CURRENT ISSUES IN FLAVOR PHYSICS

Flavor highlights as of May 2023

Avital Dery
Overview

Highlights* in flavor physics

B physics
- The B anomalies
  \[ |V_{cb}|, |V_{ub}| \]
- Puzzles in \( B_s \rightarrow KK \)

Charm physics
- Charm CPV

Kaon physics
- \( K \rightarrow \pi\nu\nu \)
- \( K \rightarrow \mu\mu \)

* my personal favorites!
The vast, unprecedented production statistics of hadrons in the current era allow us to peer into the extremely rare and achieve extreme precision.

“Make sure you can see how insignificant I am.”
Flavor physics sensitivity

Sensitive to high scales of generic NP - SM rates often suppressed by GIM, CKM, etc.

Flavor physics pushes the limits of the SM - subjecting it to meticulous scrutiny.

Naturally related to BIG questions - flavor puzzles, neutrino masses and the baryon asymmetry of the universe.
Several hints of Lepton Flavor Universality (LFU) violation appeared since 2012 in semileptonic B decays

- **Charged current**, $b \to c \ell \nu$

\[
R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}
\]

- **Neutral current**, $b \to s \ell \ell$

\[
R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}
\]

What is the current status?
**B physics: The B anomalies**

Charged current, $b \to c \ell \nu$

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau \nu)}{\mathcal{B}(B \to D^{(*)}\ell \nu)}$$

First results in 2012 from the B factories - BaBar, then Belle (exp. clean, low stats)
Today LHCb is strong in the game (high bkg, high stats)

Average has gotten closer to SM, but uncertainty has shrunk accordingly -
Still $\sim 3\sigma$ tension with SM for world average.

Individual measurements taken alone do not exhibit severe tension.

SOON:
Belle II enters the picture. Uncertainties expected under 10%
B physics: The B anomalies

Charged current, \( b \to c \ell \nu \)

\[
R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}
\]

If the tension persists, this will strengthen the case for New Physics, naively pointing to TeV scales contributing at tree-level.

Many relevant direct searches are being carried out by ATLAS & CMS.
**B physics:** The B anomalies

Neutral current, $b \to s \ell \ell$

$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \to K^{(*)} e^+ e^-)}$$

LHCb results from December 2022 improve Bkg estimation previously underestimated (misidentification of $\pi$ & $K$ as $e$).

Latest results are consistent with SM for both $R(K)$, $R(K^*)$. 

$LHCb$ results from December 2022 improve Bkg estimation previously underestimated (misidentification of $\pi$ & $K$ as $e$).

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Latest results are consistent with SM for both $R(K)$, $R(K^*)$.
**B physics: The B anomalies**

- LFU ratios with other final state hadrons (partial list):
  
  **Charged current**
  
  \[
  \begin{align*}
  R(J/\psi) & \quad \text{measured} \\
  R(\Lambda_c) & \\
  R(D_s) & \\
  R(D^{**}) & \\
  \text{Inclusive } R(X) & \quad (\text{Belle II}) \\
  R(\pi) & 
  \end{align*}
  \]

  **Neutral current**
  
  \[
  \begin{align*}
  R(pK) & \quad \text{measured} \\
  R(K_s) & \\
  R(K^{*+}) & \\
  R(\phi) & \\
  R(K\pi\pi) & \\
  R(\Lambda) & 
  \end{align*}
  \]

- Belle II - potential to better understand feed down from $D^{**}$ (e.g., $D^{**}\mu\nu$ can mimic $D^*(\tau \to \mu\nu\nu)$)

- Important Lattice QCD progress

- ATLAS & CMS also working towards semileptonic B decay measurements
B physics: The B anomalies - Looking forward:

Clearly precision observables such as LFU ratios are interesting.
Still room for $\mathcal{O}(10\%)$ deviations even in the neutral current.

Difficult Bkg estimations are being better understood.
Many more measurements in various channels to appear.
B physics: \(|V_{cb}|, |V_{ub}|\)

\(|V_{ub}|, |V_{cb}|\) also determined from semileptonic B decays.

Large tension between inclusive and exclusive measurements.
Enters into many SM predictions as large parametric uncertainties (e.g., \(\epsilon_K \propto |V_{cb}|^4\)).

Can also extract from loop observables (meson mixing and rare decays)

\[\text{Belle II expected to improve on both inclusive and exclusive measurements of}\]
\(|V_{cb}|\) and \(|V_{ub}|\)
### B physics: Puzzles in $B_s \to KK$

Three puzzles identified related to $b \to d\bar{d}s$ transitions measured by LHCb and Belle

<table>
<thead>
<tr>
<th>#</th>
<th>Expression</th>
<th>Value</th>
<th>Deviation</th>
<th>Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>$R_{KK}^{sd} \equiv \left</td>
<td>\frac{V_{td}}{V_{ts}} \right</td>
<td>^2 \frac{\Gamma(B_s \to K^0\bar{K}^0)}{\Gamma(B^0 \to K^0\bar{K}^0)}$</td>
<td>$0.61 \pm 0.13$</td>
</tr>
<tr>
<td>#2</td>
<td>$R_{KK}^{ss} \equiv \frac{\Gamma(B_s \to K^0\bar{K}^0)}{\Gamma(B_s \to K^+K^-)}$</td>
<td>$0.66 \pm 0.13$</td>
<td>$\neq 1$</td>
<td>Approximate Isospin limit prediction</td>
</tr>
<tr>
<td>#3</td>
<td>$R_{KK}^{ss}/R_{\pi K}^{ud} \equiv \left( \frac{\Gamma(B_s \to K^0\bar{K}^0)}{\Gamma(B_s \to K^+K^-)} \right)/\left( \frac{\Gamma(B^+ \to \pi^+K^0)}{\Gamma(B^0 \to \pi^-K^+)} \right)$</td>
<td>$0.59 \pm 0.12$</td>
<td>$\neq 1$</td>
<td>SU(3)-flavor prediction</td>
</tr>
</tbody>
</table>

Each of these exhibits a $\sim 3\sigma$ deviation from the SM prediction.
B physics: Puzzles in $B_s \to KK$

Three puzzles identified related to $b \to d\bar{d}s$ transitions measured by LHCb and Belle

\[ \#1 \quad R_{KK}^{sd} \equiv \left| \frac{V_{td}}{V_{ts}} \right|^2 \frac{\Gamma(B_s \to K^0\bar{K}^0)}{\Gamma(B^0 \to K^0\bar{K}^0)} = 0.61 \pm 0.13 \neq 1 \quad \text{U-spin limit prediction} \]

\[ \#2 \quad R_{KK}^{ss} \equiv \frac{\Gamma(B_s \to K^0\bar{K}^0)}{\Gamma(B_s \to K^+K^-)} = 0.66 \pm 0.13 \neq 1 \quad \text{Approximate Isospin limit prediction} \]

\[ \#3 \quad \frac{R_{KK}^{ss}}{R_{KK}^{ud}} \equiv \frac{\Gamma(B_s \to K^0\bar{K}^0)}{\Gamma(B_s \to K^+K^-)} / \frac{\Gamma(B^+ \to \pi^+K^0)}{\Gamma(B^0 \to \pi^-K^+)} = 0.59 \pm 0.12 \neq 1 \quad \text{SU(3)-flavor prediction} \]

Possible SM effects such as rescattering, SU(3) breaking etc. cannot account for all three combined.

If the real value of $\mathcal{B}(B_s \to K^0\bar{K}^0)$ turns out to be $3\sigma$ above the current average measured value, that would solve all three puzzles. Stay tuned!
Moving on to a second arena: Kaon physics
Kaon physics: A crucial and unique test of the SM

The flavor program has managed to measure the parameters of the CKM matrix in many independent ways, creating a remarkably consistent picture.

However, almost all of these cross-checks arise from B physics.

What is the corresponding picture from K physics?
Kaon physics: A crucial and unique test of the SM

still many values of both $\tilde{\eta}$ and $\tilde{\rho}$ consistent with measurement
Kaon physics: A crucial and unique test of the SM

**Kaon physics picture:**

- $K^+ \to \pi^+ \bar{\nu}\nu$ Evidence by NA62
- $K_L \to \pi^0 \bar{\nu}\nu$ KOTO

Recent progress - a *third kaon golden mode*

- $K(t) \to \mu^+ \mu^-$

[AD Ghosh Grossman Schacht 2104.06427]

- Same SM CKM dependence as $K_L \to \pi^0 \bar{\nu}\nu$
- Different dependence on effective NP operators

[AD Ghosh 2112.05801]

* see backup slide for details!
Kaon physics: A crucial and unique test of the SM

Kaon physics FUTURE PROSPECTS

• NA62 to reach $\sim 5\%$ precision on $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$

• KOTO collaboration continued efforts to observe the elusive $K_L \to \pi^0\nu\bar{\nu}$

• Next generation kaon program at CERN currently being developed.

• Recent theory and lattice QCD progress
Charm physics: CPV in charm

Charm physics is challenging.

• Strong GIM suppression $\Rightarrow$ rare decays are much rarer compared to B physics

• No small parameter to expand in $\Rightarrow$ calculations are harder, difficult to interpret measurements
Charm physics: CPV in charm

- Discovery of CPV in Kaons: 1964
- Discovery of CPV in B mesons: 2001
- Discovery of CPV in Charm mesons: 2019

\[
\Delta A_{CP} \equiv A_{CP}(D^0 \rightarrow K^+K^-) - A_{CP}(D^0 \rightarrow \pi^+\pi^-)
\]

\[
= (-1.54 \pm 0.29) \times 10^{-3}
\]

\[
A_{CP}(D^0 \rightarrow K^+K^-) = (6.8 \pm 5.4 \pm 1.6) \times 10^{-4}
\]

LHCb 2019

\[
a^d_{K^+K^-} = (7.7 \pm 5.7) \times 10^{-4}
\]

\[
a^d_{\pi^+\pi^-} = (23.2 \pm 6.1) \times 10^{-4}
\]

First evidence for CPV in a single mode, 3.8σ

LHCb Sep 2022

Avital Dery

LHCP 2023, Belgrade
Charm physics: CPV in charm

Both results are somewhat surprising -

1) \[ \Delta A_{CP} = (-1.54 \pm 0.29) \times 10^{-3} \] \[ \text{LHCb 2019} \]

=> requires large rescattering or NP

2) \[ a_{K^+K^-}^d = (7.7 \pm 5.7) \times 10^{-4} \]
\[ a_{\pi^+\pi^-}^d = (23.2 \pm 6.1) \times 10^{-4} \] \[ \text{LHCb 2019 +. LHCb 2022} \]

Implies U-spin breaking of \( (173^{+85}_{-74}) \% \) compared to the expectation of \( \mathcal{O}(30\%) \).

More statistics are needed to see if this behavior persists.
Charm physics: CPV in charm

FUTURE PROSPECTS

• More charm CPV measurements are coming in

  e.g., local CPV in $D_{(s)}^{+} \rightarrow K^{-}K^{+}K^{+}$   LHCb March 2023

• In the future, can expect more to appear (partial list)

<table>
<thead>
<tr>
<th>LHCb</th>
<th>Belle II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{CP}(D^{0} \rightarrow K_{S}^{0}K_{S}^{0})$</td>
<td>$D^{+} \rightarrow K^{-}K^{+}\pi^{+}$</td>
</tr>
<tr>
<td>$A_{CP}(D^{0} \rightarrow K_{S}^{0}K^{*0})$</td>
<td>$D^{+} \rightarrow \pi^{-}\pi^{+}\pi^{+}$</td>
</tr>
<tr>
<td>$A_{CP}(D_{s}^{+} \rightarrow K_{S}^{0}\pi^{+})$</td>
<td>$D^{+} \rightarrow \pi^{-}K^{+}\pi^{+}$</td>
</tr>
<tr>
<td>$A_{CP}(D^{+} \rightarrow K_{S}^{0}K^{+})$</td>
<td>$D^{0} \rightarrow \pi^{-}\pi^{+}\pi^{-}\pi^{+}$</td>
</tr>
<tr>
<td>$A_{CP}(D^{+} \rightarrow \phi\pi^{+})$</td>
<td>$D^{0} \rightarrow K^{-}K^{+}\pi^{-}\pi^{+}$</td>
</tr>
<tr>
<td>$A_{CP}(D_{(s)}^{+} \rightarrow \eta^{'}\pi^{+})$</td>
<td>These can then be used together to test sum rules</td>
</tr>
</tbody>
</table>

[Grossman Robinson 1211.3361]  
[Müller Nierste Schacht 1506.04121]
Summary

B physics - Many measurements expected to provide a more comprehensive picture. In particular, Belle II, ATLAS, CMS, will supply additional independent takes.

Kaon physics - A unique and crucial SM test. Recent progress on $K \rightarrow \mu\mu$ introduces promising directions.

Charm physics - Intriguing first charm CPV measurements at LHCb. Many relevant future results.

Interplay of th. and exp. efforts on all fronts -

=> Tests of the SM  => Look for New Physics leads
=> A playground to test understanding of non-perturbative physics

=> STAY TUNED!
Thank you for your attention!

ChatGPT poetry
(Full version in backup)

In the realm of particles, small and unseen,
Lies a captivating dance, a cosmic machine.
Flavor physics, the science so grand,
Unveiling the secrets of particles and their brand.

Oh, flavors of quarks, diverse and distinct,
Up, down, charm, strange, beauty, and truth linked.
Intricate symphony, a subatomic ballet,
Where flavors entwine in a mysterious array.

In the tapestry of particles, flavor's embrace,
Lies the gateway to knowledge, a cosmic chase.
Flavor physics, a voyage with no end,
Unveiling the universe, its mysteries to comprehend.

So let us delve deeper into this enigmatic terrain,
Where particles twirl, their secrets to attain.
With each discovery, a step closer we stride,
Flavor physics, our intellectual guide.
BACKUP
**B physics: The B anomalies**

**Charged current, $b \to c\ell\nu$**

$$R(D^*) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

### $R(D)$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
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<tbody>
<tr>
<td>BaBar 2012, had. tag</td>
<td>$0.332 \pm 0.024 \pm 0.018$</td>
</tr>
<tr>
<td>Belle 2015, had. tag</td>
<td>$0.293 \pm 0.058 \pm 0.015$</td>
</tr>
<tr>
<td>Belle 2017, (hadronic tau)</td>
<td>$0.270 \pm 0.035 \pm 0.027$</td>
</tr>
<tr>
<td>LHCb 2023, (hadronic tau)</td>
<td>$0.257 \pm 0.012 \pm 0.018$</td>
</tr>
<tr>
<td>Belle 2019, sl.tag</td>
<td>$0.283 \pm 0.018 \pm 0.014$</td>
</tr>
<tr>
<td>LHCb 2022</td>
<td>$0.281 \pm 0.018 \pm 0.024$</td>
</tr>
<tr>
<td>Average</td>
<td>$0.284 \pm 0.013$</td>
</tr>
<tr>
<td>SM Average</td>
<td>$0.254 \pm 0.005$</td>
</tr>
<tr>
<td>PRD 95 (2017) 115008</td>
<td>$0.257 \pm 0.003$</td>
</tr>
<tr>
<td>JHEP 1712 (2017) 060</td>
<td>$0.257 \pm 0.005$</td>
</tr>
<tr>
<td>PLB 795 (2019) 386</td>
<td>$0.254 \pm 0.007$</td>
</tr>
<tr>
<td>PRL 123 (2019) 9,091801</td>
<td>$0.253 \pm 0.005$</td>
</tr>
<tr>
<td>EPIC 80 (2020) 2, 74</td>
<td>$0.247 \pm 0.006$</td>
</tr>
<tr>
<td>EPIC 82(2022) 12,1141</td>
<td>$0.265 \pm 0.013$</td>
</tr>
<tr>
<td>Average</td>
<td>$0.356 \pm 0.029$</td>
</tr>
<tr>
<td>SM Average</td>
<td>$0.298 \pm 0.004$</td>
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<td>PRD 105 (2022) 034503</td>
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<td>FNAL/MILC (2015)</td>
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<td>Belle 2015, had. tag</td>
<td>$0.026 \pm 0.064 \pm 0.375$</td>
</tr>
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<td>Belle 2019, sl. tag</td>
<td>$0.016 \pm 0.037 \pm 0.307$</td>
</tr>
<tr>
<td>LHCb 2022</td>
<td>$0.066 \pm 0.060 \pm 0.441$</td>
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Avital Dery  
LHCP 2023, Belgrade
The Cabibbo anomaly

Measurements of the Cabibbo angle from pion, kaon and tau decays are inconsistent with the most precise determination, from super-allowed beta decays.

\[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(5) \]

\[ |V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 0.9970(18) \]

\( G_F \) at low energies is an important input for beta decay \( \Rightarrow \) NP explanations related to muon decay and EWPT

\[ \text{[Crivellin 2207.02507]} \]
Kaon physics: $K(t) \rightarrow \mu^+ \mu^-$

Third golden mode

$\mathcal{B}(K_L \rightarrow \mu^+ \mu^-)_{exp.} = (6.84 \pm 0.11) \cdot 10^{-9}$

$\mathcal{B}(K_S \rightarrow \mu^+ \mu^-)_{LHCb\ 2020} < 2.1 \cdot 10^{-10}$

Each of the integrated rates exhibits **large hadronic uncertainties** -

Hadronic uncertainty

$\mathcal{B}(K_L \rightarrow \mu^+ \mu^-)_{SM} = \left\{ \begin{array}{l}
(6.85 \pm 0.80 \pm 0.06) \times 10^{-9} \ (+) \\
(8.11 \pm 1.49 \pm 0.13) \times 10^{-9} \ (-)
\end{array} \right.$

Hadronic uncertainty

$\mathcal{B}(K_S \rightarrow \mu^+ \mu^-)_{SM} = (5.18 \pm 1.50 \pm 0.02) \times 10^{-12}$

$K_L - K_S$ interference in a measurement of the **time dependent rate** is **cleanly sensitive** to the CKM parameter $\tilde{\eta}$ with theory uncertainty of $O(1\%)$. 

[D’Ambrosio Kitahara 1707.06427]
[AD Ghosh Grossman Schacht 2104.06427]
[AD Ghosh 2112.05801]
[AD Ghosh Grossman Kitahara Schacht 2211.03804]
write a poem about flavor physics

In the realm of particles, small and unseen,
Lies a captivating dance, a cosmic machine.
Flavor physics, the science so grand,
Unveiling the secrets of particles and their brand.

Oh, flavors of quarks, diverse and distinct,
Up, down, charm, strange, beauty, and truth linked.
Intricate symphony, a subatomic ballet,
Where flavors entwine in a mysterious array.

Lepton flavors, electrons, muons, and more,
Leptons that oscillate, changing their chore.
Universality challenged, anomalies arise,
In the quest for new physics, our curious eyes.

Neutrinos, elusive messengers, ethereal and light,
Their flavors and masses, veiled from sight.
Hierarchy unknown, a puzzle profound,
Through oscillations, we seek answers unfound.

CP violation, a mystery profound and deep,
Matter and antimatter, an imbalance to peep.
In B meson decays, a subtle hint,
New physics whispers, waiting to imprint.

Anomalies arise, both alluring and bold,
Deviant paths, the standard model's threshold.
Do they herald new particles, realms yet unseen,
Or mere statistical quirks within the machine?

Flavor-changing neutral currents, a realm sublime,
Exquisite transitions, a tantalizing rhyme.
Rare decays whisper of physics anew,
Beyond the standard model, where insights accrue.

In the tapestry of particles, flavor's embrace,
Lies the gateway to knowledge, a cosmic chase.
Flavor physics, a voyage with no end,
Unveiling the universe, its mysteries to comprehend.

So let us delve deeper into this enigmatic terrain,
Where particles twirl, their secrets to attain.
With each discovery, a step closer we stride,
Flavor physics, our intellectual guide.

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