Outline

• Introduction
• Hints for Lepton Flavour Universality Violation
  ➢ Semi-leptonic B decays
  ➢ Anomalous magnetic moment of the muon
  ➢ Cabbibo Angle Anomaly
• Explanations of the Anomalies
• Common explanations
• Conclusions and outlook
Introduction
Discovering New Physics

• Cosmic Frontier
  – Cosmic rays and neutrinos
  – Dark Matter
  – Dark Energy

• Energy Frontier
  – LHC
  – Future colliders

• Intensity Frontier
  – Flavour
  – Neutrino-less double-β decay
  – Test of fundamental symmetries
  – Proton decay
Finding New Physics with Flavour

- At colliders one produces many (up to $10^{14}$) heavy quarks or leptons and measures their decays into light flavours.

Flavour observables probe higher energy scales than collider searches.

Experiment

Standard Model

New Physics

Direct searches

Flavour observables
Global Fit to the CKM Matrix

• Tree-level determinations of CKM elements (with light leptons) agree with $\Delta F=2$ processes
• Picture of CKM Flavour violation established, but sub-leading NP possible

Still room for New Physics effects of $O(10\%)$
Lepton Flavour (Universality) Violation

In the Standard Model accidental symmetry:

• Lepton Flavour is conserved (for vanishing neutrino masses)
  ➢ Excellent approximation: branching ratios smaller than $10^{-45}$

➤ Any observation proves new physics

• Gauge Interactions are Lepton Flavour Universal
• Only Yukawa couplings distinguish flavors
 ➢ Very small effect (except for phase space)

LFUV is an excellent probe of the SM
Overview on hints for Lepton Flavour Universality Violation
LFUV in $b \rightarrow s \ell^+ \ell^-$

$$R(K) = \frac{B \rightarrow K \mu^+ \mu^-}{B \rightarrow Ke^+e^-}$$

$$R(K^*) = \frac{B \rightarrow K^* \mu^+ \mu^-}{B \rightarrow K^* e^+e^-}$$

- Muon and electron masses can be neglected
- Clean prediction
- Supported by

$$\frac{\Lambda_b \rightarrow Kp\mu^+ \mu^-}{\Lambda_b \rightarrow Kpe^+e^-} = 0.86^{+0.14}_{-0.11} \pm 0.05$$

LFUV in $B$ decays $>4\sigma$
Global Fit to $b \to s \mu^+ \mu^-$ Data

- Perform global model independent fit to include all observables ($\approx 180$)
- Several NP hypothesis give a good fit to data significantly preferred over the SM hypothesis

$$O_9 = \bar{s} \gamma^\mu P_L b \bar{l} \gamma_\mu l$$
$$O_{10} = \bar{s} \gamma^\mu P_L b \bar{l} \gamma_\mu \gamma^5 l$$

Fit is $>7 \sigma$ better than the SM
b → cτν Transitions

- LFU test of the charged current
- Tau mode consistently enhanced
- Supported by

\[
R(D) = \frac{B_c \to J/\Psi \tau \nu}{B_c \to J/\Psi \ell \nu}
\]

- Tree-level need larger NP effect

O(10%) constructive preferred effect at 3σ
Muon Anomalous Magnetic Moment

- Theory prediction intricate (hadronic effects)
  \[ \Delta a_\mu = (251 \pm 49) \times 10^{-11} \]
  T. Aoyama et al., arXiv:2006.04822
- Need NP of the order of the SM EW contribution
- Chiral enhancement necessary for heavy NP
- Soon more experimental results from Fermilab
- Vanishes for \( m_\mu \to 0 \) → **measure of LFUV**

4.2σ deviation from the SM prediction
Cabibbo Angle Anomaly (CAA)

- Deficit in first row and first column CKM unitarity

\[
\left| V_{ud}^2 \right| + \left| V_{us}^2 \right| + \left| V_{ub}^2 \right| = 0.9985 \pm 0.0005 \\
\left| V_{ud}^2 \right| + \left| V_{cd}^2 \right| + \left| V_{td}^2 \right| = 0.9970 \pm 0.0018
\]

(PDG)

- NP in the determination of \( V_{ud} \) from beta decays needed

- Can be interpreted as
  - NP in beta decays
  - NP in the Fermi constant
  - LFUV (modified \( W_\mu\nu \) coupling)

3\( \sigma \) tension
Non-Resonant Di-Leptons

• Excess in di-electrons at $m_{ee} > 1800\text{GeV}$
  • Observed: 44 events
  • Expected $29.2 \pm 3.6$ events
  • Also ATLAS (2006.12946) and HERA (1902.03048) observe slightly more electrons than expected.
  • No excess in muon data

$\approx 3\sigma$ hint for LFUV
Hints for New Physics

- $\tau \rightarrow \mu \nu \nu$: 2σ
- $a_\mu$: 4.2σ
- $b \rightarrow c \tau \nu$: >3σ
- $b \rightarrow s \mu \mu$: >7σ
- $pp \rightarrow e^+e^-$: >3σ

LFUV
New Physics Explanations

\[ R(D^{(*)}) \]  
\[ \text{Leptop-quarks} \]  
\[ a_\mu \]  
\[ W' \]  
\[ pp \rightarrow e^+e^- \]  
\[ Z' \]  
\[ \text{new scalars/fermions} \]  
\[ b \rightarrow s\mu\mu \]  

SU(2) triplet
Simultaneous Explanations
b → sℓℓ and b → cτν with a Vector Leptoquark

Pati-Salam LQ can explain the flavour anomalies

AC, C. Greub, D. Müller, F. Saturnino, PRL 2018
Vector Triplet in the CAA & $b \to s\ell\ell$

- Region from EW fit overlaps with $b \to s\ell\ell$ region
- Correlations between e.g. $\pi \to \mu\nu/\pi \to e\nu$ and $R(K^{(*)})$ are predicted
- Global fit significantly improved

B. Capdevilla, AC, C. Manzari, M. Montull, PRD 2020

Common explanation possible
CAA and Non-Resonant Di-Leptons

4.5σ better than SM, prediction for $R(\pi)$

AC, C. Manzari, M. Montull, 2103.12003
Model for $b \rightarrow s\ell\ell$, CAA, $Z \rightarrow bb$ and $\tau \rightarrow \mu\nu\nu$

Simple model provides combined explanation

- $Z'$ penguin + modified $Z sb$ coupling give very good fit to $b \rightarrow s\ell\ell$ data
Outlook

- Flavour Anomalies require NP at the TeV scale
  
  Direct Searches at (HL-) LHC, FCC-pp

- This new particles in general also affect EW precision observables

  Z decays at CLIC and FCC-ee, CEPC

- Flavour is directly linked to the Higgs boson

  CLIC, FCC

The flavour anomalies strengthen the physics case for future colliders significantly
Backup
Cabibbo Angle Anomaly and EW Fit

- Modified $W_{ud}$ coupling
- Tree-level effects in beta decays disfavoured by LHC searches
- $W-W'$ mixing
- Vector-like leptons
  - $SU(2)_L$ singlet $N$ coupling to electrons
  - $SU(2)_L$ triplet $\Sigma$ coupling to muon

$>5\sigma$ improvement over SM hypothesis
Model for $b\to s\ell\ell$, CAA, $Z\to bb$ and $\tau \to \mu\nu\nu$

| $SU(3)_c$ | $q_L$ | $d_R$ | $u_R$ | $H$ | $\ell_L$ | $e_R$ | $SU(2)_L$ | $2$ | $1$ | $1$ | $2$ | $2$ | $1$ | $U(1)_Y$ | $\frac{1}{6}$ | $\frac{-1}{3}$ | $\frac{2}{3}$ | $\frac{1}{2}$ | $\frac{-1}{2}$ | $-1$ | $U(1)'$ | $0$ | $0$ | $0$ | $0$ | $(0, 1, -1)$ | $Q_L$ | $Q_R$ | $D_L$ | $D_R$ | $\phi^+$ | $S$ |
|----------|-------|-------|-------|-----|---------|-------|----------|-----|-----|-----|-----|-----|-----|----------|-------|-------|-------|-------|-------|-----|----------|-------|-------|-------|-------|-------|-----|
| $SU(3)_c$ | $3$   | $3$   | $3$   | $1$ | $1$     | $1$   | $3$      | $3$ | $3$ | $3$ | $3$ | $1$ | $1$ | $SU(2)_L$ | $2$   | $2$   | $1$   | $1$   | $1$   | $1$ | $U(1)_Y$ | $\frac{-5}{6}$ | $\frac{-5}{6}$ | $\frac{-1}{3}$ | $\frac{-1}{3}$ | $1$   | $0$ |
| $U(1)'$   | $0$   | $0$   | $0$   | $0$ | $(0, 1, -1)$ | $0$   | $1$      | $1$ | $0$ | $-1$ | $-1$ | $Z'$

Tree effect in $Zbb$ and loop in $Z'sb$
Model for $b \to s \ell \ell$, CAA, $Z \to bb$ and $\tau \to \mu \nu \nu$

- $Z \to bb$
- $\tau \to \mu \nu \nu$
- CAA

- $Z'$ penguin + modified $Zs\bar{b}$ coupling give very good fit to $b \to s\ell \ell$ data

Simple model provides combined explanation
W’ Explanation of R(V_{us})

- W’ effects in LFU and EW observables
- Z’ effects in LHC di-jet and di-lepton tail searches

R(V_{us}) can be explained by a left-handed W’
Correlations the neutron EDM with S1

Effect in B predicts measurable nEDM effect

AC, F. Saturnino
arxiv:1905:08257

1905:08257
$R(J/\Psi) = B_c \rightarrow J/\Psi \tau \nu / B_c \rightarrow J/\Psi 1 \nu$

LHCb $R(J/\psi)$
LHCb-PAPER-2017-035
0.71 ± 0.17 ± 0.18

SM predictions
PLB 452 (1999) 129
PRD 73 (2006) 054024
PRD 74 (2006) 074008
Range 0.25 - 0.28

Supports $R(D) \& R(D^*)$
$R(D^{(*)})$, $b \rightarrow s\nu\nu$ with 2 Scalar LQs

$\lambda^L_{jk} \equiv \lambda^{1L}_{jk}$

$\lambda^{3L}_{jk} = e^{i\pi j} \lambda^L_{jk}$
Hadronic Vacuum Polarization

- New BMWc lattice QCD result

Up to 4σ tension in EW fit

A.C. M. Hoferichter, C. Manzari, M. Montull 2003.04886
b\rightarrow c\tau\nu Transitions

- B\rightarrow D\tau\nu, B \rightarrow D^{*}\tau\nu, \Lambda_b \rightarrow \Lambda_c \tau\nu
- Tree-level decays in the SM
- Form factors needed
- With light leptons (\mu, e) used to determine the CKM elements
- CKM fit works very well, i.e. tree-level in agreement with \Delta F=2 processes

Largest B branching ratios, used to determine the CKM elements, usually assumed to be free of NP
• Pure scalar-tensor explanations in tension with the $B_c$ lifetime

• Pure left-handed vector, i.e. contribution to the SM operator gives good fit

Global fit give up to $4\sigma$ preference for NP
Two Scalar Leptoquarks

- $\Phi_1$ scalar leptoquark singlet with $Y=-2/3$
- $\Phi_3$ scalar leptoquark triplet with $Y=-2/3$

Constructive in $R(D^{(*)})$
Destructive in $b \rightarrow s \mu \mu$
R(D(\(\ast\))), b\(\rightarrow\)sll and \(a_\mu\)

- 4 benchmark points

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<th>(p_2)</th>
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<td>(\lambda_{23})</td>
<td>1.34</td>
<td>-1.47</td>
<td>1.23</td>
</tr>
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\[
C_{\mu\mu} = -C_{\bar{\mu}\bar{\mu}}
\]

\[
C_{\ell\ell} = C_{\bar{\ell}\bar{\ell}}
\]

\[
R(D) = \frac{R(D)}{R(D)_{SM}}
\]

\[
R(D^*) = \frac{R(D^*)}{R(D^*)_{SM}}
\]

\[
B_{s \rightarrow \tau\tau} = \left| \frac{B_{s \rightarrow \tau\tau}}{B_{s \rightarrow \tau\tau}_{SM}} \right|
\]

\[
\tau \rightarrow \mu\gamma = 4.35 \times 10^8
\]

\[
\delta a_\mu = 207 \times 10^{11}
\]

\[
\Delta \frac{V_{e_b}^e}{V_{e_b}^\mu} - 1 = 934 \times 10^6
\]

\[
Z \rightarrow \tau\mu = 0.117 \times 10^{10}
\]

\[
C_{\tau\tau}^{\mu\mu} = -4C_{\tau\tau}^{\bar{\mu}\bar{\mu}}
\]

\[
C_{\tau\tau}^{\ell\ell} = C_{\bar{\tau}\bar{\tau}}^{\ell\ell}
\]

\[
R_{\nu\nu}^{K^{(*)}} = \frac{\Delta m_{NP}^{B_s}}{\Delta m_{SM}^{B_s}}
\]

\[
B \rightarrow K_{\tau\mu} = \frac{1.27}{10^{10}}
\]

\[
\tau \rightarrow \mu\gamma = \frac{44.94}{10^{10}}
\]

\[
\Delta \frac{L_{33}^{LQ(0)}}{L_{33}^{NSM}} = \frac{-3.64}{10^{-5}}
\]

Common explanation possible

AC, D. Mueller, F. Saturnino
arxiv:1912.04224
Outlook: Physics at Future Colliders

- Flavour Anomalies require NP at the TeV scale

  ➡️ Direct Searches at HL-LHC, HE-LHC, FCC-pp

- This new particles in general also affect EW precision observables

  ➡️ $Z$ decays at CLIC and FCC-ee

- Flavour is directly linked to the Higgs boson

  ➡️ CLIC, FCC

Flavour Anomalies (if confirmed) strengthen the physics case for future colliders significantly
Important Loop-Effects

• Explanation of $b \to c \tau \nu$ requires large $b \tau$ and $s \tau$ couplings (follows from SU(2) invariance)

AC, C. Greub, D. Müller, F. Saturnino, PRL 2018
R(D\(^{(\ast)}\)) and b\(\rightarrow s\tau\tau\)

- Large couplings to the second generation

B. Capdevila, AC, S. Descotes-Genon, L. Hofer and J. Matias, PRL.120.181802
Important Loop-Effects

• Explanation of $b \rightarrow c\tau\nu$ requires large LQ-$b\tau$ and LQ-$c\nu_\tau$ couplings
• Via SU(2) invariance this leads to large effects in $b \rightarrow s\tau\tau$ processes
• Closing the tau-loop gives a LFU effect in $b \rightarrow sll$
• Effect goes in the right direction

Explanation of $b \rightarrow c\tau\nu$ leads to loop effects in $b \rightarrow s\mu\mu$

M. Algueró, B. Capdevila, S. Descotes-Genon, P. Masjuan, J. Matias, PRD, 2019

AC, C. Greub, D. Müller, F. Saturnino, PRL 2018
Vector LQ Phenomenology

Compatible with constraints for generic couplings
Possible UV completions

- $\text{SU}(4) \times \text{SU}(3)' \times \text{SU}(2)_L \times \text{U}(1)_Y + \text{Vector-like fermions}$
  

- $\text{SU}(4) \times \text{U}(2)_L \times \text{SU}(2)_R + \text{Vector-like fermions}$
  
  L. Calibbi, AC, T. Li, arXiv:1709.00692

- $\text{SU}(4) \times \text{SU}(4) \times \text{SU}(4)$
  

- $\text{SU}(4) \times \text{U}(2)_L \times \text{SU}(2)_R$ including scalar LQs and light right-handed neutrinos
  
  J. Heeck, D. Teresi, arXiv:1808.07492

- $\text{SU}(8)$ might even explain $\epsilon'/\epsilon$
  

- $\text{SU}(4) \times \text{U}(2) \times \text{SU}(2)_R$ in RS background
  
  M. Blanke, AC, arXiv:1801.07256

Good solution, but challenging UV completion
Pati-Salam RS Phenomenology

Model well motivated + limited but sizable effect

\[ M = 3 \text{ TeV}, \quad s_2^\xi = 0.2, \quad s_3^\xi = 1/\sqrt{2} \text{ and } s_3^g = \sqrt{3}/2 \]

M. Blanke, AC, PRL 2018
$B_s \rightarrow \mu \mu$ and $B_s \rightarrow \phi \mu \mu$

- $B_s \rightarrow \mu \mu$ theoretically clean but chirality suppressed and therefore statistically limited

- $B_s \rightarrow \phi \mu \mu$ has a higher $Br$, but knowledge of the form-factor needed

$Br's \approx 20\%$ below SM expectations
Leptoquarks in $a_\mu$

- Chirally enhanced effects via top-loops

- $m_t/m_\mu$ enhanced effect $h \to \mu\mu$
- $m_t^2/m_Z^2$ enhanced effect in $Z \to \mu\mu$

Correlations with $h \to \mu\mu$ and $Z \to \mu\mu$
$a_\mu$ vs $h \rightarrow \mu\mu$

- Chirally enhanced effects via top-loops
- Same coupling structure $\rightarrow$ direct correlation

A.C., D. Mueller, F. Saturnino, 2008.02643

$h \rightarrow \mu\mu$ at future colliders
$\tau \rightarrow \mu \nu \nu$ and $\tau \rightarrow e \nu \nu$

- Ratios of leptonic tau decays

\[
\frac{A_{\text{EXP}}(\tau \rightarrow \mu \nu \bar{\nu})}{A_{\text{SM}}(\mu \rightarrow e \nu \bar{\nu})} = 1.0029 \pm 0.0014
\]

\[
\frac{A_{\text{EXP}}(\tau \rightarrow \mu \nu \bar{\nu})}{A_{\text{SM}}(\tau \rightarrow e \nu \bar{\nu})} = 1.0018 \pm 0.0014
\]

\[
\frac{A_{\text{EXP}}(\tau \rightarrow e \nu \bar{\nu})}{A_{\text{SM}}(\mu \rightarrow e \nu \bar{\nu})} = 1.0010 \pm 0.0014
\]

\[
\rho = \begin{pmatrix}
1.00 & 0.49 & 0.51 \\
0.49 & 1.00 & -0.49 \\
0.51 & -0.49 & 1.00
\end{pmatrix}
\]

- NP in muon decay constrained from EW data

$\approx 2\sigma$ hint for LFUV in tau decays
The $P_5^\prime$ Anomaly

- $P_5^\prime$ angular observables in $B \rightarrow K^* \mu \mu$
- Constructed in such a way that the form factor dependence is minimized
- Confirmed by latest LHCb analysis for the charged mode

> $3\sigma$ deviation from the SM prediction
b→sμ^+μ^- Processes

- Flavour Changing Neutral Current (FCNC)
- In the SM it is suppressed by
  - The CKM elements $V_{cb} \approx 0.04$
  - Electroweak scale
  - Loop-factor
- Wilson coefficients precisely known  

Bobeth et al. PRD, 2013

Suppressed in the SM and very sensitive to NP
τ → μνν

- $L_\mu - L_\tau Z'$ (box diagrams)
- LFV violating $Z'$
- Modified $W_\nu$ couplings
- $W'$
- Singly charged scalar


Scenarios can be distinguished by $\pi \rightarrow \mu\nu / \pi \rightarrow e\nu$