HIghlights of Recent Charm Results @ LHCb

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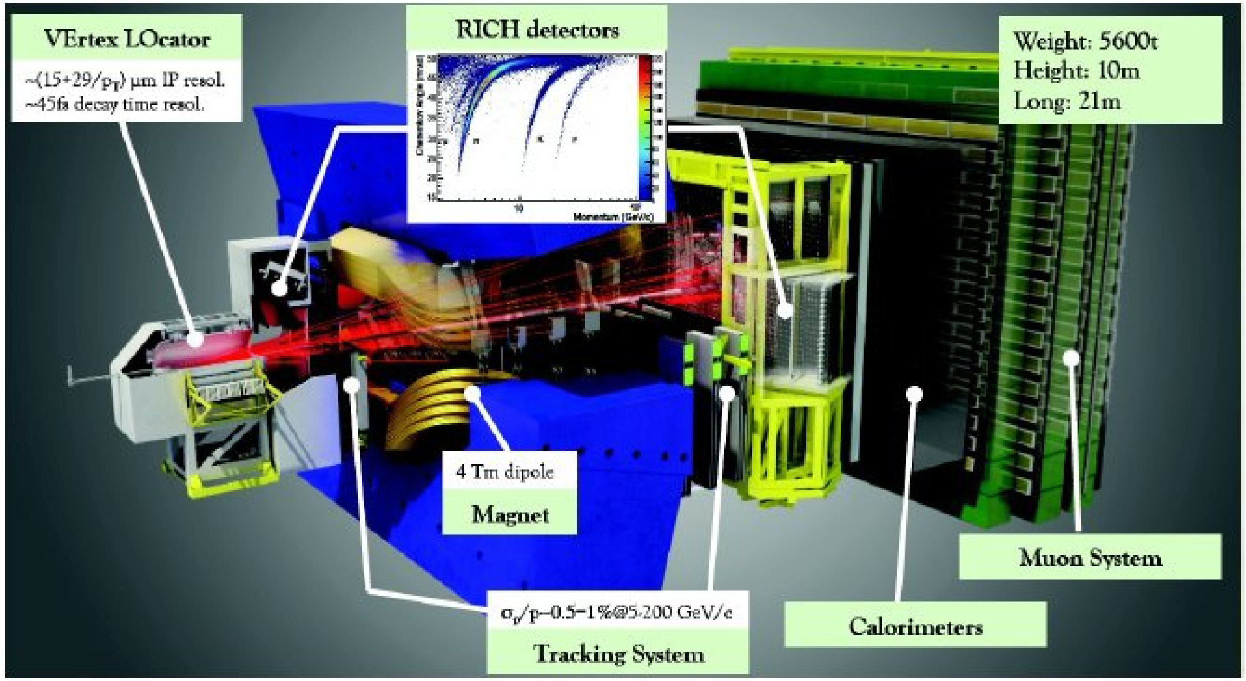
全国第二十届重味物理和CP破坏研讨会，复旦大学

Outline

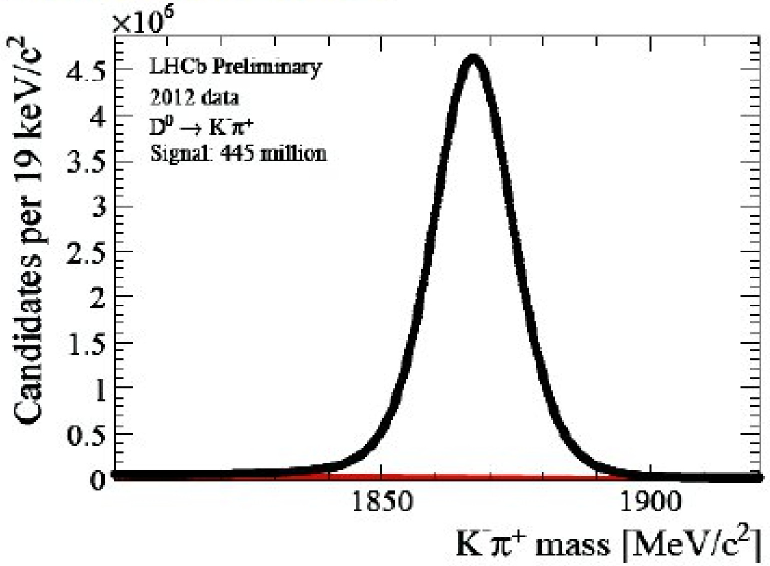
- Experimental details
- Charm mixing & CPV
- Direct CPV in multi-body charm decays
- Rare charm decays
- Prospects & outlook

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]

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

- 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]

Charm mixing & CPV

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

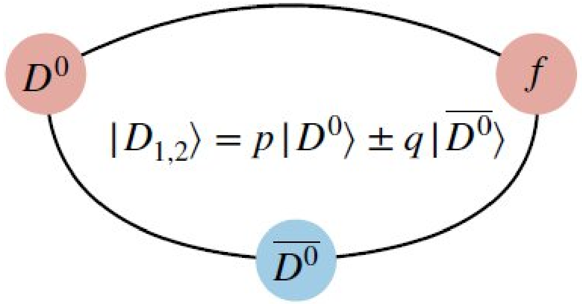
Direct *CP* violation $\left|\frac{\overline{A}_f}{A_f}\right|^{\pm 2} \approx 1 \pm A_d \rightarrow a_{CP}^{dir} \approx -\frac{1}{2}A_d$

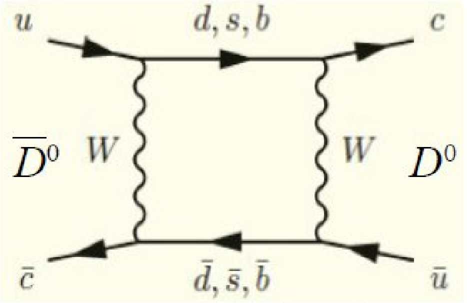
  - In mixing: rates of $D^0 \to \overline{D^0}$ and $\overline{D^0} \to D^0$ differ

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

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$$
$$\sim\lambda \qquad \sim\lambda \qquad \sim\lambda^5$$
$$\lambda = \sin(\theta_C) \sim 0.23$$

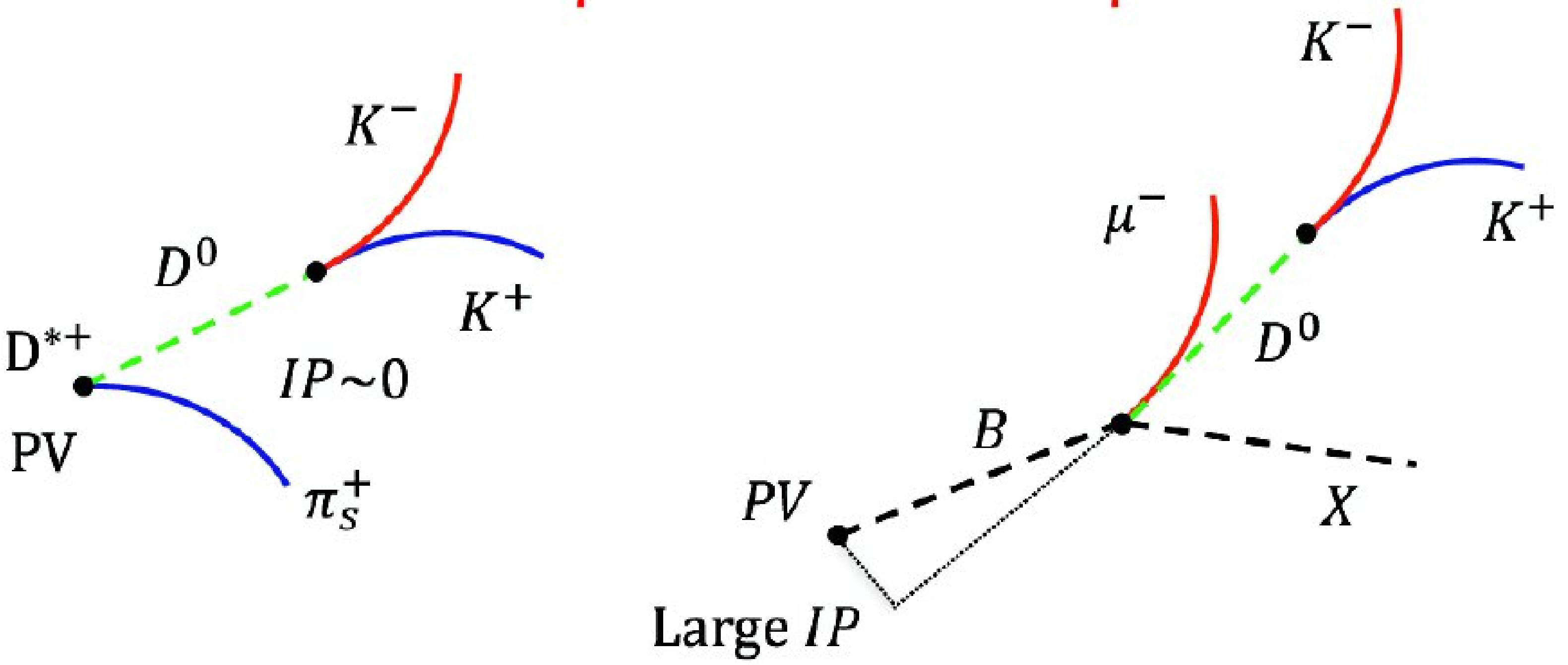
Expected CPV very small in charm
- Effectively 2-generation system
- 3rd generation and CPV enter through loops

NP if CPV found?

D^0 production at LHCb

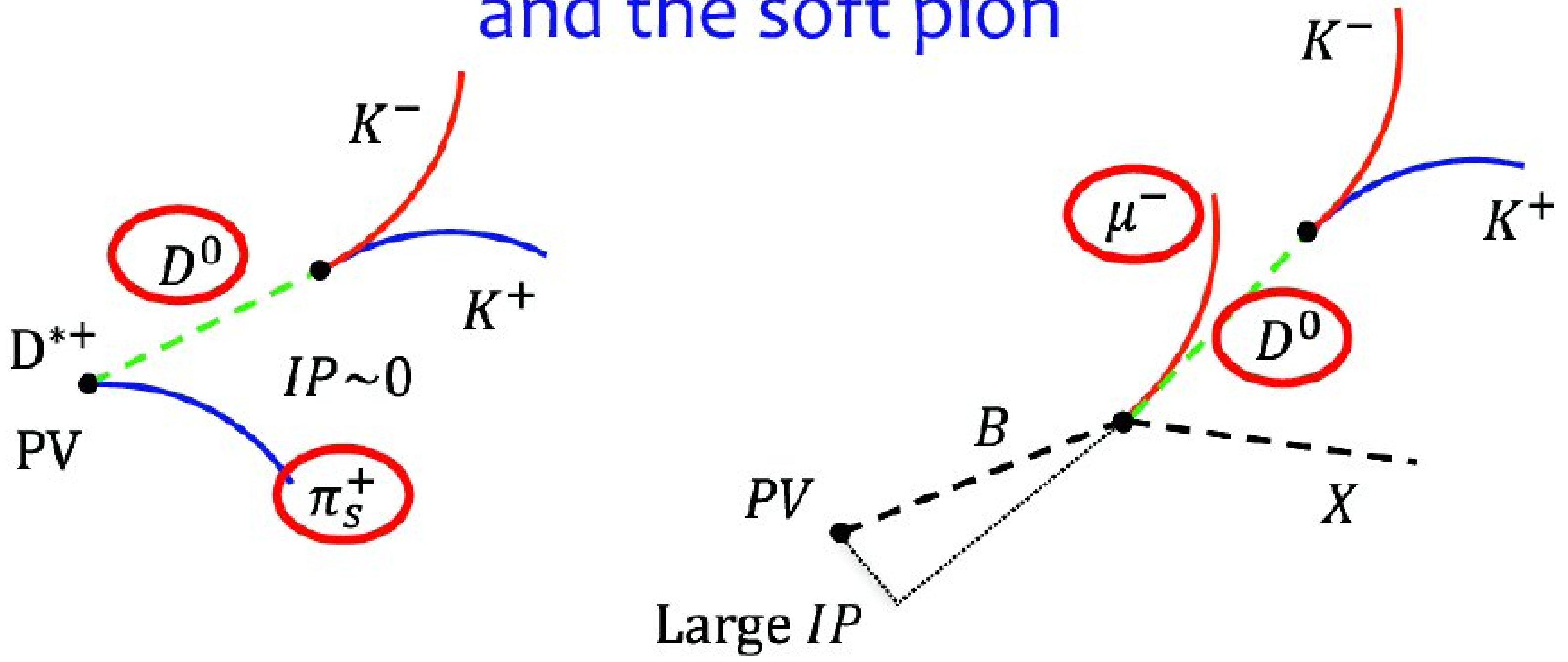
Two mechanisms of D^0 production

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



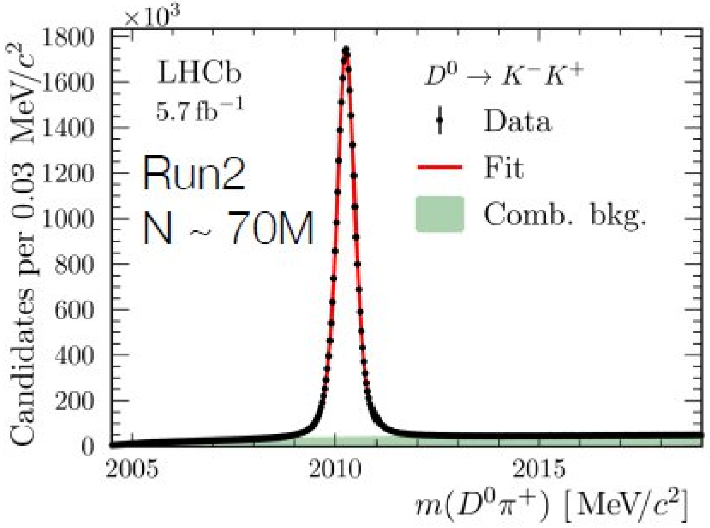
[PRL 131 (2023) 091802]

Editors' Suggestion

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

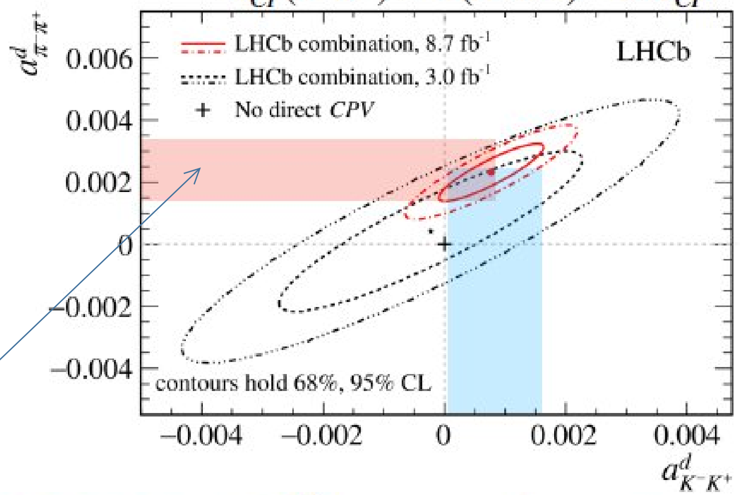
$$A_{CP}(K^+K^-) = [6.8 \pm 5.4(\text{stat}) \pm 1.6(\text{sys})] \times 10^{-4}$$



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

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

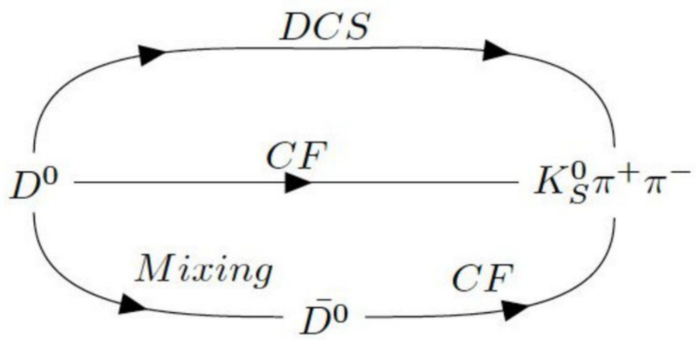
$A_{CP}(\pi^+\pi^-) = A(K^+K^-) - \Delta A_{CP}$



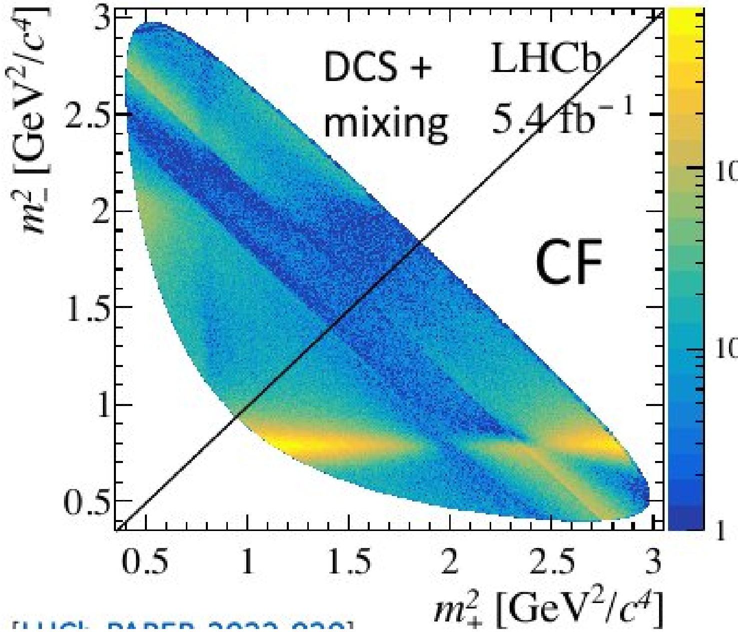
First evidence (3.8σ) of CPV in $D^0 \to \pi^+\pi^-$!

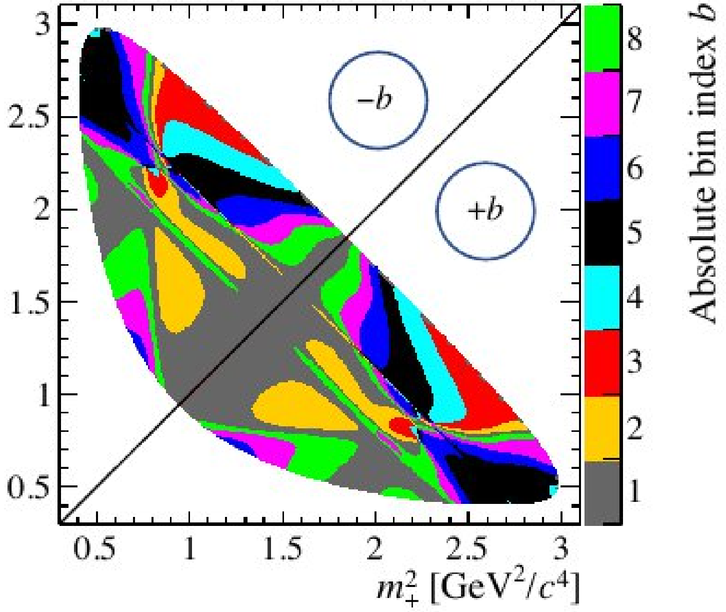
[PRL 127 (2021) 111801]
[PRD 108 (2023) 052005]

$D^0 - \overline{D}^0$ 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 $D^0/\bar{D}^0$) between $+b$ and $-b$ in bins of D^0 decay time t:

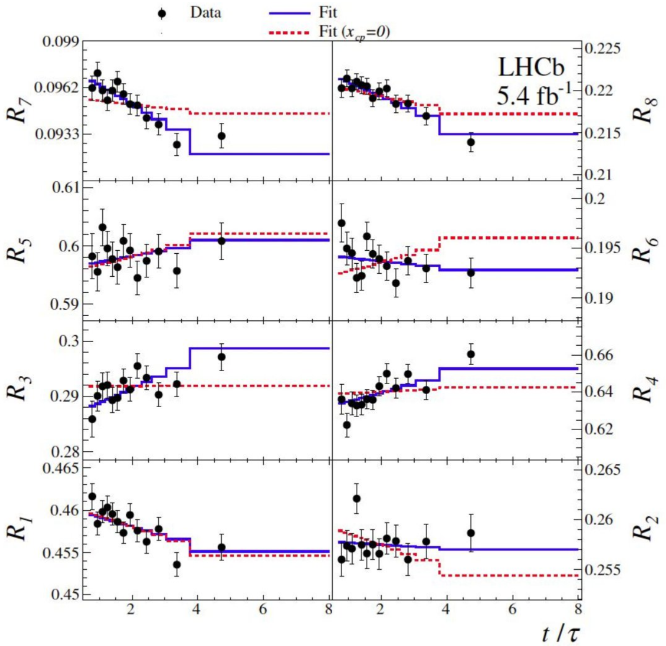
$$R_b^{\pm}(t) \approx r_b - \sqrt{r_b}[(1-r_b)c_b y - (1+r_b)s_b x]\Gamma t$$

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

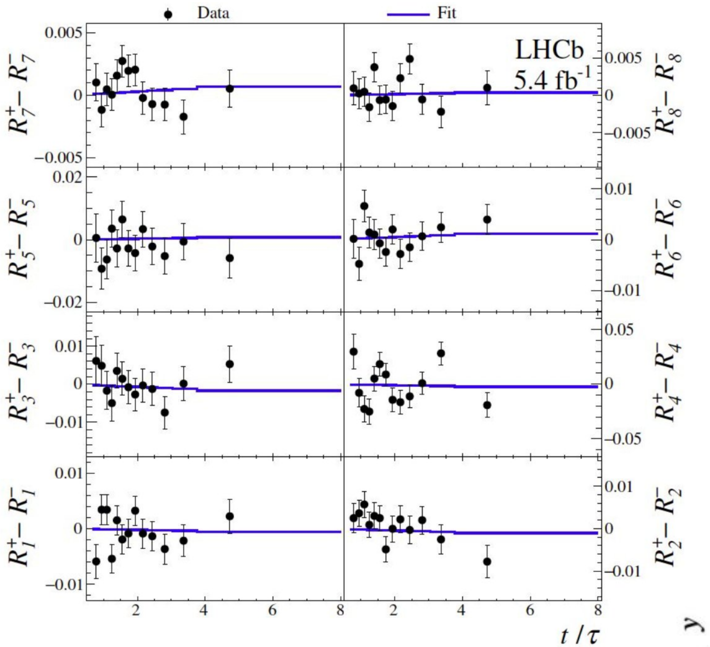
[PRL 127 (2021) 111801]

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

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



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



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

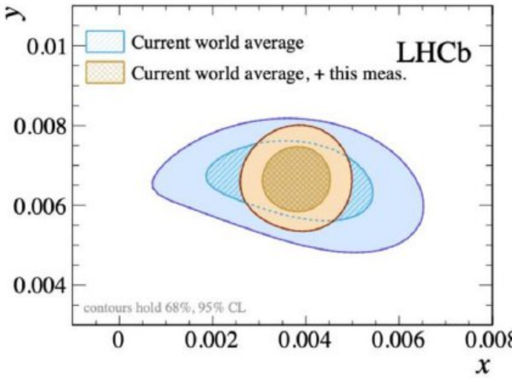
$$\Delta x = (-0.27 \pm 0.18 \pm 0.01) \times 10^{-3}$$
$$\Delta y = (\ \ 0.20 \pm 0.36 \pm 0.13) \times 10^{-3}$$

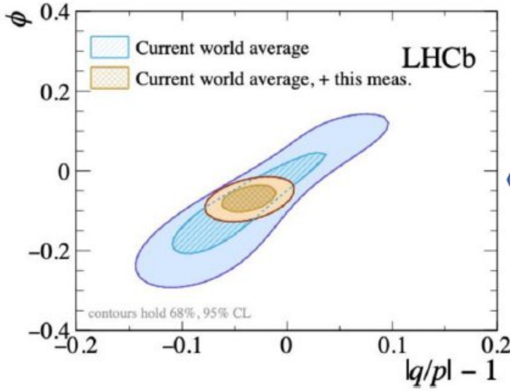
$$x = (3.98^{+0.56}_{-0.54}) \times 10^{-3},$$
$$y = (\ 4.6^{+1.5}_{-1.4} \ ) \times 10^{-3},$$
$$|q/p| = 0.996 \pm 0.052,$$
$$\phi = 0.056^{+0.047}_{-0.051}.$$

First observation of non-zero x (>7σ)

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

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





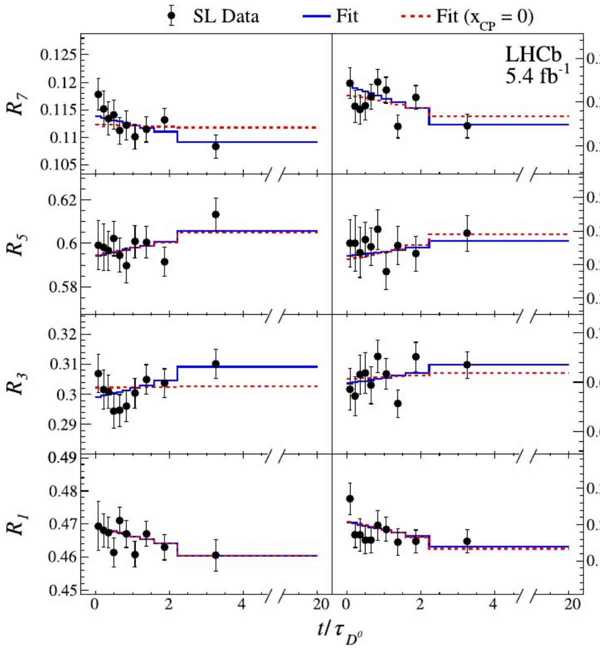
LHCb measures tiny mass difference between particles

World Averages significantly improved!

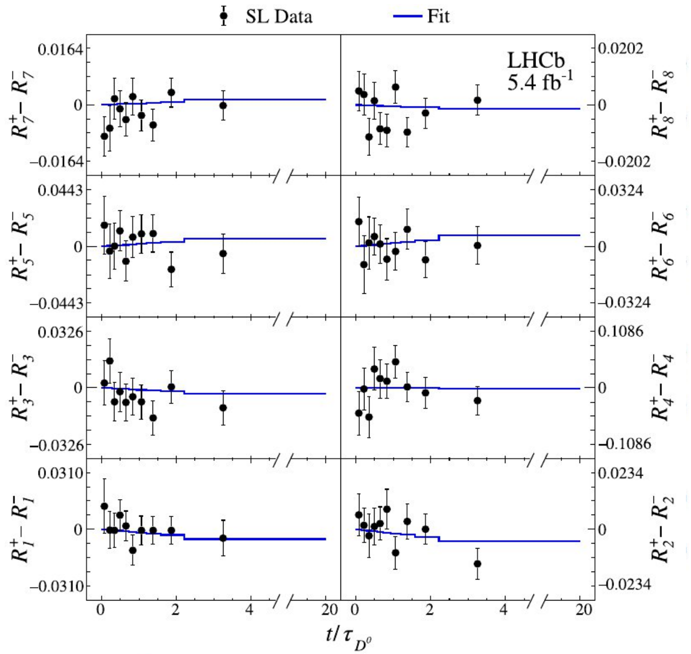
[PRL 127 (2021) 111801]
[PRD 108 (2023) 052005]

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

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



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



$$x_{CP} = [4.01 \pm 0.45(\text{stat}) \pm 0.20(\text{syst})] \times 10^{-3},$$
$$y_{CP} = [5.51 \pm 1.16(\text{stat}) \pm 0.59(\text{syst})] \times 10^{-3},$$
$$\Delta x = [-0.29 \pm 0.18(\text{stat}) \pm 0.01(\text{syst})] \times 10^{-3},$$
$$\Delta y = [0.31 \pm 0.35(\text{stat}) \pm 0.13(\text{syst})] \times 10^{-3}.$$
$$x = (4.01 \pm 0.49) \times 10^{-3},$$
$$y = (5.5 \pm 1.3) \times 10^{-3},$$
$$|q/p| = 1.012^{+0.050}_{-0.048},$$
$$\phi = -0.061^{+0.037}_{-0.044} \text{ rad.}$$

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

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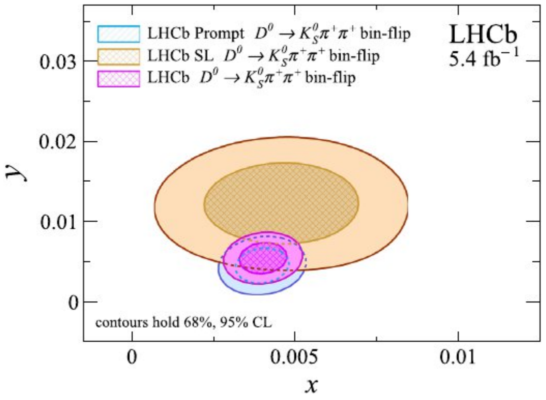
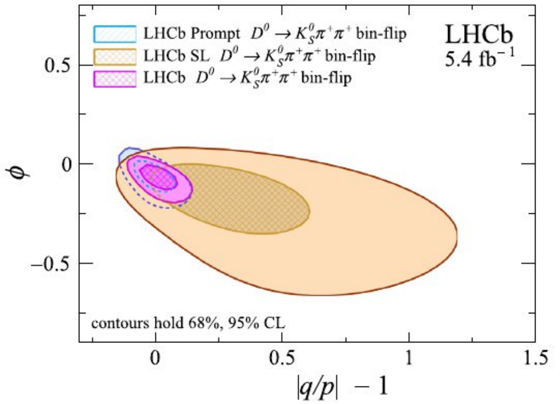




World Averages significantly improved!

Direct CPV in 3-body D decays

- In multi-body decays, strong phase δ vary across the phase space
- Locally enhanced CPV effects possible due to interference
  - Already observed in chameless 3-body B^+ decays by LHCb [see e.g. PRD 108 (2023) 012008]
- Recent model-independent searches for direct CPV on Dalitz-plot planes of:
  - $\mathrm{D}^+_{(\mathrm{s})} \rightarrow K^- K^+ K^+$ [JHEP 07 (2023) 067]
  - $D^0 \rightarrow \pi^+ \pi^- \pi^0$ [JHEP 09 (2023) 129]
  - $D^0 \rightarrow K^0_S K^\pm \pi^\mp$ [arXiv:2310.19397]

All dominated by CS/DCS amplitudes

Direct CPV in $D^+_{(s)} \to K^- K^+ K^+$

- Run 2 (5.6 fb^{-1}) data
- Binned method:

$$S^i_{CP} = \frac{N^i_+ - \alpha N^i_-}{\sqrt{\alpha(\delta^2_{N^i_+} + \delta^2_{N^i_-})}} \qquad \alpha = \frac{\sum N^i_+}{\sum N^i_-}$$

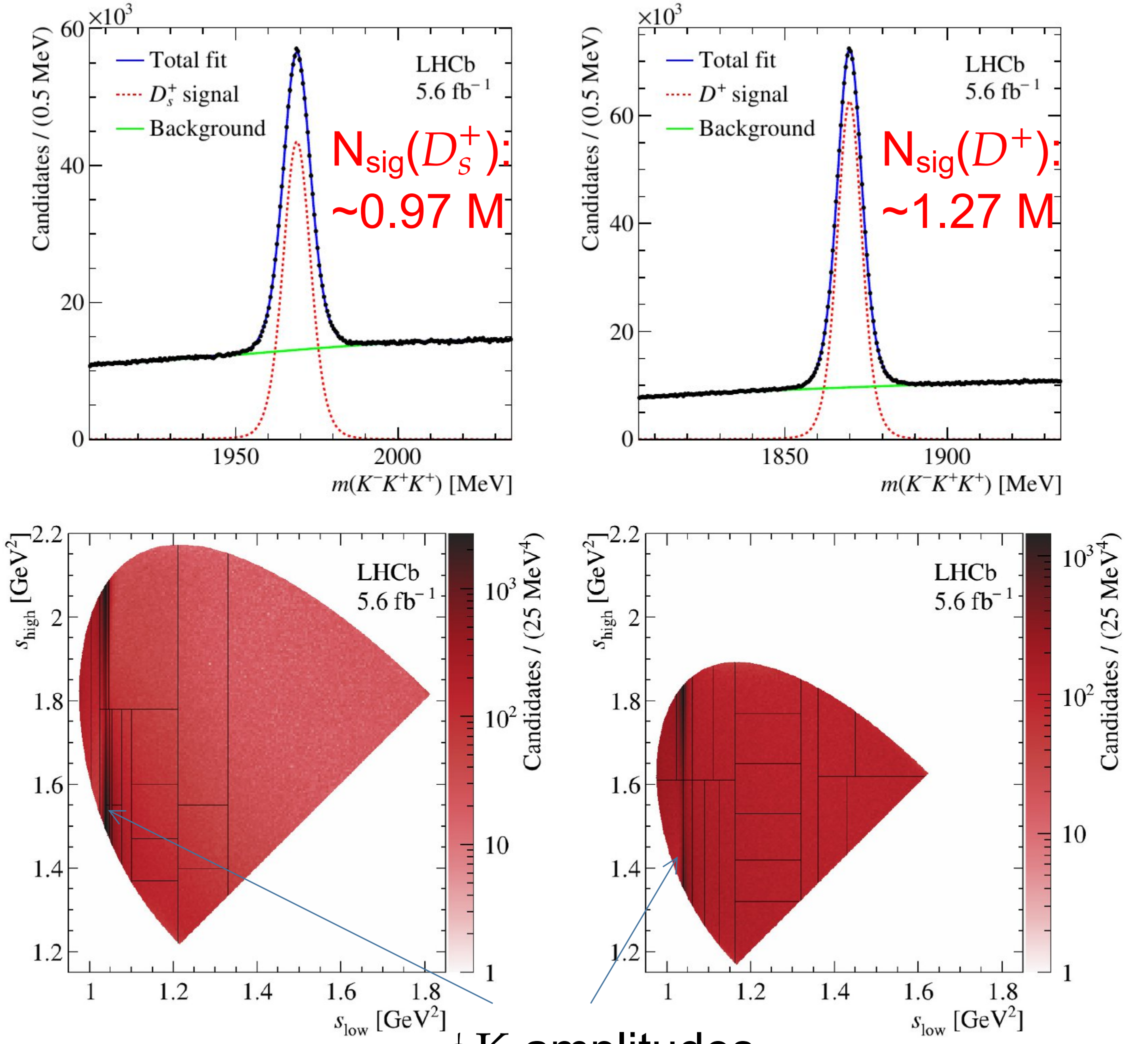
Global asymmetry

  - S^i_{CP} follows standard normal distribution if no CPV

$$\chi^2 = \sum (S^i_{CP})^2$$

exclude CP conservation if $p < 3 \times 10^{-7}$ (n_{dof}=$n_{bins(21)}$-1)

- Validation with CF decays $D^+_s \to K^- K^+ \pi^+$ and $D^+ \to K^- \pi^+ \pi^+$
- Measured p-values 13.3% (31.6%) for D^+_s (D^+) decays



ϕK amplitudes

Adaptive binning with improved sensitivity to S-wave/P-wave interference effects

Direct CPV in $D^+_{(s)} \to K^- K^+ K^+$

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$$S^i_{CP} = \frac{N^i_+ - \alpha N^i_-}{\sqrt{\alpha(\delta^2_{N^i_+} + \delta^2_{N^i_-})}} \qquad \alpha = \frac{\sum N^i_+}{\sum N^i_-}$$

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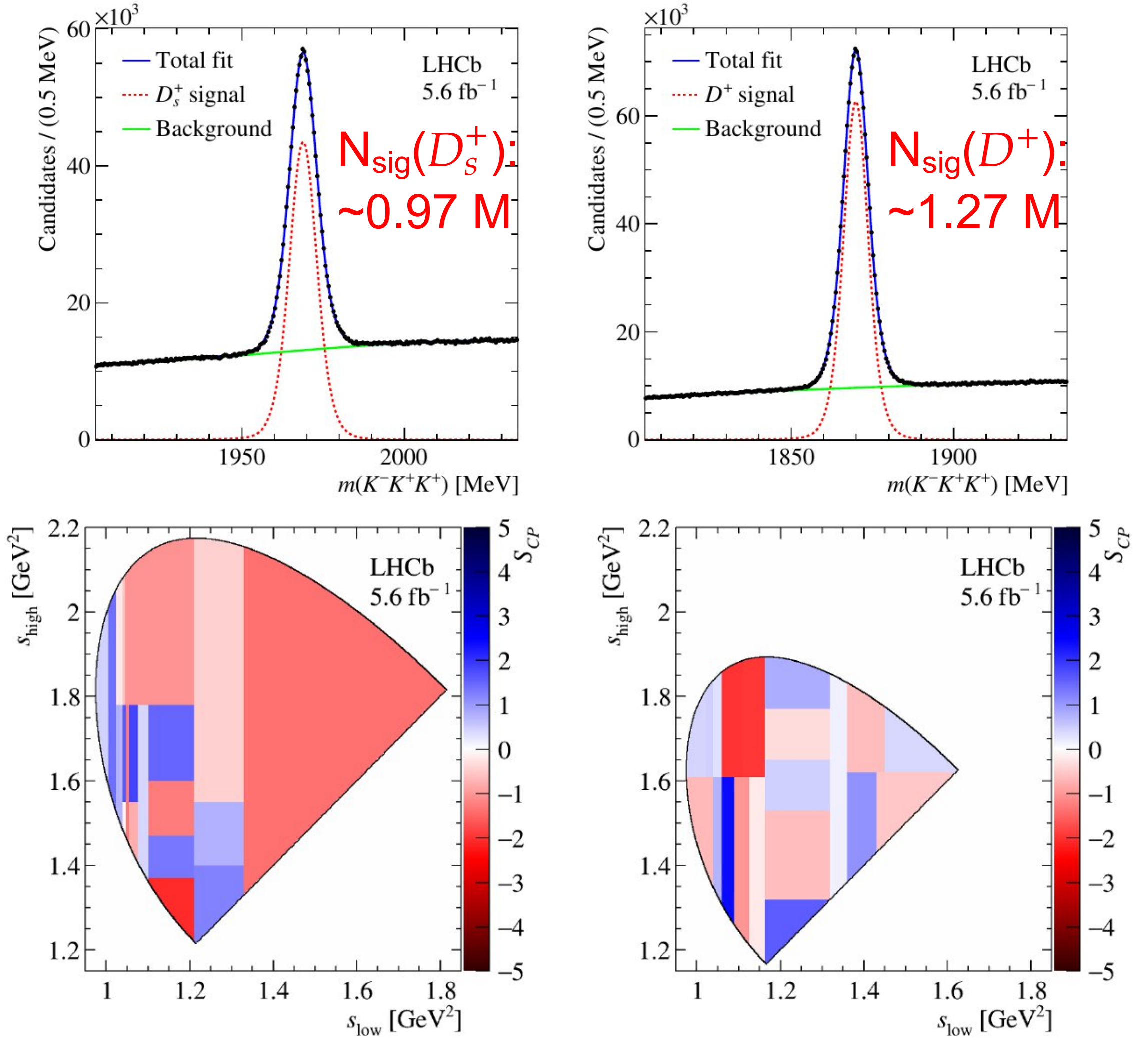


[JHEP 09 (2023) 129]

Direct CPV in $D^0 \to \pi^+\pi^-\pi^0$

- Dominated by $D^0 \to \rho^\pm\pi^\mp$ amplitudes
  - Could be related to recent evidence of CPV in $D^0 \to \pi^+\pi^-$
- Run 2 (6 fb^{-1}) data with D^0 from D^{*+} and tagged by π_s^+
- Unbinned energy test method by comparing weighted distance between pairs in phase space:

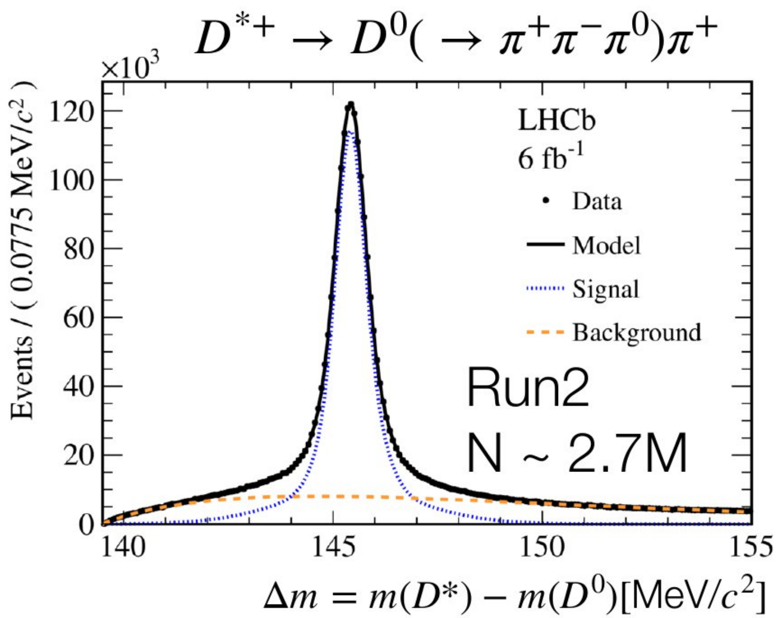
$$T = \sum_{i,j>i}^{n} \frac{\Psi_{ij}}{2n(n-1)} + \sum_{i,j>i}^{\bar{n}} \frac{\Psi_{ij}}{2\bar{n}(\bar{n}-1)} - \sum_{i,j}^{n.\bar{n}} \frac{\Psi_{ij}}{n\bar{n}}$$

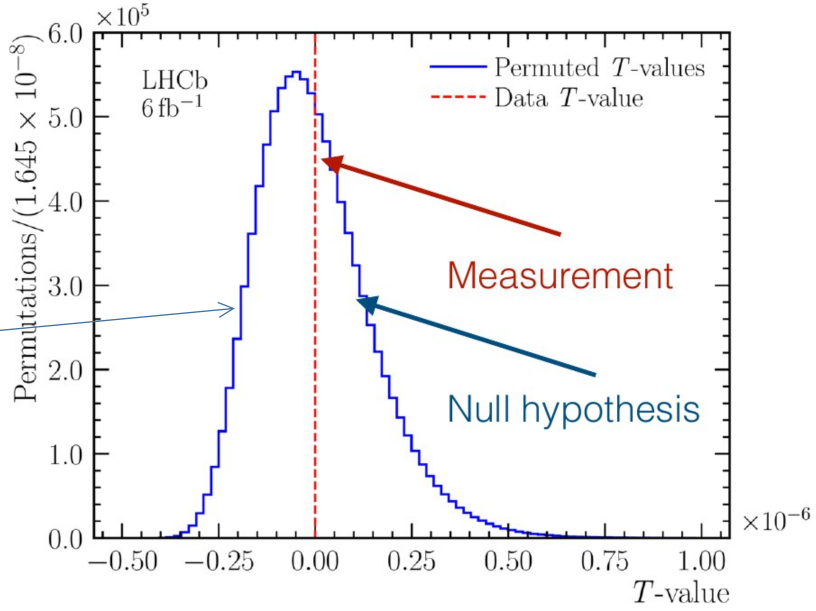
Average distance candidates same flavour — Average distance candidates opposite flavour

$$\Psi_{ij} = e^{-d_{ij}^2/2\delta^2}$$

$$d_{ij} = [(\Delta s_{12})^2_{ij} + (\Delta s_{13})^2_{ij} + (\Delta s_{23})^2_{ij}]$$

- Null hypothesis from permulations of T-values with randomized tags
- Validation with CF decay $D^0 \to K^-\pi^+\pi^0$
- Measured p-value 62%: no hint for CPV!

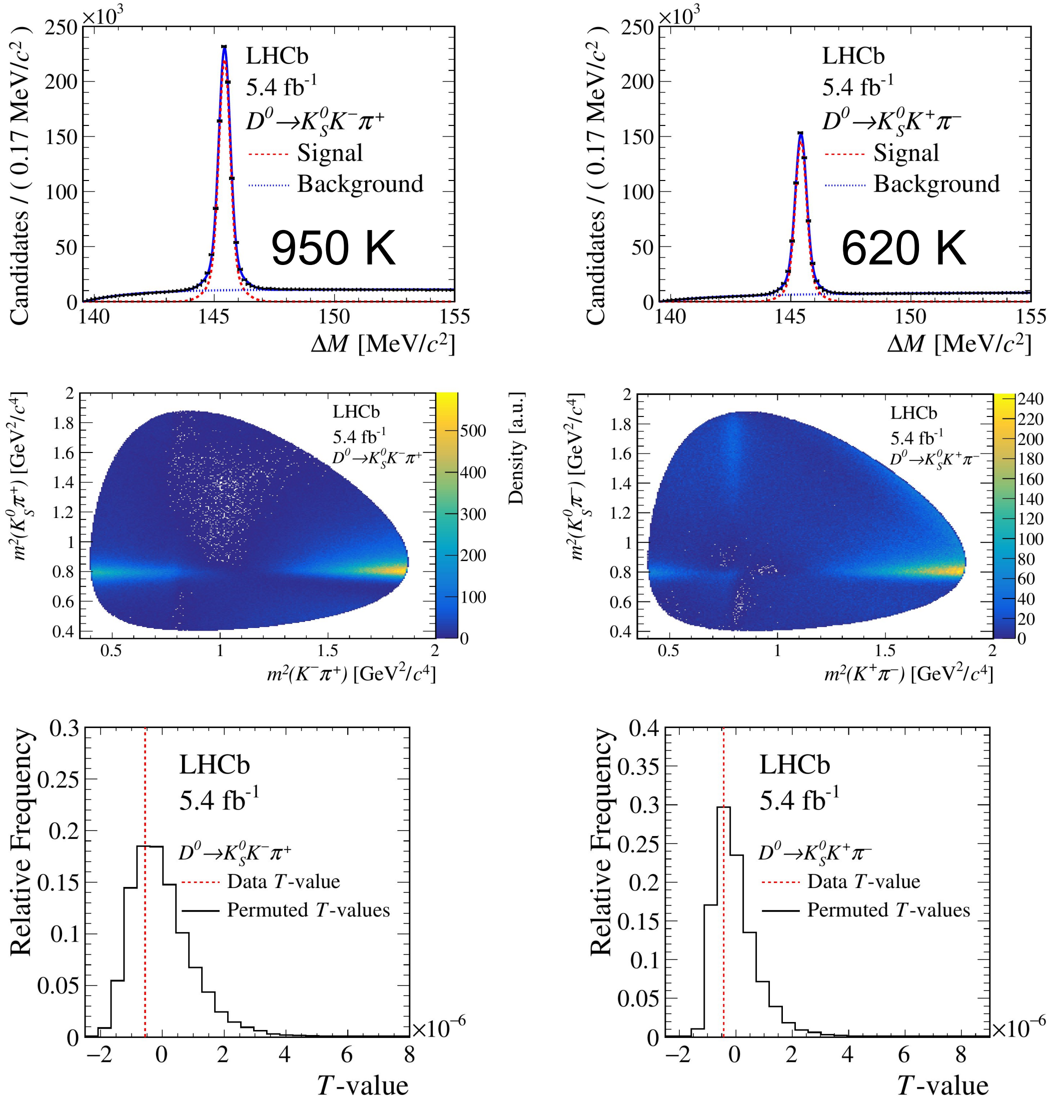




[arXiv:2310.19397]

Direct CPV in $D^0 \to K_S^0 K^\pm \pi^\mp$

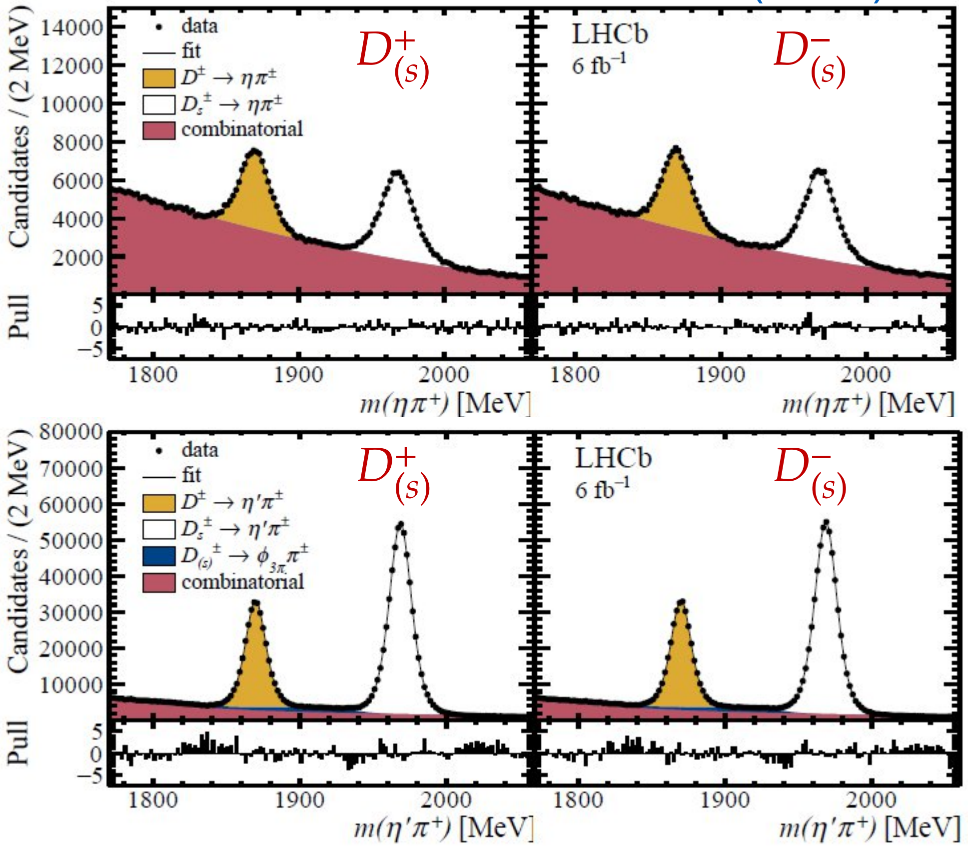
- Dominated by SCS amplitudes including $D^0 \to K^{*\mp} K^\pm / K^{*0} K_S^0$
- Run 2 (5.4 fb^{-1}) data with D^0 from D^{*+} and tagged by π_s^+
- Unbinned energy test method as in $D^0 \to \pi^+\pi^-\pi^0$
- Control modes: $D^0 \to K^-\pi^+\pi^+\pi^- / K_S^0\pi^+\pi^-$
- Measured p-values 70% (66%) for $D^0 \to K_S^0 K^-\pi^+$ ($D^0 \to K_S^0 K^+\pi^+$): no hint for CPV!



Hadronic decays with π^0/η

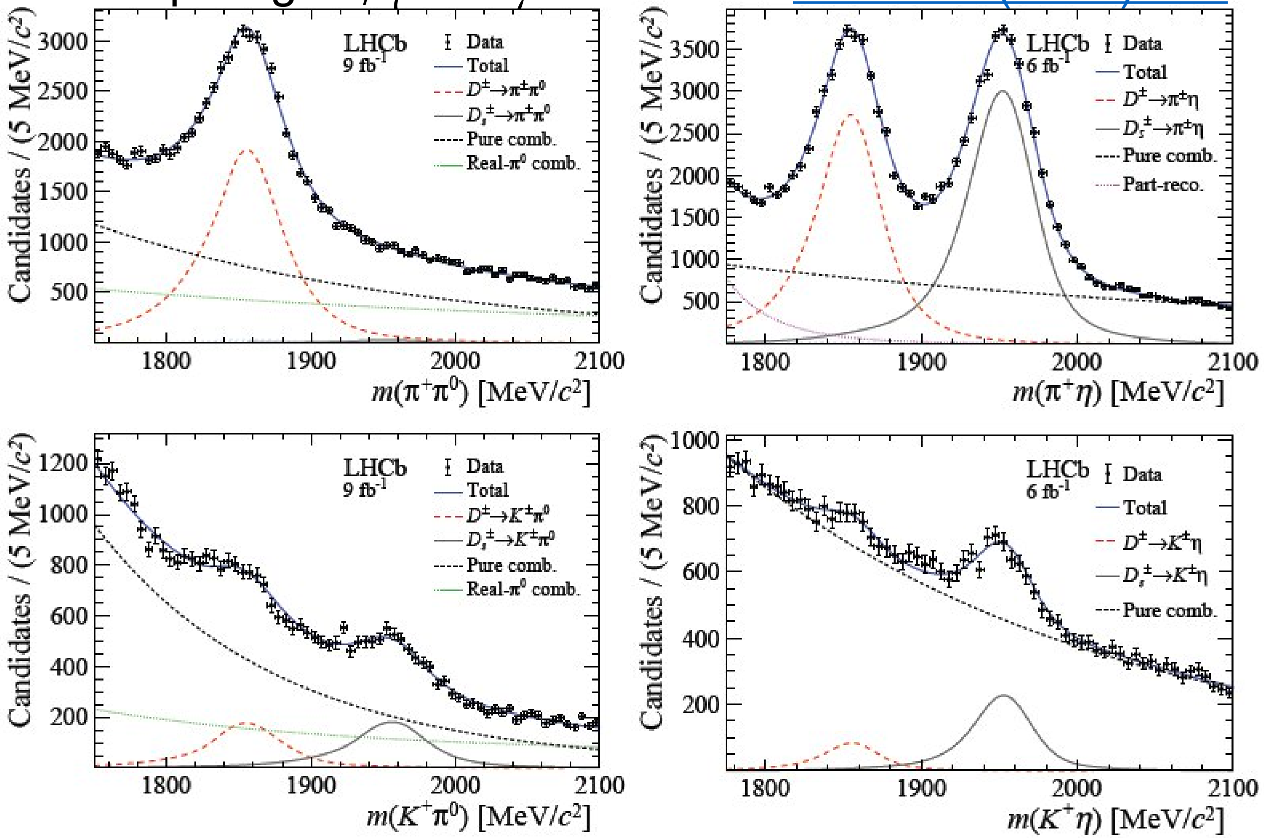
No CPV found
Almost all are world's best!

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

Overview of rare charm decays @ LHCb

branching ratios, especially regions away from the resonances

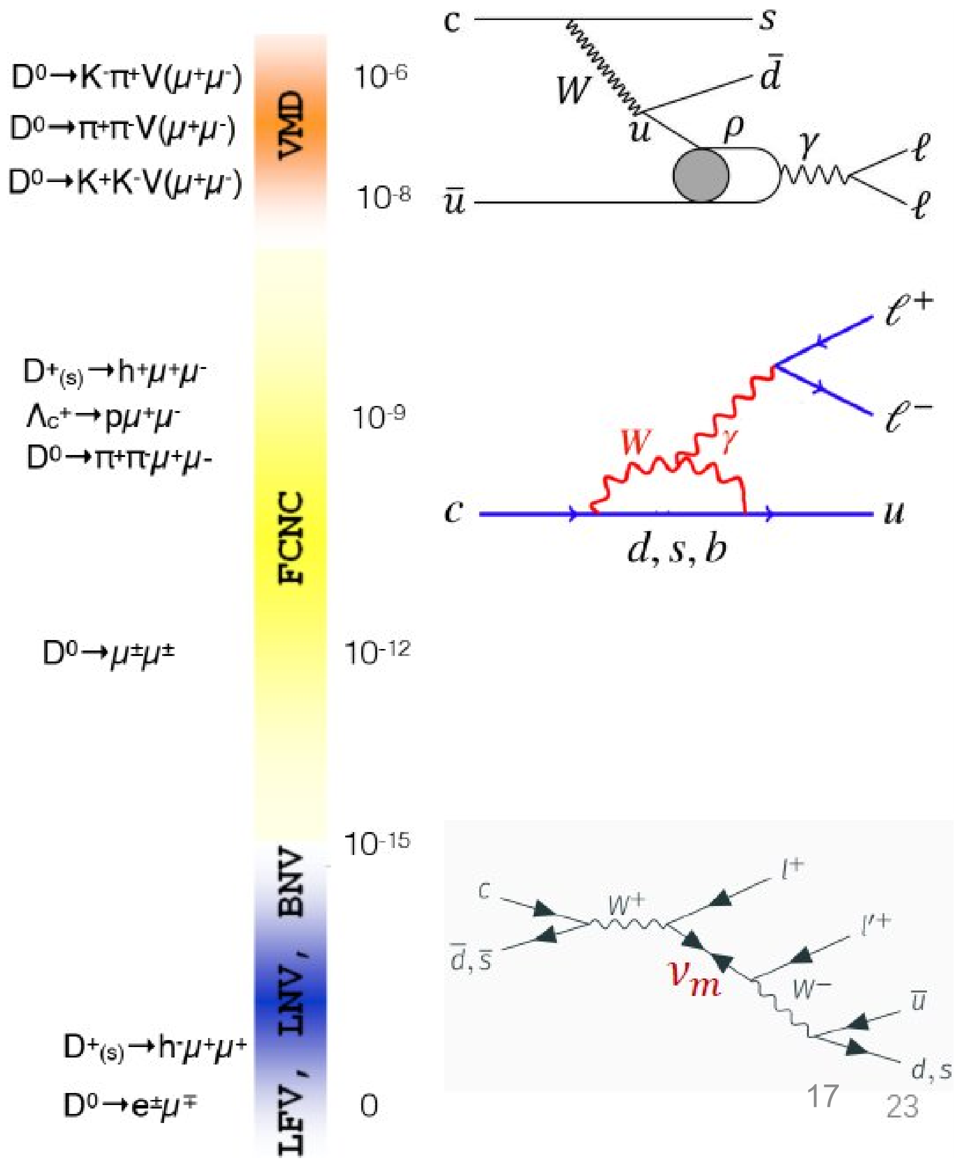
- search for $D^0 \to \mu^+\mu^-$ [PLB 725 15-24 (2013)] [PRL 131 (2023) 041804]
- search for $D^+_{(s)} \to h^+l^+l^-$ [PLB 724 203-212 (2013)] [JHEP 06 44 (2021)]
- search for $\Lambda_c^+ \to p\mu^+\mu^-$ [PRD 97 091101 (2018)]
- search for $D^0 \to \pi^+\pi^-\mu^+\mu^-$ [PLB 728 234-243 (2014)]
-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

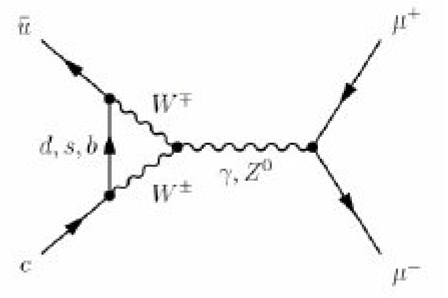
- lepton-flavor/number-violation
  - search for $D^0 \to \mu^+e^-$ [PLB 754 167 (2016)]
  - search for $D^+_{(s)} \to h^-l^+l^{(\prime)+}$, $D^+_{(s)} \to h^+\mu^\pm e^\mp$ [JHEP 06 44 (2021)]
- angular observables and CP asymmetries
  - angular analysis and search for CPV in $D^0 \to h^+h^-\mu^+\mu^-$

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

[PRL 128 (2022) 221801]

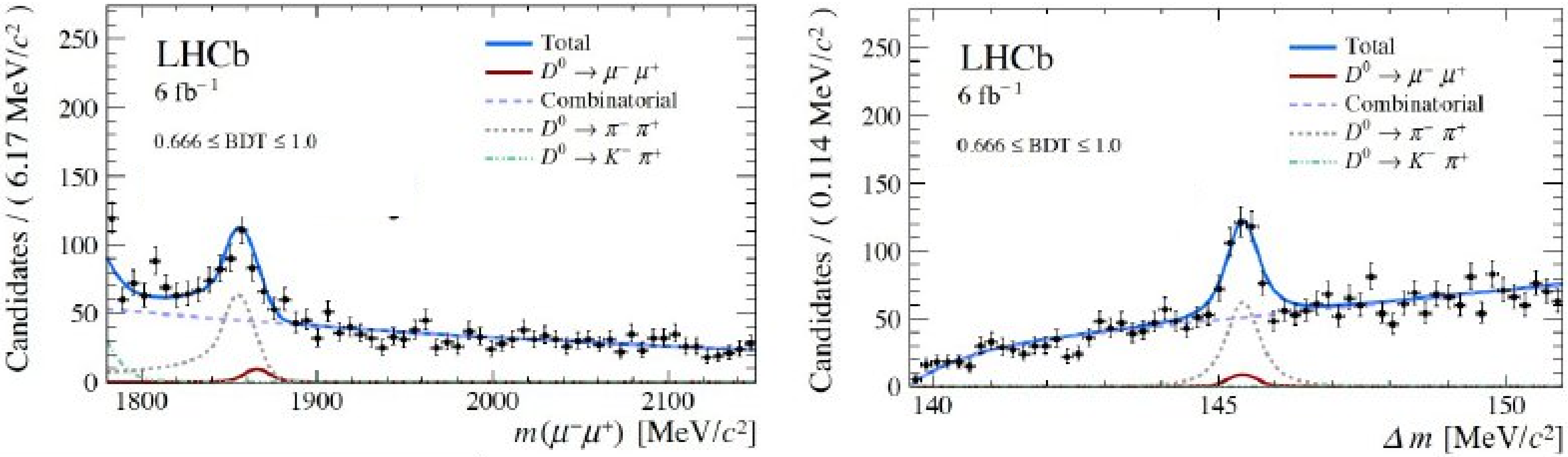


Search for $D^0 \to \mu^+\mu^-$



- 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: $\mathcal{B}(D^0 \to \mu^+\mu^-) = \alpha N_{D^0\to\mu^+\mu^-}$, $\alpha \sim \frac{\mathcal{B}(D^0\to h^-\pi^+)}{N_{D^0\to h^-\pi^+}} \frac{\varepsilon_{D^0\to h^-\pi^+}}{\varepsilon_{D^0\to\mu^+\mu^-}} \sim 2 \times 10^{-11}$
- 2D simultaneous fits in 3 BDT bins per run:

  Peaking mostly from π/μ misID



- Final result:

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

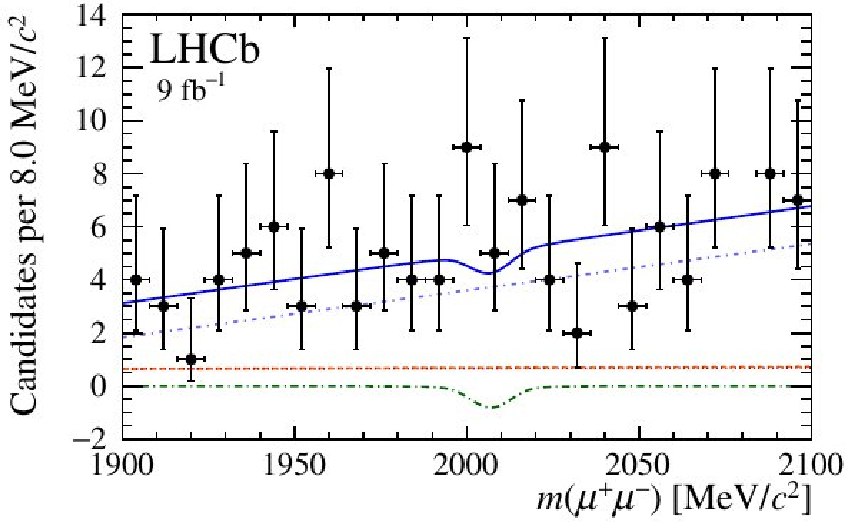
Improvement of more a factor of two!

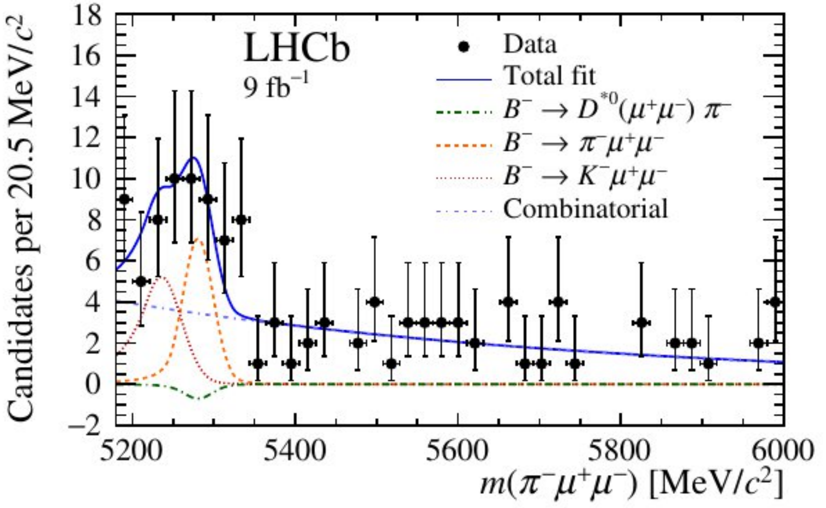
Search for $D^{*0} \to \mu^+ \mu^-$ in B decay

- Leptonic D* decays offer a complementary approach to constraining Wilson coefficients
- Highly suppressed in SM: BF ~10^{-18}
- Search in the decay chain of $B^- \to D^{*0}(\to \mu^+ \mu^-)\pi^-$
- Normalization channel: $B^- \to J/\psi(\to \mu^+ \mu^-)K^-$
- First search:

$\varepsilon_{J/\psi K^-}/\varepsilon_{D^{*0}\pi^-}$	1.21 ± 0.03
$N_{J/\psi K^-}$	$(2316 \pm 8) \times 10^3$

$$\mathcal{B}(D^{*0} \to \mu^+ \mu^-) < 2.6 \times 10^{-8} \text{ at } 90\% \text{ CL}$$





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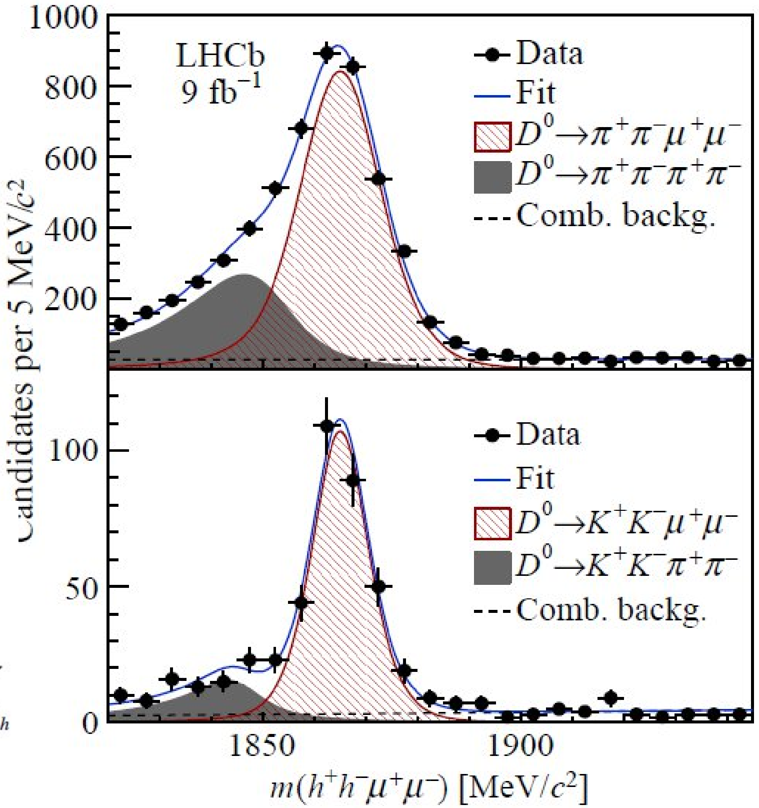
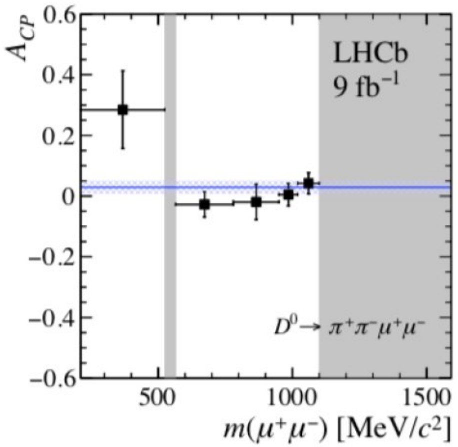
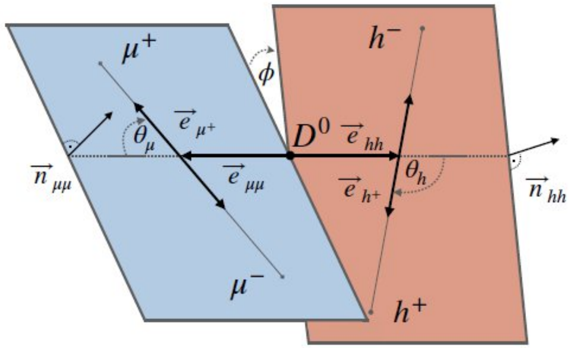
CPV & angular analysis of $D^0 \to hh\mu^+\mu^-$

- 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





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

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

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

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})	Upgrade I (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

A new detector & no hw drigger: expecting benefits to A_{CP} measurements in hadronic channels, esp. for those with at least one K_S

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, radiative charm decays, charm baryons, ...
- Run3 for LHCb has started, expecting fruitful years to come...
- Synergy across different experiments on charm physics: BESIII, BELLE(II), future STCF, ...

Backup Slides