Rare $B$ decays

- $b$ is heavy $\rightarrow$ many secondary products
- couples from QCD ($\mu_b \rightarrow QCD$) $\rightarrow$ better precision

Forbidden at tree level
- loops only
- branching fraction $\approx 10^{-6}$ or less

- Our goal is to find Physics Beyond the Standard Model
- $b$ decays only weakly $\rightarrow$ we look into $b \rightarrow s l^+ l^-$ transitions
  - Flavor Changing Neutral Current (FCNC)

- **Box diagram**

- **Penguin diagram**

Possible contribution from NP:
- probing virtual particles
- high mass reach

- depending on the spectator quark:
  - $B \rightarrow K^* l^+ l^-$
  - $B \rightarrow K l^+ l^-$
  - $B_s \rightarrow \phi l^+ l^-$

- properties of these decays are measured in $q^2$
  - $q^2$ = dilepton invariant mass
  - different physics in different $q^2$ regions

\[
\frac{dI}{dq^2} \uparrow
\]

- $J/\psi (1S)$
- $\psi (2S)$
- Long distance contributions from $cc$ above open charm
- $C_7^{(1)}$, $C_9^{(1)}$, $C_7^{(1)}$, $C_9^{(1)}$ interference
- $C_7^{(2)}$, $C_9^{(2)}$
We can measure branching fractions (BF) angular distributions and contributions from different leptons.

Measured by many experiments, the most and best results from LHCb and Belle, which I will focus on.

**LHCb**

High rate (ν MHz)

Busy events

All kinds of b-hadrons

Unknown event energy

**Belle**

Low rate (n kHz)

Cleaner events

π(40)

E-event = E-beam

Branching fractions

- 1st results consistent with SM
  - BaBar, hep-ex/0604002
  - LHCb, 1112.3515
  - Belle, 0904.0440
  - CDF, 1168.0635

- e.g., LHCb result using 1.8±1 (1304.6385)

- with more statistics, discrepancies start to appear:

  - High q^2 region (above 4(πN)) [10^{-5}]:

    \[ \frac{\partial L}{\partial q^2} dq^2 = 6.7 \pm 1.1 \, \text{10}^{-5} \mu \text{B} \]

    SM pred = 9.9 ± 1

  - Other region:

    \[ \frac{\partial L}{\partial q^2} dq^2 = 8.5 \pm 0.5 \, \text{10}^{-5} \mu \text{B} \]

    SM pred = 10.7 ± 1.2

- All consistently below the SM prediction

- Note that the theory uncertainties are very correlated. Integrated BF has no same theory uncertainty, while the experimental uncertainty shrinks.
\(B_s \to \phi \mu^\pm \nu \mu\) BF follows a similar story

\[\text{Theory prediction for BF predicted by the light flavour quark model} \]
\[\text{SM prediction} \]
\[\text{Leading order} \quad \text{SM prediction scaled to the fitted BF} \]

1305.2168
\[\frac{\alpha_{\text{SM}}}{\alpha_{\text{BF}}} = (1.70 \pm 0.64 \pm 0.72 \pm 0.39) \times 10^{-5} \]
\[\text{SM: } 15 \pm 1 \% \]

- If we measure with 2x more statistics, the discrepancy will remain at 3\sigma due to theory uncertainties (hadronic uncertainties are the biggest)
- All experimental BF results consistently below SM predictions

Angular observables

- First measurements already together with BF measurements
- We can measure form-factor independent angular observables
- Smaller theoretical uncertainties
- Defined as \(P_j = \frac{S_j}{\sqrt{F_j (1 - F_j)}}\)

1512.04442
\[\text{LHCb} \quad \text{SM from ABSZ} \]

1506.08707
\[\text{LHCb} \quad \text{SM pred.} \quad \text{Data} \]

1512.04442
\[\text{LHCb} \quad \text{SM from DHMV} \]
First measurement of $P_1$ by LHCb in 2013
(1308.1704) using 1.0 fb^{-1}

\[ \begin{align*}
\text{LHCb} & \quad \text{SM Predictions} \\
\text{Data} & \\
\end{align*} \]

- 1 out of 24 measurements is 3.7δ away
- Assuming they are independent measurements, statistical probability of this happening is 0.5%

This measurement was followed by many:

- LHCb 1512.04442
  \( B^0 \rightarrow \bar{K}^* \pi^- \mu^+ \mu^- \)
  1.88 ± 0.18

- Belle 1612.05014
  \( B \rightarrow K^* \pi^+ \mu^- \pi^- \)

- ATLAS 1805.04000
  \( B^0 \rightarrow \bar{K}^* \mu^- \mu^+ \)

- CMS 1712.02846
  \( B^0 \rightarrow K^* \mu^- \mu^+ \)

- LHCb has more $P_1$ measurements ongoing
- Small excluded region, 0.28 < q^2 < 1.1 due to $\phi(1020)$ pollution

LHCb has

Belle has worse statistics

\[ \begin{align*}
\text{LHCb data} & \quad \text{ATLAS data} \\
\text{Belle data} & \quad \text{CMS data} \\
\text{SM from DHMV} & \\
\text{SM from ASZB} & \\
\end{align*} \]

Small excluded region, 0.28 < q^2 < 1.1 due to $\phi(1020)$ pollution

For ATLAS

- Angular distributions were similarly measured in $B \rightarrow \phi \mu^+$
  - All agrees with SM predictions

- Third lecture
Lepton flavor universality

- We are looking into $b$-quark transitions.
- NP can occur in the loops AND it might prefer more $\mu$ (or $\tau$).
  → Let's investigate ratios of $b \rightarrow X \mu \nu / b \rightarrow X e \nu$.
  - Again, done in bins of $q^2$.
- We define a variable $R_x$: 
  \[ R_x = \frac{\int_{q_{min}}^{q_{max}} d\sigma (B \rightarrow X \mu \nu) dq^2}{\int_{q_{min}}^{q_{max}} d\sigma (B \rightarrow X e \nu) dq^2} \]
- $R_x$ has very small theoretical uncertainties:
  - QED contribution $\sim 10^{-2}$ (details in 1605.04633).
  - QCD contribution $\sim 10^{-3}$.
    - Mostly cancels out.
- Unfortunately, experimental uncertainties are much larger than the theory ones.
- Let's have a look at $R_x$ and $R_{K^*}$.

\[ \begin{array}{c}
| q^2 [\text{GeV}^2/c^4] | \ \\
-3 & -2 & 0 & 2 & 3 & 4 \ \\
LHCb \ & \ & \ & \ & \ & \ \\
0.5 & 0.6 & 0.7 & 0.8 & 0.9 & 1.0 \ \\
\end{array} \]

$q^2$ range up to 6 GeV (again radiative tails, but in all channels).
- At low $q^2$, $R_{K^*} < 1$ due to the mass difference $\mu^-/e^-$.
- Error bars: 35.4% and 96.7% CL.
- Belle also have results:
  \[ \begin{array}{c}
  \begin{array}{c}
  0 \leq q^2 \leq 22 \text{ GeV} \\
  LHCb has the most precise results. \\
  \text{more on } e^- \text{ reconstruction next week!} \\
  \end{array} \\
\end{array} \]
Outlook

- There are a lot of tensions of 2-3 SD with the SM
  - Most of them are in the same direction
    → Consistent picture

- Very attractive for theorists, but not in the expected direction
  - Some SM extensions can explain all anomalies

- There are other tensions with SM outside of 6-8SD
  - E.g. $R_D^*$, $R_D$ (1406.08614) or $R_{1/4}$ (1711.05626)

- Future measurements and theory predictions will be very exciting whether the anomalies hold or not!