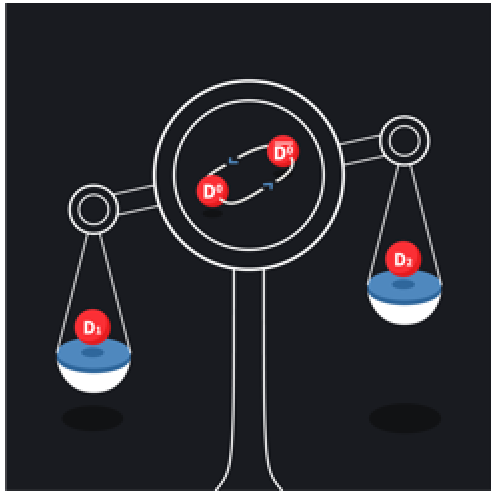
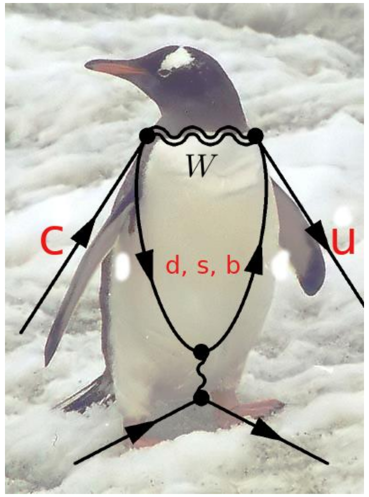
Charm Physics at LHCb



Liang Sun

Wuhan University



HFCPV 2021

Nov. 12 2021, Guangzhou (Virtual), China

Outline

- Recent LHCb results on charm CPV:
  - **Mixing and time-dependent CPV in $D^0 \to K_S^0\pi^+\pi^-$(06.2021)**
  - **Time-dependent CPV in $D^0 \to K^+K^-, \pi^+\pi^-$ (05.2021)**
  - **Time-integrated CPV in $D^0 \to K_S^0 K_S^0$ (05.2021)**
  - **Time-integrated CPV in $D_{(s)}^+ \to h^+\pi^0$ and $D_{(s)}^+ \to h^+\eta$ (03.2021)**
  - **Time-integrated CPV in $\Xi_c^+ \to pK^-\pi^+$ (06.2020)**
- Recent results on rare charm decays:
  - **Search for 25 decays of $D_{(s)}^+ \to h^\pm\ell^+\ell^{(\prime)\mp}$ (10.2020)**
  - **CPV and angular analysis in $D^0 \to hh\mu^+\mu^-$ (11.2021)**
- Run3 and beyond
- Summary and discussions

NB: For non-CPV & non-rare charm results from LHCb, please see here.

CP violation in charm

- Only way to probe CP violation in up-type quark
- Complementary to K and B mesons with observed CPV
- Difficult to calculate SM predictions, but small (10^{-3} – 10^{-4}) CP asymmetry is expected → hints of NP if higher values are observed
- CPV in charm sector eventually observed in 2019

PRL 122 (2019) 211803

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

– Observation of CP violation with **5.3σ** significance!

Unitarity triangle for charm

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

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

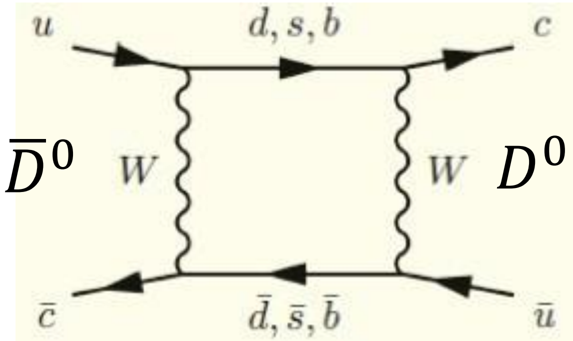
$$\lambda = \sin(\theta_c) \sim 0.23$$

Expected CPV very small in charm

- Effectively 2-generation system
- Third generation and CPV enter through loops

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

- Charm mixing – a well established fact
  - Mass eigenstates are related to their flavor eigenstates via $|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\overline{D}^0\rangle$, 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



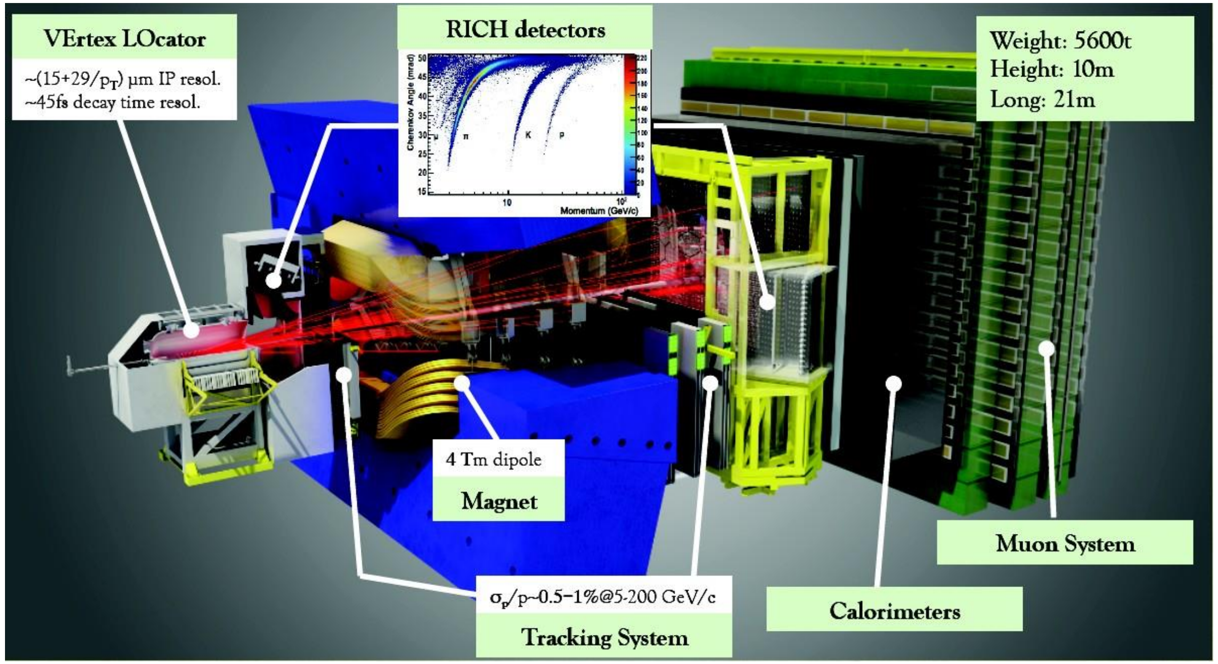
  - In decays, amplitudes for a process and its conjugate differ

    Direct CP violation $\left|\frac{\overline{A}_{\bar{f}}}{A_f}\right|^{\pm 2} \approx 1 \pm A_d \rightarrow a_{CP}^{dir} \approx -\frac{1}{2}A_d$
  - In mixing: rates of $D^0 \to \overline{D}^0$ and $\overline{D}^0 \to D^0$ differ

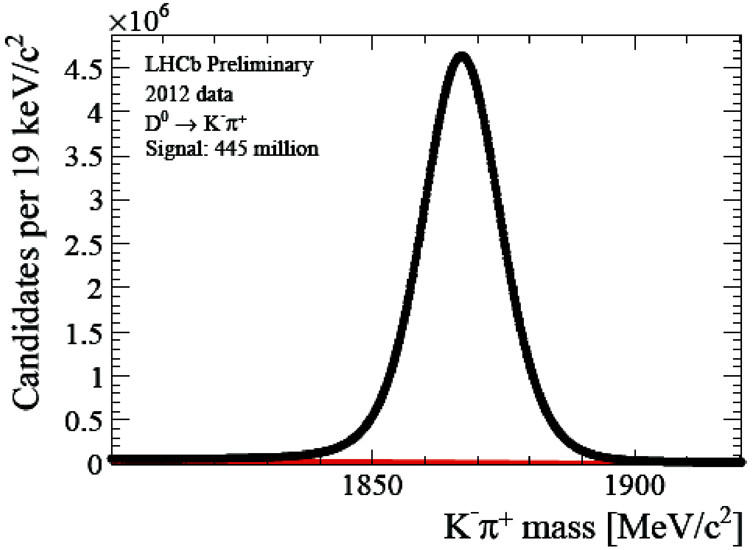
    Indirect CP violation $\left|\frac{q}{p}\right|^{\pm 2} \approx 1 \pm A_m \rightarrow a_{CP}^{ind} = -\frac{A_m}{2} y\cos\phi + x\sin\phi$

    ϕ: weak phase,
    A_m: CPV from mixing
  - In interference between mixing and decays diagrams

LHCb as a Charm factory



LHCb-CONF-2016-005



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

[JHEP 03 (2016) 159]

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

- 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]

$$\mathcal{A}^{raw} \equiv \frac{N_{D^0} - N_{\bar{D}^0}}{N_{D^0} + N_{\bar{D}^0}}$$

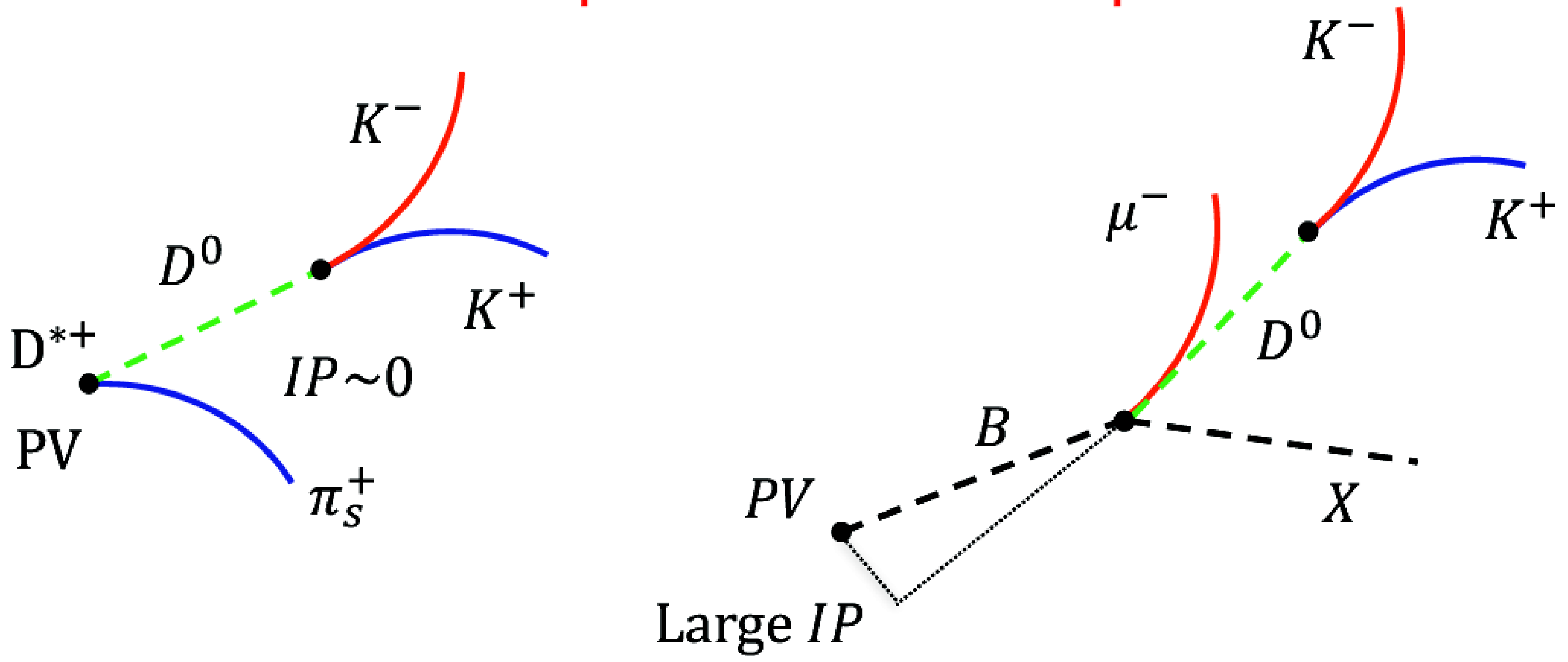
$$\mathcal{A}^{raw} \approx \mathcal{A}^{CP} + \mathcal{A}^{prod} + \mathcal{A}^{det}$$

D^0 production at LHCb

NB: For A_{CP} in D^0, control channel needed to cancel the production-level asymmetry $\mathcal{O}(1\%)$

Two mechanisms of D^0 production

Independent data sample



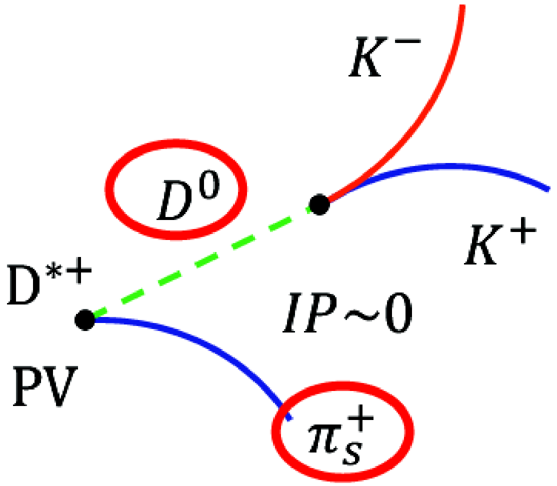
$$\mathcal{A}^{raw} \equiv \frac{N_{D^0} - N_{\bar{D}^0}}{N_{D^0} + N_{\bar{D}^0}}$$

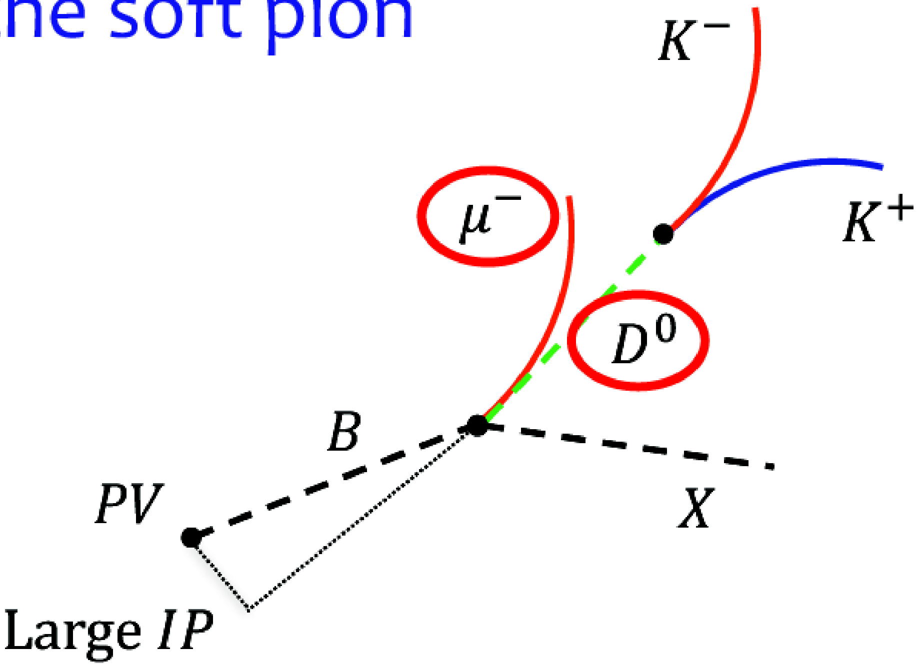
$$\mathcal{A}^{raw} \approx \mathcal{A}^{CP} + \mathcal{A}^{prod} + \mathcal{A}^{det}$$

D^0 flavor tagging at LHCb

NB: For A_{CP} in D^0, control channel needed to cancel the tagging asymmetry $\mathcal{O}(1\%)$

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



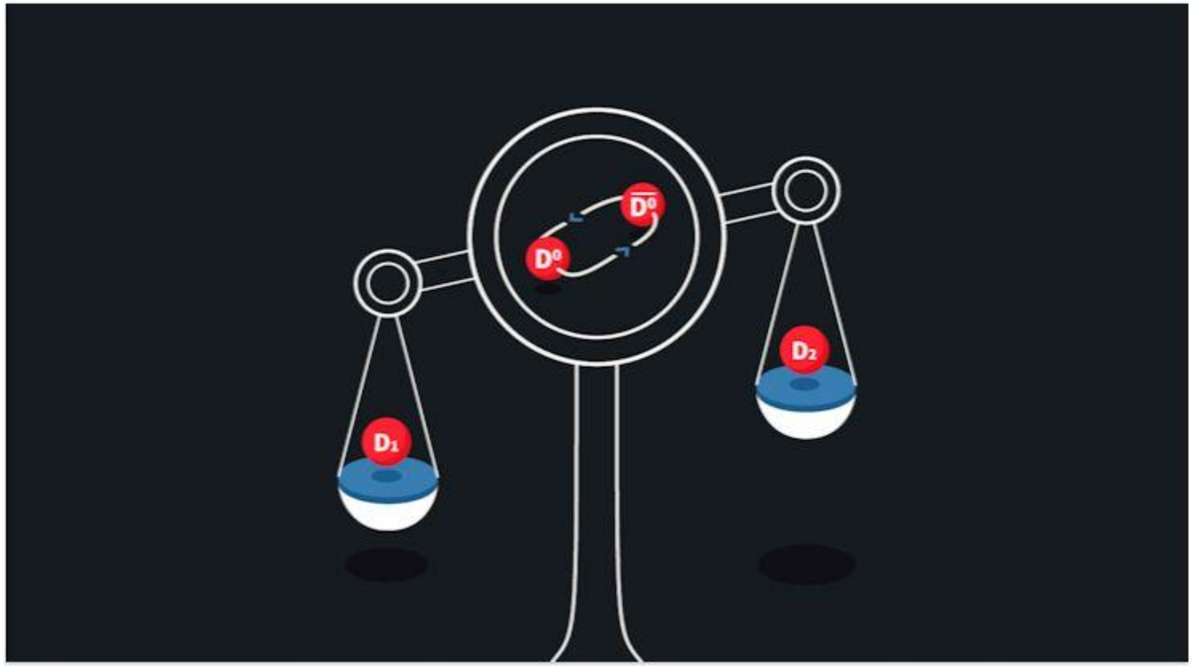


$D^0 - \bar{D}^0$ oscillation in $D^0 \to K_S^0 \pi^+ \pi^-$

LHCb measures tiny mass difference between particles

The result is a milestone in the study of how a particle known as a D0 meson changes from matter into antimatter and back

8 JUNE, 2021 | By Ana Lopes

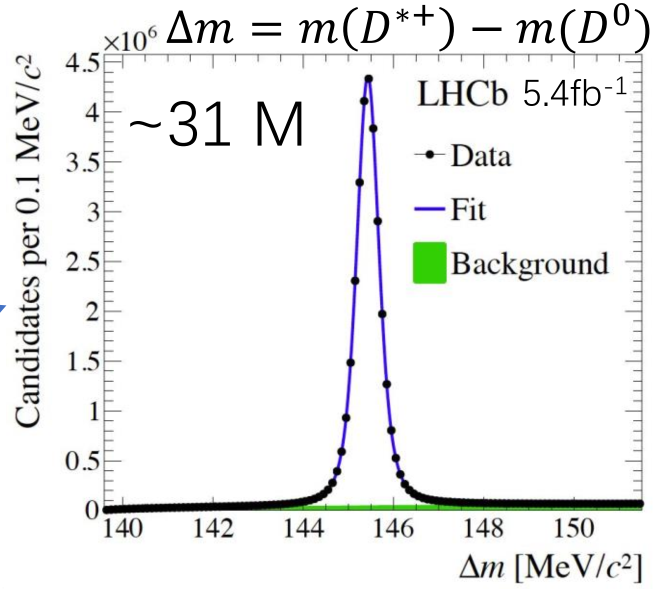


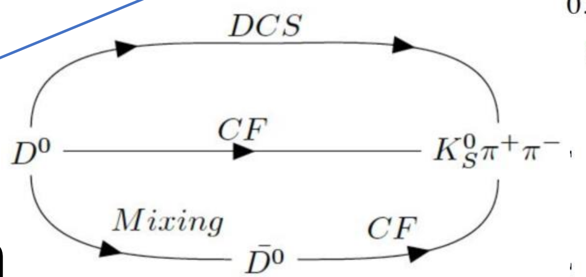
The LHCb collaboration has measured the tiny mass difference between the D1 and D2 mesons, which are a manifestation of the quantum superposition of the D0 particle and its antiparticle. This mass difference controls the speed of the D0 oscillation into its antiparticle and back. (Image: CERN)

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

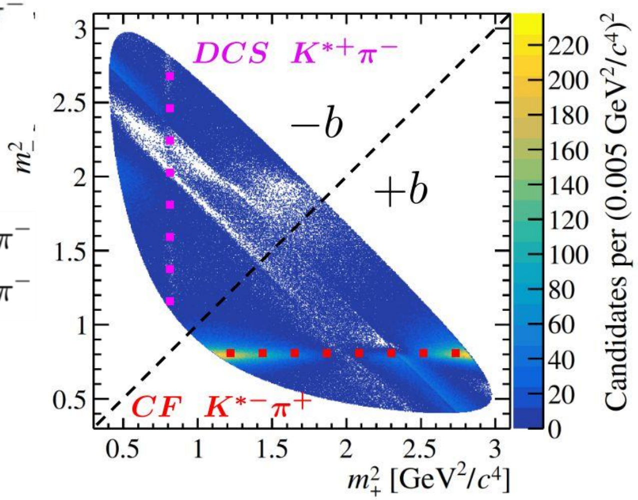
$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D^0}\rangle \quad x \equiv \frac{m_1 - m_2}{\Gamma}; y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

- x determines the oscillation rate
  - Very tiny for D^0, but x and CPV can be enhanced by NP
  - CPV can occur in the mixing → oscillation rates differ for D^0 and $\bar{D}^0$
- Run2 π-tagged dataset
- Self-conjugate $D^0 \to K_S^0\pi^+\pi^-$ has rich resonance structure
- Model-independent approach (bin-flip method) [PRD 99 (2019) 012007]
  - To avoid modeling of efficiency variation

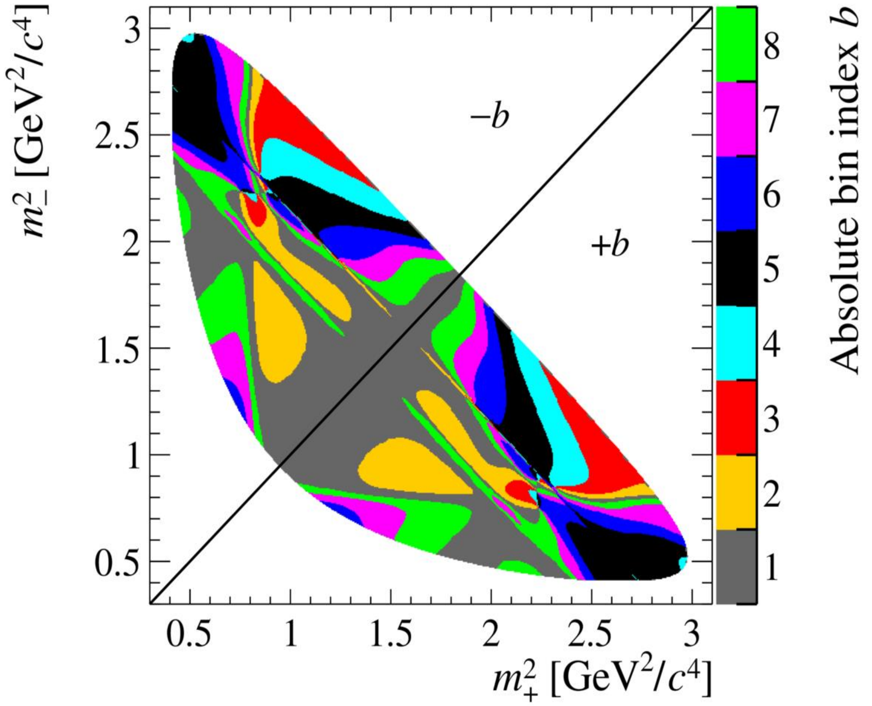




$$m_\pm^2 \equiv \begin{cases} m^2(K_S^0\pi^\pm) & \text{for } D^0 \to K_S^0\pi^+\pi^- \\ m^2(K_S^0\pi^\mp) & \text{for } \bar{D}^0 \to K_S^0\pi^+\pi^- \end{cases}$$



Model-independent bin-flip method



- Use strong-phase info c_b, s_b from CLEO-c and BESIII [PRD 101 (2020) 112002]
- Bin Dalitz-plot into $\pm b$ about $m^2_+ = m^2_+$ with almost constant $\Delta\delta(m^2_-, m^2_+)$
- Measure ratio of signal in $-b$ and $+b$ in D^0 decay time bin j (13 in total)

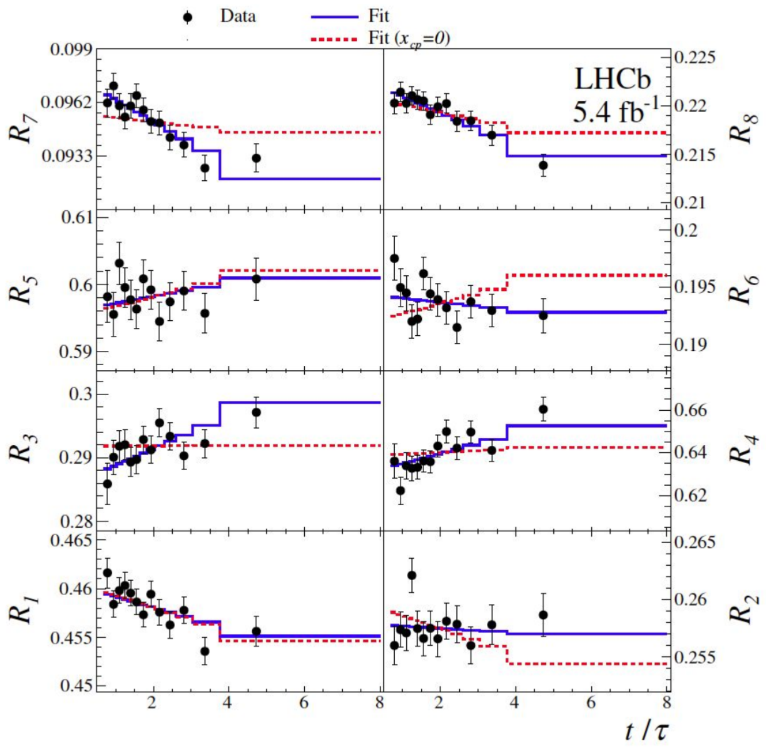
$R^\pm$ **changes with time** $\Rightarrow$ **Mixing**
$R^+ \neq R^-$ $\Rightarrow$ **Indirect CPV**

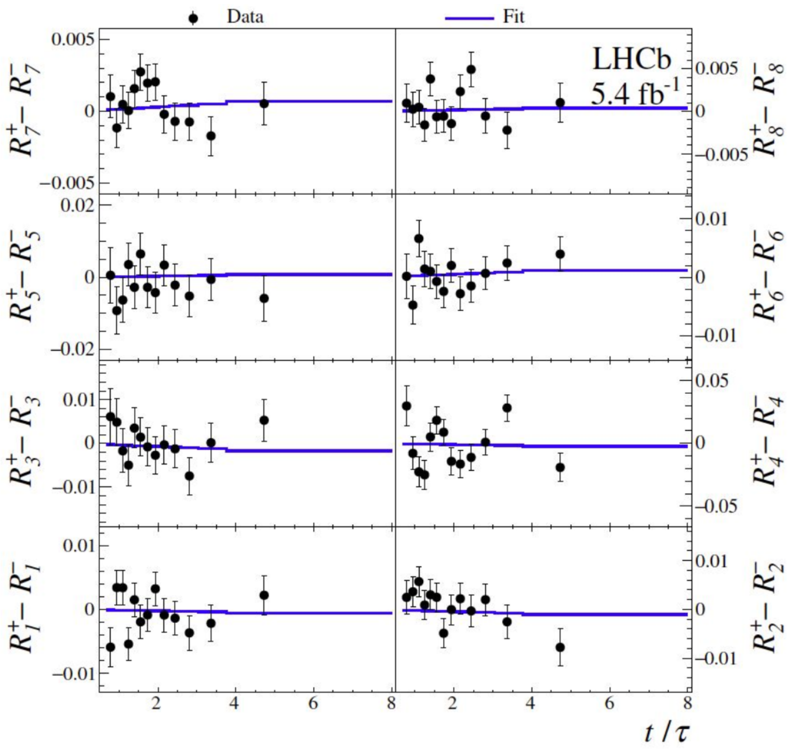
$$R^{\pm}_{bj} = \frac{r_b\left[1+\frac{1}{4}t_j^2 Re(z^2_{CP}-\Delta z^2)\right]+\frac{1}{4}t_j^2|\,z_{CP}\pm\Delta z\,|^2+\sqrt{r_b}t_j Re\left[\mathbf{X}^*_\mathbf{b}(z_{CP}\pm\Delta z)\right]}{\left[1+\frac{1}{4}t_j^2 Re(z^2_{CP}-\Delta z^2)\right]+r_b\frac{1}{4}t_j^2|\,z_{CP}\pm\Delta z\,|^2+\sqrt{r_b}t_j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

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

PRL 127 (2021) 111801

$D^0 \to K_S^0\pi^+\pi^-$ bin-flip results





Uncertainties statistically dominated!

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

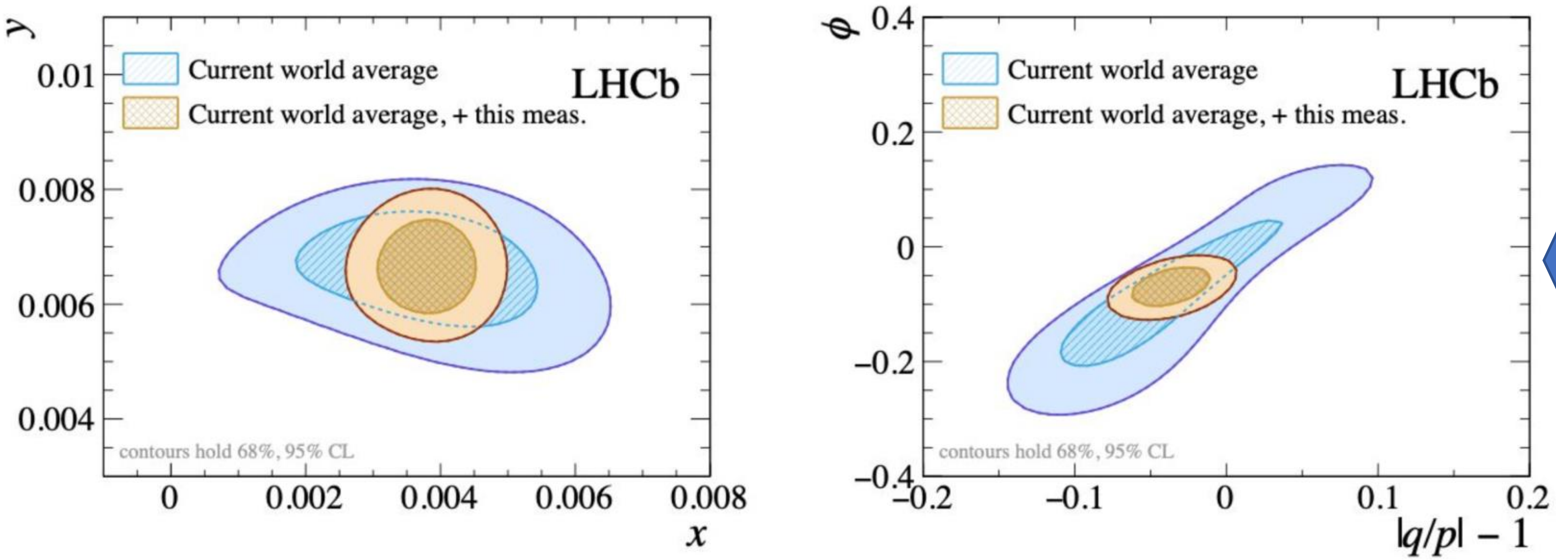
$$\Delta x = (-0.27 \pm 0.18 \pm 0.01) \times 10^{-3}$$
$$\Delta y = (\ \ 0.20 \pm 0.36 \pm 0.13) \times 10^{-3}$$

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

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

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

$D^0 \to K_S^0 \pi^+ \pi^-$ bin-flip results



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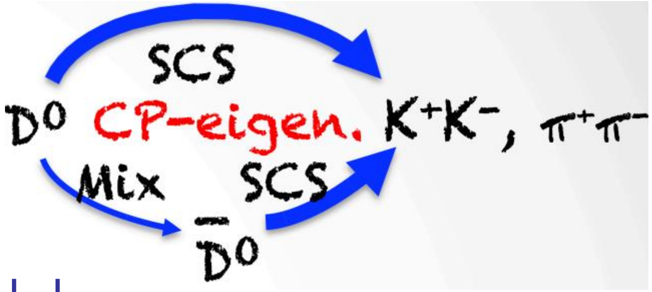
World Averages significantly improved!

First observation of non-zero x (>7σ)

Time-dependent CPV in SCS $D^0 \to h^+h^-$



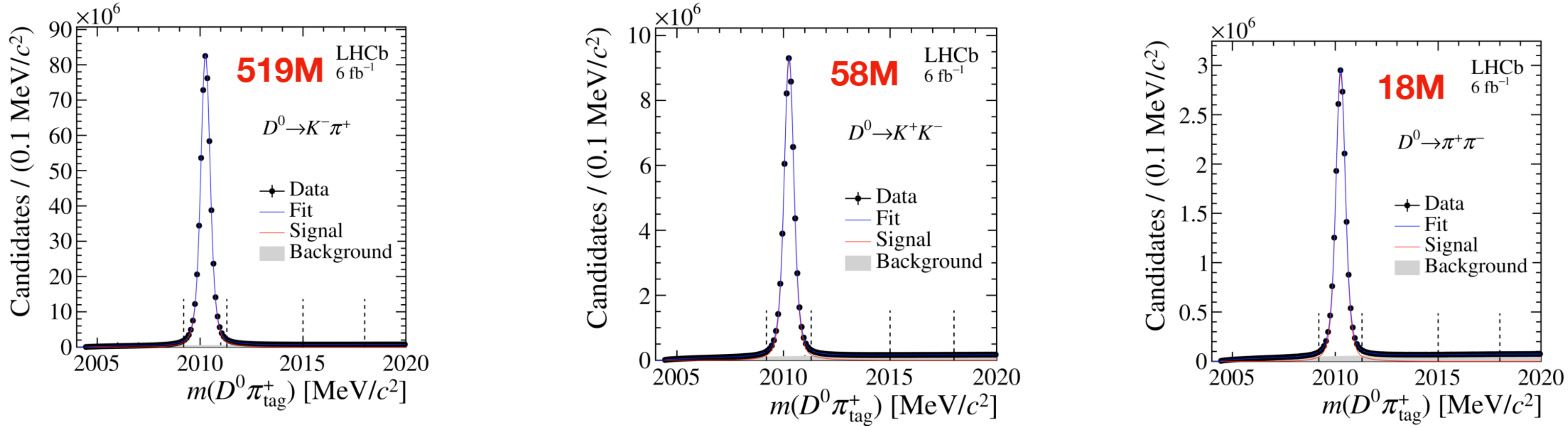
- A_{CP} of SCS as one of the most sensitive CPV test:

$$A_{CP}(f,t) \equiv \frac{\Gamma(D^0 \to f,t) - \Gamma(\bar{D}^0 \to f,t)}{\Gamma(D^0 \to f,t) + \Gamma(\bar{D}^0 \to f,t)} \overset{x_{12},y_{12} \ll 1}{\approx} a_f^d + \Delta Y_f \frac{t}{\tau_{D^0}}$$

$$\Delta Y_f \approx -A_\Gamma \approx x\phi_{\lambda_f} - y\left(\left|\frac{q}{p}\right| - 1\right)$$

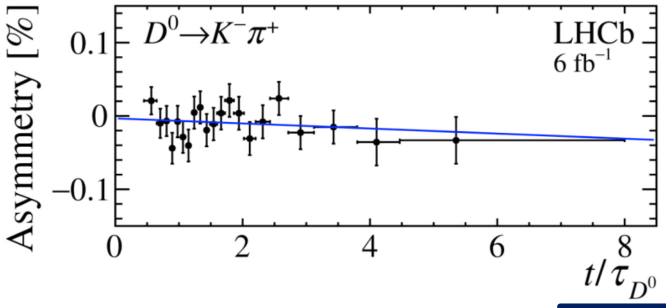
- SM expectation for $f = K^+K^-, \pi^+\pi^-$: $\Delta Y_f \sim \mathcal{O}(10^{-5} - 10^{-4})$
- Run2 π-tagged dataset
- Binned ML mass fits in 21 bins of decay time

Kagan & Silvestrini, PRD 103 (2021) 053008
Li & Umeeda, PLB 810 (2020) 135802



Time-dependent CPV in SCS $D^0 \to h^+h^-$

Control channel:

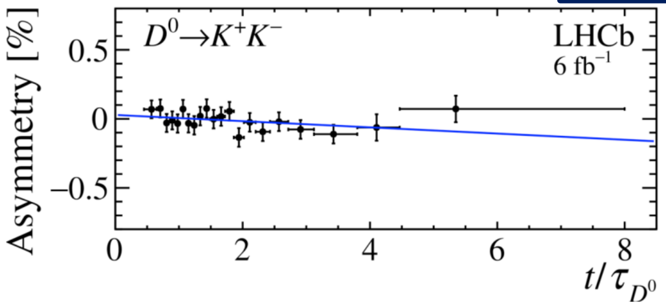


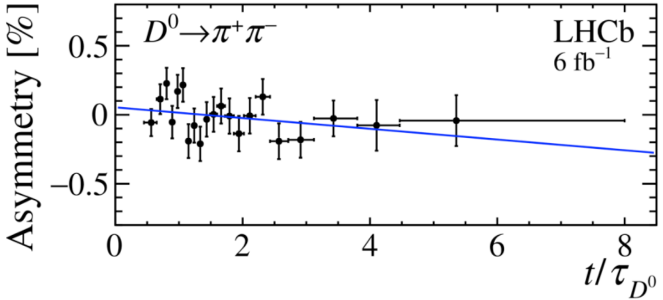
$\Delta Y_{K^-\pi^+} = (-0.4 \pm 0.5 \pm 0.2) \times 10^{-4}$

Compatible with being zero

Signal channels:

$$A_{raw}(t) \approx a_f^d + \Delta Y_f \frac{t}{\tau_{D^0}} + A_D^{\pi_s^+}(t) + A_P^{D^{*+}}(t)$$





$\Delta Y_{K^+K^-} = (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4}$

Mutually compatible

$\Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4}$

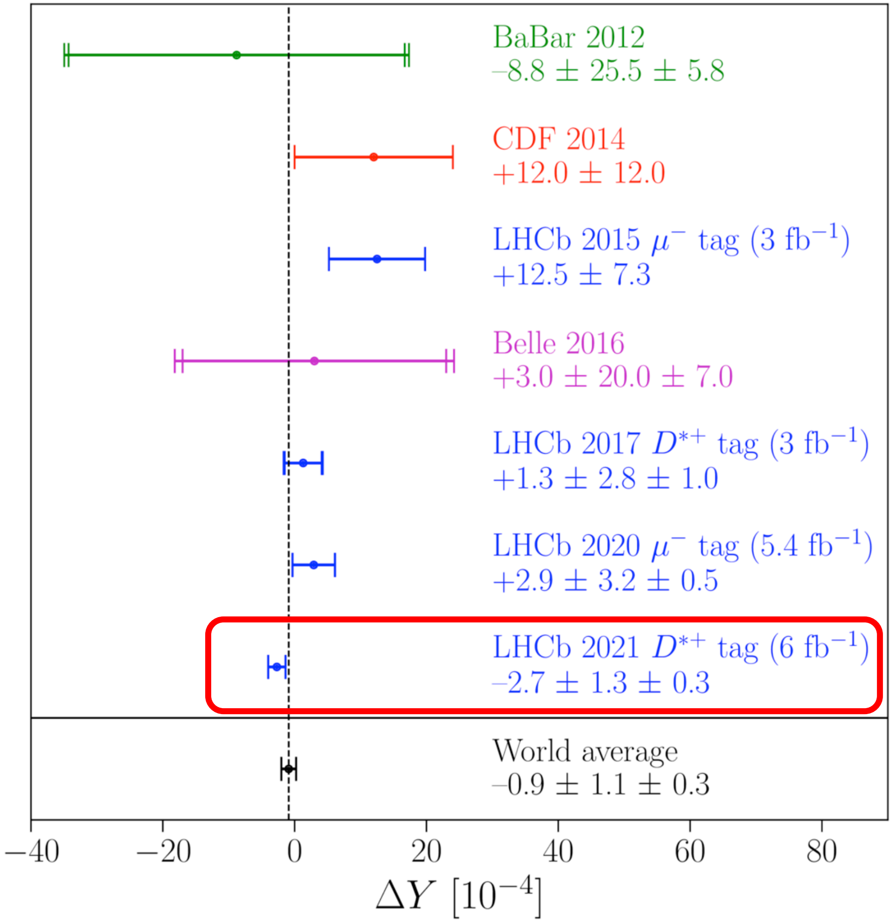
$\Delta Y_{comb} = (-2.7 \pm 1.3 \pm 0.3) \times 10^{-4}$

Neglecting final-state dependent contributions

- Time-dependent detector/production effects are corrected for → will slightly dilute ΔY_f
- Linear fits to extract ΔY_f as slope parameters
- Statistically dominated uncertainty

Time-dependent CPV in SCS $D^0 \to h^+h^-$

$$\Delta Y_f \approx -A_\Gamma \approx x\phi_{\lambda_f} - y(\left|\frac{q}{p}\right| - 1)$$



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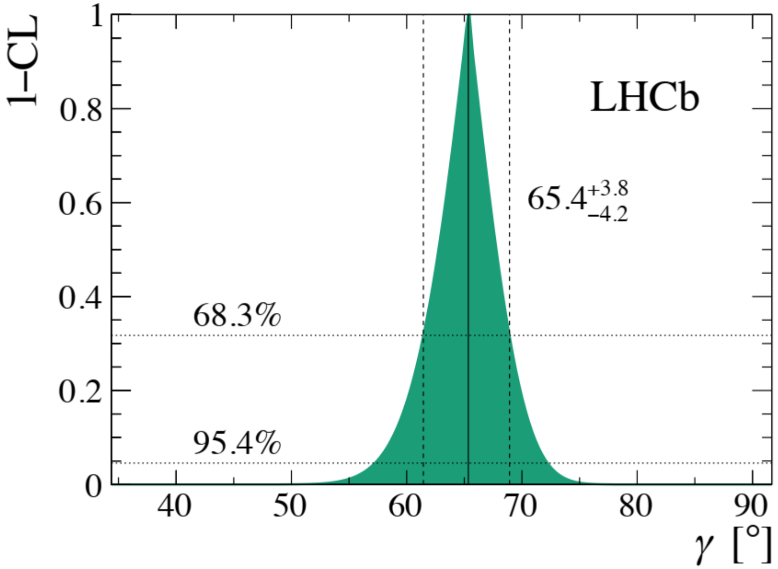
$\Delta Y_{comb} = (-2.7 \pm 1.3 \pm 0.3) \times 10^{-4}$

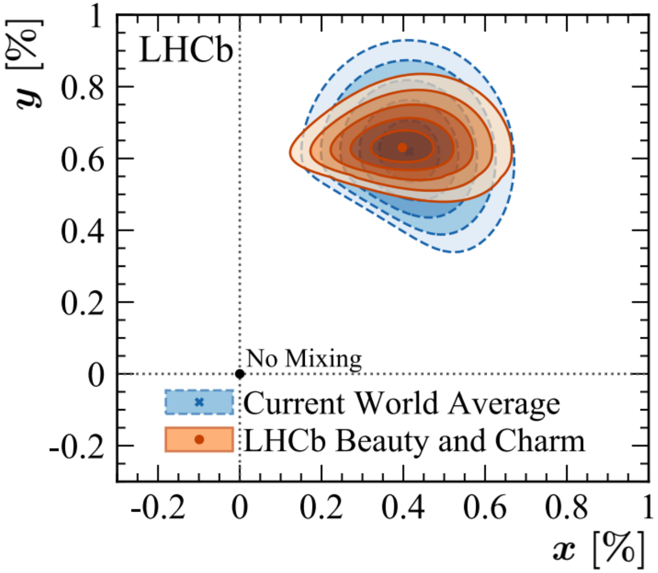
Neglecting final-state dependent contributions

LHCb γ+charm combination

$$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$

Most precise determination from a <u>single</u> experiment





$$x_D = (4.00^{+0.52}_{-0.53}) \times 10^{-3}$$

$$y_D = (6.30^{+0.33}_{-0.30}) \times 10^{-3}$$

$$\delta_D^{K\pi} = (190.0^{+4.2}_{-4.1})^\circ$$

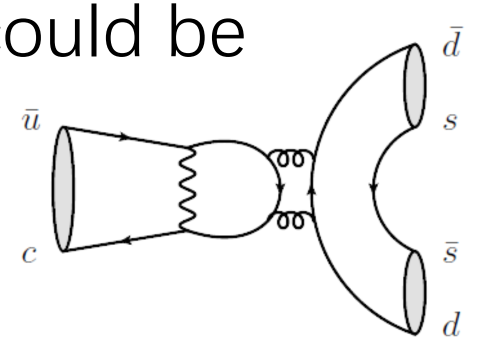
$$r_D^{K\pi} = (58.67 \pm 0.15) \times 10^{-3}$$

- Inclusion of most recent LHCb beauty & charm measurements
- Auxiliary inputs from experiments near charm threshold including BESIII

Also mentioned in Wenbin's talk yesterday

A_{CP} in $D^0 \to K_S^0 K_S^0$

- Contributions of penguin annihilation diagrams, CPV could be greatly enhanced ($\mathcal{O}(1\%)$) [PRD 92 (2015) 054036]



- Run2 data, π-tagged + μ-tagged
- Raw asymmetry:

$$A_{\rm raw}(K_S^0 K_S^0) = A_{CP}(K_S^0 K_S^0) + A_P(D^{*+}) + A_{\rm tag}(\pi^+)$$

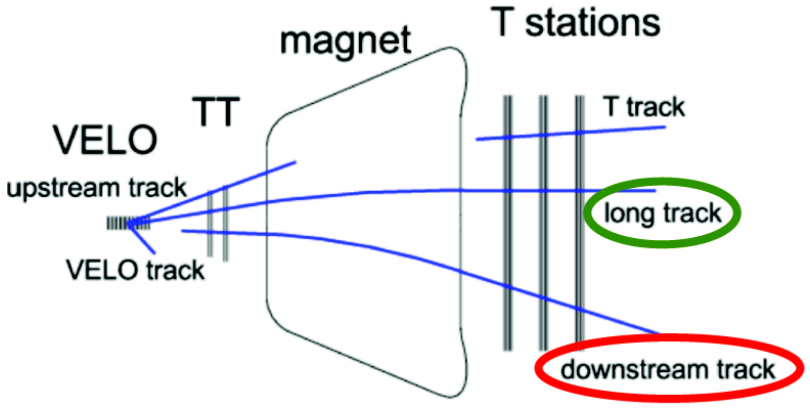
- Control channel $D^0 \to K^+K^-$ to remove production & tagging asymmetries:

$$\Delta A_{CP} = A_{\rm raw}(K_S^0 K_S^0) - A_{\rm raw}(K^+K^-)$$
$$= A_{CP}(K_S^0 K_S^0) - A_{CP}(K^+K^-)$$

$A_{CP}(K^+K^-) = (0.04 \pm 0.12 \pm 0.10)\%$ measured by LHCb PLB 767 (2017) 177

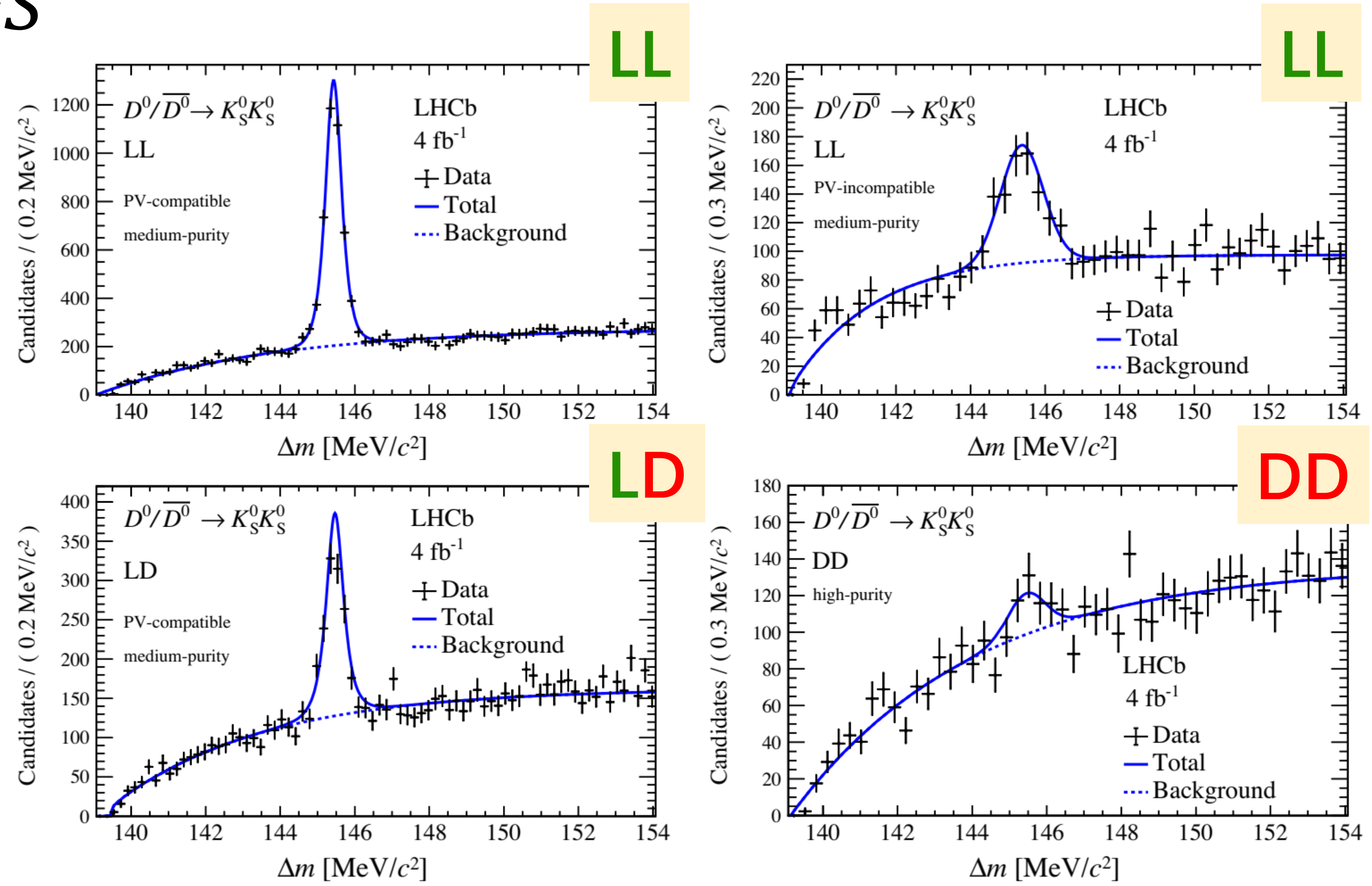
A_{CP} in $D^0 \to K_S^0 K_S^0$

K_S^0 reconstruction types



$$\mathcal{A}^{CP}(D^0 \to K_S^0 K_S^0) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$$

compatible with no CP asymmetry at the level of 2.4 standard deviations.

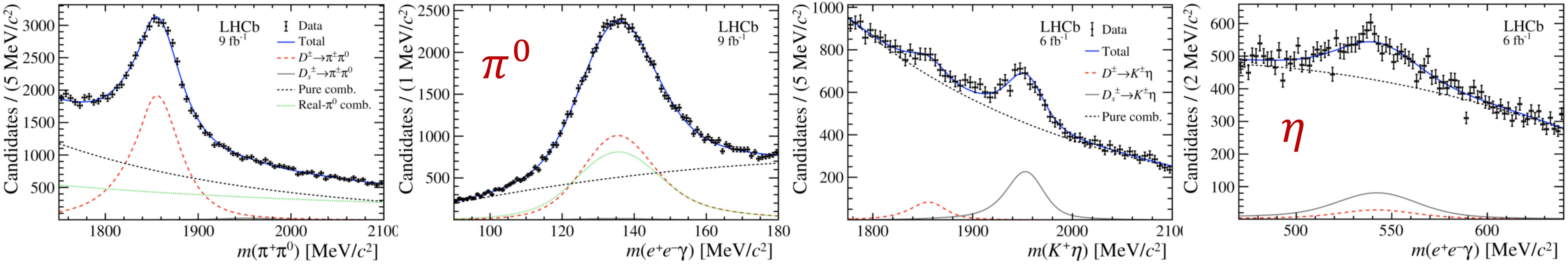


Separation of data also based on compatibility with originating in the Interaction Point or not

JHEP 06 (2021) 019

A_{CP} in $D_{(s)}^{+} \to h^{+}\pi^{0}$ and $D_{(s)}^{+} \to h^{+}\eta$

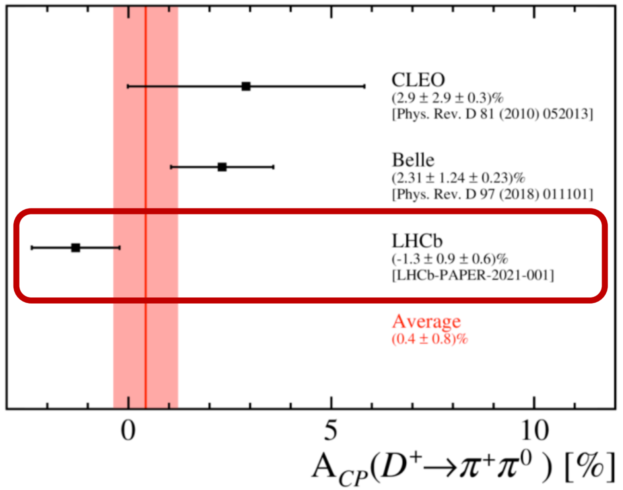
- SCS decays w/ loop: $D^{+} \to \pi^{+}\eta$, $D_{s}^{+} \to K^{+}(\pi^{0},\eta)$ (A_{CP} ~10^{-4} – 10^{-3}) and w/o loop: $D^{+} \to \pi^{+}\pi^{0}$ (no CPV in SM!)
- Neutral hadrons difficult in hadron colliders, reco'ed via $e^{+}e^{-}\gamma$
- Runs 1+2 for π^{0} modes and only Run2 for η modes
- Nuisances asymmetries removed using $D_{(s)}^{+} \to K_{S}^{0}h^{+}$



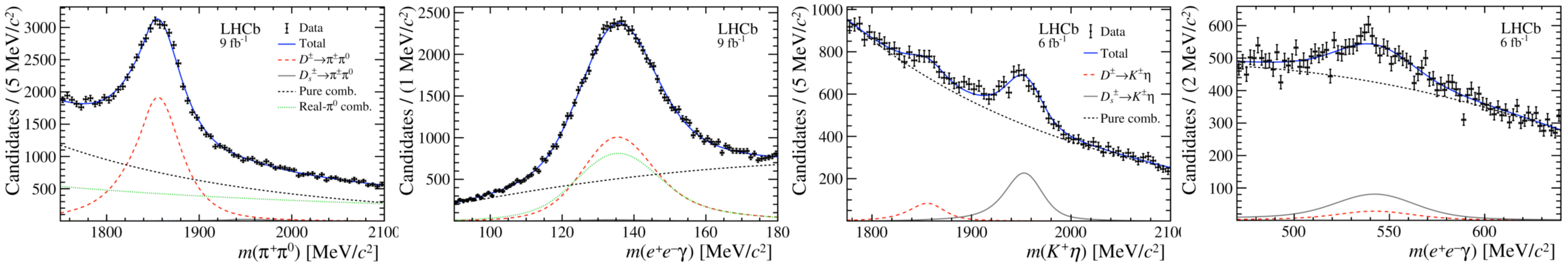
A_{CP} in $D^+_{(s)} \to h^+\pi^0$ and $D^+_{(s)} \to h^+\eta$

$$\mathcal{A}_{CP}(D^+ \to \pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%$$
$$\mathcal{A}_{CP}(D^+ \to K^+\pi^0) = (-3.2 \pm 4.7 \pm 2.1)\%$$
$$\mathcal{A}_{CP}(D^+ \to \pi^+\eta) = (-0.2 \pm 0.8 \pm 0.4)\%$$
$$\mathcal{A}_{CP}(D^+ \to K^+\eta) = (-6 \pm 10 \pm 4)\%$$
$$\mathcal{A}_{CP}(D_s^+ \to K^+\pi^0) = (-0.8 \pm 3.9 \pm 1.2)\%$$
$$\mathcal{A}_{CP}(D_s^+ \to \pi^+\eta) = (0.8 \pm 0.7 \pm 0.5)\%$$
$$\mathcal{A}_{CP}(D_s^+ \to K^+\eta) = (0.9 \pm 3.7 \pm 1.1)\%$$

most precise measurements to date



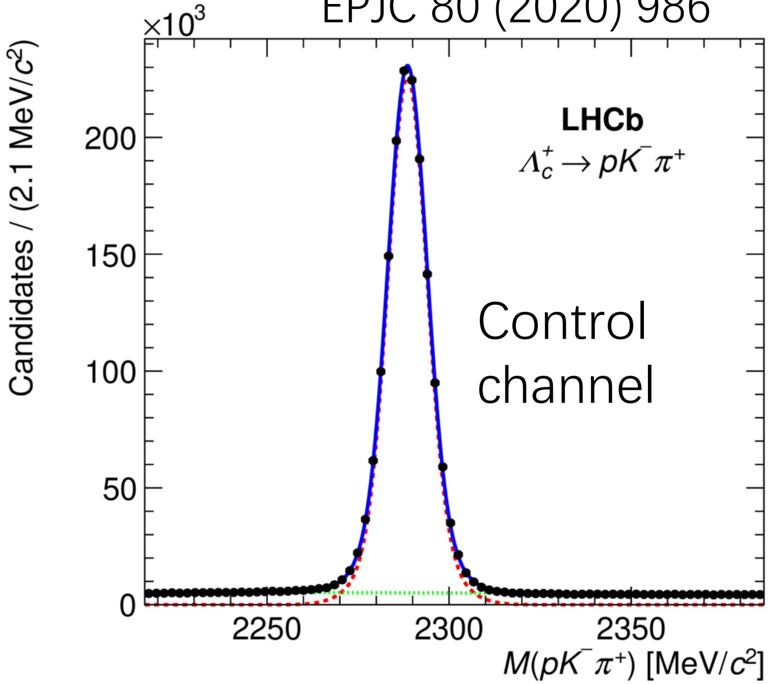
All results compatible with zero

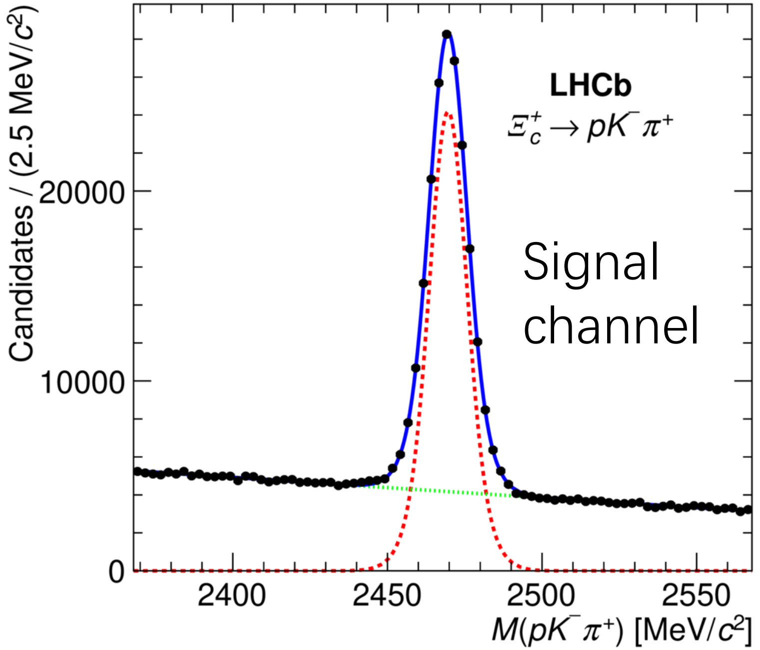


A_{CP} in $\Xi_c^+ \to pK^-\pi^+$

- Based on Run1 3 fb^{-1} data
- Direct comparison for compatibility between Ξ_c^+ and Ξ_c^- Dalitz plots (total yield ~ 190k) using two model-independent techniques
  - Divided into bins
  - Divided into regions around expected resonances
- Procedures tested on control channel $\Lambda_c^+ \to pK^-\pi^+$ (total yield ~ 1.9M) before applied to the signal

EPJC 80 (2020) 986





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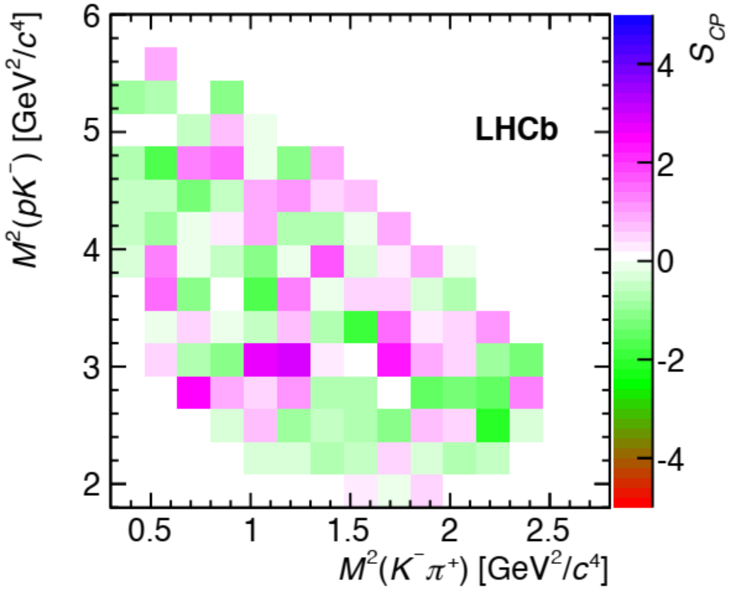
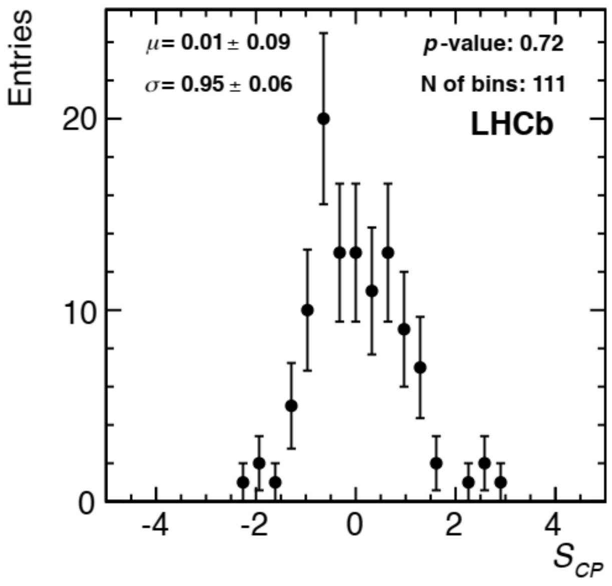
A_{CP} in $\Xi_c^+ \to p K^- \pi^+$

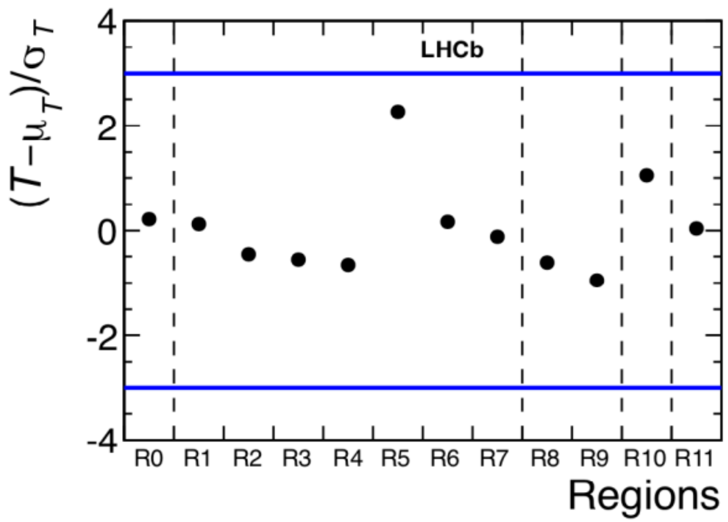


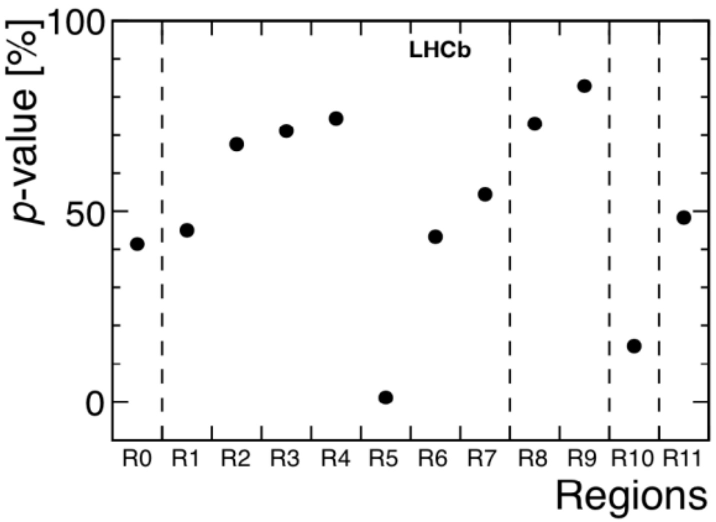


$$S_{CP}^i = \frac{n_+^i - \alpha n_-^i}{\sqrt{\alpha(n_+^i + n_-^i)}}, \quad \alpha = \frac{n_+^i}{n_-^i}$$

large
p-values

No evidence of CP violation





$$T = \frac{1}{n_k(n_+ + n_-)} \sum_{i=1}^{n_+ + n_-} \sum_{k=1}^{n_k} I(i,k)$$

Overview of rare charm decays @ LHCb

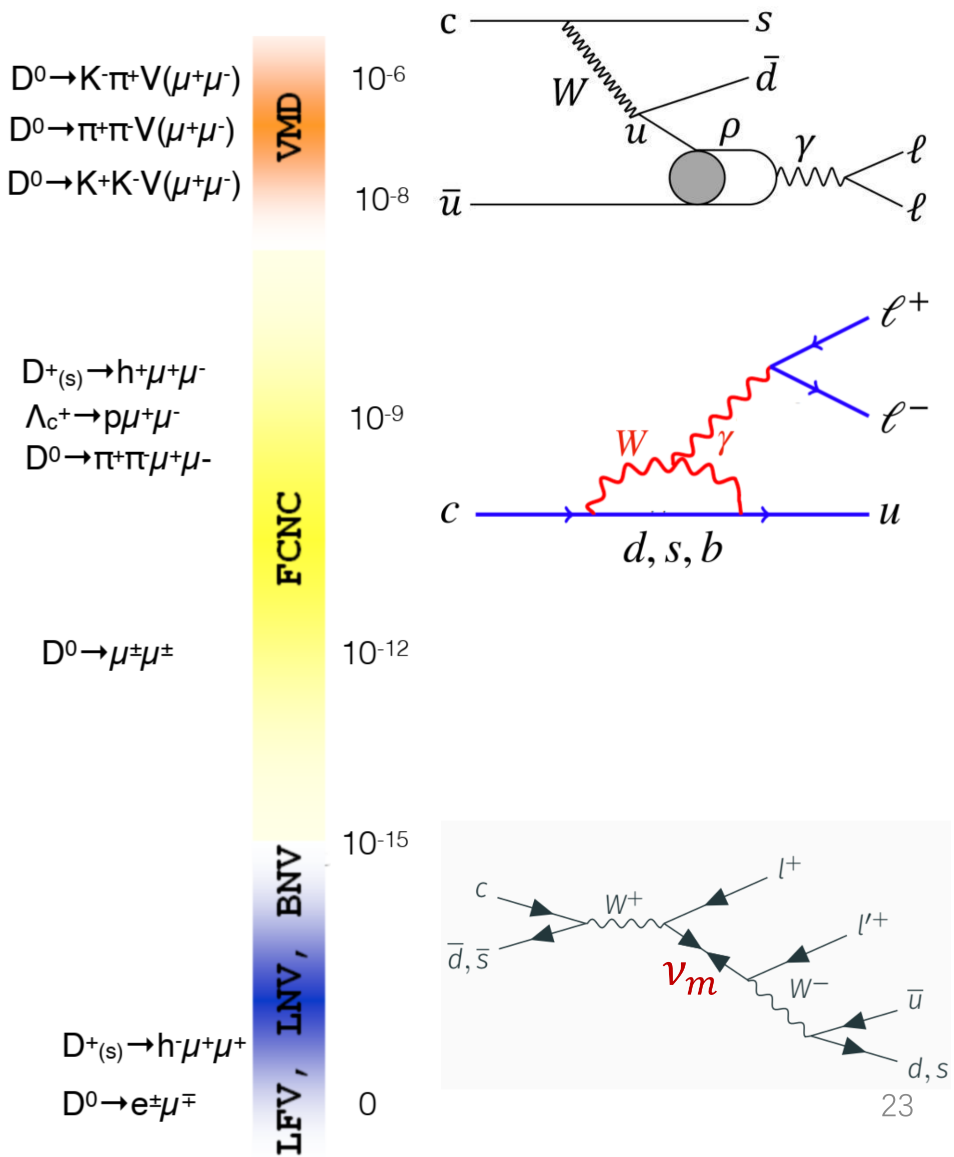
branching ratios, especially regions away from the resonances

- search for $D^0 \to \mu^+\mu^-$ [PLB 725 15-24 (2013)]
- 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]



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

- 25 decays

  LFV & LNV included

- Normalized with $D^+_{(s)} \to \phi(\ell\ell)\pi^+$
- Analysis based on 2016 dataset (1.7 fb^{-1})

$D^+ \to \pi^+\mu^+\mu^-$
$D^+ \to \pi^-\mu^+\mu^+$
$D^+ \to \pi^+\mu^+e^-$
$D^+ \to \pi^-\mu^+e^+$
$D^+ \to \pi^+e^+\mu^-$

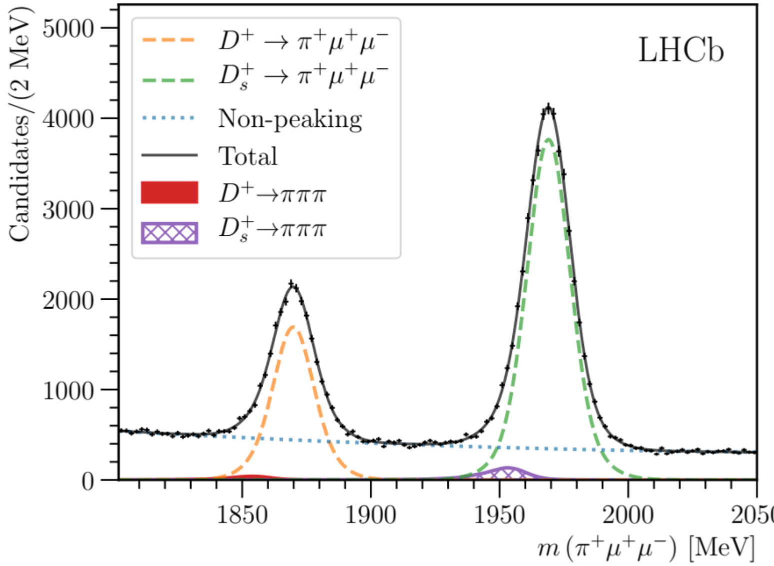
$D^+ \to \pi^+e^+e^-$
$D^+ \to \pi^-e^+e^+$
$D^+ \to K^+\mu^+\mu^-$
$D^+ \to K^+\mu^+e^-$
$D^+ \to K^+e^+\mu^-$

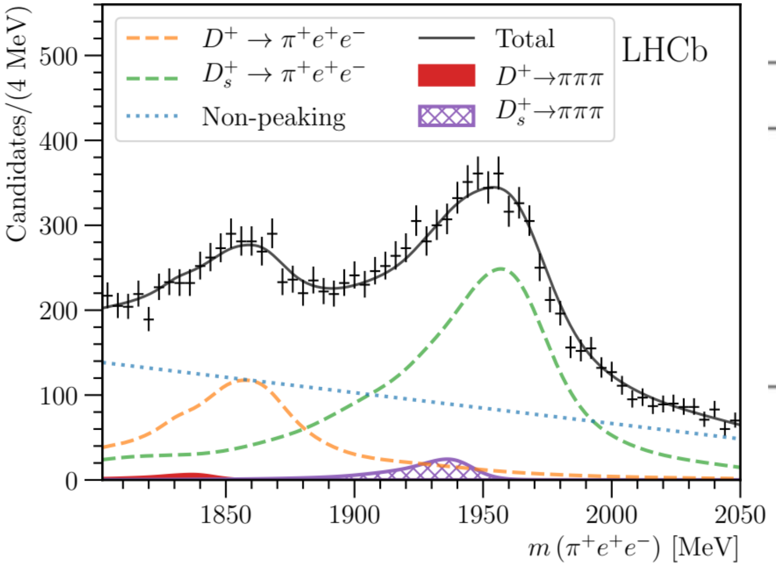
$D^+ \to K^+e^+e^-$
$D_s^+ \to \pi^+\mu^+\mu^-$
$D_s^+ \to \pi^-\mu^+\mu^+$
$D_s^+ \to \pi^+\mu^+e^-$
$D_s^+ \to \pi^-\mu^+e^+$

$D_s^+ \to \pi^+e^+\mu^-$
$D_s^+ \to \pi^+e^+e^-$
$D_s^+ \to \pi^-e^+e^+$
$D_s^+ \to K^+\mu^+\mu^-$
$D_s^+ \to K^-\mu^+\mu^+$

$D_s^+ \to K^+\mu^+e^-$
$D_s^+ \to K^-\mu^+e^+$
$D_s^+ \to K^+e^+\mu^-$
$D_s^+ \to K^+e^+e^-$
$D_s^+ \to K^-e^+e^+$

Allowed in the SM, Forbidden in the SM

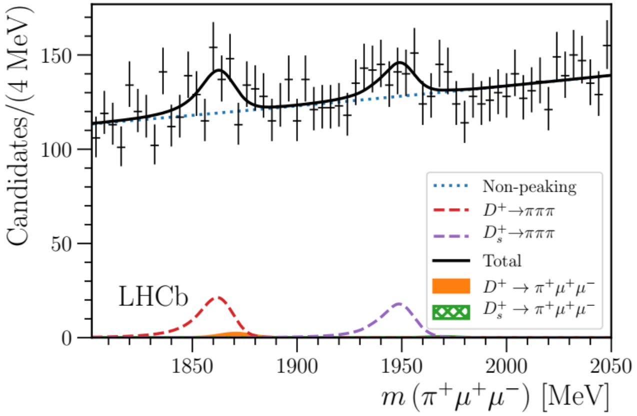


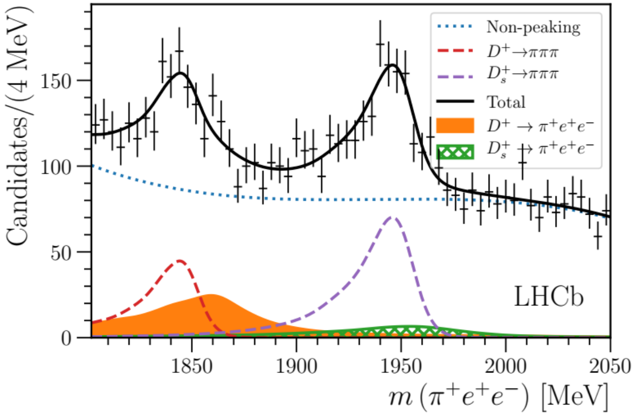


Channel	Fitted yield
$D^+ \to (\phi \to \mu^-\mu^+)\,\pi^+$	18 100±340
$D^+ \to (\phi \to e^-e^+)\,\pi^+$	2160±180
$D_s^+ \to (\phi \to \mu^-\mu^+)\,\pi^+$	42 000±400
$D_s^+ \to (\phi \to e^-e^+)\,\pi^+$	5320±180

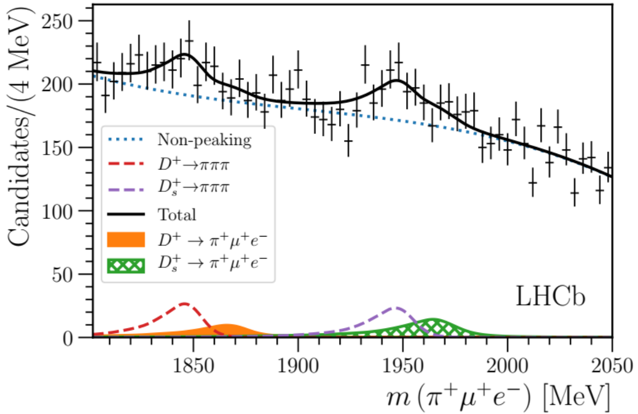
Search for $D_{(s)}^{+} \to h^{\pm}\ell^{+}\ell^{(\prime)\mp}$ decays

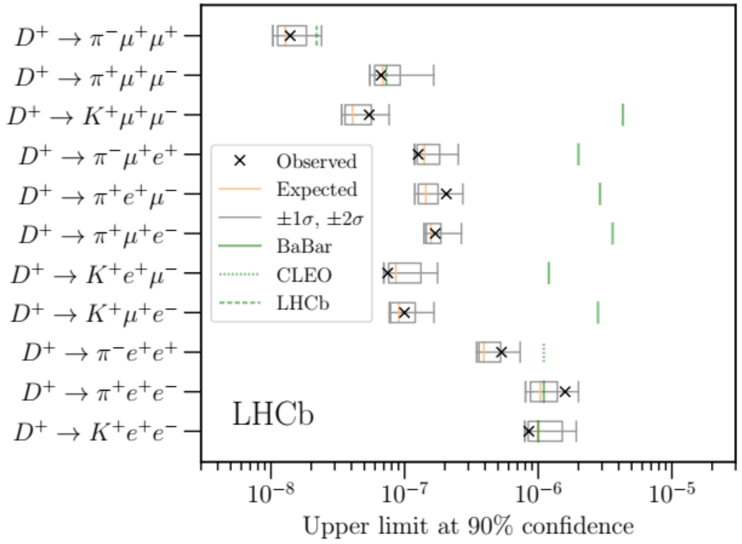
- No signal observed, BF limits are set down to $\mathcal{O}(10^{-8})$
- Results improve the prior world's best by up to a factor of **500**

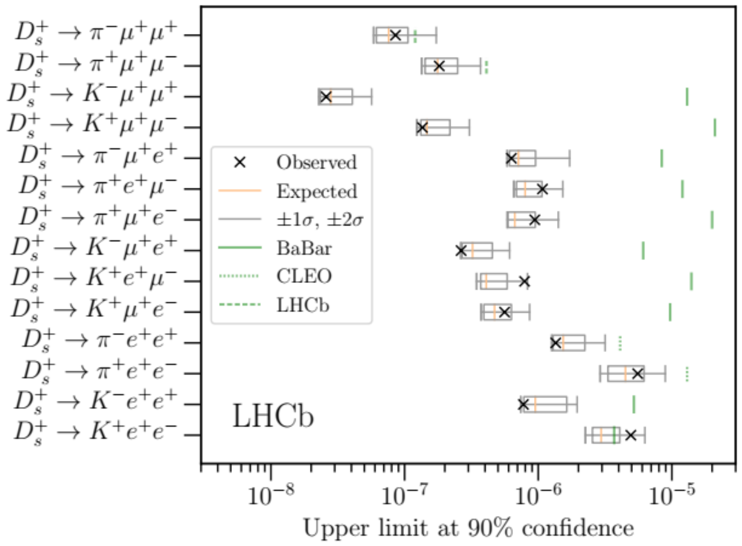




Regions dominated by resonances in dilepton mass spectrum are vetoed







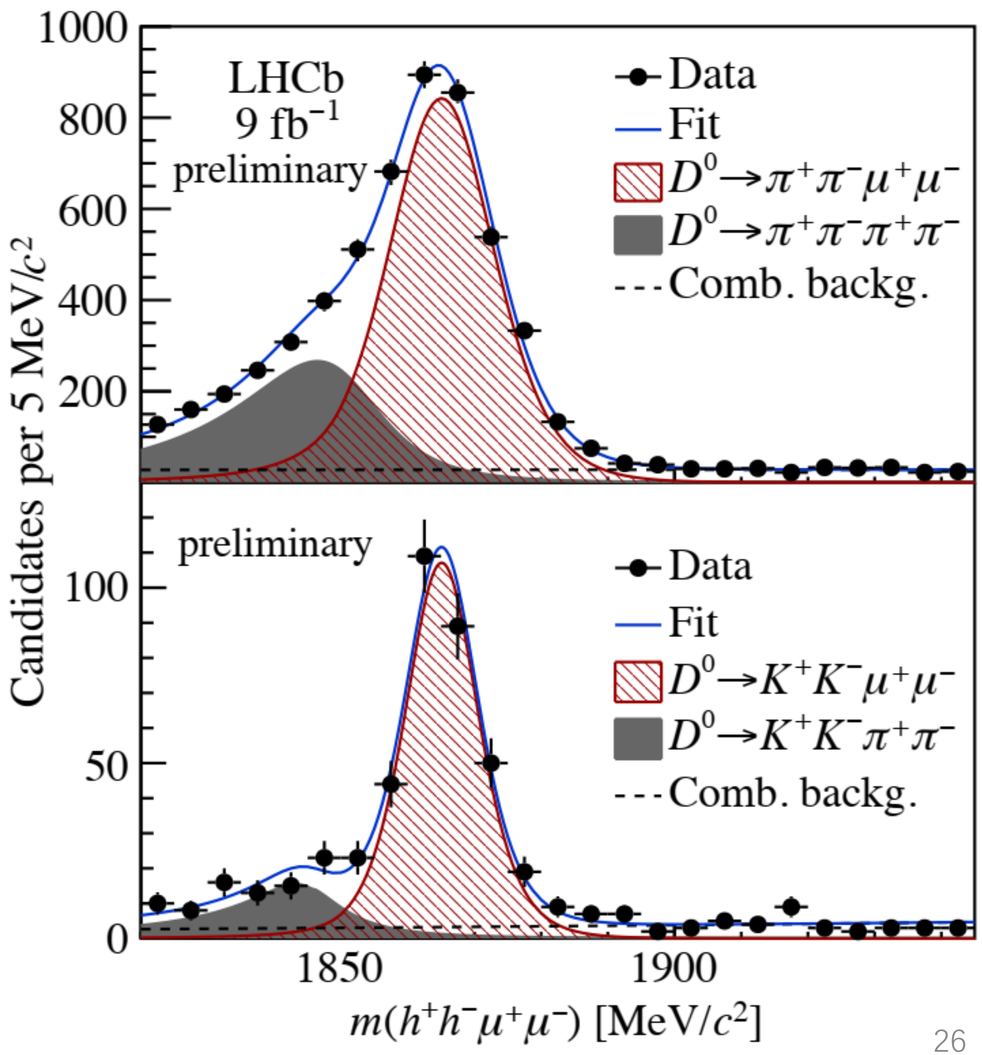
CPV and angular analysis in $D^0 \to hh\mu^+\mu^-$

- Rarest charm meson decays observed, dominated by resonant contributions

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

- First full angular analysis with 9 fb^{-1} data
- D^0 selected from flavor specific $D^{*+} \to D^0\pi^+$

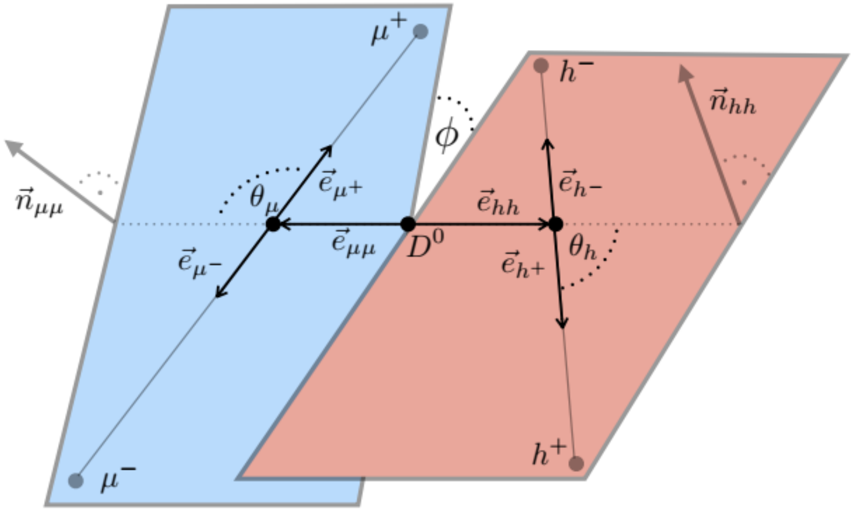
N($D^0 \to \pi^+\pi^-\mu^+\mu^-$) ~3500
N($D^0 \to K^+K^-\mu^+\mu^-$) ~ 300



Differential decay rate in $D^0 \to hh\mu^+\mu^-$

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

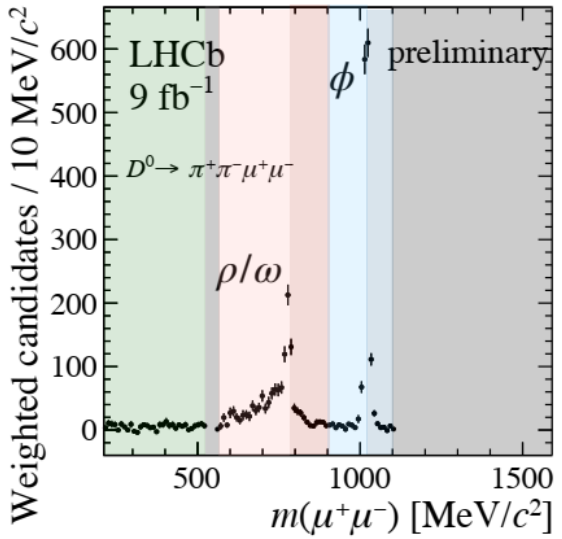
I_5, I_6, I_7 clean null tests!

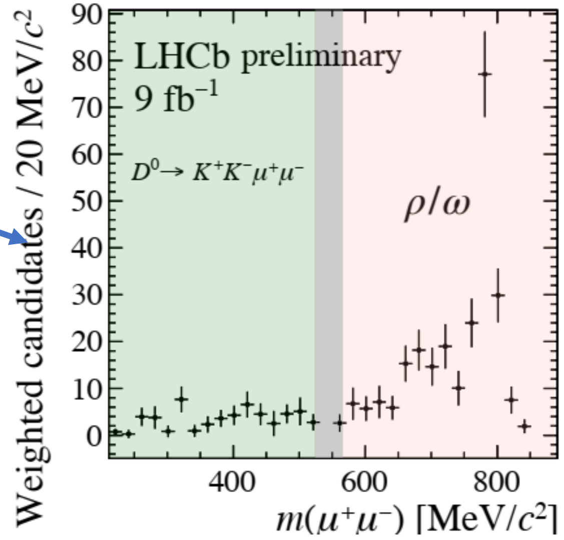


$p^2 = m^2(h^+h^-)$
$q^2 = m^2(\mu^+\mu^-)$

$I_{2,3,4,7}$ $I_{5,6,8,9}$

- Measure p^2, $\cos\theta_h$ integrated $\langle I_i \rangle$ separately for $D^0/\overline{D}^0$ in q^2 bins





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

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

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

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

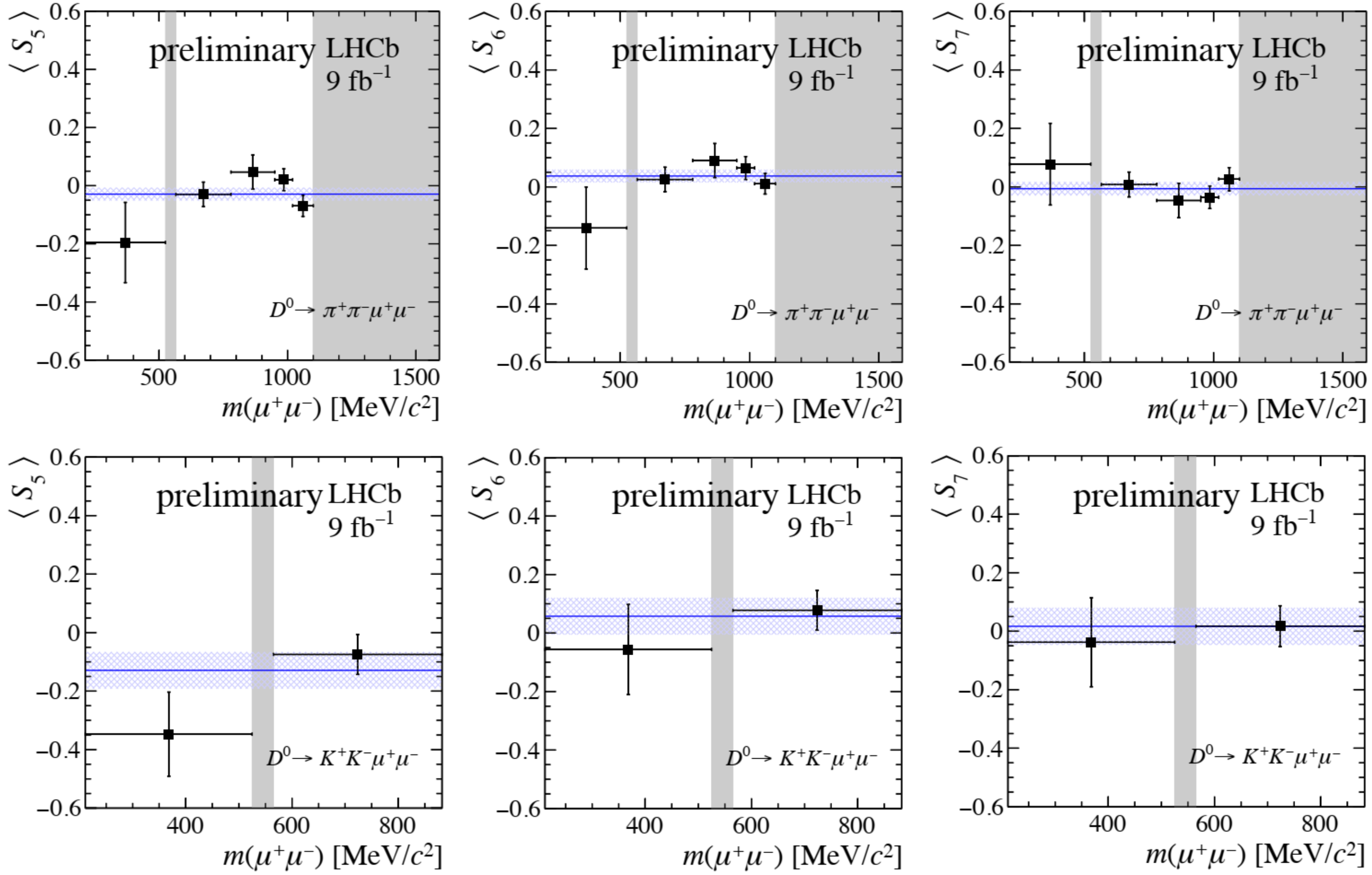
i=2,..,9

for CP even (CP odd) coefficients

arXiv:2111.03327

Flavor-averaged observables $\langle S_i \rangle$

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



$$\langle S_i \rangle = \frac{1}{2}\left[\langle I_i \rangle + (-)\langle \overline{I}_i \rangle\right]$$

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

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

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

Angular observables measured via yield asymmetries

agreement with SM predictions

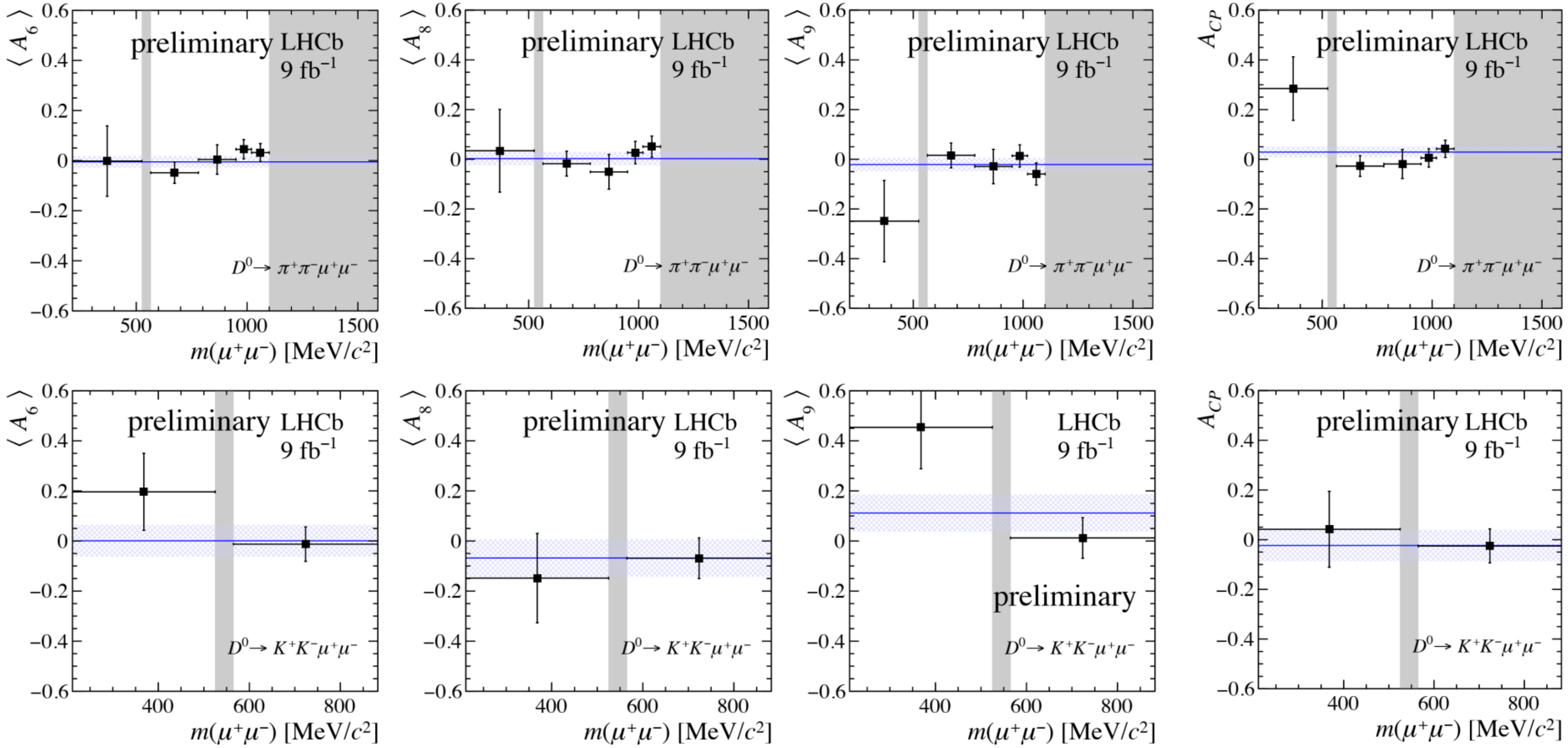
[JHEP 04 135 (2013), PRD 98, 035041(2018)] arXiv:2111.03327

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

CP asymmetries $\langle A_i \rangle$

From D. Mitzel's talk @ 11th workshop on "Implications of LHCb measurements and future prospects"

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



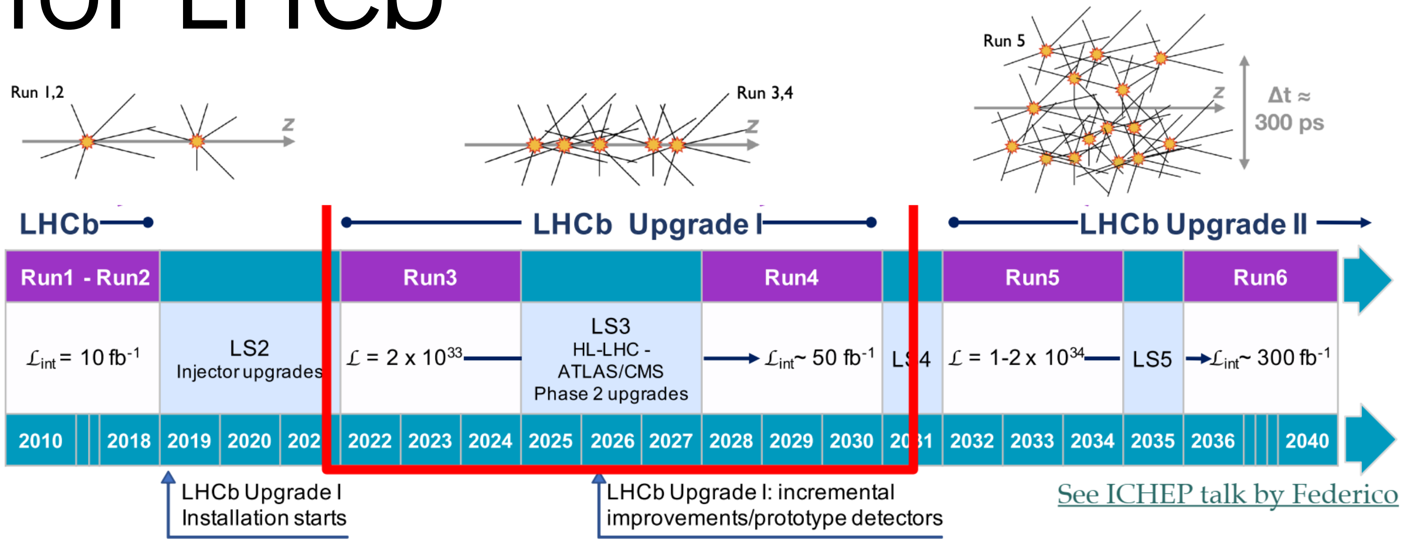
- overall agreement wrt. to SM hypothesis considering A_{CP}, $\langle A_{2-9} \rangle$ & $\langle S_{5,6,7} \rangle$:

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

consistent with SM

Run3 and beyond for LHCb

- A new LHCb detector for Run3 with much higher instantaneous luminosity
- Real time trigger with GPUs
- Goals for Runs 3-4: collect 10x in hadronic channels
- Reaching for sub-10^{-4} precision



See ICHEP talk by Federico

Ready for HL-LHC

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 ($D^0 \to K^0_S \pi^+\pi^-$)	18×10^{-5} [37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}

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 decays ($D^0 \to h(hh)l\nu$), CF charm decays involving a K_S, charm baryons, ...
- Longer term: LHCb will start taking data next year
- Synergy with BESIII important for CPV searches in the charm sector

Backup Slides

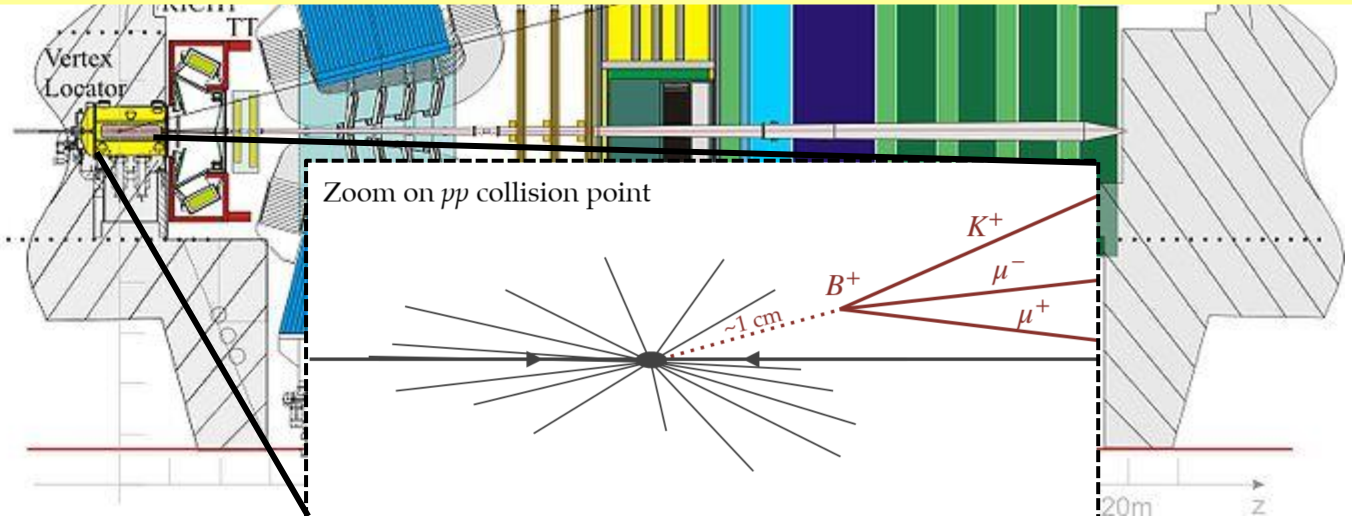
LHCb detector in a nutshell

By design: study CP-violating processes and rare b-hadron decays

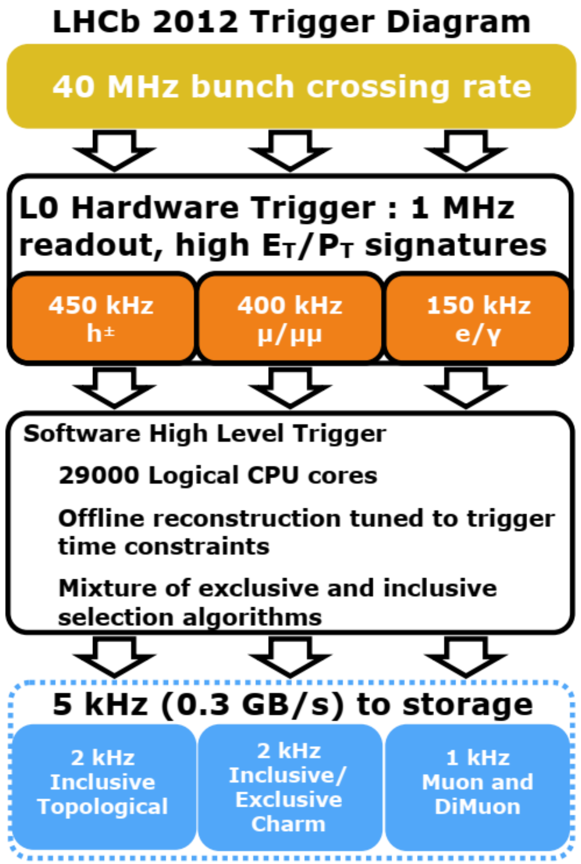
- Particle detection in the forward region (down to the beam-pipe)
- Excellent resolution for localization of decay vertices (Vertex Locator) → Excellent time resolution, enough to resolve $B_s - B_s$ oscillation
- Excellent momentum resolution ($\sigma(m_B)$~25 MeV for 2-body decays)
- Excellent particle identification to distinguish p, $K^\pm$, $\pi^\pm$, $\mu^\pm$
- Excellent leptonic and hadronic triggers

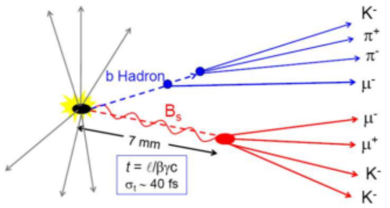
m the large $b\bar{b}$ and
ons and from the
tion at high
y
$) = 144 \pm 1 \pm 21\,\mu\text{b}$
the LHCb acceptance
$\Rightarrow\sim$ 25% of the total inside LHCb
[Phys.Rev.Lett. 118, 052002]

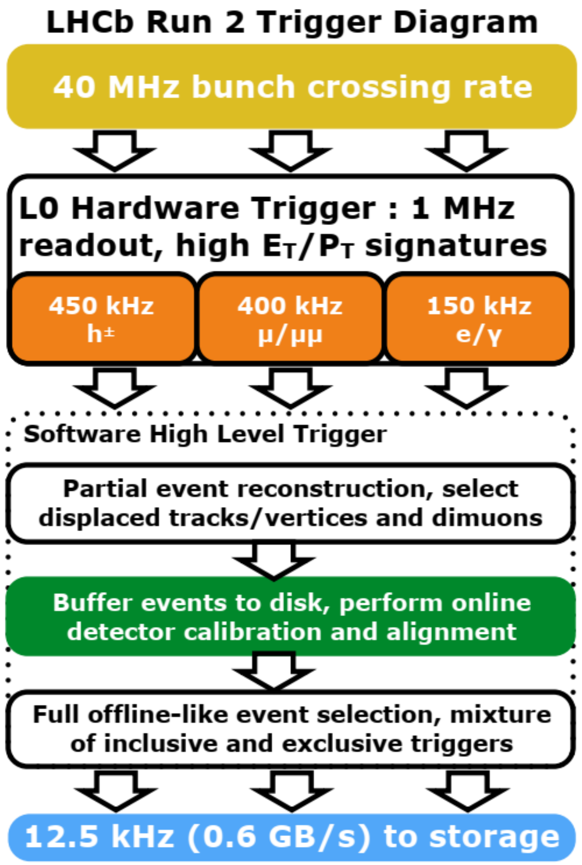
- $\sigma(pp \to c\bar{c}X) \sim 2.5$ mb $\Rightarrow$ 1 MHz $c\bar{c}$ pairs in the LHCb acceptance [JHEP 05 (2017) 074]



LHCb trigger scheme



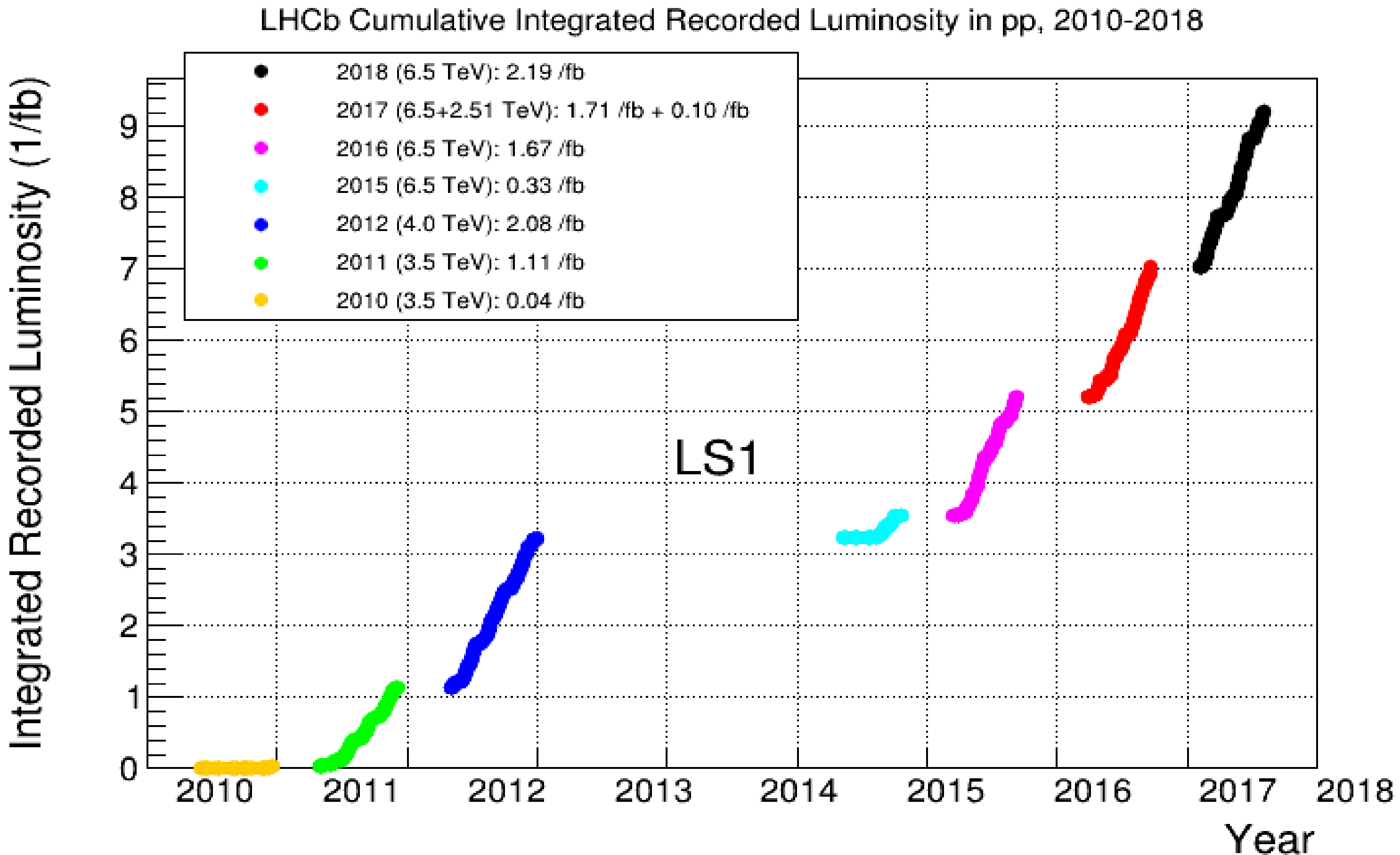




trigger efficiency: $\sim$ 90% on muons, $\sim$ 30% for multi-body hadronic final states

LHCb data samples

- **levelled** instantaneous luminosity of $\mathcal{L} = 4 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Run 1: $\sim 3\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 7\text{-}8\,\mathrm{TeV}$
- Run 2: $\sim 6\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$
- $\sigma(pp \to Q\bar{Q}X) \propto \sqrt{s} \Rightarrow$ 4x b- and c-hadrons in Run 2



From A. Carbone's talk @ CHARM 2021

Current experimental status on SCS decays

Observable	Current precision $\times 10^4$	Experiments (ordered by precision)	Perspectives
$\Delta A_{CP}^{dir} = A_{CP}(KK) - A_{CP}(\pi\pi)$	-15.4 ± 2.9	LHCb, CDF, BaBar, Belle	Run1+Run2
$A_{CP}(D^0 \to K^- K^+)$	-9 ± 11	LHCb, CDF, Cleo, Focus, BaBar, Belle	update expected soon full Run1+Run2
$A_{CP}(D^0 \to \pi^- \pi^+)$	-1 ± 14	LHCb, CDF, Cleo, Focus, BaBar, Belle	update expected soon Run1+Run2
$A_{CP}(D^0 \to \pi^0 \pi^0)$	-3 ± 64	Cleo, Belle	
$A_{CP}(D^0 \to K_S^0 K_S^0)$	-150 ± 110	LHCb, Belle, Cleo	recently updated Run2
$A_{CP}(D^+ \to \pi^+ \pi^0)$	40 ± 80	LHCb, Belle, Cleo	recently updated Run2
$A_{CP}(D^+ \to K_S^0 K^+)$	1 ± 7	LHCb, Belle, BaBar	missing 30% of data Run2
$A_{CP}(D^+ \to \phi \pi^+)$	0.1 ± 5	LHCb, Belle, BaBar	missing 30% of data Run2
$A_{CP}(D_s^+ \to K_S^0 \pi^+)$	16 ± 18	LHCb, BaBar	missing 30% of data Run2
$A_{CP}(D_s^+ \to K^+ \pi^0)$	200 ± 300	LHCb, Belle, Cleo	recently updated

Prospects for rare charm sensitivity

Mode	Upgrade ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
$D^0 \to \mu^+\mu^-$	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}

Mode	Upgrade ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
$D^+ \to \pi^+\mu^+\mu^-$	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%

A. Contu, Towards the Ultimate Precision in Flavour Physics, Durham, United Kingdom, 2 - 4 Apr 2019