Workshop on FCC-ee and Lepton Colliders

22–24 Jan 2025
Laboratori Nazionali Frascati, Rome

New physics at the Muon Collider

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International MUON Collider Collaboration

MuCol

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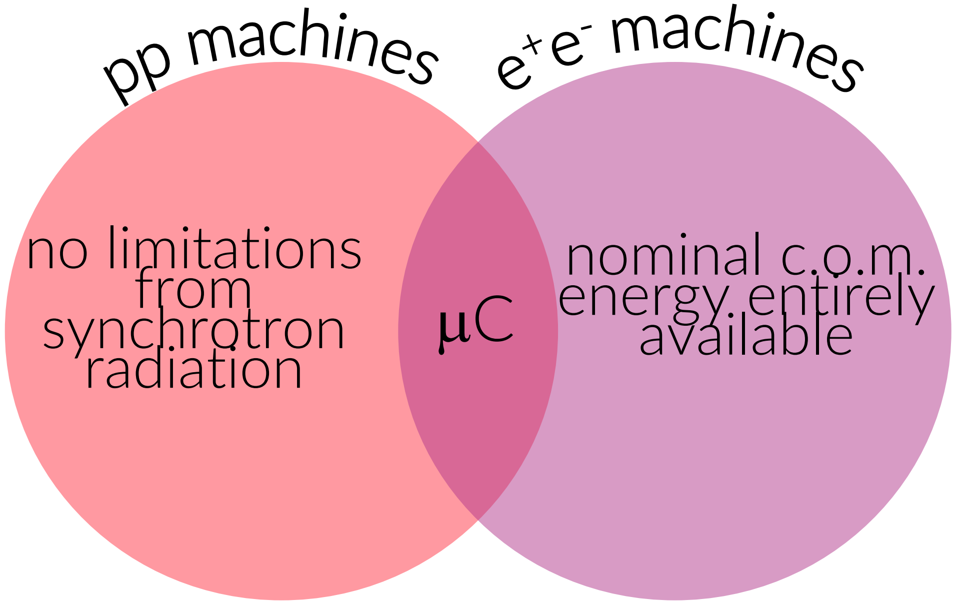
INFN
Istituto Nazionale di Fisica Nucleare

Muon collider (μC)

OPPORTUNITIES

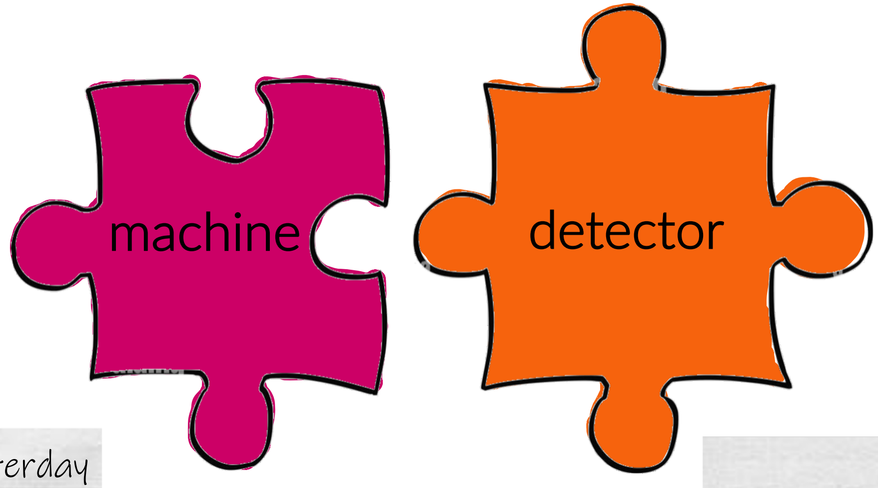


yesterday
D. Lucchesi
Muon Collider

CHALLENGES

$$L_{\text{int}} = 10\,\text{ab}^{-1}\left(\frac{E\text{cm}}{10\,\text{TeV}}\right)^2$$

	3 TeV	10 TeV	14 TeV
luminosity	1.8 10^{34} cm^{-2} s^{-1}	2 10^{35} cm^{-2} s^{-1}	4 10^{35} cm^{-2} s^{-1}



yesterday
R. Losito
Muon Cooling and demonstrator

yesterday
D. Calzolari
Muon collider machine detector interface

tomorrow
D. Zuliani
Overview of muon collider detectors

Physics highlights

Precision
Electroweak (EW) sector
Higgs sector
- double Higgs
- triple Higgs coupling

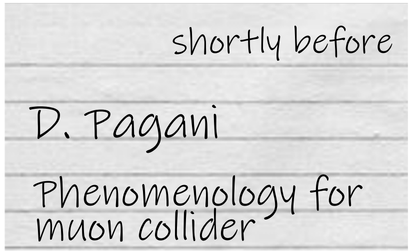
Energy & Precision
cross sections measurements
- Z'
- Higgs compositeness

Energy
new particles
- scalar singlet
- WIMP

Muons and neutrinos
muon beams
- muon g-2
- leptoquarks

neutrino beams

+ theory frontier
EW radiation



Further results:

[1] Interim report for the International Muon Collider Collaboration arXiv:2407.12450 [physics.acc-ph]
[2] Towards a muon collider 10.1140/epjc/s10052-023-11889-x

Precision

Electroweak (EW) sector

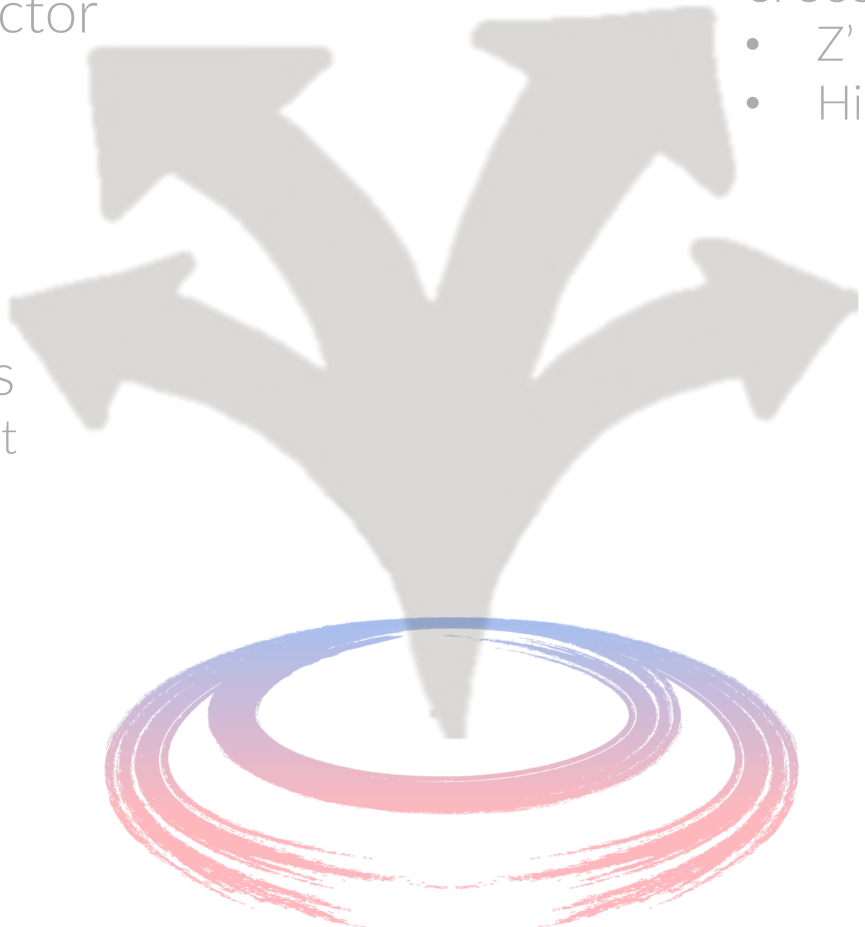
Higgs sector

- double Higgs
- triple Higgs coupling

Energy & Precision

cross sections measurements

- Z'
- Higgs compositeness



Energy

new particles

- scalar singlet
- WIMP

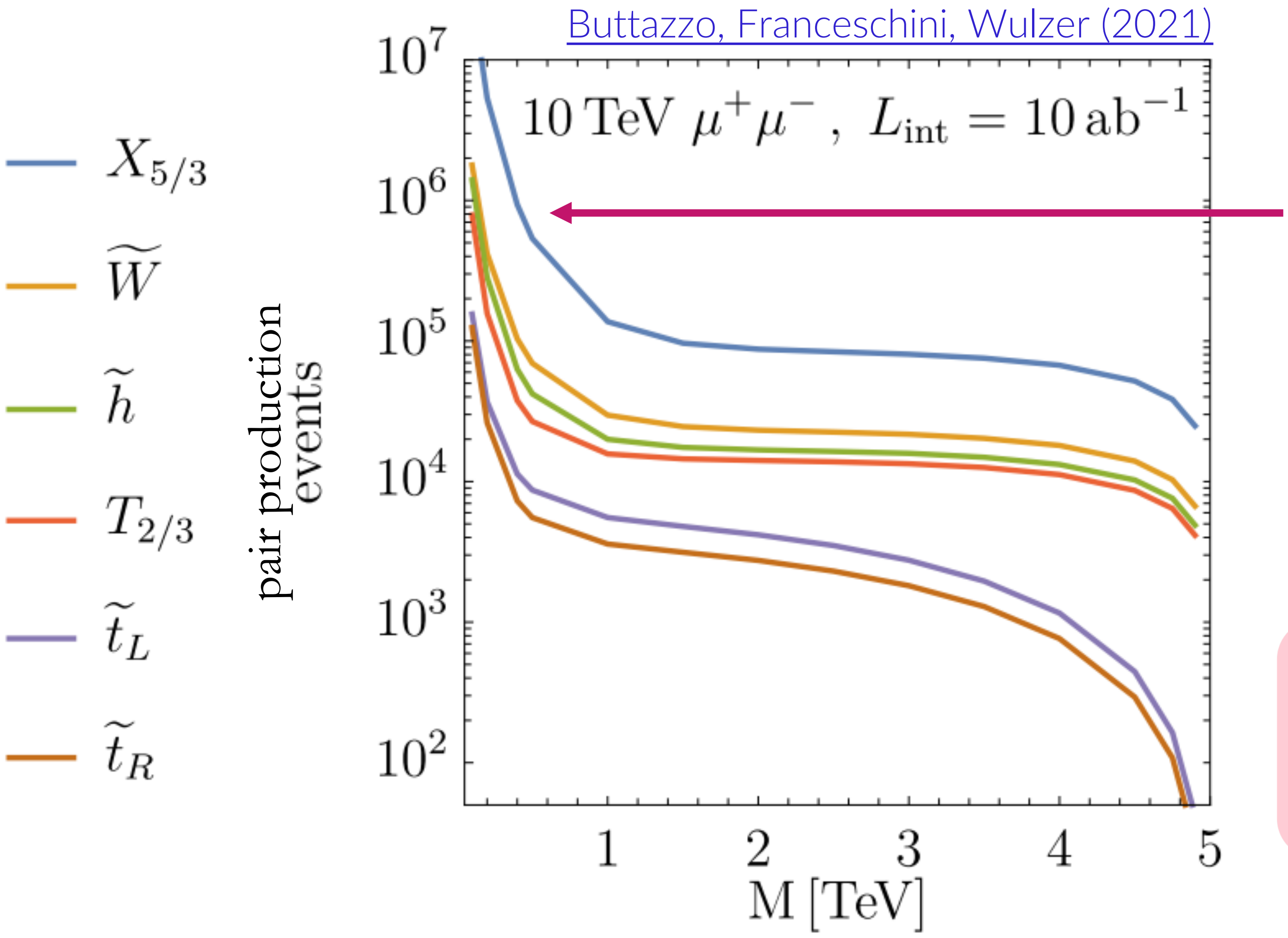
Muons and neutrinos

muon beams

- muon g-2
- leptoquarks

neutrino beams

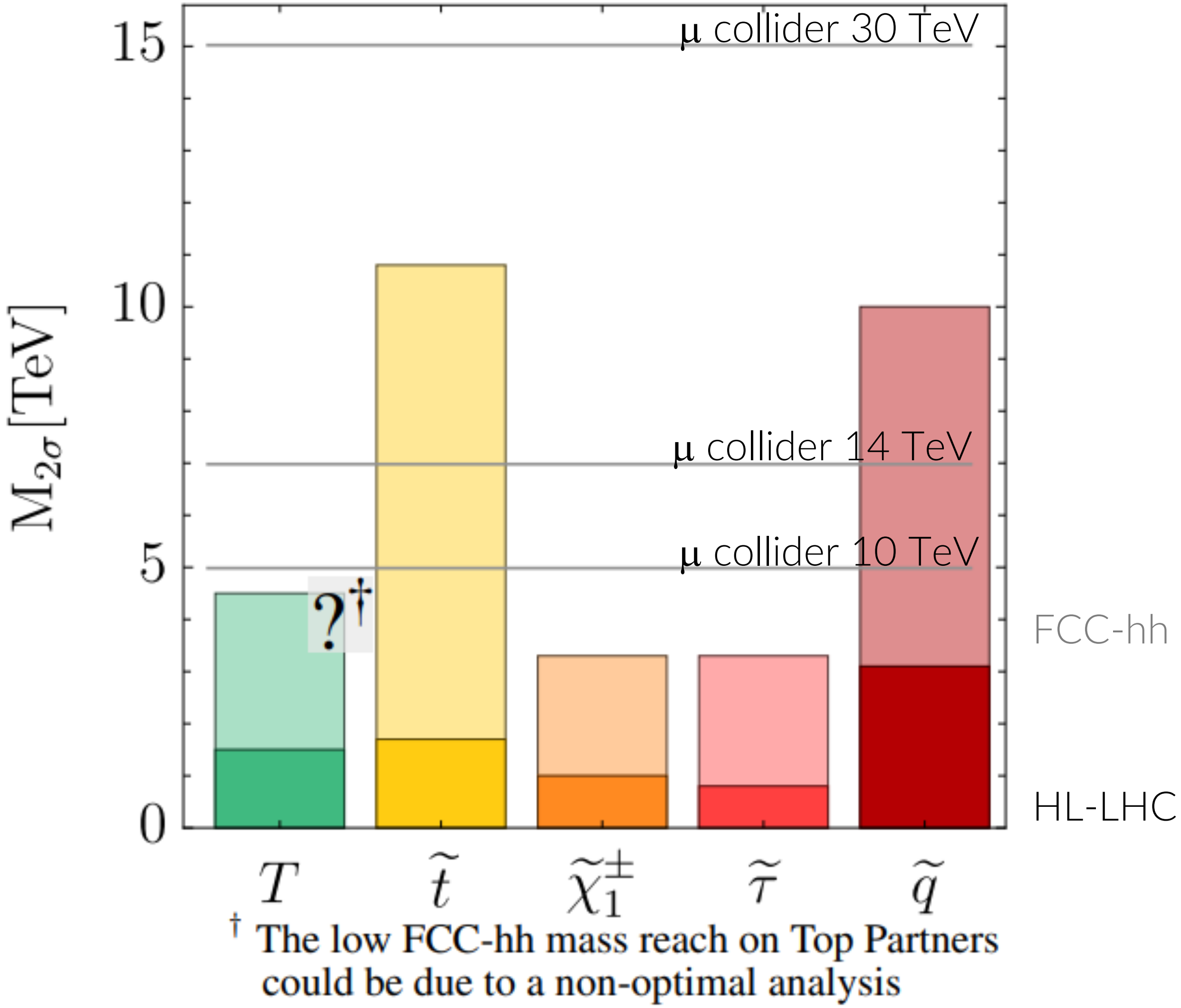
Production of new particles



MadGraph + Effective Photon Approximation for neutral Vector Boson Fusion (VBF)

A 10 TeV μC can produce beyond Standard Model (SM) particles abundantly

Physics Briefing Book 2020



Pair production by electroweak interactions (σ = 0.1 -10 fb @ 10 TeV)

Model independent (only EW and spin quantum numbers)

The μC reach exceeds hadron colliders for many particles

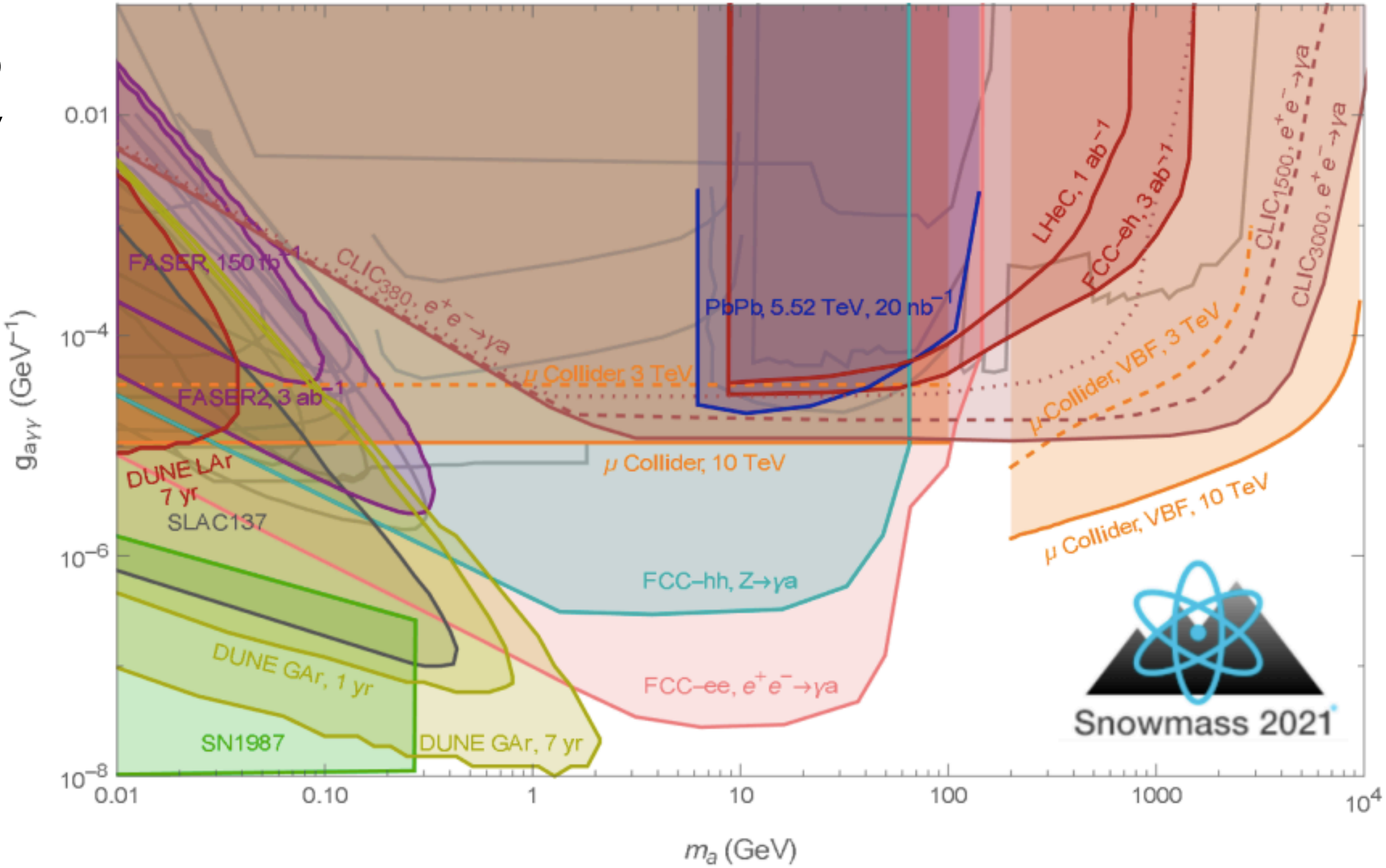
Axion like particles (ALP)

CP-odd scalars, pseudo Nambu-Goldstone bosons associated to spontaneous global U(1) symmetry breaking

$$\mathcal{L}_{\text{eff}} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} F^{\mu\nu}$$

- Production: annihilation or VBF
- Decay: $a \to \gamma\gamma$

Physics BSM at Energy Frontier (Snowmass 2021)



A 10 TeV μC is the most sensitive machine to high ALP masses (m_a > 200 GeV)

Real singlet extended SM

Model to provide first order EW Phase Transition
⟶ electroweak baryogenesis mechanism
⟶ explain matter-antimatter asymmetry

Direct search: heavy scalar h_2 produced via VBF + small contributions from Zh_2 associated production

$$h_2 \rightarrow h_1 h_1 \rightarrow b\bar{b}b\bar{b} \quad \text{or} \quad 4\ell$$

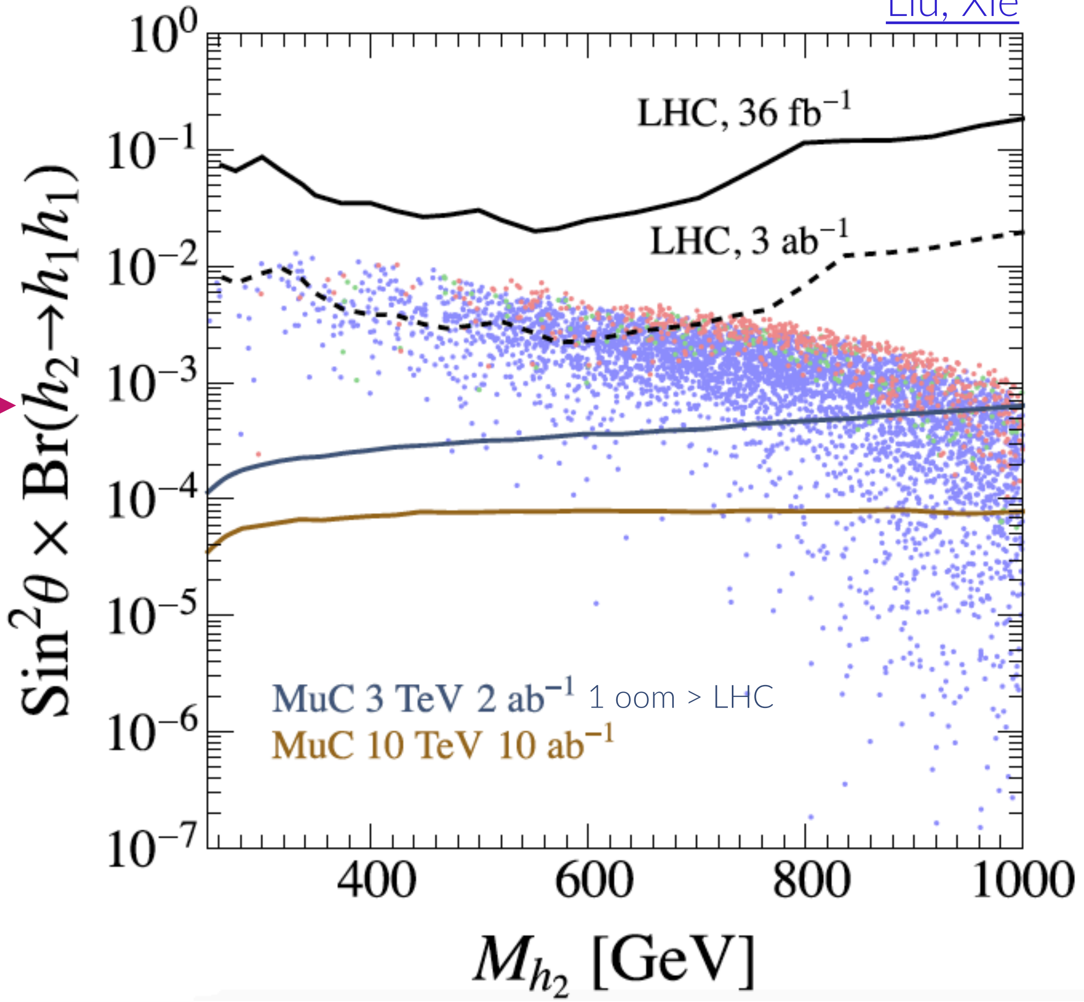
jet $\Delta E/E$ = 10% ; b-tagging efficiency = 70%

- θ = mixing angle between mass eigenstates h_1 and h_2

Indirect search: SM Higgs couplings deviations

A 10 TeV μC covers almost completely all parameters of the models and is complementary to gravitational waves detection

Liu, Xie



Red and green points: gravitational waves at LISA
Production: WW fusion (90% of total σ) + ZZ fusion with final state muons not detected

Dark matter (DM)

Weakly Interacting Massive Particles (WIMPS) are the simplest candidate for dark matter:

- EW charge SU(2) x U(1)
- abundance explain by thermal freeze-out mechanism

Minimal model: $SU(2)_L$ n-plet

⟶ predict the DM mass to explain observed relic
the larger the n, the larger the mass

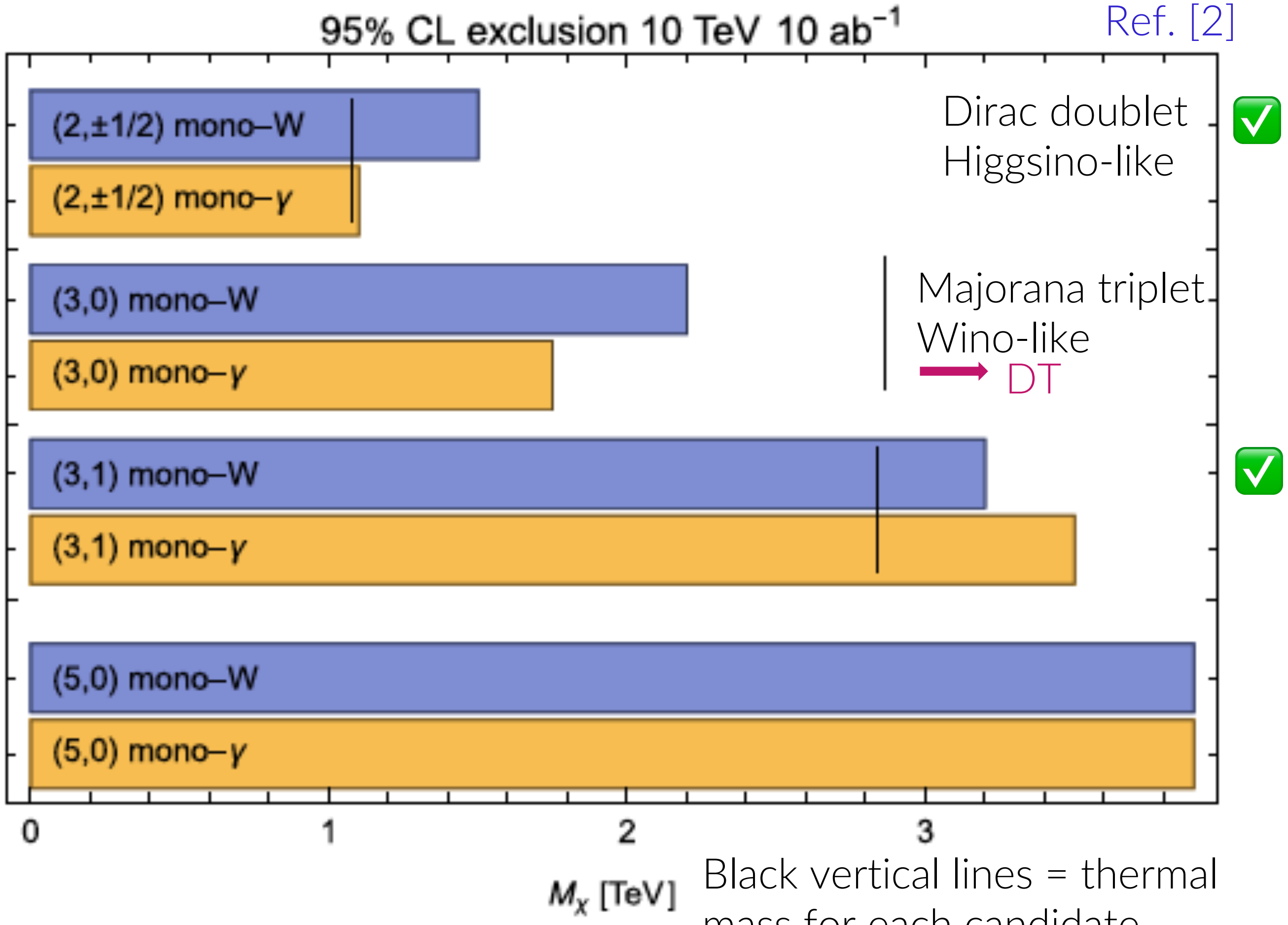
$$M_\chi \sim n^{\frac{5}{2}}$$

1° detection strategy: MONO-X

$$\mu^+\mu^- \to \chi\chi + X$$

X= γ, W, Z, μ, $\mu^+\mu^-$

Ref. [2]



Black vertical lines = thermal mass for each candidate

Mono-γ e mono-W provides the best mass reach for some DM candidates

2° detection strategy: DISAPPEARING TRACKS (DT)

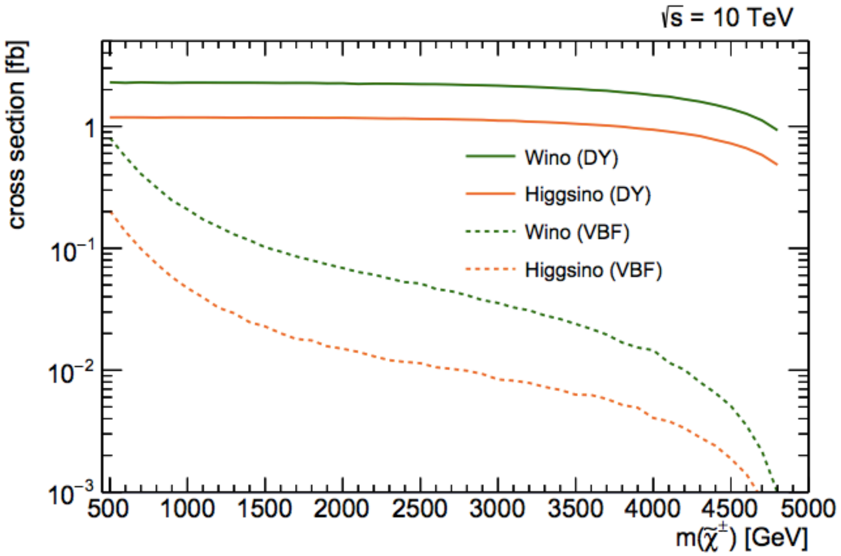
Pure Higgsino (Dirac doublet)

- thermal mass = 1.1 TeV
- mass splitting charged - neutral states = 344 MeV
  ⟶ charged state decay length = 6.6 mm

All figures from
Capdevilla *et al* (2021)

Pair production: Drell-Yan (DY) + small contribution from VBF

Events are more central and with higher transverse momentum wrt hadron colliders

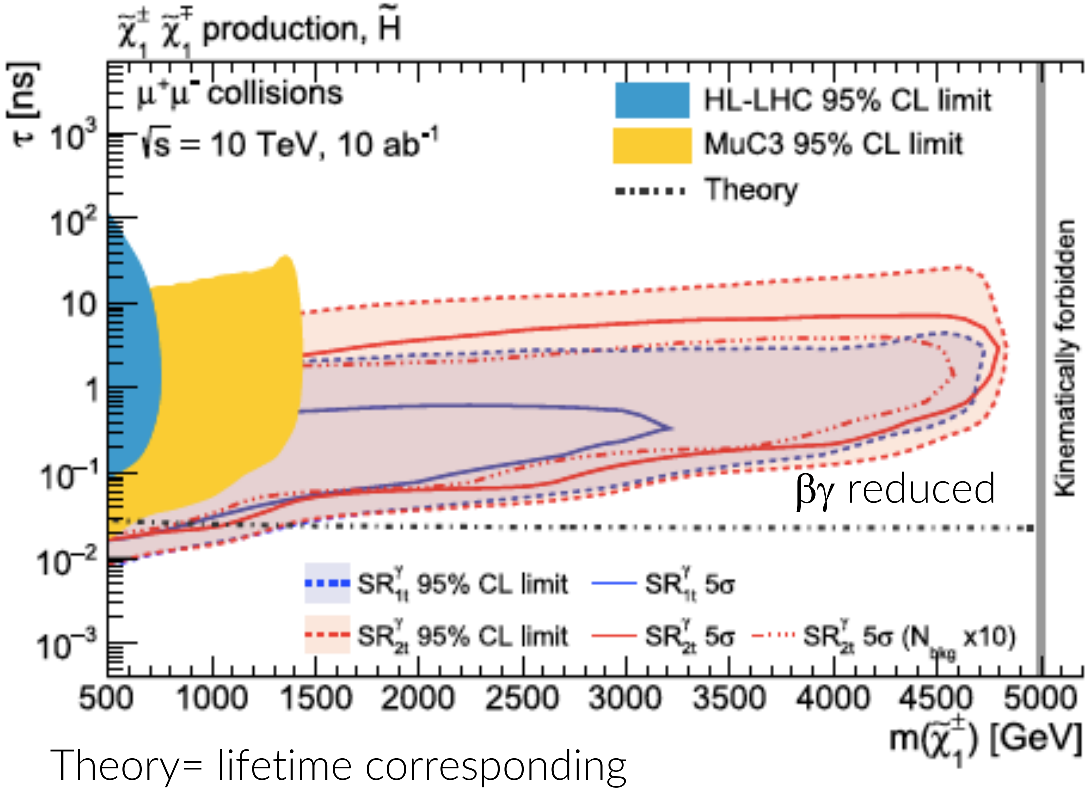


~10000 electroweakino pairs

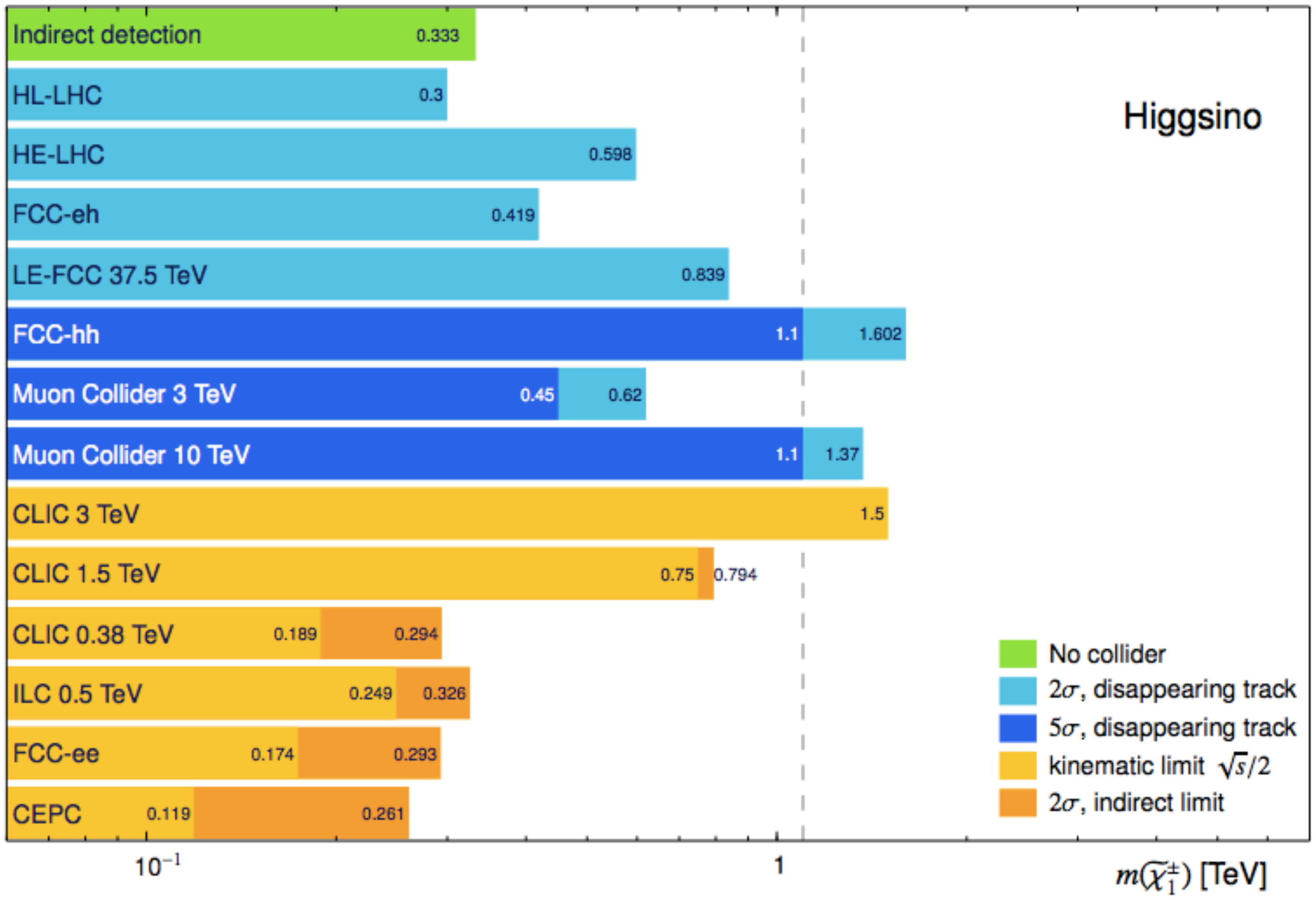
Signature: 1 or 2 DT + ISR γ + no leptons/jets
MadGraph + Pythia + Geant4 simulation + Beam Induced Background

Requirement / Region	SR^{γ}_{1t}	SR^{γ}_{2t}
Vetoes	leptons and jets	
Leading tracklet p_T [GeV]	> 300	> 20
Leading tracklet θ [rad]	$[2/9\pi, 7/9\pi]$	
Subleading tracklet p_T [GeV]	-	> 10
Tracklet pair Δz [mm]	-	< 0.1
Photon energy [GeV]	> 25	> 25

reject fake tracklets



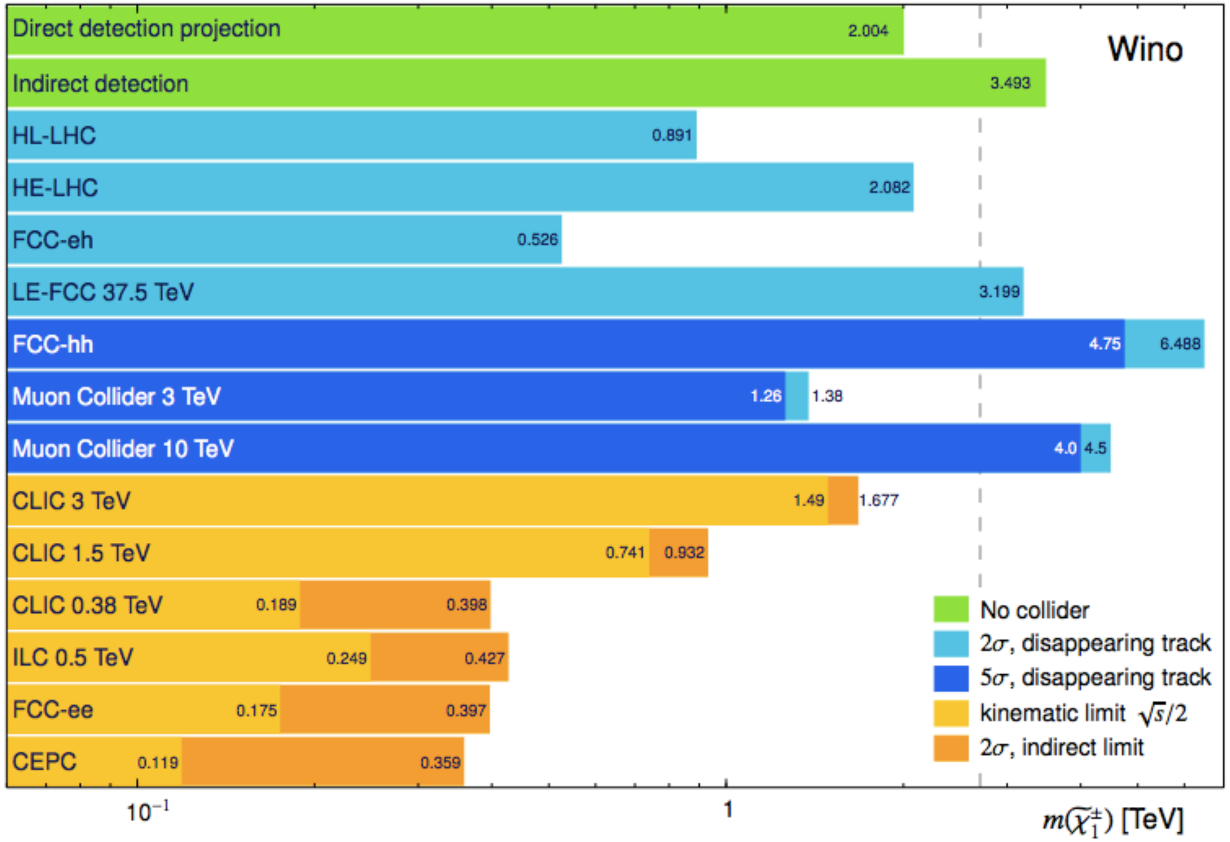
Theory= lifetime corresponding
to the thermal mass

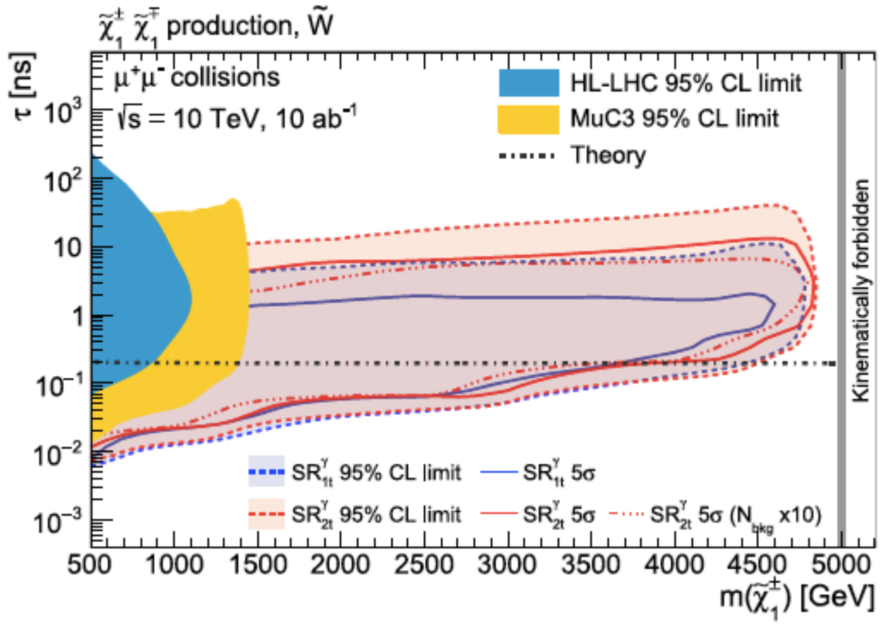


Multi-TeV μC is a perfect tool to look for unconventional signatures, such as DT, from particles with masses up to the value close to the kinematic limit ($E_{cm}/2$)

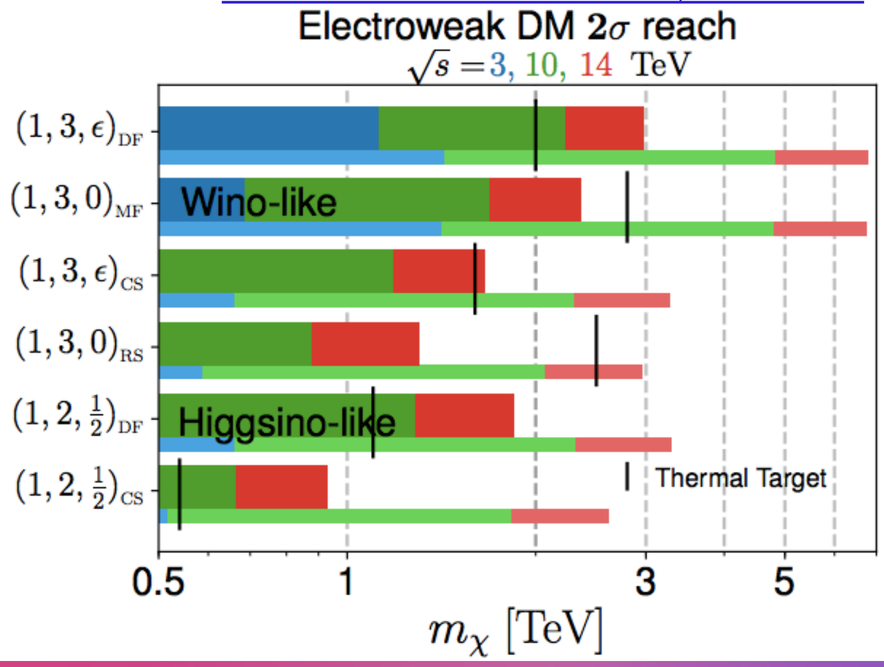
Pure wino (Majorana Triplet)

- thermal mass = 2.86 TeV
- mass splitting charged -neutral states: 166 MeV
  ⟶ charged state decay length: 6 cm





[Muon Collider Forum Report 2024]



thin=mono-γ + 1DT
thick=inclusive missing mass

Precision

Electroweak (EW) sector

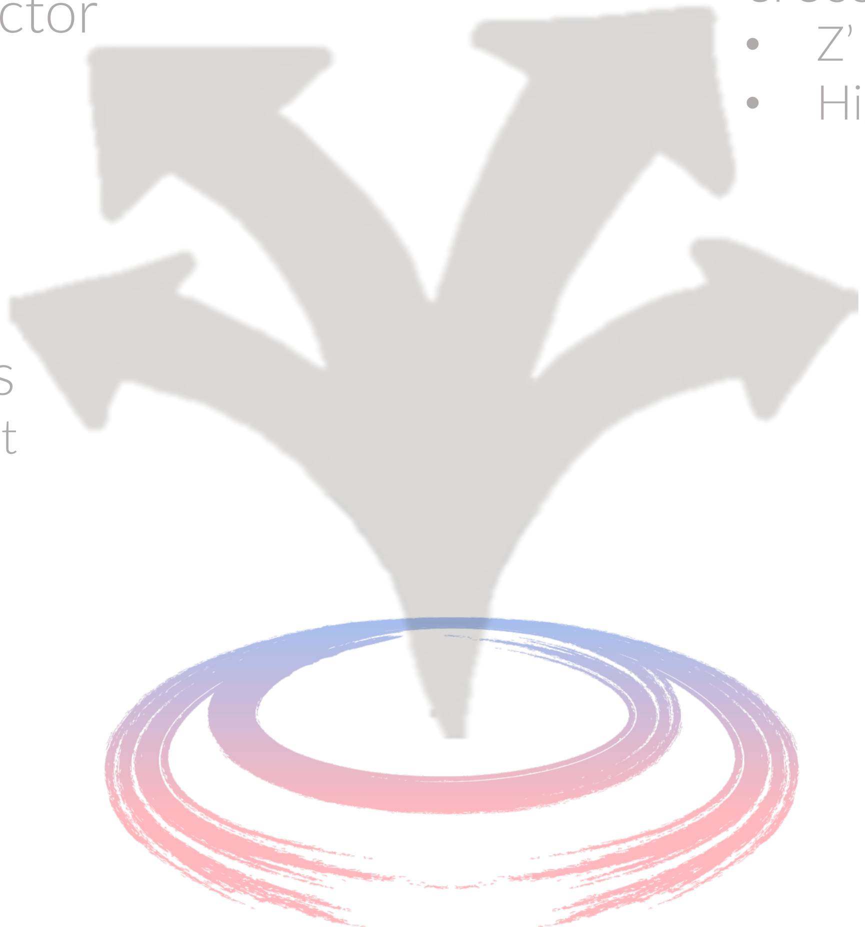
Higgs sector

- double Higgs
- triple Higgs coupling

Energy

new particles

- scalar singlet
- WIMP



Energy & Precision

cross sections measurements

- Z'
- Higgs compositeness

Muons and neutrinos

muon beams

- muon g-2
- leptoquarks

neutrino beams

3° detection strategy: INDIRECT SEARCH

WIMP mass range: 10 GeV - PeV
(e.g. thermal mass for Majorana 7-plet ~ 50 TeV)

$$M_\chi \sim n^{\frac{5}{2}}$$

$$\Omega_{DM} \sim \frac{1}{\sigma} \sim \frac{M^2}{C_{n,\text{eff}}} \sim \frac{M^2}{n^3}$$

Generation: MadGraph +
Q graph (for one loop triangle) +
FORM

No mixing between n-plet considered

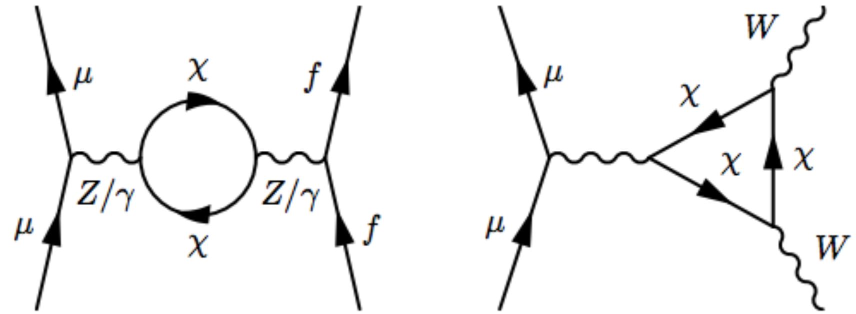
$$\mu^+\mu^- \to f\bar{f} + X$$

$$\mu^+\mu^- \to f'\bar{f} + X$$

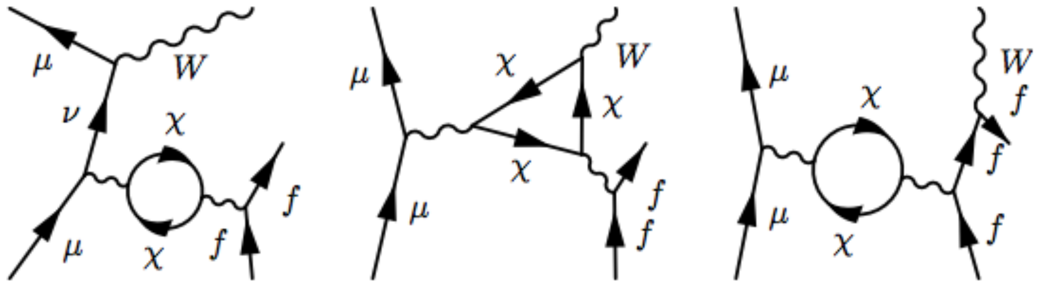
$$\mu^+\mu^- \to Zh/W^+W^- + X$$

EW radiation enhanced the 2 → 3 process cross section

Precise measurements of high energy cross sections cover the heaviest WIMPS whose mass reach is above the direct production threshold

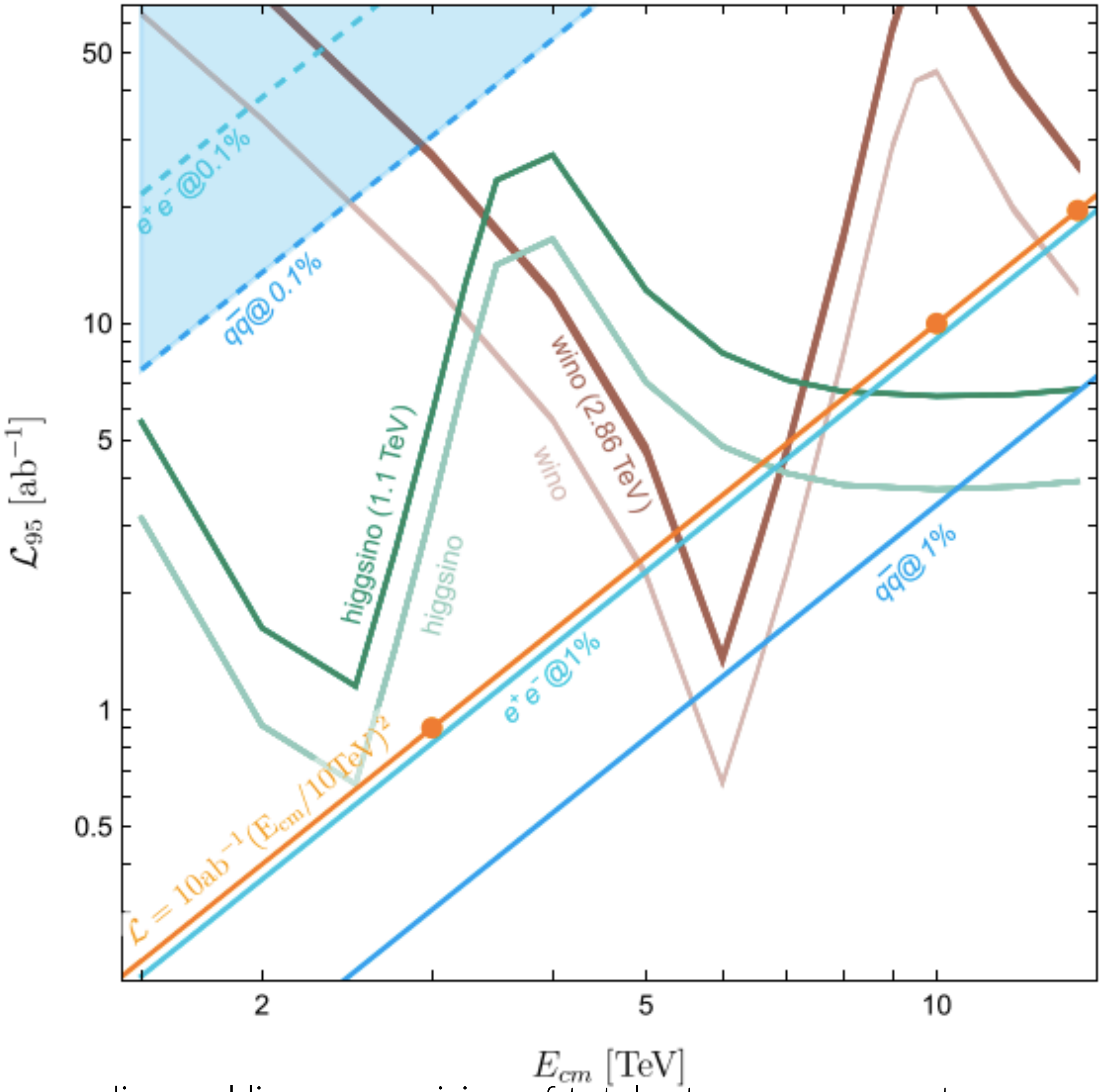


Neutral Current (NC) diagrams



Charged Current diagrams - complementary to NC

Franceschini, Zhao (2022)



diagonal lines = precision of total rate measurement

dark: not polarized
light: polarized (30% LH for μ^- and -30% for μ^+)

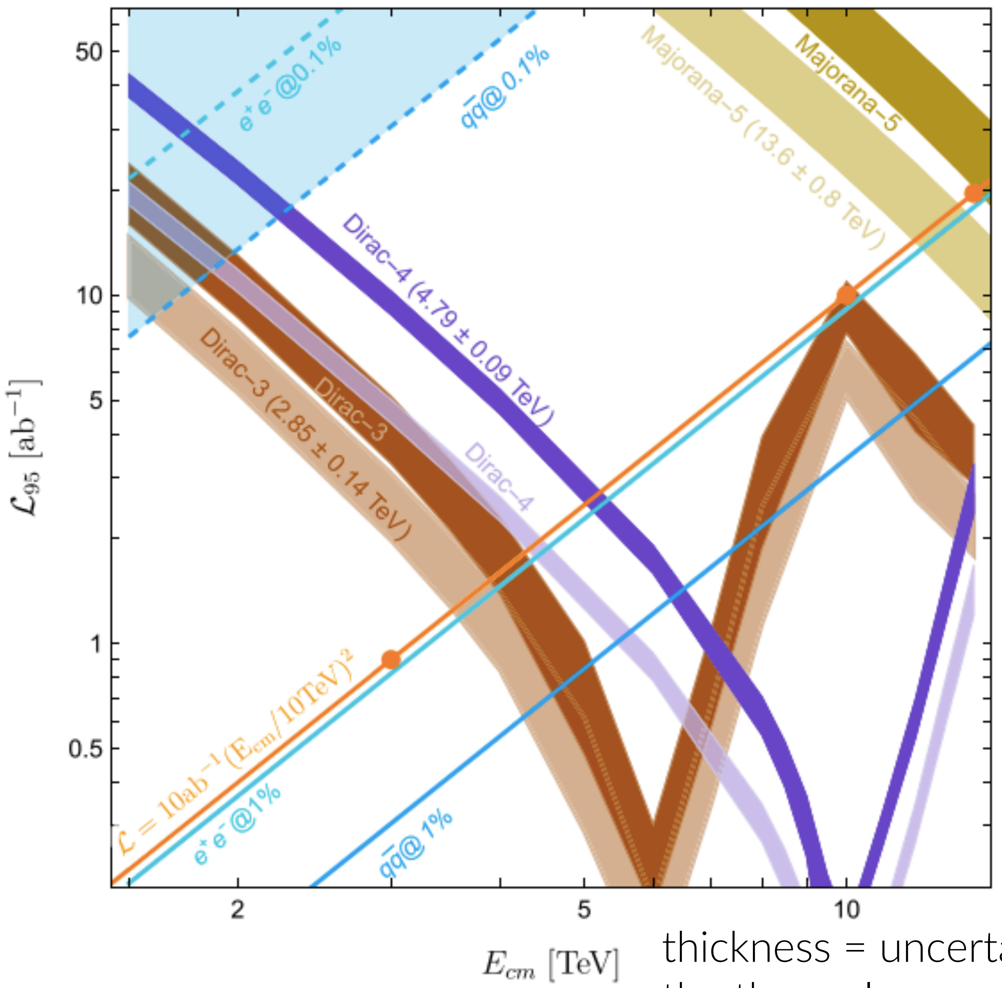
Luminosity features:

- minimum at production threshold $E_{cm}=2M_X$
- increase below threshold for the effect of virtual n-plet (E^2_{cm}/M^2_X)
- increase above threshold for loop function up to second threshold
- smooth decrease

Luminosity required is lower in case of polarized beams because of larger weak boson mediated scattering

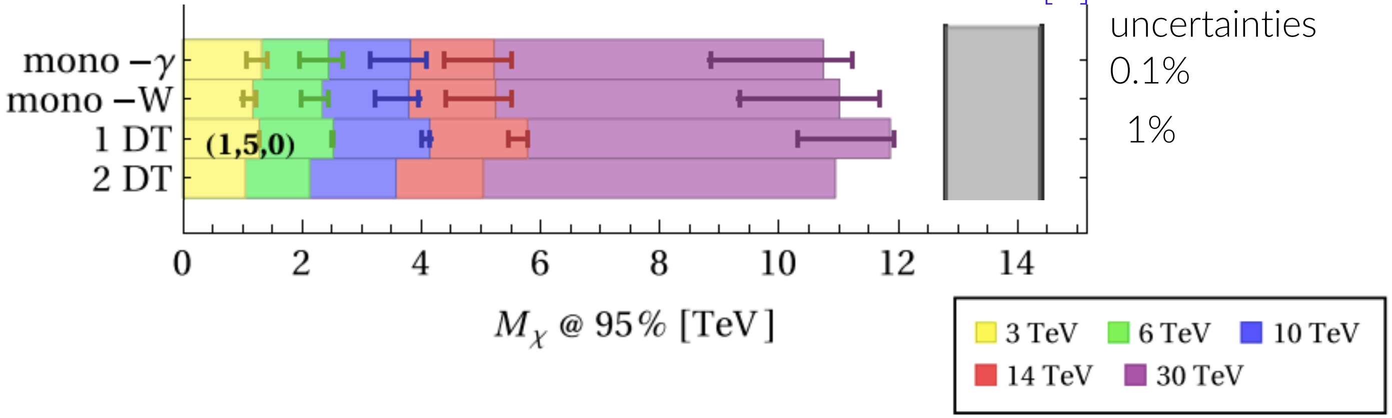
A 10 TeV μC is sensitive to Higgsino

[Franceschini, Zhao (2022)](#)

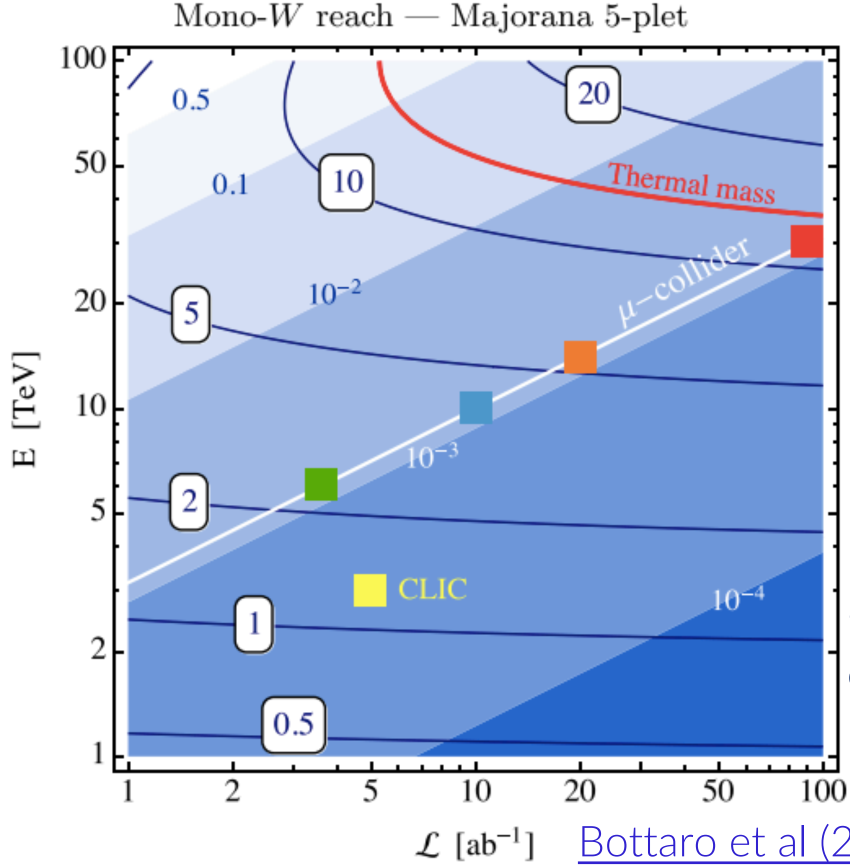


thickness = uncertainty of the thermal mass calculation

Ref. [2]



Systematic uncertainties
0.1%
1%



6 TeV
10 TeV
14 TeV
30 TeV

95% CL reach on mass

[Bottaro et al (2022)](#)

A μC with E_{cm} < 14 TeV is sensitive to all fermionic WIMPs up to n=5

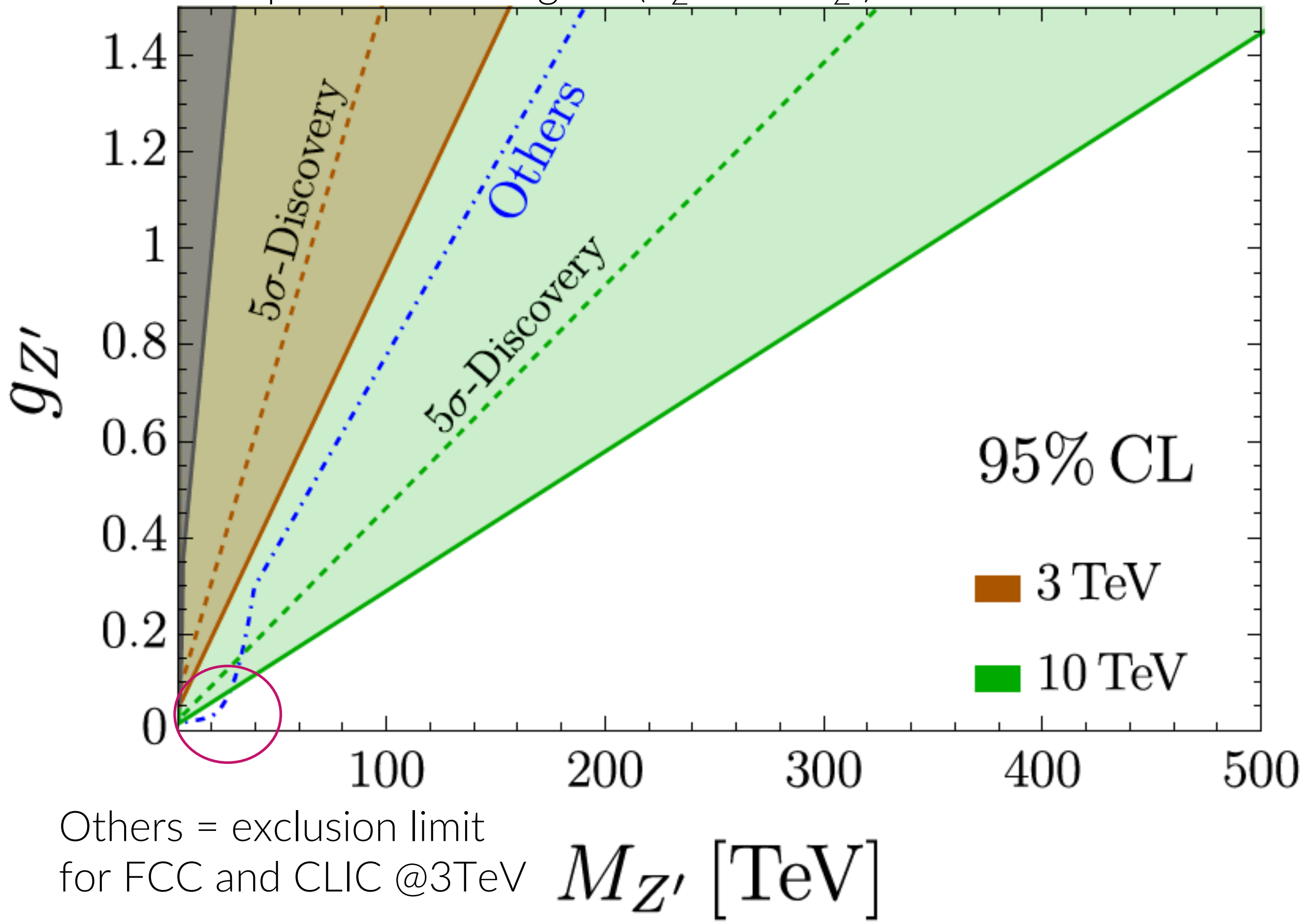
Y universal Z' model

universal parameter $Y = \left(\frac{g_{Z'} m_W}{g' m_{Z'}} \right)^2$

Dimension-6 SM Effective Field Theory

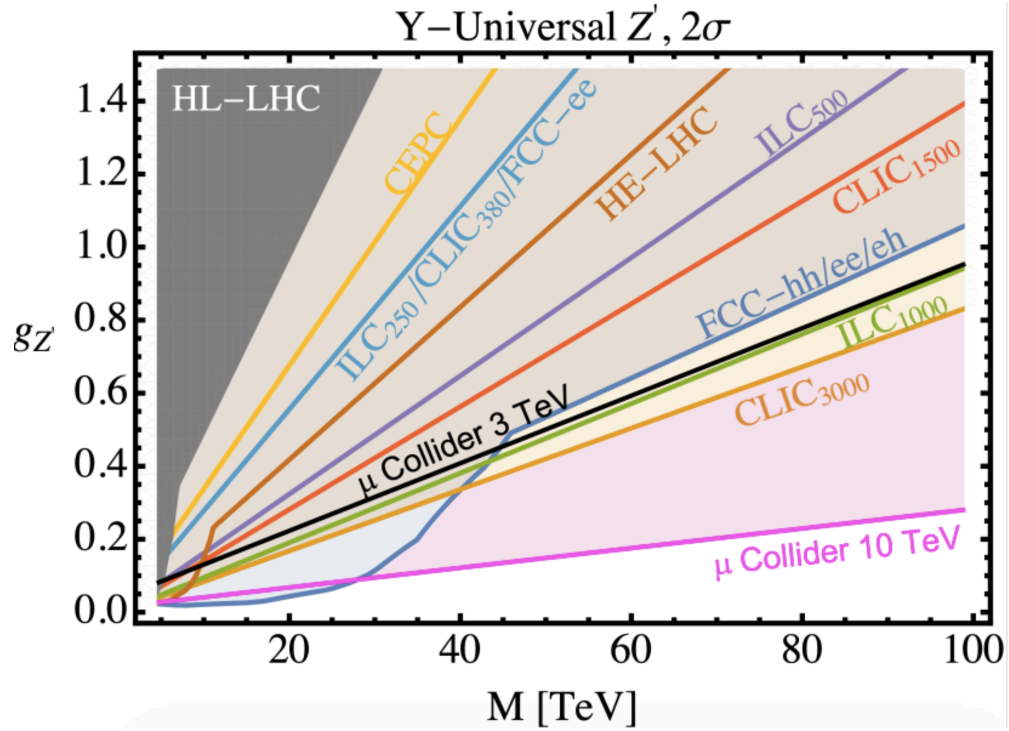
⟶ Simple model: SM + heavy gauge boson Z'

1.5 = limit for perturbative regime ($\Gamma_{Z'} < 0.3 M_{Z'}$) Chen *et al* (2022)



Others = exclusion limit
for FCC and CLIC @3TeV

Physics BSM at Energy Frontier (Snowmass 2021)



A 10 TeV μC has the highest mass reach for a universal Z' with large couplings $g_{Z'}$

exception: $m_{Z'} < 28$ TeV

Composite Higgs

Dimension-6 SM Effective Field Theory
⟶New scenario: Higgs boson as composite particle

Two parameters:
- m* = Higgs compositeness scale, (Higgs radius)$^{-1}$
- g* = effective coupling of the new strongly interacting sector

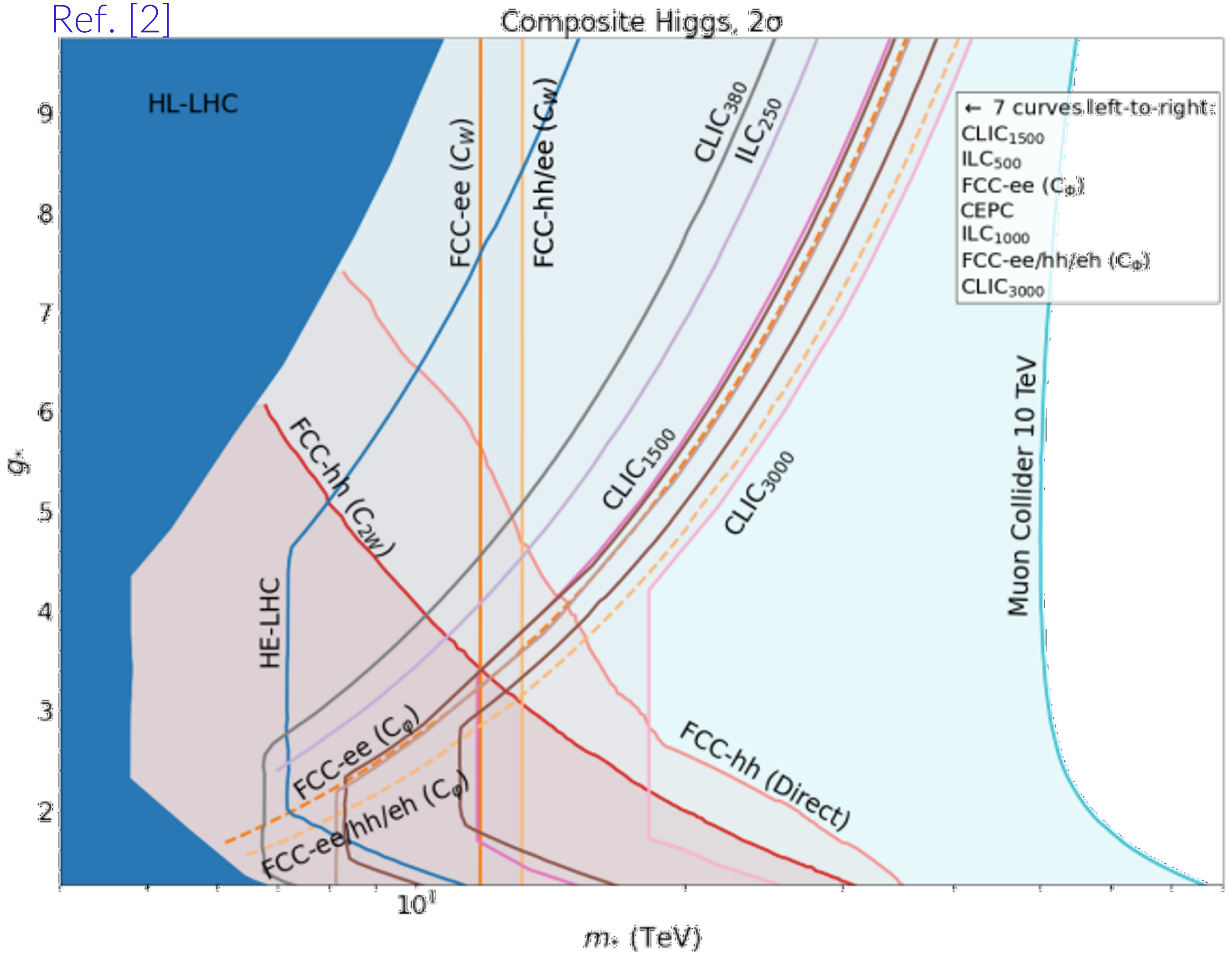
$$C_\phi \sim \frac{g_*^2}{m_*^2}$$ impact on Higgs coupling measurements

$$C_W \sim \frac{1}{m_*^2}$$

$$C_{2W} \sim \frac{1}{g_*^2 m_*^2}$$

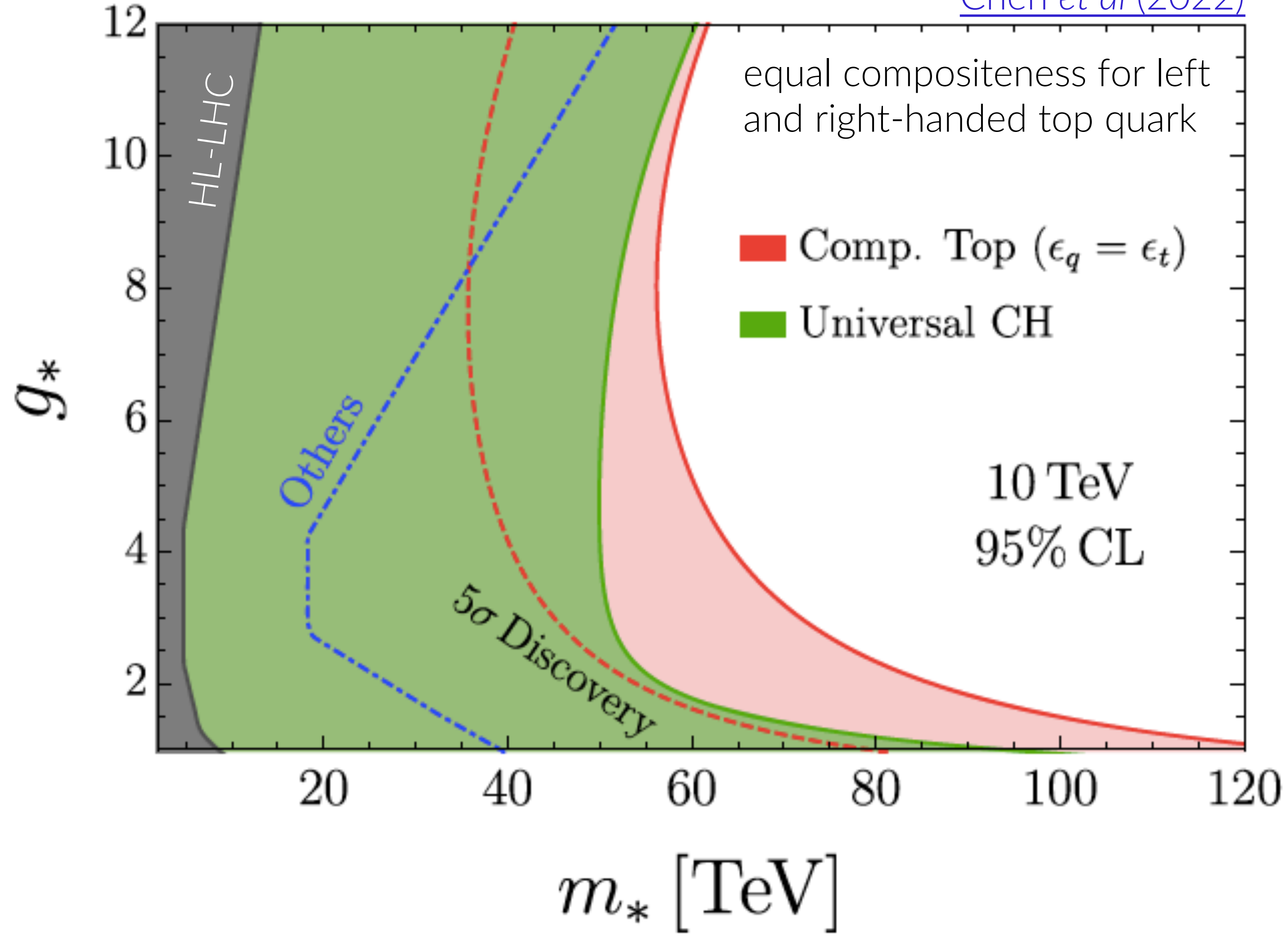
up to 4π (unitarity limit)
Ref. [2]

Physics BSM at Energy Frontier (Snowmass 2021)



Tree level process: $\mu^+\mu^- \to hh\nu\bar{\nu}$
unpolarized beams

Chen *et al* (2022)



Others = 95% CL sensitivity projection for future collider projects

Composite Higgs +
Composite top quark

A 10 TeV μC is a superior device to test this scenario

Precision

Electroweak (EW) sector

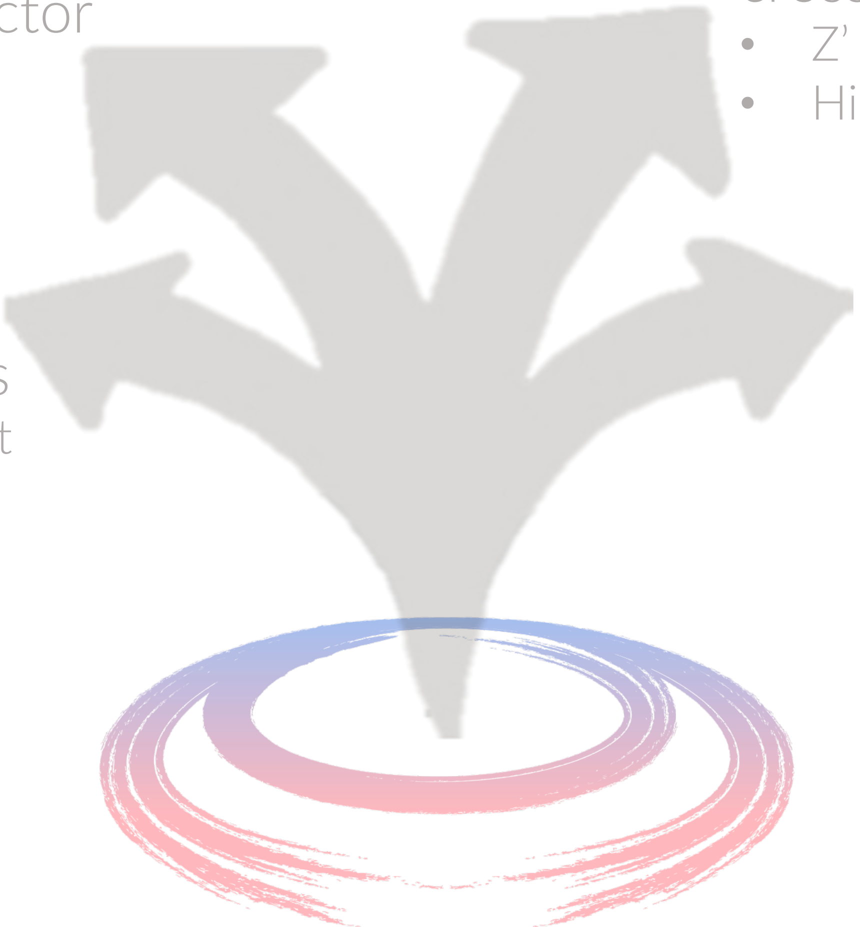
Higgs sector

- double Higgs
- triple Higgs coupling

Energy

new particles

- scalar singlet
- WIMP



Energy & Precision

cross sections measurements

- Z’
- Higgs compositeness

Muons and neutrinos

muon beams

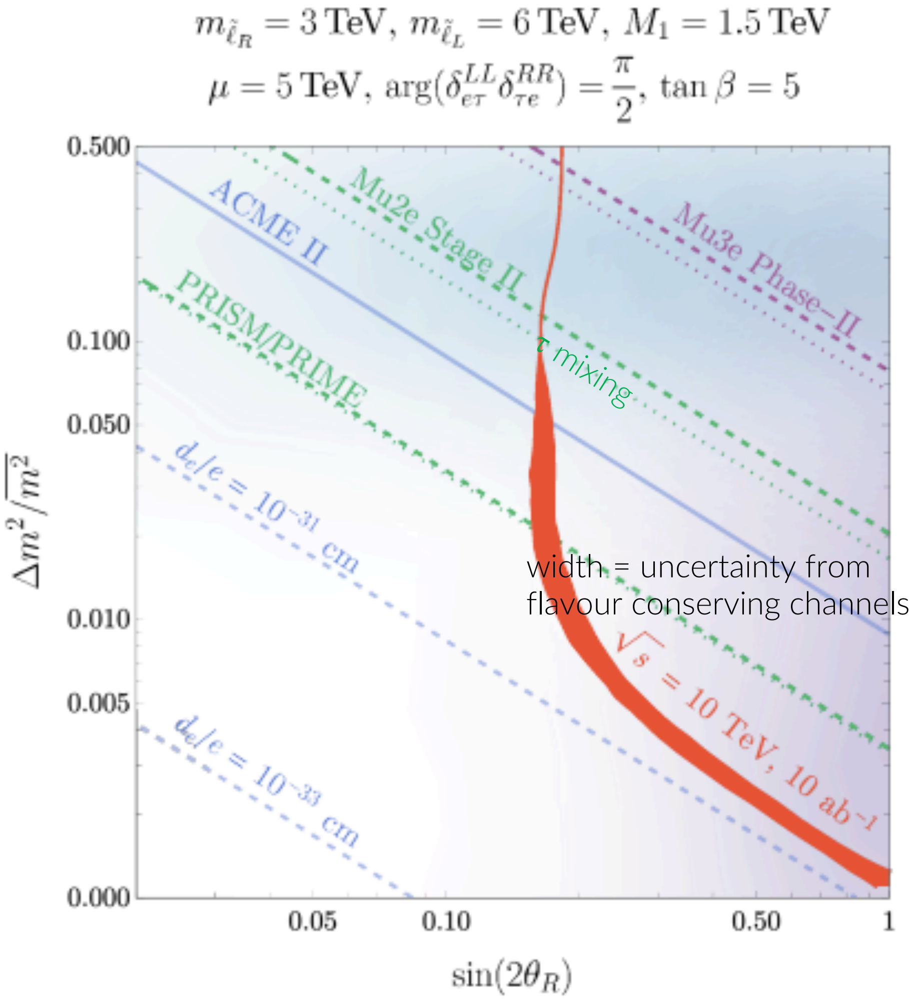
- muon g-2
- leptoquarks

neutrino beams

Lepton Flavour Violation

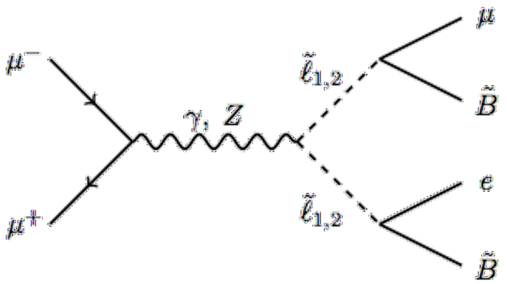
Minimal Supersymmetric Standard Model (MSSM)
⟶ SUSY soft breaking
  ⟶ sleptons mass matrix with off-diagonal contribution
  ⟶ interaction of sleptons and SM leptons mix flavours

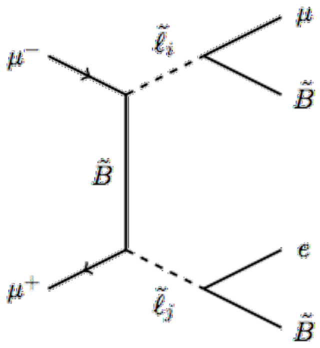
Homiller, Lu, Reece (2022)



Simple model tested with pair production

$$\tilde{l}_j \to l_j \tilde{B}$$





Four parameters:

- $\overline{m}^2$ = mean slepton mass squared
- $\Delta m^2/\overline{m}^2$ = mass splitting
- $\sin(2\theta_R)$ = mixing angle
- M_1 = lightest neutralino mass (bino)

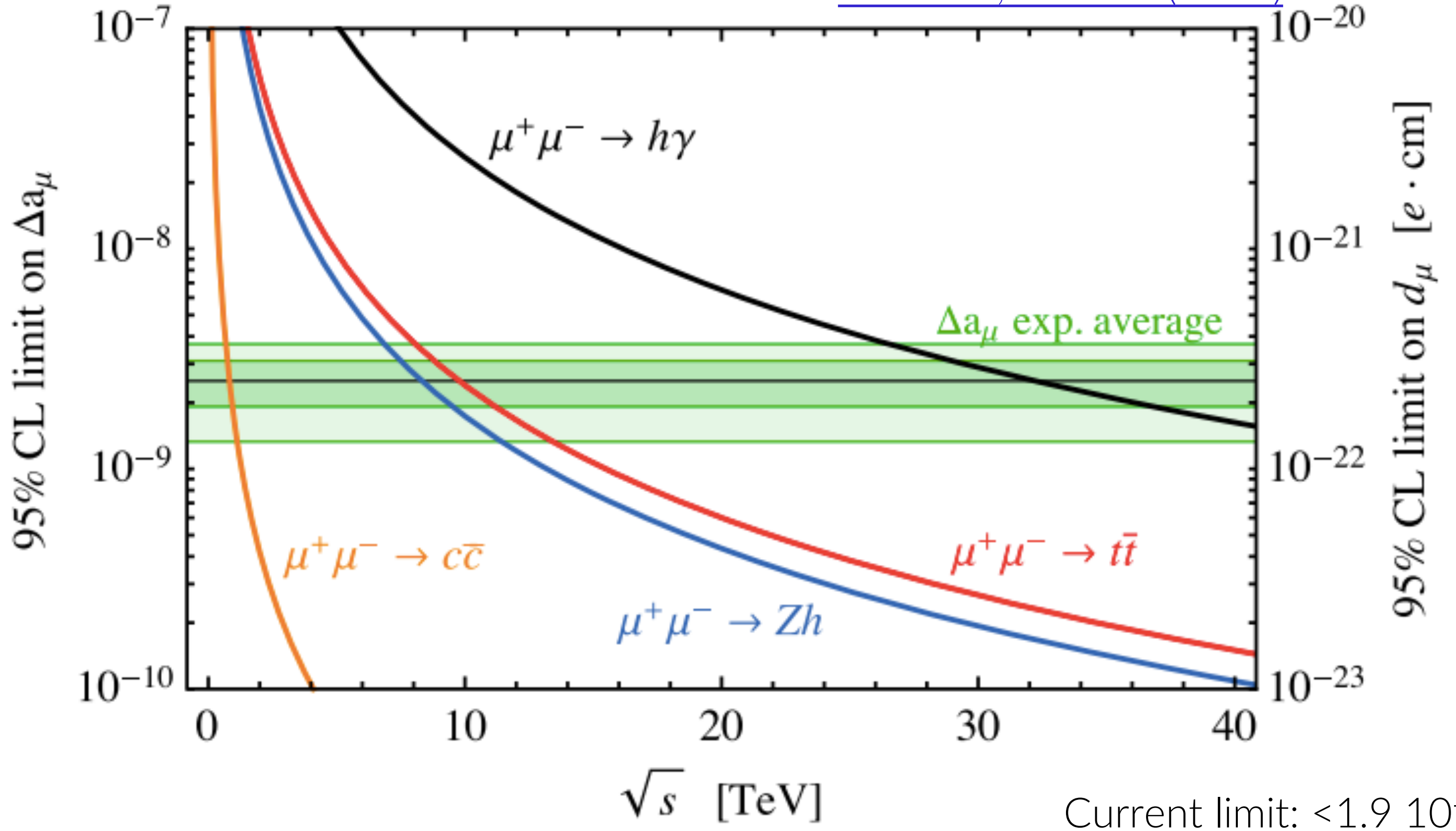
amount of flavour violation $\delta_{\mu e}^{RR} = \Delta m^2/(2\overline{m}^2)\sin(2\theta_R)$

The discovery reach of a 10 TeV μC would cover a large and overlapping range of parameter space to future μ→e and electron EDM experiments

g-2 related measurements

$C_{e\gamma}$, C_{eZ}, C_T: couplings in the effective Lagrangian contributing to g-2
if complex ⟶ muon has an Electric Dipole Moment d_μ

Buttazzo, Paradisi (2021)



$$\frac{d_\mu}{\tan\phi_\mu} = \frac{\Delta a_\mu}{2m_\mu} e \simeq 3 \times 10^{-22} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) e\,\text{cm},$$

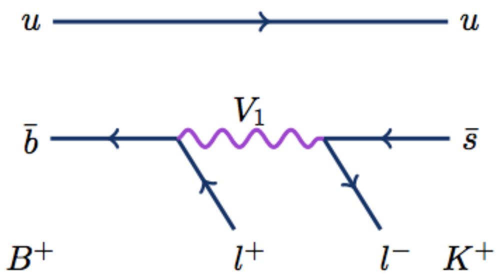
The μC offers a unique opportunity to test the muon EDM with a sensitivity comparable to the one expected at Fermilab and J-PARC

Current limit: <1.9 10^{-19} ecm
BNL E821

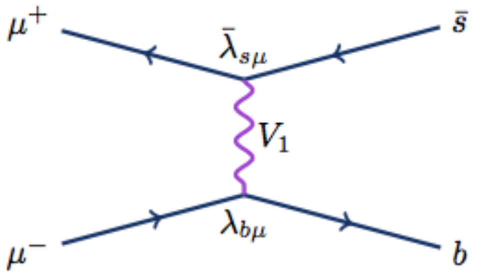
Leptoquarks

Heavy vector singlet

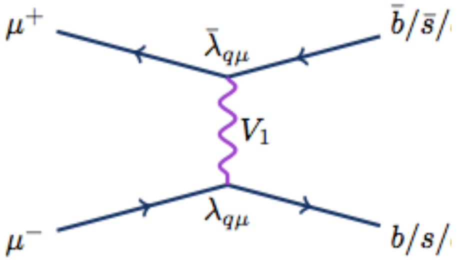
$$\mathcal{L}_{\text{int}} = \left(\lambda_{\bar{Q}L}\bar{Q}_L\gamma_\mu L_L \lambda_{\bar{D}E}\bar{D}_R\gamma_\mu E_R\right) V_1^\mu \qquad \lambda_{\bar{Q}L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \lambda_{s\mu} & \lambda_{s\tau} \\ 0 & \lambda_{b\mu} & \lambda_{b\tau} \end{pmatrix}$$



Final states: di-jet
(jet flavour tagging efficiency as in CMS)



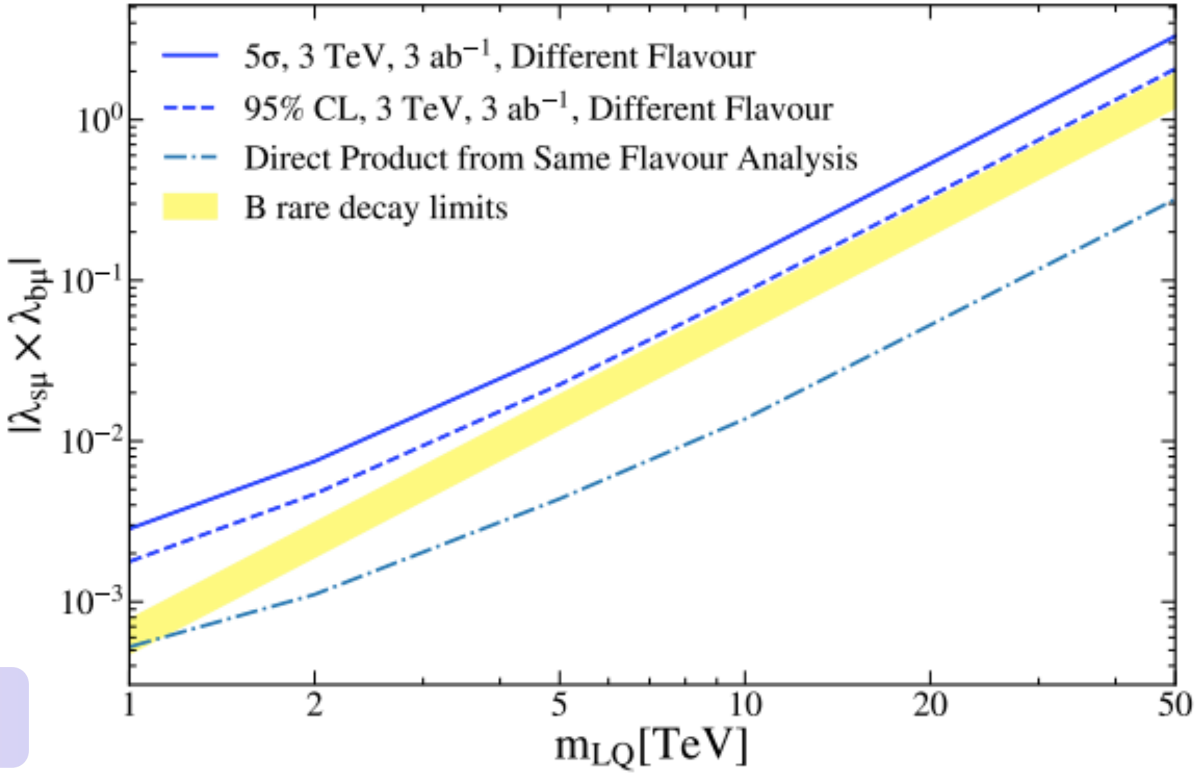
Different flavour



Same flavour

Also: di-jet + dilepton

[Qian *et al* (2021)]

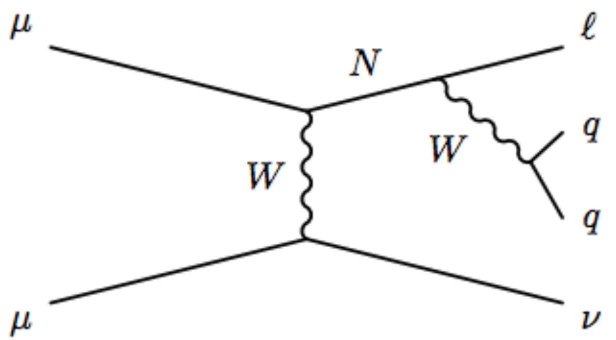


A 3 TeV μC is sufficient to explain B anomalies

Heavy neutral leptons

Phenomenological Type 1- See Saw mechanism

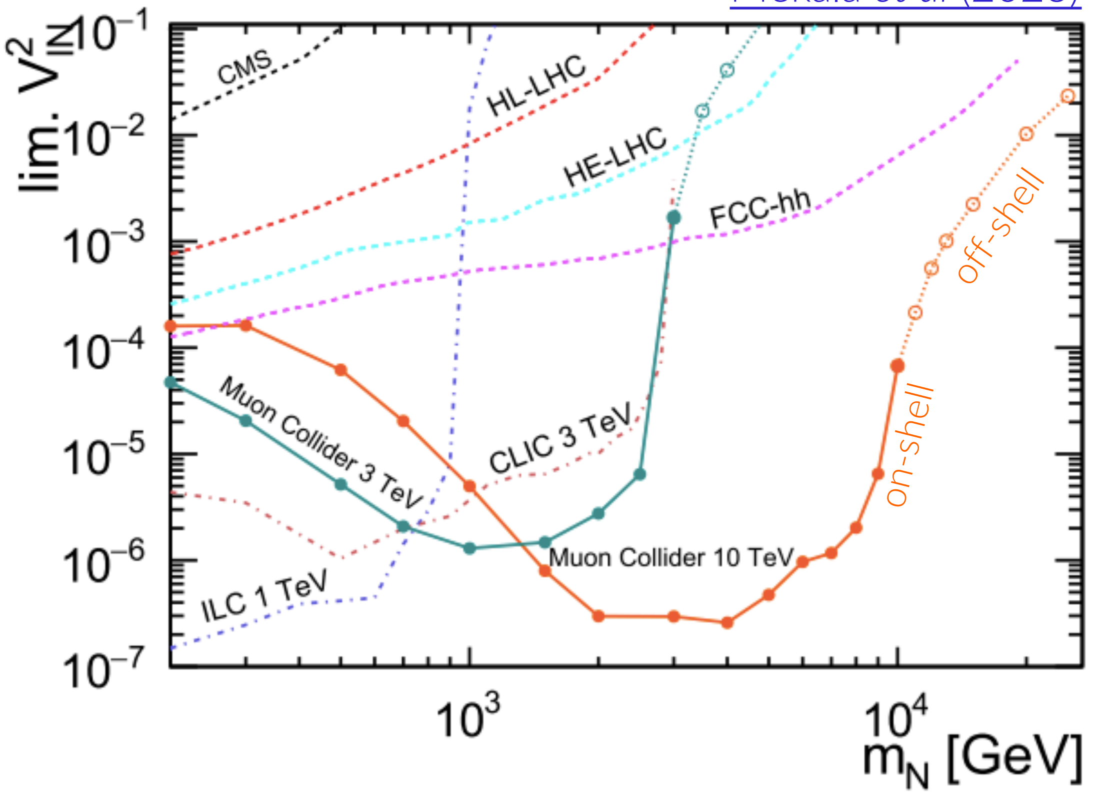
- only one Dirac right-handed heavy neutrino: $m_N \gtrsim m_H$
- equal coupling to all SM leptons V^2_{lN}



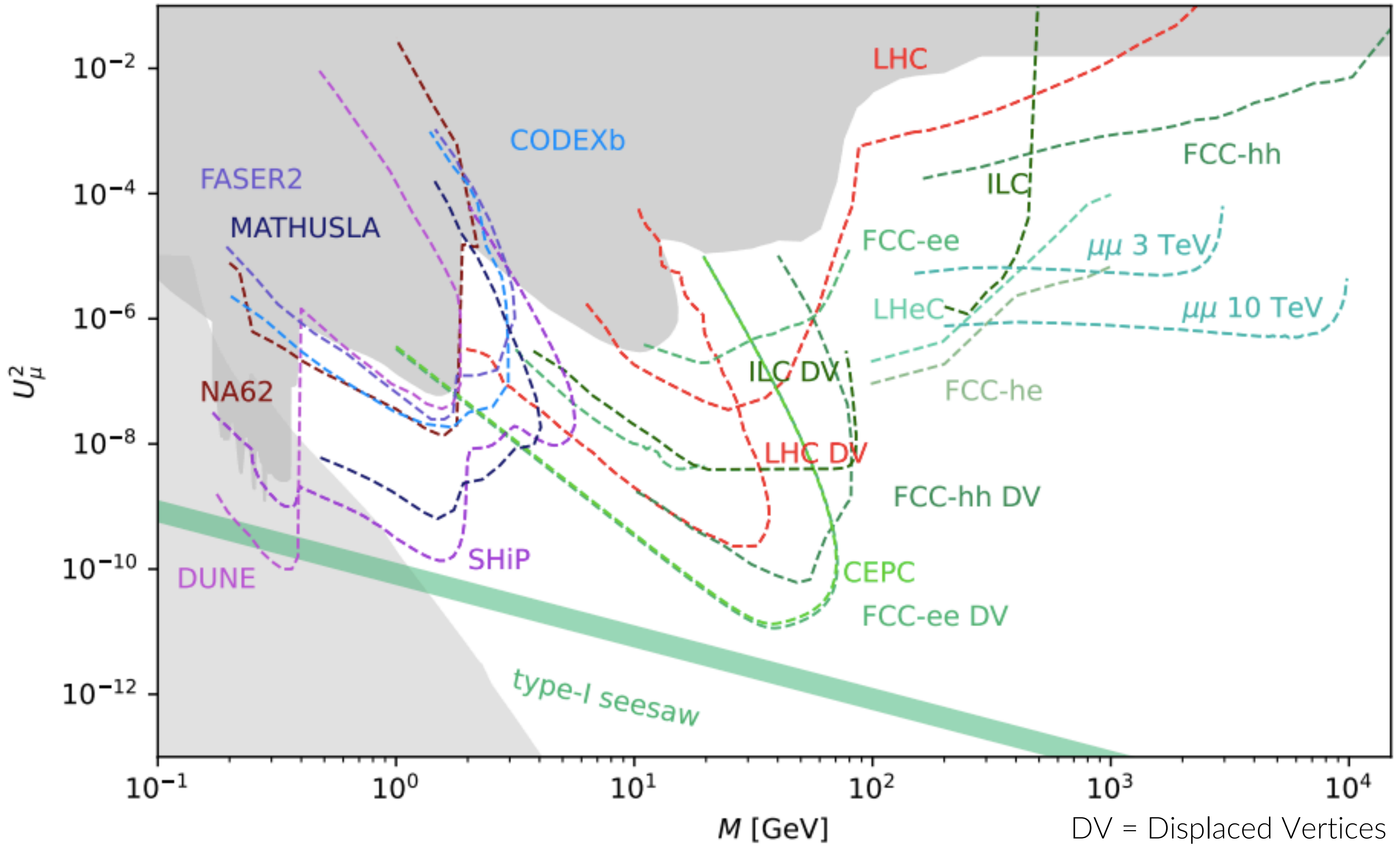
Production channel: t- channel $\mu^+\mu^- \rightarrow N\nu$
(σ = 1-10 fb)
Decay: $N \rightarrow 2\ \text{jet} + \ell + \nu$

Generation and simulation: Whizard +
Pythia +
Delphes

Mekala *et al* (2023)



μC provides the furthest discovery reach for TeV-scale neutrinos



DV = Displaced Vertices

B-L model

Two right-handed neutrinos highly degenerate
⟶ resonant leptogenesis - CP violation ε_i is O(1)
⟶ explanation for Baryon Asymmetry in the Universe with neutrinos masses O(TeV)

$$\epsilon_i = \frac{\sum_j \Gamma_{N_i\to\ell_j H} - \Gamma_{N_i\to\bar{\ell}_j H^*}}{\sum_j \Gamma_{N_i\to\ell_j H} + \Gamma_{N_i\to\bar{\ell}_j H^*}}$$

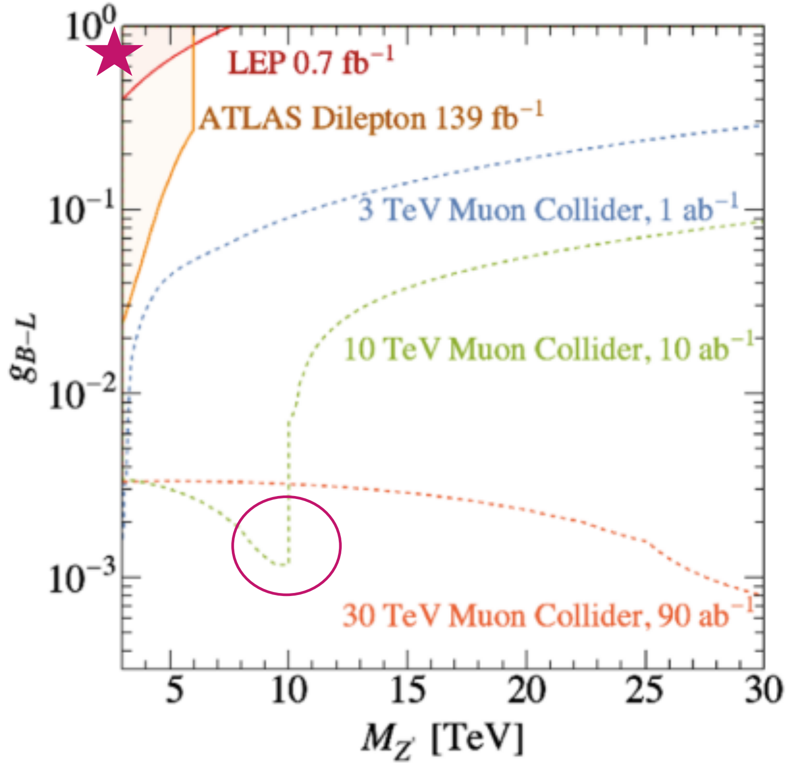
Particles in the model:

- 3 generations of right- handed neutrinos (B-L=-1)
- Z' gauge boson
- Φ complex scalar (B-L=2)

Production: radiative return $\mu^+\mu^- \to Z'\gamma/Z'Z \quad M_{Z'} < \sqrt{s}$

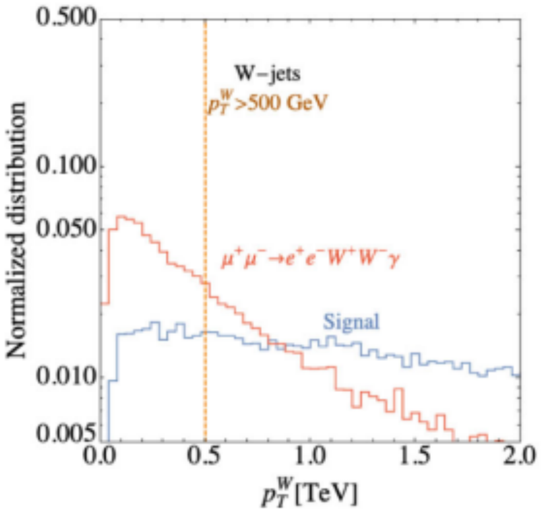
$\mu^+\mu^- \to Z' \quad M_{Z'} > \sqrt{s}$

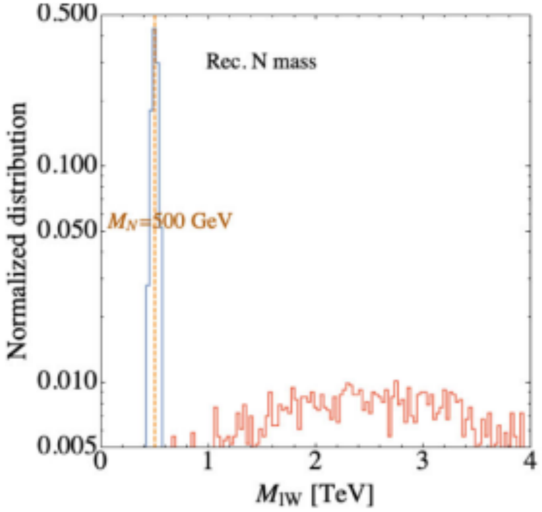
Decay: $Z' \to NN \to \ell^\pm\ell^\pm + \text{jets}$
just first generation of leptons $e^\pm e^\pm W^\mp W^\mp$

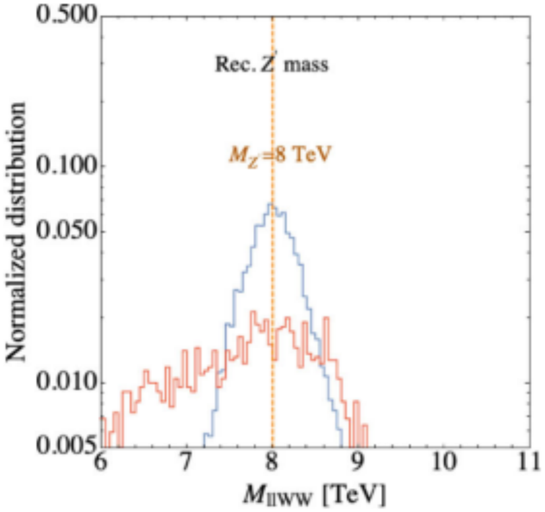


g_{B-L} fixed to 0.8

All figures from
[Liu, Xie, Yi (2022)]

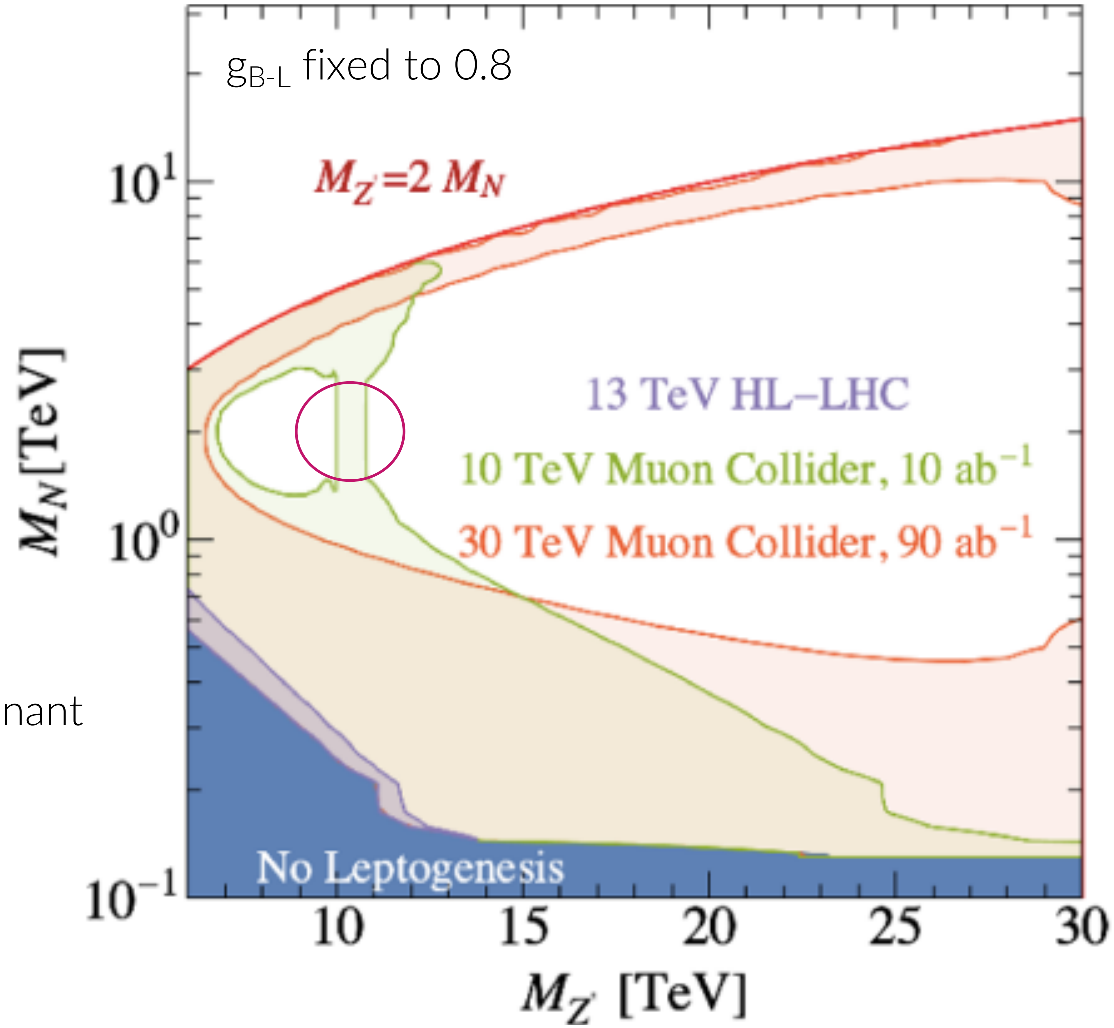






$$\epsilon = \frac{1}{2}\left|\frac{N_+ - N_-}{N_+ + N_-}\right|$$

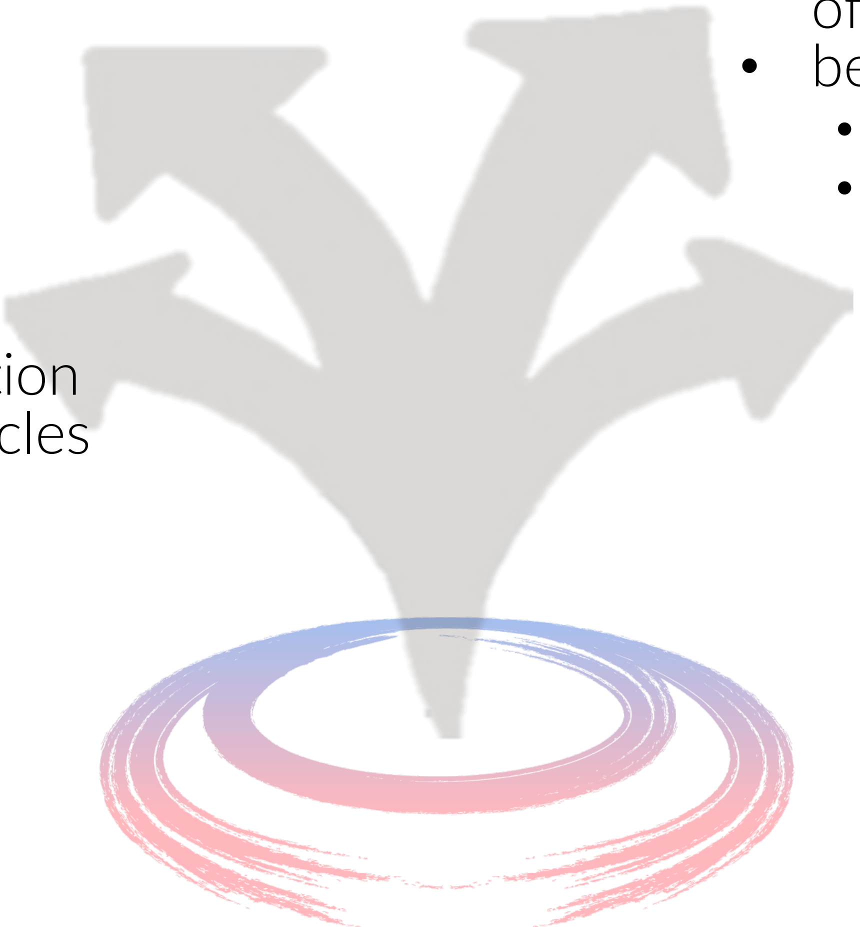
enhancement from resonant production of Z'



A considerable fraction of parameter space can be probed at the future muon colliders

Conclusions

Precision



Energy & Precision

- indirect search for DM with exclusion of many fermionic n-plet
- best reach for:
  - Z'
  - Composite Higgs

Energy

- abundant production of new BSM particles
- high sensitivity to high mass:
  - ALP
  - real scalar
  - WIMPs

Muons and neutrinos

high discovery reach for:

- LFV
- muon EDM
- leptoquark
- HNL

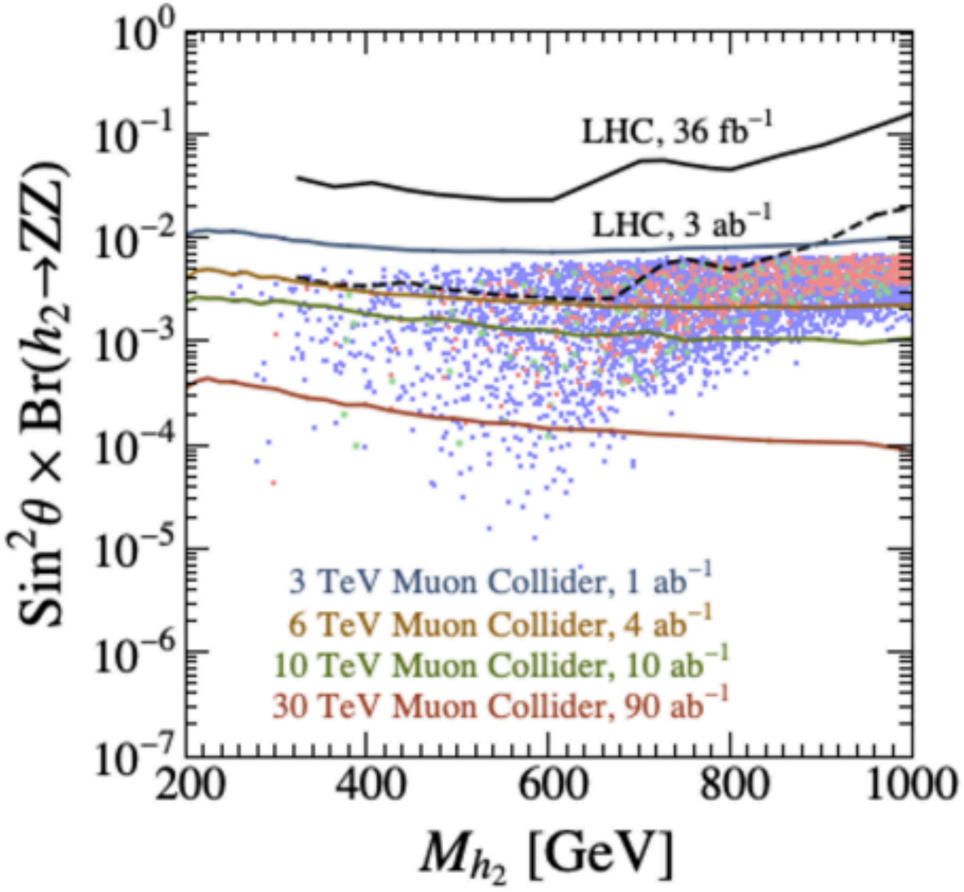
A multi-TeV μC offers a wide and unprecedented physics program

BACKUP

Real singlet extended SM

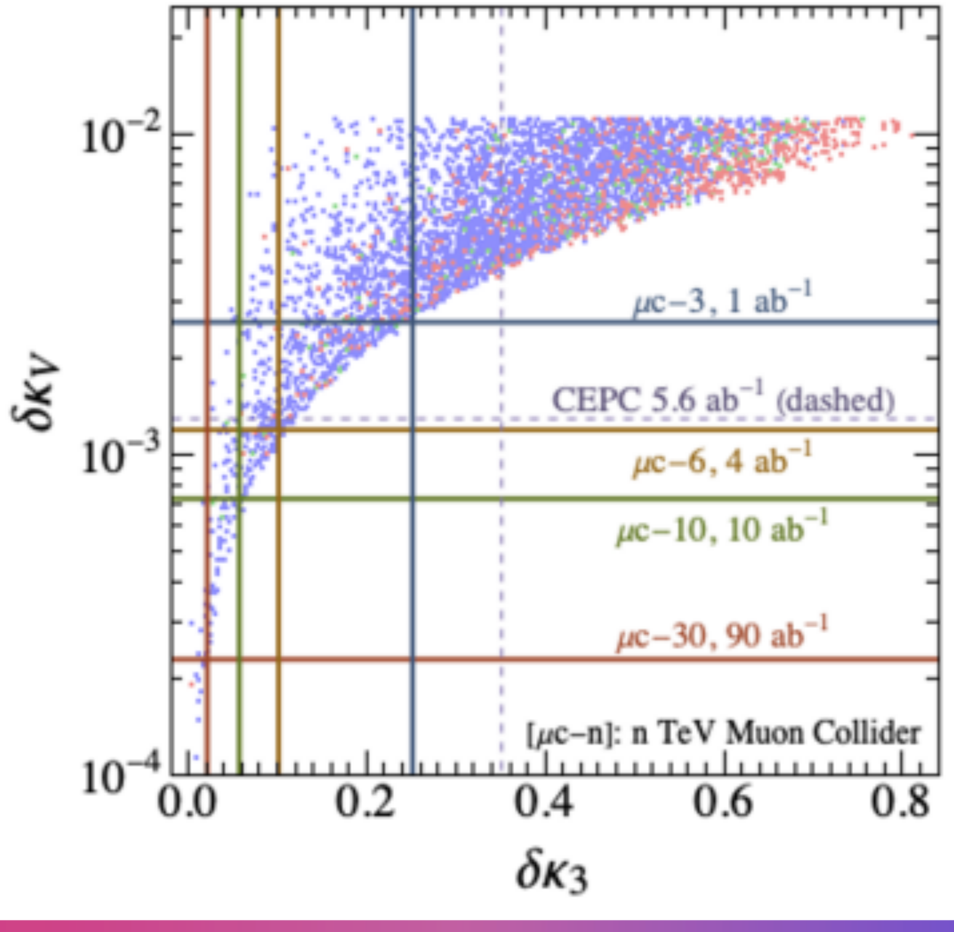
Liu, Xie

Direct search with heavy scalar h_2 decaying in two Z boson leading to 4 leptons



Indirect search

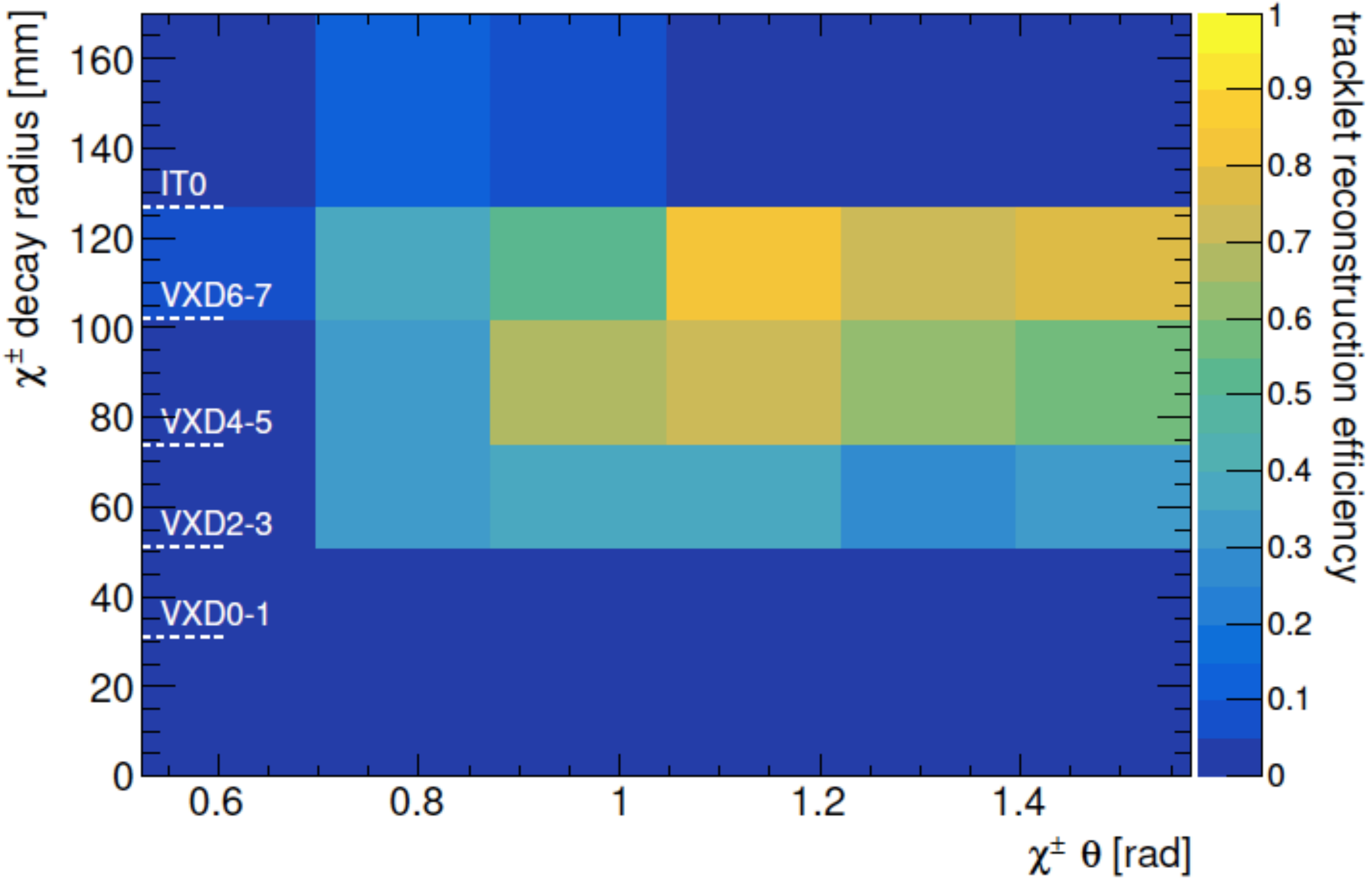
$$\mathcal{L}_{\rm xSM} \supset \kappa_V \left(M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu \right) \frac{2h_1}{v} - \kappa_3 \frac{M_h^2}{2v} h_1^3,$$



2° detection strategy: DISAPPEARING TRACKS (DT)

Tracklet reconstruction efficiency

All figures from
[Capdevilla *et al* (2021)]



Efficient track = 70% of total hits associated to the track are matched to the generator level X
Reconstructable track = X transverses at least 4 layers
Tracklet = veto hits in the first layer of the IT

Lepton Flavour Violation

Homiller, Lu, Reece (2022)

Explanation of the deterioration in $\sin(2\theta_R)$

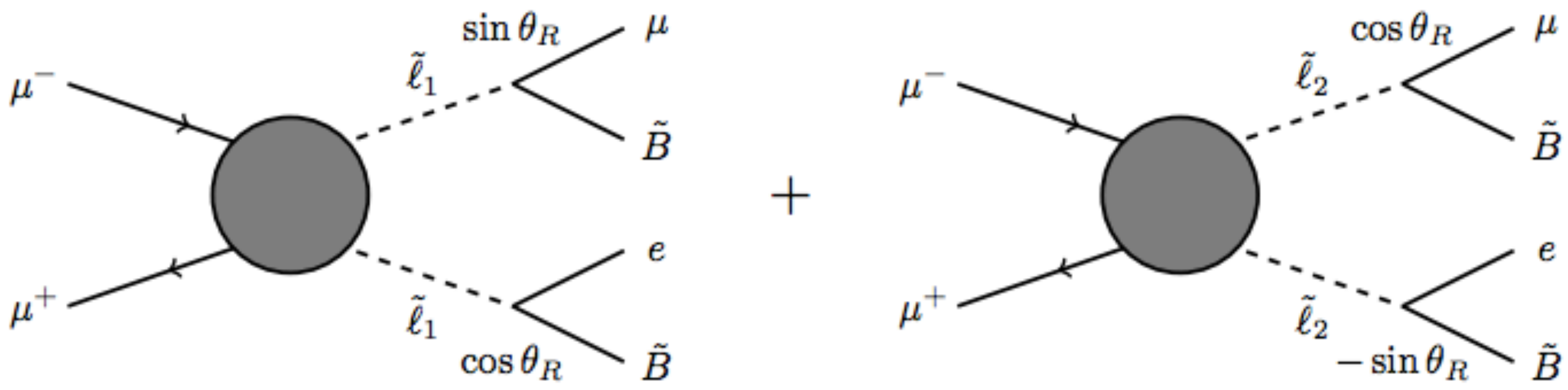


Figure 5. When mass splitting of the two mass eigenstates are small, interference between the two Feynman diagrams suppresses signal cross section due to the opposite coupling.