Phenomenology Symposium
Pittsburgh, USA, 07 May 2012

Charm mixing and CPV at LHCb

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on behalf of the LHCb Collaboration

Outline

- **Motivation:**
  - CPV and mixing D^0−anti-D^0
    - ✓ current constraints for CPV in charm physics (without the the latest CDF and LHCb measurements)
    - ✓ types of CPV
    - ✓ why are we interested in charm physics?

- **Measurements of CPV in charm sector at LHCb** (including the latest CDF result)
  - ✧ **time dependent measurements** (provide information about CP violation in mixing and in interference)
    - ✓ y_{CP} and A_{Γ} in $D^0 \rightarrow K^- K^+$, $D^0 \rightarrow K^- \pi^+$
    - ✓ Wrong-sign $D^0 \rightarrow K^+ \pi^-$
  - ✧ **time integrated measurements** (provide information about CP violation in decays and in mixing)
    - ✓ ΔA_{CP} in $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$
    - ✓ Dalitz plots in $D^+ \rightarrow K^- K^+ \pi^+$

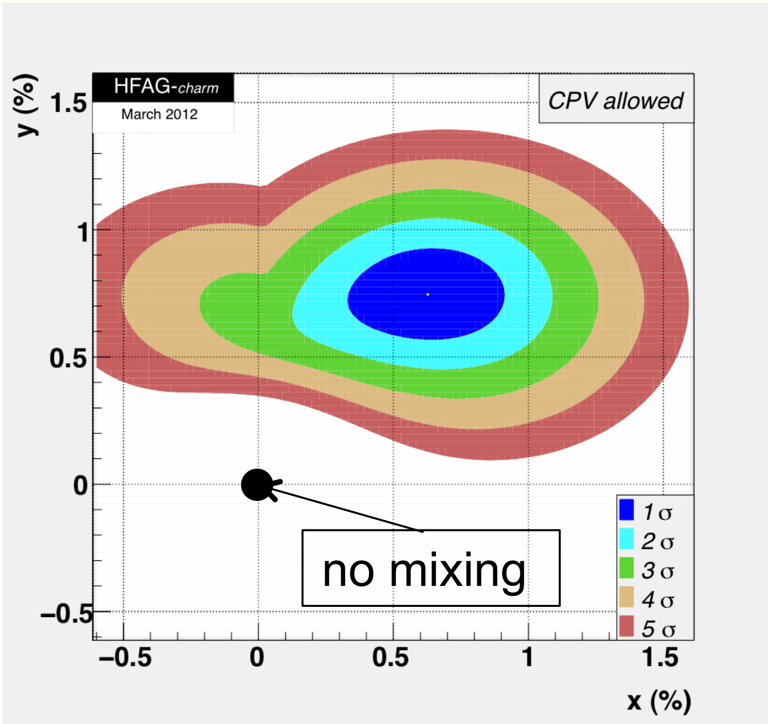
- **Summary and conclusions**

Motivation

First measurements of mixing D^0-anti-D^0, 2007, Belle, BaBar

- open possibilities of rich structure of CP violation in charm sector

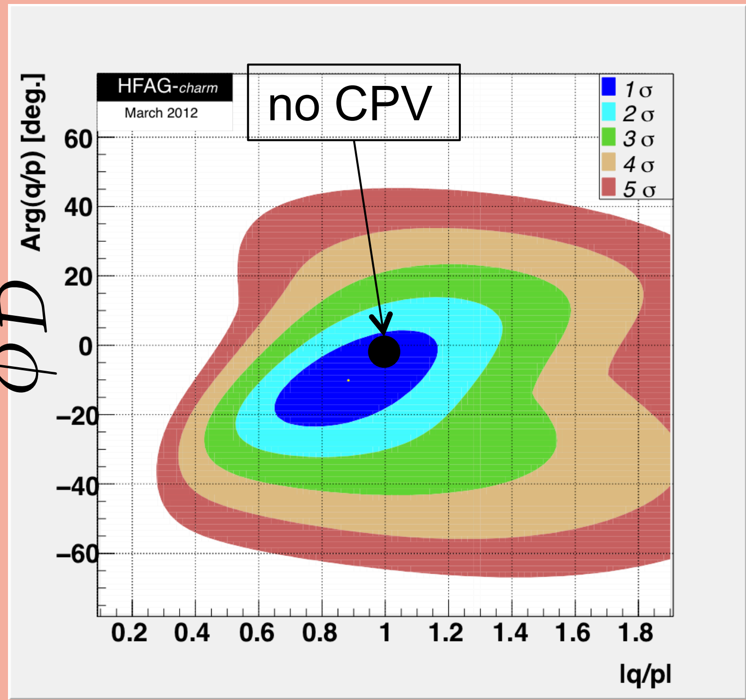
$$y = \frac{\Delta\Gamma}{2\Gamma}$$



$$x = \frac{\Delta m}{\Gamma}$$

Results 10σ away from no-mixing hypothesis

ϕ_D



$$\phi_D \equiv arg(-M_{12}/\Gamma_{12})$$

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

CPV: if $\phi_D \neq 0$ or $|q/p| \neq 1$

So far there was no experimental evidence for CPV in charm sector

Three types of CP violation

1. **in mixing** (indirect): $D^0 \rightarrow$ anti-D^0 ≠ anti-$D^0 \rightarrow D^0$

2. **in decay amplitudes** (direct): $D^0 \rightarrow f$ ≠ anti-$D^0 \rightarrow$ anty-f

3. **in the interference** (indirect):

Mixing and decay processes can be mediated via loop diagrams.
New physics is most likely to enter in loops and new particles can be exchanged

- In SM expected CPV in charm sector is small ($\lesssim 10^{-3}$)
  - much smaller than in the beauty sector

→ perfect place for New Physics searching (**small background from SM**)

- Input to b physics
  - many b mesons decay to c particles ($b \rightarrow c$) ~50% transitions

Charm is a tool for New Physics searches

Charm particles at LHCb

LHCb was built for b physics:

- for precise measurements of CPV in b decays and their very rare decays

- also c particle decays are reconstructed
  - measured at LHCb cross-sections at 7 TeV pp:

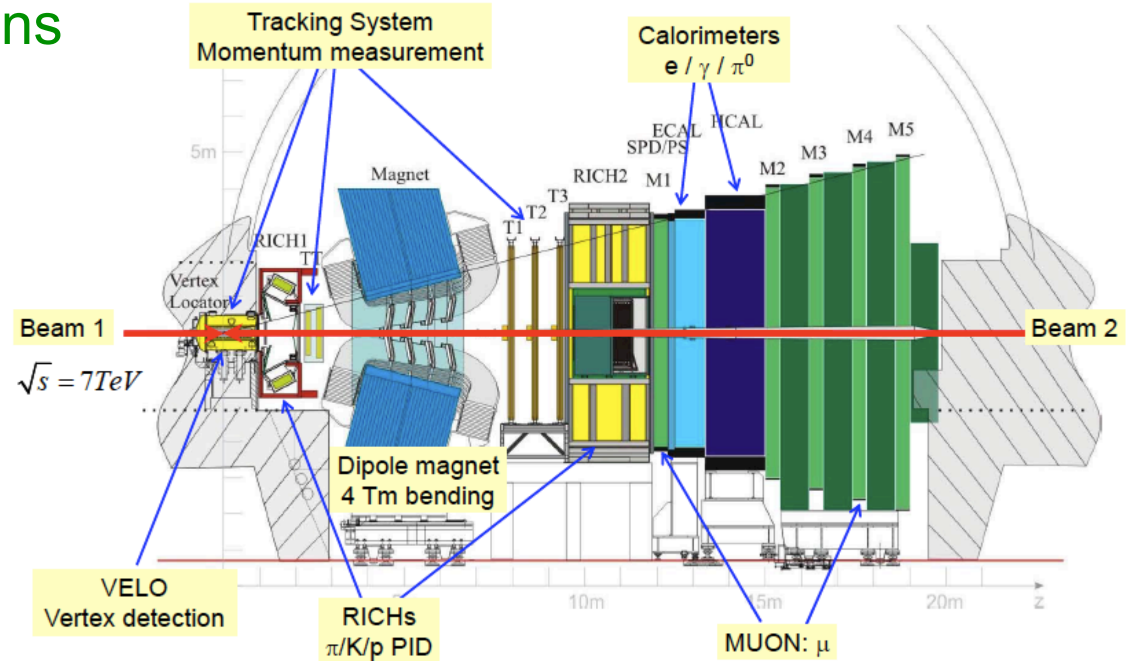
$$\sigma(b\bar{b}) \sim 0.3\ mb$$

LHCB-CONF-2010-013

$$\sigma(c\bar{c}) \sim 6\ mb \sim 20 \times \sigma(b\bar{b})$$

~ 10% of σ_{inel}

Phys.Lett.B694(2010) 209-216



- large cross-section

→ a lot of charm particles produced

- LHCb is a precision detector
  - **VELO** – resolution of IP: 38 μm for $p_T \approx 1$ GeV
  - **Track reconstruction system** – lifetime resolution ~ 50 fs: 0.1 $\tau(D^0)$
  - **RICH** – very good particle identification for π and K: misidentification < 5%

LHCb has possibilities of very precise measurements of charm particles

Mixing parameters

1. Compare ratio of lifetimes in D^0 decays to the CP-even eigenstate f_{CP} ($D^0 \to K^+K^-$) with respect to decays to the CP non-eigenstate RS $f_{non\text{-}CP}$ ($D^0 \to K^-\pi^+$):

$$y_{CP} \equiv \frac{\Gamma(D^0 \to f_{CP})}{\Gamma(D^0 \to f_{non-CP})} - 1 = \frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to K^-\pi^+)} - 1$$
$$= y\cos\phi - \frac{1}{2}A_m x \sin\phi$$

$\cos\phi \neq 1$: CPV in interference between mixing and decay
$A_m \neq 0$: CPV in mixing

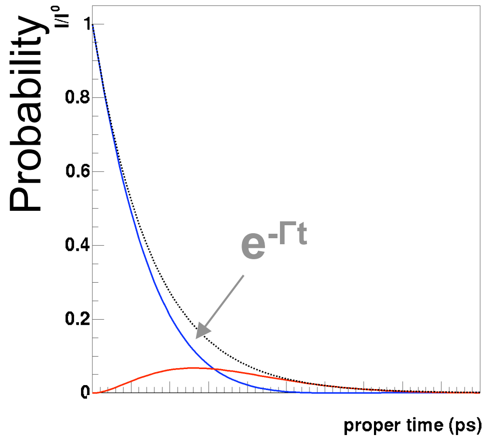
$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

Mass difference:
$$x \equiv \frac{m_2 - m_1}{\Gamma} = \frac{\Delta m}{\Gamma}$$

Width difference:
$$y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma} = \frac{\Delta\Gamma}{2\Gamma}$$

Weak phase:
$$\phi \equiv arg(-M_{12}/\Gamma_{12})$$

if only D^0 decays then
disappearing is exponential
but D^0-anti-D^0 mixing then
disappearing is non exponential
Test deviations from exponent



2. Asymmetry of lifetimes in decays of D^0 and anti-D^0 to the CP eigenstate K^+K^-:

$$A_\Gamma \equiv \frac{\Gamma(D^0 \to f_{CP}) - \Gamma(\bar{D}^0 \to f_{CP})}{\Gamma(D^0 \to f_{CP}) + \Gamma(\bar{D}^0 \to f_{CP})} = \frac{\Gamma(D^0 \to K^+K^-) - \Gamma(\bar{D}^0 \to K^+K^-)}{\Gamma(D^0 \to K^+K^-) + \Gamma(\bar{D}^0 \to K^+K^-)}$$
$$\approx \frac{1}{2}(A_m + A_d)\cos\phi - x\sin\phi$$

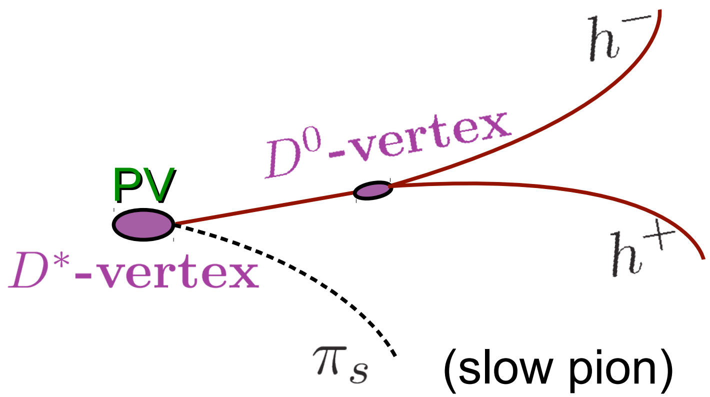
M.Gersabeck et al, J.Phys.G39 (2012) 045005

The measurement requires distinguishing the D^0 flavors at the production state.

The tagging

- **To identify D^0 and anti-D^0** we use $D^{*\pm}$ decays
  - ✧ the sign of slow pion is used to tag the initial D^0 flavour:

$D^{*+} \rightarrow D^0 \pi^+_s$
$D^{*-} \rightarrow \text{anti-}D^0 \pi^-_s$

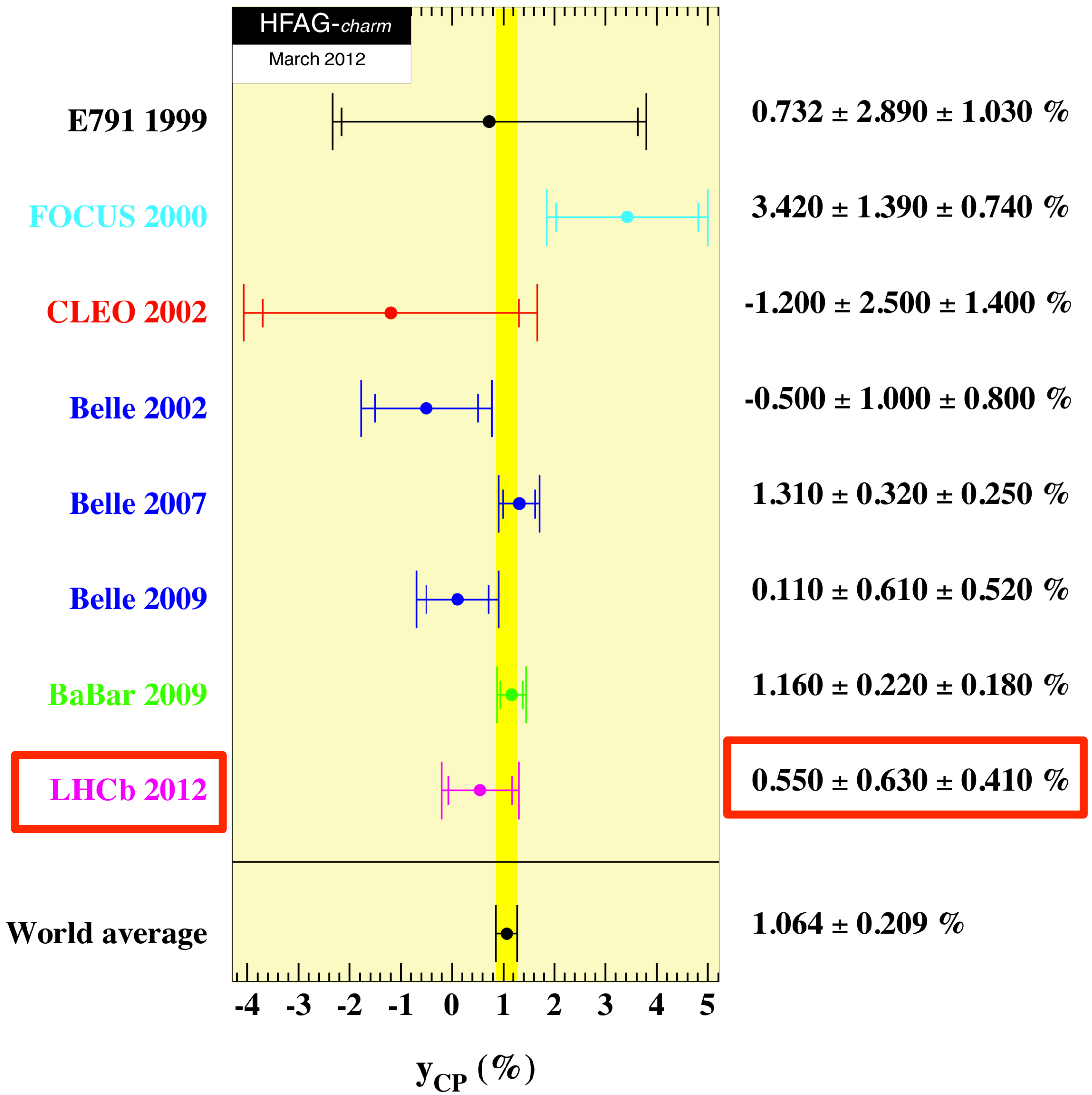


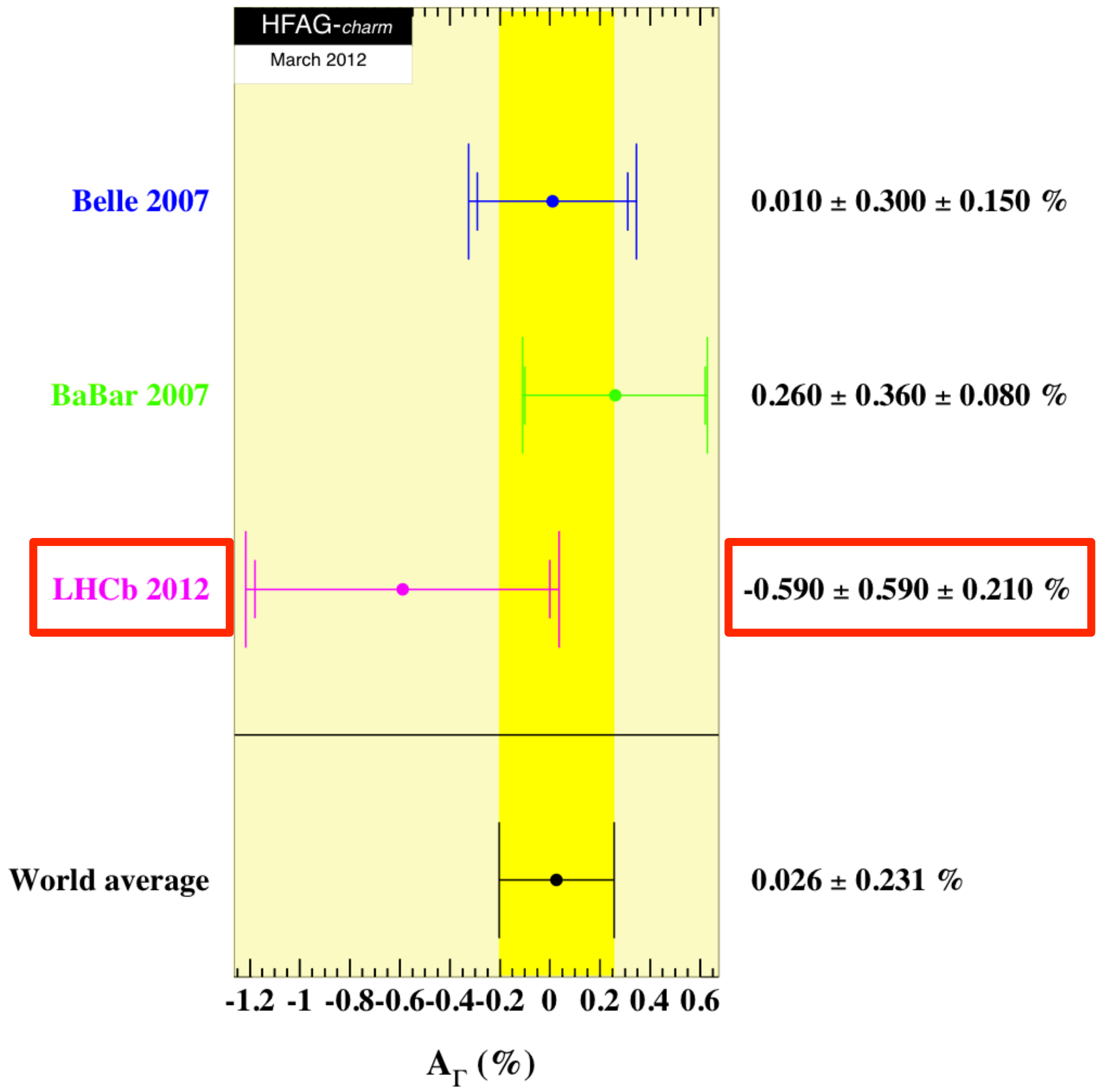
$D^0 \rightarrow h^- h^+$

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

y_{CP} and A_Γ

JHEP04(2012)129
LHCb-PAPER-2011-032





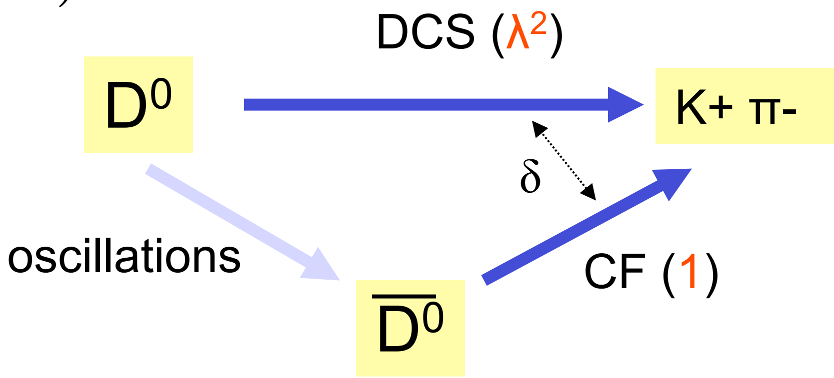
- Both results are in agreement with the current world averages.
- No evidence for indirect CP violation in charm.
- These results are from a tiny fraction of our data set: 2010, 28/pb.
- Updating to full 2011 data set: 1/fb.

Wrong-sign mixing $D^0 \to K^+\pi^-$

Measure time integrated ratio of wrong-sign (WS) to right-sign (RS) $D^0 \to K\pi$ decays:

$$R = \frac{\Gamma_{WS}}{\Gamma_{RS}} = \frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)}$$

In WS $D^0 \to K^+\pi^-$ decays include contribution from DCS (0.4%) and a much smaller contribution from mixing.



The time evolution of WS decay rate can be approximated by

$$\Gamma_{\mathrm{WS}}(t) \propto e^{-\Gamma t}\left(\underbrace{R_{\mathrm{D}}} + \underbrace{\sqrt{R_{\mathrm{D}}}\, y' \,\Gamma t} + \underbrace{\frac{x'^2 + y'^2}{4}(\Gamma t)^2}\right)$$

the rate of the DCS events

the interference of the DCS mixed decays

mixing parameters

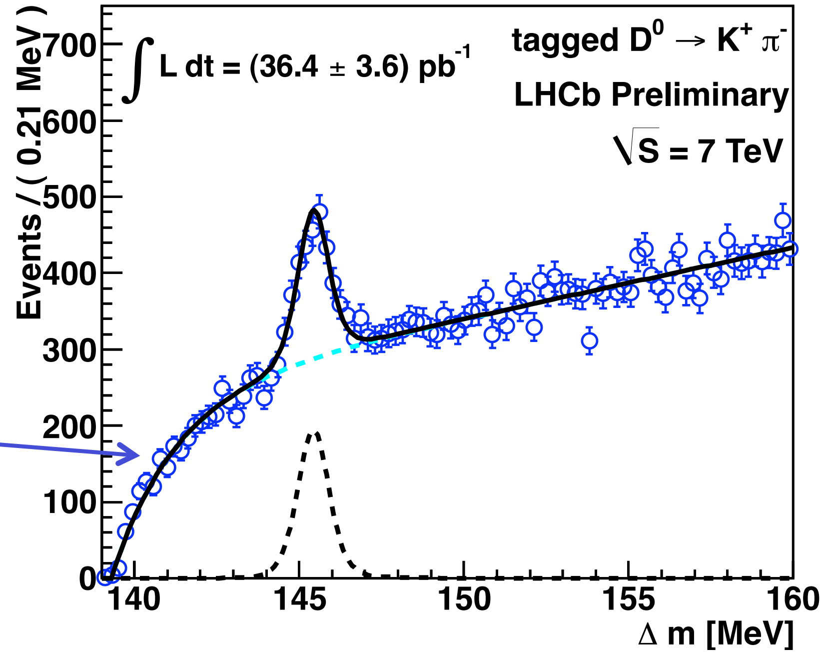
This analysis is a first step towards a time dependent analysis which allows to extract the mixing parameters

Wrong-sign mixing $D^0 \to K^+\pi^-$

- LHCb 2010 data: L=36/pb
- D^0 mesons are reconstructed from $D^{*+} \to D^0\pi^+$
- Charge of the π allows to determine flavour of D^0 mesons

- Charge of the K classifies the decay mode:
  RS: $D^0 \to K^-\pi^+$: 287 038 candidates
  WS: $D^0 \to K^+\pi^-$: 34 997 candidates

mass difference of D* and the D^0
WS candidates



The measured time integrated WS/RS ratio:

$(0.442 \pm 0.033^{stat} \pm 0.042^{syst})\%$

After correction for time acceptance (LHCb Preliminary):

$(0.409 \pm 0.031^{stat} \pm 0.039^{syst})\%$

LHCb-CONF-2011-029

PDG: $(0.380 \pm 0.018)\%$

Result agrees very well with the world average value.

Time integrated CPV

We want to measure asymmetry between charm particles and antiparticles:

$$A_{CP} \equiv \frac{N_{CP}(D^0 \to h^- h^+) - N_{CP}(\bar{D}^0 \to h^- h^+)}{N_{CP}(D^0 \to h^- h^+) + N_{CP}(\bar{D}^0 \to h^- h^+)}$$

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

We use decays of $D^{*\pm}$: $D^{*+} \to D^0 \pi^+_s$ and $D^{*-} \to D^0 \pi^-_s$

Measured total raw asymmetry A_{RAW} is a sum of a few physical asymmetries:

$$A_{RAW}(f)^* = A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^*)$$

- $A_{CP}(f)$: CP asymmetry what we want to measure
- $A_D(f)$: detector asymmetry of D^0 reconstruction
- $A_D(\pi_s)$: detector asymmetry of π_s reconstruction
- $A_P(D^*)$: production asymmetry of D* **in primary vertex** (different numbers of D^{*+} and D^{*-})

Detector asymmetries for $K^- K^+$ and $\pi^- \pi^+$ cancel since the final states are symmetric

$$A_D(K^- K^+) = A_D(\pi^- \pi^+) = 0$$

Detector $A_D(\pi_s)$ and production $A_P(D^*)$ asymmetries will cancel in the first order if we subtract raw asymmetries A_{RAW} for $K^- K^+$ and $\pi^- \pi^+$

- for this reason we measure their difference

$$\Delta A_{CP} \equiv A_{CP}(K^+ K^-) - A_{CP}(\pi^+ \pi^-) = A_{RAW}(K^+ K^-)^* - A_{RAW}(\pi^+ \pi^-)^*$$

We have checked that second order effects are negligible by measured ΔA_{CP} in many kinematic bins.

Invariant mass of K^-K^+ and $\pi^-\pi^+$

D^0 decays come from
$D^{*+} \rightarrow D^0\pi^+$ decays
in region:
$0 < \delta m < 15$ MeV

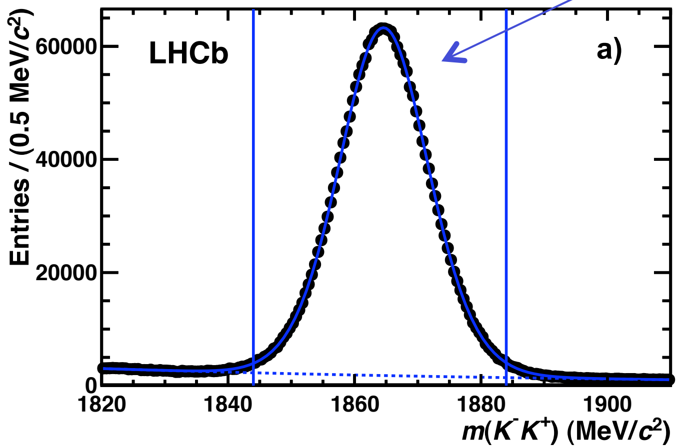
$\delta m = m(D^0\pi^+) - m(D^0) - m(\pi^+)$

For window mass:
$1844 < m(D^0) < 1884$ MeV
K^-K^+: 1.4million events
$\pi^-\pi^+$: 381k events

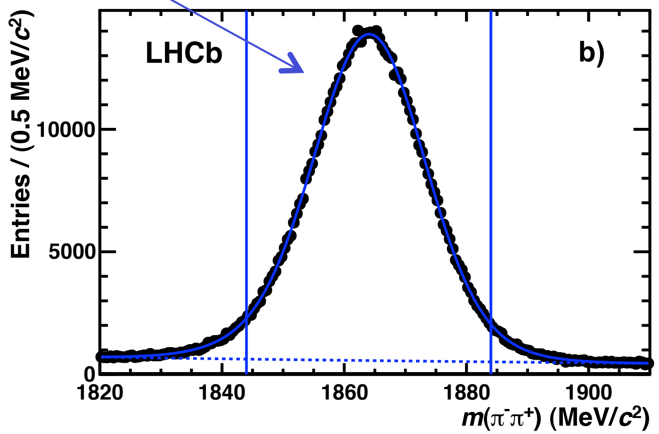
L = 0.62/fb (2011)

This is NOT a Monte Carlo

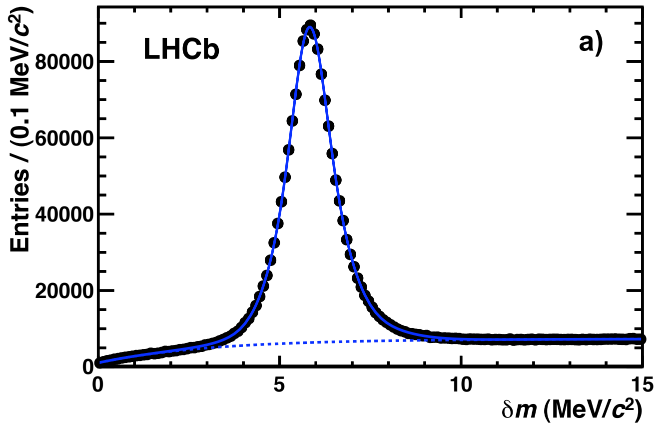
$D^0 \rightarrow K^-K^+$



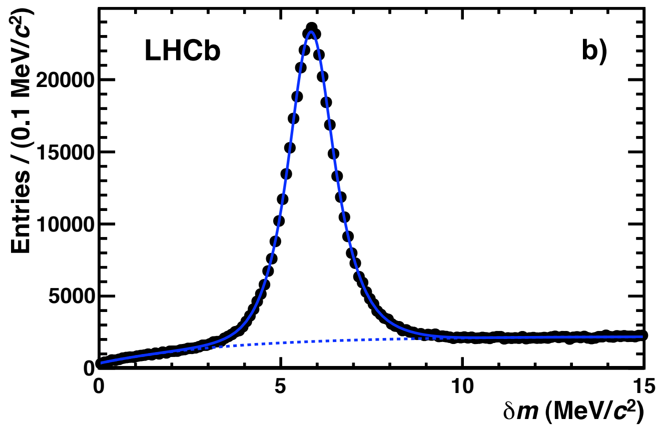
$D^0 \rightarrow \pi^-\pi^+$



$1844 < m(D^0 \rightarrow K^-K^+) < 1884$MeV



$1844 < m(D^0 \rightarrow \pi^-\pi^+) < 1884$MeV



From simultaneous fits for both distributions (D^0 and anti-D^0) to δm we measure:

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

$$\Delta A_{CP} = [-0.82 \pm 0.21^{stat} \pm 0.11^{syst}]\%$$

significance: **3.5** σ

Phys.Rev.Lett 108(2012)111602
LHCb-PAPER-2011-023

ΔA_{CP} interpretation

CPV asymmetry of each final state is a sum of:
CPV in decays and in mixing

$$A_{CP}(f) = a_{CP}^{dir}(f) + \frac{\langle t \rangle}{\tau} a_{CP}^{ind}$$

[JHEP 1106 (2011) 089]

Mean proper time in used sample (acceptances are functions of time and for K^-K^+ and $\pi^-\pi^+$ are not the same)

Lifetime of D^0 (PDG)

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

$$\Delta A_{CP} = [a_{CP}^{dir}(K^-K^+) - a_{CP}^{dir}(\pi^-\pi^+)] + \frac{\Delta\langle t \rangle}{\tau} a_{CP}^{ind}$$

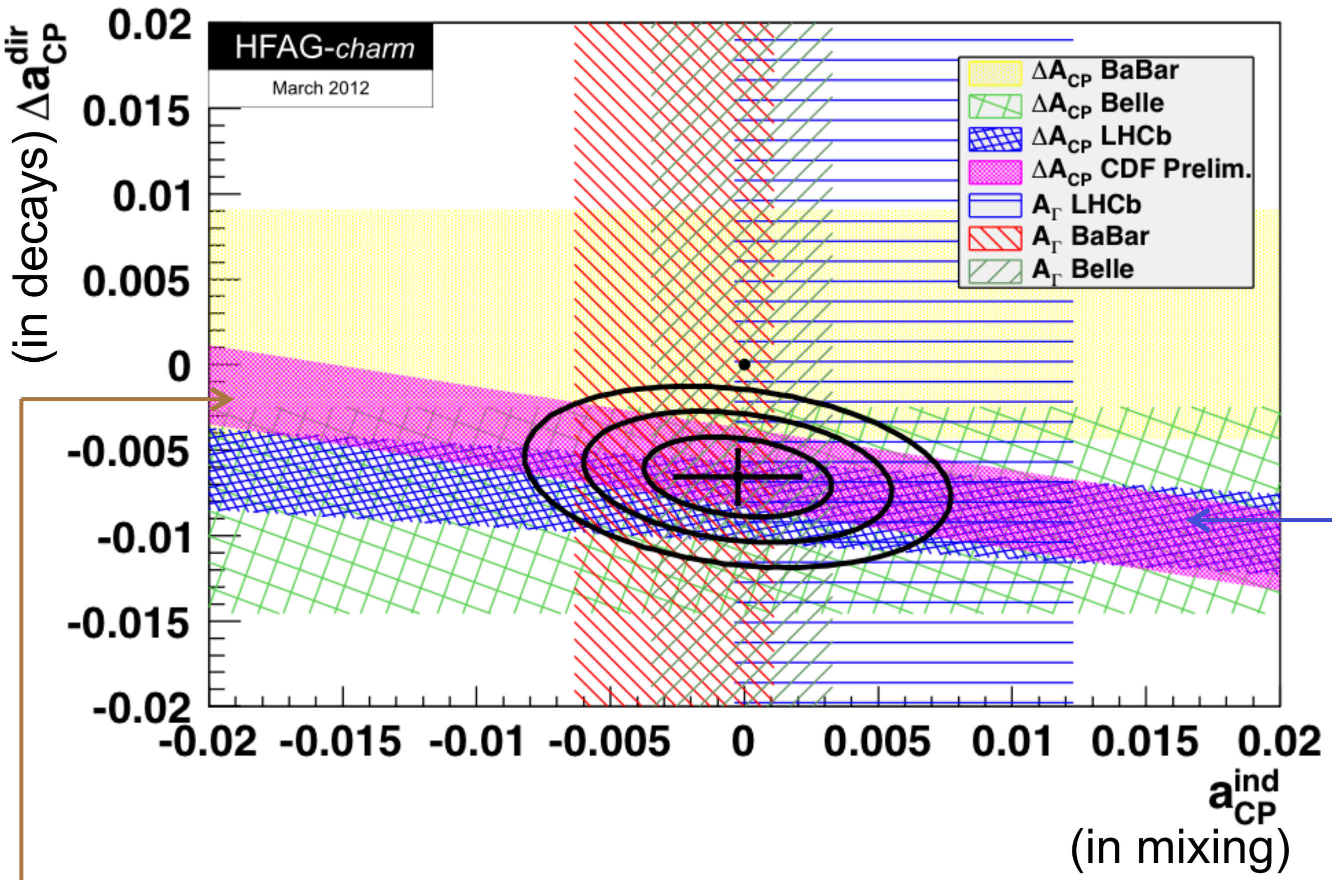
Since CPV in mixing is universal and does not depend on a final state, contributions from mixing would cancel in subtraction, but the mean proper time difference of D^0 is not zero in used samples for K^-K^+ and $\pi^-\pi^+$:

$$\frac{\Delta\langle t \rangle}{\tau} = \frac{\langle t_{KK} \rangle - \langle t_{\pi\pi} \rangle}{\tau} = (9.8 \pm 0.9)\%$$

Contributions from CPV in mixing suppressed in one order of magnitude

In good approximation **we measure the difference of CPV in charm decays**

LHCb and CDF combined



World average before LHCb:
Δa^{dir}_{CP} = (-0.42 ± 0.27) %
1.6σ from zero

LHCb: first evidence for CP violation in charm decays

LHCb 2011 (0.62/fb), Phys.Rev.Lett 108(2012)111602

$$\Delta A_{CP} = [-0.82 \pm 0.21^{stat} \pm 0.11^{syst}]\%$$ 3.5 σ

remaining ~400/pb has been analyzing

CDF (9.7/fb), 28 Feb.2012, CDF Note 10784:

$$\Delta A_{CP} = [-0.62 \pm 0.21^{stat} \pm 0.10^{syst}]\%$$ 2.7 σ

Unofficial HFAG average including both results: **3.8 σ evidence for CPV in charm**

Searches for CP violation in $D^{\pm} \rightarrow hhh$ decays

Finding the evidence for CP violation in $D^0 \rightarrow hh$ decays gives hope to find this asymmetry in other decays as well, for example in $D^{\pm} \rightarrow hhh$

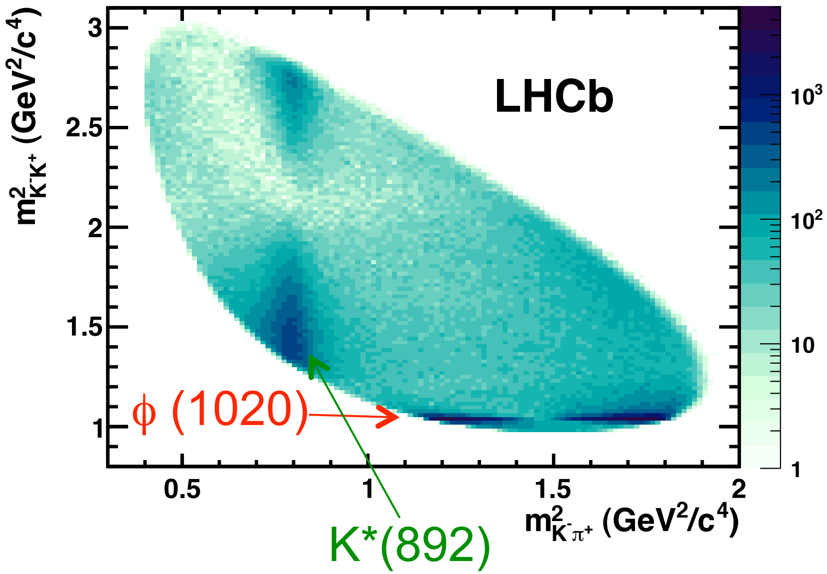
- Partition the Dalitz plot into bins
- For each bin measure **local charge asymmetry**

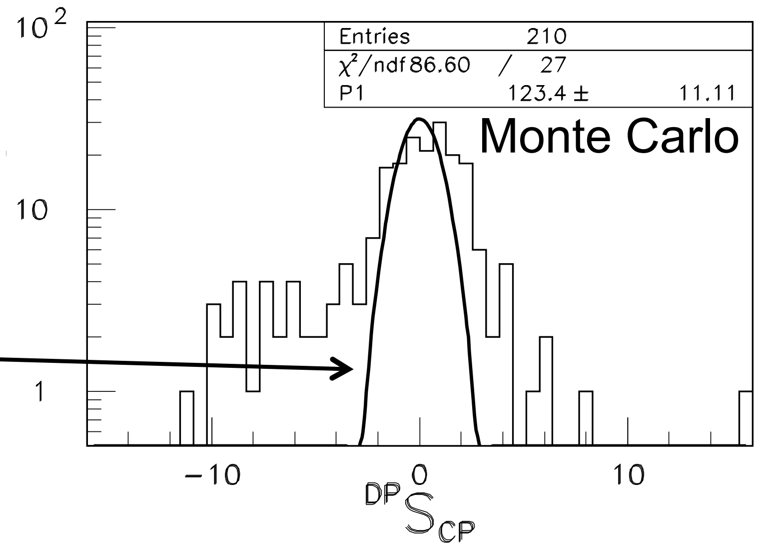
$$S^i_{CP} \equiv \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}} \qquad \alpha = \frac{N(D^+)}{N(D^-)}$$

[Bediaga et al. Phys.Rev.D80(2009)096006]

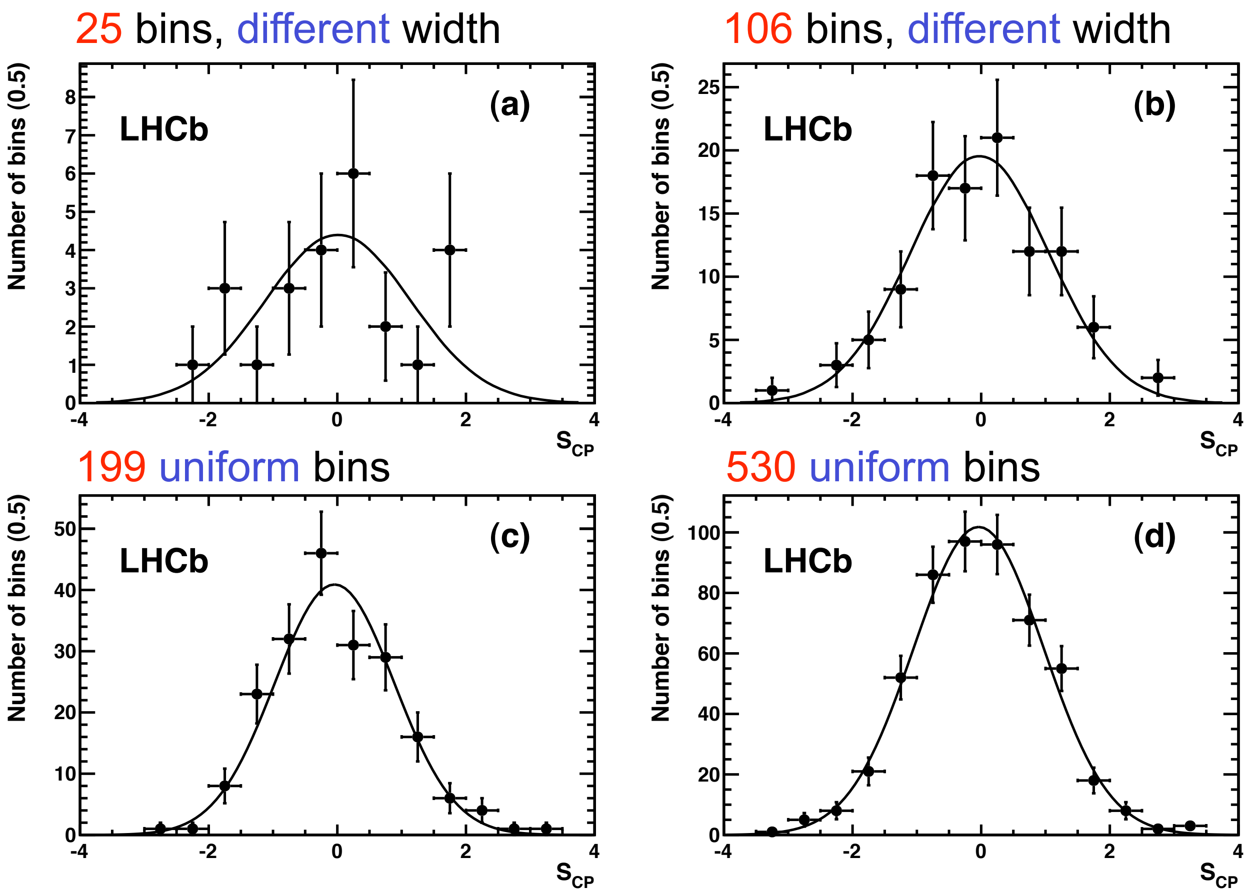
- Normalization cancels most global asymmetries (example production asymmetry)
- S_{CP} is a significance of a difference between D^+ and D^-
- Two equivalent methods:
  - ✧ If no CPV (only statistical fluctuations) then S_{CP} is Gauss distribution (μ=0, σ=1)
  - ✧ Also χ^2 test can be used: $\chi^2 = \Sigma {S^i_{CP}}^2$ → p-value

$D^+ \rightarrow K^- K^+ \pi^+$





Results for $D^+ \to K^- K^+ \pi^+$ (signal of CPV)



- Several binnings in the Dalitz plot used to probe a range of CPV scenarios
- Binning shown consistent with no CPV at p=10%
- Also S_{CP} distributions consistent with standard Gauss distribution (μ~0, σ~1)
- No evidence for CP violation in the 2010 data set of 38/pb, 370k signal (SCS) $D^+ \to K^- K^+ \pi^+$

	μ	σ	χ^2/ndf	P-value
(a)	0.01±0.23	1.13±0.16	32.0/24	12.7%
(b)	-0.024±0.010	1.078±0.074	123.4/105	10.6%
(c)	-0.043±0.073	0.929±0.051	191.3/198	82.1%
(d)	-0.039±0.045	1.011±0.34	519.5/529	60.5%

LHCb-PAPER-2011-017, Phys.Rev.D84.112008

Update to full 2011 data set: 1/fb: ~30 times more signal decays, ~10 million SCS $D^+ \to K^- K^+ \pi^+$ decays

Summary

- LHCb has an important charm physics programme.
- Using data collected in 2010 and 2011, LHCb has performed extensive studies of physics in the charm sector.
- All measurements being improved with larger data sets:
    - ✧ 2011: 1/fb
    - ✧ 2012: we expect to double the 2011 data set.
- The LHCb experiment is more than beauty.

Backup

The trigger and charm physics

LHC rate ~15 MHz

hardware

L0 ~1 MHz
3 subdetectors:
ECAL, HCAL, Muon

c-anti-c ~10%

c-anti-c ~50%

After L0 **~500 kHz c-anti-c** events

No possibility of an inclusive charm trigger!

Possible only dedicated exclusive trigger lines tuned for the needs of specific analyses to deliver high signal efficiency and purity

software

Hlt1 (partial reconstruction) **~50 kHz** (efficiency ~50 %)

Hlt2 (full reconstruction) **3 kHz**
2 kHz – b physics
1 kHz – dedicated exclusive lines of **$D \to hh/3h/4h$** (efficiency 50-90%)

example: 5k $D^{*\pm} \to (D^0 \to K^{\pm}K^{-+})\pi^{\pm}$ for 1 pb^{-1} (**2010:** 38 pb^{-1}, **2011:** 1.1 fb^{-1})

Selection of prompt $D^{*\pm}$ (D^0)

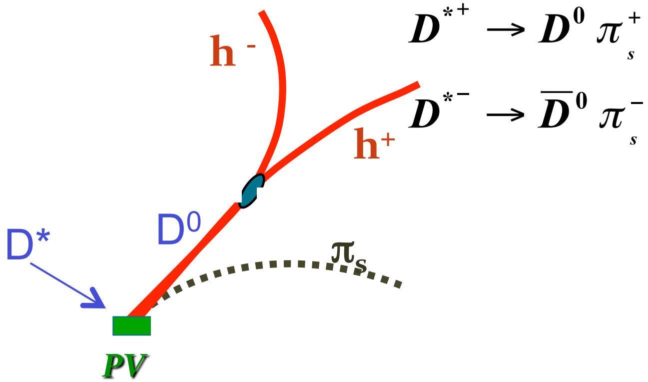
We use $D^{*\pm}$ produced in primary vertex

To separate prompt $D^{*\pm}$ and secondary $D^{*\pm}$ decays we use χ^2(IP) parameter

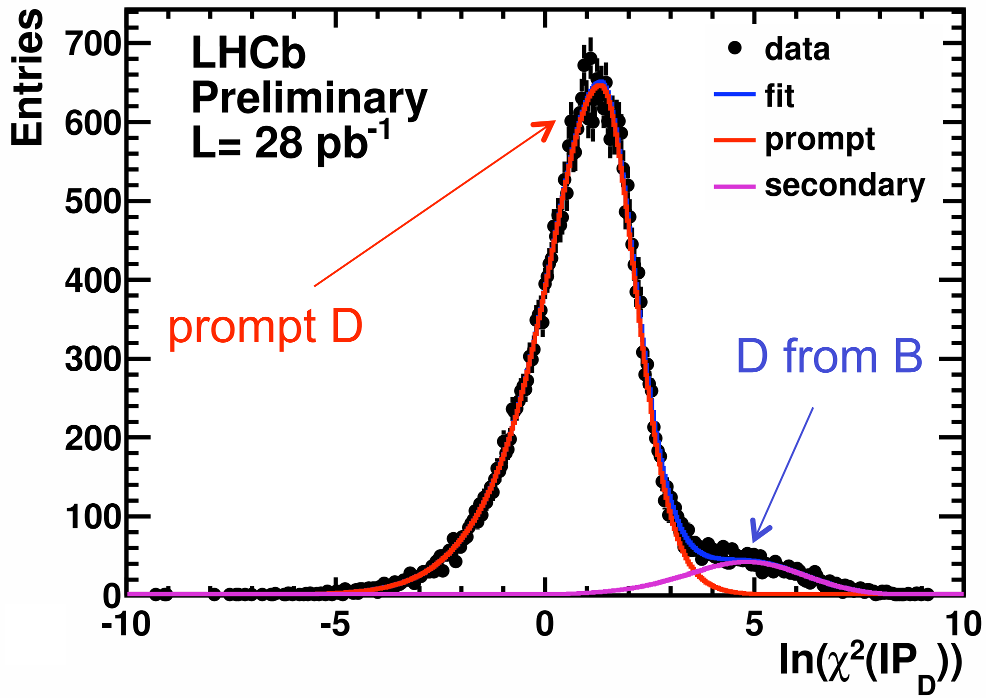
Two production types of $D^{*\pm}$ (D^0):

- **prompt** – produced in primary vertex (PV)

IP(D^0)~0
χ^2(IP)~0

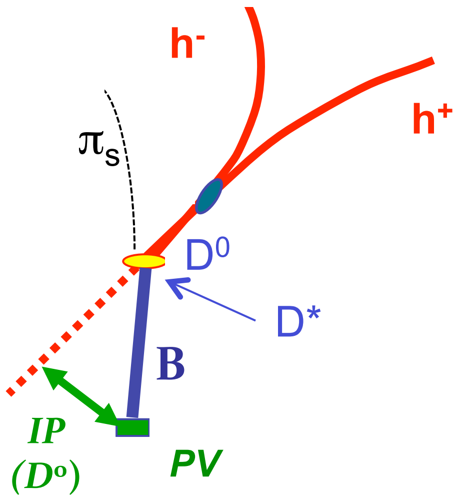


Example for $D^0 \to K^+K^-$



- **secondary** – produced in B decays [B(B→$D^{*\pm}$(D)X)]

IP(D^0)>0
χ^2(IP)>0



IP – impact parameter with respect to the PV

χ^2(IP) – IP significance

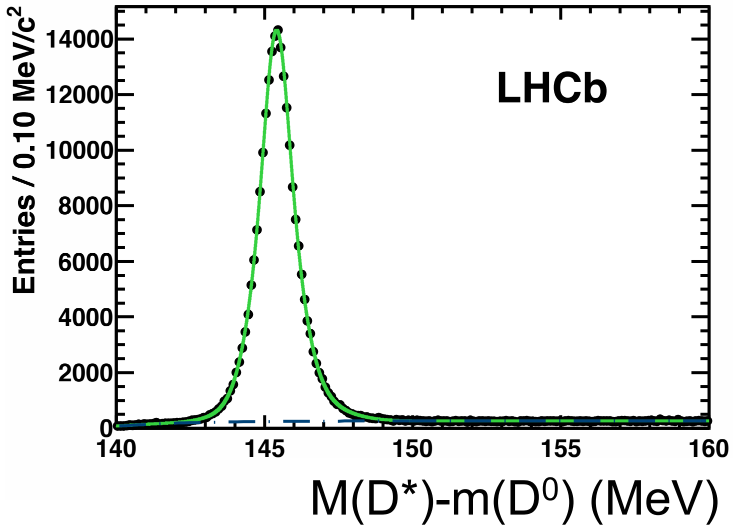
We use χ^2 since it is more effective

Time dependent CPV and mixing

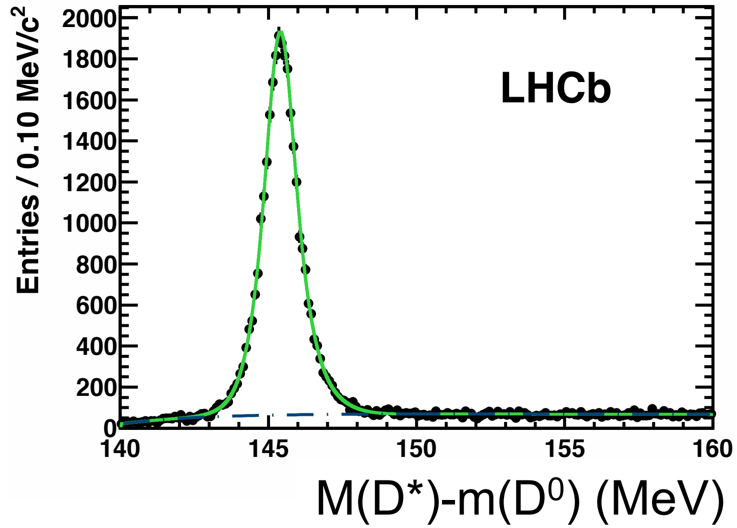
Mass difference between the reconstructed invariant masses of D^{*+} and D^0 candidates

The measurements of y_{CP} and A_Γ are performed based on the same data set:
LHCb 2010: 29/pb

$D^0 \to K^-\pi^+$ 290k candidates



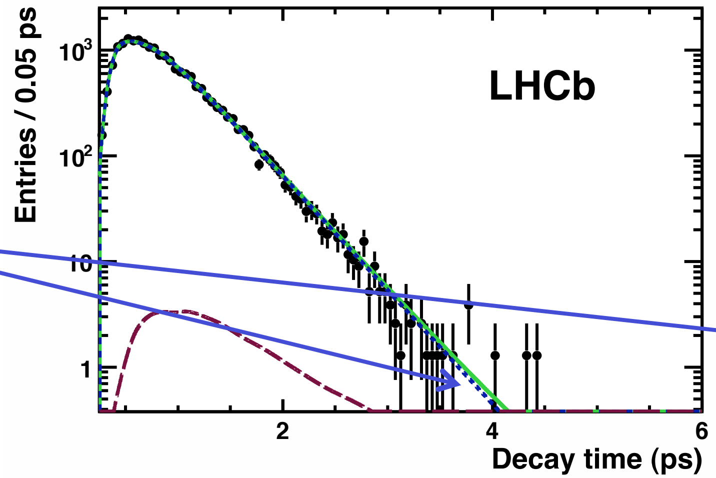
$D^0 \to K^-K^+$ 39k candidates



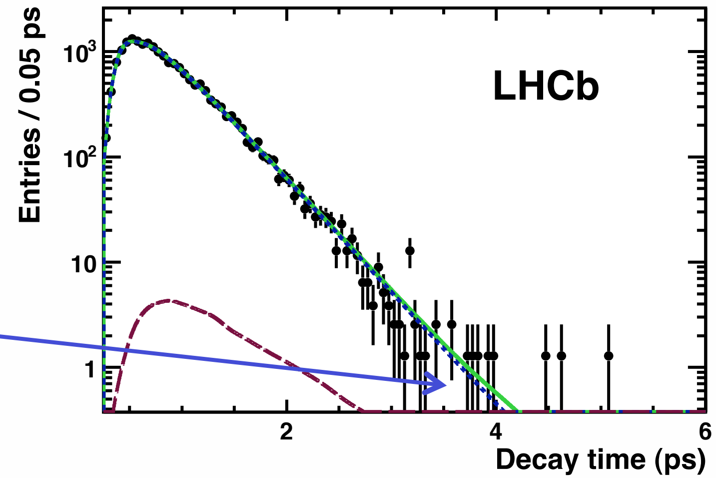
We use particles produced in the primary vertex

Proper-time fit projections

$D^0 \to K^-K^+$



anti-$D^0 \to K^-K^+$



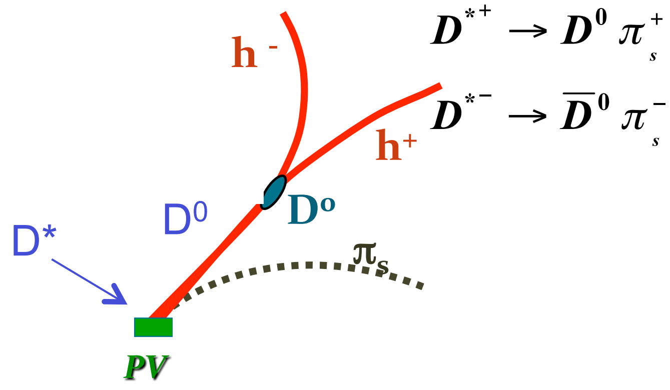
Points – data
Green solid – the total fit
Blue short-dashed (mostly hidden by green) – the prompt signal
Dark red long-dashed – the secondary signal, background from $B \to D\ldots$

Selection criteria

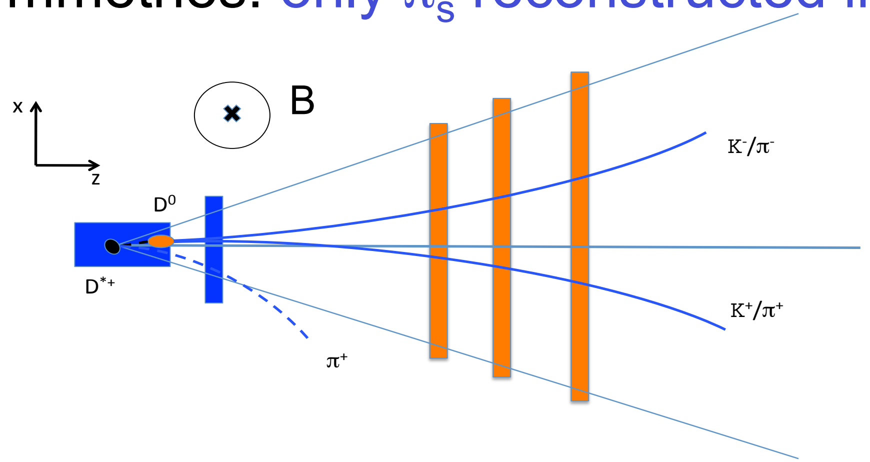
$D^{*+} \rightarrow D^0 \pi^+_s$, $D^{*-} \rightarrow$ anti-$D^0 \pi^-_s$

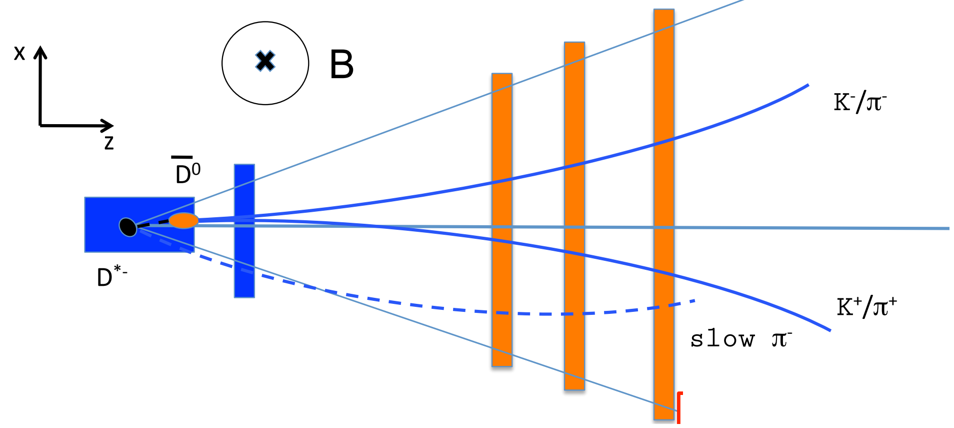
$D^0 \rightarrow K^- K^+$, $D^0 \rightarrow \pi^- \pi^+$

- Impact parameter significance for D^0: χ^2 IP(D^0)<9
- Vertex fit quality of D^0 (D^*)
- Track fit quality for all the tracks $K^- K^+ \pi^\pm_s$, $\pi^- \pi^+ \pi^\pm_s$
- Transverse momentum of D^0: $p_T(D^0)$>2 GeV
- Proper lifetime of D^0: $c\tau$>100 μm
- Identification of K and π



- Fiducial cuts to exclude edges where we have large D^{*+}/D^{*-} acceptance asymmetries: only π_s reconstructed in central part of the detector are considered





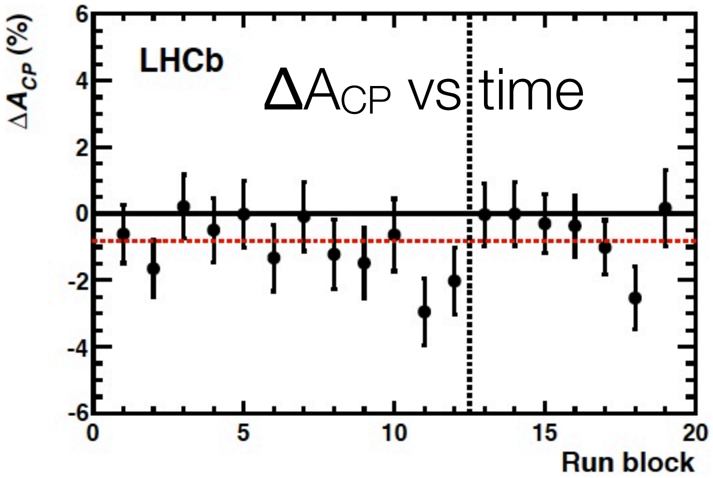
$D^{*+} \rightarrow D^0 \pi^+$ unreconstructed $D^{*-} \rightarrow$ anti-$D^0 \pi^-_s$ reconstructed

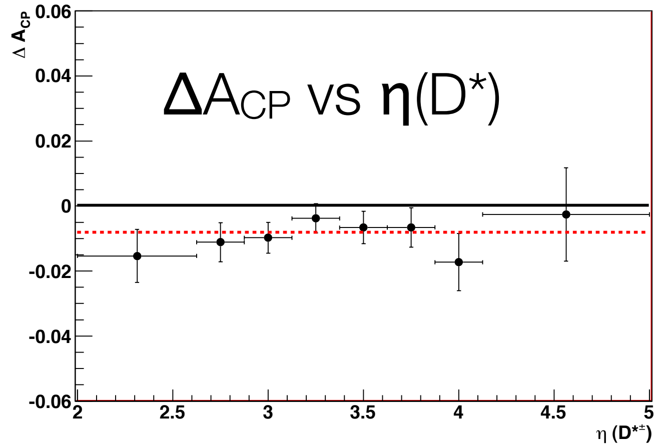
$\rightarrow$ large asymmetry between D^{*+} and D^{*-} in edges of acceptance region

- Mass window of D^0: 1844 < m(D^0) < 1884 MeV

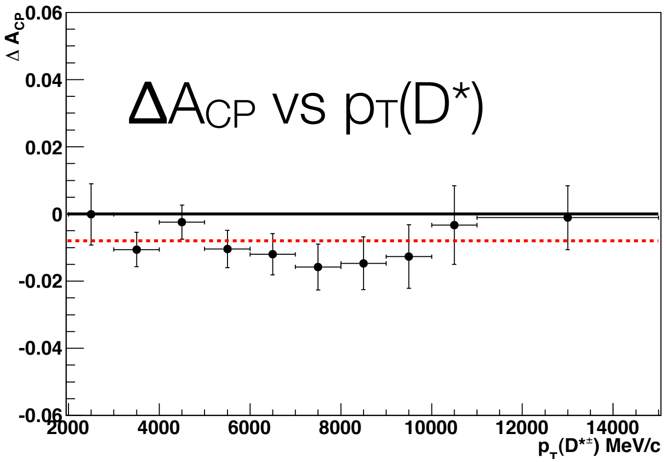
Many cross checks. Here 4 of them

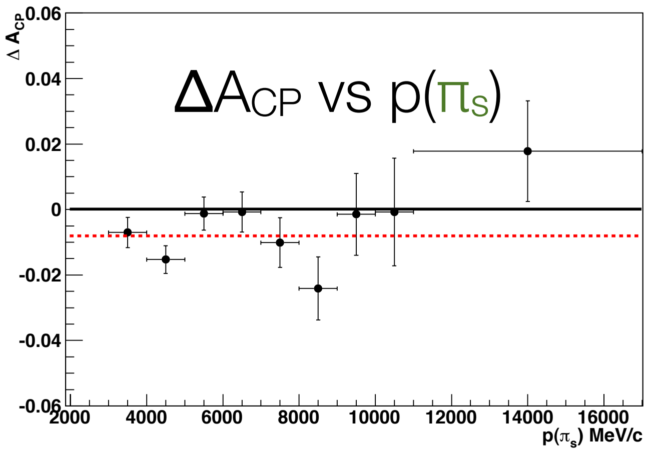
Measured ΔA_{CP} in bins of run blocks, $\eta(D^*)$, $p_T(D^*)$ i $p(\pi_s)$





Red line – final result



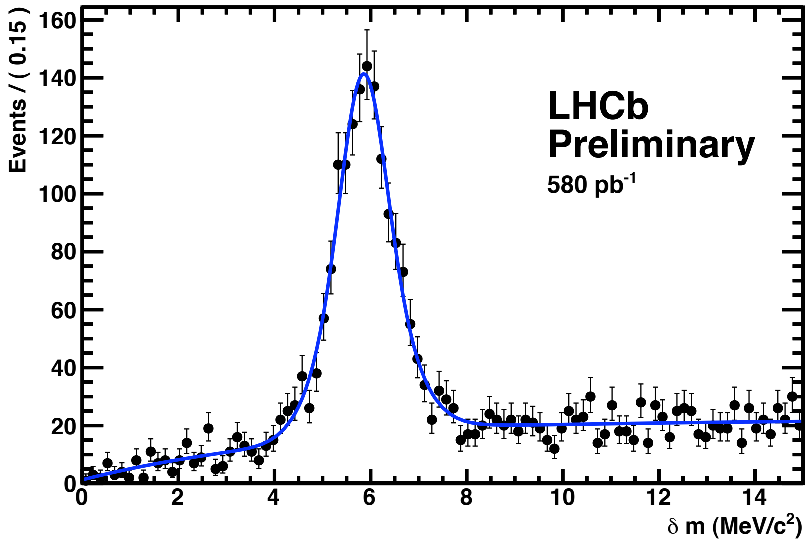


No dependence of measured ΔA_{CP} on run blocks, $\eta(D^*)$, $p_T(D^*)$ and $p(\pi_s)$
→ possible second order asymmetries are negligible

Measurement procedure of ΔA_{CP} at LHCb

- Raw asymmetries $A_{RAW}(K^-K^+)$ and $A_{RAW}(\pi^-\pi^+)$ are obtained from simultaneous fits for both distributions (D^0 and anti-D^0) $\delta m = m(D^0\pi^+) - m(D^0) - m(\pi^+)$ in **216 bins**:
  - 54 kinematic bins of $p_T(D^*)$, $\eta(D^*)$, $p(\pi_s)$
    - production and detector asymmetries can depend on p_T and η
    - reconstruction efficiencies for K^- and K^+ or π^- and π^+ can be different
  - x 2 = 108 bins
    two polarizations of magnetic field
  - x 2 = 216 bins
    two periods of data taking: before and after technical stop: 350 pb^{-1}, 270 pb^{-1}
  - 432 independent fits for $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$

Example: first bin for $D^0 \to K^-K^+$, MagUp



- **216 values of ΔA_{CP}:**

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$
$$= A_{RAW}(K^+K^-)^* - A_{RAW}(\pi^+\pi^-)^*$$

It was checked that measured asymmetries are consistent in all bins

- Final $\Delta A_{CP} \to$ weighted average
- **Total statistical uncertainty of ΔA_{CP}: 0.21%**

Systematic uncertainties

Systematic uncertainties which have the highest contribution:

- Fit procedure: **0.08 %**
  - evaluated as a change in ΔA_{CP} between baseline fit and not using any fitting at all (just sideband subtraction in δm for KK and $\pi\pi$ modes)
- Multiple candidates: **0.06 %**
  - evaluated as a mean change in ΔA_{CP} when removing multiple candidates, keeping only one candidate per event chosen at random
- Kinematic binning: **0.02%**
  - evaluated as a change in ΔA_{CP} between full 216-bin kinematic binning and "global" analysis with just one giant bin

Total systematic uncertainty: **0.11%**

Final result (weighted average, LHCb 2011, **0.62 fb^{-1}**):

$$\Delta A_{CP} = [-0.82 \pm 0.21^{stat} \pm 0.11^{syst}]\%$$

significance: **3.5** σ → FIRST EVIDENCE

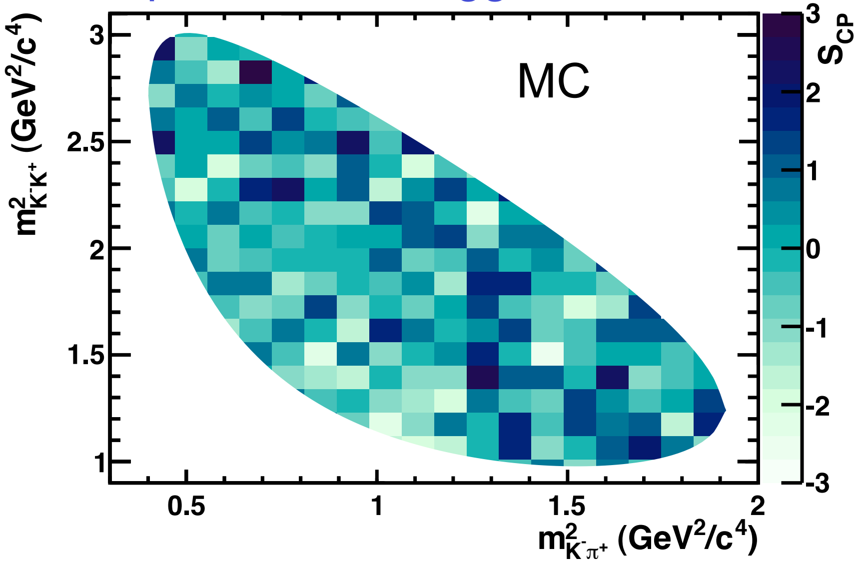
Tests of the method

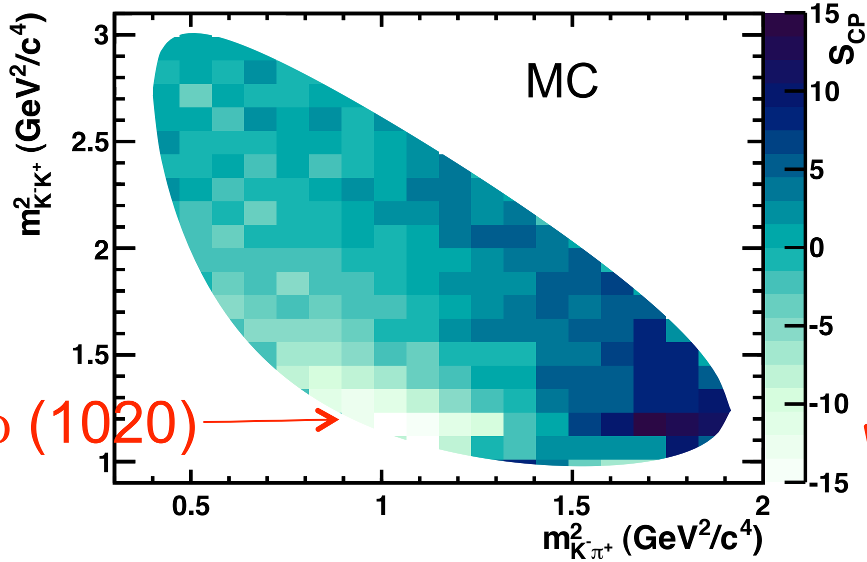
- **Check the response of the method on Monte Carlo (Dalitz models from CLEO-c, arXiv:0807.4545):**
  - should not generate signal where it is not expected
  - should give a visible signal where it is expected

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

Sample 50 times bigger than 2010

5×10^7 events with 4^0 weak phase difference between amplitudes for resonance of $\phi(1020)$ from $D^+ \to \phi\pi^+$ a $D^- \to \phi\pi^-$





ϕ (1020)

The same bins
Different scale of S_{CP}

If no CPV then no signal (good)
P-value ~5%
→ no CP asymmetry

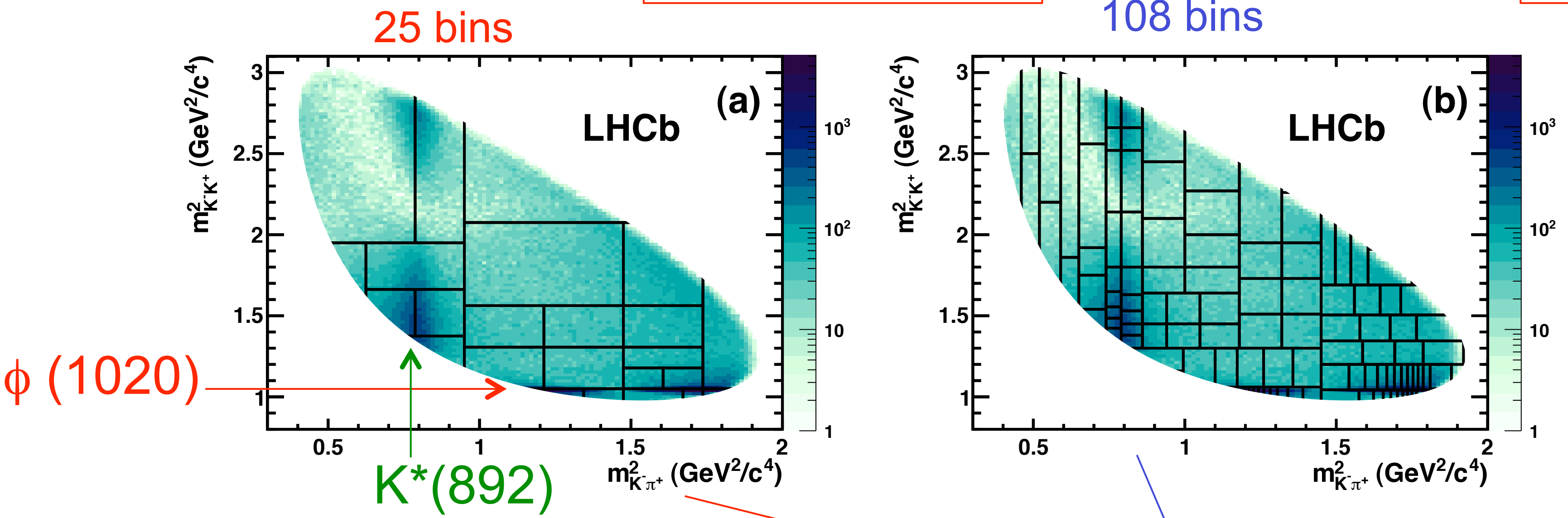
If CPV then P-value ~10^{-100}
– there is CP asymmetry
– visible sign change of S_{CP} in ϕ region

Number of bins test

Bins with different widths

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

Monte Carlo



	P(3σ)	P(3σ)
No CPV	0%	1%
6^0 weak phase difference in ϕ(1020)	99%	98%
4^0 weak phase difference in ϕ(1020)	76%	41%

Version with 25 bins is better

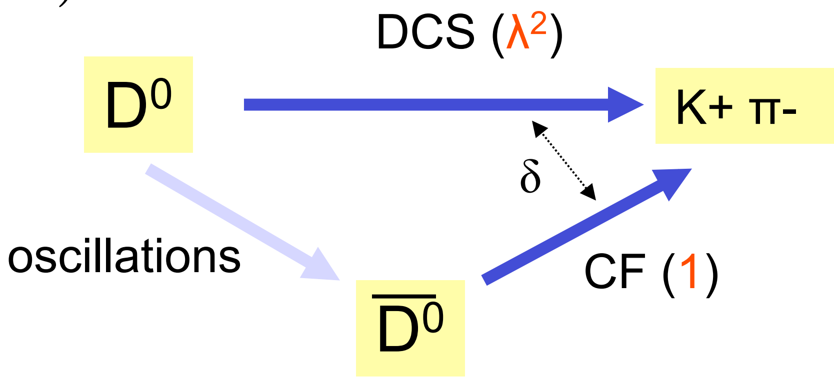
100 the same experiments and check how many times obtained 3σ

Wrong-sign mixing $D^0 \to K^+\pi^-$

Measure time integrated ratio of wrong-sign (WS) to right-sign (RS) $D^0 \to K\pi$ decays:

$$R = \frac{\Gamma_{WS}}{\Gamma_{RS}} = \frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)}$$

In WS $D^0 \to K^+\pi^-$ decays include contribution from DCS (0.4%) and a much smaller contribution from mixing.



The time evolution of WS decay rate can be approximated by

$$\Gamma_{\mathrm{WS}}(t) \propto e^{-\Gamma t}\left(\underbrace{R_{\mathrm{D}}} + \underbrace{\sqrt{R_{\mathrm{D}}}\, y'\, \Gamma t} + \underbrace{\frac{x'^2 + y'^2}{4}}(\Gamma t)^2 \right)$$

- R_{D}: the rate of the DCS events
- $\sqrt{R_{\mathrm{D}}}\, y'\, \Gamma t$: the interference of the DCS mixed decays
- $\frac{x'^2 + y'^2}{4}$: mixing parameters

$$x' \equiv x\cos\delta + y\sin\delta$$
$$y' \equiv -x\sin\delta + y\cos\delta$$

This analysis is a first step towards a time dependent analysis which allows to extract the mixing parameters

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix} = \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$