The Role of Flavor in 2016

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CKM2016
9th International Workshop on the CKM Unitarity Triangle
TIFR, Mumbai
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The year of many mood changes...

• Sometimes it feels like being in heaven, sometimes... not quite...
  Key roles of $\Delta m_K$ and $\epsilon_K$ remain — vs. flood of $CP$ viol. data, exploring Higgs flavor, etc.

• The LHC runs amazingly well $\Rightarrow$ many new results soon
  – Some hints of NP come and go ($750$ GeV...)
  – 2016 data more than $10 \times$ that in 2015
    Big increase in mass scale sensitivity — long time until the next such

Congratulations to India on becoming an Associate Member State of CERN a week ago!

• Exp.: NA62 data taking, Belle II approaching, LHCb future upgrade discussions
  + improving EDM, CLFV, dark matter, etc., experiments

Guaranteed excitement of probing and understanding the SM much better
(recent discoveries of unexpected hadronic states)

Hope of discovering BSM phenomena
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?)

May be connected to the TeV scale: wimp, baryogenesis, but many other options

- Hierarchy puzzle (Is 126 GeV scalar = SM Higgs? why so light? why so heavy?)

In the 90s, most theorists expected NP discoveries well before current sensitivities
(Many talks on how SUSY cascades would cause problems to understand LHC signals)

Since then, Dark energy: missing something completely? asking the right questions?
The scale of new physics?

• Theoretical prejudices about new physics did not work as expected 10–20 yrs ago. Arguments quite compelling, eagerly awaiting 13 TeV LHC results.

• Leave no stone unturned searching for NP — but no guarantees after Higgs.

• Maybe measures of fine tuning are off, and NP is an order of magnitude heavier? Flavor may be even more important (deviation from SM → upper bound on scale).

• New physics at LHC — MFV probably useful approximation to its flavor structure.

  New physics at $10^{1–2}$ TeV — less strong flavor suppression (MFV less motivated).

• Discovering deviations from the SM flavor sector is possible in either case (LHC-scale MFV-like, or heavier more generic scenarios).

• Potential for surprises: lepton flavor violation, dark sectors (invisible), etc.
CP violation itself was a surprise

PROPOSAL FOR $K_2^0$ 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 $K_1^0$ 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 $K_2^0 \to \pi^+ \pi^-$, 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

Portuitously 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 $\mu$-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
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   BaBar Collaboration (Bernard Aubert, Annecy, LAPP et al.), Jun 2005. 7 pp.
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   e-Print: hep-ex/0506081 [PDF]
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   ADS Abstract Service: BaBar Publications Database; BaBar Password Protected Publications Database; link to PRESS RELEASE: Phys. Rev. Lett. Server; SLAC Document Server
   Detailed record - Cited by 500+ records

2. Study of the $B \to J/\psi K^- \pi^+ \pi^-$ decay and measurement of the $B \to X(3872)K^-$ branching fraction
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   SLAC-PUB-10475, BABAR-PUB-04-011
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   SLAC-PUB-8690, BABAR-PUB-01-138
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KPPREPRINT-2001-33, BELLE-PREPRINT-2001-2
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CERN Document Server | ADS Abstract Service | Interactions.org article | Link to BBC News articles | Link to Synthetically interesting news article | Link to Nature News article | Link to PBS website | Link to Scientific American article
Detailed record - Cited by 273 records

Hints: lepton flavor violation?
(Come & gone @ BaBar & Belle)

Surprises: more “new” QCD

SM-like: $B_s \to \mu^+ \mu^-$
$CP$ violation in $B_s$
Outline — rest of this talk

• Near future: current tensions with SM — most often talked about
  best chance to become decisive soon (unless fluctuations)

• Far future: large improvements in new physics sensitivity
  two examples: meson mixing & vector-like fermions

• LHC high-$p_T$ flavor: top, higgs, BSM
The standard model CKM fit

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

- 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 $V_{ub}$ & $\gamma$) vs. loop-dominated measurements crucial
- $\mathcal{O}(20\%)$ NP contributions to most loop-level processes (FCNC) are still allowed
Flavor anomalies: (subjective) status

- Intriguing tensions with the SM predictions
- Some could be unambiguous BSM signals

Except for theoretically cleanest modes, cross-checks are needed case
- measurements of related observables
- independent theory / lattice calculations

- Each could be a whole talk — only a few comments
The $B \rightarrow D^{(*)}\tau\bar{\nu}$ decay rates

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

  Nearly $4\sigma$ from the SM predictions!

|                  | $R(D)$    | $R(D^*)$  |
|------------------|-----------|-----------|
| World average    | 0.397 ± 0.049 | 0.316 ± 0.016 |
| SM expectation   | 0.300 ± 0.010  | 0.252 ± 0.005  |
| Belle II, 50/ab  | ±0.010     | ±0.005     |

Robust SM predictions: heavy quark symmetry + lattice QCD (only $D$ so far)

- **Tension:** $R(D^{(*)})$ vs. $B(b \rightarrow X\tau^+\nu) = (2.41 \pm 0.23)\%$ (LEP) [Freytsis, ZL, Ruderman]

SM: $R(X_c) = 0.223 \pm 0.004$ — no $B(B \rightarrow X\tau\bar{\nu})$ measurement since LEP

Need NP at a fairly low scale (leptoquarks, $W'$, etc.), likely visible at the LHC [Fajfer, Kamenik, Nisandzic, Zupan, many others]

- **Next:** LHCb result with hadronic $\tau$ decays, measure $R(D)$, maybe $\Lambda_b$ decay

- **Future experimental precision will match current theory uncertainty (improvable)**

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ZL – p. 11
B → K*μ⁺μ⁻: 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

- 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 many observables: semileptonic & nonleptonic, interpreting $CP$ viol., etc.
Dark sectors: bump hunting in $B \rightarrow K^* \mu^+ \mu^-$

- Nearly and 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)

- Several future LHCb dark photon search proposals

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ZL – p. 13
Some other highlights

**CP violation in** $B_s \rightarrow \psi \phi$

now consistent with SM

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

Measurements of $\gamma$ crucial, LHCb is now most precise

- Uncertainty of predictions $\ll$ current experimental errors ($\Rightarrow$ seek lot more data)

- I have nothing new to add about $h \rightarrow \tau \mu$ and hint of violation of lepton universality in $B \rightarrow K \mu^+ \mu^-$ vs. $B \rightarrow K e^+ e^-$ — dramatic implications if established
Charm $CP$ violation and mixing

- $CP$ 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 $\Delta m$? Not even 2$\sigma$ yet

- Connections to FCNC top decays

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

[New from Alan at midnight!]

$ZL - p. 15$
Future progress samples
Reducing theory uncertainty of $\beta \equiv \phi_1$

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

  Claims of large effects, many proposals, encouraging experimental bounds

  Complicated literature: diagrammatic assumptions, there is no $SU(3)$ relation between $\phi$ and $\rho$

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

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

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

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

- 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? ...?
New physics in $B$ mixing

- Meson mixing:

  \[ M_{12} = M_{12}^{SM} \times (1 + h e^{2i\sigma}) \]

  NP parameters

  \[ \Lambda \]

  What is the scale $\Lambda$? How different is $C_{NP}$ from $C_{SM}$?

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

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

- Modified: loop-mediated ($\Delta m_d, \Delta m_s, \beta, \beta_s, \alpha, \ldots$)

  Unchanged: tree-dominated ($\gamma, |V_{ub}|, |V_{cb}|, \ldots$)

  (Importance of these constraints is known since the 70s, conservative picture of future progress)
Future sensitivity to new physics in $B$ mixing

- At 95% CL: NP $\lesssim (0.3 \times \text{SM})$
  $\Rightarrow$ NP $< (0.05 \times \text{SM})$

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

- Scale: $h \simeq \frac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \left( \frac{4.5 \text{ TeV}}{\Lambda} \right)^2$
  $\Rightarrow \Lambda \sim \begin{cases} 2.3 \times 10^3 \text{ TeV} \\ 20 \text{ TeV (tree + CKM)} \\ 2 \text{ TeV (loop + CKM)} \end{cases}$

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

- $B_d$ vs. $B_s$, MFV vs. non-MFV will have comparable constraints (unlike in the past)
Sensitivity to vector-like fermions

- Do not make hierarchy problem worse; vector-like fermions can Yukawa couple to the SM fermions via the Higgs in 11 models ($\Rightarrow$ FCNC $Z$ couplings)

| Model | Quantum numbers | $ij = 12$ | $ij = 13$ | $ij = 23$ |
|-------|-----------------|-----------|-----------|-----------|
| II (1, 3, $-1$) | $220^a$ | $4.9^b$ | $5.2^c$ |
| III (1, 2, $-1/2$) | $1400^a$ | $13^b$ | $15^c$ |
| $\Delta F = 1$ | $\Delta F = 2$ | $\Delta F = 1$ | $\Delta F = 2$ |
| 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, $-5/6$) | $66^d [100]^e$ | $\{42, 670\}^f$ | $30^g$ | $25^h$ | $18^k$ | $6.4^j$ |
| | $280^d$ | $\{100, 1000\}^f$ | $60^l$ | $61^h$ | $39^k$ | $14^j$ |

Upper (lower) rows are current (future) sensitivities for 5 models [Ishiwata, ZL, Wise, 1506.03484; Bobeth et al., 1609.04783]

Strongest bounds from many processes, nominally 1-2 generation is most sensitive, many options in concrete models

- Planned experiments increase mass scale sensitivity by factor 2.5 – 7
Semileptonic decays and time travel

- I am working on several topics that could have been done 10–20 years ago... motivated by $R(D^{(*)})$ and inclusive/exclusive $|V_{xb}|$ issues

- **SIMBA** [F. Bernlochner, H. Lacker, ZL, I. Stewart, F. Tackmann, K. Tackmann] ⇒ Frank’s talk
  Optimally combine all information on $B \to X_u \ell \bar{\nu}$ & $B \to X_s \gamma$
  Consistently treat uncertainties and correlations (exp, theo, param’s)

- **HAMMER** [F. Bernlochner, S. Duell, ZL, M. Papucci, D. Robinson] See: 1610.02045 + in progress
  Analytic treatment of fully differential rates of the visible final states in $B \to X \ell \bar{\nu}$ + efficient MC to reweight simulations to any NP model

- $B \to D^{**} \ell \bar{\nu}$ [Bernlochner & ZL, 1606.09300] + in progress
  A large systematic uncertainty in $R(D^{(*)})$ and some $|V_{xb}|$ measurements
  Measuring $R(D^{**})$: additional discriminating power between models

Amusingly, few days ago was just looking at Cho, Wise, Trivedi, hep-ph/9408352, “Gluon fragmentation into polarized charmonium”
Couple of $B \rightarrow D^{**}\tau\bar{\nu}$ plots

- Complementary sensitivities

Type II 2HDM

For fixed $S_R + S_L = 0.25$, favored by BaBar

Different patterns in two blue bands

[ZL – p. 21]
top / higgs / BSM flavor
The LHC is a top factory: top flavor physics

- FCNC top decays not too strongly constrained
  - SM predictions: $< 10^{-12}$
  - Best current bound: $\lesssim \text{few} \times 10^{-4}$ [ATLAS, CMS]

- Sensitivity will improve $\sim 2$ 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

- Richness due to Yukawa couplings: same as origin of \( \text{GeV-scale flavor physics} \)
  - Many production and decay channels, fermion couplings crucial

- Higgs flavor param’s: 3rd gen: \( \kappa_t, \kappa_b, \kappa_\tau \)  2nd gen: \( \kappa_c, \kappa_\mu \)  Do \( \kappa_{tc}, \kappa_{\tau\mu} \) vanish?

**ZL – p. 23**
New particles, e.g., SUSY

• Any new particle that couples to quarks or leptons ⇒ new flavor parameters
  (Squark & slepton couplings may modify FCNCs and $C\bar{P}$ violation, e.g., $B \rightarrow \ell^+\ell^-$, $\mu \rightarrow e\gamma$, ...)

$C\bar{P}$ violation also possible in flavor diagonal processes (EDMs), neutral currents

Couplings of new particles to quarks and leptons will be important (e.g.: Higgs)

• New physics flavor structure can be:

  – (Near) minimally flavor violating (mimic SM)
  – Related but not identical to SM
  – Unrelated to the SM, or completely anarchic

new physics mass scale:

  can be “light”

  must be heavy

• The heavier the new particles are, the less the flavor structure need to be SM-like
• Despite lore, squarks need not be as degenerate as often thought / assumed (triggered by studying charm CPV)  
   [Gedalia, Kamenik, ZL, Perez]

Top plot: each LHC search becomes weaker  
   [Mahbubani, Papucci, Perez, Ruderman, Weiler]

Bottom plot: unshaded region still allowed if 4–4 squarks (but not all 8) are degenerate

• If 4 pairs of $u, d, s, c$ squarks not degenerate, lot weaker LHC bounds: 1.2 TeV $\Rightarrow$ 600 GeV

• Ways for naturalness to survive...
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)
  - $A_{SL}^{d,s}$ — new ideas to get around exp. syst. limits?
  - Probably $CP$ violation in $D$ mixing (firm up theory)
  - CLFV, EDM, etc.

[I guess until $\sim 10^2 \times$ Belle II & LHCb upgrade data, sensitivity to higher scales would improve]

- In some decay modes, even in 2030 we’ll have: $(\text{exp. bound})/\text{SM} \gtrsim 10^3$
  
  E.g., $B_{d,s} \to \tau^+\tau^-$, $e^+e^-$ — can build models... I hope to be wrong!

- Precision of $f_s/f_d$? $0.259 \pm 0.015$ appears near the $\sim 5\%$ systematic limit [LHCb-CONF-2013-011]

Ultimately normalize to semileptonic, e.g.,

$$\frac{\mathcal{B}(B_s \to \mu^+\mu^-)}{\mathcal{B}(B_s \to D_s^- \mu^+\nu)} \times \frac{\mathcal{B}(B_d \to D \mu\nu)}{\mathcal{B}(B_d \to \mu^+\mu^-)}$$
Push $B_{s,d} \rightarrow \mu^+ \mu^-$ to theory limit

- For $B_d$, CMS (LHCb) expect ultimately 15–20% (30–40%) precision at SM level
- SM uncertainty $\simeq (2\%) \oplus f_{B_q}^2 \oplus \text{CKM}$ [Bobeth, FPCP’15]

- Theoretically cleanest $|V_{ub}|$ I know, only isospin: $\mathcal{B}(B_u \rightarrow \ell \bar{\nu})/\mathcal{B}(B_d \rightarrow \mu^+ \mu^-)$
- A decay with mass-scale sensitivity (dim.-6 operator) that competes w/ $K \rightarrow \pi \nu \bar{\nu}$
A test that can improve $\times 10$

- 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 $\beta$ and $\Delta m_{d,s}$)
Some theory challenges

• New methods & ideas: recall that the best $\alpha$ and $\gamma$ 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)
  – How big can $CP$ violation be in $D^0 - \bar{D}^0$ mixing (and in $D$ decays) in the SM?
  – Better understanding of semileptonic form factors; bound on $S_{K_S \pi^0 \gamma}$ in SM?
  – Inclusive & exclusive semileptonic decays
  – Many lattice QCD calculations (operators within and beyond SM)
  – 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?

ZL – p. 29
Conclusions

- Flavor physics probes scales $\gg 1 \text{ TeV}$; sensitivity limited by statistics
- New physics in FCNCs may still be $\gtrsim 20\%$ of the SM
- Few tensions with the SM; some of these (or others) may become decisive
- Large future improvements in many channels (+ CLFV + EDM)
- Many open theoretical questions which are important for experimental sensitivity
- Let’s hope there is NP within reach to be discovered and understood

Flavor & high-$p_T$ info complementary

\[ \text{Current flavor bounds} \quad \text{Future flavor + ATLAS/CMS} \]

\[ \left\{ \begin{array}{c}
\text{EXCLUDED} \\
\text{MFV} \\
\text{ATLAS/CMS} \\
[\text{arXiv:0904.4262}] \\
\end{array} \right. \]
STOP

Extra slides
Flavor: very high scale sensitivity

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

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

- Hypothetical particle:

  \[
  \left| \frac{\Delta m_K^{(X)}}{\Delta m_K} \right| \sim \frac{g^2 \Lambda_{QCD}^3}{M_X^2 \Delta m_K} \Rightarrow \frac{M_X}{g} \gtrsim 2 \times 10^3 \text{ TeV}
  \]
  (The bound from $\epsilon_K$ is even stronger)

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

  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
Aside: 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
- If new TeV-scale particles carry lepton number (e.g., sleptons), then they have their own mixing matrices ⇒ charged lepton flavor violation
- Many interesting processes:
  $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, $\mu + N \rightarrow e + N^{(i)}$, $\mu^+ e^- \rightarrow \mu^- e^+$
  $\tau \rightarrow \mu\gamma$, $\tau \rightarrow e\gamma$, $\tau \rightarrow \mu\mu\mu$, $\tau \rightarrow eee$, $\tau \rightarrow \mu me$
  $\tau \rightarrow \mu ee$, $\tau \rightarrow \mu\pi$, $\tau \rightarrow e\pi$, $\tau \rightarrow \mu K_S$, $eN \rightarrow \tau N$
- Next 10–20 years: $10^2$–$10^5$ improvement; any signal would trigger broad program
Aside: Electric dipole moments and SUSY

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

- Neutron EDM bound: “The strong $CP$ problem”, $\theta_{QCD} < 10^{-10}$ — axion?
  $\theta_{QCD}$ 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 (TeV-scale, no small param’s) above current bounds; if $m_{SUSY} \sim \mathcal{O}(10 \text{ TeV})$, may still discover EDMs

- Expected $10^2$–$10^3$ improvements: complementary to LHC
  Discovery would give (rough) upper bound on NP scale
Belle II — LHCb: complementarity & competition

- Details depend on Belle II and LHC LS2–3 schedules [Urquijo, private communications]

NB: these plots show statistical errors only, important issues swept under the rug
### LHCb 50/fb summary

| Type                  | Observable                                                                 | LHC Run 1 | LHCb 2018 | LHCb upgrade | Theory   |
|-----------------------|---------------------------------------------------------------------------|-----------|-----------|--------------|----------|
| $B^0_s$ mixing        | $\phi_s(B^0_s \to J/\psi \phi)$ (rad)                                    | 0.049     | 0.025     | 0.009        | $\sim 0.003$ |
|                       | $\phi_s(B^0_s \to J/\psi f_0(980))$ (rad)                                | 0.068     | 0.035     | 0.012        | $\sim 0.01$  |
|                       | $A_{s1}(B^0_s)$ ($10^{-3}$)                                              | 2.8       | 1.4       | 0.5          | 0.03      |
| Gluonic penguin       | $\phi_s^{\text{eff}}(B^0_s \to \phi \phi)$ (rad)                        | 0.15      | 0.10      | 0.018        | 0.02      |
|                       | $\phi_s^{\text{eff}}(B^0_s \to K^{*0}K^{*0})$ (rad)                     | 0.19      | 0.13      | 0.023        | $< 0.02$ |
|                       | $2\beta^{\text{eff}}(B^0_s \to K^0_s K^0_s)$ (rad)                      | 0.30      | 0.20      | 0.036        | 0.02      |
| Right-handed currents | $\phi_s^{\text{eff}}(B^0_s \to \phi \gamma)$ (rad)                      | 0.20      | 0.13      | 0.025        | $< 0.01$ |
|                       | $\tau^{\text{eff}}(B^0_s \to \phi \gamma)/\tau_{B^0_s}$                | 5%        | 3.2%      | 0.6%         | 0.2%     |
| Electroweak penguin   | $S_3(B^0 \to K^{*0} \mu^+ \mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$        | 0.04      | 0.020     | 0.007        | 0.02     |
|                       | $q_0^2 A_{FB}(B^0 \to K^{*0} \mu^+ \mu^-)$                               | 10%       | 5%        | 1.9%         | $\sim 7\%$ |
|                       | $A_1(K \mu^+ \mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$                      | 0.09      | 0.05      | 0.017        | $\sim 0.02$|
|                       | $\mathcal{B}(B^+ \to \pi^+ \mu^+ \mu^-)/\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)$ | 14%       | 7%        | 2.4%         | $\sim 10\%$|
| Higgs penguin         | $\mathcal{B}(B^0_s \to \mu^+ \mu^-)$ ($10^{-9}$)                        | 1.0       | 0.5       | 0.19         | 0.3       |
|                       | $\mathcal{B}(B^0 \to \mu^+ \mu^-)/\mathcal{B}(B^0_s \to \mu^+ \mu^-)$   | 220%      | 110%      | 40%          | $\sim 5\%$ |
| Unitarity triangle    | $\gamma(B \to D^* K^{(*)})$                                              | 7°        | 4°        | 0.9°         | negligible |
|                       | $\gamma(B^0_s \to D^+_s K^\pm)$                                         | 17°       | 11°       | 2.0°         | negligible |
|                       | $\beta(B^0 \to J/\psi K^0_s)$                                            | 1.7°      | 0.8°      | 0.31°        | negligible |
| Charm                 | $A_\Gamma(D^0 \to K^+ K^-)$ ($10^{-4}$)                                   | 3.4       | 2.2       | 0.4          | –         |
| CP violation          | $\Delta A_{CP}$ ($10^{-3}$)                                              | 0.8       | 0.5       | 0.1          | –         |

- Many measurements with BSM sensitivity improve a lot — 50/fb not enough.
Belle II 50/ab summary

| Observables | Belle (2014) | Belle II 5 ab^{-1} 50 ab^{-1} [ab^{-1}] | \mathcal{L}_s |
|-------------|--------------|----------------------------------------|-------------|
| \sin 2\beta | 0.667 ± 0.023 ± 0.012 ± 0.012 ± 0.008 | 6 | 50 ab^{-1} |
| \alpha      | ±2° ± 1°     | 6 | 50 ab^{-1} |
| \gamma      | ±14° ± 6° ± 15° | 50 |  | 50 ab^{-1} |
| S(B \to \phi K^0) | 0.90^{+0.09}_{-0.19} ± 0.053 ± 0.018 | >50 |  | 50 ab^{-1} |
| S(B \to \eta' K^0) | 0.68 ± 0.07 ± 0.03 | >50 |  | 50 ab^{-1} |
| S(B \to K_s^0 K_S^0 K_S^0) | 0.30 ± 0.32 ± 0.08 | 44 |  | 50 ab^{-1} |
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Not understood: the $B \rightarrow K\pi$ puzzle

- Have we seen new physics in CPV?
  
  \[ A_{K+\pi^-} = -0.082 \pm 0.006 \quad (P + T) \]
  \[ A_{K+\pi^0} = 0.040 \pm 0.021 \quad (P + T + C + A + P_{ew}) \]

- Large difference — small SM sources?
  
  \[ A_{K+\pi^0} - A_{K+\pi^-} = 0.122 \pm 0.022 \]

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

- Large fluctuations? Breakdown of \( 1/m \) exp.? Missing something subtle? BSM?

No similar tension in branching ratio sum rules and \( SU(3) \) relations

- Can we unambiguously understand theory, so that such data could disprove SM?
\textbf{LHCb: $|V_{ub}|$ from $\Lambda_b \rightarrow p\mu\bar{\nu}$}

- $|V_{ub}|$ crucial for improving constraints on NP
  
  $|V_{ub}|_{\text{LHCb}} = (3.27 \pm 0.15 \pm 0.17 \pm 0.06) \times 10^{-3}$
  
  $|V_{ub}|^2_{\text{LHCb}} \propto B(\Lambda_c \rightarrow pK\pi)$

  PDG: 25% $\rightarrow$ Belle: 5%

  (BES III result soon)

- $\sim 3 \sigma$ tension among $|V_{ub}|$ measurements

  Too early to conclude, measurements and theory will improve

- A BSM option: right-handed current — less good fit now

\[ ZL – p. viii \]
LHCb results on $B^0 \to K^{*0} \chi (\mu^+ \mu^-)$

Distribution of $m(\mu^+ \mu^-)$ in the (black) prompt and (red) displaced regions. The shaded bands denote regions where no search is performed due to (possible) resonance contributions.

Upper limits at 95% CL. The sparseness of the data leads to rapid fluctuations in the limits.
Example 1: NP in mixing

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

- Simple & general description:

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

  \[\text{NP parameters} \uparrow \uparrow\]

- Need many measurements and lattice QCD progress

- If NP discovery hinges on one ingredient, will need cross-checks (e.g., lattice with different formulations)

- $\gamma$ and $|V_{ub}|$ are crucial (tree / reference UT): hope that $2 - 3\%$ $|V_{ub}|$ uncertainty can be obtained from several measurements: $B \to \tau \nu, B \to \mu \nu, B \to \pi \ell \nu, \Lambda_b \to p \mu \nu$