Future Flavor Frontiers

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Snowmass 2021

Rare Processes and Precision Measurements Frontier
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Flavor physics: many open questions

- 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 Yukawa couplings break flavor symm.

- 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

  Generic TeV-scale flavor structure excluded $\Rightarrow$ new suppression mechanisms

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

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

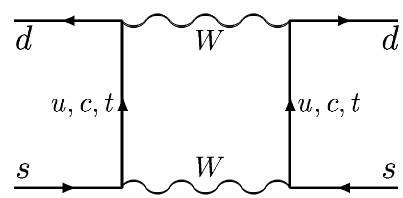
  Any new particle that couples to quarks or leptons $\Rightarrow$ new flavor parameters

Spectacular track record

- Uncertainty principle $\Rightarrow$ heavy particles, cannot be produced on-shell, affect lower energy processes, E^2/M^2 suppressed in interference $\Rightarrow$ probe very high scales
- High mass-scale sensitivity due to suppressed SM predictions
  - Absence of $K_L \to \mu\mu \Rightarrow$ charm quark (Glashow, Iliopoulos, Maiani, 1970)
  - $\epsilon_K \Rightarrow 3$rd generation (t, b quarks) (Kobayashi & Maskawa, 1973)
  - $\Delta m_K \Rightarrow m_c \sim 1.5\,\mathrm{GeV}$ (Gaillard & Lee; Vainshtein & Khriplovich, 1974)

    Why is $\Delta m_K/m_K \approx 7 \times 10^{-15}$ so small?

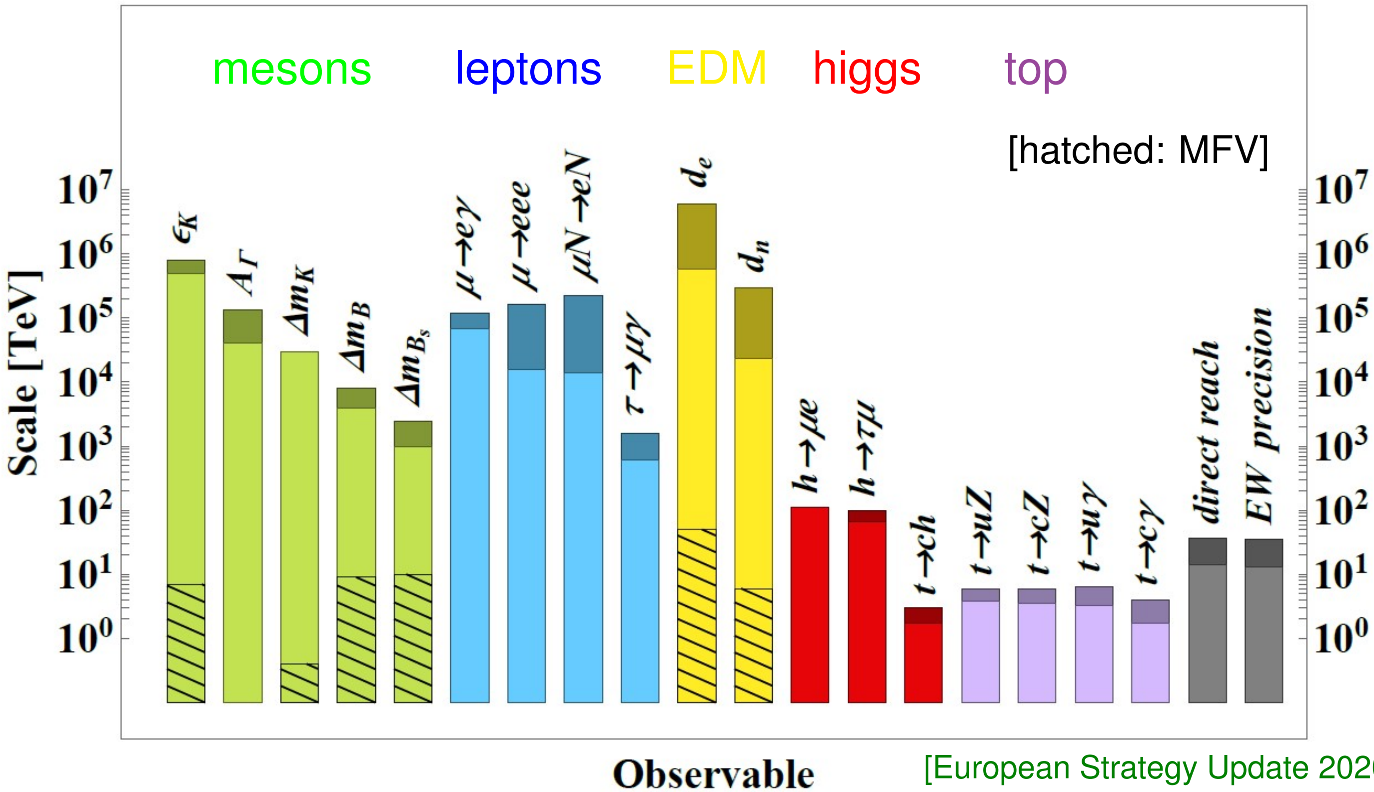
    SM: $\Delta m_K/m_K \sim \dfrac{g_2^4}{16\pi^2}\,|V_{cs}V_{cd}|^2\,\dfrac{m_c^2}{m_W^4}\,f_K^2$



  - $\Delta m_B \Rightarrow m_t \gtrsim 100\,\mathrm{GeV}$ (bound in 1987: $23\,\mathrm{GeV}$) $\Rightarrow$ large CP violation & FCNC
- Critical in developing SM — what can future data tell us about BSM physics?

Anticipated increases in sensitivity

- Scales of dim-6 operators probed — various mechanisms devised so that TeV-scale NP not ruled out (Patterns more interesting than precise values — hatched: MFV)



[European Strategy Update 2020, arXiv:1910.11775]

- $\mu N \to eN$ may be the largest increase in mass-scale sensitivity in next 10–15 yrs

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Some flavor-related questions

- Will LHC see new physics beyond the Higgs?

  Any new particle that couples to SM fermions has a flavor sector to explore (recall: $Htc?$, $H\tau\mu$?)

- Will NP be seen in the quark sector?

  Current data: several hints of lepton universality violation

- Will NP be seen in charged lepton sector? $\mu N \to eN$, $\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to 3\mu$?

- Neutrinos: Is 3 flavor oscillation paradigm OK? What is the nature of ν mass?

- No one knows — an exploratory era!

  Michelson 1894: "... it seems probable that most of the grand underlying principles have been firmly established ..."

  (n.b.: 2 generations $+$ superweak is "more minimal" to accommodate CPV, than 3 generations...)

- Near future: "anomalies", both in quark & lepton sector, might first be established

  Long term: large increase in discovery potential in many modes

Program planning pieces, 40 years ago

- "Lederman's Shoulder, Weinberg's Nose, and Other Lessons from the Past" [Politzer, 1982]

  "Planning for discovery is both absolutely necessary and fundamentally silly. We can't know what will be. However, we can look back. The unexpected has come sometimes at the highest energy frontier ... and sometimes in a careful look over old ground, such as CP violation ... Whatever the current theoretical beliefs, our future plans should not stifle the possibility of discovery."

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- Before P5, there was P8! ☺ [Politzer, 1982]

  "Problems, Puzzles and Prospects: A Personal Perspective on Present Particle Physics"

  "When is the soonest that something dramatic <u>might</u> happen? The answer here is clearly tomorrow. The answer might even be yesterday"

  "I firmly believe that anything that can be measured well is worth doing."

  "I think the experimental prospects are wide open. All we have to do is try."

experiment with notation...

- Key drivers: experiment & technology; as theory convener, I'll label role of theory:

$(\not{t})$: no theory needed for discovery (at current level of sensitivity)

e.g.: $R_{K^{(*)}}$ lepton universality violation, CLFV, EDMs, etc.

caveats: interpretation of a discovery would require theory
some backgrounds may need to be estimated

(t): theory essential for discoveries

e.g.: $R(D^{(*)})$, $g-2$, unitarity triangle fits, etc.

- Subject to some ambiguity, of course

- Flavor physics had immense impacts on theory:
HQET, SCET, LQCD, multi-loop techniques, model building [Talks today: El Khadra, Zupan]

Outline

- Lepton flavor: basic open questions, some processes very clean

  Observing CLFV would jumpstart broader program

- Quark flavor: rich program, diverse connections

  Recent hints for lepton universality violation

  Vast spectrum of increasing BSM sensitivity

- Many exciting areas: Higgs & top, charged lepton flavor violation, EDM searches,

  BSM scenarios may have nontrivial flavor: SUSY, dark sectors, LLPs, etc.

Lepton and quark mixing

- Magnitudes of mixing matrix elements, assuming 3-generation unitarity:

$$|U_{\rm PMNS}| = \begin{pmatrix} 0.823 \pm 0.007 & 0.546 \pm 0.011 & 0.150 \pm 0.002 \\ 0.372 \pm 0.042 & 0.599 \pm 0.031 & 0.700 \pm 0.023 \\ 0.395 \pm 0.041 & 0.570 \pm 0.033 & 0.692 \pm 0.023 \end{pmatrix}$$

[νfit 2021, 3σ, converted]

$$|V_{\rm CKM}| = \begin{pmatrix} 0.97435 \pm 0.00016 & 0.22500 \pm 0.00067 & 0.00369 \pm 0.00011 \\ 0.22486 \pm 0.00067 & 0.97349 \pm 0.00016 & 0.04182^{+0.00085}_{-0.00074} \\ 0.00857^{+0.00020}_{-0.00018} & 0.04110^{+0.00083}_{-0.00072} & 0.999118^{+0.000031}_{-0.000036} \end{pmatrix}$$

[PDG 2022]

- Are the origin of quark and lepton masses and mixings related?
- Some lepton processes are especially clean; quark sector much more rich
- Neutrino FCNCs seem impossible to search for; e.g., $\nu_i \to \nu_j\, \gamma$, $X \to \nu_i \bar\nu_j (Y)$
- SM flavor puzzle extended: why lepton & quark masses and mixings so different?

Neutrinos — many unknowns

- We do not know what is the Lagrangian that describes the observed particles!

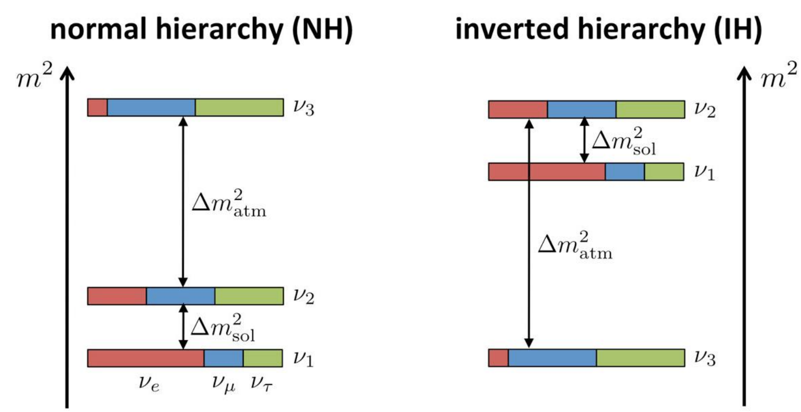
  Not known: $\mathcal{L}_Y = -Y_e^{ij}\,\overline{L_{Li}^I}\,\phi\,e_{Rj}^I - \begin{cases} \frac{Y_\nu^{ij}}{\Lambda}\,L_{Li}^I L_{Lj}^I\,\phi\,\phi & \text{violates lepton number} \\ Y_\nu^{ij}\,\overline{L_{Li}^I}\,\tilde{\phi}\,\nu_{Rj}^I & \text{requires } \nu_R \text{ fields} \end{cases}$

  Are neutrinos their own antiparticles? (favored by theory, most leptogenesis models, but not known)

- What is the absolute mass scale?

  At least one has $m_{\nu_i} \gtrsim 50\,\text{meV}$

  Cosmology: $\sum m_i < 0.12 - 0.3\,\text{eV}$ [Planck 2018]



- Is the mass hierarchy "normal" or "inverted"?

  If inverted, $0\nu\beta\beta$ experiments will determine if $\nu = \overline{\nu}$ or $\nu \neq \overline{\nu}$, otherwise no guarantee

- Value of CP violating phase δ?

CLFV and Mu2e: huge sensitivity increase (✗)

- Expect 10^4 better sensitivity (Mu2e, COMET) $\Rightarrow$ $10\times$ higher mass scales probed!
- $m_\nu \neq 0$ $\Rightarrow$ lepton flavor is violated, no reason to impose it as a symmetry on NP

  If there are new TeV-scale particles that carry lepton number (e.g., sleptons), then they have their own mixing matrices $\Rightarrow$ charged lepton flavor violation (CLFV)
- Experimental sensitivity is at exciting level for complementarity with LHC searches
- Flavor vs. naturalness: heavier NP $\Rightarrow$ less constraints on its flavor structure
- CLFV measurements can discover NP signals due to TeV-scale NP with SM-like flavor structure, or 10–$1000\,\mathrm{TeV}$ NP with generic flavor $\Rightarrow$ cast a wide net

Maximizing sensitivity with Mu2e-II is a clear case to me 2203.07569]

Operators, patterns, connections (t)

- **Most sensitive:** $\mu \to e\gamma$ or $\mu \to eee$? (Mu2e also sensitive to tree-level LQ exchange)

  Depends on NP: $$\mathcal{L} \sim \frac{\lambda_1}{\Lambda^2}\, m_\mu\, \bar\mu_R \sigma_{\alpha\beta} F^{\alpha\beta} e_L + \frac{\lambda_2}{\Lambda^2}\, (\bar\mu_L \gamma^\alpha e_L)(\bar e_L \gamma_\alpha e_L)$$

  λ_1 term mediates $\mu \to e\gamma$ at tree level, and generates $\mu \to eee$ at order α

  λ_2 term mediates $\mu \to eee$ at tree level, and generates $\mu \to e\gamma$ at order α

- **Flavor:** $\mu \to e\gamma$ and $(g-2)_\mu$ operators are similar: $\frac{m_\mu}{\Lambda^2}\, \bar\mu \sigma_{\alpha\beta} F^{\alpha\beta} e\,, \quad \frac{m_\mu}{\Lambda^2}\, \bar\mu \sigma_{\alpha\beta} F^{\alpha\beta} \mu$

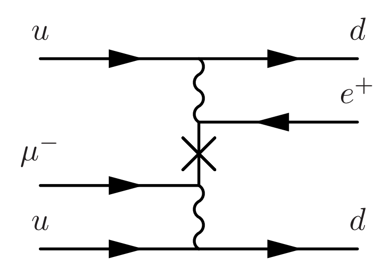
  If coefficients are comparable, $\mu \to e\gamma$ gives much stronger bound already

  If $(g-2)_\mu$ is due to NP, large hierarchy of coefficients ($\Rightarrow$ model building lessons)

- **Lepton number violation:** search for $pp\mu^- \to nne^+$

  in simplest scenario sensitive to $|\Sigma_{i=1}^3\, m_i\, U_{ei} U_{\mu i}|$

  similar to $0\nu\beta\beta$ measuring $|m_{ee}| = |\Sigma_{i=1}^3\, m_i\, U_{ei}^2|$



- Patterns would tell us about underlying structures

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Many complementary CLFV processes

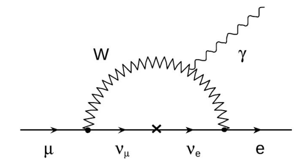
- SM w/ $m_\nu = 0 \Rightarrow$ lepton flavor conservation

  Given $m_\nu \neq 0$, no reason to impose it as a sym.

  TeV-scale loop-level NP may be observable

SM predictions incredibly small

rates $\propto \dfrac{m_\nu^4}{m_W^4} < 10^{-50}$



- Many interesting processes; NP-dependent which is most sensitive:

  $\mu \to e\gamma,\ \mu \to eee,\ \mu + N \to e + N^{(\prime)},\ \mu^- pp \to e^+ nn, \tau \to \mu\gamma,\ \tau \to e\gamma,\ \tau \to \mu\mu\mu,$

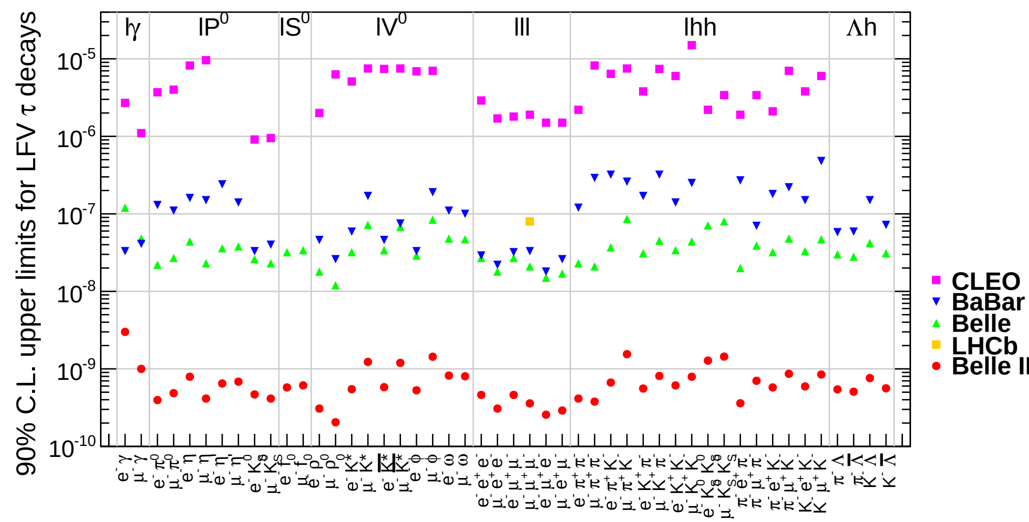
  $\tau \to eee,\ \tau \to \mu\mu e, \tau \to \mu ee, \tau \to \mu\pi,\ \tau \to e\pi,\ \tau \to \mu K_S,\ eN \to \tau N$

- τ decays: $\mu \to e\gamma, eee$ vs. $\tau \to \mu\gamma, \mu\mu\mu$

  Either can "win", huge NP model dependence: $\mathcal{B}(\tau \to \mu\gamma)/\mathcal{B}(\mu \to e\gamma) \sim 10^{4\pm3}$

- Belle II: improve 2 orders of magnitude

- Any discovery $\Rightarrow$ broad program to map out the detailed structure



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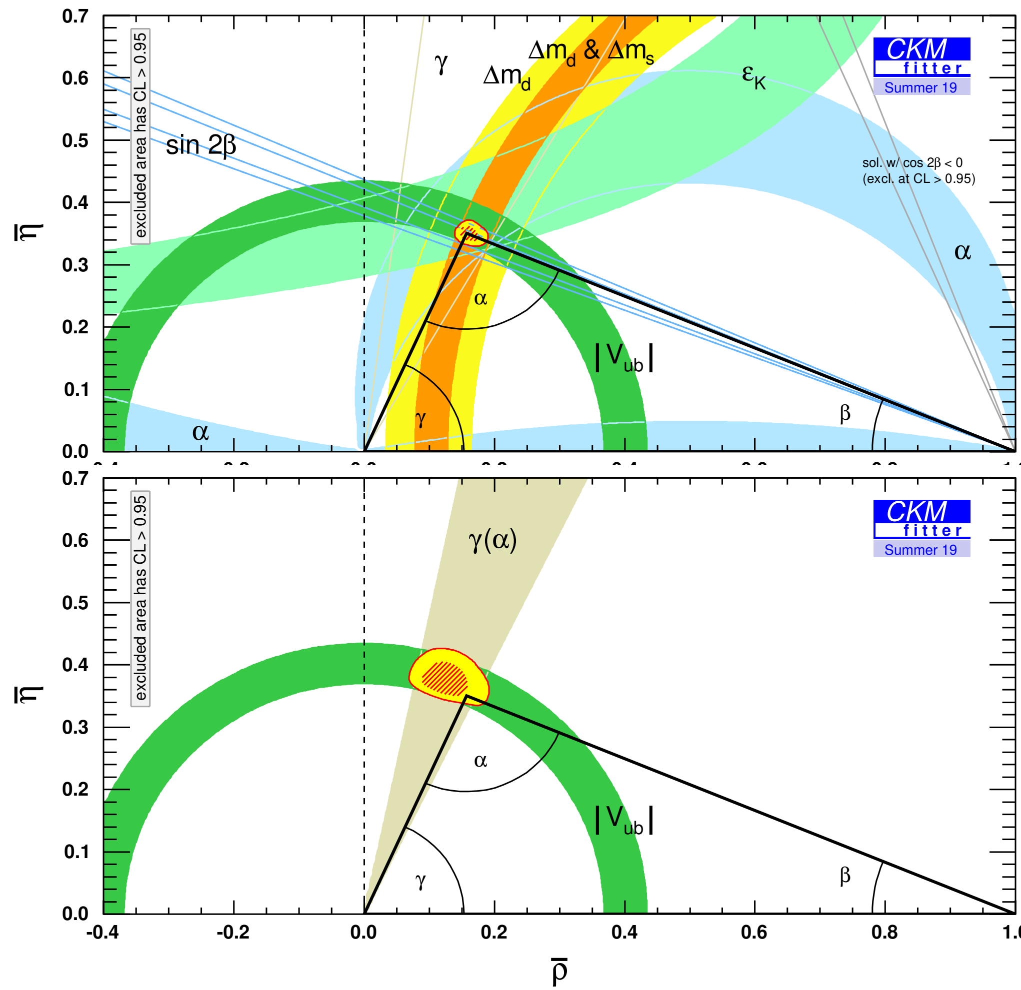
Quark flavor

The B-factories money plot

- Spectacular progress in last 20 years
- The CKM mechanism dominates CP violation & flavor changing processes
- The implications of the consistency of measurements are often overstated

  Larger allowed region if there is NP
- Compare tree-level (lower plot) and loop-dominated measurements
- LHCb: constraints in the B_s sector (2nd–3rd gen.) caught up with B_d



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

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Reasons to seek higher precision

- Expected deviations from the SM, induced by TeV-scale NP?

  Generic flavor structures ruled out; can find any size deviations, detectable effects in many models

- Theoretical uncertainties?

  Highly process dependent, under control in many key measurements

- Expected experimental precision?

  Useful data sets will increase by $\sim 10^2$, and probe fairly generic BSM scenarios

- What will the measurements teach us if deviations from the SM are (not) seen?

  Complementary with LHC high-p_T program; synergy can teach us what the NP is (what it's not)

- No guaranteed discoveries — truly exploratory era!

  Near future: "anomalies" might first be established

  Long term: large increase in discovery potential in many modes

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

- Major LHCb upgrade in LS2 (raise instantaneous luminosity to $2 \times 10^{33}/\text{cm}^2/\text{s}$)
  Major ATLAS and CMS upgrades come in LS3 for HL-LHC
- LHCb plans to upgrade in LS4 to take data at $2 \times 10^{34}/\text{cm}^2/\text{s}$ [Parkes, tomorrow]

  ATLAS & CMS will be competitive in some B physics measurements

Tables of impressive sensitivity projections: 1808.08865, 1812.07638

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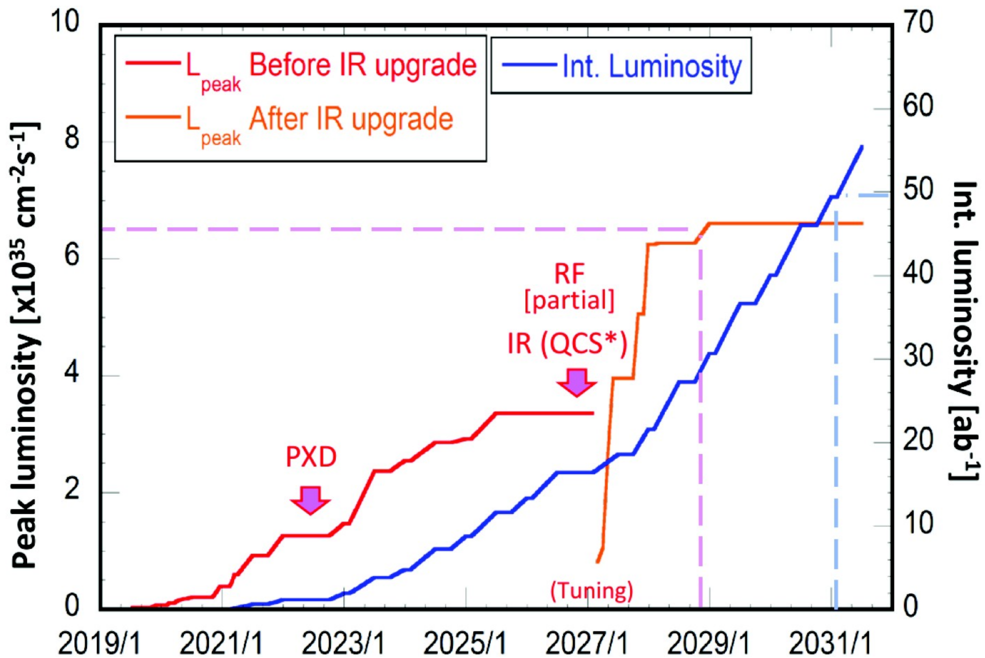
Belle II — SuperKEKB

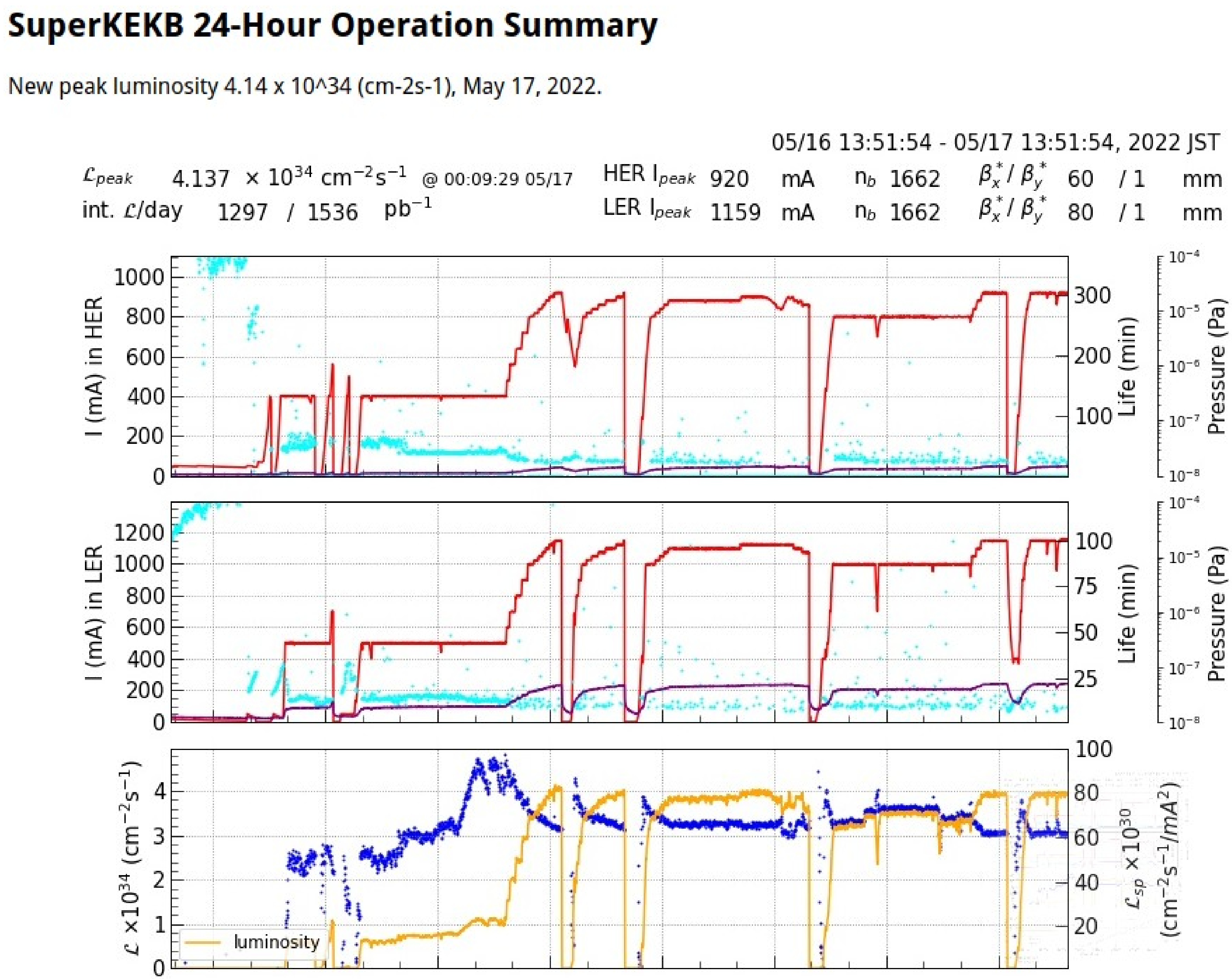


- First collisions 2018 (unfinished detector), with full detector starting spring 2019
  Goal: $50\times$ the Belle and nearly $100\times$ the $B\textsc{a}B\textsc{ar}$ data set

- Discussions started about physics case and feasibility of a factor ~ 5 upgrade, aiming 50/ab $\to$ 250/ab (would parallel LHCb Upgrade 2) [Browder, tomorrow]

Tables of impressive sensitivity projections: 1808.10567

Earlier today (!)



Tera-Z: impressive flavor program

- Very large and clean samples of B decays ($\sim 10^6 \times$ LEP) [Monteil, tomorrow]

- 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
FCC-ee (5×10^{12} Z)	400	400	100	100	550	170

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

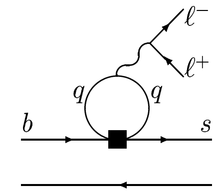
- WW threshold: $W \to b\bar{c}$ can give a qualitatively new determination of $|V_{cb}|$
Estimate 0.3% uncertainty, using 10^8 WW, independent of B measurements

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

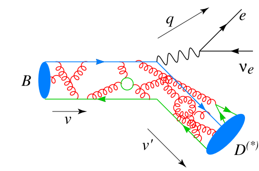
Lepton universality violation

The current B "anomalies" (t) (t)

- Lepton non-universality would be clear evidence for NP



2014, LHCb: R_K & R_{K^*} $(B \to X\mu^+\mu^-)/(B \to Xe^+e^-) \sim 20\%$ of SM loop



2012, BaBar: $R(D)$ & $R(D^*)$ $(B \to X\tau\bar{\nu})/(B \to X(e,\mu)\bar{\nu}) \sim 20\%$ of SM tree

Scales: $R_{K^{(*)}} \lesssim$ few $\times\, 10^1\,\text{TeV}$, $R(D^{(*)}) \lesssim$ few $\times\, 10^0\,\text{TeV}$ Would bound NP scale!

Simplest models to accommodate the data do not (easily) connect to DM and the hierarchy puzzle

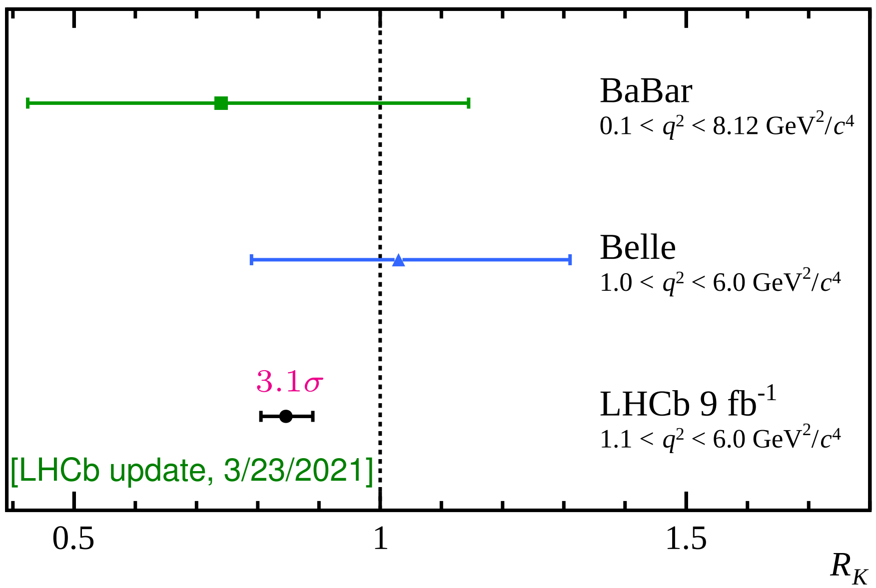
- Connection to LFV: "departure from lepton universality is necessarily associated with the violation of lepton flavor conservation" (caveats) [Glashow, Guadagnoli, Lane, 1411.0565]

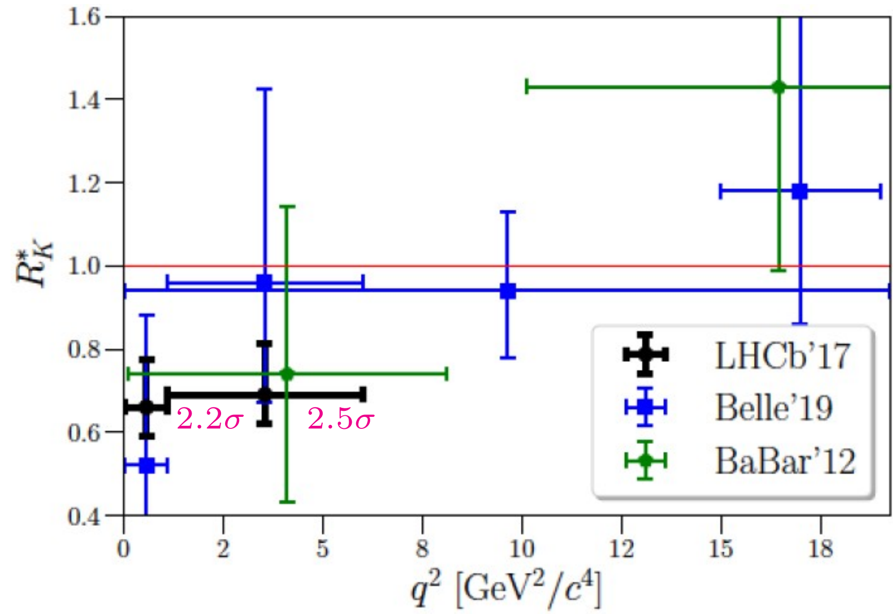
- Forced both theory and experiment to rethink program, discard some prejudices: broader searches, previously neglected measurements

  New directions: model building, high-p_T searches, lepton flavor violation searches

R_K and R_{K^*}: theoretically cleanest (✗)

- LHCb: $R_{K^{(*)}} = \dfrac{B \to K^{(*)}\mu^+\mu^-}{B \to K^{(*)}e^+e^-} < 1$ both ratios $\sim 3\sigma$ from lepton universality





- Combined fits only by theorists (some include P_5' and/or $B_s \to \phi\mu^+\mu^-$)

- Modifying one Wilson coefficient in $\mathcal{H}_{\text{eff}}$ gives good fit: $\delta\, C_{9,\mu} \sim -1$

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Aside: P_5' in $B^0 \to K^{*0}\mu^+\mu^-$ decay (t)

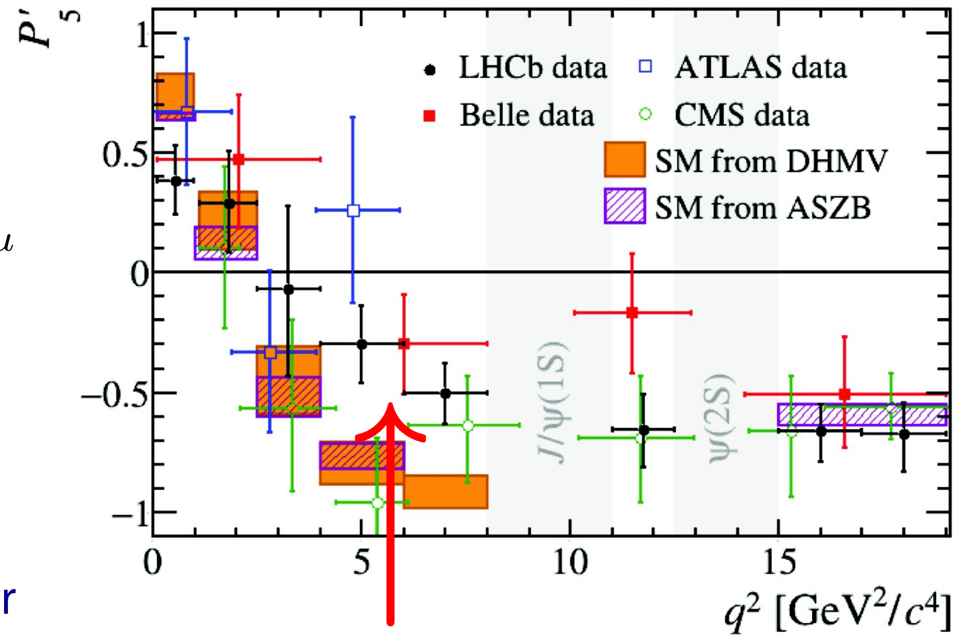
- "Optimized observables" [1202.4266 + long history]
  (assumptions about theory uncertainties)

  Global fits: best solution: NP reduces $C_{9\mu}$

  [Altmannshofer, Straub; Descotes-Genon, Matias, Virto; Jager, Martin Camalich; Bobet, Hiller, van Dyk; many more]

  Difficult for lattice QCD, large recoil

  What is the calculation which detremines how far below the J/ψ this comparison can be trusted?



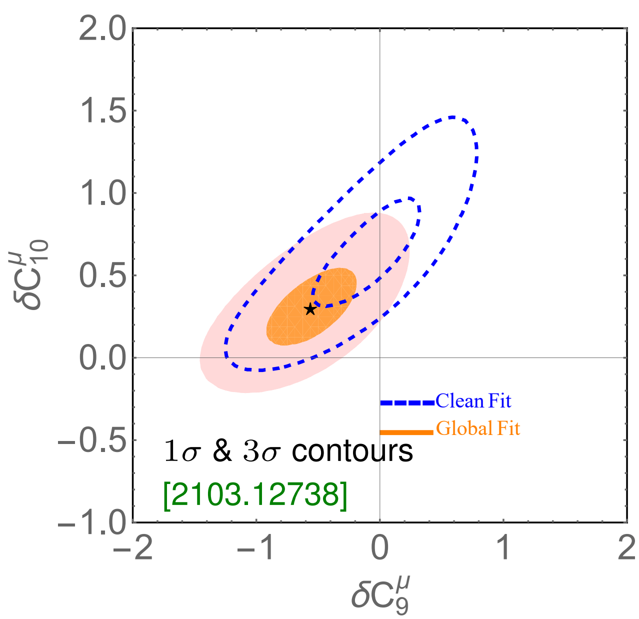
NP, fluctuation, SM theory?

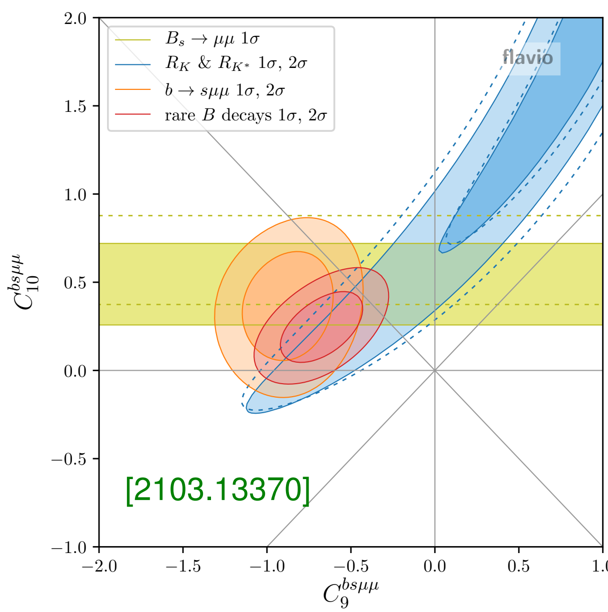
- Tests: other observables, q^2 dependence, B_s and Λ_b decays, other final states

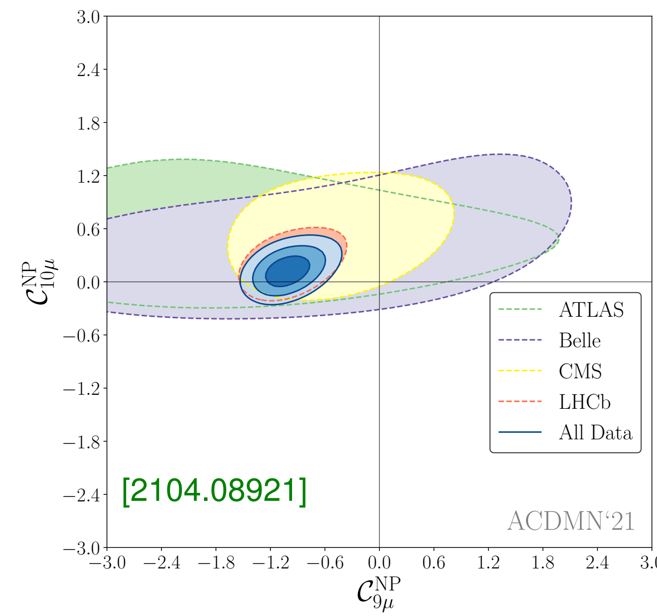
- Connected to many other processes: Is the $c\bar{c}$ loop tractable perturbatively at small q^2 ? Can one calculate form factors (ratios) reliably at small q^2 ?
  Impacts: semileptonic & nonleptonic, interpreting CP viol., etc.

Global fits to $B \to s\ell^+\ell^-$ decays (t)

- Combined fits to $C_{9\mu}$ and $C_{10\mu}$ (incl. $B_s \to \mu^+\mu^-$; see later)







- Somewhat different assumptions and inputs, somewhat different results

- All obtain significant tension with the SM

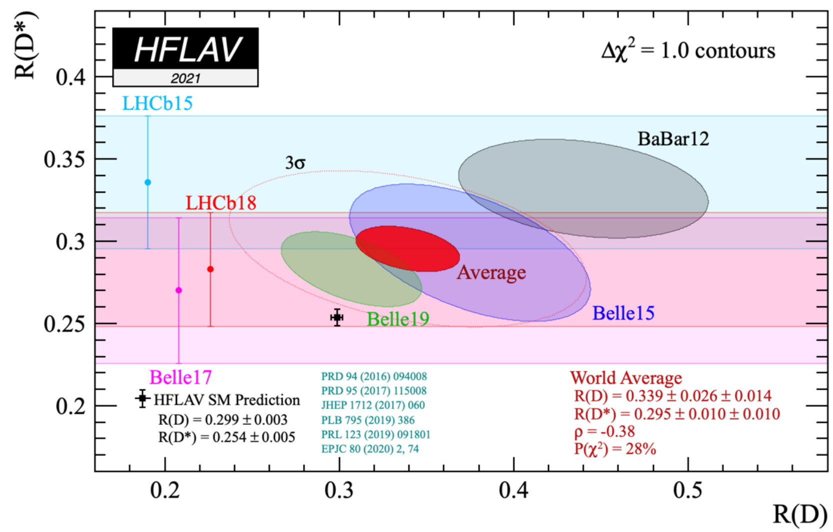
The $B \to D^{(*)}\tau\bar{\nu}$ decay rates (t)

- BaBar, Belle, LHCb: $R(X) = \dfrac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X(e/\mu)\bar{\nu})}$

  3.few σ from SM — robust due to heavy quark symmetry + lattice QCD

  many channels: $R(D^*)$ with $\tau \to \nu 3\pi$ [1708.08856]

  $B_c \to J/\psi\, \tau\bar{\nu}$ [1711.05623]



- Imply NP at a fairly low scale (leptoquarks, W', etc.), likely visible at ATLAS / CMS

  Many models Fierz (mostly) to the SM operator: SM-like distributions and τ polarization

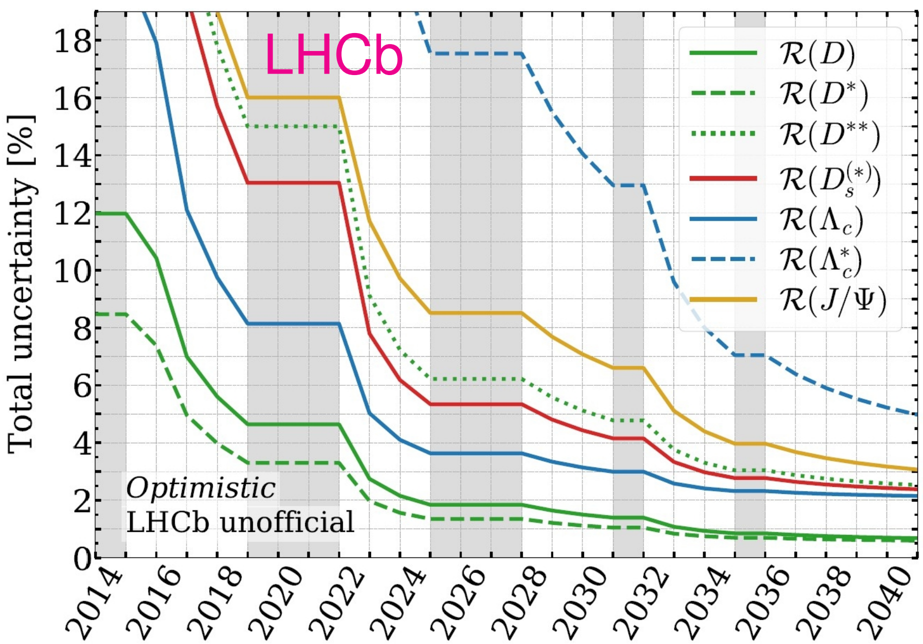
- Tree level: three ways to insert mediator: $(b\nu)(c\tau)$, $(b\tau)(c\nu)$, $(bc)(\tau\nu)$

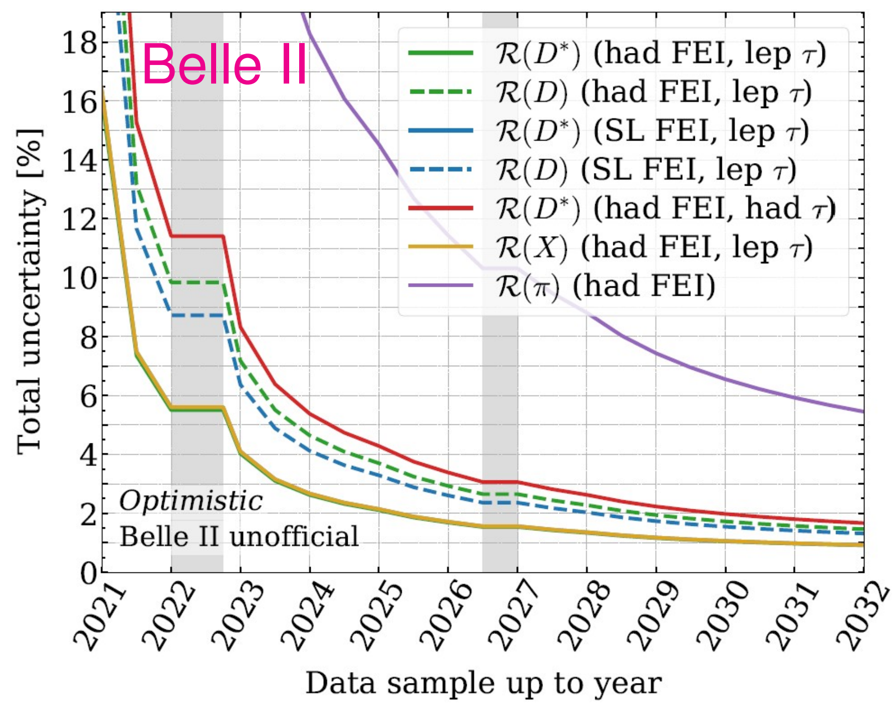
  overlap with ATLAS & CMS searches for $\tilde{b}$, leptoquark, $H^\pm$

- Models built to fit these anomalies have impacted ATLAS & CMS searches

Exciting future prospects

- $R_{K^{(*)}}$ sensitivity will improve a lot
- LHCb and Belle II: increase $pp \to b\bar{b}$ and $e^+e^- \to B\overline{B}$ data sets by factor ~ 50





[See: 2101.08326]

(Even if central values change, plenty of room for establishing deviations from SM)

- Competition, complementarity, cross-checks between LHCb and Belle II

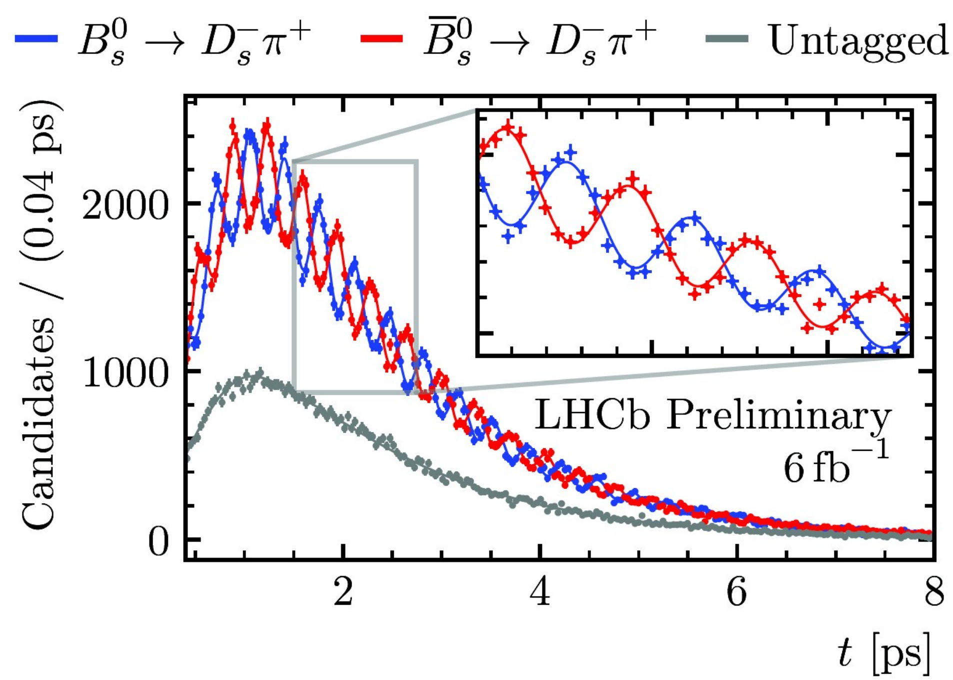
BSM sensitivity in mixing

B_s mixing incredibly precise (t)

- Recently refined, textbook measurement
- $\Delta m_{B_s} = (17.7656 \pm 0.0057)\,\text{ps}^{-1}$
  Relative precision: 3×10^{-4} [LHCb, 2104.04421]

  The most precise neutral meson mass difference (much better than Δm_K!)

  Possible tension emerging w/ LQCD? [1602.03560]



- The most precise CKM-related measurement, except for $|V_{ud}|$

  $|V_{ud}|$ uncertainty is 1.6×10^{-4} — possibly underestimated

  $|V_{tb}V_{ts}|$ uncertainty would be 1.6×10^{-4}, if it were not dominated by lattice QCD

- Lattice QCD breakthroughs could make big impact on BSM sensitivity

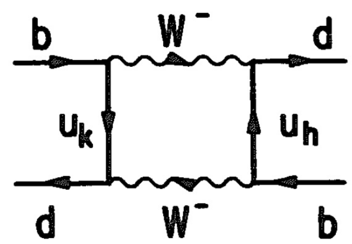
New physics in B mixing (t)

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

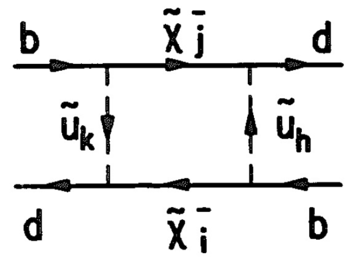
General parametrization of many models
by two real parameters (in addition to SM):

$$h\, e^{2i\sigma} = A_{\rm NP}(B^0 \to \overline{B}^0)/A_{\rm SM}(B^0 \to \overline{B}^0)$$

↖ ↑ NP parameters



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



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

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

- If we find that $h_{d,s} \ll 1$, then BSM contribution $\ll$ SM contribution

Relies on many measurements and theoretical inputs!

Redo CKM fit w/ NP param's: tree-dominated unchanged, loop-mediated modified

Importance known since 1970s ($\Delta m_K/m_K \sim 7 \times 10^{-15}$), conservative view of future progress

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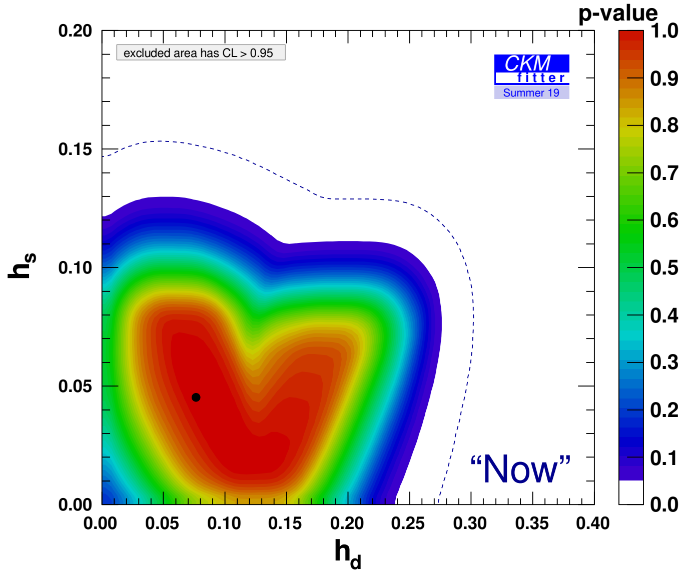
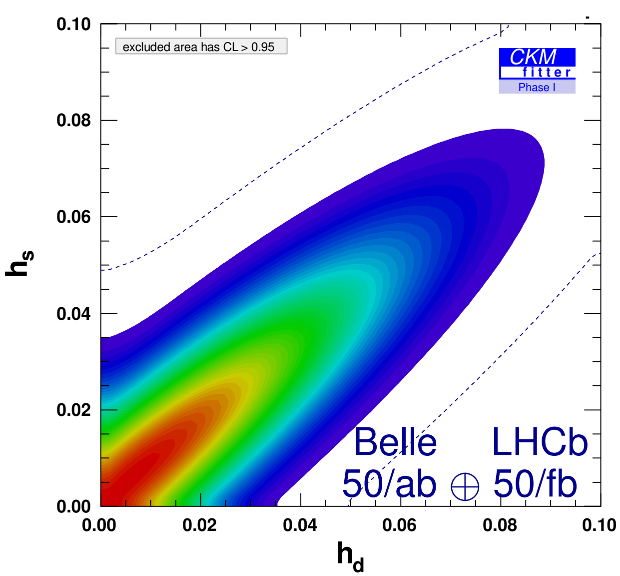
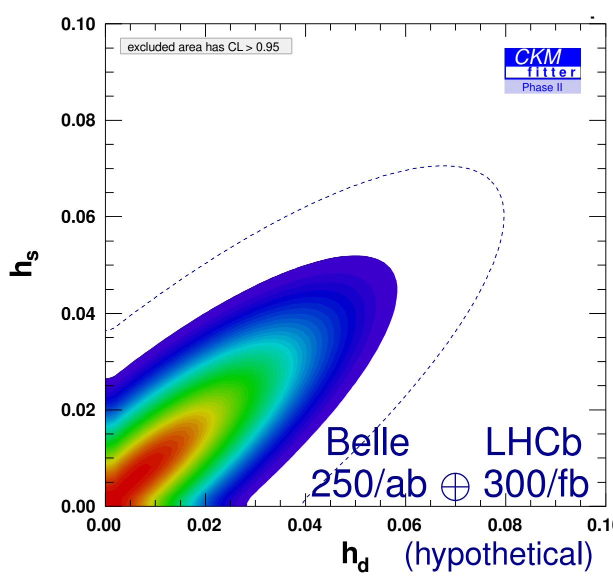
Future sensitivity to NP in B mixing (t)



- What NP parameter space can be probed?
- $h_{d,s} \Leftrightarrow$ NP scale: $h \simeq \dfrac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \left(\dfrac{4.5\ \text{TeV}}{\Lambda}\right)^2$ [2006.04824]

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





Big improvements in 2020s

Complementary to high-p_T searches

Then theory improves or progress slows

Main bottlenecks: (i) $|V_{cb}|$ precision,

(ii) mixing param's from LQCD and η_B

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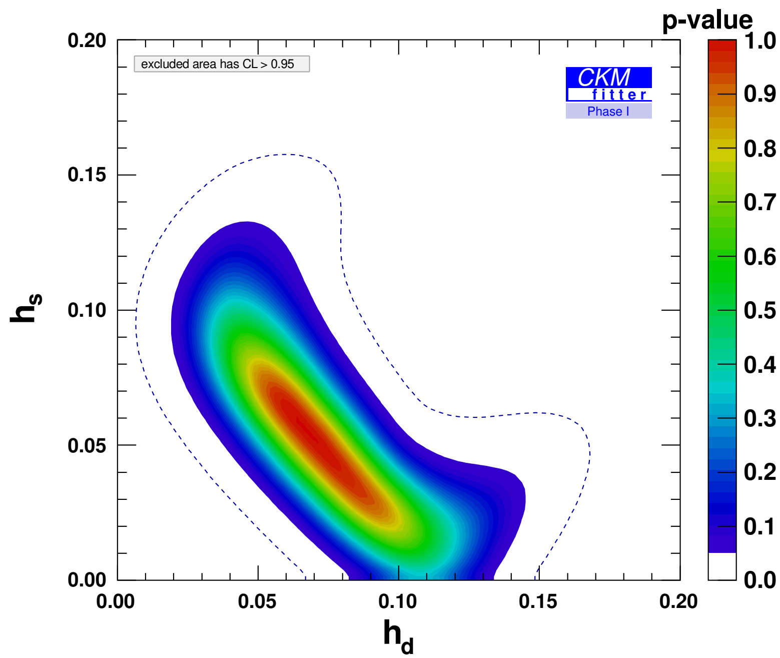
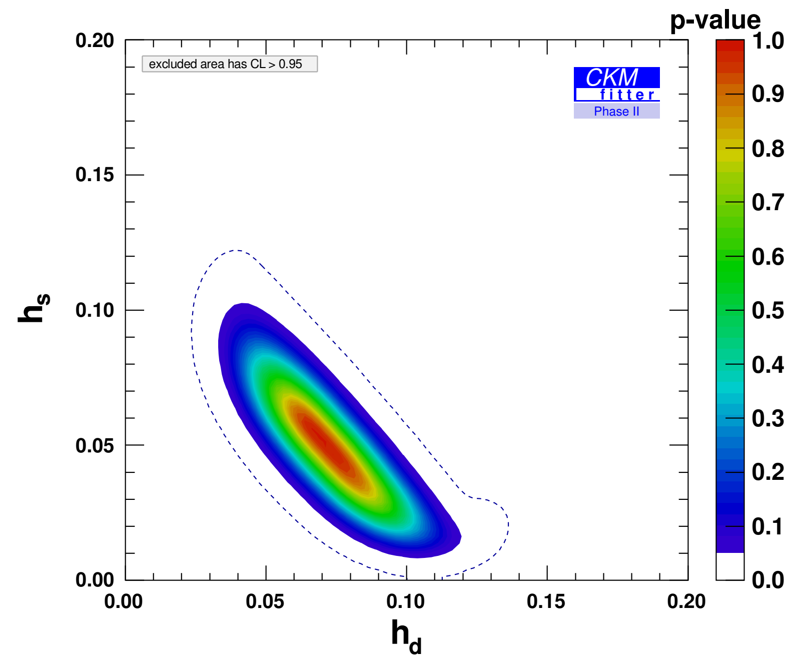
Example of discovery potential (t)

- Discovery significance at Phase I and II, if central values remain as in current fit

(Assume future measurements have the central values corresponding to current best fit parameters) [2006.04824]





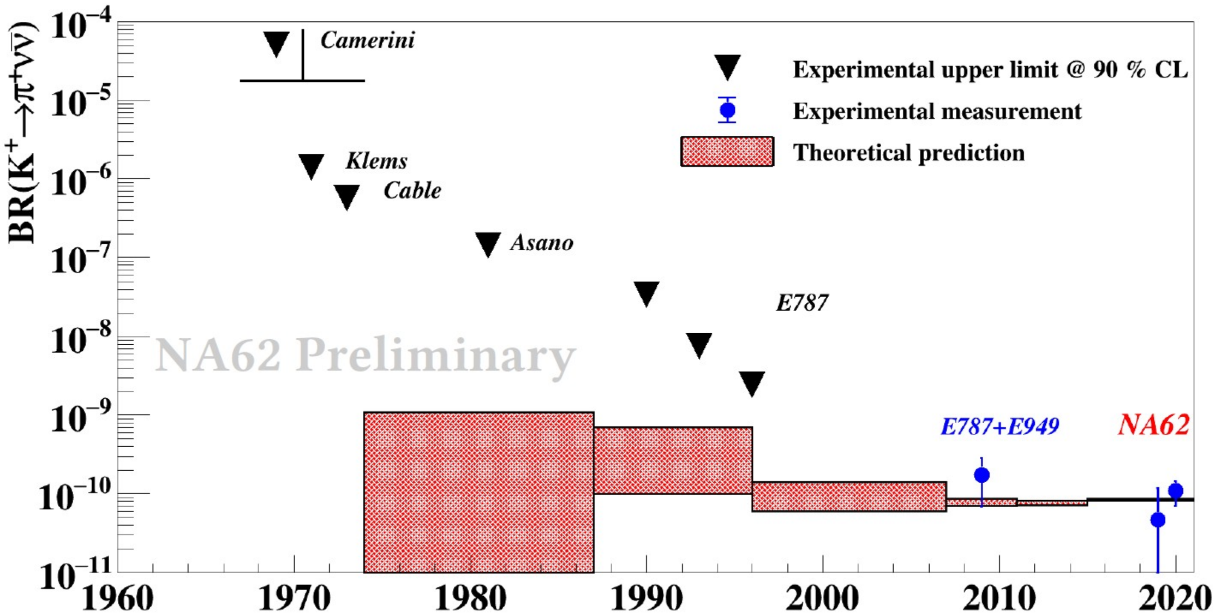
- If new physics contributes to semileptonic decays, as hinted at by the $R(D^{(*)})$ anomaly, then things get more complicated, may still isolate sources

Richness of directions

The quest for $K \to \pi\nu\bar{\nu}$

- Theoretically clean: $K_L \to \pi^0\nu\bar{\nu}$ is CP violating, $K^+ \to \pi^+\nu\bar{\nu}$ is dominantly so

  50 years of searches, sensitivity $\mathcal{O}(100\,\text{TeV})$ ("waiting longer than for Higgs" — Mary K Gaillard)



- NA62: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.6} \pm 0.9) \times 10^{-11}$ — at SM level [2103.15389]
- KOTO: 4 $K_L \to \pi^0\nu\bar{\nu}$ events in 2019; then $4 \to 3$, w/ 1.22 ± 0.26 BG [2012.07571]
- Exciting prospects, plenty of room for new physics

A recent idea: CPV in $K \to \mu^+\mu^-$ (t)

- Time-dependent interference measurements can determine $\mathcal{B}(K_S \to \mu^+\mu^-)_{\ell=0}$

  Clean interpretation for short distance physics [Dery, today, 2104.06427, 1707.06999]

  Allows testing the SM (measure η) with 1% theoretical uncertainty

  In SM same CKM dep. as $K \to \pi\nu\bar{\nu}$; in BSM complementary [2112.05801]

- Promising experimentally [3/31/22 miniworkshop: `https://indico.classe.cornell.edu/event/2061/`]

  Idea: move target closer to NA62 detector, so that interference can be studied

  (rough estimate: 10^{19} POT may give an error $< 10\%$ on η)

- New ideas will keep coming up, independent of Snowmass deadlines ☺

Charm physics (t)

- CPV in D decay recently established:

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

  Recall Nov. 2011: $\Delta A_{CP} = -(8.2 \pm 2.4) \times 10^{-3}$ (a stretch in the SM, imho)

- I think we still don't know how big an effect could (not) be accommodated in SM

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

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

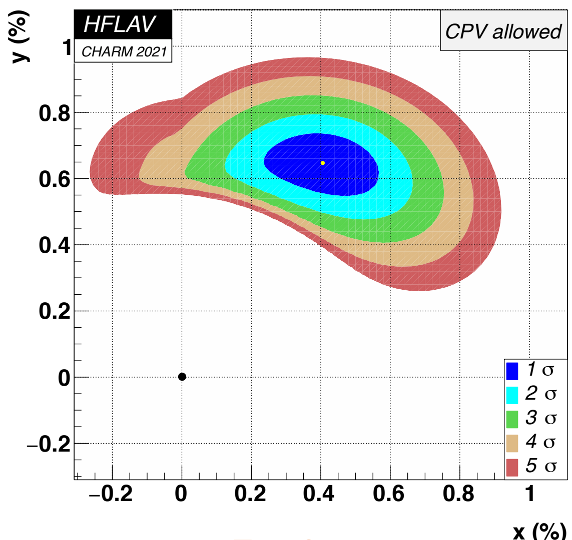
  Only in 2021 was $\Delta m \neq 0$ established with greater than 3σ significance!

- Great interest in rare D decays; challenge is establishing BSM sensitivity

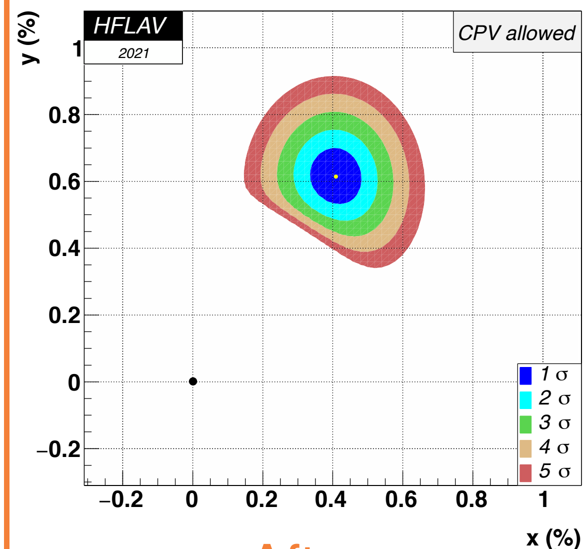
- CP violation in D mixing remains very interesting

- Room for BSM recently shrunk a lot — "old" measurements can also leap forward

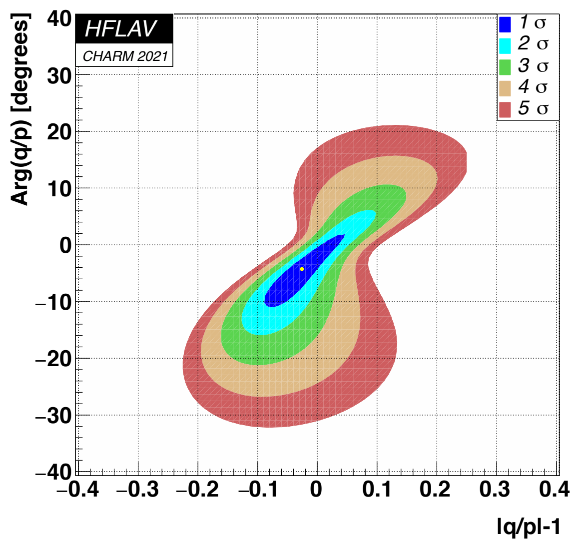
D mixing: huge recent progress

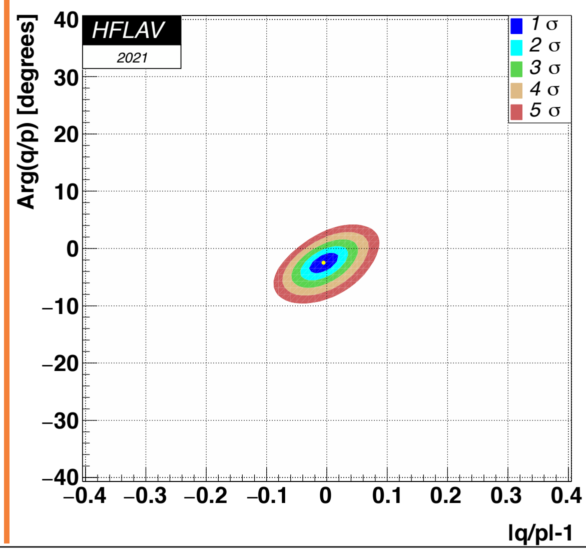


Before



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

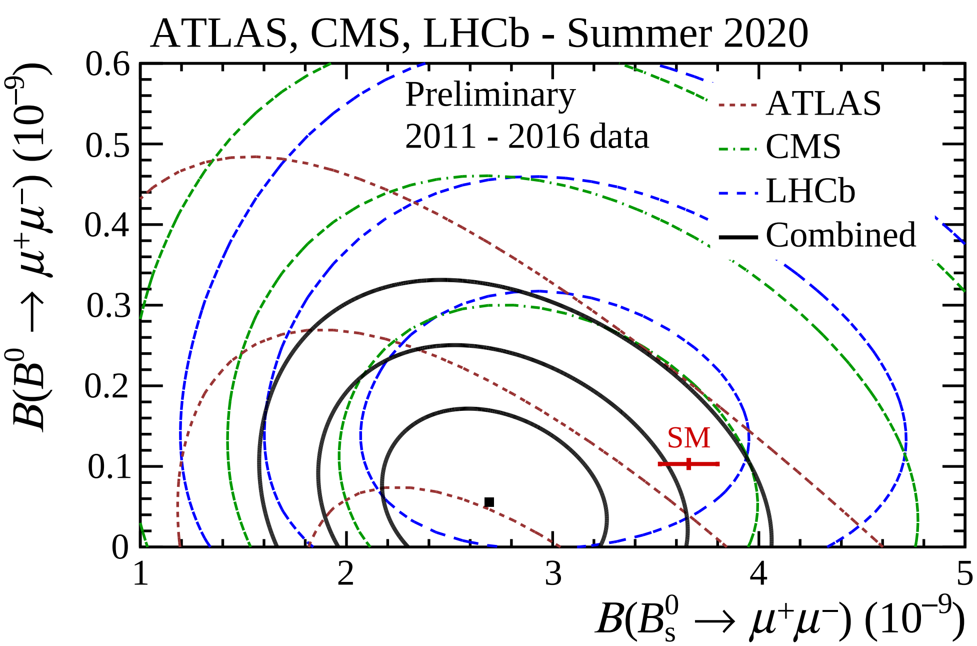


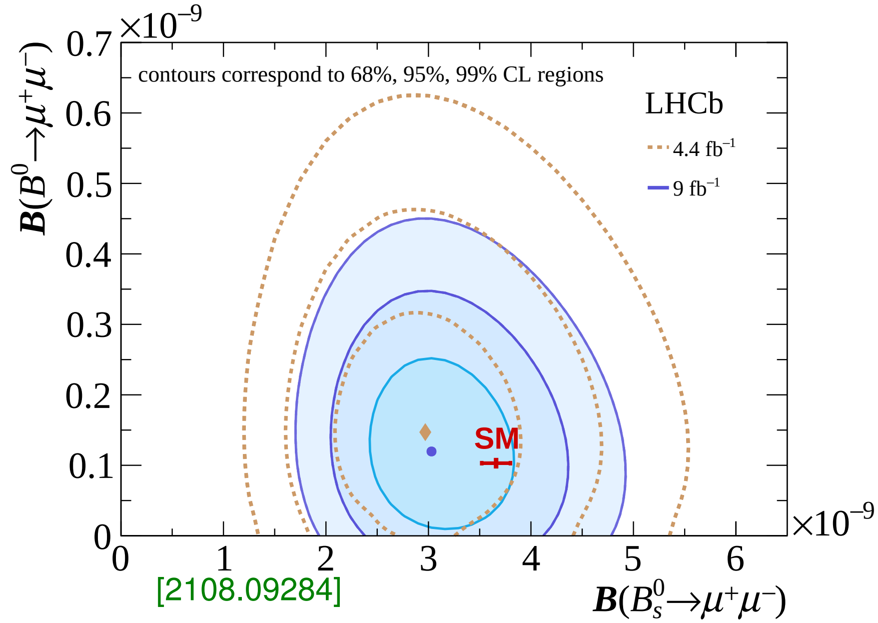


$B \to \mu^+\mu^-$: interesting well beyond HL-LHC (t)

- $B_d \to \mu^+\mu^-$ in SM, 10^{-10}: LHCb expects 10% $(300/\text{fb})$, CMS expects 15% $(3/\text{ab})$

  SM uncertainty $\simeq (2\%) \oplus f_{B_q}^2 \oplus \text{CKM}$ [Bobeth, FPCP'15] and may be further reduced





[2108.09284]

- Theoretically cleanest $|V_{ub}|$ I know, use isospin: $\mathcal{B}(B_u \to \ell\bar\nu)/\mathcal{B}(B_d \to \mu^+\mu^-)$
- A decay with mass-scale sensitivity (dim.-6 operator) that competes w/ $K \to \pi\nu\bar\nu$

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Many “exotic” searches (t)

- Better tests of (exact or approximate) conservation laws
- Exhaustive list of dark / hidden sector searches
- LFV meson decays, e.g., $M^0 \to \mu^- e^+$, $B^+ \to h^+ \mu^- e^+$, etc.
- Invisible modes, even baryonic, $B \to N + \text{invis.}\ [+\text{mesons}]$ [1708.01259, 1810.00880, 2101.02706]
- Hidden valley inspired scenarios, e.g., multiple displaced vertices, even with $\ell^+\ell^-$
- Exotic Higgs decays, e.g., high multiplicity, displaced vertices $(H \to XX \to abab)$
- Search for “quirks” (non-straight “tracks”) at LHCb using many velo layers
- Hot topics 10 years from now are probably not what we have thought about yet

  (Whether or not NP is discovered by then)

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Semileptonic CPV: $A_{\rm SL}^{d,s}$ approach SM @ Tera-Z $(\not{t})$

- 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

Tera-Z: (very) rare decays (t)

- 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

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

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

Final remarks

What are the largest useful data sets?

- No one has seriously explored it! (Recall, Sanda, 2003: the question is not 10^{35} or 10^{36}...)
- Which measurements will remain far from being limited by theory uncertainties?
  - For $\gamma \equiv \phi_3$, theory uncertainty only from higher order EW
  - $B_{s,d} \to \mu\mu$, $B \to \mu\nu$ and other leptonic decays (lattice QCD, [double] ratios)
  - $A_{\rm SL}^{d,s}$ — can it keep scaling with statistics?
  - Lepton flavor violation & lepton universality violation searches
  - Possibly CP violation in D mixing (firm up theory)
- Very broad program
- In some decay modes, even in 2030s we'll have: (exp. bound)$/$SM $\gtrsim 10^3$

  E.g., $B_{d,s} \to e^+e^-$, $\tau^+\tau^-$, etc. — can build models... (Please prove me wrong!)
- Sensitivity to NP would improve with data $\gg$ LHCb & Belle II

Conclusions

- Flavor physics probes scales $\gg 1\,\mathrm{TeV}$; sensitivity limited by statistics

  New physics in FCNCs may still be $\gtrsim 20\%$ of SM, could show up any time measurements improve

- Discovering NP would give a target and upper bound on the next scale to explore

- Theory essential for fully exploiting the experimental program ($+$open questions)

- Complementarity between flavor & LHC probes of BSM (and understanding it)

- Ample reasons to aim for the largest possible data sets that technology allows

- Significantly improving (not systematics limited) measurements very worthwhile

RPF offers many fantastic opportunities!

Extra slides

Theory challenges / opportunities

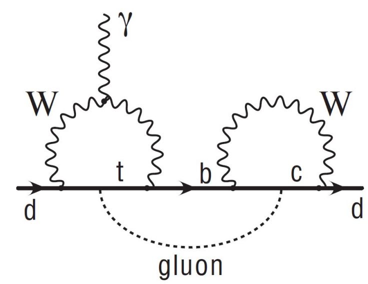
- New methods & ideas: recall that the best α and γ measurements are in modes proposed in light of Belle & BaBar data (i.e., not in the BaBar Physics Book)
  - Better SM upper bounds on $S_{\eta' K_S} - S_{\psi K_S}$, $S_{\phi K_S} - S_{\psi K_S}$, and $S_{\pi^0 K_S} - S_{\psi K_S}$ And similarly in 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?

Electric dipole moments

- SM $+ m_\nu$: CPV can occur in: (i) quark mixing; (ii) lepton mixing; and (iii) $\theta_{\rm QCD}$
  Only observed $\delta_{\rm KM} \neq 0$, baryogenesis implies there must be more

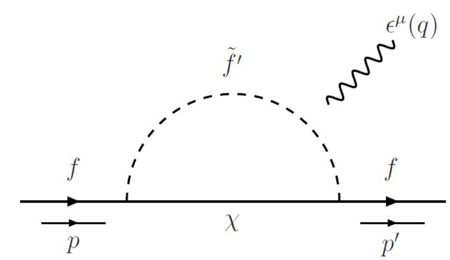
- Neutron EDM bound: "the strong CP problem", $\theta_{\rm QCD} < 10^{-10}$ — axion?
  $\theta_{\rm QCD}$ is negligible for CPV in flavor-changing processes

- EDMs from CKM: vanish at one- and two-loop
  large suppression at three-loop level



- E.g., SUSY: quark and lepton EDMs can be generated at one-loop

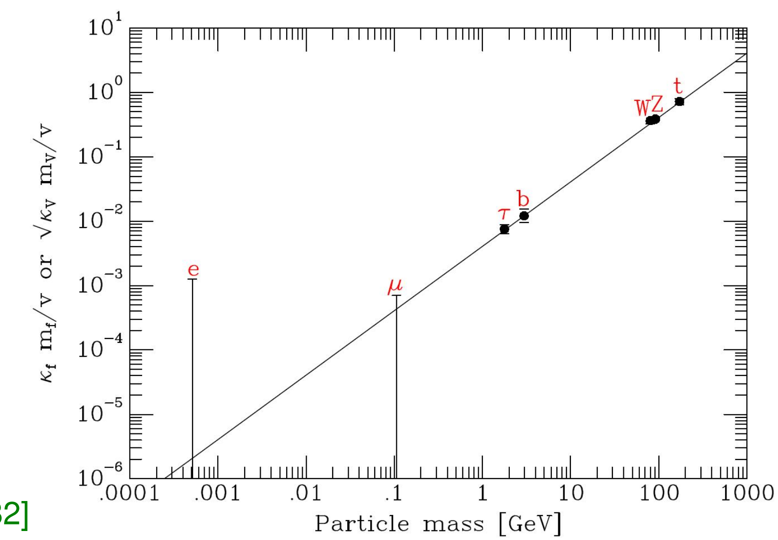
  Generic prediction ($\rm TeV$-scale, no small param's) above current bounds; if $m_{\rm SUSY} \sim \mathcal{O}(10\,\rm TeV)$, may still discover EDMs



- Expected 10^2–10^3 improvements: complementary to LHC
  Discovery would give (rough) upper bound on NP scale

Higgs flavor prospects

- Higgs couplings to gauge bosons, τ, t, (b) have been constrained with some precision, $\mathcal{O}(10\%)$
- ICHEP 2020: Evidence for $H \to \mu^+\mu^-$
- Reducing uncertainties is a key long-term goal



Future precision of flavor-diagonal couplings [Heinemann & Nir, 1905.00382]

Observable	Current range	HL-LHC	ILC250	ILC250+500	CLIC380	CLIC3000	CEPC	FCC240	FCC365	LHeC
		$\delta y/y$ (%)								
y_t/y_t^{SM}	$1.02^{+0.19}_{-0.15}$ [35] $1.05^{+0.14}_{-0.13}$ [36]	3.4	–	6.3	–	2.9	–	–	–	–
y_b/y_b^{SM}	$0.91^{+0.17}_{-0.16}$ [35] $0.85^{+0.13}_{-0.14}$ [36]	3.7	1.0	0.60	1.3	0.2	1.0	1.4	0.67	1.1
y_τ/y_τ^{SM}	0.93 ± 0.13 [35] 0.95 ± 0.13 [36]	1.9	1.2	0.77	2.7	0.9	1.2	1.4	0.78	1.3
y_c/y_c^{SM}	< 6.2 [40, 41]	< 220	1.8	1.2	4.1	1.3	1.9	1.8	1.2	3.6
y_μ/y_μ^{SM}	$0.72^{+0.50}_{-0.72}$ [35] < 1.63 [36]	4.3	4.0	3.8	–	5.6	5.0	9.6	3.4	–
y_e/y_e^{SM}	< 611 [42]	–	–		–	–	–	–	$< 1.6^{(+)}$	–

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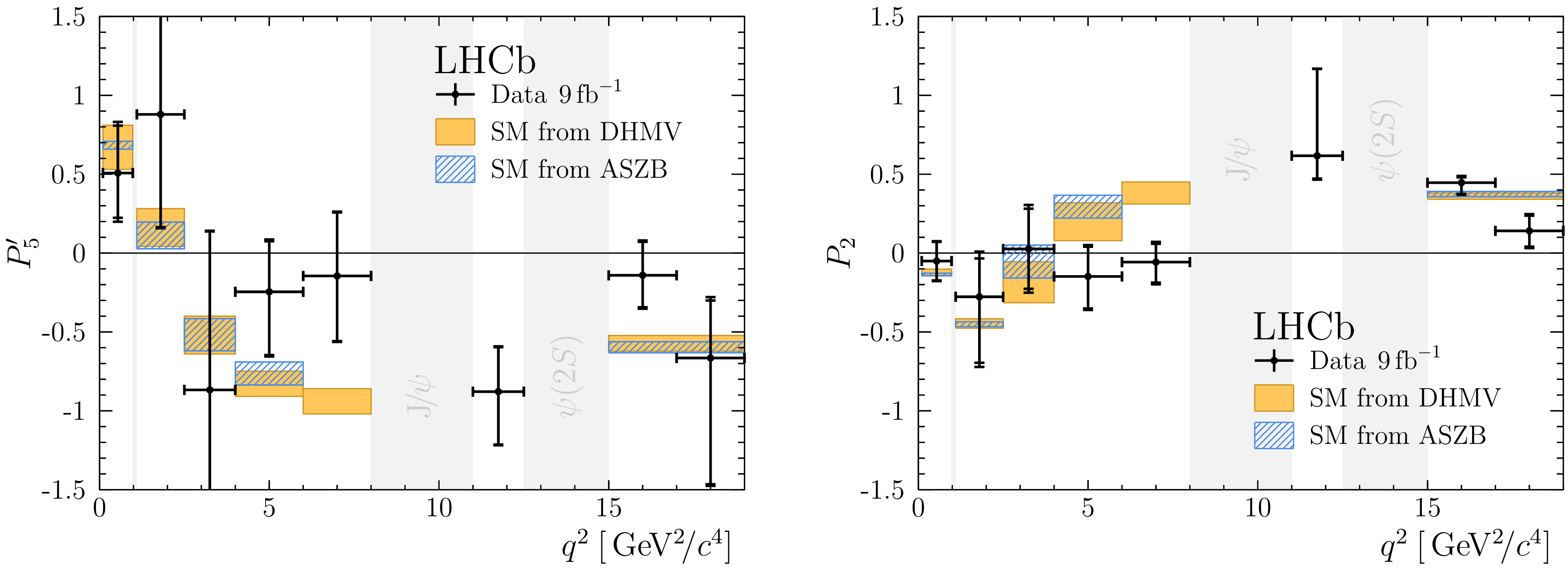
Recently: P_5' in $B^+ \to K^{*+}\mu^+\mu^-$

- Anomaly also seen (with smaller significance) in isospin partner [2012.13241]

  At the LHC, $K^{*+} \to K_S^0\pi^+$ harder than $K^{*0} \to K^+\pi^-$ (see also CMS [2010.13968])



- Tension in P_2 with SM, not in $B^0 \to K^{*0}\mu^+\mu^-$ [2003.04831] mode $\Rightarrow$ Need more data

Rare D decays

- Very broad subject, many interesting decay modes

  Charm FCNCs highly suppressed in SM, need to control long-distance contrib.

  (Some CP violating observables, e.g., in semileptonic modes, insensitive to long distance)

- Just like D mixing, probes of NP complementarity to FCNC $B_{(s)}$ and K decays

  Interesting experimental and theoretical questions:
  Beyond current bounds, in which modes can one establish deviations from SM?

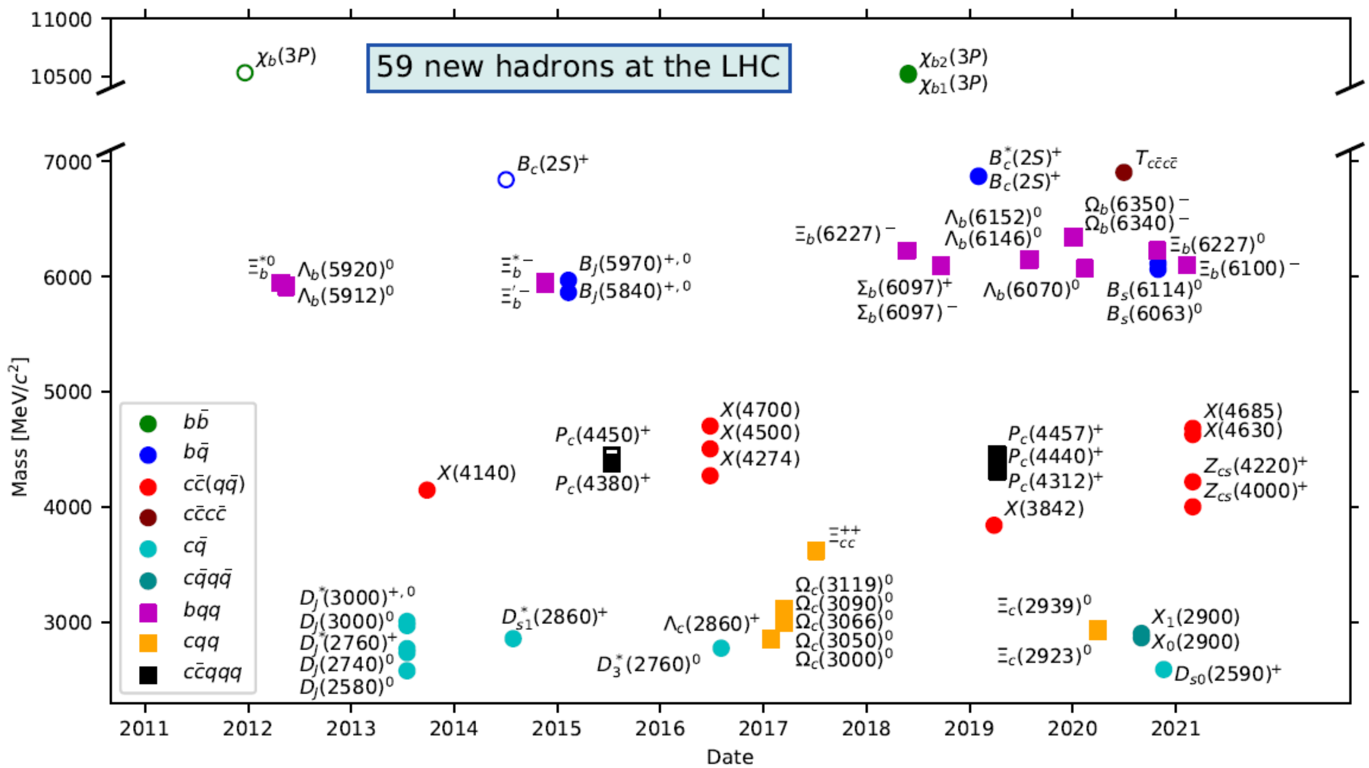
- E.g., $D \to \pi\nu\bar{\nu}$ may be observable due to leptoquarks explaining $R(D^{(*)})$ [1506.08896]

  Active topic for theory, e.g, $c \to u\ell^+\ell^-$ [1909.11108]; $c \to u\gamma$ [2009.14212]; $c \to u\nu\bar{\nu}$ [2010.02225]

Spectroscopy at B experiments

- Started in 2003 with $D^*_{s0}(2317)$ (BaBar) and $X(3872)$ (Belle) discoveries
- LHCb's most cited paper: pentaquark discovery in 2015 (1200 cites $> R_K$ in 2014)

[plot credit]



- How complex the spectrum of strongly interacting theories can be...