP violation in two-body decays

We study prompt $D^0 \rightarrow K\bar{K}$ and $D^0 \rightarrow \pi\bar{\pi}$.

To keep detection and production asymmetries under control, we measure:

$$\begin{aligned}\Delta A_{CP} &= A_{\text{raw}}(K^+K^-) - A_{\text{raw}}(\pi^+\pi^-) = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \\ &\approx \Delta a_{CP}^{\text{dir}} \left(1 + \frac{\overline{\langle t \rangle}}{\tau} y_{CP} \right) + \frac{\Delta \langle t \rangle}{\tau} a_{CP}^{\text{ind}}\end{aligned}$$

y_{CP} is the deviation from unity of the ratio of the effective lifetimes of decays to flavor specific and CP -even final states.

Some residual experiment-dependent contribution from indirect CP violation can still be present (from $\langle t \rangle$, integrated with decay time acceptance). This contribution is estimated in data:

$$\frac{\Delta \langle t \rangle}{\tau(D^0)} = 0.1153 \pm 0.0007(\text{stat}) \pm 0.0018(\text{syst})$$

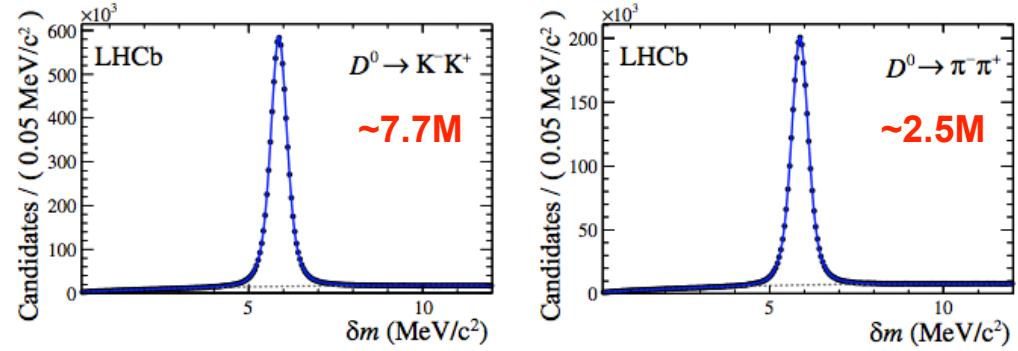
$$\frac{\overline{\langle t \rangle}}{\tau(D^0)} = 2.0949 \pm 0.0004(\text{stat}) \pm 0.0159(\text{syst})$$

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Prompt two-body decays

Analysis summary:

- uses full run 1 statistics (3 fb^{-1})
- tight selection for all possible sources of asymmetry (multibody background, secondary charm, instrumental asymmetries);
- simultaneous fits to D^* - and D^{**} -samples to $\delta m = m(D^*) - m(D^0) - m(\pi)$;
- extensive checks of result stability.



$$\Delta A_{CP} = (-0.10 \pm 0.08 \text{ (stat)} \pm 0.03 \text{ (syst)}) \%$$

Compatible with null hypothesis with a statistical precision below 10^{-3} CP asymmetry.

Systematic uncertainty already approaching 10^{-4} level.

Two-body ΔA_{CP} world average status

New result supersedes previous published LHCb result on 0.6 fb^{-1}

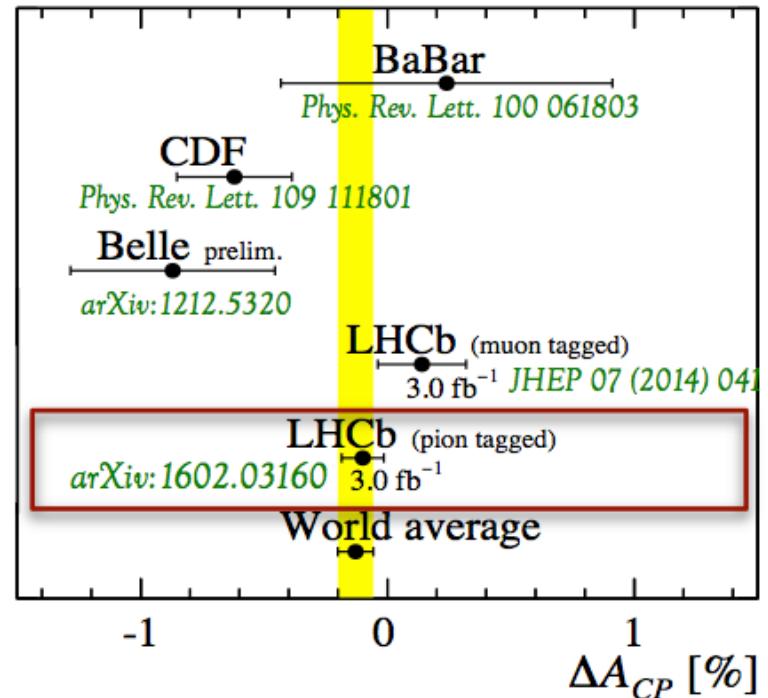
$\Delta A_{CP} = (-0.82 \pm 0.21)\%$ [PRL 108(2012), 111602].

and preliminary result on 1 fb^{-1}

$\Delta A_{CP} = (-0.34 \pm 0.18)\%$ [LHCb-CONF-2013-003].

Fully compatible with independent semi-leptonic LHCb result:

$\Delta A_{CP} = (+0.14 \pm 0.16 \text{ (stat)} \pm 0.08 \text{ (syst)})\%$



Naïve weighted average (neglecting indirect CPV contribution) gives
 $\Delta A_{CP} = (-0.129 \pm 0.072)\%$ fully dominated by LHCb results.

Time-dependent study

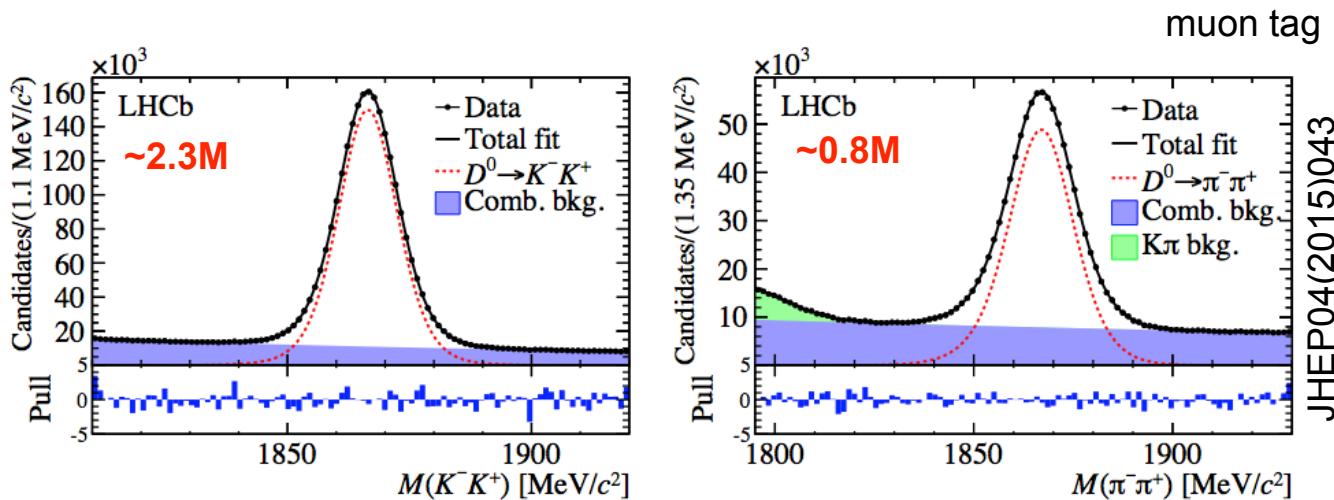
A_Γ asymmetry

Now, we deal with the time-dependent asymmetry:

$$A_{CP}(t) = \frac{\Gamma(D^0(t) \rightarrow f) - \Gamma(\bar{D}^0(t) \rightarrow f)}{\Gamma(D^0(t) \rightarrow f) + \Gamma(\bar{D}^0(t) \rightarrow f)} \simeq a_{CP}^{dir} - \frac{t}{\tau_{D^0}} A_\Gamma$$

with A_Γ taking contributions only from CPV in the mixing and in the decay (x, y and ϕ are mixing parameters):

$$A_\Gamma \equiv \frac{\hat{\Gamma}_{D^0} - \hat{\Gamma}_{\bar{D}^0}}{\hat{\Gamma}_{D^0} + \hat{\Gamma}_{\bar{D}^0}} \approx (A_{CP}^{\text{mix}}/2 - A_{CP}^{\text{dir}}) y \cos \phi - x \sin \phi$$

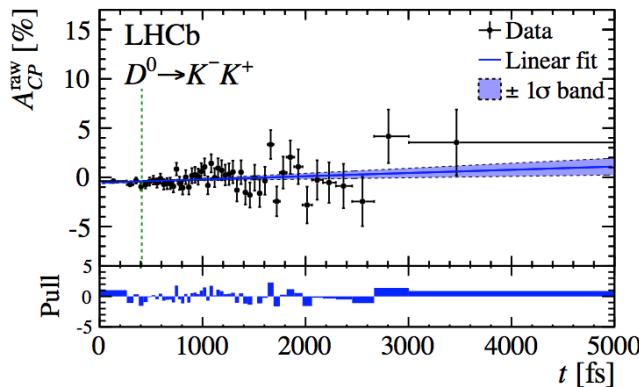


A_Γ measurements

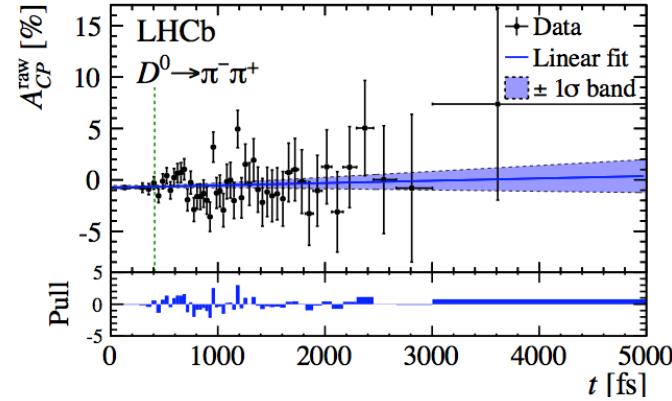
Measure yields asymmetry in various bin of D^0 proper time and than fit the straight line:

$$A_{CP}(t) \simeq a_{CP}^{dir} - \frac{t}{\tau_{D^0}} A_\Gamma$$

muon tag analysis used 3 fb^{-1}



$$A_\Gamma(K^- K^+) = (-0.134 \pm 0.077 {}^{+0.026}_{-0.034})\%$$



$$A_\Gamma(\pi^- \pi^+) = (-0.092 \pm 0.145 {}^{+0.025}_{-0.033})\%$$

Consistent with A_Γ from prompt decays (using 1 fb^{-1}):

$$A_\Gamma(\pi\pi) = (0.033 \pm 0.106 \pm 0.014)\%$$

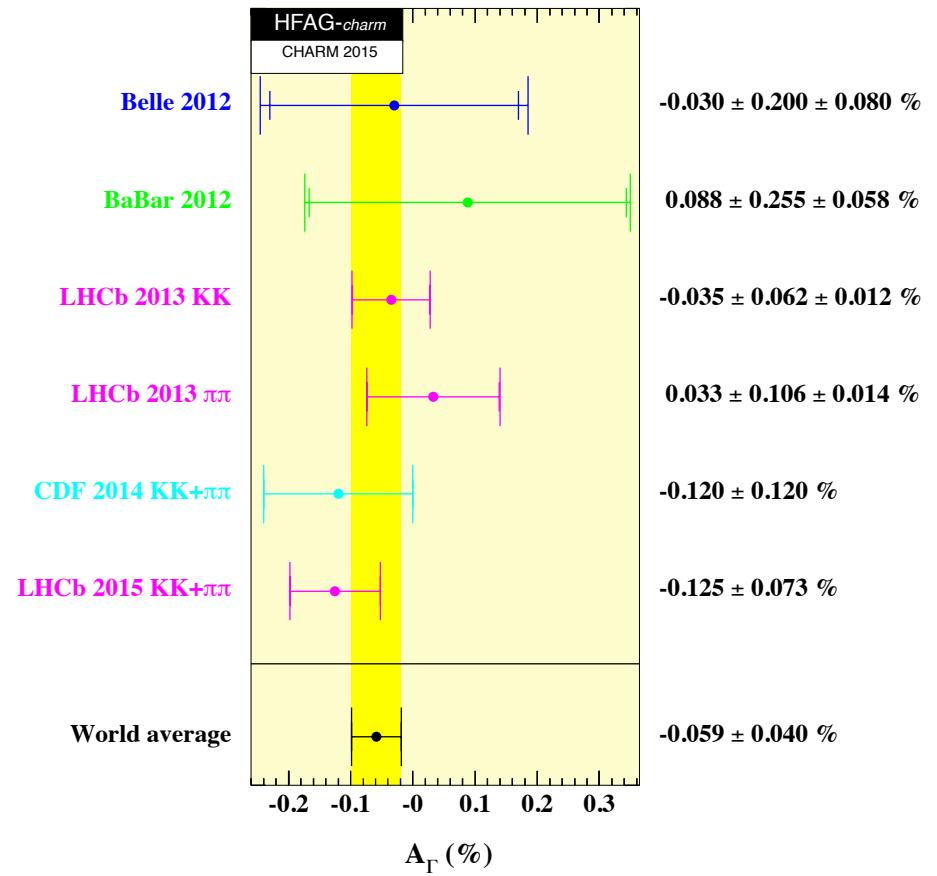
$$A_\Gamma(KK) = (-0.035 \pm 0.062 \pm 0.012)\%$$

PRL 112 (2014) 041801

A_Γ world averages

World best measurement is LHCb prompt using 1 fb^{-1} of integrated luminosity.

The leading contributions are coming from LHCb.



Standard Model Test for Two-Body Decays

Extensive LHCb study in the sector allowed for the SM comparison

ΔA_{CP} :

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JHEP07(2014)041

$A_\Gamma \approx -a_{ind}$:

PRL112(2014)041801
JHEP04(2015)043

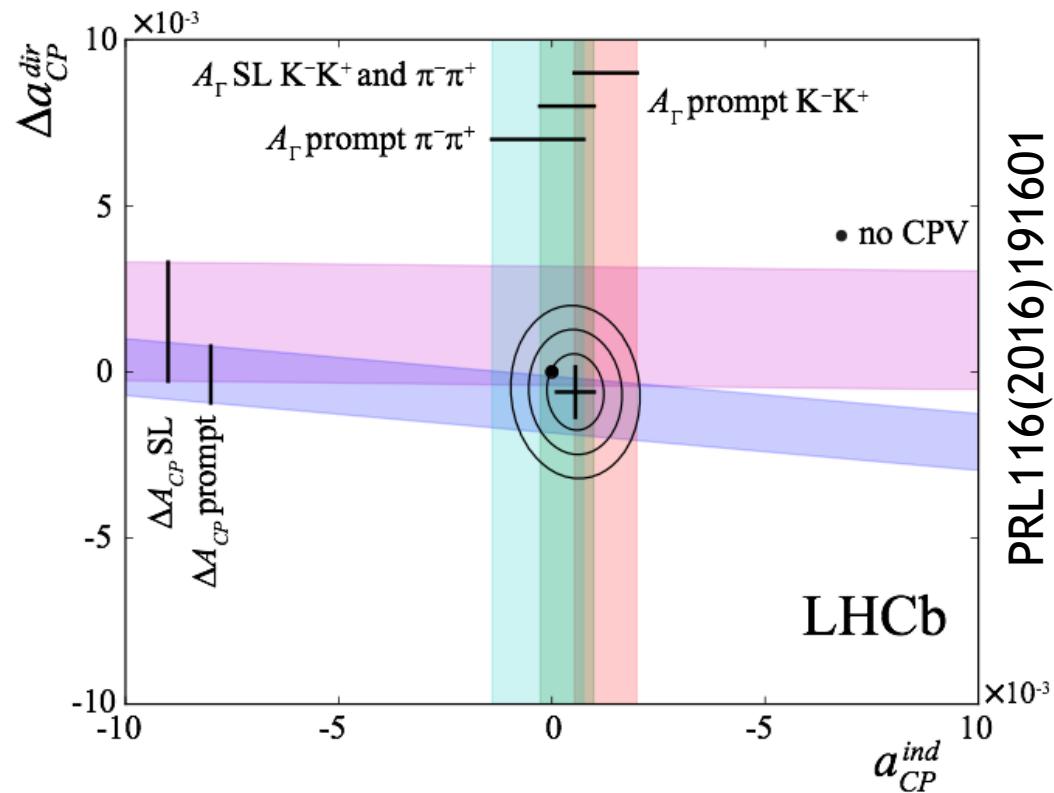
y_{CP} :

JHEP04(2012)129

LHCb average:

$a_{ind} = 0.058 \pm 0.044 \%$

$\Delta a_{dir} = -0.061 \pm 0.076 \%$



No CP-Violation from LHCb only: p-value = 0.32

Multi-body decays

Amplitude analysis of $D^0 \rightarrow K_s K \pi$

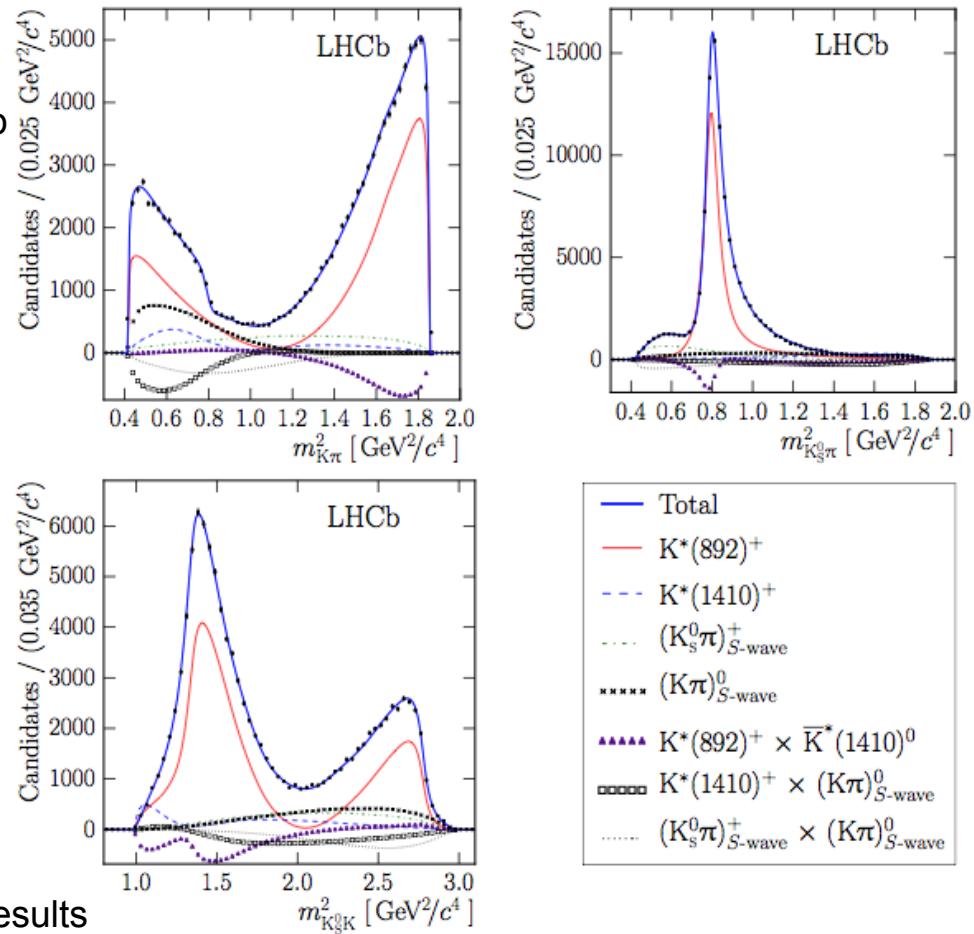
Features:

- First charm amplitude analysis in LHCb
- Large statistics ($\sim 180K$)
- Complex Dalitz plot structure
- Used GPUs

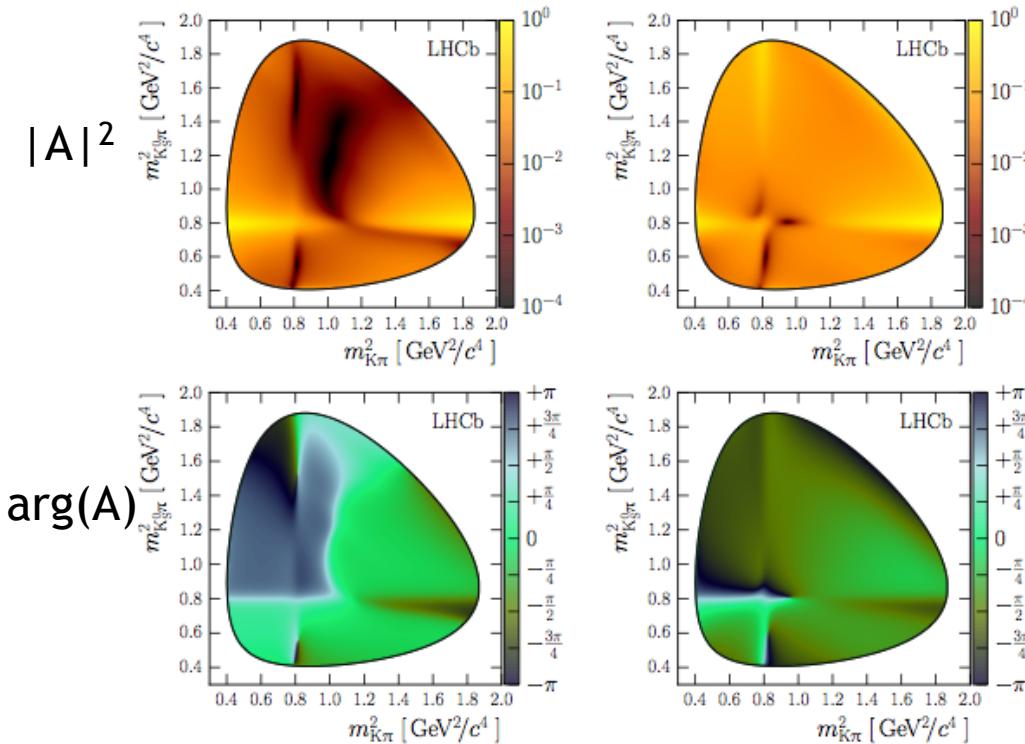
Aims:

- Isobar model is useful for CKM angle γ measurements;
- Tests of SU(3) flavour symmetry
- Model-dependent search for CPV.

S-wave: GLASS vs. LASS give consistent results



CP violation in $D^0 \rightarrow K_S K\pi$



$$D^0 \rightarrow K_S^0 K^- \pi^+ \quad D^0 \rightarrow K_S^0 K^+ \pi^-$$

Once you have an isobar model

$$A = \sum_R a_R e^{i\phi_R} A_R$$

Substitute

$$A = \sum_R a_R (1 \pm \Delta a_R) e^{i(\phi_R \pm \Delta \phi_R)} A_R$$

Resonance 'lineshape'
Resonance amplitude

With the sign dependent on the D^0 flavour tag
and refit the models

- Perform χ^2 test w.r.t. no-CPV hypothesis ($\Delta = 0$).
- Find $\chi^2/\text{ndf} = 32.3/32 = 1.01$, p-value 0.45 (including systematics).

SU(3) flavour symmetry tests:

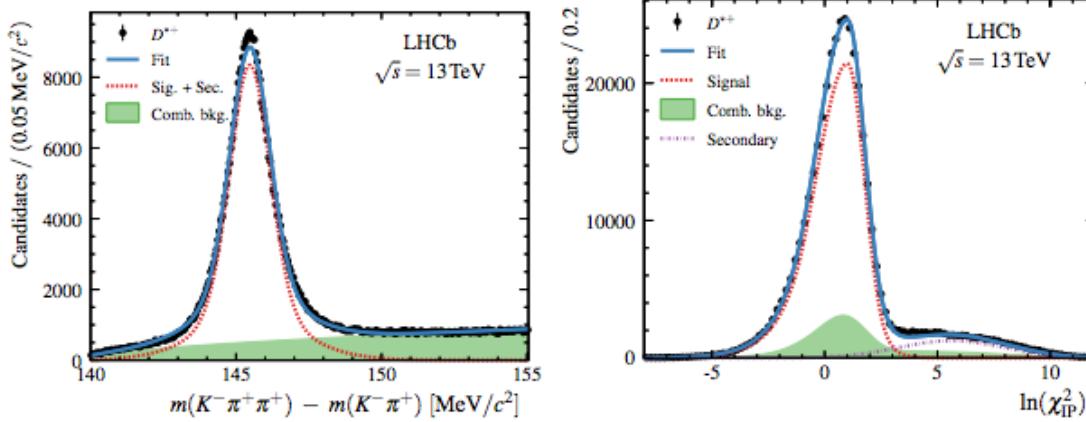
Results in agreement between LASS and GLASS and in favour of theoretical scenario with small η - η' mixing angle.

Conclusions and Outlook

In Run I:

- Achieved statistical precision below 10^{-3} (for two-body decays), and systematics already close to the impressive value of 10^{-4} .
- This precision is already world-leading in many decay modes.
- No hints of CP -violation (or anomalies) have been found so far, however LHCb has just started to approach SM expectations.

See results for Run II:



300K of tagged prompt $D^0 \rightarrow K\pi$ decays in first 5 pb^{-1} of data.

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