Recent results in charm physics at LHCb

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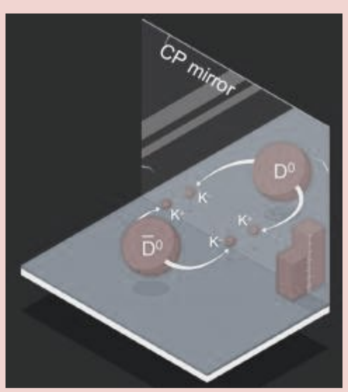
on behalf of the
LHCb collaboration

5 July 2023

Charm Physics at LHCb*

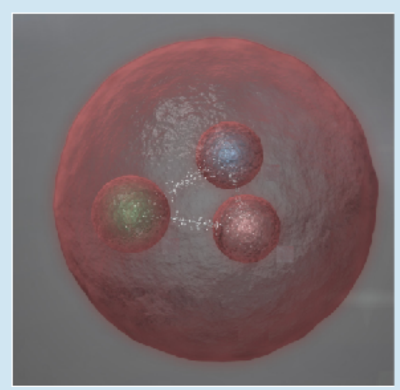
Mixing and CPV

- Meson oscillations
- **Time-integrated CPV**
- Time-dependent CPV
- **Locally-enhanced CPV**
- …



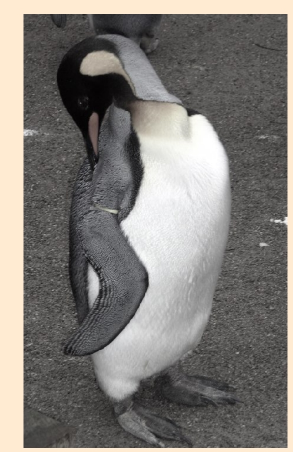
Production and decay properties

- Doubly charmed baryons
- Charm production
- **Excited charm baryons**
- …



Rare decays

- **Flavour-changing neutral current processes**
- Lepton-flavour, lepton-number violation
- …

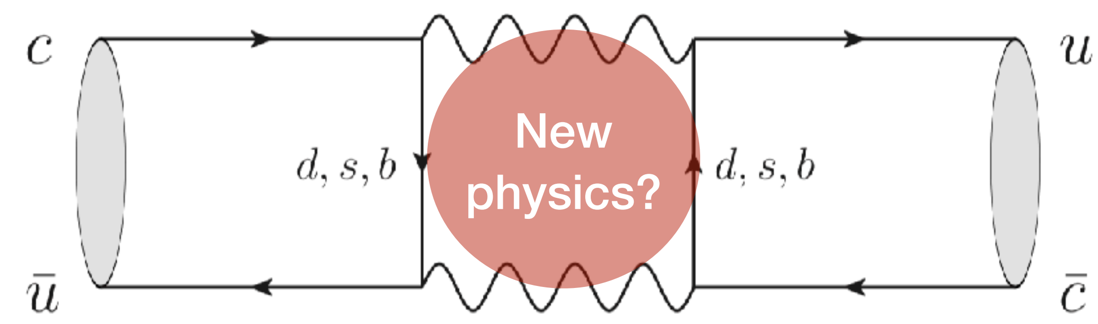


*only LHCb analyses discussed in this talk, for charm results at Belle II and BES III see talks by Takeo Higuchi and Wei Xu

Why care about Charm* @BEAUTY?

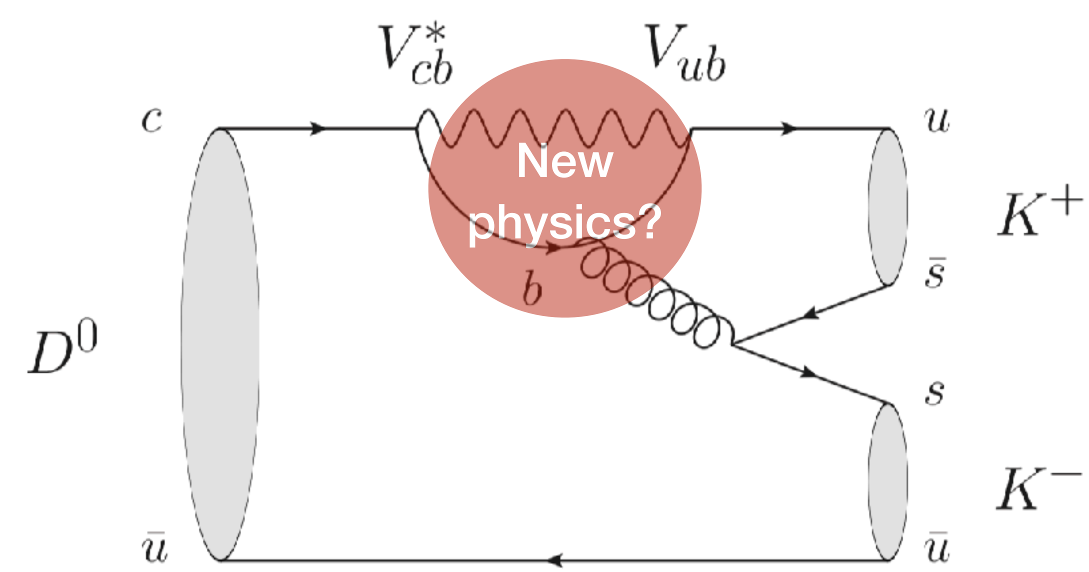
Unique:

- Only bound HF system made of up-type quarks, complementary sensitivity to BSM couplings wrt to K and $B_{(s)}$ decays
- $m_c \sim 1.3$ GeV$/c^2$ makes theoretical predictions hard, but allows for insights into QCD from a unique perspective



Discovery tool:

- All processes involving quantum-loops are highly suppressed in the SM
  - Charm meson oscillation probability very low
  - CP violating effects tiny ($\lesssim \mathcal{O}(10^{-3})$)
  - Rare decays extremely rare ($\lesssim \mathcal{O}(10^{-9})$)



Room for new physics to show up!

*hope to see many of you in two weeks at CHARM in Siegen

Charming beauty detector

JINST3(2008)S08005
Int.J.Mod.Phys.A30(2015)no.07 1530022

- Large production cross-sections of charm hadrons at LHCb

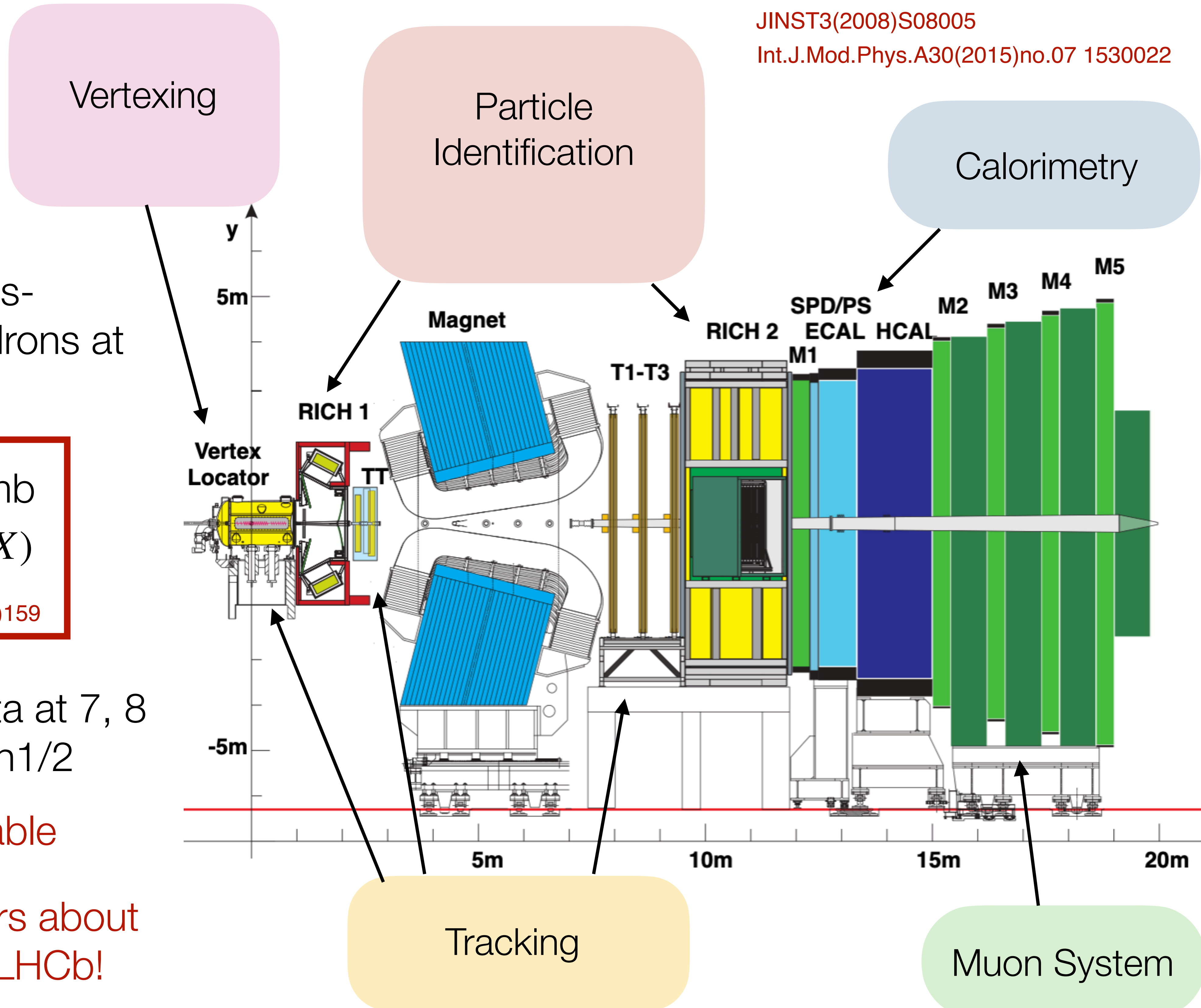
$$\sigma(pp \to c\bar{c}X) \approx 2.4 \text{ mb}$$
$$\sim 20 \times \sigma(pp \to b\bar{b}X)$$

$@\sqrt{s} = 13\text{TeV}$ JHEP03(2016)159

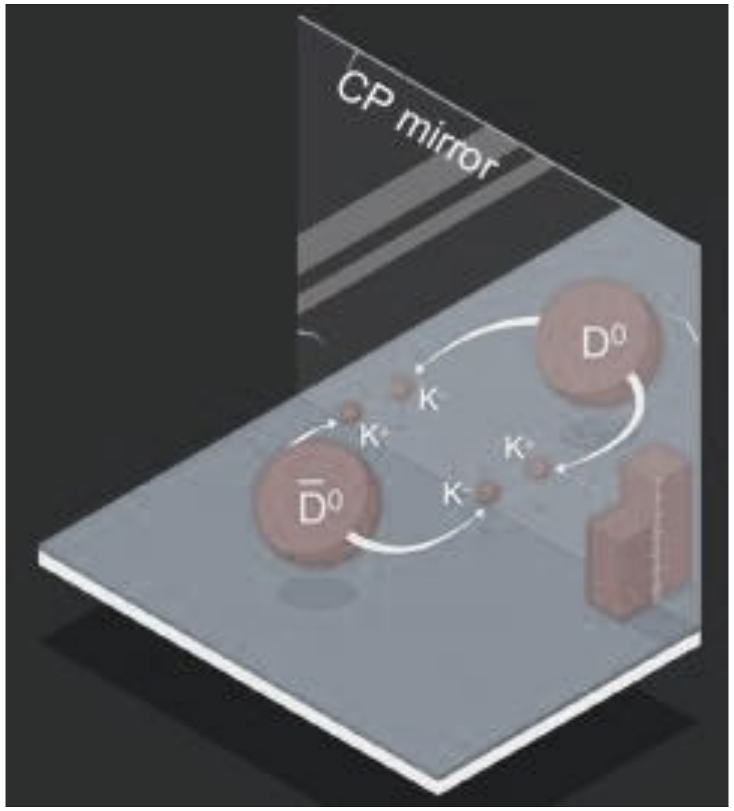
- Collected 9 fb^{-1} of data at 7, 8 and 13 TeV during Run1/2

enormous yields available

Total of 95(!) papers about charm physics at LHCb!



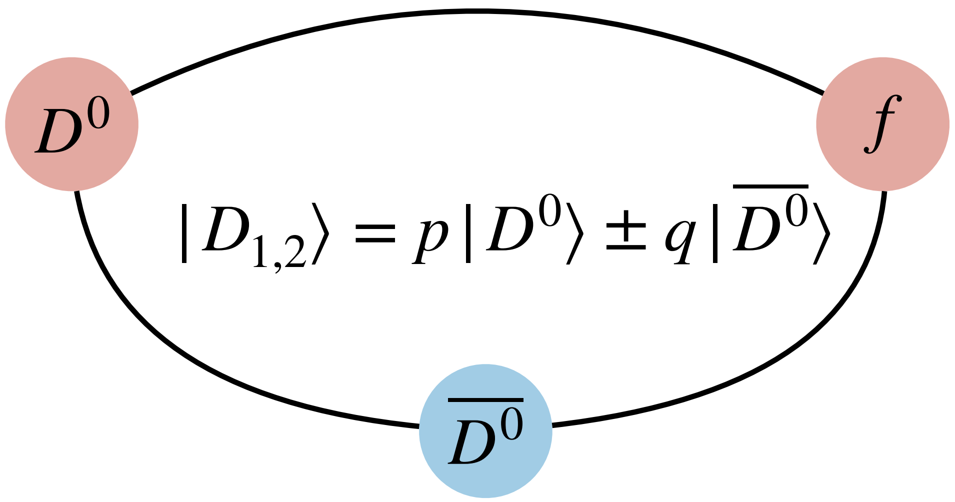
Mixing & CPV



More: Mod.Phys.Lett.A 37 (2022) 24, 2230012

Charm mixing & CPV

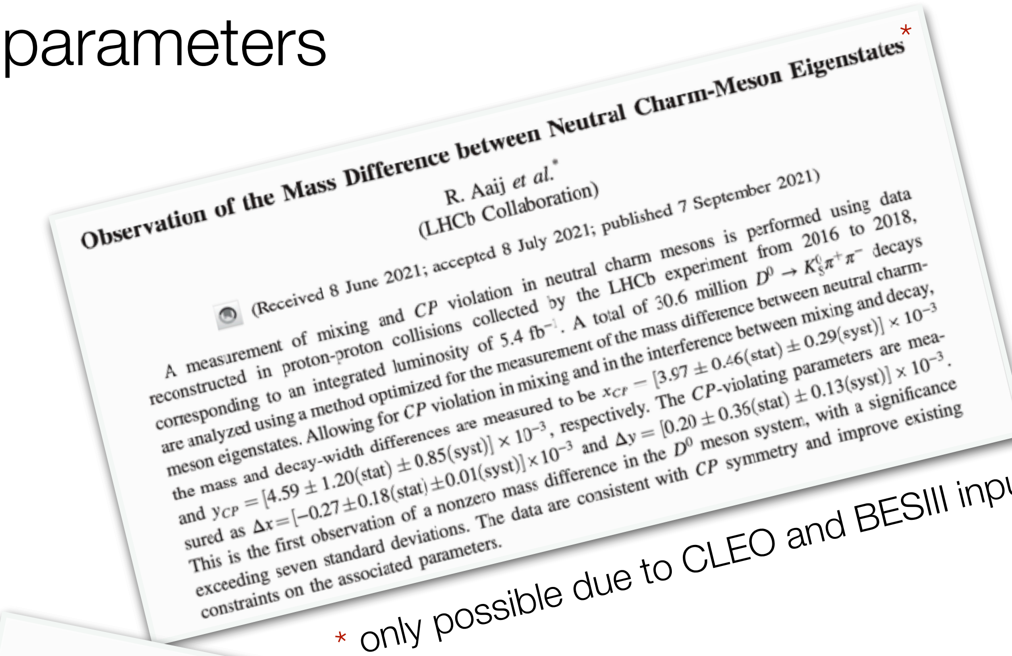
- Measurements of mixing (x, y) and CPV $(A_{CP}, |q/p|, \phi)$ parameters



$$x = \frac{m_1 - m_2}{\Gamma}$$

$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

arXiv: 2208.06512
PRL 127 (2021) 111801
PRL 122 (2019) 211803



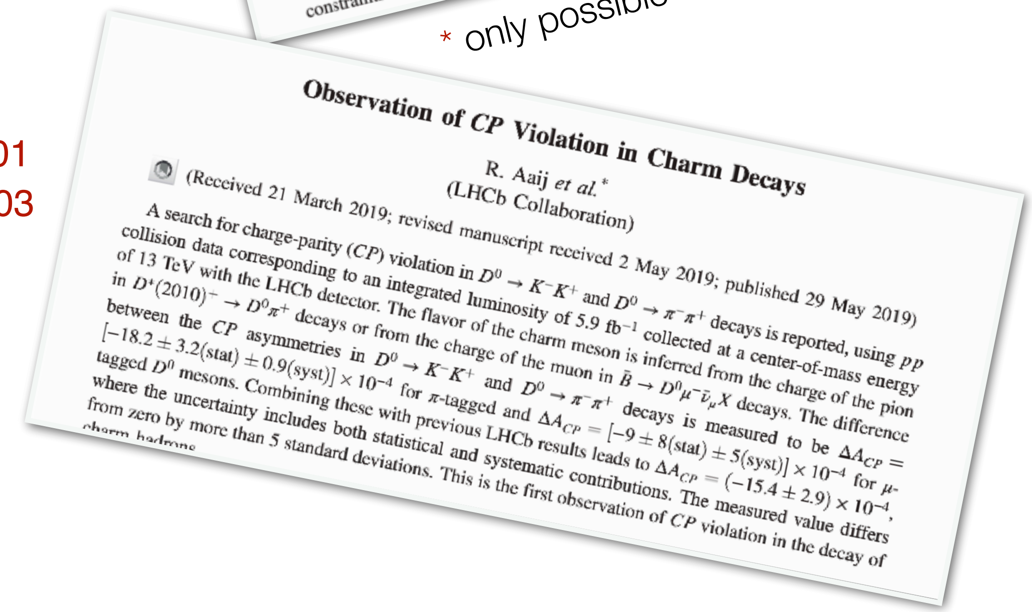
Observation of the Mass Difference between Neutral Charm-Meson Eigenstates

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 8 June 2021; accepted 8 July 2021; published 7 September 2021)

A measurement of mixing and CP violation in neutral charm mesons is performed using data reconstructed in proton-proton collisions collected by the LHCb experiment from 2016 to 2018, corresponding to an integrated luminosity of 5.4 fb^{-1}. A total of 30.6 million $D^0 \to K^0_S\pi^+\pi^-$ decays are analyzed using a method optimized for the measurement of the mass difference between neutral charm-meson eigenstates. Allowing for CP violation in mixing and in the interference between mixing and decay, the mass and decay-width differences are measured to be $x_{CP} = [3.97 \pm 0.46(\text{stat}) \pm 0.29(\text{syst})] \times 10^{-3}$ and $y_{CP} = [4.59 \pm 1.20(\text{stat}) \pm 0.85(\text{syst})] \times 10^{-3}$, respectively. The CP-violating parameters are measured as $\Delta x = [-0.27 \pm 0.18(\text{stat}) \pm 0.01(\text{syst})] \times 10^{-3}$ and $\Delta y = [0.20 \pm 0.36(\text{stat}) \pm 0.13(\text{syst})] \times 10^{-3}$. This is the first observation of a nonzero mass difference in the D^0 meson system, with a significance exceeding seven standard deviations. The data are consistent with CP symmetry and improve existing constraints on the associated parameters.

* only possible due to CLEO and BESIII inputs



Observation of CP Violation in Charm Decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 21 March 2019; revised manuscript received 2 May 2019; published 29 May 2019)

A search for charge-parity (CP) violation in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays is reported, using pp collision data corresponding to an integrated luminosity of 5.9 fb^{-1} collected at a center-of-mass energy of 13 TeV with the LHCb detector. The flavor of the charm meson is inferred from the charge of the pion in $D^*(2010)^+ \to D^0\pi^+$ decays or from the charge of the muon in $\bar{B} \to D^0\mu^-\bar{\nu}_\mu X$ decays. The difference between the CP asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays is measured to be $\Delta A_{CP} = [-18.2 \pm 3.2(\text{stat}) \pm 0.9(\text{syst})] \times 10^{-4}$ for π-tagged and $\Delta A_{CP} = [-9 \pm 8(\text{stat}) \pm 5(\text{syst})] \times 10^{-4}$ for μ-tagged D^0 mesons. Combining these with previous LHCb results leads to $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$, where the uncertainty includes both statistical and systematic contributions. The measured value differs from zero by more than 5 standard deviations. This is the first observation of CP violation in the decay of charm hadrons.

- CPV in the decay $\left|\frac{A_f}{\bar{A}_{\bar{f}}}\right| \neq 1$

- CPV in mixing $\left|\frac{q}{p}\right| \neq 1$

- CPV in interference between mixing and decay

$$\phi_f = arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \approx arg\left(\frac{q}{p}\right) \neq 0$$

We are in the post-mixing & post-CPV-observation phase, but…

Interpretation of observed size of CPV highly debated!

Time-Integrated CP Asymmetries in $D^0 \to K^+K^-$

ARXIV:2209.03179

- Measurement of decay-time integrated CP asymmetries

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

- How experimentally?

$$A(D^0 \to f) = A_{CP}(f) + A_{det} + A_{prod}$$

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

Detection asymmetry of tagging track

The asymmetry we want to measure

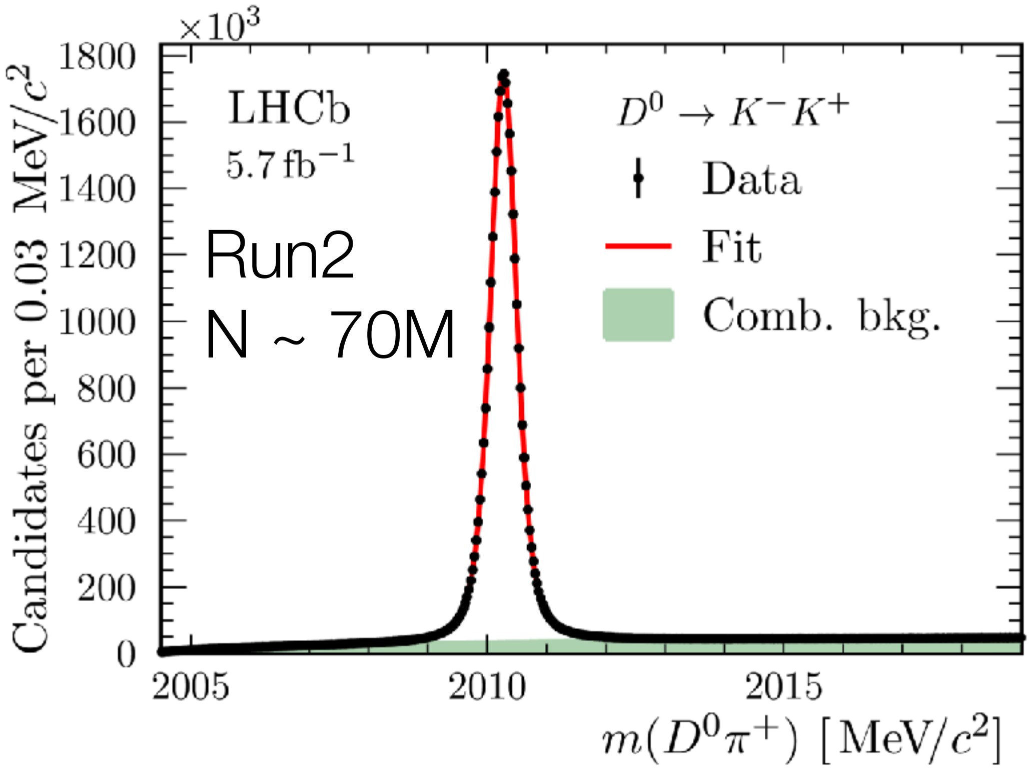
Production asymmetry

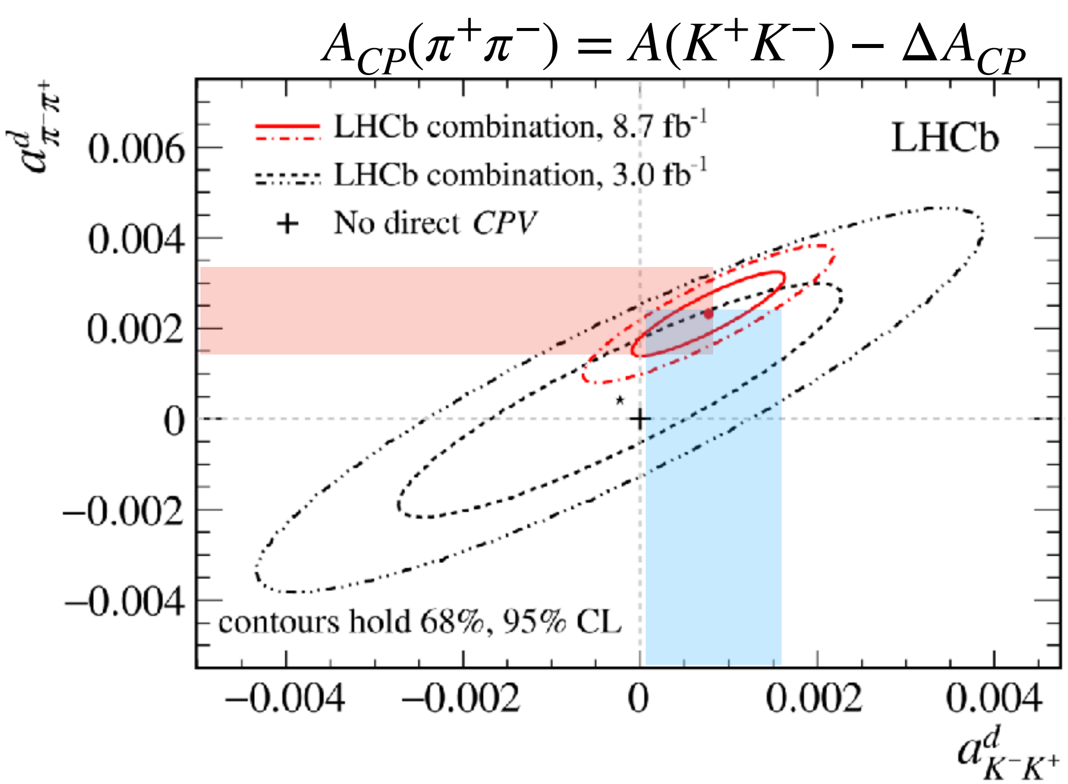
- This is why we started with $\Delta A_{CP} = A(D \to K^+K^-) - A(D \to \pi^+\pi^-)$ PRL 122 (2019) 211803

- Now: Two methods to cancel detector asymmetries using Cabibbo-favoured (no CPV) D^0, D^+, D_s^+ decays to get individual CP asymmetries in $D^0 \to K^+K^-$ decays

Time-Integrated CP Asymmetries in $D^0 \to K^+K^-$

ARXIV:2209.03179





- Run 2 (5.6fb-1) data ~70M $D^0 \to K^+K^-$ candidates

Combination of correction methods results (Run2 only):

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

- Combination with previous measurements

PRL 122 (2019) 211803

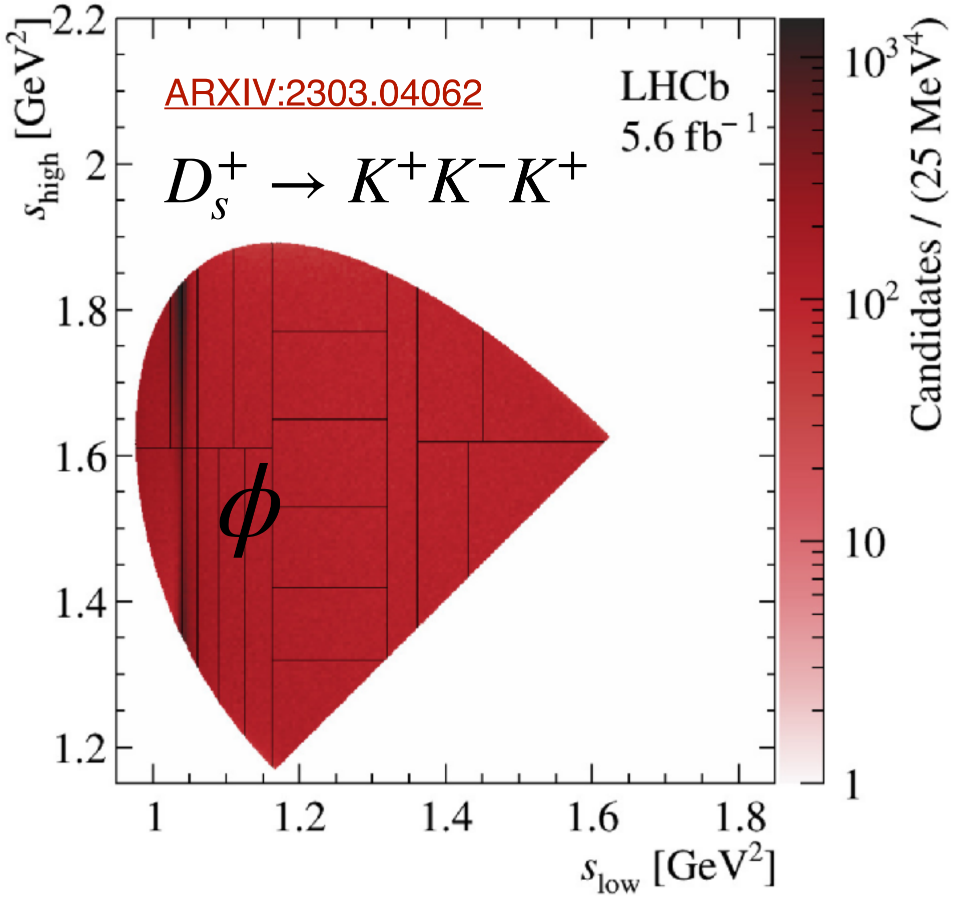
Run1+Run2 + combination with ΔA_{CP}

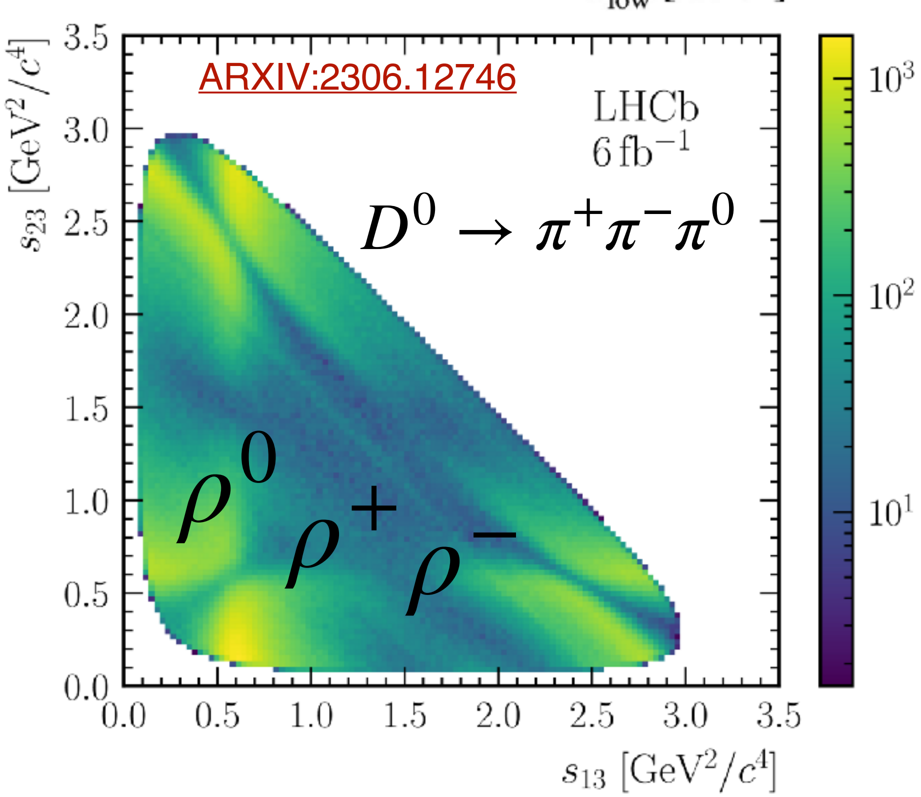
$$a^d_{CP}(K^+K^-) = [7.7 \pm 5.7] \times 10^{-4}$$
$$a^d_{CP}(\pi^+\pi^-) = [23.2 \pm 6.1] \times 10^{-4}$$

$$\rho(a^d_{KK}, a^d_{\pi\pi}) = 88\,\%$$

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

Model-independent searches in multibody decays





- CP asymmetries generated via interference of at least two amplitudes A_1 and A_2

$$A_{CP} \sim \frac{|A_1|}{|A_2|} \sin(\Delta\delta) \sin(\Delta\phi)$$

Strong phase difference — Weak phase difference

- In multibody decays strong phase δ dynamically varies across the phase space
- Locally enhanced CPV effects possible (known from the b system arXiv:2206.07622!)
- New (model-independent) analyses at LHCb:
  - Search for CPV in $D^+_{(s)} \to K^+K^-K^+$ ARXIV:2303.04062
  - Search for CPV in $D^0 \to \pi^+\pi^-\pi^0$ ARXIV:2306.12746

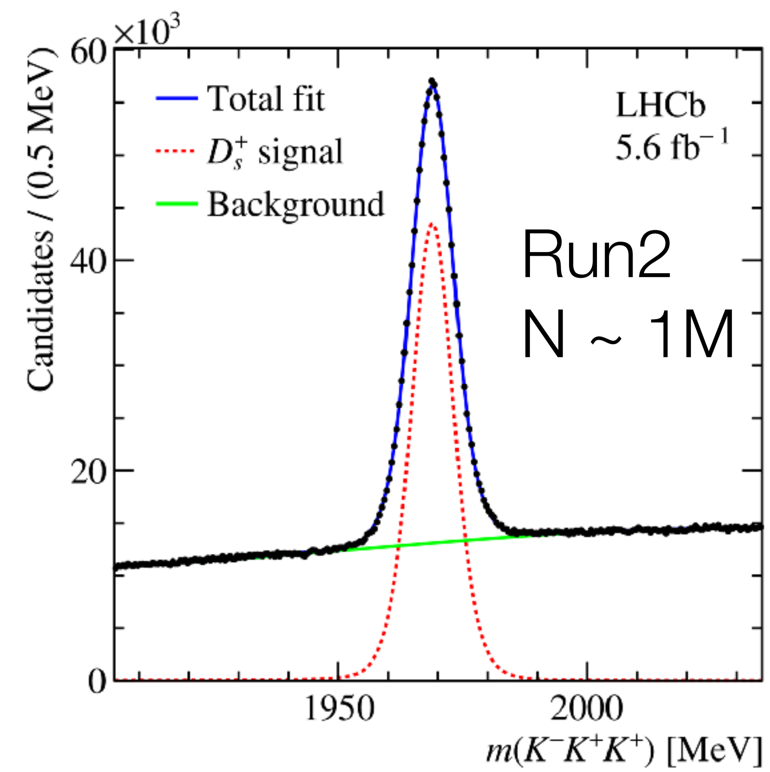
Search for CPV in $D^+_{(s)} \to K^+K^-K^+$

ARXIV:2303.04062

- Run2 (5.6fb^{-1}) data ~0.97M (1.27M) D_s^+ (D^+) candidates
  - validation with $D_s^+ \to K^-K^+\pi^+$ and $D^+ \to K^-\pi^+\pi^+$

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

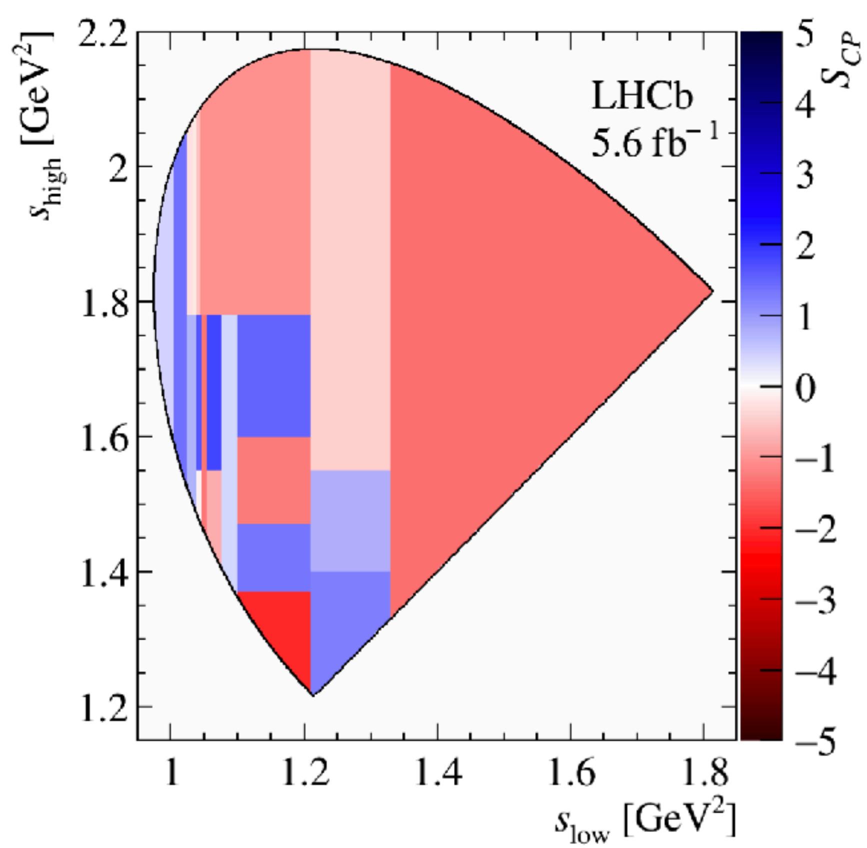
Global asymmetry



- If no CPV the S^i_{CP} are gaussian distributed with zero mean and width of unity

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

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



- Measured p-value 13% (31.6%) for D_s^+ (D^+) decays

No hint for CPV!

Search for CPV in $D^0 \to \pi^+\pi^-\pi^0$

ARXIV:2306.12746

- Run2 (6fb^{-1}) data ~2.7M $D^0 \to \pi^+\pi^-\pi^0$ candidates

- Energy Test = hypothesis test comparing weighted distance between pairs in phase space

PRD 84 054015 (2011)

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

Average distance candidates same flavour | Average distance candidates opposite flavour

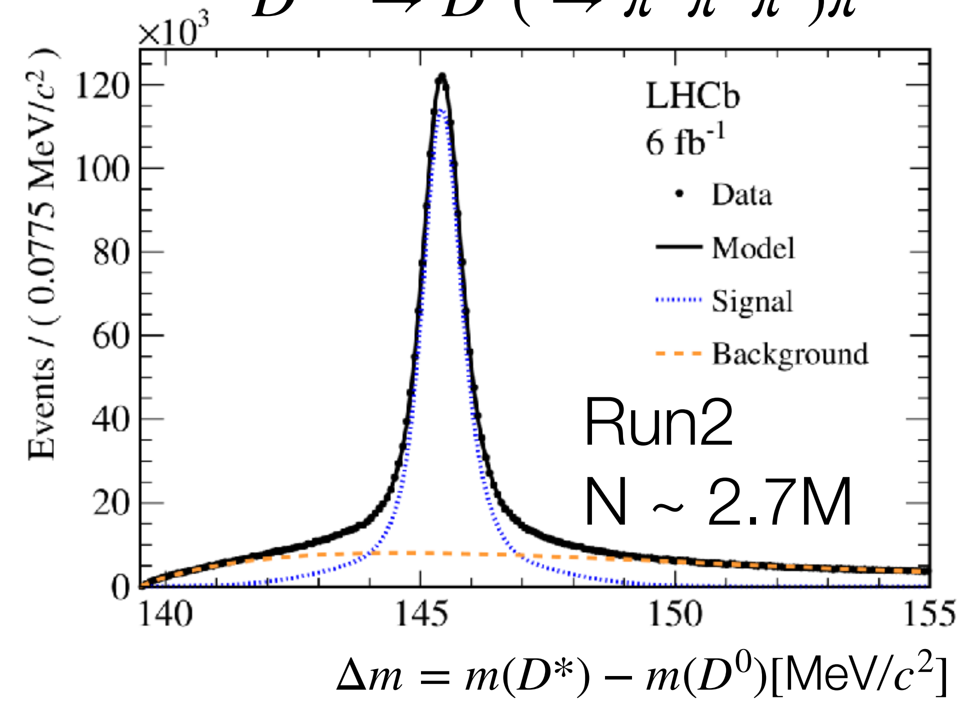
$$\Psi_{ij} = e^{-d_{ij}^2/2\delta^2}$$

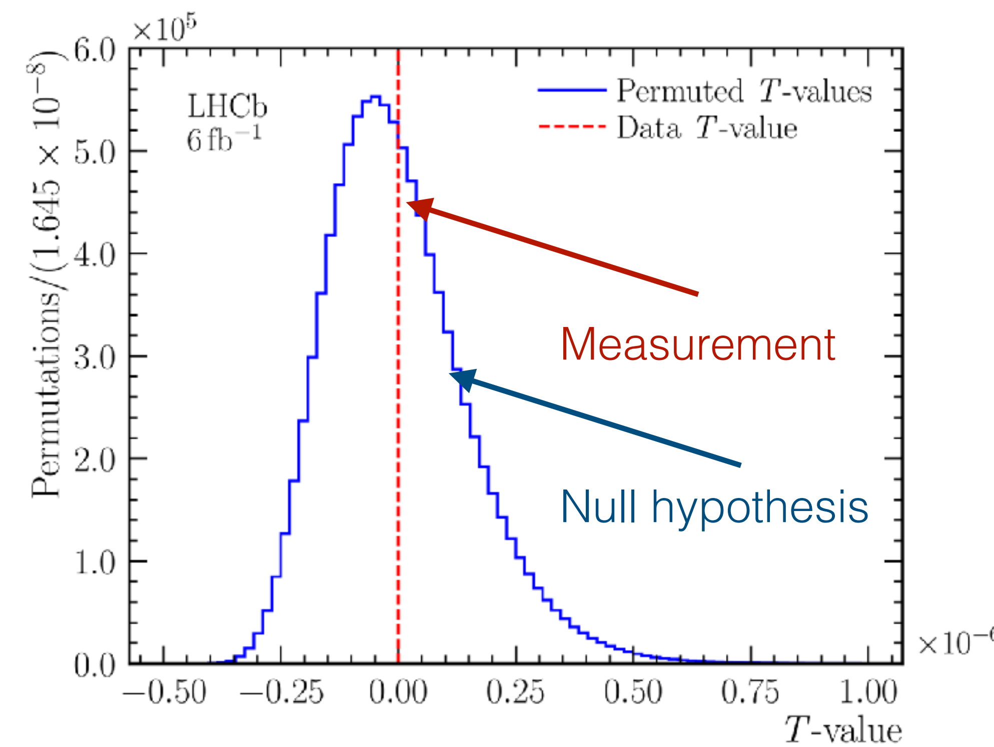
$$d_{ij} = [(\Delta s_{12})^2_{ij} + (\Delta s_{13})^2_{ij} + (\Delta s_{23})^2_{ij}]$$

- Null hypothesis from permutations of T-value with randomised tags

- Measured p-value 62%

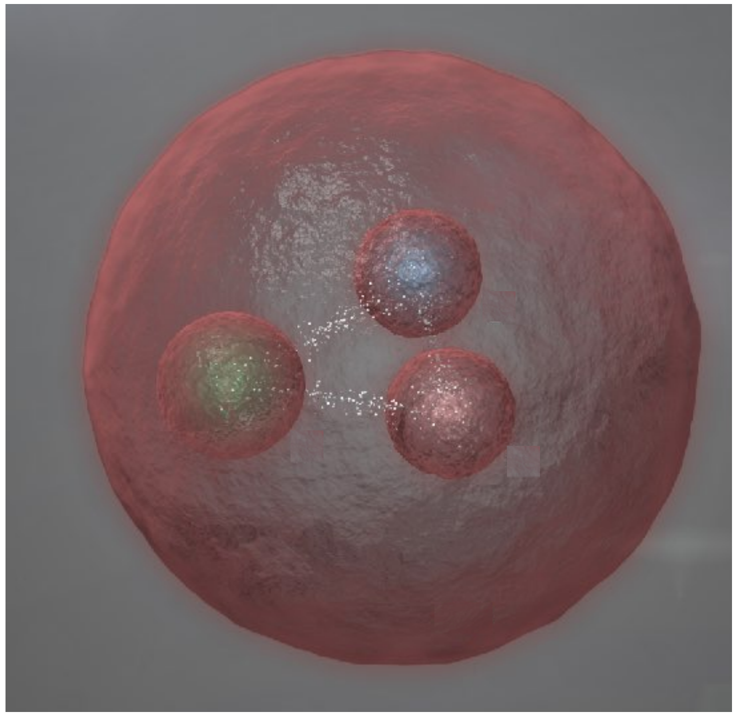
$D^{*+} \to D^0(\to \pi^+\pi^-\pi^0)\pi^+$





Also here no hint for CPV!
Still a lot to be understood in the future!

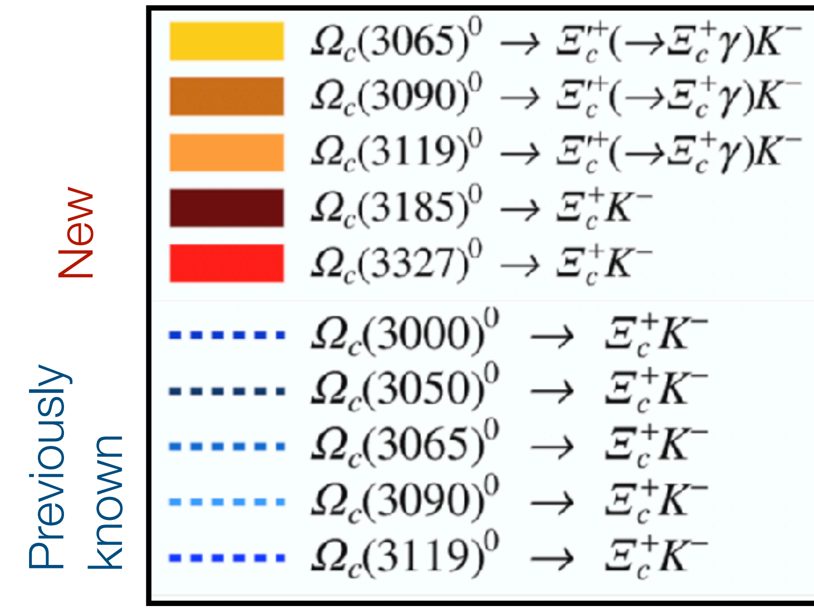
Production & decay properties



Observation new Ω_c^0 states

ARXIV:2302.04733

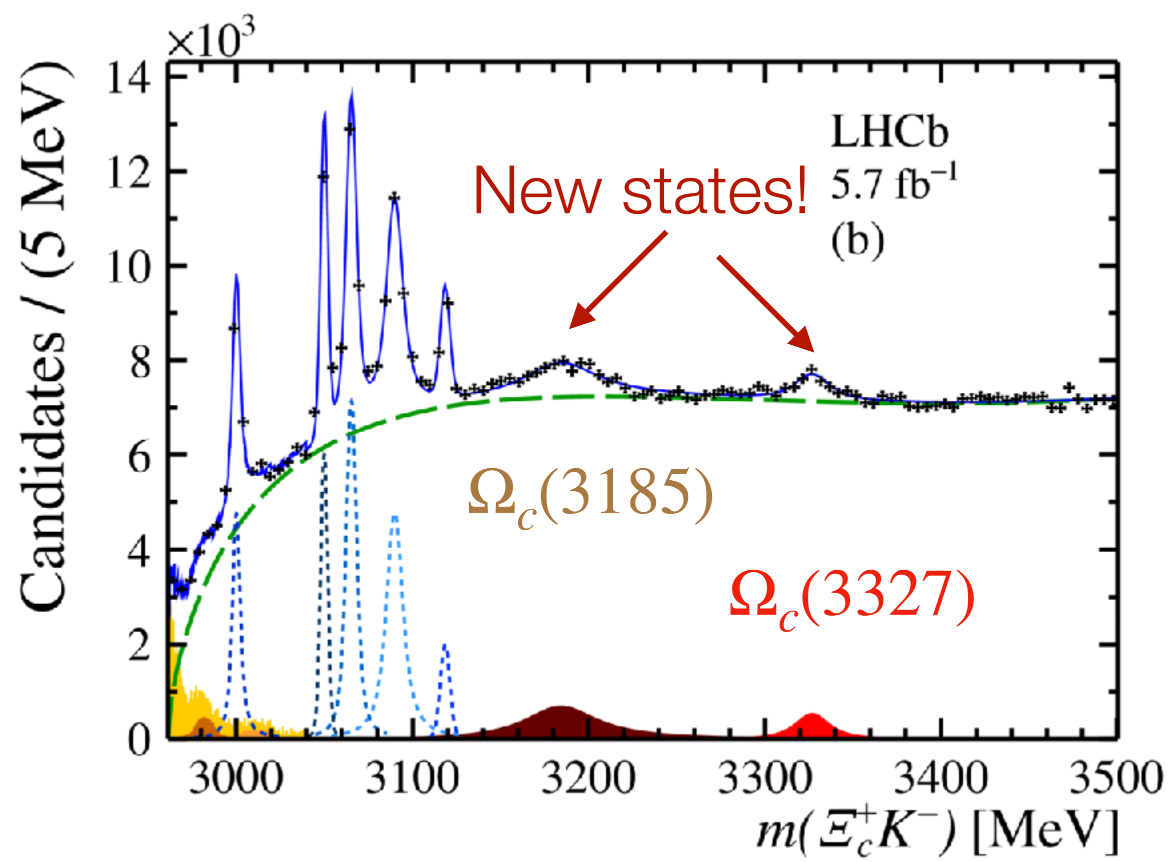
- Studies of production and (decay) properties of charmed hadrons (ground states + excited states) with increasing importance
- Crucial for understanding of QCD, effective models and the nature of bound states in a peculiar energy regime



- Full Run1/2 (9fb^{-1}) update studying the $\Xi_c^+K^-$ invariant-mass spectrum
  - Seven excited states observed
  - Two new states

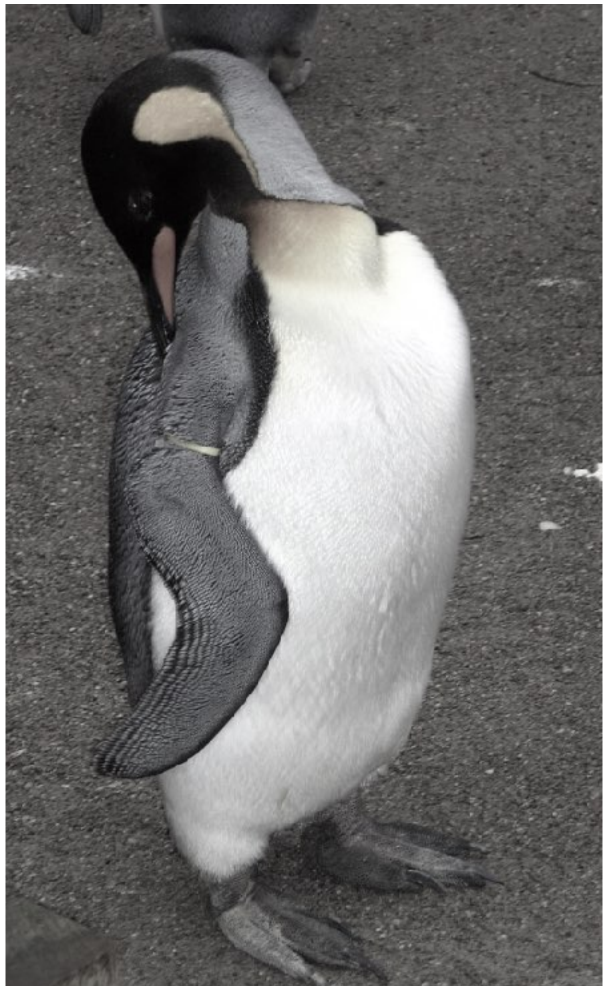
Resonance	m (MeV)	Γ (MeV)
$\Omega_c(3185)^0$	$3185.1 \pm 1.7\,^{+7.4}_{-0.9} \pm 0.2$	$50 \pm 7\,^{+10}_{-20}$
$\Omega_c(3327)^0$	$3327.1 \pm 1.2\,^{+0.1}_{-1.3} \pm 0.2$	$20 \pm 5\,^{+13}_{-1}$

More: Talk by Liming Zhang



QN yet to be determined!

Rare Charm decays



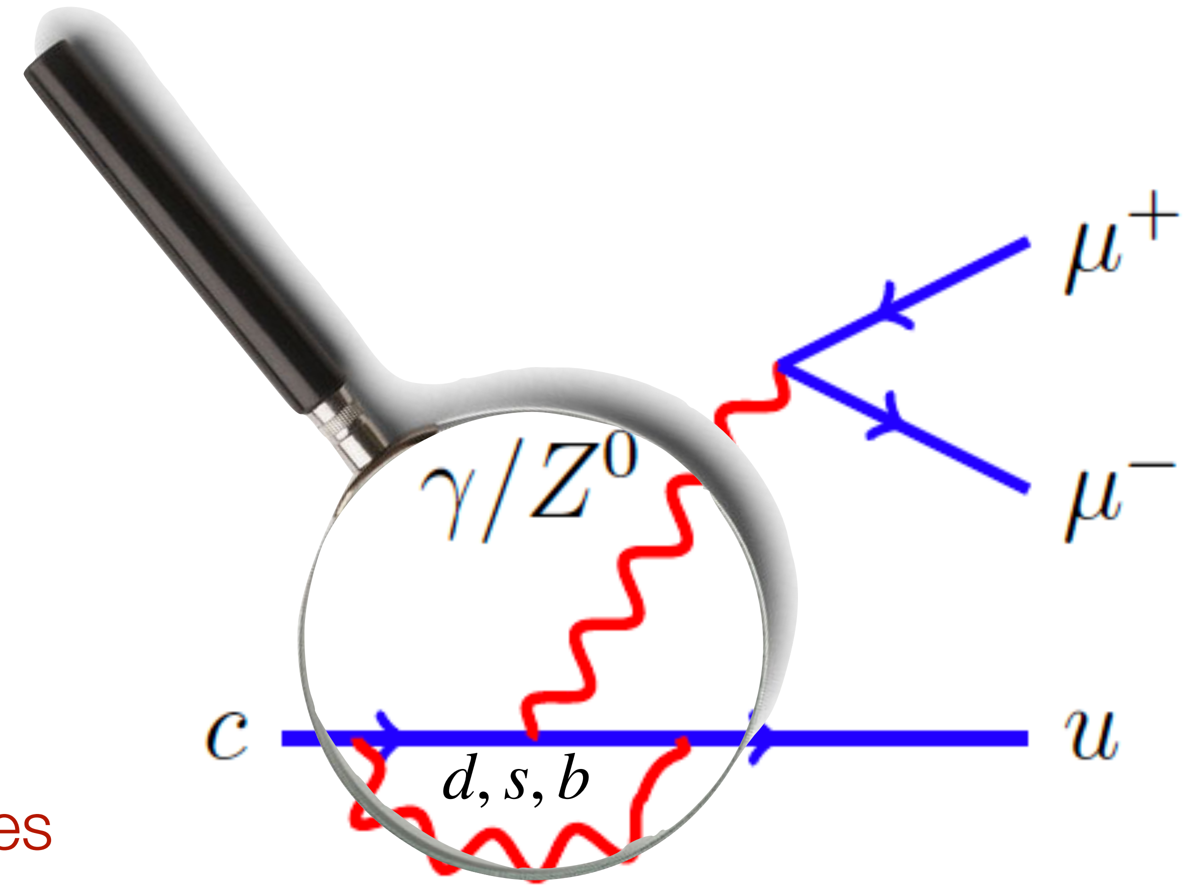
More: Mod.Phys.Lett.A 36 (2021) 04, 2130002

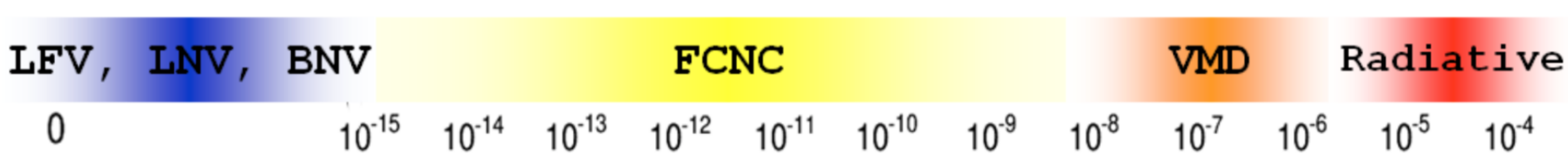
Rare charm decays

- Mainly investigation of processes involving FCNC $c \to u\ell\ell$ transitions

More: Talk by Hector Gisbert

- Covering a very large variety of analyses
  - BF measurements
  - Angular+CP asymmetries PRL 128 (2022) 221801
  - Searches for forbidden/extremely rare modes

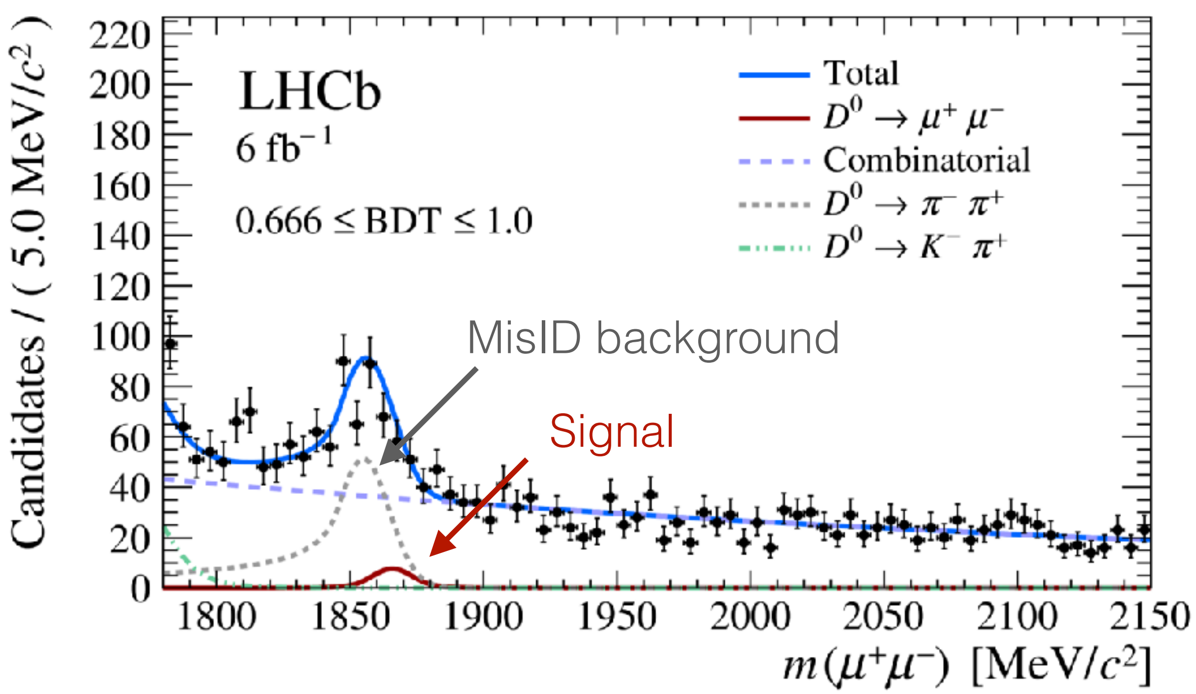


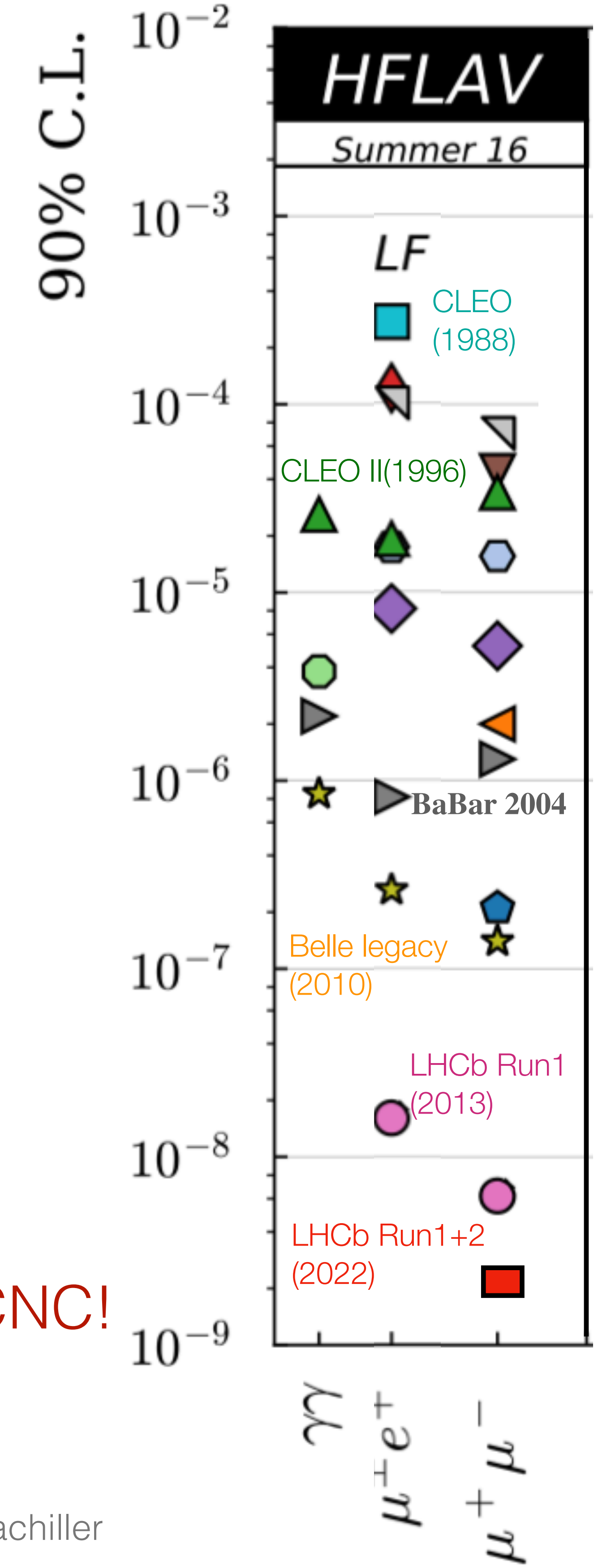


Search for $D^0 \to \mu^+\mu^-$

ARXIV: 2212.11203

- CKM and helicity suppressed → SM BF extremely low dominated by 2γ intermediate state $\lesssim O(10^{-13})$
- NP scenarios $BF_{NP} \lesssim BF_{EXP}$
- Full Run1/2 ($9 fb^{-1}$) update





$$B(D^0 \to \mu^+\mu^-) < 2.94 \times 10^{-9} \text{ @ } 90\,\%\,\text{CL}$$

(LHCb 9/fb Run1+2)

Most stringent limit on charm FCNC!

- Furthermore: $B(D^{0*}(2007) \to \mu^+\mu^-) < 2.6 \times 10^{-8}$ @ 90 % CL

ARXIV: 2304.019821

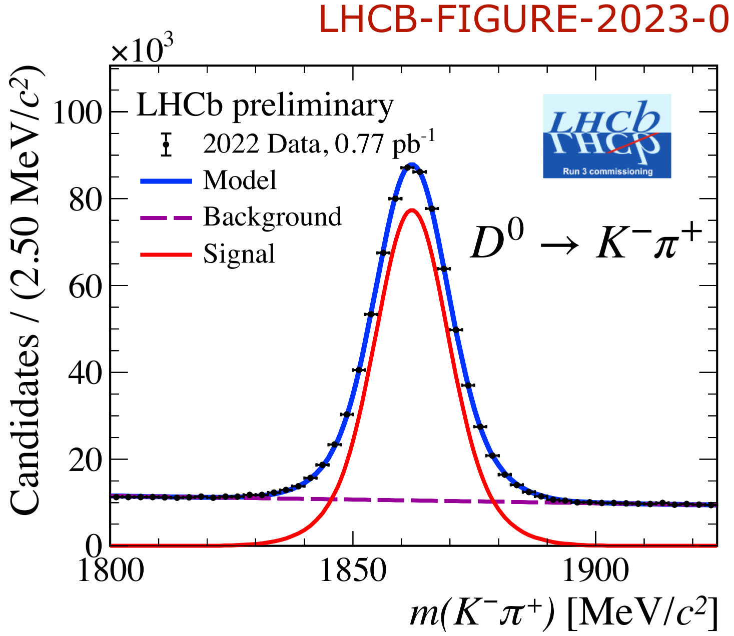
More: Talk by Irene Bachiller

Future prospects

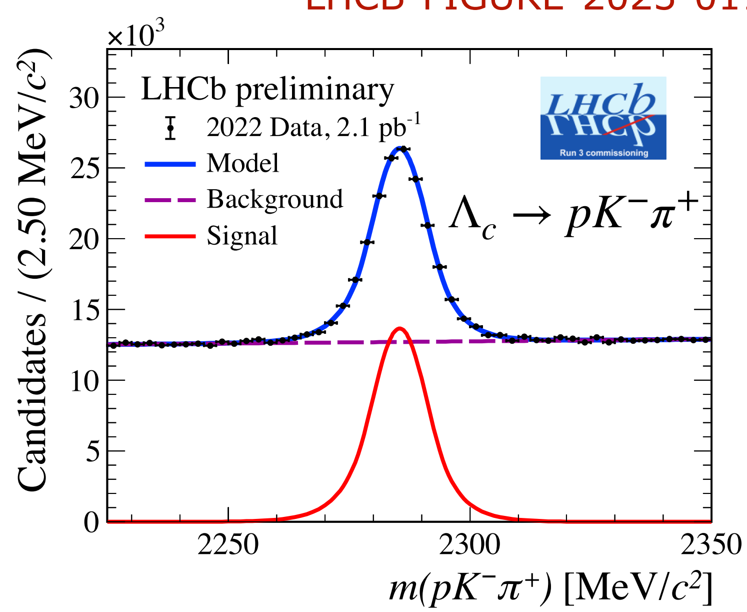
- We are working on fully exploiting the total Run1/2 data set (9/fb)
  - More to come for mixing and CPV, production and decay properties & rare decays!

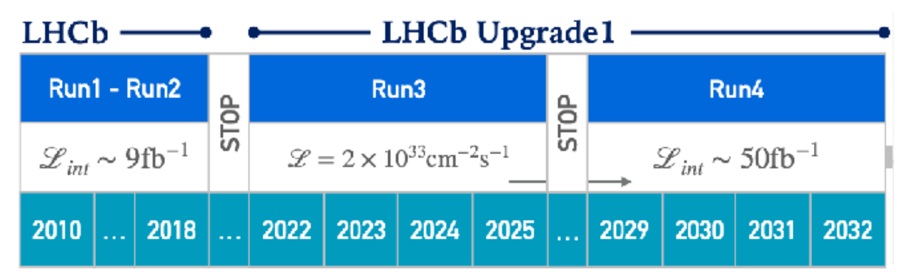
- Commissioning and Run3 data taking with the upgraded detector ongoing!

LHCB-FIGURE-2023-011



LHCB-FIGURE-2023-011





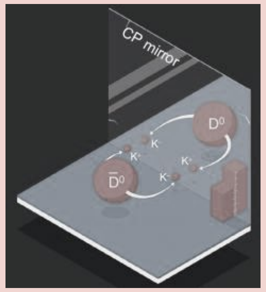
See Federica Oliva's and Alessandro Minotti's talks on Friday!

- Upgrade II is in preparation, eventually plan to collect up to 300fb^{-1} by ~2038

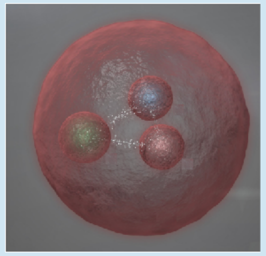
- Projections for specific modes can be found in CERN-PUB-LHCC-2018-027

Summary

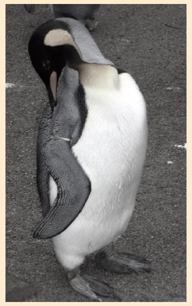
- Post-mixing & post-CPV-observation phase has started!
  - First evidence for CPV in a single decay channel
  - CPV results highly debated! See talks by Maria Laura Piscopo, Tim Höhne
  - No hints for CPV in multibody D^0, D^+, D_s^+ decays so far



- Studies of charmed hadrons integral part of our physics program
  - At LHCb > 40 new states with charm quark content, 2 shown today
  - Results receive a lot of attention
  - Much more: Amplitude analyses, searches for doubly charmed baryons,…

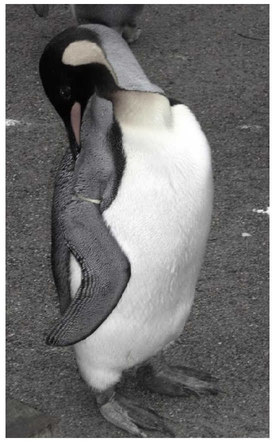


- Promising and rather unexplored field!
  - Limits on BF of rare decays significantly pushed down
  - More results are soon to come with full Run2 data set, including CPV in rare/radiative decays and angular distributions

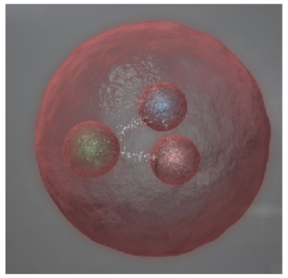


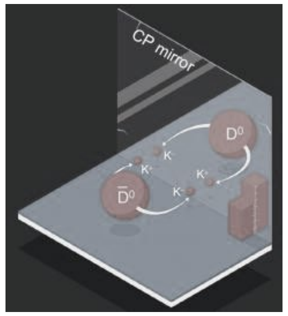
More: https://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_Charm.html

Thank you!



Supplemental





Time-Integrated CP Asymmetries in $D^0 \to K^+K^-$

ARXIV:2209.03179

- methods to cancel detector asymmetries

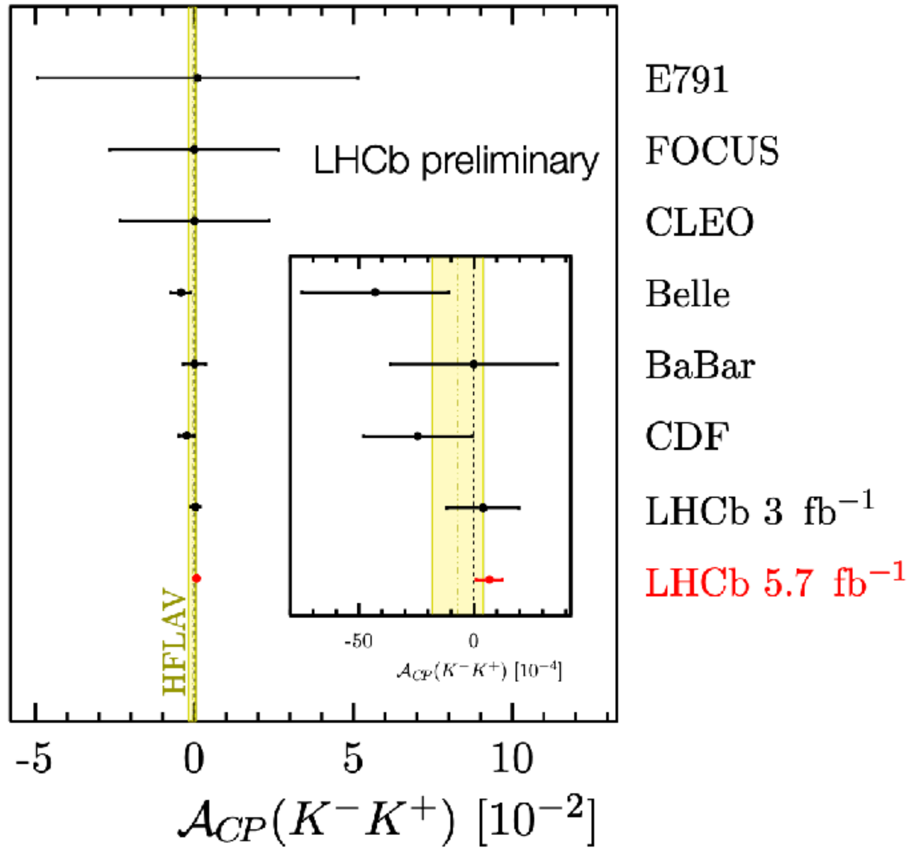
C_{D+}: $$A_{CP}(D^0 \to K^-K^+) = +A(D^{*+} \to (D^0 \to K^-K^+)\,\pi^+_{soft}) - A(D^{*+} \to (D^0 \to K^-\pi^+)\,\pi^+_{soft}) + A(D^+ \to K^-\pi^+\pi^+) - \left[A(D^+ \to \overline{K}^0\,\pi^+) - A(\overline{K}^0)\right]$$

C_{Ds+}: $$A_{CP}(D^0 \to K^-K^+) = +A(D^{*+} \to (D^0 \to K^-K^+)\,\pi^+_{soft}) - A(D^{*+} \to (D^0 \to K^-\pi^+)\,\pi^+_{soft}) + A(D_s^+ \to \phi\pi^+) - \left[A(D_s^+ \to \overline{K}^0\,K^+) - A(\overline{K}^0)\right]$$

- Computation Acp(ππ)

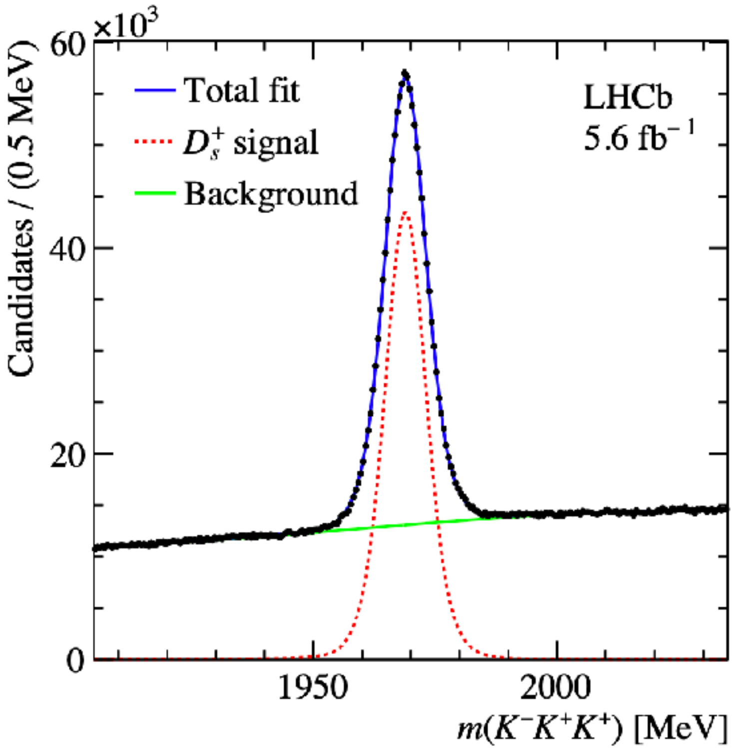
$$A_{CP}(K^-K^+) = a^d_{KK} + \frac{\langle t \rangle_{KK}}{\tau_{D^0}}\Delta Y$$

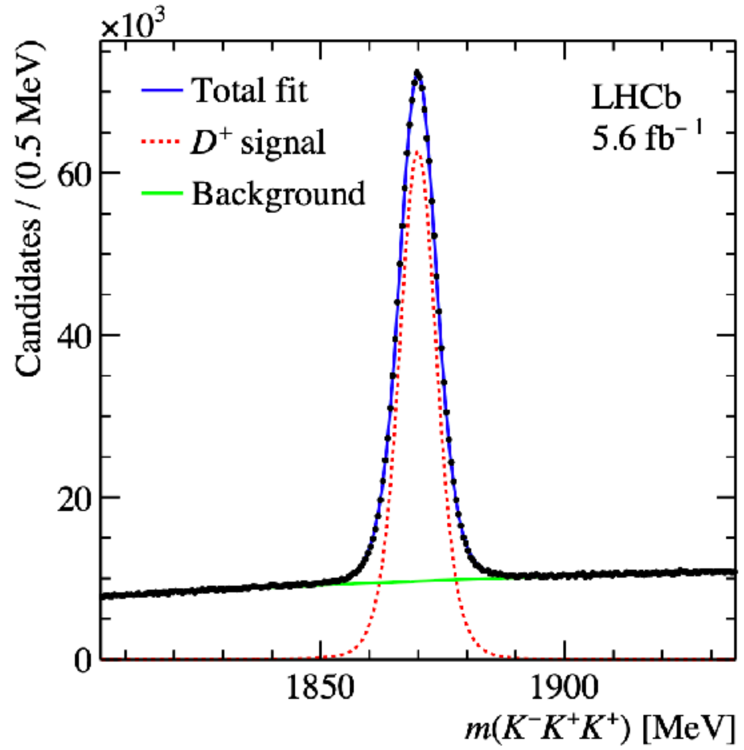
$$\Delta A_{CP} = a^d_{KK} - a^d_{\pi\pi} + \frac{\langle t \rangle_{KK} - \langle t \rangle_{\pi\pi}}{\tau_{D^0}}\Delta Y$$

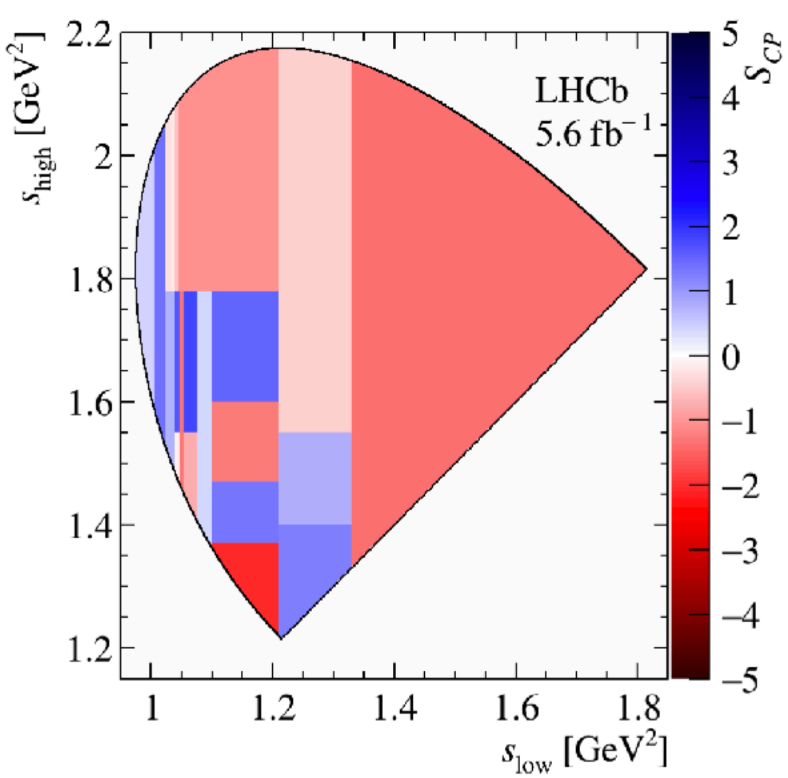


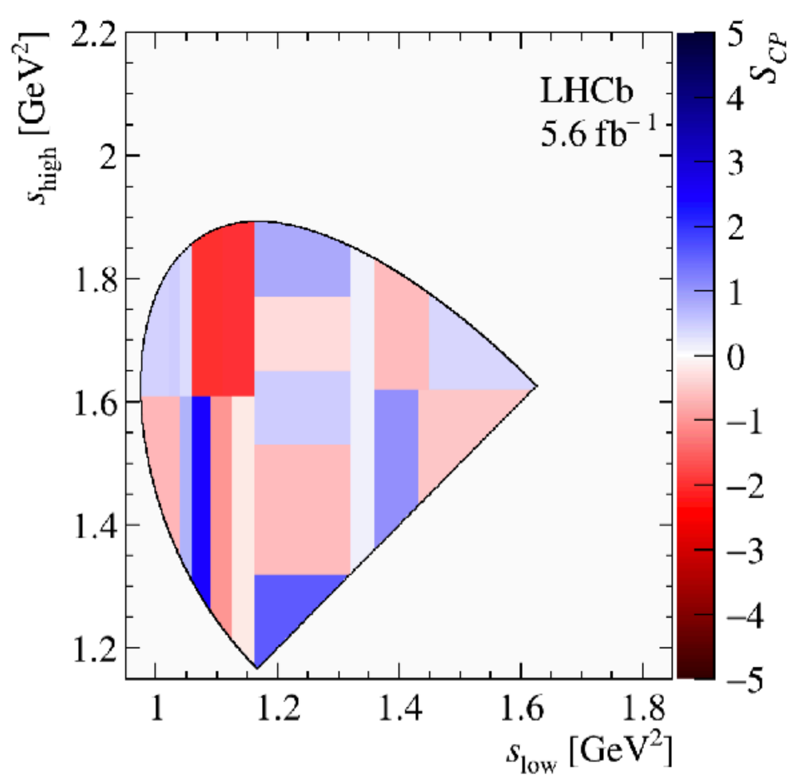
Search for CPV in $D^+_{(s)} \to K^+K^-K^+$

ARXIV:2303.04062





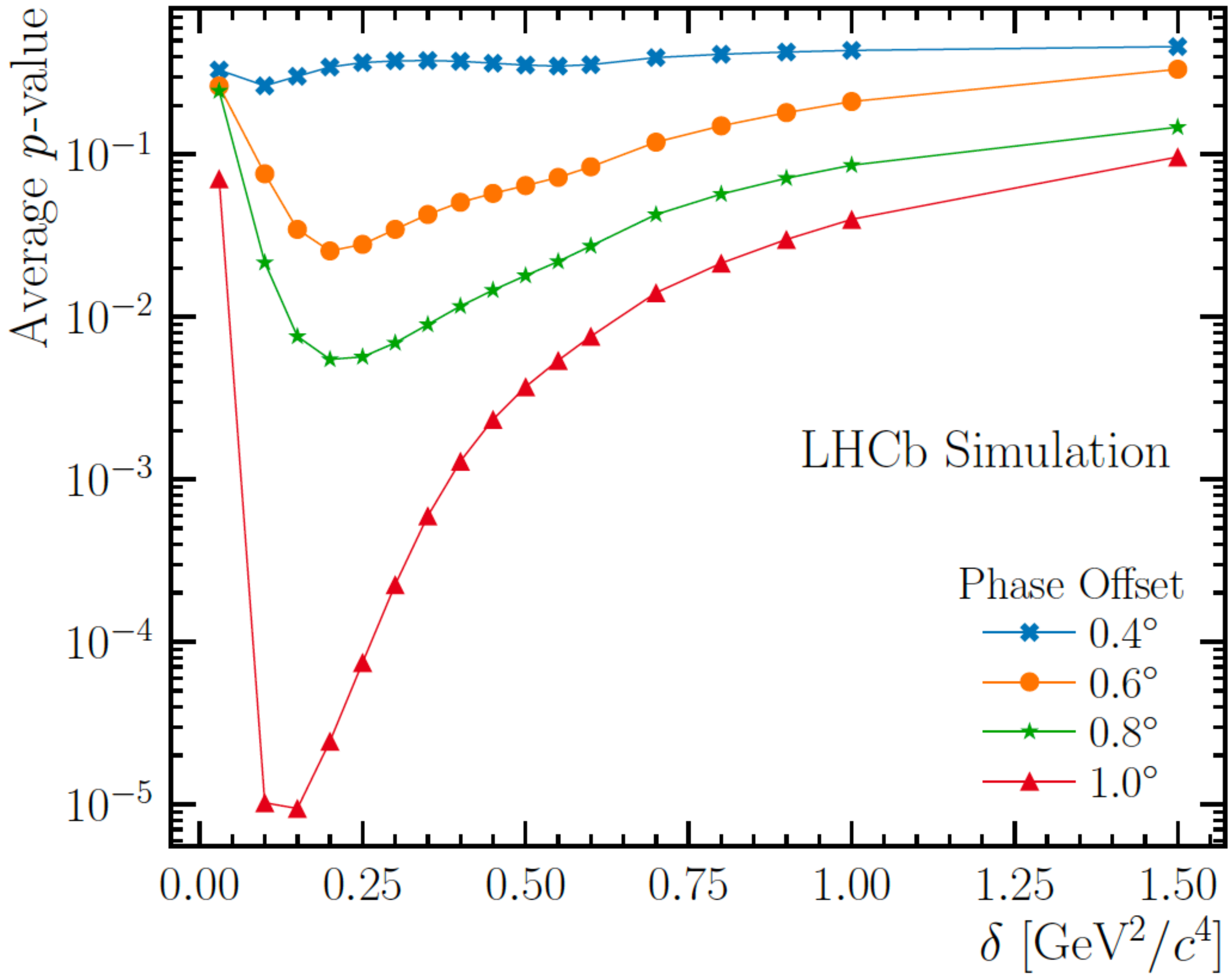




	$D_s^+ \to K^-K^+K^+$	$D^+ \to K^-K^+K^+$
$\sum_i N^i(D^+_{(s)})$	$(487.8 \pm 1.1) \times 10^3$	$(638.8 \pm 1.1) \times 10^3$
$\sum_i N^i(D^-_{(s)})$	$(484.4 \pm 1.1) \times 10^3$	$(631.4 \pm 1.0) \times 10^3$
α	1.007 ± 0.003	1.012 ± 0.002

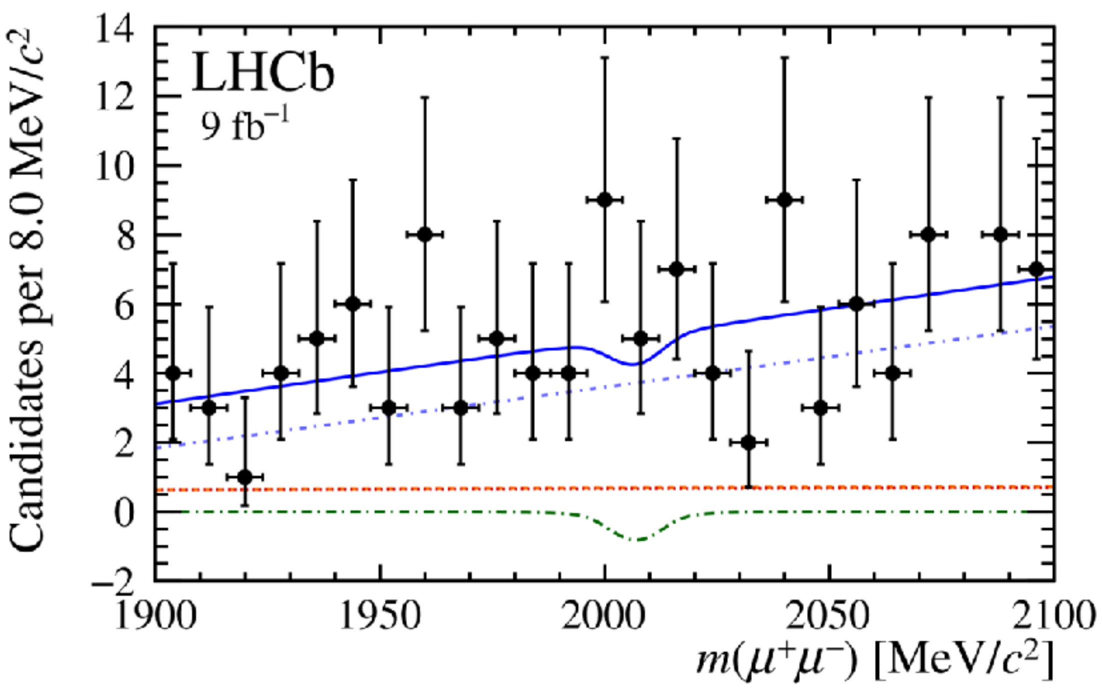
Search for CPV in $D^0 \to \pi^+\pi^-\pi^0$

ARXIV:2306.12746

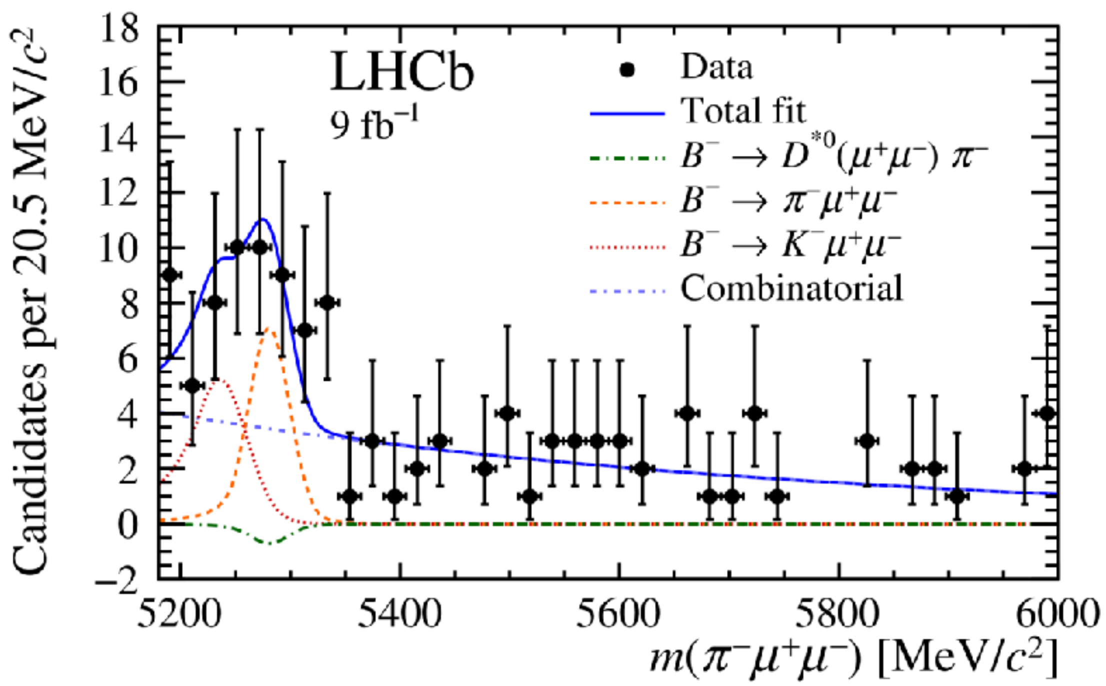


Search for $D^{0*}(2007) \to \mu^+\mu^-$

ARXIV: 2304.019821



- First limit $B(D^{0*}(2007) \to \mu^+\mu^-)$ using 9/fb Run1/2
  - No chiral suppression, but same contributing operators in EFT
  - Complementary approach to constrain NP couplings



- First search for rare charm exploding production via b decay $B^- \to D^{*0}(\to \mu^+\mu^-)\pi^-$

$B(D^{0*}(2007) \to \mu^+\mu^-) < 2.6 \times 10^{-8}$ @ 90 % CL

(LHCb 9/fb Run1+2)

Most stringent limit of leptonic decay of D^{*0} meson!

Prospects selected measurements (I)

CERN-PUB-LHCC-2018-027

Table 6.1: Extrapolated signal yields, and statistical precision on the mixing and CP-violation parameters, from the analysis of promptly produced WS $D^{*+} \to D^0(\to K^+\pi^-)\pi^+$ decays. Signal yields of promptly produced RS $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decays are typically 250 times larger.

Sample ($\mathcal{L}$)	Yield ($\times 10^6$)	$\sigma(x'^2_{K\pi})$	$\sigma(y'_{K\pi})$	$\sigma(A_D)$	$\sigma(\lvert q/p \rvert)$	$\sigma(\phi)$
Run 1–2 ($9\,\text{fb}^{-1}$)	1.8	1.5×10^{-5}	2.9×10^{-4}	0.51%	0.12	10°
Run 1–3 ($23\,\text{fb}^{-1}$)	10	6.4×10^{-6}	1.2×10^{-4}	0.22%	0.05	4°
Run 1–4 ($50\,\text{fb}^{-1}$)	25	3.9×10^{-6}	7.6×10^{-5}	0.14%	0.03	3°
Run 1–5 ($300\,\text{fb}^{-1}$)	170	1.5×10^{-6}	2.9×10^{-5}	0.05%	0.01	1°

Table 6.3: Extrapolated signal yields, and statistical precision on the mixing and CP violation parameters, for the analysis of the decay $D^0 \to K^0_S\pi^+\pi^-$. Candidates tagged by semileptonic B decay (SL) and those from prompt charm meson production are shown separately.

Sample (lumi $\mathcal{L}$)	Tag	Yield	$\sigma(x)$	$\sigma(y)$	$\sigma(\lvert q/p \rvert)$	$\sigma(\phi)$
Run 1–2 (9 fb^{-1})	SL	10M	0.07%	0.05%	0.07	4.6°
	Prompt	36M	0.05%	0.05%	0.04	1.8°
Run 1–3 (23 fb^{-1})	SL	33M	0.036%	0.030%	0.036	2.5°
	Prompt	200M	0.020%	0.020%	0.017	0.77°
Run 1–4 (50 fb^{-1})	SL	78M	0.024%	0.019%	0.024	1.7°
	Prompt	520M	0.012%	0.013%	0.011	0.48°
Run 1–5 (300 fb^{-1})	SL	490M	0.009%	0.008%	0.009	0.69°
	Prompt	3500M	0.005%	0.005%	0.004	0.18°

Prospects selected measurements (II)

CERN-PUB-LHCC-2018-027

Table 6.5: Extrapolated signal yields and statistical precision on direct CP violation observables for the promptly produced samples.

Sample ($\mathcal{L}$)	Tag	Yield $D^0 \to K^- K^+$	Yield $D^0 \to \pi^- \pi^+$	$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
Run 1–2 (9 fb^{-1})	Prompt	52M	17M	0.03	0.07
Run 1–3 (23 fb^{-1})	Prompt	280M	94M	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	1G	305M	0.007	0.015
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007

Table 6.4: Extrapolated signal yields, and statistical precision on indirect CP violation from A_Γ.

Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)$
Run 1–2 (9 fb^{-1})	Prompt	60M	0.013%	18M	0.024%
Run 1–3 (23 fb^{-1})	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	5.3G	0.0014%	1.6G	0.0025 %

$D^0 \to h^+h^-\mu^+\mu^-$ decays at LHCb

PRL 128 (2022) 221801

- rarest charm meson decays observed, dominated by resonant contributions

$$\mathscr{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) \sim 9.6 \times 10^{-7}$$
$$\mathscr{B}(D^0 \to K^+K^-\mu^+\mu^-) \sim 1.5 \times 10^{-7}$$

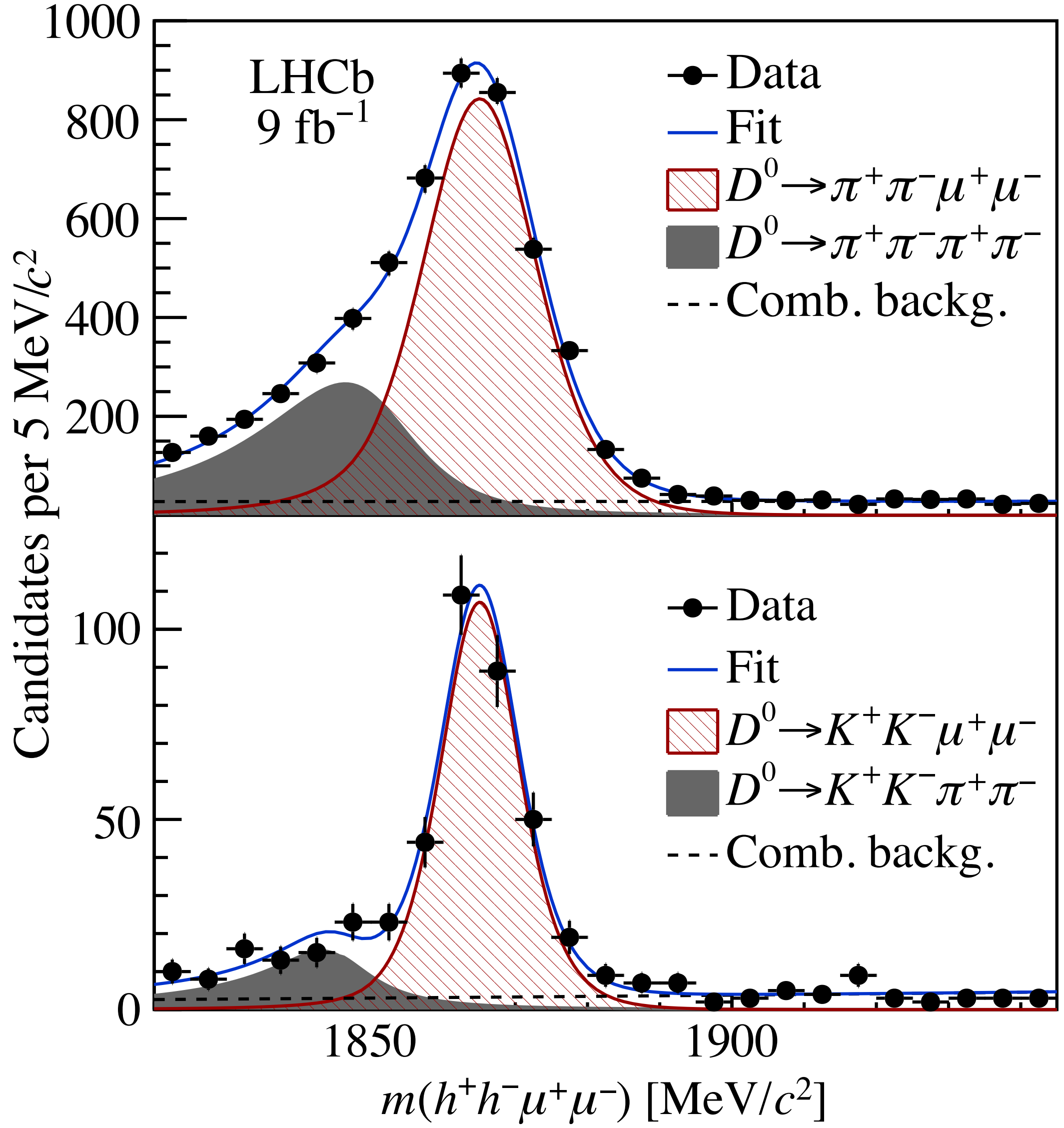
PRL 119 (2017) 181805

- measurement selected angular and CP asymmetries with 5/fb consistent with SM

PRL 121 (2018) 091801

- TODAY: First full angular analysis with 9/fb from 2011-2018 LHCb-PAPER-2021-035
  - select D^0 from flavour sepecific $D^{*+} \to D^0\pi^+$ decays

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

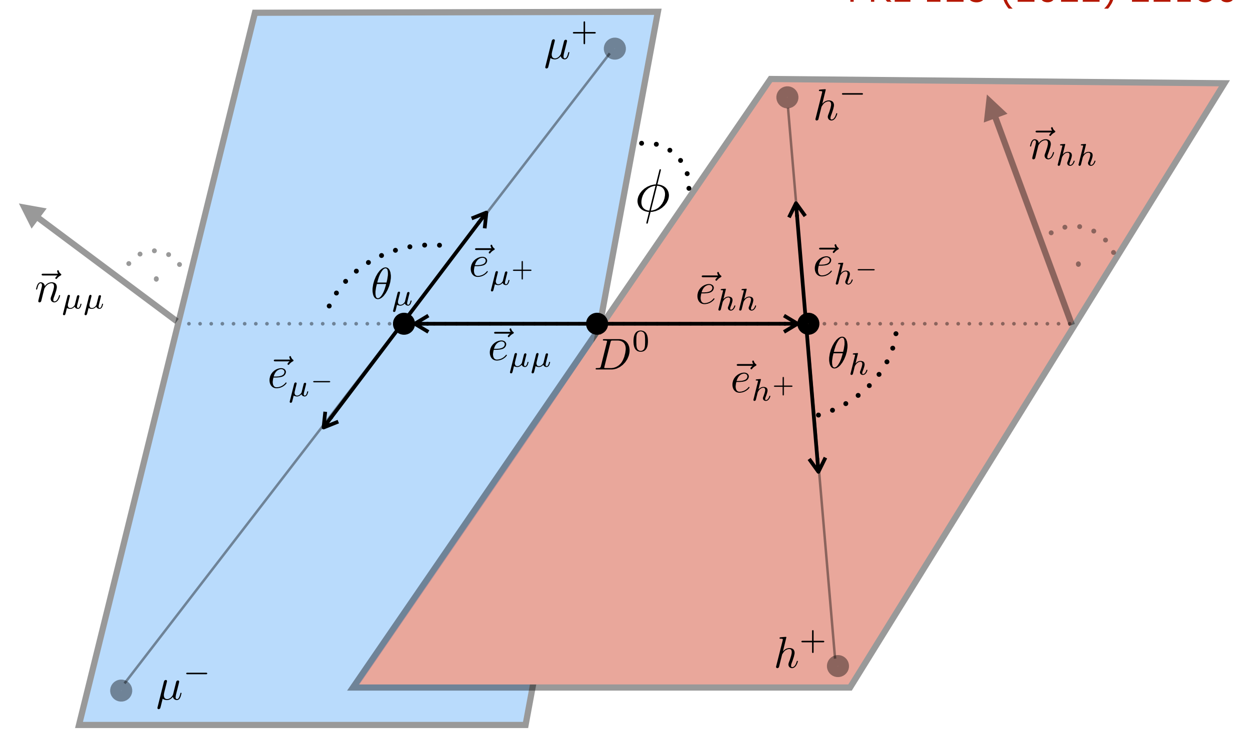


Differential decay rate

PRL 128 (2022) 221801

$$\frac{d\Gamma}{d\cos\theta_\mu d\cos\theta_h d\phi} = \begin{aligned} &I_1 + \\ &I_2 \cdot \cos 2\theta_\mu + \\ &I_3 \cdot \sin^2 2\theta_\mu \cos 2\phi + \\ &I_4 \cdot \sin 2\theta_\mu \cos\phi + \\ &I_5 \cdot \sin\theta_\mu \cos\phi + \\ &I_6 \cdot \cos\theta_\mu + \\ &I_7 \cdot \sin\theta_\mu \sin\phi + \\ &I_8 \cdot \sin 2\theta_\mu \sin\phi + \\ &I_9 \cdot \sin^2\theta_\mu \sin 2\phi \end{aligned}$$

I_5, I_6, I_7 clean null tests!



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

- measure $p^2, \cos\theta_h$ integrated* observables $\langle I_i \rangle$ separate for D^0 and $\overline{D^0}$

$$\langle I_{2,3,6,9}\rangle(q^2) = \frac{1}{\Gamma}\int_{4m_h}^{p^2_{max}} dp^2 \int_{-1}^{1} d\cos\theta_h \; I_{2,3,6,9}$$

$$\langle I_{4,5,7,8}\rangle(q^2) = \frac{1}{\Gamma}\int_{4m_h}^{p^2_{max}} dp^2 \left[\int_{-1}^{0} d\cos\theta_h - \int_{0}^{1} d\cos\theta_h\right] I_{4,5,7,8}$$

*optimal for p-Wave in hadron system

Measured observables and binning

PRL 128 (2022) 221801

- report flavour average $\langle S_i \rangle$ and CP asymmetries $\langle A_i \rangle$

$$\langle S_i \rangle = \frac{1}{2}\left[\langle I_i \rangle + (-)\langle \overline{I}_i \rangle\right] \qquad \langle S_{5,6,7} \rangle \overset{SM}{=} 0$$

$$\langle A_i \rangle = \frac{1}{2}\left[\langle I_i \rangle - (+)\langle \overline{I}_i \rangle\right] \qquad \langle A_i \rangle \overset{SM}{=} 0$$

i=2,..,9

for CP even (CP odd) coefficients

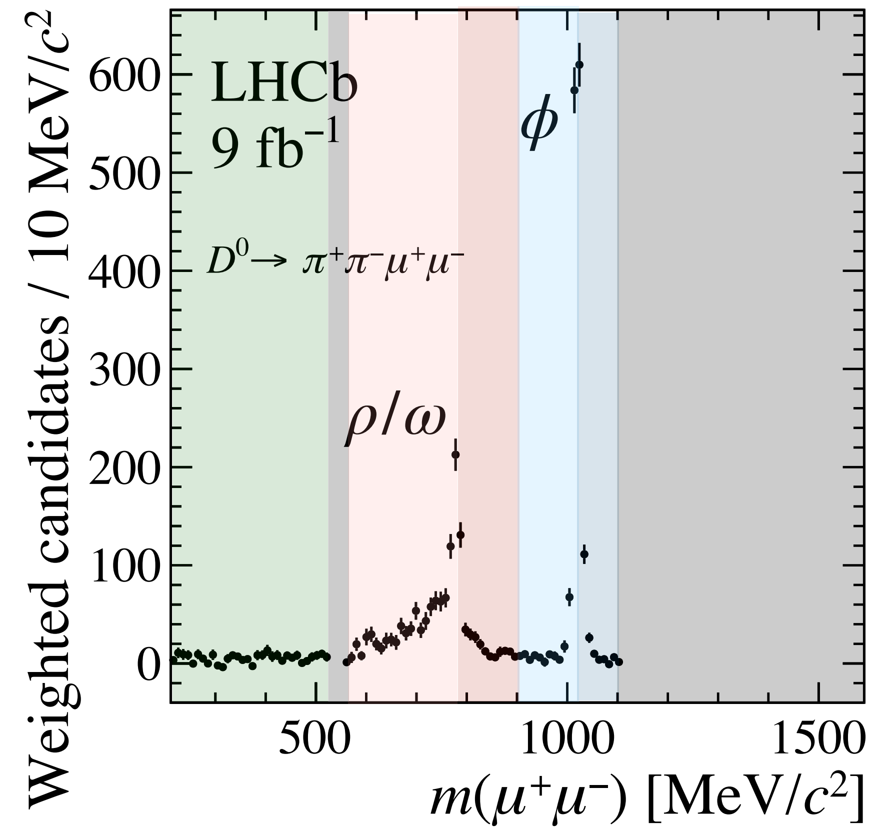
- updated measurement of A_{CP}

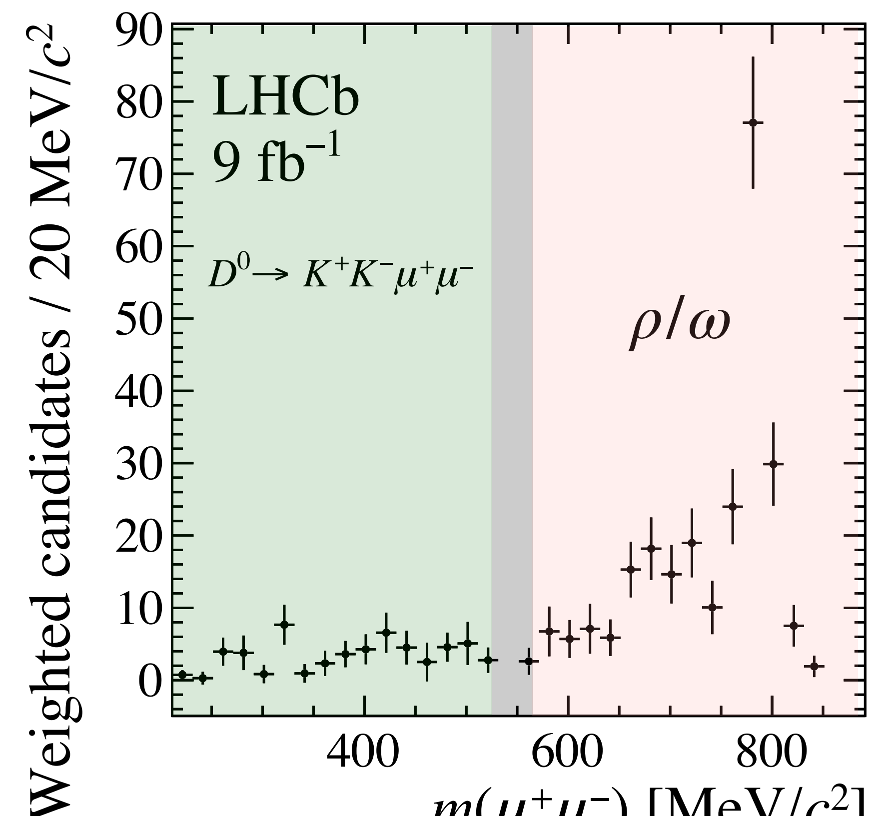
$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) - \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) + \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}$$

- 17 obs./channel [12 SM null-tests] in $m(\mu^+\mu^-)$ regions ["*resonance enhanced NP effects*"]

Decay mode	low mass	η	ρ/ω		ϕ		high mass
	$m(\mu^+\mu^-)$ [MeV/c^2]						
$D^0 \to K^+K^-\mu^+\mu^-$	< 525	NS	> 565		NA		NA
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	< 525	NS	565-780	780-950	950-1020	1020-1100	NS

[NA = not available NS = no signal]





Experimental strategy

- measure angular observables via yield asymmetries, eg:

$$\langle I_6 \rangle = \frac{1}{\Gamma}\left[\int_0^1 d\cos\theta_\mu - \int_{-1}^0 d\cos\theta_\mu\right]\frac{d\Gamma}{d\cos\theta_\mu}$$

$$\langle I_6 \rangle = \frac{N(\cos\theta_\mu > 0) - N(\cos\theta_\mu < 0)}{N(\cos\theta_\mu > 0) + N(\cos\theta_\mu < 0)}$$

[see LHCb-PAPER-2021-035 for others]

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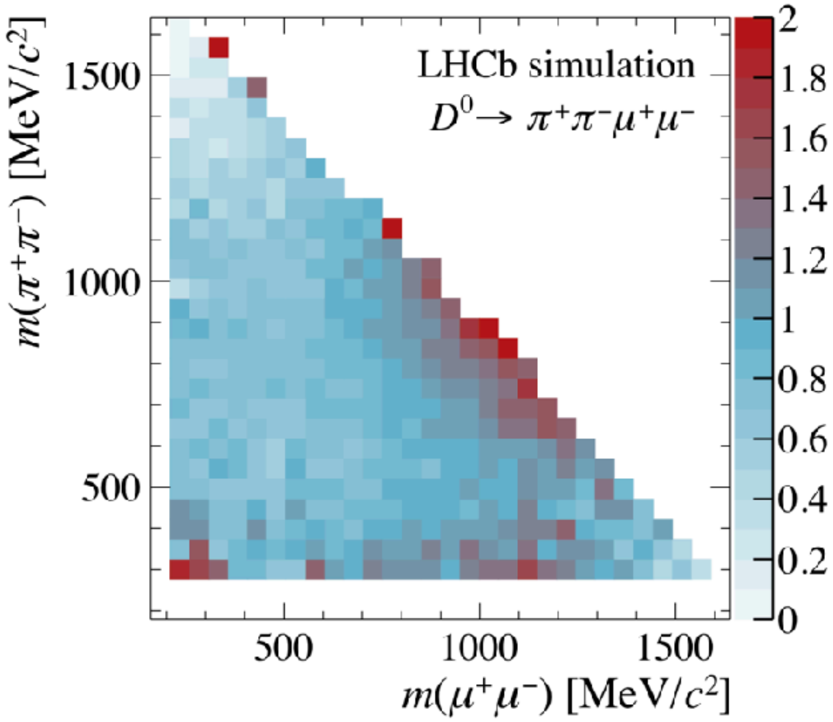


PRL 121 (2018) 091801

- correct for acceptance effects across the 5D phase space

- correct A_{CP} for nuisance asymmetries

$$A_{CP}^{raw}(f) = \frac{N(D^{*+} \to D^0(\to f)\pi^+) - N(D^{*-} \to \overline{D^0}(\to f)\pi^-)}{N(D^{*+} \to D^0(\to f)\pi^+) + N(D^{*-} \to \overline{D^0}(\to f)\pi^-)} \approx A_{CP} + A_d(\pi^\pm) + A_p(D^{*\pm})$$

[use $D^{*+} \to D^0(\to K^+K^-)\pi^+$ decays]

- evaluate systematic uncertainties

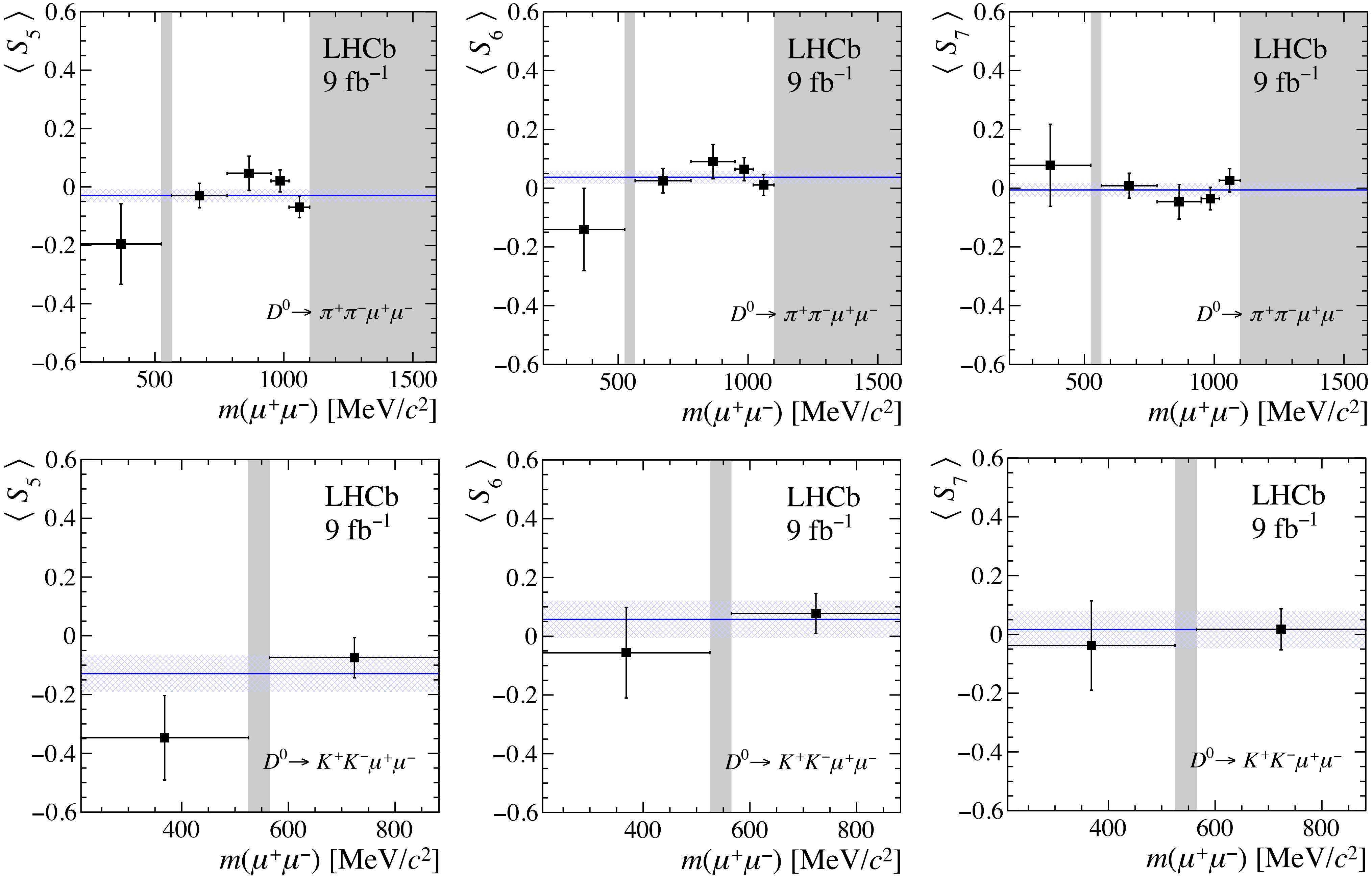
typically $\frac{\sigma_{sys}}{\sigma_{stat}} \sim (10-50)\,\%$

limited by statistics!

Flavour-averaged observables $\langle S_i \rangle$

PRL 128 (2022) 221801

- Shown examples: SM null tests $\langle S_{5,6,7} \rangle$ [$\langle S_6 \rangle \sim A_{FB}$]



agreement with SM predictions
[JHEP 04 135 (2013), PRD 98, 035041(2018)]

- all observables in backup, tabulated version & correlation matrices in LHCb-PAPER-2021-035

CP asymmetries $\langle A_i \rangle$

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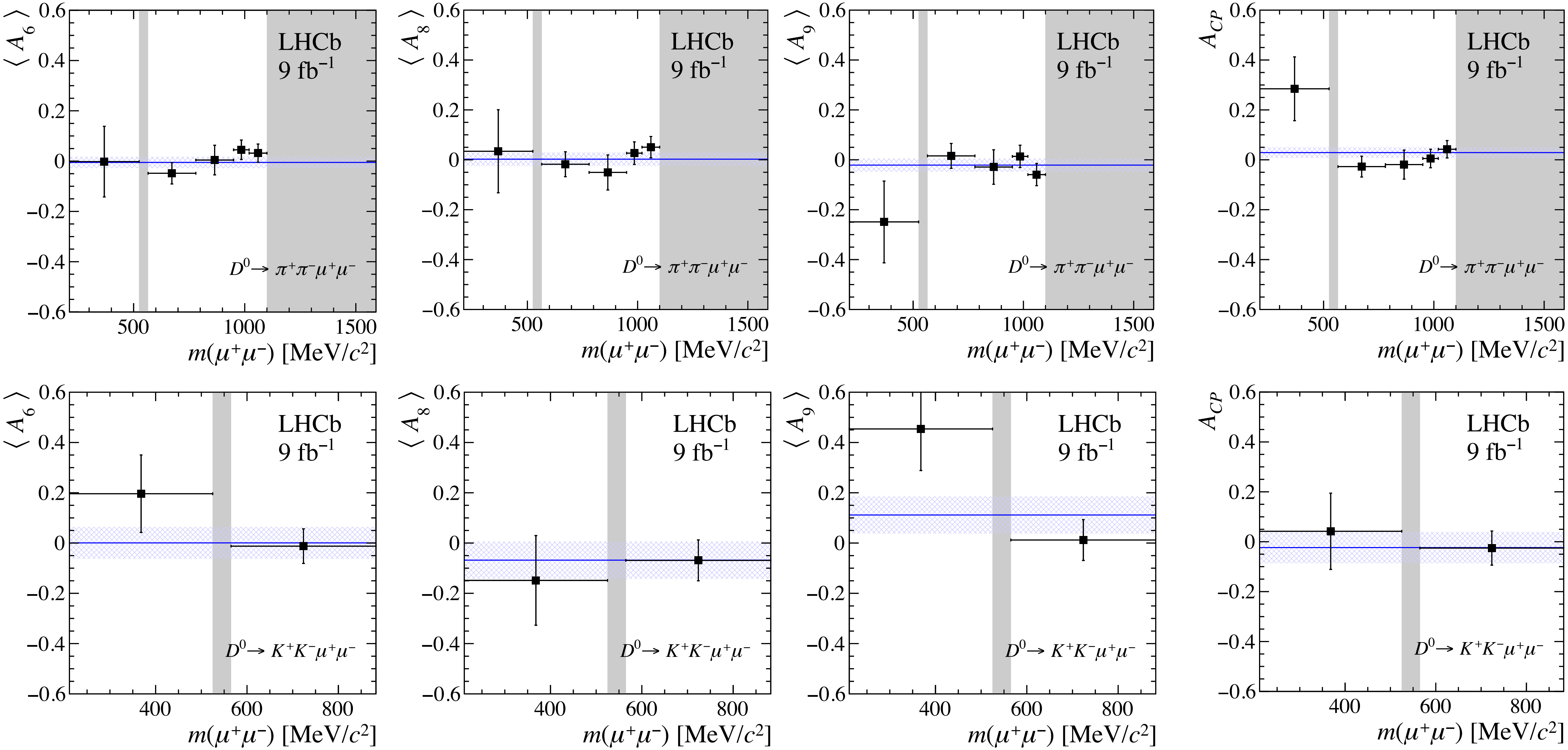
- Shown: $\langle A_6 \rangle$ [$\langle A_6 \rangle \sim A_{FB}^{CP}$], $\langle A_{8,9} \rangle$ [triple-product-asym.] & A_{CP}



- overall agreement wrt. to SM hypothesis considering A_{CP}, $\langle A_{2-9} \rangle$ & $\langle S_{5,6,7} \rangle$:

$D^0 \to \pi^+\pi^-\mu^+\mu^-$ p = 79% (0.3σ)
$D^0 \to K^+K^-\mu^+\mu^-$ p = 0.8% (2.7σ)

consistent with SM