Karlsruhe Institute of Technology

Flavour physics Beyond the Standard Model

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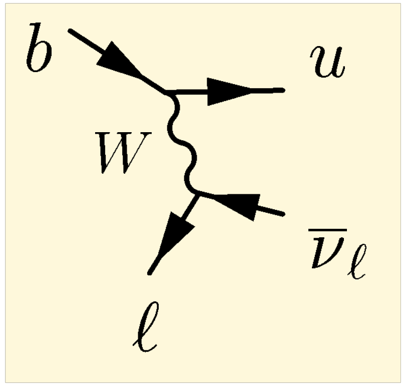
Contents

- Why Beyond-Standard-Model (BSM) flavour physics?
- Heavy BSM physics
- Light BSM physics
- Flavour model building

Why BSM flavour physics?

In the Standard Model flavour-changing (FC) transitions…

- …solely stem from W couplings, so that at tree-level FC transitions are limited to charged-current processes with left-handed fields,



- …are suppressed by small elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix V. Flavour-changing neutral current (FCNC) transitions are further suppressed by an electroweak loop and are often propotional to small mass ratios like m_c^2/M_W^2 .

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Heavy BSM physics

$\Rightarrow$ Flavour physics probes virtual effects from mass scales way above the energy of the studied process.

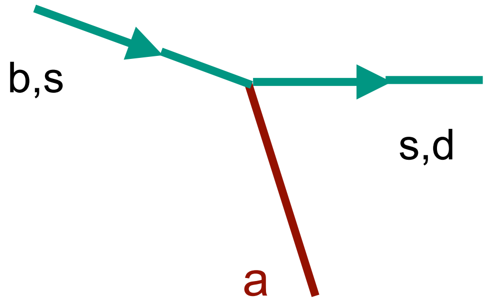
Example:

1964: Discovery of CP violation in $K \to \pi\pi$ decays. The size of the effect is governed by the mass of the top quark (of which no one had a clue at the time).

$$m_t \approx 350 \times m_K$$

Light BSM physics

Flavour physics can also probe theories with new light particles which couple very feebly to the SM particles and may be produced in FCNC decays of mesons and baryons.



a could be an axion (→ strong CP problem)
or any boson related to a dark sector

Rare decays

Experimentalists measure branching ratios, e.g. $\frac{\Gamma(B \to f)}{\Gamma_{\text{total}}(B)}$
for a *B* decay into some final state *f*.

Compare:

$\Gamma_{\text{total}}(b)$	$\Gamma_{\text{total}}(t)$
$\|V_{cb}\|^2 \sim 0.04^2$	$\|V_{tb}\|^2 \sim 1$
three-body phase space	two-body phase space
$\propto \frac{m_b^5}{M_W^4}$	$\propto m_t$

$$\Rightarrow \quad \Gamma_{\text{total}}(b) \sim 3 \cdot 10^{-13}\, \Gamma_{\text{total}}(t)$$

$\Rightarrow$ $\Gamma(B \to f)$ of very rare decays accessible

Small $\Gamma_{\text{total}}(b)$ $\Rightarrow$ large lifetime of b-flavoured hadrons, which travel over macroscopic distances before they decay

- enables b physics at hadron colliders (displaced decay vertices)
- permits time-dependent studies of $B-\bar{B}$ oscillations
  → measure CP asymmetries determining complex phases of new-physics amplitudes

BSM flavour physics

Directions:

- search for virtual effects of heavy BSM particles
- seach for light feebly coupled BSM particles
- flavour model-building to address the *flavour puzzle*:
  Why are most Yukawa couplings small, with hierarchical sizes?
  Which symmetry/dynamics determines their sizes?
  Are there connections between quark and lepton flavour physics?

  → invoke flavour symmetries to reduce the number of 20 or 22 parameters of the quark and lepton Yukawa sectors

BSM flavour physics in the CRC

From Januar 2020 to now I have found 16 P3H papers on BSM flavour physics.

- Heavy BSM:
  - flavour anomalies: 21-025, 21-021, 21-017, 21-007, 21-005, 20-064, 20-046, 20-027
  - flavour-collider connection: 21-016, 21-002
- Light BSM:
  - cosmology/astrophysics: 20-083, 20-022
  - other: 20-024, 20-017
- Flavour model-building: 20-047, 20-021

Flavour anomalies

Experimental data show statistically significant deviations in observables related to

- $b \to s\mu^+\mu^-$

  and
- $b \to c\tau^-\bar{\nu}$

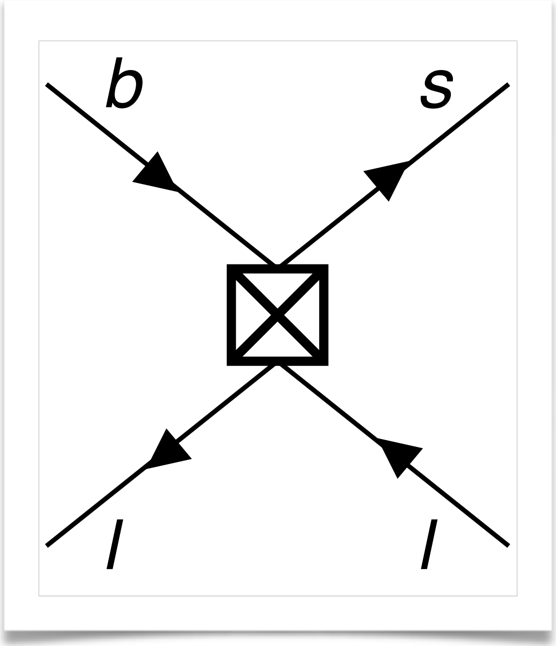
decays.
Often also $a_\mu \equiv (g-2)_\mu$ is included in the list of flavour anomalies.

The drivers are lepton-flavour universality violating (LFUV) ratios, in which $b \to s\mu^+\mu^-$ is normalised to $b \to se^+e^-$ and $b \to c\tau^-\bar{\nu}$ is normalised to $b \to c\ell^-\bar{\nu}$.

Flavour anomalies

$b \to s\ell^+\ell^-$ deviations from the SM in these measurements:

- $B \to K^*\mu^+\mu^-$ angular distribution observable P_5' for low $q^2=M^2(\mu^+\mu^-)$
- $R(K) = \dfrac{B(B \to K\mu^+\mu^-)}{B(B \to Ke^+e^-)}$ for low q^2
- $R(K^*) = \dfrac{B(B \to K^*\mu^+\mu^-)}{B(B \to K^*e^+e^-)}$ for low q^2
- $B_s \to \phi\mu^+\mu^-$ angular distribution



Flavour anomalies

Fit observables to Wilson coefficients C_j of dim-6 operators Q_j. Different measurements involve different combinations of the same set of coefficients.

$\Longrightarrow$ correlations and redundancies

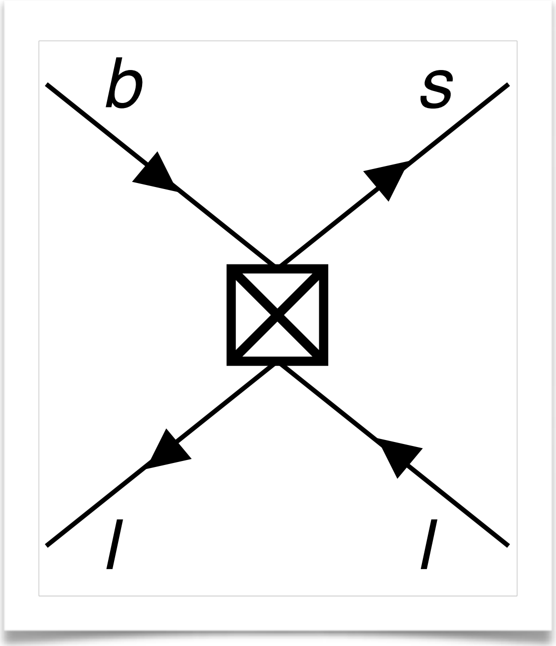
Likelihood ratio test of new-physics hypothesis with arbitrary C_j and the SM hypothesis $C_j = C_j^{\mathrm{SM}}$:

Key operators:

$$Q_7 = \frac{e}{16\pi^2} m_b \, \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$$

$$Q_9^\ell = \frac{e^2}{16\pi^2} \, \bar{s}_L \gamma_\mu b_L \, \bar{\ell} \gamma^\mu \ell$$

$$Q_{10}^\ell = \frac{e^2}{16\pi^2} \, \bar{s}_L \gamma_\mu b_L \, \bar{\ell} \gamma^\mu \gamma_5 \ell$$



$b \to s\ell^+\ell^-$ analysis in P3H-020-064

Complete Q_9^ℓ and Q_{10}^ℓ to SU(2)-invariant operators (SM-effective field theory, SMEFT)

$$O_{2223}^{LQ^{(1)}} = (\bar{L}_2\gamma_\mu L_2)(\bar{Q}_2\gamma^\mu Q_3)\,, \quad \longrightarrow \quad Q_9^\ell - Q_{10}^\ell$$

$$O_{2223}^{LQ^{(3)}} = (\bar{L}_2\gamma_\mu \tau^A L_2)(\bar{Q}_2\gamma^\mu \tau^A Q_3)\,, \quad \longrightarrow \quad Q_9^\ell - Q_{10}^\ell$$

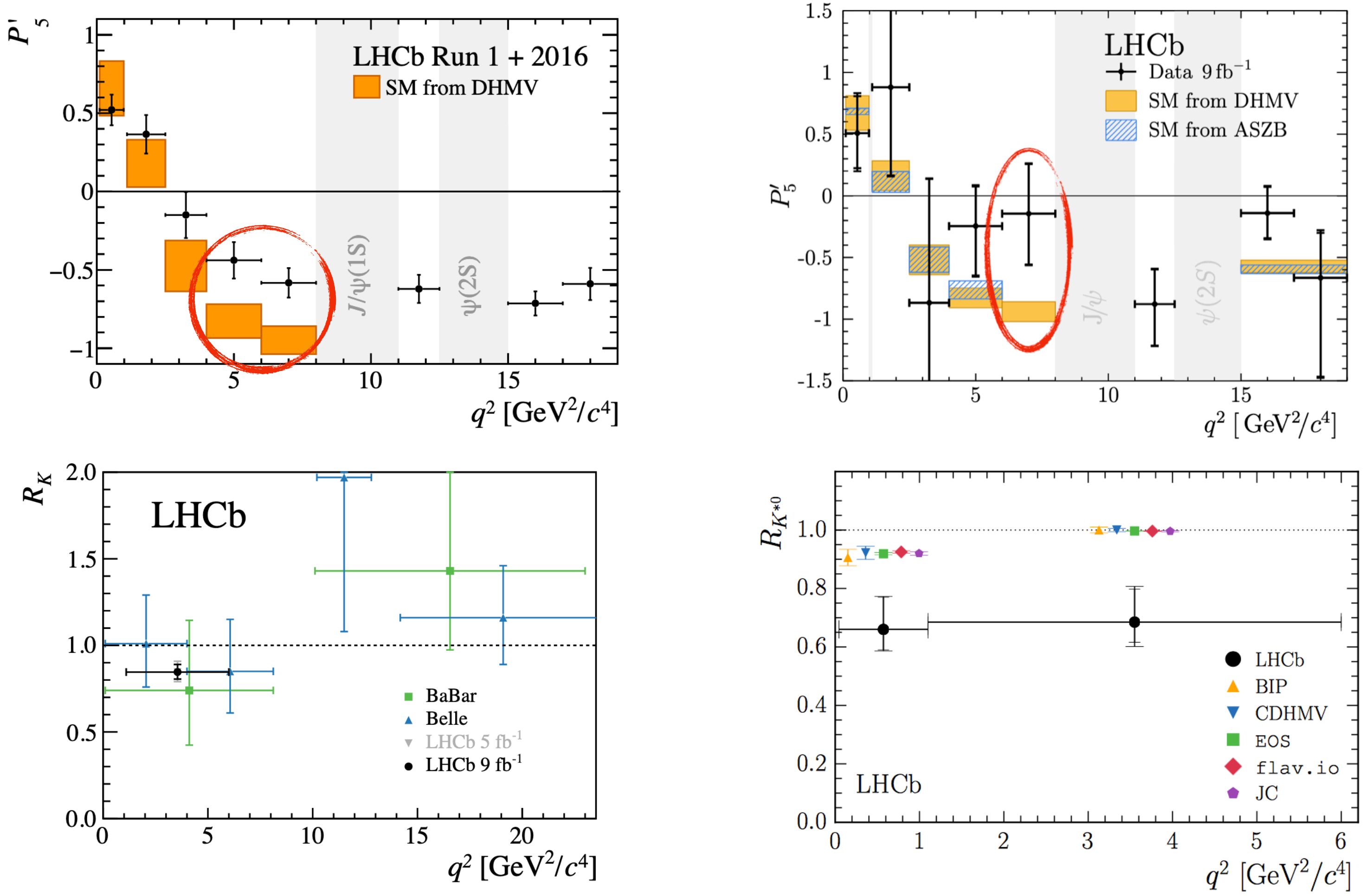
$$O_{2322}^{Qe} = (\bar{Q}_2\gamma_\mu Q_3)(\bar{e}_2\gamma^\mu e_2)\,, \quad \longrightarrow \quad Q_9^\ell + Q_{10}^\ell$$

$$O_{2223}^{Ld} = (\bar{L}_2\gamma_\mu L_2)(\bar{d}_2\gamma^\mu d_3)\,,$$

$$O_{2223}^{ed} = (\bar{e}_2\gamma_\mu e_2)(\bar{d}_2\gamma^\mu d_3)\,,$$

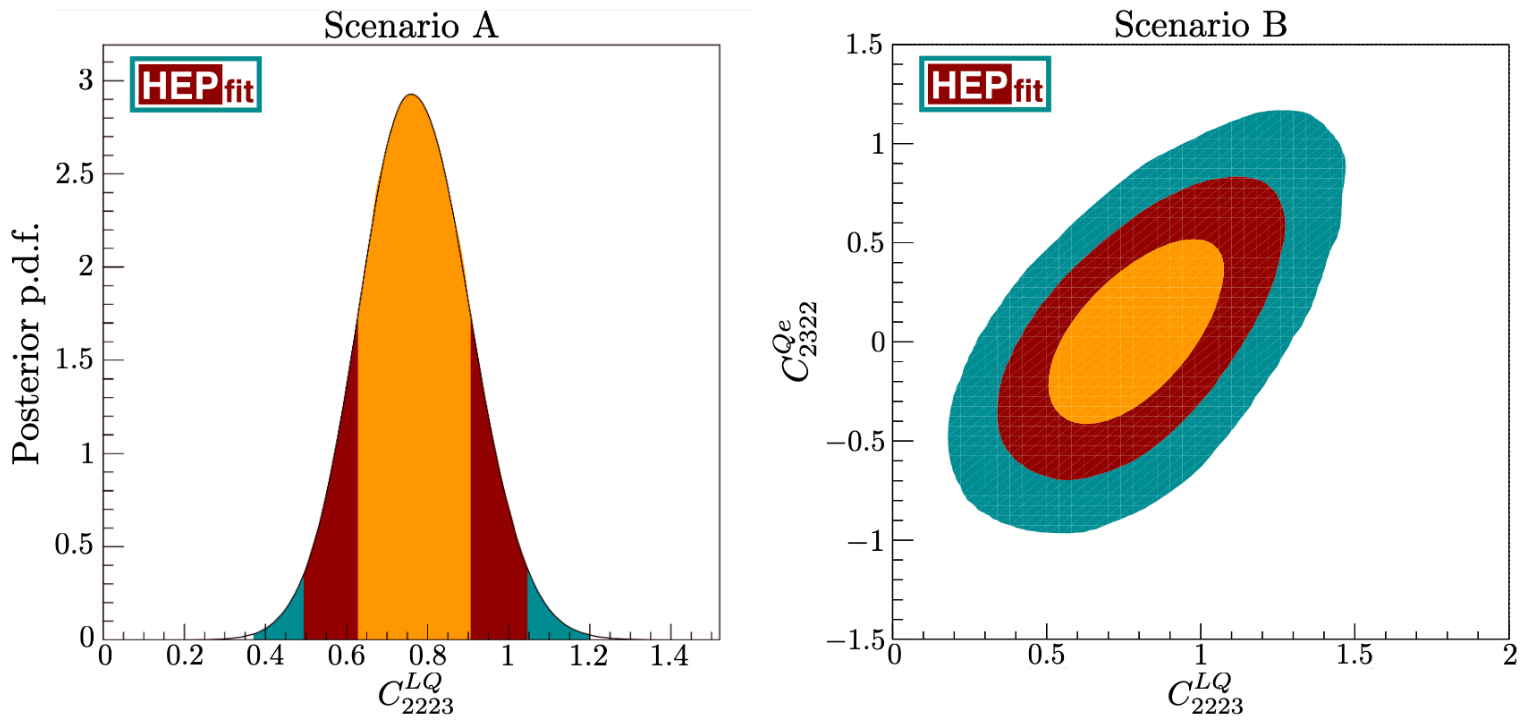
P3H-20-064: updated global fit to B anomalies

Some of the latest anomalous measurements…



Updated fit to NP WCs by M. Fedele and collaborators ("Rome group"), right before Moriond '21 (post-Moriond results basically unchanged)

P3H-20-064: updated global fit to B anomalies



$$C_9 = \mathcal{N}_\Lambda (C^{LQ}_{2223} + C^{Qe}_{2322}) \quad C_{10} = \mathcal{N}_\Lambda (-C^{LQ}_{2223} + C^{Qe}_{2322})$$

$|\mathcal{N}_\Lambda| \simeq 0.7$

$Q^\mu_9 - Q^\mu_{10}$

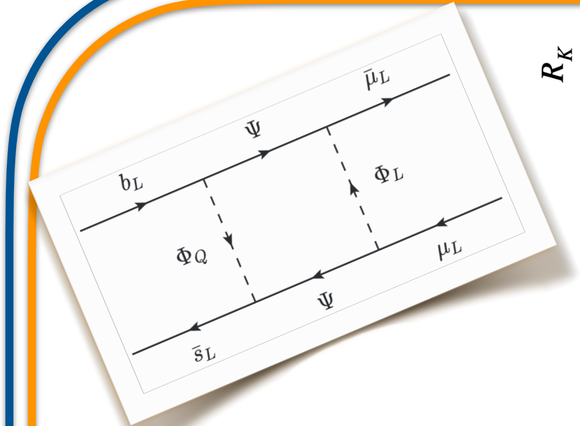
NP scenario	mean(std)
A: C^{LQ}_{2223}	0.77(13)
	0.92(12)
B: $\{C^{LQ}_{2223}, C^{Qe}_{2322}\}$	{0.80(18), 0.05(30)}
	{1.03(12), 0.71(13)}
C: $\{C^{LQ}_{2223}, C^{Qe}_{2322}, C^{Ld}_{2223}, C^{ed}_{2223}\}$	{1.11(23), 0.49(36), -0.42(23), -0.28(43)}
	{1.10(12), 0.83(15), -0.33(19), 0.04(37)}

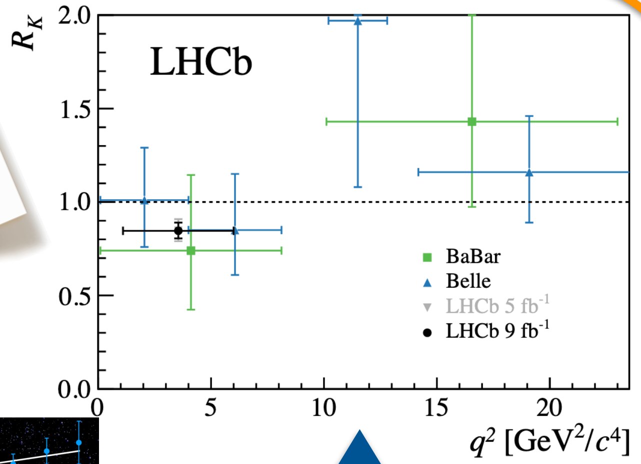
Strong evidence of NP coupling(s) even above the 6σ level (according to NP scenarios and hadronic treatments)!

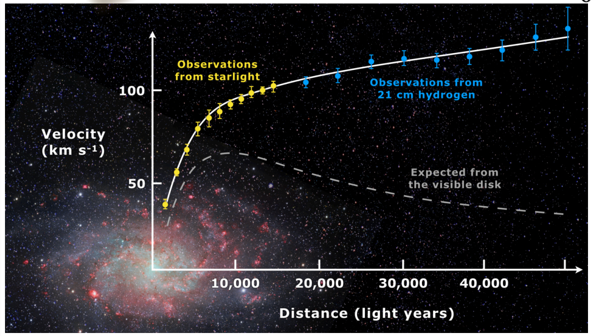
Allowing for larger hadronic contributions

2011.01212 (P3H-20-064) Ciuchini, Fedele, Franco, Paul, Silvestrini, Valli

P3H-21-017, P3H-21-025: Loop models for anomalies



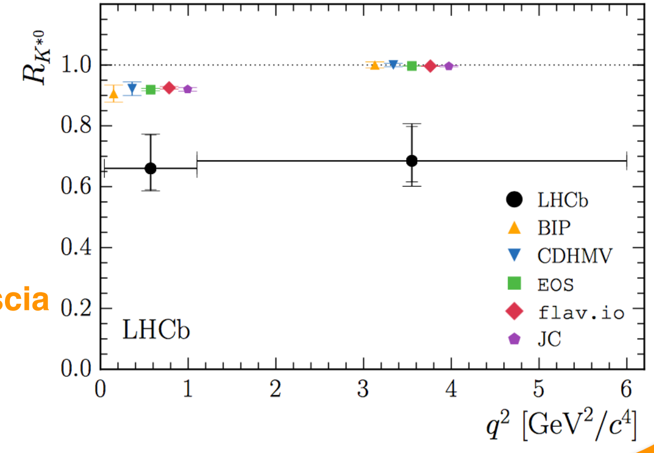


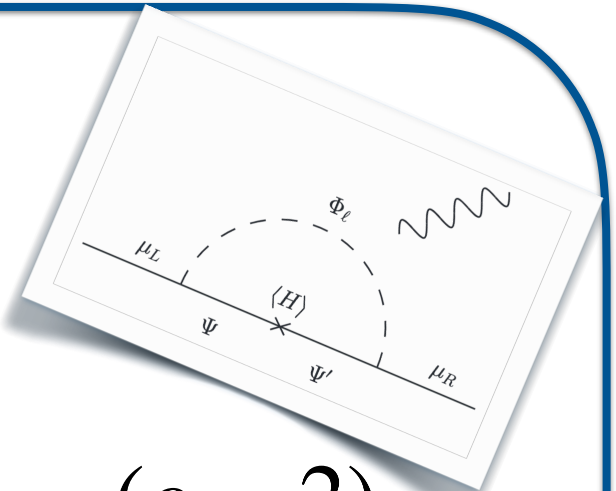


LFUV ratios

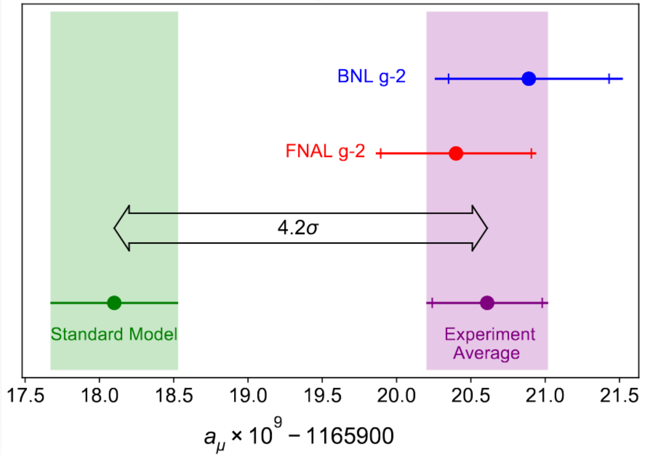
DM

2103.09835 (P3H-21-017)
Arcadi, Calibbi, Fedele, Mescia





$(g-2)_\mu$

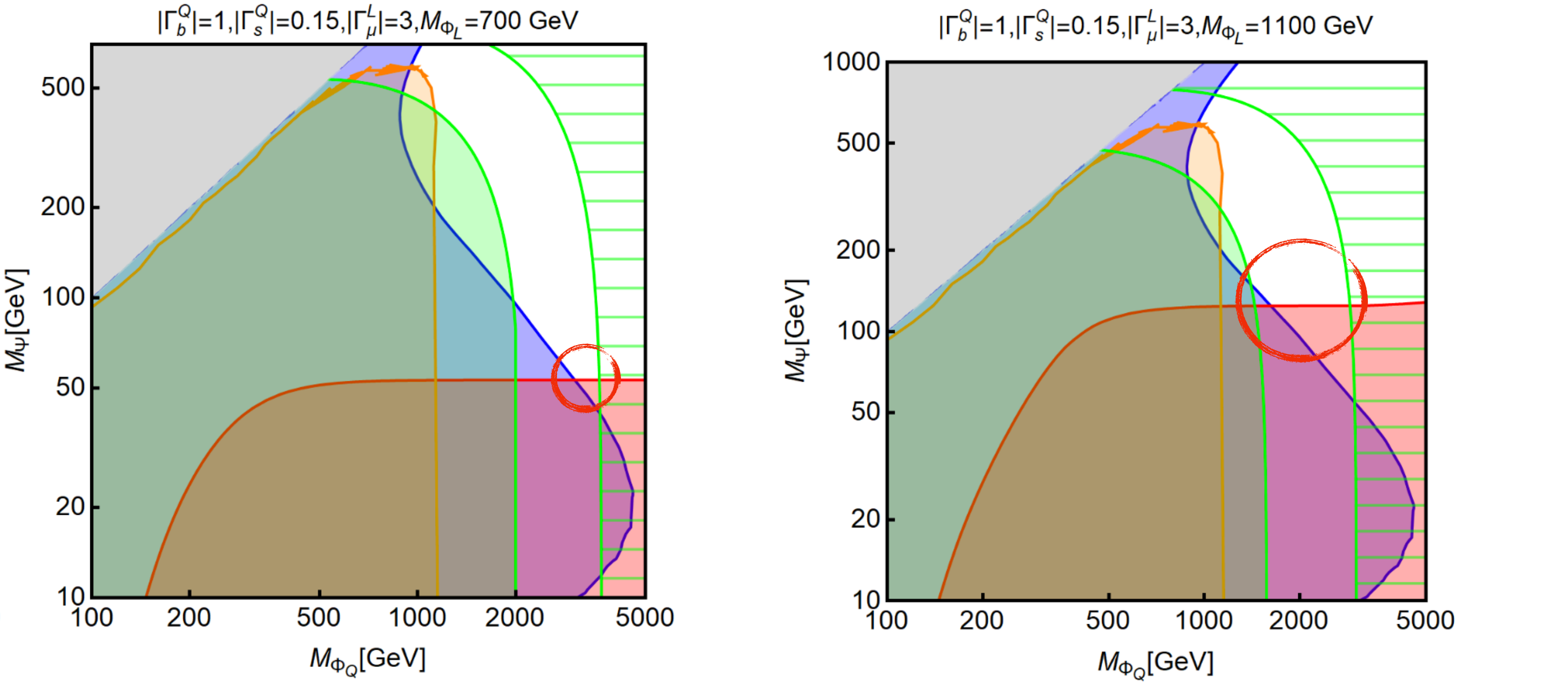


2104.03228 (P3H-21-025)
Arcadi, Calibbi, Fedele, Mescia

P3H-21-017: B anomalies and DM

$$\mathcal{L}_{\mathcal{F}} \supset \Gamma_i^Q \, \bar{Q}_i \, P_R \Psi \, \Phi_Q + \Gamma_i^L \, \bar{L}_i \, P_R \Psi \, \Phi_L + \text{h.c.}$$

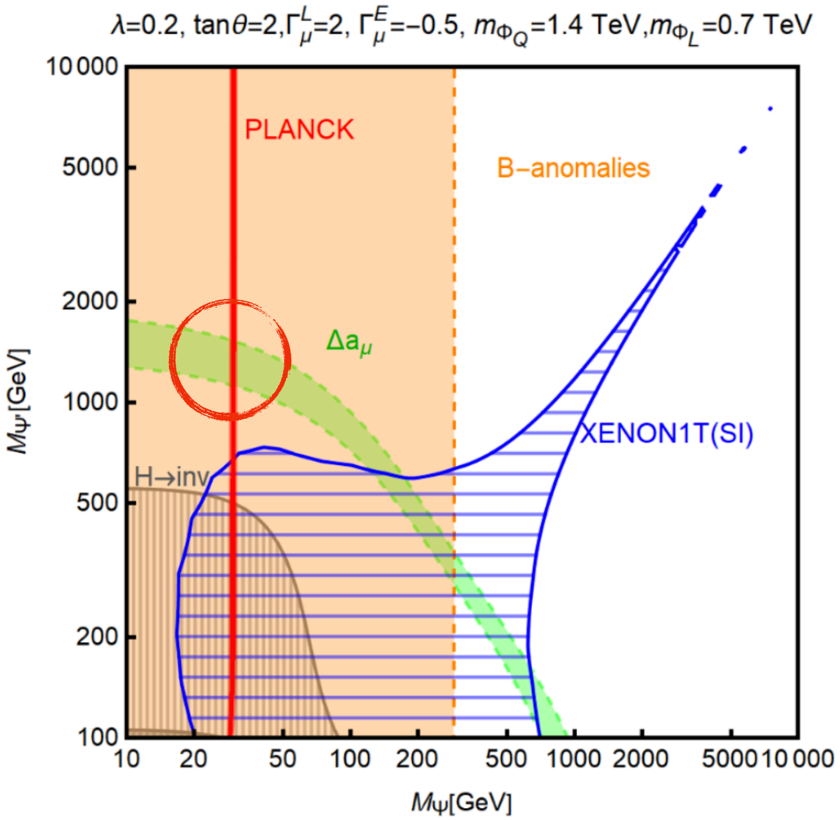
Φ_Q	Φ_L	Ψ(DM)
$(\mathbf{3}, \mathbf{2}, 1/6)$	$(\mathbf{1}, \mathbf{2}, -1/2)$	$(\mathbf{1}, \mathbf{1}, 0)^\star$



A viable model capable to address B-anomalies while evading LHC bounds and DM Direct Detection, providing also the observed relic density!

P3H-21-025: B anomalies, $(g-2)_\mu$ and DM

$$\mathcal{L}_{\mathcal{F}}^{\Psi\Psi'} \supset \Gamma_i^Q \bar{Q}_i P_R \Psi \Phi_q + \Gamma_i^L \bar{L}_i P_R \Psi \Phi_\ell + \Gamma_i^E \bar{E}_i P_L \Psi' \Phi_\ell + \lambda_{HL} \bar{\Psi} P_L \Psi' H + \lambda_{HR} \bar{\Psi} P_R \Psi' H + \text{h.c.}$$



(Singlet-Doublet mixed DM)

Φ_Q	Φ_L	Ψ	Ψ'
$(\mathbf{3},\mathbf{2},1/6)$	$(\mathbf{1},\mathbf{2},-1/2)$	$(\mathbf{1},\mathbf{1},0)^\star$	$(\mathbf{1},\mathbf{2},-1/2)^\star$

Extension of the previous model, capable to address $(g-2)_\mu$ as well thanks to couplings to right-handed muons!

For more details on the project, follow M. Fedele's talk tomorrow during YSF!

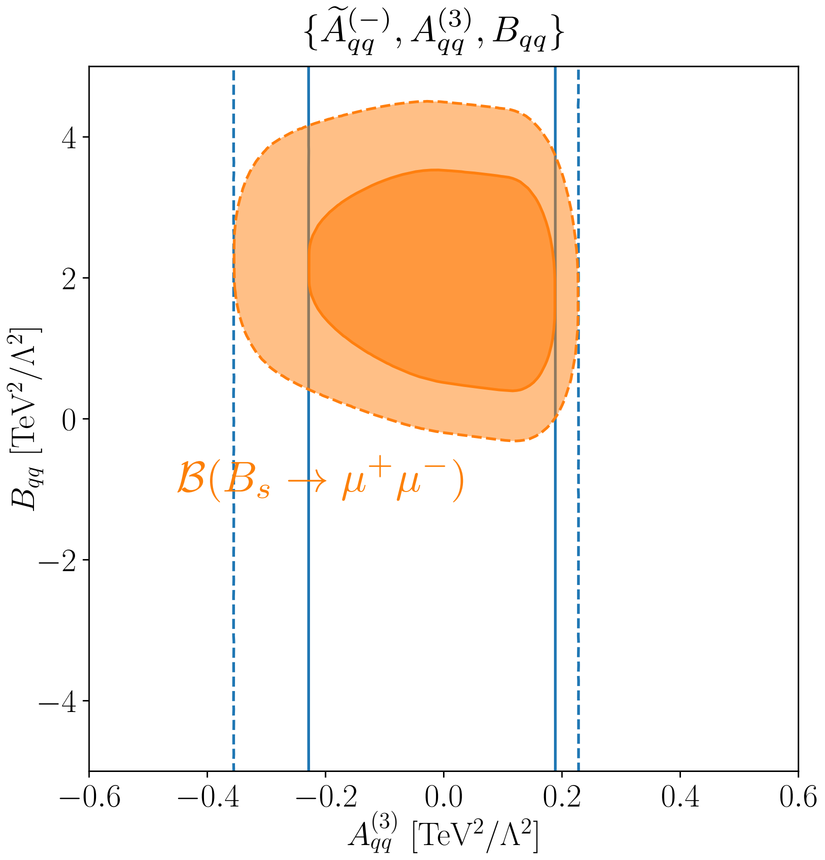
Top-bottom connection in P3H-21-002

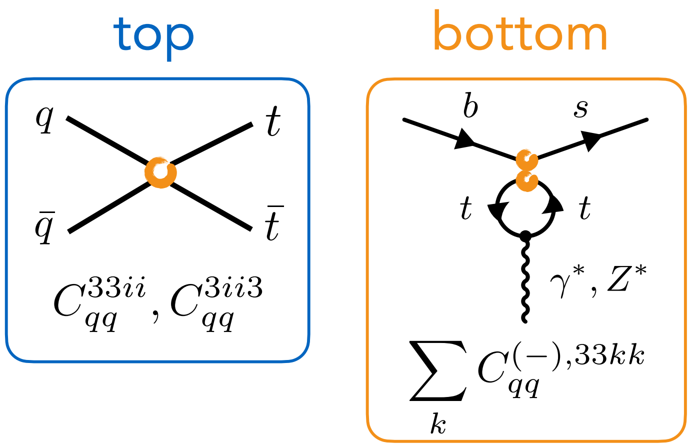
FCNC decays of b quarks proceed through top loops

$\Rightarrow$ SMEFT operators with top fields can be probed in b physics

P3H-21-002 Flavor breaking in four-quark couplings

$$\mathcal{C}_{10}(m_b) = 0.29\Big(A_{qq}^{(3)}(m_t) + B_{qq}^{(3)}(m_t)y_t^2\Big) + 0.03\Big(\widetilde{A}_{qq}^{(-)}(m_t) + B_{qq}^{(-)}(m_t)y_t^2\Big)$$





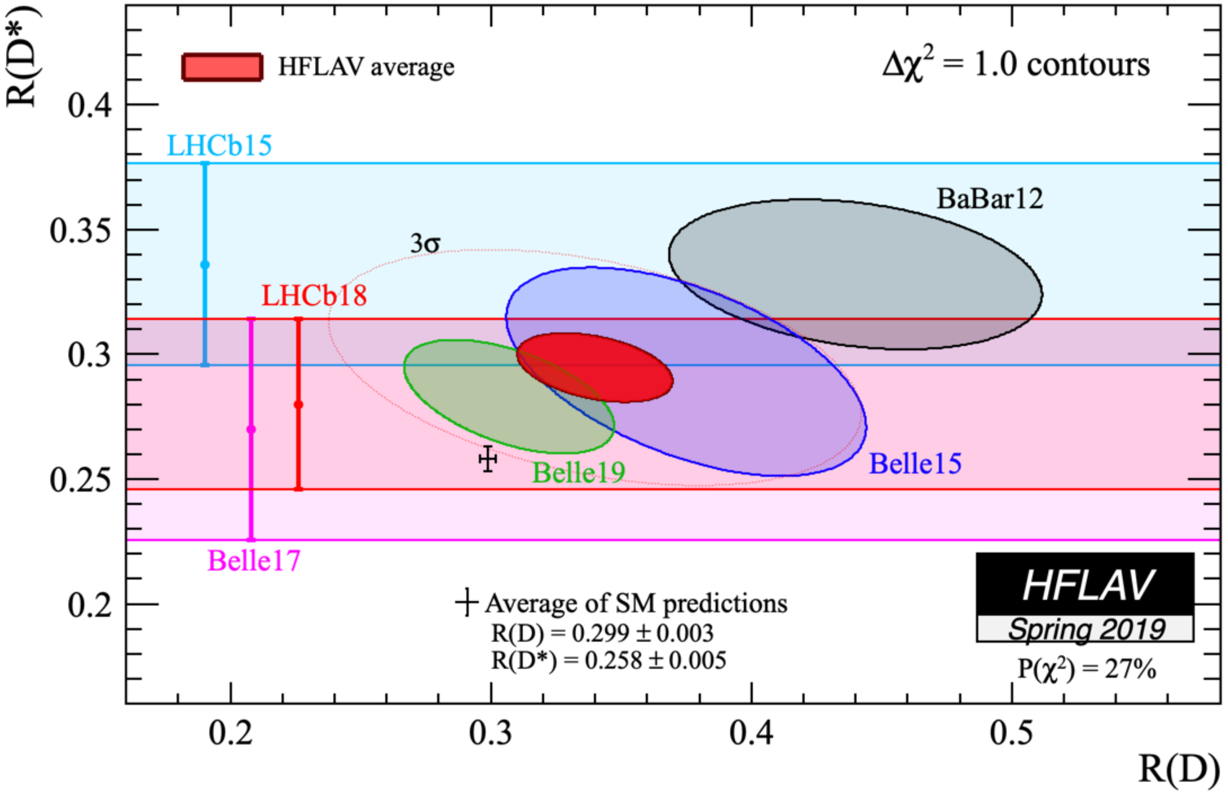
$$O_{qq}^{(1)} = (\overline{Q}\gamma_\mu Q)(\overline{Q}\gamma^\mu Q)$$

$$O_{qq}^{(3)} = (\overline{Q}\gamma_\mu \tau^a Q)(\overline{Q}\gamma^\mu \tau^a Q)$$

Bruggisser, Schäfer, van Dyk, Westhoff 2101.07273

Flavour anomalies

$b \to c\tau\bar{\nu}$ is probed in $R(D) \equiv \frac{B(B \to D\tau\bar{\nu})}{B(B \to D\ell\bar{\nu})}$ and $R(D^*) \equiv \frac{B(B \to D^*\tau\bar{\nu})}{B(B \to D^*\ell\bar{\nu})}$



HFLAV finds a 3.1σ tension with the SM.

Tension increases if $R(J/\psi)$ is included.

$B \to D^* \ell \bar{\nu}$ in P3H-21-021

What do the data tell about LFUV for μ vs. e?

Lepton-Flavour Non-Universality of $B \to D^* \ell \bar{\nu}$ angular distributions in and beyond the Standard Model

Bobeth, Bordone, Gubernari, Jung, van Dyk

$B \to D^*\ell\bar{\nu}$ in P3H-21-021

The authors find a 4σ discrepancy in 2018 Belle data which was hidden in a redundant parameterisation used by the collaboration.

However, this redundancy is not reflected in the error correlation matrices of this analysis, pointing to an inconsistency which must be resolved before definite conclusions can be drawn.
Possible BSM explanations show a different pattern than those explaining in $b \to c\tau^-\bar{\nu}$.

Light BSM physics

Light BSM particles could be mediators between SM particles and a Dark Sector comprising Dark Matter and dark force carriers.

Dark flavour astrophysics:

P3H-20-083

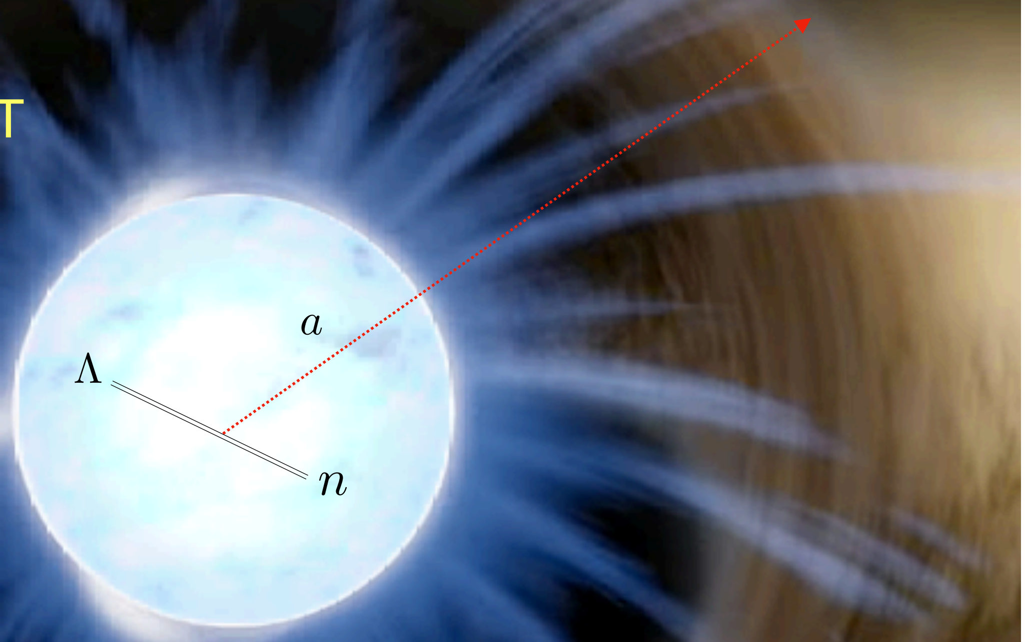
Supernova Constraints on Dark Flavored Sectors

Martin Camalich, Terol-Calvo, Tolos, Ziegler

Flavor Physics with SN1987A

Constrain flavor-violating hyperon decays to neutron + invsis. $\Lambda \to na$

Many hyperons in hot proto-neutron star formed during core-collapse supernovae [T ≈ 40 MeV]



Hyperon decays to longlived invisible particle provide extra cooling that would have shorten observed neutrino pulse of SN1987A

Estimate energy loss rate per volume:

$$Q \simeq n_n (m_\Lambda - m_n) \Gamma(\Lambda \to na) \; e^{-\frac{m_\Lambda - m_n}{T}}$$

Gives best bound on invisible hyperon decays! $(\mathrm{BR} \lesssim 10^{-8}, \mathrm{BR}_{\mathrm{lab}} \lesssim 10^{-2})$

Energy Loss Rate

- Additional energy loss rate should be smaller than total luminosity carried away by neutrinos in cooling proto-neutron star (PNS)

“Raffelt Bound” (RB)

$$L_{\rm d} \lesssim 3 \times 10^{52} \quad {\rm erg\ s^{-1}}$$

- Calculate energy loss from 2-body hyperon decays to invisible

$$\frac{d\mathcal{N}_{\rm em}}{d\omega} = \frac{m_\Lambda^2 \Gamma}{2\pi^2 \bar{\omega}} \int_{E_0}^{\infty} dE\, f_\Lambda (1 - f_n)$$

Emission rate per unit volume

Hyperon vacuum decay rate

Lost energy

Lost energy in CMS

Hyperon energy in PNS frame

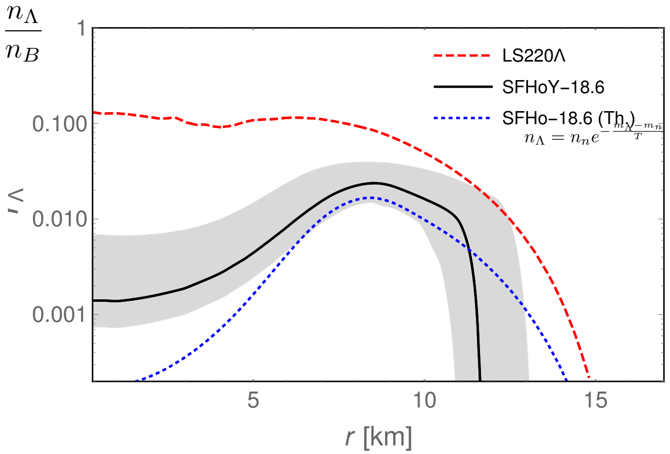
Neutron number density (taken from simulations)

→ Total energy loss rate is $L_{\rm d} = \int dV \int_0^\infty d\omega \frac{d\mathcal{N}_{\rm em}}{d\omega}\omega$

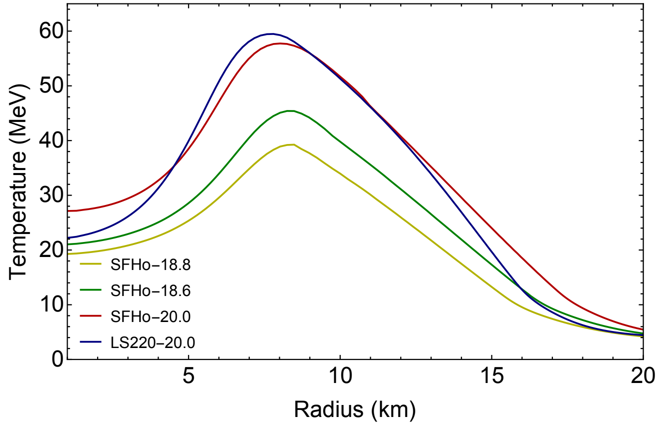
SN Simulations

- Compare SN simulations with different EoS and NS masses

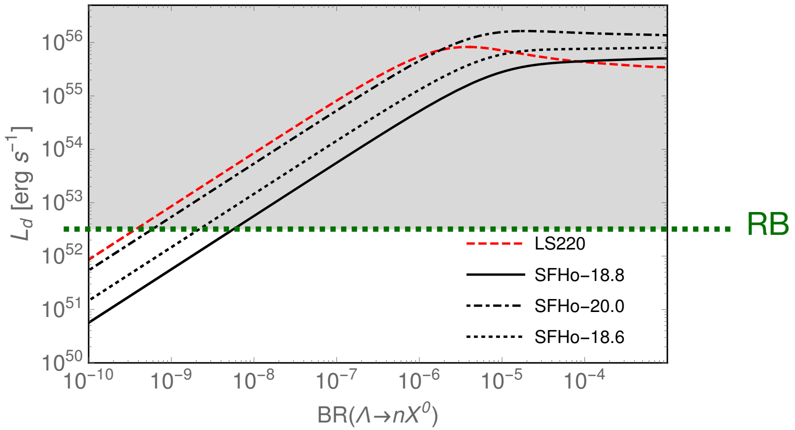
Hyperon number density



Temperature Profiles



Invisible Luminosity



Final bound using most conservative simulation:

$$\mathrm{BR}(\Lambda \to n X^0) \lesssim 5.0 \times 10^{-9}$$

Flavour model building

Especially interesting: Lepton sector, because there are unknown parameters like the neutrino mass scale and the leptonic CP phase

P3H-20-047

Neutrino Observables from a U(2) Flavor Symmetry

Linster, Lopez-Pavon, Ziegler

Flavor Physics with U(2)

✳ Construct **realistic** extension of old U(2) flavor models by Barbieri & al.

R. Barbieri, G. Dvali, L. Hall '96

- ★ viable CKM (old models in conflict with $V_{ub}/V_{cb} \neq \sqrt{m_u/m_c}$)
- ★ neutrinos sector adressed
- ★ no need for Supersymmetry

✳ Reproduce all Yukawa hierarchies with 1 small parameter + many O(1) coefficients

$$m_{\{u,d,e,\nu\}} \sim \begin{pmatrix} 0 & \varepsilon^2 & 0 \\ \varepsilon^2 & \varepsilon^2 & \{\varepsilon, \varepsilon^2, \varepsilon, \varepsilon^2\} \\ 0 & \{\varepsilon, \varepsilon, \varepsilon^2, \varepsilon^2\} & \{1, \varepsilon, \varepsilon, \varepsilon^2\} \end{pmatrix}$$

M. Linster, R. Ziegler '18

$\epsilon \sim V_{cb}$

✳ Texture 0's allow predictions for neutrino sector observables

Model Setup

- Simple setup with charges compatible with SU(5) or Pati-Salam

	Fermion				**Scalar**		
$SU(5)$	$\mathbf{10}_a$	$\overline{\mathbf{5}}_a$	$\mathbf{10}_3$	$\overline{\mathbf{5}}_3$	H	ϕ_a	χ
$SU(2)_F$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_F$	1	1	0	1	0	-1	-1

1st and 2nd generation ($\mathbf{10}_a$, $\overline{\mathbf{5}}_a$) — **third generation** ($\mathbf{10}_3$, $\overline{\mathbf{5}}_3$) — **two flavons with VEVs small against UV scale** (ϕ_a, χ)

- Construct Yukawa Lagrangian with appropriate Flavon insertions

$$\mathcal{L}_u = \frac{\lambda^u_{11}}{\Lambda^6}\chi^4(\phi^*_a Q_a)(\phi^*_b U_b)H + \frac{\lambda^u_{12}}{\Lambda^2}\chi^2\epsilon_{ab}Q_a U_b H + \frac{\lambda^u_{13}}{\Lambda^3}\chi^2(\phi^*_a Q_a)U_3 H + \cdots$$

- Flavon vevs generate hierarchical Yukawa structure

$$Y_u \approx \begin{pmatrix} \lambda^u_{11}\varepsilon^2_\phi\varepsilon^4_\chi & \lambda^u_{12}\varepsilon^2_\chi & \lambda^u_{13}\varepsilon_\phi\varepsilon^2_\chi \\ -\lambda^u_{12}\varepsilon^2_\chi & \lambda^u_{22}\varepsilon^2_\phi & \lambda^u_{23}\varepsilon_\phi \\ \lambda^u_{31}\varepsilon_\phi\varepsilon^2_\chi & \lambda^u_{32}\varepsilon_\phi & \lambda^u_{33} \end{pmatrix} \approx \begin{pmatrix} 0 & \lambda^u_{12}\varepsilon^2_\chi & 0 \\ -\lambda^u_{12}\varepsilon^2_\chi & \lambda^u_{22}\varepsilon^2_\phi & \lambda^u_{23}\varepsilon_\phi \\ 0 & \lambda^u_{32}\varepsilon_\phi & \lambda^u_{33} \end{pmatrix}$$

dropping sub-leading corrections $\mathcal{O}(\epsilon^2_\phi) \sim 10^{-4}$

Neutrino Sector Predictions

✳ Three different scenarios depending on charged lepton sector

Scenario	Free parameters	NO/IO	$\sum m_i$ [meV]	m_β [meV]	$m_{\beta\beta}$ [meV]
DCL	none	NO	$65.0^{+0.9}_{-0.6}$	$10.0^{+0.3}_{-0.2}$	0^{+0}_{-0}
			$(64 \to 68)_{2\sigma}$	$(10 \to 11)_{2\sigma}$	$(0 \to 0)_{2\sigma}$
			$(63 \to 69)_{3\sigma}$	$(9 \to 12)_{3\sigma}$	$(0 \to 0)_{3\sigma}$
$\mathrm{U}(2)_{\mathrm{PS}}$	s_{23}^{Re}, β	NO	$65.7^{+3.8}_{-2.1}$	$9.8^{+1.6}_{-0.3}$	$1.2^{+0.5}_{-0.3}$
			$(62 \to 72)_{2\sigma}$	$(9 \to 13)_{2\sigma}$	$(0 \to 2)_{2\sigma}$
			$(62 \to 75)_{3\sigma}$	$(9 \to 14)_{3\sigma}$	$(0 \to 2)_{2\sigma}$
$\mathrm{U}(2)_5$	$s_{23}^{Le}, \beta_1, \beta_2$	NO	$63.7^{+4.4}_{-2.1}$	$9.5^{+1.5}_{-0.3}$	$1.8^{+1.3}_{-0.8}$
			$(60 \to 74)_{2\sigma}$	$(9 \to 13)_{2\sigma}$	$(0 \to 4)_{2\sigma}$
			$(59 \to 272)_{3\sigma}$	$(9 \to 85)_{3\sigma}$	$(0 \to 54)_{3\sigma}$
		IO	$224.2^{+173.8}_{-36.1}$	77^{+54}_{-10}	$68.0^{+31.0}_{-12.2}$
			$(173 \to 1070)_{2\sigma}$	$(65 \to 303)_{2\sigma}$	$(49 \to 255)_{2\sigma}$
			$(167 \to 5584)_{3\sigma}$	$(63 \to 497)_{3\sigma}$	$(1 \to 299)_{3\sigma}$

charged leptons diagonal

Pati-Salam charged leptons

SU(5) charged leptons

neutrino mass parameter of beta decay

neutrino mass parameter of 0νββ decay

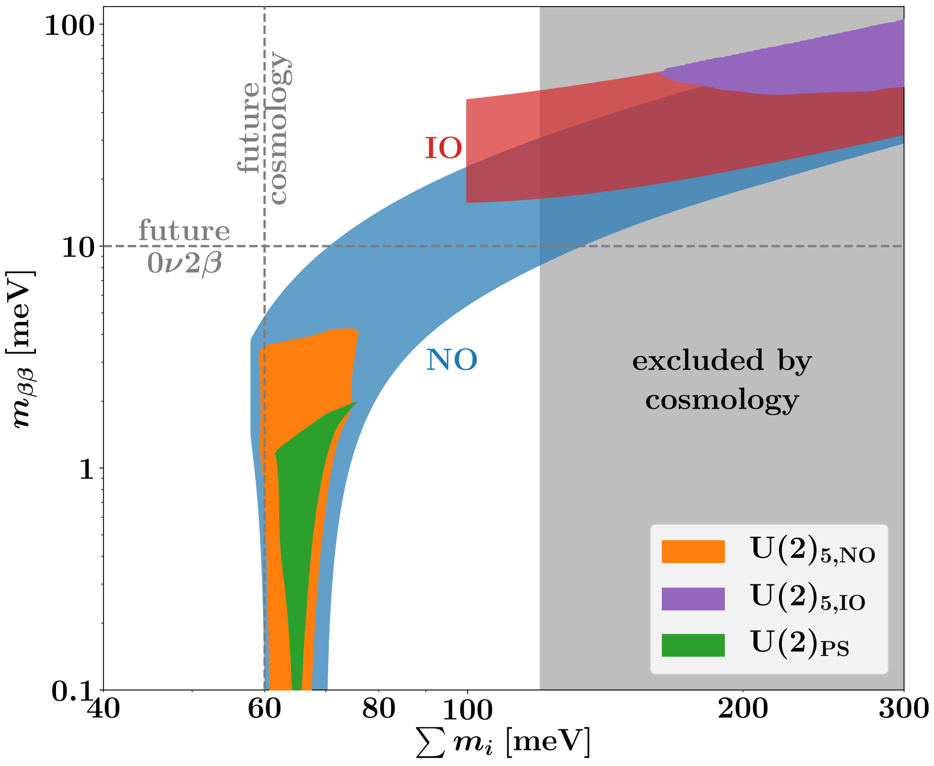
Neutrino Sector Predictions

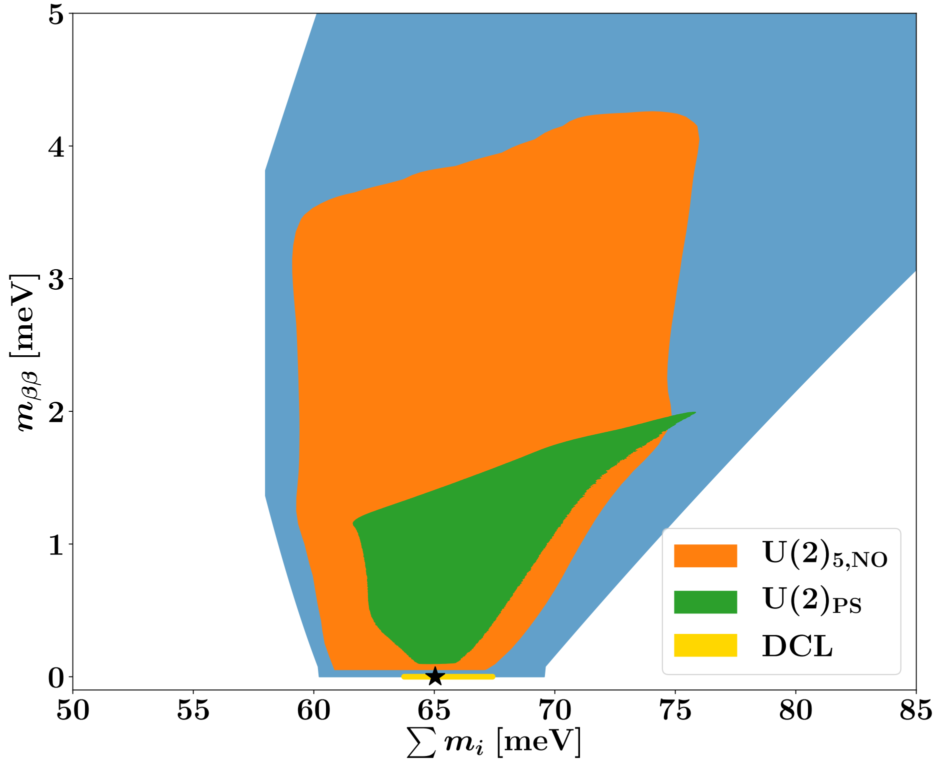
✳ Numerical analysis scanning over free parameters in CL sector

★ **Only NO is viable**

★ **Small absolute scale**

★ **0νββ is out of reach**





Outlook

- The $b \to s\ell^+\ell^-$ flavour anomaly is robust, with steadily increasing statistical significance since 2013, pointing to left-handed new physics. It implies a new particle lighter than 50 TeV, underpinning a scientific case for the FCC-hh. CRC activity linking it to $a_\mu \equiv (g-2)_\mu$ and dark matter.

- Flavour physics constrains light BSM physics (axions, mediators to a Dark Sector) and astrophysics contributes to dark flavour physics.

- The CRC is well-positioned to explore the top-bottom and BSM-Higgs-flavour connections.