CP violation in multi-body final states at LHCb

Louis Henry, on behalf of the LHCb collaboration
Implications workshop, CERN, 18/10/2019

Outline

- Multi-body decays: motivation and common features

- CPV in multi-body from beauty decays
  - $B^+ \to h^+ h^- h^+$ decays [**arxiv:1905.09244**],[**arxiv:1909.05212**]
  - $B^0 \to K_S h^+ h'^-$ decays [**PRL. 120, 261801 (2018)**][**JHEP 06 (2019) 114**]
  - $B^0 \to VV$ decays [**JHEP 05 (2019) 026**][**JHEP 07 (2019) 032**]

- CPV in multi-body from charm decays
  - $D^0 \to K_S \pi^+ \pi^-$ [**PRL. 122 (2019) 231802**]
  - $D^0 \to h^+ h^- h^+ h^-$ [**JHEP 02 (2019) 126**][**Phys.Lett. B769 (2017) 345**]
  - $D^+ \to h^+ h^- h^+$ decays
  - $D^0 \to h^+ h^- \mu^+ \mu^-$ [**PRL. 121 (2018) 091801**]

- Conclusion and perspectives

CPV in multi-body decays

CPV in multi-body decays: the theory side

- Does the Standard Model account for all observed CPV?
  - Predictions are difficult because of limited knowledge of the strong phases.
    - Model-dependent approach
    - Or model-independent → depends on external input

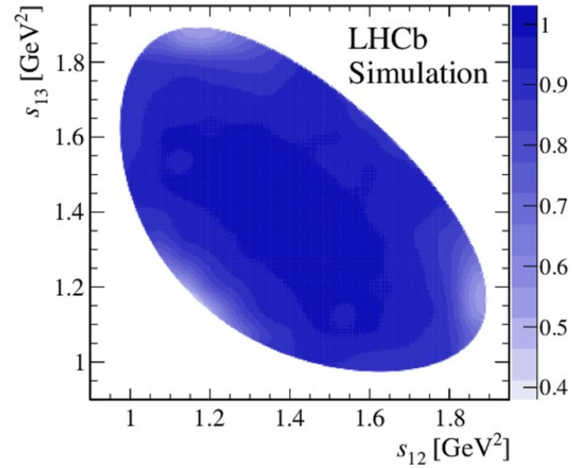
- Multi-body decays help in two ways here:
  - Several quasi-two-body amplitudes interfering → access to strong and weak phases.
  - CPV needs interfering amplitudes with different weak and strong phases.
  - Generally, many isospin partner decays → some observables are way better controlled that way.

- Integrated CP asymmetries generally smaller than localised
  - Example: 2011 analysis of $B^+ \to \pi^+\pi^-\pi^+$ yields ~5% (integrated), ~45% in the $f_2(1270)$ region.

Amplitude dependence both a plus and a minus: analyses are **more complicated** and **possibly model-dependent**, but **many more observables**.

CPV in multi-body decays: the experimental side

- Efficiencies vary across the phase space in a way that is often modelled using MC
  - Systematics that decrease with simulation statistics and reliability.
- In general, detector response is not uniform in particle types and charges.
- Magnet reversal cancels most of the asymmetries, but not all of them.



- Production and detection asymmetries have to be carefully modelled using simulation and data-driven techniques.

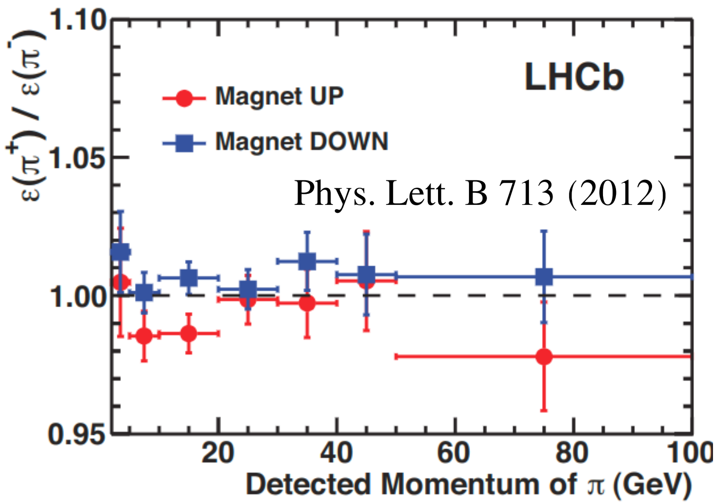
Orders of magnitude:

PHYS. REV. D95 (2017) 052005

$$\mathcal{A}_{\text{prod}}(B^+, \sqrt{s} = 7\text{TeV}) = (-0.41 \pm 0.49 \pm 0.10) \times 10^{-2},$$
$$\mathcal{A}_{\text{prod}}(B^+, \sqrt{s} = 8\text{TeV}) = (-0.53 \pm 0.31 \pm 0.10) \times 10^{-2},$$

$A_{\text{detection}}(\pi) \sim 0.1\%$

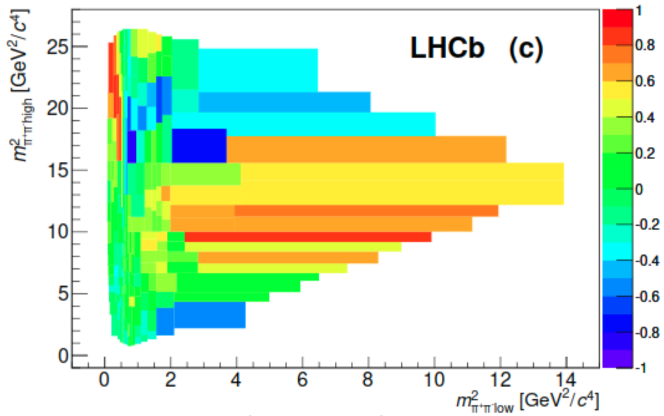
$A_{\text{detection}}(K) \sim 1\%$



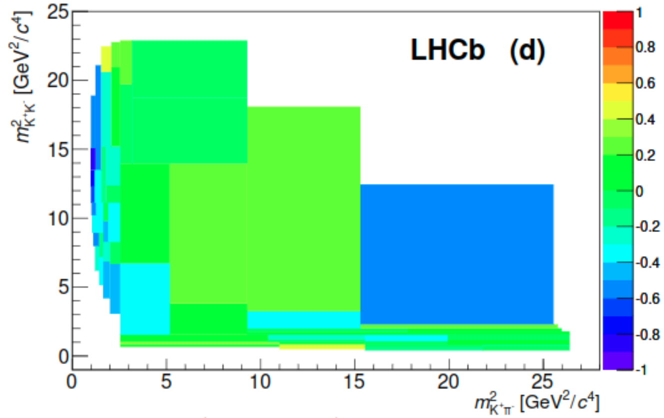
CPV in multi-body **beauty** decays

$B^+ \to h^+h^-h^+$: status and common features

- LHCb had reported large localised CPV [**Phys. Rev. D90 (2014) 112004**] in both $B^+ \to \pi^+\pi^-\pi^+$ and $B^+ \to \pi^+K^+K^-$.
  - $B^+ \to \pi^+\pi^+\pi^-$: rich structures from tree- and penguin-level contributions
  - $B^+ \to \pi^+K^+K^-$: smaller branching fraction, fewer resonances.
  - … but the two are related by $\pi\pi \leftrightarrow KK$ rescattering.

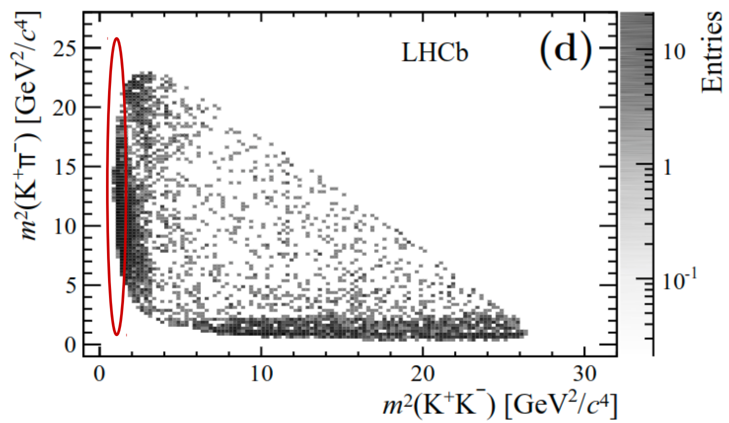


$B^\pm \to \pi^\pm\pi^+\pi^-$



$B^\pm \to \pi^\pm K^+K^-$

- Coincidentally, accumulation of events (incompatible with a ϕ resonance) seen in the rescattering region of πKK, associated with a large CPV.



$B^+ \to \pi^+ K^- K^+$: model and results with 3fb^{-1}

- Isobar model analysis. Amplitude described as coherent sum of:
  - Resonances: $K^*(892)$, $K_0^*(1430)$, $\phi(1020)$, $f_2(1270)$, $\rho(1450)$.
  - Nonresonant πK contribution: single-pole form factor from [PhysRevD.92.054010]

$$\mathcal{A}_{\text{source}} = \left(1 + \frac{s}{\Lambda^2}\right)^{-1}, \ \Lambda = 1 \text{ GeV}/c^2$$

  - Rescattering amplitude taken from Pelaez and Yndurain [PhysRevD.71.074016]

Contribution	Fit Fraction(%)	A_{CP}(%)
$K^*(892)^0$	$7.5 \pm 0.6 \pm 0.5$	$+12.3 \pm 8.7 \pm 4.5$
$K_0^*(1430)^0$	$4.5 \pm 0.7 \pm 1.2$	$+10.4 \pm 14.9 \pm 8.8$
Single pole	$32.3 \pm 1.5 \pm 4.1$	$-10.7 \pm 5.3 \pm 3.5$
$\rho(1450)^0$	$30.7 \pm 1.2 \pm 0.9$	$-10.9 \pm 4.4 \pm 2.4$
$f_2(1270)$	$7.5 \pm 0.8 \pm 0.7$	$+26.7 \pm 10.2 \pm 4.8$
Rescattering	$16.4 \pm 0.8 \pm 1.0$	$-66.4 \pm 3.8 \pm 1.9$
$\phi(1020)$	$0.3 \pm 0.1 \pm 0.1$	$+9.8 \pm 43.6 \pm 26.6$

- Observed CPV in rescattering is the largest one observed in a single amplitude to date.
  - It is also the only significant CPV in all components.
  - Most of previously observed CPV could originate from this contribution.
- Larger $\rho(1450)$ contribution than expected.
- A_{CP} is statistically limited.
- Main systematics arise from **modelling of resonance contributions.** Alternative models not included.

$B^+ \to \pi^+\pi^-\pi^+$: dealing with the S-wave

ARXIV:1909.05212

- Large contribution, both direct and through interference, of the $(\pi\pi)$ S-wave.
  - Difficult to model: channel openings, many broad, badly known contributions.
- Vector and tensor resonances are well isolated → modelled by isobar contributions.
- Three approaches used simultaneously to model the S-wave

$B^+ \to \pi^+\pi^-\pi^+$: isobar model

ARXIV:1909.05212

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- Three approaches used simultaneously to model the S-wave

- **Isobar model:**
  - Masses, widths of resonances fixed, except for consistency checks; magnitudes and phases free.
- Rescattering modelled using a form-factor from [Phys. Rev. D89, 094013 (2014)]

$$A(s) = \frac{\hat{T}}{1 + \frac{s}{\Delta^2_{PP}}}$$

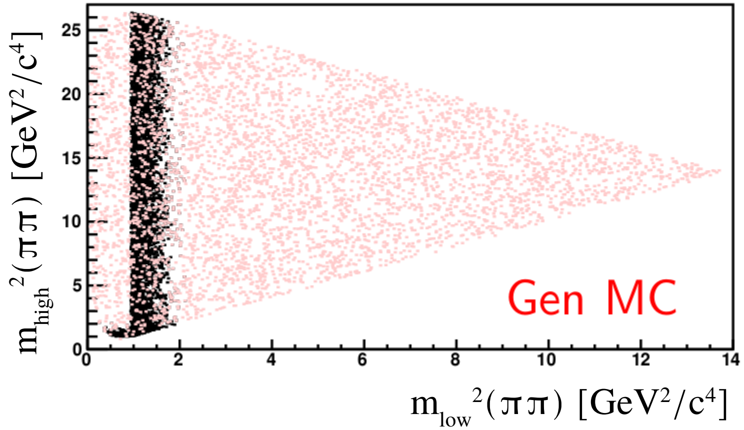
$$\hat{S} = 1 + 2i\hat{T}$$

$$\hat{S}(s) = \begin{pmatrix} \eta(s)e^{2i\delta_{\pi\pi}(s)} & i\sqrt{1-\eta^2(s)}e^{i(\delta_{\pi\pi}(s)+\delta_{KK}(s))} \\ i\sqrt{1-\eta^2(s)}e^{i(\delta_{\pi\pi}(s)+\delta_{KK}(s))} & \eta(s)e^{2i\delta_{KK}(s)} \end{pmatrix}$$

- Need modelling for phase shifts $\delta_{\pi\pi}(s)$ and $\delta_{KK}(s)$, and the inelasticity $\eta(s)$.
  - J.R. Pelaez and F.J. Yndurain, [**Phys. Rev. D 71, 074016 (2005)**]
- Σ contribution included, modelled as:

$$A_\sigma(m) = \frac{1}{(m_\sigma - i\Gamma_\sigma)^2 - m^2}$$ **[Phys. Rev. D.71.054030]**

Rescattering vs phase space



$B^+ \to \pi^+\pi^-\pi^+$: K-matrix approach

ARXIV:1909.05212

- Large contribution, both direct and through interference, of the $(\pi\pi)$ S-wave.
  - Difficult to model: channel openings, many broad, badly known contributions.
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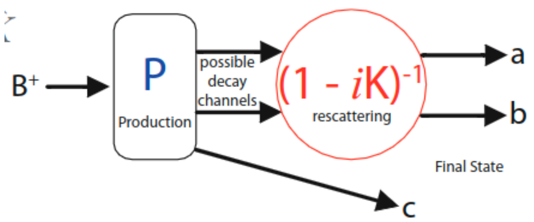
- Three approaches used simultaneously to model the S-wave

- **K-matrix approach:**
  - S-wave modelled in its entirety (including channel openings) using:



$$\hat{P}_j(s) \equiv \sum_R \frac{\beta_R^{\text{prod}} g_j^R}{m_R^2 - s} + f_j^{\text{prod}} \frac{c - s_0^{\text{prod}}}{s - s_0^{\text{prod}}}$$

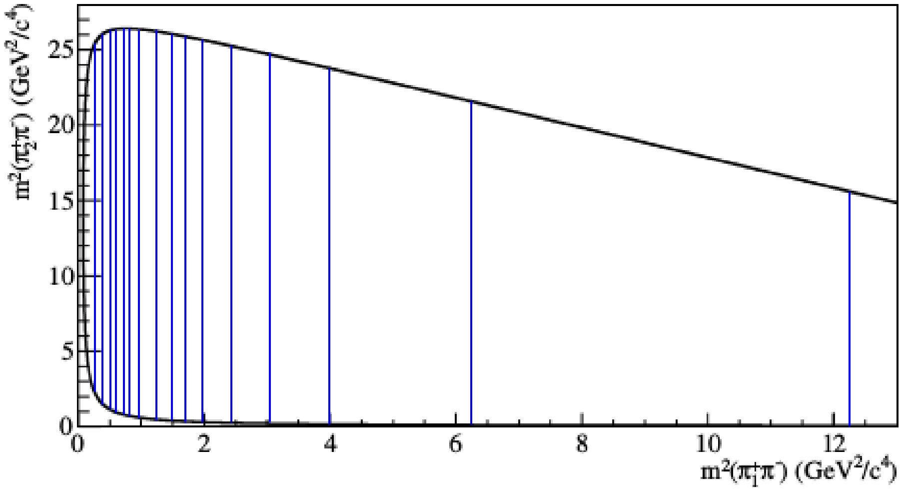
  - Unitarity in scattering and 3-body interaction enforced in the formalism.
  - Pole parameters in the K matrix fixed to scattering data → "masses and widths".
    - Natural interface with scattering data.
  - Production vector left free to float → "couplings to poles".

$B^+ \to \pi^+\pi^-\pi^+$: quasi-model-independent

ARXIV:1909.05212

- Large contribution, both direct and through interference, of the $(\pi^+\pi^-)$ S-wave.
  - Difficult to model: channel openings, many broad, badly known contributions.
- Vector and tensor resonances are well isolated → modelled by isobar contributions.
- Three approaches used simultaneously to model the S-wave

- **Quasi-model-independent approach:**
  - Vector and tensor resonances are well isolated → usual isobar model.
  - S-wave modelled as uncorrelated bins with floating magnitude and phase.



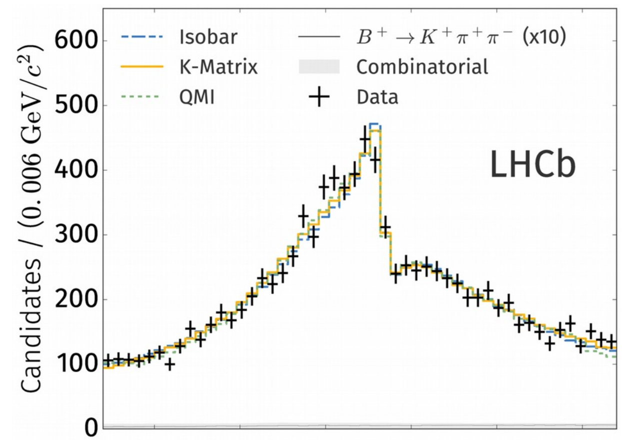
- Binning is chosen according to event density
  - 17 bins in $m(\pi\pi)$.

- This fit method is implemented using another fitter than the two others → additional crosscheck.

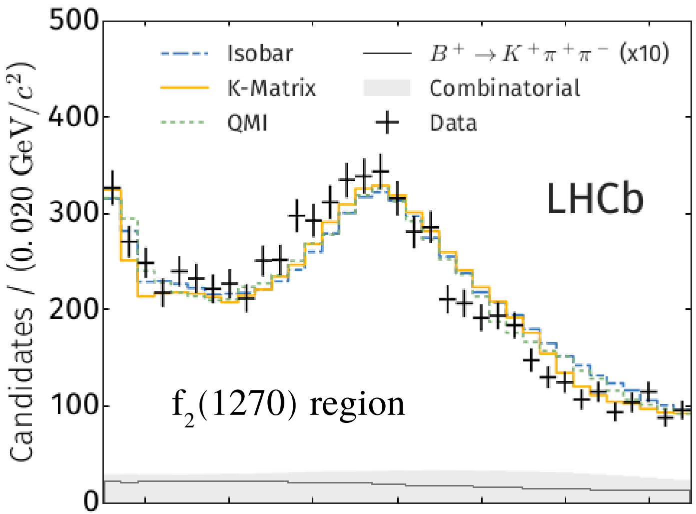
$B^+ \to \pi^+\pi^-\pi^+$: results with $3fb^{-1}$

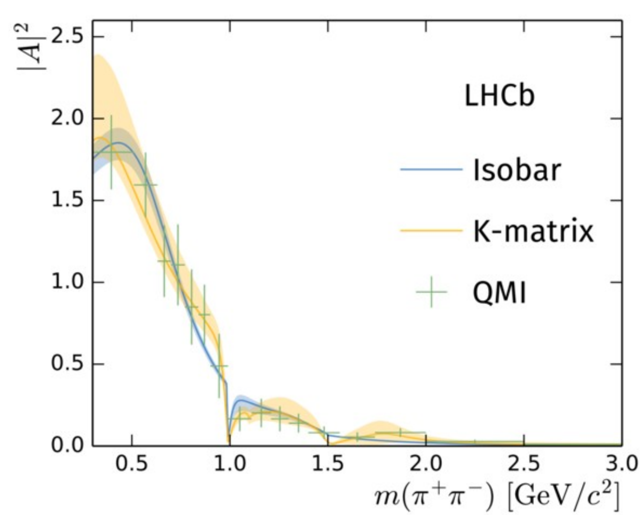
ARXIV:1909.05212

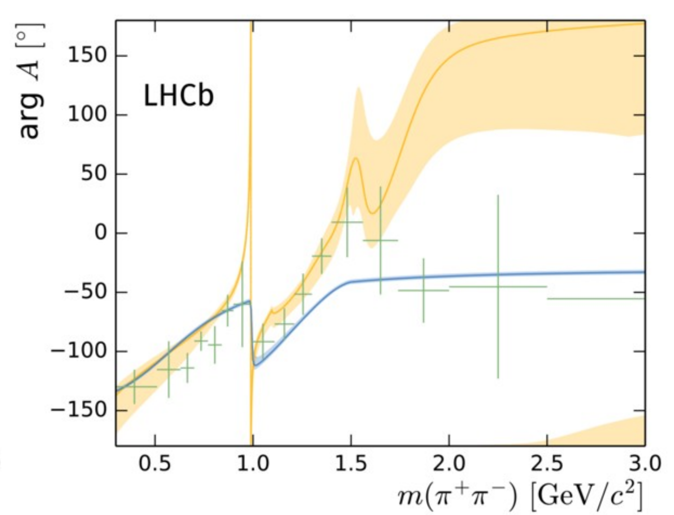
- All three approaches converge to a similar description of the amplitude, dominated by:
  - $\rho(770)$ (fit fraction: ~55%)
  - S-wave (~25%, mostly σ in the isobar model)
  - $f_2(1270)$ (~10%).
- Clear ρ-ω mixing, consistent with the models.
- Fit not describing the $f_2(1270)$ region well. Can be solved by
  - floating the parameters → models disagree with PDG and each other.
  - including another f_2 resonance → new state found consistent with speculative $f_2(1430)$ but inconsistent between themselves.



- Large disagreement between S-waves in the low $m(\pi^+\pi^-)$ interval.



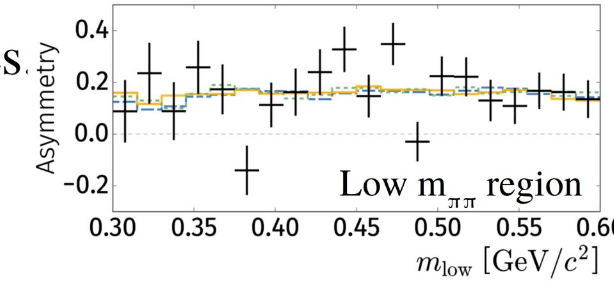




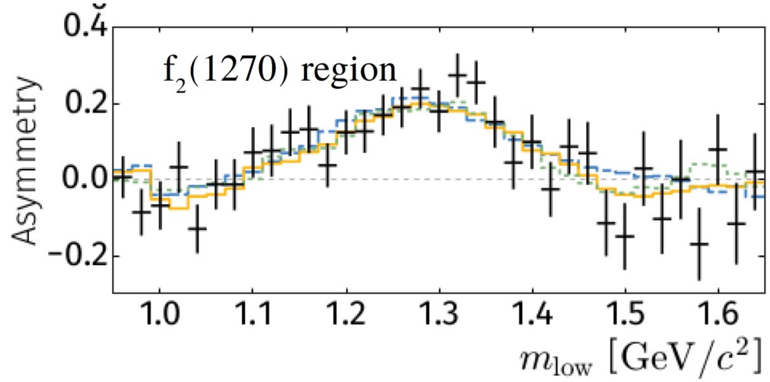
$B^+ \to \pi^+\pi^-\pi^+$: results with 3fb^{-1}

ARXIV:1909.05212

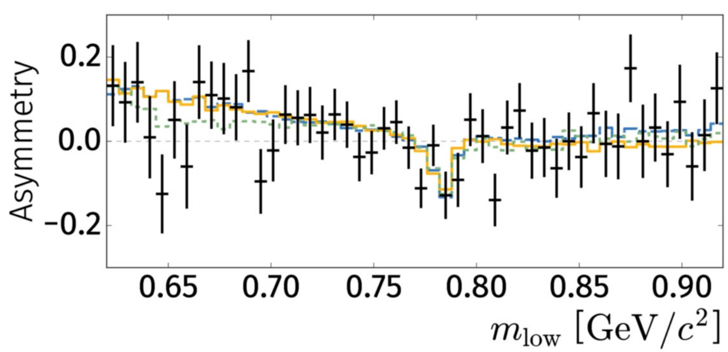
- Significant CPV at low m($\pi^+\pi^-$) where only S-wave contributes.
  - Constant until ~ 2m_K, and then changes sign.

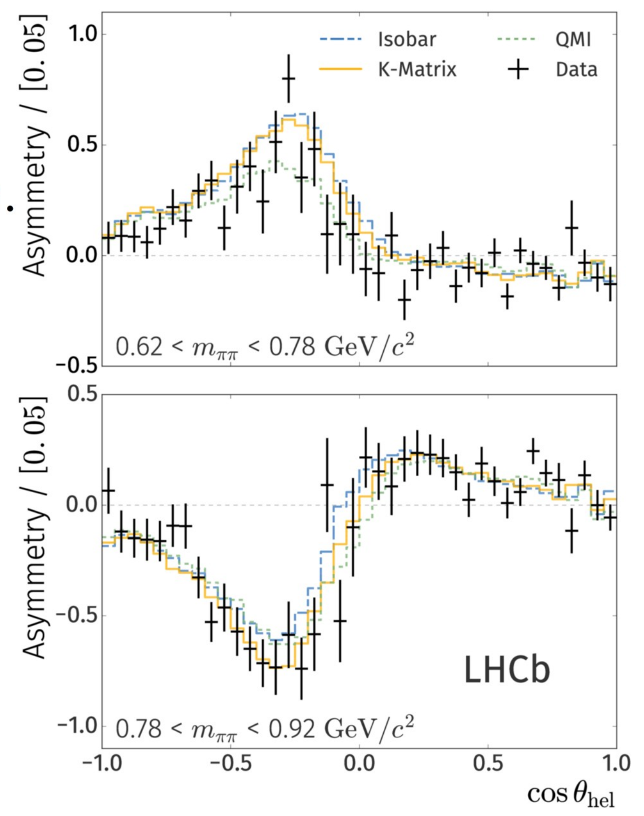


- Large (~40%) CPV in the region where $f_2(1270)$ is dominant.



- Interference between S- and P- waves is significant beyond 25σ.
  - Right: A_{CP} as a function of the helicity below (top) and above (bottom) the (ρ-ω) pole
  - Below: integrated A_{CP} vs mass → no integrated A_{CP}.





$B^+ \to h^+h^-h^+$: prospects

- Huge leap forward: from "there is localised CPV" to pinpointing rescattering and tensor contributions, as well as S-P interferences.
- Current analyses offer possibilities to test theoretical understanding of amplitudes.
  - Largest sample available in the rescattering region.
- Open topics, e.g. contribution of $\rho(1450)$ larger than expected in $B^+ \to \pi^+ K^- K^+$, possible $f_2(1430)$ contribution to $B^+ \to \pi^+\pi^-\pi^+$, S-wave discrepancies between models.
- Current systematics are dominated by:
  - Modelling of signal and backgrounds in the invariant-mass fit
  - Efficiency modelling
  - Fixed parameters of resonances (masses, widths), model refinement

Scales down with data
Scales down with MC stat
Does not necessarily scale down

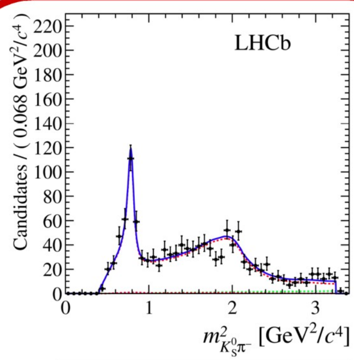
- Work ongoing on $B^+ \to K^+K^-K^+$ and $B^+ \to K^+\pi^+\pi^-$.
- Even depends on the technique, e.g in $B^+ \to \pi^+\pi^-\pi^+$ (first is statistical, second experimental, third is model).

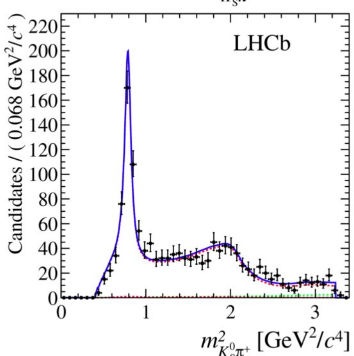
Component	Isobar	K-matrix	QMI
$\rho(770)^0$	$55.5 \pm 0.6 \pm 0.4 \pm 2.5$	$56.5 \pm 0.7 \pm 1.5 \pm 3.1$	$54.8 \pm 1.0 \pm 1.9 \pm 1.0$
$\omega(782)$	$0.50 \pm 0.03 \pm 0.01 \pm 0.04$	$0.47 \pm 0.04 \pm 0.01 \pm 0.03$	$0.57 \pm 0.10 \pm 0.12 \pm 0.12$
$f_2(1270)$	$9.0 \pm 0.3 \pm 0.7 \pm 1.4$	$9.3 \pm 0.4 \pm 0.6 \pm 2.4$	$9.6 \pm 0.4 \pm 0.7 \pm 3.9$
$\rho(1450)^0$	$5.2 \pm 0.3 \pm 0.2 \pm 1.9$	$10.5 \pm 0.7 \pm 0.8 \pm 4.5$	$7.4 \pm 0.5 \pm 3.9 \pm 1.1$
$\rho_3(1690)^0$	$0.5 \pm 0.1 \pm 0.1 \pm 0.3$	$1.5 \pm 0.1 \pm 0.1 \pm 0.4$	$1.0 \pm 0.1 \pm 0.5 \pm 0.1$
S-wave	$25.4 \pm 0.5 \pm 0.5 \pm 3.6$	$25.7 \pm 0.6 \pm 2.6 \pm 1.4$	$26.8 \pm 0.7 \pm 2.0 \pm 1.0$

$B \rightarrow K_s h^+ h'^-$: current status with $3 fb^{-1}$ and plans

- Another way of understanding hadronic amplitudes better → through symmetries.
  - From "Physics case for an LHCb Upgrade II" [CERN-LHCC-2018-027]: B→3h decays may help constrain rescattering info and reduce systematics.

$B_d \rightarrow K_S \pi^+ \pi^-$	$B_d \rightarrow K_S K^+ \pi^-$	$B_d \rightarrow K_S K^- \pi^+$	$B_d \rightarrow K_S K^+ K^-$
$B_s \rightarrow K_S \pi^+ \pi^-$	$B_s \rightarrow K_S K^+ \pi^-$	$B_s \rightarrow K_S K^- \pi^+$	$B_s \rightarrow K_S K^+ K^-$



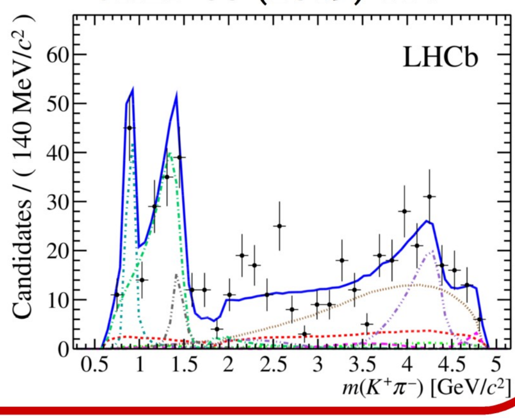


>6σ CPV in K* Q2B

PRL. 120, 261801 (2018)

- First amplitude analysis of the mode.
  - Paves way for time-dependent measurement
- (Kπ) S-wave modelled using LASS.

JHEP 06 (2019) 114



Lot of work on $K_s h^+ h'^-$ modes, but K_S is difficult in LHCb
First amplitude analyses start to come out, statistically limited

Will give info about S-waves & measure time-dependent CPV → sensitivity to CKM parameters.

$B^0 \to VV$: latest results with 3fb^{-1}

- Both analyses performed using isobar model, including angular dependencies.
  - See Katia's talk for the $\phi_s^{s\bar{s}}$ implications.

- $B \to (\pi^+\pi^-)(K^-\pi^+)$:

JHEP 05 (2019) 026

  - Small longitudinal polarisation fraction & > 5σ significance on direct CPV in $B^0 \to K^{*0}\rho$

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

    - Hint of colour-allowed EW penguin contribution
  - Phase differences between parallel and perpendicular polarisations found to be close to π (CP-averaged) and 0 (CP-difference) → good agreement with QCDf and pQCD.

- $B_{(s)} \to K^{*0}\overline{K}^{*0}$:

JHEP 07 (2019) 032

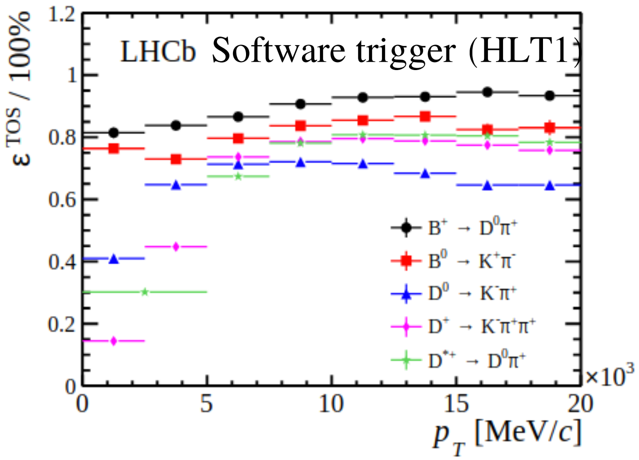
  - Observed $B^0 \to K^{*0}\overline{K}^{*0}$ and confirmed strong polarisation: $f_L = 0.724 \pm 0.051\,(\text{stat}) \pm 0.016\,(\text{syst})$
  - Confirmed small polarisation of the B_s decay: $f_L = 0.240 \pm 0.031\,(\text{stat}) \pm 0.025\,(\text{syst})$
  - Tension with theory: $R_{sd} = \frac{\mathcal{B}(B_s^0 \to K^{*0}\overline{K}^{*0}) f_L(B_s^0 \to K^{*0}\overline{K}^{*0})}{\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0}) f_L(B^0 \to K^{*0}\overline{K}^{*0})} \frac{1-y^2}{1+y\cos\phi_s}$ $= 3.48 \pm 0.38$ (this work) $\neq 16.4 \pm 5.2$ (theory)
  - Statistically dominated.

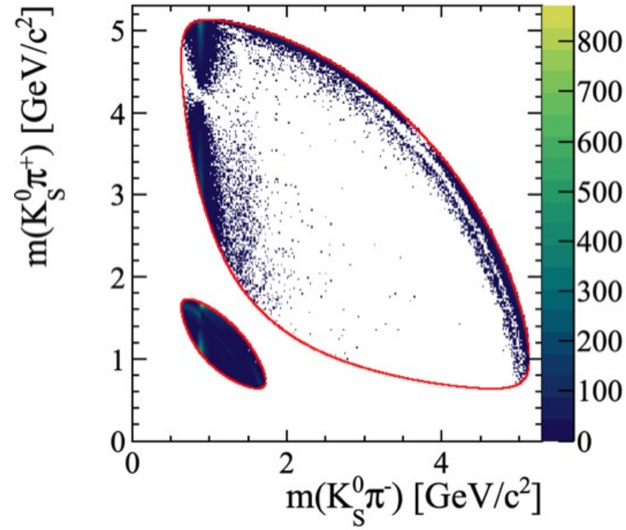
CPV in multi-body **charm** decays

Specificities of charm multi-body

- Compared to beauty decays, specific problems:
  - Lower momentum, transverse momentum, smaller lifetimes → lower trigger efficiency/harder cuts
  - Secondary production by B decays non negligible
- However:
  - Very large production rates
  - Possibility to tag with a D* or a semi-leptonic decay (μ tag)
  - Possibility to reject background only using semi-leptonic *B* decays.
- Much smaller phase space than beauty decays.
  - Right: comparison of Dalitz from B and D, same amplitude model
- D* and semileptonic taggings complementary as they cover different kinematic ranges, lifetimes, and purity rates.
  - **Different dominant systematics.**

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

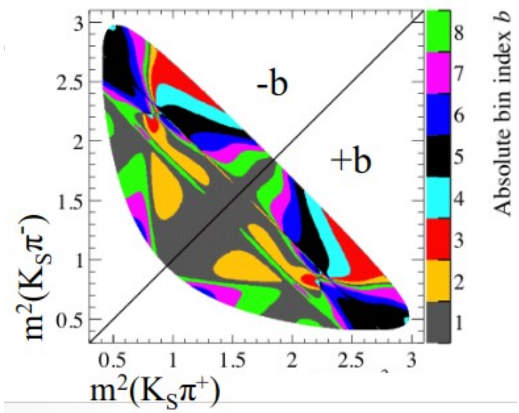




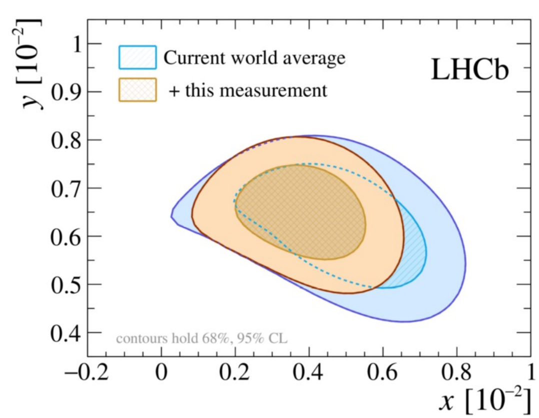
$D^0 \rightarrow K_s \pi^+ \pi^-$: results with 3 fb^{-1}

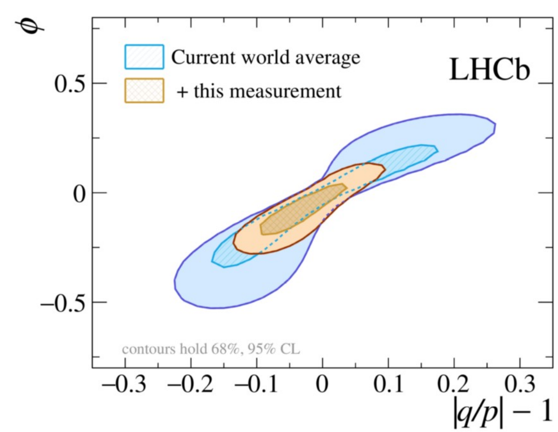
PHYS. REV. LETT. 122 (2019) 231802

- Includes both Cabibbo-favoured & doubly Cabibbo-suppressed in the same decay → allows to measure x, y, |q/p| and ϕ to be measured without external input.
- Analysis on Run 1 using bin-flip (model independent) [**Phys. Rev. D 99, 012007 (2019)**], D*- and μ-tagged.
  - Phase-space binned in regions of quasi-constant strong phase difference between D^0 and $\overline{D}^0$.
    - One part dominated by oscillated D mesons (flavour known at production)
  - Evolution of ratio top/bottom with time related to oscillation parameters
    - Robust against efficiency estimations
  - Relies on external input for strong phases [**Phys. Rev. D 82, 112006 (2010)**].



Parameter	Value $[10^{-3}]$
x_{CP}	$2.7 \pm 1.6 \pm 0.4$
y_{CP}	$7.4 \pm 3.6 \pm 1.1$
Δx	$-0.53 \pm 0.70 \pm 0.22$
Δy	$0.6 \pm 1.6 \pm 0.3$

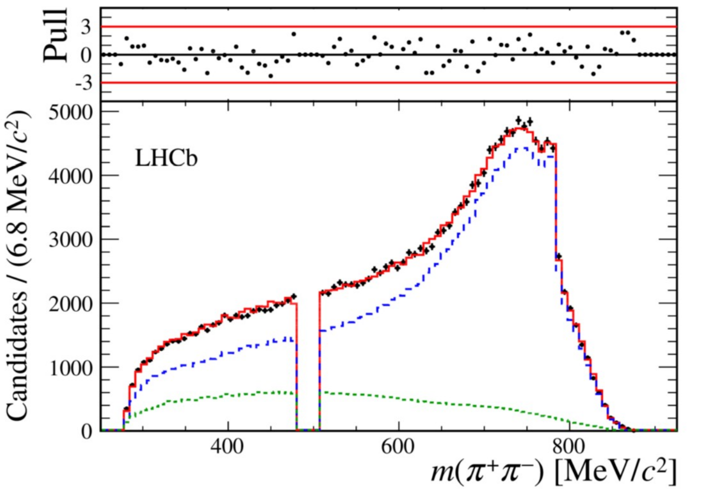




Most precise from a single experiment, draws picture towards nonvanishing mass difference

$D^0 \to h^+h^-h^+h^-$: results with 3fb^{-1} and plans

- $D \to K^+K^-\pi^+\pi^-$ from $B \to D\mu X$ [**JHEP 02 (2019) 126**]:
  - More than 25 amplitudes, dominated by $(\phi\text{-}\omega)_{L=0}$, $K_1(1400)$, $(K\pi)_{L=0}(K\pi)_{L=0}$, and $K_1(1270)$.
  - No CPV found, sensitivity between 1% and 15%.
  - Small systematics on CPV measurement, and they can scale down with luminosity (fixed parameters)
  - Amplitude model can be used in γ extraction to reduce systematics.

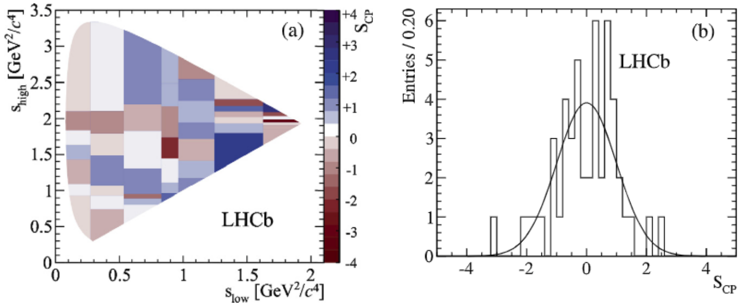


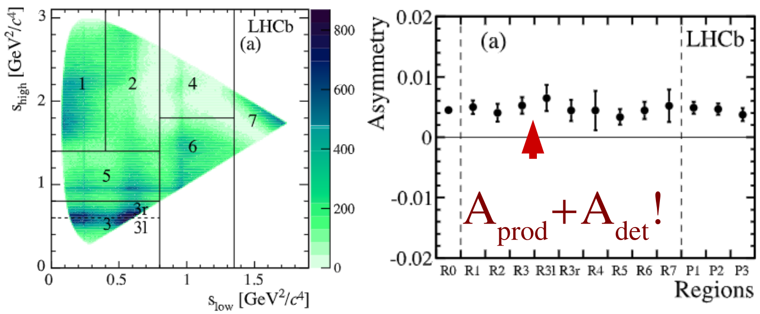
- Plan to add Run 2 statistics to a dedicated analysis to look for CPV using the energy test (see next slide)
  - Already applied to $D^0 \to \pi^+\pi^-\pi^+\pi^-$ [**Phys.Lett. B769 (2017) 345**], plan to be updated and extended to $D^0 \to K^+K^-\pi^+\pi^-$.

- See also Tommaso Pajero's talk about $D^0 \to K^+\pi^-\pi^+\pi^-$ (mind the sign!).

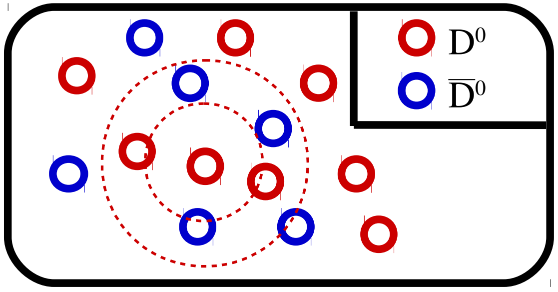
Model-independent searches for CPV in charm

- Charm analyses often have to deal with huge datasets → need fast methods to probe for CPV.
- Binned methods:
  - For instance used in [**Physics Letters B 728 (2014) 585**]
  - Can be corrected for global asymmetries.
- Unbinned methods:
  - For instance used in [**Physics Letters B 728 (2014) 585**]
  - Calculate p-values in regions





- Energy test: model-independent, unbinned, sensitive to local asymmetries [**Phys. Rev. D 84, 054015 (2011)**]
  - Can be applied to probe *P*-even CPV or *P*-odd, using triple product.
  - Based on closest neighbour approach



$D_{(s)}^{+} \to h^+h^-h^+$: plans for Run 2 analysis

- First analysis on $D^+ \to \pi^+\pi^-\pi^+$ looked for CPV in model-independent binned and unbinned ways→ no hint for CPV [**Physics Letters B 728 (2014) 585**].

- Diverse modes: Cabibbo-favoured (CF), Cabibbo-suppressed (CS) and double Cabibbo-suppressed (DCS).

Control modes: CF

* $D^+ \to K^-\pi^+\pi^+$
* $D^+_s \to K^-K^+\pi^+$
* $D^+_s \to \pi^-\pi^+\pi^+$

$D^+ \to K^-\pi^+\pi^+$: $O(10^9)$ events

Potential discovery modes: CS

* $D^+ \to K^-K^+\pi^+$
* $D^+ \to \pi^-\pi^+\pi^+$
* $D^+_s \to K^-K^+K^+$
* $D^+_s \to \pi^-\pi^+K^+$

$D^+ \to K^-K^+\pi^+$: $O(10^8)$ events

Search for NP effects: DCS

* $D^+ \to K^-K^+K^+$
* $D^+ \to \pi^-\pi^+K^+$
* $D^+_s \to \pi^-K^+K^+$

$D^+ \to K^-K^+K^+$ $O(10^6)$ events

- Run 2 analysis will keep using model-independent methods to check for possible CPV in these decays.
  - If found, more refined analysis needed to pinpoint source(s) of CPV.
  - Big challenge: dealing with nuisance asymmetries (production, detection).

$D^0 \to h^+h^-\mu^+\mu^-$: results with $5 fb^{-1}$ and plans

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- Long-distance dominated decay, BR ~ 10^{-7}, short-distance very suppressed but can be increased by NP → would showcase resonances.
  - Rarest charm decay observed to date.
  - **Asymmetries are a null test of the SM.**
- Measured asymmetries are consistent with 0, both integrated and in regions of the $(\mu^+\mu^-)$ invariant mass.

$$A_{\rm FB}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (\;\;3.3 \pm 3.7 \pm 0.6)\%,$$
$$A_{2\phi}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (-0.6 \pm 3.7 \pm 0.6)\%,$$
$$A_{CP}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (\;\;4.9 \pm 3.8 \pm 0.7)\%,$$
$$A_{\rm FB}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\%,$$
$$A_{2\phi}(D^0 \to K^+K^-\mu^+\mu^-) = (9 \pm 11 \pm 1)\%,$$
$$A_{CP}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\%,$$

- Strongly statistically limited, but "easy" mode in LHCb (dimuon pair, charm production rates).
  - $O(10^4)$ $h^+h^-\mu^+\mu^-$ events expected just for Upgrade I → amplitude analysis
  - Poster-child for Upgrade II. From "Physics case for an LHCb Upgrade II" [CERN-LHCC-2018-027]

of measuring branching-fraction ratios between dimuon and dielectron modes. Since the main limit for these studies comes from the available statistics, excellent prospects are foreseen for the LHCb Upgrade I. Projected signal yields for the muonic modes of (10^4) will allow more sensitive studies of angular asymmetry and first amplitude analyses to attempt to disentangle SD and LD components. However, it is with the $300\,\mathrm{fb}^{-1}$ upgrade that the full potential for these decays will be exploited. The enormous event yields and improved calorimetry of Upgrade II will allow to perform studies of both the dimuon and dielectron modes with high precision.

Perspectives and conclusion

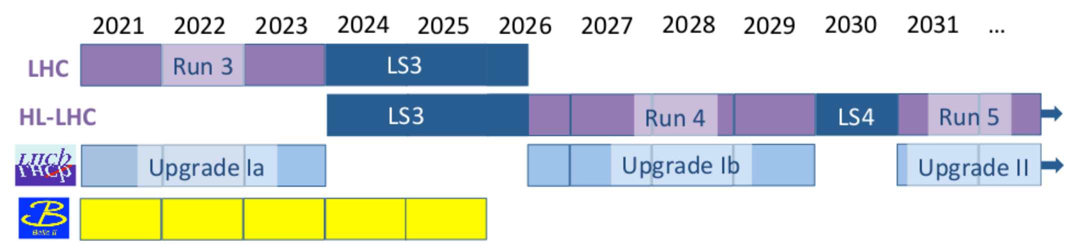
Future of these measurements

- $B \to K_S h^+ h'^-$, $B \to VV$, $D^0 \to K^+ K^- \pi^+ \pi^-$, $D^0 \to h^+ h^- \mu^+ \mu^-$ are **statistically limited**, and have been performed on part of the full dataset → update planned, and will bring foreseeable improvements.
  - Could add D*-tagged sample to $D^0 \to K^+ K^- \pi^+ \pi^-$.
- $B^+ \to h^+ h^- h^+$ measurements start to be **systematics-limited**. Part of it will go down with more data, part of it needs a bit more work (e.g. leaving resonance masses free in the fit).
  - Easier said than done: can lead to large timing increases and potential disagreement between methods.
- $D^0 \to K^+ K^- \pi^+ \pi^-$ was analysed in model-dependent way → **update with model-independent energy test**, coupled with $D^0 \to \pi^+ \pi^- \pi^+ \pi^-$, planned.
- $D^0 \to K_S \pi^+ \pi^-$ was analysed in model-independent way → update with **both model-independent and model-dependent** planned. Extension to $D^0 \to K_S K^+ K^-$.

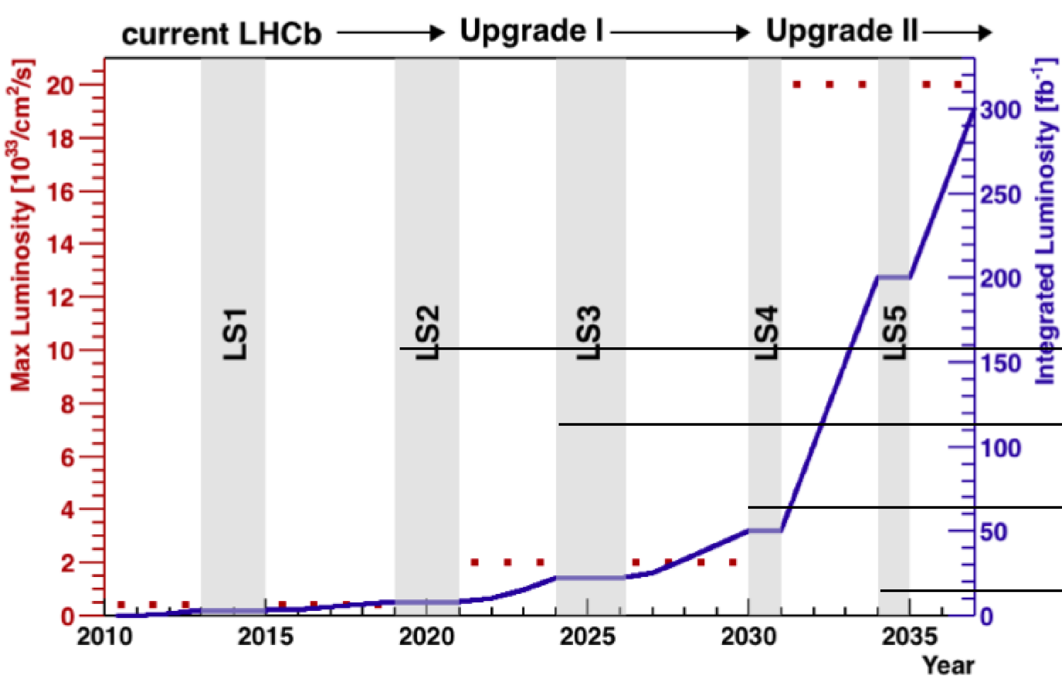
No cookie-cutter way of improving systematics → solution depends on mode
Combination of model-dependent and model-independent is crucial to improve measurements

The near and far future

- LHCb is still analysing Run 2 data (especially for amplitude analyses) → new results are on the way even during the Upgrade period.



- Belle 2 has started its operations.
  - Large impact expected on modes with neutrals and some modes that LHCb cannot do.
  - Cross-check of LHCb (very different experimental and physics environment).
- Additional data not only improves uncertainties (both statistical and some systematics), but unlocks new analysis techniques that help disentangle contributions.



For the $D^0 \to K_S \pi^+ \pi^-$ analysis

(From CERN-LHCC-2018-027)

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

The near and far future (systematics)

[Units of 10^{-3}]	Current syst	Stat (Run1-2)	Stat (Run1-3)	Stat (Run1-5)
$x(K_S\pi\pi)$	0.4	0.4	0.2	0.04
$y(K_S\pi\pi)$	1.1	0.4	0.2	0.04

- Projected statistical uncertainties → **challenge for systematics to keep up**.
- Current systematic uncertainties can be broken down in several categories
  - **Parameterisation of backgrounds**: will go down with more data.
  - **Control channel**: goes down with luminosity.
  - **Efficiency estimation**: rely on more MC events, more uniform efficiencies. Can have a statistical price.
  - **Production/Detection asymmetries**: at very high precision, can be extremely difficult to deal with. Building dedicated observables more robust is the current way of dealing with it (e.g. ΔA_{CP}).
  - **Fixed parameters of the models** (especially masses): can be freed in the fit, statistical price to be paid. Need to understand if we can do that.
  - **Alternative models**: the more data we accumulate and the better our parameterisations become, the smaller it will be → need external input and discussions.

Lots of work to not only deliver the luminosity, but make the most of it… and we will need help!

Thank you!