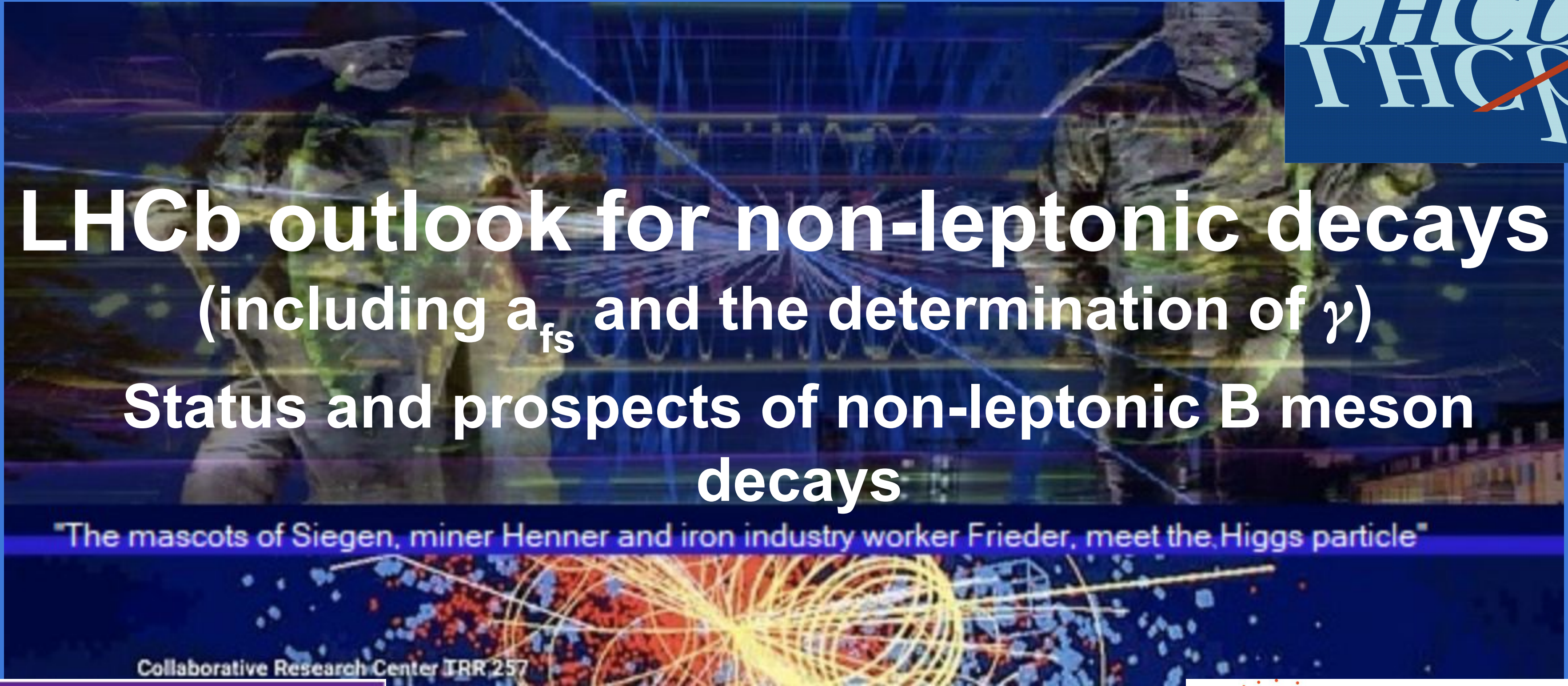
LHCb outlook for non-leptonic decays

(including a_{fs} and the determination of γ)

Status and prospects of non-leptonic B meson decays



N. Skidmore on behalf of the LHCb collaboration

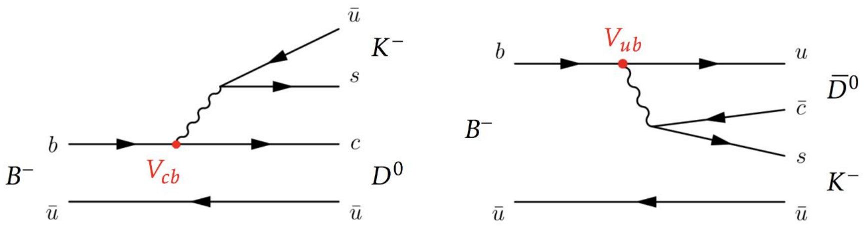
June 2022

The many measurements of γ…

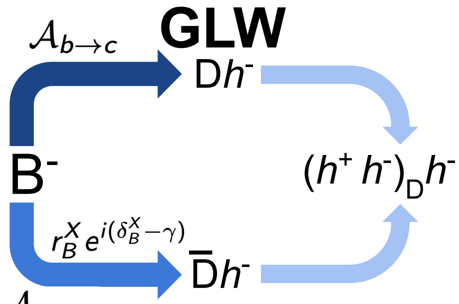
Here we discuss TI measurements, for TD see Stephie's talk

CKM phase γ can be measured solely with **tree-level *B->Dh*** decays

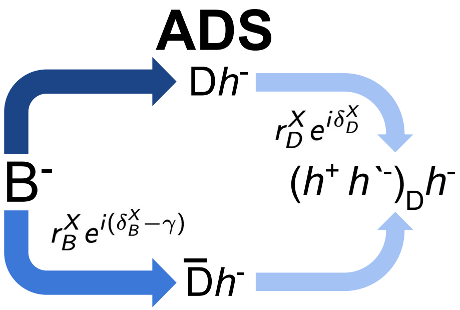
In the absence of NP effects at tree-level - SM benchmark- negligible theoretical uncertainties when interpreting observables in terms of γ



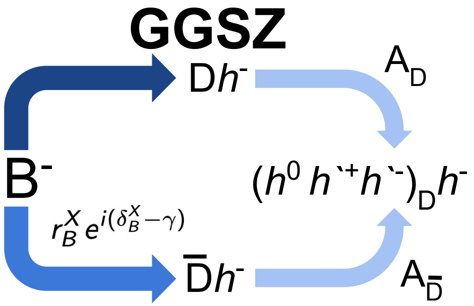
Compare to γ interpretations from decays susceptible to NP contributions → sensitive to **BSM effects at mass scales greater than those accessible directly**



CP-eigenstate



Non-charge conjugate state



Self-conjugate 3 body final state

+ variations

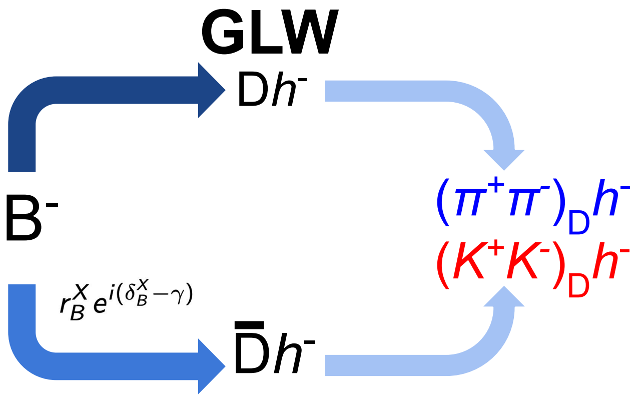
Choice of measured observables is dependent on the method that is most appropriate for the *D* decay analysed - all sensitive to the same *B* decay parameters, r_B^X, $\boldsymbol{\delta}_B^X$, γ → combination fits

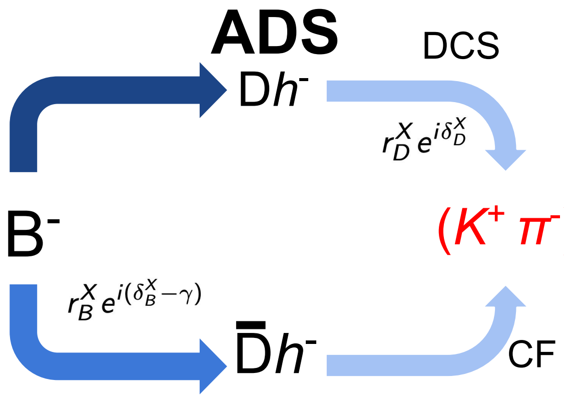
CP observables in $B^\pm \to D^{(*)} h^\pm$ decays

$8.7\,\mathrm{fb}^{-1}$

JHEP 04 (2021) 081

Use $B^\pm \to D^{(*)} h^\pm$ decays to measure experimentally robust CP observables in GLW and ADS modes





Similar magnitude of $r_D^{K\pi}$ and r_B^{DK} leads to large A_{CP} for ADS modes

$$\Gamma(B^\mp \to [[h^+h^-]_D h^\mp]_X) \propto 1 + (r_B^X)^2 + 2r_B^X \cos(\delta_B^X \mp \gamma) - \alpha y (1 + (r_B^X)^2) - \alpha y 2 r_B^X \cos(\delta_B^X \mp \gamma)$$

$$\Gamma(B^\mp \to [[K^\pm\pi^\mp]_D h^\mp]_X) \propto (r_D^{K\pi})^2 + (r_B^X)^2 + 2 r_D^{K\pi} r_B^X \cos(\delta_B^X + \delta_D^{K\pi} \mp \gamma) - \alpha y (1 + (r_B^X)^2) r_D^{K\pi} \cos\delta_D^{K\pi} - \alpha y (1 + (r_D^{K\pi})^2) r_B^X \cos(\delta_B^X \mp \gamma) + \alpha x (1 - (r_B^X)^2) r_D^{K\pi} \sin\delta_D^{K\pi} - \alpha x (1 - (r_D^{K\pi})^2) r_B^X \sin(\delta_B^X \mp \gamma)$$

- 28 CP observables are measured - partial width ratios, double ratios and A_{CP}s
- Can be interpreted in terms of $\gamma, r_B^{DK}, \delta_B^{DK}, r_B^{D\pi}, \delta_B^{D\pi}, r_B^{D^*K}, \delta_B^{D^*K}, r_B^{D^*\pi}, \delta_B^{D^*\pi}$

$r_D^{K\pi}, \delta_D^{K\pi}$ and **charm mixing parameters x and y** taken from HFLAV average Eur. Phys. J. C (2021) 81: 226

CP observables in $B^{\pm} \to D^{(*)} h^{\pm}$ decays

8.7fb^{-1}

JHEP 04 (2021) 081

First measurements of CP observables using $B^{\pm} \to D^{*} h^{\pm}$ in ADS modes

$D^{*} \to D^0\pi^0/\gamma$ is partially reconstructed - missing neutral

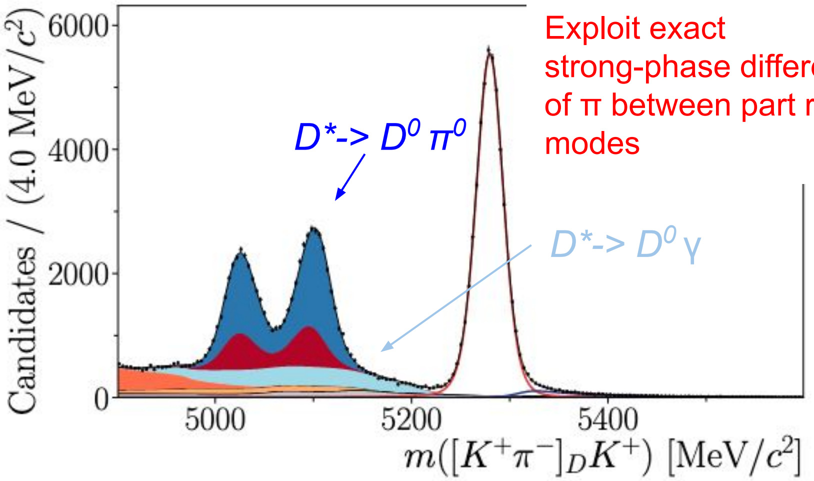
Reconstruction efficiency for low momentum neutral pions and photons is low - partial reconstruction provides significantly larger yields

Small m_{D^*}-m_D and angular structure of $D^{*} \to D^0\pi^0/\gamma$ decays result in distinctive line shapes in m($Dh^{\pm}$) - yields can be obtained

Measurements of $\mathcal{B}(B^- \to D^{*0}\pi^-)$ and $\mathcal{B}(D^{*0} \to D^0\pi^0)$ are made and agree with current world averages

Demonstrates method of partial reconstruction accurately measures $B^{\pm} \to D^{*} h^{\pm}$ modes despite presence of multiple partially reconstructed background sources

ADS favoured decay - used for normalisation



Exploit exact strong-phase difference of π between part reco modes

CP observables in $B^{\pm}\to D^{(*)}h^{\pm}$ decays

8.7fb^{-1}

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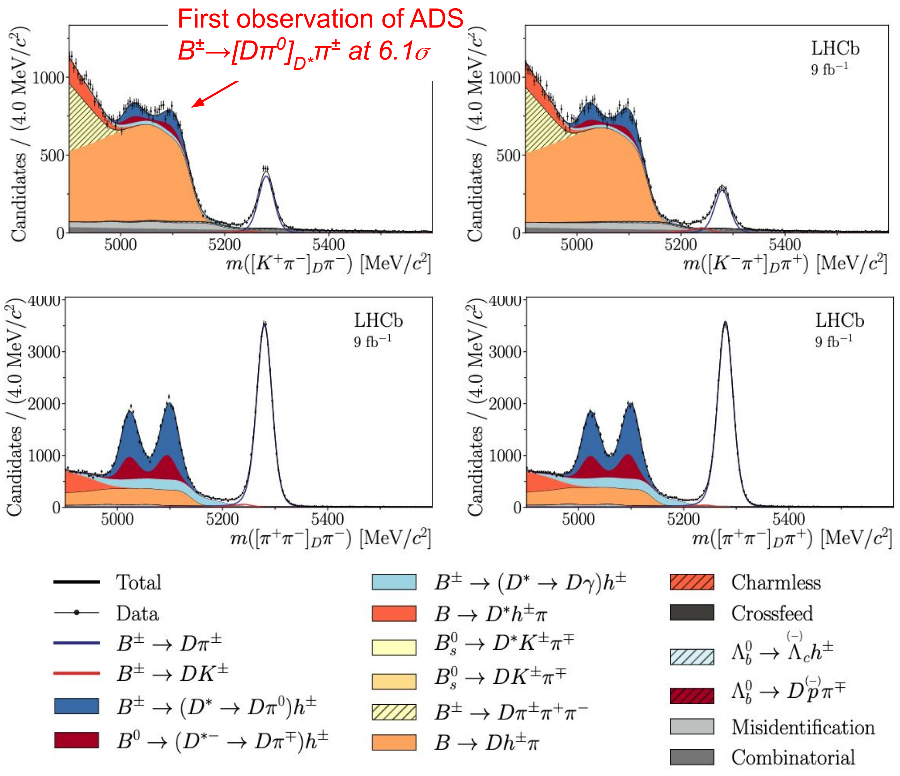
ADS

GLW

First observation of ADS $B^{\pm}\to[D\pi^0]_{D^*}\pi^{\pm}$ at 6.1σ

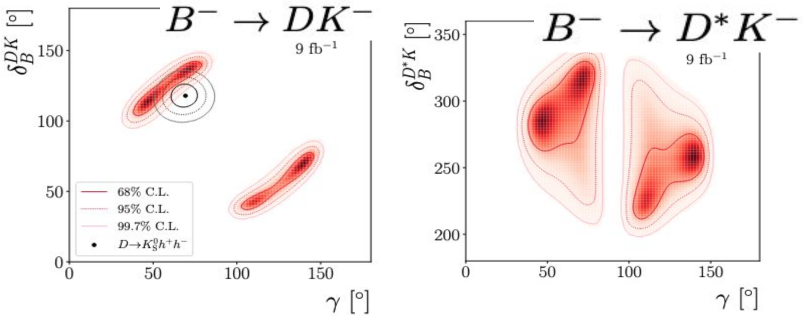


16 independent samples fit simultaneously

All CP observables measured to worlds best precision

Profile likelihood contours dominated by $B^{\pm}$->$DK^{\pm}$ - good agreement with LHCb/B factory results

Constructed using charm parameters taken as external constraints from HFLAV average but these modes provide significant sensitivity to these parameters → motivates combination of gamma and charm results

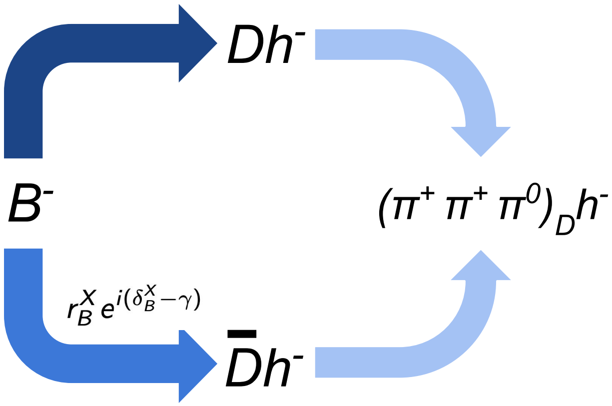


Constraints on γ from $B^{\pm} \rightarrow Dh^{\mp}$ with $D \rightarrow h^{\pm}h'^{\mp}\pi^0$

9fb^{-1}

arXiv:2112.10617, submitted to JHEP

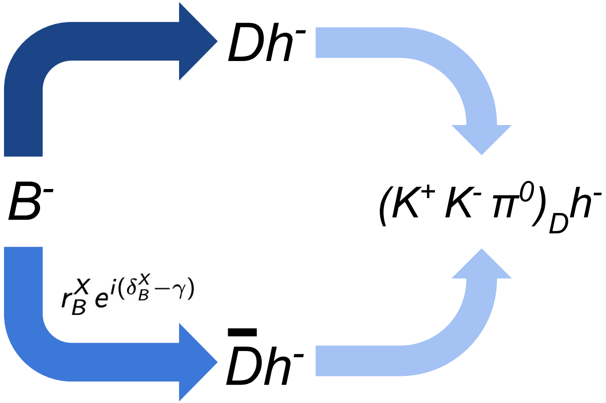
Quasi-GLW
3-body D decay



Close to being CP-even

$F_+^{\pi\pi\pi 0} = 0.973 \pm 0.017$

$F_+^{KK\pi 0} = 0.732 \pm 0.055$



$$\Gamma(B^{\mp} \to [\pi^+\pi^-\pi^0]_D h^{\mp}) \propto 1 + r_B^2 + 2r_B(2F_+^{\pi\pi\pi^0} - 1)\cos(\delta_B \mp \gamma) - \alpha y(1 + r_B^2)(2F_+^{\pi\pi\pi^0} - 1) - 2\alpha y r_B \cos(\delta_B \mp \gamma)$$

$$\Gamma(B^{\mp} \to [K^+K^-\pi^0]_D h^{\mp}) \propto 1 + r_B^2 + 2r_B(2F_+^{KK\pi^0} - 1)\cos(\delta_B \mp \gamma) - \alpha y(1 + r_B^2)(2F_+^{KK\pi^0} - 1) - 2\alpha y r_B \cos(\delta_B \mp \gamma)$$

- Admixture of CP-odd and CP-even eigenstates
- Integration over 3-body *D* decay phasespace dilutes A_{CP}
- CP-even fractions, $F_+^{hh\pi 0}$, measured at CLEO-c

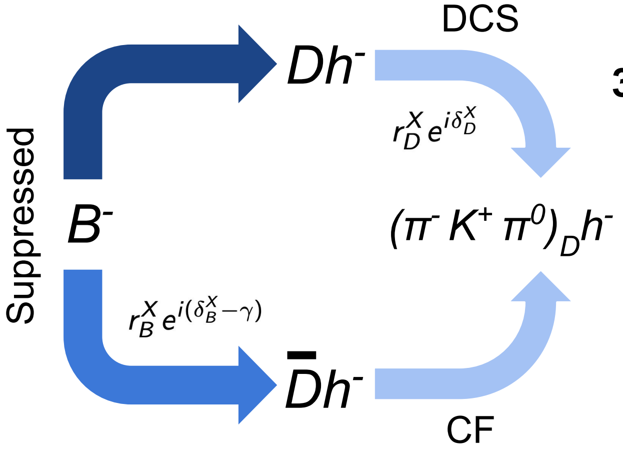
Constraints on γ from $B^{\pm} \to Dh^{\mp}$ with $D \to h^{\pm}h'^{\mp}\pi^0$

$9\,\mathrm{fb}^{-1}$

arXiv:2112.10617, submitted to JHEP

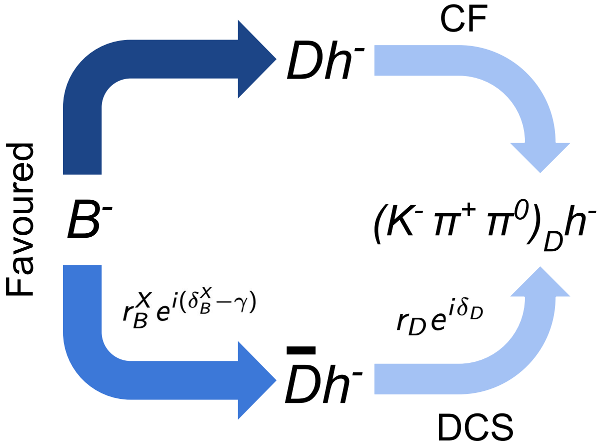
Quasi-ADS

3-body D decay



κ_D=0.79±0.04

Dilution relatively small



Balanced competing amplitudes maximises interference

Not as sensitive to CP effects - interference term not at leading order

$$\Gamma(B^{\mp} \to [\pi^{\mp}K^{\pm}\pi^0]_D h^{\mp}) \propto r_D^2 + r_B^2 + 2r_D r_B \kappa_D \cos(\delta_B + \delta_D \mp \gamma) - \alpha y(1 + r_B^2) r_D \kappa_D \cos\delta_D - \alpha y(1 + r_D^2) r_B \cos(\delta_B \mp \gamma) + \alpha x(1 - r_B^2) r_D \kappa_D \sin\delta_D - \alpha x(1 - r_D^2) r_B \sin(\delta_B \mp \gamma)$$

$$\Gamma(B^{\mp} \to [\pi^{\pm}K^{\mp}\pi^0]_D h^{\mp}) \propto 1 + r_D^2 r_B^2 + 2r_D r_B \kappa_D \cos(\delta_B - \delta_D \mp \gamma) - \alpha y(1 + r_B^2) r_D \kappa_D \cos\delta_D - \alpha y(1 + r_D^2) r_B \cos(\delta_B \mp \gamma) - \alpha x(1 - r_B^2) r_D \kappa_D \sin\delta_D + \alpha x(1 - r_D^2) r_B \sin(\delta_B \mp \gamma)$$

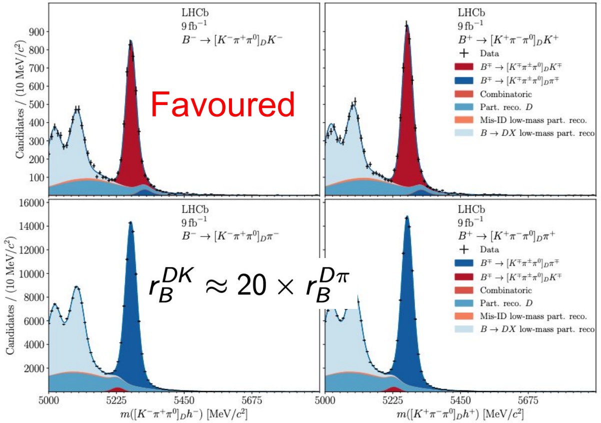
- Integration over 3-body D decay phasespace dilutes sensitivity
- Dilution factor, κ_D, and average strong phase, $\boldsymbol{\delta}_D$ taken from BESIII/ CLEO-c/ LHCb

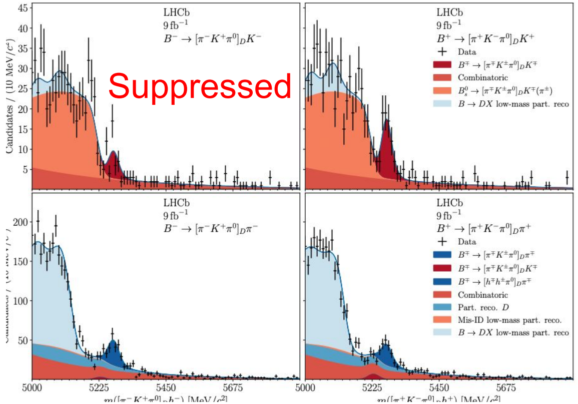
Constraints on γ from $B^{\pm} \rightarrow Dh^{\mp}$ with $D \rightarrow h^{\pm}h'^{\mp}\pi^0$

9fb^{-1}

arXiv:2112.10617, submitted to JHEP

Quasi-ADS





World's best precision on observables

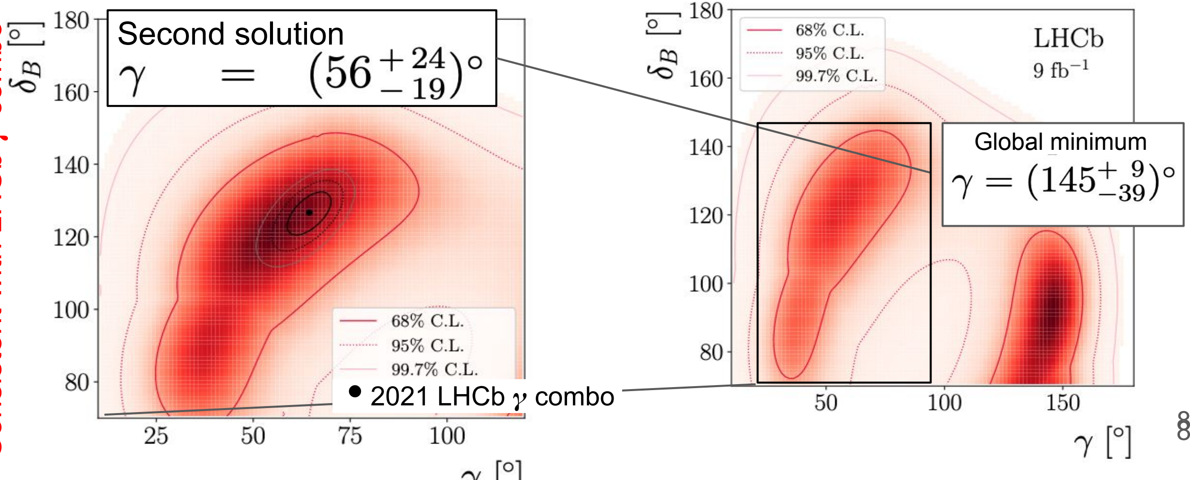
First observation of $B^{\mp} \rightarrow [\pi^{\mp}K^{\pm}\pi^0]_D K^{\mp}$ at >7σ!

Interpreted as γ, r_B, $\boldsymbol{\delta}_B$ using inputs from CLEO-c/BES III
Due to trigonometric ambiguities 4 solutions for γ

$$r_B = (9.3^{+1.0}_{-0.9})\text{x}10^{-2}$$

$$\delta_B = (122^{+19}_{-23})^{\circ}$$

Consistent with LHCb γ combo



Measurement of gamma in $B^{\pm}\to D[Kshh]h^{\pm}$ GGSZ

9fb^{-1}

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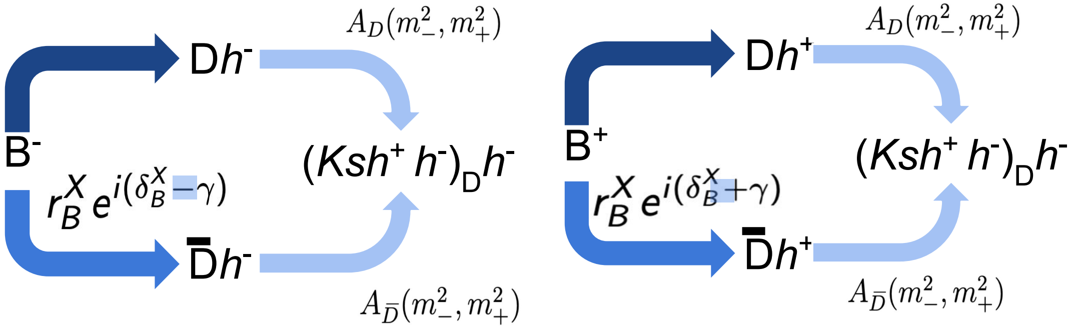


Analyse $B^{\pm}\to D[Kshh]h^{\pm}$ decays in bins of *D*-decay phasespace

To access gamma need knowledge of how strong phase of *D* decay varies over phasespace

$$A_D(m_-^2, m_+^2) = |A_D(m_-^2, m_+^2)|e^{i\delta_D(m_-^2, m_+^2)}$$

Can construct yield observables for each bin i

$$N_{+i}^- = h_{B^-}\left[F_{+i} + \left((x_-^{DK})^2 + (y_-^{DK})^2\right)F_{-i} + 2\sqrt{F_i F_{-i}}\left(x_-^{DK} c_{+i} + y_-^{DK} s_{+i}\right)\right]$$

Normalisation absorbs production and detection asymmetries

Efficiency corrected fraction of events that fall in bin i

Cosine/sine of strong phase difference between D^0 and $\bar{D}^0$ averaged over bin i

c_i and s_i inputs taken from combination of BESIII and CLEO results
PRD101 (2020) 112002, PRD102 (2020) 052008

F_i normally determined through semileptonic decays (no CPV) however to increase sensitivity B->Dπ channel is fit simultaneously with B->DK

Negligible contribution to gamma precision from B->Dπ as $r_B^{DK} \approx 20 \times r_B^{D\pi}$

Use of Dπ channel controls selection and reconstruction effects

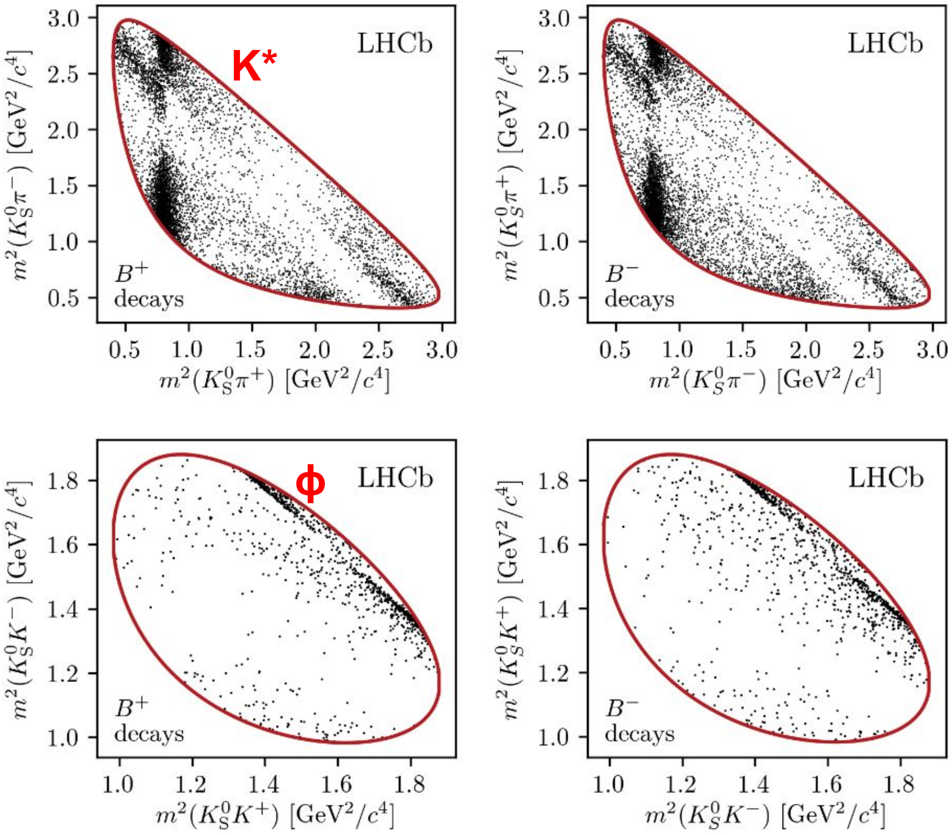
See also Martin's Belle (II) talk

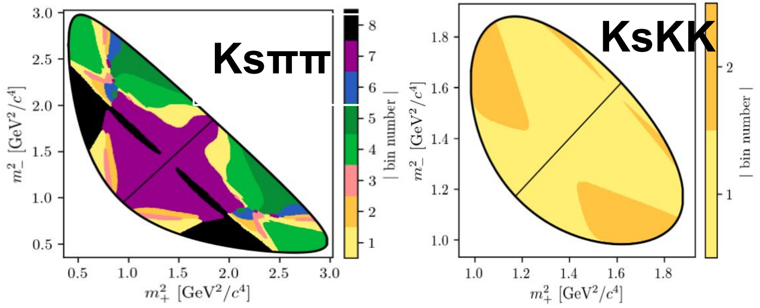
Measurement of gamma in $B^{\pm} \to D[Ks0hh]h^{\pm}$

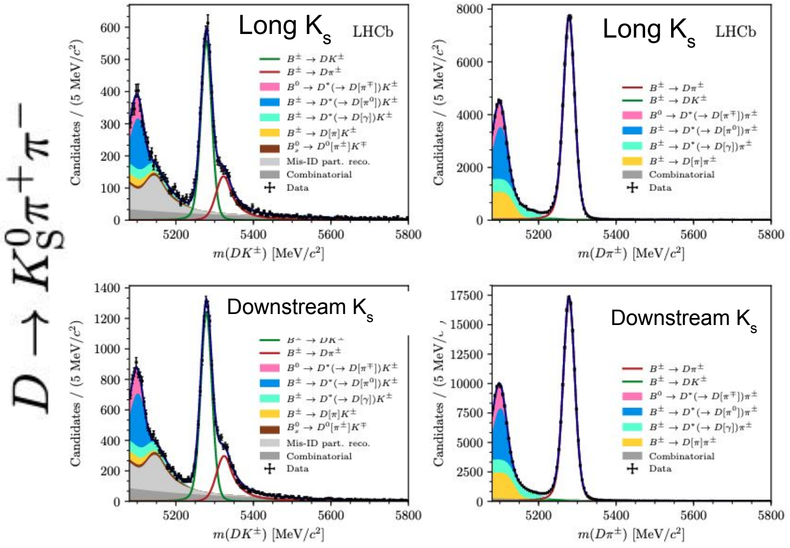
$9 fb^{-1}$

D decay has rich resonance structure - increases sensitivity

CPV -> differences in distributions of *D* decay from B^+ and B^-







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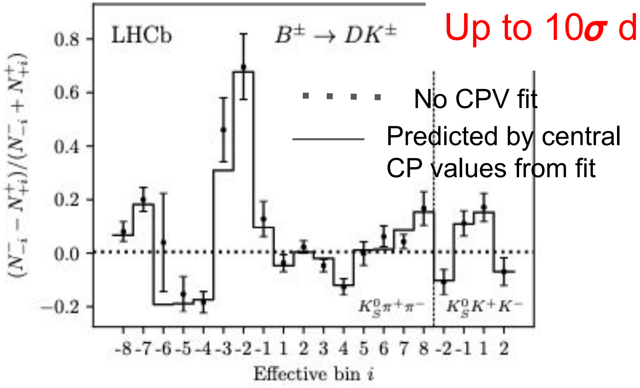
Measurement of gamma in $B^{\pm}\to D[Kshh]h^{\pm}$

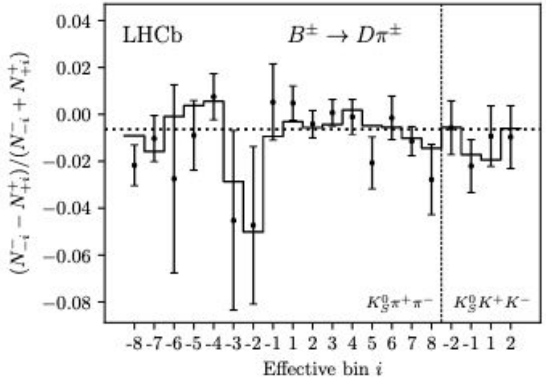
9fb-1

Binned asymmetries

Up to 10σ deviations



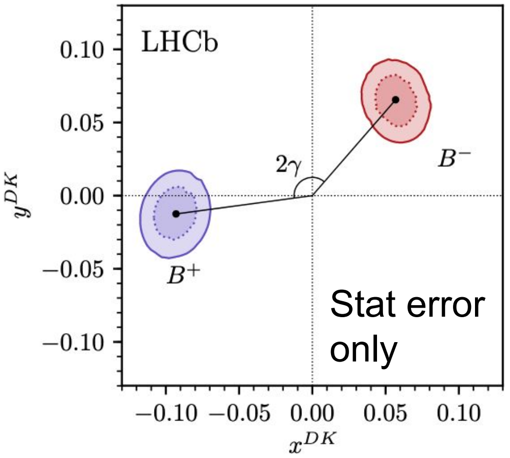
No significant asymmetries



$$
\begin{aligned}
\gamma &= (68.7^{+5.2}_{-5.1})^\circ, \\
r_B^{DK^\pm} &= 0.0904^{+0.0077}_{-0.0075}, \\
\delta_B^{DK^\pm} &= (118.3^{+5.5}_{-5.6})^\circ, \\
r_B^{D\pi^\pm} &= 0.0050 \pm 0.0017, \\
\delta_B^{D\pi^\pm} &= (291^{+24}_{-26})^\circ.
\end{aligned}
$$

Most precise measurement of gamma from a single analysis

Systematic due to precision of strong phase parameters is of similar size to total LHCb-related systematic ~ 1 degree



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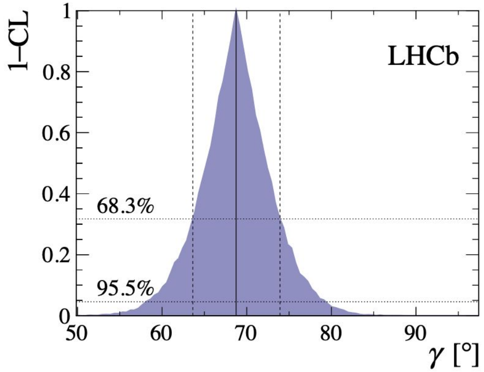
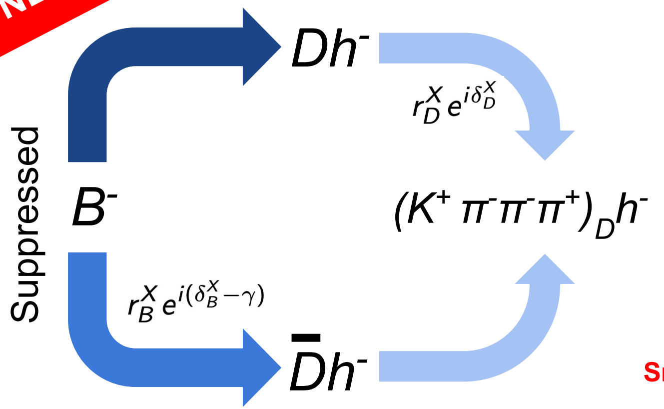


Measurement of γ using $B^{\pm}\to D[K\pi\pi\pi]h^{\pm}$ - binned

9fb^{-1}

NEW!



Interference term at first order

Quasi-ADS

$\mathcal{B}(D\to K^{\pm}\pi^{\mp})\approx 3.9\%$

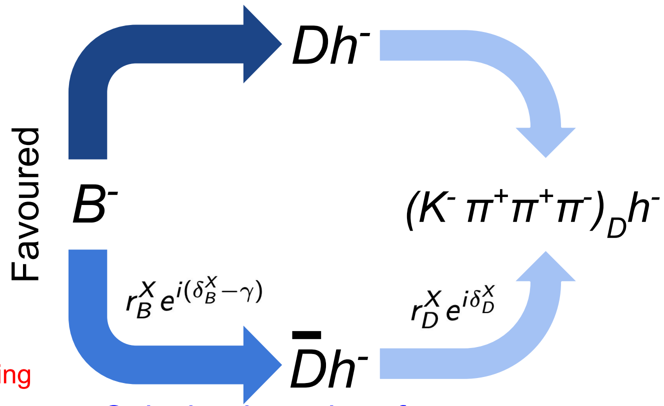
$\mathcal{B}(D\to K^{\pm}\pi^{\mp}\pi^0)\approx 14.4\%$

$\mathcal{B}(D\to K^{\pm}\pi^{\mp}\pi^{\mp}\pi^{\pm})\approx 8.2\%$

High branching fraction and charged final state

κ_D~0.4

Small coherence factor - many contributing resonances - reduces sensitivity to γ



Sub-dominant interference term

Determine CP asymmetry of suppressed modes using favoured mode as a normalisation channel

Small coherence factor - bin phasespace into 4 regions such that local coherence factor, κ_D, in each bin is higher than phase-space integrated value. Binning scheme uses LHCb model but $\boldsymbol{\kappa_D}$ and average strong phase taken from CLEO-c/BESIII - Analysis remains model-independent

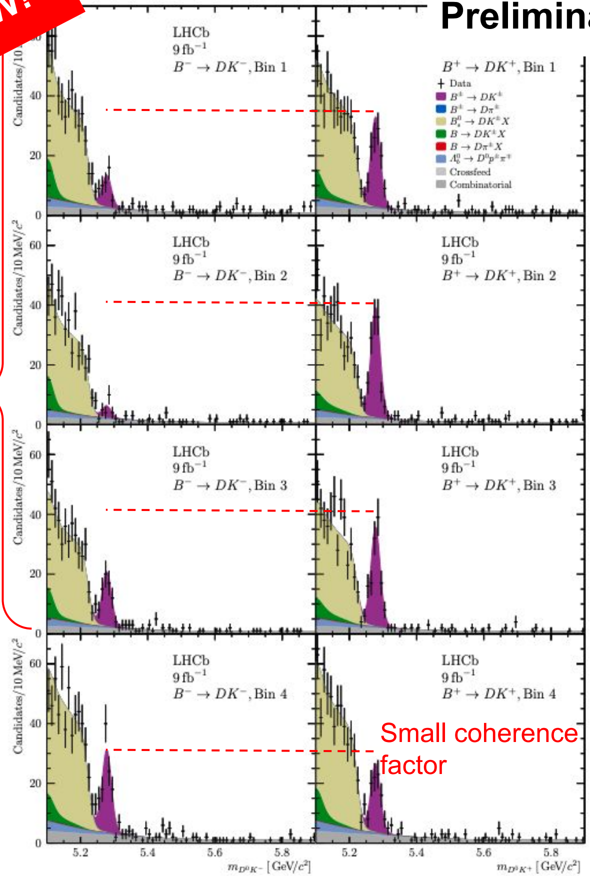
Simultaneously measure flavor tagged D^0 decays from inclusive SL modes to provide additional constraints to D parameters

Measurement of γ using $B^{\pm}\rightarrow D[K\pi\pi\pi]h^{\pm}$ - binned

9fb^{-1}

NEW!

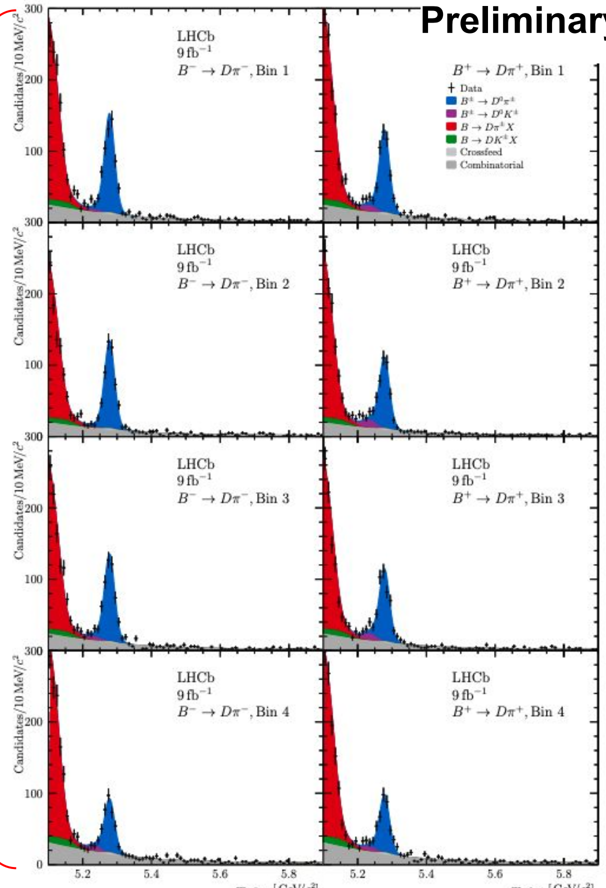
Large CP asymmetry



More abundant but lower interference effects as r_B^{π}~0.005 compared with r_B^K~0.1

CPV at 10**σ** - largest CP asymmetry observed so far

Opposite sign asymmetries - “strong phase” difference of π



Measurement of γ using $B^{\pm}\rightarrow D[K\pi\pi\pi]h^{\pm}$ - binned

9fb^{-1}

NEW!

A_{CP} results of phase space integrated analysis consistent with Run 1 result

A_K = -0.321 ± 0.039 ± 0.005
A_π = 0.070 ± 0.019 ± 0.006

This analysis

A_K= -0.313 ± 0.102 ± 0.038
A_π = 0.023 ± 0.048 ± 0.005

Run 1 result

Uncertainties factor ~2.5 smaller

Using binned phasespace results with hadronic parameters of the *D* decay constrained from BESIII, CLEO-c and LHCb charm mixing results

$$\delta_B^K = \left(134.6^{+\ 6.0+0.7+\ 8.6}_{-\ 6.0-0.7+\ 8.7}\right)^\circ$$
$$\delta_B^\pi = \left(311.8^{+14.7+3.0+14.7}_{-15.0-2.3+15.0}\right)^\circ$$
$$r_B^K = \left(94.6^{+3.1+0.5+3.0}_{-3.1-0.5+2.3}\right) \times 10^{-3}$$
$$r_B^\pi = \left(\ 4.5^{+1.1+0.3+0.4}_{-1.0-0.3+0.3}\right) \times 10^{-3},$$

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

Key input to next gamma combination!

Second most precise determination of gamma using any single *D* decay mode - systematic uncertainty order of magnitude smaller than statistical

First analysis of this kind!

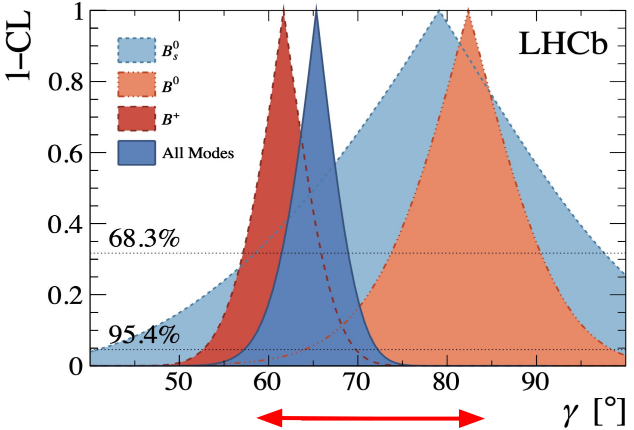
Beauty and Charm LHCb gamma combination

Measurements of gamma in *B* decays include charm mixing parameters and strong phases of subsequent *D* decays

151 observables to determine 52 parameters using GammaCombo package

Decay	Parameters	Source
$B^\pm \to DK^{*\pm}$	$\kappa_{B^\pm}^{DK^{*\pm}}$	LHCb
$B^0 \to DK^{*0}$	$\kappa_{B^0}^{DK^{*0}}$	LHCb
$B^0 \to D^\mp\pi^\pm$	β	HFLAV
$B_s^0 \to D_s^\mp K^\pm(\pi\pi)$	ϕ_s	HFLAV
$D \to h^+h^-\pi^0$	$F_{\pi\pi\pi^0}^+$, $F_{K\pi\pi^0}^+$	CLEO-c
$D \to \pi^+\pi^-\pi^+\pi^-$	$F_{4\pi}^+$	CLEO-c
$D \to K^+\pi^-\pi^0$	$r_D^{K\pi\pi^0}$, $\delta_D^{K\pi\pi^0}$, $\kappa_D^{K\pi\pi^0}$	CLEO-c+LHCb+BESIII
$D \to K^\pm\pi^\mp\pi^+\pi^-$	$r_D^{K3\pi}$, $\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$	CLEO-c+LHCb+BESIII
$D \to K_S^0K^\pm\pi^\mp$	$r_D^{K_S^0K\pi}$, $\delta_D^{K_S^0K\pi}$, $\kappa_D^{K_S^0K\pi}$	CLEO
$D \to K_S^0K^\pm\pi^\mp$	$r_D^{K_S^0K\pi}$	LHCb

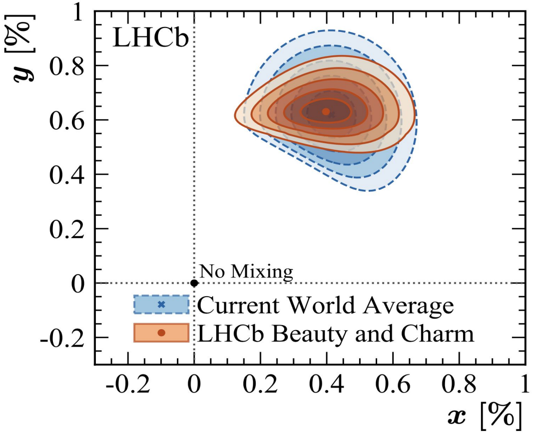
Rely on inputs from independent measurements



2σ tension between B^+ and B^0

Wait for full Run 1+2 B^0 results

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



Factor 2 more precise in y!

$$x = (0.400^{+0.052}_{-0.053})\%$$
$$y = (0.630^{+0.033}_{-0.030})\%$$

Dedicated CERN seminar

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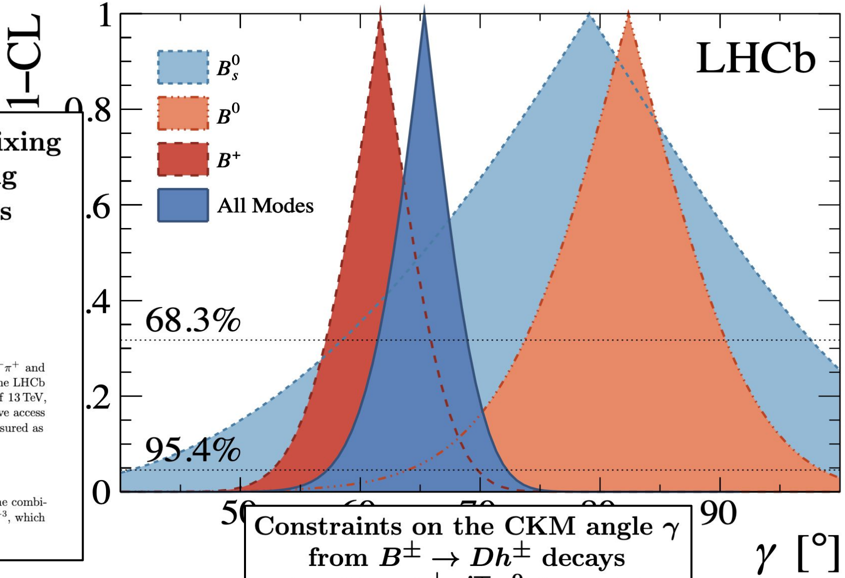
New inputs to γ combination



Measurement of the charm mixing parameter $y_{CP} - y_{CP}^{K\pi}$ using two-body D^0 meson decays

LHCb collaboration†

Abstract

A measurement of the ratios of the effective decay widths of $D^0 \to \pi^-\pi^+$ and $D^0 \to K^-K^+$ decays over that of $D^0 \to K^-\pi^+$ decays is performed with the LHCb experiment using proton–proton collisions at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 6 fb^{-1}. These observables give access to the charm mixing parameters $y_{CP}^{\pi\pi} - y_{CP}^{K\pi}$ and $y_{CP}^{KK} - y_{CP}^{K\pi}$, and are measured as

$$y_{CP}^{\pi\pi} - y_{CP}^{K\pi} = (6.57 \pm 0.53 \pm 0.16) \times 10^{-3},$$
$$y_{CP}^{KK} - y_{CP}^{K\pi} = (7.08 \pm 0.30 \pm 0.14) \times 10^{-3},$$

where the first uncertainties are statistical and the second systematic. The combination of the two measurements is $y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}$, which is four times more precise than the previous world average.

Dedicated [CERN seminar]

Measurement of the CKM angle γ with $B^\pm \to D[K^\mp\pi^\pm\pi^\pm\pi^\mp]h^\pm$ decays using a binned phase-space approach

LHCb collaboration†

Abstract

The CKM angle γ is determined from *CP*-violating observables measured in $B^\pm \to D[K^\mp\pi^\pm\pi^\pm\pi^\mp]h^\pm$, $(h = K, \pi)$ decays, where the measurements are performed in bins of the decay phase space of the D meson. Using the full Run 1 and Run 2 LHCb data sets, γ is determined to be

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

where the first uncertainty is statistical, the second systematic and the third from the external inputs on the coherence factors and strong phases of the D-meson decay.

Constraints on the CKM angle γ from $B^\pm \to Dh^\pm$ decays using $D \to h^\pm h'^\mp\pi^0$ final states

LHCb collaboration†

This paper is dedicated to our friend and colleague Bernhard Spaan.

Abstract

A data sample collected with the LHCb detector, corresponding to an integrated luminosity of 9 fb^{-1}, is used to measure *CP* observables in $B^\pm \to Dh^\pm$ decays, where $h^{(\prime)}$ is either a kaon or a pion, and the neutral D meson decay is reconstructed in the three-body final states $K^\pm\pi^\mp\pi^0$, $\pi^\pm\pi^\mp\pi^0$, and $K^\pm K^\mp\pi^0$. The most suppressed of these modes, $B^\pm \to [\pi^\pm K^\mp\pi^0]_D K^\pm$, is observed with a significance greater than seven standard deviations and constraints on the CKM angle γ are calculated from the combination of the measurements.

CP violation in $B^+ \to K^+ \pi^0$

$5.4 fb^{-1}$

Family of $B \to K\pi$ decays proceed via several processes - CPV arises from interference - great probe for new physics contributions

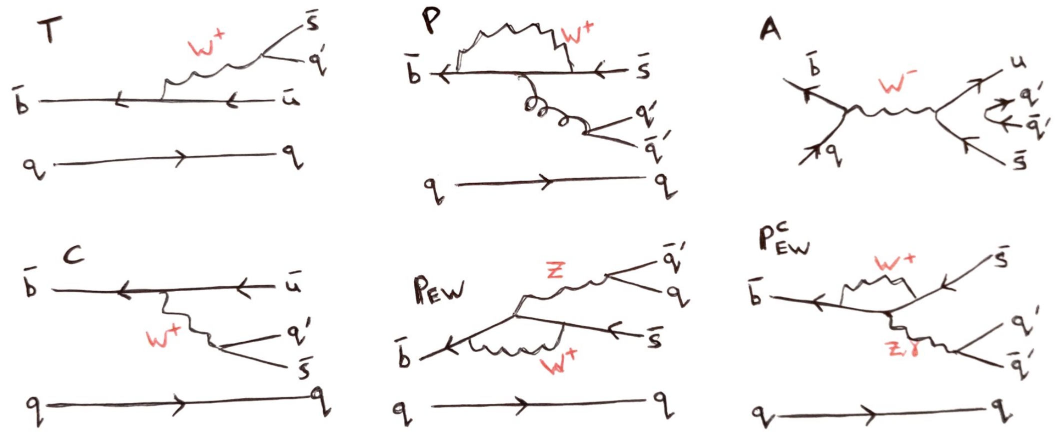
Mode	Quark-level amplitude
$B^0 \to K^+\pi^-$	$\mathrm{T} + \mathrm{P} + \mathrm{P}^{\mathrm{C}}_{\mathrm{EW}}$
$B^+ \to K^+\pi^0$	$\mathrm{T} + \mathrm{P} + \mathrm{C} + \mathrm{P}_{\mathrm{EW}} + \mathrm{P}^{\mathrm{C}}_{\mathrm{EW}} + \mathrm{A}$
$B^+ \to K^0\pi^+$	$\mathrm{P} + \mathrm{P}^{\mathrm{C}}_{\mathrm{EW}} + \mathrm{A}$
$B^0 \to K^0\pi^0$	$\mathrm{P} + \mathrm{C} + \mathrm{P}_{\mathrm{EW}} + \mathrm{P}^{\mathrm{C}}_{\mathrm{EW}}$

arxiv:1101.0675

Tree and penguin contributions dominate, expect sizable A_{CP} with ~ same magnitude and sign

Almost pure penguin - no sizable A_{CP} expected in SM

PRL126 (2021) 091802



CP violation in $B^+ \rightarrow K^+ \pi^0$

5.4fb^{-1}

PRL126 (2021) 091802

Within SM amplitudes should obey relations of Isospin symmetry - can predict branching fractions, A_{CP} and lifetime relations amongst the four $B \rightarrow K\pi$ channels

Full SM Isospin sum rule [PLB627 (2005) 82-88]

$$\left[A_{CP}^{K^0\pi^+}\frac{\mathcal{B}^{K^0\pi^+}}{\mathcal{B}^{K^+\pi^-}} - A_{CP}^{K^+\pi^0}\frac{2\mathcal{B}^{K^+\pi^0}}{\mathcal{B}^{K^+\pi^-}}\right]\frac{\tau_{B^0}}{\tau_{B^\pm}} + \left[A_{CP}^{K^+\pi^-} - A_{CP}^{K^0\pi^0}\frac{2\mathcal{B}^{K^0\pi^0}}{\mathcal{B}^{K^+\pi^-}}\right] = 0$$

$$A_{CP} = \frac{\Gamma(B^- \to K^-\pi^0) - \Gamma(B^+ \to K^+\pi^0)}{\Gamma(B^- \to K^-\pi^0) + \Gamma(B^+ \to K^+\pi^0)}$$

K*π* puzzle: (long standing *b* anomaly)

Expect

$$A_{CP}^{K^+\pi^-} \sim A_{CP}^{K^+\pi^0}$$

$$A_{CP}(K_S^0\pi^0) = -0.150 \pm 0.032$$

(non-zero)

Observe

5.5σ deviation from equity (BaBar/Belle/LHCb)

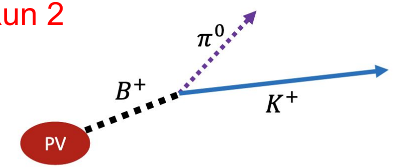
$$A_{CP}(K_S^0\pi^0) = 0.01 \pm 0.10$$

CP violation in $B^+ \to K^+ \pi^0$

$5.4 fb^{-1}$

$B^+ \to h^+ \pi^0$ poses unique challenges for p-p collision environment
- One track + one ECAL cluster → First analysis of one track *b* hadron decay at hadron collider
- No reconstructible displaced vertex - key signature of *b* hadron decays

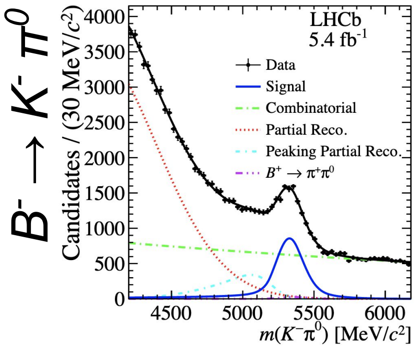
Introduced dedicated trigger for Run 2

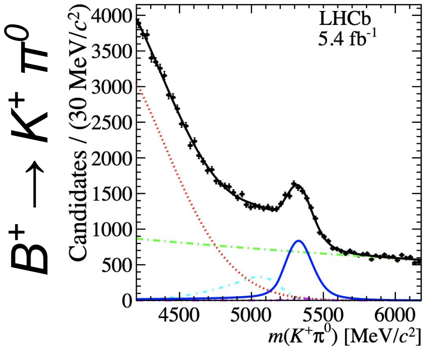


PRL126 (2021) 091802

$$A_{CP}(B^+ \to K^+\pi^0) = A_{\rm raw}(B^+ \to K^+\pi^0) - \boxed{A^B_{\rm prod.} - A^K_{\rm det.}}$$

Combined effect of nuisance asymmetries measured with high statistics B->J/ψK control channel





$$A_{CP}(B^+ \to K^+\pi^0) = 0.025 \pm 0.015 \pm 0.006 \pm 0.003$$

Result is consistent with world average but more precise

$A_{CP}^{K^+\pi^-} \sim A_{CP}^{K^+\pi^0}$ does not hold at > 8σ

Using result in sum rule $A_{CP}(B^0 \to K^0\pi^0) = -0.138 \pm 0.025$ - inconsistent with zero at 5.5σ

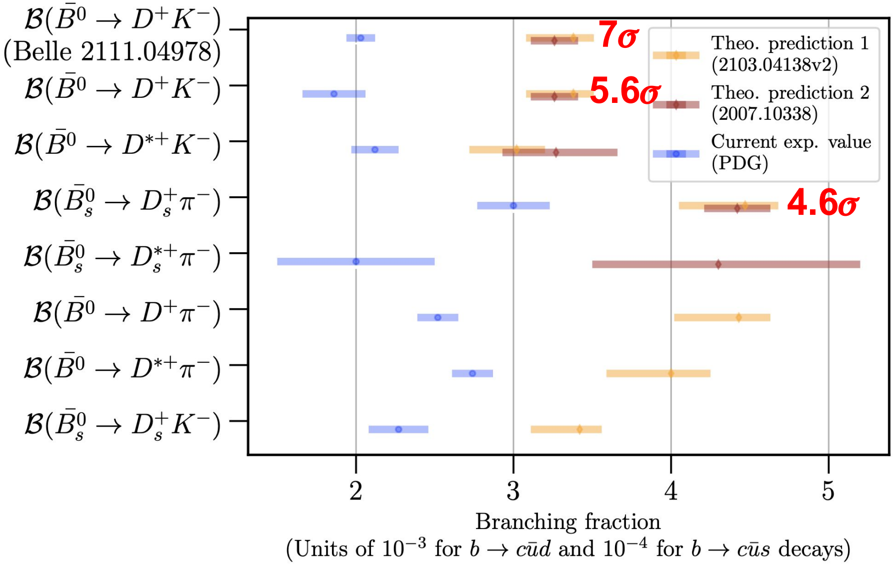
With Run 3 data projected statistical uncertainty 0.005

Proof of concept for $B^0 \to K^0\pi^0$ - run 3 trigger in place!

Confirms and strengthens Kπ puzzle!

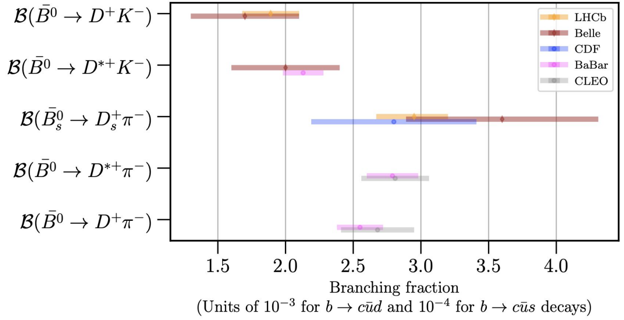
$b \to c\, \bar{u}\, q$ anomaly

Rates of colour allowed non-leptonic decays are not in agreement with SM expectations based on QCDf - tensions pull in the same direction



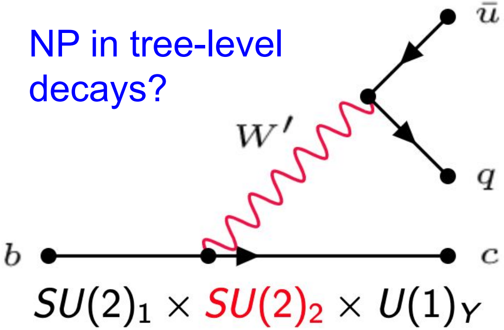
Potential causes?

Experimental inaccuracies?



Unaccounted for QCD effects?

NP in tree-level decays?



Non-leptonic tree-level decays have been considered insensitive to NP - how does this affect our interpretations of gamma? JHEP07(2020)177

$b \to c\, \bar{u}\, q$ anomaly - $A^s_{\rm fs}$

Arxiv: 2111.04478, accepted by PRD

In SM $\bar{B}_s \to D_s^+ \pi^-$ is flavour specific and CP-conserving

$$C1 : \mathcal{A}_{\bar{f}} = 0 = \bar{\mathcal{A}}_f \qquad C2 : \bar{\mathcal{A}}_{\bar{f}} = \mathcal{A}_f$$

Standard Model

$$A^s_{\rm fs} = \frac{\Gamma\left(\bar{B}_s(t) \to f\right) - \Gamma\left(B_s(t) \to \bar{f}\right)}{\Gamma\left(\bar{B}_s(t) \to f\right) + \Gamma\left(B_s(t) \to \bar{f}\right)}$$

$$= a^s_{\rm fs} \quad --> \quad \text{CPV in mixing}$$

$$= a^s_{\rm sl} = (-60 \pm 280) \cdot 10^{-5}$$

Dominated by SL decays

General BSM model

Challenge C2 with general BSM contribution

$$\begin{aligned} \mathcal{A}_f &= \left|\mathcal{A}_f^{\rm SM}\right| e^{i\phi^{\rm SM}} e^{i\varphi^{\rm SM}} + \left|\mathcal{A}_f^{\rm BSM}\right| e^{i\phi^{\rm BSM}} e^{i\varphi^{\rm BSM}} \\ &=: \left|\mathcal{A}_f^{\rm SM}\right| e^{i\phi^{\rm SM}} e^{i\varphi^{\rm SM}} \left(1 + r e^{i\phi} e^{i\varphi}\right) , \end{aligned}$$

$$\phi = \phi^{\rm BSM} - \phi^{\rm SM} \qquad \varphi = \varphi^{\rm BSM} - \varphi^{\rm SM} \qquad r = |\mathcal{A}_f^{\rm BSM}| / |\mathcal{A}_f^{\rm SM}|$$

$$\begin{aligned} A^s_{\rm fs} &\approx a^s_{\rm fs} - 2r \sin\phi \sin\varphi \\ &= a^s_{\rm fs} - A^s_{\rm dir} \end{aligned}$$

New physics effects may modify value of A^s_{fs} in $\bar{B}_s \to D_s^+ \pi^-$ to 10^{-2} or above

Neither $A^s_{\rm fs}(D_s^+\pi^-)$ or its friend $A^s_{\rm fs}(D^+K^-)$ has been explicitly measured.

$b \to c\,\bar{u}\,q$ anomaly - $A^s_{\rm fs}$

Arxiv: 2111.04478, accepted by PRD

Experimentally favourable to measure untagged, time-integrated asymmetry

→ Significant gain in statistics as no longer need flavour tagging (tagging efficiency ~6% at LHCb)

$$\langle A^q_{\rm untagged}\rangle \approx A^q_{\rm dir} - \frac{a^q_{\rm fs}}{2}(1-\rho_q)$$

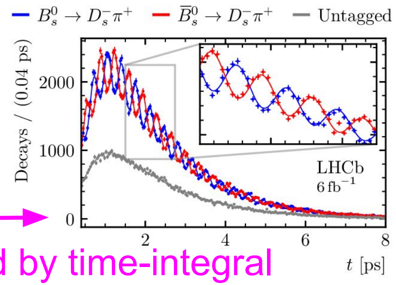
Lose no sensitivity to $A_{\rm dir}$

$(\rho_d \approx 0.63$ and $\rho_s \approx 0.001)$

$$A_{\rm raw} = \frac{N(D_s^+\pi^-) - N(D_s^-\pi^+)}{N(D_s^+\pi^-) + N(D_s^-\pi^+)}$$

Symmetric KKππ or ππππ final state

$$\begin{aligned}\langle A^s_{\rm untagged}\rangle &= A_{\rm raw} - A_{\rm det} \\ &- A_{\rm prod}\frac{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cos(\Delta M_s t)\epsilon(t)dt}{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cosh(\frac{\Delta\Gamma_s t}{2})\epsilon(t)dt} \\ &- \sum_i f^i_{\rm bkg}\cdot A^i_{\rm bkg}\end{aligned}$$



Nature Physics 18, (2022) 1-5

Small $A_{\rm prod}$ is diluted by time-integral

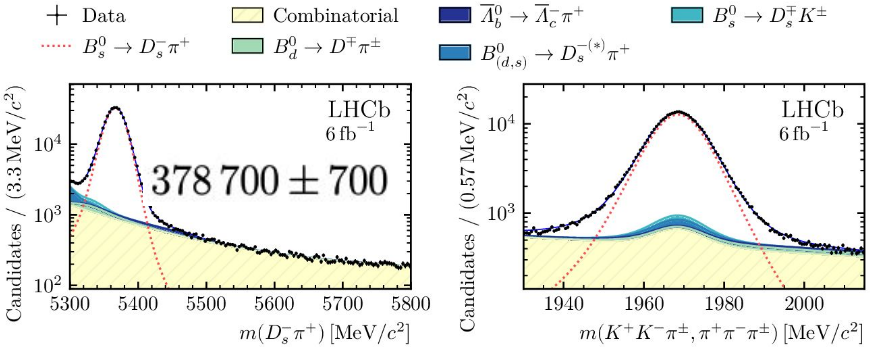
Backgrounds well understood through control samples - not a limiting systematic

$b \to c\, \bar{u}\, q$ anomaly - A^s_{fs}

LHCb has best prospects for such a measurement

Run 2 sensitivity of $2\text{x}10^{-3}$
Run 3 sensitivity of $6\text{x}10^{-4}$

- 15fb^{-1}
- New software trigger enhancing efficiency of hadronic modes in particular



Nature Physics 18, (2022) 1-5

Existing limits on A^s_{fs} from SL decays are consistent with tiny SM value - if $\langle A^s_{\mathrm{untagged}} \rangle$ non-zero at 10^{-2} level would be clear evidence of NP causing direct CPV independent of any theoretical uncertainties

With much improved precision can consider

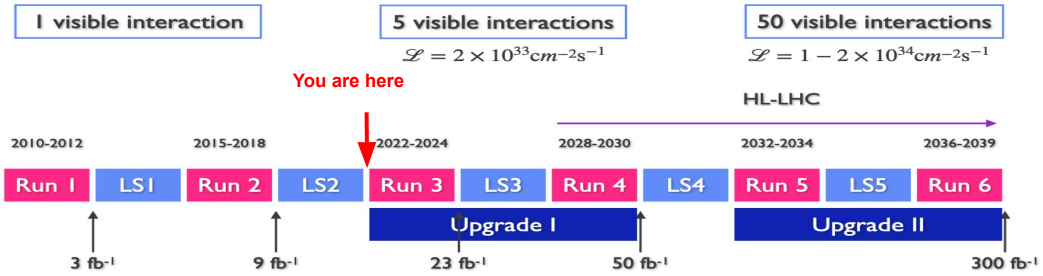
$$A^s_{fs}(D^+_s \pi^-) - A^s_{fs}(D^+_s \ell^- \bar{\nu}_\ell) = A^s_{dir}(D^+_s \pi^-)$$

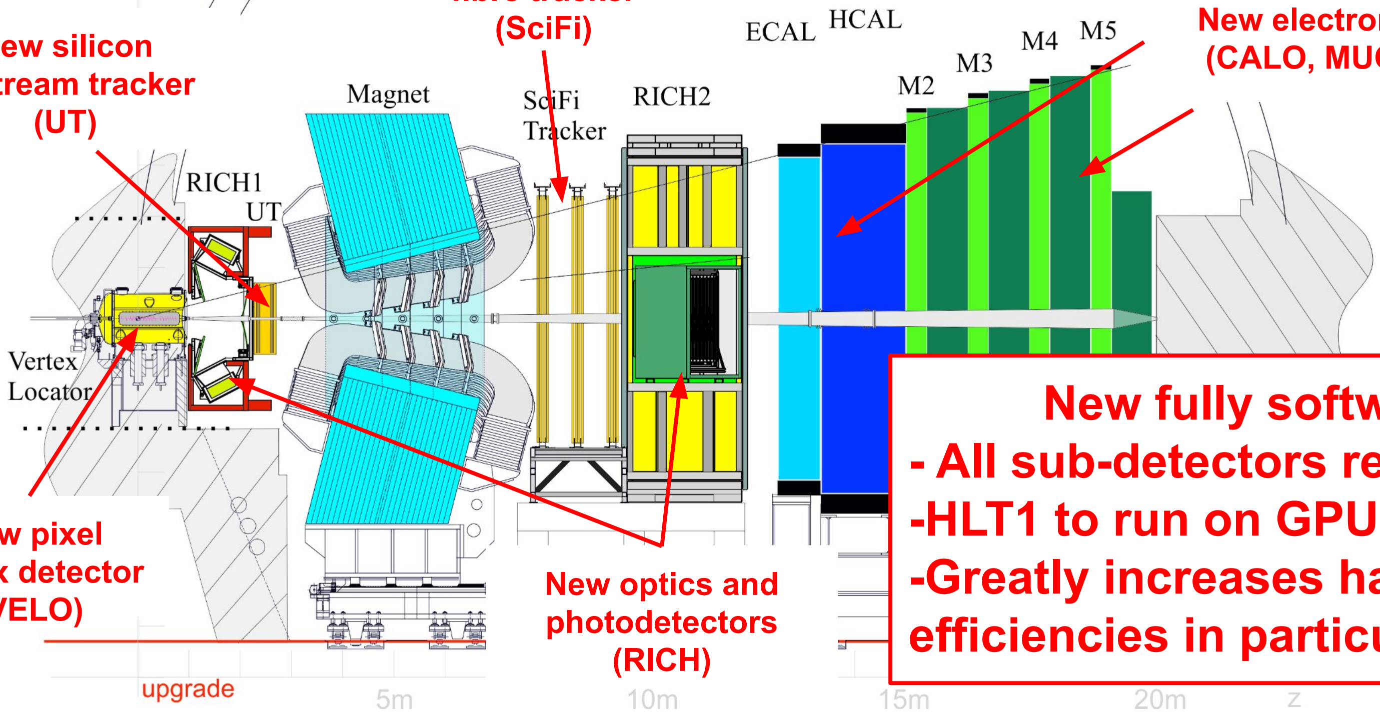
Any significant non-zero value would be unambiguous signal of NP independent of any theoretical assumptions

Arxiv: 2111.04478, accepted by PRD

LHCb Upgrade I

Inst. Lumi. increasing by factor 5



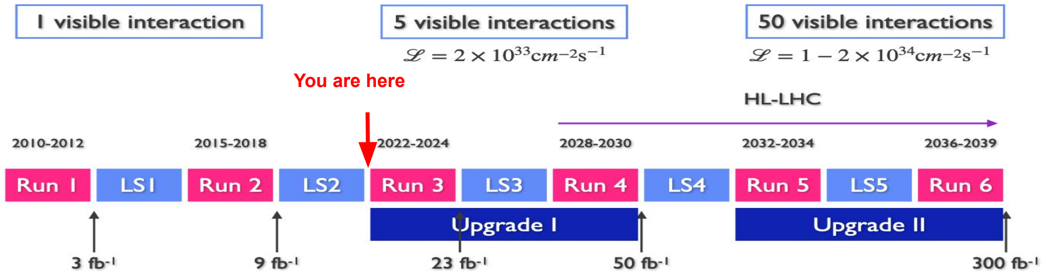


LHCB-TDR-12
LHCB-TDR-13
LHCB-TDR-14
LHCB-TDR-15
LHCB-TDR-16
LHCB-TDR-17
LHCB-TDR-18

New fully software trigger
- All sub-detectors read out at 40MHz
- HLT1 to run on GPUs
- Greatly increases hadronic decay efficiencies in particular

LHCb Upgrade II

Inst. Lumi. increasing by factor 10

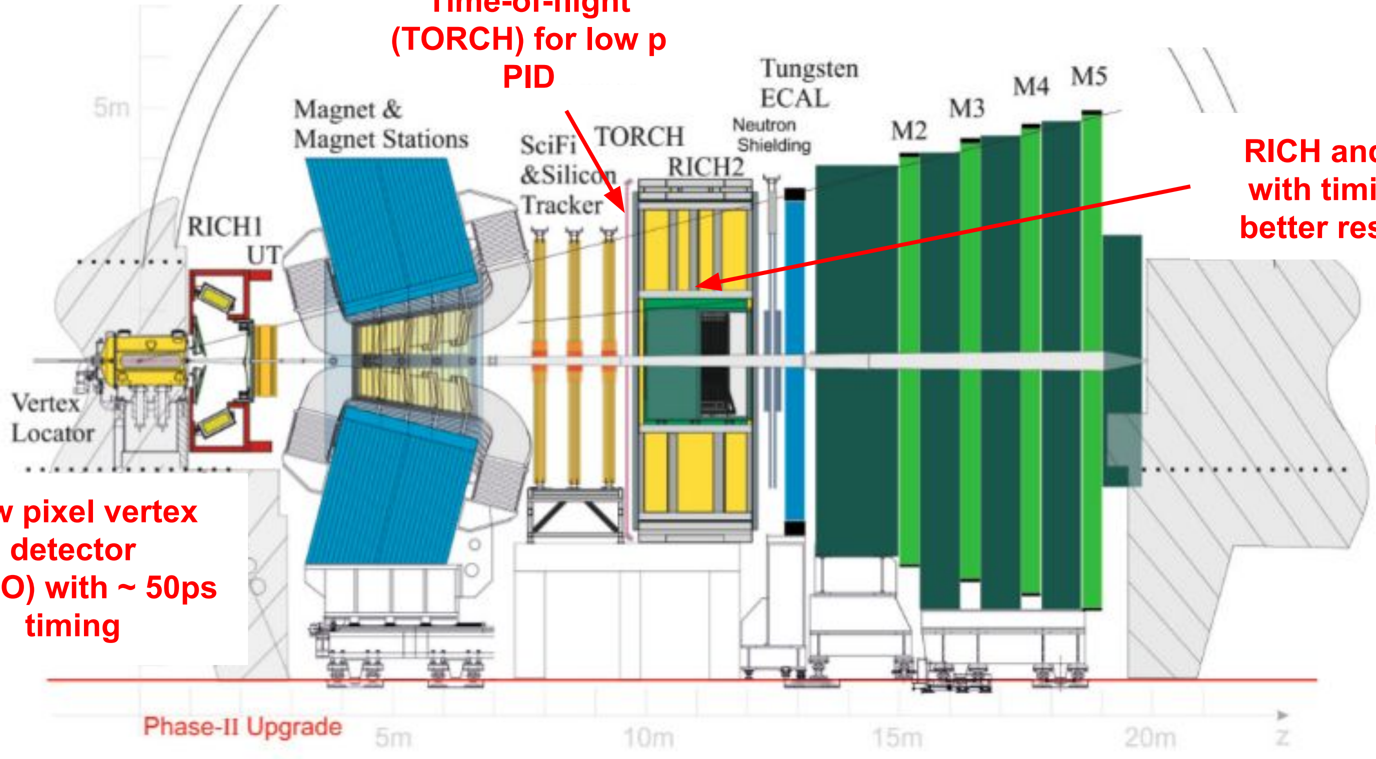


Time-of-flight (TORCH) for low p PID

RICH and CALO with timing and better resolution

New technologies for high occupancy regions

New pixel vertex detector (VELO) with ~ 50ps timing



[Upgrade II Physics case]

Prospects for γ measurements

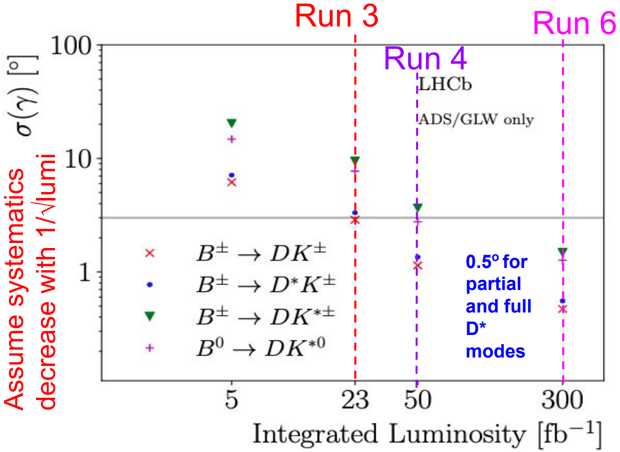
All **ADS/GLW** observables are statistically limited. Will the systematic uncertainty scale with statistics?

- Increased calibration samples for production and reconstruction asymmetries
- Larger MC samples for efficiencies - fast simulation methods
- Background uncertainties that will improve with higher statistics studies

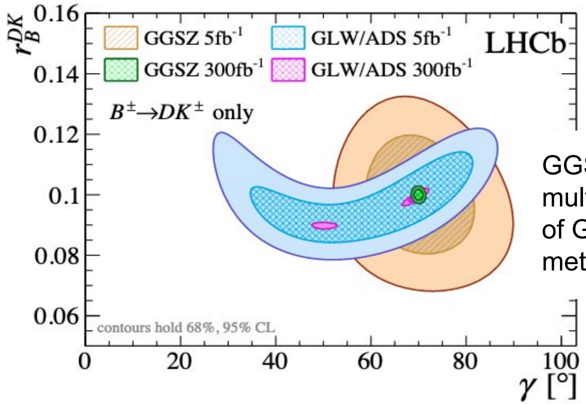
GGSZ golden-mode model-independent analysis gives the most precise single measurement of gamma to date - also statistically limited

- Largest systematic due to external inputs from CLEO-c/BESIII($3fb^{-1}$) currently 1 degree
- With $20fb^{-1}$ planned from BESIII will reduce to 0.5 degrees [arxiv:1912.05983]

Can extend methods to $B^0 \to D[\to K_s\pi^+\pi^-]K^+\pi^-$ "Double Dalitz" model-independent measurements, $r_B \sim 0.25$ - high sensitivity!



[Upgrade II Physics case]



GGSZ resolves multiple solutions of GLW/ADS methods

Prospects for γ measurements

Sensitivity to π^0 modes will increase

D->K$\pi\pi^0$, D->KKπ^0 , D-> $\pi\pi\pi^0$

Branching fractions 3-10x larger than 2-body decays

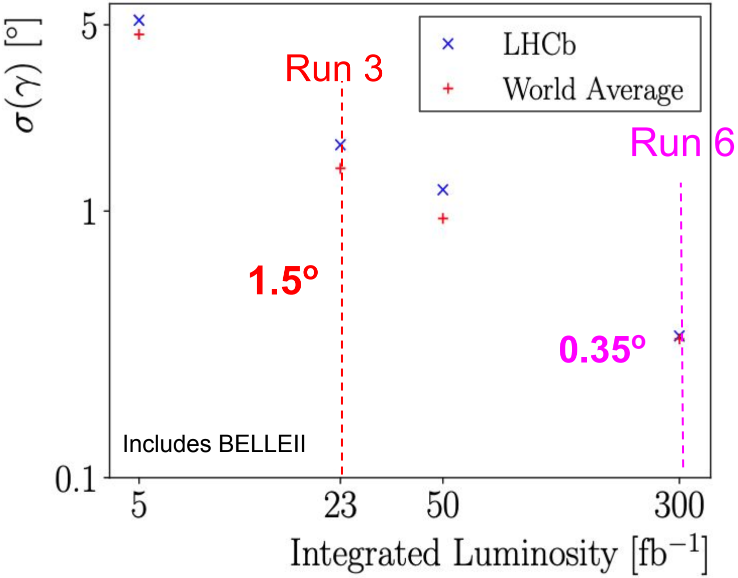
Reconstruction and selection efficiency of π^0 3% currently

In Upgrade II can fully exploit ADS/GLW and GGSZ modes with additional π^0 due to CALO granularity and energy resolution improvements

B->D[Ks$\pi\pi\pi^0$]K will have sensitivities approaching that of golden B->D[Ks$\pi\pi$]K channel

CALO improvements also will drive B->Kπ^0 and B->$K^0\pi^0$ measurement sensitivity

LHCb combination vs. world average

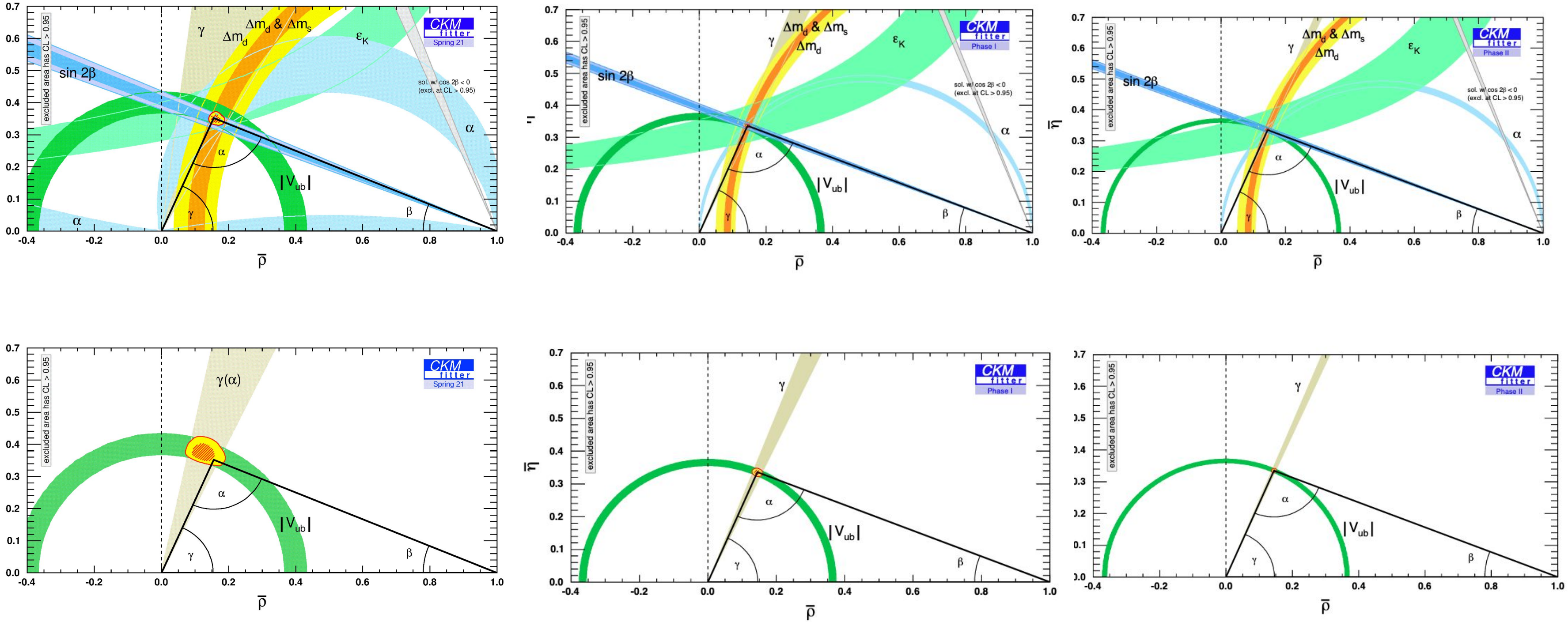


Upgrade II Physics case

Prospects for γ measurements

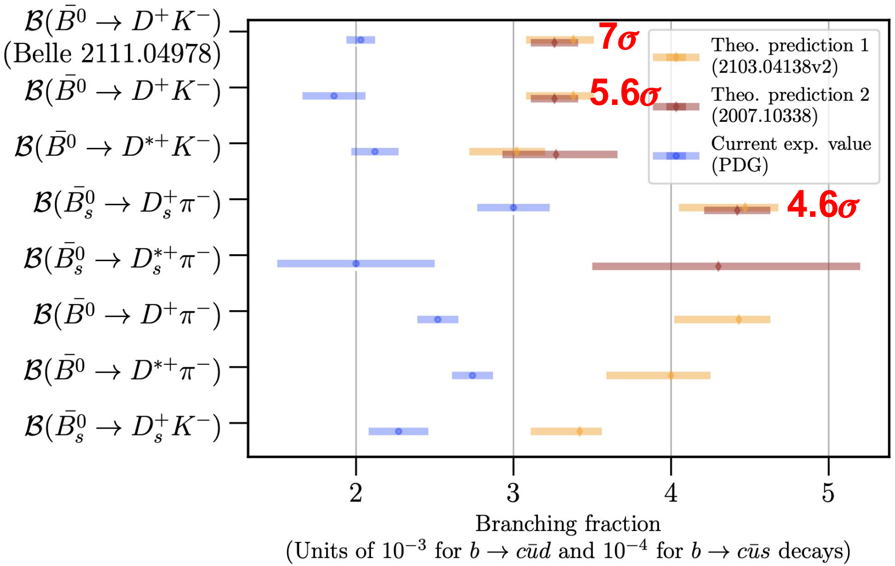
Now | **End of Run 3** | **End of HL-LHC**

Global / **Tree only**



ckmfitter.in2p3.fr, arxiv:1812.07638

Prospects for $b \to c\,\bar{u}\,q$ anomaly



With 300fb^{-1} LHCb will be able to bring statistical and systematic uncertainties down by almost an order of magnitude.

Normalisation channel is limiting systematic- need improvements on $B^0 \to D\pi$ and Bs mode or fs/fd

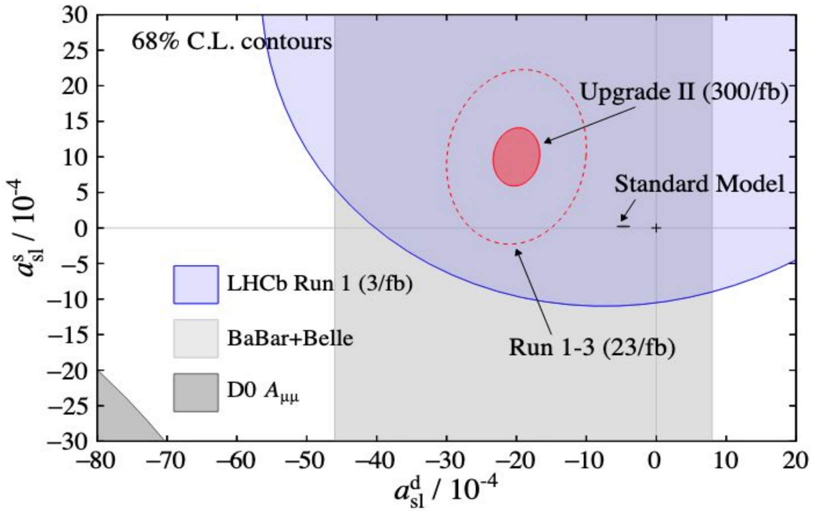
With 300fb^{-1} expect uncertainties on A^s_{sl} and A^s_{fs} at 10^{-4} *

Can study

** All predictions here are my own ;)*

$$A^s_{fs}(D^+_s\pi^-) - A^s_{fs}(D^+_s\ell^-\bar{\nu}_\ell) = A^s_{dir}(D^+_s\pi^-)$$

Any significant non-zero value would be unambiguous signal of NP independent of any theoretical assumptions

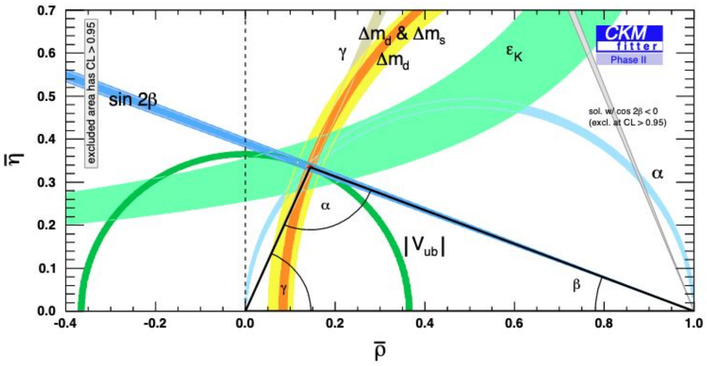


Summary

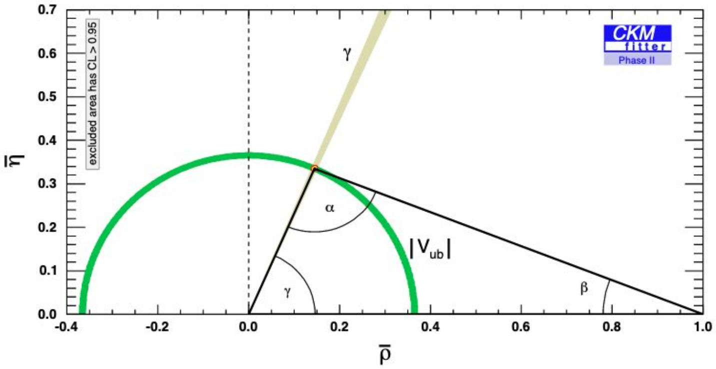
- LHCb continues to perform a uniquely wide range of CP violation studies in non-leptonic *B* meson decays with Run 1 and Run 2 data
- With upgrades I and II LHCb will be sensitive to new modes
- Extremely exciting prospects for anomalies such as K-π puzzle and b→c ū q anomaly

End of HL-LHC

Global



Tree

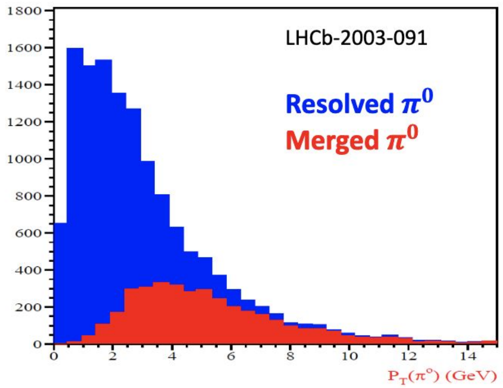


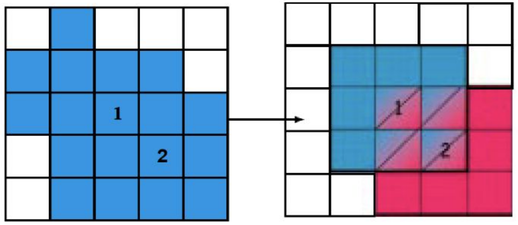
Backup - pi0 reconstruction

π^0 Reconstruction

- Neutral pions identified by decay to two photons
- Below $p_T = 3$ GeV photons can be resolved in two separate clusters, at higher energies clusters merge
- Cluster separated into two subclusters centered on highest energy deposits according to expected transverse profile
- Photon separation and invariant mass required to be consistent with π^0
- Merged π^0:
  - \+ Higher p_T
  - \+ Reduced combinatorial
  - − Wider mass resolution
- For $B^+ \to K^+\pi^0$, keep only **merged π^0** to preserve trigger bandwidth

π^0 from $B^0 \to \pi^+\pi^-\pi^0$





19

Taken from Will Parker

Backup - Beauty and Charm LHCb gamma combination

B decay	D decay	Dataset	Status since Ref. [17]
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-$	Run 1&2	**Updated**
$B^{\pm} \to Dh^{\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	Run 1	As before
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-\pi^0$	Run 1	As before
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S h^+h^-$	Run 1&2	**Updated**
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S K^{\pm}\pi^{\mp}$	Run 1&2	**Updated**
$B^{\pm} \to D^*h^{\pm}$	$D \to h^+h^-$	Run 1&2	**Updated**
$B^{\pm} \to DK^{*\pm}$	$D \to h^+h^-$	Run 1&2(*)	As before
$B^{\pm} \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	Run 1&2(*)	As before
$B^{\pm} \to Dh^{\pm}\pi^+\pi^-$	$D \to h^+h^-$	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	Run 1&2(*)	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	Run 1&2(*)	**New**
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	Run 1	As before
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^-\pi^+\pi^+$	Run 1	As before
$B^0_s \to D^{\mp}_s K^{\pm}$	$D^+_s \to h^+h^-\pi^+$	Run 1	As before
$B^0_s \to D^{\mp}_s K^{\pm}\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	Run 1&2	**New**

JHEP 12(2021)141

151 observables to determine 52 parameters using GammaCombo package

Backup - Beauty and Charm LHCb gamma combination

D decay	Observable(s)	Dataset	Status since Ref. [17]
$D^0 \to h^+h^-$	ΔA_{CP}	Run 1&2	**New**
$D^0 \to h^+h^-$	y_{CP}	Run 1	**New**
$D^0 \to h^+h^-$	ΔY	Run 1&2	**New**
$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	Run 1	**New**
$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	Run 1&2(*)	**New**
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	Run 1	**New**
$D^0 \to K^0_S\pi^+\pi^-$	x, y	Run 1	**New**
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	Run 1	**New**
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	Run 2	**New**

JHEP 12(2021)141

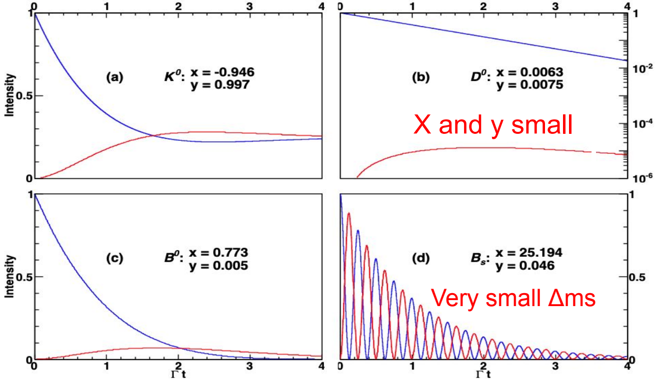
151 observables to determine 52 parameters using GammaCombo package

Backup - Charm mixing parameter $y_{CP} - y_{CP}^{K\pi}$

6fb-1

Arxiv:2202.09106, submitted to PRD

$$\text{Prob}(D^0 \to \bar{D}^0, t) = \left|\frac{q}{p}\right|^2 \frac{e^{-\Gamma t}}{2}(\cosh(y\Gamma t) - \cos(x\Gamma t))$$



arxiv: 1209.5806

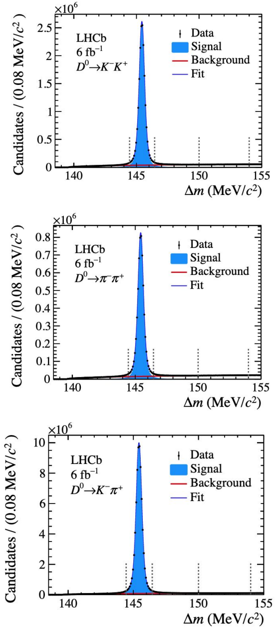
$$\frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to f)} - 1 = y_{CP}^f - y_{CP}^{K\pi} \approx y(1 + \sqrt{R_D})$$

$f = K^-K^+$ and $\pi^-\pi^+$

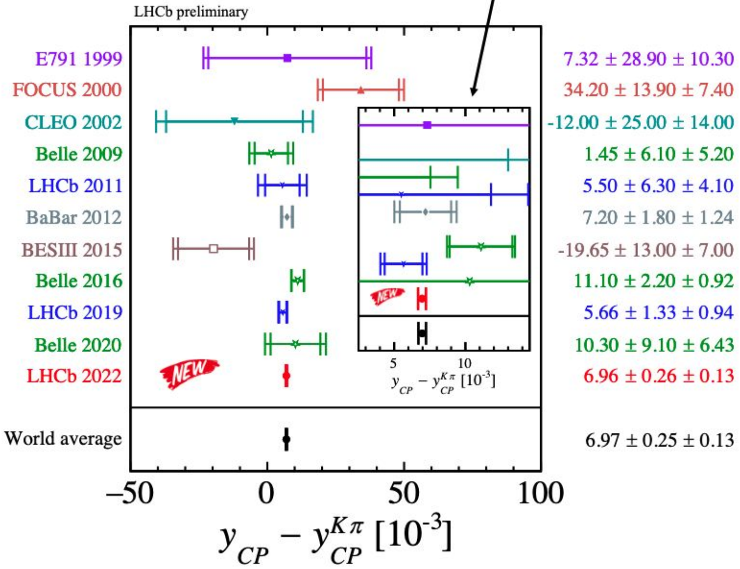
$$= \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \approx 0.6\%$$

$$= \sqrt{\frac{\mathcal{B}(D^0 \to K^+\pi^-)}{\mathcal{B}(D^0 \to K^-\pi^+)}} \approx 6\%$$

Extremely high yields and signal purity



ZOOM



Result compatible with the present world average and more precise by a factor of four!

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

Result will be added to LHCb Beauty and Charm combination soon!

Dedicated CERN seminar

Backup - Measurement of gamma in $B^\pm \to D[K_S hh] h^\pm$

$9 fb^{-1}$

Can construct observables for each bin i

$$N_{+i}^{-} = h_{B^-}\left[F_{+i} + \left(\left(x_-^{DK}\right)^2 + \left(y_-^{DK}\right)^2\right)F_{-i} + 2\sqrt{F_i F_{-i}}\left(x_-^{DK} c_{+i} + y_-^{DK} s_{+i}\right)\right]$$

Normalisation absorbs production and detection asymmetries

Efficiency corrected fraction of events that fall in bin i

Cosine/sine of strong phase difference between D^0 and $\overline{D}^0$ averaged over bin i

c_i and s_i inputs taken from combination of BESIII and CLEO results

PRD101 (2020) 112002, PRD102 (2020) 052008

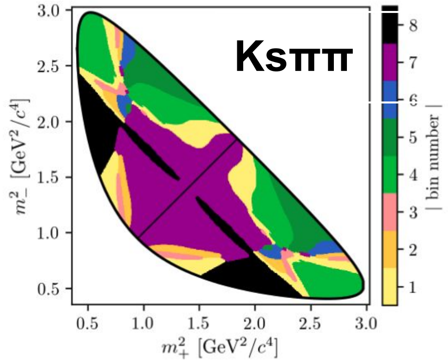
F_i normally determined through semileptonic decays (no CPV) however to increase sensitivity B->Dπ channel is fit simultaneously with B->DK to determine

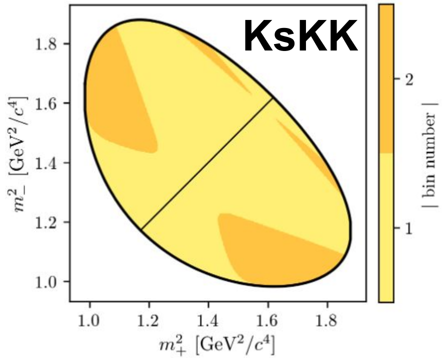
$$F_i, x_\pm^{DK}, y_\pm^{DK}, x_\pm^{D\pi}, y_\pm^{D\pi}$$

In fact a slightly different parameterisation is used for fit stability

Use of Dπ channel controls selections and reconstruction effects

Negligible contribution to gamma precision for B->Dπ as $r_B^{DK} \approx 20 \times r_B^{D\pi}$





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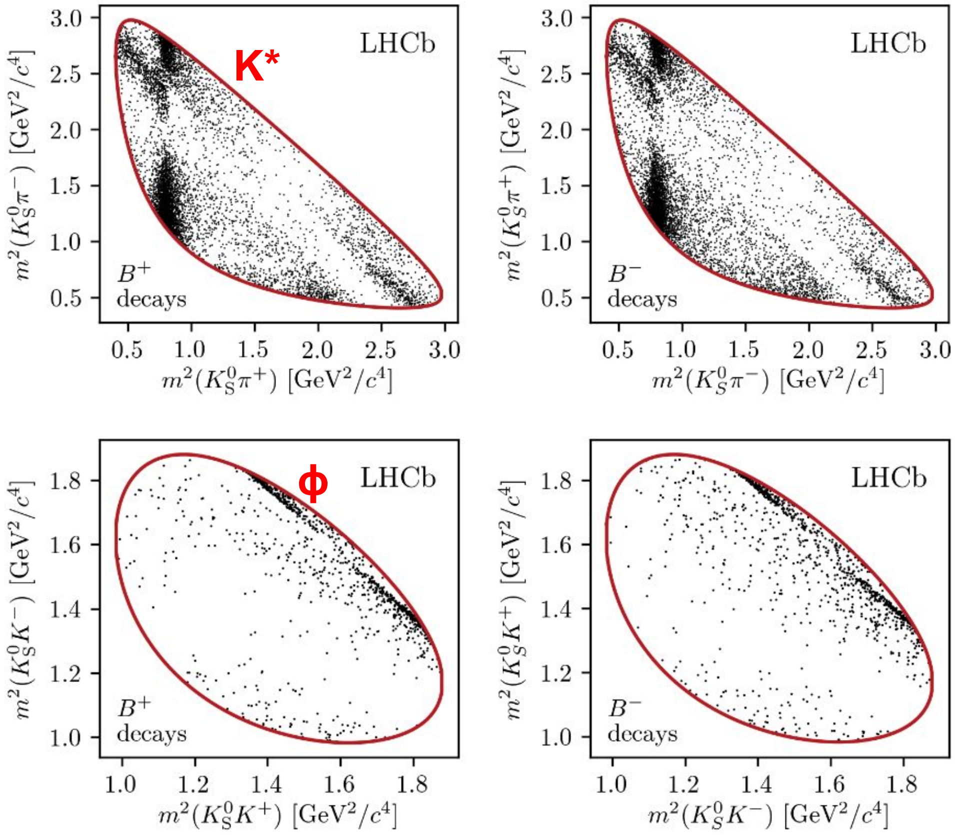
Choice of binning scheme affects only the statistical sensitivity to gamma - model independent measurement

Backup - Measurement of gamma in $B^{\pm}\to D[Ks0hh]h^{\pm}$

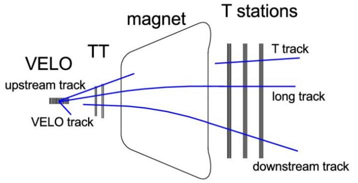
9fb-1

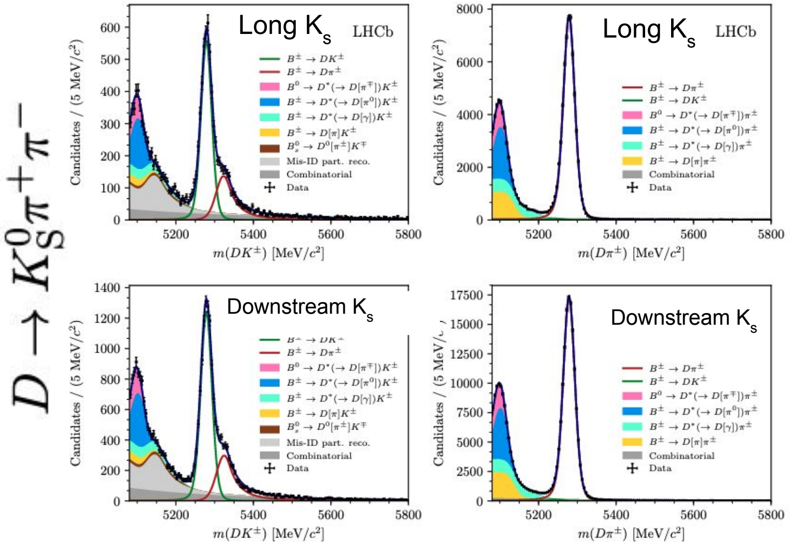
D decay has rich resonance structure - increases sensitivity



Simultaneous fit to mass distributions in 16 categories

- B->DK and B->Dπ
- B charge
- D->KK, D->ππ
- Ks reconstruction





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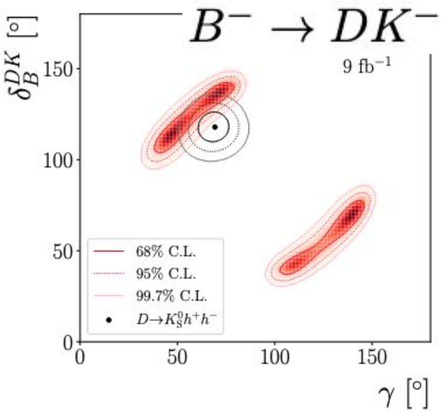
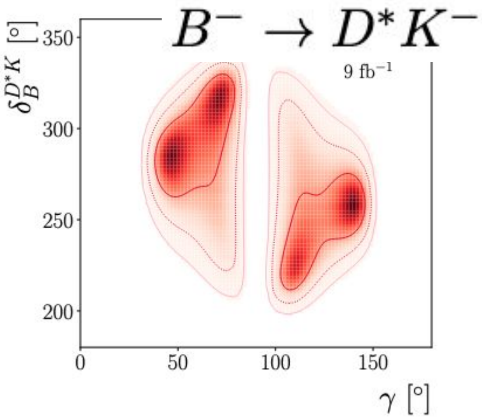
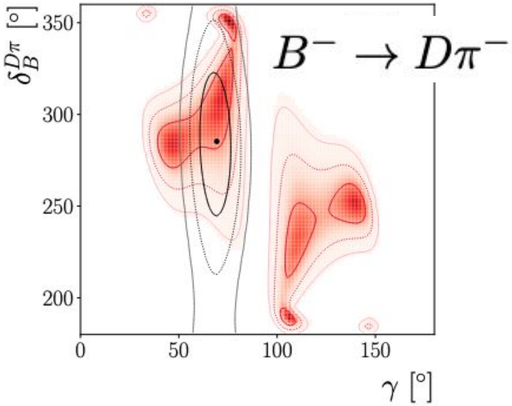
Backup - CP observables in $B^{\pm}\to D^{(*)}h^{\pm}$ decays

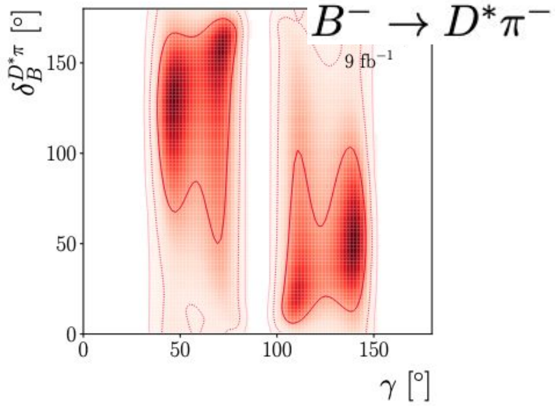
8.7fb-1

JHEP 04 (2021) 081









Profile likelihood contours dominated by $B^{\pm}$->$DK^{\pm}$ - good agreement with previous LHCb and B factory results

Constructed using charm parameters taken as external constraints from HFLAV average

However $B^{\pm}\to D^{(*)}h^{\pm}$ provide significant sensitivity to these parameters → motivates combination of gamma and charm results

Backup - Constraints on γ from $B^{\pm} \to Dh^{\mp}$ with $D \to h^{\pm}h'^{\mp}\pi^0$

$9fb^{-1}$

arXiv:2112.10617, submitted to JHEP

Eleven experimentally robust CP observables measured through a simultaneous fit to the 16 invariant mass distributions

GLW - asymmetries, double ratios of partial widths

ADS - ratios of partial decay rates, A_{CP} of favoured mode

First observation of $B^{\mp} \to [\pi^{\mp}K^{\pm}\pi^0]_D K^{\mp}$ at >7σ!

Quasi-ADS

Quasi-GLW