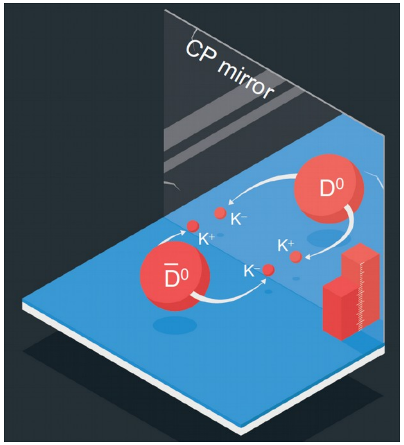
CP Violation in Charm Decays at LHCb



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HFCPV-2019
2019/7/31, Hohhot, China

Outline

- Recent LHCb results (since HFCPV-2018):

For a complete paper list on charm, see LHCb link

  - Search for CPV in $D^+ \to K_S K^+$, $D_s^+ \to K_s \pi^+$, and $D^+ \to \phi\pi^+$ [PRL 122 (2019) 191803]
  - A_Γ in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ [LHCb-CONF-2019-001]
  - Oscillation of charm mesons in $D^0 \to K_S\pi\pi$ [PRL 122 (2019) 231802]
  - **ΔA_{CP} in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ [PRL 122 (2019) 211803]**

First observation of charm CPV!

- Summary & outlook

CP Violation in Charm

- Only way to probe CP violation in up-type quark
- Complementary to K and B mesons with observed CPV
- Difficult to calculate SM predictions, but small ($10^{-3} – 10^{-4}$) CP asymmetry is expected → hints of NP if higher values are observed
- CPV in charm sector yet to be found (by 2018)

Unitarity triangle for charm

$$V_{ud}V_{cd}^{*} + V_{us}V_{cs}^{*} + V_{ub}V_{cb}^{*} = 0$$

$$\sim\lambda \qquad \sim\lambda \qquad \sim\lambda^{5}$$

$$\lambda = \sin(\theta_C) \sim 0.23$$

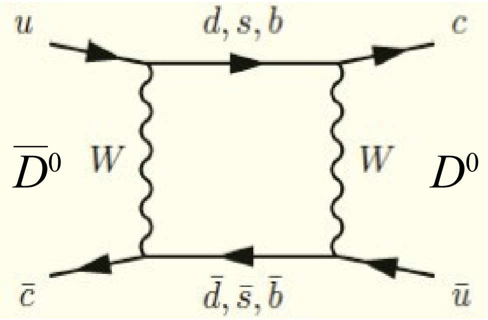
Expected CPV very small in charm

- Effectively 2-generation system
- 3rd generation and CPV enter through loops

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

- Charm mixing – a well-established fact:
  - Mass eigenstates are related to their flavor eigenstates via $|D_{1,2}> \equiv p|D^0> \pm q|\overline{D}^0>$, with $|q|^2 + |p|^2 \equiv 1$
  - 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 $\Gamma \equiv (\Gamma_2 + \Gamma_1)/2$
- *CP* violation contributions:
  - In decays: amplitudes for a process and its conjugate differ

Direct *CP* violation $$\left|\frac{\overline{A}_f}{A_f}\right|^{\pm 2} \approx 1 \pm A_d \;\rightarrow\; a_{CP}^{dir} \approx -\frac{1}{2}A_d$$



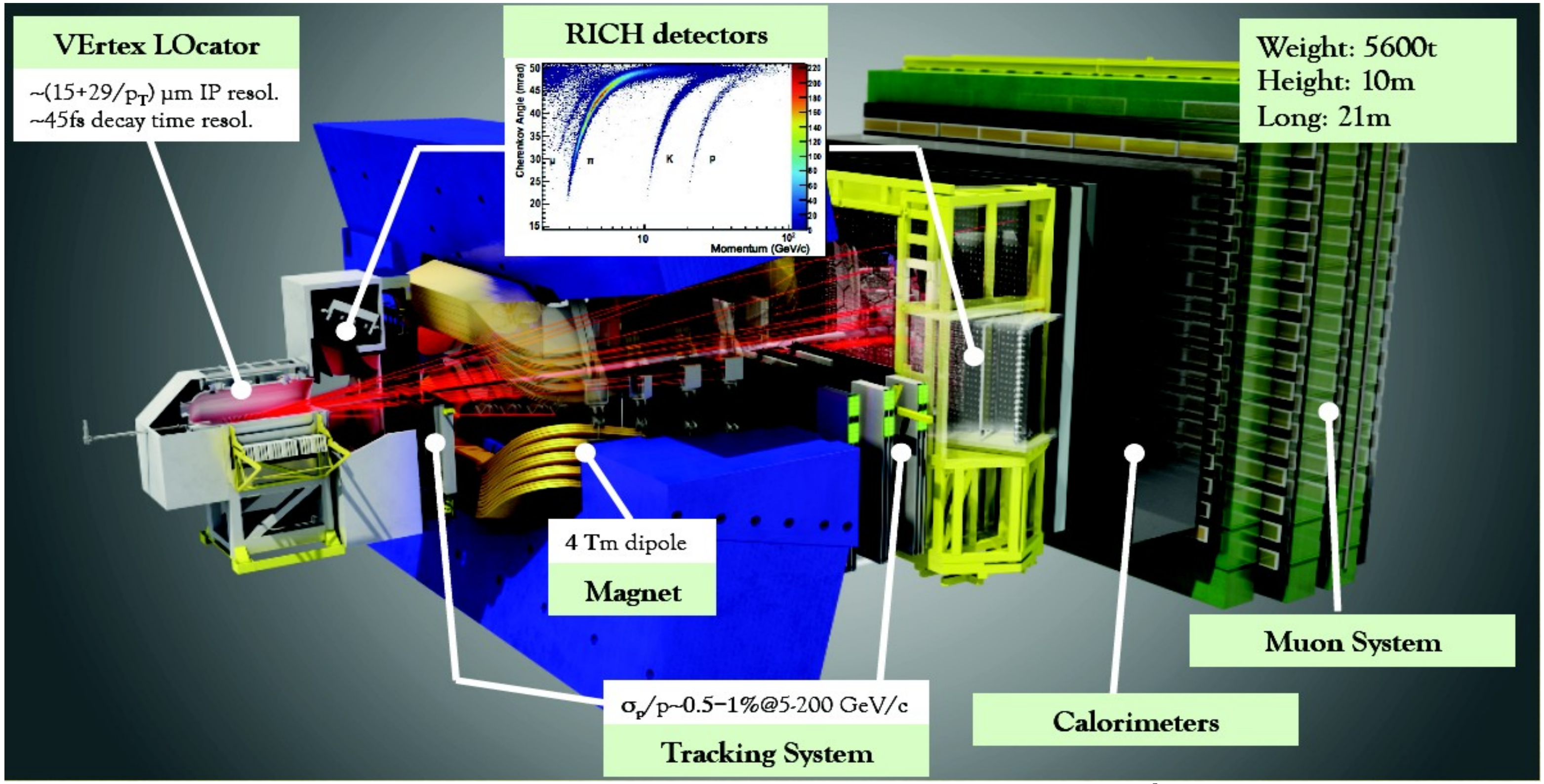
  - In mixing: rates of $D^0 \rightarrow \overline{D}^0$ and $\overline{D}^0 \rightarrow D^0$ differ

Indirect *CP* violation $$\left|\frac{q}{p}\right|^{\pm 2} \approx 1 \pm A_m \;\rightarrow\; a_{CP}^{ind} = -\frac{A_m}{2} y\cos\phi + x\sin\phi$$

ϕ: *weak phase*, A_m: *CPV from mixing*

  - In interference between mixing and decay diagrams

LHCb experiment



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

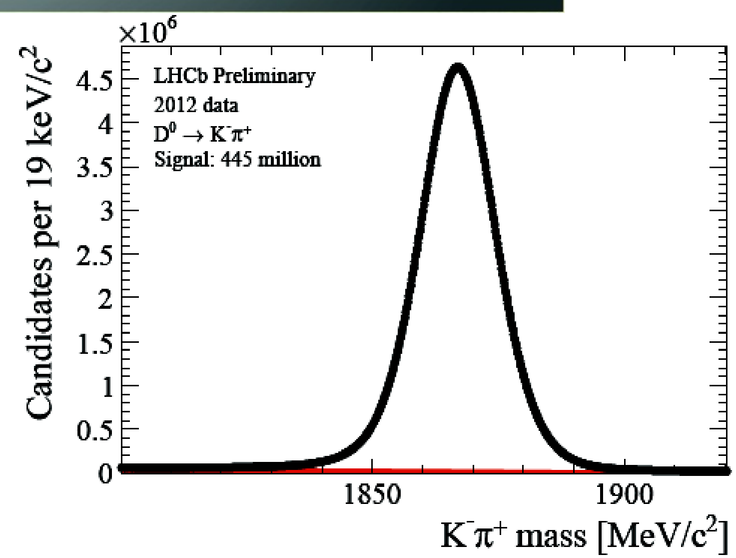
- LHCb acceptance: $2 < \eta < 5$ (forward region)
- Large $c\bar{c}$ production cross-section

[JHEP 03 (2016) 159]

  - $\sigma(pp \rightarrow c\bar{c}) = (2369 \pm 3 \pm 152 \pm 118)\,\mu b\ @\ 13\,TeV$

- More than 1 billion $D^0 \rightarrow K^-\pi^+$ collected by LHCb between 2011 and 2018
- Run2: Turbo stream from online reconstruction

[Comput. Phys. Commun. 208 (2016) 35]

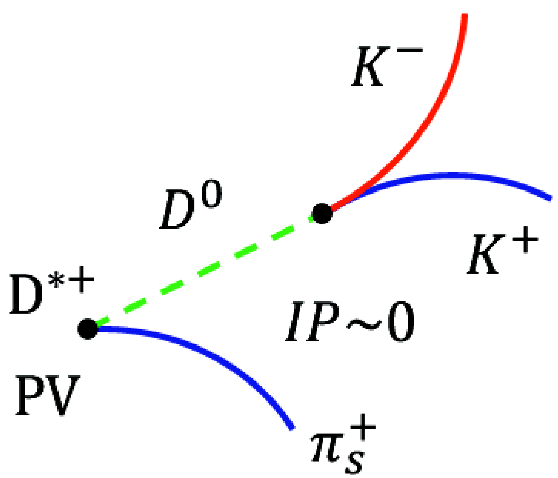


LHCb-CONF-2016-005

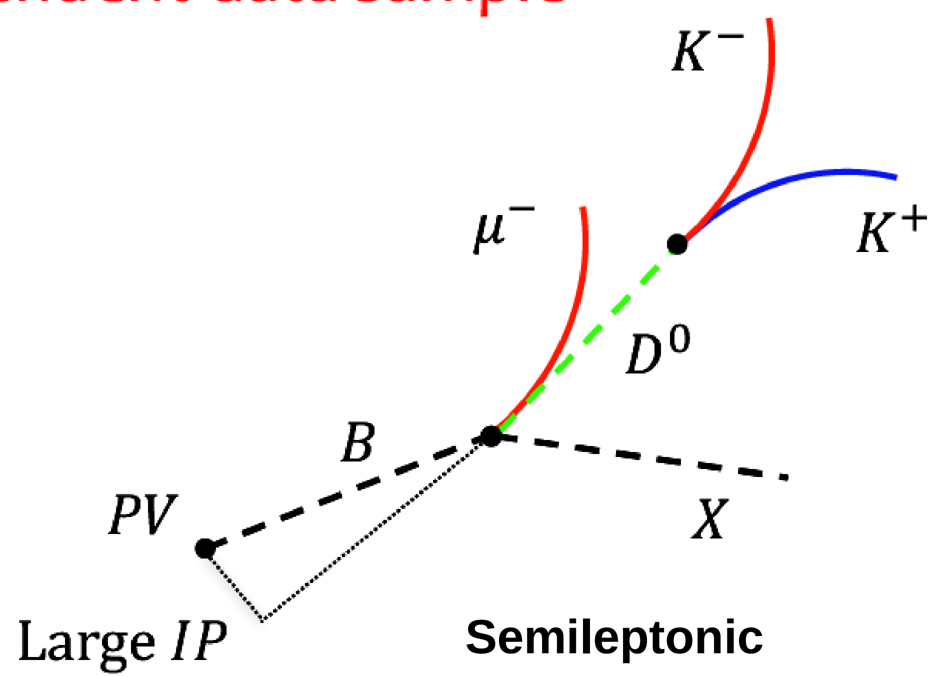
D^0 production and flavor tagging at LHCb

Two mechanisms of D^0 production

Independent data sample



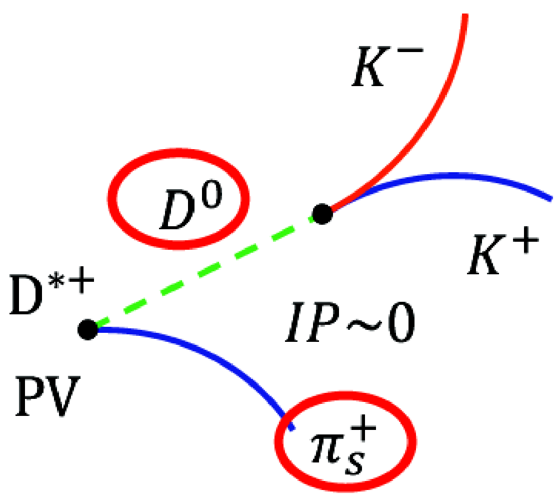
Prompt



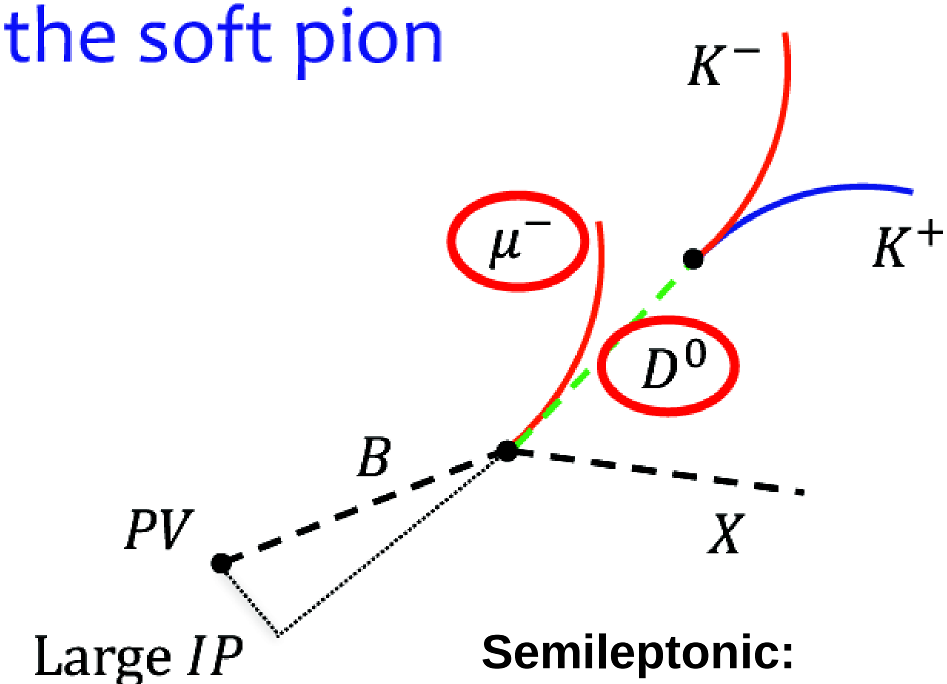
Semileptonic

D^0 production and flavor tagging at LHCb

Experimentally we can tag D^0 flavour at production by means of the charge of the muon and the soft pion



Prompt:
Tagged by π^+



Semileptonic:
Tagged by μ^-

[PRL 122 (2019) 191803]

Search for CPV in $D_{(s)}^+$ decays

- CPV can arise from interference between $c \to d\bar{d}u$ and $c \to s\bar{s}u$
- Simultaneous fits to extract raw asymmetries

$$A(D_{(s)}^+ \to f^+) \equiv \frac{N(D_{(s)}^+ \to f^+) - N(D_{(s)}^- \to f^-)}{N(D_{(s)}^+ \to f^+) + N(D_{(s)}^- \to f^-)}$$

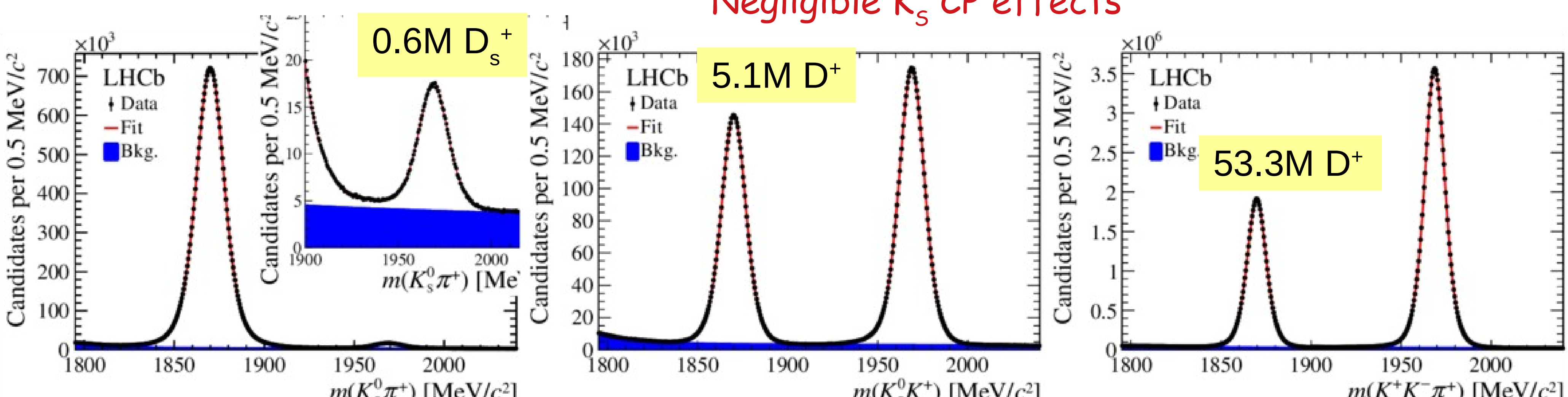
$$A_{CP}(D_s^+ \to K_S^0\pi^+) \approx A(D_s^+ \to K_S^0\pi^+) - A(D_s^+ \to \phi\pi^+)$$

$$A_{CP}(D^+ \to K_S^0K^+) \approx A(D^+ \to K_S^0K^+) - A(D^+ \to K_S^0\pi^+) - A(D_s^+ \to K_S^0K^+) + A(D_s^+ \to \phi\pi^+)$$

$$A_{CP}(D^+ \to \phi\pi^+) \approx A(D^+ \to \phi\pi^+) - A(D^+ \to K_S^0\pi^+)$$

- Run2 3.8 fb^{-1} (2015+2016+2017) prompt $D_{(s)}^+$ data:

Negligible K_s CP effects



KK mass required to be within 10 MeV of nominal ϕ mass

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$$A(D_{(s)}^+ \to f^+) \equiv \frac{N(D_{(s)}^+ \to f^+) - N(D_{(s)}^- \to f^-)}{N(D_{(s)}^+ \to f^+) + N(D_{(s)}^- \to f^-)}$$

$$A_{CP}(D_s^+ \to K_S^0\pi^+) \approx A(D_s^+ \to K_S^0\pi^+) - A(D_s^+ \to \phi\pi^+)$$
$$A_{CP}(D^+ \to K_S^0K^+) \approx A(D^+ \to K_S^0K^+) - A(D^+ \to K_S^0\pi^+) - A(D_s^+ \to K_S^0K^+) + A(D_s^+ \to \phi\pi^+)$$
$$A_{CP}(D^+ \to \phi\pi^+) \approx A(D^+ \to \phi\pi^+) - A(D^+ \to K_S^0\pi^+)$$

- Results with Run2 3.8 fb^{-1} (2015+2016+2017) data:

$$\mathbf{A_{CP}(D_s^+ \to K_S^0\pi^+) = (1.3 \pm 1.9 \pm 0.5) \times 10^{-3}}$$
$$\mathbf{A_{CP}(D^+ \to K_S^0K^+) = (-0.09 \pm 0.65 \pm 0.48) \times 10^{-3}}$$
$$\mathbf{A_{CP}(D^+ \to \phi\pi^+) = (0.05 \pm 0.42 \pm 0.29) \times 10^{-3}}$$

- Results with Run1 & Run2 combined:

$$\mathbf{A_{CP}(D_s^+ \to K_S^0\pi^+) = (1.6 \pm 1.7 \pm 0.5) \times 10^{-3}}$$
$$\mathbf{A_{CP}(D^+ \to K_S^0K^+) = (-0.04 \pm 0.61 \pm 0.45) \times 10^{-3}}$$
$$\mathbf{A_{CP}(D^+ \to \phi\pi^+) = (0.03 \pm 0.40 \pm 0.29) \times 10^{-3}}$$

Best A_{CP} measurements on these channels!

Search for CPV: measuring A_Γ

- Measure of indirect CPV in D^0 SCS decays to *CP* eigenstates:

$$A_{\rm CP}(t) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} \approx A_{\rm CP}^{\rm dir} - A_\Gamma \left(\frac{t}{\tau}\right), \qquad f = K^+K^-,\ \pi^+\pi^-$$

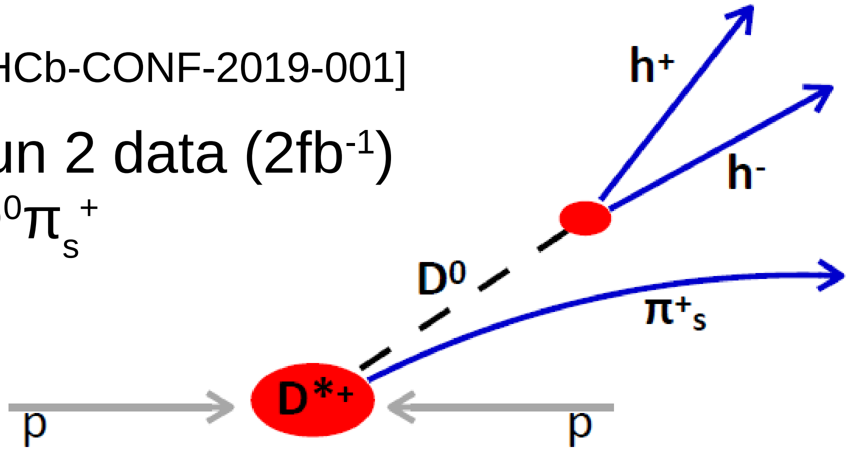
$$A_\Gamma = \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos\phi + \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin\phi\right] \approx y\left(\left|\frac{q}{p}\right| - 1\right) - x\phi$$

with $\phi = \arg\left(-\frac{q}{p}\frac{\bar{A}_f}{A_f}\right)$

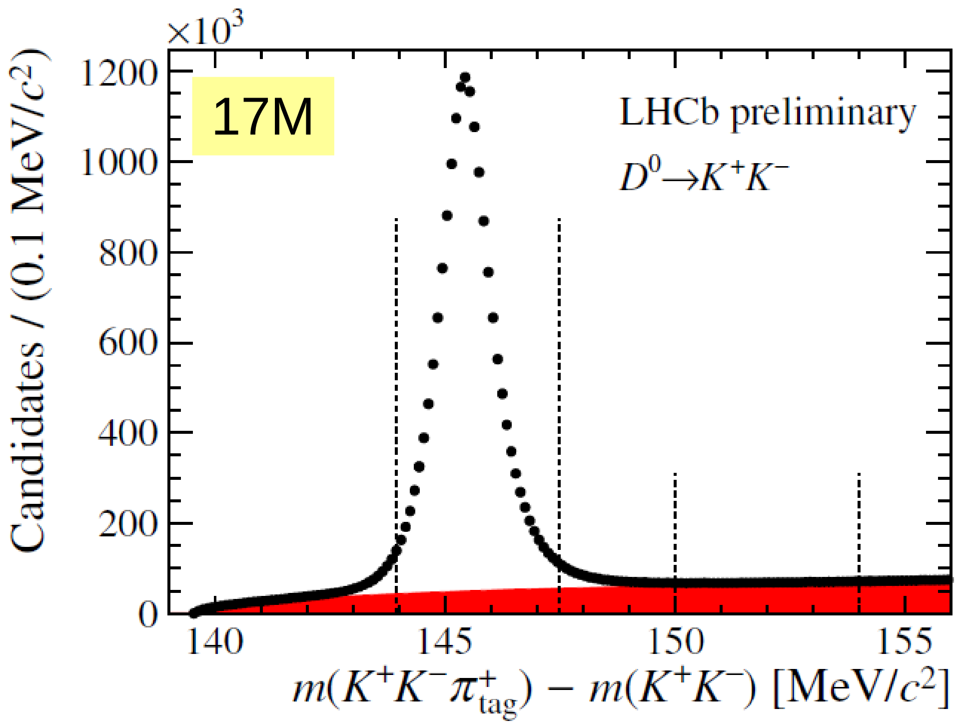
- If $A_\Gamma \neq 0 \rightarrow$ indirect CPV

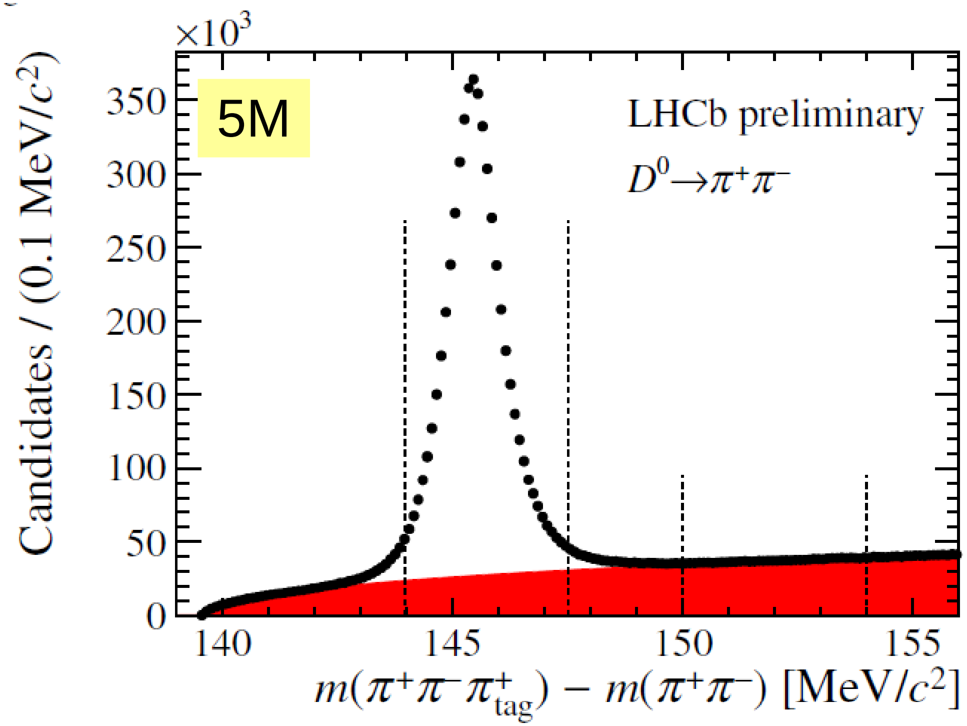
[LHCb-CONF-2019-001]

- At LHCb: measurement performed with Run 2 data (2fb^{-1})
- D^0 flavor tagged from strong decay $D^{*+} \rightarrow D^0\pi_s^+$



Search for CPV: measuring A_Γ





- At LHCb: measurement performed with Run 2 data (2fb^{-1})
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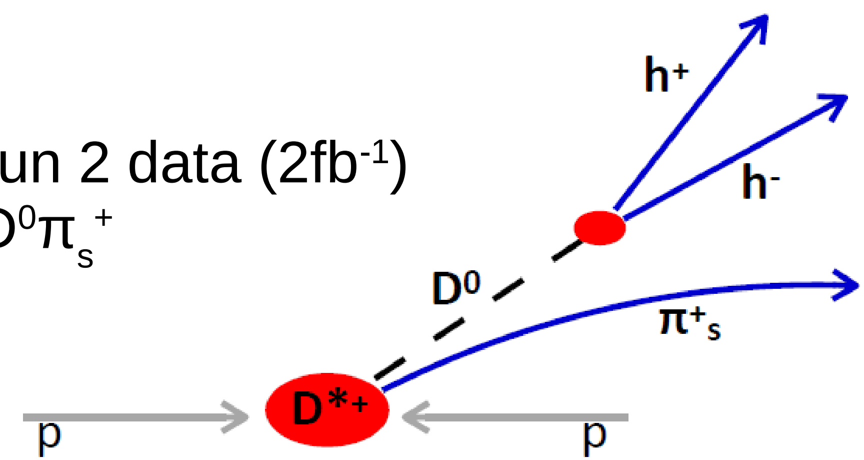
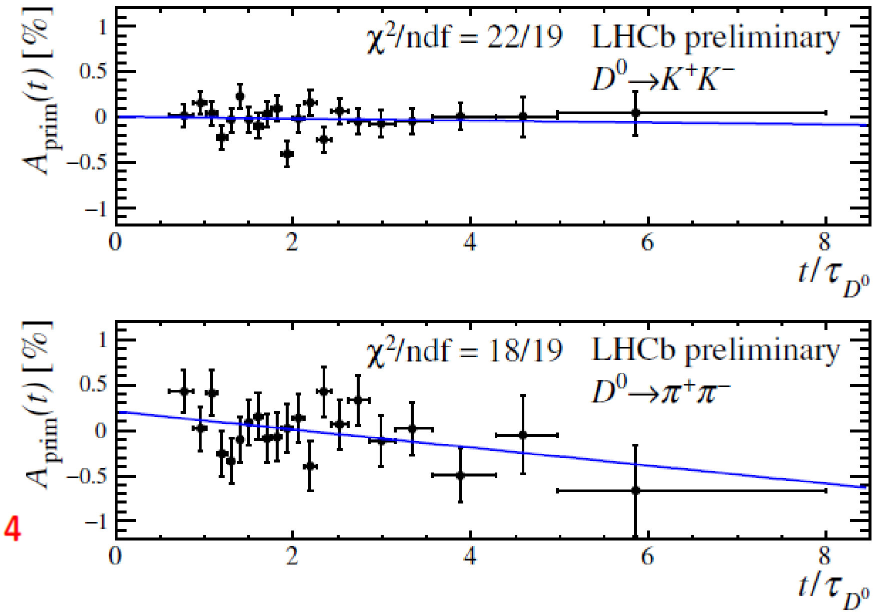


A_Γ in $D^0 \to K^+K^-, \pi^+\pi^-$

- A_Γ probes CPV in mixing and interference

$$A_{CP}(f,t) \approx A_{CP}^{\text{decay}}(f) - \boxed{A_\Gamma} \frac{t}{\tau_{D^0}}$$

  - A linear fit to A_{CP} in bins of D^0 decay time extracts A_Γ as slope parameter



- With Run2 2fb^{-1} data we have

$$\mathbf{A_\Gamma(D^0 \to K^+K^-) = (1.3 \pm 3.5 \pm 0.7) \times 10^{-4}}$$
$$\mathbf{A_\Gamma(D^0 \to \pi^+\pi^-) = (11.3 \pm 6.9 \pm 0.8) \times 10^{-4}}$$

- A_Γ does not depend on D decay channel, the two values can be combined

$$\mathbf{A_\Gamma(D^0 \to h^+h^-) = (3.4 \pm 3.1 \pm 0.6) \times 10^{-4}} \quad (h = K, \pi)$$

- Combining with Run1 results [PRL 118 (2017) 261803]:

$$\mathbf{A_\Gamma(D^0 \to h^+h^-) = (0.9 \pm 2.1 \pm 0.7) \times 10^{-4}} \quad (h = K, \pi)$$

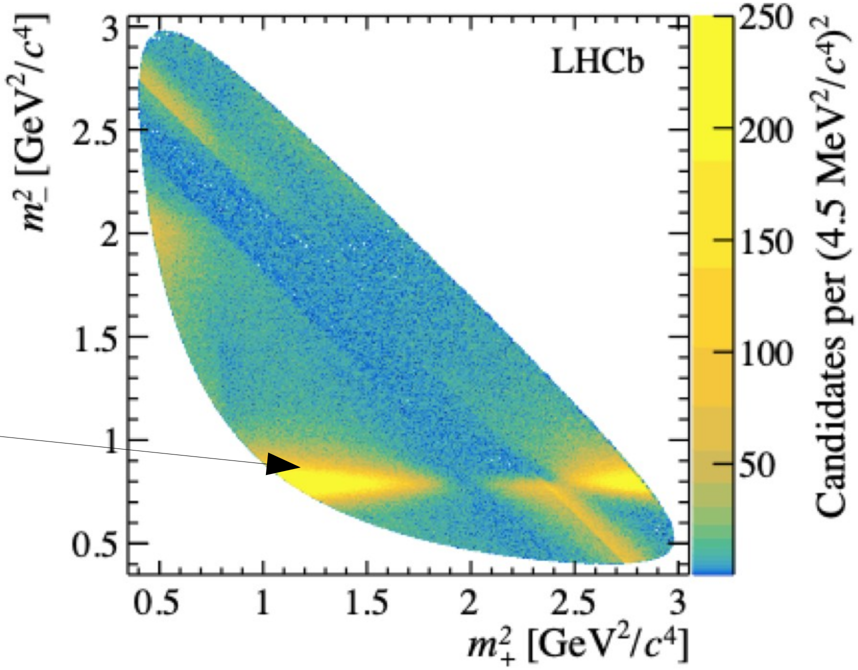
A_Γ is consistent with SM!

[PRL 122 (2019) 231802]

Oscillations of charm mesons in $D^0 \to K_S^0 \pi\pi$

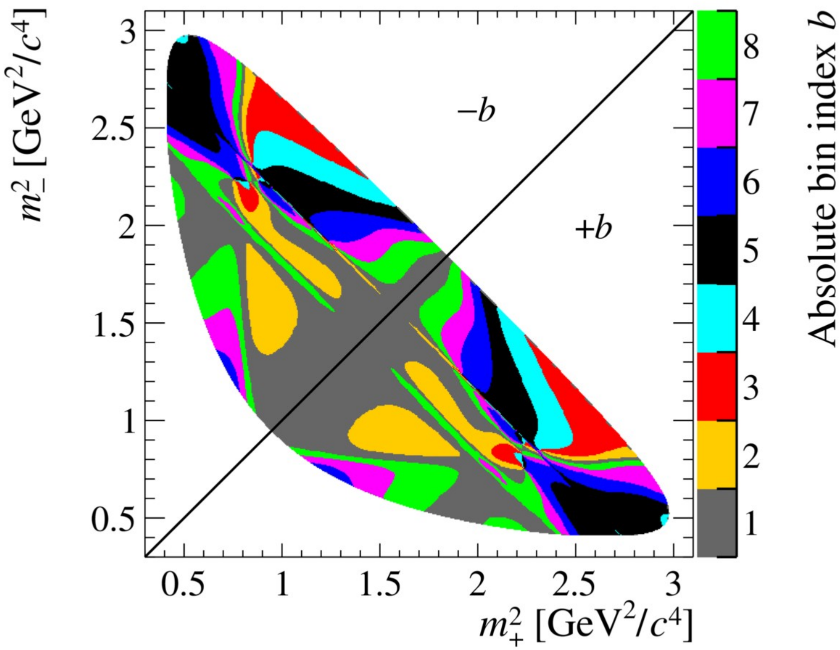
- $|D_{1,2}\rangle = p\,|D^0\rangle \pm q\,|\overline{D^0}\rangle$ $\quad x \equiv \frac{m_1 - m_2}{\Gamma};\ y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$
- x determines the oscillation rate
  - x is very small for D^0, but x and CPV can be enhanced by NP
  - CPV can occur in the mixing → oscillation rates differ for D^0 and $\overline{D}^0$
- LHCb Run1, tagged $D^0 \to K_S^0\pi\pi$ decay yields
  - Prompt: ~1.3M, Semileptonic: ~1M
- $D^0 \to K_S^0\pi\pi$ has rich resonance structures
- Model-independent approach (bin-flip method) [PRD 99 (2019) 012007]
  - To avoid efficiency modeling

$$m_\pm^2 \equiv \begin{cases} m^2(K_S^0\pi^\pm) & \text{for } D^0 \to K_S^0\pi^+\pi^- \\ m^2(K_S^0\pi^\mp) & \text{for } \overline{D}^0 \to K_S^0\pi^+\pi^- \end{cases}$$



Model-independent Bin-flip method

- Use strong-phase info c_b, s_b from CLEO-c [PRD 82 (2010) 112006]



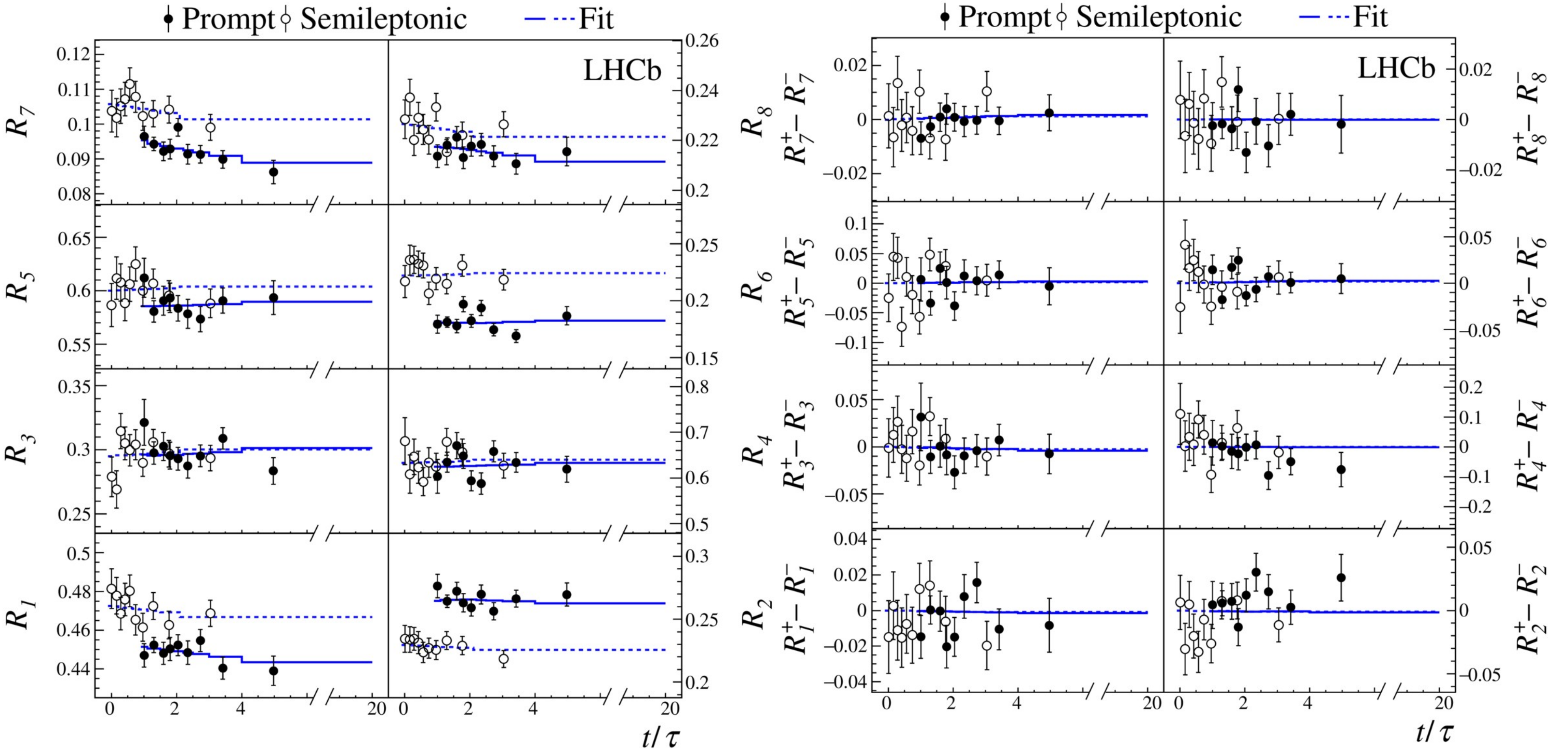
- Bin Dalitz-plot into $\pm b$ about $m_+^2 = m_-^2$ with almost constant $\Delta\delta_D$
- D decay time into bins j
- Measure ratio of signal in $-b$ and $+b$ in bin j

$$R_{bj}^{\pm} = \frac{r_b\left[1+\frac{1}{4}t_j^2 Re(z_{CP}^2-\Delta z^2)\right]+\frac{1}{4}t_j^2|\, z_{CP}\pm\Delta z\,|^2+\sqrt{r_b}t_j Re\left[\mathbf{X}_\mathbf{b}^*(z_{CP}\pm\Delta z)\right]}{\left[1+\frac{1}{4}t_j^2 Re(z_{CP}^2-\Delta z^2)\right]+r_b\frac{1}{4}t_j^2|\, z_{CP}\pm\Delta z\,|^2+\sqrt{r_b}t_j Re\left[\mathbf{X}_\mathbf{b}^*(z_{CP}\pm\Delta z)\right]},$$

where $z_{CP}\pm\Delta z = -(\frac{q}{p})^{\pm}(y+ix)$ and r_b is ratio without mixing $\mathbf{X_b} = \mathbf{c_b} - \mathbf{i s_b}$

$R^{\pm}$ **changes with time** $\Rightarrow$ **Mixing**
$R^{+} \neq R^{-}$ $\Rightarrow$ **Indirect CPV**

$\propto (\mathbf{D^0} + \overline{\mathbf{D^0}})$ $(\mathbf{D^0} - \overline{\mathbf{D^0}})$ [PRL 122 (2019) 231802]



$$R^{\pm}_{bj} = \frac{r_b\left[1 + \frac{1}{4}t_j^2 Re(z_{CP}^2 - \Delta z^2)\right] + \frac{1}{4}t_j^2 \left| z_{CP} \pm \Delta z \right|^2 + \sqrt{r_b}\, t_j Re\left[\mathbf{X_b^*}(z_{CP} \pm \Delta z)\right]}{\left[1 + \frac{1}{4}t_j^2 Re(z_{CP}^2 - \Delta z^2)\right] + r_b \frac{1}{4}t_j^2 \left| z_{CP} \pm \Delta z \right|^2 + \sqrt{r_b}\, t_j Re\left[\mathbf{X_b^*}(z_{CP} \pm \Delta z)\right]},$$

where $z_{CP} \pm \Delta z = -(\frac{q}{p})^{\pm}(y + ix)$ and r_b is ratio without mixing $\mathbf{X_b} = \mathbf{c_b} - i\mathbf{s_b}$

$R^{\pm}$ **changes with time** $\Rightarrow$ **Mixing**
$R^+ \neq R^-$ $\Rightarrow$ **Indirect CPV**

[PRL 122 (2019) 231802]

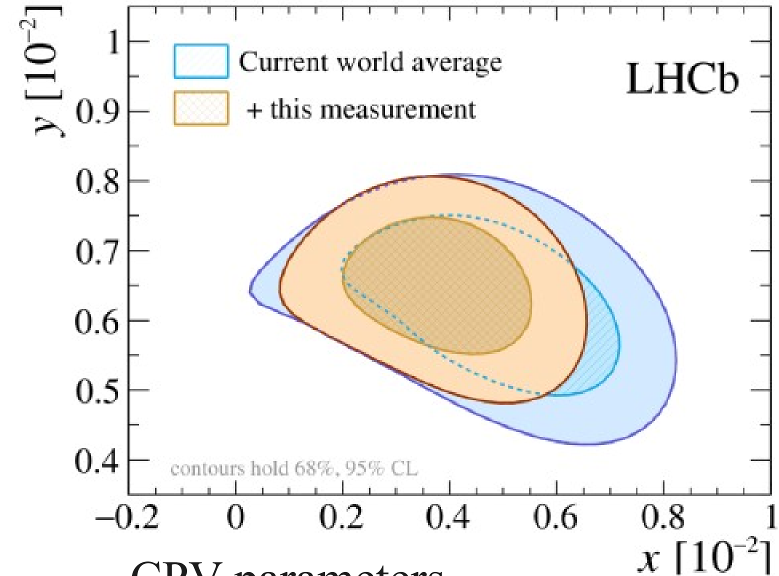
Oscillations of charm mesons in $D^0 \to K_S^0 \pi\pi$

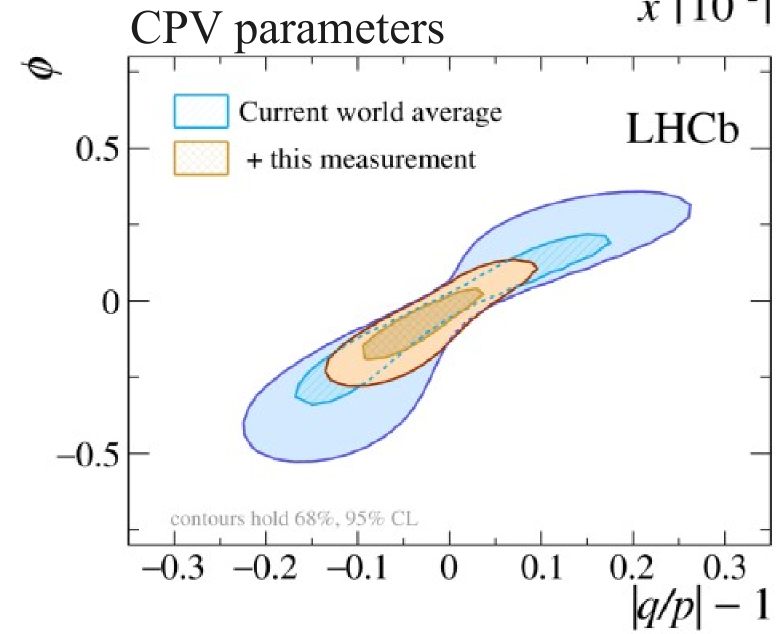
- Results with run1 data:

$$y_{CP} = [0.74 \pm 0.36\,(stat) \pm 0.11\,(syst)]\%$$
$$\Delta y = [-0.06 \pm 0.16\,(stat) \pm 0.03\,(syst)]\%$$
$$x_{CP} = [0.27 \pm 0.16\,(stat) \pm 0.04\,(syst)]\%$$
$$\Delta x = [-0.053 \pm 0.070\,(stat) \pm 0.022\,(syst)]\%$$

  - Best precision on x from a single experiment!

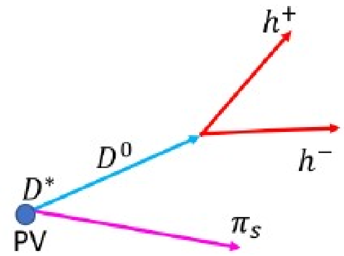
- Combination with current global knowledge gives x > 0 at more than 3σ
  - First evidence that masses of D^0 eigenstates differ





[PRL 122 (2019) 211803]

ΔA_{CP} measurement



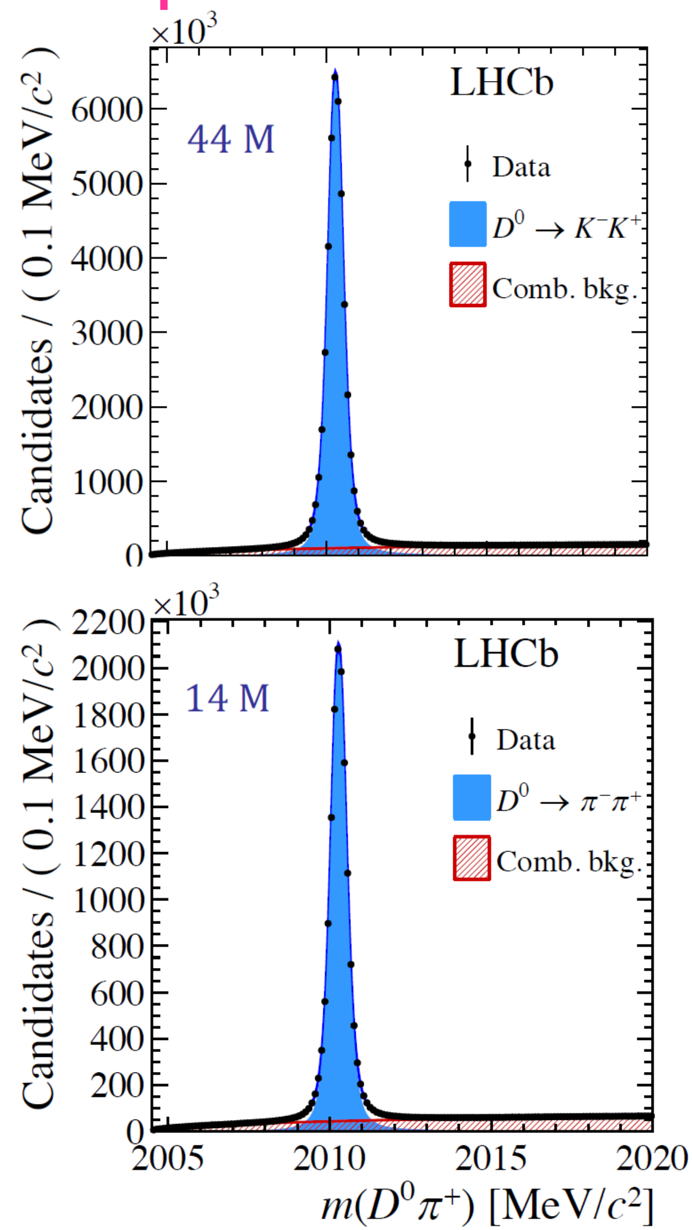
- LHCb uses full Run2 5.9 fb^{-1} data
- Raw asymmetry for tagged D^0 decays to a final state f (K^+K^-, $\pi^+\pi^-$):

$$A_{\text{raw}}(f) = \frac{N(D^0 \to f) - N(\overline{D}^0 \to f)}{N(D^0 \to f) + N(\overline{D}^0 \to f)}$$

- $A_{raw} = A_{CP} + A_D + A_P$
  - A_D: Detection asymmetry from π_s (prompt)
  - A_P: Production asymmetry of D^* (prompt)
- With many systematics canceled at first order, it is relatively easy to measure time-integrated difference in CP asymmetry

$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

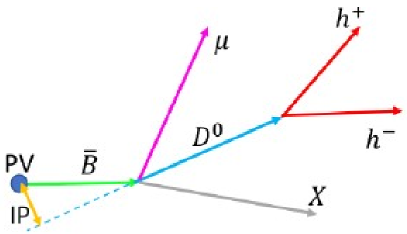
Prompt D^0



[PRL 122 (2019) 211803]

ΔA_{CP} measurement

- LHCb uses full Run2 5.9 fb^{-1} data
- Raw asymmetry for tagged D^0 decays to a final state f (K^+K^-, $\pi^+\pi^-$):

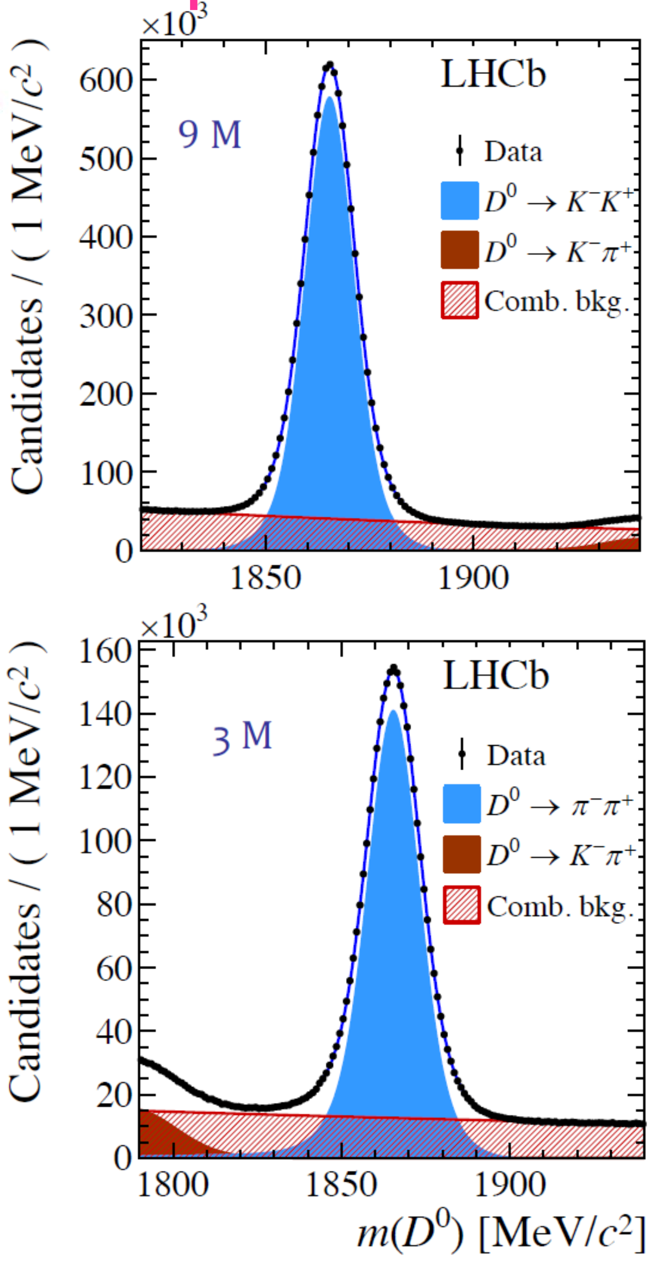


$$A_{\rm raw}(f) = \frac{N(D^0 \to f) - N(\overline{D}^0 \to f)}{N(D^0 \to f) + N(\overline{D}^0 \to f)}$$

- $A_{raw} = A_{CP} + A_D + A_P$
  - A_D: Detection asymmetry from μ (semileptonic)
  - A_P: Production asymmetry of B (semileptonic)
- With many systematics canceled at first order, it is relatively easy to measure time-integrated difference in CP asymmetry

$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

Semileptonic D^0



Observation of charm CPV

- From full Run2 5.9 fb^{-1} data:

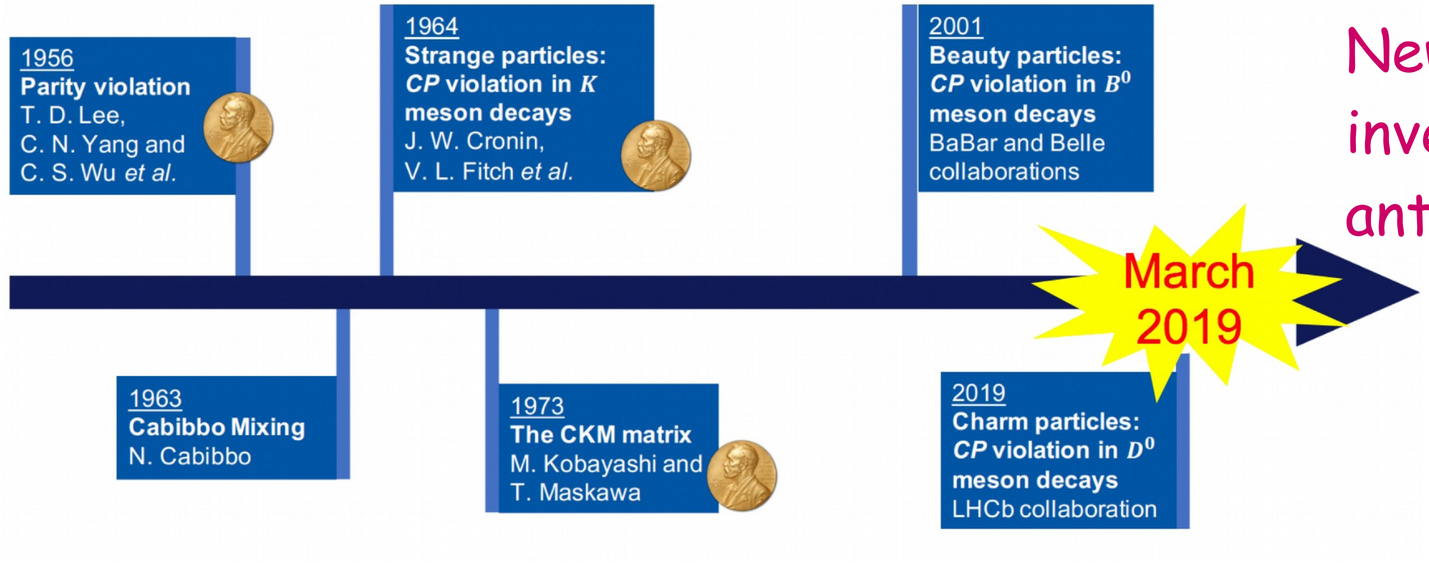
$$\Delta A_{CP}^{\pi-tag} = (-18.2 \pm 3.2 \pm 0.9) \times 10^{-4},$$

$$\Delta A_{CP}^{\mu-tag} = (-9 \pm 8 \pm 5) \times 10^{-4}$$

- Combination with Run1 results:

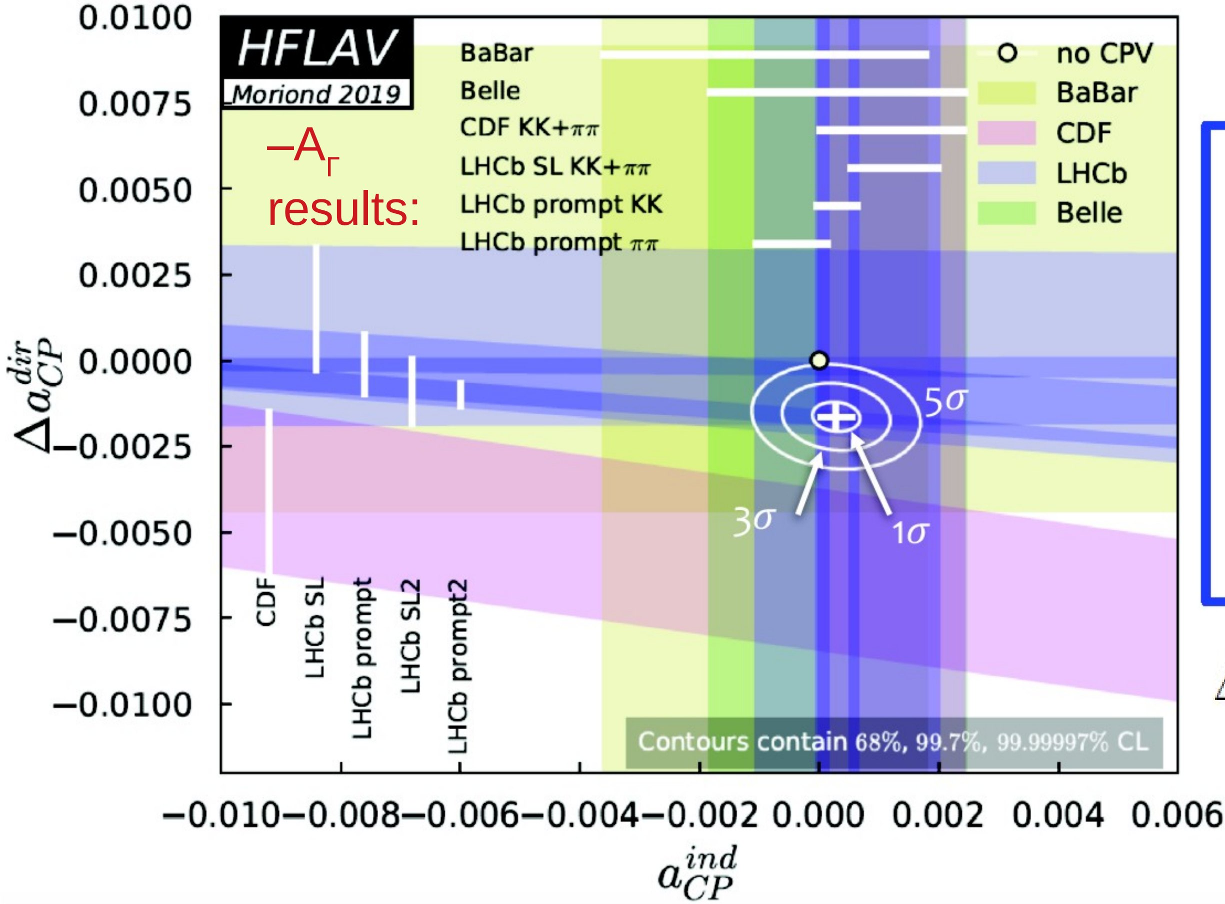
$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

  - Observation of CP violation with **5.3σ** significance!
  - Result is consistent with, although at upper end of SM expectations (10^{-3} – 10^{-4})



New window opened to investigate matter-antimatter symmetry!

HFLAV updates



HFLAV combination

$a_{CP}^{\text{ind}} = (0.028 \pm 0.026)\%$

$\Delta a_{CP}^{\text{dir}} = (-0.164 \ \pm 0.028\ )\%$

Consistency with NO CPV hypothesis: 5×10^{-8}

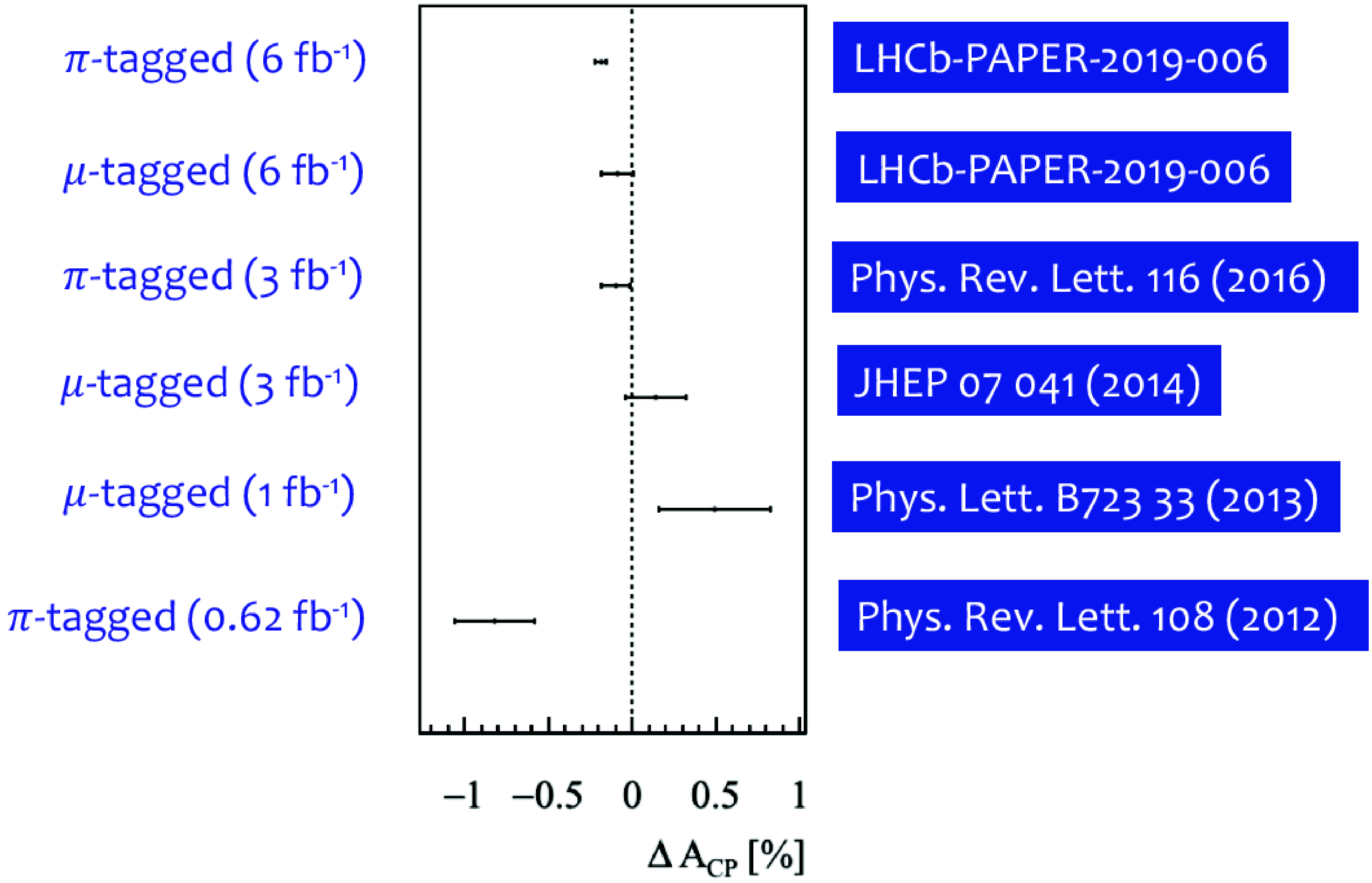
$$\Delta A_{CP} = \boxed{\left[a_{CP}^{\text{dir}}(K^-K^+) - a_{CP}^{\text{dir}}(\pi^-\pi^+)\right]} + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{\text{ind}}$$

$\Delta\, a_{CP}^{dir}$

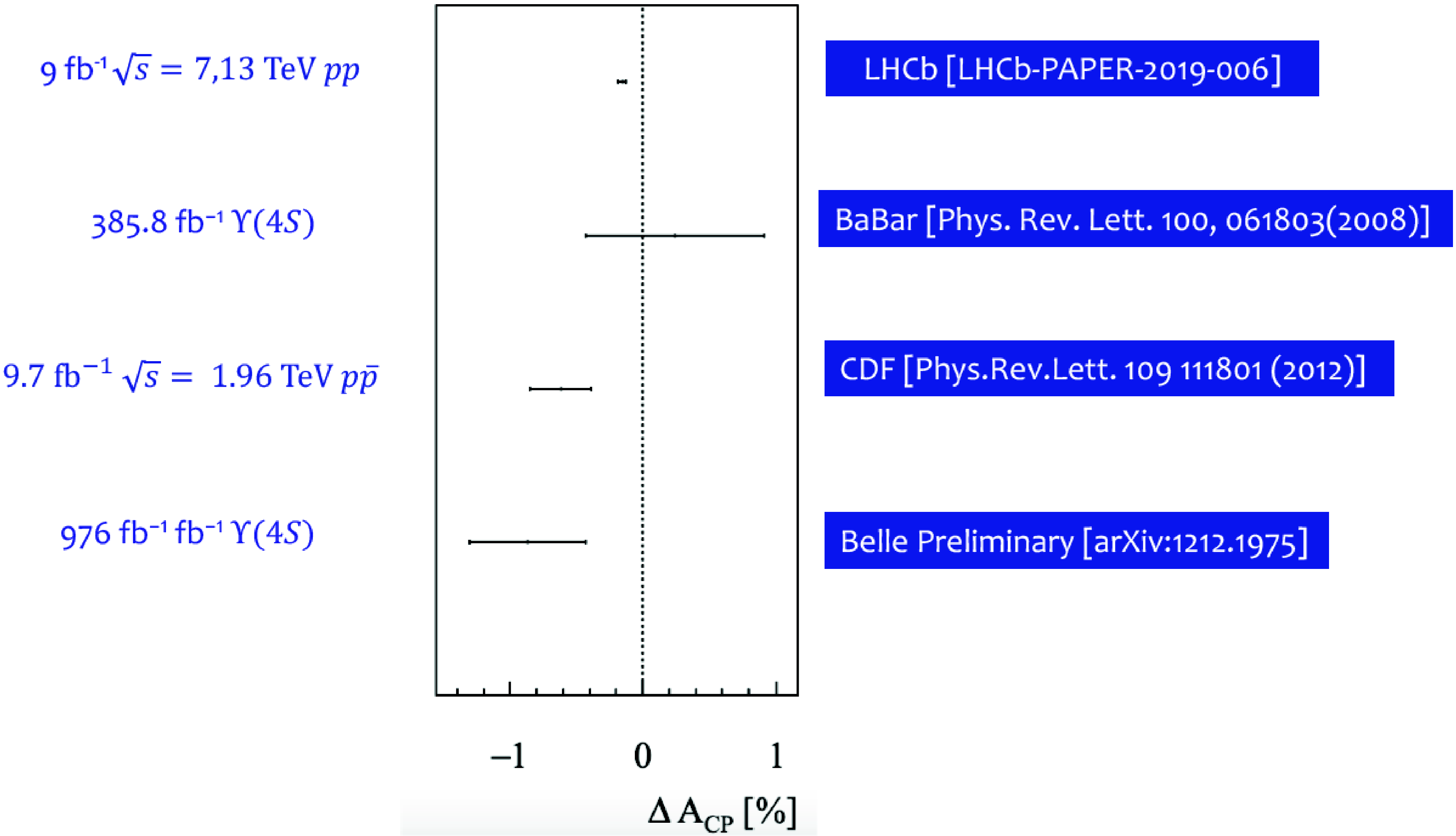
World average dominated by LHCb results

provided by the courtesy of M. Gersabeck

ΔA_{CP} history in LHCb

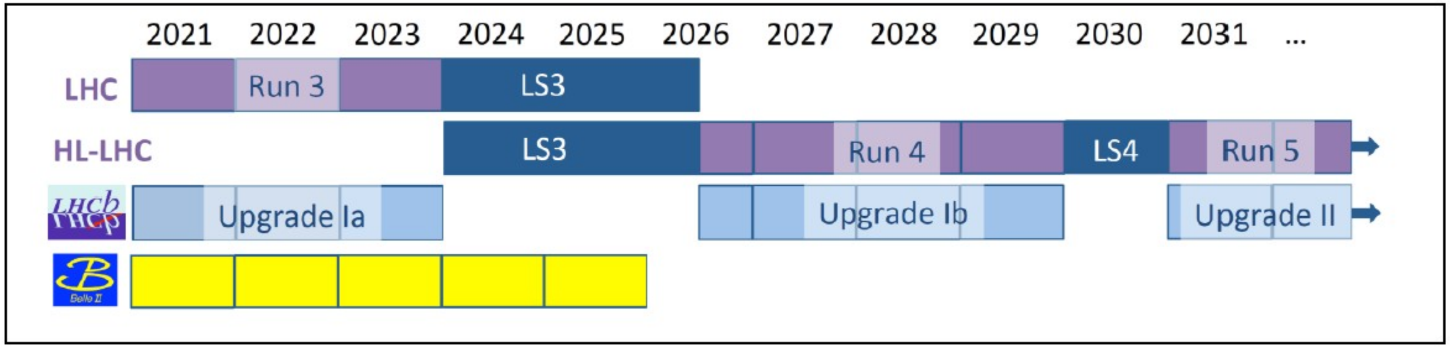


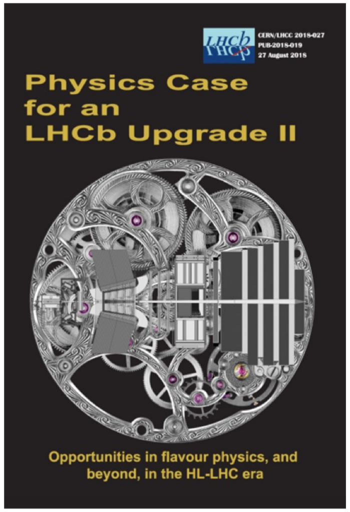
ΔA_{CP} experimental status



Prospects of LHCb

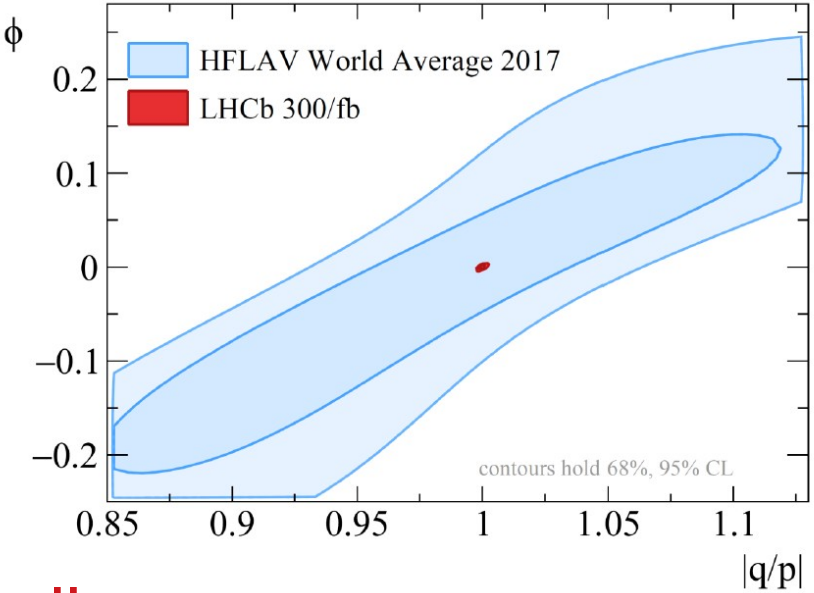
- Major upgrade phases





  - Upgrade (2020-2023) will provide 3x larger dataset
  - Upgrade (2025-) will be for HL-LHC to collect > 300/fb (30x of current level)

→ Ambitious but extremely rewarding



Prospects of LHCb

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
EW Penguins				
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [274]	0.025	0.036	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [275]	0.031	0.032	0.008
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05
CKM tests				
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [606]	0.011	0.005	0.003
ϕ_s, with $B_s^0 \to J/\psi \phi$	49 mrad [44]	14 mrad	–	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%
$B_s^0, B^0 \to \mu^+\mu^-$				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%
$S_{\mu\mu}$	–	–	–	0.2
$b \to c\ell^-\bar{\nu}_l$ LUV studies				
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002
$R(J/\psi)$	0.24 [220]	0.071	–	0.02
Charm				
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [610]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}

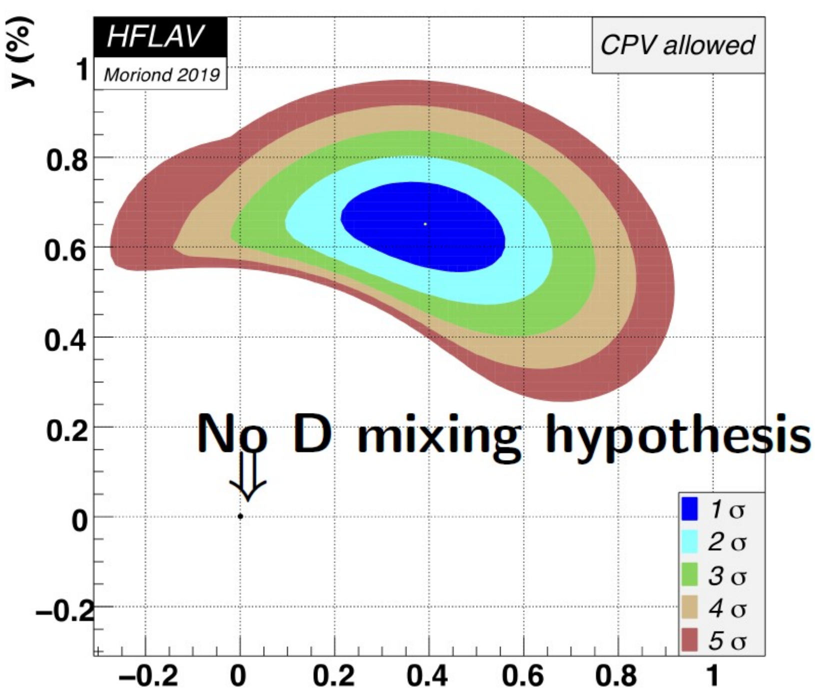
Summary

- LHCb is in fact a charm factory and has the world's largest sample of charm decays
- High statistics and superb detector performance allow for high precision measurements on charm CP
- Still more charm CPV results in the pipeline with full Run1+2 data, stay tuned!
  - For example, semileptonic D decays, CF charm decays involving a K_S, charm baryons, ...
- Longer term: LHCb's first upgrade has already begun
  - Will allow for measurements with 10x larger samples within a few years
- Synergy with BESIII important for CPV searches in the charm sector

Backup Slides

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

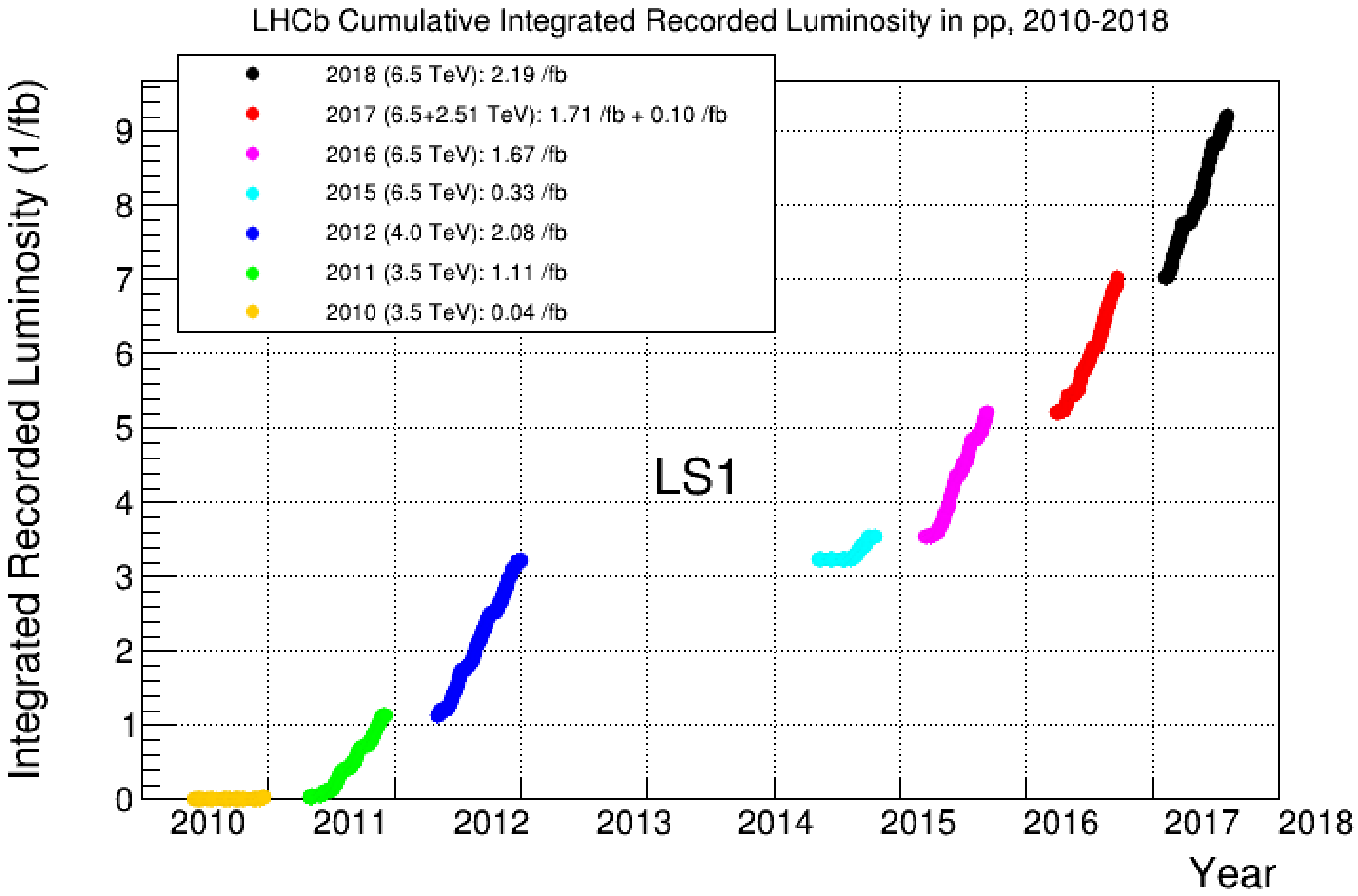
- Charm mixing: a well-established fact:
  - Mass eigenstates are related to their flavor eigenstates via $|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|D^0\rangle$, with $|q|^2 + |p|^2 \equiv 1$
  - Mixing parameters based on the mass and width differences: $x \equiv (m_2 - m_1)/\Gamma$, $y \equiv (\Gamma_2 - \Gamma_1)/2\Gamma$, with $\Gamma \equiv (\Gamma_2 + \Gamma_1)/2$



Current CPV allowed world averages:

$$x = \left(0.39^{+0.11}_{-0.12}\right)\%$$
$$y = \left(0.651^{+0.063}_{-0.069}\right)\%$$

LHCb data-taking



- Run I: 1.0 fb^{-1} @ 7 TeV (2011) + 2.0 fb^{-1} @ 8 TeV (2012)
- Run II: 0.3 fb^{-1} (2015) + 1.7 fb-1 (2016) + 1.7 fb^{-1} (2017) + 2.2 fb^{-1} (2018) @ 13 TeV

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$(\times 10^{-4})$

Source	π-tagged	μ-tagged
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
Peaking background	0.5	–
B fractions	–	1
B reco. efficiency	–	2
Total	0.9	5

- Dominant systematic uncertainty:
  - **Prompt:**
    - **fit model:** evaluated by pseudo-experiments
    - **peaking ($m(D^0\pi)$) background ($D^0 \to K^-\pi^+\pi^0$, $D^0 \to \pi^-\ell^+\nu_\ell$):** evaluated via measuring yields and background asymmetries in $m(D^0)$ distributions
  - **Semileptonic:**
    - **Mistag** evaluated from $B \to D^0(K^-\pi^+)\mu X$ sample