Can penguin-free measurements of $\phi_{d,s}$ be competitive?

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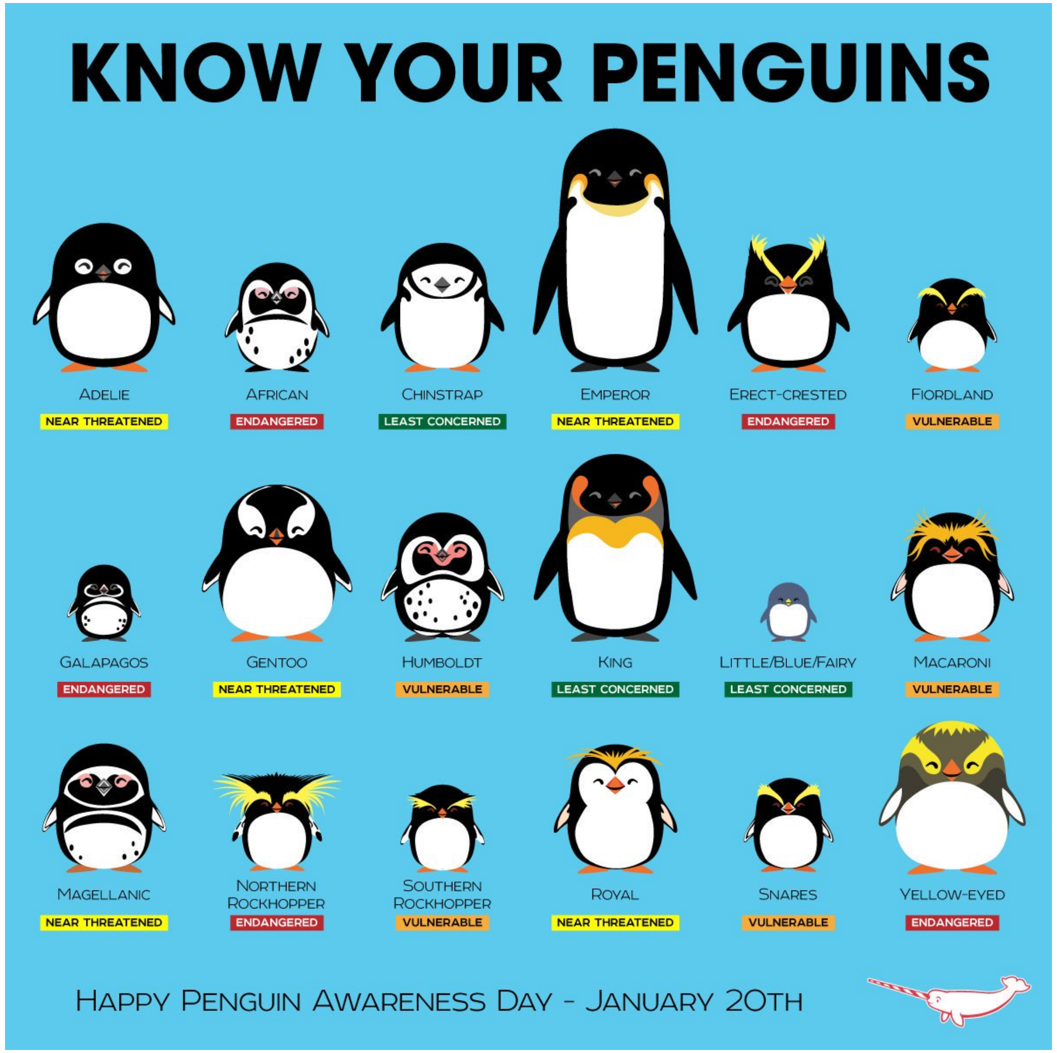
Introduction

- The precise measurements of $\phi_{d,s}$ come from $B \to J/\psi X$ decays
  - Dominated by tree-level $b \to c\bar{c}s$ transitions
  - DCS penguin contributions also present

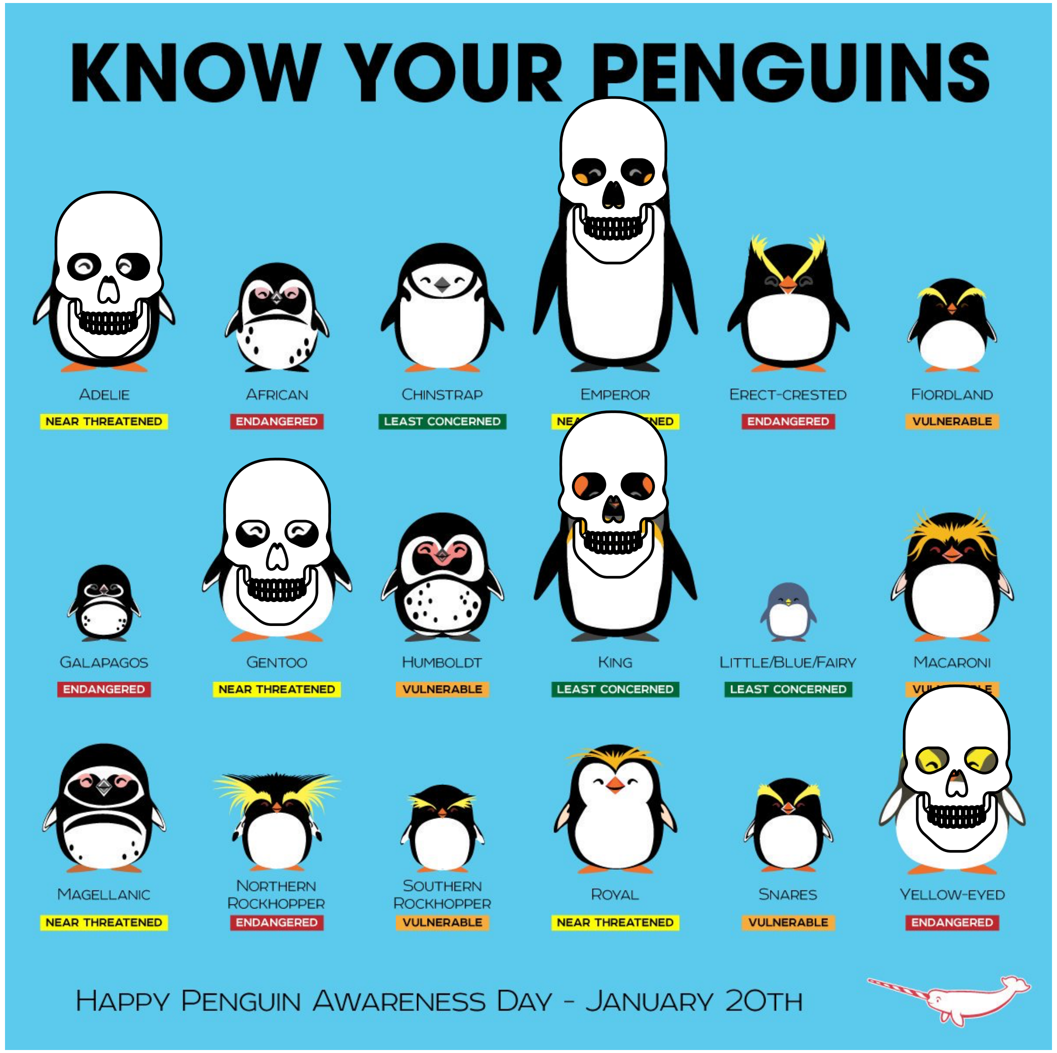
- The penguins bring uncertainty with them
  - A shift in the phase of interest $\Delta\phi_{d,s}$
  - Can estimate the shift from control modes
    - SU(3) symmetry
  - Still have a residual systematic uncertainty
  - Will these become limiting?



Introduction

- Focus on ϕ_d for now
- Amongst other options are $b \to c\bar{u}d$ decays
  - Tree-level decays without penguin diagrams

- The value of ϕ_d is independent of the decay
  - Test the SM using different processes
  - Any discrepancies are interesting
  - New physics (if we understand the penguins)

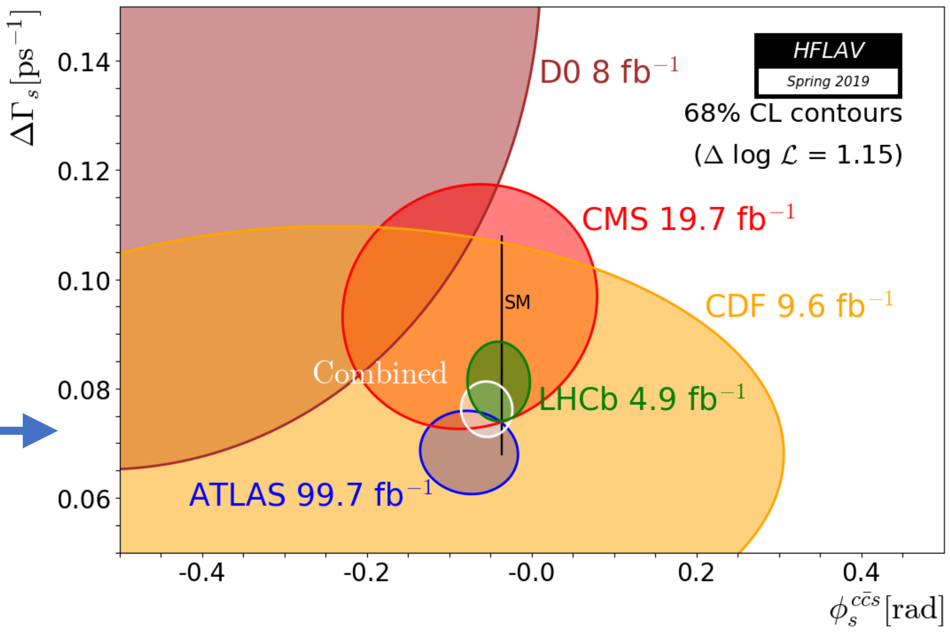


Current status

- World averages from the golden modes

$\sin(\phi_d) = 0.699 \pm 0.017$ Belle, BaBar and LHCb

$\phi_s = -0.021 \pm 0.031$ rad HFLAV WA 2018
$\phi_s = -0.054 \pm 0.021$ rad HFLAV Prelim 2019 →



- What about $b \to c\bar{u}d$ decays?
  - Measurement of $B^0 \to D^{(*)0}h^0$ decays from BaBar + Belle
  - Includes CP eigenstates and $K_S^0\pi\pi$

$\sin(\phi_d) = 0.71 \pm 0.09$ HFLAV WA 2018

$\cos(\phi_d) = 0.91 \pm 0.25$

For all things ϕ_s, please see Francesca's talk!

Latest results from BaBar + Belle

- Studies of $B^0 \to D^{(*)}h^0$, $D \to K_S^0\pi^+\pi^-$ decays, where $h^0 = \pi^0, \eta, \omega$
  - New DP model for the D decay, based on Belle data from $e^+e^- \to c\bar{c}$ decays

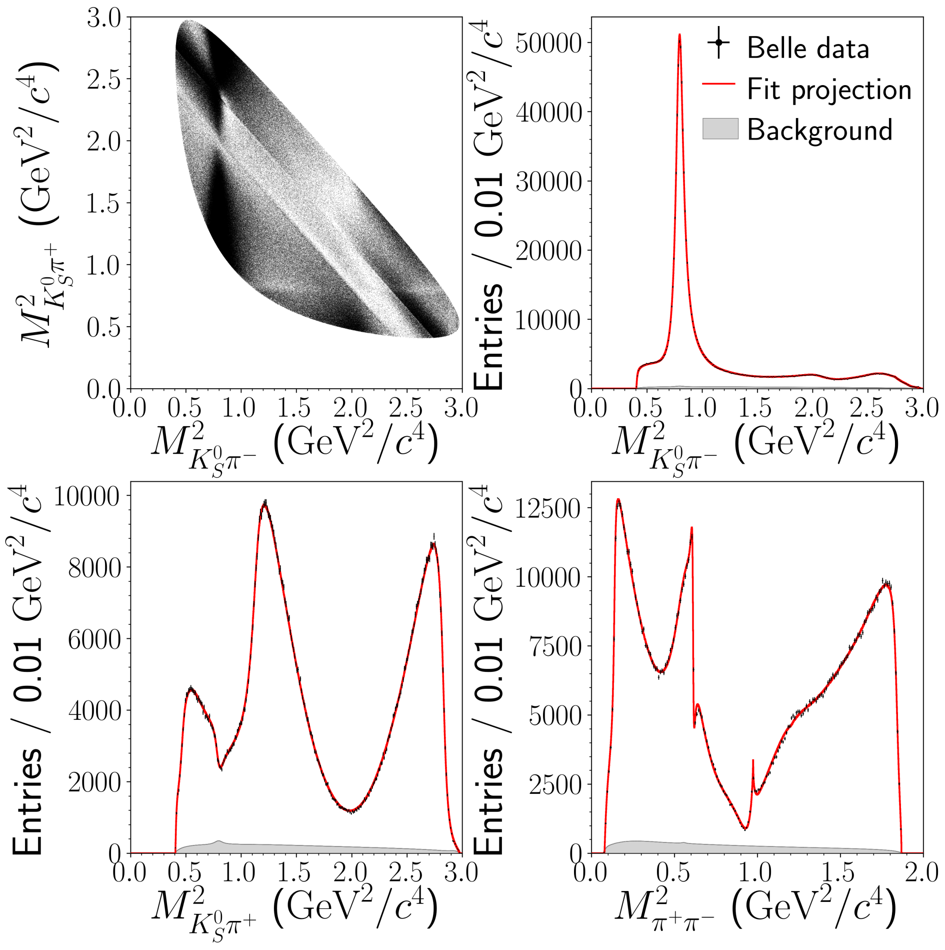
Phys. Rev. Lett. 121, 261801 (2018), Phys. Rev. D 98, 112012 (2018)

- Time-dependent decay rate

$$\frac{e^{\frac{-|\Delta t|}{\tau_{B^0}}}}{2}\Big\{\left[|\mathcal{A}_{\bar{D}^0}|^2 + |\mathcal{A}_{D^0}|^2\right] - q\left(|\mathcal{A}_{\bar{D}^0}|^2 - |\mathcal{A}_{D^0}|^2\right)\cos(\Delta m_d \Delta t) + 2q\eta_{h^0}\,(-1)^L\,\mathrm{Im}\left(e^{-2i\beta}\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0}\right)\sin(\Delta m_d \Delta t)\Big\}$$

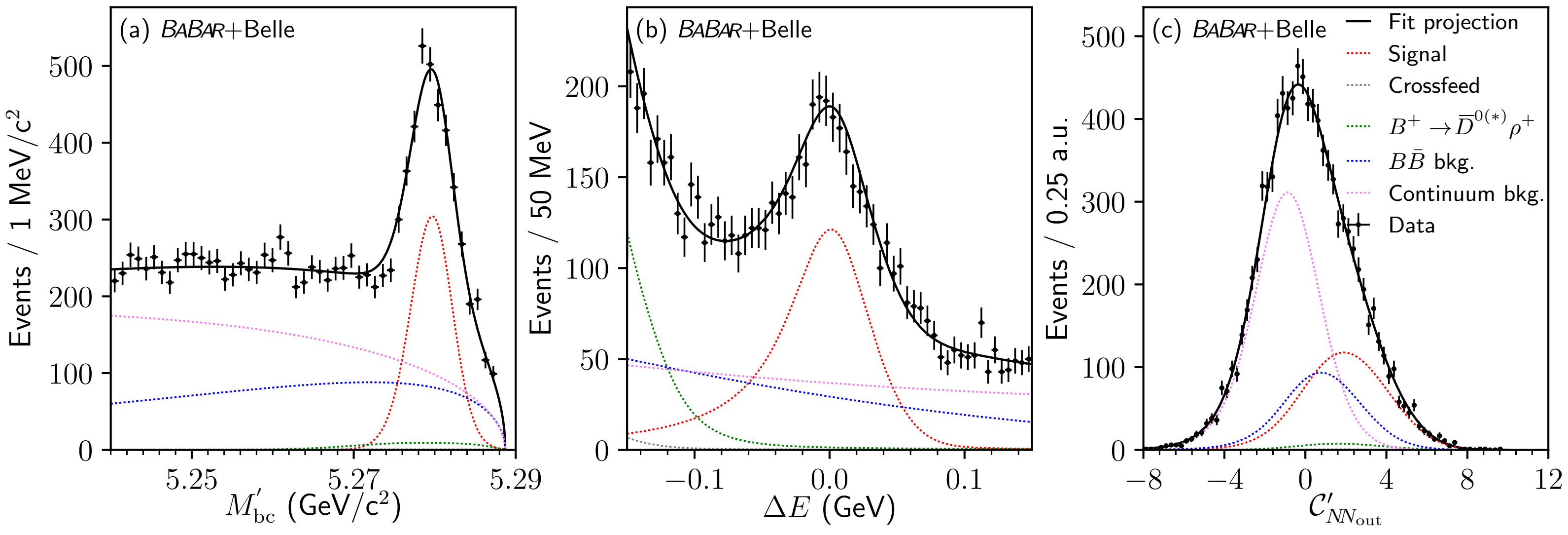
  - Or, to fit for $\sin(2\beta)$, $\cos(2\beta)$

$$\mathrm{Im}\left(e^{-2i\beta}\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0}\right) = \mathrm{Im}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0}\right)\cos 2\beta - \mathrm{Re}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0}\right)\sin 2\beta$$



Latest results from BaBar + Belle

- Find approximately 2700 signal decays



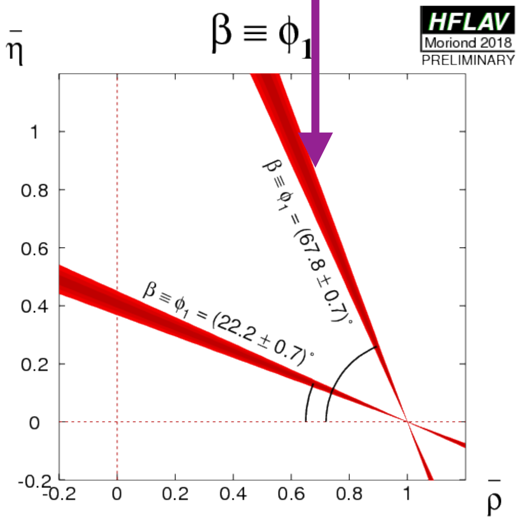
- Combining with the new DP model for the D decay gives

$$\sin 2\beta = 0.80 \pm 0.14\,(\text{stat.}) \pm 0.06\,(\text{syst.}) \pm 0.03\,(\text{model})$$

$$\cos 2\beta = 0.91 \pm 0.22\,(\text{stat.}) \pm 0.09\,(\text{syst.}) \pm 0.07\,(\text{model})$$

$$\beta = (22.5 \pm 4.4\,(\text{stat.}) \pm 1.2\,(\text{syst.}) \pm 0.6\,(\text{model}))^\circ$$

Ruled out at over 7σ



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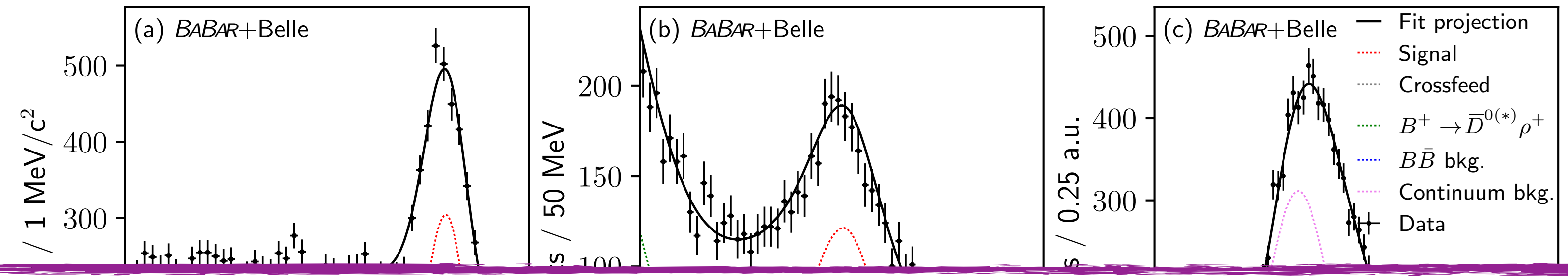

Ruled out at

Good prospects for Belle II (see later), more challenging for LHCb (upgrade)

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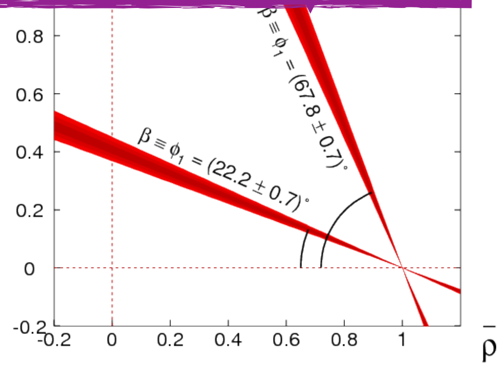
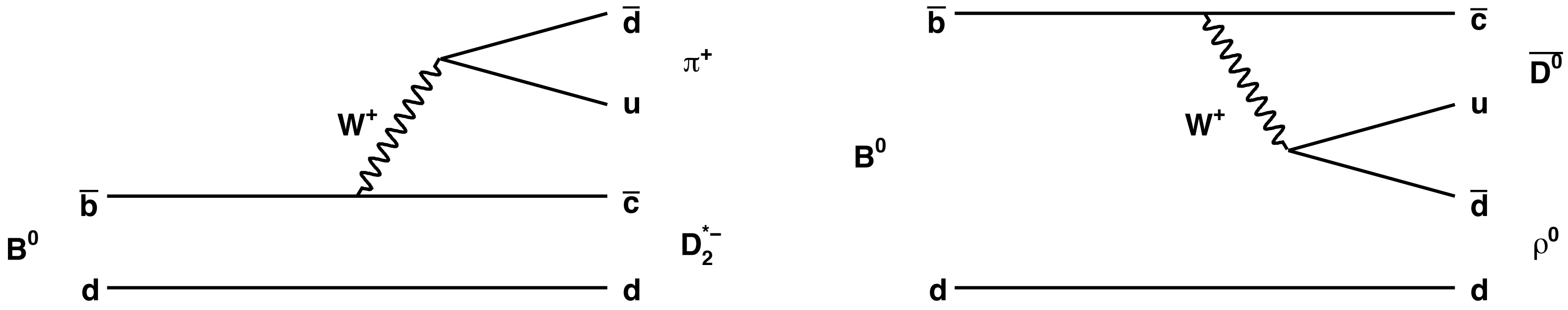


What can LHCb do?

- Best suited to fully charged final states e.g. $B^0 \to \bar{D}^0 \pi^+ \pi^-$ J.Phys.G36:025006,2009



- Simultaneous, time-dependent, Dalitz plot analysis
  - Consider (at least) CP even $D \to K^+K^-, \pi^+\pi^-$ decays to measure ϕ_d
  - Favoured, flavour specific $\bar{D}^0 \to K^+\pi^-$ decays to minimise systematics
    - An order of magnitude higher statistics than the CP even modes
    - Helps for both the amplitude model and flavour tagging uncertainties
  - Don't forget about the suppressed $b \to u\bar{c}d$ transition
    - Brings sensitivity to γ that should be considered

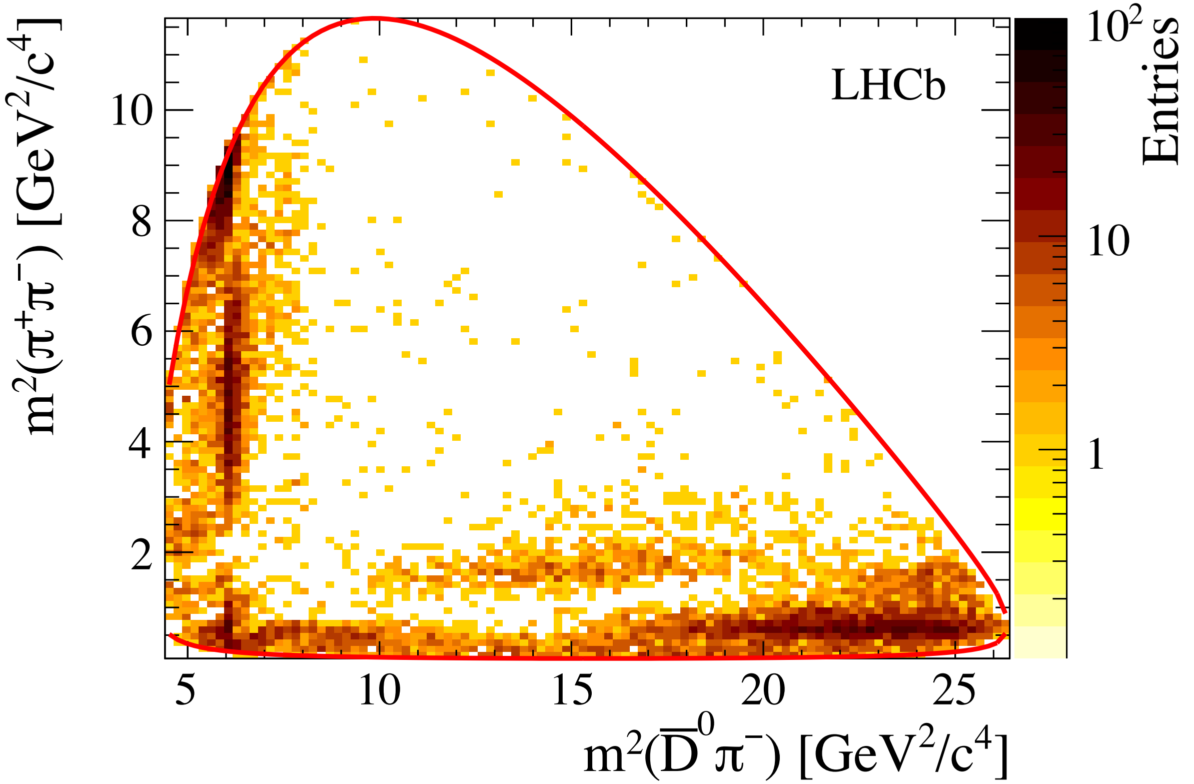
What do we know about B->Dpipi?

- Latest study of the Dalitz plot structure from LHCb

Phys. Rev. D 92, 032002 (2015)

  - About 10000 candidates at 98% purity
  - Updated branching fraction measurement: $(8.46 \pm 0.14 \pm 0.40) \times 10^{-4}$

Resonance	Spin	Model	m_r (MeV/c^2)	Γ_0 (MeV)
$\bar{D}^0\pi^-$ P-wave	1	Eq. 14	Floated	
$D_0^*(2400)^-$	0	RBW	Floated	
$D_2^*(2460)^-$	2	RBW	Floated	
$D_J^*(2760)^-$	3	RBW	Floated	
$\rho(770)$	1	GS	775.02 ± 0.35	149.59 ± 0.67
$\omega(782)$	1	Eq. 13	781.91 ± 0.24	8.13 ± 0.45
$\rho(1450)$	1	GS	1493 ± 15	427 ± 31
$\rho(1700)$	1	GS	1861 ± 17	316 ± 26
$f_2(1270)$	2	RBW	1275.1 ± 1.2	$185.1^{+2.9}_{-2.4}$
$\pi\pi$ S-wave	0	K-matrix	See Sec. 4	
$f_0(500)$	0	Eq. 15	See Sec. 4	
$f_0(980)$	0	Eq. 18	See Sec. 4	
$f_0(2020)$	0	RBW	1992 ± 16	442 ± 60
Nonresonant	0	Eq. 20	See Sec. 4	



What do we know about B->Dpipi?

- Latest study of t... Rev. D 92, 032002 (2015)
  - About 10000 ca...
  - Updated branc...

Resonance	Spin	M...
$\bar{D}^0\pi^-$ P-wave	1	E...
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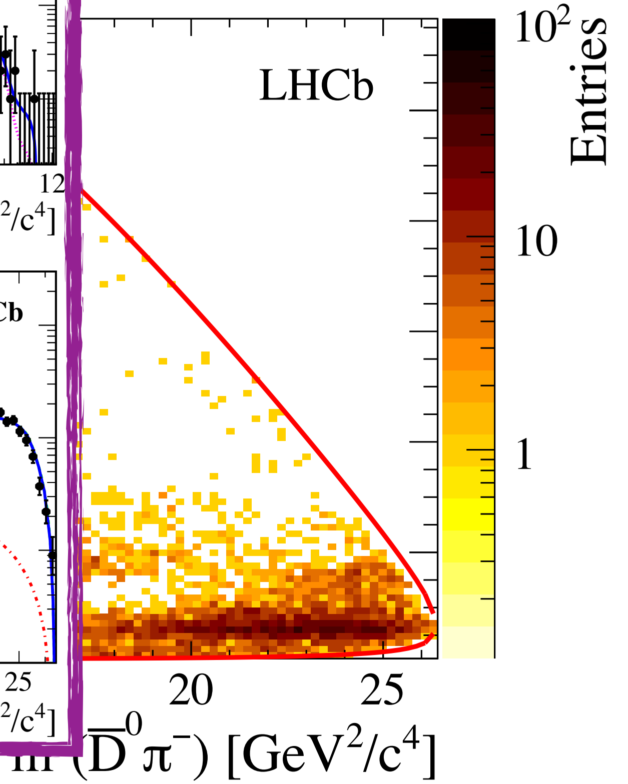

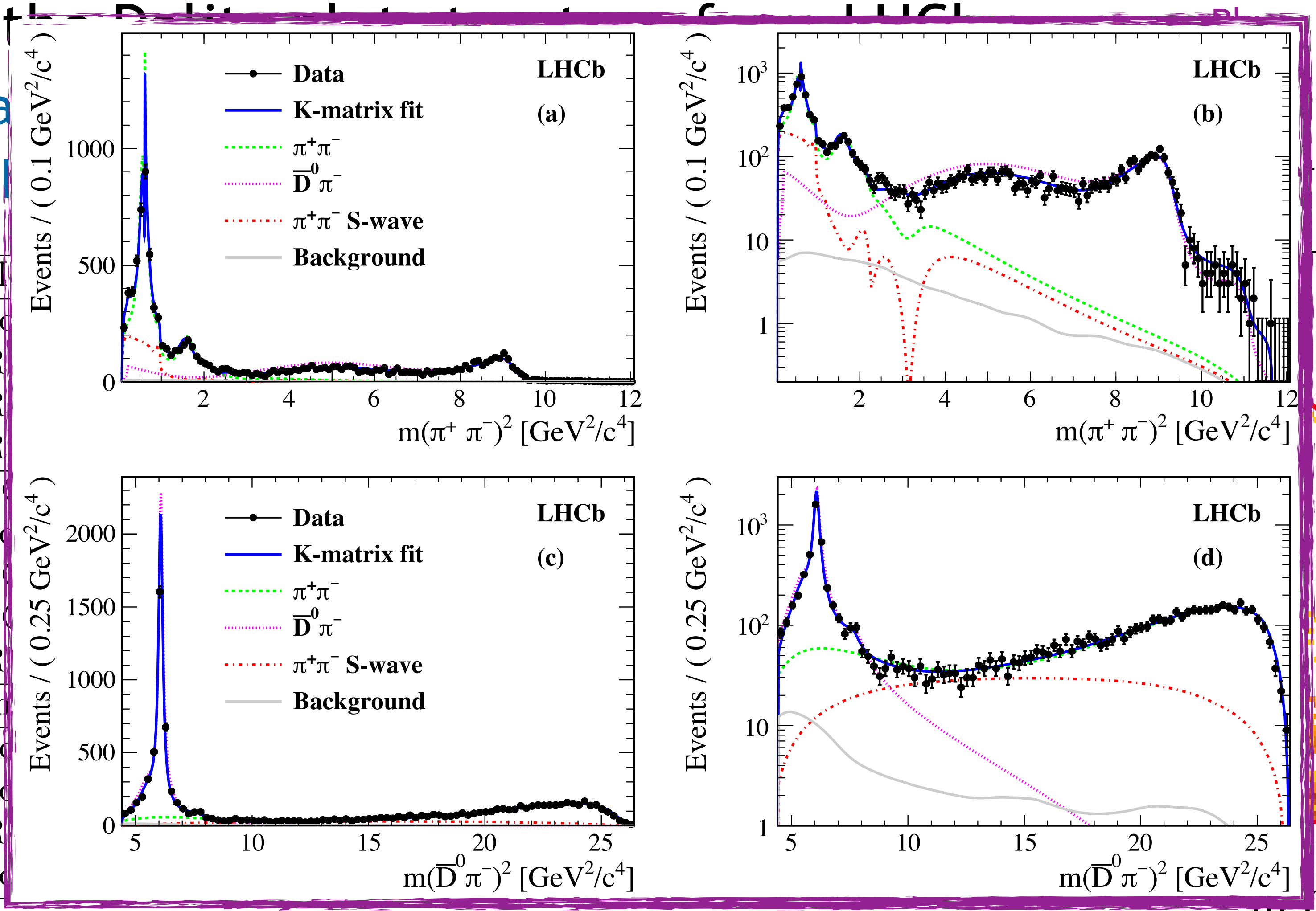

Model dependent approach @ LHCb

- Time-dependent decay rates

J.Phys.G36:025006,2009

$$\Gamma(B^0_{\rm phys} \to f(\Delta t)) \propto e^{-|\Delta t|/\tau_{B^0}} \left(1 - S_f \sin(\Delta m \Delta t) + C_f \cos(\Delta m \Delta t)\right)$$

$$\Gamma(\bar{B}^0_{\rm phys} \to f(\Delta t)) \propto e^{-|\Delta t|/\tau_{B^0}} \left(1 + S_f \sin(\Delta m \Delta t) - C_f \cos(\Delta m \Delta t)\right)$$

- With

$$S(m_+^2, m_-^2) = \frac{2\,{\rm Im}\left(e^{-2i\beta}\eta_D A^* \bar{A}\right)}{|A|^2+|\bar{A}|^2} = \frac{2\,{\rm Im}\left(e^{-2i\beta}\eta_D \sum_i c_i^* F_i(m_+^2, m_-^2)^* \sum_j \bar{c}_j \bar{F}_j(m_+^2, m_-^2)\right)}{|\sum_i c_i F_i(m_+^2, m_-^2)|^2 + |\sum_i \bar{c}_i \bar{F}_i(m_+^2, m_-^2)|^2}$$

$$C(m_+^2, m_-^2) = \frac{|A|^2-|\bar{A}|^2}{|A|^2+|\bar{A}|^2} = \frac{|\sum_i c_i F_i(m_+^2, m_-^2)|^2 - |\sum_i \bar{c}_i \bar{F}_i(m_+^2, m_-^2)|^2}{|\sum_i c_i F_i(m_+^2, m_-^2)|^2 + |\sum_i \bar{c}_i \bar{F}_i(m_+^2, m_-^2)|^2}.$$

- The numerator for S can be written as $2\eta_D\left(\cos(2\beta){\rm Im}(A^*\bar{A}) - \sin(2\beta){\rm Re}(A^*\bar{A})\right)$
  - Highlights the additional sensitivity to $\cos(\phi_d)$ from the interference effects in the DP

Model dependent approach @ LHCb

- I've run some toys in Laura++ to get a feeling for the sensitivity
  - Estimate yields from Run 1 analysis and Run 2 conditions and 5% flavour tagging efficiency
  - Statistical precision for Run 1+2 (9fb-1): $\sin(\phi_d) : \pm 0.06,\ \cos(\phi_d) : \pm 0.10$
  - Statistical precision for upgrade (50fb-1): $\sin(\phi_d) : \pm 0.018,\ \cos(\phi_d) : \pm 0.03$

- Reminder of the $b \to c\bar{c}s$ world average: $\sin(\phi_d) = 0.699 \pm 0.017$
  - Expected to scale with statistics in the LHCb upgrade era
  - Can't compete directly with the statistics available - but not so far away
  - Run 1+2 a big improvement on current $b \to c\bar{u}d$ results

- Do not expect to be systematically limited
  - Control modes should keep them in check

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- Reminder of the $b \to c\bar{c}s$ world average: $\sin(\phi_d) = 0.699 \pm 0.017$
  - Expected to scale with statistics in the LHCb upgrade era

With the 300fb in upgrade II can expect

$$\sin(\phi_d) : \pm 0.007,\ \cos(\phi_d) : \pm 0.017$$

Depending how well the penguin effects can be controlled, these can be very interesting…

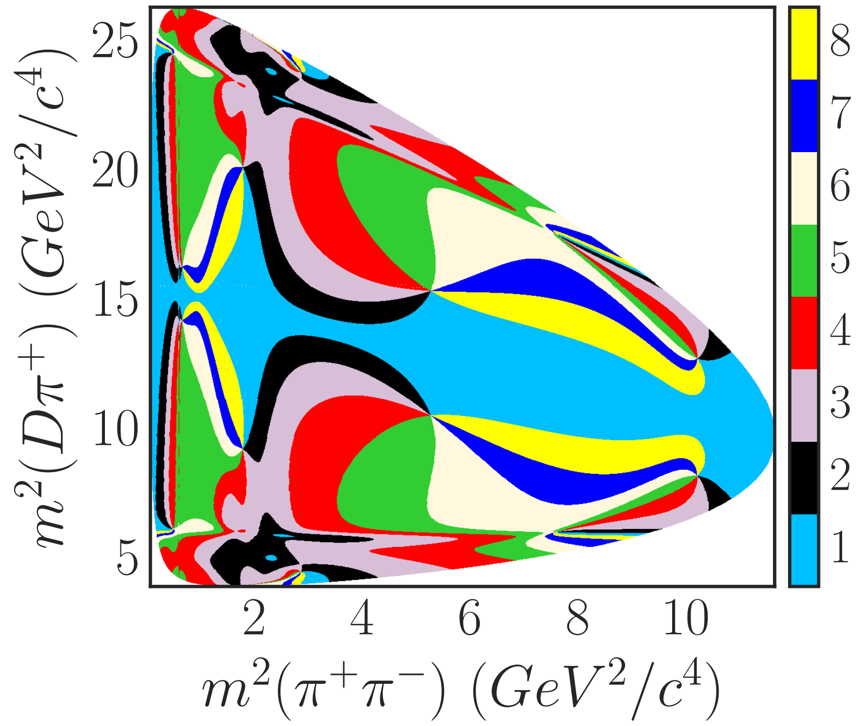
- D
  - Control modes should keep them in check

Model independent approach

JHEP03(2018)195

- An alternative model independent approach
  - Focuses on the channel $B^0 \to D\pi^+\pi^-$, $D \to K^0_S\pi^+\pi^-$
  - Simultaneous analysis with CP eigenstates possible
  - Double Dalitz analysis - binning in both (like GGSZ²)
  - Removes model uncertainties

Mode	Belle	Belle II	LHCb Run I	LHCb Run II	LHCb Upgr.
$B^0 \to D_{\mathcal{CP}}\pi^+\pi^-$	$1.0 \cdot 10^3$	$50 \cdot 10^3$	$2.0 \cdot 10^3$	$8 \cdot 10^3$	$140 \cdot 10^3$
$B^0 \to [K^0_S\pi^+\pi^-]_D\pi^+\pi^-$	$1.3 \cdot 10^3$	$65 \cdot 10^3$	$1.2 \cdot 10^3$	$5 \cdot 10^3$	$84 \cdot 10^3$
$B^0 \to D_{\mathcal{CP}}h^0$	$0.8 \cdot 10^3$	$40 \cdot 10^3$	—	—	—
$B^0 \to [K^0_S\pi^+\pi^-]_Dh^0$	$1.0 \cdot 10^3$	$50 \cdot 10^3$	—	—	—



Double Dalitz approach from e.g. Phys.Rev.D81:014025,2010

Model independent approach

- Decay probability density

JHEP03(2018)195

$$N_{ij}(\Delta t) \propto e^{-\frac{|\Delta t|}{\tau_B}} [1 + q_B \mathcal{D}_{ij} \cos(\Delta m_B \Delta t) - q_B \mathcal{F}_{ij} \sin(\Delta m_B \Delta t)]$$

Flavour tag

Where

$$\mathcal{D}_{ij} = \frac{K_i k_j - K_{-i} k_{-j}}{K_i k_j + K_{-i} k_{-j}}, \quad \mathcal{F}_{ij} = 2\frac{\sqrt{K_i K_{-i} k_j k_{-j}}}{K_i k_j + K_{-i} k_{-j}} \times [(C_i s_j - S_i c_j)\cos 2\beta - (C_i c_j + S_i s_j)\sin 2\beta]$$

- Upper case terms from the D Dalitz plot, lower case from the B Dalitz plot
- Typically D Dalitz parameters are from CLEO or BESIII
- Input small k's from a time-integrated measurement with $\bar{D}^0 \to K^+ \pi^-$ decays

$$N_j \approx k_j - r_D^2 \frac{1-z}{1+z}(k_j - k_{-j})$$

Very small

- Boils down to the fraction of events in each bin. Can now solve for c_j, s_j, β

Model independent approach

- Results from toys (with realistic D and B Dalitz plot distributions)
  - Expected yields

Mode	Belle	Belle II	LHCb Run I	LHCb Run II	LHCb Upgr.
$B^0 \to D_{\mathcal{CP}}\pi^+\pi^-$	$1.0 \cdot 10^3$	$50 \cdot 10^3$	$2.0 \cdot 10^3$	$8 \cdot 10^3$	$140 \cdot 10^3$
$B^0 \to [K_S^0\pi^+\pi^-]_D\pi^+\pi^-$	$1.3 \cdot 10^3$	$65 \cdot 10^3$	$1.2 \cdot 10^3$	$5 \cdot 10^3$	$84 \cdot 10^3$
$B^0 \to D_{\mathcal{CP}}h^0$	$0.8 \cdot 10^3$	$40 \cdot 10^3$	—	—	—
$B^0 \to [K_S^0\pi^+\pi^-]_D h^0$	$1.0 \cdot 10^3$	$50 \cdot 10^3$	—	—	—

  - Other inputs

Parameter	Belle & Belle II	LHCb
Time resolution σ_t (ps)	1.25	0.06
Tagging power ε_{tag} (%)	30	8
Background fraction (%)	30	5

Model independent approach

- Results from toys (with realistic D and B Dalitz plot distributions)
  - Exp
  - Oth

Measuring scheme	Belle	Belle II	LHCb Run I	LHCb Run II	LHCb Upgr.
$B^0 \to D\pi^+\pi^-$	$\approx 10°$	$1.5°$	$\approx 15°$	$6°$	$1.5°$
Only $D \to K_S^0\pi^+\pi^-$	$\approx 15°$	$2°$	$\approx 20°$	$7°$	$2°$
$B^0 \to D\pi^+\pi^-$ (symm)	$\approx 15°$	$2°$	$\approx 20°$	$10°$	$2°$
Only $D \to K_S^0\pi^+\pi^-$	$\approx 20°$	$2.5°$	$\approx 25°$	$13°$	$3°$
$B^0 \to D^{(*)}h^0$	$5°$	$0.7°$	—	—	—
Only $D \to K_S^0\pi^+\pi^-$	$7°$	$1.1°$	—	—	—
Only $D \to f_{\mathcal{CP}}$	$6°$	$0.8°$	—	—	—

0.02 on $\sin(\phi_d)$

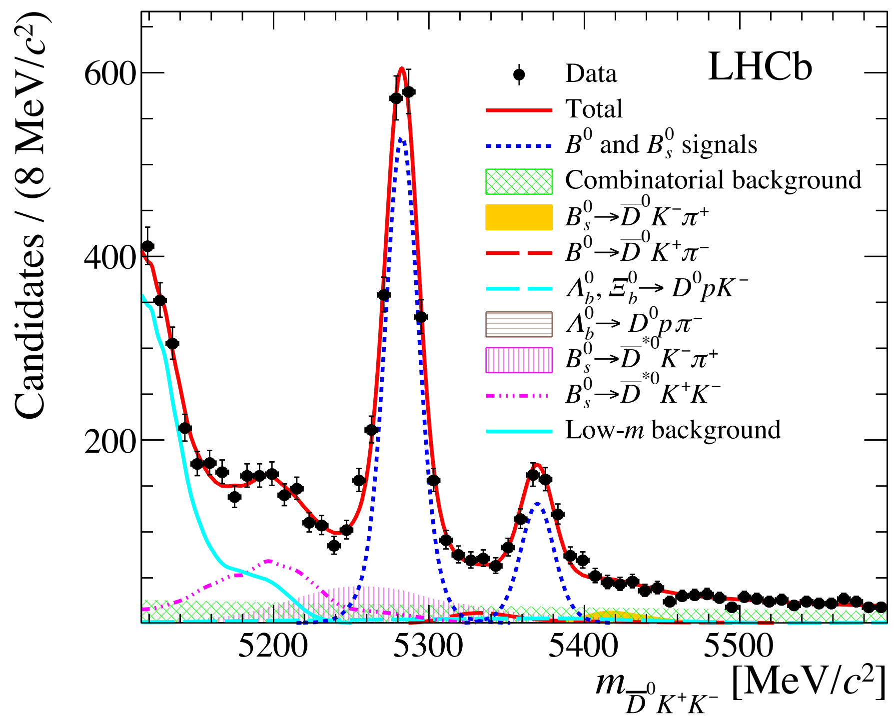
What about ϕ_s?

- Much less progress on this topic

Phys. Rev. D 85, 114015 (2011)

  - Can use $B_s^0 \to DK^+K^-$ decays in a similar way to the $B^0 \to D\pi^+\pi^-$ case
  - Signal yields are much lower (factor ~10 from BF and ~4 from Bs production)

Phys. Rev. D 98, 072006 (2018)



- First observation came last year
  - Around 500 signal events in Run 1

- Looking forwards
  - Expect ~2500 in Run 1+2
  - Upgrade should see ~20000 decays in the $\bar{D}^0 \to K^+\pi^-$ mode and ~2000 for $D \to K^+K^-$, $\pi^+\pi^-$
  - Adding flavour tagging, possible but will not be precise!

What about ϕ_s?

- We also have some nice γ modes
  - Analyses of decays like $B_s \to D_s K$ measure $\gamma - \phi_s$
  - Currently measuring γ using the known value of ϕ_s
  - Can swap this when γ is known more precisely

- How precisely can we measure this channel and the input for γ?
  - Will only reach current golden mode precision after Run 5!

Parameter	Run II	Upgrade	Upgrade II
$\gamma - \phi_s$	10°	2.5°	1°
γ	4°	1.5°	0.4°

$\phi_s = -0.021 \pm 0.031$ rad HFLAV WA 2018

$\phi_s = -0.054 \pm 0.021$ rad HFLAV Prelim 2019

Conclusion

- Can penguin-free measurements of $\phi_{d,s}$ be competitive?
  - The golden modes are named for good reason…
  - For ϕ_d, things are not so far away though
  - Will provide an interesting test of the SM
- Currently things look more difficult for ϕ_s
  - Can't rely on equivalent help from Belle II
  - New ideas?
- Perhaps a better question is "Are penguin-free measurements of $\phi_{d,s}$ worthwhile?"
  - Absolutely