

Charm physics at LHCb

Chris Thomas (Oxford University)

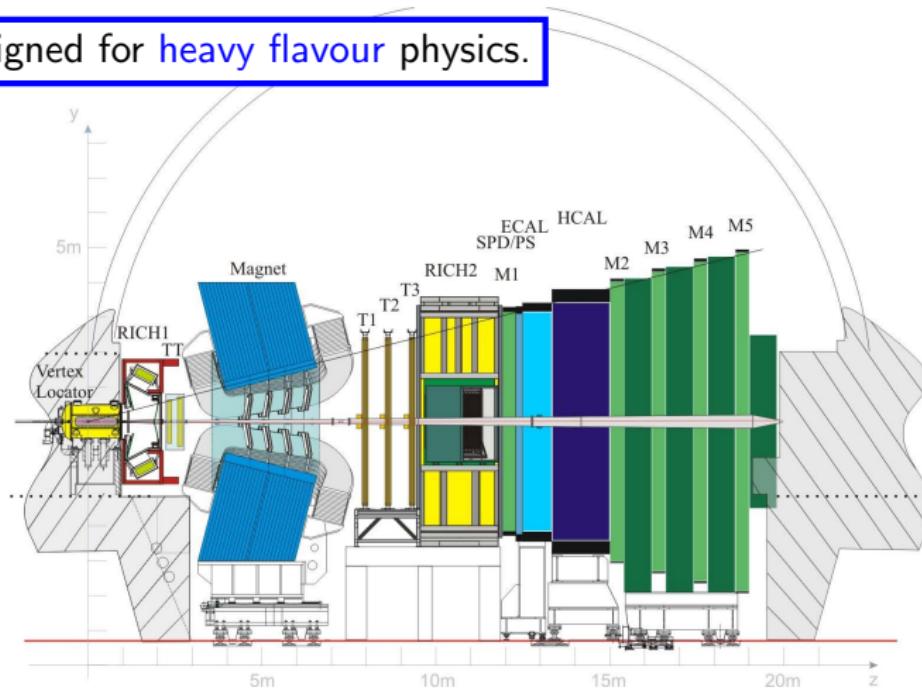
On behalf of the LHCb collaboration

SM@LHC 2012, Copenhagen

13 April 2012

The LHCb detector

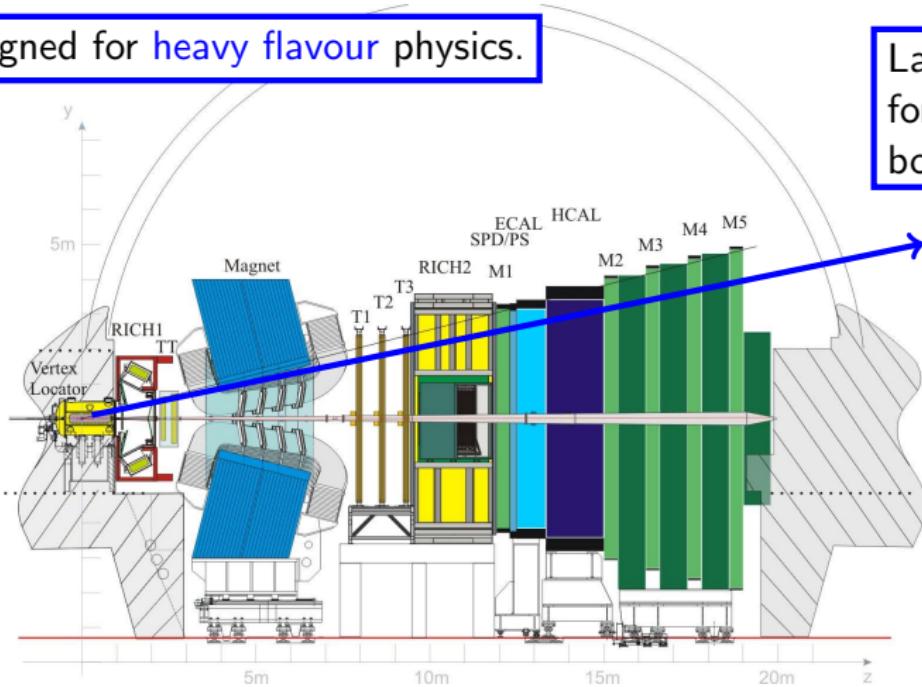
LHCb designed for **heavy flavour** physics.



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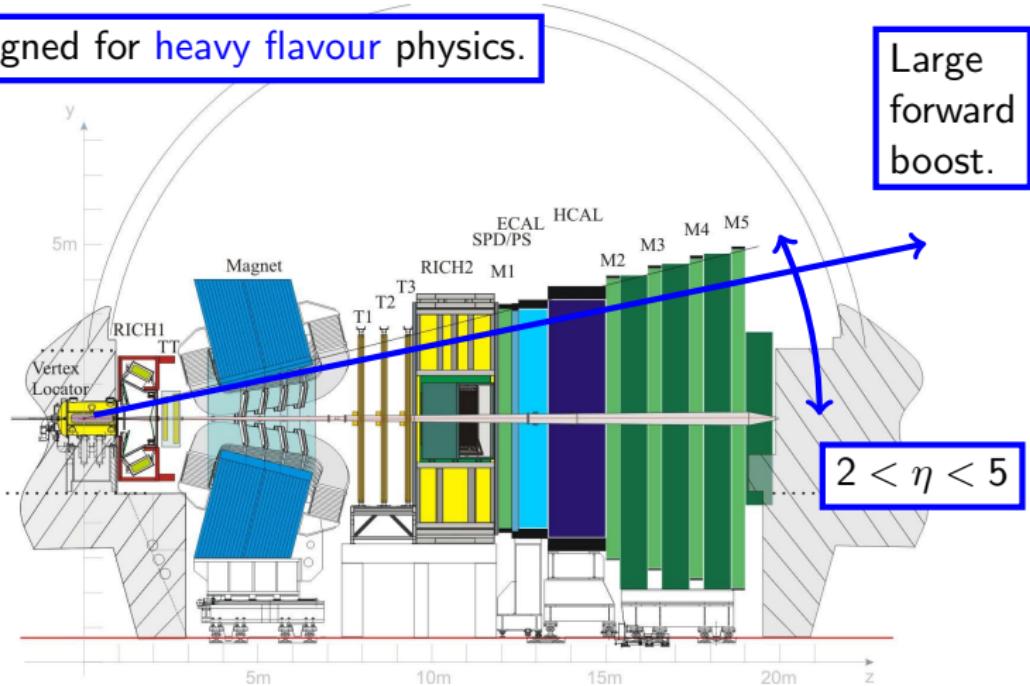
Large forward boost.



The LHCb detector

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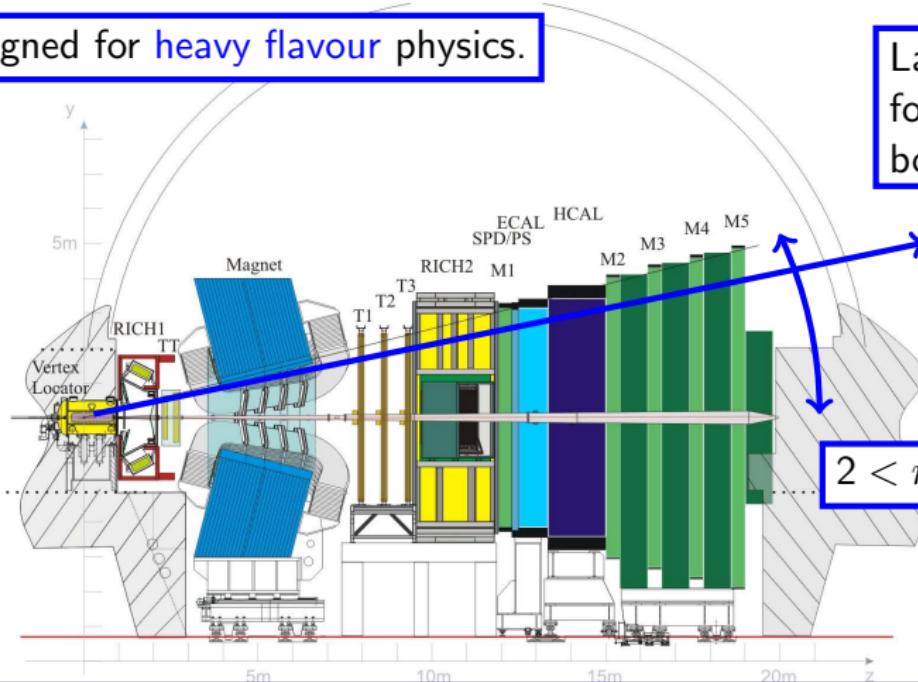
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The LHCb detector

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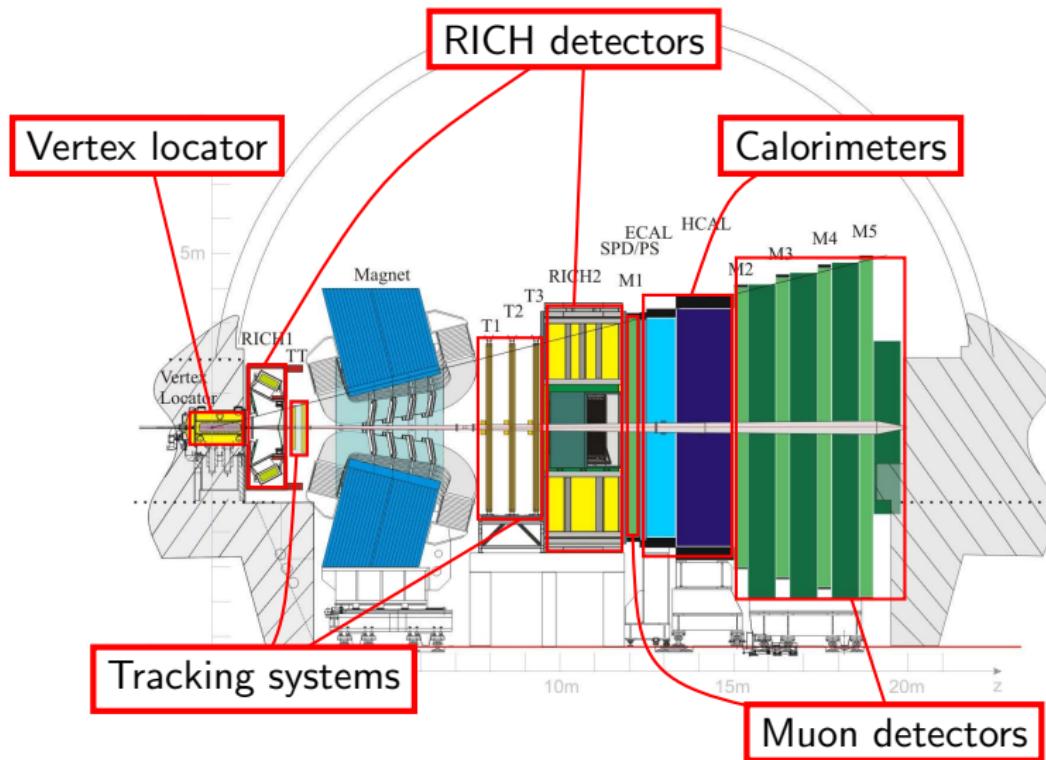
Large forward boost.



$2 < \eta < 5$

Huge open charm cross section: (6.10 ± 0.93) mb [LHCb-CONF-2010-013]
 Approximately $20 \times b\bar{b}$ cross section: (284 ± 53) μb [PLB 694: 209 (2010)]

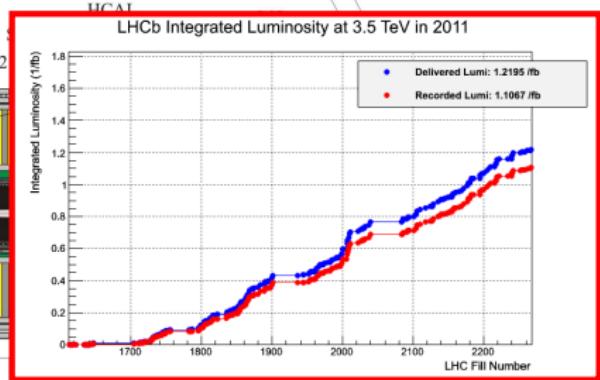
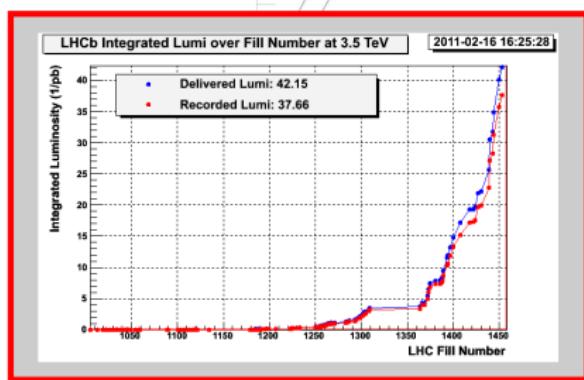
The LHCb detector



The LHCb detector

2010: 38 pb^{-1}

2011: 1.0 fb^{-1}



Data taking efficiency $> 90\%$

Charm physics at LHCb

LHCb has an [extensive charm physics program](#).

Large part of data-taking bandwidth ($\sim 1/3$) devoted to charm decays.

World-leading samples of charm events available.

Presented today:

- Mixing and CP violation in $D^0 \rightarrow h^+ h^-$ decays,
- Time-integrated CP violation in $D^0 \rightarrow h^+ h^-$ decays,
- Search for the rare decay $D^0 \rightarrow \mu^+ \mu^-$.

There is also active research on:

- Wrong-sign mixing measurements [[LHCb-CONF-2011-029](#)],
- Charmonium spectroscopy [[LHCb-PAPER-2011-034](#)],
- Charm cross-section measurements [[LHCb-PAPER-2011-019](#)],
[\[LHCb-CONF-2010-013\]](#),
- CPV searches in $D^\pm \rightarrow h^\pm h^+ h^-$ decays [[PRD 84: 112008 \(2011\)](#)].

Mixing and CP violation in $D^0 \rightarrow h^+ h^-$ decays

Observables of interest

Two observables quantifying mixing and CPV:

$$y_{CP} \equiv \frac{\tau(D^0 \rightarrow K^-\pi^+)}{\tau(D^0 \rightarrow K^+K^-)} - 1 \simeq y \cos \phi - \frac{1}{2} A_m x \sin \phi + \frac{1}{8} A_m^2 y \cos \phi,$$

where mixing parameters $x \equiv \Delta m/\Gamma$, $y \equiv \Delta\Gamma/2\Gamma$,

A_m is CPV contribution from mixing, $\phi = \arg(q\bar{A}_f/pA_f)$.

In the absence of CPV, $y_{CP} = y$.

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

where A_d is direct CPV contribution.

Measure **lifetimes** in order to access these parameters.

LHCb analysed 29 pb^{-1} of data taken in 2010 [[LHCb-PAPER-2011-032](#)].

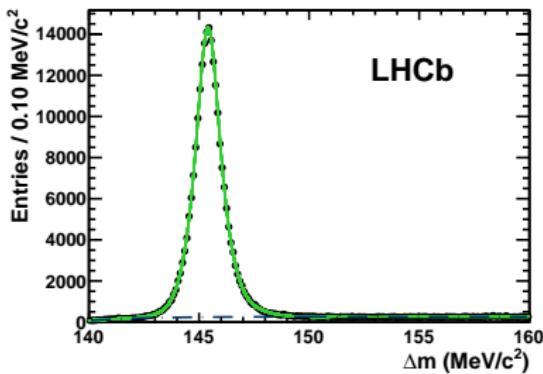
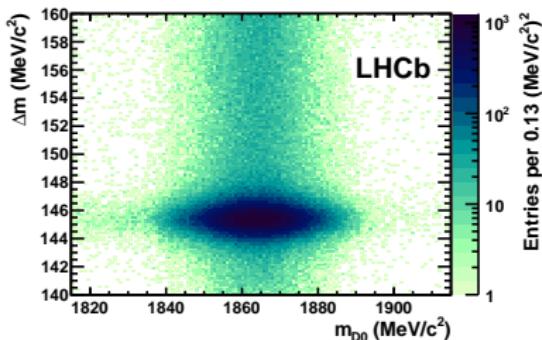
Accepted for publication last week!

Event selection

[LHCb-PAPER-2011-032]

Flavour tagging at production using $D^{*\pm} \rightarrow D\pi_s^\pm$ decays.

Signal and background differentiated using m_{D^0} and $\Delta m \equiv m_{D^*} - m_{D^0}$.
 $(m_{D^0}, \Delta m)$ plane and Δm distribution for tagged $D^0 \rightarrow K^\pm \pi^\mp$ decays:



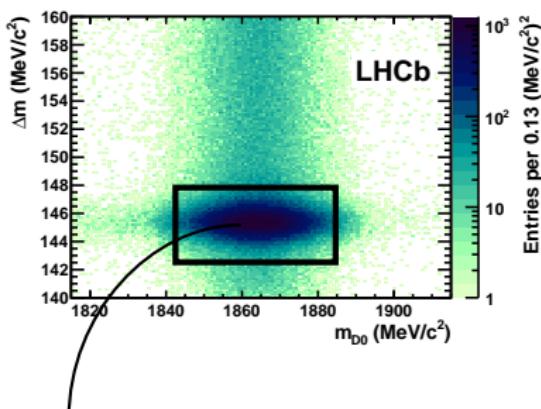
In 29 pb^{-1} : 286k $K^\pm \pi^\mp$,
 39k $K^+ K^-$ candidates.
 Purity > 97%.

Event selection

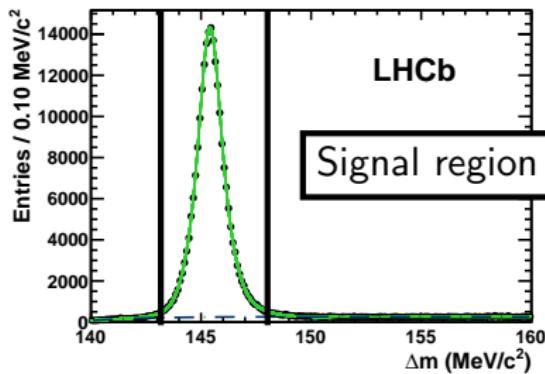
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Signal region



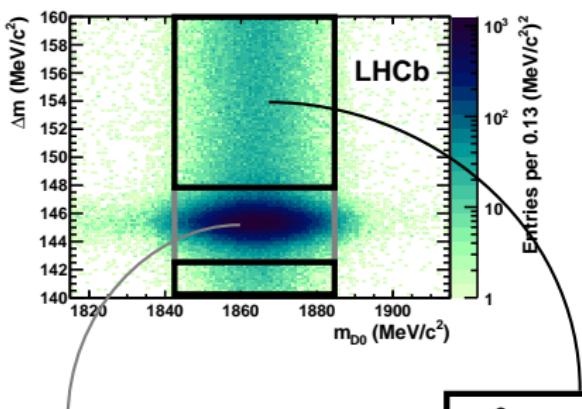
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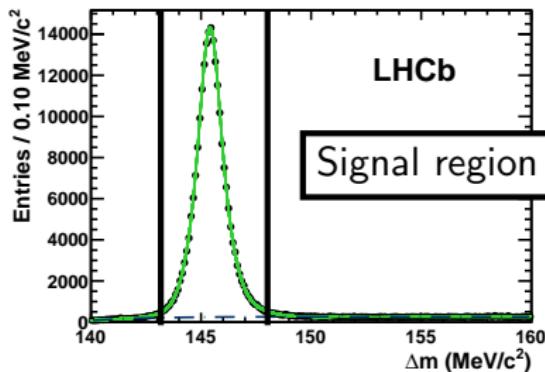
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Signal region

$D^0 +$ random slow pion



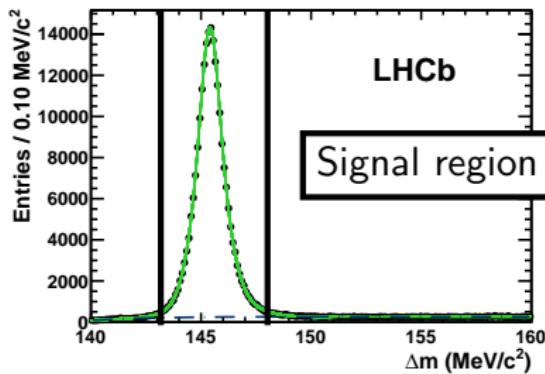
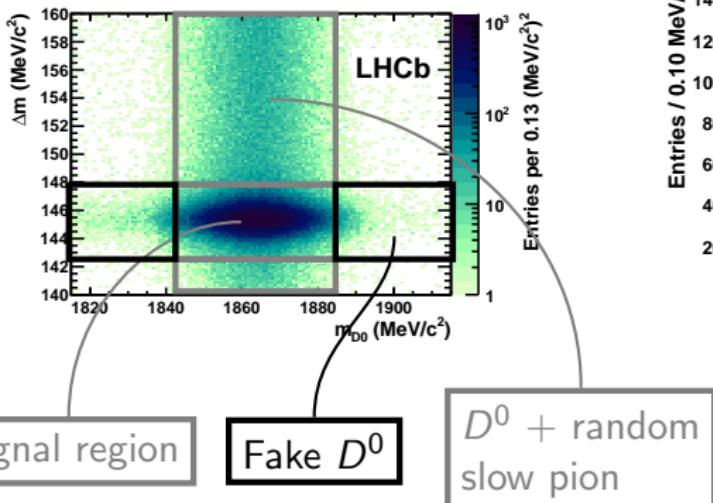
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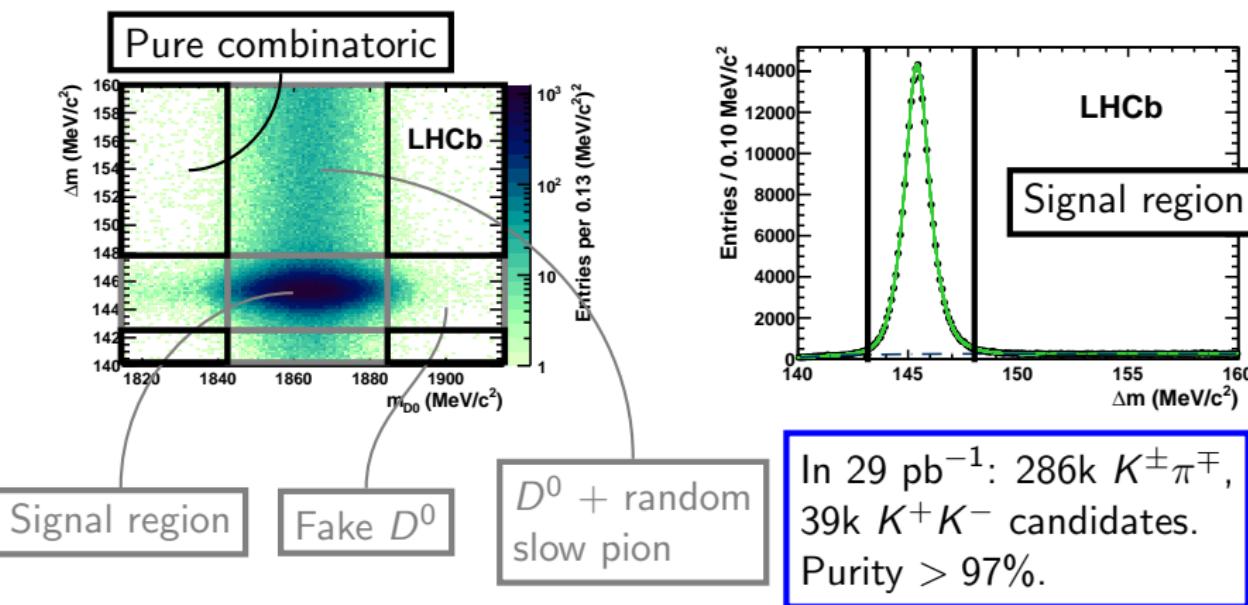
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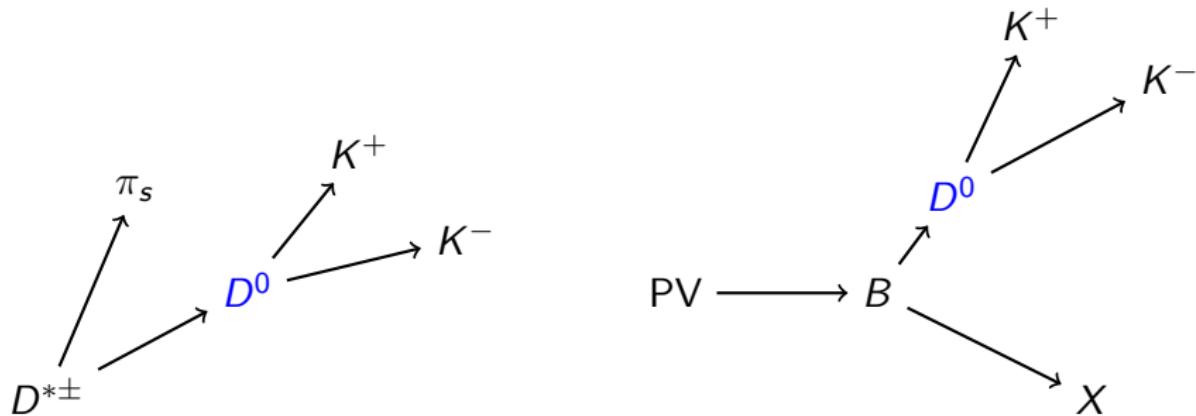
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Prompt and secondary discrimination

[LHCb-PAPER-2011-032]

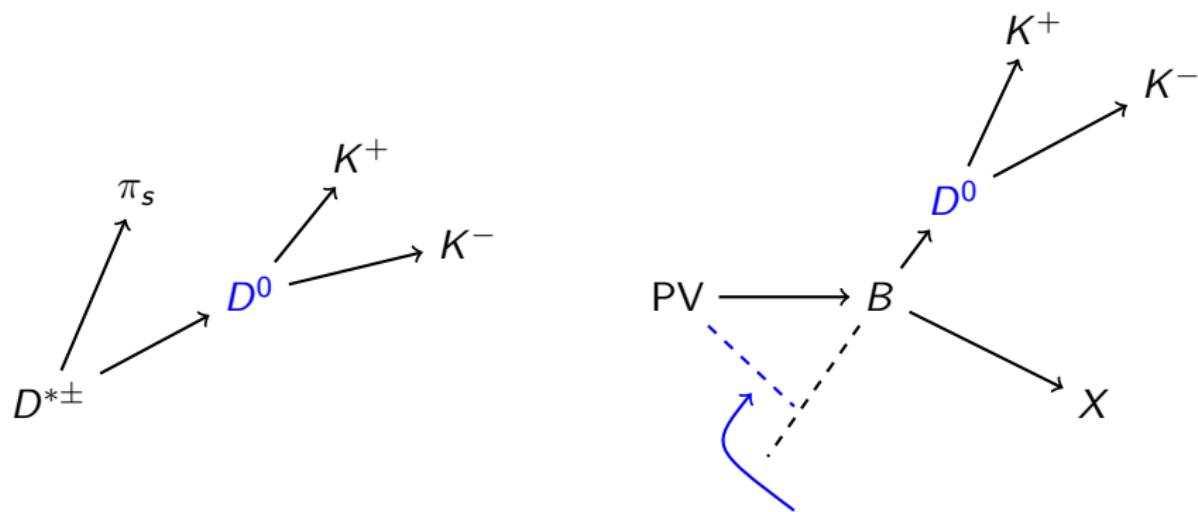
Essential to distinguish between **prompt** and **secondary** ($B \rightarrow DX$) decays.
 Secondary contamination biases lifetime measurement.



Prompt and secondary discrimination

[LHCb-PAPER-2011-032]

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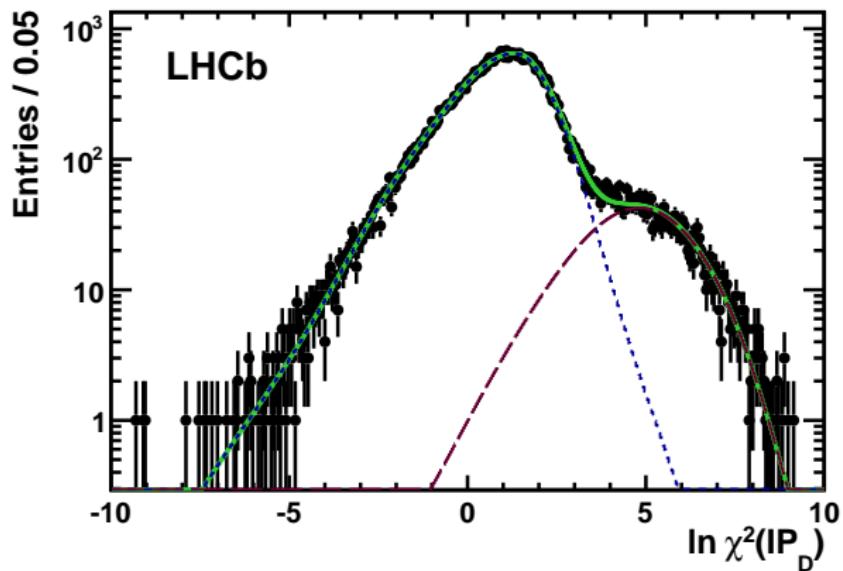


Secondary decays typically have a larger D^0 impact parameter with respect to the primary vertex than prompt decays.

$\ln(\text{IP} \chi^2)$ used to discriminate between prompt and secondary decays.

Prompt and secondary discrimination

[LHCb-PAPER-2011-032]

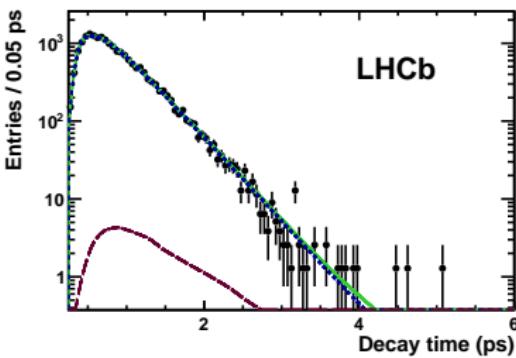
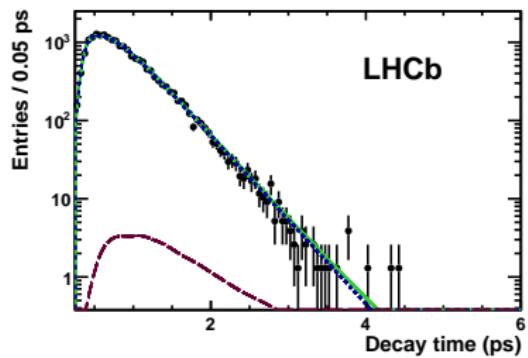
 $\ln(\text{IP}\chi^2)$ distribution for $D^0 \rightarrow K^+ K^-$ decays:

Components: prompt, secondary, total.

Results

[LHCb-PAPER-2011-032]

Decay time distribution of D^0 decays to $K^+ K^-$ (left), $K^\pm \pi^\mp$ (right):



Components: **prompt**, **secondary**, **total**.

Lifetimes found to be in agreement with world average values.

Event-by-event lifetime acceptance determined to avoid bias induced by trigger cuts.

Results

[LHCb-PAPER-2011-032]

CP violation parameters:

$$y_{CP} = (5.5 \pm 6.3 \text{ (stat)} \pm 4.1 \text{ (syst)}) \times 10^{-3},$$
$$A_\Gamma = (-5.9 \pm 5.9 \text{ (stat)} \pm 2.1 \text{ (syst)}) \times 10^{-3}.$$

Significant improvement in precision possible with 2011 data.
Systematic uncertainties will be reduced, primarily treatment of background.

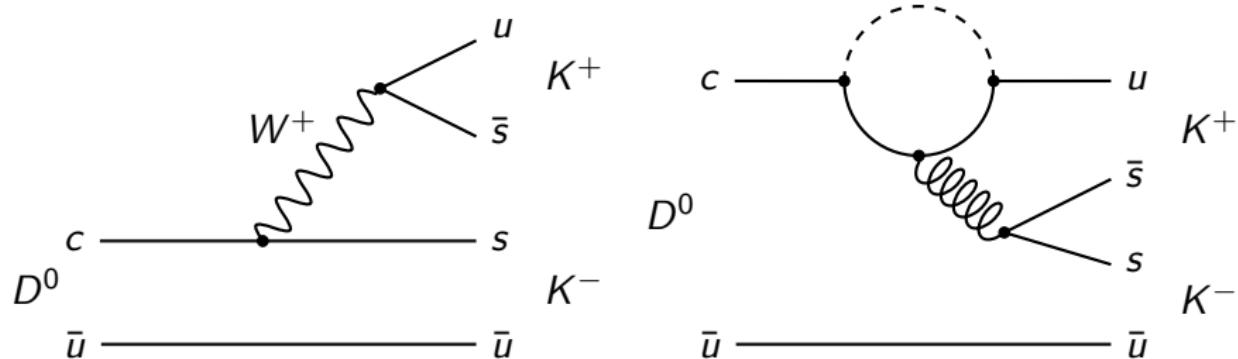
Time-integrated CP violation in $D^0 \rightarrow h^+ h^-$ decays

Time-integrated CP violation

CP asymmetry in D decays to CP eigenstate $h^+ h^-$ ($h = \pi, K$):

$$A_{CP}(h^+ h^-) \equiv \frac{\Gamma(D^0 \rightarrow h^+ h^-) - \Gamma(\bar{D}^0 \rightarrow h^+ h^-)}{\Gamma(D^0 \rightarrow h^+ h^-) + \Gamma(\bar{D}^0 \rightarrow h^+ h^-)}.$$

Singly Cabibbo suppressed; both tree-level and penguin amplitudes:



CP asymmetries of both $K^+ K^-$ and $\pi^+ \pi^-$ predicted to be small in the Standard Model, e.g. [PRD 75: 036008 (2007)], [JHEP 1003: 009 (2010)], [Riv. Nuovo Cim. 26N7: 1 (2003)], [PoS BEAUTY 2009 024 (2009)].

Time-integrated CP violation

Both **direct** (A_{CP}^{dir}) and **indirect** (A_{CP}^{ind}) contributions are possible.

U-spin symmetry: $A_{CP}^{\text{dir}}(K^+ K^-) \simeq -A_{CP}^{\text{dir}}(\pi^+ \pi^-)$ [PRD 75: 036008 (2007)].

Measuring the **difference** between $A_{CP}(K^+ K^-)$ and $A_{CP}(\pi^+ \pi^-)$ is an effective way to separate physics asymmetries from other sources.

Indirect CPV contribution almost entirely cancels in the difference
⇒ this is a measurement of **direct** CP violation.

LHCb studied 0.62 fb^{-1} data taken in 2011 [PRL 108: 111602 (2012)].

Reconstructed **1.44M** $K^+ K^-$ and **0.38M** $\pi^+ \pi^-$ candidates.

Asymmetries

Use $D^{*\pm} \rightarrow D^0 \pi_s^\pm$ decays in which the D decays to final state f .
 Raw, measured, asymmetry is:

$$A_{\text{raw}}(f) = A_{CP}(f) + A_{\text{det}}(f) + A_{\text{det}}(\pi_s) + A_{\text{prod}}(D^{*\pm}),$$

where A_{det} is detector asymmetry, A_{prod} is production asymmetry.
 Measure difference between raw asymmetries of D decays to $K^+ K^-$ and $\pi^+ \pi^-$. Expect:

- A_{prod} and $A_{\text{det}}(\pi_s)$ cancel in the difference,
- $A_{\text{det}}(f)$ will be zero for D^0 decays to $h^+ h^-$.

i.e. all D^* -related production and detection effects cancel.

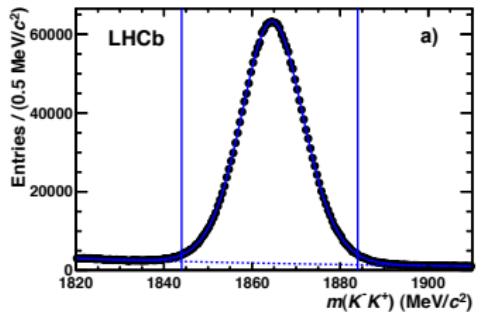
All that remains is:

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

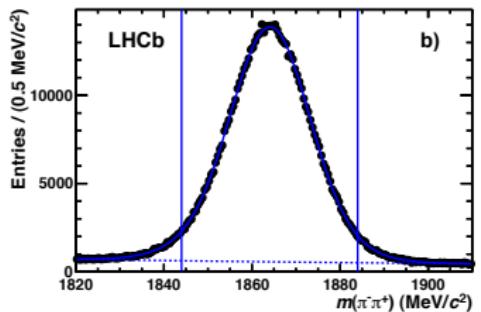
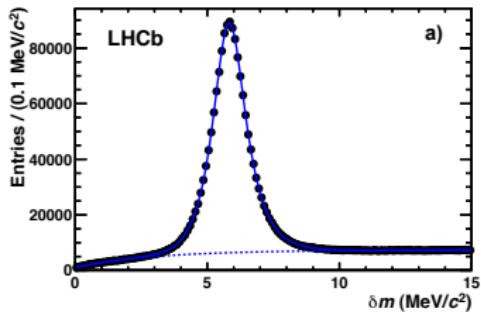
Signal and background discrimination

[PRL 108: 111602 (2012)]

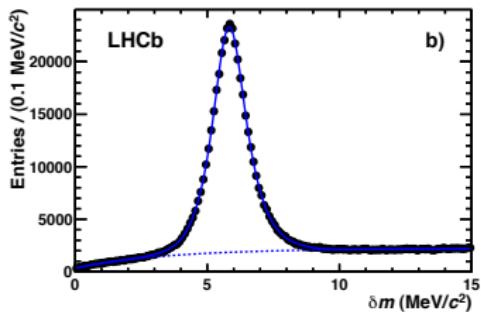
As in y_{CP}/A_Γ measurement, fit to m_{D^0} and Δm :



K^+K^-
1.44M



$\pi^+\pi^-$
0.38M



Second-order effects

[PRL 108: 111602 (2012)]

Double difference is **robust against systematic effects**.

Employ safeguards against possible second-order effects:

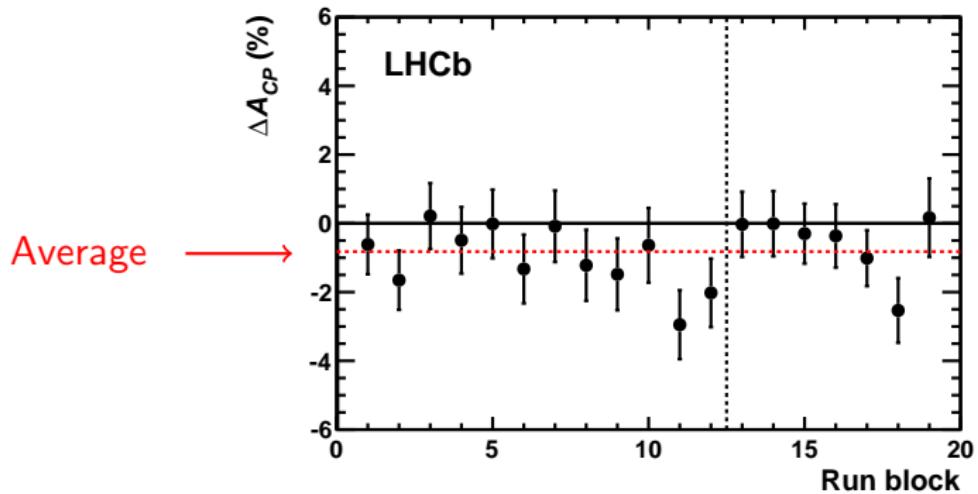
- Detector acceptance
 - **Magnetic field** can sweep slow pion out of acceptance or into beampipe.
 - Behaviour different for D^{*+} , D^{*-} . Induces **large raw asymmetries**.
 - **Fiducial cuts** applied to exclude edge regions and beampipe.
 - Regular **reversal** of LHCb magnetic polarity provides further protection.
- Differences between $K^+ K^-$ and $\pi^+ \pi^-$ kinematics
 - Production and detection asymmetries can **vary with kinematics** (e.g. η , \mathbf{p}_T).
 - Correlated variation with $K^+ K^-$ and $\pi^+ \pi^-$ **detection efficiency** would lead to artificial asymmetry.
 - Divide sample into **bins** to mitigate this effect.

Cross-checks

[PRL 108: 111602 (2012)]

Robustness of result checked against several criteria (kinematic regions, magnet polarity, particle ID, time period).

Stability over run period:



No significant deviation observed.

Results

[PRL 108: 111602 (2012)]

$$\Delta A_{CP} = (-0.82 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst)})\%.$$

3.5 σ deviation from zero: first evidence for CPV in the charm sector.

Results

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Systematic uncertainties:

- Fit procedure: 0.08%
- Kinematic binning: 0.02%
- Peaking background: 0.04%
- Multiple candidates: 0.06%
- Fiducial cuts: 0.01%

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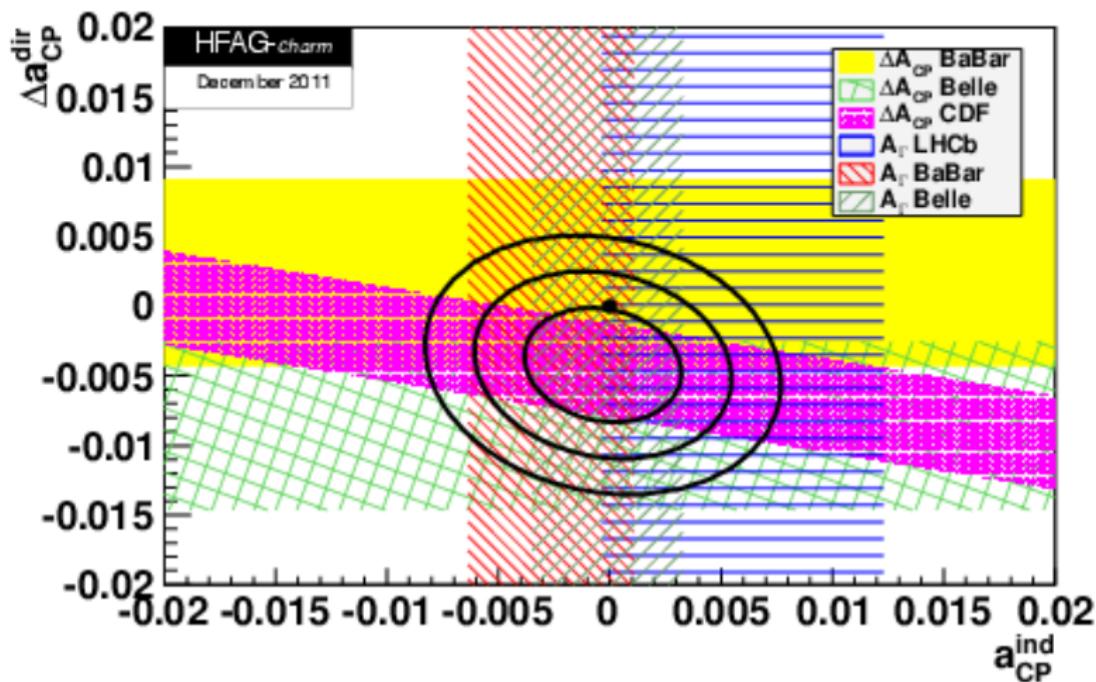
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Recent CDF analysis of 9.7 fb⁻¹ found

$$\Delta A_{CP} = (-0.62 \pm 0.21 \text{ (stat)} \pm 0.10 \text{ (syst)})\%. \quad [\text{CDF note 10784}].$$

Interpretation

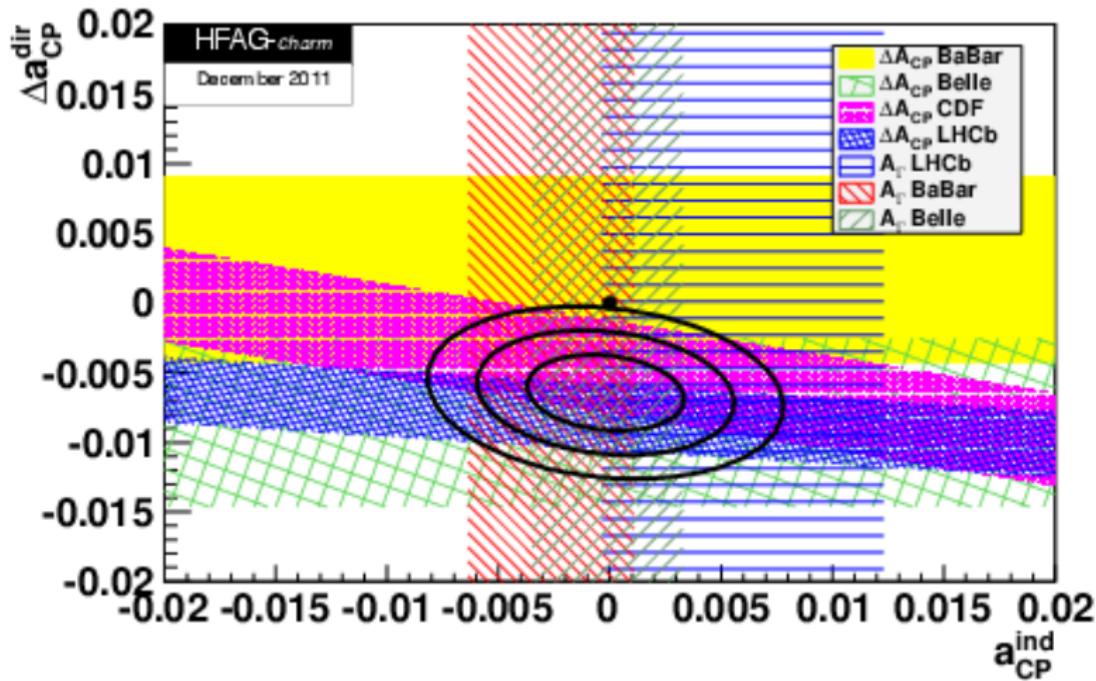
HFAG combination before LHCb result:



$$a_{CP}^{ind} = (-0.03 \pm 0.23)\%, \quad \Delta a_{CP}^{dir} = (-0.42 \pm 0.27)\%$$

Interpretation

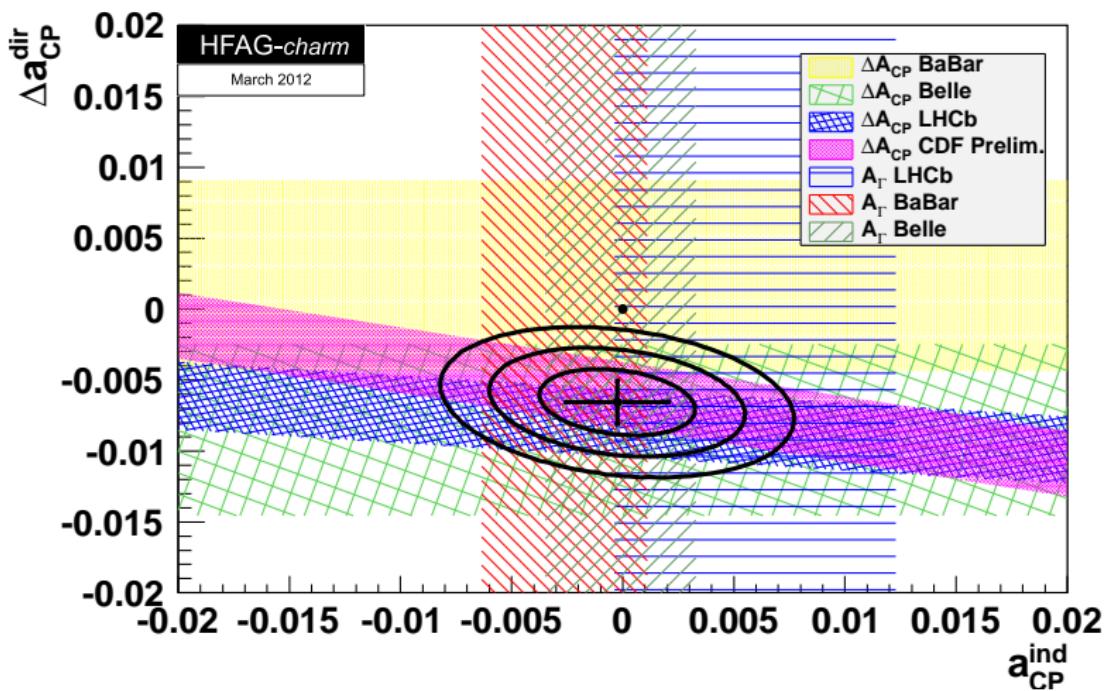
HFAG combination after LHCb result, before CDF result:



$$A_{CP}^{ind} = (-0.02 \pm 0.23)\%, \quad \Delta A_{CP}^{dir} = (-0.65 \pm 0.18)\%$$

Interpretation

Most recent HFAG combination:

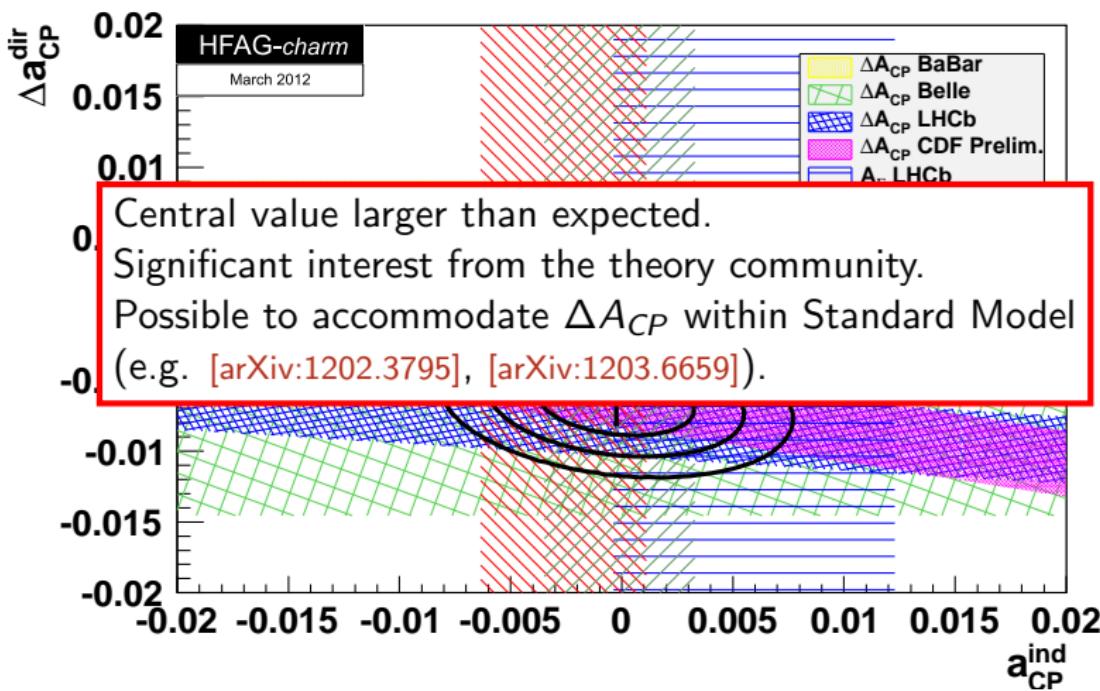


$$A_{CP}^{ind} = (-0.03 \pm 0.23)\%,$$

$$\Delta A_{CP}^{dir} = (-0.66 \pm 0.15)\%$$

Interpretation

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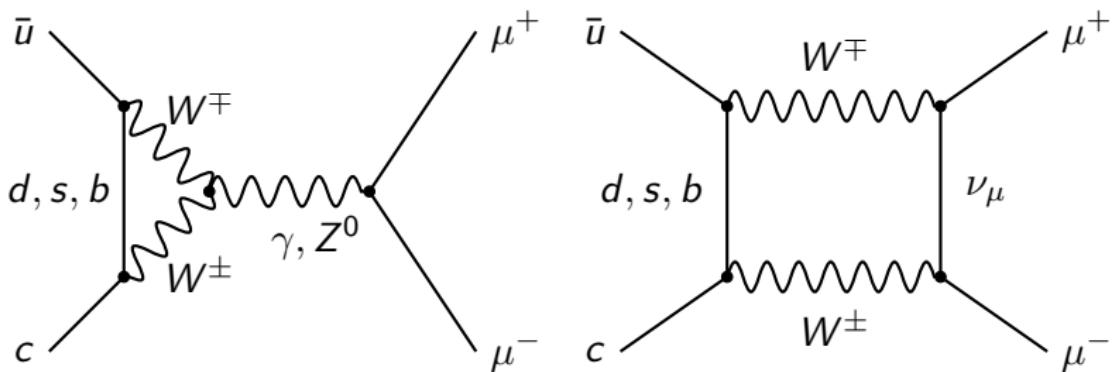


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Search for the rare decay $D^0 \rightarrow \mu^+ \mu^-$

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

Very rare decay. Standard model BF $< 6 \times 10^{-11}$ (90% C.L.).



Significant enhancement possible in NP models such as R SUSY
[\[PRD 66: 014009 \(2002\)\]](#), [\[Ann. Rev. Nucl. Part. Sci. 53: 431 \(2003\)\]](#).
 Couplings also appear in $D^0 \bar{D}^0$ mixing amplitudes [\[PRD 79: 114030 \(2009\)\]](#).

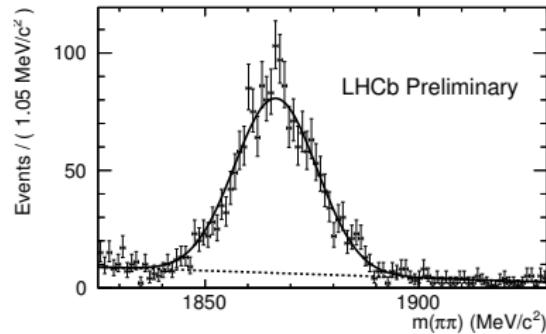
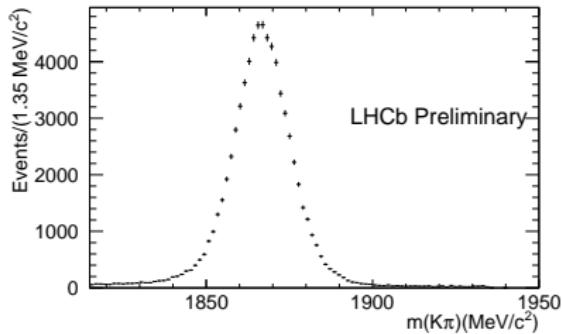
Search for $D^0 \rightarrow \mu^+ \mu^-$

LHCb studied 0.9 fb^{-1} of data [LHCb-CONF-2012-005].

Channels reconstructed:

- $D^{*\pm} \rightarrow D^0(\mu^+ \mu^-)\pi^\pm$. Use discriminating variables m_{D^0} and Δm .
- Normalisation channel $D^{*\pm} \rightarrow D^0(\pi^+ \pi^-)\pi^\pm$: very similar kinematics.
- Abundant mode $D^{*\pm} \rightarrow D^0(K^\pm \pi^\mp)\pi^\pm$ used to cross-check $\mu - \pi$ misID.

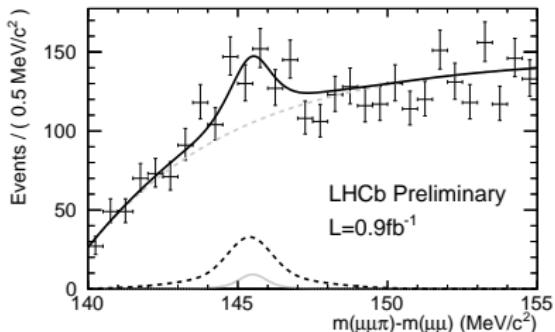
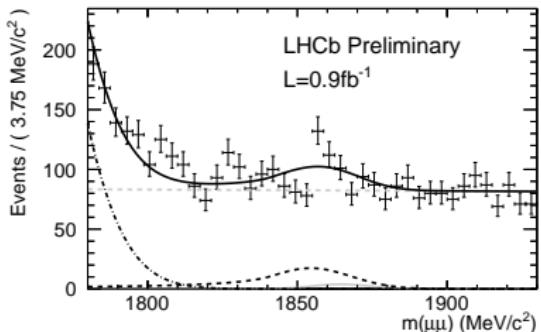
Mass distributions for $K^\pm \pi^\mp$ (left), $\pi^+ \pi^-$ (right):



Results

[LHCb-CONF-2012-005]

$D^0 \rightarrow \mu^+ \mu^-$ mass (left), Δm (right):



$\mathcal{O}(8k)$ events. Fit components:

- Signal ———
- $D^0 \rightarrow \pi^+ \pi^-$ -----
- $D^0 \rightarrow K^\pm \pi^\mp$
- Combinatorial background - - - -

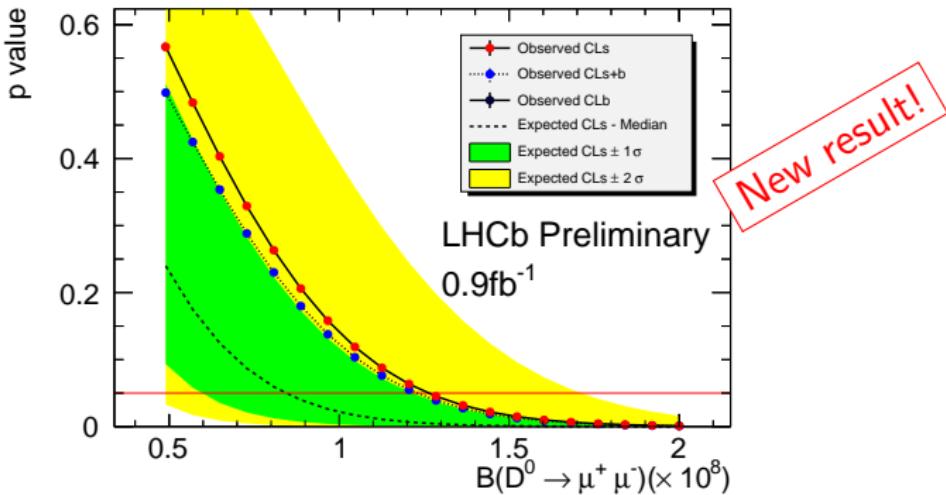
Fit quantity of signal **consistent with zero**.

Search for $D^0 \rightarrow \mu^+ \mu^-$

[LHCb-CONF-2012-005]

CL_s method used to determine upper limit on branching ratio:

$$\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) < 1.3 \text{ (1.1)} \times 10^{-8} \text{ at 90 (95)\% C.L.}$$



Previous best upper limit 1.4×10^{-7} [PRD 81: 091102(R) (2010)].
SM prediction several orders of magnitude lower.

Conclusions

Using data collected in 2010 and 2011, LHCb has performed extensive studies of physics in the charm sector.

Results shown today:

- Mixing and CPV in two-body D^0 decays:
 $y_{CP} = (5.5 \pm 6.3 \text{ (stat)} \pm 4.1 \text{ (syst)}) \times 10^{-3}$,
 $A_\Gamma = (-5.9 \pm 5.9 \text{ (stat)} \pm 2.1 \text{ (syst)}) \times 10^{-3}$;
- Time-integrated CPV: $\Delta A_{CP} = (-0.82 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst)})\%$;
- Search for the rare decay $D^0 \rightarrow \mu^+ \mu^-$.

These will all be updated to use entirety of 2011 dataset.

In 2012 will collect at least double the 2011 dataset.

Significant number of active analyses not shown.

LHCb is grateful for theorists' interest in our charm results.

Expect great things for 2012 and beyond!

Backup

Charm mixing and CP violation

Time evolution of flavour eigenstates:

$$\begin{aligned} |D^0(t)\rangle = \frac{1}{2p} & \left[e^{-i(m_1 - i\Gamma_1/2)t} (p|D^0\rangle + q|\bar{D}^0\rangle) \right. \\ & \left. + e^{-i(m_2 - i\Gamma_2/2)t} (p|D^0\rangle - q|\bar{D}^0\rangle) \right]. \end{aligned}$$

where $m_{1,2}$ and $\Gamma_{1,2}$ are masses and widths of mass eigenstates.

Parameters conventionally used are:

Mixing: $x \equiv \frac{m_2 - m_1}{(\Gamma_2 + \Gamma_1)/2}, \quad y \equiv \frac{\Gamma_2 - \Gamma_1}{\Gamma_2 + \Gamma_1},$

CP violation in mixing: $\left| \frac{q}{p} \right|, \quad \arg \left(\frac{q}{p} \right).$

CP violation in mesons

CP violation arises when a decay can proceed via **two different amplitudes with different strong and weak phases**. Three types of CPV are possible in neutral meson systems. For the final state f :

- **Decay**: A_f , the rate of $D^0 \rightarrow f$, is not equal to $\bar{A}_{\bar{f}}$, the rate of $\bar{D}^0 \rightarrow \bar{f}$. Direct CPV.
- **Mixing**: the rate of $D^0 \rightarrow \bar{D}^0$ transitions is not equal to the rate of $\bar{D}^0 \rightarrow D^0$; $|q/p| \neq 1$. Indirect CPV.
- **Interference between decay and mixing**, e.g. between $D^0 \rightarrow f$ and $D^0 \rightarrow \bar{D}^0 \rightarrow f$; $Im(q\bar{A}_{\bar{f}}/pA_f) \neq 0$.

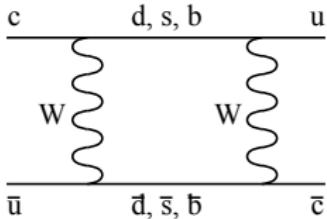
In charged meson systems only direct CPV is possible.

New physics could significantly enhance both direct and indirect CPV.

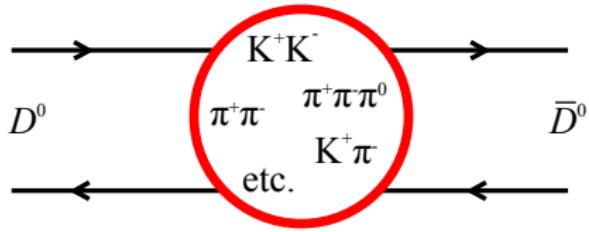
Charm mixing

Charm mixing is small in the Standard Model. Contributions from:

- Short range **box diagrams**: contribute mostly to x . Intermediate b are CKM suppressed; intermediate d, s are GIM suppressed. $x \sim 10^{-5}$.

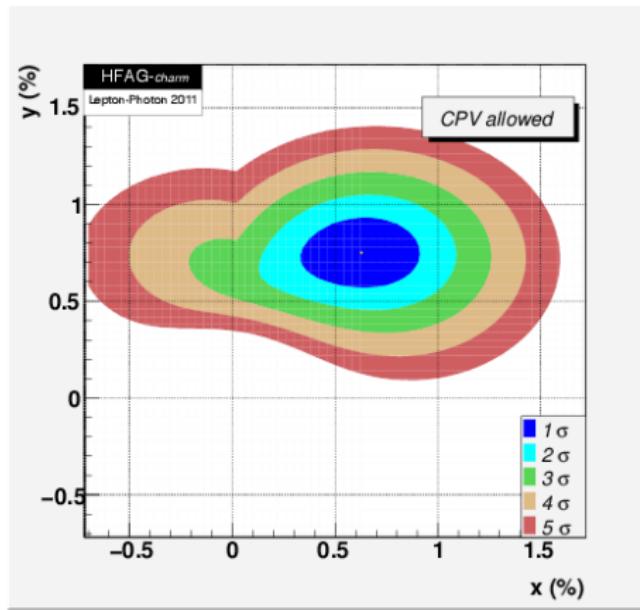


- Long range **hadronic intermediate states** (e.g. $D^0 \rightarrow K^+ K^- \rightarrow \bar{D}^0$). Non perturbative, hard to predict SM contribution. $|x|, |y| < 0.01$.



Current values of x and y

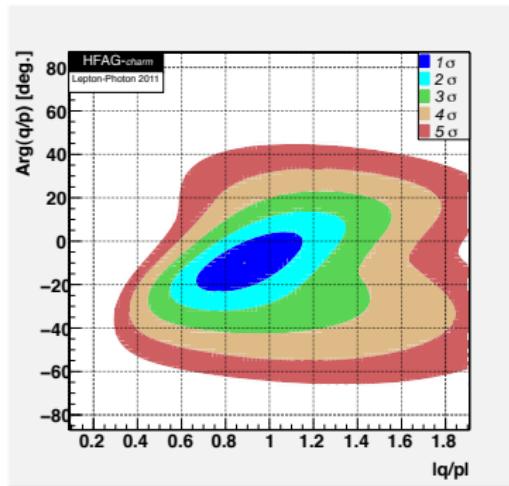
Current state of x and y allowing for CPV (HFAG):



Excludes no-mixing hypothesis by 10σ .

Current values of q and p

Current state of q and p (HFAG):



CP asymmetries are very small ($\mathcal{O}(10^{-4})$), e.g.:

$$2A_\Gamma = (|q/p| - |p/q|)\mathbf{y}\cos(\phi) - (|q/p| + |p/q|)\mathbf{x}\sin(\phi)$$

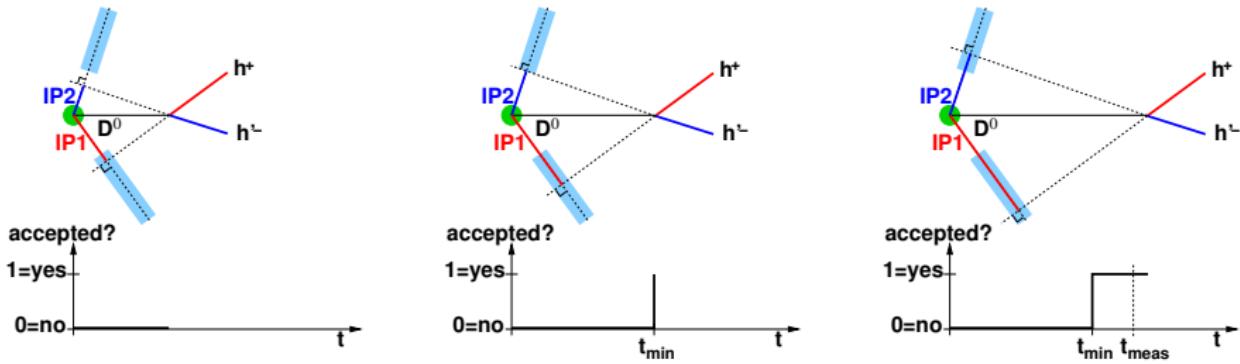
Terms in red $\ll 1$.

Swimming: event-by-event lifetime acceptance

Swimming used in order to determine event-by-event lifetime acceptances. Suited to LHCb because can reproduce trigger exactly in software. Use data instead of MC.

Ideally would shift D^0 decay vertex, but very challenging. Have to move all VELO hits, for example.

Instead, move primary vertices in the opposite direction. Almost the same; systematic uncertainty for difference.



Direct and indirect CP asymmetry

CP asymmetry can be decomposed into **direct** (A_{CP}^{dir}) and **indirect** (A_{CP}^{ind}) contributions:

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

where $\langle t \rangle$ is average decay time in sample, τ is D^0 lifetime.

A_{CP}^{ind} thought to be **universal** between D decays to different CP eigenstates. Therefore:

$$\begin{aligned} \Delta A_{CP} &\equiv A_{CP}(K^+ K^-) - A_{CP}(\pi^+ \pi^-) \\ &= [A_{CP}^{\text{dir}}(K^+ K^-) - A_{CP}^{\text{dir}}(\pi^+ \pi^-)] + \frac{\Delta \langle t \rangle}{\tau} A_{CP}^{\text{ind}} \\ &\equiv \Delta A_{CP}^{\text{dir}} + \frac{\Delta \langle t \rangle}{\tau} A_{CP}^{\text{ind}}, \end{aligned}$$

where $\Delta \langle t \rangle \equiv \langle t \rangle_{K^+ K^-} - \langle t \rangle_{\pi^+ \pi^-}$.

ΔA_{CP} systematic uncertainties in more detail

- Fit procedure: 0.08%
 - Change in ΔA_{CP} between baseline and no fitting, just sideband subtraction.
- Kinematic binning: 0.02%
 - Change in ΔA_{CP} between default binning and one giant bin.
- Peaking background: 0.04%
 - Toy studies; inject a peaking background with a size and asymmetry set according to D^0 mass sidebands.
- Multiple candidates: 0.06%
 - Mean change in ΔA_{CP} when removing multiple candidates, keeping one per event chosen at random.
- Fiducial cuts: 0.01%
 - Change in ΔA_{CP} when significantly loosening the cuts.

Sum in quadrature: 0.11%.

CP violation searches in $D^\pm \rightarrow h^\pm h^+ h^-$ decays

D^\pm decays to $h^\pm h^+ h^-$

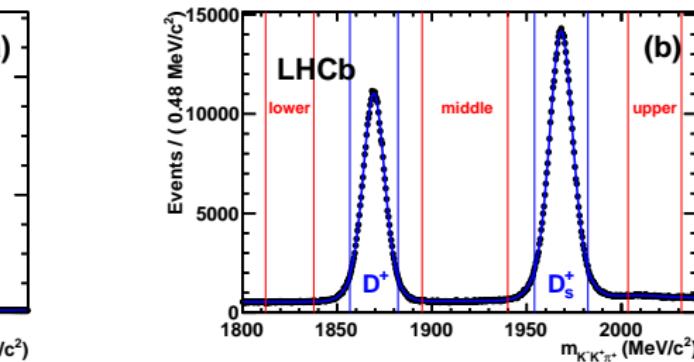
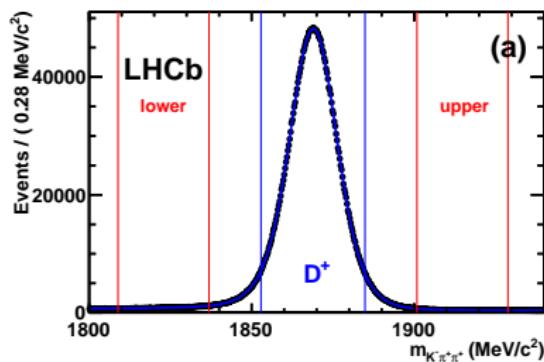
Measure direct CP violation across three-body Dalitz plot. LHCb analysis of 35 pb^{-1} of 2010 data [PRD 84: 112008 (2011)].

Cleanest, most abundant mode is the SCS $D^\pm \rightarrow K^+ K^- \pi^\pm$.

Approximately 370k events available.

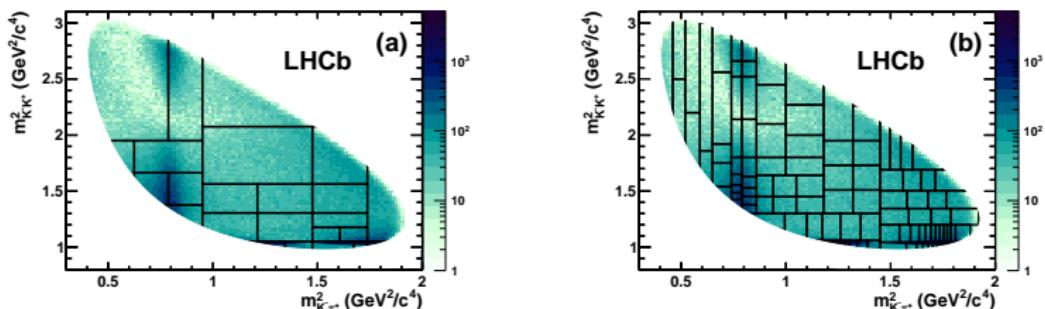
Similar decay modes, including D_s decays, are selected as controls.

Mass spectra of $D^\pm \rightarrow K^\mp \pi^+ \pi^-$ (left) and $D^\pm, D_s \rightarrow K^+ K^- \pi^\pm$ (right):



D^\pm decays to $h^\pm h^+ h^-$

Bin Dalitz plot either uniformly or adaptively based on event density:



In each bin determine

$$S_{CP}^j = \frac{N_j^+ - N_j^- R}{\sqrt{N_j^+ + N_j^- R^2}},$$

where $R = N^+/N^-$. Sum $(S_{CP}^j)^2$ to create a χ^2 which is converted to p -value of consistency with no CPV.

Result: no deviation from the 'no-CPV' hypothesis.

Wrong-sign D^0 mixing measurements

Wrong-sign mixing

Measure time-dependent ratio of wrong-sign to right-sign D^0 decays:

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

Time evolution of WS rate:

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

R_D is rate of DCS D^0 decays,

$$x' = x \sin \delta_{K\pi} + y \cos \delta_{K\pi}, \quad y' = -x \sin \delta_{K\pi} + y \cos \delta_{K\pi}$$

Wrong-sign mixing

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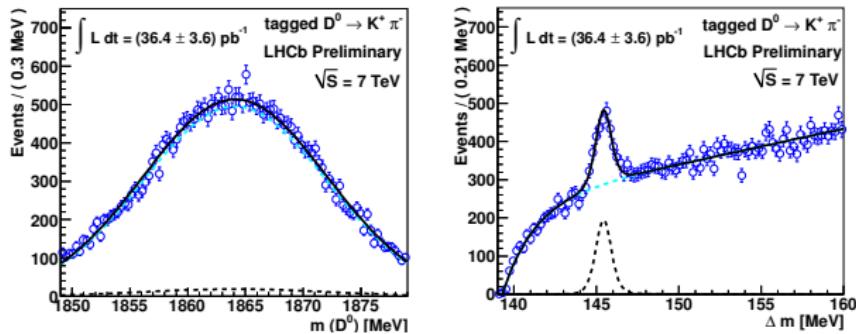
DCS decays

DCS/mixing interference

Mixed decays

Wrong-sign mixing

LHCb analysed 37 pb^{-1} of 2010 data [LHCb-CONF-2011-029].
 m_{D^0} and Δm fits for wrong-sign candidates:



Time-integrated WS/RS ratio:

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

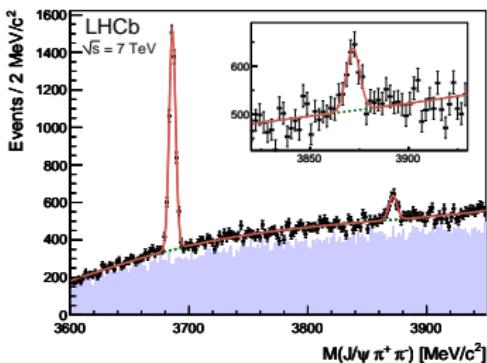
After correction for time acceptance:

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

Charmonium spectroscopy

$X(3872)$

$X(3872)$ mass distribution measured in 2010 data [LHCb-PAPER-2011-034].



$$m_{X(3872)} = 3871.95 \pm 0.48 \text{ (stat)} \pm 0.12 \text{ (syst)} \text{ MeV}/c^2.$$

Inclusive cross section

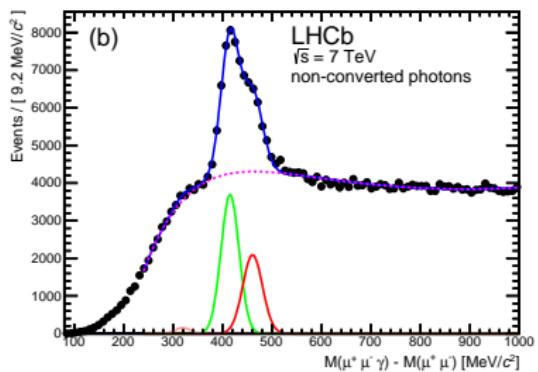
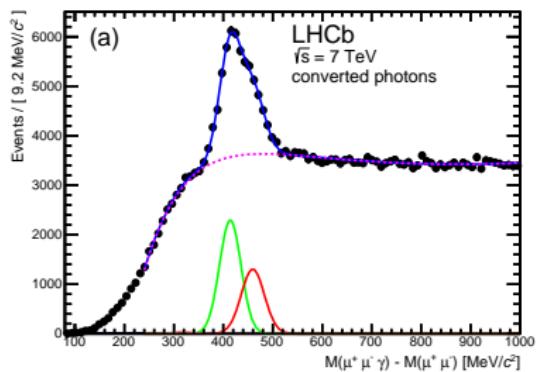
$$\begin{aligned} \sigma(pp \rightarrow X(3872) + \text{anything}) \times \mathcal{B}(X(3872) \rightarrow J/\psi \pi^+ \pi^-) \\ = 4.7 \pm 1.1 \text{ (stat)} \pm 0.7 \text{ (syst)} \text{ nb}, \end{aligned}$$

given $2.5 < y < 4.5$, $5 < \mathbf{p}_T < 20 \text{ GeV}/c$.

Cross section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$

LHCb study of 2010 data [LHCb-PAPER-2011-019]. Charmonium decays into $J/\psi(\mu^+\mu^-)\gamma$.

Mass spectra of converted (left) and non-converted (right) photons:



Components: χ_{c0} , χ_{c1} , χ_{c2} , background.

Cross section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$

Cross section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ measured in bins of J/ψ \mathbf{p}_T :

