Theory perspective on the flavour anomalies

Monika Blanke

Karlsruher Institut für Technologie

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Planck 2021

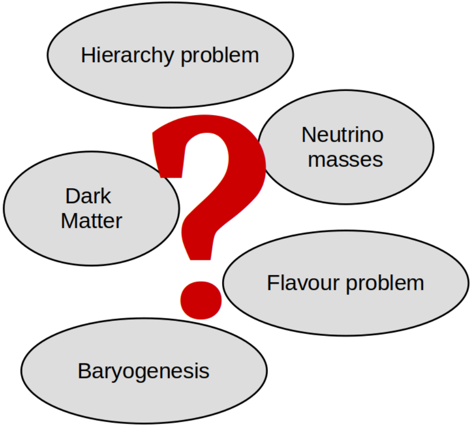
Durham/Zoom – June 30, 2021

New Physics, where are you?

After a decade of LHC operation

- discovery of Higgs boson
  ➢ apparent completion of Standard Model
- Higgs, electroweak and top measurements in impressive agreement with SM
- no evidence for TeV-scale new particles, increasingly stringent bounds

➢ **huge success of the Standard Model!**



The quest for high precision

Possible paths to New Physics

↙ ↘

Direct searches – energy frontier

- increased luminosity
- higher energies (➢ new collider)
- new observables

Indirect probes – precision frontier

- rare processes
- theoretically clean
- experimentally under control

↘ ↙

complementarity & interplay

Flavour physics at the precision frontier

Quark flavour physics

- SM flavour violation strongly suppressed by CKM hierarchy
- additional GIM suppression for neutral current processes
- plethora of measurable meson (and baryon) decays
- many processes theoretically well understood
- overall good agreement with SM predictions

Lepton flavour physics

Lepton flavour violation

- absent in the SM
- unambiguous sign of New Physics
- small rates, no interference with SM contribution

Lepton flavour universality

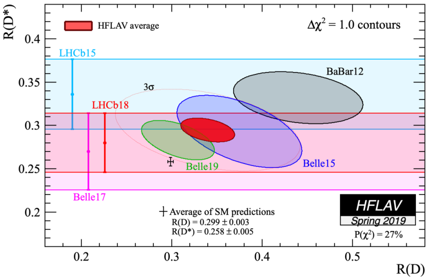
- approximately conserved in the SM, broken only by small Yukawa couplings
- theoretically clean
- measurable rates

(Not-so-)Recent news from lepton flavour universality tests

- $\boldsymbol{R(D^{(*)})}$ **anomaly** – 3.1σ anomaly in charged current semi-tauonic B decays, exhibiting LFU violation
- $\boldsymbol{R(K^{(*)})}$ **anomaly** – various *consistent* $2-3\sigma$ deviations in neutral current semi-leptonic B decays
- $\boldsymbol{(g-2)_\mu}$ **anomaly** – 4.2σ tension between SM prediction and data in anomalous magnetic moment of the muon
- **Cabibbo angle anomaly** – 3σ deviation from first-row CKM unitarity, hinting at possible violation of LFU in charged-current transitions

The $R(D^{(*)})$ anomaly

Test of lepton flavour universality in semi-tauonic B decays



➢ **3.1σ discrepancy with SM**

$$R(D^{(*)}) = \frac{\text{BR}(B \to D^{(*)}\tau\nu)}{\text{BR}(B \to D^{(*)}\ell\nu)} \qquad (\ell = e, \mu)$$

- theoretically clean, as hadronic uncertainties largely cancel in ratio
- measurements by BaBar, Belle, LHCb ($\mathcal{R}(D^*)$ only)
- model-independent sum-rule relating values of $R(D)$, $R(D^*)$ and $R(\Lambda_c)$
  - ➢ experimental consistency check

MB, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić (2018), (2019)

Effective Hamiltonian for $b \to c\tau\nu$

New Physics above B meson scale described model-independently by

$$\mathcal{H}_{\text{eff}}^{\text{NP}} = 2\sqrt{2}G_F V_{cb}\Big[(1+C_V^L)O_V^L + C_S^R O_S^R + C_S^L O_S^L + C_T O_T\Big]$$

with

$$O_V^L = (\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau) \qquad O_S^R = (\bar{c}P_R b)\,(\bar{\tau}P_L\nu_\tau)$$

$$O_T = (\bar{c}\sigma^{\mu\nu}P_L b)\,(\bar{\tau}\sigma_{\mu\nu}P_L\nu_\tau) \qquad O_S^L = (\bar{c}P_L b)\,(\bar{\tau}P_L\nu_\tau)$$

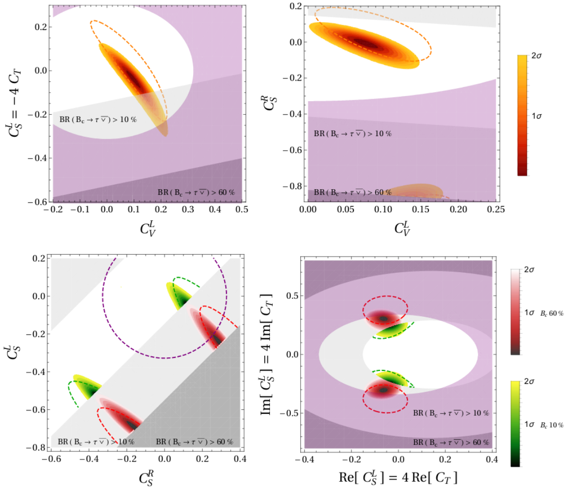
Possible (tree-level) NP scenarios:

- charged Higgs contributions ➢ $C_S^{L,R} \neq 0$ — Kalinowski (1990); Hou (1993) Crivellin, Kokulu, Greub (2013)...
- charged vector boson W' ➢ $C_V^L \neq 0$ — He, Valencia (2012); Greljo, Isidori, Marzocca (2015)...
- (scalar or vector) leptoquark ➢ various $C_j \neq 0$ (depending on model)

see e. g. Tanaka, Watanabe (2012); Deshpande, Menon (2012); Kosnik (2012); Freytsis et al (2015) Alonso et al (2015); Calibbi et al (2015); Fajfer, Kosnik (2015); Becirevic et al (2016),(2018)

Single particle scenarios

MB, Crivellin, Kitahara, Moscati, Nierste, Nišandžić (2019)
see also Murgui et al (2019); Shi et al (2019)



Main results

- W' solution disfavoured by LHC direct searches Faroughy, Greljo, Kamenik (2016)
- significant improvement possible with various leptoquark scenarios
- charged Higgs scenario predicts very large $\mathrm{BR}(B_c \to \tau\nu) \simeq 50\%$
  see Alonso, Grinstein, Martin Camalich (2016)
  Akeroyd, Chen (2017); MB et al (2018)
  Aebischer, Grinstein (2021)
- constraints from LHC mono-τ constraints
  Greljo, Martin Camalich, Ruiz-Alvarez (2018)

More flavour observables to test NP in $R(D^{(*)})$

Direct probes of NP structure

- $B \to D^{(*)}\tau\nu$ differential distributions, angular and polarisation observables

Nierste et al (2008); Celis et al (2016); Becirevic et al (2016)
Iguro et al (2018); MB, Crivellin et al (2018); Alonso et al (2018; Becirevic et al (2019)

Additionally: implied by $SU(2)_L$ symmetry

- large impact on $B \to K^{(*)}\nu\bar{\nu}$, $B_s \to \tau^+\tau^-$, $B \to K\tau^+\tau^-$ — Crivellin, Müller, Ota (2017)
- contributions to $\Upsilon \to \tau^+\tau^-$ and $\psi \to \tau^+\tau^-$ — Aloni et al. (2017)

Complementary probes in high-p_T searches

- strong constraints from $b\bar{b} \to \tau\bar{\tau}$ and mono-τ at ATLAS and CMS

Faroughy, Greljo, Kamenik (2016); Altmannshofer, Dev, Soni (2017)
Greljo, Martin Camalich, Ruiz-Alvarez (2018)

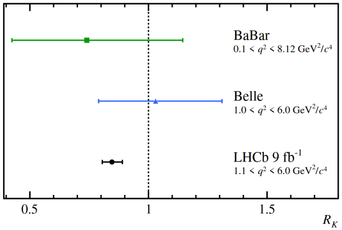
➢ **full NP resolution of $R(D^{(*)})$ anomaly challenging**

The $R(K^{(*)})$ anomaly

Test of LFU in $b \to s\ell^+\ell^-$ transitions

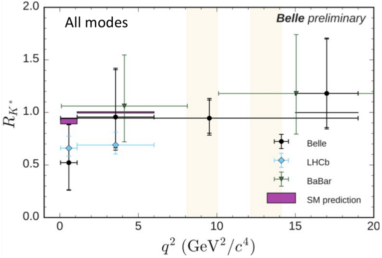
$$R(K^{(*)}) = \frac{\text{BR}(B \to K^{(*)}\mu^+\mu^-)}{\text{BR}(B \to K^{(*)}e^+e^-)}$$

- recent LHCb update lifted $R(K)$ anomaly above 3σ
- $R(K^*)$ and $R(Kp)$ hint in same direction



Anomalies seen in various $b \to s\mu^+\mu^-$ observables

- angular distribution of $B \to K^*\mu^+\mu^-$ (mainly P_5')
- less significant tensions in other decays, e. g. $B_s \to \phi\mu^+\mu^-$, $B_s \to \mu^+\mu^-$

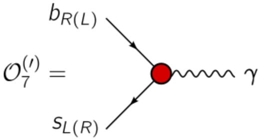


New Physics in $b \to s\ell^+\ell^-$

Effective $b \to s\ell^+\ell^-$ Hamiltonian:

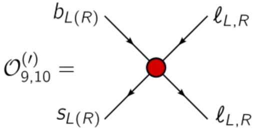
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \frac{e^2}{16\pi^2} \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i') + h.c.$$

with the operators most sensitive to New Physics



electromagnetic dipole operators $O_7^{(\prime)}$

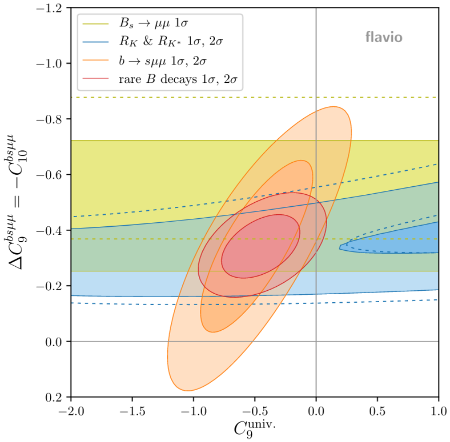
- govern inclusive and exclusive $b \to s\gamma$ transitions
- enhanced contribution to $B \to K^*\ell^+\ell^-$ in low q^2 region



semileptonic four-fermion operators $O_9^{(\prime)}, O_{10}^{(\prime)}$

- loop-suppressed in the SM, but potentially tree level in the presence of NP

Status of global fits



Altmannshofer, Stangl (2021)
see also Geng, Grinstein, Jäger, Li, M. Camalich, Shi (2021)

Main results

- best 1D fit solutions ($\sim 6\sigma$ pulls):
  - $C_9^{bs\mu\mu} \simeq -0.80$
  - $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu} \simeq -0.41$
- non-zero $C_{10}^{bs\mu\mu}$ preferred by deviation in BR$(B_s \to \mu^+\mu^-)$
- small flavour-universal contribution to C_9 possibly generated by RGE effects ($b \to s\tau\tau$) (or non-perturbative SM charm loops)

see also Crivellin et al (2018)

Popular NP models

Variety of NP models on the market

- tree-level flavour changing Z' — Altmannshofer, Straub (2013); Gauld et al (2013) Altmannshofer et al (2014); Crivellin et al (2015)...
- loop-induced NP — Belanger et al (2015); Gripaios et al (2015); Arnan et al (2016) Kamenik et al (2017)
- leptoquarks — Hiller, Schmaltz (2014); Alonso et al (2015); Crivellin et al (2015) Fajfer, Kosnik (2015); Becirevic et al (2016)...

Most popular (subject to personal taste): $SU(2)_L$-singlet vector leptoquark U_1

- least constrained by complementary data (e. g. B_s mixing, direct searches)
- potential common origin of $R(K^{(*)})$ and $R(D^{(*)})$ anomalies
- contained in the Pati-Salam gauge group $SU(4) \times SU(2)_L \times SU(2)_R$

➢ **plenty of model-building effort for UV-complete model**

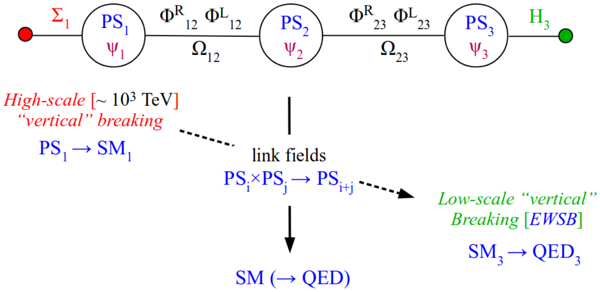
Barbieri, Murphy, Senia (2016); Di Luzio, Greljo, Nardecchia (2017); Calibbi, Crivellin, Li (2017) Bordone, Cornella, Fuentes-Martin, Isidori (2017); MB, Crivellin (2018); Greljo, Stefanek (2018) Heeck, Teresi (2018); Balaji, Foot, Schmidt (2018)...

PS^3 – a leptoquark model for flavour hierarchies

Bordone, Cornella, Fuentes-Martin, Isidori (2017)
model sketch from Isidori, CKM'18

PS^3 in a nutshell

- three copies of PS gauge group for each fermion generation
- cascade of symmetry breakings generates flavour hierarchy in leptoquark couplings
- SM Yukawa couplings governed by same hierarchies as U_1 couplings



Complementary U_1 leptoquark signatures – flavour physics

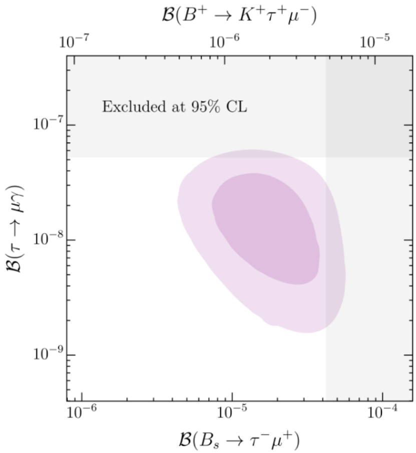
Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert (2021)
see also Angelescu et al. (2021)

UV-insensitive observables

- Lepton flavour violating decays
  $B \to K^{(*)}\tau\mu$, $B_s \to \mu^+\tau^-$, $\tau \to \mu\gamma\ldots$
- di-tau final states
  $B_s \to \tau^+\tau^-$, $B \to K^{(*)}\tau^+\tau^-$

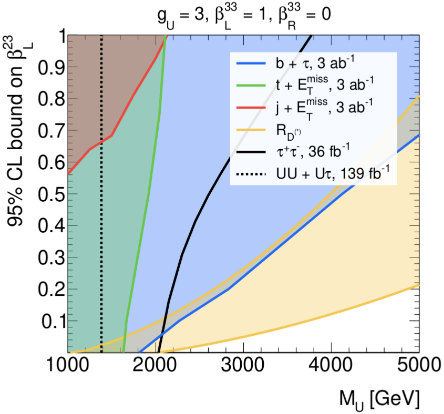
Depending on UV-completion (loop-induced)

- $B_s - \bar{B}_s$ mixing
- $B \to K^{(*)}\nu\bar{\nu}$
- $D - \bar{D}$ mixing



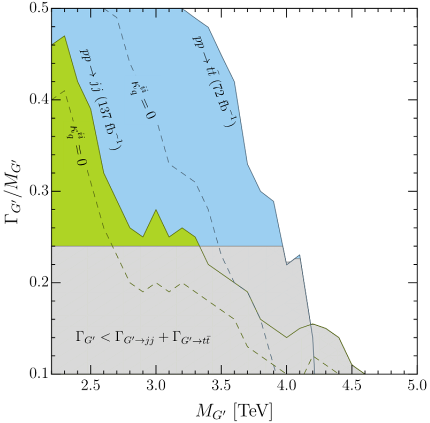
Complementary U_1 leptoquark signatures – LHC

U_1 pair and resonant production



Haisch, Polesello (2020)

Coloron $t\bar{t}$, jj resonances



Cornella et al. (2021)

The Cabibbo angle anomaly

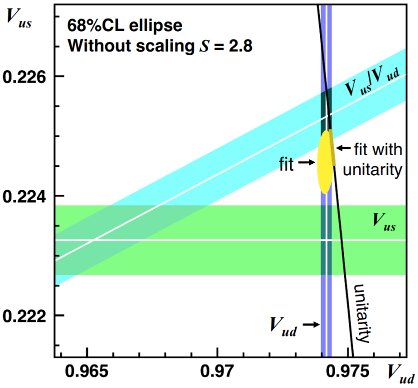
Test of first-row CKM unitarity

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 < 1 \qquad (\sim 3\sigma)$$

Possible NP influence

- New Physics in nuclear β decay
- New Physics in G_F from $\mu \to e\nu\bar{\nu}$
- violation of LFU in $W\mu\nu$ coupling

➢ **connection to $R(K^{(*)})$?**



Belfatto et al. (2019); Grossman, Passemar, Schacht (2019)
Kirk (2020); Crivellin, Hoferichter, Manzari (2021) . . .

Common origin of the Cabibbo angle and $R(K^{(*)})$ anomalies?

Capdevila, Crivellin, Manzari, Montull (2020)

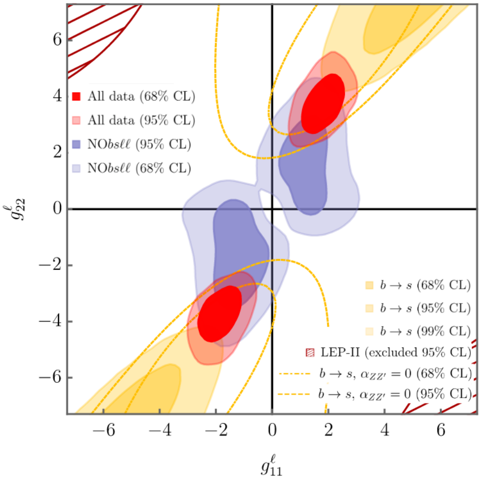
Simplified model

spin-1 $SU(2)$-triplet with flavour-specific couplings

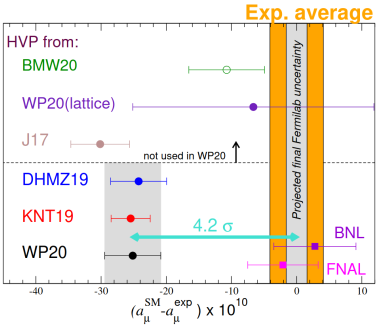
- W-W' mixing modifies $W\mu\nu$ coupling
- significant Z' contribution to $b \to s\ell^+\ell^-$

➢ parameter regions resolving anomalies overlap: **good overall fit**

➢ **correlations** predicted between observables e. g. $R(K^*)$ and $\pi \to \mu\nu/e\nu$



The $(g-2)_\mu$ anomaly



4.2σ tension in muon $(g-2)$

Experiment

- recent FNAL result confirmed BNL result
- significant reduction of uncertainties with larger dataset
- upcoming J-PARC experiment to measure $g-2$ with different method

SM prediction

- consensus by $g-2$ theory initiative ➢ whitepaper 2020
- tension reduced by recent lattice determination of hadronic vacuum polarisation, but inconsistent with global EW fit Crivellin et al. (2020)

New Physics options for $(g-2)_\mu$

Observed anomaly requires **NP contribution of similar size as SM EW contribution**

Heavy ($\gtrsim$EW scale) New Physics
chiral enhancement required to avoid m_μ suppression

- SUSY: enhancement by $\tan\beta \sim 50$
- leptoquarks: enhancement by $m_t/m_\mu \sim 1600$
- ...

Light New Physics
enhanced by scale ratio $\Lambda_{\text{EW}}/\Lambda_{\text{NP}}$

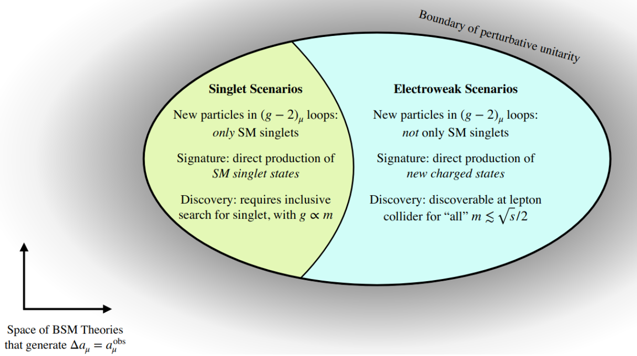
- axion/ALP models
- light scalars
- light Z'
- ...

$(g-2)_\mu$ – a no-lose theorem for muon colliders

Path to NP discovery

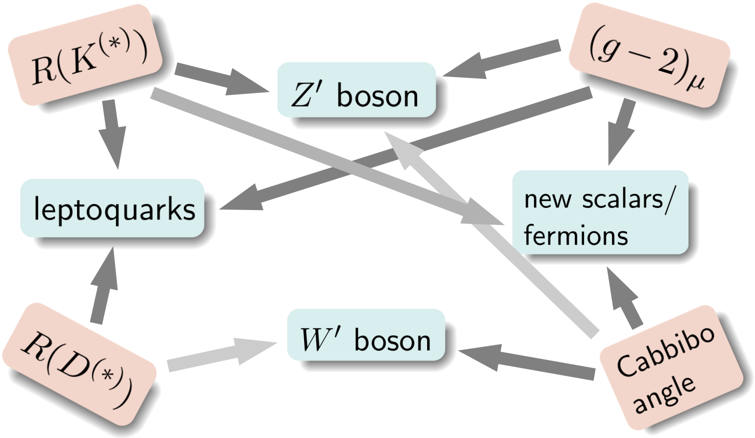
CAPDEVILLA, CURTIN, KAHN, KRNJAC (2021)

1. discover/falsify low-scale EW singlet scenario at fixed-target experiments & Belle II
2. discover/falsify any singlet scenario at 3 TeV muon collider
3. discover EW scenarios $\lesssim 10$ TeV via direct NP production at 10 TeV muon collider
4. probe unitarity ceiling ($\lesssim 100$ TeV) through $\mu^+\mu^- \to h\gamma$



Note: muon collider also tests NP in $b \to s\mu^+\mu^-$!

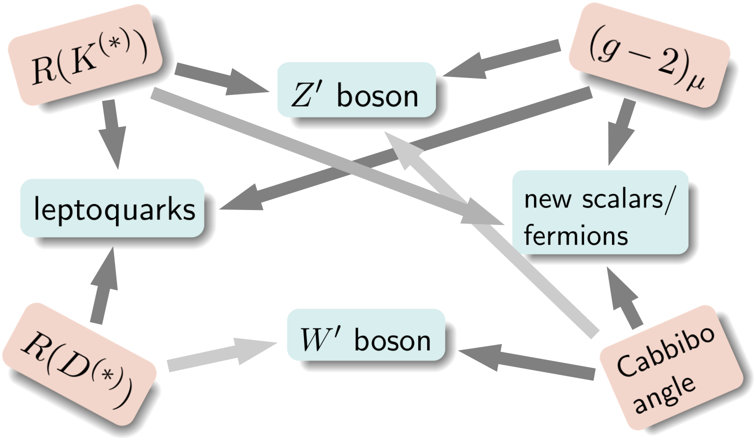
Towards combined explanations – model building 101

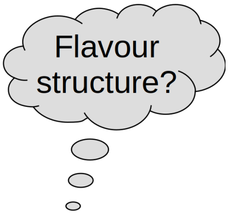


see also Crivellin, LHCP'21

Towards combined explanations – model building 101

see also Crivellin, LHCP'21





Summary & outlook

- various intriguing anomalies in observables testing lepton flavour universality
- resolution requires TeV-scale New Physics (or lighter)
- complementary probes in
  - ➢ related flavour observables
  - ➢ high-p_T collider data
  - ➢ Dark Matter phenomenology

  distinguish between underlying NP scenarios

Summary & outlook

- various intriguing anomalies in observables testing lepton flavour universality
- resolution requires TeV-scale New Physics (or lighter)
- complementary probes in
  - ➢ related flavour observables
  - ➢ high-p_T collider data
  - ➢ Dark Matter phenomenology

  distinguish between underlying NP scenarios