Flavor Physics in the LHC Era

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Outline

✧ Snapshot of particle physics
✧ Precision studies of the CKM matrix
✧ Particle physics at a crossroad
✧ Beyond the Standard Model
✧ Potential impact of Super B-factory
✧ Summary
Snapshot of particle physics
Too good to be true ...
Hints from experiment

✧ Standard Model (SM) of elementary particle interactions works marvelously
✧ A triumph of 20th century science!
✧ No compelling evidence for New Physics from electro-weak precision measurements (Z pole and beyond)
✧ Preference for a light Higgs
Hints from experiment

\( A_{FB}^b \) and NuTeV off by 3\( \sigma \), but not readily explained by New Physics (stat. fluct.?)
Hints from experiment

✧ Other 2-3σ effects present in low-energy precision measurements
✧ Muon anomalous magnetic moment, \((g-2)_\mu\)
✧ B physics (several small, but intriguing effects)
Higgs sector

- Comprehensive exploration of scalar sector main challenge for coming decade
- In SM, flavor physics intimately connected with Higgs sector via Yukawa matrices ($V_{\text{CKM}}=U_u^\dagger U_d$), hence indispensible part of this program
Higgs sector

✧ LHC is a discovery machine, but not a precision tool
✧ Many properties of new particles (if discovered) will not be measured at LHC
✧ Requires facilities offering high precision: high-luminosity facilities at low energies (B, K, neutrinos, g-2, EDMs, 0νββ decay, etc.)
Precision studies of the CKM matrix

Overdetermining the unitarity triangle

\[ V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \]
Determinations of the UT
Determinations of the UT

- Determination of $|V_{ub}|$ in semilept. B decays
- Theoretical uncertainty recently reduced to 5%

[Bosch, Lange, MN, Paz (2004, 2005)]
Determinations of the UT

- Determination of $|V_{td}|$ in $B^0$-$\bar{B}^0$ mixing
- Hadronic uncertainties (lattice QCD)
Determinations of the UT

* Determination of $\text{Im}(V_{td}^2)$ in $K^0$-$\bar{K}^0$ mixing

* Hadronic uncertainties (lattice QCD)
Determinations of the UT

- Determination of $\sin 2\beta$ in $\Bz - \Bzb$ mixing
- No theor. uncertainties!
Determination of $\gamma$ in $B \rightarrow \pi\rho$

* B→PV modes receive smaller penguin contributions than B→PP modes
* Allows extraction of $\gamma$ with small theoretical errors from time-dependent $B \rightarrow \pi\rho$ rates
* Result:

$$\gamma = (62 \pm 8)^\circ$$

[Beneke, MN (2003)]
Tree vs. penguin processes
CP-conserving vs. CP-violating processes
Sides vs. angles
CKM model of flavor and CP violation works spectacularly!
Definitely the main source of these effects
New Physics can only give corrections to the CKM picture
Still, there is a possibility for finding some significant New Physics effects in the flavor sector
CP asymmetries in $B \to \Phi K_S, \eta' K_S$

- Interference of mixing and decay:
- Penguin graph real to excellent approx.
- Phase structure identical to golden decay $B \to J/\psi K_S$
- Theor. prediction:

$$S(\Phi K_S) - S(J/\psi K_S) = 0.02 \pm 0.01$$

[Beneke, MN (2003)]

[Grossman, Worah (1996)]
2005: 7 reasons for excitement

- \(\phi K^0\) 
  - \(0.34 \pm 0.20\)
- \(\eta^\prime K_S^0\) 
  - \(0.43 \pm 0.11\)
- \(f_0 K_S^0\) 
  - \(0.39 \pm 0.26\)
- \(\pi^0 K_S^0\) 
  - \(0.34 \pm 0.29\)
- \(\omega K_S^0\) 
  - \(0.55 \pm 0.32\)
- \(K^+ K^- K_S^0\) 
  - \(0.53 \pm 0.17\)
- \(K_S^0 K_S^0 K_S^0\) 
  - \(0.26 \pm 0.34\)

**Average (s-penguin)**
- \(0.43 \pm 0.07\)

\(-\eta_f \times S_f\) Avg.: \(0.42 \pm 0.08\)

Deviation of 3.8σ!
Current situation

New Physics in penguin processes?
Current situation

✧ Combined average $\sin^2 \theta = 0.638 \pm 0.026$ lies below the “tree” value $\sin^2 \theta = 0.794 \pm 0.045$ deduced from $|V_{ub}|$ and $|V_{td}|$

✧ Important:
  ✧ Increased precision in determination of $|V_{ub}|$
  ✧ Measurement of $B_s - \bar{B}_s$ mixing (D0, CDF)
New Physics in $B_d$-$\bar{B}_d$ mixing?

✧ Plausible explanation of these effects
✧ Possible and even natural in extensions of SM with new particles near TeV scale (e.g. SUSY, new Z’ bosons, extra dimensions ...)

→ *see talk by L. Silvestrini*
New Physics in $B_d$-$\bar{B}_d$ mixing?

✧ General parametrization:

$$\Delta m_d = \Delta m_d^{SM} * r_d^2 e^{i2\theta_d}$$

✧ New Physics contributions up to 50% of SM allowed

✧ Best fit prefers new, CP-violating phase $\theta_d \neq 0$

✧ After discovery of new particles at LHC $\rightarrow$ allowed parameter space for new flavor parameters
Other small deviations

✧ $B_s - \bar{B}_s$ mixing phase 2σ off SM value
  [Lenz, Nierste, hep-ph/0612167]

✧ NNLO prediction for $B \to X_s \gamma$ is 1.4σ lower than world-average experimental result

\[
\text{Br}(\bar{B} \to X_s \gamma) = (2.98^{+0.13}_{-0.17} \text{pert} \pm 0.16_{\text{hadr}} \pm 0.11_{\text{pars}} \pm 0.09_{m_c}) \cdot 10^{-4}
\]

\text{Combined theory error: ±9%}

$B_{\exp}(E_\gamma>1.6 \text{ GeV}) = (3.55 \pm 0.24 \pm 0.09 \pm 0.03) \cdot 10^{-4}$

✧ Re-opens possibility for sizable New Physics contributions!
Crucial question

Are any of these effects real?

What one would need to explain them are $O(0.1-0.2)$ New Physics contributions to the decay amplitudes!
Crucial question

✧ We probably won’t establish New Physics in any of these channels prior to LHC data.
✧ After LHC (or Tevatron) discovery, we would reinterpret the effects in terms of measurements of new flavor parameters.
✧ Yet, it’s fundamentally important that some of the effects are real, because only then will we be able to distinguish New Physics effects from SM backgrounds!
Flavor physics is hard

✧ Interpretation of New Physics signals in weak decays is difficult due to SM background
✧ In presence of New Physics, methods that are clean in the SM often become sensitive to hadronic uncertainties
✧ Consider how difficult is has been to determine the 4 parameters of the CKM matrix, for which there is no background
Particle physics at a crossroad

On the verge of discovery?
The big questions

Despite great efforts in >30 years, have made little progress on really hard questions:

✧ Mechanism of electroweak symmetry breaking, responsible for masses of elementary particles?
  ✧ Nature of scalar sector?
  ✧ How stabilized?

✧ Curiously: most of mass in Universe from chiral symmetry breaking (QCD effect, well understood)!
The big questions

✧ Why $SU(3)_C \times SU(2)_L \times U(1)_Y$?
✧ Do other forces exist?
✧ Right-handed currents?
✧ Why 3 generations?
✧ Dynamics of flavor?
✧ New quantum number?
✧ Curiously: required for CP violation, but not responsible for matter-antimatter asymmetry!
History of the Universe

Accelerators: CERN-LHC, FNAL-Tevatron, BNL-RHIC, CERN-LEP, SLAC-SLC

Inflation

Big Bang

Key:
- w, z: bosons
- photon
- q: quark
- g: gluon
- e: electron
- m: muon
- n: neutrino
- t: tau

Particle Data Group, LBNL, © 2000. Supported by DOE and NSF
The big questions

✧ What explains hierarchy of Yukawa matrices?
  ✧ Fermion masses and mixings
  ✧ Why different for quarks and leptons?
✧ What creates neutrino masses?
  ✧ Do right-handed neutrinos exist?
  ✧ Majorana or Dirac masses?
  ✧ Sterile neutrinos?
  ✧ See-saw mechanism?
The big questions

New questions:

✧ What is dark matter? What is dark energy?
✧ Theory of inflation?
Conventional picture

- Indirect exp. probes
- Direct exp. probes

$10^{-1}$ GeV $10^2$ $10^3$ MeV $10^6$ $10^8$ $10^{16}$ $10^{18}$

$\Lambda_{\text{QCD}}$ $m_W$ $m_{\text{EWSB}}$ $M_{\text{GUT}}$ $M_{\text{Pl}}$

Weak scale

Sector of EW symmetry breaking (stabilization of weak scale)

Many ideas: SUSY, extra dimensions, technicolor, composite Higgs, little Higgs, fat Higgs, ...

Quantum gravity (superstrings?)

Unification of gauge couplings
Conventional picture

**Indirect exp. probes**

$10^{-1}$ GeV

**Direct exp. probes**

$10^2$ $10^3$

**Standard Model**

$\Lambda_{\text{QCD}}$

$m_W$ $m_{\text{EWSB}}$

**Weak scale**

Sector of EW symmetry breaking (stabilization of weak scale)

**Great desert?**

Series of ever more fundamental Effective field theories?

How many layers of New Physics?

**Many ideas:**

SUSY, extra dimensions, technicolor, composite Higgs, little Higgs, fat Higgs, ... 

**Indirect exp. probes**

$10^{16}$ $10^{18}$

**Unification of gauge couplings**

$M_{\text{GUT}}$ $M_{\text{Pl}}$

**Sector of EW symmetry breaking** (stabilization of weak scale)

**Quantum gravity** (superstrings?)
A note of caution

✧ All hope for New Physics at TeV scale rests on fine-tuning problem
✧ Experiment tells us the contrary!
✧ Either we’ve been unlucky and New Physics is really just around the corner, or something may be wrong with this reasoning
✧ Worth questioning some of the salient assumptions
Radical questions

✧ How sure are we that $M_{Pl}$ and $M_{GUT}$ are fundamental scales?

✓ Unification of gauge couplings and neutrino masses hint at New Physics near $M_{GUT}$

✗ But gravity only tested down to 0.1mm, corresponding to scale $\sim 10^{-11}$ GeV

✗ Assumption that Newton’s law holds over another 30 orders of magnitude seems preposterous

✧ Models with extra dimensions eliminate Planck scale (ADD) or explain it in terms of warped geometry (RS)
Grand unification

SM

MSSM
Radical questions

How sure are we about existence of New Physics at the TeV scale?

- Hierarchy problem (stabilization of weak scale), based on naturalness assumption
- Unification of gauge couplings with TeV-scale SUSY
- Need for dark matter (WIMP with $m_{DM}$-TeV would fit well)

- World is full of “unnaturally” small ratios; fine-tuning problematic only if heavy particles exist that couple to scalar sector
- Unification possible in alternative ways
- Alternative explanations for dark matter exist (e.g. axions, warm sterile neutrinos, …) [Kusenko et al. (2003)]

Split-SUSY models ignore fine-tuning problem and postulate New Physics only at very high scales [Arkani-Hamed, Dimopoulos (2004)]
Beyond the Standard Model

Some scenarios
Starting point

✧ SM is an effective field theory, tested to energies \(\sim 100 \text{ GeV}\), and believed to break down and some higher scale \(\Lambda\)

\[
H_{\text{eff}} = H_{\text{SM}} + \frac{1}{\Lambda} \sum_i b_i O_i^{(5)} + \frac{1}{\Lambda^2} \sum_i c_i O_i^{(6)} + \ldots
\]

✧ Flavor-conserving ops.: \(\Lambda_{\text{EWSB}} > 1\text{-}10 \text{ TeV}\) (“little hierarchy problem”)
✧ Flavor-violating ops.: \(\Lambda_{\text{FV}} > 10^2\text{-}3 \text{ TeV}\) provided \(c_i = O(1)\) (“flavor problem”)

\(EWSB\geq1\text{-}10 \text{ TeV}\)
Complication

\[ H_{\text{eff}} = H_{\text{SM}} + \frac{1}{\Lambda} \sum_i b_i O_i^{(5)} + \frac{1}{\Lambda^2} \sum_i c_i O_i^{(6)} + \ldots \]

✧ Already know examples where cutoff is much higher, \( \Lambda \sim 10^{14-16} \text{ GeV} \)

✧ Neutrino masses (d=5 operators)

✧ Proton and lepton-number violating processes

✧ In first case there is a well-motivated mechanism explaining this (heavy right-handed neutrino, seesaw); in second case some symmetry needs to be invoked (e.g. R-parity in SUSY)
Complication

Below, will assume that there exists some New Physics at scales not too far from TeV scale (otherwise particle physics is dead ...
Possible interpretations

A. Flavor violation related to EWSB ($\Lambda_{\text{FV}} \sim \Lambda_{\text{EWSB}}$), then:
   ✦ Need a symmetry to keep many $c_i$ small, e.g. minimal flavor violation (MFV) hypothesis
   ✦ There should be measurable effects in present data (i.e., some puzzles should be true)
   ✦ Is indeed “natural” to get $O(0.1)$ effects with New Physics at TeV scale
   ✦ Best possible scenario! Super B-factories would do for New Physics what B-factories did for SM!
Possible interpretations

B. Flavor violation not related to EWSB ($\Lambda_{FV} \gg \Lambda_{EWSB}$), then:

✧ Sad ...
✧ Strange, since virtually any extension of SM that can solve the hierarchy problem contains a zoo of new flavor parameters
✧ E.g., extra dimension models offer a new approach to understand “generations” in terms of fermion localization

[Arkani-Hamed, Schmaltz (1999); Grossman, MN (1999)]
Possible interpretations

C. Flavor violation related to EWSB ($\Lambda_{\text{FV}} \sim \Lambda_{\text{EWSB}}$), but $\Lambda_{\text{EWSB}} \gg 1$ TeV much higher than anticipated, then:

✧ Pessimistic, but not excluded
✧ Examples of such models exist (“finely tuned SM”)
  e.g.:
  ✧ Little Higgs models (or a tower of such models) with UV completion at a high scale (involve some New Physics, but effects can be kept small using MFV)

✧ LHC will test this scenario. If true, we’ll only explore Higgs sector, not much more
Possible interpretations

✧ In this scenario, flavor physics (and other low-energy measurements) can probe mass scales far extending beyond LHC/ILC range

✧ However, there won’t be a tool for a direct confirmation of a potential indirect discovery
Overview scenarios

Flavor violation related to EWSB?

- \( \Lambda_{\text{FV}} \sim \Lambda_{\text{EWSB}} \) (yes)
  - \( \Lambda \sim 1 \text{ TeV} \)
    - Expect visible effects @ B-factories;
      Need symmetry (MFV?) to suppress large FCNC
  - \( \Lambda \sim 10^{2-3} \text{ TeV} \)
    - Limited potential of LHC/ILC;
      Low-E experiments extend New Physics reach,
      but interpretation difficult

- \( \Lambda_{\text{FV}} \gg \Lambda_{\text{EWSB}} \) (no)
  - \( \Lambda \sim 1 \text{ TeV} \)
    - Limited potential of LHC/ILC;
      Low-E experiments offer important clues about TeV-scale physics
  - \( \Lambda \sim 10^{2-3} \text{ TeV} \)
    - Must explain why;
      Low-E experiments offer important clues about TeV-scale physics
Potential impact of a Super B-factory

Never stop exploring!
Role of Super B-factory

✧ In best case scenario (A): help to determine or place constraints on flavor parameters of some new particles (e.g., quark-squark-gluino couplings in SUSY, KK fermions, ...)

✧ Much like B-factories did for b- and t-quarks ($V_{cb}, V_{ub}, V_{ts}, V_{td}, \beta, \gamma$)
Role of Super B-factory

✧ In more pessimistic scenario (B): absence of new sources of flavor-violation at TeV scale would teach us important lessons about nature of EWSB, and perhaps even SUSY breaking, fermion localization in extra dimensions, etc.

✧ In some very rare or forbidden processes ($\mu \rightarrow e\gamma$, or $B \rightarrow X_s \nu \bar{\nu}$) one can probe scales into the $10^{2-3}$ TeV range or even higher
Role of Super B-factory

✧ Like in electroweak precision measurements, New Physics effects must show up at some level of precision in flavor physics.
✧ In the worst case that we would not see any large signals in B physics, a Super B-factory would play a similar role as LEP played for the understanding of EWSB.
✧ It would then impose most severe constraints on model building for the post LHC era.
Role of Super B-factory

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In worst case scenario (C): flavor physics our only hope to learn anything beyond the SM, but would this be sufficient to keep the field alive?
Summary
Conclusions

✧ Flavor physics a vital component in the exploration of the TeV scale
✧ Complementarity with LHC/ILC
✧ Impact will depend on whether there is some flavor structure near TeV scale
✧ Compelling physics case for a Super B-factory; would be a “no-brainer” if any of the present hints turn out to be true ...