XI International Conference on Hyperons, Charm and Beauty Hadrons
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Charm mixing and CP violation at LHCb

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Outline

- **Introduction**
  - ✧ Why are we interested in charm physics?
    - ✓ phenomenology of D^0 – anti-D^0 mixing and CPV
    - ✓ SM predictions
- **Measurements of mixing and CPV in charm sector at LHCb**
  - ✧ observation of D^0 – anti-D^0 mixing
  - ✧ A_Γ asymmetry from $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$
  - ✧ ΔA_{CP} in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ from $B \to D^0\mu X$
  - ✧ Search for CPV in:
    - ✓ $D^+_{(s)} \to K^0_{(s)}h^+$
    - ✓ $D^+ \to \pi\pi\pi$
    - ✓ $D^0 \to KK\pi\pi$
- **Summary and prospects**

Mixing of neutral mesons

Neutral mesons can oscillate between matter and anti-matter,
mass eigenstates are different from flavour eigenstates

$$i\frac{d}{dt}\begin{pmatrix}|D^0\rangle\\|\overline{D}^0\rangle\end{pmatrix}=\left[\begin{pmatrix}M_{11} & M_{12}\\ M_{12}^* & M_{22}\end{pmatrix}-\frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12}\\ \Gamma_{12}^* & \Gamma_{22}\end{pmatrix}\right]\begin{pmatrix}|D^0\rangle\\|\overline{D}^0\rangle\end{pmatrix}$$

$$m\equiv(m_1+m_2)/2$$
$$\Gamma\equiv(\Gamma_1+\Gamma_2)/2$$

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

(D^0 – as an example, the same for B^0, B^0_s)

Two parameters describe mixing (*x*,*y*):

mass difference Δm:

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

decay width difference ΔΓ:

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

experiment theory

$$\Delta m = M_H - M_L = 2|M_{12}|(1+\tfrac{1}{8}\tfrac{|\Gamma_{12}|^2}{|M_{12}|^2}sin^2\phi+...)$$

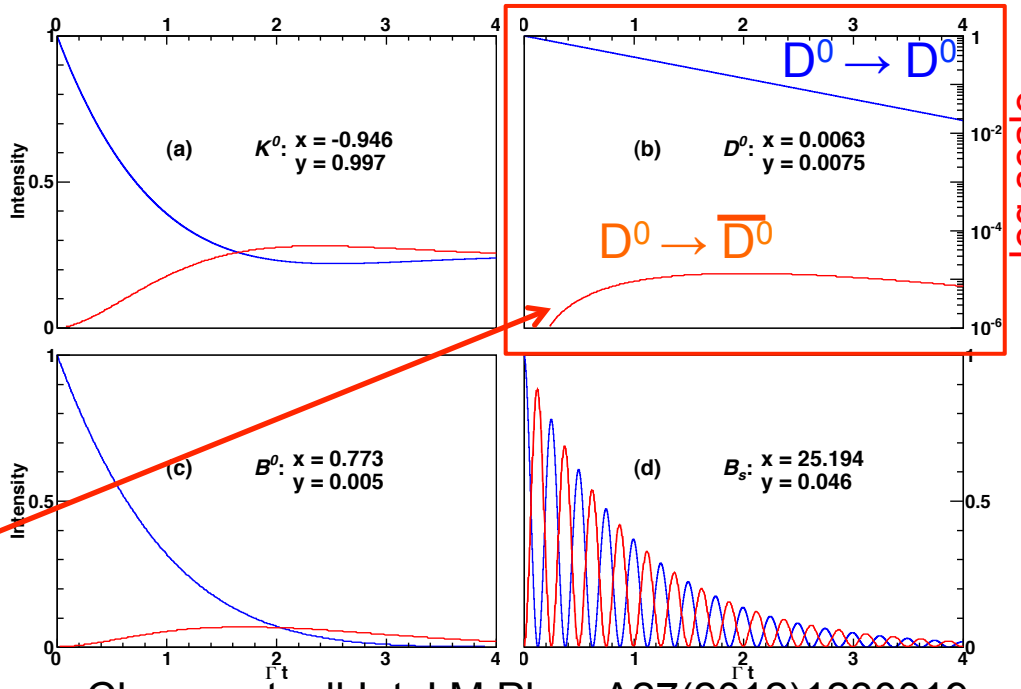
$$\Delta\Gamma = \Gamma_H - \Gamma_L = 2|\Gamma_{12}|cos\phi(1-\tfrac{1}{8}\tfrac{|\Gamma_{12}|^2}{|M_{12}|^2}sin^2\phi+...)$$

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

Δm, ΔΓ, φ – measured experimentally

For charm: *x* and *y* are small

- Mixing is very slow
- Very precise measurements needed

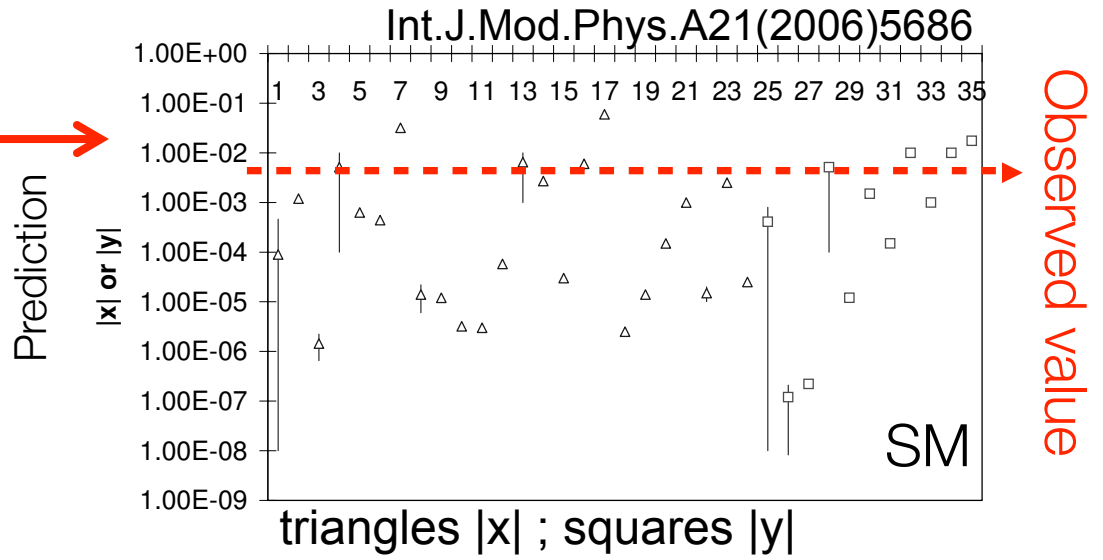


Chavez et. all Int.J.M.Phys.A27(2012)1230019

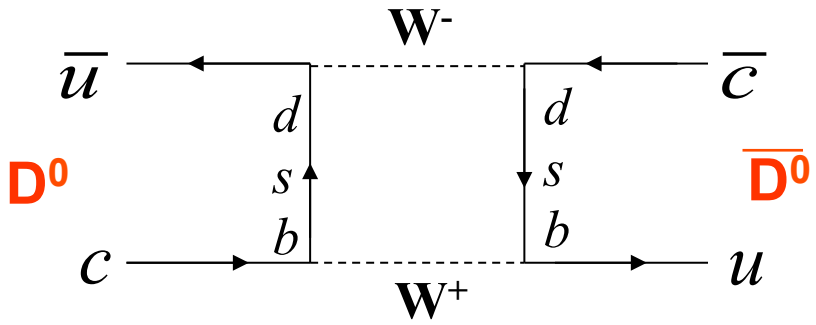
SM predictions for charm

- In SM:
  - ✧ the charm mixing rate is expected to be small: $|x|,|y| \lesssim 10^{-2}$
  - ✧ expected CPV in charm sector is small $\lesssim 10^{-3}$ (much smaller than in the beauty sector)
  - ✧ SM predictions vary widely
  - ✧ New Physics contributions can enhance CPV up to 10^{-2}

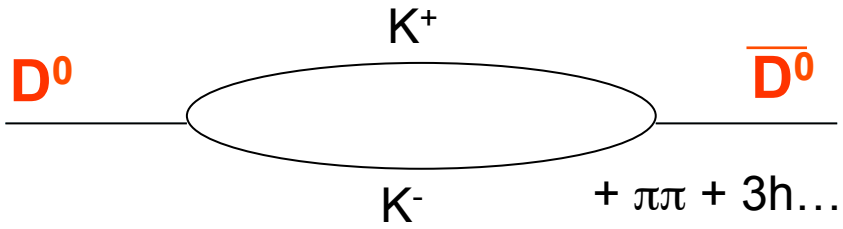
Int.J.Mod.Phys.A21(2006)5381 ;
Ann.Rev.Nucl.Part.Sci.58(2008)249



- Perfect place for New Physics searching (small background from SM)



Mixing via box-diagram, short range



Mixing via hadronic intermediate states, long range (difficult to calculate)

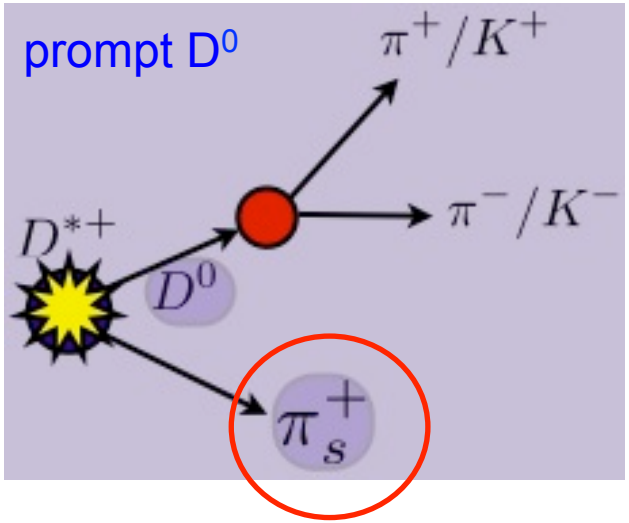
The tagging of D^0 flavour

LHCb uses two statistically independent methods to identify D^0 flavour

- pion-tagged method (exclusive)
  the sign of slow pion from D* decays is used to tag the initial D^0 flavour

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

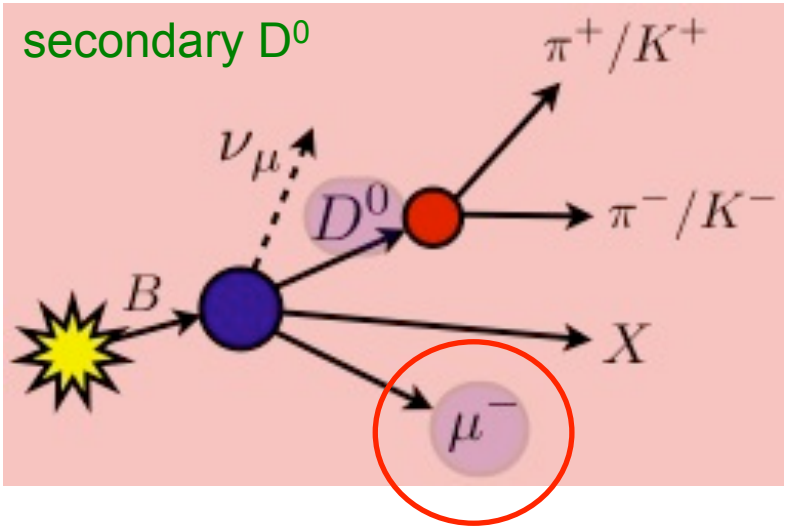
  $D^{*-} \rightarrow \text{anti-}D^0 \pi^-_s$



- muon-tagged method (inclusive)
  the sign of muon from semileptonic B decays is used to tag D^0 flavour

  $B \rightarrow D^0 \mu^- \nu_\mu X$

  $B \rightarrow \text{anti-}D^0 \mu^+ \nu_\mu X$

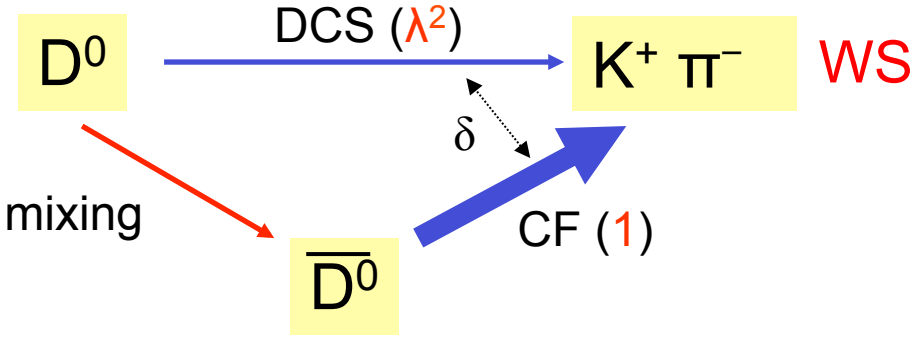


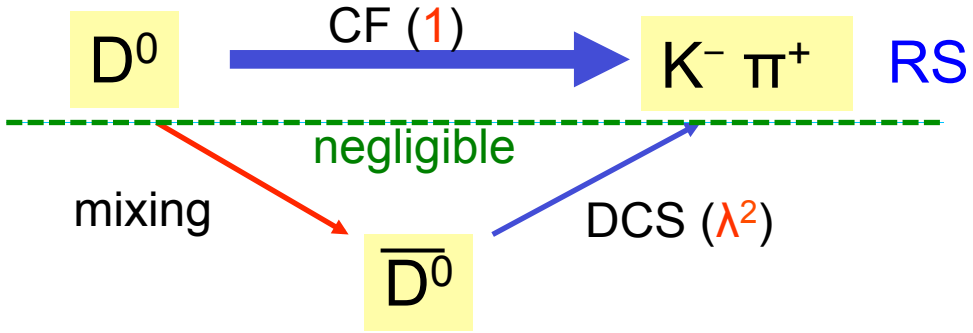
D^0 – anti-D^0 mixing

Measure the time-dependent ratio of D^0 decays with Wrong Sign to Right Sign

$$R(t) = \frac{N(D^0 \to K^+\pi^-)}{N(D^0 \to K^-\pi^+)}$$

PRL 111 (2013) 251801





In the limit of small mixing |x|,|y| << 1 and for no CPV:

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D}\,y't + \frac{x'^2 + y'^2}{4}t^2$$

DCS – double Cabibbo suppressed
CF – Cabibbo favoured

the ratio of DCS to CF decay rates

the interference of the DCS and mixed decays

mixing parameters

$$x' = x\cos\delta + y\sin\delta \qquad y' = y\cos\delta - x\sin\delta$$

If CPV not negligible

$R^+(t)$ (for D^0) $\neq$ $R^-(t)$ (for anti-D^0)

δ is a strong phase difference between DCS and CF amplitudes

Results for D^0 – anti-D^0 mixing

We determine the time-dependent WS/RS ratios in thirteen D^0 decay time bins

R^+ for $D^{*+} \to D^0 \pi^+_s$

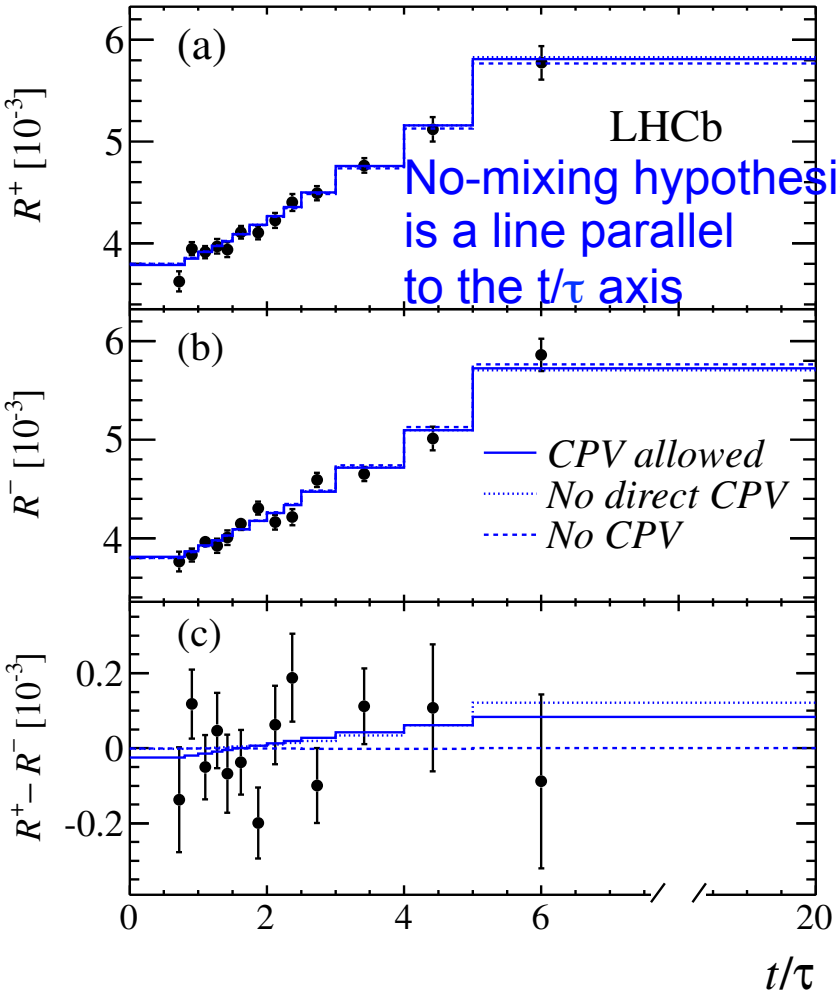
R^- for $D^{*-} \to$ anti-$D^0 \pi^-_s$

PRL 111 (2013) 251801

LHCb 3/fb (2011+2012):

0.23M WS decays
$D^0 \to K^+\pi^-$

54M RS decays
$D^0 \to K^-\pi^+$



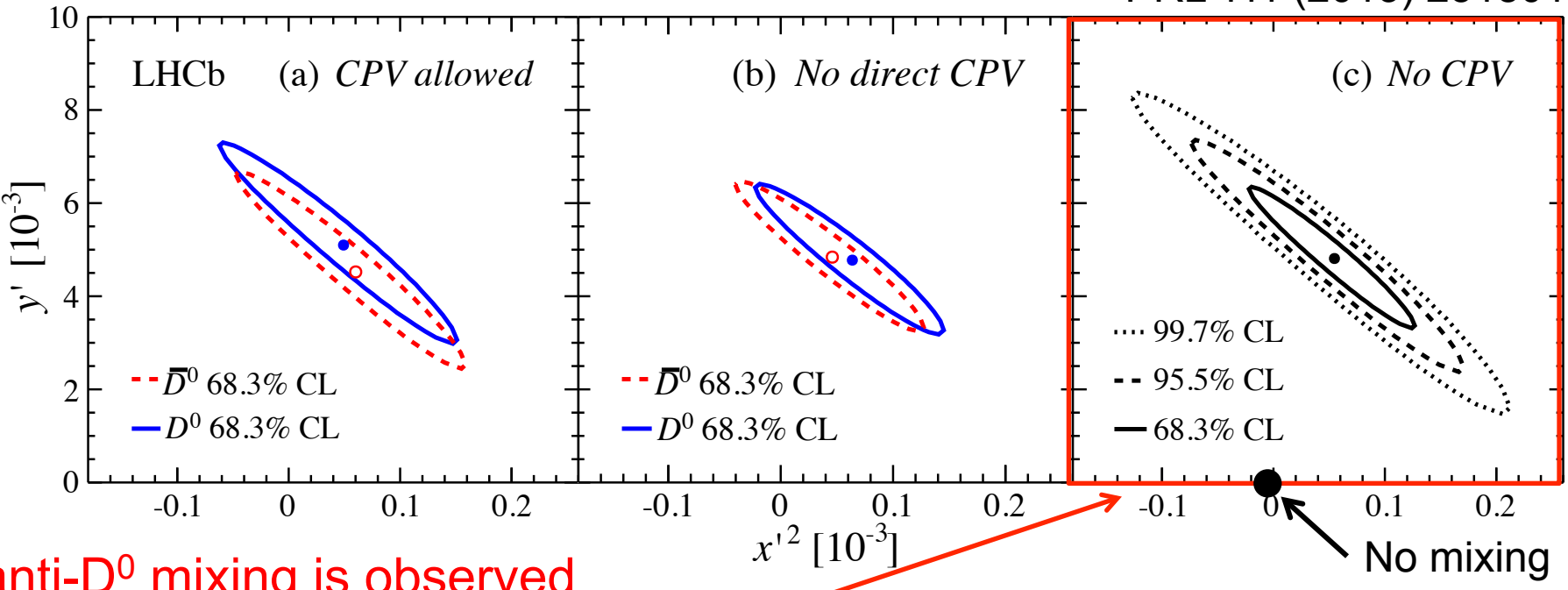
Direct and indirect *CP* violation		
R_D^+	$[10^{-3}]$	$3.545 \pm 0.082 \pm 0.048$
y'^+	$[10^{-3}]$	$5.1 \pm 1.2 \pm 0.7$
x'^{2+}	$[10^{-5}]$	$4.9 \pm 6.0 \pm 3.6$
R_D^-	$[10^{-3}]$	$3.591 \pm 0.081 \pm 0.048$
y'^-	$[10^{-3}]$	$4.5 \pm 1.2 \pm 0.7$
x'^{2-}	$[10^{-5}]$	$6.0 \pm 5.8 \pm 3.6$
χ^2/ndf		85.9/98
No direct *CP* violation		
R_D	$[10^{-3}]$	$3.568 \pm 0.058 \pm 0.033$
y'^+	$[10^{-3}]$	$4.8 \pm 0.9 \pm 0.6$
x'^{2+}	$[10^{-5}]$	$6.4 \pm 4.7 \pm 3.0$
y'^-	$[10^{-3}]$	$4.8 \pm 0.9 \pm 0.6$
x'^{2-}	$[10^{-5}]$	$4.6 \pm 4.6 \pm 3.0$
χ^2/ndf		86.0/99
No *CP* violation		
R_D	$[10^{-3}]$	$3.568 \pm 0.058 \pm 0.033$
y'	$[10^{-3}]$	$4.8 \pm 0.8 \pm 0.5$
x'^2	$[10^{-5}]$	$5.5 \pm 4.2 \pm 2.6$
χ^2/ndf		86.4/101

D^0 – anti-D^0 mixing is observed

Translation into D^0 – anti-D^0 mixing parameters

Estimated confidence-level (CL) regions

PRL 111 (2013) 251801



D^0 – anti-D^0 mixing is observed

Results assuming CP conservation:

$x'^2 = (5.5 \pm 4.9) \times 10^{-5}$

$y' = (4.8 \pm 1.0) \times 10^{-3}$

$R_D = (3.568 \pm 0.066) \times 10^{-3}$

x'^2 is very small

Measurement is more sensitive to y'

CP-violating parameters:

1. CPV in mixing
   $0.75 < |q/p| < 1.24$ (68.3% CL)
2. Direct CPV

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.7 \pm 1.9)\%$$

No indication of direct or indirect CPV

A_Γ asymmetry

The asymmetry of the inverse of effective lifetimes in decays of D^0 and anti-D^0 to CP eigenstate: K^-K^+ and $\pi^-\pi^+$

PRL 112 (2014) 041801

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

$$A_m \equiv \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2} \qquad A_d \equiv \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2}$$

A_m: in mixing; A_d: direct

A_Γ makes a measurement of indirect CPV, as the contributions from direct CPV are measured to be small compared to the current precision

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

- We measure the ratio of D^0 / anti-D^0 yields as a function of decay time
- The time dependence of this ratio allows the calculation of A_Γ from a simple linear χ^2 minimization with

$$R(t) \approx \frac{N_{\bar{D}^0}}{N_{D^0}}\left(1 + \frac{2A_\Gamma}{\tau_{KK}}t\right)\frac{1-e^{-\Delta t/\tau_{\bar{D}^0}}}{1-e^{-\Delta t/\tau_{D^0}}}$$

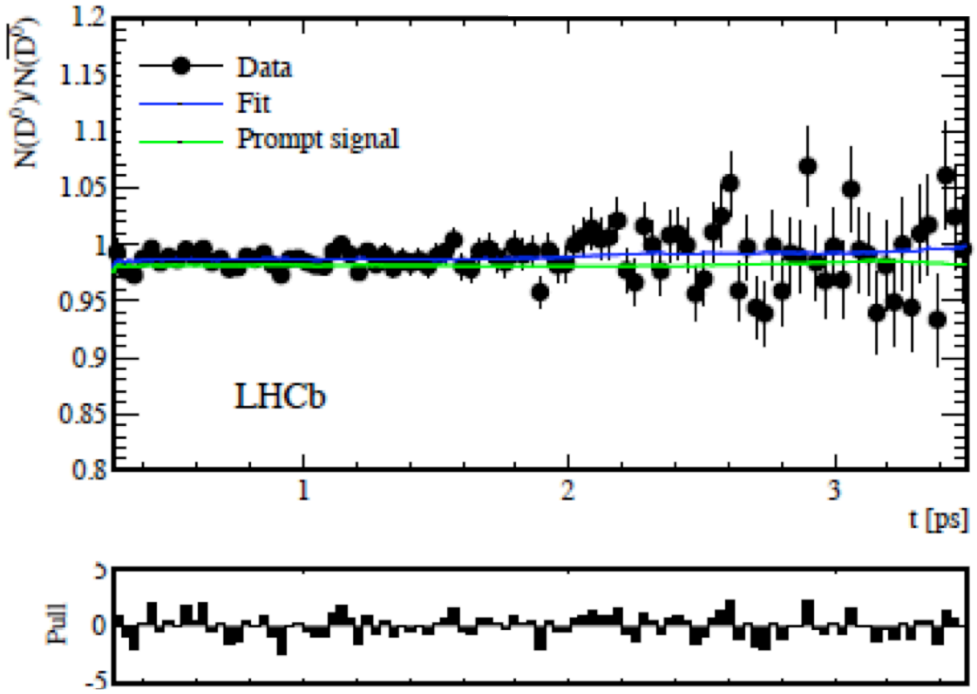
$\tau_{KK} = \tau_{K\pi} / (1+y_{CP})$ used from an external input based on world averages
$N_{anti\text{-}D0} / N_{D0}$ is the signal yield ratio integrated over all decay times
Δt is the bin width

A_Γ asymmetry

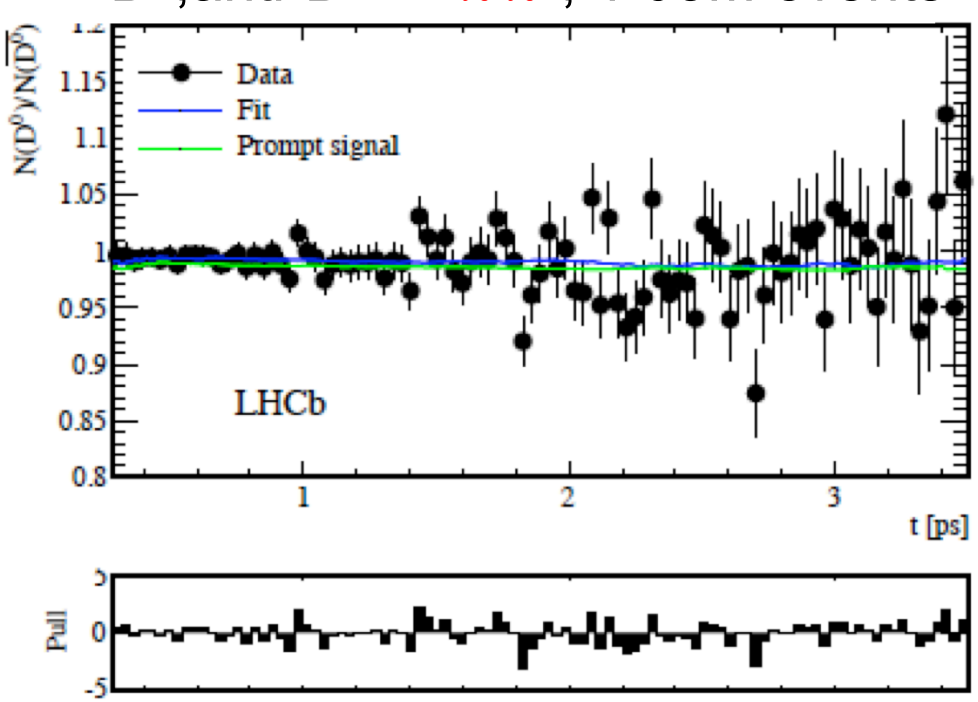
LHCb 1/fb (2011), we use D* to identify D^0 flavour

PRL 112 (2014) 041801

D^0,anti-$D^0 \to K^-K^+$, 3.11M events



D^0,anti-$D^0 \to \pi^-\pi^+$, 1.03M events



$A_\Gamma(K^-K^+) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3}$

$A_\Gamma(\pi^-\pi^+) = (-0.33 \pm 1.06 \pm 0.14) \times 10^{-3}$

The world's best measurements up to now (2012 (2/fb) data is being studied)

1) No significant difference between the two final states

2) No evidence for indirect CPV within 1 per mil
   Expected value of CPV in SM is small $\lesssim 10^{-3}$, predictions vary widely

Time-integrated CPV in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays

We want to measure asymmetry between particles and antiparticles:

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

arXiv: 1405.2797

We use two methods:

1) pion-tagged: $D^{*+} \to D^0 \pi^+_s$, $D^{*-} \to \text{anti-}D^0 \pi^-_s$
2) muon-tagged: $B \to D^0 \mu^- \nu_\mu X$, $B \to \text{anti-}D^0 \mu^+ \nu_\mu X$

Measured raw asymmetry A_{RAW} includes physics and detector effects:

$$A_{RAW}(f) = A_{CP}(f) + A_{det} + A_{prod}$$

CP asymmetry what we want to measure

detector asymmetry of particles reconstruction

production asymmetry of D* (B) in primary vertex

- taking the difference cancels detection and production asymmetries
- to a good approximation this is a measure of direct CP violation

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

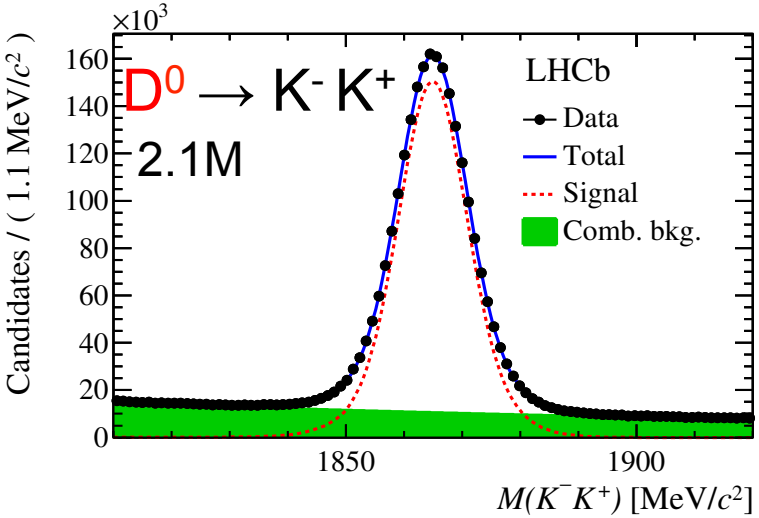
[JHEP 1106 (2011) 089]

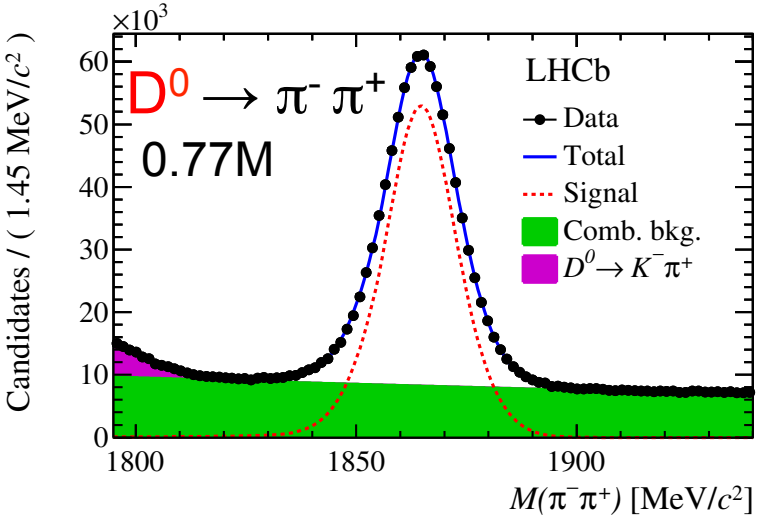
Time-integrated CPV in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays

Using 3/fb (2011+2012) semileptonic $B \to D^0 \mu^- \nu_\mu X$ decays

Extract yields from fit

arXiv: 1405.2797



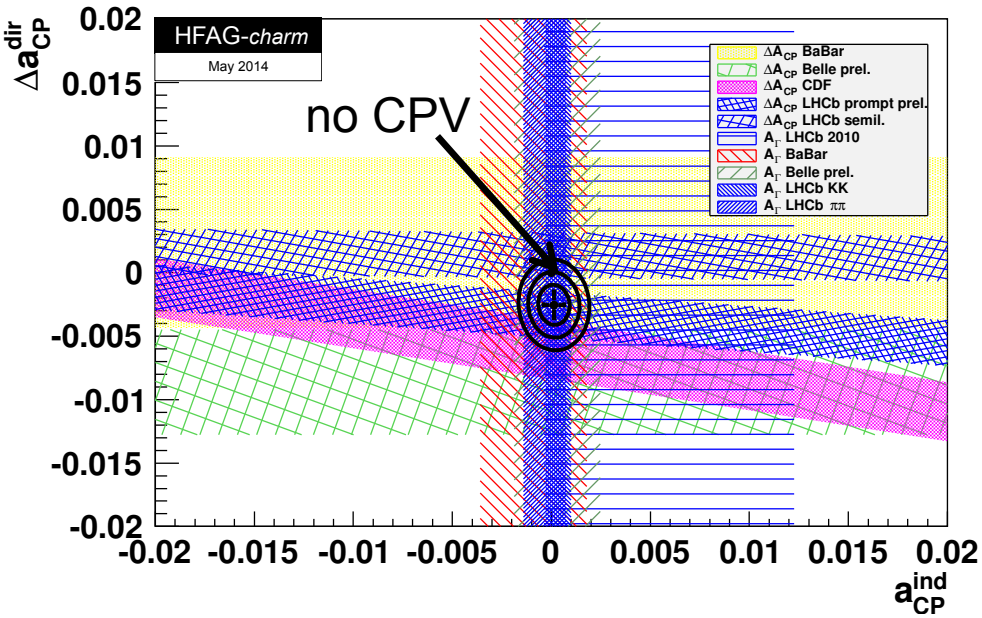


$$\Delta A_{CP} = (+0.14 \pm 0.16 \pm 0.08)\%$$

Extract individual CP asymmetries using a combination of CF modes where CP asymmetry is not expected

$$A_{CP}(K^+K^-) = (-0.06 \pm 0.15 \pm 0.10)\%$$

$$A_{CP}(\pi^+\pi^-) = (-0.20 \pm 0.19 \pm 0.10)\%$$



No CP Violation is observed

Search for direct CPV in $D^+ \to K^0_S K^+$ and $D^+_s \to K^0_S \pi^+$

The goal is to measure the CP asymmetry for SCS decays $D^+_{(s)} \to K^0_S h^+$ (h=K,π)

$$A_{CP} \equiv \frac{\Gamma(D^+_{(s)} \to K^0_s h^+) - \Gamma(D^-_{(s)} \to K^0_s h^-)}{\Gamma(D^+_{(s)} \to K^0_s h^+) + \Gamma(D^-_{(s)} \to K^0_s h^-)}$$

arXiv: 1406.2624

Measured raw asymmetry A_{RAW} includes pollution asymmetries:

$$A_{RAW} = \frac{N^+ - N^-}{N^+ + N^-} \approx A_{CP} + A_{det}(h) + A_{prod}(D^+_{(s)}) + A_{K^0/\bar{K}^0}$$

Mixing and CPV in K^0-anti-K^0 and detection asymmetry between K^0 and anti-K^0

The contribution from the neutral kaon asymmetries (arXiv:1405.2797):

$$A_{K^0} \equiv (N_{K^0} - N_{\bar{K}^0})/(N_{K^0} + N_{\bar{K}^0}) = -A_{\bar{K}^0} = (+0.07 \pm 0.02)\%$$

We use CF modes $D^+ \to K^0_S \pi^+$ and $D^+_s \to K^0_S K^+$ and construct the double difference to cancel detection and production asymmetries

$$\begin{aligned} A^{DD}_{CP} &= [A_{RAW}(D^+_s \to K^0_s \pi^+) - A_{RAW}(D^+_s \to K^0_s K^+)] - \\ &\quad [A_{RAW}(D^+ \to K^0_s \pi^+) - A_{RAW}(D^+ \to K^0_s K^+)] - 2A_{K^0} \\ &\approx A_{CP}(D^+ \to K^0_s K^+) + A_{CP}(D^+_s \to K^0_s \pi^+) \end{aligned}$$

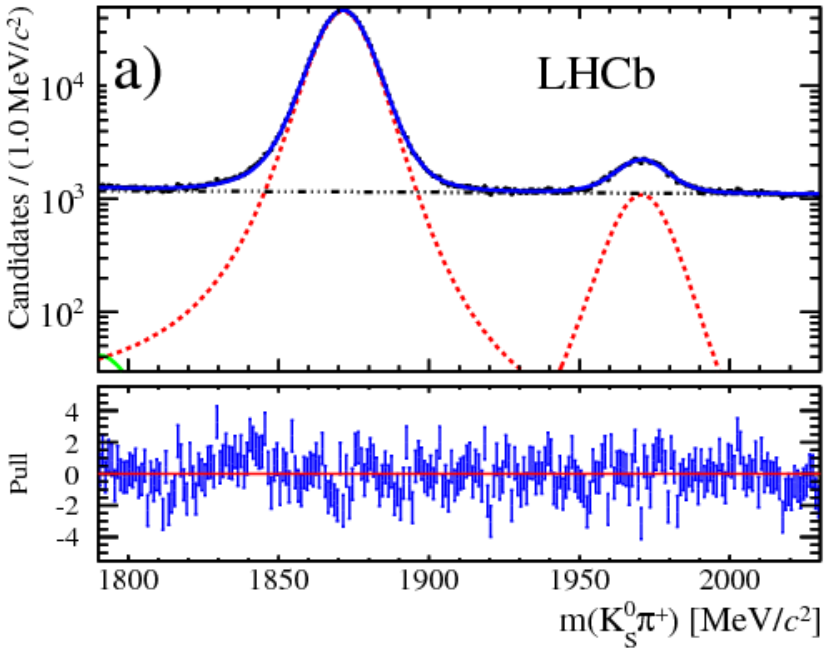
We use a combination with CF mode $D^+_s \to \phi\pi^+$ to extract the individual asymmetries

Search for direct CPV in $D^+ \to K^0_S K^+$ and $D^+_s \to K^0_S \pi^+$

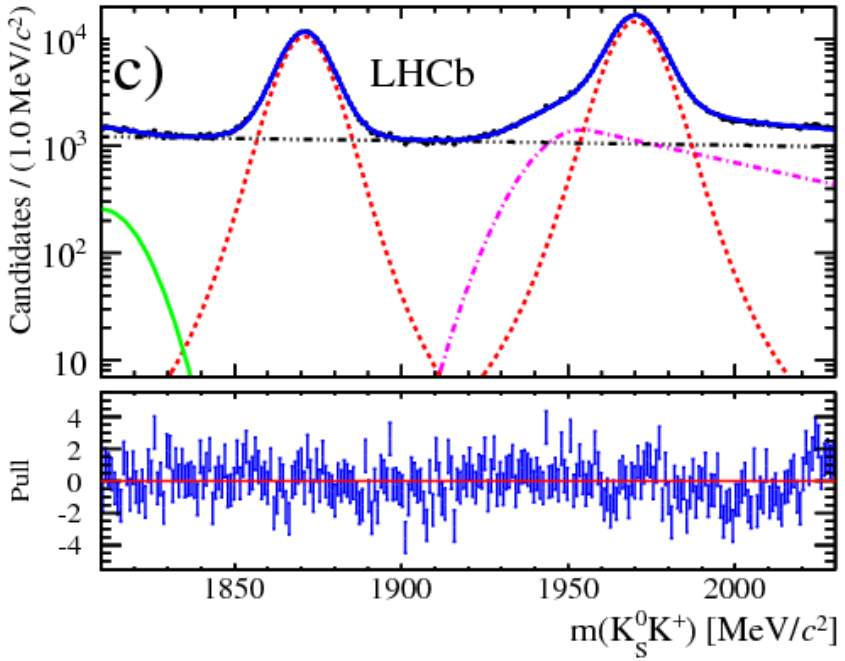
LHCb 3/fb (2011+2012), extract yields from fit

arXiv: 1406.2624

$D^+_{(s)} \to K^0_S \pi^+$



$D^+_{(s)} \to K^0_S K^+$



$$A_{CP}(D^\pm \to K^0_s K^\pm) = (+0.03 \pm 0.17 \pm 0.14)\%$$

$$A_{CP}(D^\pm_s \to K^0_s \pi^\pm) = (+0.38 \pm 0.46 \pm 0.17)\%$$

$$A^{DD}_{CP} = A_{CP}(D^\pm \to K^0_s K^\pm) + A_{CP}(D^\pm_s \to K^0_s \pi^\pm) = (+0.41 \pm 0.49 \pm 0.26)\%$$

The results show no evidence for CP violation

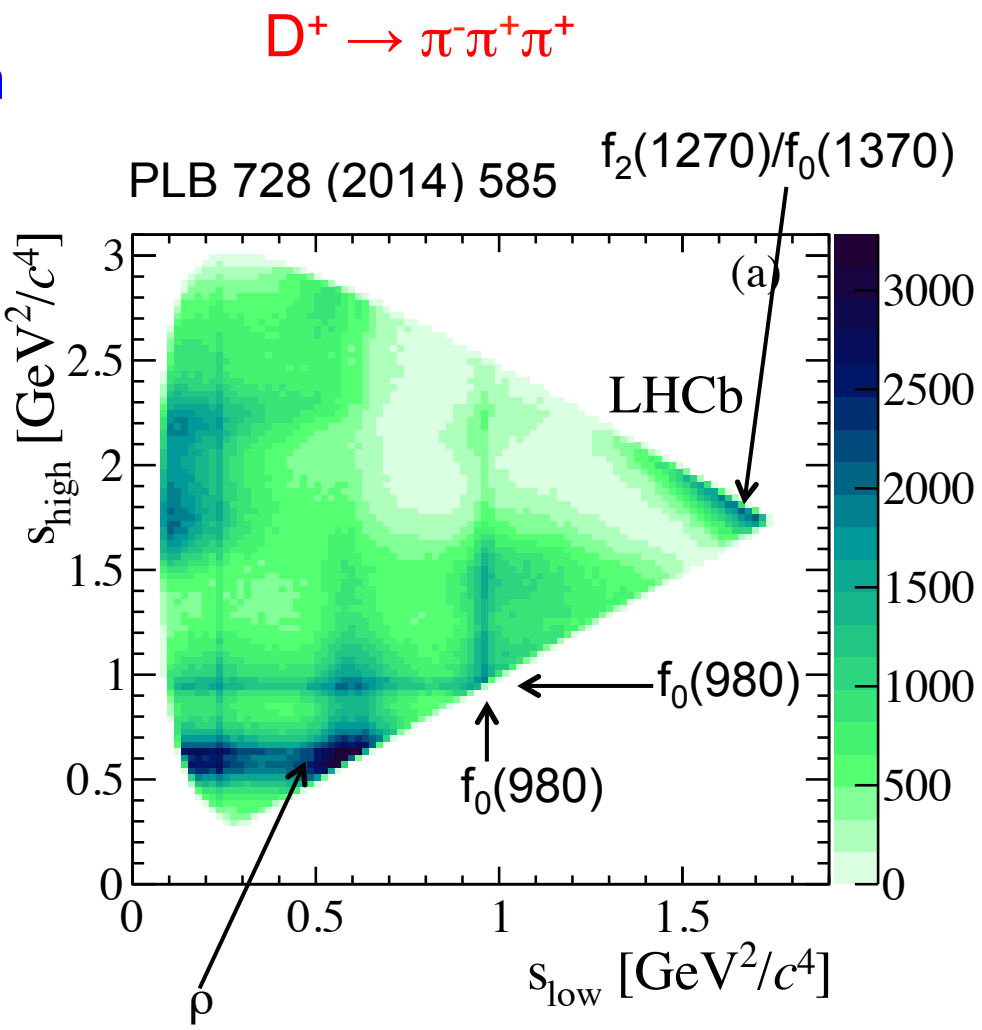
Searches for CPV in multi-body charm decays

- Decay products form many resonance states visible in Dalitz plot
  ⇒ strong phases vary from region to region

$$A_{CP} \propto sin(\phi_1 - \phi_2) sin(\delta_1 - \delta_2)$$

weak phases strong phases

- The charge asymmetry can be measured locally in the regions of Dalitz plots
- No clear indications where CPV would appear
- To find asymmetries we compare locally Dalitz plots for D^+ and D^- (we perform here searches based on techniques that are model-independent)



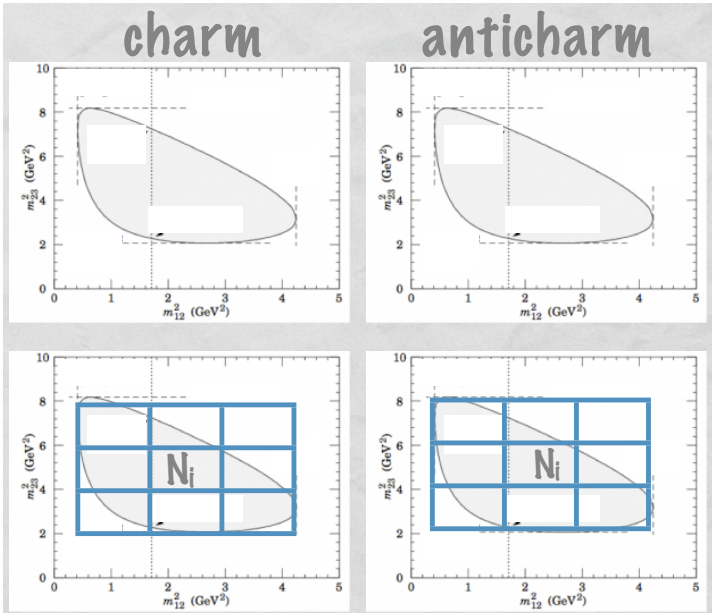
Searches for CPV in multi-body charm decays

Binned method

PLB 728 (2014) 585

- In each bin we calculate a significance of a difference between D^+ and D^-

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



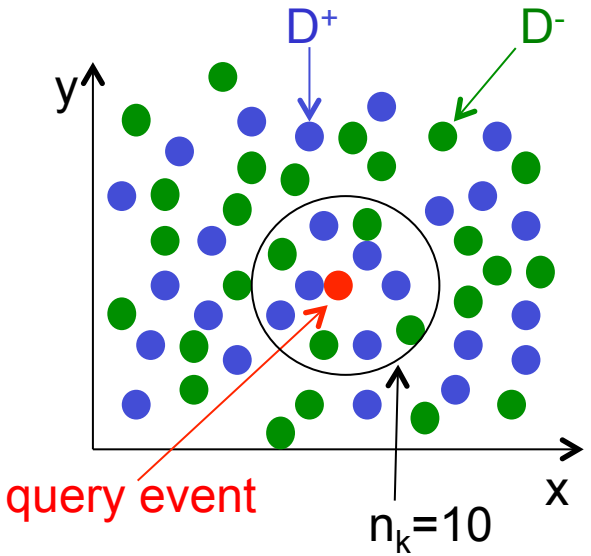
- To cancel global asymmetries (production asymmetry, etc.) we normalize Dalitz plots

- If no CPV (only statistical fluctuations) then S_{CP} is Gauss distributed (μ=0, σ=1)

Unbinned (k-nearest neighbour) method

- To compare D^+ and D^- we define a test statistic T which is based on the counting particles with the same sign to each event for a given number of the nearest neighbour event

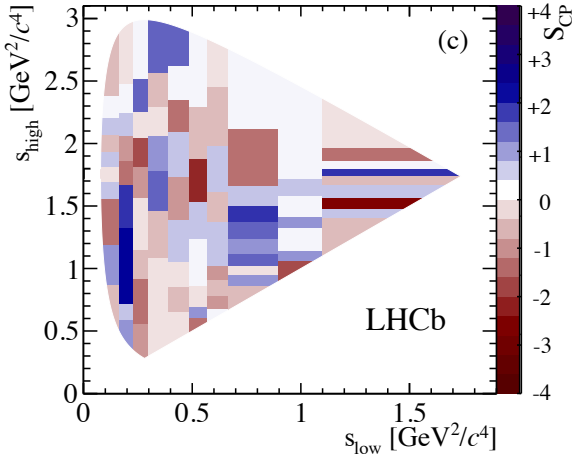
- T is the mean fraction of like pairs in the pooled sample of the two datasets

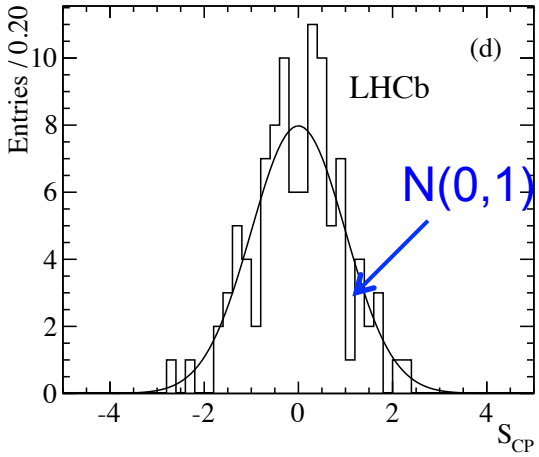


Searches for CPV in $D^+ \to \pi^-\pi^+\pi^+$

Binned method

100 adaptive bins





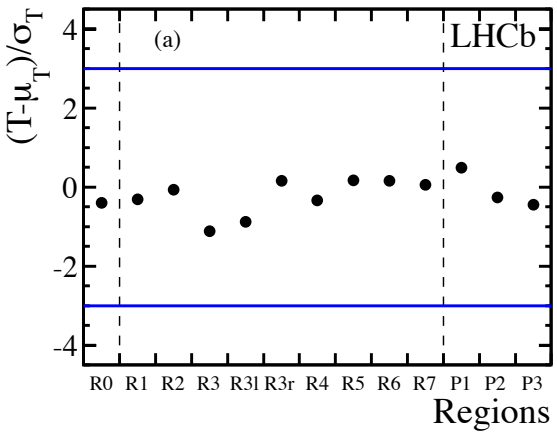
LHCb 2011, 1/fb ~3.1M $D^+ \to \pi^-\pi^+\pi^+$
PLB 728 (2014) 585

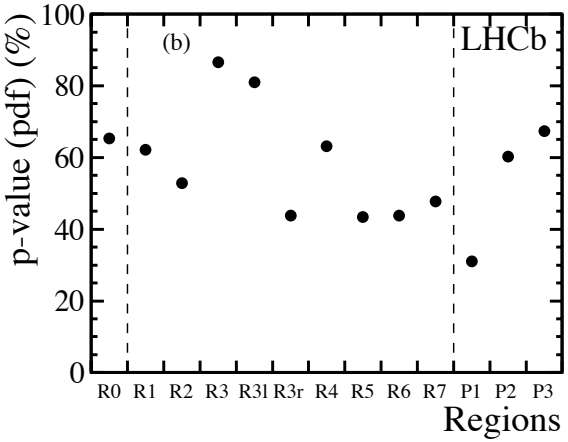
We tested uniform and adaptive binning schemes with different bin numbers

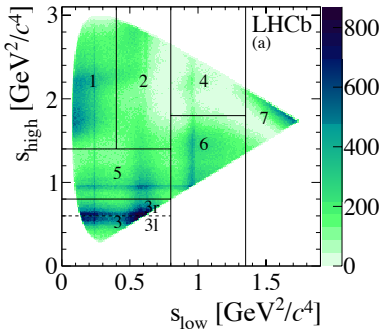
S_{CP} distributions agree with the normal Gaussian function

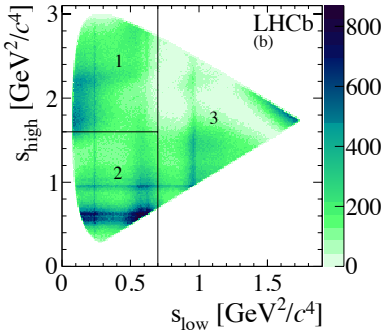
Unbinned method

To increase the sensitivity of the method we divide the Dalitz plot into regions
Two different divisions: 7 and 3 regions defined around resonances









All p-values are above 30%

No evidence for CP asymmetry using binned and unbinned methods and both methods provide similar sensitivities for CPV searches

Search for CPV in $D^0 \to K^+K^-\pi^+\pi^-$

LHCb-PAPER-2014-046

We measure CP-violating observable $\mathcal{A}_T$ which is built using triple products of final state particle momenta in the D^0 center-of-mass frame

for D^0: $C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$ $\quad A_T \equiv \frac{\Gamma_{D^0}(C_T>0)-\Gamma_{D^0}(C_T<0)}{\Gamma_{D^0}(C_T>0)+\Gamma_{D^0}(C_T<0)}$

for anti-D^0: $\bar{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$ $\quad \bar{A}_T \equiv \frac{\Gamma_{\bar{D}^0}(-\bar{C}_T>0)-\Gamma_{\bar{D}^0}(-\bar{C}_T<0)}{\Gamma_{\bar{D}^0}(-\bar{C}_T>0)+\Gamma_{\bar{D}^0}(-\bar{C}_T<0)}$

But A_T and anti-A_T can be non zero if there are final state interactions

$$\mathcal{A}_T \equiv \tfrac{1}{2}(A_T - \bar{A}_T)$$

In the first case,

- CPV vanishes when strong phase of two interfering amplitudes (δ_1-δ_2) is zero
- while $\mathcal{A}_T$ is maximal

$$A_{CP} \propto sin(\phi_1 - \phi_2) sin(\delta_1 - \delta_2)$$

weak phases strong phases

$$\mathcal{A}_T \propto sin(\phi_1 - \phi_2) cos(\delta_1 - \delta_2)$$

Search for CPV in $D^0 \to K^+K^-\pi^+\pi^-$

To probe direct and indirect CPV, $\mathcal{A}_T$ is measured:

LHCb 3/fb (2011+2012)
LHCb-PAPER-2014-046

1) in integrated the phase space

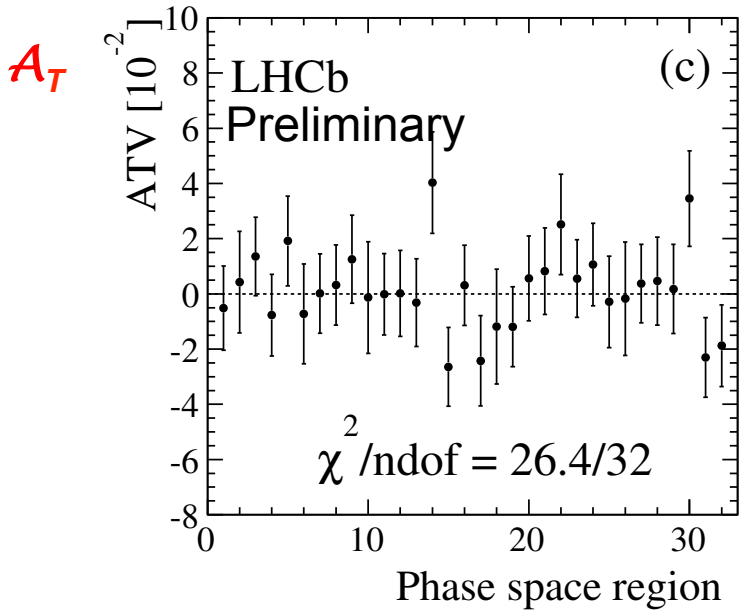
for D^0: $A_T = (-7.18 \pm 0.41 \pm 0.13)\%$

for anti-D^0: anti-$A_T = (-7.55 \pm 0.41 \pm 0.12)\%$

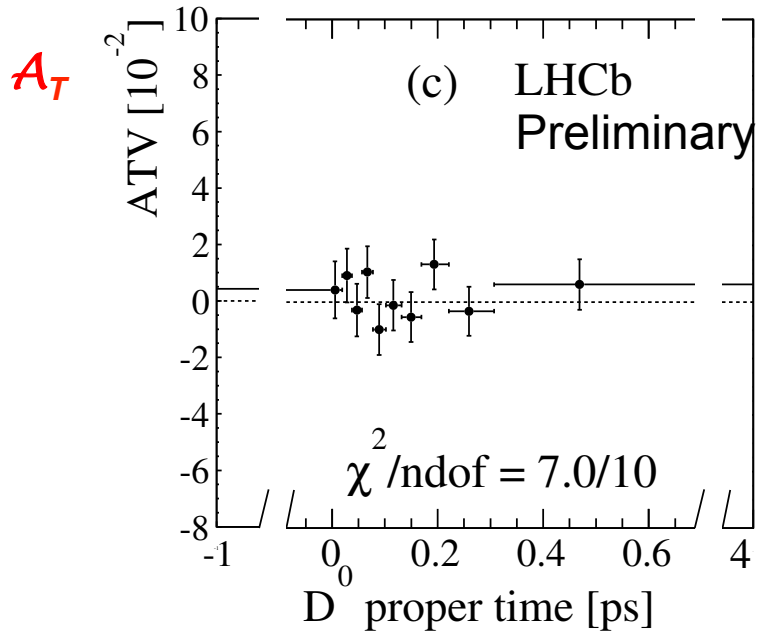
$\mathcal{A}_T = (0.18 \pm 0.29 \pm 0.04)\%$

Large asymmetries due to final state interaction effects

2) in different regions of the phase space done by dividing the sample using variables $m^2(K^+K^-)$, $m^2(\pi^+\pi^-)$, $\cos(\theta(K^+))$, $\cos(\theta(\pi^+))$, ϕ



3) as a function of D^0 proper time

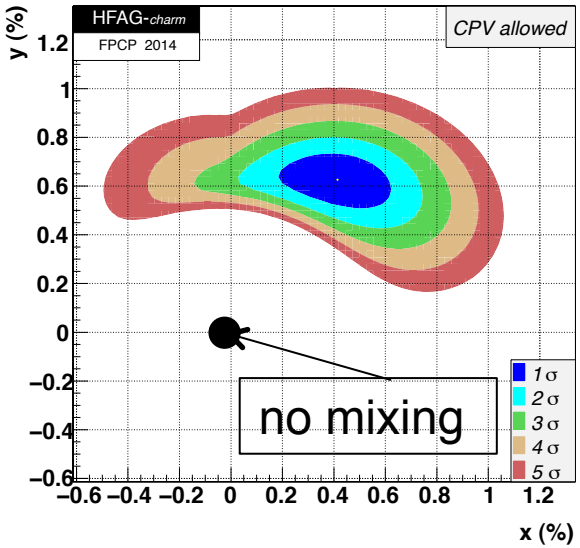


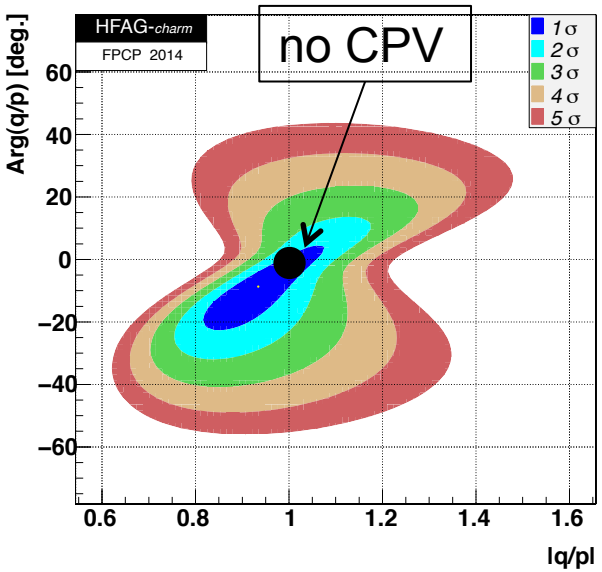
No evidence for CP asymmetry

Measurements have small syst. uncertainties (larger datasets will improve result)

Summary and prospects

- LHCb experiment has broad and important beauty and charm physics program
- Many world's most sensitive measurements



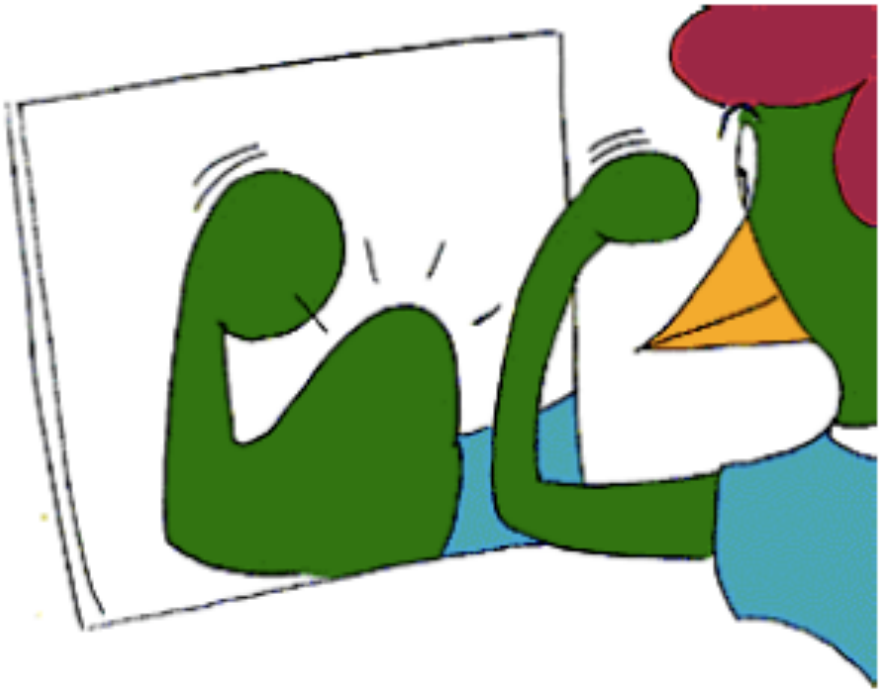


- ✧ first observation of charm mixing in a single measurement
- ✧ so far, all results are consistent with CP conservation in charm
- ✧ we are within 1 per mil sensitivity (very close to the SM expectations)
- ✧ many more…

Prospects:

- We enhance discovery potential during 2015-17 >5/fb at √s=14TeV
- LHCb upgrade (starting 2019) plans to collect ~50/fb data and will have huge statistics for charm decays

Backup



LHCb upgrade

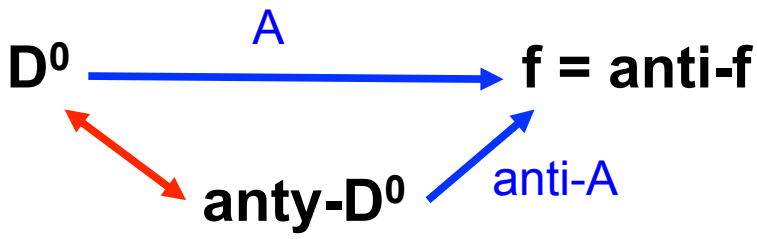
EPJ C73(2013)2373

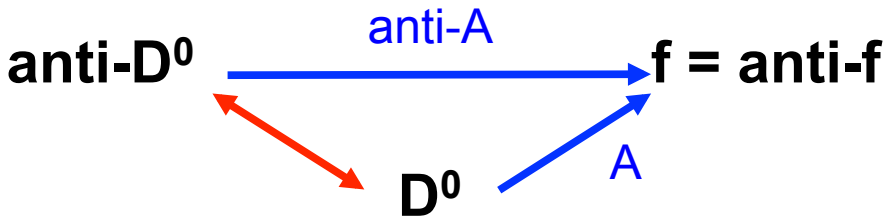
Table 16: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with $50\,\text{fb}^{-1}$ by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities. Note that the current sensitivities do not include new results presented at ICHEP 2012 or CKM2012.

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [138]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [214]	0.045	0.014	~ 0.01
	a_{sl}^s	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [43]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0\, A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [76]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [85]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [244, 258]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_{\text{S}}^0)$	0.8° [43]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

Three ways of CP violation

1. in mixing (indirect)
   $D^0 \to \text{anti-}D^0 \neq \text{anti-}D^0 \to D^0$
2. in decay amplitudes (direct)
   $D \to f \neq \text{anti-}D \to \text{anti-}f$
3. in interference (indirect)
   between direct decays and decays with mixing





- CPV in mixing does not depend on final state (universal)
- Direct CPV depends on final states and it has to be searched everywhere it is possible: D → hh, hhh, hhhh, ……

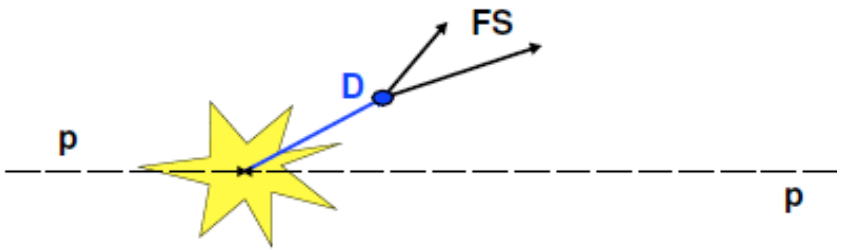
Charm production at LHCb

JHEP04(2012)129

Two production types of charm:

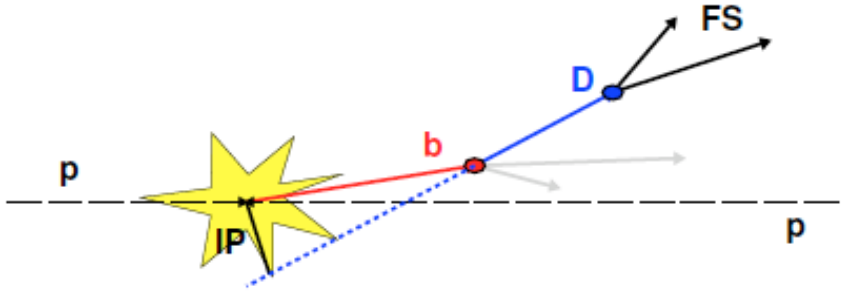
- **prompt** – produced directly in the primary vertex (PV)

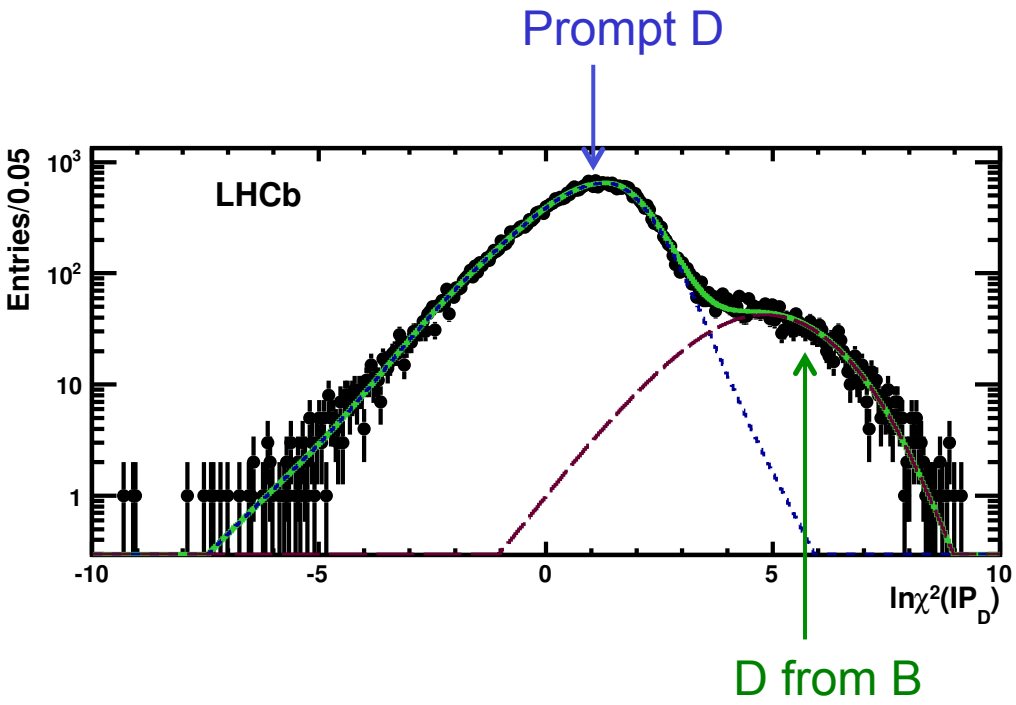
IP(D^0)~0



- **secondary** – produced in B decays (>50% of B→DX)

IP(D^0)>~0





IP – impact parameter wrt. the PV

To separate prompt charm and secondary charm decays we use the cut on χ^2(IP) parameter

Consequences for CPV from D^0 – anti-D^0 mixing

PRL 111 (2013) 251801

1. CPV in mixing

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$ if |q/p| ≠ 1 then CPV

The relations could be used to calculate constraints for |q/p|

$$x'^{\pm} = |q/p|^{\pm 1}(x'\cos\phi \pm y'\sin\phi)$$
$$y'^{\pm} = |q/p|^{\pm 1}(y'\cos\phi \mp x'\sin\phi)$$

R_D,x',y'$^{(+)}$ for $D^{*+} \to D^0 \pi^+_s$
R_D,x',y'$^{(-)}$ for $D^{*-} \to$ anti-$D^0 \pi^-_s$

Result: 0.75 < |q/p| < 1.24 (68.3% CL)

Consistent with no CPV in mixing

2. Direct CPV is measured by the asymmetry

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.7 \pm 1.9)\%$$

R_D – the ratio of DCS to CF decay rates

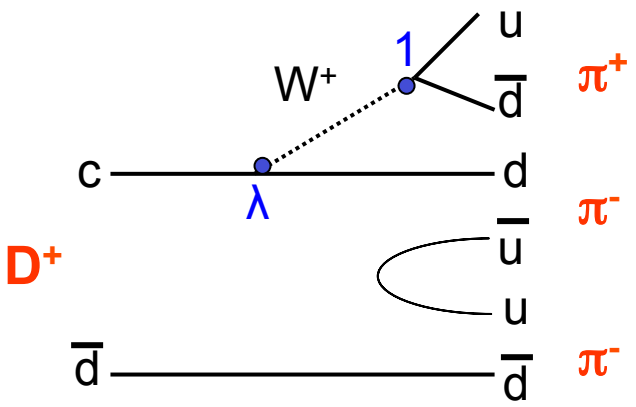
Direct CP asymmetry is consistent with zero

No indication of direct or indirect CPV

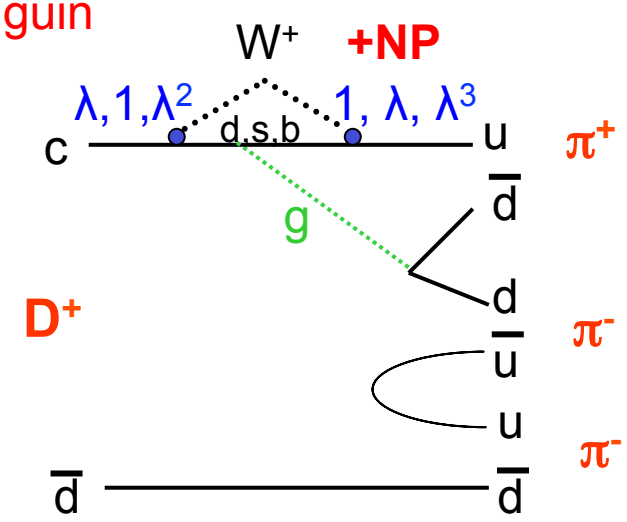
Search for CPV in $D^+ \to \pi^-\pi^+\pi^+$

$D^+ \to \pi^-\pi^+\pi^+$ is singly-Cabibbo Suppressed (SCS) and gets contribution from penguin diagram

tree



penguin



- If tree and penguin amplitudes interfere with different phases then CP symmetry is broken

$$Asym_{CP} \sim |A_1||A_2| sin(\phi_1 - \phi_2) sin(\delta_1 - \delta_2)$$

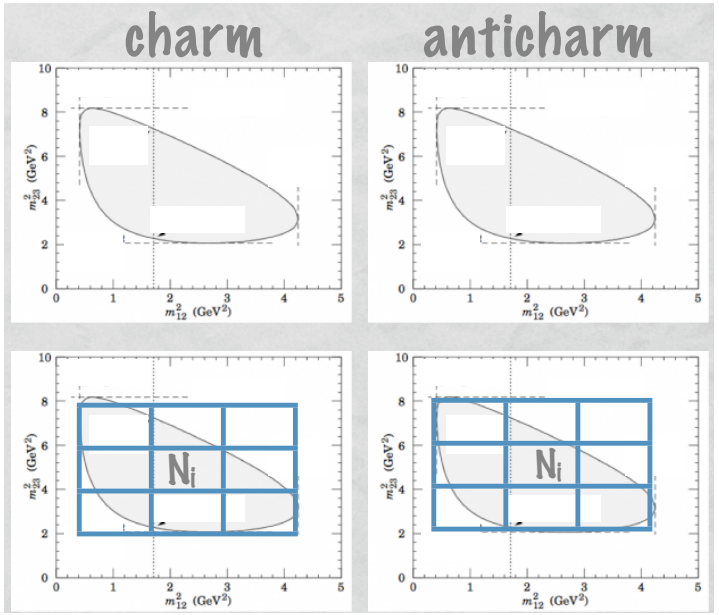
weak phases — strong phases

- Only CP violation in decay amplitudes (direct) since there is no mixing
- Penguin diagram opens possibilities for finding New Physics

Searches for CPV in multi-body charm decays

To find asymmetries we compare locally Dalitz plots for D^+ and D^-

We perform searches based on techniques that are model-independent: binned and unbinned methods



Binned method

- In each bin we calculate a significance of a difference between D^+ and D^-

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

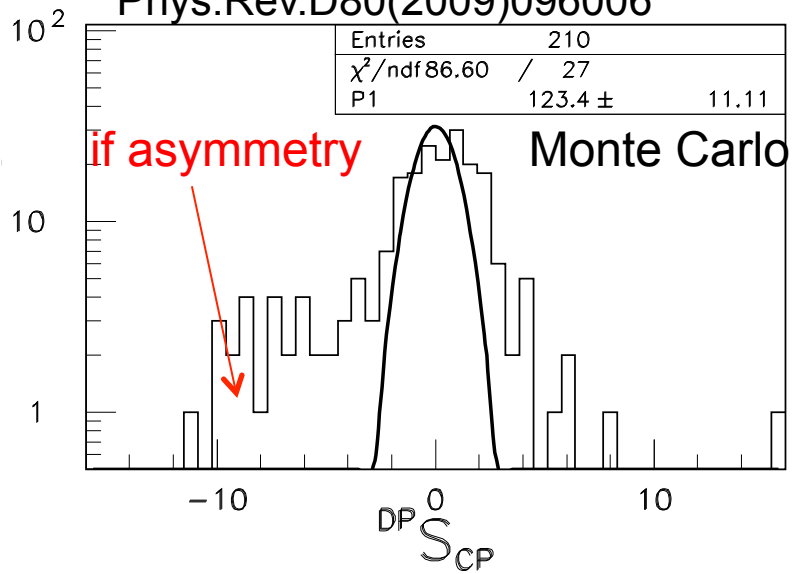
- To cancel global asymmetries (production asymmetry, etc.) we normalize Dalitz plots for D^+ and D^- $\quad \alpha = \frac{N(D^+)}{N(D^-)}$

- If no CPV (only statistical fluctuations) then S_{CP} is Gauss distributed (μ=0, σ=1)

- We calculate $\chi^2 = \Sigma S^i{}_{CP}{}^2$ to obtain p-value for the null hypothesis to test if D^+ and D^- distributions are statistically compatible

p-value $\ll$ 1 in case of CPV

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

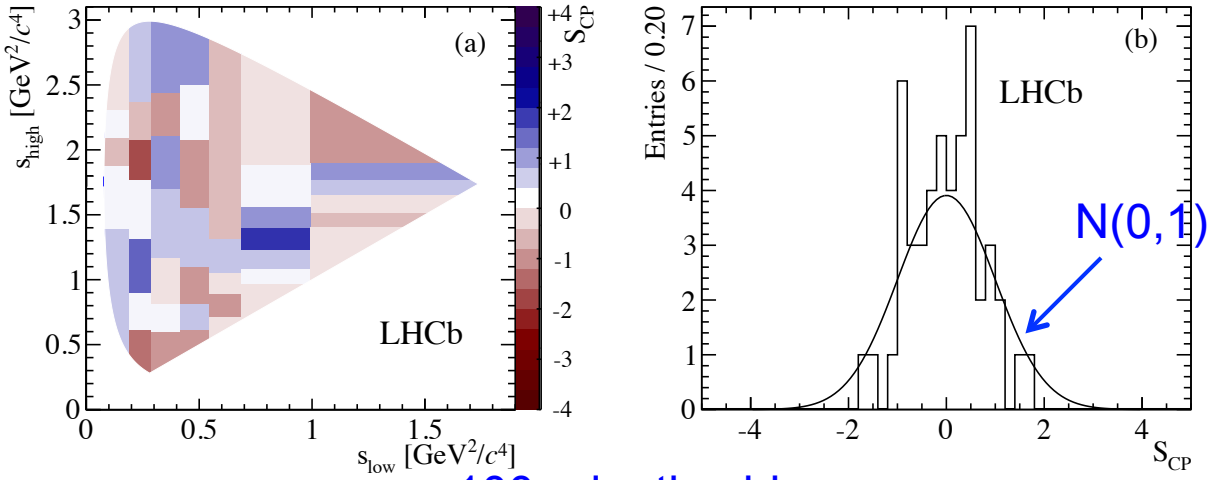


Search for CPV in $D^+ \to \pi^-\pi^+\pi^+$

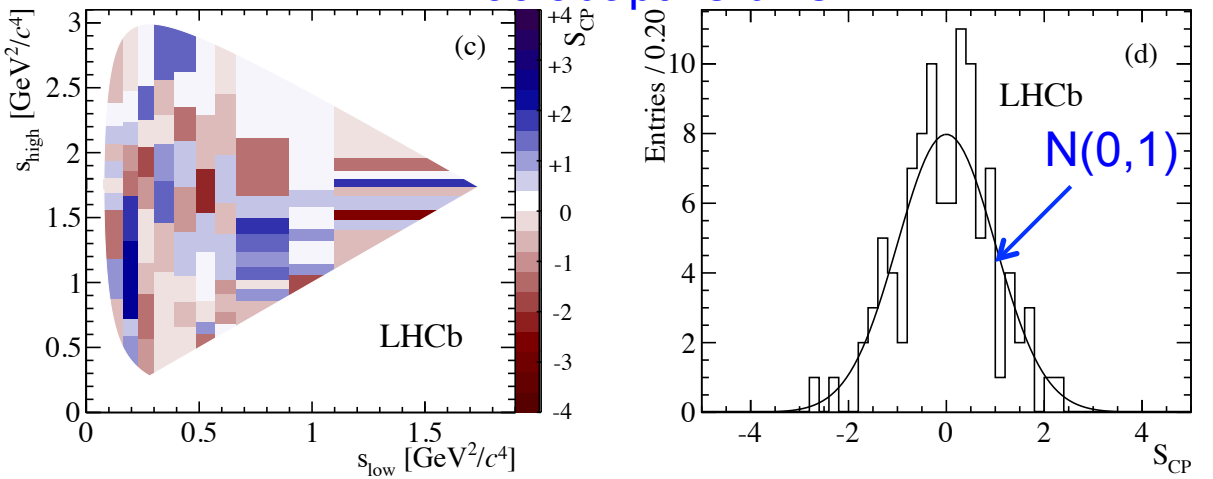
Results for binned method

To increase the sensitivity of the method we use uniform and adaptive binning schemes with different bin numbers

49 adaptive bins



100 adaptive bins



LHCb 2011, 1/fb, PLB 728 (2014) 585

Number of bins	χ^2	p-value (%)
20	14.0	78.1
30	28.2	50.6
40	28.5	89.2
49	26.7	99.5
100	89.1	75.1

All p-values for null CPV hypothesis are above 50%

S_{CP} distributions agree with the standard normal Gaussian function

No evidence for CP asymmetry using binned and unbinned methods

Searches for CPV in $D^+ \to \pi^-\pi^+\pi^+$

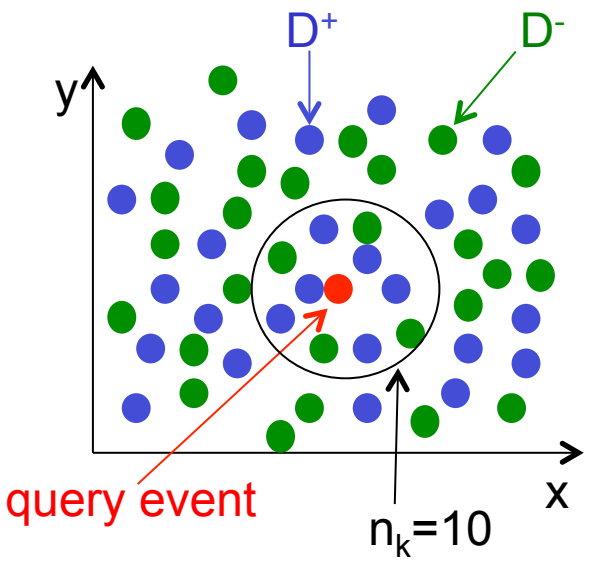
To find asymmetries we compare locally Dalitz plots for D^+ and D^-

We perform searches based on techniques that are model-independent: binned and unbinned (k-nearest neighbour) methods

- To compare D^+ and D^- we define a test statistic T which is calculated for a pooled sample of D^+ and D^-:

$$T = \frac{1}{n_k(n_+ + n_-)} \sum_{i=1}^{n_+ + n_-} \sum_{k=1}^{n_k} I(i,k)$$

  - ✧ I(i,k) = 1 if i^{th} event and its kth nearest neighbor have the same charge (D^+—D^+ , D^-—D^-)
  - ✧ I(i,k) = 0 if pair has opposite charge (D^+—D^-)



- T is the mean fraction of like pairs in the pooled sample of the two datasets

- We calculate p-value for case of no CPV by comparing T with expected mean

$$\mu_T = \frac{n_+(n_+ - 1) + n_-(n_- - 1)}{n(n-1)}$$

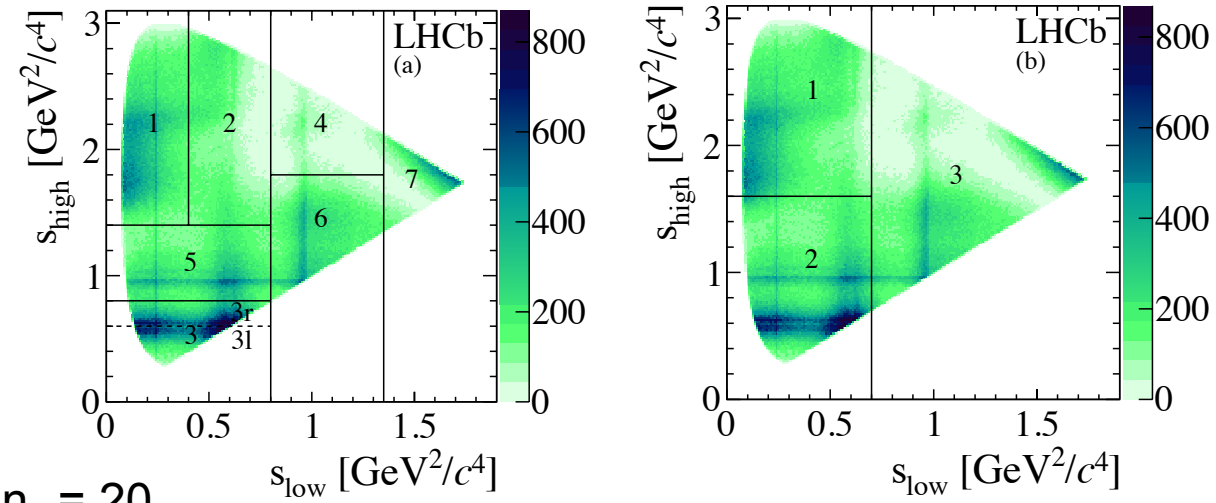
$$\lim_{n,n_k,D\to\infty} \sigma_T^2 = \frac{1}{nn_k}\left(\frac{n_+ n_-}{n^2} + 4\frac{n_+^2 n_-^2}{n^4}\right)$$

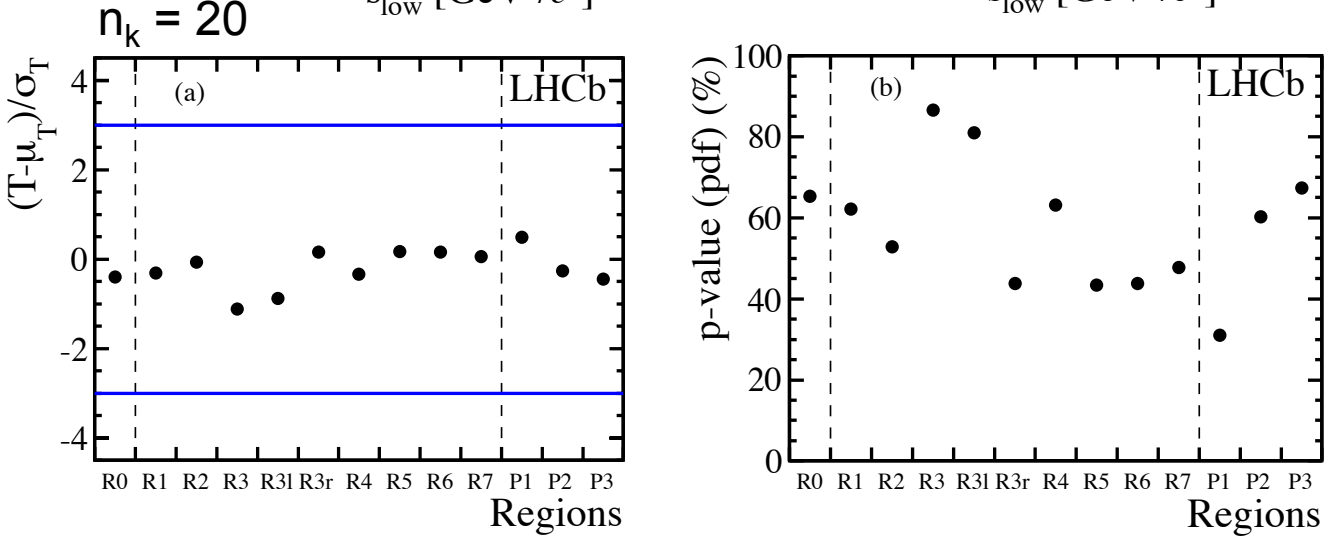
If $n_+ = n_-$ then $\mu_T \approx 1/2$ (mean value) and $\sigma_T^2 = \frac{1}{nn_k}(0.25 + 0.25)$

Searches for CPV in $D^+ \to \pi^-\pi^+\pi^+$

To increase the sensitivity of the method we divide the Dalitz plot into regions

PLB 728 (2014) 585





LHCb 2011, 1/fb
~3.1M $D^+ \to \pi^-\pi^+\pi^+$

Two different divisions

- 7 and 3 regions defined around resonances

LHCb results for $B \to hhh$ show large CPV in the regions not associated to resonances

- All p-values are above 30%, no evidence for CP asymmetry in $D^+ \to \pi^-\pi^+\pi^+$
- Consistent results we obtained with the binned analysis

Search for CPV in $D^0 \to K^-K^+\pi^-\pi^+$ and $D^0 \to \pi^-\pi^+\pi^-\pi^+$

While three-body decay kinematics can be described completely in 2D Dalitz plot, a four-body decay has 5 dimensions phase space to fully describe the decay

Here we divide 5D phase space into bins and in each ith bin we calculate S_{CP}

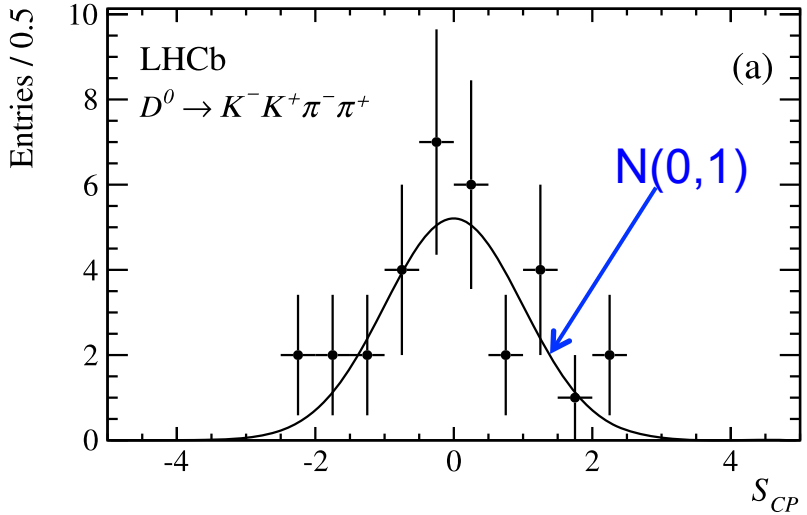
$$S^i_{CP} \equiv \frac{N^i(D^0) - \alpha N^i(\bar{D}^0)}{\sqrt{N^i(D^0) + \alpha^2 N^i(\bar{D}^0)}} \qquad \alpha = \frac{N(D^0)}{N(\bar{D}^0)}$$

LHCb 2011, 1/fb

PLB 726 (2013) 623

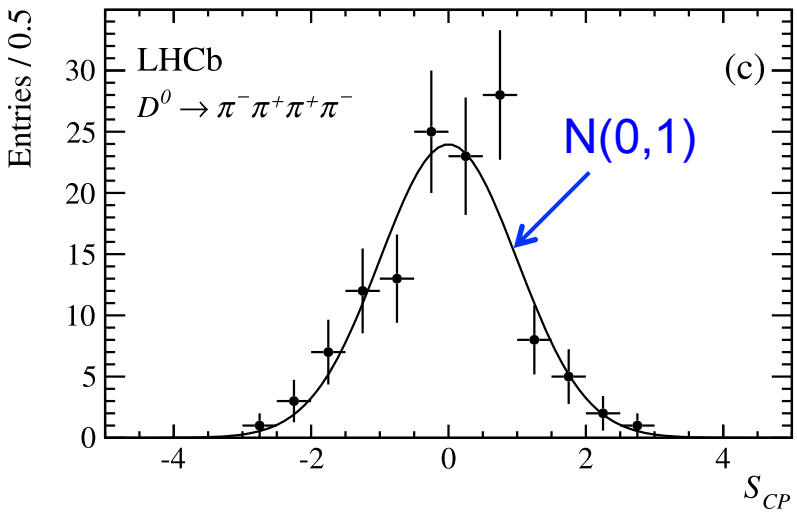
57k $D^0 \to K^-K^+\pi^-\pi^+$ decays

32 bins, ~1800 events in each



330k $D^0 \to \pi^-\pi^+\pi^-\pi^+$ decays

128 bins, ~2500 events in each



S_{CP} distributions agree with normal Gauss distributions

All results are consistent with CP conservation at the current sensitivity (a phase difference of 10^0 or a magnitude difference of 10%)

LHCb – precision detector

Single-arm forward spectrometer covering range: $2<\eta<5$

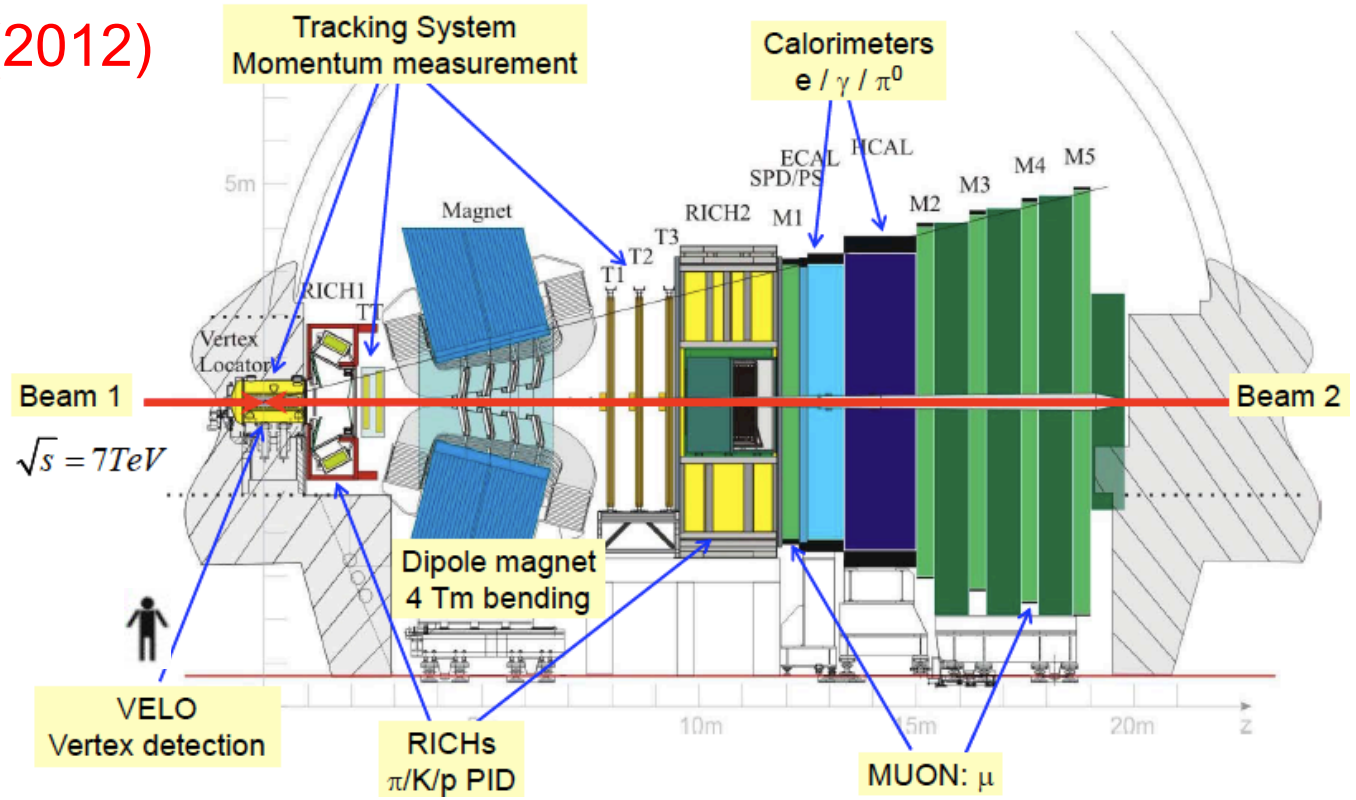
37/pb (2010), 1/fb (2011), 2/fb (2012)

For each 1/fb:

~7k $B^0_s \rightarrow J/\psi(\mu\mu)\, f_0(\pi^+\pi^-)$

~28k $B^0_s \rightarrow J/\psi(\mu\mu)\, \phi(K^+K^-)$

~2M $D^{*\pm} \rightarrow D^0(\rightarrow K^-K^+)\pi^\pm$



- VELO – resolution of IP: 20 μm, decay lifetime resolution ~ 45 fs: 0.1 $\tau(D^0)$
- Excellent tracking resolution: $\Delta p/p$ = 0.4% at 5 GeV to 0.6% at 100 GeV
- RICH – very good particle identification for π and K
- Dedicated trigger lines for beauty and charm with high efficiency
- The polarity of the magnet is reversed repeatedly during data taking
- LHCb has possibilities of precise measurements of beauty and charm particles