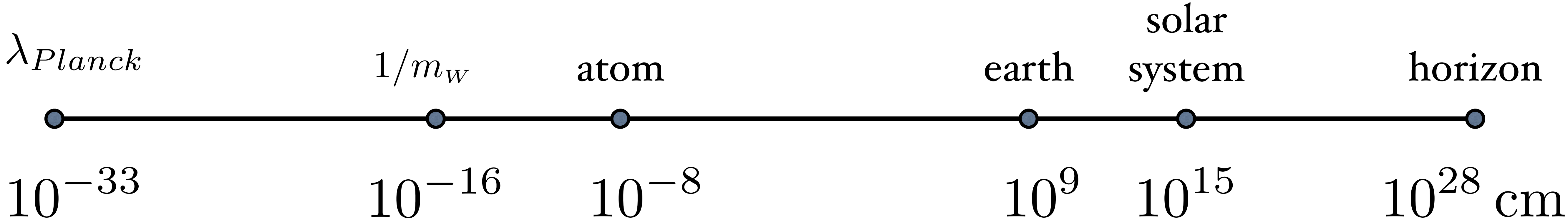
The Enduring Importance of the Weak Scale

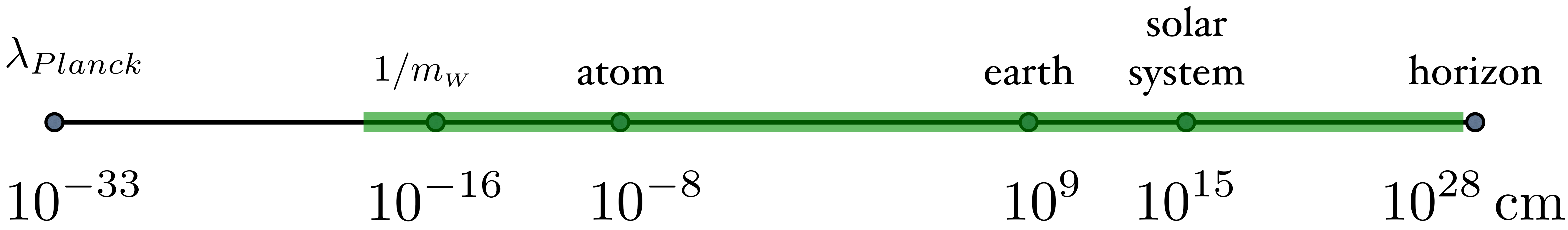
Riccardo Rattazzi - EPFL

- Alfredo Glioti, RR, Lorenzo Ricci, Luca Vecchi '24
- Kaustubh Agashe, Gian Giudice, RR, Raman Sundrum, in progress

Physics ⟷ Separation of Scales



Physics ⟷ Separation of Scales



★ Standard Model + General relativity

- Dark Matter ?
- Dark Energy "?"
- Why the hierarchies ?

The Hierarchy Paradox

$$\mathcal{L}_{SM} = \underbrace{\mathcal{L}^{d\leq 4}}_{\text{seen}} + \underbrace{\frac{1}{m_*}\mathcal{L}^{d=5} + \frac{1}{m_*^2}\mathcal{L}^{d=6} + \ldots}_{\text{unseen or tiny}}$$

Observations speak for Simplicity

$$m_* \gg m_{weak}$$

$\mathcal{L}_{SM} \to \mathcal{L}^{d\leq 4}$

automatic B, L, “GIM”, ...

Theory expects Naturalness

$$m_h^2 \sim \frac{y_t^2}{4\pi^2} m_*^2 + \cdots$$

$$m_* \lesssim 0.5\,\text{TeV}$$

Clash between Simplicity and Naturalness

Made concrete by all available Natural models (SUSY, Comp Higgs,...)

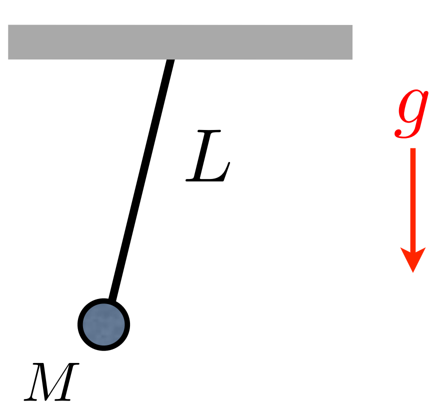
A matter of symmetry and selection rules

$$m_h^2 \sim c\,\frac{y_t^2}{4\pi^2}\,m_*^2 + \cdots$$

high spin symmetry

dilatation symmetry

As good as dimensional analys in mechanics



$$\omega = c\sqrt{\frac{g}{L}}$$

$$c\, m_{UV}^2\, H^\dagger H \rightarrow m_{IR} = c^{\frac{1}{2}}\, m_{UV}$$

un-Natural hierarchy

Natural hierarchy

slowly evolving coupling $\mu \frac{dg}{d\mu} = \frac{b\, g^3}{8\pi^2} \ll 1$

$$m_{IR} = m_{UV}\, e^{-16\pi^2/bg_{UV}^2}$$

Ex: QCD, Supersymmetry, Composite Higgs

The two Chief Systems

Simplicity

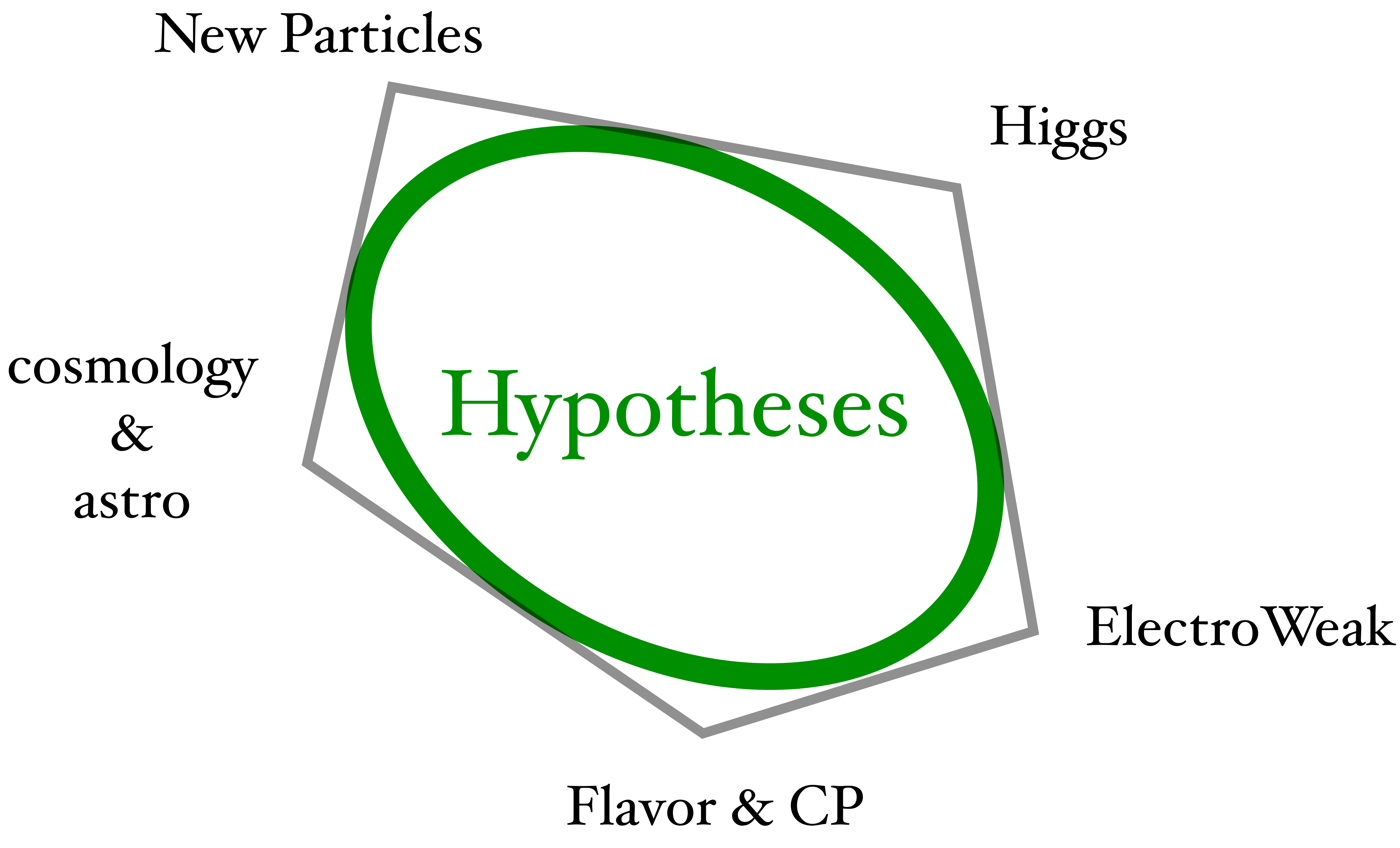
I. SM up to $m_* \gg$ TeV

- B, L & Flavor ☺
- m_h points beyond Naturalness
    - multiverse
    - "cosmological relaxation, Nnaturalness, ..."
    - failure of EFT (UV/IR connection)

II. Naturalizing New Physics at $m_* \sim$ TeV

- Constraints on B, L, Flavor & CP met by *clever* model building

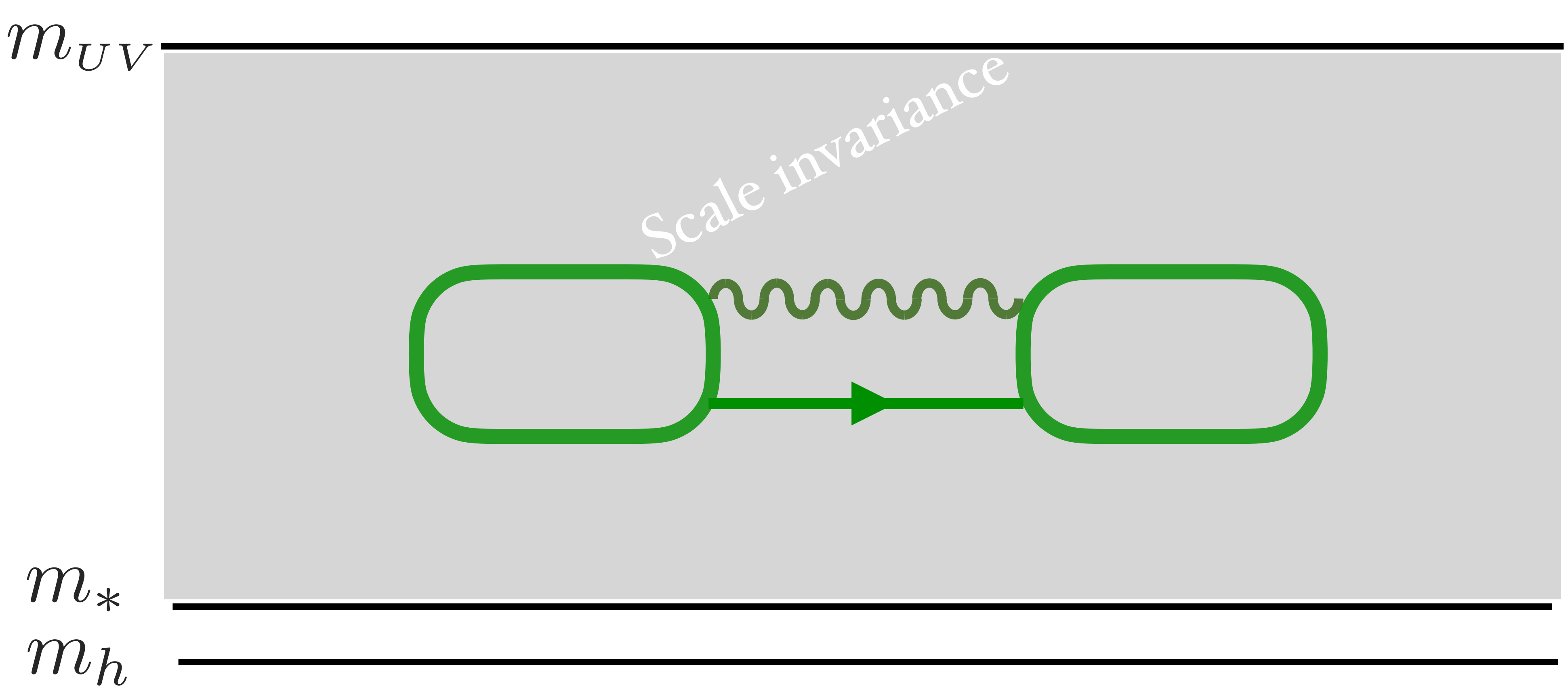
Naturalness


New Particles
Higgs
cosmology
&
astro
Hypotheses
ElectroWeak
Flavor & CP

Modern Composite Higgs

H. Georgi, D.B. Kaplan ’84
D.B. Kaplan ’91
...
Agashe, Contino, Pomarol ‘04

$$\mathcal{L} = \mathcal{L}_{SM'} + \mathcal{L}_{CFT_H} + g A_\mu J^\mu_{CFT_H} + y_{ia}\psi_i \mathcal{O}_a$$



$$\mathcal{L}_{eff} = \mathcal{L}_{SM'} + \mathcal{L}(H) + Y_{ij} H \psi_i \psi_j + \cdots$$

$m_*,\ g_*,\ y_{ia}$

‘Educated’ SMEFT: SILH

Giudice, Grojean, Pomarol, RR ‘07

Higgs potential & Naturalness

$m_h,\, m_*$

Higgs potential & Naturalness

m_*

Higgs is a pseudo-Nambu-Goldstone boson

m_h

Higgs potential & Naturalness

m_*

m_h

Higgs is a pseudo-Nambu-Goldstone boson

▲ $V(H)$ is 'calculable'

$$m_h^2 = \frac{1}{8\pi^2}\left(\# y_t^2 + \# g^2 + \cdots\right) m_*^2$$

$$\lambda_h = \frac{\# g_*^2}{8\pi^2} y_t^2 + \cdots$$

$$g_* \sim 2 \div 4$$

▲ Naturalness

$$m_* \lesssim 0.5 \text{ TeV}$$

$$v^2 \sim \frac{m_*^2}{g_*^2} \equiv f^2$$

$$\frac{v^2}{f^2} \sim \left(\frac{m_*}{0.5\,\text{TeV}}\right)^2 \equiv \epsilon_{FT}$$

LHC

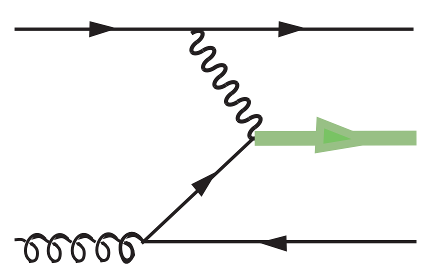
▲ Higgs non-linearities:  + ...

$$\frac{v^2}{f^2} \lesssim 0.1$$

$$\frac{H^\dagger H}{f^2} \Rightarrow \frac{\delta g_h}{g_h|_{SM}} \sim \frac{v^2}{f^2} \sim \epsilon_{FT}$$

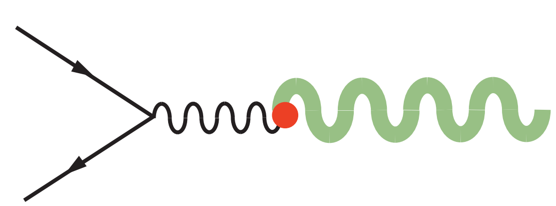
▲ Composite resonances:

top partners



$m_* \gtrsim 1 \div 2\,\mathrm{TeV}$

W/Z partners



$m_* \gtrsim 4 \div 5\,\mathrm{TeV}$

LHC

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$$\frac{v^2}{f^2} \lesssim 0.1$$

$$\frac{H^\dagger H}{f^2} \quad \Rightarrow \quad \frac{\delta g_h}{g_h|_{SM}} \sim \frac{v^2}{f^2} \sim \epsilon_{FT}$$

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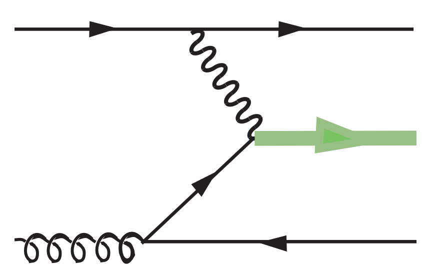

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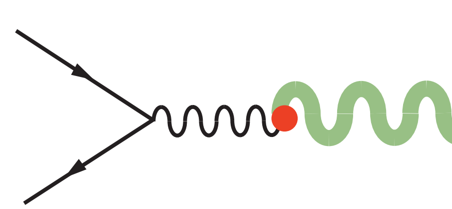
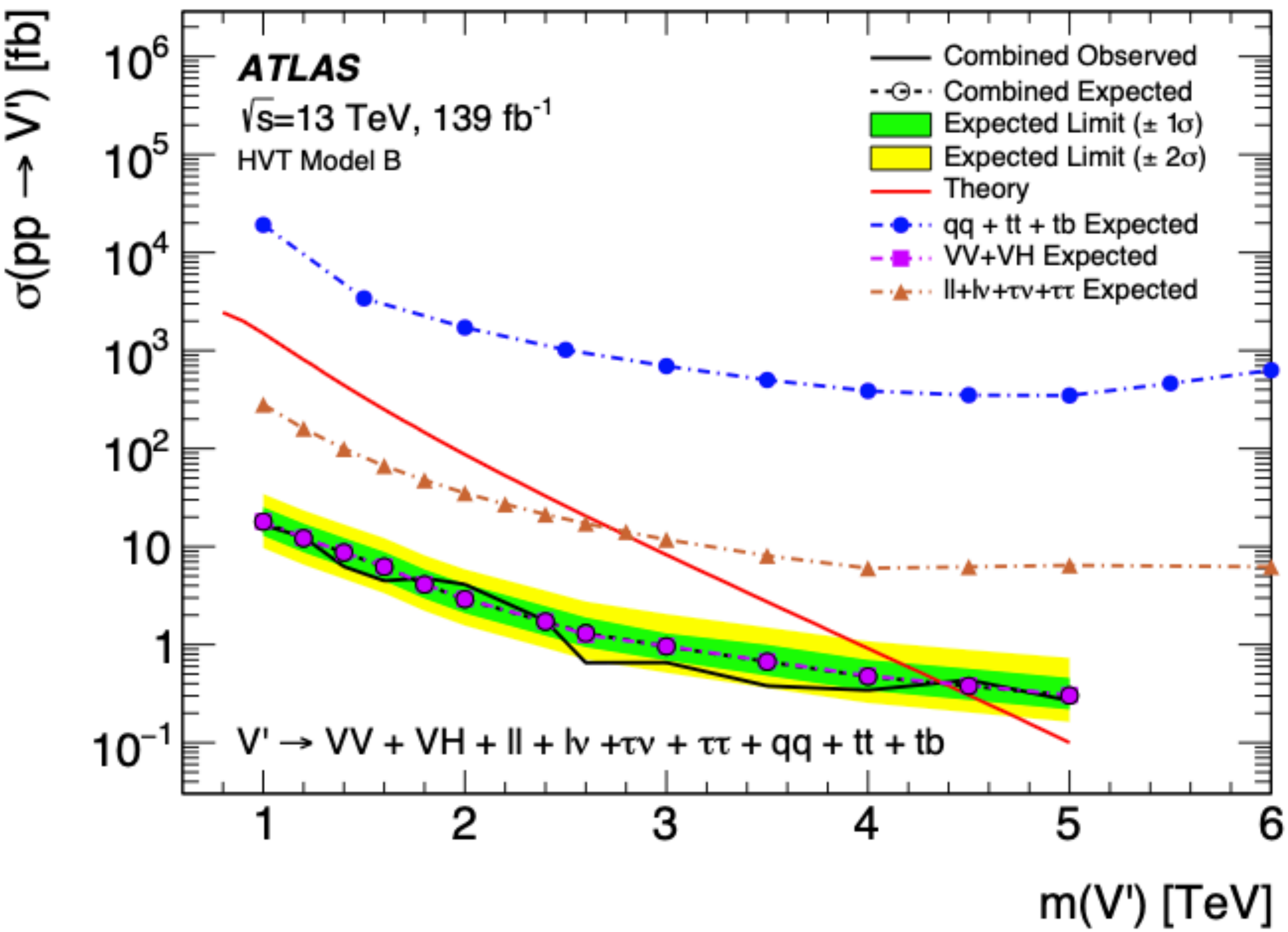
W/Z partners

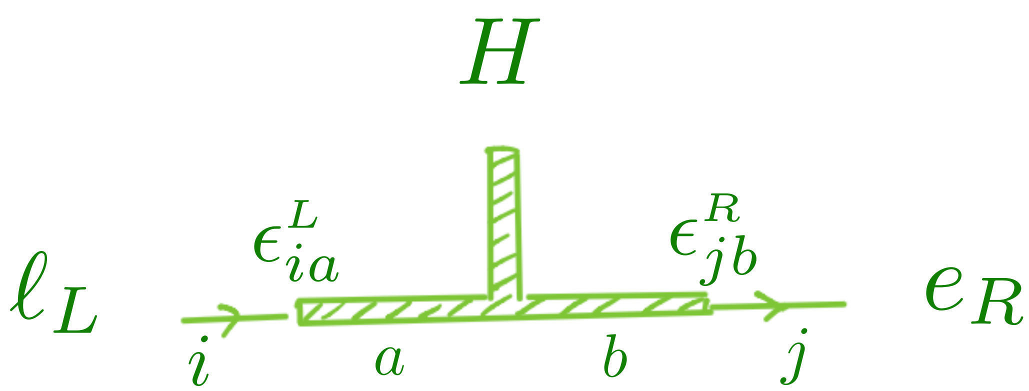


$\epsilon_{FT} \lesssim 0.01$

$m_* \gtrsim 4 \div 5\,\mathrm{TeV}$


ATLAS
√s=13 TeV, 139 fb^-1
HVT Model B
Combined Observed
Combined Expected
Expected Limit (± 1σ)
Expected Limit (± 2σ)
Theory
qq + tt + tb Expected
VV+VH Expected
ll+lν+τν+ττ Expected
V' → VV + VH + ll + lν +τν + ττ + qq + tt + tb
σ(pp → V') [fb]
m(V') [TeV]
10^6
10^5
10^4
10^3
10^2
10
1
10^-1
1
2
3
4
5
6

... and then there came Flavor



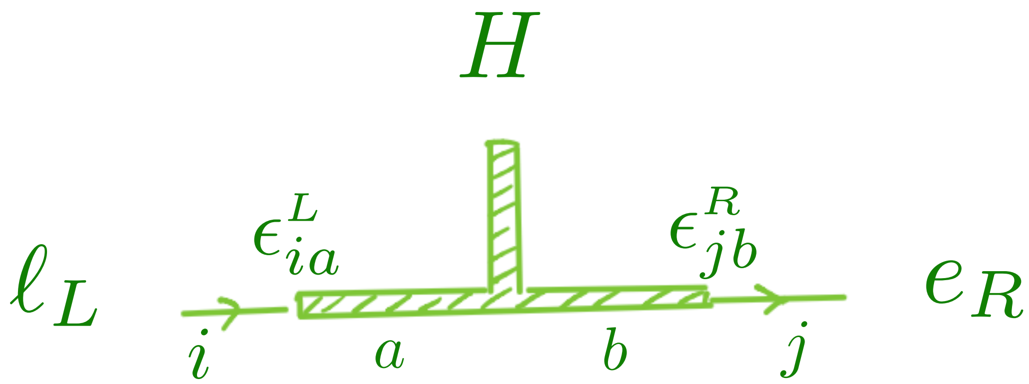
$$Y_{ij} = g_* \, \epsilon^L_{ia} \epsilon^R_{jb} c_{ab}$$

☺

RG-flow induced hierarchy

D.B. Kaplan '91
A. Nelson, M. Strassler '00

… and then there came Flavor



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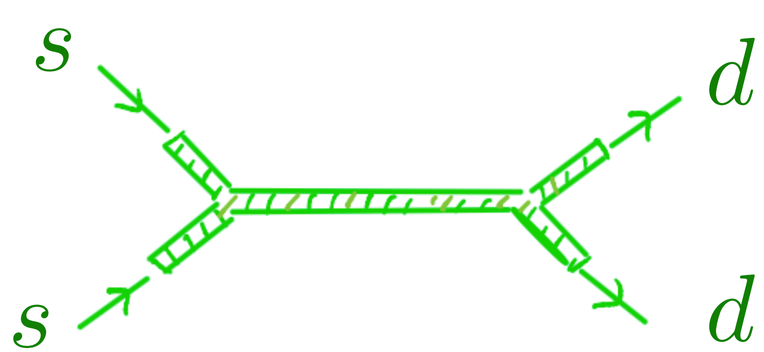
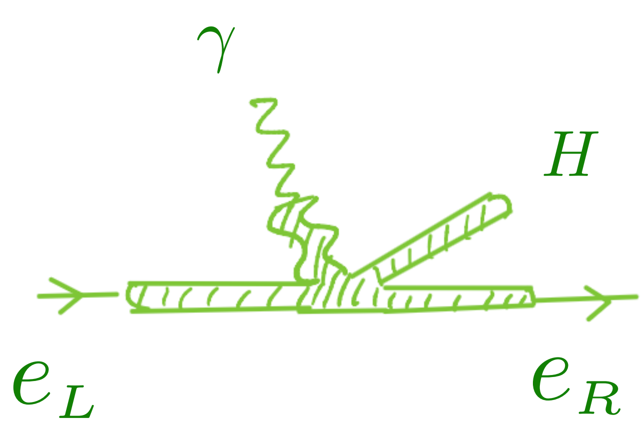


ϵ_K → $m_* \gtrsim 30$ TeV

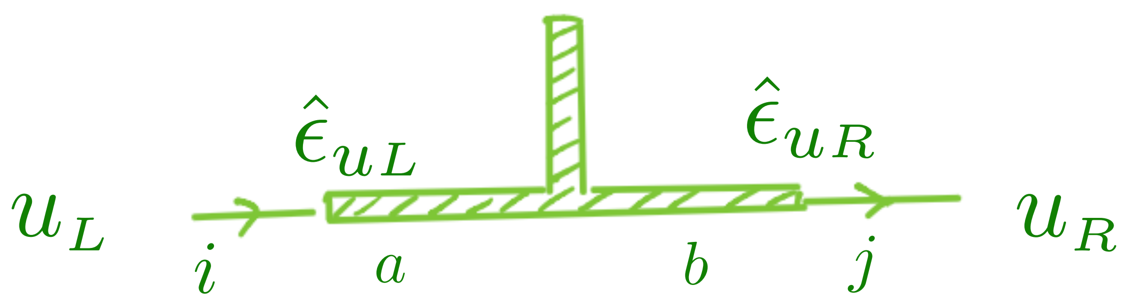


d_e → $m_* \gtrsim 2 \times 10^3$ TeV

To allow for low m_* must assume Flavor & CP Symmetries

→ explanation of fermion spectrum is lost

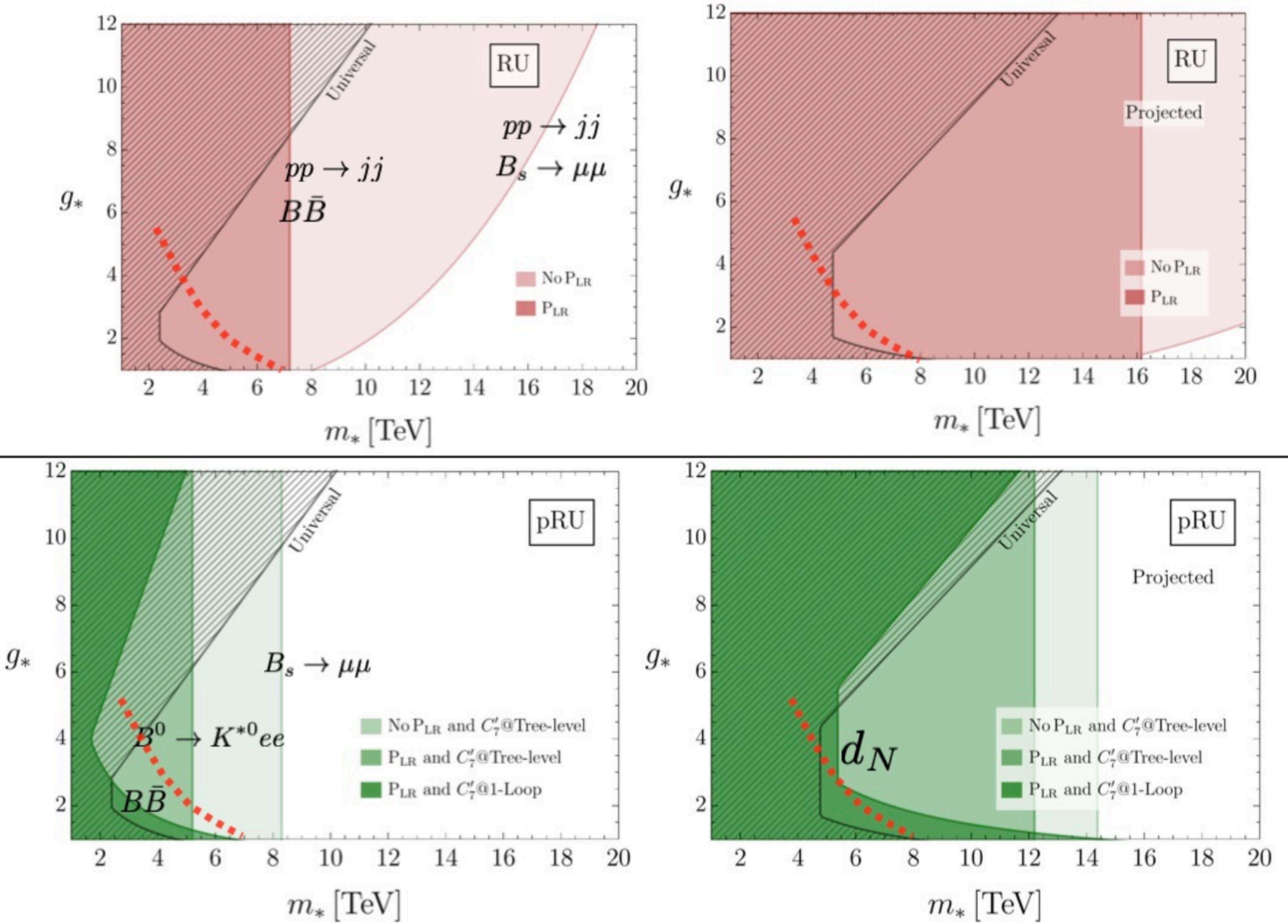
Glioti, RR, Ricci, Vecchi '24



classify the possible symmetries of $\hat{\epsilon}_{uL}, \hat{\epsilon}_{uR}, \hat{\epsilon}_{dL}, \hat{\epsilon}_{dR}$

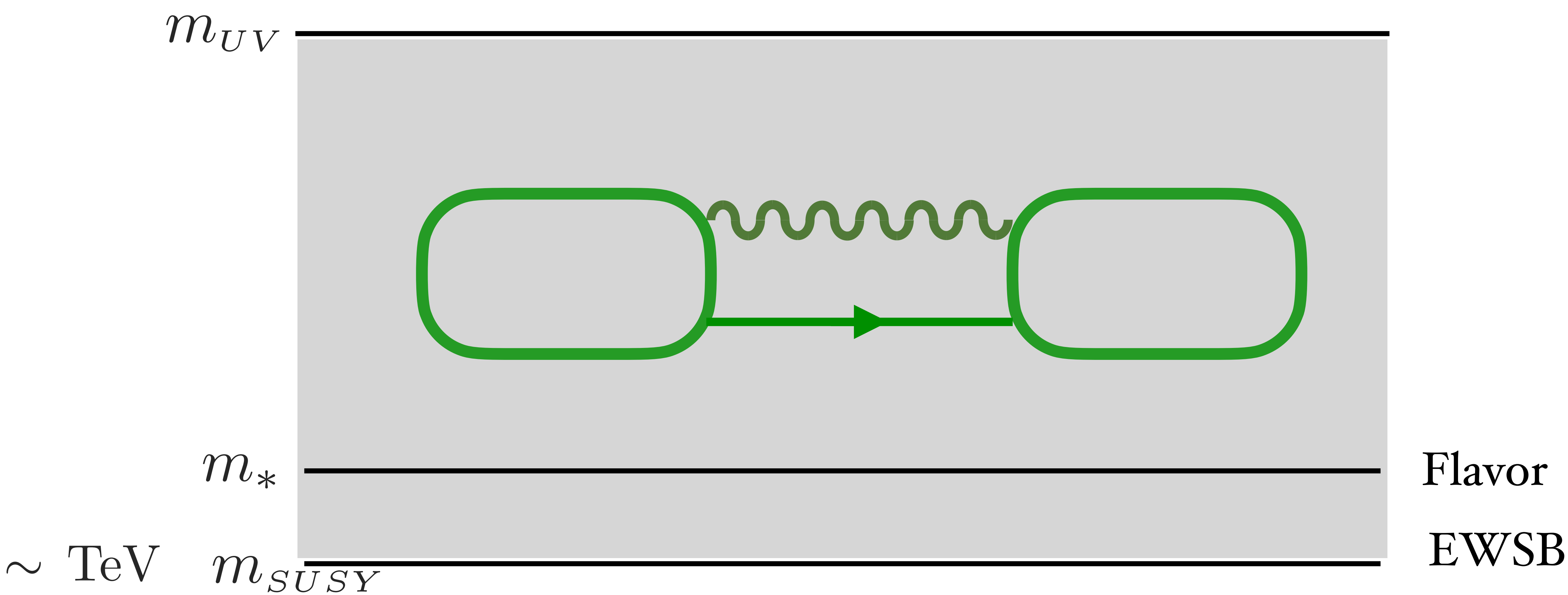
→ Scenarios

- Right Universality — $U(3)_q \times U(3)_{U+u} \times U(3)_{D+d}$
- Partial Right UP Universality — $U(3)_q \times [U(2) \times U(1)]_{U+u} \times U(3)_{D+d}$
- Partial Right Universality — $U(3)_q \times [U(2) \times U(1)]_{U+u} \times [U(2) \times U(1)]_{D+d}$
- Partial Left Universality — $U(3)_{q+Q} \times U(3)_u \times U(3)_d$
- Partial Left Universality — $[U(2) \times U(1)]_{q+Q} \times U(3)_u \times U(3)_d$


RU
Universal
pp → jj
B B̄
pp → jj
B_s → μμ
No P_LR
P_LR
g_*
m_* [TeV]
RU
Universal
Projected
No P_LR
P_LR
g_*
m_* [TeV]
pRU
Universal
B_s → μμ
B^0 → K^{*0}ee
B B̄
No P_LR and C'_7@Tree-level
P_LR and C'_7@Tree-level
P_LR and C'_7@1-Loop
g_*
m_* [TeV]
pRU
Universal
Projected
d_N
No P_LR and C'_7@Tree-level
P_LR and C'_7@Tree-level
P_LR and C'_7@1-Loop
g_*
m_* [TeV]

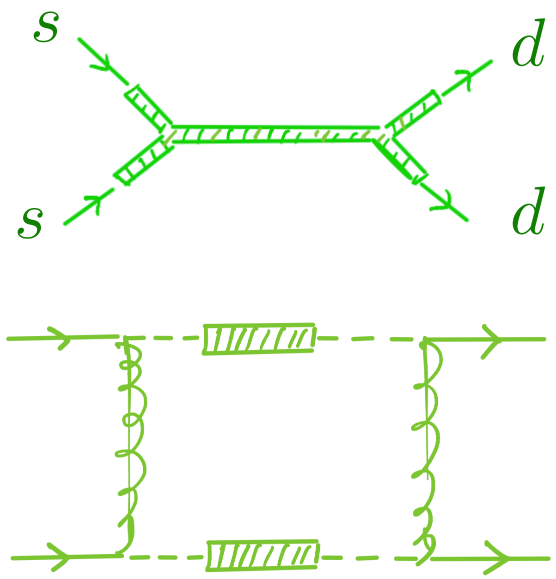
Supersymmetric Composite Higgs

Nomura, Papucci, Stolarski '08
Okada, Yamada '11
...
Agashe, Giudice, RR, Sundrum, in prog



has the chance to offer realistic scenarios
with 'natural' EWSB and low scale flavor dynamics !

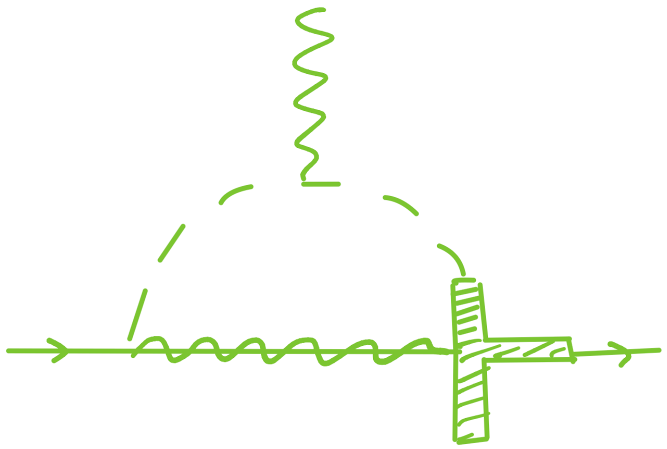
ϵ_K



$$m_* \gtrsim 30\,\mathrm{TeV} \times \tan\beta$$

$$m_{\tilde{g},\tilde{q}} \gtrsim 1\,\mathrm{TeV}$$

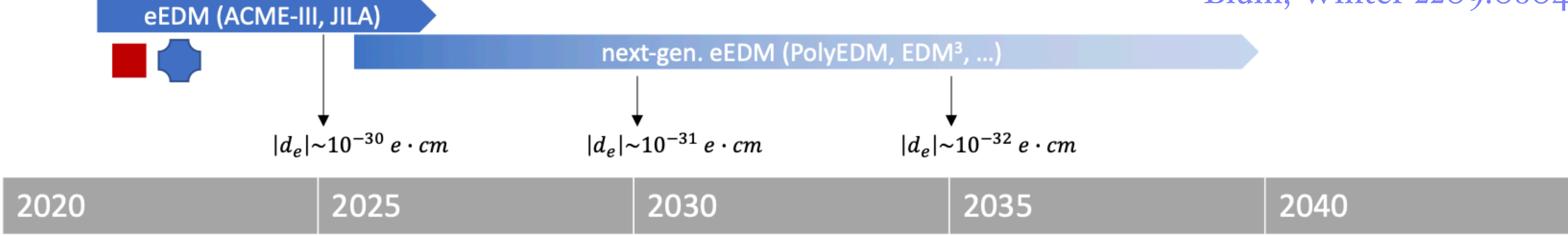
edm



$$\frac{d_e}{e} \sim 4 \times 10^{-30}\,\mathrm{cm} \times \frac{100\,\mathrm{TeV}}{m_*} \times \frac{\mathrm{TeV}}{m_{\tilde{\ell},\tilde{w}}}$$

$$\frac{d_e}{e} \sim 4 \times 10^{-30}\,\mathrm{cm} \times \frac{5\,\mathrm{PeV}}{m_*} \times \frac{\mathrm{TeV}}{m_{\tilde{\ell},\tilde{w}}}$$

Blum, Winter 2209.08041



calculable EWSB: $m_h^2 = \sum_i c_i m_i^2$ →

$$\epsilon_{FT} \equiv \frac{m_h^2|_{obs}}{\max\{c_i m_i^2\}}$$

$$\epsilon_{FT} \lesssim \frac{\delta g_h}{g_h|_{SM}}$$

LHC

Direct Searches

$$\epsilon_{FT} \lesssim 10^{-1} \div 10^{-2} \div 10^{-3}$$

Higgs couplings

$$\epsilon_{FT} \lesssim 10^{-1} \xrightarrow{\text{HL-LHC}} 10^{-2}$$

$$\delta g_{hZZ} \xrightarrow{\text{FCCee}} 10^{-3}$$

The irresistible fascination for the Higgs trilinear

- generically unspecial: $\frac{\delta\lambda_3}{\lambda_3} \sim \frac{\delta g_{hZZ}}{g_{hZZ}} \sim \epsilon_{FT}$ not competitive

- in peculiar cases $\frac{\delta\lambda_3}{\lambda_3} \sim \frac{g_*^2}{\lambda_h} \times \frac{\delta g_{hZZ}}{g_{hZZ}}$ $\lesssim 100 \times \frac{\delta g_{hZZ}}{g_{hZZ}}$

  Falkowski, RR, '19
  Durieux, Mccullough, Salvioni '23
  Degrassi, Giardino, Maltoni, Pagani '16

  - possibly motivated by EW baryogenesis, but sizeable CPV needed

- electron-edm bound → standard scenarios ruled-out/borderline

- scenarios evading edm bound → $\delta\lambda_3$ small

  spontaneous CPV, symmetry non restoration — Espinosa, Gripaios, Konstandin, Riva '11; Meade, Ramani, '18; Baldes, Servant '18, Glioti, RR, Vecchi '18

What is the origin of the weak scale?

How much un-Natural or Clever did Nature decide to be?