Flavor physics: past & future

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Belle II
Academie

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Outline

• Why are we (still) interested in all these measurements?
  (i) Many open questions
  (ii) Unexpected discoveries are... unpredictable

• Introduction

• Kaons

• $B$ past

• $B$ future
  + other probes: charm, top, EDMs, higgs

• Please interrupt with any questions or comments. I mean it! (Can’t see raised hands)
Disclaimer: won’t talk about spectroscopy

- Most cited Belle & LHCb and 2nd most cited BaBar papers are on spectroscopy (main detector papers aside)

- Could easily be the subject of many talks
What is particle physics?

• Elementary interactions and d.o.f.? Observed phenomena consistent with SM
  (Michelson 1894: “... it seems probable that most of the grand underlying principles have been firmly established ...”)

• Standard Model of particle physics: Standard Model of cosmology:

• Inconsistent: Two very successful theories, but this cannot be the full story
  – Dark matter
  – Baryon asymmetry of the Universe
  – Neutrino mass
  – Inflation in the early universe
  – Dark energy
The crucial role of symmetries

- Intimate connection between symmetries and conservation laws

  Much of what we know is determined by symmetries, their range of validity, if and how they are violated... interactions, conservation laws, selection rules, forbidden / suppressed processes

  - Continuous symmetries... e.g.: translation — momentum conservation
  - Gauge (internal) symmetries... e.g.: $U(1)$ — electromagnetic interaction

- Discrete symmetries:

  $C =$ charge conjugation

  $P =$ parity $(x \leftrightarrow -x)$

  $T =$ time reversal $(t \leftrightarrow -t$, initial $\leftrightarrow$ final states)

  $CPT$ cannot be violated in a relativistically covariant local quantum field theory

- Discovered 1957: weak interactions (maximally) violate $P$ and $C$ [Lee & Yang, Nobel 1957]
The Universe: matter vs. antimatter

- Gravity, electromagnetism, strong interaction are same for matter and antimatter

- As the early Universe cooled, quarks and antiquarks annihilated

\[ \frac{N(\text{baryon})}{N(\text{photon})} \sim 10^{-9} \Rightarrow \frac{N_q - N_{q'}}{N_q + N_{q'}} \sim 10^{-9} \]

\[ t < 10^{-6} \text{ s} \ (T > 10^{13} \text{ K} \sim 1 \text{ GeV}) \]

- SM prediction: \( \sim 10^{10} \) times smaller

[Nonzero! Sakharov (1966): (i) baryon number violation; (ii) charge \((C)\) and charge-parity \((CP)\) violation; (iii) deviation from thermal equilibrium]

- All present in SM; additional \(CP\) violation is required

What is the microscopic theory of \(CP\) violation? How precisely can we probe it?
What is $CP$ violation?

- Different behavior for particles and antiparticles
  
  E.g.: $\Gamma(A \rightarrow B) \neq \Gamma(\bar{A} \rightarrow \bar{B})$, such as $\Gamma(B^0 \rightarrow \pi^+\pi^-) \neq \Gamma(\bar{B}^0 \rightarrow \pi^+\pi^-)$

- $CP$ violation does not exist classically, requires interference (physical phases)
Why is $CP$ violation interesting?

• SM cannot explain baryon asymmetry $\Rightarrow$ additional $CP$ violation must exist
  – Electroweak baryogenesis? (testable at LHC)
  – Leptogenesis? (Connection to neutrinos?)
  – Something else?

• SM: a single $CP$ violating parameter
  (In the quark sector, neglecting strong $CP$ phase, $\theta_{QCD}$, negligible in flavor changing processes)
  – Strong predictive power (correlations, zeros)
  – Stringent tests of the standard model

• NP: many sources of $CP$ violation possible — neutral current, Higgs, new sectors
**CP violation involving known particles: 2, 3, 5?**

- **Gauge symmetry:** $SU(3)_c \times SU(2)_L \times U(1)_Y$
  
  - 8 gluons $W^\pm, Z^0, \gamma$
  
- **Particle content:** 3 generations of quarks and leptons
  
  - $Q_L(3, 2)_{1/6}$, $u_R(3, 1)_{2/3}$, $d_R(3, 1)_{-1/3}$
  
  - $L_L(1, 2)_{-1/2}$, $\ell_R(1, 1)_{-1}$
  
  - Quarks: $\begin{pmatrix} u & c & t \\ d & s & b \end{pmatrix}$
  
  - Leptons: $\begin{pmatrix} \nu_1 & \nu_2 & \nu_3 \\ e & \mu & \tau \end{pmatrix}$

- **Symmetry breaking:** $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$
  
  - $\phi(1, 2)_{1/2}$ Higgs, with vev: $\langle \phi \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$

- **Not known:** $\mathcal{L}_Y = -Y_{ie}^{ij} \overline{L}_Li \phi e^I R_j - \left\{ \frac{Y_{\nu}^{ij}}{\lambda} \overline{L}_Li \overline{L}_Lj \phi \phi \right\}$ violates lepton number

  - $Y_{\nu}^{ij} \overline{L}_Li \bar{\phi} \nu^I R_j$ requires $\nu_R$ fields

- **We do not know what is the Lagrangian that describes the observed particles!**

---

**ZL – p. 8**
Brief history of $CP$ violation

- **1964 – 1999:** $CP$ violation discovered in $K$ decay, “$\epsilon$” [fitted w/ CKM phase, not a test]
- **1999:** second $CP$ violation measured in kaons, “$\epsilon'/\epsilon$” [notoriously hard to calculate]
- **1999 – 2010:**
  - $e^+e^- B$-factory experiments, $BABAR$ (Stanford) and Belle (Tsukuba), measured dozens of $CP$ violating observables in $B$ meson processes
- **2009 – 2019:**
  - LHCb: improvements + $CP$ violation in $B_s$ mesons with comparable precision
- **2019:**
  - LHCb: discovery of $CP$ violation in $D$ meson decay $(A_{K^+K^-} - A_{\pi^+\pi^-})$
- $CP$ violation in itself is no longer automatically interesting, only if sensitive to NP
- One $CP$ violating parameter (KM phase) can account for it all so far
Kaons
1964: \( CP \) symmetry is broken

- The \( CP \) symmetry was expected to hold

- Two neutral states, nearly equal mass, but lifetime ratio > 500 — phase space
  \[ CP |K^0\rangle = e^{i\varphi}|\bar{K}^0\rangle, \quad CP |\bar{K}^0\rangle = e^{-i\varphi}|K^0\rangle \]

If \( CP \) conserved: \( CP \) eigenstates = mass eigenstates
  \[ |K_{S,L}\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle \pm e^{i\varphi}|\bar{K}^0\rangle) \]

\( \pi\pi \) in \( J = 0 \) state has \( CP = +1 \), so only \( K_S \rightarrow \pi\pi \)

- Discovered in 1964:
  \( (0.2\%) \) (Nobel prize, 1980)

- A new \( CP \) violating interaction? Is \( CP \) an approximate symmetry?
  [Before charm and much of the SM; could involve new particles / interactions; SM not “minimal”]

Many options... No other independent observation of \( CP \) violation until 1999
It was a surprise...

PROPOSAL FOR $K^0_2$ DECRY 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 $K^0_1$ 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 $K^0_2 \rightarrow \pi^+ \pi^-$, a new limit for the presence (or absence) of neutral currents as observed through $K^0_2 \rightarrow \mu^+ \mu^-$. In addition, if time permits, the coherent regeneration of $K^1_1$'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 $\mu$-$p$ 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 $K^0_2$ went entirely to two pions. This means that one can set a limit of about one in a thousand for the partial rate of $K^0_2 + 2\pi$ in one hour of operation. The actual limit is set, of course, by the number of three-body $K^0_2$ 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 $K^0_1$'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 $K^0_1$'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
A near miss: factor-of-2 improvements matter
Timeline of discovery, superweak, KM paper

• History often different from what may seem “obvious” later:

EVIDENCE FOR THE $2\pi$ 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)

VIOLATION OF $CP$ INVARIANCE AND THE POSSIBILITY OF VERY WEAK INTERACTIONS*
L. Wolfenstein
Carnegie Institute of Technology, Pittsburgh, Pennsylvania
(Received 31 August 1964)

$CP$-Violation in the Renormalizable Theory of Weak Interaction
Makoto KOBAYASHI and Toshihide MASKAWA
Department of Physics, Kyoto University, Kyoto
(Received September 1, 1972)
The quest for $K \rightarrow \pi \nu \bar{\nu}$

- Theoretically clean: $K_L \rightarrow \pi^0 \nu \bar{\nu}$ is $CP$ violating, $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is dominantly so.
- 50 years of searches, sensitive to $\mathcal{O}(100 \text{ TeV})$ (“longer than for Higgs” — Mary K Gaillard)

- NA62 @ ICHEP: $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (11.0^{+4.0}_{-3.5}) \times 10^{-11}$ — at the SM level
- KOTO, 2019: 4 events in $K_L \rightarrow \pi^0 \nu \bar{\nu}$ search; @ ICHEP: $4 \rightarrow 3$ w/ $1.05 \pm 0.28$ BG
$CP$ violation in $B$ decays

$b$ quark ($\Upsilon$ resonance) discovered 1977
1981 plans: not mixing nor CPV

Fig. 3. A Program to Understand B Decay

1. Search for exotic B decays.
   If found, explore details;
   otherwise-

2. Search for flavor changing neutral currents.
   If found, measure \((b \rightarrow dZ^0)/(b \rightarrow sZ^0)\);
   otherwise-

3. Measure semileptonic decay branching ratio.
4. Measure ratio \((b \rightarrow uW^-)/(b \rightarrow cW^-)\).
5. Measure \(e\nu:\mu\nu:\tau\nu\) ratio in semileptonic decay.

⇒ dark sector searches? symmetry violations?

⇒ big part of the program

⇒ Prophecy of \(R(D^*)\)?
(Hardly ever discussed 1982 – 2012, as far as I know)

⇒ big part of the program

⇒ |\(V_{ub}/V_{cb}\)|: essential to constrain NP

⇒ Less important
⇒ Was the first on this list discovered
⇒ Became a central focus of the field
Past surprises exploring $b$ quark properties

- **1977:** $\Upsilon$ discovery — after 6 GeV “Oops-Leon” in 1976 [Lederman et al. @ Fermilab]

- **1983:** Long $B$ meson lifetime $\Rightarrow |V_{cb}|$ is small [MAC & Mark II @ SLAC]

  If $|V_{cb}|$ were as large as $|V_{us}|$, no time dependent measurements...

- **1987:** $B^0 - \bar{B}^0$ mixing discovered, ARGUS, PLB 192 (1987) 245

  \[ r = 0.21 \pm 0.08 = (\text{decay, after mixing})/(\text{decay, no mixing}) \]

  Few months earlier: CLEO, PRL 58 (1987) 183: $r < 0.24$ (90% CL)

  (Took 2 more years to confirm ARGUS — can be rather different to set limits vs. observe signals)

  Implied: $m_t > m_W$ (bound was 23 GeV) $\Rightarrow$ no top hadrons, maximal $B_s$ mixing

  $\Rightarrow$ SM predicts large $CP$ violation, and large FCNC $B$ decay rates

- **Also in 1987:** idea of asymmetric $e^+e^-$ $B$ factory [P. Oddone]
FEASIBILITY STUDY
for an
ASYMMETRIC B FACTORY
BASED ON PEP

October 1989

Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, California 94720

Stanford Linear Accelerator Center
Stanford University • Stanford, California 94305

California Institute of Technology
Pasadena, California 91125

1.2. APIARY: PEP plus a New 3.1-GeV Ring

We have conducted preliminary investigations of a design for a B factory to be sited at SLAC. The specific scenario we consider, APIARY (Asymmetric Particle Interactions Accelerator Research Yard), involves a high-luminosity, asymmetric, 9 GeV $\times$ 3.1 GeV electron-positron collider with a high-energy storage ring based on PEP and a newly constructed low-energy ring.

(APIARY is no more contrived than BaBar as an abbreviation)
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Questions, 1999: is SM qualitatively correct?

- Until 1999, $\epsilon$ was the only measured CPV; $\epsilon'/\epsilon \neq 0$ only established in 1999
- Not known if the SM picture of CPV even approx. correct; other sources of CPV?
  - CPV in $\Delta F = 2$ only (superweak)? Also in $\Delta F = 1$?
  - Are all CPV effects small? Or only small in kaons due to small mixing angles?
  - One or more CPV parameters?
  - CPV relates to charged currents only? Also in neutral currents?
  - Does CPV treat 3rd generation special? Up / down sectors?
  - CPV in flavor changing interactions only? EDM searches?
  - CPV only in quark sector? Also in lepton sector?
  - Find new sources of CPV that could help with baryogenesis?
Questions, now: solutions to flavor puzzles?

- **Flavor** ≡ what distinguishes generations? [break $U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_L \times U(3)_e$]
  Experimentally, rich and sensitive ways to probe SM, and search for NP

- **SM flavor**: masses? mixing angles? 3 generations? — most of the SM param’s
  Flavor in SM is simple: only Higgs–fermion couplings break flavor symmetries

- **BSM flavor**: TeV scale (hierarchy problem) $\ll$ “naive” flavor & $CP$ viol. scale
  Most TeV-scale new physics contain new sources of $CP$ and flavor violation
  E.g., SUSY: $\sim 10 \times$ increase in flavor parameters ($CP$ and flavor problems?)
  Generic TeV-scale flavor structure excluded $\Rightarrow$ new mechanisms to reduce signals

- Many BSM models have observable signals, baryogenesis remains a puzzle

- Any new particle that couples to quarks or leptons $\Rightarrow$ new flavor parameters
  (Understanding these param’s can be crucial; e.g., Higgs, or squark & slepton couplings [if exists])
\( B \) physics: key ingredients

- Many interesting processes with clean theoretical interpretations:
  - Top quark loops not strongly suppressed (GIM less effective)
  - Large \( CP \) violating effects possible, some with clean interpretation
  - Some of the hadronic physics understood model independently \((m_b \gg \Lambda_{QCD})\)

- Experimentally feasible to study:
  - \( \Upsilon(4S) \) resonance is clean source of \( B \) mesons
  - Long \( B \) meson lifetime
    (If \(|V_{cb}| \) were as large as \(|V_{us}|\), no \( B \) factories built, this talk would not take place, etc.)
  - Timescale of oscillation and decay comparable: \( \Delta m/\Gamma \simeq 0.77 \) (and \( \Delta \Gamma \ll \Gamma \))

- Time-dependent measurements: asymmetric \( e^+e^- \) colliders (essential before LHC)
$CP$ violation
CPV in interference between decay and mixing

- Can get theoretically clean information in some cases when $B^0$ and $\bar{B}^0$ decay to same final state

Mass eigenstates: $|B_{H,L}\rangle = p|B^0\rangle \mp q|\bar{B}^0\rangle$

- Time-dependent $CP$ asymmetry:

\[
a_{fCP} = \frac{\Gamma[\bar{B}^0(t) \to f_{CP}] - \Gamma[B^0(t) \to f_{CP}]}{\Gamma[\bar{B}^0(t) \to f_{CP}] + \Gamma[B^0(t) \to f_{CP}]}
\]

- If amplitudes with one weak phase dominate, hadronic physics drops out:

\[
a_{fCP} = (\pm 1) \sin(\text{phase difference between decay paths}) \sin(\Delta m t) \ arg[(q/p)(\bar{A}/A)]
\]

- Measure phases in the Lagrangian with small theoretical uncertainties
Quantum entanglement — use EPR

- $B^0\bar{B}^0$ pair created in a $p$-wave ($L = 1$) evolve coherently and undergo oscillations.

Two identical bosons must be in a symmetric state — if one decays as a $B^0$ ($\bar{B}^0$), then at the same time the other $B$ must be $\bar{B}^0$ ($B^0$).

- EPR effect used for precision physics:

  Coherent $B^0\bar{B}^0$ production:

  Measure $B$ decays and $\Delta z$.

  First decay ends quantum correlation and determines flavor of other $B$ at $t = t_1$.

$ZL$ — p. 20
Hadron colliders — no quantum correlation

- $B^0_s$ with sufficient boost to study CPV at Tevatron & LHC (+ Belle data on rates)

- $gg, q\bar{q} \rightarrow b\bar{b}$: measure flavor of a $b$ hadron, and flavor of $B^0_s$ as a function of time

Need excellent time resolution, and fully reconstructed $B^0_s$ to know its boost
**CP violation in B \( \rightarrow \psi K_{S} \) by the naked eye**

- **CP violation is an \( O(1) \) effect:** \( \sin 2\beta = 0.699 \pm 0.017 \)

\[
\Gamma[B^0(t) \rightarrow \psi K] - \Gamma[B^0(t) \rightarrow \psi K] = \sin 2\beta \sin(\Delta m t)
\]

- **CP violation in K decays is small because of small CKM elements, not because CP violation is generically small — it is \( O(1) \) in some B decays**

---

\( ZL - p. 22 \)
\[
\sin(2\beta_{\text{eff}}) \equiv \sin(2\phi_{1\text{ff}})
\]

- In the SM, very close to \(S_{\psi K}\) — earlier hints of tensions gone, e.g., in \(S_{\phi K}, S_{\eta'K}\)

\[
\sin(2\beta_{\text{eff}}) \equiv \sin(2\phi_{1\text{ff}}) \quad \text{vs} \quad C_{\text{CP}} \equiv -A_{\text{CP}}
\]

Contours give \(-2(\ln L) = \Delta \chi^2 = 1\), corresponding to 39.3% CL for 2 dof

- Interesting to significantly reduce current experimental uncertainties

\[
\begin{array}{|c|c|}
\hline
-b\rightarrow c\bar{c}s & \text{World Average} \\
\hline
\phi_{K^0} & 0.70 \pm 0.02 \\
\hline
B\bar{A}\tilde{B}\bar{A} & 0.66 \pm 0.17 \pm 0.07 \\
Belle & 0.90 \pm 0.09 \pm 0.19 \\
Average & 0.74 \pm 0.11 \\
\hline
\eta'K^0 & 0.57 \pm 0.08 \pm 0.02 \\
Belle & 0.68 \pm 0.07 \pm 0.03 \\
Average & 0.63 \pm 0.06 \\
\hline
K^0S_{K^0S} & 0.30 \pm 0.32 \pm 0.08 \\
Belle & 0.72 \pm 0.19 \\
Average & 0.67 \pm 0.31 \pm 0.08 \\
\hline
\rho^0K^0 & 0.55 \pm 0.20 \pm 0.02 \\
Belle & 0.67 \pm 0.06 \pm 0.03 \\
Average & 0.57 \pm 0.17 \\
\hline
\omega K^0 & 0.36 \pm 0.31 \pm 0.06 \\
Belle & 0.64 \pm 0.28 \pm 0.09 \pm 0.10 \\
Average & 0.54 \pm 0.18 \\
\hline
f_0^0K^0 & 0.91 \pm 0.32 \pm 0.05 \\
Belle & 0.71 \pm 0.21 \\
Average & 0.94 \pm 0.21 \\
\hline
\kappa K^0 & 0.32 \pm 0.21 \pm 0.09 \\
Belle & 0.69 \pm 0.19 \\
Average & 0.69 \pm 0.19 \\
\hline
\end{array}
\]
$CP$ violation
Testing quark flavor (take I)

- The $(u, c, t) W^\pm (d, s, b)$ couplings:

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

**CKM matrix**

Only 4 parameters: $\lambda$ (“Cabibbo angle”, from $K \to \pi \ell \nu$), $A$ (from $b \to c \ell \nu$)

used to be less precise: $\bar{\rho}$ and $\bar{\eta}$ (only source of $CP$ violation)

**CKM measurements**: magnitudes $\sim$ decay rates, phases $\sim CP$ violation

9 complex observables $\Rightarrow$ many testable relations

- Many observables are $f(\rho, \eta)$ — want to compare:

  - $b \to u\ell\bar{\nu} \Rightarrow |V_{ub}/V_{cb}|^2 \propto \rho^2 + \eta^2$
  - $\Delta m_{B_d}/\Delta m_{B_s} \Rightarrow |V_{td}/V_{ts}|^2 \propto (1 - \rho)^2 + \eta^2$
  - $CP$ violation in $K$, $B$, $B_s$ decay

$ZL$ – p. 24
The $B$-factories money plot

- Spectacular progress in last 20 years
- The CKM mechanism dominates $CP$ violation & flavor changing processes
- The implications of the consistency of measurements are often overstated
- Larger allowed region if there is NP
The $B$-factories money plot

- Spectacular progress in last 20 years
- The CKM mechanism dominates $CP$ violation & flavor changing processes
- The implications of the consistency of measurements are often overstated
- Larger allowed region if there is NP
- Compare tree-level (lower plot) and loop-dominated measurements
- LHCb: constraints in the $B_s$ sector (2nd–3rd gen.) caught up with $B_d$
- $O(20\%)$ NP contributions to most loop-level processes (FCNC) are still allowed

$ZL - p. 25$
Testing quark flavor (take II)

- Assume that NP is negligible in tree-level processes, arbitrary in FCNCs (loops)
- Consider tree-level + meson mixing:

General parametrization of many models by two real parameters (in addition to SM):

$$ h e^{2i\sigma} = A_{NP}(B^0 \rightarrow \bar{B}^0)/A_{SM}(B^0 \rightarrow \bar{B}^0) $$

NP parameters

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

- Is $h = O(1)$ allowed? If not, the CKM mechanism dominates

To answer, redo CKM fit: tree-dominated unchanged, loop-mediated modified

(Importance of these constraints known since the 1970s, conservative picture of future progress)
Future sensitivity to NP in $B$ mixing

- What NP parameter space can be probed?
- $h_{d,s} \Leftrightarrow$ NP scale: $h \sim \frac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \left( \frac{4.5 \text{ TeV}}{\Lambda} \right)^2$ [2006.04824]

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<tbody>
<tr>
<td>$</td>
<td>C_{ij}</td>
<td>=</td>
<td>V_{ti}^* V_{tj}</td>
<td>$ (CKM-like)</td>
</tr>
<tr>
<td>$</td>
<td>C_{ij}</td>
<td>= 1$ (no hierarchy)</td>
<td>tree level one loop</td>
<td>$1 \times 10^3$</td>
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Big improvements in 2020s
Complementary to high-$p_T$ searches
Then theory improves or progress slows

$ZL - p. 27$
Future

Huge increases in data sets

Does not matter if $CP$ violating or conserving — only sensitivity to NP
### LHCb — LHC at CERN

<table>
<thead>
<tr>
<th></th>
<th>LHC era</th>
<th>HL-LHC era</th>
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<tbody>
<tr>
<td>ATLAS, CMS</td>
<td>25 fb⁻¹</td>
<td>150 fb⁻¹</td>
</tr>
<tr>
<td>LHCb</td>
<td>3 fb⁻¹</td>
<td>9 fb⁻¹</td>
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* assumes a future LHCb upgrade to raise the instantaneous luminosity to $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

- Major LHCb upgrade in LS2 (raise instantaneous luminosity to $2 \times 10^{33} / \text{ cm}^2/\text{s}$)
  Major ATLAS and CMS upgrades come in LS3 for HL-LHC

- LHCb, 2017, Expression of Interest for an upgrade in LS4 to $2 \times 10^{34} / \text{ cm}^2/\text{s}$
Belle II — SuperKEKB in Japan

- First collisions 2018 (unfinished detector), with full detector starting spring 2019
- Goal: $50 \times$ the Belle and nearly $100 \times$ the $B_{ABAR}$ data set
- Discussions started about physics case and feasibility of a factor $\sim 5$ upgrade, similar to LHCb Phase-II upgrade aiming $50/fb \rightarrow 300/fb$, after LHC LS4
New accelerator, novel concepts & techniques to achieve $10^{36}$ luminosity

2/13/2017: LER superconducting final focusing magnet installed
$D - \bar{D}$ mixing and $CP$ violation

- **$CP$ violation in $D$ decays:**
  
  LHCb, Nov. 2011: $\Delta A_{CP} \equiv A_{K^+K^-} - A_{\pi^+\pi^-} = -(8.2 \pm 2.4) \times 10^{-3}$
  
  LHCb, Mar. 2019: $\Delta A_{CP} = -(1.82 \pm 0.33) \times 10^{-3}$ (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
  
  Connections to FCNC top decays

- Value of $\Delta m$? Not even 3$\sigma$ yet

- SM allowed range of $|q/p| - 1$?

- SUSY: interplay of $D$ & $K$ bounds: alignment, universality, heavy squarks?
The current $B$ “anomalies”

- Lepton non-universality would be clear evidence for NP

1) $R_K$ and $R_{K^*}$: 
\[
\frac{B \to X\mu^+\mu^-}{B \to Xe^+e^-} \sim 20\% \text{ correction to SM loop}
\]

2) $R(D)$ and $R(D^*)$: 
\[
\frac{B \to X\tau\bar{\nu}}{B \to X(e,\mu)\bar{\nu}} \sim 20\% \text{ correction to SM tree}
\]

Scales: $R_{K(*)} \lesssim \text{few} \times 10^1 \text{ TeV}$, $R(D^{(*)}) \lesssim \text{few} \times 10^0 \text{ TeV}$ Would bound NP scale!

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

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

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

Attention to many BSM scenarios previously less explored

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

ZL – p. 31
\( R_K \) and \( R_{K^*} \): theoretically cleanest

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

[Tomorrow: https://indico.cern.ch/event/976688/]

- Combined fits only by theorists (some include \( P_5' \) and/or \( B_s \to \phi\mu^+\mu^- \))
- Modifying one Wilson coefficient in \( \mathcal{H}_{\text{eff}} \) gives good fit: \( \delta C_{9,\mu} \sim -1 \) (NP or QCD?)
The $B \to D^{(*)}\tau\bar{\nu}$ decay rates

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

  $3.1\sigma$ 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, $\tau$ polarization = SM

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

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

- Models built to fit these anomalies have impacted many ATLAS & CMS searches
Exciting future

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

![Graph showing measurements over time]

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

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

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

Measurements will improve a lot!

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

- Competition, complementarity, cross-checks between LHCb and Belle II.
Some key measurements, done much better

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

\( A_{SL} \): important, indep. of DØ anomaly

Measurements of \( \gamma \) crucial, LHCb is now most precise

- Breadth crucial, often have to combine many measurements and theory
  (“The interesting messages are not simple, the simple messages are not interesting”)

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

\[ ZL - p. 35 \]
$B \rightarrow \mu^+\mu^-$: interesting well beyond HL-LHC

- $B_d \rightarrow \mu^+\mu^-$ in SM, $10^{-10}$: LHCb expects $10\%$ (300/fb), CMS expects $15\%$ (3/ab)

SM uncertainty $\sim (2\%) \oplus f_{B_q}^2 \oplus$ CKM [Bobeth, FPCP’15] and may be further reduced

- Theoretically cleanest $|V_{ub}|$ I know, use 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/ $K \rightarrow \pi\nu\bar{\nu}$
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)
  - $A_{SL}^{d,s}$ — can it keep scaling with statistics?
  - Lepton flavor violation & lepton universality violation searches
  - Possibly $CP$ violation in $D$ mixing (firm up theory)

- Very broad program

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

- Sensitivity to NP would improve with data $\gg$ LHCb & Belle II (nb: Belle II / ARGUS $\sim 10^5$)
Many “exotic” searches

• Better tests of (exact or approximate) conservation laws

• Exhaustive list of dark / hidden sector searches

• LFV meson decays, e.g., $M^0 \rightarrow \mu^− e^+$, $B^+ \rightarrow h^+ \mu^− e^+$, etc.

• Invisible modes, even baryonic, $B \rightarrow N + \text{invis.} \ [\pm \text{mesons}]$ [1907.10612, 1810.00880, 1708.01259]

• Hidden valley inspired scenarios, e.g., multiple displaced vertices, even with $\ell^+ \ell^−$

• Exotic Higgs decays, e.g., high multiplicity, displaced vertices ($H \rightarrow XX \rightarrow abab$)

• Search for “quirks” (non-straight “tracks”) at LHCb using many velo layers

• I do not know how many $CP$ violating quantities have been measured... neither how many new hadronic states discovered by $BABAR$, Belle, LHCb ...
Theory challenges / opportunities

- 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, and for $\sin 2\beta_{(s)}$ itself
  - 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?
  - 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?
Some conclusions

- Flavor physics probes scales $\gg 1\ TeV$; sensitivity limited by statistics, not theory
  $\Rightarrow$ New physics could show up any time measurements improve

- In FCNCs, $\text{NP}/\text{SM} \gtrsim 20\%$ still allowed; any discovery $\Rightarrow$ upper bound on NP scale

- Precision tests of SM will improve in the next decade by $10 - 10^4$

- Few tensions with SM; some of these (or others) could soon become decisive

- Discovering lepton universality violation would focus even more attention on LFV

- Many interesting theoretical questions relevant for optimal experimental sensitivity

- Flavor measurements will tell us a lot, whether NP is discovered or not:

<table>
<thead>
<tr>
<th>Evidence for BSM?</th>
<th>FLAVOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

ZL – p. 40
STOP

Extra slides
Direct CPV is also $\mathcal{O}(1)$

- Have we seen new physics in CPV?
  
  \[ A_{K^+\pi^-} = -0.084 \pm 0.004 \quad (P+T) \]
  
  \[ A_{K^+\pi^0} = 0.040 \pm 0.021 \quad (P+T+C+A+P_{ew}) \]

- Large difference — small SM sources?
  
  \[ A_{K^+\pi^0} - A_{K^+\pi^-} = 0.124 \pm 0.022 \]

SCET / factorization $\Rightarrow$ $\arg \left( \frac{C}{T} \right) = \mathcal{O}(\Lambda_{QCD}/m_b)$ and $A + P_{ew}$ small

- Large fluctuations? Breakdown of $1/m$ exp.? Missing something subtle? BSM?

- Can we understand theory well enough, to possibly disprove SM?

- Even larger $A_{CP}(B_s \to \pi^+K^-) = 0.213 \pm 0.017$ understood in terms of $SU(3)$
  
  [Grossman, ZL, Robinson, 1308.4143]
$CP$ violation everywhere: three-body decays

Left: $B^\pm \rightarrow \pi^\pm K^+ K^-$ yields

Right: $B^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ $CP$ asymmetry

[CP violation everywhere: three-body decays

background subtracted and acceptance corrected asymmetries

[LHCb, arXiv:1408.5373]

[CERN Courier, 2019]
Anticipated increases in sensitivity

- Scales of dim-6 operators probed — various mechanisms devised to let TeV-scale NP obey these bounds (Pattern and orders of magnitudes matter more than precise values)

- $\mu N \rightarrow eN$ may be the largest increase in mass-scale sensitivity in next 10–15 yrs

Electric dipole moments

- **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 (\( \text{TeV-scale, no small param's} \)) above current bounds; if \( m_{\text{SUSY}} \sim \mathcal{O}(10 \, \text{TeV}) \), may still discover EDMs

- **Expected \( 10^2 - 10^3 \) improvements:** complementary to LHC
  Discovery would give (rough) upper bound on NP scale
Example of discovery potential

- Discovery significance at Phase I (left) and Phase II (right), if central values (CKM param's, $h_{d,s}$, and $\sigma_{d,s}$) remain as in the current fit (on p.12)

  (Assume future measurements have the corresponding central values, with uncertainties as in the Table on p.11)

- If new physics contributes to semileptonic decays, as hinted at by the $R(D^{(*)})$ anomaly, then things get more complicated, may still isolate sources (see paper)

  ZL – p. iv
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:
  new physics mass scale:
  – Minimally flavor violating (mimic the SM)
  – Related but not identical to the SM
  – Unrelated to the SM, or even completely anarchic
  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 (\( B_s \rightarrow \ell^+\ell^-, \mu \rightarrow e\gamma \))

ZL – p. v
Known for decades: $K^0 - \bar{K}^0$ mixing and BSM

- E.g.: \[
\frac{\left(\Delta m_K\right)^{\text{SUSY}}}{\left(\Delta m_K\right)^{\text{exp}}} \sim 10^4 \left(\frac{1 \text{ TeV}}{\tilde{m}}\right)^2 \left(\frac{\Delta \tilde{m}_{12}^2}{\tilde{m}^2}\right)^2 \Re\left[(K^d_L)_{12}(K^d_R)_{12}\right]
\]
  \hspace{1cm} (oversimplified)

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

- Constraint from $\epsilon_K$: replace $10^4 \Re\left[(K^d_L)_{12}(K^d_R)_{12}\right]$ with $\sim 10^6 \Im\left[(K^d_L)_{12}(K^d_R)_{12}\right]$
  \hspace{1cm} (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: $\tilde{m} \gg 1 \text{ TeV}$ (e.g., split SUSY)
  - (ii) Universality: $\Delta m^2_{\tilde{Q}, \tilde{D}} \ll \tilde{m}^2$ (e.g., gauge mediation)
  - (iii) Alignment: $\left|(K^d_{L,R})_{12}\right| \ll 1$ (e.g., horizontal symmetry)

- All viable BSM models incorporate some of the above — known since the ’70s
The MSSM parameters and flavor

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

- **Soft SUSY breaking terms:**
  \[
  \mathcal{L}_{\text{soft}} = - \left( A^u_{ij} H_u \tilde{Q}_i \tilde{U}_j + A^d_{ij} H_d \tilde{Q}_i \tilde{D}_j + A^\ell_{ij} H_d \tilde{L}_i \tilde{E}_j + BH_u H_d \right)
  \]

  \[
  - \sum_{\text{scalars}} (m^2_S)_{ij} S_i S_j - \frac{1}{2} \left( M_1 \tilde{B} \tilde{B} + M_2 \tilde{W} \tilde{W} + M_3 \tilde{g} \tilde{g} \right)
  \]

  - **3 $Y^f$ Yukawa and 3 $A^f$ matrices** — 6×(9 real + 9 imaginary) parameters
  - **5 $m^2_S$ 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)
CMS “B – parking” in 2018

- Collected $10^{10}$ $B$-s; hope to compete w/ LHCb on $R_{K(*)}$ anomaly

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

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

Now studying processing strategy

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

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