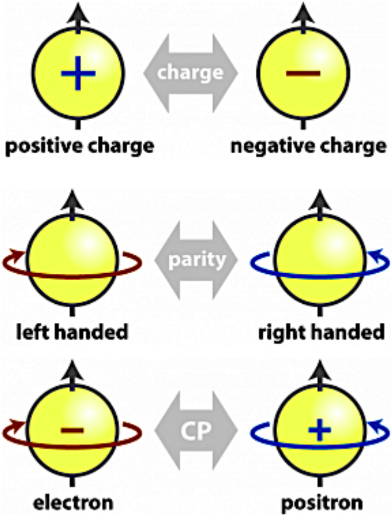
CP violation in heavy-flavour hadrons at LHCb

Donal Hill on behalf of the LHCb collaboration

Kruger 2018: Discovery Physics at the LHC

6 December 2018

What is CP?



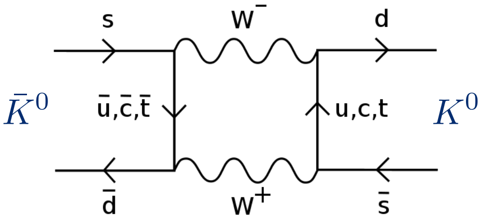
charge
positive charge
negative charge
parity
left handed
right handed
CP
electron
positron

1964

CP violation

- **Weak interaction** does <u>not</u> respect CP

- Effect was first seen in **kaons** in 1964



- CP violation is one of the **Sakharov conditions** for early universe Baryogenesis - they ensure matter was left over to make stuff with!

Does CP violation fit into the Standard Model?

- **CKM matrix**
- Connects u- and d- type quarks via the weak force
- 3×3 matrix with four parameters - **one complex phase**

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

only source of CPV in SM

Three types of CP violation

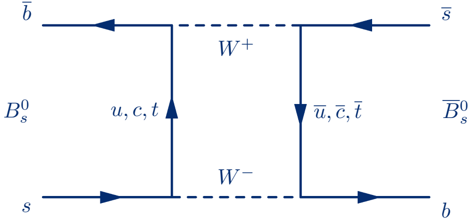
- **Mixing**
  $\mathcal{P}(B^0 \to \bar{B}^0) \neq \mathcal{P}(\bar{B}^0 \to B^0)$

- **Decay**
  $\mathcal{P}(B \to f) \neq \mathcal{P}(\bar{B} \to \bar{f})$

- **Interference**
  $\mathcal{P}(B^0 \to \bar{B}^0 \to f) \neq \mathcal{P}(\bar{B}^0 \to B^0 \to \bar{f})$

Neutral B meson mixing

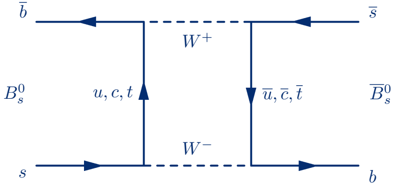
- Box diagram enables $B^0_{(s)} \leftrightarrow \bar{B}^0_{(s)}$ oscillation
  - If u, c, t had the same masses, this wouldn't happen!



- **Mass** and **flavour** eigenstates not the same:

$$|B_H^0\rangle = p|B^0\rangle - q|\bar{B}^0\rangle \qquad |B_L^0\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$$

Neutral B meson mixing



- Can describe mixing with the 2×2 effective Hamiltonian $H_{ij} = M_{ij} - i\Gamma_{ij}/2$

- Solving the Schrödinger equation, we get:
  - $\Delta m = m_H - m_L$ oscillation frequency
  - $\Delta\Gamma = \Gamma_H - \Gamma_L$ small lifetime difference
  - $\phi_{\text{mix}} = -\text{arg}(M_{12}/\Gamma_{12})$ CP-violating phase

Δm - the oscillation frequency [arXiv:1304.4741]

- To look for CP violation in mixing, need to know Δm
- B^0 oscillations are fast! 2 million times a second
    - And B_s^0 are **35 times faster**...
- LHCb has excellent time resolution: 14% of B_s^0 period

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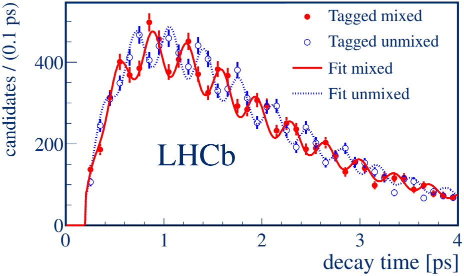


CP violation in neutral B mesons

- CP violation governed by $\lambda_f = \frac{q}{p}\frac{\bar{A}(\bar{B}^0 \to f)}{A(B^0 \to f)}$
- Shows up in a time-varying CP asymmetry, containing three terms related to λ_f

$$a_{CP}(t) = \frac{\Gamma(\bar{B}^0_{(s)} \to f) - \Gamma(B^0_{(s)} \to f)}{\Gamma(\bar{B}^0_{(s)} \to f) + \Gamma(B^0_{(s)} \to f)}$$

$$= \frac{-C_f \cos(\Delta m t) + S_f \sin(\Delta m t)}{\cosh(\Delta\Gamma t/2) + A_{\Delta\Gamma}\sinh(\Delta\Gamma t/2)}$$

What do C_f, S_f and $A_{\Delta\Gamma}$ tell us?

- **Decay**

  $C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$

- **Interference**

  $S_f = \frac{2\mathsf{Im}\lambda_f}{1+|\lambda_f|^2}$

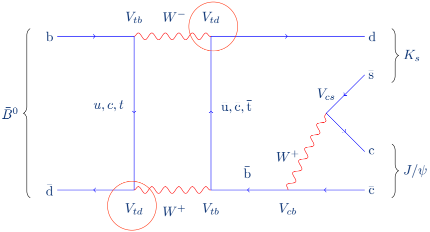
- **Admixture of B_L and B_H decaying to final state**

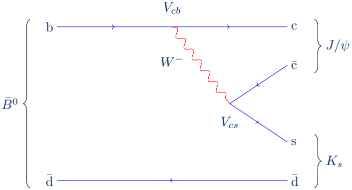
  $A_{\Delta\Gamma} = \frac{2\mathsf{Re}\lambda_f}{1+|\lambda_f|^2}$

- Lifetime difference negligible for B^0 ($\Delta\Gamma = 0$), so no $A_{\Delta\Gamma}$

$B^0 \to J/\psi K_s$

- f is a CP eigenstate
- Only one decay diagram, so expect $C_f = 0$
- Mixing and decay diagrams interfere $(V_{td} = A\lambda^3(1 - \rho - i\eta))$

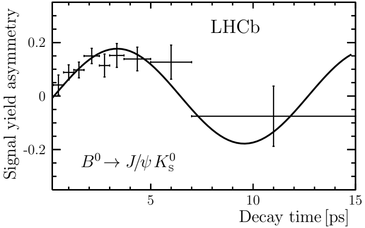




Mixing & decay (left), decay (right)

$B^0 \to J/\psi K_s$ [arXiv:1709.03944]

- Amplitude measures amount of CP violation ($\sin 2\beta$), diluted by flavour-tagging

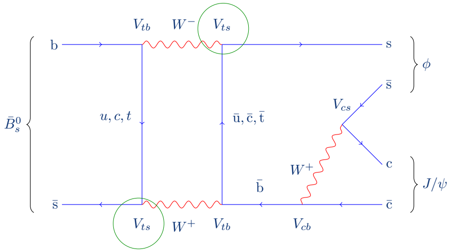


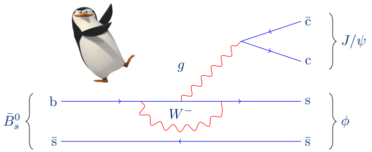
- C_f consistent with zero (no CP violation in decay), visible asymmetry is mixing-induced CP violation

$$\boxed{\begin{aligned} C_f &= -0.014 \pm 0.030 \\ S_f &= \quad 0.75 \pm 0.04 \end{aligned}}$$

Squeezing the Standard Model - $B_s^0 \to J/\psi\phi$

- No large CP violation in SM
- Measure $\phi_s = \phi_{\text{mix}} - 2\phi_{\text{dec}} = -\text{arg}(\lambda)$

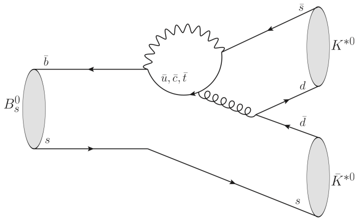




- NP sensitivity: $\phi_s = \phi_s^{SM} + \Delta\phi_s$
  - $\phi_s^{SM} = -0.0376 \pm 0.0008$ rad [arXiv:1501.05013]
  - $\phi_s = -0.030 \pm 0.033$ rad [arXiv:1612.07233]

$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ **[arXiv:1712.08683]**

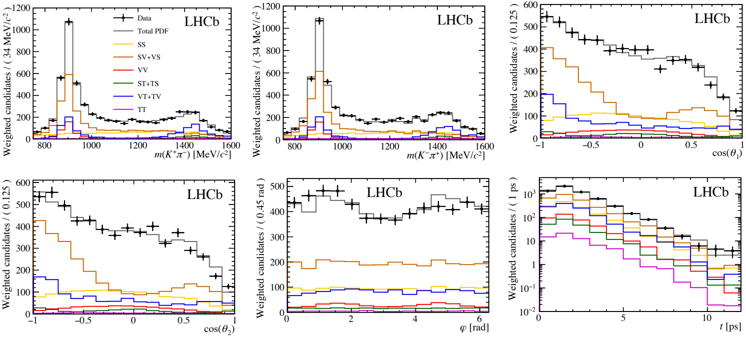
- **Dominant penguin** in SM
    - Highly sensitive to **loop-level New Physics amplitudes**



- Measure $\phi_s^{d\bar{d}}$ and $|\lambda|$
    - **Angular amplitude analysis** separates different polarisation amplitudes e.g. $K^{*0}K^{*0}$
    - $\phi_s^{d\bar{d}}$ and $|\lambda|$ common to all polarisations

3 fb^{-1} results [arXiv:1712.08683]

- Time-dependent angular amplitude fit

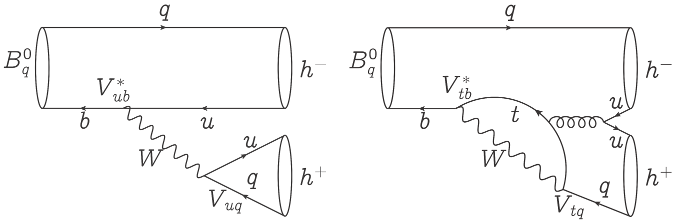


$$\phi_s^{d\bar{d}} = -0.10 \pm 0.13 \pm 0.14 \text{ rad}, |\lambda| = 1.035 \pm 0.034 \pm 0.089$$

- Consistent with SM prediction [Phys. Rev. D 88, 016007] and $B_s^0 \to \phi\phi$ [LHCb-CONF-2018-001]

$B^0_{(s)} \to h^+h^-$ - CP violation in mixing <u>and</u> decay

- Neutral B meson decays to charmless final states
- CKM-suppressed tree and penguin interfere - expect CP violation in decay



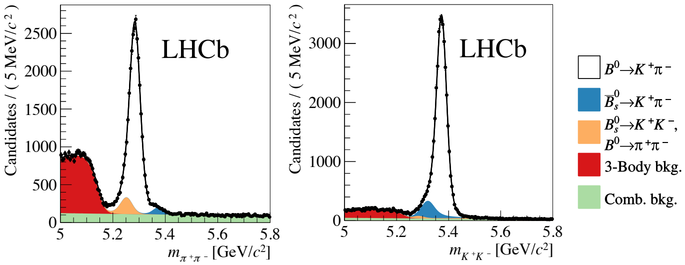
- Two classes of decay:
  - $B^0 \to \pi^+\pi^-, B^0_s \to K^+K^-$ - **time-dependent asymmetry**
  - $B^0 \to K^+\pi^-, B^0_s \to K^-\pi^+$ - **time-integrated asymmetry**

$B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ [arXiv:1805.06759]

- Time-dependent asymmetry

$$a_{CP}(t) = \frac{-C_{CP}\cos(\Delta m t) + S_{CP}\sin(\Delta m t)}{\cosh(\Delta\Gamma t/2) + A_{\Delta\Gamma}\sinh(\Delta\Gamma t/2)}$$

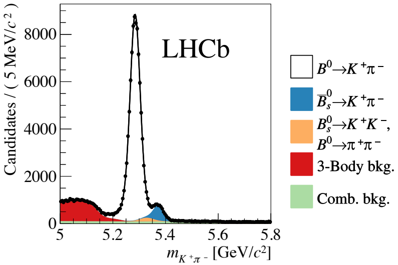
- $\Delta\Gamma_d = 0$, so just have the top part for B^0



$B^0 \to K^+\pi^-$ and $B_s^0 \to K^-\pi^+$ [arXiv:1805.06759]

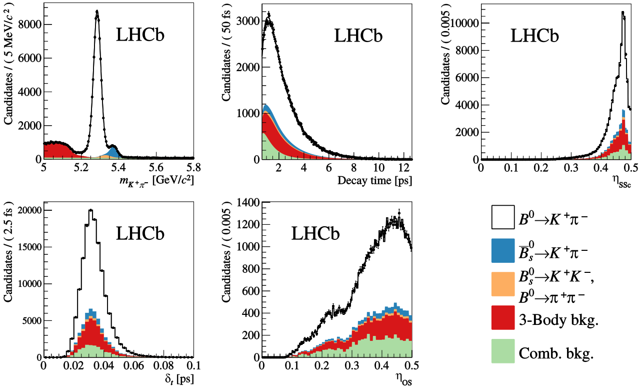
- $B^0 \to K^+\pi^-$ and $B_s^0 \to K^-\pi^+$ are **flavour-specific**
- Measure **time-integrated** asymmetries

$$A_{CP} = \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2}$$



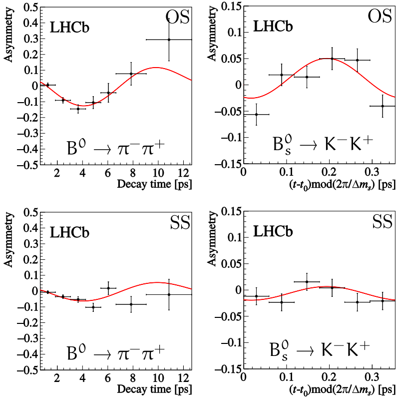
Measurement strategy [arXiv:1805.06759]

- **Simultaneous fit to all modes**: $m(h^+h^-)$, decay time, per-event decay time uncertainty and tagging parameters η
- Fit measures asymmetries directly



3 fb^{-1} results [arXiv:1805.06759]

- Clear time-dependence in $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$
- 4σ significance for TD CP violation in the B_s^0 system

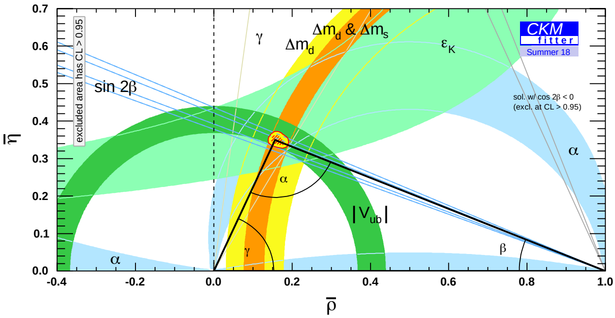


$$C_{\pi^+\pi^-} = -0.34 \pm 0.06 \pm 0.01$$
$$S_{\pi^+\pi^-} = -0.63 \pm 0.05 \pm 0.01$$
$$C_{K^+K^-} = +0.20 \pm 0.06 \pm 0.02$$
$$S_{K^+K^-} = +0.18 \pm 0.06 \pm 0.02$$
$$A^{\Delta\Gamma}_{K^+K^-} = -0.79 \pm 0.07 \pm 0.10$$

$$A_{CP}^{K^+\pi^-} = -0.084 \pm 0.004 \pm 0.003$$
$$A_{CP}^{K^-\pi^+} = +0.213 \pm 0.015 \pm 0.007$$

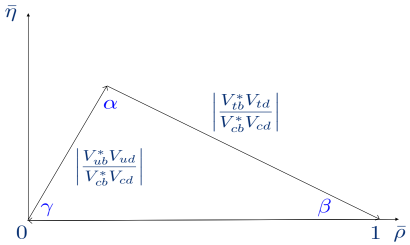
Measuring the fundamental CKM angles

- CP violation in SM embodied by **Unitarity Triangle**
- Total CP violation $\propto$ Area
- $B^0_{(s)}$ decays constrain β and the hypotenuse
  - But they involve **loop-level** diagrams, and so **could contain New Physics**



What about γ?

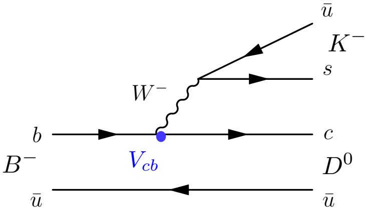
$$\gamma = \text{arg}\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$



- No **top quark** in the definition of γ
  - Can measure pure SM γ with **tree level decays**
- Look for direct CP violation by comparing V_{ub} and V_{cb}

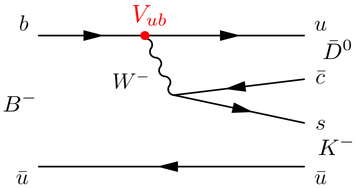
Measuring γ with $B^- \to DK^-$ decays

- $D = D^0$ or $\bar{D}^0$ decaying to the same final state
- There are **two competing diagrams**
  - One suppressed by a factor r_B
- $B^{\pm}$ diagrams have a relative phase $\theta = \delta_B \pm \gamma$



Favoured b → c

$$\mathcal{A} \sim 1$$

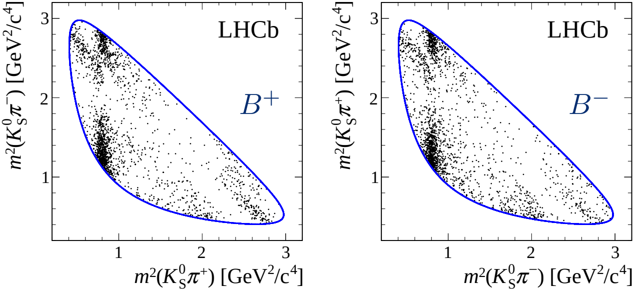


Suppressed b → u

$$\mathcal{A} \sim r_B e^{i\theta}$$

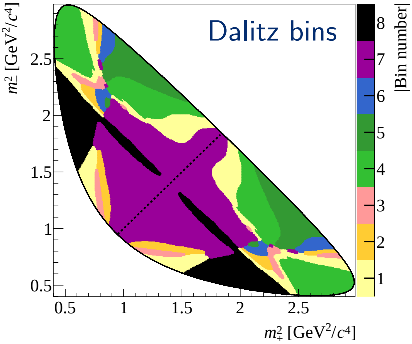
$D \to K_s h^+ h^-$: one of many D final states

- Measuring $B^\pm \to DK^\pm$ rates across several different D modes places strong constraints on γ
- Different r_B and δ_B values, but γ is shared
- $D \to K_s h^+ h^-$ particularly powerful



[arXiv:1806.01202]

- $B^+ \to DK^+$ and $B^- \to DK^-$ yields measured in **Dalitz bins**
- D decay hadronic parameters vary across bins - control using CLEO-c input [PRD 82:112006]

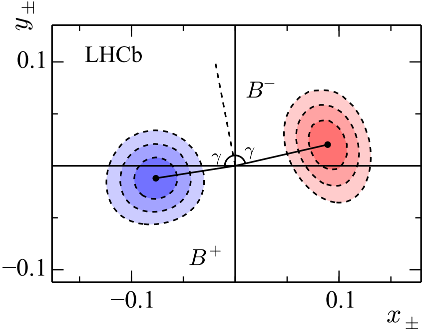


Binned $B^{\pm}$ yields combine to form $x_{\pm}$ and $y_{\pm}$ observables:

$$x_{\pm} = r_B \cos\left(\delta_B \pm \gamma\right)$$
$$y_{\pm} = r_B \sin\left(\delta_B \pm \gamma\right)$$

2 fb^{-1} results (2015-2016 data) [arXiv:1806.01202]

- Angle between blobs gives you γ
- Uncertainties have halved compared to Run 1 only result

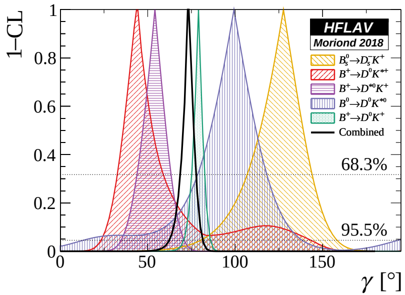


Run 1 + 2 (5 fb^{-1}) results combined:

$$\gamma = (80^{+10}_{-9})^\circ$$
$$r_B = 0.080^{+0.011}_{-0.011}$$
$$\delta_B = (110^{+10}_{-10})^\circ$$

Can γ hint at New Physics? [HFLAV Moriond 2018]

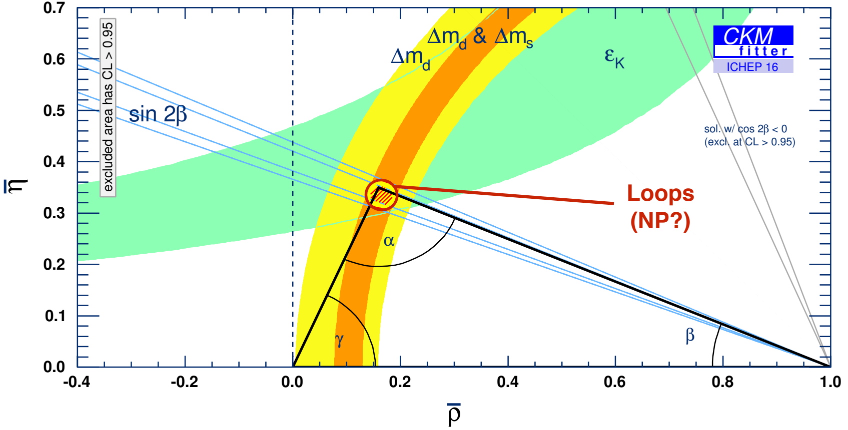
- SM γ from tree-level $B^{\pm} \to DK^{\pm}$
  - LHCb dominates the world-average [LHCb-CONF-2018-002]
- Can infer γ from knowledge of β e.t.c from loop-level $B^0_{(s)}$
  - **Loop decays are NP sensitive - could cause a shift in γ compared to SM...**



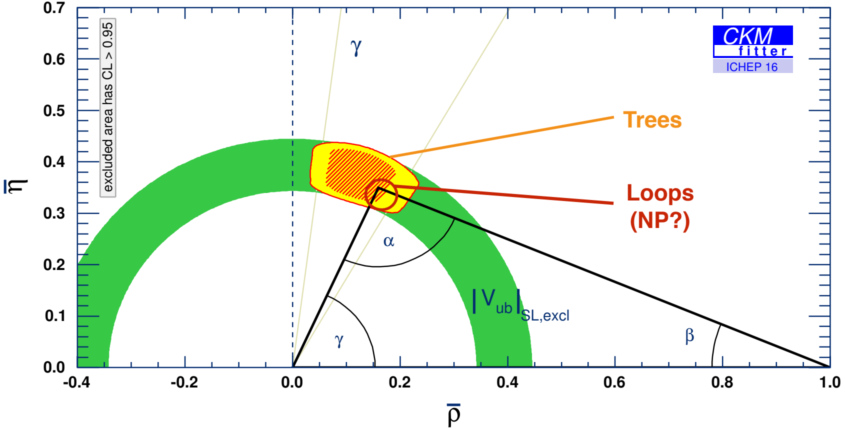
$$\gamma_{\text{trees}} = (73.5^{+4.2}_{-5.1})^{\circ}$$

$$\gamma_{\text{loops}} = (65.3^{+1.0}_{-3.4})^{\circ}$$

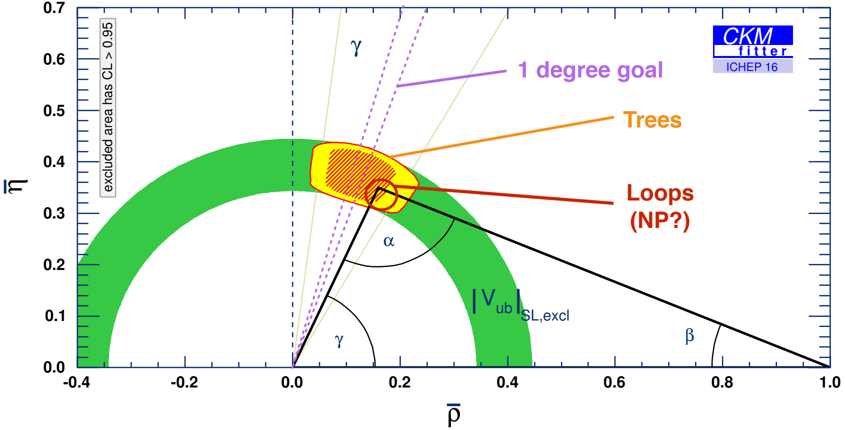
γ inferred from loops



SM γ from trees



LHCb Upgrade I target precision



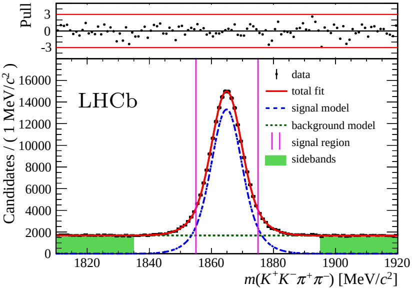
Let's not forget charm!

- CP violation requires **interference**
- **Mixing**: very small D^0 mixing amplitude (x & $y < 1\%$)
- **Decay**: tree-level D decays have **same CKM elements**
  - Only suppressed $c \to d$ will interfere with $c \to u$ loops
- a_{CP} predicted to be $\mathcal{O}(10^{-3})$ in SM [PLB 774 (2017)]


@letsstalked

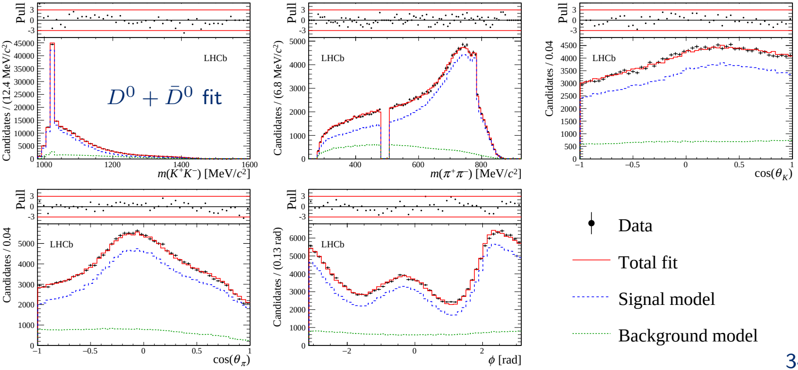
$D \to K^+K^-\pi^+\pi^-$ amplitude analysis [arXiv:1811.08304]

- Rich resonant structure in $D^0 \to K^+K^-\pi^+\pi^-$
- Strong phase varies across phase space: may enhance CP violation sensitivity in some regions
- Amplitude fit to 5D phase space, fully allowing for CP violation



3 fb^{-1} results [arXiv:1811.08304]

- Allow for asymmetries in amplitude coefficients, and differences in phase
- All **consistent with zero** within $1 - 15\%$ uncertainty
  - **no evidence of large CP violation**



D^0 decay width differences [arXiv:1810.06874]

- **Mixing**: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$
- Without CP violation ($p = q$), mass eigenstate width difference is

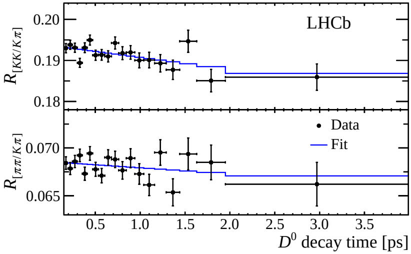
  $y = \frac{(\Gamma_1 - \Gamma_2)}{2\Gamma}$
- Because of mixing, the width to CP-even decays ($K^+K^-, \pi^+\pi^-$) can differ from the average Γ

  $y_{CP} = \frac{\Gamma_{CP+}}{\Gamma} - 1$

3 fb^{-1} results [arXiv:1810.06874]

- Without any CP violation, $y_{CP} \equiv y$
  - $p \neq q$ can move y_{CP} away from well-known y value

- Measure y_{CP} from width ratios $\frac{\Gamma(D^0 \to h^+h^-)}{\Gamma(D^0 \to K^-\pi^+)}$ $(h \in \{K, \pi\})$



$D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ consistent, and y_{CP} combination agrees with world average y:

$$y_{CP} = (0.57 \pm 0.13 \pm 0.10)\%$$

$y = (0.62 \pm 0.07)\%$ [HFLAV]

Summary

- LHCb continues to operate at the CP violation frontier
- World-best results across beauty and charm, both time-dependent and time-integrated
- Expect reduction in ϕ_s, γ, y_{CP} uncertainties as Run 1 + 2 measurements continue to appear
- Stay tuned for more results soon, and keep an eye on our **Upgrade plans** (Olaf's talk this afternoon)