CKM global fits and new physics in meson mixing

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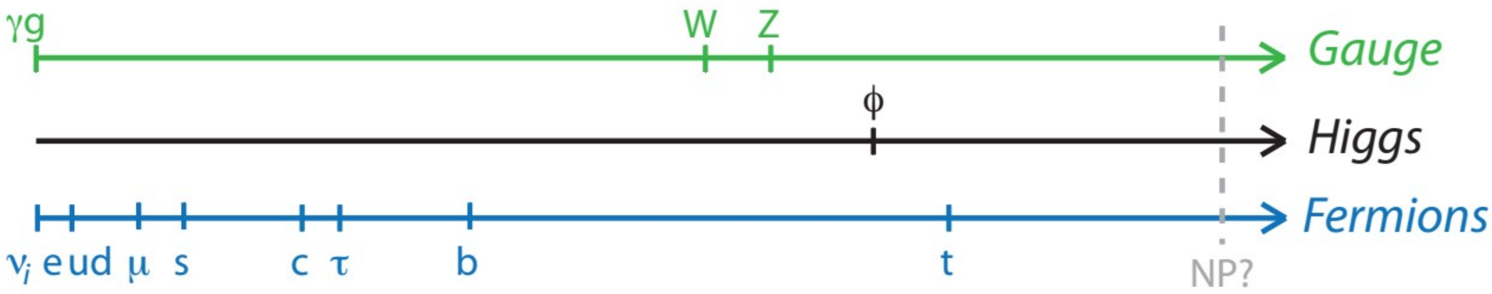
[Charles, Descotes-Genon, Ligeti, Monteil, Papucci, Trabelsi, LVS, PRD 102, 056023 (2020), arXiv:2006.04824]

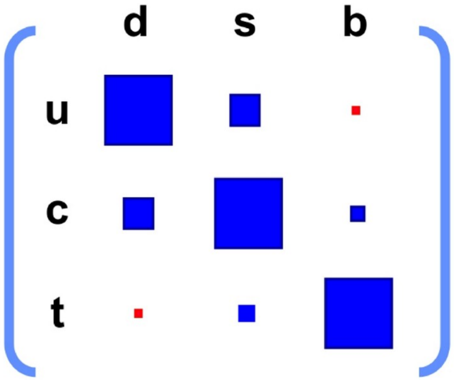
Mini-workshop in Theory, IAS & HKUST, 13/02/2023

The Standard Model (SM) and Beyond

- **Flavour physics** played a central role in the **formulation of the SM** (new fermion generations, manifestation of CP Violation, etc.)
- **Many flavour observables enjoy the status of *precision physics*, thanks to progress in different fronts (e.g.** QCD inputs)
- **Flavour physics** can play a **leading role** in addressing the questions left open by the SM, and reveal New Physics sectors

Hierarchies in the spectrum of particles and CKM matrix:

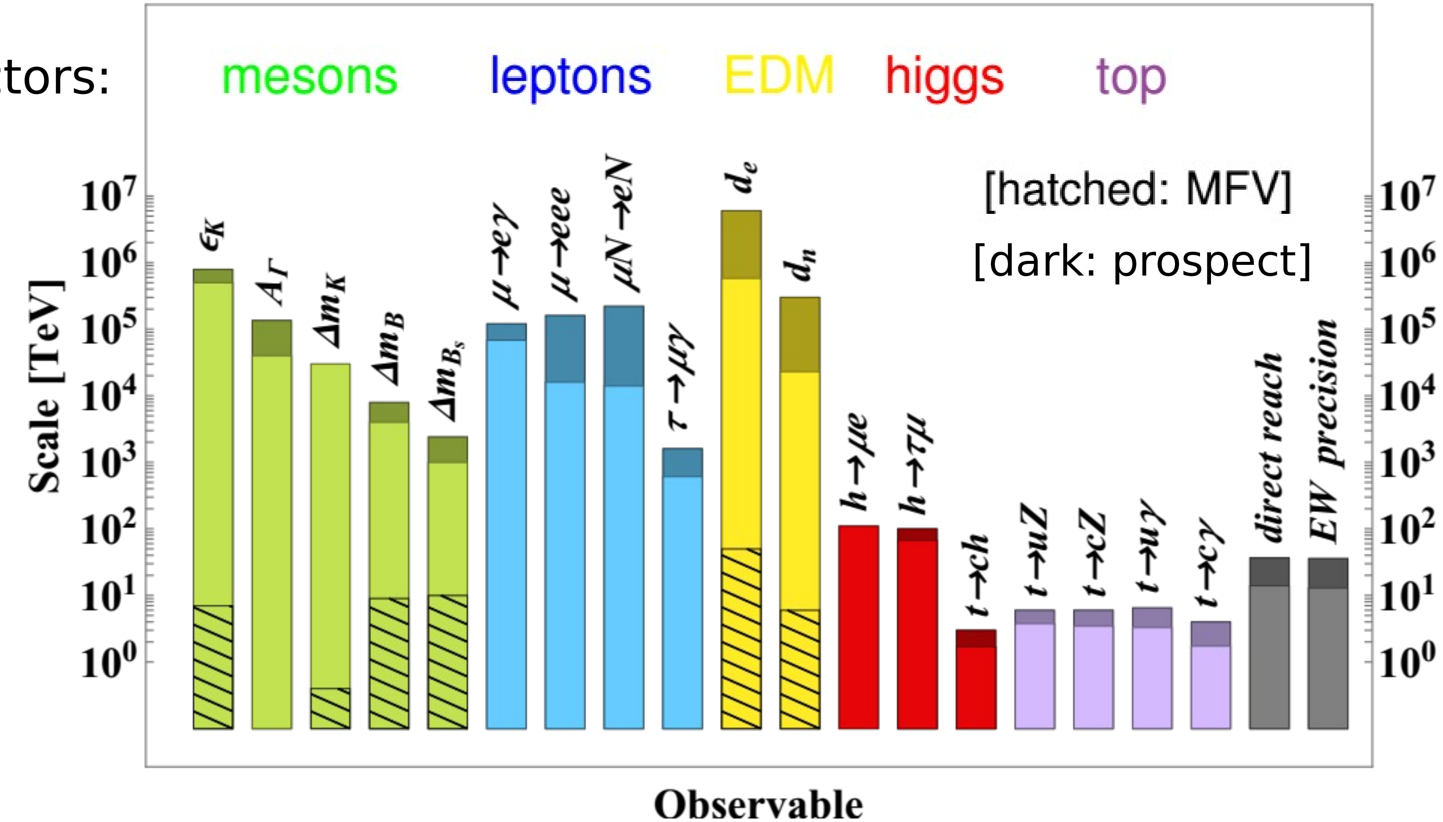




Reach to New Physics (NP)

- **Low-energy observables** → probe energies much beyond the reach of direct searches
- **The bounds on non-SM contributions shape NP candidates**
- **If deviation seen, possible NP manifestation!**

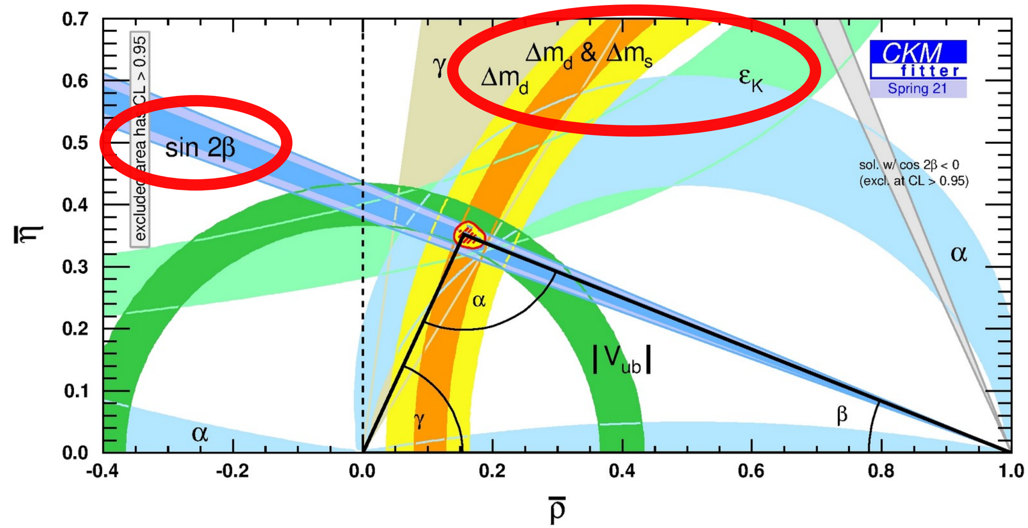
Different sectors:



[European Strategy Update 2020, arXiv:1910.11775]

Current status of flavour

- **Overall agreement w/ the SM, but some existing tensions (e.g., incl. vs excl. $|V_{xb}|$)**



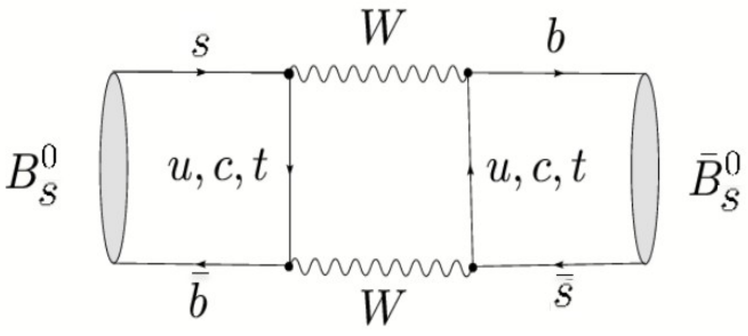
[CKMfitter update as of Spring ‘21]

- **Flavour is one of the main physics cases for future experiments**
- **Future data will guide the field**, testing present anomalies and possibly revealing new ones

NP in B meson mixing

- **HERE: address <u>present and future bounds</u> on NP in $|\Delta B|=2$, and discuss <u>future limitations</u>**

- **$|\Delta B|=2$: NP competes with suppressions in the SM (loop/CKM), and enjoys the status of precision physics**



- **Not discussing D meson mixing**

[K meson mixing: PRD 89, 033016 (2014), arxiv:1309.2293]

- **Combine projections for future data**: need global fit including "tree" and "loop" observables

[see e.g. CKMfitter]

NP in B meson mixing

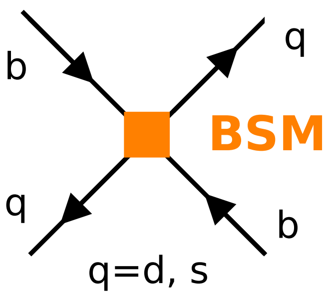
- **NP in |ΔB|=2:**
  h_d and h_s set sizes

CKM (in presence of NP),
bag parameters,
↓ decay constants

$$M_{12} = M_{12}^{\mathrm{SM}} \times (1 + h\, e^{2i\sigma})$$

↑ ↗
NP parameters

- **Assumptions**:
  - No NP in |ΔF|=1:
    tree level in SM (γ, $|V_{ub}|$, $|V_{cb}|$, ...) free of NP
  - NP is short-distance
  - Unitarity of the CKM 3x3 matrix
  - Unrelated NP in B_d and B_s systems



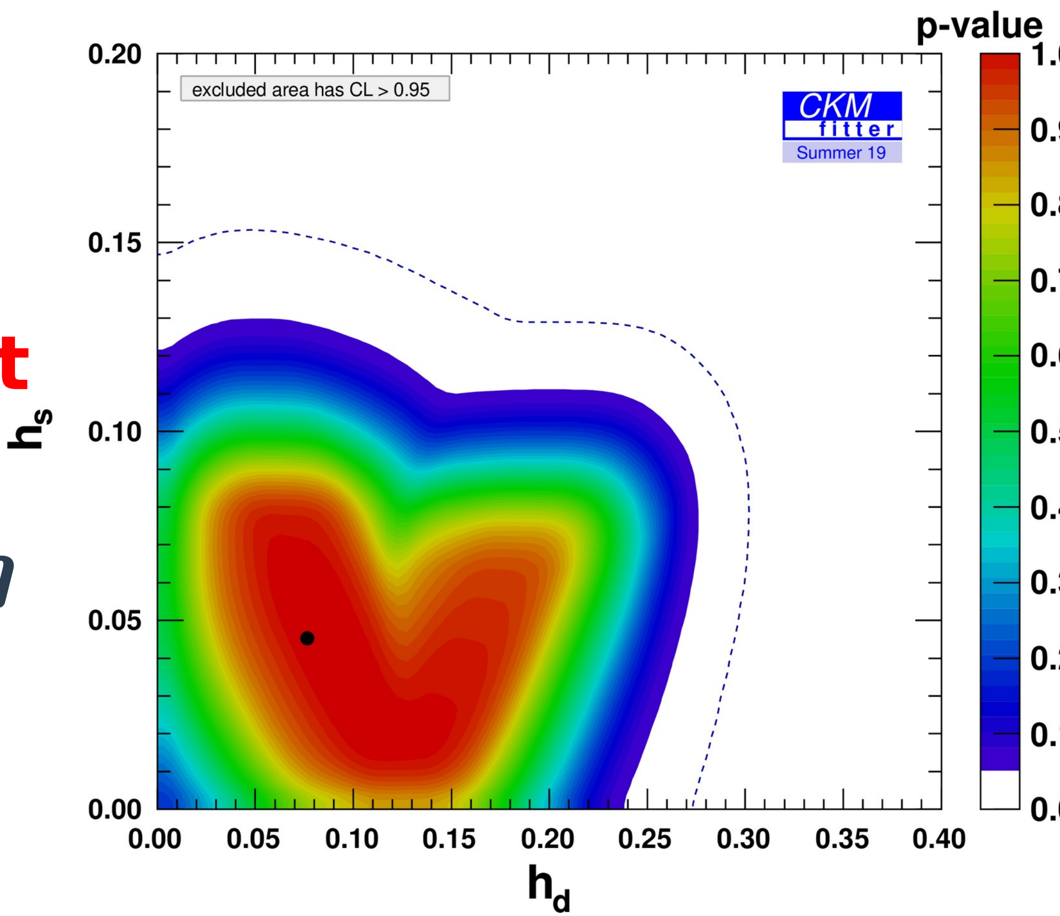
[See: PRD 89, 033016 (2014), arxiv:1309.2293]

- SMEFT: **four-quark operators** of different chiral structures

Present status of NP in B meson mixing

- **Agreement with the SM (h_d=h_s=0) at ~1σ**
- **Allowed size for NP at the level of O(20%)!**
- **Extractions of ρ and η** (Wolfenstein parm.) degrade by factor ~3

Status as of Summer '19



Black dot: best fit point; σ_d and σ_s are unconstrained

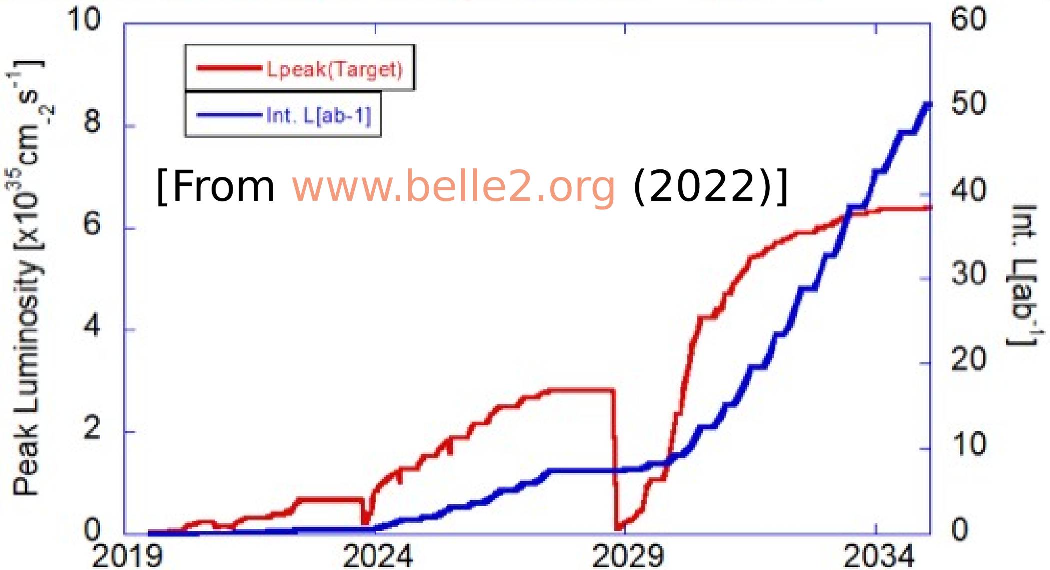
New era of flavour ahead

	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
ATLAS, CMS	25 fb^{-1}	150 fb^{-1}	300 fb^{-1}	⟶	3000 fb^{-1}
LHCb	3 fb^{-1}	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	*300 fb^{-1}

* assumes a future LHCb upgrade to raise the instantaneous luminosity to $2\text{x}10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$

[↑ See arXiv:1808.08865]

- Expression of interest for an **LHCb Upgrade II**
- **Belle II**: 50x the Belle and nearly 100x the BaBar data sets; ongoing discussions about **upgrade**



[From www.belle2.org (2022)]

Benchmarks for the future

- **Phase I**: **LHCb-upgrade I** 50/fb, & **Belle II** 50/ab
- **Phase II: LHCb-upgrade II** 300/fb, & **Belle II upgrade** 250/ab
- **Phase III: Phase II + FCC-ee**

FCC-ee: initial phase of FCC; operates at different EW thresholds: **5x10^{12} Z bosons**, **10^{8} WW pairs**, >10^{6} Higgses, >10^{6} tt pairs

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

Particle species	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	310	310	75	65	1.5	600	170

[FCC Physics Opportunities, Conceptual Design Report]

[Flavour cases: EPJPlus 136, 837 arXiv:2106.01259, and EPJPlus 136, 912 arXiv:2106.12168]

Experimental and theoretical inputs

	Central values	Uncertainties				Reference Phases I–III
		Current [28]	Phase I	Phase II	Phase III	
$\|V_{ud}\|$	0.97437	± 0.00021	id	id	id	[28]
$\|V_{us}\| f_+^{K\to\pi}(0)$	0.2177	± 0.0004	id	id	id	[28]
$\|V_{cd}\|$	0.2248	± 0.0043	± 0.003	id	id	[40,41]
$\|V_{cs}\|$	0.9735	± 0.0094	id	id	id	[28,40,41]
Δm_d [ps^{-1}]	0.5065	± 0.0019	id	id	id	[17]
Δm_s [ps^{-1}]	17.757	± 0.021	id	id	id	[17]
$\|V_{cb}\|_{\rm SL} \times 10^3$	42.26	± 0.58	± 0.60	± 0.44	id	[29]
$\|V_{cb}\|_{W\to cb} \times 10^3$		…	…	…	± 0.17	[34–36]
$\|V_{ub}\|_{\rm SL} \times 10^3$	3.56	± 0.22	± 0.042	± 0.032	id	[29]
$\|V_{ub}/V_{cb}\|$ (from Λ_b)	0.0842	± 0.0050	± 0.0025	± 0.0008	id	[30]
$\mathcal{B}(B\to\tau\nu)\times 10^4$	0.83	± 0.24	± 0.04	± 0.02	± 0.009	[29,34]
$\mathcal{B}(B\to\mu\nu)\times 10^6$	0.37	…	± 0.03	± 0.02	id	[29]
$\sin 2\beta$	0.680	± 0.017	± 0.005	± 0.002	± 0.0008	[29,30,34]
$\alpha[^\circ]$ (mod 180°)	91.9	± 4.4	± 0.6	id	id	[29]
$\gamma[^\circ]$ (mod 180°)	66.7	± 5.6	± 1	± 0.25	± 0.20	[29,30,34]
β_s[rad]	-0.035	± 0.021	± 0.014	± 0.004	± 0.002	[30,34]
$A_{\rm SL}^d \times 10^4$	-6	± 19	± 5	± 2	± 0.25	[14,17,34,37]
$A_{\rm SL}^s \times 10^5$	3	± 300	± 70	± 30	± 2.5	[14,17,34,37]
$\bar{m}_t$ [GeV]	165.30	± 0.32	id	id	± 0.020	[28,34]
$\alpha_s(m_Z)$	0.1185	± 0.0011	id	id	± 0.00003	[28,34]
$f_+^{K\to\pi}(0)$	0.9681	± 0.0026	± 0.0012	id	id	[30]
f_K [GeV]	0.1552	± 0.0006	± 0.0005	id	id	[30]
f_{B_s} [GeV]	0.2315	± 0.0020	± 0.0011	id	id	[30]
B_{B_s}	1.219	± 0.034	± 0.010	± 0.007	id	[30]
f_{B_s}/f_{B_d}	1.204	± 0.007	± 0.005	id	id	[30]
B_{B_s}/B_{B_d}	1.054	± 0.019	± 0.005	± 0.003	id	[30]
$\tilde{B}_{B_s}/\tilde{B}_{B_d}$	1.02	± 0.05	± 0.013	id	id	[30,42,43]
$\tilde{B}_{B_s}$	0.98	± 0.12	± 0.035	id	id	[30,42,43]
η_B	0.5522	± 0.0022	id	id	id	[44]

[See for refs.: PRD 102, 056023 (2020), arXiv:2006.04824
and also EPJPlus 136, 837 arXiv:2106.01259,
and EPJPlus 136, 912 arXiv:2106.12168]

Experimental and theoretical inputs

- **Caveat**: experimental sensitivity studies for FCC still in progress...
- **$|V_{ub}|_{SL}$ & $|V_{cb}|_{SL}$**: respectively 0.9% & 1.0% @ Phase II (Belle II U.)

  $|V_{cb}|$ accuracy ~0.4% @ FCC-ee: $W \to bc$ [Schune, Monteil]

  [incl. vs excl. inputs and impact on extraction of NP in $|\Delta F|=2$: De Bruyn, Fleischer, Malami, van Vliet]

  [recent B_c to $\tau\nu$ @ Tera-Z: Zheng, Xu, Cao, Yu, Wang, Prell, Cheung, Ruan; Amhis, Hartmann, Helsens, Hill, Sumensari]
- **Future stat. accuracy in angles (α, β, β_s, γ)** ~< 1°

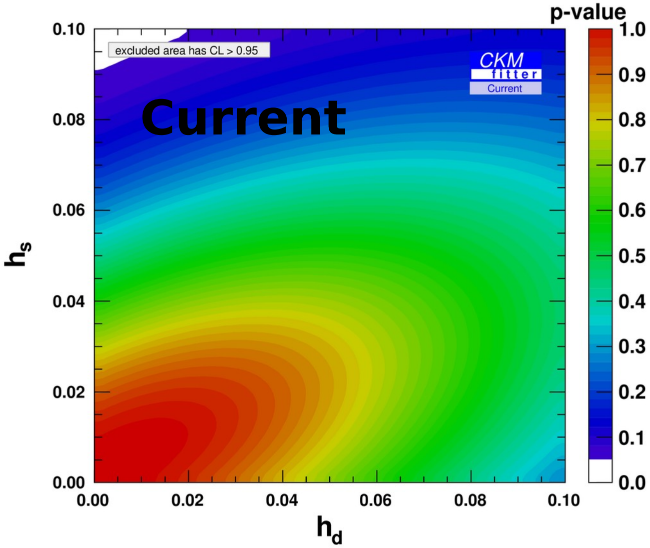
  At this level of exp. accuracy: need for theo. studies of isospin breaking corrections, penguin pollution, etc.

  [recent dedicated α @ Tera-Z (B^0 to $\pi^0\pi^0$): Wang, Descotes-Genon, Deschamps, Li, Chen, Zhu, Ruan]

  [recent Tera-Z studies of β_s, etc.: Aleksan, Oliver, Perez; Aleksan, Oliver, Perez; Li, Ruan, Zhao]
- Phases I and II uncs. for **Lattice QCD** (decay constants, bag parameters) < 1%

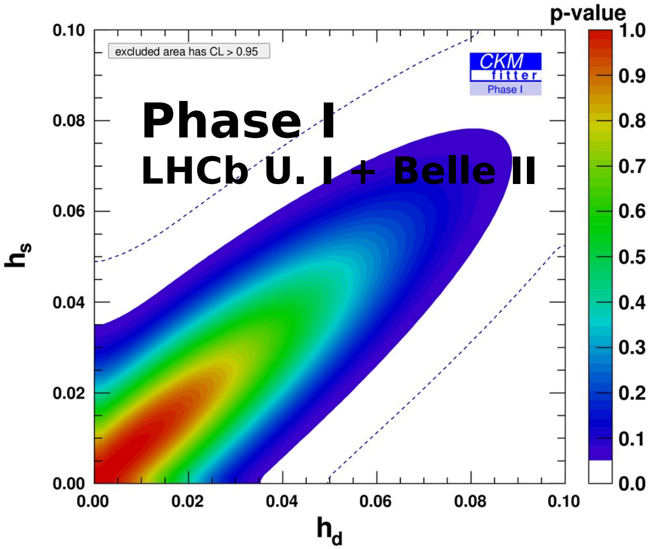
  Literature discusses Lattice QCD projections up to Phase II

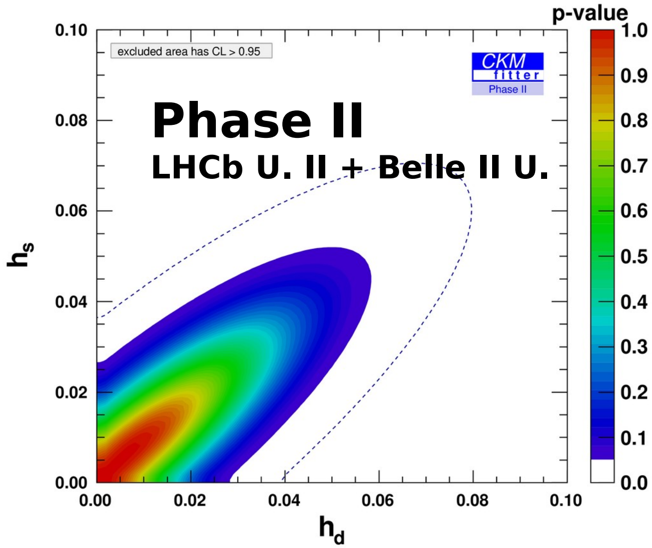
Future improvements



- SM reference: <u>shift the central values</u>
- Compared to Current, **improvement by factor >3 (5) at Phase I (II)**

Sensitivities	Summer 2019	Phase I	Phase II
h_d	0.26	0.073	0.049
h_s	0.12	0.065	0.044

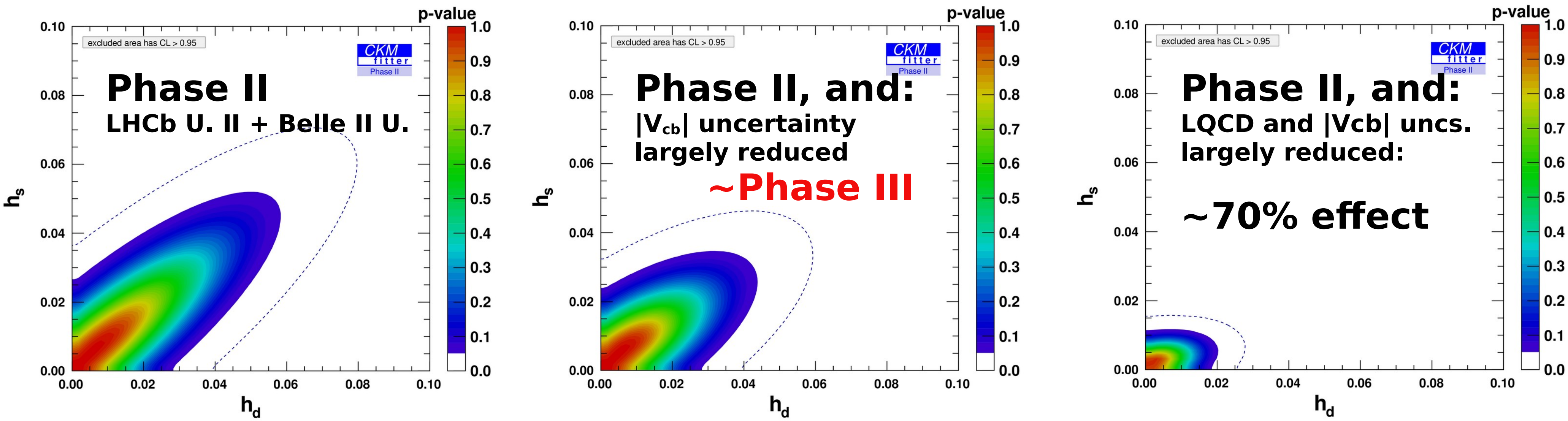




Bottlenecks

Necessary improvements beyond current expectations **for enhancing sensitivity to NP**:

- **Lattice QCD** (also short-distance QCD corrections)
- **$|V_{cb}|$**, overall normalization (Wolfenstein parameter A)
- **Individual impacts on h_d and h_s**: O(20-30)%



Future reach to NP in B meson mixing

$$\frac{C_{ij}^2}{\Lambda^2}(\bar{q}_{i,L}\gamma_\mu q_{j,L})^2, \quad \Rightarrow \quad h \simeq 1.5 \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2}\frac{(4\pi)^2}{G_F\Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2}\left(\frac{4.5\ \text{TeV}}{\Lambda}\right)^2, \quad \sigma = \arg(C_{ij}\lambda_{ij}^{t*}),$$

- In the absence of suppressions: **NP scale >> TeV**
- Possible flavour and loop suppressions: **alleviate bounds on NP**

		Sensitivity for Summer 2019 [TeV]		Phase I Sensitivity [TeV]		Phase II Sensitivity [TeV]	
Couplings	NP loop order	B_d mixing	B_s mixing	B_d mixing	B_s mixing	B_d mixing	B_s mixing
$\|C_{ij}\| = \|V_{ti}V_{tj}^*\|$	Tree level	9	13	17	18	20	21
(CKM-like)	One loop	0.7	1.0	1.3	1.4	1.6	1.7
$\|C_{ij}\| = 1$	Tree level	1×10^3	3×10^2	2×10^3	4×10^2	2×10^3	5×10^2
(No hierarchy)	One loop	80	20	2×10^2	30	2×10^2	40

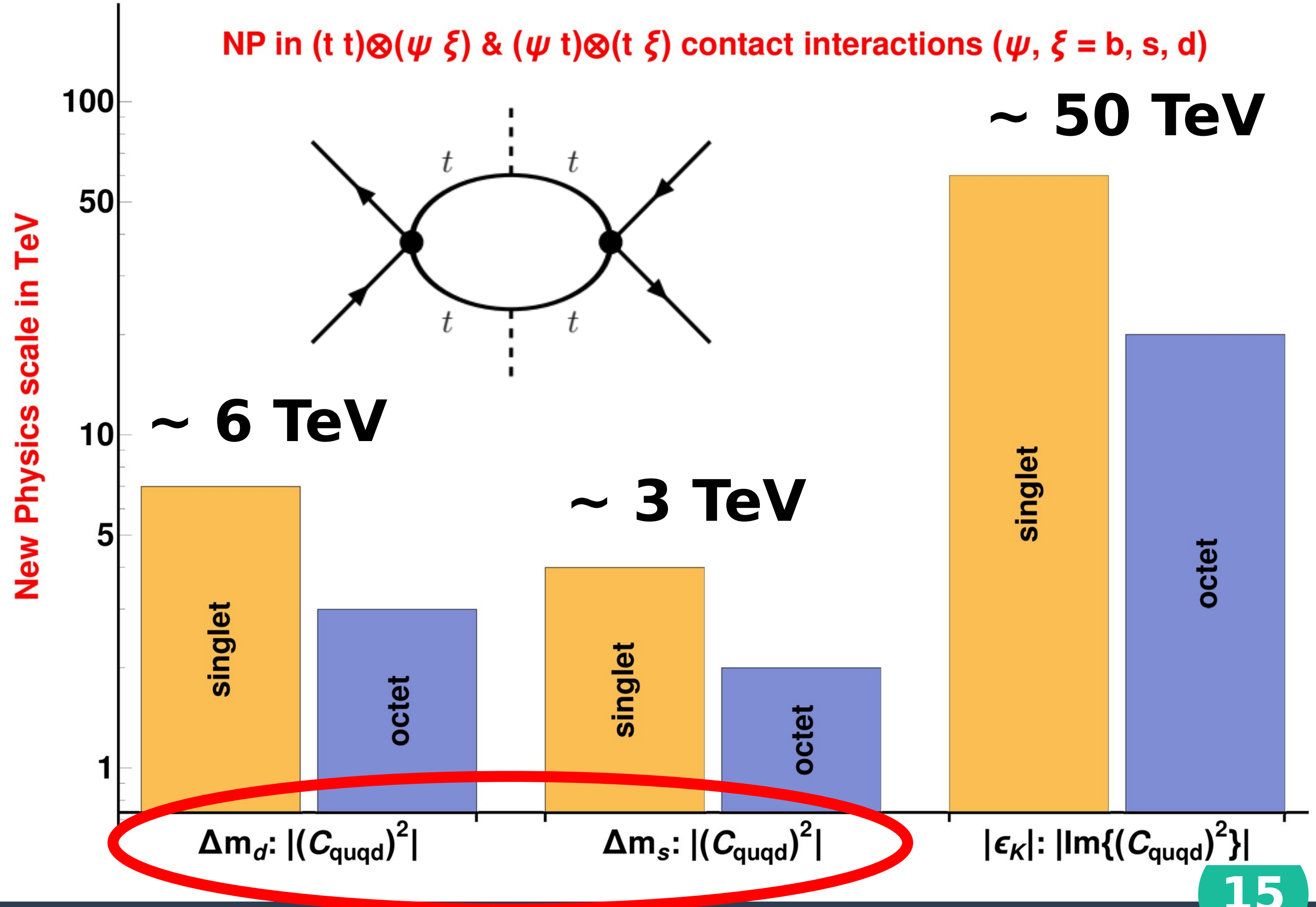
Sensitivity to SMEFT operators

|ΔF|=2 dim.-8: sensitivity to multi-TeV NP effects

- |ΔF|=2 dim.-6 operators: previous slide set bounds for (V-A)x(V-A)
- (|ΔF|=1 dim.-6)²=(|ΔF|=2 dim.-8 operators)
- |ΔF|=1 qugd-operator does not change global fit analysis

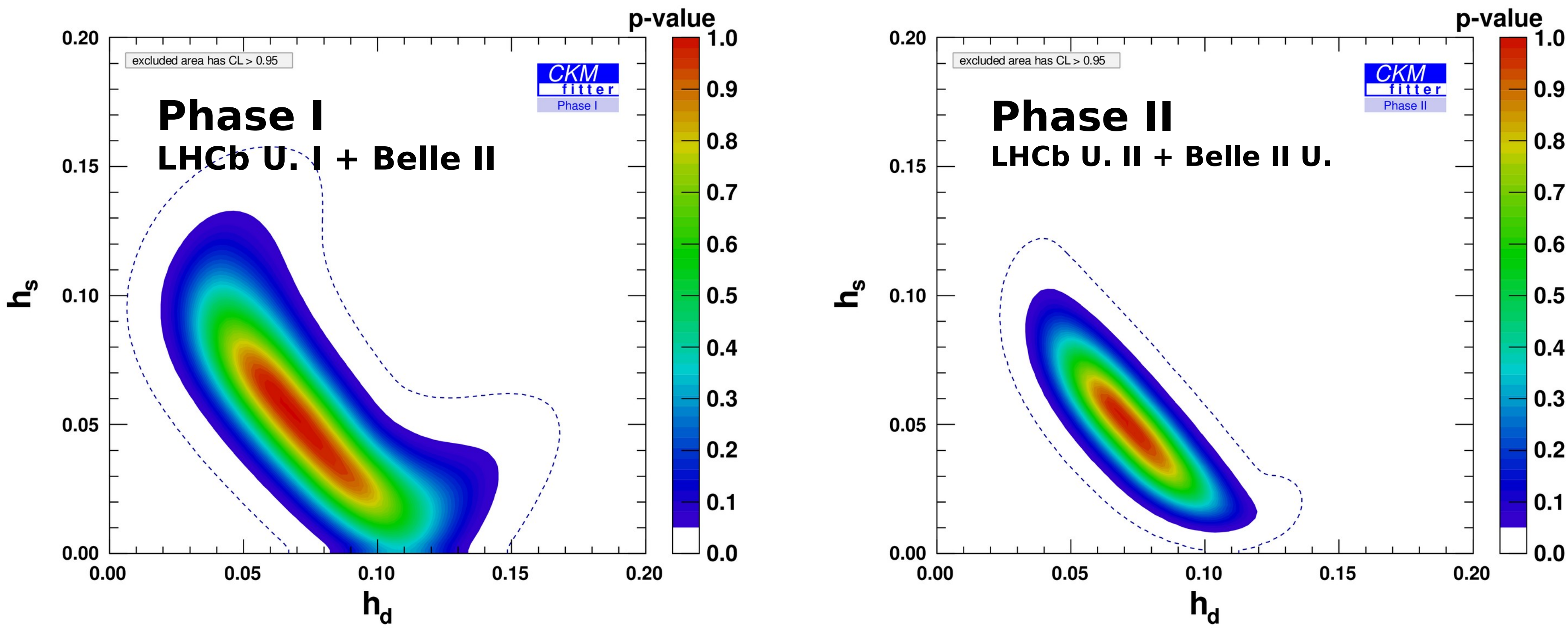
NP bag parameters: [ETM ’15, HPQCD ’19]

[LVS, arXiv:2201.03038]



Discovery prospects

B meson mixing observables also provide potential **discovery for NP**



Conclusions

- Flavour physics: crucial in **shaping the SM**, but also in looking for **candidates of NP**
- $|\Delta B|=2$: only one flavour aspect of future experimental and theoretical progress
- Allowed NP in B meson mixing **still large**: bounds will largely improve
- Identified future limitations in Phase II:

  LQCD and $|V_{cb}|$
- FCC-ee (Tera-Z) partially addresses $|V_{cb}|$ bottleneck

BACK UP!

Experimental quantities vs. theoretical ones

Observables considered in the fit that are modified by NP in |ΔB|=2:

$$\Delta_q = |\Delta_q| e^{i2\Phi_q^{\mathrm{NP}}}$$

parameter	prediction in the presence of NP
Δm_q	$\lvert\Delta_q^{\mathrm{NP}}\rvert \times \Delta m_q^{\mathrm{SM}}$
2β	$2\beta^{\mathrm{SM}} + \Phi_d^{\mathrm{NP}}$
$2\beta_s$	$2\beta_s^{\mathrm{SM}} - \Phi_s^{\mathrm{NP}}$
2α	$2(\pi - \beta^{\mathrm{SM}} - \gamma) - \Phi_d^{\mathrm{NP}}$
$\Phi_{12,q} = \mathrm{Arg}[-\frac{M_{12,q}}{\Gamma_{12,q}}]$	$\Phi_{12,q}^{\mathrm{SM}} + \Phi_q^{\mathrm{NP}}$
A_{SL}^q	$\frac{\Gamma_{12,q}}{M_{12,q}^{\mathrm{SM}}} \times \frac{\sin(\Phi_{12,q}^{\mathrm{SM}} + \Phi_q^{\mathrm{NP}})}{\lvert\Delta_q^{\mathrm{NP}}\rvert}$
$\Delta\Gamma_q$	$2\lvert\Gamma_{12,q}\rvert \times \cos(\Phi_{12,q}^{\mathrm{SM}} + \Phi_q^{\mathrm{NP}})$

Different representation

$$\langle B_q | \mathcal{H}^{\rm SM+NP}_{\Delta B=2} | \bar{B}_q \rangle \equiv \langle B_q | \mathcal{H}^{\rm SM}_{\Delta B=2} | \bar{B}_q \rangle \times (\mathrm{Re}(\Delta_q) + i\,\mathrm{Im}(\Delta_q))$$

$$\mathrm{Re}(\Delta_q) + i\mathrm{Im}(\Delta_q) = r_q^2 e^{i2\theta_q} = 1 + h_q e^{i\sigma_q}$$

Soares & Wolfenstein, PRD 47, 1021 (1993)
Deshpande, Dutta & Oh, PRL77, 4499 (1996)
Silva & Wolfenstein, PRD 55, 5331 (1997)
Cohen et al., PRL78, 2300 (1997)
Grossman, Nir & Worah, PLB 407, 307 (1997)