Recent charm results at LHCb

Xiao-Rui Lyu (吕晓睿)
University of Chinese Academy Sciences

第5届LHCb前沿物理研讨会

Outline

- **Charm mixing and CPV**
  - direct CPV with $D^+ \to K^+K^-\pi^+$
  - time-dependent CPV with $D^0 \to K^-\pi^+$
  - CPV with Λ_c^+ two-body decays
- **Charm rare decay**
  - search for $D^0 \to K^+K^-e^+e^-$
  - search for $\Lambda_c^+ \to p\mu^+\mu^-$
  - asymmetry around ϕ resonance in $\Lambda_c^+ \to p\mu^+\mu^-$
- **Summary**

Neutral D meson oscillation

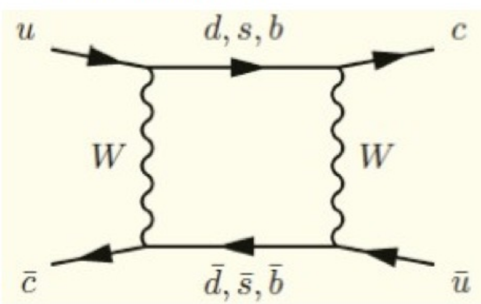
- Time evolution can be described with effective hamiltonian

$$i\frac{\partial}{\partial t}\begin{pmatrix} M^0(t) \\ \overline{M}^0(t) \end{pmatrix} = \left[\begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}\right]\begin{pmatrix} M^0(t) \\ \overline{M}^0(t) \end{pmatrix}$$

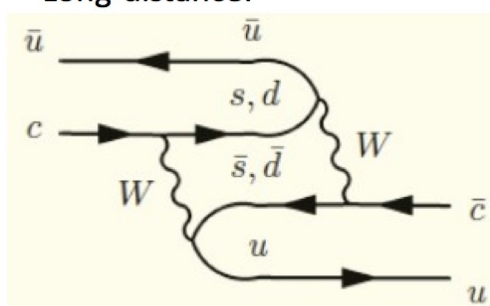
- Mixing parameters defined as

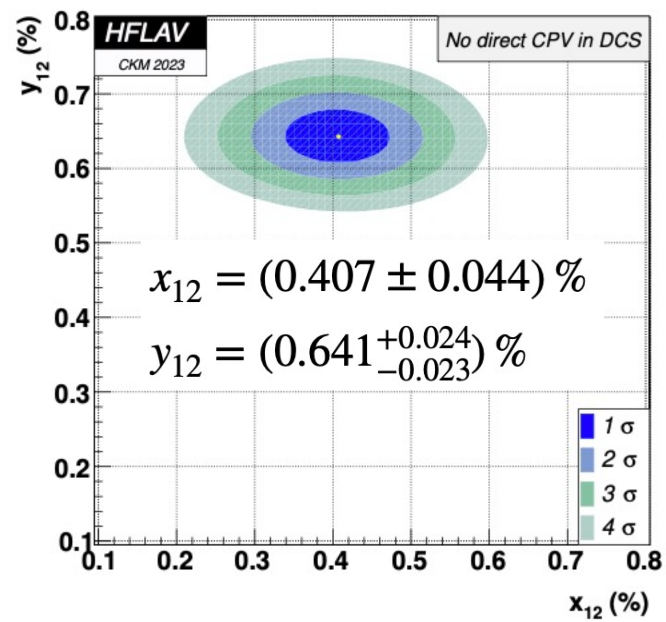
$$x_{12} \equiv \frac{2|M_{12}|}{\Gamma} \simeq \frac{\Delta m}{\Gamma}, \quad y_{12} \equiv \frac{|\Gamma_{12}|}{\Gamma} \simeq \frac{\Delta\Gamma}{\Gamma}$$

Short-distance:



Long-distance:





CKM suppression: *b*
GIM suppression: *d, s*

$$\Delta m_{D^0} \underset{\times 200}{\ll} \Delta m_{B^0} \underset{\times 35}{\ll} \Delta m_{B_s^0}$$

x mixing: Channel for New Physics.

y (long-distance) mixing: SM background.

Charm CP violation

- CP Violation (CPV) highly suppressed in CKM hierarchy

$$CPV \propto \mathrm{Im}\left(\frac{V_{cb}V_{bu}^{*}}{V_{cs}V_{su}^{*}}\right) \approx -6\times 10^{-4}$$ sensitive to NP effects

- LHCb discovered charm direct CPV in $D \to h^{+}h^{-}$ in 2019

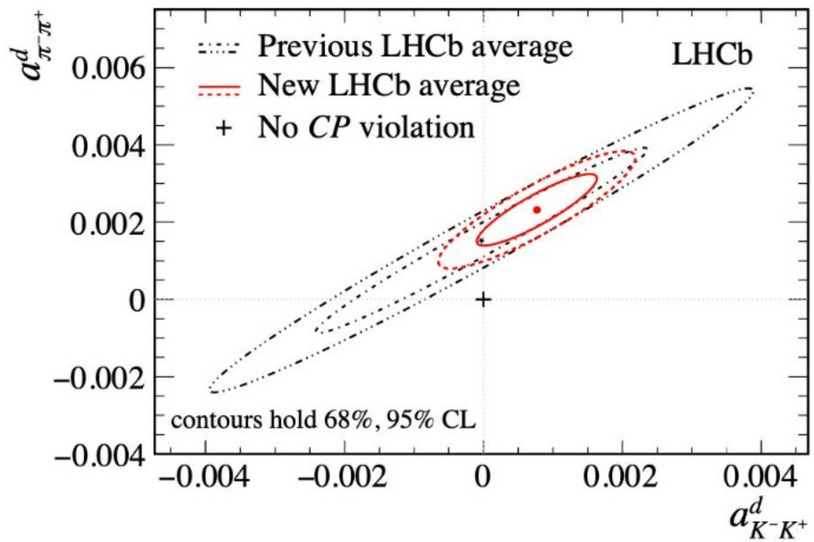
$$\Delta\mathcal{A}^{CP} = \mathcal{A}^{CP}(K^{+}K^{-}) - \mathcal{A}^{CP}(\pi^{+}\pi^{-}) = (-15.4 \pm 2.9)\times 10^{-4}$$

$$a^{d}_{K^{+}K^{-}} = (\ 7.7 \pm 5.7)\times 10^{-4}$$

$$a^{d}_{\pi^{+}\pi^{-}} = (23.2 \pm 6.1)\times 10^{-4}$$

3.8σ first evidence of charm CPV in a single channel

PRL131, 091802 (2023)



- Another type of mixing-induced CPV has not been observed yet

Local CPV in three-body decays $D^+ \to K^+K^-\pi^+$

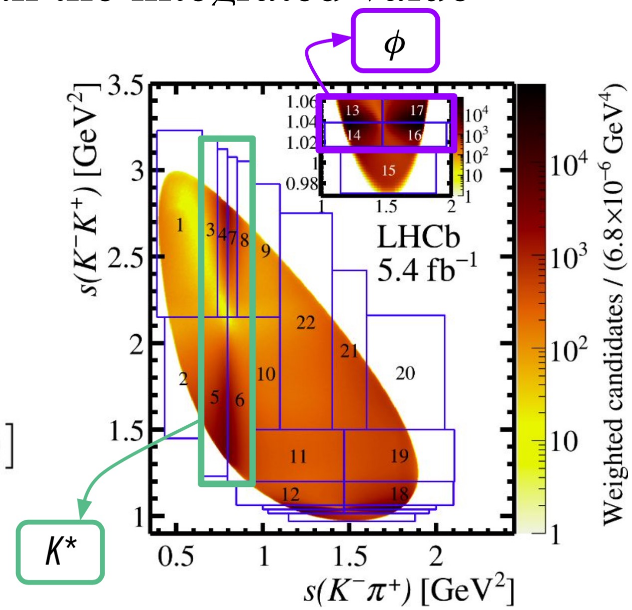
PRL133, 251801(2024)

- Variations of the strong phase across the Dalitz phase space may enhance the local CP asymmetries, being considerably larger than the integrated value
- The Cabibbo-favored mode $D_s^+ \to K^+K^-\pi^+$ is taken as control channel (C)
- A_{CP} around the K^* and ϕ resonances is measured as

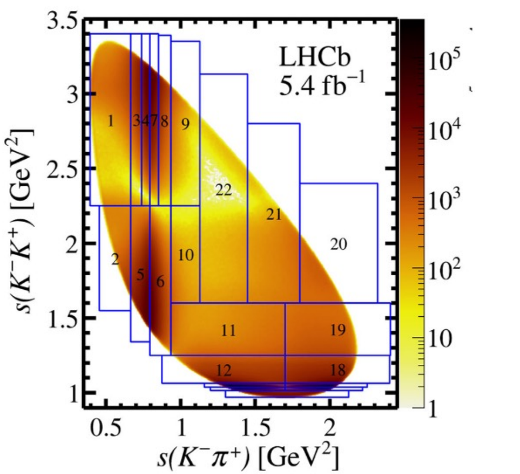
$$A_{\rm raw}^{i,X} = \frac{N_+^{i,X} - N_-^{i,X}}{N_+^{i,X} + N_-^{i,X}} \qquad \Delta A_{CP}^{i} = A_{\rm raw}^{i,S} - A_{\rm raw}^{i,C}$$

$$A_{CP|S} = \frac{1}{2}\left[\left(\Delta A_{\rm raw}^{\text{top-left}} + \Delta A_{\rm raw}^{\text{bottom-right}}\right) - \left(\Delta A_{\rm raw}^{\text{top-right}} + \Delta A_{\rm raw}^{\text{bottom-left}}\right)\right]$$

Sign of CP asymmetry changes when acrossing resonance vertically and horizontally [PRD78, 072003 (2008)]



D_s^+



$$A_{CP|S}^{\phi\pi^+} = (0.95 \pm 0.43 \pm 0.26) \times 10^{-3}$$

$$A_{CP|S}^{\overline{K}^{*0}K^+} = (-0.26 \pm 0.56 \pm 0.18) \times 10^{-3}$$

Compatible with zero asymmetries.

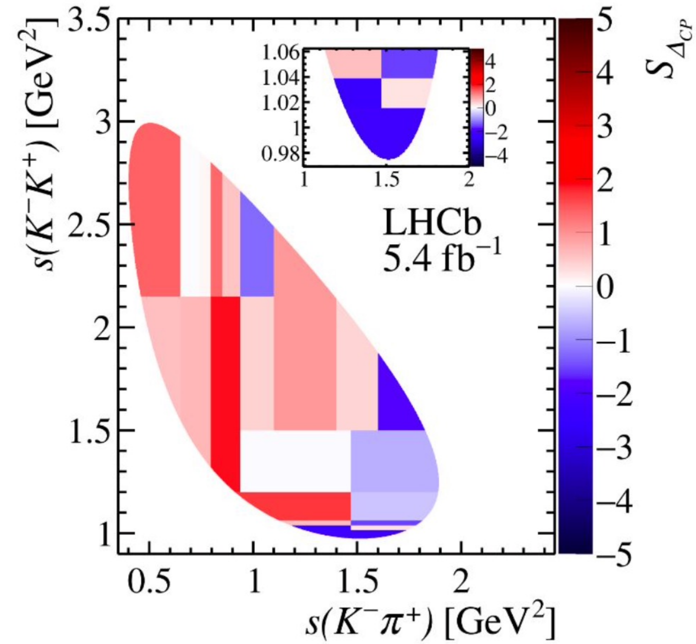
Local CPV in three-body decays $D^+ \to K^+K^-\pi^+$

PRL133, 251801(2024)

- Simultaneous model-independent search for any CPV across all Dalitz regions

- A_{CP} is measured in all Dalitz bins

$$\Delta A_{CP}^{i} = A_{\rm raw}^{i,S} - A_{\rm raw}^{i,C} - \Delta A_{\rm raw}^{\rm global} \qquad \Delta A_{\rm raw}^{\rm global} = \frac{\sum_i^{N_{\rm bins}} \frac{A_{\rm raw}^{i,S} - A_{\rm raw}^{i,C}}{\sigma^2_{A_{\rm raw}^{i,S}} + \sigma^2_{A_{\rm raw}^{i,C}}}}{\sum_i^{N_{\rm bins}} \frac{1}{\sigma^2_{A_{\rm raw}^{i,S}} + \sigma^2_{A_{\rm raw}^{i,C}}}}$$



- $\Delta A_{\rm raw}^{\rm global}$ is the global difference in asymmetries averaged over all bins in the Dalitz plots. Any global asymmetry difference between the Signal and Control channels is cancelled.
- The significance is estimated with the χ^2 test statistic as

$$S_{\Delta_{CP}}^{i} = \frac{\Delta A_{CP}^{i}}{\sigma_{\Delta A_{CP}^{i}}} \qquad \chi^2(S_{\Delta_{CP}}) = \sum_{i}^{N_{\rm bins}} (S_{\Delta_{CP}}^{i})^2$$

χ^2/NDF=31.8/22, corresponding p value is 8.1%.
Consistent with CP symmetry.

Mixing and CPV parameters with $D^0 \to K^-\pi^+$

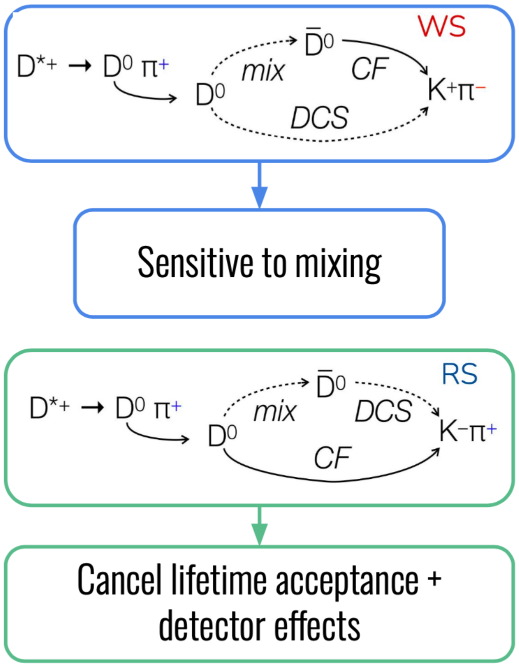
PRD111, 012001 (2025)

- Full RUN2 data are analyzed to select prompt production of $D^{*+} \to D^0\pi^+$
- The ratio of the time-dependent decay rates between the DCS ($K^+\pi^-$) and CF ($K^-\pi^+$) modes
- Two decay configurations are measured

$$R^+_{K\pi}(t) \equiv \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\bar{D}^0(t) \to K^+\pi^-)} \qquad R^-_{K\pi}(t) \equiv \frac{\Gamma(\bar{D}^0(t) \to K^-\pi^+)}{\Gamma(D^0(t) \to K^-\pi^+)}$$

- Up to x_{12}^2 and y_{12}^2

$$R^{\pm}_{K\pi}(t) \approx R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} \pm \Delta c_{K\pi})\, t + (c'_{K\pi} \pm \Delta c'_{K\pi})\, t^2$$



mixing parameters

$$c_{K\pi} \approx y_{12} \cos\phi_f^{\Gamma} \cos\Delta_f + x_{12}\cos\phi_f^{M} \sin\Delta_f$$

$$c'_{K\pi} \approx \frac{1}{4}(x_{12}^2 + y_{12}^2)$$

strong phase difference $\Delta_f = -10° \pm 3°$

CPV parameters

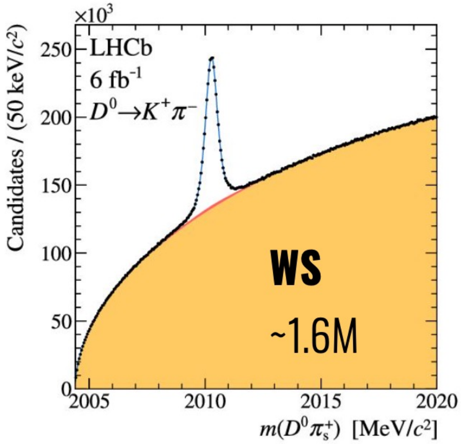
$$A_{K\pi} \equiv \frac{|A_{\bar{f}}/\bar{A}_{\bar{f}}|^2 - |\bar{A}_f/A_f|^2}{|A_{\bar{f}}/\bar{A}_{\bar{f}}|^2 + |\bar{A}_f/A_f|^2} \approx a^d_{\mathrm{DCS}}$$ direct CPV

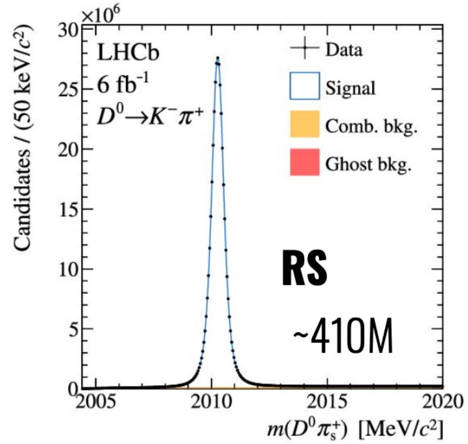
$$\Delta c_{K\pi} \approx x_{12}\sin\phi_f^{M}\cos\Delta_f - y_{12}\sin\phi_f^{\Gamma}\sin\Delta_f$$ mixing CPV

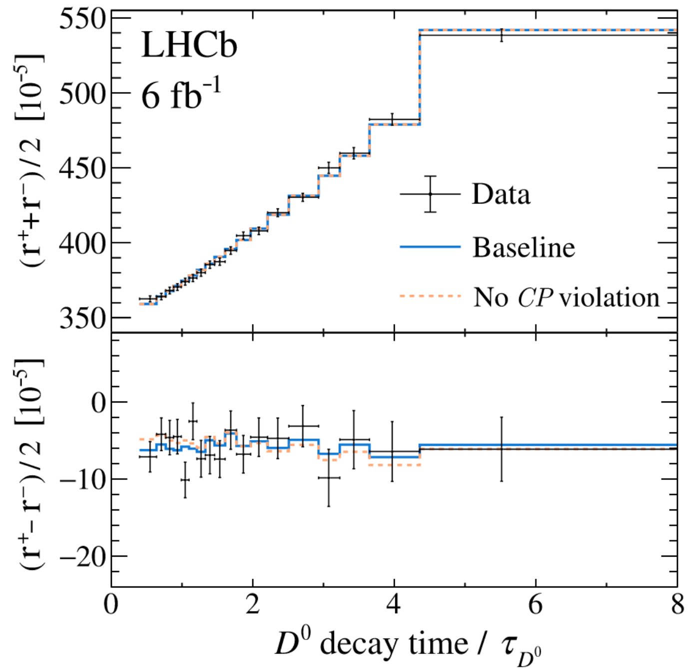
$$\Delta c'_{K\pi} \approx \frac{1}{2}x_{12}y_{12}\sin(\phi_f^{M} - \phi_f^{\Gamma})$$ interference CPV

Mixing and CPV parameters with $D^0 \to K^-\pi^+$

PRD111, 012001 (2025)







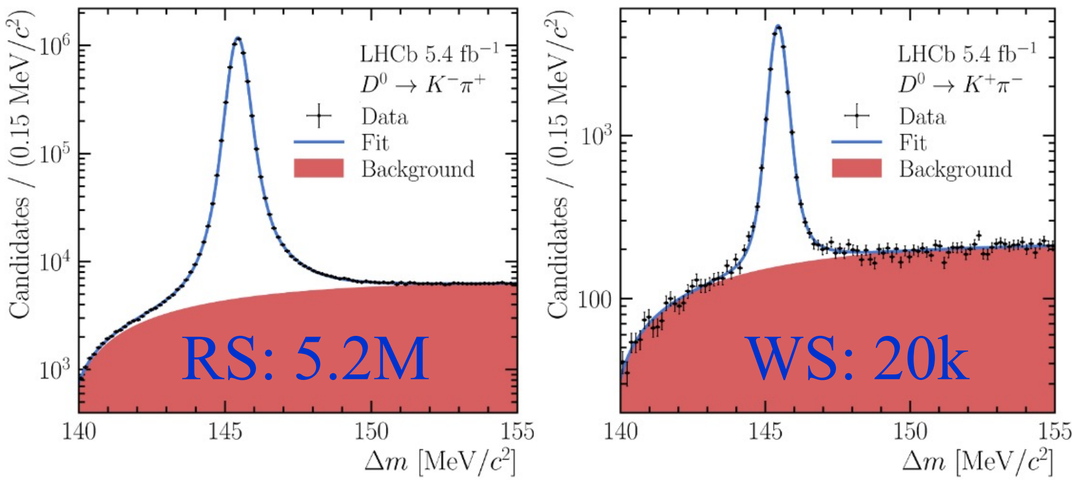
Parameters	
$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$
$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$

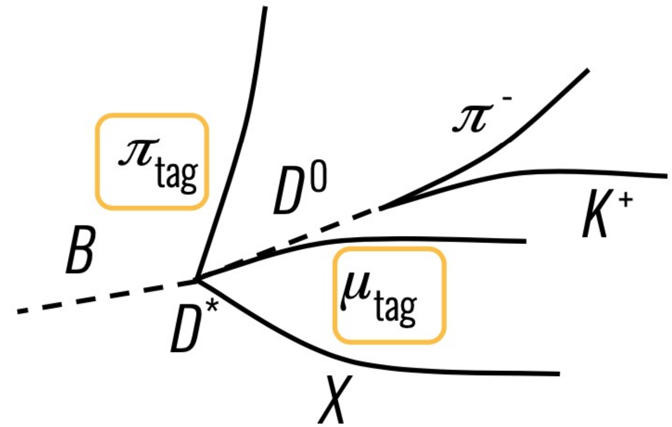
- $c_{K\pi}^{(\prime)}$ are improved from previous LHCb measurement based on RUN1 data: stat. error down by 1.6 and syst. error down by 2
- No CPV is seen

Mixing and CPV in SL-tagged $D^0 \to K^-\pi^+$

JHEP03, 149 (2025)

Complementary measurement to the prompt one with higher sensitivity to lower decay time





$\bar{B} \to D^*(2010)^+\mu^- X$

WS/RS ratio is measured as before (slightly different parametrization)

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

$$R_D^+ \equiv \left|\frac{\mathcal{A}_{K^+\pi^-}}{\bar{\mathcal{A}}_{K^+\pi^-}}\right|^2, \quad R_D^- \equiv \left|\frac{\bar{\mathcal{A}}_{K^-\pi^+}}{\mathcal{A}_{K^-\pi^+}}\right|^2 \qquad \begin{pmatrix} x'^\pm \\ y'^\pm \end{pmatrix} = |q/p|^{\pm 1} \begin{pmatrix} \cos[\delta \pm \phi] & \sin[\delta \pm \phi] \\ -\sin[\delta \pm \phi] & \cos[\delta \pm \phi] \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

Mixing and CPV in SL-tagged $D^0 \to K^- \pi^+$

JHEP03, 149 (2025)

No direct CPV

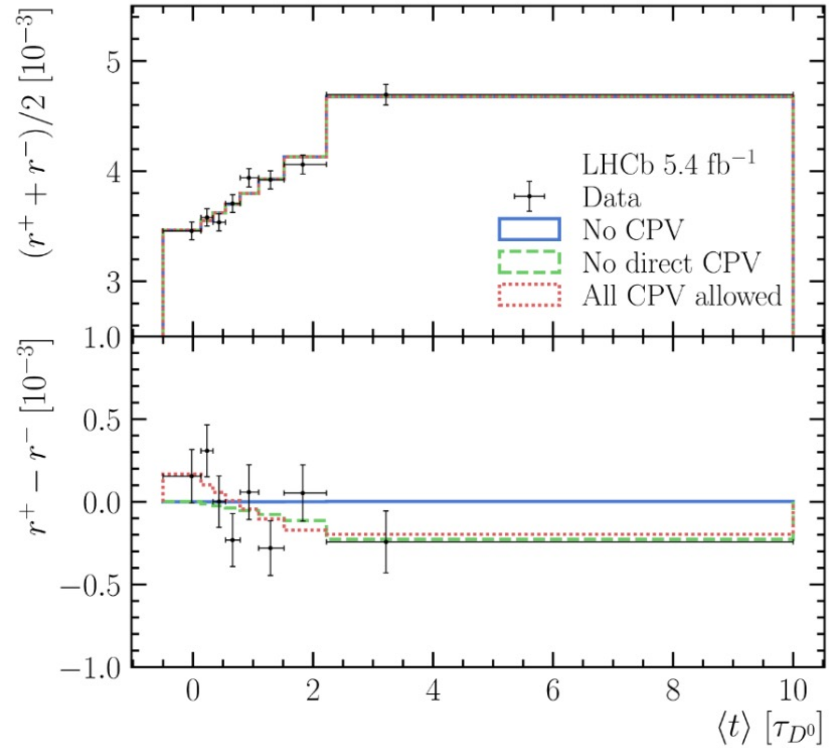
R_D	$(347.1 \pm 5.5 \pm 1.3) \times 10^{-5}$
y'^+	$(5.4 \pm 1.9 \pm 0.5) \times 10^{-3}$
$(x'^+)^2$	$(0.0 \pm 1.5 \pm 0.3) \times 10^{-4}$
y'^-	$(6.3 \pm 1.9 \pm 0.4) \times 10^{-3}$
$(x'^-)^2$	$(0.1 \pm 1.6 \pm 0.3) \times 10^{-4}$

Allow CPV

R_D^+	$(355.2 \pm 7.9 \pm 2.3) \times 10^{-5}$
y'^+	$(3.6 \pm 2.2 \pm 0.3) \times 10^{-3}$
$(x'^+)^2$	$(1.1 \pm 1.6 \pm 0.1) \times 10^{-4}$
R_D^-	$(339.1 \pm 7.9 \pm 2.3) \times 10^{-5}$
y'^-	$(8.1 \pm 2.3 \pm 0.3) \times 10^{-3}$
$(x'^-)^2$	$(-1.1 \pm 1.9 \pm 0.1) \times 10^{-4}$

$$A_D \equiv \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (2.3 \pm 1.7)\,\%$$

consistent with CP symmetry



No CPV

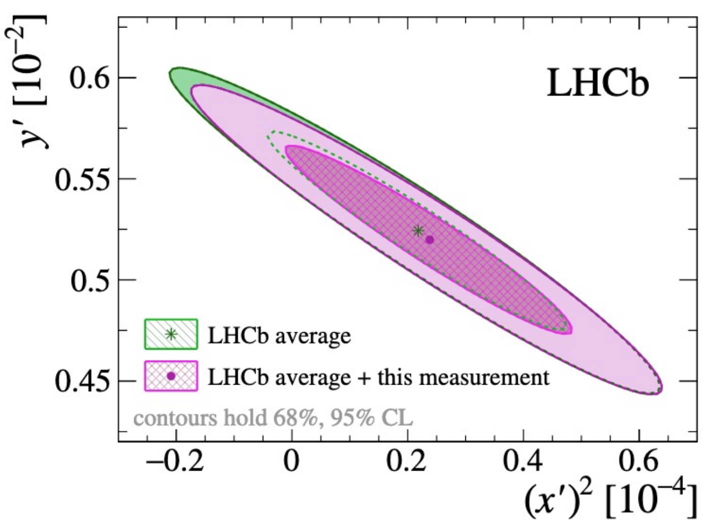
R_D	$(347.0 \pm 5.5 \pm 1.4) \times 10^{-5}$
y'	$(5.8 \pm 1.6 \pm 0.2) \times 10^{-3}$
$(x')^2$	$(0.0 \pm 1.2 \pm 0.1) \times 10^{-4}$

Combinations of prompt and SL-tagged results

JHEP03, 149 (2025)

Parameters	prompt
$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$
$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$

	SL-tagged
R_D	$(347.2 \pm 5.8) \times 10^{-5}$
$c_{K\pi}$	$(5.8 \pm 1.6) \times 10^{-3}$
$c'_{K\pi}$	$(0.9 \pm 2.6) \times 10^{-5}$
A_D	$(2.3 \pm 1.7) \times 10^{-2}$
$\Delta c_{K\pi}$	$(-2.3 \pm 1.6) \times 10^{-3}$
$\Delta c'_{K\pi}$	$(2.1 \pm 2.6) \times 10^{-5}$



about a few percent improvement

Charm impact to γ measurement

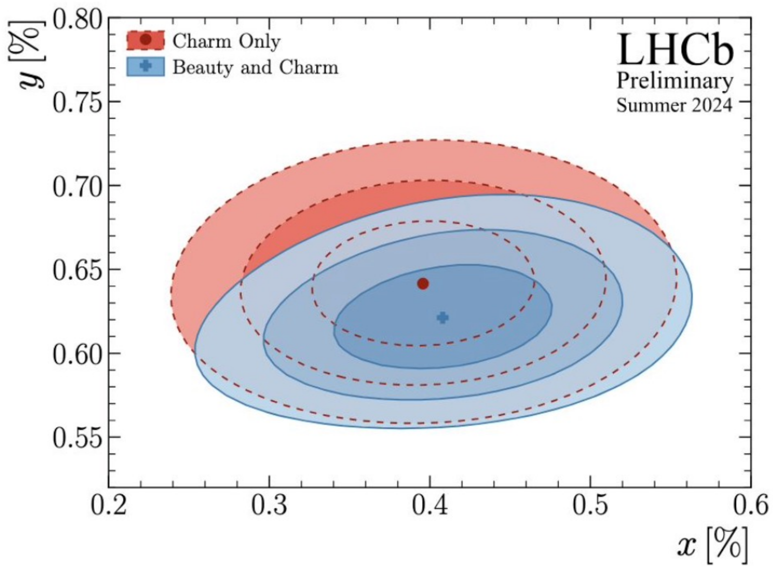
LHCb-CONF-2024-004

- CKM angle γ, Charm mixing and CPV parameters measurement included in a single fit
  ➔ improves precision on single observables exploiting full information
- 9 new LHCb measurements during 2023-2024 are included

$$x = (0.41 \pm 0.05)\%$$
$$y = (0.621^{+0.022}_{-0.021})\%$$
$$|q/p| = 0.989 \pm 0.015$$
$$\phi = (-2.5 \pm 1.2)^\circ$$
$$a^d_{\pi^+\pi^-} = (22 \pm 6) \times 10^{-4}$$
$$a^d_{K^+K^-} = (6^{+6}_{-5}) \times 10^{-4}$$
$$\gamma = (64.6 \pm 2.8)^\circ$$

Previous determination

$$\gamma = (63.8^{+3.5}_{-3.7})^\circ$$



Global fits to constraint CPV

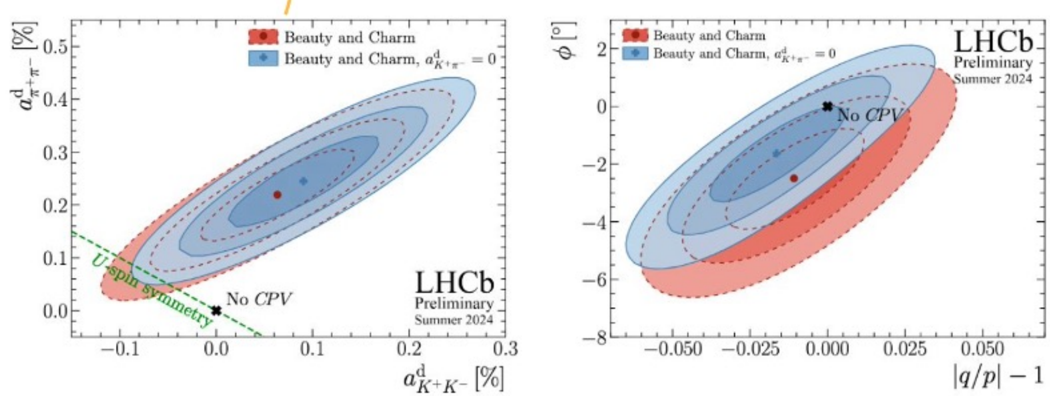
LHCb-CONF-2024-004

Assuming CPV for DCS within SM is 0, a^d_{DCS}=0, i.e, only one amplitude contributing to decay

Fit is repeated applying external constraint to a^d_{DCS}. Hence, it improves sensitivity to charm CPV observables.

$$x = (0.41 \pm 0.05)\%$$
$$y = (0.619 \pm 0.021)\%$$
$$|q/p| = 0.984^{+0.014}_{-0.015}$$
$$\phi = (-1.6^{+1.1}_{-1.2})^\circ$$
$$a^d_{\pi^+\pi^-} = (24 \pm 6) \times 10^{-4}$$
$$a^d_{K^+K^-} = (9 \pm 5) \times 10^{-4}$$

Enhancing $\pi^+\pi^-$ CPV evidence!



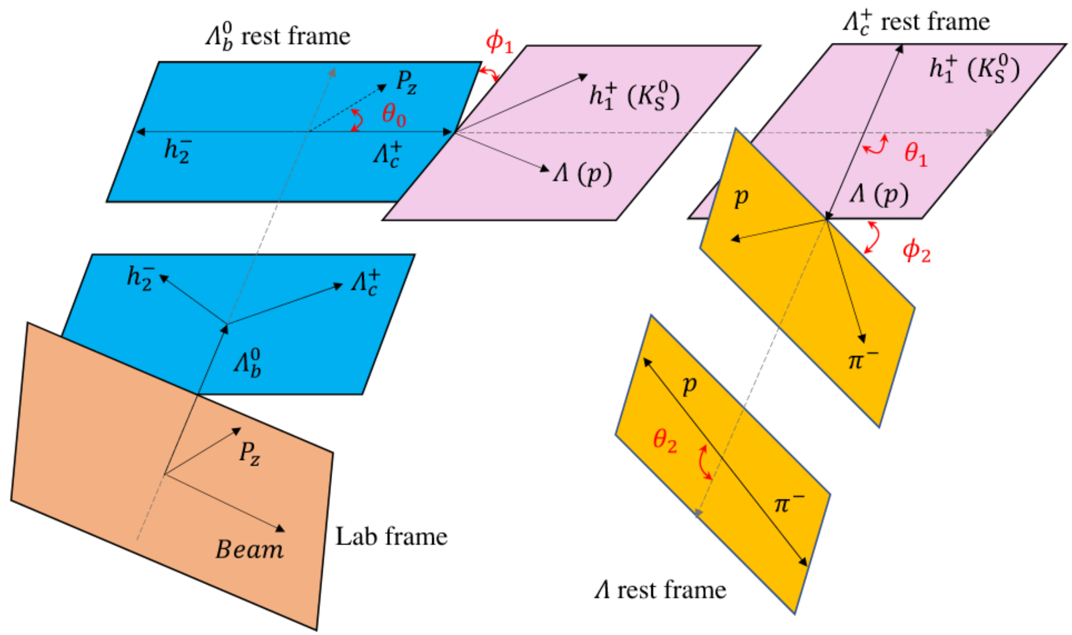
CPV search in Λ_c^+ two-body decays

- CP symmetry can be precisely tested in baryon weak decay by studying the polarization of the produced daughter particles.
- For simple case of Λ_c^+ decaying into $\frac{1}{2}^+$ baryon and a 0^- meson, decay asymmetries can be defined as

$$\alpha = \frac{2\mathrm{Re}(S^* \cdot P)}{|S|^2 + |P|^2}$$

$$\beta = \frac{2\mathrm{Im}(S^* \cdot P)}{|S|^2 + |P|^2} = \sqrt{1-\alpha^2}\sin\Delta$$

$$\gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2} = \sqrt{1-\alpha^2}\cos\Delta,$$

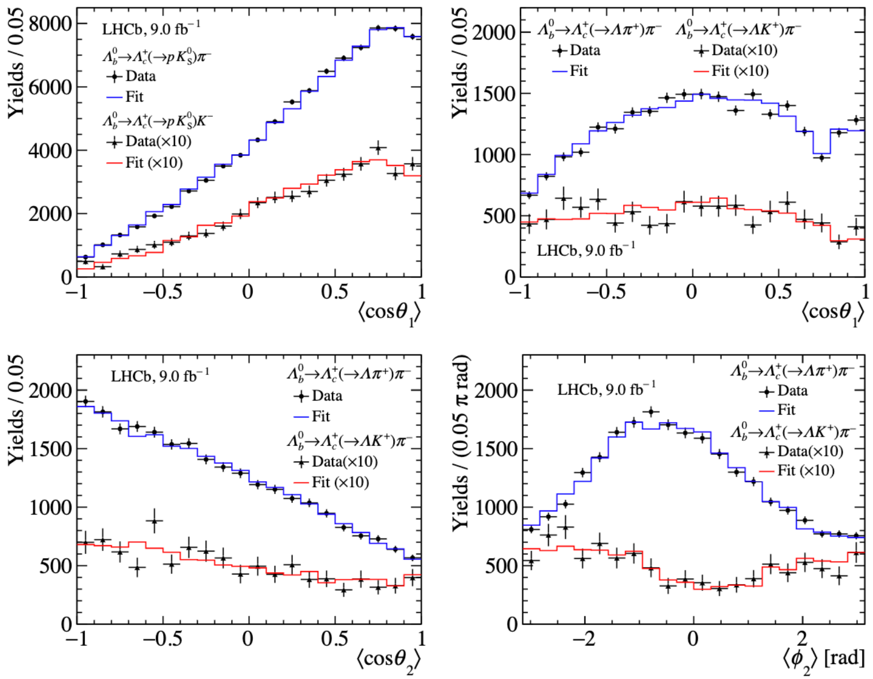


- This study takes advantage of nearly 100% longitudinal polarization of the Λ_c^+ from $\Lambda_b^0 \to \Lambda_c^+ h^-$

CPV search in Λ_c^+ two-body decays

PRL133 (2024) 26, 261804

RUN1+2 data



Simultaneous fit to five decay modes: $\Lambda_b^0 \to \Lambda_c^+(\to pK_S)\pi^-$, $\Lambda_c^+(\to pK_S)K^-$, $\Lambda_c^+(\to \Lambda\pi^+)\pi^-$, $\Lambda_c^+(\to \Lambda\pi^+)K^-$, $\Lambda_c^+(\to \Lambda K^+)\pi^-$

$$A_\alpha = (\alpha + \bar{\alpha})/(\alpha - \bar{\alpha}) = -\tan\Delta\delta \tan\Delta\phi$$

no CPV is seen

Decay	$\langle\alpha\rangle$	A_α	
$\Lambda_b^0 \to \Lambda_c^+\pi^-$	$-1.003 \pm 0.008 \pm 0.005$	$0.007 \pm 0.008 \pm 0.005$	first measurement
$\Lambda_b^0 \to \Lambda_c^+K^-$	$-0.964 \pm 0.028 \pm 0.015$	$-0.032 \pm 0.029 \pm 0.006$	first measurement
$\Lambda_c^+ \to \Lambda\pi^+$	$-0.785 \pm 0.006 \pm 0.003$	$-0.003 \pm 0.008 \pm 0.002$	most precise
$\Lambda_c^+ \to \Lambda K^+$	$-0.516 \pm 0.041 \pm 0.021$	$0.102 \pm 0.080 \pm 0.023$	most precise
$\Lambda_c^+ \to pK_S^0$	$-0.754 \pm 0.008 \pm 0.006$	$-0.014 \pm 0.011 \pm 0.008$	most precise
$\Lambda \to p\pi^-$	$0.733 \pm 0.012 \pm 0.006$	$-0.022 \pm 0.016 \pm 0.007$	consistent with BESIII

CPV search in Λ_c^+ two-body decays

PRL133 (2024) 26, 261804

The parameters β, γ, and Δ are measured for the first time

Decay	$\Lambda_c^+ \to \Lambda\pi^+$	$\Lambda_c^+ \to \Lambda K^+$
β	$0.368 \pm 0.019 \pm 0.008$	$0.35 \pm 0.12 \pm 0.04$
$\bar{\beta}$	$-0.387 \pm 0.018 \pm 0.010$	$-0.32 \pm 0.11 \pm 0.03$
γ	$0.502 \pm 0.016 \pm 0.006$	$-0.743 \pm 0.067 \pm 0.024$
$\bar{\gamma}$	$0.480 \pm 0.016 \pm 0.007$	$-0.828 \pm 0.049 \pm 0.013$
Δ (rad)	$0.633 \pm 0.036 \pm 0.013$	$2.70 \pm 0.17 \pm 0.04$
$\bar{\Delta}$ (rad)	$-0.678 \pm 0.035 \pm 0.013$	$-2.78 \pm 0.13 \pm 0.03$
R_β	$0.012 \pm 0.017 \pm 0.005$	$-0.04 \pm 0.15 \pm 0.02$
R'_β	$-0.481 \pm 0.019 \pm 0.009$	$-0.65 \pm 0.17 \pm 0.07$

$R_\beta = (\beta + \bar{\beta})/(\alpha - \bar{\alpha}) = \tan\Delta\phi$ $\quad$ $R'_\beta \equiv (\beta - \bar{\beta})/(\alpha - \bar{\alpha}) = \tan\Delta\delta$

no CPV is seen

$\Lambda_c^+ \to \Lambda\pi^+$

$\Delta\phi = 0.01 \pm 0.02$
$\Delta\delta = 2.693 \pm 0.017$

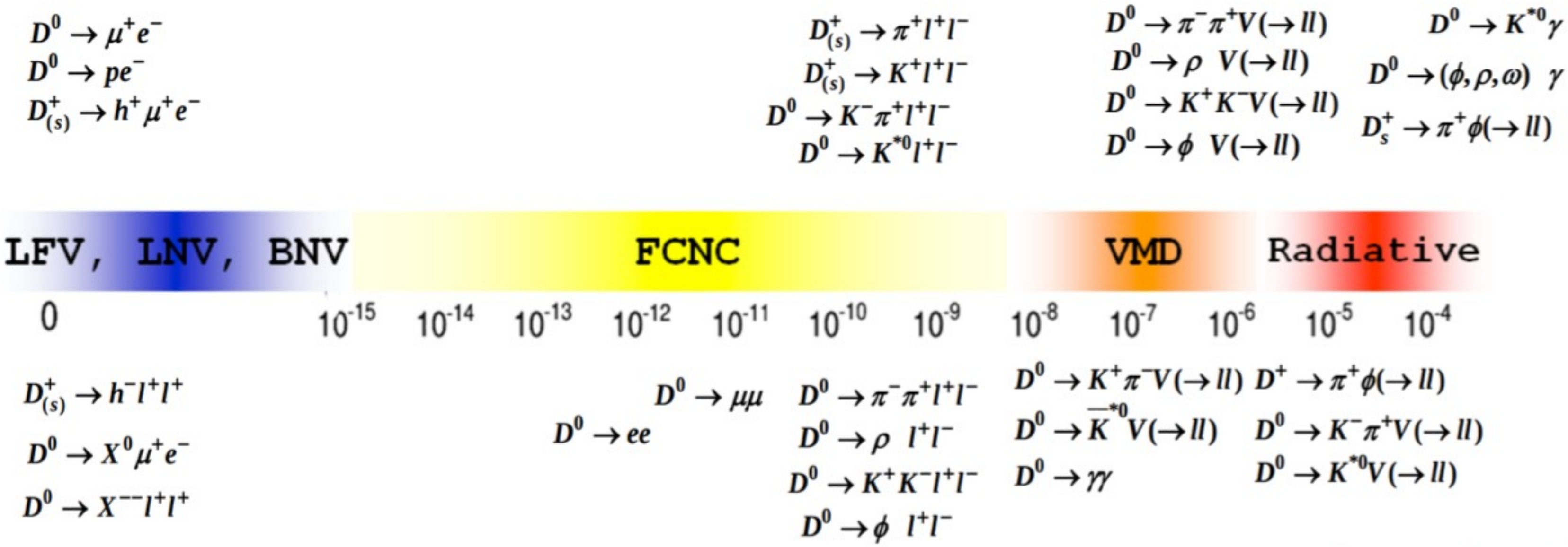
$\Lambda_c^+ \to \Lambda K^+$

$\Delta\phi = -0.03 \pm 0.15$
$\Delta\delta = 2.57 \pm 0.19$

Charm Rare Decays

Rainbow of the Charm decays:

from forbidden to not-so-rare decays



[PRD 66 (2002) 014009]

FCNC

- short distance contributions to effective c → u transitions are tiny ($< 10^{-9}$)
- Short distance : interested, computable by pQCD, directly test SM $\mathcal{B}_{D^0 \to X_u^0 e^+ e^-} \simeq 8 \cdot 10^{-9}$ $\mathcal{B}_{D^+ \to X_u^+ e^+ e^-} \simeq 2 \cdot 10^{-8}$

FCNC suppressed in SM

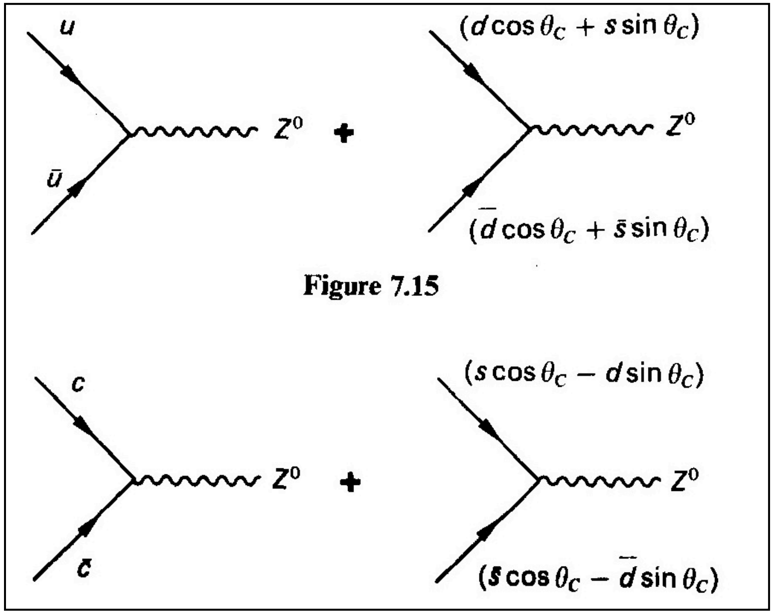
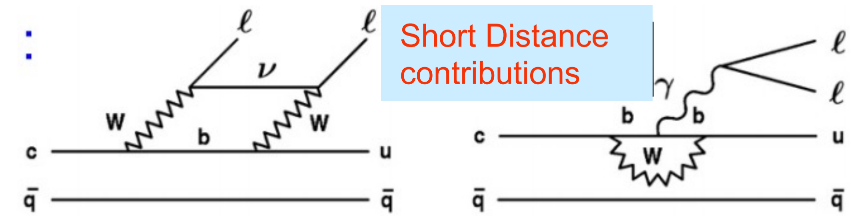


Figure 7.15

$D \to h l^+ l^-$

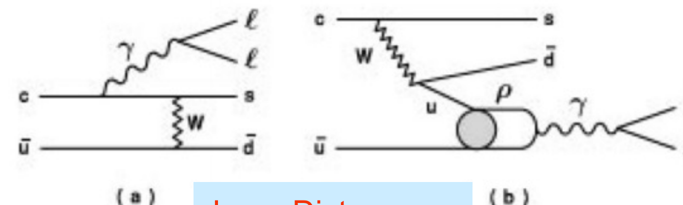
$c \to u l^+ l^-$:

Stronger diagram cancellation than down-types

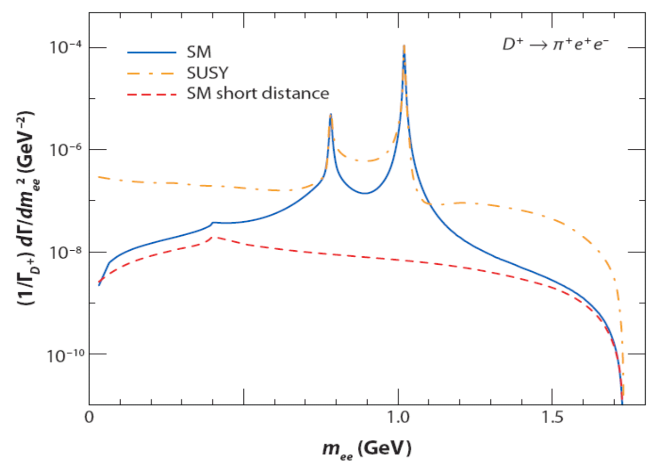


$$\mathcal{L}_{eff}^{SD} = \frac{G_F}{\sqrt{2}} V_{cb}^* V_{ub} \sum_{i=7,9,10} C_i Q_i,$$

Sensitive to new physics

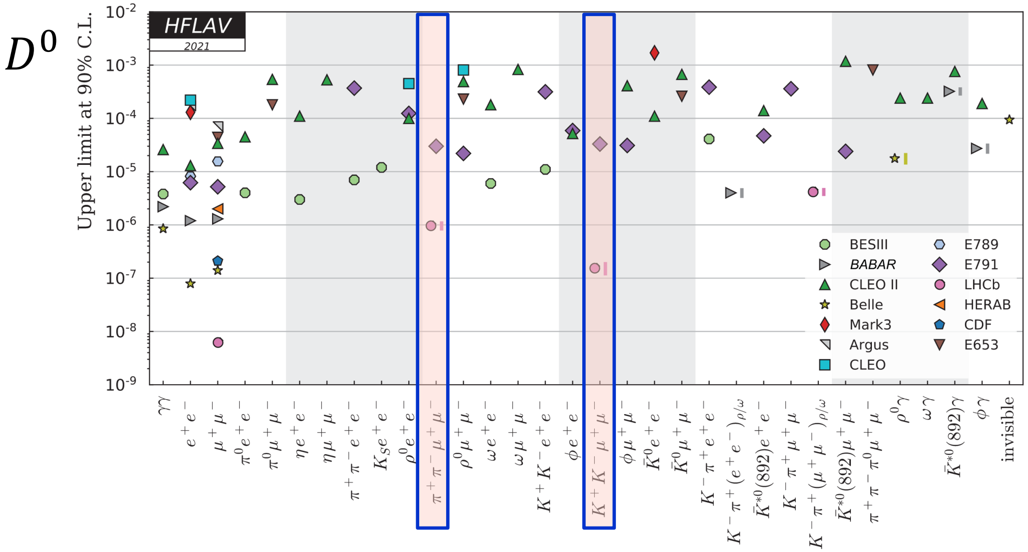


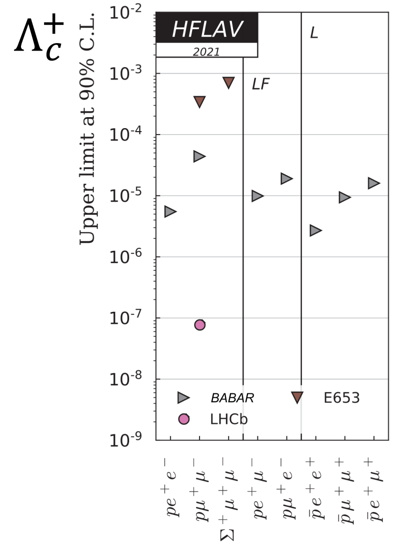
Long Distance contributions

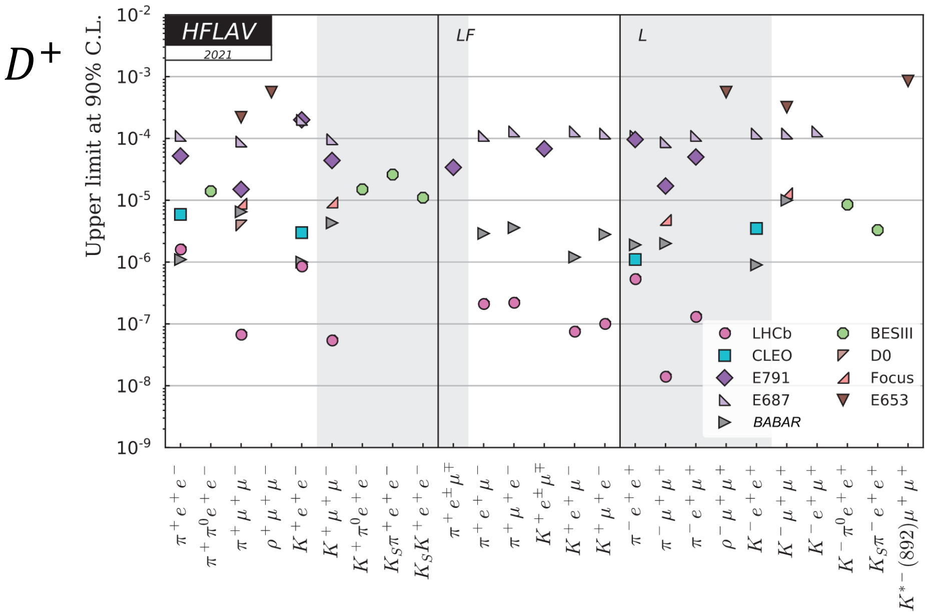


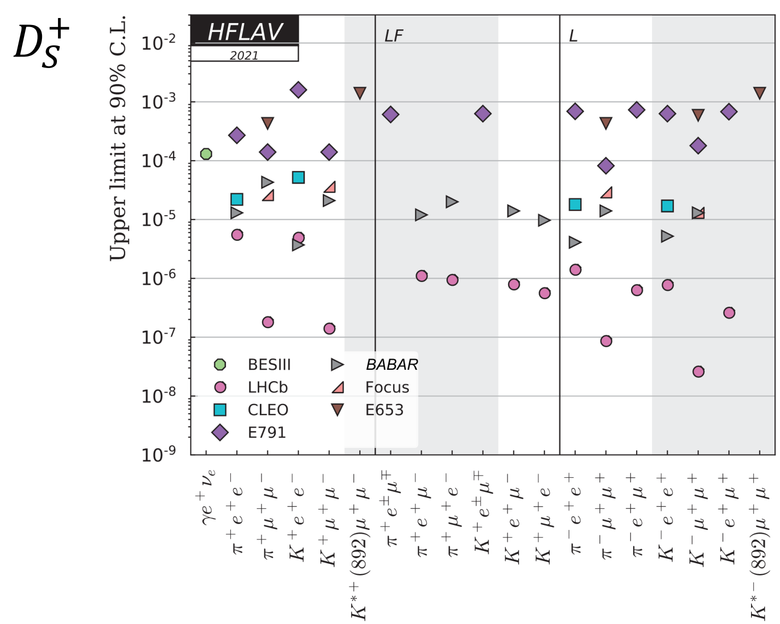
- Long distance effect can enhance the rate to $10^{-6} \sim 10^{-7}$, dominantly, such as $D \to X_u Y, Y \to l^+ l^-$ ($Y = \rho^0, \omega, \eta, or\ \phi$)
- Allow with sizeable decay rate in NP

World-wide searches until 2021









Search for $D^0 \to h^+h^-e^+e^-$ decays

- LHCb firstly observed the FCNC processes $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $K^+K^-\mu^+\mu^-$ [PRL119, 181805(2017)]
  $B(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 1.10)\times10^{-7}$
  $B(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.18)\times10^{-7}$
- It is well motivated to search for the di-electron mode, to probe the universality of the electroweak interaction couplings to leptons of different generations
- Previous best upper limits (ULs) on branching fractions (BFs) are from BESIII

Decay	Upper limit ($\times10^{-6}$)	Experiment	Year
$D^0 \to \pi^0 e^+e^-$	0.4	BESIII	2018
$D^0 \to \eta e^+e^-$	0.3	BESIII	2018
$D^0 \to \omega e^+e^-$	0.6	BESIII	2018
$D^0 \to K_S^0 e^+e^-$	1.2	BESIII	2018
$D^0 \to \rho e^+e^-$	124.0	E791	2001
$D^0 \to \phi e^+e^-$	59.0	E791	2001
$D^0 \to \bar{K}^{*0} e^+e^-$	47.0	E791	2001
$D^0 \to \pi^+\pi^- e^+e^-$	0.7	BESIII	2018
$D^0 \to K^+K^- e^+e^-$	1.1	BESIII	2018
$D^0 \to K^-\pi^+ e^+e^-$	4.1	BESIII	2018

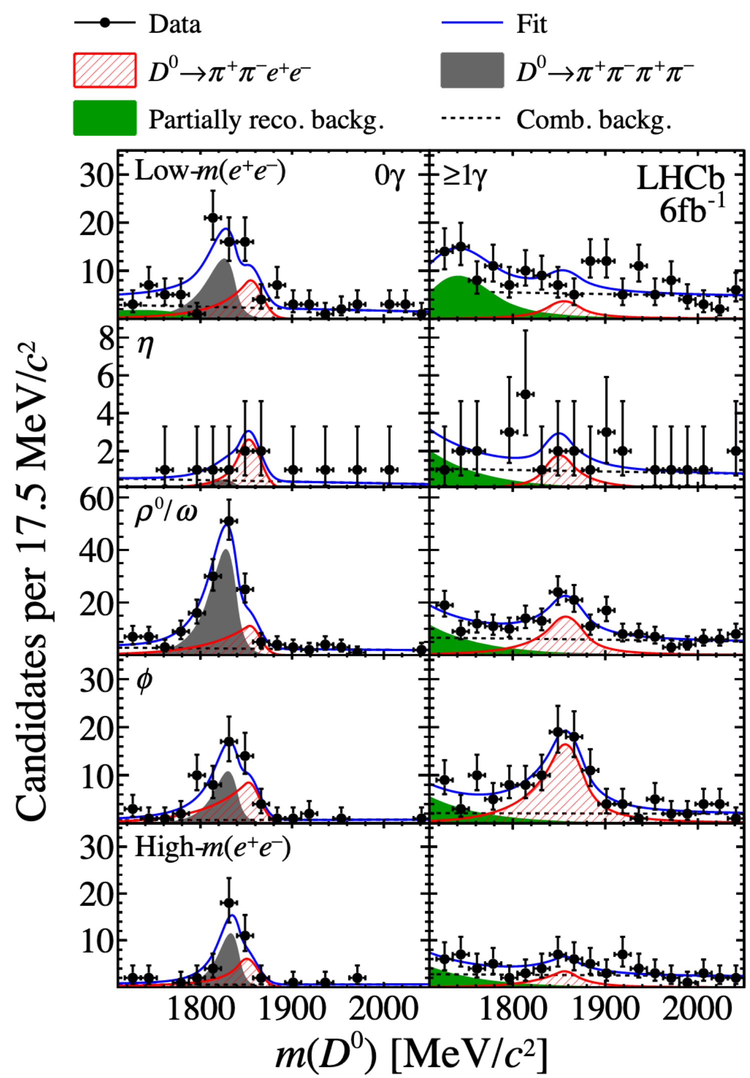
Search for $D^0 \to \pi^+\pi^-e^+e^-$

arXiv:2412.09414

D^0 are selected from the decays of $D^{*+} \to D^0\pi^+$

- Observation of $D^0 \to \pi^+\pi^-e^+e^-$ in ρ/ω and ϕ mass regions
- The current best upper limits on BF in other regions have been established.
- The BF in the di-electron mode is compatible with the one of the di-muon mode.

$D^0 \to \pi^+\pi^-e^+e^-$		
$m(e^+e^-)$ region	$[\text{MeV}/c^2]$	$\mathcal{B}\ [10^{-7}]$
Low mass	211–525	$< 4.8\,(5.4)$
η	525–565	$< 2.3\,(2.7)$
ρ^0/ω	565–950	$4.5 \pm 1.0 \pm 0.7 \pm 0.6$
ϕ	950–1100	$3.8 \pm 0.7 \pm 0.4 \pm 0.5$
High mass	> 1100	$< 2.0\,(2.2)$
Total	–	$13.3 \pm 1.1 \pm 1.7 \pm 1.8$

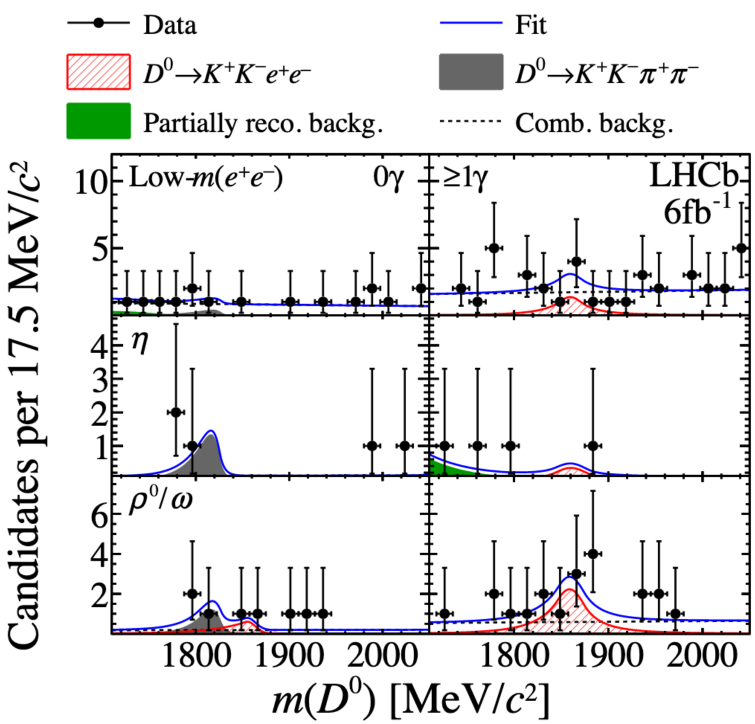


Search for $D^0 \to K^+K^-e^+e^-$

arXiv:2412.09414

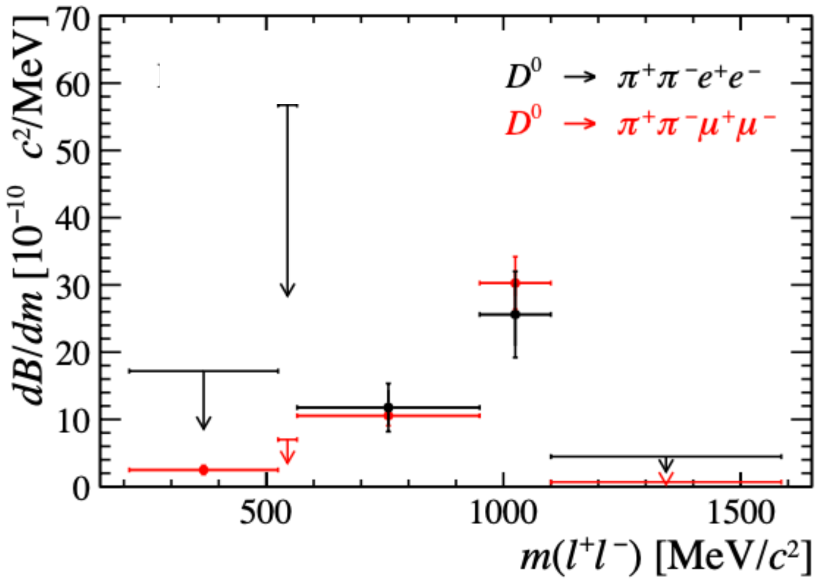
D^0 are selected from the decays of $D^{*+} \to D^0\pi^+$

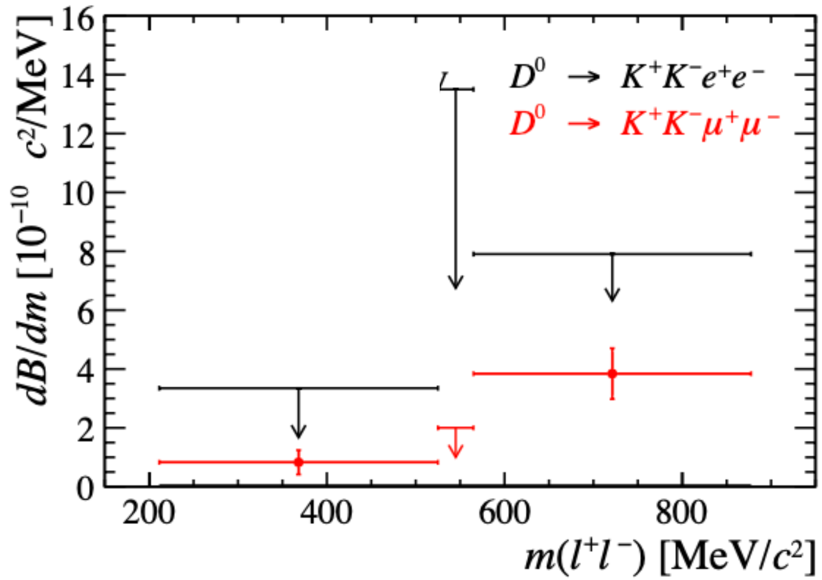
- No evidences with the current precision.
- The current best upper limits on the BFs have been established.
- Observation of $D^0 \to \pi^+\pi^-e^+e^-$ in ρ/ω and ϕ mass regions



$D^0 \to K^+K^-e^+e^-$		
$m(e^+e^-)$ region	[MeV/c^2]	$\mathcal{B}$ [10^{-7}]
Low mass	211–525	$< 1.0\,(1.1)$
η	525–565	$< 0.4\,(0.5)$
ρ^0/ω	> 565	$< 2.2\,(2.5)$

Comparison for $D^0 \to h^+h^-l^+l^-$





no evidence for lepton flavour universality violation

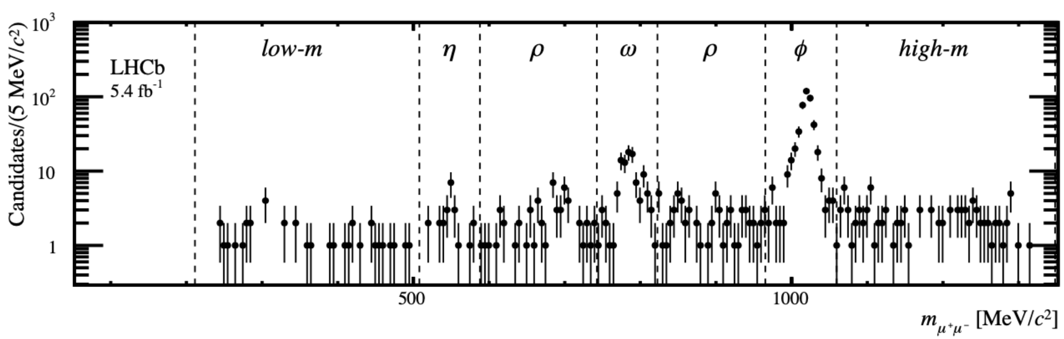
Search for $\Lambda_c^+ \to p\mu^+\mu^-$

PRD110, 052007 (2024)

- LHCb searched for $\Lambda_c^+ \to p\mu^+\mu^-$ based on RUN1 data and place the best UL in 2018

Mode	Limit × 10^6	Experiment
pe^+e^-	5.5	*BABAR*
$p\mu^+\mu^-$	340.0	E653
	44.0	*BABAR*
	0.077	LHCb

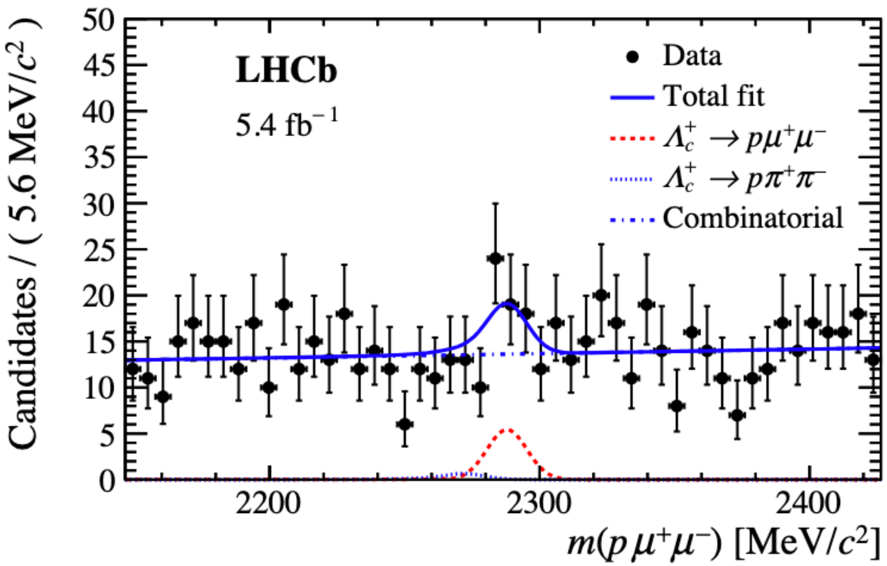
- LHCb searched for $\Lambda_c^+ \to p\mu^+\mu^-$ in the resonant and non-resonant di-muon mass regions with LHCb RUN2 (5.4 fb^{-1}) data
  - ✓ Determine the branching fractions in the ρ, ω and η resonant regions;
  - ✓ Search the FCNC process in the non-resonant region;
  - ✓ uses the ϕ resonant region as normalization.

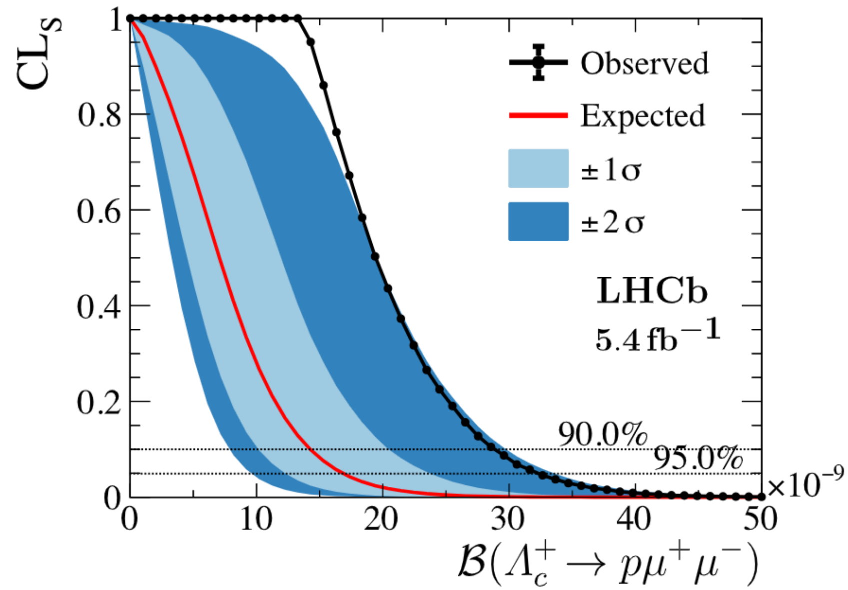


Search for $\Lambda_c^+ \to p\mu^+\mu^-$

PRD110, 052007 (2024)

No signal evidence for the FCNC process in the non-resonant region

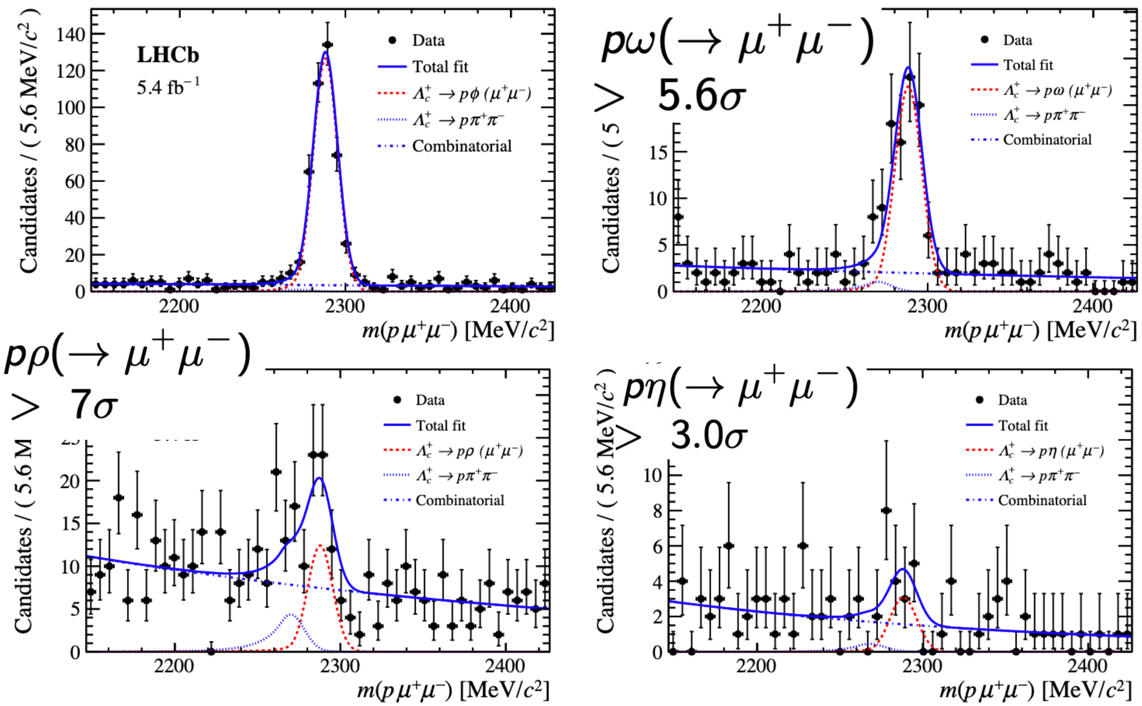




The best upper limit: $\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 2.9\ (3.2) \times 10^{-8}$ at 90% (95%) CL.

Search for $\Lambda_c^+ \to p\mu^+\mu^-$

PRD110, 052007 (2024)



	BF($\times 10^{-3}$)	
$\Lambda_c^+ \to p\eta$	1.24 ± 0.30	BESIII(2017)[87]
	1.42 ± 0.12	Belle(2021)[88]
	1.57 ± 0.12	BESIII(2023)[91]
	1.63 ± 0.33	BESIII(2024)[89]
	1.67 ± 0.80	LHCb(2024)[92]
$\Lambda_c^+ \to p\eta'$	$0.56^{+0.25}_{-0.21}$	BESIII(2022)[94]
	0.47 ± 0.10	Belle(2022)[93]
$\Lambda_c^+ \to p\rho$	1.52 ± 0.44	LHCb(2024)[92]
$\Lambda_c^+ \to p\omega$	0.94 ± 0.39	LHCb(2018)[95]
	0.83 ± 0.11	Belle(2021)[96]
	1.11 ± 0.21	BESIII(2023)[91]
	0.98 ± 0.31	LHCb(2024)[92]

$$\mathcal{B}(\Lambda_c^+ \to p\omega) = (9.82 \pm 1.23\ (\text{stat.}) \pm 0.73\ (\text{syst.}) \pm 2.79\ (\text{ext.})) \times 10^{-4},$$

$$\mathcal{B}(\Lambda_c^+ \to p\rho) = (1.52 \pm 0.34\ (\text{stat.}) \pm 0.14\ (\text{syst.}) \pm 0.24\ (\text{ext.})) \times 10^{-3},$$

$$\mathcal{B}(\Lambda_c^+ \to p\eta) = (1.67 \pm 0.69\ (\text{stat.}) \pm 0.23\ (\text{syst.}) \pm 0.34\ (\text{ext.})) \times 10^{-3},$$

consistent with those measurements from BESIII and BELLE via non-leptonic decays

Resonance enhanced asymmetries in $\Lambda_c^+ \to p\mu^+\mu^-$

- Angular distributions and CP asymmetries on $\Lambda_c^+ \to p\mu^+\mu^-$ in the resonant regions can be used to separate the short and long-distance contributions.
- Interference effects between SM resonant and beyond-SM amplitudes can produce asymmetries as large as $O(\%)$

arXiv:2502.04013

Two asymmetries are probed:

- CP asymmetry

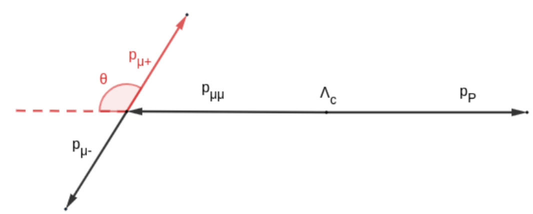
$$A_{CP} \equiv \frac{\Gamma(\Lambda_c^+ \to p\mu^+\mu^-) - \Gamma(\overline{\Lambda}_c^- \to \overline{p}\mu^+\mu^-)}{\Gamma(\Lambda_c^+ \to p\mu^+\mu^-) + \Gamma(\overline{\Lambda}_c^- \to \overline{p}\mu^+\mu^-)}$$

In real practice, raw asymmetry A_{CP}^{raw} is measured directly and A_{CP} is determined after correcting the production and detection asymmetries

$$A_{CP}^{raw} = \frac{N(\Lambda_c^+) - N(\overline{\Lambda}_c^-)}{N(\Lambda_c^+) + N(\overline{\Lambda}_c^-)} = A_{CP} + A_P(\Lambda_c^+) + A_D(p) + \left(A_D(\mu^+\mu^-) = 0\right)$$

$\Lambda_c^+ \to pK_S^0, K_S^0 \to \pi^+\pi^-$ is used as control sample to estimate the nuisance asymmetries

- Forward-backward asymmetry



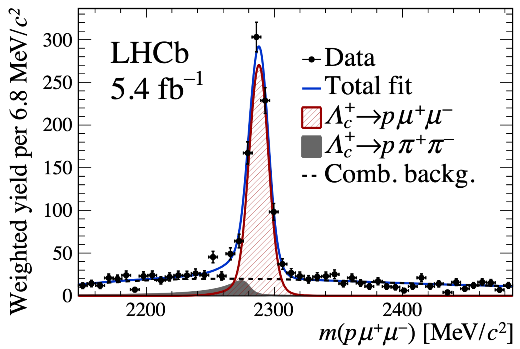
$$A_{FB} \equiv \frac{\Gamma(\cos\theta > 0) - \Gamma(\cos\theta < 0)}{\Gamma(\cos\theta > 0) + \Gamma(\cos\theta < 0)}$$

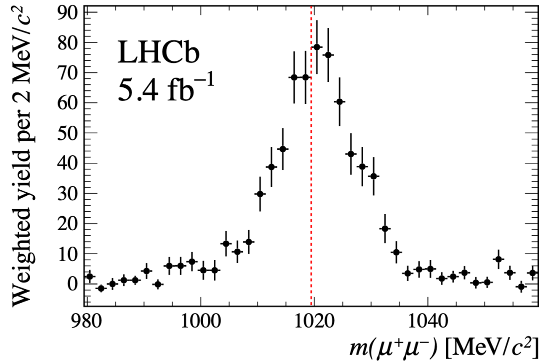
CP-average and CP asymmetry can enhance sensitivity to real and imaginary parts of NP couplings

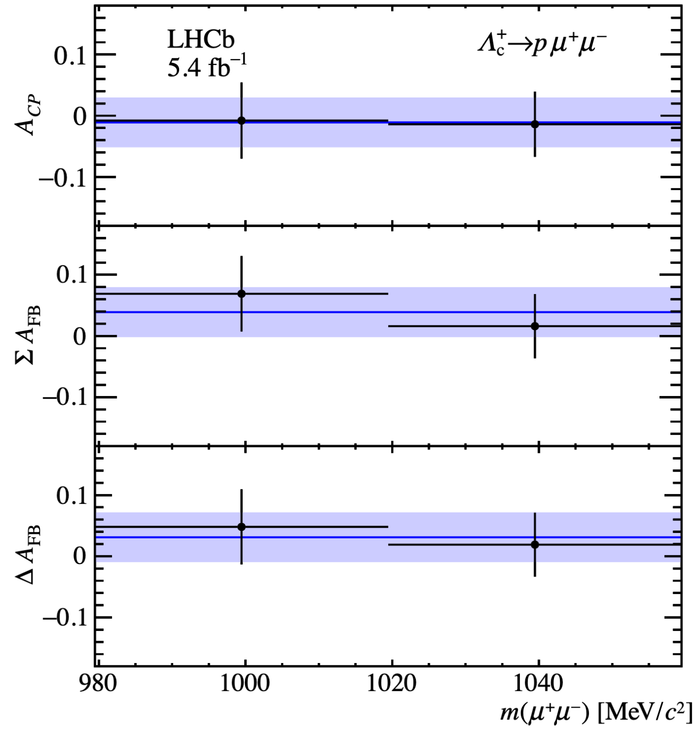
$$\Sigma A_{FB} = \frac{1}{2}\left(A_{FB}^{\Lambda_c^+} + A_{FB}^{\overline{\Lambda}_c^-}\right) \qquad \Delta A_{FB} = \frac{1}{2}\left(A_{FB}^{\Lambda_c^+} - A_{FB}^{\overline{\Lambda}_c^-}\right)$$

Resonance enhanced asymmetries in $\Lambda_c^+ \to p\mu^+\mu^-$

arXiv:2502.04013







	Efficiency-weighted yields		
$m(\mu^+\mu^-)$	Signal	Misid. back.	Comb. back.
ϕ_{low}	346 ± 22	57 ± 21	437 ± 26
ϕ_{high}	435 ± 22	35 ± 17	390 ± 25

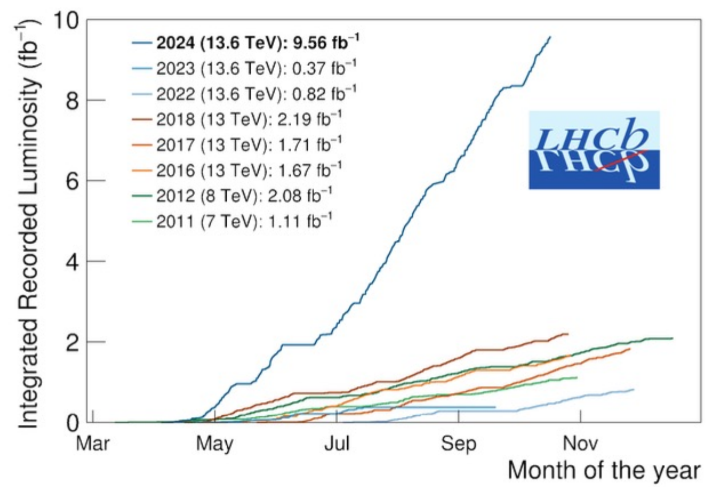
	Asymmetries		
$m(\mu^+\mu^-)$	A_{CP} [%]	$A_{FB}^{\Lambda_c^+}$ [%]	$A_{FB}^{\bar{\Lambda}_c^-}$ [%]
ϕ_{low}	$-0.8 \pm 6.2 \pm 0.6$	$11.7 \pm 8.5 \pm 1.1$	$2.2 \pm 8.7 \pm 1.4$
ϕ_{high}	$-1.4 \pm 5.3 \pm 0.6$	$3.5 \pm 7.2 \pm 0.9$	$-0.3 \pm 7.4 \pm 1.1$

- **confirm the SM prediction**
- **help to constrain the parameter space of NP models**
  [Hiller et al, arXiv 2410.00115]

Summary

- Charm physics is a unique probe to test the SM and search for new physics
- Many new measurement in the charm physics with many different observables
  - ✓ improved precisions on mixing and CPV parameters
  - ✓ except $D^0 \to h^+h^-$, no evidence of CP violation seen yet
  - ✓ best precisons in constraining the rates of the charmed FCNC decays

- Great prospects from LHCb with Run 3 dataset
  - ✓ new precision measurement will be possible
  - ✓ record luminosity of > 9.5 fb^{-1}



Thank you!

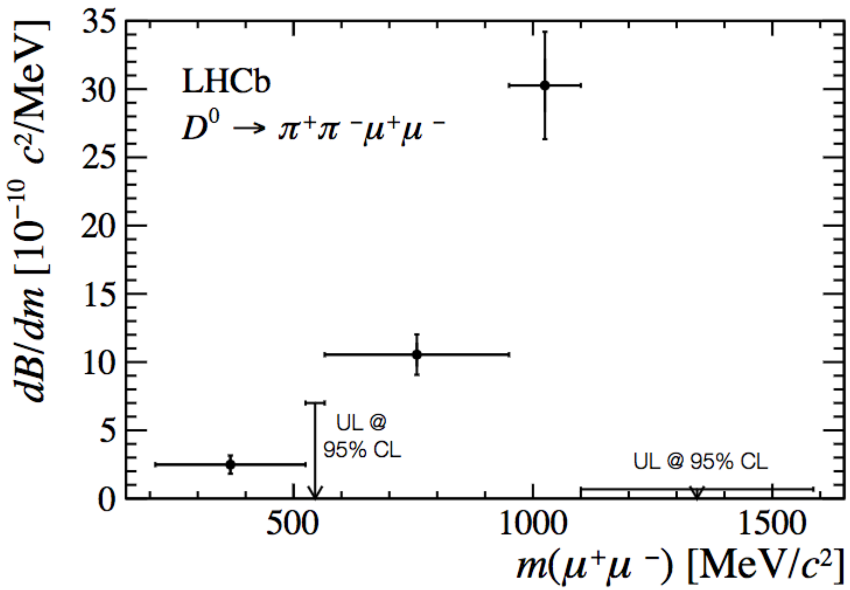
谢谢！

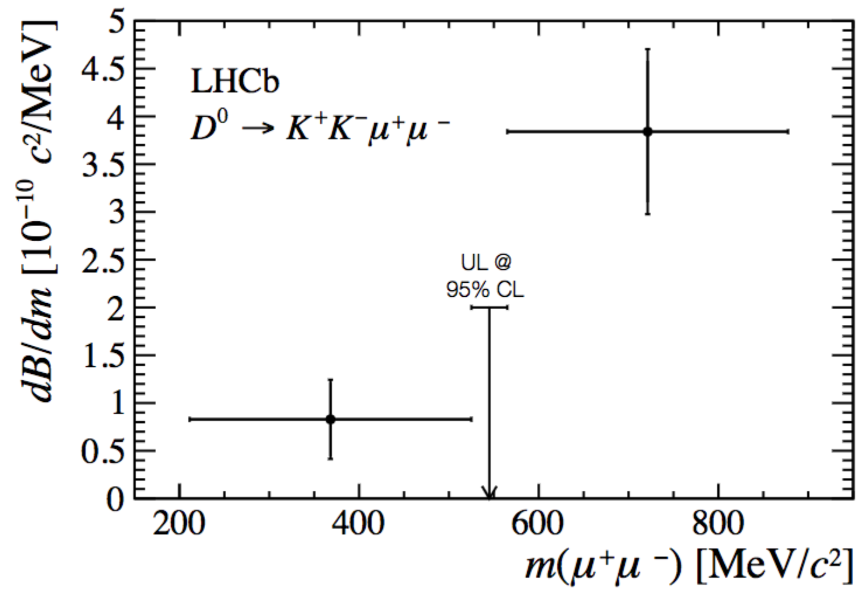
Backup Slides

$D^0 \to h^+h^-\mu^+\mu^-$

Run I (2/fb)

PRL 119, 181805 (2017)





- Rarest charm-hadron decays ever observed:

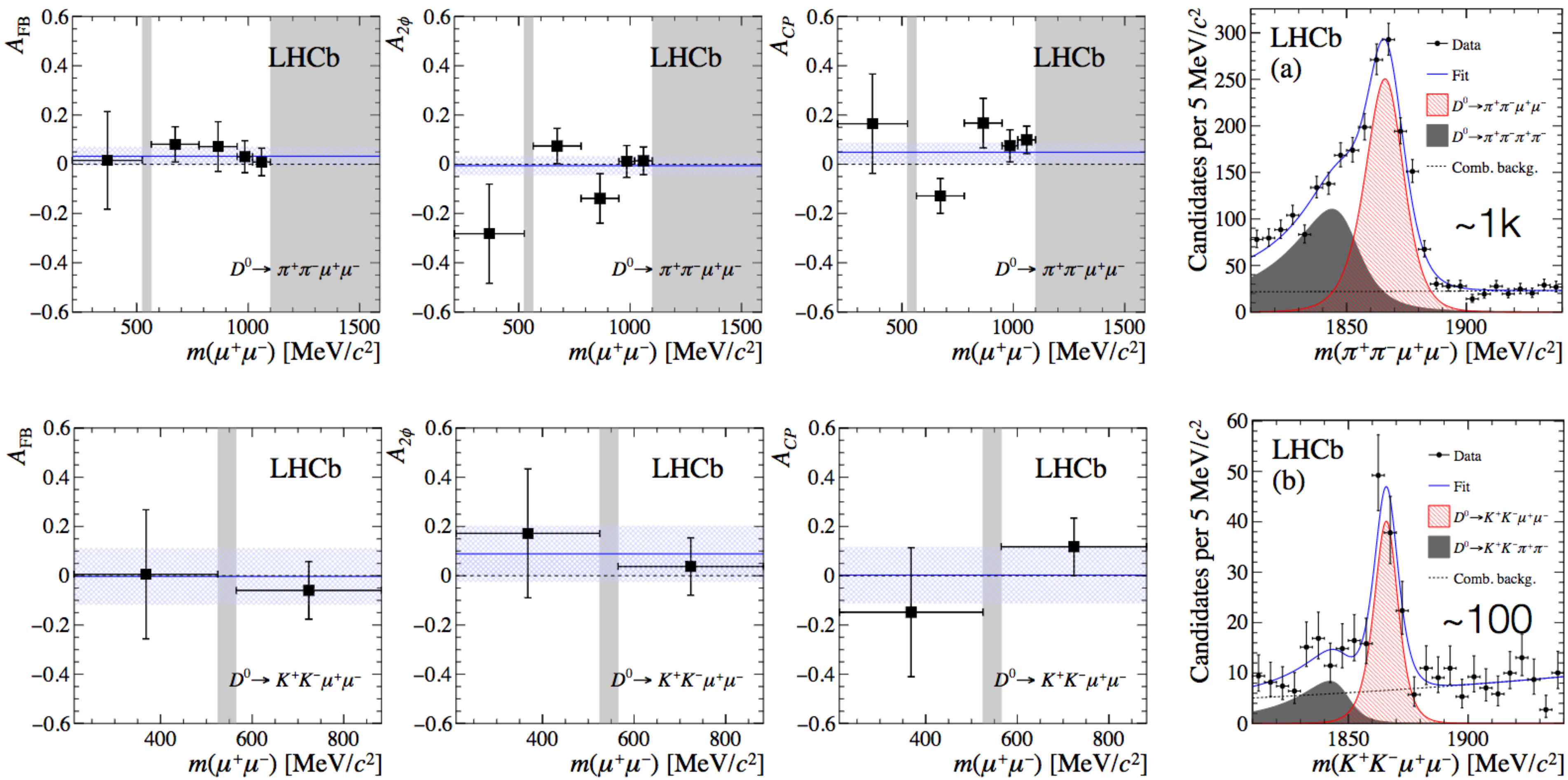
$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$$
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$$

where the uncertainties are statistical, systematic and due to the BF of the normalization decay

$D^0 \to h^+h^-\mu^+\mu^-$: angular and CP asymmetries

PRL 121, 091801 (2018)

Run 1+2 (5/fb)



- All asym. consistent with zero
- No dependency on dimuon mass

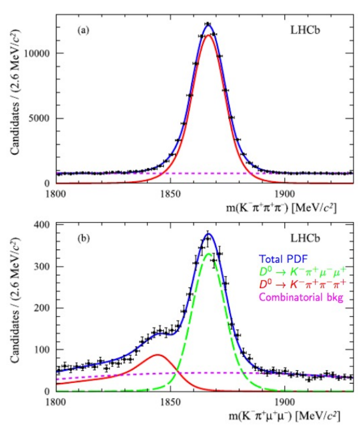
Observation of the decay $D^0 \to K^-\pi^+e^+e^-$ at BaBar

[PRL 122 081802 (2019)]

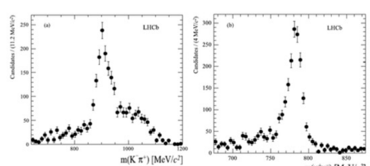
LHCb

First observation of the decay $D^0 \to K^-\pi^+\rho^0/\omega(\to \mu^-\mu^+)$

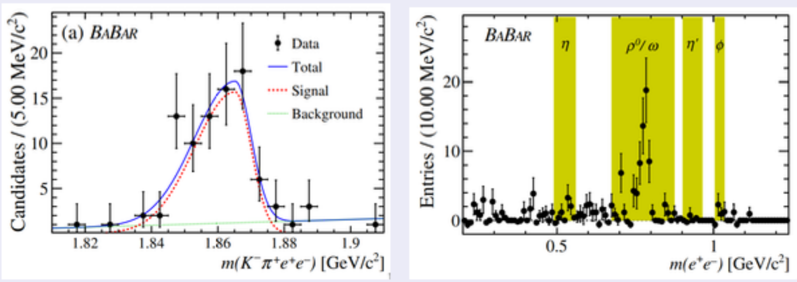
[PLB 757 (2016) 558-567]



- Measurement restricted to $675 < m_{\mu\mu} < 875\,\mathrm{MeV}/c^2$
- $BF(D^0 \to K^-\pi^+\mu^-\mu^+) = (4.12 \pm 0.12_{stat} \pm 0.38_{syst}) \times 10^{-6}$
- In agreement with SM predictions [JHEP 04 (2013) 135]
- Ideal normalisation mode for $D^0 \to h^+h^-\mu^+\mu^-$



BaBar



Observation for $675 < m_{ee} < 875\,\mathrm{MeV}/c^2$

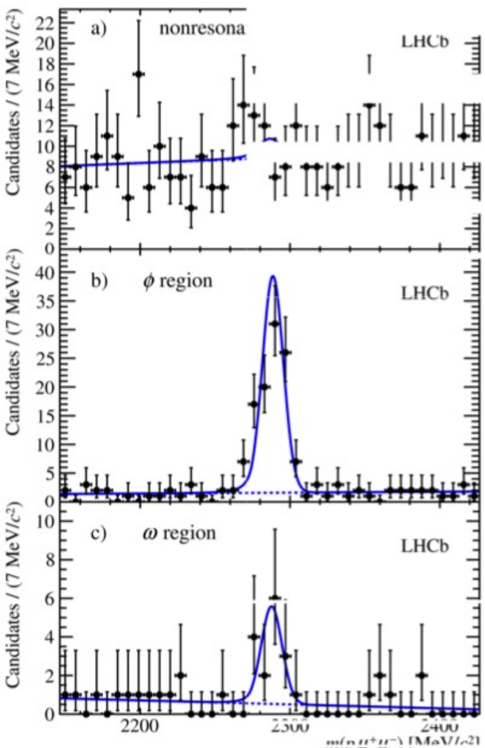
$BF(D^0 \to K^-\pi^+e^-e^-) =$
$(4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$

In agreement with LHCb's $D^0 \to K^-\pi^+\mu^+\mu^-$

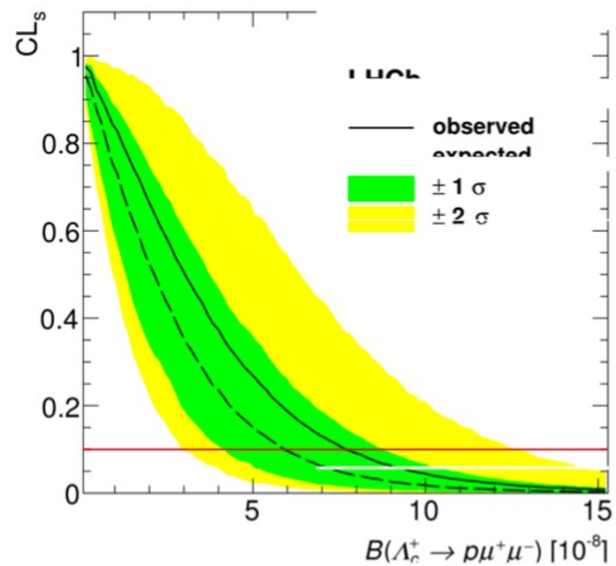
Limits elsewhere at 10^{-6} level

Search for $\Lambda_c^+ \to p\mu^+\mu^-$

- Similar approach to $D_s^+ \to h^+\mu^+\mu^-$ search analysis (split in dimoun mass regions, normalise to ϕ region)



- Significant signal (5σ) in the ω region
- Best limit on the non-resonant component, $\mathcal{B}(\Lambda_c \to p\mu^+\mu^-) < 7.7 \times 10^{-8}$ at 90% CL



Acceptance corrections

The detector and the offline selection may have different efficiencies in different regions of the $(m_{\mu\mu}, \cos\theta)$-phase space.

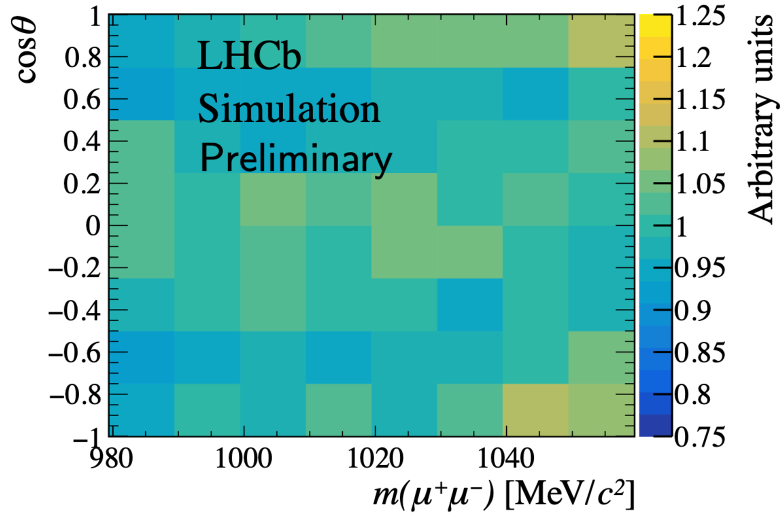
The distributions **at generation level** and **after the offline selection** are compared.

The **relative efficiencies** in the phase space are:

$$\epsilon\left(m_{\mu\mu}, \cos\theta\right) = \frac{f_{selected}\left(m_{\mu\mu}, \cos\theta\right)}{f_{generated}\left(m_{\mu\mu}, \cos\theta\right)}$$

and the **acceptance weights**:

$$\lambda_{corr} = \frac{1}{\epsilon}$$



Alternative parametrization

$$\bar{R}^{\pm}(t) \approx R_D(1 \pm A_D) + \sqrt{R_D(1 \pm A_D)}(c_{K\pi} \pm \Delta c_{K\pi}) \left(\frac{t}{\tau_{D^0}}\right) + (c'_{K\pi} \pm \Delta c'_{K\pi}) \left(\frac{t}{\tau_{D^0}}\right)^2, \quad \text{(A.3)}$$

where

$$R_D = \frac{R_D^+ + R_D^-}{2}, \quad \text{(A.4)}$$

$$c_{K\pi} = \frac{y'^+ + y'^-}{2}, \quad \text{(A.5)}$$

$$c'_{K\pi} = \frac{1}{2}\left[\frac{(x'^+)^2 + (y'^+)^2}{4} + \frac{(x'^-)^2 + (y'^-)^2}{4}\right], \quad \text{(A.6)}$$

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}, \quad \text{(A.7)}$$

$$\Delta c_{K\pi} = \frac{y'^+ - y'^-}{2}, \quad \text{(A.8)}$$

$$\Delta c'_{K\pi} = \frac{1}{2}\left[\frac{(x'^+)^2 + (y'^+)^2}{4} - \frac{(x'^-)^2 + (y'^-)^2}{4}\right]. \quad \text{(A.9)}$$

Formula

$$
\begin{aligned}
\frac{\mathrm{d}^5\Gamma}{\mathrm{d}\cos\theta_0 \mathrm{d}\cos\theta_1 \mathrm{d}\phi_1 \mathrm{d}\cos\theta_2 \mathrm{d}\phi_2} \propto\ & (1 + \alpha_{\Lambda_b^0}\alpha_{\Lambda_c^+}\cos\theta_1 + \alpha_{\Lambda_c^+}\alpha_{\Lambda}\cos\theta_2 + \alpha_{\Lambda_b^0}\alpha_{\Lambda}\cos\theta_1\cos\theta_2 \\
& - \alpha_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_{\Lambda}\sin\theta_1\sin\theta_2\cos\phi_2 + \alpha_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_{\Lambda}\sin\theta_1\sin\theta_2\sin\phi_2) \\
& + P_z \cdot (\alpha_{\Lambda_b^0}\cos\theta_0 + \alpha_{\Lambda_c^+}\cos\theta_0\cos\theta_1 + \alpha_{\Lambda_b^0}\alpha_{\Lambda_c^+}\alpha_{\Lambda}\cos\theta_0\cos\theta_2 \\
& + \alpha_{\Lambda}\cos\theta_0\cos\theta_1\cos\theta_2 - \gamma_{\Lambda_b^0}\alpha_{\Lambda_c^+}\sin\theta_0\sin\theta_1\cos\phi_1 + \beta_{\Lambda_b^0}\alpha_{\Lambda_c^+}\sin\theta_0\sin\theta_1\sin\phi_1 \\
& - \gamma_{\Lambda_c^+}\alpha_{\Lambda}\cos\theta_0\sin\theta_1\sin\theta_2\cos\phi_2 + \beta_{\Lambda_c^+}\alpha_{\Lambda}\cos\theta_0\sin\theta_1\sin\theta_2\sin\phi_2 \\
& - \gamma_{\Lambda_b^0}\alpha_{\Lambda}\sin\theta_0\sin\theta_1\cos\theta_2\cos\phi_1 + \beta_{\Lambda_b^0}\alpha_{\Lambda}\sin\theta_0\sin\theta_1\cos\theta_2\sin\phi_1 \\
& + \beta_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_{\Lambda}\sin\theta_0\sin\theta_2\cos\phi_1\cos\phi_2 + \beta_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_{\Lambda}\sin\theta_0\sin\theta_2\cos\phi_1\sin\phi_2 \\
& + \gamma_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_{\Lambda}\sin\theta_0\sin\theta_2\sin\phi_1\cos\phi_2 + \gamma_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_{\Lambda}\sin\theta_0\sin\theta_2\sin\phi_1\sin\phi_2 \\
& - \gamma_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_{\Lambda}\sin\theta_0\cos\theta_1\sin\theta_2\cos\phi_1\cos\phi_2 \\
& + \gamma_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_{\Lambda}\sin\theta_0\cos\theta_1\sin\theta_2\cos\phi_1\sin\phi_2 \\
& + \beta_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_{\Lambda}\sin\theta_0\cos\theta_1\sin\theta_2\sin\phi_1\cos\phi_2 \\
& - \beta_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_{\Lambda}\sin\theta_0\cos\theta_1\sin\theta_2\sin\phi_1\sin\phi_2),
\end{aligned}
$$

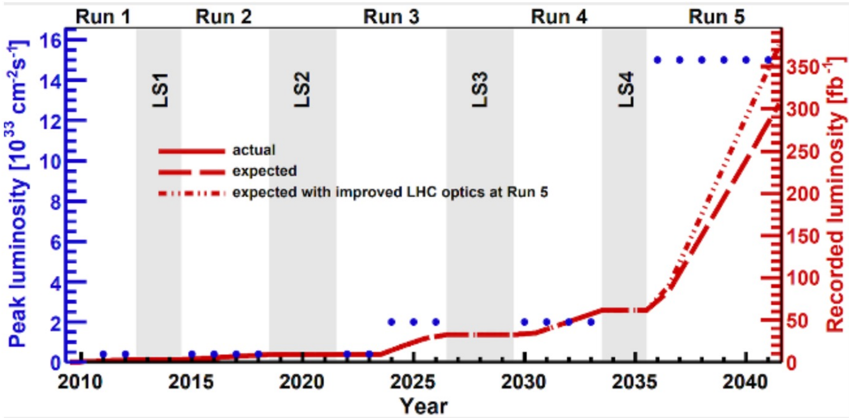
Current facilities for charm study

- Hadron colliders (huge cross-section, energy boost)
  - LHCb: $9fb^{-1}$ until now; world's largest sample of c-hadron decays in charged modes (x40 current B factories)
  - B-factories (Belle (II), BaBar): ~e^+e^- Colliders (more kinematic constrains, clean environment, ~100% trigger efficiency)
  - Threshold production (BESIII)
    - Pair production and double tag technique
    - Low backgrounds and high efficiency
    - Quantum correlations and CP-tagging are unique

Charm samples

Type	Exp	$\sqrt{s}$	L_{int}	$\sigma(c\bar{c})$	$N(c\bar{c})$
		prompt $c\bar{c}$			
Hadron colliders	LHCb	7, 8 TeV	3/fb	1.4 mb	3.6×10^{12}
		13 TeV	6/fb	2.6 mb	13.2×10^{12}
	CDF	2 TeV	10/fb	0.1 mb	2.3×10^{11}
		$c\bar{c}$ from continuum			
e^+e^- collider	Belle	10.6 GeV	1/ab	1.3 nb	1.3×10^{9}
	BaBar	10.6 GeV	550/fb	1.3 nb	0.7×10^{9}
		Charm factories at $D\bar{D}$ threshold			
	BESIII	3.7 GeV	3/fb	3 nb	20×10^{6}
	Cleo-c	3.7 GeV	0.8/fb	3 nb	5×10^{6}

LHCb prospects for future measurements



Limits on BFs (away from resonances for multibody)

Mode	Upgrade (50 fb^{-1})	Upgrade II (300 fb^{-1})
$D^0 \to \mu^+\mu^-$	4.2×10^{-10}	1.3×10^{-10}
$D^+ \to \pi^+\mu^+\mu^-$	10^{-8}	3×10^{-9}
$D_s^+ \to K^+\mu^+\mu^-$	10^{-8}	3×10^{-9}
$\Lambda \to p\mu\mu$	1.1×10^{-8}	4.4×10^{-9}
$D^0 \to e\mu$	10^{-9}	4.1×10^{-9}

Statistical precision on A_{CP} (PS integrated)

Mode	Upgrade (50 fb^{-1})	Upgrade II (300 fb^{-1})
$D^+ \to \pi^+\mu^+\mu^-$	0.2%	0.08%
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	1%	0.4%
$D^0 \to K^-\pi^+\mu^+\mu^-$	0.3%	0.13%
$D^0 \to K^+\pi^-\mu^+\mu^-$	12%	5%
$D^0 \to K^+K^-\mu^+\mu^-$	4%	1.7%