Perspectives on flavor at HL / HE LHC

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HL / HE LHC Workshop

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Snapshot: where I think we are

- Theoretical prejudices about new physics did not work as expected before LHC

  After Higgs discovery, no more guarantees, situation may resemble around 1900

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

- Hierarchy puzzle: fine tuning measures off? Is NP an order of magnitude heavier?

- New physics at LHC — MFV probably useful approximation

  $\Updownarrow$ "naturalness' loss = flavor's gain" [Nima]

  New physics at $10 - 100\,\mathrm{TeV}$ — less flavor suppression (MFV less motivated)

- In either case, discovering deviations from the SM flavor sector are possible (LHC-scale MFV-like, or heavier more generic scenarios)

- Unambiguous BSM discovery would change things qualitatively, and refocus field

The SM cannot be the full story

- Evidence that the SM is incomplete:
  - Dark matter
  - Baryon asymmetry of the Universe
  - Neutrino mass (lepton number violated?)

  Maybe connected to TeV scale: wimp, EW baryogenesis, many other options

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

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- Experiments: ATLAS, CMS, LHCb, Belle II, NA62 $+$ EDM, CLFV, DM, neutrinos, etc.
- Future: $\dfrac{\text{(LHCb Phase-2)}}{\text{(LHCb now)}} \sim \dfrac{\text{(Belle II data set)}}{\text{(Belle data set)}} \sim \dfrac{\text{(ATLAS \& CMS 3/ab)}}{\text{(ATLAS \& CMS now)}} \sim 50$
- New / improved methods: more progress than simply scaling with statistics

  New theory ideas motivated by data? New questions to address $+$ Surprises

Some references

- A large number of reviews & reports w/ discussions of key observables

  "Impact of the LHCb upgrade detector design choices on physics and trigger performance," LHCb-PUB-2014-040

  "EoI for Phase-II LHCb Upgrade," LHCC-2017-003
  "Physics case for an LHCb Upgrade-II" — by LHCC in May

  B2TIP workshop report (Belle II physics book), to appear soon
  "Impact of Belle II on flavor physics," BELLE2-NOTE-0021

- Apologies for many missing references

- I will not show (very impressive!) tables & plots of sensitivity projections...

Only at the beginning of the road...

- Imagine driving across US, West to East

  consider: 1 mile $\longleftrightarrow$ 1/fb

  Present: start to see the Sierras, you decide:

  (i) A long drive ahead to get to the Atlantic...

  (ii) Not a glimpse yet of beautiful NV, UT, CO...

- Bored, or looking forward to the journey?

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.

$\Rightarrow$ Cronin & Fitch, Nobel Prize, 1980

$\Rightarrow$ 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

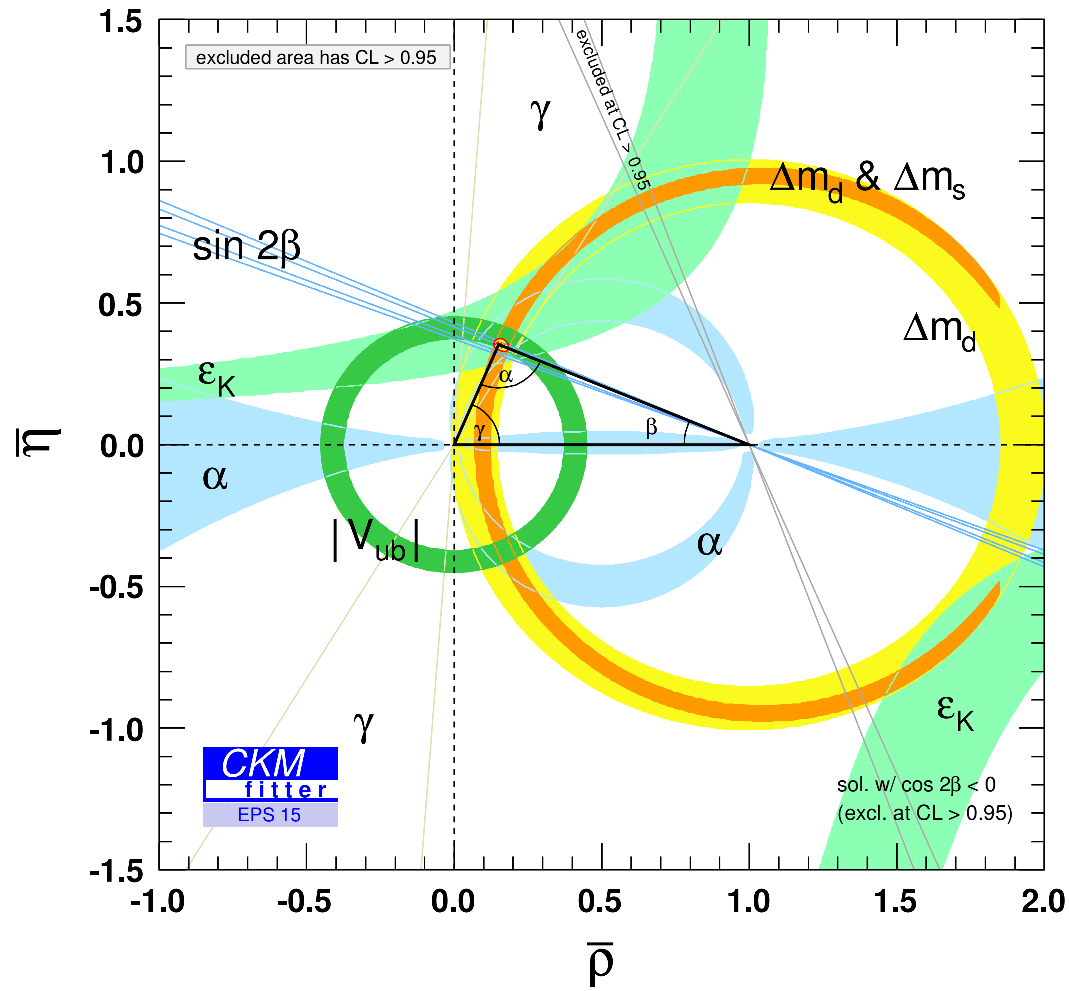
EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

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-

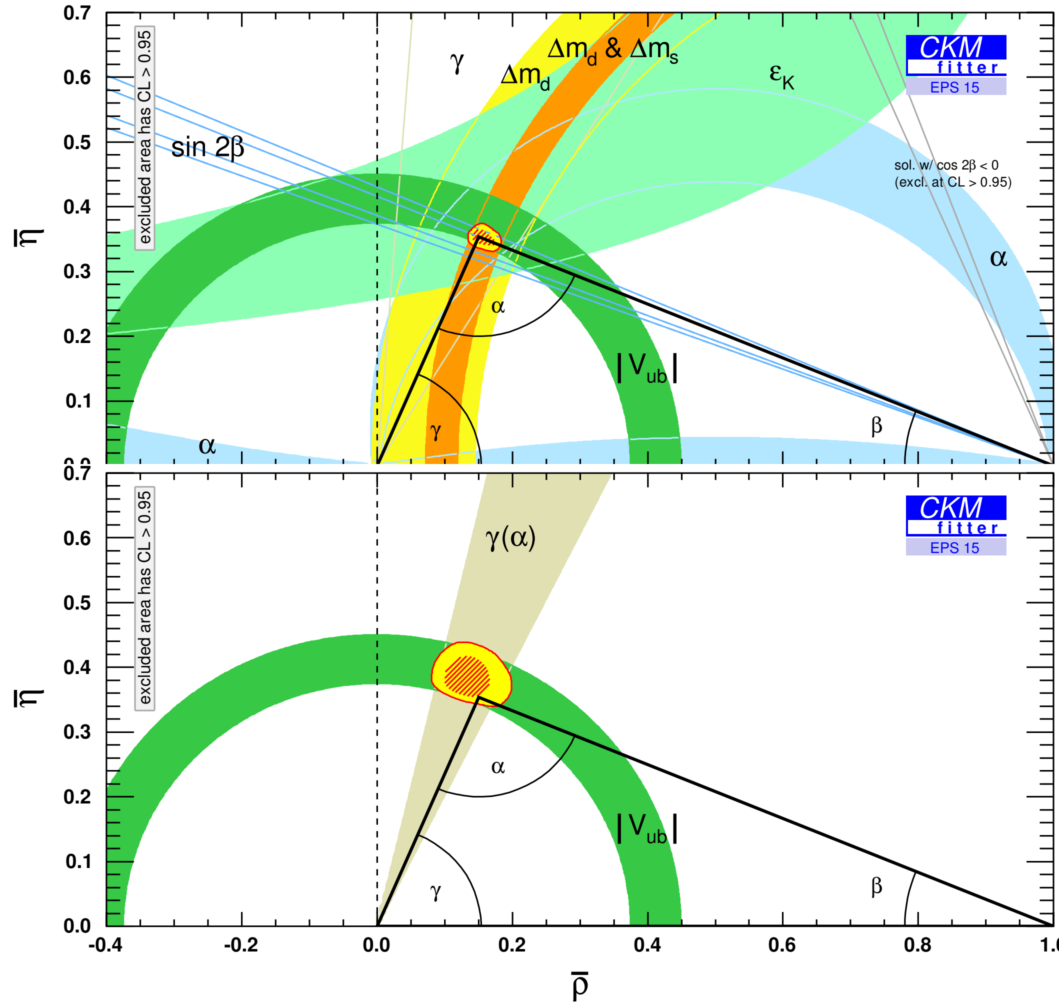
The CKM fit: lots of room for new physics

- SM dominates CP viol. $\Rightarrow$ KM Nobel
- The implications of the consistency often overstated



The CKM fit: lots of room for new physics

- SM dominates CP viol. $\Rightarrow$ KM Nobel
- The implications of the consistency often overstated
- Larger allowed region if the SM is not assumed
- Tree-level (mainly V_{ub} & γ) vs. loop-dominated measurements crucial



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

Reasons to seek higher precision

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

  Generic flavor structure already ruled out by orders of magnitudes — can find any size deviations

  In a large class of scenarios, expect observable deviations.

- Theoretical uncertainties?

  Highly process dependent, under control in many key measurements

- Expected experimental precision?

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

- What will the measurements teach us if deviations from the SM are [not] seen?

  Flavor physics data will be complementary with the high-p_T part of the LHC program

  The synergy of measurements can teach us about what the new physics at the TeV scale is [not].

The rest of this talk

- Mode / model independent: Large improvements in NP sensitivity — 3 examples

- Mode / model specific: Current tensions with SM — might soon be decisive

  (I care more about the case independent of current data)

- Richness of directions: top, higgs, DM, long lived, dark sectors, quirks, etc.

(1) A case for high luminosity

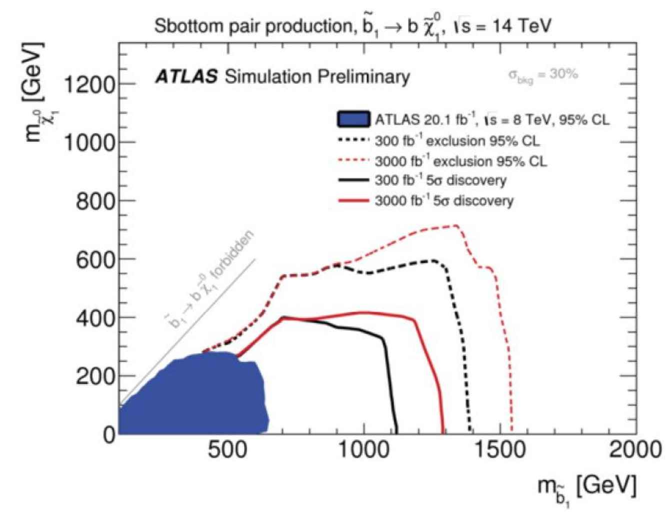
- Focus: ATLAS/CMS $300/\mathrm{fb} \to 3000/\mathrm{fb}$, LHCb $50/\mathrm{fb} \to 300/\mathrm{fb}$ (latter not yet approved)

  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)

  Do not know what new physics is $\Rightarrow$ mass-scale sensitivity (at fixed couplings)?

- 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 (uncertainties $\sim \sqrt{\mathcal{L}}$)

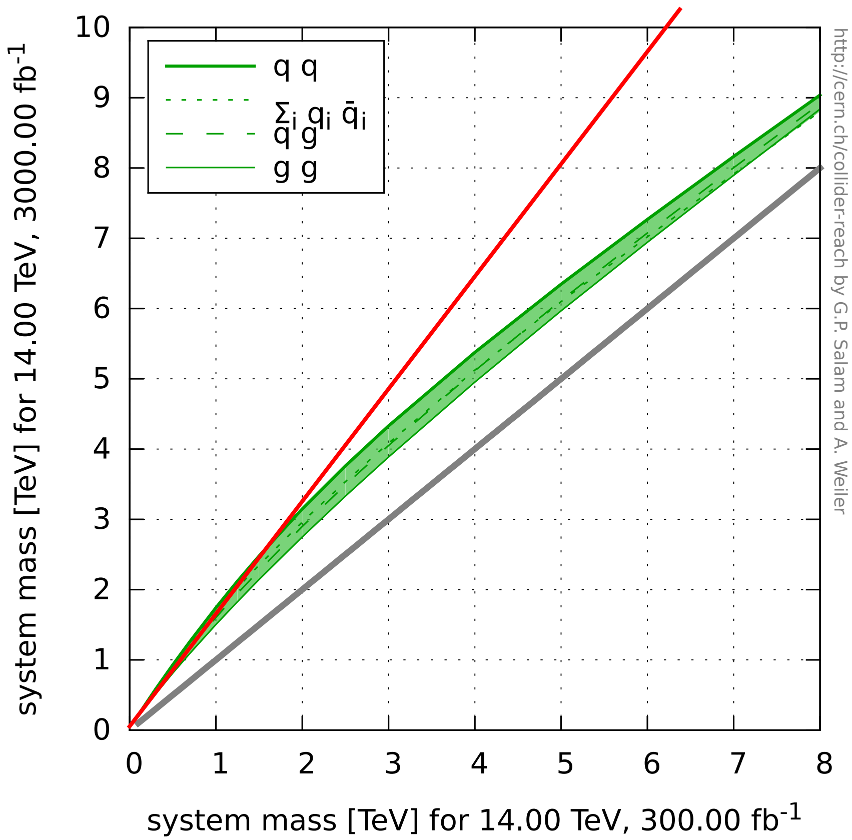


- Statistics $\times 10$ can make $1.5\sigma \to \sim 5\sigma$, even without analysis improvements

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

High-p_T searches vs. $\sqrt{\mathcal{L}}$ improvements

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

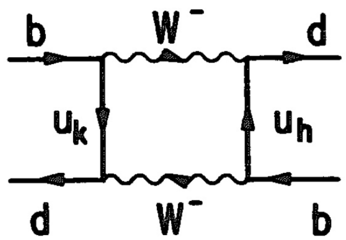


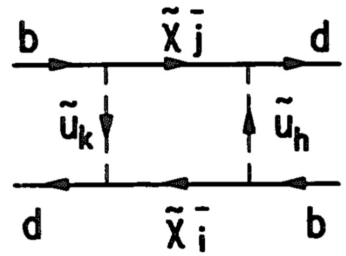
- Increase in mass limit > 1.6, iff (w/ caveats) limit with 300/fb at 14TeV is $\lesssim 1\,\mathrm{TeV}$

  Weakly produced particles and/or difficult decays — not your typical Z', $\tilde{q}$, $\tilde{g}$, ...!

(2) New physics in B mixing

- Meson mixing:





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

General parametrization:

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

NP parameters

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)

Sensitivity to NP in B mixing

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

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

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

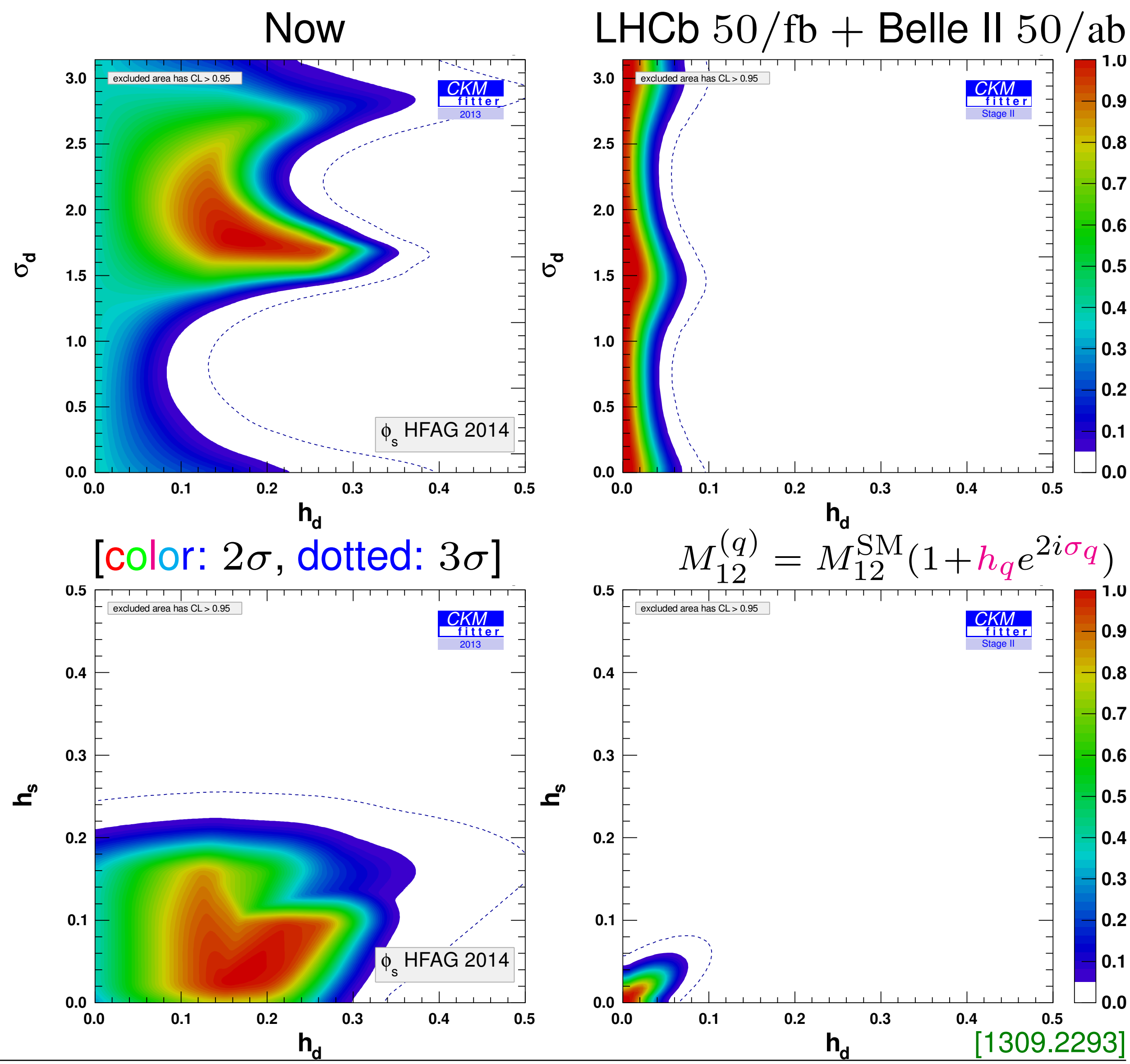
  $$\Rightarrow \Lambda \sim \begin{cases} 2.3 \times 10^3\ \text{TeV} \\ 20\ \text{TeV (tree + CKM)} \\ 2\ \text{TeV (loop + CKM)} \end{cases}$$

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

- Sensitivity would continue to increase beyond 300/fb

  Complementary to high p_T

  [Will update when LHCb document is available]



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(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 $\sim 2.5 \sim \sqrt[4]{50}$

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Mode / model dependent

My personal views of B anomalies

- Lepton non-universality would be clear evidence for NP

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

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

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

  3) P_5' angular distribution (in $B \to K^*\mu^+\mu^-$) 4) $B_s \to \phi\mu^+\mu^-$ rate

- Theoretically cleanest: 1) and 2)

  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 to fit all... Leptoquarks? (Fairly wild scenarios still viable)

  No immediately obvious connection to DM & hierarchy puzzle

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

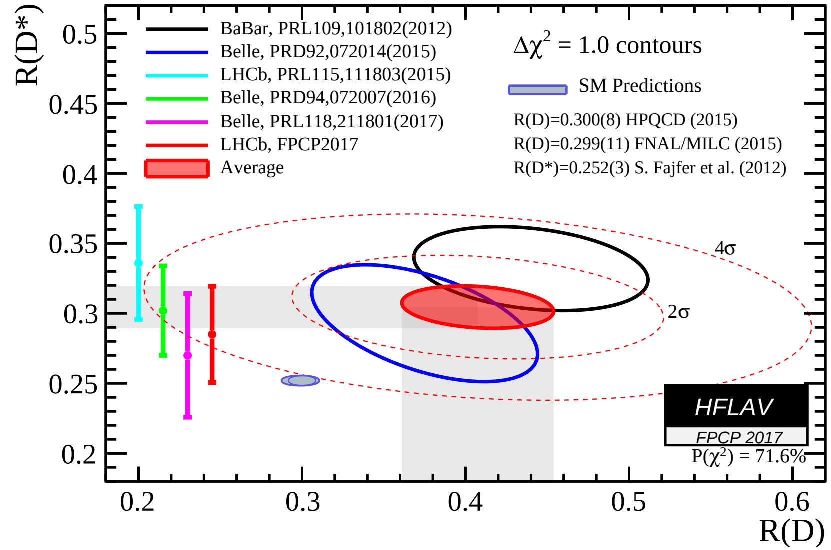
The $B \to D^{(*)}\tau\bar\nu$ decay rates

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

  4.1σ 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

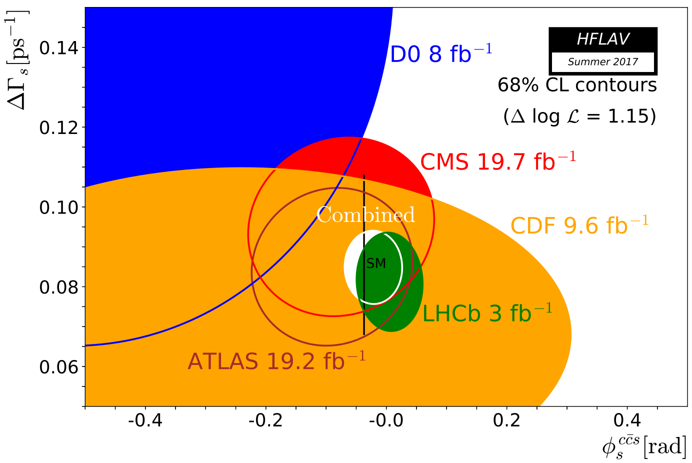
  Some of the models Fierz (mostly) to the same (SM) operator: distributions, τ polarization $=$ SM

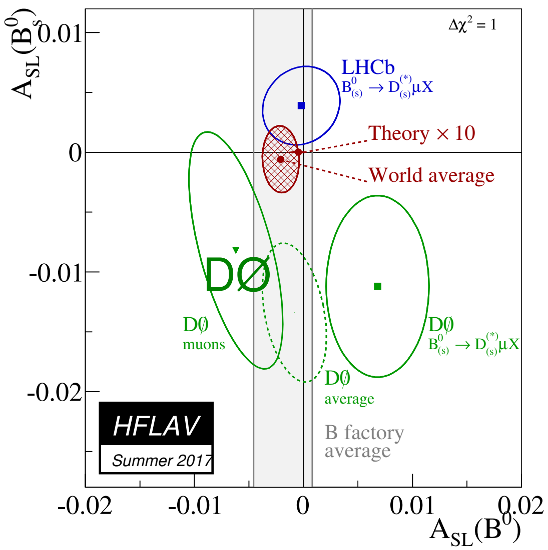
- Tree level: three ways to insert mediator: $(b\nu)(c\tau)$, $(b\tau)(c\nu)$, $(bc)(\tau\nu)$

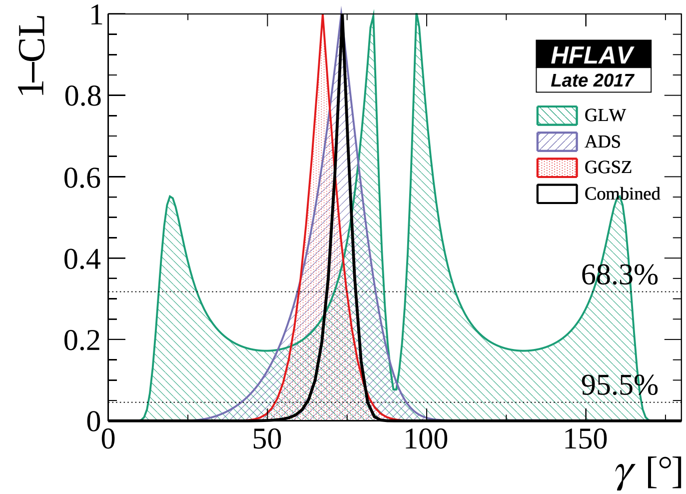
  overlap with ATLAS & CMS searches for $\tilde b$, leptoquark, $H^\pm$

- Future experimental precision will be much better than current uncertainties

Other key measurements (well known)







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

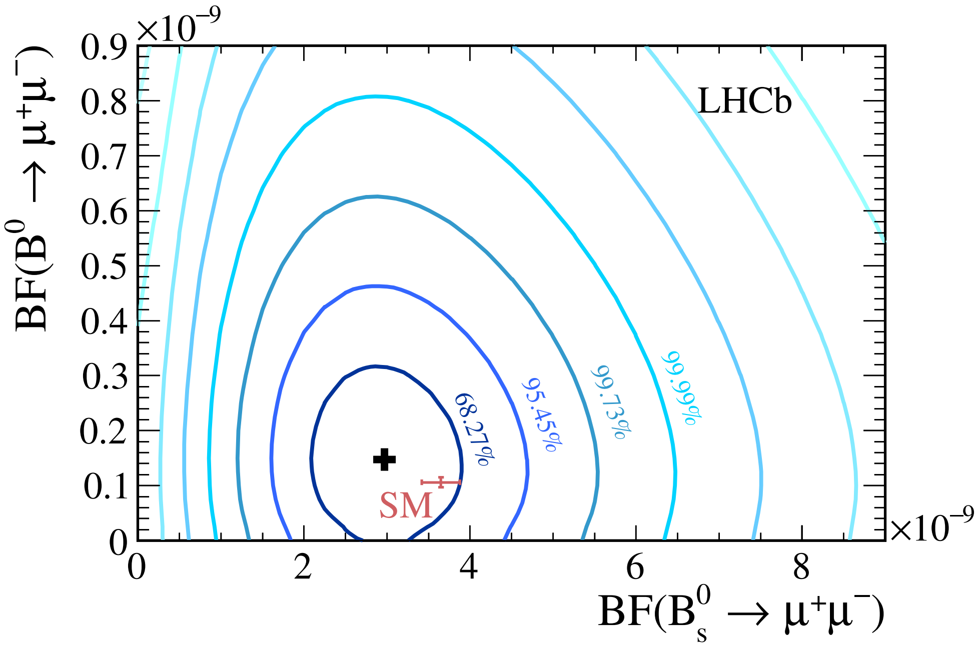
- Uncertainty of predictions $\ll$ current experimental errors ($\Rightarrow$ seek lot more data)
- Breadth crucial, often have to combine many measurements and theory

("The interesting messages are not simple, the simple messages are not interesting")

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

- B_d at SM level: CMS expects $15\text{–}20\%$ (3/ab), LHCb expects $30\text{–}40\%$ (50/fb)

  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/ $K \to \pi\nu\bar\nu$

Richness of directions

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

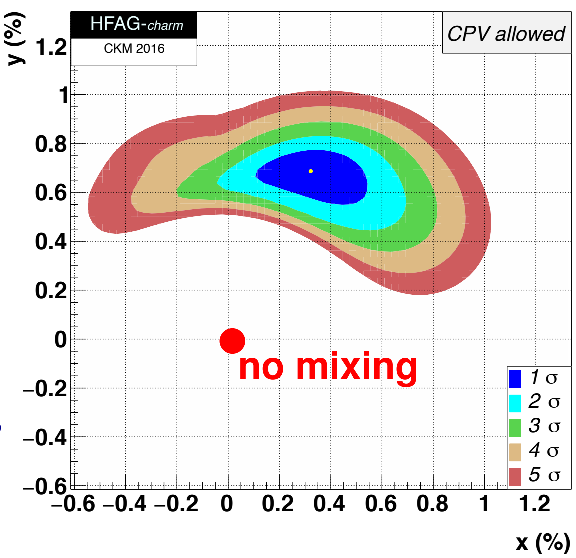
- CP violation in D decay

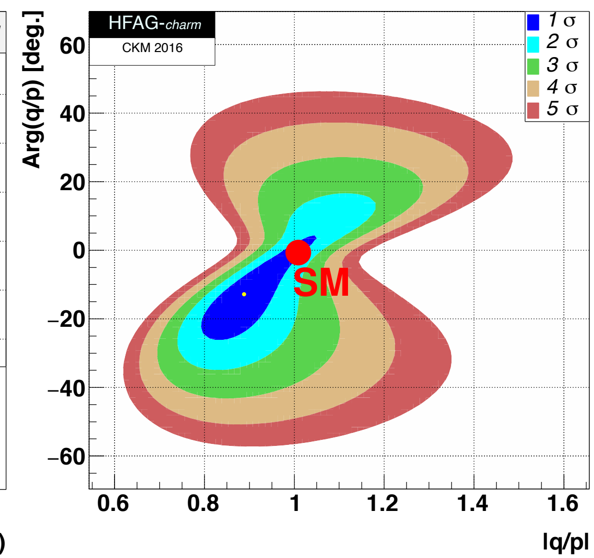
LHCb, late 2011: $\Delta A_{CP} \equiv A_{K^+K^-} - A_{\pi^+\pi^-} = -(8.2 \pm 2.4) \times 10^{-3}$

Current WA: $\Delta A_{CP} = -(2.5 \pm 1.0) \times 10^{-3}$ (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





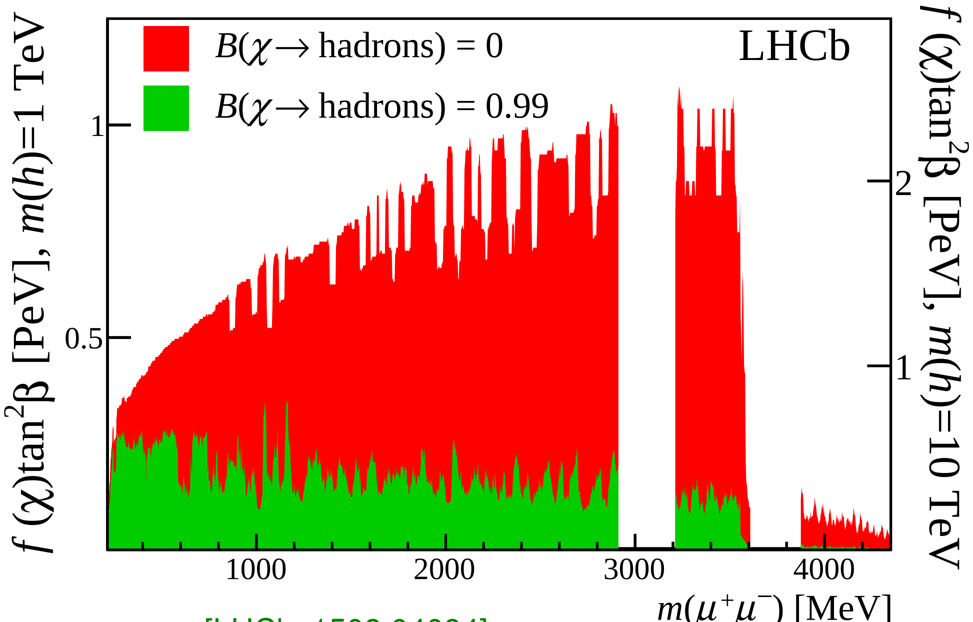
- SUSY: interplay of D & K bounds: alignment, universality, heavy squarks?

Dark sectors: Mike Williams' talk an hour ago...

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

  Nearly an order of magnitude improvement due to dedicated LHCb analysis

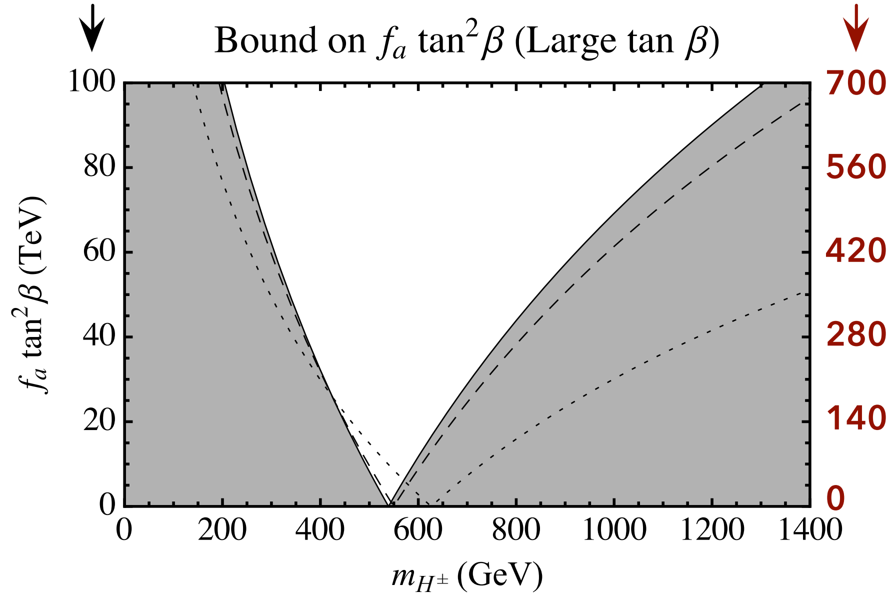
  In axion portal models, scalar couples as $(m_\psi / f_a)\, \bar\psi \gamma_5 \psi\, a$ (m_t coupling in loops)



[LHCb, 1508.04094]

Freytsis, Ligeti, Thaler [0911.5355]

LHCb, m(a) = 600 MeV [1508.04094]



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

Future trends prediction attempt...

- Increase in papers dealing with new scenarios where LHCb can be competitive:
- Besides $h \to c\bar{c}$, search for exotic Higgs decays: e.g., high multiplicity decays, or modest multiplicity with displaced vertices (e.g., $h \to XX \to abab$)
  (Might LHCb compete with ATLAS [1802.04329] & CMS?)
- Searching for "quirks" at LHCb using many velo layers
  (new "quarks" with low confinement scale; non-straight "tracks")
- Hidden valley inspired scenarios, e.g., multiple displaced vertices, even with $\ell^+\ell^-$
- FCNC in some top decay (since $t_L \leftrightarrow b_L$, obvious connections to B decay data)
- Hot topics of the 2030s are probably (certainly?) not what we have thought about
  (Whether or not NP is discovered by then)

Some other interesting channels...

- Testing (exact or approximate) conservation laws substantially better than before, is always very interesting
- Maximize sensitivity to $\tau \to 3\mu$, $\tau \to h\mu\mu$, etc.
- Search for $M^0 \to \mu^- e^+$, $B^+ \to h^+ \mu^- e^+$, etc.
- Search for $B \to N + \text{invis.}\ [+\text{mesons}]$? [Aitken, McKeen, Nelson, Neder, 1708.01259]

HE LHC

- I am not aware of dedicated flavor physics studies — the obvious:
  - Increased $b\bar{b}$ cross section [good]
  - Larger mean boost of b hadrons [mode-dependent impact]
- It would be a missed opportunity not to utilize HE-LHC for the broadest set of measurements that extend BSM sensitivity

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- Higgs quartic: no immediate implication for flavor in itself, deviations from SM do!
- If BSM seen: SUSY: $\sim 10\times$ increase in flavor param's (CP and flavor problems?)
  anything coupling to SM quarks and leptons — new flavor param's
  (Recall $h \to \tau\mu$ driven literature)

(Flavor in SM is simple! Only Higgs – fermion couplings break flavor symmetries)

Final remarks

What are the largest useful data sets?

- 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 & universality violation searches, etc.
  - Possibly CP violation in D mixing (firm up theory)
- In some decay modes, even in 2030s we'll have: (exp. bound)/SM $\gtrsim 10^3$

  E.g., $B_{d,s} \to e^+e^-$, etc. — can build models... Please prove me wrong!
- Precision of f_s/f_d? 0.259 ± 0.015 appears near the $\sim 5\%$ systematic limit [LHCb-CONF-2013-011]

  Most precisely calculable? $\dfrac{\mathcal{B}(B_s \to \mu^+\mu^-)}{\mathcal{B}(B_s \to D_s^-\mu^+\nu)} \times \dfrac{\mathcal{B}(B_d \to D\mu\nu)}{\mathcal{B}(B_d \to \mu^+\mu^-)}$?
- Maximal useful B physics data $\gg$ LHCb & Belle II (nb: Belle II / ARGUS $\sim 10^6$)

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?

Conclusions

- Flavor physics probes scales $\gg 1\,\mathrm{TeV}$, sensitivity limited by statistics
- New physics in FCNCs may still be $\gtrsim 20\%$ of the SM, sensitivity will improve a lot
- Several tensions with the SM; some of these (or others) may become decisive
- Discovering NP would also give a target and upper bound on next scale to explore
- Many interesting theoretical questions relevant for optimal experimental sensitivity

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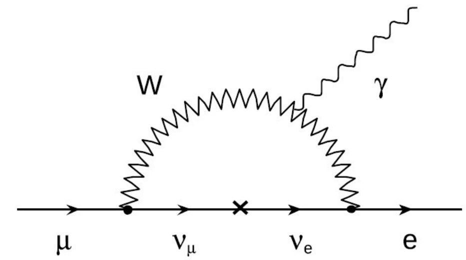
- Ample physics reasons to study even larger b hadron samples than envisioned
- LHC is a one-time opportunity — aim for the most that technology might allow

Extra slides

Charged lepton flavor violation

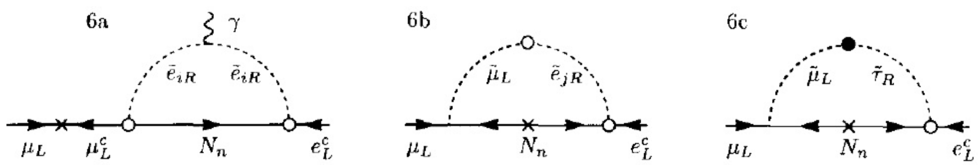
- SM predicted lepton flavor conservation with $m_\nu = 0$

  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

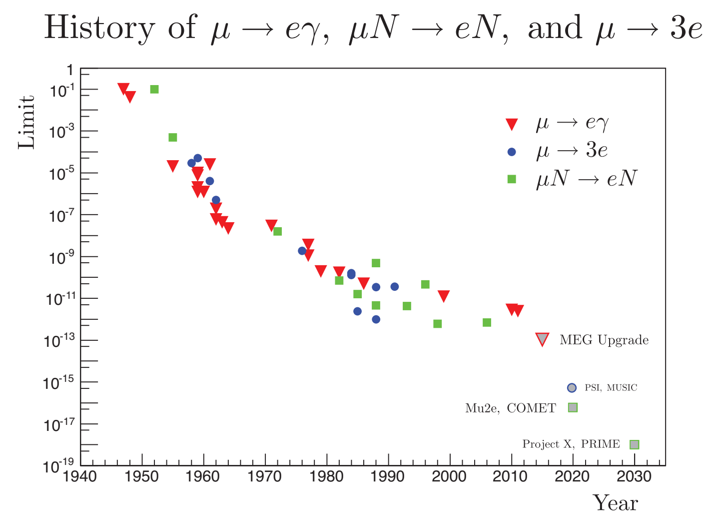


- Many interesting processes:

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

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

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



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

$B \to K^* \mu^+ \mu^-$: the P_5' anomaly

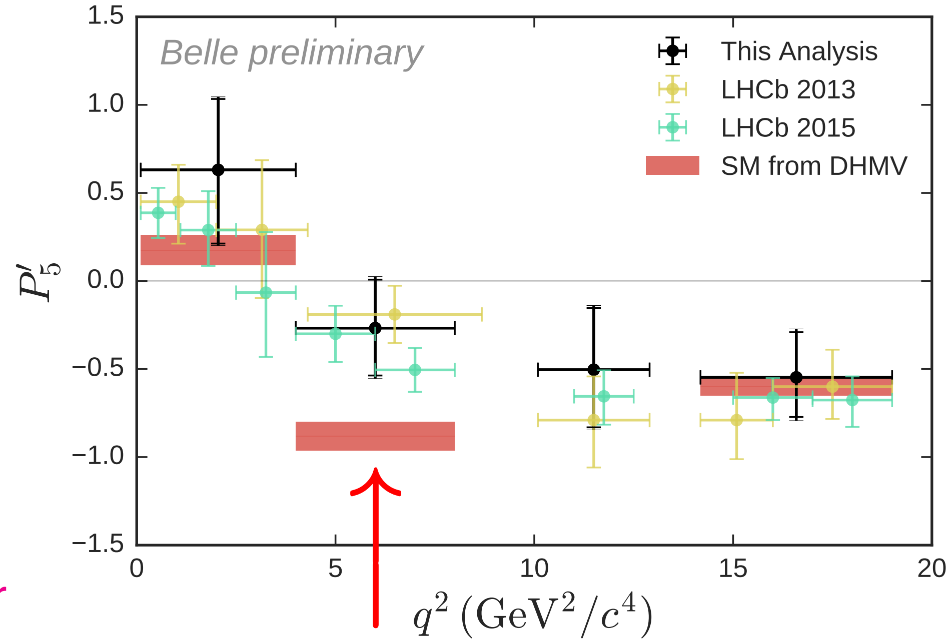
- "Optimized observables" [1202.4266 + long history]
  (some assumptions about what's optimal)

  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?



NP, fluctuation, SM theory?

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

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

Reducing theory uncertainty of $\beta \equiv \phi_1$

- Hadronic uncertainty: $|V_{ub}V_{us}/(V_{cb}V_{cs})| \times (\text{“}P/T\text{”}) \simeq 0.02 \times$ (ratio of matrix elem.)

  Claims of large effects, many proposals, encouraging experimental bounds

  Complicated literature: diagrammatic assumptions, there is no $SU(3)$ relation between ϕ and ρ

- Can suppress V_{ub} contribution by $SU(3)$ breaking:

$$\sin 2\beta = \frac{S_{K_S} - \lambda^2 S_{\pi^0} - 2(\Delta_K + \lambda^2 \Delta_\pi) \tan\gamma \cos 2\beta}{1+\lambda^2}$$

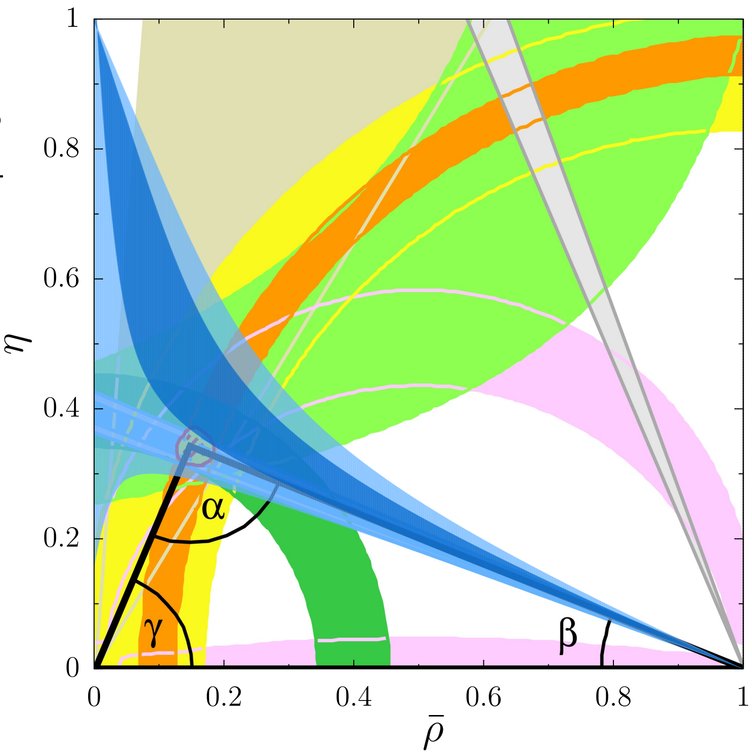
$$\Delta_K = \frac{\bar\Gamma(B_d \to J/\psi K^0) - \bar\Gamma(B^+ \to J/\psi K^+)}{\bar\Gamma(B_d \to J/\psi K^0) + \bar\Gamma(B^+ \to J/\psi K^+)}$$

$$\Delta_\pi = \frac{2\bar\Gamma(B_d \to J/\psi \pi^0) - \bar\Gamma(B^+ \to J/\psi \pi^+)}{2\bar\Gamma(B_d \to J/\psi \pi^0) + \bar\Gamma(B^+ \to J/\psi \pi^+)}$$

- Control uncertainties with data [ZL & Robinson, 1507.06671]

  Get: $\beta = (27.2 \pm 2.6)^\circ$ vs. CKM fit: $(21.9 \pm 0.7)^\circ$

  Isospin asymmetries are difficult [Jung, 1510.03423]



- Mild tension: fluctuation in $\Delta_K = -(4.3 \pm 2.4) \times 10^{-2}$? isospin violation? ...?

Future surprises...?

- It's now 18 years before the end of Run-5 around 2036
- 18 years ago, 2000: nonzero ϵ'/ϵ in 1999, had no info about CPV in B sector

  start of SCET, QCD factorization; theory develops in unpredictable ways

- Predict Belle & BaBar physics from 1992, 18 yrs before end of Belle data taking:
  - ICHEP 1992 was at Dallas, anticipating the SSC
  - The arXiv just started, access via email only
  - Handwritten slides, no laptops yet in academia
  - Start inclusive B decay OPE calculations, γ methods ('91), $B \to \rho\pi$ Dalitz ('93)
  - Before CLEO observation of $B \to K^*\gamma$ ('93) and $B \to K\pi$ (large penguins, '97)
  - Windows 3.1, Mathematica 2, first linux release

($\Rightarrow$ Who are we kidding?)

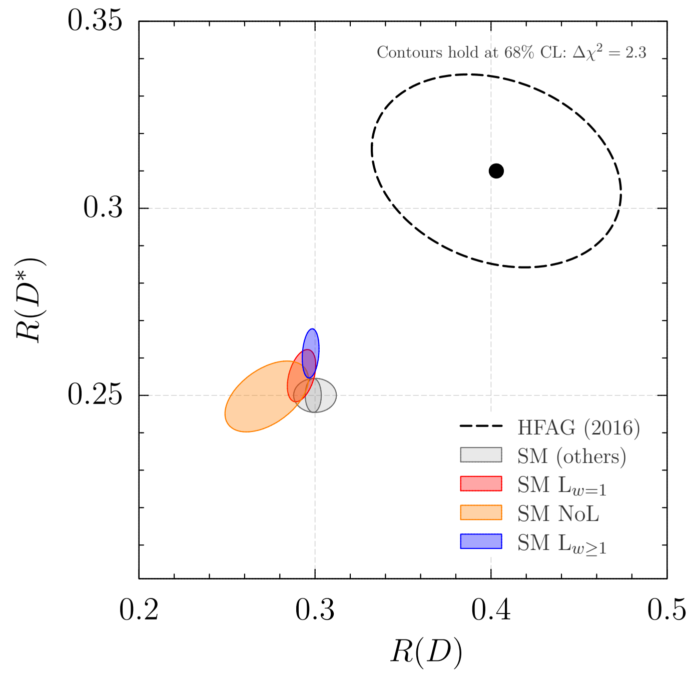
New predictions related to $B \to D^{(*)}\tau\bar{\nu}$

- All past calculations of $R(D^{(*)})$ (except $R(D)$ in LQCD) did not account for uncertainties properly

  Related to use of QCD sum rule inputs plot without $\Rightarrow$

  Also an issue for past $B \to D^* l\bar{\nu}$ form factor measurements

  Explored 7 fits w/ various theory / experiment inputs: significance of the tension is (surprisingly) stable



[Bernlochner, ZL, Papucci, Robinson, 1703.05330]

- Study $B \to D^{**}\ell\bar{\nu}$: both signal and background

- Goal: fully implement all 6 $B \to D^{(*,**)}\ell\bar{\nu}$ modes

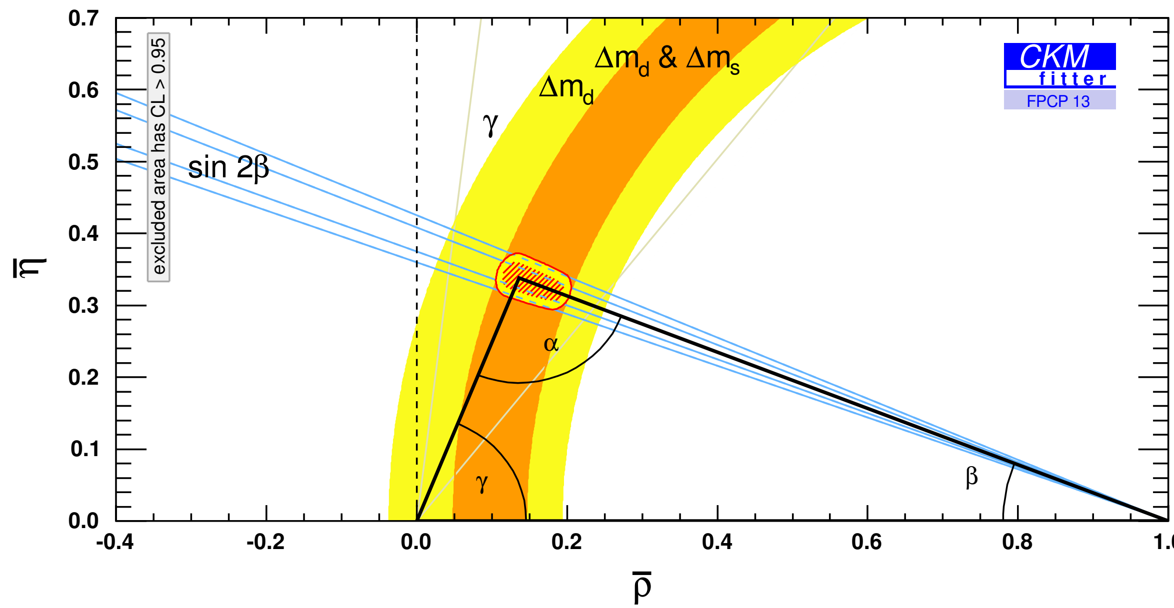
  Even if the anomaly goes away, it will likely result in understanding inclusive vs. exclusive $|V_{cb}|$

- None of the NP models appear to nicely fit together with mainstream expectations

  If experimentally established beyond doubt, there will be a lot to figure out...

A test that will remain statistics limited

- Order of magnitude improvement in this comparison is possible



- More data will directly translate to improved sensitivity to new physics

- Ultimate reach does depend on theory progress (uncertainty of β and $\Delta m_{d,s}$)

  (On this time scale improvements in $\sin 2\beta$ needed)