LHCb Highlights

Niels Tuning
On the menu

- Introduction
  - Precision measurements
  - The LHCb physics menu

- Selection of dishes:
  - Recent highlights on CP violation
  - Recent highlights on Rare decays (*aka* Flavour Anomalies)
History of Flavour physics

GIM mechanism in $K^0 \rightarrow \mu \nu$

Weak Interactions with Lepton-Hadron Symmetry
S. L. Glashow, J. Iliopoulos, and L. Maiani
Leyser Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Mills theory is discussed.

splitting, beginning at order $G(GA^2)$, as well as contributions to such unobserved decay modes as $K_2 \rightarrow \mu^+ \mu^-$, $K^+ \rightarrow \pi^+ + l^+ l^-$, etc., involving neutral lepton

We wish to propose a simple model in which the divergences are properly ordered. Our model is founded in a quark model, but one involving four, not three, fundamental fermions; the weak interactions are medi-n new quantum number $\xi$ for charm.

CP violation, $K_L^0 \rightarrow \pi \pi$

27 JULY 1964

EVIDENCE FOR THE 2$\pi$ DECAY OF THE $K^0$ MESON
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2$\pi$ decay of the $K^0_L$ meson. Several previous experiments have

Progress of Theoretical Physics, Vol. 89, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction
Makoto Kobayashi and Toshihide Maskawa
Department of Physics, Kyoto University, Kyoto
(Received September 1, 1972)

doublet with the same charge assignment. This is because all phases of elements of a $3 \times 3$ unitary matrix cannot be absorbed into the phase convention of six fields. This possibility of CP violation will be discussed later on.

Kobayashi, Maskawa, Prog.Theor. Phys. 49 (1973) 652

B$^0 \leftrightarrow \bar{B}^0$ mixing

DESY 87-029
April 1987

OBSERVATION OF $B^0$-$\bar{B}^0$ MIXING
The ARGUS Collaboration

In summary, the combined evidence of the investigation of $B^0$ meson pairs, lepton pairs and $\bar{B}^0$ meson lepton events on the T(4S) leads to the conclusion that $B^0$-$\bar{B}^0$ mixing has been observed and is substantial.

Parameters

<table>
<thead>
<tr>
<th>Comments</th>
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<td>$x &gt; 0.44$</td>
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<td>$B_{f_2} \approx f_2 &lt; 160$ MeV</td>
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<tr>
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<tr>
<td>$m_{t} &gt; 500$ GeV/c$^2$</td>
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</table>

ARGUS Coll.

Flavour physics has a track record

GIM mechanism in $K^0 \rightarrow \mu$

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S. L. Glashow, J. Imaizumi, and L. Maiani
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts (Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Mills theory is discussed.

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new quantum number $\xi$ for charm.

\[ \xi \]

\[ q, q \]

\[ \xi \]

“...a quark model, but involving four, not three fundamental fermions...”

CP violation, $K_L^0 \rightarrow \pi^0$

EVIDENCE FOR THE 2$\pi$ DECAY OF THE $K_2^0$ MESON$^+$
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2$\pi$ decay of the $K_2^0$ meson. Several previous experiments have

CP-violation in the Renormalizable Theory of Weak Interaction

Makoto Kobayashi and Toshihide Maskawa
Department of Physics, Kyoto University, Kyoto
(Received September 1, 1972)

doublet with the same charge assignment. This is because all phases of elements of a 3x3 unitary matrix cannot be absorbed into the phase convention of six fields. This possibility of $CP$ violation will be discussed later on.

Rare decay implied 2nd up quark “discovery” of charm?

Critical decay implied 3rd family: “discovery” of bottom?

Mixing implied heavy quark: “discovery” of top?

B$^0 \leftrightarrow \bar{B}^0$ mixing

DESY 87-029
April 1987

OBSERVATION OF $B^0 \rightarrow \bar{B}^0$ MIXING

The ARGUS Collaboration

In summary, the combined evidence of the investigation of $B^0$ meson pairs, lepton pairs and $\bar{B}^0$ meson-antimeson events on the $T(45)$ leads to the conclusion that $B^0\bar{B}^0$ mixing has been observed and is substantial.

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<td>$r &gt; 0.099$</td>
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<td>$x &gt; 0.44$</td>
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<tr>
<td>$B_{\gamma B} \approx f_\gamma &lt; 160$ MeV</td>
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<tr>
<td>$m_\beta &lt; 56 GeV/c^2$</td>
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<tr>
<td>$\tau_\beta &lt; 1.4 \times 10^{-18}$</td>
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<tr>
<td>$</td>
</tr>
<tr>
<td>$\alpha_{QCD} &lt; 0.86$</td>
</tr>
<tr>
<td>$m_t &gt; 50 GeV/c^2$</td>
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</table>

“$m_t > 50$ GeV/c$^2$ $t$ quark mass”
# Precise flavour measurements

- **Historical record of indirect discoveries:**

<table>
<thead>
<tr>
<th>Particle</th>
<th>Indirect</th>
<th>Direct</th>
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</thead>
<tbody>
<tr>
<td>$\nu$</td>
<td>$\beta$ decay</td>
<td>Fermi 1932</td>
</tr>
<tr>
<td>$W$</td>
<td>$\beta$ decay</td>
<td>Fermi 1932</td>
</tr>
<tr>
<td>$c$</td>
<td>$K^0 \rightarrow \mu\mu$</td>
<td>GIM 1970</td>
</tr>
<tr>
<td>$b$</td>
<td>CPV $K^0 \rightarrow \pi\pi$</td>
<td>CKM, 3rd gen 1964/72</td>
</tr>
<tr>
<td>$Z$</td>
<td>$\nu$-NC</td>
<td>Gargamelle 1973</td>
</tr>
<tr>
<td>$t$</td>
<td>$B$ mixing</td>
<td>ARGUS 1987</td>
</tr>
<tr>
<td>$H$</td>
<td>$e^+e^-$</td>
<td>EW fit, LEP 2000</td>
</tr>
</tbody>
</table>

- **What’s next?**

---

Diagram: 
- $d \rightarrow W^- e^-$
- $K^0 \rightarrow W^+ W^- \nu$ 
- $e^+ \rightarrow Z \rightarrow l^+ l^-$
- $B^0 \rightarrow t W W t \rightarrow b \bar{B}^0 e^-$
Precise flavour measurements

Direct discoveries rightfully higher valued:

<table>
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</tr>
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</table>
Precise flavour measurements

- Depending on your model, sensitive to multi-TeV scales, eg:

\[ \Lambda \gtrsim \frac{v}{\sqrt{0.2}} \times \begin{cases} \sqrt{4\pi} \\ g |V_{tb}^* V_{ts}| \\ 1 \end{cases} \approx \begin{cases} 50 \text{ TeV} & \text{anarchic tree} \\ 0.6 \text{ TeV} & \text{MFV loop} \end{cases} \]

\[ \mu_{B \rightarrow \mu \mu} \text{ is ratio } \frac{\text{BR}^{\text{exp}}}{\text{BR}^{\text{SM}}} \]
Precise flavour measurements

- Depending on your model, sensitive to multi-TeV scales, eg:

\[ M_{12}^q = (M_{12}^q)_{\text{SM}} \left( 1 + h_q e^{2i\sigma_q} \right) \]

\( h_q \) parametrizes magnitude of NP in \( B_q \) mixing

\[ h_d \lesssim 5\% \quad \implies \quad \Lambda \gtrsim \begin{cases} 
2 \cdot 10^3 \text{ TeV, anarchic tree} \\
1.4 \text{ TeV, MFV loop}
\end{cases} \]

From Uli Haisch, 31 Aug 2016
On the menu

- Introduction
  - Precision measurements
  - The LHCb physics menu

- Selection of dishes:
  - Recent highlights on CP violation
  - Recent highlights on Rare decays (*aka* Flavour Anomalies)
LHCb Physics Landscape

QCD

W/Z

Heavy Ion & Fixed Target

$b \rightarrow sll$

$B_s^0 \rightarrow \mu^+ \mu^-$

$R_K$

Charm

CP violation & rare decays

CP violation:

$\gamma$

CP violation:

$\alpha$

$|V_{cb}|, |V_{ub}|$

$R(D)$

Tetra- & Pentaquarks

CP violation:

$\beta$

$\phi_s$
LHCb Physics Landscape: more than b

**Impressive sin\(^2\)θ\(_W\)**


**Resolve b and c jets**

![Two-dimensional SV-tag BDT distribution and fit for events in the subsample with \(p_T(\mu) > p_T(j)\).](image)

**Anti-proton flux for cosmic rays**

![Anti-proton flux for cosmic rays](image)

**Improve proton pdf’s**

![Graph showing NNPDF3.1x NLO and NNPDF3.1x+LHCb NLO](image)

**Discovery of pentaquarks**

![Discovery of pentaquarks](image)

where

$A_{\text{CP}}(f; t) \equiv \frac{\Gamma(D^0(t) \rightarrow f) - \Gamma(\bar{D}^0(t) \rightarrow f)}{\Gamma(D^0(t) \rightarrow f) + \Gamma(\bar{D}^0(t) \rightarrow f)}$

$\Delta A_{\text{CP}} \equiv A_{\text{CP}}(K^-K^+) - A_{\text{CP}}(\pi^-\pi^+)$

$\Delta A_{\text{CP}} = (-15.4 \pm 2.9) \times 10^{-4}$
What is the nature of 4- or 5-quark states?
Why are some states so narrow?
Test QCD (HQET) models
LHCb Physics Landscape

Today

$b \rightarrow s \ell \ell$

$B_s^0 \rightarrow \mu^+ \mu^-$

$R_K$

$|V_{cb}|, |V_{ub}|$

$R(D)$

CP violation:

$\gamma$
On the menu

- Introduction
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- Selection of dishes:
  - Recent highlights on CP violation
  - Recent highlights on Rare decays (aka Flavour Anomalies)
On the menu

- Introduction
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- Selection of dishes:
  - Recent highlights on CP violation
  - Recent highlights on Rare decays (*aka Flavour Anomalies*)

- New results
  1) $|V_{cb}|$ with decay $B_s^0 \rightarrow D_s^{-}\mu^+\nu$
  2) $\gamma$ with decay $B^- \rightarrow D^0(\rightarrow K_S^0 K^+\pi^-) K^-$
  3) $\gamma$ with decay $B^0 \rightarrow D^0 K^{*0}$

- A remark on consistency
1) Matrix to transform weak- and mass-eigenstates:

\[
\begin{bmatrix}
|d'\rangle \\
|s'\rangle \\
|b'\rangle \\
\end{bmatrix}
=
\begin{bmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb} \\
\end{bmatrix}
\begin{bmatrix}
|d\rangle \\
|s\rangle \\
|b\rangle \\
\end{bmatrix}.
\]
1) Matrix to transform weak- and mass-eigenstates:

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\]

Weak eigenstates

Mass eigenstates

2) Matrix has imaginary numbers:
(CKM: a quick reminder…)

1) Matrix to transform weak- and mass-eigenstates:

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\end{pmatrix} \\
\begin{pmatrix}
|d\rangle \\
|s\rangle \\
|b\rangle \\
\end{pmatrix}.
\]

2) Matrix has imaginary numbers:

\[
\begin{pmatrix}
|V_{ud}| & |V_{us}| & V_{ub}e^{-i\gamma} \\
-|V_{cd}| & |V_{cs}| & V_{cb} \\
|V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & V_{tb} \\
\end{pmatrix}
\]

3) Matrix is unitary:

\[
V^*V = \begin{pmatrix}
V^{*\,ud} & V^{*\,cd} & V^{*\,td} \\
V^{*\,us} & V^{*\,cs} & V^{*\,ts} \\
V^{*\,ub} & V^{*\,cb} & V^{*\,tb} \\
\end{pmatrix} \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb} \\
\end{pmatrix} = \\
\begin{pmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1 \\
\end{pmatrix}
\]

\[
V^{*\,V_{ud}} + V^{*\,V_{cd}} + V^{*\,V_{tb}} = 0
\]

\[
\gamma \quad \beta
\]

\[
(0,0) \quad \frac{V^{*\,V_{ub}}}{V^{*\,V_{cd}}} \quad \frac{V^{*\,V_{tb}}}{V^{*\,V_{cd}}} \equiv 1 \quad (1,0)
\]
Figure 2.1: Limits on the CKM parameters ($1\sigma$) $\rho$ and $\eta$ for $m_t = 174$ GeV. The annular region cen-
Letter-of-Intent 1995

Figure 2.1: Limits on the CKM parameters ($1\sigma$) $\rho$ and $\eta$ for $m_t = 174$ GeV. The annular region cen-

Figure 2.2: The Unitarity Triangle
New measurement on $|V_{cb}|$

- Measure decay rate of $B^0_s \to D_s^* \mu^+\nu$
  - Depends on momentum transfer $q^2$:

$$
\frac{d\Gamma(B^0_s \to D_s^* \mu^+\nu)}{dq^2} = G_F^2 |V_{cb}|^2 |\eta_{EW}|^2 |\vec{p}|q^2 \left(1 - \frac{m_\mu^2}{q^2}\right) ^2 \\
\times \left[ |H_+|^2 + |H_-|^2 + |H_0|^2 \right] \left(1 + \frac{m_\mu^2}{2q^2}\right) + \frac{3m_\mu^2}{2q^2}|H_t|^2
$$

- Determine $|V_{cb}|$ and form factors

(Suzanne Klaver et al.)

LHCb, "Measurement of the shape of the $B^0_s \to D_s^* \mu^+\nu$ differential decay rate", arXiv:2003.08453
New measurement on $|V_{cb}|$

- Measure rate relative to known $B^0$ decay rate from B-factories:
  
  $$R^* \equiv \frac{BR(B_s^0 \to D_s^{*-} \mu^+\nu)}{BR(B^0 \to D^{*-} \mu^+\nu)} \sim \frac{|V_{cb}|^2}{BR_{\text{measured B-factories}}}$$

- Result depends on the assumed form factor parametrization:

  $$|V_{cb}|_{\text{CLN}} = (41.4 \pm 0.6 \text{ (stat)} \pm 0.9 \text{ (syst)} \pm 1.2 \text{ (ext)}) \times 10^{-3}$$

  $$|V_{cb}|_{\text{BGL}} = (42.3 \pm 0.8 \text{ (stat)} \pm 0.9 \text{ (syst)} \pm 1.2 \text{ (ext)}) \times 10^{-3}$$

Conclusions:

- First measurement of $V_{cb}$ with $pp$
- First measurement using $B_s^0$
- Parametrisation is not responsible for inclusive vs exclusive disagreements
- Result in agreement with the exclusive and inclusive averages

(Suzanne Klaver et al.)
LHCb, "Measurement of $|V_{cb}|$ with $B_s^0 \to D^{(*)} \mu^+\nu$ decays", arXiv:2001.03225
New constraints on angle $\gamma$  

- Different yields for $B^+$ and $B^-$ decays
  - two amplitudes contribute with different relative phase: $V_{ub} = |V_{ub}|e^{-i\gamma}$

LHCb, "Measurement of CP observables in $B^*\to DK^*$ and $B^*\to D\eta^*$ with $D\to K^{0,\pm}K^{*0,\pm}$ decays", arXiv:2002.08858
Different yields for $B^+$ and $B^-$ decays

- two amplitudes contribute with different relative phase: $V_{ub} = |V_{ub}|e^{-i\gamma}$

- $B^\pm \rightarrow DK^\pm$ with $D \rightarrow K^0_S K^\pm n^\mp$:

\[
\begin{align*}
N_{SS}^{DK^\pm} & \propto 1 + r_B^2 r_D^2 + 2r_Br_Dk_D \cos(\delta_B \pm \delta_D) \\
N_{OS}^{DK^\pm} & \propto r_B^2 + r_D^2 + 2r_Br_Dk_D \cos(\delta_B \pm \delta_D) \\
N_{SS}^{Da\pi^\pm} & \propto 1 + (r_B^2) r_D^2 + 2r_Br_Dk_D \cos(\delta_B^\pi \pm \delta_D) \\
N_{OS}^{Da\pi^\pm} & \propto (r_B^2) r_D^2 + 2r_Br_Dk_D \cos(\delta_B^\pi \pm \delta_D)
\end{align*}
\]

<table>
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<tr>
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<th>non-$K^{*+}$ region</th>
<th>$K^{*+}$ region</th>
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</thead>
<tbody>
<tr>
<td>$N_{SS}^{DK^\pm}$</td>
<td>266 ± 27</td>
<td>715 ± 37</td>
</tr>
<tr>
<td>$N_{OS}^{DK^\pm}$</td>
<td>336 ± 27</td>
<td>217 ± 22</td>
</tr>
<tr>
<td>$N_{SS}^{Da\pi^\pm}$</td>
<td>3304 ± 73</td>
<td>8977 ± 106</td>
</tr>
<tr>
<td>$N_{OS}^{Da\pi^\pm}$</td>
<td>4686 ± 76</td>
<td>3471 ± 66</td>
</tr>
</tbody>
</table>

\[
A_{SS}^{D\pi} = -0.020 \pm 0.011 \pm 0.003 \\
A_{OS}^{D\pi} = 0.007 \pm 0.017 \pm 0.003 \\
A_{SS}^{DK} = 0.084 \pm 0.049 \pm 0.008 \\
A_{OS}^{DK} = 0.021 \pm 0.094 \pm 0.017
\]
Different yields for $B^0$ and $\bar{B}^0$ decays

- two amplitudes contribute with different relative phase: $V_{ub} = |V_{ub}|e^{-i\gamma}$

- $B^0 \rightarrow DK^{*0}$ with $D \rightarrow h^\pm h^\mp (h^\pm h^\mp)$:

$$A_{CP} = \frac{2k_r^{DK^{*0}} \sin \delta^{DK^{*0}} \sin \gamma}{R_{CP}}$$

$LHCb$, "Measurement of CP observables in the process $B^0 \rightarrow DK^{*0}$ with two- and four-body $D$ decays", arXiv:1906.08297
CKM angle $\gamma$

- Different yields for $B$ and anti-$B$ decays
  - two amplitudes contribute with different relative phase: $V_{ub} = |V_{ub}|e^{-i\gamma}$
  - many $D^{(*)}_s$ final states:

<table>
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<tr>
<th>$B$ decay</th>
<th>$D$ decay</th>
<th>Method</th>
<th>Ref.</th>
<th>Dataset</th>
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<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to h^+h^-$</td>
<td>GLW</td>
<td>[14]</td>
<td>Run 1 &amp; 2</td>
<td>Minor update</td>
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<td>$B^+ \to DK^+$</td>
<td>$D \to h^+h^-$</td>
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<td>$B^+ \to DK^+$</td>
<td>$D \to h^+\pi^-\pi^+$</td>
<td>GLW/ADS</td>
<td>[15]</td>
<td>Run 1</td>
<td>As before</td>
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<td>$B^+ \to DK^+$</td>
<td>$D \to h^+h^-$</td>
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<td>[16]</td>
<td>Run 1</td>
<td>As before</td>
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<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to h^+h^-$</td>
<td>GGSZ</td>
<td>[17]</td>
<td>Run 1</td>
<td>As before</td>
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<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to K^0\pi h^-$</td>
<td>GGSZ</td>
<td>[18]</td>
<td>Run 2</td>
<td>New</td>
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<td>$B^+ \to DK^+$</td>
<td>$D \to K^0h^-$</td>
<td>GLS</td>
<td>[19]</td>
<td>Run 1</td>
<td>As before</td>
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<tr>
<td>$B^+ \to D^*K^+$</td>
<td>$D \to h^+h^-$</td>
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<tr>
<td>$B^+ \to D^*K^+$</td>
<td>$D \to h^+h^-$</td>
<td>GLW/ADS</td>
<td>[20]</td>
<td>Run 1 &amp; 2</td>
<td>Updated results</td>
</tr>
<tr>
<td>$B^+ \to D^*K^{**}$</td>
<td>$D \to h^+h^-$</td>
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<td>Run 1 &amp; 2</td>
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<td>$B^0 \to DK^{**}$</td>
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<td>As before</td>
</tr>
</tbody>
</table>

1 Run 1 corresponds to an integrated luminosity of 3 fb$^{-1}$ taken at centre-of-mass energies of 7 and 8 TeV.
2 Run 2 corresponds to an integrated luminosity of 2 fb$^{-1}$ taken at a centre-of-mass energy of 13 TeV.
CKM angle $\gamma$

- Different yields for $B$ and anti-$B$ decays
  - two amplitudes contribute with different relative phase: $V_{ub} = |V_{ub}| e^{-i\gamma}$
  - many $D^{(*)}_s$ final states:

<table>
<thead>
<tr>
<th>$B$ decay</th>
<th>$D$ decay</th>
<th>Method</th>
<th>Ref.</th>
<th>Dataset(^1)</th>
<th>Status since last combination ([3])</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow h^+ h^-$</td>
<td>GLW</td>
<td>[14]</td>
<td>Run 1 &amp; 2</td>
<td>Minor update</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow h^+ h^-$</td>
<td>ADS</td>
<td>[15]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow h^+ \pi^- \pi^+$</td>
<td>GLW/ADS</td>
<td>[15]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow h^+ h^- \pi^0$</td>
<td>GLW/ADS</td>
<td>[16]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow h^+ h^- \pi^0$</td>
<td>GGSZ</td>
<td>[17]</td>
<td>Run 1</td>
<td>As before</td>
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<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow K^0 h^- h^-$</td>
<td>GGSZ</td>
<td>[18]</td>
<td>Run 2</td>
<td>New</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow K^0 h^- h^-$</td>
<td>GLS</td>
<td>[19]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^+ \rightarrow D^0 K^+$</td>
<td>$D \rightarrow h^- h^-$</td>
<td>GLW</td>
<td>[14]</td>
<td>Run 1 &amp; 2</td>
<td>Minor update</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^{*+}$</td>
<td>$D \rightarrow h^- h^-$</td>
<td>GLW/ADS</td>
<td>[20]</td>
<td>Run 1 &amp; 2</td>
<td>Updated results</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^{*+}$</td>
<td>$D \rightarrow h^- h^- \pi^+$</td>
<td>GLW/ADS</td>
<td>[20]</td>
<td>Run 1 &amp; 2</td>
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<tr>
<td>$B^+ \rightarrow DK^{*+}$</td>
<td>$D \rightarrow h^- h^- \pi^+$</td>
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<td>[20]</td>
<td>Run 1 &amp; 2</td>
<td>Updated results</td>
</tr>
<tr>
<td>$B^0 \rightarrow DK^{*0}$</td>
<td>$D \rightarrow h^- h^-$</td>
<td>ADS</td>
<td>[22]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^0 \rightarrow DK^{*0}$</td>
<td>$D \rightarrow h^- h^-$</td>
<td>GLW-Dalitz</td>
<td>[23]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^0 \rightarrow DK^{*0}$</td>
<td>$D \rightarrow h^- h^- \pi^+$</td>
<td>GGSZ</td>
<td>[24]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^+ K^+$</td>
<td>$D^+ \rightarrow h^+ h^- \pi^+$</td>
<td>TD</td>
<td>[25]</td>
<td>Run 1</td>
<td>Updated results</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^+ K^+$</td>
<td>$D^+ \rightarrow h^+ h^- \pi^+$</td>
<td>TD</td>
<td>[26]</td>
<td>Run 1</td>
<td>New</td>
</tr>
</tbody>
</table>

\(^1\) Run 1 corresponds to an integrated luminosity of 3 fb\(^{-1}\) taken at centre-of-mass energies of 7 and 8 TeV. Run 2 corresponds to an integrated luminosity of 2 fb\(^{-1}\) taken at a centre-of-mass energy of 13 TeV.

LHCb

- $\gamma = 74.0^{+5.0}_{-5.8}$

BaBar

- $\gamma = 69^{+17}_{-16}$

World Avg (HFLAV)

- $\gamma = 71.1^{+4.6}_{-5.3}$

LHCb-2018-002, Update of the LHCb combination of the CKM angle $\gamma$
- Continuous improvement over the years
- All consistent?
All consistent...?

\[ \Delta m_d = m_{B_d} \xi^2 \left| V_{ts} \right|^2 \]

\[ \Delta m_s = m_{B_s} \xi^2 \left| V_{ts} \right|^2 \]

QCD
Interesting ~2σ tension:

<table>
<thead>
<tr>
<th></th>
<th>γ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb</td>
<td>74.0 +5.0 -5.8</td>
</tr>
<tr>
<td>World Avg (HFLAV)</td>
<td>71.1 +4.6 -5.3</td>
</tr>
<tr>
<td>QCD (Δm^{exp}, ξ(Sum Rules))</td>
<td>63.4 ± 0.9</td>
</tr>
</tbody>
</table>

\[
\frac{\Delta m_s}{\Delta m_d} = \frac{m_{Bs}}{m_{Bd}} \xi^2 \left| \frac{V_{ts}}{V_{td}} \right|^2
\]
On the menu

- Introduction
  - Precision measurements
  - The LHCb physics menu

- Selection of dishes:
  - Recent highlights on CP violation
  - Recent highlights on Rare decays (aka Flavour Anomalies)
On the menu

- Introduction
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- Selection of dishes:
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- New results
  1) Lepton flavour non-universality
     \[ \Lambda_b^0 \rightarrow p K^+ \mu^- \]
  2) Angular analysis of decay
     \[ B^0 \rightarrow K^{*0} \mu^+ \mu^- \]
     \[ B^0 \rightarrow K^{*0} \tau^+ \mu \]
  3) Search for LFV
     \[ B_s^0 \rightarrow e^+ e^- \]
  4) New limit on
  5) New limit on
  6) New limit on (x25 !)

- A remark on consistency
What are the (anomalous) measurements?
- FCNC: $b \rightarrow sll$
- LFNU: $b \rightarrow sll$ and $b \rightarrow clv$
FCNC: $b \rightarrow sll$

- $b \rightarrow s$ transition forbidden at tree level in SM
FCNC: $b \rightarrow sll$

- $b \rightarrow s$ transition occurs at loop level
  - Suppressed in SM
  - NP can compete with SM

Flavour-Changing-Neutral-Current-Electro-Weak-Weak-Penguin diagram
FCNC: $b \rightarrow sll$

- $b \rightarrow s$ transition occurs at loop level
  - Suppressed in SM
  - NP can compete with SM

The first penguin:
FCNC: $b \rightarrow sll$

- $b \rightarrow s$ transition occurs at loop level
  - LQ quite fashionable these days

```
deVolkskrant
Moeder aller deeltjes: de zoektocht naar de leptoquark
Is het fundamenteelste deeltje in het universum altijd over het hoofd gezien? Komende week kan de wereld opgeschud worden, als natuurrundigen in Seoul hun resultaten bekendmaken. Leptoquark, onthoud dat woord.
```
$R_K: B^+ \to K^+ \mu^+ \mu^- \text{ and } B^+ \to K^+ e^+ e^-$

- Similar loop diagram!
- Measure ratio \( \mu/e \)
- SM expectation: \( R_K = 1 \)

$$R_K = \frac{\Gamma(B^+ \to K^+ \mu^+ \mu^-)}{\Gamma(B^+ \to K^+ e^+ e^-)}$$
$R_K: \frac{B^+ \to K^+ \mu^+ \mu^-}{B^+ \to K^+ e^+ e^-}$

- Similar loop diagram!
- Measure ratio $\mu/e$
- SM expectation: $R_K = 1$

$R_K = \frac{\Gamma(B^+ \to K^+ \mu^+ \mu^-)}{\Gamma(B^+ \to K^+ e^+ e^-)}$

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

- Lepton flavour “non-universal”?

LHCb, PRL 113 (2014) 151601
**R_K**: \( B^+ \rightarrow K^+ \mu^+ \mu^- / B^+ \rightarrow K^+ e^+ e^- \)

- Similar loop diagram!
- Measure ratio \( \mu/e \)
- SM expectation: \( R_K = 1 \)

\[
R_K = \frac{\Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\Gamma(B^+ \rightarrow K^+ e^+ e^-)}
\]

\[
R_K = 0.846 \pm 0.060 \pm 0.016 - 0.054 - 0.014
\]

➢ **Lepton flavour “non-universal” ?**
**$R_{K^*}$: $B^0 \rightarrow K^0*\mu^+\mu^-$ and $B^0 \rightarrow K^0*e^+e^-$**

- Similar loop diagram!
- Measure ratio $\mu/e$
- SM expectation: $R_{K^*}=1$

- Extra bin at low $q^2$...
  - $q^2 \sim 0$ not helicity suppressed
  - But dominated by photon pole
  - EM coupling to photon un debated...!!

$$R_{K^*0} = \begin{cases} 
0.66 \pm 0.11 \text{(stat)} \pm 0.03 \text{(syst)} & \text{for } 0.045 < q^2 < 1.1 \text{ GeV}^2/c^4 \\
0.69 \pm 0.11 \text{(stat)} \pm 0.05 \text{(syst)} & \text{for } 1.1 < q^2 < 6.0 \text{ GeV}^2/c^4 
\end{cases}$$

- **Lepton flavour**
  - "non-universal"?
Similar loop diagram!

Measure ratio $\mu/e$

SM expectation: $R_{pK}=1$

$R_{pK}: \Lambda_b^0 \rightarrow pK\mu^+\mu^- / \Lambda_b^0 \rightarrow K^0* e^+ e^-$

$R_{pK}|_{0.1 < q^2 < 6 \text{ GeV}^2/c^4} = 0.86 \pm 0.14 \pm 0.05$

Lepton flavour "non-universal"?
More LFNU? Semileptonic decays: $b \to c l \nu$

- $B^0 \to D^(*)l\nu$  Measured ratio $\tau/\mu$
  - Multiple experiments:
  - Multiple c-modes:
  - Multiple tau final states:
  - Multiple tags:

Belle, BaBar, LHCb
$D, D^*, J/\psi$
$\mu, 1$-prong, $3$-prong semileptonic, hadronic

and with $B_c^+$:

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

LHCb Coll. arXiv:1711.05623
More LFNU? Semileptonic decays: $b \rightarrow c l \nu$

- Discrepancy in 2D about $3\sigma$
Decay rates: $b \rightarrow sll$

- Study **same** process with different hadrons:
Decay rates: $b \rightarrow sll$

- Decay rate is consistently low:

![Graphs showing decay rates for $B^+ \rightarrow K^+ \mu^+ \mu^-$, $B^0 \rightarrow K^0 \mu^+ \mu^-$, $B^0 \rightarrow K^0 \mu^+ \mu^-$, and $B_s^0 \rightarrow \phi \mu^+ \mu^-$ with data points and error bars.](image)
$B^0 \rightarrow K^{0*} \mu^+ \mu^- : P_5'$

- Similar loop diagram!
- More observables
  - Invariant mass of $\mu \mu$-pair
  - Angles of $K$ and $\mu$

Figure 8: The optimised angular observables in bins of $q^2$, determined from a maximum likelihood fit to the data. The shaded boxes show the SM prediction taken from Ref. [14].

\[ B^0 \rightarrow K^{0}\ast \mu^+\mu^- : P_5' \]

- Similar loop diagram!
- More observables
  - Invariant mass of $\mu\mu$-pair
  - Angles of $K$ and $\mu$

---

Figure 8: The optimised angular observables in bins of $q^2$, determined from a maximum likelihood fit to the data. The shaded boxes show the SM prediction taken from Ref. [14].

---

$B^0 \rightarrow K^0*\mu^+\mu^- : P_5'$

- Similar loop diagram!
- More observables
  - Invariant mass of $\mu\mu$-pair
  - Angles of $K$ and $\mu$
- Many experiments contribute!

$P_5'$

$P_5' = \frac{S_5}{p_{F_L}(1 - F_L)}$

Private compilation, courtesy T. Blake
Similar loop diagram!

More observables
- Invariant mass of $\mu\mu$-pair
- Angles of $K$ and $\mu$

Debate on SM calculation
- Non-perturbative “charm loop” effects?

Interpretation of global fits

Optimist’s viewpoint
- Vector-like contribution could come from new tree level contribution from a $Z'$ with a mass of a few TeV (the $Z'$ will also contribute to mixing, a challenge for model builders)

Pessimist’s viewpoint
- Vector-like contribution could point to a problem with our understanding of QCD, e.g. are we correctly estimating the contribution for charm loops that produce dimuon pairs via a virtual photon.

More work needed from experiment/theory to disentangle the two

- ATLAS, arXiv:1805.04000
- LHCb, JHEP02 (2016) 104
- Belle, PRL 118 (2017) 111801
Updated with (part of) run-2 data

![Graphs showing signal yields for different data sets: LHCb Run 1 and LHCb 2016.](image)

- LHCb Run 1:
  - 2398 ± 57 candidates

- LHCb 2016:
  - 2187 ± 53 candidates
**Fit validation**

- S-wave

- Angular acceptance

- Systematics

- Compatibility
  - Run1/2, Magnet polarity, Yields, angular, control channel, ...

\[
\frac{1}{d(\Gamma + \Gamma')/dq^2} \left. \frac{d^4(\Gamma + \Gamma')}{dq^2 d\Omega^2} \right|_p = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{3} (1 - F_L) \sin^2 \theta_K \cos 2\theta_l - F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi + S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]
\]

- The efficiency across the angles and $q^2$ is not flat

<table>
<thead>
<tr>
<th>Source</th>
<th>$F_L$</th>
<th>$S_3 - S_9$</th>
<th>$P_{L-P_\pi}$</th>
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<tbody>
<tr>
<td>Acceptance stat. uncertainty</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
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<tr>
<td>Acceptance polynomial order</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.02</td>
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<td>Data-simulation differences</td>
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<td>Acceptance variation with $q^2$</td>
<td>&lt; 0.03</td>
<td>&lt; 0.01</td>
<td>&lt; 0.09</td>
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<td>$m(K^+\pi^-)$ model</td>
<td>&lt; 0.01</td>
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<tr>
<td>Background model</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.02</td>
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<tr>
<td>Peaking backgrounds</td>
<td>&lt; 0.01</td>
<td>&lt; 0.02</td>
<td>&lt; 0.03</td>
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<tr>
<td>$m(K^+\pi^-\mu^+\mu^-)$ model</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
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<tr>
<td>$K^+\mu^+\mu^-\text{ veto}$</td>
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<td>Trigger</td>
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<td>&lt; 0.01</td>
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<tr>
<td>Bias correction</td>
<td>&lt; 0.02</td>
<td>&lt; 0.01</td>
<td>&lt; 0.03</td>
</tr>
</tbody>
</table>
Many measurements:

\[ B^0 \rightarrow K^{0*} \mu^+ \mu^- : \text{more than just } P_{5}' \]

\[ P_{5}' = S_5' / \sqrt{F_L (1 - F_L)} \]
Excellent agreement run-1 and 2016:
What about the tension?

- Similar tension in $P_5'$
- What about overall significance?

*if same theory knowledge is used, significance reduces to 2.8σ
Flavour anomalies? Why excitement?

- **Individually**, measurements are consistent with SM
- **Combined** they give an intriguing picture
  - Difference between (lepton) generations?
  - Consistent New Physics scenario possible
  - Simple New Physics scenario possible
On the menu

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  - Precision measurements
  - The LHCb physics menu

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  - Recent highlights on CP violation
  - Recent highlights on Rare decays (aka Flavour Anomalies)

New results

1) Lepton flavour non-universality
   \[ \Lambda_b^0 \rightarrow pK\mu^+\mu^- \]
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   \[ B_s^0 \rightarrow e^+e^- \]
5) New limit on
   \[ K_S^0 \rightarrow \mu^+\mu^- \]
6) New limit on (x25 !)
   \[ D^+_{(s)} \rightarrow hll' \]

A remark on consistency
Intermezzo: Effective couplings

- Historical example

Both are correct, depending on the energy scale you consider

\[
\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}
\]
Intermezzo: Effective couplings

- Historical example

- Analog: Flavour-changing neutral current
Intermezzo: Effective couplings

- Effective coupling can be of various “kinds”
  - Vector coupling
  - Axial coupling
  - Left-handed coupling (V-A)
  - Right-handed (to quarks)
  - ...

**Analog:** Flavour-changing neutral current

\[ \mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{\text{CKM}} \sum_i C_i(\mu) Q_i \]
**Intermezzo: Effective couplings**

- Effective coupling can be of various "kinds"
  - Vector coupling: $C_9$
  - Axial coupling: $C_{10}$
  - Left-handed coupling (V-A): $C_9 - C_{10}$
  - Right-handed (to quarks): $C_9', C_{10}', ...$
  - Many more!

- Analog: **Flavour-changing neutral current**

\[
\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{\text{CKM}} \sum_i C_i(\mu) Q_i
\]

Semi-Leptonic Operators (fig. 11f):
- $Q_{3V} = (\bar{s}b)_{V-A} (\bar{\mu}\mu)_V$
- $Q_{19A} = (\bar{s}b)_{V-A} (\bar{\mu}\mu)_A$

See e.g. Buras & Fleischer, hep-ph/9704376
Intermezzo: Effective couplings

Model independent fits:

- $C_9^{NP}$ deviates from 0 by $>4\sigma$
- Independent fits by many groups favour:
  - $C_9^{NP} = -1$ or
  - $C_9^{NP} = -C_{10}^{NP}$

- All measurements (175) agree with a single (simple?) shift...

$$\Delta \text{Re}(C_9) = -1.04 \pm 0.25$$
**Intermezzo: Effective couplings**

Model independent fits:
- \( C_9^{\text{NP}} \) deviates from 0 by \( > 4\sigma \)
- Independent fits by many groups favour:
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$$\Delta \text{Re}(C_9) = -1.04 \pm 0.25$$
B^0 \rightarrow K^0*\mu^+\mu^- : P_5^{'}

- All (175) measurements favor C^{NP}_9 = -1.0

- New P_5^{'} closer to SM, but also in \textit{better} agreement with C^{NP}_9 = -1.0

- It is not only about P_5^{'}
This decay is described by 3 angles ($\theta$, $\phi$, $\lambda$) and the di-muon invariant mass squared ($q^2$).

Many variables; all sensitive to effective couplings:

- $C_7$ (photon), $C_9$ (vector) and $C_{10}$ (axial) couplings hide everywhere.
Best fit

- Improved fit for $C_9^{NP} = -1.0$

Likelihood vs $C_9$

$C_{10}$ vs $C_9$ (run-1)

$C_{10}$ vs $C_9$ (2016)

More consistent among variables
Emerging patterns of New Physics with and without Lepton Flavour Universal contributions

Marcel Algueró\textsuperscript{a, b}, Bernat Capdevila\textsuperscript{a, b, c}, Andreas Crivellin\textsuperscript{d, e}, Sébastien Descotes-Genon\textsuperscript{f}, Pere Masjuan\textsuperscript{a, b}, Joaquim Matias\textsuperscript{a, b}, Martín Novoa Brunet\textsuperscript{f} and Javier Virto\textsuperscript{g}.

<table>
<thead>
<tr>
<th>1D Hyp.</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1σ/2σ</td>
</tr>
<tr>
<td>(C_{9\mu}^{NP})</td>
<td>-1.03</td>
</tr>
<tr>
<td>(C_{9\mu}^{NP} = C_{10\mu}^{NP})</td>
<td>-0.50</td>
</tr>
</tbody>
</table>

- There is a reduction of the internal tensions between some of the most relevant observables of the fit, in particular, between the new averages of \(R_{K}\) and \(P_{\beta}\). This leads to an increase in consistency between the different anomalies. This is illustrated.
- The reduced uncertainties of the \(B \to K^*\mu\mu\) data and its improved internal consistency sharpen statistical statements on the hypotheses considered. There is a significant increase of the statistical exclusion of the SM hypothesis as its p-value is reduced down to 1.4\% (i.e. 2.5\σ). The Pull\textsubscript{SM} of the 6D fit is now higher (5.8\σ).

arXiv:1903.09578, addendum 6 Apr 2020

- Similar picture as before
- Reduction of internal tensions
- Increase of statistical exclusion of SM hypothesis
  - p-value 1.4\%, Pull 5.8\σ
## Outlook

<table>
<thead>
<tr>
<th>Year</th>
<th>Run III</th>
<th>Run IV</th>
<th>Run V</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>LHCb 40 MHz UPGRADE I</td>
<td>L = 2 x 10^{33}</td>
<td>LHCb UPGRADE II</td>
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<td>2021</td>
<td>?</td>
<td>LHCb Consolidate: Upgr Ib</td>
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<td>2022</td>
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<td>2035</td>
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</tbody>
</table>

### ATLAS

- **Phase I Upgr**
  - L = 2 x 10^{34} 300 fb^{-1}

- **Phase II UPGRADE**

### CMS

- **Phase I Upgr**
  - 300 fb^{-1}

- **Phase II UPGRADE**
  - L = 8 x 10^{35} 50 ab^{-1}

### Belle II

- L = 8 x 10^{35} 50 ab^{-1}

---

LHC schedule: Frederick Bordry, 2019
Conclusions

- Precision measurements to scrutinize the Standard Model
- Precision measurements reach very high mass scales
- Precision measurements are not yet precise enough

![Graphs showing C10_{NP} vs C9_{NP}](image1.png)

![Graphs showing CKM: γ, V_{ub}, Δm_s](image2.png)

![Graphs showing 3D contours](image3.png)
What NP could it be?

- If interpreted as NP signals, both set of anomalies are not in contradiction among themselves & with existing low- & high-energy data. 
  
  **Taken together,** they point out to NP coupled mainly to 3rd generation, with a flavor structure connected to that appearing in the SM Yukawa couplings

- Anomalous measurements:
  - FCNC: \( b \to sll \)
  - LFNU: \( b \to sll \) and \( b \to clv \)

- What are the interpretations?
Model building

- Most popular models: Z' or Leptoquark

- **SM**
- **SU(2)’**
- **Leptoquark**
Model building

- Step 1: Effective theory

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{\mathcal{g}^2} \lambda^q_{ij} \lambda^\ell_{\alpha \beta} \left[ C_T (Q^i_L \gamma_\mu Q^j_L)(L^\alpha_L \gamma^\mu \sigma^a L^\beta_L) + C_S (Q^i_L \gamma_\mu Q^j_L)(L^\alpha_L \gamma^\mu L^\beta_L) \right] \]

<table>
<thead>
<tr>
<th>Observable</th>
<th>Experimental bound</th>
<th>Linearised expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{\text{Di}}^T )</td>
<td>1.237 ± 0.053</td>
<td>[ 1 + 2C_T(1 - \lambda^q_{tb}V^\ast_{tb}/V^\ast_{ts})(1 - \lambda^\ell_{\mu\mu}/2) ]</td>
</tr>
<tr>
<td>( \Delta C^\mu_9 )</td>
<td>-0.61 ± 0.12 [36]</td>
<td>[ - \frac{\pi}{\alpha^\text{em}} \lambda^q_{tb} \lambda^\ell_{tb}(C_T + C_S) ]</td>
</tr>
<tr>
<td>( R^\text{ee}_{\ell \to \gamma} - 1 )</td>
<td>0.00 ± 0.02</td>
<td>[ 2C_T(1 - \lambda^q_{tb}V^\ast_{tb}/V^\ast_{ts}) \lambda^\ell_{\mu\mu} ]</td>
</tr>
<tr>
<td>( B_{K^{(*)}\pi\pi} )</td>
<td>0.0 ± 2.6</td>
<td>[ 1 + \frac{\pi}{\alpha^\text{em}} \lambda^q_{tb} \lambda^\ell_{tb}(C_T - C_S) \lambda^q_{\mu\mu}(1 + \lambda^\ell_{\mu\mu}) ]</td>
</tr>
<tr>
<td>( \delta g^T_L )</td>
<td>-0.0002 ± 0.0006</td>
<td>[ 0.033C_T - 0.043C_S ]</td>
</tr>
<tr>
<td>( \delta g^T_{\tau} )</td>
<td>-0.0040 ± 0.0021</td>
<td>[ -0.033C_T - 0.043C_S ]</td>
</tr>
<tr>
<td>(</td>
<td>g^T_w/g^T_W</td>
<td>)</td>
</tr>
<tr>
<td>( B(\tau \to 3\mu) )</td>
<td>(0.0 ± 0.6) × 10^{-8}</td>
<td>[ 2.5 \times 10^{-4}(C_S - C_T)^2(\lambda^\ell_{\mu\mu})^2 ]</td>
</tr>
</tbody>
</table>

- Step 2: Simplified models

\[ SU(2)_L\text{-singlet vector leptoquark, } U^\mu \equiv (3, 1, 2/3) \]

\[ \mathcal{L}_U = - \frac{1}{2} U^\dagger_{1,\mu \nu} U^1,\mu \nu + M^2_U U^\dagger_1 U^1 + g_U (J^\mu_U U_{1, \mu} + \text{h.c.}) \]

\[ J^\mu_U \equiv \beta_{1\alpha} Q_1 \gamma^\mu L_\alpha. \]
Model building

- Many models! See e.g.:

Possible BSM models

- Heavy $Z'$ model
- $SU(2)_L$ singlet or triplet
- arXiv:1403.1269, 1501.00993, 1503.03477, 1611.02703, ...
- Leptoquark model
- Spin 0 or 1
- arXiv:01511.01900, 1503.01084, 1704.05835, 1511.06024, 1408.1627, ...
- Other new heavy scalars/vectors also leptoquark possible
- arXiv:01509.05020, 1608.07832, 1704.05438, 1607.01659, 1704.07845, hep-ph/0610037, ...

arXiv:1706.07808

ICHEP 2018 @Seoul

Courtesy, Geng CHEN, ICHEP 2018 , 7 July 2018
Model building

- **Ingredients**
  - **NP: large coupling $b \rightarrow c \tau \nu$**
    - Large coupling to 3rd gen leptons
    - Left-handed coupling (no RH neutrino)
  - **NP: small (non-vanishing) coupling $b \rightarrow s \mu \mu$**
    - Small coupling to 2nd gen leptons
    - Left-handed coupling (from $C_9$)
Three main problems identified in the recent literature:

- **EFT-type considerations**
  - Experimental constraints
    - High $p_T$ searches
    - Radiative constr. $\tau \rightarrow \mu \nu \nu$
    - $B_{s}^0$ mixing
    - $B_{c}^+$ lifetime
  - $B_{s}^0$ mixing
    - No tree level NP: small $b\bar{s}$ implies large $\tau\nu$
  - $B_{c}^+$ lifetime
    - Scalar LQ increases BR($B_{c}^+ \rightarrow \tau^+\nu$)

- **NP: large coupling $b \rightarrow c\tau\nu$**
  - Large coupling to 3rd gen leptons
  - Left-handed coupling (no RH neutrino)

- **NP: small (non-vanishing) coupling $b \rightarrow s\mu\mu$**
  - Small coupling to 2nd gen leptons
  - Left-handed coupling (from $C_9$)

**Experimental constraints**

**Vector LQ** favoured over

**Scalar LQ or Z'**
Model building

- Many more experimental handles; predictions can be checked!

- Universal for all $b \to c \tau \nu$:
  - Accurate $R(D^*)$, $R(J/\psi)$, ...

- Strong coupling to tau's:
  - Measure e.g. $B^0 \to K^* \tau \nu$

- LFNU linked with LFV:
  - Look for e.g. $B^0 \to K^* \tau \mu$
  - $BR(\tau \to \mu \mu) \sim 10^{-9}$

- c, u symmetry:
  - Study suppressed semileptonic

- $B_s$ mixing
  - $O(1-10\%)$ effect on $\Delta m_s$

$SU(2)_L$-singlet vector leptoquark emerges as a particularly simple and successful framework.
Model building

- Many more experimental handles; predictions can be checked!
- High $p_T$ signatures?
  - LQ pairs
  - LQ t-channel in $bb \rightarrow \tau \tau$
    Reachable during HL-LHC
  - Single production channel (dominant?)

N.B.:
- The single production (for which so far there are no dedicated searches) might be the dominant production channel.
The need for more precision

Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed”

– A.Soni

“A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L^0 \rightarrow \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky.”

– L.Okun

(remember: $B(K_L^0 \rightarrow \pi^+\pi^-) \sim 2 \times 10^{-3}$)