Flavor physics prospects and opportunities at Tera-Z

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[See: Grossman & ZL, Eur. Phys. J. Plus 136:912 (2021), 2106.12168

Charles, Descotes-Genon, ZL, Monteil, Papucci, Trabelsi, Vale Silva, PRD 102, 056023 (2020), 2006.04824]

Flavor physics — many puzzles

- Flavor $\equiv$ what distinguishes generations? [break $U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_L \times U(3)_e$]

  Experimentally, rich and sensitive ways to probe SM, and search for NP

- SM flavor: masses? mixing angles? 3 generations? — most of the SM param's

  Flavor in SM is simple: only Higgs – fermion couplings break flavor symmetries

- BSM flavor: TeV scale (hierarchy problem) $\ll$ "naive" flavor & CP viol. scale

  Most TeV-scale new physics contain new sources of CP and flavor violation

  E.g., SUSY: $\sim 10\times$ increase in flavor parameters (CP and flavor problems?)

  Generic TeV-scale flavor structure excluded $\Rightarrow$ new mechanisms to reduce signals

- Many BSM models have observable signals, baryogenesis remains a puzzle

- Any new particle that couples to quarks or leptons $\Rightarrow$ new flavor parameters

  (Understanding these param's can be crucial; e.g., Higgs, or squark & slepton couplings [if exists])

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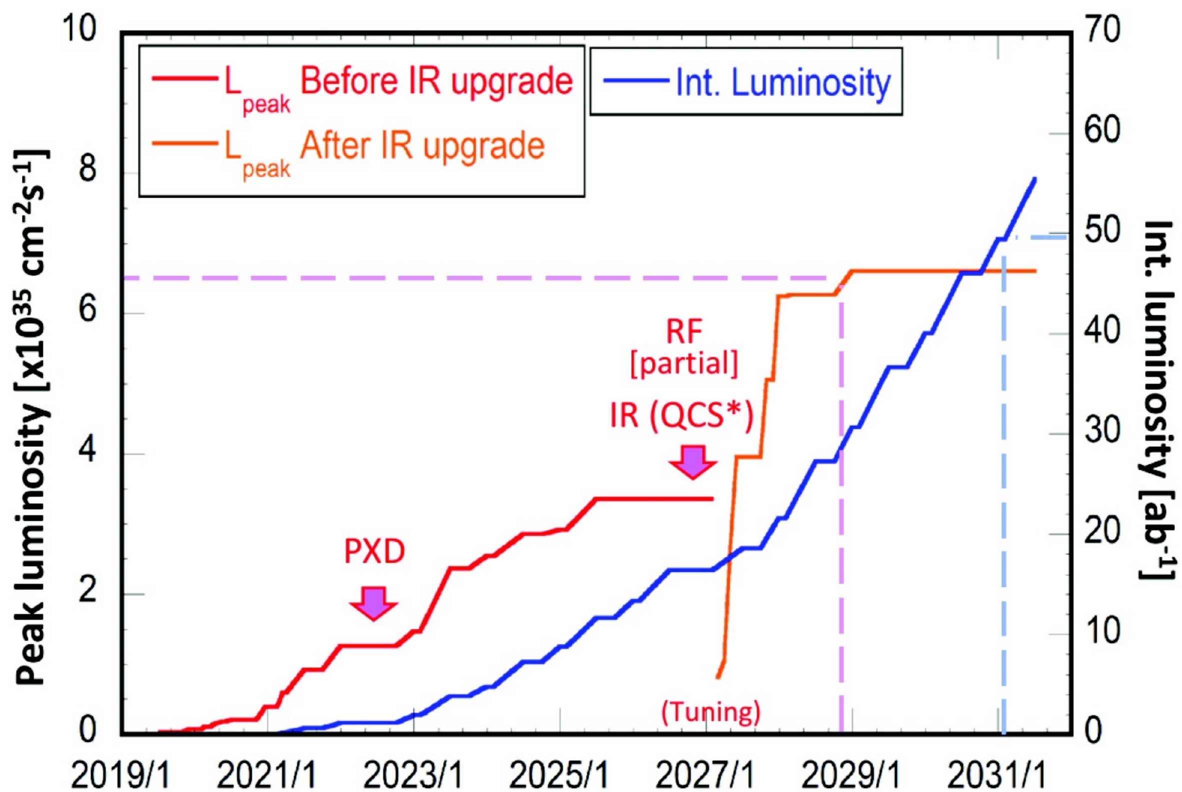
Before tera-Z (1) — LHC

	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}	$\longrightarrow$	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 $2\text{x}10^{34}$ $cm^{-2}s^{-1}$

- Current LHCb upgrade in LS2 (raise instantaneous luminosity to $2 \times 10^{33}/\mathrm{cm}^2/\mathrm{s}$)
  Major ATLAS and CMS upgrades in LS3 for HL-LHC
- LHCb, 2017, Expression of Interest for an upgrade in LS4 to $2 \times 10^{34}/\mathrm{cm}^2/\mathrm{s}$

Before tera-Z (2) — Belle II



- First collisions 2018 (unfinished detector), with full detector starting spring 2019
  Goal: $50\times$ the Belle and nearly $100\times$ the BaBar data set
- Discussions started about physics case and feasibility of a factor ~ 5 upgrade, similar to LHCb Phase-II upgrade aiming 50/fb $\to$ 300/fb, after LHC LS4

Some tera-Z highlights

- Production yields at tera-Z compared to Belle II (from CERN-ACC-2018-0056)

Particle production (10^9)	$B^0 + \overline{B}^0$	$B^\pm$	$B_s^0 + \overline{B}_s^0$	$\Lambda_b + \bar{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II (50 ab^{-1})	27.5	27.5	—	—	65	45
tera-Z (5×10^{12} Z)	400	400	100	100	550	170

Most often this is the sole focus of talks on flavor @ tera-Z

Comparison with LHCb more complex: trigger is essential (LHCb), LHCb has advantage if final state is fully reconstructed, if there are neutrals, tera-Z may win

- WW threshold: $W \to b\bar{c}$ can give a qualitatively new determination of $|V_{cb}|$
Estimate 0.3% uncertainty, using 10^8 WW, independent of B measurements

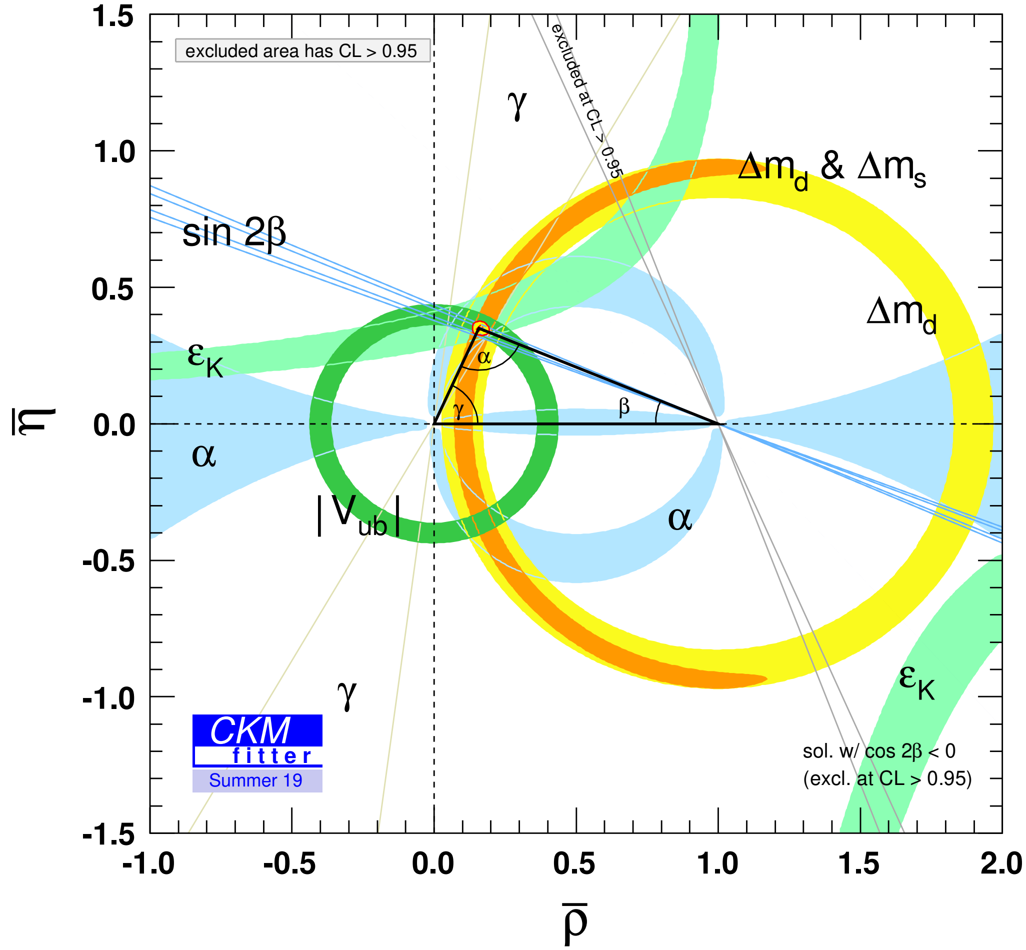
[Schune @ 3rd FCC Physics and Experiments Workshop, Jan 2020; Azzurri @ 4th FCC Physics and Experiments Workshop, Nov 2020]

- $t\bar{t}$ threshold: some improvements in FCNC top decay searches, $t \to \{H, Z, \gamma\}\, q$
(I'll not talk about this)

Status: the B-factory money plot

- Many constraints from K, B, and B_s decays consistent with each other
- Very likely, the CKM mechanism dominates CP violation and flavor changing interactions
- $\Rightarrow$ KM Nobel Prize, 2008

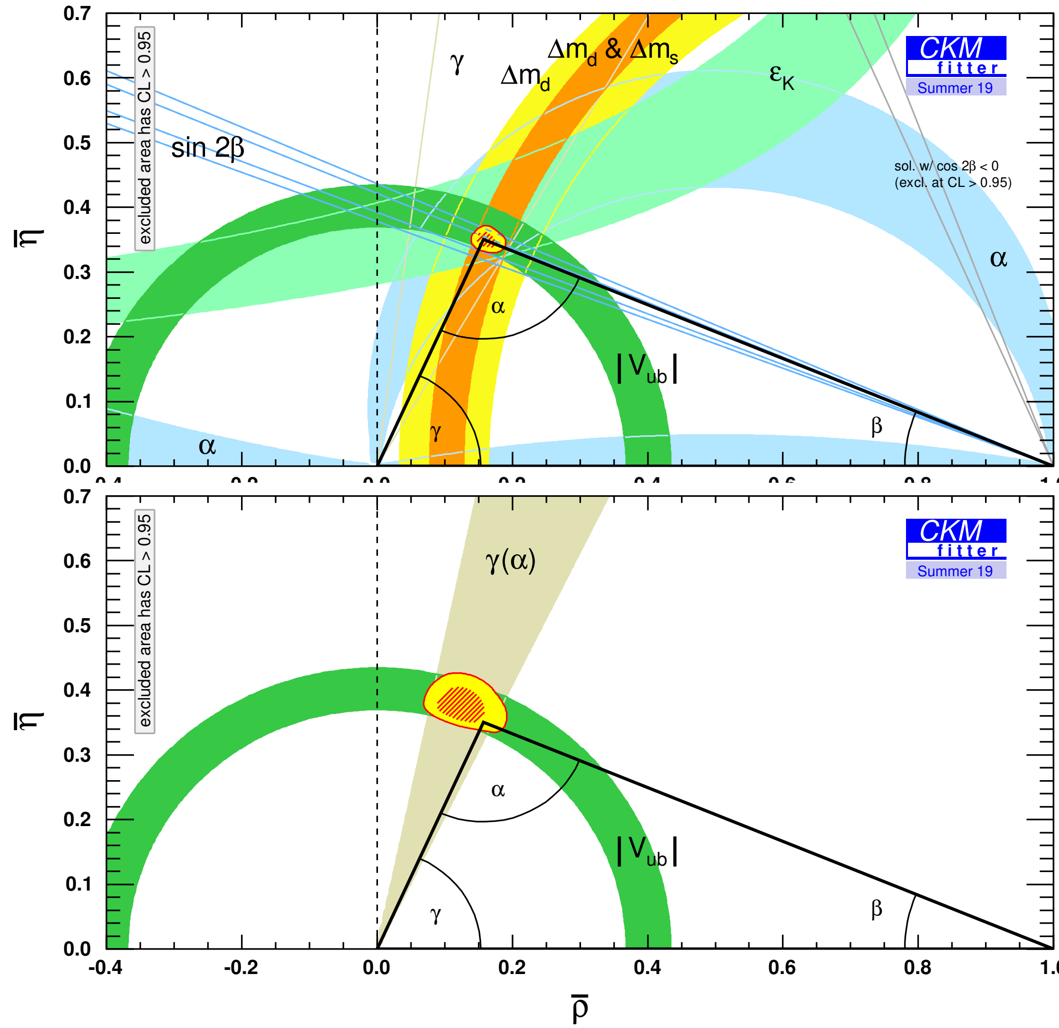
Before BABAR & Belle, NP/SM ~ 1 was possible in CP violating observables



- The implications of this consistency of measurements is often overstated

Plenty of room for new physics

- Larger allowed region if the SM is not assumed
- Tree-level (lower plot) vs. loop-dominated measurements crucial
- LHCb: improved many constraints, also in B_s sector (2nd–3rd gen.)



- $\mathcal{O}(20\%)$ NP contributions to most loop-level processes (FCNC) are still allowed

Status of experiment & theory unpredictable

- New physics may or may not have been discovered before tera-Z operates
- There may be a lot of theoretical progress before tera-Z (look back at history...)
  The most interesting are probably the unpredictable ones!
- Lattice QCD: no extrapolations of expected (or hoped) uncertainties that far out

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- Complementarity to Belle II and LHCb, and for some channels superior
- Extends LHCb and Belle II discovery potentials in many channels
- Extends sensitivity to BSM contributions from higher scales (think SMEFT)
- IF BSM discovered: may play a critical role in understanding its flavor structure

6 topics: some highlights

CP violation in hadronic B decays

- Shaped our understanding that CPV in hadron decays is due to single KM phase
- Tera-Z expectation of uncertainties:

  $\gamma \sim 0.004$ rad, $\beta \sim 0.005$, $\phi_s \sim 0.002$ [see Table 7.3 in FCC Physics Opportunities: CDR, vol.1]

  Modest improvements over LHCb (w/ 300/fb) in channels that are "easy" for LHCb

  Tera-Z will have greater advantage in modes w/ neutrals, few sensitivity studies
- Can probe in many decay modes CPV in angular distributions ("triple products")

  (Need theory to progress for cleaner interpretation)
- If deviation from SM discovered: verify and refine in environment with different systematic uncertainties (and combine results from different experiments)

Semileptonic CP violation: $A_{\rm SL}^{d,s}$

- CPV in mixing, BSM may not contain an m_c^2/m_b^2 suppressions specific to the SM

[hep-ph/0202010]

$$A_{\rm SL} = \frac{\Gamma[\overline{B}^0(t) \to \ell^+ X] - \Gamma[B^0(t) \to \ell^- X]}{\Gamma[\overline{B}^0(t) \to \ell^+ X] + \Gamma[B^0(t) \to \ell^- X]}$$

In large classes of BSM models, the dominant deviations from the SM may be in neutral meson mixing amplitudes, with smaller impacts on decay rates

- Current status:

Data: $A_{\rm SL}^d = -(2.1 \pm 1.7) \times 10^{-3}$ $\qquad A_{\rm SL}^s = -(0.6 \pm 2.8) \times 10^{-3}$

SM: $A_{\rm SL}^d = -(4.7 \pm 0.6) \times 10^{-4}$ $\qquad A_{\rm SL}^s = (2.22 \pm 0.27) \times 10^{-5}$ [1603.07770]

Plenty of room between current sensitivity and the SM predictions

(Hard to extrapolate whether LHCb becomes systematics limited)

- Tera-Z expectation: exp uncertainty $\sim 2.5 \times 10^{-5}$ for both

(Very) rare decays

- Unique capabilities for decays with large missing energy, i.e., ν or τ in final state

  (And better than LHCb for $e^{\pm}$)

  Many decays mediated by $b \to s\nu\bar{\nu}$ or $b \to s\tau^+\tau^-$, and their $b \to d$ counterparts

- Tera-Z could be the first to measure [see Li's talk just before this]

  $B \to K^{(*0)}\tau^+\tau^-$, $\Lambda_b \to \Lambda\tau^+\tau^-$, $B \to K^{(*)}\nu\bar{\nu}$, $B_s \to \phi\nu\bar{\nu}$, $\Lambda_b \to \Lambda\nu\bar{\nu}$, maybe $B \to \pi(\rho)\nu\bar{\nu}$

- Two-body $B \to \ell^+\ell^-$ decays sensitive to very high scales (comparable to $K \to \pi\nu\bar{\nu}$)

  $B_{s,d} \to \mu^+\mu^-$: tera-Z expected to be comparable to HL-LHC for

  $B_{s,d} \to e^+e^-$: tera-Z is much more sensitive & measure $B_s \to \tau^+\tau^-$ at SM level

  (In SM: $\mathcal{B}(B_s \to \tau^+\tau^-) = (7.7 \pm 0.5) \times 10^{-7}$, [1311.0903])

- Another important 2-body decay: $B_c \to \tau\bar{\nu}$ [see Amhis' talk in 4 hours]

- $R_{K^{(*)}}$ and $R(D^{(*)})$: in many models, correlated effects in many of these processes

Polarized baryons and quarks

- Baryons can probe short-distance physics in some ways that mesons cannot

  b and c quarks in Z decays are highly polarized, largely retained by baryons

- Baryon polarization tells us about Dirac structure of operators that create them

  (Washed out by hadronization for mesons)

  Need to know how well the quark polarization is retained by the baryons

  (More work needed, connections with top decays [1505.02771])

- With highly polarized Λ_b from Z decay, semileptonic $\Lambda_b \to \Lambda_c \ell \nu$ can test the chirality of weak interaction in similar ways to the Michel parameters in μ decay

  Similar studies in rare FCNC decays, e.g., $\Lambda_b \to \Lambda \ell^+ \ell^-$ (+ analogous Λ_c decays)

Exclusive hadronic Z decays

- Exclusive Z decays: e.g., $Z \to X\gamma$ is sensitive to the light-cone distribution amplitude of the meson X

  An interesting channel: $Z \to J/\psi\,\gamma$, expected branching ratio $\mathcal{O}(10^{-7})$

  Important calibration for $H \to X\,\gamma$, which can probe Higgs to light quark couplings

- Search for FCNC Z decays: e.g., $Z \to B_s\gamma$ or $Z \to B_s\mu^+\mu^-$

  (In the SM, suppressed relative to $Z \to J/\psi\gamma$ by $[|V_{cb}|/(16\pi^2)]^2 \sim 10^{-7}$, resulting in $\lesssim 10^{-14}$)

  BSM could enhance these rates to observable level — synergy with $B_{(s)}$ decays

- Not yet studied modes may be interesting probes of FCNC, e.g., $Z \to B^+K^-(\gamma)$

- Search for LFV Z decays [see Marcano's talk this pm]

Charm physics

- CPV in D decay recently established:

  $A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = -(1.54 \pm 0.29) \times 10^{-3}$ LHCb, [1903.08726]

  (In K and B decays, CPV involving mixing was first observed, in D and $B_{(s)}$, CPV in decay)

- tera-Z will be able to measure many such asymmetries, w/o taking differences

  As LHCb probes small CP asymmetries, have to control production asymmetry of c vs. $\bar{c}$ — not an issue for tera-Z

- On tera-Z time scale, lattice may address (some) hadronic D decay amplitudes

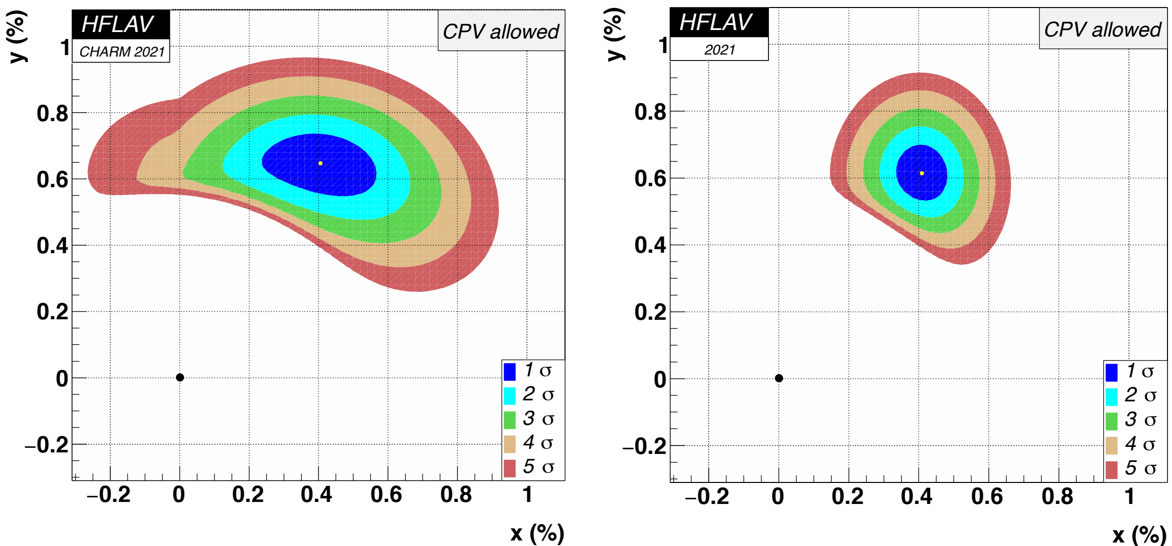
- D^0 mixing and CPV in mixing probe very high scales, complementary to K & $B_{(s)}$

  (Mixing generated by down quarks, or in SUSY by up-type squarks)

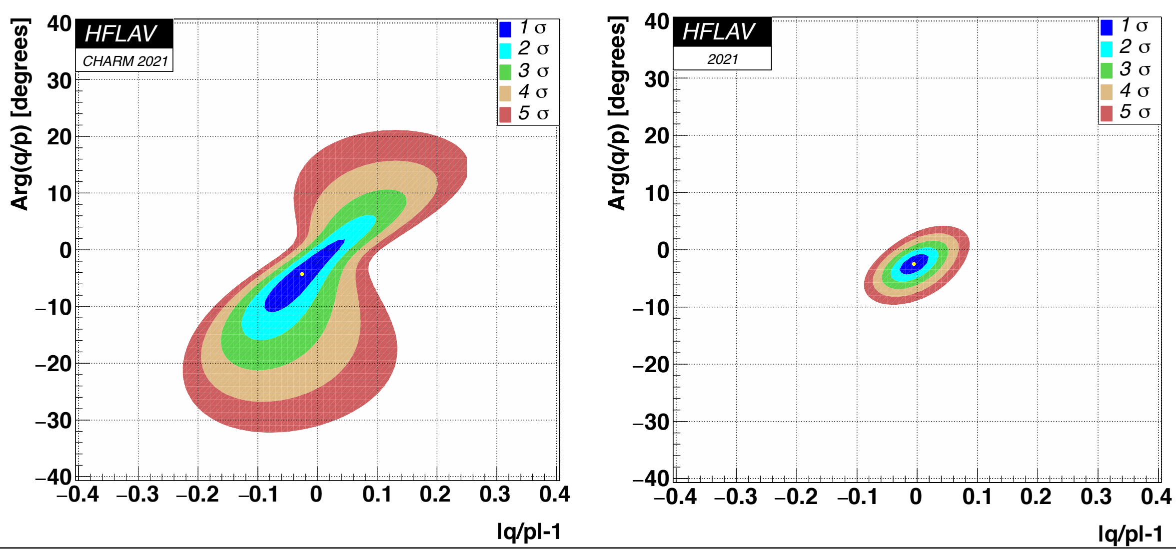
  Only last month was $\Delta m \neq 0$ established with greater than 3σ significance!

  CP violation in D mixing remains very interesting, room for BSM has shrunk a lot

D mixing: huge recent progress



Before After [LHCb, $D^0 \to K_S^0 \pi^+ \pi^-$, 2110.02350]

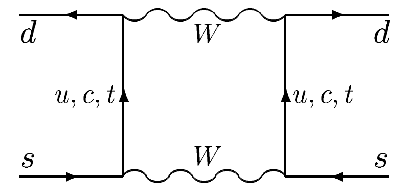


One example in more detail

(Triggered by changing experimental prospects, 2006.04824 update of 1309.2293)

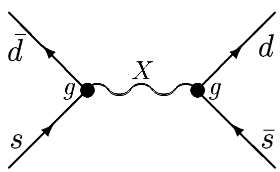
Meson mixing as a probe of new physics

- High mass-scale sensitivity due to very small SM predictions
- Why is $\Delta m_K / m_K \sim 7 \times 10^{-15}$?



In the SM: $$\frac{\Delta m_K}{m_K} \sim \alpha_w^2 \, |V_{cs} V_{cd}|^2 \, \frac{m_c^2}{m_W^4} \, f_K^2$$

- If exchange of a heavy particle X was responsible for a fraction of Δm_K :



$$\frac{\Delta m_K^{(X)}}{\Delta m_K} \sim \frac{g^2 \, \Lambda_{\rm QCD}^3}{M_X^2 \, \Delta m_K} \quad \Rightarrow \quad M_X > g \times 10^3 \, {\rm TeV}$$

TeV-scale particles with loop-suppressed coupling can still be visible $[g \sim \mathcal{O}(10^{-3})]$

Even stronger constraints from ϵ and ϵ' on some models

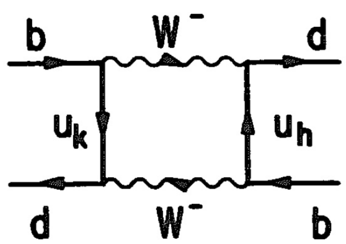
- Critical in developing SM, and in guiding BSM model building

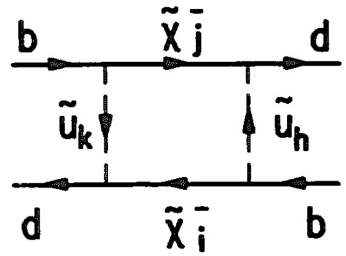
(Flavor has been mostly an input rather than output of model building: evade constraints, or dead)

- These constraints have guided model building since 70s $\Rightarrow$ conservative view of future progress

Simplest parametrization

- Meson mixing:





General parametrization:

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

NP parameters

SM: $\sim \dfrac{C_{\rm SM}}{m_W^2}$ NP: $\sim \dfrac{C_{\rm NP}}{\Lambda^2}$

If $h \ll 1$, then BSM $\ll$ SM

What is the scale Λ? How different is the $C_{\rm NP}$ coupling from $C_{\rm SM}$?

If deviation from SM seen $\Rightarrow$ upper bound on Λ

- Assume: (i) 3×3 CKM matrix is unitary; (ii) tree-level decays dominated by SM

- Modified: loop-mediated (Δm_d, Δm_s, β, β_s, α, ...)

  Unchanged: tree-dominated (γ, $|V_{ub}|$, $|V_{cb}|$, ...)

  (Importance of these constraints is known since the 70s, conservative picture of future progress)

Benchmarks considered

- We considered the following future "Phases", as benchmarks: (some hypothetical)

  Phase I: LHCb 50/fb, Belle II 50/ab (late 2020s)

  Phase II: LHCb 300/fb, Belle II 250/ab (late 2030s)

  Phase III: Phase II + tera-Z (5×10^{12} Z decays)

  "Phase I" coincides with and updates "Stage II" in arXiv:1309.2293

- Some caveats:
  - There are no lattice QCD estimates of uncertainties for the Phase III time scale
  - Many experimental sensitivity studies are simplistic or not yet available

- Are there bottlenecks that limit future improvements?

Status and future sensitivities

- Lots of inputs to consider:

  Many different measurements

  Many different calculations

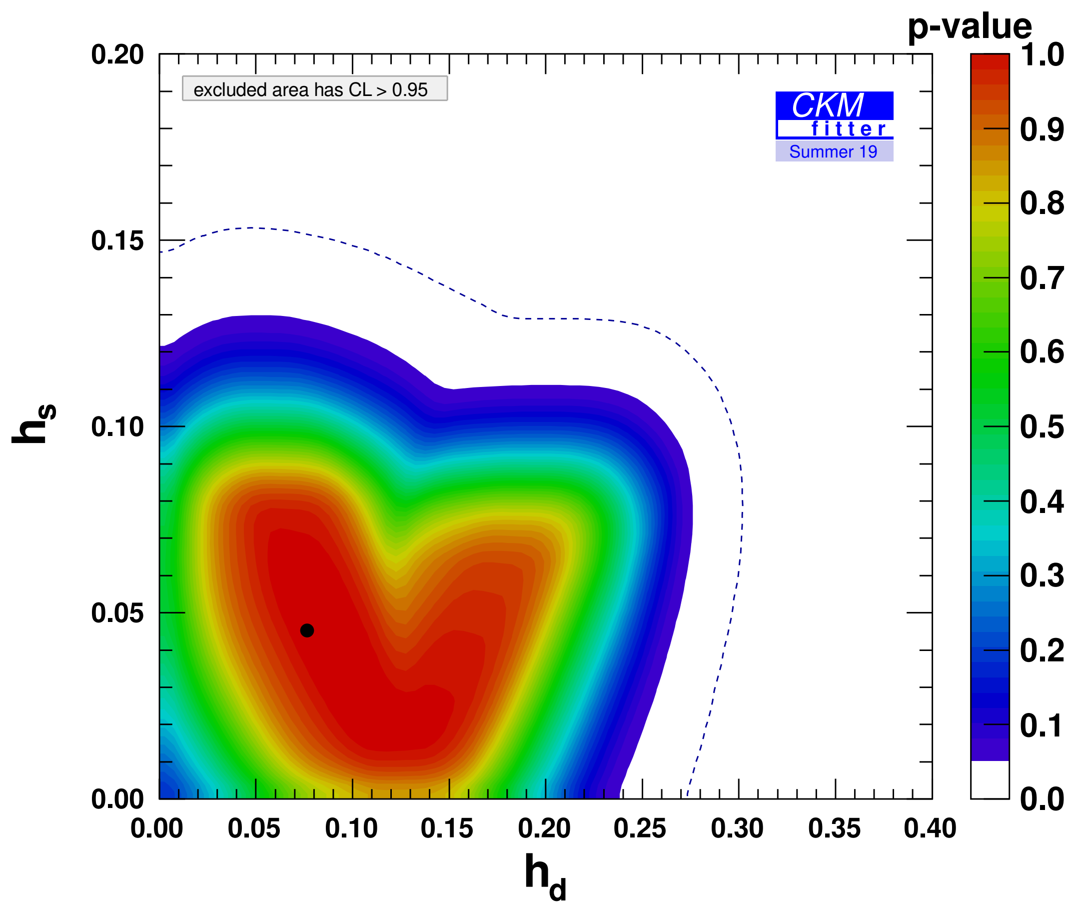
  Many lattice QCD quantities

- tera-Z may be a bit too far to know many of the improvements which will no doubt occur

- A flagship measurement: $A_{\rm SL}^{d,s}$ much better than LHCb & Belle II

	Central values	Uncertainties Current [18]	Phase I	Phase II	Phase III	Reference Phases I–III
$\lvert V_{ud}\rvert$	0.97437	±0.00021	id	id	id	[18]
$\lvert V_{us}\rvert\, f_+^{K\to\pi}(0)$	0.2177	±0.0004	id	id	id	[18]
$\lvert V_{cd}\rvert$	0.2248	±0.0043	±0.003	id	id	[19, 20]
$\lvert V_{cs}\rvert$	0.9735	±0.0094	id	id	id	[18–20]
Δm_d [ps^{-1}]	0.5065	±0.0019	id	id	id	[17]
Δm_s [ps^{-1}]	17.757	±0.021	id	id	id	[17]
$\lvert V_{cb}\rvert_{\rm SL}\times10^3$	42.26	±0.58	±0.60	±0.44	id	[21]
$\lvert V_{cb}\rvert_{W\to cb}\times10^3$		—	—	—	±0.17	[22–24]
$\lvert V_{ub}\rvert_{\rm SL}\times10^3$	3.56	±0.22	±0.042	±0.032	id	[21]
$\lvert V_{ub}/V_{cb}\rvert$ (from Λ_b)	0.0842	±0.0050	±0.0025	±0.0008	id	[25]
$\mathcal{B}(B\to\tau\nu)\times10^4$	0.83	±0.24	±0.04	±0.02	±0.009	[21, 22]
$\mathcal{B}(B\to\mu\nu)\times10^6$	0.37	—	±0.03	±0.02	id	[21]
$\sin 2\beta$	0.680	±0.017	±0.005	±0.002	±0.0008	[21, 22, 25]
α [°] (mod 180°)	91.9	±4.4	±0.6	id	id	[21]
γ [°] (mod 180°)	66.7	±5.6	±1	±0.25	±0.20	[21, 22, 25]
β_s [rad]	-0.035	±0.021	±0.014	±0.004	±0.002	[22, 25]
$A_{\rm SL}^d\times10^4$	-6	±19	±5	±2	±0.25	[14, 17, 22, 26]
$A_{\rm SL}^s\times10^5$	3	±300	±70	±30	±2.5	[14, 17, 22, 26]
$\overline{m}_t$ [GeV]	165.30	±0.32	id	id	±0.020	[18, 22]
$\alpha_s(m_Z)$	0.1185	±0.0011	id	id	±0.00003	[18, 22]
$f_+^{K\to\pi}(0)$	0.9681	±0.0026	±0.0012	id	id	[25]
f_K [GeV]	0.1552	±0.0006	±0.0005	id	id	[25]
f_{B_s} [GeV]	0.2315	±0.0020	±0.0011	id	id	[25]
B_{B_s}	1.219	±0.034	±0.010	±0.007	id	[25]
f_{B_s}/f_{B_d}	1.204	±0.007	±0.005	id	id	[25]
B_{B_s}/B_{B_d}	1.054	±0.019	±0.005	±0.003	id	[25]
$\tilde{B}_{B_s}/\tilde{B}_{B_d}$	1.02	±0.05	±0.013	id	id	[25, 27, 28]
$\tilde{B}_{B_s}$	0.98	±0.12	±0.035	id	id	[25, 27, 28]
η_B	0.5522	±0.0022	id	id	id	[29]

Current status



- Slight tension with the SM (well known) — black dot: best fit (h_d, h_s)
- For future studies, move experimental central values to current best fit SM params

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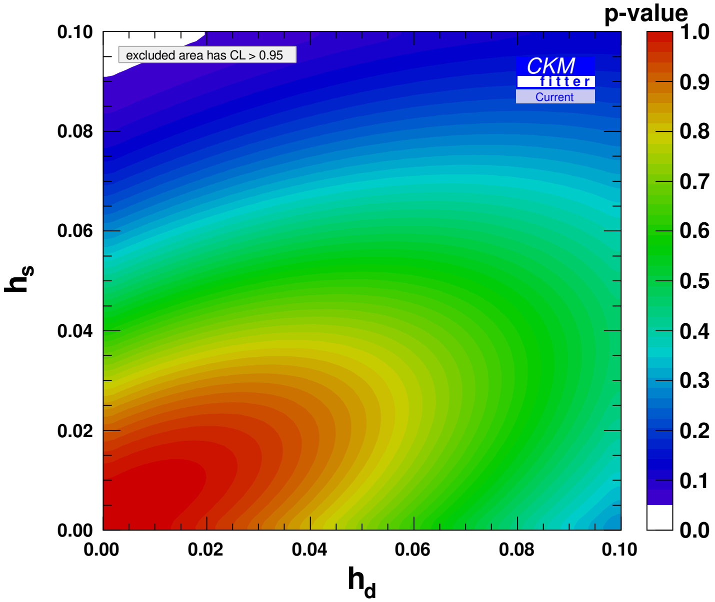
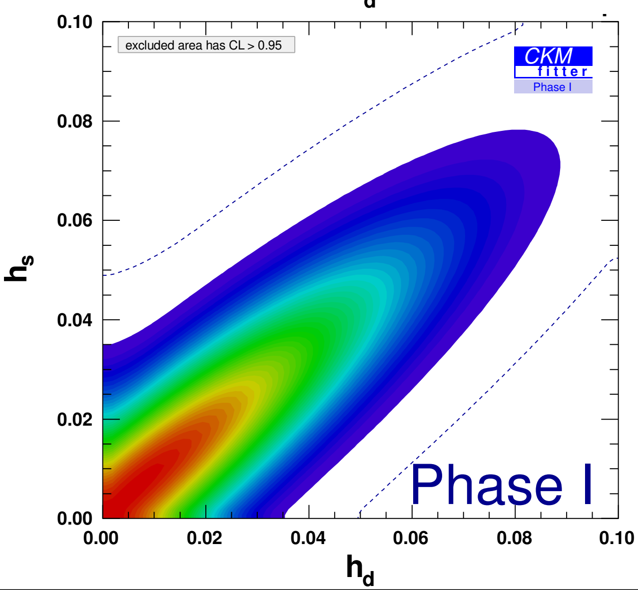
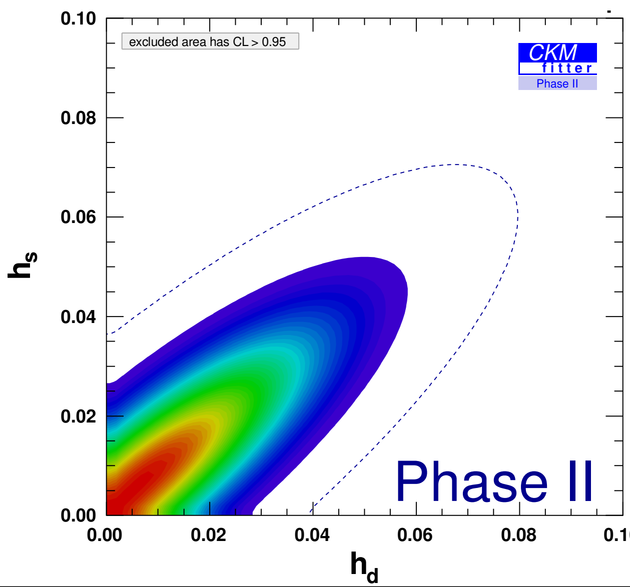
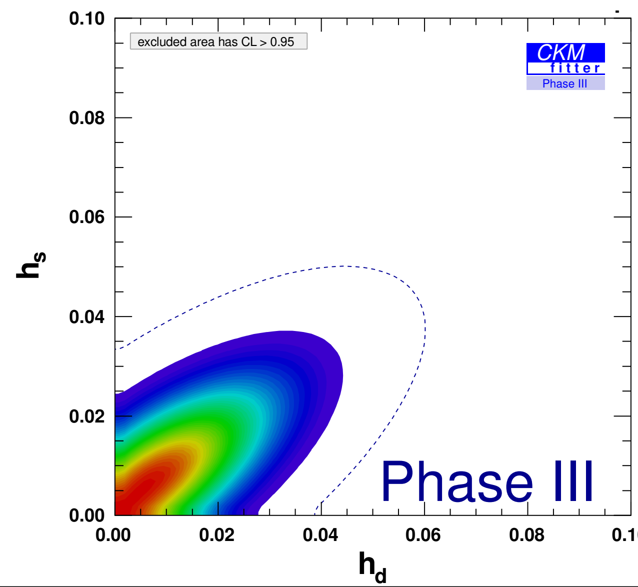
Prospects



- Central values moved to SM; what is the NP parameter space that can be probed?
- Large improvement from now to Phase I
  Less dramatic progresses afterwards







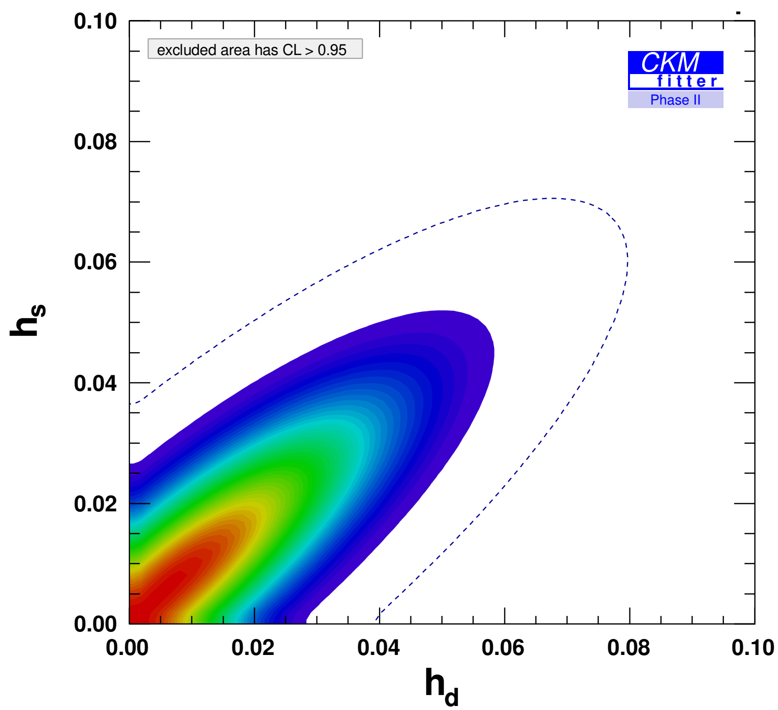
Bottlenecks

- Sensitivity does not improve as expected from Phase I to Phase II and Phase III

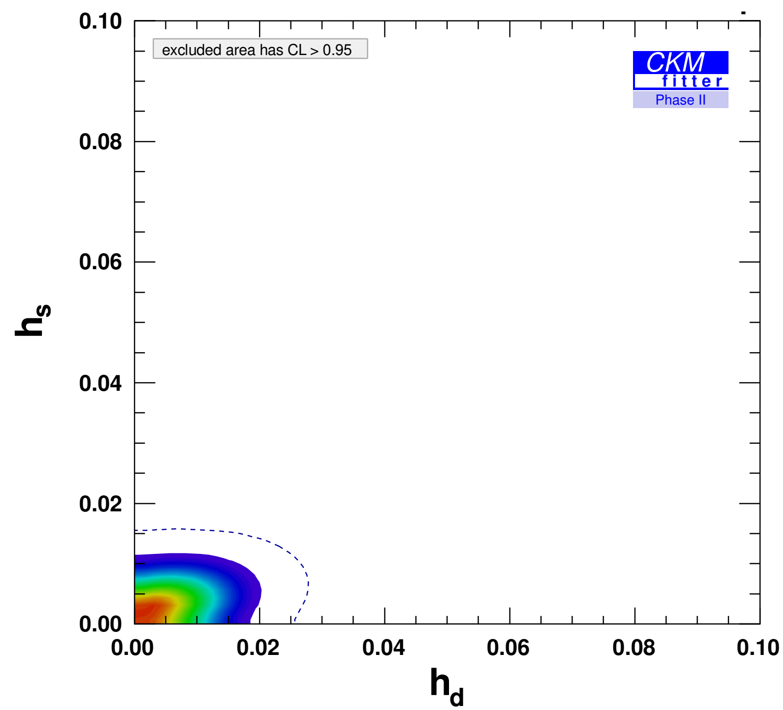
  Main bottlenecks: (i) $|V_{cb}|$ precision, (ii) mixing parameters from LQCD and η_B

- The Phase II sensitivity, as an example:

Same plot as previous page

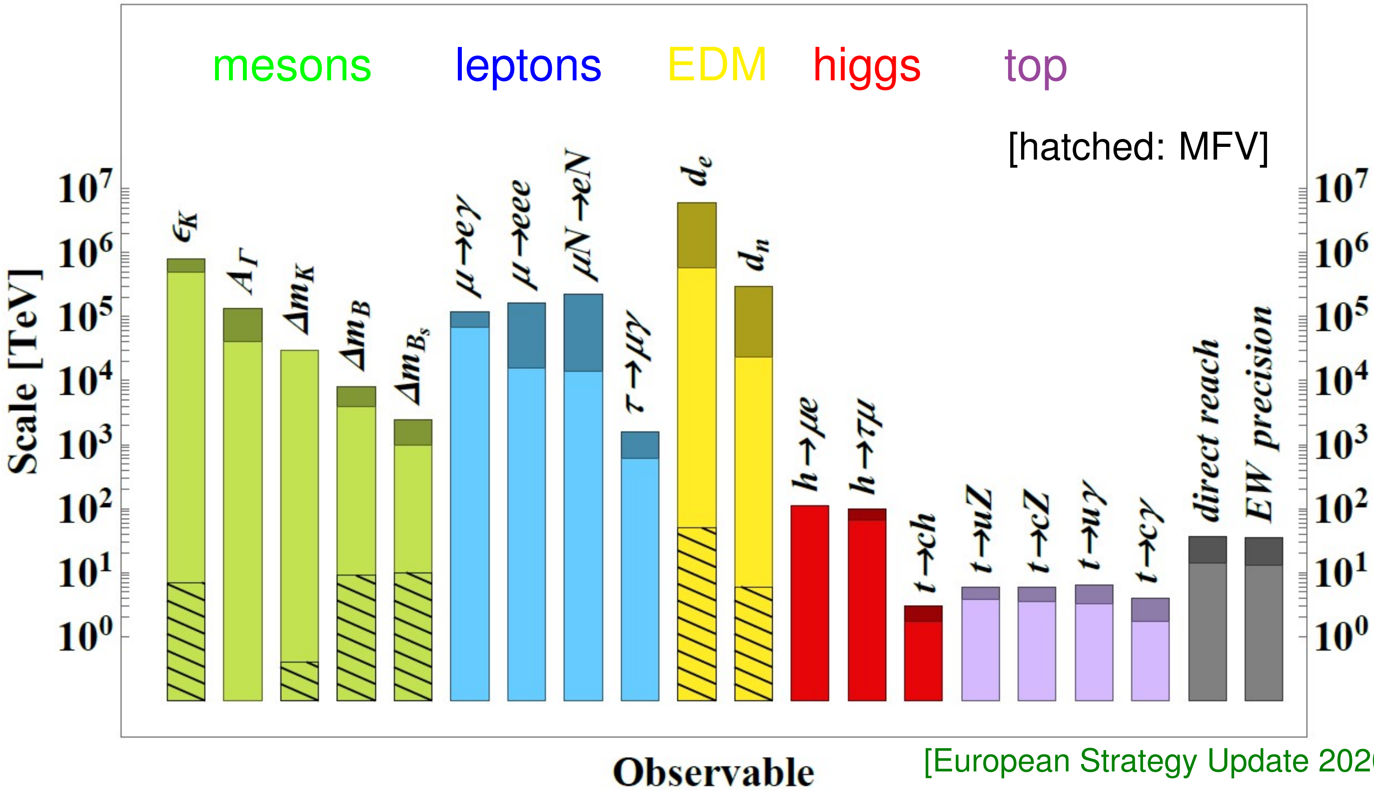


Set uncertainty of $|V_{cb}|$ and mixing param's $\to$ 0



In MFV models $\Delta m_{B_{d,s}}$ even more important

- Question: what is needed to increase improvements in $\Delta m_{B_{d,s}}$ sensitivity?



[European Strategy Update 2020, arXiv:1910.11775]

- Scales of dim-6 operators probed — various mechanisms devised to let TeV-scale NP obey these bounds (Pattern and orders of magnitudes matter more than precise values)

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Interpretations

- Sensitivities to h_d, h_s $\Longleftrightarrow$ NP scales

Scale: $h \simeq \dfrac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \left(\dfrac{4.5\ \text{TeV}}{\Lambda}\right)^2$

Sensitivities	Summer 2019	Phase I	Phase II	Phase III
h_d	0.26	0.073	0.049	0.038
h_s	0.12	0.065	0.044	0.031

Couplings	NP loop order	Sensitivity for Summer 2019 [TeV]		Phase I Sensitivity [TeV]		Phase II Sensitivity [TeV]	
		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

- With SM-like CKM & loop suppressions (e.g., MFV), similar to few-TeV LHC reach

  Without either suppression, much higher scales

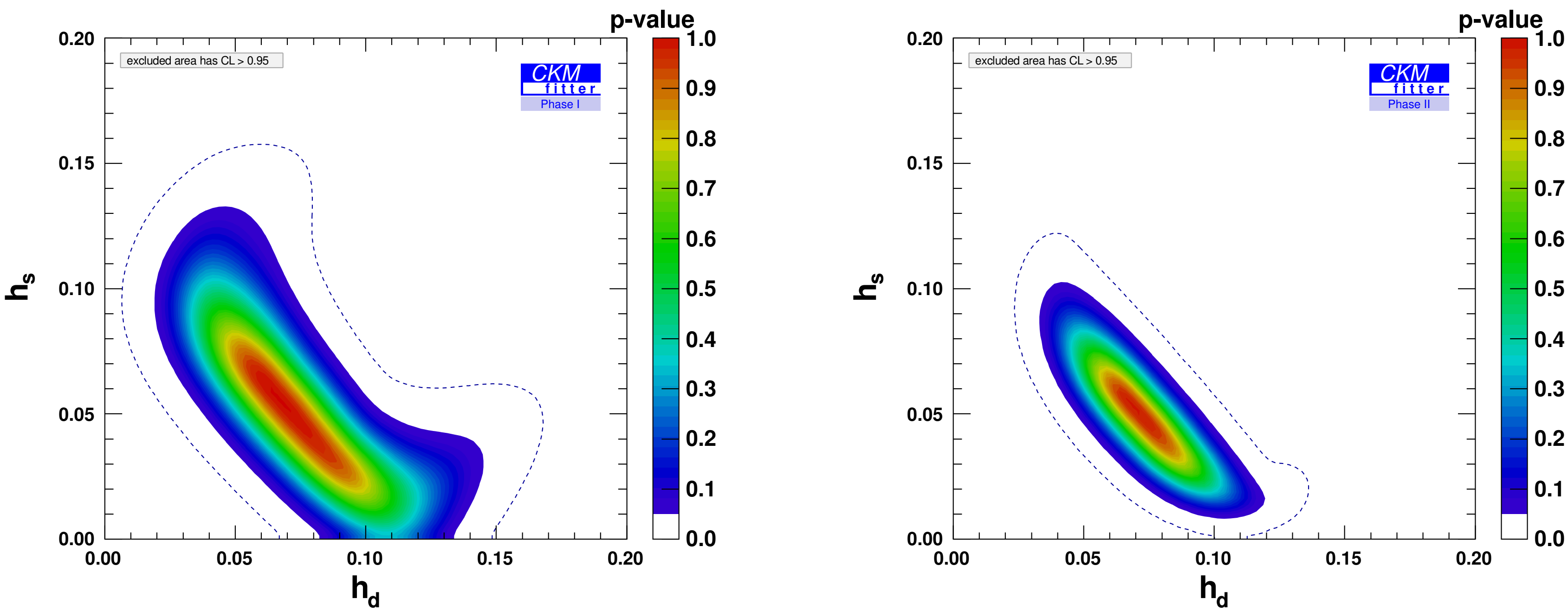
- Need theory progress for sensitivity to NP in mixing to improve beyond LHC and Belle II — I think it's possible, precise ways unpredictable

- Will remain complementary to high p_T searches

Example of discovery potential

- Discovery significance at Phase I (left) and Phase II (right), if central values (CKM param's, $h_{d,s}$, and $\sigma_{d,s}$) remain as in the current fit (on p.12)

(Assume future measurements have the corresponding central values, with uncertainties as in the Table on p.11)



- If new physics contributes to semileptonic decays, as hinted at by the $R(D^{(*)})$ anomaly, then things get more complicated, may still isolate sources (see paper)

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Conclusions

- Flavor physics probes scales $\gg 1\,\mathrm{TeV}$, sensitivity limited by statistics
- Discovering NP would give a target and upper bound on the next scale to explore
- New physics in $B_{d,s}$ mixing may still be $\gtrsim 20\%$ of SM, sensitivity will improve a lot
  (Unexpectedly large impact of $|V_{cb}|$ on future progress)
- tera-Z flavor physics program is much broader than discussed here
- If tera-Z is realized, it will stimulate immense progress in theory, too

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- Ample physics reasons to study the largest possible B decay data sets that current and future technologies allow
- tera-Z will shed light on many open questions after the end of LHC & Belle II

Extra slides

Theory challenges / opportunities

- New methods & ideas: recall that the best α and γ measurements are in modes proposed in light of Belle & BaBar data (i.e., not in the BaBar Physics Book)
  - Better SM upper bounds on $S_{\eta' K_S} - S_{\psi K_S}$, $S_{\phi K_S} - S_{\psi K_S}$, and $S_{\pi^0 K_S} - S_{\psi K_S}$ And similarly in B_s decays, and for $\sin 2\beta_{(s)}$ itself
  - How big can CP violation be in $D^0 - \overline{D}^0$ mixing (and in D decays) in the SM?
  - Better understanding of semileptonic form factors; bound on $S_{K_S \pi^0 \gamma}$ in SM?
  - Many lattice QCD calculations (operators within and beyond SM)
  - Inclusive & exclusive semileptonic decays
  - Factorization at subleading order (different approaches), charm loops
  - Can direct CP asymmetries in nonleptonic modes be understood enough to make them "discovery modes"? [$SU(3)$, the heavy quark limit, etc.]
- We know how to make progress on some + discover new frameworks / methods?