CP Violation in charm decays with LHCb

Denis Derkach
Higher School of Economics and Yandex School of Data Analysis
on behalf of the LHCb collaborations.

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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.

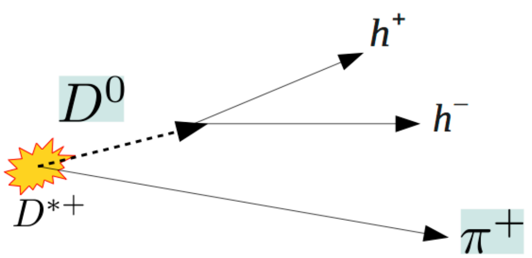
LHCb has got this statistics and sensitivity.

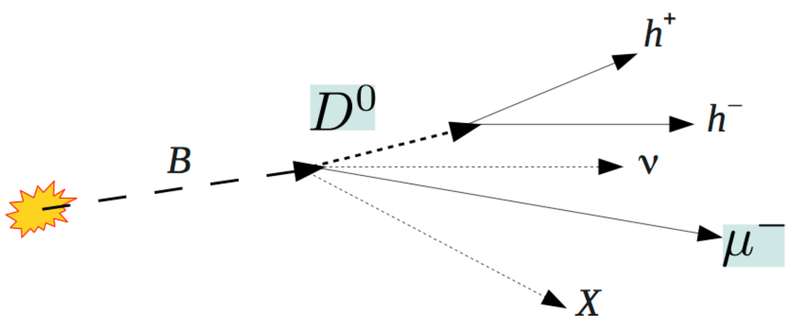
How we do it?

There are three ways of CPV:

- in mixing (indirect), $D^0 \rightarrow$ anti-$D^0 \neq$ anti-$D^0 \rightarrow D^0$
- in decay amplitudes (direct), $D \rightarrow f \neq$ anti-$D \rightarrow$ 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

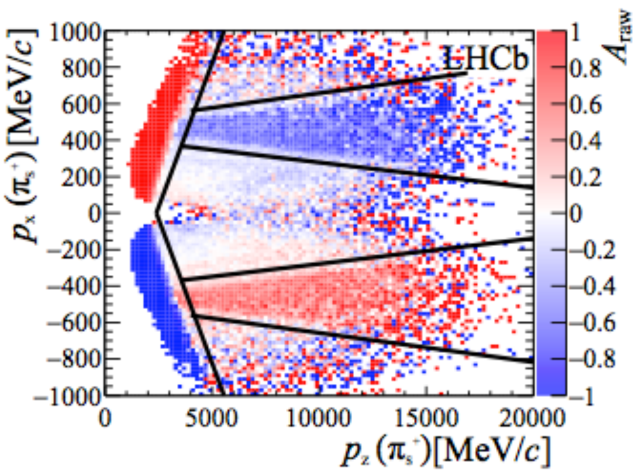
Experimentally yields are measured

$$A_{\rm raw}(f) = \frac{N(D^{*+} \to D^0(\to f)\pi^+) - N(D^{*-} \to \overline{D}^0(\to f)\pi^-)}{N(D^{*+} \to D^0(\to f)\pi^+) + N(D^{*-} \to \overline{D}^0(\to f)\pi^-)}$$

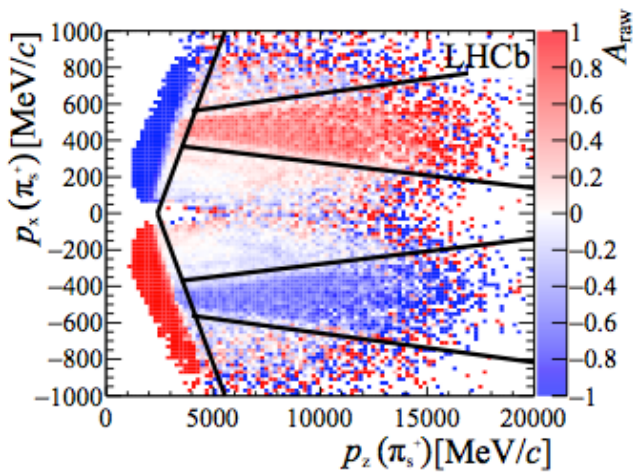
$$\approx A_{CP}(f) + A_D(f) + A_D(\pi) + A_P(D^*)$$

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

We also check that the instrumental asymmetry is healthy:



magnet up



magnet down

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Direct *CP* violation in two-body decays

We study prompt $D^0 \to KK$ and $D^0 \to \pi\pi$.
To keep detection and production asymmetries under control, we measure:

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

some residual experiment-dependent contribution from indirect CP violation can still be present (from <t>, 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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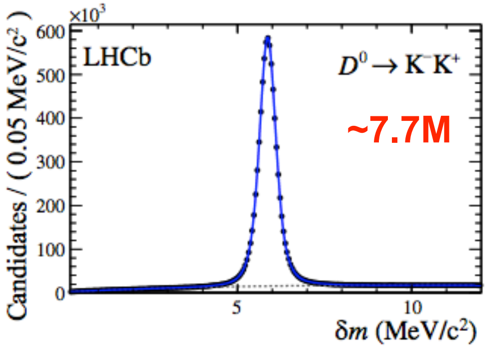
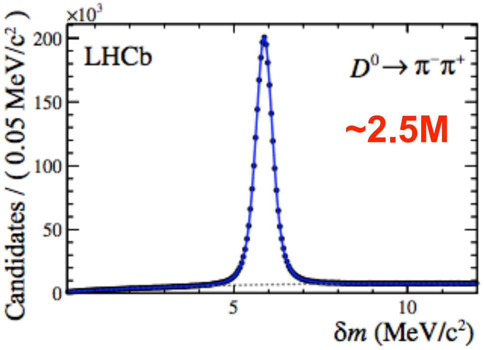
Prompt two-body decays

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 in the charm sector from a single experiment.

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

Two-body ΔAcp world average status

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

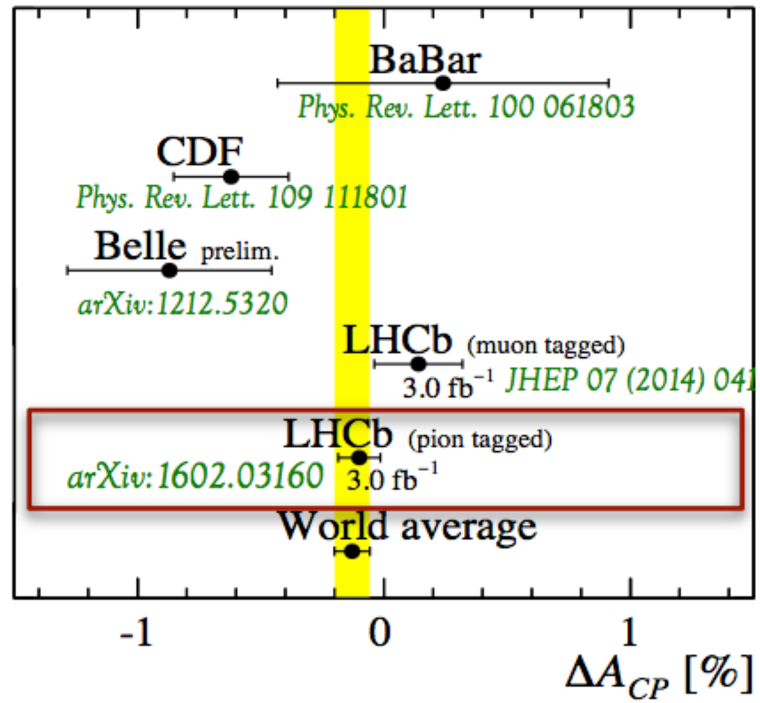
ΔA_{CP} = (-0.82 ±0.21)% [PRL 108(2012), 111602].

and preliminary result on 1fb^{-1}

ΔA_{CP} = (-0.34 ±0.18)% [LHCb-CONF-2013-003].

Fully compatible with independent semi-leptonic LHCb result:

ΔA_{CP} = (+0.14 ± 0.16 (stat) ± 0.08 (syst))%



Naïve weighted average (neglecting indirect CPV contribution) gives ΔA_{CP}= (-0.129 ± 0.072)% fully dominated by LHCb results.

Time-dependent study

A_Γ asymmetry

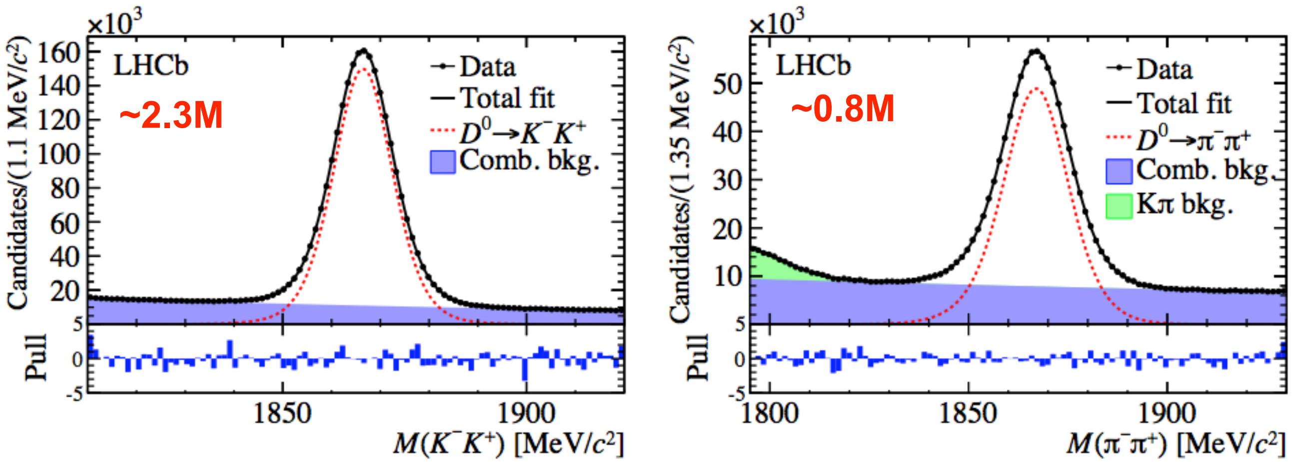
Now, we deal with the time-dependent asymmetry:

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

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

$$A_\Gamma \approx (A_{CP}^{\text{mix}}/2 - A_{CP}^{\text{dir}})\, y \cos\phi - x \sin\phi$$

muon tag



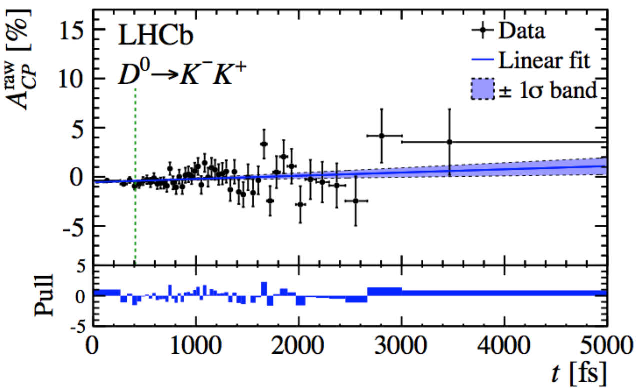
JHEP04(2015)043

A_Γ measurements

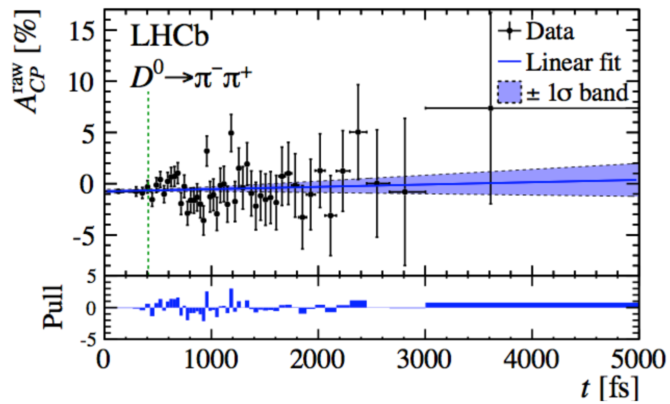
Measure yields asymmetry in various bin of D^0 proper time and than fit the straight line:

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

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_Γ (ππ)= (0.033 ± 0.106 ± 0.014)%

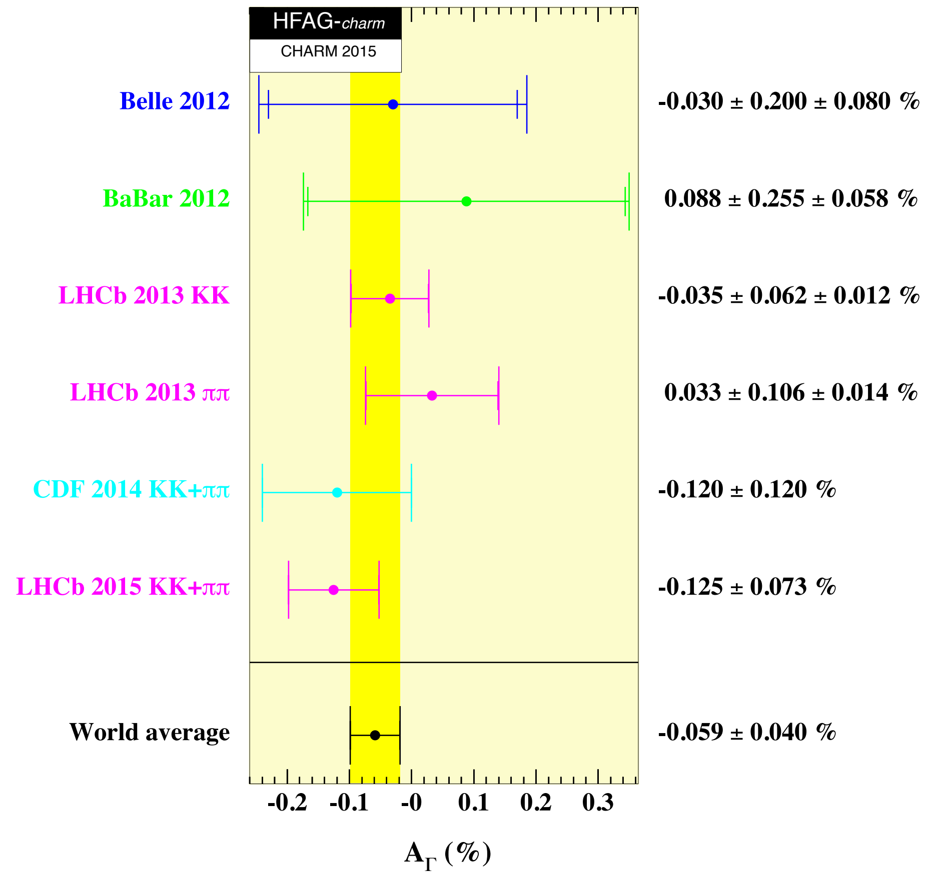
A_Γ (KK)= (-0.035 ± 0.062 ± 0.012)%

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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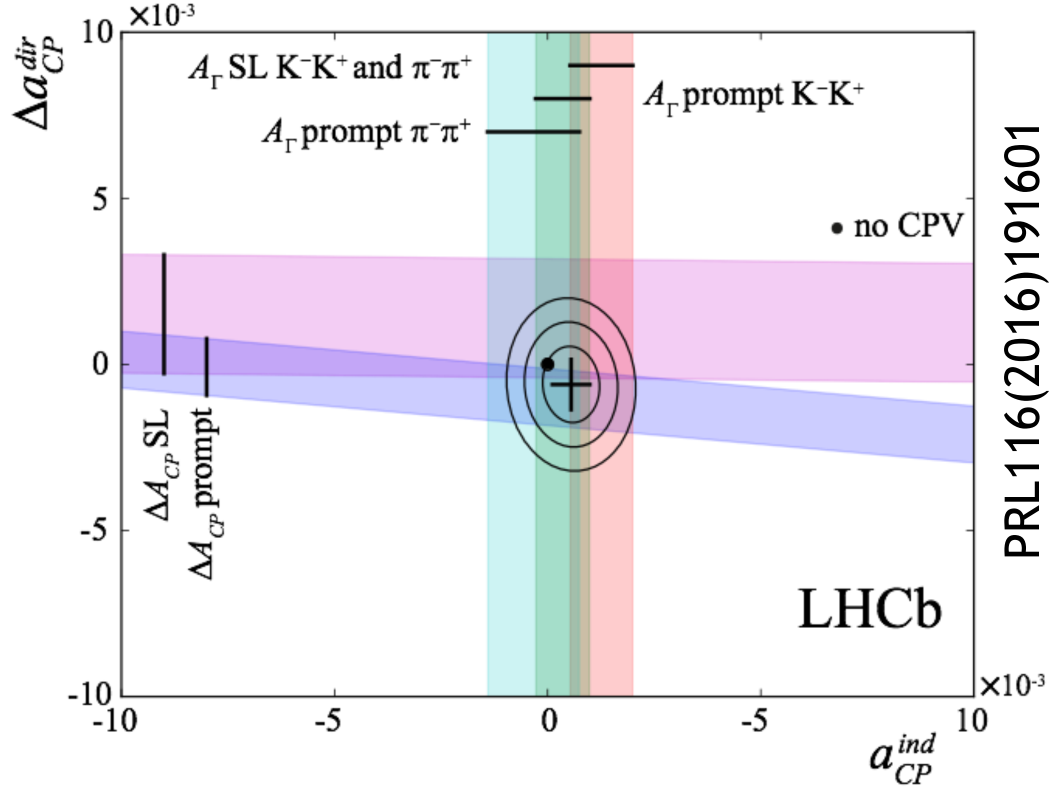
JHEP07(2014)041

$A_\Gamma \simeq -a_{ind}$:
PRL112(2014)041801
JHEP04(2015)043

y_{CP}:
JHEP04(2012)129

LHCb average:
a_{ind} = 0.058 ± 0.044 %
Δa_{dir} = -0.061 ± 0.076 %



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

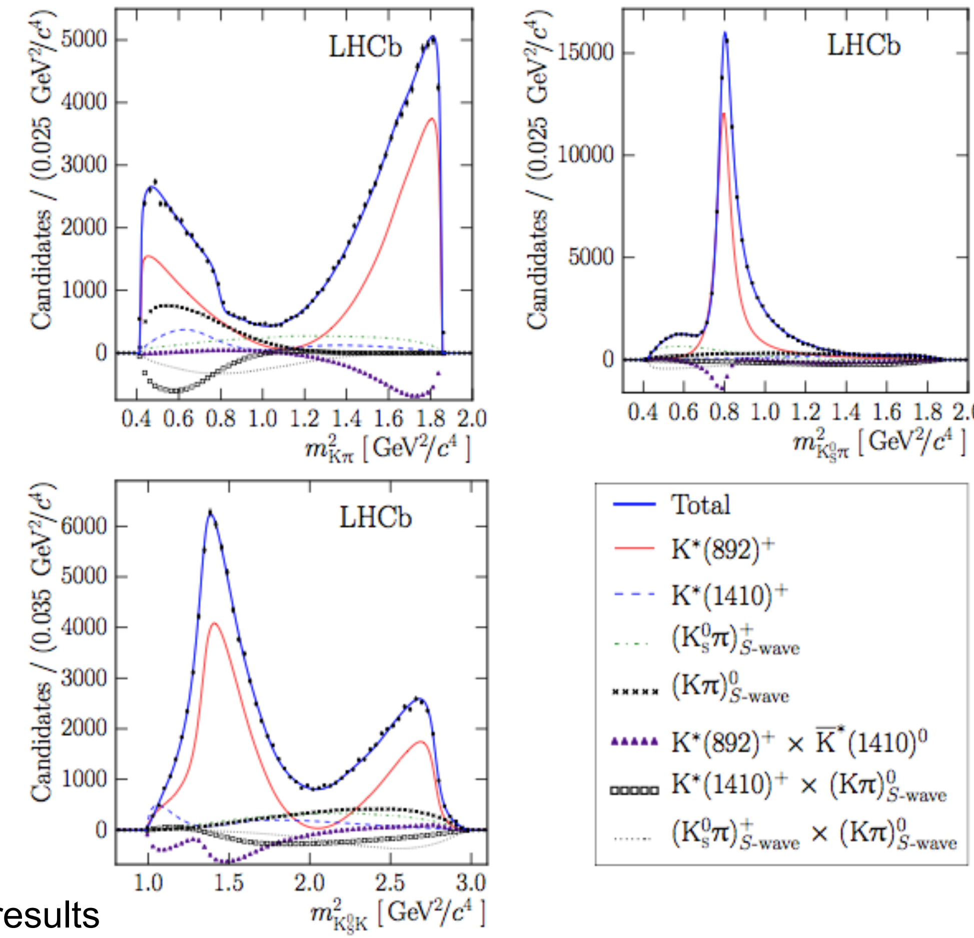
Multi-body decays

PRD93(2016)052018

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

Features:
- First LHCb amplitude analysis
- Large statistics (~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.

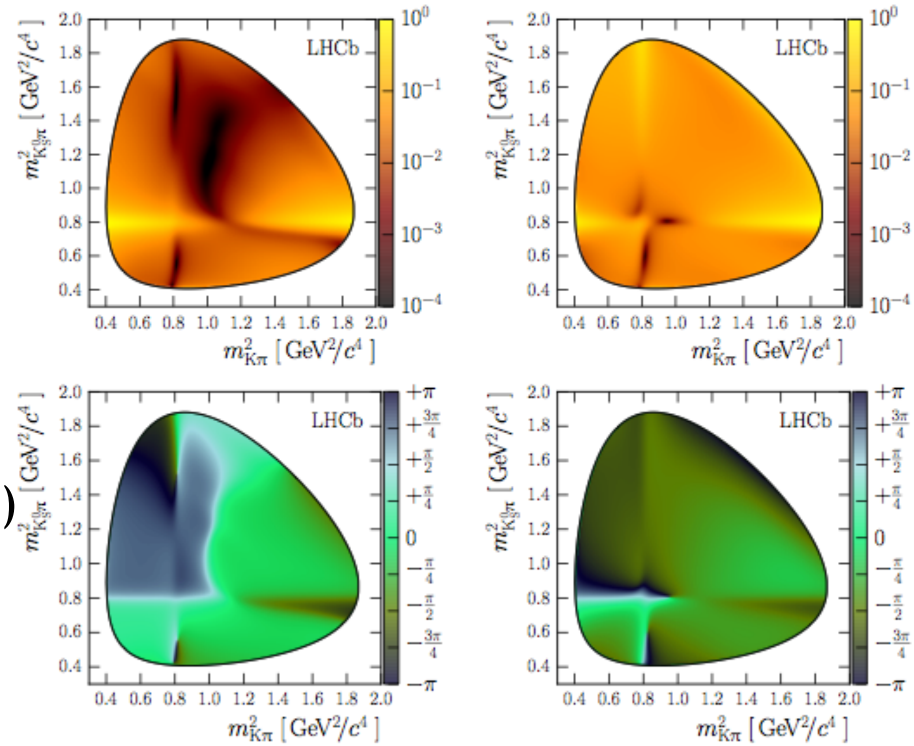


S-wave: GLASS vs. LASS give consistent results

CP violation in $D^0 \to K_s K \pi$

$|A|^2$

arg(A)



$D^0 \to K^0_S K^- \pi^+$ $\qquad$ $D^0 \to K^0_S K^+ \pi^-$

Once you have an isobar model

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

Resonance \`lineshape'

Resonance amplitude

Substitute

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

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 χ^2/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

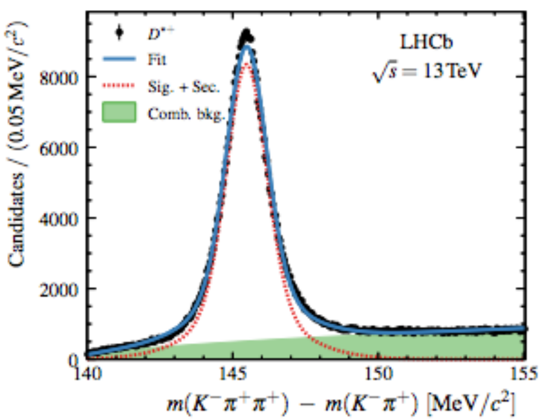
In Run I:

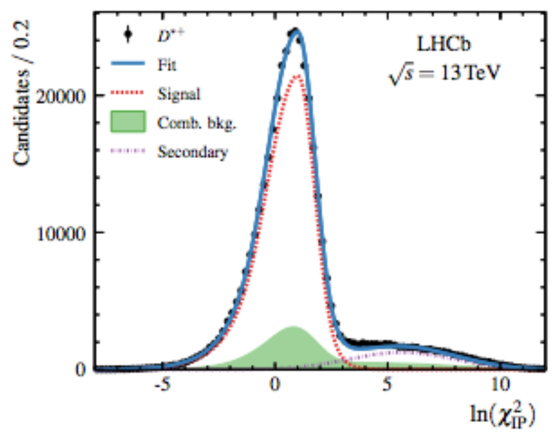
— Achieved statistical precision below 10^{-3} (for two-body decays) , and systematics already close to the impressive value of 10^{-4}.

— 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 $D^0 \to K\pi$ decays in first 5 pb^{-1} of data.

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