Elisa Manoni (INFN Perugia), Christoph M. Langenbruch (RWTH Aachen),
Diego Guadagnoli (CNRS Annecy)
Mon 22 Nov: Rare B decays I

Tue 23 Nov: Rare B decays II

Wed 24 Nov: Radiative B and rare D decays

Joint WG2 & WG3 session

Thu 25 Nov: K decays
Rare B decays I

- LHCb results on rare $b \rightarrow s \ell\ell$ decays (Michal Kreps)

- EW-penguin decays with missing energy and LFV at Belle II (Tao Luo)

- Rare $b \rightarrow s \ell\ell$ decays: progress on QCD uncertainties (Danny van Dyk)

- Searching for New Physics in rare K and B decays without $|V_{cb}|$ and $|V_{ub}|$ uncertainties (Elena Venturini)
In the SM, $b \to s \ell\ell$ cannot happen at tree level
- FCNC decays through loop diagrams
- SM predicts BF of the order $10^{-6}$
- Typically such decays have complex angular structure offering variety of observables
  - Precision of SM prediction varies depending on sensitivity to form factors
- Sensitive probe of NP contribution
- Many intriguing measurements in the past
LHCb results on rare $b \to s \ell\ell$ decays (Michal Kreps)

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- Sensitive probe of NP contribution
- Many intriguing measurements in the past and in the present!
$B_s \rightarrow \phi \mu \mu : \text{BR}$

In $q^2$ between 1.1 and 6.0 GeV$^2$ measurement deviates by 3.6σ from the SM (LCSR+Lattice)
$B_s \to \phi \mu \mu$: angular

- The best fit gives NP contribution $\Delta \text{Re}[C_9] = -1.3^{+0.7}_{-0.6}$
- Preferred by 1.9σ over SM value

Full set of obs. measured, including T-odd $A_8$ and $A_9$
$B^+ \rightarrow K^{*-}\mu\mu$ angular analysis

- General pattern observed similar to $B^0 \rightarrow K^{*0}\mu\mu$
- Largest local deviation from SM has significance of 3.0$\sigma$
- To evaluate consistency with SM, fit for Re[$C_9$] from measured observables using Flavio
  - Uses subset of $q^2$ intervals
- Best fit value Re[$C_9$]=-1.9
- Consistency with SM at 3.1$\sigma$
• In short, tensions persist and these modes are as interesting as ever
• Many additional measurements not shown (e.g. photon polarization in $B^0 \rightarrow K^{*0} \, ee$)
• New measurements expected
• And an upgraded detector
EWP(enguin) decays with $E_{\text{miss}}$ and LFV at Belle II (Tao Luo)

**Belle**

- Search for $B^0 \to K^*\tau^+\tau^-$ at Belle
  
  (arXiv: 2110.03871)

- Search for $B^0_{(d)} \to \tau^{\pm} \ell^{\mp}$ at Belle
  
  (arXiv: 2108.11649)

**Belle II**

- Search for $B^+ \to K^+\nu\bar{\nu}$ at Belle II
  
EWP(enguin) decays with $E_{\text{miss}}$ and LFV at Belle II (Tao Luo)

$B \rightarrow K^* \tau \tau$

The overall selection efficiency, $\epsilon = 1.2 \times 10^{-5}$

$N_{\text{sig}} = -4.9 \pm 6.0$

The upper limit:

$\mathcal{B}(B^0 \rightarrow K^{*0}\tau^+\tau^-) < 2.0 \times 10^{-3}$ at 90% C.L.

The first experimental limit on the decay $B^0 \rightarrow K^{*0}\tau^+\tau^-$.\n
The upper limits: $\mathcal{B}(B^0 \rightarrow \tau\mu) < 1.5 \times 10^{-5}$, $\mathcal{B}(B^0 \rightarrow \tau e) < 1.6 \times 10^{-5}$ at 90 C.L.

Electron mode: the most stringent limit to date
EWP(enguin) decays with $E_{\text{miss}}$ and LFV at Belle II (Tao Luo)

$$B \rightarrow K \nu \bar{\nu}$$

$B(B^+ \rightarrow K^+\nu\bar{\nu}) < 4.1 \times 10^{-5}$ at 90 C.L

Similar upper limit as Belle and BaBar
Rare $b \to s \ell\ell$ decays: progress on QCD errors (Danny van Dyk)

$$L_{\text{SM}}^{\text{eff}} = L_{\text{QCD}} + L_{\text{QED}} + \frac{4G_F}{\sqrt{2}} \left[ \lambda_t \sum_i C_i O_i + \lambda_c \sum_i C_i^c O_i^c + \lambda_u \sum_i C_i^u O_i^u \right]$$

\[ O_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma^{\mu\nu} P_R b) F_{\mu\nu} \]
\[ O_8 = \frac{g_5}{16\pi^2} m_b (\bar{s}\sigma^{\mu\nu} P_R T^A b) G_{\mu\nu}^A \]
\[ O_9 = \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \]
\[ O_{10} = \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \]
\[ O_{1q} = (\bar{q}\gamma_\mu P_L b)(\bar{s}\gamma^\mu P_L q) \]
\[ O_{2q} = (\bar{q}\gamma_\mu P_L T^0 b)(\bar{s}\gamma^\mu P_L T^0 q) \]

\[ \mathcal{A}_\lambda^\chi = \mathcal{N}_\lambda \left\{ (C_9 - C_{10}) \mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2} \left[ C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\} \]

nomenclature of the essential hadronic matrix elements

- $\mathcal{F}_\lambda$: local form factors of dimension-three $\bar{s}\gamma^\mu b$ & $\bar{s}\gamma^\mu \gamma_5 b$ currents
- $\mathcal{F}_\lambda^T$: local dipole form factors of dimension-three $\bar{s}\sigma^{\mu\nu} b$ currents
- $\mathcal{H}_\lambda$: nonlocal form factors of dimension-five nonlocal operators

all three needed for consistent description to leading-order in $\alpha_e$

$q^2 = m_{\ell\ell}$
\[ \mathcal{H}_\lambda(q^2) = P(\lambda) \mu \langle H_S | \int d^4x \, e^{i\mathbf{q} \cdot \mathbf{x}} \, T \{ J^\mu_{\text{em}}(x), [C_1 O^c_1 + C_2 O^c_2](0) \} | H_b \rangle \]

- for \( q^2 - 4m_c^2 \ll \Lambda_{\text{had}} m_b \), **expand** T-product in light-cone operators
- leading contributions expressed through **local form factors** \( \mathcal{F}_\lambda \)
- correction suppressed by \( 1/(q^2 - 4m_c^2) \) can be systematically obtained

\[ O^c_{1,2} \sim [\bar{s} \Gamma b] [\bar{c} \Gamma' c] \]

[sketch from Blake, Gershon, Hiller 1501.03309]

[Khodjamirian, Mannel, Pivovarov, Wang 2010]
The elephant in the room

\[ \mathcal{H}_\lambda(q^2) = P(\lambda)_\mu \langle H_s \rangle \int d^4x e^{iq \cdot x} \mathcal{T} \{ J_{em}^\mu(x), [C_1 O_1^c + C_2 O_2^c](0) \} |H_b\rangle \]

\[ \Rightarrow O_{1,2}^c \sim [S^b] [c\bar{c}'c] \]

new strategy

- compute \( \mathcal{H}_\lambda \) at spacelike \( q^2 \)
- extrapolate to timelike \( q^2 \leq 4M_D^2 \) using suitable parametrization
- include information from non-leptonic decays to narrow charmonia \( J/\psi \) and \( \psi(2S) \)

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[Bobeth, Chrzaszcz, DvD, Virto '17]
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\( \mathcal{O}_1^c \sim [\Sigma b][c\Gamma'c] \)

[Bobeth,Chrzaszcz,DvD,Virto '17]
The elephant in the room

Reappraisal of KMPW in

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    \end{itemize}
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Reappraisal of KMPW in

\[ \text{see also Gubernari, DvD, Virto '20} \]

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The elephant in the room

\[ H_{\lambda}(q^2) = P(\lambda)_\mu \langle H_s | \int d^4x e^{iq\cdot x} \mathcal{T} \{ J^\mu_{em}(x), [C_1 O_1^c + C_2 O_2^c](0) \} | H_b \rangle \]

Global analysis in progress: stay tuned

- New strategy:
  - Compute \( H_{\lambda} \) at spacelike \( q^2 \)
  - Extrapolate to timelike \( q^2 \leq 4M_D^2 \) using suitable parametrization
  - Include information from non-leptonic decays to narrow charmonia \( J/\psi \) and \( \psi(2S) \)

\[ \mathcal{O}_{1,2}^c \sim [\mathcal{S} \Gamma b] [\mathcal{C} \Gamma' c] \]

[Bobeth, Chrzaszcz, DvD, Virto '17]
Large uncertainties on K and B decays

- $|V_{cb}|^2 \rightarrow 16\%$, e.g. in $\text{Br}(B_{s,d} \rightarrow \mu\mu)$ and $\Delta M_{s,d}$
- $|V_{cb}|^3 \rightarrow 24\%$, e.g. in $\text{Br}(K^+ \rightarrow \pi^+\nu\nu)$ and $|\epsilon_K|$\n- $|V_{cb}|^4 \rightarrow 32\%$, e.g. in $\text{Br}(K_L \rightarrow \pi^0\nu\nu)$ and $\text{Br}(K_S \rightarrow \mu\mu)$

$$R_{s(d)\mu} \equiv \frac{\text{Br}(B_{s(d)} \rightarrow \mu^+\mu^-)}{\Delta M_{s(d)}} = C_{\tau_{B_{s(d)}}} \frac{f(x_t)}{\hat{B}_{s(d)}}$$

Idea of:
0303060 [Buras]
2104.09521 [Bobeth, Buras]

$4.291 \cdot 10^{-10}$

$[R_{s\mu}]_{\text{SM}} = (2.04^{+0.08}_{-0.06}) \cdot 10^{-10}\text{ps}$ vs $[R_{s\mu}]_{\text{exp}} = (1.61^{+0.19}_{-0.17}) \cdot 10^{-10}\text{ps}$

**2.1σ tension with SM**

WITHOUT CKM uncertainties
Searching for NP without $V_{cb}$ and $V_{ub}$ errors (Elena Venturini)

Then systematically define $|V_{cb}|$-independent ratios

\[
R_5 \equiv \frac{\text{Br}(K^+ \to \pi^+\nu\nu)}{[\text{Br}(B^+ \to K^+\nu\nu)]^{1.4}} \propto [\sin \gamma]^{1.39}
\]

\[
R_6 \equiv \frac{\text{Br}(K^+ \to \pi^+\nu\nu)}{[\text{Br}(B^0 \to K^{0*}\nu\nu)]^{1.4}} \propto [\sin \gamma]^{1.39}
\]

\[
R_7 \equiv \frac{\text{Br}(B^+ \to K^+\nu\nu)}{\text{Br}(B_s \to \mu\mu)} \propto [F_{B_s}]^{-2}
\]

\[
R_8 \equiv \frac{\text{Br}(B^0 \to K^{0*}\nu\nu)}{\text{Br}(B_s \to \mu\mu)} \propto [F_{B_s}]^{-2}
\]

\[
R_9 \equiv \frac{|\epsilon_K|}{(\Delta M_d)^{1.7}} \propto [\sin \gamma]^{-1.73}[\sin \beta]^{0.87}
\]

\[
R_{10} \equiv \frac{|\epsilon_K|}{(\Delta M_s)^{1.7}} \propto [\sin \gamma]^{1.67}[\sin \beta]^{0.87}
\]

\[
R_{11} \equiv \frac{\text{Br}(K^+ \to \pi^+\nu\nu)}{|\epsilon_K|^{0.82}} \propto [\sin \gamma]^{0.015}[\sin \beta]^{-0.71}
\]

\[
R_{12} \equiv \frac{\text{Br}(K_L \to \pi^0\nu\nu)}{|\epsilon_K|^{1.18}} \propto [\sin \gamma]^{0.03}[\sin \beta]^{0.98}
\]

Almost depending only on $\beta$:
accurately determined from $S_{\psi K_S}$

\[
R_0 \equiv \frac{\text{Br}(K^+ \to \pi^+\nu\nu)}{\text{Br}(K_{L} \to \pi^0\nu\nu)^{0.7}} \propto [\sin \beta]^{-1.4}
\]

\[
R_{SL} \equiv \frac{\text{Br}(K_S \to \mu\mu)_{SD}}{\text{Br}(K_{L} \to \pi^0\nu\nu)} \propto \text{const}
\]

\[
R_{s\mu} \equiv \frac{\text{Br}(B_s \to \mu\mu)}{\Delta M_s} \propto \text{const}
\]

\[
R_{d\mu} \equiv \frac{\text{Br}(B_d \to \mu\mu)}{\Delta M_d} \propto \text{const}
\]

CKM independent
Rare B decays II

- Rare B decays at CMS and ATLAS (Pavel Reznicek)
- Very rare B decays (Francesco Dettori)
- Wilson coefficients and global fits (Peter Stangl)
- Model-building for rare B-decay anomalies (Claudia Cornella)
The $B_{d,s}^0 \rightarrow \mu^+ \mu^-$ decays

Extremely rare decays
- Flavour changing neutral currents
- Helicity suppressed

Most recent Standard Model predictions $^\dagger$

$$B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$
$$B(B^0 \rightarrow \mu^+ \mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$


- Impressively precise predictions
- Any significant deviations from these values is sign of new interactions beyond the SM
- Dominated by parametric uncertainties

Using the correlation of $\Delta F = 1$ rare decays with $\Delta F = 2$ B mixing, using experimental $\Delta M$ values can also be predicted to be:

$$B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.62^{+0.15}_{-0.10}) \times 10^{-9}$$
$$B(B^0 \rightarrow \mu^+ \mu^-) = (0.99^{+0.05}_{-0.03}) \times 10^{-10}$$

[Buras, Venturini -2109.11032]
Very rare B decays at LHCb  (Francesco Dettori)

\[ \mathcal{B}(B^0 \to \mu^+ \mu^-) = \left( 3.09^{+0.46+0.15}_{-0.43-0.11} \right) \times 10^{-9} \]

\[ \mathcal{B}(B^0 \to \mu^+ \mu^-) = \left( 1.2^{+0.8}_{-0.7} \pm 0.1 \right) \times 10^{-10} < 2.6 \times 10^{-10} \]

\[ \mathcal{B}(B^0 \to \mu^+ \mu^- \gamma)_{m_{\mu\mu}>4.9\text{ GeV}} = (-2.5 \pm 1.4 \pm 0.8) \times 10^{-9} < 2.0 \times 10^{-9} \]

No significant signal for \( B^0 \to \mu^+ \mu^- \) and \( B^0 \to \mu^+ \mu^- \gamma \), upper limits at 95%

First world limit on \( B_s^0 \to \mu^+ \mu^- \gamma \) decay
Very rare B decays at LHCb  (Francesco Dettori)

**Combined measurement of hadronisation fraction**

...and $B_s^0$ branching fractions

Breaking the recursive problem: combine information of different measurements
Measure production ratios from ratio of decays with known rate (semileptonic) or
known rate ratios ($B \rightarrow Dh$), and cross-check dependencies with decays of high rate
($B \rightarrow J/\psi X$).
Recent LHCb combination $\frac{f_s}{f_d} (13 \text{ TeV}) = 0.2539 \pm 0.0079$

... plus many other measurements that we can’t detail unfortunately

- $\tau_{\text{eff}} (B_s^0 \rightarrow \mu^+ \mu^-) = 2.07 \pm 0.29 \pm 0.03 \text{ ps}$

- Updated $B_{(s)}^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ search
  * First search for $B \rightarrow aa$ with mass also around 1 GeV
  * Strong constraints on all branching fractions

- Search for $B^0 \rightarrow \phi \mu^+ \mu^-$ decays leads world best limit
Rare $B$ decays at CMS and ATLAS (Pavel Reznicek)

- Program focused mostly on muonic final states, fully reconstructable; exceptions exist:
  - CMS B-parking Run 2 data collecting huge unbiased ($\sim 10^{10}$) $b$-hadron events
  - Di-electron triggers in Run 2 at ATLAS

$B_s \rightarrow \mu \mu$

Eff. lifetime measured as well!
Rare $B$ decays at CMS and ATLAS

$B^0 \rightarrow K^{*0}\mu\mu$: Results (CMS, ATLAS)

CMS: $P_1, P'_5, A_{FB}, F_L$; full $q^2$ range

- Consistent with SM predictions

<table>
<thead>
<tr>
<th>Source</th>
<th>$P_1(\times 10^{-3})$</th>
<th>$P'_5(\times 10^{-3})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation mismodeling</td>
<td>1–33</td>
<td>10–23</td>
</tr>
<tr>
<td>Fit bias</td>
<td>5–78</td>
<td>10–120</td>
</tr>
<tr>
<td>Finite size of simulated samples</td>
<td>29–73</td>
<td>31–110</td>
</tr>
<tr>
<td>Efficiency</td>
<td>17–100</td>
<td>5–65</td>
</tr>
<tr>
<td>$K/\pi$ misstagging</td>
<td>8–110</td>
<td>6–66</td>
</tr>
<tr>
<td>Background distribution</td>
<td>12–70</td>
<td>10–51</td>
</tr>
<tr>
<td>Mass distribution</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>Feed-through background</td>
<td>4–12</td>
<td>3–24</td>
</tr>
<tr>
<td>$F_5, F_6, A_S$ uncertainty propagation</td>
<td>0–210</td>
<td>0–210</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>2–68</td>
<td>0.1–12</td>
</tr>
<tr>
<td>Total</td>
<td>100–230</td>
<td>70–250</td>
</tr>
</tbody>
</table>

ATLAS: $P_1, P'_4, P'_5, P'_6, P'_8, F_L$; low $q^2$ range only

- $P'_5$ and $P'_4$ deviation of $2.7\sigma$ in $q^2 = (4 - 6)$ GeV$^2$ following direction of the LHCb deviation
- But still compatible with SM prediction
Setup

- Quantify agreement between theory and experiment by $\chi^2$ function

$$
\chi^2(\vec{C}) = \left( \vec{o}_{\text{exp}} - \vec{o}_{\text{th}}(\vec{C}) \right)^T \left( C_{\text{exp}} + C_{\text{th}}(\vec{C}) \right)^{-1} \left( \vec{o}_{\text{exp}} - \vec{o}_{\text{th}}(\vec{C}) \right).
$$

- **theory errors** and **correlations** in covariance matrix $C_{\text{th}}$

- **experimental errors** and available **correlations** in covariance matrix $C_{\text{exp}}$

- Theory errors depend on new physics (NP) Wilson coefficients $C_{\text{th}}(\vec{C})$ *NEW*

- $\Delta \chi^2$ and pull

$$
pull_{1D} = 1\sigma \cdot \sqrt{\Delta \chi^2}, \quad \text{where } \Delta \chi^2 = \chi^2(\vec{o}) - \chi^2(\vec{C}_{\text{best fit}}).
$$

$$
pull_{2D} = 1\sigma, 2\sigma, 3\sigma, \ldots \quad \text{for } \Delta \chi^2 \approx 2.3, 6.2, 11.8, \ldots
$$

- New physics scenarios in **Weak Effective Theory (WET)** at scale 4.8 GeV
Scenarios with a single Wilson coefficients

<table>
<thead>
<tr>
<th>Wilson coefficient</th>
<th>$b \to s_{\mu\mu}$ best fit</th>
<th>pull</th>
<th>$\text{LFU, } B_s \to \mu\mu$ best fit</th>
<th>pull</th>
<th>all rare $B$ decays best fit</th>
<th>pull</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NP err.</strong></td>
<td></td>
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</tr>
<tr>
<td>$C^{bs_{\mu\mu}}_9$</td>
<td>$-0.70^{+0.21}_{-0.22}$</td>
<td>$3.3\sigma$</td>
<td>$-0.74^{+0.20}_{-0.21}$</td>
<td>$4.1\sigma$</td>
<td>$-0.71^{+0.15}_{-0.15}$</td>
<td>$5.1\sigma$</td>
</tr>
<tr>
<td>$C^{bs_{\mu\mu}}_{10}$</td>
<td>$+0.45^{+0.22}_{-0.23}$</td>
<td>$1.9\sigma$</td>
<td>$+0.60^{+0.14}_{-0.14}$</td>
<td>$4.7\sigma$</td>
<td>$+0.54^{+0.12}_{-0.12}$</td>
<td>$4.8\sigma$</td>
</tr>
<tr>
<td>$C^{bs_{\mu\mu}}<em>9 = -C^{bs</em>{\mu\mu}}_{10}$</td>
<td>$-0.55^{+0.13}_{-0.13}$</td>
<td>$3.8\sigma$</td>
<td>$-0.35^{+0.08}_{-0.08}$</td>
<td>$4.6\sigma$</td>
<td>$-0.39^{+0.07}_{-0.07}$</td>
<td>$5.6\sigma$</td>
</tr>
<tr>
<td><strong>SM err.</strong></td>
<td></td>
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<tr>
<td>$C^{bs_{\mu\mu}}_9$</td>
<td>$-0.83^{+0.22}_{-0.20}$</td>
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<td>$4.1\sigma$</td>
<td>$-0.77^{+0.15}_{-0.15}$</td>
<td>$5.3\sigma$</td>
</tr>
<tr>
<td>$C^{bs_{\mu\mu}}_{10}$</td>
<td>$+0.45^{+0.21}_{-0.20}$</td>
<td>$2.3\sigma$</td>
<td>$+0.60^{+0.14}_{-0.14}$</td>
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Visible effect of theory errors depending on new physics, in particular for $C^{bs_{\mu\mu}}_9$.
Scenarios with two Wilson coefficients

Combination of $B_s \to \mu^+ \mu^-$ and LFU observables $(R_K, R_{K^*}, D_{P_{A',5'}})$

- LFU obs. & $B_s \to \mu \mu$ : very clean theory prediction, insensitive to universal $C^\text{univ}_9$.
- $b \to s \mu \mu$ sensitive to univ. coeff. possibly afflicted by underestimated hadr. uncert.
- Agreement between $b \to s \mu \mu$ observables and $R_K$ & $R_{K^*}$ could be further improved by LFU contribution to $C^\text{univ}_9$.

possible connection to $b \to c \ell \nu$ anomalies see backup slides and talk by Claudia Cornella

Global fit in $C^b_{9,10}$ plane prefers negative $C^b_{9} = -C^b_{10}$
Robustness of global fits

ACDMN (Algueró, Capdevila, Descotes-Genon, Matias, Novoa-Brunet), arXiv:2104.08921
AS (Altmannshofer, PS), arXiv:2103.13370
HMMN (Hurth, Mahmoudi, Martínez-Santos, Neshatpour), arXiv:2104.10058
Apologies for having to skip other interesting aspects, including

- global fits in the SMEFT
- global fits within Leptoquark models
- specific models of muonic anomalies
Model-building for the anomalies (Claudia Cornella)

\[ \sim 4 \times 10^{-5} \, G_F \Rightarrow \frac{g_{\text{NP}}^2}{\Lambda^2} \sim \frac{1}{(40 \, \text{TeV})^2} \]

\[ \sim 10^{-2} \, G_F \]
Why both?

No obvious connection. Why combine both anomalies in a single NP framework?

\[
\begin{align*}
    b & \rightarrow sll \\
    (\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L) & \quad \text{SU}(2)_L & \quad (\bar{c}_L \gamma^\mu b_L)(\bar{\nu}_L \gamma_\mu \nu_L)
\end{align*}
\]

⇒ Minimal sol: left-handed NP in semi-leptonic operators (RH currents also possible)

- Three possibilities for a combined explanation:
  - \( S_1 + S_3 \) [Crivellin et al. 1703.09226; Buttazzo et al. 1706.07808; Marzocca 1803.10972...]
  - \( R_2 + S_3 \) [Bečirević et al., 1806.05689]
  - \( U_1 \sim (3, 1, 2/3) \) [di Luzio et al., 1708.08450; Calibbi et al., 1709.00692; Bordone, CC, et al. 1712.01368; Barbieri, Tesi 1712.06844; Heck, Teresi 1808.07492...]

✓ no \( b \rightarrow s\nu\bar{\nu} \) at tree level
Model-building for the anomalies (Claudia Cornella)

Low-energy predictions for the $U_1$

- large $b \to s\tau\tau$
- large $\tau/\mu$ LFV in $b \to s\tau\mu$ and $\tau$ decays

High-pT bounds for the $U_1$

The same interaction can be probed in *di-tau tails.*
Expected excess in $pp \to \tau^+\tau^-$!  
[Faroughy et al., 1609.07138]
Model-building for the anomalies (Claudia Cornella)

UV-sensitive low-energy observables

- $B_s - \bar{B}_s$ mixing
  \[
  \frac{C_{bs}^{NP-\text{tree}}}{C_{bs}^{\text{SM}}} \propto (\beta_{L}^{\text{st}})^2 M_{L}^2
  \]
- $B \rightarrow K \nu \bar{\nu}$

\[\Rightarrow U(2)_{4} \text{ breaking (for } R_{D_{s}})\]

UV-completing the $U_1$: the gauge path

$G_{4321} = SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$

- $SU(4)$ decorrelated from $SU(3)_c$. High-pT problem solved for $g_4 \gg g_1, g_3$
- both $Z'$ and $U_1$ can be flavor non-universal

[Selimovic et al., 2009.11298]
[CC, Fuentes et al., 2103.16558]

$4321/\text{SM} \ni U_1, Z', G' \sim (8,1,0)$

[Georgi and Y. Nakai, 1606.05865;
Diaz, Schmaltz, Zhong, 1706.05033;
Di Luzio, Grejo, Nardecchia, 1708.08450]
Radiative B and rare D decays

- On the $\bar{B} \rightarrow X_s \gamma$ accuracy (Abdur Rehman)
- Radiative B decays at LHCb (Carla Marin Benito)
- Radiative B decays at Belle & Belle II (Markus Roerken)
- Rare D decays at LHCb (Davide Brundu)
- Rare D decays at BES III (Liang Sun)
On the $\bar{B} \to X_s \gamma$ accuracy (Abdur Rehman)

Branching fraction, HFLAV [arXiv:1909.12524]

$\mathcal{B}_{s\gamma}$: CP- and isospin-averaged BR of $\bar{B} \to X_s \gamma$ and $B \to X_{\bar{s}} \gamma$

$\bar{B} = B^- (b\bar{u})$ or $\bar{B}^0 (b\bar{d})$

$\mathcal{B}^{\text{exp}}_{s\gamma} = (3.32 \pm 0.15) \cdot 10^{-4}$ (for $E_{\gamma} > 1.6$ GeV)

(4.5%)

Background grows for smaller $E_{\gamma}$! Average CLEO, BELLE and BABAR with $E_0 \in [1.7, 2.0]$ GeV. Then, extrapolate to $E_0 = 1.6$ GeV $\simeq m_b/3$.

**THEORY:** $E_0$ should be large ($\sim m_b/2$) but not too close to the endpoint ($m_b - 2E_0 \gg \Lambda_{\text{QCD}}$), $E_0 = 1.6$ GeV is now conventional.
On the $\bar{B} \to X_s \gamma$ accuracy (Abdur Rehman)

The matrix elements can be "effectively" evaluated in perturbation theory.

$$\mathcal{B}(\bar{B} \to X_s \gamma)_{E_\gamma > E_0} = \mathcal{B}(\bar{B} \to X_c e\bar{\nu})_{\text{exp}} \left| \frac{V_{tb} V_{ts}^*}{V_{cb}} \right|^2 \frac{6\alpha_{\text{em}}}{\pi C} \left[ P(E_0) + N(E_0) \right]$$

$$\Gamma(b \to X_s^p \gamma)_{E_\gamma > E_0} \simeq N \sum_{i,j=1}^{8} C_i(\mu_b) C_j(\mu_b) \hat{G}_{ij}(E_0, \mu_b)$$

This talk $G^{(2)}_{27}(z)$: (an interference of $Q_2$ and $Q_7$ operators) for arbitrary charm quark mass
Updated SM predictions for $\mathcal{B}_{s\gamma}$ and $R_\gamma \equiv \mathcal{B}_{(s+d)\gamma}/\mathcal{B}_{c\ell\bar{\nu}}$

Mikolaj Misiak, Abdur Rehman, Matthias Steinhauser

\[ \mathcal{B}_{s\gamma}^{\text{SM}} = (3.40 \pm 0.17) \times 10^{-4} \pm 5.0\% \]
\[ R_\gamma = (3.35 \pm 0.16) \times 10^{-3} \pm 4.8\% \]
\[ \mathcal{B}_{c\ell\bar{\nu}} \]

Mikolaj Misiak et al.
[arXiv:1503.01789]

\[ (3.36 \pm 0.23) \times 10^{-4} \pm 6.9\% \]
\[ (3.31 \pm 0.22) \times 10^{-3} \pm 6.7\% \]

Belle-II: Better accuracy is expected, $\sim 2.6\%$; [arXiv:1808.10567]
Radiative $B$ decays at LHCb (Carla Marin Benito)

Photon polarization in $B_s \rightarrow \phi \gamma$

Time dependent decay rate for $f_{CP}$ states gives access to photon polarization:

$$
\Gamma(t) \propto e^{-\Gamma_{st}} \left[ \cosh \left( \frac{\Delta \Gamma_{(s)}}{2} \right) - A^\Delta \sinh \left( \frac{\Delta \Gamma_{(s)}}{2} \right) \pm C_{CP} \cos (\Delta m_{(s)} t) \mp S_{CP} \sin (\Delta m_{(s)} t) \right]
$$

Accessible from decay time distribution

Require knowledge of the $B_s$ flavour at production

In terms of Wilson coefficients:

$$
A^\Delta_{\phi \gamma} \approx \frac{\text{Re} (e^{-i\phi_s} C_7 C_7')}{|C_7|^2 + |C_7'|^2}, \quad S_{\phi \gamma} \approx \frac{\text{Im} (e^{-i\phi_s} C_7 C_7')}{|C_7|^2 + |C_7'|^2}
$$

First measurement in $B_s$ system

$$
S_{\phi \gamma} = 0.43 \pm 0.30 \pm 0.11 \\
C_{\phi \gamma} = 0.11 \pm 0.29 \pm 0.11 \\
A^\Delta_{\phi \gamma} = -0.67^{+0.37}_{-0.41} \pm 0.17
$$
First observation of $\Lambda_b^0 \rightarrow \Lambda\gamma$

Using 2016 dataset (1.7 fb$^{-1}$)

Significance of $5.6\sigma \rightarrow$ First observation!

Normalising to the well-known $B^0 \rightarrow K^*\gamma$:

$$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda\gamma) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \times 10^{-6}$$
Photon polarisation in $\Lambda_0^b \rightarrow \Lambda \gamma$

New constraints on $C_7$ and $C'_7$: discard 2 so-far allowed solutions

Constraints at 1σ
- $\Lambda_0^b \rightarrow \Lambda \gamma$
- $B(B \rightarrow X_s \gamma)$
- $B^0 \rightarrow K^0_{S\pi^0}\gamma$
- $B^0 \rightarrow \phi \gamma$
- $B^0 \rightarrow K^{*0}e^+e^-$
- Global no $\Lambda_0^b \rightarrow \Lambda \gamma$
- Global

arXiv:2111.10194
Radiative B decays at Belle & Belle II (Markus Roehrken)

Exclusive

- Belle measurement with fill dataset (711 fb⁻¹):
  - 3% precision on BF CP asymmetry consistent with zero and SM prediction
  - first evidence of isospin asymmetry at 3.1σ

- Preliminary Belle II (62.8 fb⁻¹) consistent with expectation:

<table>
<thead>
<tr>
<th>Mode</th>
<th>$B_{\text{meas}}$ [$10^{-5}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to K^*[0][K^+\pi^-]\gamma$</td>
<td>$4.5 \pm 0.3 \pm 0.2$</td>
</tr>
<tr>
<td>$B^0 \to K^*[0][K_S^0\pi^-]\gamma$</td>
<td>$4.4 \pm 0.9 \pm 0.6$</td>
</tr>
<tr>
<td>$B^+ \to K^{*+}[K^0\pi^+][K^+\pi^-]\gamma$</td>
<td>$5.0 \pm 0.5 \pm 0.4$</td>
</tr>
<tr>
<td>$B^+ \to K^{*+}[K^0\pi^+][K^0\pi^+]\gamma$</td>
<td>$5.4 \pm 0.6 \pm 0.4$</td>
</tr>
</tbody>
</table>

- Prospects at Belle II (62.8 fb⁻¹):

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle 0.71 ab⁻¹</th>
<th>Belle II 5 ab⁻¹</th>
<th>Belle II 50 ab⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta_{0+}(B \to K^*\gamma)$</td>
<td>2.0%</td>
<td>0.70%</td>
<td>0.53%</td>
</tr>
<tr>
<td>$A_{CP}(B^0 \to K^{*0}\gamma)$</td>
<td>1.7%</td>
<td>0.58%</td>
<td>0.21%</td>
</tr>
<tr>
<td>$A_{CP}(B^+ \to K^{*+}\gamma)$</td>
<td>2.4%</td>
<td>0.81%</td>
<td>0.29%</td>
</tr>
<tr>
<td>$\Delta A_{CP}(B \to K^*\gamma)$</td>
<td>2.9%</td>
<td>0.98%</td>
<td>0.36%</td>
</tr>
<tr>
<td>$S_{K^{*0}\gamma}$</td>
<td>0.29</td>
<td>0.090</td>
<td>0.030</td>
</tr>
</tbody>
</table>

[The Belle II Physics Book, BELLE2-PAPER-2018-001]
Radiative $B$ decays at Belle & Belle II (Markus Roehrken)

**Inclusive**

- $B \to X_s \gamma$ reconstruction at $B$ factories, how to:

  - Fully inclusive, no tagging: $B \to \text{anything}$
    - $\epsilon \approx O(10\%)$
  - Lepton tagging: $B \to lX$
    - $\epsilon \approx O(1\%)$
  - Semileptonic tagging: $B \to D^{(*)} l \nu \pi$
    - $\epsilon \approx O(0.2\%)$
  - Hadronic tagging: $B \to \text{hadrons, e.g. } B \to D^{(*)} \pi$
    - $\epsilon \approx O(0.1\%)$

**Belle/Belle II status and Belle II prospects**

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle 0.71 ab$^{-1}$</th>
<th>Belle II 5 ab$^{-1}$</th>
<th>Belle II 50 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Br}(B \to X_s \gamma)_{\text{lep-tag}}$</td>
<td>5.3%</td>
<td>3.9%</td>
<td>3.2%</td>
</tr>
<tr>
<td>$\text{Br}(B \to X_s \gamma)_{\text{had-tag}}$</td>
<td>13%</td>
<td>7.0%</td>
<td>4.2%</td>
</tr>
<tr>
<td>$\text{Br}(B \to X_s \gamma)_{\text{sum-of-ex}}$</td>
<td>10.5%</td>
<td>7.3%</td>
<td>5.7%</td>
</tr>
<tr>
<td>$\Delta_{0+}(B \to X_{s\gamma})_{\text{sum-of-ex}}$</td>
<td>2.1%</td>
<td>0.81%</td>
<td>0.63%</td>
</tr>
<tr>
<td>$\Delta_{0+}(B \to X_{s+d\gamma})_{\text{had-tag}}$</td>
<td>9.0%</td>
<td>2.6%</td>
<td>0.85%</td>
</tr>
<tr>
<td>$\text{ACP}(B \to X_s \gamma)_{\text{sum-of-ex}}$</td>
<td>1.3%</td>
<td>0.52%</td>
<td>0.19%</td>
</tr>
<tr>
<td>$\text{ACP}(B^0 \to X_s^0 \gamma)_{\text{sum-of-ex}}$</td>
<td>1.8%</td>
<td>0.72%</td>
<td>0.26%</td>
</tr>
<tr>
<td>$\text{ACP}(B^0 \to X_s^+ \gamma)_{\text{sum-of-ex}}$</td>
<td>1.8%</td>
<td>0.69%</td>
<td>0.25%</td>
</tr>
<tr>
<td>$\text{ACP}(B \to X_{s+d\gamma})_{\text{lep-tag}}$</td>
<td>4.0%</td>
<td>1.5%</td>
<td>0.48%</td>
</tr>
<tr>
<td>$\text{ACP}(B \to X_{s+d\gamma})_{\text{had-tag}}$</td>
<td>8.0%</td>
<td>2.2%</td>
<td>0.70%</td>
</tr>
<tr>
<td>$\Delta\text{ACP}(B \to X_s \gamma)_{\text{sum-of-ex}}$</td>
<td>2.5%</td>
<td>0.98%</td>
<td>0.30%</td>
</tr>
<tr>
<td>$\Delta\text{ACP}(B \to X_{s+d\gamma})_{\text{inc}}$</td>
<td>16%</td>
<td>4.3%</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

Rare D decays at LHCb (Davide Brundu)

- Plethora of D decay modes, from forbidden to not-so-rare, to search for new physics effect

<table>
<thead>
<tr>
<th>Search for NP in branching fractions</th>
</tr>
</thead>
</table>
| • search for $D^0 \rightarrow \mu^+\mu^-$  
  [PLB 725:15-24 (2013)] |
| • search for $D_{s}^{+} \rightarrow h^{+}\ell^{+}\ell^-$  
  [JHEP 06 44 (2021)] |
| • search for $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$  
  [PLB 728:234-243 (2014)] |
| • observation of $D^0 \rightarrow K^+\pi^-\mu^+\mu^-$  
  [PLB 757:558-567 (2016)] |
| • search for $\Lambda_c^+ \rightarrow p\mu^+\mu^-$  
  [PRD 97:091101 (2018)] |
| • observation of $D^0 \rightarrow h^+h^-\mu^+\mu^-$  
  [PRL 110:181605 (2013)] |

<table>
<thead>
<tr>
<th>Search for NP based on symmetries</th>
</tr>
</thead>
</table>
| • search for $D^0 \rightarrow \mu^+e^-$  
  [PLB 754:167 (2016)] |
| • search for $D_{s}^{+} \rightarrow \pi^+\ell^+\ell^-$  
  [JHEP 06 44 (2021)] |
| • search for CPV and angular asymmetries in $D^0 \rightarrow h^+h^-\mu^+\mu^-$  
  [PRL 121:091801 (2018)] |
| • full angular analysis and search for CPV in $D^0 \rightarrow h^+h^-\mu^+\mu^-$  
  [arXiv:2111.03327 [hep-ex]] |

- $D_{(s)}^{+} \rightarrow h^+\ell^+\ell^-$  
  [JHEP 06 44 (2021)]

- $D^0 \rightarrow h^+h^-\ell^+\ell^-$  
  [arXiv:2111.03327]

- angular analysis and CP asymmetry measurement to test SM

- No evidence for signal, large improvement on BF wrt previous measurement

New updates are coming very soon ($D^0$ 4-body decays with electrons in the final state, update on $D^0$ 3-body decays presented today, update of $D^0 \rightarrow \mu^+\mu^-$).
Rare $D$ decays at BES III (Liang Sun)

- **Majorana neutrino indirect search with** $D \to K\pi e^+e^+$
  
  [PRD 99, 112002 (2019)]

  - BF Upper limits @ 90% CL are determined:
    
    | Channels          | Upper Limit |
    |-------------------|-------------|
    | $D^0 \to K^-\pi^-e^+e^+$ | $2.8 \times 10^{-6}$ |
    | $D^+ \to K^0\pi^-e^+e^+$ | $3.3 \times 10^{-6}$ |
    | $D^+ \to K^-\pi^0e^+e^+$ | $8.5 \times 10^{-6}$ |

  First searches on both channels so far!

- **Testing Baryon number violation with** $D^+ \to \Lambda (\Sigma_0)e$
  
  [PRD 101, 031102 (2020)]

  - BF Upper limits @ 90% CL are determined:
    
    | Channels          | Upper Limit |
    |-------------------|-------------|
    | $D^+ \to \Lambda e^+$ | $1.1 \times 10^{-6}$ |
    | $D^+ \to \bar{\Lambda} e^+$ | $6.5 \times 10^{-7}$ |
    | $D^+ \to \Sigma^0 e^+$ | $1.7 \times 10^{-6}$ |
    | $D^+ \to \bar{\Sigma}^0 e^+$ | $1.3 \times 10^{-6}$ |

  First searches

- More analyses on rare/forbidden decays are on the way:
  - A wide range of topics: invisible final states, LNV, BNV, FCNC, etc.
  - Still great potentials on $D_s^+$ and $\Lambda^+_c$ decays
  - More $\psi(3770)$ data: $\int \mathcal{L} \sim 20 \text{ fb}^{-1}$ in a few years [Chin. Phys. C 44, 040001 (2020)]
Joint WG2 & WG3 session

- $R(D(\ast))$ at LHCb  (Luke Scantlebury-Smead)  
  [covered by WG2]

- $R_{K(\ast)}$ at LHCb and Belle II  (Renato Quagliani)

- QED corrections: open challenges  (Robert Szafron)

- On the $R_{K(\ast)}$ theory error  (Saad Nabebaccus)
$R_{K}(r) \text{ at } LHCb$ and Belle II (Renato Quagliani)

$R_{K}(r) \text{ at } LHCb$

3.1σ from SM

- Same test at resonances also performed
  - $r_{J/\psi} = 0.981 \pm 0.020 (stat + sys)$
  - $R_{\psi(2S)} = 0.997 \pm 0.011 (stat + sys)$

<table>
<thead>
<tr>
<th>$R(K^{*0})$</th>
<th>$q^2 [0.045,1.1] \text{ GeV}^2 / c^4$</th>
<th>$q^2 [1.1,6] \text{ GeV}^2 / c^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$0.66^{+0.11}_{-0.07} \pm 0.03$</td>
<td>$0.69^{+0.11}_{-0.07} \pm 0.05$</td>
</tr>
<tr>
<td>2.1-2.3 σ below SM</td>
<td>2.4-2.5 σ below SM</td>
<td></td>
</tr>
</tbody>
</table>
More R’s at LHCb

\[ R(pK) = 0.86^{+0.14}_{-0.11} \pm 0.05 \]

\[ R_{K^0} = 0.66^{+0.20}_{-0.15} \text{(stat)}^{+0.02}_{-0.04} \text{(syst)} \]

[1.1 < q^2/\text{GeV}^2 < 6.0]

Significance w.r.t SM: 1.5\sigma

\[ R_{K^{*+}} = 0.70^{+0.18}_{-0.13} \text{(stat)}^{+0.03}_{-0.04} \text{(syst)} \]

[0.045 < q^2/\text{GeV}^2 < 6.0]

Significance w.r.t SM: 1.4\sigma

Same enticing pattern everywhere
$R_{K(*)}$ at LHCb and Belle II (Renato Quagliani)

$R_{Xs}$ at Belle II

Promising expectations for inclusive $B \rightarrow X_s\ell\ell$ at Belle II

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle (0.71 ab$^{-1}$)</th>
<th>Belle II (5 ab$^{-1}$)</th>
<th>Belle II (50 ab$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{Xs}$ ([1.0, 6.0] GeV$^2$/c$^4$)</td>
<td>32%</td>
<td>12%</td>
<td>4.0%</td>
</tr>
<tr>
<td>$R_{Xs}$ ([&gt; 14.4] GeV$^2$/c$^4$)</td>
<td>28%</td>
<td>11%</td>
<td>3.4%</td>
</tr>
</tbody>
</table>
Why are QED corrections to $B \rightarrow K\ell^+\ell^-$ important?

Expected to be small, since $\frac{\alpha}{\pi} \approx 2 \cdot 10^{-3}$.

Due to kinematic effects however, QED corrections are enhanced to $O(\frac{\alpha}{\pi}) \ln \hat{m}_\ell \gtrsim 2 - 3\%$ [Note: $\hat{m}_\ell = \frac{m_\ell}{m_B}$].

Bordone et al. (1605.07633) already performed a calculation to estimate QED corrections to $R_K$, working in single differential in $q^2$.

More general study in Isidori, Nabeebaccus, Zwicky (+ work in progress)

We work with full matrix elements (real and virtual), starting from an EFT Lagrangian description. Hence, we can capture effects beyond collinear $\ln \hat{m}_\ell$ terms, such as $\ln \hat{m}_K$ which are not necessarily small.
Q: Do we miss any $\ln \hat{m}_\ell$ contributions due to structure dependence, by doing an EFT calculation?

A: No, gauge invariance ensures that there are no such additional contributions. [Sec. 3.4, Isidori, SN, Zwicky ’20]

However, using the EFT analysis, we do not capture $\ln \hat{m}_K$ effects, which are not so small.

$\implies$ Structure Dependent Contributions: LCSR approach [Ongoing].

- $\bar{B} \to \bar{K}\ell^+\ell^-$ differential distribution through Monte Carlo: Check PHOTOS and investigate effects of charmonium resonances [Ongoing].
Phenomenology

1. Structure dependent corrections for semi-leptonic heavy-to-light and $R_K^{(*)}$ ratios

\[ \Delta_{QED}^R = \frac{1 + \Delta_{QED}^\mu}{1 + \Delta_{QED}^e} \sim \frac{1 + \mathcal{O}(\alpha) \mathcal{O} \left( \frac{m_\mu^2}{\Lambda_{QCD}^2} \right) \mathcal{O} \left( \ln \frac{m_\mu^2}{...} \right)}{1 + \mathcal{O}(\alpha) \mathcal{O} \left( \frac{m_e^2}{\Lambda_{QCD}^2} \right) \mathcal{O} \left( \ln \frac{m_e^2}{...} \right)} = 1 + \mathcal{O}(\alpha) \mathcal{O} \left( \ln \frac{m_\mu^2}{...} \right) \]

Worst case scenario: additional few % uncertainty from structure dependent corrections!

2. Lattice evaluation of QED corrections for heavy mesons: complementary to the EFT approach

\[ \ln \frac{m_\mu}{\Delta E} \sim 2.5; \quad \ln \frac{m_B}{m_\mu} \sim 4; \quad \ln \frac{m_B}{\Lambda_{QCD}} \sim 3; \quad \ldots \]
Theory

1. **Non-perturbative matching between point-like EFT and microscopic description**

   ![Diagram showing the energy spectrum with virtualities labeled as ultrasonic, soft/collinear, hard-collinear, hard, and electroweak. QCD and dof categories are also shown with non-perturbative and perturbative, hadronic, and partonic labels.]

2. **Non-perturbative soft matrix elements in QCD×QED (LCDA)**

3. **Dedicated Monte Carlo for QED compatible with EFT description above \( \Lambda_{QCD} \)**

4. **Going beyond leading power in \( 1/M_B \) expansion**
Rare K session

- Review of $K \to \pi \nu \bar{\nu}$ (Yu-Chen Tung)
- Rare K decays (Evgueni Goudzovski)
- LQCD status of $\epsilon'/\epsilon$, $\epsilon_K$, $K \to \pi \nu \bar{\nu}$ (Mattia Bruno)
- $\epsilon'/\epsilon$ in the SM & beyond (Andrzej Buras)
- $K \to \pi \nu \bar{\nu}$ and B anomalies (David Marzocca)
**Review of $K \to \pi \nu \bar{\nu}$ (Yu-Chen Tung)**

<table>
<thead>
<tr>
<th></th>
<th>$K^+ \to \pi^+ \nu \bar{\nu}$</th>
<th>$K_L \to \pi^0 \nu \bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{BR}_{\text{SM}}$</td>
<td>$(8.4 \pm 1.0) \times 10^{-11}$</td>
<td>$(3.4 \pm 0.6) \times 10^{-11}$</td>
</tr>
</tbody>
</table>

- NA62 provided the current best measurement on $\text{BR}(K^+ \to \pi^+ \nu \bar{\nu})$.
  - $\text{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = [10.6^{+4.0}_{-3.4}(\text{stat}) \pm 0.9(\text{syst})] \times 10^{-11}$ at 68% C.L. [JHEP06.093]
  - Expect to achieve O(10%) statistical precision on $\text{BR}(K^+ \to \pi^+ \nu \bar{\nu})$ by LS3.
- KOTO 2015 data results set the current current best limit on $\text{BR}(K_L \to \pi^0 \nu \bar{\nu})$.
  - $\text{BR}(K_L \to \pi^0 \nu \bar{\nu}) < 3.0 \times 10^{-9}$ at 90% C.L. [PRL.122.021802]
- KOTO expects to improve the S.E.S. to O(10^{-11}) by 2026.
- New experiments, KOTO Step-II and KLEVER, are planned, both aiming to measure $\text{BR}(K_L \to \pi^0 \nu \bar{\nu})$ with O(10^{-13}) S.E.S.
Rare $K$ decays (Evgueni Goudzovski)

- Recent results on hidden-sector mediator production and other BSM physics in kaon decays:
  - extension of the $K^+\rightarrow\pi^+\nu\nu$ analysis: search for $K^+\rightarrow\pi^+X$ and $\pi^0\rightarrow\text{inv}$;
  - searches for $K^+\rightarrow\ell^+N$ and $K^+\rightarrow\mu^+\nu X$ decays;
  - searches for LNV/LFV $K^+$ and $\pi^0$ decays (six modes so far).

- Expected background: $0.91\pm0.41$ evt
  - Candidates observed: 1
  - $\text{BR}(K^+\rightarrow\pi^\pm\mu^+\mu^-)<4.2\times10^{-11}$ at 90% CL

- Expected background: $0.43\pm0.09$ evt
  - Candidates observed: 0
  - $\text{BR}(K^+\rightarrow\pi^-e^+e^-)<5.3\times10^{-11}$ at 90% CL

- $K^+$ decays in FV: $(1.33\pm0.02)\times10^{12}$
  - Expected background: $1.07\pm0.20$ evt
  - Candidates observed: 0
  - $\text{BR}(K^+\rightarrow\pi^-\mu^+e^-)<4.2\times10^{-11}$ at 90% CL

- Expected background: $0.92\pm0.34$ evt
  - Candidates observed: 2
  - $\text{BR}(K^+\rightarrow\pi^+\mu^-e^-)<6.6\times10^{-11}$ at 90% CL
  - $\text{BR}(\pi^0\rightarrow\mu^-e^-)<3.2\times10^{-10}$ at 90% CL

- Expected background: $0.044\pm0.020$ evt
  - Candidates observed: 0
  - $\text{BR}(K^+\rightarrow\pi^0e^+e^-)<8.5\times10^{-10}$ at 90% CL

- First search for this mode.

Based on world’s largest decay samples:
- $K^+\rightarrow\pi^+\mu^+\mu^-$ analysis based on 28k candidates;
- $K^+\rightarrow\pi^0e^+\nu\gamma$ analysis based on 130k candidates.
**LQCD status of \( \epsilon'/\epsilon , \epsilon_K , K \rightarrow \pi \nu \bar{\nu} \) (Mattia Bruno)**

\[ \Re \left( \frac{\epsilon'}{\epsilon} \right) = \frac{\omega}{\sqrt{2}|\epsilon|} \Re \left[ i e^{i(\delta_2-\delta_0-\phi_\epsilon)} \right] \left[ \frac{\Im A_2}{\Re A_2} - \frac{\Im A_0}{\Re A_0} \right] \]

1. use \( \omega, \Re A_0, \Re A_2 \) from experiment
2. phases either from dispersive or lattice, no difference
3. take \( \Im A_2 \) from previous LQCD
4. take \( \Im A_0 \) from new work

\[ \Re \left( \frac{\epsilon'}{\epsilon} \right) = 21.7(2.6)(6.2)(5.0) \cdot 10^{-4} \text{ from lattice} \]  
\[ \Re \left( \frac{\epsilon'}{\epsilon} \right) = 16.6(2.3) \cdot 10^{-4} \text{ from experiment} \]

Errors:
(2.6) statistical, (6.2) systematic, (5.0) isospin-breaking
**LQCD status of $\epsilon'/\epsilon$, $\epsilon_K$, $K \to \pi\nu\bar{\nu}$ (Mattia Bruno)**

### $\Delta m_K$ & $\epsilon_K$

#### $\Delta m_K$

\[
\Delta m_K^{\text{exp}} = 3.483(6) \cdot 10^{-12} \text{ MeV}
\]

*first numerical results only in PoS*  

**preliminary** results at $m_\pi^{\text{phys}} \to \Delta m_K = 6.7(1.7) \cdot 10^{-12} \text{ MeV}$  

dominated by **discr. errors from charm**  

$m_\pi^{\text{phys}} \to$ large $L \oplus$ charm $\to$ fine $a$: challenging

#### $\epsilon_K$

\[|\epsilon_K^{\text{exp}}| = 2.228(11) \cdot 10^{-3}\]

*conference papers, latest $\epsilon_K^{\text{LD}} = 0.17(1) \cdot 10^{-3}$*  

significant amount of Wick contractions and topologies  

preliminary results at $m_\pi \simeq 390$ MeV, unphys. charm  

approx 5% consistent w/ expectation but requires improvements

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*$[Wang Lattice '18 '19]$  
*$[Bai Lattice '16]$
$K \rightarrow \pi \bar{\nu} \nu$

FCNC ideal probes for new physics effects, mostly dominated by short-distance effects, QCD input from $K_{\ell 3}$ current theory predictions around 10% [Buras et al '15]

LD effects potentially up to 6% in $K^+ \rightarrow \pi^+ \bar{\nu} \nu$

Exploratory calculation at unphys. kinematics [RBC/UKQCD '17 '18]

Cancellation of $WW$ vs $Z$-exchange $\rightarrow$ will survive at $m_\pi^{\text{phys}}$?

2nd calculation $m_\pi \simeq 170$ MeV, unphys. charm [RBC/UKQCD '19]

Small mom. dependence, clarified role of intermediate ($\pi \pi$)
$\epsilon'/\epsilon$ in the SM & beyond (Andrzej Buras)

**Controversy**

$\frac{\epsilon'}{\epsilon}_{\text{exp}} = (16.6 \pm 2.3) \cdot 10^{-4}$

(NA48, KTeV)

$\frac{\epsilon'}{\epsilon}_{\text{SM}} = (14 \pm 5) \cdot 10^{-4}$

Chiral Perturbation Theory (Pich et al)

No Anomaly

$\frac{\epsilon'}{\epsilon}_{\text{SM}} = (5 \pm 2) \cdot 10^{-4}$

Hep-arxiv: 2101.00020

Insight from Dual QCD + NNLO QCD (AJB + Gérard)

Anomaly

$\frac{\epsilon'}{\epsilon}_{\text{SM}} = (21.7 \pm 8.4) \cdot 10^{-4}$

RBC – UKQCD

No Anomaly
Important Message for Non-Experts to take Home

RBC-UKQCD collaboration and ChPT Experts do not claim that there is no New Physics in $\varepsilon'/\varepsilon$. But as of 2021 their methods are not sufficiently powerful to see an anomaly in $\varepsilon'/\varepsilon$.

Dual QCD approach, even if approximate, can much faster see the underlying dynamics, even analytically. Both in $\varepsilon'/\varepsilon$ and the $\Delta l = \frac{1}{2}$ rule!!
Main Homework for Coming Years

**RBC-UKQCD**
- a) Isospin breaking and QED Corrections (including $\eta-\eta'$ mixing)
- b) Inclusion of charm

**ChPT**
- a) Matching to short distance ($L_5$)
- b) Better inclusion of $\eta-\eta'$ mixing ($L_7$)

**DQCD**
- Final state interactions

Inclusion of NNLO QCD to QCD Penguins

BSM hadronic matrix elements from LQCD

Contributions from other LQCD Groups

Ishizuka et al. 1809.03893; Hernandez et al. 2003.10293
**EFT level**

The hierarchy in NP couplings to the three generations, same as hierarchy in SM fermion masses, suggests a possible $U(2)^5$ flavor structure:

$$G_F = U(2)_q \times U(2)_\ell \times U(2)_u \times U(2)_d \times U(2)_e$$

Assuming **minimal breaking** of the flavor symmetry:

$$R(N^{(k)}) : C_{bc e\nu} \sim \frac{1}{(4 \text{ TeV})^2} \sim V_{cb} \frac{g_{b \nu}}{M^2}$$

Effect in $K \rightarrow \pi \nu \nu$:

$$C_{s d \nu_e \nu_e} \sim V_{td} V_{ts} \frac{g_{b \nu}}{M^2} \sim \frac{1}{(4 \text{2 TeV})^2}$$

same order as the NA62 bound!

$$C_{s d \nu_e \nu_e} \epsilon \left[ -\frac{1}{(50 \text{ TeV})^2} , \frac{1}{(81 \text{ TeV})^2} \right] \quad @ \quad 95\% \text{ CL}$$

A **UV model** is required to fix the O(1) coefficients.
Leptoquarks + U(2)⁵

LQ couplings to LH fermions:

\[
\lambda^{(3)\text{L}} = \lambda^{(1)\text{L}} (\begin{pmatrix}
\chi_{q_L}^{(3)} & s_e V_L & V_{td} \\
\chi_{q_L}^{(3)} & s_e V_L & V_{ts} \\
\chi_{q_L}^{(1)} & s_e V_L & V_{ts} \\
\chi_{q_L}^{(1)} & s_e V_L & V_{ts} \\
\chi_{q_L}^{(1)} & s_e V_L & V_{ts} \\
\chi_{q_L}^{(1)} & s_e V_L & V_{ts} \\
\end{pmatrix})
\]

Exact relations (selection rules)

\[
\chi_{dL}^{(3)L} = \chi_{sL}^{(3)L} \frac{V_{td}}{V_{ts}} \\
\chi_{i e}^{(3)L} = \chi_{i \mu}^{(3)L} \sin \delta_e
\]

S. Trifinopoulos, E. Venturini, D. Marzocca [2106.15630]