The $\mathcal{R}(D^{(*)})$ anomaly and complementary collider probes

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P3H
Particle Physics Phenomenology after the Higgs Discovery

Pushing the Limits of Theoretical Physics
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Happy birthday MITP!
Happy birthday Matthias!

and a big

THANK YOU

from a frequent MITP visitor*

*** As participant**

Effective Theories and Dark Matter

NA62 Kaon Physics Handbook

LHCb and Belle II Opportunities for Model Builders

Flavor of BSM in the LHC Era

Pushing the Limits of Theoretical Physics

*** As organiser**

Effective Field Theories as Discovery Tools

Electroweak Precision Physics from Beta Decays to the Z Pole

*** As lecturer**

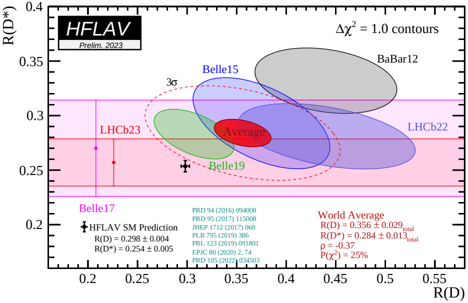
MITP Summer School: Towards the Next Quantum Theory of Nature

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

Test of lepton flavour universality in semi-leptonic B decays

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

➢ persisting tension between SM prediction and data, **older than MITP!**



- theoretically clean, as hadronic and $|V_{cb}|$ uncertainties largely cancel in ratio
- measurements by BaBar, Belle, and LHCb in decent agreement with each other
- LHCb found $\mathcal{R}(J/\psi)$ to be larger than expected in SM

➢ **3.2σ anomaly**

$\mathcal{R}(\Lambda_c)$ – a sum rule challenging the anomaly?

LHCb 2022: $\mathcal{R}(\Lambda_c^+) = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$

$$\mathcal{R}(\Lambda_c) = \frac{\text{BR}(\Lambda_b \to \Lambda_c \tau\nu)}{\text{BR}(\Lambda_b \to \Lambda_c \ell\nu)}$$

Approximate sum rule relating $\mathcal{R}(D^{(*)})$ and $\mathcal{R}(\Lambda_c)$

MB, Crivellin et al. (2018), (2019)
Fedele, MB et al. (2022)

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\text{SM}}(\Lambda_c)} \simeq 0.280\frac{\mathcal{R}(D)}{\mathcal{R}_{\text{SM}}(D)} + 0.720\frac{\mathcal{R}(D^*)}{\mathcal{R}_{\text{SM}}(D^*)}$$

- enhancement of $\mathcal{R}(D^{(*)})$ implies $\mathcal{R}(\Lambda_c) > \mathcal{R}_{\text{SM}}(\Lambda_c) = 0.324 \pm 0.004$
- consistent with expectation from heavy-quark symmetry
- model-independent – holds for NP in τ and/or light lepton channels

Model-independent prediction: $\mathcal{R}(\Lambda_c) \simeq 0.380 \pm 0.012_{\mathcal{R}(D^{(*)})} \pm 0.005_{\text{form factors}}$

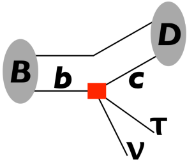
Effective Hamiltonian for $b \to c\tau\nu$

New Physics above B meson scale described model-independently[1] by

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

with the vector, scalar and tensor operators

$$\begin{aligned} O_V^L &= (\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau) \\ O_S^R &= (\bar{c}P_R b)\,(\bar{\tau}P_L \nu_\tau) \\ O_S^L &= (\bar{c}P_L b)\,(\bar{\tau}P_L \nu_\tau) \\ O_T &= (\bar{c}\sigma^{\mu\nu}P_L b)\,(\bar{\tau}\sigma_{\mu\nu}P_L \nu_\tau) \end{aligned}$$



Note: $(\bar{c}\gamma^\mu P_R b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau)$ not generated at dimension-six level in the $SU(2)_L \times U(1)_Y$-invariant theory

[1] assuming heavy/no ν_R and NP only in τ channel

Possible single-particle explanations

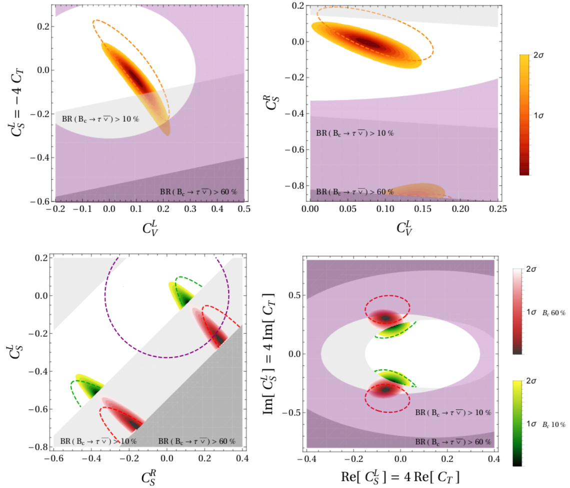
Possiblle New Physics scenarios (tree level contributions!)

C_V^L	vector SU(2)$_L$-triplet W' boson
(C_S^R, C_S^L)	charged Higgs boson
(C_V^L, C_S^R)	SU(2)$_L$-singlet vector leptoquark
$(C_V^L, C_S^L = -4C_T)$	SU(2)$_L$-singlet scalar leptoquark
$(\mathrm{Re}[C_S^L = 4C_T], \mathrm{Im}[C_S^L = 4C_T])$	scalar SU(2)$_L$-doublet leptoquark with CP-violating couplings

Confronting New Physics scenarios with data

(plots from 2019, changes are minor)

MB, Crivellin, Kitahara, Moscati, Nierste, Nišandžić (2019)
see also Murgui et al (2019); Shi et al (2019)
Iguro, Kitahara, Watanabe (2022)

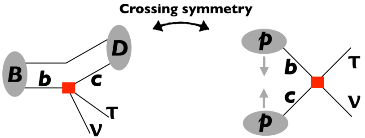


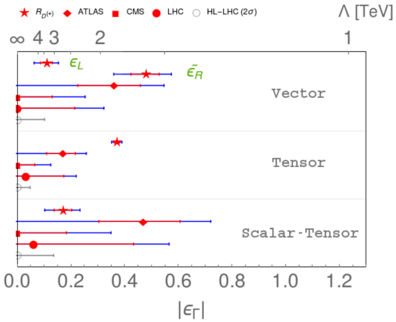
- W' solution disfavoured by LHC direct searches and EWP constraints
  Faroughy, Greljo, Kamenik (2016)
  Ferruglio, Paradisi, Pattori (2017)
- significant improvement possible with various leptoquark (LQ) scenarios
- charged Higgs: enhancement of $\mathcal{R}(D^*)$ correlates with large $\mathrm{BR}(B_c \to \tau\nu)$
  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 on LHC mono-τ searches

Greljo, Martin Camalich, Ruiz-Alvarez (2018)

- crossing symmetry relates $b \to c\tau\nu$ to $pp \to X\tau\nu$
- mono-$\tau + \not{E}_T$ signature probes NP models for $\mathcal{R}(D^{(*)})$ anomaly





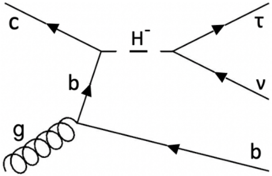
➢ **LHC has become competitive in testing the $\mathcal{R}(D^{(*)})$ anomaly**

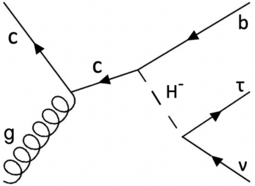
- charged Higgs ruled out for $m_{H^-} > 400$ GeV

  Iguro, Omura, Takeuchi (2018)
- leptoquark models less pressured
- HL-LHC should be able to *probe all possible NP models* solving anomaly

What about a light charged Higgs?

- light charged Higgs ($m_{H^-} < 400\,\text{GeV}$) not excluded by mono-$\tau$ data due to huge $W \to \tau\nu$ background
- efficient background suppression by requiring additional b-tagged jet

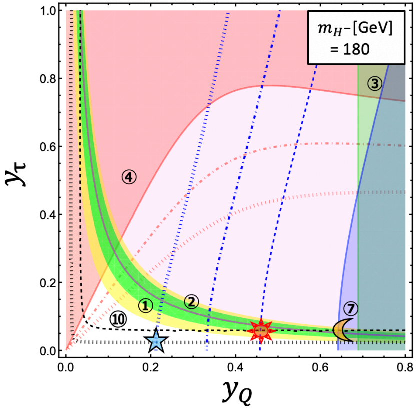




➢ **Is this sufficient to exclude the charged Higgs solution to the $\mathcal{R}(D^{(*)})$ anomaly?**

MB, Iguro, Zhang (2022)

Reach of the $b\tau\nu$ signature



Minimal coupling scenario MB, Iguro, Zhang (2022)
(additional couplings do not alter conclusions)

$$\mathcal{L}_{\text{int}} = +y_Q H^- (\bar{b} P_R c) - y_\tau H^- (\bar{\tau} P_L \nu_\tau)$$

- H^- close to top threshold most difficult to test
- relevant constraints from SUSY stau and (flavoured) dijet searches at the LHC Iguro (2022)
- performing (flavoured) dijet and **proposed $b\tau\nu$ search** with Run 2 data would *almost* exclude charged Higgs solution for $\mathcal{R}(D^{(*)})$
- **final verdict** from future LHC runs

Remaining option: leptoquarks

- "exotic"? – present in *any* theory unifying quarks and leptons (but: TeV scale?)
- plausible solution for the "B anomalies"
- popular scenario: $SU(2)$-**singlet vector leptoquark** $U_1 \equiv \Delta$

  - compatible with other flavour constraints (B_s mixing, $B \to K\nu\bar{\nu}\dots$)
  - can potentially solve $b \to s\mu\mu$ anomalies through τ loops
  - no proton decay induced
  - contained in Pati-Salam gauge group $SU(4)_c \times SU(2)_L \times SU(2)_R$

  Pati, Salam (1974)

Model-building challenge: non-trivial flavour structure

Simplified vector leptoquark model

Tau isolation pattern

- minimal coupling scenario solving $\mathcal{R}(\mathcal{D}^{(*)})$
  – coupling to left-handed fermions only

$$\lambda_{dl}^{[\tau]} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \lambda_{s\tau} \\ 0 & 0 & \lambda_{b\tau} \end{pmatrix}$$

- compatible with residual family symmetry ansatz

Bernigaud, de Medeiros, Talbert (2019)

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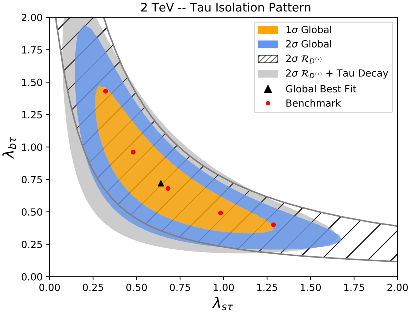


➢ global flavour fit shows good agreement with $\mathcal{R}(D^{(*)})$ data

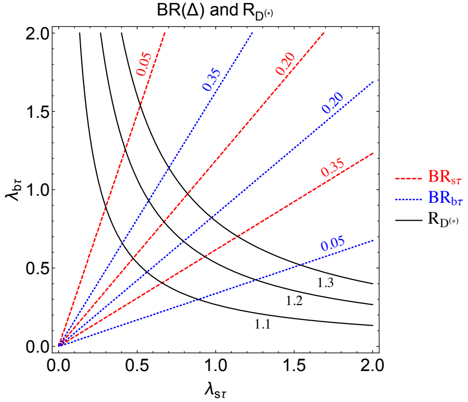
➢ benchmark points for subsequent collider analysis

Bernigaud, MB, de Medeiros, Talbert, Zurita (2021)

What can we learn from direct leptoquark searches?

Bernigaud, MB, de Medeiros, Talbert, Zurita (2021)

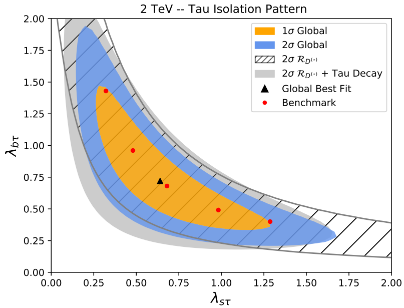
- $\mathcal{R}(D^{(*)})$ constrain $\frac{\lambda_{b\tau}\lambda_{c\nu}}{M^2} \simeq \frac{\lambda_{b\tau}\lambda_{s\tau}}{M^2}$
- LQ mass M can be measured at LHC from pair-production cross-section and invariant mass
- branching ratios $\text{BR}_{b\tau} \simeq \text{BR}_{t\nu}$, $\text{BR}_{s\tau} \simeq \text{BR}_{c/u\nu}$ determine ratio of couplings $\lambda_{b\tau}/\lambda_{s\tau}$



➢ **synergy between flavour and collider data fully determines leptoquark parameters**

Leptoquark branching ratios: pair production

Bernigaud, MB, de Medeiros, Talbert, Zurita (2021)



➢

BR(ΔΔ → QLQL) [%]

	$b\tau b\tau$	$t\nu t\nu$	$b\tau t\nu$	$b\tau s\tau$	$b\tau c\nu$	$t\nu s\tau$	$t\nu c\nu$	$s\tau s\tau$	$s\tau c\nu$	$c\nu c\nu$
BP_1	0.2	0.1	0.3	4.0	3.9	3.0	3.0	20.8	40.5	19.7
BP_2	1.0	0.7	1.7	8.0	7.9	6.7	6.6	16.0	31.6	15.6
BP_3	6.3	5.2	11.5	12.6	12.9	11.5	11.8	6.3	12.9	6.6
BP_4	16.1	14.5	30.6	8.1	8.9	7.7	8.5	1.0	2.2	1.2
BP_5	22.9	21.5	44.4	2.3	3.1	2.3	3.0	0.1	0.2	0.1

Constraints from $b\tau\, t\nu$ – and $\not{E}_T$ final states

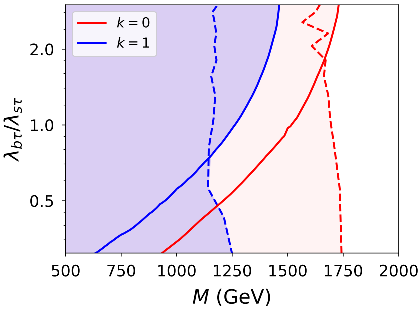
BERNIGAUD, MB, DE MEDEIROS, TALBERT, ZURITA (2021)

Mixed channel $\Delta\Delta \to b\tau\, t\nu$ ATLAS, CMS (2021)

- reinterpretation of existing experimental analysis

  see also BELANGER ET AL. (2021)

- strong sensitivity to coupling ratio $\lambda_{b\tau}/\lambda_{s\tau}$



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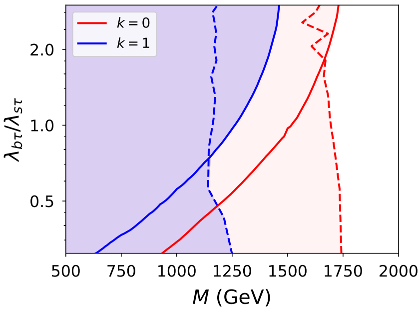
$\not{E}_T$ from final-state neutrinos

- stringent constraint, obtained through CheckMATE analysis
- less sensitive to leptoquark coupling structure
- complementary to $b\tau\, t\nu$
- also: bounds from leptoquark single-production. . .



Summary & outlook

$\mathcal{R}(D^{(*)})$ **anomaly** persists, but scrutinised by complementary LHC searches

reach of **light $\tau\nu$ resonance** search improved by **additional b-tagged jet**

➢ strong constraint on H^- scenario

leptoquark branching ratios determine flavour structure of **coupling matrix**

➢ search limits depend on couplings

To fully unravel the underlying NP, we need to explore the complementarity between flavour and collider data!