Flavour Physics

LECTURE 3

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Moscow International School of Physics 2020
Outline of the three lectures

1. What is flavour physics and why it is interesting
   - CP Violation and baryogenesis
   - Some historical remarks
   - The CKM Matrix
   - The rise of b physics

   What we have learned from current experiments and the excitement of the field

2. LHCb: a heavy-flavour physics detector at the LHC - experimental aspects, the LHCb upgrade
   - CKM metrology and selected CP violation measurements

3. Selected results on rare decays, tests of LFU and conclusions
Why rare $b$ decays

• In the SM, processes involving flavour changes between two up-type quarks (u,c,t) or between two down-type quarks (d,s,b) are forbidden at tree level and can only occur at loop level (penguin and box) → Rare FCNCs

![Diagrams of rare $b$ decays](image)

• A new particle, too heavy to be produced at the LHC, can give sizeable effects when exchanged in a loop

![Diagrams of new particle effects](image)

• Strategy: use well-predicted observables to look for deviations
• Indirect approach to New Physics searches, complementary to that of ATLAS/CMS
A lesson from history

- New physics can show up at precision frontier before energy frontier
  - GIM mechanism before discovery of charm
  - CP violation and CKM before discovery of beauty and top
  - Neutral currents before the discovery of Z

- In general, a data-driven approach, in which we test precise SM predictions looking for discrepancies, has historically paved the way to important discoveries in particle physics.

- This approach is particularly relevant in the absence of direct collider production of new particles
A window on NP at high scales
The flavour problem

- A systematic data-theory comparison, allowing for possible New Physics effects has been completed for all $\Delta F = 2$ observables (meson-anti-meson mixing amplitudes) → from yesterday lecture no significant deviations (at the 5 to 30% depending on the amplitudes) → this can be translated into quantitative bounds on couplings and masses of possible new particles.

\[ M(B_d - \bar{B}_d) \sim \frac{(V_{tb} * V_{td})^2}{16\pi^2m_W^2} + c_{NP} \frac{1}{\Lambda^2} \]

- Serious constraints on NP models and serious quantitative bounds on couplings and masses of possible new particles.
Energy reach of various indirect precision tests of physics beyond the SM compared to direct searches

Matt Reece, private communication
Ways out

• Either New Physics is very heavy

• or if we want to keep the NP scale in the TeV range, it must have a highly non-generic flavour breaking pattern, (e.g. Minimal Flavour Violation, in which the flavour breaking structure of the SM also holds beyond the SM and bounds on NP scale are reduced to few TeV)

• Can we see deviations from the SM with more precise measurements? If yes, where?

• Rare $K$ and $B$ decays are potential candidates
leptonic B decays
One of the milestones of flavour programme $B_{(s)} \rightarrow \mu^+\mu^-$

- Very suppressed in the SM
  - Loop, CKM ($|V_{ts}|^2$ for $B_s$) and helicity $\sim \left(\frac{m_\mu}{M_B}\right)^2$
  - Theoretically “clean” $\rightarrow$ precisely predicted:

  \[
  \mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9} \quad (~6\%)
  \]
  \[
  \mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}
  \]
  - Some uncertainties cancel in the ratio $R = B(B^0 \rightarrow \mu^+\mu^-)/B(B^0_s \rightarrow \mu^+\mu^-)$, which is also a very useful observable

- Sensitive to NP
  - A large class of NP theories, such as SUSY, predict significantly higher values for the $B_{(s)}$ decay probability

- Very clean experimental signature
  - Studied by all high-energy hadron collider experiments

Bobeth et al.
PRL 112 (2014) 101801
30 years of effort!

“I’m too old for limits! I want to see signals!” (F. Halzen, EPS 2015)
30 years of effort!

"I’m too old for limits! I want to see signals! “ (F.Halzen, EPS 2015)
Finding a needle in a haystack!

We found it!

We found $B_s \rightarrow \mu^+\mu^-$!
LHCb update with Run 2 data

- LHCb analysis based on Run 1 and Run 2 data (3+1.4 fb⁻¹)
- First observation from a single experiment with a significance of 7.8 σ

\[ B(B_s^0 \rightarrow \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \ (20\%) \quad B_{SM} = (3.65 \pm 0.23) \times 10^{-9} \]

\[ B(B^0 \rightarrow \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ at 95\% CL} \]

- Consistent with SM expectation at current level of precision

PRL 118 (2017) 191801
PRL 112 (2014) 101801
$B_{(s)} \rightarrow \mu^+ \mu^-$ analysis features

- Basic selection requirements:
  - two oppositely-charged muon tracks with common vertex displaced from primary vertex
  - $m_{\mu \mu}$ peaking at the $B^0_{(s)}$ mass

- In practice, complex analysis due to very low signal and large background rates

- Most abundant background is combinatorial
  - muons from two different $b$-quark decays,
  - strongly suppressed with multivariate operator (BDT) trained on data as much as possible, using, e.g., track isolation, topological and geometrical information

- Use of normalisation channels with well-known BRs, same topology and/or trigger. Cancel uncertainties in ratios
  - Normalise to large samples of $B^+ \rightarrow J/\psi K^+$ and $B^0 \rightarrow K^+ \pi^-$
  - The normalisation introduces the largest systematics to $B_s \rightarrow \mu^+ \mu^-$ from knowledge of the $b$-quark fragmentation probability ratio $f_s/f_d (\sim 6\%)$
Era of precision measurements of $B(s) \rightarrow \mu^+ \mu^-$

- **LHCb**, PRL 118 (2017) 191801
  \[ B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \]
  \[ B(B^0 \rightarrow \mu^+ \mu^-) < 3.4 \times 10^{-10} @ 95\% \text{ C.L.} \]

- **CMS**, PRL 111, 101804 (2013)
  \[ B(B_s^0 \rightarrow \mu^+ \mu^-) = (2.8^{+1.1}_{-0.9}) \times 10^{-9} \]
  \[ B(B^0 \rightarrow \mu^+ \mu^-) = (4.4^{+2.2}_{-1.9}) \times 10^{-10} \]

- **ATLAS**, JHEP 04 (2019) 098
  \[ B(B_s^0 \rightarrow \mu^+ \mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9} \]
  \[ B(B^0 \rightarrow \mu^+ \mu^-) < 2.1 \times 10^{-10} @ 95\% \text{ C.L.} \]

- Naive combination from the three experiments gives:
  \[ B(B_s^0 \rightarrow \mu^+ \mu^-) = (2.7^{+0.5}_{-0.4}) \times 10^{-9} \]
  roughly 2σ below SM prediction
The SM stands its ground

- Sizeable effects expected in many MSSM models (cancellation of helicity suppression)

Straub, arXiv:1107.0266

Pre-LHC
The SM stands its ground

- Sizeable effects expected in many MSSM models (cancellation of helicity suppression)

[Graph showing BR(B_d \rightarrow \mu\mu) \times 10^9 vs BR(B_s \rightarrow \mu\mu) \times 10^9]

Straub, arXiv:1107.0266
Effective $B_s$ lifetime

- An observable sensitive to NP and complementary to branching fraction

$$
\tau_{\mu^+ \mu^-} \equiv \frac{\int_0^\infty t \Gamma(B_s(t) \to \mu^+ \mu^-) dt}{\int_0^\infty \Gamma(B_s(t) \to \mu^+ \mu^-) dt}
$$

- Measured from the decay time distributions of the samples of untagged $B_s$ events by fitting a single exponential function

$$
\Gamma(B_s(t) \to \mu^+ \mu^-) \equiv \Gamma(B_s^0(t) \to \mu^+ \mu^-) + \Gamma(\overline{B}_s^0(t) \to \mu^+ \mu^-)
\propto (1 - A_{\Delta \Gamma_s}) e^{-\Gamma_L t} + (1 + A_{\Delta \Gamma_s}) e^{-\Gamma_H t}
$$

$$
A_{\Delta \Gamma} \equiv \frac{\Gamma(B_s^H \to \mu^+ \mu^-) - \Gamma(B_s^L \to \mu^+ \mu^-)}{\Gamma(B_s^H \to \mu^+ \mu^-) + \Gamma(B_s^L \to \mu^+ \mu^-)}
$$

- Measurement not yet sensitive to $A_{\Delta \Gamma}$, interesting as a proof-of-principle which can be scaled to higher luminosities
$B_{(s)} \rightarrow \mu^+ \mu^-$ projections

**CMS PAS FTR-14-015**

### Phase I scenario

**CMS Simulation**
- Scaled to $L = 300$ fb$^{-1}$
- $\ln(\mu |<1.4$

**Weighted Events (0.01 GeV)**

<table>
<thead>
<tr>
<th>$m_{\mu\mu}$ (GeV)</th>
<th>Data</th>
<th>full PDF</th>
<th>$B_S \rightarrow \mu^+\mu^-$</th>
<th>$B_S \rightarrow \mu^+\nu\nu$</th>
<th>combinatorial bkg</th>
<th>semileptonic bkg</th>
<th>peaking bkg</th>
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<td>100</td>
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### Phase II scenario

**CMS Simulation**
- Scaled to $L = 3000$ fb$^{-1}$
- $\ln(\mu |<1.4$

**Weighted Events (0.01 GeV)**

<table>
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<tr>
<th>$m_{\mu\mu}$ (GeV)</th>
<th>Data</th>
<th>full PDF</th>
<th>$B_S \rightarrow \mu^+\mu^-$</th>
<th>$B_S \rightarrow \mu^+\nu\nu$</th>
<th>combinatorial bkg</th>
<th>semileptonic bkg</th>
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**LHCb: Physics case for an LHCb Upgrade II, CERN/LHCC 2018-027**

<table>
<thead>
<tr>
<th>$\mathcal{L}$ (fb$^{-1}$)</th>
<th>$N(B^0_S)$</th>
<th>$N(B^0)$</th>
<th>$\frac{\delta B(B^0 \rightarrow \mu^+\mu^-)}{B(B^0_S \rightarrow \mu^+\mu^-)}$</th>
</tr>
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<tr>
<td>20</td>
<td>18.2</td>
<td>2.2</td>
<td>&gt; 100%</td>
</tr>
<tr>
<td>100</td>
<td>159</td>
<td>19</td>
<td>66%</td>
</tr>
<tr>
<td>300</td>
<td>478</td>
<td>57</td>
<td>43%</td>
</tr>
<tr>
<td>300 (barrel)</td>
<td>346</td>
<td>42</td>
<td>50%</td>
</tr>
<tr>
<td>3000 (barrel)</td>
<td>2250</td>
<td>271</td>
<td>21%</td>
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**LHCb**

- $B_S(23/300 \text{ fb}^{-1})$
  - ~34 %
  - ~10 %

**ATLAS**

- Trigger thresholds:
  - $(p_T^{\mu_1}, p_T^{\mu_2})$: (6 GeV, 10 GeV)

- $B(\tau_{eff})$
  - ~8 %
  - ~2 %

**LHCb**

- $\tau_{eff}$
  - $LHCb \pm 9.0 \times 10^{-1}$
  - 2025
  - $LHCb \pm 3.4 \times 10^{-1}$
  - HL-LHC
  - $LHCb \pm 1.0 \times 10^{-1}$
In the SM, larger BF due to larger $\tau$ mass (less helicity suppressed $m_\tau^2/m_B^2$)

\[ \mathcal{B}(B_s^0 \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7} \]
\[ \mathcal{B}(B^0 \to \tau^+\tau^-) = (2.22 \pm 0.19) \times 10^{-8} \]

Bobeth et al.
PRL 112 (2014) 101801

Experimentally challenging due to undetected neutrinos in final state

Searched by LHCb through the decay $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$

$B_{s,d}$ unresolvable in mass → analysis optimised for $B_s$

Limits set (Run1 data):

\[ \mathcal{B}(B_s \to \tau^+\tau^-) < 6.8 \times 10^{-3} \text{ at } 95\% \text{ C.L.} \]
\[ \mathcal{B}(B_d \to \tau^+\tau^-) < 2.1 \times 10^{-3} \text{ at } 95\% \text{ C.L.} \]

→ first direct limit
→ best limit
$B^0_{(s)} \rightarrow e^+e^-$

- In SM, smaller BF wrt $B(B_s \rightarrow \mu^+\mu^-)$ due to tiny $(m_e)^2$ factor
  $B_s \rightarrow e^+e^- = (8.54 \pm 0.55) \times 10^{-14}$

  - out of reach from the experimental point of view \rightarrow very little attention

- Current limit by CDF (from 2009) $B_s \rightarrow e^+e^- = < 2.8 \times 10^{-7}$ @ 90 % CL

- Ongoing LHCb measurement based on Run1 and partial Run 2 relative to $B^+ \rightarrow K^+J/\psi(\rightarrow e^+e^-)$

- Analysis in very advanced stage, with Interesting projected sensitivity (one order of magnitude improvement expected)
$b \rightarrow s \ell^+ \ell^-$ transitions
Other interesting rare decays: $b \rightarrow s \ell^+ \ell^-$ transitions

- Can only proceed via loop diagrams
- NP can be competitive with SM processes
- Rates, angular distributions and asymmetries sensitive to NP
- A lot of phenomenological work invested in defining observables with "clean" theoretical predictions.
  - Observables form-factor free at leading order
  - Still susceptible to non-factorisable corrections
  - E.g: Are we estimating correctly contributions from charm loops that produce a $\ell^+ \ell^-$ pair via a virtual photon?
- Question: how clean?
Intriguing set of results in differential branching fractions for $b \to s \mu \mu$ transitions

- In general, data tend to be lower than theory predictions at low $q^2$
- Comparison limited by theoretical knowledge of form factors
Angular observables

- One such observable is so-called $P'_5$, not intuitive, but constructed from angular observables to be robust from ‘form-factor uncertainties’

- Is the SM prediction less precise than what is claimed?
- Update analysis of LHCb data up to 2016 to be shown at 2020 winter conferences
Tests of Lepton Flavour Universality
Lepton Flavour Universality

• The property that the three charged leptons (e, μ, τ) couple in a universal way to the SM gauge bosons

• In the SM the only flavour non-universal terms are the three lepton masses: $m_\tau, m_\mu, m_e \leftrightarrow 3477/207/1$ (boring!)

• Turn this “boring” property into a powerful tool to discover physics beyond the SM

• The SM quantum numbers of the three families could be an “accidental” low-energy property: the different families may well have a very different behaviour at high energies, as signaled by their different mass

• If NP couples in a non-universal way to the three lepton families, then we can discover it by comparing classes of rare decays involving different lepton pairs (e.g. e/μ or μ/τ)

• Test LFU in $b \rightarrow s\ell^+\ell^-$ transitions, i.e. flavour-changing neutral currents with amplitudes involving loop diagrams
The family of $R$ ratios

- Comparing the rates of $B \to H e^+ e^-$ and $B \to H \mu^+ \mu^-$ allows precise testing of lepton flavour universality.

$$R_H \left[ q^2_{\text{min}}, q^2_{\text{max}} \right] = \frac{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} dq^2 \frac{d\Gamma(B \to H \mu^+ \mu^-)}{dq^2}}{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} dq^2 \frac{d\Gamma(B \to H e^+ e^-)}{dq^2}}, \quad q^2 = m^2(\ell\ell)$$

- These ratios are clean probes of NP:
  
  - Sensitive to possible new interactions that couple in a non-universal way to electrons and muons.
  
  - Small theoretical uncertainties because hadronic uncertainties cancel: $R_H = 1$ in SM, neglecting lepton masses, with QED corrections at $\sim\%$ level.
Very challenging measurements

- Lepton identification is anything but universal!
- Electrons emit a large amount of bremsstrahlung, degrading momentum and mass resolution

- Two situations
  - **Downstream of the magnet**
    Photon energy in the same calorimeter cell as the electron and momentum correctly measured
  - **Upstream of the magnet**
    Photon energy in different calorimeter cells than electron and momentum evaluated after bremsstrahlung

  → bremsstrahlung recovery can partially fix this
Very challenging measurements

- Lepton identification is anything but universal!

  Higher occupancy of calorimeters $\rightarrow$ trigger thresholds are higher for electrons ($\sim 2.5$ to $3.0$ GeV) than for muons ($\sim 1.5$ to $1.8$ GeV) $\rightarrow$ Mitigate including decays with electrons also selected using hadron trigger either fired by $K^*$ products or by any other particle in the event not associated with signal.
muons vs electrons

Partially reconstructed background, mainly from $B^0,+ \rightarrow K^{*0,+}e^+e^-$ where a pion is lost

Leakage from $B^+ \rightarrow KJ/\psi(e^+e^-)$

Longer radiative tail due to bremsstrahlung
Measure as a double ratio

- To mitigate muon and electron differences due to bremsstrahlung and trigger, measurement performed as a double ratio with “resonant” control modes $B^0 \to J/\psi H$, which are not expected to be affected by NP:

$$R_H = \frac{\mathcal{B}(B^0 \to H \mu^+ \mu^-)}{\mathcal{B}(B^0 \to H J/\psi(\to \mu^+ \mu^-))} / \frac{\mathcal{B}(B^0 \to H e^+ e^-)}{\mathcal{B}(B^0 \to H J/\psi(\to e^+ e^-))}$$

- Relevant experimental quantities: yields & (trigger, reconstruction and selection) efficiencies for the four decay modes

$$\rightarrow r_{J/\psi} = \frac{B(B \to H J/\psi(\mu^+ \mu^-))}{B(B \to H J/\psi(e^+ e^-))}$$

known to be compatible with unity within 0.4%

- Similarities between the experimental efficiencies of the non resonant and resonant modes ensure a substantial reduction of systematic uncertainties in the double ratio

- Analyses performed blind
The $R_K$ ratio

- LHCb published an analysis of $R_K$ based on Run 1 data

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\to e^+e^-))}$$

in $q^2$ interval: $1.1 < q^2 < 6 \text{GeV}^2$

- Result compatible with SM at 2.6 $\sigma$: $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$

- Performed a re-optimised analysis of 2011-2016 data (total of 5 fb$^{-1}$) in $1.1 < q^2 < 6 \text{GeV}^2$

- Factor 2 larger yields than in previous analysis, still statistically dominated by electron mode ($\sim 760 e^+e^-$ candidates vs $\sim 1940 \mu^+\mu^-$ candidates)
Updated $R_K$ result

- New result compatible with previous analysis and $\sim 2.5 \sigma$ from SM

$$R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$$

- $r_{J/\psi}$ cross-check:

$$r_{J/\psi} = 1.014 \pm 0.035$$

- Very stringent test, which does not benefit from the cancellation of the experimental systematics provided by the double ratio

- Still x2 B decays recorded by LHCb being analysed
Updated $R_K$ from Belle

- New results from Belle based on full data sample (711 fb$^{-1}$)
- Both charged and neutral modes ($K^+, K^0_s$) and $R_K$ measured as the weighted average
- $R_K$ measured in various $q^2$ bins: $[0.1, 4.0], [4.0, 8.12], [1.0, 6.0], > 14.18$ and $> 0.1$
- $R_K = 0.98^{+0.27}_{-0.23} \pm 0.06$ for $1.0 < q^2 < 6 \text{GeV}^2$
- Results compatible with SM expectations and with LHCb
Another ratio: $R_{K^*}$

$$R_{K^*} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi(\rightarrow \mu^+ \mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \rightarrow K^{*0} e^+ e^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi(\rightarrow e^+ e^-))}$$

$K^{*0}(892) \rightarrow K^+ \pi^-$

- LHCb performed measurement in two $q^2$ bins that are sensitive to different NP contributions (Run 1 data, 3 fb$^{-1}$):
  - Low-$q^2$ bin: [0.045,1.1] GeV$^2$
  - Central-$q^2$ bin: [1.1,6.0] GeV$^2$

JHEP 08 (2017) 055
Fit to the invariant masses

Low-$q^2$

$B^0 \rightarrow K^* J/\psi (\rightarrow \ell^+ \ell^-)$

- Precision of measurement driven by statistics of electron sample: $\sim 90$ and 110 signal candidates in low-$q^2$ and central-$q^2$, muon sample 3-5 times larger

$285 \pm 18$

$353 \pm 21$

$274 \text{k}$
Crosschecks

- Large number of crosschecks performed before unblinding the results

\[ r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^*0 J/\psi(\to \mu^+ \mu^-))}{\mathcal{B}(B^0 \to K^*0 J/\psi(\to e^+ e^-))} = 1.043 \pm 0.006 \pm 0.045 \]

- test of absolute scale of the efficiencies

\[ R_{\psi(2S)} = \frac{\mathcal{B}(B^0 \to K^{*0} \psi(2S)(\to \mu^+ \mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+ \mu^-))} / \frac{\mathcal{B}(B^0 \to K^{*0} \psi(2S)(\to e^+ e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+ e^-))} \to \text{compatible with expectation} \]

- \( \mathcal{B}(B^0 \to K^{*0} \mu^+ \mu^-) \) in agreement with JHEP 04 (2017) 142

- \( \mathcal{B}(B^0 \to K^{*0} \gamma) \) compatible with expectations

- If corrections to simulation are not accounted for, the ratio of the efficiencies (and thus \( R_{K^*} \)) changes by less than 5%
$R_{K^*}$ results

Comparison with SM predictions

$R_{K^*} = \begin{cases} 
0.66^{+0.11}_{-0.07} \text{ (stat)} \pm 0.03 \text{ (syst)} & \text{for } 0.045 < q^2 < 1.1 \text{ GeV}^2 \\
0.69^{+0.11}_{-0.07} \text{ (stat)} \pm 0.05 \text{ (syst)} & \text{for } 1.1 < q^2 < 6.0 \text{ GeV}^2 
\end{cases}$

Comparison with BaBar & Belle

2.1 - 2.3 $\sigma$

2.4 - 2.5 $\sigma$

below SM expectations
Updated $R_{K^*}$ from Belle

- Full data set analysed using neutral and charged modes:
  
  \[
  B^0 \rightarrow K^{*0} \ell^+ \ell^- \\
  B^+ \rightarrow K^{*+} \ell^+ \ell^- \\
  K^{*0} \rightarrow K^+ \pi^-, \ K^{*+} \rightarrow K^+ \pi^0, \ K^{*+} \rightarrow K^0_s \pi^+
  \]

- $R_{K^*}$ measured as single ratio
  
  - $B(B \rightarrow K^*J/\psi)$ in agreement with world averages
  - $r_{J/\psi} = 1.015 \pm 0.025 \pm 0.038$, validating efficiency

\[
N_{ee} \sim 100 \\
N_{\mu\mu} \sim 140
\]

$q^2 > 0.045 \text{ GeV}^2$

arXiv:1904.02440
Updated $R_{K^*}$ from Belle

• Results compatible with SM

arXiv:1904.02440
$R_{K^*}$ putting everything together...

![Graph showing $R_{K^*}$ versus $q^2$ with data points for LHCb, BaBar, and Belle.]

[LHCb, JHEP 08 (2017) 055]
[BaBar, PRD 86 (2012) 032012]
[Belle, PRL 103 (2009) 171801]
[Belle, arXiv:1904.02440]
What happens next?

- Run 2 updates of $R_K, R_{K^*}$
- Can make analogous measurement with $R_\phi(B_s \rightarrow \phi\ell^+\ell^-)$ and other similar modes ($\Lambda_b^0 \rightarrow pK^-\ell^+\ell^-$ just published)

### Run 2

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current LHCb</th>
<th>LHCb 2025</th>
<th>Belle II</th>
<th>Upgrade II</th>
</tr>
</thead>
<tbody>
<tr>
<td>EW Penguins</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_K (1 &lt; q^2 &lt; 6 \text{ GeV}^2c^4)$</td>
<td>0.1</td>
<td>0.05</td>
<td>0.022</td>
<td>0.036</td>
</tr>
<tr>
<td>$R_{K^*} (1 &lt; q^2 &lt; 6 \text{ GeV}^2c^4)$</td>
<td>0.1</td>
<td>0.06</td>
<td>0.029</td>
<td>0.032</td>
</tr>
<tr>
<td>$R_\phi, R_{pK}, R_\pi$</td>
<td></td>
<td></td>
<td>0.07, 0.04, 0.11</td>
<td>–</td>
</tr>
</tbody>
</table>

- ATLAS/CMS also getting more interested, e.g. CMS devised a new strategy of parking a very large sample of $\sim 10^{10}$ B hadrons to be able to measure $R_K, R_{K^*}$ in a competitive way ($\rightarrow$ no prompt reconstruction, opportunistic reconstruction during LS2)

- LHCb: Physics case for an LHCb Upgrade II, CERN/LHCC 2018-027

arXiv:1912.08139
Another puzzling result in tree-level $b \rightarrow c$ transitions
LFU studies in $B \to D^{(*)}\tau\nu$ decays

- Different class of decays (tree-level charged current with $V_{cb}$ suppression)

- Not at all rare: $B(B^0 \to D^{*-}\tau^+\nu_\tau) \sim 1\%$, problem is the background

Lepton-universality ratio $R(D^*)$:

$$R(D^*) = \frac{B(B^0 \to D^{*-}\tau^+\nu_\tau)}{B(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

- sensitive to any NP model coupling preferentially to third generation leptons

- Predicted theoretically at $\sim 1\%$:
  
  $R(D)_{SM} = 0.299 \pm 0.003$
  
  $R(D^*)_{SM} = 0.258 \pm 0.005$

- Studied by Belle, BaBar and LHCb

HFLAV average, 2019
**Experimental challenges**

- At least two neutrinos in the final state (three if using $\tau \rightarrow \mu \nu \nu$)

- At the LHC, as opposed to B factories, the rest of the event does not provide any useful kinematic constraint. However, profit from large boost and huge B production

- Latest LHCb measurement:
  \[
  \begin{aligned}
  \tau^+ &\rightarrow \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau \\
  D^{*-} &\rightarrow \overline{D}^0 (\rightarrow K^+\pi^-)\pi^-
  \end{aligned}
  \]

  - A semileptonic decay with no (charged) lepton in final state (one $K$, five $\pi$)
  - Zero background from $B^0 \rightarrow D^{*-}\mu^+\nu_\mu X$

  - However, signal to noise ratio less than 1% $\rightarrow$ need at least $10^3$ rejection!

  - Large background, notably from $B \rightarrow D^{*-}3\pi X$ (BF$\sim$100 x signal) and $B \rightarrow D^{*-}D^+_s(X)$ (BF$\sim$10 x signal, same vertex topology)
Background reduction

- Separation between $B$ and $3\pi$ vertices ($\Delta z > 4\sigma_{\Delta z}$) crucial to obtain the required rejection of $B \rightarrow D^*3\pi X$

![Signal](image1)

![Background](image2)

- Remaining double-charm background ($D^*D(S)X$) suppressed by employing a multivariate classifier

- Signal normalised to $B \rightarrow D^{*-}3\pi$ to minimize experimental systematics

\[ R(D^{*-}) = 0.291 \pm 0.019 \text{ (stat)} \pm 0.026 \text{ (syst)} \pm 0.013 \text{ (ext)} \sim 1.1\sigma > \text{SM} \]
$R(D)$ vs $R(D^*)$

Prospects (LHCb)

- Extend to full Run2 statistics
  - from ~1300 to ~6000 events
  - goal is to be competitive with world average
- A whole programme of semi-tauonic measurements, e.g.

$$\begin{cases} 
R(D) : B^+ \rightarrow D^0 \tau^+ \nu_\tau \\
R(D^*) : B^0 \rightarrow D^{*-} \tau^+ \nu_\tau \\
R(D_s^{(*)}) : B^0_s \rightarrow D_s^{(*)} \tau^+ \nu_\tau \\
R(\Lambda_b) : \Lambda_b \rightarrow \Lambda_c^{(*)} \tau^+ \nu_\tau 
\end{cases}$$

Waiting for Belle II

- ~1.5% projected sensitivity on $R(D^*)$ with 5 ab$^{-1}$

- All experiments see an excess wrt SM predictions
- Tension $\lesssim 4\sigma$
- ~20% effect on $R(D^*)$
Belle: Update of $R(D)$ & $R(D^*)$

- Simultaneously measure $R(D)$ and $R(D^*)$ with SL tagging, using the full $Y(4S)$ statistics

\[
R(D) = 0.307 \pm 0.037 \pm 0.016 \\
R(D^*) = 0.283 \pm 0.018 \pm 0.014
\]

- New HFLAV average: $\sim 3.1\sigma$ away from SM
- Intriguing as it occurs in a tree-level SM process!
Testing LFU with $B_c$ decays

- Generalization of $R(D^*)$ to $B_c$:
  \[
  R(J/\psi) = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)}
  \]

- Signal reconstructed using $\tau \rightarrow \mu \nu \nu$

- Largest background from light $b$ hadrons to $J/\psi$ with a $\pi$ or $K$ misidentified as $\mu$

\[
R(J/\psi) = 0.71 \pm 0.17\text{(stat)} \pm 0.18\text{(syst)}
\]

2σ away from SM prediction (0.25-0.28)
A word on LFV

- Many models proposed to explain these tensions naturally allow for LFV processes with rates that are experimentally accessible

- \( B^0 \rightarrow \tau^+ \mu^- \)

\[ \mathcal{B}(B^0 \rightarrow \tau^+ \mu^-) < 1.4 \cdot 10^{-5} \text{ @95\% CL} \rightarrow \text{Best limit} \]

\[ \mathcal{B}(B^0_s \rightarrow \tau^+ \mu^-) < 4.2 \cdot 10^{-5} \text{ @95\% CL} \rightarrow \text{First limit} \]

- \( B^+ \rightarrow K^+ \mu^\pm e^\mp \)

\[ \mathcal{B}(B^+ \rightarrow K^+ \mu^- e^+) < 9.5 \cdot 10^{-9} \text{ @95\% CL} \]

\[ \mathcal{B}(B^+ \rightarrow K^+ \mu^+ e^-) < 8.8 \cdot 10^{-9} \text{ @95\% CL} \]

→ Improving limits by one order of magnitude

Possible explanations of the anomalies

- **Statistical fluctuations**: unlikely given the number and pattern of the effects?

- **Experimental artefacts**: these are difficult measurements; have the systematic errors been correctly estimated?

- **Theoretical uncertainties**: large theoretical uncertainties from hadronic form factors but LFU tests should be robust

- **A cocktail of the above?**

- **New Physics** once all the above have been excluded...

  - “the case of an SU(2)\textsubscript{L}-singlet vector leptoquark emerges as a particularly simple and successful framework.”

- The large amount of data still to be analysed by LHCb and high-p\textsubscript{T} LHC experiments, as well as from future Belle II, will certainly shed more light on the origin of the B-physics anomalies
The SM as an emerging iceberg

What is there under the water?
Exciting New Physics in the multiTev region?
Exciting New Physics in the multiTev region?

… or SM up to $E >> \text{TeVs}$

In the current uncertain situation of particle physics it is useful/necessary to have a diversified programme in which flavour plays an important role

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Recap of these lectures

• What we have discussed
  - Introduction to flavour physics and why it is important
  - CP Violation and baryogenesis
  - Some historical aspects
  - The CKM Matrix
  - LHCb as an example of a dedicated flavour physics detector
  - The LHCb upgrade and Belle II
  - Selected results (CPV, rare decays, LFU)

• What we have not discussed
  - Many interesting things: kaon physics, lepton flavour violation searches, heavy-flavour spectroscopy, heavy flavour in heavy-ion collisions ,.....
Conclusions

• Precise measurements of flavour observables provide a powerful way to probe for NP effects beyond the SM, complementing direct searches for NP

• Flavour-physics measurements at the LHC, in particular by LHCb, are dramatically adding to the already impressive knowledge accumulated by the B-factories and Tevatron. Healthy competition from Belle II, ATLAS & CMS very welcome!

• Many world record results. For some topics we have moved from exploration to precision measurements

• Most of these results show good compatibility with the SM, so that NP new physics must have a rather non-trivial flavour structure, but the origin of this structure is still to be discovered.

• Some signs of tension have emerged but we need more data to test them: full analysis of Run 2, while waiting for the high-precision results from the LHCb upgrade and Belle II
Some excellent lectures on flavour that I should acknowledge

- Vincenzo Vagnoni: MISP 2019
- Tim Gershon: CERN Summer Student Programme 2016 lecture 1, lecture 2, lecture 3, lecture 4
- Gino Isidori: CERN, Summer Student Programme 2017, Lectures on Flavour Physics and CP Violation