

Combining low- and high-energy constraints on flavourful EFTs

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Based on work (in progress) with:

D. Faroughy, F. Jaffredo, O. Sumensari and F. Wilsch
[arXiv:2207.xxxxx](https://arxiv.org/abs/2207.xxxxx)



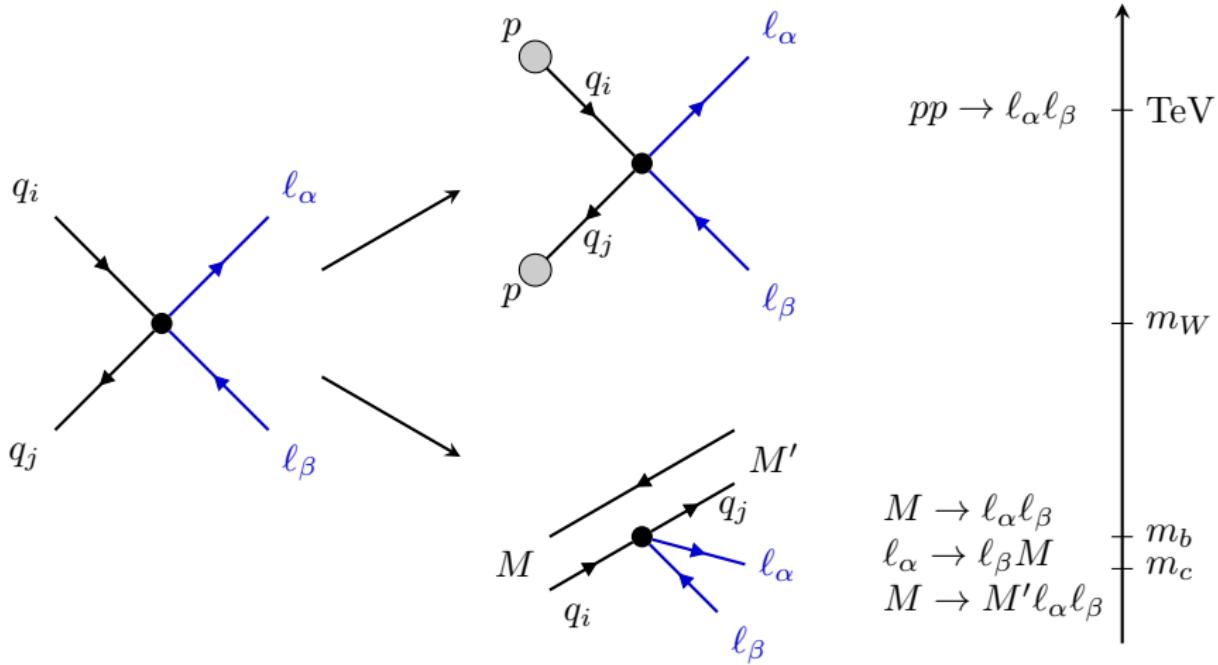
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Introduction and Motivation

- Solutions to the flavour puzzle and the hierarchy problem point to New Physics (NP) at a scale \gtrsim TeV
- Flavour-generic NP is highly constrained ($\Lambda_{NP} \gtrsim 10^5$ TeV from $\Delta F = 2$ processes)
- Assuming a flavour structure (MFV, $U(2)^5$, ...) this can be lowered to be \sim TeV
- LHC can provide useful complementary information on top of low-energy probes
- In recent years, interesting hints in low-energy data, *e.g.* B -anomalies, $(g - 2)_\mu$
- In this talk: focus on Drell-Yan measurements, i.e. semileptonic interactions, and combine low- and high-energy data within a motivated scenario



Searches at different energy scales



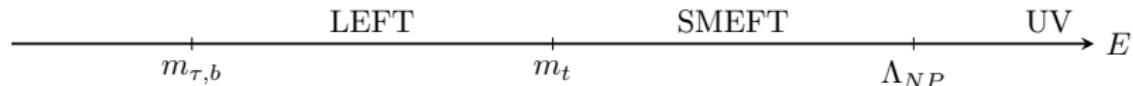
High- p_T searches can probe the same operators directly constrained by flavour-physics experiments

[see also 1609.07138, 1704.09015, 1811.07920, 2003.12421, ...]



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EFT description

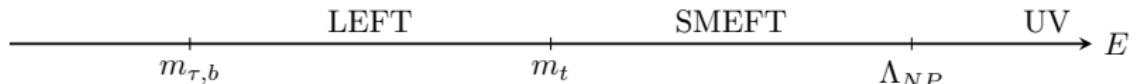


SMEFT

- Heavy NP integrated out
- $SU(3)_c \times SU(2)_L \times U(1)_Y$
- $\mathcal{L}_{\text{SMEFT}} = \frac{1}{\Lambda^2} \sum_{\alpha} \mathcal{C}_{\alpha} \mathcal{O}_{\alpha}$
- e.g. $[\mathcal{O}_{lq}^{(3)}]_{\alpha\beta ij} = (\bar{l}_{\alpha} \gamma_{\mu} \sigma^I l_{\beta})(\bar{q}_i \gamma^{\mu} \sigma^I q_j)$



EFT description



LEFT

SMEFT

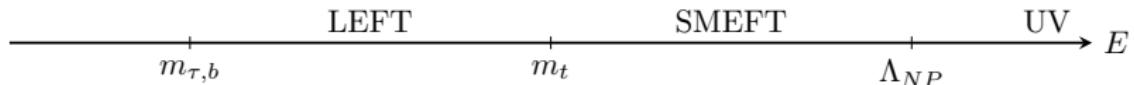
- EWSB
- $SU(3)_c \times U(1)_{em}$
- $\mathcal{L}_{\text{LEFT}} = -\frac{2}{v^2} \sum_{\alpha} C_{\alpha} O_{\alpha}$
- e.g. $[O_{V_L}^{ud\ell\nu}]_{\alpha\beta ij} = (\bar{\ell}_{L\alpha} \gamma^{\mu} \nu_{L\beta}) (\bar{u}_{Li} \gamma_{\mu} d_{Lj})$

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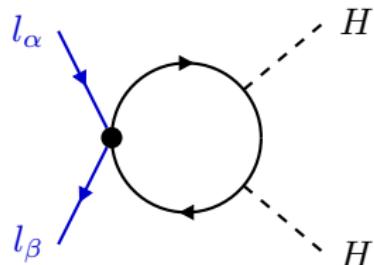
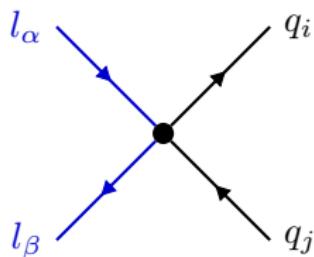
RGE effects are important!

[1308.2627, 1310.4838, 1312.2014, 1711.05270]



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Example: semileptonic operators meet pole observables



RGE:

$$[\dot{\mathcal{C}}_{Hl}^{(3)}]_{\alpha\beta} \supset 2N_c [\mathcal{C}_{lq}^{(3)}]_{\alpha\beta kl}^{[1310.4898]} [Y_d^\dagger Y_d + Y_u^\dagger Y_u]_{lk}$$

$$[\mathcal{O}_{Hl}^{(3)}]_{\alpha\beta} = (H^\dagger i D_\mu \sigma^I H)(\bar{l}_\alpha \gamma^\mu \sigma^I l_\beta)$$

Semileptonic operator at scale Λ :

$$[\mathcal{O}_{lq}^{(3)}]_{\alpha\beta ij} = (\bar{l}_\alpha \gamma_\mu \sigma^I l_\beta)(\bar{q}_i \gamma^\mu \sigma^I q_j)$$

→ Modification of W couplings to leptons:

$$\mathcal{L}_{\text{eff}}^W = -\frac{g}{\sqrt{2}} \sum_{\alpha, \beta} \left[g_{\ell_L}^{W \alpha \beta} (\bar{\ell}_{L\alpha} \gamma^\mu \nu_{L\beta}) \right] W_\mu + \text{h.c.}$$

$$g_{\ell_L}^{W \alpha \beta} = \delta_{\alpha\beta} + \frac{v^2}{\Lambda^2} [\mathcal{C}_{Hl}^{(3)}]_{\alpha\beta}$$

e.g. $W \rightarrow \tau\nu, \dots$



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Comment on Inputs: gauge parameters

- need to clearly define which are our inputs
- $\alpha, G_F, m_Z, \alpha_s$
- all other gauge parameters can be expressed in terms of these
 $\rightarrow e.g. \sin^2\theta_W = \frac{1}{2} - \sqrt{1 - \frac{4\pi\alpha}{\sqrt{2}G_F m_Z^2}}$
- NP in μ -decay changes the value of $G_F = G_F^{(0)} + \delta G_F$:

$$\frac{\delta G_F}{G_F^{(0)}} = \frac{v^2}{\Lambda^2} \left([\mathcal{C}_{Hl}^{(3)}]_{22} + [\mathcal{C}_{Hl}^{(3)}]_{11} - \frac{1}{2} [\mathcal{C}_{ll}]_{2112} - \frac{1}{2} [\mathcal{C}_{ll}]_{1221} \right) + \mathcal{O}\left(\frac{v^4}{\Lambda^4}\right)$$

this propagates into all weak-interaction observables



Comment on Inputs: CKM matrix elements

- the same issue applies for the CKM. Our choice: [1812.08163]
- $|V_{us}|$: $\mathcal{B}(K^+ \rightarrow \pi^0 e^+ \nu)$ and $\mathcal{B}(K_L \rightarrow \pi^\pm e^\mp \nu)$, PDG average
- $|V_{cb}|$: $\mathcal{B}(B^0 \rightarrow D^- \ell^+ \nu)$ and $\mathcal{B}(B^+ \rightarrow D^0 \ell^+ \nu)$, $\ell = e, \mu$ average
- $|V_{ub}|$: $\frac{d\Gamma(B \rightarrow \pi \ell \bar{\nu})}{dq^2}$ at high- q^2
- All form-factors taken from lattice (FLAG) [1902.08191]
- γ : UTfit [0707.0636]

NP contributions to the input observables:

$$\frac{\mathcal{B}(P \rightarrow P' \ell \bar{\nu})}{\mathcal{B}(P \rightarrow P' \ell \bar{\nu})^{\text{SM}}} = \frac{|V_{ij}|^2}{|V_{ij}^{(0)}|^2} = \sum_{\alpha\beta} \rho_{\alpha\beta}^{ij\ell}(\mu) C_\alpha^{ij\ell}(\mu) C_\beta^{ij\ell}(\mu)^*$$

$\rho_{\alpha\beta}$ numerical factors, C_α LEFT coefficients. NP propagates into the extracted CKM elements, e.g.

$$|V_{ud}^{(0)}| = 1 - \frac{V_{us}^2}{2} - \frac{V_{us}^4}{8} + \delta|V_{us}| \left(V_{us} + \frac{V_{us}^3}{2} \right) + \mathcal{O}(\delta|V_{us}|^2)$$





- **Mathematica** package
- compute likelihoods in the SMEFT and simplified (LQ) models
- @high- p_T : Drell-Yan ($\ell\ell$, $\ell\ell'$, $\ell\nu$)
- @low energy: flavour observables
- Includes EW pole and Higgs observables [2103.12074]

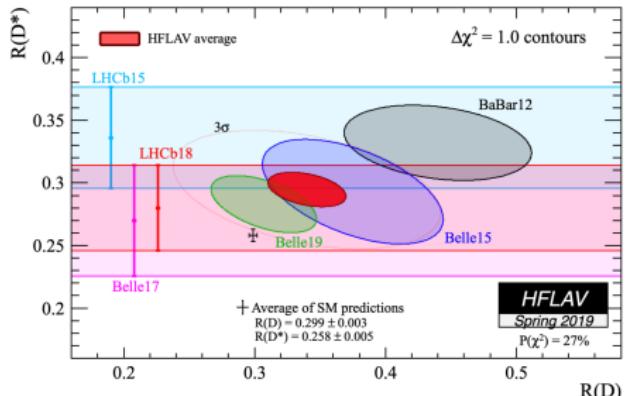
→ Combined analyses!



Example: LFU tests in charged current B decays

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \rightarrow D^{(*)}\ell\bar{\nu})}$$

$$\ell = \mu, e$$



Low-energy effective description:

$$\begin{aligned} \mathcal{L}_{\text{eff}}^{b \rightarrow c\tau\nu} = & -2\sqrt{2}G_F V_{cb} \left[(1 + C_{V_L})(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L) + C_{V_R}(\bar{c}_R \gamma_\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_L) \right. \\ & + C_{S_L}(\bar{c}_R b_L)(\bar{\tau}_R \nu_L) + C_{S_R}(\bar{c}_L b_R)(\bar{\tau}_R \nu_L) + C_T(\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu} \nu_L) \Big] + \text{h.c.}, \end{aligned}$$



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Example: LFU tests in charged current B decays

Low-energy effective description:

$$\begin{aligned} \mathcal{L}_{\text{eff}}^{b \rightarrow c\tau\nu} = & -2\sqrt{2}G_F V_{cb} \left[(1 + C_{V_L}) (\bar{c}_L \gamma_\mu b_L) (\bar{\tau}_L \gamma_\mu \nu_L) + C_{V_R} (\bar{c}_R \gamma_\mu b_R) (\bar{\tau}_L \gamma_\mu \nu_L) \right. \\ & \left. + C_{S_L} (\bar{c}_R b_L) (\bar{\tau}_R \nu_L) + C_{S_R} (\bar{c}_L b_R) (\bar{\tau}_R \nu_L) + C_T (\bar{c}_R \sigma_{\mu\nu} b_L) (\bar{\tau}_R \sigma^{\mu\nu} \nu_L) \right] + \text{h.c.}, \end{aligned}$$

SMEFT matching:

$$C_{V_L} = -\frac{v^2}{\Lambda^2} \sum_i \frac{V_{2i}}{V_{23}} \left([\mathcal{C}_{lq}^{(3)}]_{33i3} + [\mathcal{C}_{Hq}^{(3)}]_{33} - \delta_{i3} [\mathcal{C}_{Hl}^{(3)}]_{33} \right),$$

$$C_{V_R} = \frac{v^2}{2\Lambda^2} \frac{1}{V_{23}} [\mathcal{C}_{Hud}^{(3)}]_{23},$$

$$C_{S_L} = -\frac{v^2}{2\Lambda^2} \frac{1}{V_{23}} [\mathcal{C}_{lequ}^{(1)}]_{3332}^*,$$

$$C_{S_R} = -\frac{v^2}{2\Lambda^2} \sum_{i=1}^3 \frac{V_{2i}^*}{V_{23}} [\mathcal{C}_{ledq}]_{333i}^*,$$

$$C_T = -\frac{v^2}{2\Lambda^2} \frac{1}{V_{23}} [\mathcal{C}_{lequ}^{(3)}]_{3332}^*,$$

$$\begin{aligned} [\mathcal{O}_{lq}^{(1)}]_{ij\alpha\beta} &= (\bar{l}_\alpha \gamma_\mu l_\beta)(\bar{q}_i \gamma^\mu q_j) \\ [\mathcal{O}_{lq}^{(3)}]_{ij\alpha\beta} &= (\bar{l}_\alpha \gamma_\mu \sigma^I l_\beta)(\bar{q}_i \gamma^\mu \sigma^I q_j) \\ [\mathcal{O}_{lequ}^{(1)}]_{ij\alpha\beta} &= (\bar{l}_\alpha e_\beta)\epsilon(\bar{q}_i u_j) \\ [\mathcal{O}_{lequ}^{(3)}]_{ij\alpha\beta} &= (\bar{l}_\alpha \sigma^{\mu\nu} e_\beta)\epsilon(\bar{q}_i \sigma_{\mu\nu} u_j) \\ [\mathcal{O}_{ledq}]_{ij\alpha\beta} &= (\bar{l}_\alpha e_\beta)(\bar{d}_i q_j) \\ [\mathcal{O}_{Hq}^{(3)}]_{ij} &= (H^\dagger i D_\mu \sigma^I H)(\bar{q}_i \gamma^\mu \sigma^I q_j) \\ [\mathcal{O}_{Hl}^{(3)}]_{\alpha\beta} &= (H^\dagger i D_\mu \sigma^I H)(\bar{l}_\alpha \gamma^\mu \sigma^I l_\beta) \end{aligned}$$



Example: LFU tests in charged current B decays

Three possible scenarios: [2103.12504]

- U_1 :

$$[\mathcal{C}_{lq}^{(1)}]_{3323} = [\mathcal{C}_{lq}^{(3)}]_{3323}, \quad [\mathcal{C}_{lq}^{(1)}]_{3333} = [\mathcal{C}_{lq}^{(3)}]_{3333}$$

- S_1 :

$$[\mathcal{C}_{lq}^{(1)}]_{3333} = -[\mathcal{C}_{lq}^{(3)}]_{3333}, \quad [\mathcal{C}_{lequ}^{(1)}]_{3332} = -4 [\mathcal{C}_{lequ}^{(3)}]_{3332}$$

- R_2 :

$$[\mathcal{C}_{lequ}^{(1)}]_{3332} = 4 [\mathcal{C}_{lequ}^{(3)}]_{3332}$$

(see talk by Olcyr Sumensari)



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Example: LFU tests in charged current B decays

- U_1 :

$$[\mathcal{C}_{lq}^{(1)}]_{3323} = [\mathcal{C}_{lq}^{(3)}]_{3323}, \quad [\mathcal{C}_{lq}^{(1)}]_{3333} = [\mathcal{C}_{lq}^{(3)}]_{3333}$$

Computing the LHC likelihood for $pp \rightarrow \tau\tau, \tau\nu$:

```
In[7]:= x2tau = Plus @@ ChiSquareLHC["di-tau-ATLAS", Coefficients -> {
  WC["lq1", {3, 3, 3, 3}],
  WC["lq3", {3, 3, 3, 3}],
  WC["lq1", {3, 3, 2, 3}],
  WC["lq3", {3, 3, 2, 3}]
}];

Computing observable for di-tau-ATLAS search: arXiv:2002.12223
PROCESS          : pp → τ⁻τ⁺
EXPERIMENT        : ATLAS
ARXIV            : 2002.12223
SOURCE            : hepdata
OBSERVABLE        : m_T^tot
BINNING m_T^tot [GeV] : {150, 200, 250, 300, 350, 400, 450, 500, 600, 700, 800, 900, 1000, 1150, 1500}
EVENTS OBSERVED   : {1167., 1568., 1409., 1455., 1292., 650., 377., 288., 92., 57., 27., 14., 11., 13.}
LUMINOSITY [fb⁻¹] : 139
BINNING √s [GeV]  : {150, 200, 250, 300, 350, 400, 450, 500, 600, 700, 800, 900, 1000, 1150, 1500}
BINNING p_T [GeV] : {0, ∞}
```

```
In[8]:= x2taunu = Plus @@ ChiSquareLHC["mono-tau-ATLAS", Coefficients -> {
  WC["lq1", {3, 3, 3, 3}],
  WC["lq3", {3, 3, 3, 3}],
  WC["lq1", {3, 3, 2, 3}],
  WC["lq3", {3, 3, 2, 3}]
}];
```



Example: LFU tests in charged current B decays

- U_1 :

$$[\mathcal{C}_{lq}^{(1)}]_{3323} = [\mathcal{C}_{lq}^{(3)}]_{3323}, \quad [\mathcal{C}_{lq}^{(1)}]_{3333} = [\mathcal{C}_{lq}^{(3)}]_{3333}$$

Flavour + EW likelihood:

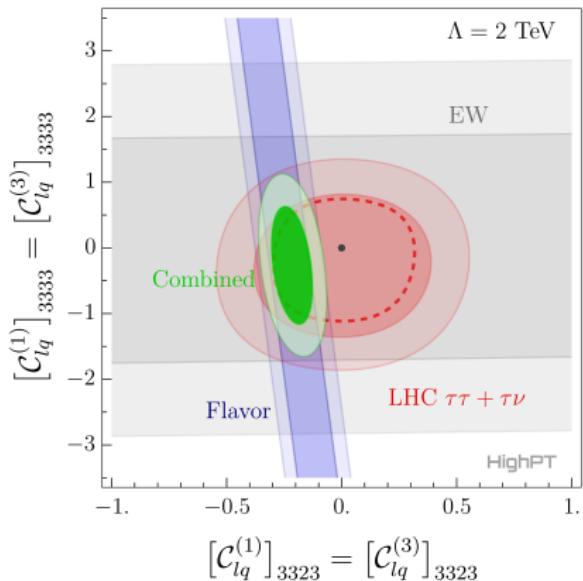
```
ChiSquareFlavor[
  Observables → FlavorObservables["b->c,semileptonic"],
  Coefficients → {
    WC["lq1", {3, 3, 3, 3}],
    WC["lq3", {3, 3, 3, 3}],
    WC["lq1", {3, 3, 2, 3}],
    WC["lq3", {3, 3, 2, 3}]
  }
]
ChiSquareEW[Coefficients → {
  WC["lq1", {3, 3, 3, 3}],
  WC["lq3", {3, 3, 3, 3}],
  WC["lq1", {3, 3, 2, 3}],
  WC["lq3", {3, 3, 2, 3}]
}]
```

HighPT takes care of RGE in LEFT,
match it to SMEFT,
and evolve the SMEFT
coefficients up to Λ_{NP}



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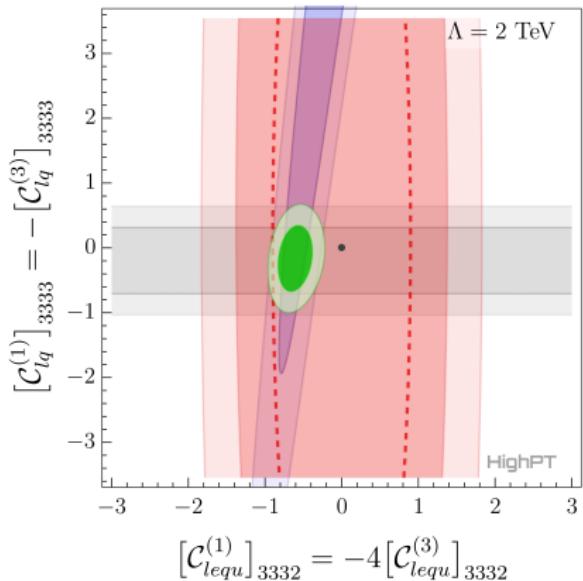
Example: LFU tests in charged current B decays



- High- p_T : $pp \rightarrow \tau\tau$, $pp \rightarrow \tau\nu$
- Flavor: R_D , R_{D^*} , $B \rightarrow K^{(*)}\nu\bar{\nu}$
- EW: W - and Z -pole observables + $H \rightarrow \tau\tau$
- dashed line: 3 ab^{-1} projection (2σ)



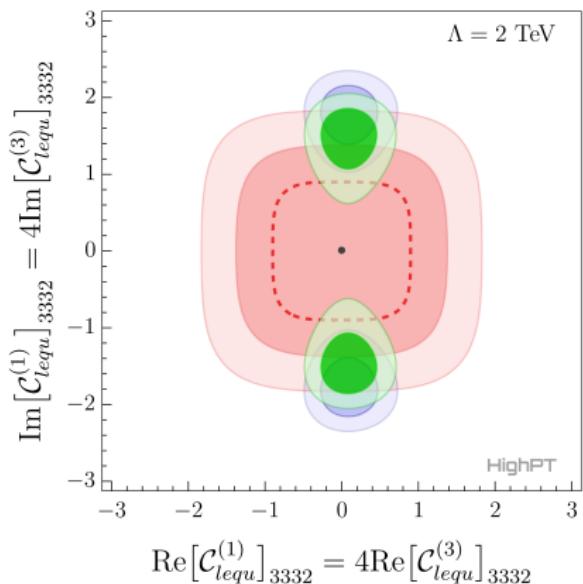
Example: LFU tests in charged current B decays



- High- p_T : $pp \rightarrow \tau\tau$, $pp \rightarrow \tau\nu$
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 $B \rightarrow K^{(*)}\nu\bar{\nu}$
- EW: W - and Z -pole
observables + $H \rightarrow \tau\tau$
- dashed line: 3 ab^{-1} projection
(2σ)
- flat direction: no $bb \rightarrow \tau\tau$

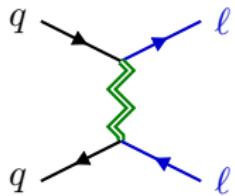


Example: LFU tests in charged current B decays



Bounds in simplified LQ models

- In the tails, the EFT expansion+truncation may reach its limits
→ include effects from the propagators of new heavy states
- Simplified model: SM + 1 heavy state: LQ
→ t - and u -channel exchange
- `InitializeModel[{"U1", 2000, 0}]`
- typically leads to weaker bounds from LHC
- Choosing two couplings at a time generally corresponds to more than two SMEFT operators
→ more correlation between the observables



Bounds in simplified LQ models: LQ matching

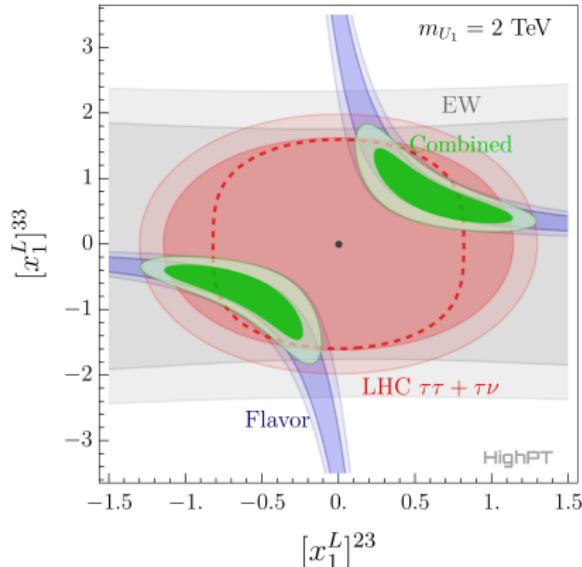
Field	S_1	R_2	U_1
Quantum Numbers	(3 , 1 , 1/3)	(3 , 2 , 7/6)	(3 , 1 , 2/3)
$[\mathcal{C}_{ledq}]_{\alpha\beta ij}$	–	–	$2[x_1^L]_{i\alpha}^*[x_1^R]_{j\beta}$
$\left[\mathcal{C}_{lequ}^{(1)}\right]_{\alpha\beta ij}$	$\frac{1}{2}[y_1^L]_{i\alpha}^*[y_1^R]_{j\beta}$	$-\frac{1}{2}[y_2^R]_{i\beta}[y_2^L]_{j\alpha}^*$	–
$\left[\mathcal{C}_{lequ}^{(3)}\right]_{\alpha\beta ij}$	$-\frac{1}{8}[y_1^L]_{i\alpha}^*[y_1^R]_{j\beta}$	$-\frac{1}{8}[y_2^R]_{i\beta}[y_2^L]_{j\alpha}^*$	–
$[\mathcal{C}_{eu}]_{\alpha\beta ij}$	$\frac{1}{2}[y_1^R]_{j\beta}[y_1^R]_{i\alpha}^*$	–	–
$[\mathcal{C}_{ed}]_{\alpha\beta ij}$	–	–	$-[x_1^R]_{i\beta}[x_1^R]_{j\alpha}^*$
$[\mathcal{C}_{\ell u}]_{\alpha\beta ij}$	–	$-\frac{1}{2}[y_2^L]_{i\beta}[y_2^L]_{j\alpha}^*$	–
$[\mathcal{C}_{qe}]_{ij\alpha\beta}$	–	$-\frac{1}{2}[y_2^R]_{i\beta}[y_2^R]_{j\alpha}^*$	–
$\left[\mathcal{C}_{lq}^{(1)}\right]_{\alpha\beta ij}$	$\frac{1}{4}[y_1^L]_{i\alpha}^*[y_1^L]_{j\beta}$	–	$-\frac{1}{2}[x_1^L]_{i\beta}[x_1^L]_{j\alpha}^*$
$\left[\mathcal{C}_{lq}^{(3)}\right]_{\alpha\beta ij}$	$-\frac{1}{4}[y_1^L]_{i\alpha}^*[y_1^L]_{j\beta}$	–	$-\frac{1}{2}[x_1^L]_{i\beta}[x_1^L]_{j\alpha}^*$



$$U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$$

$$\mathcal{L}_{U_1} = [x_1^L]_{i\alpha} \bar{q}_i \not{\! l}_1 l_\alpha + [x_1^R]_{i\alpha} \bar{d}_i \not{\! l}_1 e_\alpha + \text{h.c.}$$

$$U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$$



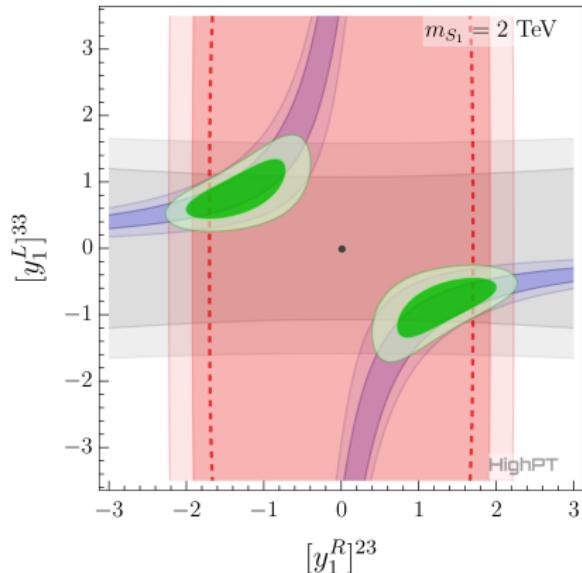
- LH couplings only
- SMEFT operators:
 $[\mathcal{C}_{lq}^{(1,3)}]_{3333,3323,3322}$



$$S_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$$

$$\mathcal{L}_{S_1} = [y_1^L]_{i\alpha} S_1 \bar{q}_i^c \epsilon l_\alpha + [y_1^R]_{i\alpha} S_1 \bar{u}_i^c e_\alpha + \text{h.c.}$$

$$S_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$$



- SMEFT operators:

$$[\mathcal{C}_{lq}^{(1,3)}]_{3333}$$

$$[\mathcal{C}_{lequ}^{(1,3)}]_{3332}$$

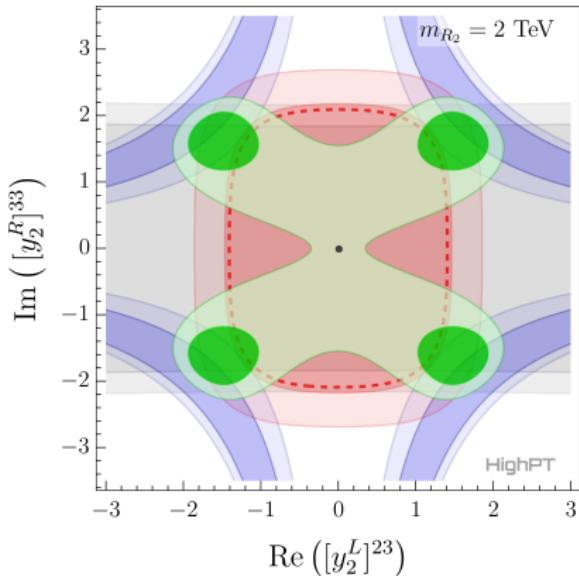
$$[\mathcal{C}_{eu}]_{3322}$$



$$R_2 \sim (\mathbf{3}, \mathbf{2}, 7/6)$$

$$\mathcal{L}_{R_2} = -[y_2^L]_{i\alpha} \bar{u}_i R_2 \epsilon l_\alpha + [y_2^R]_{i\alpha} \bar{q}_i e_\alpha R_2 + \text{h.c.}$$

$$R_2 \sim (\mathbf{3}, \mathbf{2}, 7/6)$$



- SMEFT operators:

$$[\mathcal{C}_{qe}]_{3333}$$

$$[\mathcal{C}_{lequ}^{(1,3)}]_{3332}$$

$$[\mathcal{C}_{lu}]_{3322}$$



Outlook

- The LHC can provide complementary and competitive bounds on NP compared to low-energy experiments
- HighPT will provide a combined framework to do such analyses
- v1 with all high- p_T searches (without flavour and EWPT) on arXiv this month
- Stay tuned for the low-energy observables (later this year)!

Thank you!