Charm CP Violation and Rare Decays at LHCb

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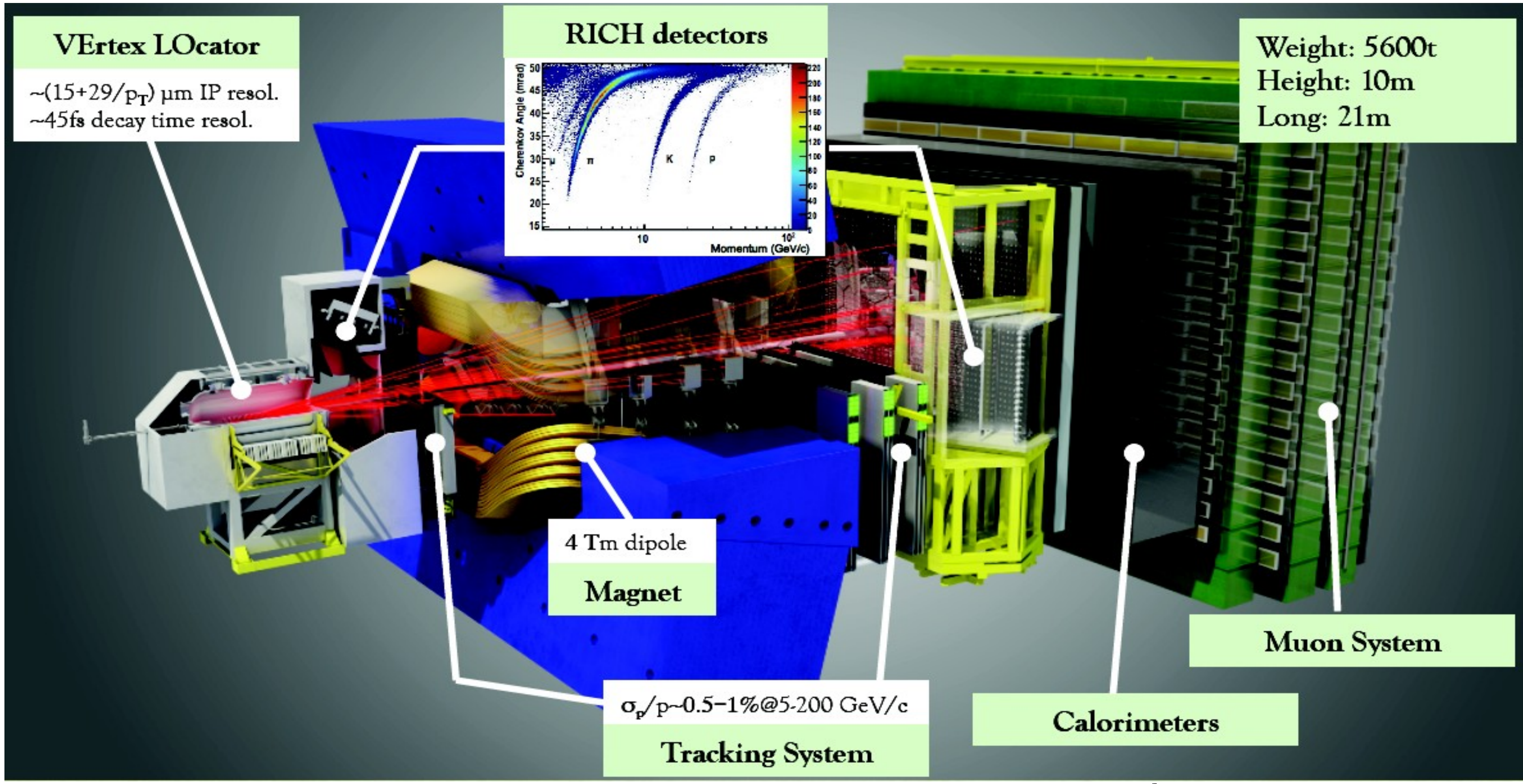
Highlighted LHCb results

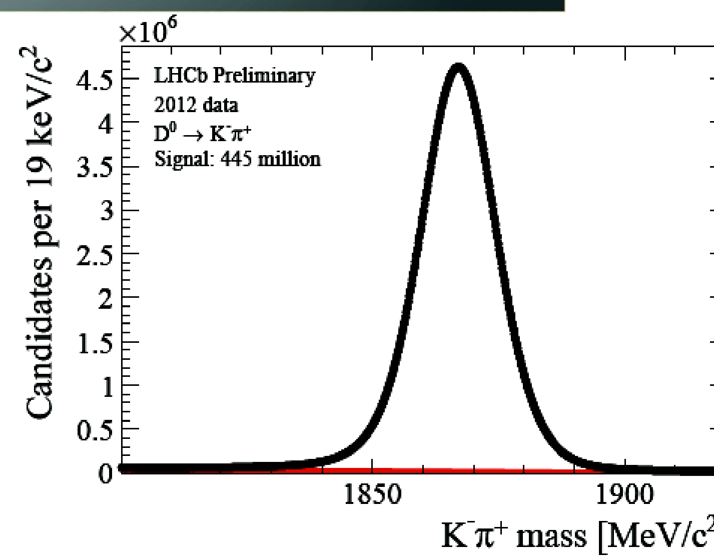
- Charm mixing and CP asymmetries
  - First observation of mixing in D0 → Kπππ decay
  - Mixing and CP asymmetry in D0 → $K^+\pi^-$ (DT, **preliminary**)
  - Difference between CP asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays, ΔA_{CP} (pion tagged)
  - CP asymmetry in $D^0 \to K^+K^-$ decay (**preliminary**)
- Rare D decays
  - First observation of D → Kπμμ decay in the ρ^0/ω region in the dimuon mass spectrum
  - Search for D → $e^+\mu^-$ decay

LHCb detector



Int. J. Mod. Phys. A 30, 1530022 (2015)

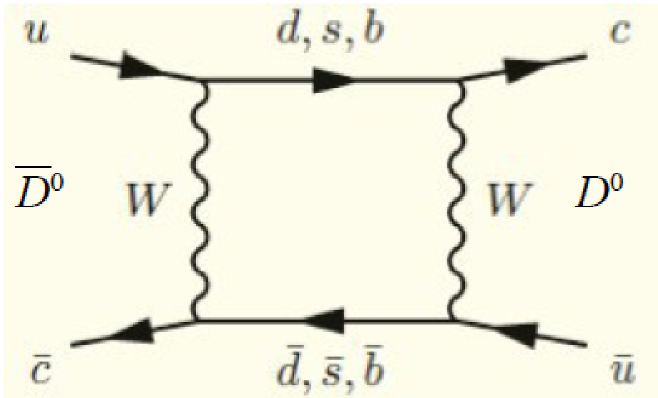
- LHCb acceptance: $2 < \eta < 5$ (forward region)
- All the results presented today are based on (a subset of) 3fb^{-1} Run1 data of LHC collected within 2011-2012
- 1.15 billion charm hadron decays reconstructed in Run1 >20X CDF samples of 10fb^{-1}



LHCb-CONF-2016-005

Mixing and CPV in $D^0 - \overline{D}^0$

- Charm mixing: unique probe of mixing in the up-type quark system
  - Mass eigenstates are related to their flavor eigenstates via $|D_{1,2}> \equiv p|D^0> \pm q|\overline{D}^0>$, with $|q|^2 + |p|^2 \equiv 1$
    - If indirect CPV is conserved, $|q/p| = 1$, $\phi \equiv \arg(q/p) = 0$
  - Mixing parameters based on the mass and width differences: $x \equiv (m_2 - m_1)/\Gamma$, $y \equiv (\Gamma_2 - \Gamma_1)/2\Gamma$, with $\Gamma \equiv (\Gamma_2 + \Gamma_1)/2$
- In the SM, expecting
  - x, y ~ 1% or less
  - CPV ~ 1% or less
- Observation of enhanced CPV in the charm sector would be a clear indication of new physics



Short-distance contribution

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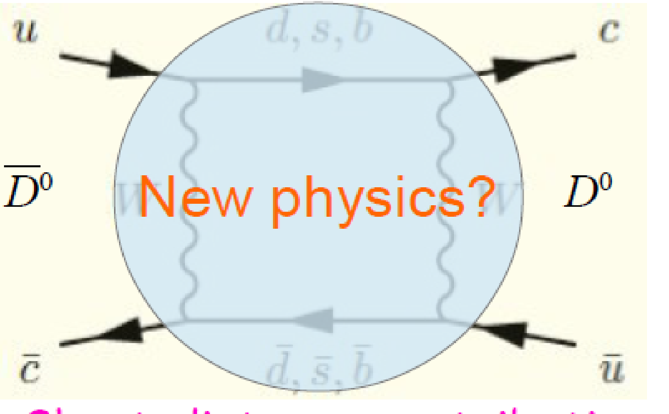
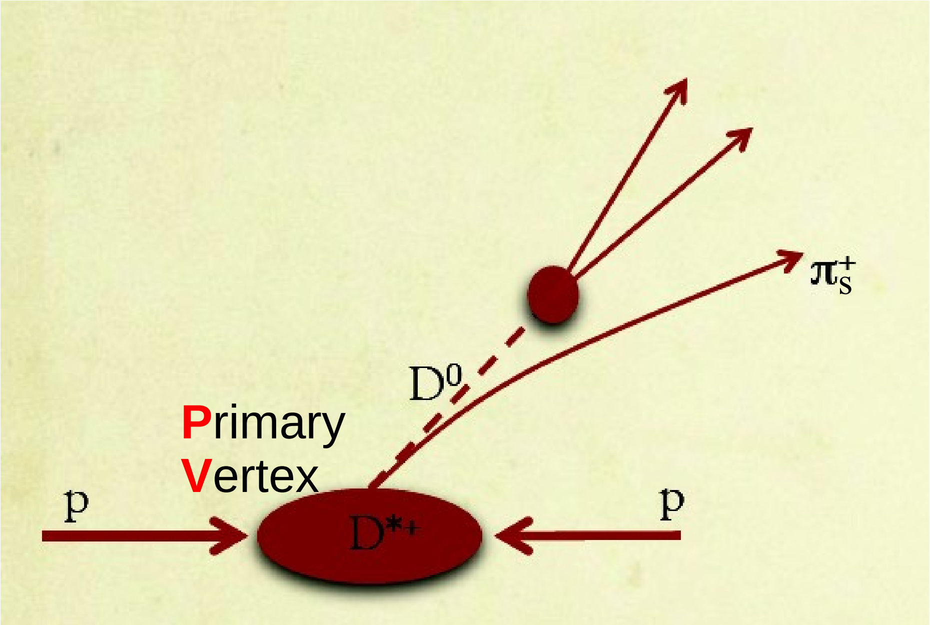
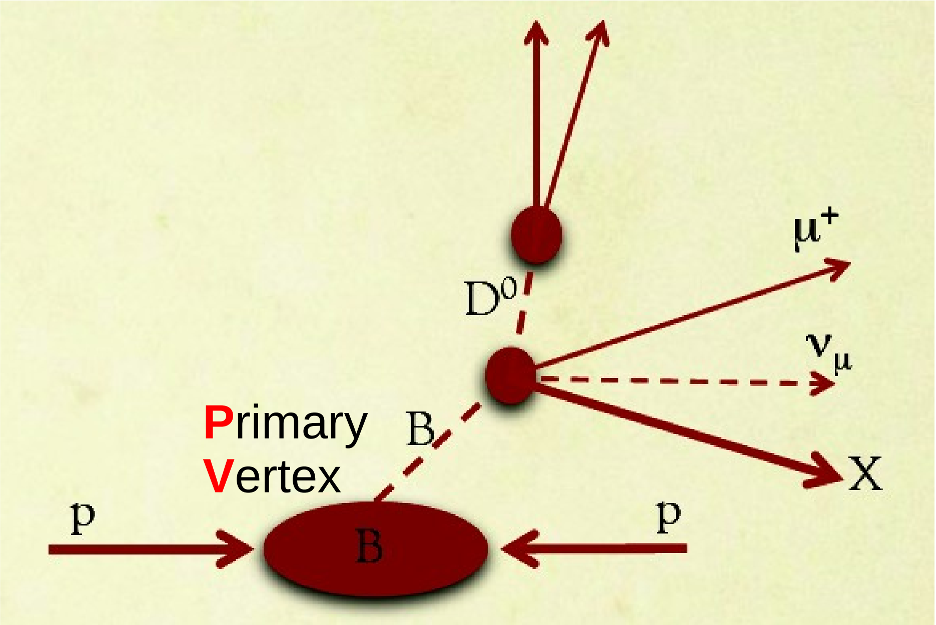


Short-distance contribution
NP might manifest in the loop

D^0 flavor tagging in LHCb





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

Pion tagged: flavor determined by charge of soft pion from "prompt" D^*

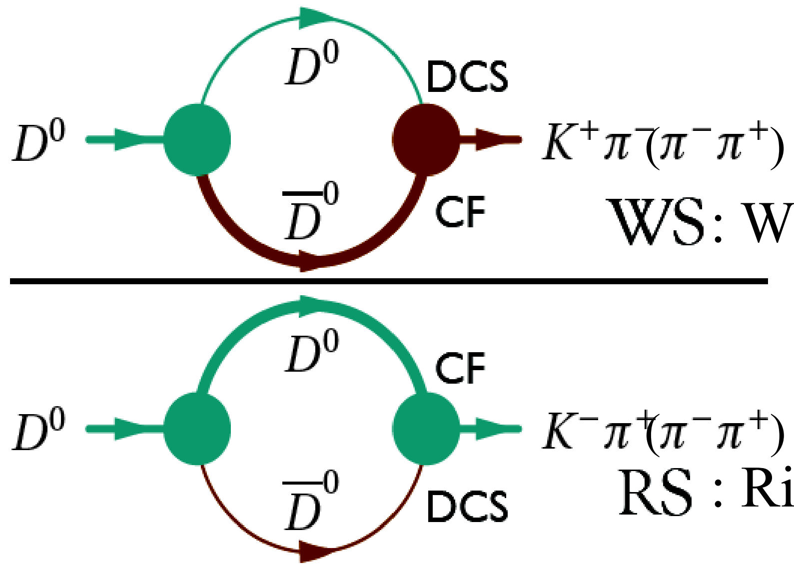
$B \rightarrow D^{(*)} \mu^+\nu_\mu X$ semi-leptonic

Muon tagged: flavor determined by charge of muon from B

Doubly tagged (DT): flavor determined by charge of soft pion from "secondary" D^*, which is from muon tagged B

Mixing in $D^0 \to K\pi(\pi\pi)$

Signal yield ratio as a function of D^0 decay-time: $R(t) =$



WS: Wrong Sign

RS : Right Sign

In the limit of x, y « 1, and assuming no CPV, the WS/RS yield ratio R varies with D^0 decay time t as:

$$R(t) \equiv \frac{N(WS)(t)}{N(RS)(t)} \approx R_D + \sqrt{R_D}\, y' \,\frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

τ: known D^0 lifetime R_D: the ratio of DCS to CF decay rates

δ: strong phase difference between DCS and CF amplitudes

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

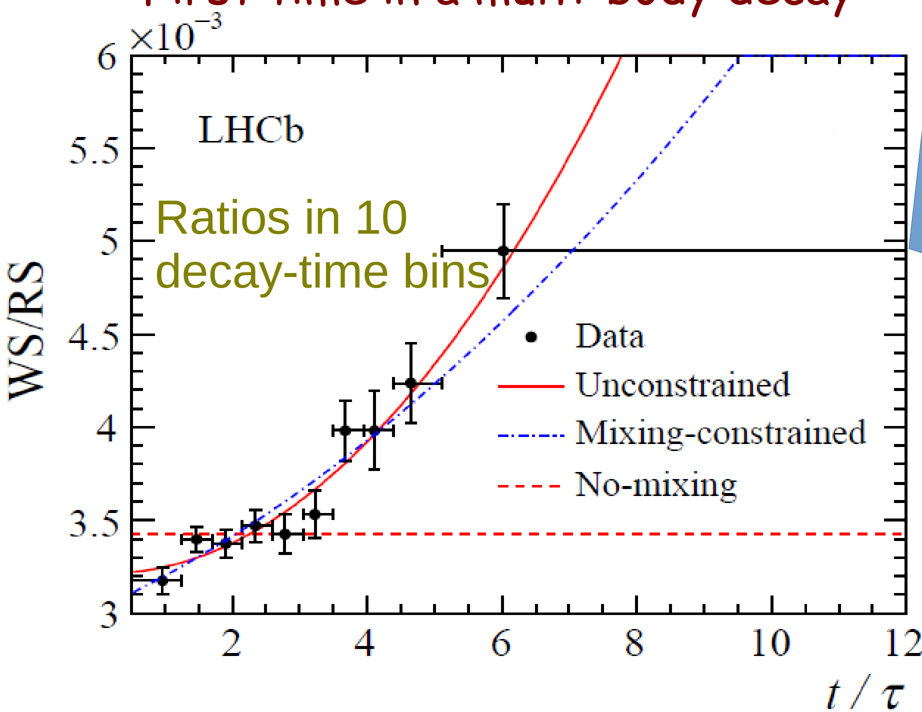
NB: Different R_D and δ in D→Kπ and D→Kπππ cases

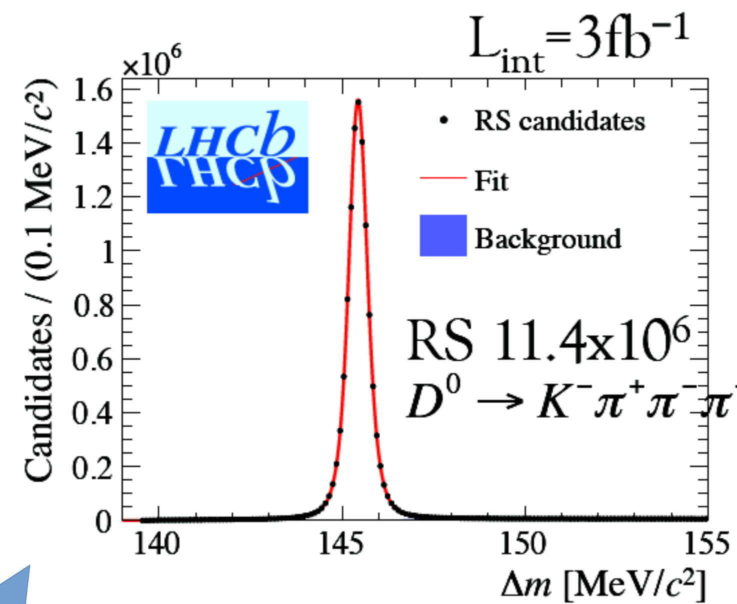
Observation of mixing in $D^0 \rightarrow K\pi\pi\pi$

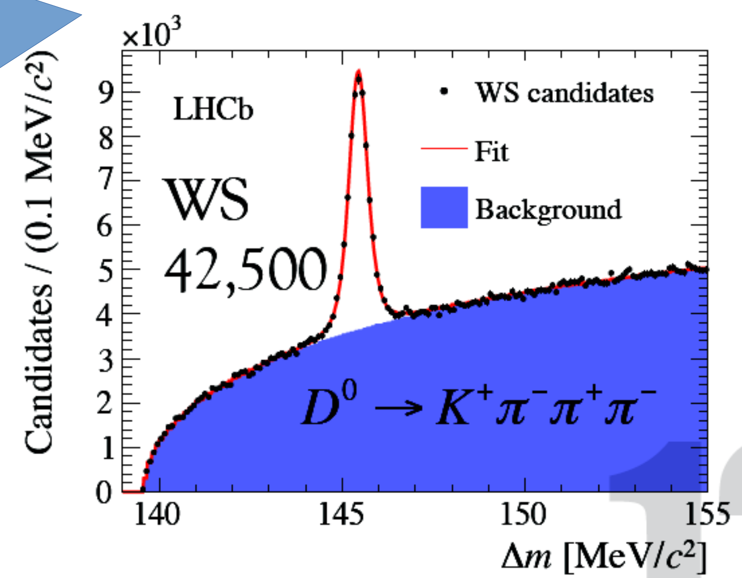
- Fully inspired by the previous LHCb analysis with $D^0 \rightarrow K\pi$, pion tagged [PRL 110 (2013),101802]
  - Was first observation of D^0 mixing from one single experiment

No mixing hypothesis rejected at 8.2σ

First time in a multi-body decay





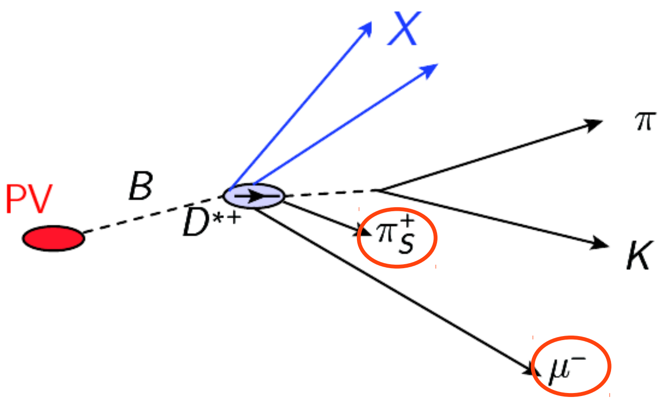


Mixing and CPV in $D^0 \to K\pi$

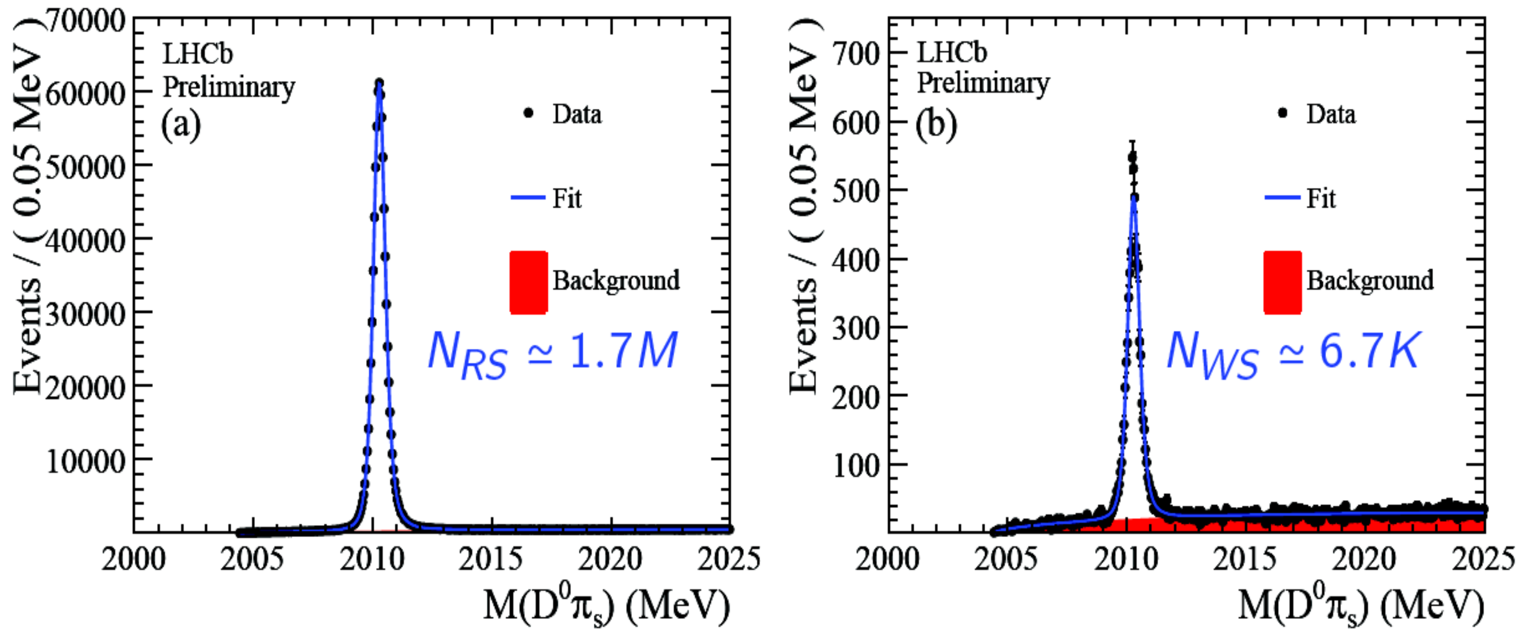
- Separate mixing measurement on D^0 and $\overline{D}^0$:

$$R^{\pm}(t) \approx R_D^{\pm} + \sqrt{R_D^{\pm}}\, y'^{\pm}\, \frac{t}{\tau} + \frac{x'^{2\pm} + y'^{2\pm}}{4} \left(\frac{t}{\tau}\right)^2$$

- Using Doubly Tagged samples, complementary to previous measurement using prompt $D^{*+} \to D^0\pi^+_s$ [PRL 111, 251801 (2013)]



Advantage for DT: improved acceptance at low decay time t & cleaner background



DT + prompt for $D^0 \to K\pi$

- Combined fits to both prompt and DT samples to extract mixing parameters ($R^{\pm}_D$, $x'^{2\pm}$, $y'^{\pm}$) separately for D^0 and $\overline{D}^0$:

$$R^{\pm}(t) \approx R^{\pm}_D + \sqrt{R^{\pm}_D}\, y'^{\pm}\, \frac{t}{\tau} + \frac{x'^{2\pm} + y'^{2\pm}}{4} \left(\frac{t}{\tau}\right)^2$$

- Sensitivity improvement over "prompt alone" results for different fit setups:

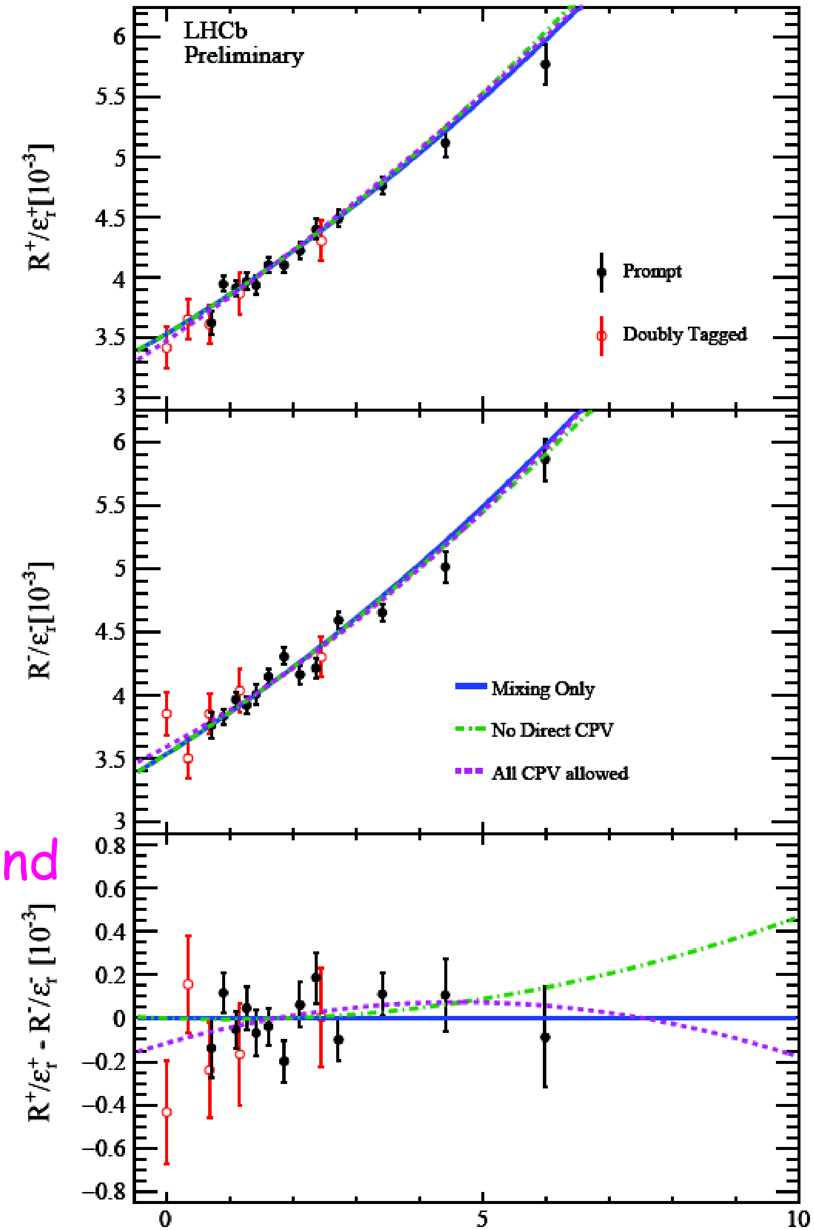
Parameter	DT+prompt combination	Prompt alone	% Error Improvement
	No CPV		
$R_D[10^{-3}]$	3.533 ± 0.054	3.568 ± 0.067	19
$x'^2[10^{-5}]$	3.6 ± 4.3	5.5 ± 4.9	12
$y'[10^{-3}]$	5.23 ± 0.84	4.80 ± 0.94	11
χ^2/NDF	96.594/111		
	No Direct CPV		
$R_D[10^{-3}]$	3.533 ± 0.054	3.568 ± 0.067	19
$x'^{2+}[10^{-5}]$	4.9 ± 5.0	6.4 ± 5.6	11
$y'^{+}[10^{-3}]$	5.14 ± 0.91	4.80 ± 1.08	16
$x'^{2-}[10^{-5}]$	2.4 ± 5.0	4.6 ± 5.5	9
$y'^{-}[10^{-3}]$	5.32 ± 0.91	4.8 ± 1.08	16
χ^2/NDF	96.147/109		
	All CPV Allowed		
$R_D^{+}[10^{-3}]$	3.474 ± 0.081	3.545 ± 0.095	15
$x'^{2+}[10^{-5}]$	1.1 ± 6.5	4.9 ± 7.0	7
$y'^{+}[10^{-3}]$	5.97 ± 1.25	5.10 ± 1.38	9
$R_D^{-}[10^{-3}]$	3.591 ± 0.081	3.591 ± 0.090	10
$x'^{2-}[10^{-5}]$	6.1 ± 6.1	6.0 ± 6.8	10
$y'^{-}[10^{-3}]$	4.50 ± 1.21	4.50 ± 1.39	13
χ^2/NDF	94.960/108		

$R^+_D = R^-_D$, $x'^{2+} = x'^{2-}$, $y'^{+} = y'^{-}$

No CPV found

$R^+_D = R^-_D$

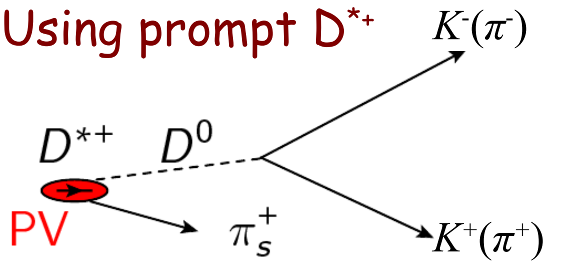
All floating



$\varepsilon^{\pm}_r$: $K^{\pm}\pi^{\mp}$ detection efficiency

A_{CP} for $D^0 \rightarrow h^+h^-$

Using prompt D^{*+}



$$A_{\text{raw}}(f) = \frac{N[D^{*+} \to D^0(f)\pi_s^+] - N[D^{*-} \to \bar{D}^0(f)\pi_s^-]}{N[D^{*+} \to D^0(f)\pi_s^+] + N[D^{*-} \to \bar{D}^0(f)\pi_s^-]}$$

Physics observable

$$A_{\text{raw}}(f) \approx \boxed{A_{CP}(f)} + \boxed{A_{\text{D}}(f)} + \boxed{A_{\text{D}}(\pi_s^+)} + \underbrace{\boxed{A_{\text{P}}(D^{*+})}}_{\sim 1\%}$$

detection asymmetries in reconstructing the final **Null for CP-eigenstates f=ππ,KK.**

detection asymmetries in reconstructing the soft pion**. It cancels out in the difference.**

D^{*+} production asymmetry, mainly arising from the hadronisation of charm quark in pp collisions. **It cancels out in the difference.**

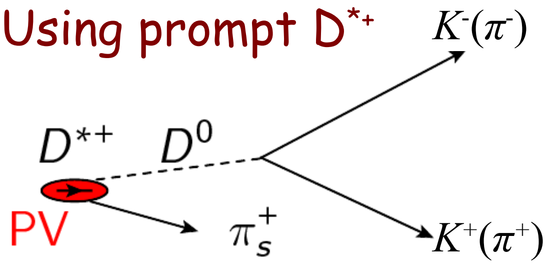
- After cancellations, we have the A_{CP} difference:

$$\Delta A_{CP} = A_{\text{raw}}(K^-K^+) - A_{\text{raw}}(\pi^-\pi^+) = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

To account for imperfect cancellations of detection and production asymmetries due to difference in the kinematic properties, distributions of D^{*+} decays of KK reweighted to those of ππ

A_{CP} for $D^0 \rightarrow h^+h^-$

Using prompt D^{*+}



$$A_{\text{raw}}(f) = \frac{N[D^{*+} \to D^0(f)\pi_s^+] - N[D^{*-} \to \bar{D}^0(f)\pi_s^-]}{N[D^{*+} \to D^0(f)\pi_s^+] + N[D^{*-} \to \bar{D}^0(f)\pi_s^-]}$$

Physics observable

~1%

$$A_{\text{raw}}(f) \approx \boxed{A_{CP}(f)} + \boxed{A_{\text{D}}(f)} + \boxed{A_{\text{D}}(\pi_s^+)} + \boxed{A_{\text{P}}(D^{*+})}$$

detection asymmetries in reconstructing the final **Null for CP-eigenstates f=ππ,KK.**

detection asymmetries in reconstructing the soft pion**. It cancels out in the difference.**

D^{*+} production asymmetry, mainly arising from the hadronisation of charm quark in pp collisions. **It cancels out in the difference.**

- To measure A_{CP} (*KK*) alone, detection and production asymmetries are eliminated using weighted control samples:

$$\boxed{\begin{aligned} A_{CP}(D^0 \to KK) =& A_{\text{raw}}(D^0 \to KK) - A_{\text{raw}}(D^0 \to K^-\pi^+) \\ &+ A_{\text{raw}}(D^+ \to K^-\pi^+\pi^+) - A_{\text{raw}}(D^+ \to \overline{K}^0\pi^+) + A_D(\overline{K}^0) \end{aligned}}$$

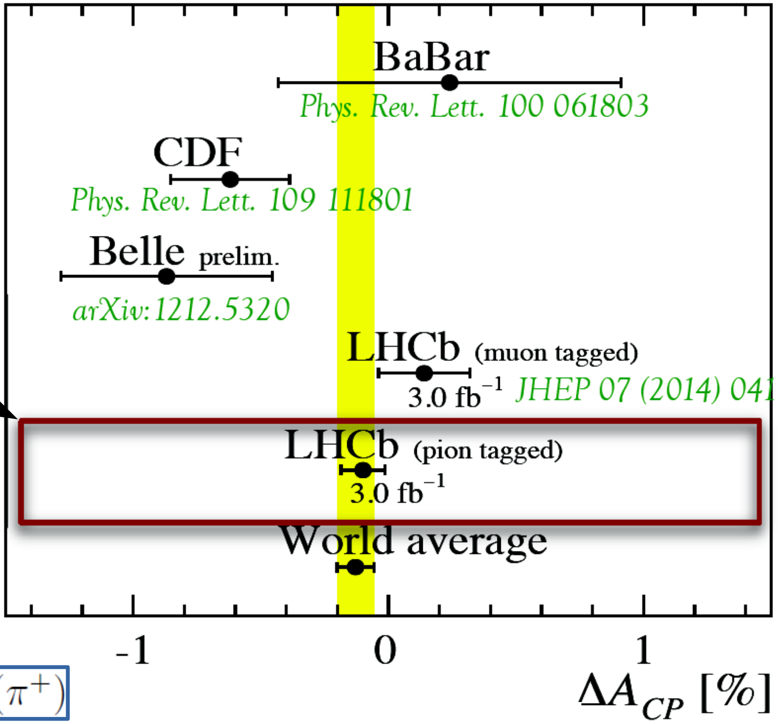
PRL 116 (2016), 191601

ΔA_{CP} result using Run1 data

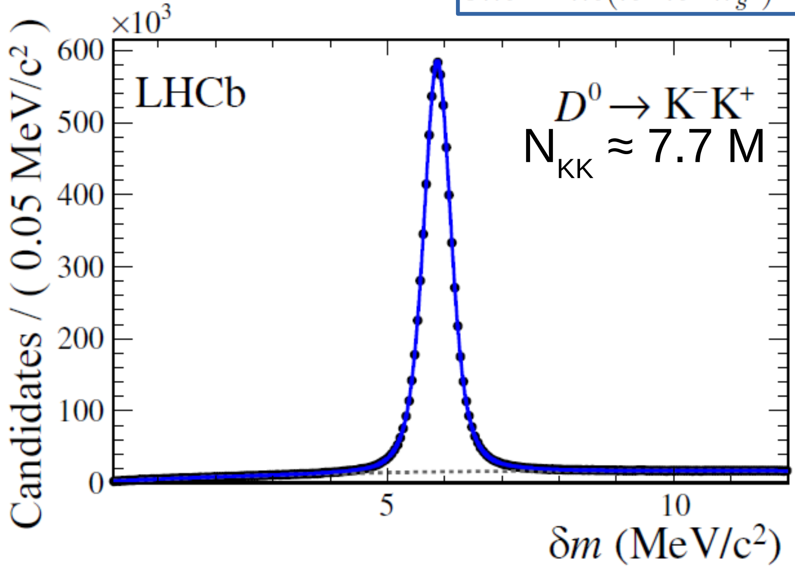
- Simultaneous fit of δm distributions for D^{*+} and D^{*-} data samples to extract ΔA_{CP}:

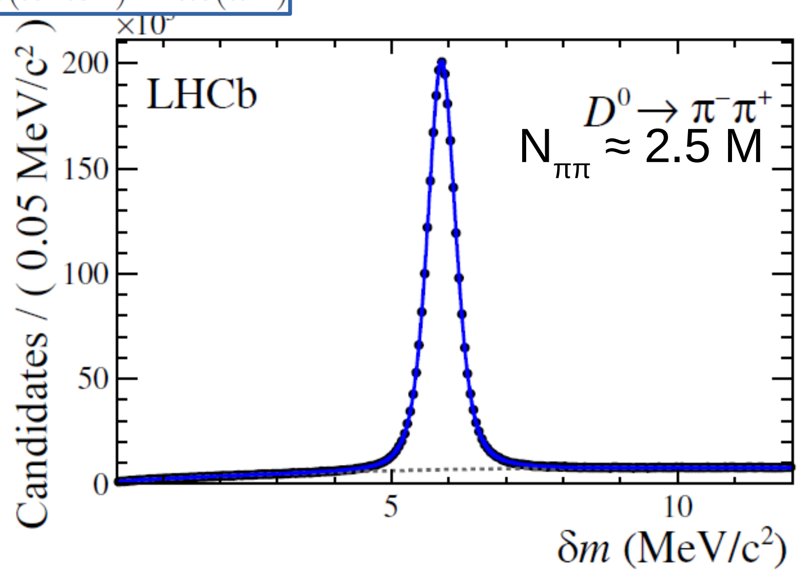
$$\boxed{\Delta A_{CP} = (-0.10 \pm 0.08\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst}))\ \%}$$

Most precise time-integrated A_{CP} measurement in the charm sector from a single experiment



$$\boxed{\delta m \equiv m(h^+h^-\pi_s^+) - m(h^+h^-) - m(\pi^+)}$$





PRL 116 (2016), 191601

LHCb CPV searches in $D^0 \to h^+h^-$

A_{CP} related to direct and indirect CP asymmetries:

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

y_{CP} and $A_\Gamma(\approx -a_{CP}^{ind})$ from LHCb-only experimental inputs

$$y_{CP} \equiv \frac{\hat{\Gamma}(D^0 \to K^+K^-)}{\hat{\Gamma}(D^0 \to K^-\pi^+)} - 1$$

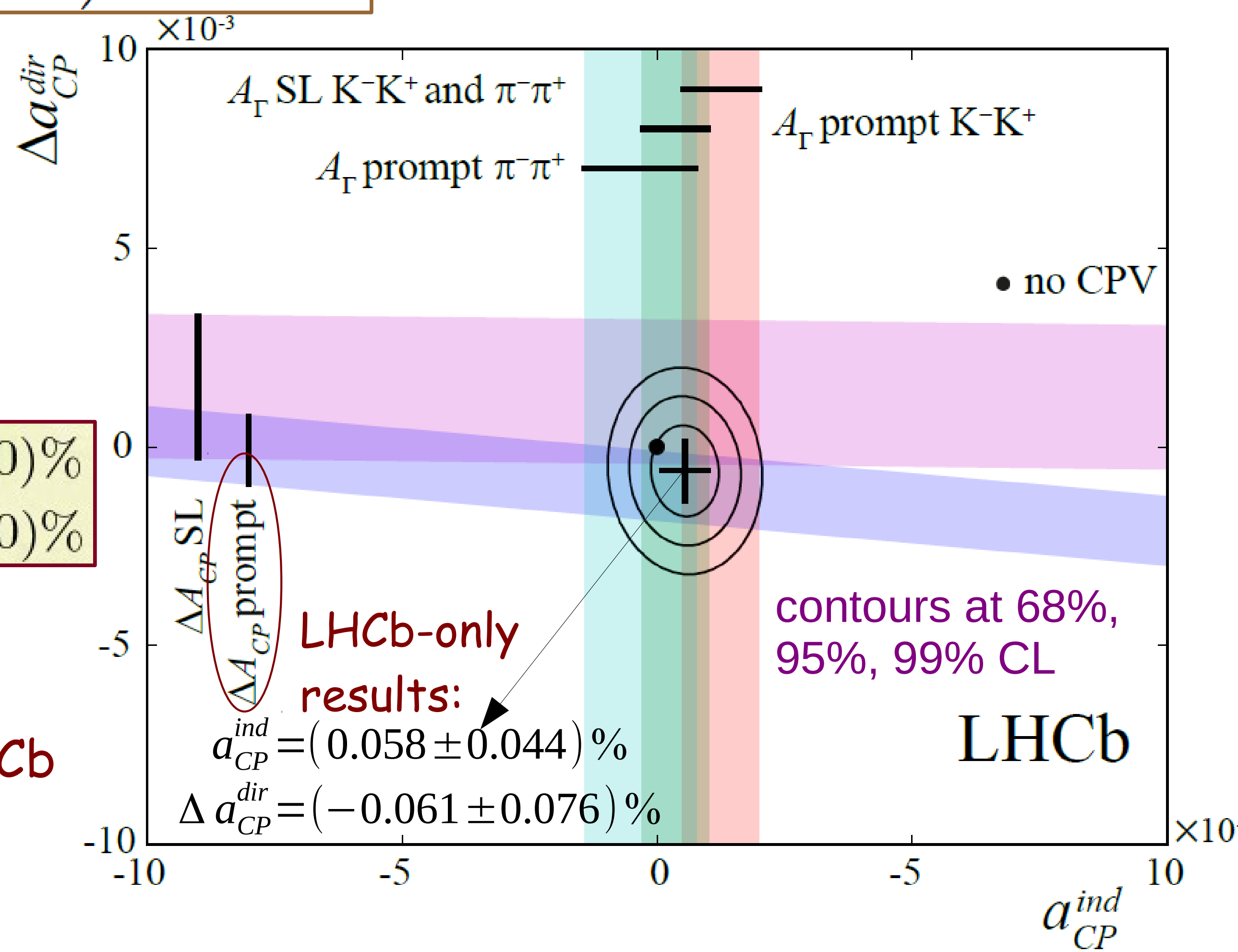
$$A_\Gamma \equiv \frac{\hat{\Gamma}(D^0 \to K^+K^-) - \hat{\Gamma}(\overline{D}^0 \to K^+K^-)}{\hat{\Gamma}(D^0 \to K^+K^-) + \hat{\Gamma}(\overline{D}^0 \to K^+K^-)}$$

HFAG (Winter-2016) averages including results from all experiments:

$$\boxed{\begin{aligned}a_{\mathrm{CP}}^{\mathrm{ind}} &= (+0.056 \pm 0.040)\%\\ \Delta a_{\mathrm{CP}}^{\mathrm{dir}} &= (-0.137 \pm 0.070)\%\end{aligned}}$$

compatible with no CPV at 6.5% CL

Averages dominated by LHCb measurements



A_{CP} for $D^0 \rightarrow K^+K^-$ using Run1 data

- Simultaneous fit across D^{*+} and D^{*-} data samples to measure:

$$\boxed{A_{CP}(KK) = (+0.14 \pm 0.15 \pm 0.10)\%}$$

  - Using $\Delta(A_{CP})$ from PRL 116, 191601

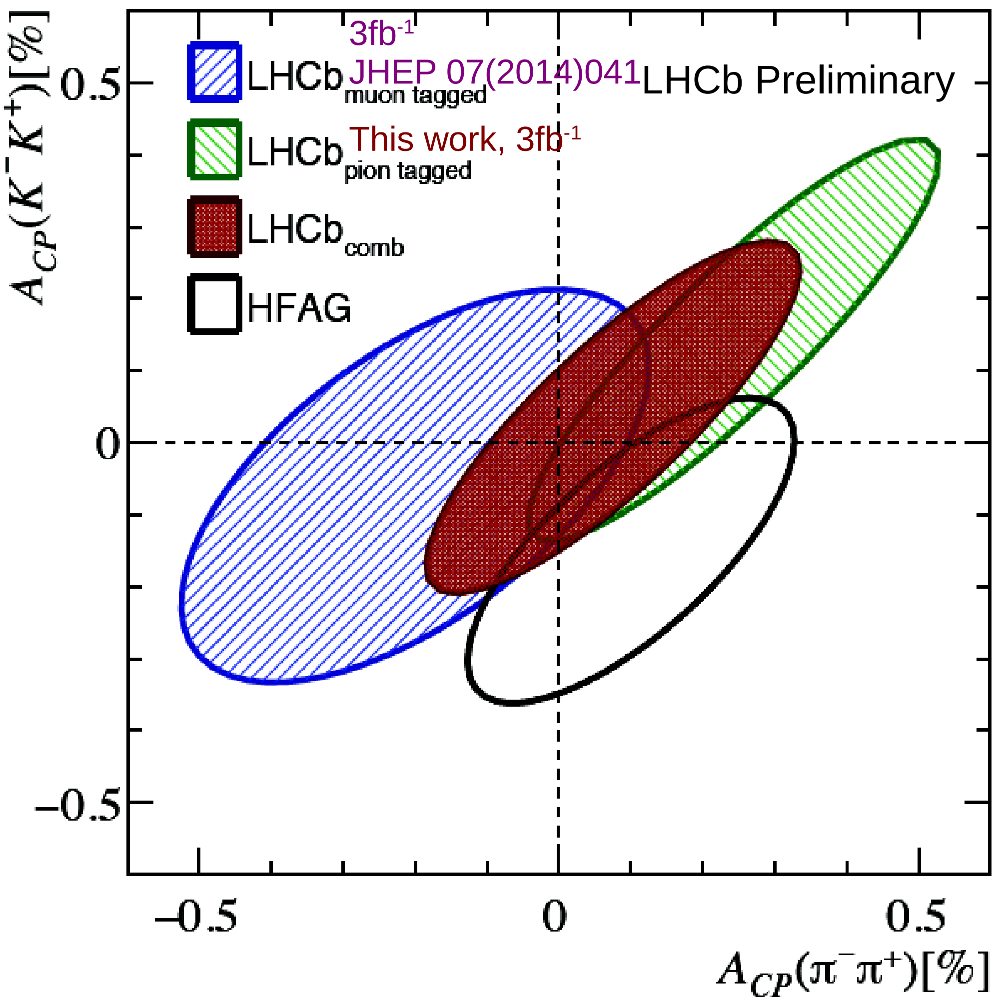
$$\boxed{A_{CP}(\pi\pi) = (0.24 \pm 0.15 \pm 0.11)\%}$$

  - Combine with muon tagged $A_{CP}(KK, \pi\pi)$ with full correlations

$$\boxed{A_{CP}^{\mathrm{comb}}(KK) = (0.04 \pm 0.12 \pm 0.10)\%}$$

$$\boxed{A_{CP}^{\mathrm{comb}}(\pi\pi) = (0.07 \pm 0.14 \pm 0.11)}$$

See backup slides for detailed info on this analysis



Consistent with *CP* conservation

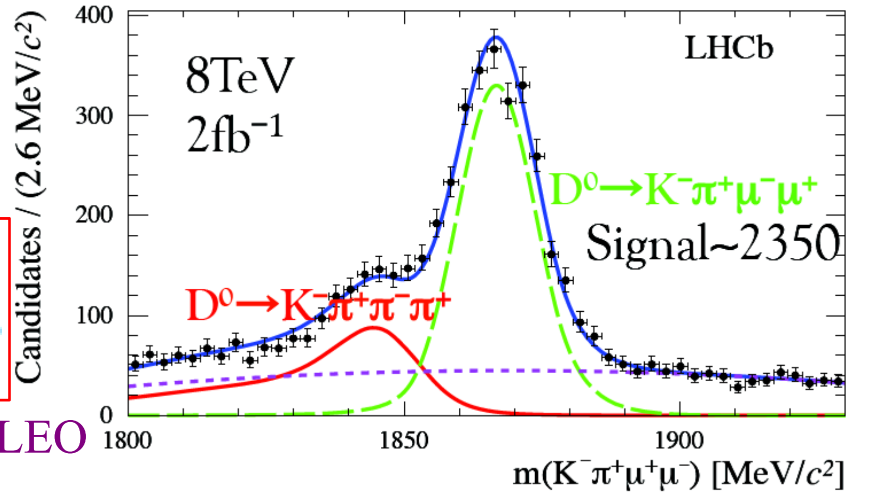
LHCb rare D decay results

- First observation of $D^0 \to K^-\pi^+\mu^+\mu^-$, in the ρ^0/ω region (675 < $m(\mu^-\mu^+)$ < 875 MeV):

$$\boxed{\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-) = (4.17 \pm 0.12\,(\text{stat}) \pm 0.40\,(\text{syst})) \times 10^{-6}}$$

  - $D^0 \to K^-\pi^+\pi^+\pi^-$ as the normalization channel, BF from CLEO
  - Compatible with SM expectation [JHEP 04(2013)135]

PL B757 (2016) 558



- Lepton Flavor Violation mode $D^0 \to e\mu$ is forbidden in the SM, while some SM extensions suggest rates up to 10^{-6}:

$$\boxed{\mathcal{B}(D^0 \to e^\pm\mu^\mp) < 1.3 \times 10^{-8} \text{ at } 90\% \text{ CL}}$$

  - $D^0 \to K^-\pi^+$ as the normalization channel
  - Most stringent constraint to date, one order of magnitude lower than the previous best one from BELLE [PRD 81 (2010) 091102]

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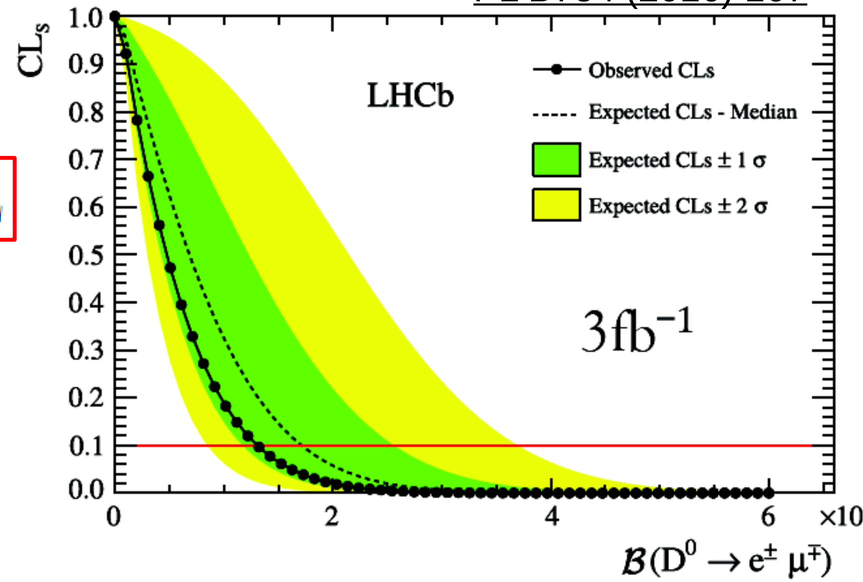


Summary

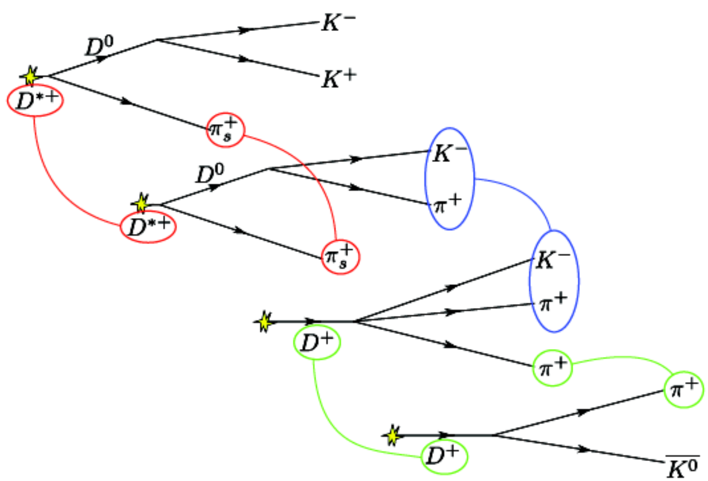
- Acting as a charm factory, LHCb has been quite successful in collecting the world's largest ever data samples
- Based on Run1 3fb^{-1} data, LHCb has recently presented a number of results related to charm decays
- No evidence for CPV is found so far, however LHCb has just started to approach SM expectations
- LHCb results on rare D decays are also the world's best
- Stay tuned for more exciting LHCb results from Run2 due to higher luminosity and improved trigger system

Backup Slides

$D^0 \to KK$ cancellation of asymmetries

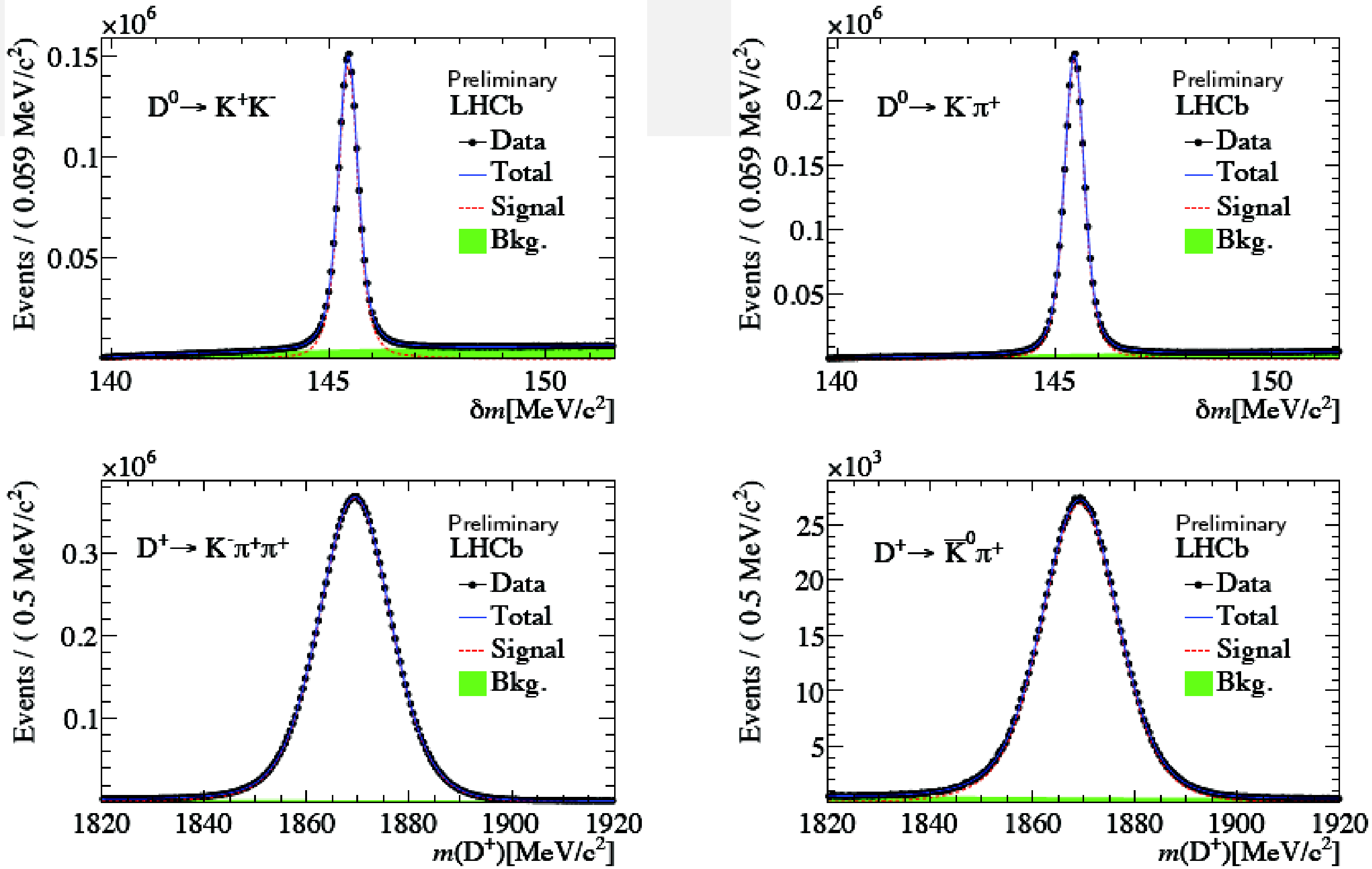
- Control Channels to cancel:

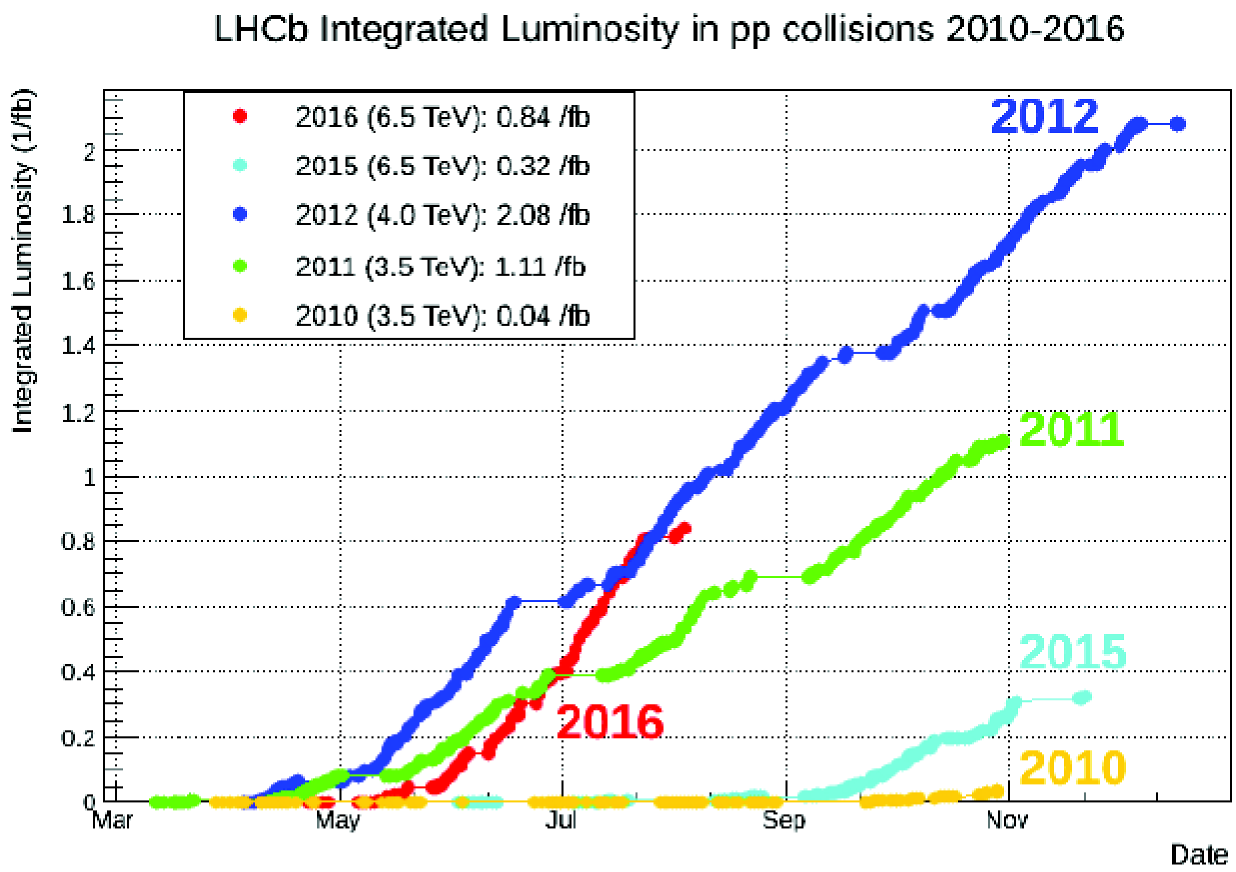
$$A_{CP}(D^0 \to KK) = A_{\text{raw}}(D^0 \to KK) - A_P(D^{*+}) - A_D(\pi_s^+) + \mathcal{O}(A^3)$$
$$A_{\text{raw}}(D^0 \to K^-\pi^+) = A_P(D^{*+}) + A_D(\pi_s^+) + A_D(K^-) + A_D(\pi^+)$$
$$A_{\text{raw}}(D^+ \to K^-\pi^+\pi^+) = A_P(D^+) + A_D(K^-) + A_D(\pi^+) + A_D(\pi^+)$$
$$A_{\text{raw}}(D^+ \to \overline{K}^0\pi^+) = A_P(D^+) + A_D(\overline{K}^0) + A_D(\pi^+)$$

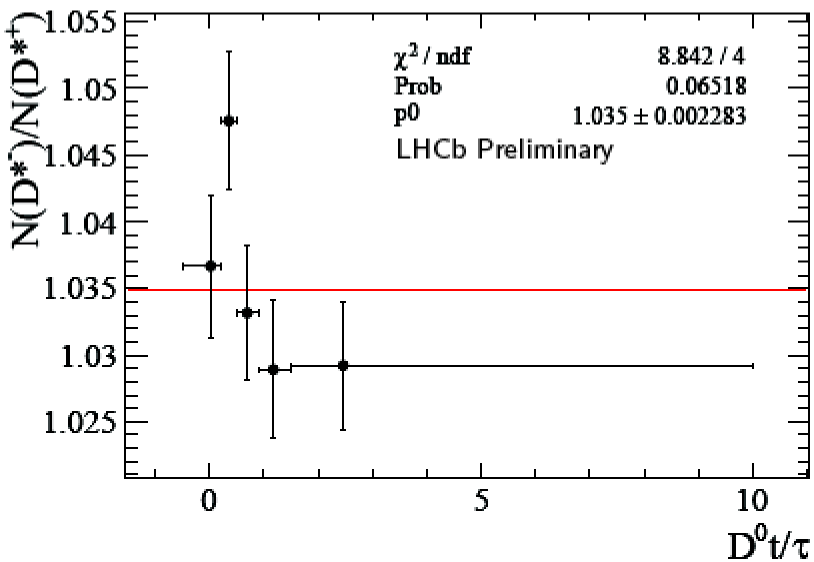


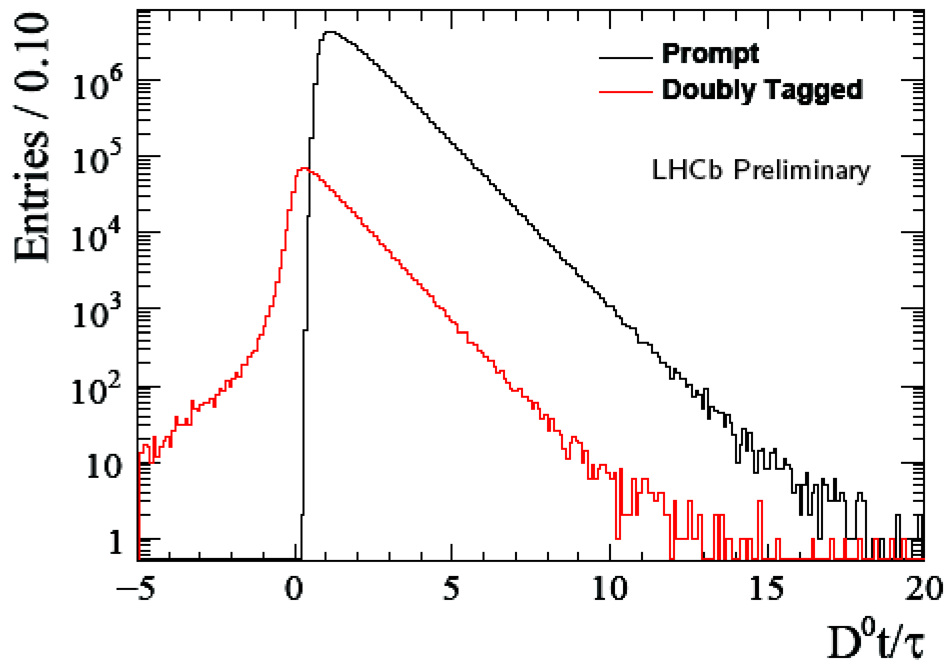
- Nominal weighting is in
  1. $D^+ \to K^-\pi^+\pi^+$ weighted to $D^+ \to \overline{K}^0\pi^+$
  2. $D^0 \to K\pi$ weighted to $D^+ \to K^-\pi^+\pi^+$
  3. $D^0 \to KK$ weighted to $D^0 \to K\pi$
- Variables weighted: $D^{*+}(p_T, \eta, \phi)$, $D^+(p_T, \eta)$,π_{bachelor}, high$p\pi inK\pi\pi(\eta, \phi)$, $K, \pi(p_T, \eta, \phi)$

Extracting yields for $A_{CP}(KK)$




LHCb Integrated Luminosity in pp collisions 2010-2016
2016 (6.5 TeV): 0.84 /fb
2015 (6.5 TeV): 0.32 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
2012
2011
2015
2016
2010
Integrated Luminosity (1/fb)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Mar
May
Jul
Sep
Nov
Date


χ^2 / ndf 8.842 / 4
Prob 0.06518
p0 1.035 ± 0.002283
LHCb Preliminary
N(D*$^-$)/N(D*$^+$)
$D^0 t/\tau$


Prompt
Doubly Tagged
LHCb Preliminary
Entries / 0.10
$D^0 t/\tau$

$$R_M = \frac{1}{2}(x^2+y^2)$$

$$\begin{aligned}
2\,y_{CP} &= \big(|q/p|+|p/q|\big) y\cos\phi - \big(|q/p|-|p/q|\big) x\sin\phi \\
2\,A_{\Gamma} &= \big(|q/p|-|p/q|\big) y\cos\phi - \big(|q/p|+|p/q|\big) x\sin\phi
\end{aligned}$$

$$\begin{aligned}
x_{K^0\pi\pi} &= x \\
y_{K^0\pi\pi} &= y \\
|q/p|_{K^0\pi\pi} &= |q/p| \\
\mathrm{Arg}\,(q/p)_{K^0\pi\pi} &= \phi
\end{aligned}$$

$$\begin{pmatrix} x'' \\ y'' \end{pmatrix}_{K^+\pi^-\pi^0} = \begin{pmatrix} \cos\delta_{K\pi\pi} & \sin\delta_{K\pi\pi} \\ -\sin\delta_{K\pi\pi} & \cos\delta_{K\pi\pi} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

$$A_M = \frac{|q/p|^2-|p/q|^2}{|q/p|^2+|p/q|^2}$$

$$\begin{aligned}
x'^{\pm} &= \left(\frac{1\pm A_M}{1\mp A_M}\right)^{1/4} (x'\cos\phi \pm y'\sin\phi) \\
y'^{\pm} &= \left(\frac{1\pm A_M}{1\mp A_M}\right)^{1/4} (y'\cos\phi \mp x'\sin\phi)
\end{aligned}$$

$$\begin{aligned}
\frac{\Gamma(D^0\to K^+\pi^-)+\Gamma(\overline{D}^0\to K^-\pi^+)}{\Gamma(D^0\to K^-\pi^+)+\Gamma(\overline{D}^0\to K^+\pi^-)} &= R_D \\
\frac{\Gamma(D^0\to K^+\pi^-)-\Gamma(\overline{D}^0\to K^-\pi^+)}{\Gamma(D^0\to K^+\pi^-)+\Gamma(\overline{D}^0\to K^-\pi^+)} &= A_D \\
\frac{\Gamma(D^0\to K^+K^-)-\Gamma(\overline{D}^0\to K^+K^-)}{\Gamma(D^0\to K^+K^-)+\Gamma(\overline{D}^0\to K^+K^-)} &= A_K + \frac{\langle t\rangle}{\tau_D}\mathcal{A}_{CP}^{\mathrm{indirect}} \\
\frac{\Gamma(D^0\to \pi^+\pi^-)-\Gamma(\overline{D}^0\to \pi^+\pi^-)}{\Gamma(D^0\to \pi^+\pi^-)+\Gamma(\overline{D}^0\to \pi^+\pi^-)} &= A_\pi + \frac{\langle t\rangle}{\tau_D}\mathcal{A}_{CP}^{\mathrm{indirect}}
\end{aligned}$$

$$2\mathcal{A}_{CP}^{\mathrm{indirect}} = \big(|q/p|+|p/q|\big) x\sin\phi - \big(|q/p|-|p/q|\big) y\cos\phi$$