Flavor physics &@ the LHC

Zoltan Ligeti

LHCP, June 2–7, 2014

• Introduction
• Recent hot topics and status
• Future NP sensitivity in $B - B\bar{B}$ mixing
• Flavor physics and high-$p_T$ LHC
• Future progress & Conclusions

[Disclaimer: not a review; what I find interesting today]
What is flavor physics?

- Theorist: (quark) flavor physics $\equiv$ what breaks $U(3)_Q \times U(3)_u \times U(3)_d \rightarrow U(1)_\text{Baryon}$

- Experimentalist: rich and sensitive ways to probe the SM and search for NP

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

- NP flavor problem: TeV scale (hierarchy problem) $\ll$ “naive” flavor & CPV scale
  - Most TeV-scale new physics contain new sources of $CP$ and flavor violation
  - The observed baryon asymmetry of the Universe requires CPV beyond the SM
    (Not necessarily in flavor changing processes, nor necessarily in quark sector)

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

Going from: $NP \lesssim (\text{few} \times \text{SM}) \rightarrow NP \lesssim (0.3 \times \text{SM}) \rightarrow NP \lesssim (0.05 \times \text{SM})$

($-10$ yrs) (now) ($+10$ yrs)
Flavor probes $10^2 – 10^5$ TeV scale

- E.g., $K$ mixing in SM: $\Delta m_K \sim \alpha_w^2 |V_{cs}V_{cd}|^2 \frac{m_c^2}{m_W^4} f_K^2 m_K$

  (strong suppressions!)

- If exchange of a heavy particle $X$ contributes $O(1)$ to $\Delta m_K$

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

  (The bound from $\epsilon_K$ is even stronger)

TeV-scale particles with loop-suppressed coupling can still be visible [$g \sim O(10^{-3})$]

- Measurements probe

  \[
  \begin{cases}
  \text{TeV-scale physics with SM-like flavor structure} \\
  100–1000 \text{ TeV physics with generic flavor structure}
  \end{cases}
  \]

- SM-like Higgs — e.g., SUSY: large $A$ terms? extended Higgs sector? $\rightarrow$ flavor?

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

---

ZL – p. 2
“It doesn’t matter how beautiful your theory is, it doesn’t matter how smart you are. If it doesn’t agree with experiment, it’s wrong.”

[Feynman]
Exciting times ahead

• What are the expected deviations from the SM induced by TeV-scale NP?
  Generic flavor structure ruled out, deviations maybe near the bounds, many models predict some

• What to expect in terms of experimental precision?
  Useful data sets will increase by $\sim 10^{2\pm1}$, and will probe fairly generic BSM predictions

• What are the theoretical uncertainties? What will the measurements teach us?
  In many key measurements, theory uncertainty $< \text{exp. sensitivity}$; complementary to high-$p_T$ info

• Future: \[
\frac{(\text{LHCb upgrade})}{(\text{LHCb } 1 \text{ fb}^{-1})} \sim \frac{(\text{Belle II data set})}{(\text{Belle data set})} \sim \frac{(\text{2009 BaBar data set})}{(\text{1999 CLEO data set})} \sim 50
\]
  Beyond $\sqrt{50} \sim 2.5$ increase in sensitivity to higher mass scales, expect also some yet unknown progress (data motivate theory, recall $\alpha, \gamma$)

• Comparable increase in reach as going from LHC7–8 $\rightarrow$ LHC13–14

ZL – p. 3
Status & recent highlights
The standard model CKM fit

- The level of agreement between the measurements is often misinterpreted.
- Much larger allowed region if SM not assumed to hold, more parameters.
- $\mathcal{O}(20\%)$ NP contributions to most loop processes (FCNC) are still allowed.
- To bound NP, compare tree vs. loop measurements $\Rightarrow \gamma$ and $|V_{ub}|$.
- Need experimental precision and theoretical cleanliness to increase NP sensitivity.
Measuring $\gamma$ from $B^\pm \rightarrow DK^\pm$

- Tree level: interference of $b \rightarrow c\bar{u}s \ (B^- \rightarrow D^0 K^-)$ and $b \rightarrow u\bar{c}s \ (B^- \rightarrow \bar{D}^0 K^-)$

Final states that both $D^0$ and $\bar{D}^0$ can decay into

Measure both $B$ & $D$ decay amplitudes — many variants depending on $D$ decay

- World average: $\gamma = (70 \pm 8)^\circ$

CKM fit: $\gamma = (67 \pm 2)^\circ$

- Coincidentally, LHCb, BaBar and Belle results are comparable just now

- Future experimental uncertainty: $\sim 1^\circ$

- Crucial for improving sensitivity to BSM (compare tree vs loop)

Statistics limited with any currently imagined data set / experiment

ZL – p. 5
Mixing and $CP$ violation in $B_s$

- CDF & LHCb: relative uncertainty of $\Delta m_s < \Delta m_d$ (discovered in 1987)
- Time dependent $B_s \to \psi \phi$ $CP$ asymmetry (analog of $B \to \psi K +$ angular anal.)
- In SM — of order $\lambda^2 \times \beta$

$$2\beta_s \equiv -\phi_s \simeq 0.037 \pm 0.00?$$

Past hints of tensions gone

- Unofficial LHCb average, incl. not shown recent result [Artuso, FPCP]

$$\phi_s = 0.07 \pm 0.05 \left[= (4.0 \pm 3.1)^\circ\right]$$

Expect w/ LHCb upgrade: $\pm 0.008$

- Uncertainty of the SM prediction $\ll$ current experimental error (⇒ LHCb upgrade)
Dilepton asymmetry

- Nearly $4\sigma$ significance of DØ measurement

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

At hadron colliders, time dependence can be integrated over:

$$A_{\text{SL}}^{\text{DØ}} = \frac{N(\mu^+\mu^+)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)} - \frac{N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}$$

Would be a clear sign of NP

SM $\sim 4 \times 10^{-4}$ in $B_d$ ($2 \times 10^{-5}$ in $B_s$)

(The absolute uncertainty of the SM prediction is not particularly small, but its magnitude is much smaller than claimed signal)

- More (maybe much more) data is needed to unambiguously understand this
The $|V_{ub}|$ saga continues...

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

  Gershon @ FPCP 2014: “Understanding this will involve a great deal of effort, but is essential for continued progress in the field”

- Too early to conclude:
  - Inclusive determination can improve
  - Exclusive measured better with full reco
  - Lattice QCD results will improve

- A BSM possibility:

  $$
  \mathcal{L} = -\frac{4G_F}{\sqrt{2}} V_{ub}^L (\bar{u}\gamma_\mu P_L b + \epsilon_R \bar{u}\gamma_\mu P_R b) (\bar{\nu}_\ell\gamma^\mu P_L \ell)
  $$

  Can we construct observables which give “more vertical” constraints?

- NB: Cleanest $|V_{ub}|$ I know, only isospin, $\mathcal{B}(B_u \to \ell \bar{\nu})/\mathcal{B}(B_d \to \mu^+\mu^-) — run LHCb @ 33 \text{ TeV}$

---

| Decay | $|V_{ub}| \times 10^4$ | adm.   |
|-------|-----------------|--------|
| $B \to \pi \ell \bar{\nu}_\ell$ | $3.23 \pm 0.30$ | $(1 + \epsilon_R)$ |
| $B \to X_u \ell \bar{\nu}_\ell$ | $4.39 \pm 0.21$ | $(1 + \epsilon_R^2)$ |
| $B \to \tau \bar{\nu}_\tau$     | $4.32 \pm 0.42$ | $(1 - \epsilon_R)$  |

[Bernlochner, ZL, Turczyk, to appear]
Decay distributions: $B \rightarrow \rho \ell \bar{\nu}, \ K^* \ell^+ \ell^-$

- Important for complementary reasons, similar 4-body final states (so is $B \rightarrow VV$)

Large $q^2$: some relations from heavy quark symmetry, easier for lattice QCD

Small $q^2$: some relations from soft-collinear effective theory, light-cone sum rules

- Need (lots of) data to understand reliability of predictions, size of corrections

ZL – p. 9
$B \rightarrow K^{(*)} \ell^+\ell^-$ decay distributions

- Isospin asymmetry: SM is close to zero, past signals at small $q^2$ — going away?

Predictions for the rate at small $q^2$ are a bit off
(fluctuations? uncertainty in light-cone sum rules?)

Interesting in its own right + form factors at small $q^2$
enter nonleptonic decays (factorization) — impact on CPV program

And then the question whether $c\bar{c}$ loops are tractable

ZL – p. 10
It’s all connected — can one calculate the form factor ratios reliably at small $q^2$? 
(more difficult for lattice QCD, large recoil)

“Optimized observables” defined using a particular approach to factorization (suppression of “factorizable” terms)  

Global fits: a plausible explanation is NP reducing $C_9$  

What set of measurements can check / firm up / refine uncertainty estimates?

Form factors at small $q^2$ also enter nonleptonic decays and interpreting $CP$ viol.
Recall: the $B \to K\pi$ 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 (Lipkin) and \( SU(3) \) relations

- Can we unambiguously understand theory, so that such data could disprove SM?
**CP asymmetries in $B_{(s)} \rightarrow PP$ and $PV$**

- Largest direct CPV (2-body): $A_{CP}(B_s \rightarrow K^-\pi^+) = 0.27 \pm 0.04$ [LHCb: 1304.6173]

Study $SU(3)$ breaking for (suitably defined) relations [Grossman, ZL, Robinson, 1308.4143]

\[ \tilde{\Delta} = \frac{\Delta_{CP}[B_d \rightarrow K^+\pi^-] + \Delta_{CP}[B_s \rightarrow K^-\pi^+]}{\Delta_{CP}[B_d \rightarrow K^+\pi^-] - \Delta_{CP}[B_s \rightarrow K^-\pi^+]} = 0.026 \pm 0.106 \]

- Derived complete set of isospin, $U$-spin, $SU(3)$ relations among CP asymmetries

- $SU(3)$ viol’ in different factorization approaches:
  - BBNS $\alpha_1 \hat{\alpha}_4$ flavor indep / BPRS $A_{c\bar{c}}$ flavor indep

- Correlations between $B_s \rightarrow K^-\pi^+$ vs $B_d \rightarrow K^+\pi^-$
  - $B_s \rightarrow K^+K^- \text{ vs } B_d \rightarrow \pi^+\pi^-$
  - $B_s \rightarrow \pi^+\pi^- \text{ vs } B_d \rightarrow K^+K^-$
  will teach us a lot about $SU(3)$ & large $m_b$ limits

- A huge number of possible tests to improve understanding of strong interaction

---

**LHCP page:** ZL – p. 13
Other interesting topics

• BaBar reported 3.4σ deviation from SM in correlated analysis of:

\[ R(X) = \frac{\Gamma(B \rightarrow X\tau\overline{\nu})}{\Gamma(B \rightarrow X\ell\overline{\nu})} \]

<table>
<thead>
<tr>
<th></th>
<th>Belle</th>
<th>BABAR</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R(D) )</td>
<td>0.430 ± 0.091</td>
<td>0.440 ± 0.058 ± 0.042</td>
<td>0.297 ± 0.017</td>
</tr>
<tr>
<td>( R(D^*) )</td>
<td>0.405 ± 0.047</td>
<td>0.332 ± 0.024 ± 0.018</td>
<td>0.252 ± 0.003</td>
</tr>
</tbody>
</table>

correlation neglected -0.27 -

[Watanabe, FPCP 2014 — BaBar 1205.5442 + Belle private combination]

SM predictions fairly robust: heavy quark symmetry + lattice QCD

• Little SM suppression: need fairly light NP, constraints from flavor & LHC searches

• \( CP \) violation in \( D \) decay

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

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

• I think we still do not know how big an effect could (not) be accommodated in SM
New physics in meson mixing
What are we after?

- Meson mixing:

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

  Simple parametrization:

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

  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

- Define: \( M_{12} = M_{12}^{SM} \times \left( 1 + h e^{2i\sigma} \right) \)
  
  (In \( K \) system introduce \( h_K \) in “tt” contribution)

- Importance known since the 70s, conservative picture of future progress
• Any future projection has uncertainties; sources of experimental and theoretical (lattice) inputs shown

[Charles et al., 1309.2293]

• Lattice QCD is essential

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

• $\gamma$ and $|V_{ub}|$ are crucial (tree / reference UT): the hope is that $2 - 3\%$ uncertainty in $|V_{ub}|$ can be obtained from several measurements: $B \to \tau\nu, B \to \mu\nu, B \to \pi\ell\nu$
New physics in $B^0_d$ mixing

- 95% CL: NP $\lesssim$ $(\text{many} \times \text{SM}) \rightarrow$ NP $\lesssim (0.3 \times \text{SM}) \rightarrow$ NP $\lesssim (0.05 \times \text{SM})$

$$h \simeq \frac{|C_{ij}|^2}{|V^*_{ti}V_{tj}|^2} \left( \frac{4.5 \text{ TeV}}{\Lambda} \right)^2$$ — by Stage II: $\Lambda \sim 20 \text{ TeV}$ (tree), $\Lambda \sim 2 \text{ TeV}$ (loop)

- Belle II 50 ab$^{-1} +$ LHCb 50 fb$^{-1}$

- Right sensitivity to be in the ballpark of gluino masses explored at LHC14

ZL – p. 17
New physics in $B_s^0$ mixing

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

- Sensitivity caught up with that in $B_d$ mixing

- Sensitivities in the future will improve comparably
  Slightly better in $B_s$ due to less “background” in SM expectation

ZL – p. 18
Constraining MFV and $U(2)^3$ flavor structures

- **MFV:**
  \[ h \equiv h_d e^{2i\sigma_d} = h_s e^{2i\sigma_s} = h_K e^{2i\sigma_K} \]
  \[ \sigma_d = \sigma_s = \sigma_K = 0 \pmod{\pi/2} \]

- **$U(2)^3$:**
  \[ h_B \equiv h_d = h_s, \quad \sigma_B \equiv \sigma_d = \sigma_s \]

[1309.2293]
Mixing of neutral mesons will remain a special process to search for new physics, sensitive to some of the highest scales.

Summary of expected sensitivities to \( \left( \frac{C_{ij}^2}{\Lambda^2} \right) \left( \bar{q}_{i,L} \gamma^\mu q_{j,L} \right)^2 \) [Charles et al., 1309.2293]

<table>
<thead>
<tr>
<th>Couplings</th>
<th>NP loop order</th>
<th>Scales (TeV) probed by</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>C_{ij}</td>
<td>=</td>
<td>V_{ti}V_{tj}^*</td>
<td>) (CKM-like)</td>
</tr>
<tr>
<td></td>
<td>one loop</td>
<td>1.4</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>(</td>
<td>C_{ij}</td>
<td>= 1 ) (no hierarchy)</td>
<td>tree level</td>
<td>2 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>one loop</td>
<td>2 \times 10^2</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>
Flavor and the LHC
The LHC is a top factory: top flavor physics

- $A_{FB}^{tt\bar{t}}$ signals and models seem to be going away

- Flavor violation in top decays not well explored
  $\text{SM} \sim 10^{-13}$, current bound $\sim 10^{-3}$

- LHC14: $\sigma_{tt\bar{t}} \sim 850 \text{ pb} \Rightarrow$ sensitivity $\lesssim 10^{-5}$

- Observable top FCNC possible in extensions of
  the SM and still allowed by $B$-factory constraints
  \[\text{[e.g., 0704.1482]}\]

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

- If top FCNC is seen, LHC & $B$ factories will both probe the NP responsible for it
The LHC is a Higgs factory

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

- Richness due to Yukawa couplings: same as origin of “GeV-scale flavor physics”

- 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?
New particles, e.g., supersymmetry

- Any new particle that couples to quarks or leptons ⇒ 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:
  - Minimally flavor violating (mimic the SM)
  - Related but not identical to the SM
  - Unrelated to the SM, or even completely anarchical
  - New physics mass scale:
    - can be “light”
    - 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 ($B_s \rightarrow \ell^+\ell^-, \mu \rightarrow e\gamma$)
Example: SUSY in $K^0 - \bar{K}^0$ mixing

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

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

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

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

  (ii) Universality: $\Delta m_{Q,D}^2 \ll \tilde{m}^2$ (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
• Exploring more general spectra is motivated by both LHC and flavor bounds

• All squarks degenerate:

\[ \tilde{Q}_{1,2,3}, \tilde{U}_{1,2,3}, \tilde{D}_{1,2,3} \]

Simplest models — strongest LHC bounds from non-observation of new particles
Exploring more general spectra is motivated by both LHC and flavor bounds.

- Gauge split

\[ \tilde{Q}_{1,2,3} \quad \tilde{D}_{1,2,3} \]

\[ \tilde{U}_{1,2,3} \]

Can have (almost) completely SM-like flavor structure.
Exploring more general spectra is motivated by both LHC and flavor bounds

Minimal flavor violation

\[m^2_{\tilde{U}} = (1 + Y_u^\dagger Y_u + \ldots)\]

Can evade flavor bounds — LHC search limits get somewhat weaker
Exploring more general spectra is motivated by both LHC and flavor bounds.

Quark-squark alignment:

\[
\tilde{Q}_1 \quad \tilde{Q}_2 \quad \tilde{Q}_3 \\
\tilde{U}_1 \quad \tilde{U}_2 \quad \tilde{U}_3 \\
\tilde{D}_1 \quad \tilde{D}_2 \quad \tilde{D}_3
\]

May come from horizontal symmetries.

We do not know which is right — need broad set of searches (both LHC & flavor).
Hide flavor signals ⇔ hide LHC signals

- Despite lore, squarks need not be as degenerate as thought earlier (triggered by studying charm CPV)  
  [Gedalia, Kamenik, ZL, Perez, 1202.5038]

  Top plot: each LHC search becomes weaker
  Bottom plot: unshaded region still allowed if 4–4 squarks (but not all 8) are degenerate  
  [Mahbubani, Papucci, Perez, Ruderman, Weiler, 1212.3328]

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

- Modify search strategies to improve coverage

- Ways for naturalness to survive: we can give up many assumptions before giving up principles

---

ZL – p. 26
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 that carry lepton number (e.g., sleptons), then they have their own mixing matrices $\Rightarrow$ charged lepton flavor violation

- Many interesting processes:
  \[
  \mu \to e\gamma, \quad \mu \to eee, \quad \mu + N \to e + N^{(t)}, \quad \mu^+e^- \to \mu^-e^+ \\
  \tau \to \mu\gamma, \quad \tau \to e\gamma, \quad \tau \to \mu\mu\mu, \quad \tau \to eee, \quad \tau \to \mu\mu e \\
  \tau \to \mu ee, \quad \tau \to \mu\pi, \quad \tau \to e\pi, \quad \tau \to \mu K_S, \quad eN \to \tau N
  \]

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

- **In SUSY, both 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

---

*ZL – p. 28*
Flavor / LHC complementarity

- Combination of LHC and flavor data can be very powerful to discriminate models

Let's hope we'll be in such a situation...

[arXiv:0904.4262]
Final remarks & Future
(Part of) a SM “to-do list” for theory

- New ideas: recall that the best $\alpha$ and $\gamma$ measurements are in modes influenced by BaBar & Belle data (not thought about before $\sim 2003$)
  
  - How big can $CP$ violation be in $D^0 - \bar{D}^0$ mixing in the SM?
  
  - How big can direct $CP$ violation be in $D$ decays in the SM?
  
  - 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)
  
  - What is the SM upper bound on $S_{K_S\pi^0\gamma}$?
  
  - What is the “ultimate” uncertainty of $|V_{ub}|$?
  
  - Can direct $CP$ asymmetries in nonleptonic modes be understood enough to make them “discovery modes”? [$SU(3)$, heavy quark limit, SCET, etc.]
Lots of “other” searches

- Cast a wide net — broad program is critical:
  
  \[ B \to (\gamma+) \text{ invisible} \]  
  \[ B \to X_s + \text{ invisible} \]  
  \[ \Upsilon(1S) \to \text{ invisible} \]  
  \[ \Upsilon(nS) \to \gamma + \text{ invisible} \]  
  \[ e^+e^- \to (\gamma+) \text{ invisible} \]  
  [Belle, 1206.5948; BaBar, 1206.2543]
  
  \[ B \to X_s + \text{ invisible} \]  
  \[ \Upsilon(1S) \to \text{ invisible} \]  
  \[ \Upsilon(nS) \to \gamma + \text{ invisible} \]  
  \[ e^+e^- \to (\gamma+) \text{ invisible} \]  
  [Belle, hep-ex/0611041; BaBar, 0908.2840]
  
  \[ \Upsilon(nS) \to \gamma + \text{ invisible} \]  
  [e.g., for 1S and 3S: BaBar, 0808.0017, 1007.4646]

- Also include “invisible” replaced by \( \ell^+\ell^- \)

- \( \tau \) and \( \mu \) lepton flavor violation

- Searches for violations of conservation laws

- Obvious! most cited Belle paper: \( X(3872) \), most cited BaBar paper: \( D^{*}_s(2317) \)
  [You may say it’s “QCD stuff”, but \( \Gamma/m < 3 \times 10^{-4} \) and \( \Gamma/m < 1.6 \times 10^{-3} \), respectively...]

ZL – p. 31
Conclusions

- Flavor physics probes scales $\gg 1$ TeV; sensitivity limited by statistics, not theory
- New physics in most FCNC processes may still be $\gtrsim 20\%$ of the SM or more
- Few discrepancies in SM fit; 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
- Flavor physics data in next decade will tell us a lot, whether NP is found or not

<table>
<thead>
<tr>
<th>Evidence for BSM?</th>
<th>FLAVOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS &amp; CMS</td>
<td></td>
</tr>
<tr>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

- 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
Backup slides
\[ B_{s,d} \rightarrow \mu^+\mu^- \text{ and other rare decays} \]

- Shrinking room for NP comparable to SM

LHCb – CMS combination:
\[
B(B_s \rightarrow \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9} \\
B(B_d \rightarrow \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}
\]

- Experimental uncertainty will decrease a lot, interpretation not theory limited

- Many other rare decays, \( b \rightarrow q\ell^+\ell^- \), \( b \rightarrow q\nu\bar{\nu} \), with much improved sensitivity

[\text{LHCb @ EPS: } \sim 4\sigma \text{ difference from a SM expectation in } B \rightarrow K^* \mu^+\mu^- \text{ angular distribution}]

- In some decay modes, even in 2025 we’ll have \( (\text{Exp. bound})/\text{SM} \gtrsim 10^3 \)

[E.g.: \( B_{(s)} \rightarrow \tau^+\tau^- \), \( e^+e^- \), can build many models...]

---

\( ZL \text{ – p. i} \)
$D$ mixing and CPV in up sector

- Mass eigenstates: $|D_{H,L}\rangle = p|D^0\rangle \mp q|\bar{D}^0\rangle$ — CP is conserved iff $|q/p| = 1$

CPV iff: (mass eigenstates) $\neq$ (CP eigenstates)

- Only meson mixing generated by down-type quarks — in SUSY by up-type squarks

Mixing observed only in 2007

Bound on CPV in mixing is 1–2 orders of magnitude weaker than in $B_{d,s}$ and $K$ mixing

- Far from hitting the “theory wall”

- Possible connections to FCNC top decays

- Complementary to $K, B$ — interplay in SUSY between $\Delta m_D$ & $\Delta m_K$ constraints

Uncertainty of $|q/p|$ is $\sim 0.2$!
Example: bump searches in $B \rightarrow K^{(*)}\ell^+\ell^-$

- Can probe certain DM models with $B$ decays
  E.g., “axion portal”: light ($\lesssim 1 \text{ GeV}$) scalar particle coupling as $(m_\psi/f_a) \bar{\psi} \gamma_5 \psi a$

- In most of parameter space best bound is from $B \rightarrow K\ell^+\ell^-$

[Freytsis, ZL, Thaler, arXiv:0911.5355]

ZL – p. iii
New physics in $K^0$ mixing

- Only $\epsilon_K$ constraint — two “chimneys”
- Precision lattice QCD calculation of $\Delta m_K$ would cut those off
- In some classes of models can combine with $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$
$K^0$ mixing, lattice QCD, other prospects

- How to best use anticipated precise lattice QCD calculation of $\Delta m_K$ in the SM?
  
  - Directly constrain $|h_K|$ [what we did]
  
  - Constrain $\eta_{cc}$, which is the largest uncertainty in $\epsilon_K$ [Buras and Girrbach, 1304.6835]

Hard to connect lattice QCD to SD/LD separation in dim.reg. (remove $\lambda_c$ vs. $\lambda_u$)

[Buras, Christ, Izubuchi, Sachrajda, Soni, Yu, 1212.5931]

\[
\sigma(\eta_{cc}) = 0.76
\]

\[
\sigma(\eta_{cc}) = 0.2
\]
Can such fits discover NP?

- Interesting to see if NP can be discovered and not only constrained

Any assumption about future NP signals is ad hoc — simplest scenario: assume all future (Stage II) experimental results correspond to the current best-fit values of $\bar{\rho}$, $\bar{\eta}$, $h_{d,s}$, $\sigma_{d,s}$
The CKM fit with NP allowed in mixing

- Much larger allowed regions when fitting more (NP) free parameters

2003  
\[
\begin{align*}
\rho &\sim -1 \text{ to } 1 \\
\eta &\sim -1 \text{ to } 1 \\
|V_{ub}| &\sim 0.05 \text{ to } 0.45
\end{align*}
\]

2013  
\[
\begin{align*}
\rho &\sim -1 \text{ to } 1 \\
\eta &\sim -1 \text{ to } 1 \\
|V_{ub}| &\sim 0.05 \text{ to } 0.45
\end{align*}
\]

Stage II  
\[
\begin{align*}
\rho &\sim -1 \text{ to } 1 \\
\eta &\sim -1 \text{ to } 1 \\
|V_{ub}| &\sim 0.05 \text{ to } 0.45
\end{align*}
\]

Qualitative change after 2003: first constraints on $\gamma$ (and $\alpha$)

- Define “Stage II”: Belle II $50 \text{ ab}^{-1}$ + LHCb $50 \text{ fb}^{-1}$ [Charles et al., 1309.2293]

- At 95% CL, $\tilde{\rho} < 0$ & $\tilde{\eta} < 0$ is still allowed now (importance of future $A^d_{\text{SL}}$)
Magnitudes on NP in $B^0_d$ and $B^0_s$ mixing

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

- Looking at $B_{d,s}$ mixing simultaneously (Connections to $K$ mixing in $U(2)^3$ flavor models)
Semileptonic $B \rightarrow \pi, \rho$ form factors

- At leading order in $\Lambda/Q$, to all orders in $\alpha_s$, two contributions at $q^2 \ll m_B^2$: soft form factor & hard scattering
  (Separation scheme dependent; $Q = E, m_b$, omit $\mu$’s)
  [Beneke & Feldmann; Bauer, Pirjol, Stewart; Becher, Hill, Lange, Neubert]

$$F(Q) = C_i(Q) \zeta_i(Q) + \frac{m_B f_B f_M}{4E^2} \int dz dx dk_+ T(z, Q) J(z, x, k_+, Q) \phi_M(x) \phi_B(k_+)$$

- Symmetries ⇒ nonfactorizable (1st) term obey form factor relations
  [Charles et al.]
  $$3 \ B \rightarrow P \ and \ 7 \ B \rightarrow V \ form \ factors \ related \ to \ 3 \ universal \ functions$$

- Relative size?  
  QCDF: 2nd $\sim \alpha_s \times (1st)$  
  SCET: 1st $\sim$ 2nd

- Whether first term factorizes (involves $\alpha_s(\mu_i)$, as 2nd term does) involves same physics issues as hard scattering, annihilation, etc., contributions to $B \rightarrow M_1 M_2$
The MSSM parameters and flavor

- Superpotential:
  \[ W = \sum_{i,j} \left( Y^u_{ij} H_u Q_i \bar{U}_j + Y^d_{ij} H_d Q_i \bar{D}_j + Y^\ell_{ij} H_d L_i \bar{E}_j \right) + \mu H_u H_d \]

- Soft SUSY breaking terms:
  \[ \mathcal{L}_{\text{soft}} = - \left( A^u_{ij} H_u \tilde{Q}_i \tilde{U}_j + A^d_{ij} H_d \tilde{Q}_i \tilde{D}_j + A^{\ell}_{ij} H_d \tilde{L}_i \tilde{E}_j + B H_u H_d \right) \]
  \[ - \frac{1}{2} \left( m^2_s \right)_{ij} s_i \bar{s}_j - \frac{1}{2} \left( M_1 \tilde{B} \tilde{B} + M_2 \tilde{W} \tilde{W} + M_3 \tilde{g} \tilde{g} \right) \]

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

Gauge and Higgs sectors: \( g_{1,2,3}, \theta_{\text{QCD}}, M_{1,2,3}, m^2_{h_u,d}, \mu, B \) — 11 real + 5 imag.

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

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