Future Flavor Physics Program

Zoltan Ligeti

(ligeti@berkeley.edu)

New Horizon in Particle Physics

Workshop for Future Particle Accelerators

8 – 19 July 2019, KAIST, Daejeon, Republic of Korea

Preliminaries...

- A large number of reviews on key measurements, sensitivities, exclusion limits
  Won't show (large & impressive!) tables of sensitivity projections [some links below]
- Update of European Strategy for Particle Physics: open symposium flavor summary
  Cannot cover all: EDM, CLFV, kaon, charm & b physics, higgs, dark sectors, etc., VERY BROAD!
- Flavor @ existing accelerators: (many others: BES, KOTO, NA62, etc.)
  - Belle II physics book, arXiv:1808.10567 $+$ recently formed upgrade working group
  - EoI for Phase-II LHCb Upgrade, LHCC-2017-003
  - Opportunities in Flavor Physics at the HL-LHC and HE-LHC, arXiv:1812.07638
- Flavor @ future accelerators: circular colliders, linear colliders, etc.
  Flavor physics at FCC, see FCC CDR outline (3/2019), see S. Monteil's talk
- Not many detailed studies, community busy with Belle II, LHCb, and upgrades
  Strong case for flavor experiments at all proposed colliders, but unlikely to determine selection

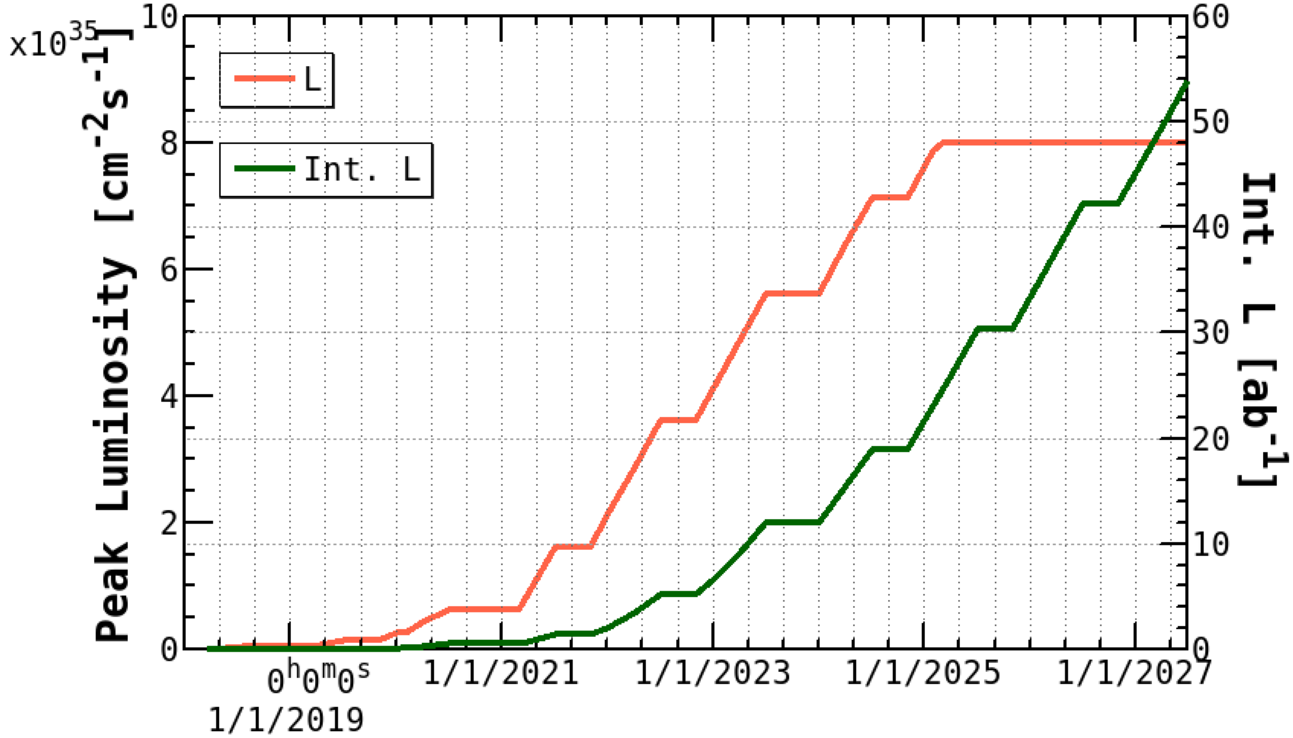
LHCb — LHC at CERN

	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}	⟶	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 $2x10^{34}$ $cm^{-2}s^{-1}$

- Major LHCb upgrade in LS2 (raise instantaneous luminosity to $2 \times 10^{33}/\mathrm{cm}^2/\mathrm{s}$)
  Major ATLAS and CMS upgrades in LS3, for HL-LHC
- LHCb, 2017, Expression of Interest for an upgrade in LS4 to $2 \times 10^{34}/\mathrm{cm}^2/\mathrm{s}$
  To me, this is obviously an integral part of the full exploitation of the LHC

Belle II — SuperKEKB at Tsukuba

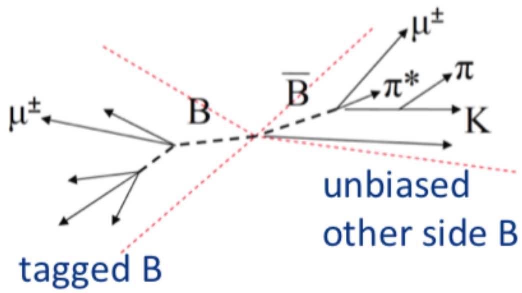


- First collisions 2018 (unfinished detector), with full detector starting spring 2019
  Goal: $50\times$ the Belle and nearly $100\times$ the $B\!A\!B\!AR$ data set [See: N. Taniguchi's talk, Thursday]

- Discussions started about physics case and feasibility of a factor ~ 5 upgrade, similar to LHCb Phase-II upgrade aiming 50/fb $\rightarrow$ 300/fb, in LHC LS4

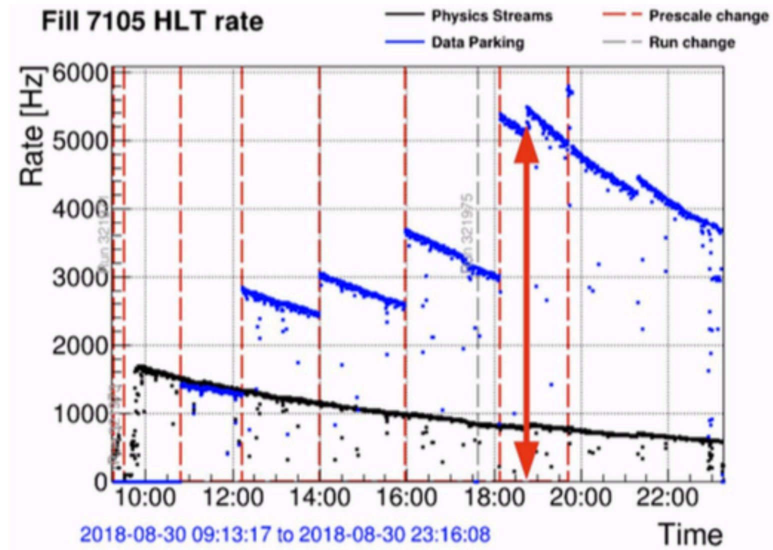
Recent surprise: CMS "$B-$parking" in 2018

- Collected 10^{10} B-s; hope to compete w/ LHCb on $R_{K^{(*)}}$ anomaly [CMS @ LHCC, Nov 2018]



Effort in 2018 paid off, 12B triggered events on tape

- Up to 5.5 kHz in the second part of the fill where events are smaller



Now studying processing strategy

- 1.1B events were already fully processed in order to help development of trigger/ reconstruction

7.6 PB on tape
Avg event size is 0.64 MB
(1MB for standard events)

16 Simone.Gennai@cern.ch

Outline

- Introduction to flavor physics
- Mode / model independent: Large improvements in NP sensitivity

  Going from: NP $\lesssim$ (few $\times$ SM) $\rightarrow$ NP $\lesssim$ $(0.3$ $\times$ SM) $\rightarrow$ NP $\lesssim$ $(0.04$ $\times$ SM)

  (-15 yrs) (now) ($+15$ yrs)
- Mode / model specific: Current tensions with SM — might soon become decisive

  Several $2-4\sigma$ tensions with SM: triggered lots of experimental & theory work
- Many exciting areas: Higgs & top, charged lepton flavor violation, EDM searches,

  BSM scenarios may have nontrivial flavor: dark sectors, long lived particles, ...

(Focus on quark sector, richest in SM, leptons equally important, esp. with NP)

Introduction

Hope to discover BSM physics

- Most experimentally observed phenomena are consistent with 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 [nonzero in SM, but too small by $\sim 10^{10}$]
  - Neutrino mass [can add in a straightforward way]
  - Inflation in the early universe [have a theoretical picture that might work]
  - Accelerating expansion [cosmological const.? need to know more?]

- Need BSM source(s) of CP violation — how precisely can we probe it?

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

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

What is flavor physics?

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

  Rich and sensitive ways to probe the SM and search for NP

- SM flavor: hierarchy of masses and mixing angles? why 3 generations?

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

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

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

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

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

- Flavor sector will be tested a lot better, many NP models have observable effects

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

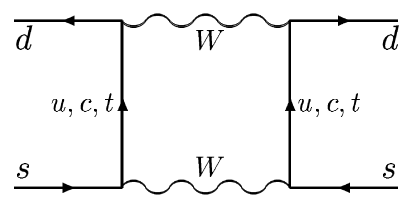
  - Absence of $K_L \to \mu\mu \Rightarrow$ charm quark (Glashow, Iliopoulos, Maiani, 1970)

  - $\epsilon_K \Rightarrow 3$rd generation (t, b quarks) (Kobayashi & Maskawa, 1973)

  - $\Delta m_K \Rightarrow m_c \sim 1.5\,\text{GeV}$ (Gaillard & Lee; Vainshtein & Khriplovich, 1974)

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

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



  - $\Delta m_B \Rightarrow m_t \gtrsim 100\,\text{GeV}$ (bound in 1987: $23\,\text{GeV}$) $\Rightarrow$ large CP violation & FCNC

- Critical in developing SM — What can future data tell us about BSM physics?

Quark mixing and unitarity triangle

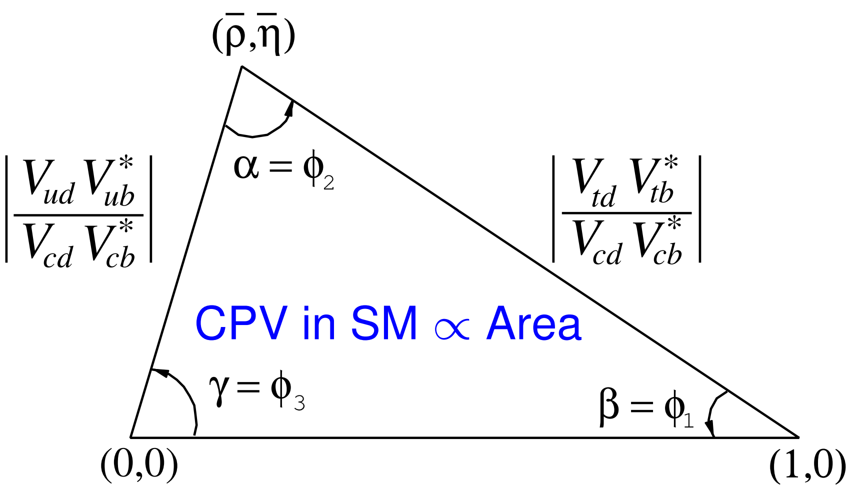
- The $(u,\, c,\, t)$ $W^{\pm}$ $(d,\, s,\, b)$ couplings: (Wolfenstein parm., $\lambda \sim 0.23$)

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

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

One complex phase in $V_{\rm CKM}$: only source of CP violation in quark mixing

- Unitarity triangle: visualize SM constraints and compare measurements



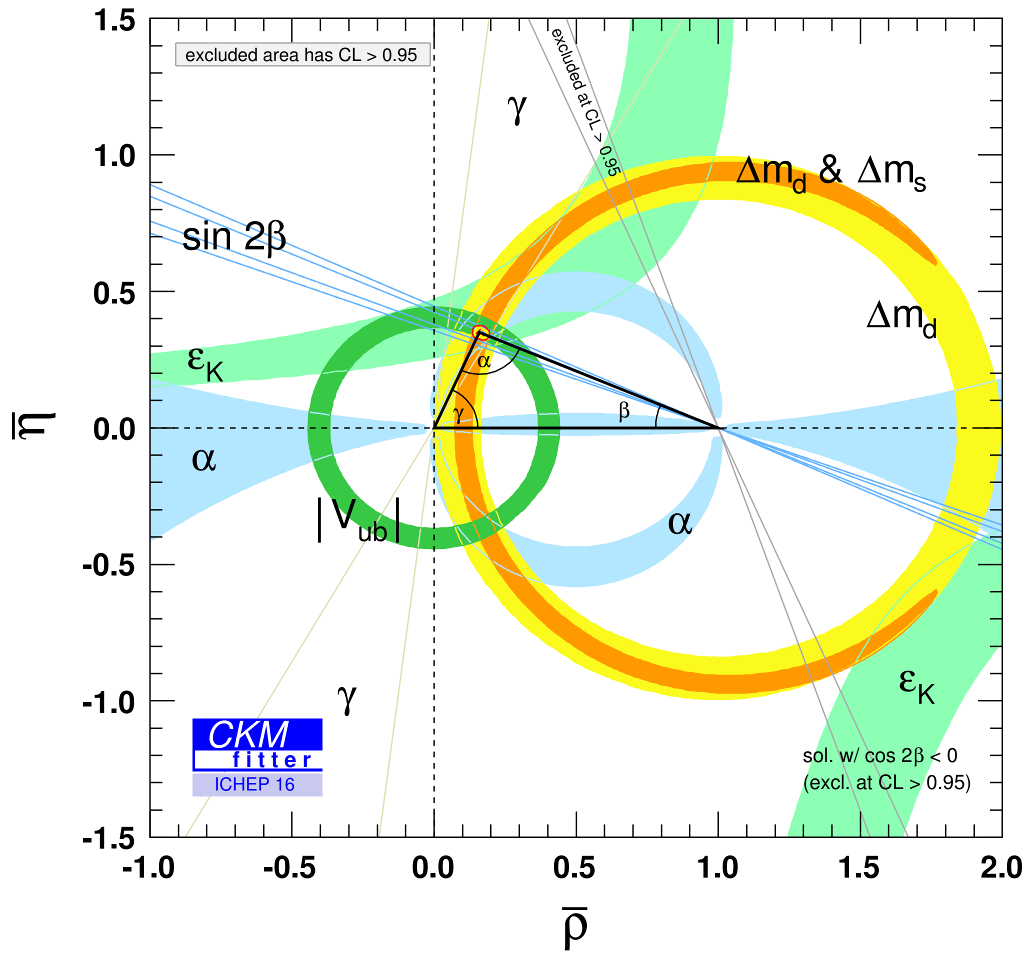
$$V_{ud}\, V_{ub}^* + V_{cd}\, V_{cb}^* + V_{td}\, V_{tb}^* = 0$$

Sides and angles measurable in many ways

Goal: overconstrain by many measurements sensitive to different short distance physics

Learned a lot, plenty of room for new physics

- Spectacular progress in last 20 years
- The implications of the consistency of measurements is often overstated
- Larger allowed region if there is NP

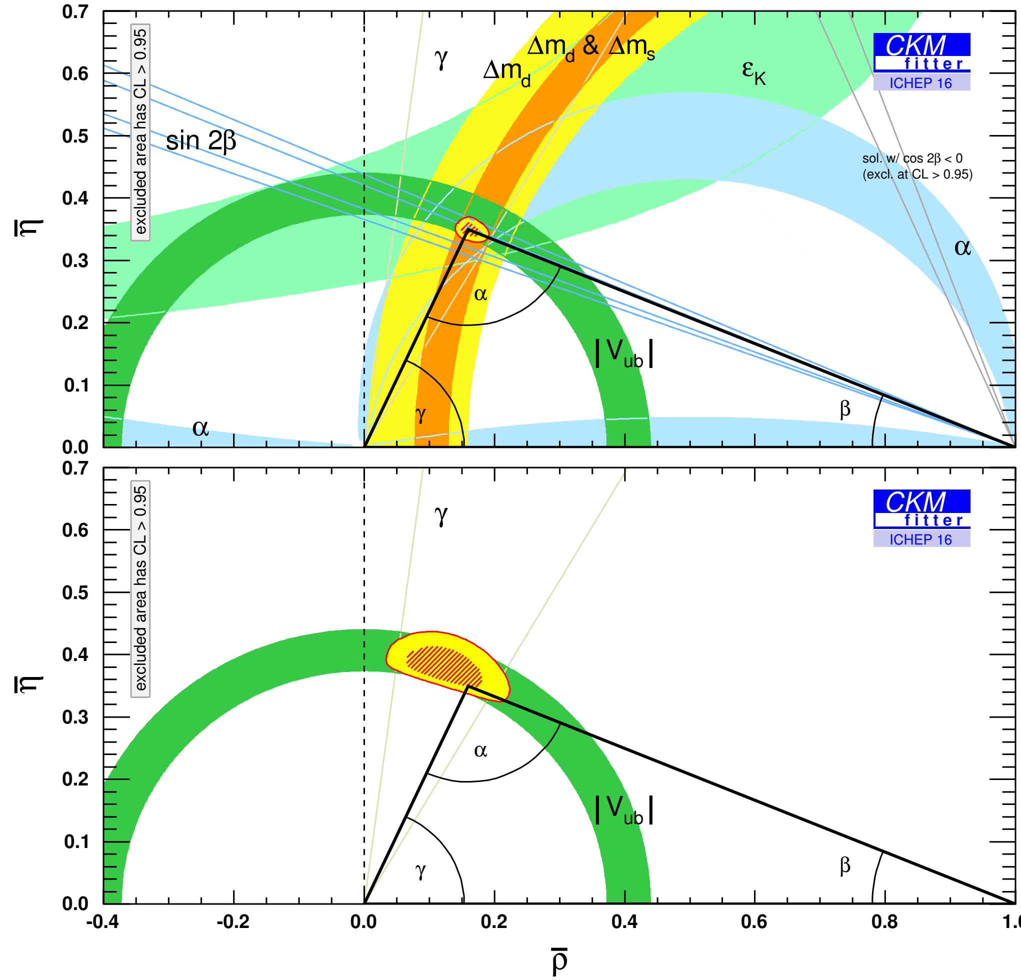


BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Learned a lot, plenty of room for new physics

- Spectacular progress in last 20 years
- The implications of the consistency of measurements is often overstated
- Larger allowed region if there is NP
- Compare tree-level (lower plot) and loop-dominated measurements
- LHCb: constraints in the B_s sector (2nd–3rd gen.) caught up with B_d



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

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Some flavor-related questions

- Will LHC see new particles beyond the Higgs?
- Will NP be seen in the quark sector?

  Current data: several hints of lepton flavor universality violation (see later)
- Will NP be seen in lepton sector (CLFV)? $\mu \to e\gamma$, $\mu \to eee$, $\tau \to \mu\gamma$, $\tau \to \mu\mu\mu$?
- Neutrinos? (3 flavors? Majorana / Dirac?)
- Dark matter / sectors may also relate to flavor

- No one knows — an exploratory era!

  (n.b.: 2 generations $+$ superweak is "more minimal" to accommodate CPV, than 3 generations...)
- Near future: current tensions might first become clear BSM signals

  Long term: large increase in discovery potential in many modes

Model independent

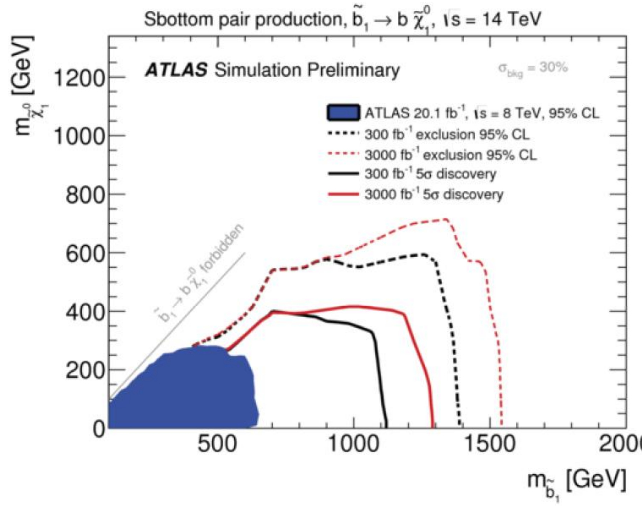
(1) Discovery potential at HL-LHC

- A possible figure of merit: mass-scale vs. coupling sensitivity
- Focus: ATLAS/CMS $300/\mathrm{fb} \to 3000/\mathrm{fb}$, LHCb $50/\mathrm{fb} \to 300/\mathrm{fb}$ (latter not yet approved)

  ATLAS & CMS searches for high-mass states: parton luminiosities fall rapidly

  LHCb Phase-2 upgrade compared to Phase-1: $\sqrt[4]{6} \sim 1.6$ mass scale (conservative)

- It is often said that what's excluded at $300/\mathrm{fb}$, cannot be discovered at $3000/\mathrm{fb}$ — so why keep going...?
  - Holds for many high-mass particle searches
  - Not true for lighter / weakly coupled particles, Higgs couplings, flavor observables (uncert. $\sim 1/\sqrt{\mathcal{L}}$)



- Statistics $\times 10$ can make $1.5\sigma \to \sim 5\sigma$, even without analysis improvements

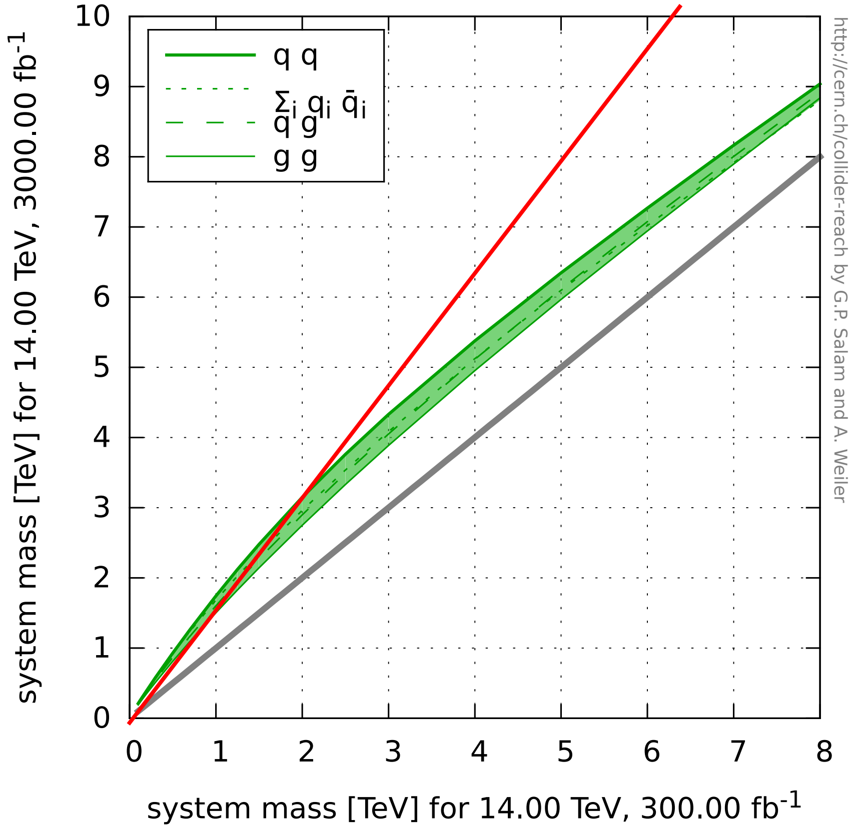
  (No one knows how many measurements are 1.5σ from SM expectation... which also improve)

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

At fixed energy, $1/\sqrt{\mathcal{L}}$ is about the best

- $\sqrt[4]{6} \sim 1.6$ vs. mass-scale increase at $14\,\mathrm{TeV}$, $300 \to 3000/\mathrm{fb}$ [http://collider-reach.web.cern.ch/]

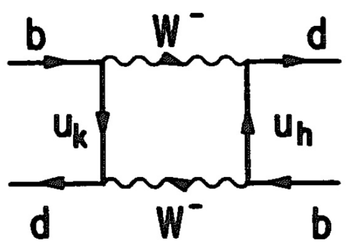


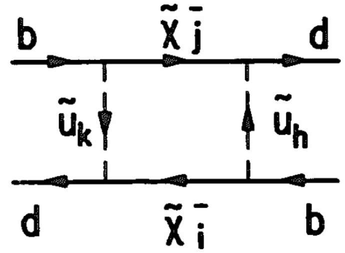
- Increase in mass limit > 1.6, iff (w/ caveats) limit with 300/fb at 14TeV is $\lesssim 1\,\mathrm{TeV}$

  Weakly produced particles ($H^\pm$, ...) or difficult decays — not the typical Z', $\tilde{q}$, $\tilde{g}$!

(2) New physics in B mixing

- Meson mixing:





General parametrization:

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

NP parameters

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

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

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

- Assume: (i) 3×3 CKM matrix is unitary; (ii) tree-level decays dominated by SM
- Modified: loop-mediated (Δm_d, Δm_s, β, β_s, α, ...)

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

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

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Sensitivity to NP in B mixing

- At 95% CL: NP $\lesssim (0.3 \times$ SM)

  $\Rightarrow$ NP $< (0.05 \times$ SM)

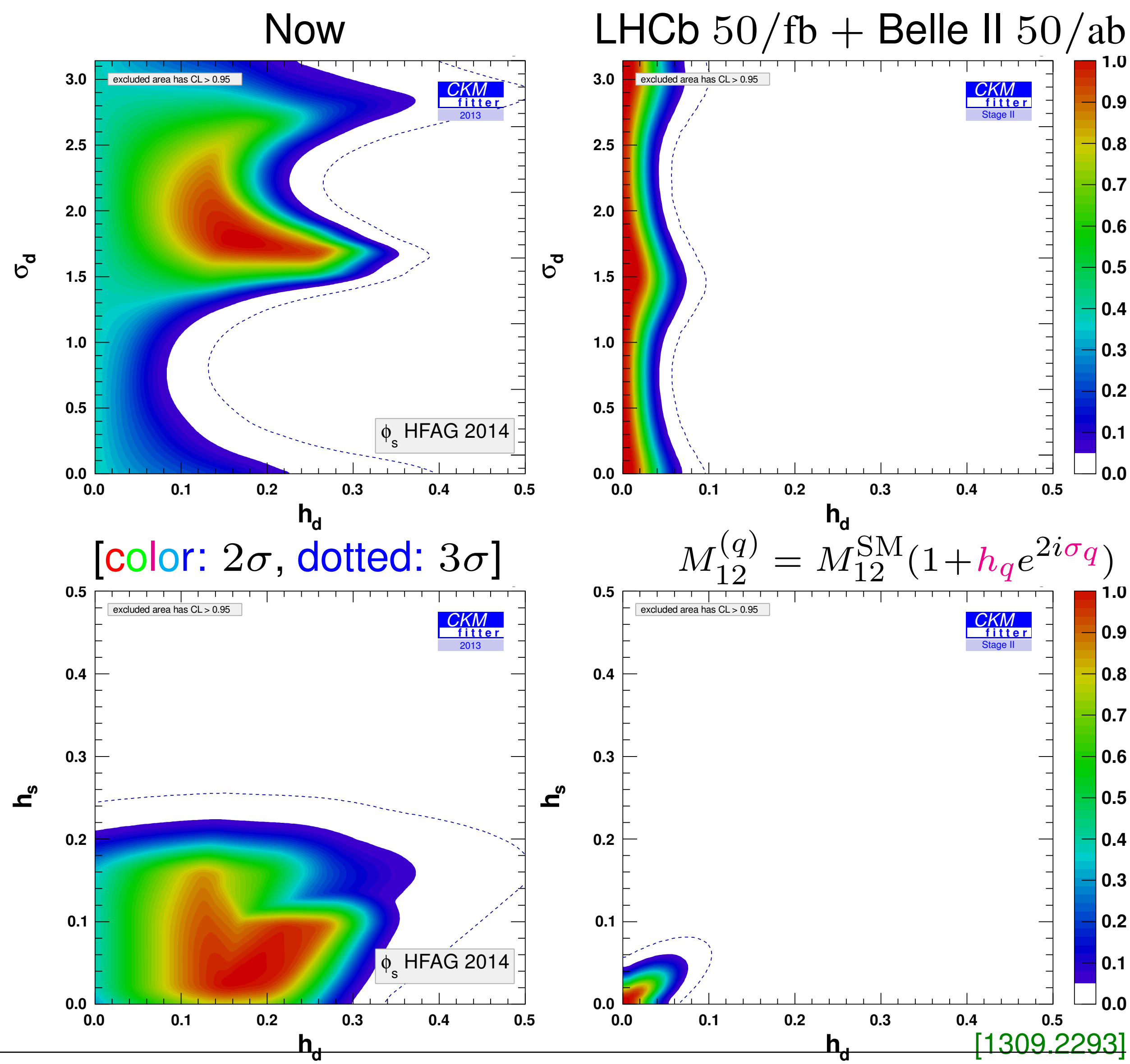
- Scale: $h \simeq \dfrac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \left(\dfrac{4.5\,\text{TeV}}{\Lambda}\right)^2$

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

- Similar to LHC $m_{\tilde{g}}$ reach

- Sensitivity would continue to increase beyond $300/\text{fb}$

  Complementary to high-p_T

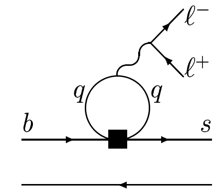


[1309.2293]

Mode / model dependent

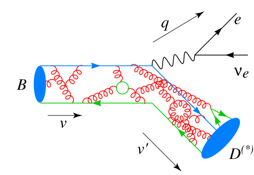
The current B "anomalies"

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

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

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

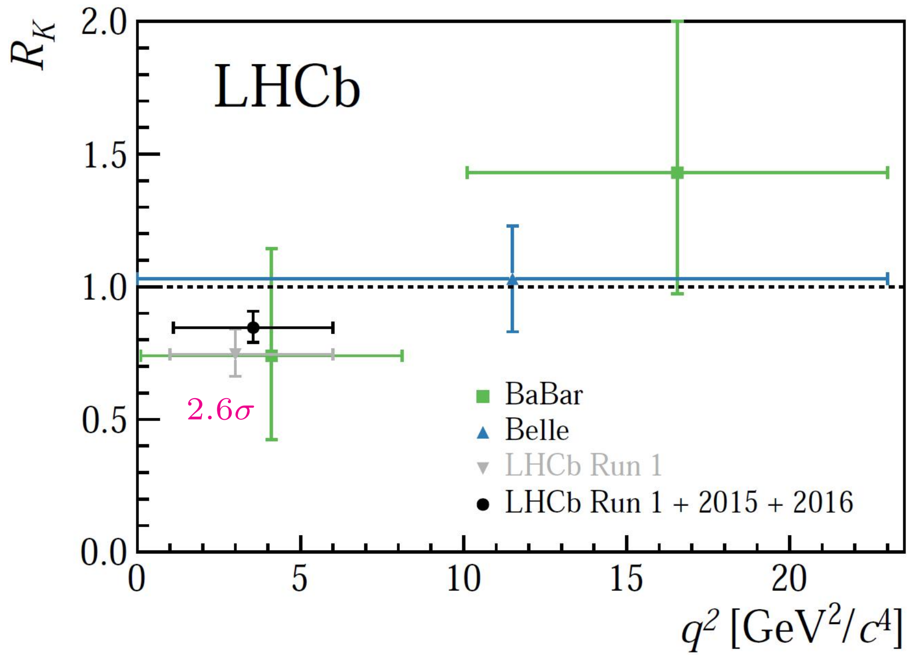
- Viable BSM models... leptoquarks? No clear connection to DM & hierarchy puzzle

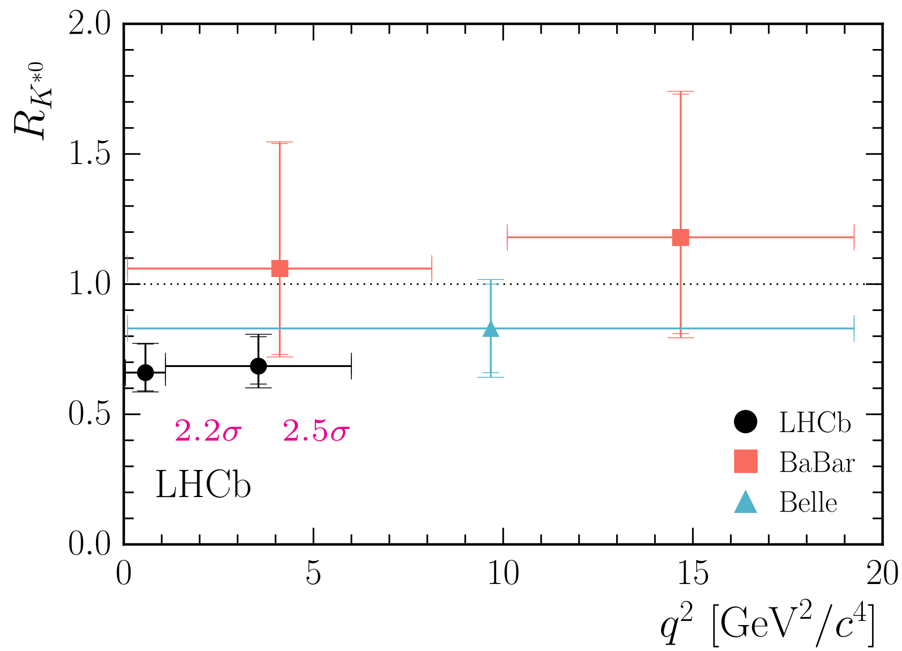
(Is the hierarchy problem or the flavor problem more pressing for Nature?)

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

R_K and R_{K^*}: theoretically cleanest

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





- Theorists' fits quote $3-5\sigma$ (sometimes including P_5' and/or $B_s \to \phi\mu^+\mu^-$)

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

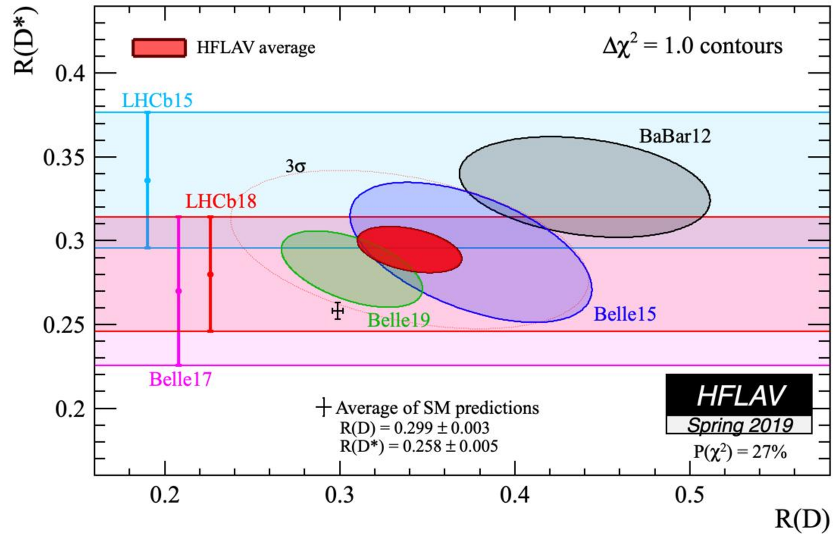
The $B \to D^{(*)}\tau\bar\nu$ decay rates

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

  3.1σ from SM predictions — robust due to heavy quark symmetry + lattice QCD (only D so far)

  more than statistics: $R(D^*)$ with $\tau \to \nu 3\pi$ [1708.08856]

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



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

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

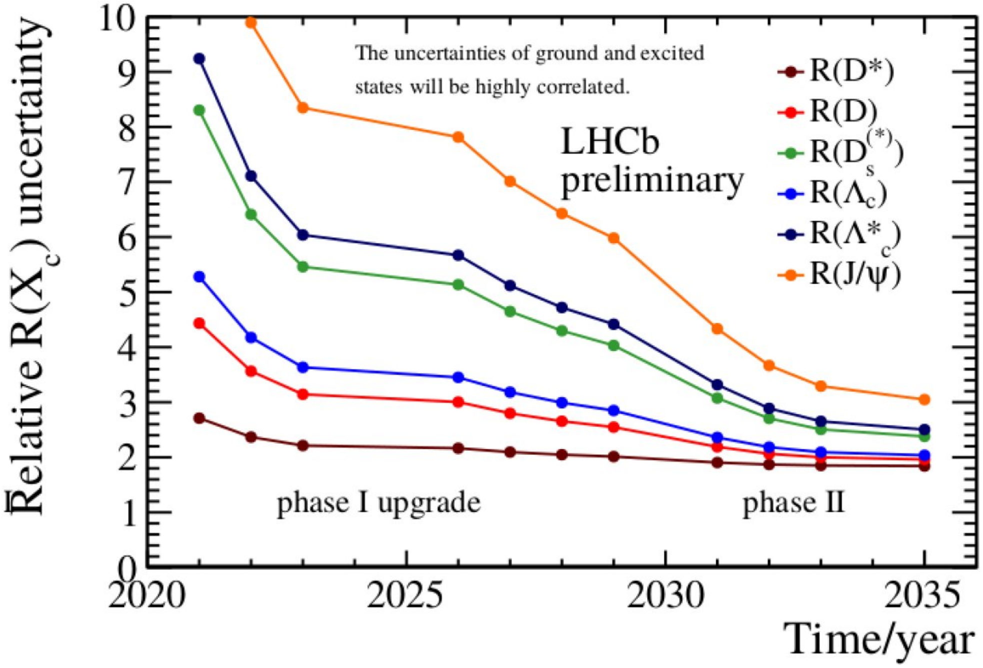
- Tree level: three ways to insert mediator: $(b\nu)(c\tau)$, $(b\tau)(c\nu)$, $(bc)(\tau\nu)$

  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

- LHCb: $R_{K^{(*)}}$ sensitivity with existing Run 1–2 data can still improve a lot
- LHCb and Belle II: increase $pp \to b\bar{b}$ and $e^+e^- \to B\overline{B}$ data sets by factor ~ 50
- LHCb:



Belle II (50/ab, at SM level):

$\delta R(D) \sim 0.005\ (2\%)$

$\delta R(D^*) \sim 0.010\ (3\%)$

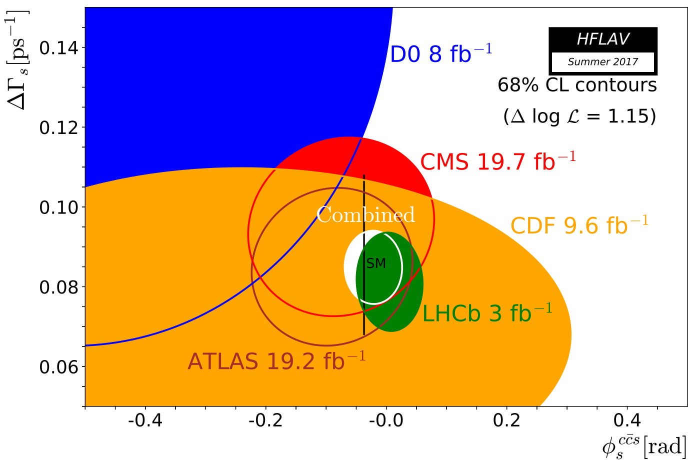
Measurements will improve a lot!

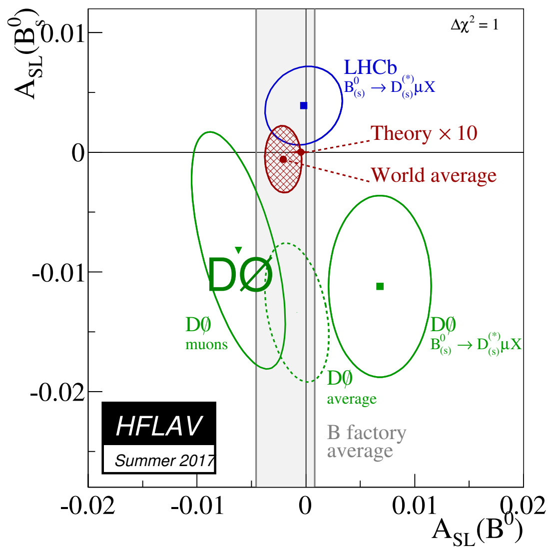
(Even if central values change, plenty of room for establishing deviations from SM)

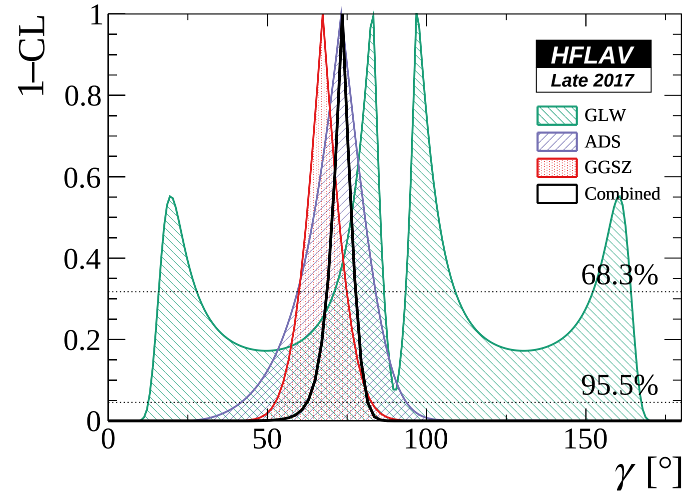
- Competition, complementarity, cross-checks between LHCb and Belle II

Richness of directions

Some key measurements, done much better







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

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

Measurements of γ crucial, LHCb is now most precise

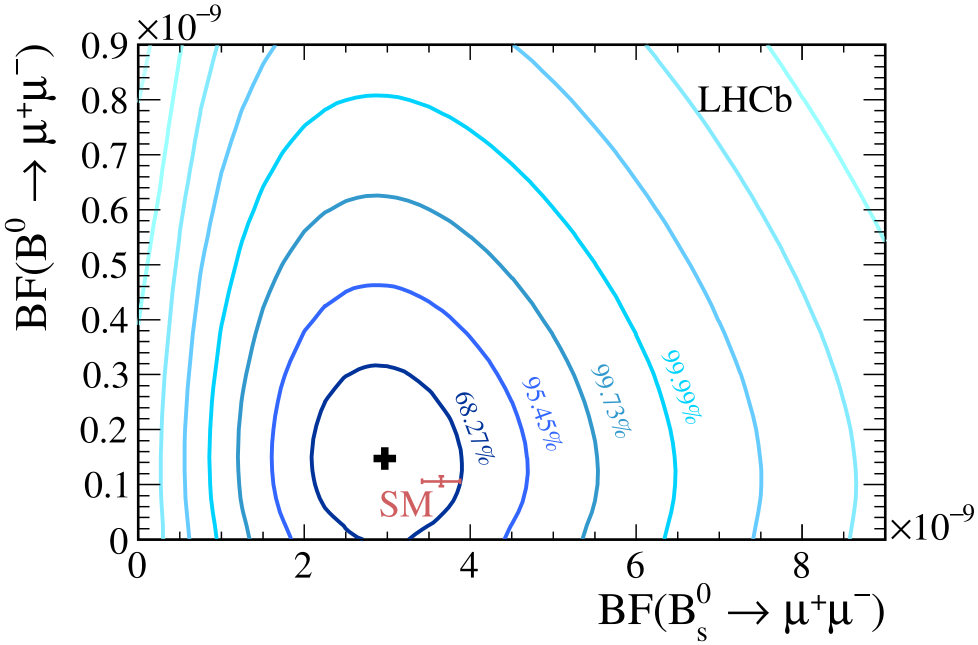
- Uncertainty of predictions $\ll$ current experimental errors ($\Rightarrow$ seek lot more data)
- Breadth crucial, often have to combine many measurements and theory

  (“The interesting messages are not simple, the simple messages are not interesting”)

$B \to \mu^+\mu^-$: 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, as of now $\simeq (2\%) \oplus f_{B_q}^2 \oplus \text{CKM}$ [Bobeth, FPCP'15]



- Theoretically cleanest $|V_{ub}|$ I know, 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/ $K \to \pi\nu\bar{\nu}$

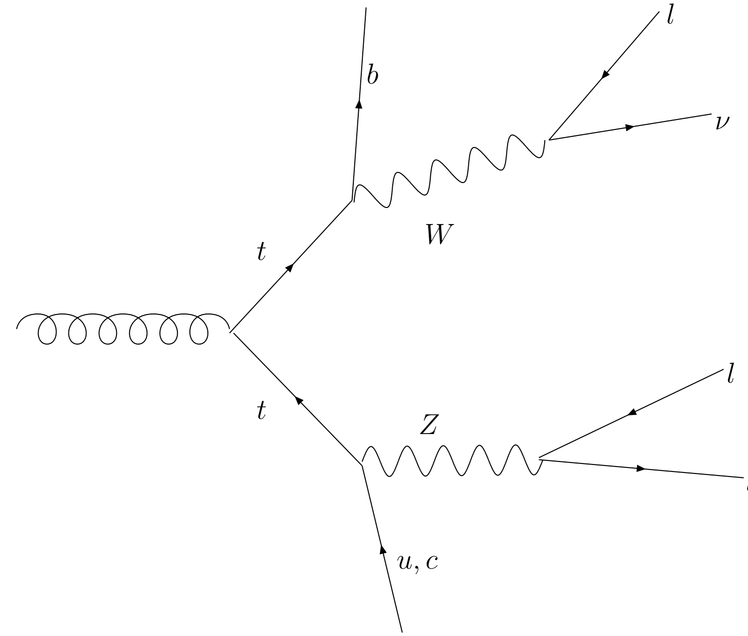
The LHC is a top factory: top flavor physics

- FCNC top decays not yet strongly constrained

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

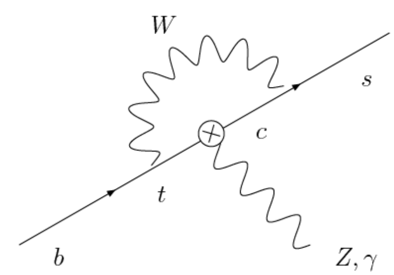
SM predictions: $< 10^{-12}$

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



- Sensitivity will improve ~ 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

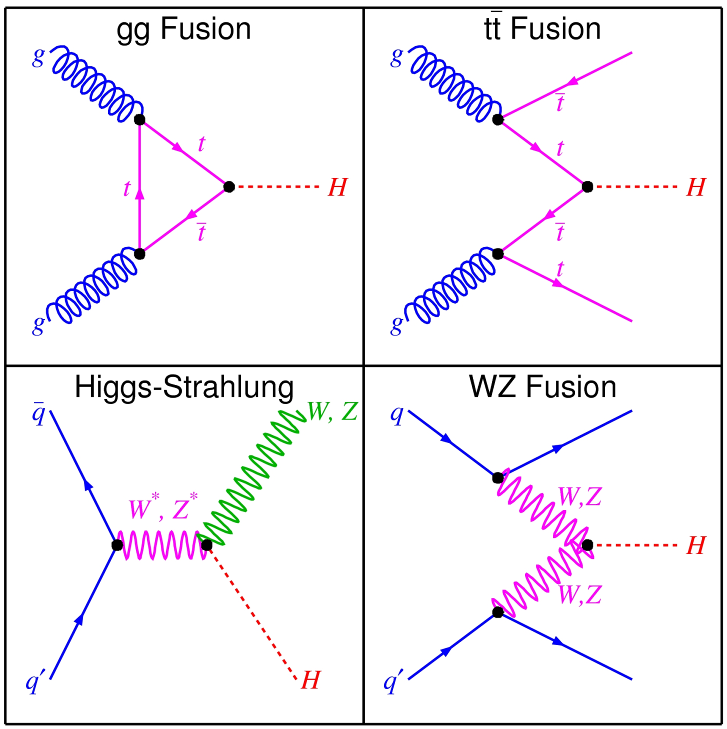


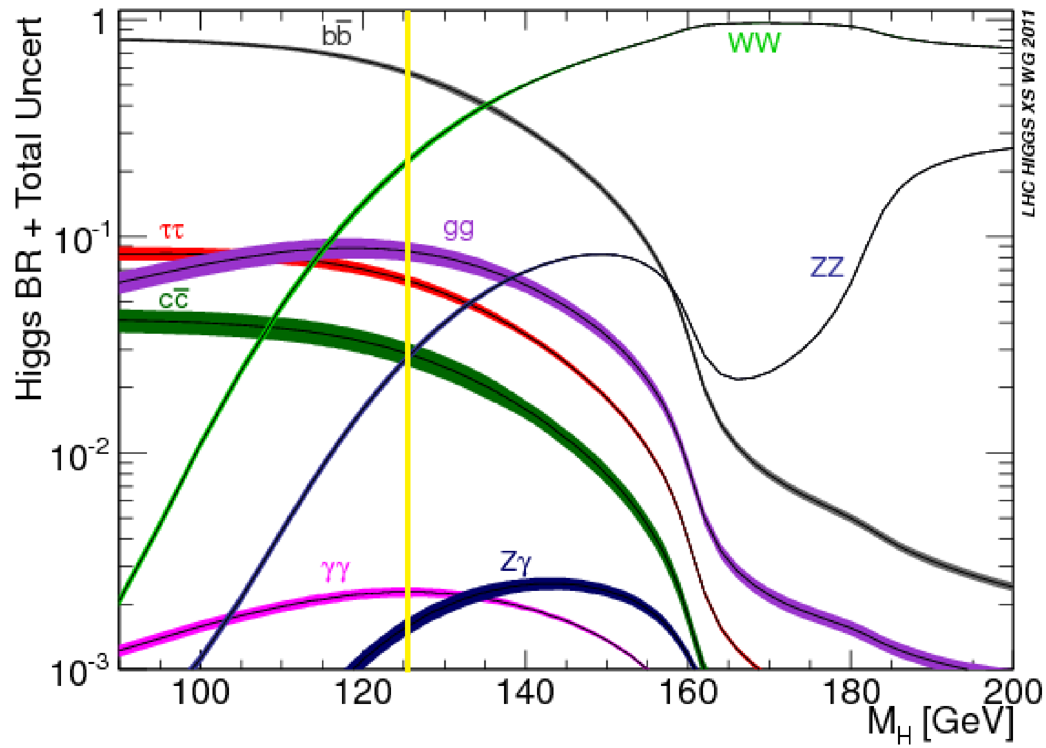
- If top FCNC is seen, LHC & B factories will both probe the NP responsible for it

The LHC is a Higgs factory

- Many production and decay channels: richness due to fermion couplings

  Yukawa matrices determine these, just like K, B, and D physics





- Higgs flavor param's: 3rd gen: κ_t, κ_b, κ_τ 2nd gen: κ_c, κ_μ Do κ_{tc}, $\kappa_{\tau\mu}$ vanish?

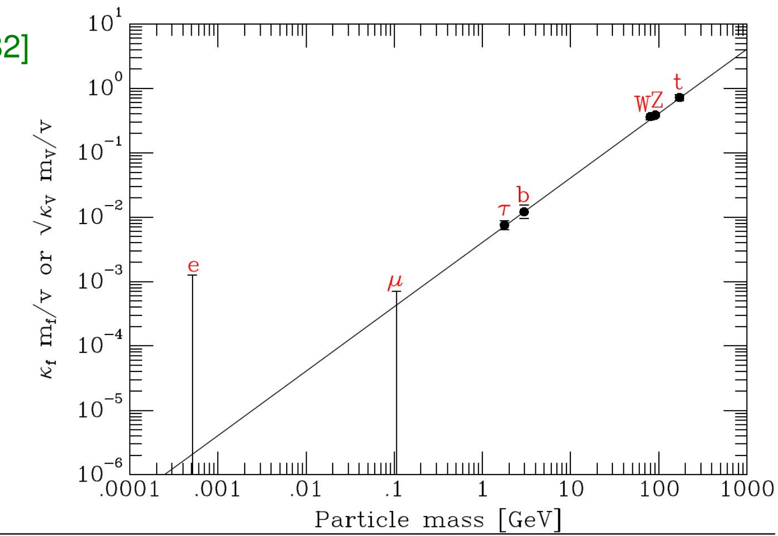
Higgs flavor physics

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

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

- Fermion masses and mixing angles all originate from the Yukawa matrices

[See: F. Yu's talk on Thursday]



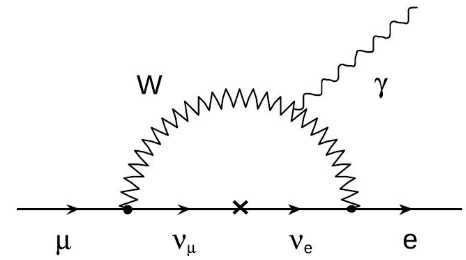
BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Charged lepton flavor violation

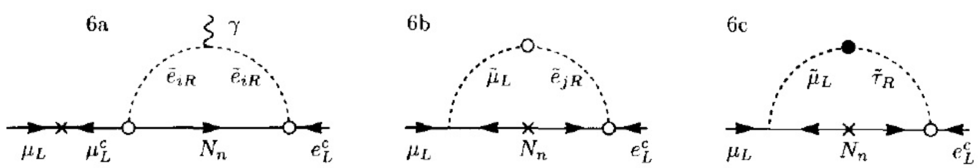
- SM predicted lepton flavor conservation with $m_\nu = 0$

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

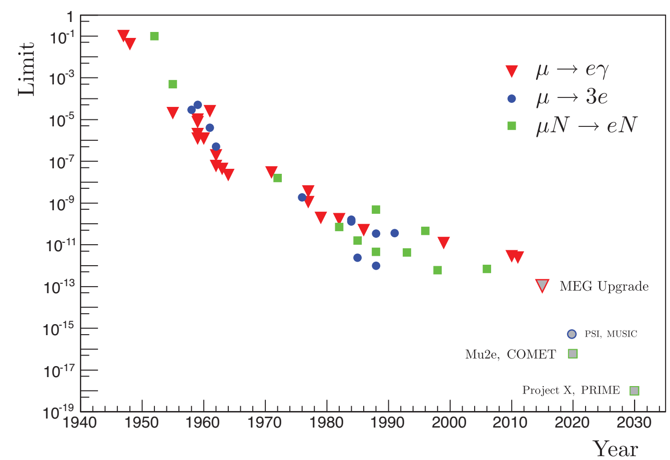


$$\mathcal{B}(\mu \to e\gamma) \sim \alpha \frac{m_\nu^4}{m_W^4} \sim 10^{-52}$$

- If new TeV-scale particles carry lepton number (e.g., sleptons), then they have 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:

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

  $\tau \to \mu\gamma,\ \tau \to e\gamma,\ \tau \to \mu\mu\mu,\ \tau \to eee,\ \tau \to \mu\mu e$

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

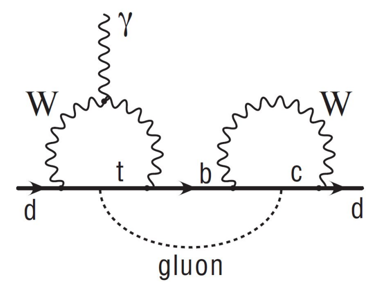
- Next 10–20 years: 10^2–10^5 improvement; any signal would trigger broad program

Electric dipole moments

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

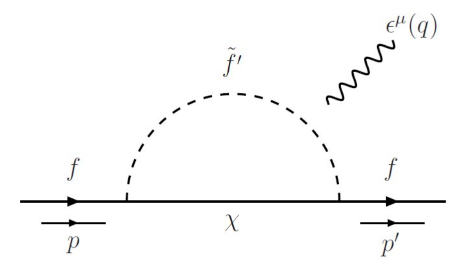
- Neutron EDM bound: “The strong CP problem”, $\theta_{\rm QCD} < 10^{-10}$ — axion?
  $\theta_{\rm QCD}$ is negligible for CPV in flavor-changing processes

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



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

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



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

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Very broad program: many directions

- Better tests of (exact or approximate) conservation laws
- Maximize sensitivity to $\tau \to 3\mu$, $\tau \to h\mu\mu$, etc.
- Exhaustive list of dark / hidden sector searches
- LFV meson decays, e.g., $M^0 \to \mu^- e^+$, $B^+ \to h^+ \mu^- e^+$, etc.
- Invisible modes, even baryonic, $B \to N + \text{invis.}\ [+\text{mesons}]$ [1708.01259]
- Hidden valley inspired scenarios, e.g., multiple displaced vertices, even with $\ell^+\ell^-$
- Exotic Higgs decays, e.g., high multiplicity, displaced vertices ($H \to XX \to abab$)
- Search for “quirks” (non-straight “tracks”) at LHCb using many velo layers
- I do not know how many CP violating quantities have been measured...
  neither how many new hadronic states discovered by BABAR, Belle, LHCb ...

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?
  - γ, theory limit only from higher order electroweak
  - $B_{s,d} \to \mu\mu$, $B \to \mu\nu$ and other leptonic decays (lattice QCD, [double] ratios)
  - CP violation in D mixing (firm up theory)
  - $A_{\rm SL}^{d,s}$ (work on exp. syst. issues)
  - CLFV, EDM, etc.
- In some decay modes, even in 2030 we'll have: (exp. bound)$/$SM $\gtrsim 10^3$

  E.g., $B \to e^+e^-$, $\tau^+\tau^-$ — can build models... (I hope to be proven wrong!)
- My guess: until $100\times$ (Belle II $\&$ LHCb Phase 2), sensitivity to NP would improve
- FCC-ee in tera-Z phase could be the ultimate B factory!

Conclusions

- Flavor physics probes scales $\gg 1\,\mathrm{TeV}$; sensitivity limited by statistics, not theory
- New physics in most FCNC processes may still be $\gtrsim 20\%$ of the SM or more
- Few tensions with SM; some of these (or others) may become decisive
- Precision tests of SM will improve in the next decade by 10–10^4 in some channels
- Many interesting theoretical questions relevant for optimal experimental sensitivity
- We'll learn a lot in the next decades, whether NP is discovered or not

Evidence for BSM?		FLAVOR yes	FLAVOR no
ATLAS & CMS	yes	complementary information	distinguish models
ATLAS & CMS	no	tells us where to look next	flavor is the best microscope

- If new physics is discovered, many new questions about its structure and origin

  E.g., possible convergence between (s)quark and (s)lepton flavor physics

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Extra slides

(3) Sensitivity to vector-like fermions

- Add one vector-like fermion: mass term w/o Higgs, hierarchy problem not worse

  11 models in which new particles can Yukawa couple to SM fermions and Higgs

  $\Rightarrow$ FCNC Z couplings to leptons or quarks [Ishiwata, ZL, Wise, 1506.03484; Bobeth et al., 1609.04783]

Upper (lower) rows are current (future, 50/fb LHCb & 50/ab Belle II) sensitivities

Model	Quantum numbers	Bounds on M/TeV and $\lambda_i\lambda_j$ for each ij pair					
		$ij = 12$		$ij = 13$		$ij = 23$	
		$\Delta F = 1$	$\Delta F = 2$	$\Delta F = 1$	$\Delta F = 2$	$\Delta F = 1$	$\Delta F = 2$
V	$(3, 1, -1/3)$	66^d $[100]^e$	$\{42, 670\}^f$	30^g	25^h	21^i	6.4^j
		280^d	$\{100, 1000\}^f$	60^l	61^h	39^k	14^j
VII	$(3, 3, -1/3)$	47^d $[71]^e$	$\{47, 750\}^f$	21^g	28^h	15^i	7.2^j
		200^d	$\{110, 1100\}^f$	42^l	68^h	28^k	16^j
XI	$(3, 2, -5/6)$	66^d $[100]^e$	$\{42, 670\}^f$	30^g	25^h	18^k	6.4^j
		280^d	$\{100, 1000\}^f$	60^l	61^h	39^k	14^j

Strongest bounds arise from many processes, nominally 1-2 generation most sensitive, large variation across models

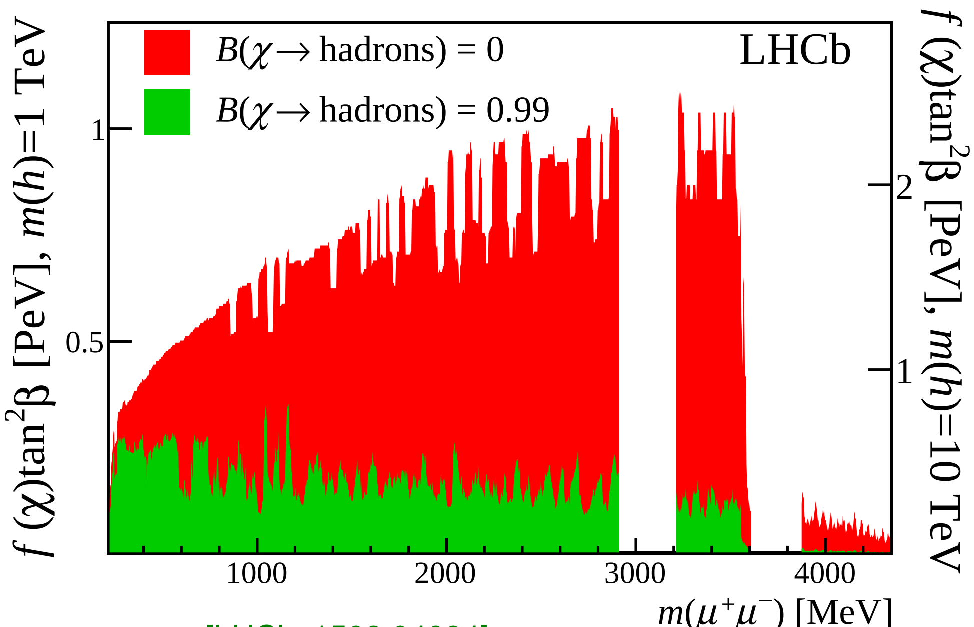
- LHCb 50/fb $+$ Belle 50/ab increase mass scale sensitivity by factor $\sim 2.5 \sim \sqrt[4]{50}$

Dark sectors: broad set of searches

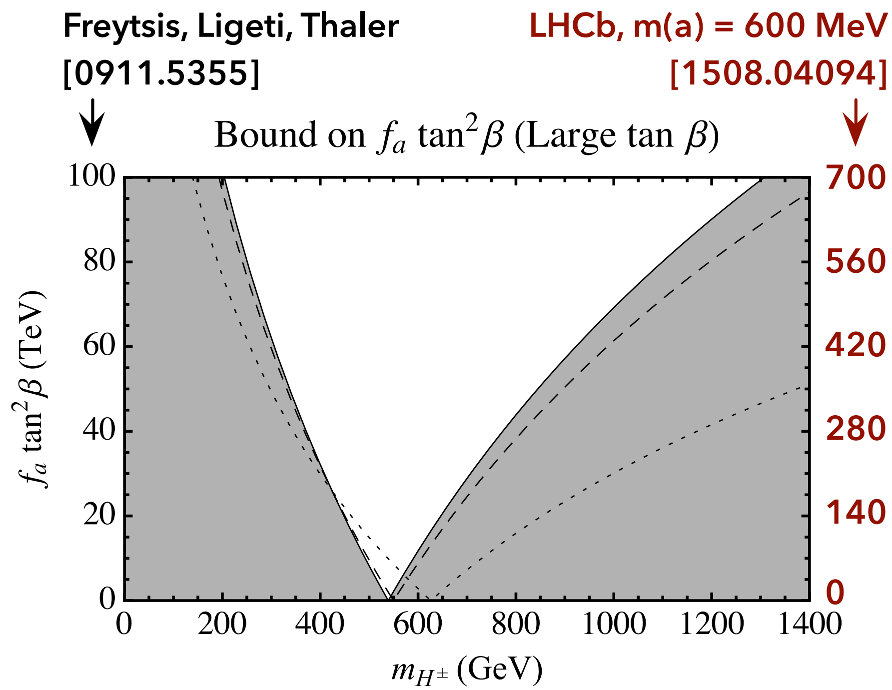
- Started with bump hunting in $B \to K^* \mu^+ \mu^-$

  Nearly an order of magnitude improvement due to dedicated LHCb analysis

  In axion portal models, scalar couples as $(m_\psi / f_a)\, \bar\psi \gamma_5 \psi\, a$ (m_t coupling in loops)



[LHCb, 1508.04094]



- Many other current / future LHCb dark photon searches [Ilten et al., 1603.08926, 1509.06765]

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

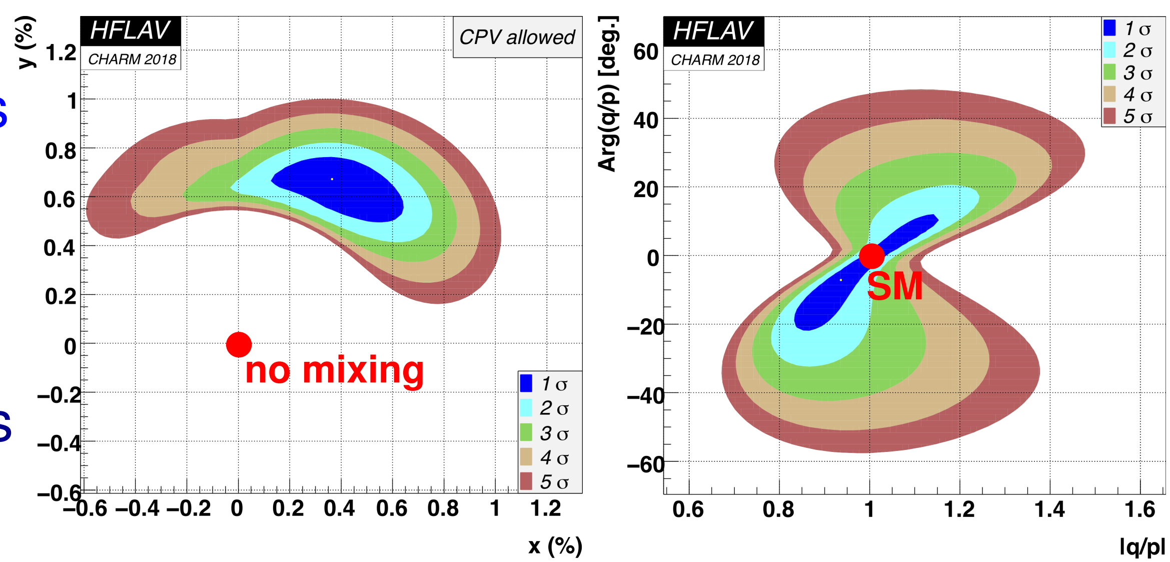
- CP violation in D decay

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

  Current WA: $\Delta A_{CP} = -(2.5 \pm 1.0) \times 10^{-3}$ $\nwarrow$ (a stretch in the SM, imho)

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

- Mixing generated by down quarks or in SUSY by up-type squarks
- Value of Δm? Not even 2σ yet
- Connections to FCNC top decays



- SUSY: interplay of D & K bounds: alignment, universality, heavy squarks?

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Theory challenges / opportunities

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

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 $\uparrow\downarrow$

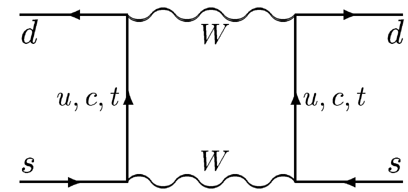
  – Unrelated to the SM, or even completely anarchic must be heavy

  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 $(B_{(s)} \to \ell^+\ell^-$, $\mu \to e\gamma)$

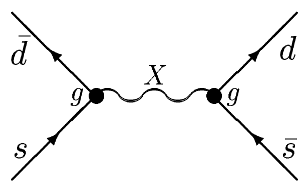
Can probe very high scales

- Example: $\Delta m_K / m_K \simeq 7 \times 10^{-15}$ — huge suppressions



- In SM: $\Delta m_K / m_K \sim \alpha_W^2 \, |V_{cs} V_{cd}|^2 \, \dfrac{m_c^2}{m_W^4} \, f_K^2$ (several small factors)

- Hypothetical particle X:



$$\left| \frac{\Delta m_K^{(X)}}{\Delta m_K} \right| \sim \left| \frac{g^2 \, \Lambda_{\rm QCD}^3}{M_X^2 \, \Delta m_K} \right| \;\Rightarrow\; \frac{M_X}{g} \gtrsim 2 \times 10^3 \, {\rm TeV}$$

(The bound from ϵ_K is even stronger)

- Measurements probe $\begin{cases} {\rm TeV} \text{ scale with SM-like CKM and loop suppressions} \\ \sim 10^3 \, {\rm TeV} \text{ scale with generic flavor structure} \end{cases}$

Kaon bounds on NP are often the strongest, since so are the SM suppressions

This has been an input to (and not output from) model building — suppression mechanisms devised to be viable

- We do not know where NP will show up $\Rightarrow$ sensitivity to highest scales is crucial

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

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

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

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

  (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: $\tilde m \gg 1\,{\rm TeV}$ (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

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

Near misses: CP violation

ANNALS OF PHYSICS: 5, 156-181 (1958)

Long-lived Neutral K Mesons*

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

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

AND

WILLIAM CHINOWSKY

Brookhaven National Laboratories, Upton, New York

set an upper limit $<0.6\%$ on the reactions

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

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

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

DECAY PROPERTIES OF K_2^0 MESONS*

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

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