

Flavor physics in the new era

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Outline

- Why flavor?
Unique sensitivities
- Recent examples of knowns and unknowns
Lots to do, both for theorists and experimenters
- Far future: FCC
Huge increases in data, what can they teach us?

What is flavor physics?

- 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 the SM, and search for NP
- SM flavor: masses? mixing angles? 3 generations? — most of the SM parameters
Flavor in SM is simple: only from Higgs interactions, many testable relations
- BSM flavor: TeV scale (hierarchy problem) \ll “naive” flavor & CP viol. scale
New particles that couple to quarks or leptons \Rightarrow new flavor param's, clues about BSM
- Baryon asymmetry: how precisely can we probe for CPV beyond the SM?
(Not necessarily related to flavor changing processes, nor necessarily to the quark sector)

Flavor physics and Oppenheimer



“Nothing about Oppenheimer was uncomplicated”

“You cannot come up with a simple version of him”

A bit like flavor physics...

- The interesting messages are not simple, the simple messages are not interesting (This is also oversimplified)

New physics scales probed

- Heavy new physics generates dimension > 4 operators in SMEFT

$$\mathcal{L} = \text{SM} + \sum_i \frac{C_{5i}}{\Lambda} \mathcal{O}_{5i} + \sum_i \frac{C_{6i}}{\Lambda^2} \mathcal{O}_{6i} + \dots$$

- Dim-5 $LL\phi\phi$ discovered, iff m_ν violates lepton # ($0\nu\beta\beta?$); No dim-6 term established yet

- Baryon number violation: $\frac{QQQL}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{16} \text{ GeV}$

- Higgs & precision electroweak: $\frac{(\phi D^\mu \phi)^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^4 \text{ GeV}$

- Flavor and CP violation (and EDMs): $\frac{QQQQ}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{(3\dots 8)} \text{ GeV}$

Flavor and CPV are the only experimental probes of the $10^2 - 10^5 \text{ TeV}$ scale

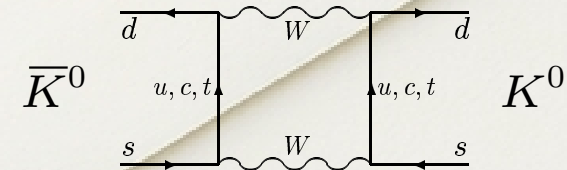
- New physics could show up any time the sensitivities improve (by a substantial amount)

Origin of high scale sensitivity

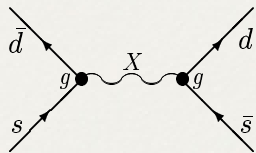
- Back of an envelope calculation of Δm_K : loop, CKM, GIM suppressions
- Why is $\Delta m_K/m_K \sim 7 \times 10^{-15}$?

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

Predicted $m_c \sim 1.5 \text{ GeV}$ (Gaillard & Lee; Vainshtein & Khriplovich, 1974)



- If exchange of a heavy particle X contributes at the SM level:

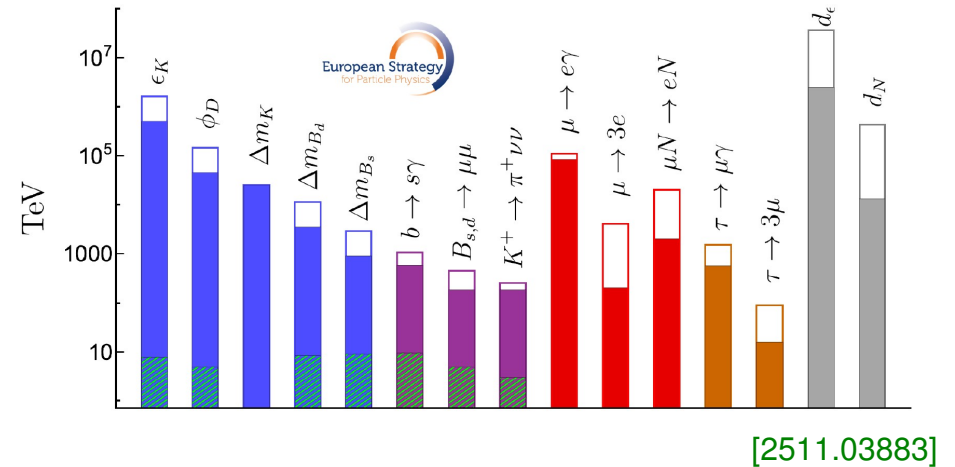
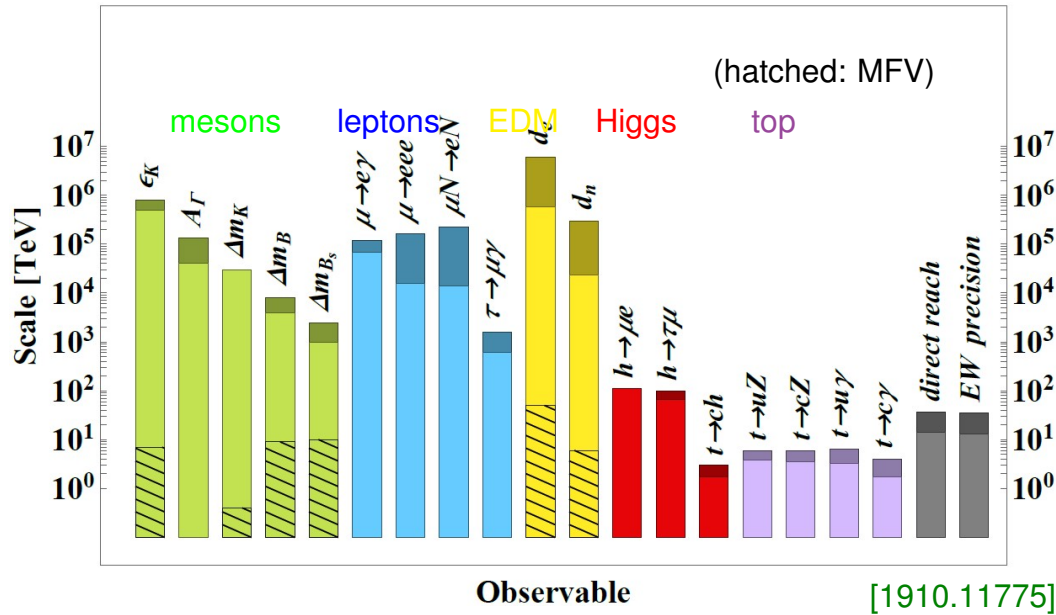


$$\frac{\Delta m_K^{(X)}}{\Delta m_K} \sim \frac{g^2 \Lambda_{\text{QCD}}^3}{M_X^2 \Delta m_K} \Rightarrow M_X > g \times 10^3 \text{ TeV}$$

- Alternatively, sensitivity to TeV-scale particles with one-loop couplings [$g \sim \mathcal{O}(10^{-3})$]

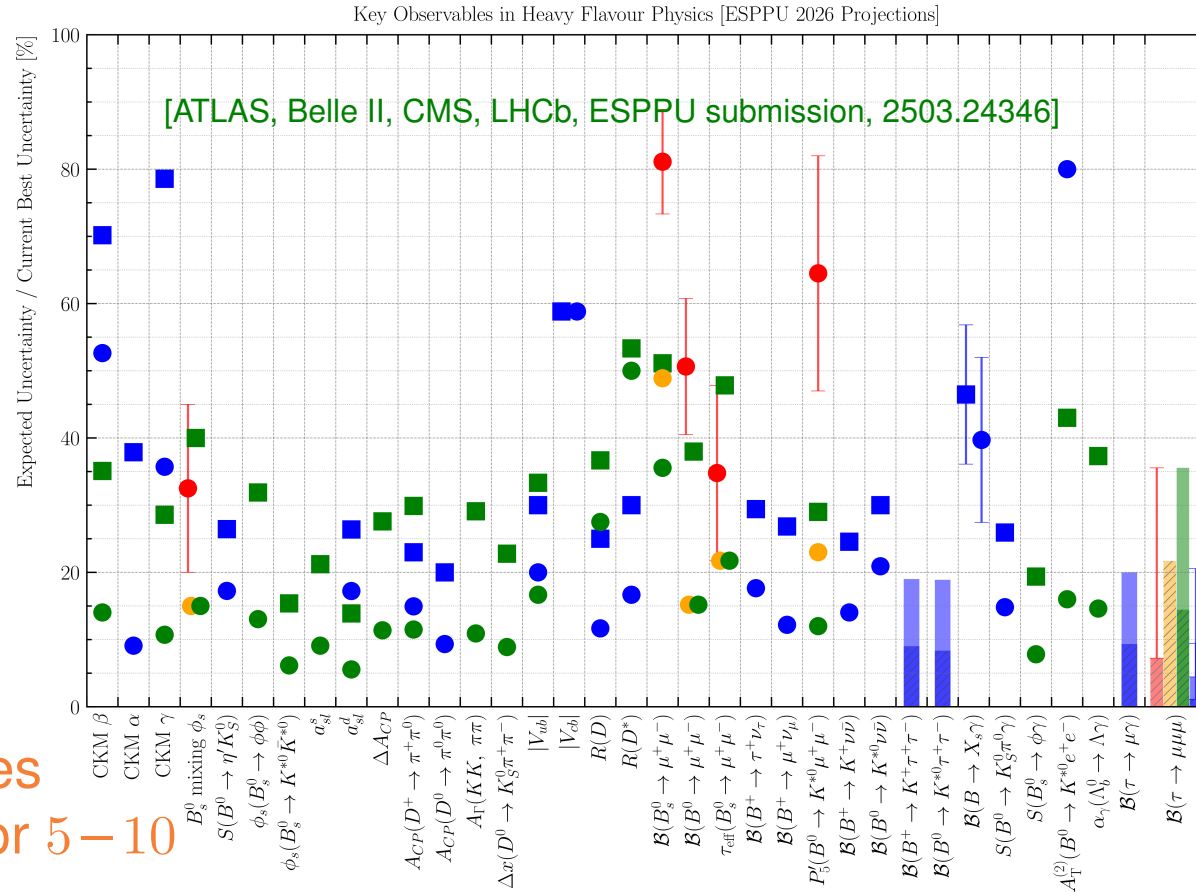
Similar story for many other flavor-changing neutral current (FCNC) processes

Scales, as shown in European strategy

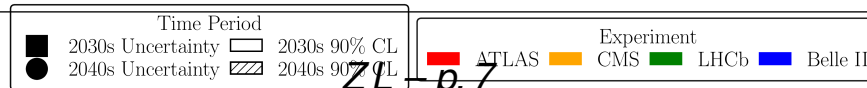


- All TeV-scale NP models must contain some mechanism to avoid violating constraints
Models devised to make deviations from SM small, revisit model building when tensions with SM arise
- Suppressions in SM are strongest for kaons, often Δm_K & ϵ_K are the most constraining

Large upcoming improvements

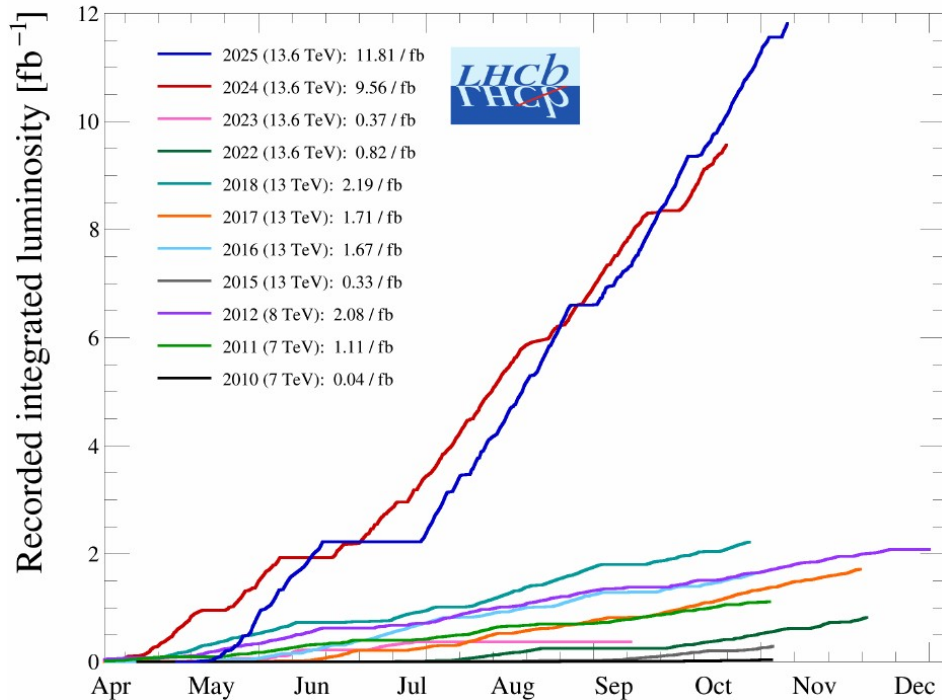


Many uncertainties will shrink by factor 5 – 10



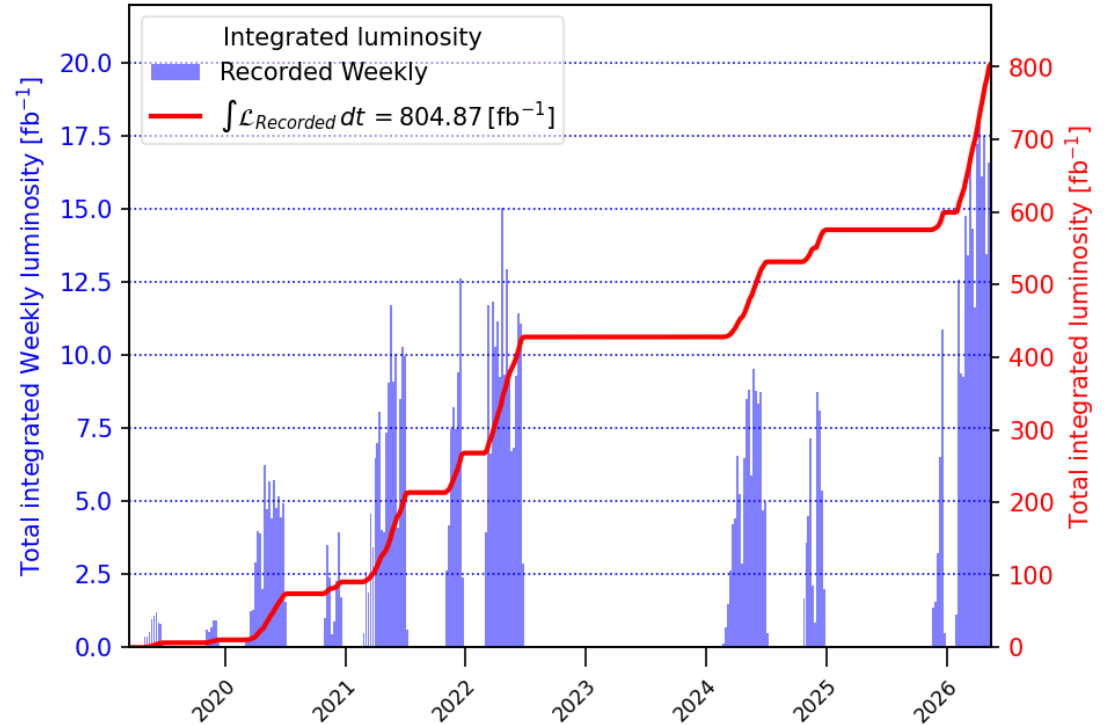
Past LHCb and Belle II data taking

Total recorded luminosity by year – pp

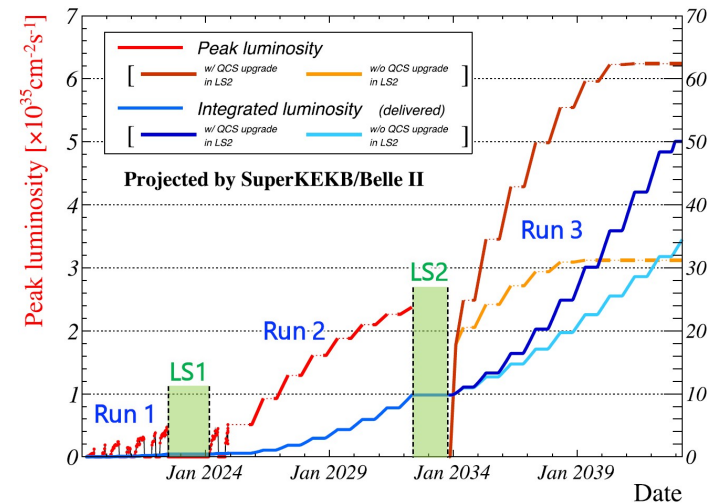
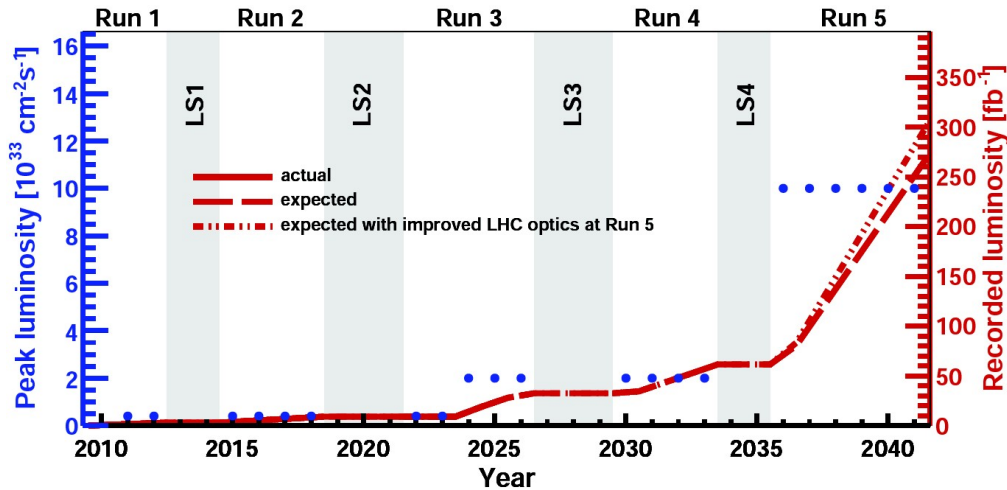


(Hardly any LHCb result is available yet from Run 3)

Belle II Online luminosity Exp: 7-42 - All runs



Future LHCb and Belle II plans



- LHCb upgrade in LS2 (inst. lumi.: 2×10^{33})
- LHCb Upgrade II in LS4 (inst. lumi.: 1.5×10^{34})
- ATLAS & CMS competitive in some modes

- Belle II goal: over $50 \times$ Belle data set
- Discussions about physics & feasibility of an upgrade (polarization? 250/ab?)

The CKM quark mixing matrix

- The $(u, c, t) W^\pm (d, s, b)$ couplings: (Wolfenstein parm., $\lambda \sim 0.23$)

$$V_{\text{CKM}} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{\text{CKM matrix}} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \dots$$

9 complex couplings depend on 4 real parameters \Rightarrow many testable relations

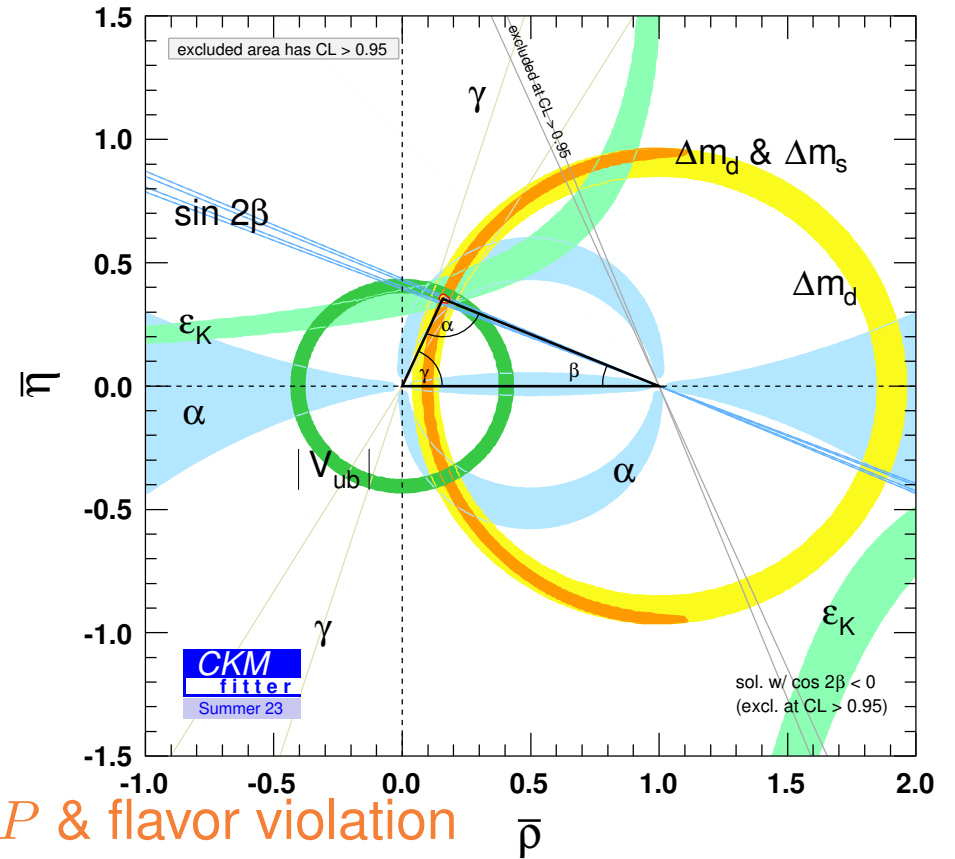
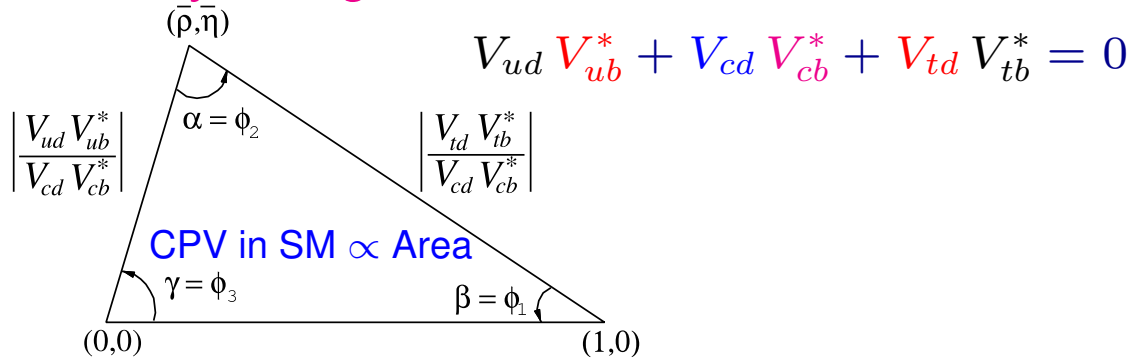
One complex phase in V_{CKM} : only source of CP violation in quark sector (besides θ_{QCD})

- Want: overconstraining measurements sensitive to different short-distance physics (E.g., separate determinations from tree-level and loop-dominated processes)

Lincoln Wolfenstein: *'I do not care what the values of the Wolfenstein parameters are, so you should not care either; the only thing that matters is whether their independent determinations are consistent'*

Snapshot: CKM fit in the SM

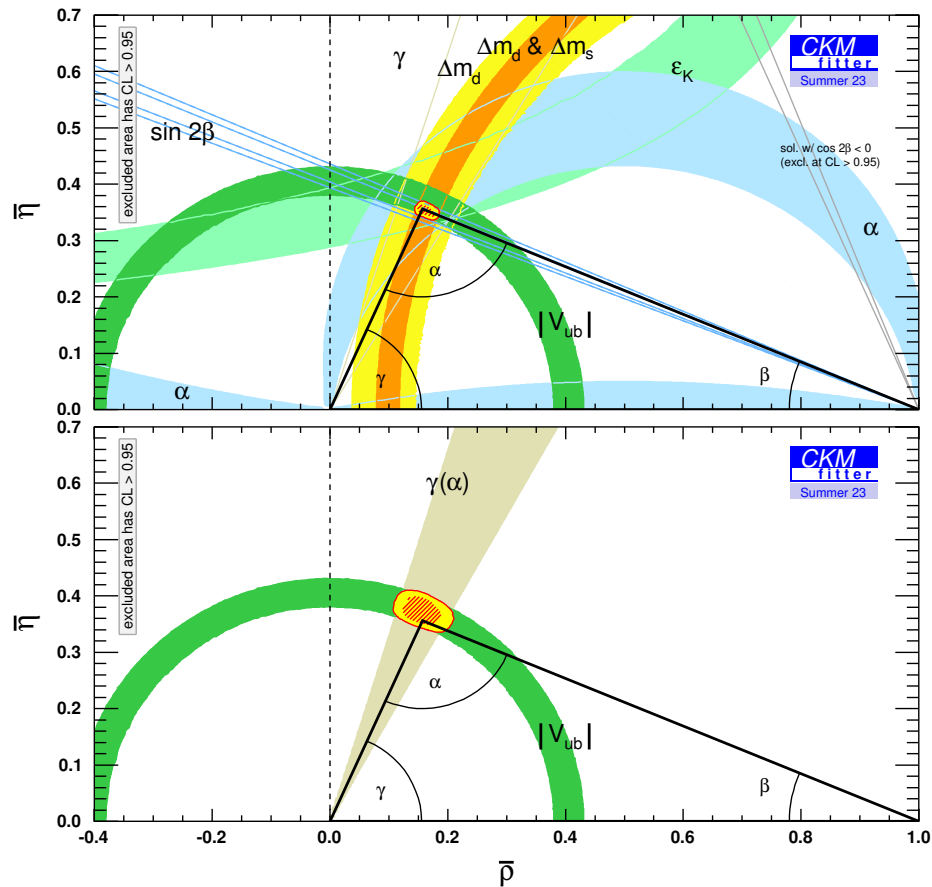
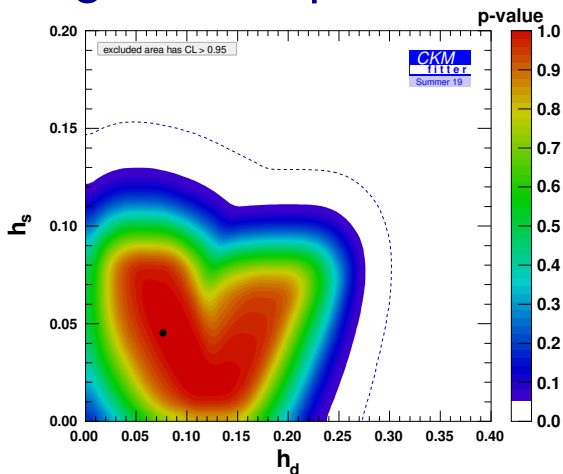
- Spectacular progress in last 25 years
- Magnitudes: Semileptonic decay rates
 $B_{d,s}$ mixing (loops: V_{td} & V_{ts})
- Relative phases: CP violation
- Unitarity triangles: visualize SM constraints



- The CKM mechanism describes consistently CP & flavor violation

Snapshot: CKM fit in the SM

- Spectacular progress in last 25 years
- Looser constraints if NP is allowed in the fit
Full fit (upper) vs. tree-dominated (lower) plot
- Implies, e.g., that 10–20% corrections to $B - \bar{B}$ mixing are still possible



Recent tensions between SM and data

Hints of deviations from the SM

- From a distance, everything looks fine... looking closer:

Less than half of B decays measured; most incalculable, but we have theories for some (HQET, SCET)

- Charged-current semileptonic $b \rightarrow c$ decays (e.g., $B \rightarrow D^{(*)} \ell \bar{\nu}$)
- Neutral-current (FCNC) semileptonic decays (e.g., $B \rightarrow K^{(*)} \ell \bar{\ell}$)
- Charged-current nonleptonic $b \rightarrow c$ decays (e.g., $B \rightarrow D^{(*)} h$ [$h = K, \pi$])
- Dominantly FCNC nonleptonic decays (e.g., $B \rightarrow Kh$)

There are more...

- Intriguing tensions with the SM \Rightarrow experimental scrutiny, new theory ideas
- What are smallest deviations from SM, which can be unambiguously established?

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

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

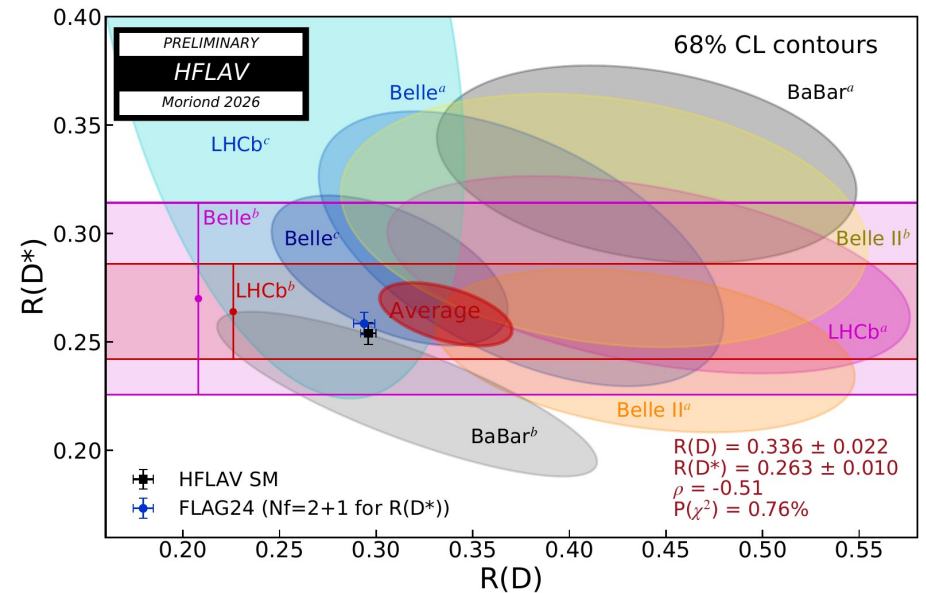
$2.x\sigma$ (was $\sim 3.5\sigma$) from SM prediction: theory robust due to heavy quark symmetry + LQCD (Some confusion due to recent BaBar analysis, bad χ^2)

- Imply NP scale \lesssim few TeV

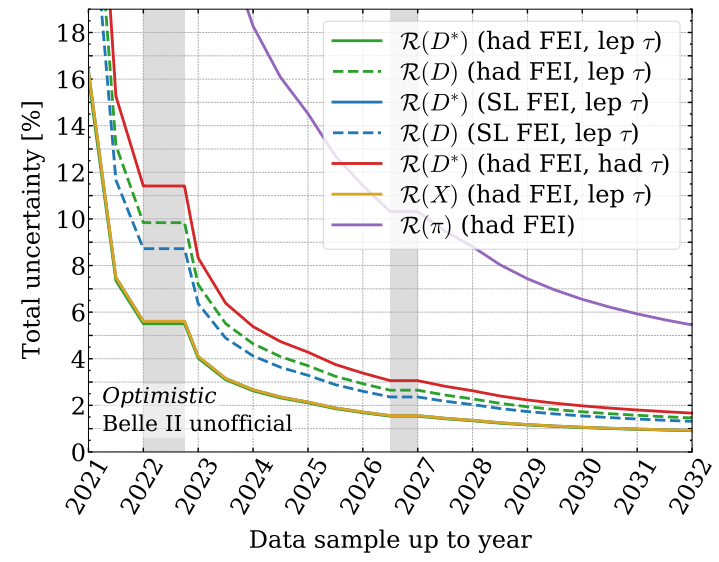
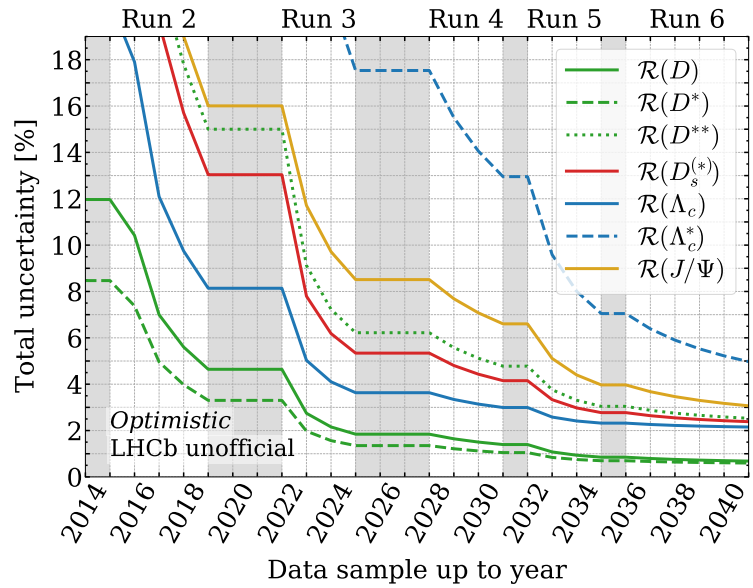
Mediators within / near ATLAS & CMS reach

- 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 impacted ATLAS & CMS searches, motivated LFV searches



Large future improvements



[2101.08326]

- Measurements will improve a lot, and reach few % in several decay modes
- May establish NP, even if deviations from SM decrease
- Will at least lead to much more robust $|V_{cb}|$ — critical for precision in many observables

$|V_{cb}|$ and pushing HQET further

- $|V_{cb}|$ impacts many rare B and K decay rate predictions (and ϵ_K), since $V_{ts}, V_{td} \propto A$
- $|V_{cb}|$ is measured from “zero recoil” limit of $d\Gamma(B \rightarrow D^{(*)} \ell \bar{\nu})/dq^2$

HQET most constraining + LQCD most precise

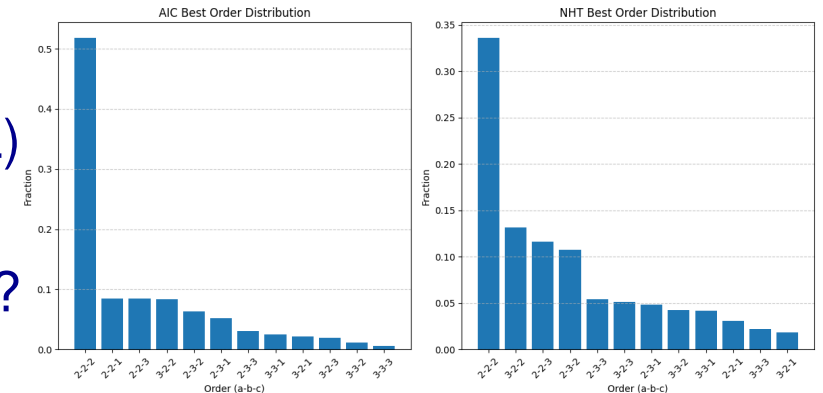
In practice, measuring all distributions helps — additional information

- Many open questions — need a lot more data:

How to fit data: truncate model independent (BGL) param.? (Many proposals, Akaike information criterion, etc.)

Optimal combination w/ unitarity constraints & LQCD?

Some tension between LQCD and data

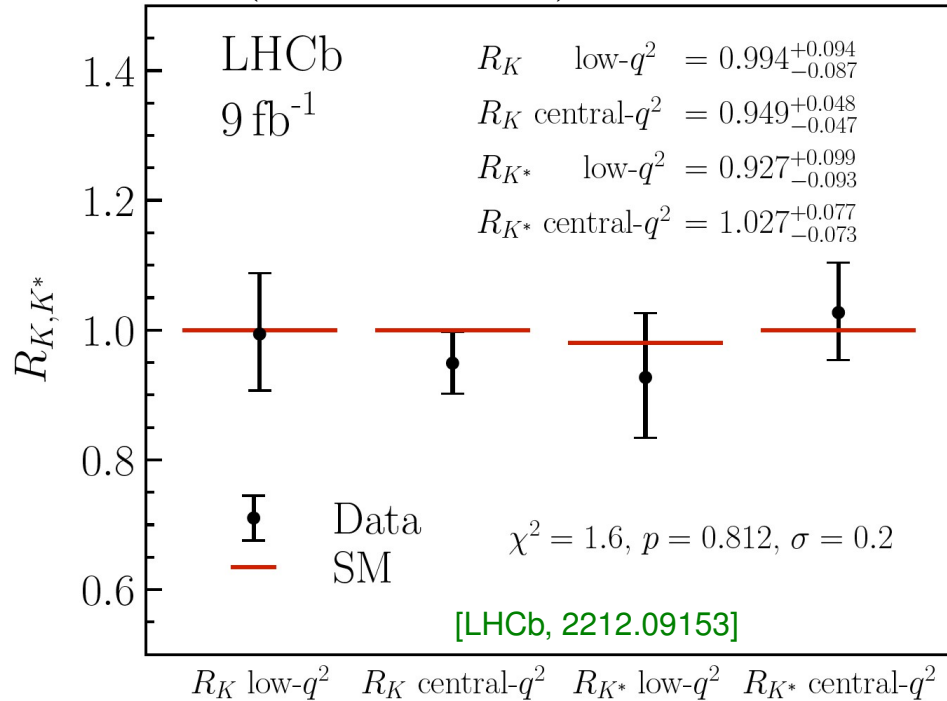


[Bernlochner, ZL, Persson, Robinson, to appear]

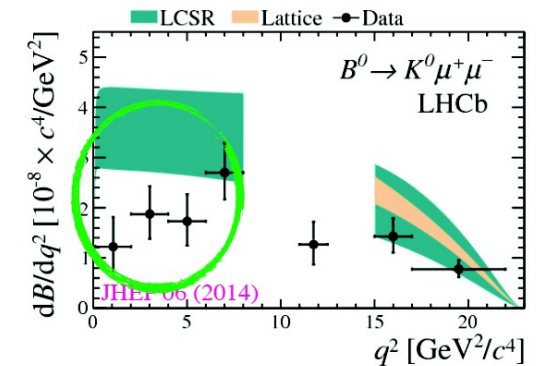
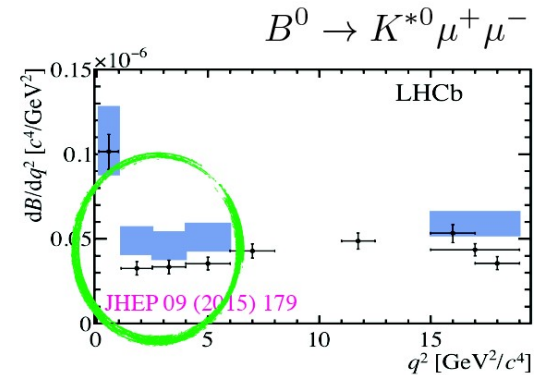
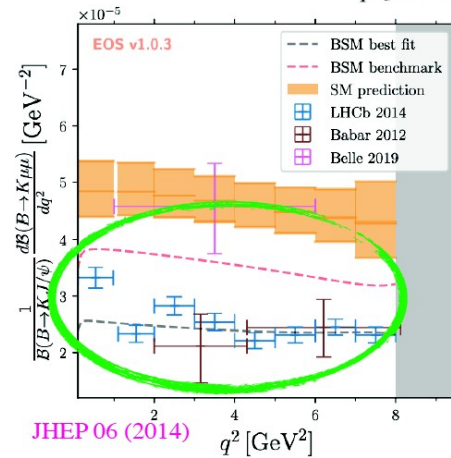
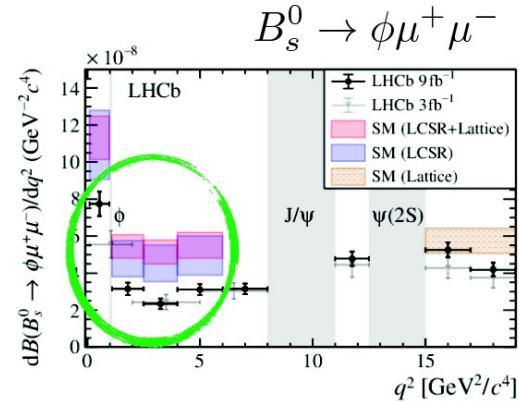
- Not to mention tension between exclusive and inclusive determination

\$R_K\$ and \$R_{K^*}\$ now: SM-like, but rates too small?

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \rightarrow K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \rightarrow K^{(*)} e^+ e^-)}$$



$0.1 < q^2 < 1.1 \text{ GeV}^2$ (low- q^2), $1.1 < q^2 < 6.0 \text{ GeV}^2$ (central)



[Smith, LHCP 2024]

The P'_5 angular distribution in $B \rightarrow K^* \mu^+ \mu^-$

- “Optimized observables” [1202.4266 + long history] (assumptions about factorizable / nonfactorizable)

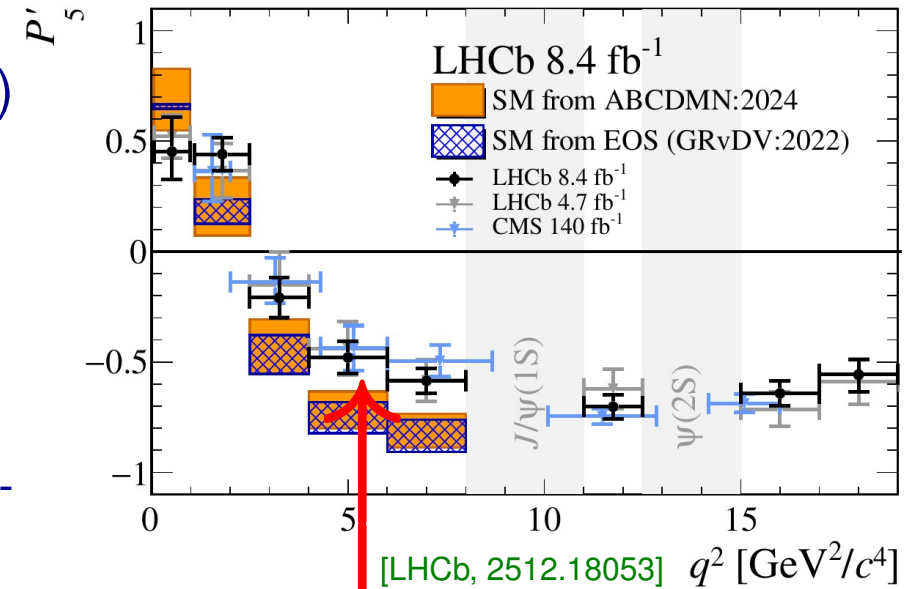
Global fits: best fit, still: NP reduces C_9

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

- Difficult for lattice QCD, large recoil

What calculation determines how far below $m_{J/\psi}$ this comparison is reliable? (Different than $e^+e^- \rightarrow$ hadrons)

- Tests: other observables, q^2 dep., B_s and Λ_b decays
- Is the $c\bar{c}$ loop tractable? Impacts many interesting decay rates & CP viol. observables

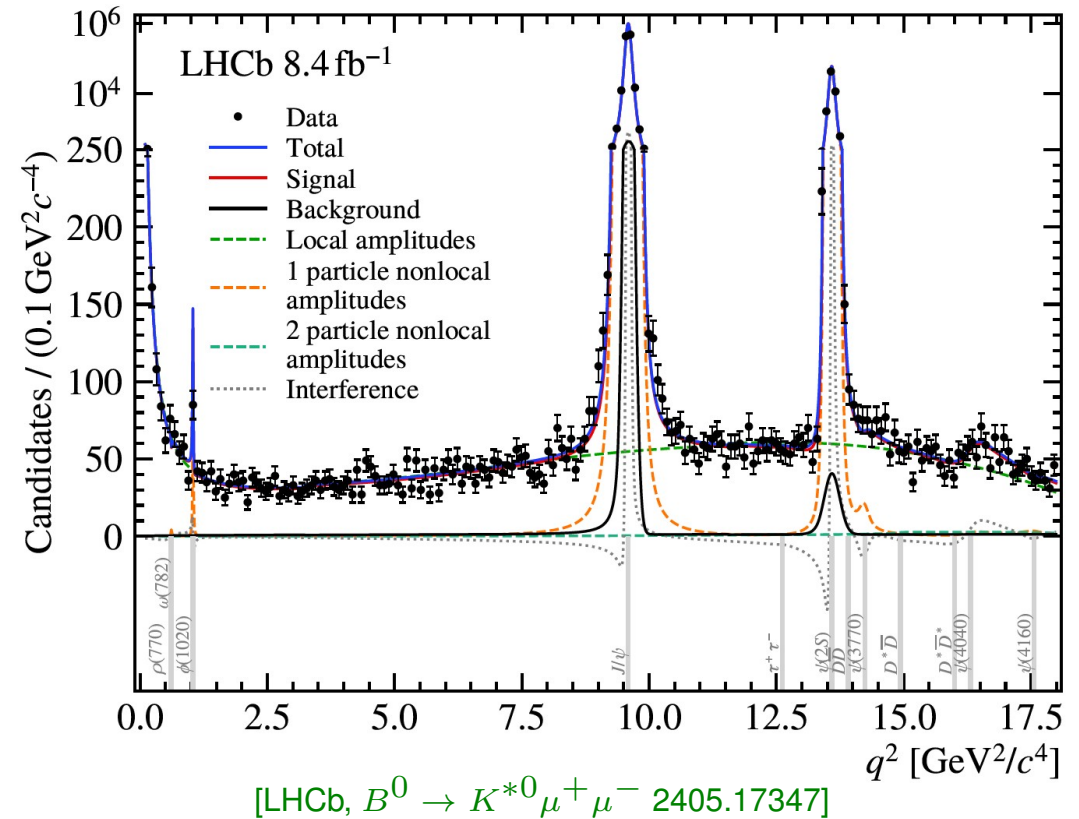


BSM, fluctuation, SM theory?

Intense discussions of theory uncertainties

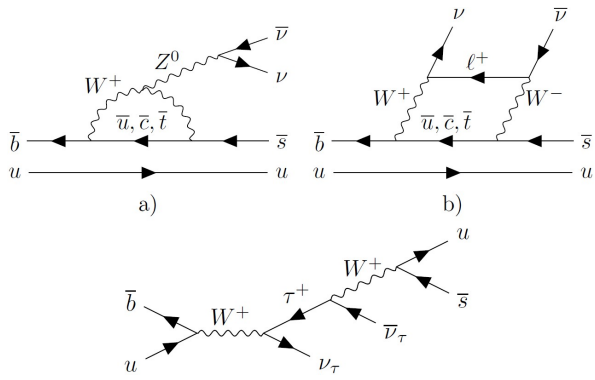
- My hope: data will help to make progress
- Large data sets often inspired progress in theory, and developing new approaches
- Only robust deviations based on model-independent theory will be seen as signs of new physics

Recent LHCb full angular analysis [2512.18053] reinvigorated study of hadronic effects: Altmannshofer, Christensen, Stangl, [2603.27753]; Alvarez-Cartelle, Capdevila, Lunghi, Matias [2605.06567]



$B \rightarrow K \nu \bar{\nu}$ — unique to e^+e^- colliders

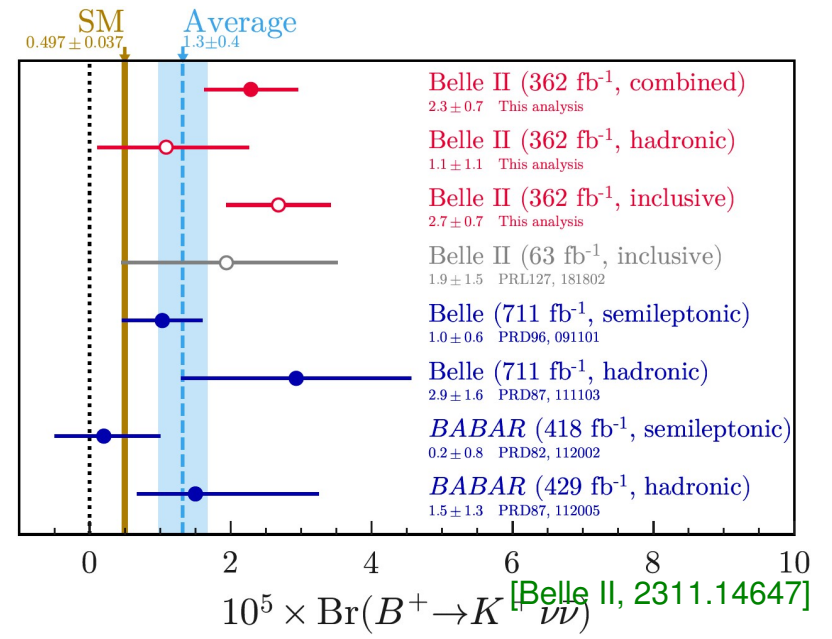
- Similar short-distance contributions, and much simpler long-distance ones



- Also relevant for dark sector searches ($B \rightarrow K + \text{invis.}$)
(Is the excess in one bin of q^2 ?) [2309.00075, 2311.14629, 2602.09666]

- Input: precise form factor calculation [HPQCD, 2207.12468]

- If this tension becomes more significant, stopping NA62 after LHC Run 3 will look even more mistaken

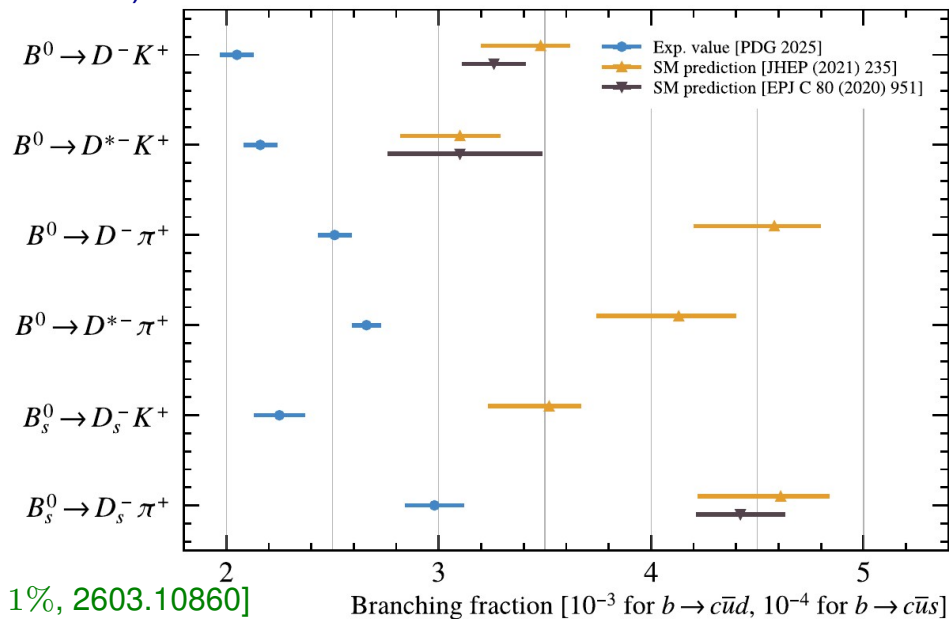


Belle II: 2.7σ from SM

Nonleptonic $b \rightarrow c$ decays

- Some $B \rightarrow Dh$ decays factorize in heavy quark limit (plus power suppressed corrections)

(Physical picture by Bjorken around 1990)



[LHCb: direct CPV in $B_s^0 \rightarrow D_s^- \pi^+ \lesssim 1\%$, 2603.10860]

- Need: semileptonic form factor near $q^2 = 0$, plus estimate of corrections

(Still) not understood: the $B \rightarrow K\pi$ puzzle

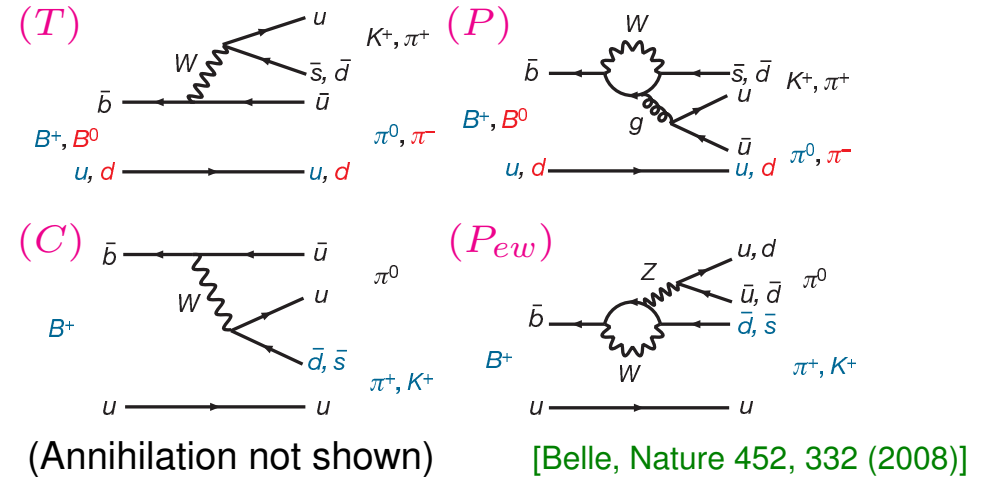
- Have we seen new physics in CPV?

$$A_{K^+\pi^-} = -0.0831 \pm 0.0031 \quad (P + T)$$

$$A_{K^+\pi^0} = 0.027 \pm 0.012 \quad (P + T + C + A + P_{ew})$$

- Large difference — small SM sources?

$$A_{K^+\pi^0} - A_{K^+\pi^-} = 0.111 \pm 0.012$$



SCET / factorization predicts: $\arg(C/T) = \mathcal{O}(\Lambda_{\text{QCD}}/m_b)$ and $A + P_{ew}$ small

- Large fluctuations? Breakdown of $1/m$ expansion? Missing something subtle? BSM?

- Can we understand the theory well enough, so that future data could disprove the SM?

Can there be a similar enhancement in B decay as the $\Delta I = \frac{1}{2}$ rule for K ? [2604.19612, 2510.13969, 2505.11492]

Belle II can make unique contribution

- Sum rule based on isospin for dominant amplitudes, and $SU(3)$ for subleading terms:

$$\delta_{K\pi} = \Delta(K^+\pi^-) + \Delta(K^0\pi^-) - 2\Delta(K^+\pi^0) - 2\Delta(K^0\pi^0) \quad \Delta(f) = \Gamma(\bar{B} \rightarrow \bar{f}) - \Gamma(B \rightarrow f)$$

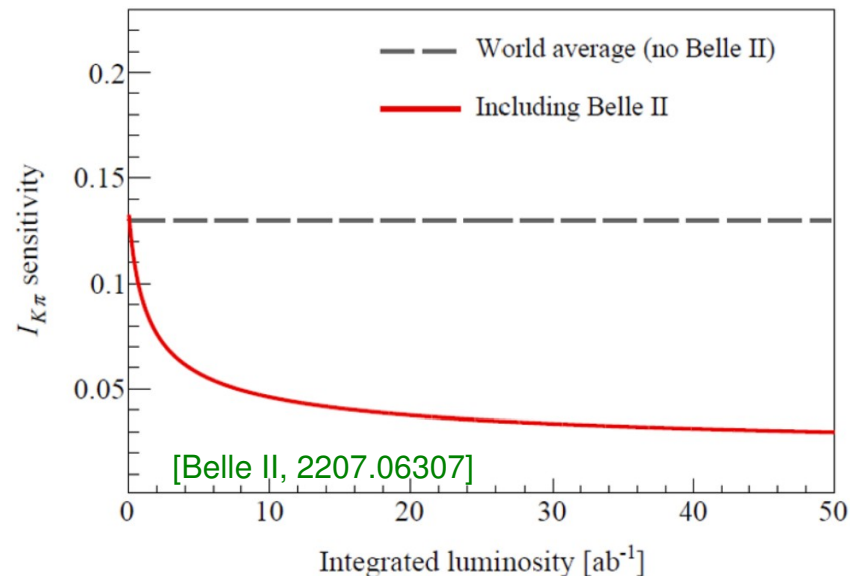
Expect: $|\delta_{K\pi}/\Delta(K^+\pi^-)| \lesssim \text{few } \%$

[Gronau, hep-ph/0508047]

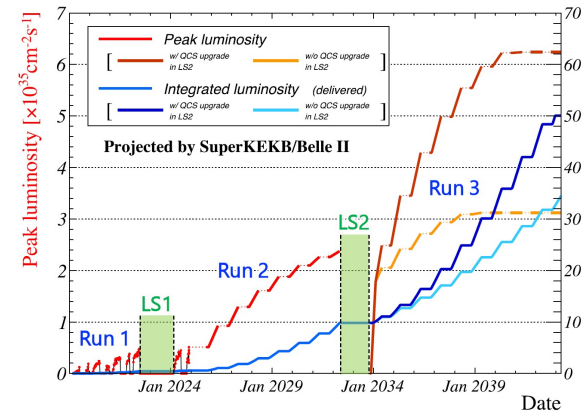
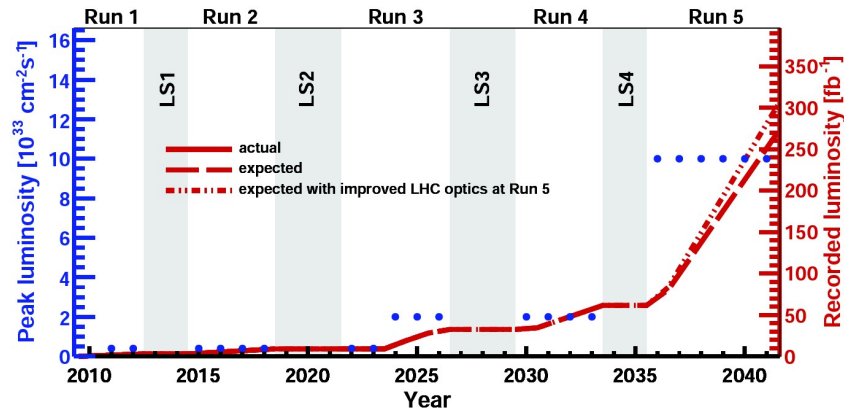
Limiting uncertainty: $\Delta(K^0\pi^0)$

$$I_{K\pi} = \frac{\delta_{K\pi}}{2\Gamma(B \rightarrow K^+\pi^-)}$$

- Interesting well beyond Belle II
sensitivity \Rightarrow FCC- ee



(Far) future



- Of the future colliders discussed, only FCC would go well beyond LHCb + Belle II goals

Breadth and surprises

- Most cited physics paper of each B factory was not a part of the planned program:

- BaBar:

Evidence for an excess of $\bar{B} \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau$ decays #2
BaBar Collaboration • J.P. Lees (Annecy, LAPP) et al. (May, 2012)
Published in: *Phys.Rev.Lett.* 109 (2012) 101802 • e-Print: [1205.5442](#) [hep-ex]
pdf links DOI cite claim reference search 1,364 citations

- Belle:

Observation of a narrow charmonium-like state in exclusive $B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$ decays #1
Belle Collaboration • S.K. Choi (Gyeongsang Natl. U.) et al. (Sep, 2003)
Published in: *Phys.Rev.Lett.* 91 (2003) 262001 • e-Print: [hep-ex/0309032](#) [hep-ex]
pdf links DOI cite claim reference search 2,938 citations

- LHCb:

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \rightarrow J/\psi K^- p$ Decays #1
LHCb Collaboration • Roel Aaij (CERN) et al. (Jul 13, 2015)
Published in: *Phys.Rev.Lett.* 115 (2015) 072001 • e-Print: [1507.03414](#) [hep-ex]
pdf links DOI cite claim reference search 2,129 citations

- Huge data sets often gave surprises, both in breadth and depth (likely same for FCC- ee)

FCC- ee data sets for flavor

- Production yields compared to Belle II goal: [2106.01259]

Particle production (10^9)	$B^0 + \bar{B}^0$	B^\pm	$B_s^0 + \bar{B}_s^0$	$\Lambda_b + \bar{\Lambda}_b$	B_c^\pm	$c\bar{c}$	$\tau^+\tau^-$
Belle II (50 ab^{-1})	27	27	tbd	—	—	65	45
tera- Z ($5 \times 10^{12} Z$)	600	600	150	130	3	600	170

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

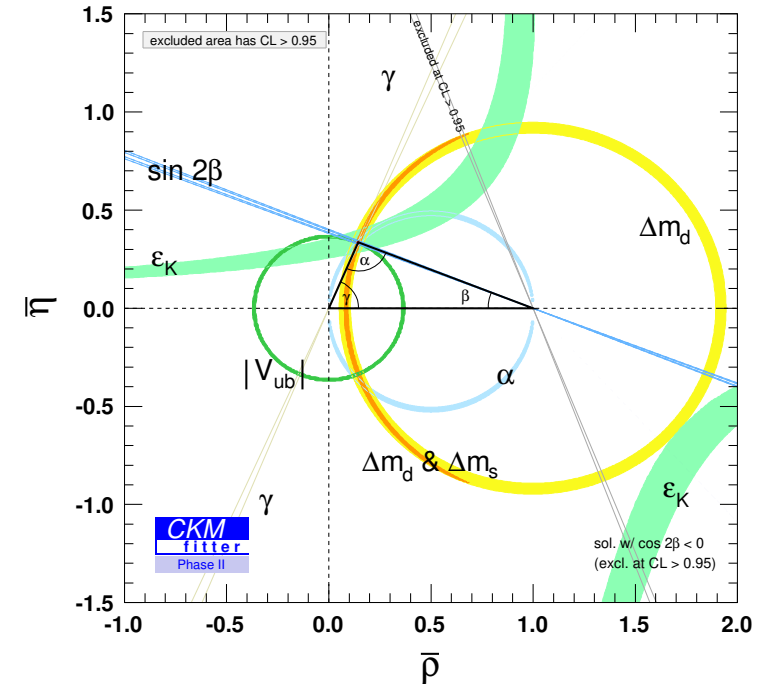
- WW threshold ($10^8 WW$): $W \rightarrow b\bar{c}$ can give a qualitatively new determination of $|V_{cb}|$
 Estimate 0.2% uncertainty, independent of B decays [Monteil @ 7th FCC Workshop, Jan 2024]; [2405.08880]
- $t\bar{t}$ threshold: m_t is a flavor parameter... can FCNC sensitivity surpass that of HL-LHC?

Flavor physics at FCC- ee

- $10^5 \times \text{LEP}$ is the right target (mass scale) \propto (uncertainty) $^{-1/2} \propto$ (stat) $^{-1/4}$
- Can one appreciate / anticipate a 10^5 improvement? (Recall: Belle II / ARGUS $\sim 10^5$)
Theory and experimental techniques both changed a lot! (e.g., full hadronic reconstruction)
Asymmetric B factories on $\Upsilon(4S)$ were devised for CP violation, less ideal for (semi)leptonic decays
- What was not even tried at LEP? (due to lack of statistics or lack of physics interest)
- Some rare decay sensitivities may improve linearly with statistics; e.g., $Z \rightarrow \mu\tau, \mu e$, etc.
- A lot of what's usually called precision electroweak, also concern flavor (τ lifetime & mass, R_b, R_ℓ for each ℓ flavor, etc.)

Towards theory at the per mille level

- Theory uncertainty of γ is negligible (2nd order EW)
World average $\gamma = (66.4 \pm 2.8)^\circ$
- Theory uncert. of everything else nontrivial at $\sim 1\%$ level
- Most precise so far: $\sin 2\beta = 0.710 \pm 0.011$ ($22.62 \pm 0.45)^\circ$
Precision of γ may overtake that of β
- Can the precision of β keep up with statistics?
There are claims of possibly large V_{ub} (“penguin”) contamination
- Which other measurements can reach such precision?
(Both theory and experiment)



[2006.04824 — expectation early 2040s]

$B_q \rightarrow J/\psi h$ using $SU(3)$ flavor

- Expand amplitudes: $A = (V_{cb}^* V_{cq}) (A_c^{(0)} + \varepsilon A_c^{(1)}) + (V_{ub}^* V_{uq}) A_u^{(0)} + \dots$
- $SU(3)$ flavor symmetry $\Rightarrow 5 A_c^{(0)}, 4 A_c^{(1)}, 3 A_u^{(0)}$ relations [ZL & Robinson, 1507.06671]
- 16 observables vs. 6 independent complex amplitudes: 1 $A_c^{(0)}$, 2 $A_c^{(1)}$, 3 $A_u^{(0)}$
- 4 relations when working to this order

-
- “New” relation: (might have been implicitly known)

$$S_{\psi K_S}^d - s_{2\beta} = -|V_{cd}/V_{cs}|^2 (c_{2\beta}/c_{2\beta_s}) (S_{\psi K_S}^s + s_{2\beta_s})$$
$$\Rightarrow S_{\psi K_S}^d - \sin 2\beta = 0.001 \pm 0.015$$

[ZL, Y. Nir, R. Schein, 2506.21675]

- Uncertainty can be reduced by better measurement of $S_{\psi K_S}^s$ in $B_s \rightarrow \psi K_S$ (Run 1 only!)

CP violation in $B^\pm \rightarrow \pi^\pm \pi^0$

- Direct CP asymmetry: $A_{CP}(B^\pm \rightarrow \pi^\pm \pi^0) = \frac{\Gamma(B^- \rightarrow \pi^- \pi^0) - \Gamma(B^+ \rightarrow \pi^+ \pi^0)}{\Gamma(B^- \rightarrow \pi^- \pi^0) + \Gamma(B^+ \rightarrow \pi^+ \pi^0)}$

World average: $A_{CP}(B^\pm \rightarrow \pi^\pm \pi^0) = -0.01 \pm 0.04$

- Theory: $A_{CP}(B^\pm \rightarrow \pi^\pm \pi^0) = 0$ in the “isospin limit”, however: [Grossman, ZL, Nir, 2605.04137]

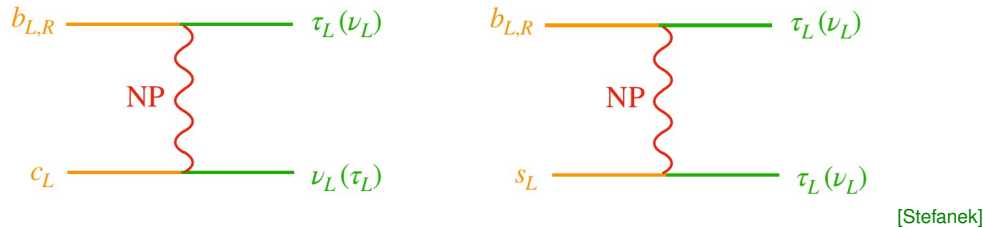
electroweak penguins, $\pi - \eta$ mixing, isospin violation in QCD penguins, $\Delta I = 5/2$

SM prediction: $A_{CP}(B^\pm \rightarrow \pi^\pm \pi^0) \sim 3 \times 10^{-3} \Rightarrow$ try to measure better!

- Understanding the accuracy of isospin relations in charmless B decays is important:
 - $A_{CP}(B^\pm \rightarrow \pi^\pm \pi^0)$ has direct implications for the extraction of α from $B \rightarrow \pi\pi$
 - May help understand the $K\pi$ puzzle (Gronau’s sum rule based on isospin)
 - $A_{CP}(D^\pm \rightarrow \pi^\pm \pi^0)$ may shed light on the puzzle regarding the large value of ΔA_{CP}

If BSM in $b \rightarrow c\tau\bar{\nu}$, must study $\nu\bar{\nu}$ & $\tau\tau$ modes

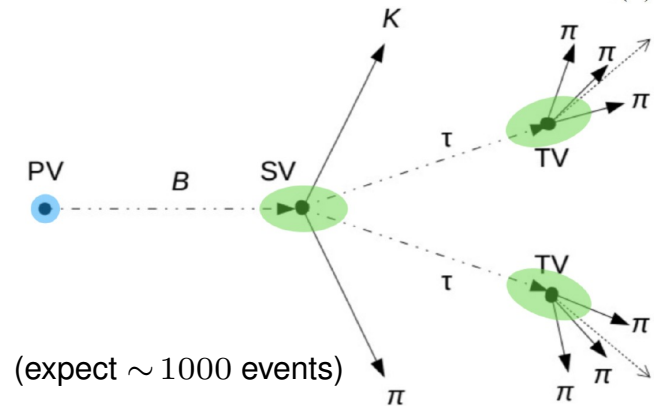
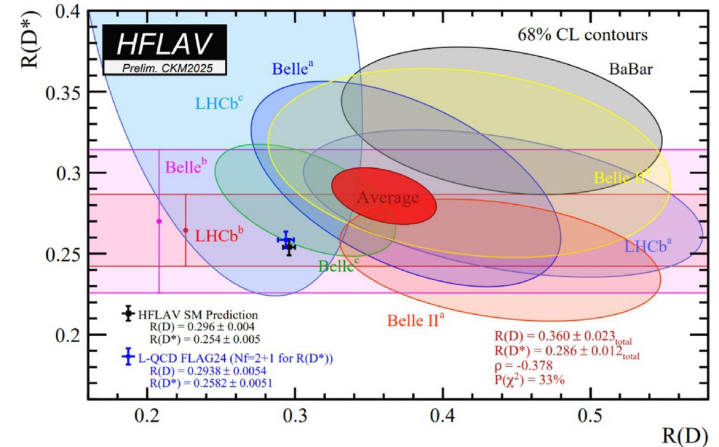
- SM and data in 3σ tension in $R(D^{(*)})$, if established, requires $\mathcal{O}(10\%)$ correction to a tree-level SM process
- If NP is charged under $SU(2)$, **unavoidable connection** to $b \rightarrow s\tau^+\tau^-$ or $b \rightarrow s\nu\bar{\nu}$ — correlations distinguish models



Only Z can measure $B \rightarrow K^*\tau^+\tau^-$, $K^*\nu\bar{\nu}$ at SM level

Belle II: $\mathcal{B}(B \rightarrow K^*\tau^+\tau^-) < 1.8 \times 10^{-3}$ (SM $\sim 10^{-6}$) [2504.10042]

- Boost of B in Z decay provides ideal environment



$B_{d,s} \rightarrow \mu^+ \mu^-$: interesting at all imaginable statistics

- $\mathcal{B}_{\text{SM}}(B_s \rightarrow \mu^+ \mu^-) \sim 3 \times 10^{-9}$, BSM predictions extended orders of magnitudes higher
- $\mathcal{B}_{\text{SM}}(B_d \rightarrow \mu^+ \mu^-) \sim 10^{-10}$, LHCb expects 10% (300/fb), CMS expects 15% (3/ab)

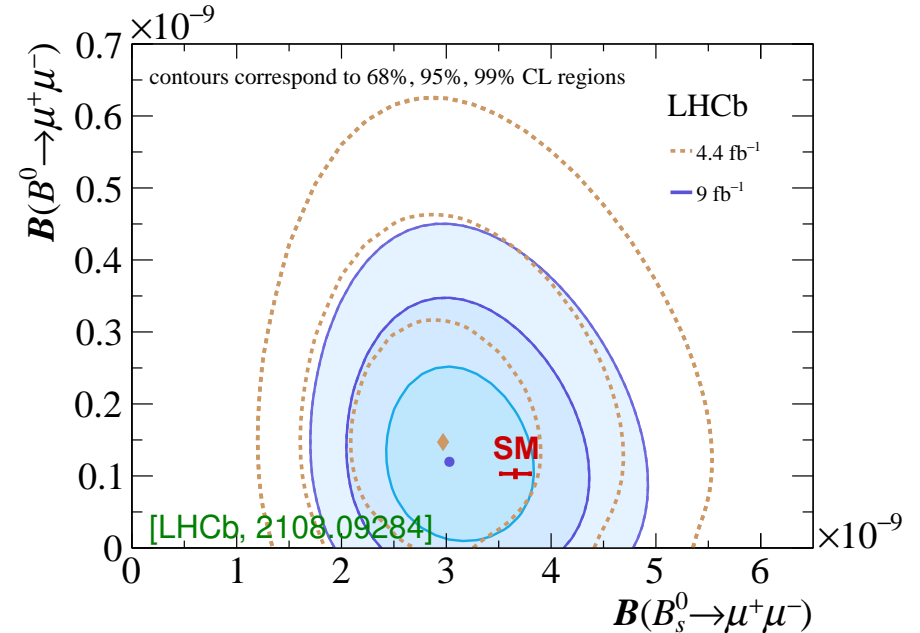
SM uncertainty $\simeq (2\%) \oplus f_{B_q}^2 \oplus \text{CKM}$, and may be further reduced

- Measure $|V_{ub}|$, using only isospin, from:

$$\mathcal{B}(B_u \rightarrow \ell \bar{\nu}) / \mathcal{B}(B_d \rightarrow \mu^+ \mu^-)$$

(Most precise $|V_{ub}|$... at FCC- hh statistics...?)

- A decay with mass-scale sensitivity (dim.-6 operator) that competes with $K \rightarrow \pi \nu \bar{\nu}$



PDG average:

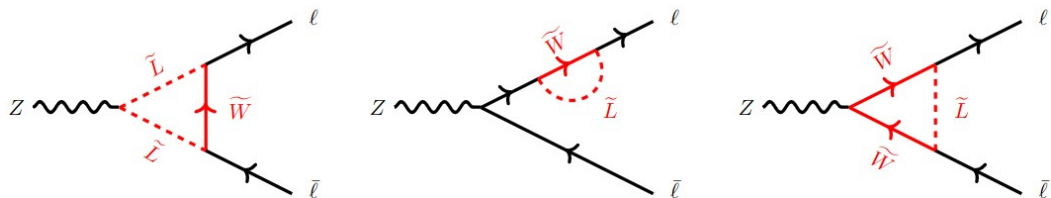
$$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) = (3.34 \pm 0.27) \times 10^{-9}$$

[LHCb, CMS, ATLAS]

Actual discovery potential? E.g., SUSY in $Z \rightarrow \ell^+ \ell^-$

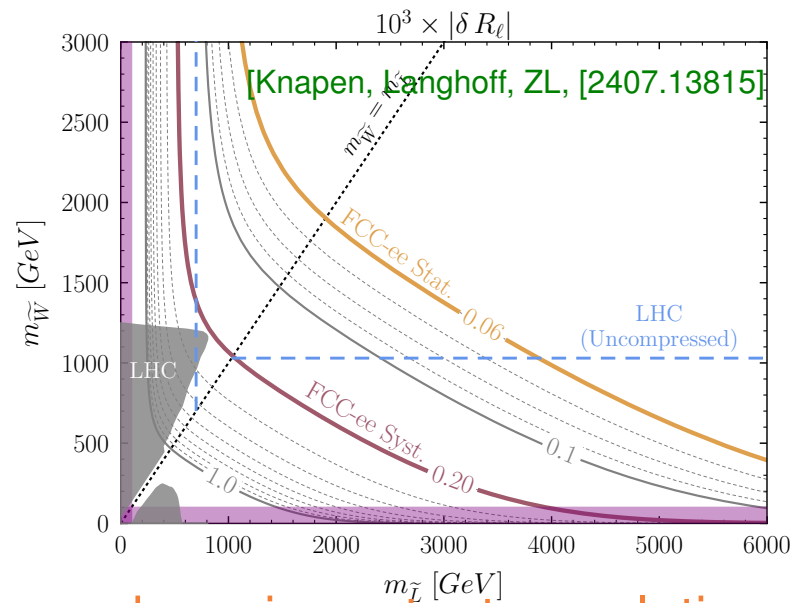
- Consider a SUSY simplified model: \tilde{q}, \tilde{g} heavy, only electroweakinos & sleptons light

- Measurement: $R_\ell = \frac{\Gamma_{\ell^+ \ell^-}}{\Gamma_{\text{hadrons}}}$
- | | | | | |
|--------------------------|---|-------------|------------------------|-----------------------------|
| $R_\ell^Z (\times 10^3)$ | 20767 ± 25 | 0.05 | 0.05 | Ratio of hadrons to leptons |
| | Systematic limitation in Midterm Report resolved by Feasibility Study | | Acceptance for leptons | |



- Ultimate sensitivity depends on $\alpha_s, \sin^2 \theta_w$, etc. Several measurements combined for best physics reach Even better sensitivity to flavor violating effects ($e/\mu/\tau$)

- Can probe beyond (or between) HL-LHC exclusions
- Complementary to SMEFT studies, a specific model may have important correlations



Final remarks

What are the largest useful data sets?

- No one has seriously explored it!
 - Many measurements will remain far from being limited by theory uncertainties:
 - For $\gamma \equiv \phi_3$, theory uncertainty only from higher order EW
 - $B_{s,d} \rightarrow \mu\mu$, $B \rightarrow \mu\nu$ and other leptonic decays (lattice QCD, [double] ratios)
 - $A_{\text{SL}}^{d,s}$ — will experimental systematics become limiting?
 - Lepton flavor violation & lepton universality violation searches
 - Dark sector searches, etc...
 - In some decays, even in 2040s we'll have (exp. bound)/SM $\gtrsim 10^3$ (E.g., $B_{d,s} \rightarrow e^+e^-$, $\tau^+\tau^-$)
 - NP sensitivity would improve with data \gg LHCb, Belle II, tera-Z
- \Rightarrow Case for an experiment to exploit flavor @ FCC- hh

Workshop advertisement



Physics at the Flavoured Circular Collider — Next workshop @ CERN: June 16–19

Goal: deepen understanding of the potential of the FCC for flavor physics

Conclusions

- Flavor physics probes scales $\gg 1$ TeV, sensitivity limited by statistics
New physics could show up any time when measurements improve
- There is much to be learned from future measurements at LHCb, Belle II, ATLAS, CMS
- If any of the tensions with SM becomes decisive \Rightarrow compelling case for largest statistics
- Interesting challenges both for experiment and theory to maximize sensitivity
Explosion of data always triggered unforeseen developments
- FCC- ee has very rich physics program, can be a discovery machine
In flavor physics, the only way to go well beyond Belle II and LHC(b)
- Clear reasons to aim for the largest data sets that technology may allow



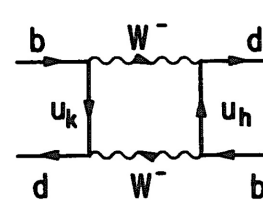
Extra slides

Constraints on NP parameters added to the SM

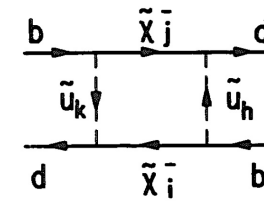
- In a large class of NP models, dominant contributions are to neutral meson mixing

- General parametrization of many scenarios by two real BSM parameters; redo CKM fit:

$$h e^{2i\sigma} = A_{\text{NP}}(B^0 \rightarrow \bar{B}^0) / A_{\text{SM}}(B^0 \rightarrow \bar{B}^0)$$



$$\text{SM: } \frac{C_{\text{SM}}}{m_W^2}$$



$$\text{NP: } \frac{C_{\text{NP}}}{\Lambda^2}$$

Tree-level decays dominated by SM, BSM only significant in FCNCs (loops)

- Is $h \gtrsim 1$ allowed? If not, then CKM mechanism is dominant

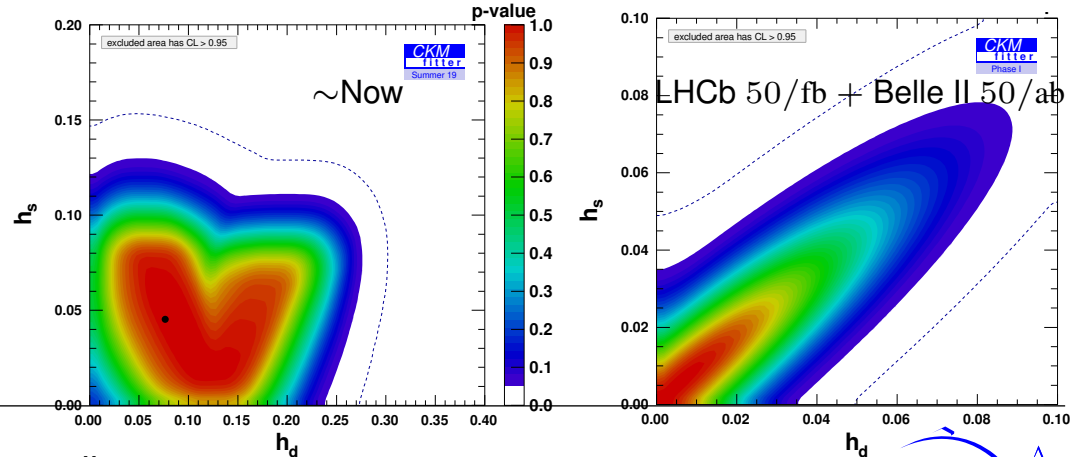
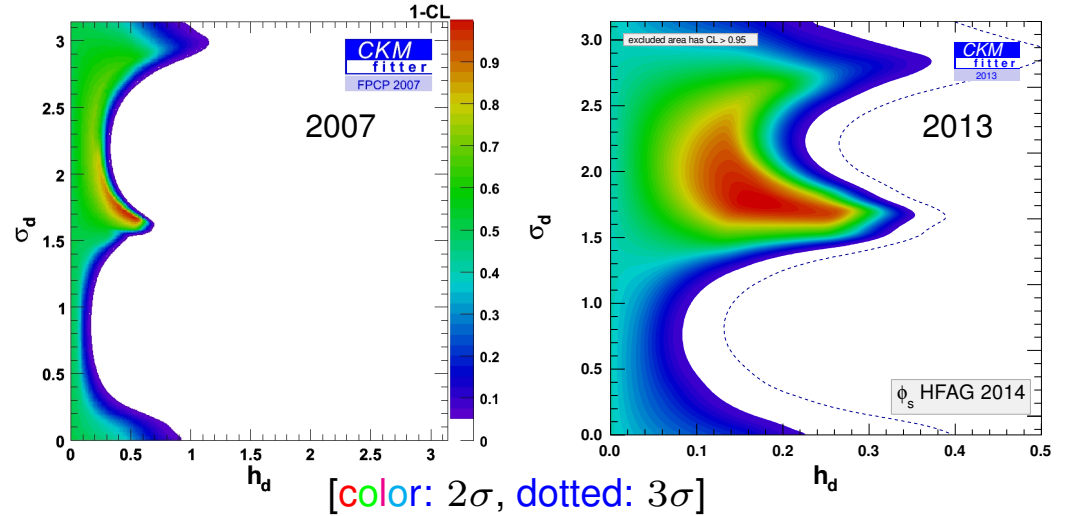
- E.g., for $\frac{C_{ij}}{\Lambda^2} (\bar{q}_{i,L} \gamma^\mu q_{j,L})^2$ operator: $h \simeq \frac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \left(\frac{4.5 \text{ TeV}}{\Lambda} \right)^2$, so $h < 0.08$ implies $\Lambda > \frac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \times 16 \text{ TeV}$

Evolving bounds on $h_{d,s}$

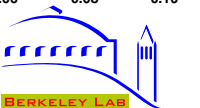
- CKM fit including $h_{d,s}$ and $\sigma_{d,s}$ param's:

$$h e^{2i\sigma} = A_{\text{NP}}(B^0 \rightarrow \bar{B}^0) / A_{\text{SM}}(B^0 \rightarrow \bar{B}^0)$$

- LHCb: BSM contributions to B_s mixing are constrained similar to those to B_d
- Weak interaction dominates observed CP violation: $\text{BSM}/\text{SM} \lesssim 20\%$
- Complementary to high- p_T searches (E.g., similar to HL-LHC $m_{\tilde{g}}$ reach)
- BSM sensitivity will continue to improve



ZL - p. ii



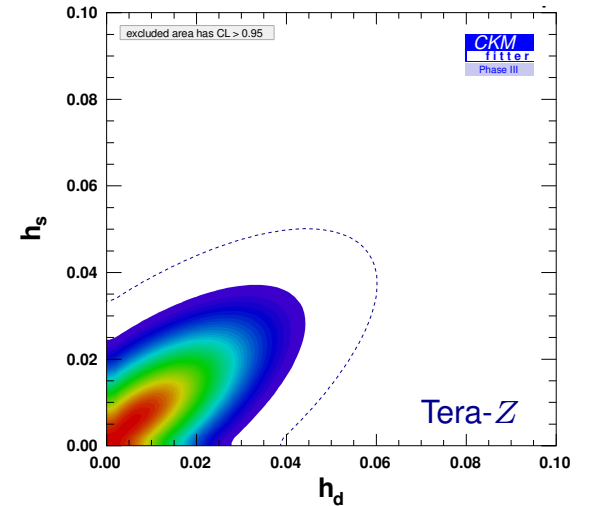
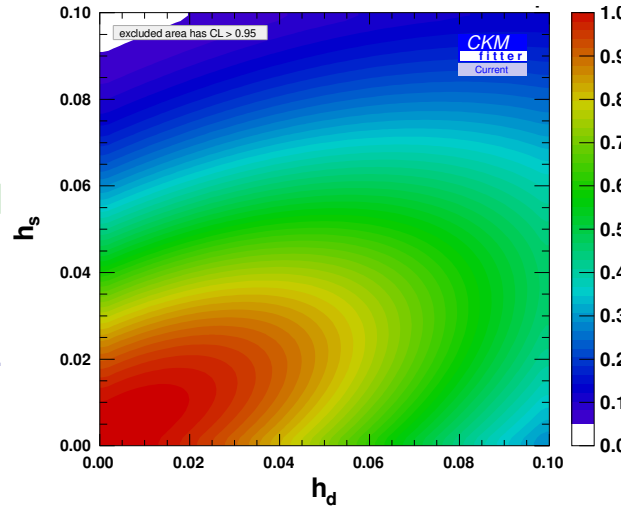
Sensitivity to new physics in B mixing

- In many BSM scenarios, dominant deviations from SM may be in neutral meson mixing

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

General parametrization: $h e^{2i\sigma} = A_{\text{NP}}(B^0 \rightarrow \bar{B}^0)/A_{\text{SM}}(B^0 \rightarrow \bar{B}^0)$ ($h_{d,s}, \sigma_{d,s}$: NP param's)

- CKM fit with 4 BSM param's added; combines many measurements and theory inputs [Charles *et al.*, 2006.04824] (\Rightarrow conservative view of future progress)



- $|V_{cb}|$ becomes a bottleneck; Tera-Z sensitivity will be better (no LQCD extrapolations)

4 relations for $B_q \rightarrow J/\psi h$ at this order

- $A_{\psi K^+}/A_{\psi \pi^+} = -|V_{cd}/V_{cs}|^2$
- $C_{\psi K^0}^d/C_{\psi \bar{K}^0}^s = -|V_{cd}/V_{cs}|^2$
- $(1 + \bar{\lambda}^2)s_{2\beta} = S_{\psi K_S}^d - \bar{\lambda}^2 S_{\psi \pi}^d - 2(\Delta_K + \bar{\lambda}^2 \Delta_\pi)c_{2\beta} \tan \gamma + \mathcal{O}(\varepsilon R_u \bar{\lambda}^2, R_u^2 \bar{\lambda}^2, \delta)$ [1507.06671]

where: $\Delta_K = \frac{\Gamma(B_d \rightarrow \psi K^0) - \Gamma(B^+ \rightarrow \psi K^+)}{\Gamma(B_d \rightarrow \psi K^0) + \Gamma(B^+ \rightarrow \psi K^+)}$, $\Delta_\pi = \frac{2\Gamma(B_d \rightarrow \psi \pi^0) - \Gamma(B^+ \rightarrow \psi \pi^+)}{2\Gamma(B_d \rightarrow \psi \pi^0) + \Gamma(B^+ \rightarrow \psi \pi^+)}$

$\Rightarrow \sin 2\beta - S_{\psi K_S}^d = 0.05 \pm 0.03$ (+ issues of production asym vs. isospin violation [2306.04686])
- “New” relation: (might have been implicitly known?)

$S_{\psi K_S}^d - s_{2\beta} = -|V_{cd}/V_{cs}|^2 (c_{2\beta}/c_{2\beta_s}) (S_{\psi K_S}^s + s_{2\beta_s})$ [ZL, Y. Nir, R. Schein, 2506.21675]

$\Rightarrow S_{\psi K_S}^d - \sin 2\beta = 0.001 \pm 0.015$
- Uncertainty can be reduced by better measurement of $S_{\psi K_S}^s$ in $B_s \rightarrow \psi K_S$ (Run 1 only!)

Theory challenges / opportunities

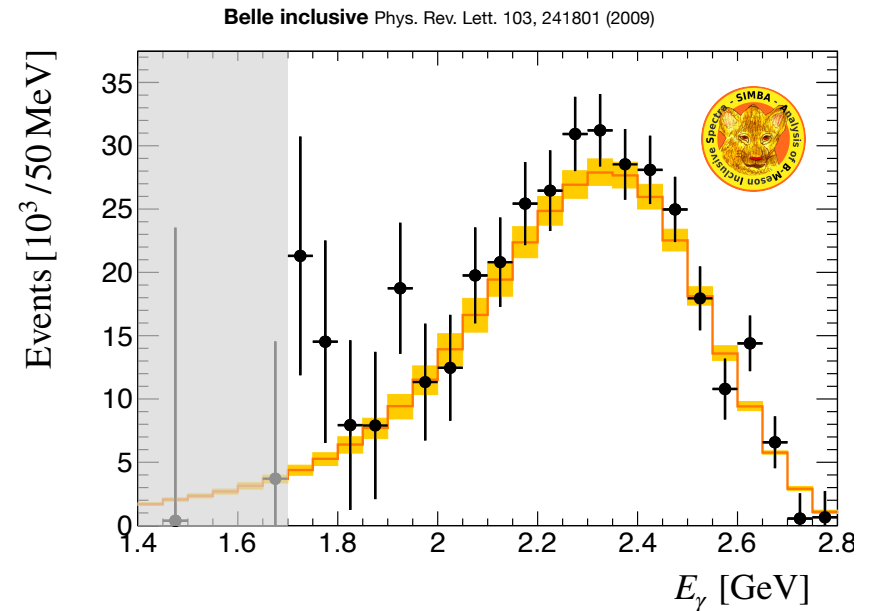
- **New methods & ideas:** recall that the most precise α and γ measurements are in modes proposed in light of Belle & BaBar data
 - Better SM upper bounds on $S_{\eta'K_S} - S_{\psi K_S}$, $S_{\phi K_S} - S_{\psi K_S}$, and $S_{\pi^0 K_S} - S_{\psi K_S}$
And similarly in B_s decays, and for $\sin 2\beta_{(s)}$ itself
 - How big can CP violation be in $D^0 - \bar{D}^0$ mixing (and in D decays) in the SM?
 - Many lattice QCD calculations (operators within and beyond SM)
 - Better understanding of 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?**

Another FCNC, $B \rightarrow X_s \gamma$

- Maybe the most complex SM calculation; develop EFTs and RGEs, multi-loop techniques, SCET
Exp. & theor. uncertainty small in different regions
- Extract from global fit short-distance and hadronic parameters (shape functions) fully consistently
[Bernlochner, Lacker, ZL, Stewart, Tackmann, Tackmann, 2007.04320]
- **SIMBA**: Consistent theory across E_γ spectrum
Model-independent treatment of shape fn.

$$|C_7^{\text{incl}} V_{tb} V_{ts}| = (14.77 \pm 0.51_{\text{fit}} \pm 0.59_{\text{theory}} \pm 0.08_{\text{param}}) \times 10^{-3}$$

$$m_b^{1S} = (4.750 \pm 0.027_{\text{fit}} \pm 0.033_{\text{theory}} \pm 0.003_{\text{param}}) \text{ GeV}$$



We find underestimated uncertainty by HFLAV
 \Rightarrow more room for NP

CP violation in D decays and mixing

- CP violation in D decays:

LHCb, Nov. 2011: $\Delta A_{CP} \equiv A_{K^+K^-} - A_{\pi^+\pi^-} = -(8.2 \pm 2.4) \times 10^{-3}$ (I think a stretch in the SM)

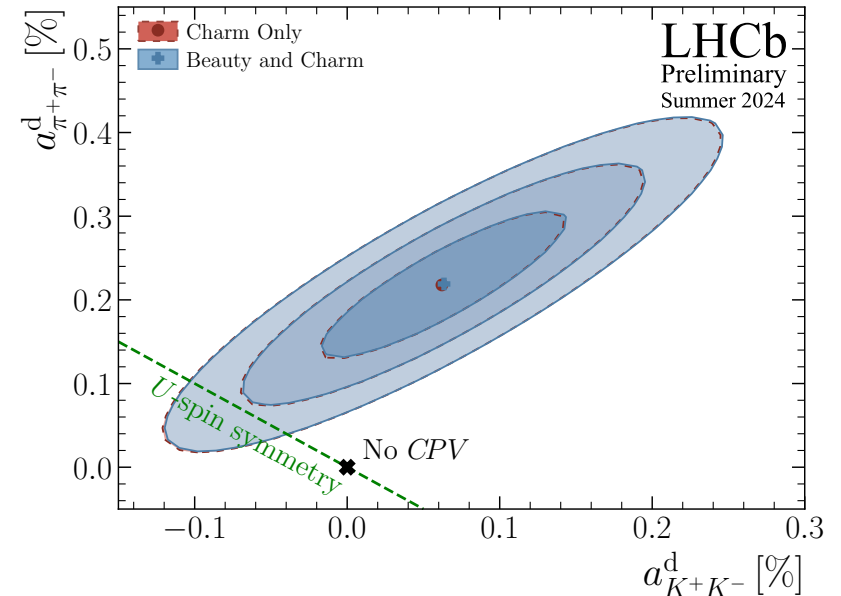
LHCb, Mar. 2019: $\Delta A_{CP} = -(1.82 \pm 0.33) \times 10^{-3}$ [1903.08726]

- What is the maximal CPV that could be due to SM?

CKM factors: $|V_{cb}V_{ub}/(V_{cd}V_{ud})| \simeq 7 \times 10^{-4}$

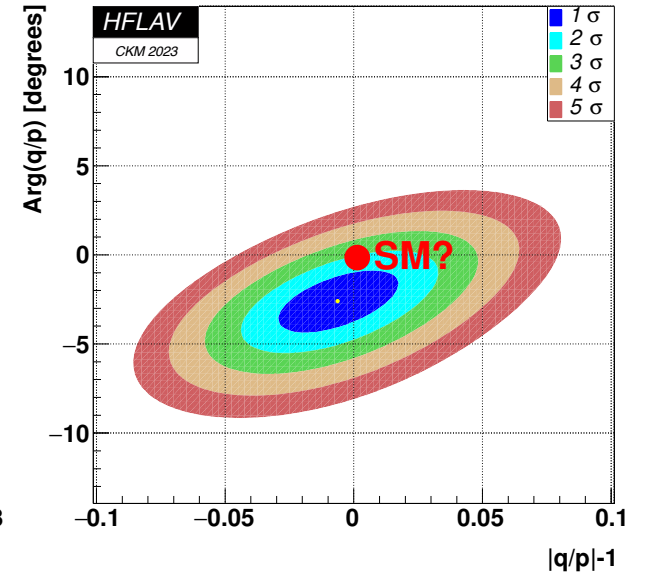
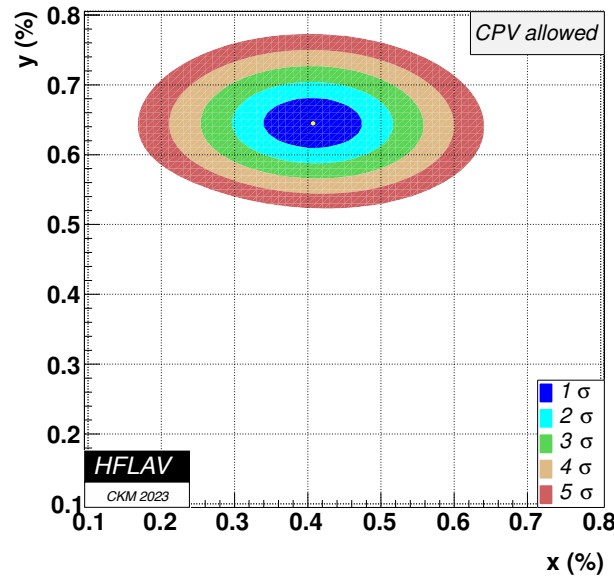
Before measurements, most theory papers stated (assumed) that strong interaction suppresses CPV further

- Can we establish if CP violation in decay or mixing (more “inclusive”) could still probe BSM?



CP violation in $D - \bar{D}$ mixing

- Mixing generated by down quarks
- **SUSY**: up-type squarks in box diagrams, interplay of D & K bounds \Rightarrow alignment, universality, heavy squarks?
- Connections to FCNC top decays
- **Only learned recently**: $x/y = \mathcal{O}(1)$
(Only in 2021 was $\Delta m \neq 0$ established at $> 3\sigma$)
- **Very high scales probed, further improvements expected**



CP violation in $B_{d,s}$ mixing: $A_{SL}^{d,s}$

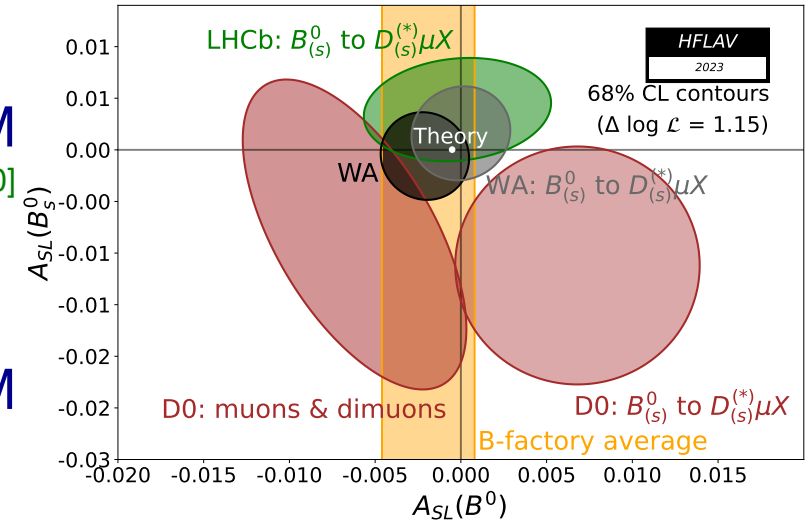
- Only observed in Kaons

$B_{(s)}$: SM suppressed by m_c^2/m_b^2 , may be lifted by BSM

[hep-ph/0202010]

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

Plenty of room between current sensitivity and SM predictions (not yet known if LHCb becomes syst. limited)



- Current status: Exp: $A_{SL}^d = -(2.1 \pm 1.7) \times 10^{-3}$ $A_{SL}^s = -(0.6 \pm 2.8) \times 10^{-3}$
SM: $A_{SL}^d = -(4.7 \pm 0.6) \times 10^{-4}$ $A_{SL}^s = (2.22 \pm 0.27) \times 10^{-5}$ [1603.07770]
- Unique to Tera-Z: uncertainty $\sim 2.5 \times 10^{-5}$ for both A_{SL}^d and A_{SL}^s , reach SM level

Aside: why not do this in SMEFT?

- Operator analysis (Lorentz invariance, not adding ν_R):

$$(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu), (\bar{c}\gamma_\mu P_R b)(\bar{\tau}\gamma^\mu P_L \nu), (\bar{c}P_R b)(\bar{\tau}P_L \nu), (\bar{c}P_L b)(\bar{\tau}P_L \nu), (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu)$$

Whether b, τ, c in L - or R -handed fields, connection to $b \rightarrow s\tau^+\tau^-, b \rightarrow s\nu\bar{\nu}, t \rightarrow c\tau^+\tau^-$

2nd and 5th terms can only arise from dim-8 \Rightarrow often neglected

Connection to different generation transitions, only if some flavor structure is imposed

- Semileptonic operators ($l\bar{l}q\bar{q}$) are a large fraction of the operator basis:

SMEFT: 1053 semileptonic operators, 42% of the 2499 parameters of the dim-6 B & L conserving terms in the 3-generation SMEFT (558 CP -even, 495 CP -odd) [\[2402.09535\]](#)

LEET: 1944 semileptonic param's, 54% of the 3631 terms (1017 CP -even, 927 CP -odd)

Similar decay of kaons: $K \rightarrow \pi \nu \bar{\nu}$

- Kaon CPV is at the right level (can fit ϵ_K with KM phase, but ϵ'_K notoriously hard)

- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ searched for since 1960s (longer than Higgs), sensitive to 100 TeV scale

Irreducible theory uncertainty few % (& $|V_{cb}|^4$)

- Recently: first $> 5\sigma$ observation [NA62, 2412.12015]

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$$

Consistent with SM ($\approx 8 \times 10^{-11}$), at 1.7σ

- KOTO: $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 2 \times 10^{-9}$

