EFT interpretation of low-PT results

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Flavour anomalies 2021

Hints of New Physics

- $B_s \rightarrow \phi \mu^+ \mu^-$
  $\sim 3.5\sigma$

- $B \rightarrow K^* \mu^+ \mu^-$
  angular distribution
  $\sim 3\sigma$

- $|V_{ub}|, |V_{cb}|$
  inclusive vs. exclusive
  $\sim 3\sigma$

- like-sign dimuon charge asymmetry
  $\sim 3.5\sigma$

- $K$ decays: $\epsilon'/\epsilon$
  $\sim 2.5\sigma$

- $B \rightarrow K\mu^+\mu^-$
  $B \rightarrow K\ell^+\ell^-$
  $\sim 2.5\sigma$

- $B \rightarrow D^{(*)}\tau\nu$
  $B \rightarrow D^{(*)}\ell\nu$
  $\sim 4\sigma$

- muon $(g - 2)$
  $2.5\sigma - 3.5\sigma$

Quark sector

Lepton sector

Federico Mescia, Red LHC 2021
Potential violation of lepton-flavour universality (LFUV)

- $R(K^{(*)}) \iff b \to s\ell^+\ell^- \, (\text{neutral current}): \mu < e$
- $R(D^{(*)}) \iff b \to c\ell\nu \, (\text{charged current}): \tau > e, \mu$
Potential violation of lepton-flavour universality (LFUV)

- $\mathcal{R} (K^{(*)}) \leftrightarrow b \to s \ell^+ \ell^-$ (neutral current): $\mu \prec e$

- $\mathcal{R} (D^{(*)}) \leftrightarrow b \to c \ell \nu$ (charged current): $\tau \succ e, \mu$

Flavour anomalies 2021

Hints of New Physics

LHCb results

[M. Borsato, Flavour Anomaly w/s 2021]

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

$B^+ \rightarrow K^{*+} \mu^+ \mu^-$

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

$B \rightarrow K^+ \mu^+ \mu^-$

$B \rightarrow K_e^+ e^-$

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

$B \rightarrow K^+ \mu^+ \mu^-$

$B \rightarrow K_e^+ e^-$

Like-sign dimuon charge asymmetry

$K \text{ decays: } \varepsilon' / \varepsilon$

$\sim 2.5\sigma$

$\sim 3.5\sigma$

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$\sim 4\sigma$

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$\epsilon'/\epsilon$
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$B \rightarrow K^{*+} \mu^- 
B \rightarrow K^{*+} e^-$
$\sim 2.5\sigma$

$B \rightarrow D^{(*)} \tau \nu 
B \rightarrow D^{(*)} \ell \nu$
$\sim 4\sigma$

muon $(g - 2)$
$2.5\sigma - 3.5\sigma$

ATLAS / CMS
**B → sℓ⁺ℓ⁻ transitions**

- **Rare** (decay rate < $10^{-6}$)
  - flavour changing neutral currents forbidden at tree-level
  - proceed through **box** or **penguin** diagrams
  - small off-diagonal CKM elements
  - new physics could enter at the same order as SM

- **Experiment-friendly**
  - neutrinos ⇒ fully defined final state
  - several complementary channels
  - several complementary observables

- **Beautiful** (involves a $b$ quark)
  - small long-distance contributions ($m_b \gg \Lambda_{QCD}$)
  - can interpret with **effective theory** ($m_b \ll m_W$)

- **Examples**
  - $B_s \rightarrow ℓ^+ℓ^-$, $B \rightarrow Kℓ^+ℓ^-$, $B \rightarrow K^*ℓ^+ℓ^-$,
  - $B_s \rightarrow φℓ^+ℓ^-$, $Λ_b \rightarrow pK^-ℓ^+ℓ^-$, ...

- **Branching ratios**
- **Angular analyses**
- **Symmetry tests** (FB, LFU ratios, ...)
Angular analysis of $b \to s \mu \mu$

- Angular distributions of the decay products in $B^0 \to K^* \mu \mu \to K^+ \pi^- \mu \mu$ sensitive to new physics
- $K^*$ is vector $\Rightarrow$ 3 polarisation states
- $B \to K^* \mu^+ \mu^-$ 4-body decay described by 3 angles and $q^2 \ (\equiv m_{\mu \mu}^2)$

$$\frac{d^4 \Gamma}{dq^2 \, d \cos \theta_K \, d \cos \theta_i \, d \phi} = \frac{9}{32 \pi} \left[ \frac{3}{4} F_L \sin^2 \theta_K + F_L \cos^2 \theta_K \right.\left. + \left( \frac{1}{4} F_L \sin^2 \theta_K - F_L \cos^2 \theta_K \right) \cos 2 \theta_i + \frac{1}{2} P_1 F_L \sin^2 \theta_K \sin^2 \theta_i \cos 2 \phi\right.\left. + \sqrt{F_L} \left( P_4 \sin 2 \theta_K \sin 2 \theta_i \cos \phi + P_5' \sin 2 \theta_K \sin \theta_i \cos \phi \right)\right.\left. - \sqrt{F_L} \left( P_6 \sin 2 \theta_K \sin \theta_i \sin \phi - \frac{1}{2} P_8' \sin 2 \theta_K \sin 2 \theta_i \sin \phi \right)\right.\left. + 2P_2 F_L \sin^2 \theta_K \cos \theta_i - P_3 F_L \sin^2 \theta_K \sin^2 \theta_i \sin 2 \phi \right]$$

$P_i$ basis: parameters optimised to reduce theoretical uncertainties
$F_L$: fraction of longitudinally polarised $K^*$

Fitting three angular distributions $\phi, \theta_\ell, \theta_K$ $\rightarrow$ Wilson coefficients (see EFT later)
$B^0 \rightarrow K^*\mu\mu$ -- calibration

- Acceptance functions for the angular variables determined from MC simulation
- Signal mass resolution calibrated from $B \rightarrow K^*J/\psi$ and $K^*\psi(2S)$ “standard candle” samples
- Simultaneous fit to $B$ candidate mass and angular distributions
  - background angular distributions described by polynomials
  - folding in angular variables permits fitting only a subset of coefficients

JHEP 10 (2018) 047
$B^0 \rightarrow K^*\mu\mu$ – ATLAS results

- Particular interest in $P'_5$, especially bin $q^2 \in [4, 6]$ GeV$^2$
  - LHCb observed a $>2\sigma$ deviation [PRL 125 (2020) 011802]
- Can see e.g. lack of expected $\cos \phi$ modulation in signal fit: $P'_5 \approx 0$ in our fit for this bin
  - simultaneous fit to $\theta_K$ and $\theta_L$ as well
  - not significant difference from predictions

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  - not significant difference from predictions
  - deviation in the same direction as other results

- Results for other coefficients: $P_1, P'_4, P'_6, P'_8$
- Compatible within $3\sigma$ with SM
**$B^0 \rightarrow K^*\mu\mu$ – CMS results and summary**

- Similar analysis from CMS measures $P_1$ and $P'_{5}$
  - limited statistics ⇒ only few parameters extracted
- Measurements are in agreement with predictions based on the standard model

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**Graphs and Data**

- $R = \frac{\sigma(B^0 \rightarrow K^*\mu\mu)}{\sigma(B^0 \rightarrow \pi^0\mu\mu)}$
- $q^2$ (GeV^2)

- **LHCb**: JHEP 02 (2016) 104
- **Belle**: PRL 118 (2017) 111801
- **ATLAS**: JHEP 10 (2018) 047
- **SM-DHMV**: JHEP 06 (2016) 092
- **SM-HEPfit**: PLB 442 (1998) 381
- **SM-HEPfit**: PRD 61 (2000) 074024
- **SM-HEPfit**: PRD 62 (2000) 094023

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Other $B \to K\mu\mu$ analyses

- $A_{FB}$: muon forward-backward asymmetry
- $F_H$: contribution from pseudoscalar, scalar and tensor amplitudes to the decay width

$B^+ \to K^+\mu^+\mu^-$

- $F_L$: $K^{*+}$ longitudinal polarization fraction

$B^+ \to K^*(892)\mu^+\mu^-$

Results consistent with previous measurements, and compatible with SM predictions


JHEP04(2021)124
Future developments & prospects

- Lepton flavour universality variables require trigger on electrons and single muons
  → CMS B-parking [CMS-DP-2019/043]
    - dynamically adjust trigger $p_T$ thresholds during fill to keep high rate despite falling luminosity within fill

- HL-LHC: Precision in measuring the $P'_5$ parameter is expected to improve by a factor of $O(10)$
  - depends on muon trigger options
  - precision improvement in other observables: $F_L$, $P_i^{(r)}$
  - with 3000 fb$^{-1}$, finer binning in $q^2$ is possible

Previously presented results obtained with $\sim 20$ fb$^{-1}$ @ 8 TeV
Deviation from SM $\Rightarrow$ New Physics?

- High-$p_T$ searches $\rightarrow$ heavy new particles at tree-level
  - respect full SM gauge symmetry
  - leptoquarks and heavy resonances ($W'$, $Z'$)
  - previous talk by Gianantonio Pezzullo
- Contact interactions $\rightarrow$ fit to data at scale $g^2/\Lambda^2 \sim (30 \text{ GeV})^{-2}$
  - Tuesday talk by Yoav Afik
- Focus on low-$p_T$ $\rightarrow$ NP in loop effects
  - EFT fit to $b \rightarrow s\ell\ell$ data
Effective field theory

- An EFT probes different couplings
  \[ \mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i \]
  - fermion operators \( O_i \), Wilson coefficients \( C_i \)
- Important Wilson coefficients (for SM and NP)
  - \( C_9^\mu \) – vector current, dominant contributions to angular observables, LFU observables
  - \( C_{10}^\mu \) – axial current, dominant contributions to \( B_s \to \mu\mu \), LFU observables
- Global fits indicate consistent deviation: reduction of \( C_9 \) for muons

EFT fit to $b \to s\ell\ell$ data – $R_K$ and $P'_5$

- $R_K$ and $P'_5$ important in indicating favoured scenarios
- Most favoured 1D scenario $\rightarrow$ vector coupling to $\mu$
  - encoded in $C_{9\mu}^{\text{NP}}$
  - preferred over SM with $\text{Pull}_{\text{SM}} 7\sigma$ fitting all $b \to s\mu\mu$ observables
- $C_{9\mu}^V = -C_{10\mu}^V, C_9^U$
  - $C_9^U$ encodes the presence of a lepton-flavour universal NP component to $C_9$, i.e., $b \to see, b \to s\mu\mu$ and $b \to s\tau\tau$
  - $b \to s\mu\mu$ LFUV NP contribution to $(C_9, C_{10})$
- $C_{9\mu}^{\text{NP}}, C_{9\mu}' = -C_{10\mu}'$
  - pattern with right-handed couplings to muons
  - large negative NP contribution to $C_{9\mu}$

More fits by other groups:

- Alok et al., [JHEP 06 (2019) 089](https://link.springer.com/article/10.1007%2FJHEP06%282019%29089)
- Datta et al., [PLB 797 (2019) 134858](https://linkinghub.elsevier.com/retrieve/pii/S0370269319304385)
- D’Amico et al., [JHEP 09 (2017) 010](https://link.springer.com/article/10.1007%2FJHEP09%282017%29010)
EFT fit to $b \rightarrow s \ell \ell$ data – $B_{s,d} \rightarrow \mu^+ \mu^-$

- Absolute branching ratio of the purely leptonic decay $B_s \rightarrow \mu \mu$ is considered as theoretically clean
- All measurements statistically limited
- $\text{BR}(B_s \rightarrow \mu \mu)$ plays an important role in constraining the Wilson coefficient $C_{10}$
- If all rare $B$ decays are considered, best fit of $(C_9^U, C_9^\mu) \simeq (-0.32, -0.34)$ with a pull $5.4\sigma$
- Overall, good agreement between fits of different groups despite different approaches $\rightarrow$ robust $b \rightarrow s \ell \ell$ global analyses
Loop-level solutions to $B$-anomalies

- Addition of **supersymmetric** fields brings new penguin and box diagrams in the $b \to s \ell \ell$ picture
  - mass insertion approximation may be required for consistency with $B$-anomalies
  - if $m(\Psi) < m(\Phi_{q,\ell})$, then $\Psi$ can be a EW gaugino: chargino $\tilde{\chi}^\pm$, neutralino $\tilde{\chi}^0$
  - if $\Psi$ is the lightest neutralino, $\tilde{\chi}_1^0$, then it can be a dark-matter candidate
  - $\Phi_{\ell}$ can be the smuon, $\tilde{\mu}$ or the sneutrino, $\tilde{\nu}_\mu$

- Collider searches have set bounds in various of the involved sparticles
- Have these SUSY scenarios been ruled out by LHC?
- Can $(g-2)_\mu$ be accommodated, too?

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- $B \rightarrow K^* \mu^+ \mu^-$, angular distribution, $\sim 3\sigma$
- $|V_{ub}|, |V_{cb}|$, inclusive vs. exclusive, $\sim 3\sigma$
- Like-sign dimuon charge asymmetry, $\sim 3.5\sigma$
- $K$ decays: $\epsilon'/\epsilon$, $\sim 2.5\sigma$

$(g-2)_\mu$ tension with SM first observed in BNL, confirmed by Muon $g-2$ @ Fermilab (that is if theory end is confirmed)

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Hints of New Physics

\[ B_s \to \phi \mu^+ \mu^- \sim 3.5\sigma \]

\[ B \to K^{*} \mu^+ \mu^- \text{ angular distribution} \sim 3\sigma \]

\[ |V_{ub}|, |V_{cb}| \text{ inclusive vs. exclusive} \sim 3\sigma \]

\[ K \text{ decays: } \epsilon'/\epsilon \sim 2.5\sigma \]

\[ B \to K \mu^+ \mu^- \]
\[ B \to K e^+ e^- \sim 2.5\sigma \]

Is it possible to find a common solution for B-anomalies and \((g - 2)_\mu\) measurement?

Muon g-2, Phys. Rev. Lett. 126 (2021) 141801
Supersymmetry: smuons & \( (g-2)_\mu \)

- ATLAS & CMS have looked for and constrained the existence of sleptons in various channels.
- Yet there is parameter space left still compatible with the observed value of \( (g-2)_\mu \).
- These scenarios may also respect the \( b \to s\ell\ell \) anomalies.

2\&0J analysis

\( (g-2)_\mu \)-relevant SUSY parameters
- \( M_2 \): wino mass parameter
- \( \mu \): higgsino mass parameter
- \( \tan \beta \): ratio of vev’s of two Higgs doublets

Compressed spectra

\[ m(\tilde{\mu}) \approx m(\tilde{\chi}^0_1) \]
Summary & prospects

• Rare $b \rightarrow s\mu\mu$ decays are sensitive probe of new physics
  ▫ global fits show a consistent set of anomalies across observables and experiments
  ▫ ATLAS & CMS are performing angular-distribution analyses

• Interesting NP scenarios enter in loop diagrams
  ▫ also in connection with $(g-2)_\mu$ tension ☞ supersymmetry

• ATLAS & CMS are adding capabilities to measure LFU observables
  ▫ $R(K^*)$, $R(K) \leftrightarrow$ electron channel
  ▫ $R(D)$, $R(D^*) \leftrightarrow$ single-muon channel, taus?

• HL-LHC will bring a $\sim\times10$ better precision in $F_L$, $P_i$ parameters

• CMS & ATLAS are exploring more and more $B$-physics observables
Thank you for your attention!
Spares
Large Hadron Collider at CERN

- Run 1: 2010 – 2012
  - proton-proton $\sqrt{s} = 7$ – $8$ TeV
- Run 2: 2015 – 2018
  - proton-proton $\sqrt{s} = 13$ TeV
- Spectacular LHC performance!