Recent CKM results from the LHC

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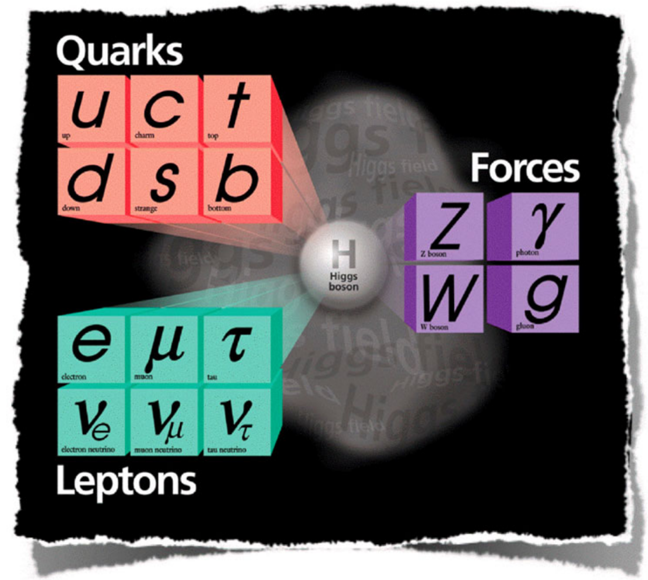
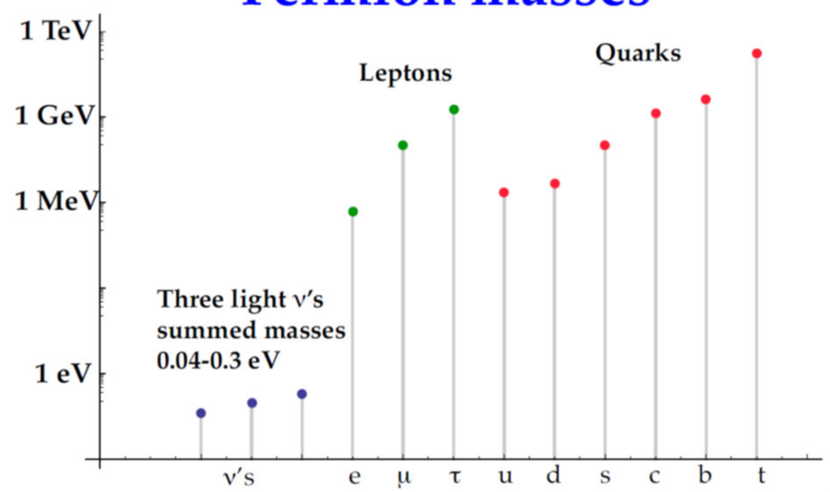
Syracuse University

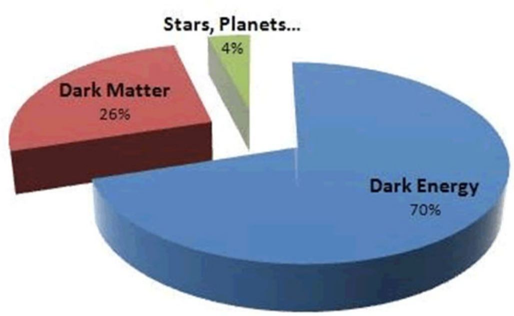
Introduction

- The **Standard Model** remarkably successful at describing the **particles of nature** and the **forces between them**.
- But, **it cannot be the end of the line**.
  - Dark matter ?
  - **BAU** (**B**aryon **A**symmetry in the **U**niverse)
  - Hierarchy problem
  - Explanation of family structure, and masses
  - …



Fermion masses





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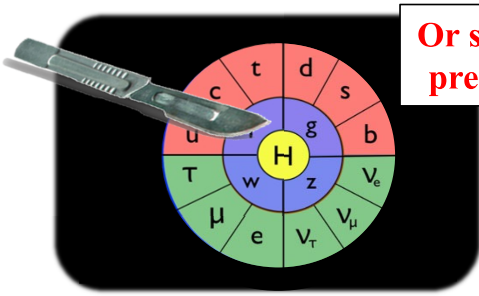

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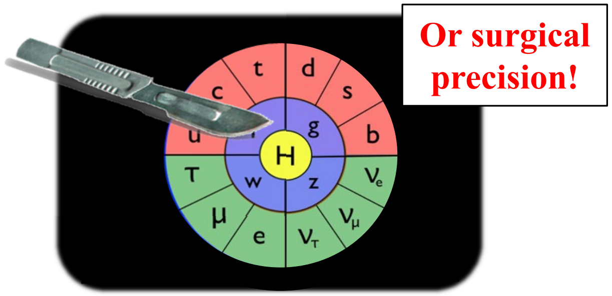

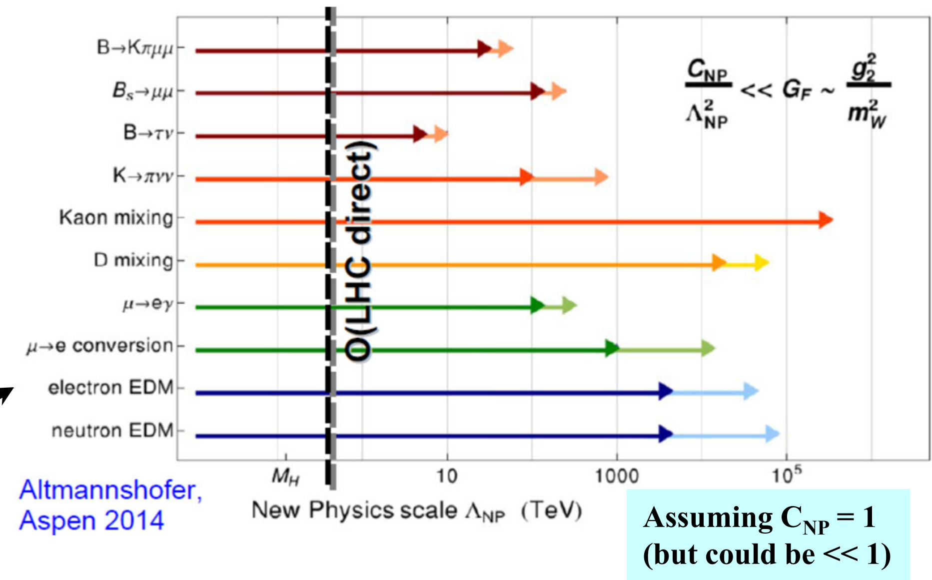

- **Indirect precision measurements complementary to direct detection.**
  - Even if $\Lambda_{NP} > E_{LHC}$ (can't produce directly), NP particles can appear in **quantum loops**,

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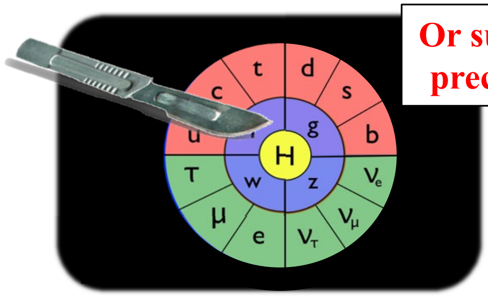

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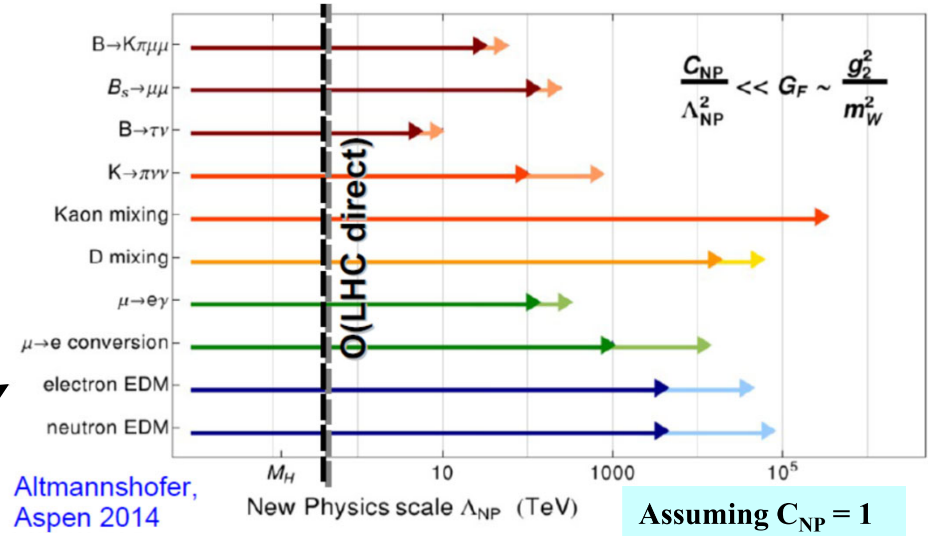

Altmannshofer, Aspen 2014

Assuming $C_{NP} = 1$ (but could be << 1)

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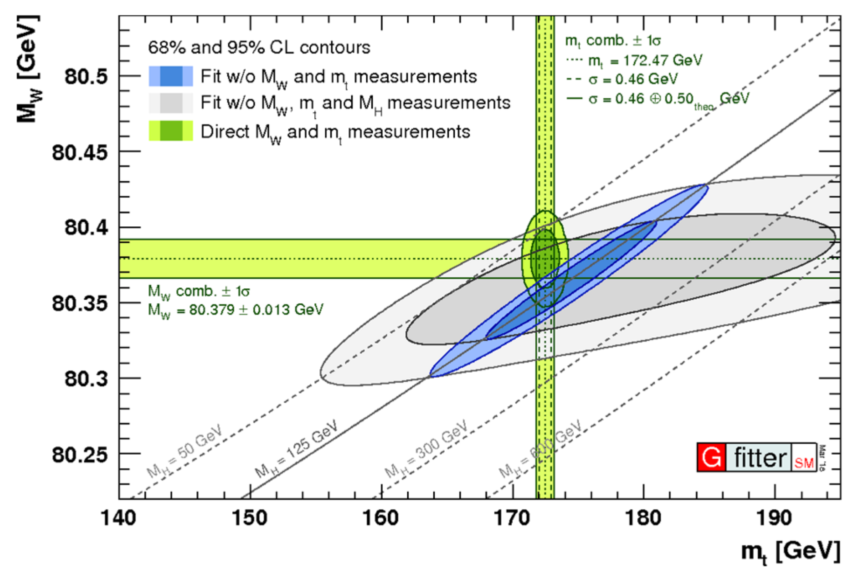
- **Examples**
  - **Precision EW → m_H**
  - **B mixing → m_{top}**



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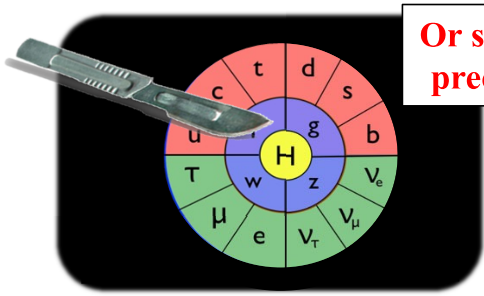

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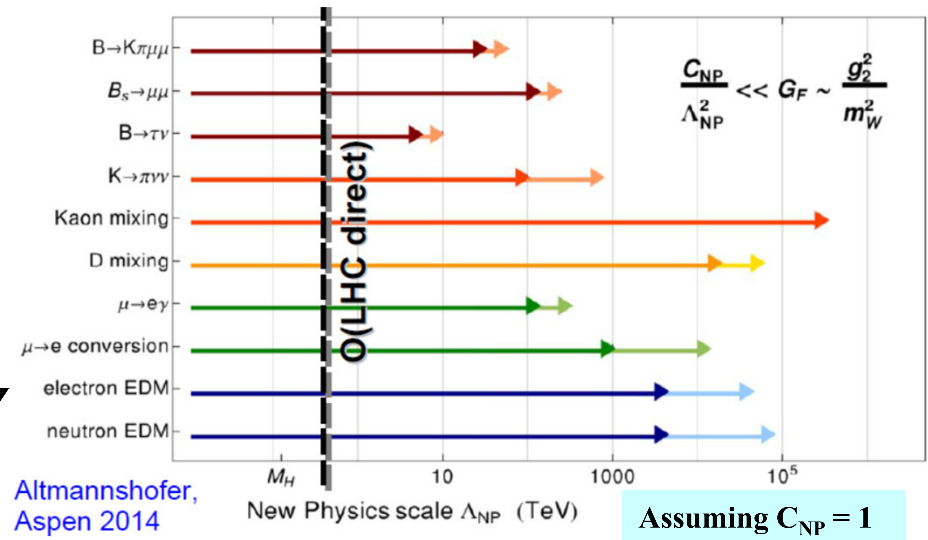

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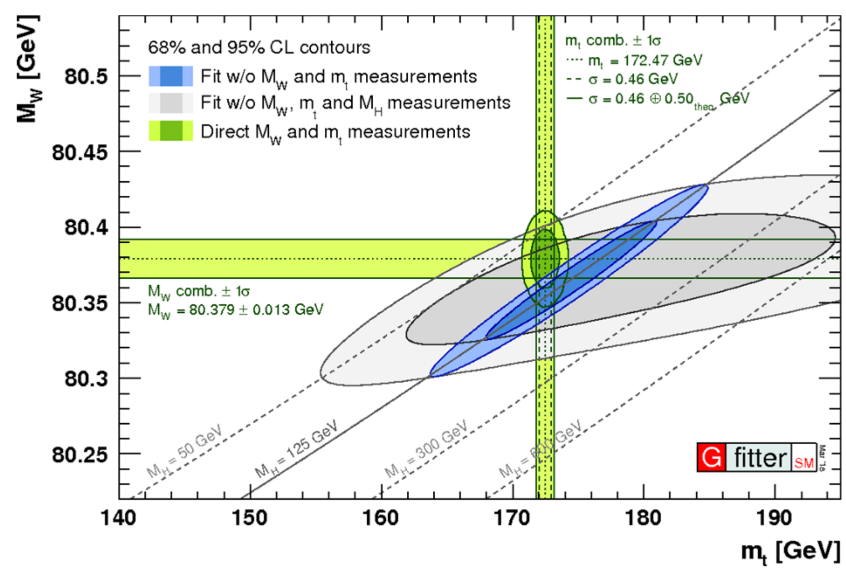
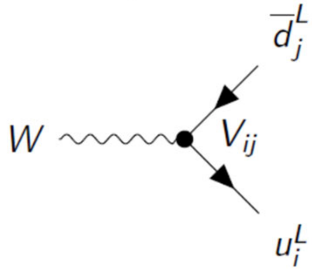


General idea

- Identify/measure "**SM-clean**" observables to high precision.
- Pattern of (non-)deviations → possible NP explanations.

CKM Matrix

- **CKM matrix** connects **weak interaction eigenstates** to the **mass eigenstates**:
  - 3 x 3 **unitary transformation** → 4 free parameters



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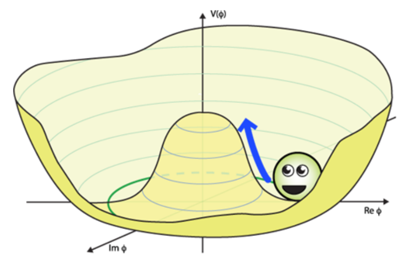

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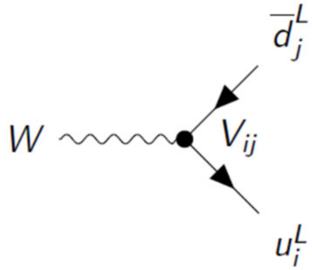

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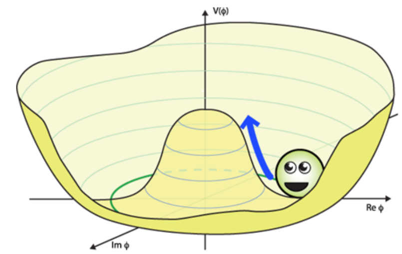

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$\lambda = \sin\theta_C \cong 0.22$

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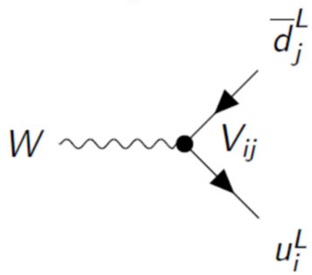

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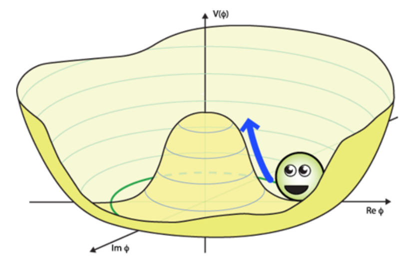

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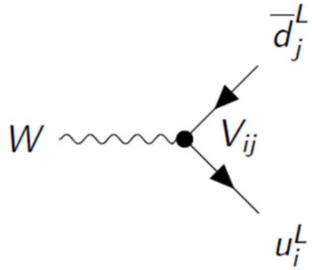

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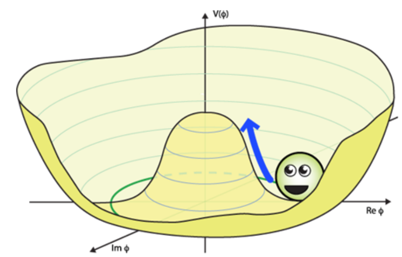

Core part of LHCb physics program

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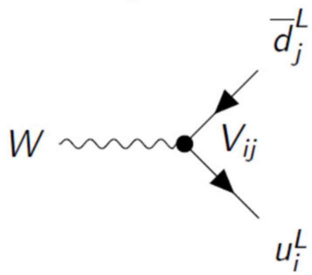

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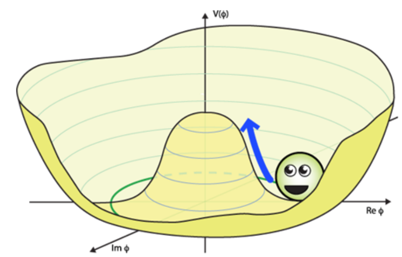

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CMS, ATLAS

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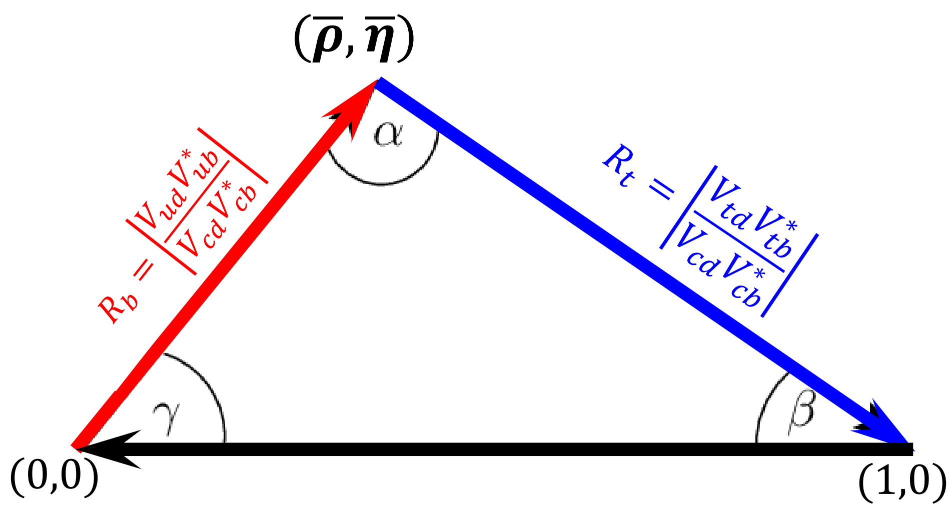

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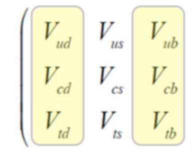

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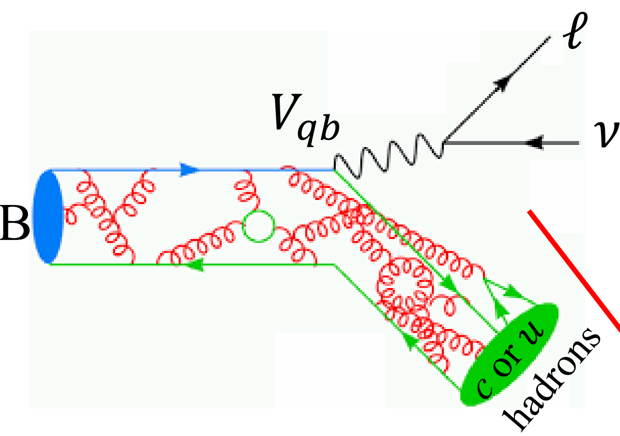

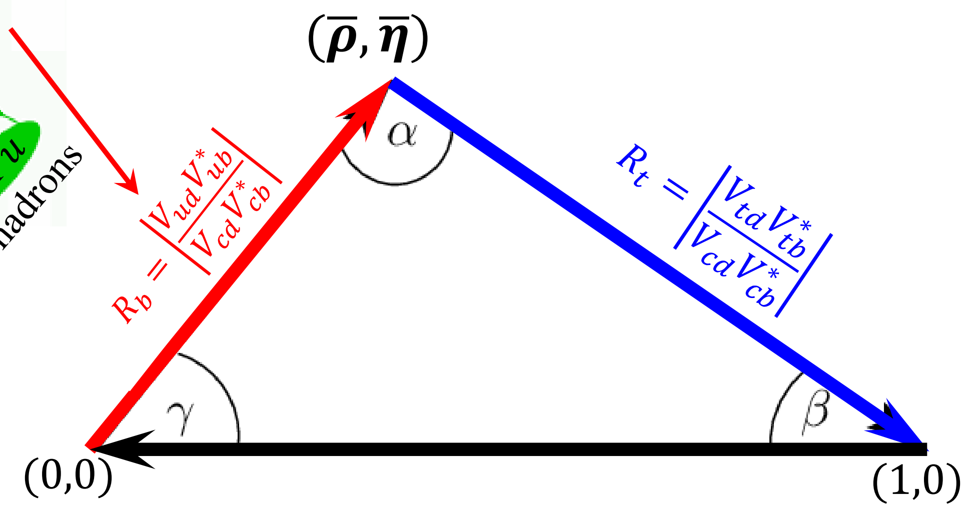

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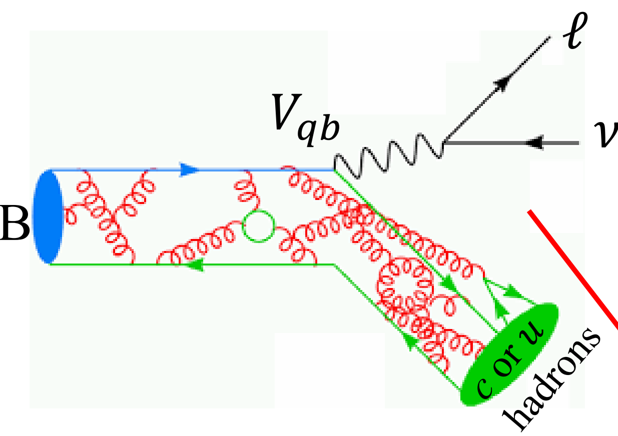

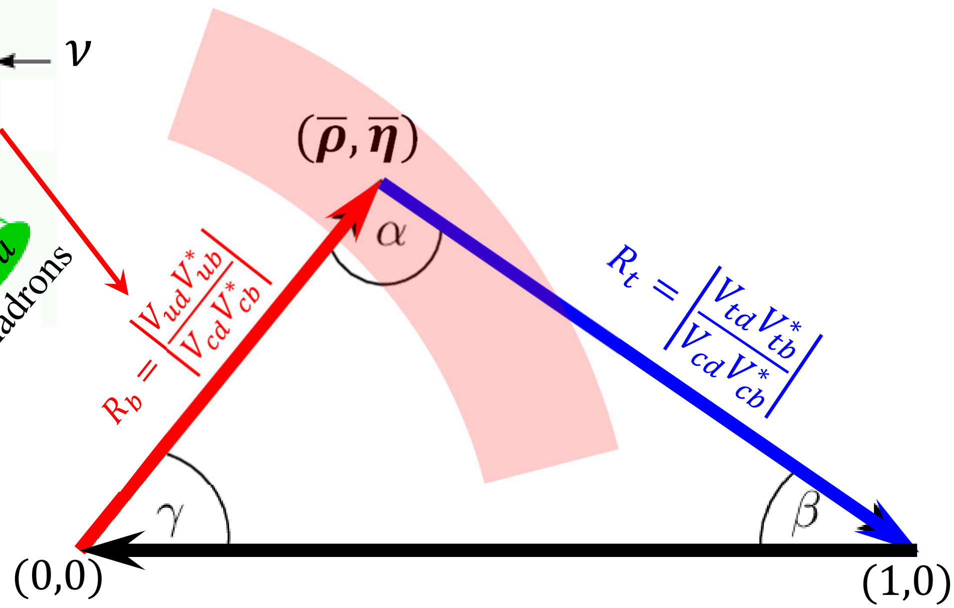

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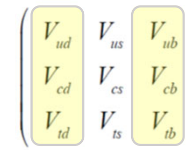

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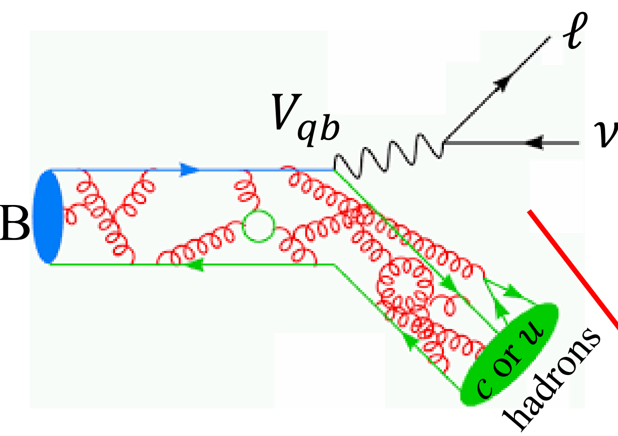

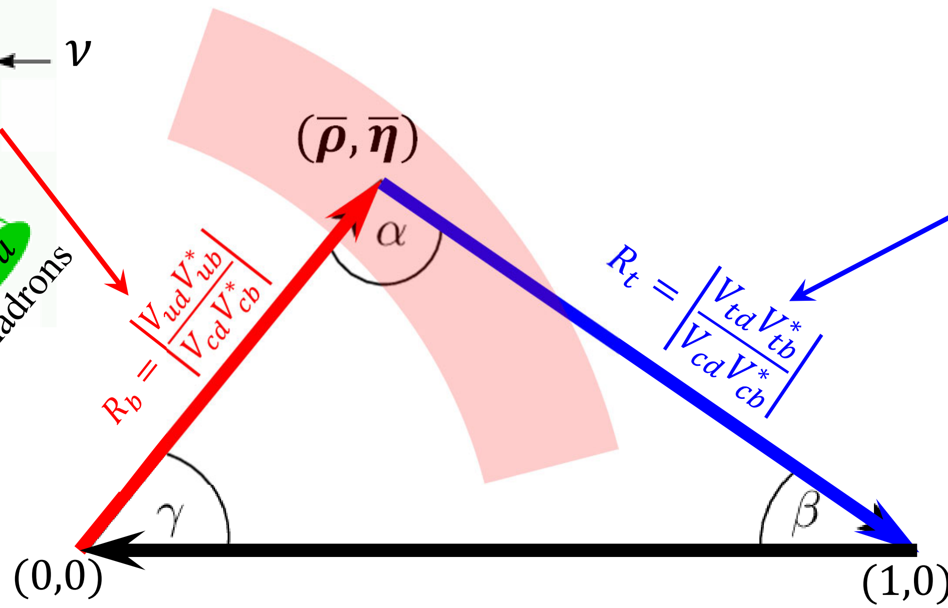

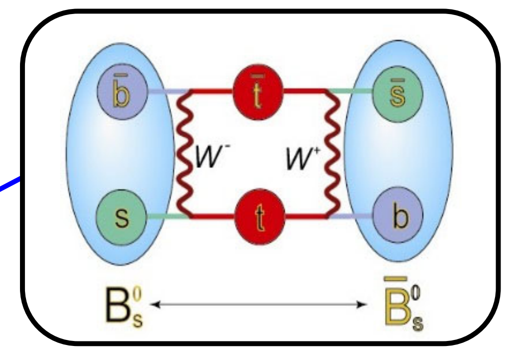

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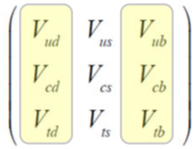

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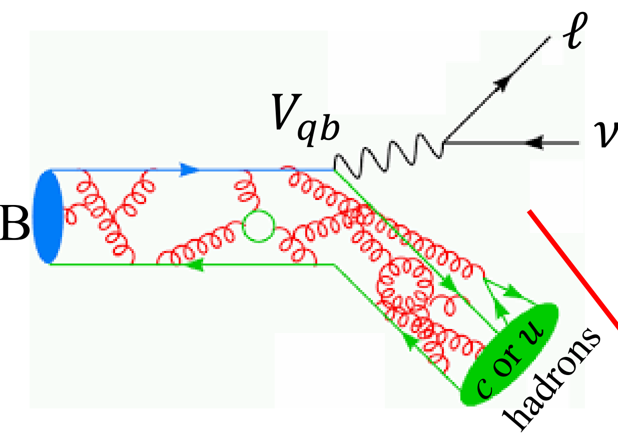

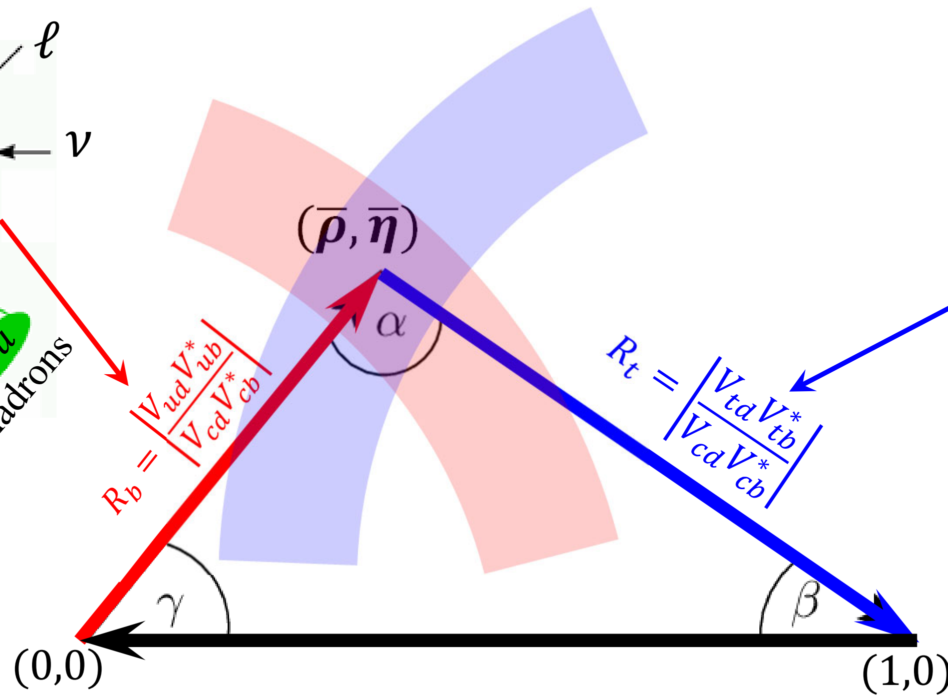

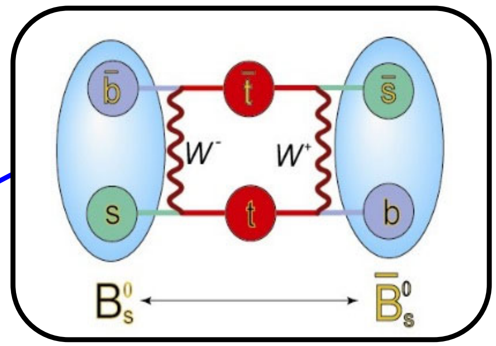

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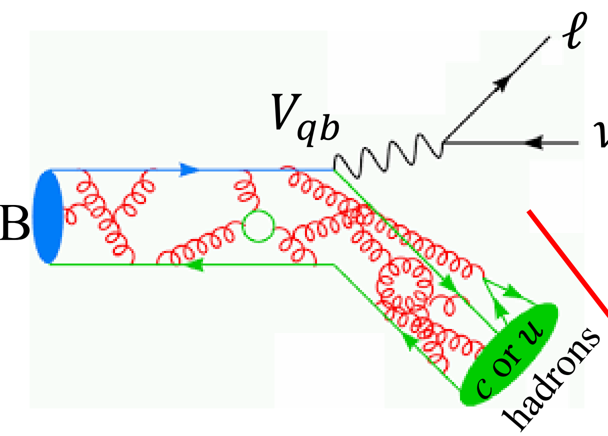

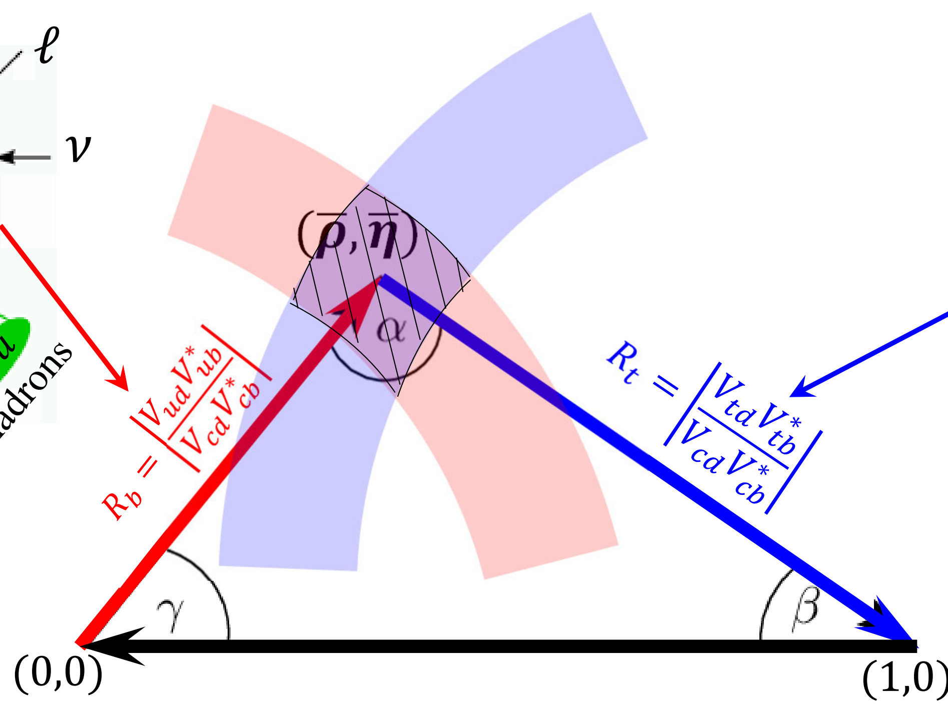

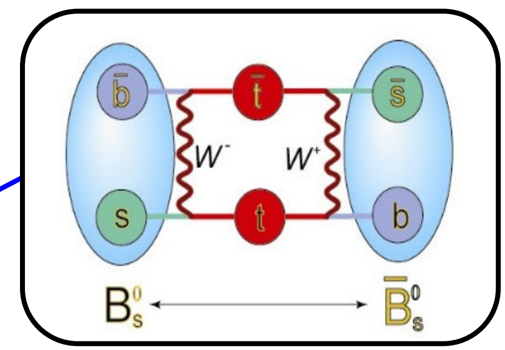

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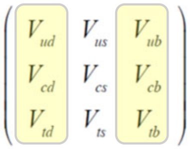
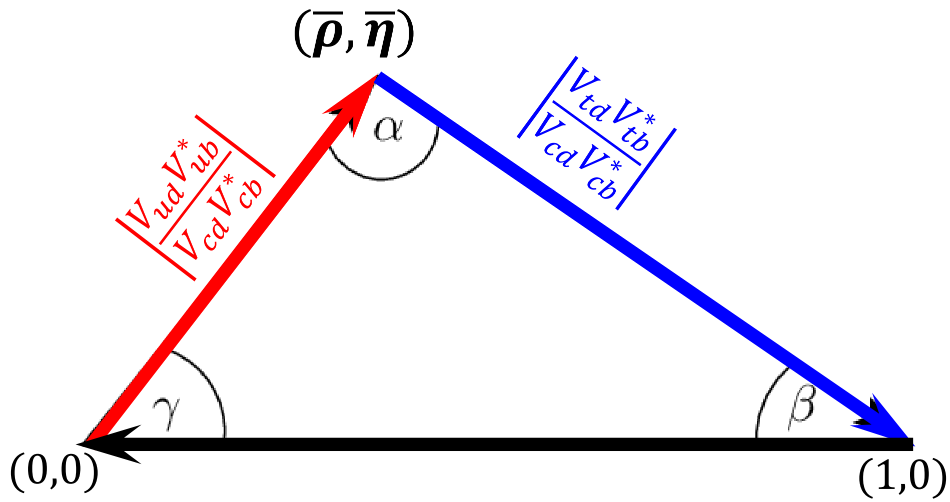
‘bd’ Unitarity triangle: Angles



- **Interference between two amplitudes that have different weak and strong phases.**
- $A_f^{CP} = \frac{\Gamma(B\to f) - \bar{\Gamma}(\bar{B}\to \bar{f})}{\Gamma(B\to f) + \bar{\Gamma}(\bar{B}\to \bar{f})}$ exposes weak phase!



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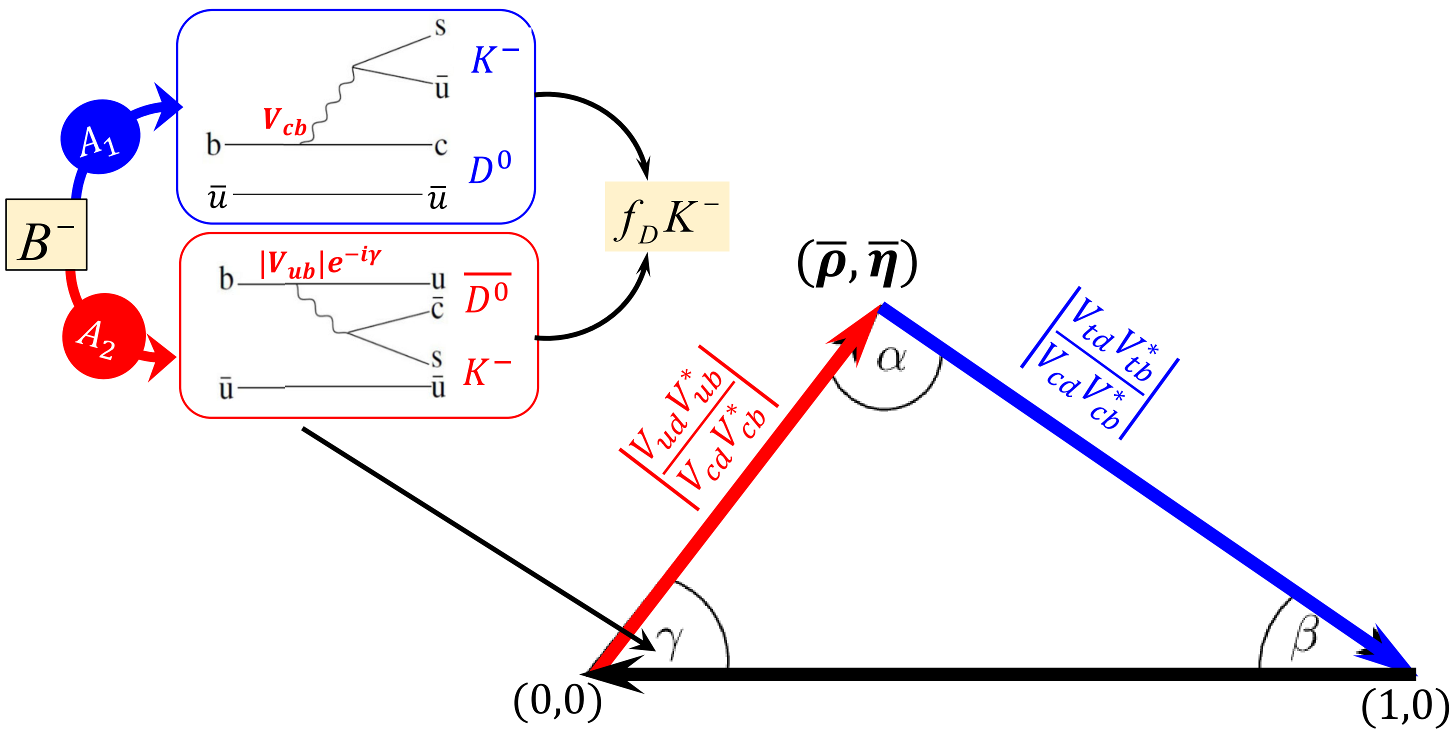

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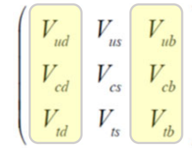

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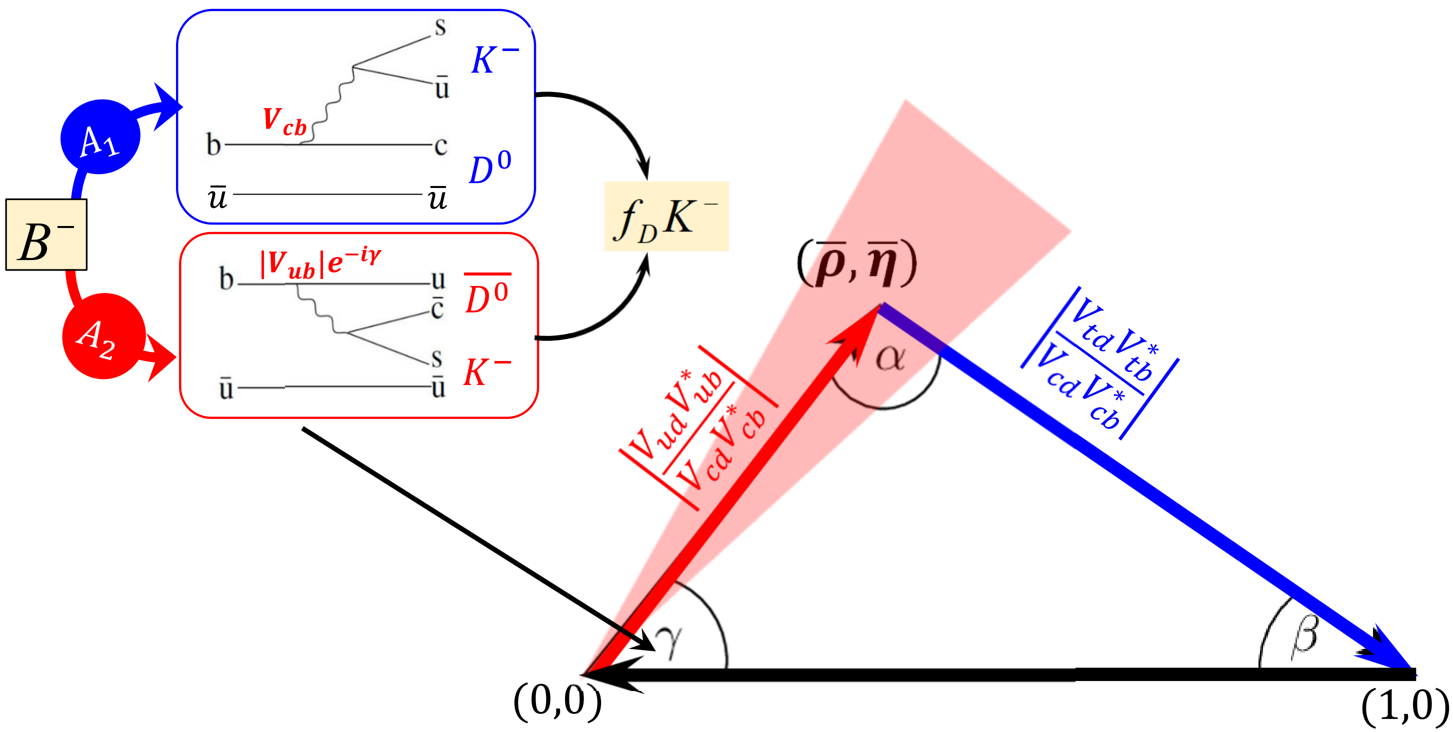

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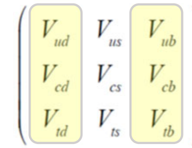

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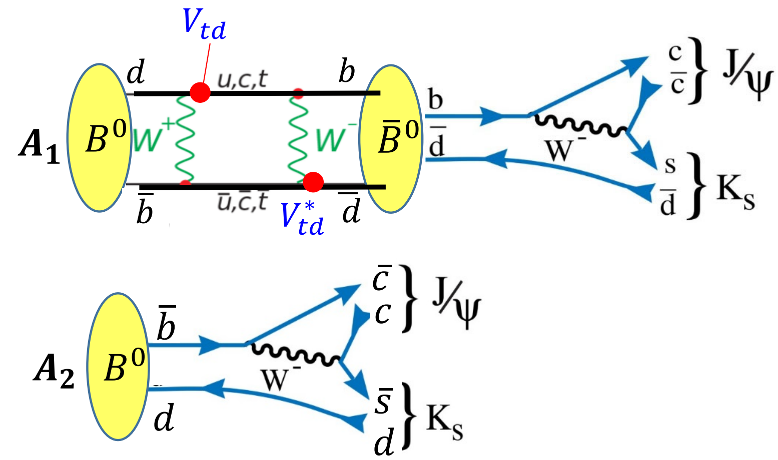

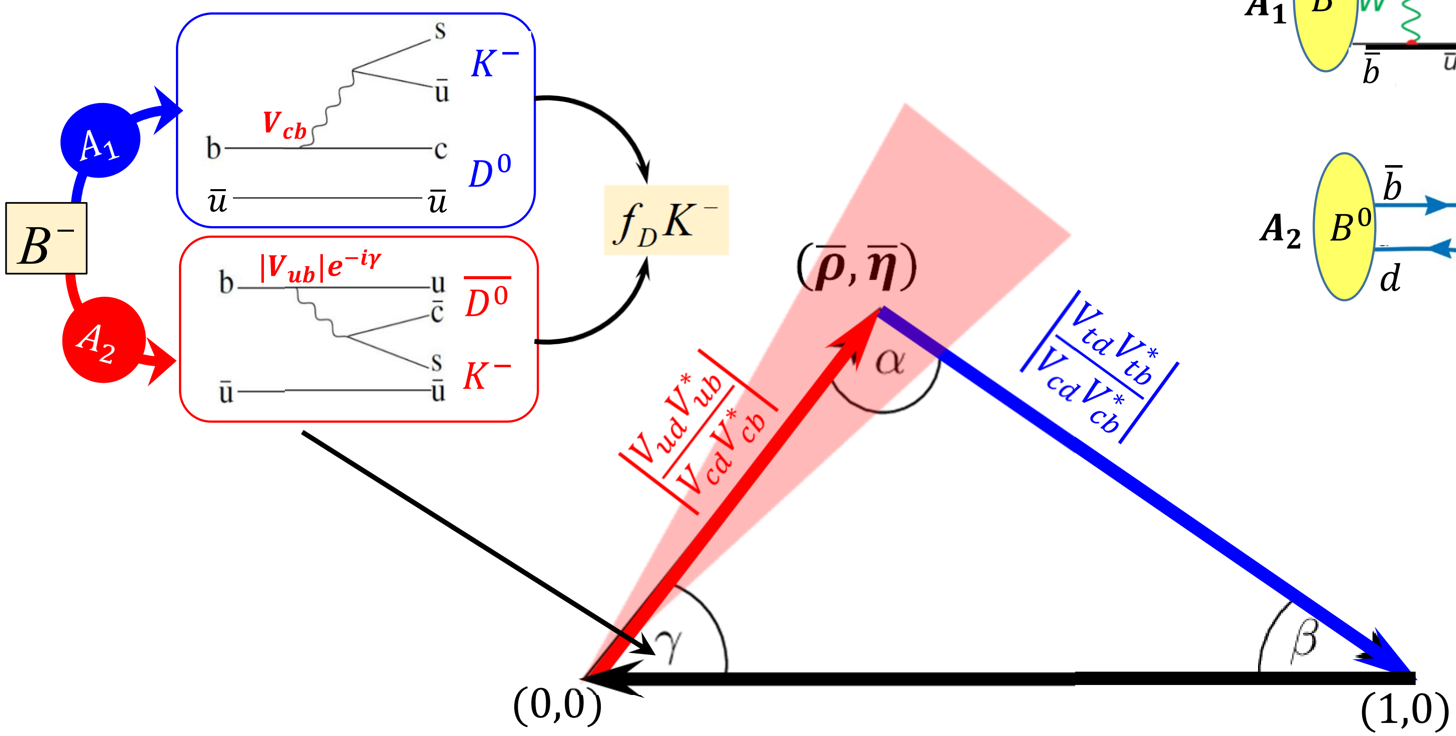

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TREE **LOOP**

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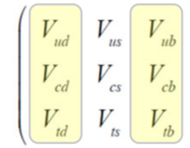

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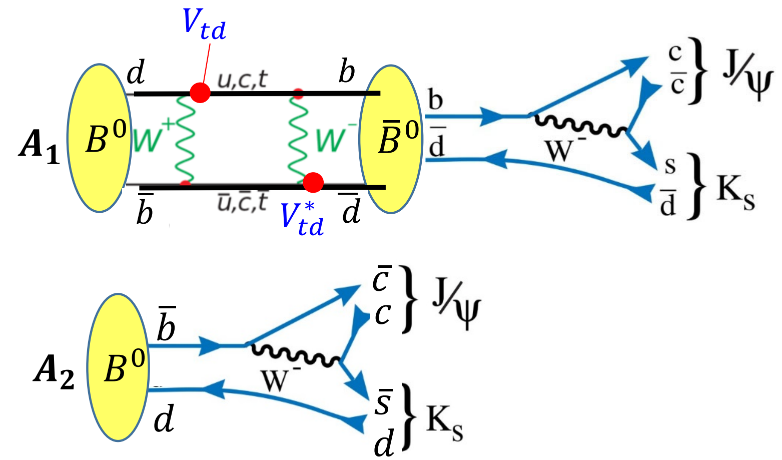

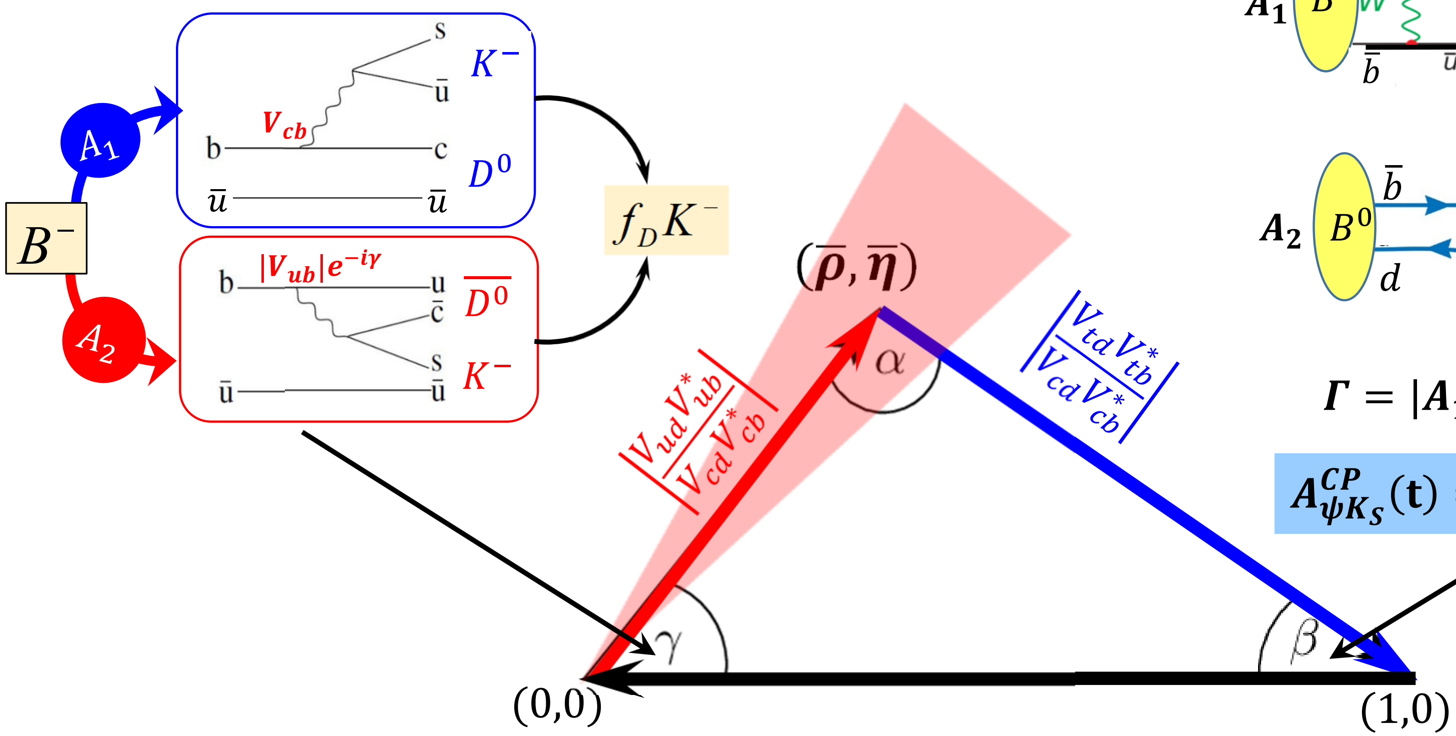

$\Gamma = |A_1 + A_2|^2$ $\qquad$ $\bar{\Gamma} = |\bar{A}_1 + \bar{A}_2|^2$

$A_{\psi K_S}^{CP}(t) = C\cos(\Delta m\, t) + S\sin(\Delta m\, t)$

Expect:
$C_{SM} \sim 0$
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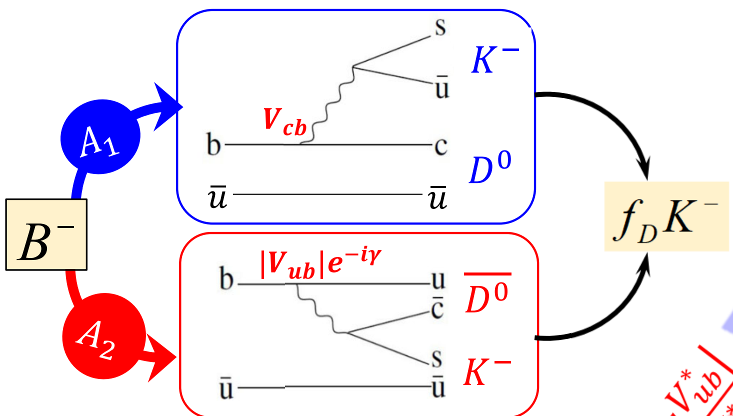

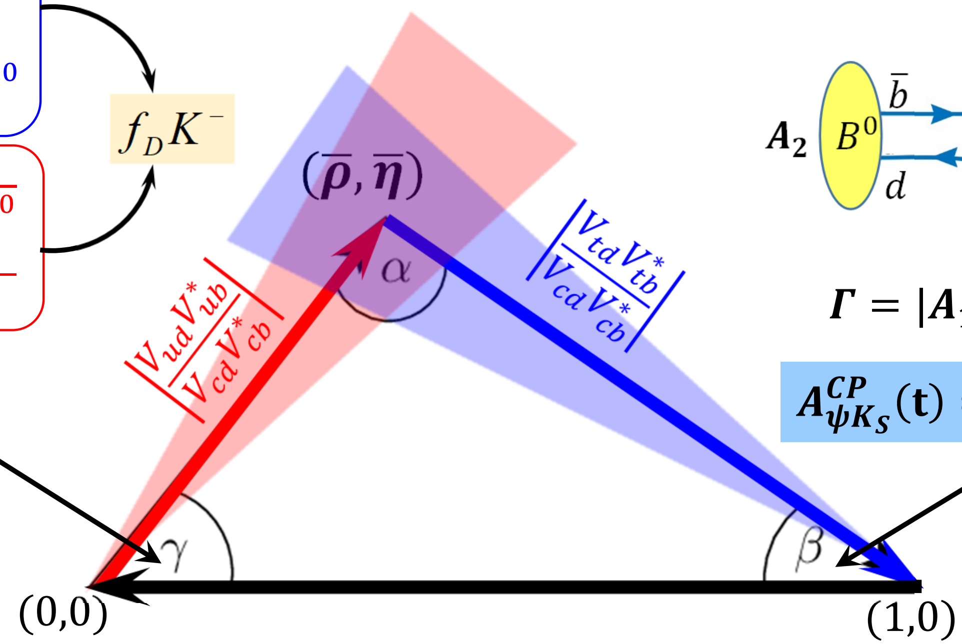

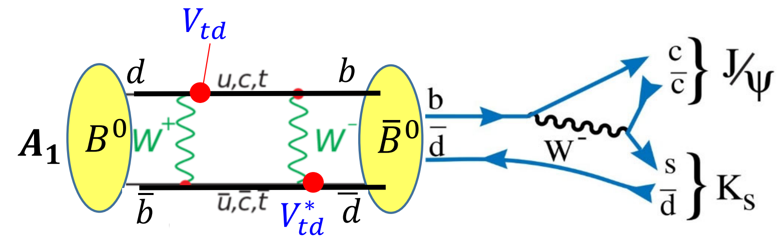

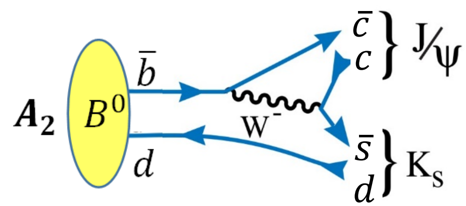

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TREE

LOOP

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TREE-LEVEL

$b \to (c,u)\ell\nu$: $\sqrt{\bar{\rho}^2 + \bar{\eta}^2}$

CPV in "$B \to DK$": γ

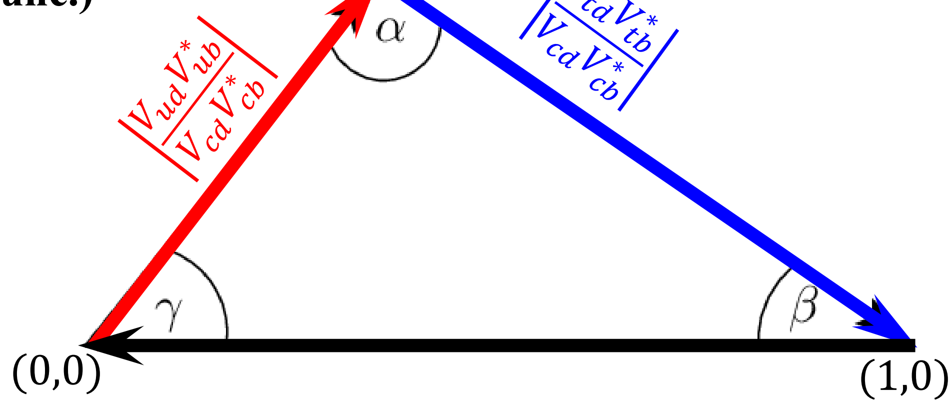
LOOP-MEDIATED

$\Delta m_d, \Delta m_s$: $\sqrt{(1-\bar{\rho})^2 + \bar{\eta}^2}$

CPV in "$B \to \psi K_S$": $\sin(2\beta)$

Both sets of measurements
THEORETICALLY CLEAN
(very small hadronic unc.)

$(\bar{\boldsymbol{\rho}}, \bar{\boldsymbol{\eta}})$



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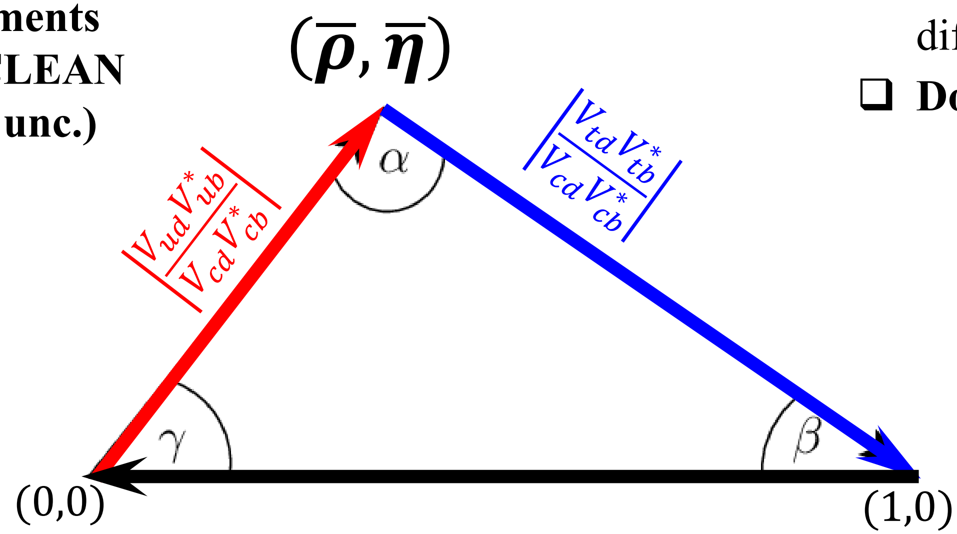
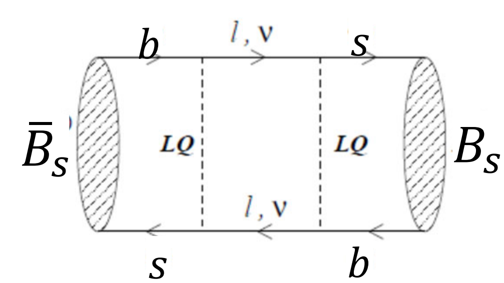


CKM Objectives:

- Precision measurement of $(\bar{\rho},\bar{\eta})$ with different modes.
- **Does** $(\bar{\rho},\bar{\eta})_{\text{Loop}} = (\bar{\rho},\bar{\eta})_{\text{Tree}}$ **?**



Recent CKM measurements from the LHC (since 2021)

γ	V_{ub} / V_{cb}	Δm_s	$\sin(2\beta)$	$\sin(2\beta_s)$		
LHCb	**LHCb**	**LHCb**	**LHCb**	**LHCb**	**CMS**	**ATLAS**
$B^\pm \to D(\gamma,\pi^0)_{D^*}h^\pm$, $D \to K_S^0 h^+ h^-$ LHCb-PAPER-2023-012	$B_s \to K^-\mu^+\nu_\mu$ PRL 126, 081804 (2021)	$B_s \to D_s^+\pi^-$ Nature Physics 18 (2022)	$B^0 \to \psi(\ell^+\ell^-)K_S^0$ LHCb-PAPER-2023-013	$B_s^0 \to J/\psi(K^+K^-)_\phi$ LHCb-PAPER-2023-013	$B_s^0 \to J/\psi(K^+K^-)_\phi$ PLB 816, 136188 (2021)	$B_s^0 \to J/\psi(K^+K^-)_\phi$ EPJ C81, 342 (2021)
$B^0 \to [K_S^0 h^+ h^-](K^+\pi^-)_{K^*}$ LHCb-PAPER-2023-009						
$B^\pm \to [K^+K^-\pi^+\pi^-]h^\pm$ $B^\pm \to [\pi^+\pi^-\pi^+\pi^-]h^\pm$ arXiv:2301.10328						
$B^\pm \to [K^\mp\pi^\pm\pi^\pm\pi^\mp]h^\pm$ arXiv:2209.03692						
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LHCb γ combination JHEP 12, 141 (2021)						
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V_{tb}
ATLAS
Single top ATLAS-CONF-2023-026

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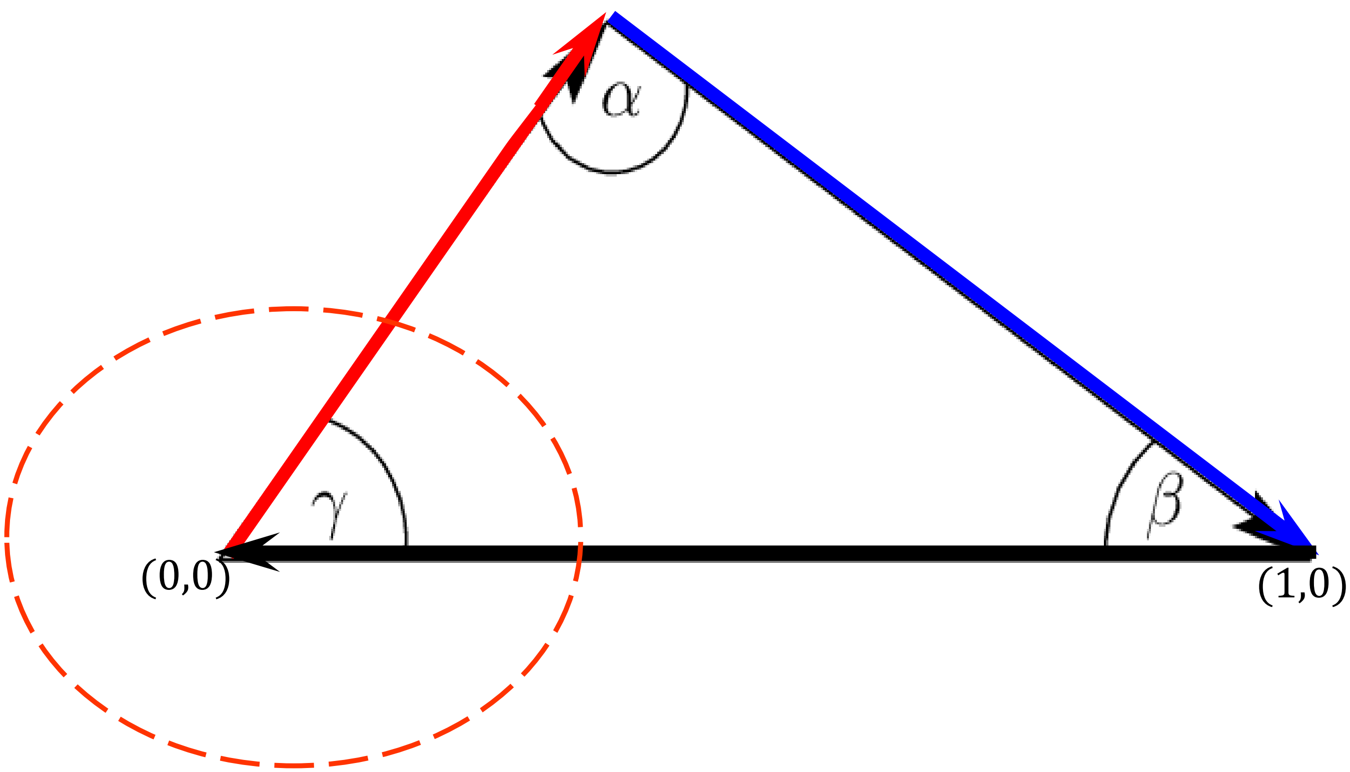
Weak phase γ



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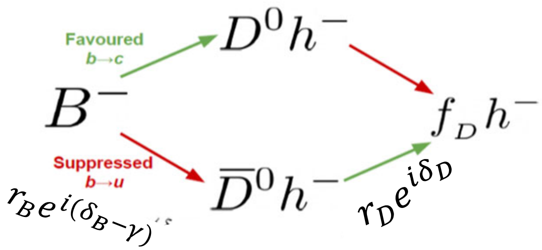

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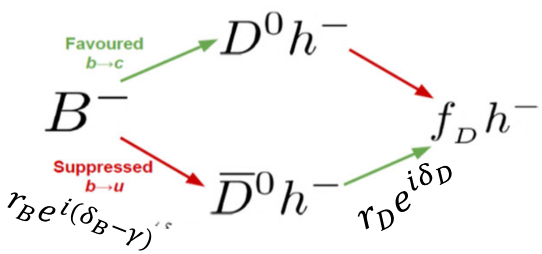

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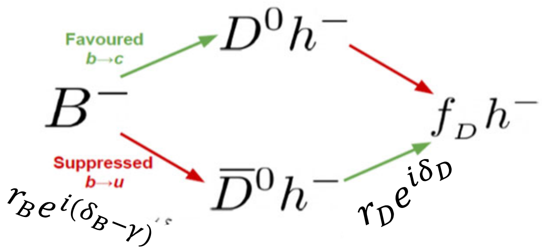

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GLW $(r_D^f = 1)$

- In **multi-body D decays**, *e.g.* GGSZ, (r_D^f, δ_D^f) vary across the phase space. Integrating over full phase space dilutes sensitivity to γ.
- Often, **independent amplitude analysis** used to **bin D phase space** to maximize sensitivity to γ

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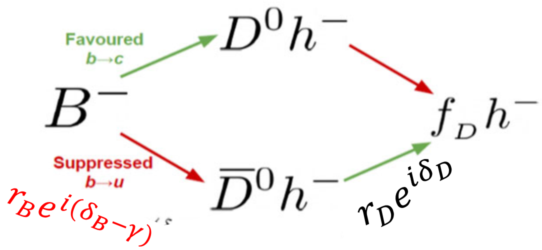

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DCS $f_D = K^\pm\pi^\mp$
GLW $(r_D^f = 1)$

- In **multi-body D decays**, *e.g.* GGSZ, (r_D^f, δ_D^f) vary across the phase space. Integrating over full phase space dilutes sensitivity to γ.
- Often, **independent amplitude analysis** used to **bin D phase space** to maximize sensitivity to γ

Bottom line: Each analysis has a number of CP observables that are sensitive to the B, D decay parameters, and γ.

LHCb γ combination, JHEP 12 (2021)

	B decay	D decay
	f_D	
$B^\pm$	$B^\pm \to Dh^\pm$	$D \to h^+h^-$
	$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$
	$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$
	$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$
	$B^\pm \to Dh^\pm$	$D \to K_S^0h^+h^-$
	$B^\pm \to Dh^\pm$	$D \to K_S^0K^\pm\pi^\mp$
	$B^\pm \to D^*h^\pm$	$D \to h^+h^-$
	$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$
	$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$
	$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$
B^0	$B^0 \to DK^{*0}$	$D \to h^+h^-$
	$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$
	$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$
	$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$
B_s	$B_s^0 \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$
	$B_s^0 \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$

Many decays used in LHCb, including B^0 and B_s decays (time-dependent analysis req'd)

LHCb, arXiv:2301.10328

Gamma measurement in $B^{\pm} \to [K^{+}K^{-}\pi^{+}\pi^{-}]_{D}\{K^{\pm}, \pi^{\pm}\}$ and $B^{\pm} \to [\pi^{+}\pi^{-}\pi^{+}\pi^{-}]_{D}\{K^{\pm}, \pi^{\pm}\}$ decays

$B^{\pm} \to [K^+K^-\pi^+\pi^-, \pi^+\pi^-\pi^+\pi^-]_D \{K^{\pm}, \pi^{\pm}\}$ [1]

LHCb, arXiv:2301.10328

- Four-body self-conjugate mode

$$\mathcal{A}_{B^-} = A_{B^-}\left[A_{D^0}(\Phi) + r_B\ e^{i\left(\delta_B - \gamma\right)} A_{\bar{D}^0}(\Phi)\right]$$

Φ = position in 5D phase space (PS) of D decay

[1] LHCb, JHEP 02, 126 (2019)

$B^{\pm} \to [K^+K^-\pi^+\pi^-, \pi^+\pi^-\pi^+\pi^-]_D \{K^{\pm}, \pi^{\pm}\}$ [1]

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Φ = position in 5D phase space (PS) of D decay

- Yields of B^+, B^- in a phase space bin i:

$$B^+ \to f_D K^+:\quad N_{+i}^{+} = h_{B^+}\left[F_{-i} + \left((x_+)^2 + (y_+)^2\right)F_{+i} + 2\sqrt{F_{+i}F_{-i}}(x_+c_i - y_+s_i)\right]$$

$$B^- \to f_D K^-:\quad N_{-i}^{-} = h_{B^-}\left[F_{-i} + \left((x_-)^2 + (y_-)^2\right)F_{+i} + 2\sqrt{F_{+i}F_{-i}}(x_-c_i - y_-s_i)\right]$$

$$x_{\pm} = r_B\ \cos(\delta_B \pm \gamma)$$

$$y_{\pm} = r_B\ \sin(\delta_B \pm \gamma)$$

$$\{c_i, s_i\} \equiv \frac{\int_i d\Phi |A_{D^0}||A_{\bar{D}^0}|\{\cos\Delta\delta_D, \sin\Delta\delta_D\}}{\sqrt{\int_i d\Phi|A_{\bar{D}^0}|^2 \int_i d\Phi|A_{D^0}|^2}}$$

[1] LHCb, JHEP 02, 126 (2019)

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$$B^- \to f_D K^-: \quad N^-_{-i} = h_{B^-}\left[F_{-i} + \left((x_-)^2 + (y_-)^2\right)F_{+i} + 2\sqrt{F_{+i}F_{-i}}(x_-c_i - y_-s_i)\right]$$

$$x_\pm = r_B \cos(\delta_B \pm \gamma)$$

$$y_\pm = r_B \sin(\delta_B \pm \gamma)$$

$$\{c_i, s_i\} \equiv \frac{\int_i d\Phi |A_{D^0}||A_{\bar{D}^0}|\{\cos\Delta\delta_D, \sin\Delta\delta_D\}}{\sqrt{\int_i d\Phi |A_{\bar{D}^0}|^2 \int_i d\Phi |A_{D^0}|^2}}$$

- Use indep. D^0 amplitude fit[1] to $B^- \to [K^+K^-\pi^+\pi^-]_D \mu^-\nu X$ to **optimize binning** for **max sensitivity to γ** and obtain c_i, s_i and F_i

[1] LHCb, JHEP 02, 126 (2019)

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$$B^- \to f_D K^-: \quad N^-_{-i} = h_{B^-}\left[F_{-i} + \left((x_-)^2 + (y_-)^2\right)F_{+i} + 2\sqrt{F_{+i}F_{-i}}(x_- c_i - y_- s_i)\right]$$

$$x_\pm = r_B \cos(\delta_B \pm \gamma)$$

$$y_\pm = r_B \sin(\delta_B \pm \gamma)$$

$$\{c_i, s_i\} \equiv \frac{\int_i d\Phi |A_{D^0}||A_{\bar{D}^0}| \{\cos\Delta\delta_D, \sin\Delta\delta_D\}}{\sqrt{\int_i d\Phi |A_{\bar{D}^0}|^2 \int_i d\Phi |A_{D^0}|^2}}$$

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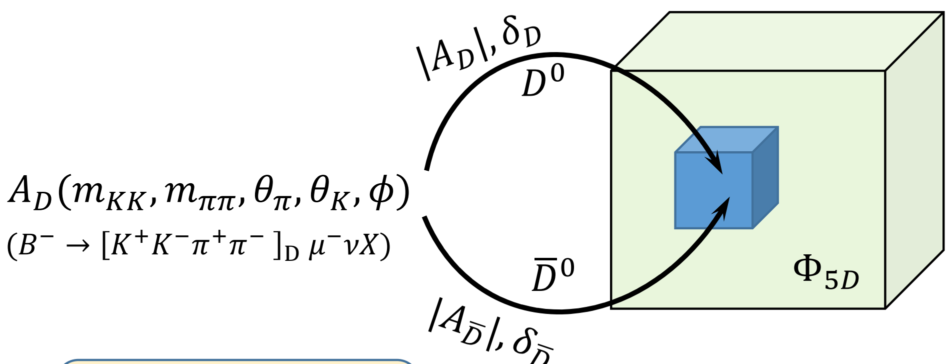

$r_D = |A_D/A_{\bar{D}}|$,

$\Delta\delta_D(\Phi) = \delta_D - \delta_{\bar{D}}$

[1] LHCb, JHEP 02, 126 (2019)

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$$B^- \to f_D K^-: \quad N_{-i}^{-} = h_{B^-}\left[F_{-i} + \left((x_-)^2 + (y_-)^2\right)F_{+i} + 2\sqrt{F_{+i}F_{-i}}(x_- c_i - y_- s_i)\right]$$

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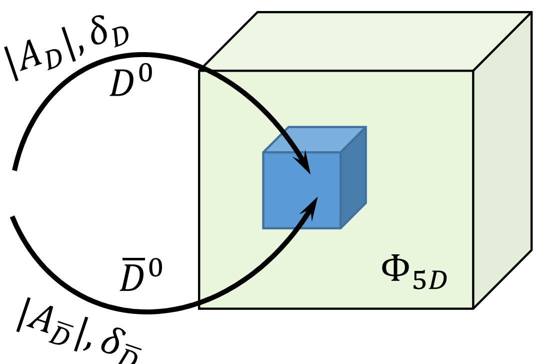
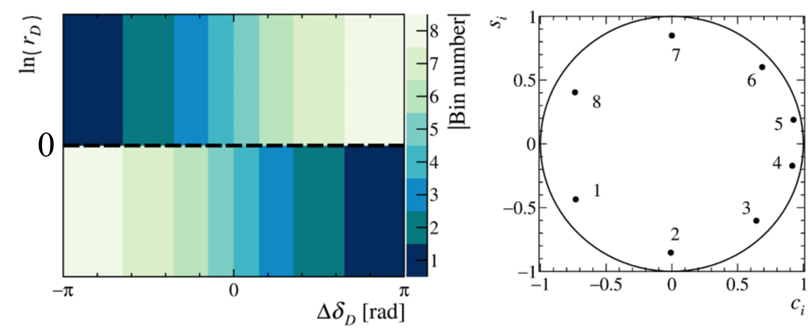
- Use indep. D^0 amplitude fit[1] to $\boldsymbol{B^- \to [K^+K^-\pi^+\pi^-]_D \mu^- \nu X}$ to **optimize binning** for **max sensitivity to γ** and obtain $\boldsymbol{c_i}$, $\boldsymbol{s_i}$ and $\boldsymbol{F_i}$

$A_D(m_{KK}, m_{\pi\pi}, \theta_\pi, \theta_K, \phi)$
($B^- \to [K^+K^-\pi^+\pi^-]_D\, \mu^- \nu X$)



$r_D = |A_D/A_{\bar{D}}|$,

$\Delta\delta_D(\Phi) = \delta_D - \delta_{\bar{D}}$



- ~90% of sensitivity to γ retained with optimal binning.

[1] LHCb, JHEP 02, 126 (2019)

$B^{\pm} \to [K^+K^-\pi^+\pi^-, \pi^+\pi^-\pi^+\pi^-]_D \{K^{\pm}, \pi^{\pm}\}$ [2]

LHCb, arXiv:2301.10328

- Fit also includes CPV observables based on integrated yields

$$A_h^{KK\pi\pi} = \frac{\Gamma(B^- \to Dh^-) - \Gamma(B^+ \to Dh^+)}{\Gamma(B^- \to Dh^-) + \Gamma(B^+ \to Dh^+)} = \frac{2r_B^{Dh}\kappa \sin(\delta_B^{Dh}) \sin\gamma}{1 + (r_B^{Dh})^2 + 2r_B^{Dh}\kappa\cos(\delta_B^{Dh})\cos\gamma}$$

$h = K, \pi$

$$R_{CP}^{KK\pi\pi} = \frac{R_{KK\pi\pi}}{R_{K\pi\pi\pi}} = 1 + (r_B^{DK})^2 + 2r_B^{DK}\kappa\cos(\delta_B^{DK})\cos\gamma\,,$$

$$R_f = \frac{\Gamma(B^- \to f_D K^-) + \Gamma(B^+ \to f_D K^+)}{\Gamma(B^- \to f_D \pi^-) + \Gamma(B^+ \to f_D \pi^+)}$$

  - $\kappa = 2F_{CP+} - 1$ = dilution from integration over PS[2]
  - Similar expression for $D \to \pi^+\pi^-\pi^+\pi^-$

[2] LHCb, arXiv:2209.03692, LHCb, PLB 747 (2015)

$B^{\pm} \to [K^+K^-\pi^+\pi^-, \pi^+\pi^-\pi^+\pi^-]_D \{K^{\pm}, \pi^{\pm}\}$ [2]

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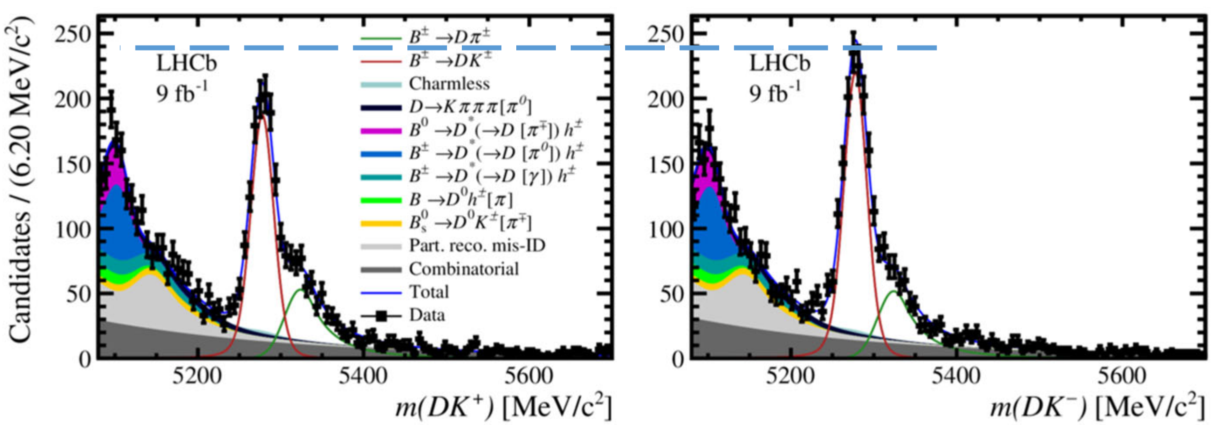
$$R_{CP}^{KK\pi\pi} = \frac{R_{KK\pi\pi}}{R_{K\pi\pi\pi}} = 1 + (r_B^{DK})^2 + 2r_B^{DK}\kappa\cos(\delta_B^{DK})\cos\gamma\,, \qquad R_f = \frac{\Gamma(B^- \to f_D K^-) + \Gamma(B^+ \to f_D K^+)}{\Gamma(B^- \to f_D \pi^-) + \Gamma(B^+ \to f_D \pi^+)}$$

  - $\kappa = 2F_{CP+} - 1$ = dilution from integration over PS[2]
  - Similar expression for $D \to \pi^+\pi^-\pi^+\pi^-$



CPV observable	Fit results $(K^+K^-\pi^+\pi^-)$
$A_K^{KK\pi\pi}$	$(9.3 \pm 2.3 \pm 0.2)\%$
$R_{CP}^{KK\pi\pi}$	$0.974 \pm 0.024 \pm 0.015$
$A_\pi^{KK\pi\pi}$	$(-0.9 \pm 0.6 \pm 0.1)\%$

CPV observable	Fit results $(\pi^+\pi^-\pi^+\pi^-)$
$A_K^{\pi\pi\pi\pi}$	$(6.0 \pm 1.3 \pm 0.1)\%$
$R_{CP}^{\pi\pi\pi\pi}$	$0.978 \pm 0.014 \pm 0.010$
$A_\pi^{\pi\pi\pi\pi}$	$(-0.82 \pm 0.31 \pm 0.07)\%$

[2] LHCb, arXiv:2209.03692, LHCb, PLB 747 (2015)

Fit for CP Observables [3]

LHCb, arXiv:2301.10328

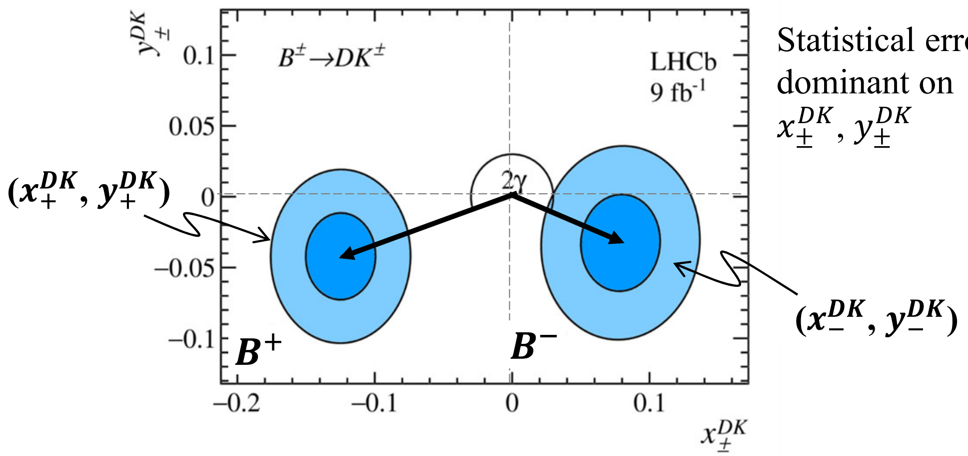
- Fit for best $(x_\pm^{DK}, y_\pm^{DK})$ given the observed yields in each bin i.

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

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

$$x_\pm^{DK} = r_B^{DK}\cos(\delta_B^{DK} \pm \gamma),$$

$$y_\pm^{DK} = r_B^{DK}\sin(\delta_B^{DK} \pm \gamma)$$



Statistical error dominant on $x_\pm^{DK}$, $y_\pm^{DK}$

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LHCb, arXiv:2301.10328

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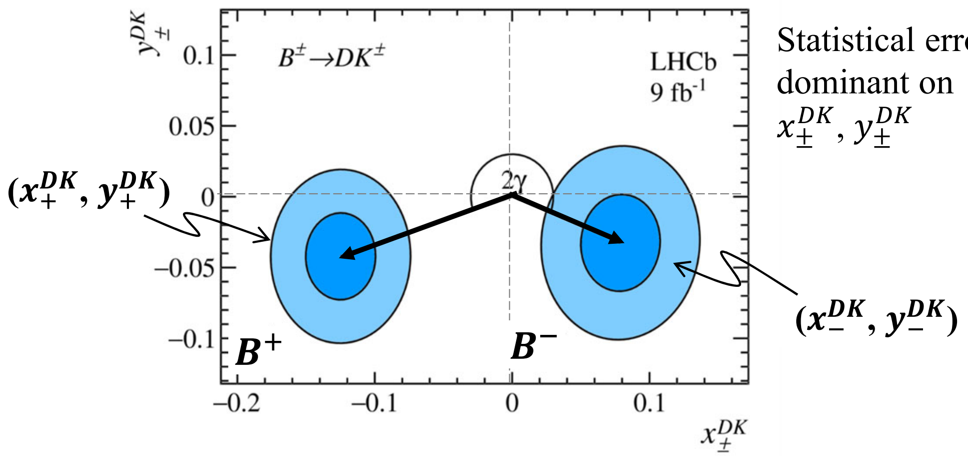
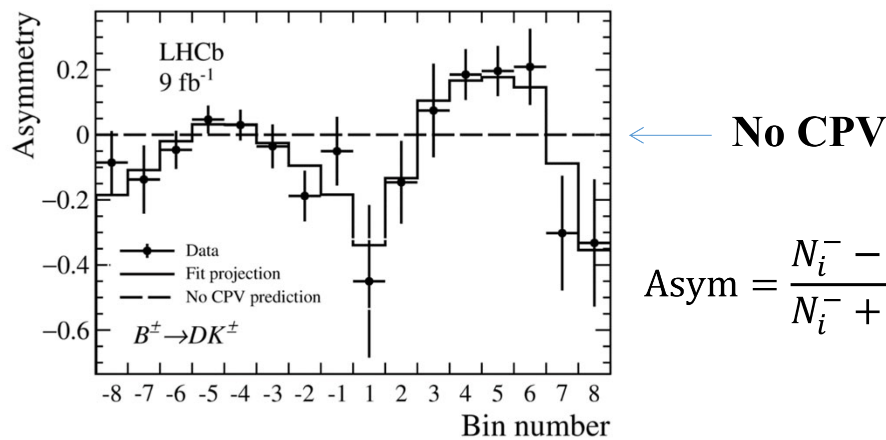
$$N_{-i}^{-}(x_-^{DK}, y_-^{DK}) = h_{B^-}\left[F_{-i} + \left((x_-^{DK})^2 + (y_-^{DK})^2\right)F_{+i} + 2\sqrt{F_{+i}F_{-i}}(x_-^{DK}c_i - y_-^{DK}s_i)\right]$$

$$x_\pm^{DK} = r_B^{DK}\cos(\delta_B^{DK} \pm \gamma),$$

$$y_\pm^{DK} = r_B^{DK}\sin(\delta_B^{DK} \pm \gamma)$$



Statistical error dominant on $x_\pm^{DK}, y_\pm^{DK}$



$$\text{Asym} = \frac{N_i^- - N_{-i}^+}{N_i^- + N_{-i}^+}$$

Fit for CP Observables [3]

LHCb, arXiv:2301.10328

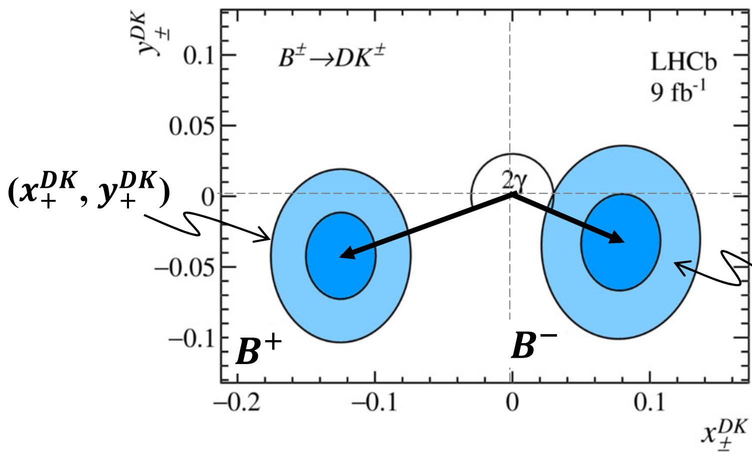
- Fit for best $(x_\pm^{DK}, y_\pm^{DK})$ given the observed yields in each bin i.

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

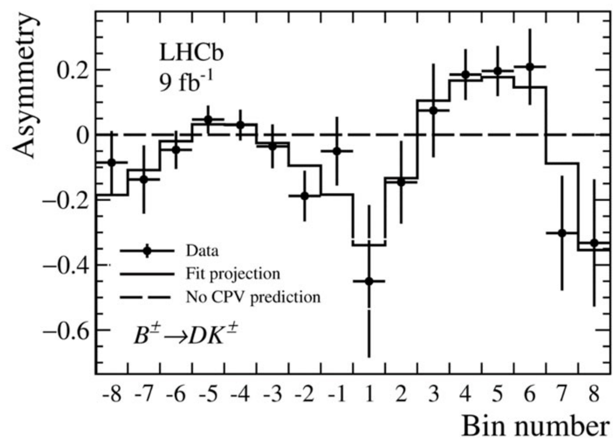
$$N_{-i}^{-}(x_-^{DK}, y_-^{DK}) = h_{B^-}\left[F_{-i} + \left((x_-^{DK})^2 + (y_-^{DK})^2\right)F_{+i} + 2\sqrt{F_{+i}F_{-i}}(x_-^{DK}c_i - y_-^{DK}s_i)\right]$$

$$x_\pm^{DK} = r_B^{DK}\cos(\delta_B^{DK} \pm \gamma),$$

$$y_\pm^{DK} = r_B^{DK}\sin(\delta_B^{DK} \pm \gamma)$$



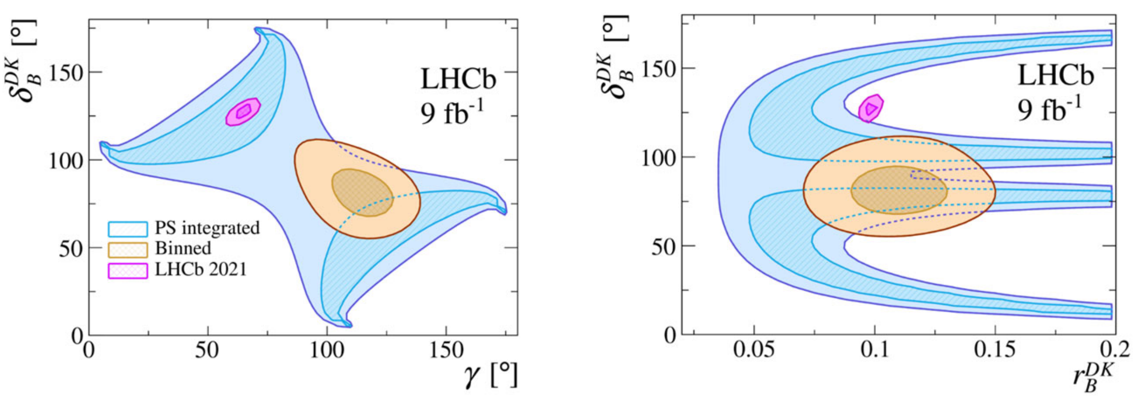
Statistical error dominant on $x_\pm^{DK}, y_\pm^{DK}$



No CPV

$$\text{Asym} = \frac{N_i^- - N_{-i}^+}{N_i^- + N_{-i}^+}$$

- **ML fit to obtain physics parameters (see LHCb, JHEP 12, 141 (2021))**



Model-dependent result

$$\boldsymbol{\gamma = \left(116^{+12}_{-14}\right)^o}$$

- **Future:** Model independent analysis; BES III can measure directly the c_i, s_i using quantum-correlated $D\bar{D}$ pairs

Overall LHCb γ combination + fit for D mixing parameters

- Including D mixing important in $B^{\pm} \to D\pi^{\pm}$, where $x,y \sim r_B$.

$$\Gamma_{\text{w D mix}}(B^{\pm} \to Dh^{\pm}) \propto \Gamma_{\text{no D mix}} + \Delta\Gamma_{\text{D mix}}$$

$$\Gamma_{\text{no D mix}}(B^{\pm} \to Dh^{\pm}) \propto r_D^2 + r_B^2 + 2\kappa_D\kappa_B r_D r_B \cos(\delta_B + \delta_D \pm \gamma)$$

$$\Delta\Gamma_{\text{D mix}} = -\alpha[(1 + r_B^2)\kappa_D r_D \cos(\delta_D) + (1 + r_D^2)\kappa_B r_B \cos(\delta_B \pm \gamma)]\boldsymbol{y}$$
$$+\alpha[(1 - r_B^2)\kappa_D r_D \sin(\delta_D) - (1 - r_D^2)\kappa_B r_B \sin(\delta_B \pm \gamma)]\boldsymbol{x}$$

LHCb, JHEP 12, 141 (2021)

	B decay	D decay	Ref.	Dataset	Status since Ref. [17]
$B^{\pm}$	$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-$	[20]	Run 1&2	**Updated**
	$B^{\pm} \to Dh^{\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[21]	Run 1	As before
	$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-\pi^0$	[22]	Run 1	As before
	$B^{\pm} \to Dh^{\pm}$	$D \to K_S^0 h^+h^-$	[19]	Run 1&2	**Updated**
	$B^{\pm} \to Dh^{\pm}$	$D \to K_S^0 K^{\pm}\pi^{\mp}$	[23]	Run 1&2	**Updated**
	$B^{\pm} \to D^*h^{\pm}$	$D \to h^+h^-$	[20]	Run 1&2	**Updated**
	$B^{\pm} \to DK^{*\pm}$	$D \to h^+h^-$	[24]	Run 1&2(*)	As before
	$B^{\pm} \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[24]	Run 1&2(*)	As before
	$B^{\pm} \to Dh^{\pm}\pi^+\pi^-$	$D \to h^+h^-$	[25]	Run 1	As before
B^0	$B^0 \to DK^{*0}$	$D \to h^+h^-$	[26]	Run 1&2(*)	**Updated**
	$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[26]	Run 1&2(*)	**New**
	$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$	[27]	Run 1	As before
	$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^-\pi^+\pi^+$	[28]	Run 1	As before
B_s	$B_s^0 \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	[29]	Run 1	As before
	$B_s^0 \to D_s^{\mp}K^{\pm}\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[30]	Run 1&2	**New**

D decay	Observable(s)	Ref.	Dataset	Status since Ref. [17]
$D^0 \to h^+h^-$	ΔA_{CP}	[31,32,33]	Run 1&2	**New**
$D^0 \to h^+h^-$	y_{CP}	[34]	Run 1	**New**
$D^0 \to h^+h^-$	ΔY	[35,36,37,38]	Run 1&2	**New**
$D^0 \to K^+\pi^-$ (Single Tag)	$R^{\pm}$, $(x'^{\pm})^2$, $y'^{\pm}$	[39]	Run 1	**New**
$D^0 \to K^+\pi^-$ (Double Tag)	$R^{\pm}$, $(x'^{\pm})^2$, $y'^{\pm}$	[40]	Run 1&2(*)	**New**
$D^0 \to K^{\pm}\pi^{\mp}\pi^+\pi^-$	$(x^2 + y^2)/4$	[41]	Run 1	**New**
$D^0 \to K_S^0\pi^+\pi^-$	x, y	[42]	Run 1	**New**
$D^0 \to K_S^0\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[43]	Run 1	**New**
$D^0 \to K_S^0\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[44]	Run 2	**New**

Overall LHCb γ combination + fit for D mixing parameters

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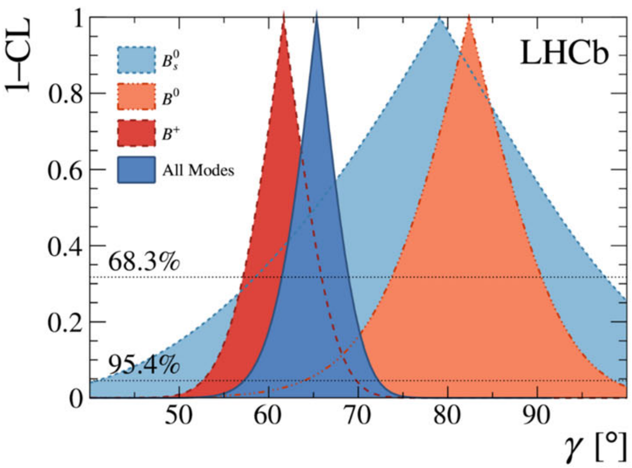
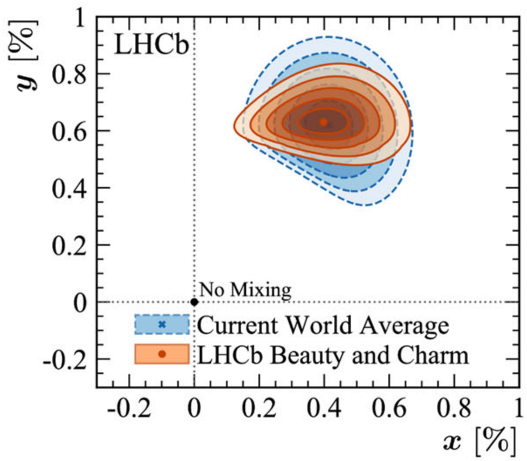
$$\Gamma_{\text{no D mix}}(B^\pm \to Dh^\pm) \propto r_D^2 + r_B^2 + 2\kappa_D\kappa_B r_D r_B \cos(\delta_B + \delta_D \pm \gamma)$$

$$\Delta\Gamma_{\text{D mix}} = -\alpha[(1 + r_B^2)\kappa_D r_D \cos(\delta_D) + (1 + r_D^2)\kappa_B r_B \cos(\delta_B \pm \gamma)]\boldsymbol{y}$$
$$+\alpha[(1 - r_B^2)\kappa_D r_D \sin(\delta_D) - (1 - r_D^2)\kappa_B r_B \sin(\delta_B \pm \gamma)]\boldsymbol{x}$$





LHCb, JHEP 12, 141 (2021)

	B decay	D decay	Ref.	Dataset	Status since Ref. [17]
$B^\pm$	$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[20]	Run 1&2	**Updated**
	$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[21]	Run 1	As before
	$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[22]	Run 1	As before
	$B^\pm \to Dh^\pm$	$D \to K_S^0h^+h^-$	[19]	Run 1&2	**Updated**
	$B^\pm \to Dh^\pm$	$D \to K_S^0K^\pm\pi^\mp$	[23]	Run 1&2	**Updated**
	$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[20]	Run 1&2	**Updated**
	$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[24]	Run 1&2(*)	As before
	$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[24]	Run 1&2(*)	As before
	$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[25]	Run 1	As before
B^0	$B^0 \to DK^{*0}$	$D \to h^+h^-$	[26]	Run 1&2(*)	**Updated**
	$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[26]	Run 1&2(*)	**New**
	$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$	[27]	Run 1	As before
	$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[28]	Run 1	As before
B_s	$B_s^0 \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	[29]	Run 1	As before
	$B_s^0 \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[30]	Run 1&2	**New**
	D decay	Observable(s)	Ref.	Dataset	Status since Ref. [17]
	$D^0 \to h^+h^-$	ΔA_{CP}	[31,32,33]	Run 1&2	**New**
	$D^0 \to h^+h^-$	y_{CP}	[34]	Run 1	**New**
	$D^0 \to h^+h^-$	ΔY	[35,36,37,38]	Run 1&2	**New**
	$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[39]	Run 1	**New**
	$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[40]	Run 1&2(*)	**New**
	$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2 + y^2)/4$	[41]	Run 1	**New**
	$D^0 \to K_S^0\pi^+\pi^-$	x, y	[42]	Run 1	**New**
	$D^0 \to K_S^0\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[43]	Run 1	**New**
	$D^0 \to K_S^0\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[44]	Run 2	**New**

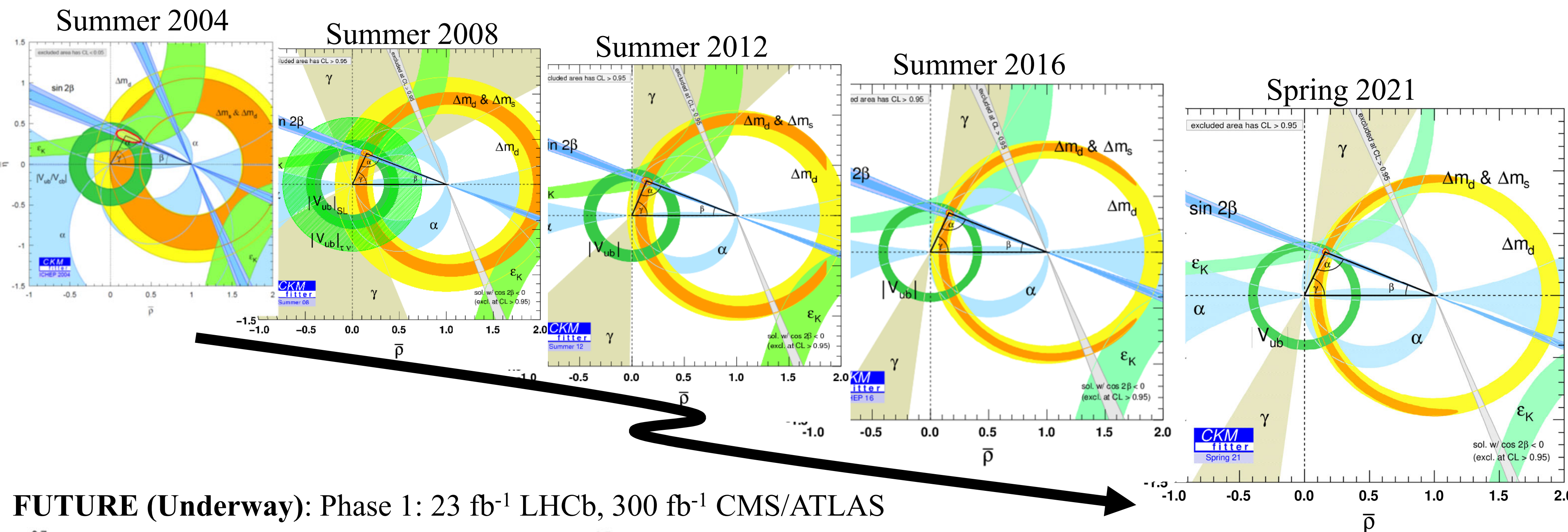
- **$B^\pm$ decays currently dominate average**

$$\gamma_{LHCb}^{direct} = (65.4^{+3.8}_{-4.2})^o$$

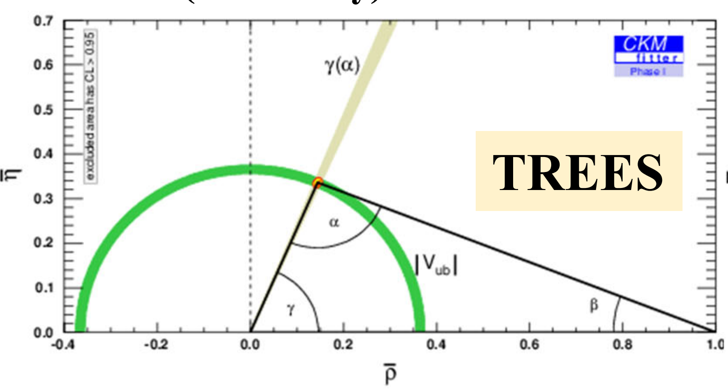
- Most precise single experiment measurement
- Consistent with WA **indirect** measurements: $\boldsymbol{\gamma = (65.66^{+1.30}_{-1.20})^o}$ [1]
- More measurements in the pipeline (LHCb, Run1, 2)

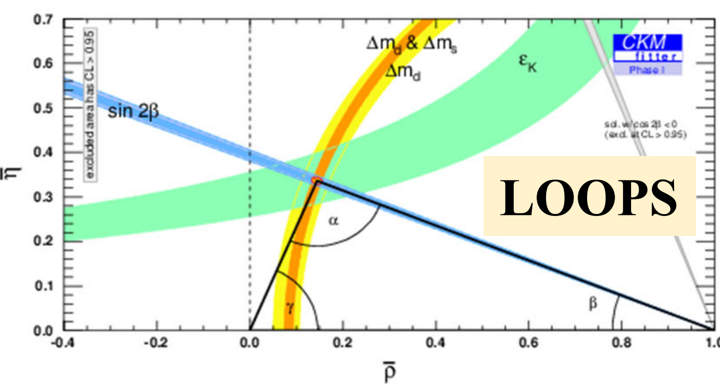
[1] CKMFitter, PR **D91** (2015)

Gamma timeline



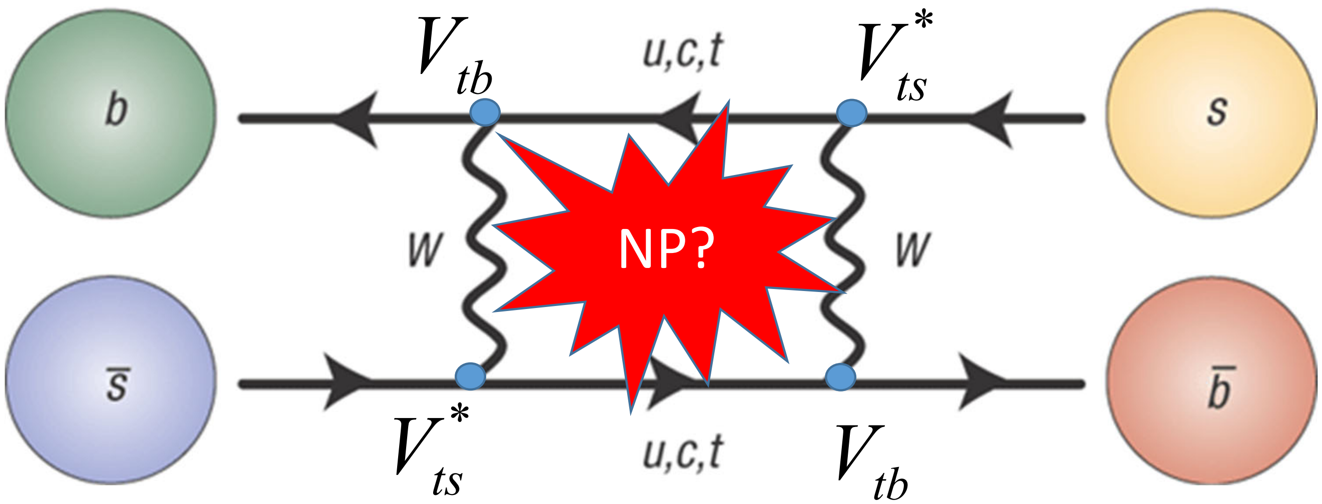
FUTURE (Underway): Phase 1: 23 fb^{-1} LHCb, 300 fb^{-1} CMS/ATLAS





- **Today: $\sigma_\gamma \sim 4^o$**
- **Phase 1 (~2032): $\sigma_\gamma \sim 1.5^o$**
- **Phase 2 (~2038-40): $\sigma_\gamma \sim 0.4^o$**
  LHCb 300 fb^{-1}, CMS/ATLAS 3000 fb^{-1}
- **Precision test of CKM paradigm!**

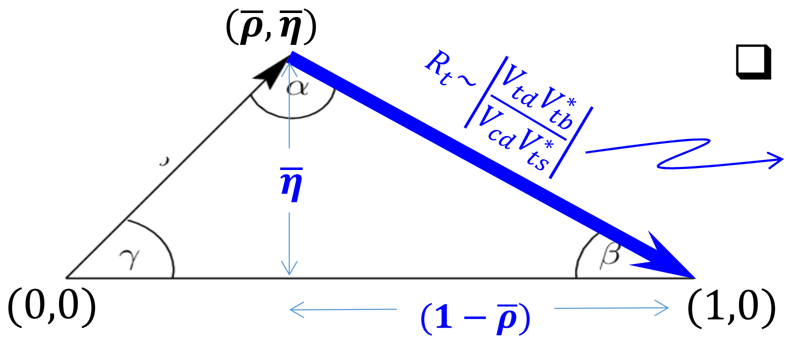
Loop Processes



- ❑ Depending on NP model, heavy particles can also enter at tree-level (*e.g* heavy Z' that allows FCNC, see Bause *et al*, EPJ *C82*, 42 (2022))

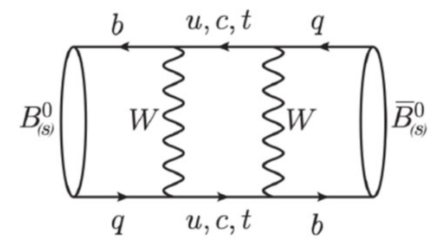
B^0/B_s mixing: Side of UT

- Occurs through box diagrams, **sensitive to heavy NP particles**.



❑ **Mixing frequencies**

$$R_t = \sqrt{(1-\bar{\rho})^2+\bar{\eta}^2} \propto \left|\frac{\Delta m_d}{\Delta m_s}\right| \propto \left|\frac{V_{td}}{V_{ts}}\right|^2$$



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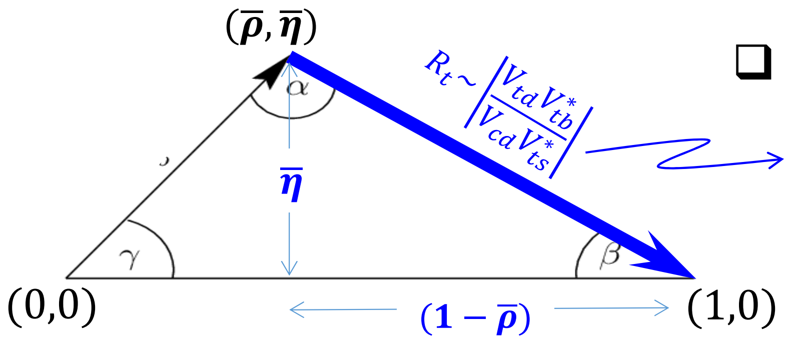
- Occurs through box diagrams, **sensitive to heavy NP particles**.



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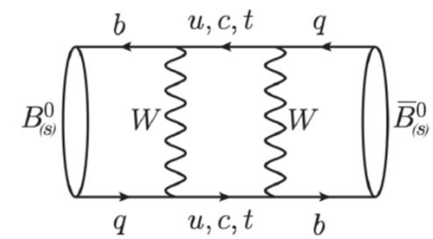
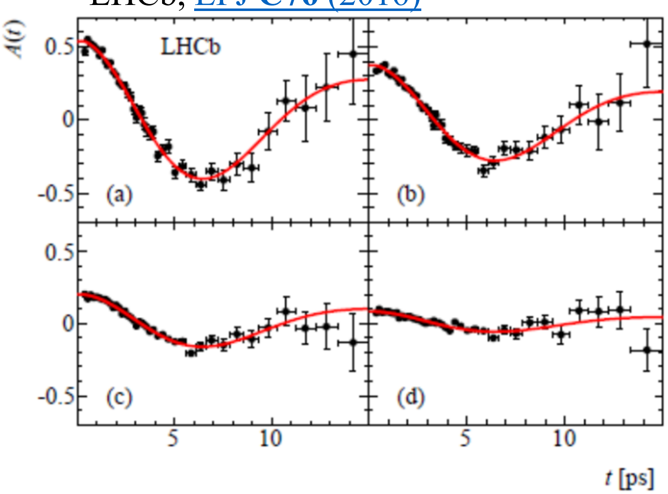


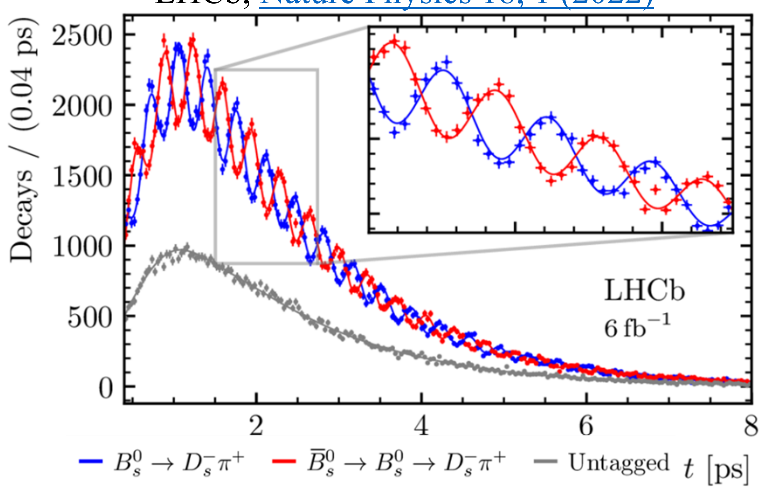
$B^0 \to D^-\mu^+\nu_\mu X$

LHCb, EPJ **C76** (2016)



$B_s \to D_s^-\pi^+$

LHCb, Nature Physics 18, 1 (2022)

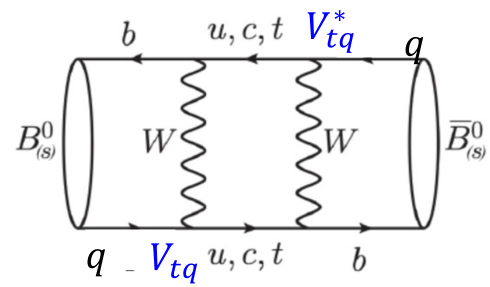


❑ $\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\ \text{ps}^{-1}$ (~0.03% precision!)

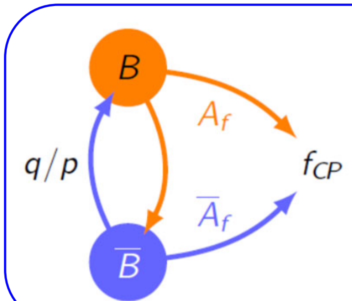
❑ $\Delta m_d = 0.5050 \pm 0.0021 \pm 0.0010\ \text{ps}^{-1}$ (~0.4% precision)

❑ R_t uncertainty dominated by QCD matrix elements, but improvements in coming years expected, O(1%) on $|V_{td}|, |V_{ts}|$ achievable.

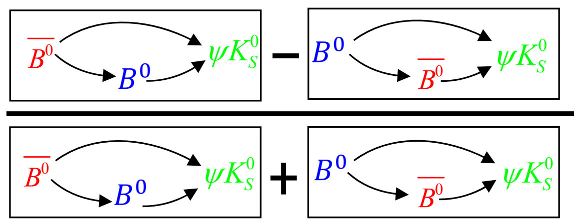
Phase of B mixing: Side of UT



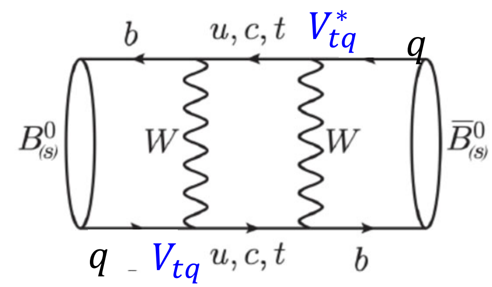
- Access by interference between $B_{(s)} \to f_{CP}$ and $B_{(s)} \to \bar{B}_{(s)} \to f_{CP}$
- Mixing diagram brings in $\text{Arg}\left(V_{tq}^* V_{tb}\right)^2 = \frac{q}{p} = \exp(-i2\beta_{(s)})$
- Expose phase through **time-dependent decay time asymmetry**



$A(t) =$



Phase of B mixing



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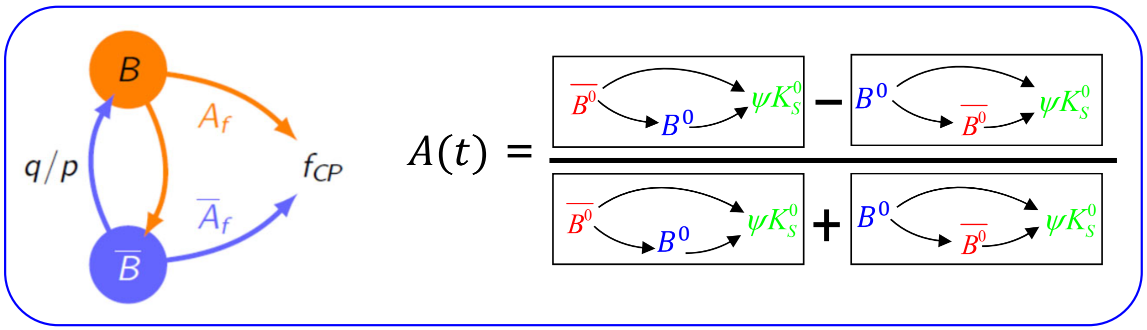

CPV interference between direct decay and mixing + decay

Direct CPV (in $\bar{A}_f / A_f$)

$$\boldsymbol{A(t) \cong S \sin(\Delta m_q\, t) + C \cos(\Delta m_q\, t)}$$

$$S = -\frac{2Im(\lambda)}{1 + |\lambda|^2} \qquad C = \frac{1 - |\lambda|^2}{1 + |\lambda|^2} \qquad \boldsymbol{\lambda = \frac{q}{p}\frac{\bar{A}}{A}}$$

- For $f_{CP} = J/\psi K_S^0$, expect **single decay amplitude dominant** → $|\lambda| = 1$
  - Expect $C \cong 0$ ➔ $\boldsymbol{A(t) = \sin(2\beta)\, \sin(\Delta m_d\, t)}$

Phase of B mixing

- Access by interference between $B_{(s)} \to f_{CP}$ and $B_{(s)} \to \bar{B}_{(s)} \to f_{CP}$
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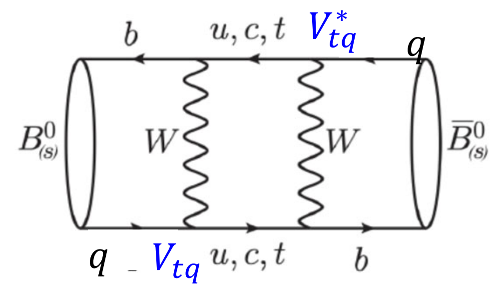
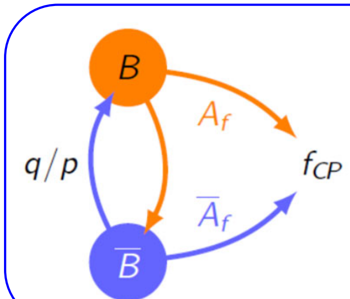
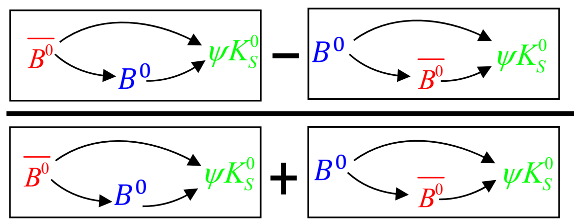




$A(t) =$ 

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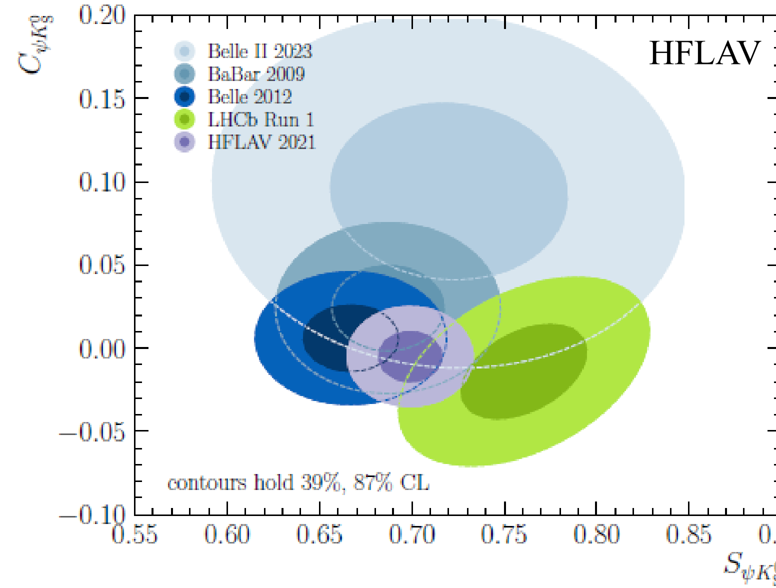
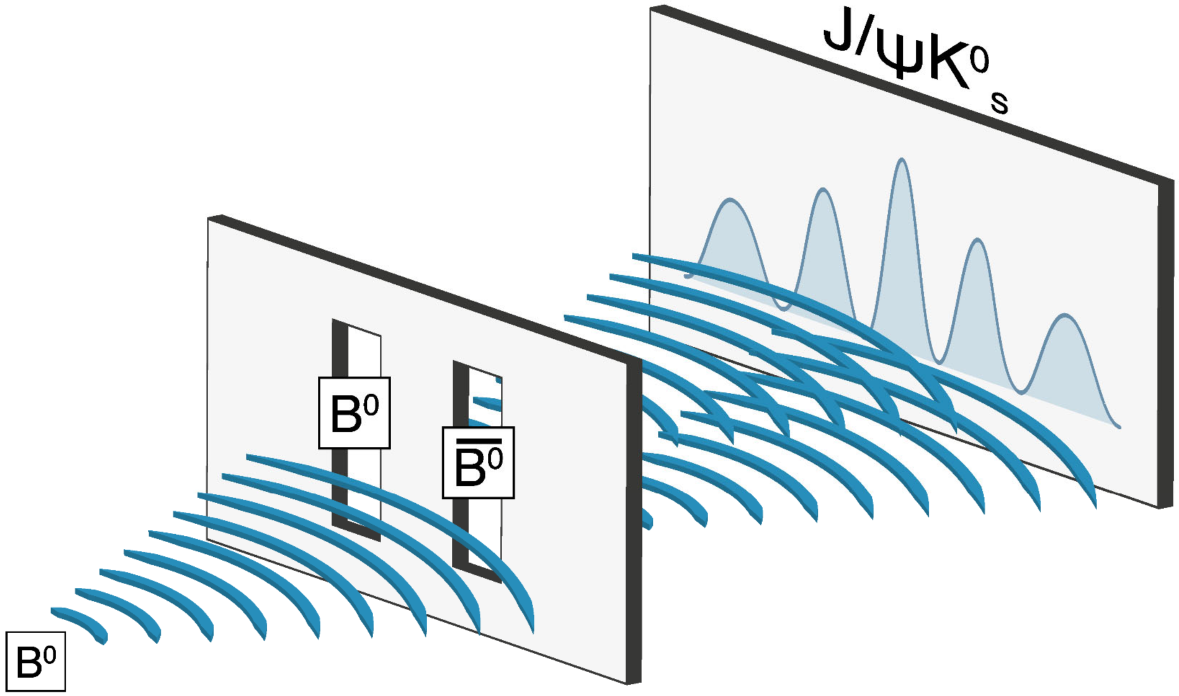
  - Expect $C \cong 0$ ➔ $\boldsymbol{A(t) = \sin(2\beta)\, \sin(\Delta m_d\, t)}$

- **Previous measurements**

$\langle \sin 2\beta \rangle_{WA}^{2021} = 0.699 \pm 0.017$ (2.4%)



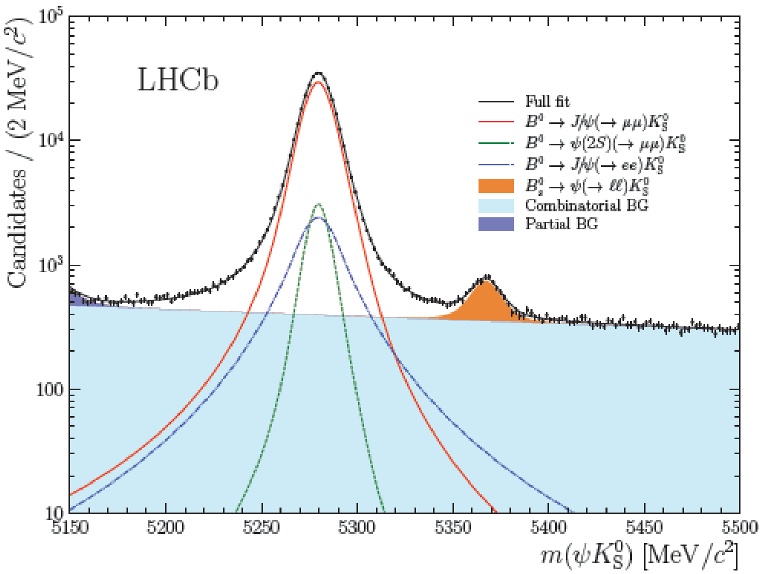
Measurement of sin(2β) in $B^0 \to \psi_{\ell^+\ell^-} K_S^0$



Measurement of CPV in $B^0 \to \psi_{\ell^+\ell^-} K_S^0$ [1]

LHCb-PAPER-2023-013
(in preparation)

- **Full Run 2 data sample (6 fb^{-1})**
- $J/\psi \to \mu^+\mu^-, e^+e^-$ and $\psi(2S) \to \mu^+\mu^-$



$B^0 \to (c\bar{c})K_S^0$	Signal (10^3) [with tag]	$\varepsilon_{tag} D^2$
$J/\psi \to \mu^+\mu^-$	306	4.71 ± 0.01
$J/\psi \to e^+e^-$	23.6	4.62 ± 0.04
$\psi(2S) \to \mu^+\mu^-$	42.7	6.48 ± 0.03

Measurement of CPV in $B^0 \to \psi_{\ell^+\ell^-} K_S^0$ [1]

LHCb-PAPER-2023-013
(in preparation)

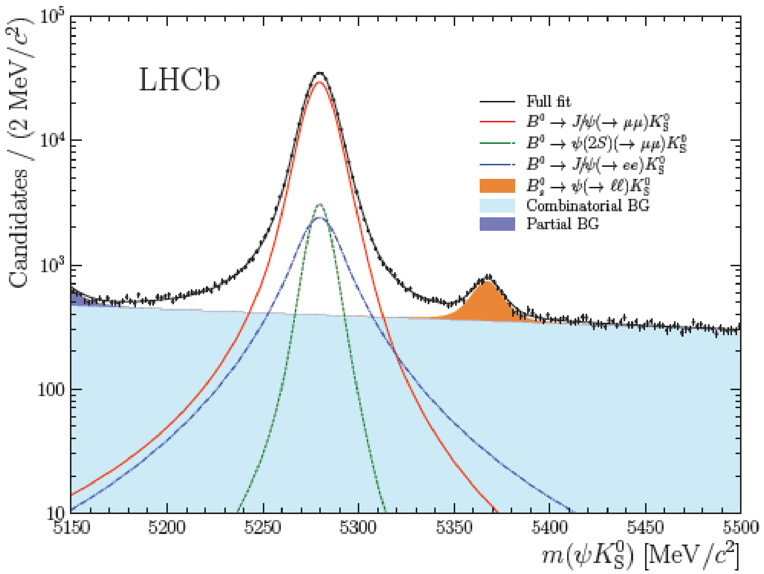
- **Full Run 2 data sample (6 fb^{-1})**
- $J/\psi \to \mu^+\mu^-, e^+e^-$ and $\psi(2S) \to \mu^+\mu^-$

$$\mathcal{P}(t,d,\tilde{\eta}) \propto e^{-\Gamma t}\left\{[1+d(1-2\omega^+(\tilde{\eta}))]P_{B^0}(t) + [1+d(1-2\omega^-(\tilde{\eta}))]P_{\bar{B}^0}(t)\right\}$$

$$P_{B^0,(\bar{B}^0)}(t) \propto (1\mp\alpha)(1\mp\Delta\epsilon_{\text{tag}})(1\mp \boldsymbol{S}\sin(\Delta m_d t) \pm \boldsymbol{C}\cos(\Delta m_d t)),$$

- ❑ $d = +1(B^0), -1\ (\bar{B}^0)$
- ❑ $\omega^+(\tilde{\eta}), \omega^-(\tilde{\eta})$: Calibrated mistag rates for $B^0, \bar{B}^0$
- ❑ $\alpha, \Delta\epsilon_{tag}$ account for production, flavor-tag asymmetry

$\sigma_t \sim 60\ fs$



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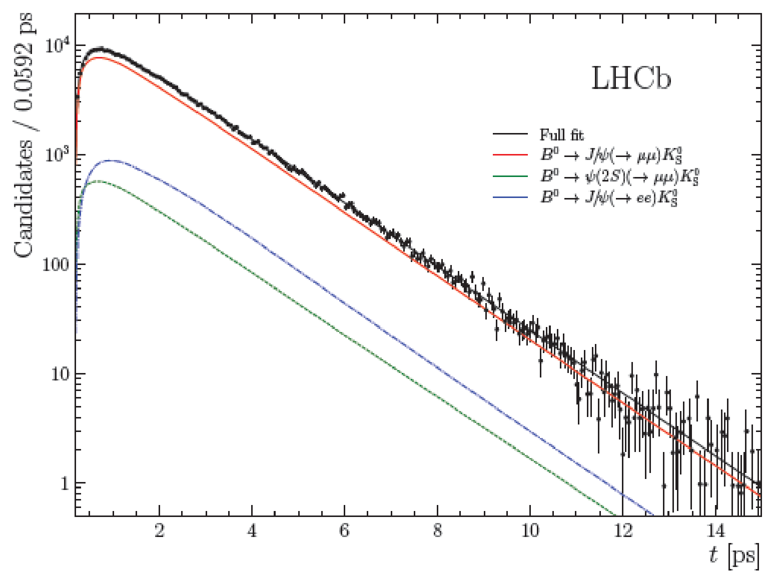
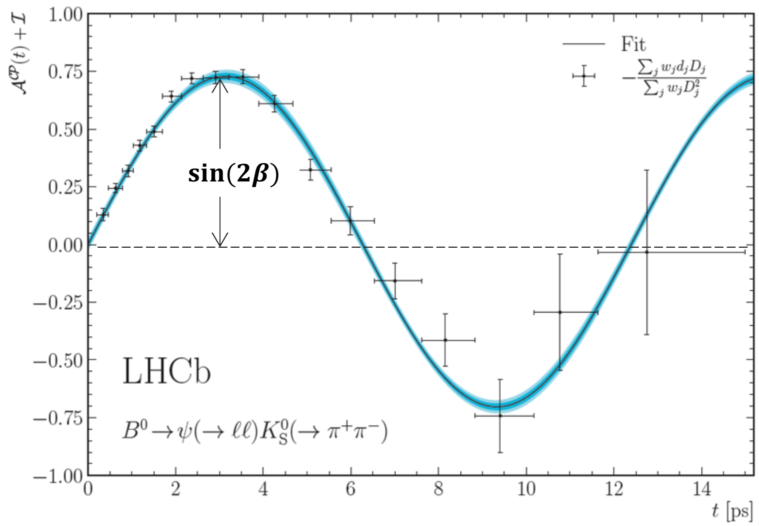


- ❑ Simultaneous fit to flavor-tagged B^0 and $\bar{B}^0$ decay time spectra.
- ❑ **S** and **C** are free parameters in the fit.

Measurement of CPV in $B^0 \to \psi_{\ell^+\ell^-} K_S^0$ [2]

LHCb-PAPER-2023-013
(in preparation)

Time-dependent asymmetry



$$S^{\text{Run 2}}_{J/\psi(\to\mu^+\mu^-)K^0_S} = 0.714 \pm 0.015\,(\text{stat}) \pm 0.0074\,(\text{syst})$$
$$C^{\text{Run 2}}_{J/\psi(\to\mu^+\mu^-)K^0_S} = 0.013 \pm 0.014\,(\text{stat}) \pm 0.0025\,(\text{syst})$$
$$S^{\text{Run 2}}_{\psi(2S)K^0_S} = 0.647 \pm 0.053\,(\text{stat}) \pm 0.018\,(\text{syst})$$
$$C^{\text{Run 2}}_{\psi(2S)K^0_S} = -0.083 \pm 0.048\,(\text{stat}) \pm 0.0053\,(\text{syst})$$
$$S^{\text{Run 2}}_{J/\psi(\to e^+e^-)K^0_S} = 0.752 \pm 0.037\,(\text{stat}) \pm 0.084\,(\text{syst})$$
$$C^{\text{Run 2}}_{J/\psi(\to e^+e^-)K^0_S} = 0.046 \pm 0.034\,(\text{stat}) \pm 0.0077\,(\text{syst})$$

LHCb Run 2 (Preliminary)

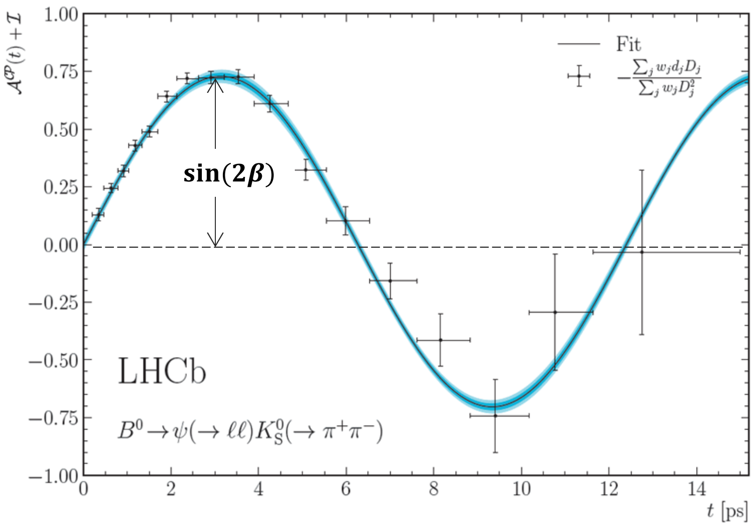
$$S^{\text{Run 2}}_{\psi K^0_S} = 0.7158 \pm 0.0133\,(\text{stat}) \pm 0.0078\,(\text{syst})$$
$$C^{\text{Run 2}}_{\psi K^0_S} = 0.0120 \pm 0.0123\,(\text{stat}) \pm 0.0029\,(\text{syst})$$

- ~2X more precise than, and compatible with B-factories
- Preliminary WA ~ 1.5% precision.

Measurement of CPV in $B^0 \to \psi_{\ell^+\ell^-}K_S^0$ [2]

LHCb-PAPER-2023-013
(in preparation)

Time-dependent asymmetry



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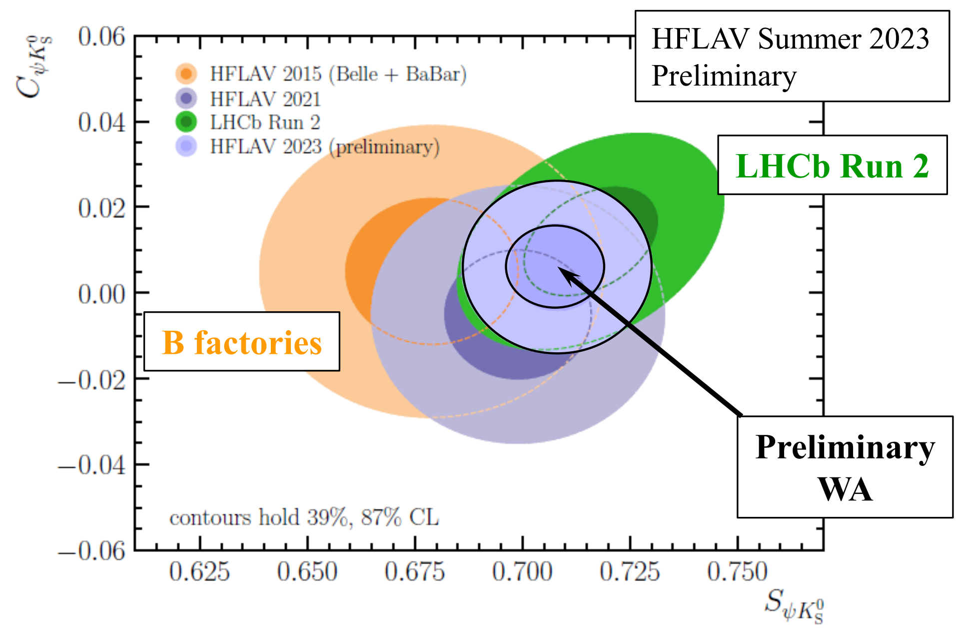

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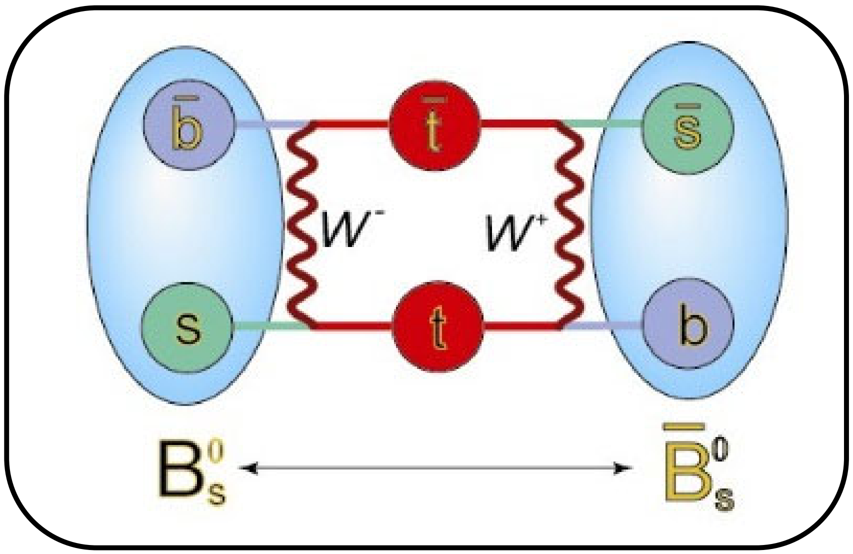
- ~2X more precise than, and compatible with B-factories
- Preliminary WA ~ 1.6% precision.

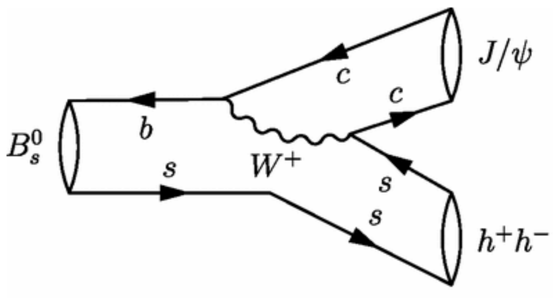
$$S^{WA}_{2021} = 0.699 \pm 0.017 \;\; (2.4\%) \;\to\; S^{WA}_{\psi K_S^0} = 0.708 \pm 0.011\;(1.6\%)$$

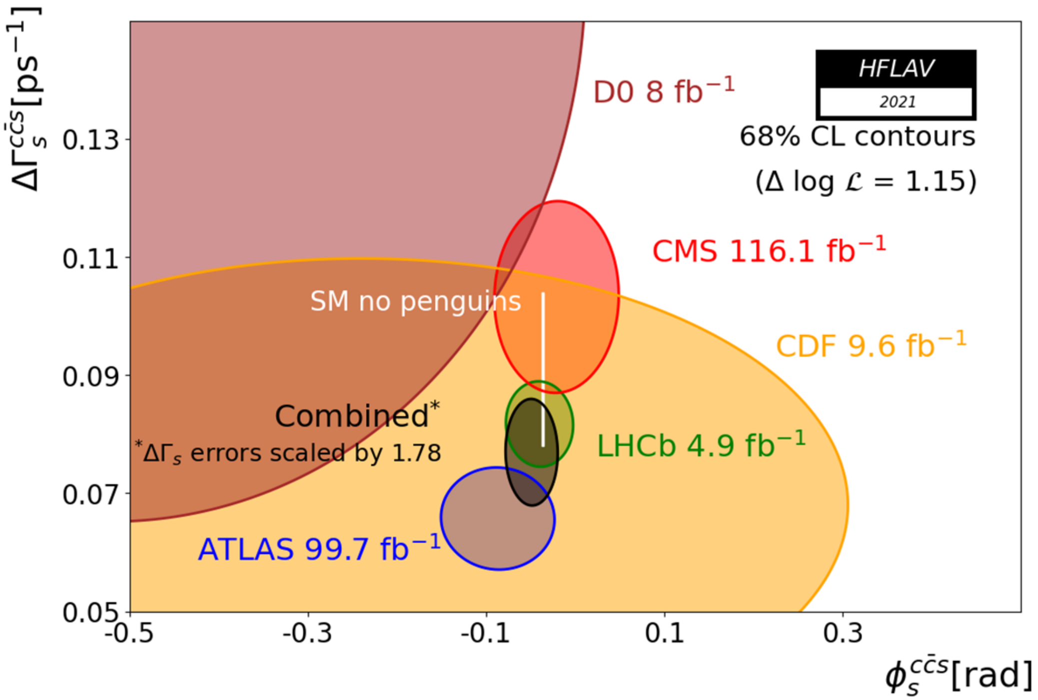
CPV phase in B_s mixing: φ_s



CPV phase φ_s

- In SM, $\boldsymbol{\varphi_s \cong -2\beta_s}$, the **phase of B_s mixing**.
- Global fits (w/o direct m'ment), $\boldsymbol{\varphi_s = -36.8^{+0.09}_{-0.06}}$ **mrad** (<< $2\beta \approx 800$ mrad)
- New CPV phases can lead to large deviations
  - Ideal modes: $J/\psi h^+h^-$, no additional CKM phase $b \to c\bar{c}s$ ($V_{cb}V_{cs}$ real)
  - Must disentangle CP+ and CP– contributions (except $D_s^+D_s^-$)





- Statistical uncertainties still dominant.
- New results from LHCb using full Run 2 data sample (6 fb^{-1}), in preparation.

$$\varphi_s^{2021}(all\ b \to c\bar{c}s) = -50 \pm 19\ \text{mrad}$$

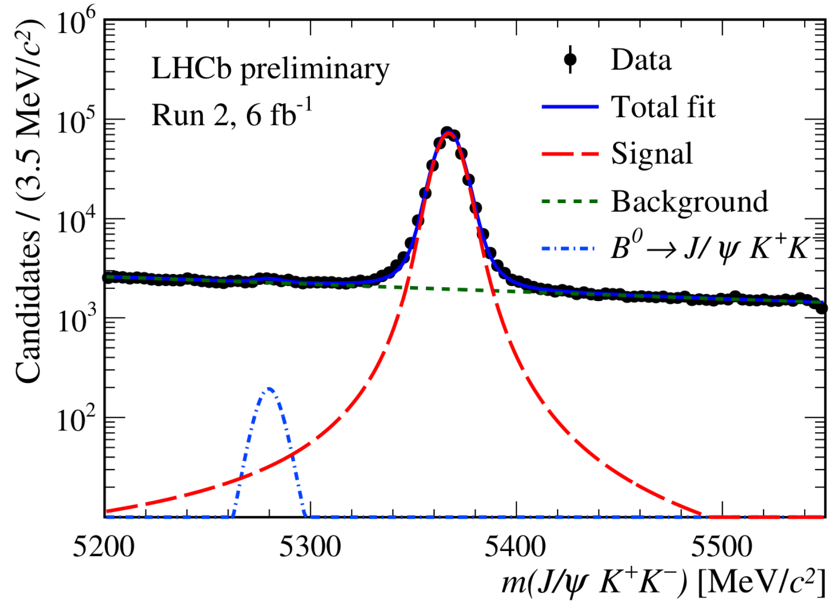
Measurement of CPV phase φ_s [1]

LHCb−PAPER−2023−016 (in prep)

- Use $B_s \to J/\psi K^+ K^-$ near φ.
- Fit time-dependent decay rates.

$$A_{CP}(t) = \frac{\Gamma(\bar{B}_s^0 \to f) - \Gamma(B_s^0 \to f)}{\Gamma(\bar{B}_s^0 \to f) + \Gamma(B_s^0 \to f)}$$
$$= \eta_f\, \mathcal{D}(t)\, \mathcal{D}(\omega)\, \sin(2\beta_s)\sin(\Delta m_s t)$$

- η_f = CP of final state
- $\mathcal{D}(t) = e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2}$: $\sigma_t \sim 42$ fs → $\mathcal{D}(t) \sim 0.76$
- $\mathcal{D}(\omega) = (1 - 2\omega)$ dilution due to mistag of flavor@production



$N_{sig} \sim 350{,}000$

Measurement of CPV phase φ_s [1]

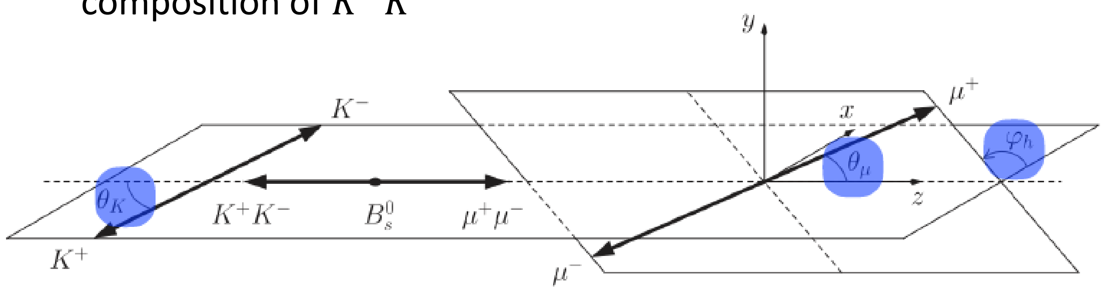
LHCb–PAPER–2023–016 (in prep)

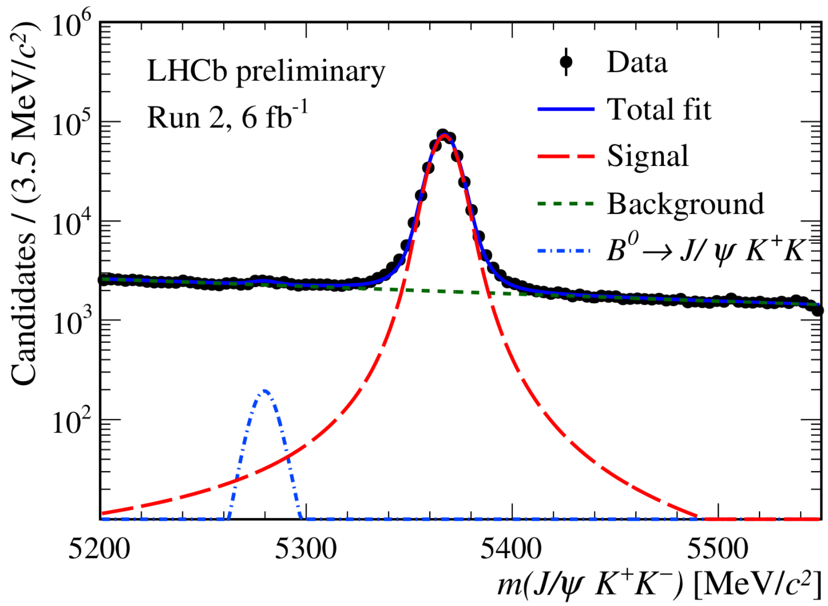
- Use $B_s \to J/\psi K^+K^-$ near φ.
- Fit time-dependent decay rates.

$$A_{CP}(t) = \frac{\Gamma(\bar{B}_s^0 \to f) - \Gamma(B_s^0 \to f)}{\Gamma(\bar{B}_s^0 \to f) + \Gamma(B_s^0 \to f)} = \eta_f\, \mathcal{D}(\mathrm{t})\, \mathcal{D}(\omega)\, \sin(2\beta_s) \sin(\Delta m_s t)$$

- η_f = CP of final state
- $\mathcal{D}(\mathrm{t}) = e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2}$: $\sigma_t \sim 42$ fs → $\mathcal{D}(\mathrm{t}) \sim 0.76$
- $\mathcal{D}(\omega) = (1 - 2\omega)$ dilution due to mistag of flavor@production

- $B_s \to J/\psi K^+K^-$: φ: L = 0, 2 (CP+), L=1 (CP-) or K^+K^- in S-wave
  - Decay rate PDFs also include decay angles, to determine CP composition of K^+K^-

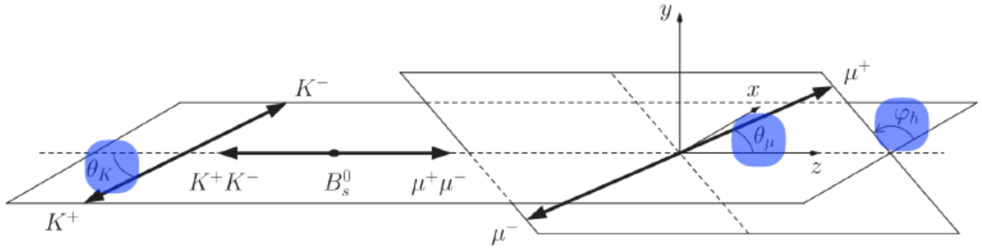


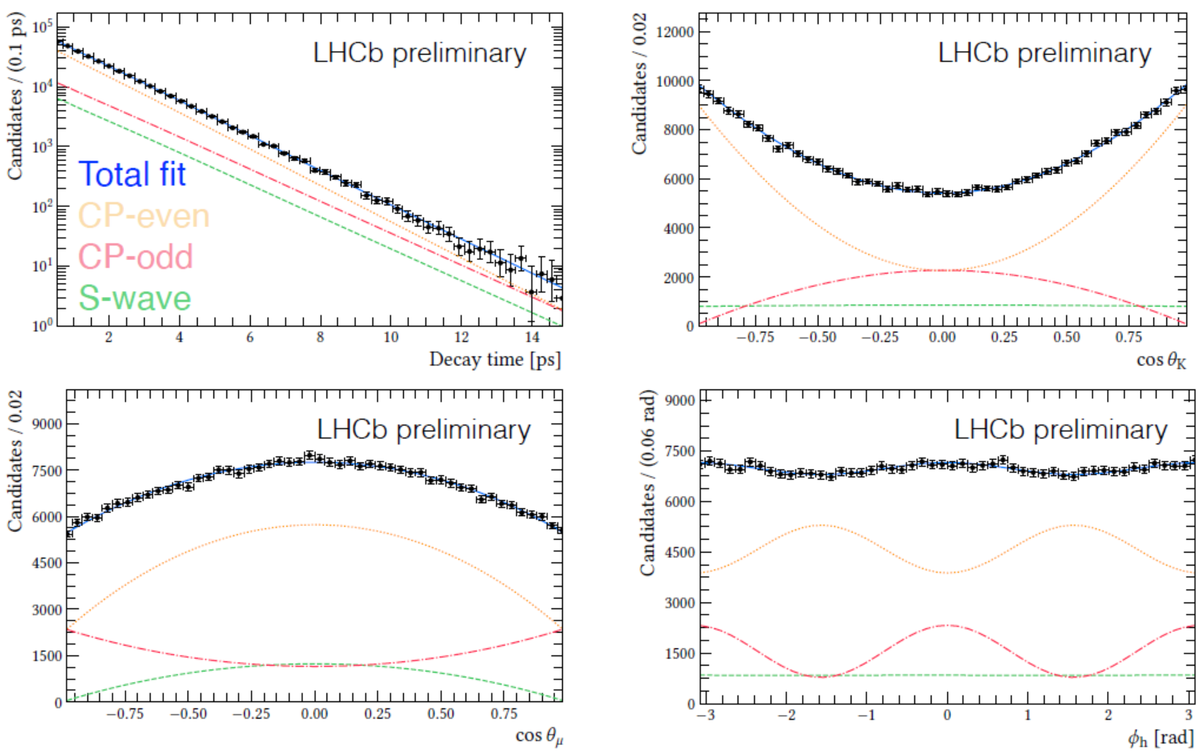


$N_{sig} \sim 350{,}000$

Measurement of CPV phase φ_s [2]

LHCb−PAPER−2023−016 (in prep)





Fit projections

$\varphi_s = -39 \pm 22 \pm 6$ mrad

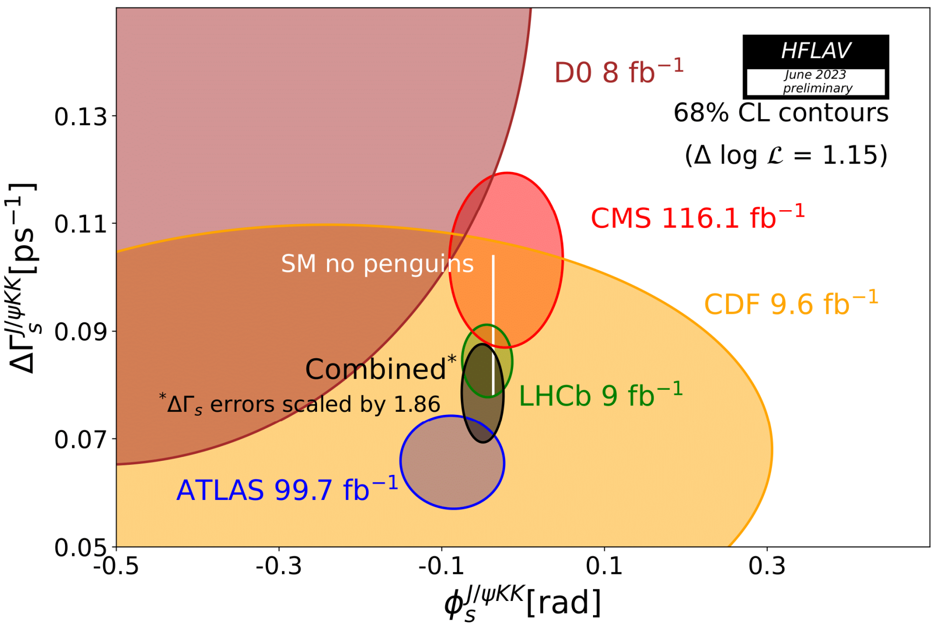
Parameter	Value with uncertainties
ϕ_s [rad]	$-0.039 \pm 0.022 \pm 0.006$
$\lvert\lambda\rvert$	$1.001 \pm 0.011 \pm 0.005$
$\Gamma_s - \Gamma_d$ [ps^{-1}]	$-0.0059\,^{+0.0013}_{-0.0014} \pm 0.0014$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0848\,^{+0.0044}_{-0.0045} \pm 0.0024$
Δm_s [ps^{-1}]	$17.743 \pm 0.033 \pm 0.009$
$\lvert A_\perp\rvert^2$	$0.2463 \pm 0.0023 \pm 0.0024$
$\lvert A_0\rvert^2$	$0.5179 \pm 0.0017 \pm 0.0032$
$\delta_\perp - \delta_0$ [rad]	$2.903\,^{+0.075}_{-0.074} \pm 0.048$
$\delta_\parallel - \delta_0$ [rad]	$3.146 \pm 0.060 \pm 0.052$

K^+K^- Polarization parameters

Measurement of CPV phase φ_s [3]

LHCb−PAPER−2023−016 (in prep)

- Most precise single φ_s analysis
- Consistent with no CPV, and with small value of $-36.8^{+0.09}_{-0.06}$ mrad, based on global CKM fit.



$$\varphi_s^{LHCb}(J/\psi\phi) = -39 \pm 22 \pm 6 \ \text{mrad}$$

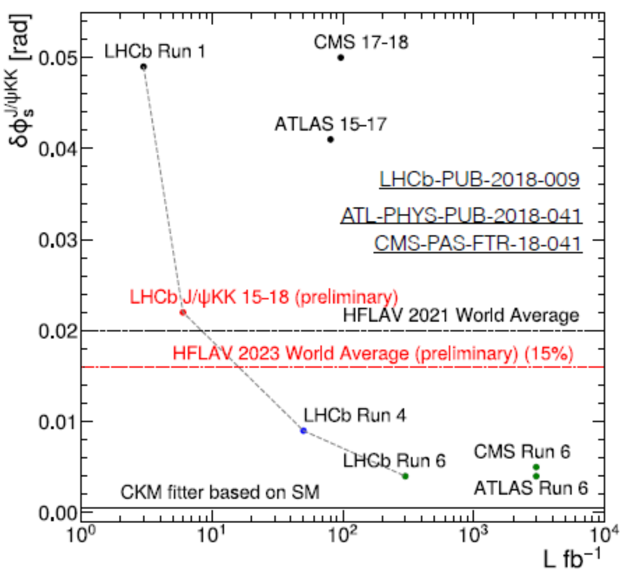
- Still statistically dominated.
- Will improve with LHCb Upgrade 1 & 2, CMS & ATLAS

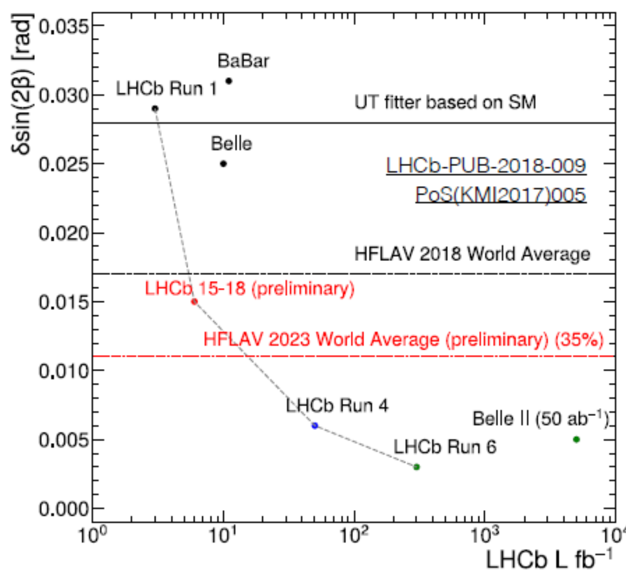
2021 WA: $\varphi_s^{2021}(all\ b \to c\bar{c}s) = -50 \pm 19 \ \text{mrad}$

2023 WA: $\varphi_s^{2023}(all\ b \to c\bar{c}s) = -39 \pm 16 \ \text{mrad}$

(Preliminary)

Future projections: $\gamma, \sin(2\beta_s), \sin(2\beta)$





	LHCb 300 fb^{-1}	CMS 3000 fb^{-1}	ATLAS 3000 fb^{-1}
$\delta(\varphi_s)$ (mrad)	3	4	4
$\delta(\sin(2\beta))$	~0.003		
$\delta(\gamma)$	0.4°		

V_{tb} (t-channel)

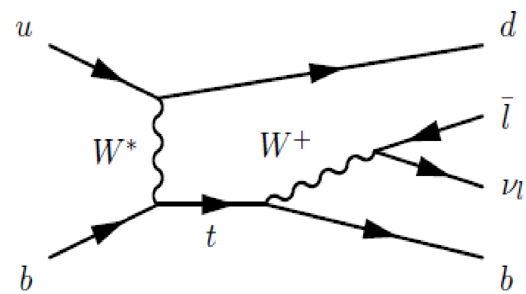
ATLAS-CONF-2023-026

- Cross-sections measured for each.
  - $\sigma(tq) = 137 \pm 8$ pb
  - $\sigma(\bar{t}q) = 84^{+6}_{-5}$ pb

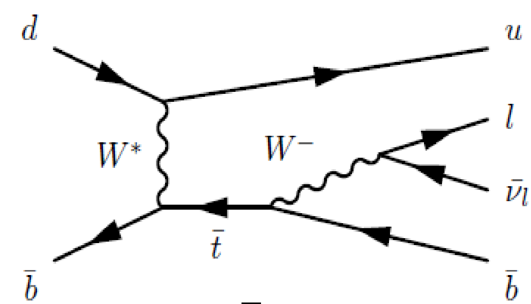
$$\frac{\sigma(tq + \bar{t}q)}{\sigma_{theo}} = f_{LV}^2 |V_{tb}|^2$$

$\sigma_{theo} = 214 \pm 3.4 \pm 1.8$ pb
Campbell *et al*, JHEP 02 (2021)

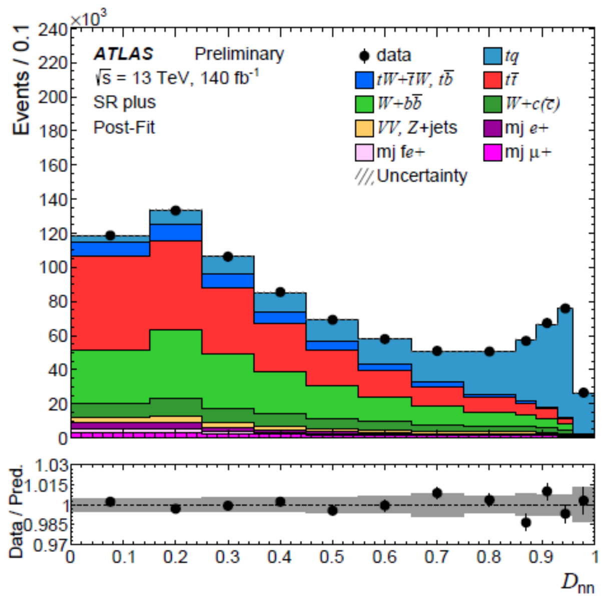
- Ignoring Wts and Wtd vertices:
  - $f_{LV}|V_{tb}| = 1.016 \pm 0.031$
- Allowing for Wts and Wtd vertices:
  - $0.955 < f_{LV}|V_{tb}| < 1.045$ @2σ

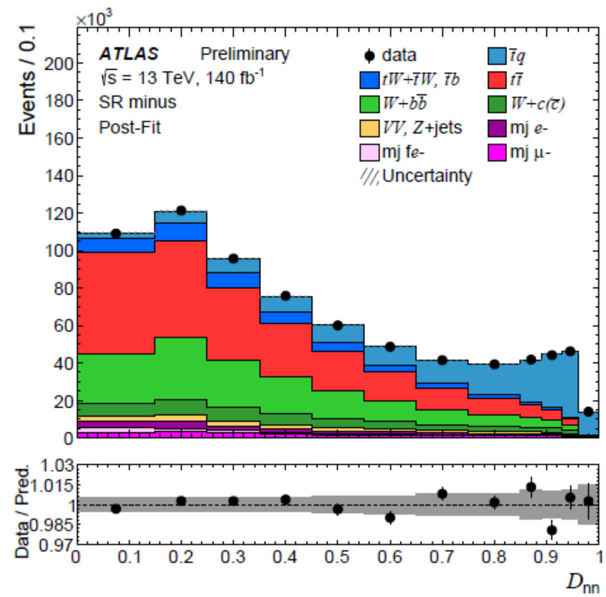


tq



$\bar{t}q$





Neural network output

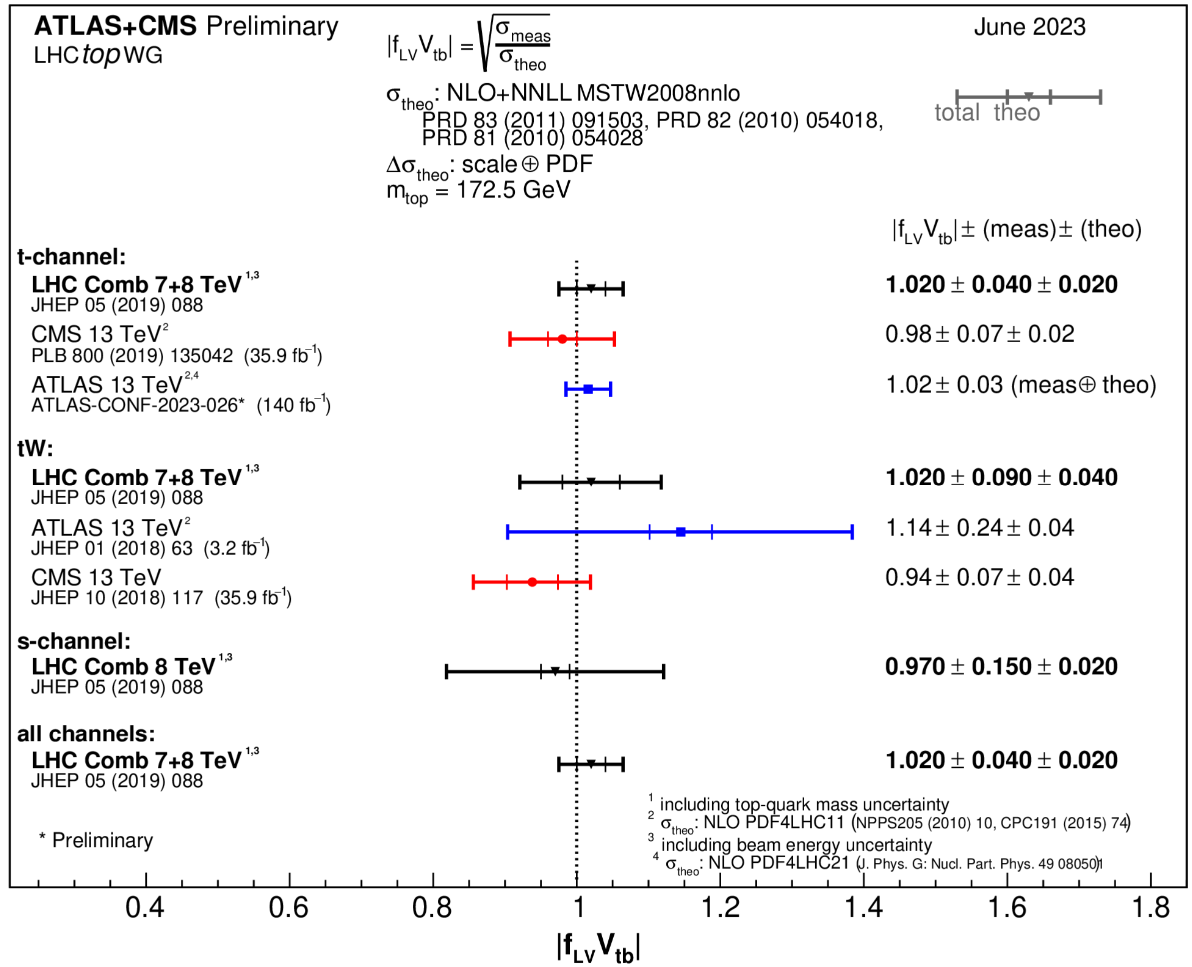
V_{tb} (t-channel)

ATLAS-CONF-2023-026

- Cross-sections measured for each process.
  - $\sigma(tq) = 137 \pm 8$ pb
  - $\sigma(\bar{t}q) = 84^{+6}_{-5}$ pb

$$\frac{\sigma(tq + \bar{t}q)}{\sigma_{theo}} = f_{LV}^2 |V_{tb}|^2$$

$\sigma_{theo} = 214 \pm 3.4 \pm 1.8$ pb
Campbell *et al*, JHEP 02 (2021)

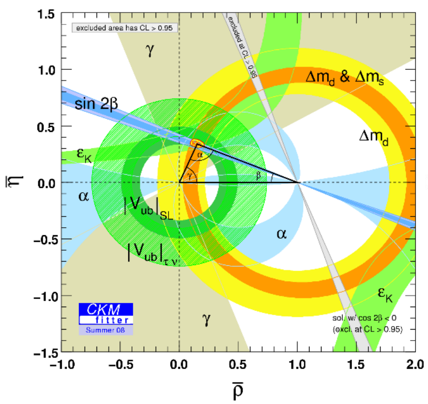


- Ignoring Wts and Wtd vertices:
  - $f_{LV}|V_{tb}| = 1.016 \pm 0.031$
- Allowing for Wts and Wtd vertices:
  - $0.955 < f_{LV}|V_{tb}| < 1.045 \quad @2\sigma$

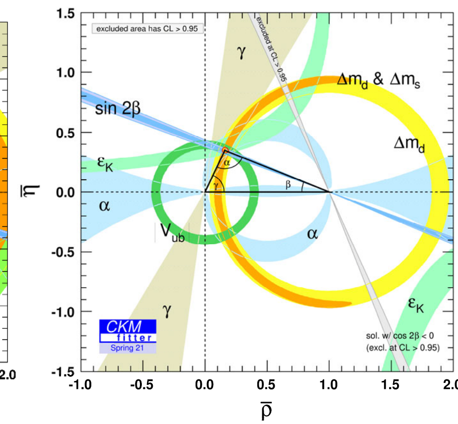
Summary

- ❑ Study of loop-mediated decays a critical part of search for NP.
- ❑ **Impressive progress in recent years** in testing CKM paradigm
- ❑ Many measurements still statistically limited
  → future LHCb upgrades critical, along with important contributions from CMS, ATLAS on $\sin(2\beta_s)$.
- ❑ Theory/LQCD communities crucial part of this program, to shrink uncertainties on relevant hadronic matrix elements.

Pre-LHC

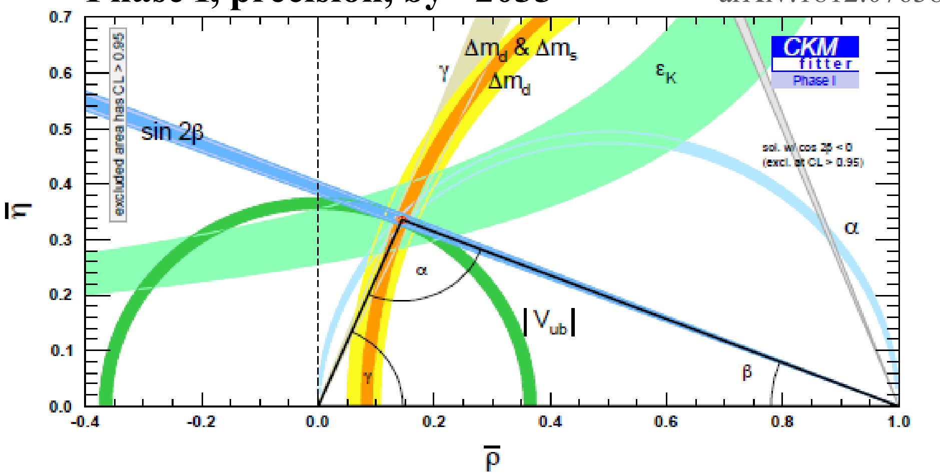


2021

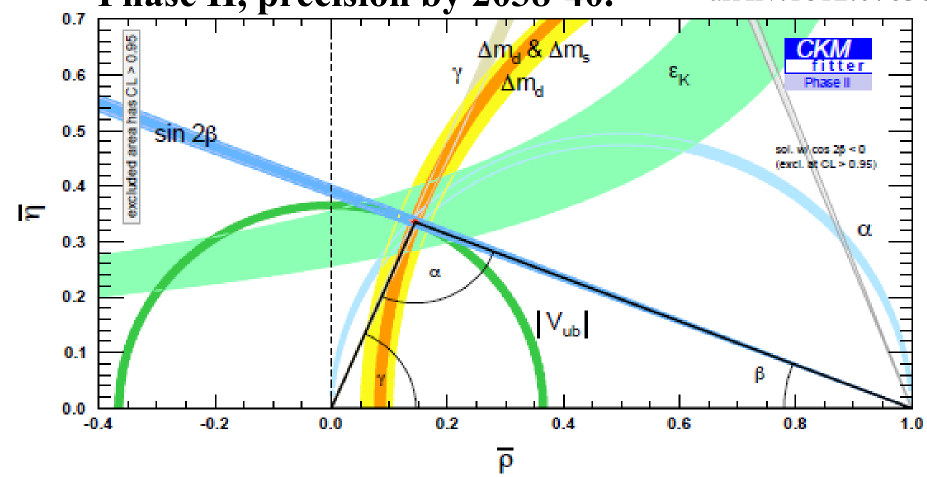


The future looks bright for precision tests of CKM sector!

Phase I, precision, by ~2033 arXiv:1812.07638



Phase II, precision by 2038-40. arXiv:1812.07638

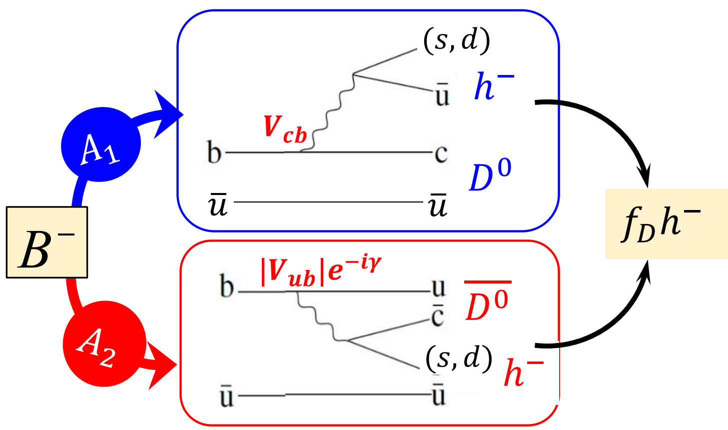


Backup

B→DK vs B→Dπ

LHCb, arXiv:2301.10328

- ❑ Why do we emphasize usage of the Cabibbo suppressed mode?



$\lambda = \sin\theta_c \cong 0.22$

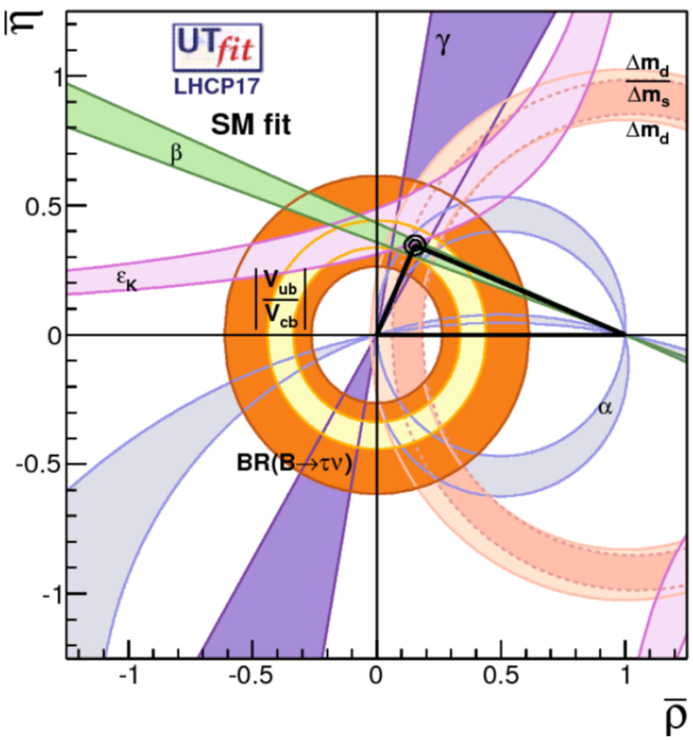
CKM factors	$h = \pi^-$	$h = K^-$
$\lvert A_1 \rvert$	$V_{cb}V_{ud} \sim O(\lambda^2)$	$V_{cb}V_{us} \sim O(\lambda^3)$
$\lvert A_2 \rvert$	$V_{ub}V_{cd} \sim O(\lambda^4)$	$V_{ub}V_{cs} \sim O(\lambda^3)$
$\lvert A_2/A_1 \rvert$	$O(0.01)$	$O(0.1)$

- ❑ A_2 is (also) color-suppressed
- ❑ In B^0 decays, can have $A_2/\, A_1 \sim O(0.4)$

- ❑ To maximize interference term, we **want the two amplitudes to be of the same order** → maximize sensitivity to angle (γ) between them!
- ❑ B→DK much more sensitive than B→Dπ, even though event rate is ~10X lower!

Constraints on NP in B decays

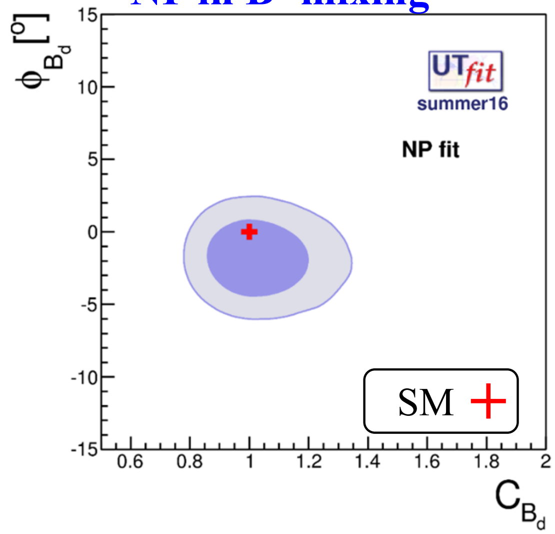
- Does $(\rho,\eta)_{tree} = (\rho,\eta)_{loop}$?



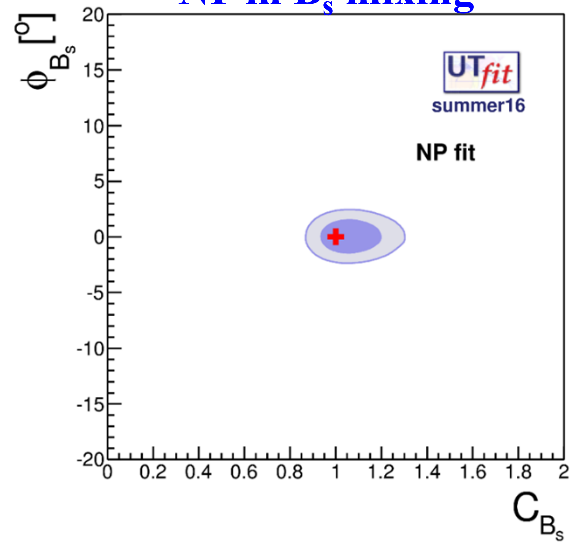
Model Independent constraints on NP in $B_{(s)}$ mixing

$$C_{B_q} e^{2i\phi_{B_q}} = \frac{\langle B_q^0 | H_{eff}^{full} | \bar{B}_q^0 \rangle}{\langle B_q^0 | H_{eff}^{SM} | \bar{B}_q^0 \rangle}$$

NP in B^0 mixing



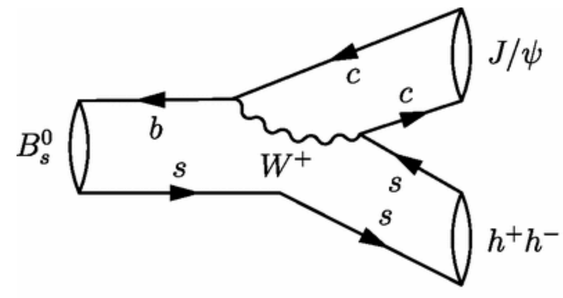
NP in B_s mixing



- No smoking gun yet … but **O(20%) NP contributions not excluded.**
- **Greater precision needed -- LHCb upgrade(s) and Belle II necessary.**
- Reduced theory errors on many inputs important & anticipated (LQCD)

CPV phase φ_s

- In SM, $\boldsymbol{\varphi_s} \cong -\mathbf{2}\boldsymbol{\beta_s}$, the **phase of B$_s$ mixing**.
- Global fits (w/o direct m'ment), $\varphi_s = -36.8^{+0.09}_{-0.06}$ **mrad** (<< $2\beta \approx 800$ mrad)
- New particles in B$_s$ box diagram can lead to large deviations
- Can measure $\boldsymbol{\varphi_s}$ via **interference between $B_s \to f_{CP}$ and $B_s \to \bar{B}_s \to f_{CP}$**.
  - Ideal modes: $J/\psi h^+h^-$, no additional CKM phase $b \to c\bar{c}s$ ($V_{cb}V_{cs}$ real)
  - Must disentangle CP+ and CP– contributions (except $D_s^+D_s^-$)
  - Measurements from LHC



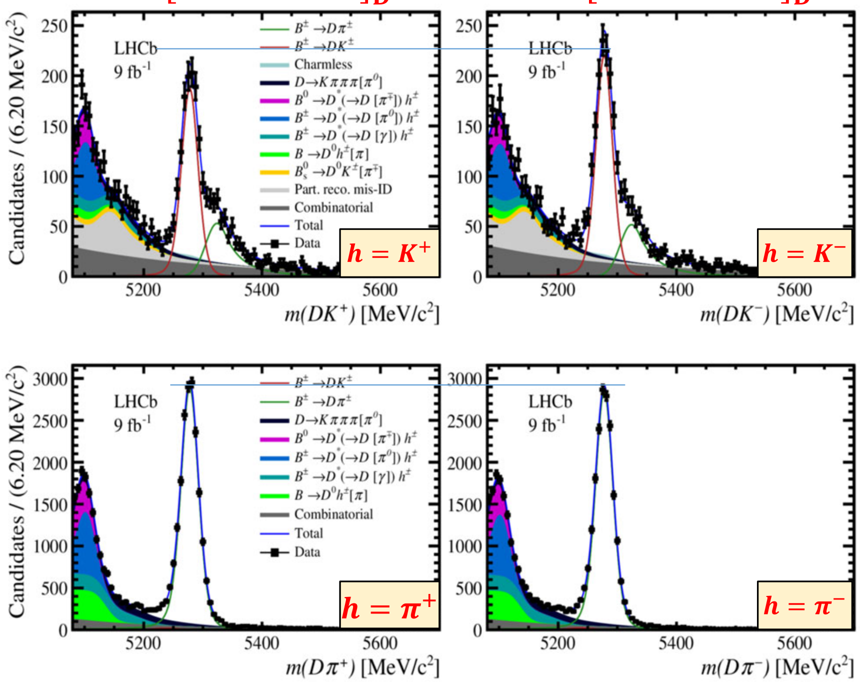
Mode	LHCb
$B_s^0 \to J/\psi K^+K^-$ (near ϕ) LHCb–PAPER–2023–016 (in prep)	$\mathbf{-39 \pm 22 \pm 6}$ 6 fb^{-1} (13 TeV)
$B_s^0 \to (J/\psi)_{ee}K^+K^-$ (near ϕ) EPJ C81, 1026 (2021)	$\mathbf{0 \pm 280 \pm 70}$ 3 fb^{-1} (7. 8 TeV)
$B_s^0 \to J/\psi K^+K^-$ ($M_{KK} > 1.05$ GeV) JHEP 34, 037 (2017)	$\mathbf{119 \pm 107 \pm 34}$ 3 fb^{-1} (7, 8 TeV)
$B_s^0 \to \psi(2S)K^+K^-$ (near ϕ) PL B113, 253 (2016)	$\mathbf{230^{+290}_{-280} \pm 20}$ 3 fb^{-1} (7, 8 TeV)
$B_s^0 \to J/\psi\pi^+\pi^-$ PL B797, 134789 (2019)	$\mathbf{2 \pm 44 \pm 12}$ 1.9 fb^{-1} + 3 fb^{-1}
$B_s^0 \to D_s^+D_s^-$ PRL 113, 211801 (2014)	$\mathbf{20 \pm 170 \pm 20}$ 3 fb^{-1} (7, 8 TeV)

CMS	ATLAS
$\mathbf{-21 \pm 44 \pm 10}$ 116.1 fb^{-1} (8 TeV)	$\mathbf{-87 \pm 36 \pm 21}$ 80.5 fb^{-1}
PLB 816, 136188 (2021)	EPJ C81, 342 (2021)

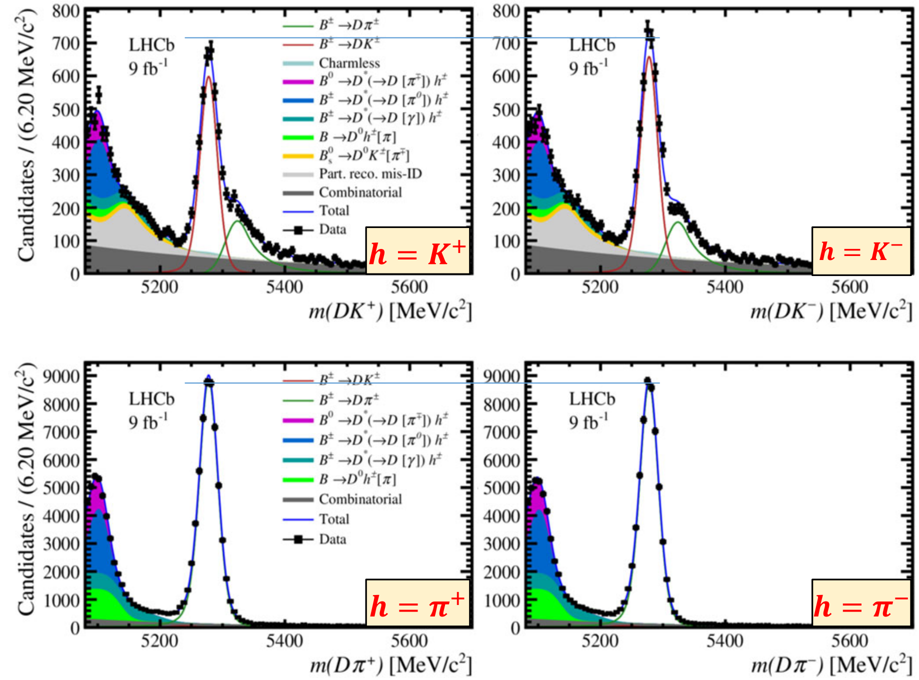
Integrated signal yields

LHCb, arXiv:2301.10328

$B^+ \to [K^+K^-\pi^+\pi^-]_D h^+$ $B^- \to [K^+K^-\pi^+\pi^-]_D h^-$



$B^+ \to [\pi^+\pi^-\pi^+\pi^-]_D h^+$ $B^- \to [\pi^+\pi^-\pi^+\pi^-]_D h^-$

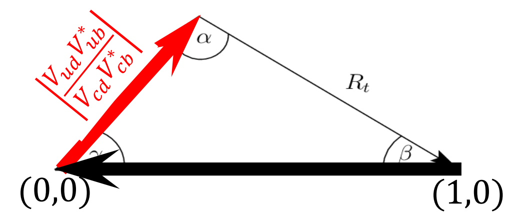


CPV observable	Fit results
$A_K^{KK\pi\pi}$	$(9.3 \pm 2.3 \pm 0.2)\%$
$R_{CP}^{KK\pi\pi}$	$0.974 \pm 0.024 \pm 0.015$
$A_\pi^{KK\pi\pi}$	$(-0.9 \pm 0.6 \pm 0.1)\%$

CPV observable	Fit results
$A_K^{\pi\pi\pi\pi}$	$(6.0 \pm 1.3 \pm 0.1)\%$
$R_{CP}^{\pi\pi\pi\pi}$	$0.978 \pm 0.014 \pm 0.010$
$A_\pi^{\pi\pi\pi\pi}$	$(-0.82 \pm 0.31 \pm 0.07)\%$

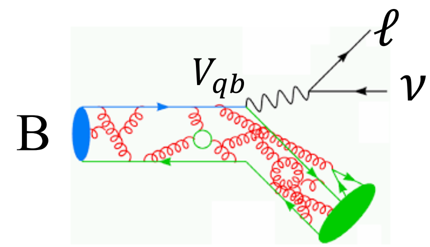
- CPV in integrated yields for $K^\pm$, very small for $\pi^\pm$ ➔ Low sensitivity to γ
- **Next up:** Measure yields in the $8_{\Delta\delta_D} \times 2_{r_D}$ bins

Semileptonic decays: $|V_{ub}/V_{cb}|$



- **Exclusive decays**
  - $B \to (\pi, \rho)\ell^-\nu$ (V_{ub}), $B \to D^{(*)}\ell^-\nu$ (V_{cb}) ← $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ (Many m'ments)
  - $B_s \to K^-\mu^+\nu$ (V_{ub}/V_{cb}), $B_s \to \bar{D}_s^{(*)}\mu^+\nu$ (V_{cb})
  - $\Lambda_b^0 \to p\mu^-\nu$ (V_{ub}/V_{cb}), $\Lambda_b^0 \to \Lambda_c^+\mu^-\nu$ (V_{cb})
  - **Form factor normalization of from theory**

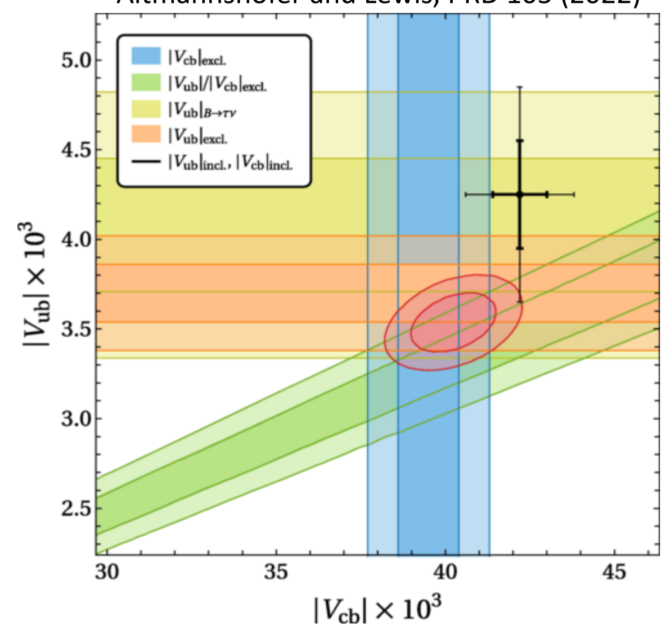
[1] LHC*b*, PRL126 (2021)
[2] LHC*b*, PRD101 (2020)
[3] LHC*b*, Nature Physics 11 (2015)



- **Inclusive decays: $B \to X_{\{u,c\}}\ \ell^-\nu$**
  - Only $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
  - **Requires theory input: HQE, shape functions (V_{ub}), etc.**

- **Tension between inclusive and exclusive determinations**
  - $|V_{ub}|$ & $|V_{cb}|$ have inflated error due to this tension.

Altmannshofer and Lewis, PRD 105 (2022)



PDG 2021	Inclusive	Exclusive	Average
$\lvert V_{ub}\rvert$ (10^{-3})	$4.13 \pm 0.12^{+0.13}_{-0.14} \pm 0.18$	$3.70 \pm 0.10 \pm 0.12$	3.82 ± 0.20
$\lvert V_{cb}\rvert$ (10^{-3})	42.2 ± 0.8	39.4 ± 0.8	40.8 ± 1.4

- Ongoing activity to understand possible sources.
  (See Tues talks by Robinson and Lytle)