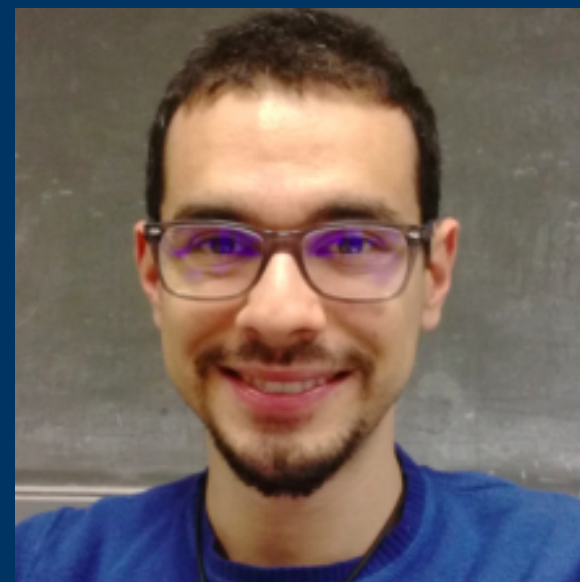


# Latest results on beauty and charm at LHCb



**Federico Betti on behalf  
of the LHCb collaboration**

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Congresso Nazionale SIF 2021

14 Settembre 2021



- $CP$  violation and mixing in  $D$  and  $B$  decays
- $\gamma$  + charm combination
- Rare decays
- Lepton flavour universality

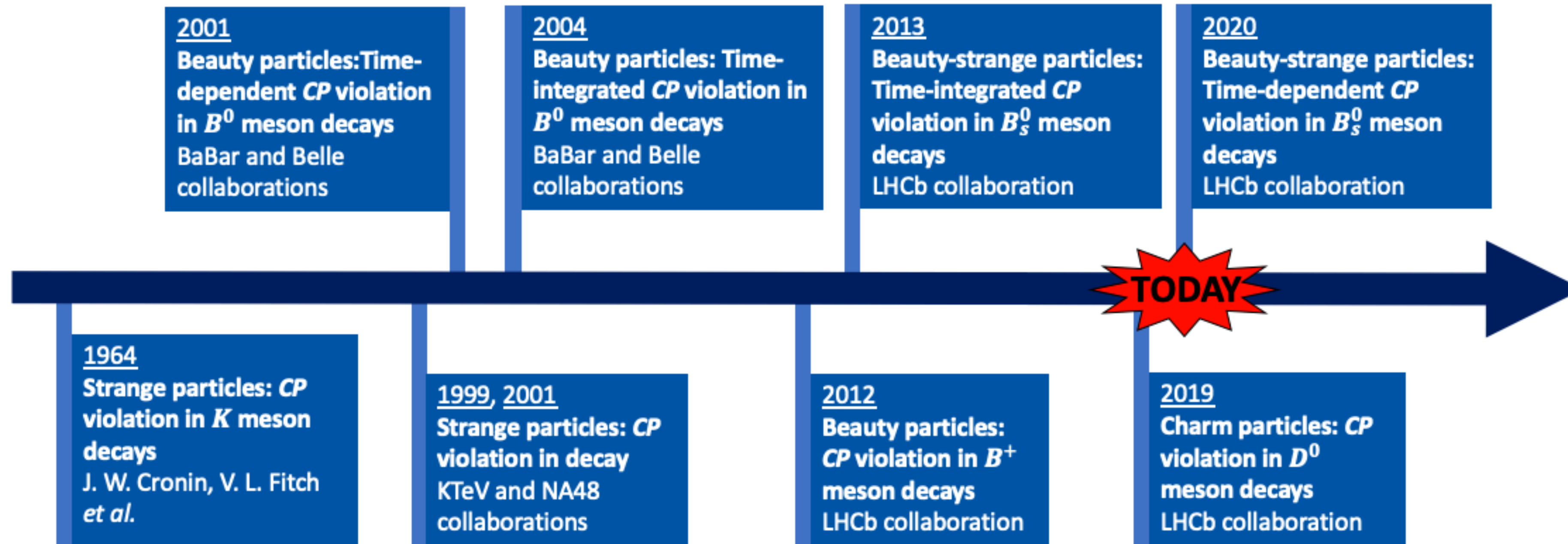
# *CP* violation and mixing in charm

$$A_{CP}(D \rightarrow f) = \frac{\Gamma(D \rightarrow f) - \Gamma(\bar{D} \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(\bar{D} \rightarrow \bar{f})}$$

- **Direct CP** violation when  $|A_f|^2 \neq |\bar{A}_{\bar{f}}|^2$
- For **oscillating** neutral mesons, mass eigenstates  $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$ 
  - **CP** violation in **mixing** when  $|q/p| \neq 1$
  - **CP** violation in decay-mixing **interference** when  $\phi_f \equiv \arg[(q\bar{A}_f)/(pA_f)] \neq 0$
- In charm decays:
  - Very difficult to compute  $A_{CP}$ , expected to be  $\mathcal{O}(10^{-4} - 10^{-3})$ , because of long-distance contributions
  - Mixing parameters are small,  $\mathcal{O}(10^{-3})$
- In beauty decays:
  - Predictions still affected by hadronic uncertainties, but they provide powerful **tests for SM**
  - $A_{CP}$  sensitive to **CKM angles**

$$i\frac{d}{dt} \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left( M - \frac{i}{2}\Gamma \right) \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

$$x \equiv \frac{2(m_1 - m_2)}{\Gamma_1 + \Gamma_2}, \quad y \equiv \frac{\Gamma_2 - \Gamma_1}{\Gamma_1 + \Gamma_2}, \quad \left| \frac{q}{p} \right| - 1$$

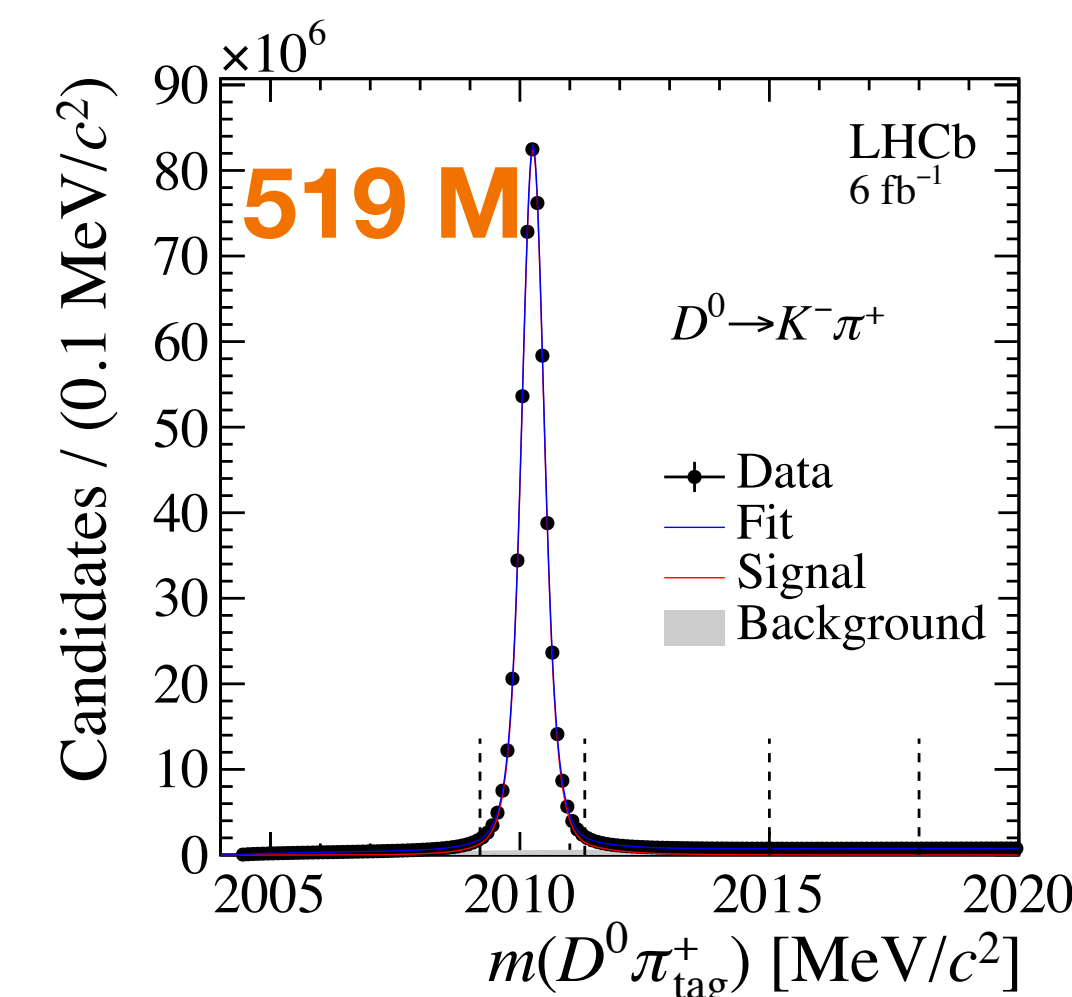
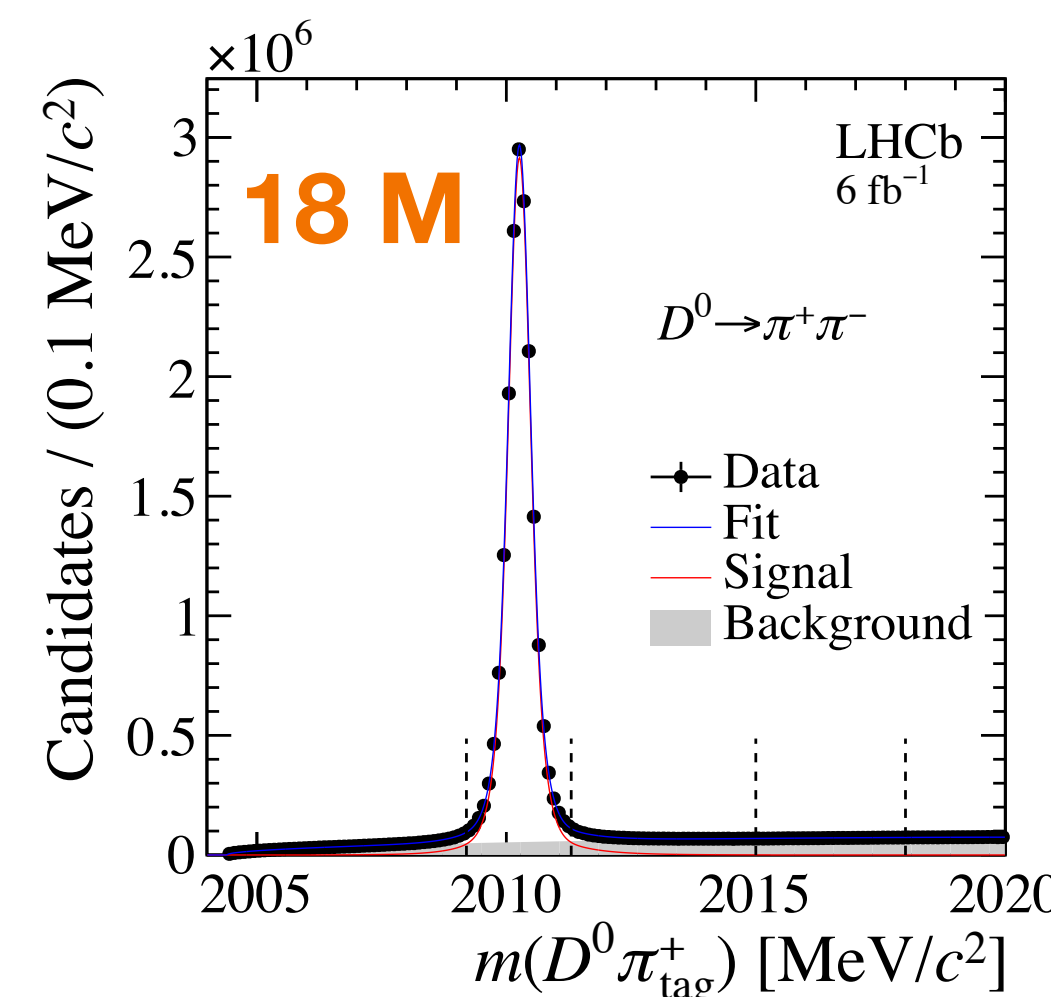
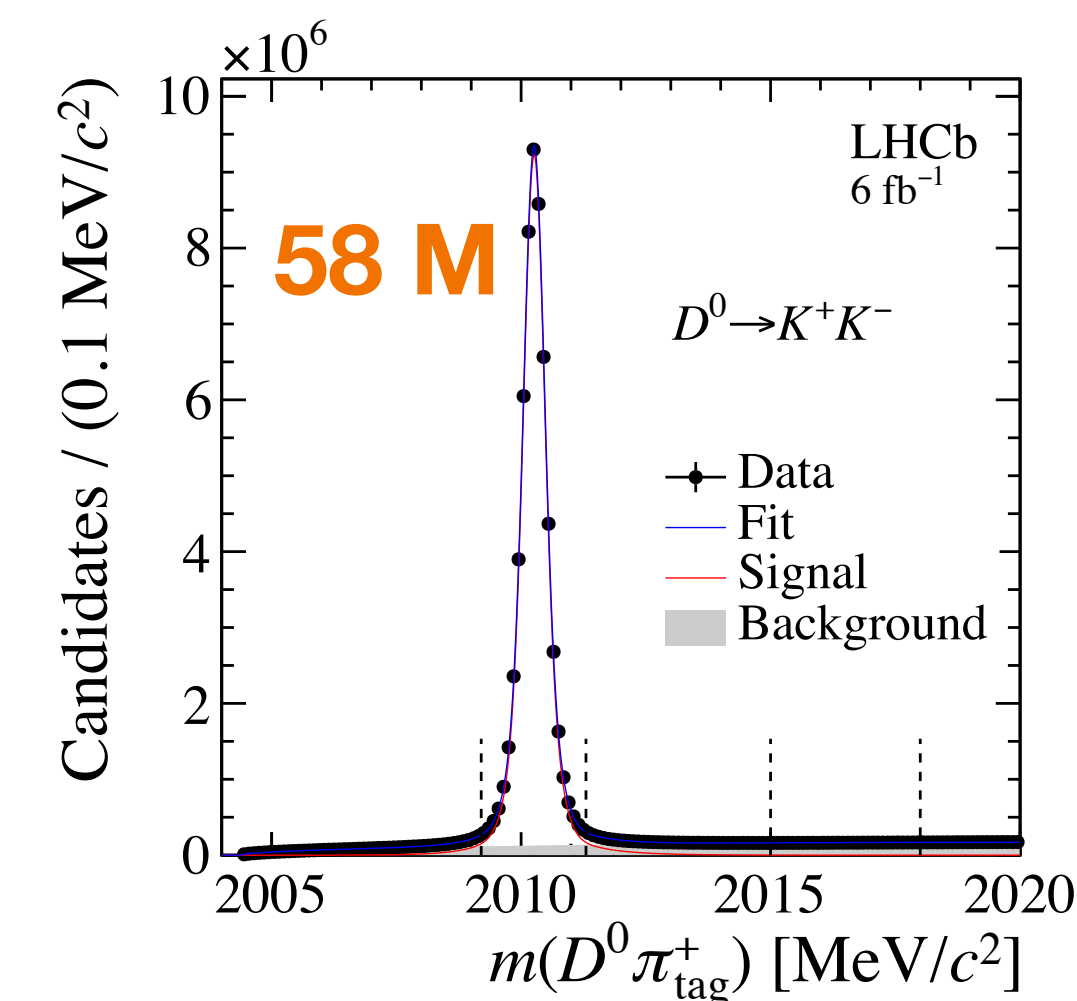


- Direct  $CP$  violation in **charm** observed for the first time by LHCb in 2019 using  $D^0 \rightarrow K^+K^-$  and  $D^0 \rightarrow \pi^+\pi^-$  decays PRL 122 (2019) 211803
  - Still looking for time-dependent  $CP$  violation
- $CP$  violation established in **beauty** sector

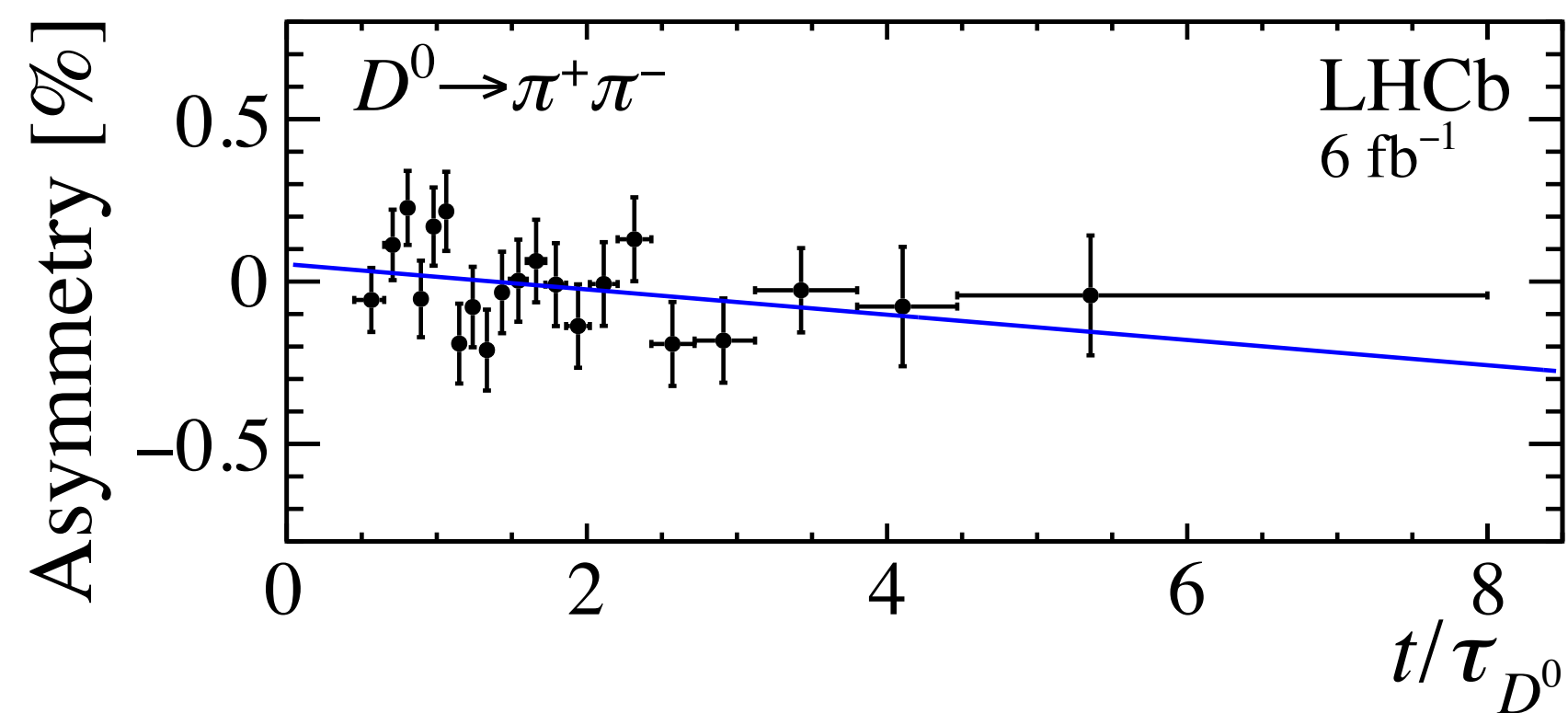
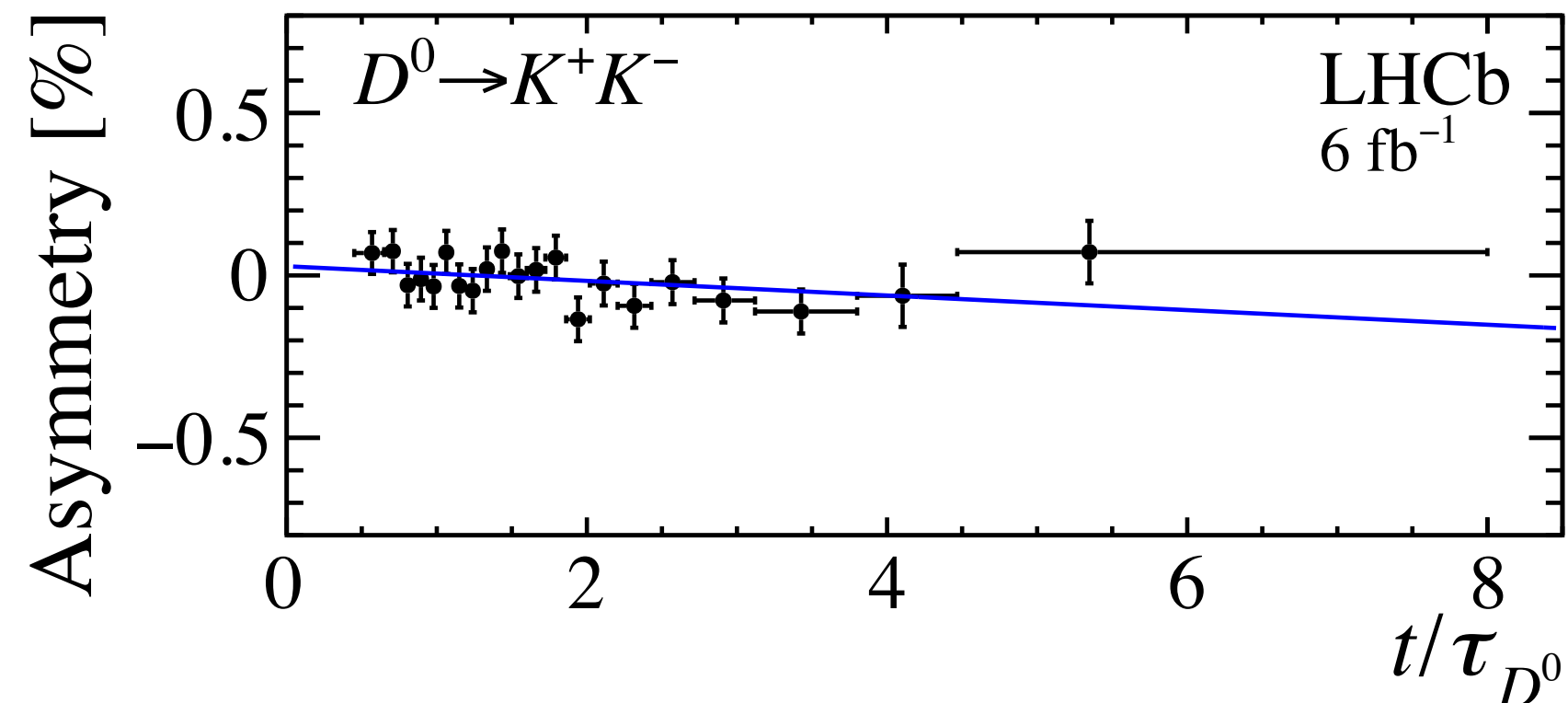
# $\Delta Y_f$ in $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$

$$A_{CP}(D^0 \rightarrow f, t) = A_{CP}^{\text{dir}}(D^0 \rightarrow f) + \Delta Y_f \frac{t}{\tau_{D^0}}$$

- SM expectation  $\sim 2 \times 10^{-5}$  PRD 103 (2021) 053008  
PLB 810 (2020) 135802
- Strategy: measure asymmetry in bins of  $D^0$  decay time and measure the linear **slope**
- Selection induces correlations between kinematics and decay time  $\Rightarrow$  possible time-dependent nuisance asymmetries are removed by **equalising  $D^0$  and  $\bar{D}^0$**  kinematics
- $D^0 \rightarrow K^- \pi^+$  is used as a control sample ( $\Delta Y_{K^- \pi^+} < 3 \times 10^{-5}$  from experimental results)



# $\Delta Y_f$ in $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$



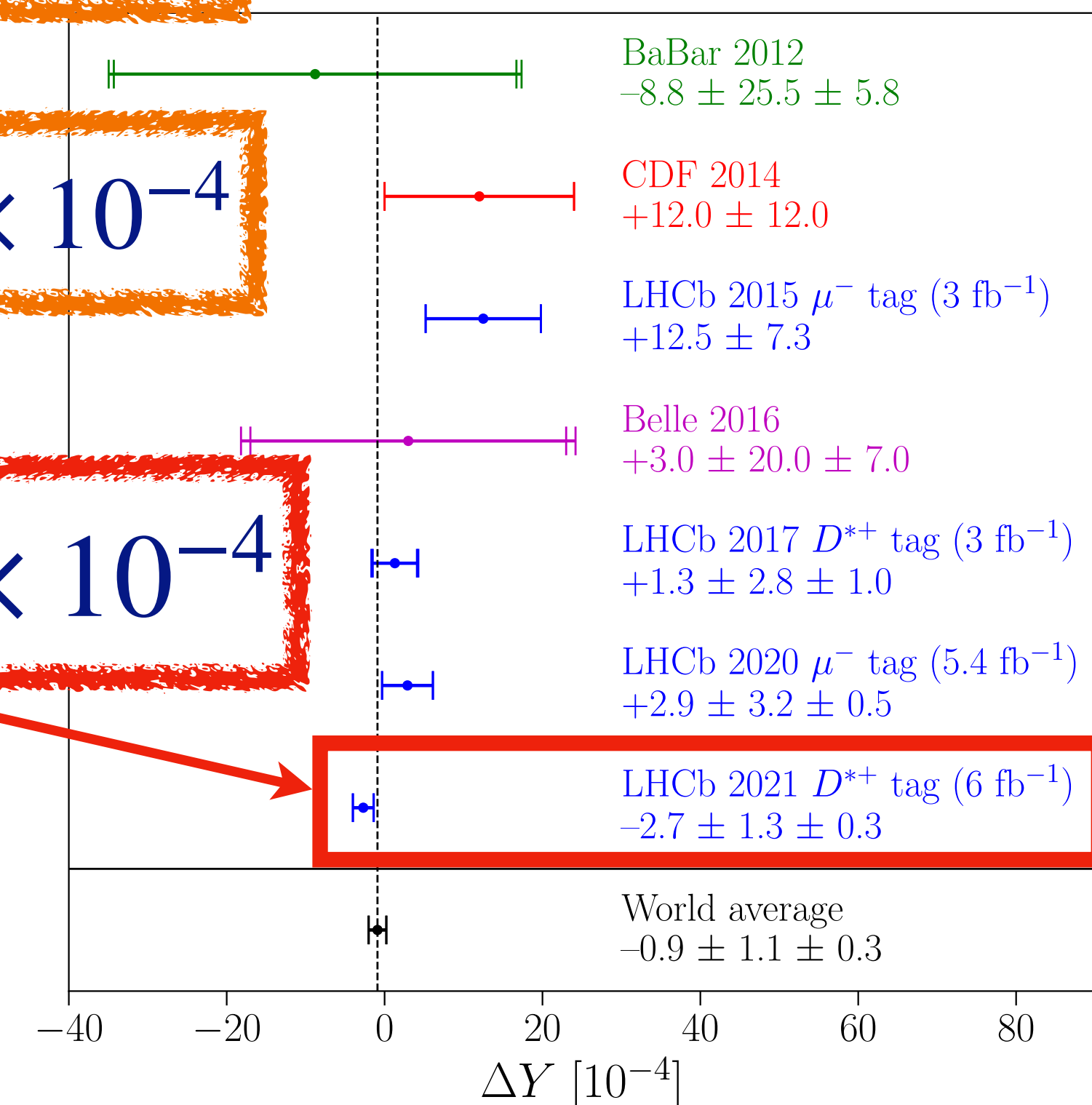
$$\Delta Y_{K^- \pi^+} = (-0.4 \pm 0.5 \pm 0.2) \times 10^{-4}$$

Result on control sample

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

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

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



- Compatible with 0 within  $2\sigma$
- This result improves by nearly a **factor 2** the precision of the previous world average

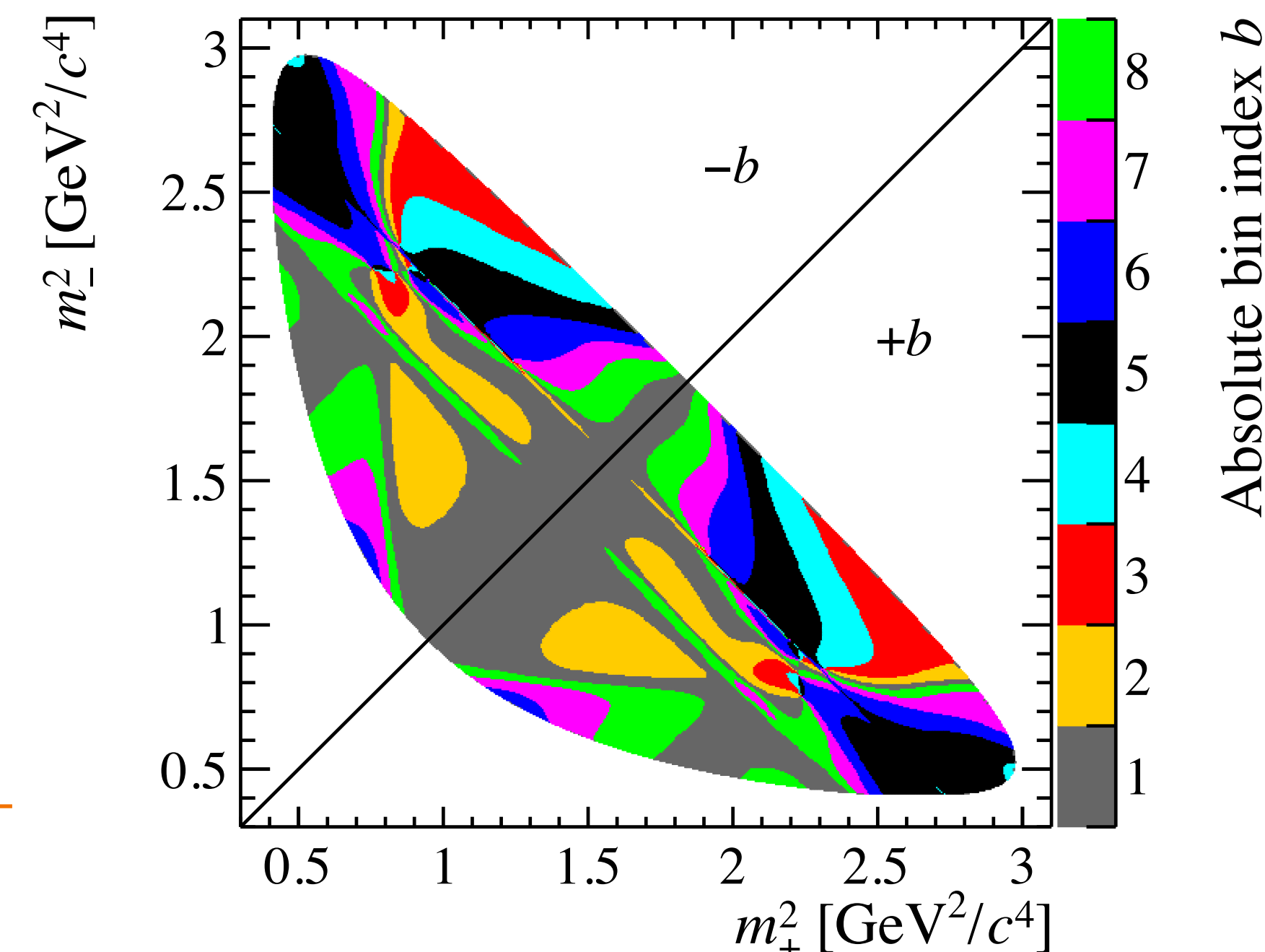
# $D^0$ mixing parameters with $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

- $D^0 \rightarrow K_S^0 \pi^+ \pi^-$  is particularly sensitive to  $x$   
PRD 99 (2019) 012007
- Analysis performed with model-independent *bin-flip* method, which does not require accurate modelling of the efficiency
- Measure, as a function of the  $D^0$  decay time, the *yield ratios* between symmetric bins in the Dalitz plot  $(m_+^2, m_-^2)$   
 ➔ they can be written as a function of  $x_{CP}$ ,  $y_{CP}$ ,  $\Delta x$  and  $\Delta y$

$$\begin{aligned}
 x_{CP} &= \frac{1}{2} \left[ x \cos \phi \left( \left| \frac{q}{p} \right| + \left| \frac{p}{q} \right| \right) + y \sin \phi \left( \left| \frac{q}{p} \right| - \left| \frac{p}{q} \right| \right) \right] \\
 \Delta x &= \frac{1}{2} \left[ x \cos \phi \left( \left| \frac{q}{p} \right| - \left| \frac{p}{q} \right| \right) + y \sin \phi \left( \left| \frac{q}{p} \right| + \left| \frac{p}{q} \right| \right) \right] \\
 y_{CP} &= \frac{1}{2} \left[ y \cos \phi \left( \left| \frac{q}{p} \right| + \left| \frac{p}{q} \right| \right) - x \sin \phi \left( \left| \frac{q}{p} \right| - \left| \frac{p}{q} \right| \right) \right] \\
 \Delta y &= \frac{1}{2} \left[ y \cos \phi \left( \left| \frac{q}{p} \right| - \left| \frac{p}{q} \right| \right) - x \sin \phi \left( \left| \frac{q}{p} \right| + \left| \frac{p}{q} \right| \right) \right]
 \end{aligned}$$

PRL 127 (2021) 111801

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



Almost **constant** strong-phase difference in each Dalitz bin ➔ external inputs from CLEO and BESIII

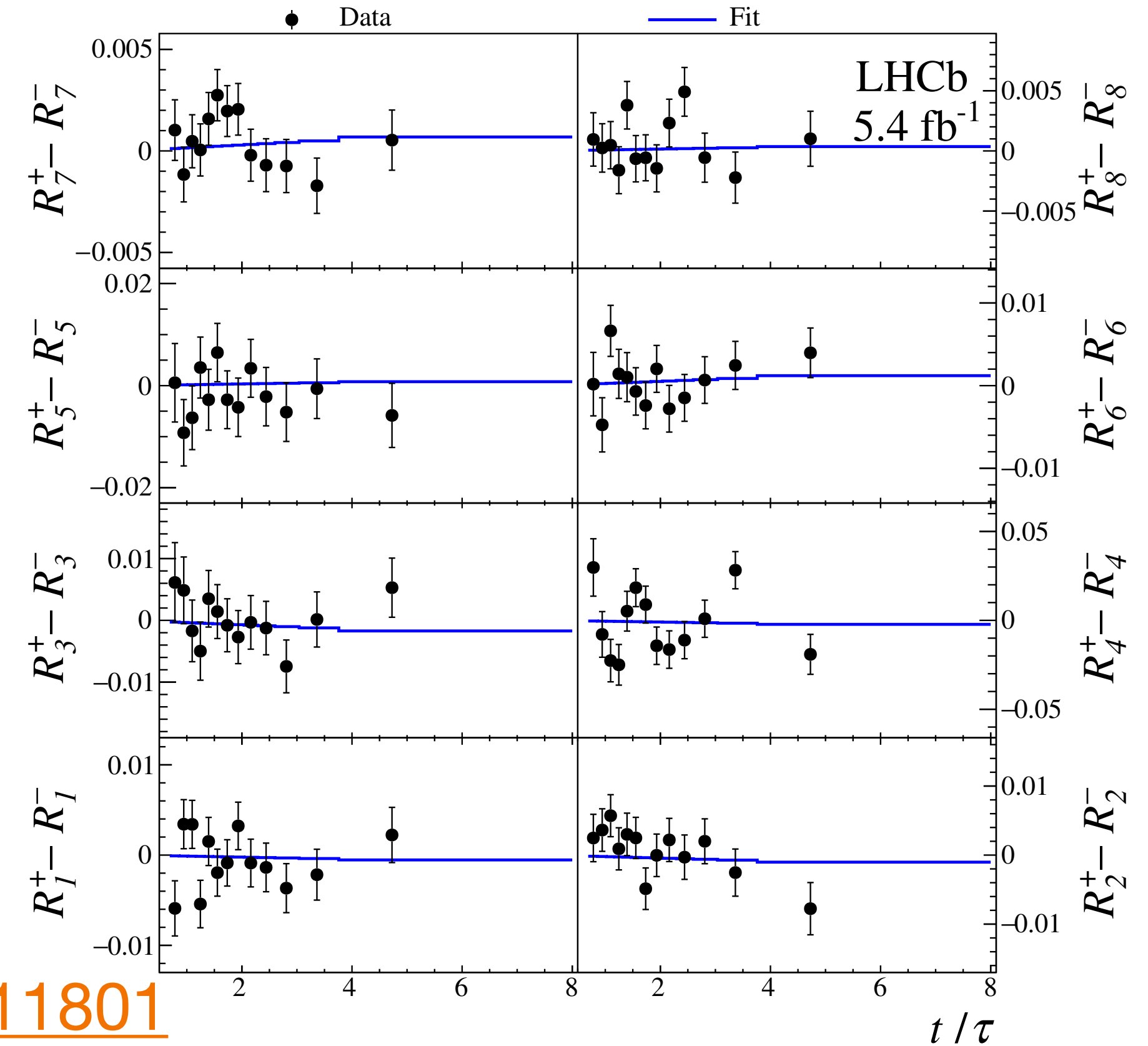
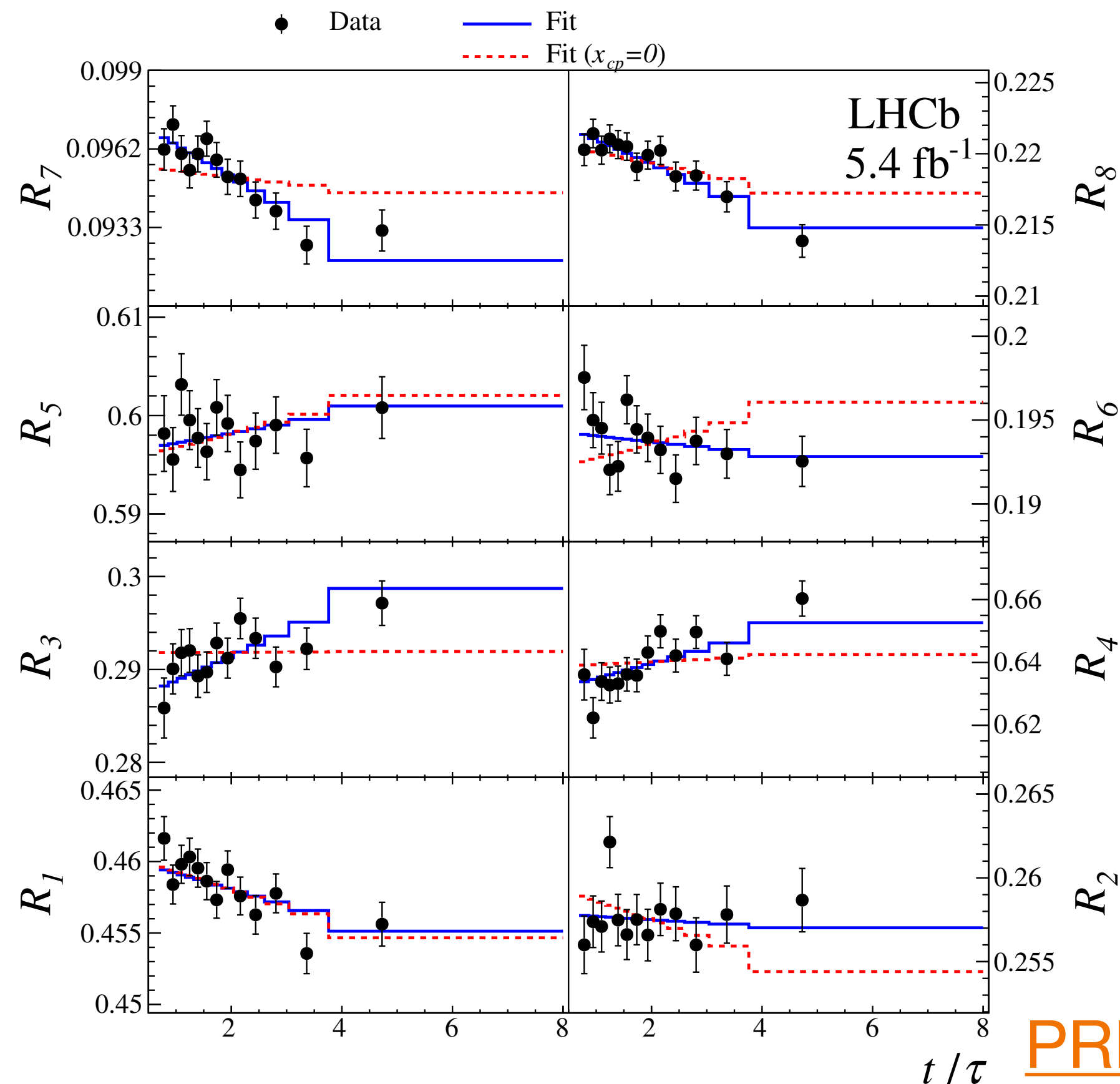
PRD 82 (2010) 112006  
PRD 101 (2020) 112002



# $D^0$ mixing parameters with $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

- $\mathcal{CP}$ -averaged ratios
- Deviations from constant values are due to **mixing**

- Differences of  $D^0$  and  $\bar{D}^0$  yield ratios
- Deviations from constant values are due to  $\mathcal{CP}$  violation



[PRL 127 \(2021\) 111801](#)

# $D^0$ mixing parameters with $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

$$\begin{aligned}x_{CP} &= (3.97 \pm 0.46 \pm 0.29) \times 10^{-3} \\y_{CP} &= (4.59 \pm 1.20 \pm 0.85) \times 10^{-3} \\ \Delta x &= (-0.27 \pm 0.18 \pm 0.01) \times 10^{-3} \\ \Delta y &= (0.20 \pm 0.36 \pm 0.13) \times 10^{-3}\end{aligned}$$



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

[PRL 127 \(2021\) 111801](#)

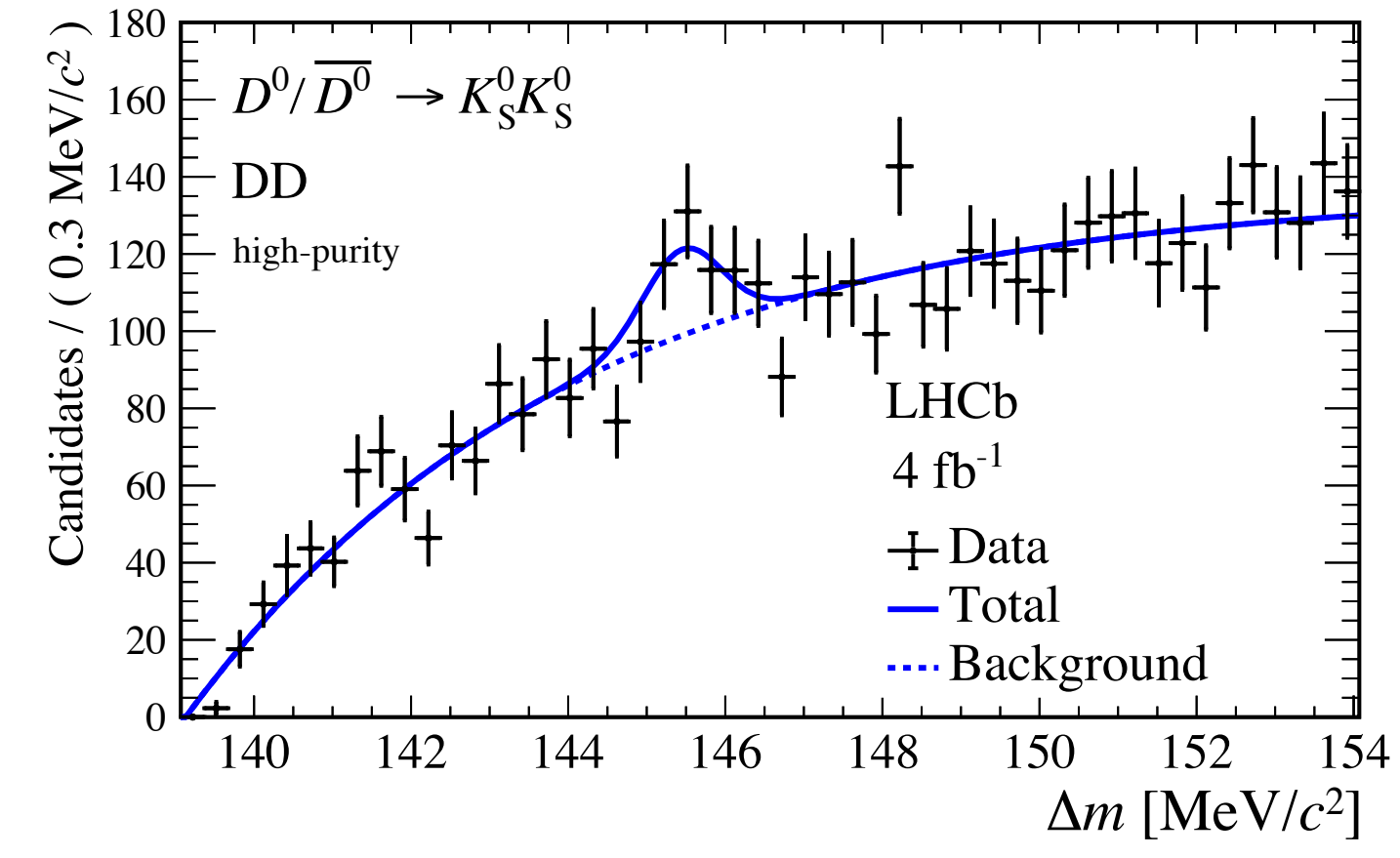
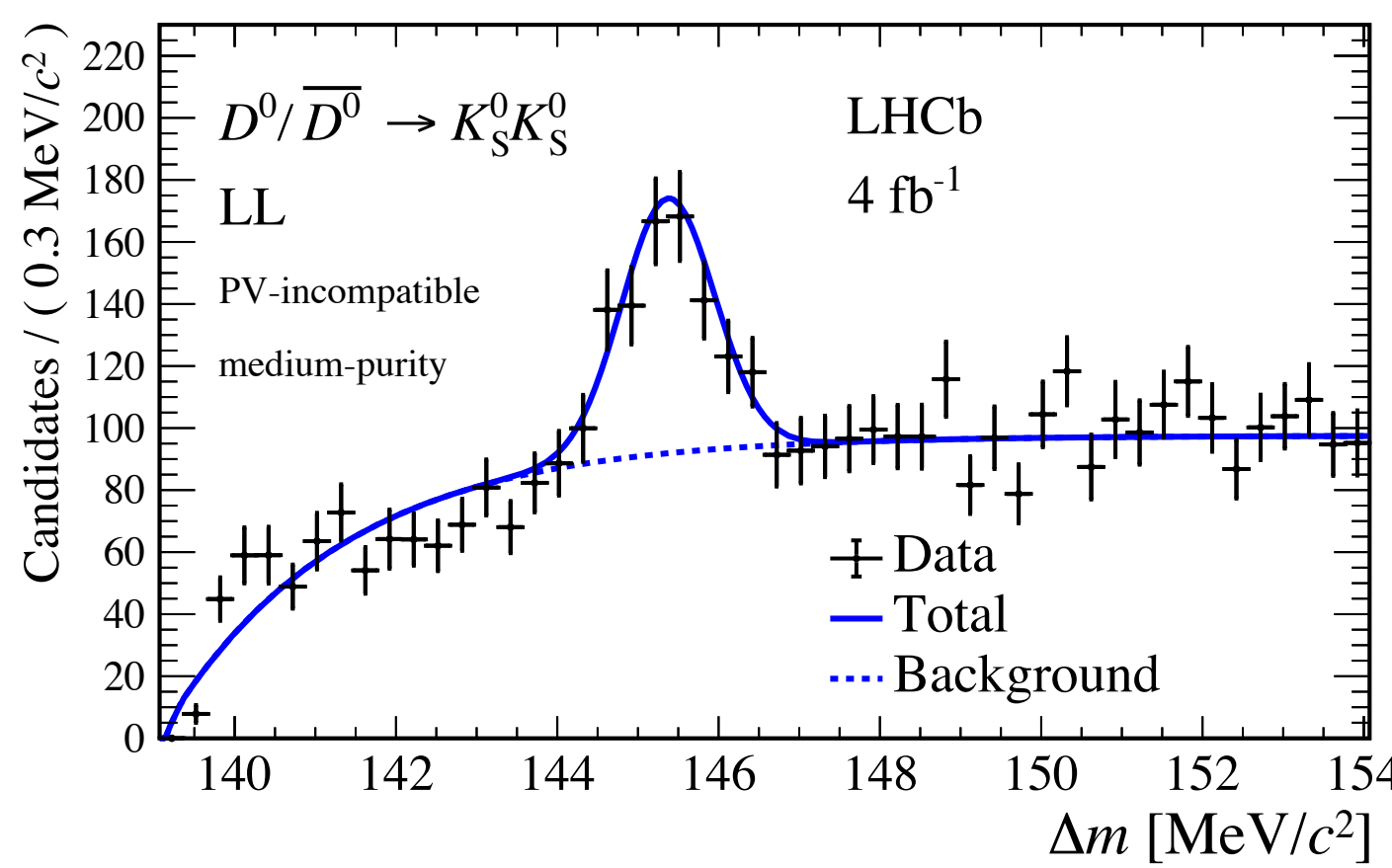
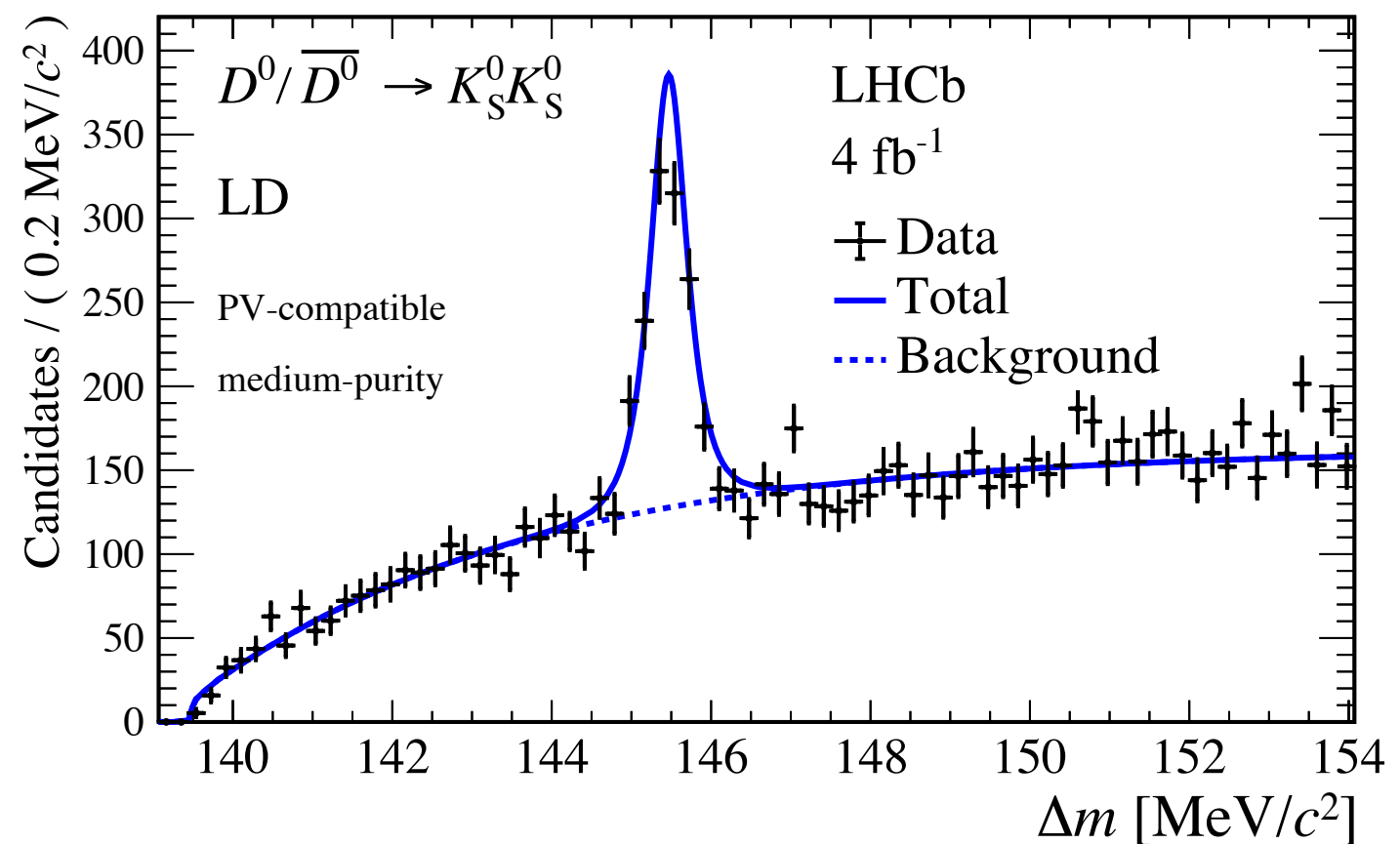
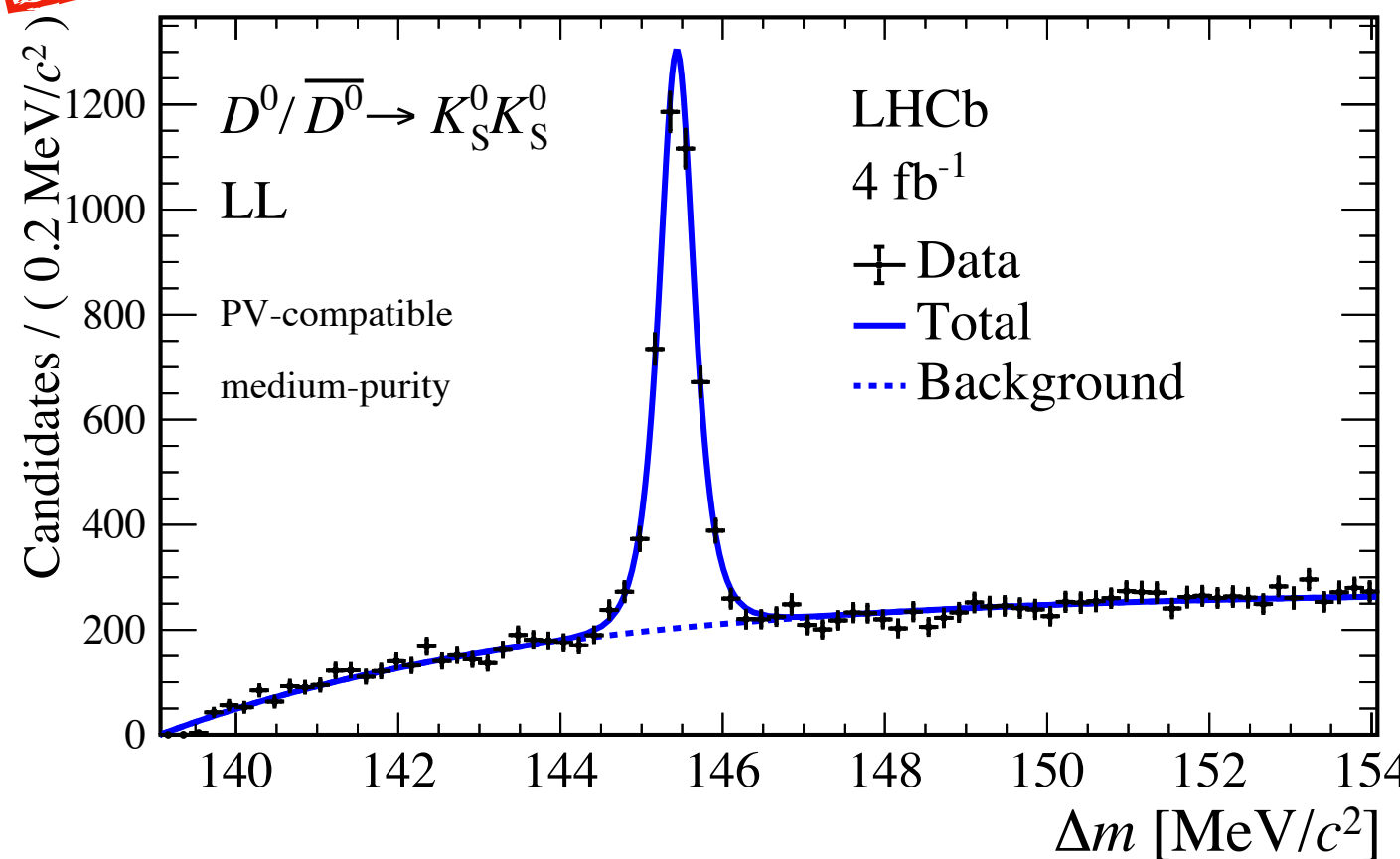
**First observation** with a significance of more than 7 standard deviations of the **mass difference** between  $D^0$  mass eigenstates

# $A_{CP}(D^0 \rightarrow K_S^0 K_S^0)$

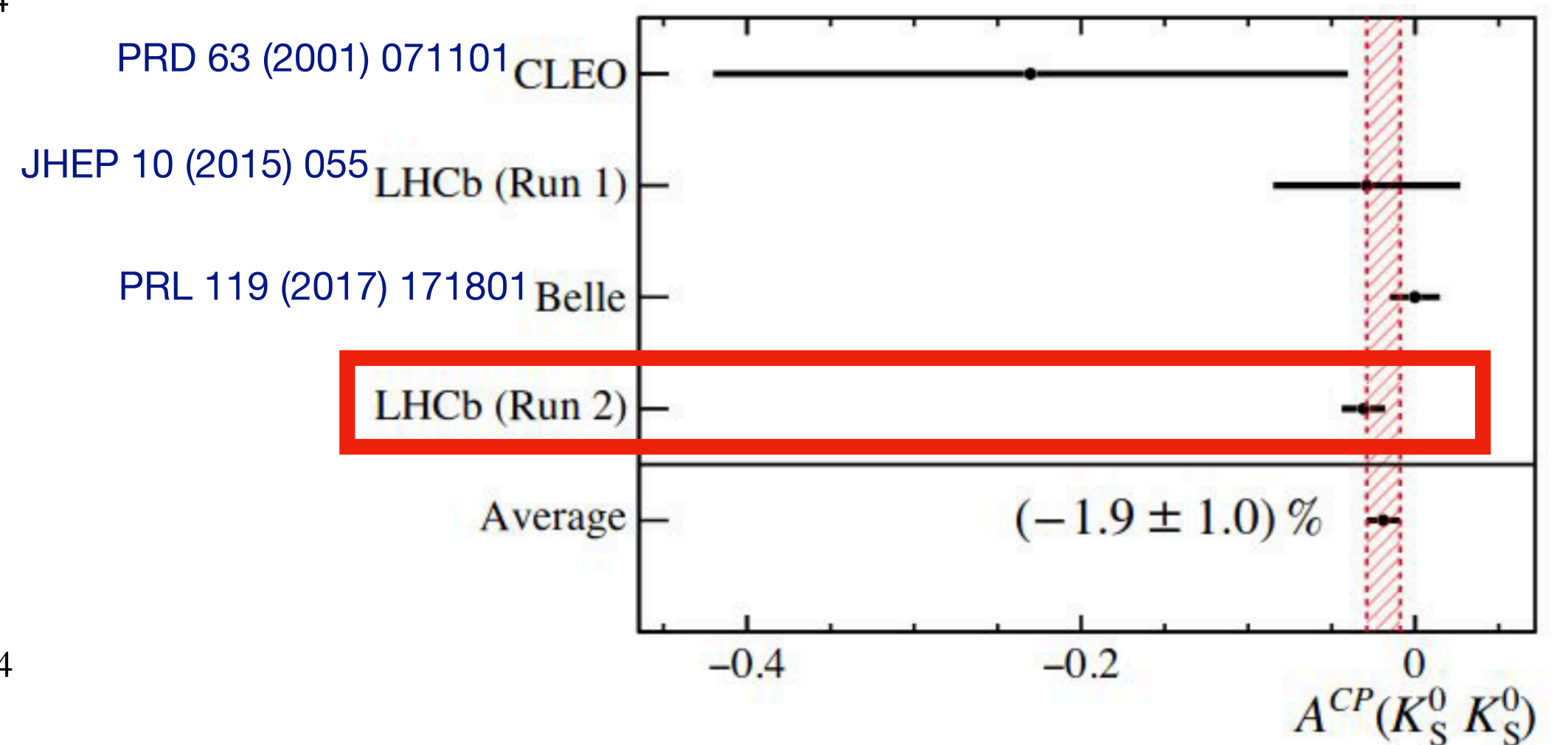
See talk by Lorenzo Pica

$$A_{CP} = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2) \%$$

PRD 104 (2021) L031102



- Consistent with no  $CP$  violation at  $2.4\sigma$
- Most precise measurement of this quantity to date

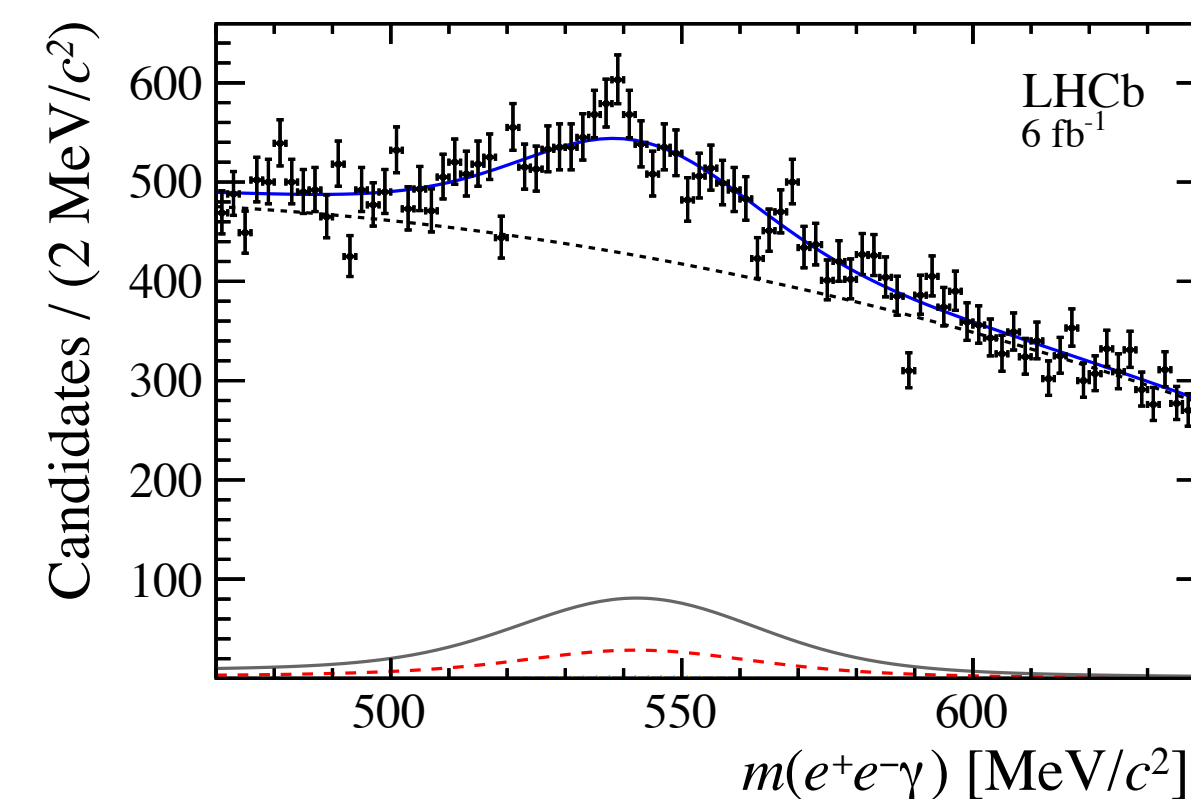
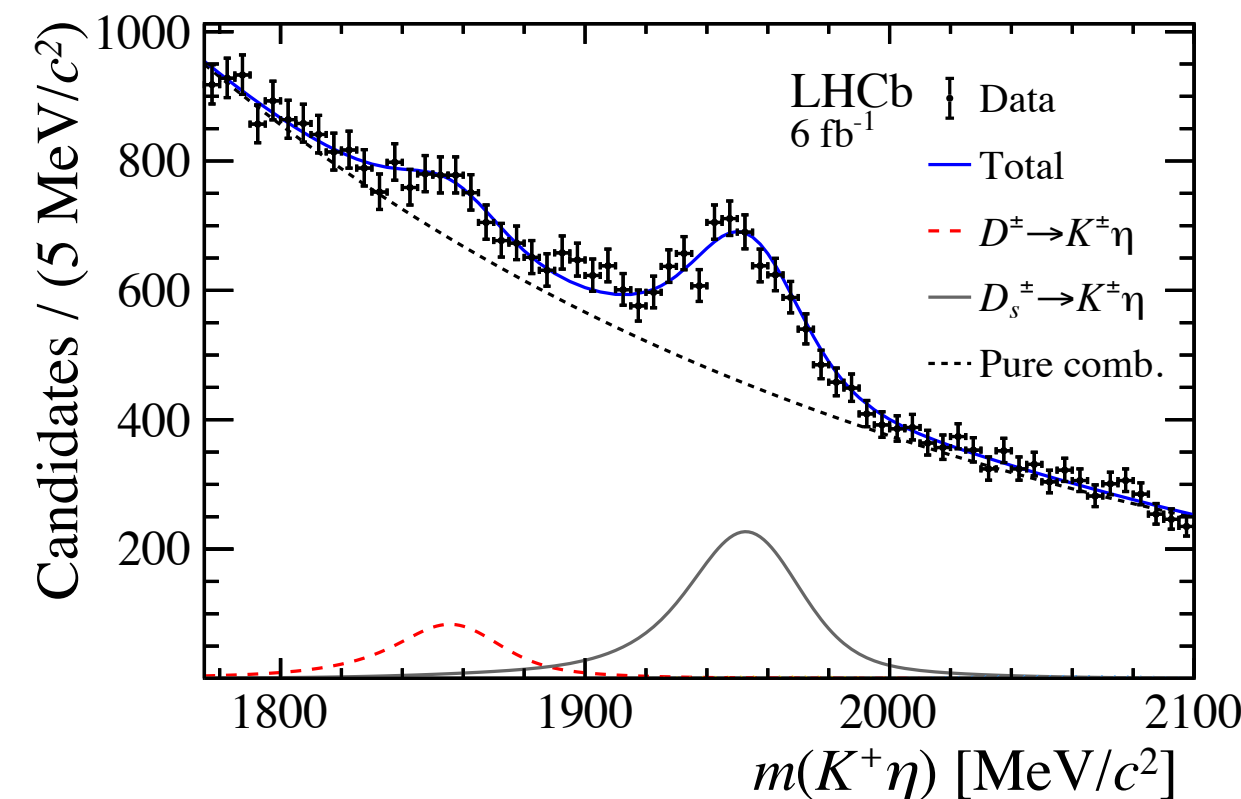
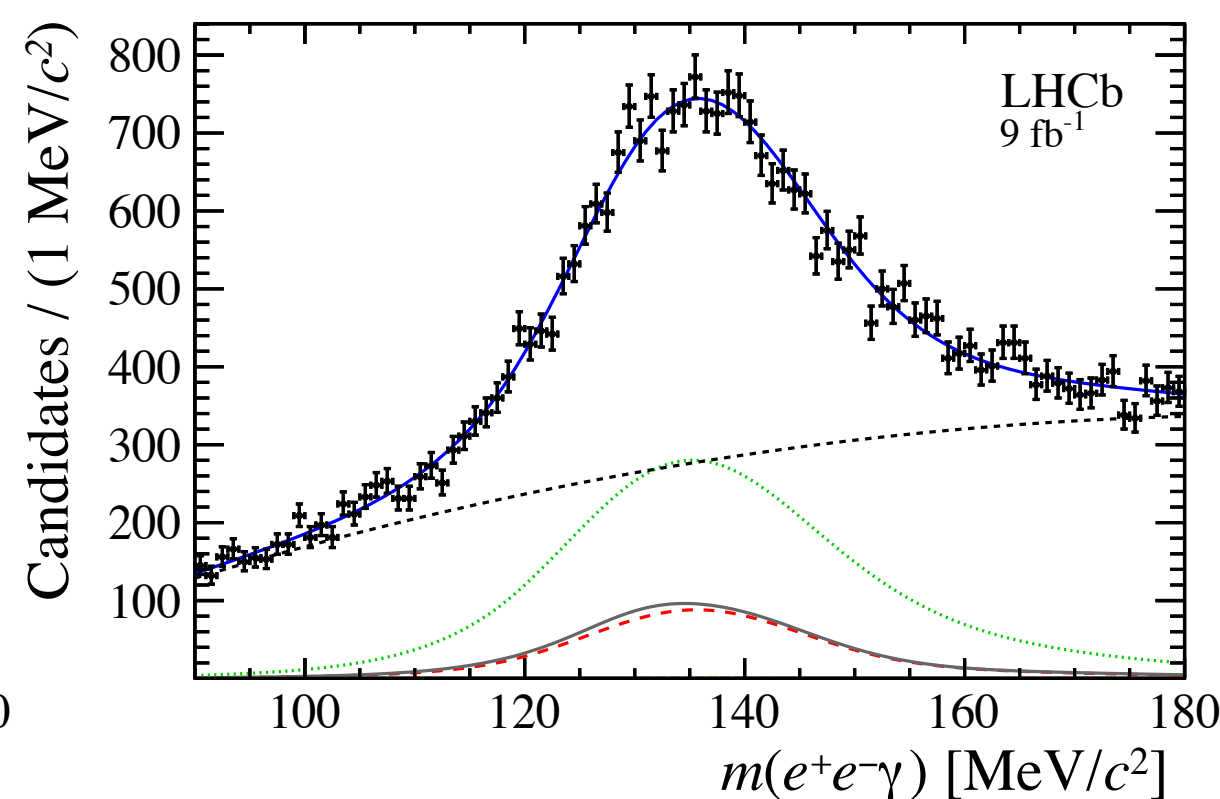
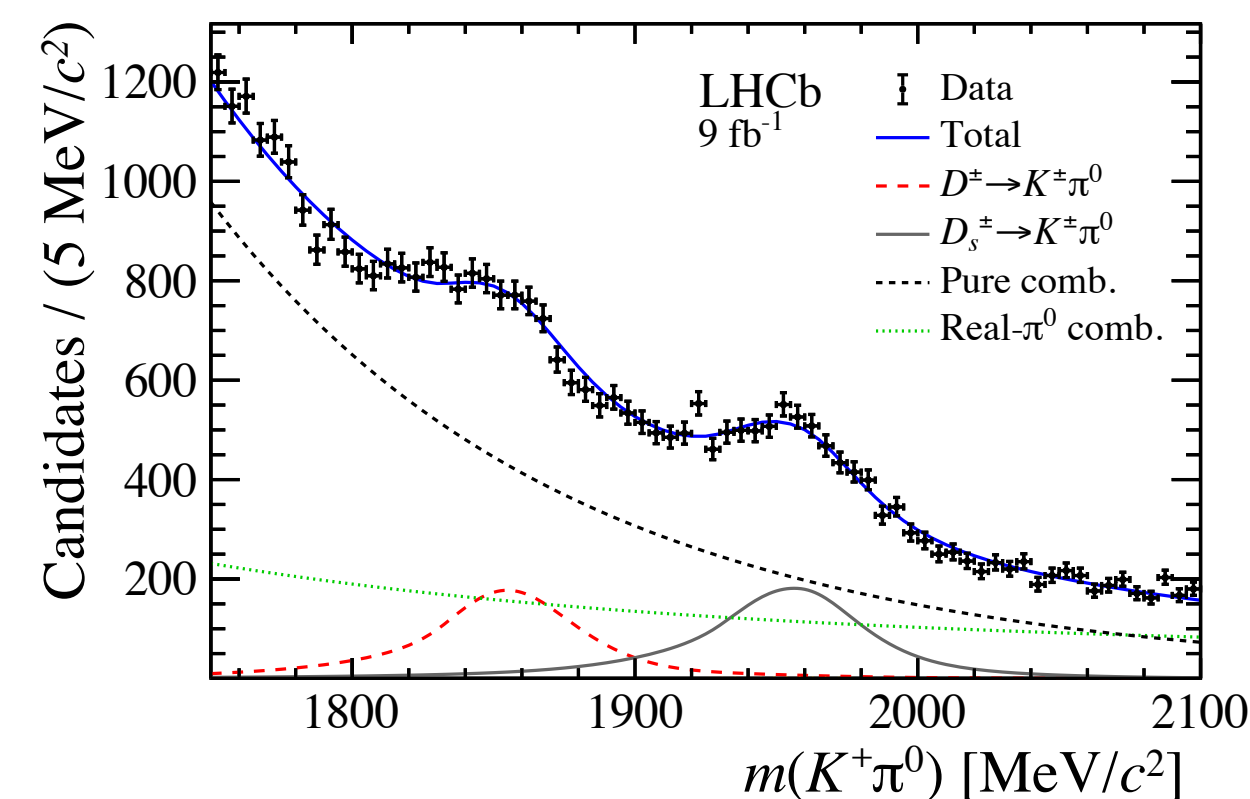
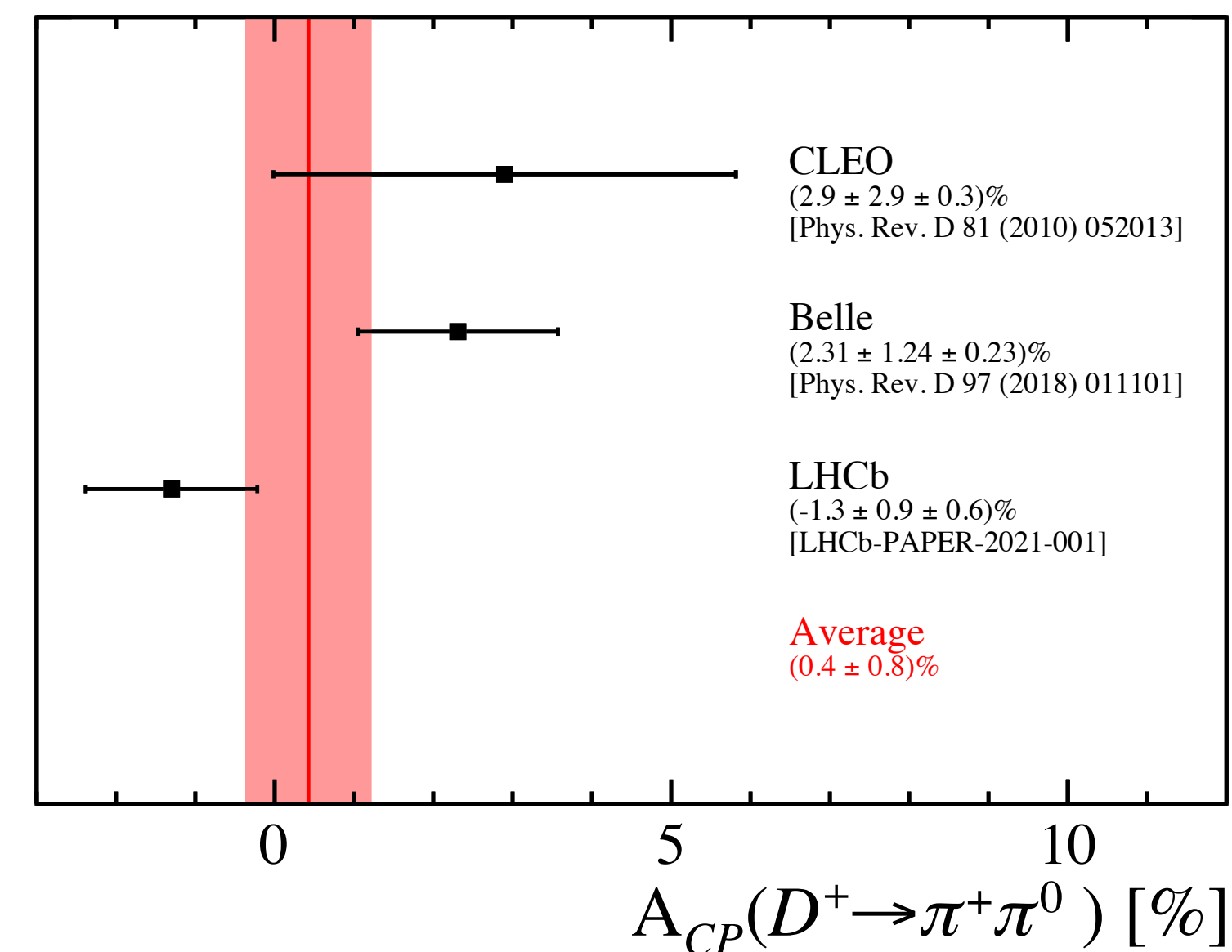


# $A_{CP}(D_{(s)}^+ \rightarrow h^+ \pi^0, h^+ \eta)$

- All compatible with  **$CP$  symmetry**
- First five results are the **most precise** measurements to date

[JHEP 06 \(2021\) 019](#)

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



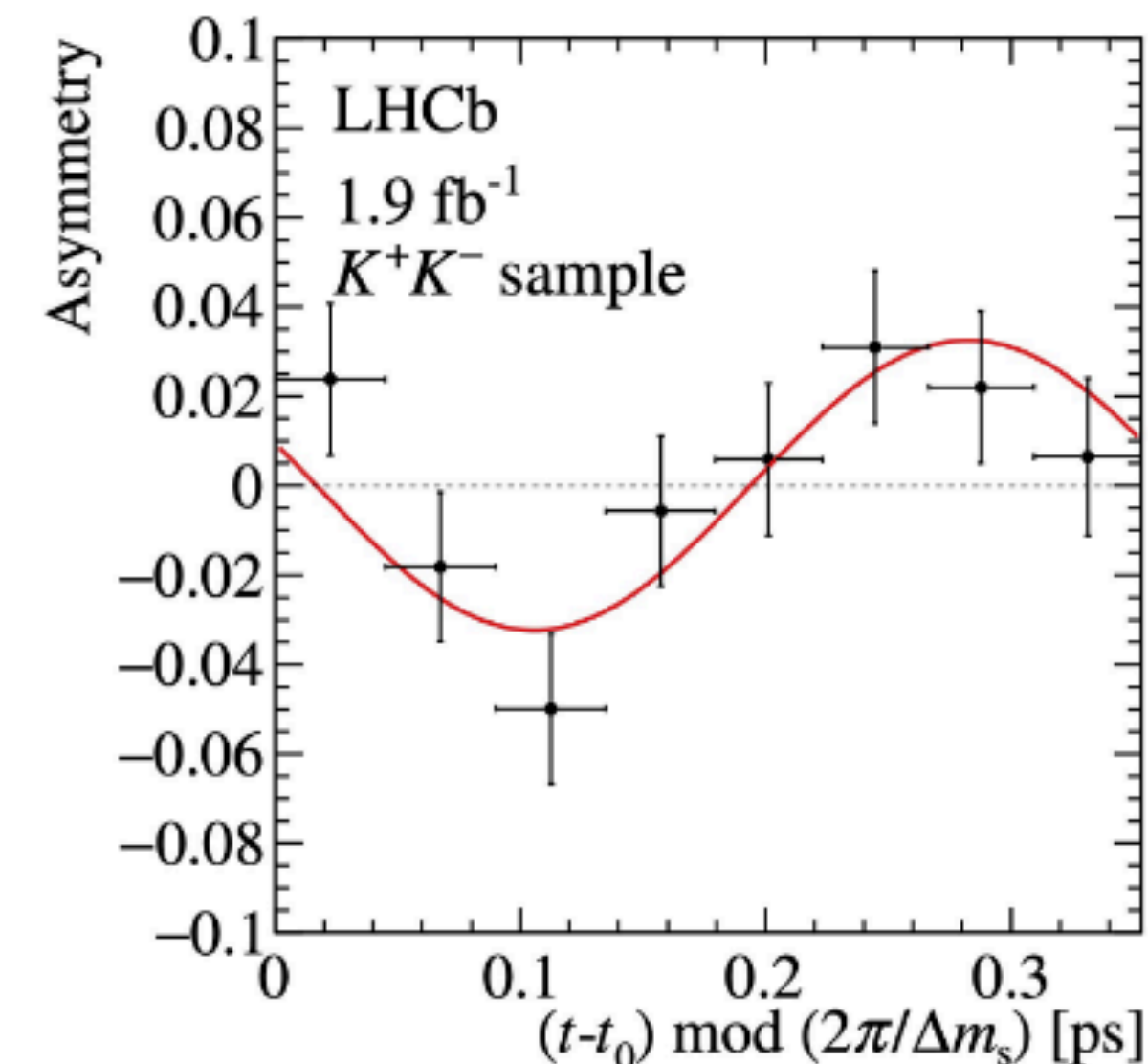
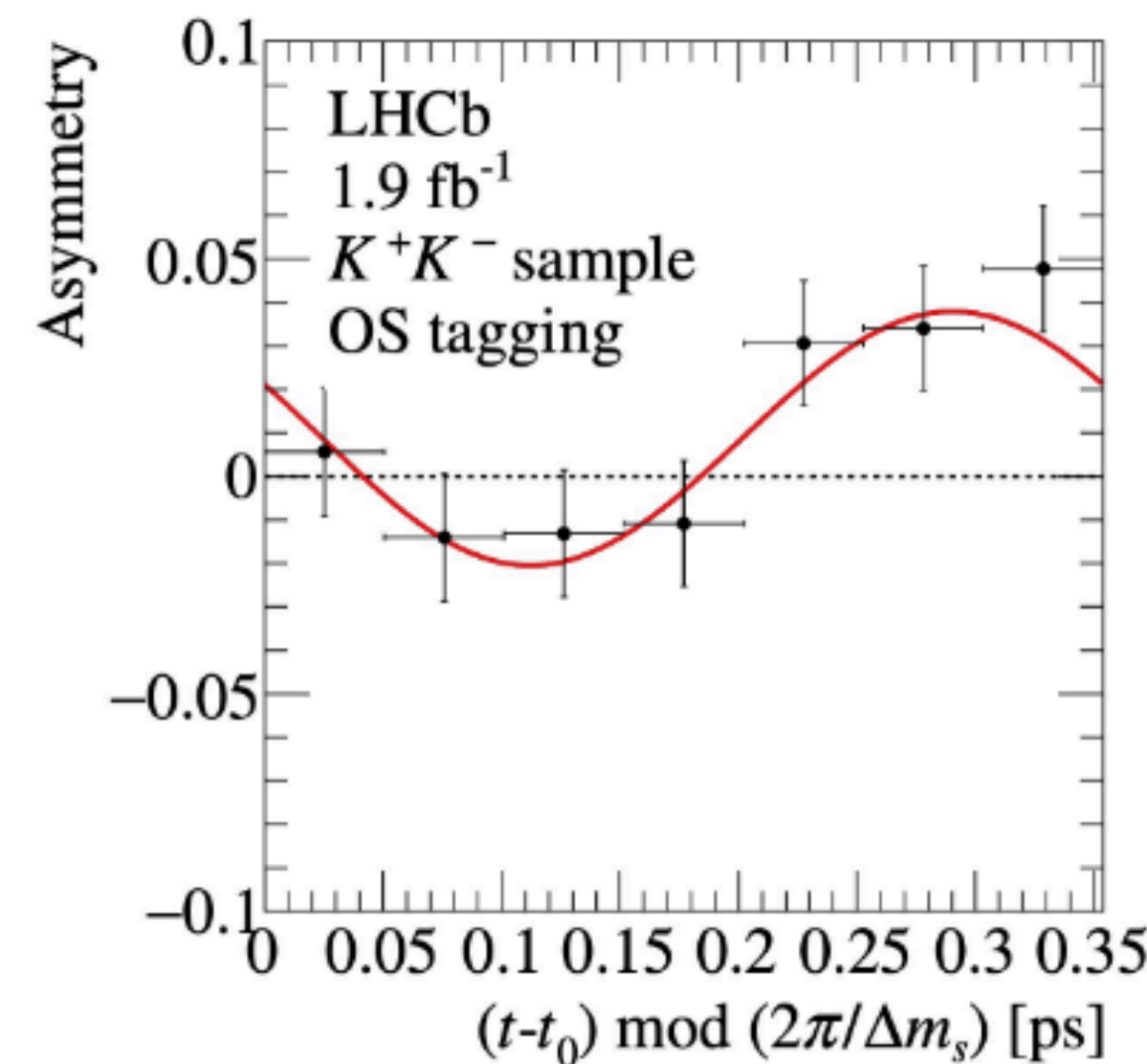
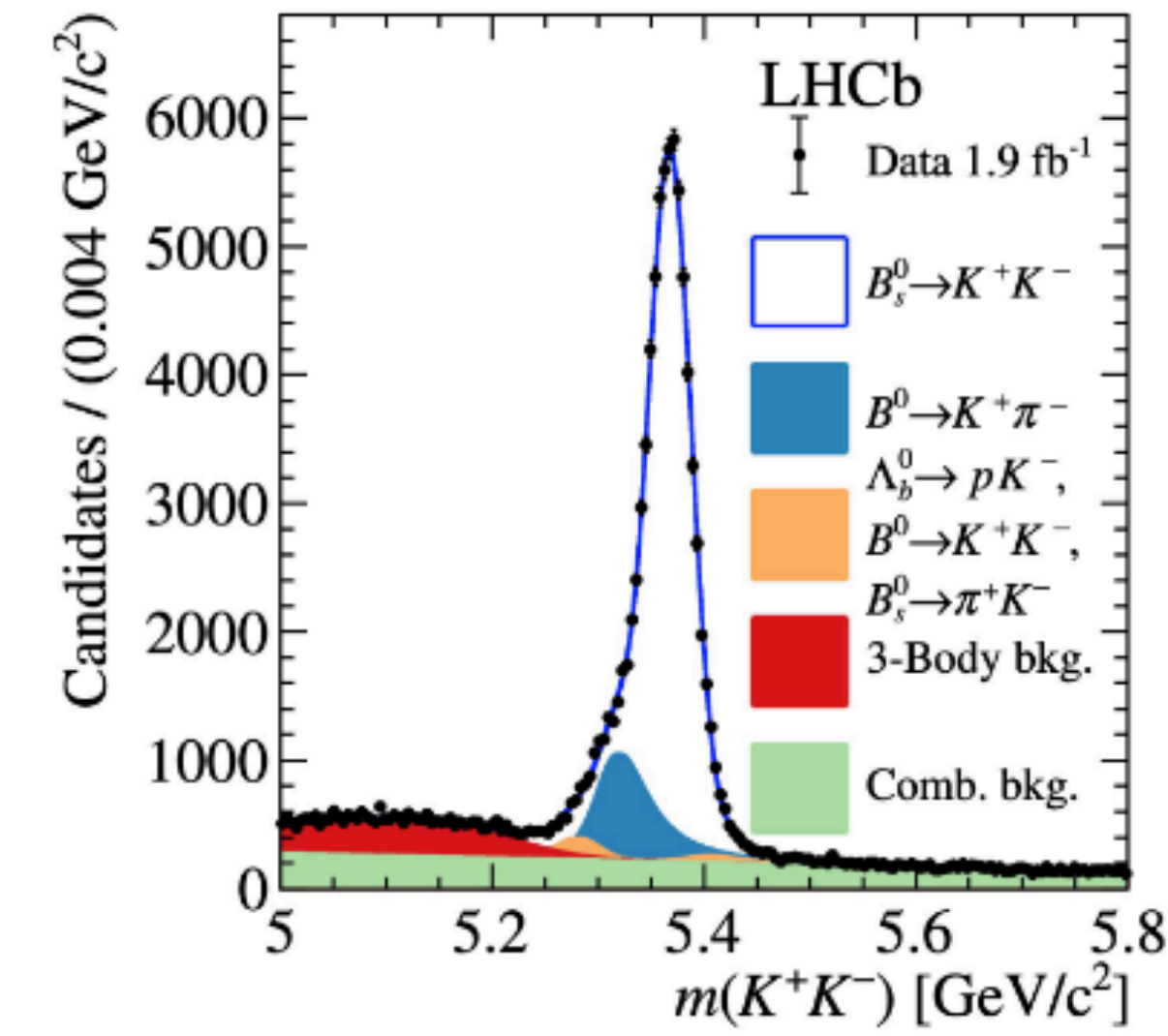
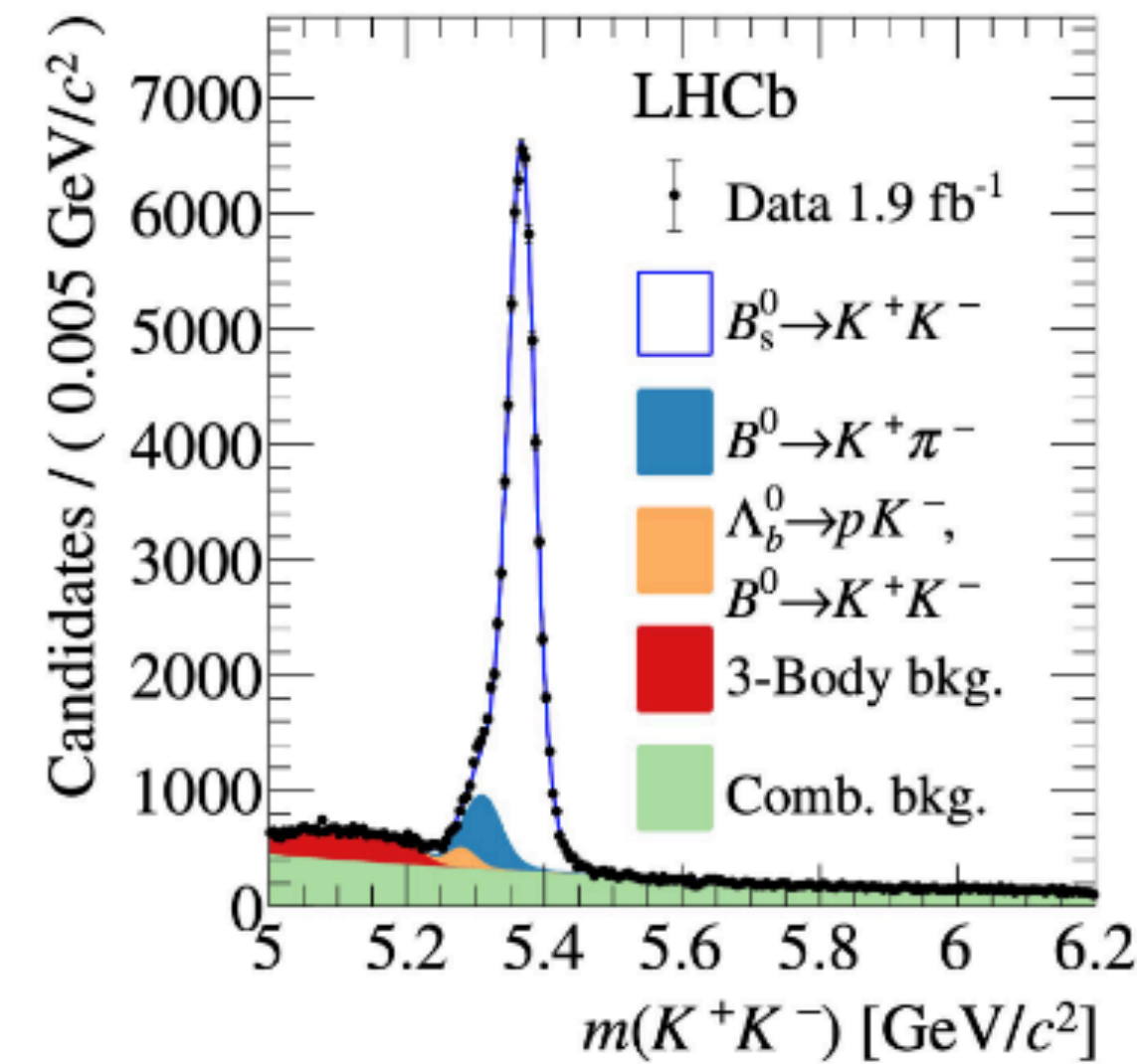
*CP* violation and mixing in beauty

$$A_{CP}(B_{(s)}^0 \rightarrow h^+ h'^-)$$

- CPV observables sensitive to CKM angles  $\gamma$  and  $\alpha$  and to possible **New Physics** contributions in loop diagrams
- Analysis based on **2015 + 2016** data
- **First observation** of time-dependent CPV in  $B_s^0$  decays

See talk by Daniele Manuzzi

[JHEP 03 \(2021\) 075](#)



# $A_{CP}(B^+ \rightarrow K^+ \pi^0)$

- **Puzzle:**  $A_{CP}(B^+ \rightarrow K^+ \pi^0) - A_{CP}(B^0 \rightarrow K^+ \pi^-)$  expected to be 0, but the current world average is  $\neq 0$  at  $5.5\sigma$   
 $A_{CP}(B^+ \rightarrow K^+ \pi^0) = 0.040 \pm 0.021$  [HFLAV Eur. Phys. J. C \(2021\) 81 226](#)  
 $A_{CP}(B^0 \rightarrow K^+ \pi^-) = -0.084 \pm 0.004$
- Discrepancy due to **strong** phases and amplitudes or **New Physics** effects?
- Analysis based on **Run 2** data
- Very **challenging** measurement (e.g. no decay vertex): background highly suppressed thanks to a multivariate algorithm based on isolation variables
- $B^+ \rightarrow J/\psi(\mu^+ \mu^-)K^+$  mode used to cancel production asymmetry of  $B^+$  and detection asymmetry of  $K^+$

[Phys. Rev. Lett. 126 \(2021\) 091802](#)

$$A_{CP}(B^+ \rightarrow K^+ \pi^0)$$

$$A_{CP} = 0.025 \pm 0.015 \pm 0.006 \pm 0.003$$

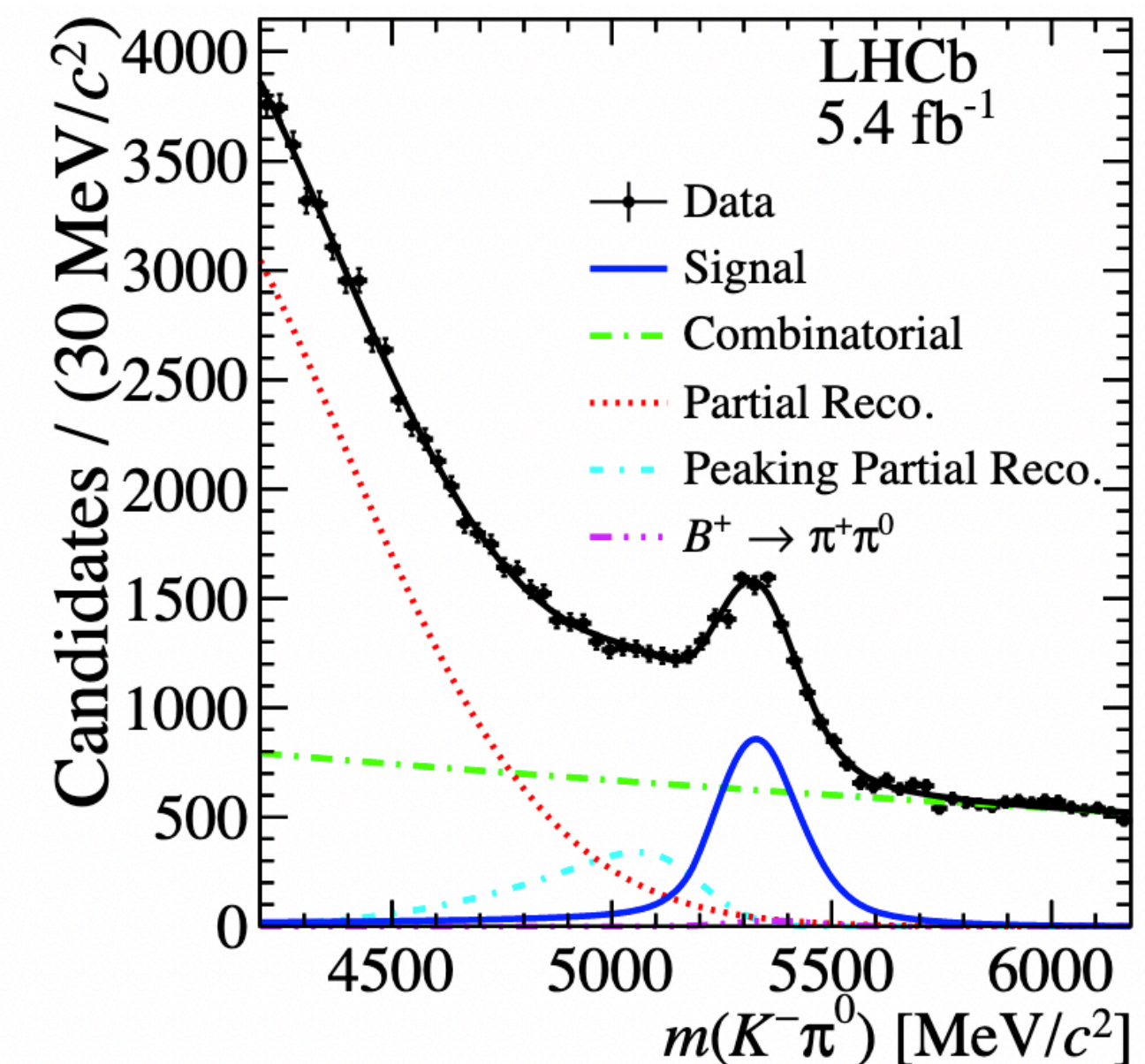
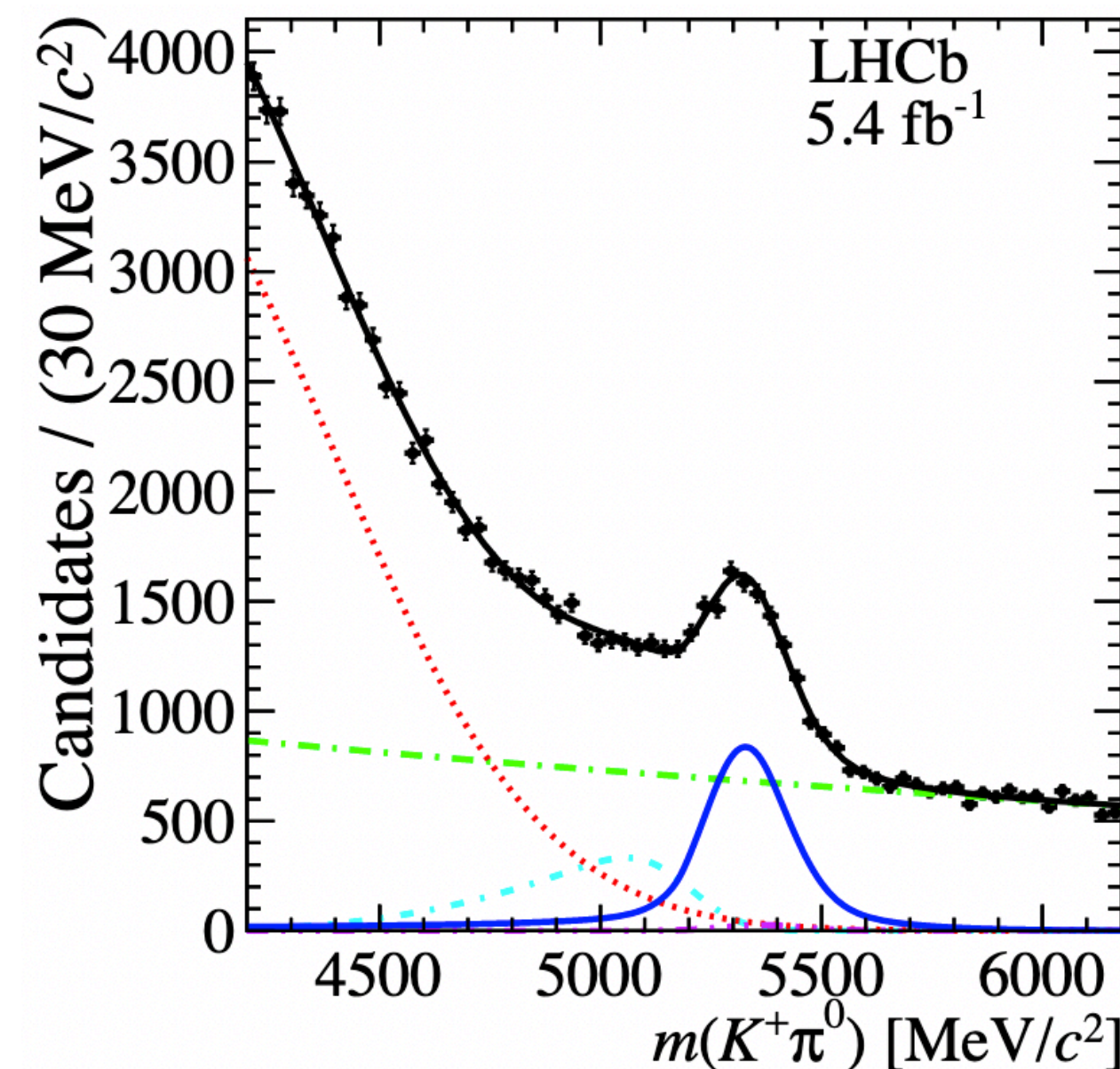
- Result **more precise** than the WA

[Phys. Rev. Lett. 126 \(2021\) 091802](#)

- Including this result in the WA:

$$A_{CP}(B^+ \rightarrow K^+ \pi^0) - A_{CP}(B^0 \rightarrow K^+ \pi^-) = 0.115 \pm 0.014$$

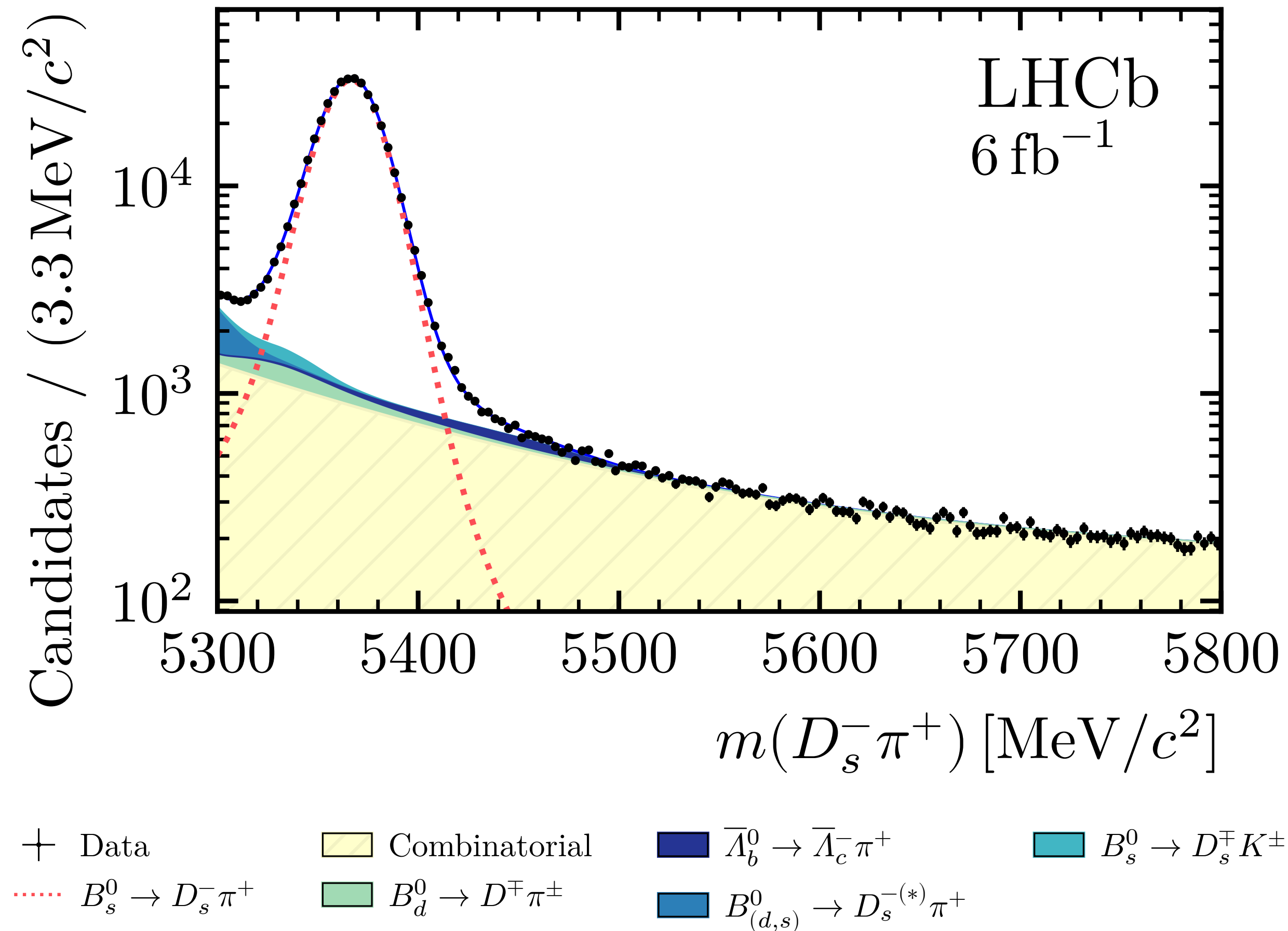
- The puzzle is confirmed and **strengthened** ( $8\sigma$  level)





# $B_s^0 - \bar{B}_s^0$ oscillation frequency

- $\Delta m_s$  measurement is a powerful constraint on **CKM** matrix and New Physics contributions
- Decay mode:  $B_s^0 \rightarrow D_s^- \pi^+$ , with  $D_s^- \rightarrow K^+ K^- \pi^-, \pi^+ \pi^- \pi^+$
- Analysis based on **Run 2** data (signal yield  $\sim 3.8 \times 10^5$ )
- Fit background-subtracted decay **time distribution** of flavour-tagged  $B_s^0$  (considering resolution, tagging power, ...)



[arXiv:2104.04421](https://arxiv.org/abs/2104.04421)

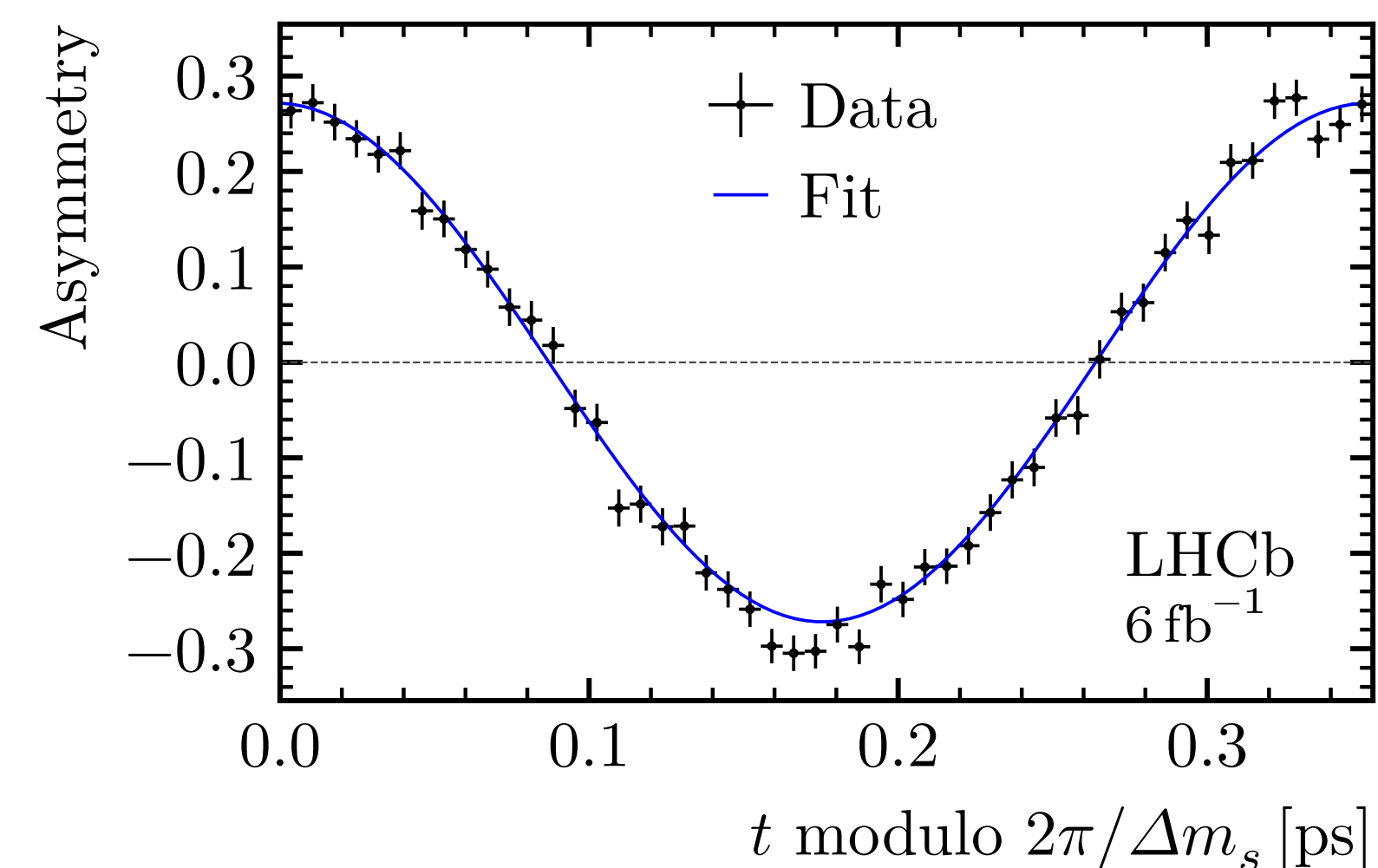
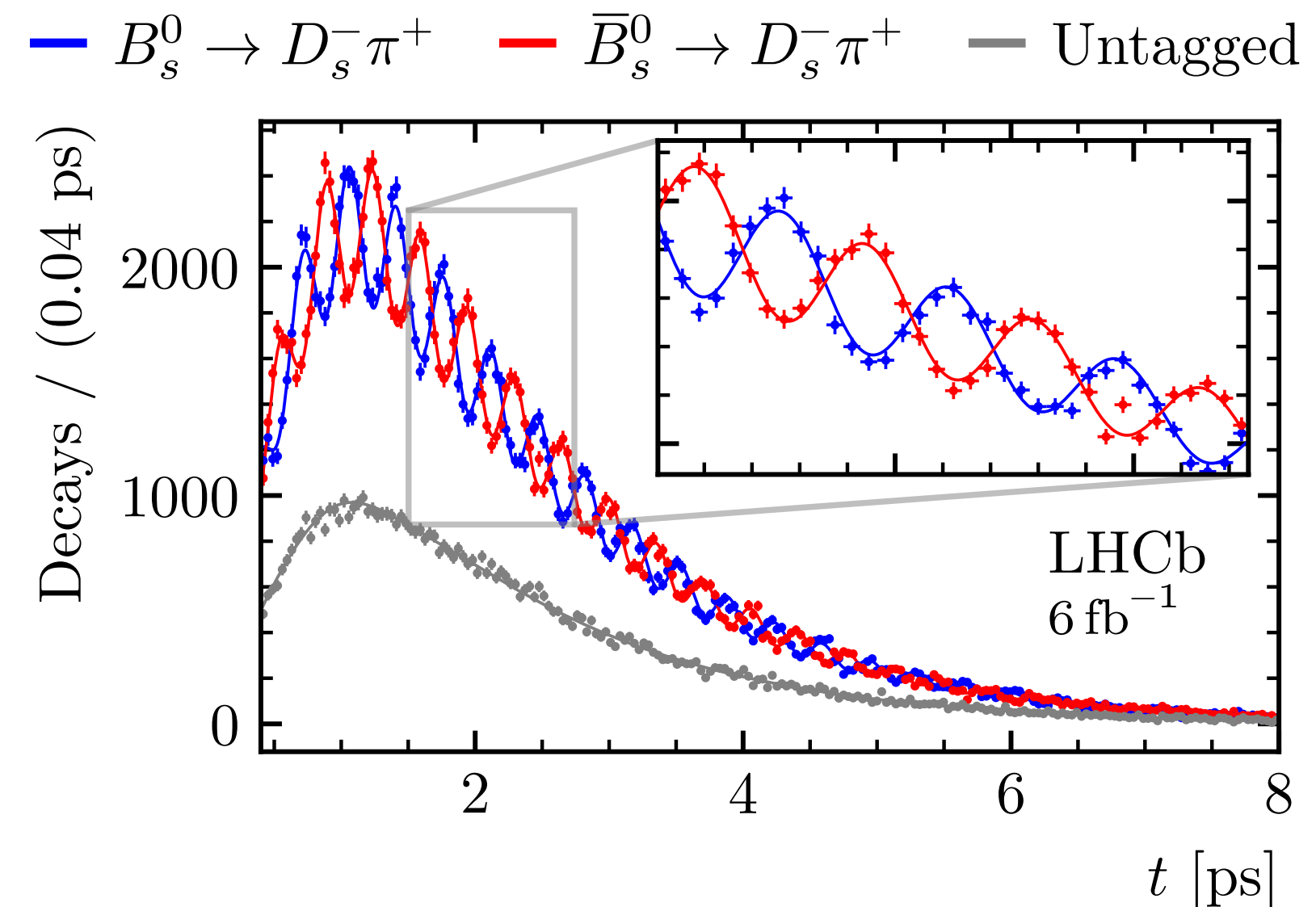
# $B_s^0 - \bar{B}_s^0$ oscillation frequency

$$\Delta m_s = (17.7683 \pm 0.0051 \pm 0.0032) \text{ ps}^{-1}$$

- Improve by a **factor 2** the precision of previous LHCb measurement
- **Combination** with all LHCb measurements gives

$$\Delta m_s = (17.7656 \pm 0.0057) \text{ ps}^{-1}$$

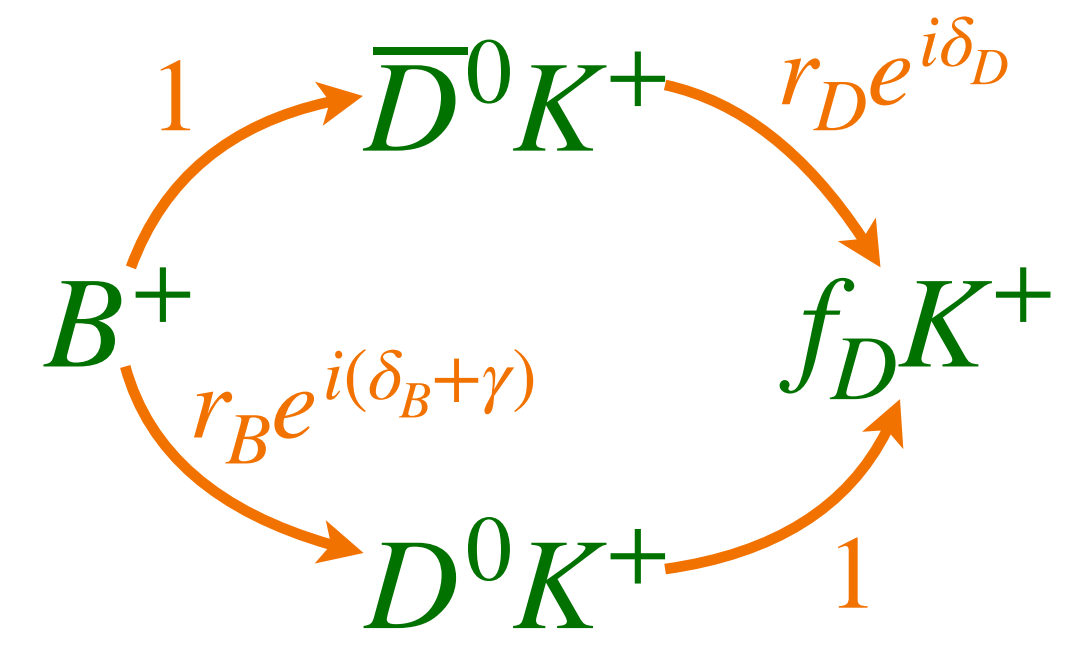
[arXiv:2104.04421](https://arxiv.org/abs/2104.04421)



$\gamma$  + charm combination

# $\gamma$ + charm combination

- $\gamma$  standard **candle** of SM
- $\gamma$  measured in **tree-level** decays that are theoretically **clean** ( $b \rightarrow cW$  and  $b \rightarrow uW$  transitions)
- Golden modes:  $B^\pm \rightarrow DK^\pm$
- $B^\pm \rightarrow DK^\pm$  with  $D \rightarrow K^\pm \pi^\mp$  are sensitive to  $\delta_D^{K\pi}$ , if  $x_D, y_D$  and  $r_D$  are taken as input  $\Rightarrow$  best option is to combine **LHCb charm+beauty** results to constrain all four parameters
- 151 observables, 52 free parameters

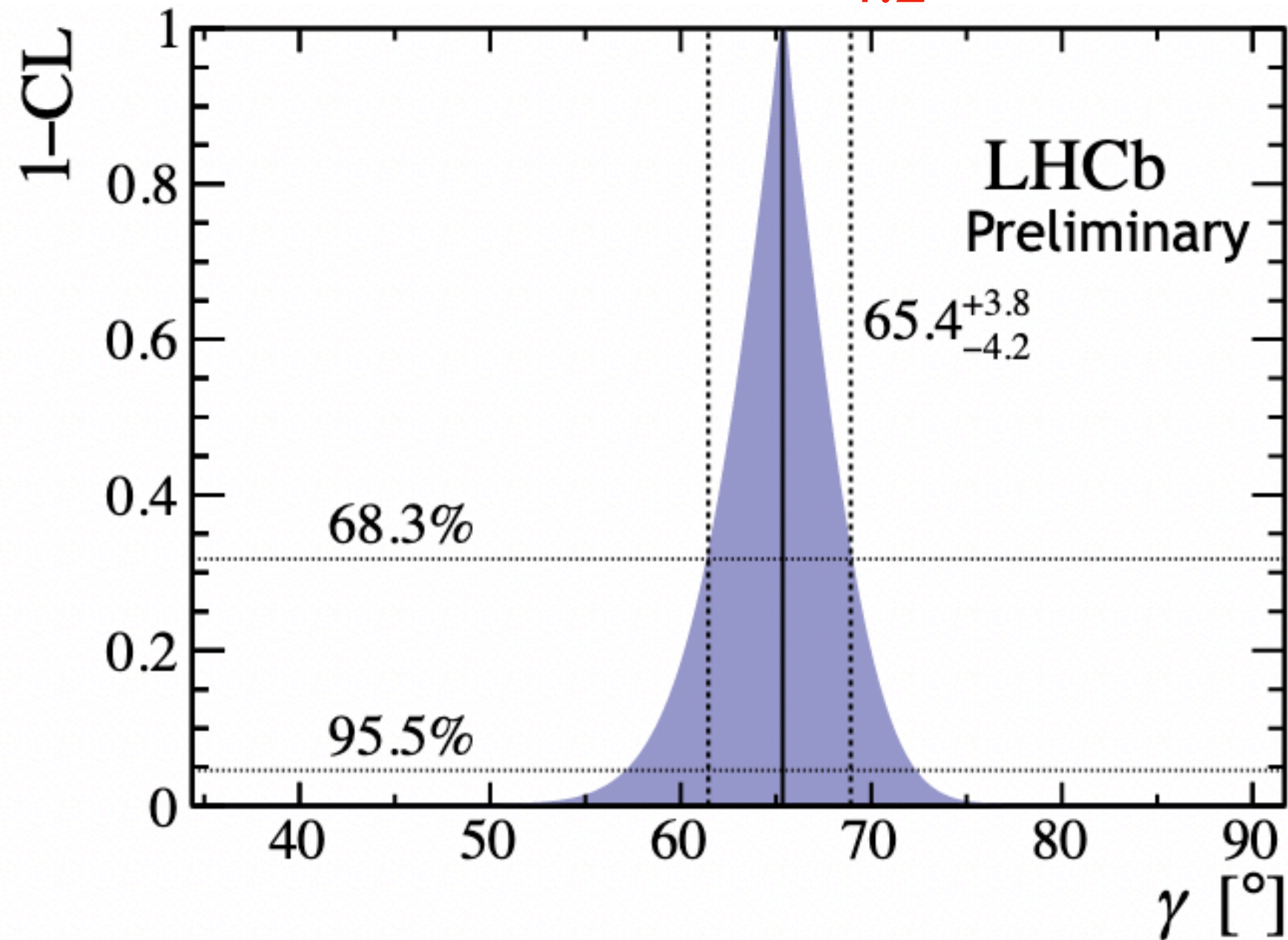


[LHCb-CONF-2021-001](#)  
[LHCb-PAPER-2021-033](#) (in preparation)

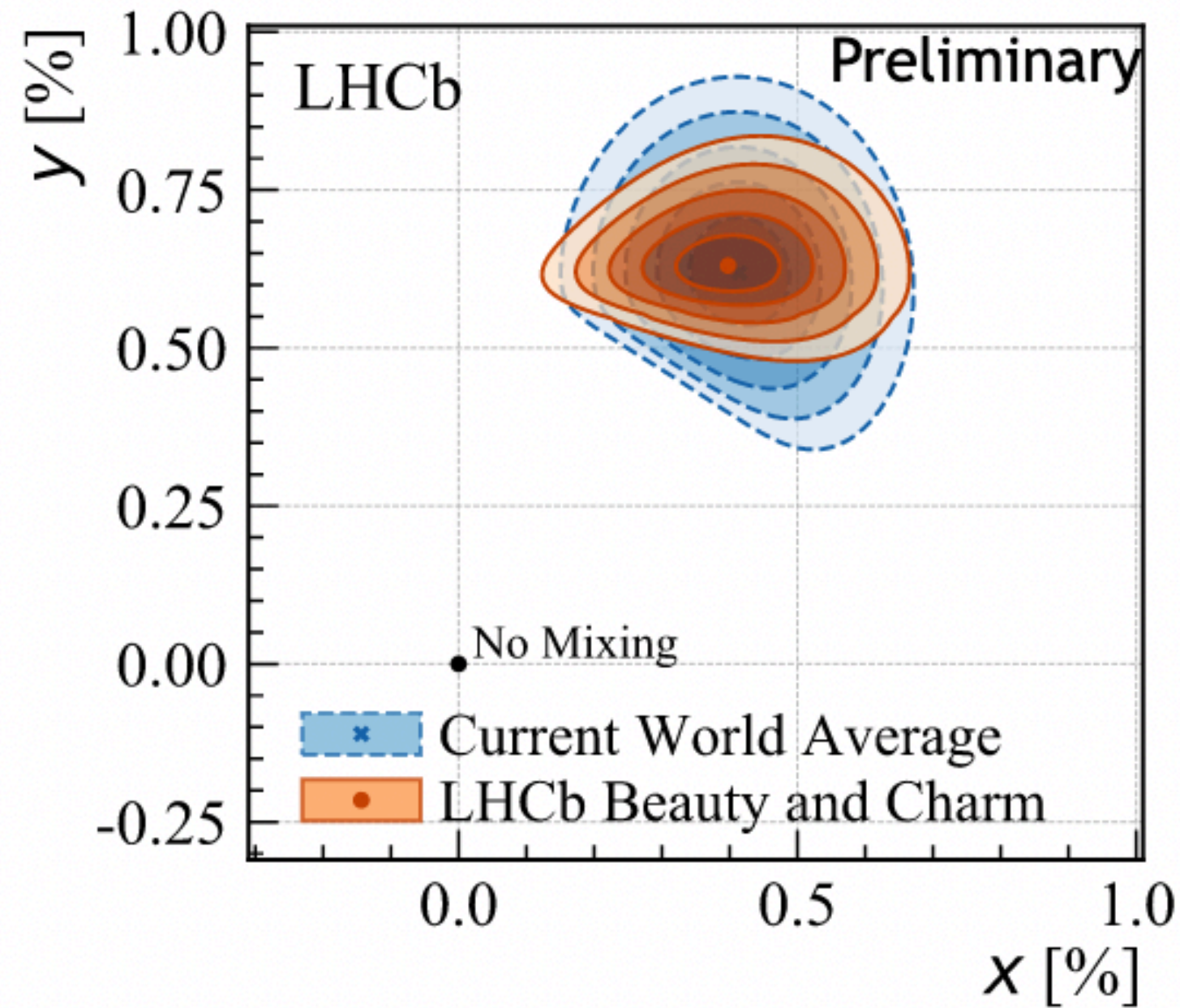
B decay	D decay	Ref.	Dataset	Status since Ref. [25]
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow h^+h^-$	[27]	Run 1&2	<b>Updated</b>
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow h^+\pi^-\pi^+\pi^-$	[28]	Run 1	As before
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow h^+h^-\pi^0$	[29]	Run 1	As before
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow K_S^0 h^+h^-$	[26]	Run 1&2	<b>Updated</b>
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow K_S^0 K^\pm \pi^\mp$	[30]	Run 1&2	<b>Updated</b>
$B^\pm \rightarrow D^*h^\pm$	$D \rightarrow h^+h^-$	[27]	Run 1&2	<b>Updated</b>
$B^\pm \rightarrow DK^{*\pm}$	$D \rightarrow h^+h^-$	[31]	Run 1&2(*)	As before
$B^\pm \rightarrow DK^{*\pm}$	$D \rightarrow h^+\pi^-\pi^+\pi^-$	[31]	Run 1&2(*)	As before
$B^\pm \rightarrow Dh^\pm \pi^+ \pi^-$	$D \rightarrow h^+h^-$	[32]	Run 1	As before
$B^0 \rightarrow DK^{*0}$	$D \rightarrow K^+ \pi^-$	[33]	Run 1&2(*)	<b>Updated</b>
$B^0 \rightarrow DK^{*0}$	$D \rightarrow h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	<b>New</b>
$B^0 \rightarrow DK^+ \pi^-$	$D \rightarrow h^+h^-$	[34]	Run 1	<b>Superseded</b>
$B^0 \rightarrow DK^{*0}$	$D \rightarrow K_S^0 \pi^+ \pi^-$	[35]	Run 1	As before
$B^0 \rightarrow D^\mp \pi^\pm$	$D^+ \rightarrow K^- \pi^+ \pi^+$	[36]	Run 1	As before
$B_s^0 \rightarrow D_s^\mp K^\pm$	$D_s^+ \rightarrow h^+h^- \pi^+$	[37]	Run 1	As before
$B_s^0 \rightarrow D_s^\mp K^\pm \pi^+ \pi^-$	$D_s^+ \rightarrow h^+h^- \pi^+$	[38]	Run 1&2	<b>New</b>
-	$D^0 \rightarrow h^+h^-$	[39] [41]	Run 1&2	<b>New</b>
-	$D^0 \rightarrow h^+h^-$	[42]	Run 1	<b>New</b>
-	$D^0 \rightarrow h^+h^-$	[43] [46]	Run 1&2	<b>New</b>
-	$D^0 \rightarrow K^+ \pi^-$	[47]	Run 1	<b>New</b>
-	$D^0 \rightarrow K^+ \pi^-$	[48]	Run 1&2(*)	<b>New</b>
-	$D^0 \rightarrow K^\pm \pi^\mp \pi^+ \pi^-$	[49]	Run 1	<b>New</b>
-	$D^0 \rightarrow K_S^0 \pi^+ \pi^-$	[50] [51]	Run 1&2	<b>New</b>
-	$D^0 \rightarrow K_S^0 \pi^+ \pi^-$	[52]	Run 1	<b>New</b>

# $\gamma$ + charm combination

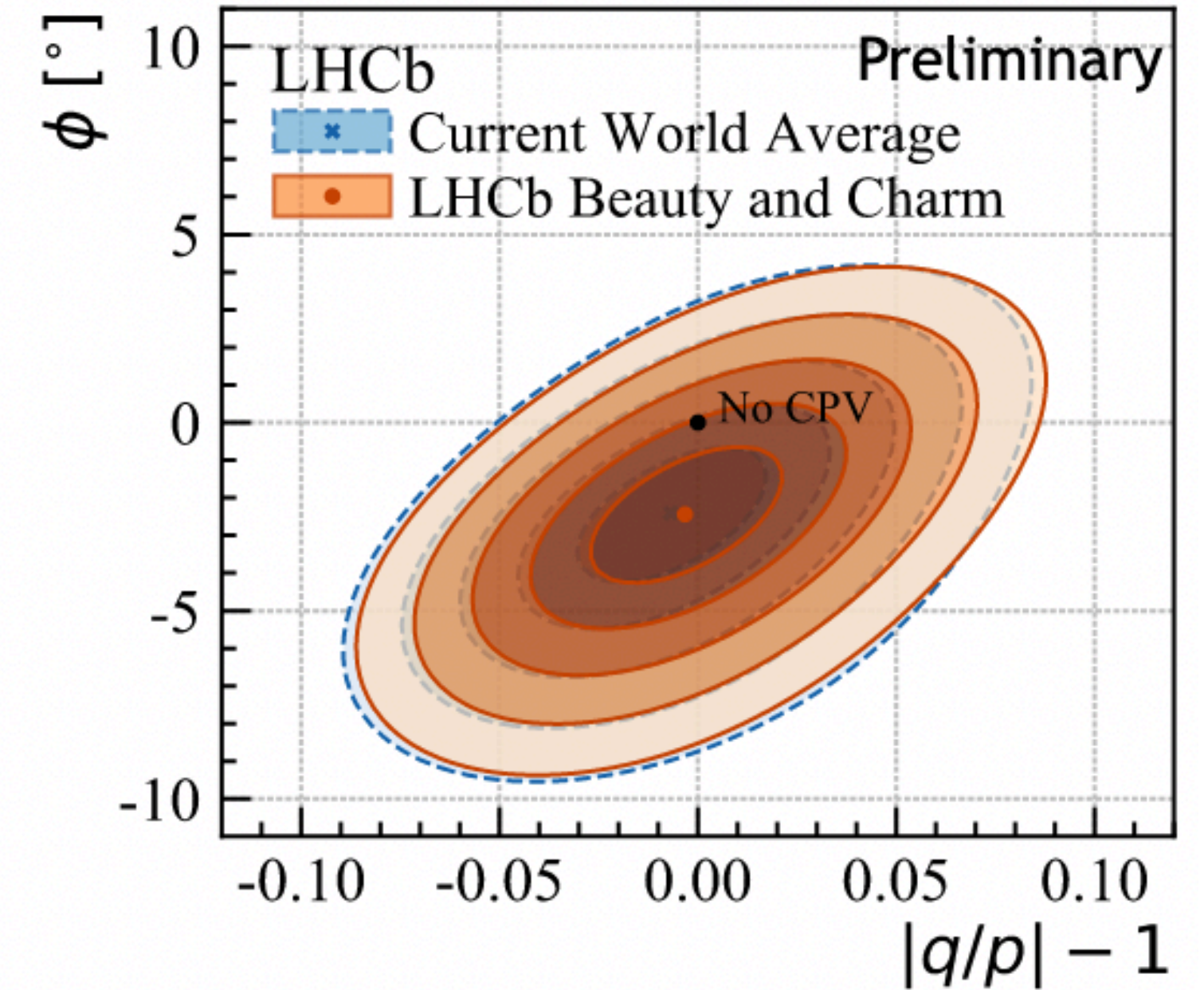
$$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$



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



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



- Excellent precision on  $\gamma$

- Agreement with indirect global CKM fitters:  $\gamma = (65.7^{+0.9}_{-2.7})^\circ$  (CKMfitter)     $\gamma = (65.8 \pm 2.2)^\circ$  (UTFit)

- Precision on  $\delta_D^{K\pi}$  and  $y_D$  improved by almost a factor 2

LHCb-CONF-2021-001  
LHCb-PAPER-2021-033 (in preparation)

# Rare decays

$$B_{(s)}^0 \rightarrow \mu^+ \mu^- (\gamma)$$

- Very rare decays, with **clean** theoretical prediction:

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

⇒ **golden** channel to search New Physics

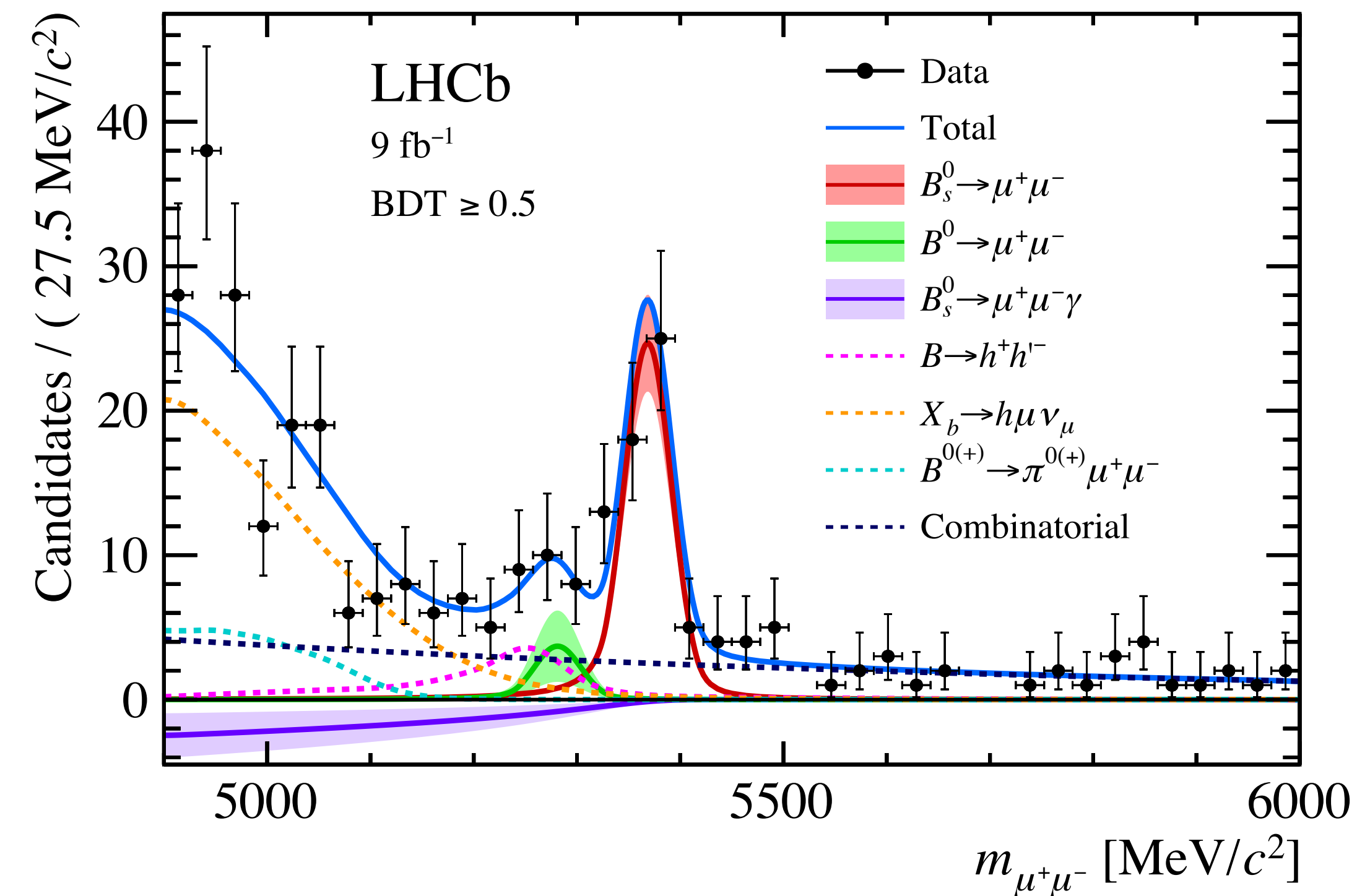
- Analysis with **Run 1 + Run 2** data

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 2.6 \times 10^{-10} \text{ at the 95\% CL}$$

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \gamma) < 2.0 \times 10^{-9} \text{ at the 95\% CL}$$

See talk by Marco Santimaria



[arXiv:2108.09283](https://arxiv.org/abs/2108.09283)

[arXiv:2108.09284](https://arxiv.org/abs/2108.09284)

$$R_K \equiv \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}$$

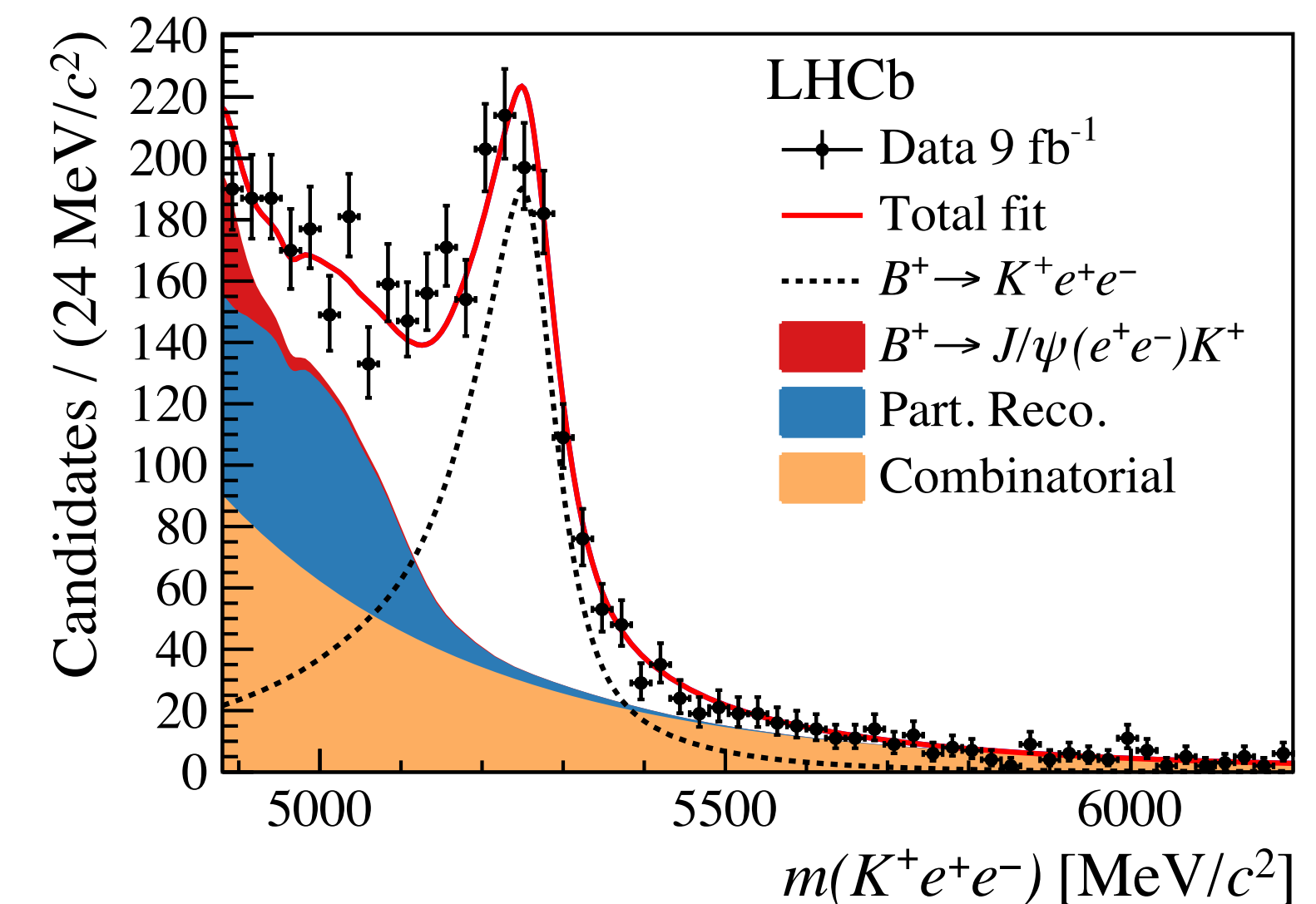
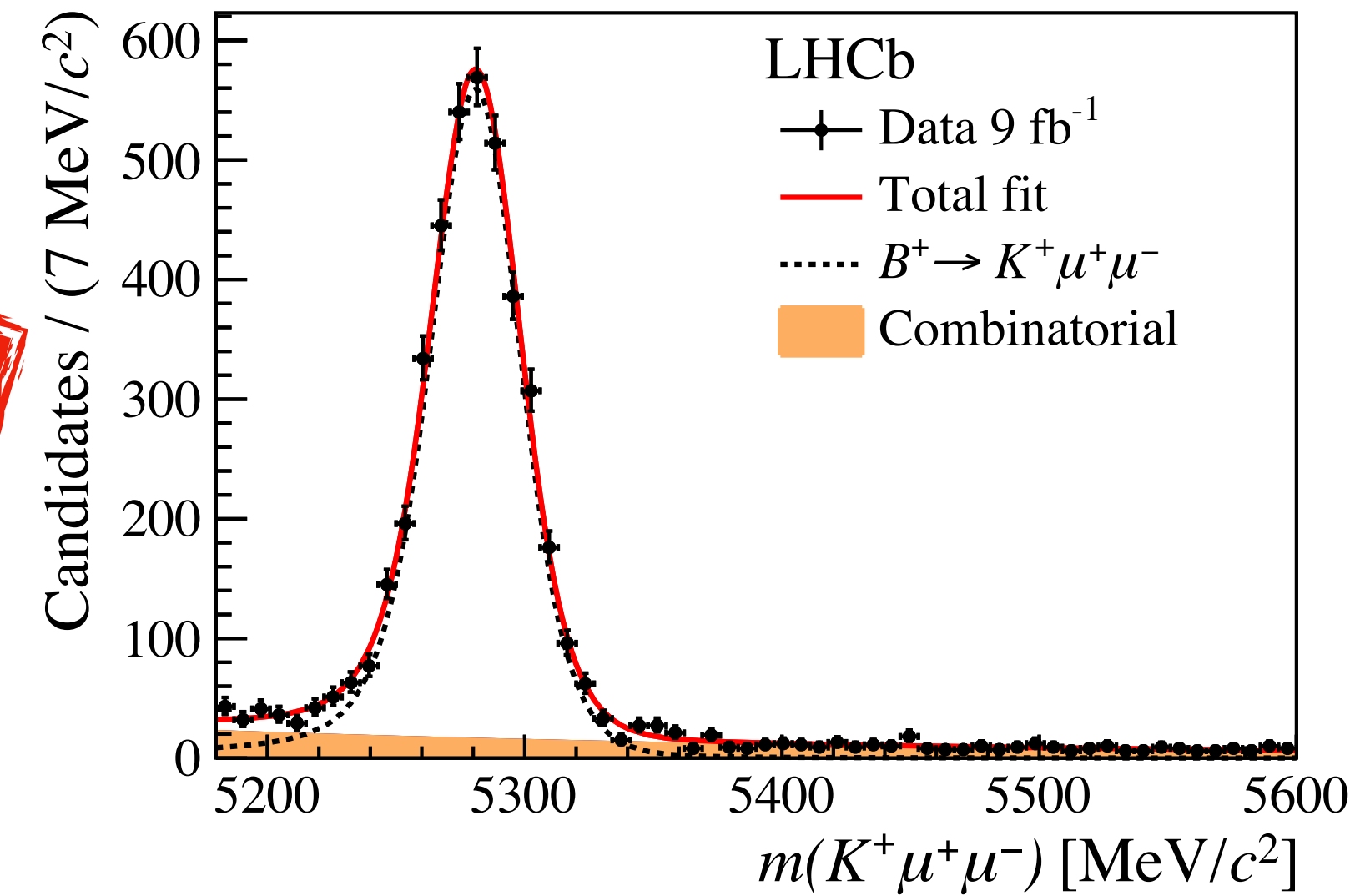
See talk by Marco Santimaria

- Lepton flavour universality test
- Clean theoretical prediction:  $R_K = 1$
- Measured in range  $1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$  (Run 1 + Run 2):

$$R_K = 0.846^{+0.044}_{-0.041}$$

- $3.1\sigma$  discrepancy with SM

[arXiv:2103.11769](https://arxiv.org/abs/2103.11769)



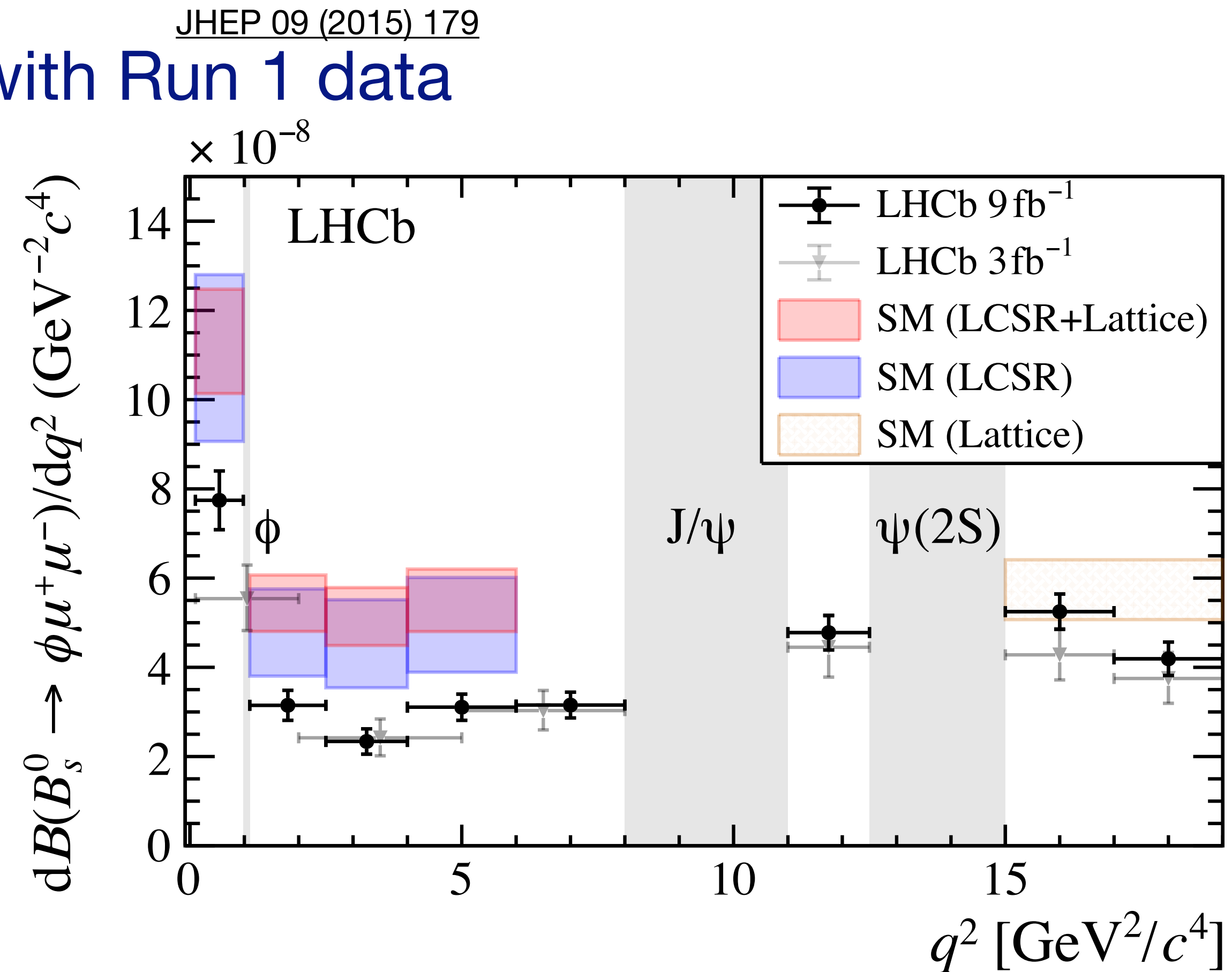


$$B_s^0 \rightarrow \phi \mu^+ \mu^-$$

- Another example of  $b \rightarrow s \ell^+ \ell^-$ , sensitive to New Physics
- $3\sigma$  discrepancy with SM already observed with Run 1 data
- Update with Run 2 data confirms discrepancy at  $3.6\sigma$  wrt SM (LCSR+Lattice) in range  $1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$ :

[arXiv:2105.14007](https://arxiv.org/abs/2105.14007)

$$\frac{d\mathcal{B}(B_s^0 \rightarrow \phi \mu^+ \mu^-)}{dq^2} = (2.88 \pm 0.22) \times 10^{-8} \text{ c}^4/\text{GeV}^2$$



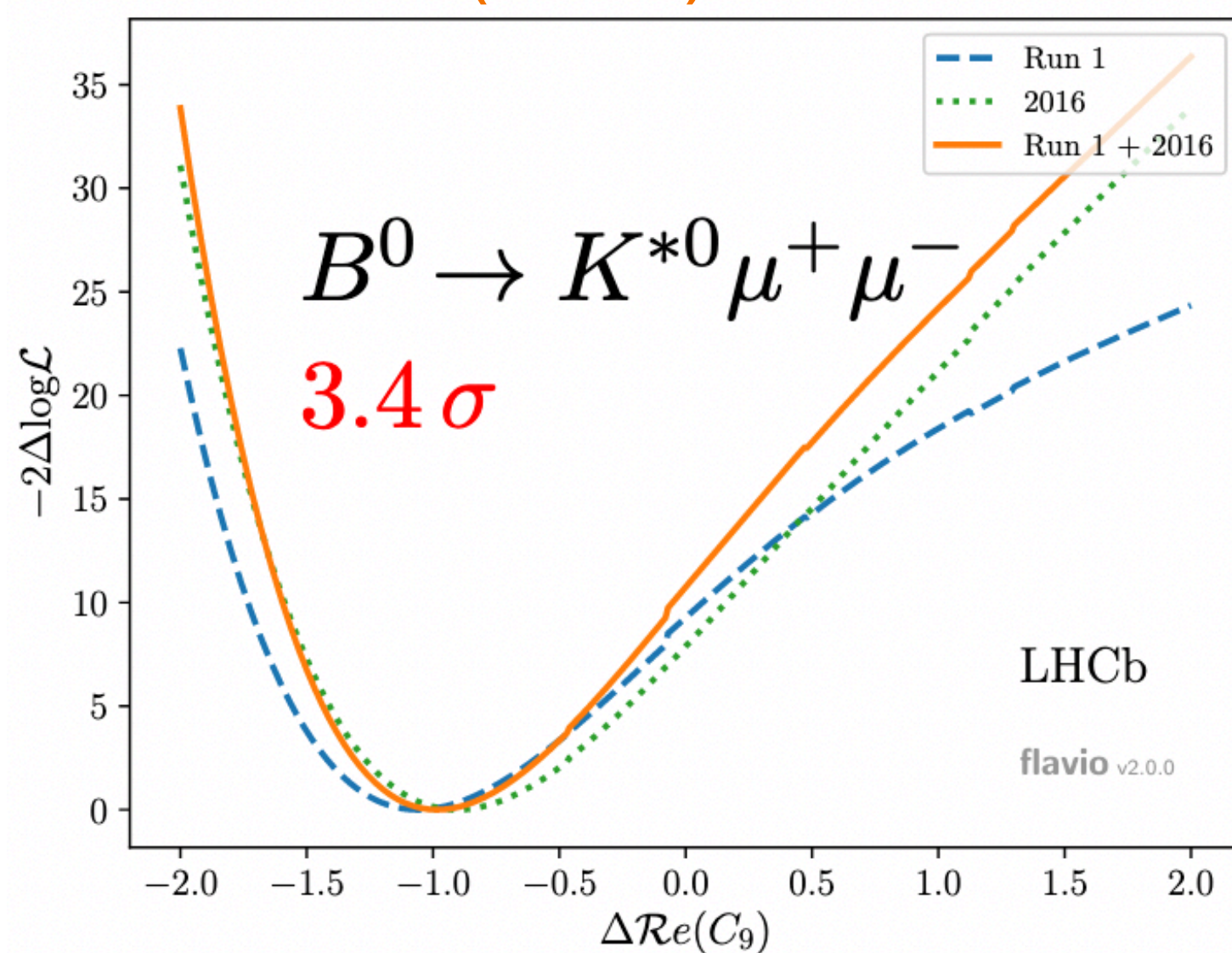
# $b \rightarrow s \ell^+ \ell^-$ angular analyses

- **Differential decay rate** as a function of the three helicity **angles** can be written in terms of **Wilson** coefficients (model-independent description in effective field theory), like ew penguin  $C_9$

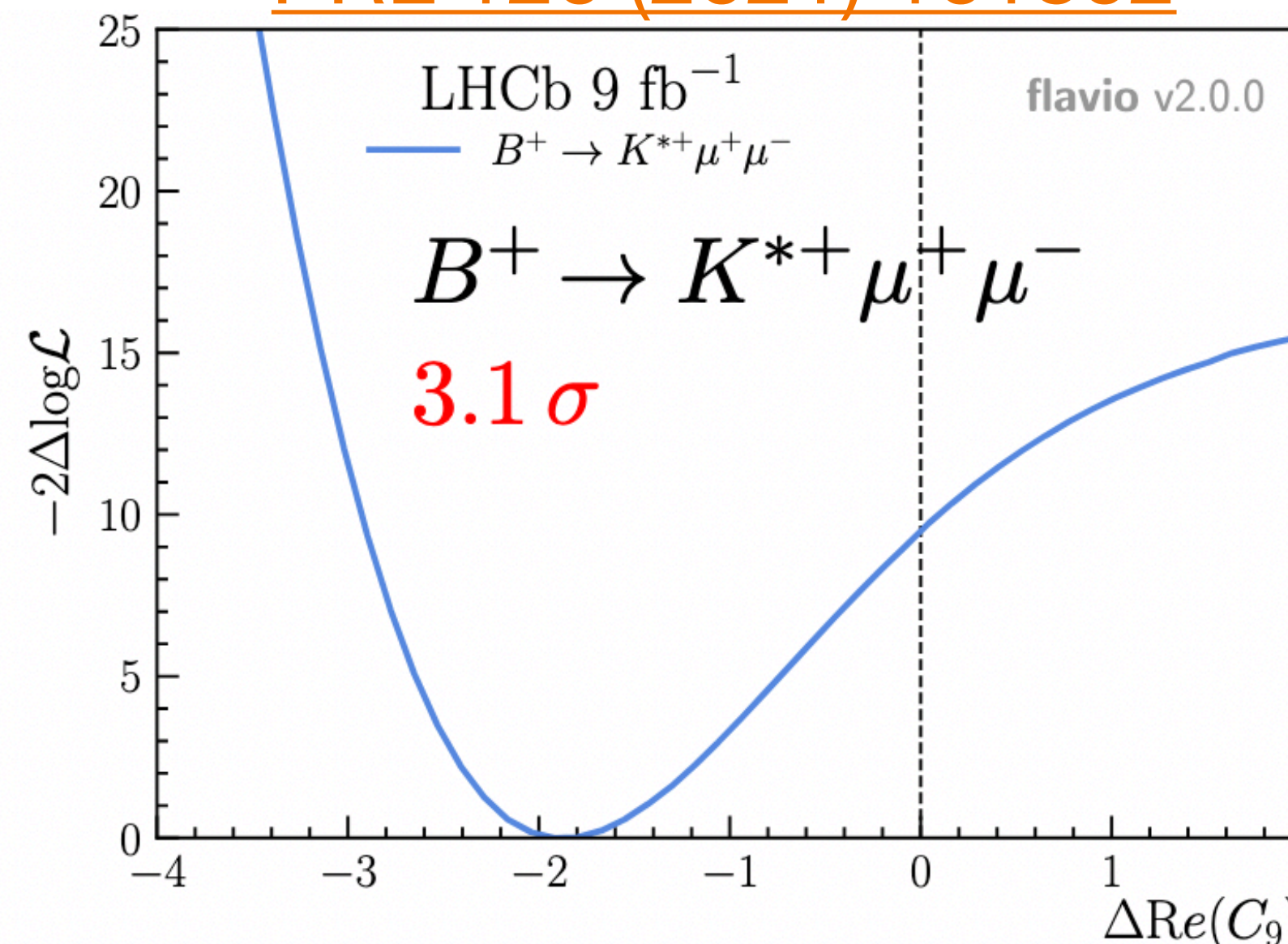
arXiv:1810.08132

- Using Flavio to fit various LHCb results, a consistent trend of **negative  $\Re(C_9)$**  preferred over SM is observed ( $2 - 3\sigma$  level)

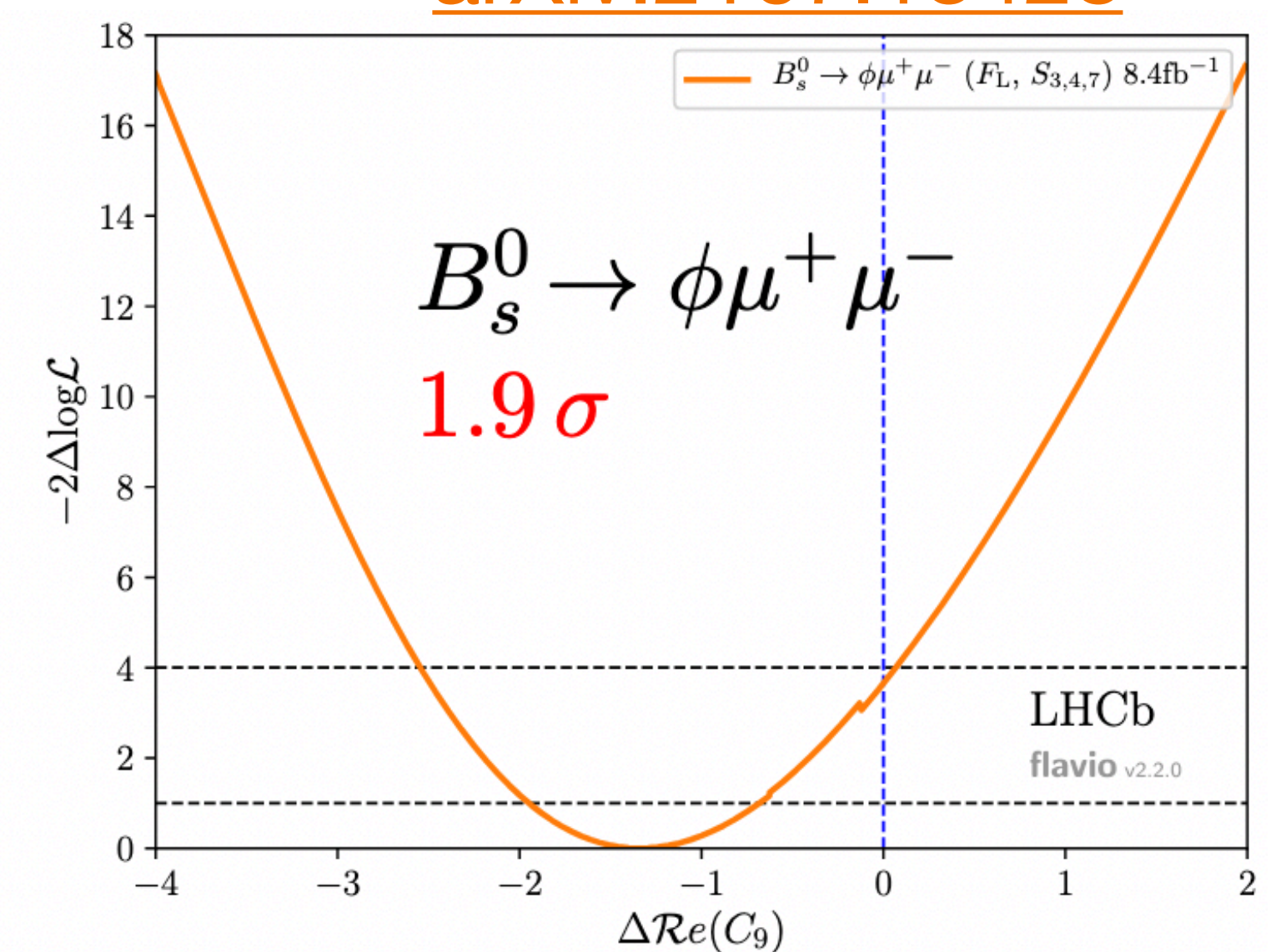
[PRL 125 \(2020\) 011802](#)



[PRL 126 \(2021\) 161802](#)



[arXiv:2107.13428](#)



# Conclusions

- Lots of important **results** by LHCb this year concerning  $CP$  violation,  $B_s^0 \rightarrow \mu^+ \mu^-$ , LFU anomalies, CKM angles
- Still many analyses **ongoing** with full Run 2 data:
  - $A_{CP}(D^0 \rightarrow K^+ K^-) \Rightarrow$  talk by Serena Maccolini
  - $y_{CP}(D^0 \rightarrow h^+ h^-) \Rightarrow$  talk by Andrea Villa
  - $y_{CP}(D^0 \rightarrow K_s^0 K^+ K^-) \Rightarrow$  talk by Edward Shields
- Many other topics not covered here:
  - **Spectroscopy**  $\Rightarrow$  talk by Daniele Marangotto
  - **EW** physics  $\Rightarrow$  talk by Davide Zuliani
  - **Semileptonic** decays  $\Rightarrow$  talks by Davide Fazzini, Simone Meloni, Lorenzo Paolucci
  - Heavy **ions**  $\Rightarrow$  talk by Roman Litvinov

**Backup**

# Charm at LHCb

- Large  $c\bar{c}$  production cross section  
 $\sigma(pp \rightarrow c\bar{c}X)_{\sqrt{s}=13 \text{ TeV}} = (2369 \pm 3 \pm 152 \pm 118) \mu\text{b}$
- More than 1 billion  $D^0 \rightarrow K^-\pi^+$  decays reconstructed with the full LHCb data sample
- LHCb detector: JINST 3 (2008) S08005
  - ◆ Excellent vertex resolution ( $13 \mu\text{m}$  in transverse plane for PV)
  - ◆ Excellent IP resolution ( $\sim 20 \mu\text{m}$ )
  - ◆ Very good momentum resolution ( $\delta p/p \sim 0.5\% - 0.8\%$ )
  - ◆ Excellent PID capabilities
  - ◆ Very good trigger efficiency ( $\sim 90\%$ )

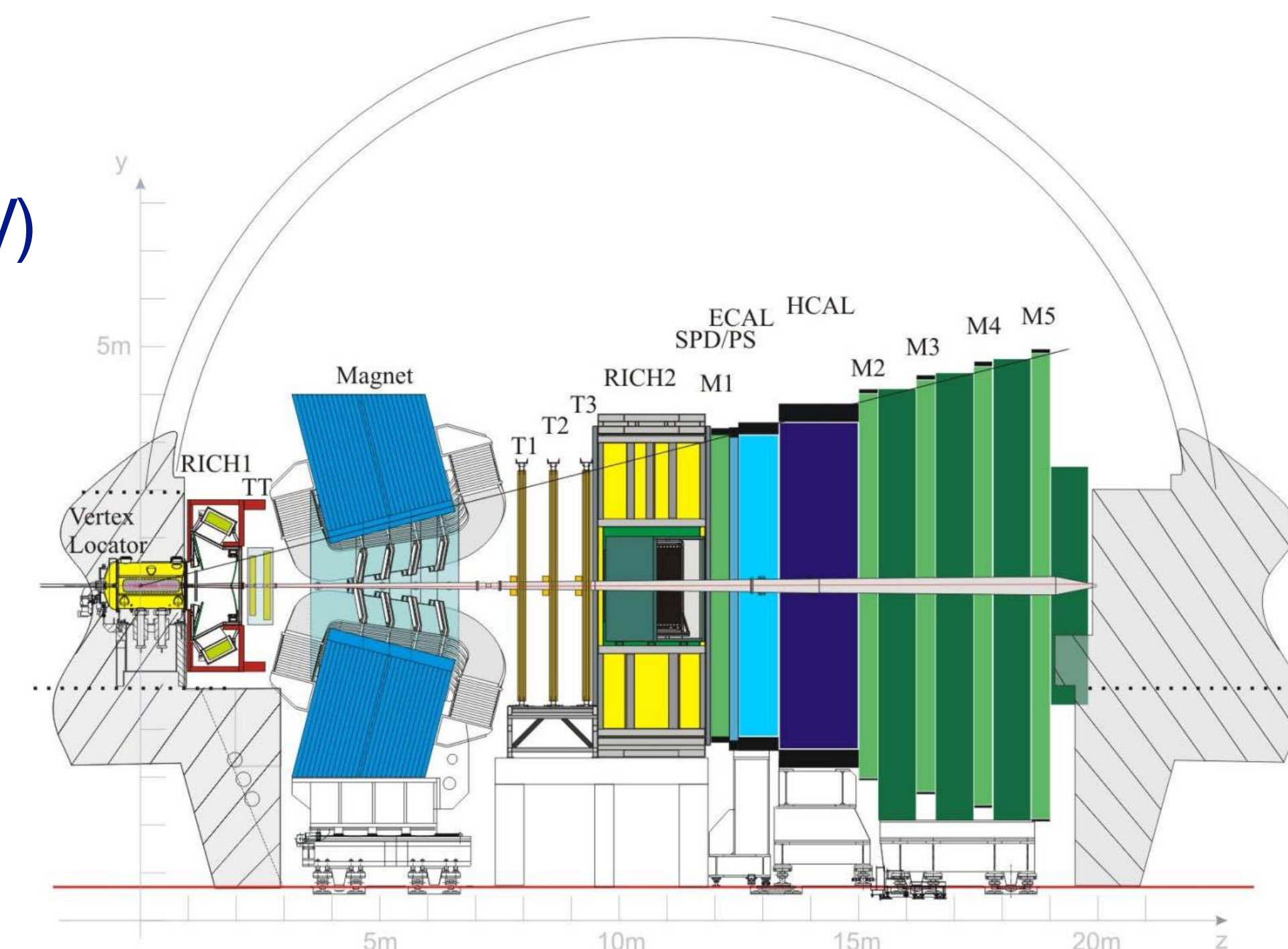
JHEP 05 (2017) 074

$$\sigma(pp \rightarrow D^0 X) = 2072 \pm 2 \pm 124 \mu\text{b}$$

$$\sigma(pp \rightarrow D^+ X) = 834 \pm 2 \pm 78 \mu\text{b}$$

$$\sigma(pp \rightarrow D_s^+ X) = 353 \pm 9 \pm 76 \mu\text{b}$$

$$\sigma(pp \rightarrow D^{*+} X) = 784 \pm 4 \pm 87 \mu\text{b}$$



$$A_{\text{raw}}(D \rightarrow f) \simeq \underbrace{A_{CP}(D \rightarrow f)}_{\text{Physical } CP \text{ asymmetry}} + \underbrace{A_{\text{det}}(f)}_{\text{Final state detection asymmetry}} + \underbrace{A_{\text{det}}(\text{tag})}_{\text{Tagging particle detection asymmetry}} + \underbrace{A_{\text{prod}}(D)}_{\text{Production asymmetry}}$$

- Measured *raw* asymmetry includes also experimental **nuisance asymmetries** that must be canceled
- One or more **calibration samples** are usually used to measure and correct for detection and production asymmetries
- $D^0$  flavour at production is determined by the charge of the **tagging** pion in the  $D^{*\pm} \rightarrow D^0 \pi^\pm$  decay

$$A_{\mathcal{CP}}(D \rightarrow f) = \frac{\Gamma(D \rightarrow f) - \Gamma(\bar{D} \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(\bar{D} \rightarrow \bar{f})}$$

- **Direct CP** violation when  $|A_f|^2 \neq |\bar{A}_{\bar{f}}|^2$
- For **oscillating** neutral mesons, mass eigenstates  $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$ 
  - **CP** violation in **mixing** when  $|q/p| \neq 1$
  - **CP** violation in decay-mixing **interference** when  $\phi_f \equiv \arg[(q\bar{A}_f)/(pA_f)] \neq 0$

$$i\frac{d}{dt} \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left( M - \frac{i}{2}\Gamma \right) \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

## Phenomenological parametrisation

$$x \equiv \frac{2(m_1 - m_2)}{\Gamma_1 + \Gamma_2}, \quad y \equiv \frac{\Gamma_2 - \Gamma_1}{\Gamma_1 + \Gamma_2}, \quad \left| \frac{q}{p} \right| - 1$$

$$\begin{aligned} x^2 - y^2 &= x_{12}^2 - y_{12}^2, \\ xy &= x_{12}y_{12} \cos \phi_{12}, \end{aligned}$$

$$\left| \frac{q}{p} \right|^{\pm 2} (x^2 + y^2) = x_{12}^2 + y_{12}^2 \pm 2x_{12}y_{12} \sin \phi_{12}$$

## Theoretical parametrisation

$$x_{12} \equiv \frac{2|M_{12}|}{\Gamma_1 + \Gamma_2}, \quad y_{12} \equiv \frac{|\Gamma_{12}|}{\Gamma_1 + \Gamma_2}, \quad \phi_{12} \equiv \arg \left( \frac{M_{12}}{\Gamma_{12}} \right)$$

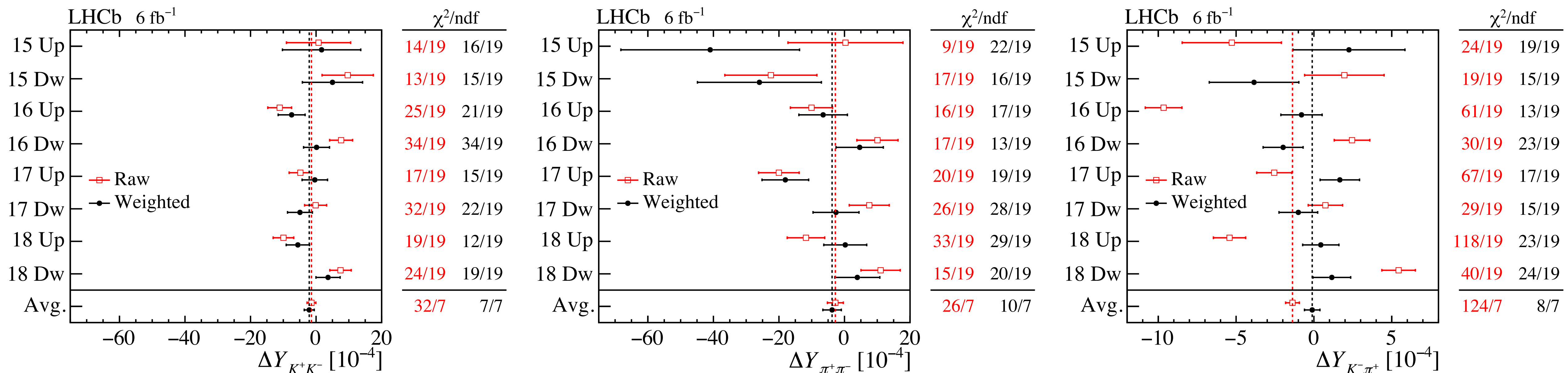
PRL 103 (2009) 071602  
 PRD 80 (2009) 076008  
 PRD 103 (2021) 053008



# $\Delta Y_f$ in $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$

- Signal yield obtained with a **sideband subtraction** in  $m(D^0 \pi^+)$  after fitting the distribution in each decay time
- A correction is applied for contamination of **secondary**  $D^0$  by measuring their size and asymmetry with a multidimensional fit on  $(IP, t)$

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



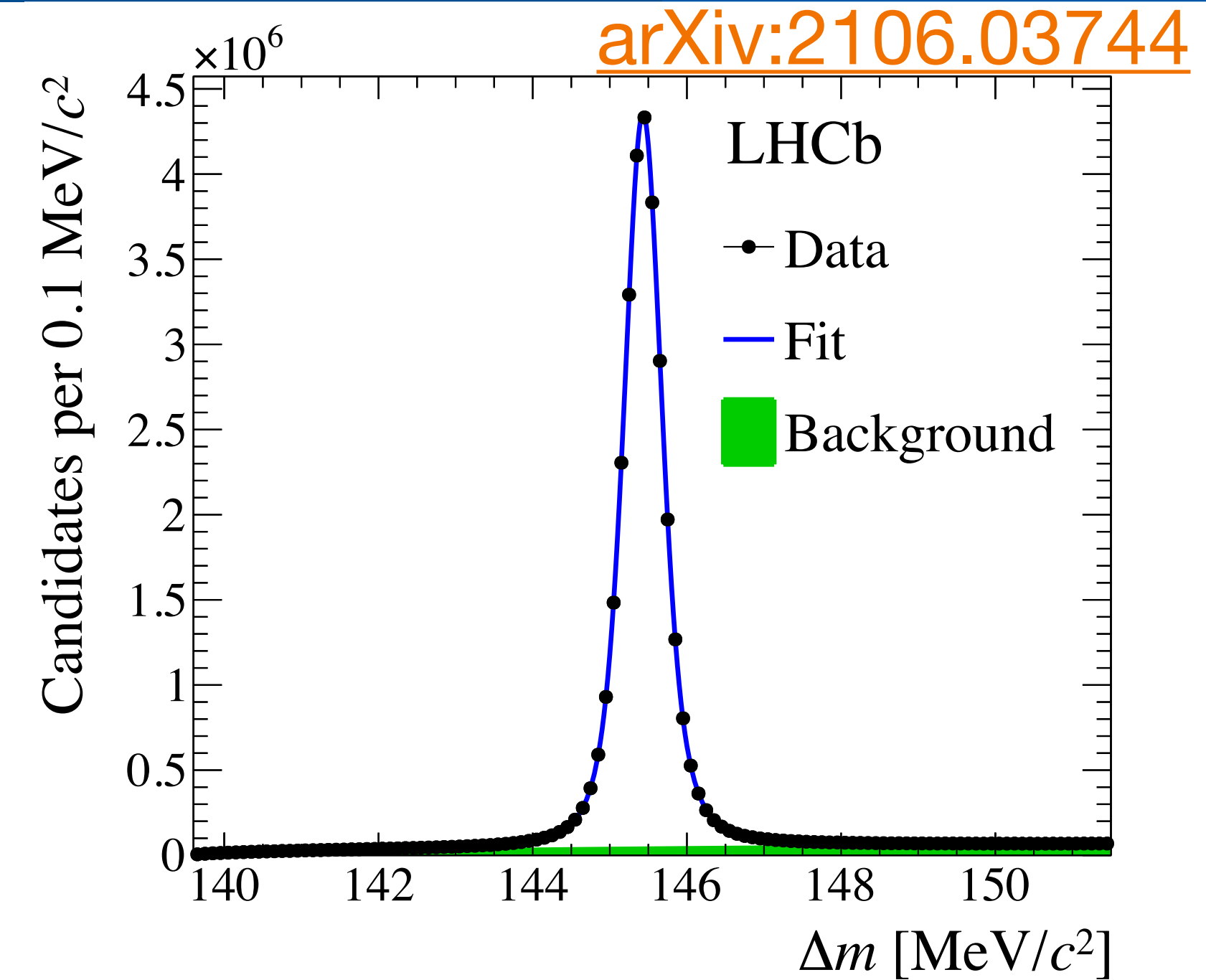
# $\Delta Y_f$ in $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$

## Systematic uncertainties

Source	$\Delta Y_{K^+ K^-}$ [ $10^{-4}$ ]	$\Delta Y_{\pi^+ \pi^-}$ [ $10^{-4}$ ]
Subtraction of the $m(D^0 \pi_{\text{tag}}^+)$ background	0.2	0.3
Flavour-dependent shift of $D^*$ -mass peak	0.1	0.1
$D^{*+}$ from $B$ -meson decays	0.1	0.1
$m(h^+ h^-)$ background	0.1	0.1
Kinematic weighting	0.1	0.1
Total systematic uncertainty	0.3	0.4
Statistical uncertainty	1.5	2.8

# $D^0$ mixing parameters with $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

- In each of the 2 (flavour) x 16 (Dalitz bin) x 13 (decay time bin) subsamples, a **fit** is performed to  $\Delta m = m(D^{*+}) - m(D^0)$  to obtain the yield  $\Rightarrow$  31 M signal decays in total
- Signal selection induces correlation between decay time and phase-space that could bias the measurement  $\Rightarrow$  a data-driven correction is applied to make the **decay-time acceptance uniform** in the phase space
- Correction is applied for **residual detection asymmetry of pions**, calculated from the difference of raw asymmetries of calibration samples  $D_s^+ \rightarrow \pi^+ \pi^+ \pi^-$  and  $D_s^+ \rightarrow \phi \pi^+$



$$A_{\text{meas}}(D_s^+ \rightarrow \pi^+ \pi^+ \pi^-) = A_{\text{det}}(\pi^+ \pi^-) + A_{\text{det}}(\pi^+) + A_{\text{prod}}(D_s^+) + A_{\text{trigger}}(D_s^+)$$

$$A_{\text{meas}}(D_s^+ \rightarrow \phi \pi^+) = A_{\text{det}}(\pi^+) + A_{\text{prod}}(D_s^+) + A_{\text{trigger}}(D_s^+)$$

# $D^0$ mixing parameters with $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

Systematic uncertainties (in units of  $10^{-3}$ )

[arXiv:2106.03744](https://arxiv.org/abs/2106.03744)

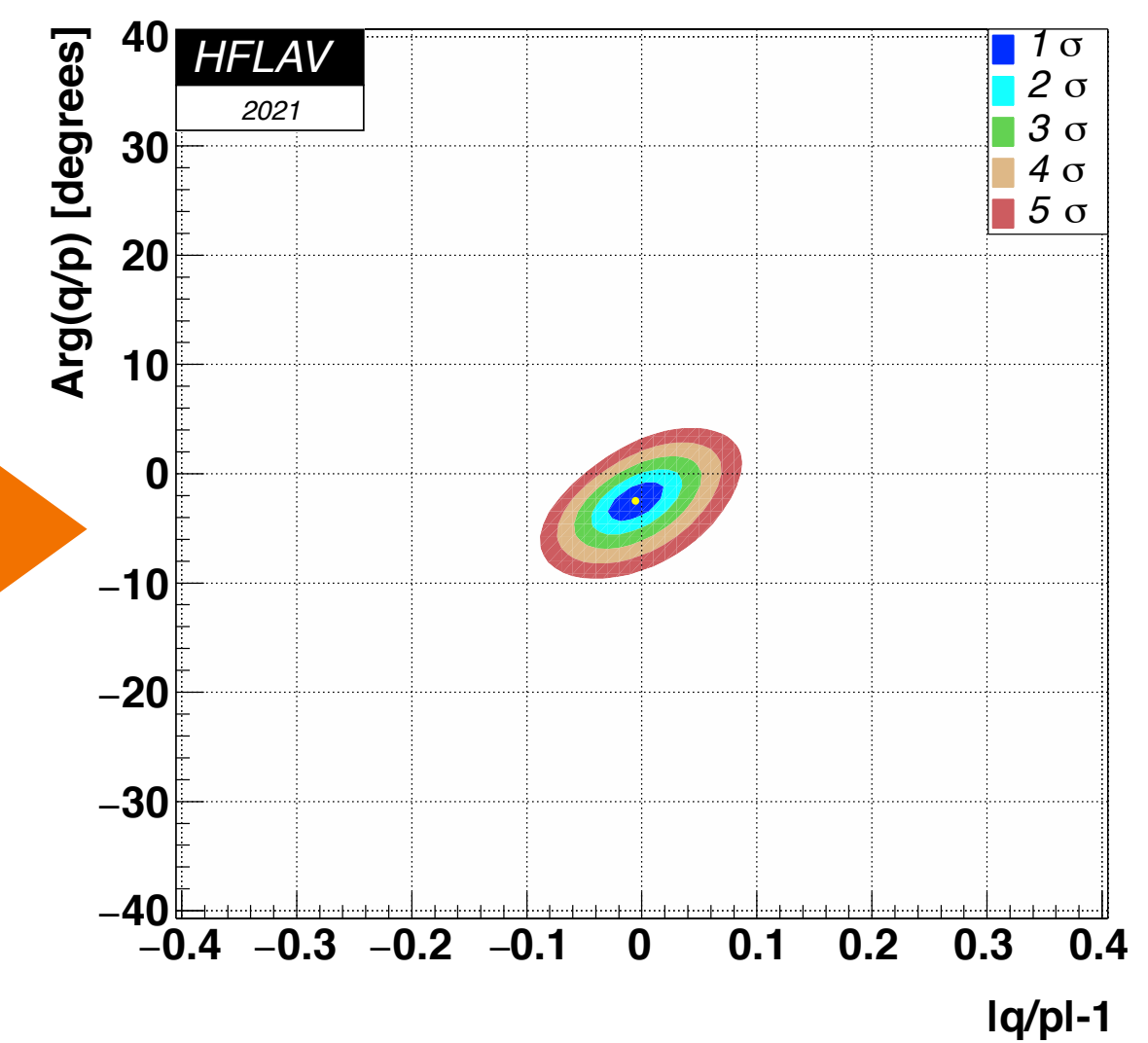
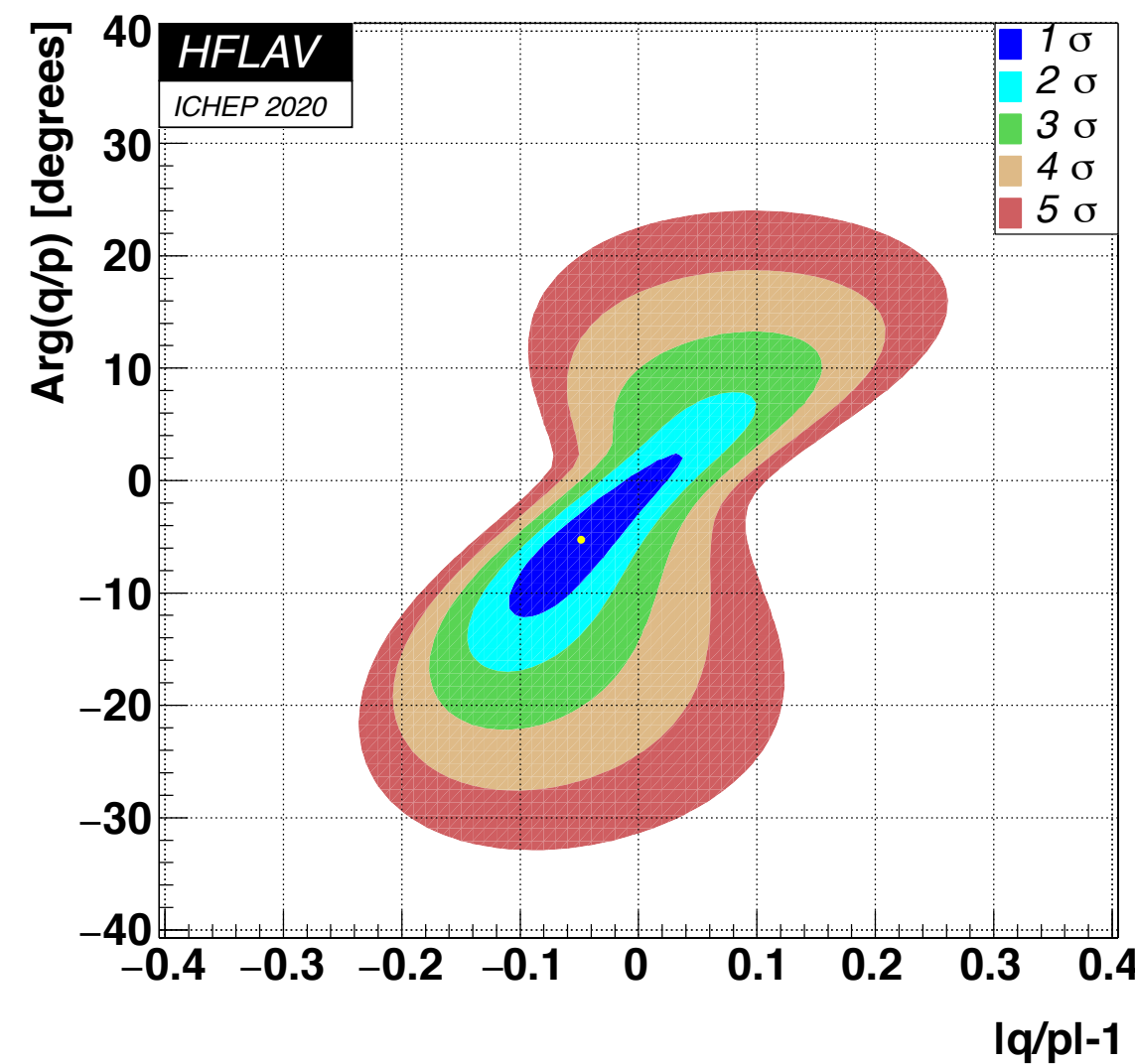
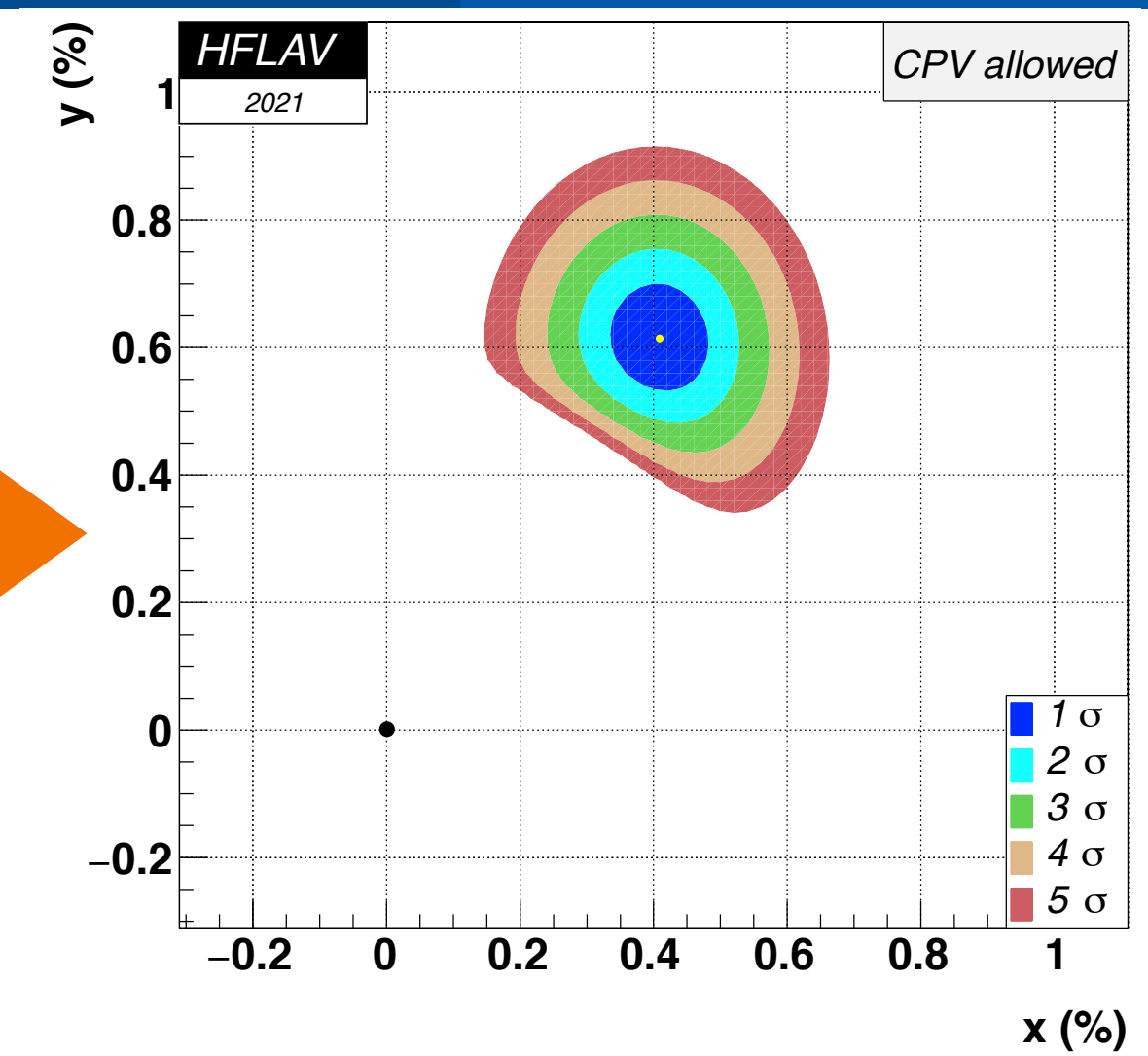
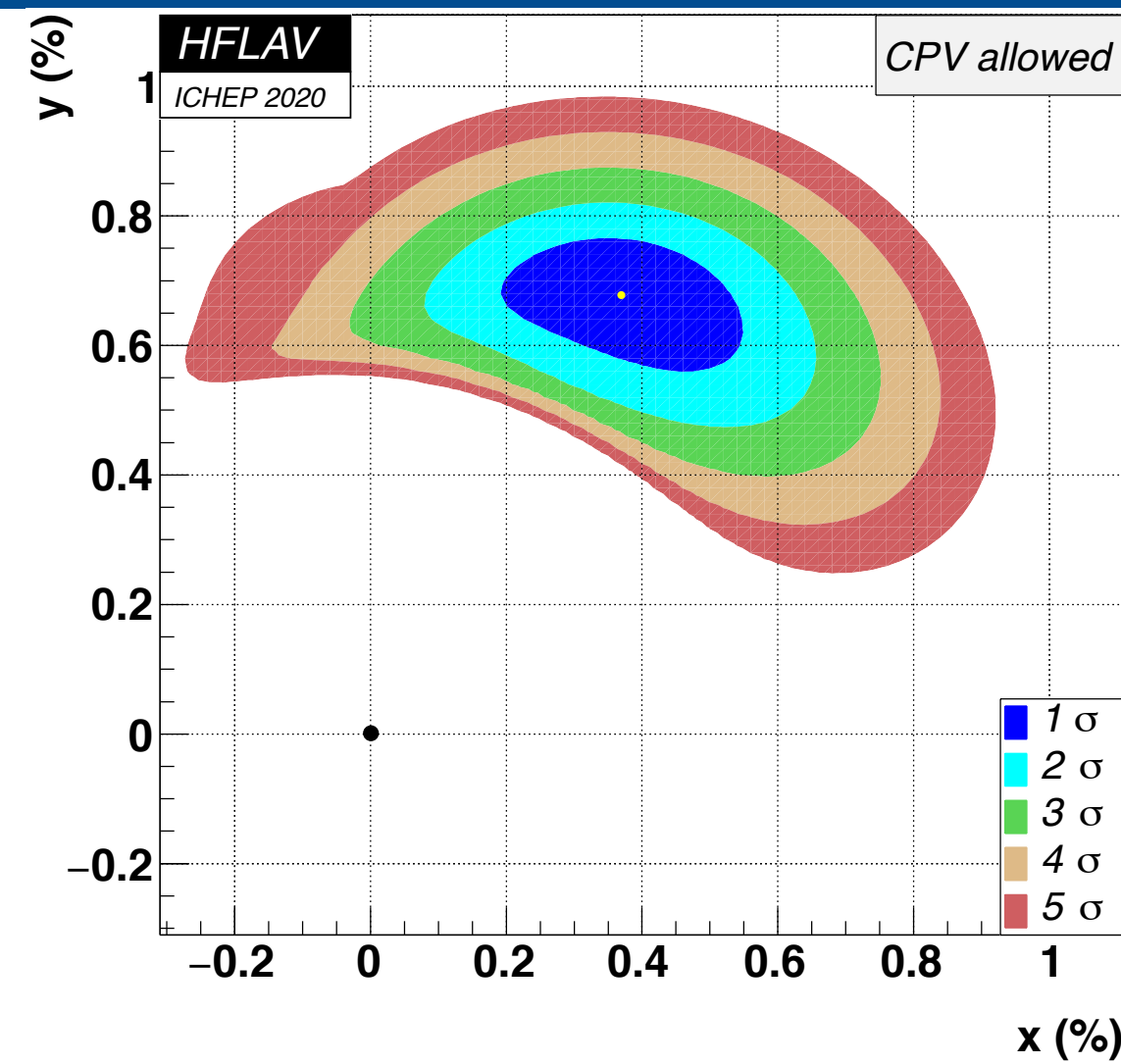
Source	$x_{CP}$	$y_{CP}$	$\Delta x$	$\Delta y$
Reconstruction and selection	0.199	0.757	0.009	0.044
Secondary charm decays	0.208	0.154	0.001	0.002
Detection asymmetry	0.000	0.001	0.004	0.102
Mass-fit model	0.045	0.361	0.003	0.009
Total systematic uncertainty	0.291	0.852	0.010	0.110
Strong phase inputs	0.23	0.66	0.02	0.04
Detection asymmetry inputs	0.00	0.00	0.04	0.08
Statistical (w/o inputs)	0.40	1.00	0.18	0.35
Total statistical uncertainty	0.46	1.20	0.18	0.36

# New world averages

## Phenomenological parametrisation

Great improvement on the  
knowledge of  $x$  and  $q/p$

HFLAV Eur. Phys. J. C (2021) 81 226  
Recently updated



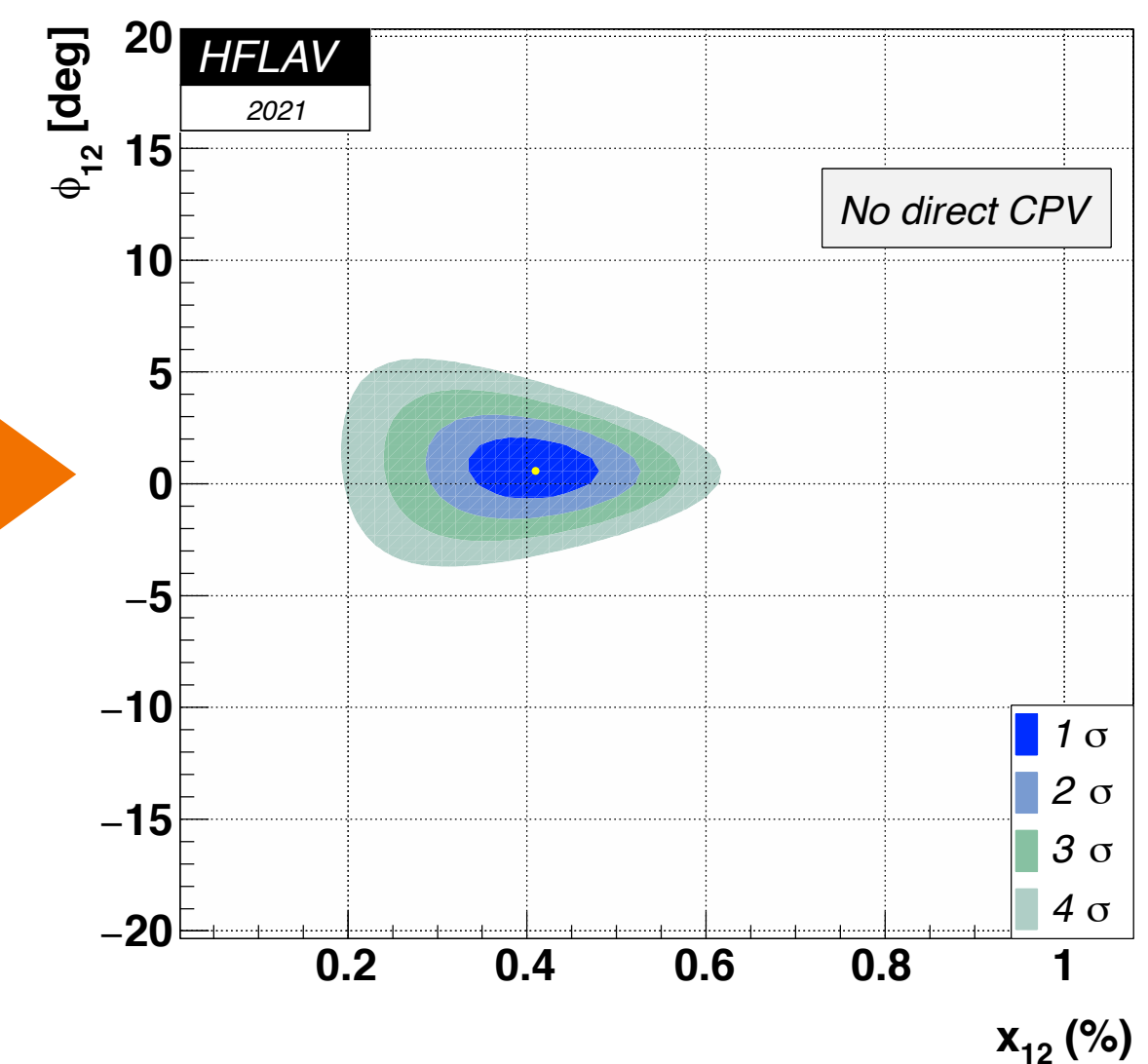
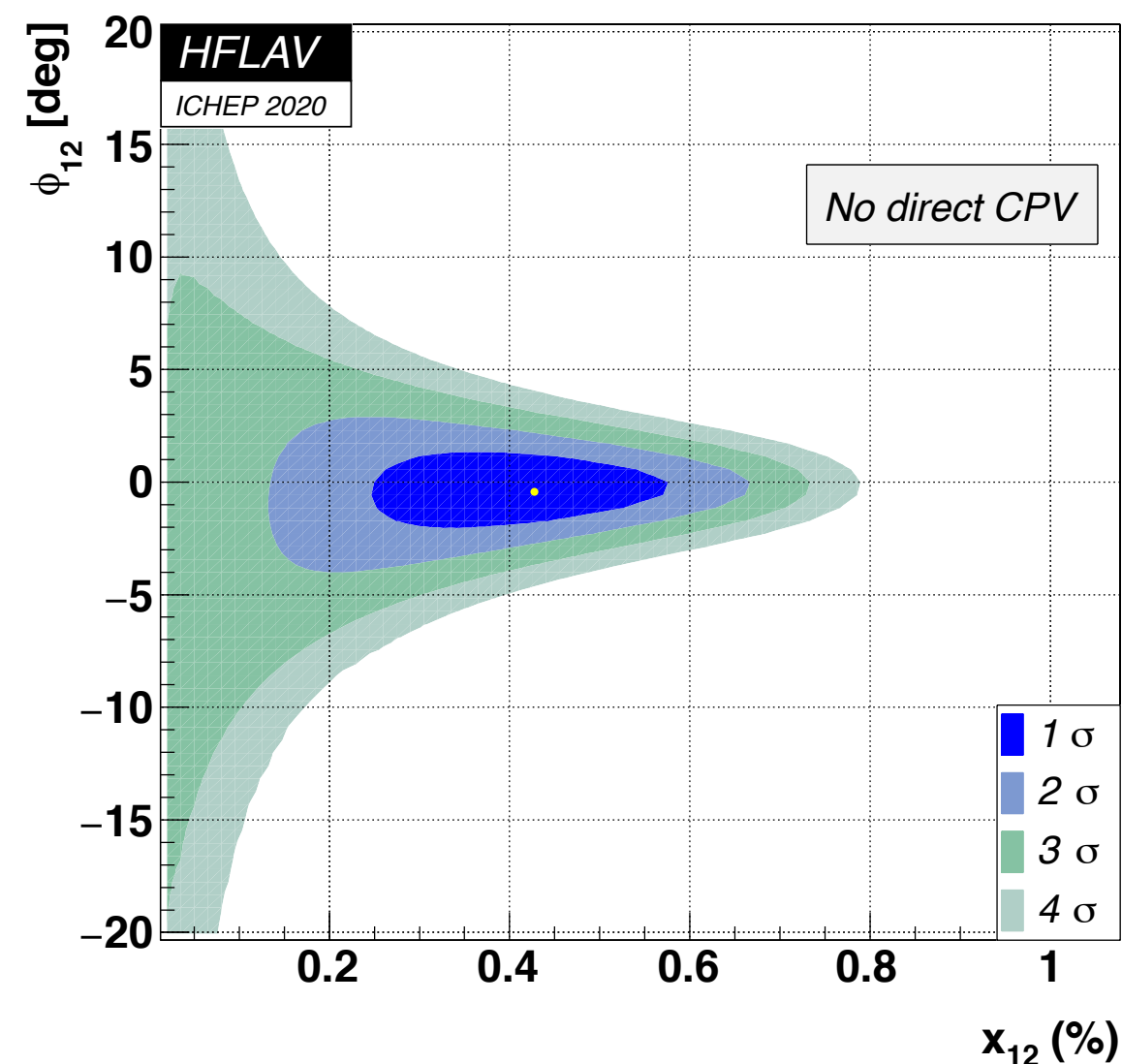
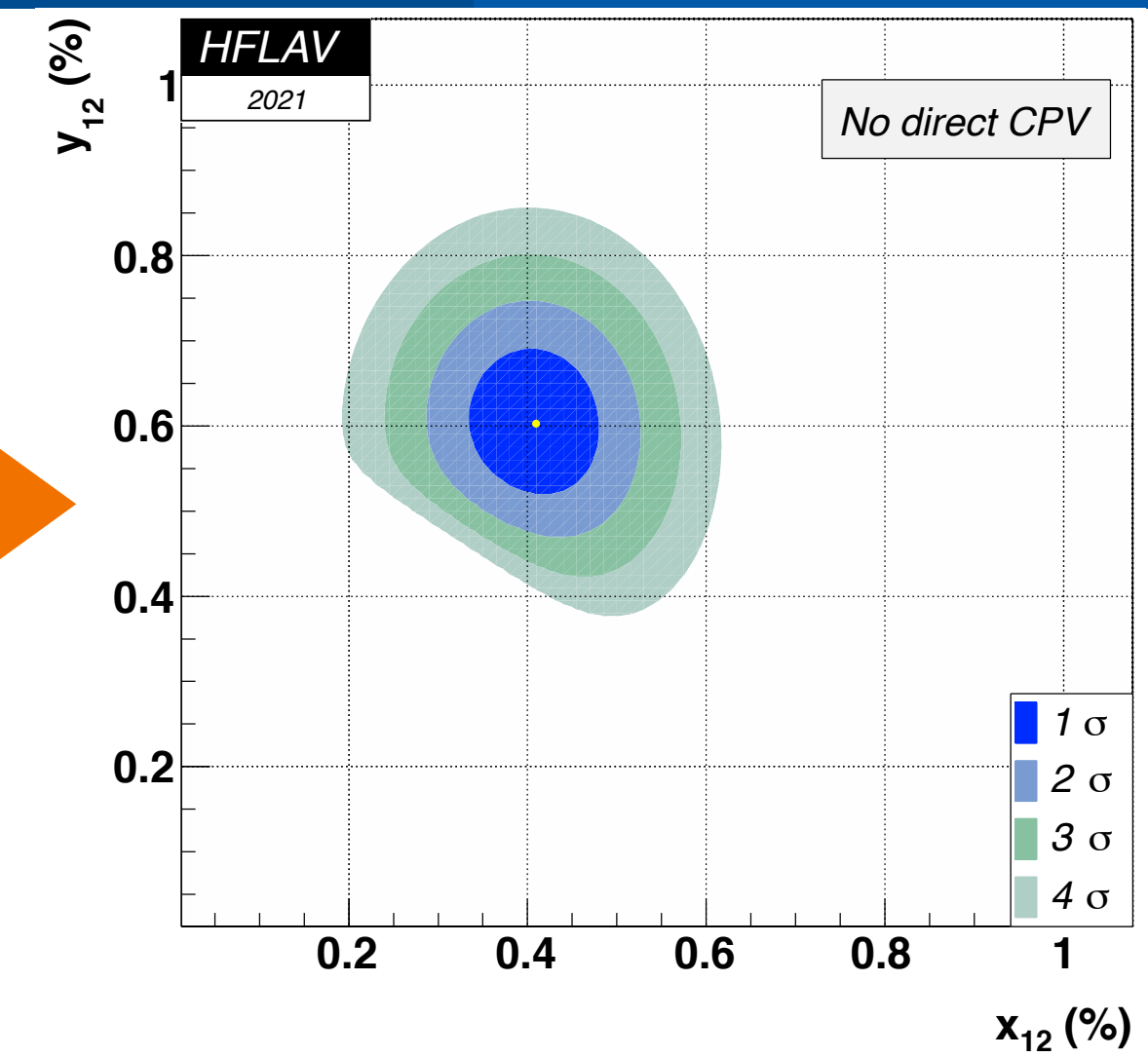
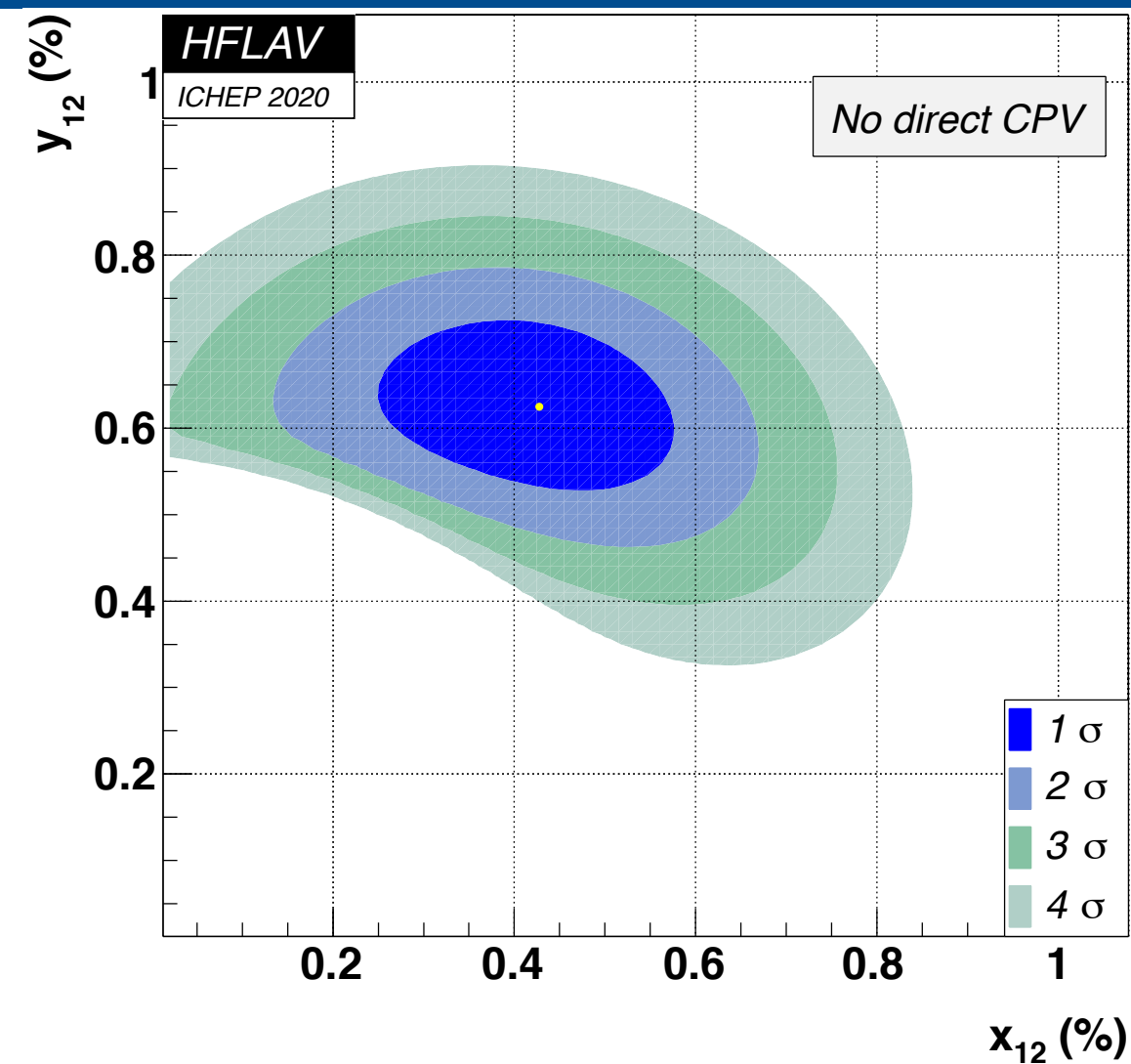
# New world averages

## Theoretical parametrisation

Bounds on the phase of the  
dispersive  $CP$ -violating  
contributions to  $D^0$  mixing  
are tightened

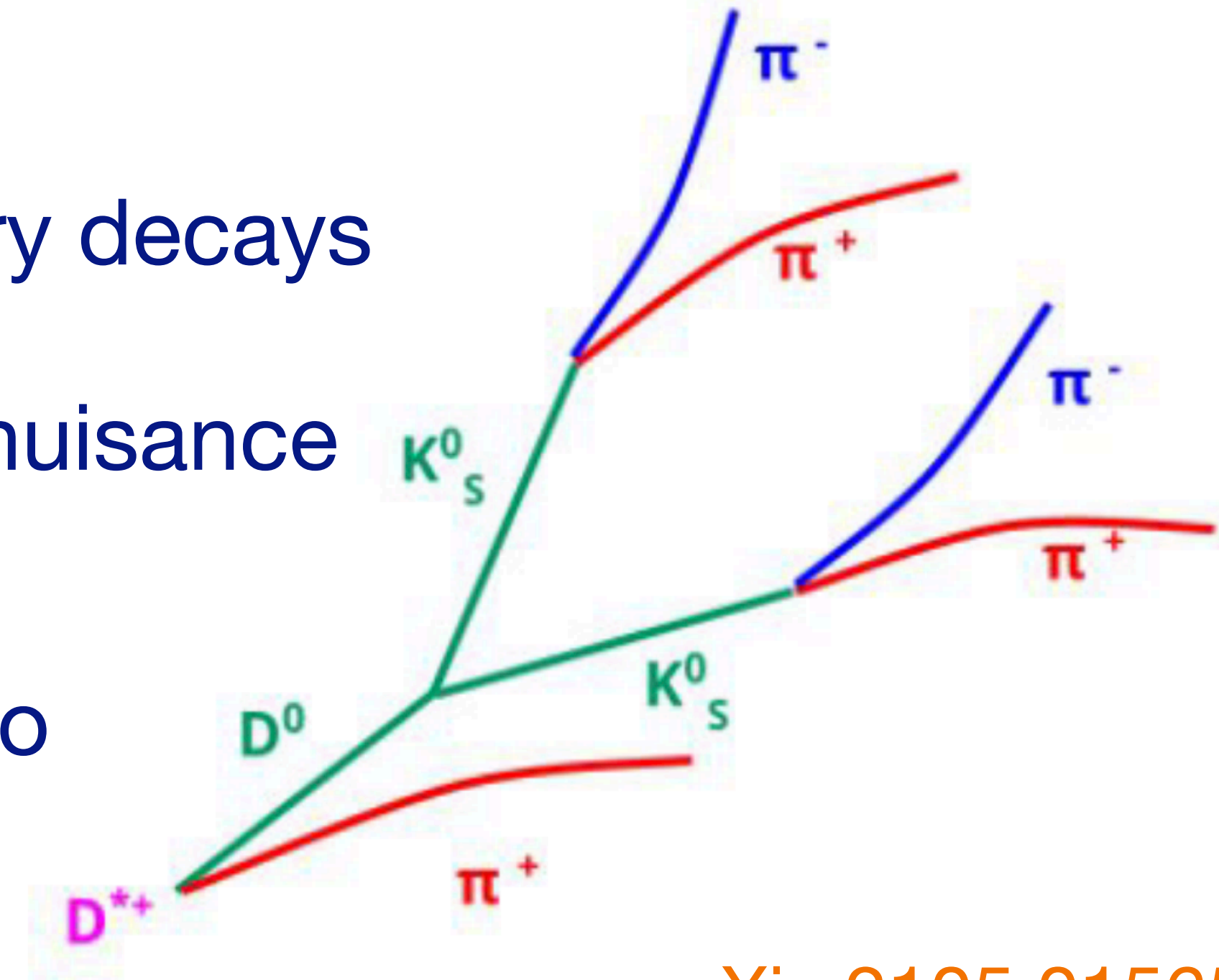
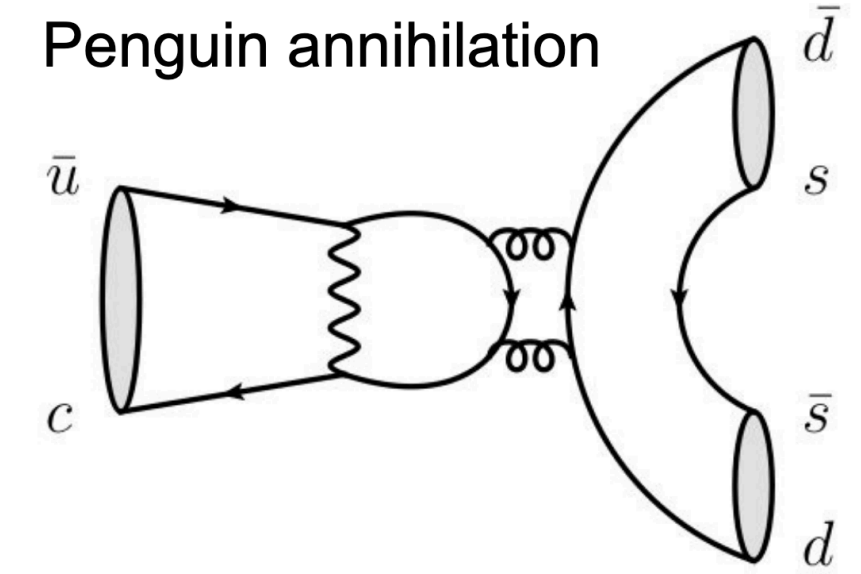
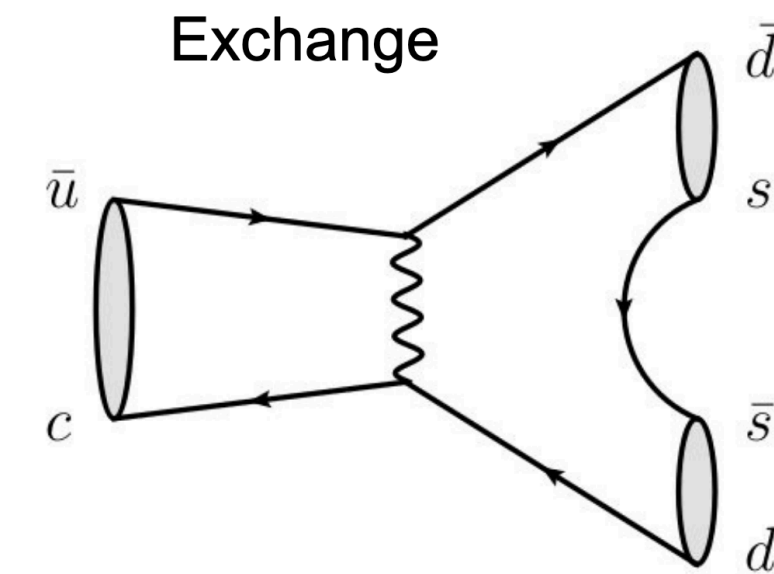
HFLAV Eur. Phys. J. C (2021) 81 226  
Recently updated

See [talk](#) by Mark to see how  
precision further improves when  
including beauty observables!



# $A_{CP}(D^0 \rightarrow K_S^0 K_S^0)$

- $A_{CP}$  expected to be as large as  $\sim 1\%$  PRD 92 (2015) 054036
- $K_S^0$  challenging  $\Rightarrow$  need to consider separately  $K_S^0$  reconstructed from **long** pions (L) and **downstream** pions (D)
- Consider  $D^{*+}$  produced both in prompt and secondary decays
- $D^0 \rightarrow K^+ K^-$  used as a **calibration** sample to cancel nuisance detection and production asymmetries
- Raw asymmetry obtained from a multidimensional **fit** to  $\Delta m = m(D^{*+}) - m(D^0)$  and  $m(K_S^0)$



[arXiv:2105.01565](https://arxiv.org/abs/2105.01565)

$$A_{CP}(D^0 \rightarrow K_S^0 K_S^0)$$

Sample	2015 + 2016 (2 fb <sup>-1</sup> )			2017 + 2018 (4 fb <sup>-1</sup> )		
	Yield	$\mathcal{A}^{CP}$ [%]		Yield	$\mathcal{A}^{CP}$ [%]	
LL PV-comp.	1388 ± 41	0.3 ± 2.5	± 0.6	4056 ± 77	-4.3 ± 1.6	± 0.4
LL PV-incomp.	178 ± 31	-11 ± 17	± 2	430 ± 41	-3.0 ± 7.9	± 1.1
LD PV-comp.	411 ± 25	-7.2 ± 5.8	± 1.1	1145 ± 49	-2.9 ± 3.8	± 0.7
LD PV-incomp.	58 ± 18	-10 ± 31	± 4	349 ± 64	-5 ± 17	± 2
DD	—	—	—	87 ± 28	-35 ± 47	± 6

Systematic uncertainties for:

- Residual background in  $D^0 \rightarrow K^+ K^-$
- Fit model
- Difference in secondaries fraction between signal and calibration

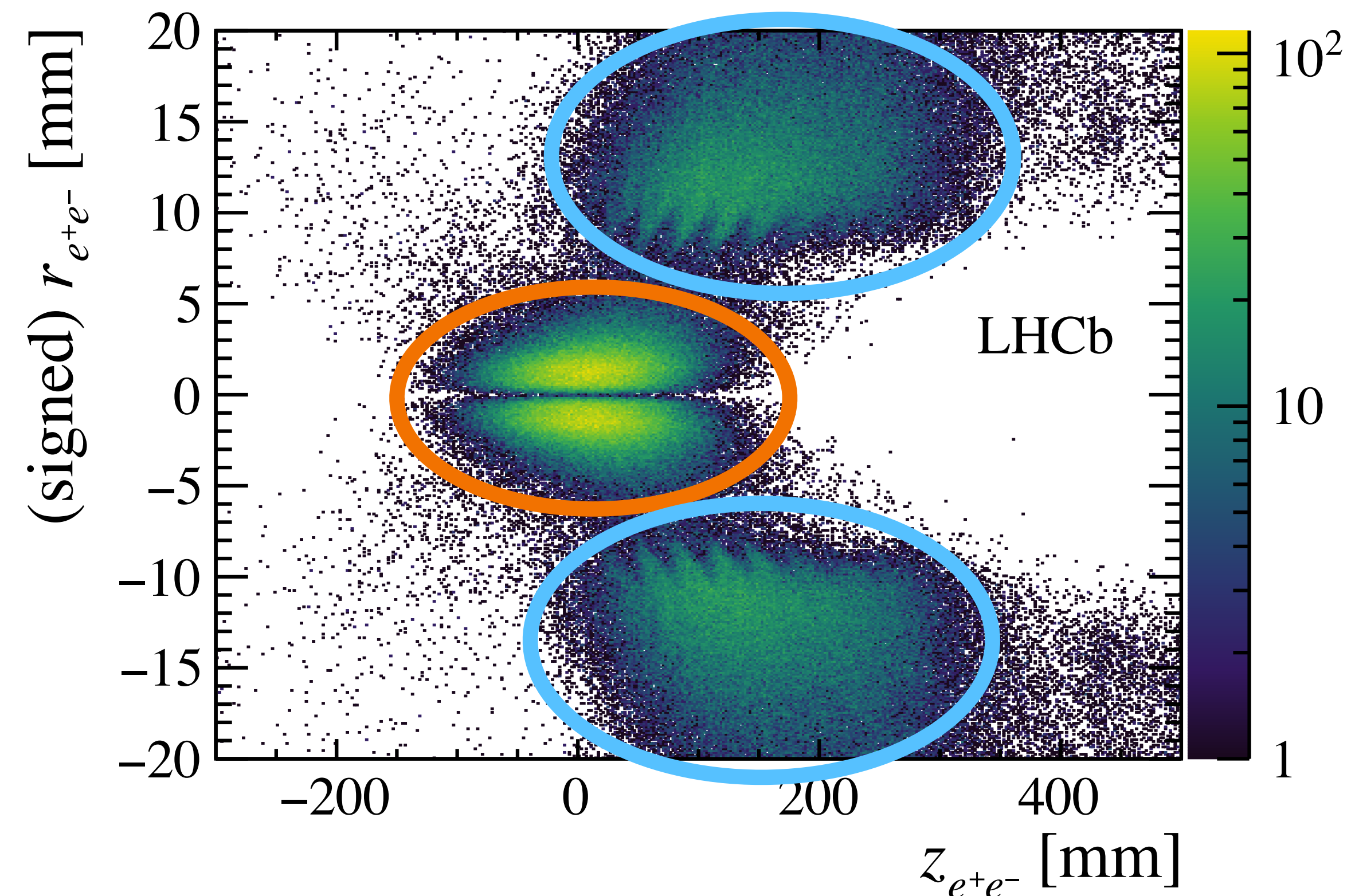
[arXiv:2105.01565](https://arxiv.org/abs/2105.01565)



$$A_{CP}(D_{(s)}^+ \rightarrow h^+ \pi^0, h^+ \eta)$$

- In the SM,  $A_{CP} \sim 10^{-3} - 10^{-4}$  for **SCS**  $D_s^+ \rightarrow K^+ \pi^0$ ,  $D_s^+ \rightarrow K^+ \eta$  and  $D^+ \rightarrow \pi^+ \eta$ , and  $A_{CP}(D^+ \rightarrow \pi^+ \pi^0) = 0$  PRD 85 (2012) 034036
- $h^0$  reconstructed in  $\gamma(\rightarrow e^+e^-)\gamma$  or  $e^+e^- \gamma$  final states to reconstruct the secondary vertex  
 ➔ useful to suppress background from  $pp$
- Raw asymmetry obtained from multidimensional **fit** to  $m(e^+e^- \gamma)$  and  $m(h^+ h^0)$
- $D_{(s)}^+ \rightarrow K_s^0 h^+$  used as a **calibration** sample to cancel nuisance detection and production asymmetries

[JHEP 06 \(2021\) 019](#)



$$A_{CP}(D_{(s)}^+ \rightarrow h^+ \pi^0, h^+ \eta)$$

## Systematic uncertainties

Source	$D^+ \rightarrow \pi^+ \pi^0$	$D^+ \rightarrow K^+ \pi^0$	$D_s^+ \rightarrow K^+ \pi^0$
Fit model	0.59	1.55	1.01
PID asymmetry	0.06	0.27	0.15
Secondary decays	< 0.01	0.01	0.02
Combined $A_{Raw}$ Run 1 and Run 2	0.23	0.65	0.30
Control modes	0.03	1.18	0.59
$A_{Mix}(K^0)$	< 0.01	< 0.01	< 0.01
$\mathcal{A}_{CP}(D_{(s)}^+ \rightarrow K_S^0 h^+)$	0.12	0.08	0.26
Total	0.65	2.07	1.24

[JHEP 06 \(2021\) 019](#)

Source	$D^+ \rightarrow \pi^+ \eta$	$D_s^+ \rightarrow \pi^+ \eta$	$D^+ \rightarrow K^+ \eta$	$D_s^+ \rightarrow K^+ \eta$
Fit model	0.35	0.15	4.04	1.08
PID asymmetry	0.06	0.01	0.87	0.16
Secondary decays	< 0.01	0.02	0.01	0.04
Control modes	0.05	0.39	0.14	0.12
$A_{Mix}(K^0)$	< 0.01	< 0.01	< 0.01	< 0.01
$\mathcal{A}_{CP}(D_{(s)}^+ \rightarrow K_S^0 h^+)$	0.12	0.20	0.08	0.26
Total	0.38	0.46	4.13	1.13

# Future prospects

- Some key measurements still to be performed with **Run 2** data, such as:

- $A_{CP}(D^0 \rightarrow K^+K^-) \Rightarrow$  expected uncertainty  $7 \times 10^{-4}$

- $y_{CP}(D^0 \rightarrow h^+h^-)$

- With Upgrade I and II, LHCb will be able to reduce the statistical uncertainty of the  $CP$  violating observables in charm by  $\sim$  **1 order** of magnitude

- No systematic uncertainties are known to have irreducible contributions which exceed the ultimate statistical precision
  - $\Rightarrow$  strong potential of **probing SM** and characterise **new physics** contributions to  $CP$  violation in the charm sector with future upgrades

$$D^0 \rightarrow K_s^0 \pi^+ \pi^-$$

Sample (lumi $\mathcal{L}$ )	Tag	Yield	$\sigma(x)$	$\sigma(y)$	$\sigma( q/p )$	$\sigma(\phi)$
Run 1-2 (9 fb <sup>-1</sup> )	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 <sup>-1</sup> )	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 <sup>-1</sup> )	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 <sup>-1</sup> )	SL	490M	0.009%	0.008%	0.009	0.69°
	Prompt	3500M	0.005%	0.005%	0.004	0.18°

## LHCb-PUB-2018-009

$$\Delta Y$$

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