Les Rencontres de Physique de la Vallée d’Aoste
La Thuile, 5–11 March 2023

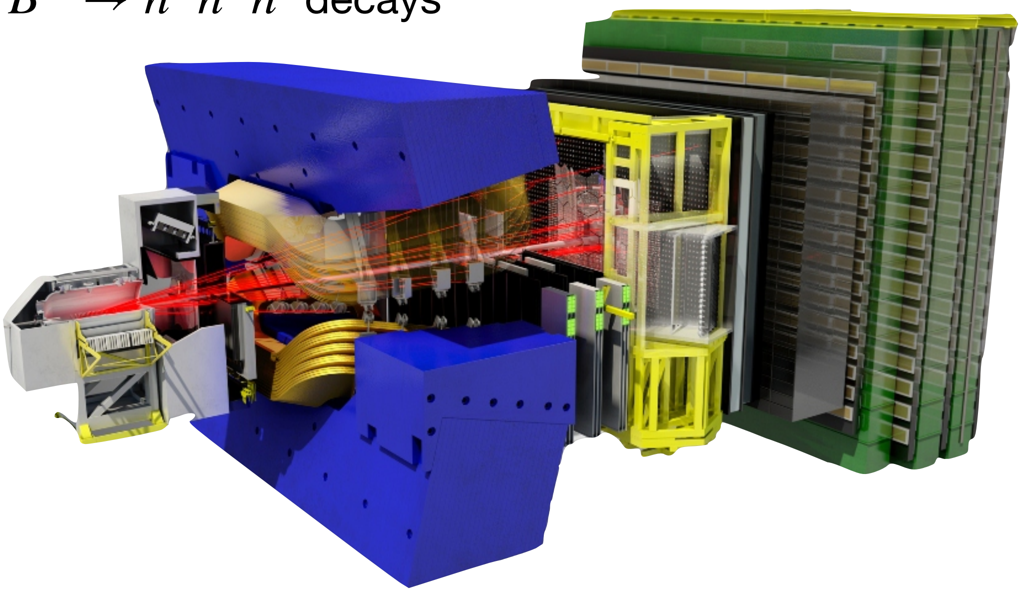
CKM and CP violation in charm and beauty at LHCb

Tommaso Pajero
on behalf of the LHCb collaboration

tommaso.pajero@cern.ch

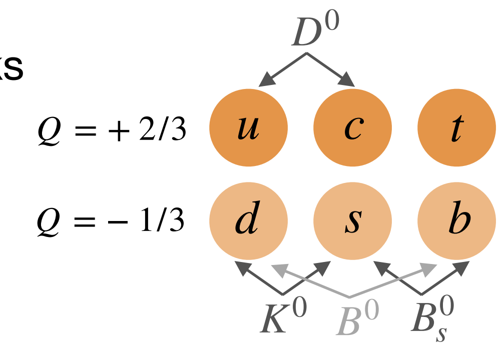
Menu

- Searches for CP violation in charm
  - $A_{CP}(D^0 \to K^+K^-)$ arXiv:2209.03179
  - local search in $D^+_{(s)} \to K^-K^+K^+$ arXiv:2303.04062 New!
- Measurements of the CKM angle γ
  - with $B^\mp \to [K^\mp\pi^\pm\pi^+\pi^-]_D h^\mp$ decays arXiv:2209.03692
  - with $B^\mp \to [h^+h^-\pi^+\pi^-]_D h'^\mp$ decays arXiv:2301.10328
- Observation and BF measurement of $B^0_s \to D^{*+}D^{*-}$ arXiv:2210.14945
- Observation of CP violation in 3-body $B^+ \to h^+h^+h^-$decays
  arXiv:2206.07622 arXiv:2206.02038



CP violation in charm

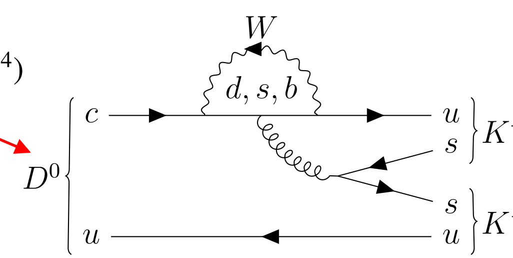
Charm neutral mesons are the only ones made up of up-type quarks
→ complementary sensitivity to BSM



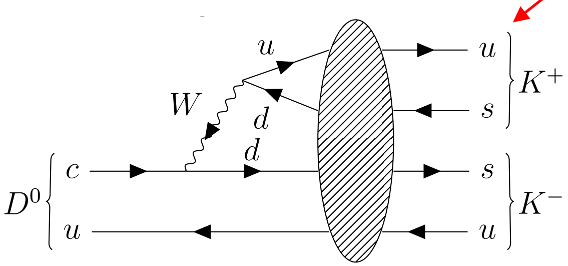
Mixing and CP violation (CPV) suppressed by

- **smallness of CKM elements involved:** $CPV \propto \mathrm{Im}\left(\frac{V_{cb}V^*_{bu}}{V_{cs}V^*_{su}}\right) \approx -6 \times 10^{-4}$
- **GIM mechanism** ($m_b/m_W \ll m_t/m_W$, d and s contributions cancel in U-spin limit)

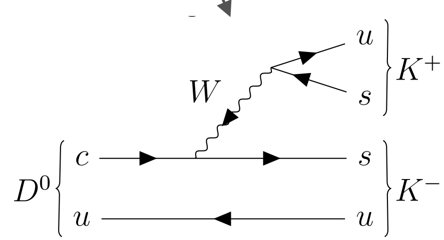
$$V_{\text{CKM}} = \begin{array}{cc} \begin{array}{ccc} d & s & b \end{array} & \\ \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda \; -iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} & \begin{array}{c} u \\ c \\ t \end{array} \end{array} + \mathcal{O}(\lambda^4)$$



QCD penguin



Tree + rescattering (e.g. $D^0 \to \pi^+\pi^- \to K^+K^-$)



Tree

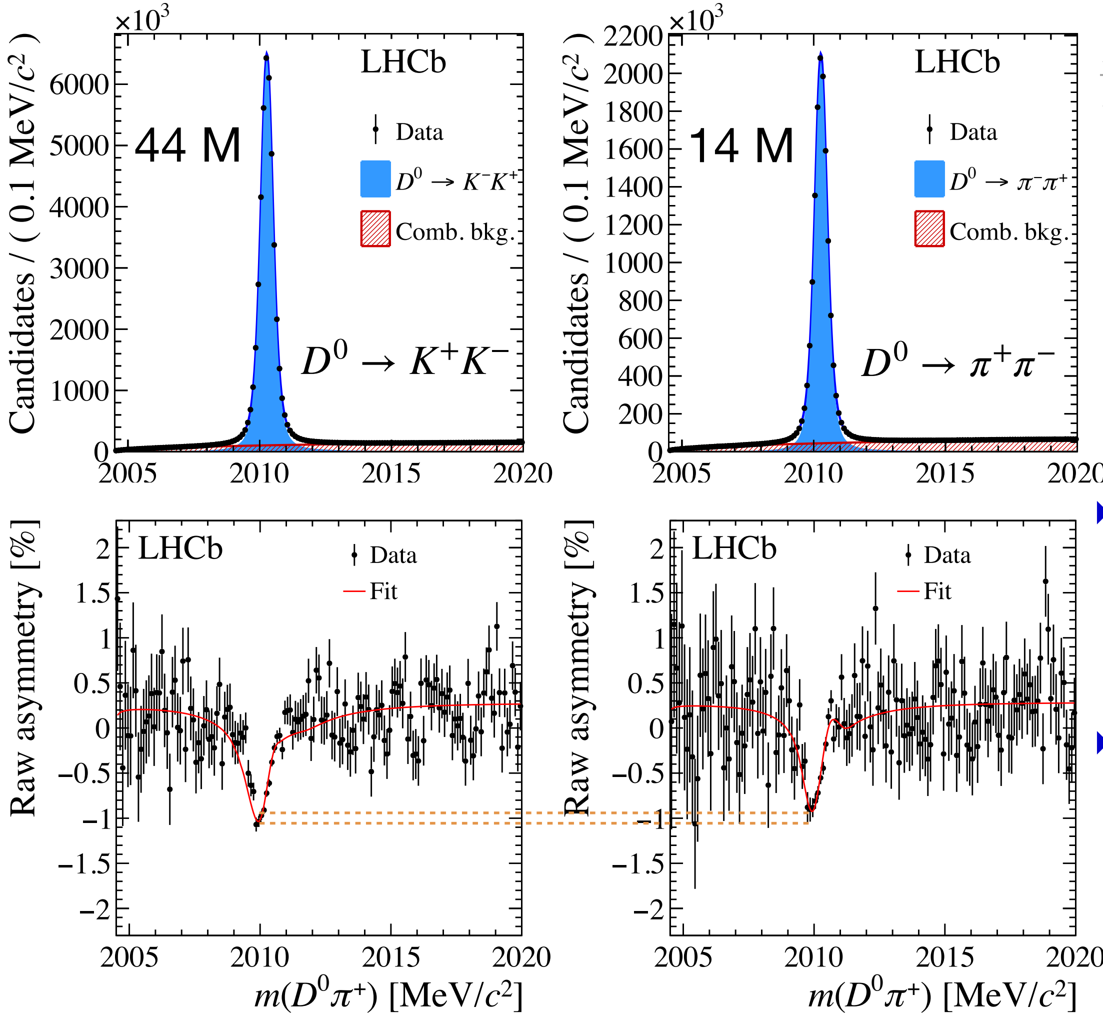
The first observation of CP violation in charm

$$\Delta A_{CP} = A_{\rm raw}(K^+K^-) - A_{\rm raw}(\pi^+\pi^-) \approx a^d_{K^+K^-} - a^d_{\pi^+\pi^-} = (-1.54 \pm 0.29) \times 10^{-3} \quad (5.3\sigma)$$

PRL 122 (2019) 211803

- Nuisance asymmetries cancel out in the difference;
- dynamical asymmetries add up ($a^d_{K^+K^-} \approx -a^d_{\pi^+\pi^-}$ in the U-spin limit).

6 fb^{-1}, 2015–2018, $D^{*+} \to D^0\pi^+$



$$\frac{N(D\to f) - N(\bar{D}\to\bar{f})}{N(D\to f) + N(\bar{D}\to\bar{f})}$$

production asymmetry

$$A_{\rm raw}(f) \approx A_{CP}(f) + A_{\rm det}(\pi^+) + A_{\rm prod}(D^{*+})$$

a^d_f (CPV in decay amplitudes) + small time-dependent contributions

detection asymmetry of tagging π^+

- Observed value at the upper end of SM predictions, challenges first-principles QCD calculations
  Grossman et al. 2007, Franco, Mishima & Silvestrini 2012, Li et. al 2012, Cheng & Chiang 2012, Khodjamirian & Petrov 2017
- O(1–10) enhancement of QCD rescattering or NP?
  Chala et al. 2019, Grossman & Schacht 2019, Buccella et al. 2019, Cheng & Chiang 2019, Soni 2019, Dery & Nir 2019, Li et al. 2019, Wang et al. 2020, Bause et al. 2020, Dery et al. 2020, Cheng & Chiang 2021, Bediaga, Frederico & Magalhaes 2022

For a review see Lenz & Wilkinson 2020, Pajero 2022

arXiv:2209.03179

Measurement of $A_{CP}(D^0 \to K^+K^-)$

Aim for 1st observation of CPV in single charm decay channel.

- nuisance asymmetries subtracted through Cabibbo-favoured decay channels
  (CPV is negligible, no QCD penguin nor chromomagnetic dipole operators contribute to $c \to us\bar{d}$)
- kinematics of equal particles in different decays must be matched as detection asymmetries are momentum-dependent
- $D^+_{(s)} \to K^0_S h^+$ is the bottleneck to final precision

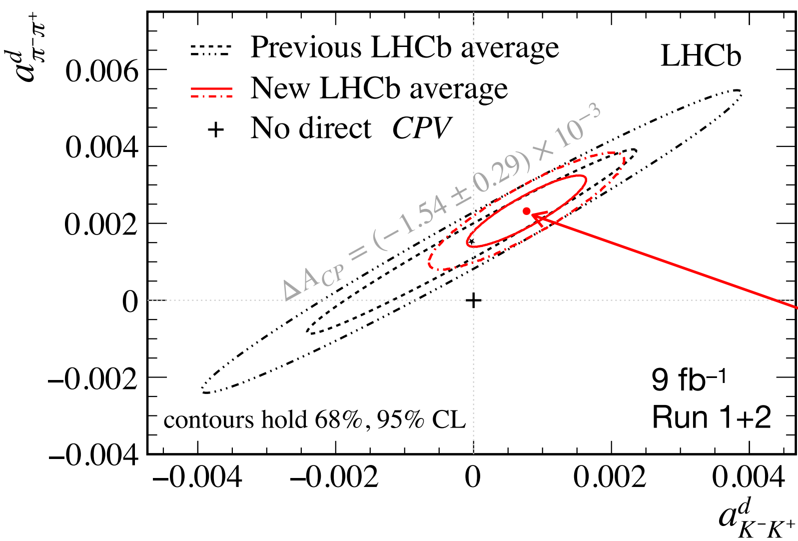
$$A_{CP}(D^0 \to K^+K^-) \approx A_{\rm raw}(D^0 \to K^+K^-) - A_{\rm raw}(D^0 \to K^-\pi^+) \boxed{+ A_{\rm raw}(D^+ \to K^-\pi^+\pi^+) - A_{\rm raw}(D^+ \to K^0_S\pi^+)} + A_{\rm det}(K^0)$$

Run 1 method

$$A_{CP}(D^0 \to K^+K^-) \approx A_{\rm raw}(D^0 \to K^+K^-) - A_{\rm raw}(D^0 \to K^-\pi^+) \boxed{+ A_{\rm raw}(D^+_s \to K^-K^+\pi^+) - A_{\rm raw}(D^+_s \to K^0_S K^+)} + A_{\rm det}(K^0)$$

New (Run 2) +40% precision

regeneration and CPV in mixing explicitly calculated
CERN-THESIS-2014-274



Combination with ΔA_{CP} + time-dependent $D^0 \to h^+h^-$ CPV
PRL 122 (2019) 211803
PRD 104 (2021) 7, 072010

$$a^d_{K^-K^+} = (7.7 \pm 5.7) \times 10^{-4} \quad 1.4\,\sigma$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4} \quad 3.8\,\sigma$$

1st evidence for CPV in a single charm decay channel

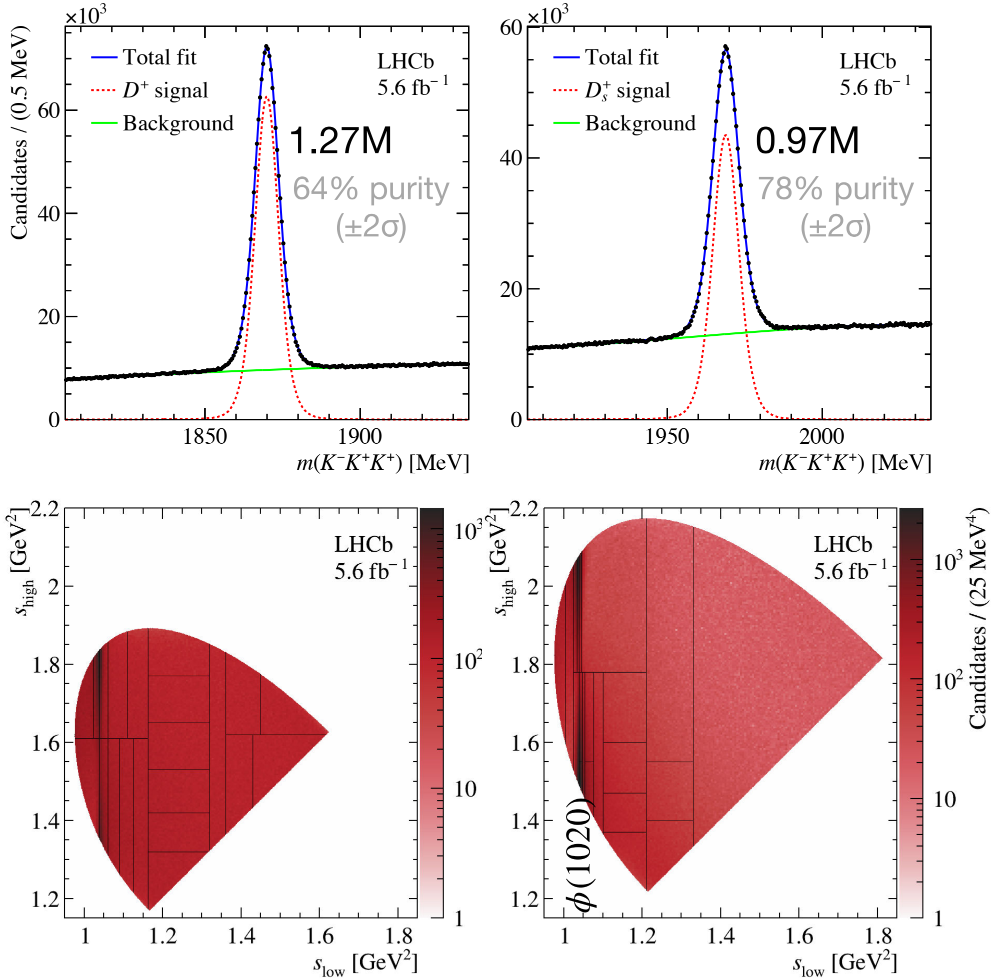
Search for local CP violation in $D^+_{(s)} \to K^-K^+K^+$

arXiv:2303.04062

- Variation of the hadronic parameters across the Dalitz plot (DP) provides a handle on QCD effects
  $A_{CP} \approx 2\,(A_{\text{penguin}}/A_{\text{tree}})\ \sin(\delta_P^{\text{strong}} - \delta_T^{\text{strong}})\ \sin\gamma$
- Look for local differences in the fractional yield in each bin of the DP to get rid of global nuisance asymmetries
  - binning optimises the sensitivity by reproducing the pattern of the main resonances (≈ const. strong phase)
  - size of residual DP-dependent asymmetries checked in simulation and Cabibbo-favoured $D^+ \to K^-\pi^+\pi^+$ and $D_s^+ \to K^-K^+\pi^+$ decays

doubly Cabibbo-suppressed
no CPV in the SM
(no QCD penguin/chromomagnetic dipole operators in $c \to u d \bar{s}$)

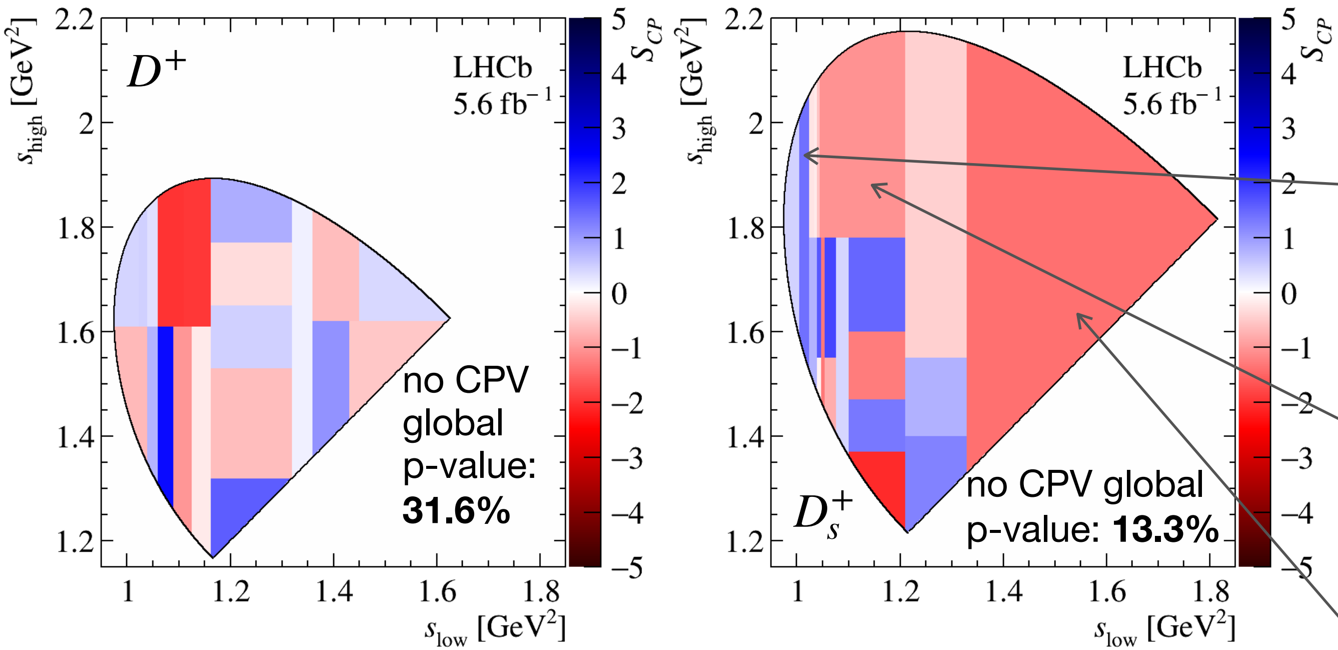
Cabibbo-suppressed
might show CPV
($c \to u s \bar{s}$)

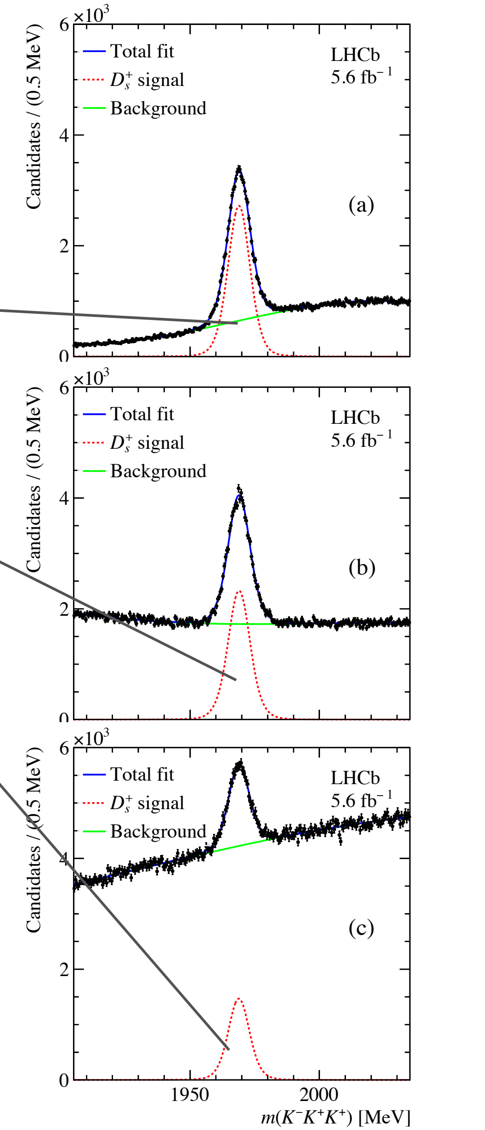


Search for local CP violation in $D_{(s)}^+ \to K^-K^+K^+$

arXiv:2303.04062

Sensitivity studies show that an observation of CPV would be possible if the weak-phase (magnitude fractional) difference between $D_{(s)}^+$ and $D_{(s)}^-$ amplitudes for $\phi(1020)K^+$ or $f_0(980)K^+$ was larger than 3–7° (3–7%)





$$S_{CP}^i = \frac{N^i(D_{(s)}^+) - \alpha N^i(D_{(s)}^-)}{\sqrt{\alpha(\delta^2_{N^i(D_{(s)}^+)} + \delta^2_{N^i(D_{(s)}^-)})}} \qquad \alpha = \frac{\sum_i N^i(D_{(s)}^+)}{\sum_i N^i(D_{(s)}^-)}$$

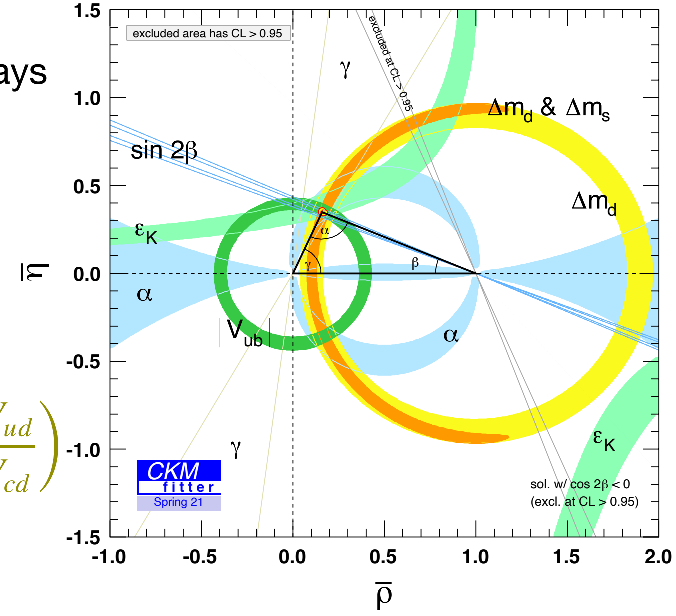
New!

Direct measurements of the CKM angle γ

- The only CKM angle that can be measured from tree-level decays
- clean theoretical interpretation

$$\begin{tikzcd} & \overline{D}^0 h^+ \arrow[dr, "r_D e^{i\delta_D}"] & \\ B^+ \arrow[ur, "1"] \arrow[dr, "r_B e^{i(\delta_B+\gamma)}"'] & & f_D\, h^+ \\ & D^0 h^+ \arrow[ur, "1"'] & \end{tikzcd}$$

$$\gamma = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$



$$\Gamma(B^\pm \to f_D\, h^\pm) \propto |r_D e^{i\delta_D} + r_B e^{i(\delta_B \pm \gamma)}|^2$$
$$= r_D^2 + r_B^2 + 2R_D r_D r_B \cos(\delta_B + \delta_D \pm \gamma)$$

coherence factor (0 < R_D < 1), suppresses the interference due to variation of relative $D^0/\bar{D}^0$ strong phase in final state

$$f_D = K^-\pi^+\pi^-\pi^+ \qquad h^+ = K^+ \quad \Longrightarrow \quad r_B \approx 0.1 \qquad r_D \approx 0.06$$

optimal size of interference term

Normalisation channels for background and efficiency determination

$$h^+ = \pi^+ \rightarrow r_B \approx 0.005$$
$$\Gamma(B^\pm \to \bar{f}_D\, h^\pm) \propto 1 + r_D^2 r_B^2 + 2R_D r_D r_B \cos(\delta_B - \delta_D \pm \gamma)$$

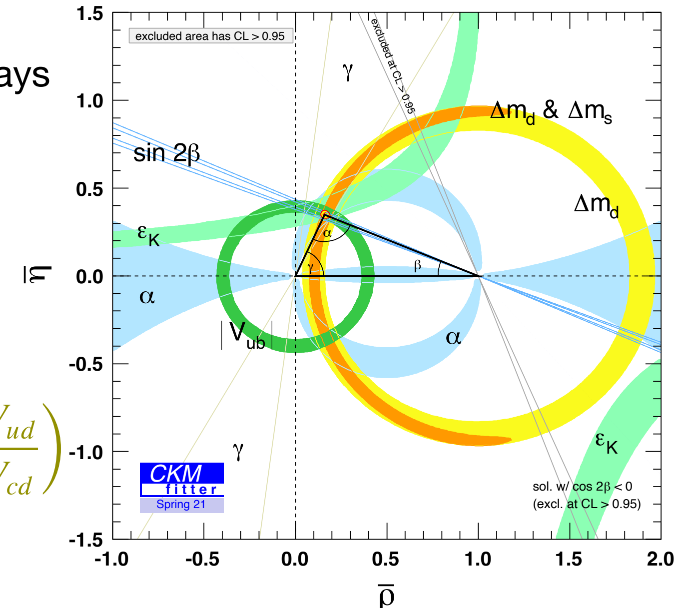
larger BR, smaller interference

Direct measurements of the CKM angle γ

- The only CKM angle that can be measured from tree-level decays
- clean theoretical interpretation

$$\begin{tikzcd}
 & \overline{D}^0 h^+ \arrow[rd, "r_D e^{i\delta_D}"] \arrow[dd, dotted, leftrightarrow, "(y+ix)\frac{t}{2\tau_{D^0}}"] & \\
B^+ \arrow[ru, "1"] \arrow[rd, "r_B e^{i(\delta_B+\gamma)}"'] & & f_D\, h^+ \\
 & D^0 h^+ \arrow[ru, "1"'] &
\end{tikzcd}$$

$$\gamma = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$



$$\Gamma(B^\pm \to f_D\, h^\pm) \propto |r_D e^{i\delta_D} + r_B e^{i(\delta_B \pm \gamma)}|^2$$
$$= r_D^2 + r_B^2 + 2R_D r_D r_B \cos(\delta_B + \delta_D \pm \gamma)$$

$$-r_D R_D(y\cos\delta_D - x\sin\delta_D) + \frac{1}{2}(x^2+y^2)$$
$$-r_B[y\cos(\delta_B \pm \gamma) + x\sin(\delta_B \pm \gamma)]$$

coherence factor (0 < R_D < 1), suppresses the interference due to variation of relative $D^0/\bar{D}^0$ strong phase in final state

Charm mixing parameters

$$x \equiv \frac{\Delta m}{\Gamma}, \quad y \equiv \frac{\Delta\Gamma}{2\Gamma}$$

$f_D = K^-\pi^+\pi^-\pi^+$
$h^+ = K^+$
⇒
$r_B \approx 0.1$
$r_D \approx 0.06$

optimal size of interference term

Normalisation channels for background and efficiency determination

$h^+ = \pi^+ \to r_B \approx 0.005$

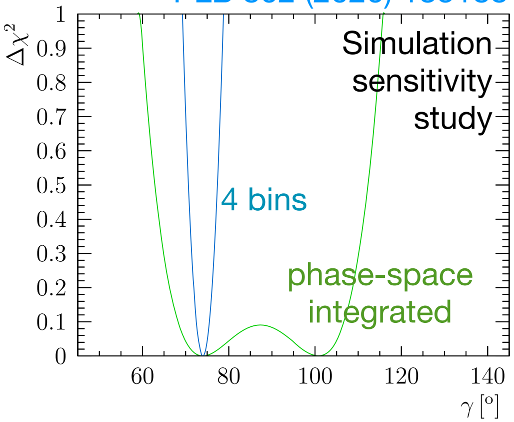
$\Gamma(B^\pm \to \bar{f}_D\, h^\pm) \propto 1 + r_D^2 r_B^2 + 2R_D r_D r_B \cos(\delta_B - \delta_D \pm \gamma)$

larger BR, smaller interference

Measurement of γ with $B^{\mp} \to [K^{\mp}\pi^{\pm}\pi^{+}\pi^{-}]_D h^{\mp}$

$R_{K3\pi} \approx 0.4$ → improvement in precision from measurement in phase-space bins

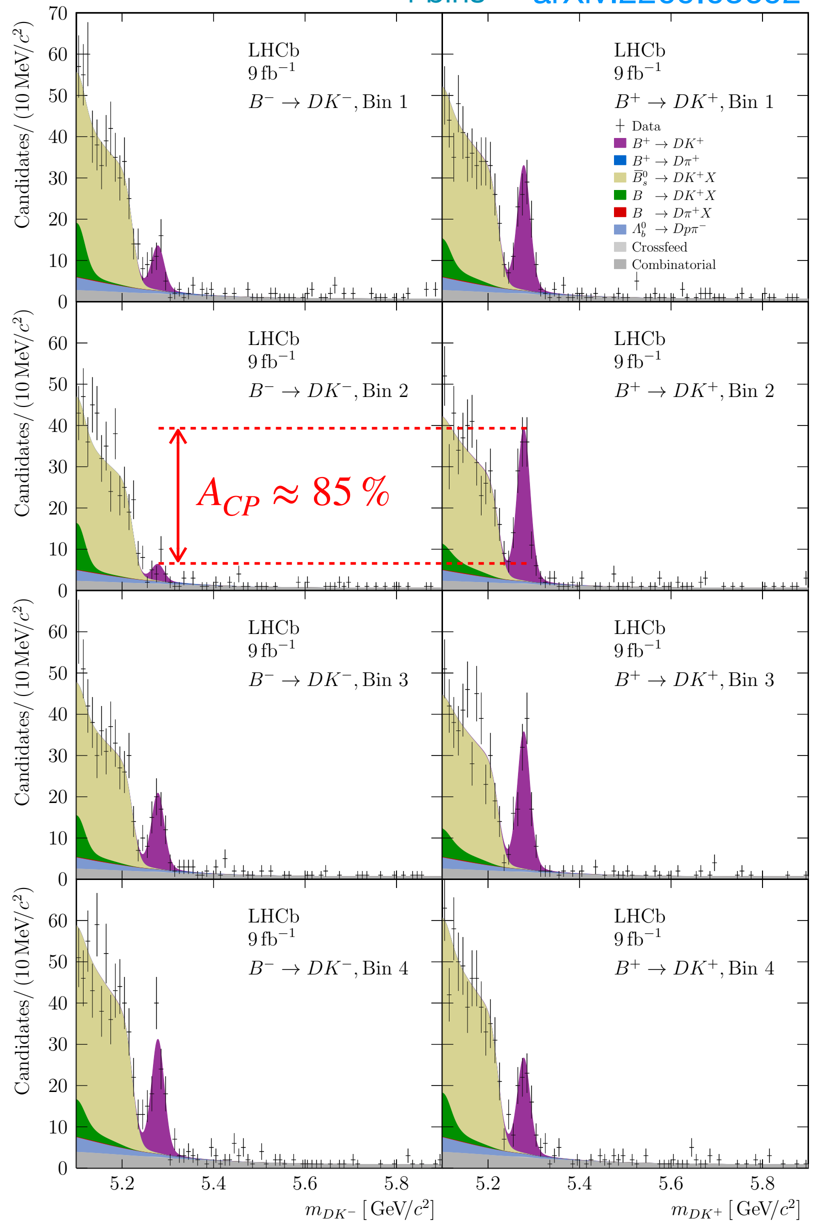
PLB 802 (2020) 135188



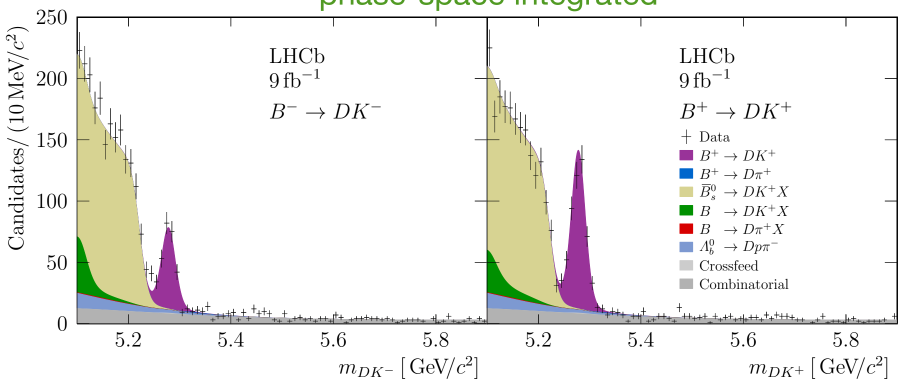
Binning optimised based on LHCb amplitude analysis

EPJC 78 (2018) 6, 443

4 bins arXiv:2209.03692



phase-space integrated



Measurement of γ with $B^{\mp} \to [K^{\mp}\pi^{\pm}\pi^{+}\pi^{-}]_D h^{\mp}$

arXiv:2209.03692

- Results combined with model-independent measurements of the charm hadronic parameters from charm factories (BES-III, CLEO-c) and charm mixing (LHCb $B \to [D^0\pi^+]_{D^{*+}} \mu^- X$): PLB 802 (2020) 135188
JHEP 05 (2021) 164

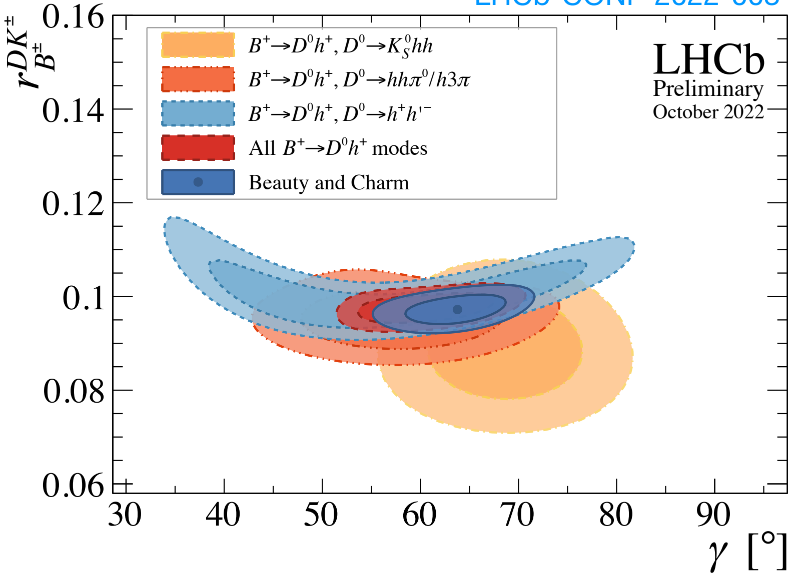
$$\gamma = \left(54.8 \,^{+\,6.0}_{-\,5.8} \,^{+\,0.6}_{-\,0.6} \,^{+\,6.7}_{-\,4.3}\right)^\circ$$

2nd most precise determination of γ

External input on charm harmonic parameters, large improvement expected from
– incoming 20 fb^{-1} of BES-III $\psi(3770)$ data
– LHCb measurement of mixing with $D^{*+} \to D^0\pi^+$ decays

$$\frac{\Gamma(D^0 \to K^+\pi^-\pi^+\pi^-; t, i)}{\Gamma(D^0 \to K^-\pi^+\pi^+\pi^-; t, i)} \approx (r^i_{K3\pi})^2 - r^i_{K3\pi} R^i_{K3\pi}(y\cos\delta^i_{K3\pi} - x\sin\delta^i_{K3\pi})\frac{t}{\tau_D} + \frac{x^2+y^2}{4}\left(\frac{t}{\tau_D}\right)^2$$

LHCb-CONF-2022-003



$$\gamma = (63.8^{+3.5}_{-3.7})^\circ$$

frequentist approach
52 parameters
173 observables
fit probability: 80%

Compatible with indirect determinations

$\gamma = (65.7^{+0.9}_{-2.7})^\circ$ CKMfitter

$\gamma = (65.8 \pm 2.2)^\circ$ UTFit

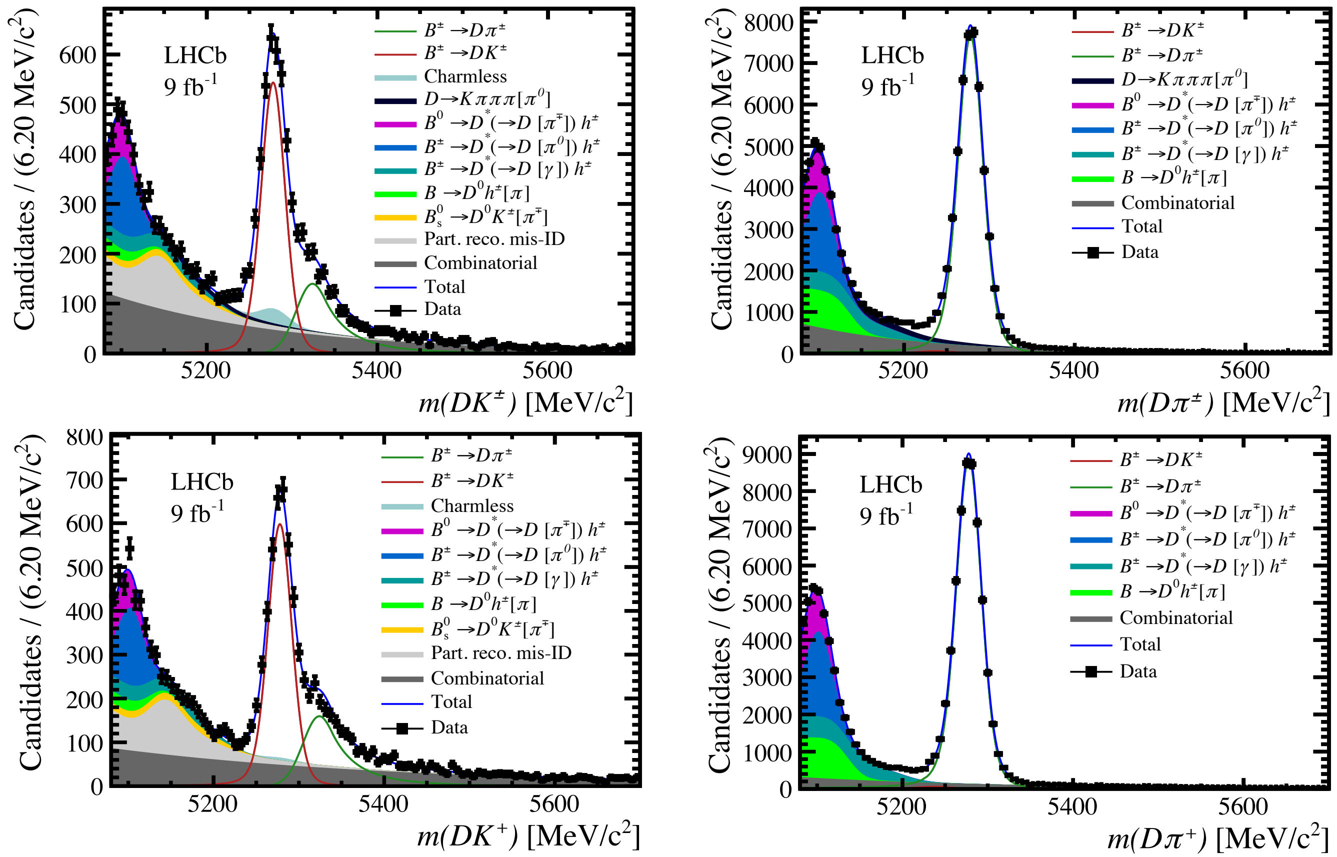
Measurement of γ with $B^{\mp} \to [h^+h^-\pi^+\pi^-]_D h'^{\mp}$

arXiv:2301.10328

$B^{\pm} \to DK^{\pm}$ | $B^{\pm} \to D\pi^{\pm}$

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

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

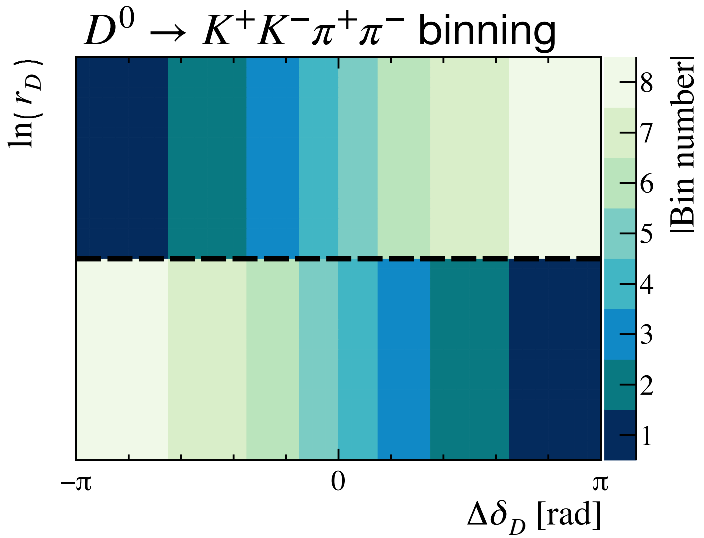


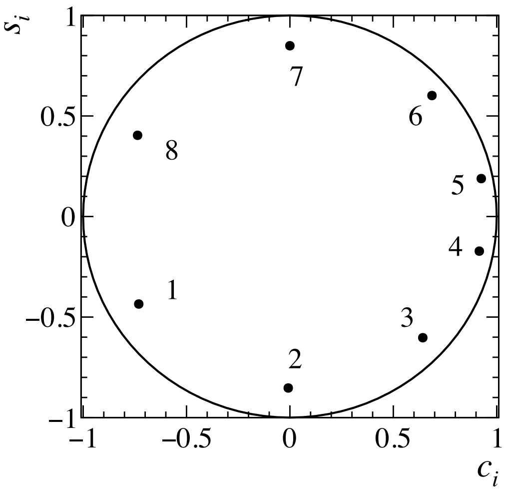
No model-independent determinations of the hadronic parameters available yet (only phase-space integrated CP-even fraction arXiv:2208.10098, arXiv:2212.06489). Rely on:

- LHCb amplitude model to calculate the parameters for $D \to K^+K^-\pi^+\pi^-$ JHEP 02 (2019) 126
- phase-space integrated measurement for $D \to \pi^+\pi^-\pi^+\pi^-$

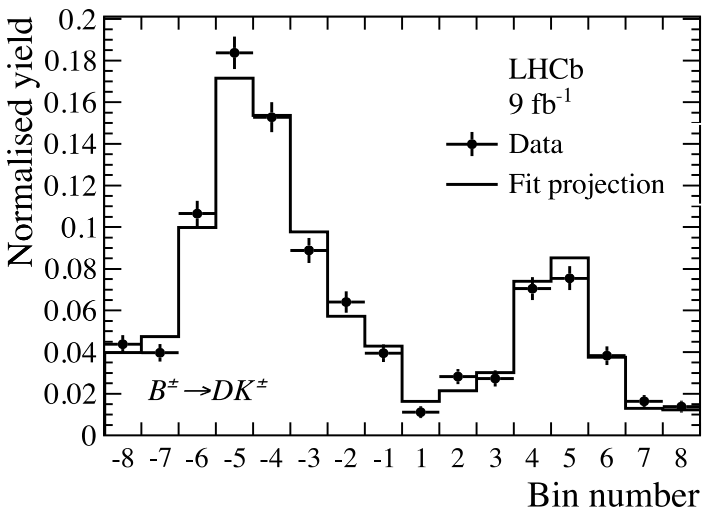
Results for binned $B^{\mp} \to [K^+K^-\pi^+\pi^-]_D K^{\mp}$

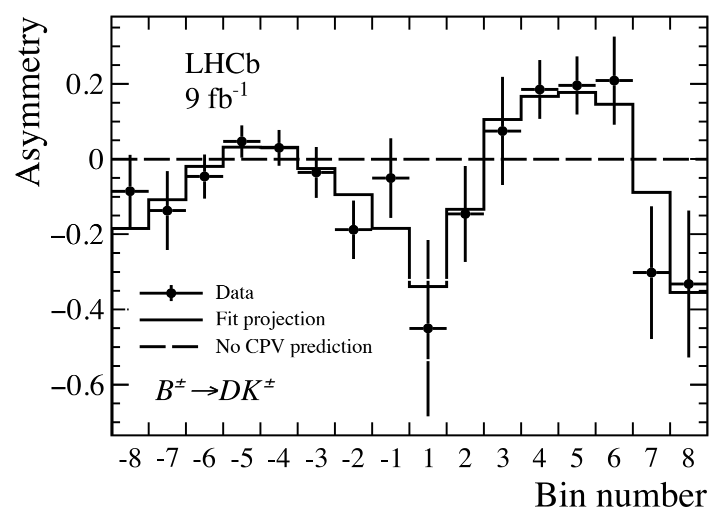
arXiv:2301.10328





Sensitivity with 8 × 2 bins better than 80% of unbinned measurement



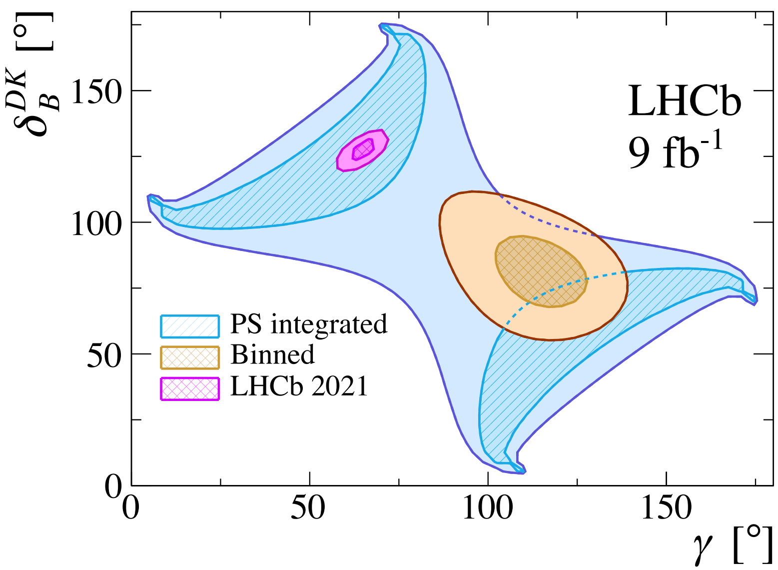


Measurement of γ with $B^{\mp} \to [h^+h^-\pi^+\pi^-]_D h'^{\mp}$

arXiv:2301.10328

Phase-space integrated results:

CP-violating observable	Fit results
$A_K^{KK\pi\pi}$	$0.093 \pm 0.023 \pm 0.002$
$A_\pi^{KK\pi\pi}$	$-0.009 \pm 0.006 \pm 0.001$
$A_K^{\pi\pi\pi\pi}$	$0.060 \pm 0.013 \pm 0.001$
$A_\pi^{\pi\pi\pi\pi}$	$-0.0082 \pm 0.0031 \pm 0.0007$
$R_{CP}^{KK\pi\pi}$	$0.974 \pm 0.024 \pm 0.015$
$R_{CP}^{\pi\pi\pi\pi}$	$0.978 \pm 0.014 \pm 0.010$



$\gamma = (116^{+12}_{-14})^\circ$

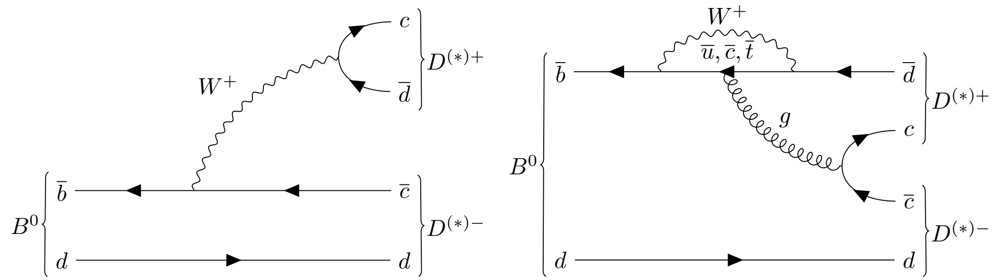
(3σ agreement with previous LHCb determinations using other channels)

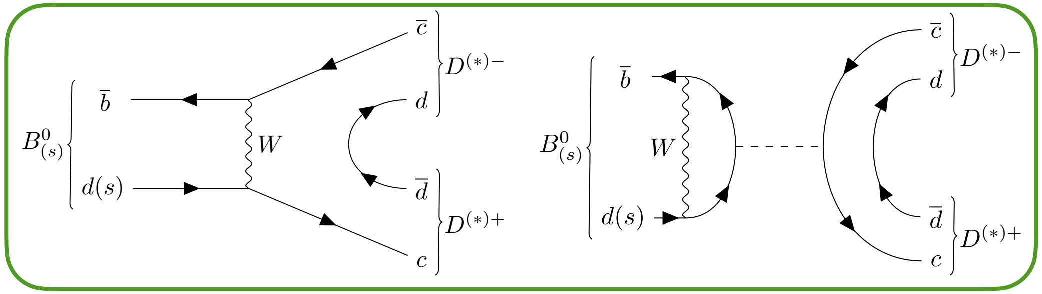
Uncertainty from external measurements of the charm hadronic parameters equal to the statistical uncertainty.

Precision will improve (and value might change) after ongoing BES-III model-independent measurement

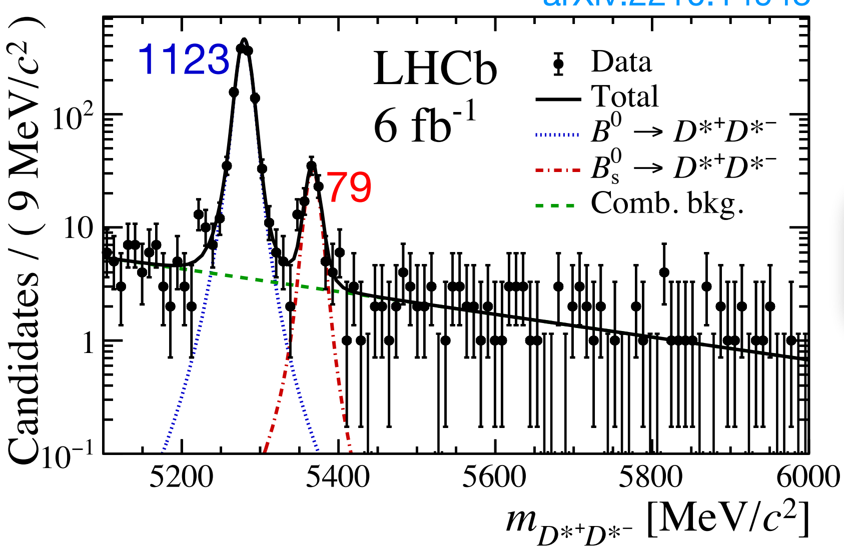
Observation of the $B_s^0 \to D^{*+}D^{*-}$ decay

- $B^0_{(s)} \to D\bar{D}$ decays are sensitive to the CKM parameter $2\beta_{(s)}$
- theoretical interpretation limited by the knowledge of second-order diagrams JHEP 07 (2015) 108 PRD 91 (2015) 3, 034027
- $B_s^0 \to D^{*+}D^{*-}$ receives contributions from W-exchange and penguin annihilation diagrams only





arXiv:2210.14945



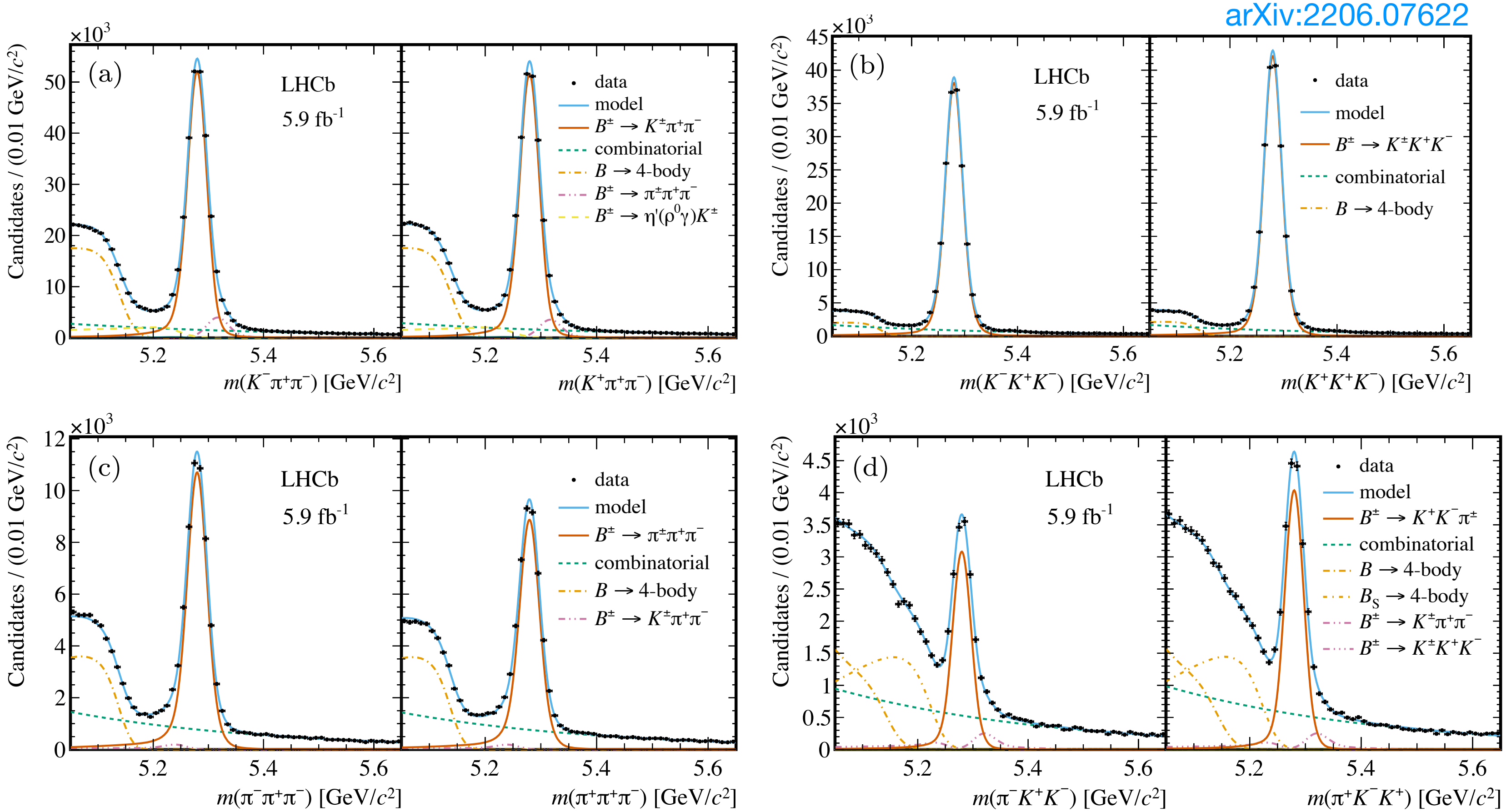
Run 1–2, $D^{*+} \to [K^-\pi^+/K^+K^-/\pi^+\pi^-]_{D^0}\,\pi^+$

$$\frac{\mathcal{B}(B_s^0 \to D^{*+}D^{*-})}{\mathcal{B}(B^0 \to D^{*+}D^{*-})} = 0.269 \pm 0.032 \pm 0.011 \pm 0.008$$

f_s/f_d

Search for direct CPV in $B^+ \to h^+h^+h^-$ decays

arXiv:2206.07622



production asymmetry corrected for by using $B^\pm \to J/\psi K^\pm$

$$A_{CP}(B^\pm \to K^\pm\pi^+\pi^-) = +0.011 \pm 0.002 \pm 0.003 \pm 0.003 \quad (2.4\ \sigma)$$

$$A_{CP}(B^\pm \to K^\pm K^+K^-) = -0.037 \pm 0.002 \pm 0.002 \pm 0.003 \quad (8.5\ \sigma)$$

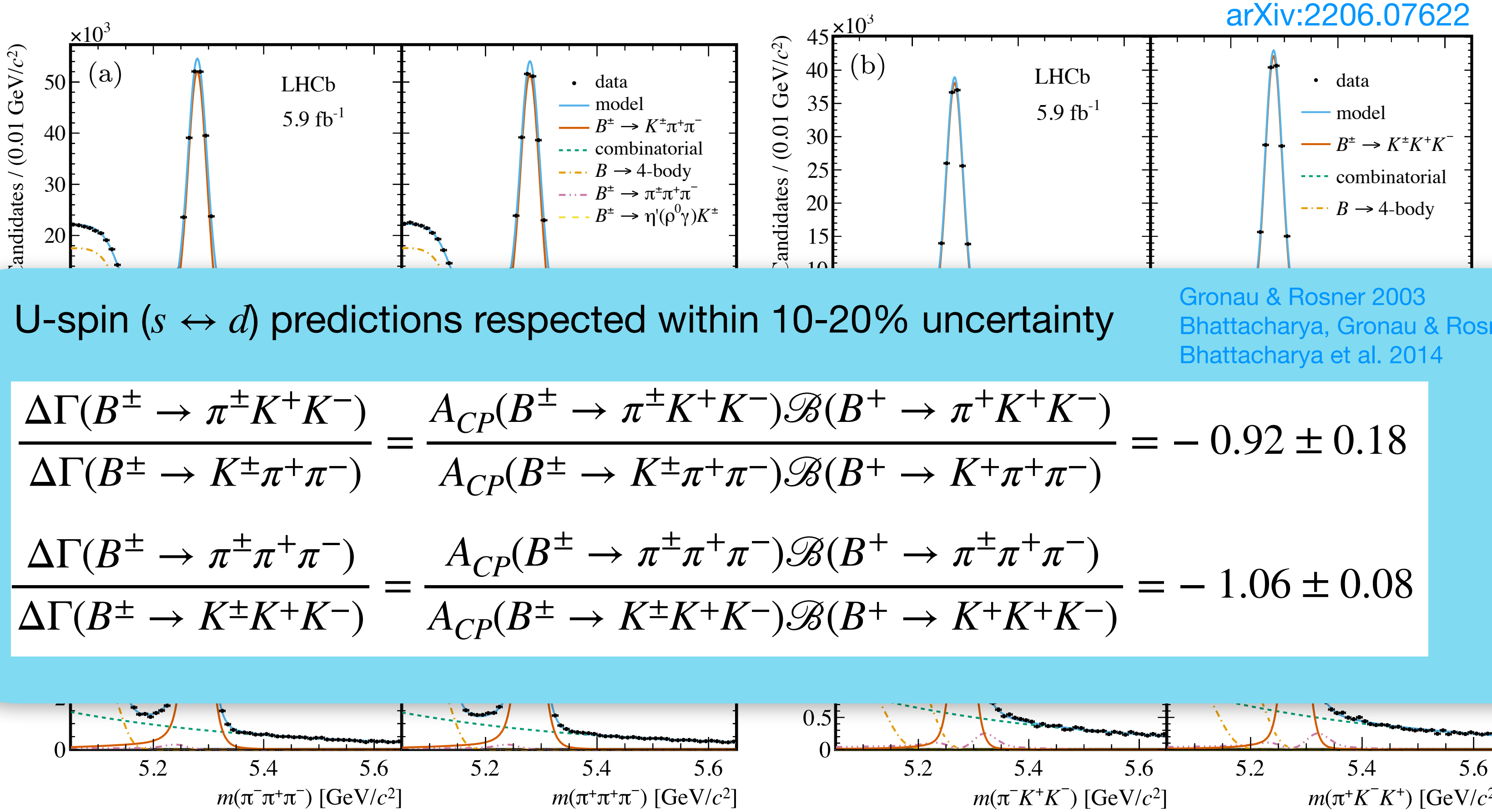
$$A_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-) = +0.080 \pm 0.004 \pm 0.003 \pm 0.003 \quad (14.1\ \sigma)$$

$$A_{CP}(B^\pm \to \pi^\pm K^+K^-) = -0.114 \pm 0.007 \pm 0.003 \pm 0.003 \quad (13.6\ \sigma)$$

1st observation

Search for direct CPV in $B^+ \to h^+h^+h^-$ decays

arXiv:2206.07622



U-spin ($s \leftrightarrow d$) predictions respected within 10-20% uncertainty

Gronau & Rosner 2003
Bhattacharya, Gronau & Rosner 2013
Bhattacharya et al. 2014

$$\frac{\Delta\Gamma(B^\pm \to \pi^\pm K^+K^-)}{\Delta\Gamma(B^\pm \to K^\pm\pi^+\pi^-)} = \frac{A_{CP}(B^\pm \to \pi^\pm K^+K^-)\mathscr{B}(B^+ \to \pi^+K^+K^-)}{A_{CP}(B^\pm \to K^\pm\pi^+\pi^-)\mathscr{B}(B^+ \to K^+\pi^+\pi^-)} = -0.92 \pm 0.18$$

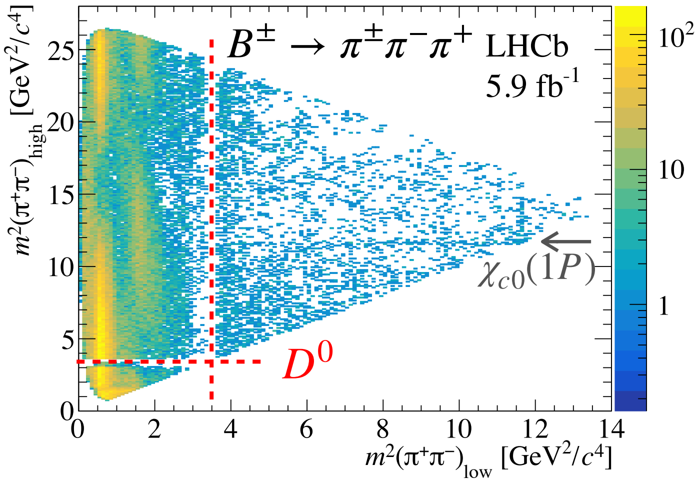
$$\frac{\Delta\Gamma(B^\pm \to \pi^\pm\pi^+\pi^-)}{\Delta\Gamma(B^\pm \to K^\pm K^+K^-)} = \frac{A_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-)\mathscr{B}(B^+ \to \pi^\pm\pi^+\pi^-)}{A_{CP}(B^\pm \to K^\pm K^+K^-)\mathscr{B}(B^+ \to K^+K^+K^-)} = -1.06 \pm 0.08$$

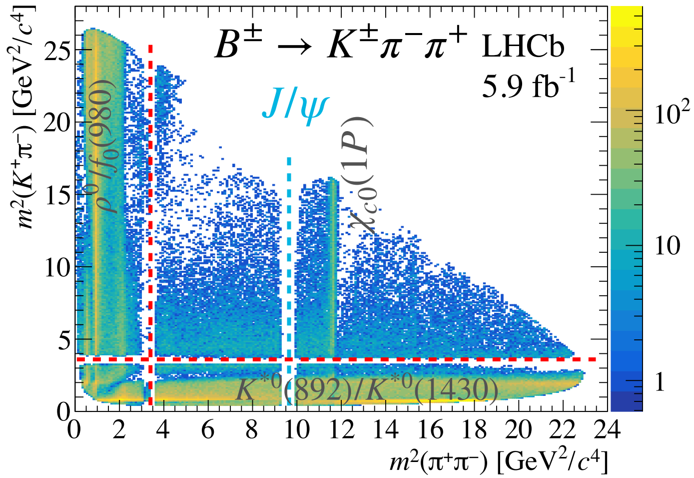
production asymmetry corrected for by using $B^\pm \to J/\psi K^\pm$

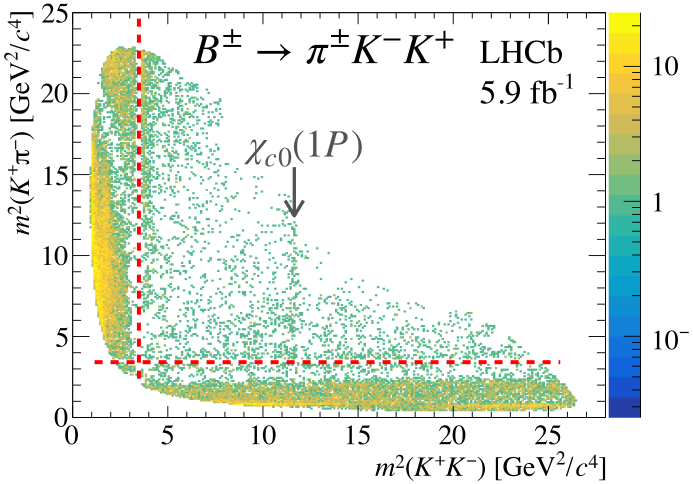
$$A_{CP}(B^\pm \to K^\pm\pi^+\pi^-) = +0.011 \pm 0.002 \pm 0.003 \pm 0.003 \quad (2.4\ \sigma)$$
$$A_{CP}(B^\pm \to K^\pm K^+K^-) = -0.037 \pm 0.002 \pm 0.002 \pm 0.003 \quad (8.5\ \sigma)$$
$$A_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-) = +0.080 \pm 0.004 \pm 0.003 \pm 0.003 \quad (14.1\ \sigma)$$
$$A_{CP}(B^\pm \to \pi^\pm K^+K^-) = -0.114 \pm 0.007 \pm 0.003 \pm 0.003 \quad (13.6\ \sigma)$$

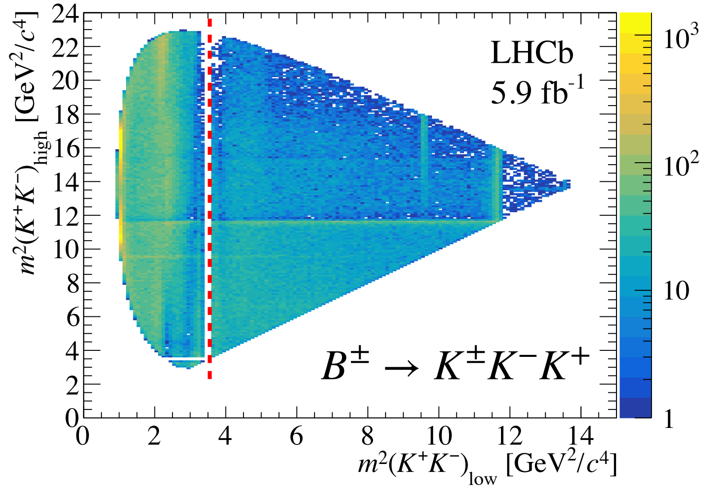
1st observation

Search for direct CPV in $B^+ \to h^+h^+h^-$ decays



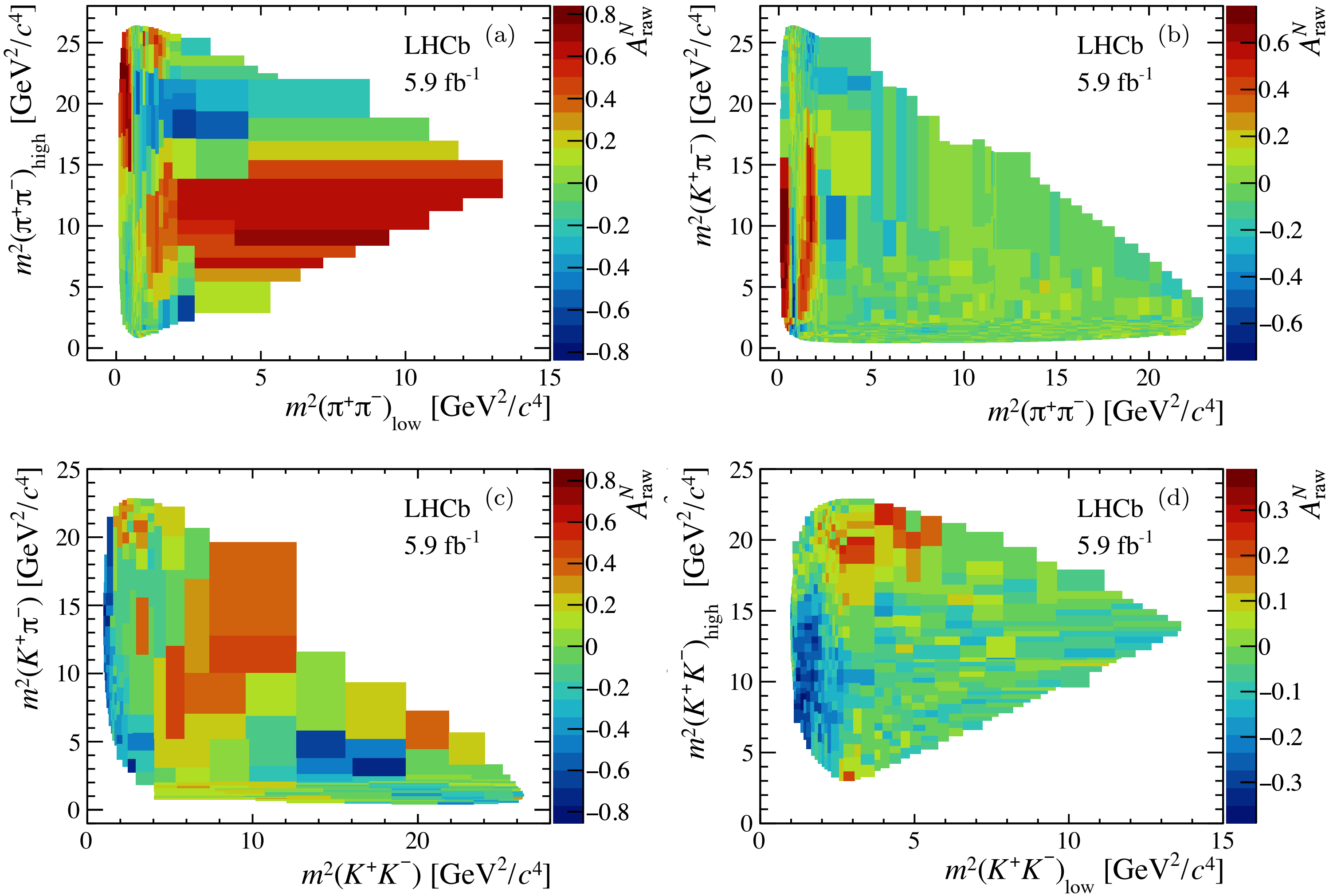






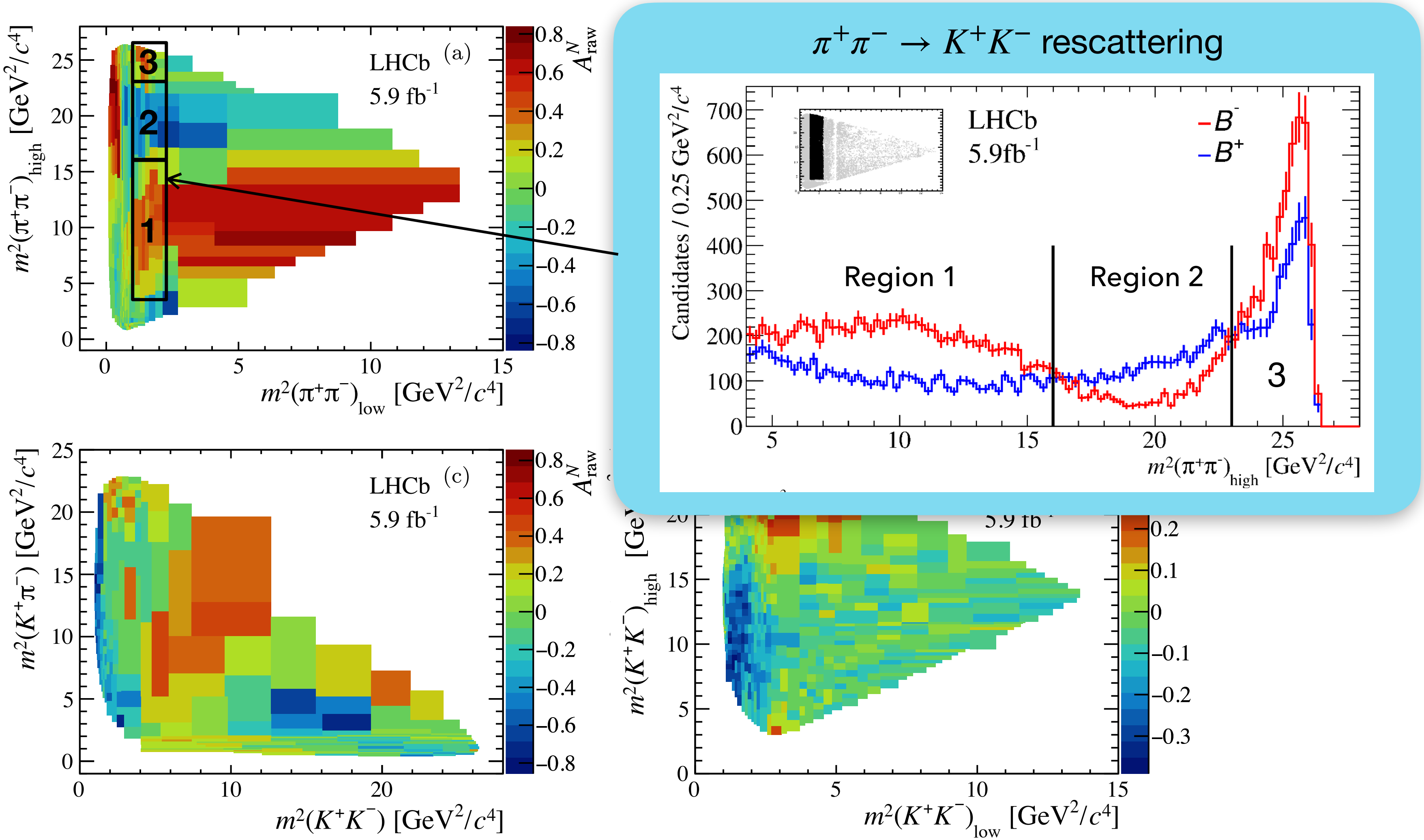
arXiv:2206.07622
LHC seminar 15 March 2022

Search for direct CPV in $B^+ \to h^+h^+h^-$ decays



arXiv:2206.07622
LHC seminar 15 March 2022

Search for direct CPV in $B^+ \to h^+h^+h^-$ decays



arXiv:2206.07622
LHC seminar 15 March 2022

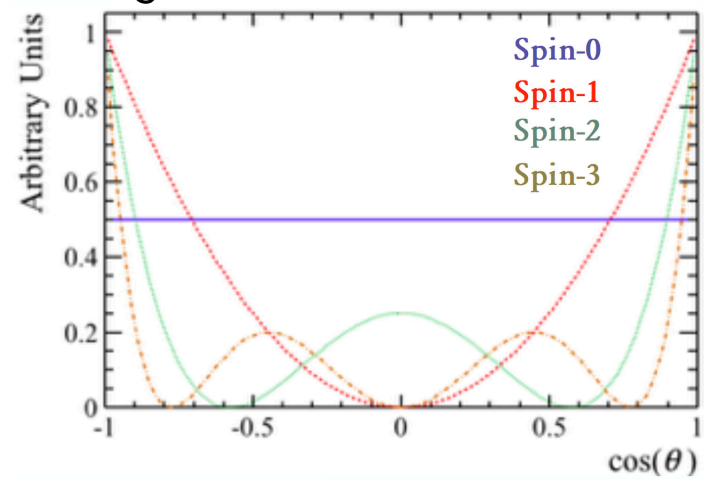
Search for direct CPV in $B^+ \to PV$ decays

arXiv:2206.02038

Based on Phys. Rev. D 94 (2016) 5, 054028

- select a narrow region around a vector resonance
  - ±150 MeV/c^2 for $\rho^0(770)$
  - ±50 MeV/c^2 for $K^{*0}(892)$
  - ±5 MeV/c^2 for $\phi^0(1020)$

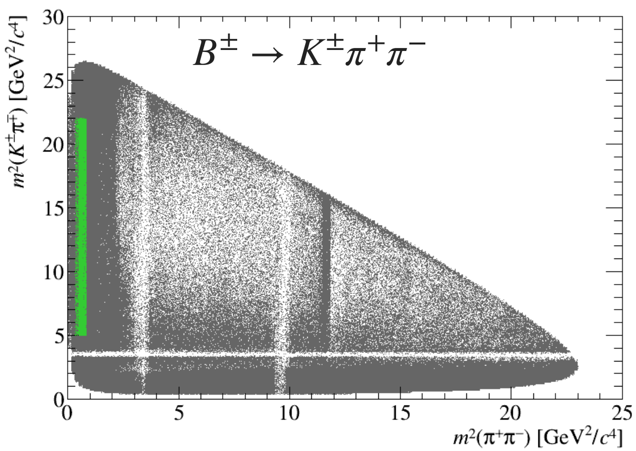
Angular distribution of resonances



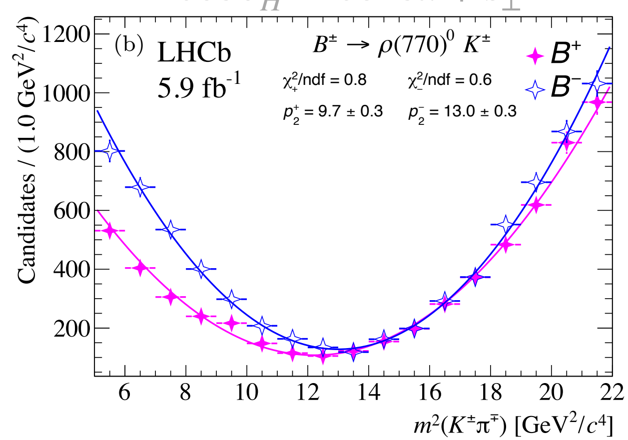
$$|M^{\pm}|^2 \approx \underbrace{p_0^{\pm}}_{\text{scalar}} + \underbrace{p_1^{\pm}\cos\theta_H}_{\text{interference}} + \underbrace{p_2^{\pm}\cos^2\theta_H}_{\text{vector}}$$

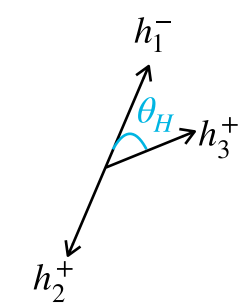
$$A_{CP}^{V} \equiv \frac{p_2^- - p_2^+}{p_2^- + p_2^+}$$

$B^+ \to V(h_1^- h_2^+) h_3^+$



$\cos\theta_H \propto \text{const.} + s_{\perp}$





$s_{\parallel} \equiv m^2(h_1^- h_2^+)$

$s_{\perp} \equiv m^2(h_1^- h_3^+)$

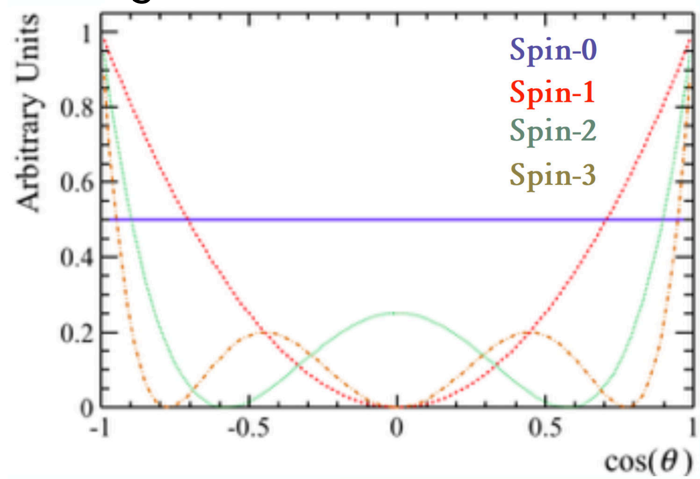
Search for direct CPV in $B^+ \to PV$ decays

arXiv:2206.02038

Based on Phys. Rev. D 94 (2016) 5, 054028

- select a narrow region around a vector resonance
  - ±150 MeV/c^2 for $\rho^0(770)$
  - ±50 MeV/c^2 for $K^{*0}(892)$
  - ±5 MeV/c^2 for $\phi^0(1020)$

Angular distribution of resonances

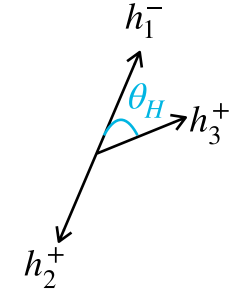


$$|M^\pm|^2 \approx \underbrace{p_0^\pm}_{\text{scalar}} + \underbrace{p_1^\pm \cos\theta_H}_{\text{interference}} + \underbrace{p_2^\pm \cos^2\theta_H}_{\text{vector}}$$

$$A_{CP}^V \equiv \frac{p_2^- - p_2^+}{p_2^- + p_2^+}$$

$\cos\theta_H \propto \text{const.} + s_\perp$

$B^+ \to V(h_1^- h_2^+) h_3^+$



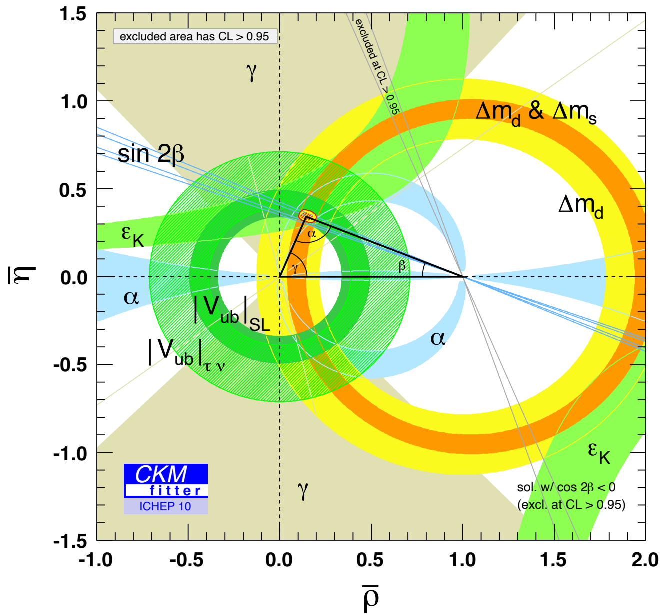
$s_\parallel \equiv m^2(h_1^- h_2^+)$

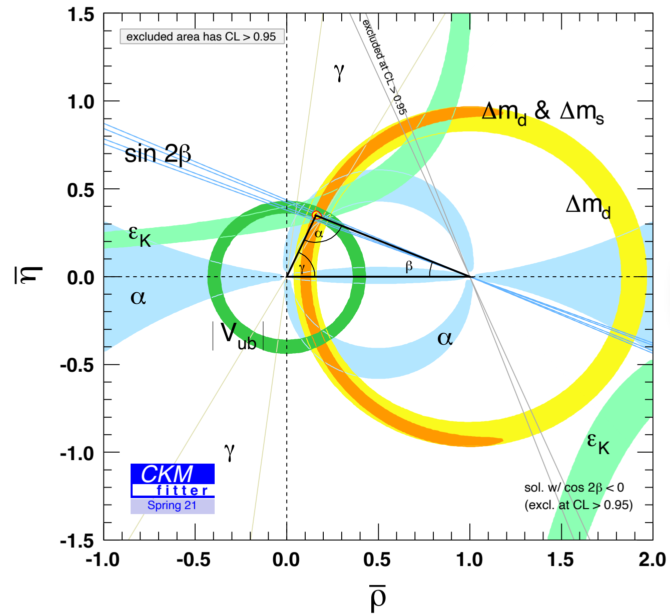
$s_\perp \equiv m^2(h_1^- h_3^+)$

Decay channel	Vector Resonance	$\mathcal{A}_{CP}^V \pm\sigma_{\rm stat} \pm \sigma_{\rm syst}$	
$B^\pm \to \pi^\pm\pi^+\pi^-$	$\rho(770)^0 \to \pi^+\pi^-$	-0.004 ± 0.017 ± 0.009	
$B^\pm \to K^\pm\pi^+\pi^-$	$\rho(770)^0 \to \pi^+\pi^-$	+0.150 ± 0.019 ± 0.011	(6.8σ) First observation
	$K^*(892)^0 \to K^\pm\pi^\mp$	-0.015 ± 0.021 ± 0.012	
$B^\pm \to \pi^\pm K^+K^-$	$K^*(892)^0 \to K^\pm\pi^\mp$	+0.007 ± 0.054 ± 0.032	
$B^\pm \to K^\pm K^+K^-$	$\phi(1020) \to K^+K^-$	+0.004 ± 0.010 ± 0.007	

Summary

- First evidence for CP violation in charm in a single decay channel was found (3.8 σ)
- The angle γ is no longer the least known angle of the CKM triangle
  - further improvements from better knowledge of hadronic parameters and time-dependent analyses expected soon





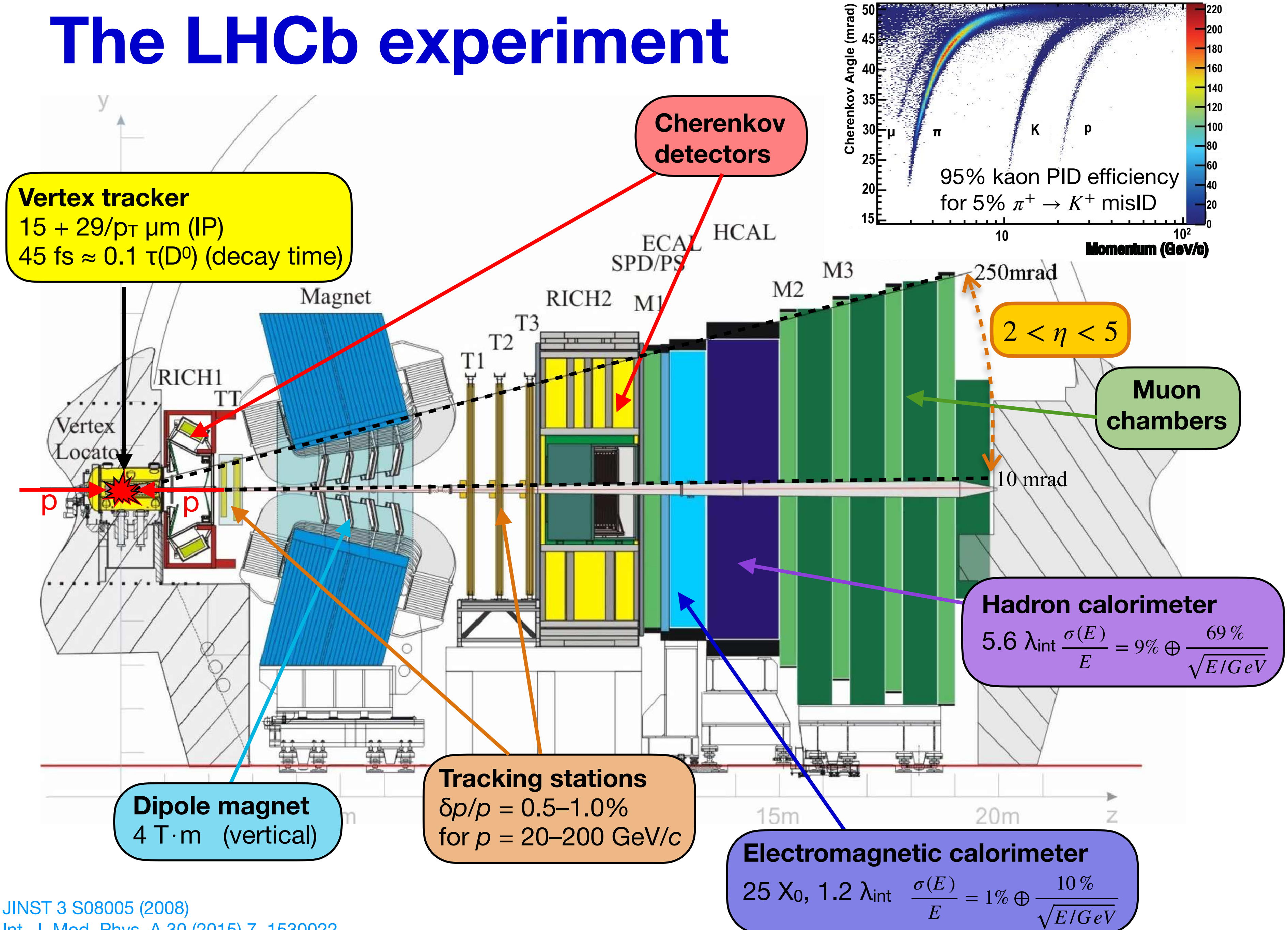
$$\gamma = (63.8^{+3.5}_{-3.7})^\circ$$

The LHCb Upgrade I will improve the Run 3 measurements in several crucial ways

- higher integrated luminosity
- removal of hardware trigger
  - higher trigger efficiency
  - smaller detection asymmetries

Backup slides

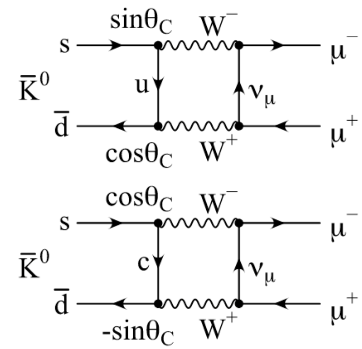
The LHCb experiment

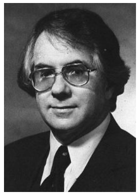


JINST 3 S08005 (2008)
Int. J. Mod. Phys. A 30 (2015) 7, 1530022

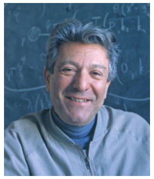
Why care about flavour physics?

Flavour changing neutral currents (FCNC) are suppressed in the SM (GIM mechanism).

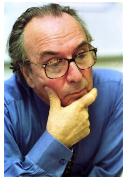




Sheldon Lee Glashow



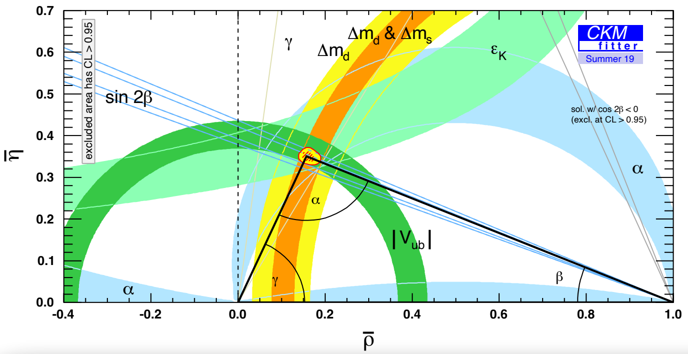
John Iliopoulos



Luciano Maiani

$$
V_{\mathrm{CKM}} = \begin{array}{c} \\ \\ \end{array}
\begin{array}{cccc}
 & \mathrm{d} & \mathrm{s} & \mathrm{b} \\
 \end{array}
$$

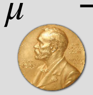
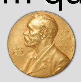
$$
V_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \begin{array}{c} \mathrm{u} \\ \mathrm{c} \\ \mathrm{t} \end{array} + \mathcal{O}(\lambda^4)
$$



Only one measured source of *CP* violation (*CPV*) in the SM (complex phase in CKM matrix):

- flavour observables are over constrained;
- deviations might be related to the baryon asymmetry.

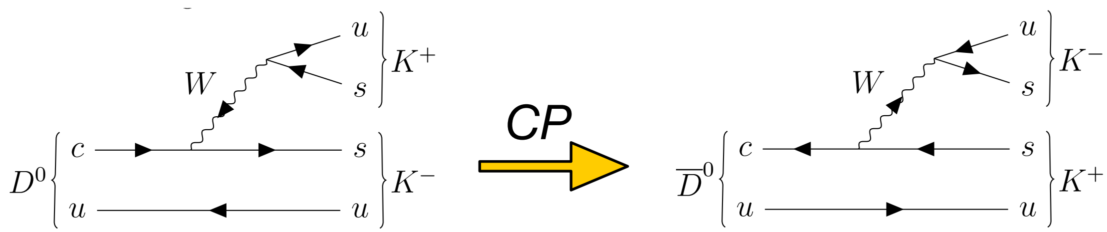
A story of success:

- ➢ low BR of $K^0_L \to \mu^+\mu^-$ → GIM mechanism  Glashow 1979, prediction of charm quark
- ➢ *CPV* in K^0 mesons  Cronin Fitch 1980 → prediction of 3rd generation of quarks  Kobayashi Maskawa 2008
- ➢ B^0 mixing → lower bound on top mass
- ➢ B^0_s oscillations, BR of $B^0_s \to \mu^+\mu^-$, etc. → bounds on SMEFT operators

Requirements to observe CP violation

Under the CP transformation:

- **strong phases** are invariant;
- **weak phases** change sign.



$A = |A|e^{i\delta}e^{i\phi}$

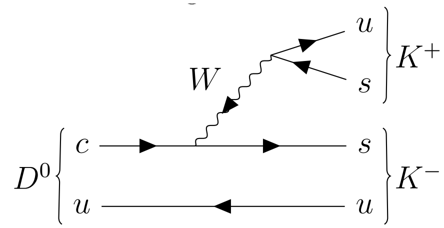
$\overline{A} = |A|e^{i\delta}e^{-i\phi}$

Since only $|A|^2$ is observable, there is no *CP* violation if only one amplitude contributes to the process.

Requirements to observe CP violation

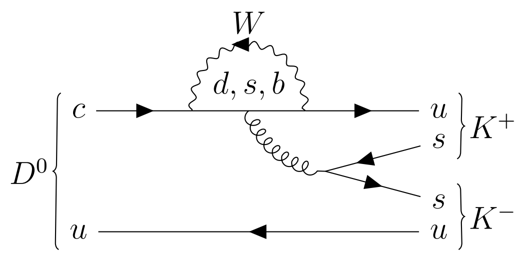
Under the CP transformation:

- **strong phases** are invariant;
- **weak phases** change sign.



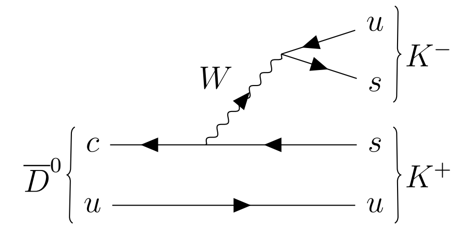
$$A_1 = |A_1| e^{i\delta_1} e^{i\phi_1}$$

+



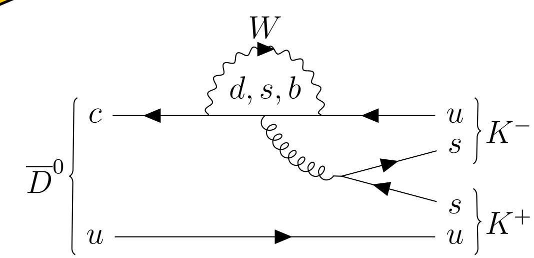
$$A_2 = |A_2| e^{i\delta_2} e^{i\phi_2}$$

CP



$$\overline{A}_1 = |A_1| e^{i\delta_1} e^{-i\phi_1}$$

+



$$\overline{A}_2 = |A_2| e^{i\delta_2} e^{-i\phi_2}$$

$$\boxed{|A_1 + A_2|^2 - |\overline{A}_1 + \overline{A}_2|^2 = -4|A_1||A_2|\sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)}$$

Need at least two interfering amplitudes with **different weak phases** and **different strong phases** to observe *CP* violation

Flavoured neutral mesons

Flavour quantum numbers are not conserved by the weak interaction
→ neutral mesons oscillate:

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\boldsymbol{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

off-shell transitions. NP? *on-shell transitions*

$$D^0 = c\bar{u} \xleftrightarrow[\text{(FCNC)}]{|\Delta C| = 2} \overline{D}^0 = \bar{c}u$$

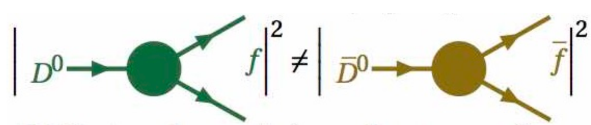
The oscillation probability is determined by the size of the transition amplitudes:

$$x_{12} \equiv \frac{2|M_{12}|}{\Gamma}, \qquad y_{12} \equiv \frac{|\Gamma_{12}|}{\Gamma}$$

"mixing parameters"

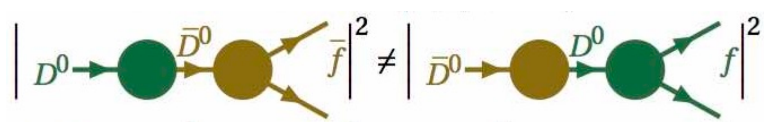
Mixing provides additional interfering amplitudes. *CPV* is classified as:

1. ***CPV in the decay***



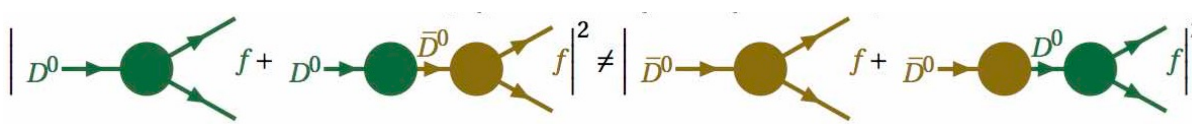
$$\boxed{a_f^d \equiv \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}}$$

2. ***CPV in the mixing***

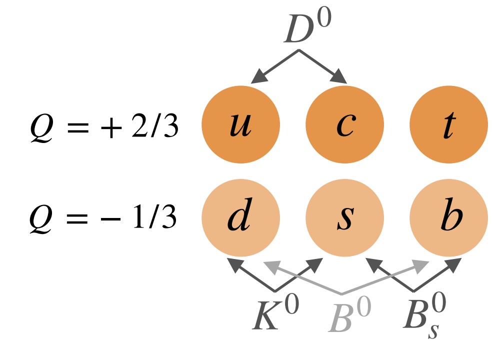


$$P(D^0 \to \overline{D}^0) \neq P(\overline{D}^0 \to D^0)$$
$$\phi_{12} \equiv \arg(M_{12}/\Gamma_{12}) \neq 0$$

3. ***CPV in the interference***
(of mixing and decay)



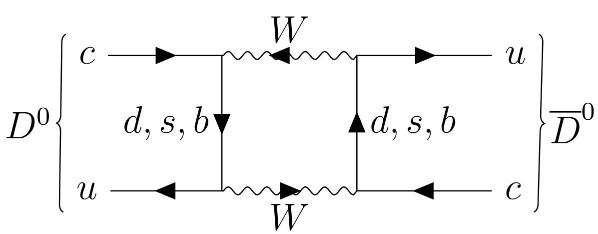
Charm: the dark horse of flavour



Charm is the only up-type quark which mixes and allows high-precision *CPV* measurements

FCNC are <u>extremely</u> suppressed

GIM mechanism broken by the beauty-quark mass (instead of top)



$$\propto \left(\frac{m_{d,s,b}}{m_W}\right)^2$$

mixing – short distance

$$\begin{array}{cccc} \text{d} & \text{s} & \text{b} & \\ \end{array}$$

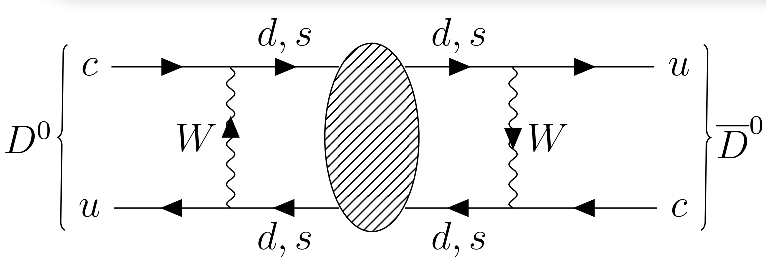
$$V_{\rm CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \begin{array}{c} \text{u} \\ \text{c} \\ \text{t} \end{array} + \mathcal{O}(\lambda^4)$$

$\lambda = \sin\theta_C \approx 0.23$

CKM suppression of **b**-quark contribution

> The third generation of quarks nearly decouples from the first two, while the contributions from **d**, **s** quarks cancel out in the limit of U-spin symmetry ($m_s = m_d$)

Experimentally $x_{12} \approx 0.4\,\%$, $y_{12} \approx 0.6\,\%$



mixing – long distance

Main contributions come from low-energy QCD interactions through on-shell resonances.

Theory predictions are challenging.

Measurement of $A_{CP}(D^0 \to K^+K^-)$

time-dep. CPV,
known with 10^{-4} precision

~1.7

$$A_{CP}(f) \approx a_f^d + \Delta Y \frac{\langle t \rangle_f}{\tau_{D^0}}$$

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

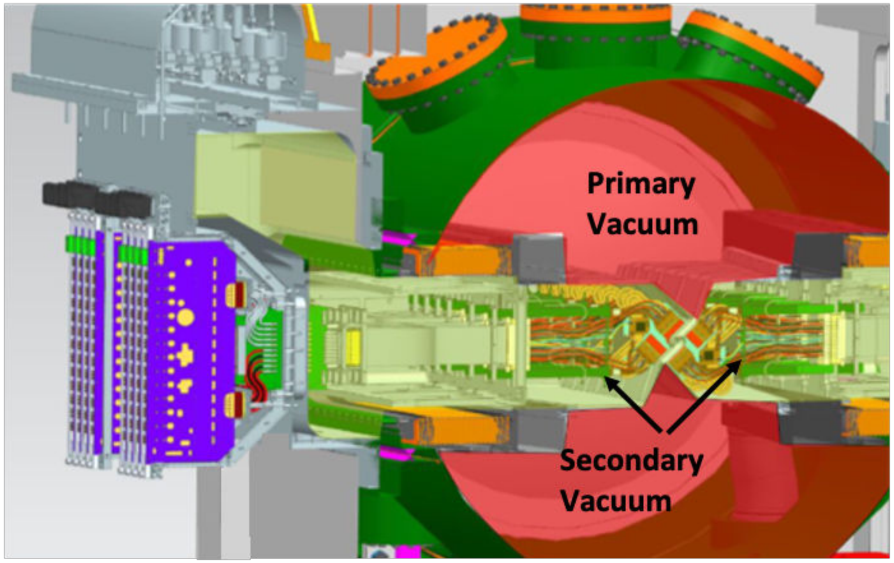
$$\approx a^d_{K^+K^-} - a^d_{\pi^+\pi^-} + \Delta Y \frac{\langle t \rangle_{K^+K^-} - \langle t \rangle_{\pi^+\pi^-}}{\tau_{D^0}}$$

~0.1

arXiv:2209.03179
PRL 122 (2019) 211803
PRD 104 (2021) 7, 072010

VELO vacuum incident

The VELO detector is installed in a secondary vacuum inside the LHC primary vacuum. The primary and secondary volumes are separated by two thin walled (180 μm) Aluminium boxes, the RF foils. The LHC vacuum control system protects against pressure differentials, both during vacuum operation and during technical stops, when all volumes are sometimes filled with Neon.



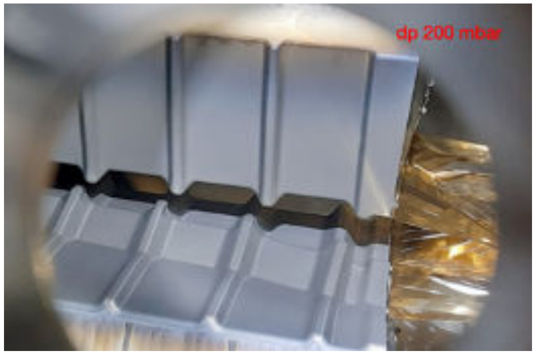
On 10th January 2023, during a VELO warm up in Neon, there was a loss of control of the protection system. A relay failed and damaged a power supply, leading to multiple equipment failures and a pumping action on the primary volume. The safety valve didn't open at the designed $\Delta P = 10$ mbar, and a pressure differential of 200 mbar built up between the two volumes, whereas the foils are designed to withstand 10 mbar only.

The system has been returned to a safe situation and VELO modules are not damaged and operational:

- correct leakage current measured in silicon sensors
- silicon microchannels show no leaks

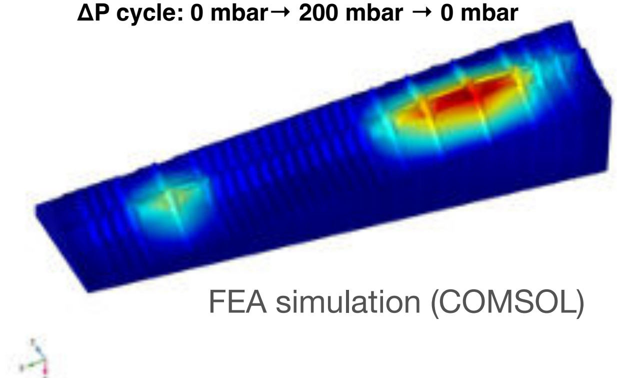
Analysis and recovery

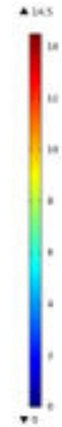
The deformation of the RF foil has been simulated, and the results have been benchmarked against measurements on a 1/2 scale prototype box.

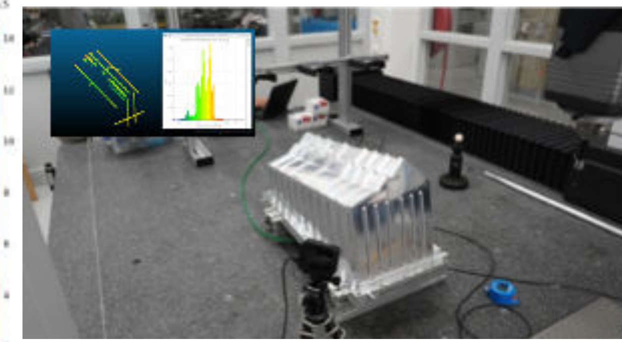


Visualisation through viewing port

Residual deformation [mm] in simulation after ΔP cycle: 0 mbar→ 200 mbar → 0 mbar


FEA simulation (COMSOL)




Benchmarking simulation/measurement

- Plastic deformation of the foils of up to 14 mm expected
    - to be validated with tomography with beam
- detector and vacua brought back to a safe state (thanks to the LHC vacuum group for their crucial help)
- commissioning of VELO and other subdetectors can continue
- VELO cannot be fully closed
- foil needs to be replaced in next YETS (~13 weeks intervention)

Physics programme in 2023 will be significantly affected: lower acceptance; slightly worse IP resolution, similar to Run 2; lower integrated luminosity — targeting ~1 fb^{-1}

- could still provide world-best measurements in some areas thanks to the new flexible software-only high-bandwidth trigger