Flavor Physics: past, present, future

Zoltan Ligeti

Particle Physics after the Higgs Discovery

Sep 30 – Oct 4, 2024, Bingen

Disclaimers

- I always give summer school lectures on the blackboard (except Summer 2020)
  - More fun for you, and also for me
  - Writing on a blackboard necessarily focuses on what matters most
  - Updating many of the plots unlikely to be useful, but I tried
- Please interrupt any time with any questions or comments! I really mean it!

- Abbreviations: SM $=$ standard model
  BSM $=$ beyond SM
  CPV $=$ CP violation
  FCNC $=$ flavor-changing neutral current (will define)

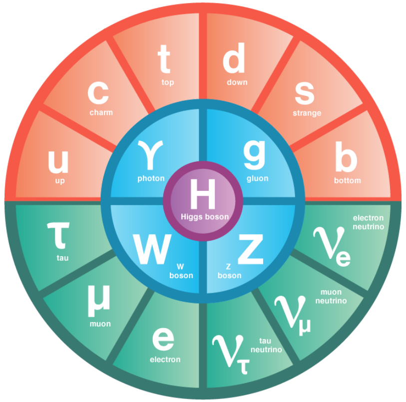
What is particle physics?

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

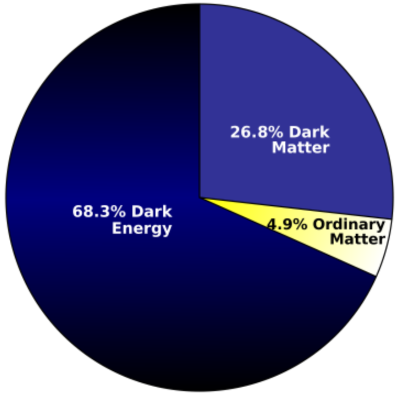
$$\mathcal{L} = ?$$

- Most experimentally observed phenomena are consistent with the “standard model”
  (Michelson 1894: “... it seems probable that most of the grand underlying principles have been firmly established ...”)

- 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 are consistent with the "standard model"
  (Michelson 1894: "... it seems probable that most of the grand underlying principles have been firmly established ...")

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

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 SM, and search for NP
- SM flavor: masses? mixing angles? 3 generations? — most of the SM param's
  Flavor in SM is simple: only from Higgs interactions, want to test as well as possible
- BSM flavor: TeV scale (hierarchy problem) $\ll$ "naive" flavor & CP viol. scale
  Any new particle that couples to quarks or leptons $\Rightarrow$ new flavor parameters
- Baryon asymmetry requires CPV beyond the SM
  (Not necessarily in flavor changing processes, nor necessarily in quark sector) [Possible caveat: 2408.12647]
- If NP is $10 - 100\,\mathrm{TeV}$, flavor especially crucial (fewer direct constraints, high reach)

The Universe: matter vs. antimatter

- Gravity, electromagnetism, strong interaction are same for matter and antimatter
- As the Universe cooled, quarks and antiquarks annihilated $\qquad t \sim 10^{-6}\,\mathrm{s}\ (T < 10^{13}\,\mathrm{K} \sim 1\,\mathrm{GeV})$

$$\frac{N(\text{baryon})}{N(\text{photon})} \sim 10^{-9} \quad \Rightarrow \quad \frac{N_q - N_{\bar{q}}}{N_q + N_{\bar{q}}} \sim 10^{-9}$$

- The SM prediction is $\sim 10^{10}$ times smaller

  [Nonzero! Sakharov conditions: (i) baryon number violation; (ii) charge (C) and charge-parity (CP) violation; (iii) deviation from thermal equilibrium]

- All present in the SM; but cannot explain observations
  What is the microscopic theory of CP violation? How precisely can we probe it?

Why is flavor physics interesting?

- Uncertainty principle $\Rightarrow$ heavy particles, which cannot be produced, affect lower energy processes, E^2/M^2 suppressed if interference $\Rightarrow$ probe very high scales
- The SM flavor puzzle: why quark flavor parameters small and hierarchical?
  (why) is neutrino flavor structure different?

  Many testable relations, sensitive to possible deviations from the standard model
- The BSM flavor puzzle: if new physics near the TeV scale, why FCNCs so small?
  future data $\Rightarrow$ clues about the structure of BSM
- Great increase of data in coming decade(s) — some tension at present with the SM

Most of SMEFT: e.g., 1053 semileptonic ($l\bar{l}q\bar{q}$) operators, i.e., 42% of the 2499 parameters of the dim-6 B & L conserving terms in the 3-generation SMEFT (558 CP-even, 495 CP-odd). In the LEET, it's 1944 semileptonic parameters (i.e., 54%) of the 3631 terms (1017 CP-even, 927 CP-odd).

Similarities: 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 oversimplified, too!)

Outline

- ~~Physics beyond the standard model must exist~~
- Giving 3 lectures, it's tempting to think Past / Present / Future...
- How it all started ... Next month is the 50th anniversary of the "November revolution"
  Intro; leptons & quarks; testing CKM; meson mixing & CP viol.; high scale sensitivity

---

- B decays & recent tensions with SM: hints of lepton universality violation
  $B \to D^{(*)}\ell\bar\nu$ and $R(D^{(*)})$, $B \to K^{(*)}\ell^+\ell^-$ and $R_{K^{(*)}}$, $B \to K\nu\bar\nu$

- Far future: FCC
  ... Higgs, precision electroweak, "traditional" flavor

50th anniversary of J/ψ discovery

(Next few slides were prepared for ICHEP...)

Thanks to: Tom Appelquist, Howard Georgi, David Politzer, Helen Quinn, Mark Wise
for sharing their recollections and enlightening conversation

The J/Ψ discovery

November revolution?

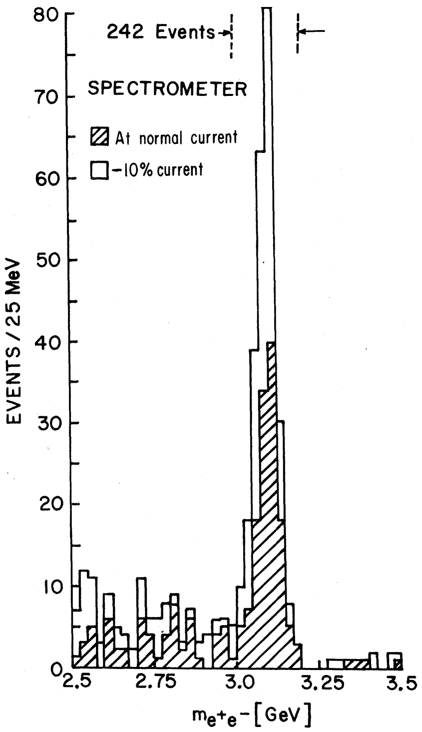
Why was it so surprising?

Usually learn things linearly

The real story is often much more confusing and complex

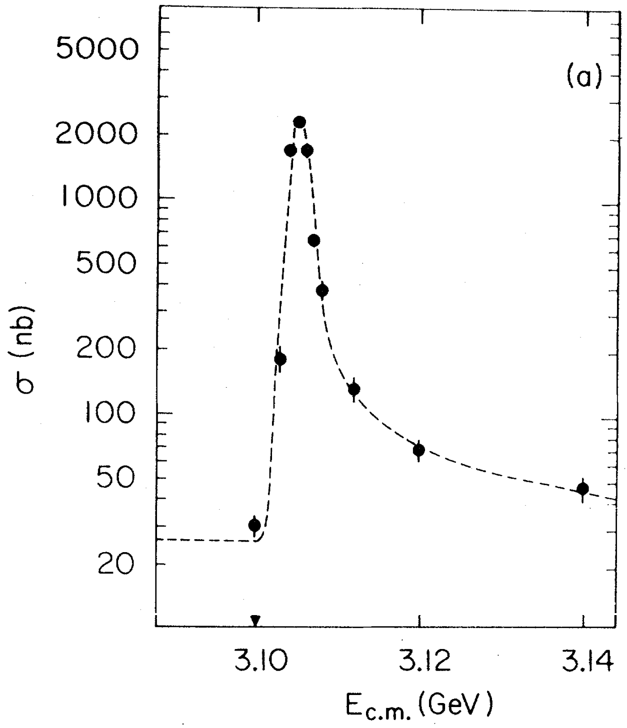
Experimental Observation of a Heavy Particle J

(Received 12 November 1974)



Discovery of a Narrow Resonance in e^+e^- Annihilation

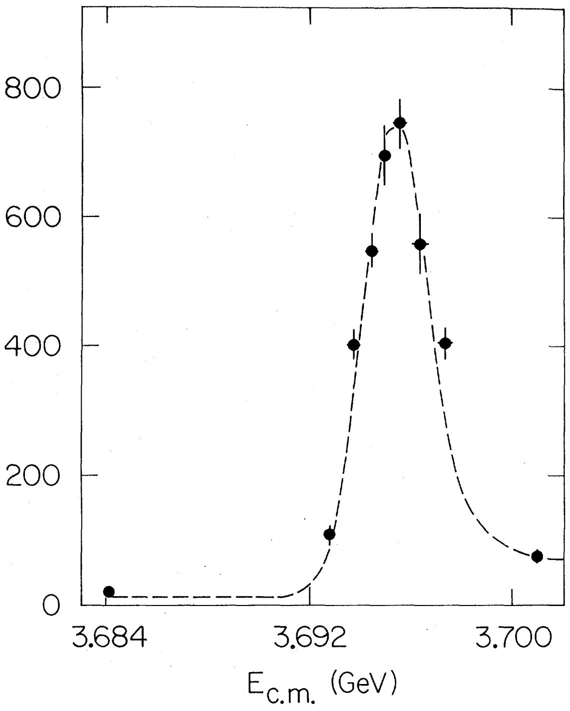
(Received 13 November 1974)



The Ψ': two weeks later — the D: two years later

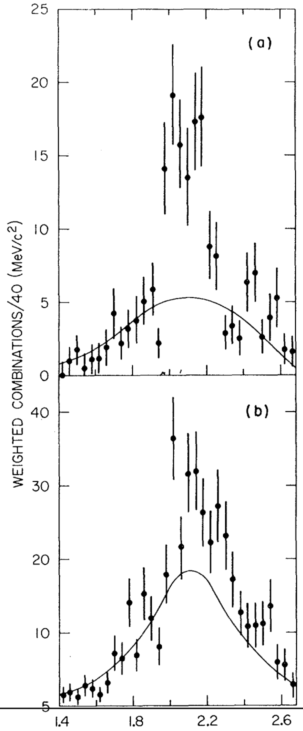
Discovery of a Second Narrow Resonance in e^+e^- Annihilation

(Received 25 November 1974)



Observation in e^+e^- Annihilation of a Narrow State at 1865 MeV/c^2 Decaying to $K\pi$ and $K\pi\pi\pi$ †

(Received 14 June 1975) → typo in PRL! preprint clearly June 1976



The state appears to be produced only in association with systems of comparable or higher mass.

The $D^\pm$ discovered a month later [PRL 37 569]

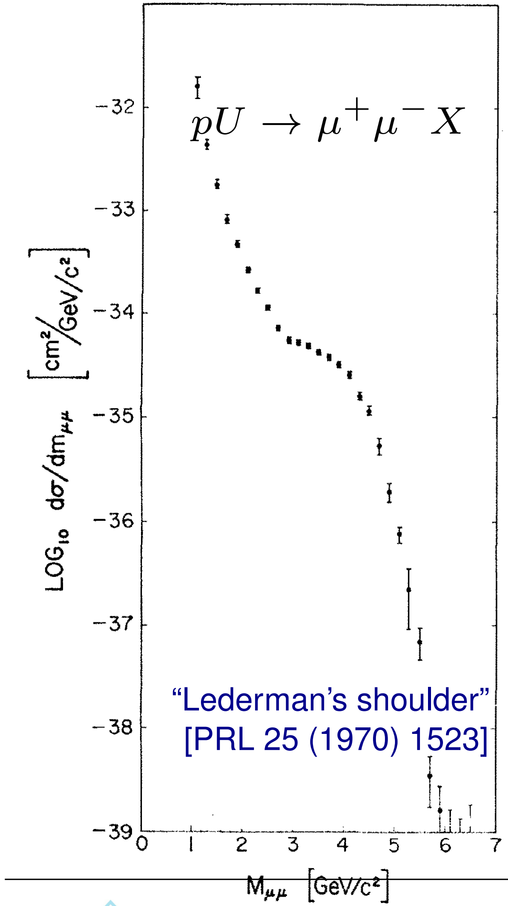
Nearly a year after the τ discovery [PRL 35 1489] $(e^+e^- \to \mu^\pm e^\mp + E_{\mathrm{miss}})$

NB: J/ψ has "charmness" $= 0$
Quantum numbers of J/ψ are same as vacuum, will play a role later

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Several earlier hints of charm



$pU \to \mu^+\mu^- X$

"Lederman's shoulder"
[PRL 25 (1970) 1523]

Prog. Theor. Phys. Vol. 46 (1971), No. 5

A Possible Decay in Flight of a New Type Particle

Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*

Institute for Nuclear Study
University of Tokyo
**Yokohama National University*

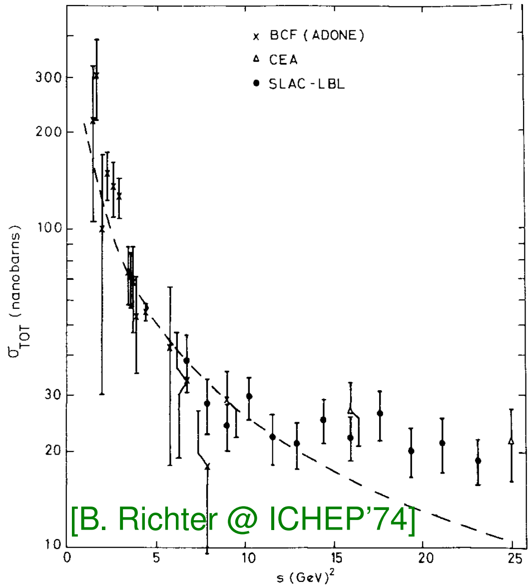
August 9, 1971

Among the secondary particles produced in a high energy jet shower and observed by emulsion chambers exposed to cosmic rays, a possible decay in flight of a new type particle was found.

One event reported as : $X \to \pi^+\pi^0$

$m_X \sim 1.78\,\text{GeV}, \tau_X \sim 2.2\times 10^{-14}\,\text{s}$

[There were other / earlier hints]

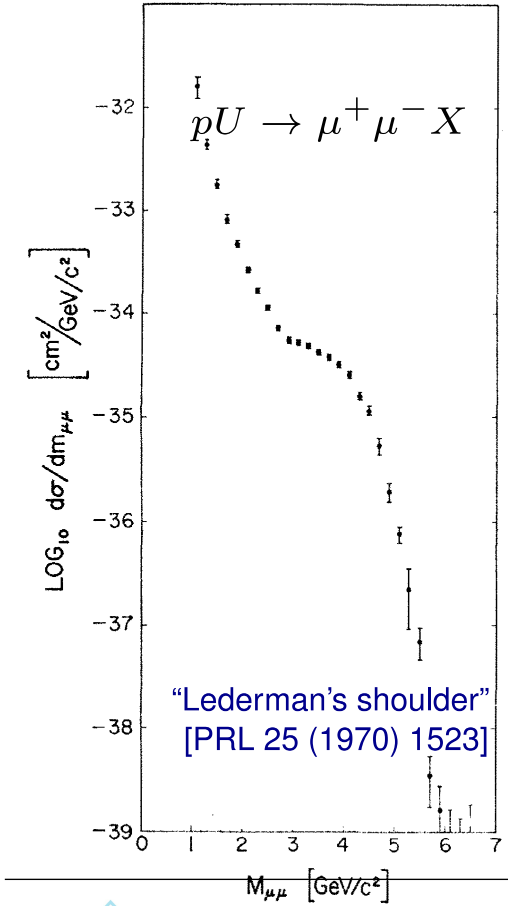


[B. Richter @ ICHEP'74]

$e^+e^- \to X$ total cross section

$c\bar{c}$ & $\tau^+\tau^-$ thresholds close to each other

Several earlier hints of charm



"Lederman's shoulder"
[PRL 25 (1970) 1523]

Prog. Theor. Phys. Vol. 46 (1971), No. 5

A Possible Decay in Flight of a New Type Particle

Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*

Institute for Nuclear Study University of Tokyo
**Yokohama National University*

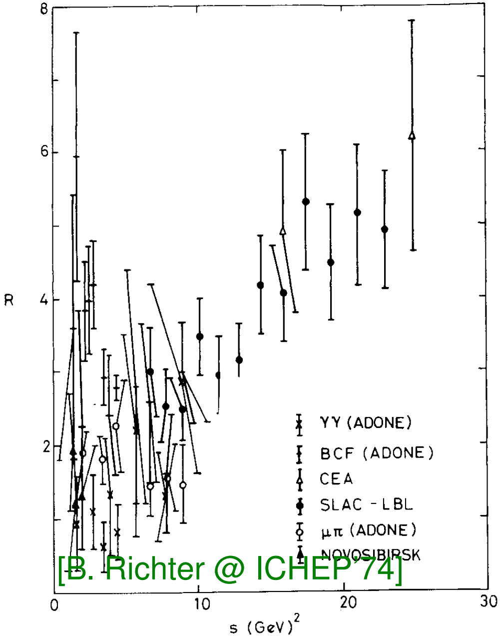
August 9, 1971

Among the secondary particles produced in a high energy jet shower and observed by emulsion chambers exposed to cosmic rays, a possible decay in flight of a new type particle was found.

One event reported as : $X \to \pi^+\pi^0$

$m_X \sim 1.78\,\mathrm{GeV}, \tau_X \sim 2.2\times 10^{-14}\,\mathrm{s}$

[There were other / earlier hints]



[B. Richter @ ICHEP'74]

$$R = (e^+e^- \to X)/(e^+e^- \to \mu^+\mu^-)$$

See also Jon Rosner's talk @ Mary K Fest

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Take 1: what's the big deal?

- GIM mechanism (1970)

PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER 1970

Weak Interactions with Lepton-Hadron Symmetry*

S. L. GLASHOW, J. ILIOPOULOS, AND L. MAIANI†

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139

(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Take 1: what's the big deal?

- GIM mechanism (1970)
- Kobayashi-Maskawa 3-generation proposal (1973)

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

Take 1: what's the big deal?

- GIM mechanism (1970)
- Kobayashi-Maskawa 3-generation proposal (1973)
- Constraints / predictions for m_c from Δm_K and $K_L \to \mu^+\mu^-$

Gaillard & Lee, March 1974

$\Delta m_K \quad \to$ "Equation (2.8) is compatible ... with ... $m_u \ll m_c$ and $m_c \simeq 1.5\,\mathrm{GeV}$"

Vainshtein & Khriplovich, July 1973

$K_L \to \mu^+\mu^- \quad \to \quad m_c < 9\,\mathrm{GeV}$

$\Delta m_K \quad \to \quad m_c - m_u \sim 1\,\mathrm{GeV}$ ("less reliable")

(NB: vacuum insertion approximation works better for Δm_K than one could have expected)

Reading these papers, one might wonder why they haven't received the Nobel Prize?

Take 2: It's a big deal!

- Eight theory papers in PRL, Jan 6, 1975 (More details: Georgi's talk at Alvaro@80)
  - Are the New Particles Baryon-Antibaryon Nuclei? A.S. Goldhaber & M. Goldhaber
  - Interpretation of a Narrow Resonance in e^+e^- Annihilation; Schwinger

A previously published unified theory of electromagnetic and weak interactions proposed a mixing between two types of unit-spin mesons, one of which would have precisely the characteristics of the newly discovered neutral resonance at 3.1 GeV. ... a substantial fraction of the small hadronic decay rate can be accounted for. It is also remarked that other long-lived particles should exist in order to complete the analogy with ρ^0, ω, and ϕ.

  - Possible Explanation of the New Resonance in e^+e^- Annihilation; Borchardt, Mathur, Okubo
  - Model with Three Charmed Quarks; Barnett
  - Heavy Quarks and e^+e^- Annihilation; Appelquist & Politzer
  - Is Bound Charm Found? De Rújula & Glashow
  - Possible Interactions of the J Particle; Nieh, Wu, Yang
  - Remarks on the New Resonances at 3.1 and 3.7GeV; Callan, Kingsley, Treiman, Wilczek, Zee

Appelquist & Politzer: charmonium

That our explanation was correct was soon widely appreciated, and it convinced almost all of the remaining skeptics of the validity of QCD. I suspect that the consensus on this issue was a major contributing factor to the Royal Swedish Academy of Sciences' recognition within just a couple of years of Richter[N] and Ting's discovery.

I hope you all now understand why I owe Tom Appelquist a huge, profound, and public apology. We certainly could have submitted for publication in September substantially the same paper we ultimately wrote two months later.

[D. Politzer, Nobel Lecture, 2004]

In spite of this weakness the charm hypothesis has attractive elements. The

existence of resonances corresponding to a charmed quark and antiquark meson was predicted before the psi particles were discovered. The existence of the particle was discussed by Thomas W. Appelquist and H. David Politzer of Harvard, who named the hypothetical entity charmonium. They also suggested that it could be formed in electron-positron annihilations.

[S. Drell, Scientific American, 1975]

Appelquist & Politzer, "Orthocharmonium and e^+e^- Annihilation"

[PRL 34 (1975) 43, received Nov.19]

(Started at the Aspen Center for Physics at a Summer 1974 workshop)

How could it be so confusing...?

- Quarks as real physical degrees of freedom were not broadly accepted
- The notion of asymptotic freedom was new and not broadly accepted
- Qualitative difference between $e^+e^- \to$ light vs. heavy quarks, and the hadronic states
- See, e.g., Drell, previous page (June 1975)
  "In spite of this weakness the charm hypothesis has attractive elements"
- The D mesons (states with $|c| = 1$) only discovered in 1976
- 3-jet events discovered @ PETRA (DESY), 1979

Some lessons

- Seeds of the idea that if a quark is heavy (compared to $\Lambda_{\rm QCD}$), it does not matter how heavy it is in the papers
- Maybe surprising that Heavy Quark Symmetry came 15 years later, NRQCD even after

---

- Since 1970s, flavor has mostly been an input to model building, since the strong constraints on TeV-scale NP have been known

  All TeV-scale BSM models must contain some mechanism to avoid violating constraints
- For many models, Δm_K and ϵ_K can be the most constraining, since the SM suppressions are the strongest for kaons

Back to flavor

The standard model + neutrino mass

- Gauge symmetry: $SU(3)_c \times SU(2)_L \times U(1)_Y$ parameters

  8 gluons $W^\pm$, Z^0, γ $3\ (+\theta_{\rm QCD})$

- Particle content: 3 generations of quarks and leptons

  $Q_L(3,2)_{1/6},\ u_R(3,1)_{2/3},\ d_R(3,1)_{-1/3}$ 10

  $L_L(1,2)_{-1/2},\ \ell_R(1,1)_{-1}$ 12 or $10\,^*$

  quarks: $\begin{pmatrix} u & c & t \\ d & s & b \end{pmatrix}$ leptons: $\begin{pmatrix} \nu_1 & \nu_2 & \nu_3 \\ e & \mu & \tau \end{pmatrix}$

- Symmetry breaking: $SU(2)_L \times U(1)_Y \ \to\ U(1)_{\rm EM}$

  $\phi(1,2)_{1/2}$ Higgs, with vev: $\langle\phi\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$ 2

- We don't know the Lagrangian that describes the observed particles!

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

Flavor changing processes

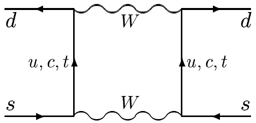
- Flavor change: Initial flavor number $\neq$ final flavor number (Only due to $W^\pm$ in SM)

  $$(\text{Flavor number})_i = (\#\ \text{particles}_i) - (\#\ \text{antiparticles}_i)$$

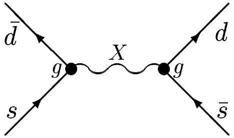
- Flavor changing neutral currents (FCNC): flavor change involving up or $down$ quarks, but not both, and/or ℓ or ν, but not both (E.g.: $K^0 - \overline{K}^0$ mixing, $\mu \to e\gamma$, $B \to K\mu^+\mu^-$)
- FCNC only at loop level in SM, suppressed by $(m_i^2 - m_j^2)/m_W^2$ [GIM mechanism]
- FCNCs are highly suppressed in the SM, probe differences between generations

Neutral meson mixing (a special FCNC)

- Why $\Delta m_K/m_K \sim 7\times 10^{-15}$? In the SM: $\dfrac{\Delta m_K}{m_K} \sim \alpha_w^2\, |V_{cs}V_{cd}|^2\, \dfrac{m_c^2}{m_W^4}\, f_K^2$



- If exchange of a heavy particle X contributed at the SM level to Δm_K:



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

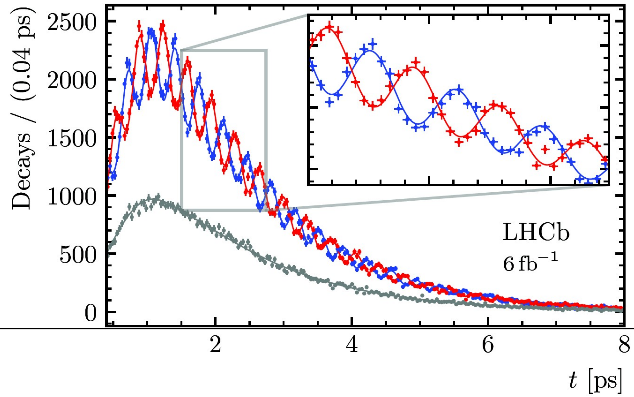
TeV-scale particles with one-loop couplings can still be seen $[g\sim \mathcal{O}(10^{-3})]$

- Four neutral mesons: $K^0\,(\bar s d)$, $B_d^0\,(\bar b d)$, $B_s^0\,(\bar b s)$, $D^0\,(c\bar u)$ [top decays before forming hadrons]

Quantum mechanical two-level systems

Oscillation between a particle and its antiparticle

E.g., $B_s^0 - \bar B_s^0$ oscillation measured by LHCb $\Longrightarrow$



Spectacular track record

- Uncertainty principle $\Rightarrow$ heavy particles, which cannot be produced, affect lower energy processes, E^2/M^2 suppressed if 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)

    (n.b.: 2 generations $+$ superweak is "more minimal" to accommodate CPV, than 3 generations)
  - $\Delta m_K \Rightarrow m_c \sim 1.5\,\mathrm{GeV}$ (Gaillard & Lee; Vainshtein & Khriplovich, 1974)
  - $\Delta m_B \Rightarrow m_t \gtrsim 100\,\mathrm{GeV}$ (bound in 1987: $23\,\mathrm{GeV}$) $\Rightarrow$ large CP violation & FCNC
- Critical in developing SM — it is only unambiguous since 1998 that $m_\nu \neq 0$

What can future data tell us about BSM physics?

Lepton flavor

Quark vs. lepton mixing

- Fermions with same quantum numbers mix, Yukawas define mass eigenstates:

$$M = \begin{pmatrix} M_{a1} & M_{a2} & M_{a3} \\ M_{b1} & M_{b2} & M_{b3} \\ M_{c1} & M_{c2} & M_{c3} \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

- If neutrinos are Majorana, multiply by: $\mathrm{diag}\,(e^{i\eta_1},\ e^{i\eta_2},\ 1)$

  The additional phases $\eta_{1,2}$ don't affect oscillation experiments, only lepton # violation

  Always think about mass eigenstates: if neutrino masses were larger, we would have gotten used to thinking of $\pi \to \mu\overline{\nu}_2$ and $\pi \to \mu\overline{\nu}_3$, instead of $\pi \to \mu\overline{\nu}_\mu$

- Leptons (PMNS): $\theta_{12} \approx 33^\circ$ (solar), $\theta_{23} \approx 49^\circ$ (atm), $\theta_{13} \approx 9^\circ$, δ unknown

- Quarks (CKM): $\theta_{12} \approx 13^\circ,\ \theta_{23} \approx 2^\circ,\ \theta_{13} \approx 0.2^\circ,\ \delta \approx 68^\circ$

Neutrino oscillation measurements

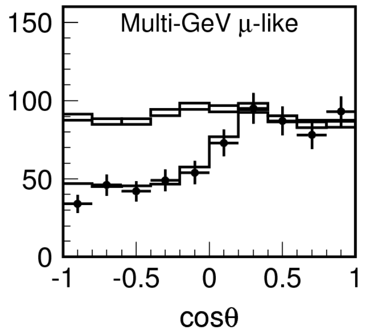
- Three mixing angles have been measured
- Oscillation between two flavors $(\delta m^2 = m_1^2 - m_2^2)$

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

- Atmospheric neutrinos:

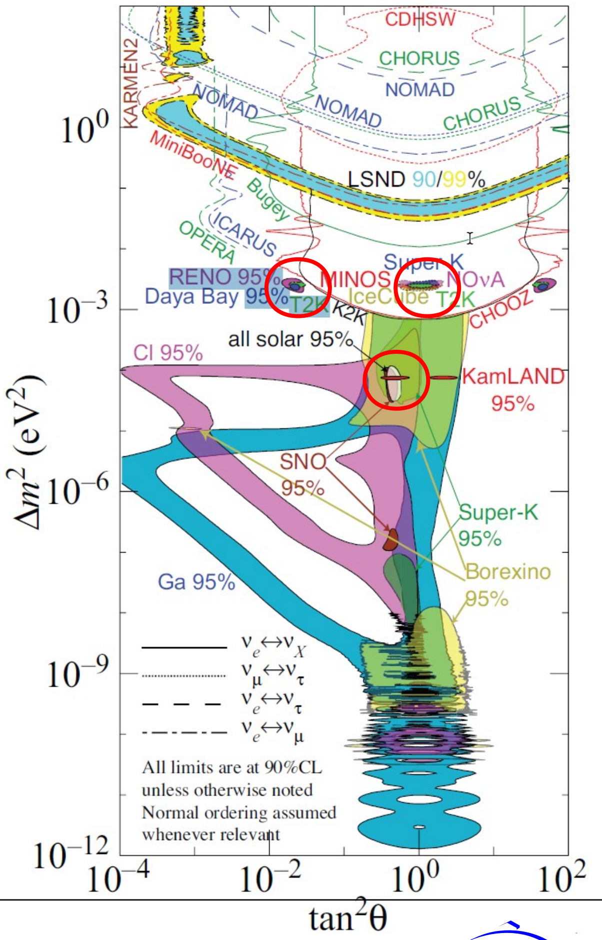
  $1 \sim (10^{-3}) \times (10^{1\ldots 4})\ /\ (10^{0\pm1})$

  half of up-going ν_μ get lost



- Solar neutrinos: $\delta m^2\, L/E \gg 1$
- Two mass-squared differences are measured, but not the absolute mass scale

  (Short baseline anomalies not easy to fit, even with 4 flavors)



Neutrinos — a history of surprises

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

    $\theta_{13} \sim 9^\circ$, not too small — helps CP violation searches

  [inspired by H. Murayama]
- Experiments crucial, independent of prevailing theoretical "guidance"
- Keep open mind about lepton partner (slepton) properties — may be unexpected!

Lepton vs. quark mixing

- Are the origin of quark and lepton masses & mixings related?
- Some lepton processes are especially clean; quark sector observables more rich
- Cannot directly measure neutrino mass eigenstates (possible for e, μ, τ and quarks)
- Neutrino FCNCs seem impossible to search for; e.g., $\nu_i \to \nu_j\, \gamma,\ X \to \nu_i \bar\nu_j (Y)$
- Magnitudes of mixing matrix elements, assuming 3-generation unitarity:

$$U_{\rm PMNS}: \quad \sin\theta_{12} = 0.550 \pm 0.011 \qquad \sin\theta_{13} = 0.148 \pm 0.002$$
$$\sin\theta_{23} = 0.756 \pm 0.025 \qquad \delta = (197^{+42}_{-25})^\circ$$

[νfit 2022, converted]

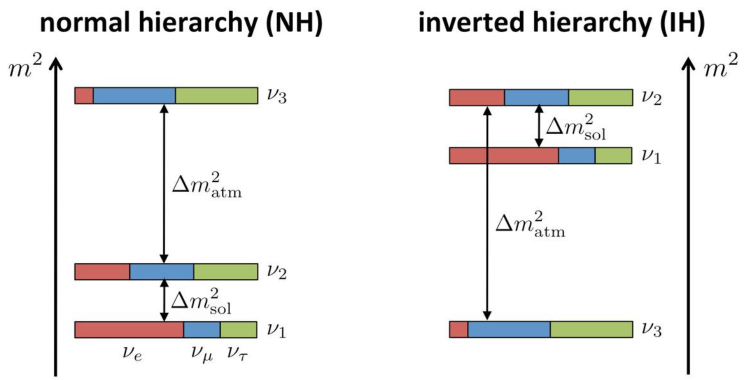
$$V_{\rm CKM}: \quad \sin\theta_{12} = 0.2250 \pm 0.0007 \qquad \sin\theta_{13} = 0.0037 \pm 0.0001$$
$$\sin\theta_{23} = 0.0418 \pm 0.0008 \qquad \delta = (65.7 \pm 1.5)^\circ$$

[PDG 2024]

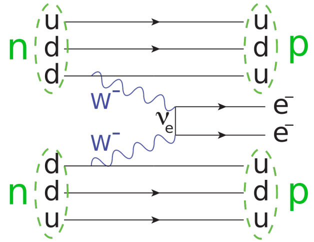
- SM flavor puzzle extended: why lepton & quark masses and mixings so different?

Neutrinos — many unknowns

- Are neutrinos $=$ their own antiparticles?
  (Different than all other known particles? Theoretically favored, most leptogenesis models)
- What is the absolute mass scale?
  We know two mass-squared differences
  At least one state has $m_{\nu_i} \gtrsim 50\,\mathrm{meV}$
  Cosmology: $\sum m_i < 0.072\,\mathrm{eV}$ [DESI 2024] (CL peaks < 0)



- Value of CP violating phase δ?
- Is the mass hierarchy "normal" or "inverted"?
  If inverted hierarchy: planned $0\nu\beta\beta$ experiments will be able to determine if $\nu = \overline{\nu}$ or $\nu \neq \overline{\nu}$
  Normal hierarchy: may or may not see $0\nu\beta\beta$, even in Majorana case



Do ν mass terms violate or conserve lepton # ?

- Key question: what is the Lagrangian? Majorana or Dirac mass?

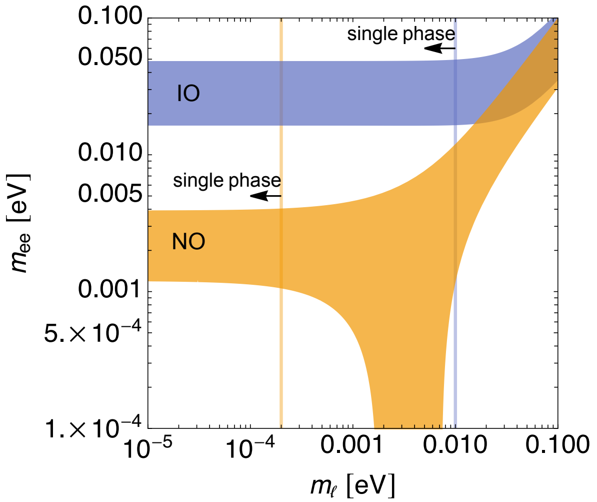
  Neutrinoless double beta decay $(0\nu\beta\beta)$ measures: $m_{ee} = \left|\sum_{i=1}^{3} m_i\, U_{ei}^2\right|$

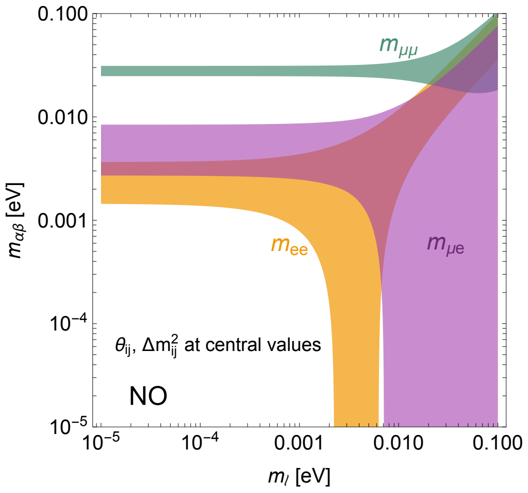
  Can vanish for NH, even if neutrinos are Majorana

  Mu2e and COMET: improve $\mu^- \to e^+$ conversion $\sim m_{\mu e} = \left|\sum_{i=1}^{3} m_i\, U_{\mu i} U_{ei}\right|$

- In principle, LNV is detectable with increased $m_{\mu e}$ sensitivity, even in case of normal ordering

- Tantalizing PMNS values: $m_{ee} + m_{\mu e}$ cannot vanish (barely, at the 2σ level)





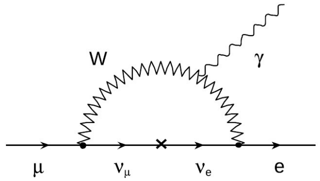
[Dery, Gori, Grossman, ZL, 2406.18647]

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

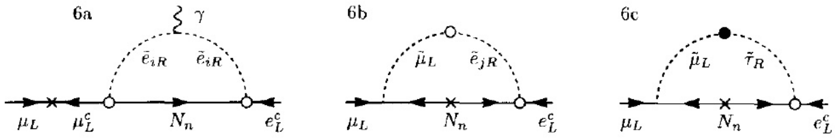
Charged lepton flavor violation (CLFV)

- SM w/ $m_\nu = 0 \Rightarrow$ lepton flavor conservation
  Given $m_\nu \neq 0$, no reason to impose it as a symmetry

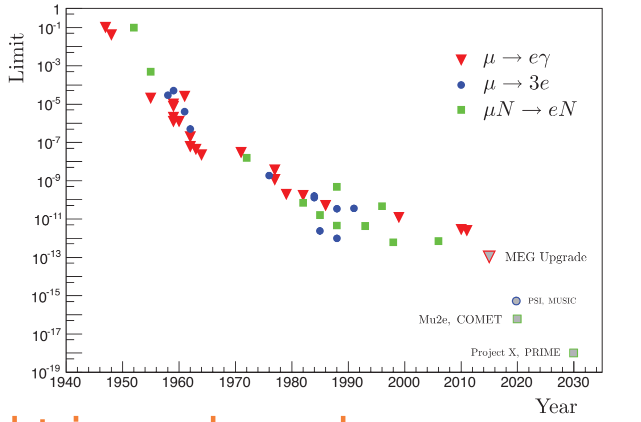


$$\mathcal{B}(\mu \to e\gamma) \sim \alpha\, \frac{m_\nu^4}{m_W^4} \sim 10^{-52}$$

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



History of $\mu \to e\gamma,\ \mu N \to eN,$ and $\mu \to 3e$



- 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

Testing quark flavor

(Expect big increases in relevant data sets)

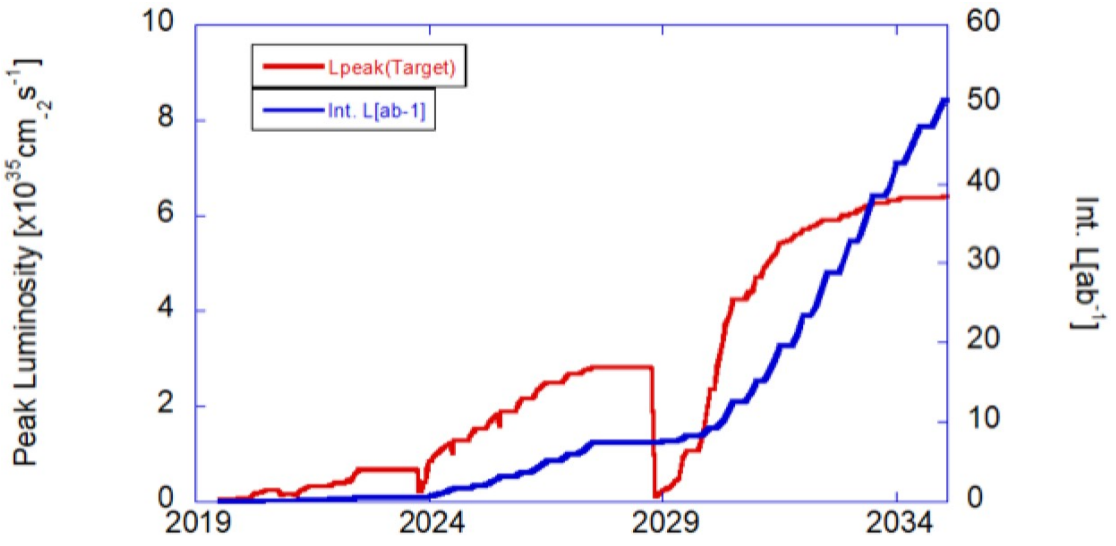
LHCb — at CERN

	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 in LS3, for HL-LHC
- LHCb, 2017, Expression of Interest for an upgrade in LS4 to $2 \times 10^{34}/\text{cm}^2/\text{s}$
  An integral part of the full exploitation of the LHC

Belle II — SuperKEKB in Japan



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

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Testing quark flavor — Take I

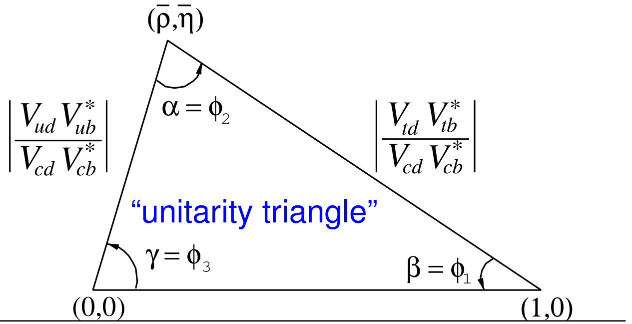
- $(u,\, c,\, t)\; W^\pm\; (d,\, s,\, b)$: 9 complex couplings $\Rightarrow$ many relations Are they consistent?

$$V_{\rm CKM} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{\text{CKM matrix}} = \begin{pmatrix} 1-\frac12\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac12\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \ldots$$

Only 4 parameters: λ ("Cabibbo angle", from $K\to\pi\ell\nu$), A (from $b\to c\ell\nu$)
used to be less precise: $\bar\rho$ and $\bar\eta$ (only source of CP violation)

CKM measurements: magnitudes $\sim$ decay rates; phases $\sim CP$ viol. (only 1 parameter!)

- Many observables are $f(\rho,\eta)$ — need to compare:
  - $b\to u\ell\bar\nu \;\Rightarrow\; |V_{ub}/V_{cb}|^2 \propto \rho^2+\eta^2$
  - $\Delta m_{B_d}/\Delta m_{B_s} \;\Rightarrow\; |V_{td}/V_{ts}|^2 \propto (1-\rho)^2+\eta^2$
  - CP violation in K, B, B_s decay



Precision SM tests with kaons

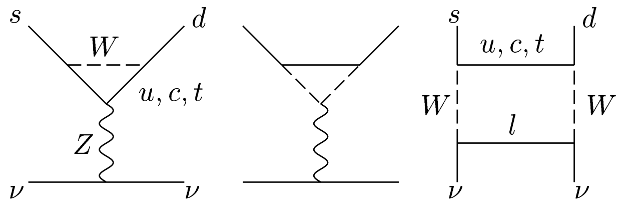
- CPV in K system is at the right level (ϵ_K accommodated with $\mathcal{O}(1)$ KM phase)
- Hadronic uncertainties precluded precision tests (ϵ'_K notoriously hard to calculate)

  Cannot rule out substantial BSM contribution to the measured value of ϵ'_K

  (N.B.: bad luck in part — heavy m_t enhanced hadronic uncertainties, but helps for B physics)

- $K \to \pi\nu\overline{\nu}$: precise theory, but tiny rates $\sim 10^{-10}\,(K^\pm),\ 10^{-11}\,(K_L)$

$$\mathcal{A} \propto \begin{cases} (\lambda^5\, m_t^2) + i(\lambda^5\, m_t^2) & t: \text{CKM suppressed} \\ (\lambda\, m_c^2) + i(\lambda^5\, m_c^2) & c: \text{GIM suppressed} \\ (\lambda\, \Lambda_{\rm QCD}^2) & u: \text{GIM suppressed} \end{cases}$$



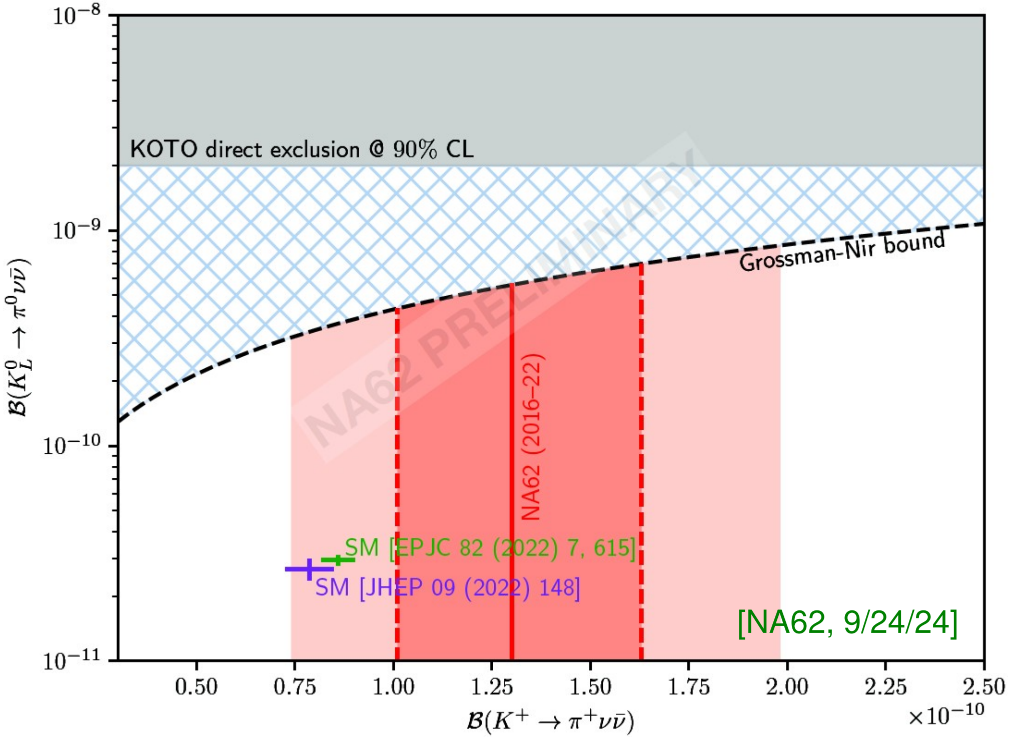
- Experimental uncertainty $\mathcal{O}(30\%)$ in $K^+ \to \pi^+\nu\bar{\nu}$, much larger in $K_L \to \pi^0\nu\bar{\nu}$

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

- Searched for since the 1960s (longer than for Higgs), sensitive to $\mathcal{O}(100\,\mathrm{TeV})$ scale
- Last week: first time that the background-only hypothesis can be rejected with $> 5\sigma$

  NA62: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (13.0^{+3.3}_{-2.9}) \times 10^{-11}$

  Consistent with SM ($\approx 8 \times 10^{-11}$), at 1.7σ
- KOTO: $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) < 2 \times 10^{-9}$



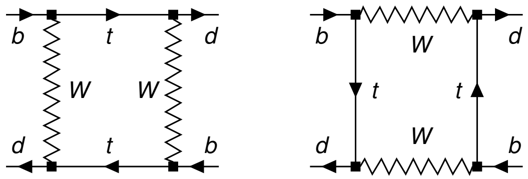
B mesons: what's special about them?

- Many interesting processes with clean theoretical interpretations:
  - Top quark loops not too strongly suppressed
  - Large CP violating effects possible, some with clean interpretation
  - Some of the hadronic physics understood model independently $(m_b \gg \Lambda_{\rm QCD})$
- Experimentally feasible to study:
  - $\Upsilon(4S)$ resonance is clean source of B mesons
  - Long B meson lifetime

    (If $|V_{cb}|$ were as large as $|V_{us}|$, no B factories built, these lectures would not take place, etc.)
  - Timescale of oscillation and decay comparable: $\Delta m/\Gamma \simeq 0.77$ (and $\Delta\Gamma \ll \Gamma$)

B meson mixing

- Quantum mechanical two-level system; flavor eigenstates: $|B^0\rangle = |\overline{b}\,d\rangle,\ |\overline{B}{}^0\rangle = |b\,\overline{d}\rangle$
- Time evolution: $i\,\dfrac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}|B^0(t)\rangle\\ |\overline{B}{}^0(t)\rangle\end{pmatrix} = \left(M - \dfrac{i}{2}\Gamma\right)\begin{pmatrix}|B^0(t)\rangle\\ |\overline{B}{}^0(t)\rangle\end{pmatrix}$



  Mass eigenstates: $|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}{}^0\rangle$

  $M,\ \Gamma$: 2×2 Hermitian matrices (*CPT* implies $M_{11} = M_{22}$ and $\Gamma_{11} = \Gamma_{22}$)

- Off-diagonal elements dominated by box diagrams with top $\Rightarrow$ short distance

  In the SM: $$M_{12} = (V_{tb}V_{td}^*)^2\,\frac{G_F^2}{8\pi^2}\,\frac{m_W^2}{m_B}\,S\!\left(\frac{m_t^2}{m_W^2}\right)\eta_B\,b_B(\mu)\,\langle B^0|(\overline{b}_L\gamma^\nu d_L)^2|\overline{B}{}^0\rangle$$

  CKM calculable perturbatively nonperturbative

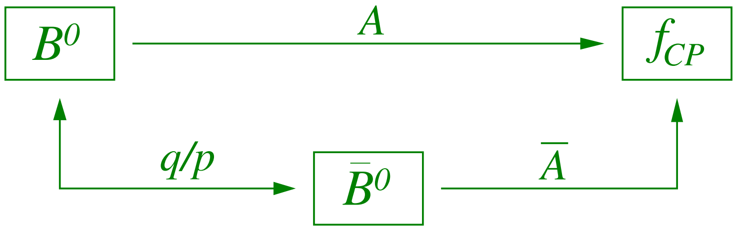
- Time dependence involves mixing & decay: $|B_{H,L}(t)\rangle = e^{-(iM_{H,L}+\Gamma_{H,L}/2)t}|B_{H,L}\rangle$
- Hadronic uncertainties in Δm (LQCD helps) and especially $\Delta\Gamma$, but not in $\arg(q/p)$

CP violation

CPV in interference between decay and mixing

- Can get theoretically clean information in some cases when B^0 and $\overline{B}^0$ decay to same final state

  Mass eigenstates: $|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle$



- Time-dependent CP asymmetry:

$$a_{f_{CP}} = \frac{\Gamma[\overline{B}^0(t) \to f_{CP}] - \Gamma[B^0(t) \to f_{CP}]}{\Gamma[\overline{B}^0(t) \to f_{CP}] + \Gamma[B^0(t) \to f_{CP}]}$$

- If amplitudes with one weak phase dominate, hadronic physics drops out:

$$a_{f_{CP}} = (\pm 1)\sin(\underbrace{\text{phase difference between decay paths}}_{\arg[(q/p)(\overline{A}/A)]})\,\sin(\Delta m\, t)$$

- Measure phases in the Lagrangian with small theoretical uncertainties

Quantum entanglement — use EPR

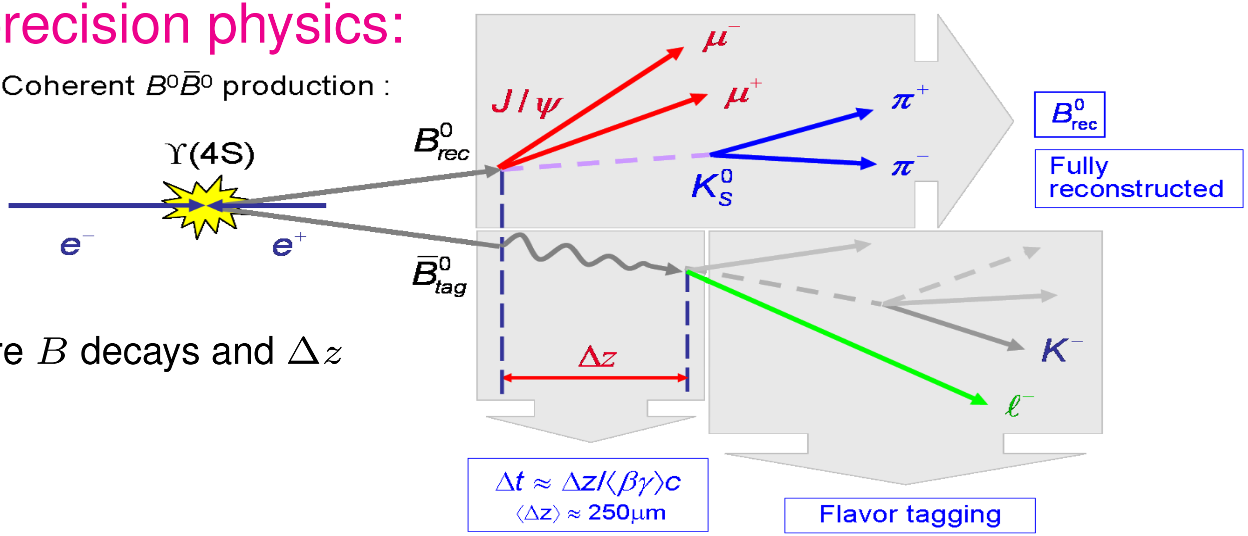
- $B^0\overline{B}^0$ pair created in a p-wave ($L = 1$) evolve coherently and undergo oscillations

  Two identical bosons must be in a symmetric state — if one decays as a B^0 ($\overline{B}^0$), then at the same time the other B must be $\overline{B}^0$ (B^0)

- EPR effect used for precision physics:

Coherent $B^0\overline{B}^0$ production :

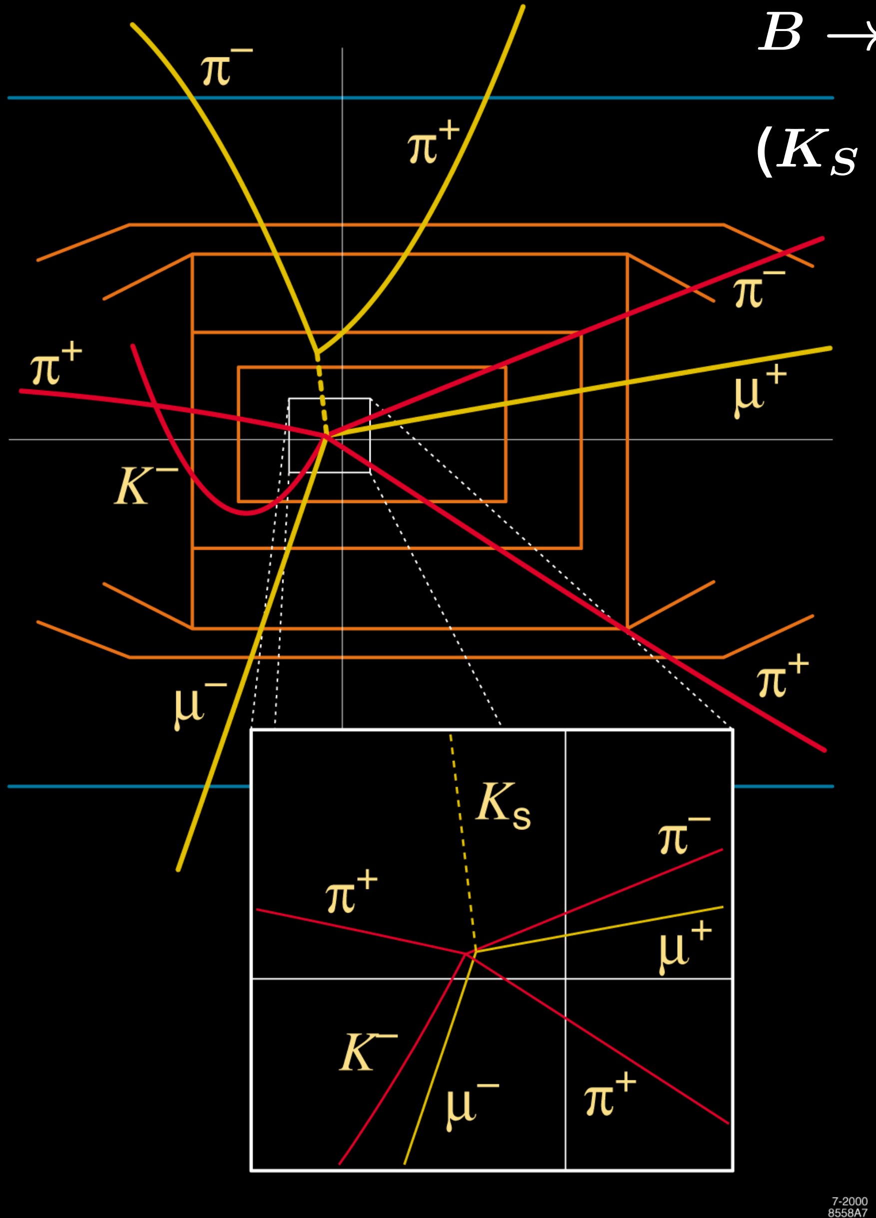
Measure B decays and Δz



- First decay ends quantum correlation and determines flavor of other B at $t = t_1$

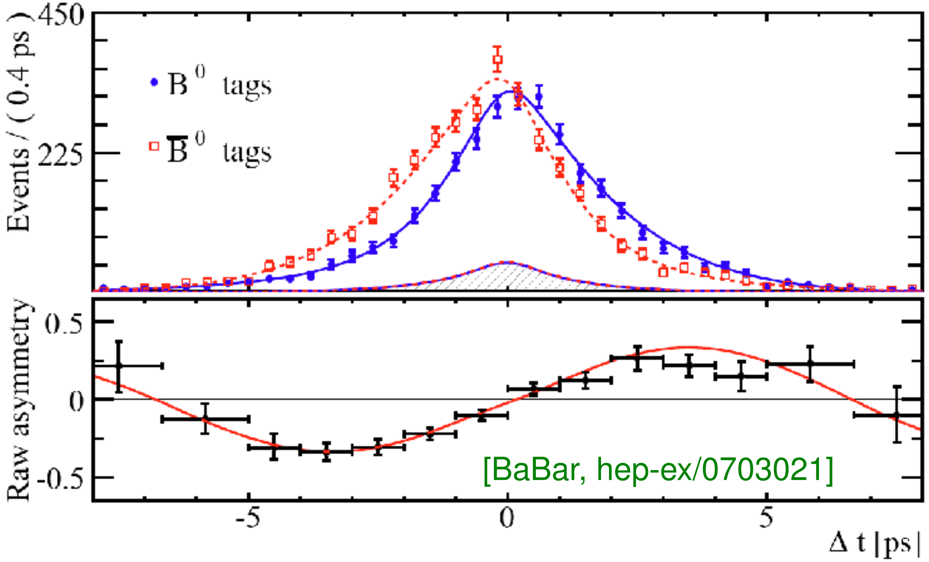
$B \to \psi K_S$ **event** $(B\textsc{a}B\textsc{ar})$

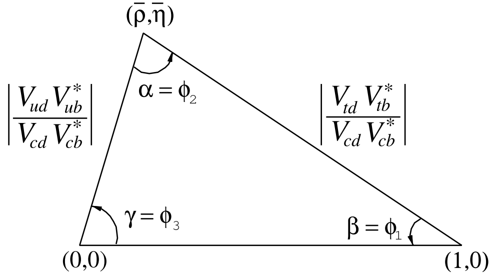
$(K_S \to \pi^+\pi^-,\ \psi \to \mu^+\mu^-)$

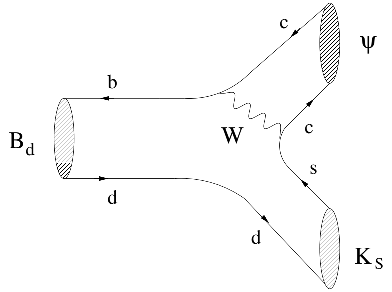


CP violation in $B \to \psi K_S$ by the naked eye

- CP violation is an $\mathcal{O}(1)$ effect, world average: $\sin 2\beta = 0.709 \pm 0.011$







$$a(t) = \frac{\Gamma[\overline{B}^0(t) \to \psi K] - \Gamma[B^0(t) \to \psi K]}{\Gamma[\overline{B}^0(t) \to \psi K] + \Gamma[B^0(t) \to \psi K]} = \sin 2\beta\, \sin(\Delta m\, t)$$

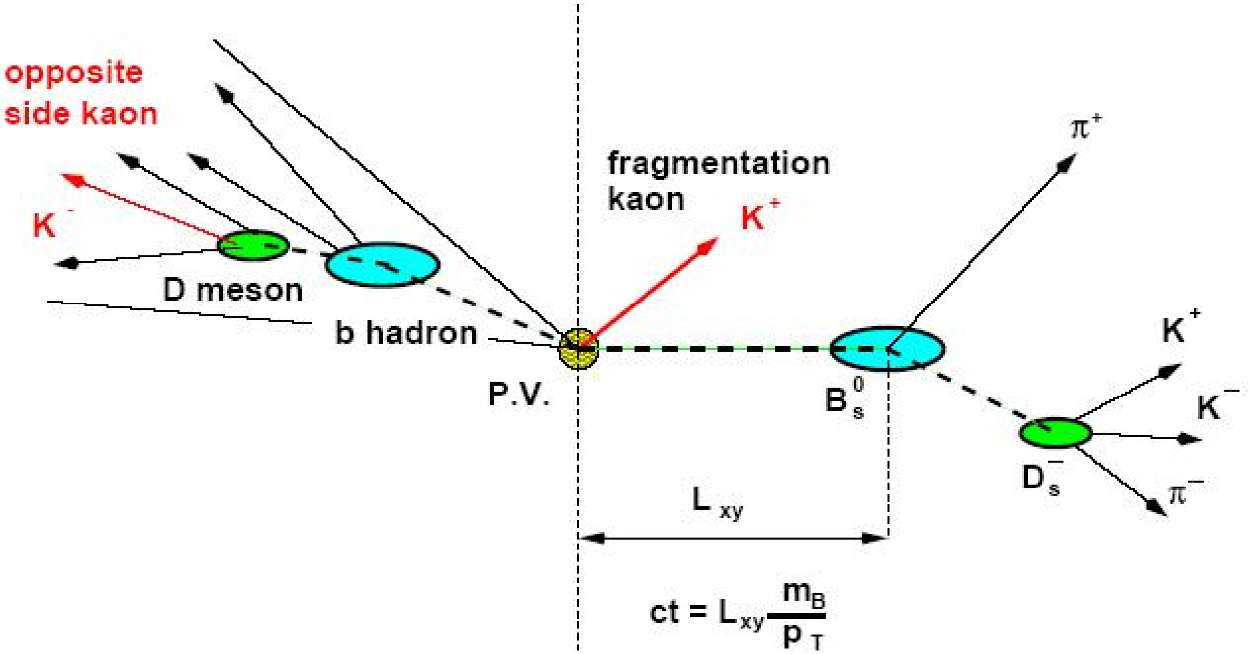
- CP violation in K decays is small because of small CKM elements, not because CP violation is generically small — it is $\mathcal{O}(1)$ in some B decays

$pp \to b\bar{b}$ or $Z \to b\bar{b}$: no quantum correlation

- B_s^0 with sufficient boost to study CPV at the LHC (and earlier at the Tevatron)

- $gg,\, q\bar{q} \to b\bar{b}$: measure flavor of a b hadron, and flavor of B_s^0 as a function of time

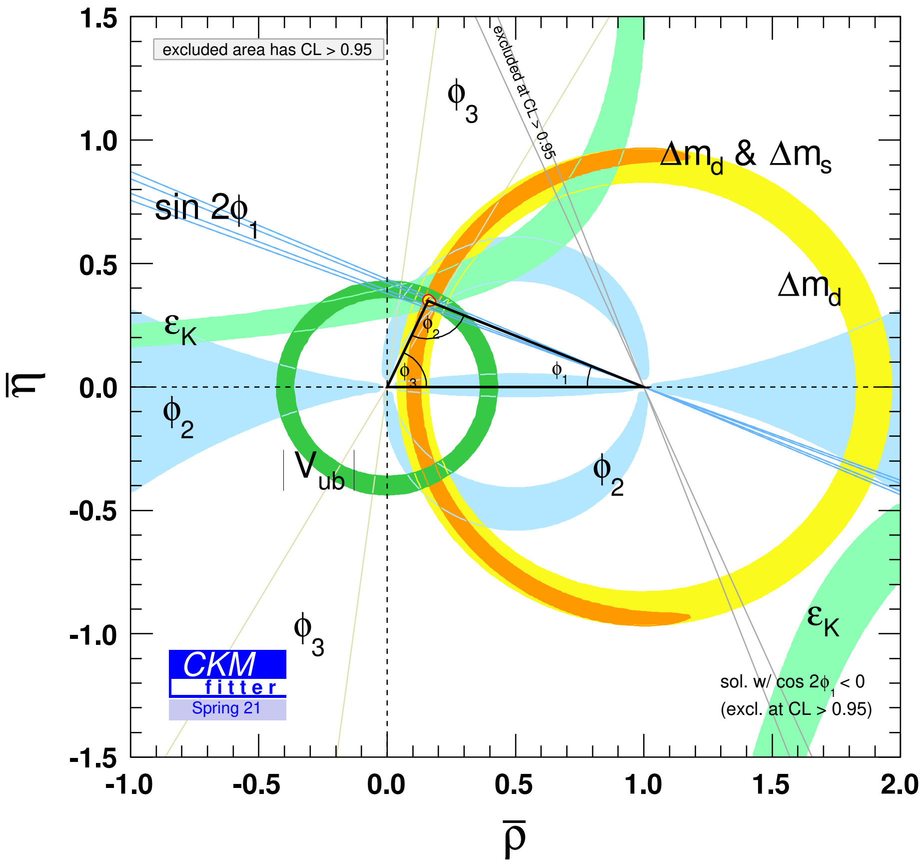
  Need excellent time resolution, and fully reconstructed B_s^0 to know its boost



CP violation

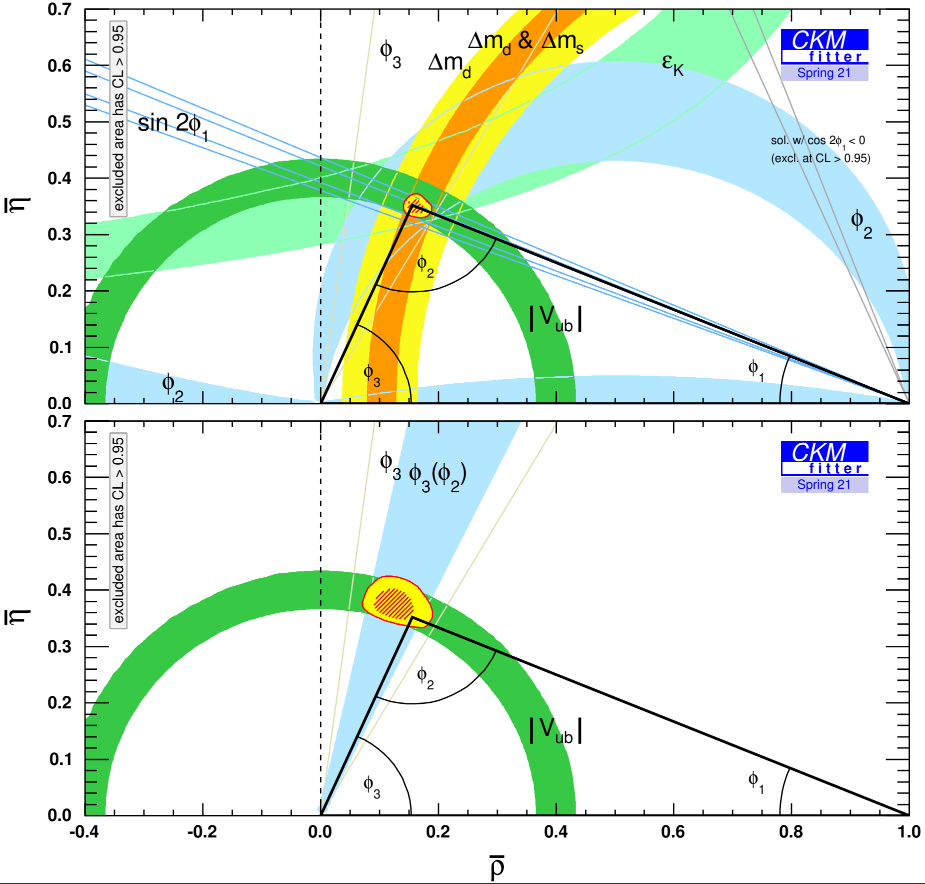
The B-factories money plot

- Spectacular progress in last 20 years
- The CKM mechanism dominates CP violation and flavor changing processes
- The implications of this consistency are often overstated; larger allowed region if there is NP



The B-factories money plot

- Spectacular progress in last 20 years
- The CKM mechanism dominates CP violation and flavor changing processes
- The implications of this consistency are often overstated; larger allowed region if there is NP
- Compare tree-level (lower plot) and loop-dominated measurements
- LHCb: B_s constraints caught up with B_d
- $\mathcal{O}(20\%)$ 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

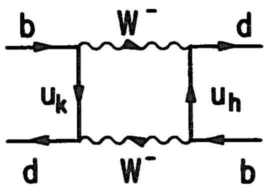
Toshihide Maskawa

Testing quark flavor — Take II

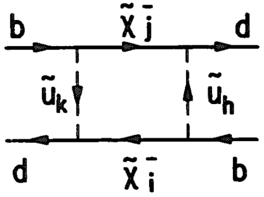
- The agreement of measurements is often interpreted as strong constraints on NP
- Assume: tree-level decays dominated by SM, BSM only significant in FCNCs (loops)
- Consider tree-level + meson mixing:

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

  $$h\, e^{2i\sigma} = A(B^0 \to \overline{B}^0)/A_{\rm SM}(B^0 \to \overline{B}^0) - 1$$



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



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

- Is $\eta = 0$ allowed? If not, the CKM mechanism plays a role in CP violation

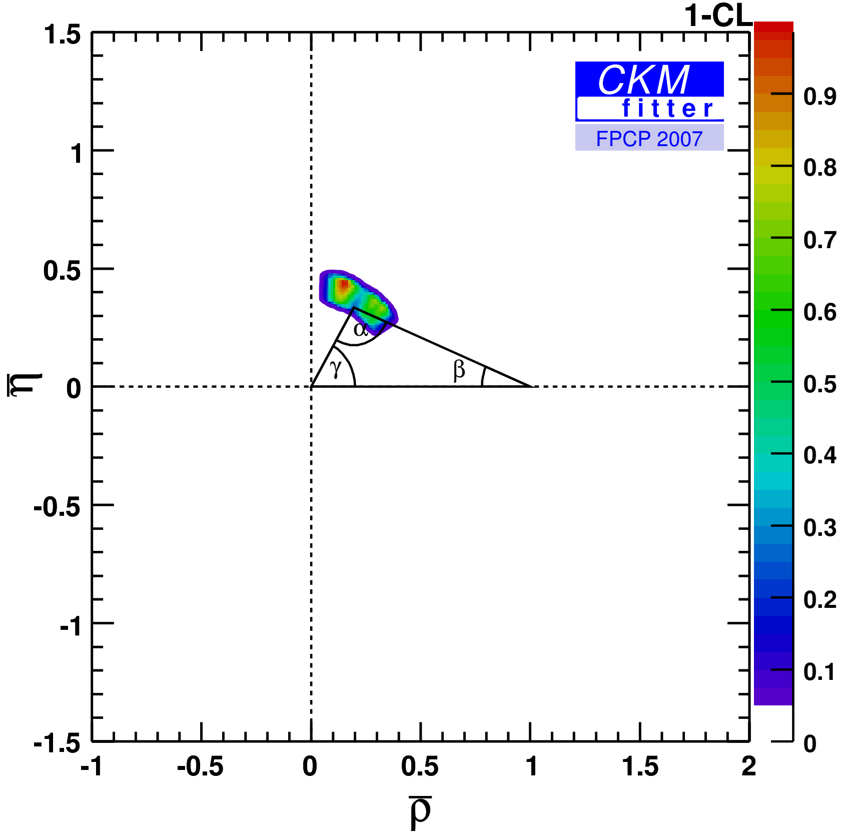
  (Recall: if $\eta = 0$, then the CKM matrix would be real, no contribution to CP violation)

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

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

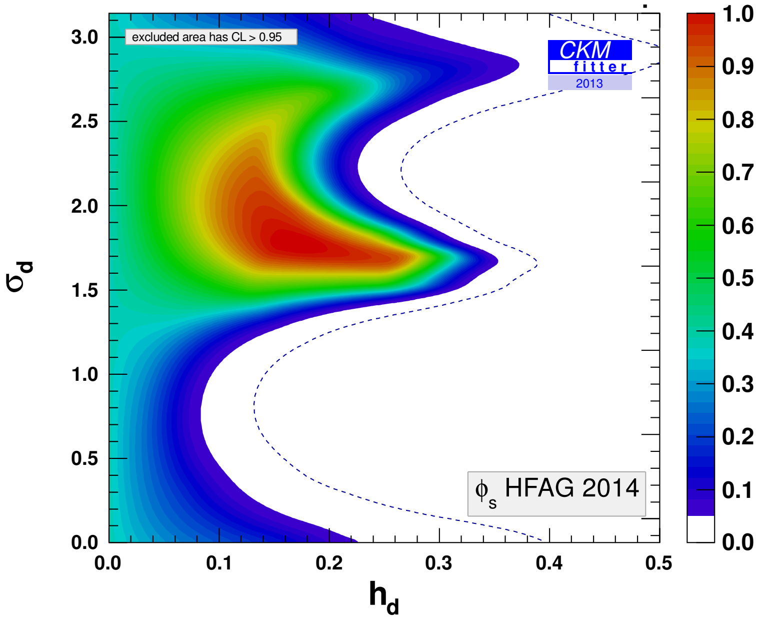
Is $\eta = 0$ allowed?

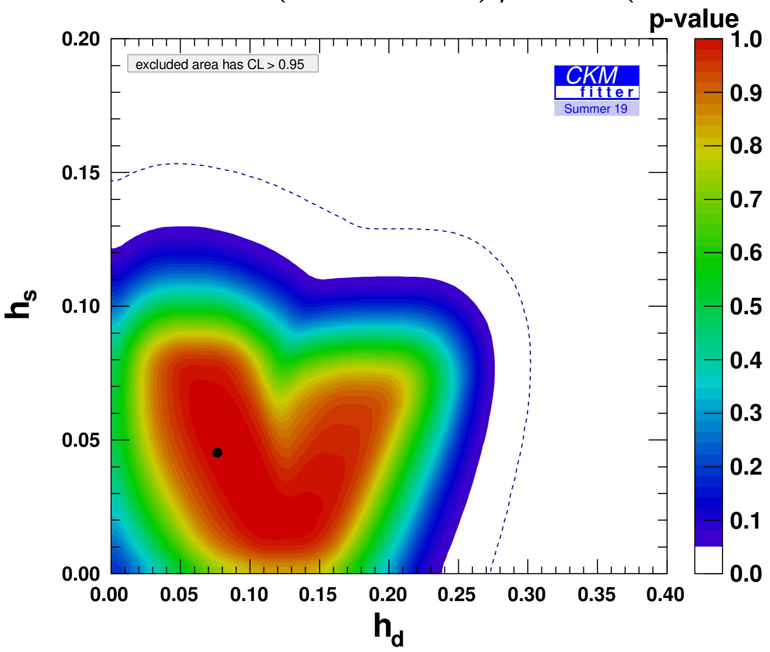
- CKM fit with h and σ parameters added:
  $h\, e^{2i\sigma} = A(B^0 \to \overline{B}^0)/A_{\rm SM}(B^0 \to \overline{B}^0) - 1$
- Weak interaction plays a role in flavor and CP violation, even if NP is present



Is $h > 1$ allowed?

- CKM fit with h and σ parameters added: $h\, e^{2i\sigma} = A_{\rm NP}(B^0 \to \overline{B}^0)/A_{\rm SM}(B^0 \to \overline{B}^0)$





- Last decade: BSM contributions to B_s mixing more constrained than those in B_d
- Weak interaction dominates CP violation: BSM / SM $\lesssim 25\%$

NP in B mixing: improvements this decade

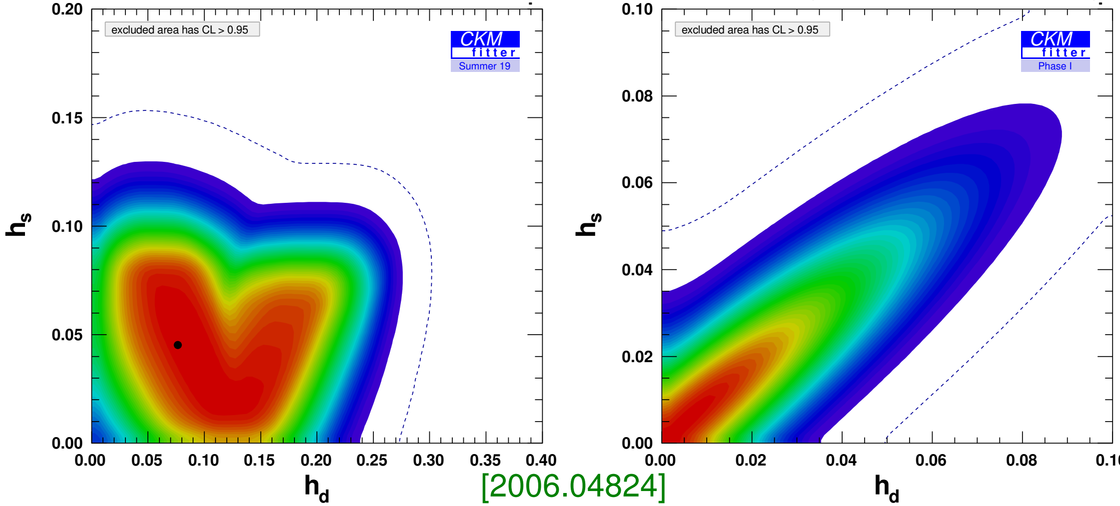
- At 95% CL: NP $\lesssim (0.25 \times$ SM$)$ $\Rightarrow$ NP $\lesssim (0.08 \times$ SM$)$

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

$$\Rightarrow \Lambda \sim \begin{cases} 2.3 \times 10^3\ \text{TeV} \\ 20\ \text{TeV}\ \text{(tree + CKM)} \\ 2\ \text{TeV}\ \text{(loop + CKM)} \end{cases}$$

- Complementary to high-p_T searches
  (E.g., similar to LHC $m_{\tilde g}$ reach)

Now | LHCb $50/\text{fb}$ + Belle II $50/\text{ab}$



[2006.04824]

[color: 2σ, dotted: 3σ]

$M_{12}^{(q)} = M_{12}^{\text{SM}} (1 + h_q e^{2i\sigma_q})$

- BSM sensitivity would continue to increase until much larger data sets
  (LHCb will collect 300/fb after second upgrade in LS4, initial plans for a possible Belle II upgrade)

Summary (1)

- Flavor physics probes scales $\gg 1\,\text{TeV}$; sensitivity limited by statistics, not theory
  $\Rightarrow$ New physics could show up any time measurements improve
- KM phase is the dominant contribution to the observed CP violation so far
- In most FCNC processes NP/SM $\sim 20\%$ still allowed (discovery $\Rightarrow$ upper bound on NP scale)
- CP violation is $\mathcal{O}(1)$, just screened by small mixing angles in K and D decays
- Data sets and sensitivities will improve by a lot
- Interesting theory and experimental challenges

- Near future: "anomalies", both in quark & lepton sector, might first be established
  Long term: large increase in discovery potential in many modes

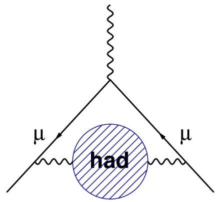
---

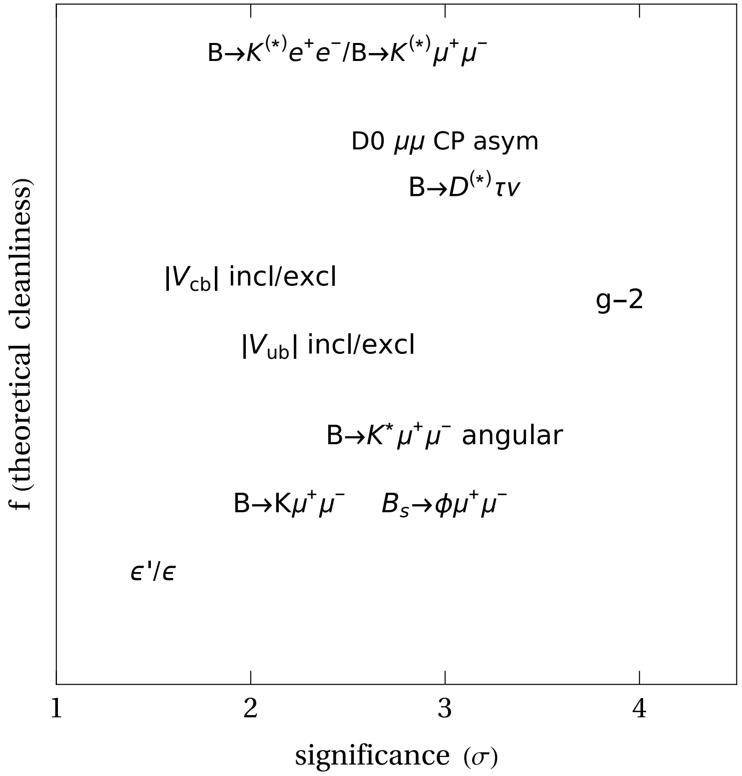
2

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.
- (Was?) most significant: $g-2$
  Hadronic contributions argued among lattice QCD groups

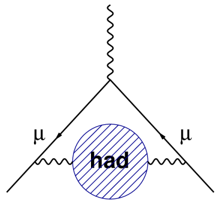


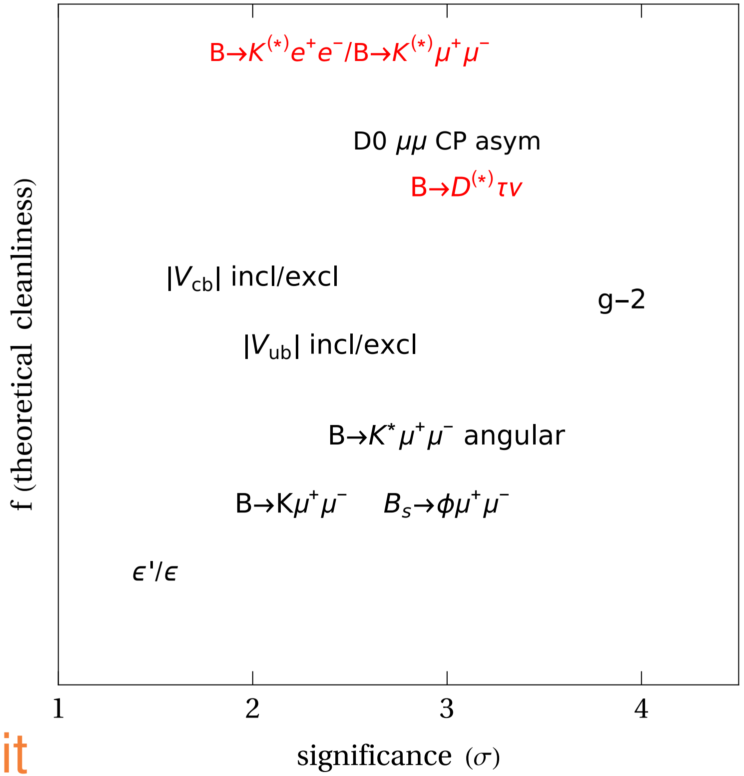


Recent hints of deviations from the SM

- 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.
- (Was?) most significant: $g-2$
  Hadronic contributions argued among lattice QCD groups

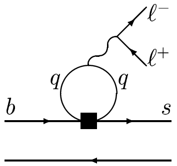




- Each could be a whole talk — I can only cover some of it

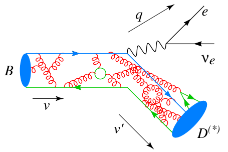
B "anomalies" — major focus in the past 10 years

- Lepton non-universality would be clear evidence for NP



1) R_K and R_{K^*} $\quad (B \to X\mu^+\mu^-)/(B \to Xe^+e^-) \sim 20\%$ correction to SM loop

2) $R(D)$ and $R(D^*)$ $\quad (B \to X\tau\bar\nu)/(B \to X(e,\mu)\bar\nu) \sim 20\%$ correction to SM tree



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

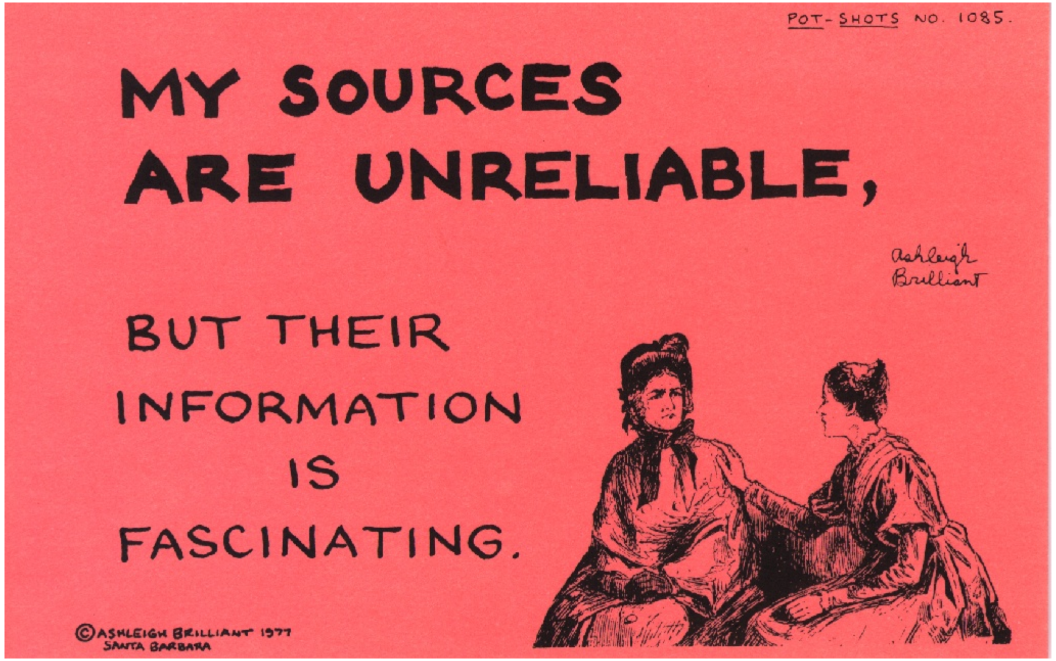
- Theor. less clean: 3) P_5' angular distribution $(B \to K^*\mu^+\mu^-)$
  4) $B_s \to \phi\mu^+\mu^-$ and related rates

Could fit 1), 3), 4) with one operator: $C_{9,\mu}^{(\mathrm{NP})}/C_{9,\mu}^{(\mathrm{SM})} \sim -0.2\,,\ \ O_{9,\mu} = (\bar s\gamma_\alpha P_L b)(\bar\mu\gamma^\alpha\mu)$

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

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

To avoid...



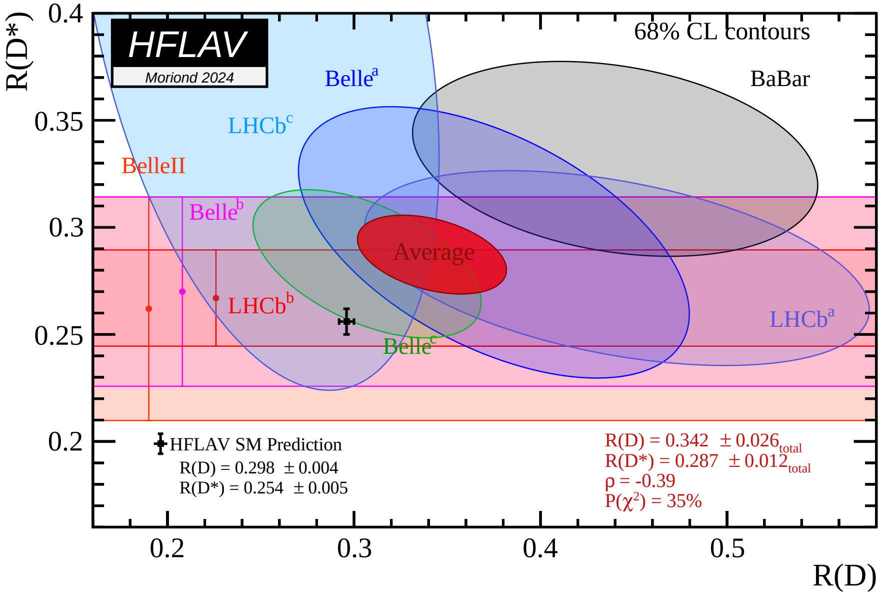
I'll try to separate what's "proven" and what's "hoped"

$$\boxed{B \to D^{(*)}\ell\bar{\nu}}$$

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

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

  3.3σ from SM predictions — theory robust due to heavy quark symmetry $+$ lattice QCD



- Imply NP at a fairly low scale

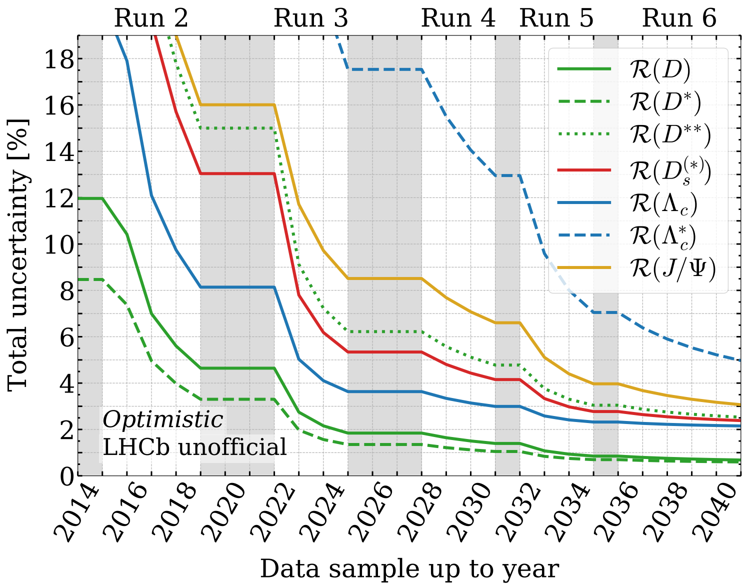
  Mediators constrained or visible at ATLAS & CMS

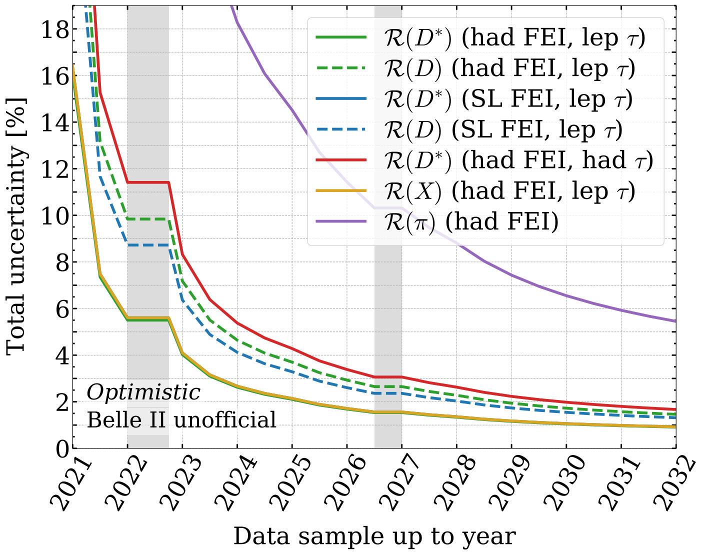
  Many models Fierz (mostly) to $V - A$ $\Rightarrow$ SM distributions

- 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 many ATLAS & CMS searches

Exciting future prospects



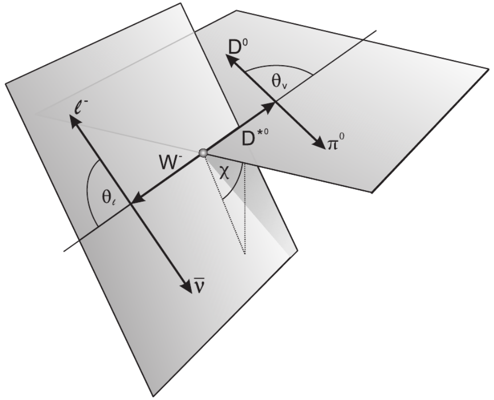


[2101.08326]

- Measurements will improve a lot, and reach few % in several decay modes
- Even if deviations from SM decrease, may establish NP
- Competition, complementarity, cross-checks between LHCb and Belle II

Unfolded distributions: not done before 2017

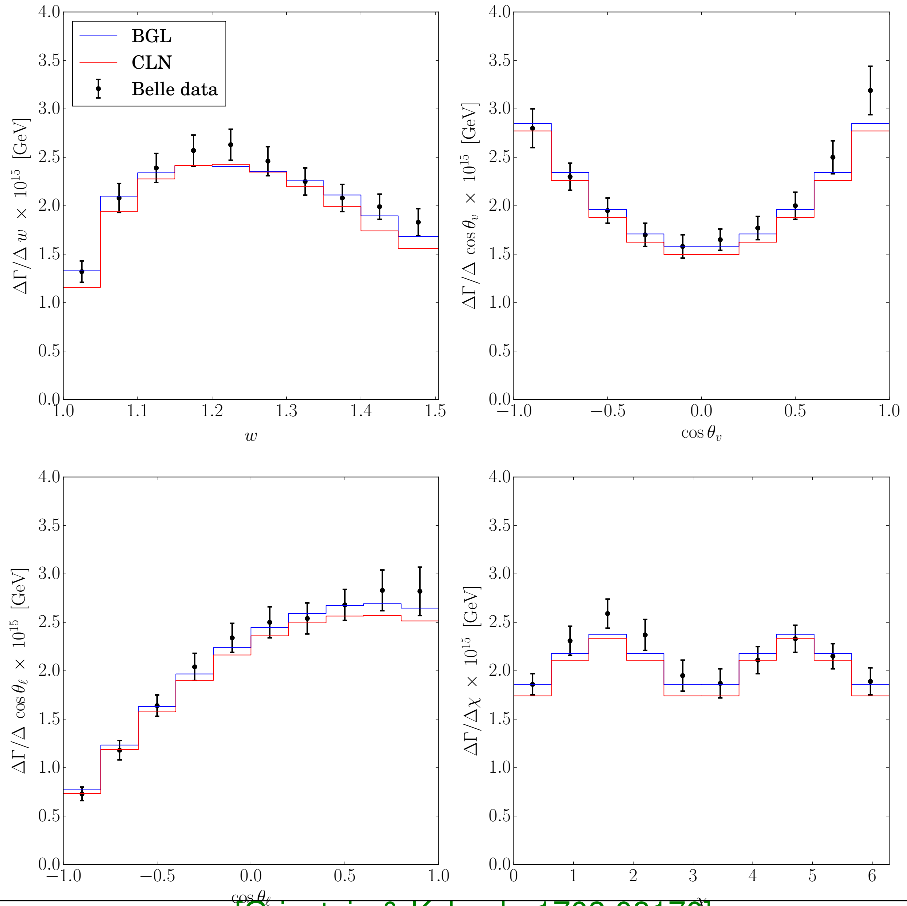
- Belle published unfolded $B \to D^* l \bar{\nu}$ $(l = e, \mu)$ distributions [1702.01521]



- Fitted shapes: BGL: Boyd, Grinstein, Lebed, '95–97
  CLN: Caprini, Lellouch, Neubert, '97

  1997–2017: all measurements used CLN

- Enabled performing many different fits to data



[Grinstein & Kobach, 1703.08170]

Analyticity $\to$ BGL and z-expansion

- Kinematics: $\quad w = v \cdot v' = \dfrac{m_B^2 + m_{D^{(*)}}^2 - q^2}{2 m_B m_{D^{(*)}}}\,, \qquad v = \dfrac{p_B}{m_B}\,, \qquad v' = \dfrac{p_{D^{(*)}}}{m_{D^{(*)}}}$

$$z(w) = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}} \qquad \text{or} \qquad z_*(w) = \frac{\sqrt{w+1} - \sqrt{2}\,a}{\sqrt{w+1} + \sqrt{2}\,a}\,, \quad a = \left(\frac{1+r_D}{2\sqrt{r_D}}\right)^{1/2}$$

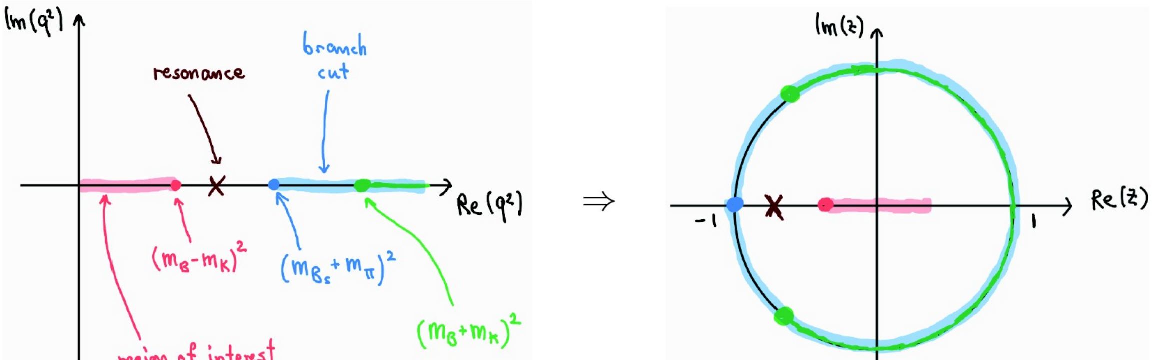
- Blaschke factors: $P \sim \prod\limits_k \dfrac{z - z_k}{1 - \bar{z}_k z}$ removes poles at z_i, and unimodular on unit circle

[Boyd, Grinstein, Lebed, hep-ph/9508211, etc.]

- BGL expansion of each F_i form factor:

$$F_i(z) P_i(z) \phi_i(z) = \sum a_n z^n \qquad \sum_{n=0}^{\infty} |a_n|^2 \le 1$$

(Illustration is for $b \to s$ transition; analytic structures very similar: replace $K \to D$, resonances are B_c states)



[image credit]

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

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

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

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

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

- 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]

Making the most of HQET in $B \to D^{(*)}\ell\bar{\nu}$

- Determine all 6 form factors from 4 distributions in e, μ modes [1703.05330]
  Measured: $B \to Dl\bar{\nu}:\ \mathrm{d}\Gamma/\mathrm{d}w \qquad B \to D^* l\bar{\nu}:\ \mathrm{d}\Gamma/\mathrm{d}w$ and $R_{1,2}(w)$ form factor ratios
- HQET: One Isgur-Wise function in heavy quark limit $+3$ more at $\mathcal{O}(\Lambda_{\mathrm{QCD}}/m_{c,b})$
- Data for $B \to D^{(*)}\, l\bar{\nu}$ determine all form factors up to $\mathcal{O}(\Lambda^2_{\mathrm{QCD}}/m^2_{c,b}\,,\ \alpha_s^2)$
- $\mathcal{O}(1/m^2_{c,b})$: number of "universal" functions proliferate
  Studied truncations of $\mathcal{O}(1/m^2)$ terms: vanishing chromomagnetic (VC) limit or residual chiral (RC) expansion
  (Other approach is to include $1/m_c^2$ uses LCSR) [2206.11281]

HQET order	Isgur-Wise functions All	RC Expansion	VC Limit
1	1	1	1
$1/m_{c,b}$	3	3	2
$1/m_c^2$	20	1	2
$1/m_{c,b}^2$	32	3	3

- Many open questions: RCE from first principles? Order of BGL truncation? Constraints from unitarity / LQCD / models? Tensions of FNAL/MILC and exp. data?

Recent progress for inclusive semileptonic decays

- $\Gamma(B \to X_s\gamma)$ motivated multi-loop developments since '90s; important to constrain SM

  [2007.04320, 2309.14707, etc., waiting for improved measurements]

- $\Gamma(B \to X_c\ell\bar{\nu})/|V_{cb}|^2$ has been calculated in the OPE with $\sim 2\%$ uncertainty

  Impressive recent 3-loop results (rate, m_b^{kin}) [2011.13654, 2011.11655, 2107.00604, 2205.03410, etc.]
  Also α_s corrections to $\mathcal{O}(1/m^3)$ [2112.03875]

  My tentative conclusion: may be hitting a wall around 1% (may be too strong?)
  (Not accounting for any experimental cuts on phase space)

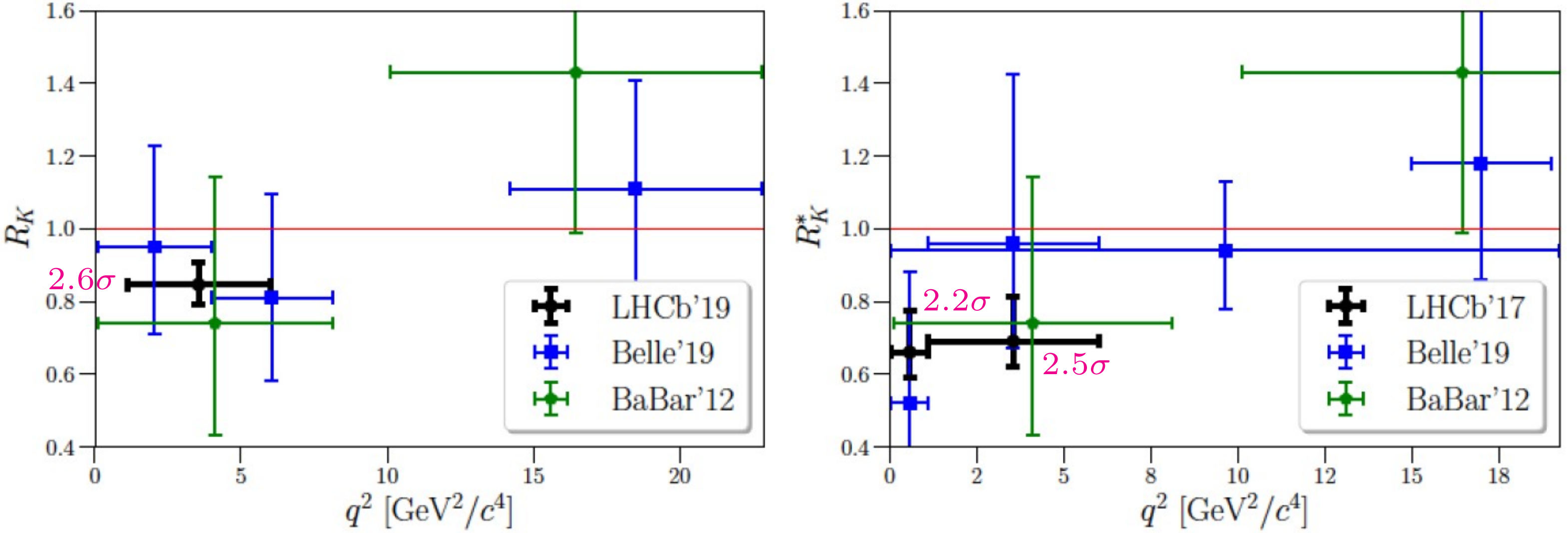
- Uncertainty of $|V_{cb}|$ may limit improving BSM sensitivity in B_d and B_s mixing

- If $\Gamma(B \to X_u\ell\bar{\nu})$ could be measured without cuts on phase space (to remove X_c background based on kinematics), uncertainty of $|V_{ub}|$ would be similar to $|V_{cb}|$

$$\boldsymbol{B \to K^{(*)}\ell^+\ell^-}$$

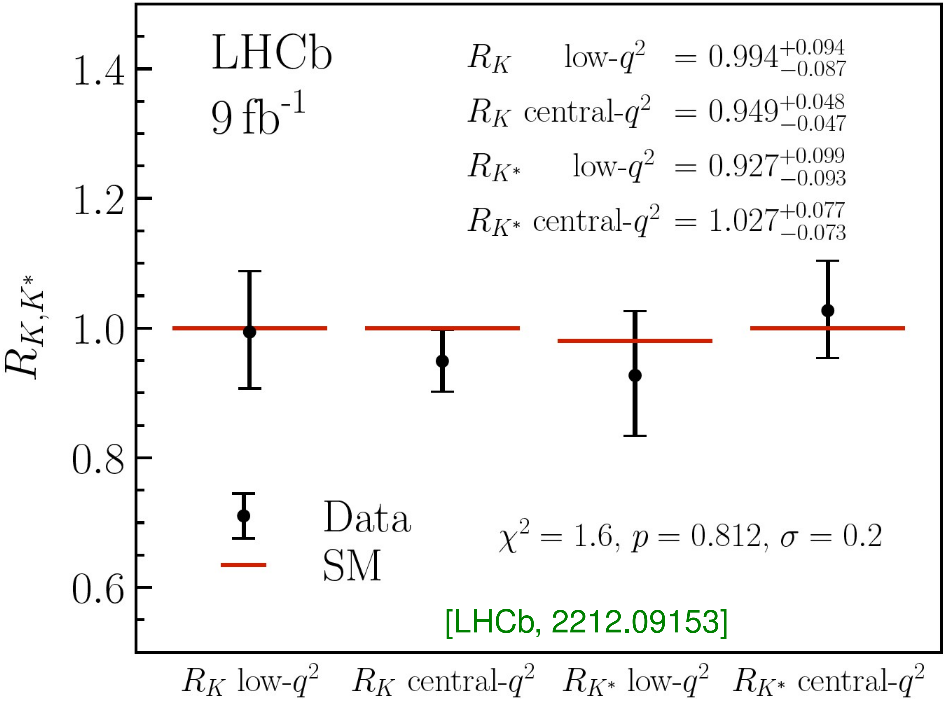
R_K and R_{K^*} before 2022: theoretically cleanest

- LHCb: $R_{K^{(*)}} = \dfrac{B \to K^{(*)}\mu^+\mu^-}{B \to K^{(*)}e^+e^-} < 1$ both ratios $\sim 2.5\sigma$ from lepton universality

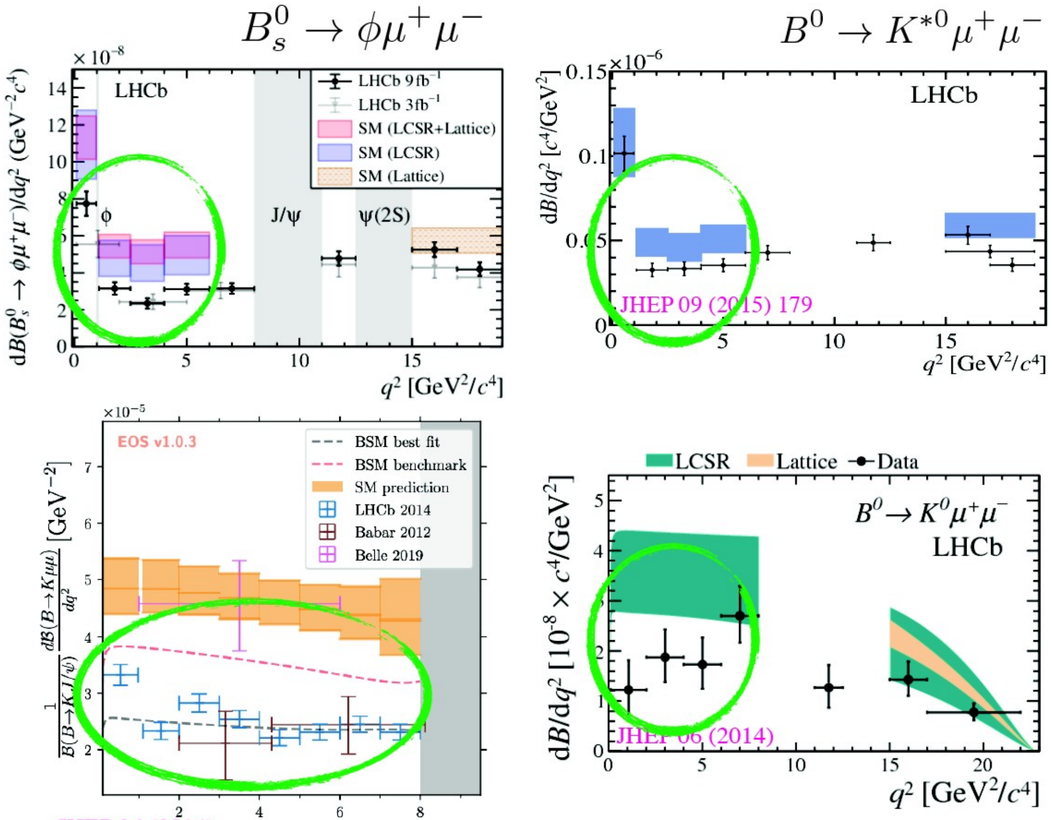


- Theorists' fits quoted $3-5\sigma$ (sometimes including P_5' and/or $B_s \to \phi\mu^+\mu^-$)
- Modifying one Wilson coefficient in $\mathcal{H}_{\text{eff}}$ (due to NP?) gives good fit: $\delta\, C_{9,\mu} \sim -1$

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



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



[Smith, LHCP 2024]

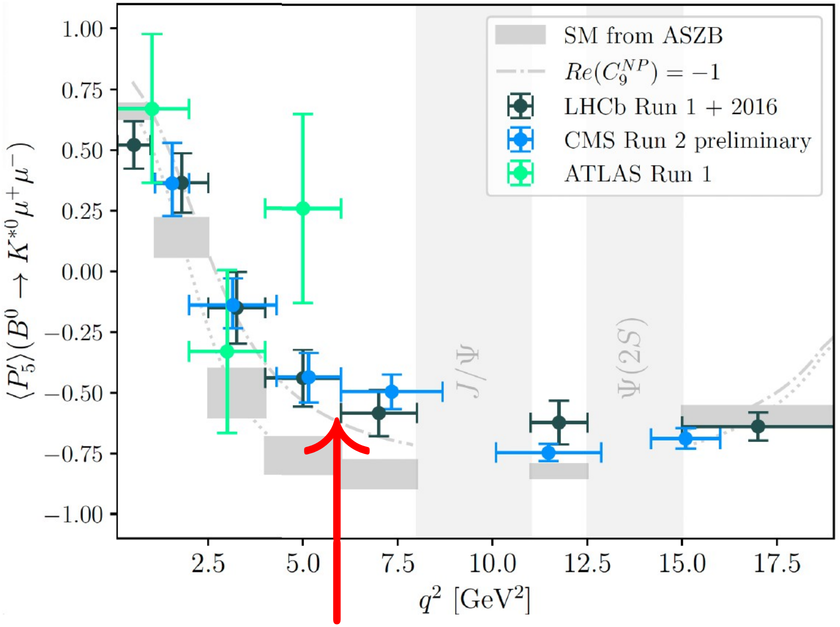
The P_5' anomaly in $B \to K^*\mu^+\mu^-$

- "Optimized observables" [1202.4266 + long history]
  (some assumptions about what's optimal)

  Global fits: best solution: 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 is the calculation which detremines how far below the J/ψ this comparison can be trusted?



BSM, fluctuation, SM theory?

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

Some concerns... maybe?

- Key players:

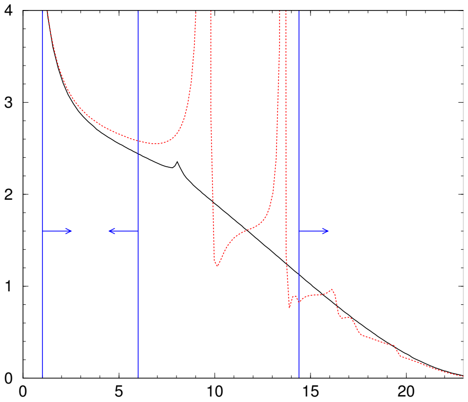
$$O_7 = \overline{m}_b\, \bar{s}\sigma_{\mu\nu} e F^{\mu\nu} P_R b$$

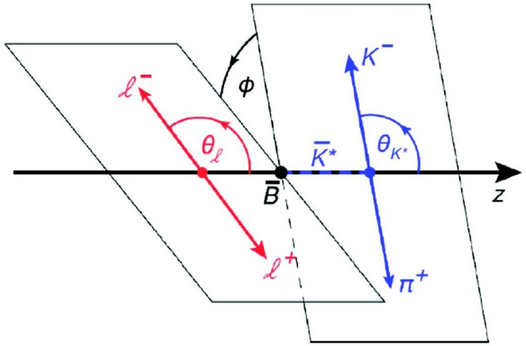
$$O_9 = e^2 (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

$$O_{10} = e^2 (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

Best fit: modify $C_{9,\mu}$

$b \to c\bar{c}s(c\bar{c} \to \ell^+\ell^-)$ contributes

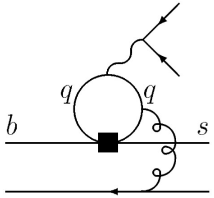




- Question: validity of perturbative methods for $c\bar{c}$ contribution

$\mathcal{B}(B \to \psi X_s \to \ell^+\ell^- X_s) \sim (4 \times 10^{-3}) \times (6 \times 10^{-2}) \sim 2 \times 10^{-4}$

Much larger than the short distance contribution

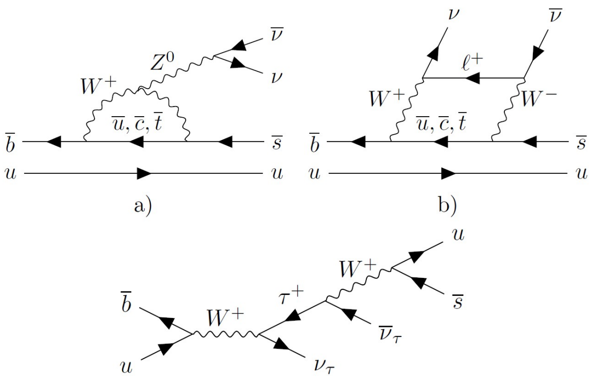


- Not well understood why so different than $e^+e^- \to$ hadrons (no effect on lepton universality)

[Long history: hep-ph/9512225, hep-ph/0401188, 0902.4446, 1707.07305, 2206.03797, 2212.10516, 2406.14608, etc.]

$B \to K\nu\bar{\nu}$

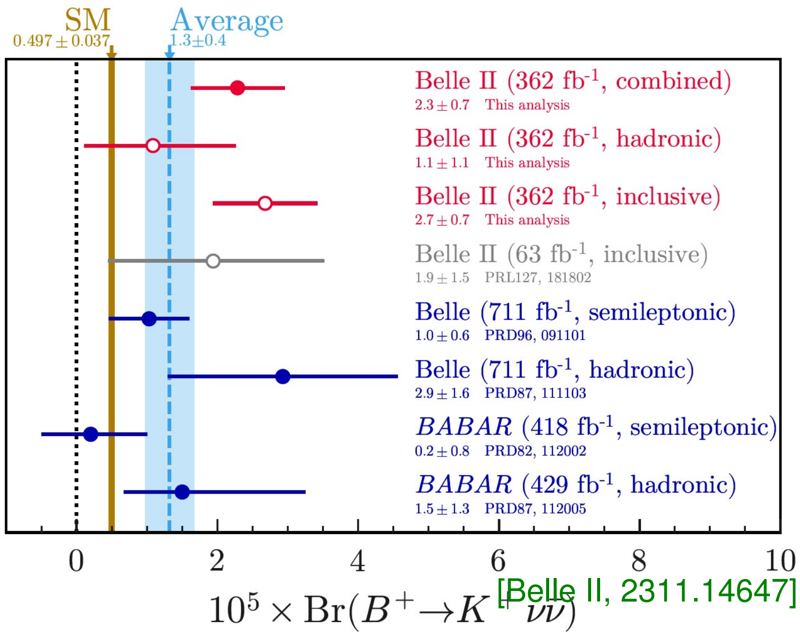
- Similar short-distance contributions, with straightforward long-distance effects



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

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

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



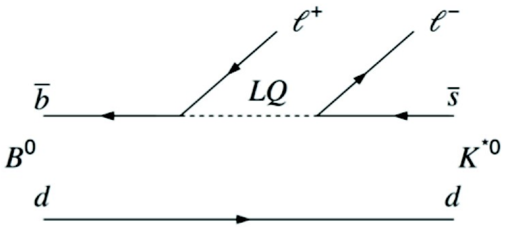
[Belle II, 2311.14647]

Belle II result is 2.7σ from the SM

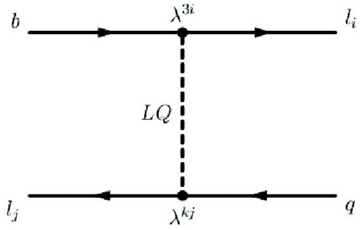
E.g., leptoquark flavor structures

- Leptoquarks were some of the most often discussed models for $R_{K^{(*)}}$ and $R(D^{(*)})$
  (A-priori no reason for the leptoquark couplings to be approximately flavor conserving)

Need this to explain $b \to s\ell^+\ell^-$ data



Need to worry about all $b \to q\ell_1^+\ell_2^-$ couplings

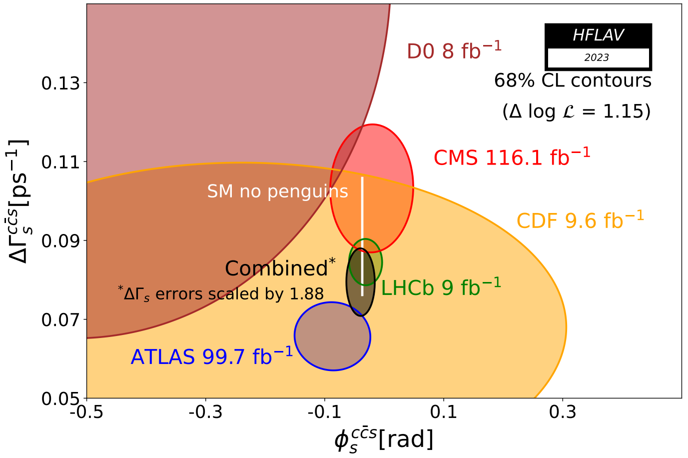


$$\lambda = \begin{pmatrix} \lambda_{de} & \lambda_{d\mu} & \lambda_{d\tau} \\ \lambda_{se} & \lambda_{s\mu} & \lambda_{s\tau} \\ \lambda_{be} & \lambda_{b\mu} & \lambda_{b\tau} \end{pmatrix}$$

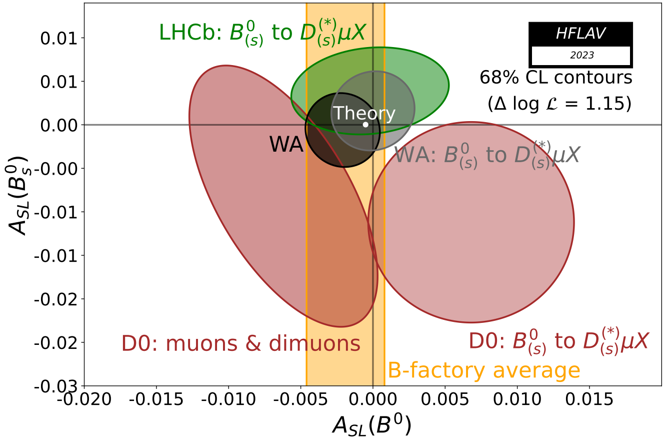
- R_{K^*} implied a range for $\mathrm{Re}(\lambda_{se}\lambda_{be}^* - \lambda_{s\mu}\lambda_{b\mu}^*)/M^2$
- Motivates LFV searches: $B \to K^{(*)}\mu^\pm e^\mp$, $B \to K^{(*)}\mu^\pm\tau^\mp$, etc., (similarly in D & K decays)
- Leptoquarks — almost by definition — connect quark and lepton flavor

Richness of directions

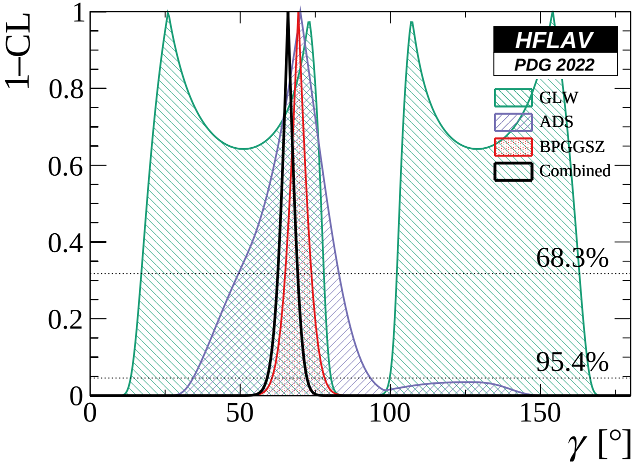
Some key measurements, improving precision



CP violation in $B_s \to \psi\phi$ now consistent with SM



$A_{\rm SL}$: important, independent of DØ anomaly



Measurements of γ crucial, LHCb is now most precise

- Uncertainty of predictions $\ll$ current experimental errors ($\Rightarrow$ seek lot more data)
- Breadth crucial, often have to combine many measurements and theory

BERKELEY CENTER FOR THEORETICAL PHYSICS

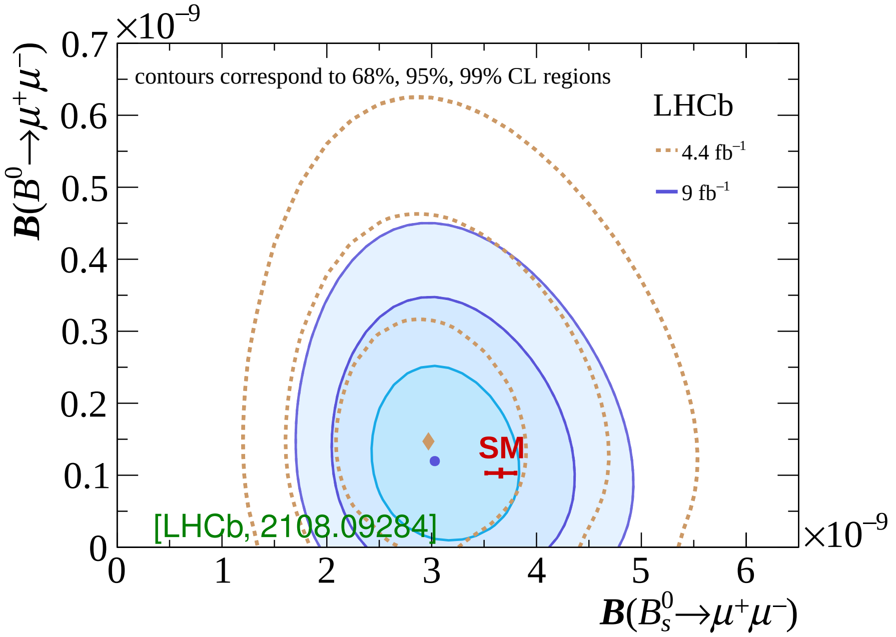
BERKELEY LAB

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

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

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

- A theoretically very clean $|V_{ub}|$, using only 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/ $K \to \pi\nu\bar{\nu}$



PDG average: [LHCb, CMS, ATLAS]

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

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)

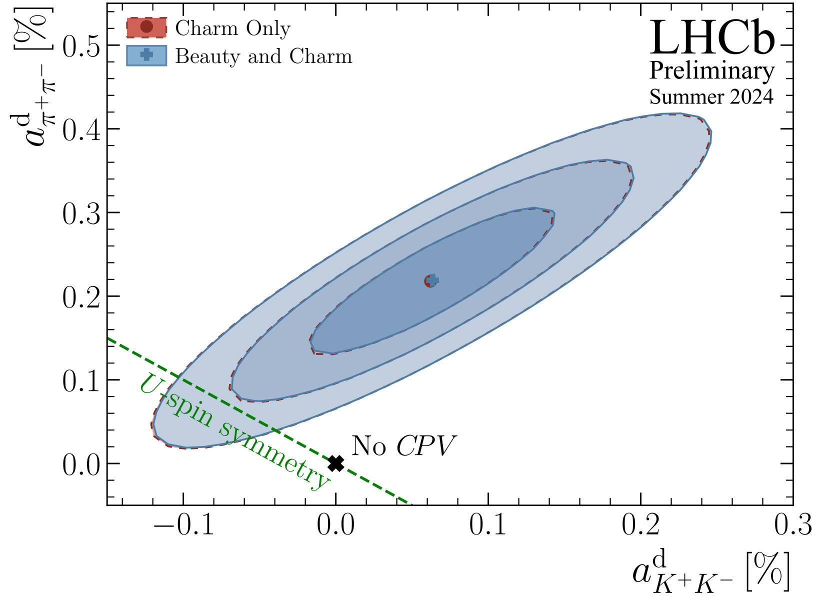
  LHCb, Mar. 2019: $\Delta A_{CP} = -(1.82 \pm 0.33) \times 10^{-3}$ [1903.08726]

- 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?

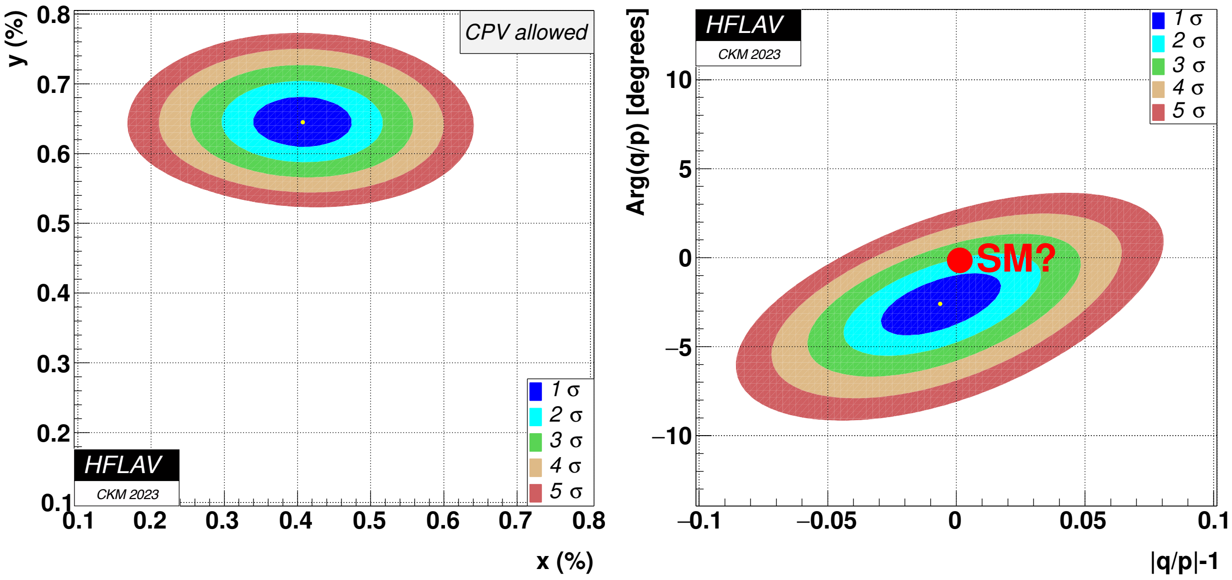


BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

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

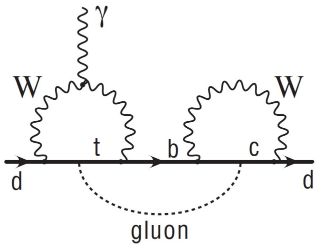
- Mixing generated by down quarks
- SUSY: up-type squarks in box diagrams, interplay of D & K bounds
  $\Rightarrow$ alignment, universality, heavy squarks?
- Connections to FCNC top decays
- Only learned recently: $x/y = \mathcal{O}(1)$
  (Only in 2021 was $\Delta m \neq 0$ established at $> 3\sigma$)



- Very high scales probed, further improvements expected

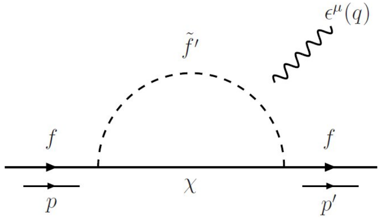
Electric dipole moments

- 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



- Many BSM scenarios: 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

The LHC is a top factory: top flavor physics

- FCNC top decays not yet strongly constrained

$$t \to cZ,\ c\gamma,\ cH,\ \ uZ,\ u\gamma,\ uH$$

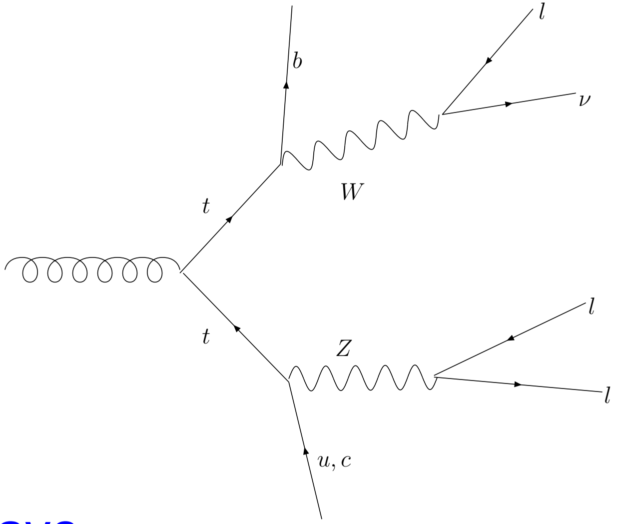
  SM predictions: $< 10^{-12}$

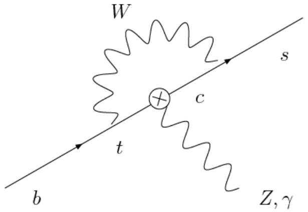
  Best current bound: $\lesssim$ few $\times\ 10^{-4}$ [ATLAS, CMS]

- Sensitivity will improve $1-2$ orders of magnitude

- Indirect constraints: $t_L \leftrightarrow b_L \Rightarrow$ tight bounds from B decays
  - Strong bounds on operators with left-handed fields
  - Right-handed operators could give rise to LHC signals

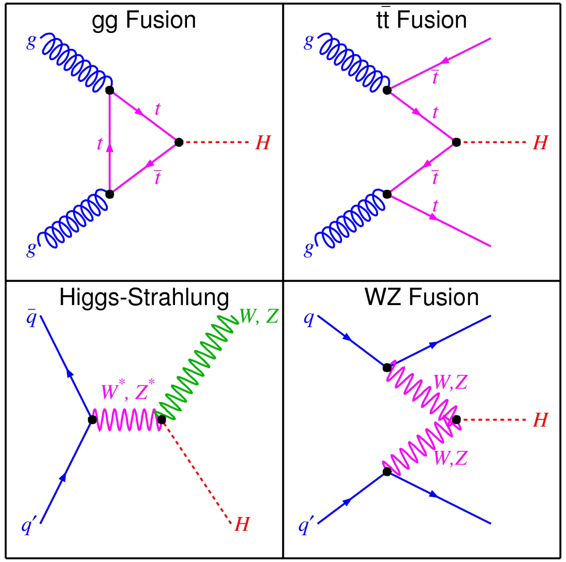
- If top FCNC is seen, LHC & B factories will both probe the NP responsible for it

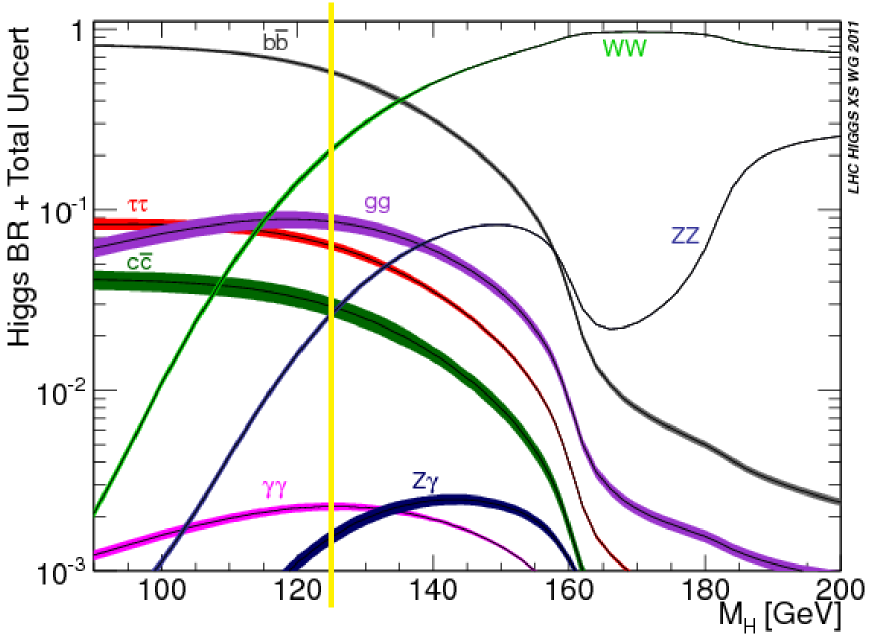




The LHC is a Higgs factory

- Rich physics: many production and decay channels (fermion couplings crucial)





- Higgs flavor param's: 3rd gen: κ_t, κ_b, κ_τ; 2nd gen: κ_c, κ_μ; do $\kappa_{t,c}$, $\kappa_{\tau\mu}$ vanish?
- Thoroughly test Higgs paradigm $\Rightarrow$ seek much higher precision

Very broad program

- Recall, most cited Belle paper is discovery of $X(3872)$, for BaBar the $D_{s0}^*(2317)$
  - γ from CP asymmetries in tree-level decays
  - CP asymmetries, e.g., $S_{B\to\psi K_S}$, $S_{B_s\to\psi\phi}$, $S_{B\to K_S\pi^0\gamma}$
  - Differences of CP asymmetries, e.g., $S_{\psi K_S} - S_{\phi K_S}$, $S_{B_s\to\psi\phi} - S_{B_s\to\phi\phi}$
  - $B_s \to \mu^+\mu^-$, search for $B_d \to \mu^+\mu^-$, other rare / forbidden decays
  - Rare decays, e.g., $B \to K^{(*)}\ell^+\ell^-$, $B_s \to \phi\gamma$, $B \to K^{(*)}\nu\bar{\nu}$
  - Search for charged lepton flavor violation, e.g., $\tau \to \mu\gamma$, $\tau \to 3\mu$
  - Search for CP violation in $D^0 - \overline{D}^0$ mixing, semileptonic decays, etc.
  - Improvements in many measurements
- Any of these measurements could establish new physics

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, "mesogenesis", $B \to N + \text{invis.}\ [+\text{mesons}]$ [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"); e.g., at LHCb using many velo layers
- I do not know how many CP violating quantities have been measured...
  neither how many "new" hadronic states discovered by BaBar, Belle, LHCb ...

Anticipated increases in sensitivity

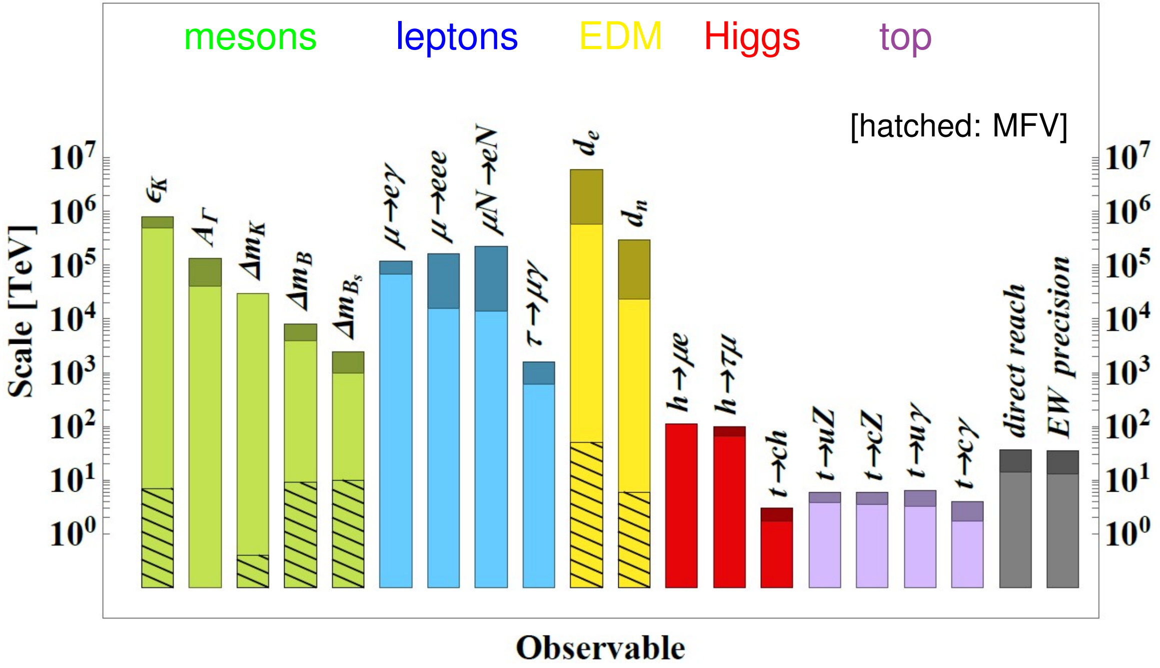
- Scales of dim-6 operators probed $\Longrightarrow$

  Various mechanisms devised so that NP obeys these bounds

  (Patterns matter more than precise values; Note special role of meson mixing)

- If NP is within any collider's reach, must have nontrivial flavor structure

  The idea of (dominantly) 3rd generation NP goes back (at least) to the '90s [hep-ph/9607394]



[European Strategy Update 2020, arXiv:1910.11775]

- Lack of NP in flavor tells us something! Motivates tera-Z, part of comprehensive search

Summary (2)

- Precision tests of SM will improve in the next decade by 10–10^4
- Few tensions with SM; some of these (or others) could soon become unambiguous
  Any of the current anomalies becoming decisive would imply NP at a fairly low scale
- Discovering lepton universality violation would focus even more attention on LFV
- Many interesting theoretical questions relevant for optimal experimental sensitivity
- Large increases in data always triggered unforeseen developments — make most of it
- Complementarity between flavor & high-p_T probes of BSM (and understanding it)

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?
  - 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?

Lepton non-universality $\rightarrow$ lepton flavor violation

quark sector

New charged current interactions generically introduce new FCNCs

Hope: new physics at LHC, couples to quarks somehow (production, decays)

However, no NP effect seen yet in FCNCs

Puzzle: How does NP know about the quarks' mass and weak eigenstates

Solution: Some symmetry of NP, minimal flavor violation, natural in GMSB

lepton sector

New lepton-nonuniversal interactions generically introduce LFV

Hope: some of the hints for lepton non-univerality survive

However, no LFV seen unambiguously

Puzzle: Same for leptons

Solution: Same, maybe... Want data on many processes to give clues

New particles, e.g., supersymmetry

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

  The LHC will measure: masses, production rates, decay modes (some), etc.

  Details of interactions of new particles with quarks and leptons will be important

- New physics flavor structure can be: new physics mass scale:
  - Minimally flavor violating (mimic the SM) can be "light"
  - Related but not identical to the SM $\uparrow\downarrow$
  - Unrelated to the SM, or even completely anarchic must be heavy

  Some aspects will be understood from ATLAS & CMS data (masses, decays, etc.)

- New sources of CP violation: squark & slepton couplings, flavor diagonal processes (e, n EDM), neutral currents; may enhance FCNCs ($B_{(s)} \to \ell^+\ell^-$, $\mu \to e\gamma$)

Example: SUSY in $K^0 - \overline{K}^0$ mixing

- $\dfrac{(\Delta m_K)^{\text{SUSY}}}{(\Delta m_K)^{\text{exp}}} \sim 10^4 \left(\dfrac{1\,\text{TeV}}{\tilde{m}}\right)^2 \left(\dfrac{\Delta\tilde{m}^2_{12}}{\tilde{m}^2}\right)^2 \text{Re}\big[(K_L^d)_{12}(K_R^d)_{12}\big]$ (oversimplified)

  $K^d_{L(R)}$: mixing in gluino couplings to left-(right-)handed down quarks and squarks

- Constraint from ϵ_K: replace $10^4\,\text{Re}\big[(K_L^d)_{12}(K_R^d)_{12}\big]$ with $\sim 10^6\,\text{Im}\big[(K_L^d)_{12}(K_R^d)_{12}\big]$

  (44 CPV phases: CKM $+$ 3 flavor diagonal $+$ 40 in mixing of fermion-sfermion-gaugino couplings)

- Classes of models to suppress each terms (structures imposed to satisfy bounds)

  (i) Heavy squarks: $\tilde{m} \gg 1\,\text{TeV}$ (e.g., split SUSY)

  (ii) Universality: $\Delta m^2_{\tilde{Q},\tilde{D}} \ll \tilde{m}^2$ (e.g., gauge mediation)

  (iii) Alignment: $|(K^d_{L,R})_{12}| \ll 1$ (e.g., horizontal symmetry)

- All models incorporate some of the above — known since the ’70s

The MSSM parameters and flavor

- Superpotential: $W = \sum_{i,j} \left(Y_{ij}^u H_u\, Q_{Li} \bar{U}_{Lj} + Y_{ij}^d H_d\, Q_{Li} \bar{D}_{Lj} + Y_{ij}^\ell H_d\, L_{Li} \bar{E}_{Lj} \right) + \mu H_u H_d$

[Haber, hep-ph/9709450]

- Soft SUSY breaking terms: $(S = \tilde{Q}_L, \tilde{\bar{D}}_L, \tilde{\bar{U}}_L, \tilde{L}_L, \tilde{\bar{E}}_L)$

$$\mathcal{L}_{\text{soft}} = -\left(A_{ij}^u H_u \tilde{Q}_{Li} \tilde{\bar{U}}_{Lj} + A_{ij}^d H_d \tilde{Q}_{Li} \tilde{\bar{D}}_{Lj} + A_{ij}^\ell H_d \tilde{L}_{Li} \tilde{\bar{E}}_{Lj} + B H_u H_d \right)$$
$$- \sum_{\text{scalars}} (m_S^2)_{ij}\, S_i \bar{S}_j - \frac{1}{2} \left(M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + M_3 \tilde{g}\tilde{g} \right)$$

$3\ Y^f$ Yukawa & $3\ A^f$ matrices — $6\times(9$ real $+\ 9$ imaginary) parameters
$5\ m_S^2$ hermitian sfermion mass-squared matrices — $5\times(6$ real $+\ 3$ imag.) param's

Gauge and Higgs sectors: $g_{1,2,3},\, \theta_{\text{QCD}},\, M_{1,2,3},\, m_{h_{u,d}}^2,\, \mu,\, B$ — 11 real $+\ 5$ imag.

Parameters: $(95 + 74) - (15 + 30)$ from $U(3)^5 \times U(1)_{\text{PQ}} \times U(1)_R \to U(1)_B \times U(1)_L$

- 44 CPV phases: CKM $+\ 3$ in M_1, M_2, μ (set $\mu B^*, M_3$ real) $+\ 40$ in mixing matrices of fermion-sfermion-gaugino couplings $(+80$ real param's)

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

History of surprises: CP violation

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

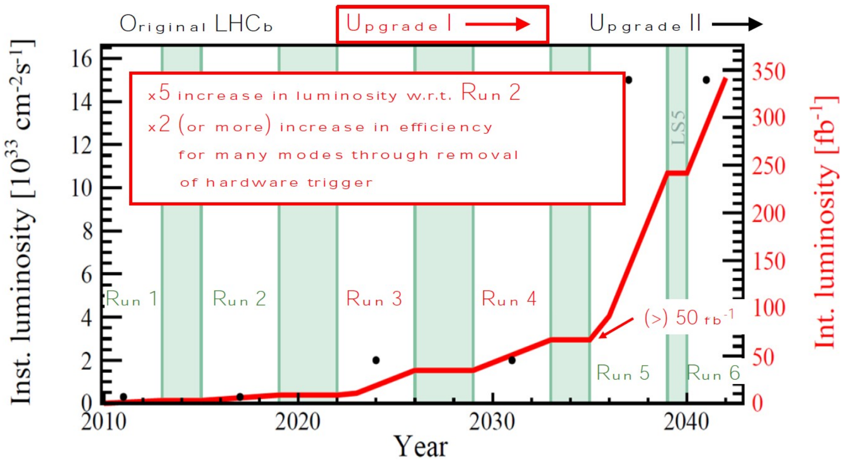
The power requirements for the experiment are extraordinarily modest. We must power one 18-in. x 36-in. magnet for sweeping the beam of charged particles. The two magnets in the di-pion spectrometer are operated in series and use a total of 20 kw.

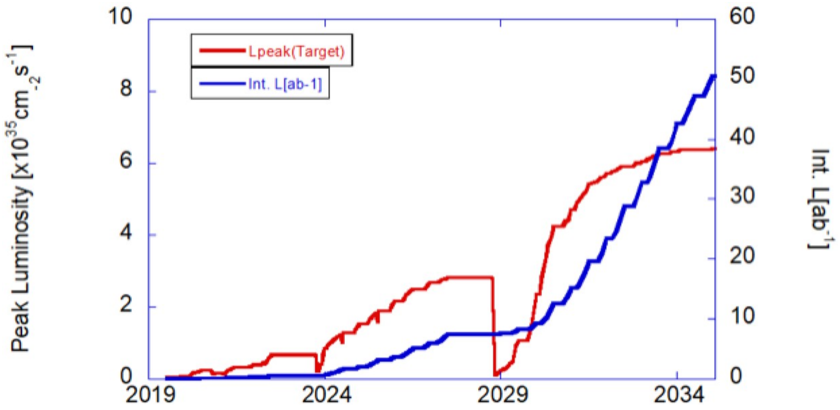
⇒ Cronin & Fitch, Nobel Prize, 1980

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

3

Flavor and future colliders





- 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

  Extensive sensitivity projections: 1808.08865, 1812.07638

- Goal: over $50\times$ the Belle data set
- Discussions about physics case and feasibility of an upgrade, aiming 50/ab $\to$ 250/ab (parallel LHCb Upgrade II)

  Extensive sensitivity projections: 1808.10567

- Only Tera-Z would go well beyond current program — clear case if BSM seen in flavor

Physics in 20 years may be very different

- Will LHC see NP beyond the Higgs? (new particle $\Rightarrow$ new flavor sector, recall $H\tau\mu$ anomaly)
- Will NP be seen in the quark sector? (Current data: hints of possible deviations from SM)
- Will NP be seen in charged lepton sector? $\mu N \to eN$, $\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to 3\mu$?
- Will DM be discovered? Axions? EDMs? Something else?
- Neutrinos: Does 3 flavor paradigm hold? What is the nature of ν mass?

- No one knows — an exploratory era! Any BSM discovery would be a game changer
- While Higgs is an obvious place to look for BSM, want broad searches on all fronts

What is the scale of new physics?

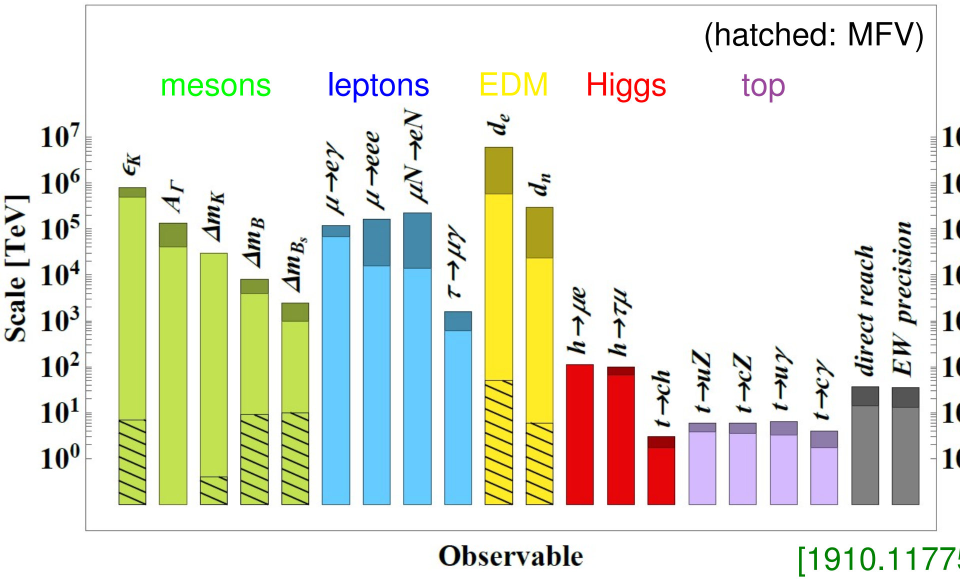
- Flavor, K, B, D: $\dfrac{(\bar{b}\,\Gamma d)^2}{\Lambda^2} \;\Rightarrow\; \Lambda \gtrsim 10^2 - 10^5\ \text{TeV}$

  (Note special sensitivity of meson mixings)

- Electroweak: $\dfrac{(H^\dagger D_\mu H)^2}{\Lambda^2} \;\Rightarrow\; \Lambda \gtrsim 10\ \text{TeV}$

- Actual scales may be much less; e.g., in SM:

$$\frac{\Delta m_K}{m_K} \sim \frac{g_2^4}{16\pi^2}\,|V_{cs}V_{cd}|^2\,\frac{m_c^2}{m_W^4}\,f_K^2 \sim 7\times 10^{-15}$$

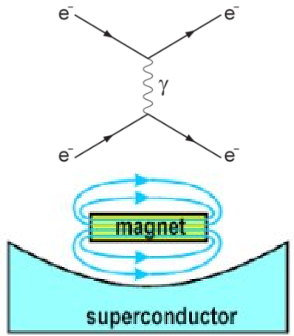


[1910.11775]

- Lack of NP in flavor tells us something; motivates tera-Z part of comprehensive search

- If NP is within any collider's reach, it must possess nontrivial structures (e.g., MFV-like)

Higgs and superconductivity



- Gauge symmetry forbids γ, W, Z masses, Coulomb's law, infinite range

  Meissner effect: photon acquires a mass, $\mathbf{B}$ field falls off exponentially

  Higgs mechanism: nonabelian analog to give masses to $W^\pm, Z^0$ (spontaneously breaking of gauge symmetry)

  The vacuum in our Universe is in a superconducting state below 10^{15} K

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

- Higgs mechanism: Is it totally different?

  As for superconductivity, microscopic explanations have phenomena at nearby scales
  (supersymmetry, little higgs, technicolor, extra dimensions, strongly interacting sectors, etc.)

- It would be unprecedented to have no "new physics" at nearby scales **(nearby = ?)**

How much improvement needed? E.g.: CP violation

ANNALS OF PHYSICS: 5, 156–18 (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

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

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

VOLUME 6, NUMBER 10 — PHYSICAL REVIEW LETTERS — MAY 1, 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 $K_2^0 \rightarrow \pi^- + \pi^+$. 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

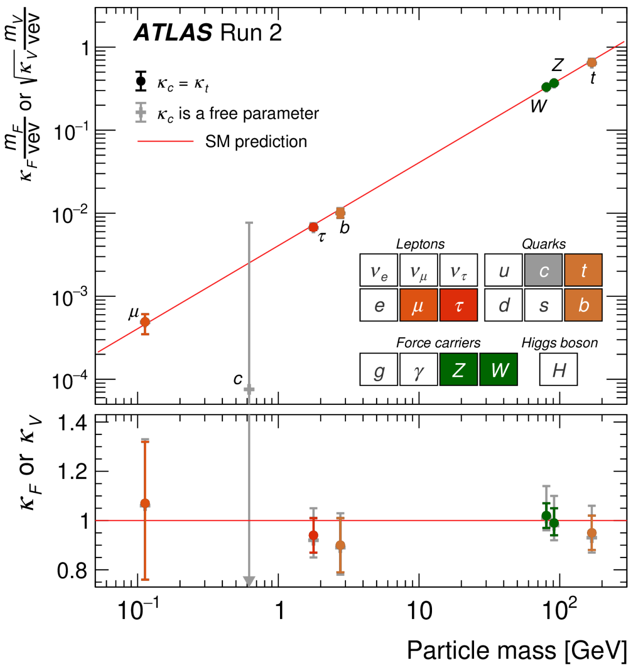
(Received 10 July 1964)

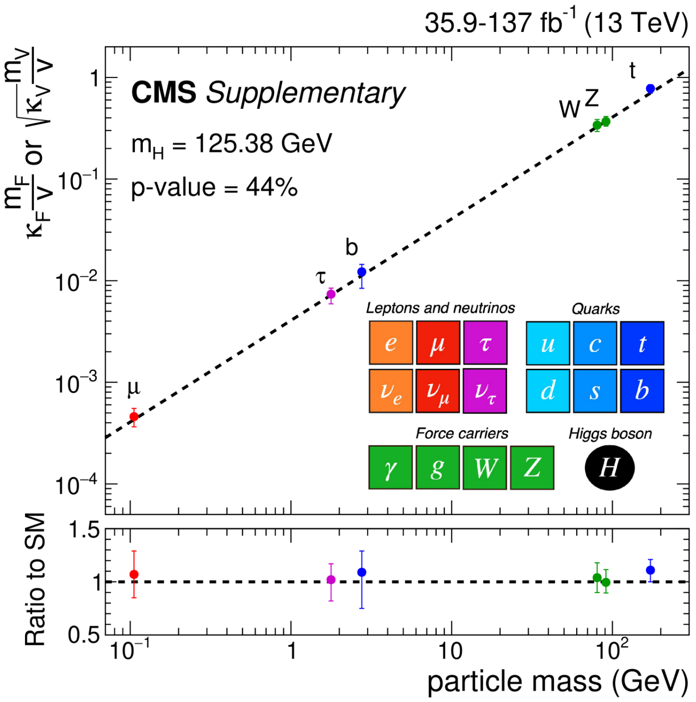
We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R = (K_2 \rightarrow \pi^+ + \pi^-)/(K_2^0 \rightarrow \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ where the error is the standard deviation. As empha-

Unexpected discovery from minor improvements. Not what the goal was. Are we looking at all places?

Higgs and flavor

LHC: impressive map of H couplings





- No constraint yet on origin of 1st generation fermion masses, mainly μ from 2nd gen.
- FCC-ee can establish role of Higgs in y_c, get close to y_s and y_e

Decays HL-LHC can probe fairly well

- Big improvements for many couplings
- Order of magnitude or more for κ_Z, κ_c, invisible, and "exotic" channels
- κ_Z especially significant
  in many models its modification is correlated with those of self coupling
- Model independent measurement of the Higgs total width is only possible in e^+e^-

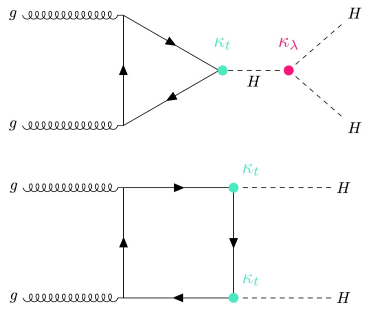
Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
$\mathrm{BR}_{\mathrm{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
$\mathrm{BR}_{\mathrm{unt}}$ (<%, 95% CL)	4*	1.0 / 0.88

($*$: no direct access to H width) [Midterm Report]

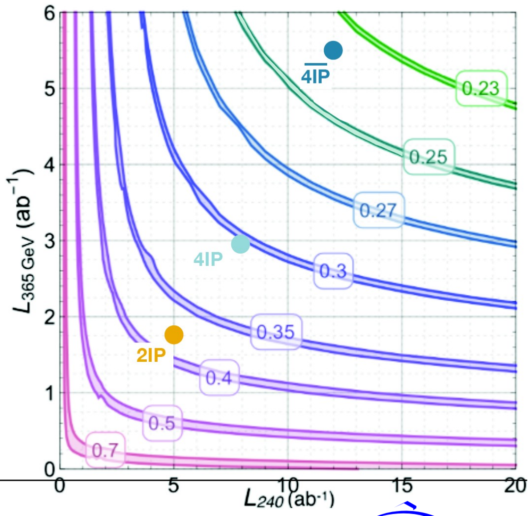
Higgs self coupling: the holy grail?

- Measure κ_λ: $\mathcal{O}(5)$ now $\Rightarrow$ $\mathcal{O}(1)$ at HL-LHC $\Rightarrow$ $\mathcal{O}(.25)$ at FCC-ee $\Rightarrow$ $\mathcal{O}(0.03)$ at FCC-hh
- Ultimate FCC-hh sensitivity requires:
  – m_t from FCC-ee
  – $t\bar{t}$ threshold scan needs α_s at max precision from Z (WW?)

destructive interference



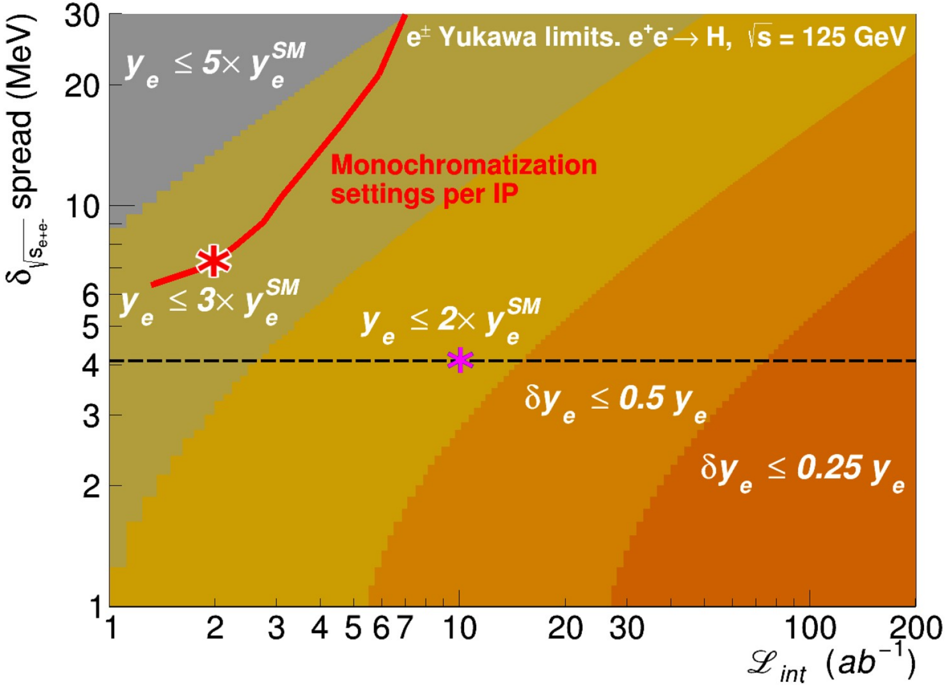
- Data at multiple CM energies important for the FCC-ee reach
(Also to constrain different SMEFT operators, resolve degeneracies)



- Precisely mapping out Higgs self-interaction is a well defined target, a "no-lose theorem" for FCC
- In many models, correlated modifications of λ and HZZ, which FCC-ee will probe to 0.14%

Approaching electron Yukawa?

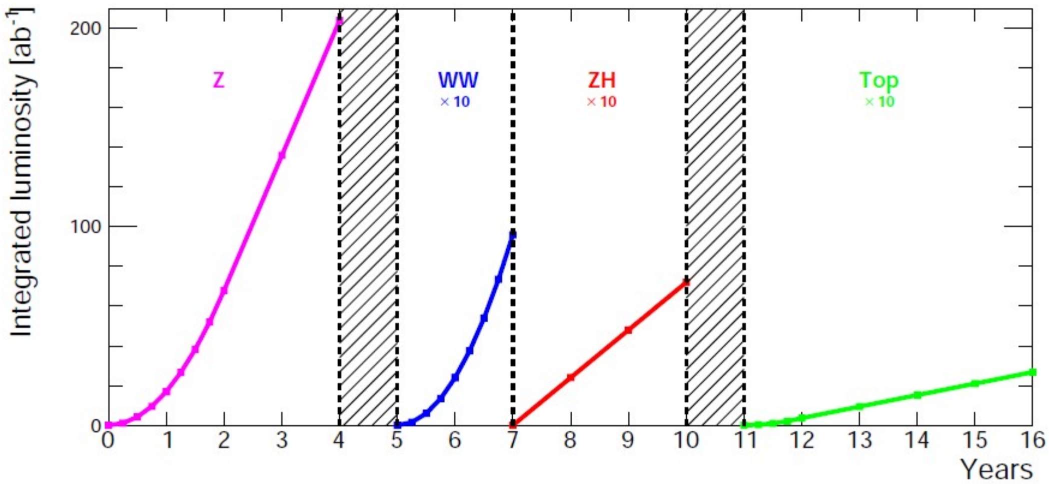
- Probing y_e at $\sqrt{s} = 125\,\mathrm{GeV}$ would be unique to FCC-ee



[2203.06520]

- Can additional measurement make this a compelling part of the run plan?

Tera-Z



Integrated luminosity [ab^{-1}]
200
100
0
Z
WW
× 10
ZH
× 10
Top
× 10
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Years

Precision electroweak observables

- 10^5 improvement over LEP is qualitatively new
  Both a huge leap forward and the right target
  (mass scale) $\propto$ (uncertainty)$^{-1/2}$ $\propto$ (statistics)$^{-1/4}$

- A lot of the precision electroweak physics also concerns flavor (τ lifetime & mass, R_ℓ for each ℓ flavor, etc.)

- Sensitive to order of magnitude heavier NP in loops
  Many interesting observables, complementary sensitivities

- Interesting experimental & theoretical challenges to reduce systematic uncertainties to statistical limits

  E.g., $A_{\rm FB}^b$, largest remaining tension from LEP/SLD
  Must improve: fragmentation, MC, higher orders, jet tagging

Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\rm eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{\rm FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\rm QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{\rm FB}^{\mu\mu}$ off peak QED&EW errors dominate
$R_\ell^Z\ (\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)\ (\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
$\sigma_{\rm had}^0\ (\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
$R_b\ (\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{\rm FB}^b, 0\ (\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{\rm FB}^{{\rm pol},\tau}\ (\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
$m_{\rm top}$ (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\Gamma_{\rm top}$ (MeV/c^2)	1410 ± 190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

Can one appreciate / anticipate a 10^5 improvement?

- What might $10^5 \times$ LEP mean? Can we predict it...? (Recall : Belle II / ARGUS $\sim 10^5$!)

  Theory and experimental techniques both changed a lot! (e.g., full hadronic reconstruction)

  Asymmetric B factories at $\Upsilon(4S)$ great 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)

  Interesting but probably not the best example: $\tau\tau$ spin correlations with 3-prong decays? (0.03×0.1^2)

  Some rare decay sensitivity can improve linear with stat, e.g., $Z \to \mu\tau, \mu e$, etc.

Very rare Z and h decays

- Intrinsic motivation: is it possible to probe Yukawa couplings in exclusive final states?

  E.g., $Z \to J/\psi\,\gamma$, expect $\mathcal{B} \sim 10^{-7}$ — calibration for $H \to J/\psi\,\gamma$ $(\mathcal{B} \sim 3 \times 10^{-6})$

  Focus of a number of papers, recently h, Z, W, t few-body decays [Study ~ 200 channels, 2312.11211]

- FCNC Z and h decays in SM probably beyond reach, jet tagging, small rates

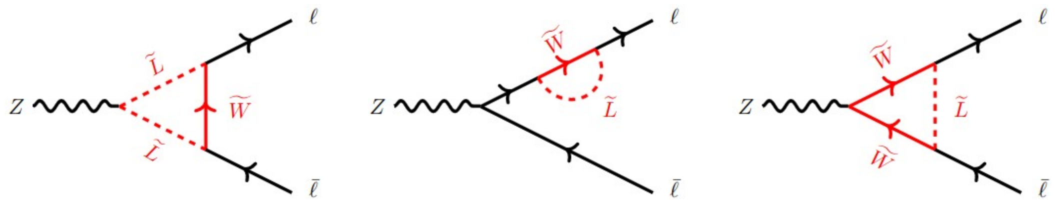
  $\mathcal{B}(Z \to b\bar{s}) \sim 4 \times 10^{-8}$ in SM, exp bound 3×10^{-3} [Tammaro, FCC workshop]
  $\mathcal{B}(h \to b\bar{s}) \sim 9 \times 10^{-8}$ in SM, exp bound 0.16 (indirect bounds much better for now)

A particular sensitivity to SUSY: $Z \to \ell^+\ell^-$

- Precisely measure: $R_\ell = \dfrac{\Gamma_{\ell^+\ell^-}}{\Gamma_{\text{hadrons}}}$

R^Z_ℓ ($\times 10^3$)	20767	$\pm$	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons

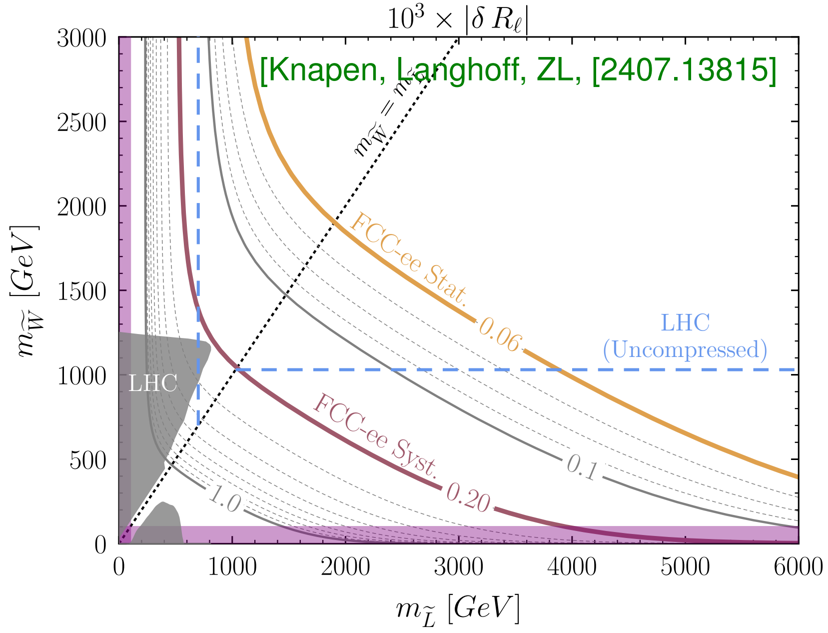
- Consider a SUSY simplified model, with $\tilde{q}, \tilde{g}$ heavy, only electroweakinos & sleptons light



- Ultimate sensitivity depends on α_s, $\sin^2\theta_w$, etc.

  Several measurements combined for best physics reach

  Even better sensitivity to flavor violating effects (e, μ, τ)



- Complementary to SMEFT based studies, any model may have important correlations

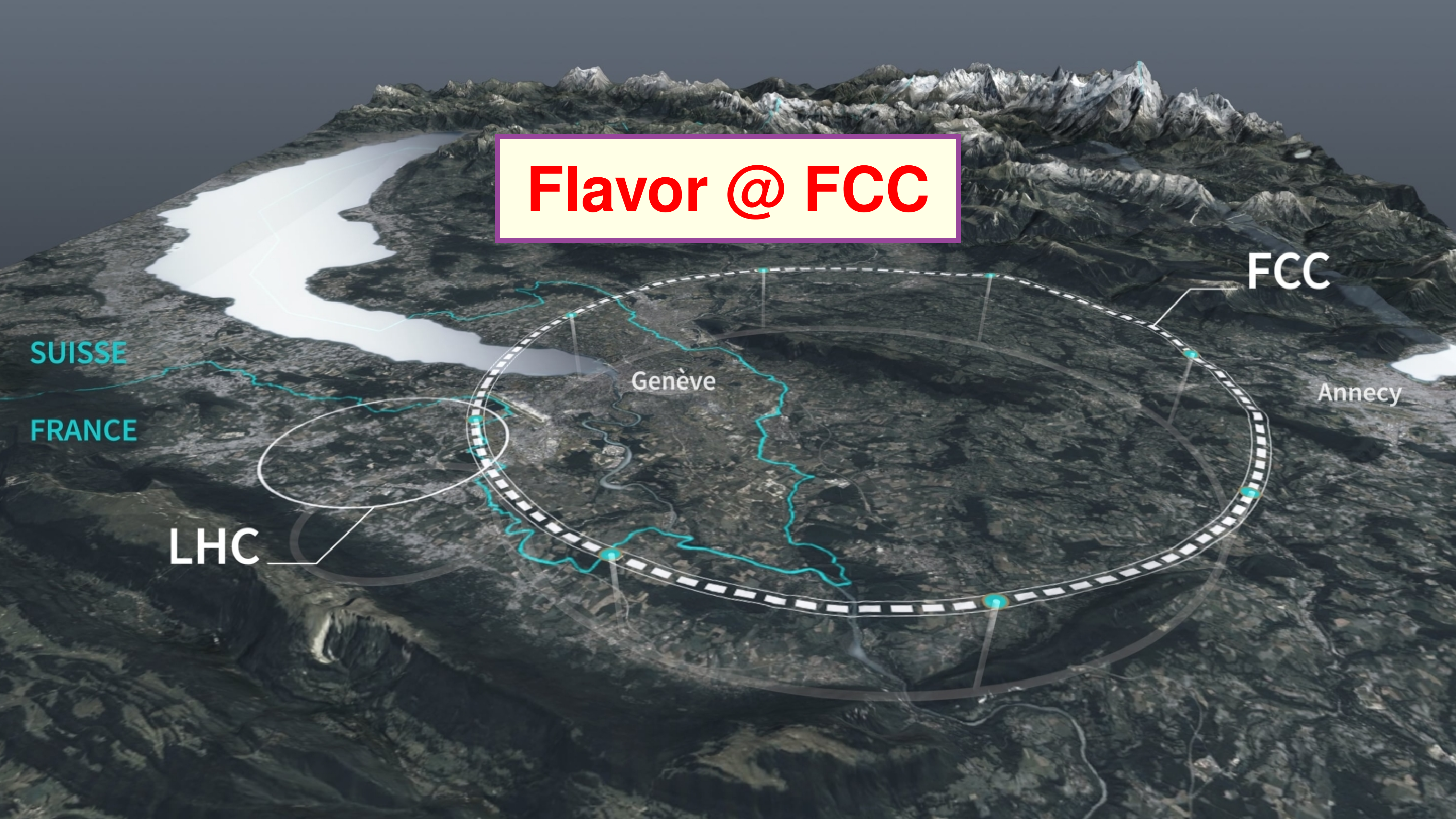
Some simple takeaways

- Need progress both on experimental and theoretical systematics

  Including: α_s, $\sin^2\theta_w$, luminosity measurements, detector acceptance
- Many theory calculations needed, improvements in Monte Carlo (e.g., for A_{FB}^b)
- Not only the "most precise" extraction of parameters matter, but also the "second best"

  (First fixes SM expectations, second to constrain BSM)
- Can probe regions that fall outside (or between) HL-LHC exclusion regions

Flavor @ FCC



Flavor physics at FCC-ee

- Only tera-Z would go well beyond current program — clear case if BSM seen in flavor

Particle production (10^9)	$B^0 + \overline{B}^0$	$B^\pm$	$B_s^0 + \overline{B}_s^0$	$\Lambda_b + \bar{\Lambda}_b$	$B_c^\pm$	$c\bar{c}$	$\tau^+\tau^-$
Belle II (50 ab^{-1})	27	27	tbd	—	—	65	45
tera-Z (6×10^{12} Z)	600	600	150	130	3	600	170

(often the sole focus of talks on flavor @ FCC) [2106.01259]

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: $W \to b\bar{c}$ can give a qualitatively new determination of $|V_{cb}|$
Estimate 0.2% uncertainty, using 10^8 WW, independent of B measurements
[Monteil @ 7th FCC Physics Workshop, Jan 2024]; also, [2405.08880]

Important, as $|V_{cb}|$ may limit improving BSM sensitivity in $B_{d,s}$ mixing [2006.04824]

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Tera-Z: an amazing flavor experiment

- Almost everything about flavor can be done better at tera-Z, focus on few unique points
- $10 \times$ Belle II statistics, extra advantage from clean environment and boost of the b

  An exciting program, whether BSM is discovered before or not

  Flavor probes BSM broadly, relates to most of the parameters of the SM, SMEFT, MSSM, etc.
- Long term: large increase in discovery potential in many modes
- Hot topics in 2040s are unlikely to be what they are now, or what we can guess now
- For many key measurements we know they won't be systematics limited

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

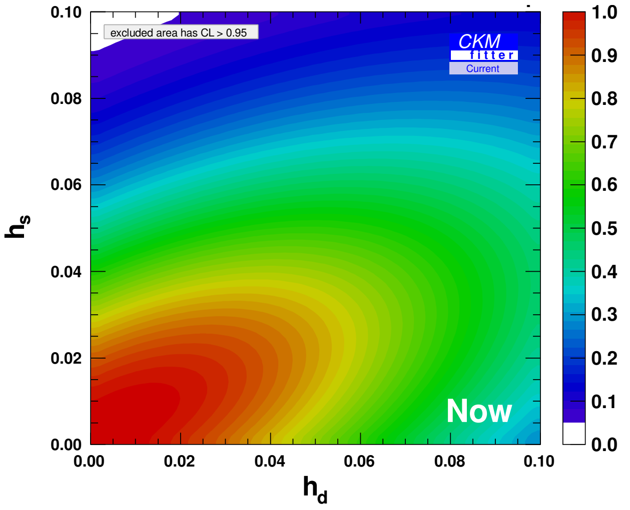
  General parametrization: $h\, e^{2i\sigma} = A_{\rm NP}(B^0 \to \overline{B}^0)/A_{\rm SM}(B^0 \to \overline{B}^0)$ ($h_{d,s}$, $\sigma_{d,s}$: NP param's)

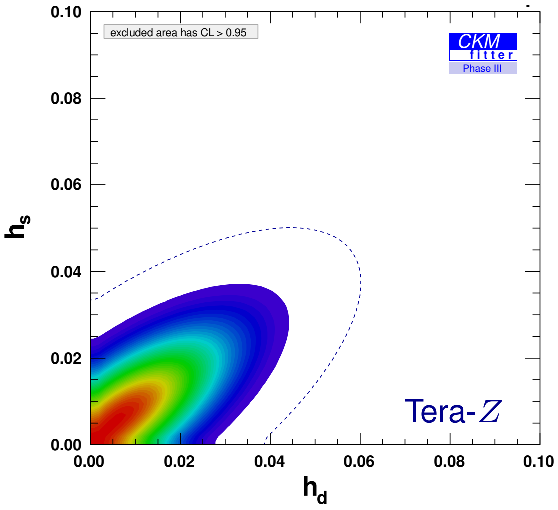
- CKM fit with 4 BSM param's added; combines many measurements and theory inputs [Charles *et al.*, 2006.04824]

  ($\Rightarrow$ conservative view of future progress)

- Sensitive to TeV scale, even if NP is MFV-like

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



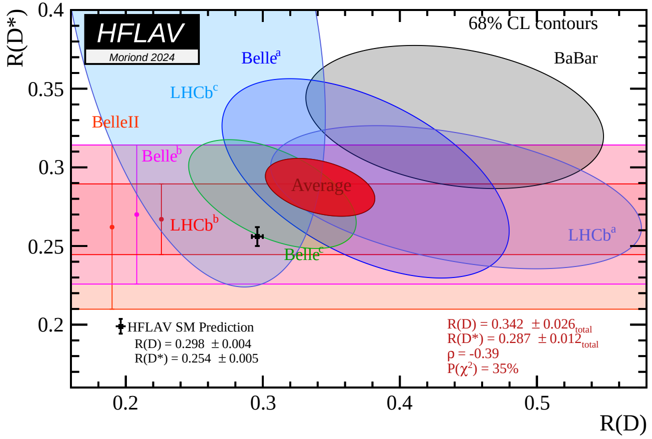


BERKELEY CENTER FOR THEORETICAL PHYSICS

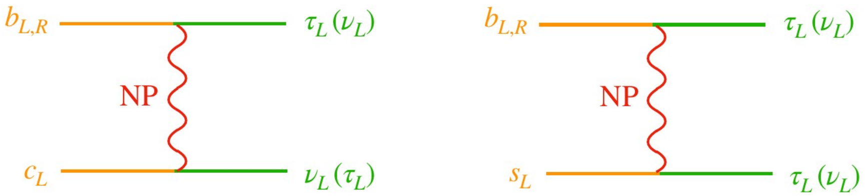
BERKELEY LAB

The $b \to c\tau\bar{\nu}$ anomalies could make compelling case

- Over 3σ tension for $R(D^{(*)})$, if it prevails, requires $\mathcal{O}(10\%)$ correction to a tree-level SM process



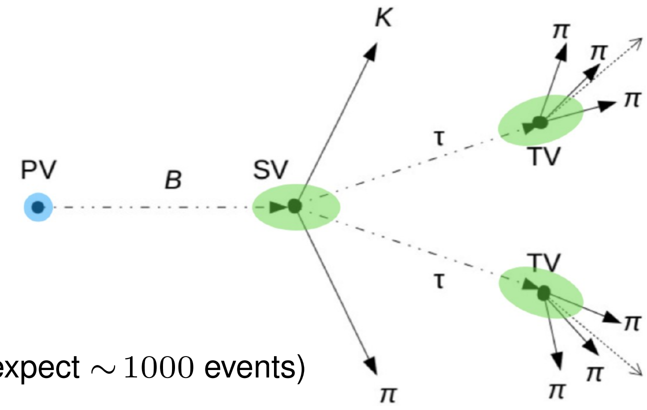
- If NP is charged under $SU(2)$, unavoidable connection to $b \to s\tau^+\tau^-$ or $b \to s\nu\bar{\nu}$ — correlations distinguish models



[image credit]

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

- Boost of B from Z decay provides ideal environment



(expect ~ 1000 events)

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

(Very) rare (semi)leptonic decays

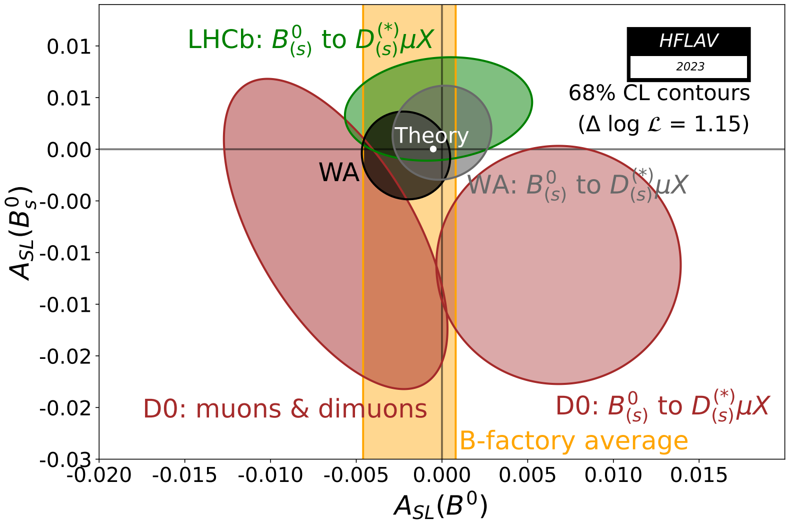
- Unique capabilities for decays with large missing energy, i.e., ν or τ in final state
  (And better than LHCb for $e^{\pm}$)
- Tera-Z could be the first to measure:
  Many decays mediated by $b \to s\nu\bar{\nu}$ or $b \to s\tau^+\tau^-$, and their $b \to d$ counterparts
  $B \to K^{(*0)}\tau^+\tau^-$, $\Lambda_b \to \Lambda\tau^+\tau^-$, $B \to K^{(*)}\nu\bar{\nu}$, $B_s \to \phi\nu\bar{\nu}$, $\Lambda_b \to \Lambda\nu\bar{\nu}$, $B \to \pi(\rho)\nu\bar{\nu}$, etc.
- 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
  $B_{s,d} \to \tau^+\tau^-$: tera-Z is much more sensitive: measure it, if $\geq$ SM level [$\sim 8 \times 10^{-7}$]
- Another important 2-body decay, to be measured by FCC-ee: $B_c \to \tau\bar{\nu}$
- $b \to c\tau\bar{\nu}$ and $s\ell^+\ell^-$ anomalies: in many models, correlated effects in many processes

CP violation in neutral meson mixing: $A_{\rm SL}^{d,s}$

- Only seen in K so far; for $B_{(s)}$, the m_c^2/m_b^2 suppression in the SM may be lifted by BSM [hep-ph/0202010]

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

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



- Current status: Exp: $A_{\rm SL}^d = -(2.1 \pm 1.7) \times 10^{-3}$ $\quad A_{\rm SL}^s = -(0.6 \pm 2.8) \times 10^{-3}$
  SM: $A_{\rm SL}^d = -(4.7 \pm 0.6) \times 10^{-4}$ $\quad A_{\rm SL}^s = (2.22 \pm 0.27) \times 10^{-5}$ [1603.07770]

- Unique to Tera-Z: uncertainty $\sim 2.5 \times 10^{-5}$ for both $A_{\rm SL}^d$ and $A_{\rm SL}^s$, reach SM level

Polarized baryons: unique, but how useful?

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

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

  Long history of interesting works, I feel we may be missing the key applications / ideas [see, e.g., Mannel *et al.*, PLB 255 (1991) 593]

- Baryon polarization tells us about Dirac structure of operators that create them
  (Washed out by hadronization for mesons)

  Need to know how well the quark polarization is retained by the baryons
  (More work needed, connections with top decays [1505.02771])

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

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

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Crazy but fun: inclusive $B \to X_u \tau \bar\nu$ doable?

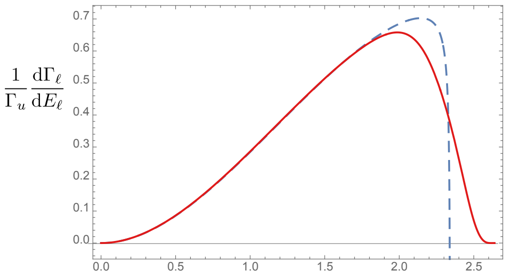
- Calculated lepton energy spectrum, τ polarization, etc. [ZL, Luke, Tackmann, 2112.07685]

  Managed to write $\mathrm{d}\Gamma/\mathrm{d}E_\ell$ at $\mathcal{O}(\alpha_s)$ in closed form (1st time for massive $\to$ massive?)

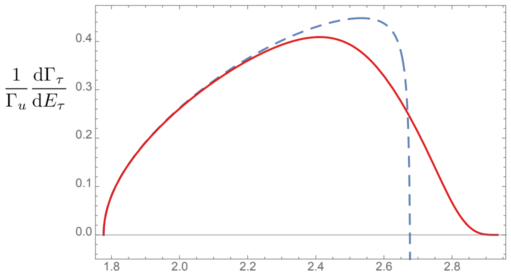
  (As far as I know, $\mathrm{d}\Gamma/\mathrm{d}E_\ell$ at $\mathcal{O}(\alpha_s)$ is not known analytically in $B \to X_c e \bar\nu$)

- The b-quark pdf is much more important in $B \to X_u \tau \bar\nu$ than in $B \to X_u e \bar\nu$ decay

  Sizable in half of the phase space

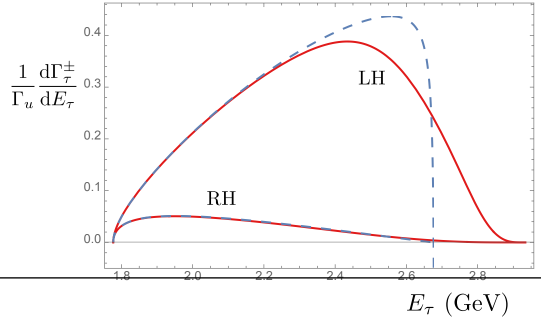


(a)



(b)

- Recent claim of a large correction from a dim-6 (“Darwin”) term in HQET [Moreno, 2402.13805]



Tidbits of τ physics

- Recent anomalies increased interest in probing lepton flavor universality

  PIONEER will soon improve $\pi \to e\nu$ vs. $\mu\nu$ by factor ~ 15 ($+$ searches for new particles)

- In τ decay, best precision from $\tau \to e\nu\bar{\nu}$ vs. $\mu\nu\bar{\nu}$ — and lifetime (n.b. $e_e \to \mu_\mu \to \tau_\tau$)

  Beyond statistics improvement, many analyses benefit from τ boost

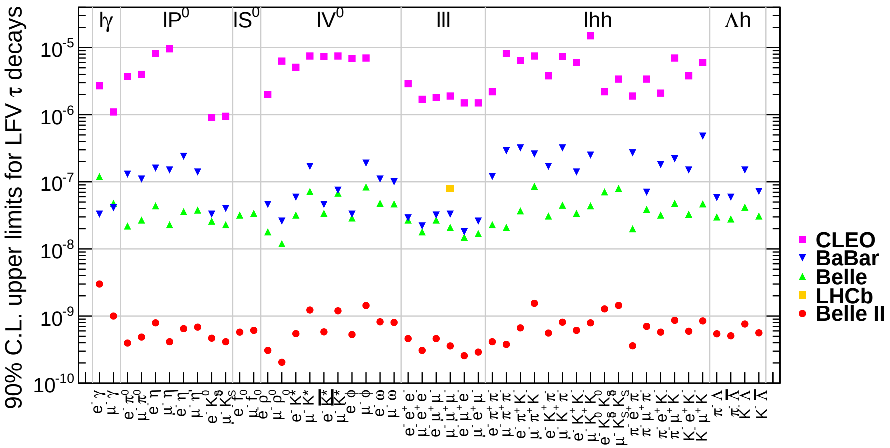
- Large improvements in CLFV τ searches

- Belle II: 2 orders of magnitude; e.g., $\tau \to \mu\gamma, \mu\mu\mu$

  Big model dependence in $\mathcal{B}(\tau \to \mu\gamma)/\mathcal{B}(\mu \to e\gamma)$

- FCC would yield further improvement

- Any discovery $\Rightarrow$ broad program to map structure



BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

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 decays, even in 2040s we'll have (exp. bound)$/$SM $\gtrsim 10^3$ (E.g., $B_{d,s} \to e^+e^-,\ \tau^+\tau^-$)
- Sensitivity to NP could improve with data $\gg$ LHCb, Belle II, tera-Z

Summary (3)

- Very rich physics program

  FCC-ee foundational, complementary to LHC and FCC-hh, necessary for making the most of FCC-hh

- FCC-ee can be a discovery machine

  Much improved sensitivity to: Higgs, PEW, flavor, light particle searches

- Z pole: a leap from LEP, qualitatively new sensitivity

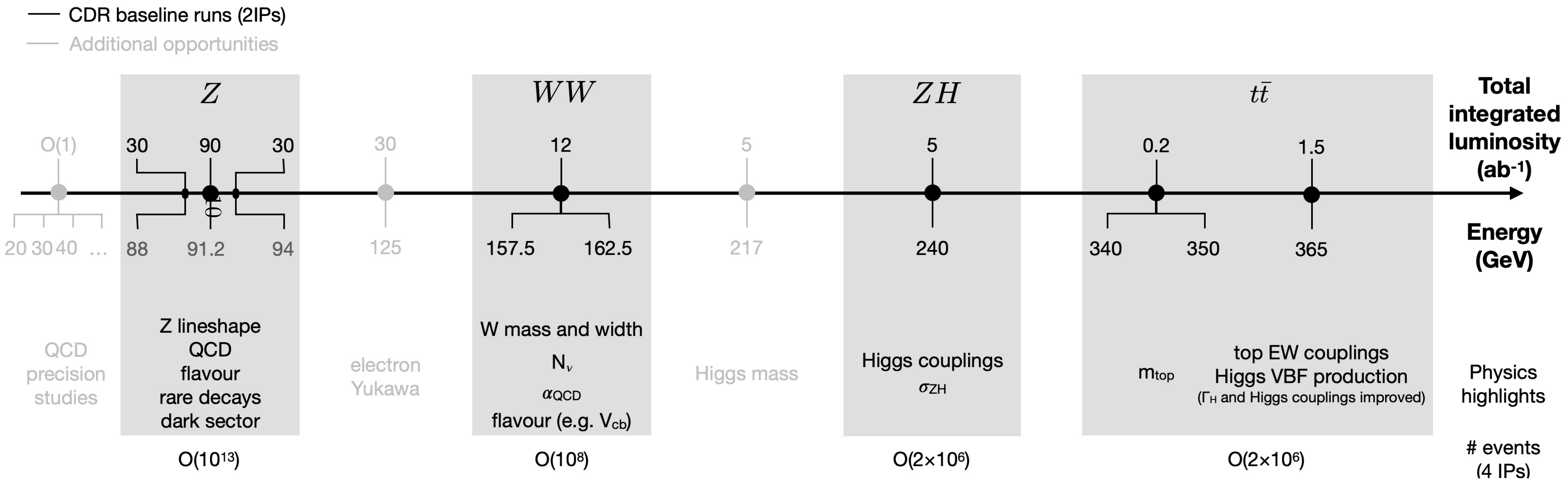
  Probes beyond HL-LHC; In flavor physics, the only way to go beyond Belle II & LHC(b)

- Interesting challenges to maximize sensitivity, both for experiment and theory

- Ample physics reasons to study the largest possible attainable data sets

Extra slides

Run plans and highlights



Sensitivity to new physics in B mixing

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

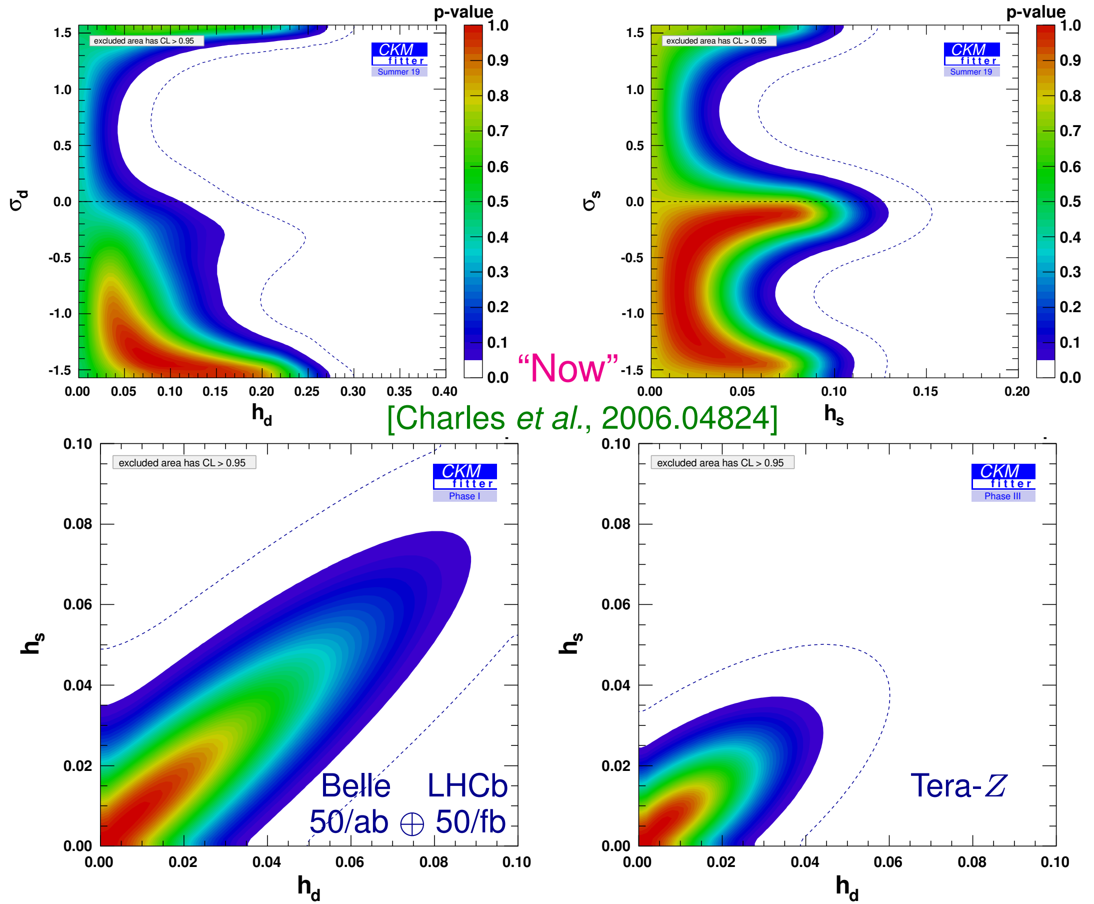
  Redo CKM fit w/ 4 BSM param's added

  Relies on many measurements & theory inputs

- Big improvements: Sensitive to TeV scale, even if NP is MFV-like (loop & CKM suppressed)

  Complementary to high-p_T searches

- $|V_{cb}|$ becomes a bottleneck; Tera-Z sensitivity will be better, not lattice QCD extrapolations yet



[Charles *et al.*, 2006.04824]