XIIIth International Conference on Heavy Quarks and Leptons,
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# Charm mixing and CP violation at the LHCb experiment

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Artur Ukleja
National Centre for Nuclear Research,
on behalf of the LHCb Collaboration

# Outline

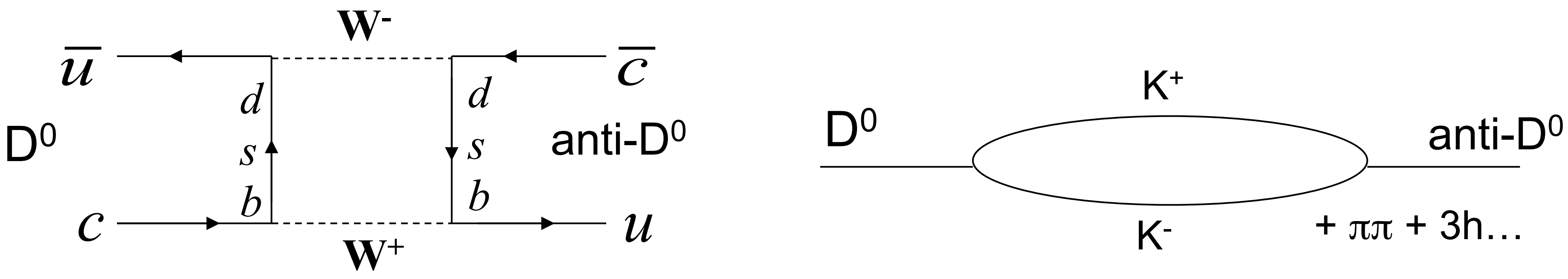
- **Introduction**
  - ✧ Why are we interested in charm physics?
  - ✧ SM predictions and phenomenology of CPV and $D^0$ – anti-$D^0$ mixing

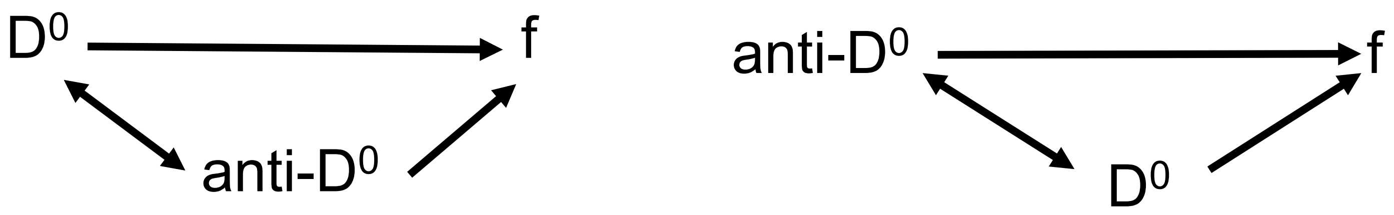
- **Measurements of mixing and CPV in charm sector at LHCb** (only a few last ones)
  - ✧ Observation of $D^0$ – anti-$D^0$ mixing in $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$
  - ✧ The difference of time-integrated CP asymmetry ($\Delta A_{CP}$) in $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$
  - ✧ The $A_\Gamma$ asymmetry from $D^0 \rightarrow K^+K^-$, $D^0 \rightarrow \pi^+\pi^-$

- **Summary and prospects**

# Why charm?

- Mixing and CP violation established in kaon and B sectors
  - ✧ in charm, we observe mixing but so far there is no CPV observation
- In the SM, expected CPV in charm sector is very small, less than $10^{-3}$ (much smaller than it is observed in the beauty sector) but predictions vary widely
  - ✧ New Physics contributions can enhance CPV up to $10^{-2}$
- There are three ways of CPV:
  1. in mixing (indirect), $D^0 \rightarrow$ anti-$D^0$ $\neq$ anti-$D^0 \rightarrow D^0$
  2. in decay amplitudes (direct), $D \rightarrow f$ $\neq$ anti-$D \rightarrow$ anti-$f$
  3. in interference (indirect) between direct decays and decays with mixing





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

# Mixing of neutral mesons

Neutral mesons can oscillate between matter and anti-matter:

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

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

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

Two parameters describe mixing:

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

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

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

$$m \equiv (m_1 + m_2)/2$$

$$\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$$

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

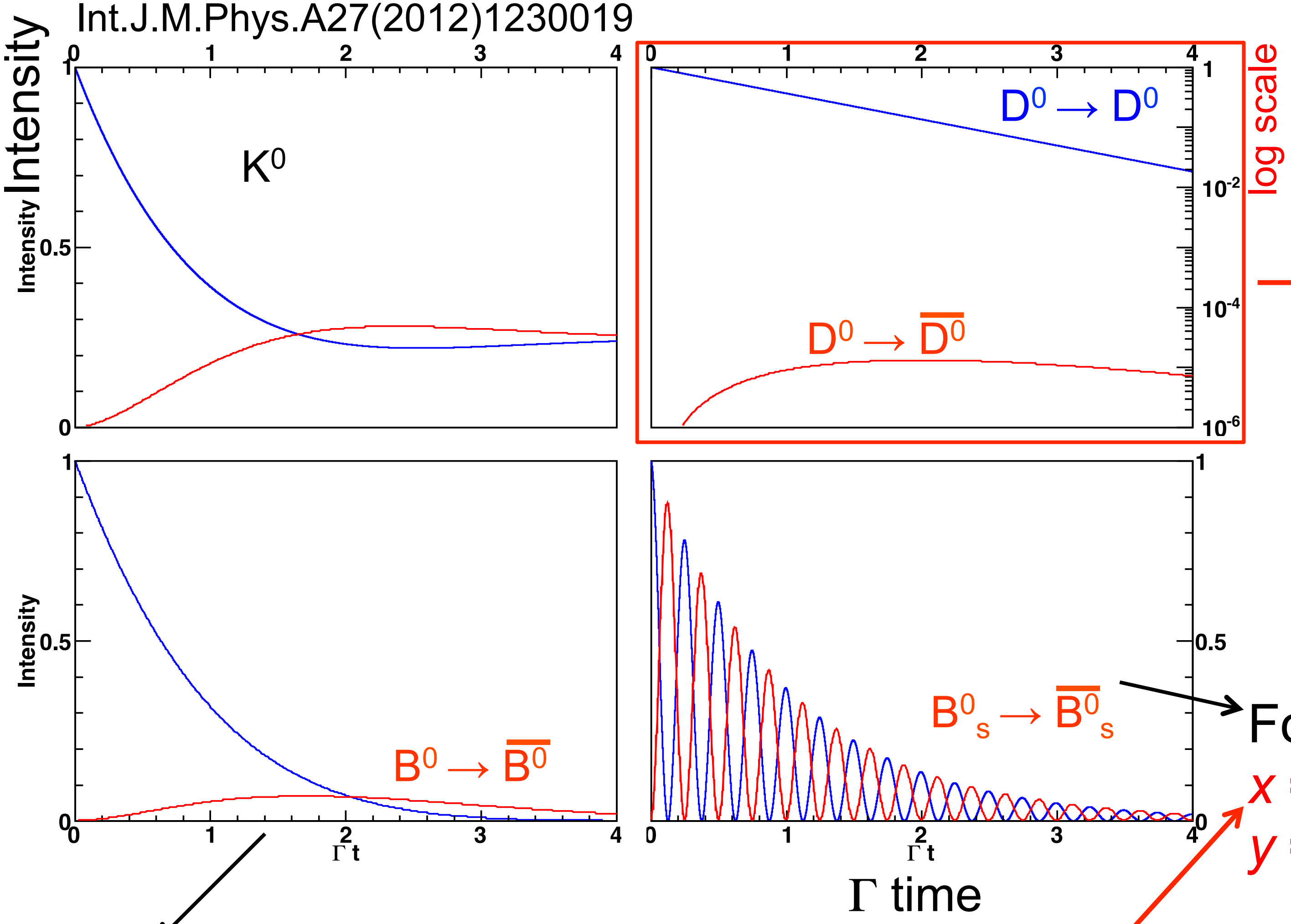
Δm, ΔΓ, ϕ – measured experimentally

# Mixing of neutral mesons

Significant enhancement of mixing or observation of CPV in charm can be an indication of New Physics

| | |
|---|---|
| • $D^0$ mesons: | *very, very* slowly |
| • $K^0$ mesons: | very slowly |
| • $B_d$ mesons: | slowly |
| • $B_s$ mesons: | fast! |

Int.J.M.Phys.A27(2012)1230019



For charm:

$x \approx 0.0074$

$y \approx 0.0048$

- *x, y* very small
- mixing is very slow
- very precise measurements needed

For $B^0_s$:

$x \approx 26.82$ (large)

$y \approx 0.058$ (much smaller than $x$)

For $B^0$:

$x \approx 0.775$

$y \approx 0.007$ (very small)

The frequency of $B^0_s$ – anti-$B^0_s$ oscillations is the highest. On average, a $B^0_s$ meson changes its flavor 9 times between production and decay

# LHCb – precision detector

The single-arm forward spectrometer (a new concept for HEP experiments)

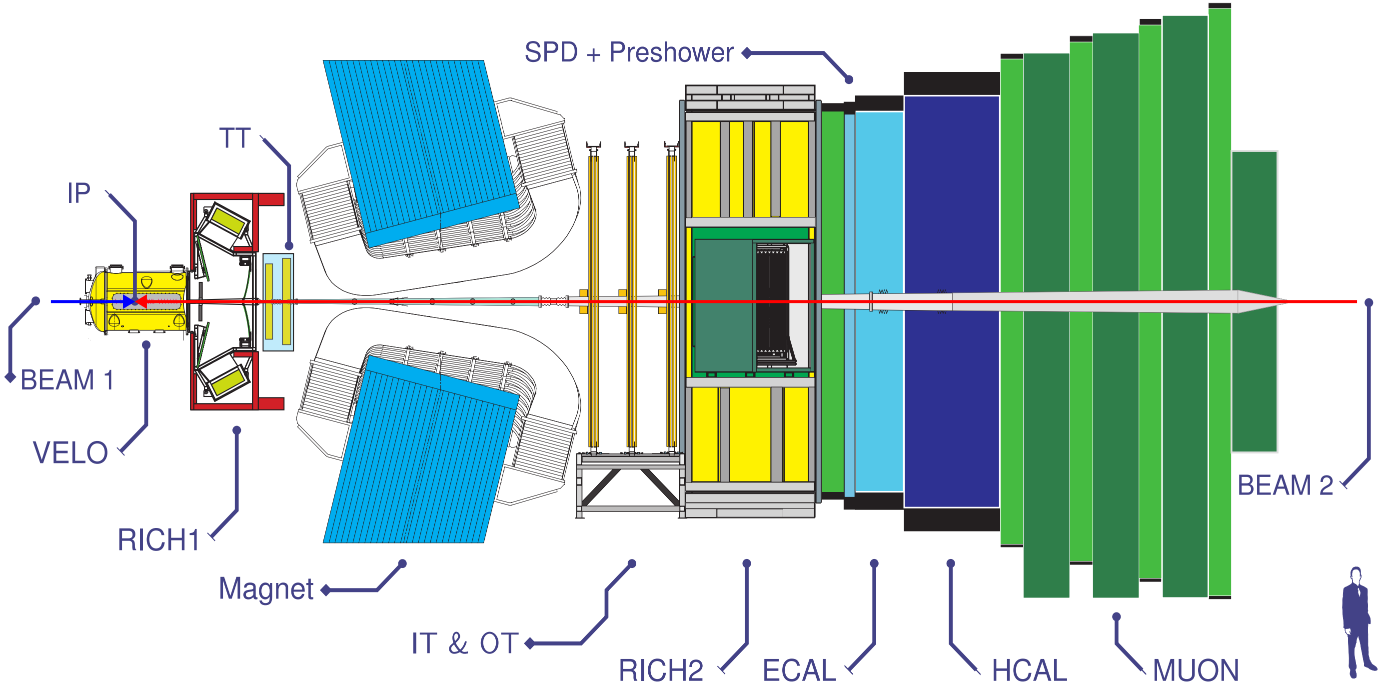
$$\sigma(pp \to c\bar{c}) = \begin{array}{llll} (1419 \pm 134)\mu b & @ \ 7\mathrm{TeV} & \mathrm{Nucl.Phys.B871(2013)1} \\ (2940 \pm 240)\mu b & @ \ 13\mathrm{TeV} & \mathrm{JHEP03(2016)159} \end{array}$$

10 < $\theta$ < 300 mrad (2<$\eta$<5)

Run 1: 1/fb (2011),
2/fb (2012)
Run 2: 0.3/fb (2015)
47/pb (2016)

For each 1/fb:
~28k $B^0_s \to J/\psi(\mu\mu)\ \phi(K^+K^-)$
~2M $D^{*\pm} \to D^0(\to K^-K^+)\pi^\pm$

JINST3(2008)S08005



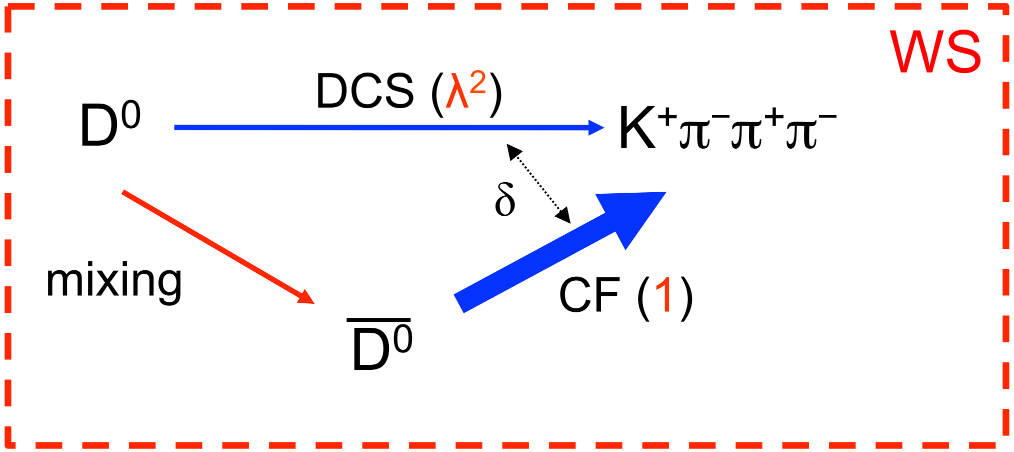
- VELO – precision primary and secondary vertex measurements, resolution of IP: 20 $\mu$m, decay lifetime resolution ~ 45 fs: 0.1 $\tau(D^0)$
- Excellent tracking resolution: $\Delta p/p$ = 0.4% at 5 GeV to 0.6% at 100 GeV
- RICH – very good particle identification for $\pi$ and K

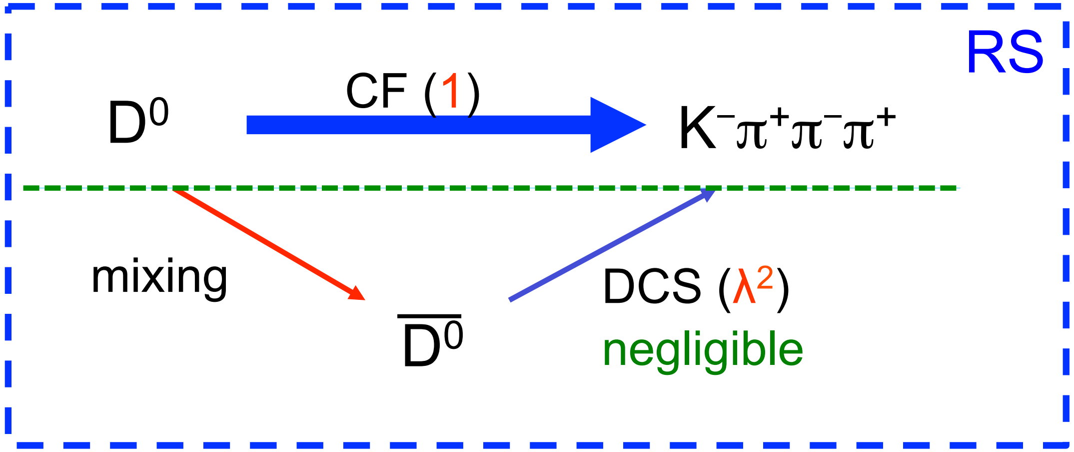
# $D^0$ – anti-$D^0$ oscillation in $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$

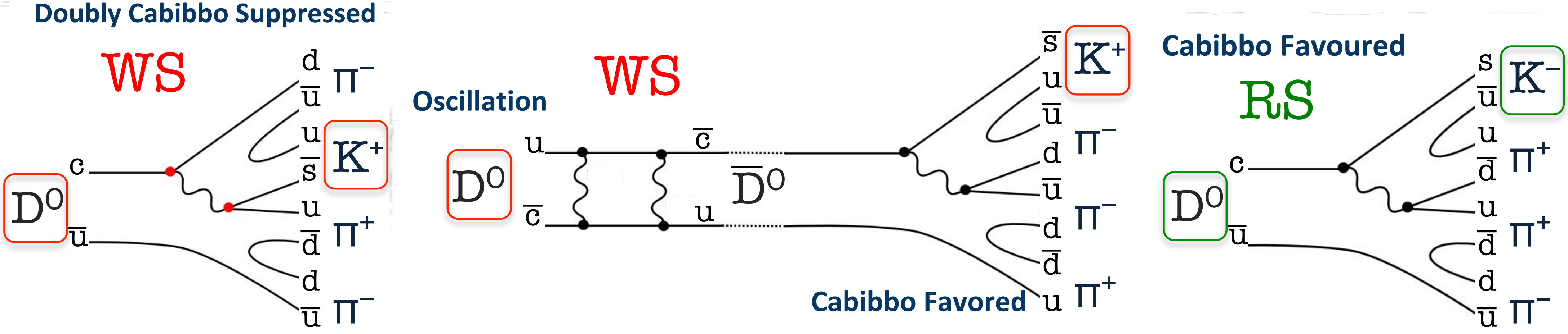
Measure the time-dependent ratio of $D^0$ decays with Wrong Sign to Right Sign

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

arXiv:1602.07224







# $D^0$ – anti-$D^0$ oscillation in $D^0 \to K^+\pi^-\pi^+\pi^-$

The mixing parameters are determined in a fit of the function to the time dependence

arXiv:1602.07224

$$R(t) = \frac{WS}{RS} \approx \underbrace{r_D^2}_{\substack{\text{the ratio of DCS to}\\ \text{CF amplitudes}}} - \underbrace{r_D R_D \cdot y' \frac{t}{\tau}}_{\substack{\text{the interference of}\\ \text{the DCS and mixed decays}}} + \underbrace{\frac{x^2+y^2}{4}\left(\frac{t}{\tau}\right)^2}_{\substack{\text{mixing}\\ \text{parameters}}}$$

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

$\delta$ is the strong phase difference between DCS and CF amplitudes
$R_D$ is the coherence factor

# $D^0$ – anti-$D^0$ oscillation in $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$

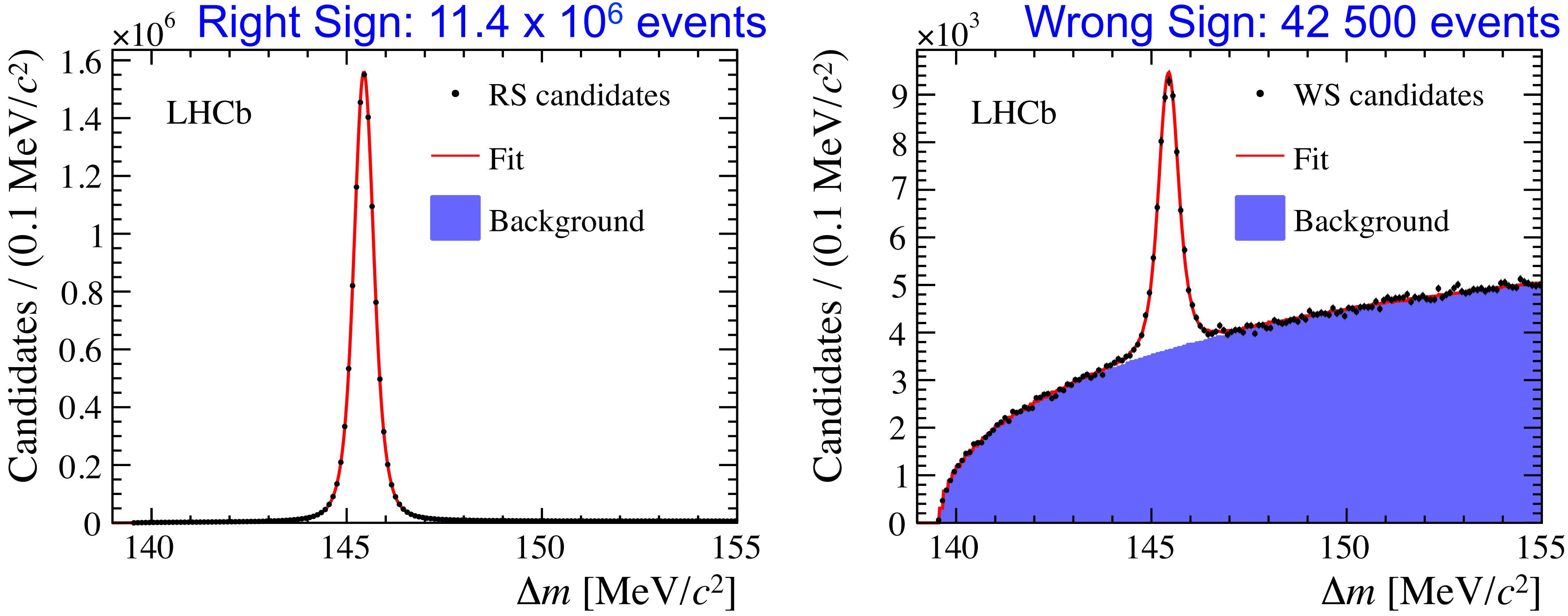
- LHCb, Run 1, 3/fb
- Initial flavor is tagged using: $D^{*+} \rightarrow D^0 \pi^+_s$ , $D^{*-} \rightarrow$ anti-$D^0 \pi^-_s$ (pion-tagged)

$$\Delta m \equiv m(K^+\pi^-\pi^+\pi^- \pi^\pm_s) - m(K^+\pi^-\pi^+\pi^-)$$

arXiv:1602.07224

Right Sign: 11.4 x $10^6$ events

Wrong Sign: 42 500 events

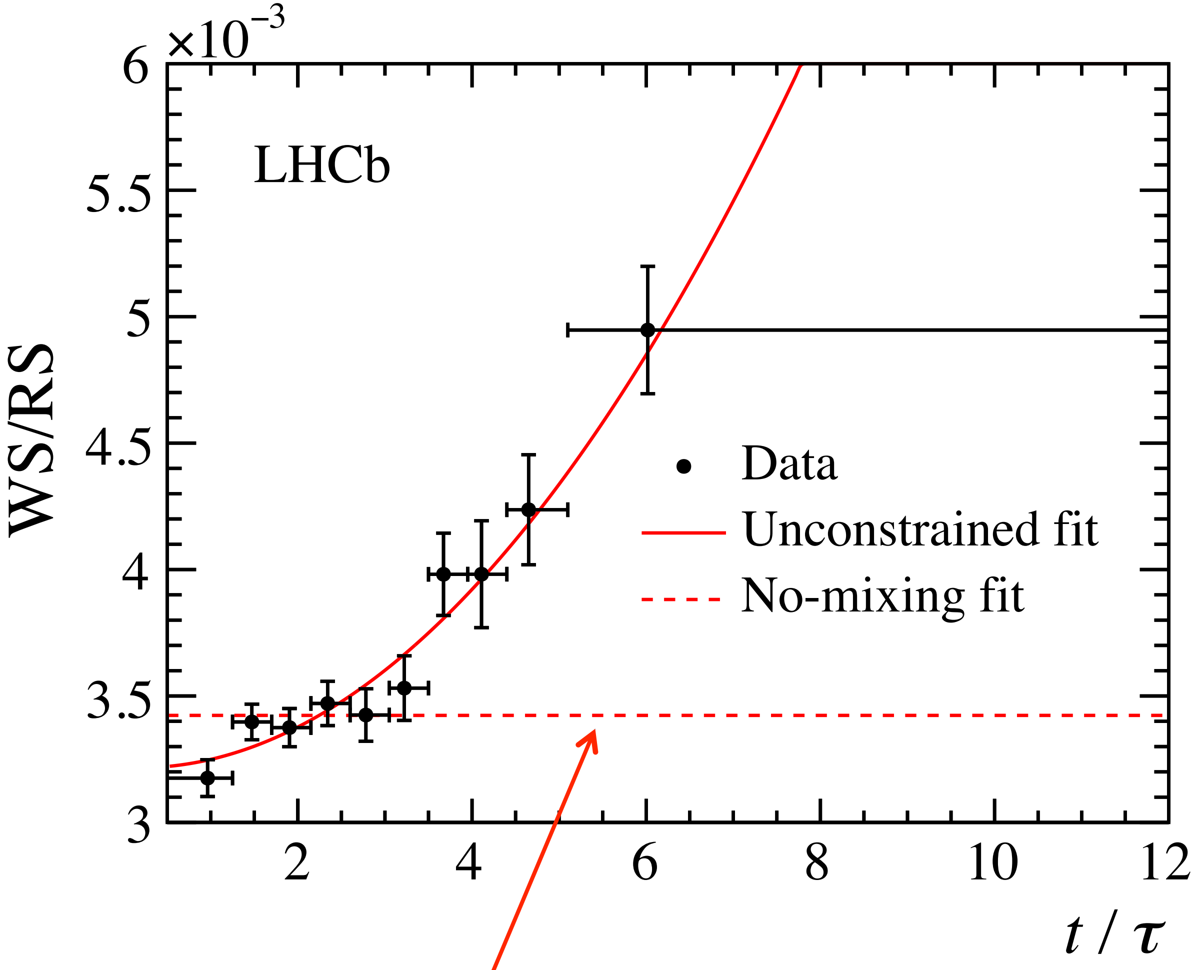


- To study the time-dependence of the WS/RS ratio, the Δm fitting procedure is repeated in ten $D^0$ decay-time bins

# $D^0$ – anti-$D^0$ oscillation in $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$

$$R(t) = \frac{WS}{RS} \approx r_D^2 - r_D R_D \cdot y' \frac{t}{\tau} + \frac{x^2+y^2}{4}\left(\frac{t}{\tau}\right)^2$$

arXiv:1602.07224



No-mixing hypothesis is rejected at 8.2σ

- First observation of $D^0$ – anti-$D^0$ mixing in a decay other than $D \rightarrow K\pi$
- Fit results:

  $r_D = (5.50 \pm 0.07) \times 10^{-2}$
  $R_d y' = (-3.0 \pm 0.7) \times 10^{-3}$
  $x = (4.1 \pm 1.7) \times 10^{-3}$
  $y = (6.7 \pm 0.8) \times 10^{-3}$

- The parameters are required to determine CKM angle γ in $B^+ \rightarrow DK^+$ decays ($D \rightarrow hh$, $D \rightarrow hh\pi^0$, $D \rightarrow K_{0s}hh$, $D \rightarrow h\pi\pi\pi$)

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

We want to measure CP asymmetry between particles and antiparticles:

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

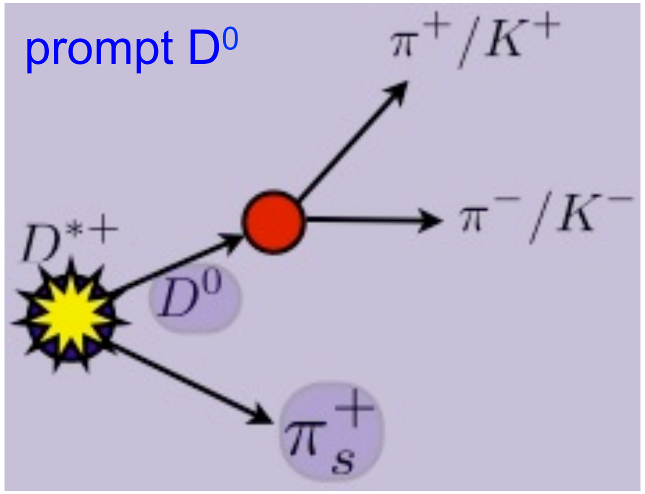
LHCb uses two statistically independent methods to tag the initial $D^0$ flavor:

1) pion-tagged method (prompt $D^0$)

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

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

PRL116(2016)191601

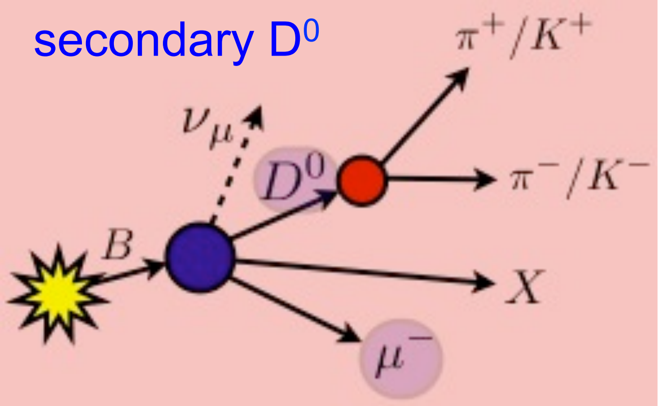


2) muon-tagged method (secondary $D^0$)

$B^-$ (anti-$B^0$) → $D^0$ $\mu^-$ anti-$\nu_\mu$ X

$B^+$ ($B^0$) → anti-$D^0$ $\mu^+$ $\nu_\mu$ X

JHEP07(2014)041



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

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

$$A_{raw}(f) = A_{CP}(f) + A_{detection}(f) + A_{detection}(\pi_s^+) + A_{production}(D^{*+})$$

CP asymmetry what we want to measure

Detector asymmetries of particles reconstruction from $D^0$ decays. They are identically zero for $K^-K^+$ and $\pi^-\pi^+$ since the final states are charge symmetric:

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

Detector asymmetries of $\pi_s$ ($\mu$) reconstruction.

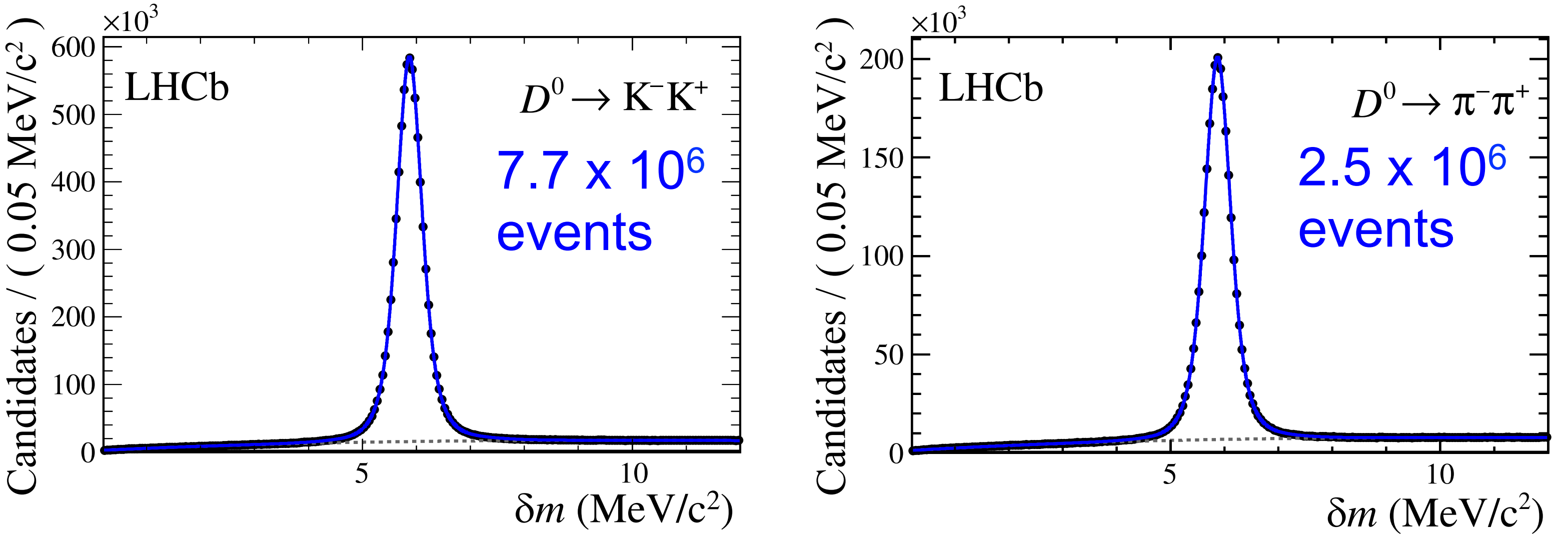
Production asymmetries of $D^*$ (B) in primary vertex (different numbers of $D^{*+}$ and $D^{*-}$ or $B^+$ and $B^-$)

- The asymmetries $A_{detection}(\pi^+_s)$ and $A_{production}(D^{*+})$ are independent of the final state. They cancel in the difference:

$$\begin{aligned} \Delta A_{CP} &\equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \\ &= A_{raw}(K^+K^-) - A_{raw}(\pi^+\pi^-) \end{aligned}$$

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

1) Pion-tagged method (Run 1, 3/fb): $D^{*+} \rightarrow D^0 \pi^+_s$ , $D^{*-} \rightarrow$ anti-$D^0 \pi^-_s$



PRL116(2016)191601

$$\delta m \equiv m(h^+h^-\pi^\pm_s) - m(h^+h^-) - m(\pi^+)$$

Signal yields and $A_{raw}(K^-K^+)$ and $A_{raw}(\pi^-\pi^+)$ are obtained from fits to the δm distributions of the $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ samples

$$\Delta A_{CP} = -0.10 \pm 0.08^{stat} \pm 0.03^{syst}\ \%$$

This is the most precise measurement of a time-integrated CP asymmetry in the charm sector from a single experiment

2) Muon-tagged method (Run1, 3/fb): $B \rightarrow D^0\mu^-X$ and $B \rightarrow$ anti-$D^0\mu^+X$

$$\Delta A_{CP} = 0.14 \pm 0.16^{stat} \pm 0.08^{syst}\ \%$$

JHEP07(2014)041

Both method agree

# Interpretation of $\Delta A_{CP}$

CP asymmetry is a combination of CPV components in decays and in mixing

$$A_{CP}(f) \approx a^{dir}_{CP}(f)\left(1 + \frac{\langle t(f)\rangle}{\tau} y_{CP}\right) + \frac{\langle t(f)\rangle}{\tau} a^{ind}_{CP}$$

[J.Phys. G39 (2012) 045005]

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

Lifetime of $D^0$ (PDG)

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = \Delta a^{dir}_{CP}\left(1 + \frac{\langle \bar{t}\rangle}{\tau} y_{CP}\right) + \frac{\Delta\langle t\rangle}{\tau} a^{ind}_{CP}$$

$\langle \bar{t}\rangle$ is the arithmetic average of $\langle t(K^-K^+)\rangle$ and $\langle t(\pi^-\pi^+)\rangle$

The difference and the average of the mean decay times in used samples are:

$$\frac{\Delta\langle t\rangle}{\tau} = 0.1153 \pm 0.0007 \pm 0.0018\%$$

$$\frac{\langle \bar{t}\rangle}{\tau} = 2.0949 \pm 0.0004 \pm 0.0159\%$$

PRL116(2016)191601

The contributions from CPV in mixing is suppressed and $\Delta A_{CP}$ is primarily sensitive to direct CPV

We can determine $\Delta a^{dir}_{CP}$ since LHCb measures also $a^{ind}_{CP}$ and $y_{CP}$

# $A_\Gamma$ asymmetry – measurement of CPV in mixing

The asymmetry of the decay frequencies of $D^0$ and anti-$D^0$ to CP eigenstates: $K^-K^+$ and $\pi^-\pi^+$

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

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

in the mixing

in the decay amplitudes

$A_\Gamma$ 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 $A_\Gamma$ in two ways:

1) in B → $D^0$ $\mu^-$ X and B → anti-$D^0$ $\mu^+$ X (JHEP 04 (2015) 043)

2) in $D^{*+} \to D^0 \pi^+_s$ and $D^{*-} \to$ anti-$D^0$ $\pi^-_s$ (PRL 112 (2014) 041801)

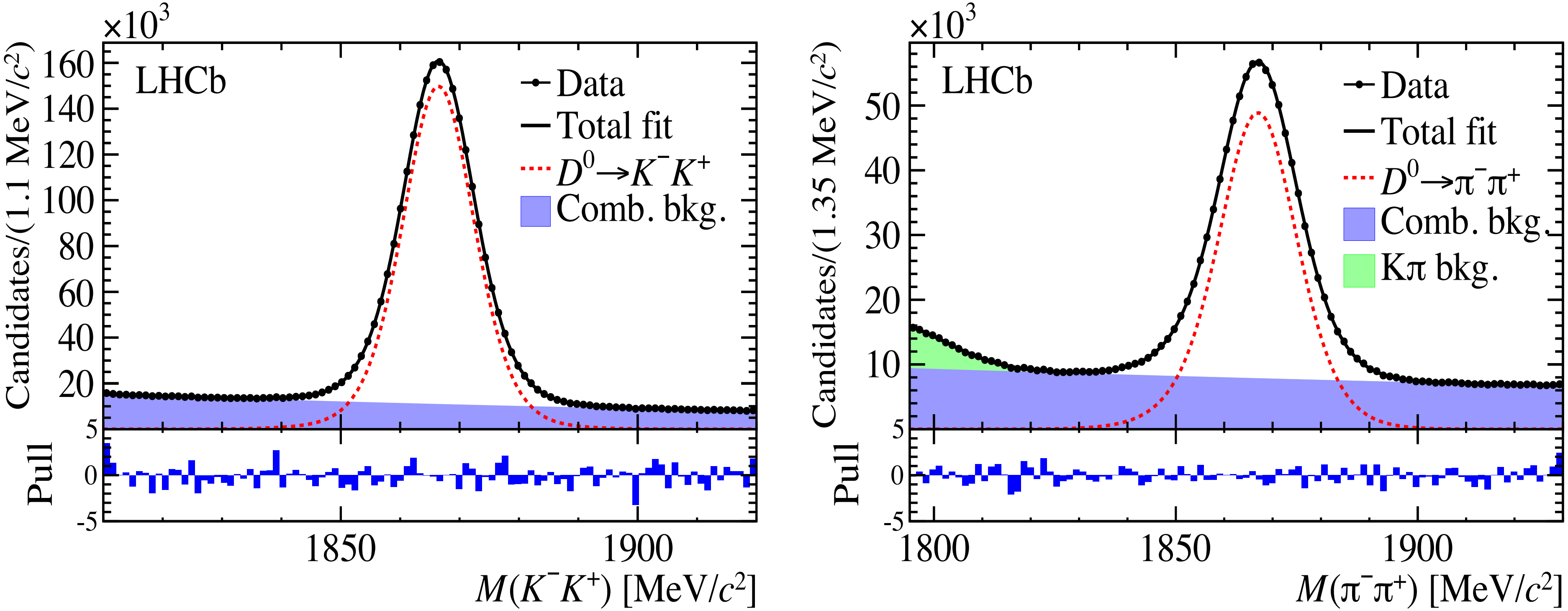
# $A_\Gamma$ asymmetry

Run 1, L = 3/fb: B → $D^0$ $\mu^-$ X and B → anti-$D^0$ $\mu^+$ X

JHEP 04(2015)043

$D^0$,anti-$D^0$ → $K^-K^+$, 2.3M events

$D^0$,anti-$D^0$ → $\pi^-\pi^+$, 0.8M events



- The raw CP asymmetry ($A^{raw}$) is determined from fits to the mass distributions in 50 bins of the $D^0$ decay-time

- The value of $A_\Gamma$ is determined from a fit of the function

$$A_{CP}^{raw}(t) \approx A_0 - A_\Gamma \frac{t}{\tau}$$

Phys.Rev.D85(2012)012009

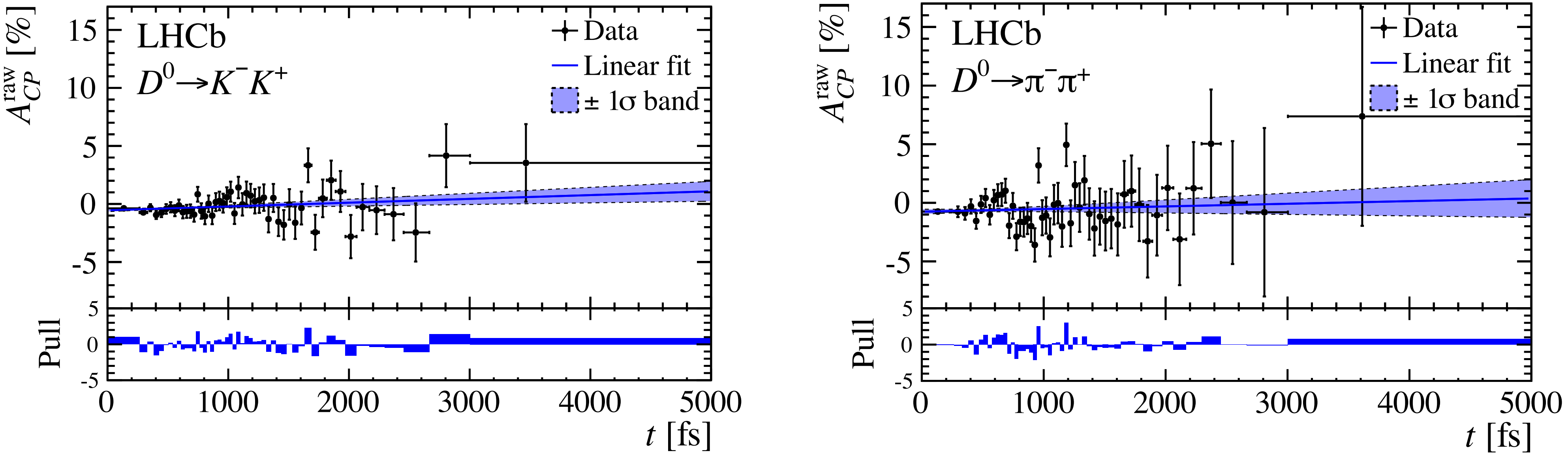
# $A_\Gamma$ asymmetry

1) L = 3/fb: B → $D^0$ $\mu^-$ X and B → anti-$D^0$ $\mu^+$ X

JHEP04(2015)043

$D^0$,anti-$D^0$ → $K^-K^+$

$D^0$,anti-$D^0$ → $\pi^-\pi^+$



$A_\Gamma(K^-K^+) = (-0.134 \pm 0.077\ ^{+0.026}_{-0.034})$ %

$A_\Gamma(\pi^-\pi^+) = (-0.092 \pm 0.145\ ^{+0.025}_{-0.033})$ %

2) Consistent with previous measurements, L=1/fb: $D^{*+} \to D^0 \pi^+_s$ and $D^{*-} \to$ anti-$D^0$ $\pi^-_s$

PRL 112 (2014) 041801

$A_\Gamma(K^-K^+) = (-0.035 \pm 0.062 \pm 0.012)$ %

$A_\Gamma(\pi^-\pi^+) = (0.033 \pm 0.106 \pm 0.014)$ %

- No significant difference between the two final states
- No evidence for indirect CPV within 1 per mil

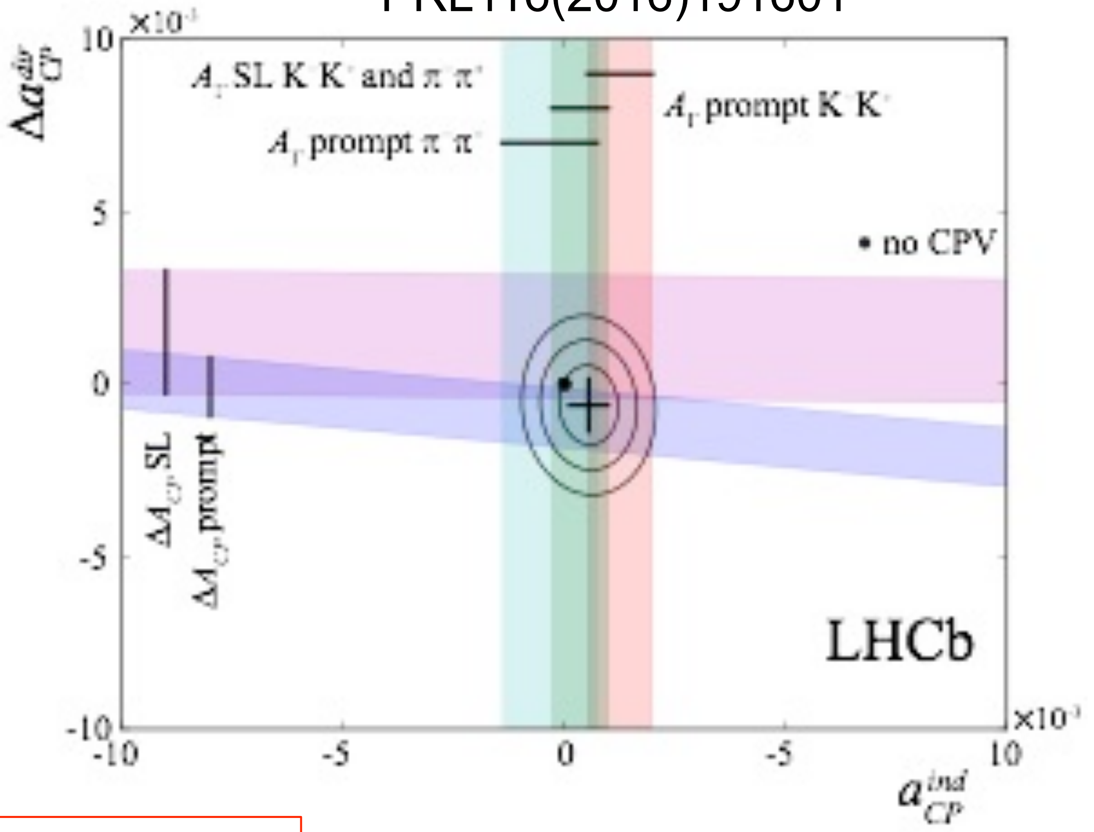
# Summary of the measurements of CPV in $D^0 \rightarrow hh$

$$\Delta A_{CP} = \Delta a_{CP}^{dir}\left(1 + \frac{\langle\bar{t}\rangle}{\tau} y_{CP}\right) + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{ind}$$

The $\Delta A_{CP}$, $a^{ind}_{CP}$ and $y_{CP}$ are measured at LHCb:

- $\Delta A_{CP}$ PRL116(2016)191601
  JHEP07(2014)041
- $A_\Gamma \simeq -a^{ind}_{CP}$ PRL112(2014)041801
  JHEP04(2015)043
- $y_{CP}$ JHEP04(2012)129

PRL116(2016)191601



$a^{ind}_{CP}$ = 0.058 ± 0.044 %
$\Delta a^{dir}_{CP}$ = - 0.061 ± 0.076 %

- Sensitivity of the measurement ($10^{-4}$) is very close to the expectations of the Standard Model ($\lesssim 10^{-3}$ but predictions vary widely)
- The common result is consistent with the hypothesis of CP symmetry with a p-value of 0.32

# Summary and conclusions

**So far:**

- The LHCb has performed very well in Run 1 (2011+2012, 3/fb) confirming so far the robustness of the Standard Model
- LHCb makes many interesting charm measurements:
  - ✧ first observation of $D^0$ – anti-$D^0$ mixing in the $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$ decay (other than D → Kπ); no-mixing hypothesis is rejected at 8.2σ
  - ✧ all results are consistent with CP conservation in charm, but we are better than 1 per mil sensitivity for CP searches in (very close to the SM):

$$a^{ind}_{CP} = 0.058 \pm 0.044\ \%$$

$$\Delta a^{dir}_{CP} = A^{dir}_{CP}(K^-K^+) - A^{dir}_{CP}(\pi^-\pi^+) = -0.061 \pm 0.076\ \%$$

**Future:**

- Data are being recorded (Run 2): 2015-18 > 8/fb at $\sqrt{s}=13$ TeV
- Expand physics programme to more modes with charm decays
- LHCb upgrade (starting 2019) plans to collect ~50/fb data in 2022 and reach sensitivity which are comparable or better than theoretical uncertainties

BACK UP!

# LHCb upgrade

EPJ C73(2013)2373

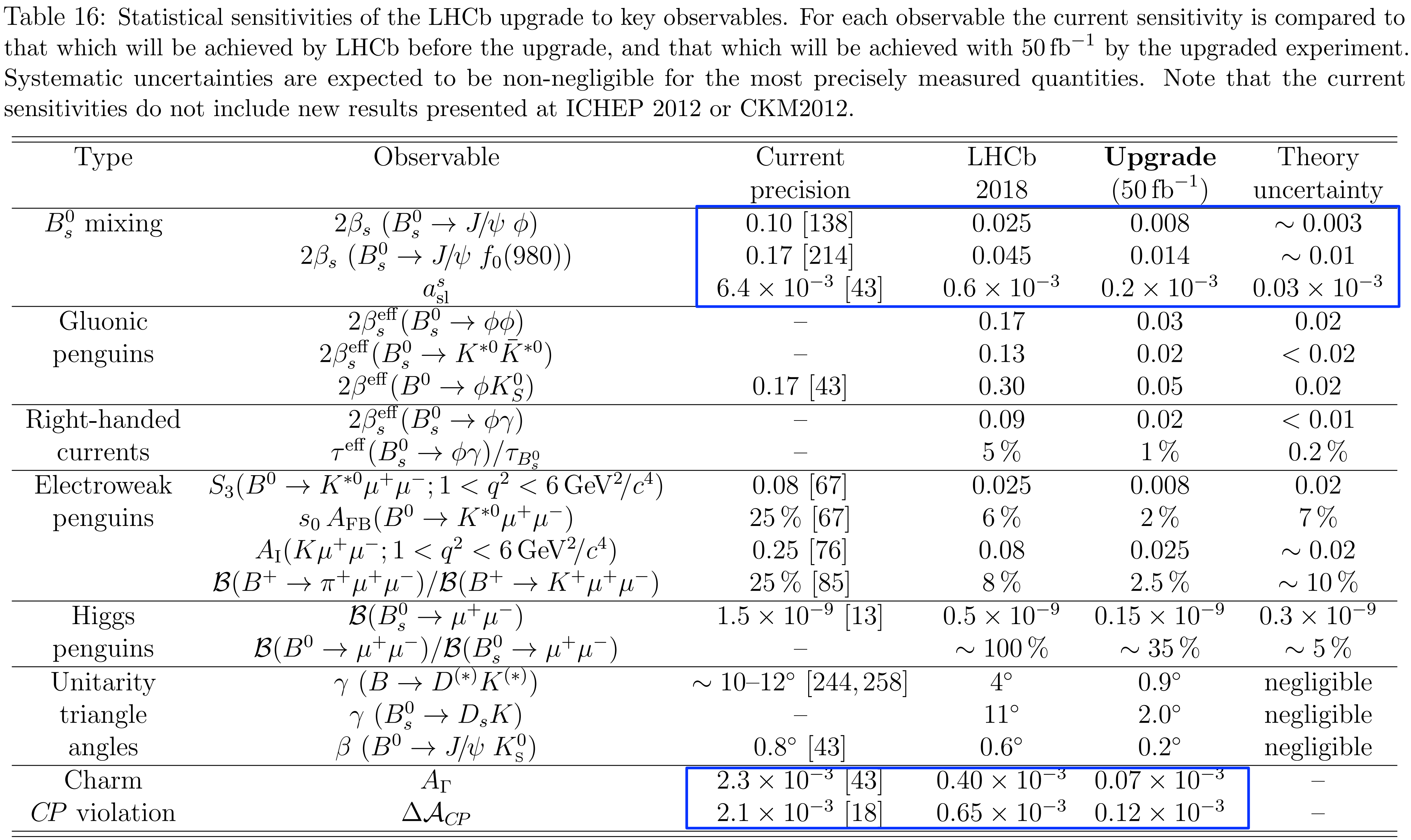


Table 16: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with 50 fb$^{-1}$ by the upgraded experiment. Systematic uncertainties are expected 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 | $\sim 0.003$ |
| | $2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$) | 0.17 [214] | 0.045 | 0.014 | $\sim 0.01$ |
| | $a_{\text{sl}}^s$ | $6.4 \times 10^{-3}$ [43] | $0.6 \times 10^{-3}$ | $0.2 \times 10^{-3}$ | $0.03 \times 10^{-3}$ |
| 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 | $\sim 0.02$ |
| | $\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$ | 25 % [85] | 8 % | 2.5 % | $\sim 10$ % |
| Higgs penguins | $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ | $1.5 \times 10^{-9}$ [13] | $0.5 \times 10^{-9}$ | $0.15 \times 10^{-9}$ | $0.3 \times 10^{-9}$ |
| | $\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ | – | $\sim 100$ % | $\sim 35$ % | $\sim 5$ % |
| Unitarity triangle angles | $\gamma$ ($B \to D^{(*)}K^{(*)}$) | $\sim 10$–$12°$ [244, 258] | 4° | 0.9° | negligible |
| | $\gamma$ ($B_s^0 \to D_s K$) | – | 11° | 2.0° | negligible |
| | $\beta$ ($B^0 \to J/\psi\ K_S^0$) | 0.8° [43] | 0.6° | 0.2° | negligible |
| Charm *CP* violation | $A_\Gamma$ | $2.3 \times 10^{-3}$ [43] | $0.40 \times 10^{-3}$ | $0.07 \times 10^{-3}$ | – |
| | $\Delta\mathcal{A}_{CP}$ | $2.1 \times 10^{-3}$ [18] | $0.65 \times 10^{-3}$ | $0.12 \times 10^{-3}$ | – |

# Mixing parameters

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

$$y_{CP} \equiv \frac{\Gamma(D^0 \rightarrow f_{CP})}{\Gamma(D^0 \rightarrow f_{non-CP})} - 1 = \frac{\Gamma(D^0 \rightarrow K^+K^-)}{\Gamma(D^0 \rightarrow K^-\pi^+)} - 1$$

$$= y \cos\phi - \frac{1}{2} A_m x \sin\phi$$

$\cos\phi \neq 1$ : 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:

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

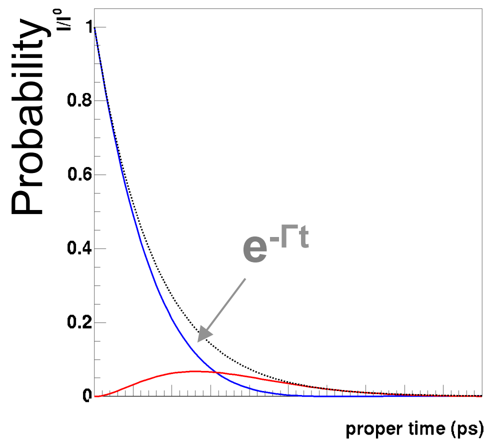
Width difference:

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

Weak phase:

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

if D$^0$ only decays then
  disappearing is exponential
but if D$^0$-anti-D$^0$ oscillates 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$^-$:

$$A_\Gamma \equiv \frac{\Gamma(D^0 \rightarrow f_{CP}) - \Gamma(\bar{D}^0 \rightarrow f_{CP})}{\Gamma(D^0 \rightarrow f_{CP}) + \Gamma(\bar{D}^0 \rightarrow f_{CP})} = \frac{\Gamma(D^0 \rightarrow K^+K^-) - \Gamma(\bar{D}^0 \rightarrow K^+K^-)}{\Gamma(D^0 \rightarrow K^+K^-) + \Gamma(\bar{D}^0 \rightarrow K^+K^-)}$$

$$\approx \frac{1}{2}(A_m + A_d)\cos\phi - x \sin\phi$$

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

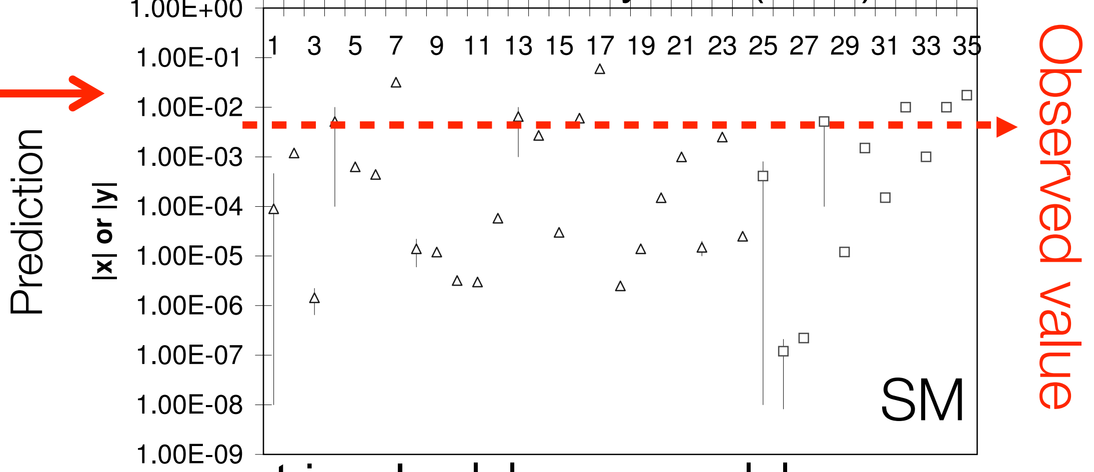
The measurement requires distinguishing the D$^0$ flavors at the production state.

# SM predictions for charm

- In the Standard Model:
  - ✧ 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 $10^{-2}$

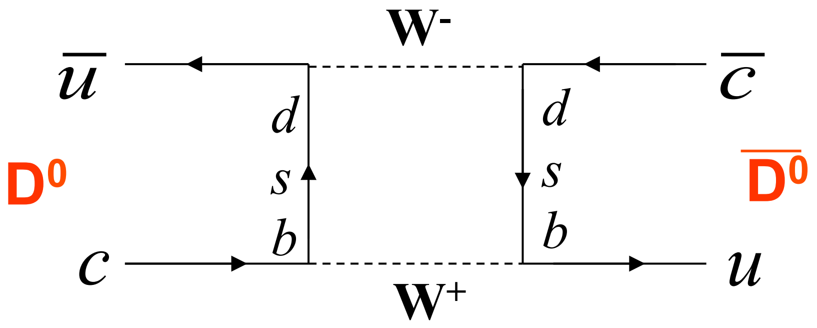
    Int.J.Mod.Phys.A21(2006)5381 ;
    Ann.Rev.Nucl.Part.Sci.58(2008)249

Int.J.Mod.Phys.A21(2006)5686

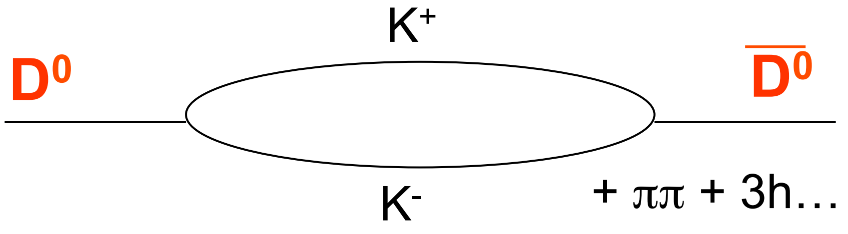


triangles |x| ; squares |y|

- Perfect place for New Physics searching (<u>small background from SM</u>)



Mixing via box-diagram, short range



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