Highlights of Charm Physics Results @ LHCb

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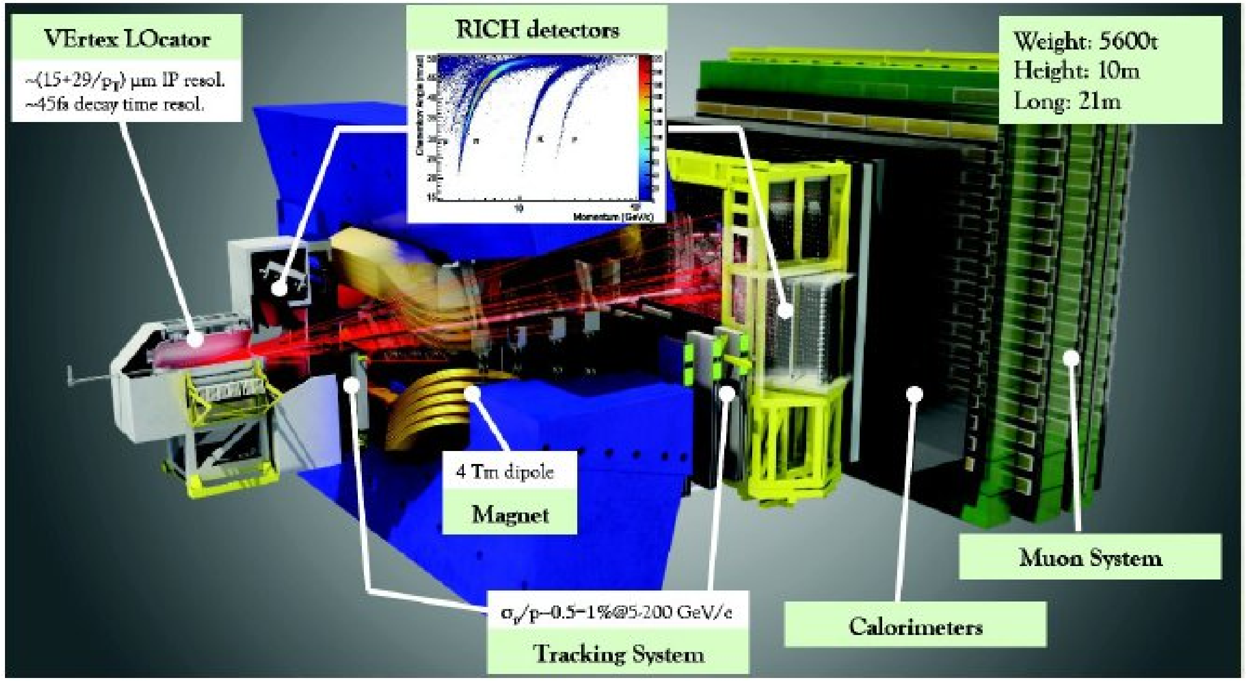
CEPC味物理-新物理和相关探测技术研讨会（复旦大学）

Outline

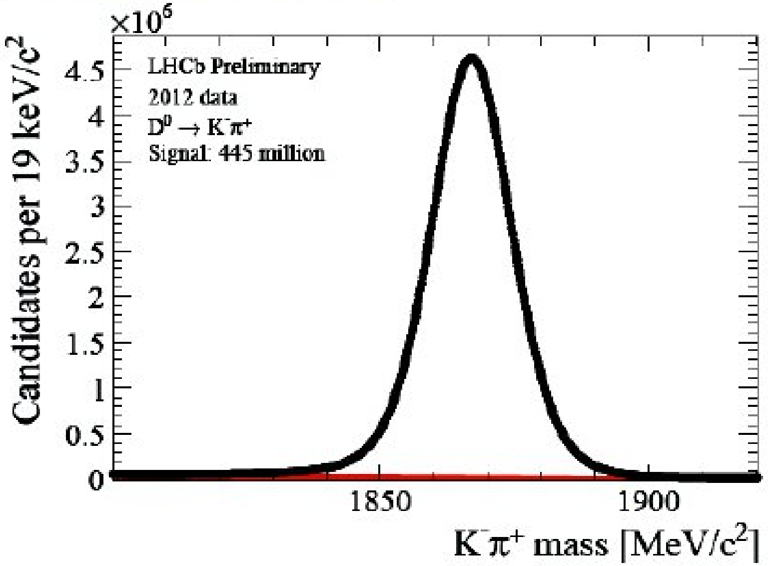
- Experimental details
- Charm mixing & CPV
- Rare charm decays
- Spectroscopy & amplitude analyses
- Other decays
- Prospects & outlook

Up-to-date LHCb charm results can be found at
https://lhcbproject.web.cern.ch/Publications/LHCbProjectPublic/Summary_Charm.html
More than 90 papers and counting!

LHCb as a charm factory



LHCb-CONF-2016-005



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

[JHEP 03 (2016) 159]

$$\sigma(pp \to c\bar{c}) = (2369 \pm 3 \pm 152 \pm 118)\,\mu b @ 13\,TeV \qquad \sim 20 \times \sigma(pp \to b\bar{b}X)$$

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

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

Charm mixing & CPV

- 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

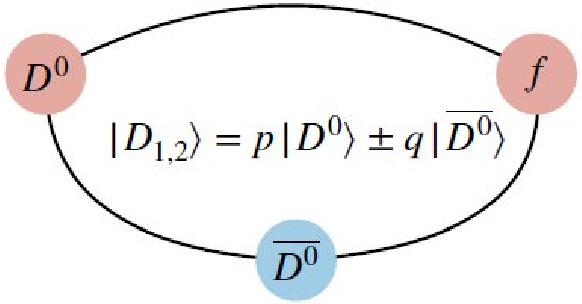
Direct *CP* violation $\left|\frac{\overline{A}_f}{A_f}\right|^{\pm 2} \approx 1 \pm A_d \rightarrow a_{CP}^{dir} \approx -\frac{1}{2} A_d$

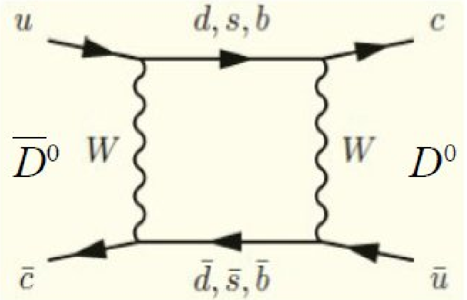
  - In mixing: rates of $D^0 \rightarrow \overline{D}^0$ and $\overline{D}^0 \rightarrow D^0$ differ

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





Unitarity triangle for charm

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

$$\sim\lambda \qquad \sim\lambda \qquad \sim\lambda^5$$

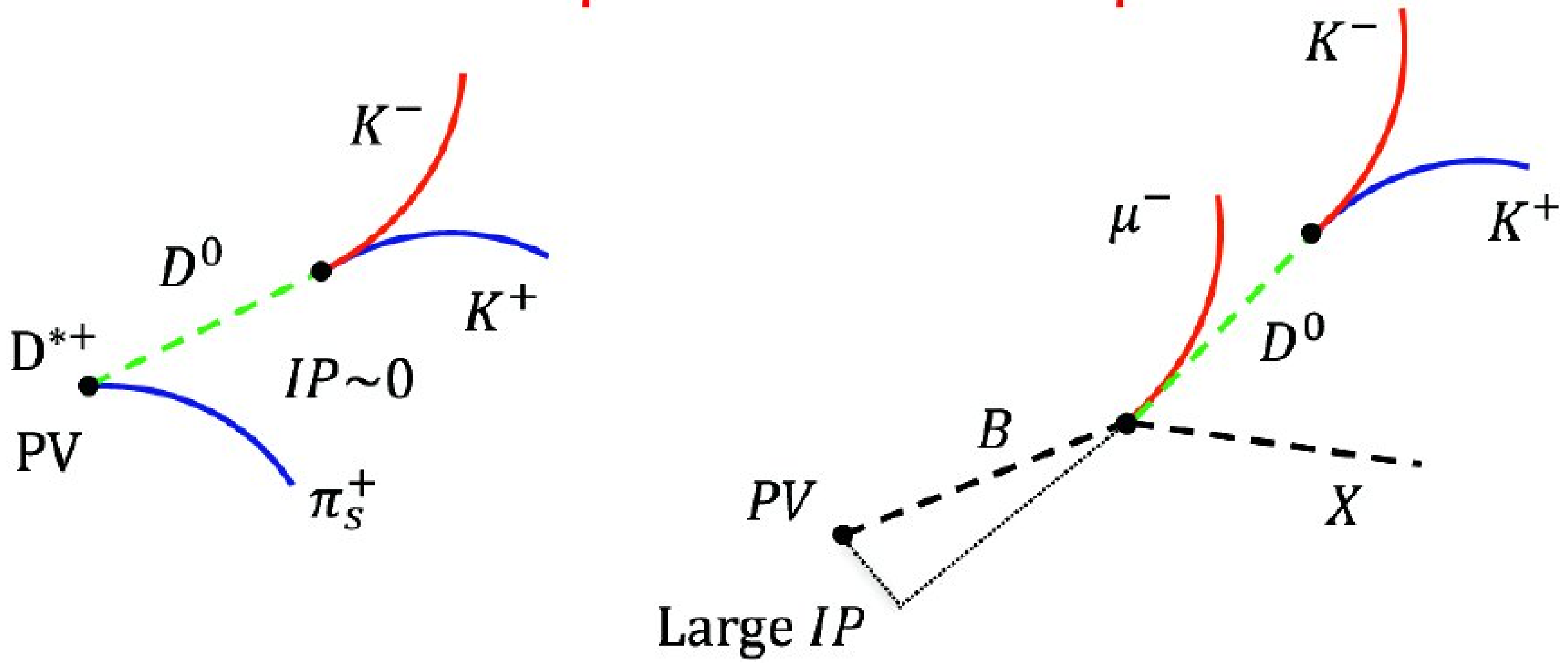
$$\lambda = \sin(\theta_C) \sim 0.23$$

Expected CPV very small in charm
- Effectively 2-generation system
- 3rd generation and CPV enter through loops

D^0 production at LHCb

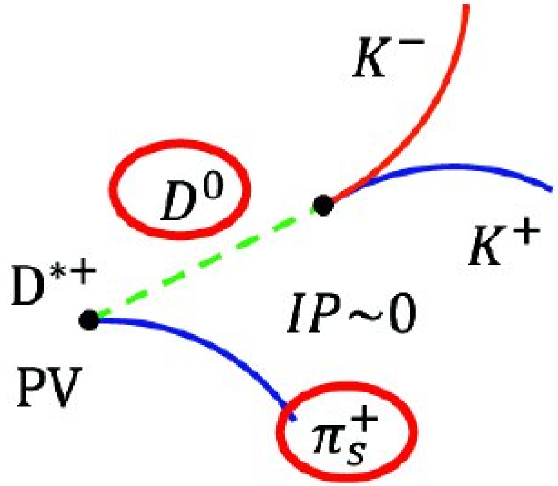
Two mechanisms of D^0 production

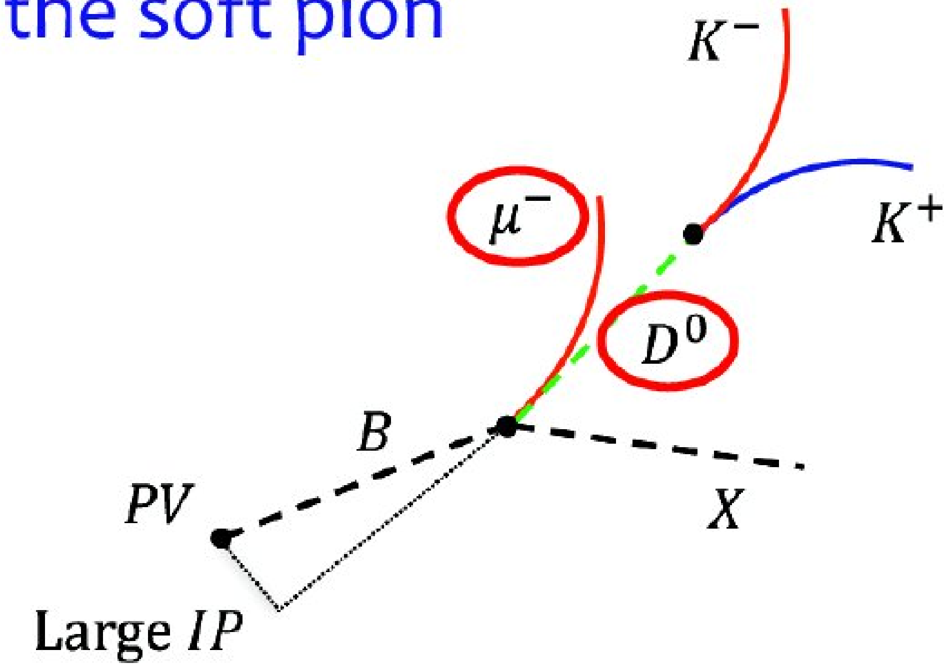
Independent data sample



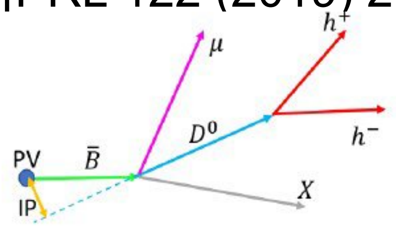
D^0 flavor tagging at LHCb

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

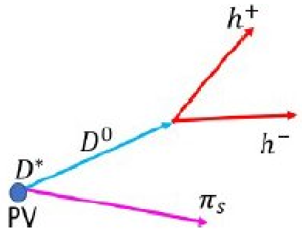




[PRL 122 (2019) 211803]



Observation of charm CPV



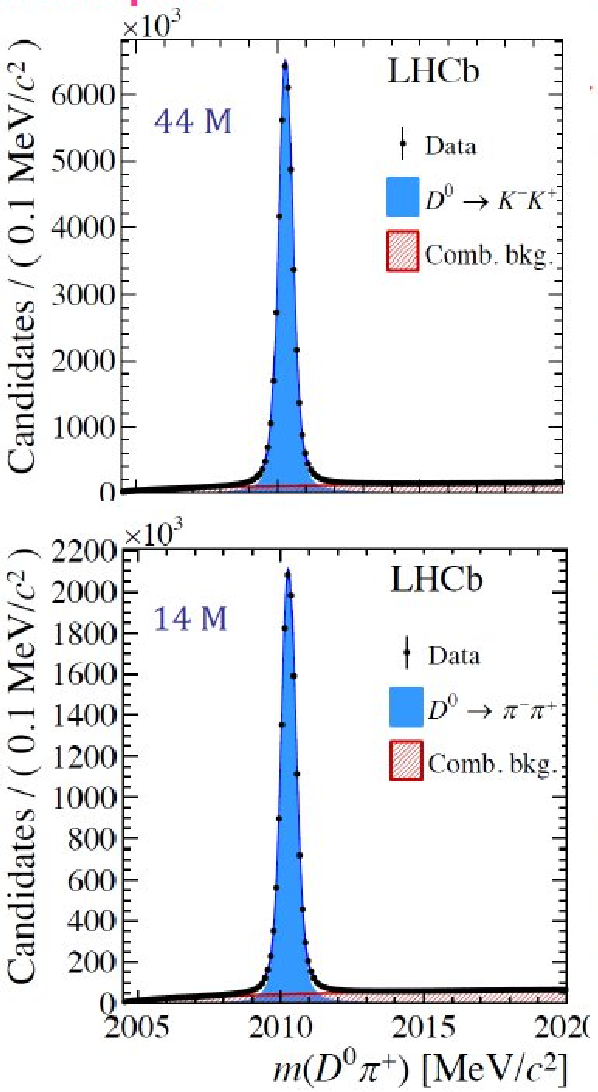
- LHCb uses full Run2 5.9 fb^{-1} data
- Raw asymmetry for tagged D^0 decays to a final state f (K^+K^-, $\pi^+\pi^-$):

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

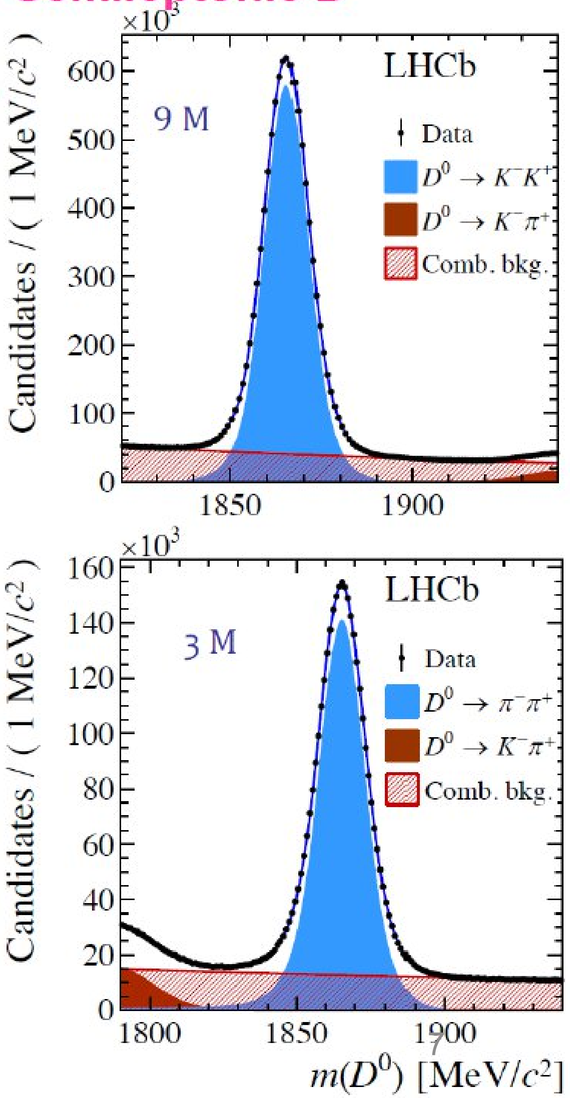
- $A_{raw} = A_{CP} + A_D + A_P$
  - A_D: Detection asymmetry from π_s (prompt)
  - A_P: Production asymmetry of D^* (prompt)
- With many systematics canceled at first order, it is relatively easy to measure time-integrated difference in CP asymmetry

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

Prompt D⁰



Semileptonic D⁰



[PRL 122 (2019) 211803]

Observation of charm CPV

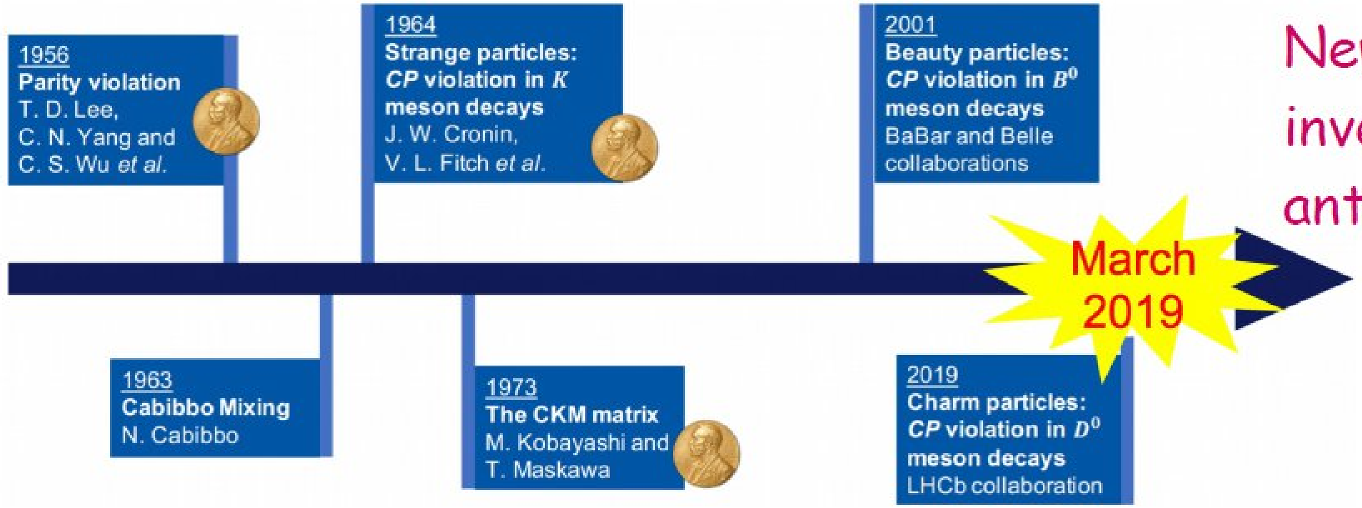
- From full Run2 5.9 fb^{-1} data:

$$\Delta A_{CP}^{\pi-tag} = (-18.2 \pm 3.2 \pm 0.9) \times 10^{-4},$$
$$\Delta A_{CP}^{\mu-tag} = (-9 \pm 8 \pm 5) \times 10^{-4}$$

- Combination with Run1 results:

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

  - 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!

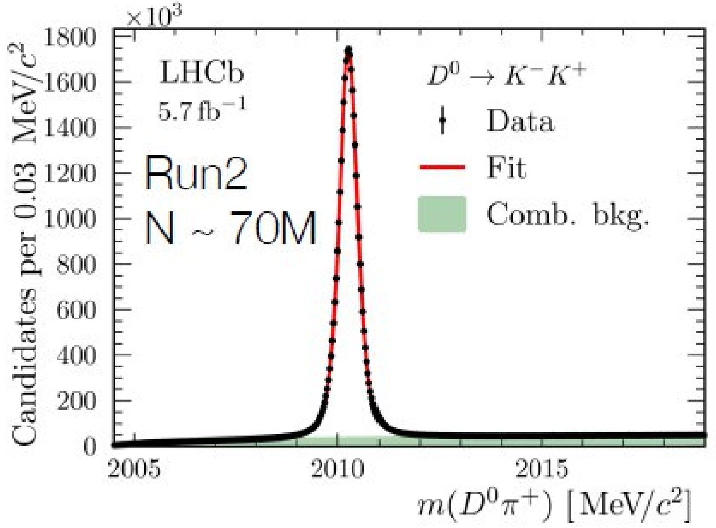
CPV in $D^0 \to K^+K^- / \pi^+\pi^-$

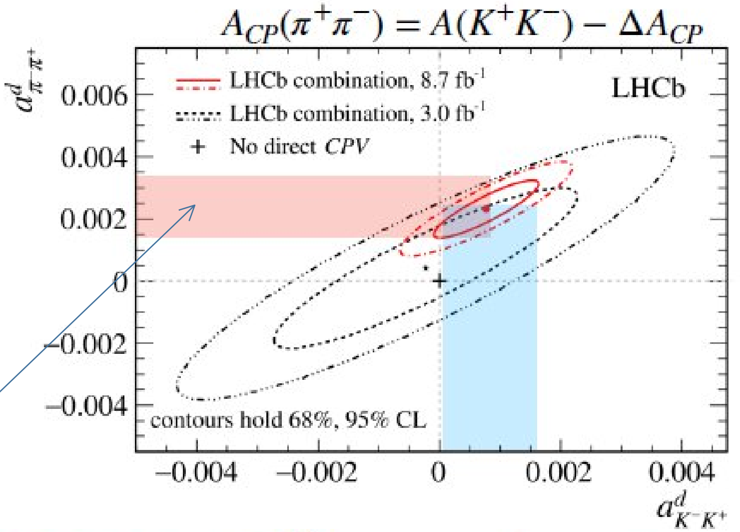
- Using Run 2 (5.6 fb^{-1}) data with ~70M $D^0 \to K^+K^-$ candidates
- Combination of two methods using Cabibbo-favored (no CPV) $D^0/D^+/D_s^+$ decays to cancel detector/production asymmetries in $D^0 \to K^+K^-$:

$$A_{CP}(K^+K^-) = [6.8 \pm 5.4(\text{stat}) \pm 1.6(\text{sys})] \times 10^{-4}$$

- Combination with Run1 & ΔA$_{CP}$ results yields:

$$a_{CP}^d(K^+K^-) = [7.7 \pm 5.7] \times 10^{-4}$$
$$a_{CP}^d(\pi^+\pi^-) = [23.2 \pm 6.1] \times 10^{-4}$$
$$\rho(a_{KK}^d, a_{\pi\pi}^d) = 88\,\%$$



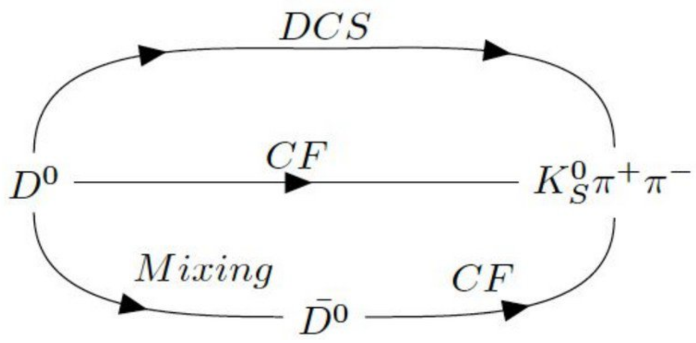


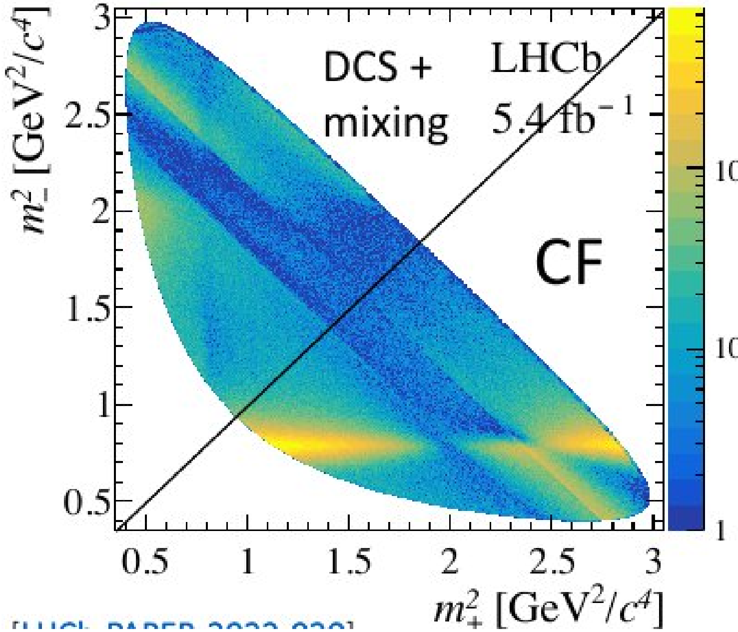
First evidence (3.8σ) of CPV in $D^0 \to \pi^+\pi^-$!

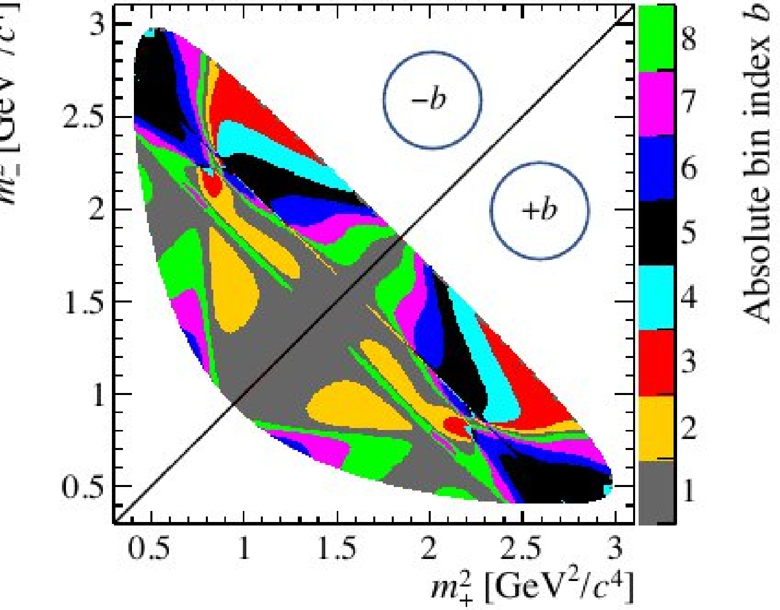
[PRL 127 (2021) 111801]
[arXiv:2208.06512]

$D^0 - \overline{D}^0$ oscillation in $D^0 \to K_S^0 \pi^+ \pi^-$

- Run2 prompt (SL) datasets with ~31M (3.7M) candidates
- Bin-flip method: model-independent approach, no need for modeling of Dalitz-plot efficiency & decay amplitudes







Simultaneous fit of the yield ratio $R_b^{\pm}$ ($\pm$ for initial $D^0/\overline{D}^0$) between $+b$ and $-b$ in bins of D^0 decay time t:

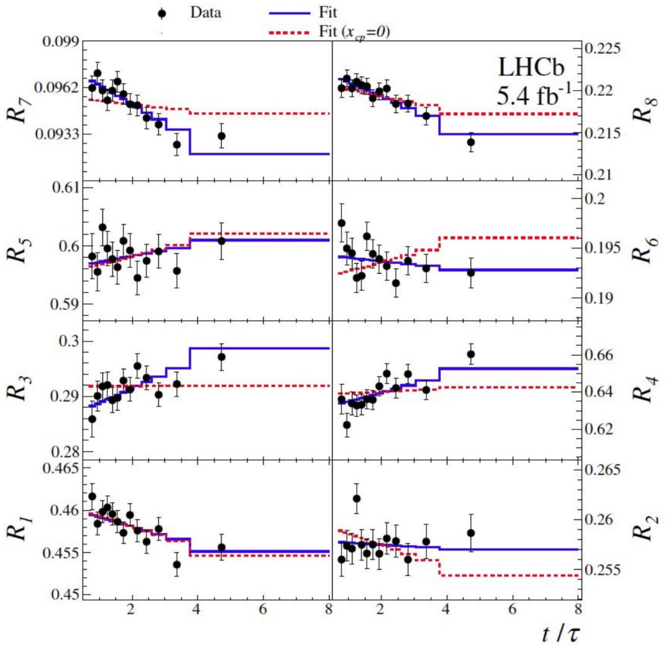
$$R_b^{\pm}(t) \approx r_b - \sqrt{r_b}[(1-r_b)c_b y - (1+r_b)s_b x]\Gamma t$$

- $r_b \equiv R_b(t=0)$
- c_b and s_b: parameters related to the strong phase differences between $\pm b$ regions (based on external inputs from CLEO and BESIII).

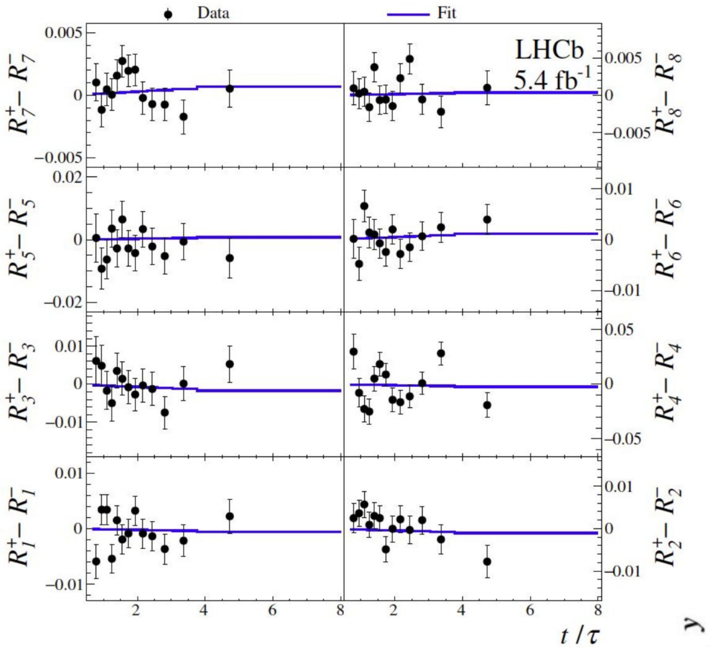
[PRL 127 (2021) 111801]

$D^0 - \overline{D}^0$ oscillation in $D^0 \to K_S^0 \pi^+ \pi^-$

Mixing measurement: $D^0 + \overline{D}^0$



CPV measurement: $D^0 - \overline{D}^0$



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

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

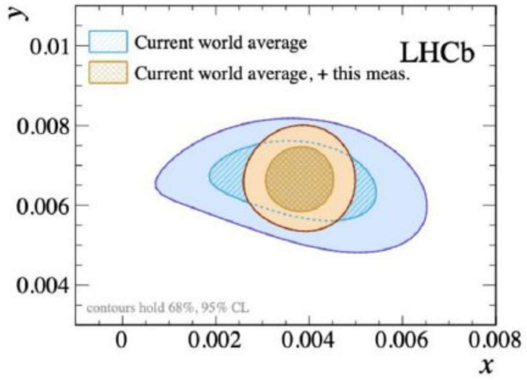
LHCb measures tiny mass difference between particles

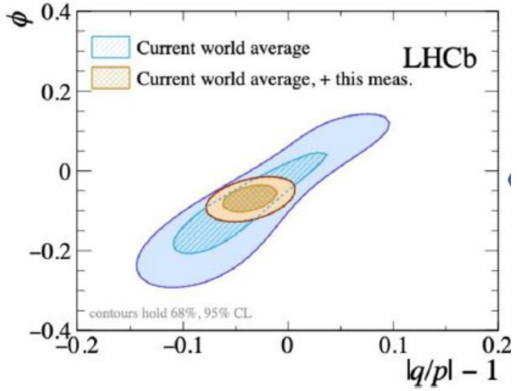
$$x_{CP} = (\ \ 3.97 \pm 0.46 \pm 0.29) \times 10^{-3}$$
$$y_{CP} = (\ \ 4.59 \pm 1.20 \pm 0.85) \times 10^{-3}$$

$$\Delta x = (-0.27 \pm 0.18 \pm 0.01) \times 10^{-3}$$
$$\Delta y = (\ \ 0.20 \pm 0.36 \pm 0.13) \times 10^{-3}$$

$$x = (3.98^{+0.56}_{-0.54}) \times 10^{-3},$$
$$y = (\ 4.6^{+1.5}_{-1.4}\ ) \times 10^{-3},$$
$$|q/p| = 0.996 \pm 0.052,$$
$$\phi = 0.056^{+0.047}_{-0.051}.$$

First observation of non-zero x (>7σ)





World Averages significantly improved!

Overview of rare charm decays @ LHCb

branching ratios, especially regions away from the resonances

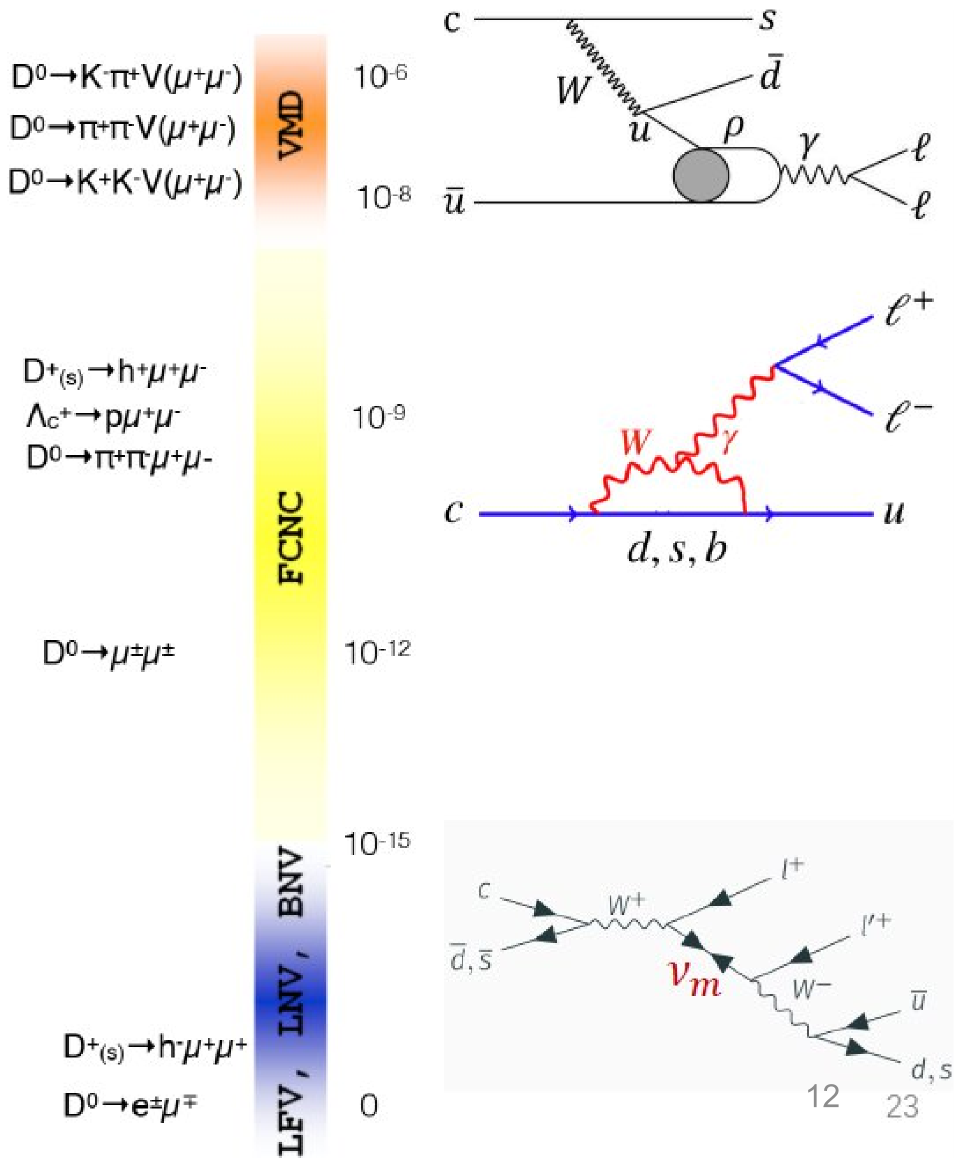
- search for $D^0 \to \mu^+\mu^-$ [PLB 725 15-24 (2013)] [PRL 131 (2023) 041804]
- search for $D^+_{(s)} \to h^+l^+l^-$ [PLB 724 203-212 (2013)] [JHEP 06 44 (2021)]
- search for $\Lambda_c^+ \to p\mu^+\mu^-$ [PRD 97 091101 (2018)]
- search for $D^0 \to \pi^+\pi^-\mu^+\mu^-$ [PLB 728 234-243 (2014)]
- observation of $D^0 \to h^-h^{(\prime)+} V(\mu^+\mu^-)$ [PLB 757 558-567 (2016)], [PRL 119, 181805 (2017)]

null tests based on (approximate) symmetries

- lepton-flavor/number-violation
  - search for $D^0 \to \mu^+e^-$ [PLB 754 167 (2016)]
  - search for $D^+_{(s)} \to h^-l^+l^{(\prime)+}$, $D^+_{(s)} \to h^+\mu^\pm e^\mp$ [JHEP 06 44 (2021)]
- angular observables and CP asymmetries
  - angular analysis and search for CPV in $D^0 \to h^+h^-\mu^+\mu^-$

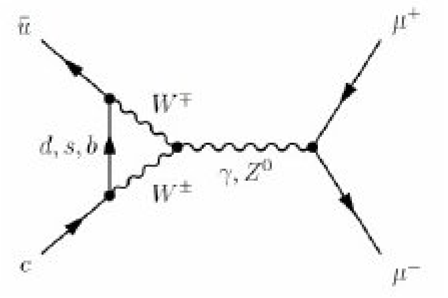
[PRL 121 091801 (2018)], [LHCb-PAPER-2021-035]

[PRL 128 (2022) 221801]



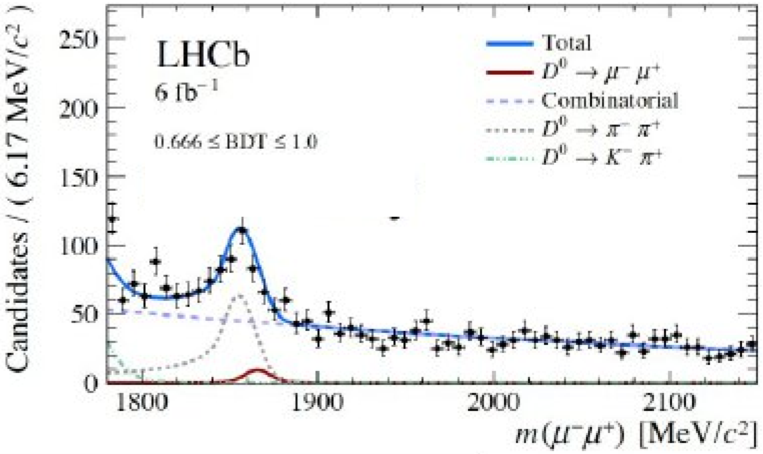
[PRL 131 (2023) 041804]

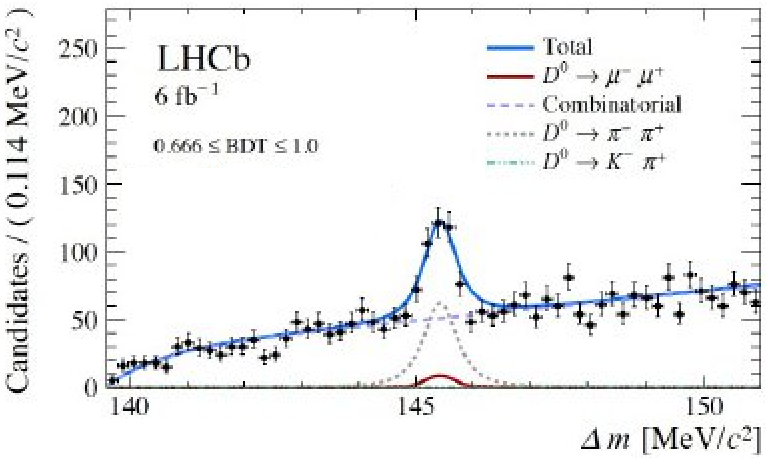
Search for $\mathrm{D}^0 \to \mu^+\mu^-$



- FCNC & helicity suppression
- Predictions: $\mathcal{B}^{s.d.}(D^0 \to \mu^+\mu^-) \sim 10^{-18}$
  $\mathcal{B}^{(\gamma\gamma)}(D^0 \to \mu^+\mu^-) < 2.3 \times 10^{-11}$
- Full Run1+2 analysis (9 fb^{-1}), D^0 from prompt $D^{*+} \to D^0\pi^+_{tag}$
- Normalization channel: $\mathcal{B}(D^0 \to \mu^+\mu^-) = \alpha N_{D^0\to\mu^+\mu^-}, \quad \alpha \sim \frac{\mathcal{B}(D^0\to h^-\pi^+)}{N_{D^0\to h^-\pi^+}} \frac{\varepsilon_{D^0\to h^-\pi^+}}{\varepsilon_{D^0\to\mu^+\mu^-}} \sim 2 \times 10^{-11}$
- 2D simultaneous fits in 3 BDT bins per run:

  Peaking mostly from π/μ misID





- Final result:

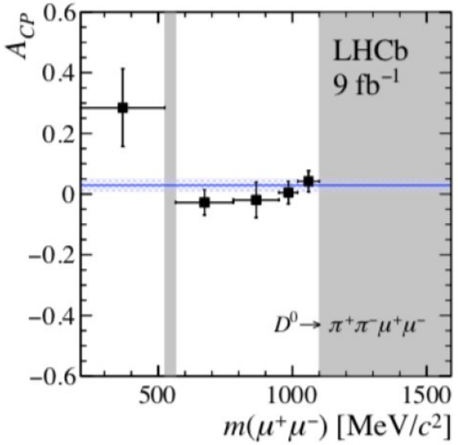
$\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.9(3.3) \times 10^{-9}$ at 90(95)% C.L.

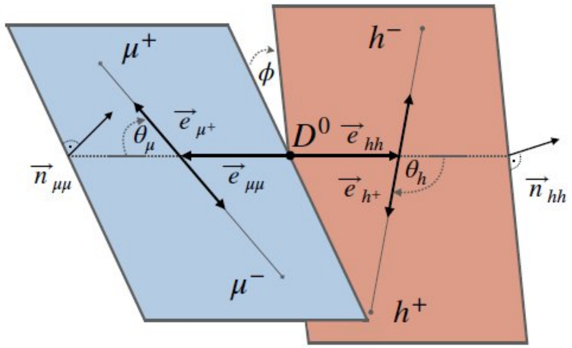
Improvement of more a factor of two!

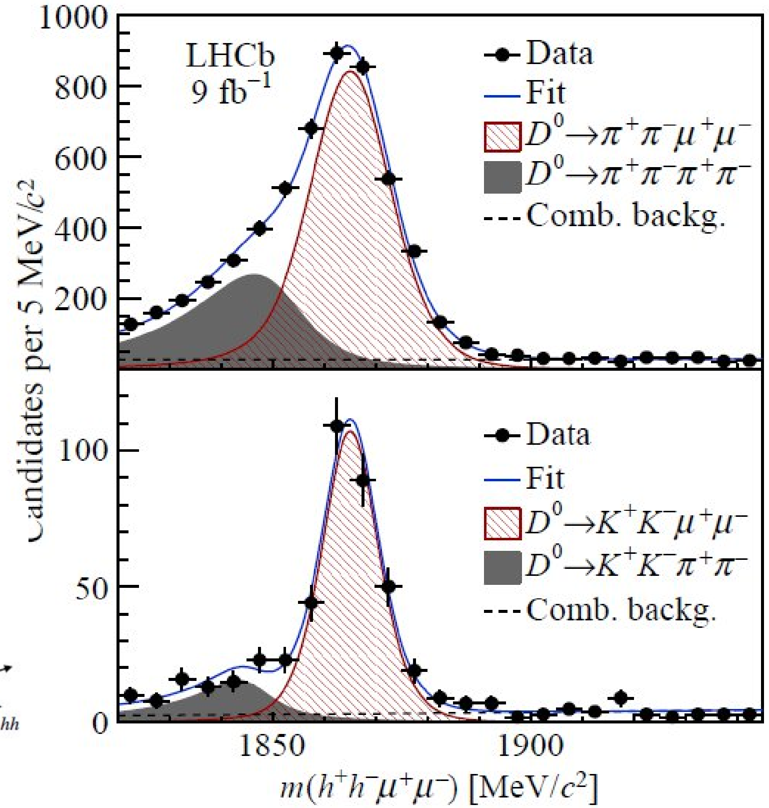
CPV & angular analysis of $D^0 \to hh\mu^+\mu^-$

- Rarest charm meson decays observed, dominated by resonant contributions
- First full angular analysis with 9 fb^{-1} data
- D^0 selected from flavor specific $D^{*+} \to D^0\pi^+$

All results consistent with SM
No CPV found







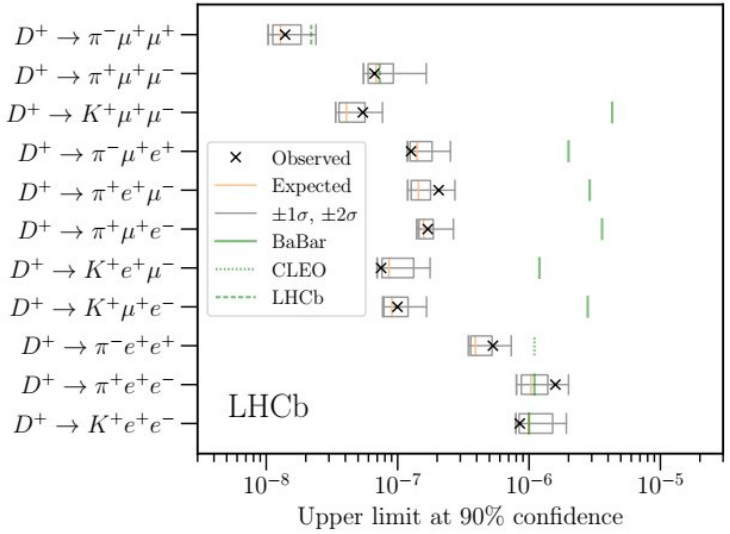
$$N(D^0 \to \pi^+\pi^-\mu^+\mu^-) \sim 3500$$
$$N(D^0 \to K^+K^-\mu^+\mu^-) \sim 300$$

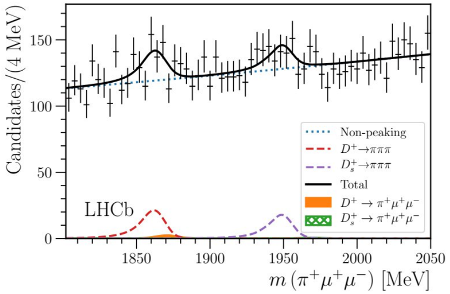
$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) - \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) + \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}$$

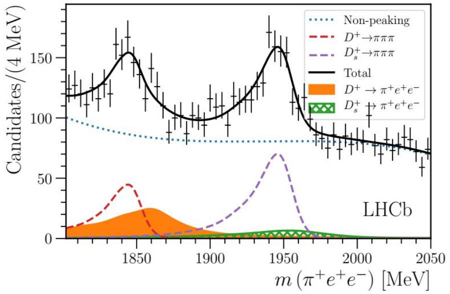
$$p^2 = m^2(h^+h^-)$$
$$q^2 = m^2(\mu^+\mu^-)$$

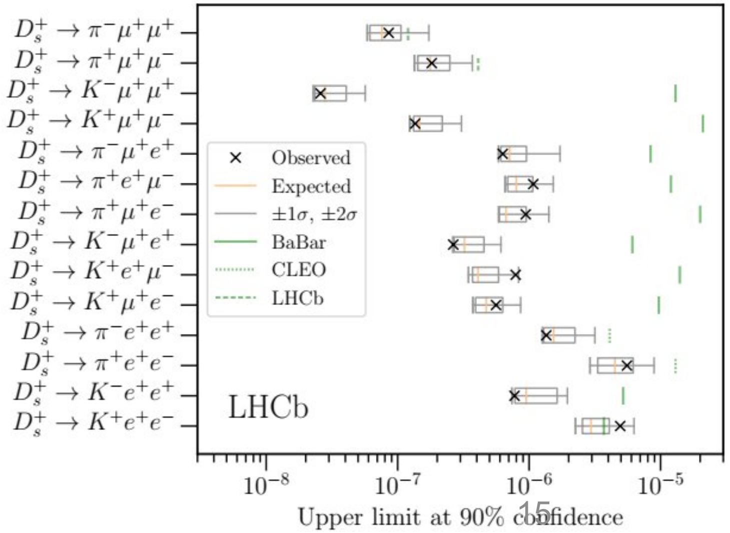
Search for $D^+_{(s)} \to h^{\pm} \ell^{+} \ell^{(\prime)\mp}$ decays

- 25 decays, LFV & LNV included
- Analysis based on 2016 1.6 fb^{-1} dataset
- Normalized with $D^+_{(s)} \to \phi(\ell\ell)\pi^+$
- No signal observed, BF limits are set down to $\mathcal{O}(10^{-8})$
- Results improve the prior world's best by up to a factor of 500

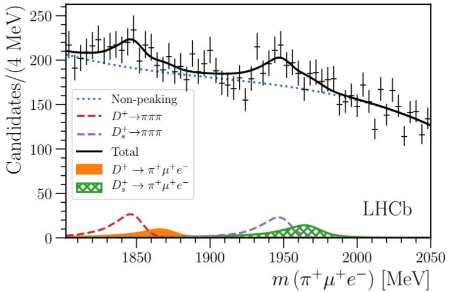






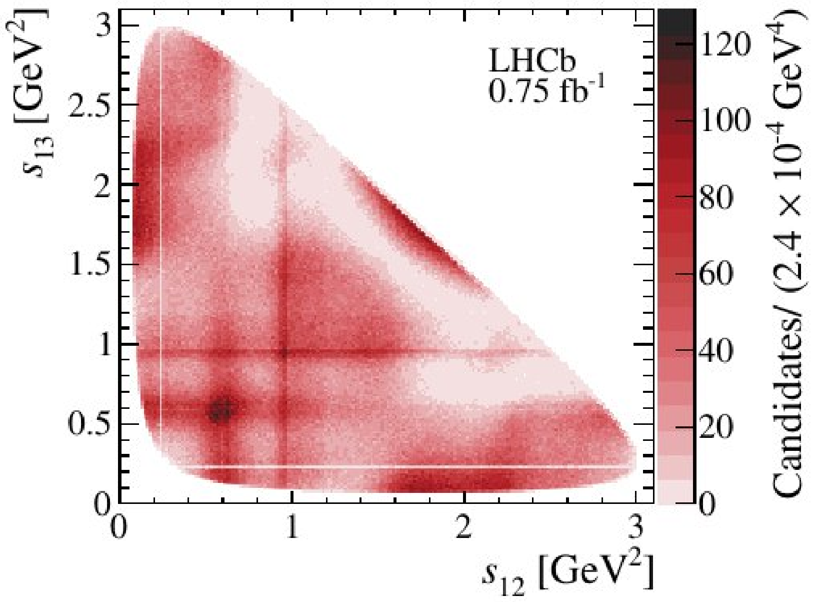


Regions dominated by resonances in dilepton mass spectrum are vetoed



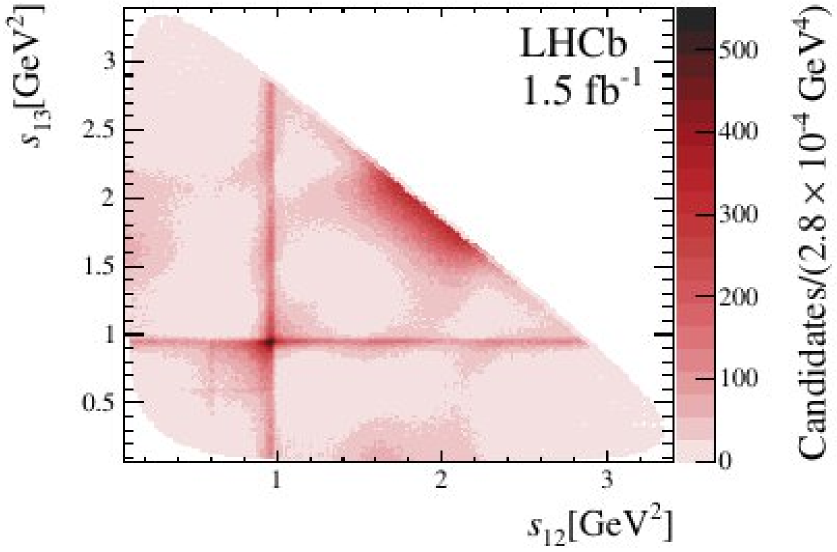
Amplitude analyses in hadronic decays

JHEP 06 (2023) 044



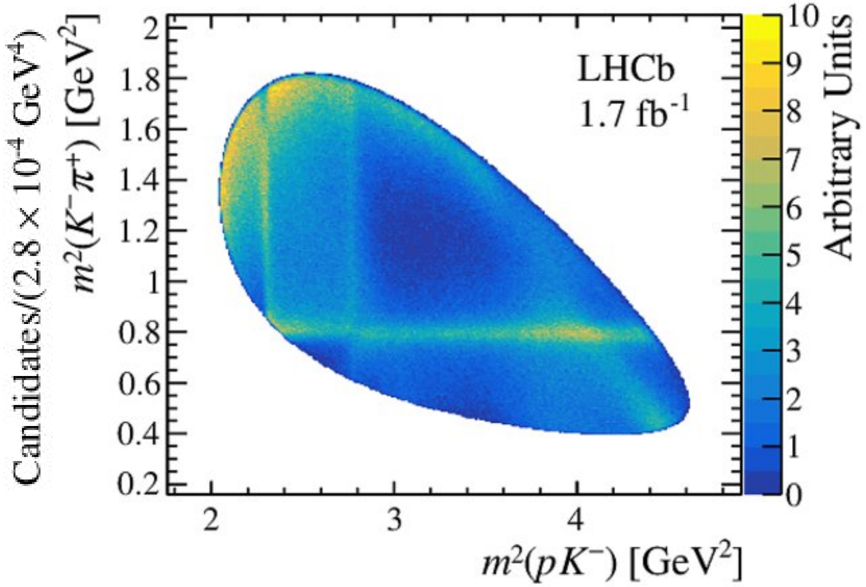
$D^+ \to \pi^-\pi^+\pi^+$: ~600 K

JHEP 07 (2023) 204



$D_s^+ \to \pi^-\pi^+\pi^+$: ~700 K

PRD 108 (2023) 012023

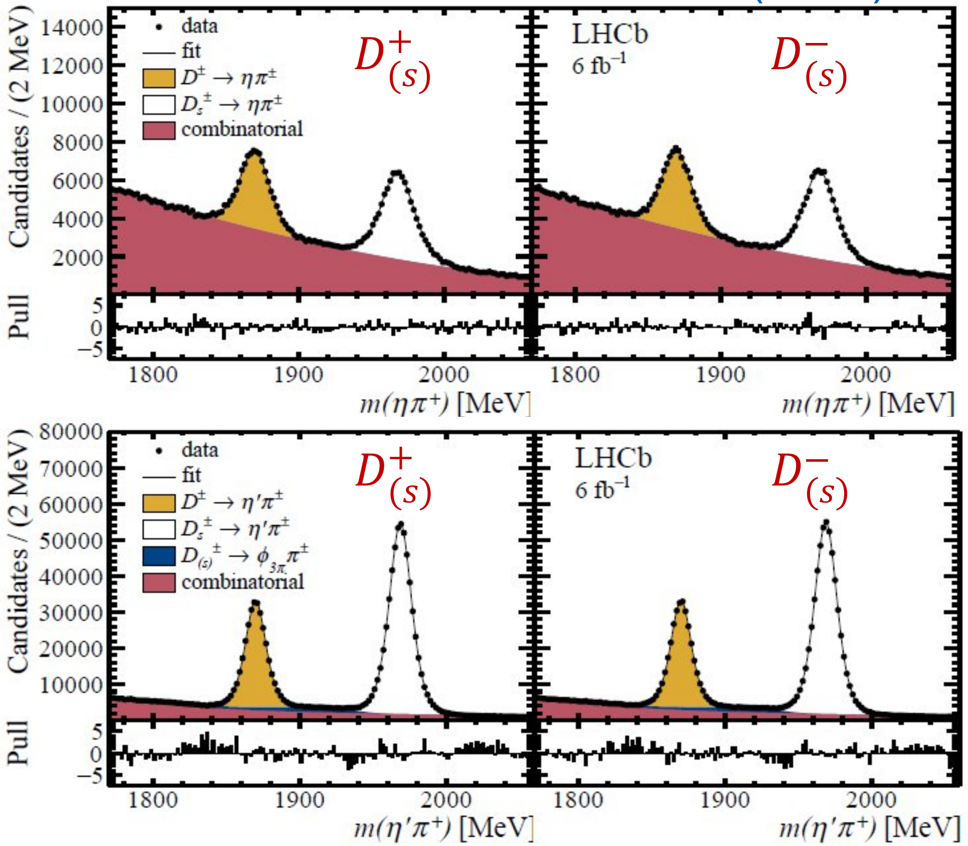


$\Lambda_c^+ \to pK^-\pi^+$: ~400 K

Hadronic decays with π^0/η

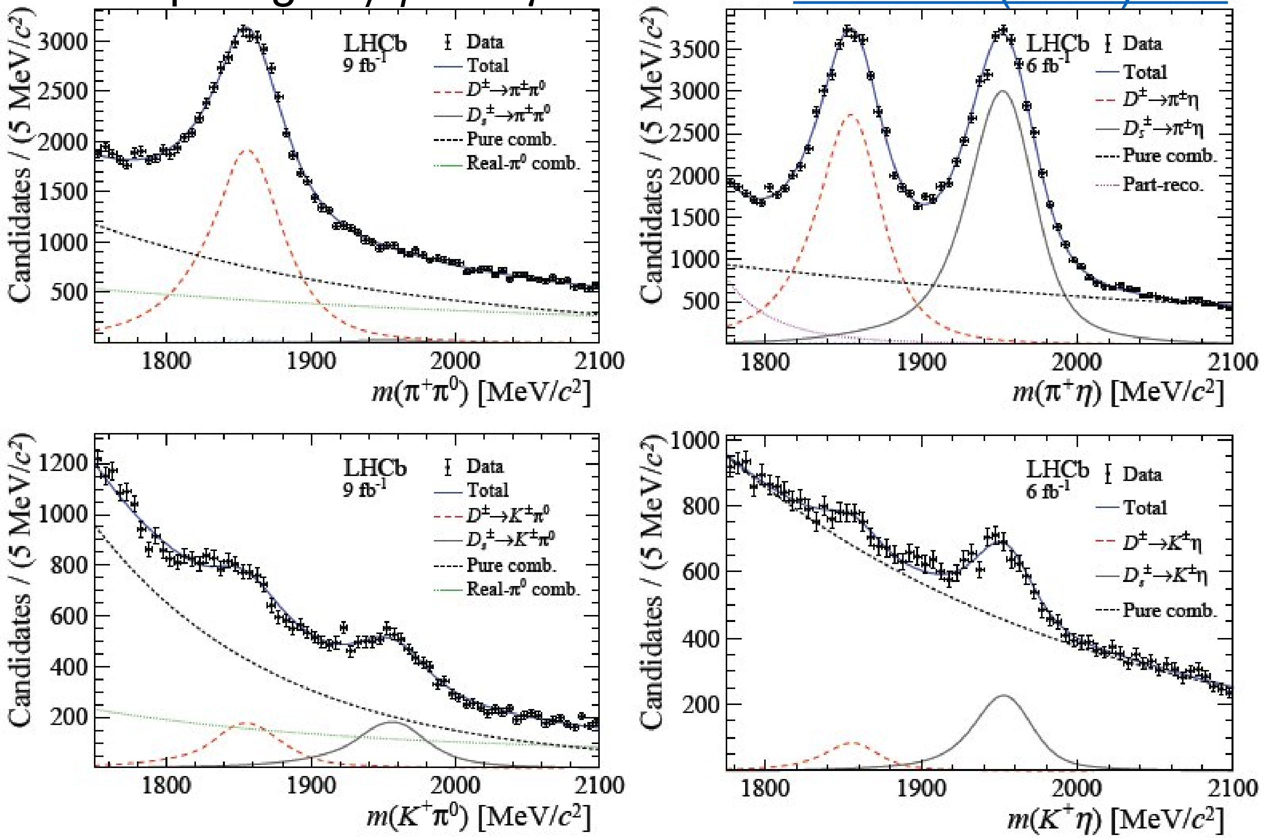
No CPV found
Almost all are world's best!

Requiring $\eta^{(\prime)} \to \pi\pi\gamma$ JHEP 04 (2023) 081



Measurement of CP asymmetries in $D^+_{(s)} \to \eta\pi^+$ and $D^+_{(s)} \to \eta'\pi^+$

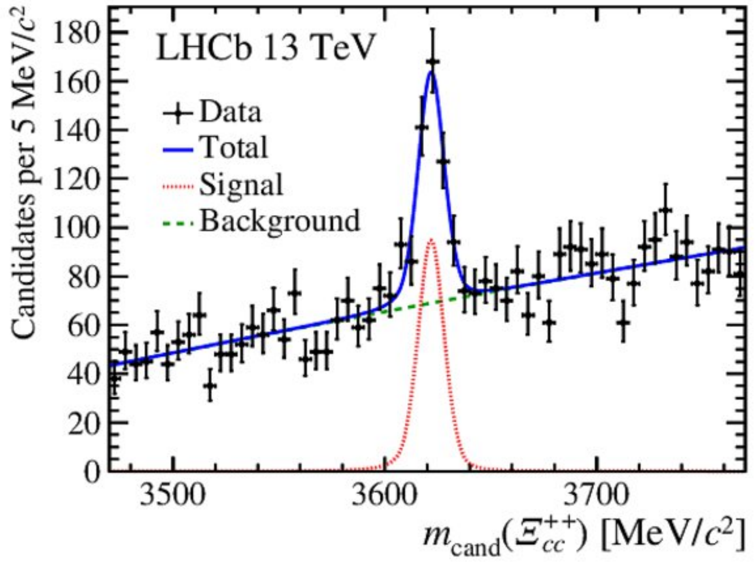
Requiring $\pi^0/\eta \to ee\gamma$ JHEP 06 (2021) 019



Search for CP violation in $D^+_{(s)} \to h^+\pi^0$ and $D^+_{(s)} \to h^+\eta$ decays

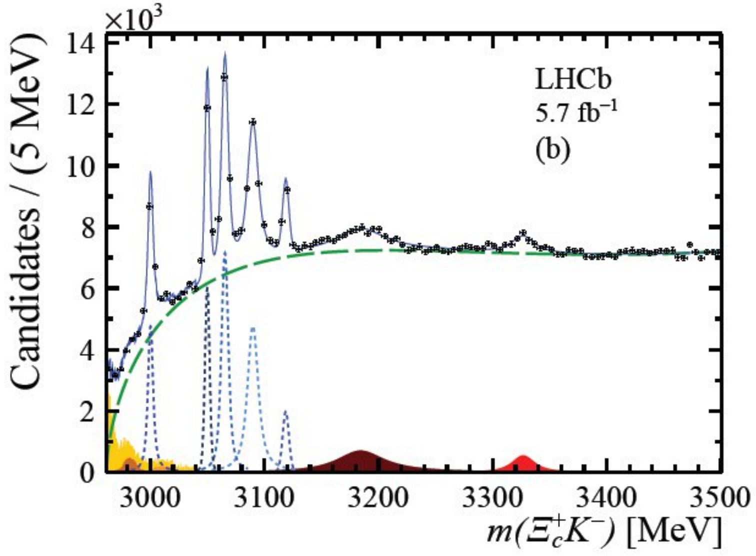
Spectroscopy & charm hadron properties

PRL 119 (2017) 112001
PRL 121 (2018) 052002
PRL 121 (2018) 162002
……



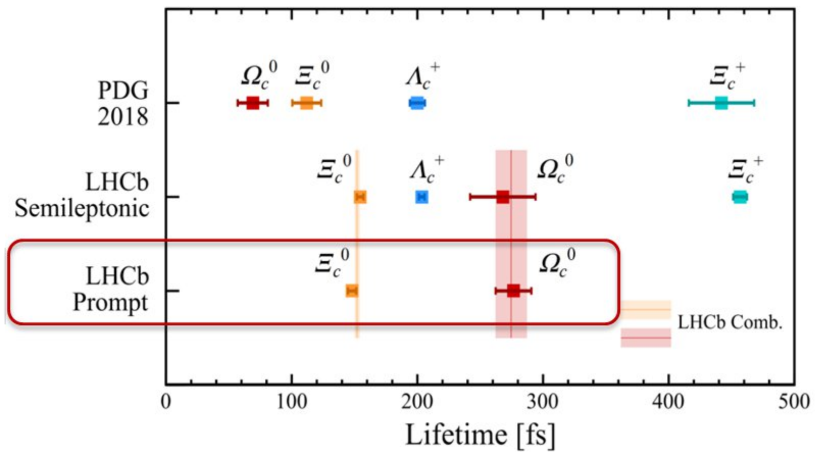
Observation of Ξ_{cc}^{++} and study of its properties, production, decay modes

PRL 118 (2017) 182001
arXiv:2302.04733 (accepted by PRL)



Observation of 5+2 Ω_c^0 states

PRL 121 (2018) 092003
PRD 100 (2019) 032001
Science Bulletin 67 (2022) 479



Establishment of charmed-hadron lifetime hierarchy:

$$\tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}.$$

Run3 and beyond...

Rare decays

	Mode	Upgrade (50 fb^{-1})	Upgrade II (300 fb^{-1})
Limits on BFs	$D^0 \to \mu^+\mu^-$	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}
	$\Lambda_c^+ \to p\mu^+\mu^-$	1.1×10^{-8}	4.4×10^{-9}
	$D^0 \to e\mu$	10^{-9}	4.1×10^{-9}
Stat. precision on asymmetries	$D^+ \to \pi^+\mu^+\mu^-$	0.2%	0.08%
	$D^0 \to \pi^+\pi^-\mu^+\mu^-$	1%	0.4%
	$D^0 \to \pi^+K^-\mu^+\mu^-$	0.3%	0.13%
	$D^0 \to K^+\pi^-\mu^+\mu^-$	12%	5%
	$D^0 \to K^+K^-\mu^+\mu^-$	4%	1.7%

Mixing & CPV

Observable	Current LHCb (up to 9 fb^{-1})	Upgrade I (23 fb^{-1})	(50 fb^{-1})	Upgrade II (300 fb^{-1})
Charm				
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5} [5]	17×10^{-5}	—	3.0×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	13×10^{-5} [38]	4.3×10^{-5}	—	1.0×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5} [37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}

Reaching for sub-10^{-4} precision

How CEPC could make impacts in charm physics

- Charm statistics of 300 fb^{-1} LHCb dataset would be much higher than CEPC due to high $\mathrm{pp} \to \mathrm{c\bar{c}X}$ cross-section
- CEPC is exected to be promising for the following measurements:
  - SL charm hadron decays: full event info + displaced vertices + low mult.
  - SL decays of Ξ_{cc}
  - Radiative charm decays: discrimination power of single photon vs. π^0/η would be the key
  - $D^0 \to V\left(h^+h^-\right) + invisible(\nu\bar{\nu},\ \gamma', etc.)$
  - Di-electron channels
  - Time-dependent study of D^0 decays with at least one π^0/η in the final state, *e.g.*, time-dependent amplitude analysis of $D^0 \to K\pi\pi^0/\pi\pi\pi^0$

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, rare decays, etc.
  - Observations of charm CPV, difference in D^0 mass eigenstates, etc.
- Still more charm results in the pipeline with full Run1+2 data, stay tuned!
  - For example, semileptonic D^0 decays, dielectron channels, charm baryons, ...
- Run3 for LHCb has started
- Experiences from LHCb in charm physics would be extremely valuable for future CEPC

Prospects for measurements with strange hadrons at LHCb

arXiv:1808.03477

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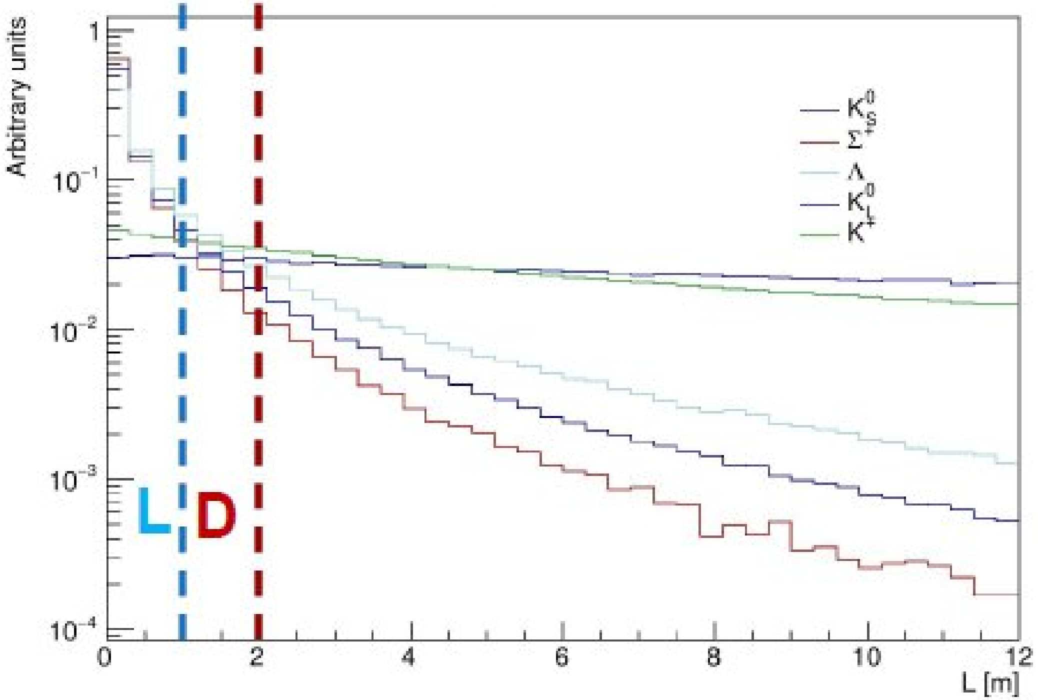

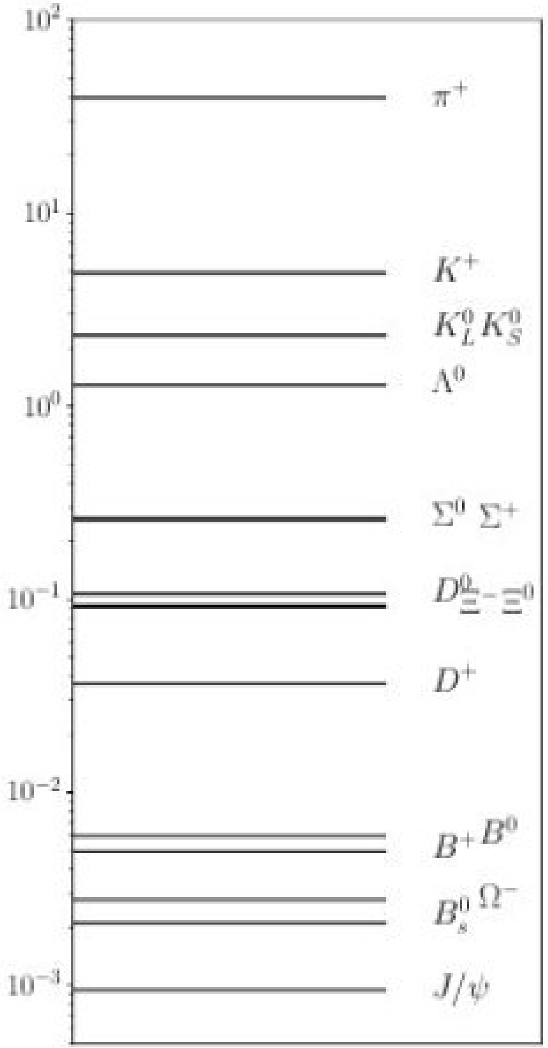

Figure 1: Multiplicity of particles produced in a single *pp* interaction at $\sqrt{s} = 13$ TeV within LHCb acceptance.

Backup Slides

Particle	Belle II	LHCb (300 fb^{-1})	CEPC (4×Tera-Z)
B^0, $\bar{B}^0$	5.4×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	4.8×10^{11}
$B^\pm$	5.7×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	4.8×10^{11}
B_s^0, $\bar{B}_s^0$	6.0×10^{8} (5 ab^{-1} on $\Upsilon(5S)$)	1×10^{13}	1.2×10^{11}
$B_c^\pm$	-	1×10^{11}	7.2×10^{8}
Λ_b^0, $\bar{\Lambda}_b^0$	-	2×10^{13}	1×10^{11}
D^0, $\bar{D}^0$		7×10^{14}	5.2×10^{11}
$D^\pm$		3×10^{14}	2.2×10^{11}
$D_s^\pm$		1×10^{14}	8.8×10^{10}
$\Lambda_c^\pm$		1×10^{14}	5.5×10^{10}
$\tau^\pm$	4.5×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)		1.2×10^{11}

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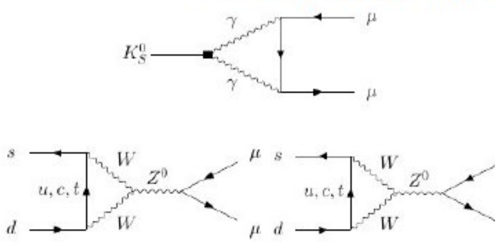
Search for $K_S^0 \to \mu^+\mu^-$

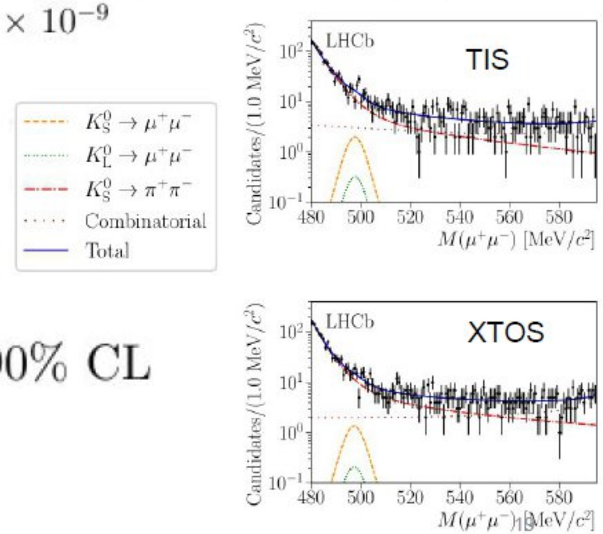


- Expected:

$\mathcal{B}(K_L^0 \to \mu^+\mu^-)_{SM} = (6.85 \pm 0.80_{LD} \pm 0.06_{SD}) \times 10^{-9}$

- Sensitive to NP contributions
- Dedicated software trigger in Run2
- Normalized to $K_S^0 \to \pi^+\pi^-$
- Combined results from Runs1-2:

$\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$ at 90% CL



arXiv:2212.04977

Search for $K_{S(L)}^0 \to \mu^+\mu^-\mu^+\mu^-$

- Expected:

$\mathcal{B}(K_S^0 \to \mu^+\mu^-\mu^+\mu^-)_{SM} \sim (1\text{–}4) \times 10^{-14}$.

$\mathcal{B}(K_L^0 \to \mu^+\mu^-\mu^+\mu^-)_{SM} \sim (4\text{–}9) \times 10^{-13}$.

- LHCb acceptance for K_L^0 ~0.2% of K_S^0
- Normalized to $K_S^0 \to \pi^+\pi^-$
- No events found in the signal mass window
- ULs @ 90% CL using 5.1 fb^{-1} Run2:

$\mathcal{B}(K_S^0 \to \mu^+\mu^-\mu^+\mu^-) < 5.1 \times 10^{-12}$,

$\mathcal{B}(K_L^0 \to \mu^+\mu^-\mu^+\mu^-) < 2.3 \times 10^{-9}$,