CPV and mixing in charm

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FUTURE FLAVOURS

04 MAY 2022

CP violation essentials

- Charge-Parity (CP) transformation: exchange particle with antiparticle and invert spatial coordinates

- CP violation in quark sector comes from single irreducible phase of the Cabibbo-Kobayashi-Maskawa (CKM) matrix

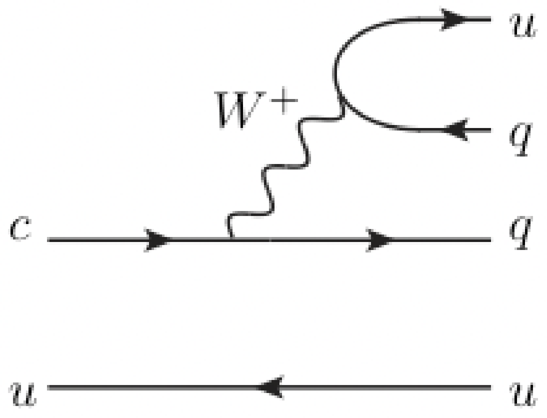
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

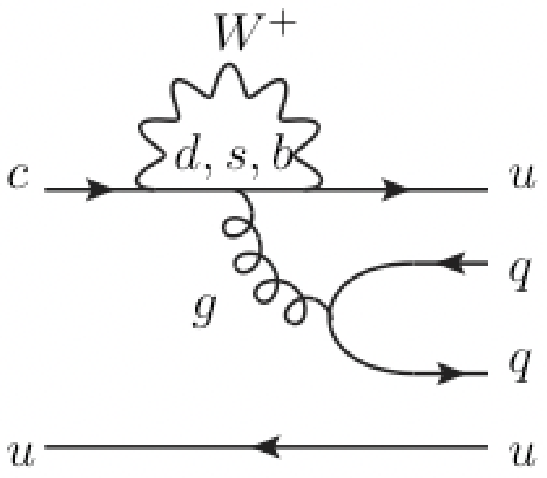
- Expansion in $\lambda \approx 0.22$ convenient way of viewing hierarchy

CP violation essentials

- Can generically write amplitudes in terms of magnitude (ρ), and CP-conserving (δ), CP-violating phase (θ)

$$A = \rho e^{i\delta} e^{i\theta}$$





Amplitude for CP-conjugate process is then

$$\bar{A} = \rho e^{i\delta} e^{-i\theta}$$

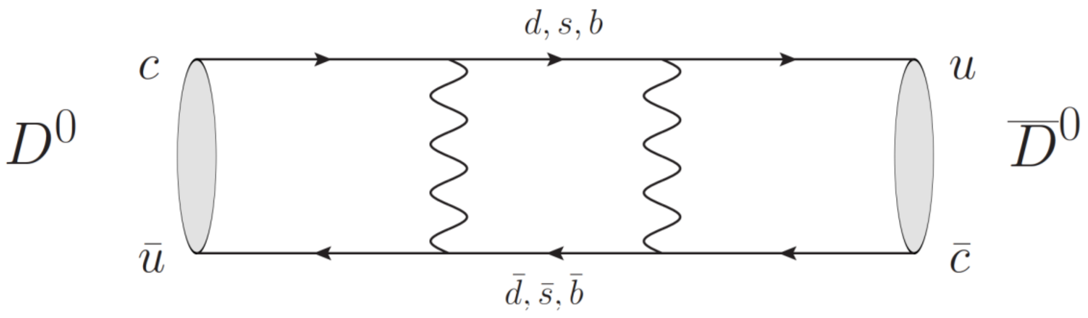
CP violation can occur in presence of multiple amplitudes if the CP-conserving and violating phases differ:

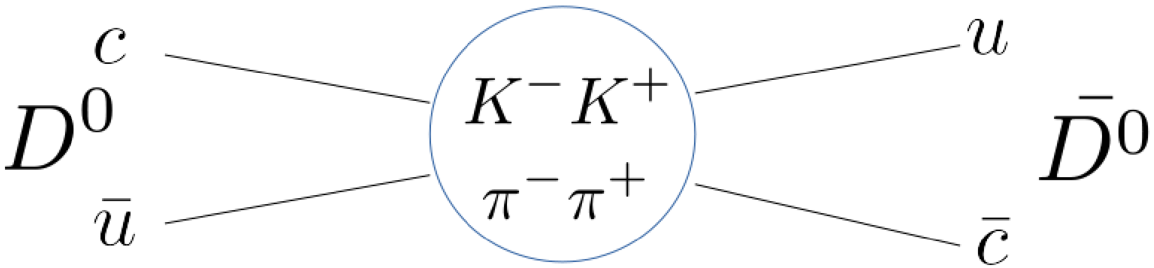
$$|\overline{A_1} + \overline{A_2}|^2 - |A_1 + A_2|^2 = 4\rho_1\rho_2 \sin(\theta_1 - \theta_2)\sin(\delta_1 - \delta_2)$$

Mixing essentials

- Evolution described by usual time-dependent Schrodinger's equation

$$i\frac{\partial}{\partial t}\begin{pmatrix}|D^0(t)\rangle \\ |\bar{D}^0(t)\rangle\end{pmatrix} = \left[\begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22}\end{pmatrix}\right]\begin{pmatrix}|D^0(t)\rangle \\ |\bar{D}^0(t)\rangle\end{pmatrix}$$



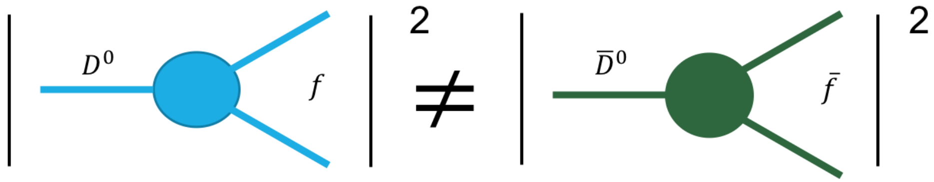


- Non-coincidence of eigenstates $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$ leads to neutral meson mixing governed by

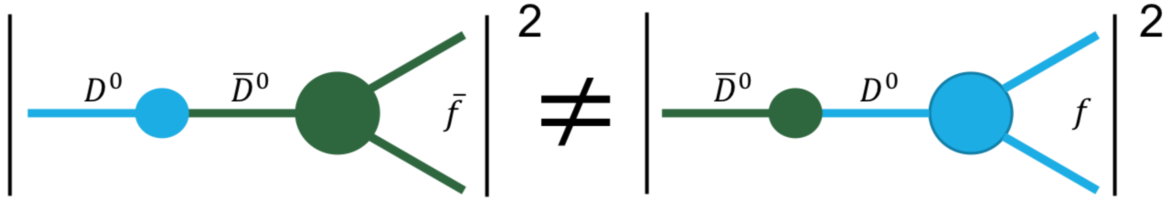
$$x = \frac{m_2 - m_1}{\Gamma} \text{ and } y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}, \text{ with } \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

Manifestations of CP violation

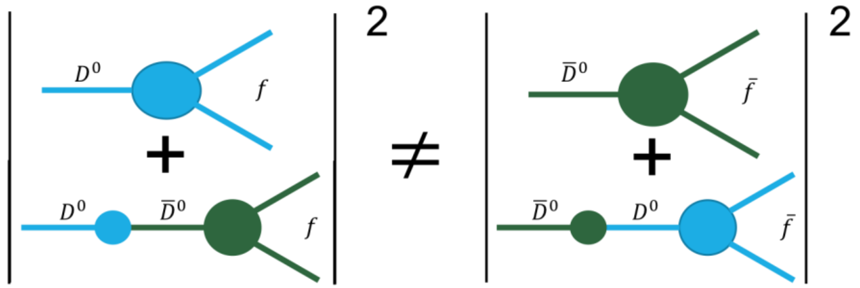
- ○ **Direct CP violation**
- ➢ Occurs if $|\bar{A}_{\bar{f}}/A_f| \neq 1$, i.e. different rates for decay and its CP conjugate



- ○ **CP violation in mixing**
- ➢ Occurs if $\left|\frac{q}{p}\right| \neq 1$

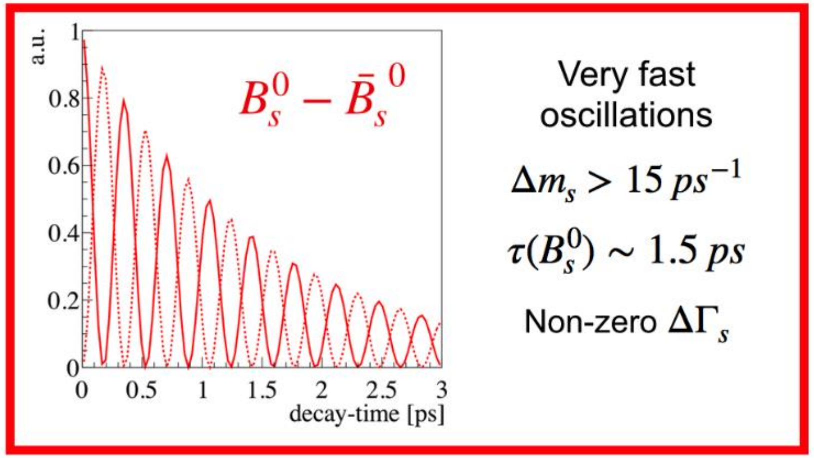


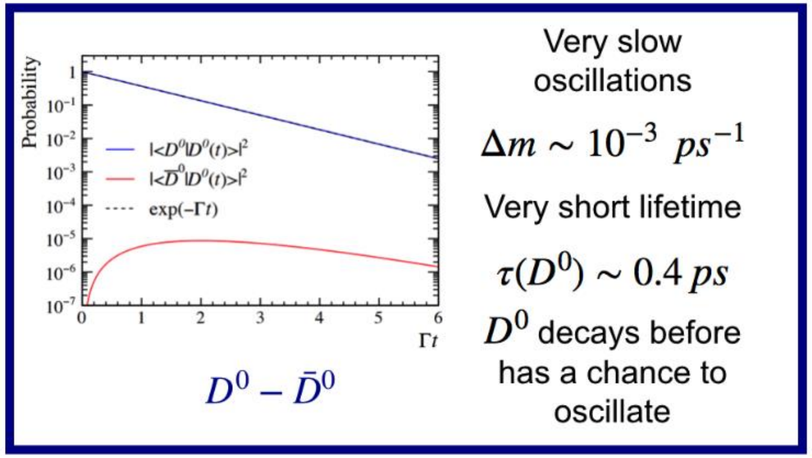
- ○ **CP violation in interference between mixing & decay**
- ➢ Occurs if $\phi \equiv \arg\left(\frac{q\bar{A}_{\bar{f}}}{pA_f}\right) \neq 0$



CP violation and mixing in charm sector

- Very small in the SM due to CKM and GIM suppression
- Relevant CKM matrix elements Im$(V_{cb}V_{ub}^{*}/V_{cs}V_{us}^{*}) \approx -6 \times 10^{-4}$
- Mixing parameters are expected to be $\leq 10^{-2}$
  - Mixing relatively slow compared to in beauty system





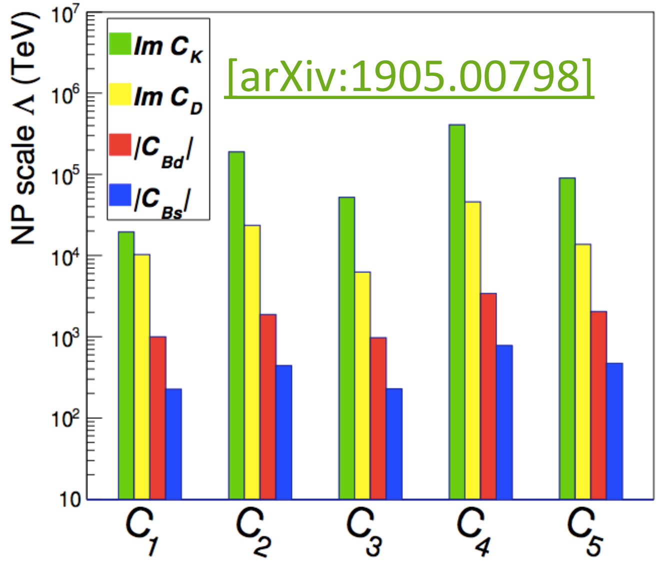
- Very challenging from experimental and theory perspectives

Why study these phenomena?

- Standard Model (SM) of particle physics clearly an incomplete theory
  - Ex: SM CP violation incapable of generating observed matter-antimatter asymmetry of universe
  - Extensions of SM can naturally include new sources of CP violation.

- "Indirect" probes have often provided first glimpse of new particles, e.g. GIM mechanism predicting charm quark.

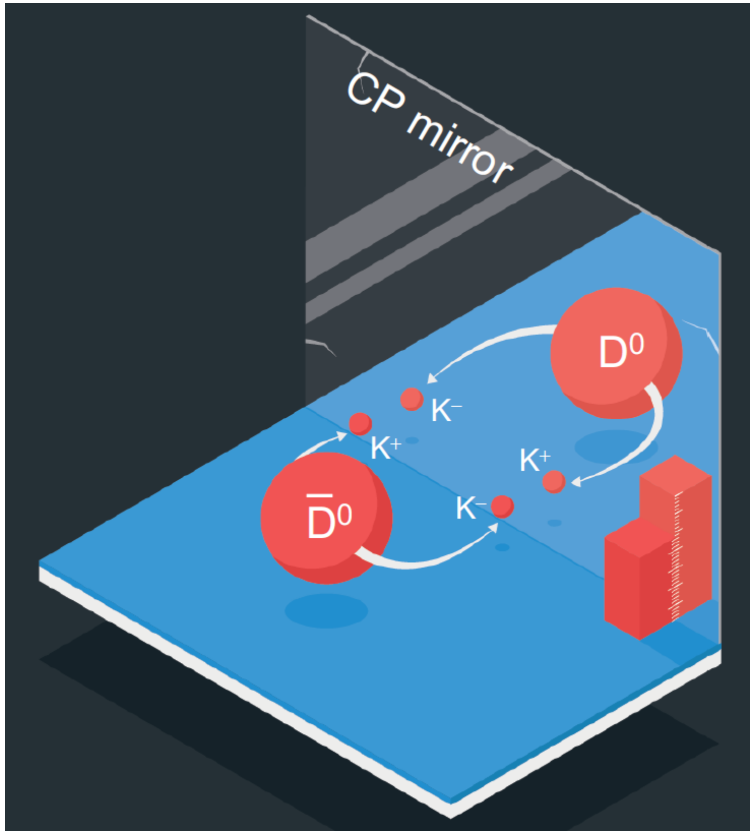
- Capable of probing quite high energy scales.



And why study charm?

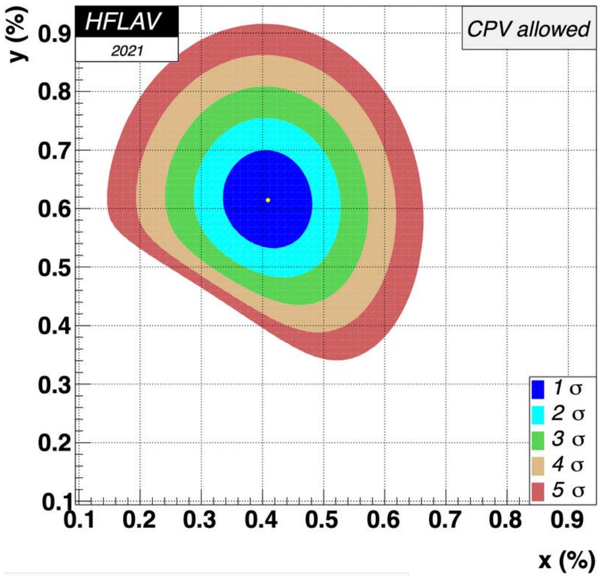
- CP violation is relatively well-measured in the K- and B-meson systems
- Charm is only laboratory for studying mixing/CP violation in mesons with up-type quarks
- Depending on details of new physics models, constraints from charm may be more powerful
- CP violation will be very small in the SM due to aforementioned CKM and GIM suppression

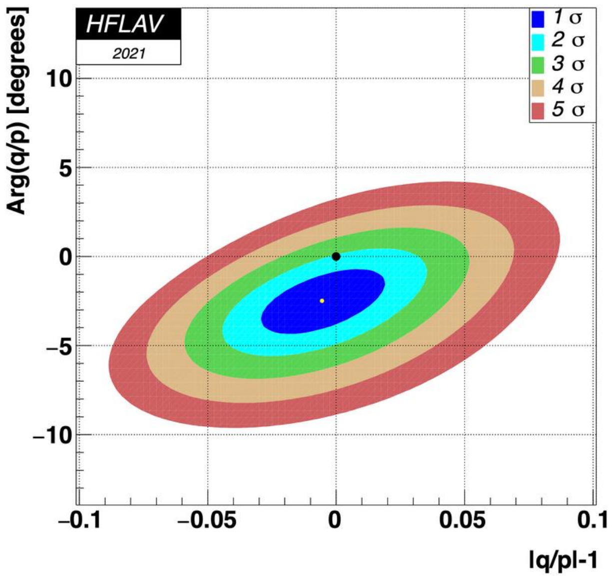
➢ Nice from a possible signal over SM background perspective.

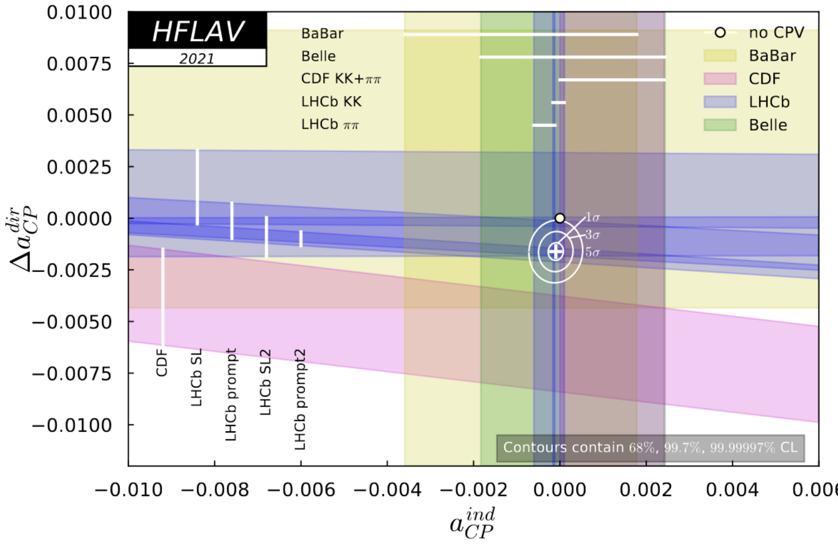


Current status

- Mixing has definitively been observed, and both x and y measured to be different to zero
- CP violation in the decay amplitudes has been observed.... Once
  - More studies needed!
- Mixing induced CP violation not yet observed!
  - Precision not yet at SM level. Room for new physics!







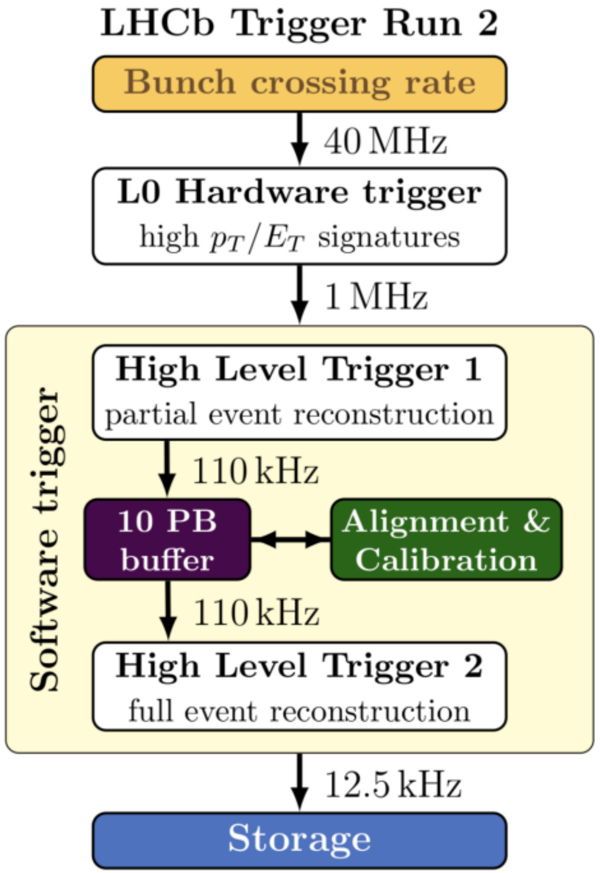
The Measurements

Disclaimer: Focusing on LHCb

- Majority of **recent** results
- Belle II talk tomorrow

Charm physics recipe

- Each second LHC produces $\mathcal{O}(1\mathrm{M})$ c-hadrons.
- Trigger selects interesting events, makes data rate manageable
- We then need to:
  - Separate signal from background (either combinatorial or similar decay modes).
  - Identify flavour of the particles at production
  - Measure time-evolution, and often kinematics of decay products.
  - Understand detector response.



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LHCb detector

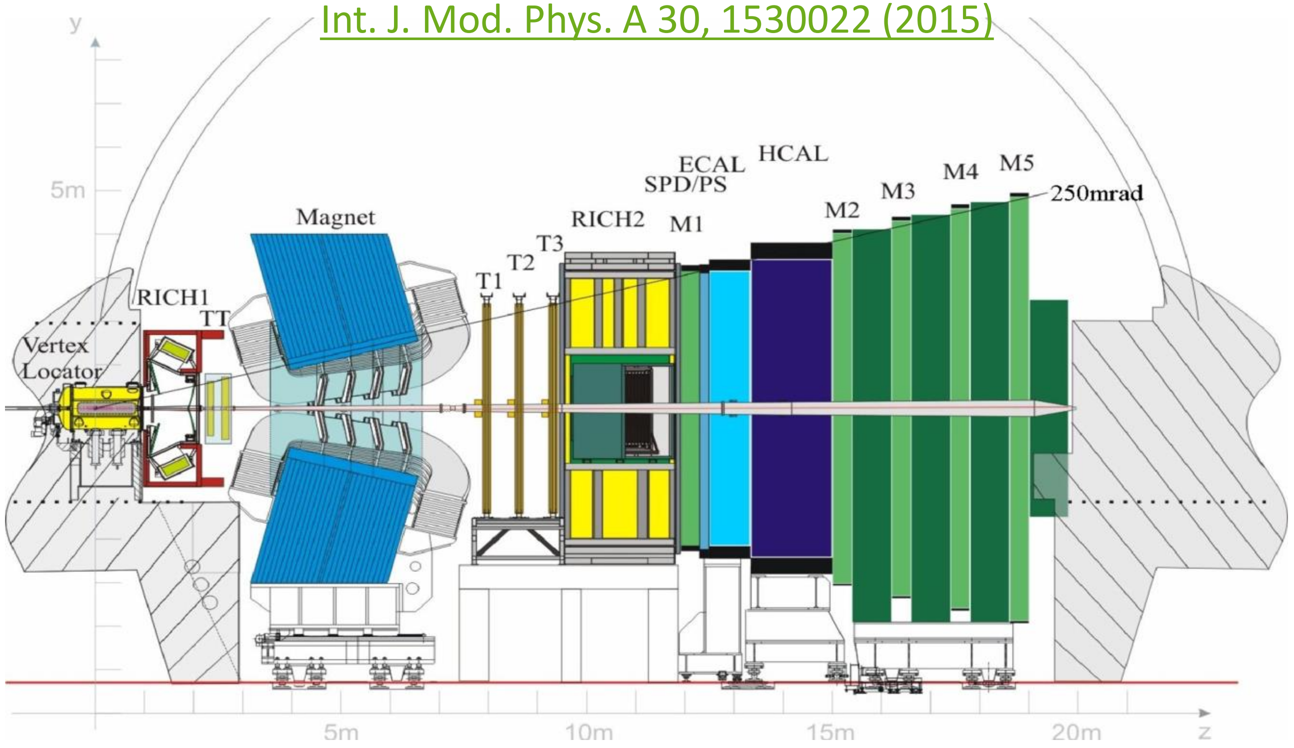
- LHCb is designed for precision measurements of b- and c-hadrons.
- Well-equipped to meet challenges.

- Precision vertexing
- 20 μm impact parameter (IP) precision
- Decay-time resolution of $\sim 0.1 \times \tau(D^0)$

- Tracking stations + magnet
- $\Delta p/p = 0.4 - 0.6\%$ at 5-100 GeV/c
- ~ 8 MeV/c $M(D^0)$ resolution
- Magnet polarity regularly changed

- Charged hadron identification

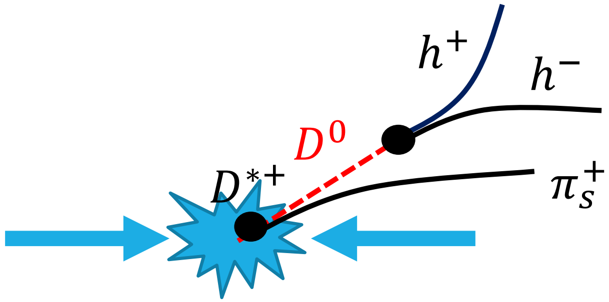
Int. J. Mod. Phys. A 30, 1530022 (2015)



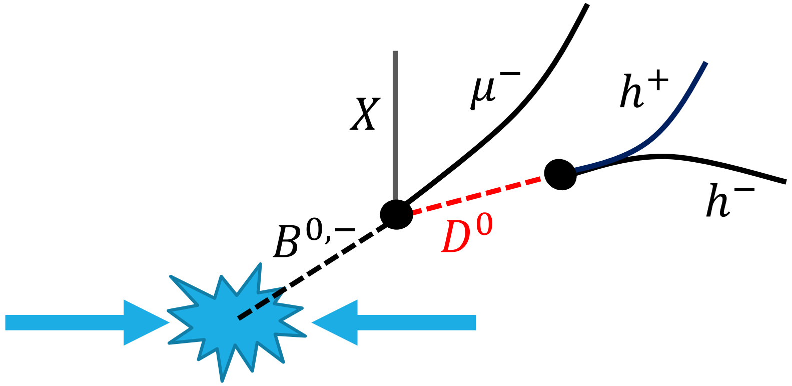
Reconstruction of D-mesons

- Make use of two (mostly) independent samples with “perfect” tagging of flavour at production.

π -tagged sample



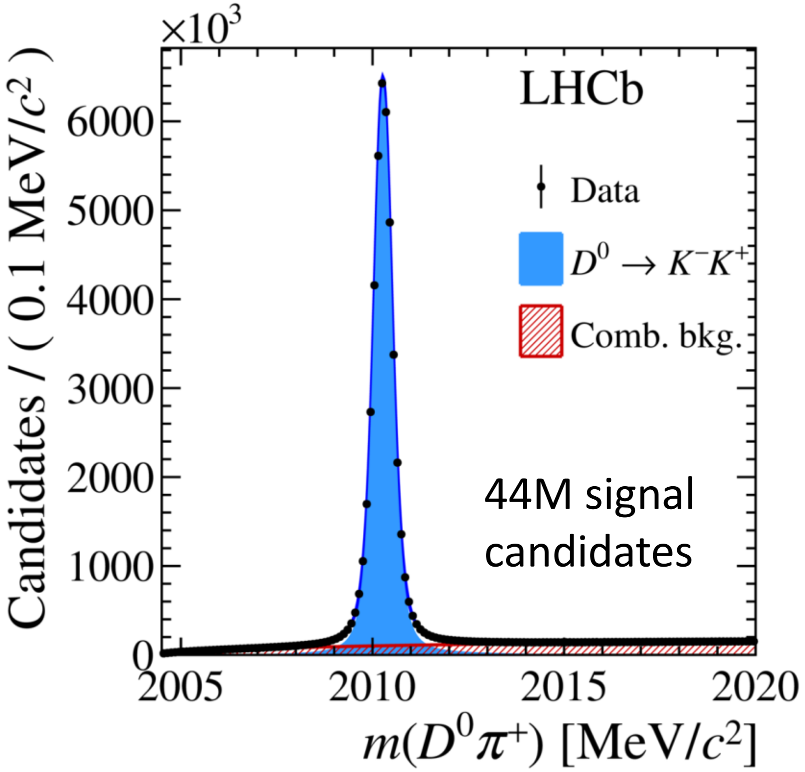
μ-tagged sample



- Each presents different challenges.
- ➢ Useful for cross-checks.
- Disentangled using IP with respect to primary vertex (PV)
  - Not perfect- need to control cross-feed between the different samples.

LHCb data selection

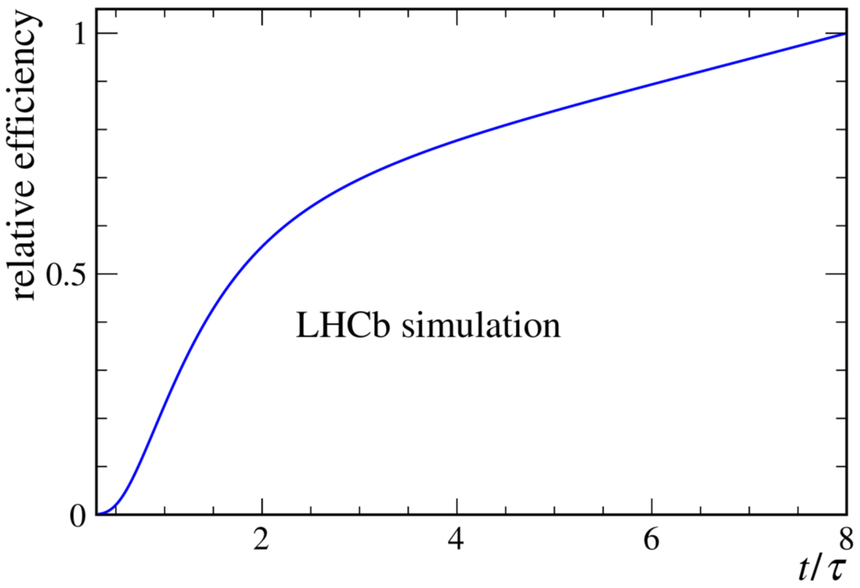
- The π –tagged sample is reconstructed and mostly selected online using Turbo stream [Comput. Phys. Commun. 208 (2016) 35].
- Fairly simple candidate selection requirements:
  - Quality of reconstructed tracks, their PID information
  - Momentum transverse to beam line (p_T) of tracks and D^0 candidate.
  - D^0 vertex quality and impact parameter
- Remaining background *mostly* smooth, combinatorial in nature
  - Dedicated studies to control small non-combinatorial backgrounds



Typical experimental challenges

- Main challenge common to all charm analyses is understanding detector response.

- Acceptance effects
  - How do reconstruction and selection requirements sculpt the data?
- Charge asymmetries
  - Detection asymmetries due to different interaction with matter
  - Reconstruction asymmetries

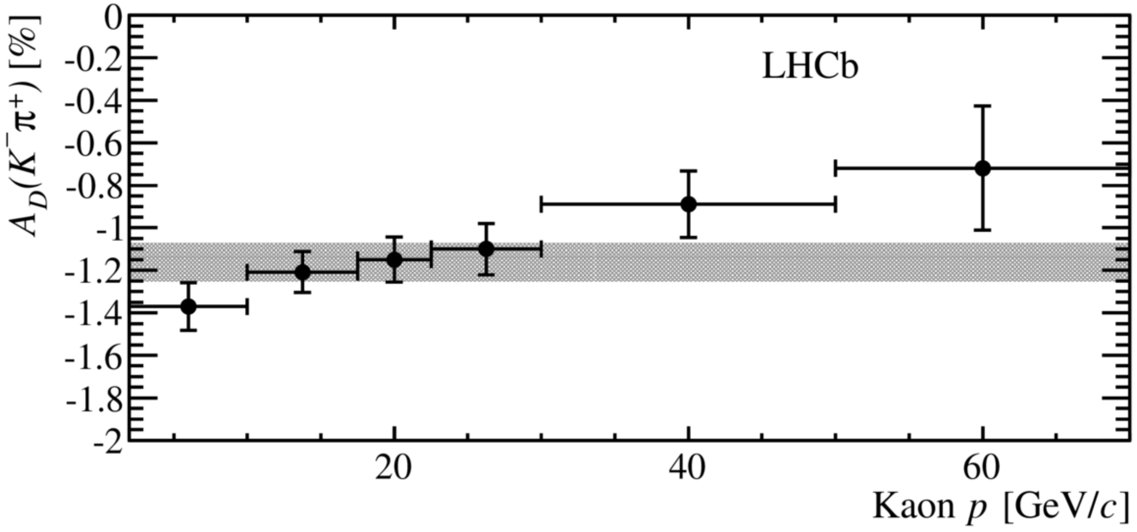


Detector response strategies

- Monte Carlo simulation can sometimes be used to study these effects.
  - Often too computationally demanding. Requires huge samples!
  - Simulations imperfect, needs corrections which have their own limitations.

- Calibration data: high statistics control samples where "physics" effects well-understood.
  - Not always possible.

- Design analyses and observables to be as insensitive as possible to these effects.



Time-integrated measurements

Search for time-integrated CP asymmetries

- Consider a classic example: measure differences in the decay rates to Cabibbo suppressed final-states ($f = K^+K^-, \pi^+\pi^-$)

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

- Experimentally, can easily measure "raw" asymmetry from number of reconstructed signal events "N"

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

- Does not correspond exactly to $A_{CP}(f)$ due to production and detection induced asymmetries!

Asymmetry definition

- To a good approximation (10^{-6}), the asymmetries can be written as

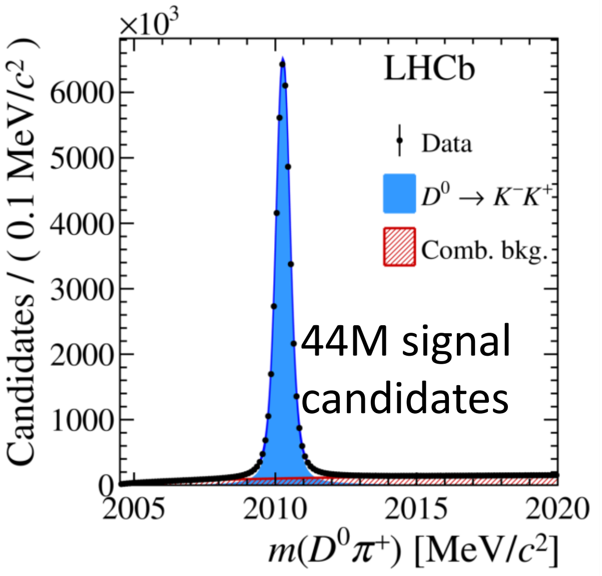
$$A_{raw}(f) = A_{CP}(f) + A_D(f) + A_D(\pi_s^+) + A_P(D^{*+})$$

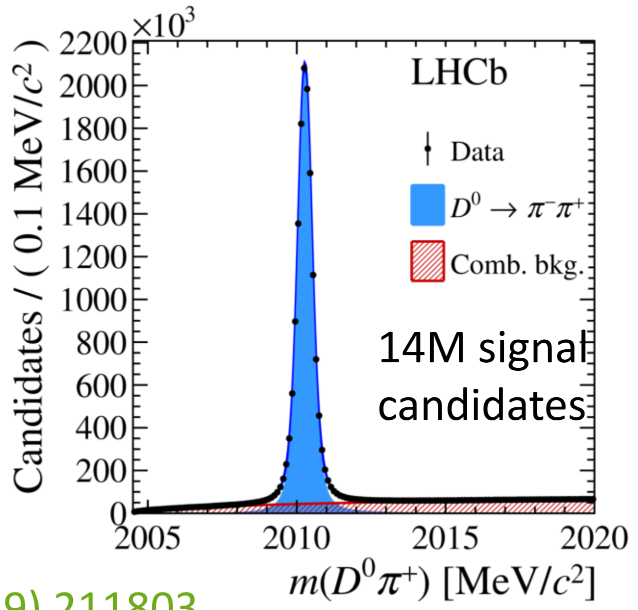
- CP asymmetry, the goal
- Charge-dependent asymmetry coming from material interaction, reconstruction, etc.
- D^{*+} production asymmetry
- We can cancel all nuisance asymmetries by taking the difference!

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

ΔA_{raw} fit

- Invariant mass distribution $m(D^0\pi)$ of reconstructed candidates allow for disentangling the signal components from backgrounds of randomly combined particles.
- Simultaneous fit to D^{*+} and D^{*-} determines ΔA_{raw}





Phys. Rev. Lett. 122 (2019) 211803

Results

- Combination of π and μ tagged sample results gives an LHCb Run 1+2 measurement of:

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

- Results are compatible with previous LHCb results and world average.

At 5.3 standard deviations from zero, this was first observation of CP violation in decay of charm hadrons!

- Great example of constructing observables to be insensitive to experimental effects

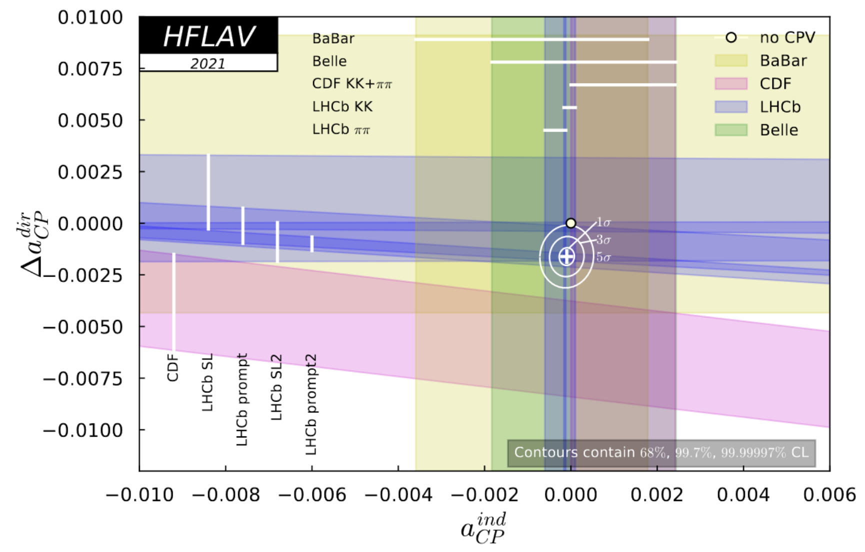
Direct vs indirect CP asymmetry

- What has been measured is a time-integrated asymmetry
  - Contributions possible from CP violation in mixing, and interference between mixing and decay
- Can extract direct CP violation from

$$A_{CP}(f) \approx a_{CP}^{\mathrm{dir}}(f) + \frac{\langle t(f)\rangle}{\tau(D^0)} a_{CP}^{\mathrm{ind}}(f)$$

- At current sensitivity can take a_{CP}^{ind} to be independent of final-state

$$\Delta A_{CP}(f) \approx \Delta a_{CP}^{\mathrm{dir}} + \frac{\Delta\langle t\rangle}{\tau(D^0)} a_{CP}^{\mathrm{ind}}$$



Current world average:

$$\Delta a_{CP}^{\mathrm{dir}} = (-16.1 \pm 2.8) \times 10^{-4}$$

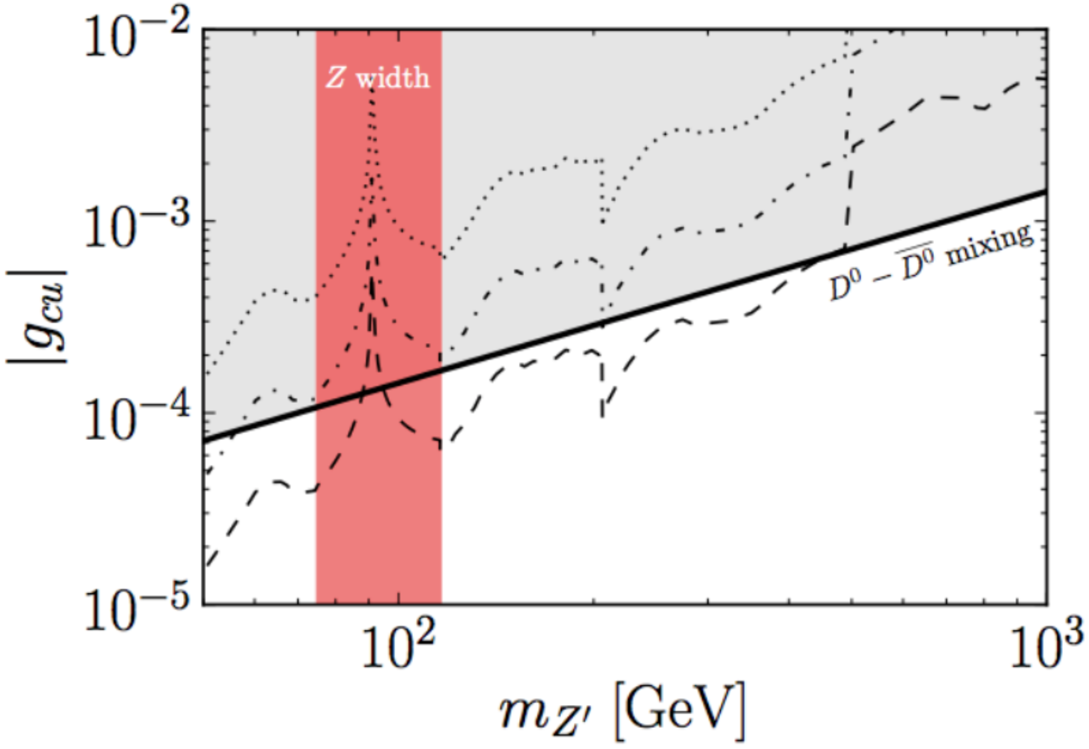
$$a_{CP}^{\mathrm{ind}}. = (-1.0 \pm 1.2) \times 10^{-4}$$

No CPV probability: 6.9×10^{-8}

SM or not?

- Comparison to SM prediction is very difficult
- Low-energy strong-interaction effects difficult to calculate.
- Renewed interest in calculating these effects in SM
- Also investigations of possible enhancements from NP contributions

[arXiv:1903.10490]



Other measurements

- More needed to test relations between CP asymmetries
  - Constrain flavour-SU(3) breaking effects
  - Give information on effect of final-state interactions and strong dynamics
- Measurements of individual asymmetries $A_{CP}(K^+K^-)$, $A_{CP}(\pi^+\pi^-)$ will be crucial
- Many more decay modes, e.g. $A_{CP}\left(K_S^0 K_S^0\right)$, …

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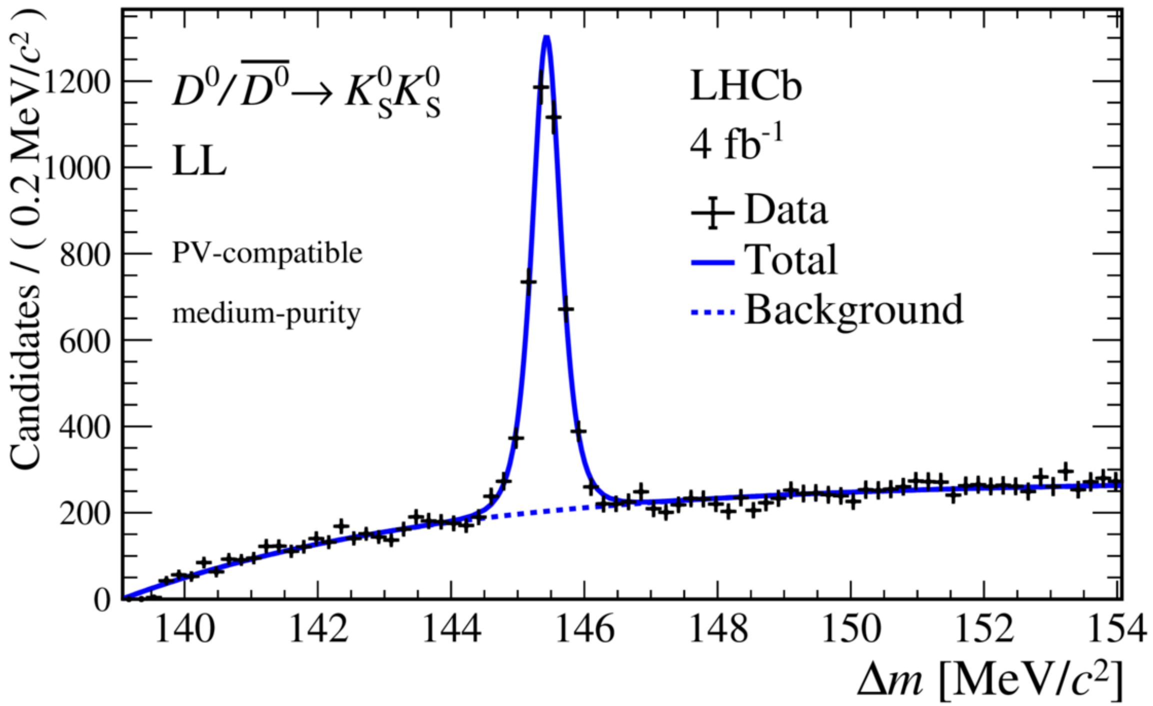


Multi-body decays

- "Multi-body" decay modes are promising
- Strong phase varies over the available phase space
  - Some regions may have enhanced sensitivity
- Challenges include:
  - Efficiencies (including charge-dependence) vary over the phase space
  - Understanding of contributing amplitudes
  - Theoretical interpretation may not be straightforward

Table 5: *CP*-violation parameters fitted simultaneously to the D^0 and (*CP*-transformed) $\overline{D}^0$ samples. The first uncertainty is statistical and the second is systematic.

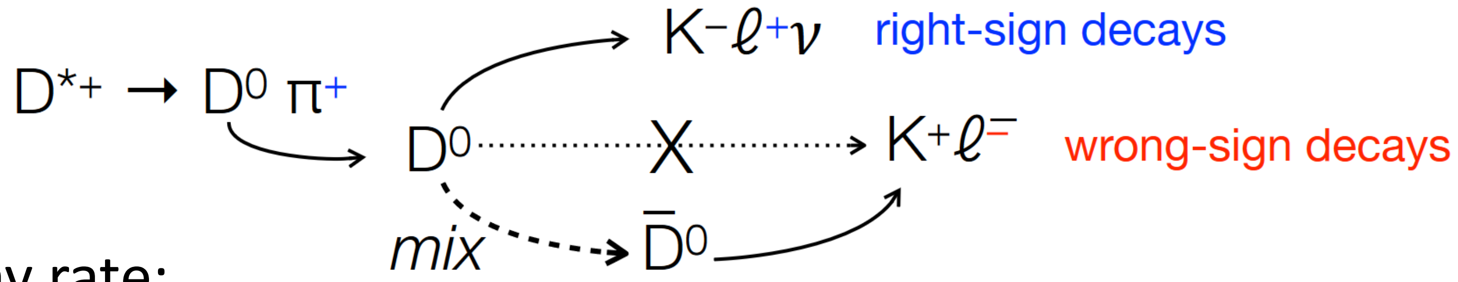
Amplitude	$A_{\lvert c_k \rvert}$ [%]	$\Delta \arg(c_k)$ [%]	$A_{\mathcal{F}_k}$ [%]
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=0}$	0 (fixed)	0 (fixed)	$-1.8 \pm 1.5 \pm 0.2$
$D^0 \to K_1(1400)^+K^-$	$-1.4 \pm 1.1 \pm 0.2$	$1.3 \pm 1.5 \pm 0.3$	$-4.5 \pm 2.1 \pm 0.3$
$D^0 \to [K^-\pi^+]_{L=0}[K^+\pi^-]_{L=0}$	$1.9 \pm 1.1 \pm 0.3$	$-1.2 \pm 1.3 \pm 0.3$	$2.0 \pm 1.8 \pm 0.7$
$D^0 \to K_1(1270)^+K^-$	$-0.4 \pm 1.0 \pm 0.2$	$-1.1 \pm 1.4 \pm 0.2$	$-2.6 \pm 1.7 \pm 0.2$
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=0}$	$-1.3 \pm 1.3 \pm 0.3$	$-1.7 \pm 1.5 \pm 0.2$	$-4.3 \pm 2.2 \pm 0.5$
$D^0 \to K^*(1680)^0[K^-\pi^+]_{L=0}$	$2.2 \pm 1.3 \pm 0.3$	$1.4 \pm 1.5 \pm 0.2$	$2.6 \pm 2.2 \pm 0.4$
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=1}$	$-0.4 \pm 1.7 \pm 0.2$	$3.7 \pm 2.0 \pm 0.2$	$-2.6 \pm 3.2 \pm 0.3$
$D^0 \to K_1(1270)^-K^+$	$2.6 \pm 1.7 \pm 0.4$	$-0.1 \pm 2.1 \pm 0.3$	$3.3 \pm 3.5 \pm 0.5$
$D^0 \to [K^+K^-]_{L=0}[\pi^+\pi^-]_{L=0}$	$3.5 \pm 2.5 \pm 1.5$	$-5.5 \pm 2.6 \pm 1.6$	$5.1 \pm 5.1 \pm 3.1$
$D^0 \to K_1(1400)^-K^+$	$0.2 \pm 2.9 \pm 0.7$	$2.5 \pm 3.5 \pm 1.0$	$-1.3 \pm 6.0 \pm 1.0$
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=0}$	$4.0 \pm 2.7 \pm 0.8$	$-5.4 \pm 2.8 \pm 0.8$	$6.2 \pm 5.2 \pm 1.5$
$D^0 \to [\overline{K}^*(1680)^0K^*(892)^0]_{L=1}$	$-0.4 \pm 2.1 \pm 0.3$	$0.4 \pm 2.1 \pm 0.3$	$-2.5 \pm 3.9 \pm 0.4$
$D^0 \to \overline{K}^*(1680)^0[K^+\pi^-]_{L=0}$	$2.1 \pm 2.0 \pm 0.6$	$-1.8 \pm 2.2 \pm 0.3$	$2.4 \pm 3.7 \pm 1.1$
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=2}$	$0.8 \pm 1.9 \pm 0.3$	$-1.2 \pm 2.0 \pm 0.5$	$-0.1 \pm 3.3 \pm 0.5$
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=2}$	$-0.6 \pm 2.5 \pm 0.4$	$0.6 \pm 2.6 \pm 0.4$	$-3.0 \pm 5.0 \pm 0.7$
$D^0 \to \phi(1020)[\pi^+\pi^-]_{L=0}$	$3.8 \pm 3.1 \pm 0.7$	$-0.5 \pm 3.9 \pm 0.7$	$5.8 \pm 6.1 \pm 0.8$
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=1}$	$1.6 \pm 2.8 \pm 0.5$	$0.7 \pm 3.0 \pm 0.4$	$1.3 \pm 5.3 \pm 0.6$
$D^0 \to [\phi(1020)\rho(1450)^0]_{L=1}$	$4.6 \pm 4.1 \pm 0.6$	$9.3 \pm 3.3 \pm 0.6$	$7.5 \pm 8.5 \pm 1.1$
$D^0 \to a_0(980)^0f_2(1270)^0$	$1.6 \pm 3.6 \pm 0.7$	$-7.3 \pm 3.3 \pm 0.8$	$1.5 \pm 7.2 \pm 1.3$
$D^0 \to a_1(1260)^+\pi^-$	$-4.4 \pm 5.6 \pm 3.7$	$9.3 \pm 6.1 \pm 1.3$	$-10.6 \pm 11.7 \pm 7.0$
$D^0 \to a_1(1260)^-\pi^+$	$-3.4 \pm 7.0 \pm 1.9$	$-5.8 \pm 5.6 \pm 4.3$	$-8.7 \pm 13.7 \pm 2.9$
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=1}$	$2.1 \pm 5.2 \pm 0.8$	$-12.2 \pm 5.5 \pm 0.6$	$2.4 \pm 11.0 \pm 1.4$
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=2}$	$5.2 \pm 7.1 \pm 1.9$	$-5.6 \pm 8.1 \pm 1.3$	$8.5 \pm 14.3 \pm 3.5$
$D^0 \to [K^+K^-]_{L=0}(\rho-\omega)^0$	$11.7 \pm 6.0 \pm 1.9$	$4.8 \pm 6.2 \pm 1.1$	$21.3 \pm 12.5 \pm 2.8$
$D^0 \to [\phi(1020)f_2(1270)^0]_{L=1}$	$2.7 \pm 6.7 \pm 1.7$	$0.9 \pm 6.0 \pm 1.7$	$3.6 \pm 13.3 \pm 3.0$
$D^0 \to [K^*(892)^0\overline{K}_2^*(1430)^0]_{L=1}$	$3.9 \pm 5.2 \pm 1.0$	$6.8 \pm 6.4 \pm 1.4$	$6.1 \pm 10.8 \pm 1.8$

JHEP 02 (2019) 126

Time-dependent measurements

Semileptonic decays

- Clear sign of mixing would be a "wrong-sign" (WS) decay



Expected decay rate:

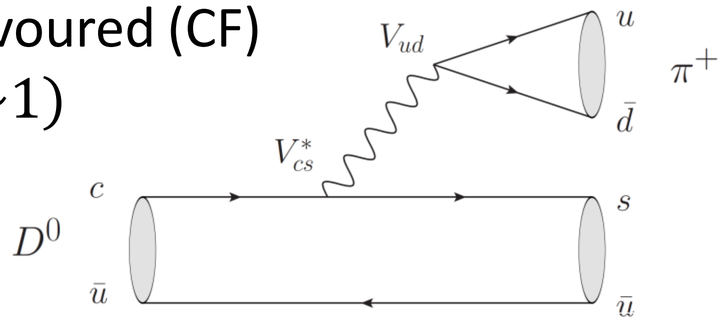
$$\Gamma(D^0(t) \to K^+ l^- \bar{\upsilon}) \propto e^{-\Gamma t} |A(\bar{D}^0 \to K^+ l^- \bar{\upsilon})|^2 \left|\frac{q}{p}\right|^2 \frac{x^2 + y^2}{4} (\Gamma t)^2$$

Time integrated wrong-sign (WS) to right-sign (RS) ratio gives

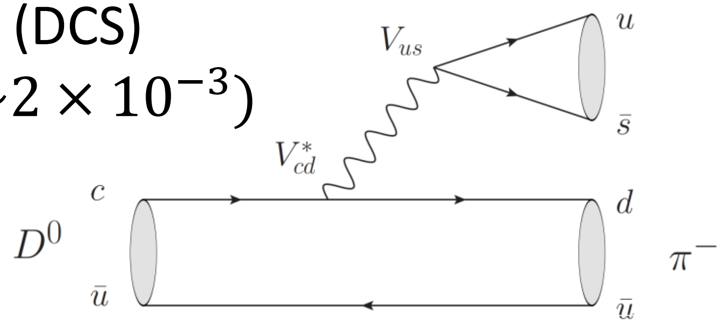
$$\mathrm{R} = \left|\frac{q}{p}\right|^2 \frac{x^2 + y^2}{2}$$

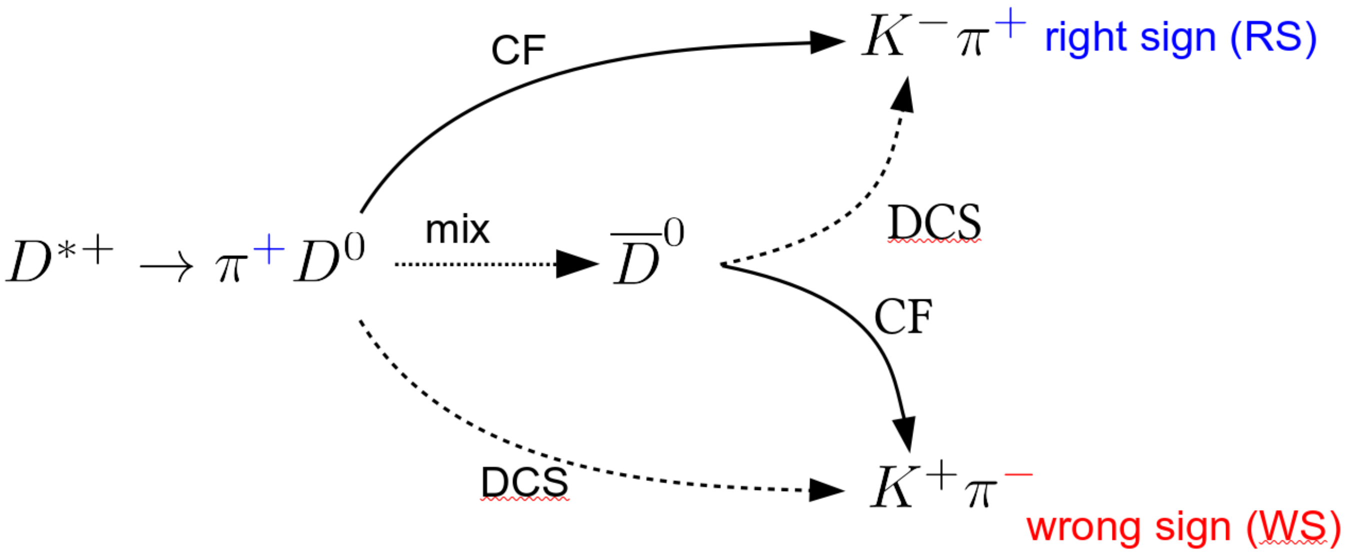
$D^0 \to K^{\mp}\pi^{\pm}$

Cabibbo-favoured (CF)
($|V_{cs}^* V_{ud}|^2 \sim 1$)



Doubly-Cabibbo suppressed (DCS)
($|V_{cd}^* V_{us}|^2 \sim 2 \times 10^{-3}$)

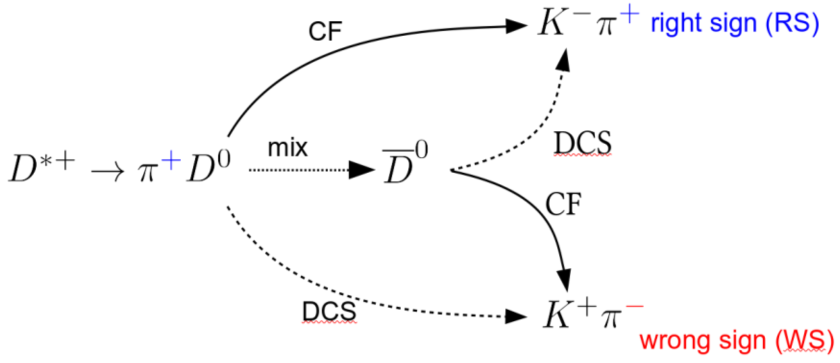




$D^0 \to K^{\mp}\pi^{\pm}$

- Measure ratio of WS to RS as a function of D^0 decay time:
  - $R(t) \propto R_D + \left|\frac{q}{p}\right| \sqrt{R_D}(y' \cos\phi - x' \sin\phi)\Gamma t + \left|\frac{q}{p}\right|^2 \frac{x^2+y^2}{4}(\Gamma t)^2$

$$\frac{q}{p}\frac{A(D^0 \to K^+\pi^-)}{A(\overline{D}^0 \to K^+\pi^-)} = -\left|\frac{q}{p}\right|\sqrt{R_D}e^{-i(\delta+\phi)} \quad , \qquad \begin{aligned} x' &= x\cos\delta + y\sin\delta \\ y' &= y\cos\delta - x\sin\delta \end{aligned}$$

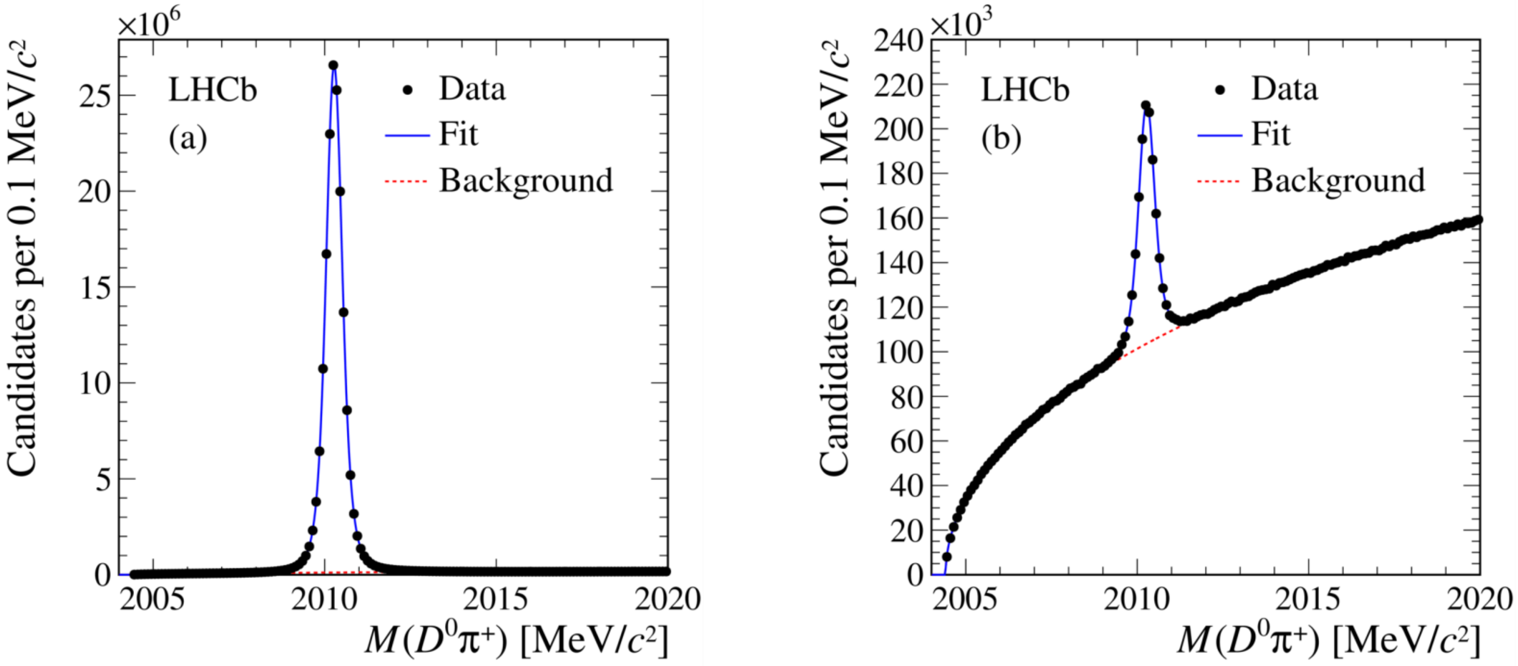


- Additional interference term:
  - More sensitive to mixing
  - Need time-dependent analysis

$D^0 \to K^{\mp}\pi^{\pm}$

- To get dependence on decay time: fit the $M(D^0\pi^+)$ distribution in bins of decay time
- Form ratio WS/RS
- Example: LHCb data up through 2016:

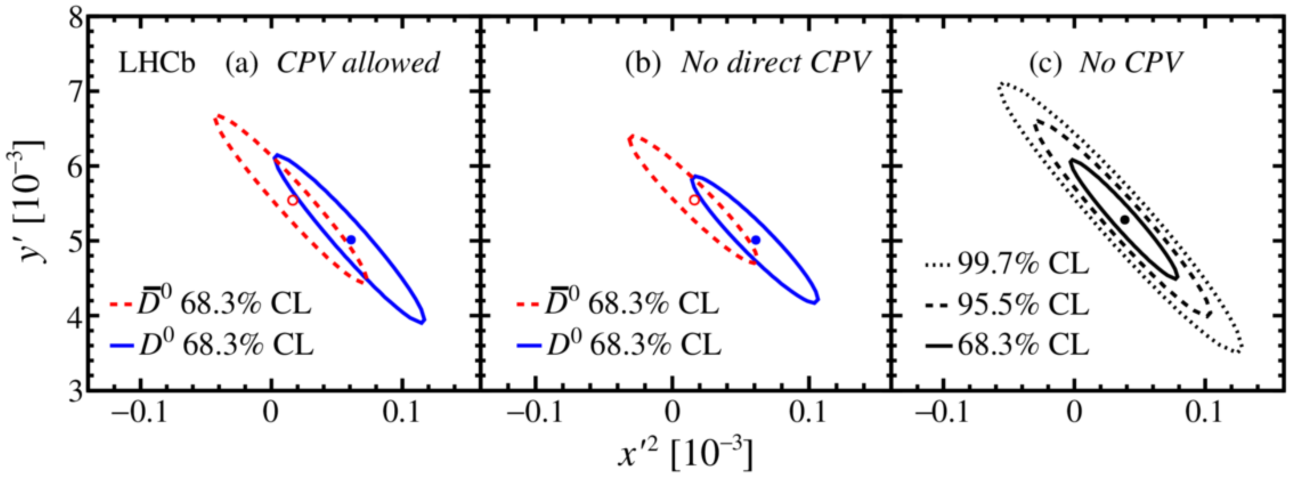
Phys. Rev. D97 (2018) 031101

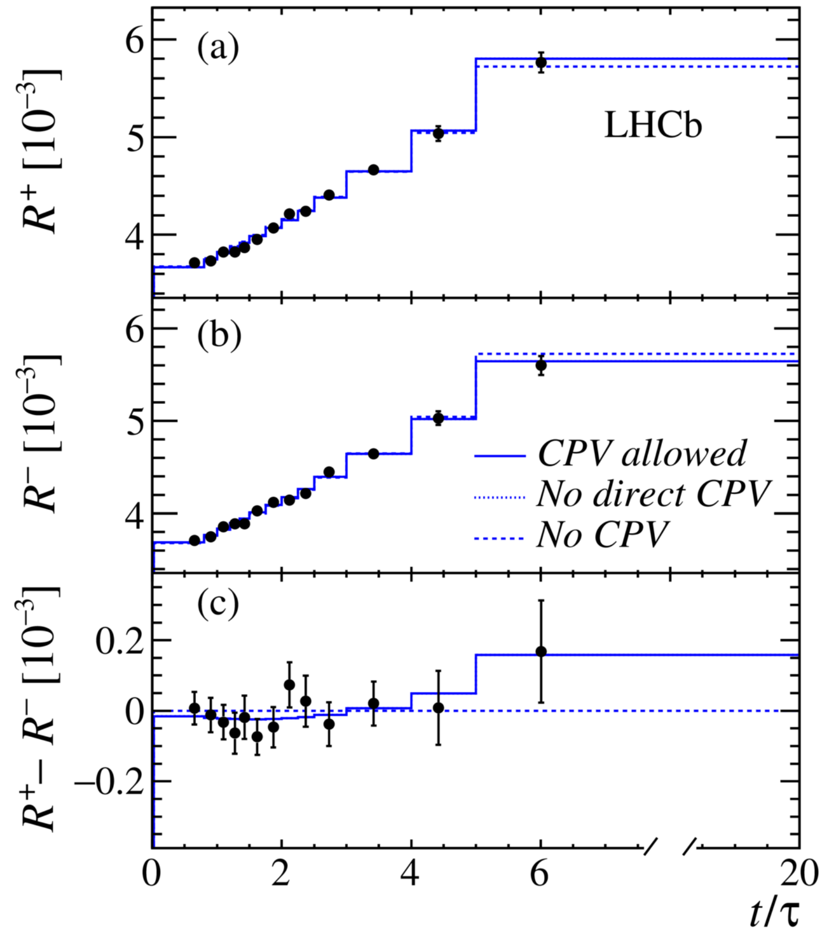


Phys. Rev. D97 (2018) 031101

$D^0 \to K^{\mp}\pi^{\pm}$

- Perform fit to ratios under three different CPV hypotheses



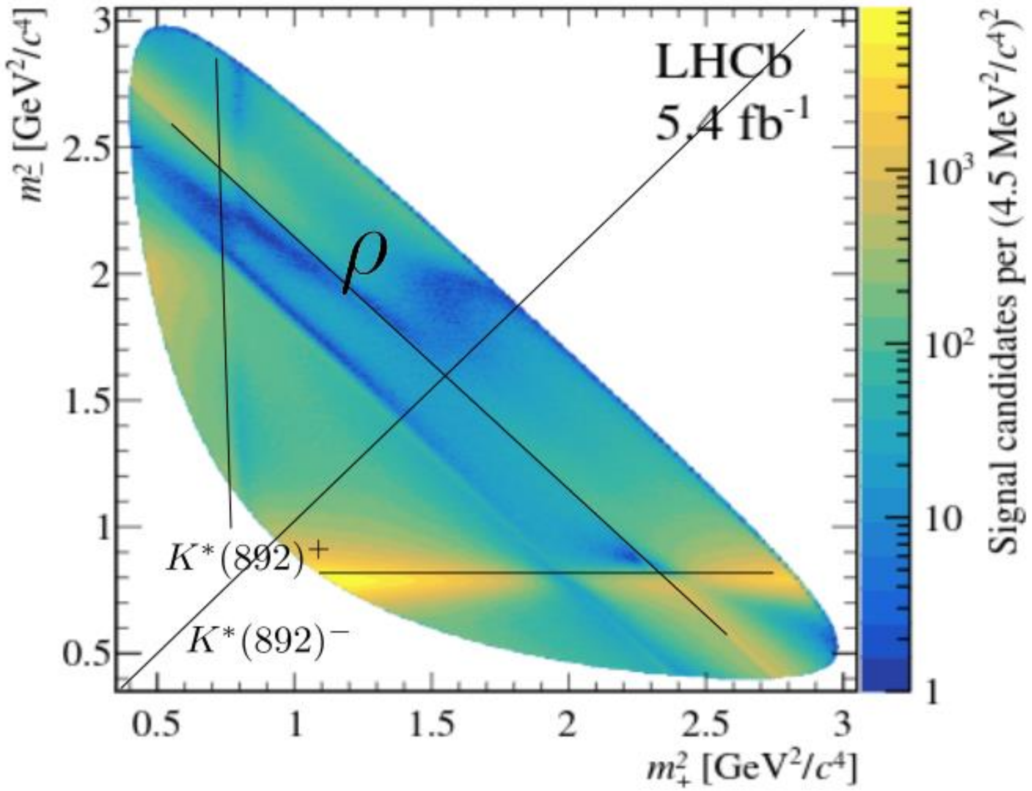


- In practice, a bit more complicated. But good illustration….

$D^0 \to K_S\pi^+\pi^-$

- Features a rich resonance substructure with varying strong phase across Dalitz plane.
  - Manifestation of mixing will vary across Dalitz plot, depending on amplitudes present

  - Pros: Good sensitivity and direct determination of $\mathrm{x}, \mathrm{y}, |q/p|$ and ϕ.
  - Cons: Requires good understanding of decay dynamics and reconstruction effects over the Dalitz plane.

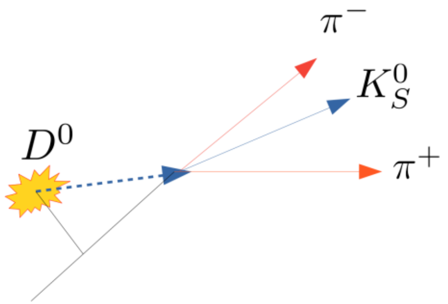


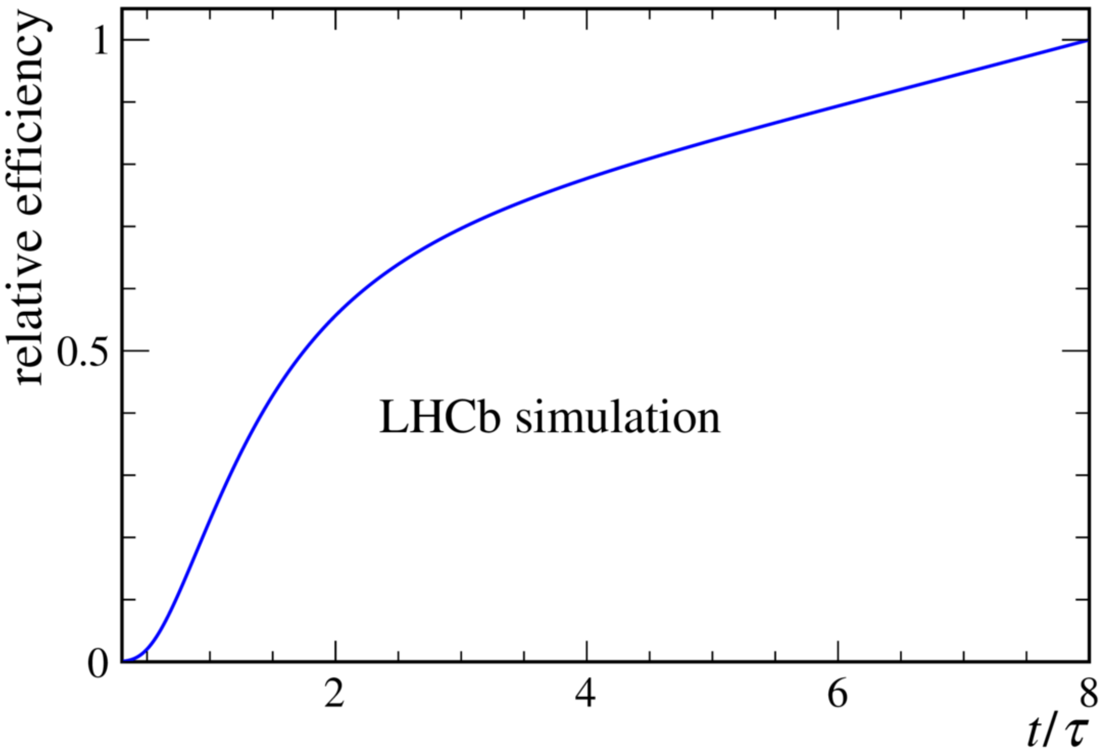
Phys. Rev. Lett. 127, (2021) 111801

Acceptance complications

Phys. Rev. Lett. 127, (2021) 111801

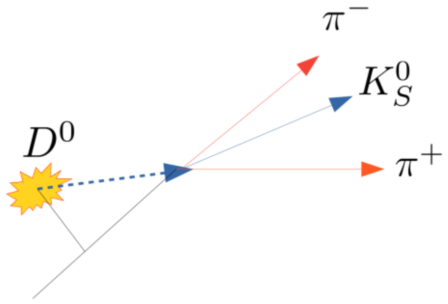
- Efficiency with which candidates can be reconstructed varies as a function of D^0 decay-time.
- ➢ Needs to be well-understood in order to disentangle mixing and CP violation effects from detector effects!



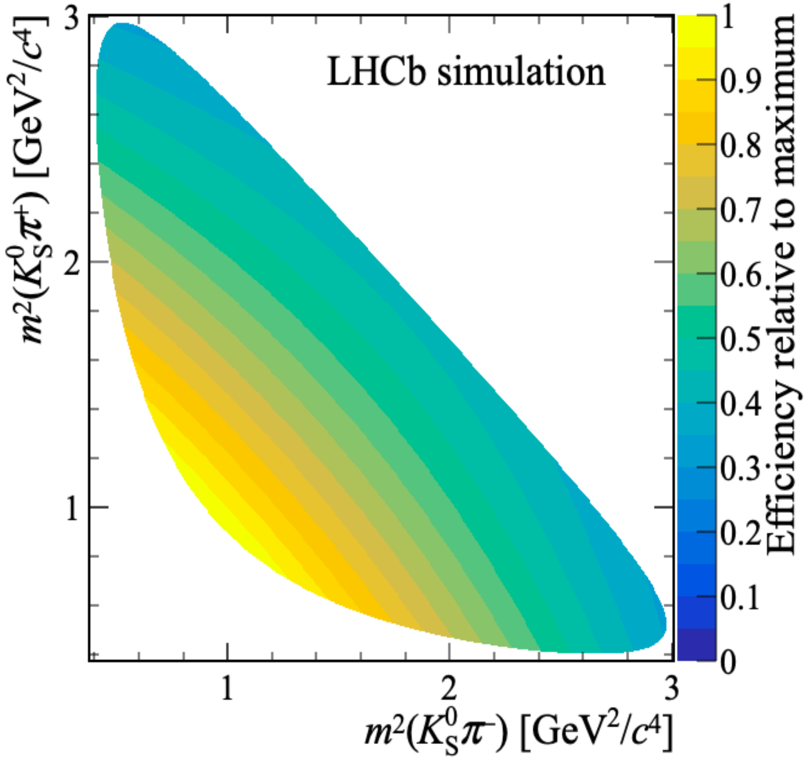


Efficiency complications

- Efficiency also varies over phase space
  - Due to correlation with kinematics, opening angles
- Necessary to understand how this shapes already complex distribution of decays over phase space.

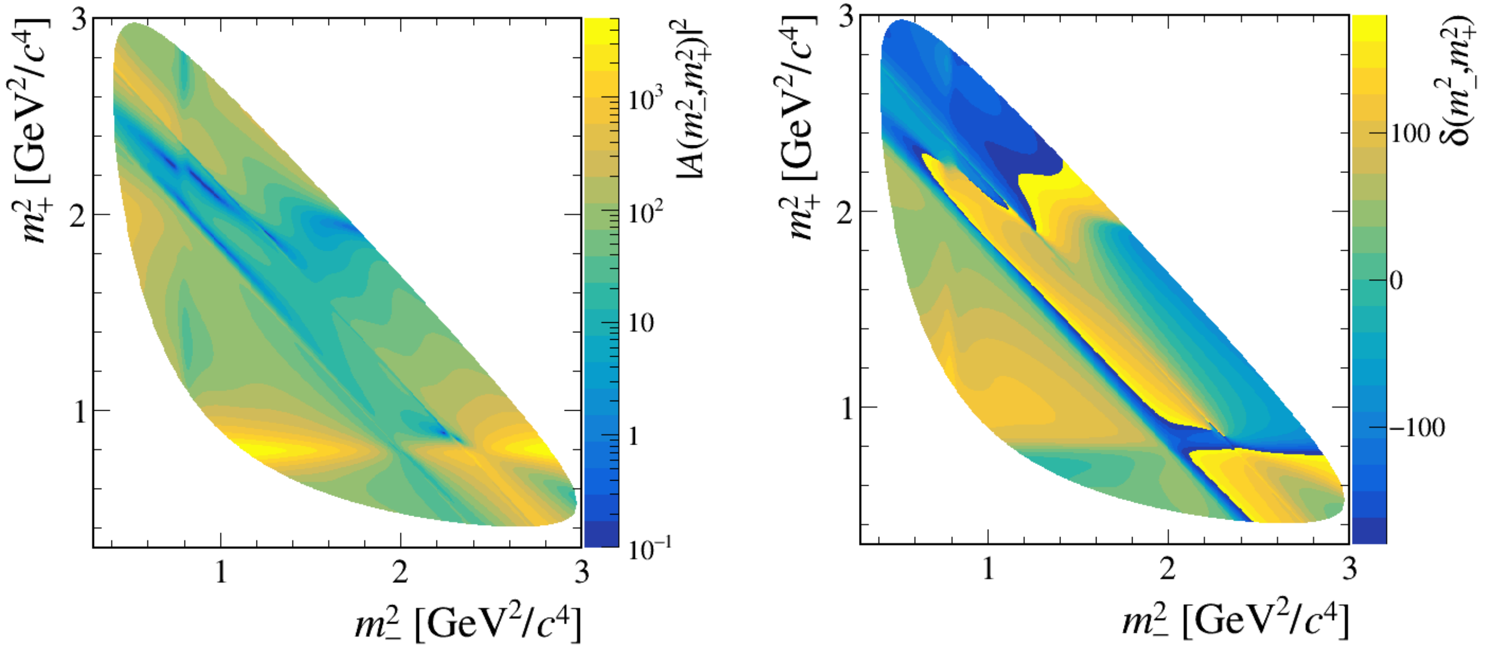


Phys. Rev. Lett. 127, (2021) 111801



$D^0 \to K_S\pi^+\pi^-$ Methods

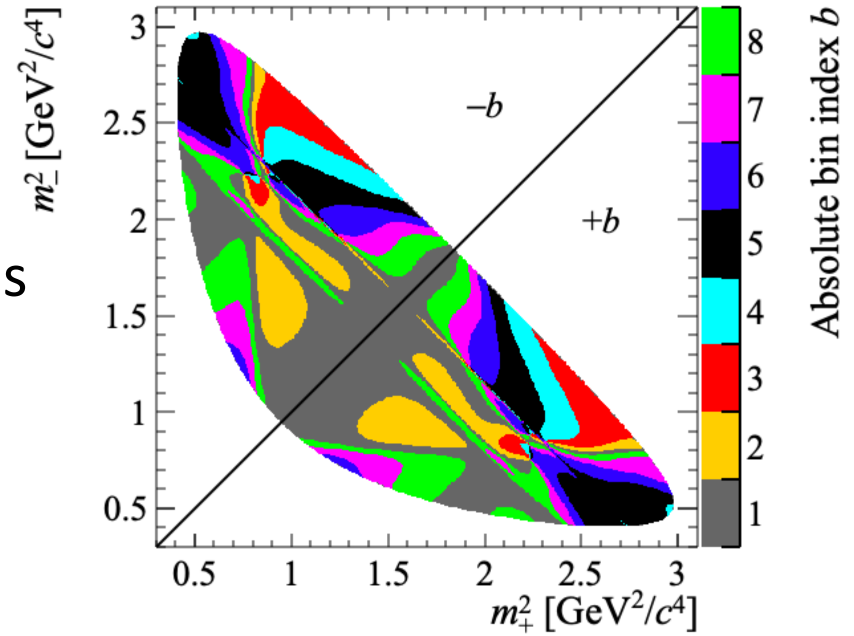
- Different approaches have been pursued
- Use amplitude model of decays
  - Used in first analyses by Belle and Babar
- Challenging for multiple reasons:
  - Determination of amplitudes
  - Assessment of systematic uncertainties



- Attractive alternatives are model-independent approaches

The "bin flip" method

- Approach for minimizing the above challenges: arXiv:1811.01032

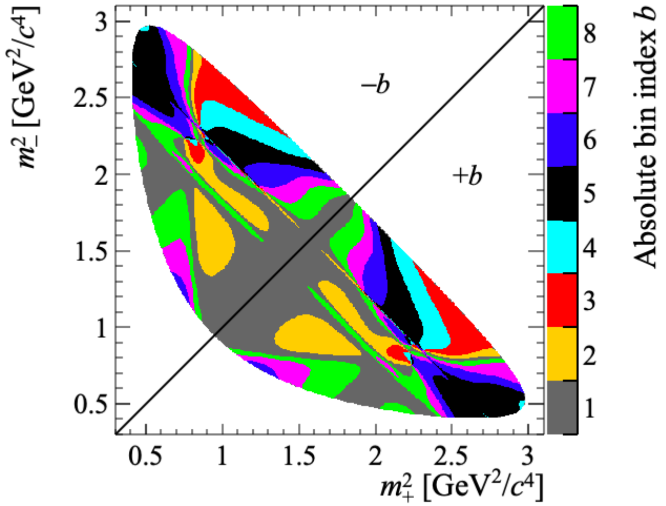


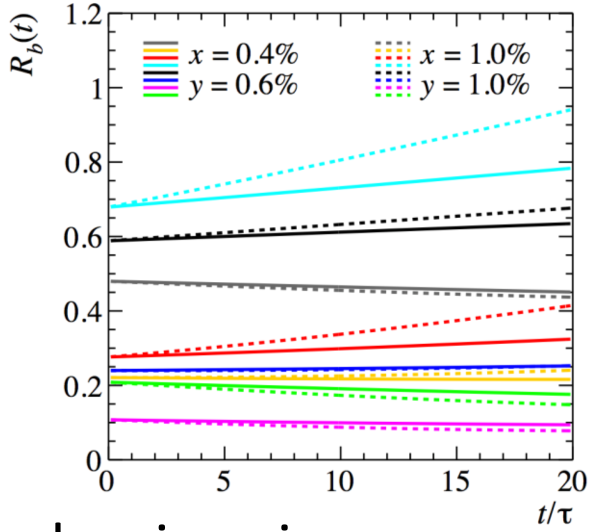
- Data is binned according to Dalitz coordinates
  - External measurements of strong-phase variation used as constraints
  - Avoids modelling dynamics of D^0 decay

- Binned also in decay time
  - Ratio of yields in opposite Dalitz bins formed as function of decay-time
  - Cancellation of **most** acceptance effects.
  - Avoids complicated acceptance modelling.

The "bin flip" method

- Ratio of yields as a function of decay time gives sensitivity to mixing and CP violation parameters



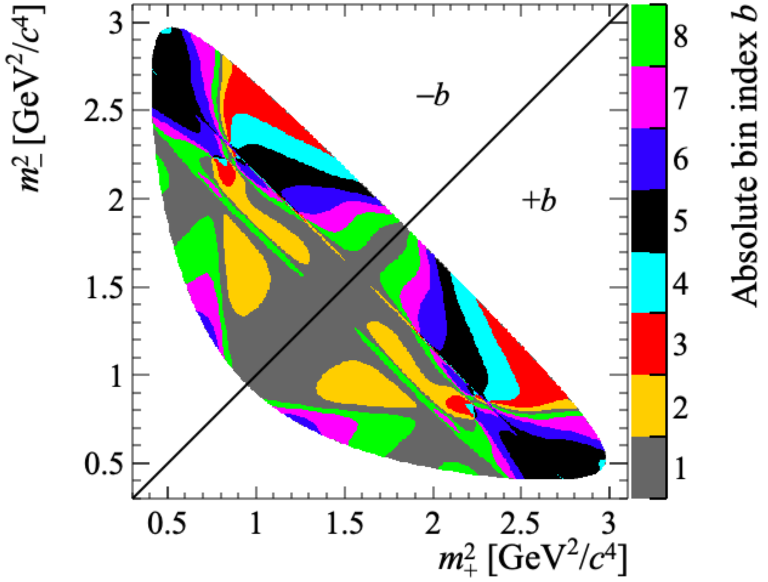


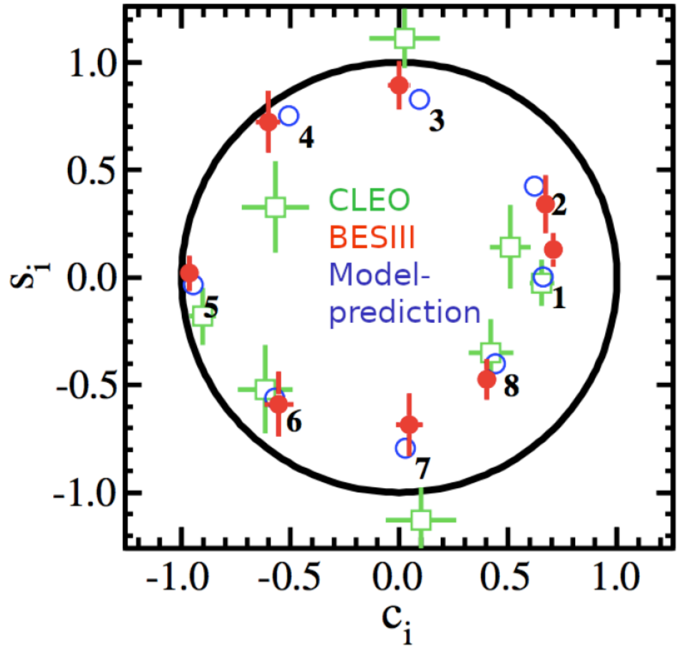
- Slopes in each bin determined by interplay of hadronic nuisance parameters and mixing parameters.

$$R_{bj}^{\pm} \approx r_b - \langle t \rangle_j \sqrt{r_b}[(1 - r_b)c_b y - (1 + r_b)s_b x]$$

Strong phase input

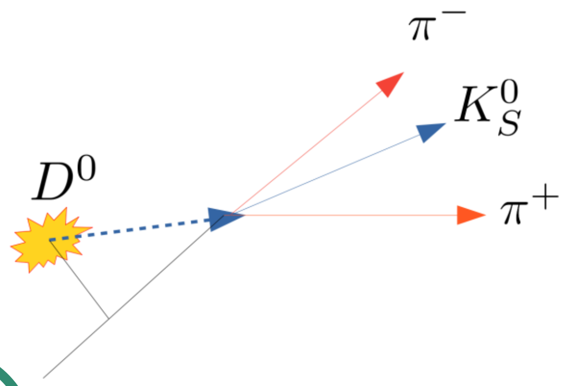
- Minimises strong phase variation within regions of phase space
- Measured to good precision with quantum-correlated $D\overline{D}$ pairs:
  - CLEO (Phys. Rev. D72, 012001 (2005))
  - BESIII (Phys. Rev. D101, 112002 (2020))

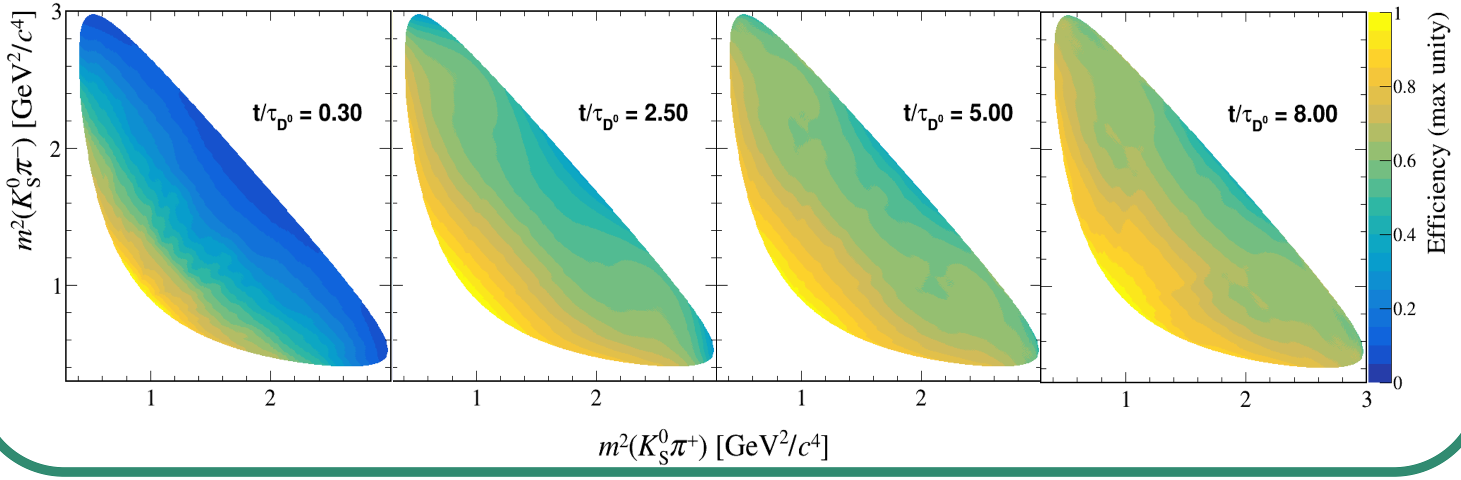




More efficiency complications

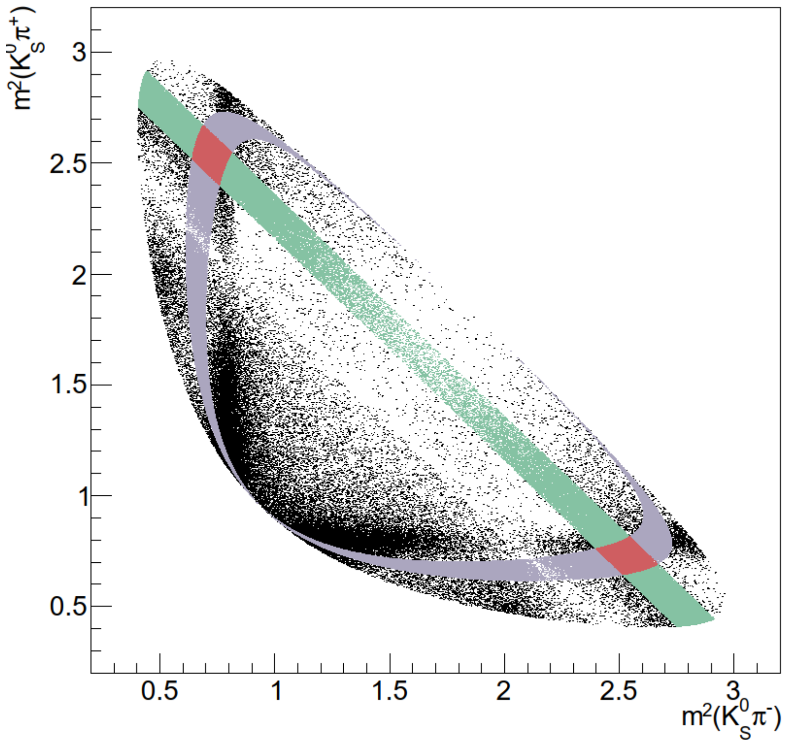
- Trigger requirements correlate Dalitz-plot coordinates with decay-time
- Can mimic mixing and create large biases if not corrected for





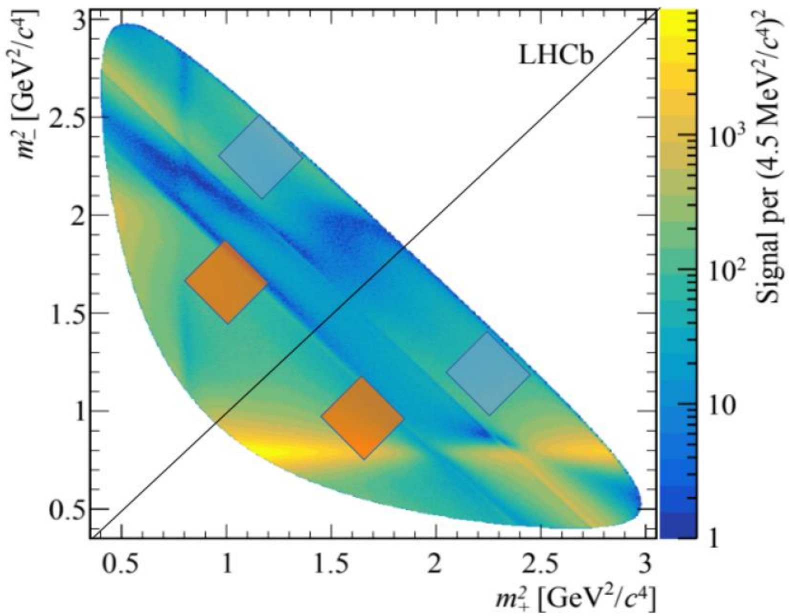
Efficiency complications

- Effect is symmetric with respect to Dalitz plot bisector (charge conjugation)
  - Insensitive to oscillations moving events from one size to the other
- Use data itself to get relative efficiencies of symmetric regions throughout phase space
- Small effect from y taken into account



More efficiency complications

- Robust against charge detection asymmetries for soft pion and K_S^0
- Momenta of $\pi^+\pi^-$ pair depend on Dalitz-plot coordinate, and opposite sign for D^0 and $\overline{D}^0$
  - Can mimic CP violation
- Asymmetry determined with Cabibbo favoured D_s^+ decays



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

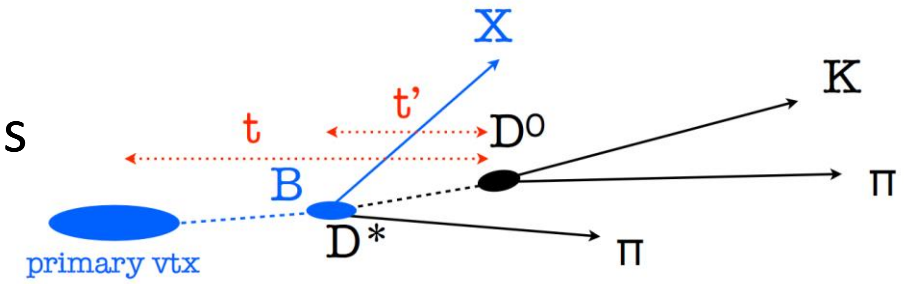
$$A_{\rm meas}(D_s^+ \to \phi\pi^+) = A_{\rm det}(\pi^+) + A_{\rm prod}(D_s^+) + A_{\rm trigger}(D_s^+)$$

➢ $\mathcal{O}(2 \times 10^{-3})$ correction applied to measured ratios

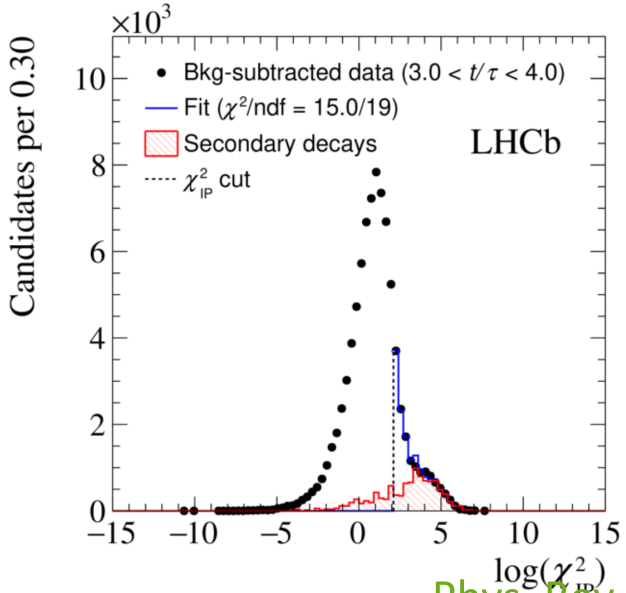
Contamination of b-hadrons in π –tagged sample

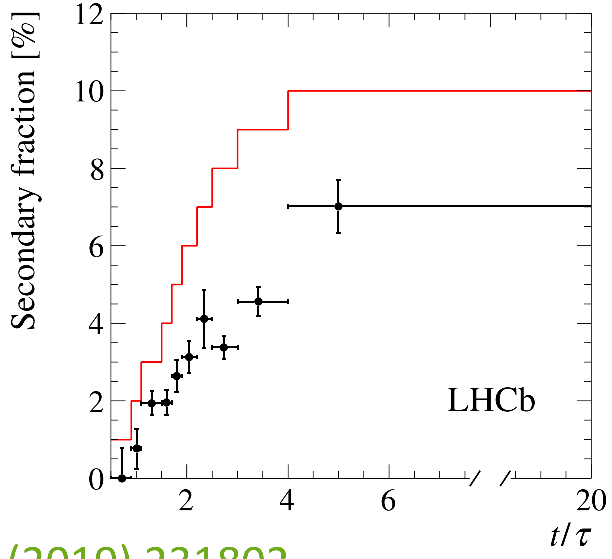
- b-hadron decays in π –tagged sample will have measured lifetime of D^0biased towards larger values

➢ The oscillation rates will be dampened, CP asymmetries may be biased



- Fraction of such events is obtained in each decay time bin by fitting quantities related to impact parameter





Phys. Rev. Lett. 122 (2019) 231802

Measurement

- The ratio in Dalitz bin b and decay time bin j is given by

$$R_{bj}^{\pm} \approx \frac{r_b\left[1+\frac{1}{4}\langle t^2\rangle_j \mathrm{Re}(z_{CP}^2-\Delta z^2)\right]+\frac{1}{4}\langle t^2\rangle_j |z_{CP}\pm\Delta z|^2+\sqrt{r_b}\langle t\rangle_j Re[X_b^*(z_{CP}\pm\Delta z)]}{\left[1+\frac{1}{4}\langle t^2\rangle_j \mathrm{Re}(z_{CP}^2-\Delta z^2)\right]+\frac{1}{4}r_b\langle t^2\rangle_j |z_{CP}\pm\Delta z|^2+\sqrt{r_b}\langle t\rangle_j Re[X_b\,(z_{CP}\pm\Delta z)]}$$

$$z_{CP}\pm\Delta z = -(q/p)^{\pm 1}(y\pm ix)$$
$$x_{CP} = -\mathrm{Im}(z_{CP}),\, y_{CP} = -\mathrm{Re}(z_{CP})$$
$$\Delta x = -\mathrm{Im}(\Delta z),\, \Delta y = -\mathrm{Re}(\Delta z)$$

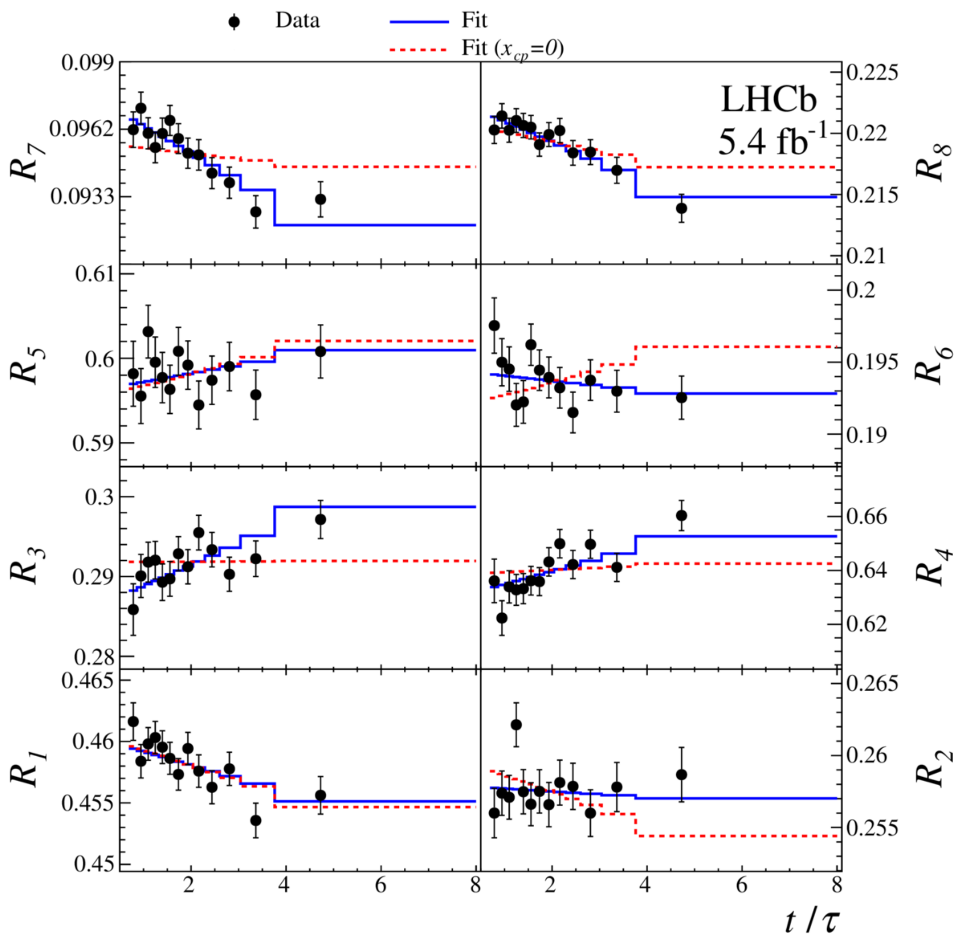
where $\langle t^{(2)}\rangle_j$ is average $t^{(2)}$ in bin j, r_b is ratio at t=0, and X_b includes strong phase information

- In limit of CP symmetry $x_{CP} = x, y_{CP} = y, \Delta x = \Delta y = 0$

Phys. Rev. Lett. 127, (2021) 111801

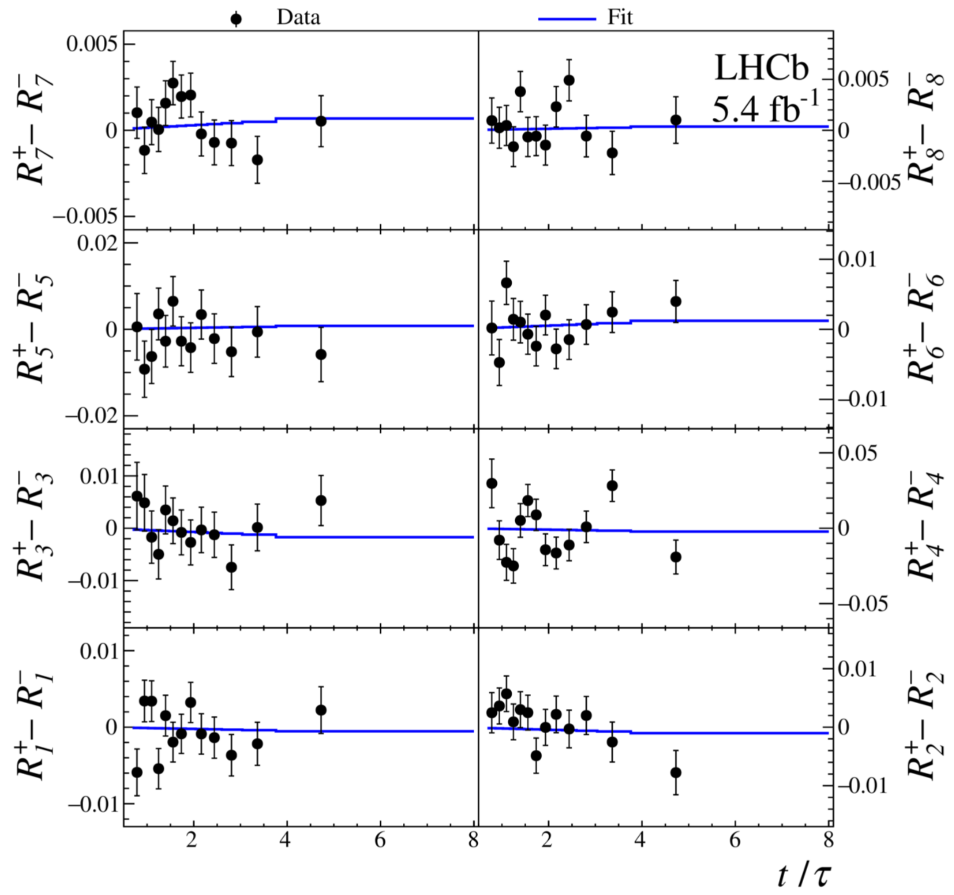
Fit to ratios

- Yields determined in each mass and decay time bin, and ratios formed.
- Departures from a constant value are due to mixing
- Clearly incompatible with no mixing and x=0



Fit to ratios

- Allow for differences between samples tagged as D^0 and $\overline{D}^0$
- Slopes would indicate presence of CP violation
- Data consistent with CP symmetry



Phys. Rev. Lett. 127, (2021) 111801

Systematic uncertainties

- Largest uncertainty is statistical
- Experimental improvements foreseen with larger samples
- Larger samples from BESIII will ensure strong phase inputs not limiting factor

Source	x_{CP}	y_{CP}	Δx	Δy
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

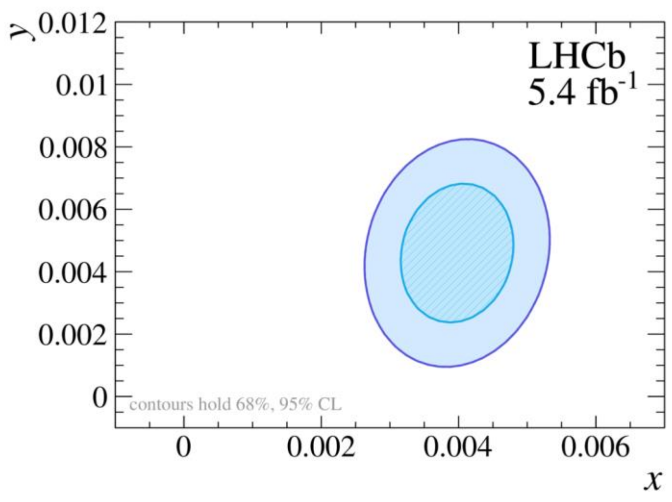
Strong phase inputs	0.23	0.66	0.02	0.04
Detection asymmetry inputs	0.00	0.00	0.04	0.08
Statistical (w/o inputs)	0.40	1.00	0.18	0.35
Total statistical uncertainty	0.46	1.20	0.18	0.36

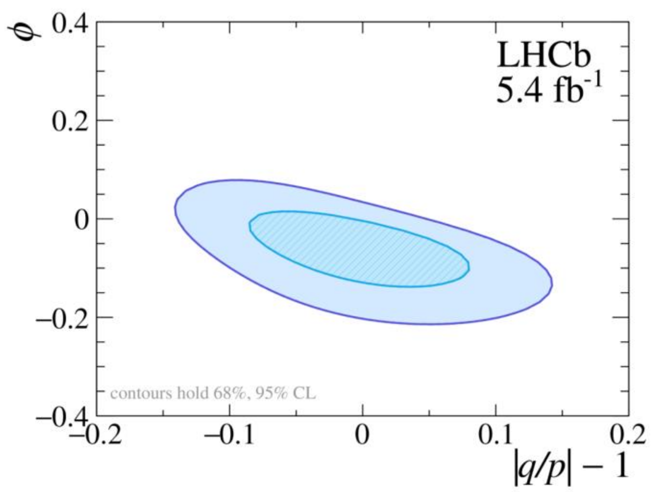
Phys. Rev. Lett. 127, (2021) 111801

Results

- First observation that x differs from zero
- Most precise single measurement of x, $|q/p|$, and ϕ

Parameter	Value	95.5% CL interval
x $[10^{-3}]$	$3.98\,^{+0.56}_{-0.54}$	$[2.9, 5.0]$
y $[10^{-3}]$	$4.6\,^{+1.5}_{-1.4}$	$[2.0, 7.5]$
$\lvert q/p\rvert$	0.996 ± 0.052	$[\ 0.890, 1.110]$
ϕ	$-0.056\,^{+0.047}_{-0.051}$	$[-0.172, 0.040]$

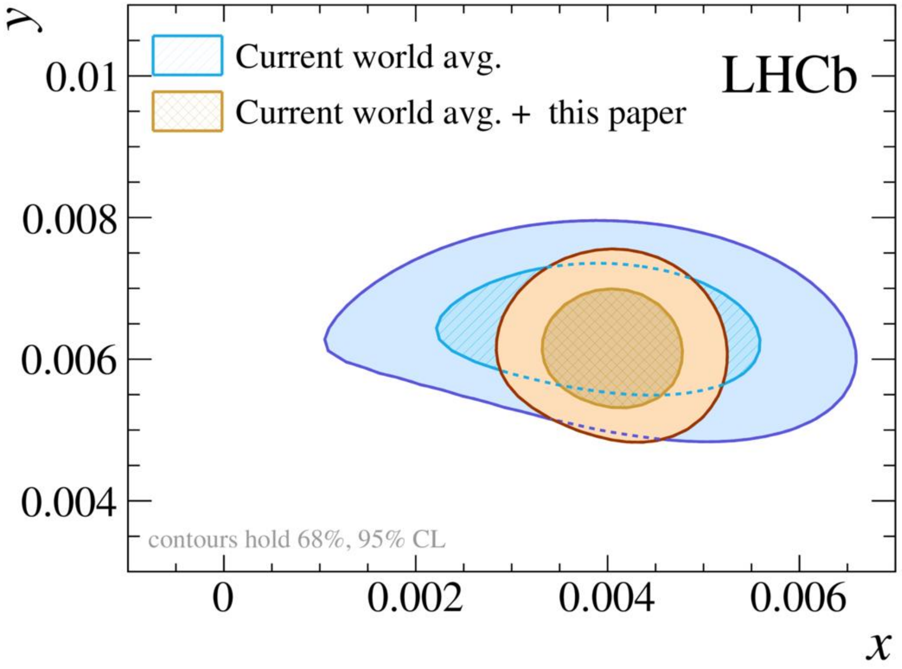


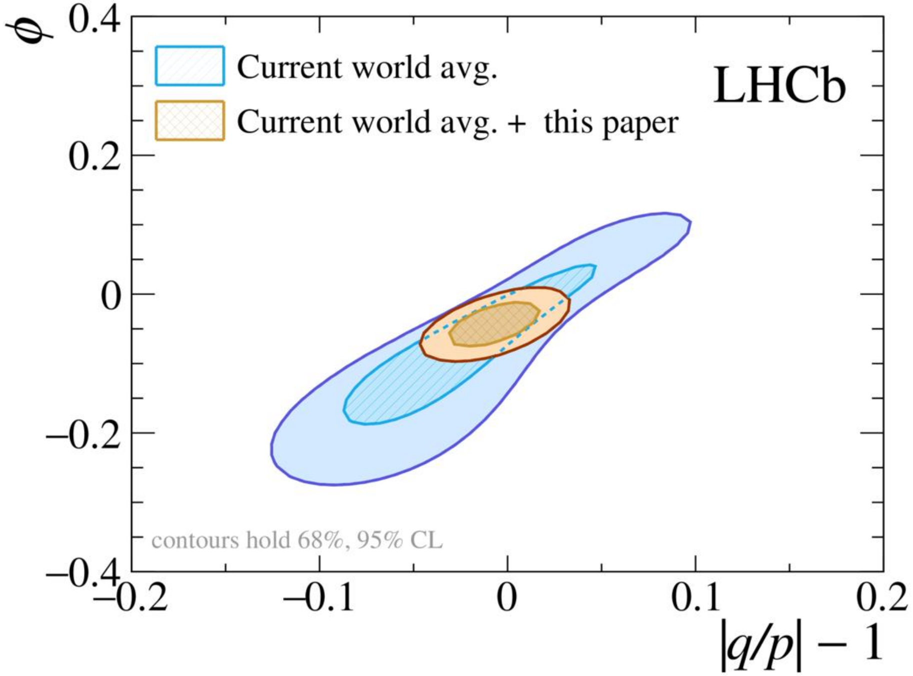


Phys. Rev. Lett. 127, (2021) 111801

Effect on world average

- Outdated by now, but to illustrate power of this decay mode

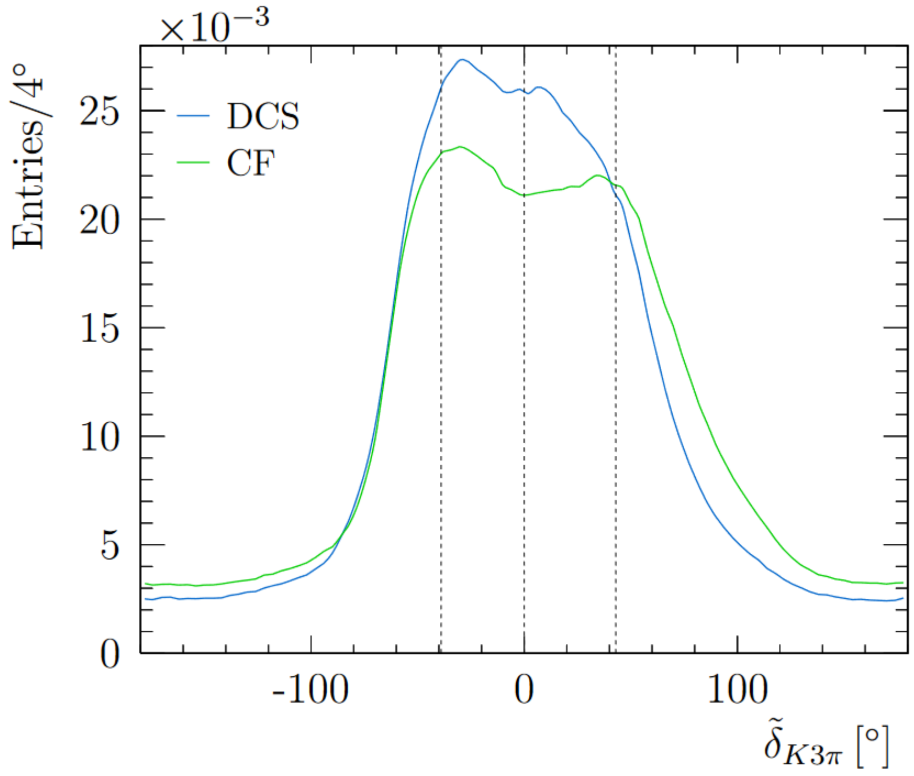




$D^0 \to K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$

- A WS/RS analysis akin to $D^0 \to K^{\pm}\pi^{\mp}$ can be performed
- ➢ Led to first single-measurement observation of mixing:

  (Phys. Rev. Lett. 116 (2016) 241801)
- Can do better utilising phase space information (as with $D^0 \to K_S\pi^{+}\pi^{-}$)
  - [arXiv:1909.10196]
- True as well for other multibody decay modes!



Time-dependent $D^0 \to h^+h^-$ asymmetry

- Cabibbo-suppressed $D^0 \to K^+K^-, \pi^+\pi^-$ decays also provide sensitive tests of mixing-induced CP violation through measurement of time-dependent asymmetry

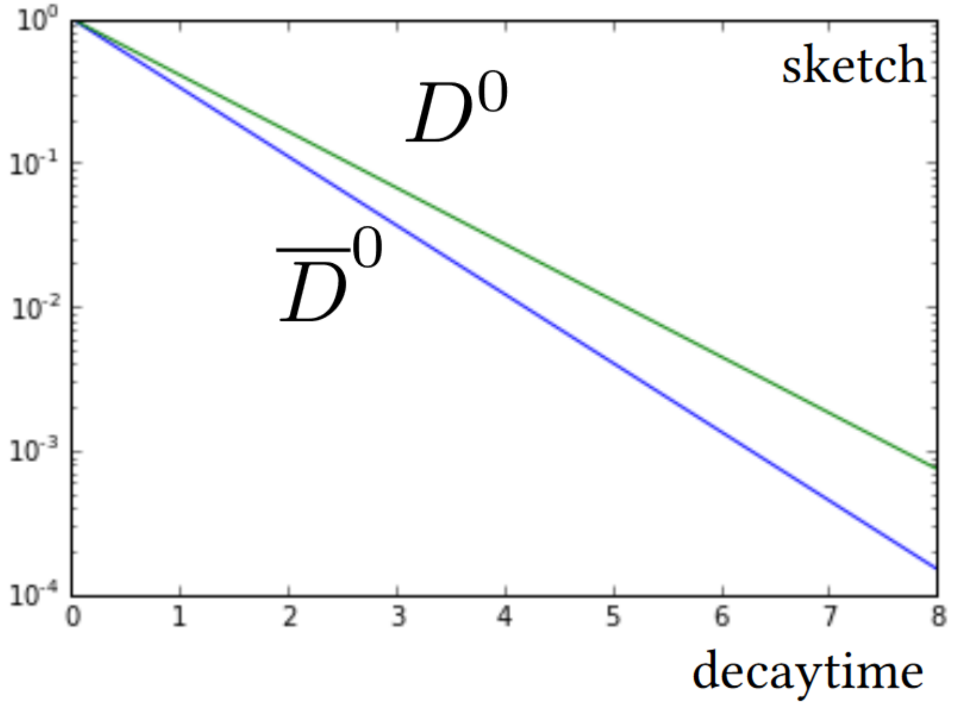
$$A_{CP}(f,t) = \frac{\Gamma(D^0\to f,t)-\Gamma(\bar{D}^0\to f,t)}{\Gamma(D^0\to f,t)+\Gamma(\bar{D}^0\to f,t)}$$

- Due to smallness of mixing parameters can be expanded to linear order

$$A_{CP}(f,t) \approx a_{CP}^{\text{dir}} + \frac{t}{\tau(D^0)}\Delta Y_f$$

- Seek to measure the slope of the asymmetry ΔY_f

- ➢SM calculations put it at $\mathcal{O}(10^{-5})$, while current sensitivity is $\mathcal{O}(10^{-4})$

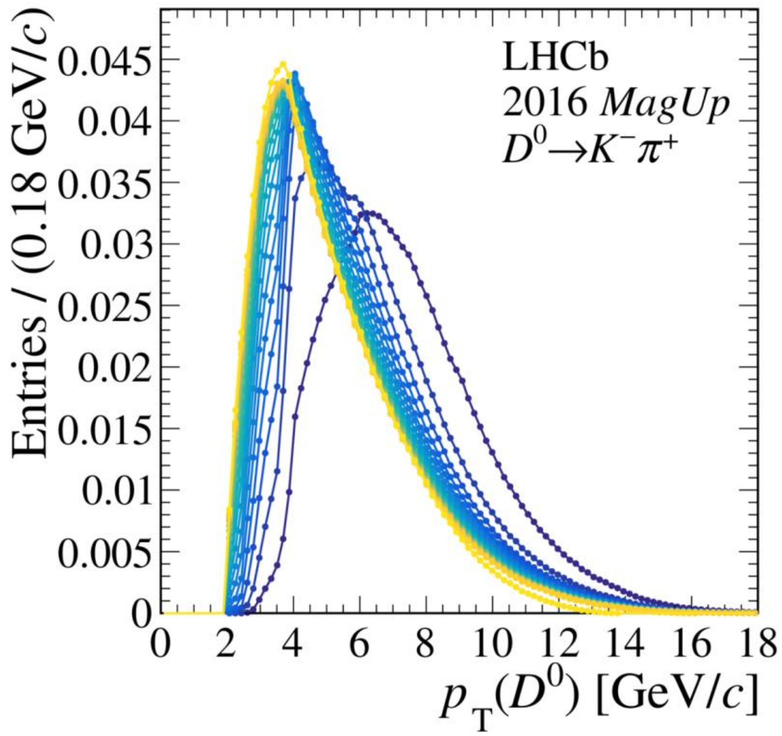


Nuisance asymmetries

Phys. Rev. D 104, 072010

- As ΔY_f is a slope, largely insensitive to time-independent asymmetries

- Selection requirements introduce correlations between momentum & decay time of the D^0
- ➢ Detection asymmetry time-dependent.
- Contamination from b-hadron decays is time-dependent.
- ➢ Production asymmetry time-dependent.



- So measured asymmetry is: $A_{raw}(f,t) = A_{CP}(f,t) + A_D(f,t) + A_D(\pi_s^+,t) + A_P(D^{*+},t)$

  $= 0$

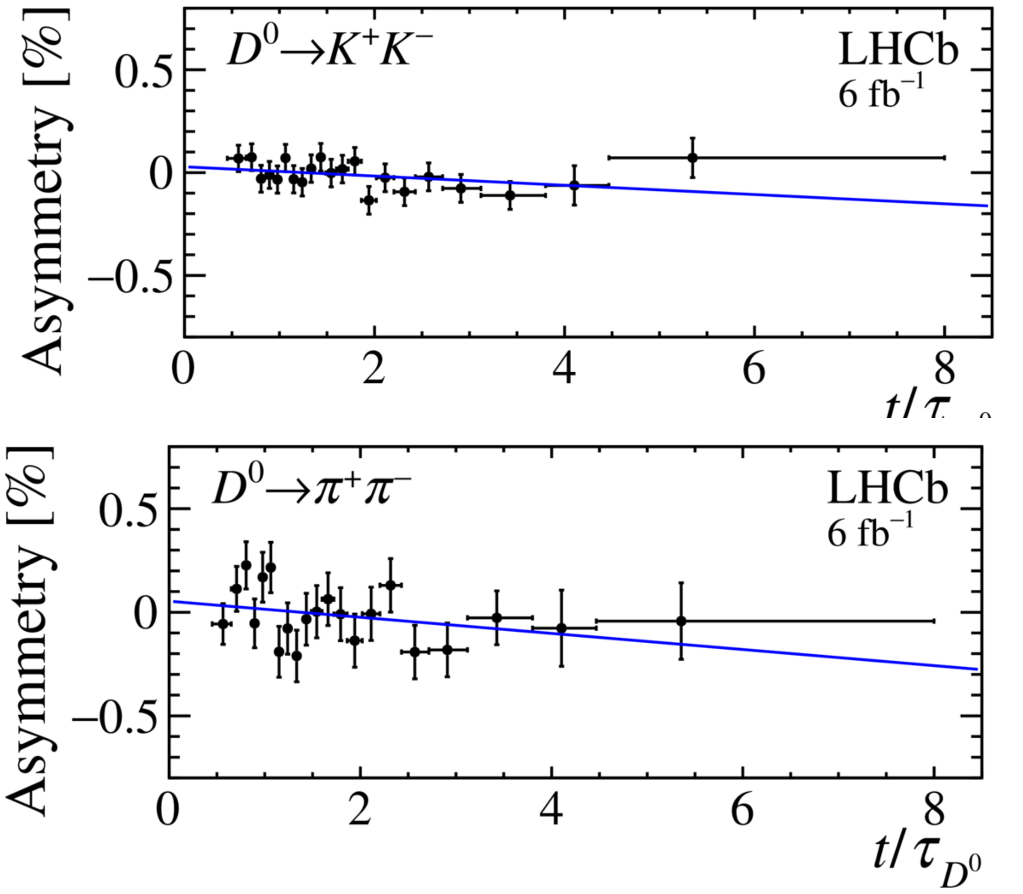
Fit to asymmetry

- The data is divided into 21 bins, and asymmetry of corrected data determined in each bin.
- A χ^2 fit of a linear trend is performed to extract ΔY
- LHCb measurements yield

$$\Delta Y_{K^+K^-} = (-0.3 \pm 1.3 \pm 0.3) \times 10^{-4}$$
$$\Delta Y_{K^+K^-} = (-3.6 \pm 2.4 \pm 0.4) \times 10^{-4}$$
$$\Delta Y = (-1.0 \pm 1.1 \pm 0.3) \times 10^{-4}$$

and dominates the world average

- Still work to be done to reach SM expectation!



Phys. Rev. D 104, 072010

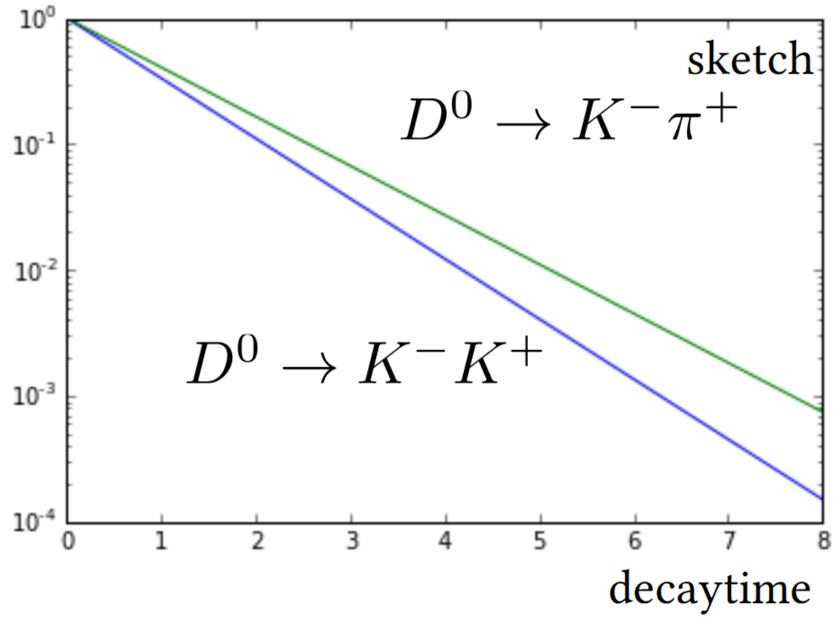
y_{CP}^{f}-$y_{CP}^{K\pi}$

- Nonzero value of y implies that decay rate of CP eigenstates like $D^0 \to h^+h^-$ will have slightly different effective decay width
- Departure from unity with respect to Γ quantified by

$$y_{CP}^{f} \equiv \frac{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\bar{D}^0 \to f)}{2\Gamma} - 1$$

- In limit of CP conservation, coincides with y
- Experimentally, measure the decay width with respect to $D^0 \to K^-\pi^+$:

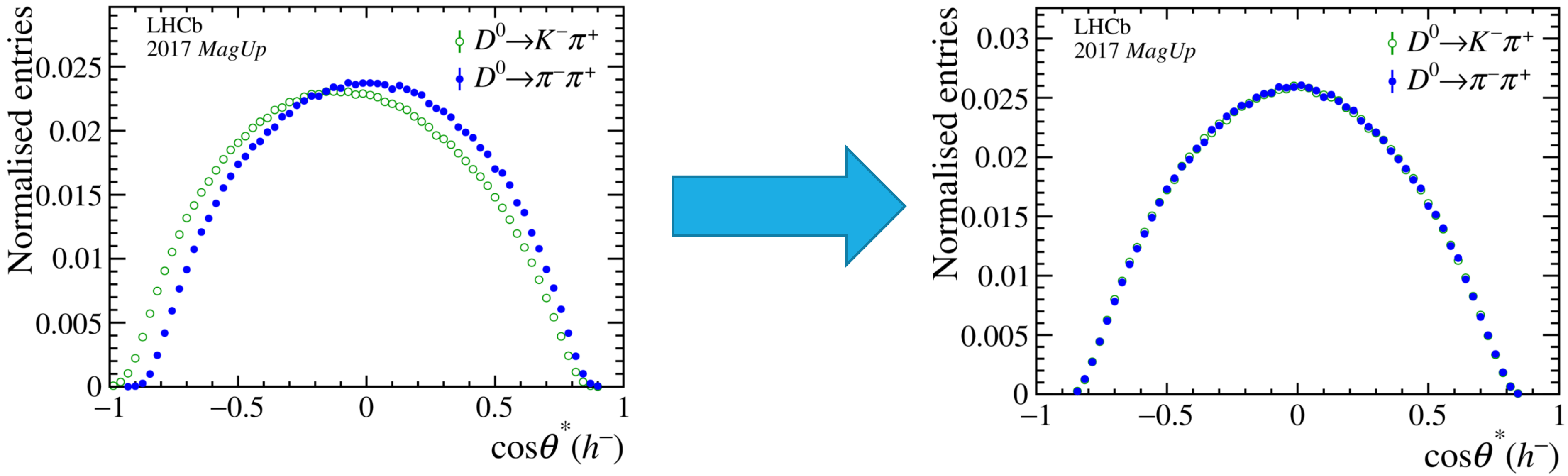
$$\frac{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\bar{D}^0 \to f)}{\hat{\Gamma}(D^0 \to K^-\pi^+) + \hat{\Gamma}(\bar{D}^0 \to K^+\pi^-)} - 1 \approx y_{CP}^{f}\text{-}y_{CP}^{K\pi}$$



arXiv:2202.09106

y_{CP}^{f}-$y_{CP}^{K\pi}$

- Main difficulty is different efficiencies coming from different final-states
  - Handled with data-driven methods to “match” kinematics, and reweight kinematic quantities



arXiv:2202.09106

y_{CP}^{f}-$y_{CP}^{K\pi}$

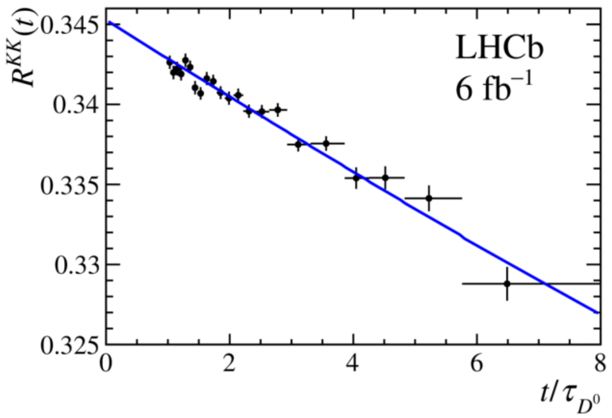
- LHCb results yield

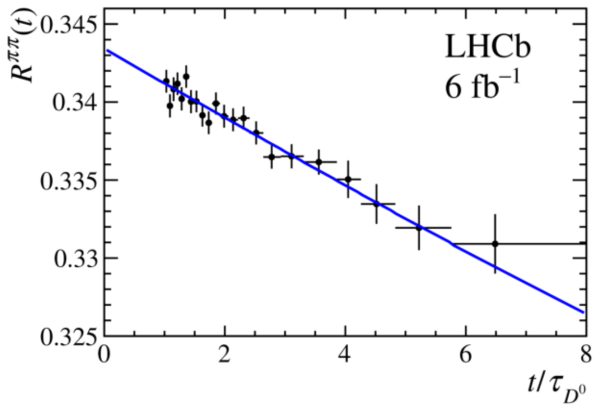
$$y_{CP}^{\pi\pi}\text{-}y_{CP}^{K\pi} = (6.57 \pm 0.53 \pm 0.16) \times 10^{-3}$$

$$y_{CP}^{KK}\text{-}y_{CP}^{K\pi} = (7.08 \pm 0.30 \pm 0.14) \times 10^{-3}$$

$$y_{CP}\text{-}y_{CP}^{K\pi} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}$$

- Four times more precise than previous world average!
- Consistent with world average value for y

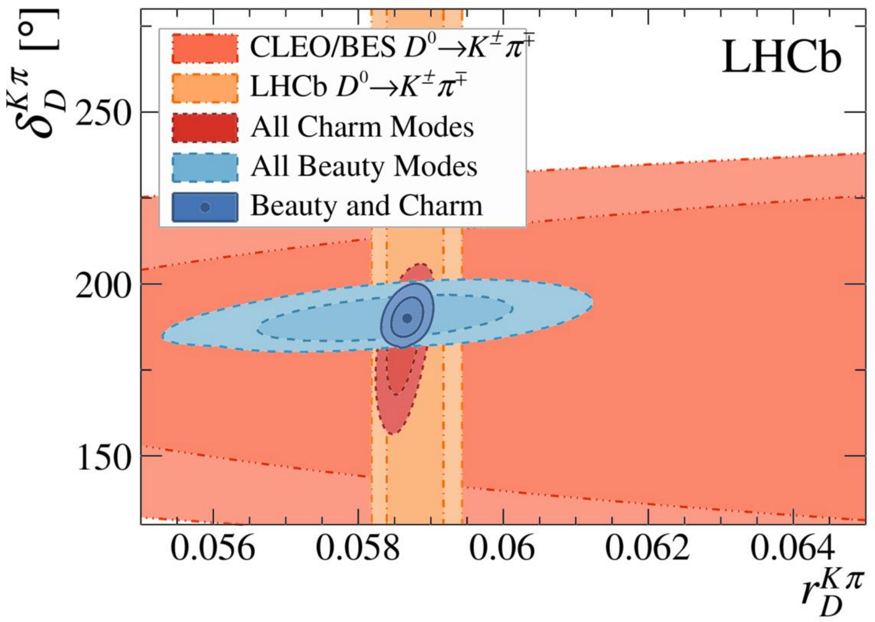


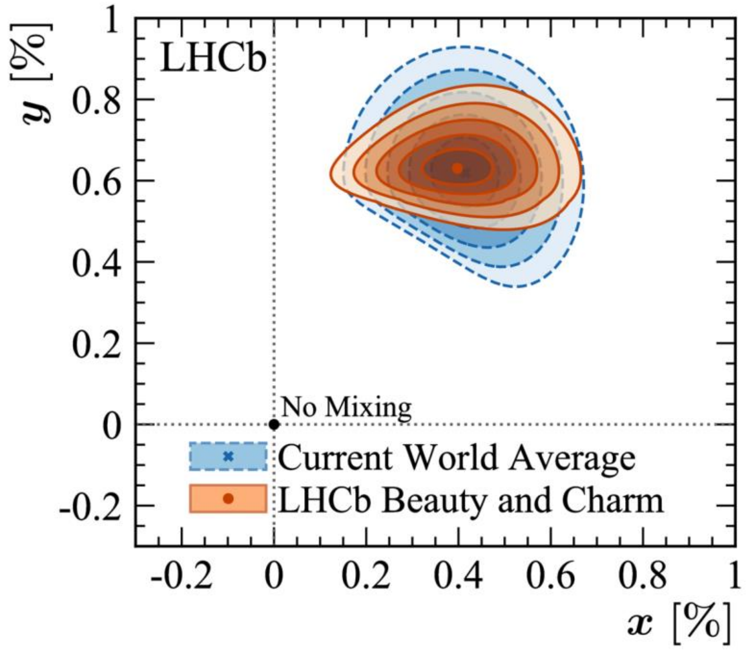


JHEP 12 (2021) 141

Including beauty samples

- Measurements of Unitarity Triangle angle γ performed with $B^{\pm} \to Dh^{\pm}$ employ $D \to K^{\pm}\pi^{\mp}$ mode
  - Sensitive to hadronic parameters f
- Simultaneous combination with beauty observables can lead to improvements in charm system!

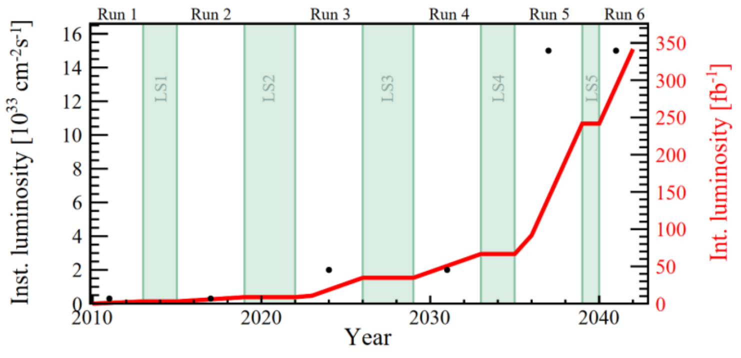


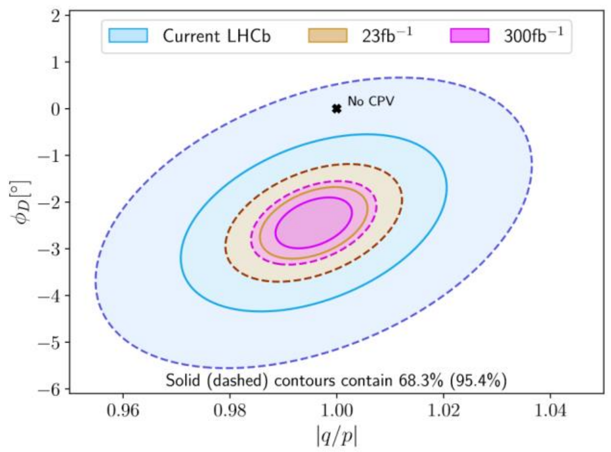


Outlook

- LHCb will begin taking data again shortly following first upgrade
- Have also put together a document presenting the physics case for an LHCb Upgrade II (arxiv:1808.08865) and a framework TDR
- Huge increases in data, and frighteningly good precisions possible!

- Significant impact from Belle II as well, especially on modes containing neutral particles
  - Recent measurement of lifetimes
  - More info and prospects in Physics Book arXiv:1808.10567





Summary

- CP violation and mixing are interesting places to look for New Physics effects
- Exiting times! Much progress has been made in recent years:
  - Observation of CP violation in the decay
  - Improved limits on mixing-induced CP violation
- More work needed to fully characterize CP violation in the charm system
- Stay tuned!