Charm mixing and CP violation at LHCb

Mark Williams, on behalf of the LHCb collaboration

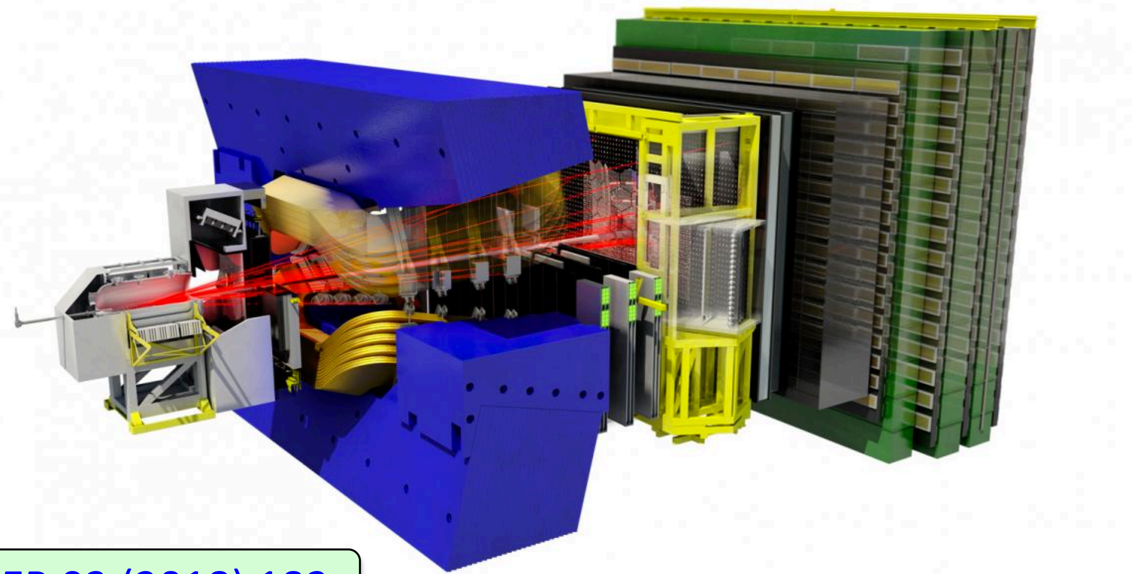
BEAUTY 2018

La Biodola, Isola d'Elba, Italy

6-11 May 2018

The University of Manchester

Overview



- CPV in charm @ LHCb
- Common themes
- **Direct CPV**
  - State of play
  - **ΔA_{CP} in $\Lambda_c^{\pm} \to ph^{+}h^{-}$**

    Published 03/2018 JHEP 03 (2018) 182
  - **Direct CPV in $D^0 \to K_S^0 K_S^0$ decays**

    NEW for BEAUTY LHCb-PAPER-2018-012
- **Charm mixing and indirect CPV**
  - State of play
  - **Wrong-sign $D^0 \to K^{+}\pi^{-}$ decays**

    Published 02/2018 PRD 97, 031101(R) (2018)
- Summary and future outlook: Run 2 and beyond

Abundance of riches

In 2017, **>5%** of all bunch crossings produced a charm meson within LHCb acceptance

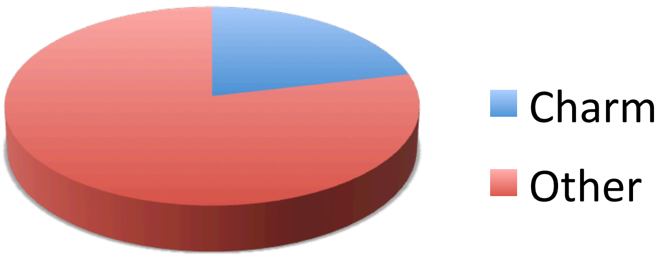
$$\sigma(pp \to D^0 X) = 2072 \pm 2 \pm 124\,\mu\text{b}$$
$$\sigma(pp \to D^+ X) = 834 \pm 2 \pm 78\,\mu\text{b}$$
$$\sigma(pp \to D_s^+ X) = 353 \pm 9 \pm 76\,\mu\text{b}$$
$$\sigma(pp \to D^{*+} X) = 784 \pm 4 \pm 87\,\mu\text{b}$$

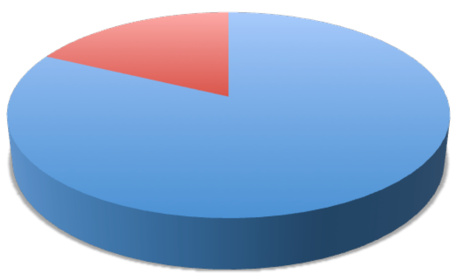
JHEP 05 (2017) 074
(13 TeV, $2 < \eta < 4.5$, $0 < p_T < 8$ GeV/c)

Early adopter of latest methods:

- Custom **'turbo'** triggers only saving required information − smaller events, **larger rates**
- Fast MC techniques − many analyses limited by MC stats, but new approaches give **~10-50x gain in speed**

'Traditional' triggers:
~10 kHz total
~600 MB/s





Turbo triggers:
~3 kHz total
~60 MB/s

Common themes: detector asymmetries

Measure **raw asymmetries** in yields of process X:

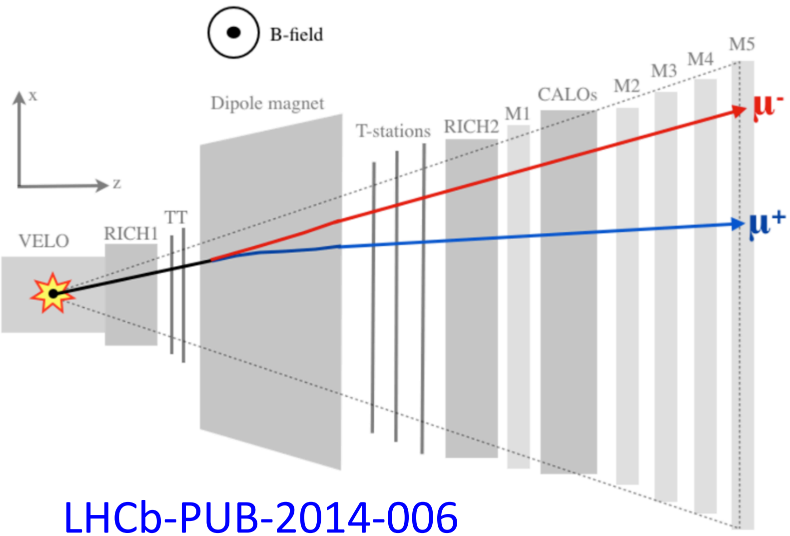
$$A_{raw}(X) = \frac{N(X) - N(\overline{X})}{N(X) + N(\overline{X})}$$

= sum of CP asymmetry and detector asymmetries

Detector asymmetries:

Magnet sweeps opposite-charged particles in different directions (detector not perfectly symmetric)

⇒



LHCb-PUB-2014-006

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Material interactions: different for particles/antiparticles

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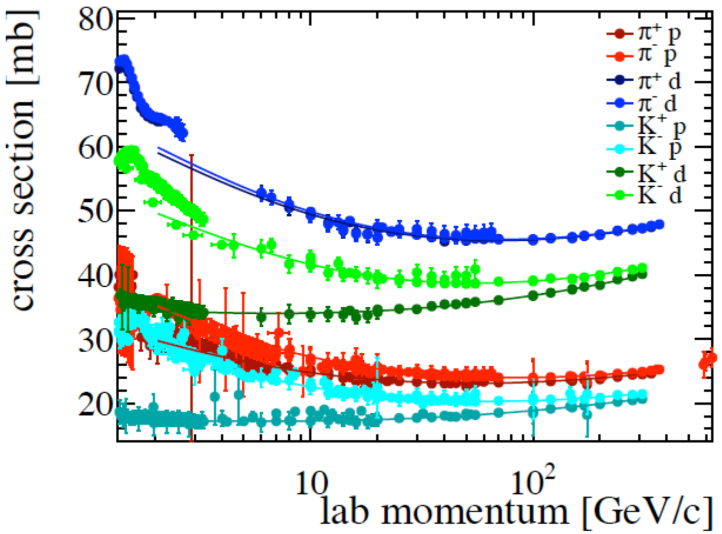
[Chin. Phys. C 38 (2014) 090001]



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Regularly reverse polarity

Fiducial cuts to remove most asymmetric regions

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$\Rightarrow$

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Material interactions: different for particles/antiparticles

$\Rightarrow$

Irreducible: measure in control channels

Depend on kinematics – ensure matching with signal sample (reweighting, or binned correction)

Charm CPV @ LHCb: The fourfold way

Direct CPV

Mixing + indirect CPV

Two-body

Direct CPV

$\Delta A_{CP}(D^0 \to hh)$ and **$A_{CP}(hh)$**:
PRL 108 (2012) 111602
PLB 723 (2013) 33
JHEP 07 (2014) 041
PRL 116 (2016) 191601
PLB 767 (2017) 177

$D_{(s)}^+ \to \eta' \pi^+$
PLB 771 (2017) 21

$D^0 \to K_S^0 K_S^0$
JHEP 10 (2015) 055

$D_{(s)}^+ \to K_S^0 h^+$
JHEP 06 (2013) 112
JHEP 10 (2014) 025

Mixing + indirect CPV

$A_\Gamma(D^0 \to hh)$:
JHEP 1204 (2012) 129 (KK), **$+y_{CP}$**
PRL 112 (2014) 041801
JHEP 04 (2015) 043
PRL 118 (2017) 261803

WS $D^0 \to K^+\pi^-$:
PRL 110 (2013) 101802 – 1st SE Obs
PRL 111 (2013) 251801
PRD 95 (2017) 052004
PRD 97 (2018) 031101

Multibody

Direct CPV

$D^0 \to \pi^+\pi^-\pi^0$
PLB 740 (2015) 158

$D^+ \to K^-K^+\pi^+$
PRD 84 (2011) 112008
JHEP 06 (2013) 112

$D^0 \to K^-K^+\pi^-\pi^+$, $\pi^-\pi^+\pi^-\pi^+$:
PLB 726 (2013) 623 (S_{CP})
JHEP 10 (2014) 005 (T-odd)
PLB 769 (2017) 345 (energy test)

$D^+ \to \pi^+\pi^-\pi^+$:
PLB 728 (2014) 585

$\Lambda_c^+ \to p h^+ h^-$
JHEP 03 (2018) 182

Mixing + indirect CPV

$D^0 \to K_S^0 \pi^+\pi^-$
JHEP 04 (2016) 033 (model-indep)

$D^0 \to K^-\pi^+\pi^-\pi^+$
PRL 116 (2016) 241801

https://lhcbproject.web.cern.ch/lhcbproject/Publications/p/LHCb-PAPER-2015-057.html

Direct CPV: state of play:

$D^{\pm}$ CP-VIOLATING DECAY-RATE ASYMMETRIES

$A_{CP}(\mu^{\pm}\nu)$ in $D^+ \to \mu^+\nu_\mu$, $D^- \to \mu^-\overline{\nu}_\mu$	0.08 ± 0.08
$A_{CP}(K_L^0 e^{\pm}\nu)$ in $D^+ \to K_L^0 e^+\nu_e$, $D^- \to K_L^0 e^-\overline{\nu}_e$	-0.006 ± 0.016
$A_{CP}(K_S^0 \pi^{\pm})$ in $D^{\pm} \to K_S^0 \pi^{\pm}$	-0.0041 ± 0.0009 *
$A_{CP}(K^{\mp} 2\pi^{\pm})$ in $D^+ \to K^- 2\pi^+$, $D^- \to K^+ 2\pi^-$	-0.0018 ± 0.0016
$A_{CP}(K^{\mp}\pi^{\pm}\pi^{\pm}\pi^0)$ in $D^+ \to K^-\pi^+\pi^+\pi^0$, $D^- \to K^+\pi^-\pi^-\pi^0$	-0.003 ± 0.007
$A_{CP}(K_S^0 \pi^{\pm}\pi^0)$ in $D^+ \to K_S^0 \pi^+\pi^0$, $D^- \to K_S^0 \pi^-\pi^0$	-0.001 ± 0.007
$A_{CP}(K_S^0 \pi^{\pm}\pi^+\pi^-)$ in $D^+ \to K_S^0 \pi^+\pi^+\pi^-$, $D^- \to K_S^0 \pi^-\pi^-\pi^+$	0.000 ± 0.012
$A_{CP}(\pi^{\pm}\pi^0)$ in $D^{\pm} \to \pi^{\pm}\pi^0$	0.029 ± 0.029
$A_{CP}(\pi^{\pm}\eta)$ in $D^{\pm} \to \pi^{\pm}\eta$	0.010 ± 0.015 (S = 1.4)
$A_{CP}(\pi^{\pm}\eta'(958))$ in $D^{\pm} \to \pi^{\pm}\eta'(958)$	-0.005 ± 0.012 (S = 1.1)
$A_{CP}(\overline{K}^0 / K^0 K^{\pm})$ in $D^+ \to \overline{K}^0 K^+$, $D^- \to K^0 K^-$	0.0011 ± 0.0017
$A_{CP}(K_S^0 K^{\pm})$ in $D^{\pm} \to K_S^0 K^{\pm}$	-0.0011 ± 0.0025
$A_{CP}(K^+K^-\pi^{\pm})$ in $D^{\pm} \to K^+K^-\pi^{\pm}$	0.0037 ± 0.0029
$A_{CP}(K^{\pm}K^{*0})$ in $D^+ \to K^+\overline{K}^{*0}$, $D^- \to K^-K^{*0}$	-0.003 ± 0.004
$A_{CP}(\phi\pi^{\pm})$ in $D^{\pm} \to \phi\pi^{\pm}$	0.0009 ± 0.0019 (S = 1.2)
$A_{CP}(K^{\pm}K_0^*(1430)^0)$ in $D^+ \to K^+\overline{K}_0^*(1430)^0$, $D^- \to K^-K_0^*(1430)^0$	$0.08^{+0.07}_{-0.06}$
$A_{CP}(K^{\pm}K_2^*(1430)^0)$ in $D^+ \to K^+\overline{K}_2^*(1430)^0$, $D^- \to K^-K_2^*(1430)^0$	$0.43^{+0.20}_{-0.26}$
$A_{CP}(K^{\pm}K_0^*(800))$ in $D^+ \to K^+\overline{K}_0^*(800)$, $D^- \to K^-K_0^*(800)$	$-0.12^{+0.18}_{-0.13}$
$A_{CP}(a_0(1450)^0\pi^{\pm})$ in $D^{\pm} \to a_0(1450)^0\pi^{\pm}$	$-0.19^{+0.14}_{-0.16}$
$A_{CP}(\phi(1680)\pi^{\pm})$ in $D^{\pm} \to \phi(1680)\pi^{\pm}$	-0.09 ± 0.26
$A_{CP}(\pi^+\pi^-\pi^{\pm})$ in $D^{\pm} \to \pi^+\pi^-\pi^{\pm}$	-0.02 ± 0.04
$A_{CP}(K_S^0 K^{\pm}\pi^+\pi^-)$ in $D^{\pm} \to K_S^0 K^{\pm}\pi^+\pi^-$	-0.04 ± 0.07
$A_{CP}(K^{\pm}\pi^0)$ in $D^{\pm} \to K^{\pm}\pi^0$	-0.04 ± 0.11

*: main input neglects K_S^0 mixing

D^0 χ^2 TESTS OF CP-VIOLATION (CPV)

Local CPV in $D^0, \overline{D}^0 \to \pi^+\pi^-\pi^0$	4.9×10^{-2}
Local CPV in $D^0, \overline{D}^0 \to \pi^+\pi^-\pi^+\pi^-$	41×10^{-2}
Local CPV in $D^0, \overline{D}^0 \to K_S^0\pi^+\pi^-$	96×10^{-2}
Local CPV in $D^0, \overline{D}^0 \to K^+K^-\pi^0$	16.6×10^{-2}
Local CPV in $D^0, \overline{D}^0 \to K^+K^-\pi^+\pi^-$	9.1×10^{-2}

$D_s^+ - D_s^-$ CP-VIOLATING DECAY-RATE ASYMMETRIES

$A_{CP}(\mu^{\pm}\nu)$ in $D_s^+ \to \mu^+\nu$, $D_s^- \to \mu^-\overline{\nu}_\mu$	0.05 ± 0.06
$A_{CP}(K^{\pm}K_S^0)$ in $D_s^{\pm} \to K^{\pm}K_S^0$	0.0008 ± 0.0026
$A_{CP}(K^+K^-\pi^{\pm})$ in $D_s^{\pm} \to K^+K^-\pi^{\pm}$	-0.005 ± 0.009
$A_{CP}(\phi\pi^{\pm})$ in $D_s^{\pm} \to \phi\pi^{\pm}$	-0.0038 ± 0.0027
$A_{CP}(K^{\pm}K_S^0\pi^0)$ in $D_s^{\pm} \to K^{\pm}K_S^0\pi^0$	-0.02 ± 0.06
$A_{CP}(2K_S^0\pi^{\pm})$ in $D_s^{\pm} \to 2K_S^0\pi^{\pm}$	0.03 ± 0.05
$A_{CP}(K^+K^-\pi^{\pm}\pi^0)$ in $D_s^{\pm} \to K^+K^-\pi^{\pm}\pi^0$	0.000 ± 0.030
$A_{CP}(K^{\pm}K_S^0\pi^+\pi^-)$ in $D_s^{\pm} \to K^{\pm}K_S^0\pi^+\pi^-$	-0.06 ± 0.05
$A_{CP}(K_S^0K^{\mp}2\pi^{\pm})$ in $D_s^{\pm} \to K_S^0K^{\mp}2\pi^{\pm}$	0.041 ± 0.028
$A_{CP}(\pi^+\pi^-\pi^{\pm})$ in $D_s^{\pm} \to \pi^+\pi^-\pi^{\pm}$	-0.007 ± 0.031
$A_{CP}(\pi^{\pm}\eta)$ in $D_s^{\pm} \to \pi^{\pm}\eta$	0.011 ± 0.031
$A_{CP}(\pi^{\pm}\eta')$ in $D_s^{\pm} \to \pi^{\pm}\eta'$	-0.022 ± 0.023
$A_{CP}(\eta\pi^{\pm}\pi^0)$ in $D_s^{\pm} \to \eta\pi^{\pm}\pi^0$	-0.01 ± 0.04
$A_{CP}(\eta'\pi^{\pm}\pi^0)$ in $D_s^{\pm} \to \eta'\pi^{\pm}\pi^0$	0.00 ± 0.08
$A_{CP}(K^{\pm}\pi^0)$ in $D_s^{\pm} \to K^{\pm}\pi^0$	-0.27 ± 0.24
$A_{CP}(\overline{K}^0 / K^0\pi^{\pm})$ in $D_s^+ \to \overline{K}^0\pi^+$, $D_s^- \to K^0\pi^-$	0.004 ± 0.005
$A_{CP}(K_S^0\pi^{\pm})$ in $D_s^{\pm} \to K_S^0\pi^{\pm}$	0.031 ± 0.026 (S = 1.7)
$A_{CP}(K^{\pm}\pi^+\pi^-)$ in $D_s^{\pm} \to K^{\pm}\pi^+\pi^-$	0.04 ± 0.05
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$A_{CP}(\pi^{\pm}\eta'(958))$ in $D^{\pm} \to \pi^{\pm}\eta'(958)$	-0.00[illegible] = 1.1)
$A_{CP}(\overline{K}^{0} / K^{0} K^{\pm})$ in $D^{+} \to \overline{K}^{0} K^{+}$, $D^{-} \to$ [illegible]	0.00[illegible] 0.0017
$A_{CP}(K_S^0\, K^{\pm})$ in $D^{\pm} \to K_S^0\, K^{\pm}$	-0.0[illegible] ± 0.002[illegible]
$A_{CP}(K^{+}K^{-}\pi^{\pm})$ in $D^{\pm} \to K^{+}K^{-}\pi^{\pm}$	0.00[illegible] 0.0029
$A_{CP}(K^{\pm}K^{*0})$ in $D^{+} \to K^{+}\overline{K}^{*0}$, $D^{-} \to K^{-}K^{*0}$	-0.0[illegible] 0.004[illegible]
$A_{CP}(\phi\pi^{\pm})$ in $D^{\pm} \to \phi\pi^{\pm}$	0.0009 [illegible] (S = 1.2)
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$\approx 0 \pm \sigma$

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[illegible]$(K^{+}K^{-}\pi^{\pm}\pi^{0})$ in [illegible] $K^{+}K^{-}$[illegible]	0.000 ± 0.030
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[illegible] $K^{\mp}2\pi^{\pm})$ in $D_s^{+} \to$ [illegible] $2\pi^{\pm}$	0.041 ± 0.028
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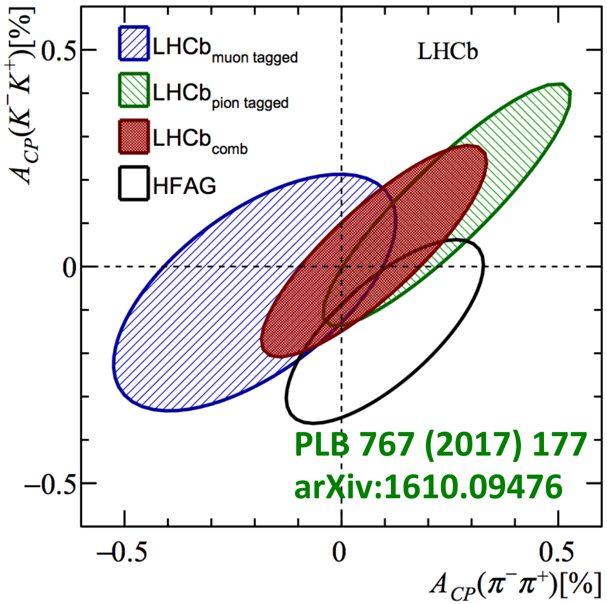
Recent LHCb highlights

Complete set of Run 1 analyses of **ΔA_{CP}**(hh) and **A_{CP}**(hh)

- Prompt and SL-tagged
- Consistent with CP symmetry

Run 2 analyses coming soon…



PLB 767 (2017) 177
arXiv:1610.09476

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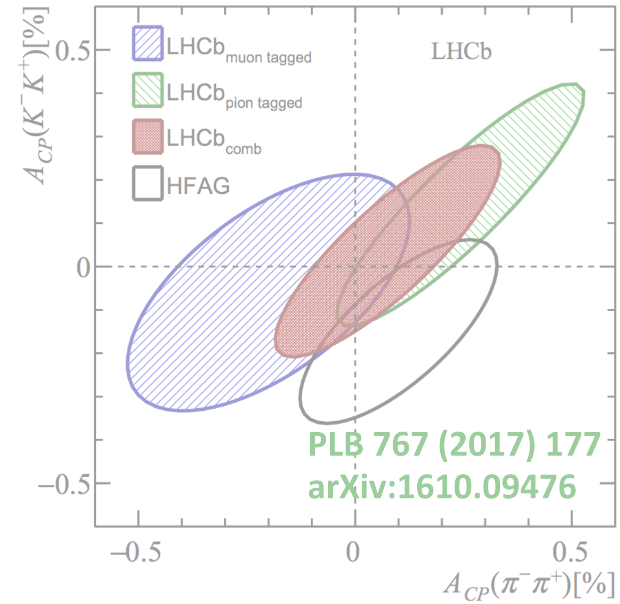

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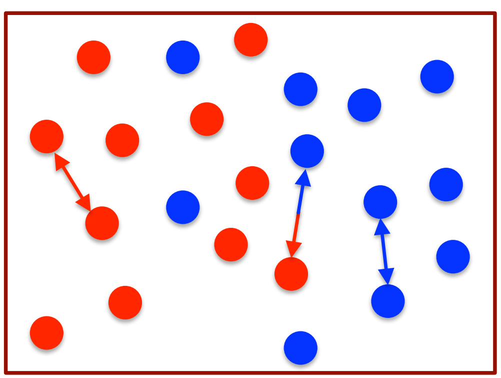
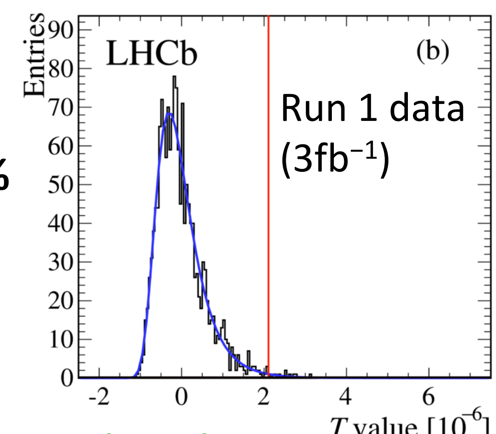
Energy test method to search for local CPV in $\mathbf{D^0 \to \pi^+\pi^-\pi^+\pi^-}$



Triple-products to check P-odd and P-even asymmetries

P-odd CPV: **p-value = (0.6 ± 0.2) %**

Run 2 data being analysed is sensitive to CPV if this effect is real



PLB 769 (2017) 345

$\Delta A_{CP}(\Lambda_c^+ \to p h^+ h^-)$

CPV in charm baryon sector almost unexplored:

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

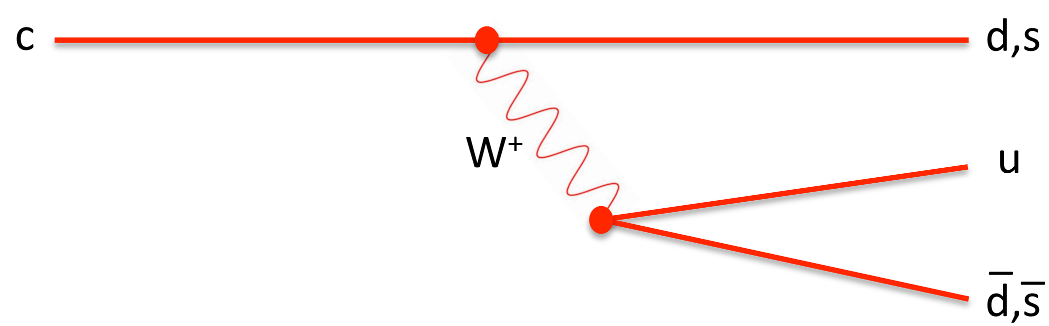
No observation yet of CPV in **charm** hadrons, or in any **baryons** ⇒ obvious place to look.

LHCb has large (and rapidly growing) samples for analysis.

Analysis overview:

$$\Delta A_{CP} = A_{CP}(\Lambda_c^+ \to p K^+ K^-) - A_{CP}(\Lambda_c^+ \to p \pi^+ \pi^-)$$

- SCS decay (analogue of $D^0 \to K^+K^-$ or $\pi^+\pi^-$)



$\Delta A_{CP}(\Lambda_c^+ \rightarrow ph^+h^-)$

CPV in charm baryon sector 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

No observation yet of CPV in **charm** hadrons, or in any **baryons** ⇒ obvious place to look.

LHCb has large (and rapidly growing) samples for analysis.

Analysis overview:

$$\Delta A_{CP} = A_{CP}(\Lambda_c^+ \rightarrow pK^+K^-) - A_{CP}(\Lambda_c^+ \rightarrow p\pi^+\pi^-)$$

- SCS decay (analogue of $D^0 \rightarrow K^+K^-$ or $\pi^+\pi^-$)
- Measure raw yield asymmetries, and correct for remaining detector effects
- Largest instrumental asymmetries cancel in the difference

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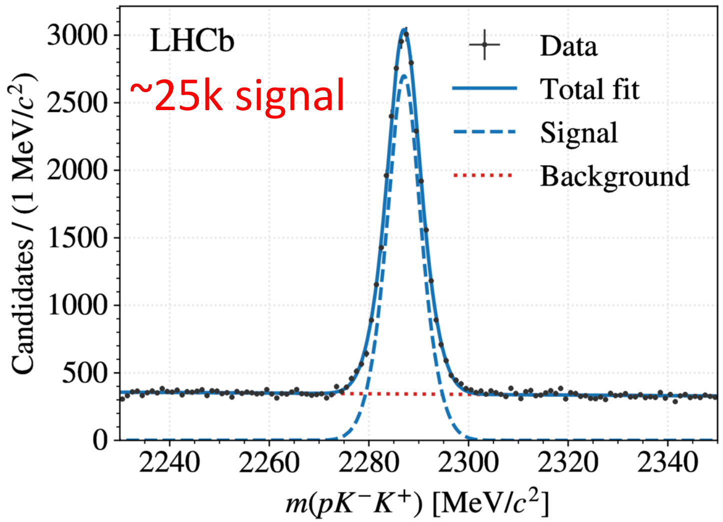
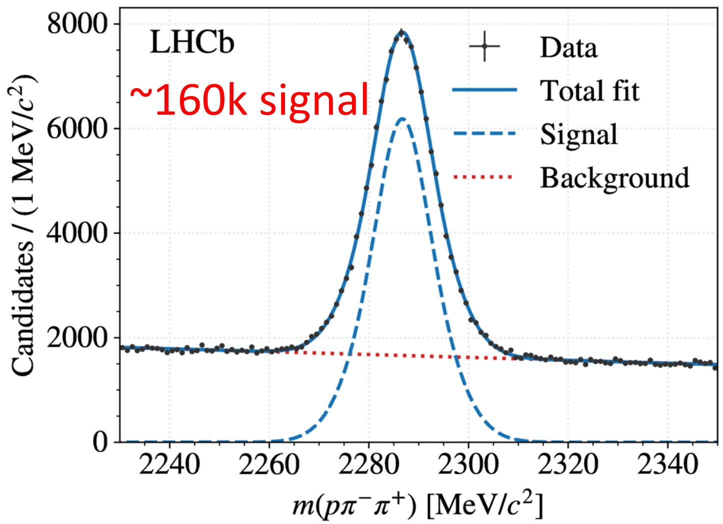
- Measure raw yield asymmetries, and correct for remaining detector effects
- Largest instrumental asymmetries cancel in the difference
- Complications compared to $D^0 \to h^+h^-$:
  - Multibody decay ⇒ multidimensional reweighting and efficiency correction
  - Peaking backgrounds from hadron mis-ID
- For this first analysis of channel, investigate **phase-space integrated CPV**

$\Delta A_{CP}(\Lambda_c^+ \to p h^+ h^-)$

Event selection

- Full Run 1 sample (1fb^{-1} @ 7TeV + 2fb^{-1} @ 8TeV)
- Reconstructed via $\Lambda_b^0 \to \Lambda_c^+ \mu^- X$ process
  $\Rightarrow$ suppress backgrounds from PV
- Cut-based selection criteria (avoid creating kinematic differences between modes)





JHEP 03 (2018) 182

$\Delta A_{CP}(\Lambda_c^+ \to ph^+h^-)$

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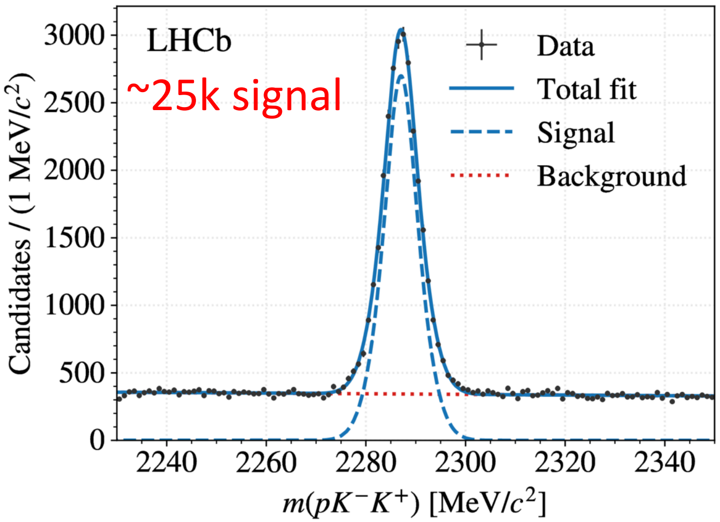
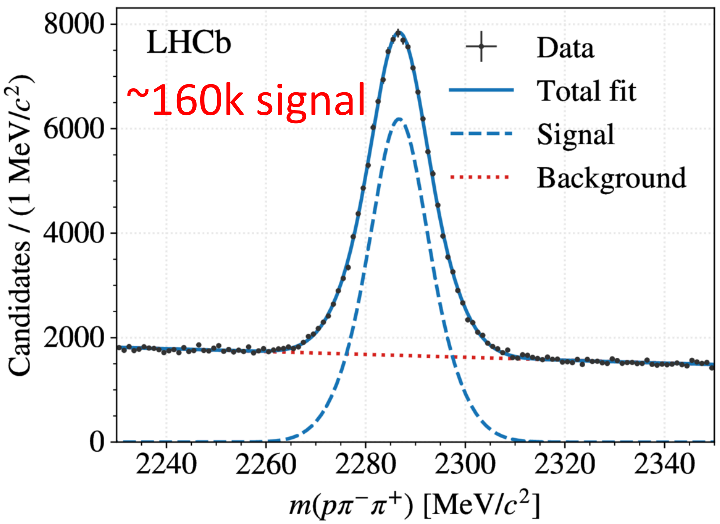
- Full Run 1 sample ($1fb^{-1}$ @ 7TeV + $2fb^{-1}$ @ 8TeV)
- Reconstructed via $\Lambda_b^0 \to \Lambda_c^+ \mu^- X$ process
  ⇒ suppress backgrounds from PV
- Cut-based selection criteria (avoid creating kinematic differences between modes)
- Several peaking backgrounds removed by mass vetoes:
  - $D_{(s)}^+ \to hhh'$ with $h \to p$ mis-ID:
    veto candidates within 8 MeV of $D_{(s)}^+$ mass
  - CF decays $\Lambda_c^+ \to pK_S^0$ and $\Lambda_c^+ \to \Lambda^0 \pi^+$:
    veto based on $M(\pi\pi)$ and $M(p\pi)$





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$\Delta A_{CP}(\Lambda_c^+ \rightarrow p h^+ h^-)$

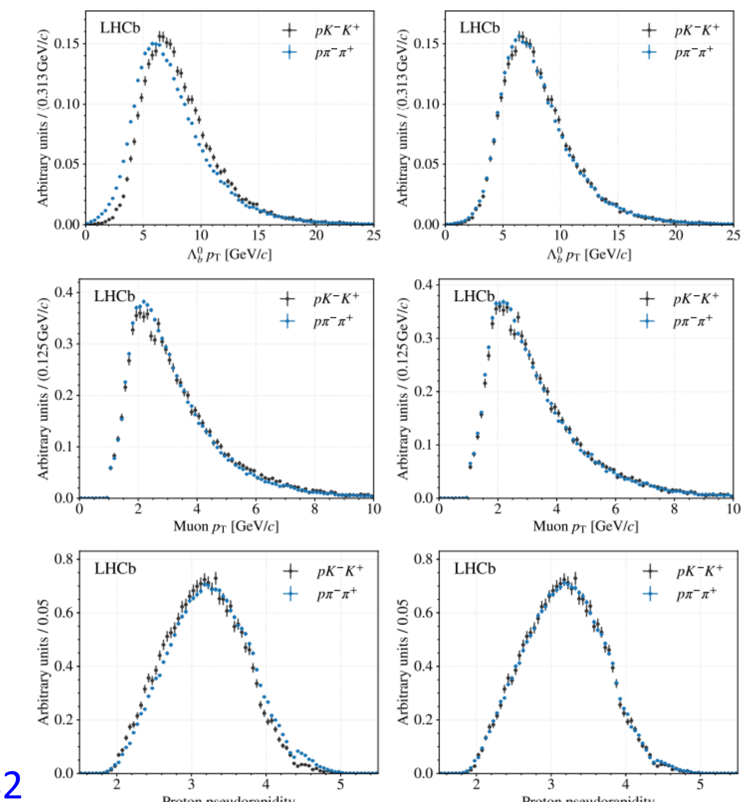
Kinematic and efficiency corrections

(if h^+ , h^- kinematics match)

$$A_{\rm raw}(f) = A_{CP}(f) + \cancel{A_{\rm P}^{\Lambda_b^0}(f\mu)} + \cancel{A_{\rm D}^{\mu}(\mu)} + \cancel{A_{\rm D}^{f}(f)}^{*}$$

Production and detector asymmetries cancel in ΔA_{CP} **for identical mode kinematics**

- Reweight pππ kinematics to match pKK, before extracting raw asymmetries from mass fits
- Machine learning (GBDT) used to derive weights to equalise sample kinematics
  ⇒ gives best matching performance
- Systematic uncertainty for residual differences
- Changes phase-space composition
  ⇒ final ΔA_{CP} is a **weighted average**
  Per candidate weights provided for theoretical interpretation



Reweighting

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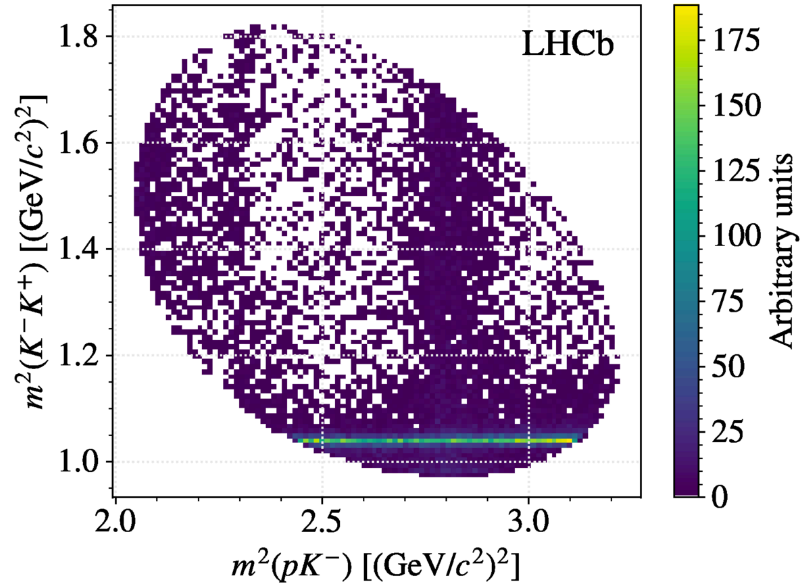
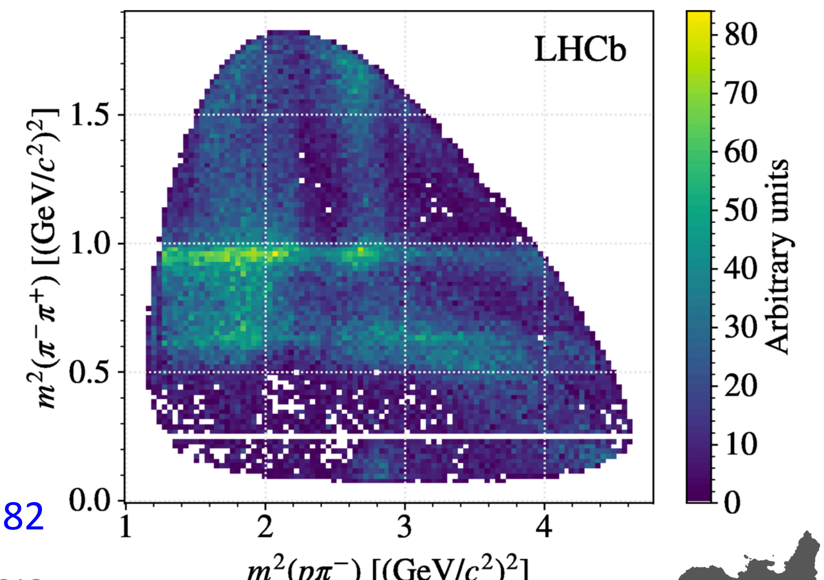
$\Delta A_{CP}(\Lambda_c^+ \to ph^+h^-)$

- Raw asymmetry corrected for efficiency variation across 5D phase-space
  ⇒ From simulation, modelled using GBDT
- Approach validated with pseudo-experiments using randomly-assigned candidate charge
- Systematics dominated by limited precision on efficiency ⇒ from simulation sample size

Source	Uncertainty [%]
Fit signal model	0.20
Fit background model	—
Residual asymmetries	0.10
Limited simulated sample size	0.57
Prompt Λ_c^+	—
Total	0.61





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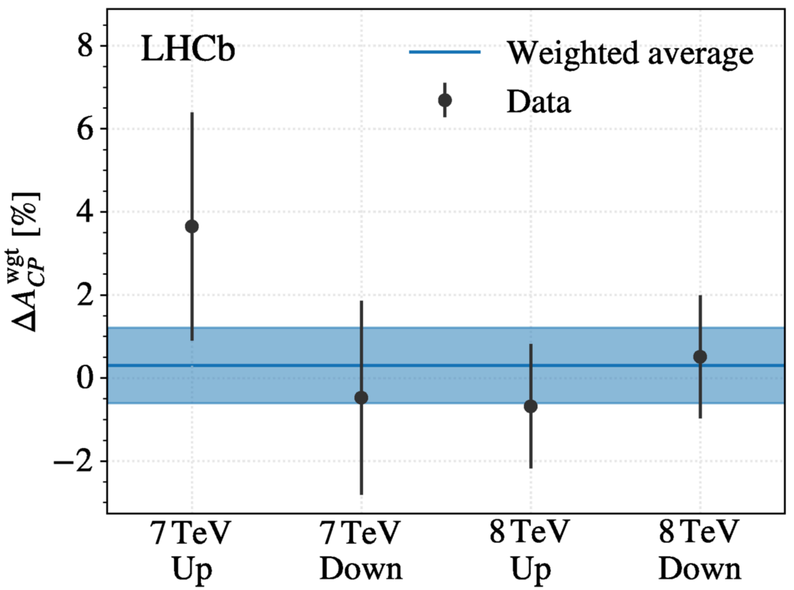


Consistent with CP symmetry

Stable results across data epochs (√s) and magnet polarity

Results

$A_{raw}(pKK) = (3.72 \pm 0.78)\%$
$A_{raw}(p\pi\pi) = (3.42 \pm 0.47)\%$
(σ_{stat} only)

⇒ $\Delta A_{CP} = (0.30 \pm 0.91 \pm 0.61)\%$

LHCb-PAPER-2017-044
arXiv:1712.07051
JHEP 03 (2018) 182

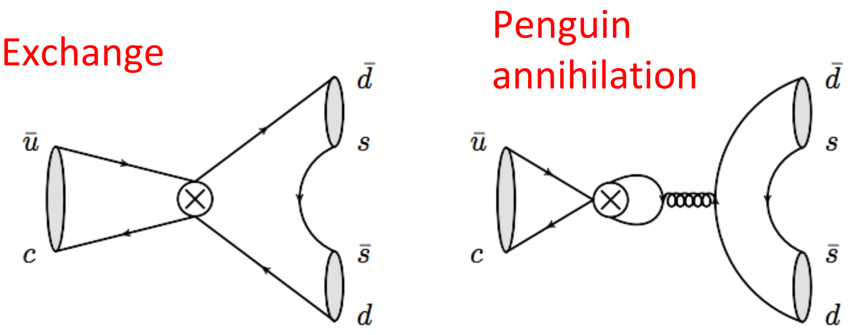
$A_{CP}(D^0 \to K_S^0 K_S^0)$

"Discovery mode" with potentially large CPV

Discovery modes: $D^0 \to K_S K_S$ and $D^0 \to K_S K^{0*}$.

$a_{CP}^{\text{dir}}(D^0 \to K_S K_S) \leq 1.1\%$ $\quad$ $a_{CP}^{\text{dir}}(\overset{(-)}{D} \to K_S K^{*0}) \leq 0.3\%$

S. Schacht, TUPIFP Workshop, Apr 2018
PRD 92 (2015) 054036 (Schacht, Nierste)
https://arxiv.org/abs/1508.00074



CP-conserving component suppressed by SU(3) symmetry
⇒ CPV can be large even if solely due to CKM phase

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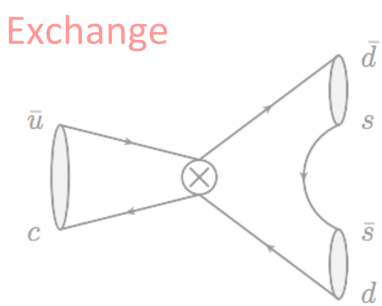
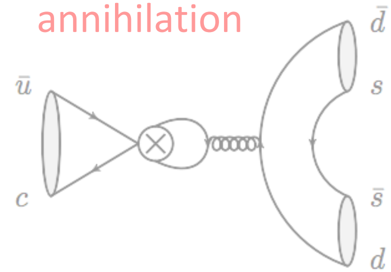




CP-conserving component suppressed by SU(3) symmetry
⇒ CPV can be large even if solely due to CKM phase

A_{CP}	Yield	Year	Collaboration
(-23 ± $\boxed{19}$)%	65 ± 14	2008	CLEO
(-2.9 ± $\boxed{5.2}$ ± 2.2) %	635 ± 74	2015	LHCb Run 1
(-0.02 ± $\boxed{1.53}$ ± 0.17) %	5399 ± 87	2016	Belle

Best measurement from Belle [PRL 119 (2017) 171801]

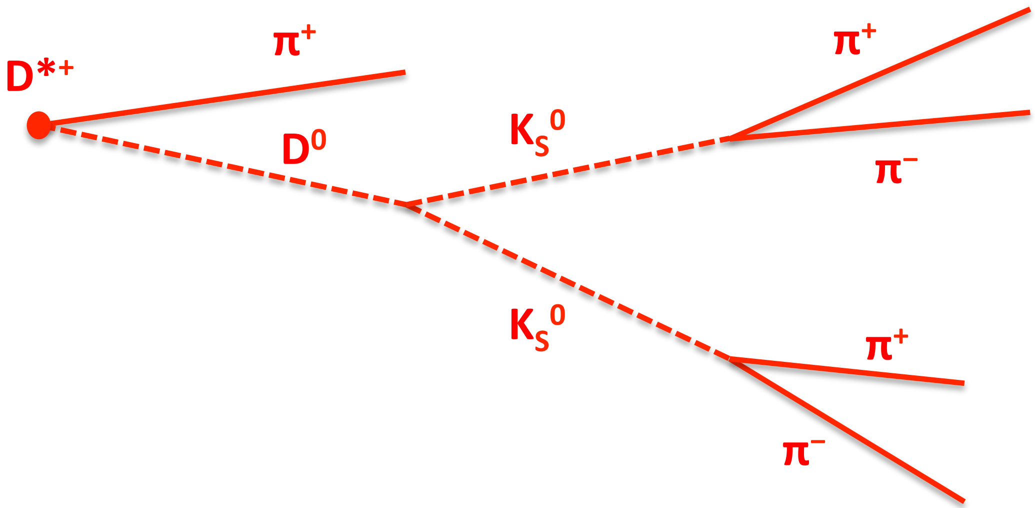
LHCb previously published with Run 1 data [JHEP 10 (2015) 055]

$A_{CP}(D^0 \rightarrow K_S^0 K_S^0)$

"Classical" A_{CP} analysis:

- Fit mass distributions for D^0 and $\bar{D}^0$ to extract raw yields, and time-integrated asymmetry
- Use control channel ($D^0 \rightarrow K^+K^-$) with precisely-known A_{CP} to cancel detector asymmetries
- Selection designed to reduce instrumental effects

Relatively low yields, so statistically limited



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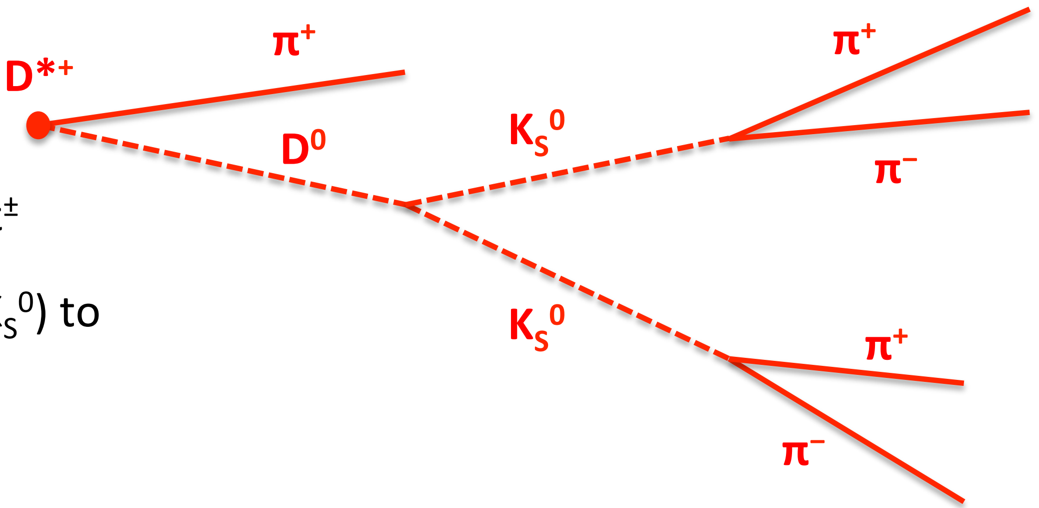
Relatively low yields, so statistically limited

Tag D^0 flavour through promptly produced $D^{*\pm} \to D^0\pi^\pm$

Fit $\delta M = M(K_S^0 K_S^0 \pi^+) - M(K_S^0 K_S^0)$ to extract raw asymmetry



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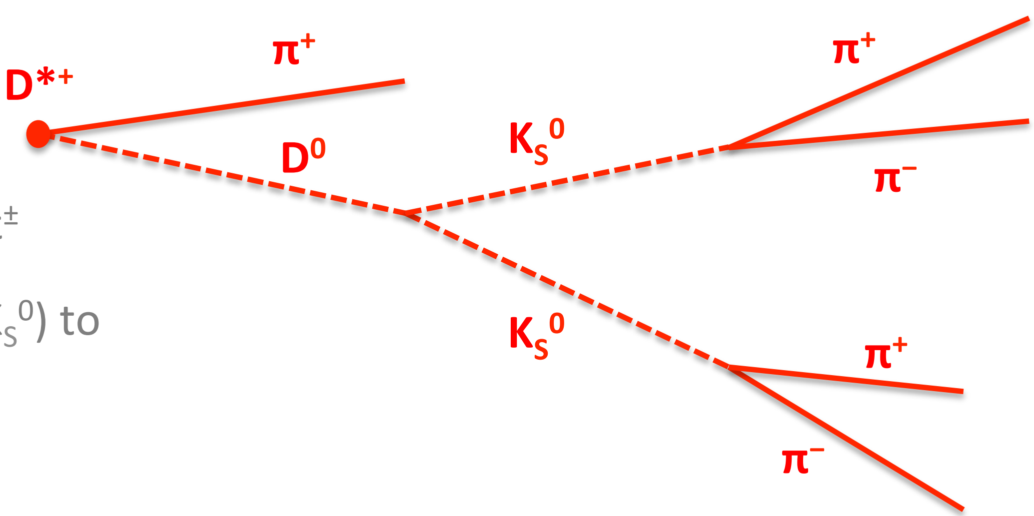


At least one K_S^0 must decay inside Vertex Locator ("Long")
Other K_S^0 can decay outside Vertex Locator("Downstream") ⇒ Two categories LL and LD

$A_{CP}(D^0 \to K_S^0 K_S^0)$

Run 2 data from 2015-2016 (~$2fb^{-1}$)

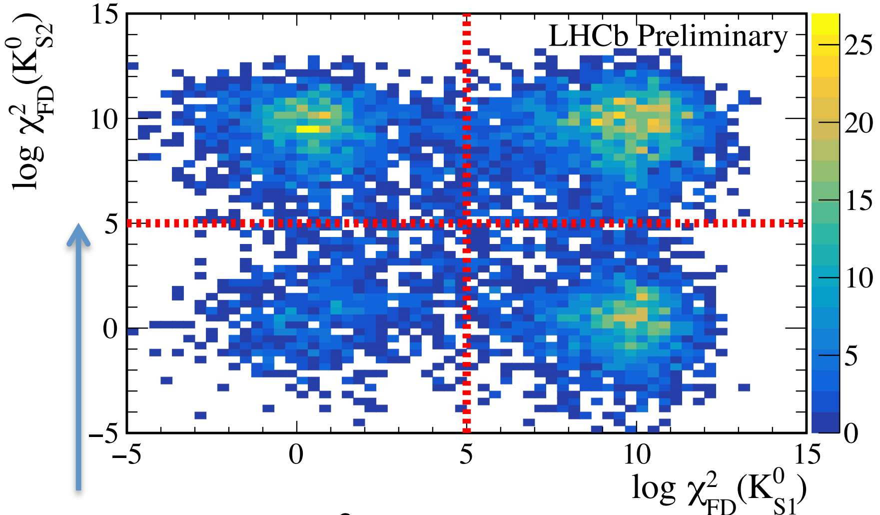
Mainly cut-based selection, with additional optimisation using kNN algorithm

Candidates with soft pion passing through known asymmetric detector regions are excluded

Specific selection requirements to suppress physics backgrounds, e.g.

- $D^0 \to K_S^0 \pi^+ \pi^-$
  [$M(K_S^0)$, and flight distance]

Dominant background is combinatorial



Significance of K_S^0 flight distance

$A_{CP}(D^0 \to K_S^0 K_S^0)$

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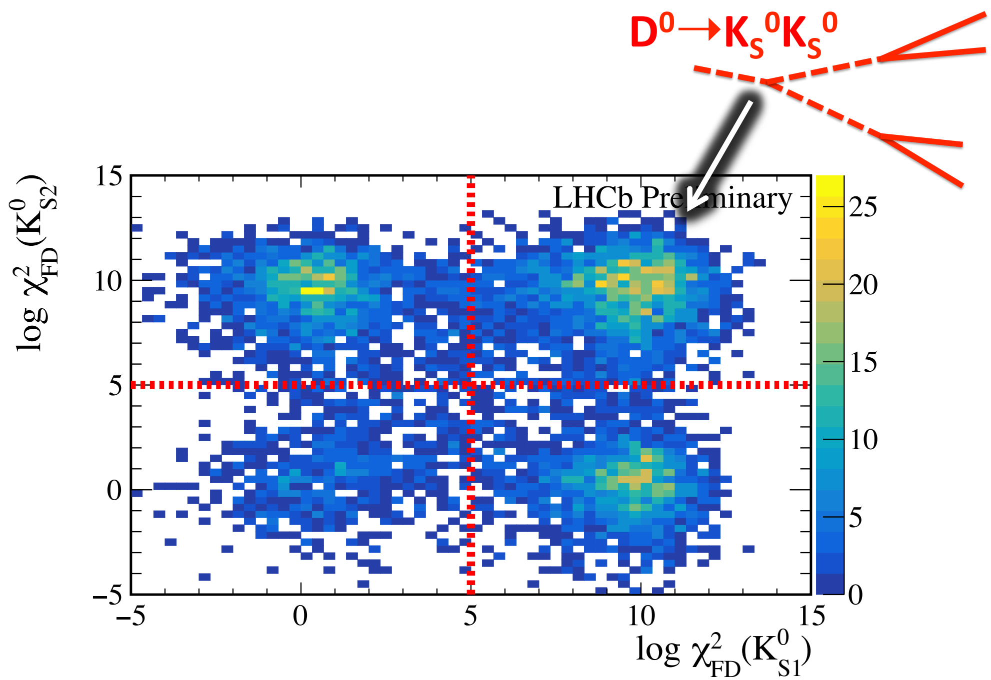

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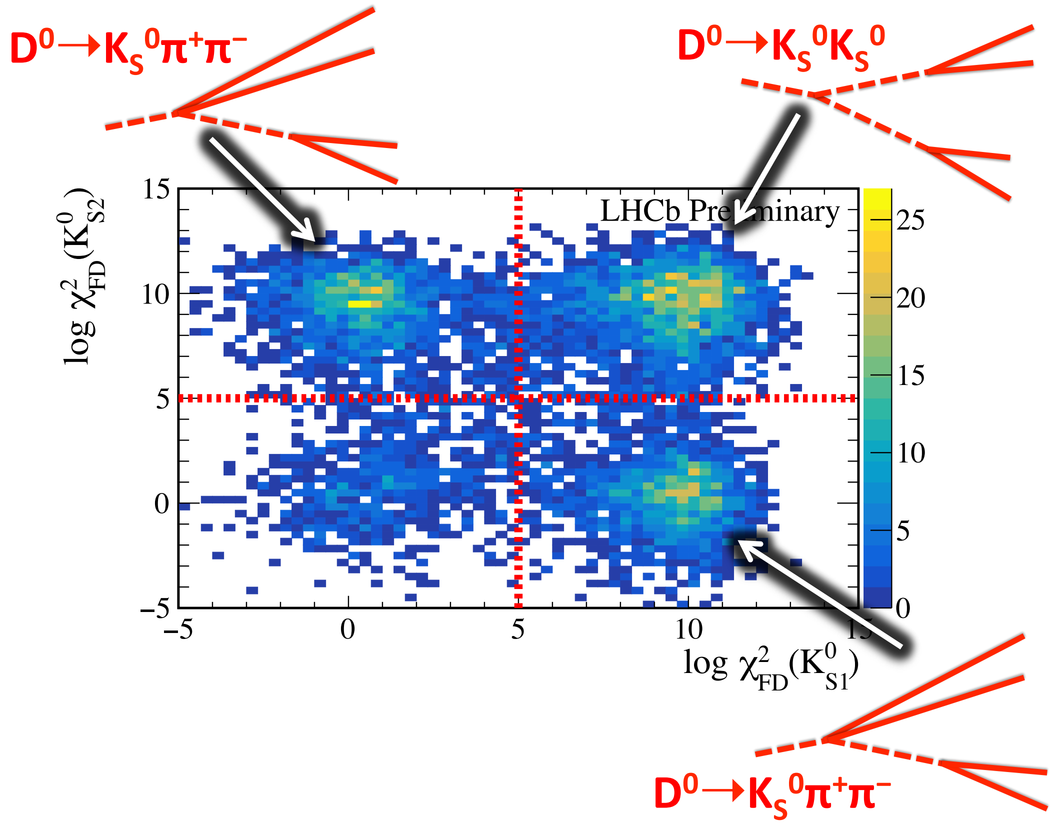

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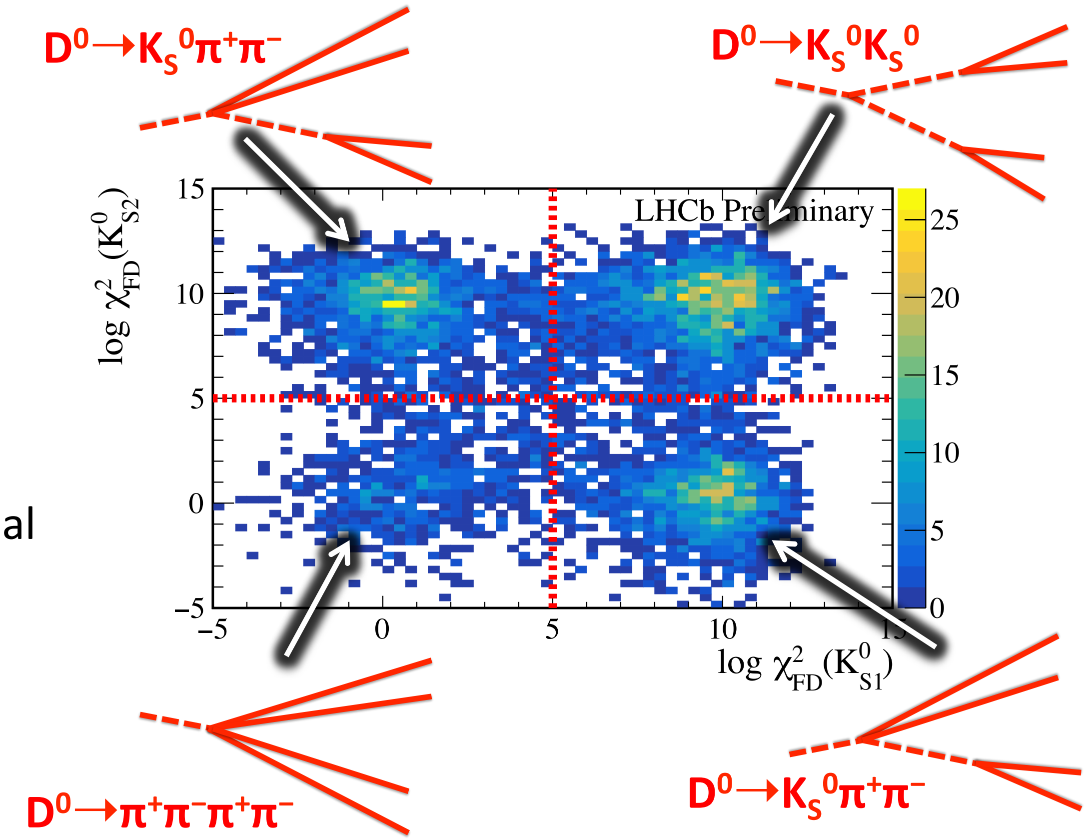


$A_{CP}(D^0 \to K_S^0 K_S^0)$

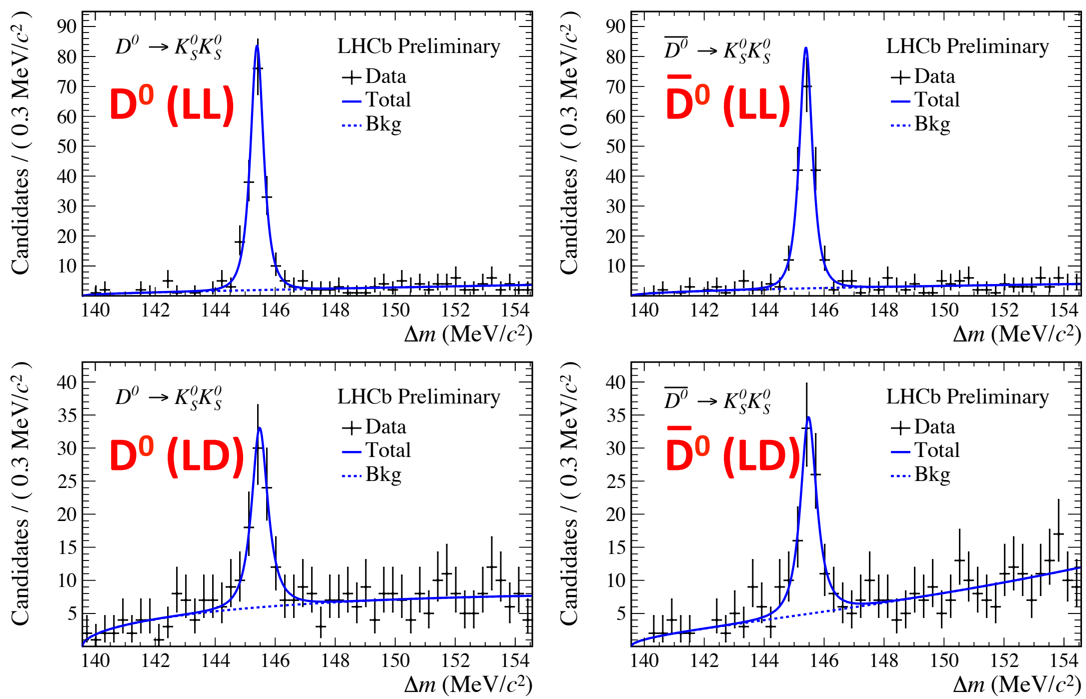
Simultaneous ML fit of D^0 and $\bar{D}^0$ samples used to extract A^{raw}, separately for:

- Signal and control channels
- MagUp / MagDown
- LL / LD K_S^0 types

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

Signal yields ~150-400 per sample
Control yields ~1.3 ×10^6

Example plots for “magnet up” polarity



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

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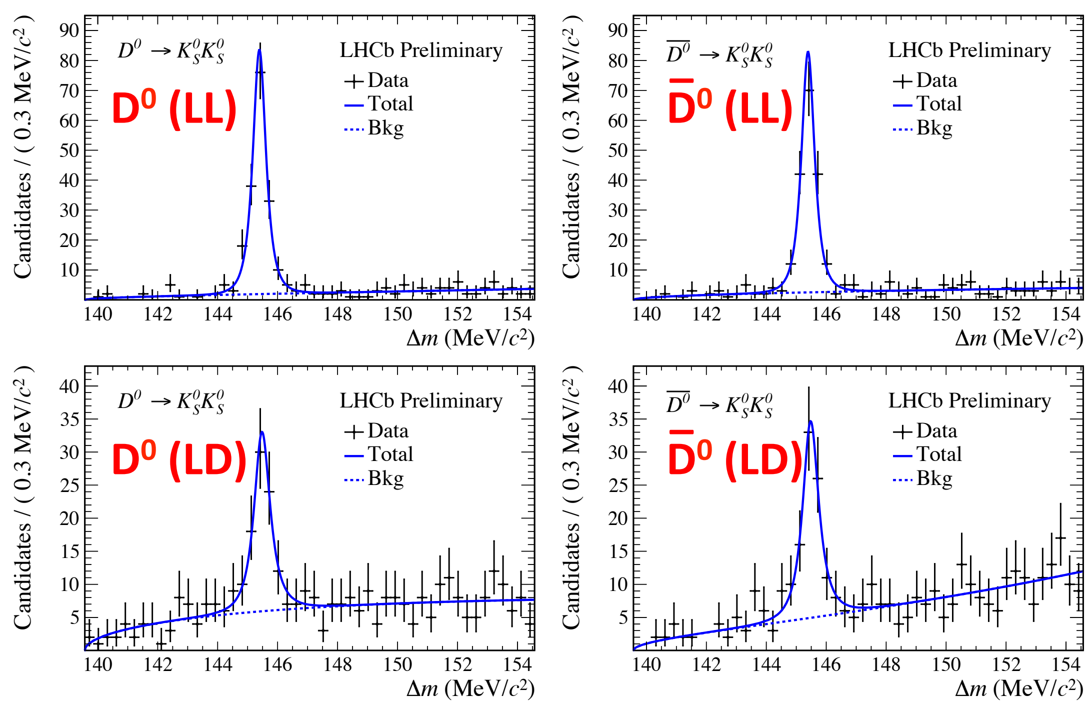


Systematic uncertainties for:

- Fit procedure (5–10 $\times 10^{-3}$)
- $K_S^0\pi\pi$ bkg (4–5 $\times 10^{-3}$)
- $B \to D$ bkg (2–3 $\times 10^{-3}$)
- Trigger (5 $\times 10^{-3}$)
- $D \to KK$ Fit (2 $\times 10^{-3}$)
- Residual A_{det} (2 $\times 10^{-3}$)

$A_{CP}(D^0 \to K_S^0 K_S^0)$

Results

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

A^{raw}(LL MagUp) = (0.8 ± 5.7)%
A^{raw}(LL MagDown) = (10.3 ± 5.2)%

A^{raw}(LD MagUp) = (−4.6 ± 10.2)%
A^{raw}(LD MagDown) = (−7.8 ± 10.7)%

A^{raw}(KK MagUp) = (−1.88 ± 0.20)%
A^{raw}(KK MagDown) = (0.30 ± 0.17)%

ΔA^{CP}(KK) = (0.04 ± 0.12 ± 0.10)%
arXiv:1610.09476

See poster by Giulia Tuci

LHCb-PAPER-2018-012 (in preparation)

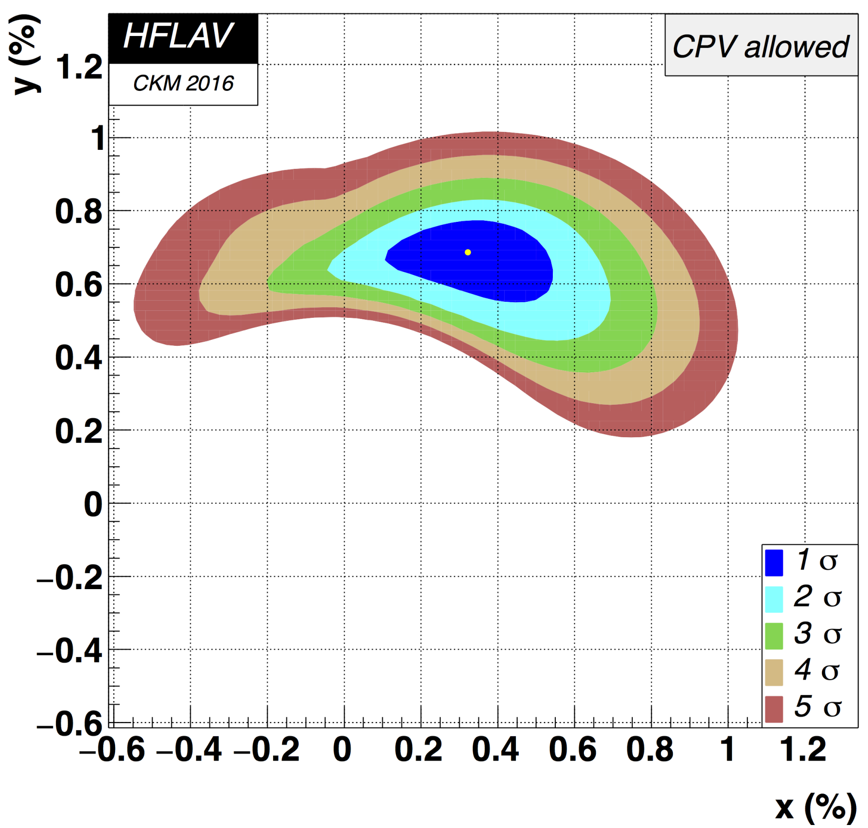
A^{CP}(LL) = (+6.7 ± 3.8 ± 0.9)%
A^{CP}(LD) = (−5.3 ± 7.4 ± 1.3)%

$\xrightarrow{\text{average}}$ $A^{CP}(K_S^0 K_S^0)$ = (+4.2 ± 3.4 ± 1.0)%
(2015-2016, preliminary)

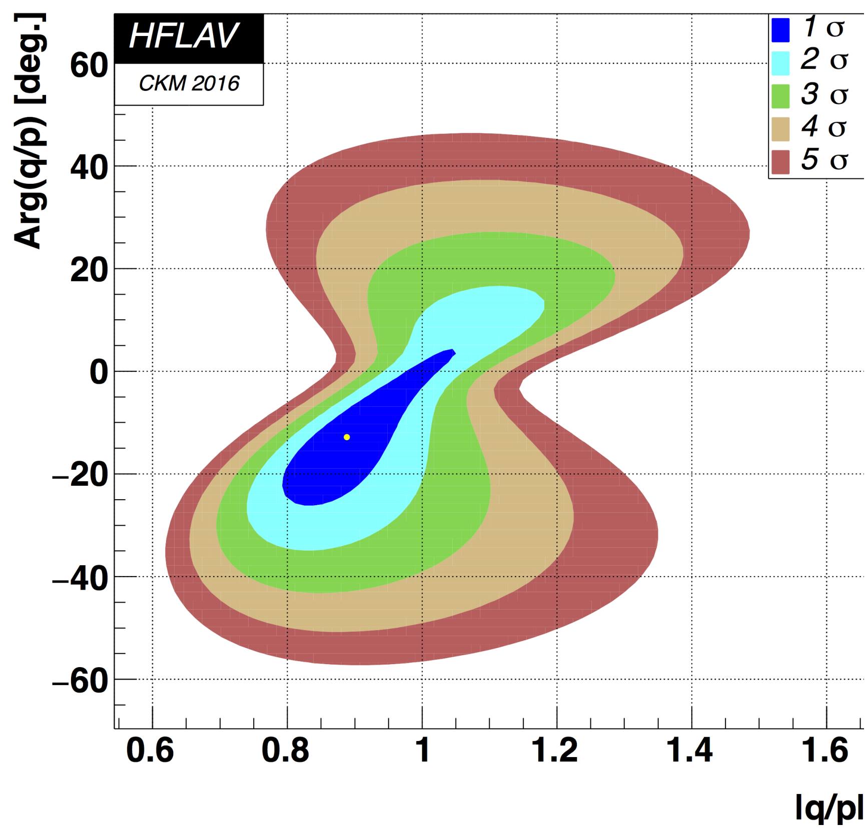
Combining with published Run 1 LHCb analysis: $A^{CP}(K_S^0 K_S^0)$ = (+2.0 ± 2.9 ± 1.0)%
(2011-2016, preliminary)

Mixing and indirect CPV: state of play

y≠0 established (and hence ΔΓ≠0)
No evidence for nonzero x (or Δm)

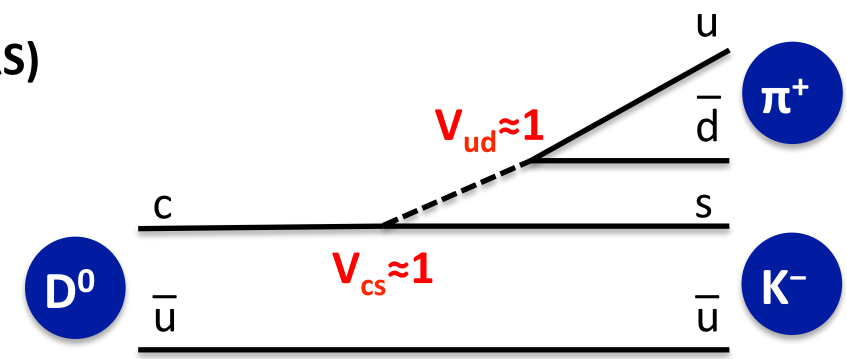


No evidence for CP violation in mixing, or interference **(i.e. q/p≠1)**

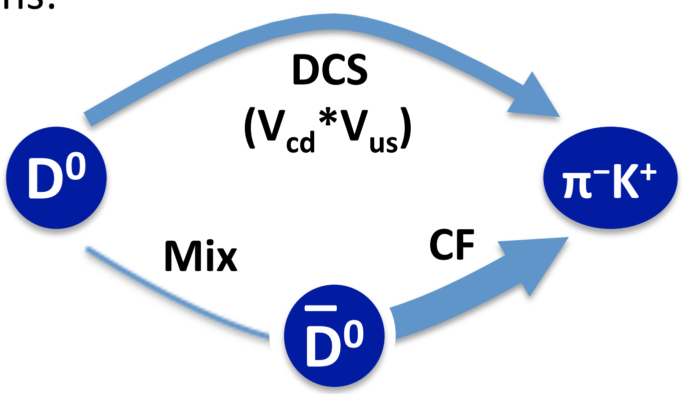


Charm Mixing: "Wrong-sign" $K\pi$

$D^0 \to K^-\pi^+$ dominated by CF decay: **Right-sign (RS)**



Wrong-sign (WS) $D^0 \to \pi^-K^+$ has two possible paths:



Mixing rate is time dependent

⇒ Ratio $\mathbf{R(t) = \Gamma_{WS}(t)/\Gamma_{RS}(t)}$ depends on x and y

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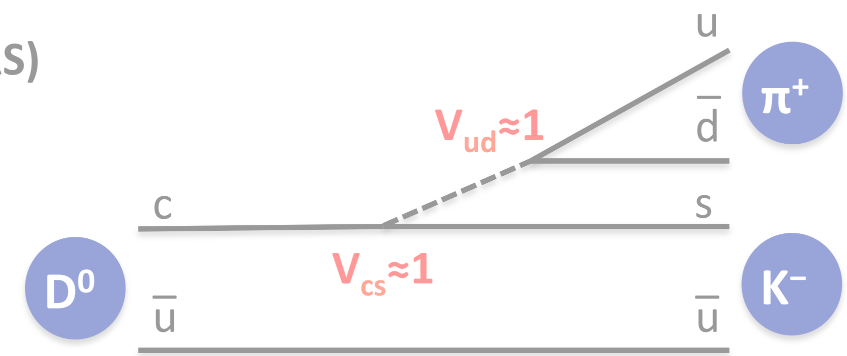

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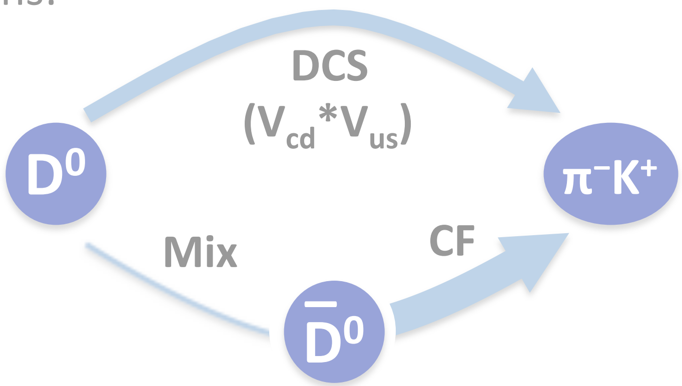

Mixing rate is time dependent

⇒ Ratio $R(t) = \Gamma_{WS}(t)/\Gamma_{RS}(t)$ depends on x and y

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

(Small x,y approximation)

DCS

Interference term

Mix+CF

Charm Mixing: "Wrong-sign" Kπ

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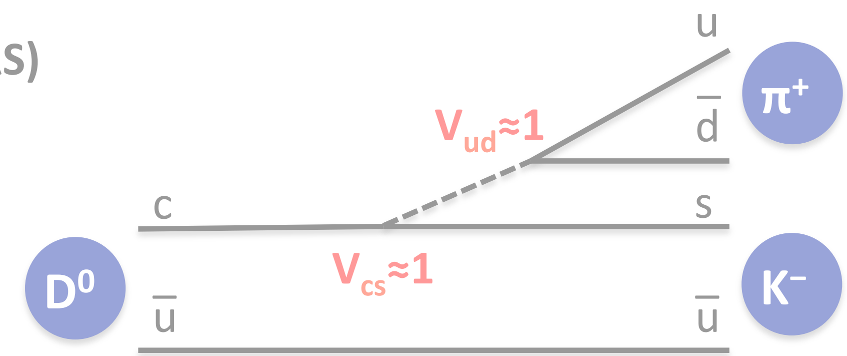

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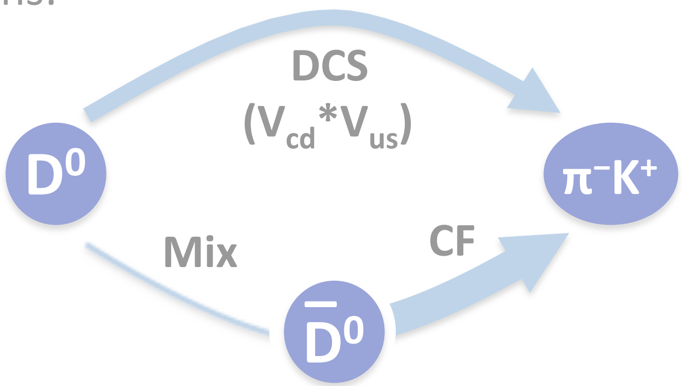

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$$\boxed{R(t) = R_D + \sqrt{R_D}\,y' \left(\frac{t}{\tau}\right) + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2}$$

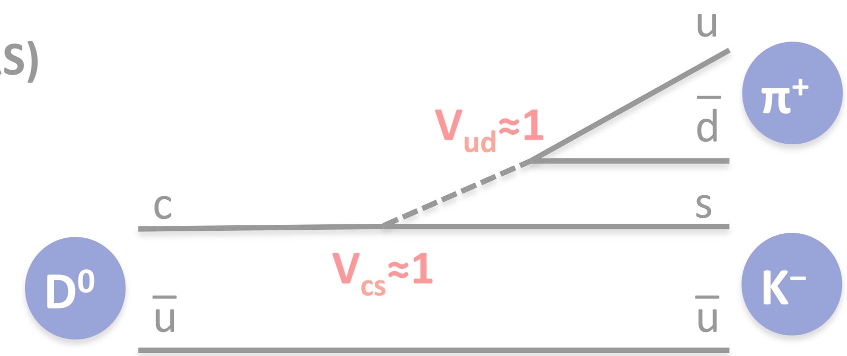
R_D = magnitude squared of DCS/CF amplitudes

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

δ = phase between CF and DCS amplitudes

Charm Mixing: "Wrong-sign" Kπ

$D^0 \rightarrow K^-\pi^+$ dominated by CF decay: **Right-sign (RS)**



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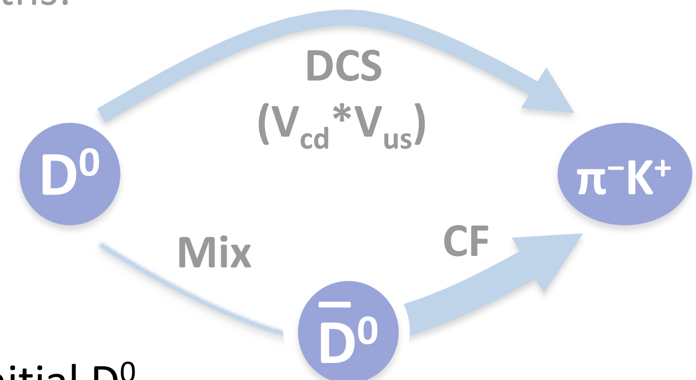

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Initial D^0

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

Initial $\bar{D}^0$

- Indirect CPV: $x'^+ \neq x'^-$ and/or $y'^+ \neq y'^-$
- Direct CPV: $R_D^+ \neq R_D^-$

If $R^+(t) \neq R^-(t)$ ⇒ CP violation

Charm Mixing: "Wrong-sign" Kπ

Experimental precision already dominated by LHCb

Today: first analysis of LHCb **Run 2** data, using prompt **D*-tagged** sample (analyse Run 1+2 ⇒ 5 fb^{-1})

	$R_D\ (10^{-3})$	$y'\ (10^{-3})$	$x'^2\ (10^{-3})$
CDF[1]	3.51 ± 0.35	4.3 ± 4.3	0.08 ± 0.18
Belle[2]	3.53 ± 0.13	4.6 ± 3.4	0.09 ± 0.22
BaBar[3]	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37
LHCb Run 1[4]	3.568 ± 0.066	4.8 ± 1.0	-0.055 ± 0.049

[1]CDF: PRL 111 (2013) 231802
[2]Belle: PRL 112 (2014) 111801
[3]BaBar: PRL 98 (2007) 211802
[4]LHCb: PRL 111,251801 (2013)

As statistical precision improves, need to consider increasingly-small effects from instrumental asymmetries and backgrounds

$$\frac{N^{\pm}_{WS}(t)}{N^{\pm}_{RS}(t)} = R^{\pm}\,\frac{(1 \pm A_P^{D^*})}{(1 \pm A_P^{D^*})}\,\frac{\varepsilon(\pi_s^{\pm})}{\varepsilon(\pi_s^{\pm})}\,\frac{\varepsilon(K^{\pm}\pi^{\mp})}{\varepsilon(K^{\mp}\pi^{\pm})}$$

Raw signal yields
⇒Determined from δM fit in bins of t(D^0)

Underlying physical quantity to be measured

Nuisance asymmetries cancel, except for **K$^{\mp}$π$^{\pm}$** detection asymmetry

Charm Mixing: "Wrong-sign" $K\pi$

Detection asymmetry $\mathbf{A^{K\pi}}$ determined from control channels:

$$A_{raw}(\mathbf{D^+ \rightarrow K^- \pi^+ \pi^+}) - A_{raw}(\mathbf{D^+ \rightarrow K^0 \pi^+}) = \mathbf{A^{K\pi}} - \mathbf{A^{K^0}}$$

Known from previous LHCb measurement [JHEP 07 (2014) 041]

Kinematics reweighted to ensure cancellation of other asymmetries (production, π_{trig}, …)

Charm Mixing: "Wrong-sign" Kπ

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Kinematics reweighted to ensure cancellation of other asymmetries (production, π_{trig}, …)

Identify and suppress **problematic backgrounds**, e.g.:

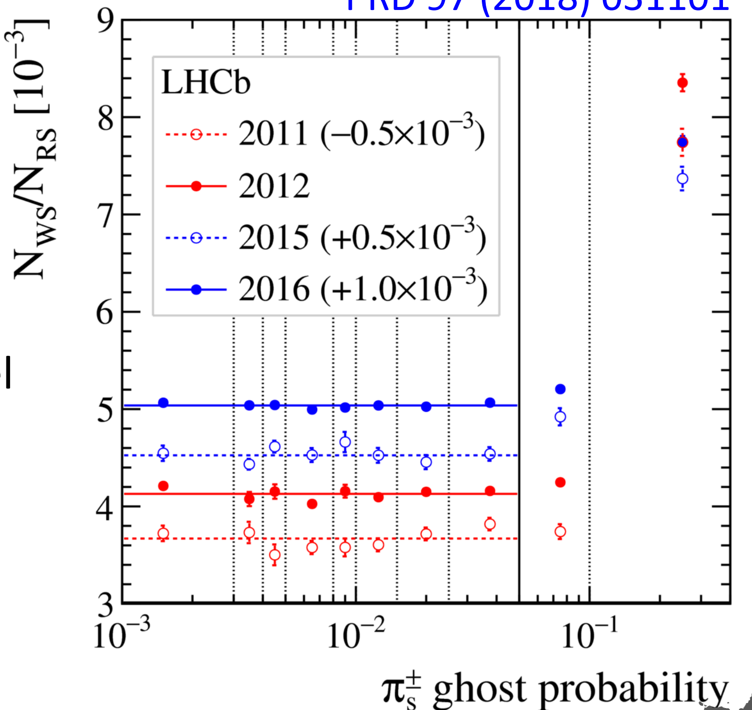
'Ghost' pions from mis-matched track segments before/after magnet

⇒ Can peak in signal δM region

⇒ Wrong charge ~50% of time: **RS→WS migration**

Cut on dedicated variable to suppress to negligible level

PRD 97 (2018) 031101



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Backgrounds from **mis-ID** of D^0 children (~0.5%) and **B→D** contamination (3–10%) remain after final selections

⇒ Account for effect of residual backgrounds in fit

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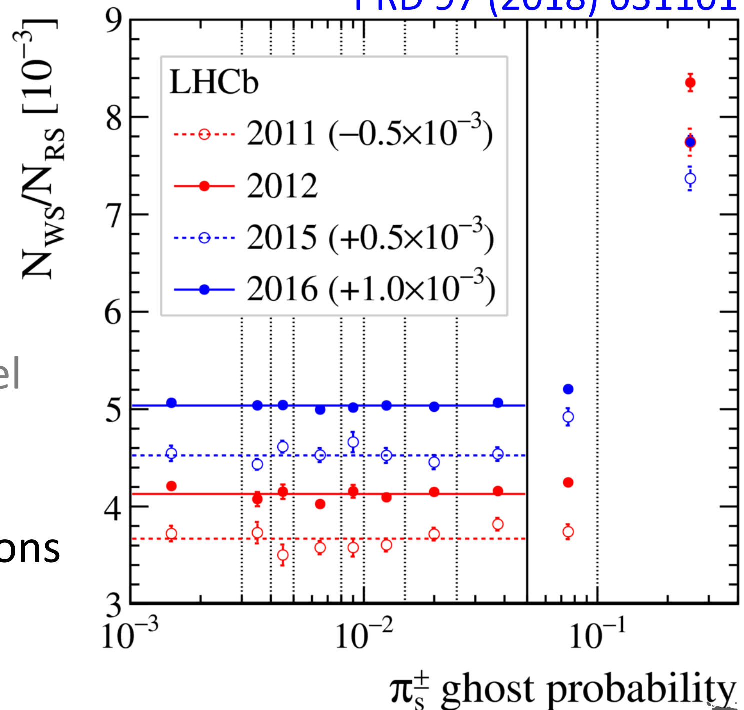

Charm Mixing: “Wrong-sign” Kπ

$R^{\pm}$ determined in **13 decay-time bins** (from δM fit)

Decay-time fit includes bin-specific corrections for Kπ asymmetry, B→D, mis-ID backgrounds

Fit validated by comparing time-integrated WS/RS ratio for pairs of disjoint samples

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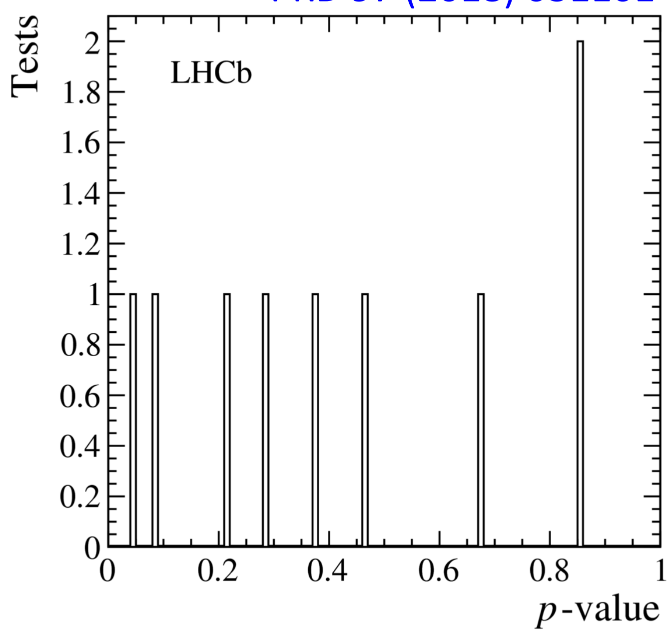
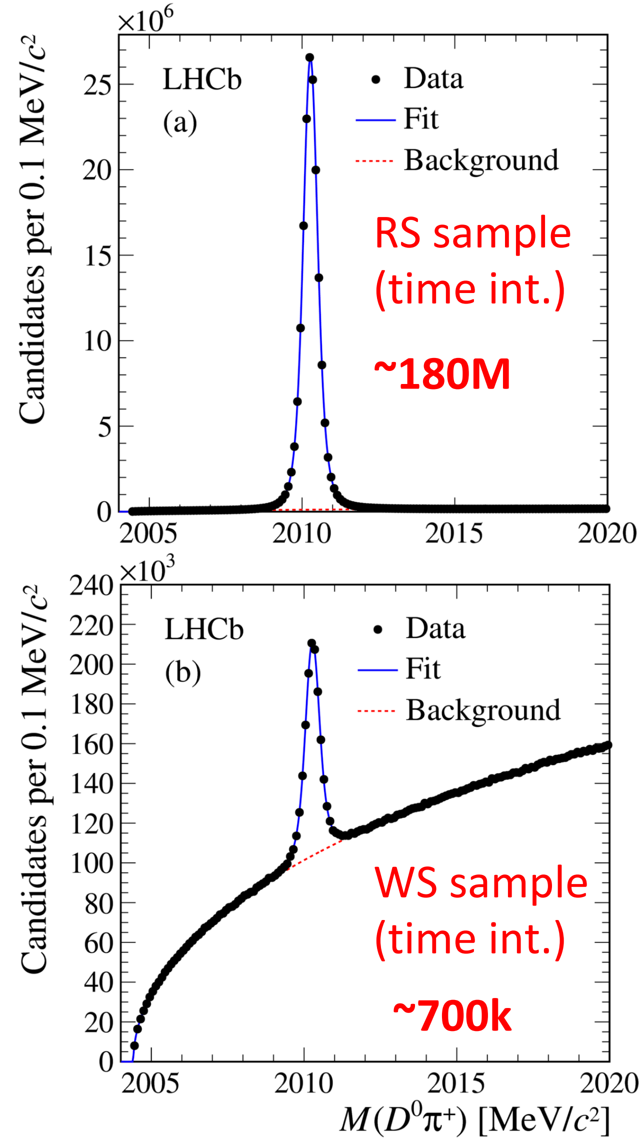
(e.g. split by year, magnet polarity, trigger type, kinematics, …)

⇒ consistent with uniform p-value distribution





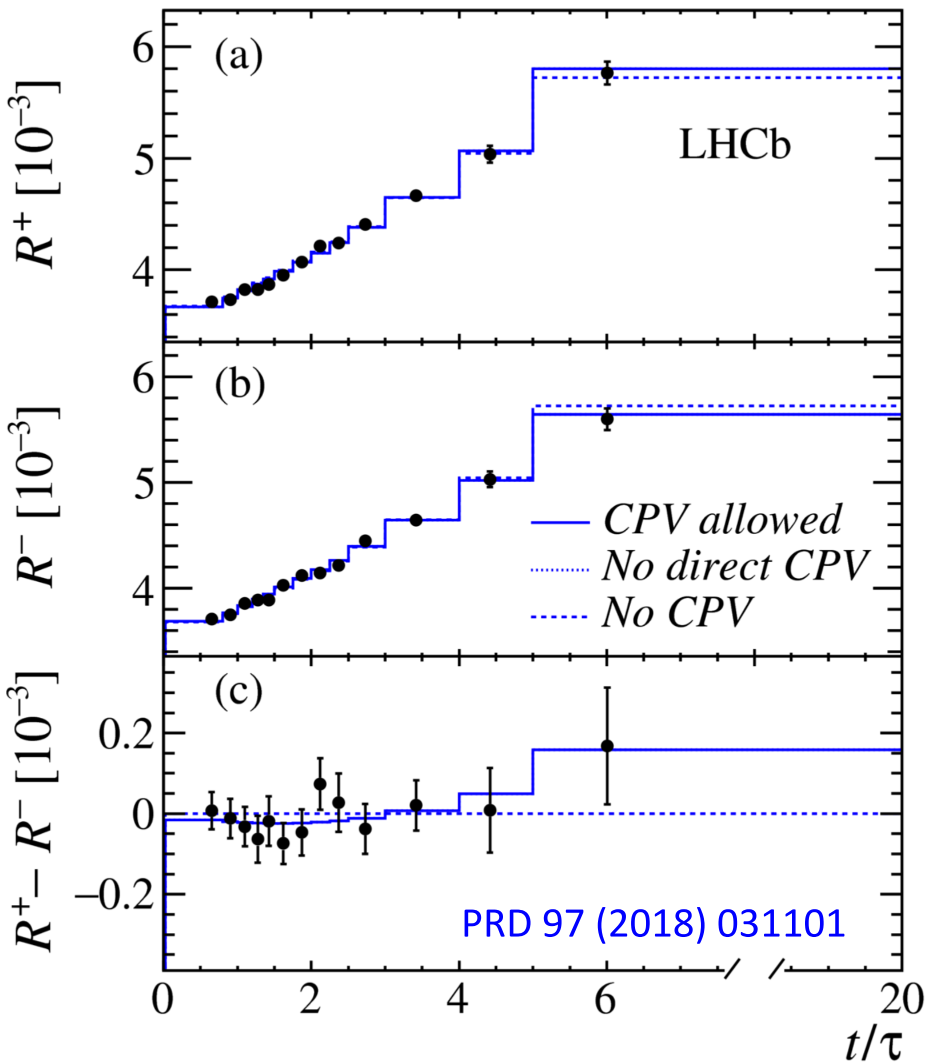
Charm Mixing: “Wrong-sign” Kπ

Systematic uncertainty ~50% of statistical precision
Dominated by limited knowledge of B→D contamination

Results:

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

⇒ No evidence of direct CPV



PRD 97 (2018) 031101

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Results:

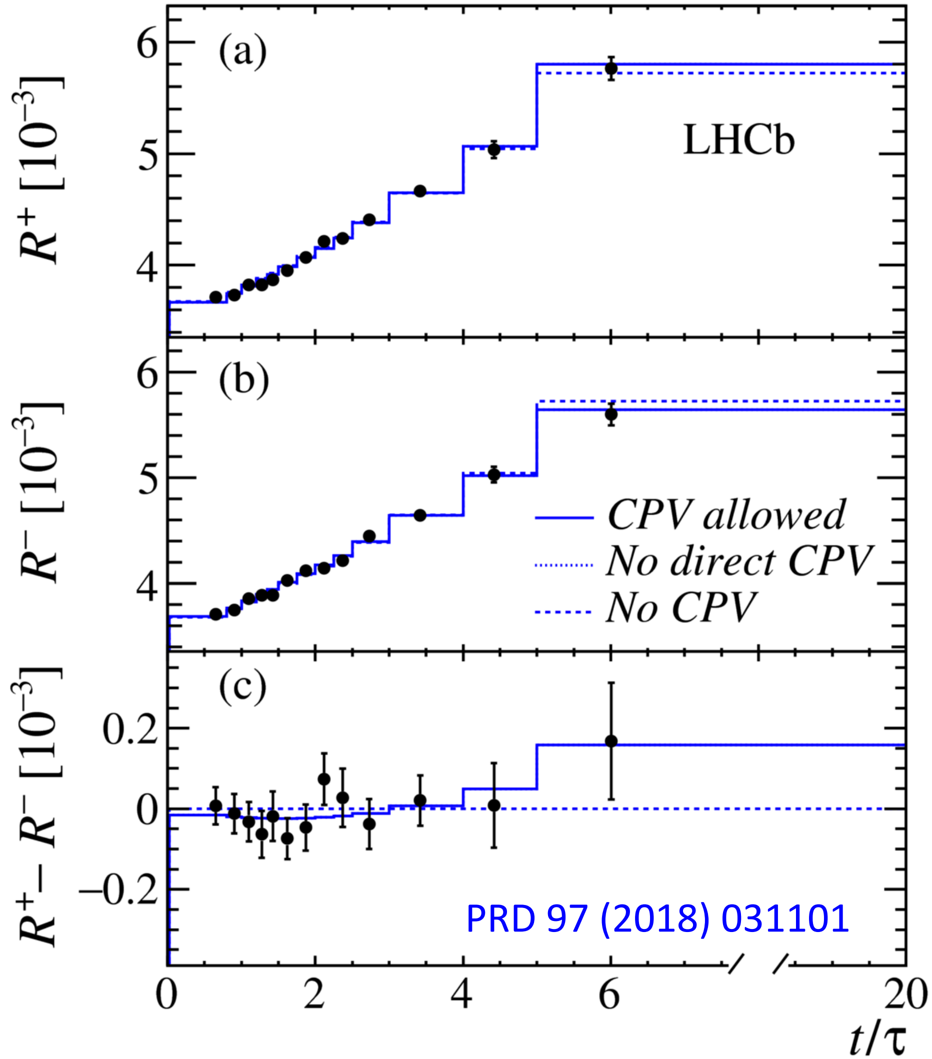
$$A_D \equiv \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.1 \pm 8.1 \pm 4.2) \times 10^{-3}$$

$y' = (5.28 \pm 0.45 \pm 0.27) \times 10^{-3}$

$x'^2 = (3.9 \pm 2.3 \pm 1.4) \times 10^{-5}$

(assuming CP symmetry)

⇒ Most precise measurements of mixing parameters



PRD 97 (2018) 031101

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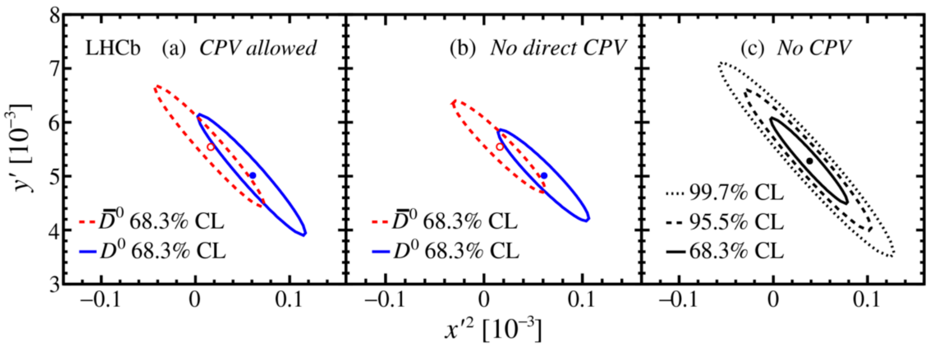

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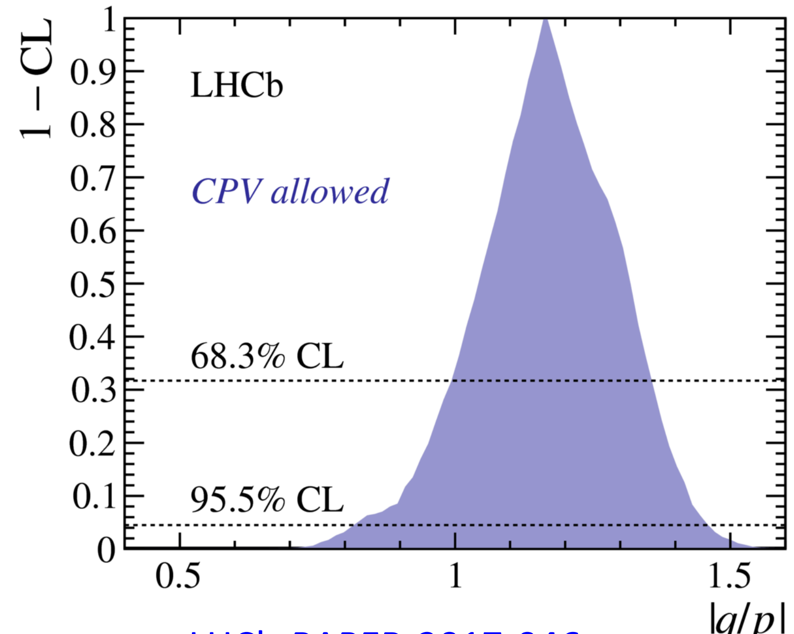
$1.00 < |q/p| < 1.35$ @ 68.3% CL
$0.82 < |q/p| < 1.45$ @ 95.5% CL

⇒ Results consistent with CP symmetry



LHCb-PAPER-2017-046
arXiv:1712.03220
PRD 97 (2018) 031101

Summary and outlook

The search continues for CP violation in the charm system at LHCb…

- Huge (growing!) samples ⇒ use latest triggering and simulation techniques
- Rely on high-precision measurements in CF control channels
- Measurements still statistically limited, and reaching 10^{-3} level
- Many systematics also scale inversely with sample size
  (control sample reweighting, data-driven background modelling, …)
- Charm baryon CPV programme in early stages ⇒ rich phase-space to explore

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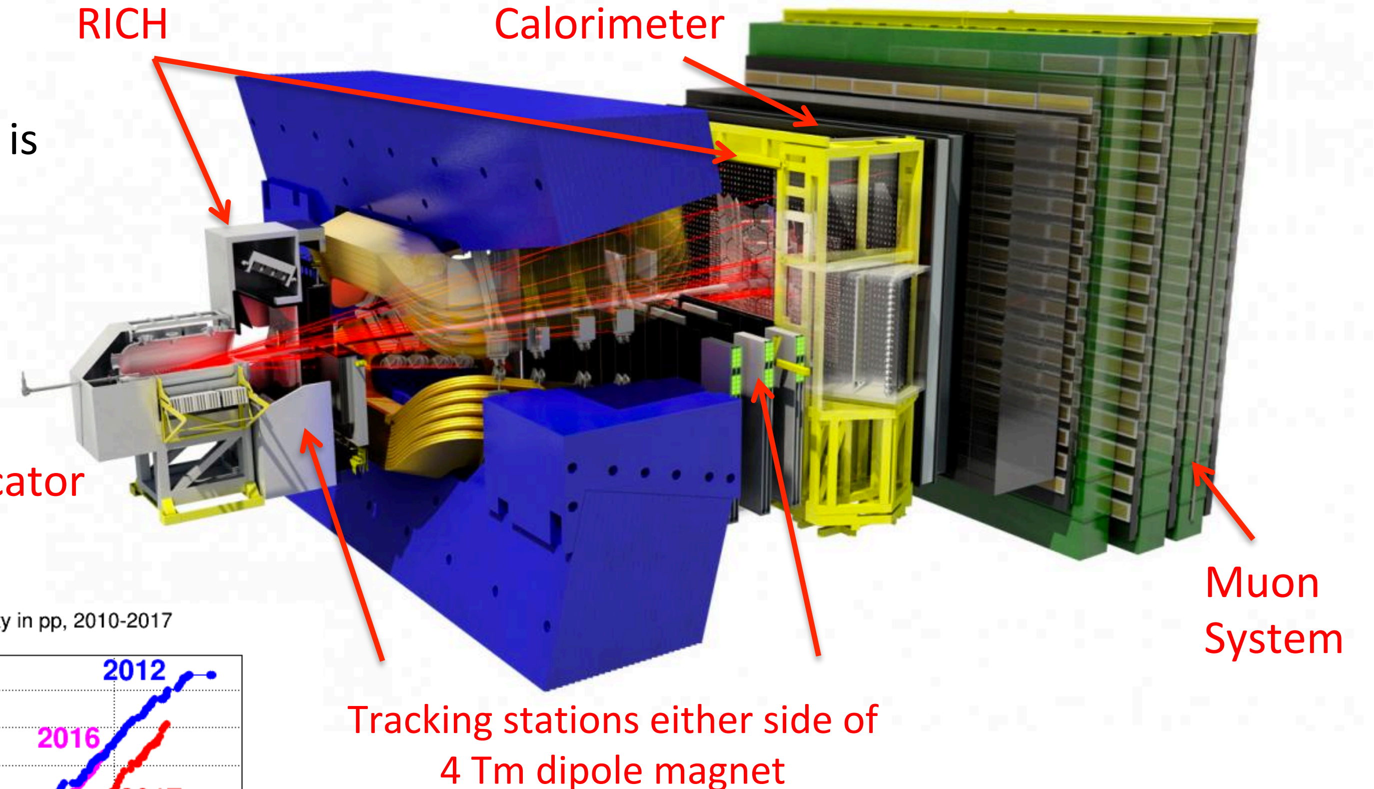
Run 2 and beyond offers significant opportunity for charm physics

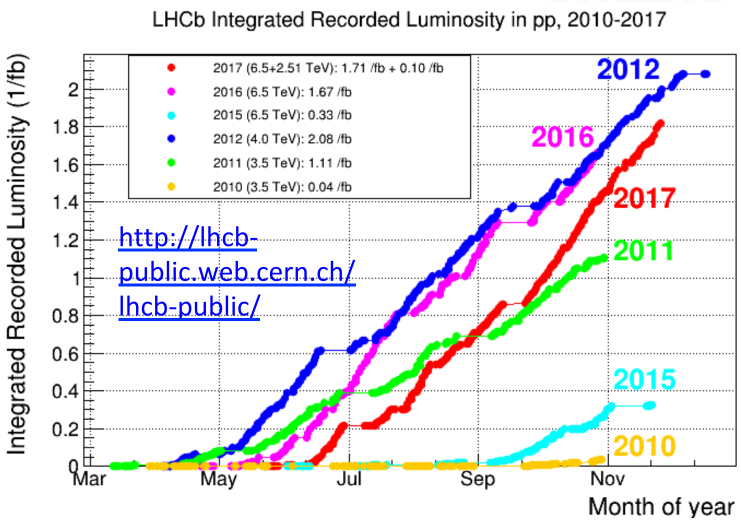
- Run 2: ×2 yield from trigger gains
- ≥Run 3: Upgraded detector – full event reconstruction at all trigger levels, & better vertex resolution (+ additional 5x luminosity)
- Much more to come! Stay tuned.

Extra Slides

CPV in charm @ LHCb

A beauty experiment that is also copiously charming





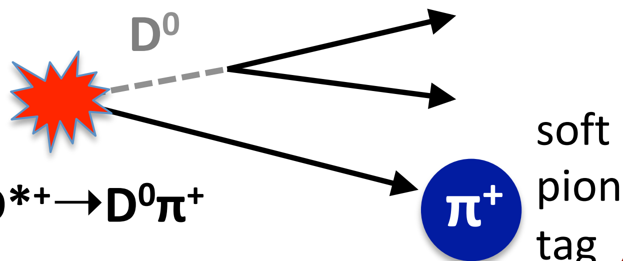
So far, collected 3.0 fb^{-1} (Run 1, 2011-2012)
+ 3.7 fb^{-1} (Run 2, 2015-2017)

Aim for 9 fb^{-1} by end of Run 2

Common themes: tagging charm

Complementary samples

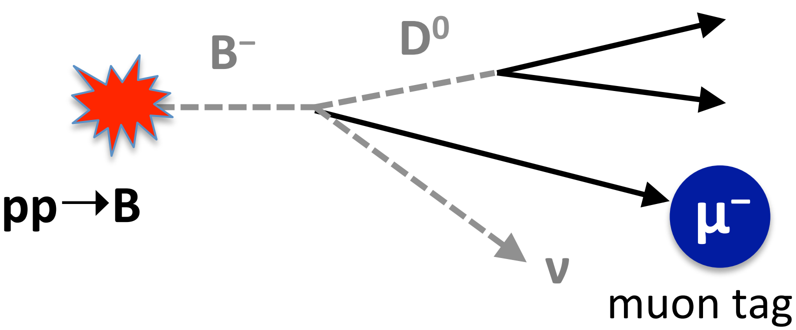
π-tagged ("prompt charm")



Lifetime-biasing trigger
⇒ must apply correction in analysis.

Narrow reconstructed D* peak
⇒ **High signal purity**

μ-tagged ("charm from B")



Lifetime unbiased trigger selection

No $D^{*\pm}$ mass peak to cut on
⇒ **higher backgrounds**

+ Double-tagged:
$(B^0 \to \mu^-\nu X)D^{*+} \to \pi^+ D^0$
Best of both worlds (but lower yields)

CPV in mixing: $A_\Gamma(KK)$, $A_\Gamma(\pi\pi)$

For small x,y, CP asymmetry of D^0 decay rates are 1st order in time:

$$A_{CP}(t) = \frac{\Gamma(D^0(t)\to f) - \Gamma(\overline{D}^0(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\overline{D}^0(t)\to f)} \simeq a_d - A_\Gamma \frac{t}{\tau_D}$$

CPV in decay

CPV in mixing/interference

$A_\Gamma = f(x, y, q, p)$

⇒ Extract A_Γ by fitting $A_{CP}(t)$ to straight line

- Two complementary methods ("binned" vs "unbinned")
- Run 1, π-tagged sample
- $D^0 \rightarrow K^-\pi^+$ used to validate methods

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Main challenge:

Detector **asymmetries**

non-uniform decay time acceptance

Candidate **kinematics**

⇒ biased A_Γ measurement

CPV in mixing: $A_\Gamma(KK)$, $A_\Gamma(\pi\pi)$

Unbinned Results (8 TeV only):

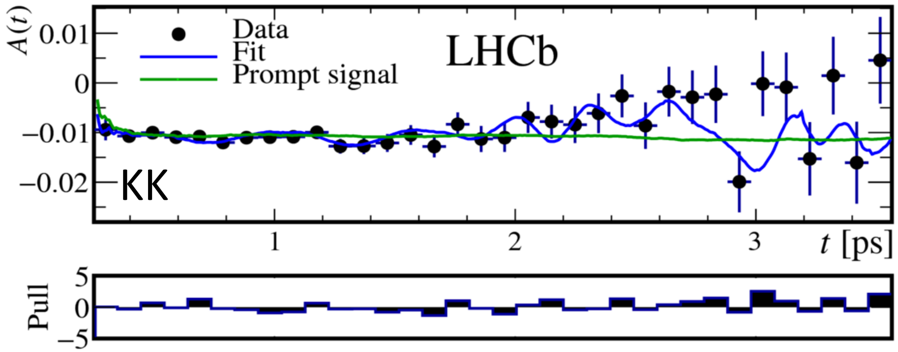
$A_\Gamma(K^+K^-) = (-0.03 \pm 0.46 \pm 0.10) \times 10^{-3}$

$A_\Gamma(\pi^+\pi^-) = (+0.03 \pm 0.79 \pm 0.16) \times 10^{-3}$

Combine with published 7 TeV result to determine Run 1 average (KK + ππ):

$A_\Gamma = (-0.07 \pm 0.34) \times 10^{-3}$

PRL 118 (2017) 261803



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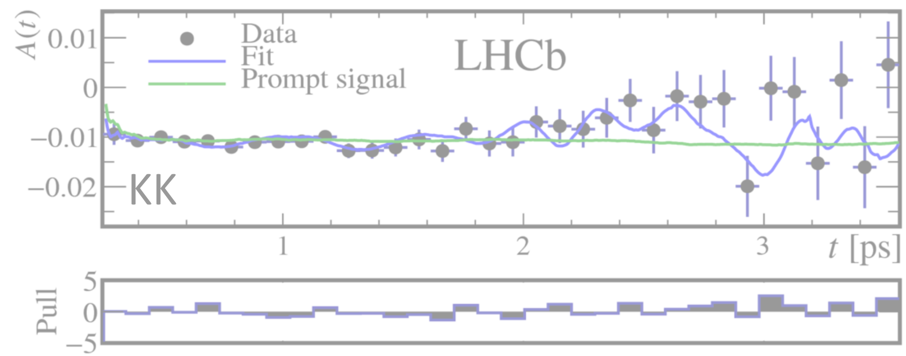

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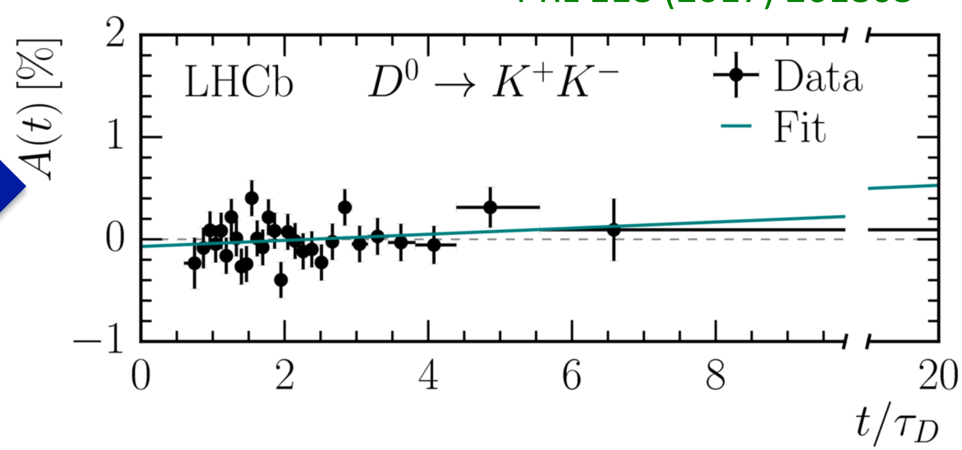
Run 1 KK+ππ average:

$A_\Gamma = (-0.13 \pm 0.30) \times 10^{-3}$

PRL 118 (2017) 261803



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Run 1 μ-tagged results:

$A_\Gamma(K^+K^-) = (-1.34 \pm 0.77\,^{+0.26}_{-0.34}) \times 10^{-3}$

$A_\Gamma(\pi^+\pi^-) = (-0.92 \pm 1.45\,^{+0.25}_{-0.33}) \times 10^{-3}$

JHEP 04 (2015) 043
arXiv:1501.06777

Full Run 1 average: $\mathbf{A_\Gamma = -0.29 \pm 0.28 \times 10^{-3}}$

- Two methods consistent
- No evidence for CPV
- Most precise measurements of CPV in charm system ever made
- **Still statistically limited**

PRL 118 (2017) 261803
arXiv:1702.06490