Flavor physics: past to future

(from BaBar & Belle to FCC)

Zoltan Ligeti

Color meets Flavor

Bad Honnef Physics School

March 17 – 22, 2024

Flavor physics: past to future

(from BaBar & Belle to FCC)

(from ARGUS to FCC)

Zoltan Ligeti

Color meets Flavor

Bad Honnef Physics School

March 17 – 22, 2024

Preliminaries

- I've never given an after dinner talk...
- The best I heard in physics: Danilov @ DESY (20th anniv. of $B^0 - \overline{B}^0$ oscillations)

"... derived a theory for the dependence of the collaboration efficiency on the organizational level. There are two obvious limits. With perfect organization the efficiency is zero. In Russia such a situation is called an Italian strike. When people fulfill all instructions everything stops to work. Another limit of zero organization has a reasonable efficiency ... Since the behavior of the efficiency at intermediate values of the organizational level was unknown we tried to be close to the familiar point of zero organization."

"ARGUS had no constitution, no Collaboration Board, no elections. Instead of Collaboration board meetings we had regular Collaboration parties and the result was excellent."

"The spokesman should not disturb good people when they are working and should defend them from bad people." "... the good human relations were the main ARGUS achievements."

- Also, J. Dorfan at BaBar's 30th (10 days ago), "Bottom line – it's about the people"

B mixing and CP violation were unexpected

PROPOSAL FOR K^o_2 DECAY AND INTERACTION EXPERIMENT

J. W. Cronin, V. L. Fitch, R. Turlay

(April 10, 1963)

I. INTRODUCTION

The present proposal was largely stimulated by the recent anomalous results of Adair et al., on the coherent regeneration of K^o_1 mesons. It is the purpose of this experiment to check these results with a precision far transcending that attained in the previous experiment. Other results to be obtained will be a new and much better limit for the partial rate of $K^o_2 \to \pi^+ + \pi^-$, a new limit for the presence (or absence) of neutral currents as observed through $K_2 \to \mu^+ + \mu^-$. In addition, if time permits, the coherent regeneration of K_1's in dense materials can be observed with good accuracy.

II. EXPERIMENTAL APPARATUS

Fortuitously the equipment of this experiment already exists in operating condition. We propose to use the present 30° neutral beam at the A.G.S. along with the di-pion detector and hydrogen target currently being used by Cronin, et al. at the Cosmotron. We further propose that this experiment be done during the forthcoming μ-p scattering experiment on a parasitic basis.

The di-pion apparatus appears ideal for the experiment. The energy resolution is better than 4 Mev in the m^* or the Q value measurement. The origin of the decay can be located to better than 0.1 inches. The 4 Mev resolution is to be compared with the 20 Mev in the Adair bubble chamber. Indeed it is through the greatly improved resolution (coupled with better statistics) that one can expect to get improved limits on the partial decay rates mentioned above.

III. COUNTING RATES

We have made careful Monte Carlo calculations of the counting rates expected. For example, using the 30° beam with the detector 60-ft. from the A.G.S. target we could expect 0.6 decay events per 10^{11} circulating protons if the K_2 went entirely to two pions. This means that one can set a limit of about one in a thousand for the partial rate of $K_2 \to 2\pi$ in one hour of operation. The actual limit is set, of course, by the number of three-body K_2 decays that look like two-body decays. We have not as yet made detailed calculations of this. However, it is certain that the excellent resolution of the apparatus will greatly assist in arriving at a much better limit.

If the experiment of Adair, et al. is correct the rate of coherently regenerated K_1's in hydrogen will be approximately 80/hour. This is to be compared with a total of 20 events in the original experiment. The apparatus has enough angular acceptance to detect incoherently produced K_1's with uniform efficiency to beyond 15°. We emphasize the advantage of being able to remove the regenerating material (e.g., hydrogen) from the neutral beam.

IV. POWER REQUIREMENTS

The power requirements for the experiment are extraordinarily modest. We must power one 18-in. x 36-in. magnet for sweeping the beam of charged particles. The two magnets in the di-pion spectrometer are operated in series and use a total of 20 kw.

⇒ Cronin & Fitch, Nobel Prize, 1980

⇒ 3 generations, Kobayashi & Maskawa, Nobel Prize, 2008

Factor-of-two improvements can matter!

ANNALS OF PHYSICS: 5, 156–181 (1958)

Long-lived Neutral K Mesons*

M. BARDON, K. LANDE, AND L. M. LEDERMAN

Columbia University, New York, New York, and Brookhaven National Laboratories, Upton, New York

AND

WILLIAM CHINOWSKY

Brookhaven National Laboratories, Upton, New York

set an upper limit <0.6% on the reactions

$$K_2^0 \to \begin{cases} \mu^{\pm} + e^{\mp} \\ e^+ + e^- \\ \mu^+ + \mu^- \end{cases}$$

and on $K_2^0 \to \pi^+ + \pi^-$.

VOLUME 6, NUMBER 10 PHYSICAL REVIEW LETTERS MAY 15, 1961

DECAY PROPERTIES OF K_2^0 MESONS*

D. Neagu, E. O. Okonov, N. I. Petrov, A. M. Rosanova, and V. A. Rusakov
Joint Institute of Nuclear Research, Moscow, U.S.S.R.
(Received April 20, 1961)

Combining our data with those obtained in reference 7, we set an upper limit of 0.3% for the relative probability of the decay $K_2^0 \to \pi^- + \pi^+$. Our

"At that stage the search was terminated by administration of the Lab."

[Okun, hep-ph/0112031]

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R = (K_2 \to \pi^+ + \pi^-)/(K_2^0 \to \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ where the error is the standard deviation. As empha-

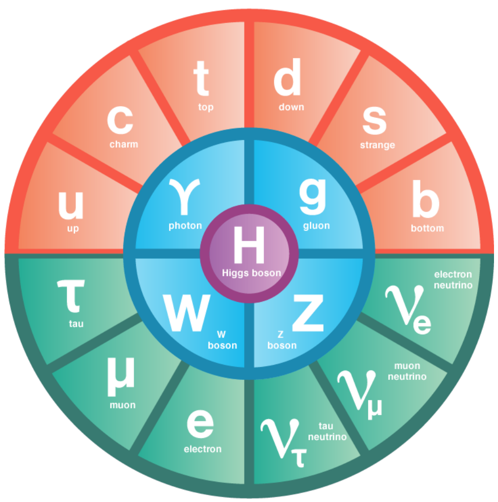
What is particle physics?

- Central question: What are the elementary degrees of freedom and interactions?

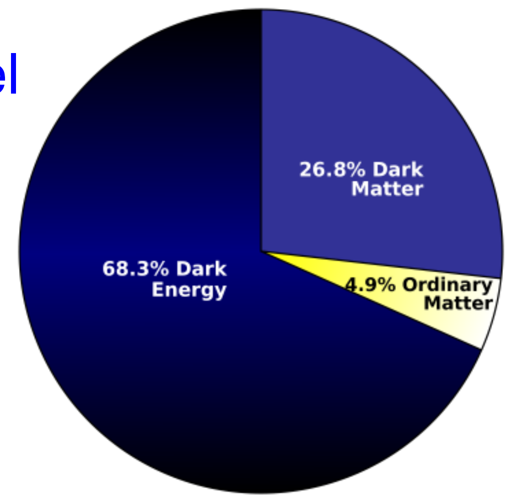
$$\mathcal{L} = ?$$

- Most experimentally observed phenomena consistent with the “standard model”

- Standard Model of particle physics:



Standard Model of cosmology:



- Inconsistent: Two very successful theories, but this cannot be the full story

What is particle physics?

- Central question: What are the elementary degrees of freedom and interactions?

$$\mathcal{L} = ?$$

- Most experimentally observed phenomena consistent with the "standard model"

- Clearest observational evidence that the SM is incomplete:
  - Neutrino mass
  - Baryon asymmetry
  - Dark matter
  - Inflation in the early universe [have a plausible theoretical picture]
  - Dark energy [cosmological constant? need to know more to understand?]

Why is flavor physics interesting?

- 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 BSM models have observable signals (new CP and flavor viol.)

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

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

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

  (Recall $H \to \mu\tau$ anomaly around 2015)

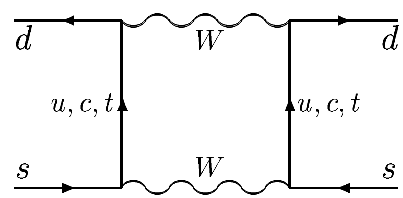
- Baryogenesis remains a puzzle, requires additional CP violation

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)
  - $\epsilon_K \Rightarrow$ 3rd generation (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 the SM — what can future data tell us about BSM physics?

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

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: many "standalone" discovery modes)

Some key questions

- Will LHC see NP beyond the Higgs?
- Are Higgs couplings SM-like? How precisely?
- Will NP be seen in the quark sector? (Current data: hints of possible deviations from SM)
- 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: Does 3 flavor paradigm hold? What is the nature of ν mass?
- Will DM be discovered? Axions? EDMs? Something else?

- No one knows — an exploratory era!

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

(NB: 2 generations $+$ superweak is "more minimal" to accommodate CPV, than 3 generations!)

Outline

- Lepton flavor: basic open questions

  Observing CLFV would jumpstart broader program

- Quarks

  BSM sensitivity in neutral meson mixing

  “Anomalies” and $|V_{cb}|$

  Charm, kaons, exotic searches, richness of directions

- Quarks – far future:

  LHCb & Belle II upgrades

  Importance of flavor probes at future colliders

Lepton flavor

Neutrino oscillation measurements

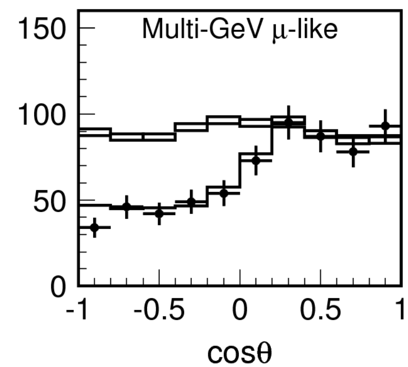
- Three mixing angles have been measured
- Oscillation between two flavors $(\delta m^2 = m_1^2 - m_2^2)$

$$P_{\rm osc} = \sin^2(2\theta)\ \sin^2\left(1.27\,\frac{\delta m^2}{\rm eV^2}\,\frac{L}{\rm km}\,\frac{\rm GeV}{E}\right)$$

- Solar neutrinos: $\delta m^2\, L/E \gg 1$
- Atmospheric neutrinos:

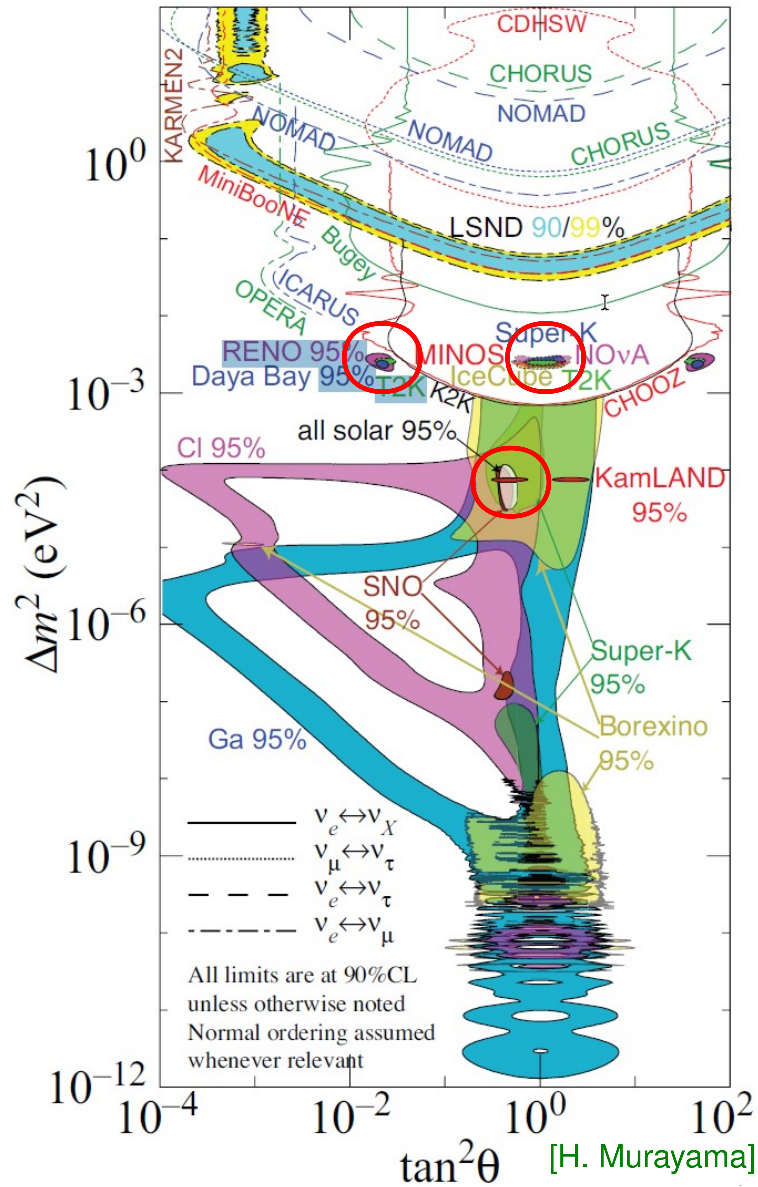
$1 \sim (10^{-3}) \times (10^{1\ldots4})\ /\ (10^{0\pm1})$

half of up-going ν_μ get lost



- Two mass-squared differences are measured, but not the absolute mass scale

(Short baseline anomalies not easy to fit, e.g., w/ 4 flavors)



[H. Murayama]

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Neutrinos — many unknowns

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

$$\mathcal{L}_Y = -Y_e^{ij}\,\overline{L_{Li}^I}\,\phi\,e_{Rj}^I - \begin{cases} \frac{Y_\nu^{ij}}{\Lambda}\,L_{Li}^I L_{Lj}^I\,\phi\,\phi & \text{violates lepton number} \\ Y_\nu^{ij}\,\overline{L_{Li}^I}\,\tilde{\phi}\,\nu_{Rj}^I & \text{requires } \nu_R \text{ fields} \end{cases}$$

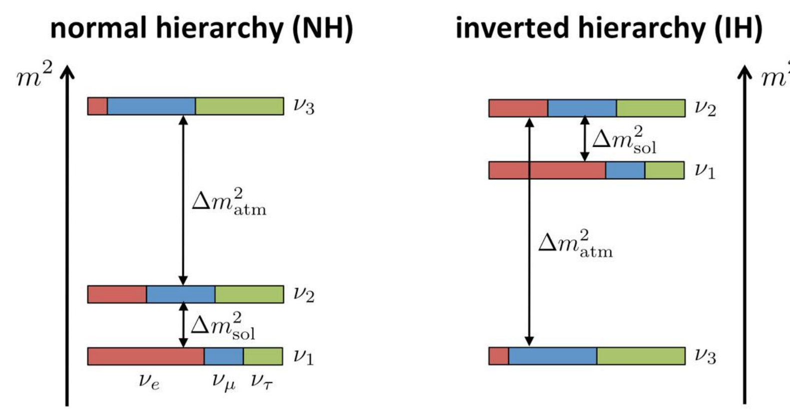
  Are neutrinos their own antiparticles? (favored by theory, most leptogenesis models, but not known)

  Does mixing matrix contain 4 (as for quarks) or 6 parameters?

- What is the absolute mass scale?

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

  Cosmology: $\sum m_i < 0.12 - 0.3\,\mathrm{eV}$ [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 ?

Neutrinos — a history of surprises

- Most theorists' expectations up to 1990s:
  - Solar neutrino problem will go away, we do not understand the Sun — Wrong
  - If it does not, solution must be small angle MSW (cute, similar to quarks) — Wrong
  - Expect $\Delta m^2_{23} \sim 10 - 100\text{eV}^2$, since it's cosmologically interesting — Wrong
  - Expect $\theta_{23} \sim V_{cb} \simeq 0.04$, motivated by simplest GUTs — Wrong
  - Atmospheric neutrino anomaly will go away, because it requires large mixing angle — the first that became compelling (⇒ Nobel, 2002) — Wrong
  - Tribimaximal mixing ansatz predicted θ_{13} near zero — Wrong

    $\sin^2 2\theta_{13} \sim 0.1$ not too small — helps CP violation searches
- Experiments crucial, independent of prevailing theoretical "guidance"

Lepton and quark mixing

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

$$|U_{\rm PMNS}| = \begin{pmatrix} 0.824 \pm 0.007 & 0.546 \pm 0.011 & 0.149 \pm 0.002 \\ 0.371 \pm 0.042 & 0.598 \pm 0.032 & 0.700 \pm 0.023 \\ 0.395 \pm 0.041 & 0.573 \pm 0.033 & 0.692 \pm 0.023 \end{pmatrix}$$

[νfit 2022, 3σ, converted]

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

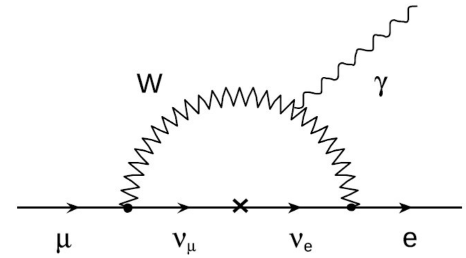
[PDG 2022]

- 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?

FCNC involving leptons

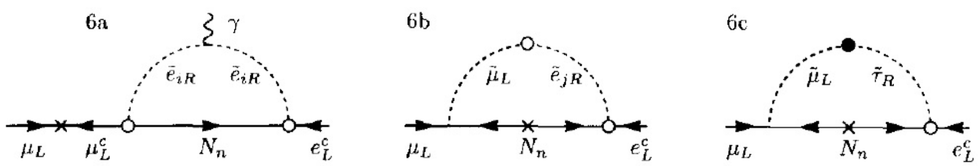
- SM w/ $m_\nu = 0 \Rightarrow$ lepton flavor conservation

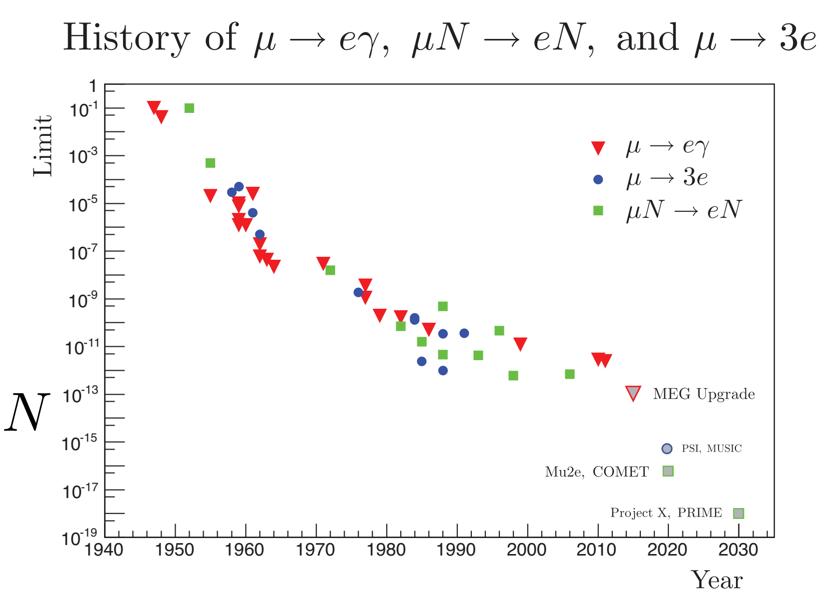
  Given $m_\nu \neq 0$, no reason to impose it as a symmetry



$$\mathcal{B}(\mu \to e\gamma) \sim \alpha \, \frac{m_\nu^4}{m_W^4} \sim 10^{-52}$$

- If new TeV-scale particles carry lepton number (e.g., sleptons), their own mixing matrices $\Rightarrow$ charged lepton flavor violation





- Many interesting processes:

  Historically best: $\mu \to e\gamma, \ \mu \to eee$

  Mu2e, COMET: $\mu \to e$ conversion, $\mu + N \to e + N$

  τ decays to: $\mu\gamma, \ e\gamma, \ \mu\mu\mu, \ \mu\mu e, \ \mu ee, \ \mu\pi$, etc.

- Next 10–20 years: 10^2–10^4 improvement; any signal would trigger broad program

Operators, patterns, connections

- 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: $\frac{m_\mu}{\Lambda^2} \, \bar{\mu} \sigma_{\alpha\beta} F^{\alpha\beta} e \,, \quad \frac{m_\mu}{\Lambda^2} \, \bar{\mu} \sigma_{\alpha\beta} F^{\alpha\beta} \mu$

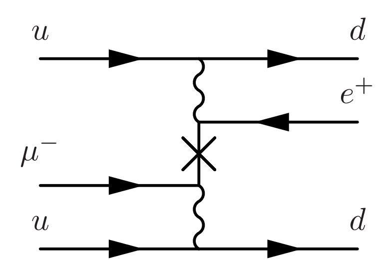
  If coefficients are comparable, $\mu \to e\gamma$ gives much stronger bound already

  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 $|m_{ee}| = |\Sigma_{i=1}^3 \, m_i \, U_{ei}^2|$



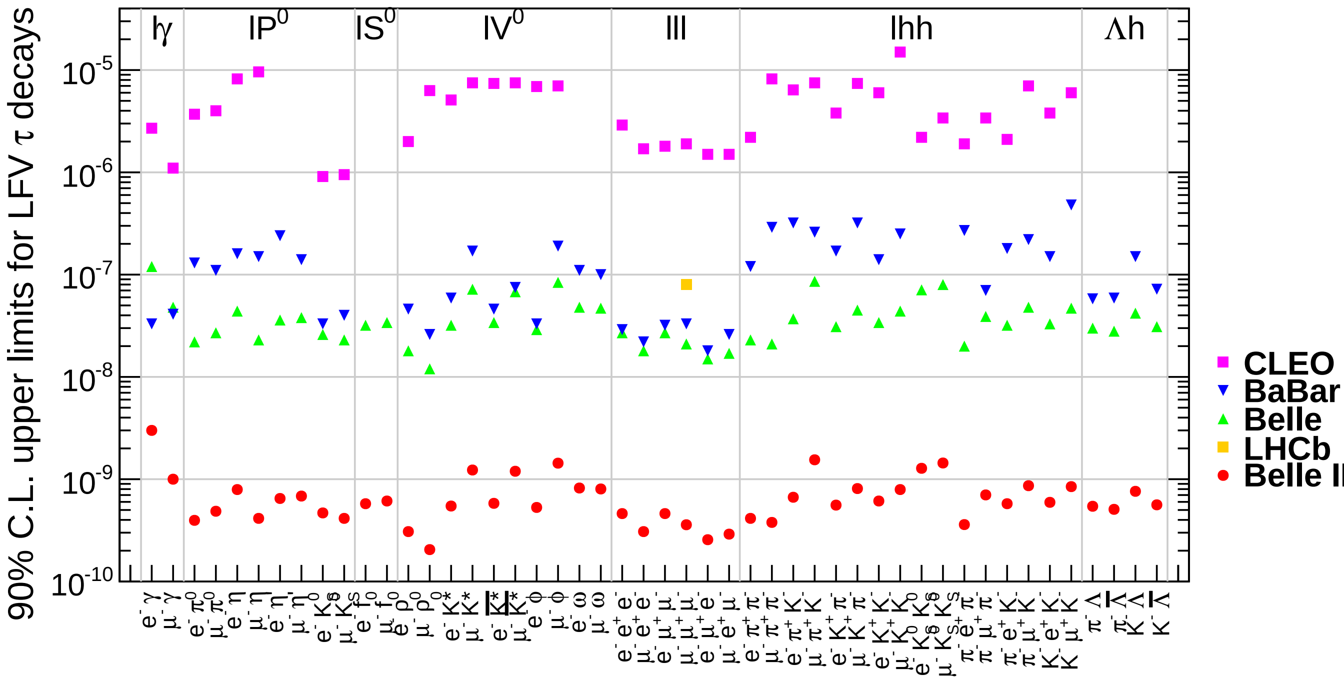
- Patterns would tell us about underlying structures

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

CLFV τ decays at Belle II

- Belle II will improve sensitivity by 2 orders of magnitude, e.g., $\tau \to \mu\gamma, \mu\mu\mu$, etc.



E.g., $\mathcal{B}(\tau \to \mu\gamma)/\mathcal{B}(\mu \to e\gamma) \sim 10^{4\pm3}$ — either can "win", big model dependence

- FCC would yield another major improvement

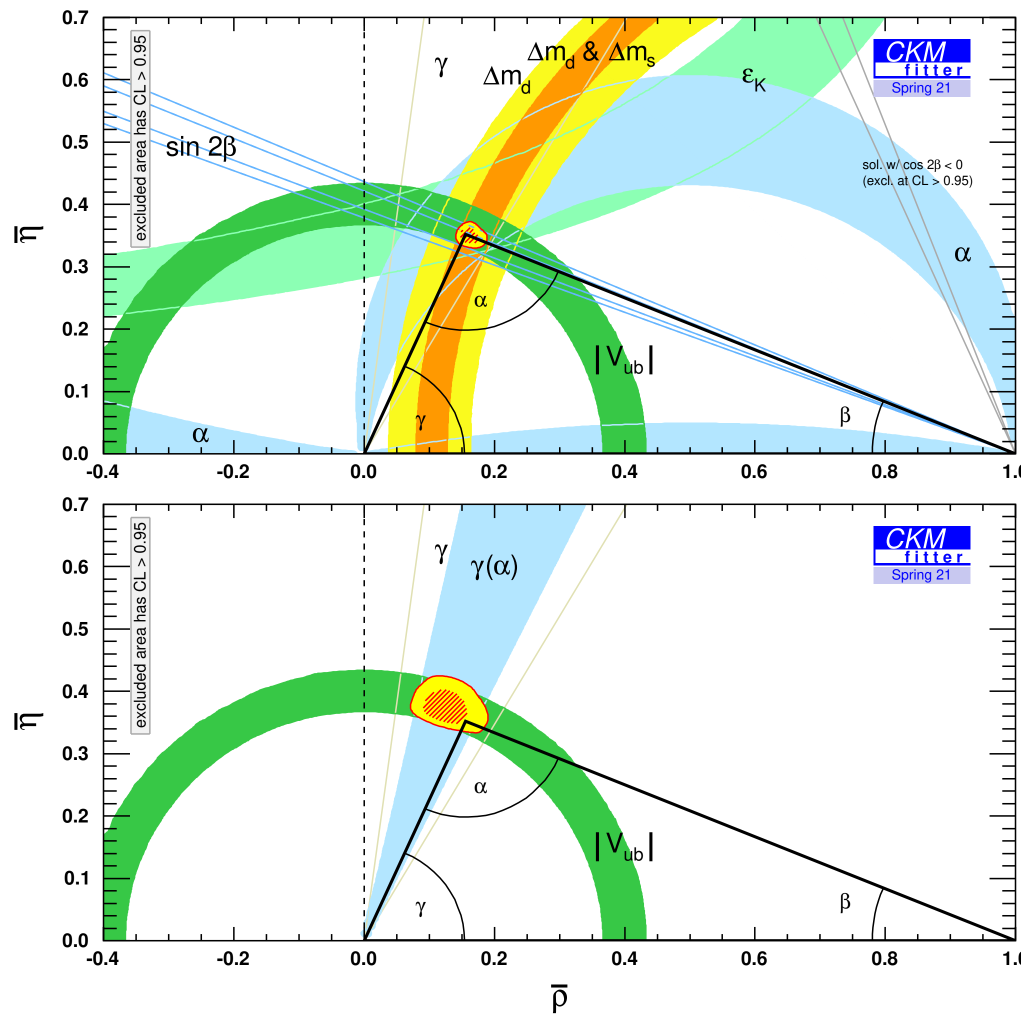
- Any discovery $\Rightarrow$ broad program to map out the detailed structure

Quarks: BSM sensitivity in mixing

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



- $(10-20)\%$ NP contributions to most loop-level processes (FCNC) are still allowed

The Nobel Prize in Physics 2008

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Photo: SCANPIX

Yoichiro Nambu

Photo: Kyodo/Reuters

Makoto Kobayashi

Photo: Kyoto University

Toshihide Maskawa

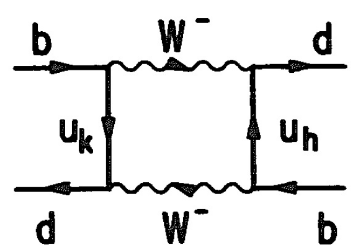
New physics in B mixing

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

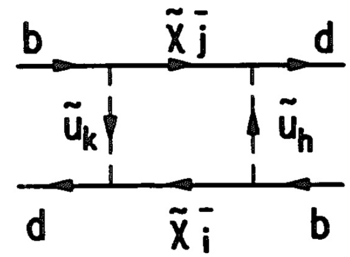
General parametrization of many models
by two real parameters (in addition to SM):

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

↖ ↑ 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 $C_{\rm SM}$?

- Only in 2004 (first α, γ measurements) was $h < 1$ established, i.e., BSM $<$ SM

Relies on many measurements and theoretical inputs

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

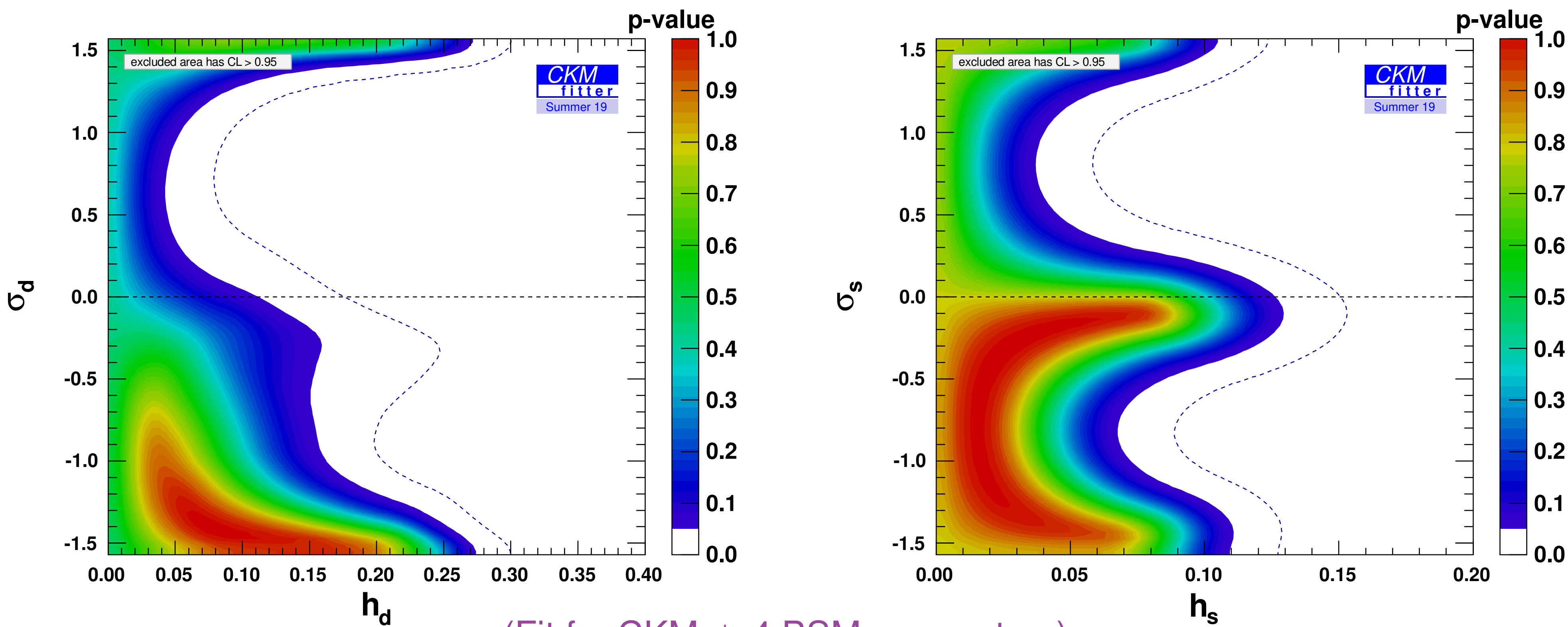
Importance known since 1970s ($\Delta m_K/m_K \sim 7 \times 10^{-15}$), conservative view of future progress

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Bounds on new physics in mixing

- Constraints on NP in B_s mixing became better than in B_d (as expected)



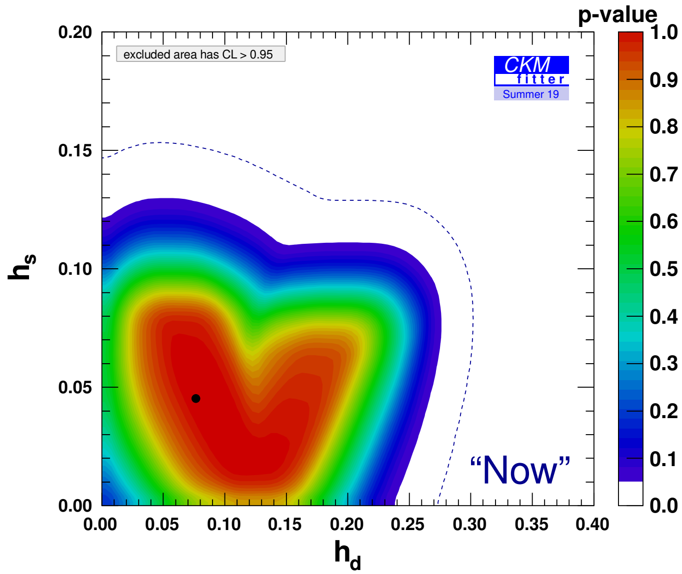
(Fit for CKM + 4 BSM parameters)

- Recall, h is the magnitude of the ratio of NP/SM contributions to M_{12}

BERKELEY CENTER FOR THEORETICAL PHYSICS

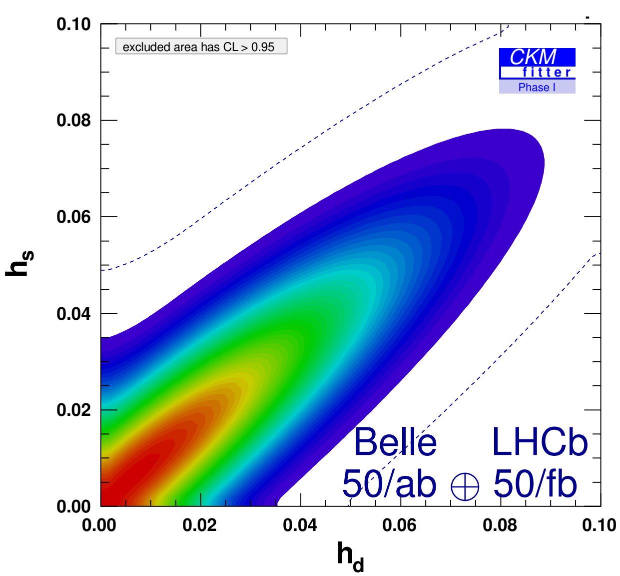
BERKELEY LAB

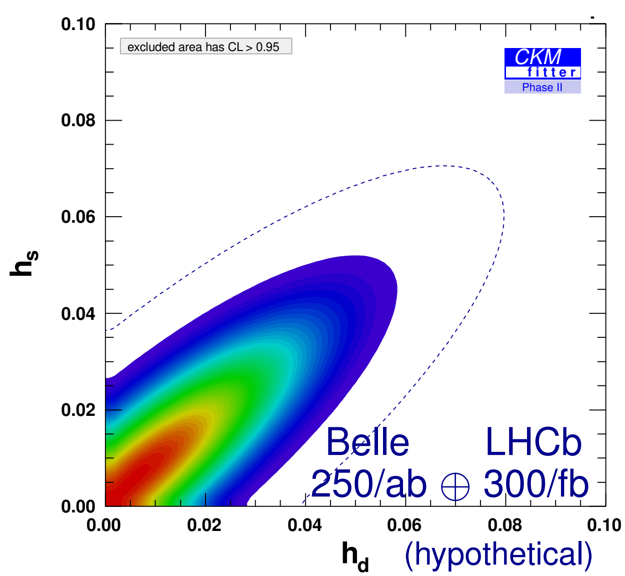
Future sensitivity to NP in B mixing



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

Couplings	NP loop order	Sensitivity for Summer 2019 [TeV] B_d mixing	Sensitivity for Summer 2019 [TeV] B_s mixing	Phase I Sensitivity [TeV] B_d mixing	Phase I Sensitivity [TeV] B_s mixing	Phase II Sensitivity [TeV] B_d mixing	Phase II Sensitivity [TeV] B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V_{tj}^*\rvert$	tree level	9	13	17	18	20	21
(CKM-like)	one loop	0.7	1.0	1.3	1.4	1.6	1.7
$\lvert C_{ij}\rvert = 1$	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

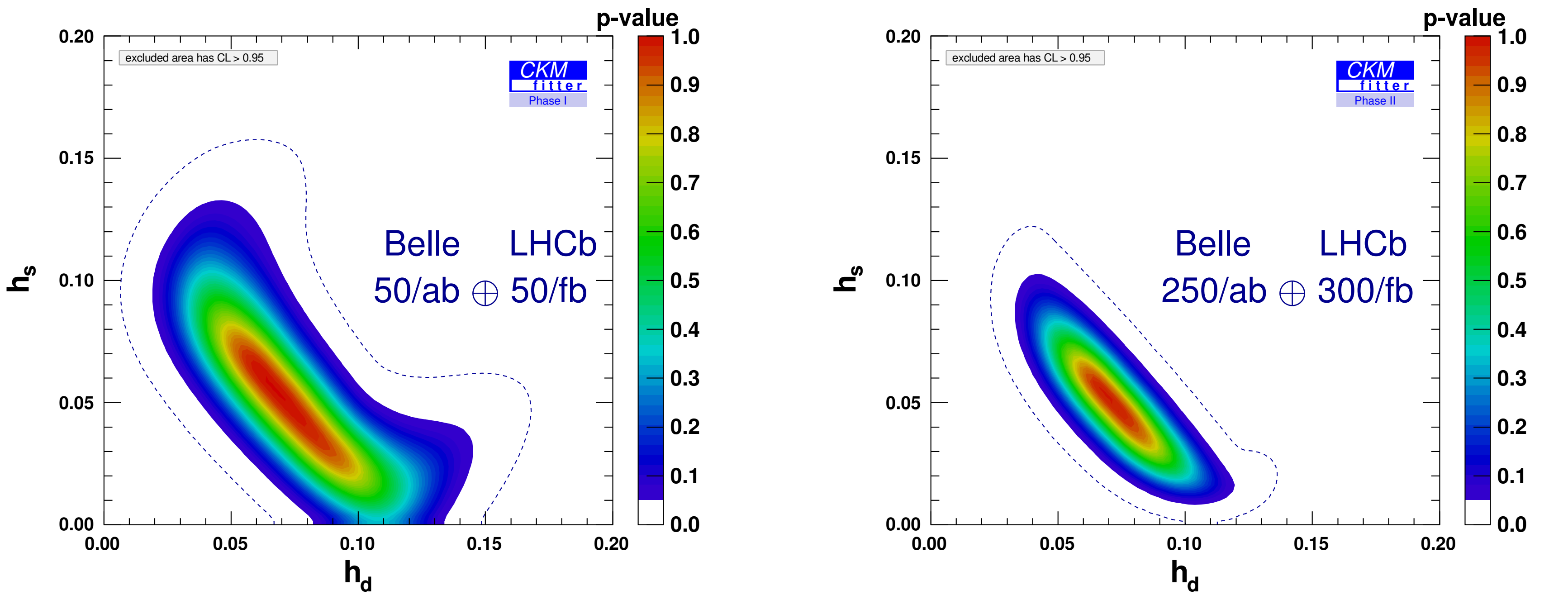
BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Example of discovery potential

- 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

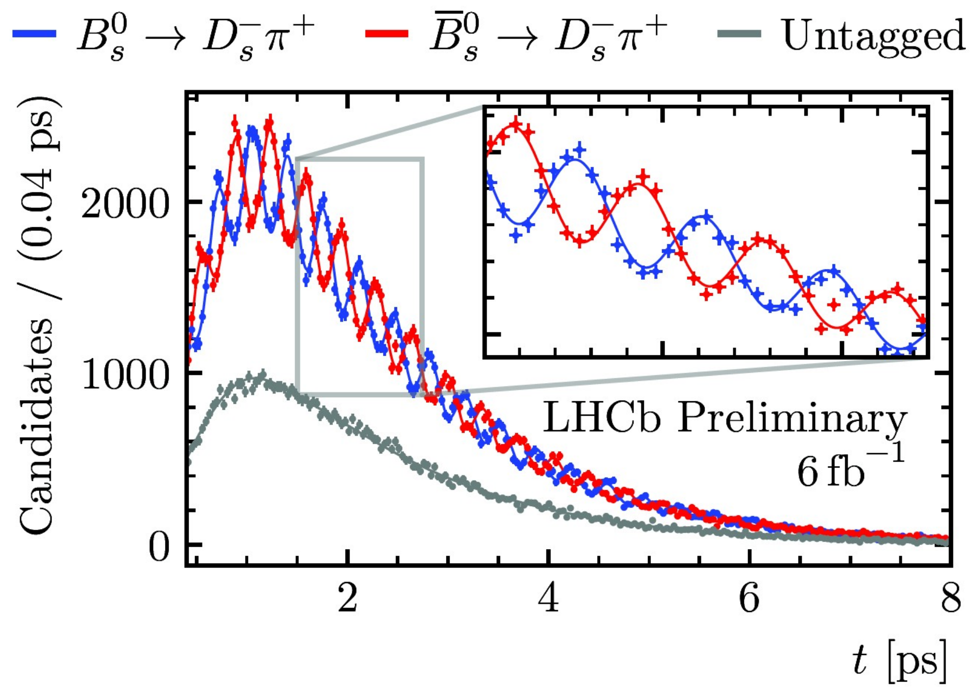
BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Aside: Δm_s became incredibly precise

- Textbook measurement: exp. uncertainty of $|V_{tb}V_{ts}|$ similar to $|V_{ud}|$
- $\Delta m_{B_s} = (17.7656 \pm 0.0057)\,\text{ps}^{-1}$
  Relative precision: 3×10^{-4} [LHCb, 2104.04421]

  The most precise neutral meson mass difference (much better than Δm_K!)
- Lattice QCD breakthroughs could make big impact on BSM sensitivity
  (Possible tension with lattice QCD? [1602.03560])



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

  Error of $|V_{ud}|$ is 1.4×10^{-4} — possibly underestimated

  Error of $|V_{tb}V_{ts}|$ would be 1.6×10^{-4}, if it were not dominated by theory

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

“Anomalies” and $|V_{cb}|$

Recent hints of deviations from the SM

- Intriguing tensions with the SM ⇒ experimental scrutiny, new theory ideas

- Some would be unambiguous NP signals

  (Note that vertical axis is an unspecified function)

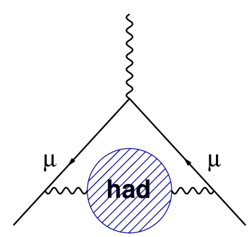
  Except for theoretically cleanest modes, cross-checks needed to build robust case

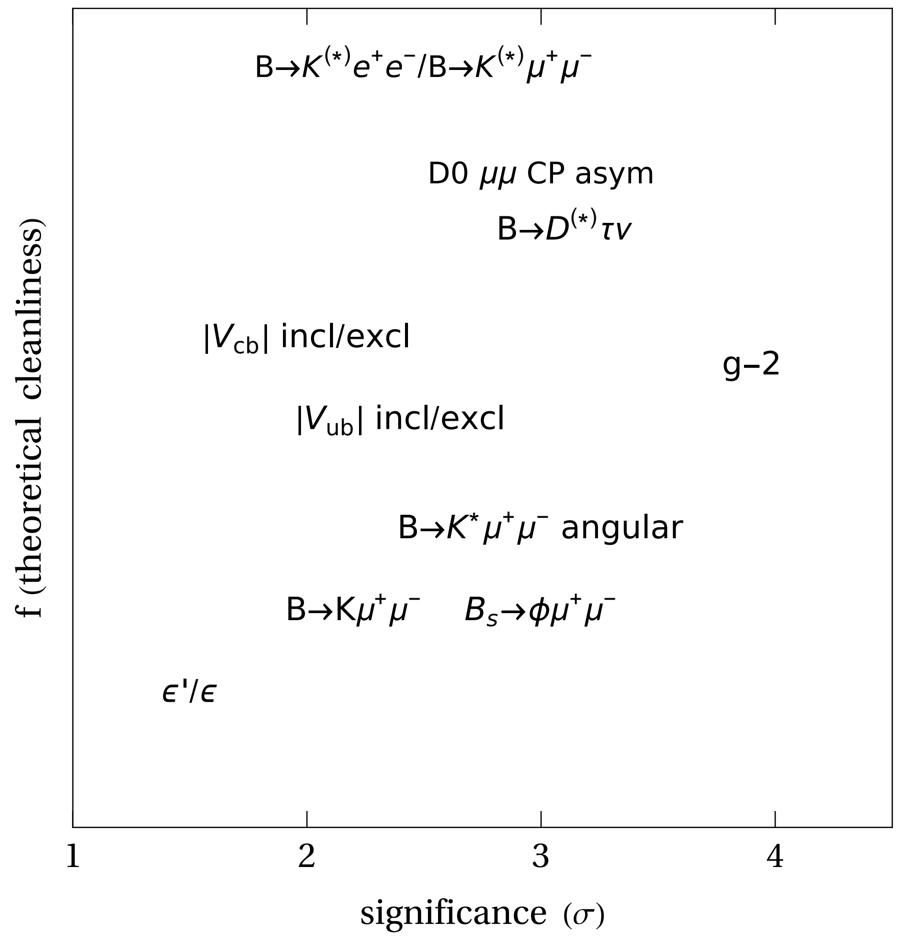
  – measurements of related observables

  – independent theory / lattice QCD calc.

- Most significant: $g-2$

  Hadronic contributions argued among lattice QCD groups





Recent hints of deviations from the SM

- Intriguing tensions with the SM $\Rightarrow$ experimental scrutiny, new theory ideas

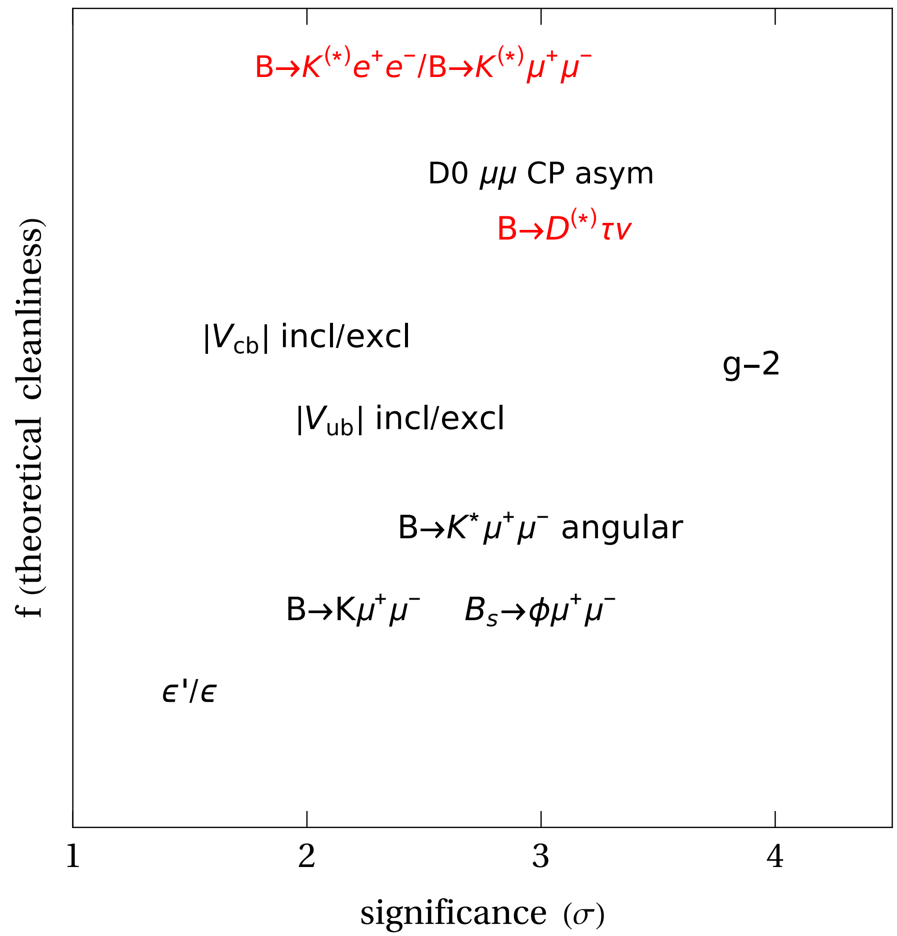
- Some would be unambiguous NP signals

  (Note that vertical axis is an unspecified function)

  Except for theoretically cleanest modes, cross-checks needed to build robust case

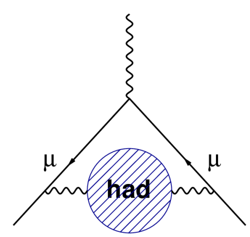
  – measurements of related observables

  – independent theory / lattice QCD calc.



- Most significant: $g-2$

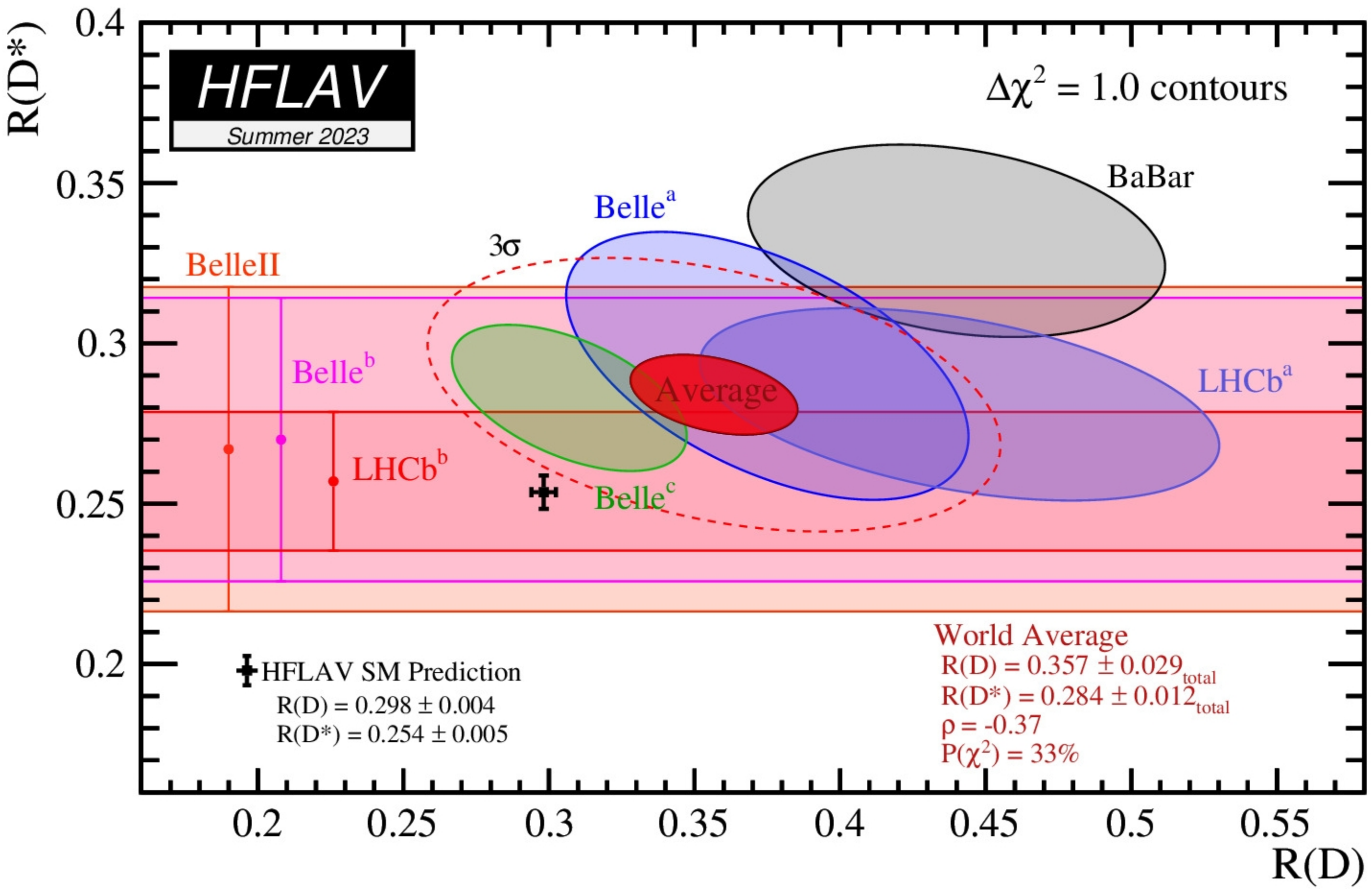
  Hadronic contributions argued among lattice QCD groups



- Each could be a whole talk — I can only touch upon a small subset

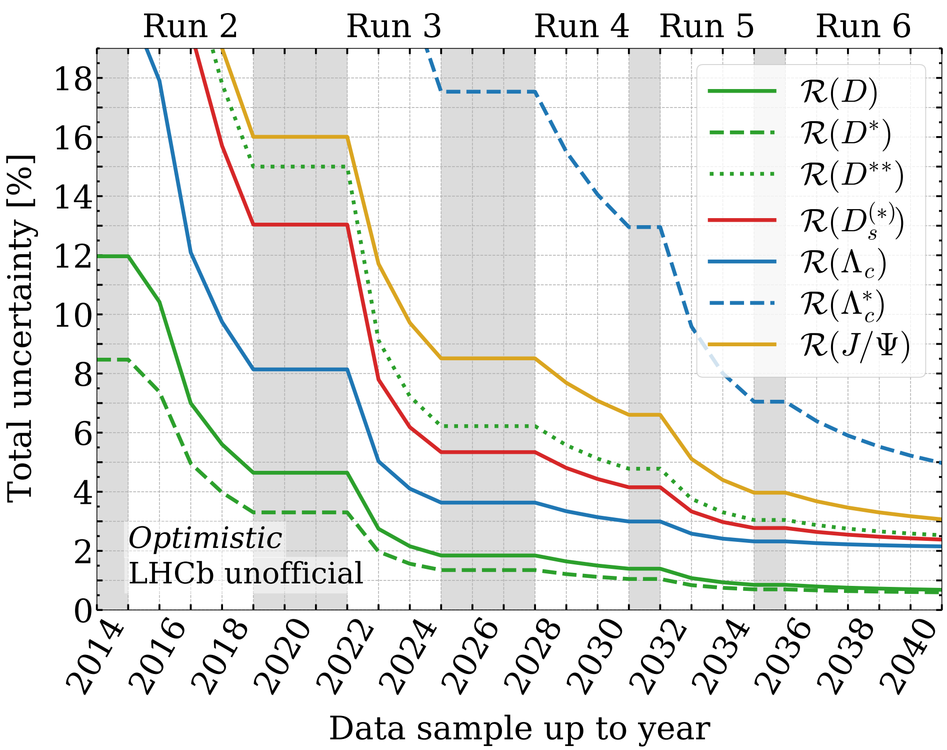
$R(D)$ and $R(D^*)$: 3σ tension with SM

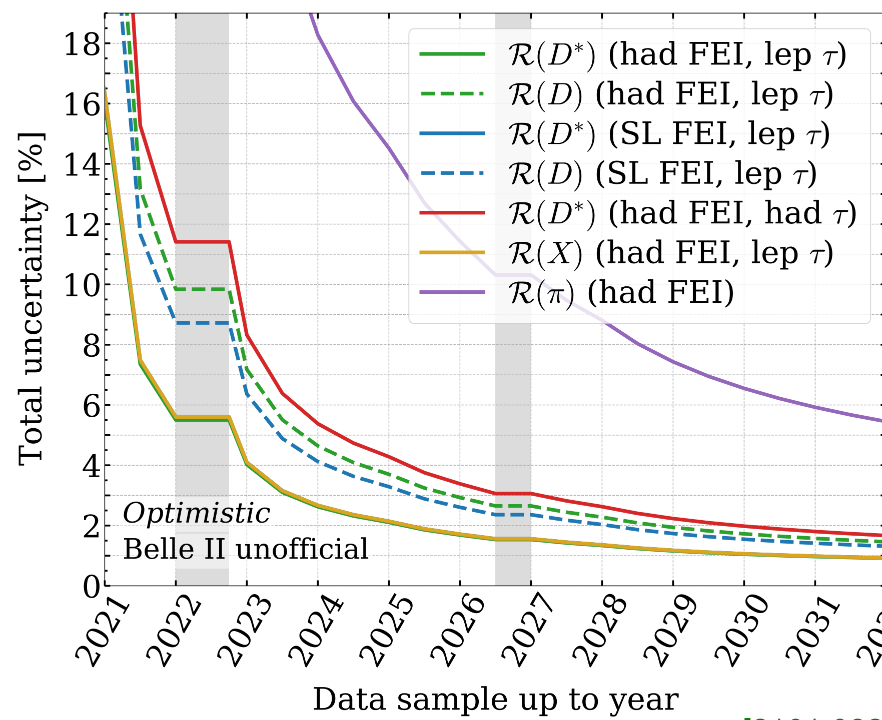
- BaBar, Belle, LHCb: enhanced τ rates, $R(D^{(*)}) = \dfrac{\Gamma(B \to D^{(*)}\tau\bar\nu)}{\Gamma(B \to D^{(*)}l\bar\nu)}$ $\qquad (l = e, \mu)$



[Enhancement also seen in $\Gamma(B_c \to J/\psi\, \ell\bar\nu)$]

Exciting future prospects





[2101.08326]

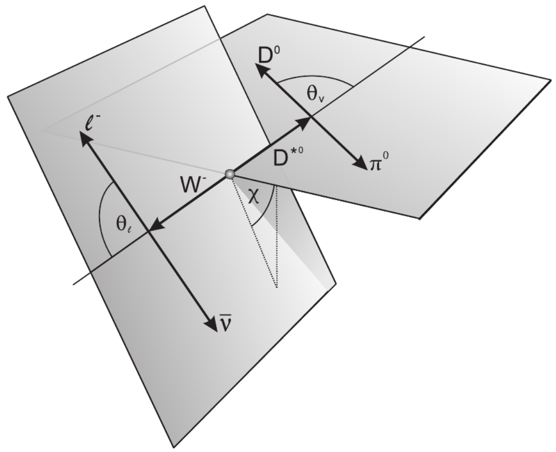
- Measurements will improve a lot!

  Even if deviations from SM decrease, may establish presence of BSM

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

Unfolded distributions: never before 2017

- Belle published unfolded $B \to D^* l \bar{\nu}$ $(l = e, \mu)$ distributions [1702.01521]



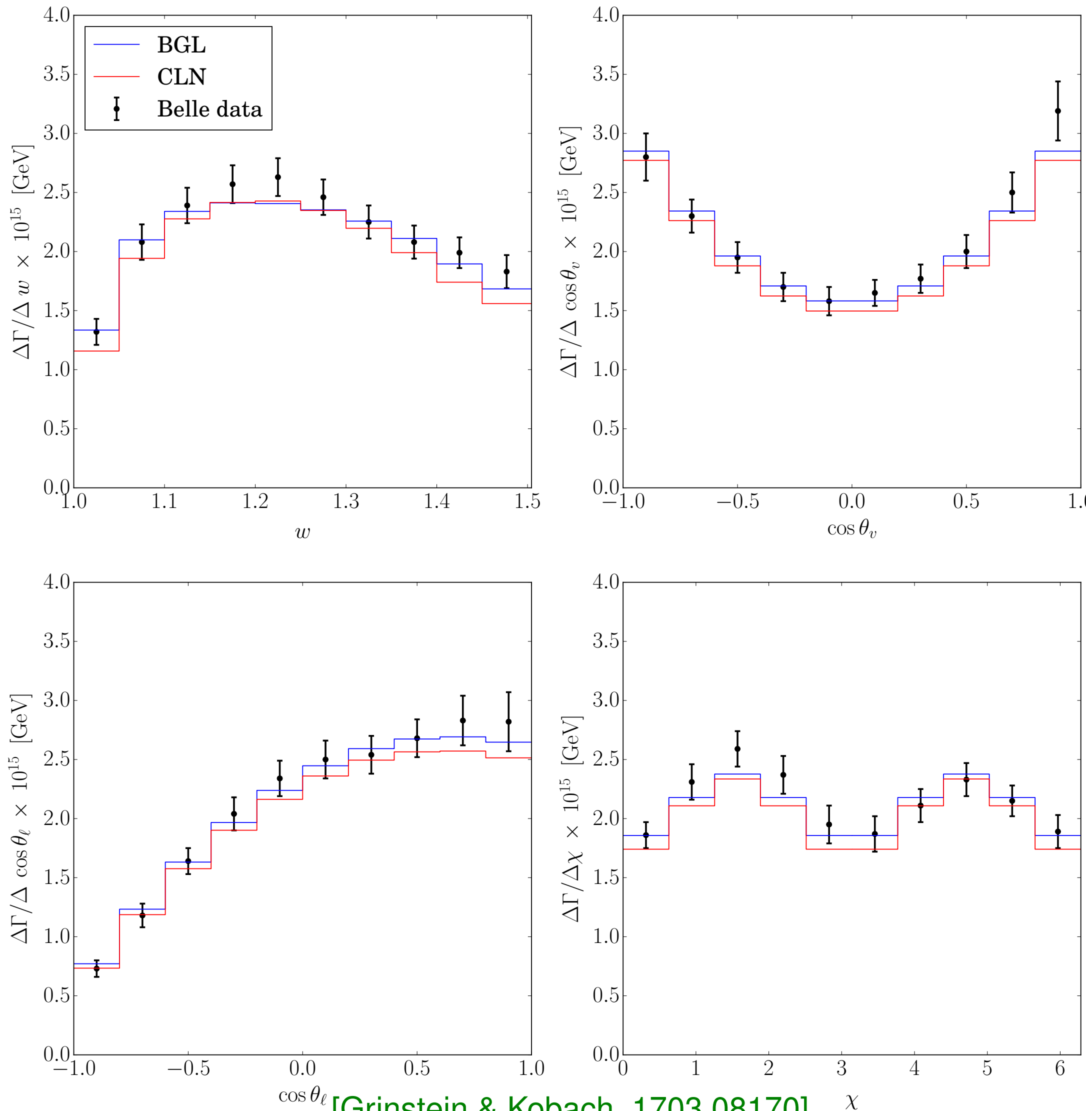
- Input on the fitted shapes:

  BGL: Boyd, Grinstein, Lebed, '95–97

  CLN: Caprini, Lellouch, Neubert, '97

  1997–2017: all measurements used CLN

- Can perform different fits to data



[Grinstein & Kobach, 1703.08170]

Motivated pushing HQET further

- Much of this could have been worked out in the 1990s... (no one would have cared)

  'When you think you can finally forget a topic, it's just about to become important'

  [Polchinski]

- Lorentz invariance: 6 functions of q^2, only 4 measurable with e, μ final states

$$\langle D|\,\bar c\gamma^\mu b\,|\overline{B}\rangle \;=\; f_+(q^2)(p_B+p_D)^\mu + \Big[f_0(q^2)-f_+(q^2)\Big]\frac{m_B^2-m_D^2}{q^2}\,q^\mu$$

$$\langle D^*|\,\bar c\gamma^\mu b\,|\overline{B}\rangle \;=\; -ig(q^2)\,\epsilon^{\mu\nu\rho\sigma}\,\varepsilon^*_\nu\,(p_B+p_{D^*})_\rho\,q_\sigma$$

$$\langle D^*|\,\bar c\gamma^\mu\gamma^5 b\,|\overline{B}\rangle \;=\; \varepsilon^{*\mu}f(q^2)+a_+(q^2)\,(\varepsilon^*\cdot p_B)\,(p_B+p_{D^*})^\mu + a_-(q^2)\,(\varepsilon^*\cdot p_B)\,q^\mu$$

  The a_- and $f_0 - f_+$ form factors $\propto q^\mu = p_B^\mu - p_{D^{(*)}}^\mu$ do not contribute for $m_l = 0$

- HQET: One Isgur-Wise function (heavy quark limit) $+\,3$ at $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b}) + \ldots$

- "Idea": fit 4 functions of w with 4 observables (1 in $B\to D\,l\bar\nu$ and 3 in $B\to D^*l\bar\nu$)

- Uncertainties are $\mathcal{O}(\Lambda_{\rm QCD}^2/m_{c,b}^2\,,\,\alpha_s^2)$ [Bernlochner, ZL, Papucci, Robinson, 1703.05330]

$B \to D^{(*)}\tau\bar{\nu}$: BSM implications

- Would imply NP at a scale that ATLAS / CMS can discover (leptoquarks, W', etc.)

  Some of the models Fierz (mostly) to the same (SM) operator: distributions, τ polarization $=$ SM

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

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

- Viable BSM models... leptoquarks? No clear connection to DM & hierarchy puzzle

- Connections to a large spectrum of lepton flavor violation searches

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

- What are smallest deviations from SM, which can be unambiguously established?

Richness of directions

CP violation in D decays

- CP violation in D decays:

  (a stretch in the SM, imho) ↙

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

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

  (And only in 2021 was $\Delta m \neq 0$ established with greater than 3σ significance)

- I think we still don't know how big an effect could (not) be due to SM physics

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

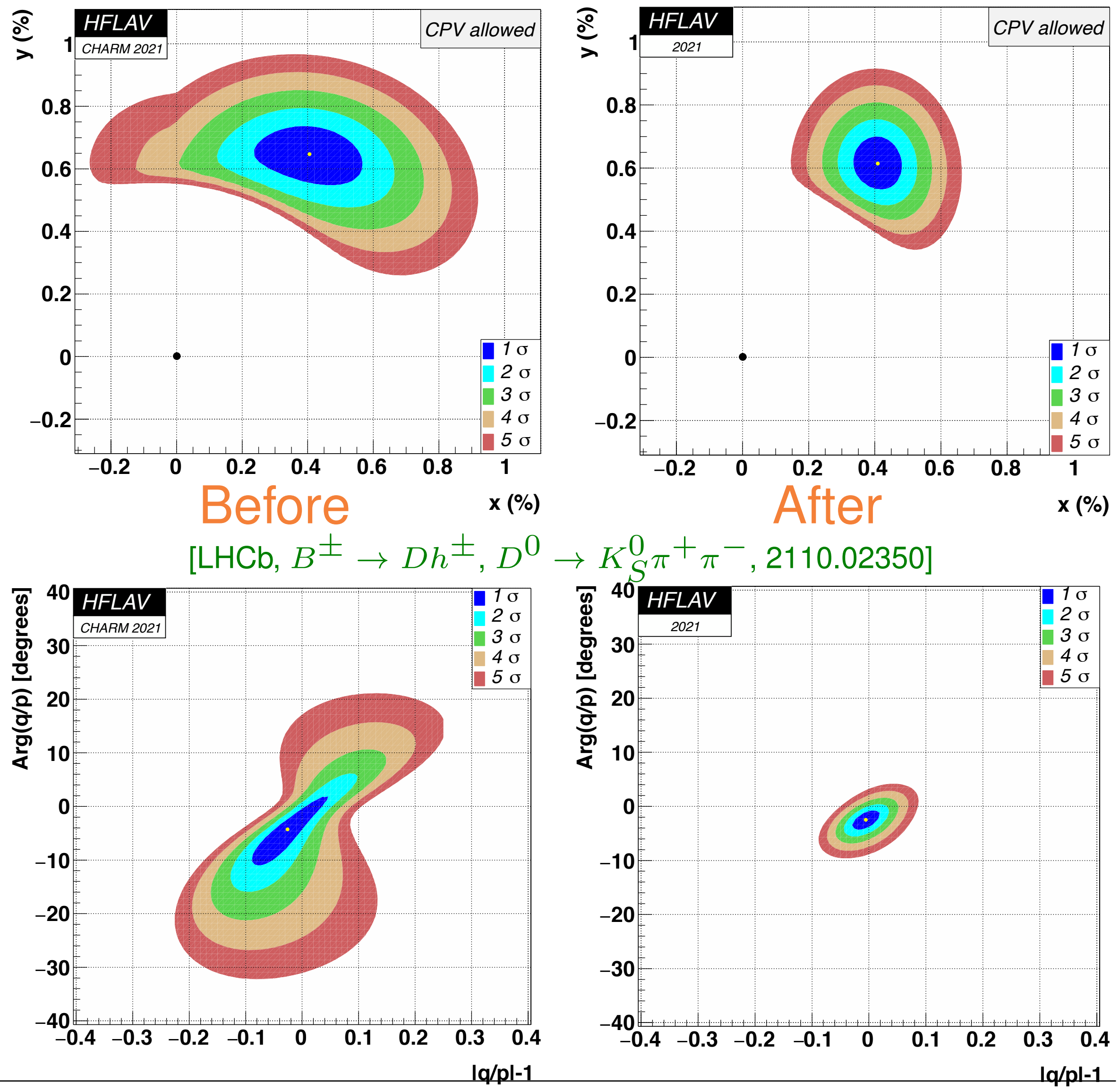
  Before data, everyone (working on it) thought (assumed) strong interaction to suppress this further

- Can we establish BSM sensitivity? Way to understand and test in which decays flavor symmetry relations work better / less well? (Same Q for FCNC D decays)

- Can we establish if CP violation in mixing would still be a clear probe of NP?

D mixing: large recent progress

- Mixing (and FCNC) generated by down quarks or in SUSY by up-type squarks in the loops
- SUSY and many BSM models: interplay of D and K bounds; e.g., alignment, universality, heavy squarks?
- CP violation in D mixing is still very interesting (need more work)



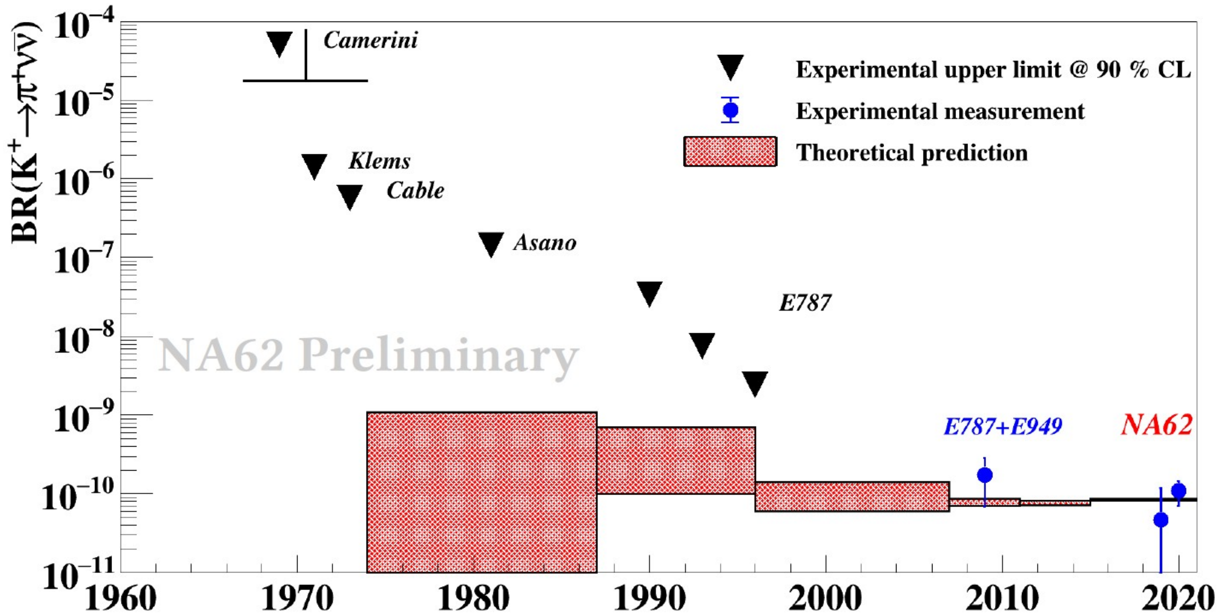
BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

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

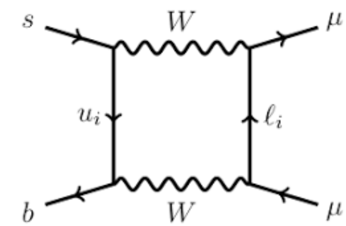
BERKELEY CENTER FOR THEORETICAL PHYSICS

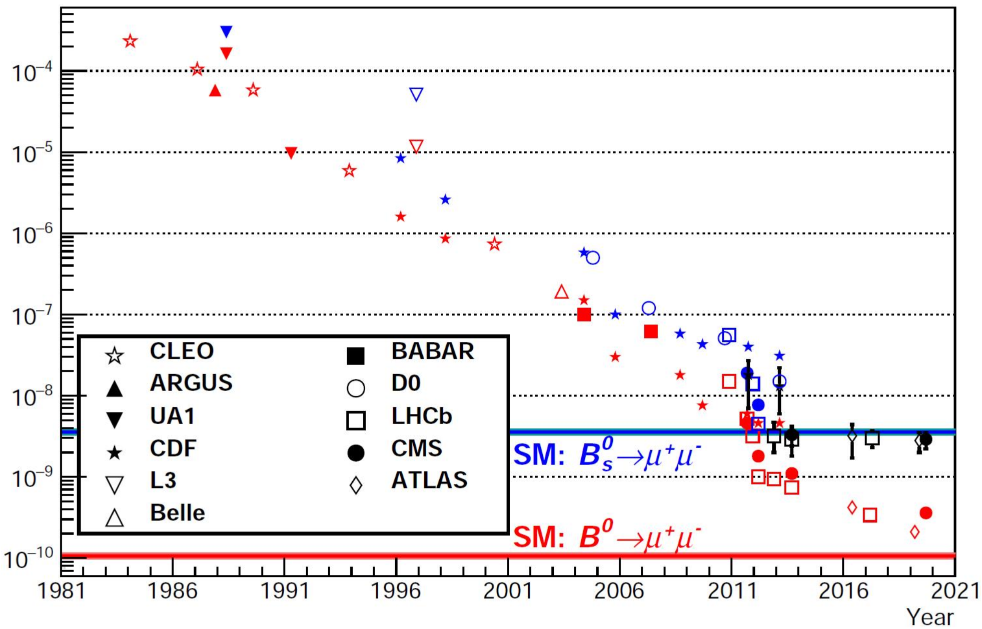
BERKELEY LAB

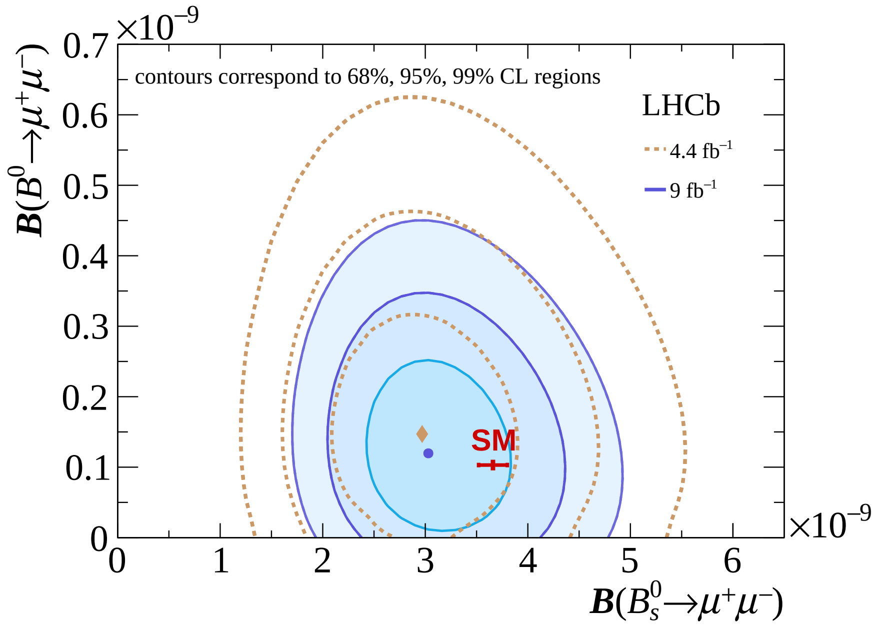
$B \to \mu^+\mu^-$: interesting well beyond HL-LHC

- $B_d \to \mu^+\mu^-$ sensitive to $\mathcal{O}(100\,\mathrm{TeV})$, similar to $K \to \pi\nu\bar\nu$

  SM prediction is very precise







- $\mathcal{B}(B_s \to \mu^+\mu^-) = (3.01 \pm 0.35) \times 10^{-9}$ consistent w/ SM, $B_d \to \mu^+\mu^-$ not yet seen

  LHCb expects $\lesssim 10\%$, and CMS expects $\lesssim 15\%$ during HL-LHC

- Theoretically cleanest (without lattice) "$|V_{ub}|$" I know: $\mathcal{B}(B_u \to \ell\bar\nu)/\mathcal{B}(B_d \to \mu^+\mu^-)$

Many "exotic" searches

- 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)

Future

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?

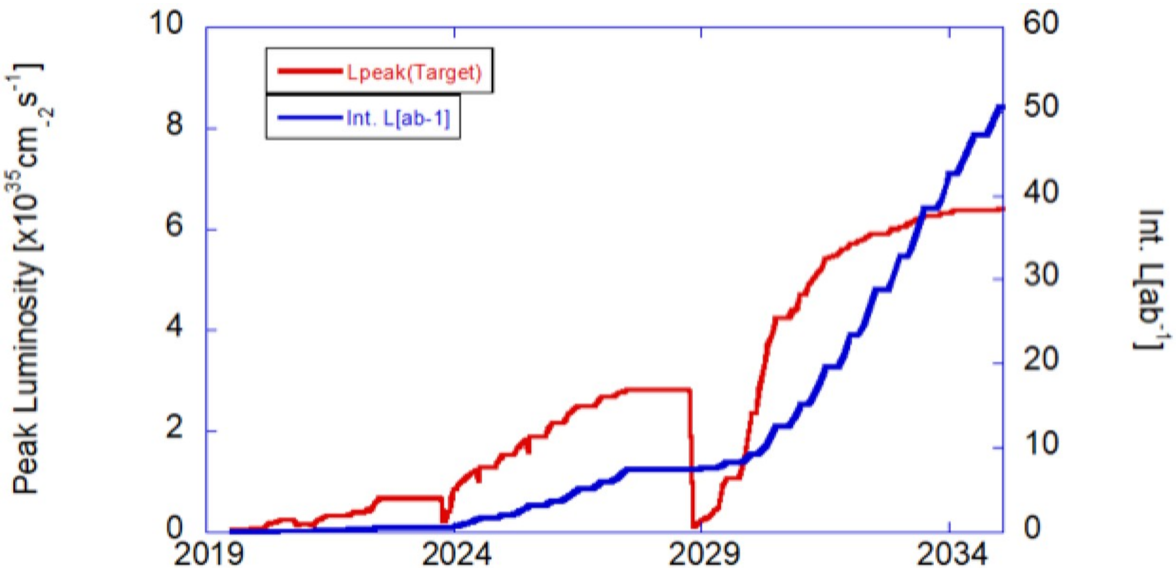
  Complementary with LHC high-p_T program; synergy can teach us what the NP is (what it's not)

- No guaranteed discoveries — truly exploratory era!

  Near future: "anomalies" might first be established

  Long term: large increase in discovery potential in many modes

Belle II and LHCb: clear plans



(Discussions about further upgrade)

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

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

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

FCC: impressive flavor program

- Very large and clean samples of B decays ($\sim 10^6 \times$ LEP)

- 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 ($5 \times 10^{12}\ Z$)	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]

- Hard to comprehend 10^5 increase in data! Tera-Z / LEP $\sim$ Belle II / ARGUS $\sim 10^5$

Semileptonic CPV: $A_{\rm SL}^{d,s}$ approach SM @ Tera-Z

- 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 (semi)leptonic 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

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

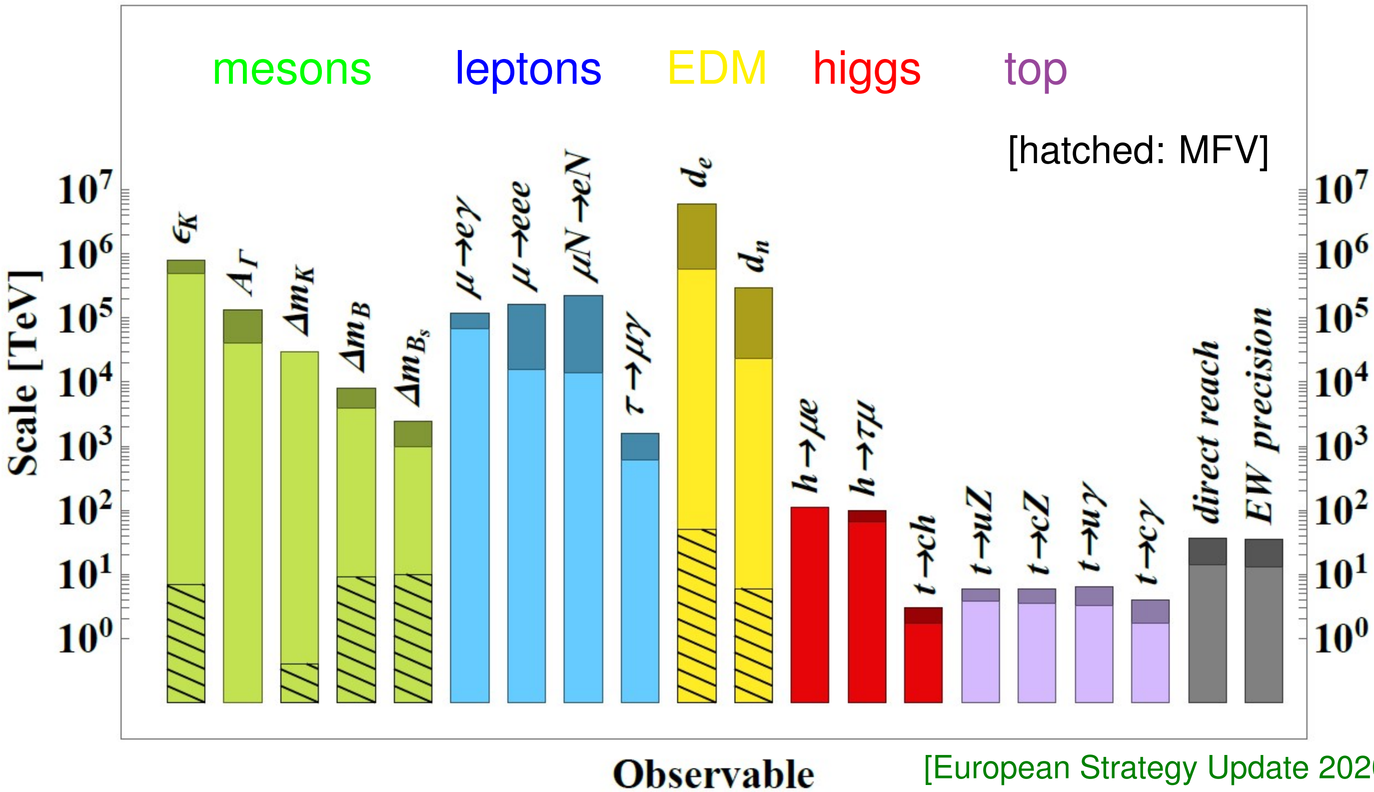
  (In SM: $\mathcal{B}(B_s \to \tau^+\tau^-) = (7.7 \pm 0.5) \times 10^{-7}$, [1311.0903])

- Another important 2-body decay: $B_c \to \tau\bar{\nu}$

- If hints of LFUV prevail: expect correlated effects in many of these processes

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 decade

Final remarks

Aside: plans, 42 yrs ago (surprisingly applicable!)

- "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."

- 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 might 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."

What are the largest useful data sets?

- No one has seriously explored it! (Sanda, in 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)
- 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!)
- Guess: until $100\times$ (Belle II $\&$ LHCb Phase 2), sensitivity to NP would improve
- FCC-ee in tera-Z phase could eclipse prior B factories

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)

- Large increases in data always triggered unforeseen developments

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

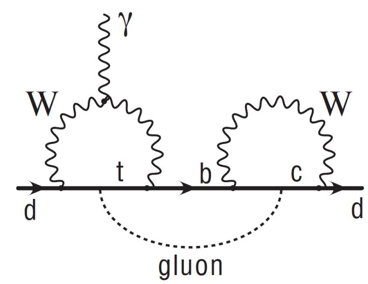
Extra slides

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?

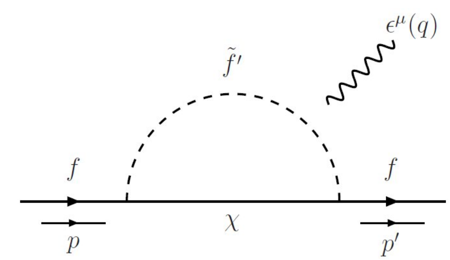
Electric dipole moments

- 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

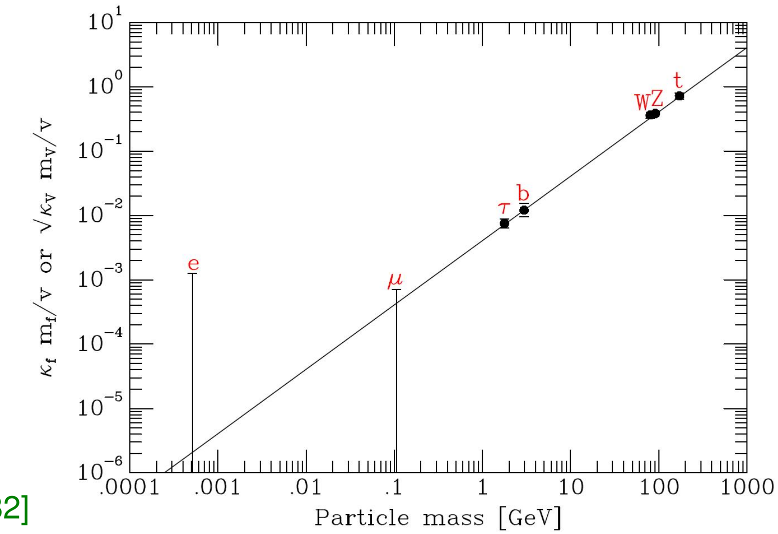
  Generic prediction ($\rm TeV$-scale, no small param's) above current bounds; if $m_{\rm SUSY} \sim \mathcal{O}(10\,{\rm TeV})$, may still discover EDMs



- 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



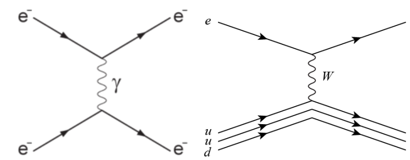
Future precision of flavor-diagonal couplings [Heinemann & Nir, 1905.00382]

Observable	Current range	HL-LHC	ILC250	ILC250+500	CLIC380	CLIC3000	CEPC	FCC240	FCC365	LHeC
		$\delta y/y$ (%)								
$y_t/y_t^{\rm SM}$	$1.02^{+0.19}_{-0.15}$ [35] $1.05^{+0.14}_{-0.13}$ [36]	3.4	–	6.3	–	2.9	–	–	–	–
$y_b/y_b^{\rm SM}$	$0.91^{+0.17}_{-0.16}$ [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
$y_\tau/y_\tau^{\rm SM}$	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
$y_c/y_c^{\rm SM}$	< 6.2 [40, 41]	< 220	1.8	1.2	4.1	1.3	1.9	1.8	1.2	3.6
$y_\mu/y_\mu^{\rm SM}$	$0.72^{+0.50}_{-0.72}$ [35] < 1.63 [36]	4.3	4.0	3.8	–	5.6	5.0	9.6	3.4	–
$y_e/y_e^{\rm SM}$	< 611 [42]	–	–		–	–	–	–	$< 1.6^{(+)}$	–

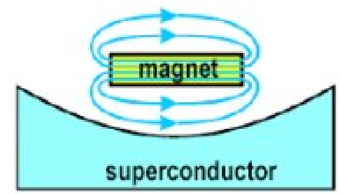
Aside: Higgs, superconductivity, and flavor

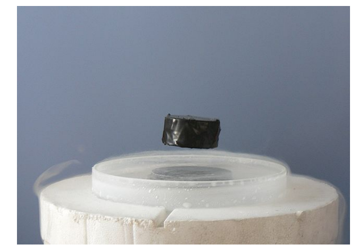
- EM: Coulomb's law $F \propto 1/r^2$, infinite range, massless photons

  Weak int.: Exponential fall-off, short range, massive $W^\pm$, Z^0



- Gauge symmetry forbids W, Z masses, understand them the same way as Meissner effect: exponential fall-off of $\mathbf{B}$ field (spontaneous symmetry breaking)





  $m_{W,Z} \neq 0$: ground state of the Universe ("vacuum") is in a superconducting state

- Higgs mechanism: nonabelian analog, coherence length $\sim m_h^{-1}$, penetration depth $\sim m_W^{-1}$

- Superconductivity: microscopic theory, Cooper pairs ("new physics")

- Is electroweak superconductivity similar? LHC may still find $m_{\rm BSM}/m_h \lesssim \text{few} \times 10$

- As for supercond., microscopic explanations have phenomena at nearby scales

  (supersymmetry, little higgs, extra dimensions, strongly interacting sectors, etc.)

Electroweak superconductivity

- Close analogy: Ginzburg–Landau theory vs. Higgs mechanism

$F \sim F_n + \alpha|\psi|^2 + \frac{\beta}{2}|\psi|^4 + (\text{terms} \propto \mathbf{A}, \mathbf{B})$

$|\psi|^2 \sim$ density of condensate

assume $\alpha \sim \alpha'(T - T_c) \quad [T_c \lesssim \mathcal{O}(100\,\mathrm{K})]$

equilibrium w/o EM field: $|\psi_0|^2 = -\alpha/\beta$

penetration depth: $\lambda = \sqrt{m_e/(4\mu_0 e^2 \psi_0^2)}$

coherence length: $\xi = \hbar/\sqrt{4m_e|\alpha|}$

$\mathcal{L} \sim |D_\mu \phi|^2 + \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2 - \frac{1}{4} W_{\mu\nu} W^{\mu\nu}$

$\phi =$ Higgs field $\quad [D_\mu = \partial_\mu + ig\tau^a W_a^\mu]$

$T_c \sim 10^{15}\,\mathrm{K}\ (10^{11}\,\mathrm{eV})$

minimum: $|\phi_0|^2 \equiv \frac{v^2}{2} = \frac{\mu^2}{2\lambda}$

masses: $m_W = vg/2$

$m_h = \sqrt{2\lambda}\, v = \sqrt{2}\, \mu$

- (coherence length)$^{-1} \sim m_h$

  (penetration depth)$^{-1} \sim m_W$ (exp falling penetration of $\mathbf{B}$ field $\sim$ “photon mass”)

- BCS superconductors: coherence length $\sim$ Cooper pair size $\sim$ Fermi energy

  “Higgs mass” $\sim$ “new physics scale” $\quad (1\,\mathrm{eV} \sim 1000\,\text{Å})$

Aside: P_5' in $B^0 \to K^{*0}\mu^+\mu^-$ decay

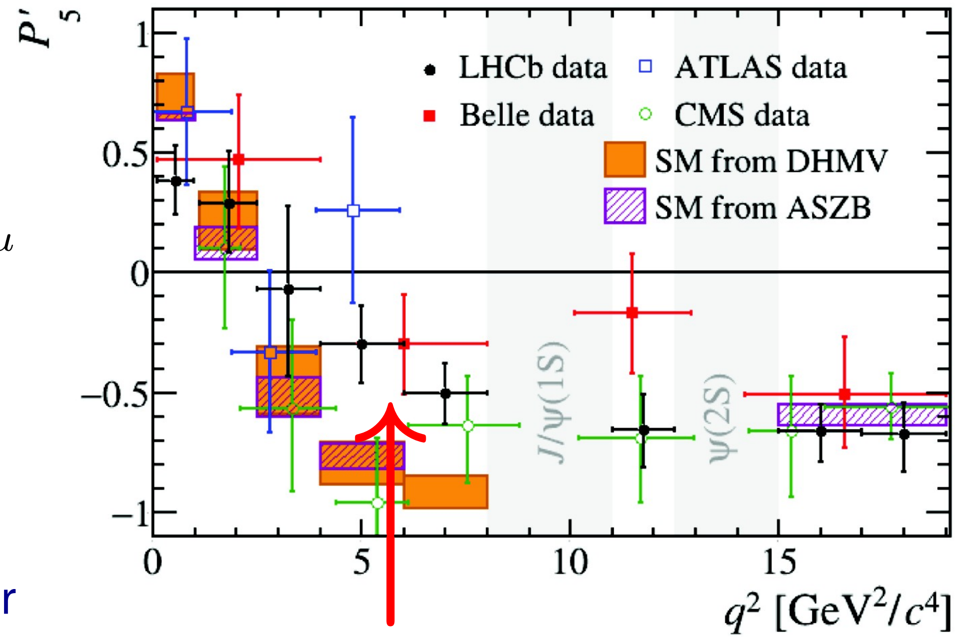
- "Optimized observables" [1202.4266 + long history]
  (assumptions about theory uncertainties)

  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.