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Flavour physics at 10 TeV pCM colliders

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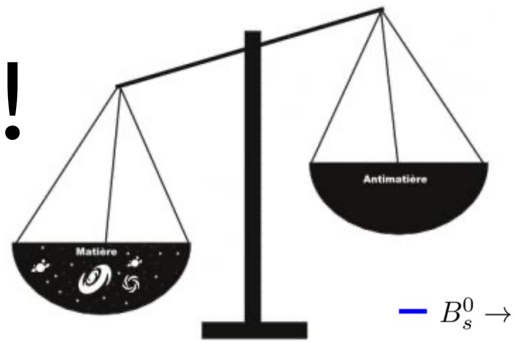
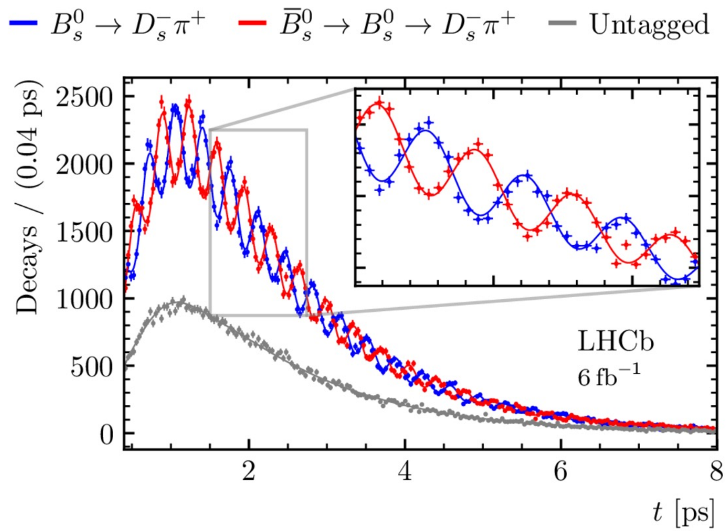
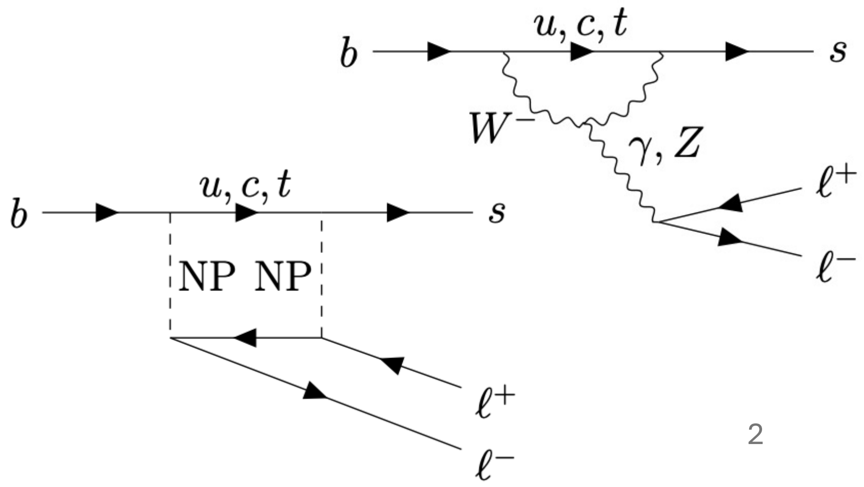
Flavour physics is exciting!



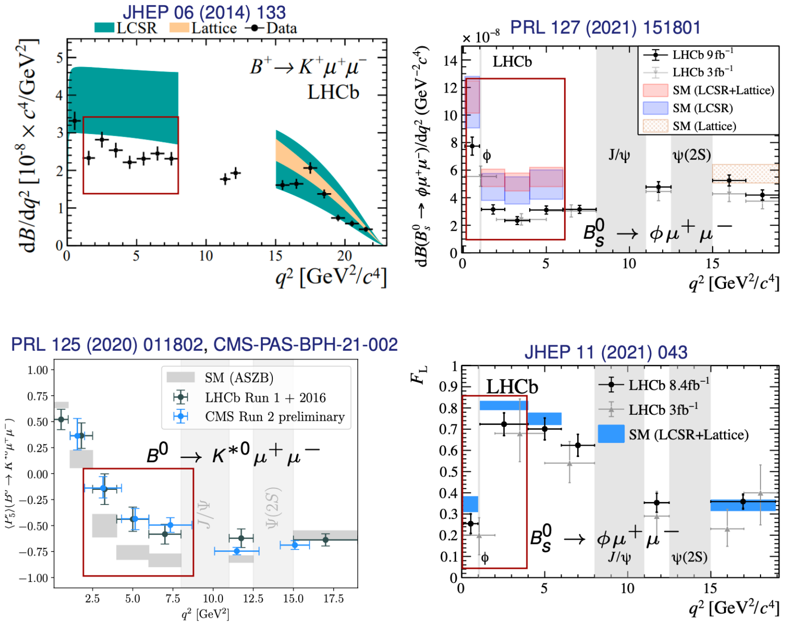
- Matter-antimatter asymmetry
- Access of higher energy scales in loop-mediated processes than directly producible in colliders
- Indirect discoveries through precision SM measurements
- Flavour anomalies
  - Anomalous magnetic moment of the muon
  - Deviations in $b \to s\ell^+\ell^-$ and $b \to c\ell^-\bar{\nu}$ transitions
- Probing flavour structure of couplings of potential BSM particles to quarks and leptons

Nature Phys. 18 (2022) 1, 1-5



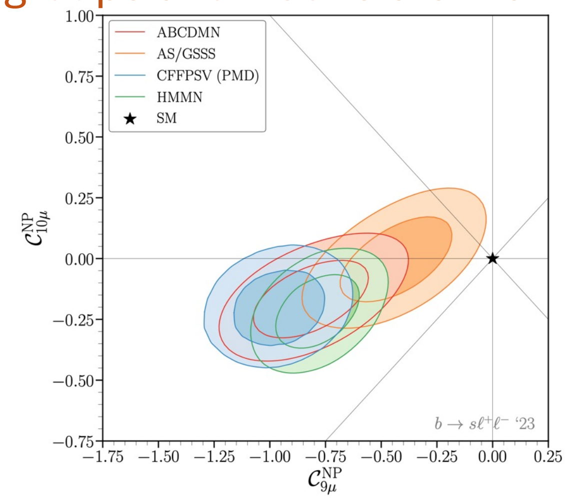


Brief recap' of current flavour anomalies



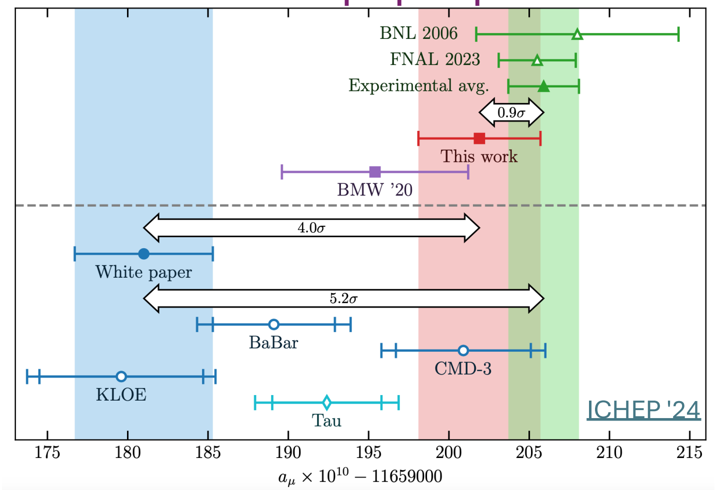
Deviations in differential BFs and angular observable measurements of electroweak penguin decays.

Global EFT fits of different theory groups show consistent shift.



PoS (FPCP 2023) 010

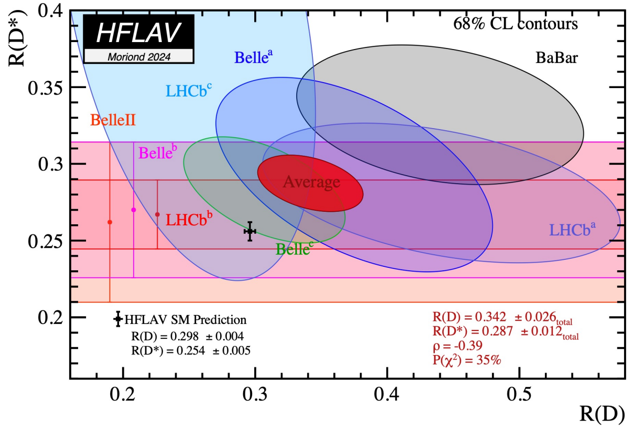
Tension of experimental muon g-2 value with white paper prediction.



ICHEP '24

Phys.Rept. 887 (2020) 1-166, Nature 593 (2021) 51, 2407.10913, PRL 131 (2023) 161802

LFU tests in semileptonic tree decays deviate from the HFLAV SM prediction.



HFLAV

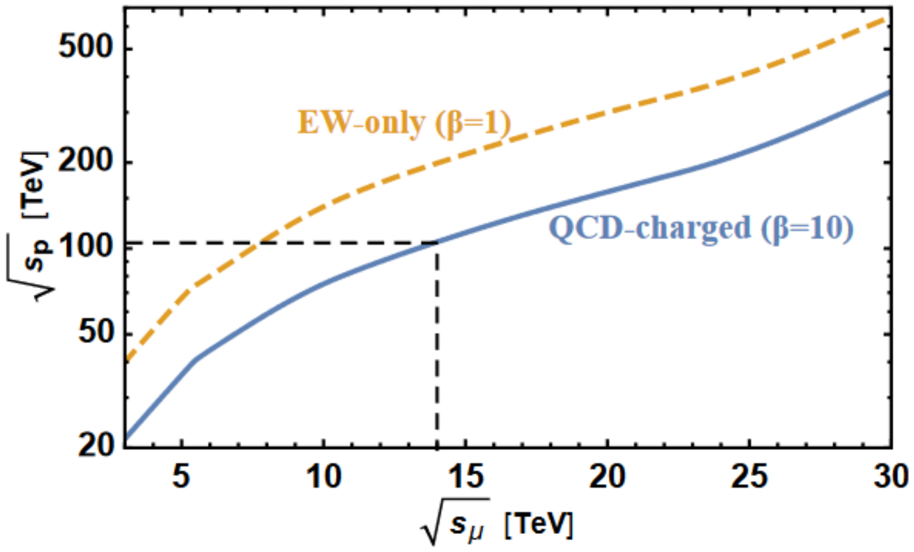
Advantages for flavour physics studies

Attribute	Υ(4S)	pp (LHC)	Z	FCC-hh	Muon collider
All hadron species		✓	✓	✓	✓
High boost		✓	✓	✓	✓
Enormous b production cross-section		✓		✓✓	
Negligible trigger losses	✓		✓		✓
Low backgrounds	✓		✓		✓
Initial energy constraint	✓		(✓)		(✓)

[Monteil, Wilkinson: Eur. Phys. J. Plus 136 (2021) 837]

Centre of mass energy for which the **cross sections for BSM** heavy particle production at pp and muon colliders are **equal**.

[Muon Colliders: 1901.06150]



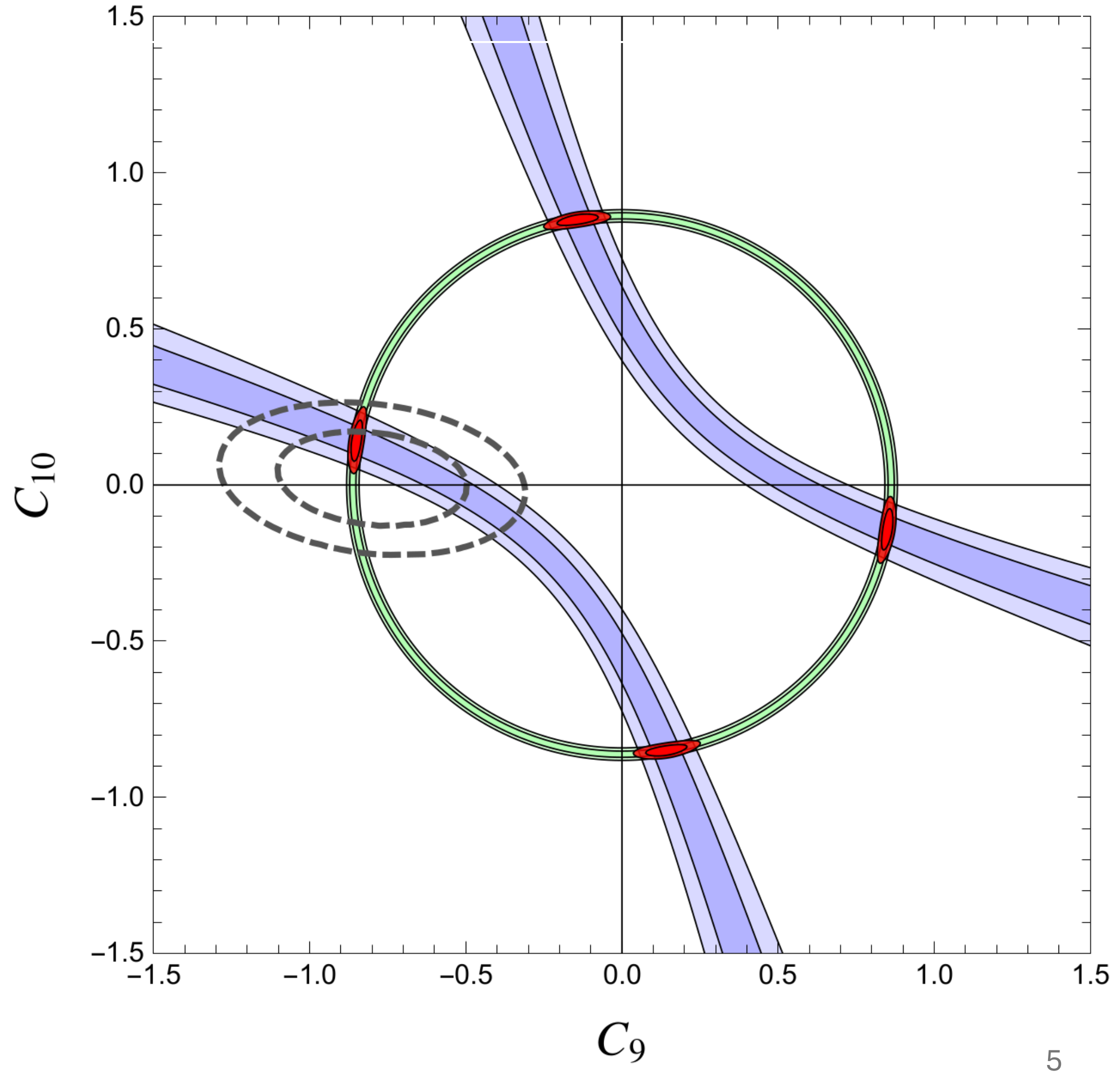
B anomalies @ muon collider. Model independent

[Altmannshofer, Gadam, Profumo: 2306.15017]

- At 10 TeV MuC, $\mu\mu \to bs$ can probe scales up to 100 TeV.
- In case of non-standard signal, forward-backward asymmetry gives insight into chirality structure of new physics.

Black: Current status from rare b-hadron decays.

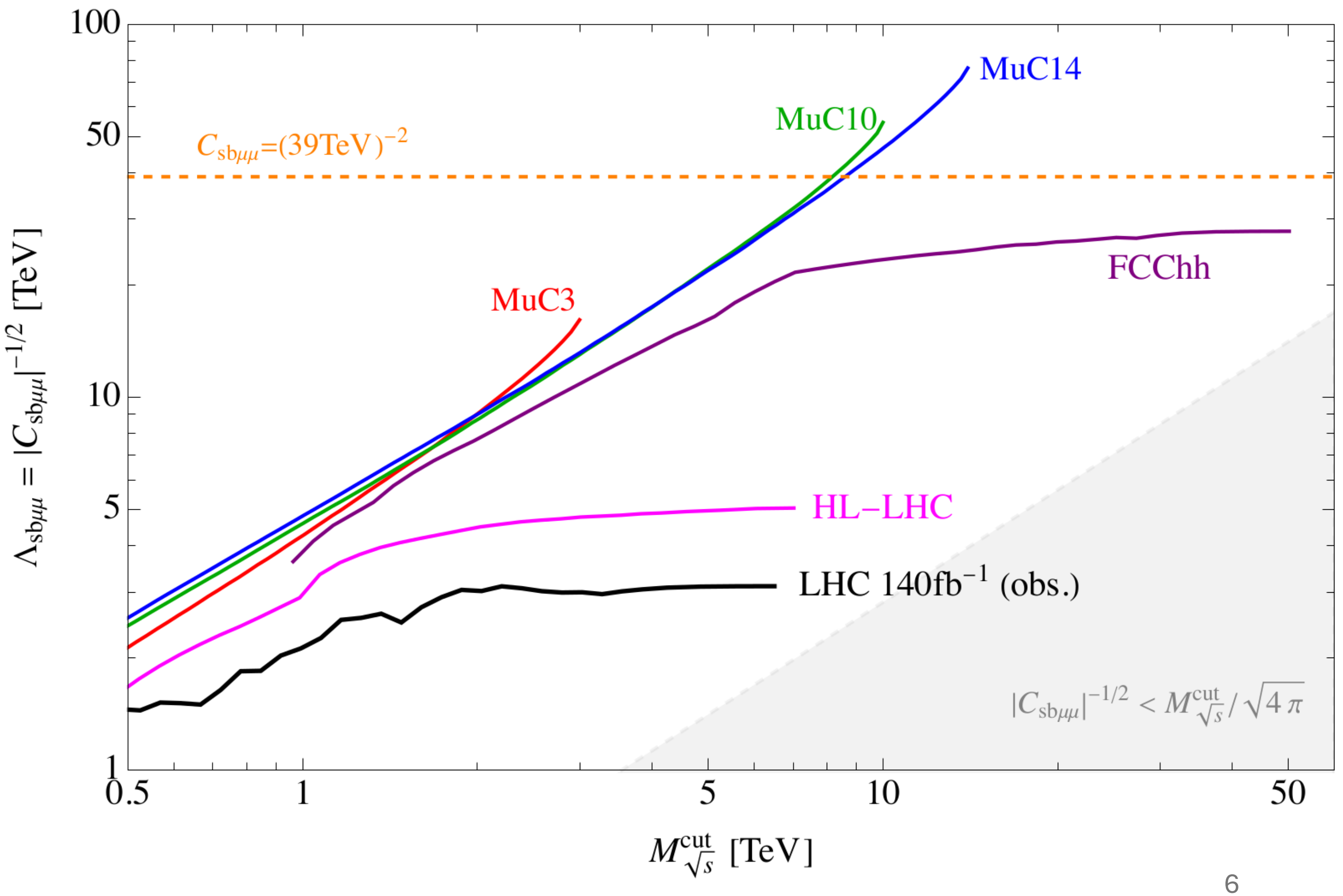
Coloured: $\mu\mu \to bs$ cross-section, forward-backward asymmetry and combining both using 10 ab^{-1} at 10 TeV.



B anomalies @ FCC-hh and muon collider Model independent

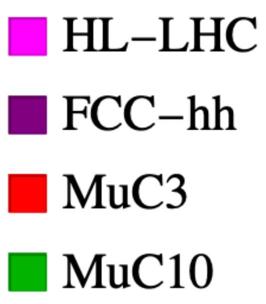
[Azatov, Garosi, Greljo, Marzocca, Salko: 2205.13552]

- At FCC-hh obtain bound on $bs \to \mu\mu$ from $pp \to \mu\mu$.
- Dashed orange line: Required Wilson coefficient to explain current B anomalies.
- Solid lines: Comparison of reach of future colliders.
- $M^{cut}_{\sqrt{s}}$: maximum invariant mass of the outgoing particles in $2 \to 2$ scattering.

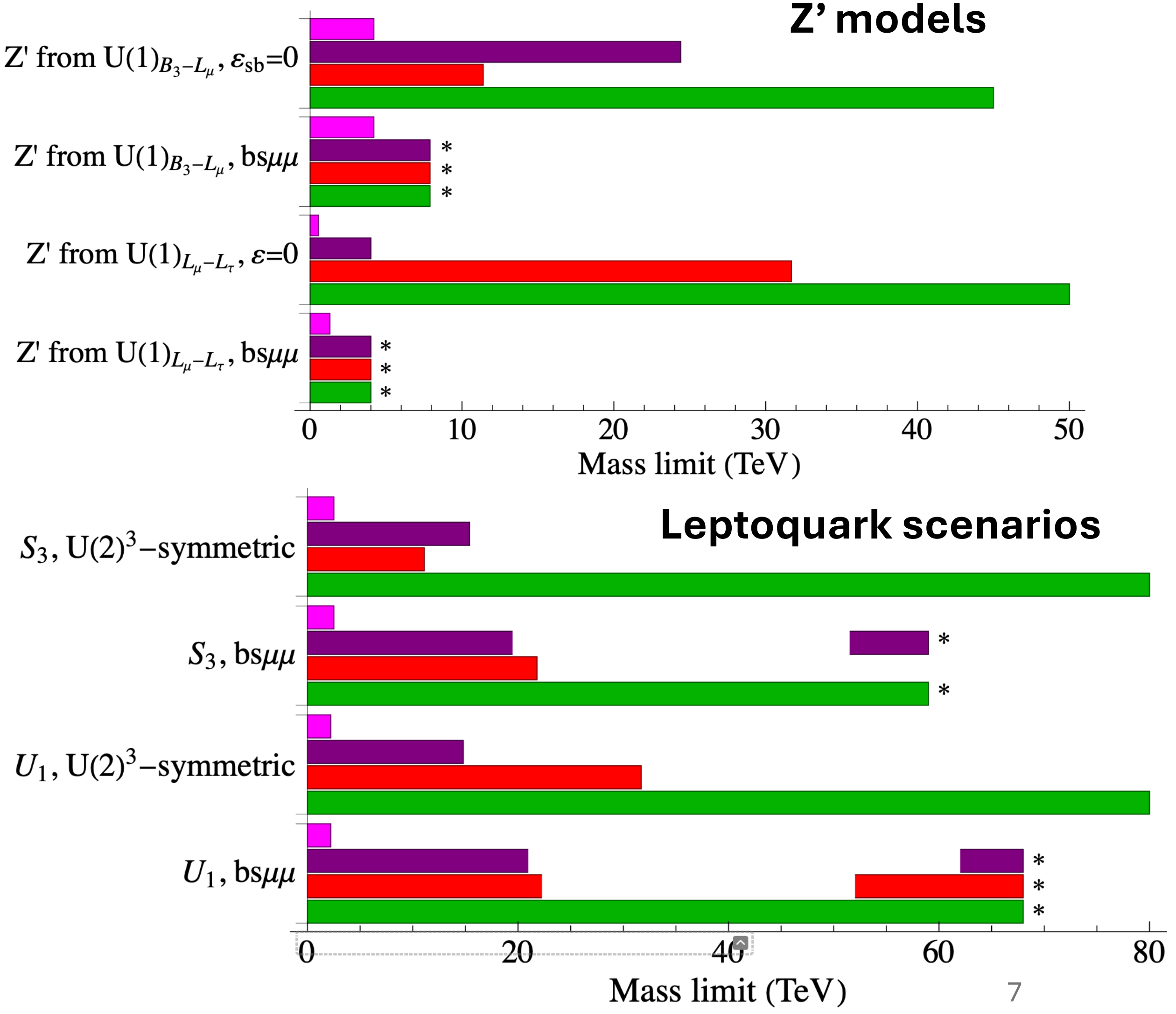


B anomalies @ FCC-hh and muon collider
Model dependent

[Azatov, Garosi, Greljo, Marzocca, Salko: 2205.13552]



- Systematic comparison of models accounting for b-anomalies at FCC-hh and muon collider.
- 3 TeV MuC similar potential as FCC-hh, but direct detection less likely.
- 10 TeV MuC has edge over FCC-hh for full exploration of parameter space.



[Capdevilla, Curtin, Kahn, Krnjaic: 2101.10334]

Muon g-2

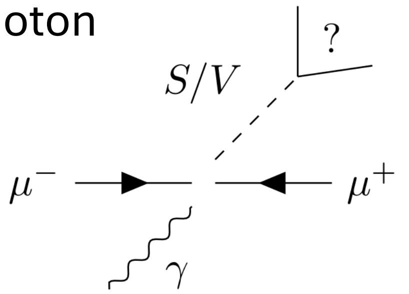
<u>"No-Lose"-Theorem:</u>

Highly likely to observe BSM physics at muon collider under two generic assumptions:

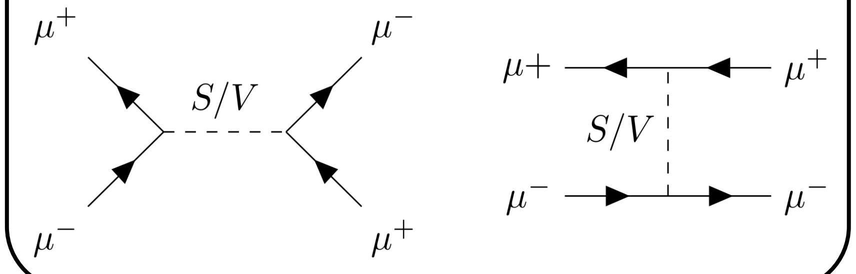
1) g-2 anomaly is genuine.
2) sub-GeV solutions are outruled.

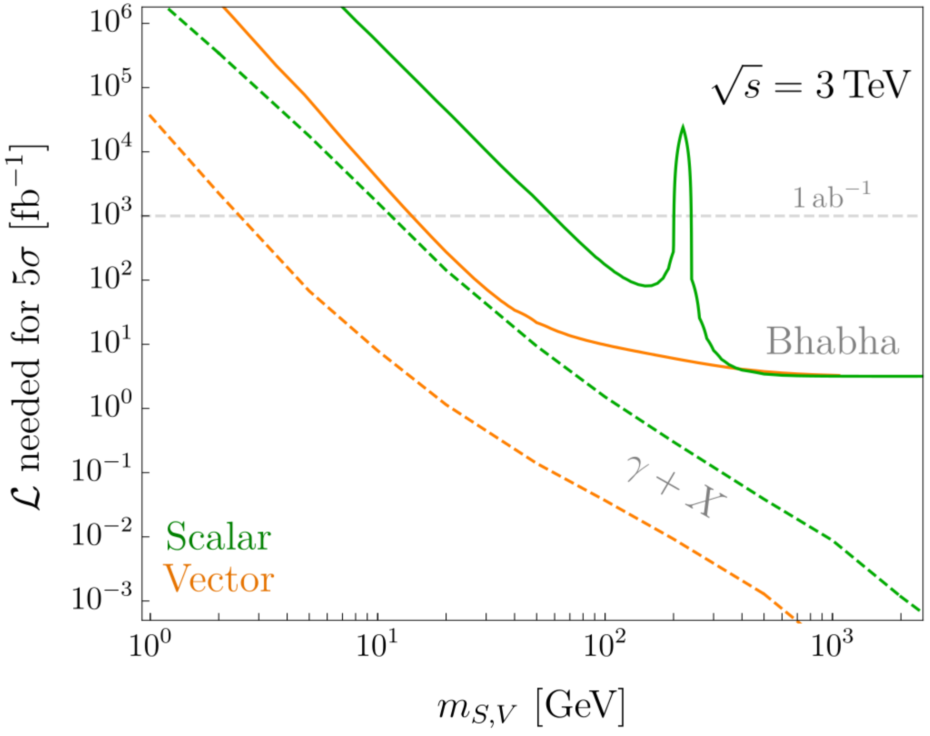
Example signatures for singlet scenario (no EW charge) with scalar and vector BSM particle.

Missing Energy + photon



Modified Bhabha scattering

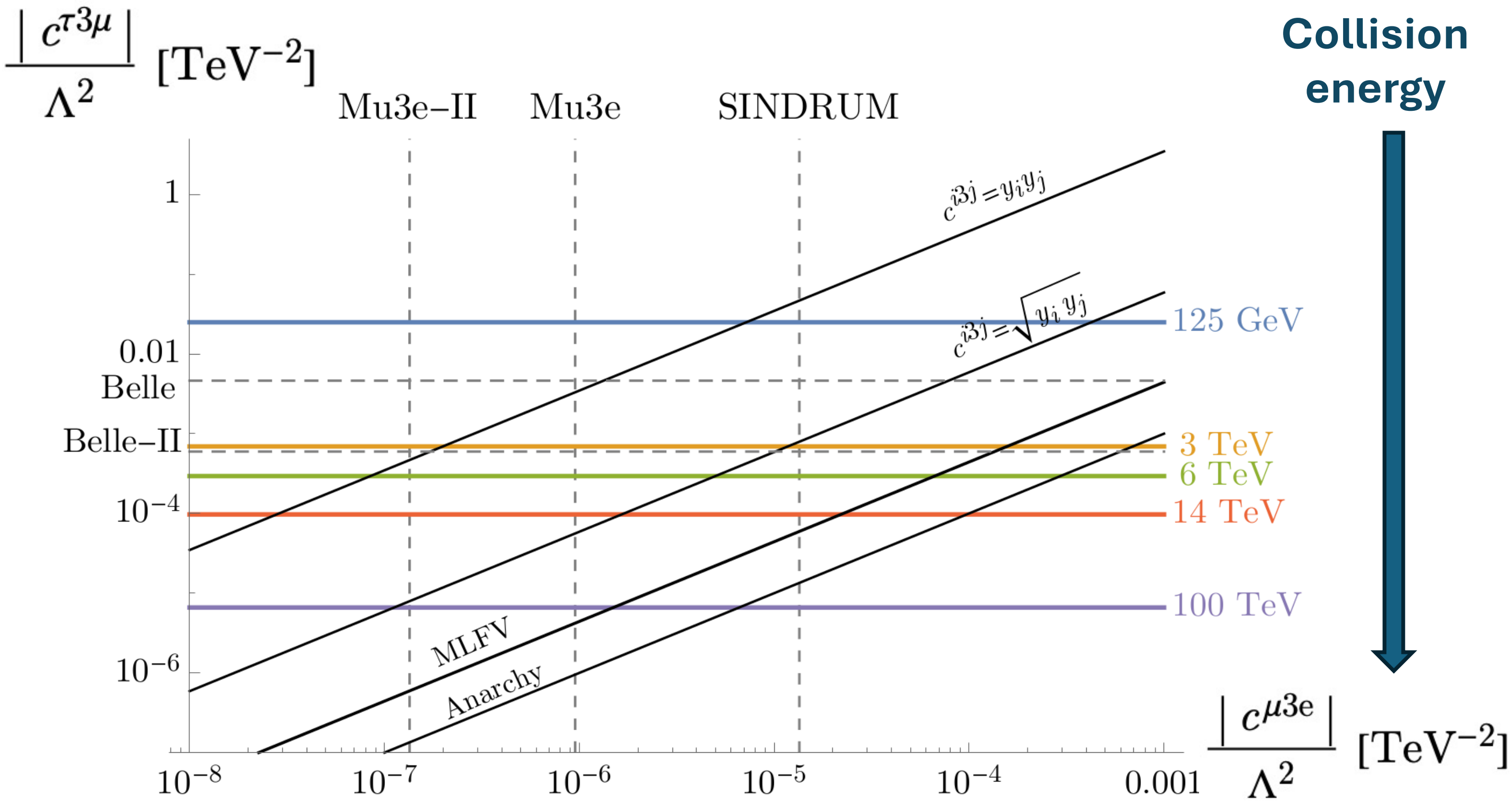




Charged Lepton Flavour Violation

[The Muon Smasher's Guide: 2103.14043]

- μμ → τμ related to τ → 3μ by crossing symmetry.
- Black: Theory scenarios correlating τ → 3μ and μ → 3e.
- Coloured: Different centre of mass energies of muon collider at 1ab^{-1}.
- μμ → eμ not competitive to μ → 3e experiments.

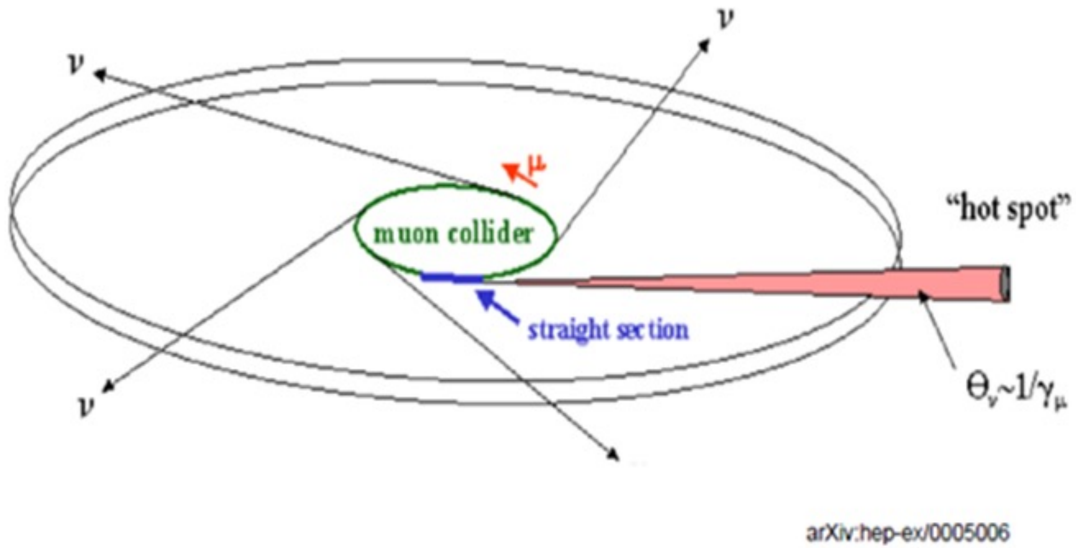


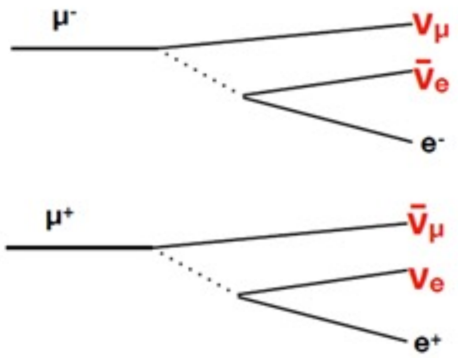
Complementary probe of charged lepton flavour violation.

Neutrinos at muon collider

[King: AIP Conf.Proc. 530 (2000) 1, 165-180]

- Neutrino radiation disk emanating out from muon collider ring
- High-intensity highly-collimated neutrino beam [radiation hot spot downstream of straight sections]
- High energy range from GeV to TeV
- Precisely known composition





Neutrinos at FCC-hh

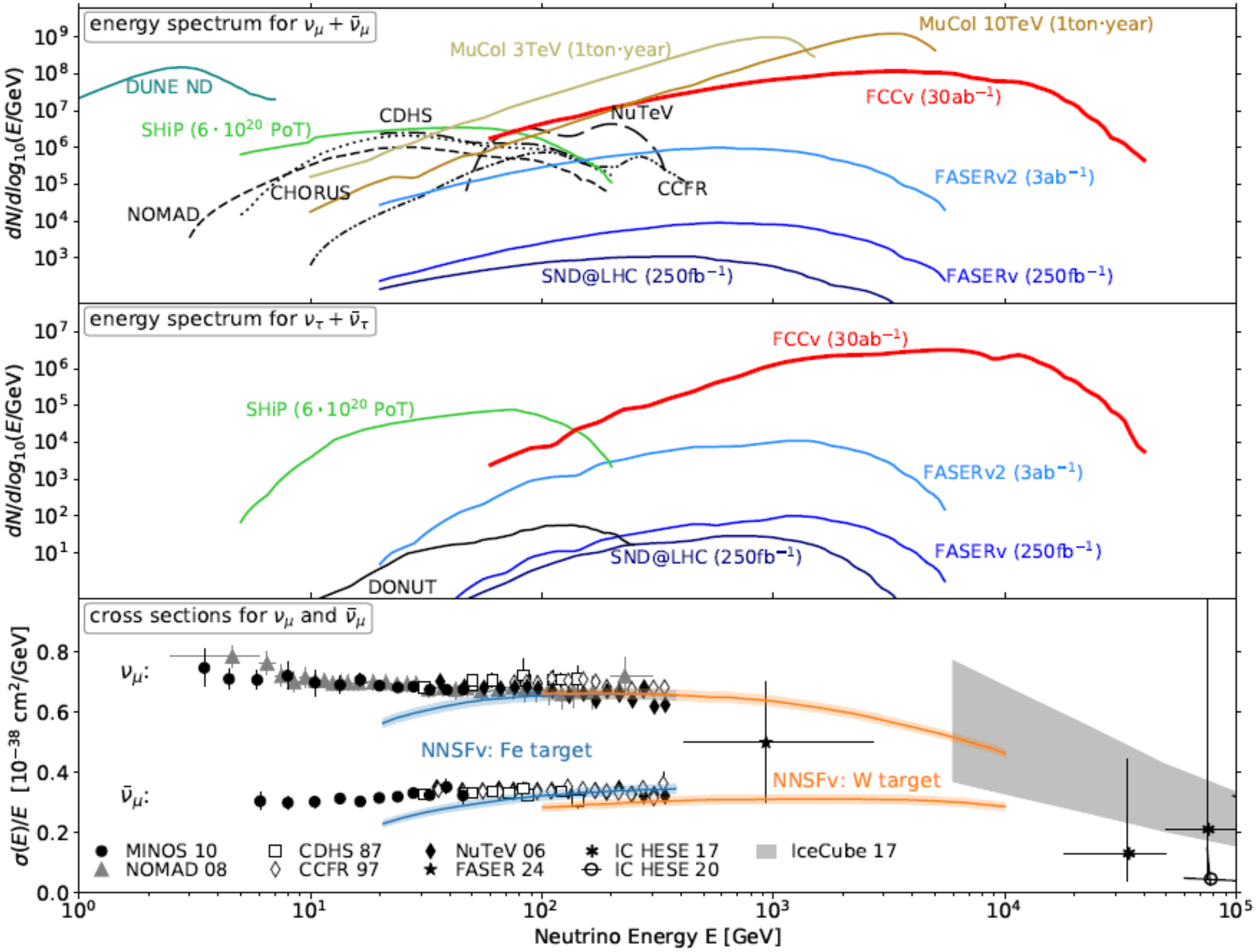
[FPF@FCC: 2409.02163]

Intense flux of high-energy neutrinos in the forward direction at FCC-hh.

In a 10t detector, 1.5 km downstream, FPF@FCC could record 10^9 electron and muon neutrinos and 3 x 10^7 tau neutrinos (!)

<u>Novel physics opportunities include:</u>

- High-precision tests of neutrino flavour interactions universality
- QCD: (Polarised) proton PDFs and nuclear nPDFs in uncharted kinematic regimes
- BSM: Measurement of neutrino charge radius



Conclusions

- Flavour physics gives a huge motivation for future collider experiments.
- Flavour anomalies have driven studies so far.
- Once new particles are found, the exploration of the flavour structure of their couplings is paramount.
- FCC-hh benefits from enormous cross section for all flavours.
- Muon colliders combine the advantages of both proton-proton and electron-positron colliders.

As a community we need a more systematic approach to fully explore the potential of both FCC-hh and muon colliders for flavour physics.

Backup

Cross-sections

[Chobanova, Santos, Prouve, Lamas: 2012.02692]

Particle	$\sigma_P^{50}/\sigma_P^{13}$	$\sigma_P^{100}/\sigma_P^{13}$	$\sigma_{\bar{P}}^{13}/\sigma_P^{13}$	$\sigma_{\bar{P}}^{50}/\sigma_P^{50}$	$\sigma_{\bar{P}}^{100}/\sigma_P^{100}$
τ^-	2.5	3.8	1.0	1.0	0.99
B_c^+	7.2	14	1.6	0.97	0.98
B_d^0	3.1	5.1	0.99	0.99	0.99
B^+	3.1	5.1	0.99	1.0	1.0
B_s^0	3.2	5.4	1.0	1.0	0.99
Λ_b^0	3.0	4.1	0.89	0.89	0.90
K^0	1.6	2.0	0.98	0.99	0.99
K^+	1.6	2.0	0.97	0.98	0.99
Λ^0	1.5	1.9	0.86	0.90	0.92
Σ^+	1.5	1.9	0.89	0.93	0.94
Ω^-	1.6	2.1	0.98	0.95	0.96
χ^-	1.6	2.0	0.96	0.97	0.97
χ^0	1.6	2.0	0.95	0.96	0.97
$D^{0,+}$	2.2	3.1	1.0	1.0	1.0
Λ_c^+	2.1	2.9	0.90	0.93	0.94

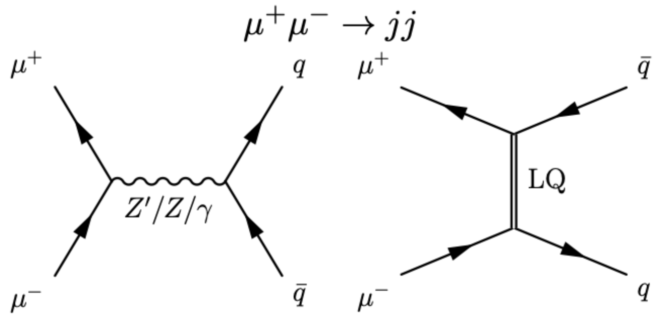
Energy and luminosity of benchmark colliders

[Azatov, Garosi, Greljo, Marzocca, Salko: 2205.13552]

Collider	C.o.m. Energy	Luminosity	Label
LHC Run-2	13 TeV	140 fb^{-1}	LHC
HL-LHC	14 TeV	6 ab^{-1}	HL-LHC
FCC-hh	100 TeV	30 ab^{-1}	FCC-hh
Muon Collider	3 TeV	1 ab^{-1}	MuC3
Muon Collider	10 TeV	10 ab^{-1}	MuC10
Muon Collider	14 TeV	20 ab^{-1}	MuC14

Scalar leptoquark search

[Azatov, Garosi, Greljo, Marzocca, Salko: 2205.13552]



As shown by the extensive literature [23, 25, 161, 162, 165–180], S_3 is the only scalar leptoquark that can accommodate $bs\mu\mu$ anomalies at the tree level. After integrating out S_3, we find the following contribution to the relevant effective operators

$$\Delta C_9^\mu = -\Delta C_{10}^\mu = \frac{\pi}{\sqrt{2} G_F \alpha V_{ts}^* V_{tb}} \frac{\lambda_{b\mu}\lambda_{s\mu}}{M_{S_3}^2} \,. \tag{6.5}$$

The fit to the $bs\mu\mu$ anomalies then implies

$$\lambda_{b\mu}\lambda_{s\mu} = 6.6 \times 10^{-4} \left(\frac{M_{S_3}}{\text{TeV}}\right)^2 \left(\frac{\Delta C_9^\mu}{-0.39}\right) \,. \tag{6.6}$$

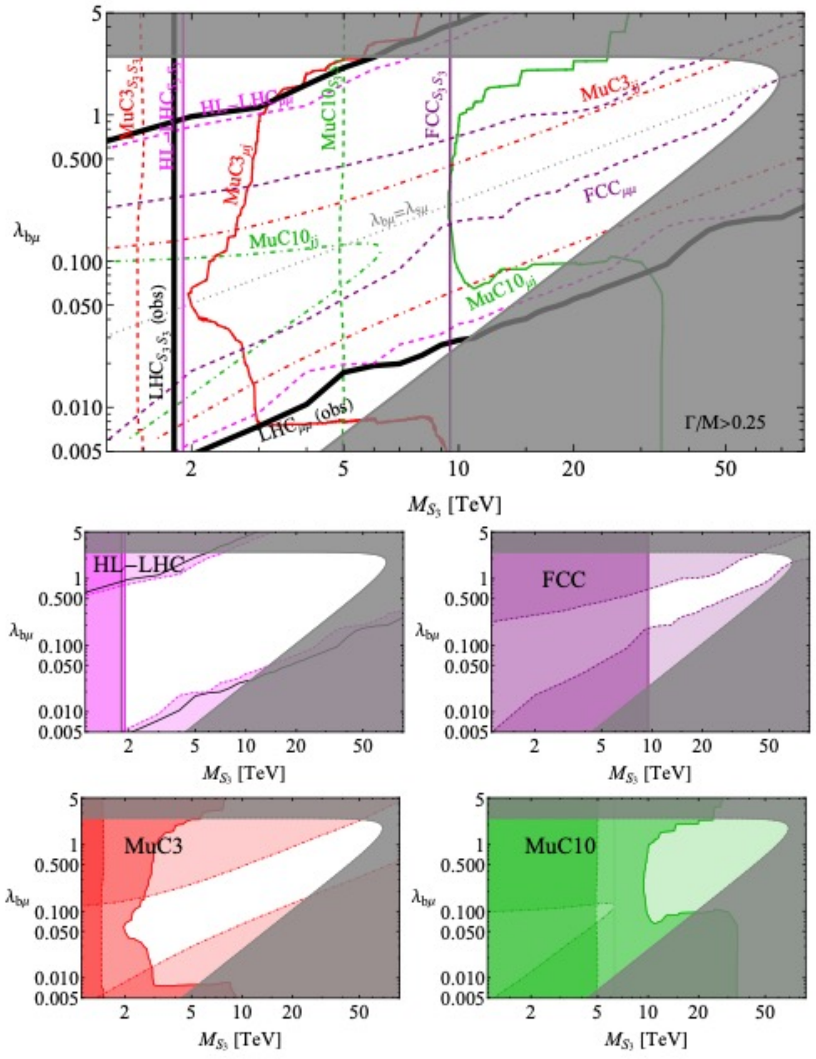


Figure 14. The 5σ discovery prospects for the S_3 leptoquark behind to $bs\mu\mu$ anomalies, i.e. imposing Eq. (6.6). The present LHC exclusions at 95% CL are shown as a thick black line. The dotted gray line corresponds to $\lambda_{b\mu} = \lambda_{s\mu}$. The perturbative limit $\Gamma_{S_3}/M_{S_3} < 0.25$ is violated in the grey region. For future colliders, the discoverable region is on the side of the line where the corresponding label is. The smaller plots below the main one highlight the reach of various future colliders separately.