Mixing and CP violation in beauty and charm at the LHC

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ON BEHALF OF THE LHCB COLLABORATION,

WITH MATERIAL FROM ATLAS, CMS, AND LHCB

LES RENCONTRES DE PHYSIQUE DE LA VALLÉE D'AOSTE, MARCH 13, 2019

Why study CP violation?

- The Standard Model (SM) does an excellent job of describing existing data, but it is clearly an incomplete theory.

- Example: SM CP violation is not capable of generating the observed matter-antimatter asymmetry of the universe.

- Most extensions of SM include new sources of CP violation.
- ➢ Likely that the CKM picture of flavour physics is modified, and hopefully at accessible energy scales.

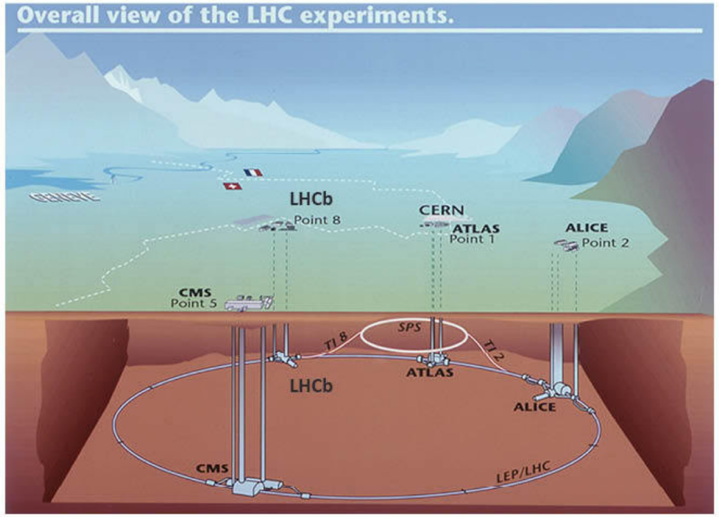
- “Indirect” searches have often provided first glimpse of new particles, e.g. the discovery of the top quark.

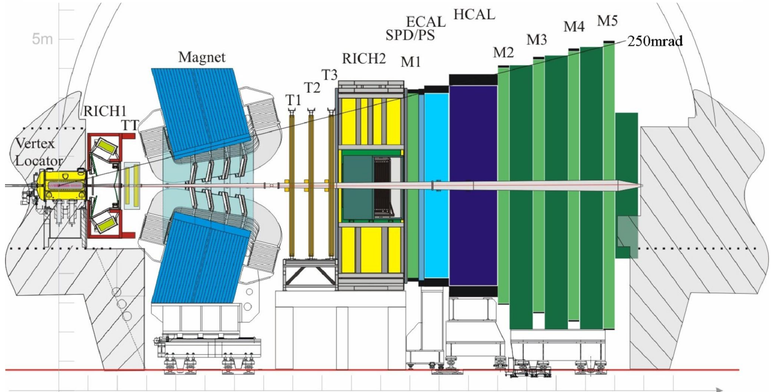
Measurements at the LHC

- Each second LHC produces $\mathcal{O}(100\text{k})$ b- and $\mathcal{O}(1\text{M})$ c-hardrons.
- ➢ ATLAS, CMS, and LHCb take advantage for studying CP violation and mixing.

- LHCb is designed for precision measurements of b- and c-hadrons.
- ➢ Unsurprisingly the source of most new results.

- And there is a lot that is new!
- ➢ Happy to be able to show some results for the first time.
- ➢ Try to give an overview of the themes studied in context of new results, but not a complete list!

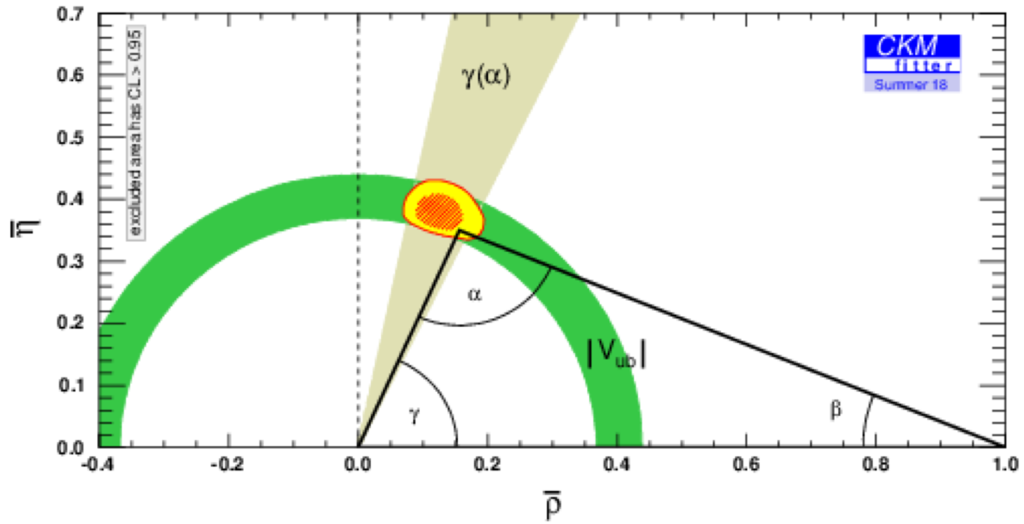


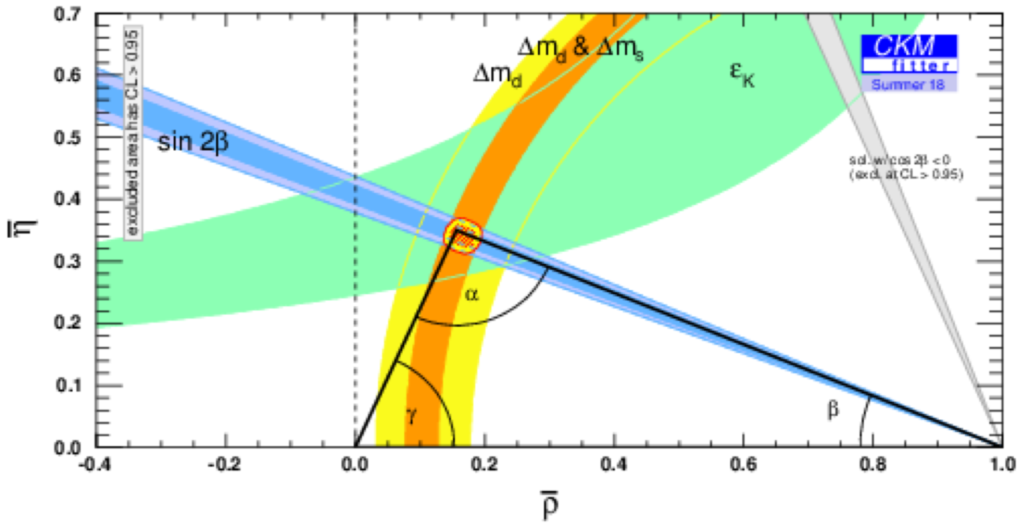


Int. J. Mod. Phys. A 30, 1530022 (2015)

Beauty

- From unitarity condition $V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$
- Goal: precisely measure these triangles to test consistency of CKM description of CPV





Measurements of γ

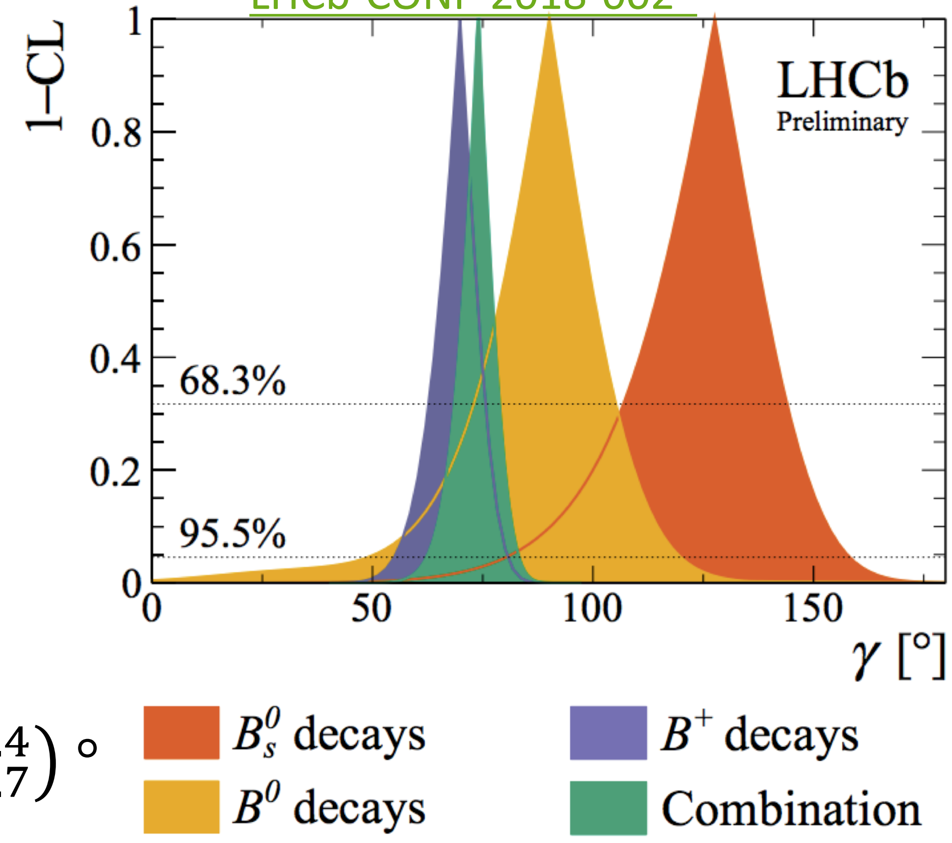
- A key part of the CP violation programme at LHCb is measurement of unitarity angle

$$\gamma \equiv \arg[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}]$$

- Accessed through exploiting the interference between $b \to cW$ and $b \to uW$ transitions.
- Combine the knowledge from several B decays and subsequent D decays.

➢ Latest LHCb average $\gamma = \left(74.0^{+5.0}_{-5.8}\right)^{\circ}$

LHCb-CONF-2018-002



- As of summer 2018, the world average is $\gamma = \left(72.1^{+5.4}_{-5.7}\right)^{\circ}$

➢ Indirect value is $\gamma = (65.64^{+0.97}_{-3.42})^{\circ}$

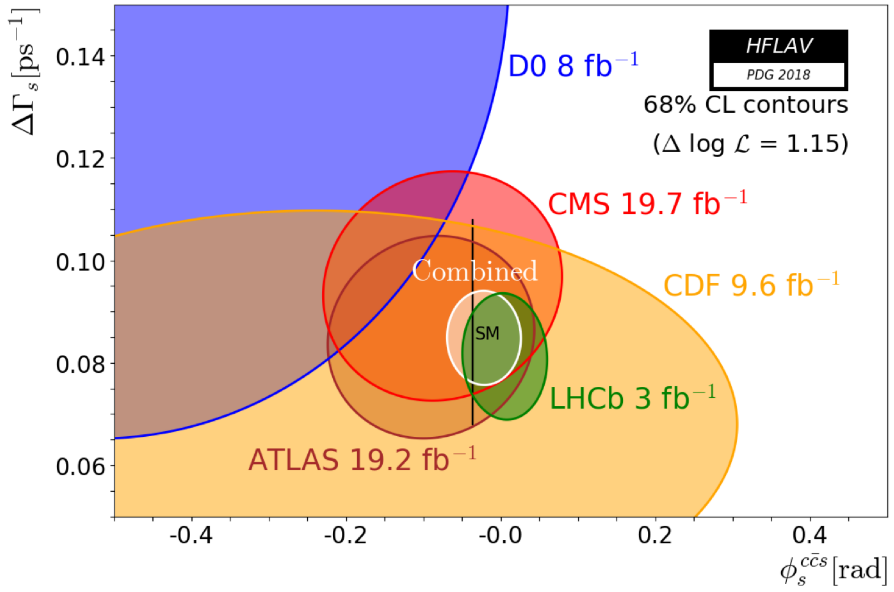
CP violation in interference of mixing and decay

- Excellent probe for physics beyond the SM.

- An important example in the B_s^0 system is that of $\phi_s \approx -2\beta_s \equiv \arg[-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*]$
  - Inferred with high precision from other measurements.
  - Can be enhanced by new physics contributions.

- Golden mode for measuring ϕ_s is $B_s^0 \to J/\psi\, K^+K^-$
  - Measurements performed by ATLAS, CMS, and LHCb using Run 1 data

- Also measured by LHCb in $B_s^0 \to J/\psi\, \pi^+\pi^-$, and similar observables in other B_s^0 decay modes.



LHCb: PRL 114, 041801 (2015)
CMS: PLB 757 (2016) 97
ATLAS: JHEP 08 (2016) 147

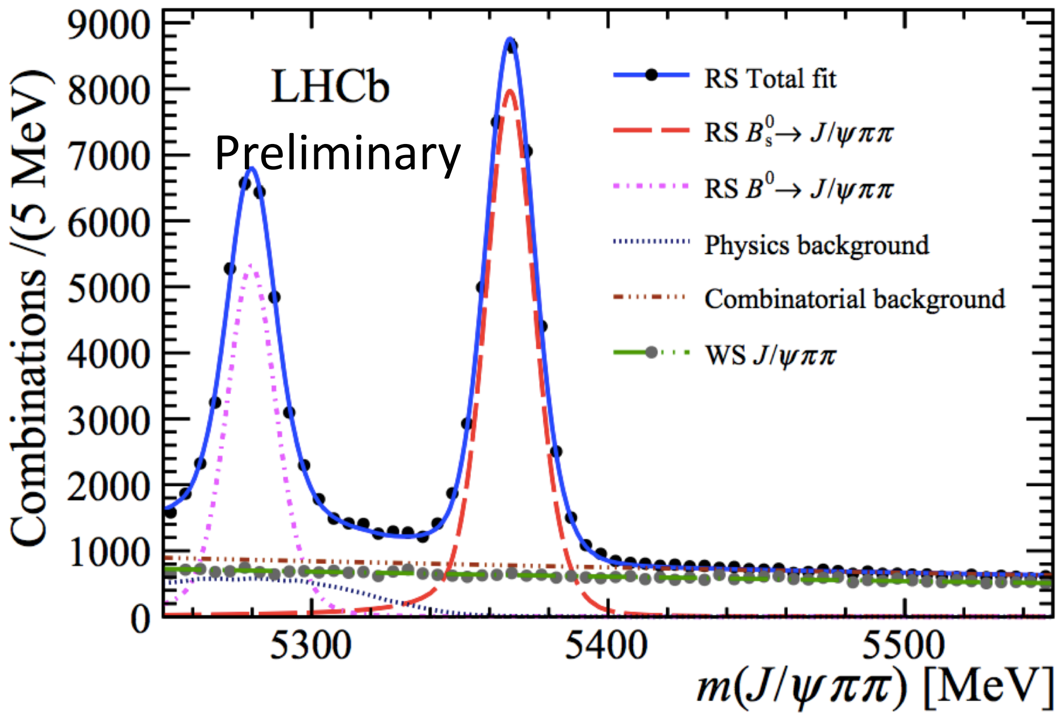
[In preparation]

"Measurement of the CP-violating phase ϕ_s from $B_s^0 \to J/\psi\,\pi^+\pi^-$ decays in 13 TeV pp collisions"

New!

- An update has been performed using 1.9fb^{-1} of LHCb data taken in 2015-2016

- Tagged, time-dependent angular analysis needed, making for a complicated analysis:
  - Acceptance modelling in 4 dimensions of the decay phase-space.
  - Decay-time acceptance and resolution.
  - Tagging the flavour of the B_s at production.
  - Description of the $\pi^+\pi^-$ resonance spectrum.

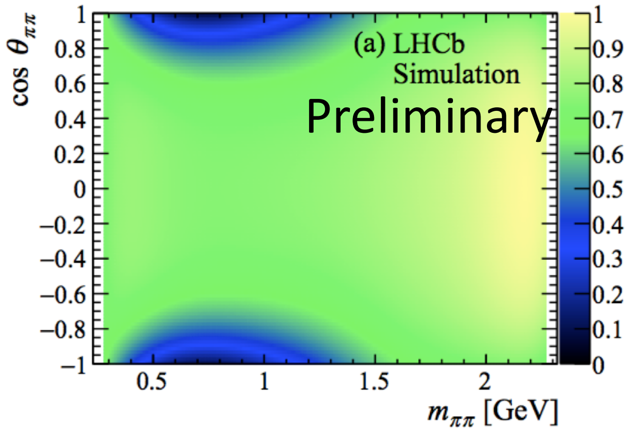


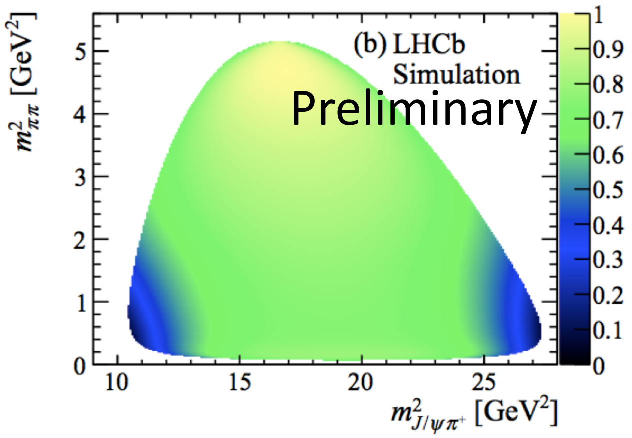
[In preparation]

Detector response and flavour tagging

- Four dimensional efficiency determined from simulation.

- Data-driven determination of decay-time acceptance and resolution (average resolution of 41.5fs)





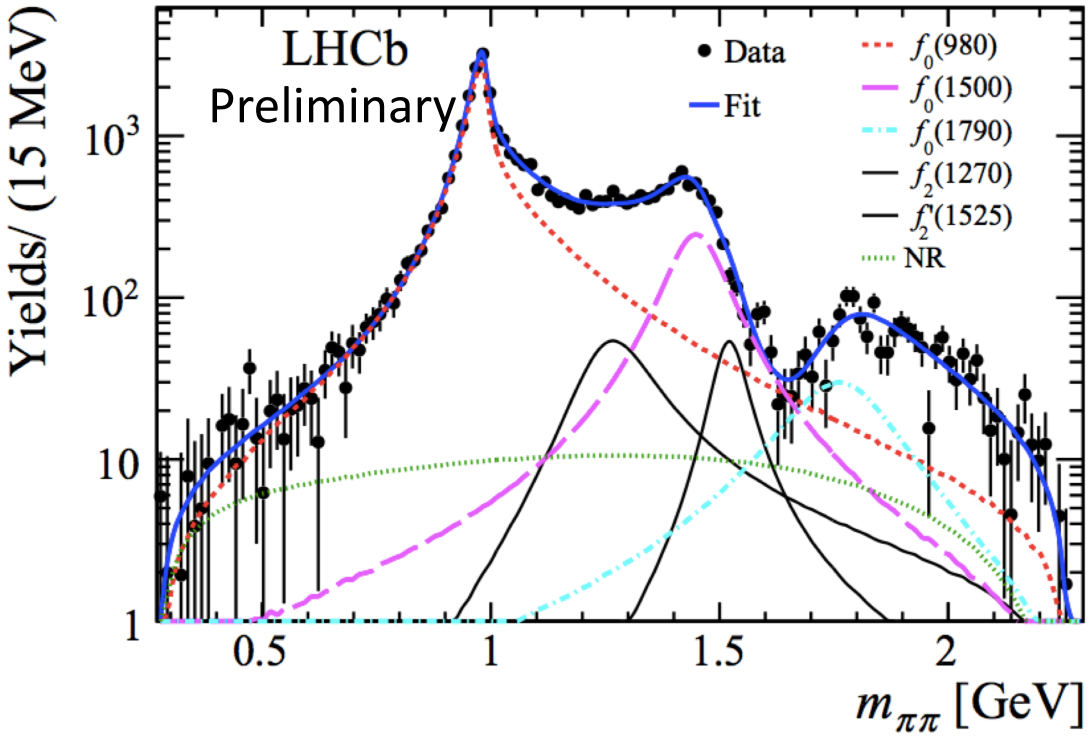
- Flavour tagging uses information from decays of other b hadron produced in the event (OS) and fragments of jet that produced B_s that contain charged K

Category	$\varepsilon_{\rm tag}$ (%)	$\varepsilon_{\rm tag}D^2$(%)
OS only	11.0 ± 0.6	0.86 ± 0.05
SSK only	42.6 ± 0.6	1.54 ± 0.33
OS and SSK	24.9 ± 0.6	2.66 ± 0.19
Total	78.5 ± 0.7	5.06 ± 0.38

Resonance model

- Several models considered, with second best used to assign associated systematic uncertainties.

Component	Fit fractions (%)	Transversity fractions (%) 0	$\parallel$	$\perp$
		Solution I		
$f_0(980)$	60.09 ± 1.48	100	–	–
$f_0(1500)$	8.88 ± 0.87	100	–	–
$f_0(1790)$	1.72 ± 0.29	100	–	–
$f_2(1270)$	3.24 ± 0.48	13 ± 3	37 ± 9	50 ± 10
$f_2'(1525)$	1.23 ± 0.86	40 ± 13	31 ± 14	29 ± 25
NR	2.64 ± 0.73	100	–	–
		Solution II		
$f_0(980)$	93.05 ± 1.12	100	–	–
$f_0(1500)$	6.47 ± 0.41	100	–	–
$f_0(1710)$	0.74 ± 0.11	100	–	–
$f_2(1270)$	3.22 ± 0.44	17 ± 4	30 ± 8	53 ± 10
$f_2'(1525)$	1.44 ± 0.36	35 ± 8	31 ± 12	34 ± 17
NR	8.13 ± 0.79	100	–	–



[In preparation]

CP-violating parameter results

	Fit result	Correlation		
Parameter		$\Gamma_{\mathrm{H}} - \Gamma_{B^0}$	$\lvert\lambda\rvert$	ϕ_s
$\Gamma_{\mathrm{H}} - \Gamma_{B^0}$ (ps^{-1})	$-0.050 \pm 0.004 \pm 0.004$	1.000	0.022	0.038
$\lvert\lambda\rvert$	$1.01^{+0.08}_{-0.06} \pm 0.03$	0.022	1.000	0.065
ϕ_s (rad)	$-0.057 \pm 0.060 \pm 0.011$	0.038	0.065	1.000

- A combination with the Run 1 measurement gives:

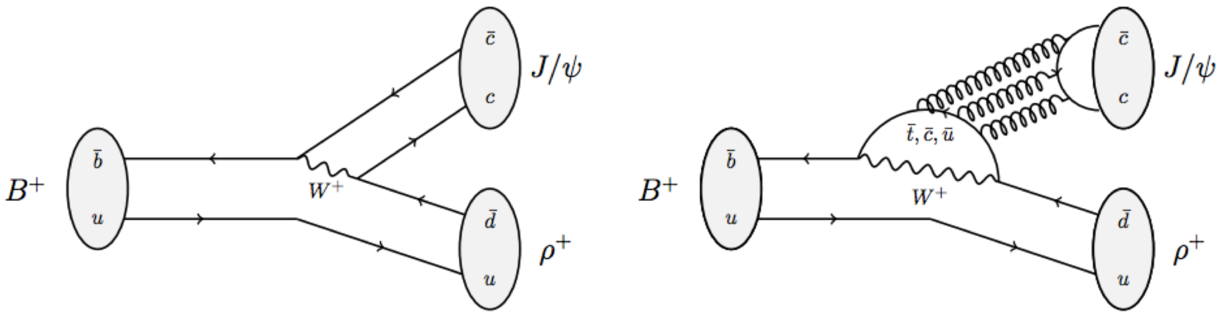
$$\Gamma_H - \Gamma_{B^0} = -0.050 \pm 0.004 \pm 0.004 \text{ ps}^{-1},$$
$$|\lambda| = 0.949 \pm 0.036 \pm 0.019, \text{ and}$$
$$\phi_s = 0.002 \pm 0.044 \pm 0.012 \text{ rad}$$

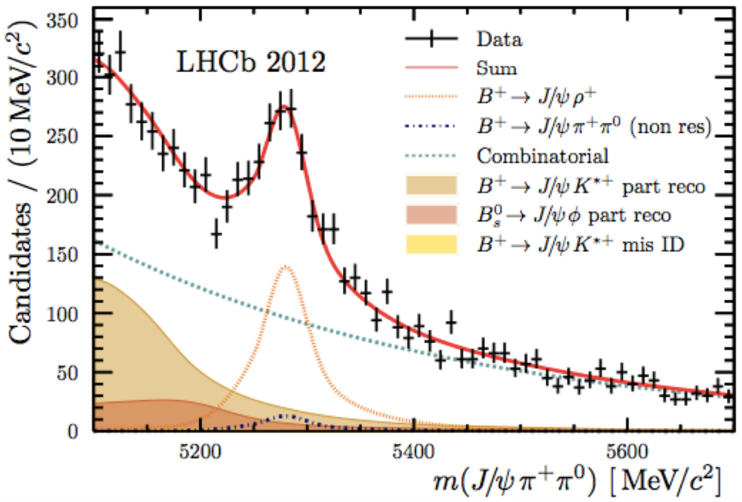
Consistent with inferred value of $-36.5^{+1.3}_{-1.2}$ mrad. (Phys. Rev. D91 (2015) 073007)

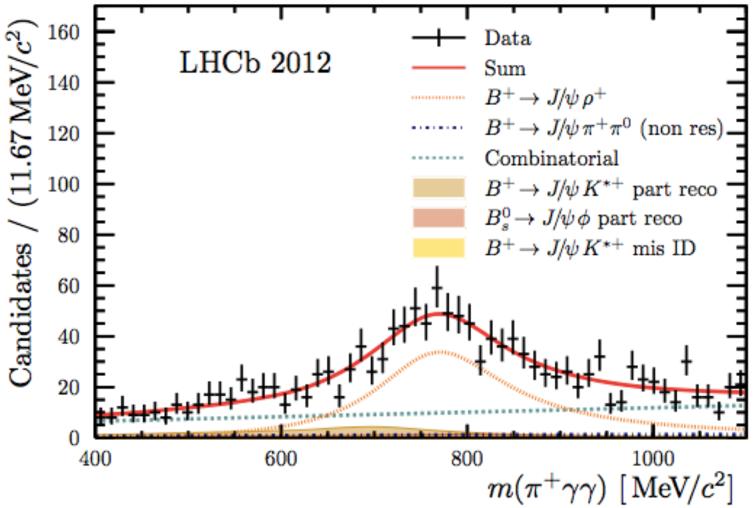
"Measurement of the branching fraction and CP asymmetry in $B^+ \to J/\psi\,\rho^+$ decays"

- Analysis of 3fb-1 of data collected by LHCb in 2011/2012

- Gives estimate of imaginary part of penguin-to-tree amplitude ratio in $b \to c\bar{c}\bar{d}$ transitions







- Asymmetry measured to be $\mathcal{A}^{CP} = -0.045^{+0.056}_{-0.057} \pm 0.008$

- Following isospin symmetry expecations, consistent with $B^0 \to J/\psi\,\rho^0$

Charmless B decays

- Suppressed at tree-level, significant higher order contributions.

- Known to exhibit large asymmetries.

- Several new results in multibody decays, some of which were covered in Cayo Costa Sobral's talk yesterday evening [link]
  - Amplitude analysis of $B^{\pm} \to \pi^{\pm}K^{-}K^{+}$ decays (In preparation)
  - Amplitude analysis of $B_s^0 \to K_S^0 K^{\pm}\pi^{\mp}$decays [arXiv:1902:07955]

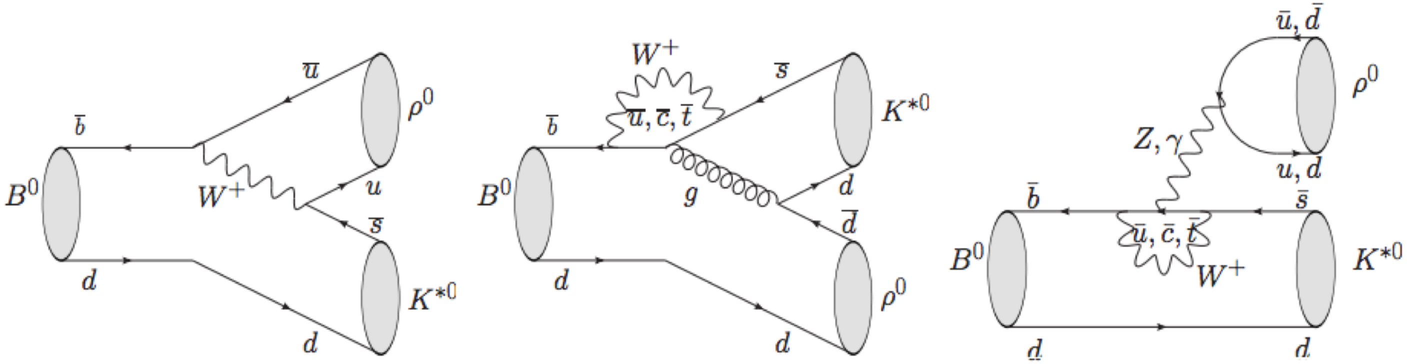
- And even more to show now!

[arXiv:1812.07008]

"Study of the $B^0 \to \rho(770)^0 K^*(892)^0$ decay with an amplitude analysis of $B^0 \to (\pi^+\pi^-)(K^+\pi^-)$ decays"

- Analysed 3 fb^{-1} collected in 2011/2012 in the range of $300 < m(\pi^+\pi^-) < 1100$ and $750 < m(K^+\pi^-) < 1200$ MeV/c^2

- Tree level $b \to u\bar{u}s$ is doubly Cabibbo suppressed
- ➢ Higher order diagrams contribute.



- Small longitudinal polarisation fraction and significant direct CP asymmetry found

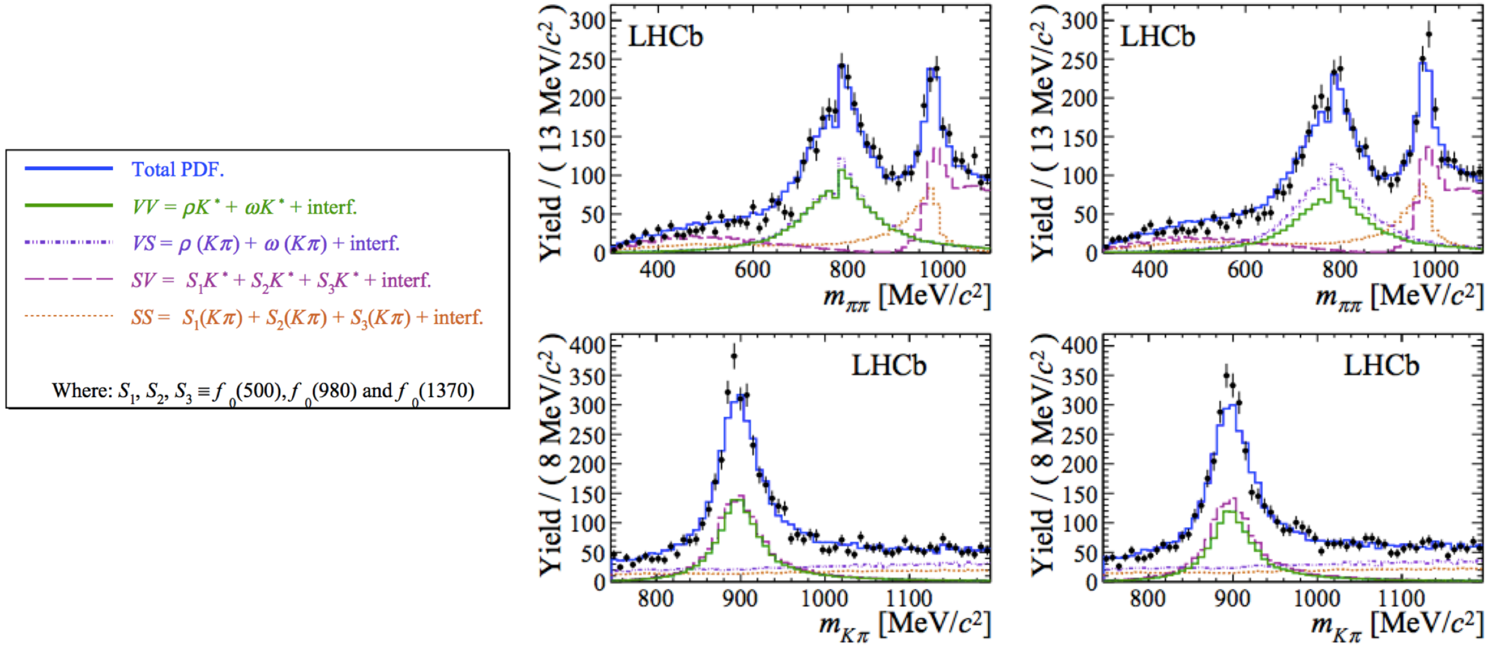
$$\tilde{f}^0_{\rho K^*} = 0.164 \pm 0.015 \pm 0.022 \qquad A^0_{\rho K^*} = -0.62 \pm 0.09 \pm 0.09$$

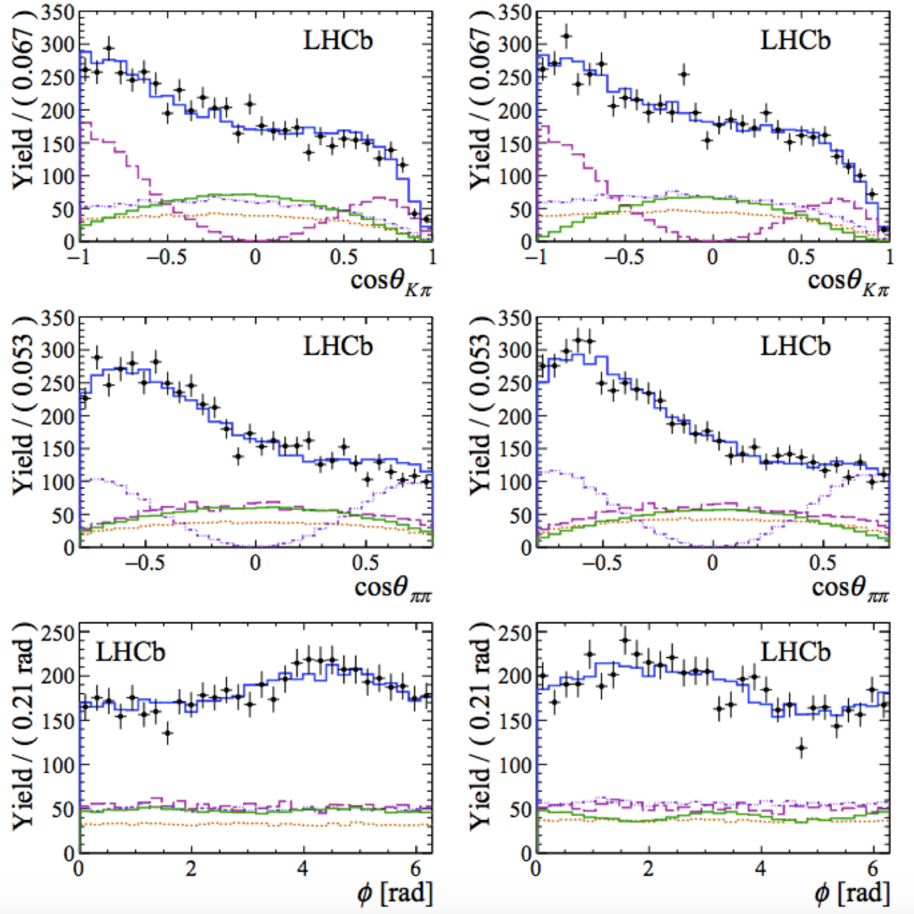
- Hints at significant contribution from penguin amplitudes.

[arXiv:1812.07008]

Study of the $B^0 \to \rho(770)^0 K^*(892)^0$ decay with an amplitude analysis of $B^0 \to (\pi^+\pi^-)(K^+\pi^-)$ decays

- CP violation in VV component clearly visible in projections.
- First significant observation of CP asymmetry in angular distributions of $B^0 \to VV$ decays.





[In preparation]

"Measurement of CP asymmetries in charmless four-body Λ_b^0 and Ξ_b^0 decays"

New!

CP violation not yet been observed in baryon decays

- LHCb has seen evidence: arXiv:1609.05216

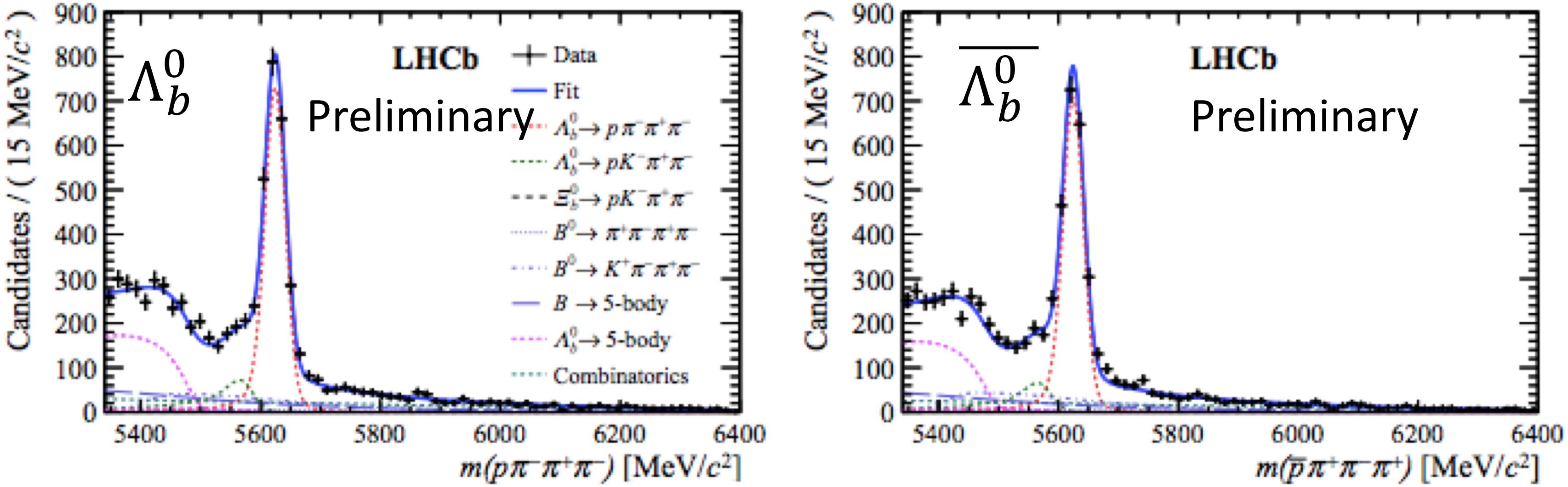
- Measurement of asymmetries in six modes made using 3fb^{-1} of data collected in 2011/2012.

- Construct difference between CP asymmetries in charmless decays and decays with an intermediate charmed baryon with the same particles in the final state.
- Cancel out production and detection charge-asymmetry effects

Charmless mode	Control channel
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	$\Lambda_b^0 \to (\Lambda_c^+ \to p\pi^-\pi^+)\pi^-$
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	$\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$
$\Lambda_b^0 \to pK^-K^+\pi^-$	$\Lambda_b^0 \to (\Lambda_c^+ \to p\pi^-\pi^+)\pi^-$
$\Lambda_b^0 \to pK^-K^+K^-$	$\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$
$\Xi_b^0 \to pK^-\pi^+\pi^-$	$\Xi_b^0 \to (\Xi_c^+ \to pK^-\pi^+)\pi^-$
$\Xi_b^0 \to pK^-\pi^+K^-$	$\Xi_b^0 \to (\Xi_c^+ \to pK^-\pi^+)\pi^-$

Results

- Asymmetries measured in full phase space as well as exploring specific regions of kinematics.
  - In total 18 asymmetries measured.



- No significant asymmetries found, the search for CP violation in baryons continues.

Mixing and CP violation in charm

- Interesting and unique opportunities:
  - SM signal is very small due to CKM and GIM suppression.
  - Only possibility for studying these phenomenon in up-type quark.
  - Complementary to the strange and beauty systems.

- Challenges:
  - Small signals require millions of candidates and good control of systematic uncertainties.
  - Tricky theoretical uncertainties due to long-distance effects.

Note: Mass and width differences denoted by $x = \frac{m_2 - m_1}{\Gamma}$ and y= $\frac{\Gamma_2 - \Gamma_1}{2\Gamma}$, with $\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$

Searches for direct CP violation

- We are of course actively pursuing searches for direct CP violation in charm

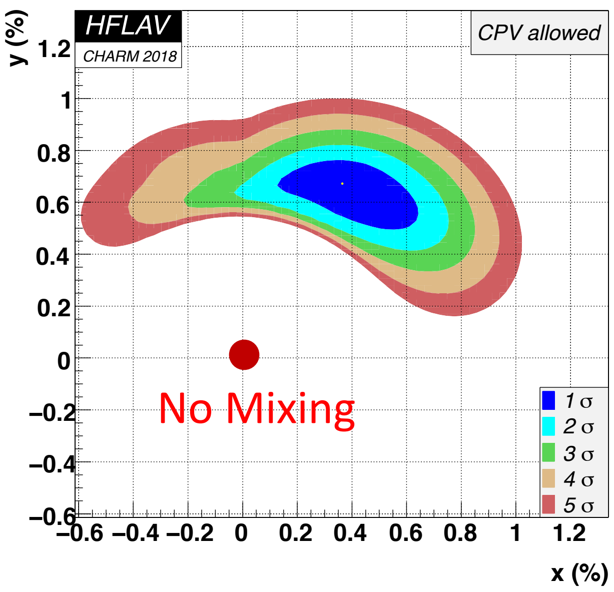
- Two such recent searches were covered by Tommaso Pajero yesterday: [link]
  - Search for CP violation in $D_s^+ \to K_S^0 \pi^+$, $D^+ \to K_S^0 K^+$, and $D^+ \to \phi \pi^+$ [arXiv:1903.01150]
  - Search for CP violation through an amplitude analysis of $D^0 \to K^+ K^- \pi^+ \pi^-$ decays [arXiv:1811.08304]

- And another will be shown by Julián García Pardiñas this afternoon [[link]
  - Measurement of angular and CP asymmetries in $D^0 \to \pi^+ \pi^- \mu^+ \mu^-$ [arXiv:1806.10793]

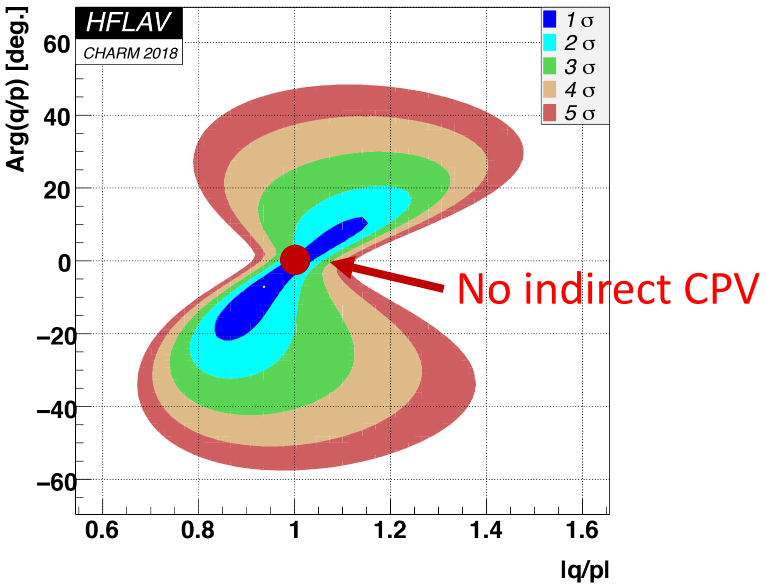
“Current” picture in time-dependent charm analyses

- A few analyses out of date, but conclusion from 2018 HFLAV fit still true.
- Non-mixing hypothesis rejected at overwhelming significance

.... but x is still consistent with zero



.... and there is no indication of indirect CPV



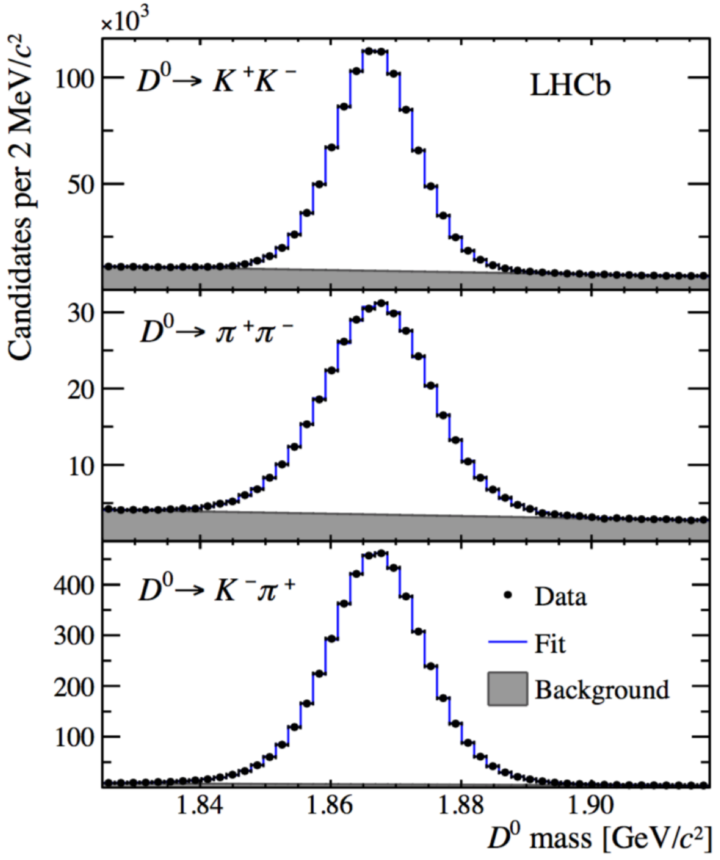
“Measurement of the charm-mixing parameter y_{CP}”

- Analysis compares decay width of D^0 to CP-even final states (Γ_{CP}) to the decay width to CP-mixed states (Γ): $\Delta_\Gamma \equiv \Gamma_{CP} - \Gamma$

- Decays to CP eigenstates $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ are reconstructed along with CP mixed $D^0 \to K^-\pi^+$.

- 3fb^{-1} of Run 1 data, using D^0mesons coming from semimuonic B^- and $\bar{B}^0$ decays

Decay	Signal yield $[10^3]$
$D^0 \to K^+K^-$	878.2 ± 1.2
$D^0 \to \pi^+\pi^-$	311.6 ± 0.9
$D^0 \to K^-\pi^+$	4579.5 ± 3.2



[arXiv:1810.06874]

"Measurement of the charm-mixing parameter y_{CP}"

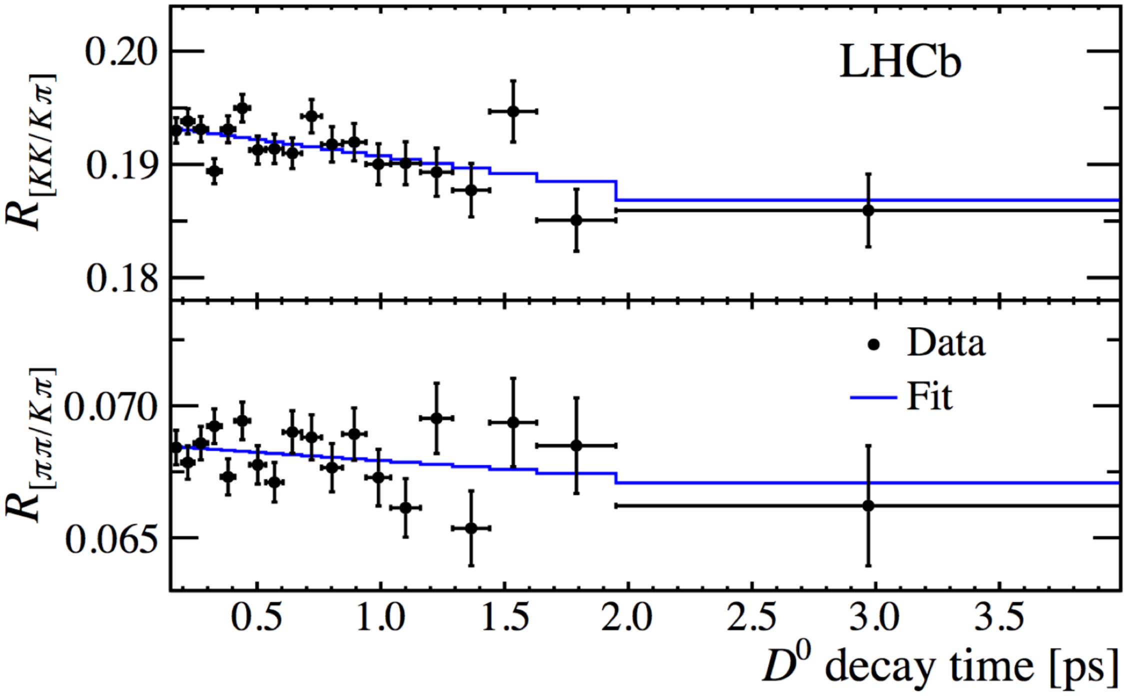
- Fit ratio of yields as a function of decay time to determine the best value of Δ_Γ.
- ➢ Known D^0 lifetime used to extract $y_{CP} = \Delta_\Gamma \tau$

- Combining the modes gives:

$$y_{CP} = (0.57 \pm 0.13(\text{stat}) \pm 0.099(\text{syst}))\%.$$

- As precise as the world average.

- Also consistent with world average value of $y = (0.62 \pm 0.07)\%$.
- ➢ No evidence of CP violation in mixing.



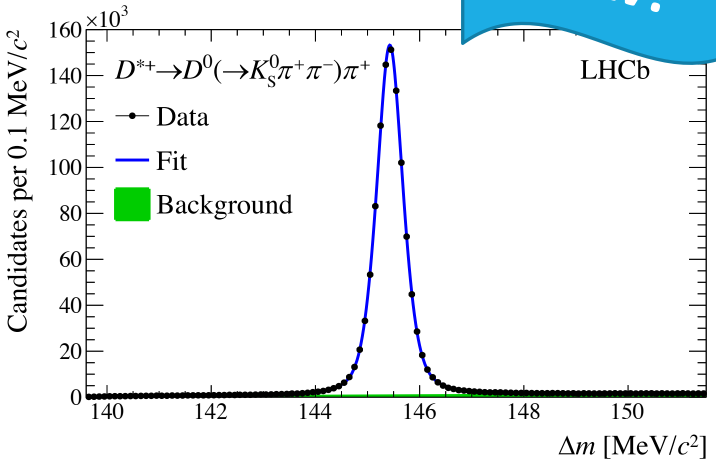
arXiv:1903.03074

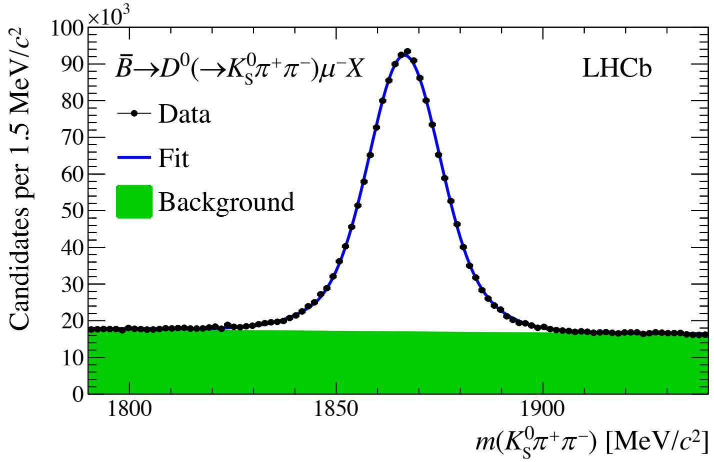
"Measurement of the mass difference between neutral charm eigenstates"

New!

- Analysis of $D^0 \rightarrow K_S\pi^+\pi^-$ decays in 1.3M prompt and 1M semileptonic decays, corresponding to 3fb^{-1} of data taken in 2011 and 2012.

- Features a rich resonance spectrum.
  - Pros: Good sensitivity due to varying strong phase differences.
  - Cons: Requires good understanding of decay dynamics and acceptance effects.



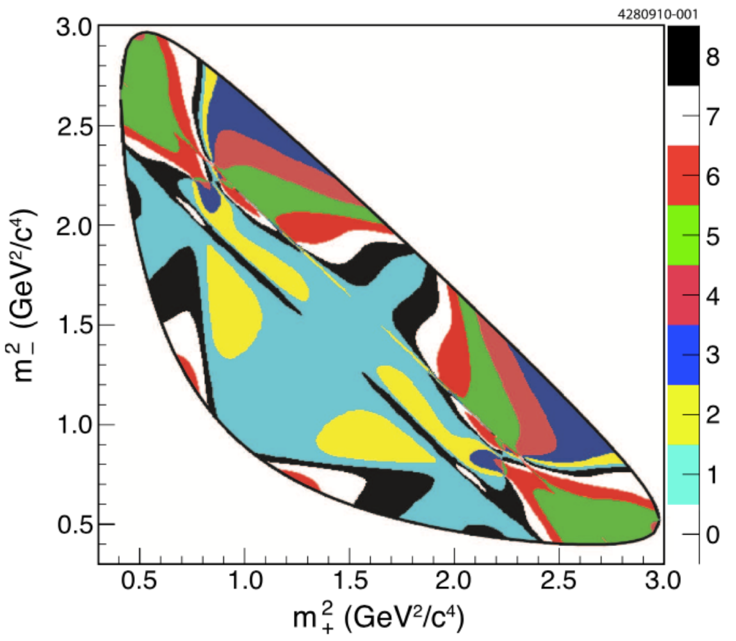


The “bin flip” method

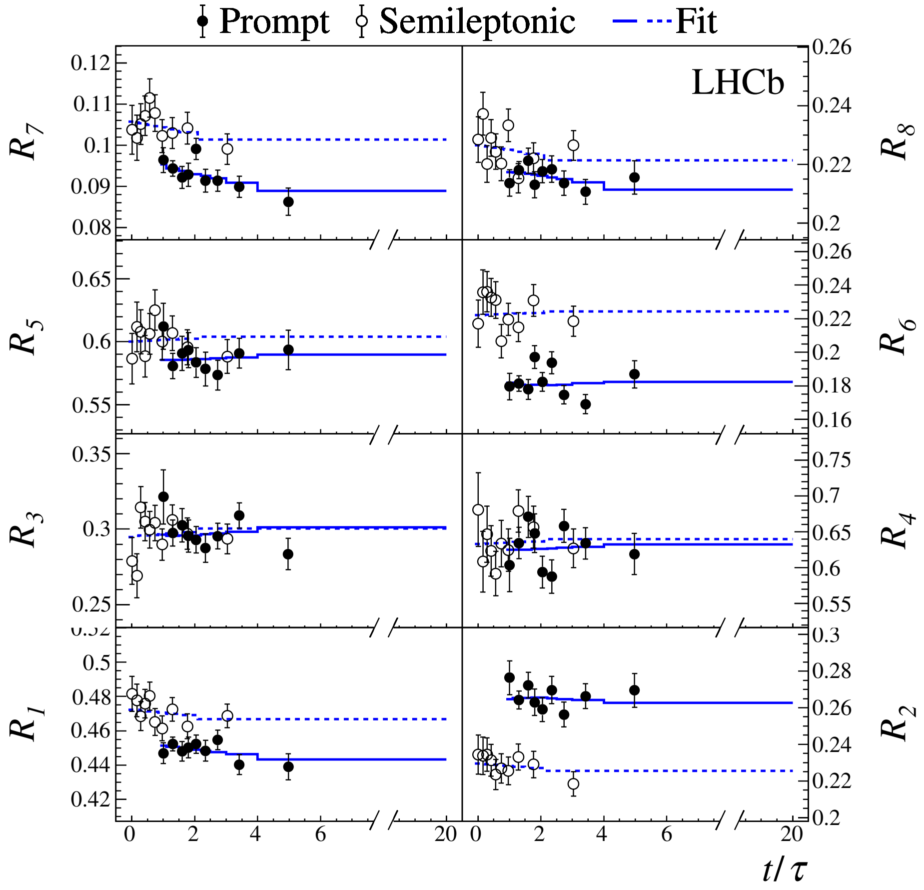
- Uses novel approach for minimising the above challenges: arXiv:1811.01032

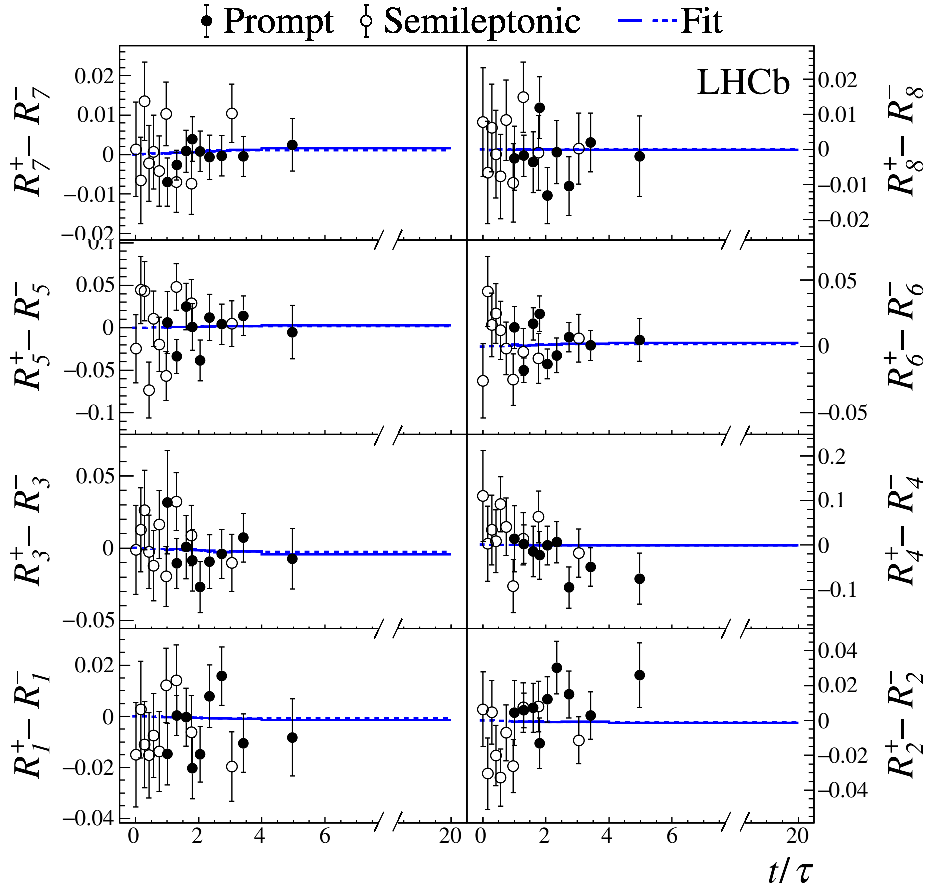
- Data is binned according to Dalitz coordinates and external measurements of strong-phase variation used as constraints.
  - Avoids modelling dynamics of D^0 decay.

- Binned also in decay time, ratio of yields in opposite bins across the symmetry line formed in each decay-time bin.
  - Cancellation of acceptance effects.
  - Particularly sensitive to measuring x.



Fit to ratios

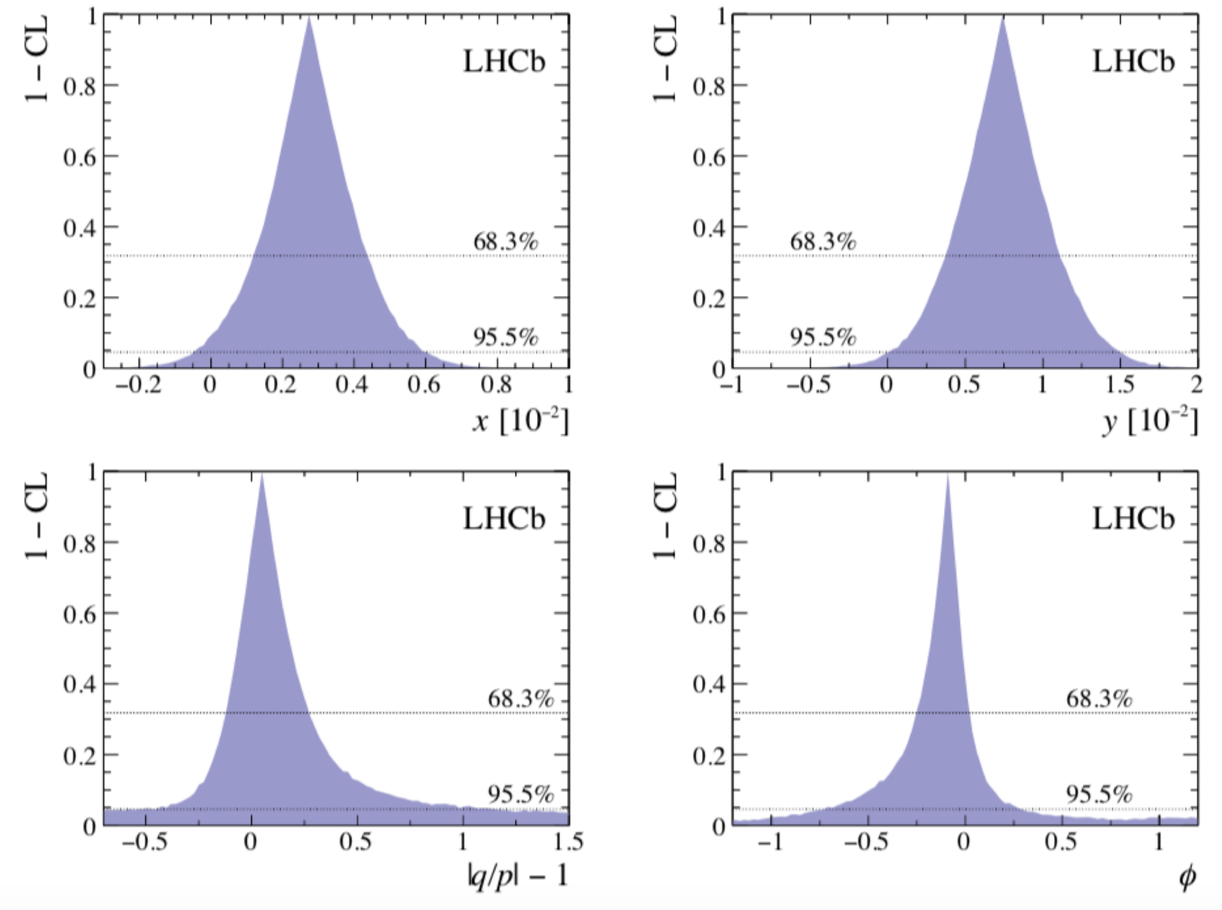




arXiv:1903.03074

Fit results

Parameter	Value	95.5% CL interval
x $[10^{-2}]$	$0.27\,^{+0.17}_{-0.15}$	$[-0.05, 0.60]$
y $[10^{-2}]$	0.74 ± 0.37	$[\ \ 0.00, 1.50]$
$\lvert q/p\rvert$	$1.05\,^{+0.22}_{-0.17}$	$[\ \ 0.55, 2.15]$
ϕ	$-0.09\,^{+0.11}_{-0.16}$	$[-0.73, 0.29]$



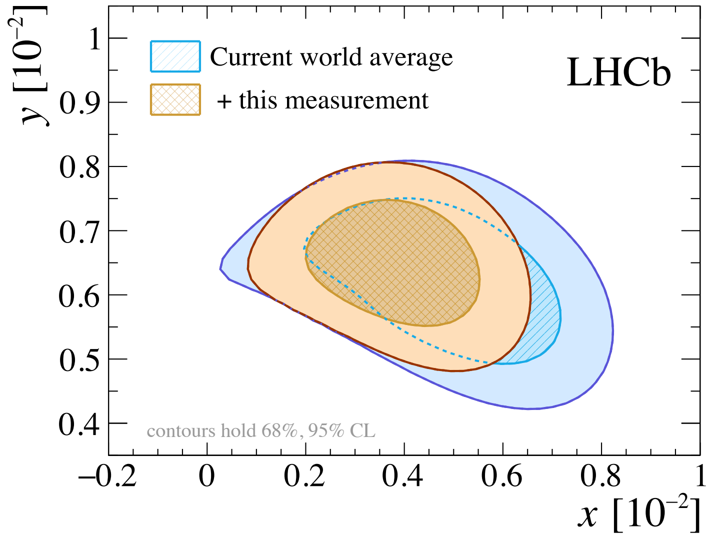
- Most precise measurement of x by a single experiment
- Consistent with CP symmetry.

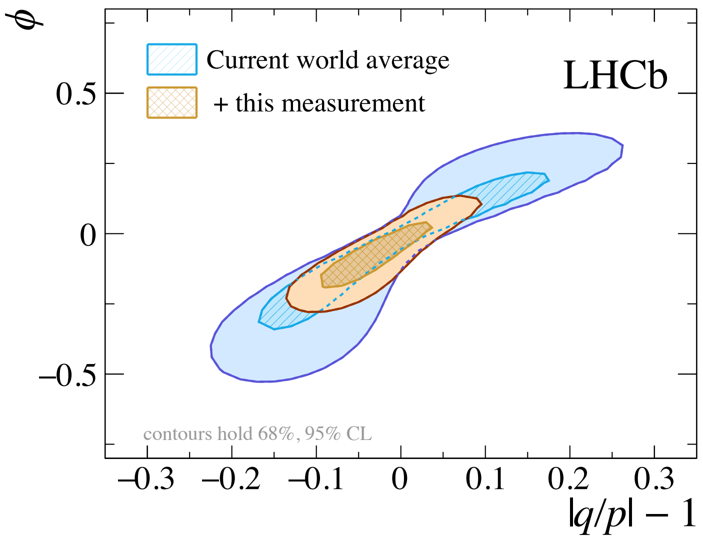
arXiv:1903.03074

Effect on world average

- The measurement helps to significantly improve the limits on the CPV paramters.

Parameter	Fit result	Allowed interval 68.3% CL	95.5% CL	99.7% CL
x $[10^{-2}]$	0.38 ± 0.12	$[\ 0.26\ \ , 0.50\ ]$	$[\ 0.14, 0.61]$	$[\ 0.02, 0.71]$
y $[10^{-2}]$	$0.655\,^{+0.062}_{-0.067}$	$[\ 0.588, 0.717]$	$[\ 0.52, 0.78]$	$[\ 0.44, 0.84]$
$\lvert q/p\rvert$	$0.967\,^{+0.050}_{-0.045}$	$[\ 0.922, 1.017]$	$[\ 0.88, 1.07]$	$[\ 0.84, 1.13]$
ϕ	$-0.070\,^{-0.081}_{+0.079}$	$[-0.151, 0.009]$	$[-0.24, 0.09]$	$[-0.33, 0.19]$





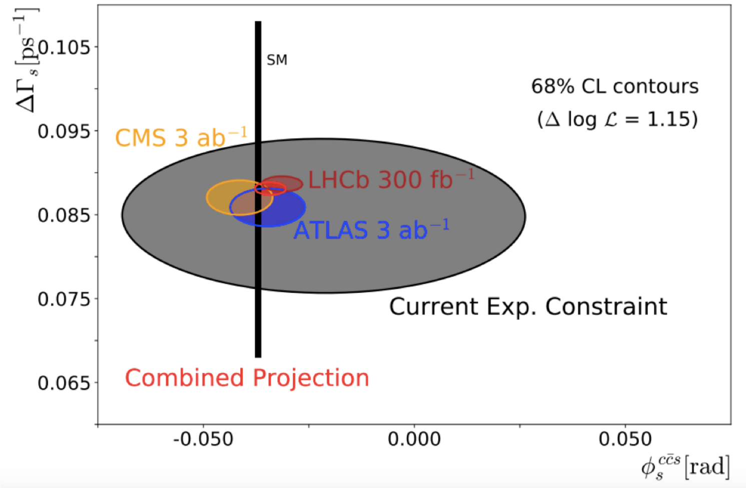
- Also note x is $> 3\sigma$ from 0 !
- Around 30 times more data was already collected during Run 2.

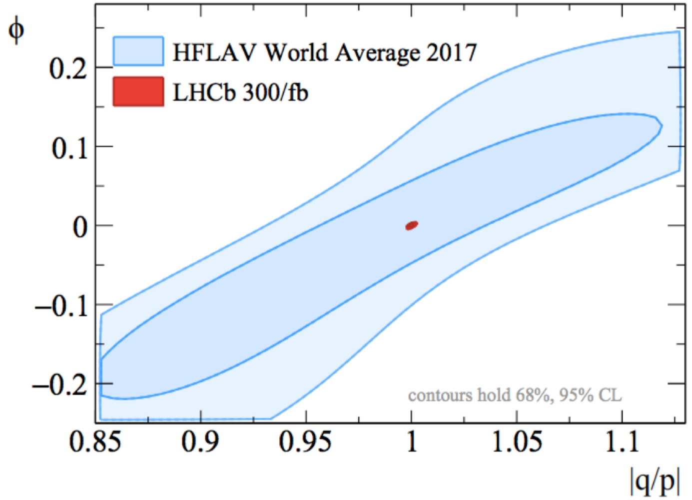
[arXiv:1812.07638]

"Opportunities in Flavour Physics at the HL-LHC and HE-LHC"

- Prepared for the European Strategy for Particle Physics.
- ➢ Physics potential from future upgrades discussed.

- Projections of uncertainties for key measurements are shown.
- ➢ Too many to go through! A beautiful and a charming example:





Conclusions

- Making precision measurements of CP violation is important for testing Standard Model description of CP violation.
- Promising area to look for new physics effects.

- There is a very exciting and active program pursuing these studies at the LHC.

- A lot (most) of data taken at LHC remains to be analysed.
- Higher statistics updates and brand new analyses on the way!

- And of course, we keep our eye on the future and much, much larger statistics.

Backup slides

CP violation in the Standard Model

- Weak interaction known to violate CP symmetry
- ➢ Not invariant under exchange particle with antiparticle and inversion of spatial coordinates

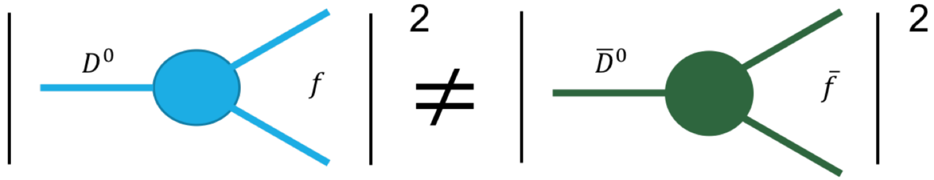
- CP violation described in the SM by the Kobayashi-Maskawa mechanism
- ➢ Due to a single irreducible phase of the Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Expansion in $\lambda \approx 0.22$ convenient way of viewing hierarchy.

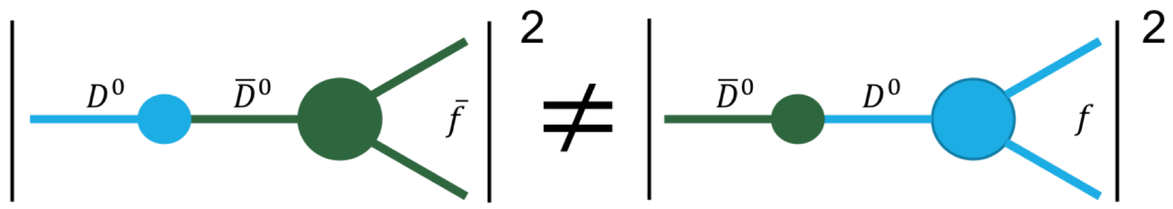
Types of CP violation

- **Direct CPV**
  - Occurs if $\left|\bar{A}_{\bar{f}}/A_f\right| \neq 1$, i.e. amplitude for decay and its CP conjugate have different magnitudes



- Only possible in flavoured neutral mesons which “mix” due to non-coincidence of flavour and mass eigenstates
  - $|M_{1,2}\rangle = p|M^0\rangle \pm q|\bar{M}^0\rangle$

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



- **CPV in interference between mixing and decay**
  - Occurs if $\phi \equiv \arg\left(\frac{q\bar{A}_{\bar{f}}}{pA_f}\right) \neq 0$