Heavy Flavor Physics

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Indirect observations of “new physics” have historically been the portal used to predict the existence of particles before experiments with sufficient energy to produce them have existed.

As a famous example, consider the β decay of the neutron: 1 GeV phenomenology reveals physics at 100 GeV.

QED&QCD conserve quark flavor making weak physics clearly visible.
Model-independent limits on new particles can be set using all quark-flavor-changing-current data.

The "C" are the Wilson coefficients and "O" are local operators of all possible Lorentz structure, e.g., (V-A)[qq']*V(ll'), (V+A)[qq']*S(ll'),...

In principle sensitive to any mass scale (limited only by experimental and theoretical precision).
Flavor Factories

BaBar

Belle

$e^+$  $e^-$
The Large Hadron Collider
The size of a BSM amplitude is inversely proportional to the BSM mass scale, so we want to focus on measuring processes where a small amplitude can cause a measurable effect (and also where we know the SM prediction).

The SM predicts the $B_s$ (bound s-b) decays into two muons once every $3.4B$ decays. BSM could significantly affect this decay rate.
How would BSM affect these decay rates? That depends on the BSM mass scale and what quark flavor-changing currents exist in the theory.

For example, this plot shows various SUSY predictions prior to LHC running.
After 30 years of searching for these decays, both LHCb and CMS crossed the 4σ significance threshold in Run 1 for the B_s decay.

Results from combined CMS & LHCb data obtain 6.2σ for the B_s decay and 3.0σ for the B_d decay.

There is some minor tension in the branching-fraction ratio, looking forward to Run 2 data.
$B_{d,s} \rightarrow \mu^+ \mu^-$

Rules out large regions of SUSY parameter space.

LHCb+CMS

Excluded

$\text{BF}(B_d \rightarrow \mu^+ \mu^-) \times 10^{9}$

$\text{BF}(B_s \rightarrow \mu^+ \mu^-) \times 10^{9}$

SM

arXiv:1107.0266
The mass scale probed depends on how BSM contributes. The highest mass scales are probed in diagrams that aren’t otherwise suppressed.

If BSM affects this process, it must also affect other processes. The game is to find all discrepancies (and agreement) with the SM, then solve the puzzle (i.e., figure out how to explain all the results in a single (new SM) model).
*b\rightarrow s* Penguins

*b→s* “penguin” decays are loop/CKM suppressed in the SM, which permits sizable BSM contributions; however, calculations require control of the hadronic effects.

The *b→sμμ* family of decays provide many sensitive observables (accessible via angular analysis) with which to test the Lorentz structure of the SM.
Many observables show consistency with the SM while probing $O(10 \text{ TeV})$.

A few do not, e.g. a $3.7\sigma$ discrepancy in a “less QCD dependent” observable.
In the SM only the Higgs boson has non-universal lepton couplings. This results in SM predictions of nearly unity for various decay-rate ratios.

\[ R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)} \approx 1 \pm \mathcal{O}(10^{-3}) \]

LHCb-PAPER-2014-024

\[ R_K = 0.745^{+0.090}_{-0.074} \text{(stat)} \pm 0.036 \text{(syst)} \]

If \( R_K \) discrepancy is due to BSM, then other similar ratios (e.g., involving \( \tau \)) should also show discrepancies.

Measurement of \( R_{D^*} \) by BaBar, Belle, and LHCb show a \( 3.7\sigma \) discrepancy with the SM prediction.

See talk by Hamilton in QLF

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Different methods of measuring the $b \rightarrow u$ coupling give inconsistent results. This “Vub puzzle” has persisted for a long time.

Possible solution: contribution from a RH current.

LHCb-PAPER-2015-013

LHCb (first ever) baryonic result removes the need for RH current.
Different methods of measuring the $b\to u$ coupling give inconsistent results. This “Vub puzzle” has persisted for a long time.

Possible solution: contribution from a RH current.

LHCb (first ever) baryonic result removes the need for RH current but the puzzle remains.
Etc

Too many amazing results to cover in this (or any) talk. We have definitely now reached the precision era in our knowledge of quark-flavor-changing couplings.

Overall, the agreement with the SM is ... frustrating.
Probing New Physics

Summary of the constraints on Wilson Coefficients from global fits of all flavor-changing data:

- \((V-A)[qq']*(V,A)(ll') < \sim \text{SM}\);
- \((V+A)[qq']*(V,A)(ll')\) roughly same as V-A;
- strong constraints on scalar, tensor, etc.

Overall the data are largely consistent with the SM and global fits place constraints on BSM particles of about 0.5-50 TeV (depending on model) ... however, global fits also show \(\sim 4\sigma\) discrepancy.

Main message: Strong constraints placed on BSM, but some intriguing anomalies remain. We need more data!

If these discrepancies are BSM and not QCD artifacts and fluctuations:

- it couples to leptonic V and/or A currents;
- it has non-universal leptonic couplings;
- it may couple to RH quark currents.

Potential candidates include O(1-10 TeV) Z’ or leptoquarks.

See talk by Altmannshofer in QLF
Hidden Sectors

$b\rightarrow s$ penguin decays are also an excellent lab to search “directly” for low-mass hidden-sector particles (e.g., anything that mixes with the Higgs sector).

Search for $B\rightarrow K^*X$, $X\rightarrow \mu\mu$ by scanning $m(\mu\mu)$ and allowing (not requiring) non-zero $\tau(\mu\mu)$. Strategy handles possible $qq$ resonance contributions in a simple manner (MW [1503.04767]). Use of novel “uniform BDT” (J.Stevens, MW [1305.7248]).

No evidence for a hidden-sector boson so model-independent limits are set.

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Very strong constraints placed on theories that invoke mixing with the Higgs sector.
A look to the future...

...Belle-II and the LHC runs 2 and 3.
LHCb has resumed taking data and expects to collect 5/ fb in Run 2, followed by about 15/fb in Run 3. The upgraded Belle-II experiment plans to collect 50/ ab by 2025.

Both experiments have gained vital experience with existing data so expect to improve beyond just statistical power.
LHCb Trigger

Run 2

40 MHz bunch crossing rate

L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures

- 450 kHz $h^\pm$
- 400 kHz $\mu/\mu$
- 150 kHz $e/\gamma$

Software High Level Trigger

- Partial event reconstruction, select displaced tracks/vertices and dimuons
- Buffer events to disk, perform online detector calibration and alignment
- Full offline-like event selection, mixture of inclusive and exclusive triggers
- 12.5 kHz Rate to storage

LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

- Full event reconstruction, inclusive and exclusive kinematic/geometric selections
- Run-by-run detector calibration
- Add offline precision particle identification and track quality information to selections
- 2-5 GB/s rate to storage

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Already analyzing online-reconstructed data: $\sigma(bb)$ @ 13 TeV!

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Dark Photons

Additional U(1)' gauge field may couple to SM particles via kinetic mixing with the photon. Huge effort worldwide to search for dark photons, with many planned near-future experiments. LHCb could “close the door” for 2m(e) < m(A') < 100 MeV in Run 3 using D* → DA'(ee).

Itten, Thaler, MW, Xue [in preparation].

Large production rates combined with triggerless readout & real-time calibration permits high-efficiency searches for light BSM particles with feeble interactions with SM particles!

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Summary

KEEP CALM AND COLLECT MORE DATA