BEACH 2018- XIII INTERNATIONAL CONFERENCE ON BEAUTY, CHARM AND HYPERON HADRONS

Charm mixing and CPV

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on behalf of the LHCb collaboration

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LHCb

IN SUPREMÆ DIGNITATIS 1343

UNIVERSITÀ DI PISA

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Outline

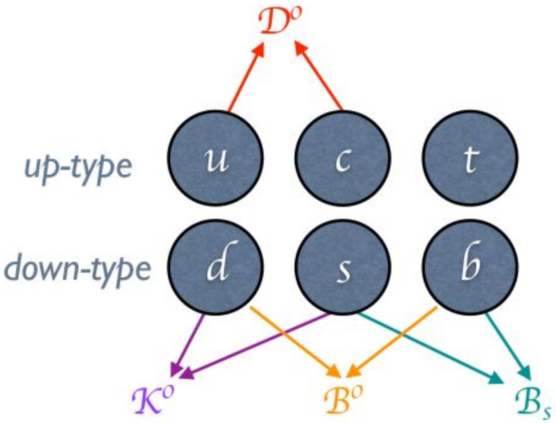
- CPV in charm @ LHCb

- **Direct CPV**:
  - ΔA^{CP} in $\Lambda_c \rightarrow ph^+h^-$ [JHEP 03(2018)182]
  - A^{CP} in $D^0 \rightarrow K_S^0 K_S^0$ [arXiv:1806.01642] submitted to JHEP **NEW**
  - A^{CP} in $D^0 \rightarrow h^+h^-\mu^+\mu^-$ [LHCb-PAPER-2018-020] in preparation **NEW**

- **Charm mixing and indirect CPV**:
  - D^0-$\overline{D}^0$ mixing and CPV with $D^0 \rightarrow K^+\pi^-$ [PRD 97(2018) 031101]

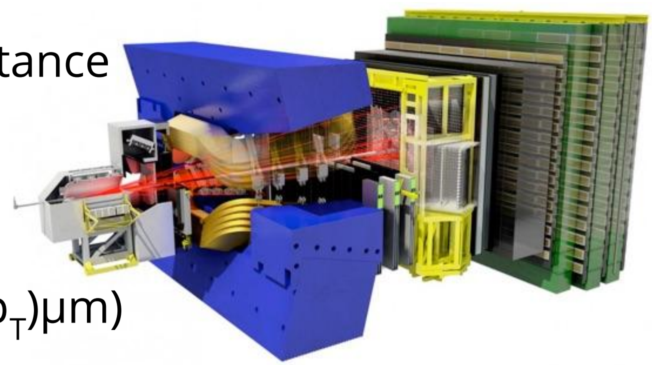
CPV in charm

- Charm transitions are a unique portal for obtaining a novel access to flavor dynamics
  - complementarity wrt B and K mesons
  - CPV in charm predicted ~O(10^{-3}):
    low SM background → sensitivity to "New Physics"



- **CPV in charm decays has not yet been observed!**

- Large samples of charm mesons decays needed → **LHCb**
  - ~10^6 $c\bar{c}$ pairs per second produced in LHCb acceptance ($2<\eta<4.5$, $0<p_T<8$ GeV/c) at LHC
  - Good momentum resolution (0.5% - 1%)
  - Excellent vertex resolution (IP resolution $(15+29/p_T)\mu$m)



JHEP 05 (2017) 074

$$\sigma(pp \to D^0 X) = 2072 \pm 2 \pm 124 \mu b \qquad \sigma(pp \to D_s^+ X) = 353 \pm 9 \pm 76 \mu b$$

$$\sigma(pp \to D^+ X) = 834 \pm 2 \pm 78 \mu b \qquad \sigma(pp \to D^{*+} X) = 784 \pm 4 \pm 87 \mu b$$

Direct CPV

- Difference of decay rate between two CP conjugate states

$$\mathcal{A}^{CP}(f) = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

- Quantity measured in LHCb

$$\mathcal{A}^{raw} \equiv \frac{N_D - N_{\bar{D}}}{N_D + N_{\bar{D}}}$$

$$\mathcal{A}^{raw} \approx \mathcal{A}^{CP} + \mathcal{A}^{prod} + \mathcal{A}^{det}$$

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Production asymmetry: initial state pp is not CP symmetric

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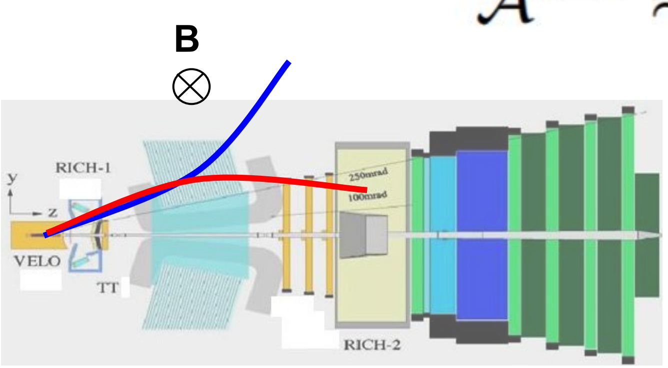


Asymmetric detector acceptance + material interaction different for particles/antiparticles

ΔA^{CP} in $\Lambda_c \rightarrow ph^+h^-$

[JHEP 03(2018)182]

- CPV in charm baryons almost unexplored

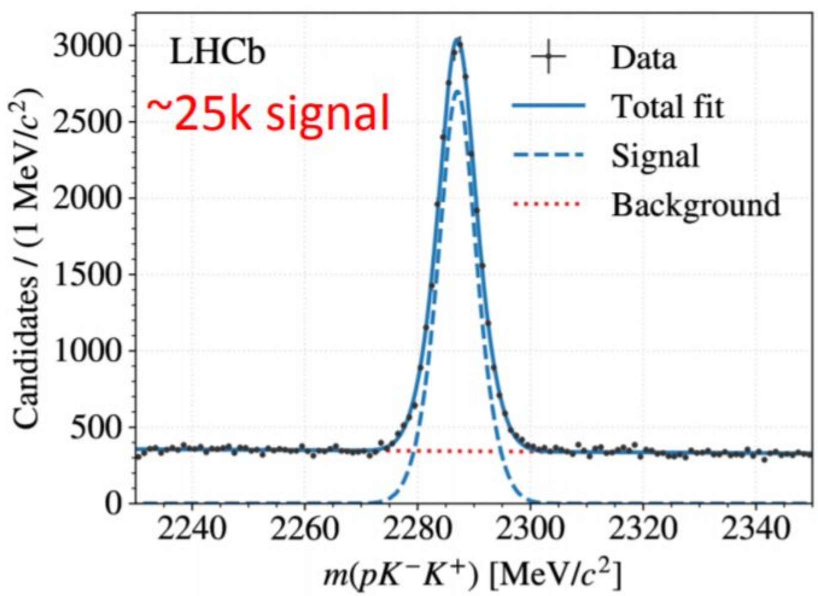
  $A_{CP}(\Lambda_c^+ \rightarrow \Lambda^0 \pi^+) = (-7 \pm 31)\%$ FOCUS, PLB 634 (**2006**) 165
  $A_{CP}(\Lambda_c^+ \rightarrow \Lambda^0 e^+ \nu_e) = (0 \pm 4)\%$ CLEO, PRL 94 (**2005**) 191801

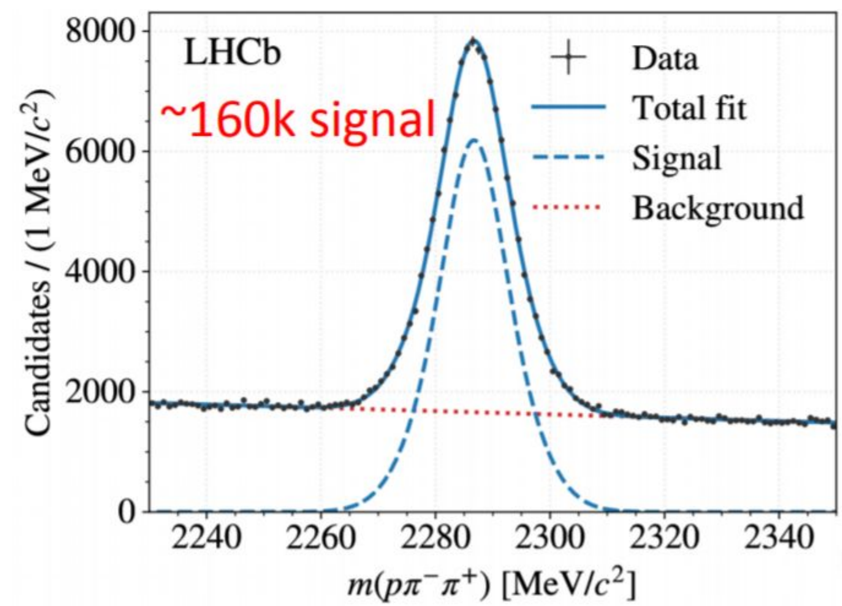
- Dataset: full Run1 sample (3 fb^{-1})
- Production mode: $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- X$
  - requirements on $\Lambda_c^+ \mu^-$ vertex displacement suppress background
- Measured quantity: $\Delta A^{CP} = A^{CP}(\Lambda_c^+ \rightarrow pK^+K^-) - A^{CP}(\Lambda_c^+ \rightarrow p\pi^+\pi^-)$
  - Detector and production asymmetries cancel if kinematics are identical
  - $p\pi^+\pi^-$ kinematics equalized to pK^+K^- kinematics before extracting raw asymmetry, weights computed using GBDT
  - Per candidate weights provided for theoretical interpretation

ΔA^{CP} in $\Lambda_c \to ph^+h^-$

[JHEP 03(2018)182]

- Measured phase-space integrated CPV
- Cut-based selection to avoid creating kinematic differences between decay modes
- A^{raw} extracted fitting ph^+h^- mass distribution and corrected for efficiency variation across 5D phase-space → from simulated events



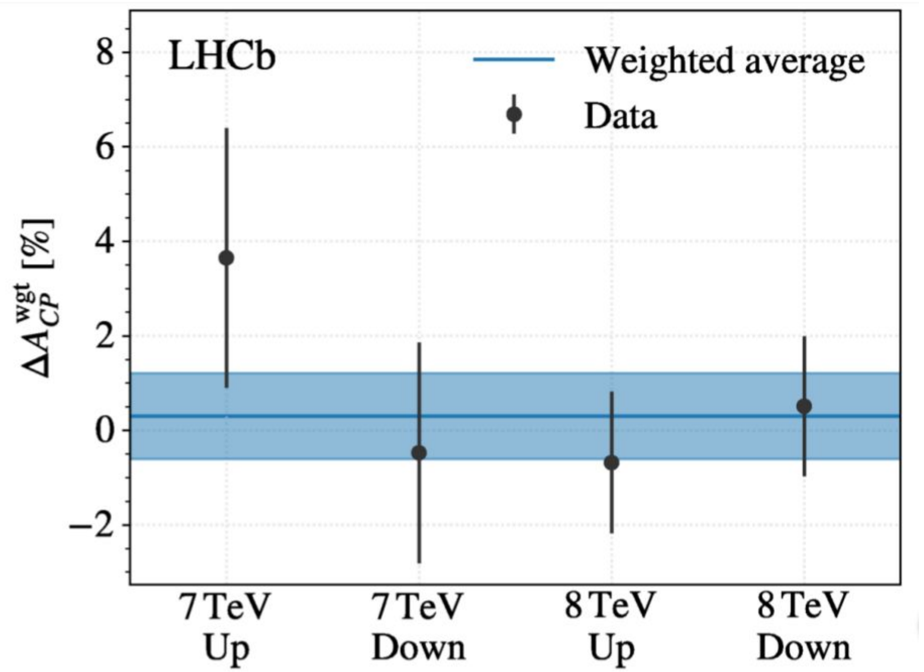


ΔA^{CP} in $\Lambda_c \to ph^+h^-$

Results

ΔA^{CP}=(0.30±0.91±0.61)%

Consistent with no-CPV hypothesis



Main systematic uncertainty arises from limited simulation sample-size.

Results consistent varying data-taking period (centre-of-mass energy) and magnet polarity

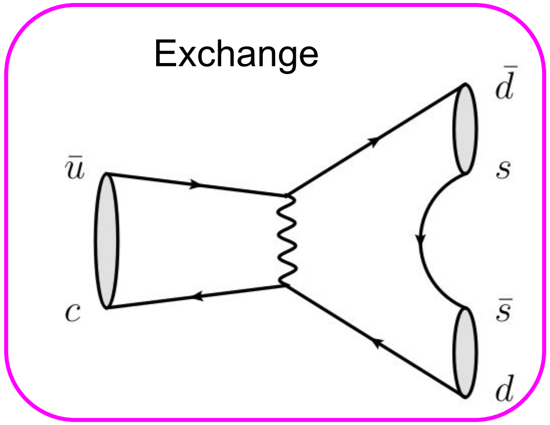
A^{CP} in $D^0 \rightarrow K_S^0 K_S^0$

[arXiv:1806.01642]

- Search of CPV in decay channels with high statistics not conclusive
- Different approach: search CPV in decay channels where amplitudes are suppressed
  - $D^0 \rightarrow K_S^0 K_S^0$, where **$A^{CP}$ could be enhanced at a level of ~1%**

PRD 92 (2015) 054036

B.R. $(D^0 \rightarrow K_S^0 K_S^0) = (1.8 \pm 0.4) \times 10^{-4}$



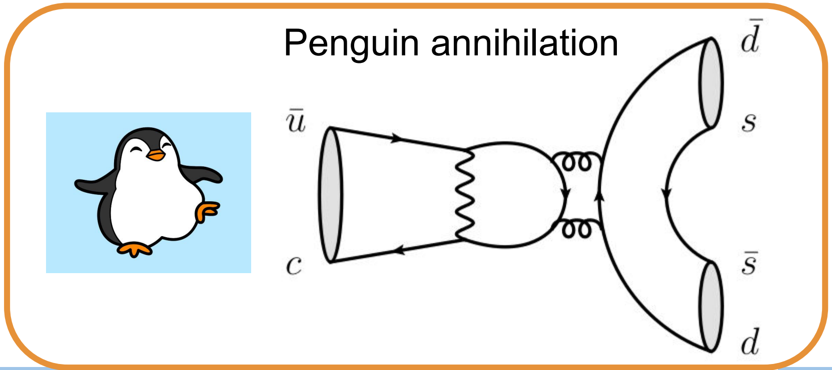
Previous measurements

$A^{CP}(K_S^0 K_S^0)$ (%)	Yield	Collaboration
$-23. \pm 19.$	65 ± 14	CLEO
$-2.9 \pm 5.2 \pm 2.2$	635 ± 74	LHCb Run-1
$-0.02 \pm 1.53 \pm 0.17$	5399 ± 87	Belle

CLEO PRD 63 (2001) 071101

LHCb (Run1) JHEP 10 (2015) 055

Belle PRL 119 (2017) 171801



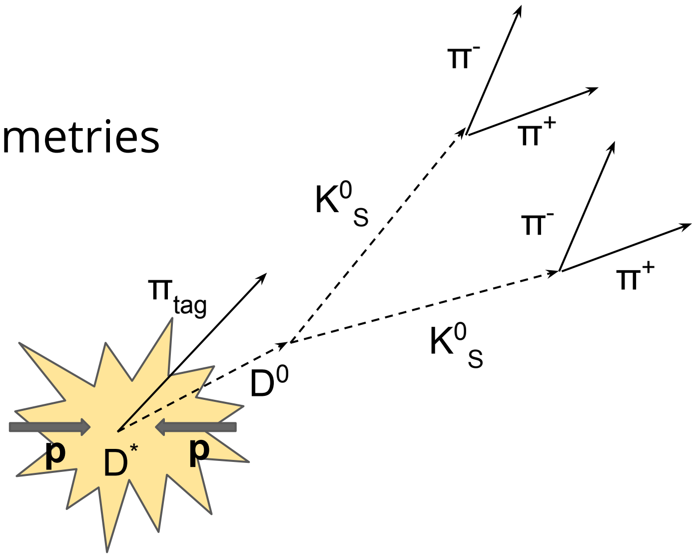
A^{CP} in $D^0 \rightarrow K_S^0 K_S^0$

[arXiv:1806.01642]

- $D^{*+} \rightarrow D^0\pi^+$ decay used to tag D^0
- To remove production and detection asymmetries

  $D^0 \rightarrow K^+K^-$ is used as a calibration channel

$$\begin{aligned}\Delta\mathcal{A}^{CP} &\equiv \mathcal{A}^{\mathrm{raw}}(K_S^0K_S^0) - \mathcal{A}^{\mathrm{raw}}(K^+K^-) \\ &= \mathcal{A}^{CP}(K_S^0K_S^0) - \mathcal{A}^{CP}(K^+K^-).\end{aligned}$$



$A^{CP}(K_S^0K_S^0) = \Delta A^{CP} + A^{CP}(K^+K^-)$

Independently measured by LHCb with a precision of ~0.1% PLB767(2017)177

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[arXiv:1806.01642]

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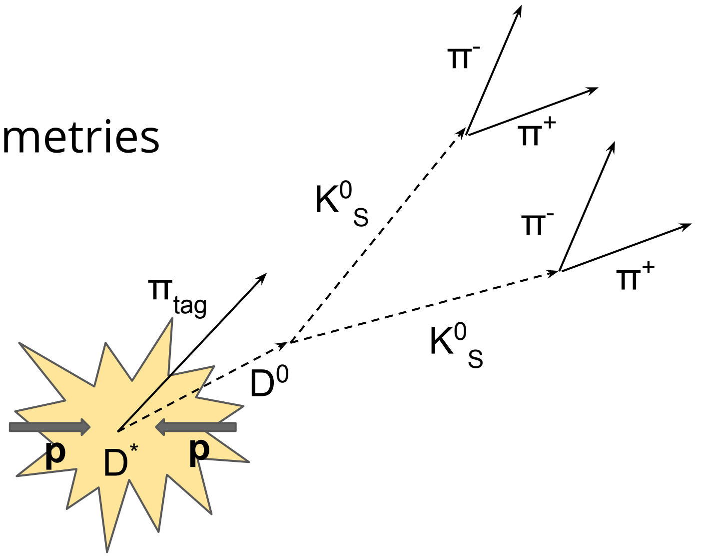
- To remove production and detection asymmetries

  $D^0 \to K^+K^-$ is used as a calibration channel

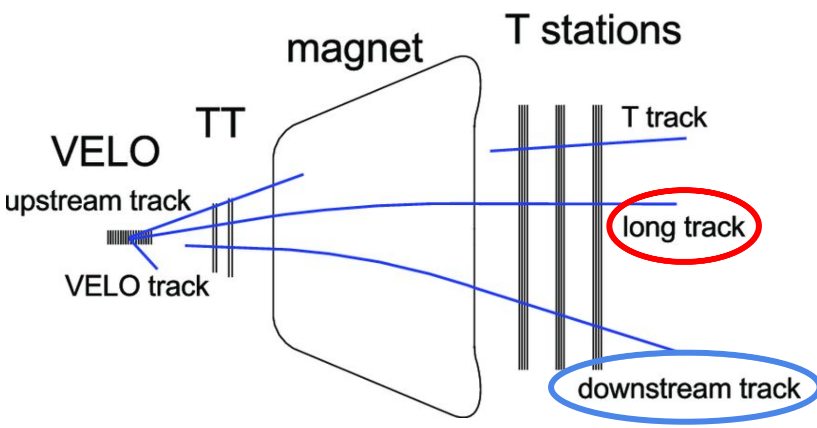
$$\Delta\mathcal{A}^{CP} \equiv \mathcal{A}^{\text{raw}}(K_S^0 K_S^0) - \mathcal{A}^{\text{raw}}(K^+K^-) = \mathcal{A}^{CP}(K_S^0 K_S^0) - \mathcal{A}^{CP}(K^+K^-).$$



➡ **$A^{CP}(K_S^0 K_S^0) = \Delta A^{CP} + A^{CP}(K^+K^-)$**

Independently measured by LHCb with a precision of ~0.1% PLB767(2017)177

- Data samples collected in 2015-2016 (~$2fb^{-1}$)
  - **LL** sample: both K_S^0 are reconstructed from **Long** tracks
  - **LD** sample: one K_S^0 is **Long** and the other one is **Downstream**

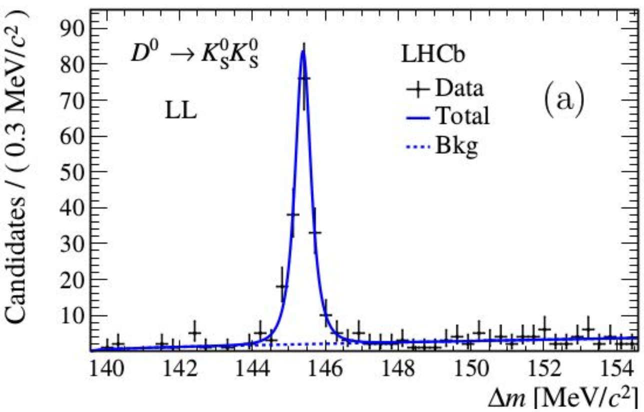


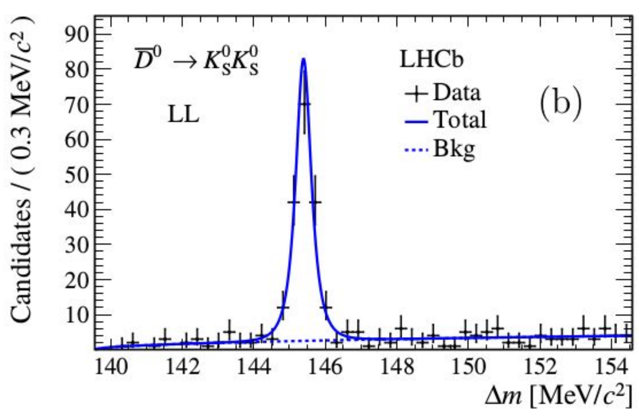
A^{CP} in $D^0 \rightarrow K_S^0 K_S^0$

[arXiv:1806.01642]

❖ A^{raw} extracted with a fit to $\Delta m = m(D^*) - m(D^0)$ distribution. **Total yields: 1067 ± 41**

"Magnet up" polarity





Results

A^{CP}(LL)=(+6.7 ± 3.8 ± 0.9)%

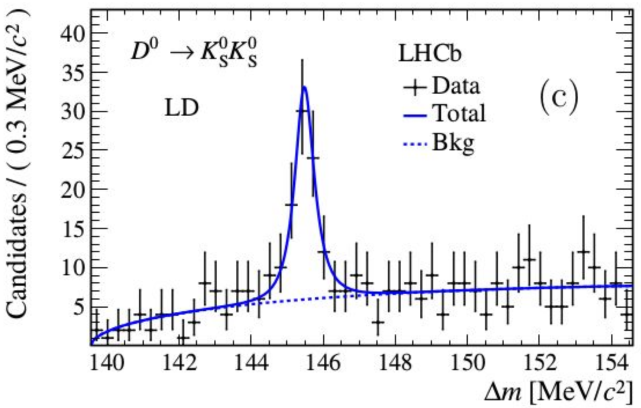
A^{CP}(LD)=(-5.3 ± 7.4 ± 1.3)%

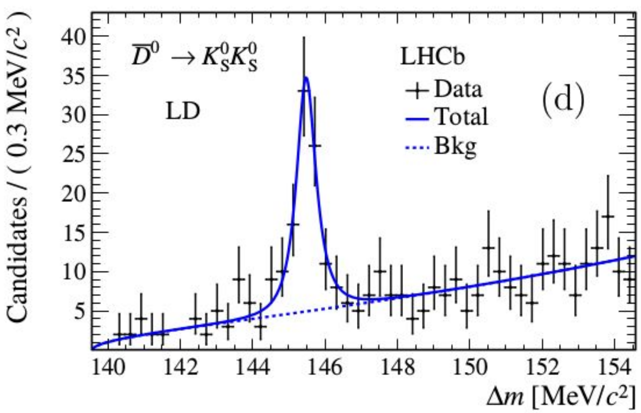
$A^{CP}(K_S^0 K_S^0)$ =(4.2±3.4±1.0)%

Combining with Run1 LHCb analysis

$A^{CP}(K_S^0 K_S^0)$ =(2.0±2.9±1.0)%

"Magnet up" polarity





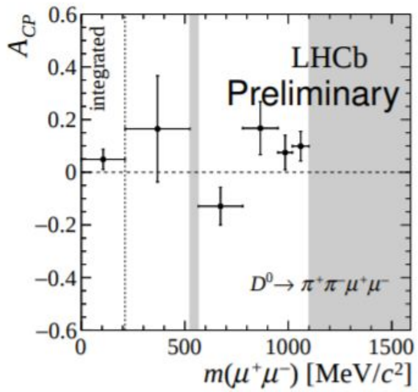
Consistent with no-CPV hypothesis and previous results. Main systematic uncertainty arises from fit model choice.

A^{CP} in $D^0 \to h^+h^-\mu^+\mu^-$

[LHCb-PAPER-2018-020] (in preparation)

- First observation of the rarest charm decays, agreement with SM PRL 119 (2017) 181805
- **Now** measured **angular and CP asymmetries** on data samples of 2011-2016 (5 fb^{-1})
- Asymmetries sensitive to SD in full range due to SD-LD interference
  - negligible SM contribution with current precision
  - O(few %) predictions for some NP models

    JHEP 1304 135 (2013), PRD 87 054026 (2013)



- Asymmetries compatible with zero, i.e. with SM prediction
- No dependence on dimuon mass

Preliminary results

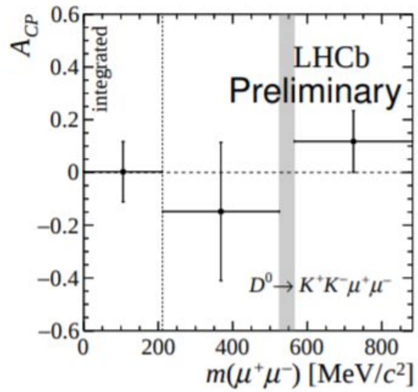
$D^0 \to \pi^+\pi^-\mu^-\mu^+$:

$$A_{CP} = (4.9 \pm 3.8 \pm 0.7)\%$$

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

$$A_{CP} = (0 \pm 11 \pm 2)\%$$

Further details on Jolanta Brodzicka presentation on "Rare Charm"



Mixing and indirect CPV

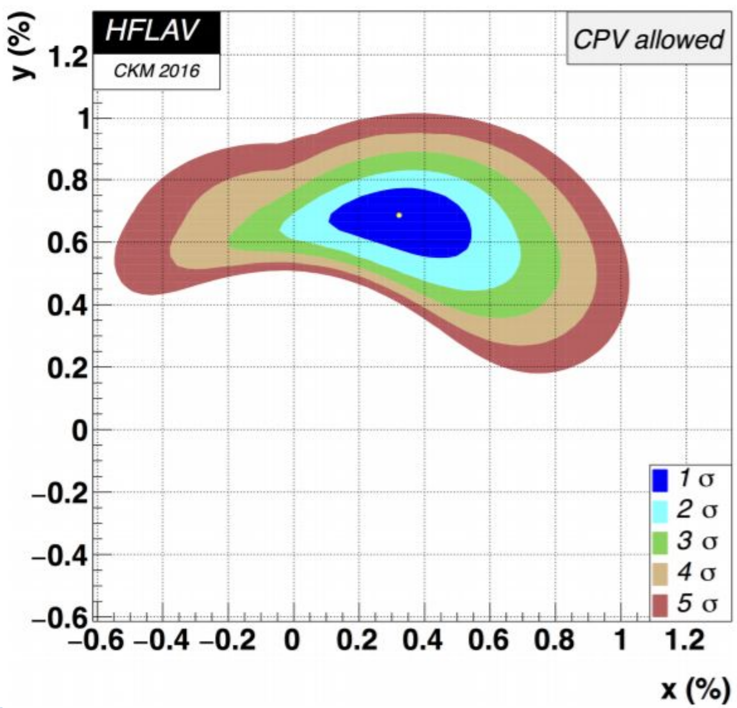
- Mass eigenstates linear combination of flavor eigenstates

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

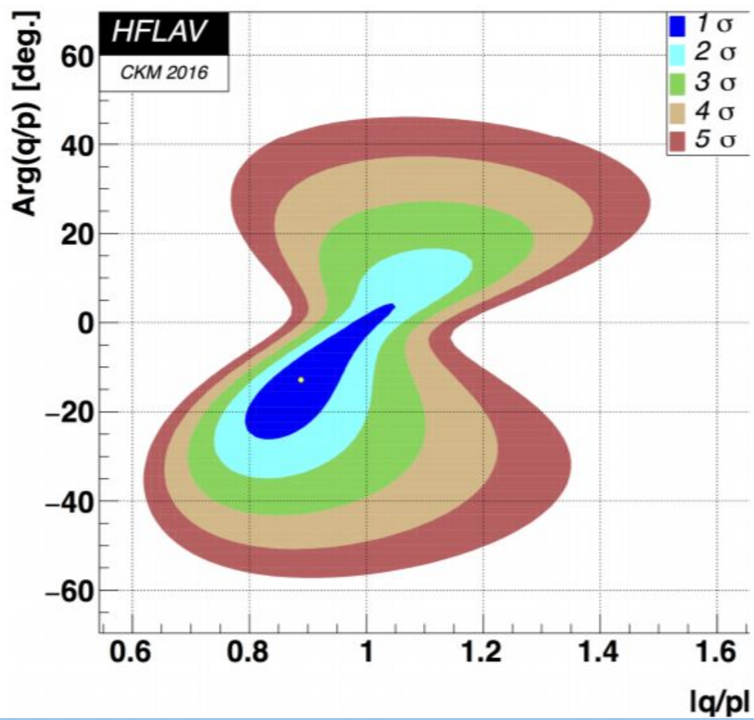
$$x \equiv \Delta m/\Gamma$$
$$y \equiv \Delta\Gamma/2\Gamma$$

Experimental status

No evidence for non-zero Δm (x)



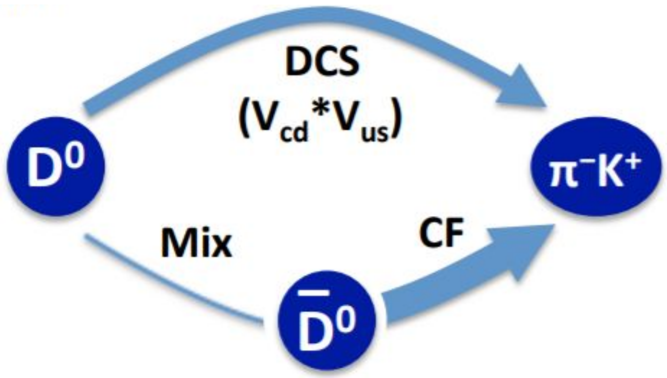
No evidence for CP violation in mixing or interference (q/p ≠ 1)



Mixing parameters and search for CPV in $D^0 \to K^+\pi^-$

[PRD 97(2018) 031101]

- Data sample: $5fb^{-1}$ (2011-2016)
- Used tagged $D^0 \to K^+\pi^-$ decays
- Measured the time dependent ratio of WS $D^0 \to K^+\pi^-$ and RS $D^0 \to K^-\pi^+$ ⟹ Dominated by CF amplitude



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

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

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

  - ➢ Approximation for x,y<<1
- τ is the average D^0 lifetime
- R_D is the ratio of suppressed to favored decay rates
- δ is the strong-phase difference between suppressed and favored amplitudes

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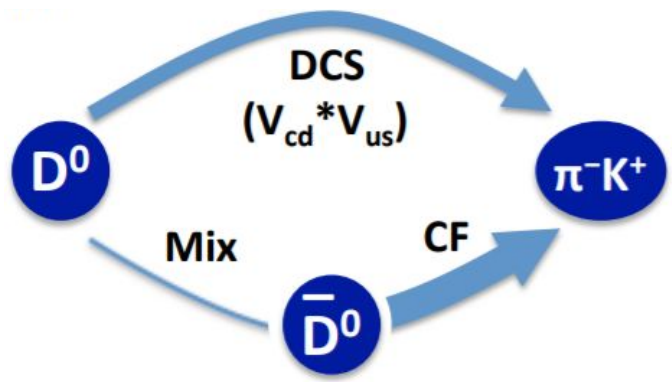


$$R(t) = \frac{N(D^0 \to K^+\pi^-)}{N(D^0 \to K^-\pi^+)}$$

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

Initial $D^0/\bar{D}^0$

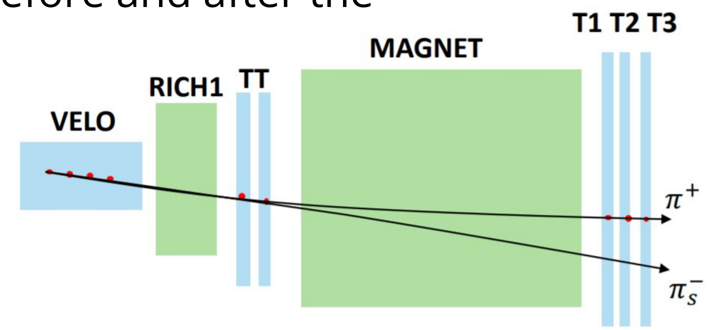
$R^+ \neq R^- \to$ CPV

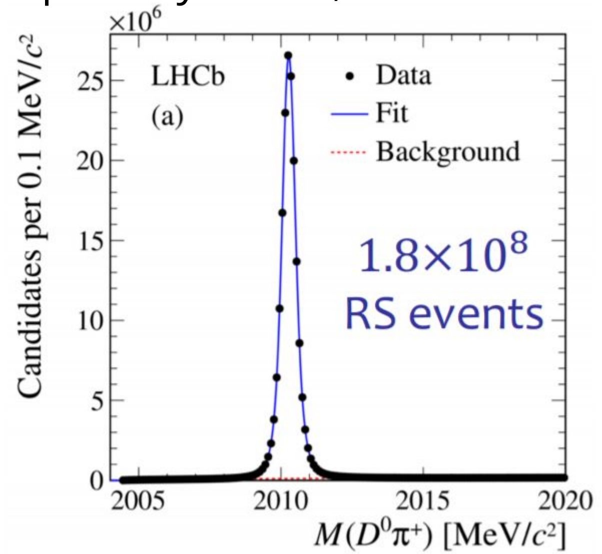
$R_D^+ \neq R_D^-$ → Direct CPV
$x'^+ \neq x'^-$ ($y'^+ \neq y'^-$) → Indirect CPV

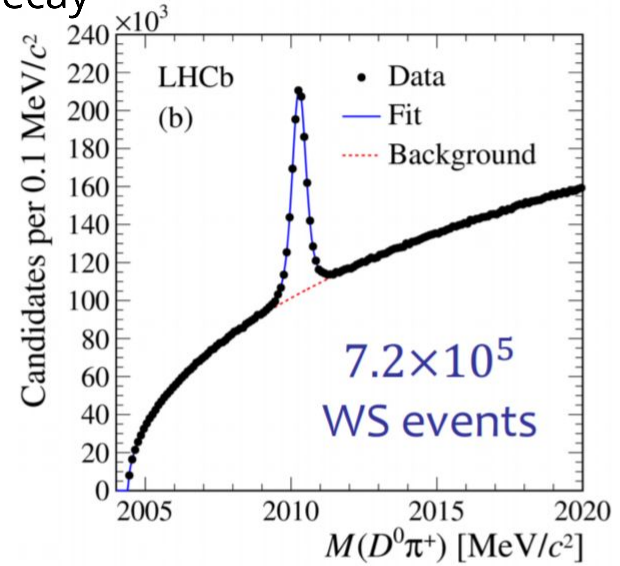
Mixing parameters and search for CPV in $D^0 \rightarrow K^+\pi^-$

[PRD 97(2018) 031101]

- $R^{\pm}$ determined in 13 decay-time bins, fitting Δm distribution
- Cuts applied to suppress problematic backgrounds, as:
  - **'Ghost' pions** from mismatched track segments before and after the magnet
    - Possible peak in Δm distribution
    - Wrong charge 50% of time: RS → WS migration
  - Backgrounds from **mis-ID of D^0 daughters**
  - Contamination from **secondary decays**: the D* is not coming form the primary vertex, but from a b-hadron decay





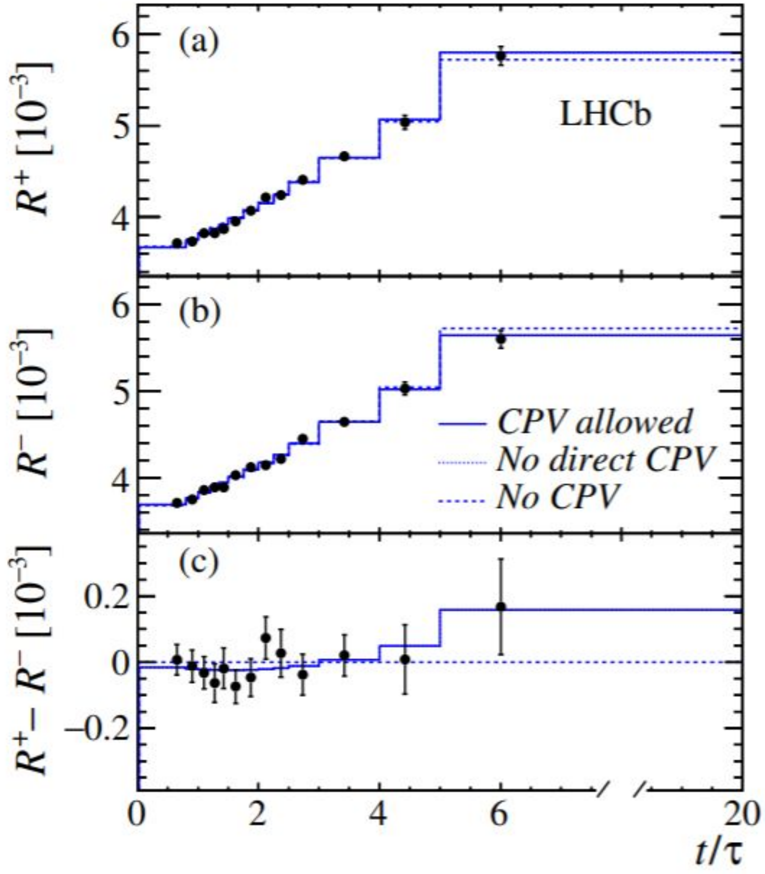


Mixing parameters and search for CPV in $D^0 \longrightarrow K^+\pi^-$

[PRD 97(2018) 031101]

Results

- Fitted efficiency-corrected data to extract ($x'^{\pm}$,$y'^{\pm}$,$R^{\pm}_D$) under three different hypotheses
- Main systematic uncertainty: residual secondary decays in the final sample



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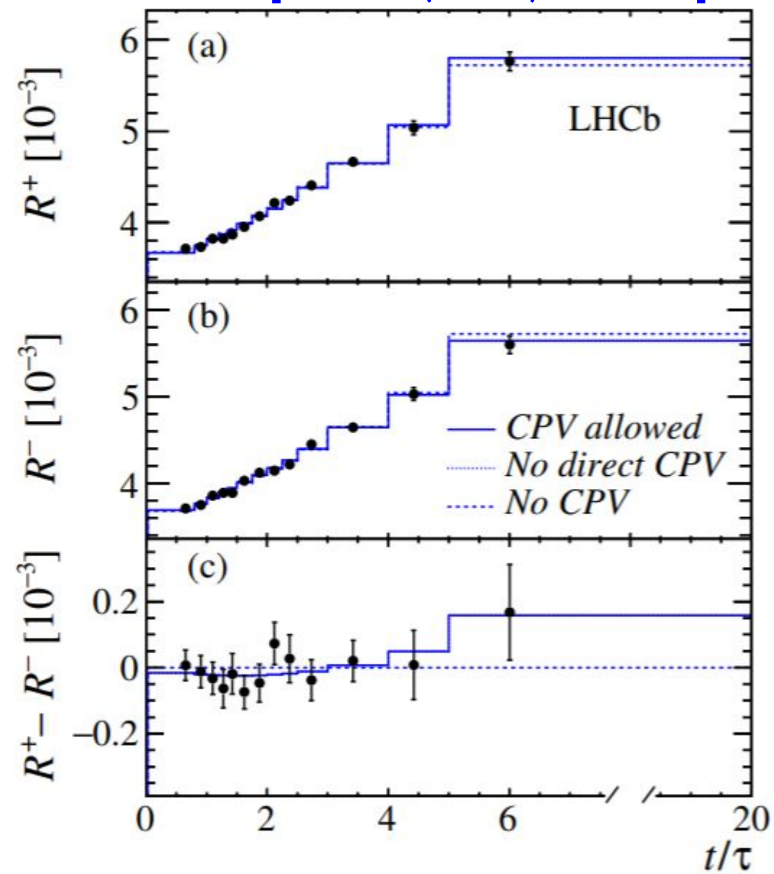
$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.1 \pm 8.1(stat) \pm 4.2(syst)\ )\times 10^{-3}$$

↑ Direct CPV



Direct and indirect CPV

Parameter	Value $\times 10^{-3}$
R_D^+	$3.454 \pm 0.040 \pm 0.020$
y'^+	$5.01 \pm 0.64 \pm 0.38$
$(x'^+)^2$	$0.061 \pm 0.032 \pm 0.019$
R_D^-	$3.454 \pm 0.040 \pm 0.020$
y'^-	$5.54 \pm 0.64 \pm 0.38$
$(x'^-)^2$	$0.016 \pm 0.033 \pm 0.020$

No direct CPV

Parameter	Value $\times 10^{-3}$
R_D	$3.454 \pm 0.028 \pm 0.014$
y'^+	$5.01 \pm 0.48 \pm 0.29$
$(x'^+)^2$	$0.061 \pm 0.026 \pm 0.016$
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No CPV

Parameter	Value $\times 10^{-3}$
R_D	$3.454 \pm 0.028 \pm 0.014$
y'	$5.28 \pm 0.45 \pm 0.27$
x'^2	$0.039 \pm 0.023 \pm 0.014$

Mixing parameters and search for CPV in $D^0 \longrightarrow K^+\pi^-$

[PRD 97(2018) 031101]

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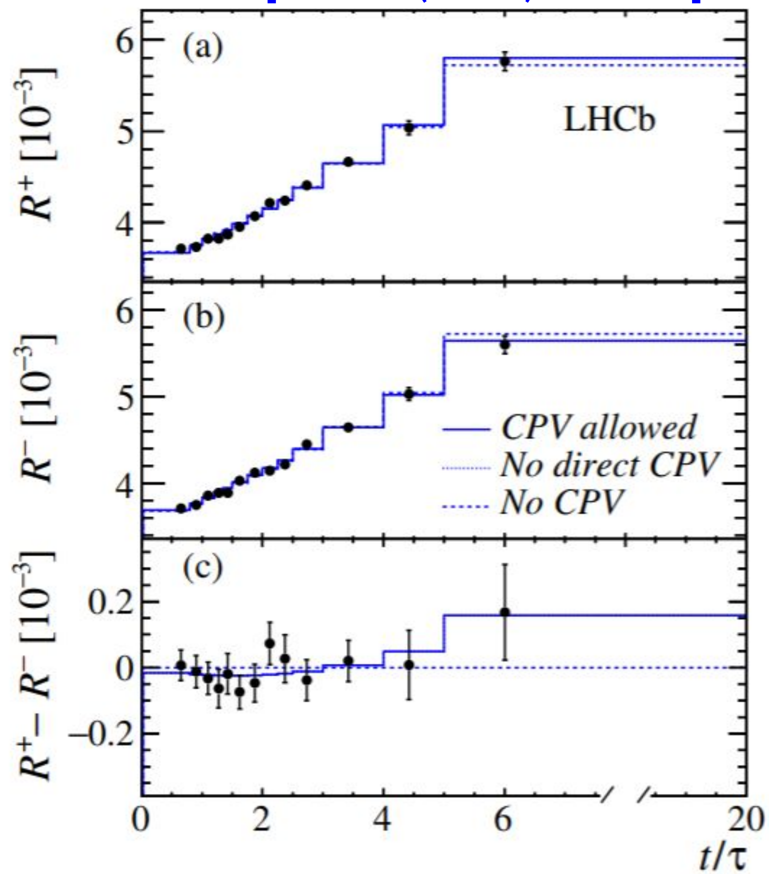

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.1 \pm 8.1(stat) \pm 4.2(syst))\times 10^{-3}$$

↑ Direct CPV

No evidence for CPV

Direct and indirect CPV

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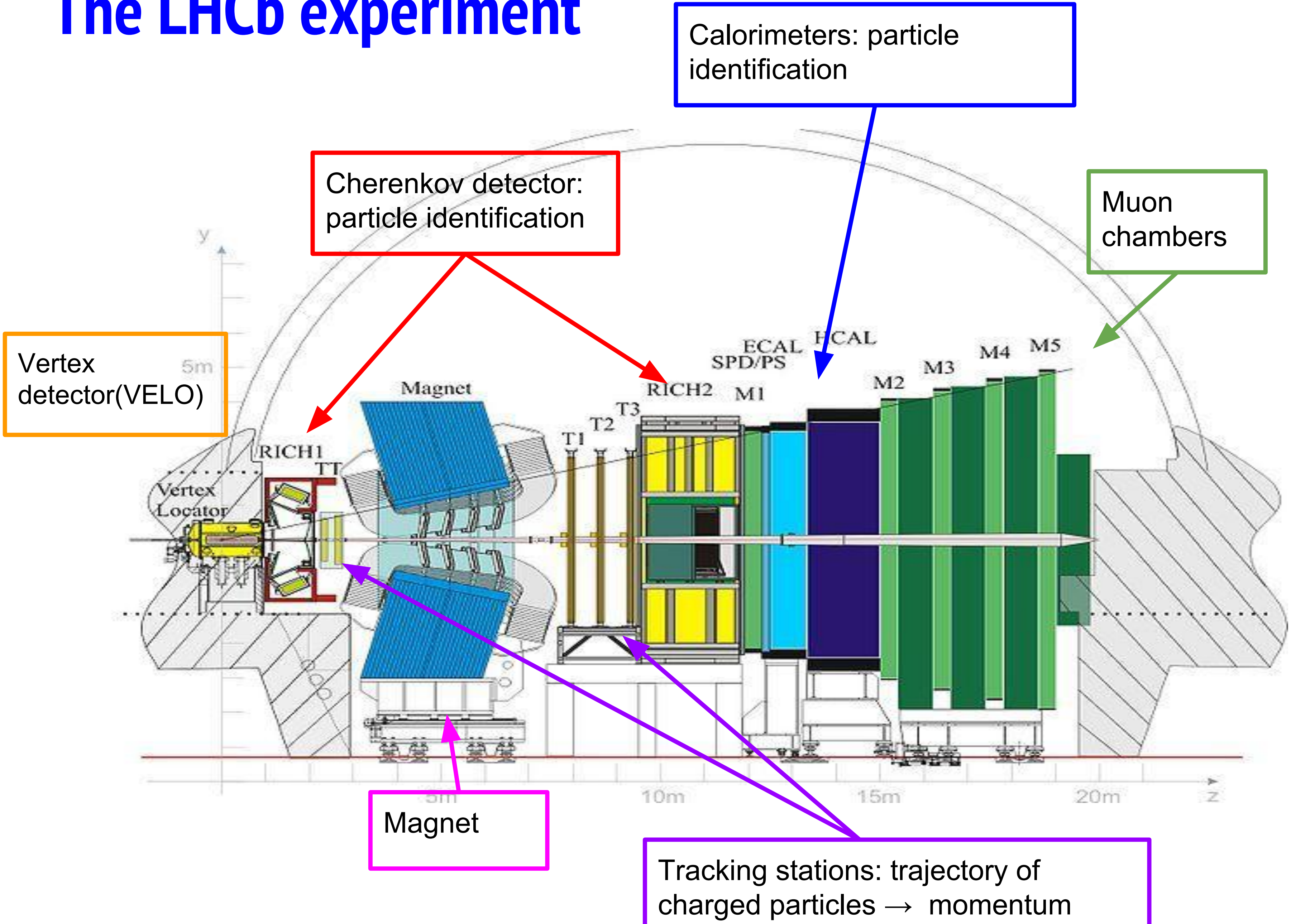
Conclusion

- Reached unprecedented precision on D^0-$\bar{D}^0$ mixing parameters
  - **$y' \rightarrow$ 5 x 10^{-4}** **$x'^2 \rightarrow$ 3 x 10^{-5}** (still compatible with 0 within uncertainty)
- The search for CP violation in charm decays continues!
- With growing data samples **LHCb is reaching the precision to observe CP violation** as expected by SM
- New results from Run1 and Run2 data samples are coming
- Stay tuned!

Backup slides

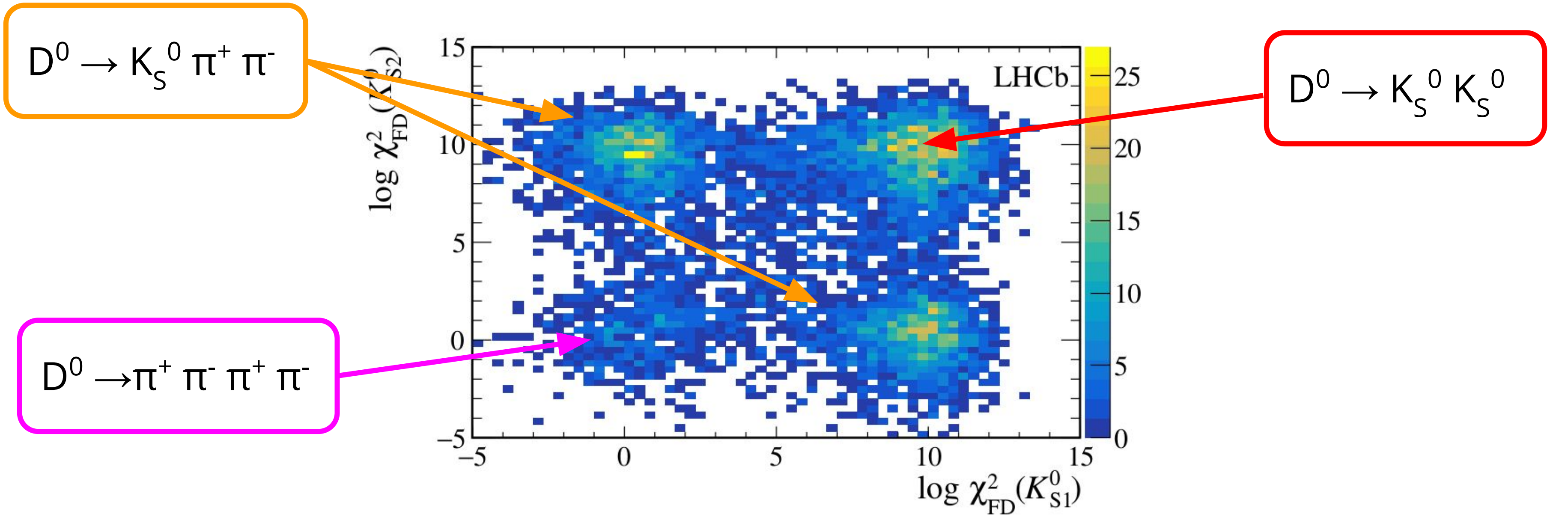
The LHCb experiment



A^{CP} in $D^0 \rightarrow K_S^0 K_S^0$

[arXiv:1806.01642]

- A^{raw} extracted with a fit to $\Delta m = m(D^*) - m(D^0)$ distribution
- Peaking background reduced with cut based selection, e.g.
  - $D^0 \rightarrow K_S^0 \pi^+ \pi^-$, reduced performing selections on $m(K_S^0)$ and flight distance



- Combinatorial background reduced using kNN classifier
- Results on LL and LD sample and on the two separate magnet polarities compatible within 2σ