B anomalies in the SMEFT: connections to high-p_T

Beyond the Flavour Anomalies III

2022-04-26

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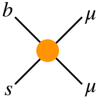
B anomalies in the SMEFT

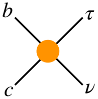
$R_{K^{(*)}}$



match to C_9, C_{10}

$\mathcal{O}_{lq}^{(1)}$	$\mathcal{O}_{lq}^{(3)}$	$\mathcal{O}_{qe}$
$(\bar{Q}^i\gamma^\mu Q^j)(\bar{L}^k\gamma_\mu L^l)$	$(\bar{Q}^i\gamma^\mu\tau^a Q^j)(\bar{L}^k\gamma_\mu\tau^a L^l)$	$(\bar{Q}^i\gamma^\mu Q^j)(\bar{e}^k\gamma_\mu e^l)$

$R_{D^{(*)}}$



matches to LH vector current	matches to tensor current	(matches to LH scalar current	matches to RH scalar current)
$\mathcal{O}_{lq}^{(3)}$	$\mathcal{O}_{lequ}^{(3)}$	$\mathcal{O}_{lequ}^{(1)}$	$\mathcal{O}_{ledq}$
$(\bar{Q}^i\gamma^\mu\tau^a Q^j)(\bar{L}^k\gamma_\mu\tau^a L^l)$	$(\bar{L}^i\sigma^{\mu\nu}e^j)(\bar{Q}^k\sigma_{\mu\nu}u^l)$	$(\bar{L}^i e^j)(\bar{Q}^k u^l)$	$(\bar{L}^i e^j)(\bar{d}^k Q^l)$

For low energy fit to $b \to c\tau\nu$ data see e.g. Shi, Geng, Grinstein, Jäger, Camalich 1905.08498

Combined explanations need $C_{lq}^{(1)} = C_{lq}^{(3)}$ mostly aligned along 3rd generations

Other operators in addition can improve the fit, and may arise 'for free', e.g.

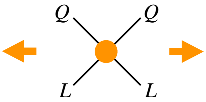
- $\mathcal{O}_{ledq}$: naturally an option in U_1 leptoquark models e.g. Cornella & al. 2103.16558
- LFU piece of C_9 generated at loop level from large $bs\tau\tau$ running below EW scale e.g. Crivellin, Greub, Saturnino, Müller 1807.02068

Operator connections to EW/top/Higgs

1) Operator enters at *tree level* in *both* B decays and EW/top/Higgs

Not many examples: need semileptonic operators for B anomalies, but operators with bosons for most EW/top/Higgs observables

$b \to s\mu\mu$
and/or
$b \to c\tau\nu$



- $t \to \tau\nu q$ or $t \to c\mu\mu$ decay
- top production at future lepton colliders
- tails of e.g. $pp \to \tau\tau$, $pp \to \mu\mu$

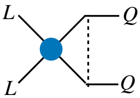
e.g. Kamenik, Katz, Stolarski 1808.00964
Coy, Frigiero, Mescia, Sumensari 1909.08567

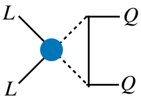
e.g. Bißmann, Grunwald, Hiller, Kröniger 2012.10456

e.g. Faroughy, Greljo, Kamenik 1609.17138
Greljo, Marzocca 1704.09015
Cornella & al. 2103.16558

2) Operator enters at *loop level* in B decays and *tree level* in EW/top/Higgs

Only possible for $b \to sll$ anomalies. Strong constraints from Z pole observables: narrowed down to semileptonic operators



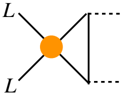


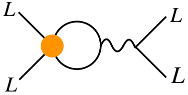
e.g. Celis, Fuentes-Martin, Vicente, Virto 1704.05672
Camargo-Molina, Celis, Faroughy 1805.04917
Coy, Frigiero, Mescia, Sumensari 1909.08567
Alasfar, Azatov, de Blas, Paul , Valli 2007.04400

3) Operator enters at *tree level* in B decays and *loop level* in EW/top/Higgs

Important for operators fitting $b \to c\tau\nu$

Correlates with LFUV in Z decays, W decays and τ decays





e.g. Feruglio, Paradisi, Pattori 1705.00929
Buttazzo, Greljo, Isidori, Marzocca 1706.07808

High-p_T measurements

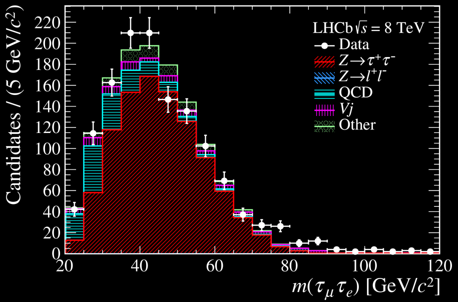
- EW: Z decays
- Top observables
- Higgs observables
- EW: W mass

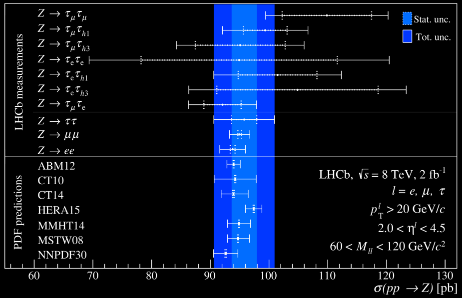
- Very large number of EW, top and Higgs measurements used to constrain SMEFT fits
- Will focus on a few more recent results related to each category

$Z^0 \to \tau^+\tau^-$

JHEP **09** (2018) 159

- Compare with $\mu^+\mu^-$ and e^-e^- for LFU test
- Deviations from LEP would indicate some underlying NP background
- Study based on LHCb 8 TeV dataset
- Reconstruct muonic, electronic, and hadronic (one- and three-track) decays
- Require at least one leptonic decay for trigger
- Combine cross section measurements from 7 channels
- Consistent with LFU at 6% level
- HL-LHC upgrade should make LHCb $Z^0 \to \mu^+\mu^-$ competitive for $\sin^2\theta_W^{\text{eff}}$





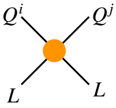
FCNC - Z pole interplays for combined explanations

Two possible quark flavour structures for $b \to c\tau\nu$:

$C^{ij} = C^{33}$

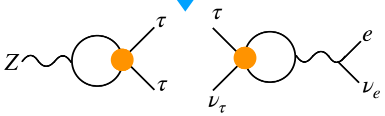
3rd gen aligned

Rely on CKM for $b \to c$ transition

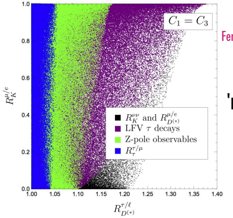


$C^{ij} = C^{32}$

Explicitly off-diagonal



Runs into LFUV Z decays and τ decays

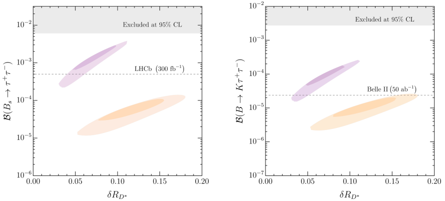


Feruglio, Paradisi, Pattori 1606.00524 & 1705.00929

'pure mixing' scenario already in tension

Large tree level $b \to s\tau\tau$ (and $b \to s\tau\mu$)

Cornella & al., 2103.16558



Forced to have at least some off-diag part $\Longrightarrow$ $b \to s\tau\tau$ *is a generic prediction (absent fine-tuning)*

High-p_T measurements

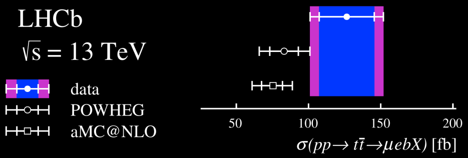
- EW: Z decays
- Top observables
- Higgs observables
- EW: W mass

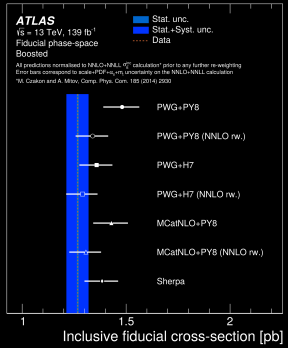
Top observables: $pp \to t\bar{t}$

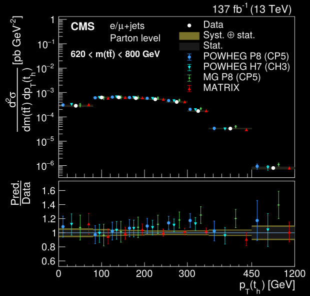
ATLAS: arXiv:2202.12134   CMS: Phys. Rev. **D104** (2021) 092013

- Recent results from ATLAS and CMS based on full 13 TeV datasets
- ATLAS study in ℓ+jets channel with boosted hadronically decaying top
- CMS study also in ℓ+jets and covers full p_T range
- Both report total and differential cross sections and use SMEFT to set limits on NP
- LHCb can also contribute to $t\bar{t}$ in forward region

  LHCb: JHEP **08** (2018) 174



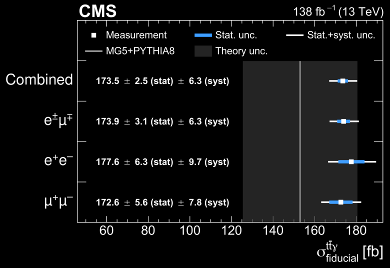


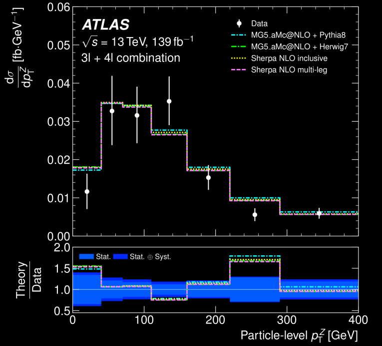


Top observables: $pp \to t\bar{t}V$

CMS: arXiv:2201.07301
ATLAS: Eur. Phys. J. C **81** (2021) 737

- New CMS study of $t\bar{t}\gamma$ using $2\times$ SL top decays
- Measure total and differential cross sections
- Combine with previous ℓ+jets measurement to set limits on SMEFT Wilson coefficients
- Recent ATLAS study of $t\bar{t}Z$ using both 3ℓ and 4ℓ events
- Total and differential cross sections in good agreement with predictions

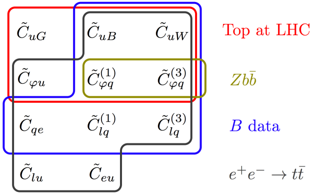




Top observables for B anomalies?

Not many *model-independent* connections between LFUV in B decays and top at LHC

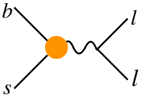
To get LFUV, leptons must be involved in the operator $\Longrightarrow$ semileptonic, or lepton-Higgs

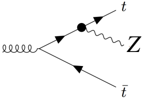


Bißmann, Grunwald, Hiller, Krönigen 2012.10456

LHC observables not v sensitive to top semileptonics

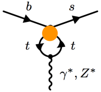
$C_{Hq}^{(1,3)}, C_{Hu} \Longrightarrow$ <u>LFU</u> $b \to sll$ and $b \to cl\nu$ and (e.g) $\bar{t}tZ$



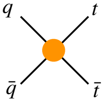


e.g. Brod, Greljo, Stamou, Uttarayat 1408.0792
Bißmann, Grunwald, Hiller, Krönigen 2012.10456
Bruggisser, Schäfer, van Dyk, Westhoff 2101.07273

4-quark operators link LFU B physics with top production



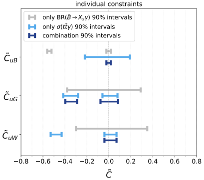
e.g. $B_s \to ll$



e.g. $pp \to t\bar{t}$

Bruggisser, Schäfer, van Dyk, Westhoff 2101.07273

$B \to X_s\gamma$ and $t\bar{t}\gamma$ are complementary for dipole operators



Bißmann, Erdmann, Grunwald, Hiller, Krönigen 1909.13632

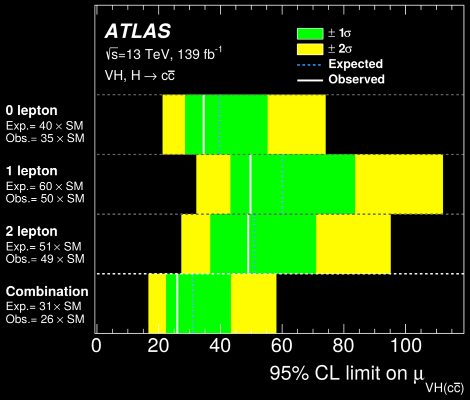
36 fb-1

High-p_T measurements

- EW: Z decays
- Top observables
- Higgs observables
- EW: W mass

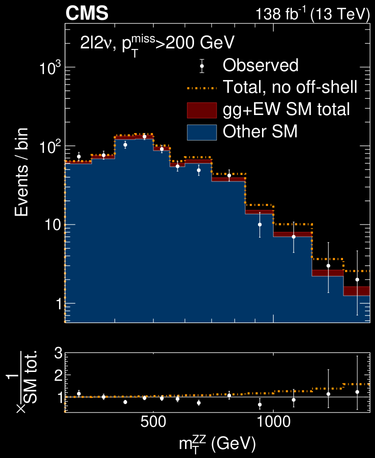
Higgs observables

- Search for $H \to c\bar{c}$ in VH
- Confirms c coupling weaker than to b at 95% Cl



arXiv:2201.11428

arXiv:2202.06923



- Evidence for $H \to ZZ$ with off-shell H
- $\Gamma^H = 3.2^{+2.4}_{-1.7}\,\mathrm{MeV}$ consistent with SM

Higgs observables for B anomalies?

In MFV, nearly all operators that produce tree level effects in Higgs and loop level effects in $b \to s$ are better constrained by Z pole

Exception: C_{uG}^{33} enters in ggF, but better constrained by $\bar{t}t$ SMEFiT Collaboration, 2105.00006

Study of C_{uG}^{33} in B physics: Kamenik, Papucci & Weiler 1107.3143

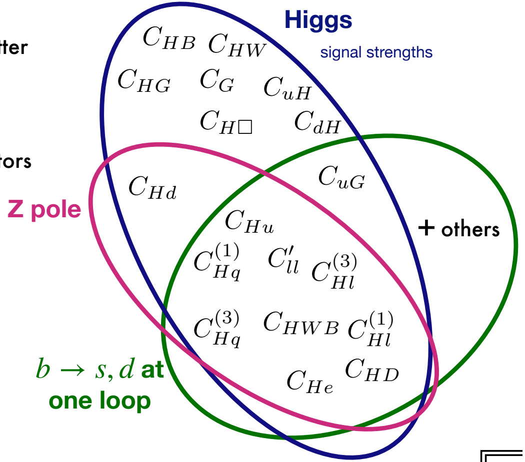
No connections to semileptonic operators *except*

$C_{lequ}^{(1)3333}$ runs into $C_{\tau H}$ which affects $H \to \tau\tau$

Feruglio, Paradisi, Sumensari 1806.10155

$C_{lequ}^{(1)3333}$ can produce $R_D^{(*)}$ but can't be the main source of the anomalies

e.g. Shi, Geng, Grinstein, Jäger, Camalich 1905.08498
Murgui, Peñuelas, Jung, Pich 1904.09311



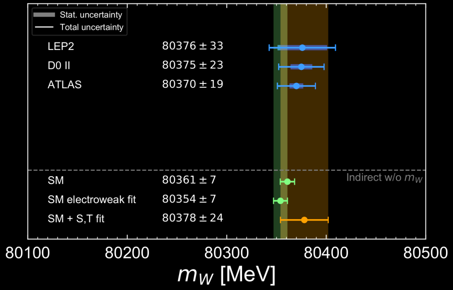
Aoude, Hurth, Renner, Shepherd 2003.05432

High-p_T measurements

- EW: *Z* decays
- Top observables
- Higgs observables
- EW: *W* mass

W mass

- Within SM, m_W related to other fundamental constants by
  $$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta)$$
- Δ term contains radiative corrections
  - Dominated by top and Higgs loops in SM
  - Sensitive to NP in loops
- Previous measurements from LEP, D0, CDF (not shown) and ATLAS consistent with SM prediction

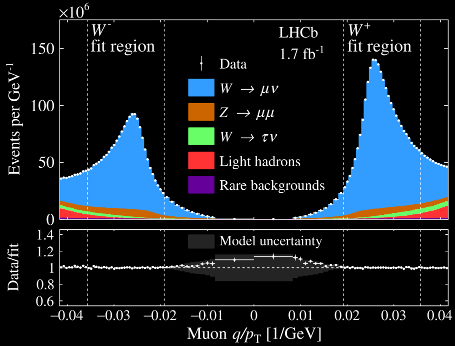


Adapted from arXiv:2204.05260

W mass: LHCb

JHEP **01** (2022) 036

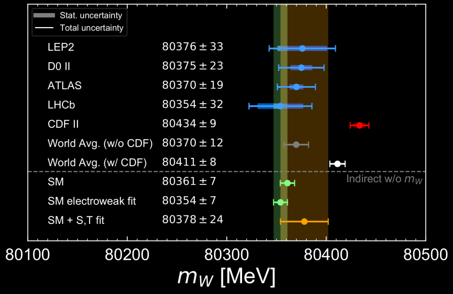
- LHCb unable to measure $\not{E}_T$ or use high-p_T electrons
  - Use p_T^{ℓ} method and muonic decays
- Extract M_W from simultaneous fit to q/p_T and (from Z candidates) $\phi^* \sim \frac{p_T^Z}{M}$
- Use NNPDF31_nlo_as_0118 PDF set
- Complementary coverage to GPDs
  - Expect reduced PDF uncertainties in combination
- Analysis of 2016 dataset yields
  $M_W = 80354 \pm 23(\text{stat.}) \pm 10(\text{exp.}) \pm 17(\text{theory}) \pm 9(\text{PDF})$
- Consistent with SM and previous measurements
- Analysis of full dataset ongoing



W mass: CDF

Science **376** (2022) 170-176

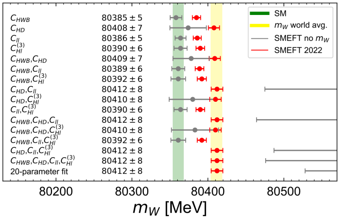
- Surprising updated W mass result from CDF
- $4\times$ data of 2012 result and many technical improvements
- 7σ tension with SM...
- but also 4σ tension with other experiments
- 47 MeV higher than previous CDF result but still consistent (2σ)
  - $\sim$ a third of this due to PDF and track reco changes



Adapted from arXiv:2204.05260

W mass

Bagnaschi & al., 2204.05260



New CDF measurement in disagreement with SM

CDF Collaboration, Science 376 (2022) 6589, 170-176

Good fit to *new world avg* with contributions to:

C_{HD} — most important ($\propto T$ parameter)

C_{ll}, $C_{Hl}^{(3)}$ — go into G_F via μ decay: need μ, e indices

C_{HWB}

Bagnaschi & al., 2204.05260
de Blas & al., 2204.04204

Can we connect the semileptonic operators responsible for the anomalies with any of these?

(my own back-of-the-envelope calculations)

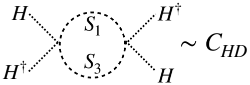
Start from $C_{lq}^{(3)\,33\mu\mu}$ to fit B anomalies → runs into $C_{Hl}^{(3)\mu\mu}$ and $C_{ll}^{\mu ee\mu}$ *but too small to fit m_W :(*

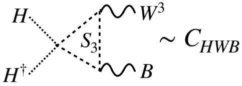
Start from $C_{Hl}^{(3)\mu\mu}$ to (partially) fit m_W → runs into $C_{lq}^{(3)\,33\mu\mu}$ *but too small to fit $R_{K^{(*)}}$:(*

BUT can be done in explicit models which generate more operators directly

e.g. model with S_1 and S_3 leptoquarks

Bhaskar, Madathil, Mandal, Mitra, 2204.09031





Questions & discussion points

Hard to link truly global fits and studies of the anomalies (& flavour in general):

How to include enough flavour structure & operator correlations
without too many parameters?

Loop level tensions can always be resolved/changed with extra tree level operators:
how to systematically deal with this in a flavourful theory?

Backup

Flavour and Higgs in Z pole flat directions

In the Wilson coeff space of Z pole data...

$$\{C_{HWB}, C_{HD}, C_{Hl}^{(1)}, C_{Hl}^{(3)}, C_{Hq}^{(1)}, C_{Hq}^{(3)}, C_{Hu}, C_{Hd}, C_{He}, C'_{ll}\}$$

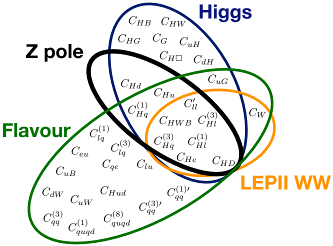
there are *two directions* that are unconstrained

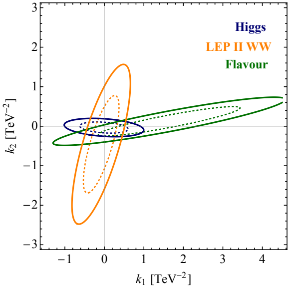
$$k_1 = 0.388\left(\frac{1}{3}C_{Hd} - 2C_{HD} + C_{He} + \frac{1}{2}C_{Hl}^{(1)} - \frac{1}{6}C_{Hq}^{(1)} - \frac{2}{3}C_{Hu}\right) + 0.22(C_{Hq}^{(3)} + C_{Hl}^{(3)}) + 0.895C_{HWB}$$

$$k_2 = -0.664(C_{Hq}^{(3)} + C_{Hl}^{(3)}) + 0.344C_{HWB}$$

Fit to this space of 10 coefficients and plot contours in the plane of the flat directions, profiling over the 8 orthogonal directions

[SMEFT predictions for Z pole observables from Brivio & Trott 1701.06424,
SMEFT predictions for LEPII WW from Berthier, Bjorn, Trott 1606.06693,
SMEFT predictions for Higgs signal strengths from Ellis, Murphy, Sanz, You 1803.03252]

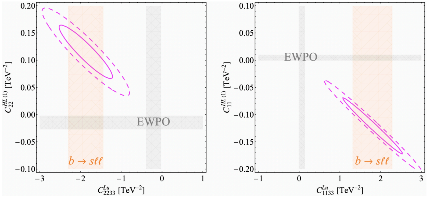




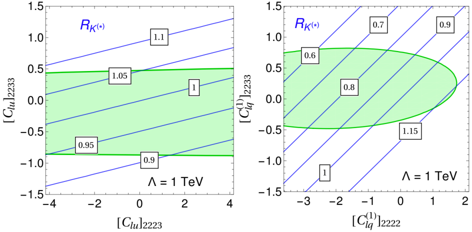
Aoude, Hurth, Renner, Shepherd 2003.05432

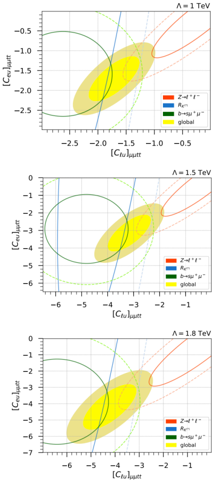
Z pole constraints vs $R_{K^{(*)}}$ at loop level

Alasfar, Azatov, de Blas, Paul , Valli 2007.04400



Coy, Frigiero, Mescia, Sumensari 1909.08567





Camargo-Molina, Celis, Faroughy 1805.04917