CKM 2018 WG3 summary
Rare B, D, K decays

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Rare B decays
New $B_{(s)} \rightarrow \mu^+ \mu^-$ result from ATLAS

Run 2 Result and Run 1 Combination

Neyman Contours yield:

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.21^{+0.96+0.49}_{-0.91-0.30}) \times 10^{-9} = (3.2^{+1.1}_{-1.0}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 4.3 \times 10^{-10} \text{ @ 95\% CL}$$

Run 1 Only:

Run 2 Only:

Run 1 + Run 2:

Run 1 + Run 2 (2015+2016) combination:

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9} \quad \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 2.1 \times 10^{-10}$$

Compatible with SM at 2.4\sigma
First observations

► Belle: Isospin violation in $B \rightarrow K^*\gamma$:
$\Delta_{0+} = (6.2 \pm 1.5 \pm 0.6 \pm 1.2)\%$ (3.1$\sigma$) [Tim Gershon]

► LHCb: $B(\Sigma^+ \rightarrow p\mu^+\mu^-) = (2.2^{+1.8}_{-1.3}) \times 10^{-8}$ (4.1$\sigma$) [Giulio Dujany]

► LHCb:
$B(\Lambda_c^+ \rightarrow p(\omega \rightarrow \mu^+\mu^-)) = (9.4 \pm 3.2 \pm 1.0 \pm 2.0) \times 10^{-4}$ [Giulio Dujany]
Upper limits

- $\mathcal{B}(B^0 \rightarrow e^\pm \mu^\mp) < 5.4 \times 10^{-9}$ (90% CL) [Giulio Dujany]
- $\mathcal{B}(B^0_s \rightarrow e^\pm \mu^\mp) < 1.0 \times 10^{-9}$ (90% CL) [Giulio Dujany]
- $\mathcal{B}(H^0 \rightarrow \mu^\pm \tau^\mp) < 26\%$ (for SM Higgs) [Giulio Dujany]
- $\mathcal{B}(B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu}) < 3 \times 10^{-5}$ [Tim Gershon]
- All compatible with the Standard Model.
B anomalies:
“Gekommen um zu bleiben”? 
Global fits

Combine branching fractions, angular measurements and $R_K(*)$.

Global fits from $R_K(*)$ and $b \rightarrow s\mu^+\mu^-$ in excellent agreement.

No right-handed currents or NP in electrons needed.

1D pulls for $C_9^\mu$, $C_{10}^\mu$ around 4$\sigma$ from SM predictions.

Lindy effect? “Every additional period of survival implies a longer remaining life expectancy”
Golden Channel: $b \rightarrow s\tau\tau$?

- Models with very large $b \rightarrow s\tau\tau$ and LFV just below observation.
- Finding $b \rightarrow s\tau\tau$ at LHCb/ Belle II would mean New Physics.
- Leptoquarks are most favoured explanation of anomalies.

Perfect agreement with data

Pati-Salam LQ can explain the flavour anomalies.
Violation of LFU and BSM physics

Leptoquarks for $R_{D(\ast)}$ and $R_{K(\ast)}$

See also [Greljo et al. '17, Di Luzio et al. '17, Bordone et al. '17...]

Several distinctive predictions wrt the SM:

- Enhancement of $B(B \to K^{\ast} \nu \bar{\nu})$ by $\gtrsim 50\%$ wrt to the SM [Belle-II]
- Upper and lower bounds on the LFV rates: $B(B \to K \mu \tau) \gtrsim 2 \times 10^{-7}$

$B(B \to K^{\ast} \mu \tau)/B(B \to K \mu \tau) \approx 1.8, B(B \to K^{\ast} \mu \tau)/B(B_s \to \mu \tau) \approx 1.25$

[Becirevic, OS, Zukanovich. 1602.00881]

- Building a model that can solve all anomalies is a very challenging task!
- Only $U_1$ can do it, but UV completion needed (more parameters).
  ⇒ Possible in Pati-Salam models: [Di Luzio et al. '17, Bordone et al. '17...]
- Two scalar LQs can also do the job (no extra parameters):
  ⇒ $S_1$ and $S_3$ [Crivellin et al. '17, Marzocca. '18], $R_2$ and $S_3$ [Becirevic et al. '18].

- $R_{D(\ast)}$ explained by vector, but also by scalar and tensor EFT couplings
- Additional observables favour scalar and vector leptoquarks
- One vector OK (but UV completion needed), but also possible to build models with two scalar LQ
- $R_2$ and $S_3$ OK with one complex coupling, with expected enhancement for $B \to K^{\ast} \ell \ell$, and observable $B \to K \mu \tau$
Radiative B decays
Photon Polarization

Photon predominantly left-handed in SM. Different polarization $\rightarrow$ New Physics.

- Can be measured in $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$. $K^+ \pi^- \pi^+$ spectrum challenging to describe (experimentally and theoretically).
- Existence of photon polarization confirmed few years ago, amplitude analysis ongoing.
Time-dependent radiative analyses

- CPV in $B^0 \rightarrow K_{res}\gamma$ decays would be a clear sign of new physics.
- Can perform Dalitz analysis of “Dilution factor” to determine Real and Imaginary part of $C_7, C'_7$.
- LHCb used flavour tagging for the first time in a radiative decay, measurement of $S_{CP}$ and $A_{CP}$ in $B_s \rightarrow \phi \gamma$ on the way.
Inclusive $B \rightarrow X_{d/s} \ell \ell$
Theory for $B \to X_s \gamma$ and $B \to X_s \ell \ell$

| $C_7$ | from the CP- and isospin-averaged branching ratio of $\bar{B} \to X_s \gamma$ with $E_\gamma > 1.6$ GeV: $B^{\exp}_{\gamma} \times 10^4 = 3.32 \pm 0.15 \pm 1.5\%$, average of Belle, Babar and CLEO; $B^{\exp}_{\gamma} \times 10^4 = 3.36 \pm 0.25 \pm 6.9\%$, average of Belle, Babar and CLEO. \(\Rightarrow \frac{|C_7|}{|C_7^{\exp}|} = 0.994 \pm 0.041 (0.15\sigma)\).

Belle II with 50 ab$^{-1}$ is going to reach $\pm 2.3\%$ in $B^{\exp}_{s\gamma}$. Thus, the TH uncertainty must be reduced.

At present, it consists of four contributions (summed in quadrature): 5% non-perturbative, 3% from the interpolation in $m_b$, 3% higher order $O(\alpha_s^3)$, 2% parametric.

Effect of the interpolated $O(\alpha_s^3)$ contribution on the branching ratio:

- $B \to X_s \gamma$ ($B \to X_s \ell \ell$) strong constraints on $C_7$ ($C_9$, $C_{10}$), with interesting experimental prospects (Belle II)
- Effect of cut on $E_\gamma$ or $M_{X_s}$ difficult to tackle (local OPE + SCET), introducing shape functions to be modelled/fitted experimentally
- $B \to X_s \gamma$: charm loops induce $m_c$ dependence, significant source of uncertainty, difficult analytic computation, now under control
Five-particle contributions to $B \to X_{d/s} \ell \ell$

<table>
<thead>
<tr>
<th>pieces in $\mathcal{B}(\bar{B} \to X_{d/s} \ell^+ \ell^-) \ (\times 10^{-8})$</th>
<th>$q^2 \in [1, 3.5]$ GeV$^2$</th>
<th>$[3.5, 6]$ GeV$^2$</th>
<th>$[1, 6]$ GeV$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R(s)$ (LO+NLO+NNLO)</td>
<td>3.79</td>
<td>3.05</td>
<td>6.84</td>
</tr>
<tr>
<td>five-particle</td>
<td>0.092</td>
<td>0.003</td>
<td>0.095</td>
</tr>
</tbody>
</table>

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<th>pieces in $\mathcal{B}(\bar{B} \to X_{d/s} \ell^+ \ell^-) \ (\times 10^{-8})$</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$R(s)$ (LO+NLO+NNLO)</td>
<td>0.86</td>
<td>0.70</td>
<td>1.56</td>
</tr>
<tr>
<td>five-particle</td>
<td>$2 \times 10^{-4}$</td>
<td>$5 \times 10^{-6}$</td>
<td>$2 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

- Ongoing effort to increase the accuracy of $B \to X_{d/s} \ell \ell$.
- Studied five-particle contributions: $b \to d/s \ell \ell u\bar{u}$.
- Effect negligible in $b \to d$ transitions, but seizable effects in $b \to s$ transitions.
Probably the longest formula at CKM 2018

\[ p_3 \cdot p_4 = [111 \text{ terms}] \pm [2179 \text{ terms}] \] (23)

\[ Z \]

\[ d_4 \]

\[ p_4 \]

\[ p_2 \]

\[ (p_b \cdot p_1) \]

\[ (p_b \cdot p_2) \]

\[ t_3 \]

\[ u_3 \]

\[ \mu_4 \]

\[ = (p_1 \cdot p_2) \cdot (p_3 \cdot p_4) \cdot (I) + p_4 (II) = (p_1 \cdot p_2) \cdot (p_3 \cdot p_4) \cdot (I) + p_4 (II) \] (24)

III. RESULTS

\[ h_d \]

\[ + \]

\[ \bar{u} \]

\[ |P| \]

\[ u_1, 2 \]

\[ |b_i| \]

\[ 2 \]

\[ (25)\]
D decays:
Plain SM or smoking guns of NP?
How about charm?

- In experiments producing B mesons there are always D mesons;
- Charm offers tests of possible NP in up sector at low-energies;
- If NP couples to weak doublets of quarks, CKM connects it with charm sector.
- Lattice QCD made progress for charm meson coupling constants and some form-factors
- Can one see NP in charm decays not being present in B meson?
NP constraints from rare $D$ decays

$D + B$ mesons: strong constraints on leptoquark models (favoured by $B$-anomalies), but also $Z'$ models and 2HDM

Analysis of rare decays possible in terms of effective Hamiltonian

Constraints on short-distance physics from $Br(D^0 \rightarrow \mu\mu)$ and $Br(D \rightarrow \pi\mu\mu)$, and also from Lepton Flavour Universality in $D \rightarrow \pi\mu\mu$
$D \to PP\ell\ell$ decays

**Long distances**

- Bremsstrahlung: pure QED effects, calculable with Low’s theorem:
  \[ M_h(D^0 \to h_1^+ h_2^- \gamma) = 2e \left[ \frac{p_1 \cdot \epsilon}{2p_1 \cdot q + q^2} - \frac{p_2 \cdot \epsilon}{2p_2 \cdot q + q^2} \right] M(D^0 \to h_1^+ h_2^-) \]
- Resonant contributions (dominant effects, estimated at $\sim 10^{-6}$).
  For comparison, short distance SM contribution estimated at $\sim 10^{-9}$.
  [Burdman et al'02].
- Charge radius (suppressed, not discussed in this talk).

**Branching ratios**

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Bremsstrahlung</th>
<th>Direct emission (E)</th>
<th>Direct emission (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \to K^-\pi^+ e^-e^+$</td>
<td>$9.9 \cdot 10^{-6}$</td>
<td>$6.2 \cdot 10^{-6}$</td>
<td>$4.8 \cdot 10^{-7}$</td>
</tr>
<tr>
<td>$D^0 \to \pi^+ \pi^- e^-e^-$</td>
<td>$5.3 \cdot 10^{-7}$</td>
<td>$1.3 \cdot 10^{-6}$</td>
<td>$1.3 \cdot 10^{-9}$</td>
</tr>
<tr>
<td>$D^0 \to K^+ K^- e^-e^-$</td>
<td>$3.7 \cdot 10^{-8}$</td>
<td>$1.7 \cdot 10^{-8}$</td>
<td>$1.3 \cdot 10^{-9}$</td>
</tr>
<tr>
<td>$D^0 \to K^-\pi^+ \mu^+\mu^-$</td>
<td>$8.6 \cdot 10^{-7}$</td>
<td>$6.2 \cdot 10^{-6}$</td>
<td>$4.8 \cdot 10^{-7}$</td>
</tr>
<tr>
<td>$D^0 \to \pi^+\pi^-\mu^+\mu^-$</td>
<td>$5.6 \cdot 10^{-8}$</td>
<td>$1.3 \cdot 10^{-6}$</td>
<td>$1.3 \cdot 10^{-9}$</td>
</tr>
<tr>
<td>$D^0 \to K^+K^-\mu^+\mu^-$</td>
<td>$3.3 \cdot 10^{-9}$</td>
<td>$1.1 \cdot 10^{-7}$</td>
<td>$5.0 \cdot 10^{-9}$</td>
</tr>
<tr>
<td>$D^0 \to K^+K^-\mu^+\mu^-$</td>
<td>$3.3 \cdot 10^{-10}$</td>
<td>$1.7 \cdot 10^{-8}$</td>
<td>$1.3 \cdot 10^{-9}$</td>
</tr>
</tbody>
</table>

- Experimental results (LHCb and BaBar):
  \[ B(D^0 \to K^-\pi^+\mu^+\mu^-) = (4.17 \pm 0.42) \cdot 10^{-6} \]
  \[ B(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \cdot 10^{-7} \]
  \[ B(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \cdot 10^{-7} \]
  \[ B(D^0 \to K^-\pi^+e^+e^-) = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \cdot 10^{-6} \]
- Good agreement overall. Approximations capture the bulk of the effect.

- $D \to PP\ell\ell$: interplay of short and long distances
- Hadronic description mandatory: Vector dominance and factorisation of weak matrix elements
- Resonance exchange parametrised by form factors $D \to V$ and $V \to \ell\ell$
- Good overall agreement with later LHCb measurements
- Additional contribution from axial resonances ($a_1(1230)$ and $K_1(1272)$) to be included ($\sim 30\%$ of vector)
Rare $D$ decays at BESIII

Search for $D \to h (h') e^+ e^-$

- UL $10^{-5}$ ~ $10^{-6}$
- Significant improvements in UL


Search for $D^+ \to \gamma e^+ \nu_e$

- Strong interaction effects theoretically simple
- SM predictions range from $10^{-6}$ to $10^{-4}$
- Data sample at $D\bar{D}$ threshold: $2.93\text{fb}^{-1} \sqrt{s} = 3.773\text{GeV}$

$BR(D^+ \to \gamma e^+\nu_e) < 3.0 \times 10^{-5}$

@ 90% C.L.


- Largest systematic from EMC shower model
- More data needed to discriminate th. models

Ongoing rich programme at BESIII

- Bounds on $D \to h(h') e^+ e^- \ (10^{-5} \text{ level})$ and $D^+ \to \gamma e^+ \nu_e$
- Measurements of $D_s^+ \to p\bar{n}$ and $D \to a_0 e^+ \nu_e$
- Ongoing analyses on $D \to K\pi e^+ e^+$, $D \to \pi^0 \nu\bar{\nu}$, baryon/lepton number violation in $D^+ \to \Lambda$ and $\Sigma$
Rare $D$ decays at LHCb

**Results**

Results integrated across $m(\mu^+\mu^-)$

- $A_F\left(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-\right) = (3.3 \pm 3.7 \pm 0.6)\%$
- $A_{FB}\left(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-\right) = (-0.6 \pm 3.7 \pm 0.6)\%$
- $A_{CP}\left(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-\right) = (4.9 \pm 3.8 \pm 0.7)\%$

- $A_F\left(D^0 \rightarrow K^+K^-\mu^+\mu^-\right) = (0 \pm 11 \pm 2)\%$
- $A_{FB}\left(D^0 \rightarrow K^+K^-\mu^+\mu^-\right) = (9 \pm 11 \pm 1)\%$
- $A_{CP}\left(D^0 \rightarrow K^+K^-\mu^+\mu^-\right) = (9 \pm 11 \pm 2)\%$

**World’s best measurements in all cases**

<table>
<thead>
<tr>
<th>Ratio</th>
<th>PDG 2018</th>
<th>This analysis</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(D^+ \rightarrow K^-K^+\pi^+)$</td>
<td>$(9.5 \pm 2.2) \times 10^{-4}$</td>
<td>$(6.541 \pm 0.025 \pm 0.042) \times 10^{-4}$</td>
<td>45</td>
</tr>
<tr>
<td>$B(D^+ \rightarrow K^-\pi^+\pi^+\pi^-)$</td>
<td>$(5.77 \pm 0.22) \times 10^{-3}$</td>
<td>$(5.231 \pm 0.009 \pm 0.023) \times 10^{-3}$</td>
<td>9</td>
</tr>
<tr>
<td>$B(D^+ \rightarrow K^-\pi^+\pi^+\pi^-)$</td>
<td>$(2.33 \pm 0.23) \times 10^{-3}$</td>
<td>$(2.372 \pm 0.024 \pm 0.025) \times 10^{-3}$</td>
<td>6.5</td>
</tr>
<tr>
<td>$B(D^+ \rightarrow K^-\pi^+\pi^+\pi^-)$</td>
<td>$(10.59 \pm 0.18)%$</td>
<td>$(10.282 \pm 0.002 \pm 0.068)%$</td>
<td>2.5</td>
</tr>
</tbody>
</table>

**Preliminary**

- All detection asymmetries are compatible with zero
- No observed dependency on dimuon mass

**LHCb not only with beauty but also with charm in abundance**

- Angular and CP-asymmetries for $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ and $D^0 \rightarrow K^+K^-\mu^+\mu^-$, potential signals of NP (vanish in SM)

- New: measurements of BRs for $D^+ \rightarrow K^-K^+K^+$, $D^+ \rightarrow \pi^-\pi^+K^+$, $D_s^+ \rightarrow \pi^-K^+K^+$ (significant improvement in all modes !)
K decays: probing NP since 1947
### Motivation

**K → ππ**

\( \varepsilon' \): direct CP violation in \( K_L \rightarrow \pi\pi \)

\( \varepsilon \): indirect CP violation in \( K_L \rightarrow \pi\pi \)

### Measurement

- **hep-ex/0208009, hep-ex/0208007**
  - NA48 and KTeV: \((\varepsilon'/\varepsilon)_{\text{exp}} = (16.6 \pm 2.3) \times 10^{-4}\)

### SM prediction

- **Lattice:** \((1.4 \pm 6.9) \times 10^{-4}\), \((1.9 \pm 4.5) \times 10^{-4}\), \((1.1 \pm 5.1) \times 10^{-4}\)
- **RBC-UKQCD:** 1502.00263, 1505.07863
- **Buras/Gorbahn/Jamin/Jäger:** 1507.06345
- **Kitahara/Nierste/Tremper:** 1607.06727
- **χPT:** \((15 \pm 7) \times 10^{-4}\)
- **Gisbert/Pich:** 1712.06147

### Master formula

\[
\left( \frac{\varepsilon'}{\varepsilon} \right)_{\text{NP}} = \sum_i P_i(\mu_W) \text{Im}[C_i(\mu_W) - C_i'(\mu_W)]
\]

with

\[
P_i(\mu_w) = \sum_j \sum_{l=0,2} p^{(l)}_{ij}(\mu_w, \mu_c) \left[ \frac{\langle O_j(\mu_c) \rangle_I}{\text{GeV}^3} \right]
\]

\( p^{(l)}_{ij}(\mu_w, \mu_c) = \text{Evolution from } \mu_c \text{ to } \mu_w \)

\( \langle O_j(\mu_c) \rangle_I = \text{Hadronic MEs} \)

### Ongoing discussion

- Ongoing discussion on the SM computation of \( \varepsilon'/\varepsilon \) with different approaches (lattice, chiral perturbation theory. . .)
- Dual QCD: large \( N_c \) + meson description + \( 1/N_c \) corrections
- Master formula to obtain \( \varepsilon'/\varepsilon \) in SMEFT
Results from NA62/KOTO

NA62:
- One event observed in signal region R2
- $\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu}) < 14 \times 10^{-10}$ @ 95% CL

KOTO:
- No signal candidates observed
- $\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu}) < 3 \times 10^{-9}$ @ 90% CL
- Both results are compatible with the SM
First lattice evaluation of $K^+ \rightarrow \pi^+ \ell\ell$ form factor

Intermediate state subtraction and renormalisation are technical challenges that can be managed

Work in progress towards real-world simulations
Connecting $K \rightarrow \pi \nu \bar{\nu}$ and $B$ anomalies

- **EFT approach based on $U(2)^n$ flavour symmetry**
- $s \rightarrow d\nu\bar{\nu}$ may distinguish between classes of models within EFT
- Interesting correlations between $\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu})$ and
  - $R_{D(\star)}$
  - $\mathcal{B}(B \rightarrow K^{(\star)}\nu\bar{\nu})$
- $PS^3$ model contains $Z'$ contributing to $K \rightarrow \pi \nu \bar{\nu}$ at tree level
  - up to $\sim 20\%$ effects on $\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu})$