Probing B-Anomalies via Dimuon Tails at the FCC-hh

B. Garland[1]

in collabertation with: S. Jäger[1] C. K. Khosa[2] S. Kvedaraitė[3]

[1]Department of Physics and Astronomy, University of Sussex

[2]Dipartimento di Fisica, Università di Genova and INFN

[3]Department of Physics, University of Cincinnati

European Physical Society Conference on High Energy Physics
30$^{\text{th}}$ July 2021

B-Anomalies

Anomalies in semi-leptonic FCNC B-decays $b \to s l^+ l^-$:

- Lepton flavour universality (LFU) ratios R_K and R_{K^*}

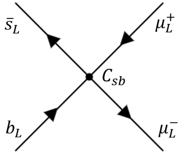
$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)} \bar{\mu}\mu)}{\mathrm{BR}(B \to K^{(*)} \bar{e}e)}$$

- Purely leptonic decays: $BR(B_S \to \bar{\mu}\mu)$.
- Angular observables of $B \to K \bar{\mu}\mu$.

Observable	Expt.	SM
R_K $[1.1, 6]$ GeV^2	0.846 ± 0.044	$1.000^{+0.0008}_{-0.0007}$
R_K^* $[0.045, 1.1]$ GeV^2	0.66 ± 0.12	$0.920^{+0.0007}_{-0.0006}$
R_K^* $[1.1, 6]$ GeV^2	0.685 ± 0.12	$0.9960^{+0.0002}_{-0.0002}$
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	$(3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$	$(2.63 \pm 0.13) \times 10^{-9}$

Theoretically Clean Fit

- The anomalies in $b \to sl^+l^-$ are well explained by a **4-fermion contact interaction**:



$$\frac{1}{\Lambda^2}(\bar{s}_L\gamma^\nu b_L)(\bar{\mu}_L\gamma_\nu\mu_L).$$

Coeff.	best fit	$\chi^2_{\min}$	p-value	SM exclusion [σ]	1σ range
δC_9^μ	-0.82	14.70 [6 dof]	0.02	4.08	$[-1.06, -0.60]$
δC_{10}^μ	0.65	6.52 [6 dof]	0.37	4.98	$[0.52, 0.80]$
δC_L^μ	-0.40	7.36 [6 dof]	0.29	4.89	$[-0.48, -0.31]$
$(\delta C_9^\mu, \delta C_{10}^\mu)$	$(-0.11, 0.59)$	6.38 [5 dof]	0.27	4.62	$\delta C_9^\mu \in [-0.41, 0.17]$

- **Best fit** value [Geng et al. 21]

$$\Lambda = 40.3^{+5.5}_{-3.5} \quad \text{TeV}.$$

- We can view the $bs\mu\mu$ contact interaction within the context of **SMEFT**:

$$\mathcal{L}^{\text{SMEFT}} = \mathcal{L}^{SM} + \sum_n c_n^{(6)} \mathcal{O}_n^{(6)} + \sum_m c_m^{(8)} \mathcal{O}_m^{(8)} + \cdots .$$

- **Dim-6** operators relevant for $(\bar{L}L)(\bar{L}L)$ $bs\mu\mu$:

$$\mathcal{L}^{\text{SMEFT}} \supset C^{(3)}_{Q_{ij}L_{22}} (\bar{Q}_i \gamma_\rho \sigma^a Q_j)(\bar{L}_2 \gamma^\rho \sigma_a L_2) + C^{(1)}_{Q_{ij}L_{22}} (\bar{Q}_i \gamma_\rho Q_j)(\bar{L}_2 \gamma^\rho L_2).$$

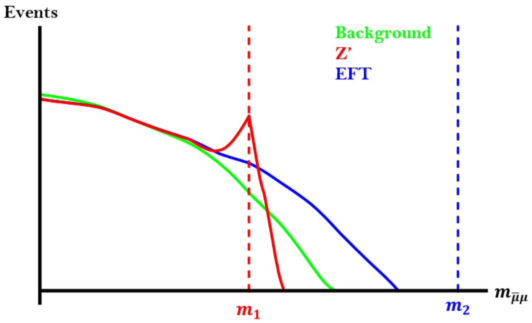
- Change of **coefficient basis**:

$$\mathcal{L}^{\text{SMEFT}} \supset \begin{array}{l} \boxed{C^+_{ij} (\bar{d}^i_L \gamma_\rho d^j_L)\, (\bar{\mu}_L \gamma^\rho \mu_L)} + V_{ik} C^+_{kl} V^*_{jl} (\bar{u}^i_L \gamma_\rho u^j_L)(\bar{\nu}_\mu \gamma^\rho \nu_\mu) \\ C^-_{ij} (\bar{d}^i_L \gamma_\rho d^j_L)\, (\bar{\nu}_\mu \gamma^\rho \nu_\mu) + V_{ik} C^-_{kl} V^*_{jl} (\bar{u}^i_L \gamma_\rho u^j_L)(\bar{\mu}_L \gamma^\rho \mu_L) \end{array} .$$

- A non-zero C^+_{sb} only generates a contact interaction involving muons with b and s quarks.

Probing Contact Interactions at a *pp*-Collider

- The EFT offers a **model-independent** framework to probe the B-anomalies.
- Investigate the **tails** of dimuon invariant mass distributions.
- Simplified models include (Z' and Leptoquark) [Allanch et al. 18, 19, 20]



- **CI Studies at the LHC:** Phenomenological [Greljo, Marzocca 17, Afik et al. 18] & experimental [CERN-EP-2021-065] studies can exclude $\Lambda \sim 2 - 8$ TeV at 95% C.L.
- What can we do with higher a c.o.m energy? Use proposed **FCC-hh** as a baseline.

Analysis Set-Up

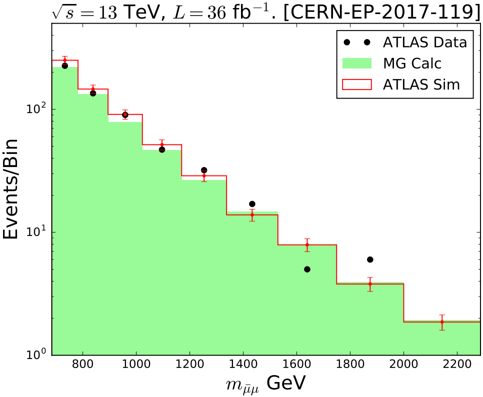
- **Inclusive dimuon** final state.
- Dominant SM background is **Drell-Yan**.
- Calculated cross-section at NLO-QCD+EW for both the EFT signal and SM background processes using MadGraph5_aMC@NLO v3.
- **NLO Signal:** UFO model with SM + EFT operators (R_2 terms needed!)

- Cuts on muons:

$$p_T > \frac{\sqrt{s}}{250} \quad |\eta| < 2.5$$

$$m_{\bar{\mu}\mu}^{\min} > \frac{\sqrt{s}}{20}.$$

- PDF: NNPDF31_luxqed
- 5 Flavour Scheme.



Statistics & Significance Calculation

- We perform two **statistical tests**:
  - **Exclusion Limits**: Test the BG+Signal Hypothesis against BG only.
  - **Discovery**: Test the BG only Hypothesis against BG+EFT Signal.

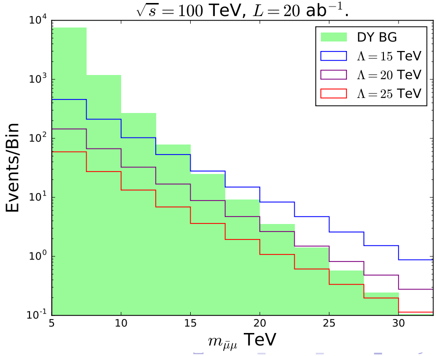
- To calculate the significance, we follow the methods detailed in [Cowan et al. 10] and construct a **profile likelihood ratio** from a binned histogram.

- **Binning Scheme:** We consider interval $\left[m_{\bar{\mu}\mu}^{\min}, m_{\bar{\mu}\mu}^{\max}\right]$ with bin size $\Delta m_{\bar{\mu}\mu}$.

- For collider c.o.m energy $\sqrt{s}$:

$$m_{\bar{\mu}\mu}^{\min} = \frac{\sqrt{s}}{20} \qquad \Delta m_{\bar{\mu}\mu} = \frac{\sqrt{s}}{40}.$$

- What abut $m_{\bar{\mu}\mu}^{\max}$?



$m_{\bar{\mu}\mu}^{\max}$ & the Validity of the EFT

- The value of $m_{\bar{\mu}\mu}^{\max}$ **cannot** be taken to be arbitrarily large!
- Most universal & conservative constraint: **Tree-level unitarity** requires [Di Luzio, Nardecchia 17]

$$m_{\bar{\mu}\mu} < \sqrt{\frac{4\pi}{\sqrt{3}}}\Lambda.$$

- **Simplified models:** unitary bound is reached sooner.
- Example: simplified Z' model:

$$m_{\bar{\mu}\mu} < m_{Z'} < \sqrt{\frac{2\pi}{\sqrt{3}}}\Lambda.$$

- As $m_{\bar{\mu}\mu} \to m_{Z'}$ operators $\mathcal{O}$ in the SMEFT with $\dim \mathcal{O} > 6$ **become relevant**.
- We give all limits as function of $m_{\bar{\mu}\mu}^{\max}$.

Results

Bounds at the LHC: $\sqrt{s} = 13$ TeV

- **Collider recast [CERN-EP-2017-119]:** 95% C.L. exclusion for C_{sb} [Greljo, Marzocca 17]:

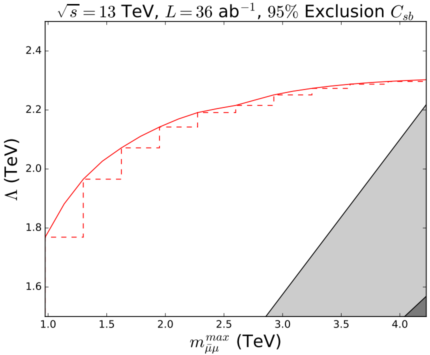
$$\Lambda < 2.6 \text{ TeV } (36 \text{ fb}^{-1}) \;\&\; \Lambda < 4.1^{*} \text{ TeV } (3000 \text{ fb}^{-1}).$$

- **NLO-QCD+EW results:**

$$\Lambda < 2.3 \text{ TeV } (36 \text{ fb}^{-1})$$

$$\Lambda < 4.2^{*} \text{ TeV } (3000 \text{ fb}^{-1})$$

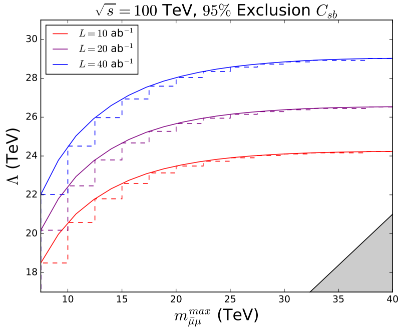
- NLO gives a **reduction** $\sim 10\%$ in the cross section of some bins. Large negative double Sudakov logarithms.

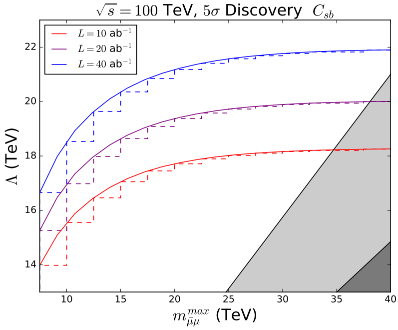


* *We calculate 95% C.L. exclusion at LO to be* $\Lambda < 4.7$ *TeV* $(3000\ fb^{-1})$

Bounds & Discovery at the FCC-hh: $\sqrt{s} = 100$ TeV

FFC-hh: $\sqrt{s} = 100$ TeV and lifetime integrate lumi of ~ 20 ab^{-1} [FCC CDR V3].





Illustrative numbers:

	Λ (TeV)		
L (ab^{-1})	95% CL	3σ	5σ
10	24.1	20.8	18.1
40	28.9	24.9	21.8

Beyond the FCC-hh (95% Exclusion)

What if we can increase the **luminosity** L at $\sqrt{s} = 100$ TeV?

- 95% Exclusion of $\Lambda' \sim 40$ TeV one needs:

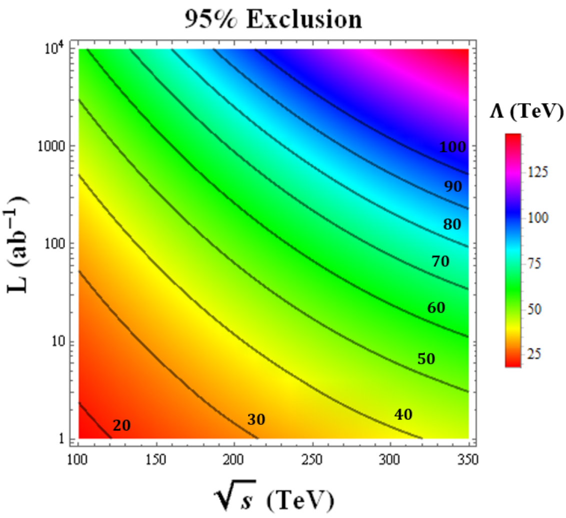
  $L' \sim 500\ \text{ab}^{-1}$.

What if we can increase the **c.o.m energy** $\sqrt{s}$ $L = 10$ and $L = 40\ \text{ab}^{-1}$?

- 95% Exclusion of $\Lambda' \sim 40$ TeV one needs:

  $\sqrt{s} \sim 220$ TeV with $L = 10\ \text{ab}^{-1}$,

  $\sqrt{s} \sim 150$ TeV with $L = 40\ \text{ab}^{-1}$.



Summary & Conclusions

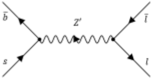
- Motivated by B-Anomalies, we have presented the prospects for a contact interaction search at $\sqrt{s} = 13$ Tev, 100 TeV and beyond.
- We improved on current LHC limits by including NLO corrections and addressing EFT validity.
- We provide 95% exclusion limits of our EFT signal along with $3, 5\,\sigma$ rejection of SM background at the FCC-hh.
- At a $\sqrt{s} = 100$ TeV, we can exclude values of Λ close to those that give a good fit for the B-Anomalies.
- Scales of $\Lambda > 40$ TeV can be probed with a higher c.o.m energy and luminosity.

Thank you for your attention!

Back-up Slides

Back-up: EFT Validity - An Example

- Simplified Z' model with mass $m_{Z'}$.
- Weakest constraint comes from perturbative-unitarity TeV $m_{z'} < \sqrt{\frac{2\pi}{\sqrt{3}}}\Lambda$. [Di Luzio, Nardecchia 17].
- Tree-level amplitude:



$$= \frac{ig}{p^2 - m_{Z'}^2}\bar{b}(p_1)\gamma^\mu s(p_2)\bar{\mu}(p_3)\gamma_\mu \mu(p_4)$$

where $g = g_{bs}g_{\mu\mu}$.

- Expanding in powers of p^2

$$\frac{ig}{p^2 - m_Z^2} = -\frac{ig}{m_{Z'}^2} - \frac{igp^2}{m_{Z'}^4} - \frac{igp^4}{m_{Z'}^6} + \mathcal{O}\left(\frac{p^6}{m_{Z'}^8}\right).$$

- Matching to EFT expansion, i.e. $g/m_{Z'}^2 = 1/\Lambda^2$,

$$p < \sqrt{g}\Lambda.$$

Back-up: Statistics

- Let N be the number of bins.
- Expected discovery significance $E[Z_0]$ is given by

$$E[Z_0] = \sqrt{-2\left[\sum_{j=1}^{N}\left(s_j + (b_j + s_j)\ln\left(\frac{b_j}{b_j + s_j}\right)\right)\right]}.$$

  An expected discovery at the $n\sigma$ level corresponds to $E[Z_e] = n$.
- Expected signal exclusion significance $E[Z_e]$ is given by

$$E[Z_e] = \sqrt{2\left[\sum_{j=1}^{N}\left(s_j + b_j\ln\left(\frac{b_j}{b_j + s_j}\right)\right)\right]}.$$

  An expected exclusion at 95% CL corresponds to $E[Z_e] = 1.64$.