Probing B-anomalies via dimuon tails at a future collider

Sebastian Jäger (University of Sussex)

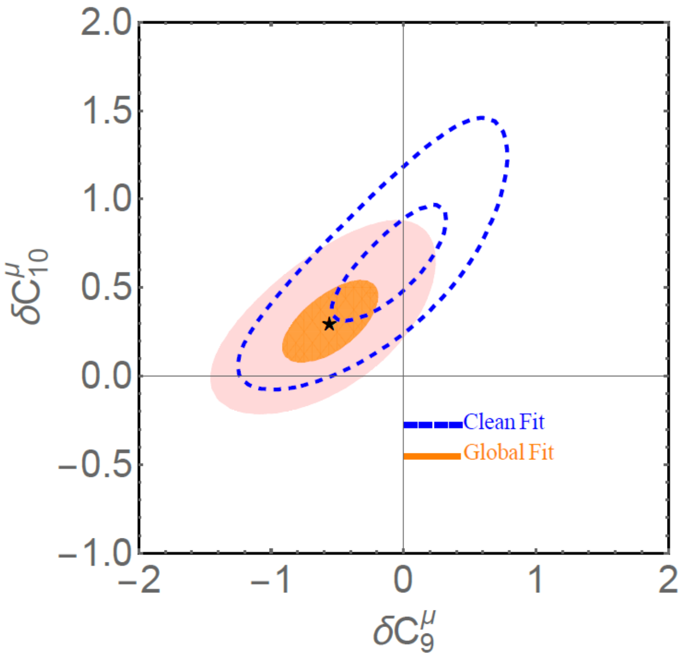
FCC Physics Workshop Liverpool

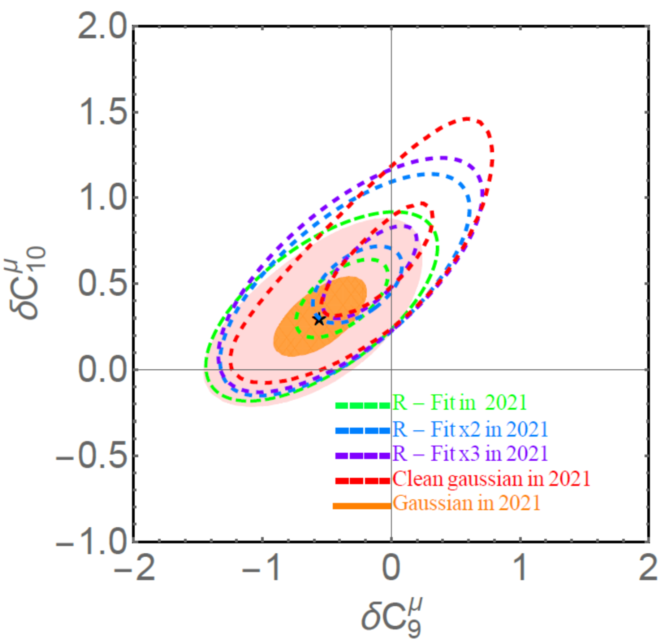
Liverpool, 08 February 2022 (online)

Base on work in collaboration with B Garland, C Kaur, S Kvedaraite
arXiv:2112.05127

Rare B-decay anomaly summary

Geng, Grinstein, SJ, Li, Martin Camalich, Shi arXiv:2103.12738





$$\mathcal{L}_{\rm eff} \supset \frac{1}{\Lambda^2}\left(\bar{b}_L \gamma_\mu s_L\right)\left(\bar{\mu}_L \gamma^\mu \mu_L\right)$$

$$\Lambda = (39 \pm 4)\mathrm{TeV}$$

Very similar results in other studies (2103.13370, 2104.08921, 2104.10058)

Robust against variation of dataset (cf figures) and against allowing additional contact interactions in the fit

Scale of new physics

Di Luzio, Nardecchia 2017

The rare B-decay anomalies point to (at least) the interaction

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

Numerically $\Lambda \sim 40$ TeV [for current data]

For a tree-level mediator,

$M_{NP} = g_{NP}\,\Lambda \leq 4\pi\,\Lambda$. Can be up to ~400 TeV

Partial-wave unitarity more stringent: maximal NP scale around 100 TeV.

If the NP is less than maximally flavour-violating, or the NP is weakly coupled, the scale will be 1-2 orders of magnitudes lower.

Collider implications

The LHC and future colliders can search for the UV physics causing the minimal contact interactions.

a) direct searches for the mediator(s)

eg Allanach et al 1710.06363, 1810.02166, 1904.10954 (Z’)
eg Bar-Shalom et al 1812.03178; Allanach et al 1911.04455,
Hiller et al 2103.12724 (leptoquark)

necessarily model-dependent; may be out of reach

b) contact interaction searches

eg Greljo et al 1704.09015, Afik et al 1805.11402 (LHC)

Can, in principle, probe beyond the direct search reach (with sufficient lumi)

LHC can probe up to a few TeV (with 3000 fb^{-1})
No FCC study prior to our work

Here: inclusive dimuon search at future colliders – FCC as baseline

Signal model - SMEFT

We can choose a SMEFT basis for LLLL operators such that

$$\mathcal{L}^{\rm SMEFT} \supset C^{+}_{ij}(\bar{d}^{\,j}_{L}\gamma_\rho\, d^{i}_{L})\,(\bar{\mu}_L\gamma^\rho\mu_L)\ + C^{-}_{ij}(\bar{d}^{\,j}_{L}\gamma_\rho\, d^{i}_{L})\,(\bar{\nu}_\mu\gamma^\rho\nu_\mu)\ + \\ \sum_{k,l} V^{*}_{ki}C^{+}_{ij}V_{lj}(\bar{u}^{\,l}_{L}\gamma_\rho u^{k}_{L})(\bar{\nu}_\mu\gamma^\rho\nu_\mu)\ + \sum_{k,l} V^{*}_{ki}C^{-}_{ij}V_{lj}(\bar{u}^{\,l}_{L}\gamma_\rho u^{k}_{L})(\bar{\mu}_L\gamma^\rho\mu_L)$$

Then the minimal signal model required by the B-anomalies is

$$C^{+} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & C^{+}_{sb} \\ 0 & C^{+*}_{sb} & 0 \end{pmatrix} \qquad C^{-} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad C^{+}_{sb} = \frac{1}{\Lambda^2} \qquad \Lambda = (39 \pm 4)\,\mathrm{TeV}$$

Conservative: any additional nonzero coefficients beyond those directly implied by B-physics **add** to the collider signal. Hence,

$$\mathcal{L}^{\rm SMEFT} \supset\ C^{+}_{sb}(\bar{b}_L\gamma_\rho\, s_L)\,(\bar{\mu}_L\gamma^\rho\mu_L)\ + \sum_{k,l} V^{*}_{ks}C^{+}_{sb}V_{lb}(\bar{u}^{\,l}_{L}\gamma_\rho u^{k}_{L})(\bar{\nu}_\mu\gamma^\rho\nu_\mu)\ + \mathrm{h.c.}$$

Note that the minimal dimuon signal **does not** receive any contributions from SU(2) doublet partners (up-type quarks)

Setup

- Inclusive dimuon signal due to the minimal contact interactions

- Simulate the relevant backgrounds

  DY: MadGraph5_aMC@NLO, NLO QCD + EW fixed order
  top (inc. tW): MadGraph5_aMC@NLO, LO contributions
  diboson: MadGraph5_aMC@NLO, LO contributions

  using NNPDF31_NLO_AS_0118_LUXQED PDF via LHAPDF6,
  5-flavour scheme (4-flavour for top)

  as well as the signal

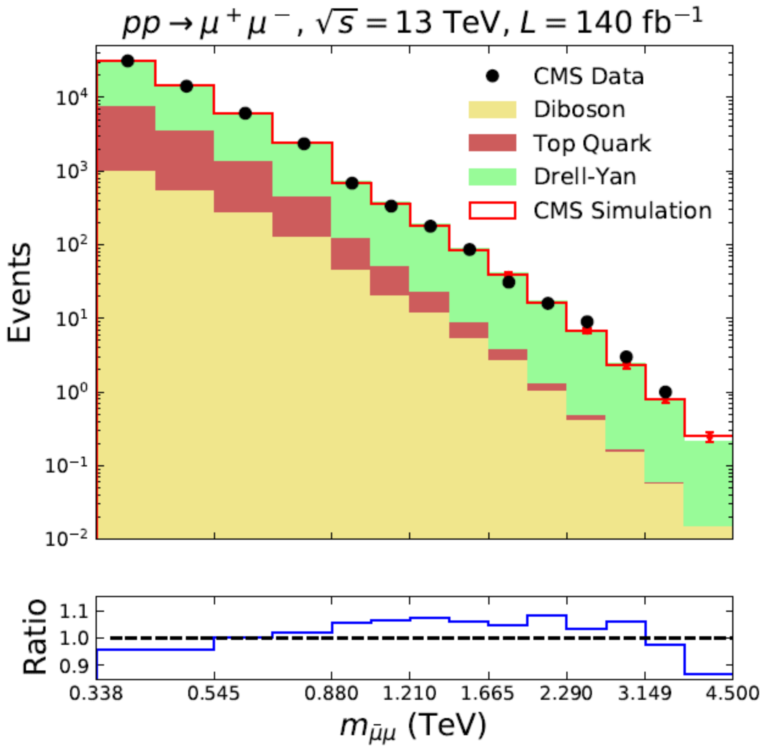
- Validate against published ATLAS (arXiv:2006.12946) & CMS (arXiv:2103.02708) simulations (and data) at 13 and 14 TeV

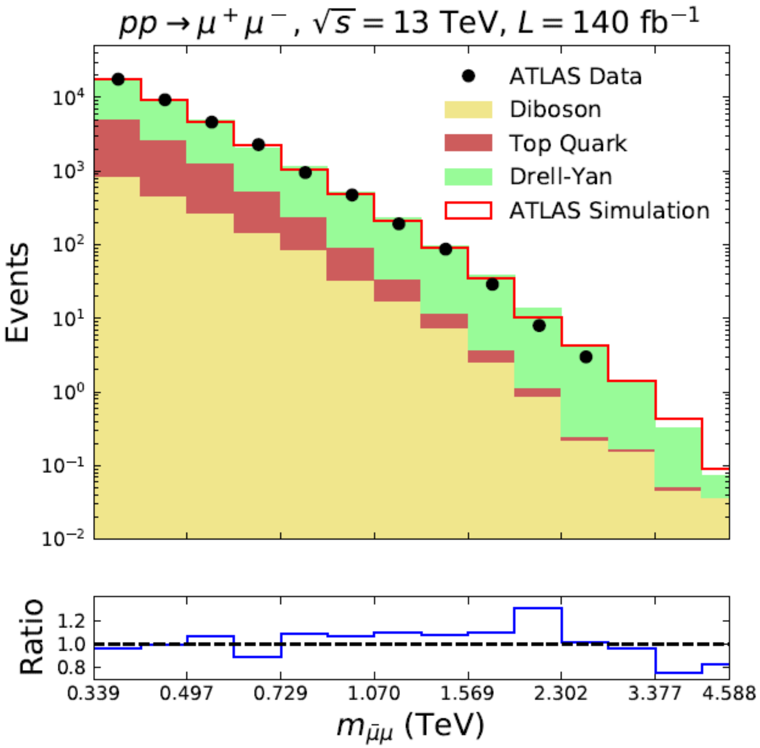
- Optimized binning scheme to maximize sensitivity (as a function of upper dimuon mass cut)

- Obtain exclusion and discovery reach for LHC and FCC

Validation – LHC energies

Garland, SJ, Kaur, Kvedaraite, arXiv:2112.05127

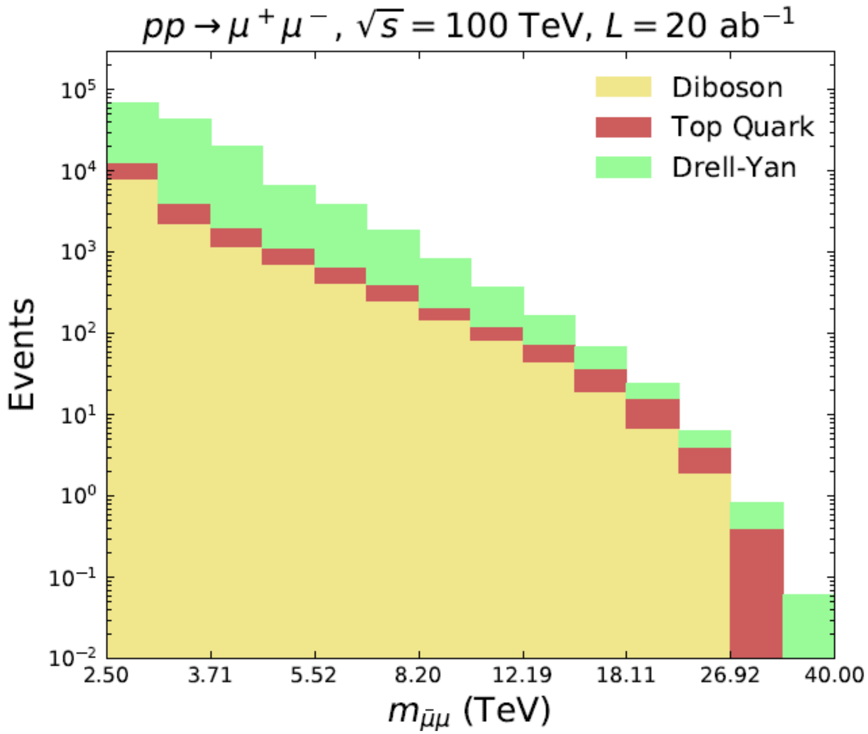




Our background simulation closely tracks the simulations performed by ATLAS and CMS

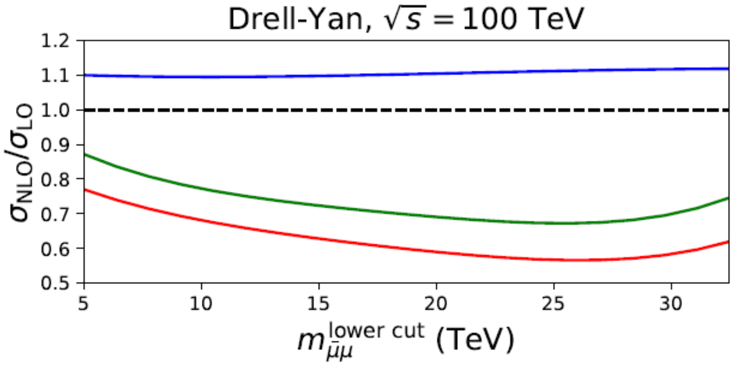
– gives confidence for our 100 TeV background simulation

Predicted background – FCC-hh



100 TeV background simulation

Garland, SJ, Kaur, Kvedaraite, arXiv:2112.05127



Relative size of NLO corrections

red – QCD
blue – EW
green – total

Event selection & significance

Consider an interval

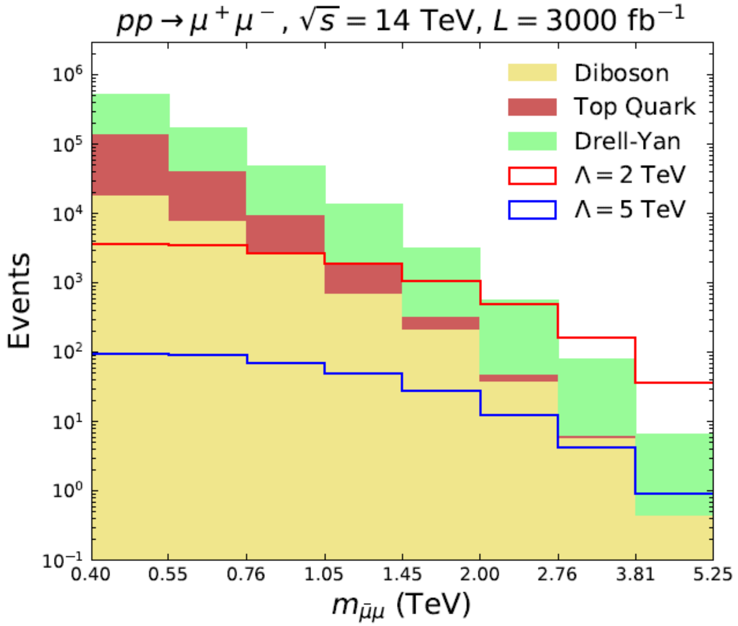
$$\left[m_{\bar{\mu}\mu}^{\min}, m_{\bar{\mu}\mu}^{\max}\right]$$

(plus further selection cuts, see paper for details)

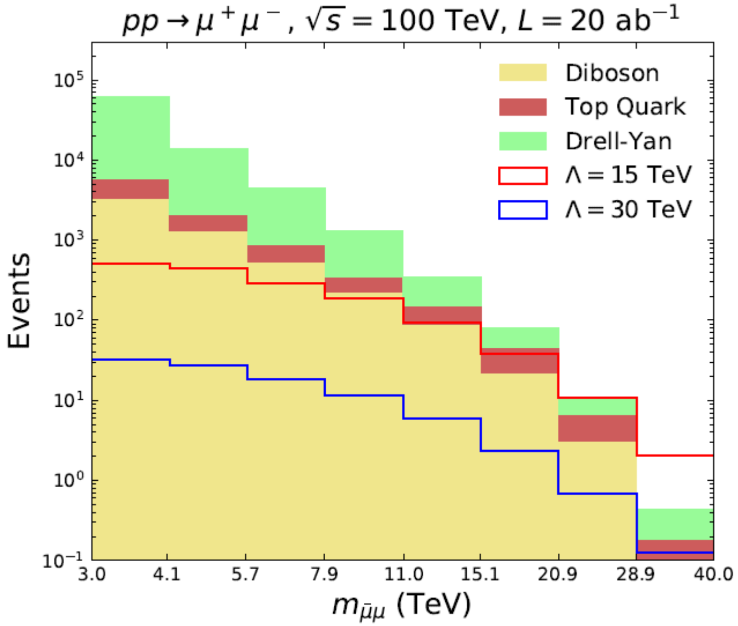
Divide into 8 bins of increasing size; calculate expected significance & exlusion limits a la Cowan et al (arXiv:1007.1727)

Binned signal vs background – LHC & FCC-hh

Garland, SJ, Kaur, Kvedaraite, arXiv:2112.05127



LHC



FCC-hh

Bounds & EFT validity

Event selection is limited by consistency of EFT

Perturbative unitarity in the EFT

$$m_{\bar\mu\mu} < \sqrt{\frac{4\pi}{\sqrt{3}}}\Lambda \equiv \Lambda_*$$

(Note that within a UV completion, the bound is generically stronger, eg in Z' models $m_{\bar\mu\mu} < m_{Z'} < \sqrt{\frac{2\pi}{\sqrt{3}}}\Lambda$)

Validity of the EFT expansion: model-dependent

e.g. for tree-level s-channel mediator (Z') one requires

$$m_{\mu\mu} < M_{Z'}$$

for t-channel mediator this is sufficient, but conservative

We present our bounds for specific dimuon mass values, or as a function of $m_{\mu\mu}$

LHC sensitivity

Garland, SJ, Kaur, Kvedaraite, arXiv:2112.05127

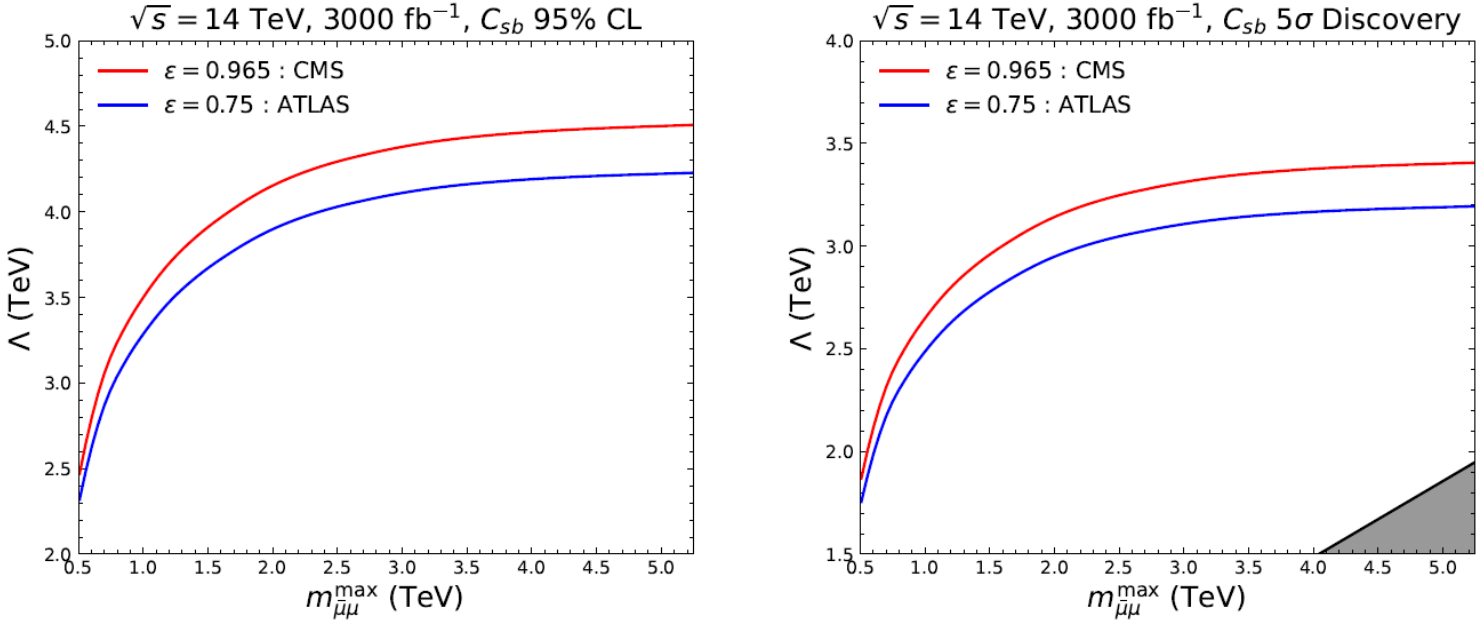
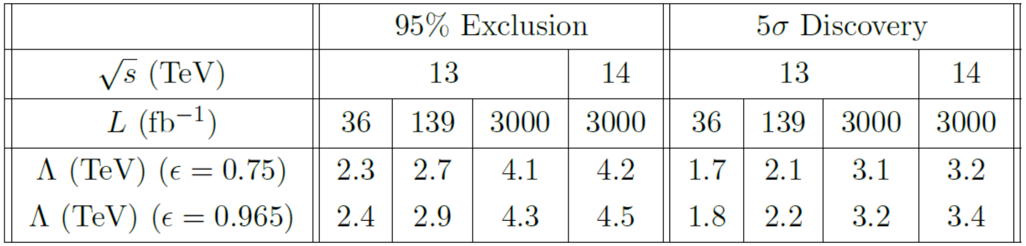


Figure 6: 95% exclusion limits and 5σ discovery sensitivities for Λ as a function of $m_{\bar{\mu}\mu}^{\max}$ at the $\sqrt{s} = 14$ TeV HL-LHC using $L = 3000$ fb^{-1}. The dark grey shaded region highlights the region in which tree-level unitary of the EFT is violated (see Eq. 3.8).



	95% Exclusion				5σ Discovery			
$\sqrt{s}$ (TeV)	13			14	13			14
L (fb^{-1})	36	139	3000	3000	36	139	3000	3000
Λ (TeV) ($\epsilon = 0.75$)	2.3	2.7	4.1	4.2	1.7	2.1	3.1	3.2
Λ (TeV) ($\epsilon = 0.965$)	2.4	2.9	4.3	4.5	1.8	2.2	3.2	3.4

FCC-hh sensitivity

Garland, SJ, Kaur, Kvedaraite, arXiv:2112.05127

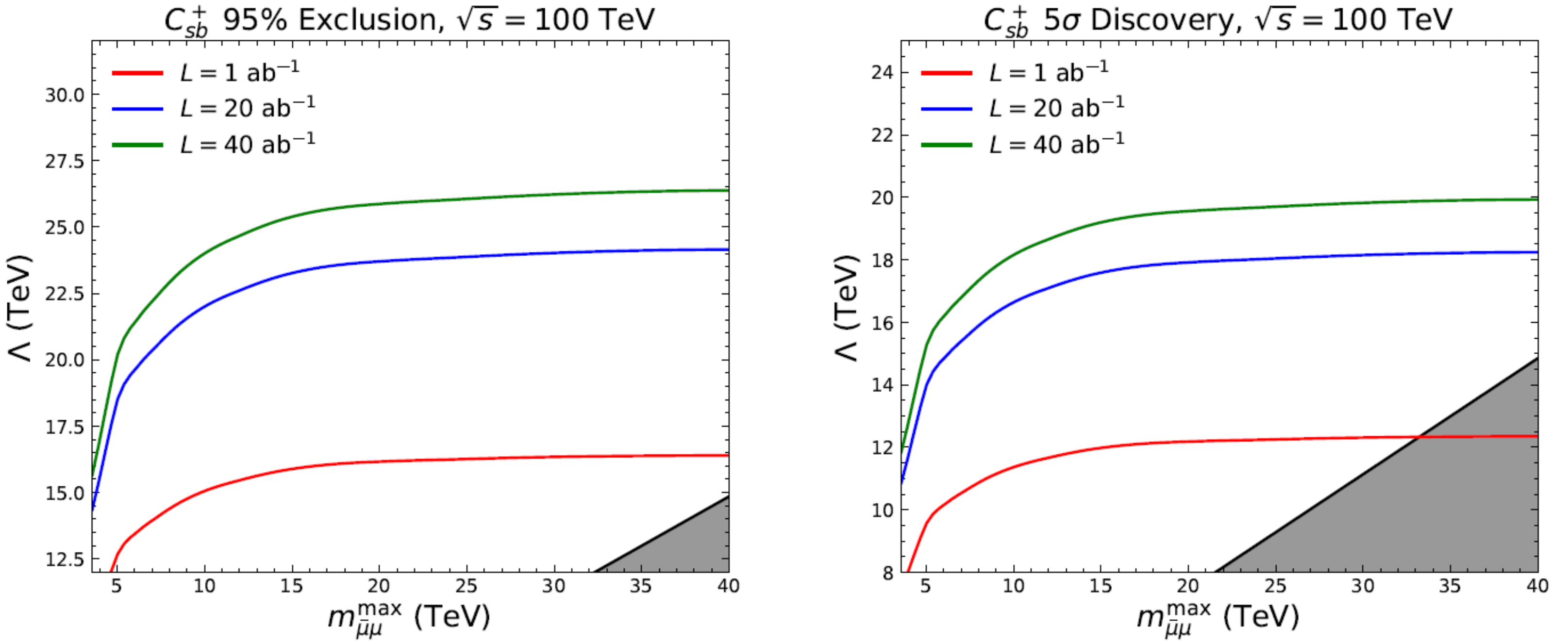
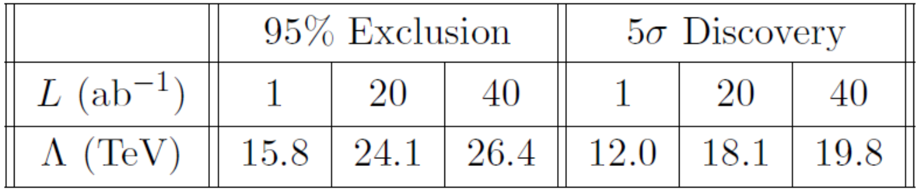


Figure 7: 95% exclusion limits and 5σ discovery sensitivities as a function of $m_{\bar{\mu}\mu}^{\max}$ at $\sqrt{s} = 100$ TeV. We plot these limits for three benchmark values of the luminosities, i.e., $L = \{1, 20, 40\}$ ab^{-1}. The dark grey shaded region highlights the region in which tree-level unitary of the EFT is violated (see Eq. 3.8).



	95% Exclusion			5σ Discovery		
L (ab^{-1})	1	20	40	1	20	40
Λ (TeV)	15.8	24.1	26.4	12.0	18.1	19.8

How much lumi to be sensitive?

Garland, SJ, Kaur, Kvedaraite, arXiv:2112.05127

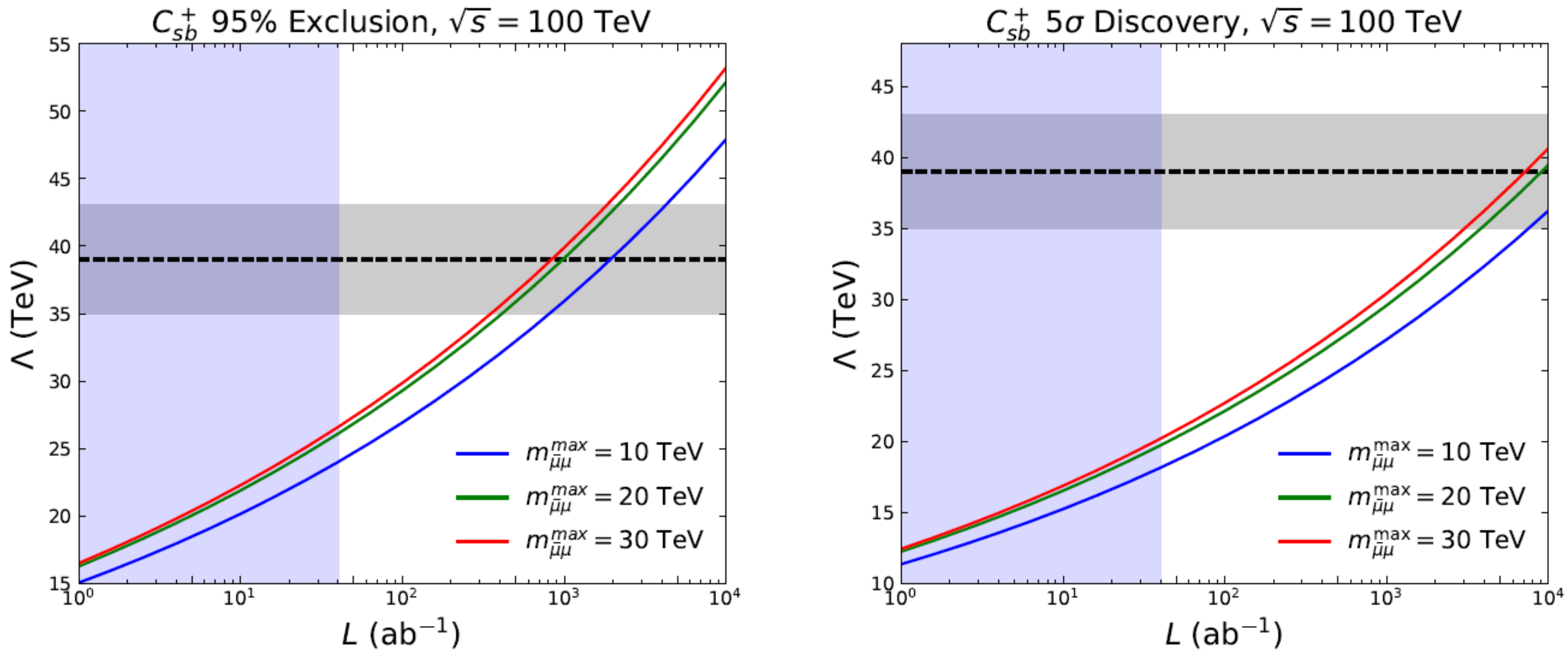


Figure 8: 95% exclusion limits and 5σ discovery sensitivities for Λ as a function of total integrated luminosity L at $\sqrt{s} = 100$ TeV. We consider three values of $m_{\bar{\mu}\mu}^{\max}$. The blue shaded region signifies $L \leq 40$ ab^{-1} the design luminosity of the FCC-hh. The dashed black line corresponds to $\Lambda = 39$ TeV with the grey shaded region corresponding to the uncertainty in Eq. 1.4.

Reach as a function of collider parameters

Garland, SJ, Kaur, Kvedaraite, arXiv:2112.05127

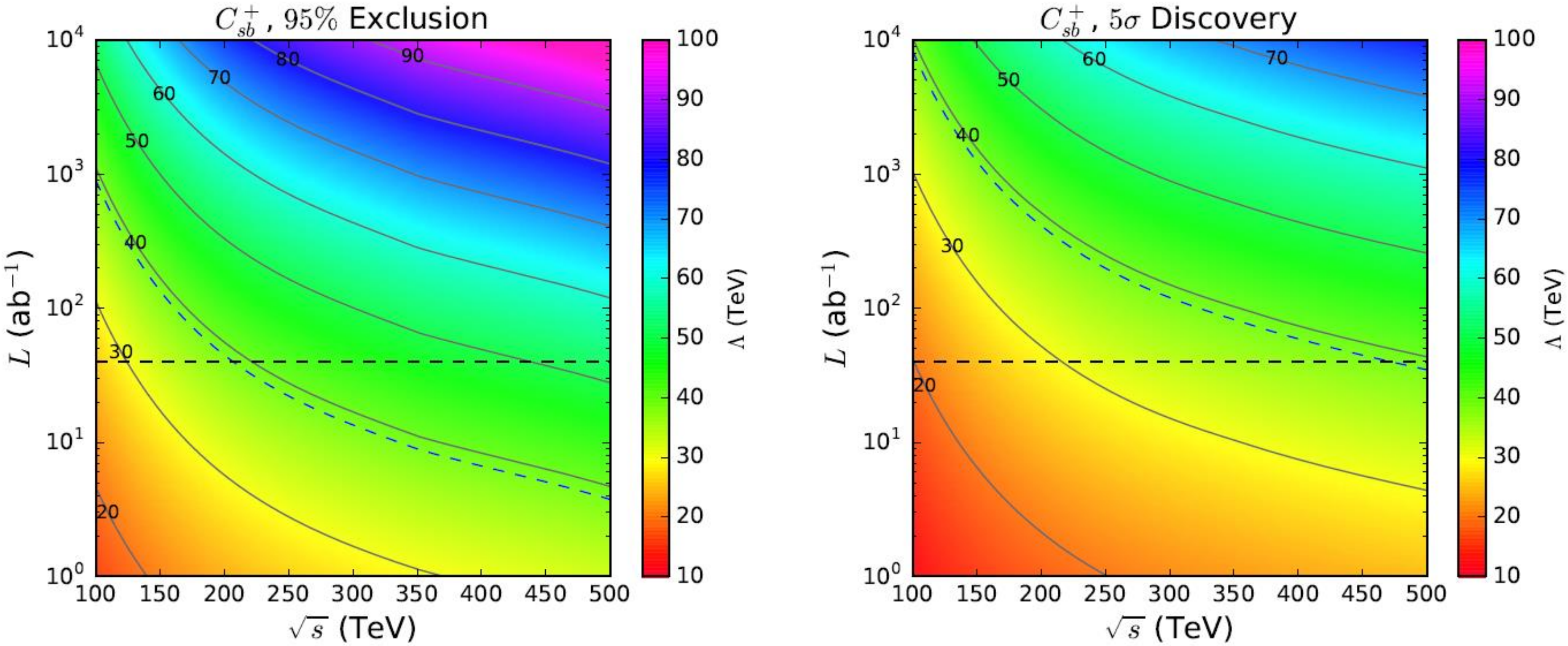


Figure 10: 95% exclusion limits and 5σ discovery sensitivities for Λ as a function of both collider c.o.m energy $\sqrt{s}$ and luminosity $L = 40$ ab^{-1}. Here $m^{\text{max}}_{\bar{\mu}\mu}$ is set to the tree level unitarity limit in Eq. 3.8. The horizontal black dashed line gives the maximal design luminosity at the FCC-hh. The blue dashed contour corresponds to $\Lambda = 39$ TeV, the current value of Λ suggested by the B-anomalies.

Summary

Rare B-decay anomalies provide a well-defined minimal BSM signal and a potential no-lose case for a future collider

Performed an NLO Monte Carlo simulation for a range of collider energies and luminosities, including validation against ATLAS/CMS simulations

An inclusive dimuon search FCC can exclude (discover) the minimal interaction up to scales of ~ 26 TeV (20 TeV) (compared to ~ 4 TeV (~ 3 TeV) at the LHC)

A machine with higher energy and/or luminosity can in principle probe the experimentally suggested value ~ 40 TeV

May be ablet to improve sensitivity with more complex final states – more work needed to quantify

BACKUP

How much energy for sensitivity?

Garland, SJ, Kaur, Kvedaraite, arXiv:2112.05127

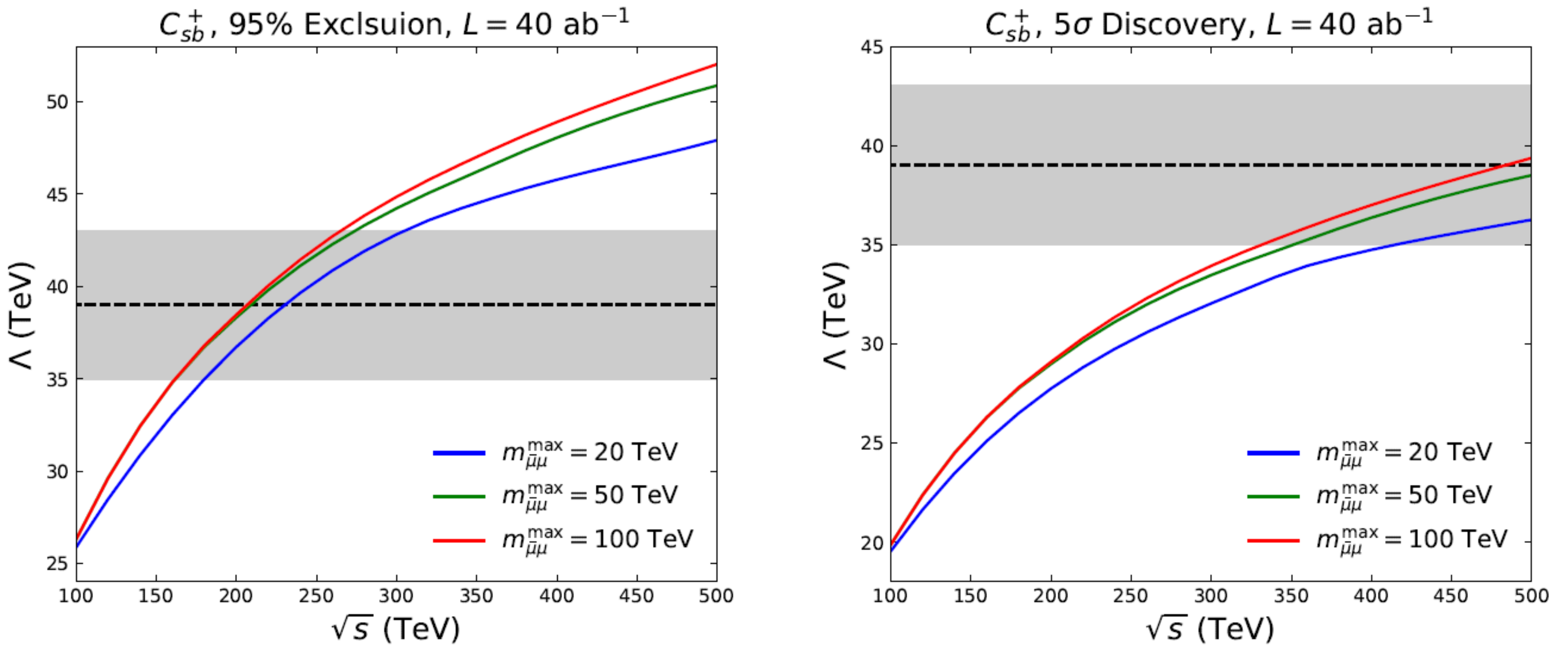
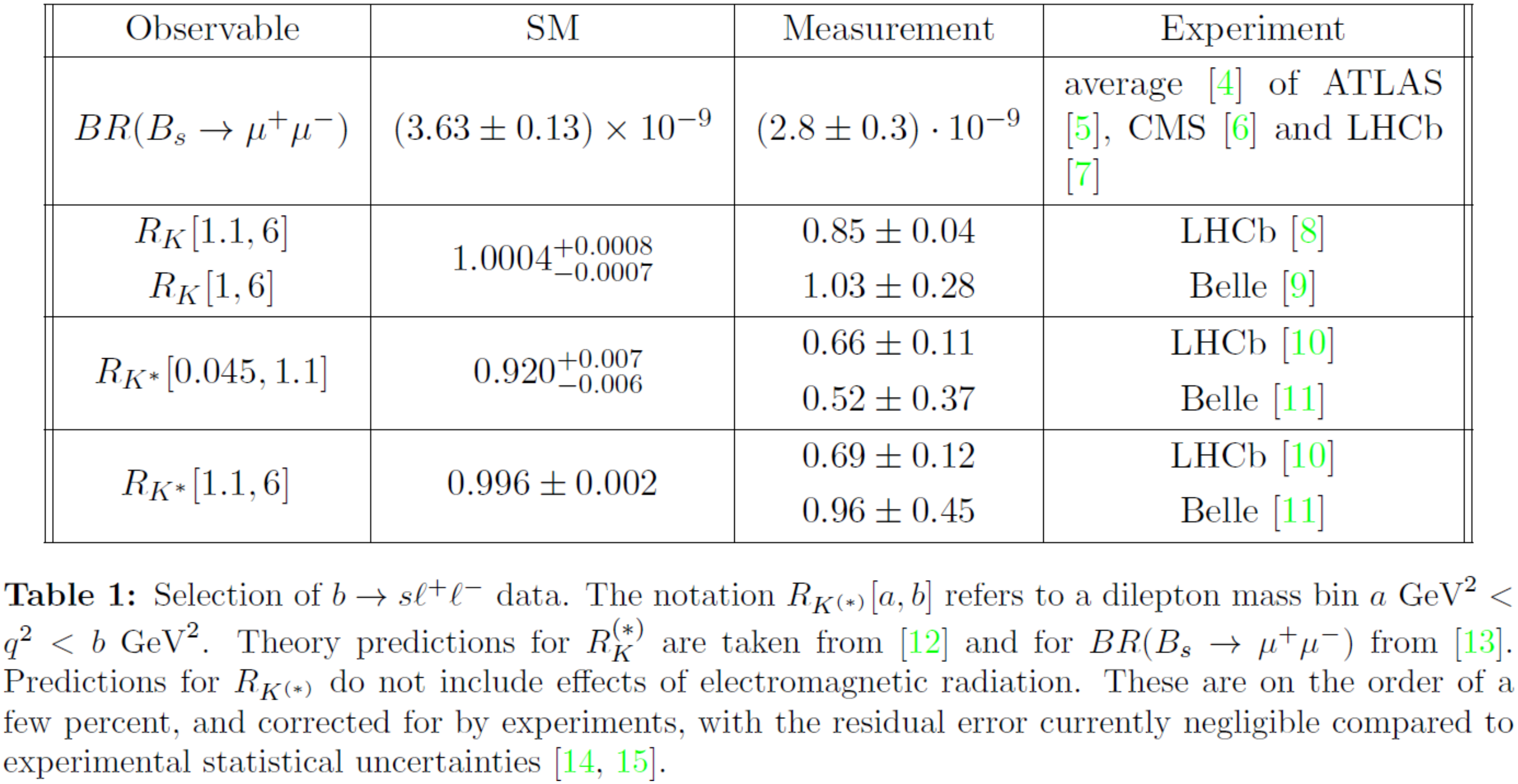


Figure 9: 95% exclusion limits and 5σ discovery sensitivities for Λ as a function of collider c.o.m energy $\sqrt{s}$ with $L = 40$ ab^{-1}. We consider three values of $m_{\bar\mu\mu}^{\max}$. The dashed black line corresponds to $\Lambda = 39$ TeV with the grey shaded region corresponding to the uncertainty in Eq. 1.4.

Selection of rare B decay anomalies



Observable	SM	Measurement	Experiment
$BR(B_s \to \mu^+\mu^-)$	$(3.63 \pm 0.13) \times 10^{-9}$	$(2.8 \pm 0.3) \cdot 10^{-9}$	average [4] of ATLAS [5], CMS [6] and LHCb [7]
$R_K[1.1, 6]$	$1.0004^{+0.0008}_{-0.0007}$	0.85 ± 0.04	LHCb [8]
$R_K[1, 6]$		1.03 ± 0.28	Belle [9]
$R_{K^*}[0.045, 1.1]$	$0.920^{+0.007}_{-0.006}$	0.66 ± 0.11	LHCb [10]
		0.52 ± 0.37	Belle [11]
$R_{K^*}[1.1, 6]$	0.996 ± 0.002	0.69 ± 0.12	LHCb [10]
		0.96 ± 0.45	Belle [11]

Table 1: Selection of $b \to s\ell^+\ell^-$ data. The notation $R_{K^{(*)}}[a, b]$ refers to a dilepton mass bin a GeV$^2 < q^2 < b$ GeV^2. Theory predictions for $R_K^{(*)}$ are taken from [12] and for $BR(B_s \to \mu^+\mu^-)$ from [13]. Predictions for $R_{K^{(*)}}$ do not include effects of electromagnetic radiation. These are on the order of a few percent, and corrected for by experiments, with the residual error currently negligible compared to experimental statistical uncertainties [14, 15].

Size of NLO – BG & signal

Garland, SJ, Kaur, Kvedaraite, arXiv:2112.05127

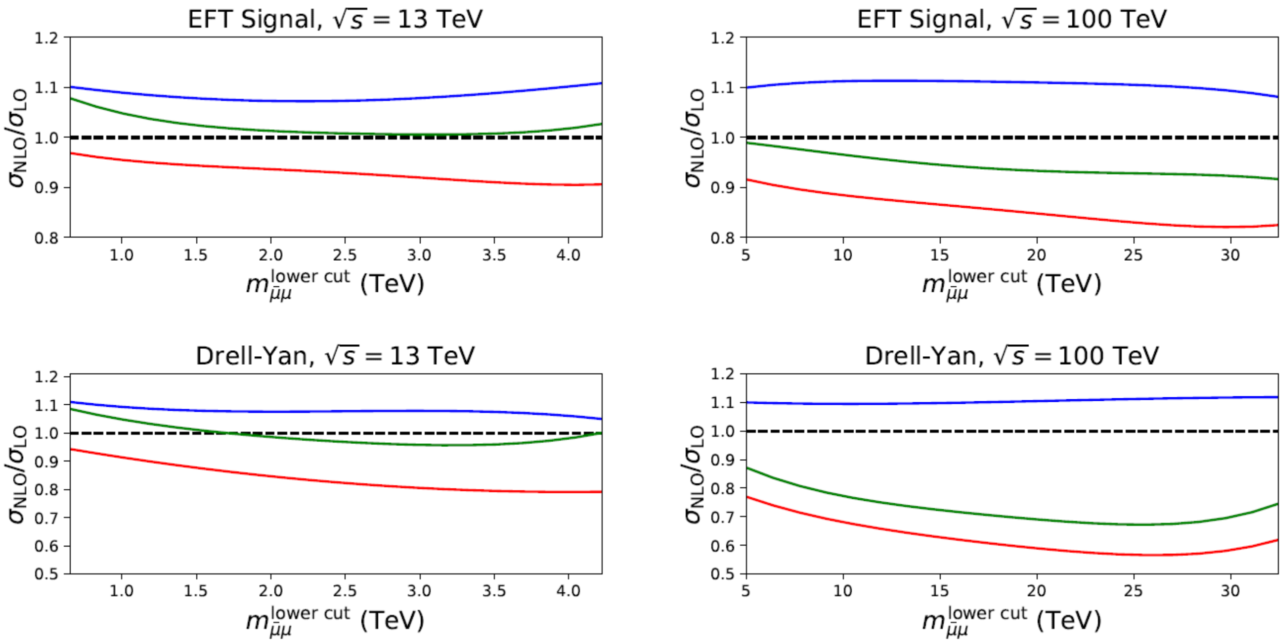


Figure 4: The ratios of the NLO-QCD, NLO-EW and NLO-QCD&EW cross sections to the LO cross section for both the EFT signal and the DY process as function of a lower cut on the dimuon invariant mass $m_{\bar\mu\mu}^{\rm lower\ cut}$. The blue lines correspond to NLO-QCD, the red to NLO-EW and the green to NLO-QCD&EW. The following cuts on muons are used: at $\sqrt{s} = 13$ TeV, $p_T = 52$ GeV and $|\eta| < 2.5$ and at $\sqrt{s} = 100$ TeV, $p_T = 400$ GeV and $|\eta| < 4.0$.