Indirect Searches of New Physics

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ENP Collaboration Meeting 2025
19/05/2025

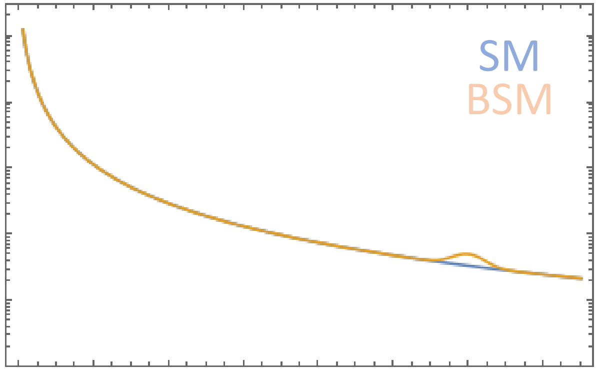
Indirect vs Direct

Direct Searches

Direct production of **new particles**

Most amount of information
Limited by collider energy

Cross-Section



Energy

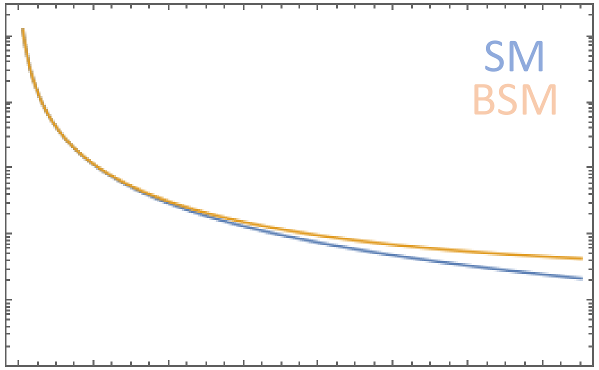
Indirect Searches

EFT

Precision tests of SM couplings
Measure rate of **rare processes**
High-Energy probes

Can probe scales above collider energy
Interpretation is less clear

Cross-Section



Energy

Effective Field Theories

Many EFTs for the **many SM energy scales**

$\sim m_?$

$\sim m_{t,Z,W,h}$

$\sim m_b$

$\sim m_c$

$\sim \Lambda_{QCD}$

SMEFT → EW physics: Higgs, W, Z, top → $\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{d,i} \frac{C_{d,i}^{\rm SMEFT}}{\Lambda^{d-4}} \mathcal{O}_{d,i}^{\rm SMEFT}$

RGE

RGE + Matching

LEFT → B physics, D physics → $\mathcal{L}_{\rm LEFT} = \mathcal{L}_{\rm QDE+QCD} + \sum_{d,i} \frac{C_{d,i}^{\rm LEFT}}{\Lambda^{d-4}} \mathcal{O}_{d,i}^{\rm LEFT}$

χPT → Light meson physics

...

SMEFT structure

At d = 6 there are **59+4 independent operators**

X^3 H^6 H^4D^2 X^2H^2	15 – **Bosonic**	Higgs & gauge mass and couplings modifications
ψ^2H^3 ψ^2H^2D ψ^2XH	19 – **2 Fermion**	Yukawa, gauge couplings, dipoles
ψ^4	25 – **4 Fermion**	Fermion contact interactions

+4 Baryon number violating, strong bounds from proton decay

Operators with fermions have **flavor indices**, so the number of coefficients is actually **much larger than 59**

Flavor hypotheses

One can do many different **assumptions** on the BSM physics to reduce the parameter space

More structure
Less parameters

Less structure
More parameters

No flavor violation

$(\bar{\psi}^i_{L/R}\psi^j_{L/R}) \propto \delta^{ij}$ $\quad (\bar{\psi}^i_{R/L}\psi^j_{L/R}) \propto Y^{ij}_\psi$ $\quad U(3)^5$ "Universal models"

Minimal flavor violation

$(\bar{\psi}^i_{L/R}\psi^j_{L/R}) \propto (Y^2)^{ij}$ $\quad (\bar{\psi}^i_{R/L}\psi^j_{L/R}) \propto Y^{ij}_\psi$ Yukawas only source of flavor violation

Anarchy

$(\bar{\psi}^i_{L/R}\psi^j_{L/R}) \propto (C)^{ij}$ $\quad (\bar{\psi}^i_{R/L}\psi^j_{L/R}) \propto C^{ij}$ Everything is allowed

+ many other possibilities…

Global Fit inputs

A complete picture of the current constraints can be obtained by global fits

→ Combination of most currently known measurements + predictions

- **EW precision**: Z pole observables, W mass/width, masses, …
- **Higgs observables**: cross sections & decay rate
- **Top quark**: pp -> tt, pp -> tt+X, pp -> t + X
- **Drell-Yan**: pp -> ff
- **Diboson**: pp -> VV
- **Flavor**: $\Delta F = 2$ transition, leptonic/semileptonic/radiative decays

HEPfit

All the running and matching procedures are automatized through software

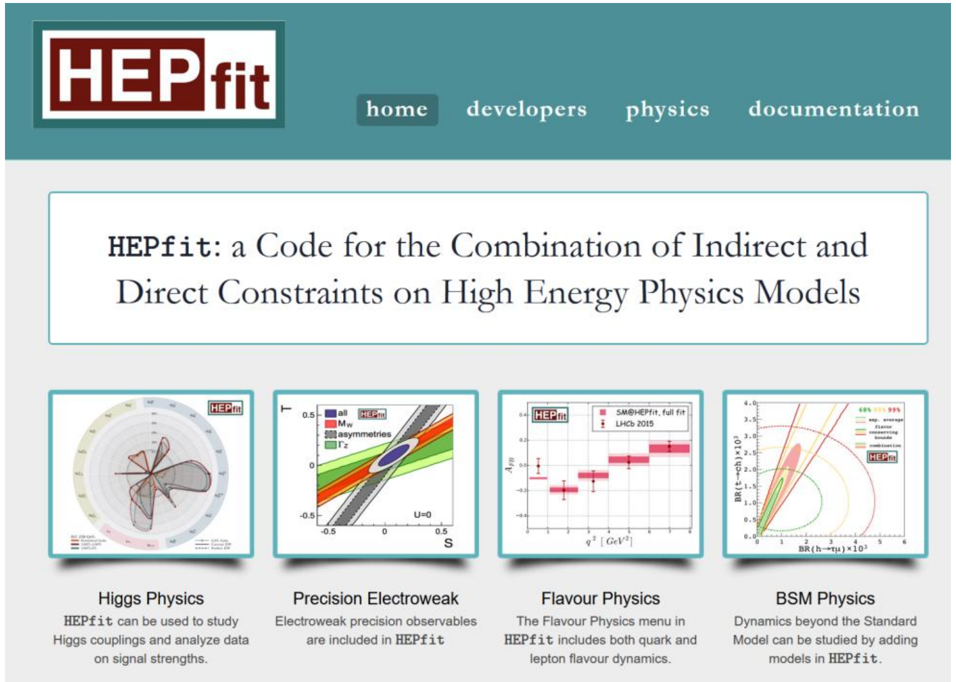
HEPfit is an open source framework for **SM & SMEFT analyses**

Statistical framework based on a **Bayesian MCMC** approach

Implemented **SM** and **SMEFT** models with automatic **RGE**

Various SMEFT Flavor structures still WIP

$$\begin{tikzcd} \text{Model} \arrow[r] & \text{Predictions} \arrow[d] \\ \text{Observations} \arrow[r] & \text{Statistical Inference} \end{tikzcd}$$



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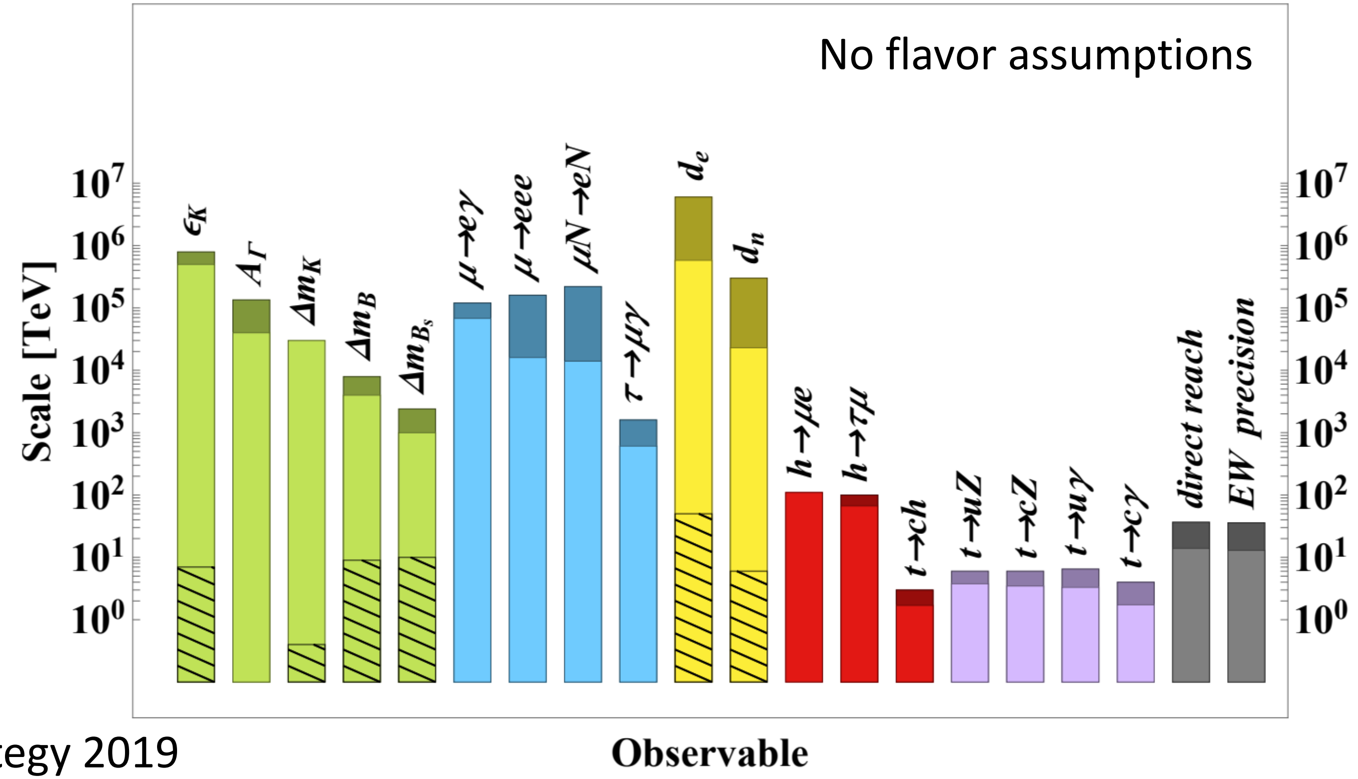
Indirect probes

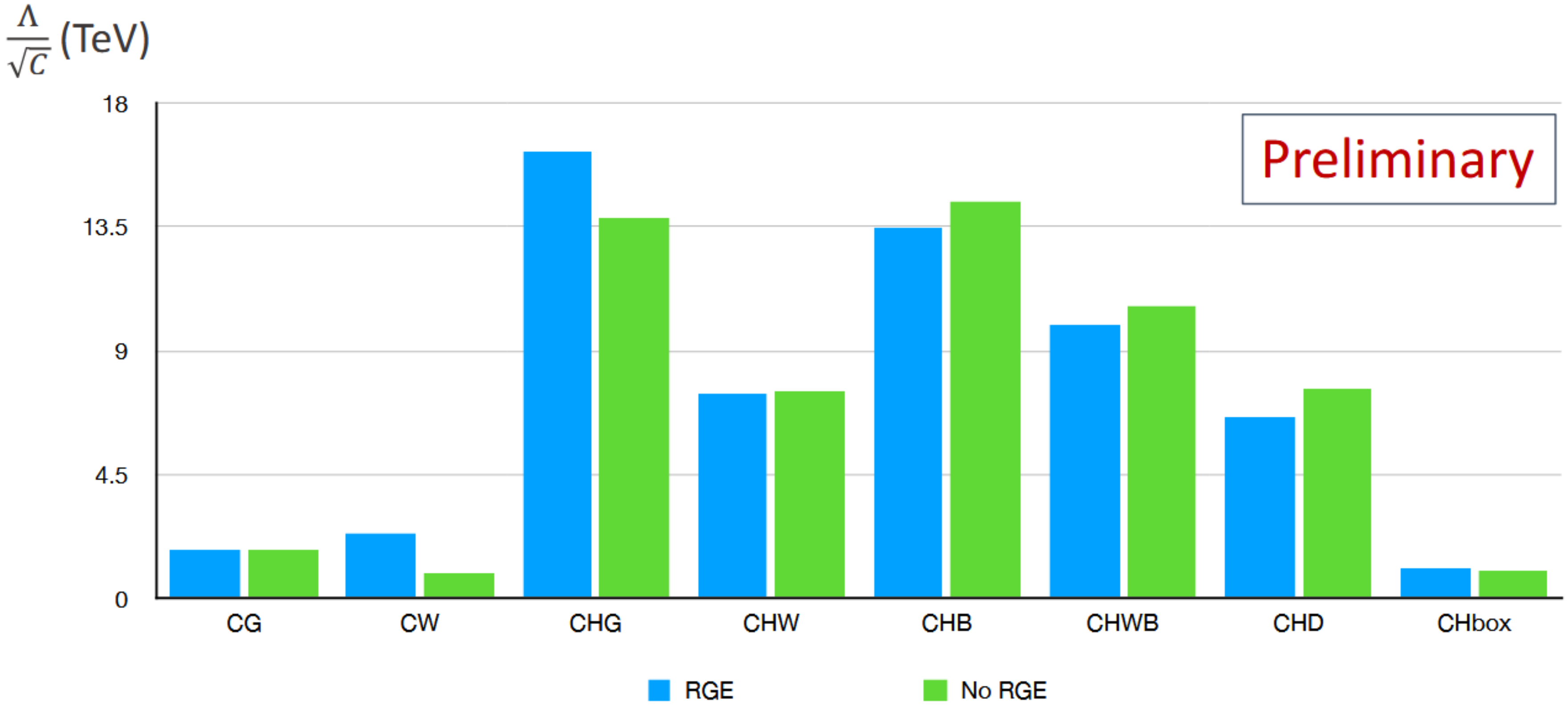
Precision measurements can indirectly probe scales much higher than the energies of colliders



European strategy 2019

Lower bounds on NP scale - Bosonic operators

SU(2)^5 - Global fit
one operator at a time



Bound on scale depends on assumptions on WC
Λ_{max} for $C \sim 4\pi \times O(1)$

$$\mathcal{O}_G = f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$$

$$\mathcal{O}_W = \varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$$

$$\mathcal{O}_{\phi G} = \phi^\dagger \phi\, G^A_{\mu\nu} G^{A\mu\nu}$$

$$\mathcal{O}_{\phi W} = \phi^\dagger \phi\, W^I_{\mu\nu} W^{I\mu\nu}$$

$$\mathcal{O}_{\phi B} = \phi^\dagger \phi\, B_{\mu\nu} B^{\mu\nu}$$

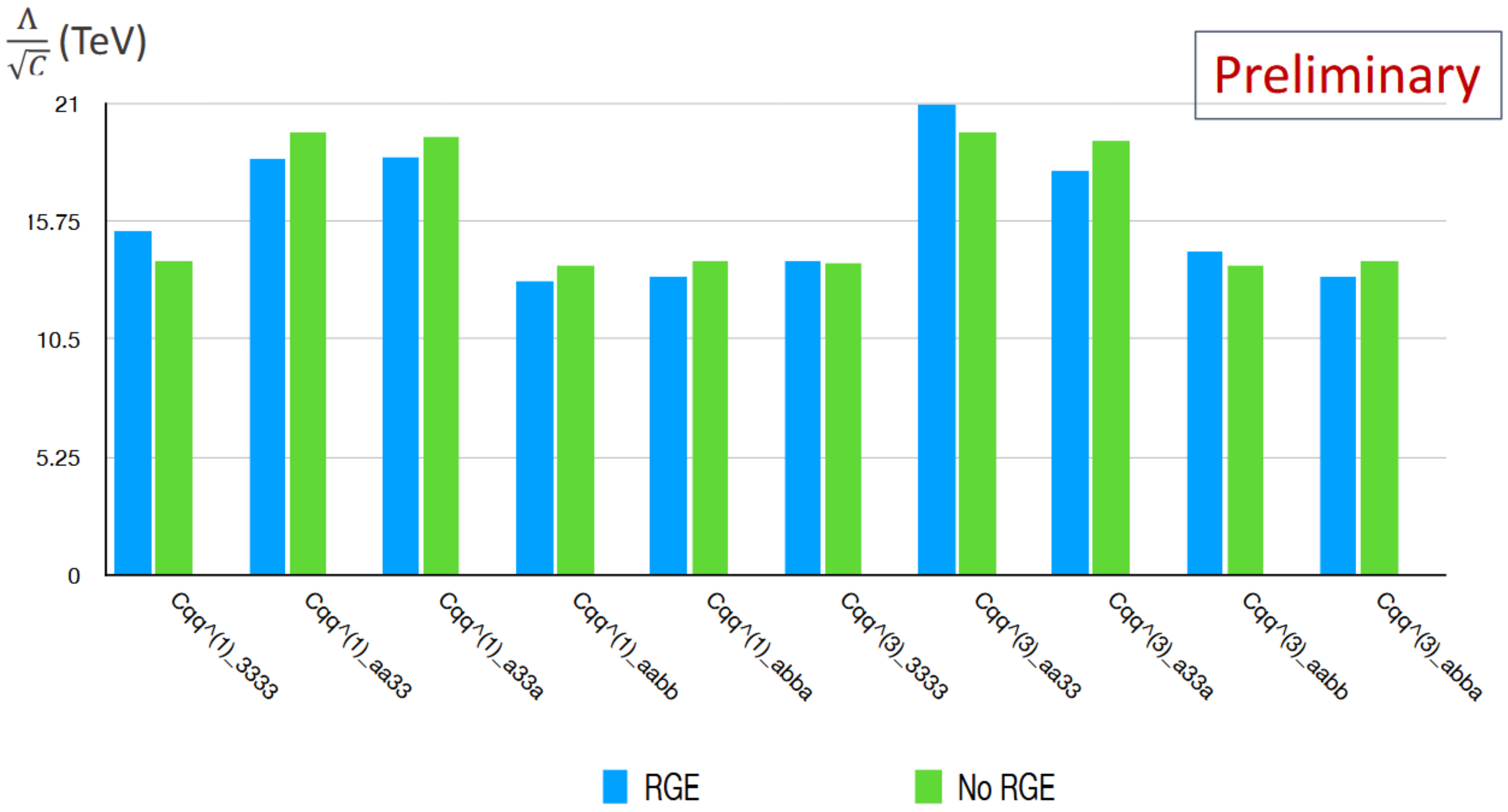
$$\mathcal{O}_{\phi WB} = \phi^\dagger \tau^I \phi\, W^I_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_{\phi \Box} = (\phi^\dagger \phi) \Box (\phi^\dagger \phi)$$

$$\mathcal{O}_{\phi D} = \left(\phi^\dagger D^\mu \phi\right)^\star \left(\phi^\dagger D_\mu \phi\right)$$

- **Most important effects from EW and Higgs observables**
  - Very strong bound from main Higgs production mode ($gg \to H$)
- RGE can enhance/suppress sensitivity to NP

Lower bounds on NP scale – Effect of B^0-$\bar{B}^0$ mixing



SU(2)^5 - Global fit
one operator at a time

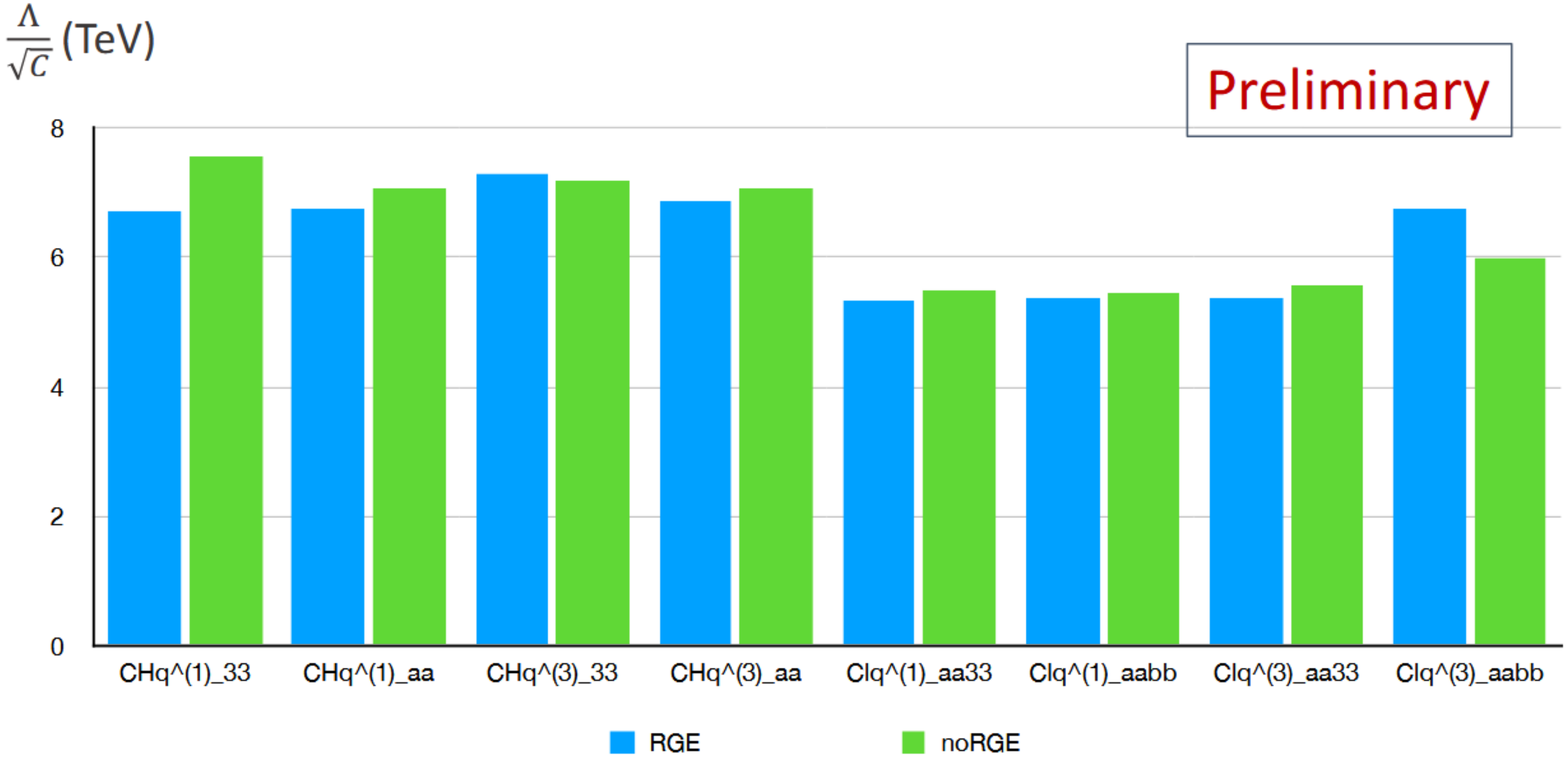
Bound on scale depends on assumptions on WC
Λ_{max} for $C \sim 4\pi \times O(1)$

(LL- 4f operators)

$$\mathcal{O}_{qq}^{(1)[prst]} = (\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$$
$$\mathcal{O}_{qq}^{(3)[prst]} = (\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$$

- Much **higher lower bound** on NP scales
- **Bound entirely from flav**our
- RGE can enhance/suppress sensitivity to NP

Lower bounds on NP scale – Effect of $B_s \to \mu^+\mu^-$



SU(2)⁵ - Global fit
one operator at a time

Bound on scale depends on assumptions on WC
Λ_{max} for $C \sim 4\pi \times O(1)$

$$\mathcal{O}_{lq}^{(1)[prst]} = (\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$$

$$\mathcal{O}_{lq}^{(3)[prst]} = (\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$$

$$\mathcal{O}_{\phi q}^{(1)[pr]} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{q}_p \gamma^\mu q_r)$$

$$\mathcal{O}_{\phi q}^{(3)[pr]} = (\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi)(\bar{q}_p \tau^I \gamma^\mu q_r)$$

- **Higher lower bound** on NP scales
- **Bound mainly from flavour**
- RGE can slightly enhance/suppress sensitivity to NP
- Pattern may be complicated by full global fit

Interpretation

SMEFT analyses give **indirect bounds** on the **new physics scale** Λ

What is the relation between this Λ and the mass at which we could find new particles?

How can we compare SMEFT bounds and direct searches into the same parameter space?

How do the various indirect searches and measurement influence each other?

The only way to answer all these questions is through a **concrete model** of the UV physics

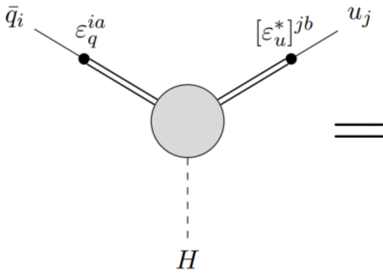
Example: Composite Higgs

SM without Higgs

Strongly Interacting Higgs EFT

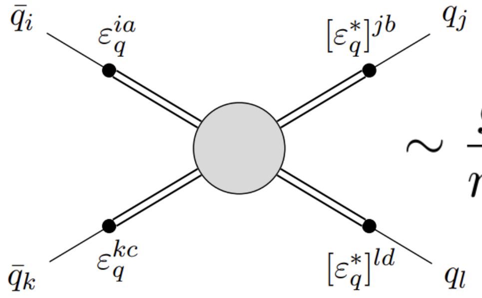
$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM'} + \frac{m_*^4}{g_*^2}\widehat{\mathcal{L}}_{\rm EFT}\left(\frac{g_* H}{m_*}, \frac{D_\mu}{m_*}, \frac{\lambda_\psi^{ia}\overline{\psi}^i}{m_*^{3/2}}, \frac{g_*^2}{16\pi^2}, \frac{g^2}{16\pi^2}, \frac{[\lambda_\psi^*]^{ia}\lambda_\psi^{ib}}{16\pi^2}\right),$$

Possible loop factors



$$\Longrightarrow Y_u^{ij} \sim g_* \varepsilon_q^i \varepsilon_u^j$$

Up to O(1) factors



$$\sim \frac{g_*^2}{m_*^2}\varepsilon_q^i\varepsilon_q^j\varepsilon_q^k\varepsilon_q^l(\overline{q}^i\gamma_\mu q^j)(\overline{q}^k\gamma^\mu q^l)$$

$$\varepsilon_\psi \equiv \lambda_\psi / g_*$$

Flavor Anarchy

Anarchic partial compositeness: structureless O(1) flavor and CP violating coefficients

Leptons

Electron EDM

$$m_* \gtrsim 2200 \frac{g_*}{4\pi}\ \mathrm{TeV}$$

μ → e γ

$$m_* \gtrsim 250 \frac{g_*}{4\pi}\ \mathrm{TeV}$$

Quarks

ΔF = 2 & b → s γ

$$m_* \gtrsim 20 - 30\ \mathrm{TeV}$$

D meson CP asymm

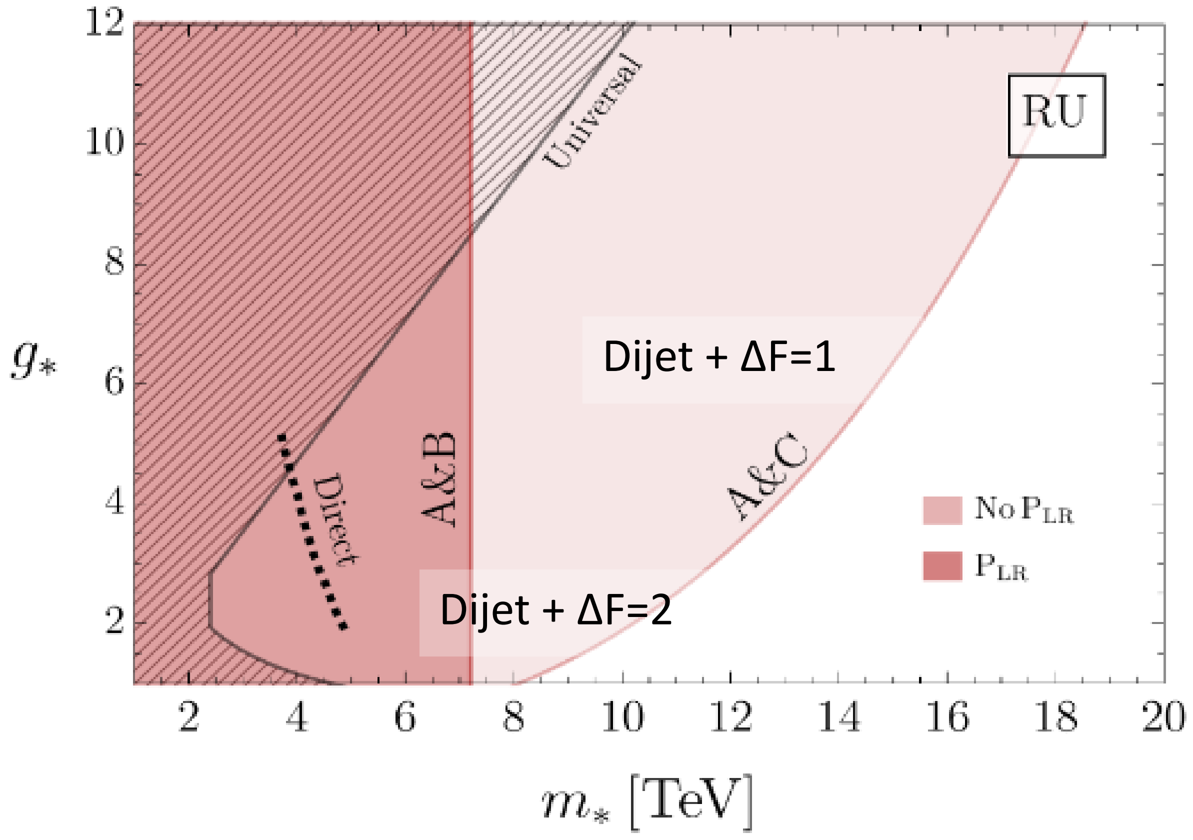
$$m_* \gtrsim 120 \frac{g_*}{4\pi}\ \mathrm{TeV}$$

Neutron EDM

$$m_* \gtrsim 40 - 60 \frac{g_*}{4\pi}\ \mathrm{TeV}$$

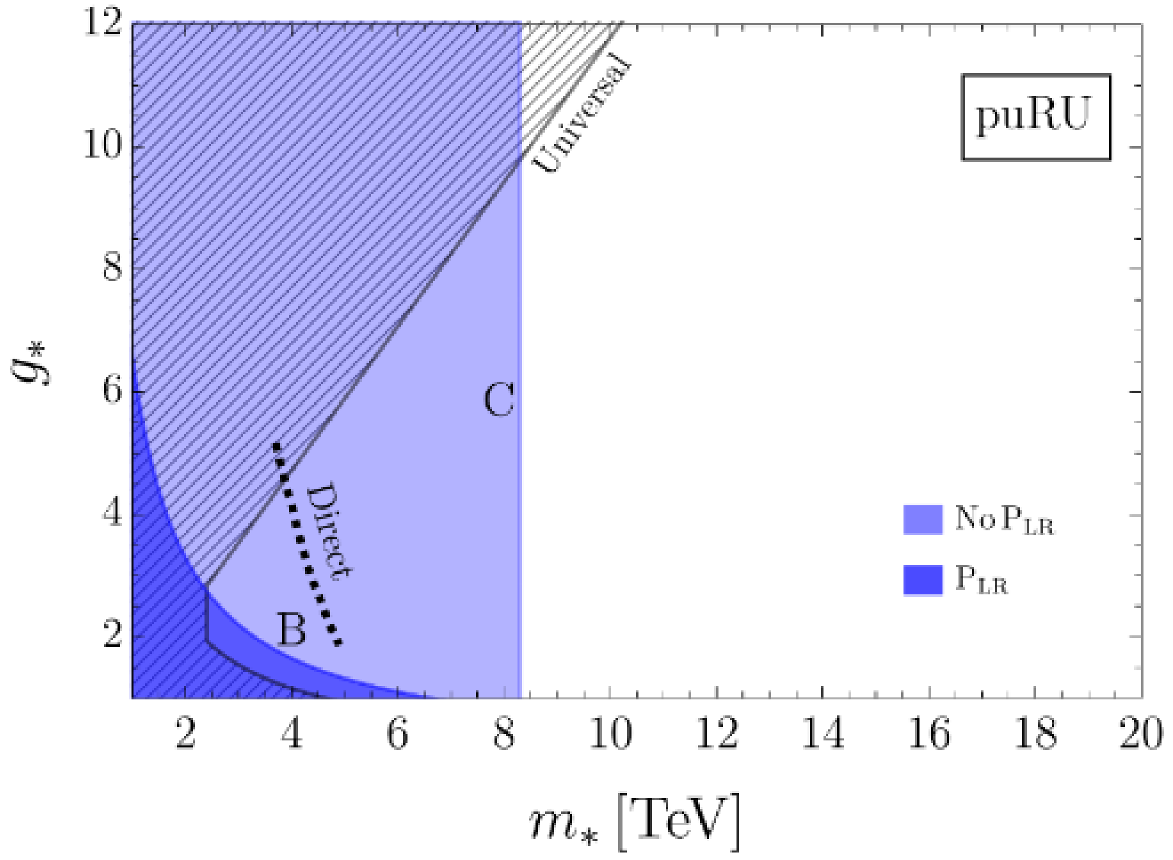
MFV

Glioti, Rattazzi, Ricci, Vecchi 2024



Partial Universality

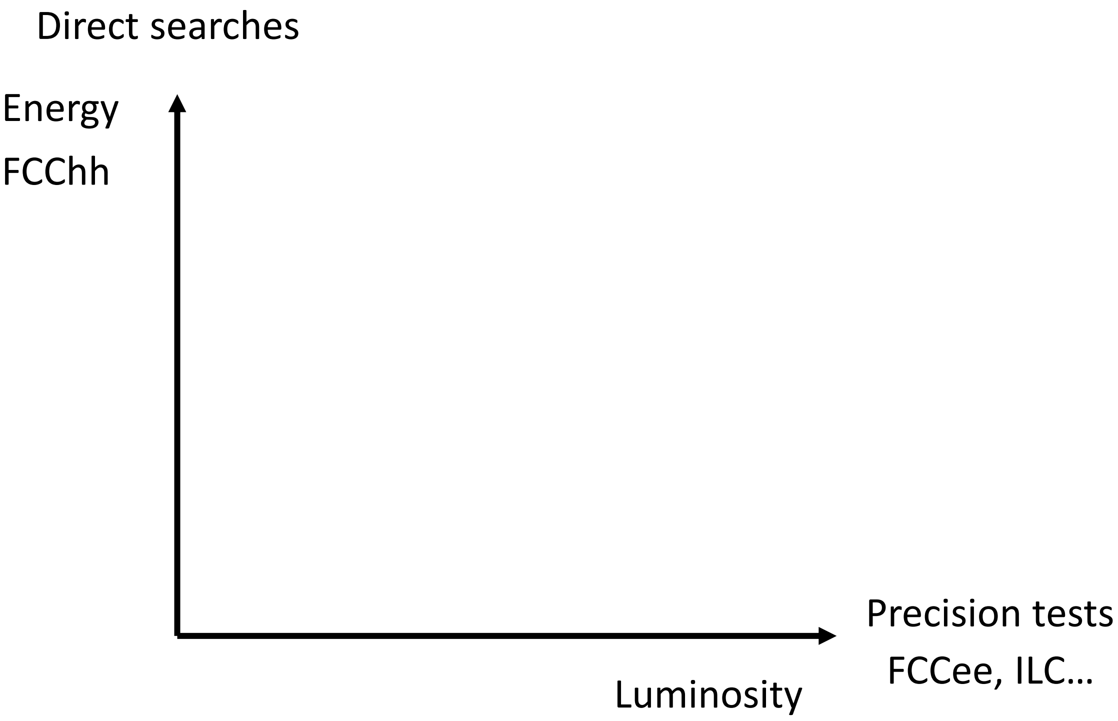
Glioti, Rattazzi, Ricci, Vecchi 2024



Label	Observable
A	$pp \to jj$
B	$\Delta F = 2\,(B_d)$
C	$B_s \to \mu^+\mu^-$
D	nEDM
E	$B^0 \to K^{*0}e^+e^-\ (C_7')$
F	$B \to X_s\gamma\ (C_7)$
G	W-coupling

The Future

LHC will finish soon → HL-LHC 10x amount of data → ?



The Future

LHC will finish soon → HL-LHC 10x amount of data → ?

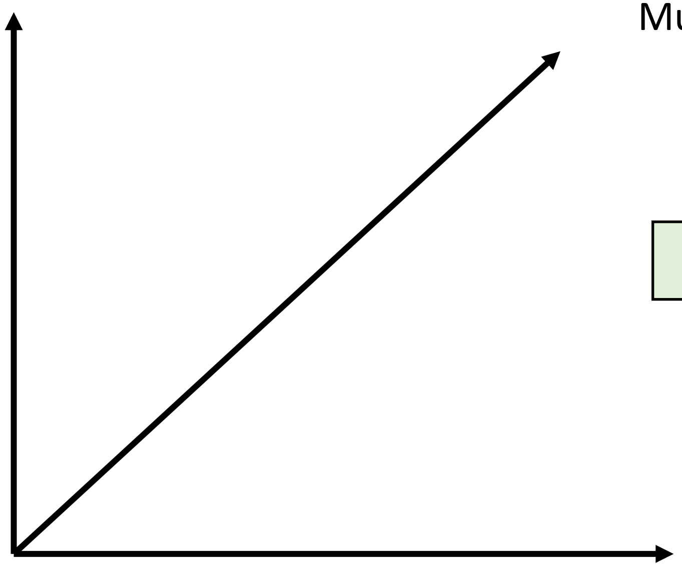
Direct searches

Energy

FCChh

High-energy probes

Muon Collider



$$\frac{\Delta O_{\rm BSM}}{O_{\rm SM}} \sim \frac{E^2}{\Lambda^2}$$

$$\boxed{1\% \text{ at } E = 10 \text{ TeV} \implies \Lambda \sim 100 \text{ TeV}}$$

Precision tests

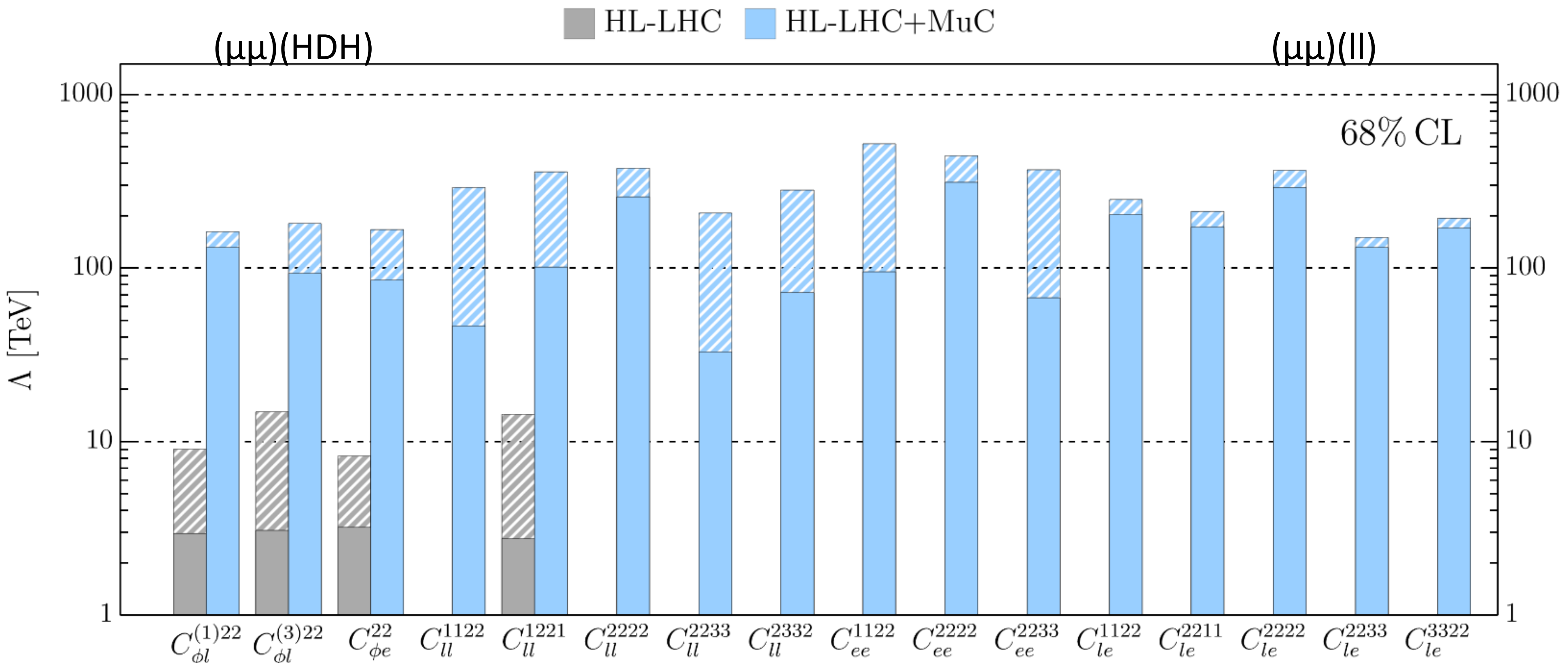
FCCee, ILC…

Luminosity

Results on effective operators

De Blas, Franceschini, Glioti, Marzocca, Wang, Wulzer, 2025

Diboson & Dilepton

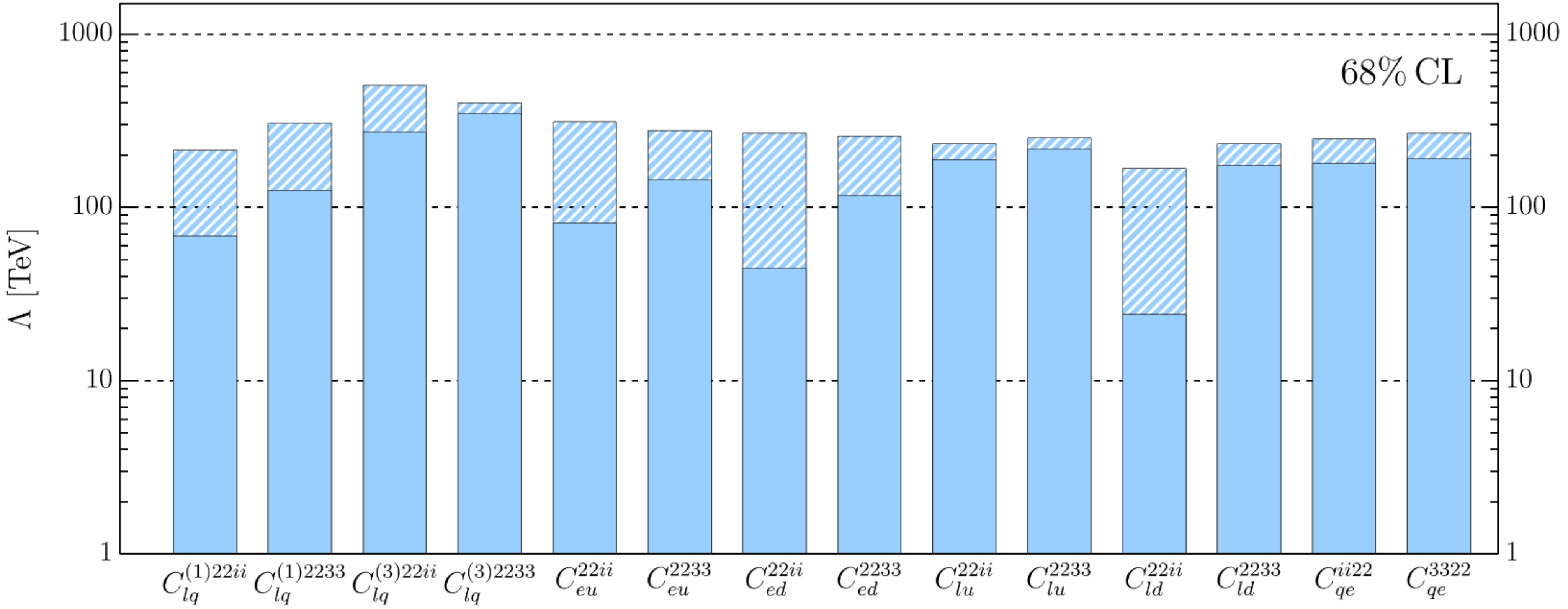


Results on effective operators

De Blas, Franceschini, Glioti, Marzocca, Wang, Wulzer, 2025

Diquark

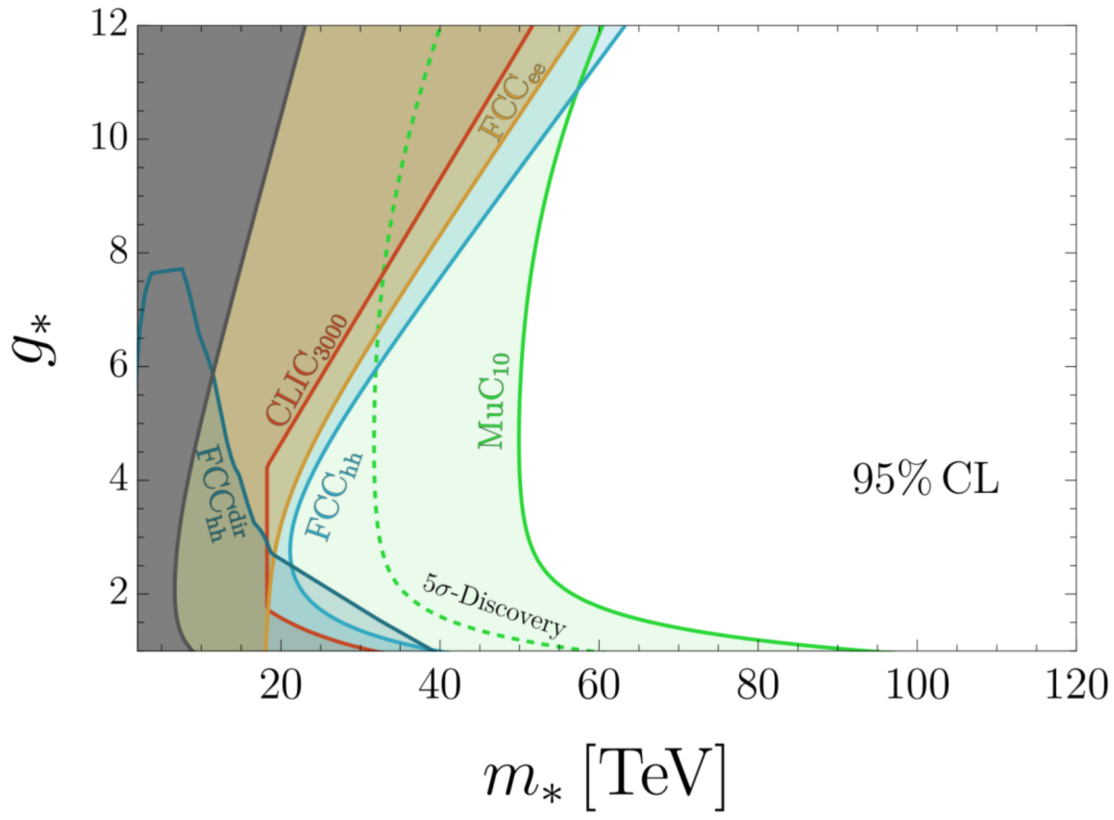
(μμ)(qq)



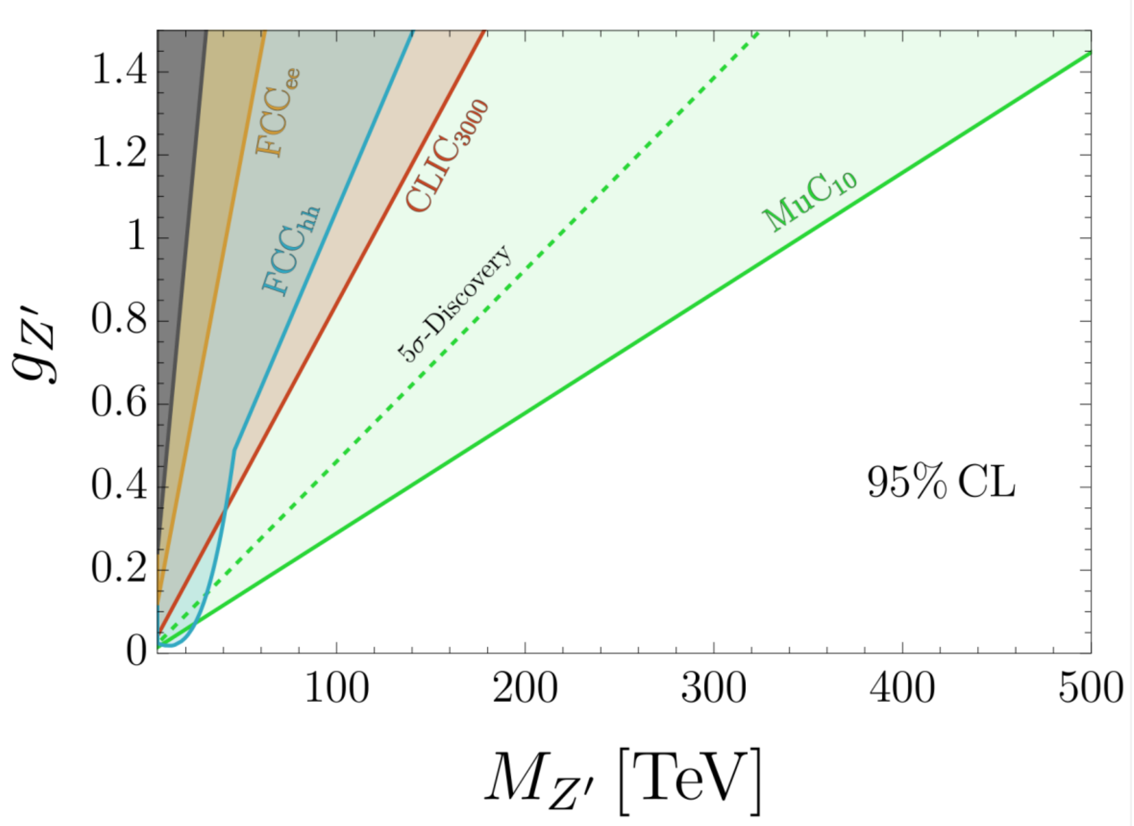
Reach on BSM models

De Blas, Franceschini, Glioti, Marzocca, Wang, Wulzer, 2025

Composite Higgs

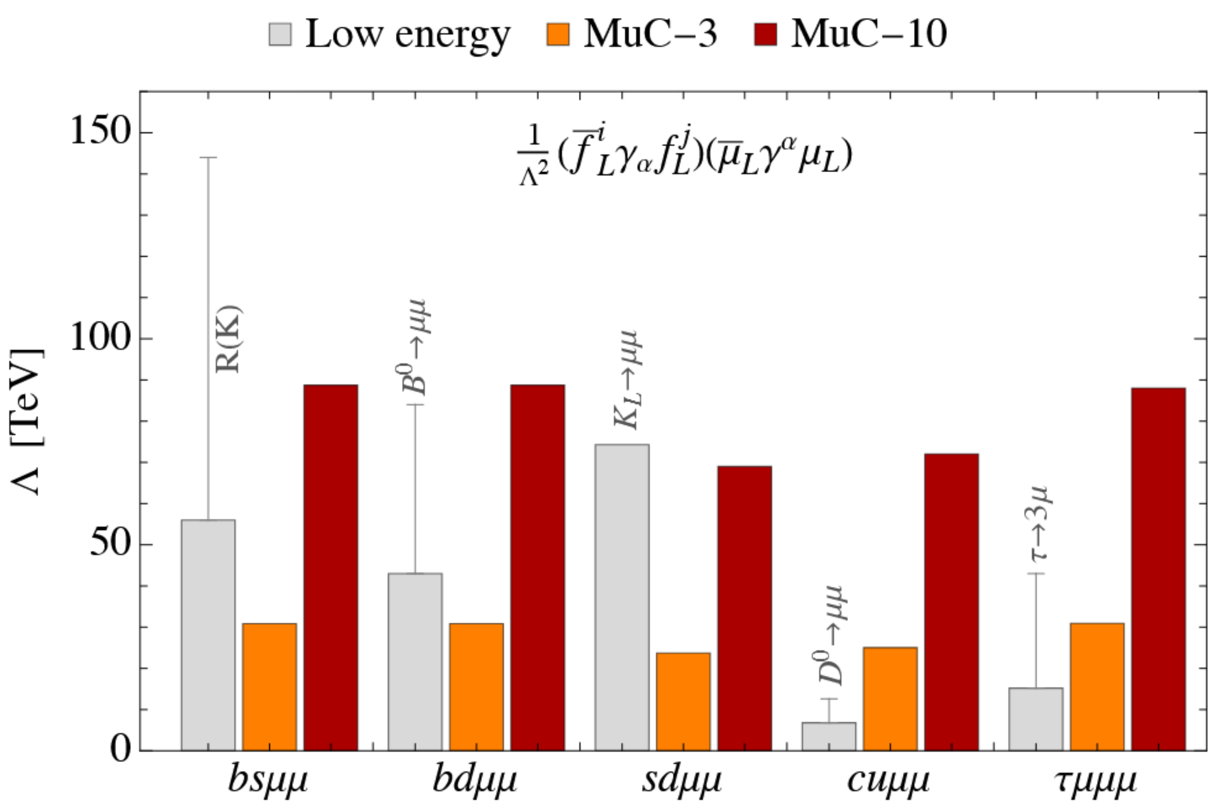


Y-universal Z'



Flavor: high vs low energy

De Blas, Franceschini, Glioti, Marzocca, Wang, Wulzer, 2025



Conclusions

- Indirect searches of new physics can give hints on what’s beyond the Standard Model even at scales far away from what’s directly experimentally accessible

- The SMEFT is a useful and general parameterization of heavy new physics

- Flavor measurements are among the most precise measurements we can do and probe the most delicate sector of the Standard Model

- Global fits are a way of combining all existing measurements in a model independent way to assess current and future constraints on physics beyond the Standard Model for a large class of scenarios