Quantum Field Theory & Particle Physics

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

Why exploring QFT?

- ✦ necessary to develop one day the Theory of Quantum Gravity from where all descends (CC, m_H, θ_{qcd}, m_e, θ_C ...)

- ✦ explain confinement in QCD

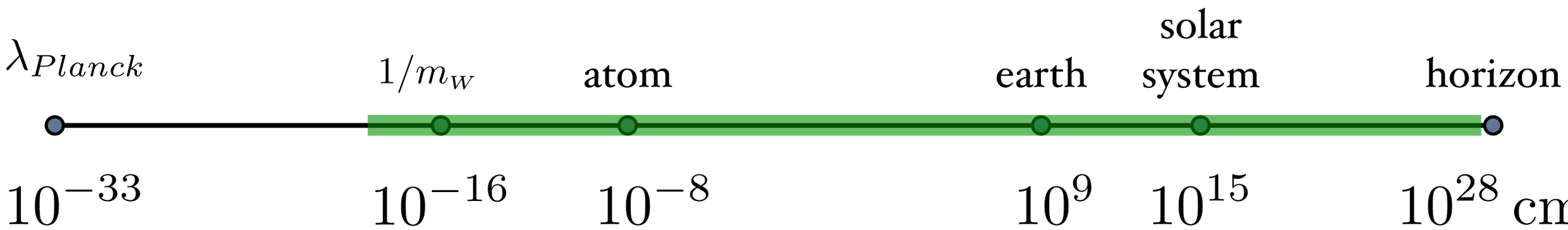
- ✦ learn about the Condensed Matter zoo

- ✦ support Particle Physics experiments

- ✦ directly address open questions (hierarchy, flavor, unification,...): build models

- ✦ get inspired and maybe serendipitously get crucial hints

Physics $\longleftrightarrow$ Separation of Scales



The Hierarchy Paradox

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

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 in construction of Natural models (SUSY, Comp Higgs,...)

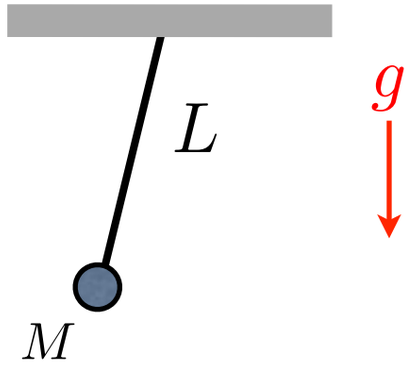
A matter of symmetry and selection rules

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

high spin symmetry

dilatation symmetry

As good as dimensional analys in mechanics



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

Of Mass Hierarchies and CFTs

M_{UV} ——————

~ scale invariance ➡ ~ CFT

M_{IR} ——————

Natural

$M_{UV} \gg M_{IR}$

★ Marginality: lowest scalar primary $\Delta_{\mathcal{O}} = 4 - \epsilon$

$\mathcal{L}_{mass} = c M_{UV}^{\epsilon} \mathcal{O}$ $M_{IR} = M_{UV} c^{1/\epsilon}$

$c \sim \epsilon \sim 0.1$ ➡ $\sim 10^{-10}$

★ Symmetry Protected Marginality

Ex: Chiral Symmetry, Supersymmetry, ...

Illustration: Conformal Technicolor

Luty, Okui '04

M_{UV} ——————————

TeV ——————————

SM → $yH\bar{q}q + m^2 H^\dagger H + \cdots$

Illustration: Conformal Technicolor

Luty, Okui '04

M_{UV} ——————

$$SM_{\not H} + CFT_H \quad \Rightarrow \quad y\mathcal{O}_H\bar{q}q + c\,\mathcal{O}_{H^\dagger H} + \cdots + \frac{(\bar{q}q)^2}{M_{UV}^2}$$

TeV ——————

$$SM \quad \Rightarrow \quad yH\bar{q}q + m^2 H^\dagger H + \cdots$$

Illustration: Conformal Technicolor

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M_{UV} ——————————

$$SM_{\not H} + CFT_H \quad \longrightarrow \quad y\mathcal{O}_H\bar{q}q + c\,\mathcal{O}_{H^\dagger H} + \cdots + \frac{(\bar{q}q)^2}{M_{UV}^2}$$

TeV ——————————

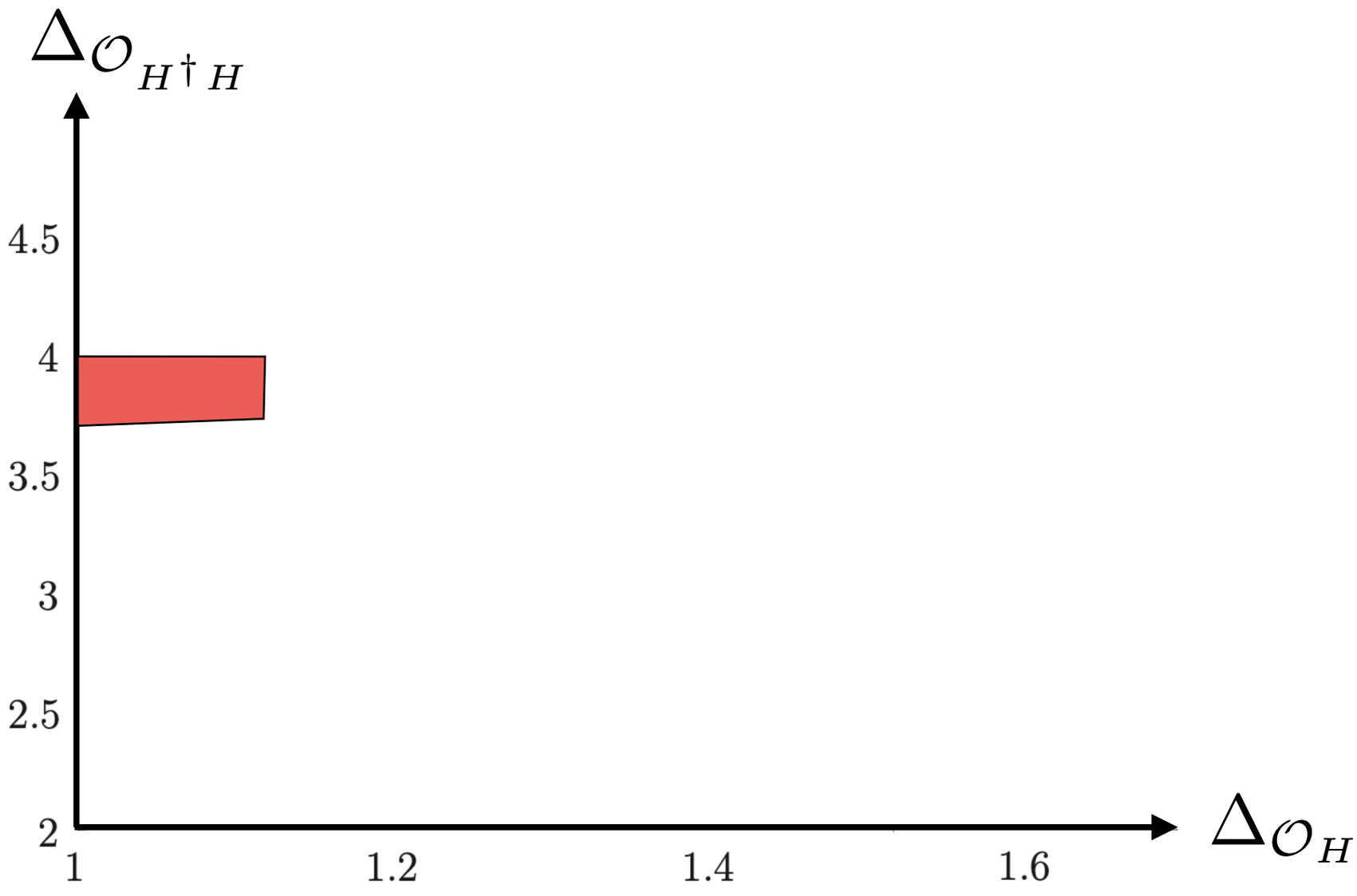
$$SM \quad \longrightarrow \quad yH\bar{q}q + m^2 H^\dagger H + \cdots$$

★ acceptably small FCNC & CPV → $M_{UV} \gg$ TeV

★ realistic (sizeable) fermion masses → $\Delta_{O_H} = 1 + \text{small}$

★ natural $M_{UV} \gg$ TeV → $\Delta_{O_{H^\dagger H}} = 4 - \text{small}$

The wishes of model building and the reality of QFT



Rattazzi, Rychkov, Tonni, Vichi ’08
Poland, Simmons Duffin, Vichi ‘11

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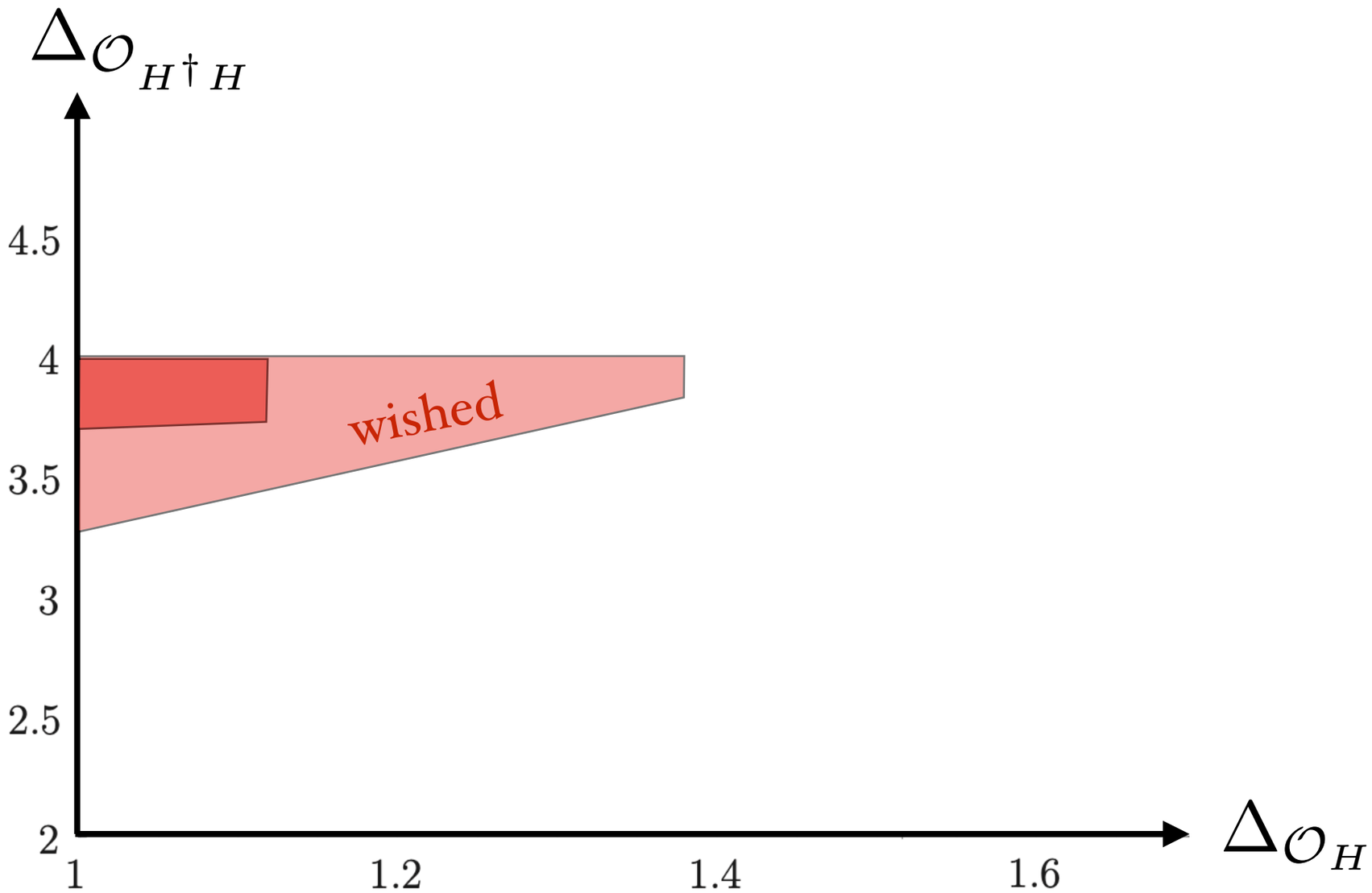

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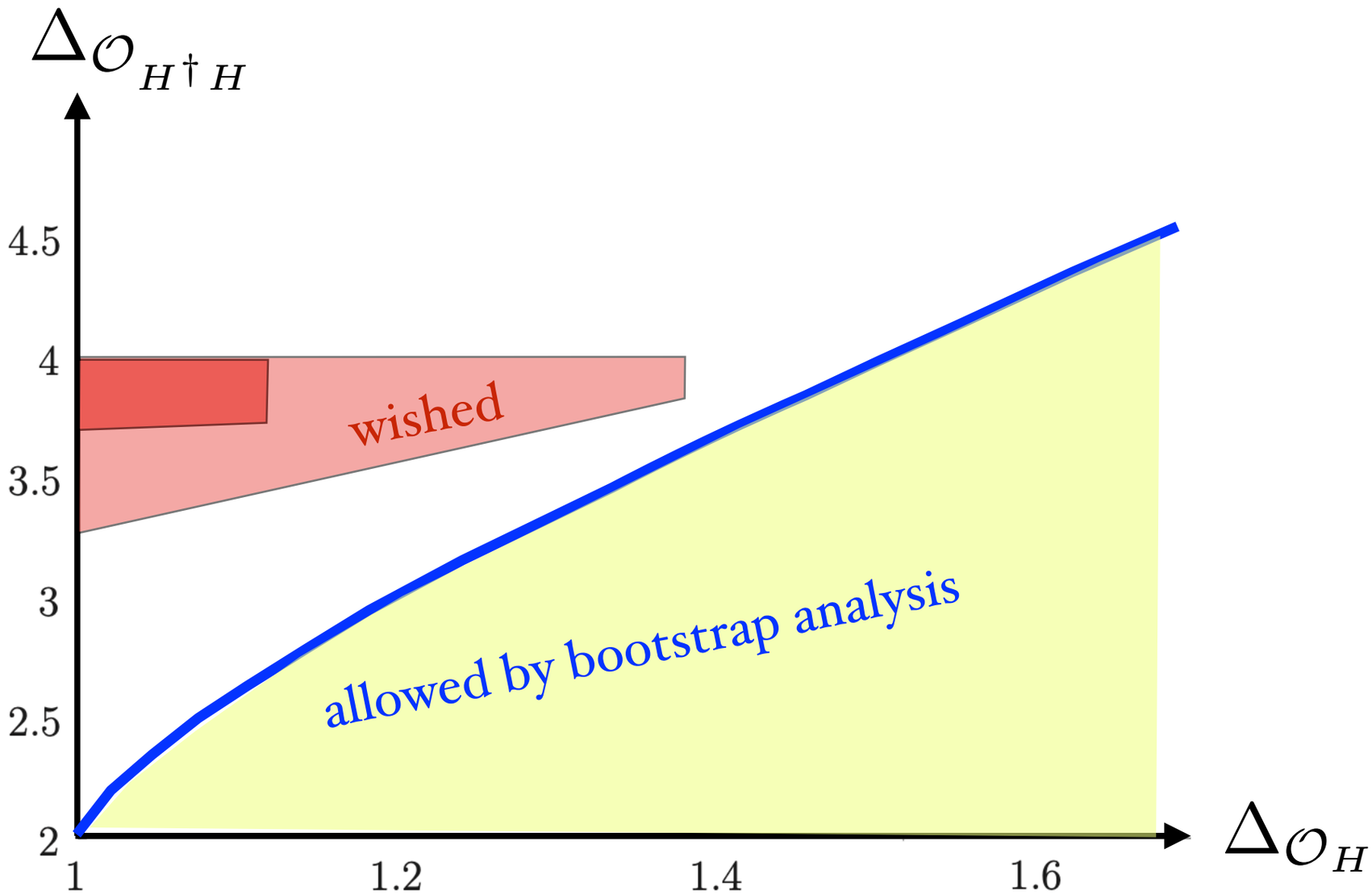

Rattazzi, Rychkov, Tonni, Vichi '08
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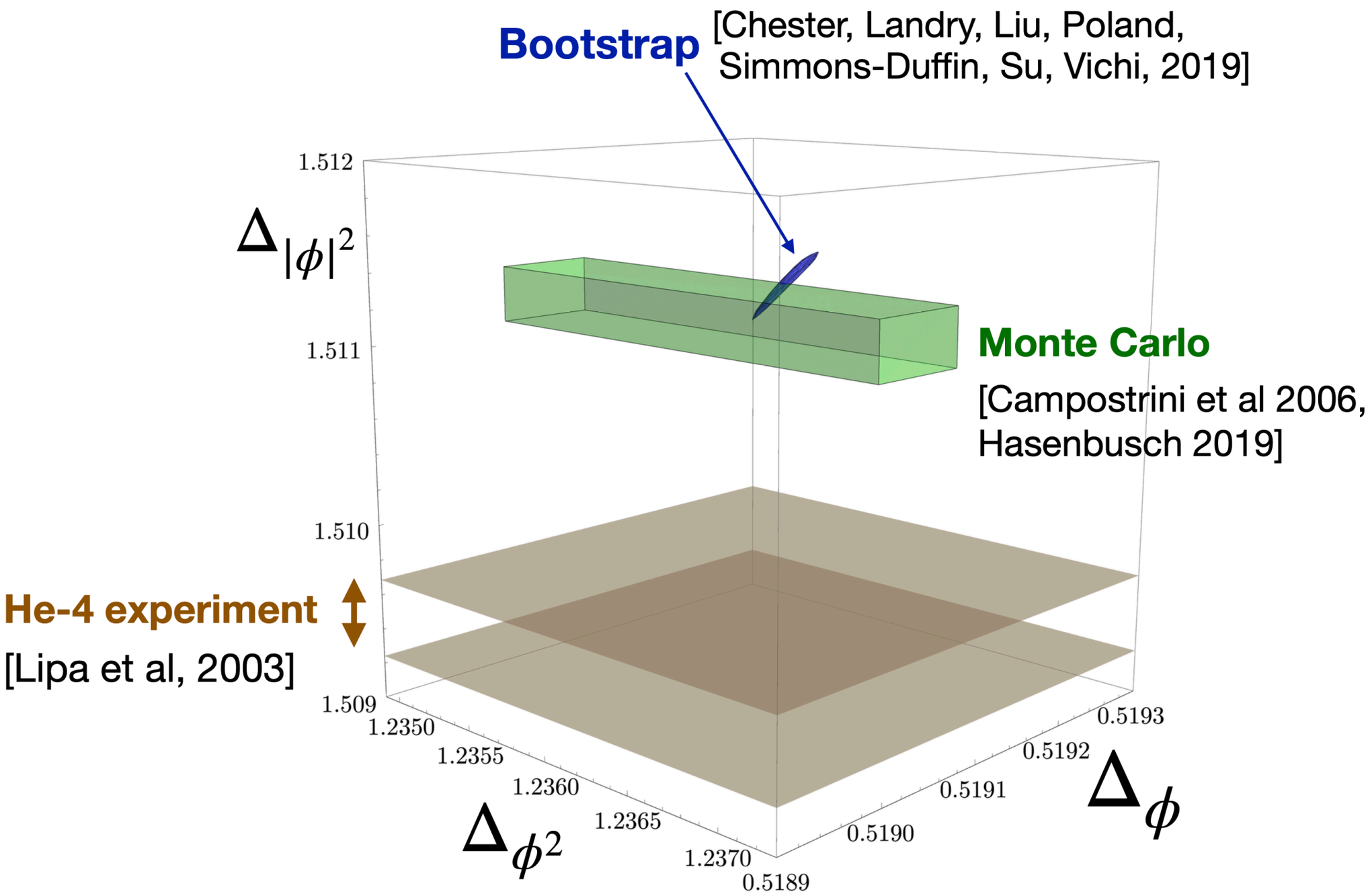
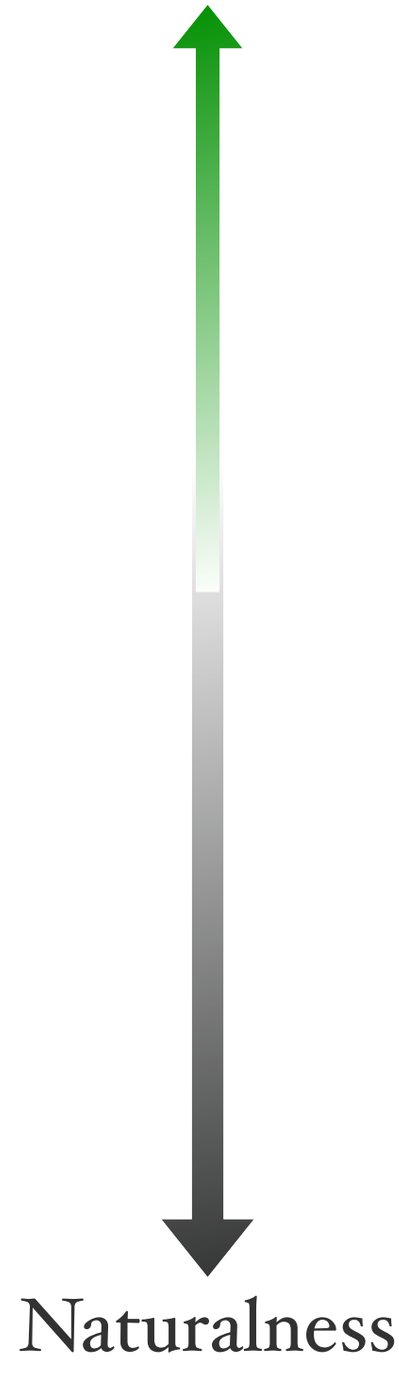
Ma la fisica è come il maiale...



The two Chief Systems

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

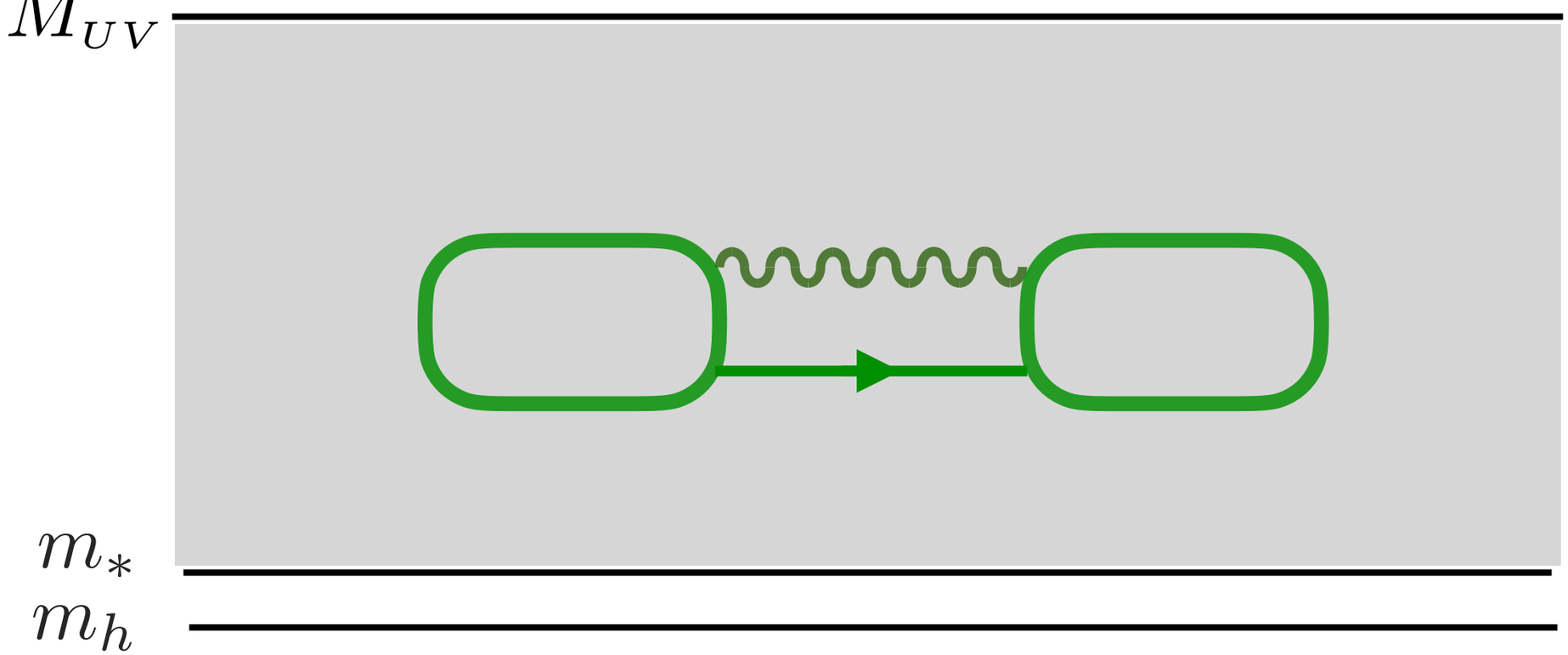
- Constraints on B, L, Flavor & CP met by *clever* model building

but with opportunity to explain fermion masses and CKM structure

Modern Composite Higgs

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

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



$$\mathcal{L}_{eff} \;=\; \mathcal{L}_{SM'} \;+\; \underbrace{\mathcal{L}(H) \;+\; Y_{ij} H \psi_i \psi_j \;+\; \cdots}_{m_*,\; g_*,\; y_{ia}}$$

'Educated' SMEFT: SILH

Giudice, Grojean, Pomarol, RR '07

Fermion spectrum: structure from anarchy via RG flow

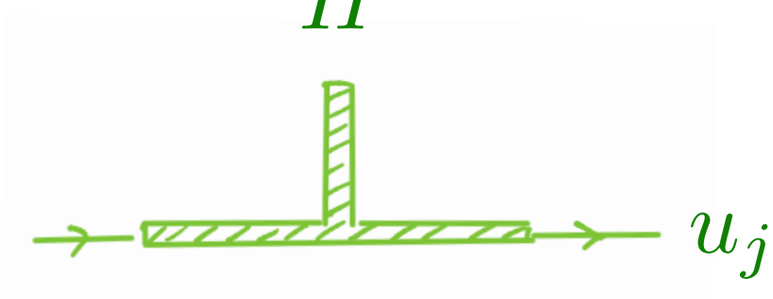
D.B. Kaplan '91
Nelson, Strassler '00

$$y^q_{ia}\, q_i\, \mathcal{O}^q_a \;+\; y^d_{ia}\, \bar{d}_i\, \mathcal{O}^d_a \;+\; y^u_{ia}\, \bar{u}_i\, \mathcal{O}^u_a \;+\; y^\ell_{ia}\, \ell_i\, \mathcal{O}^\ell_a \;+\; y^e_{ia}\, \bar{e}_i\, \mathcal{O}^e_a$$

$\frac{3}{2}$ $\qquad$ $\frac{5}{2} + \gamma^q_a$

- **RG:** $\qquad \bar{y}^F_{ia} \;=\; y^F_{ia}(m_*) \;=\; y^F_{ia}(M_{UV}) \left(\frac{m_*}{M_{UV}}\right)^{\gamma^F_a}$

- $\boxed{\gamma^F_1 > \gamma^F_2 > \gamma^F_3} \;\oplus\; \boxed{m_* \ll M_{UV}} \;\Rightarrow\; \boxed{|\bar{y}_{i1}| \ll |\bar{y}_{i2}| \ll |\bar{y}_{i3}|}$

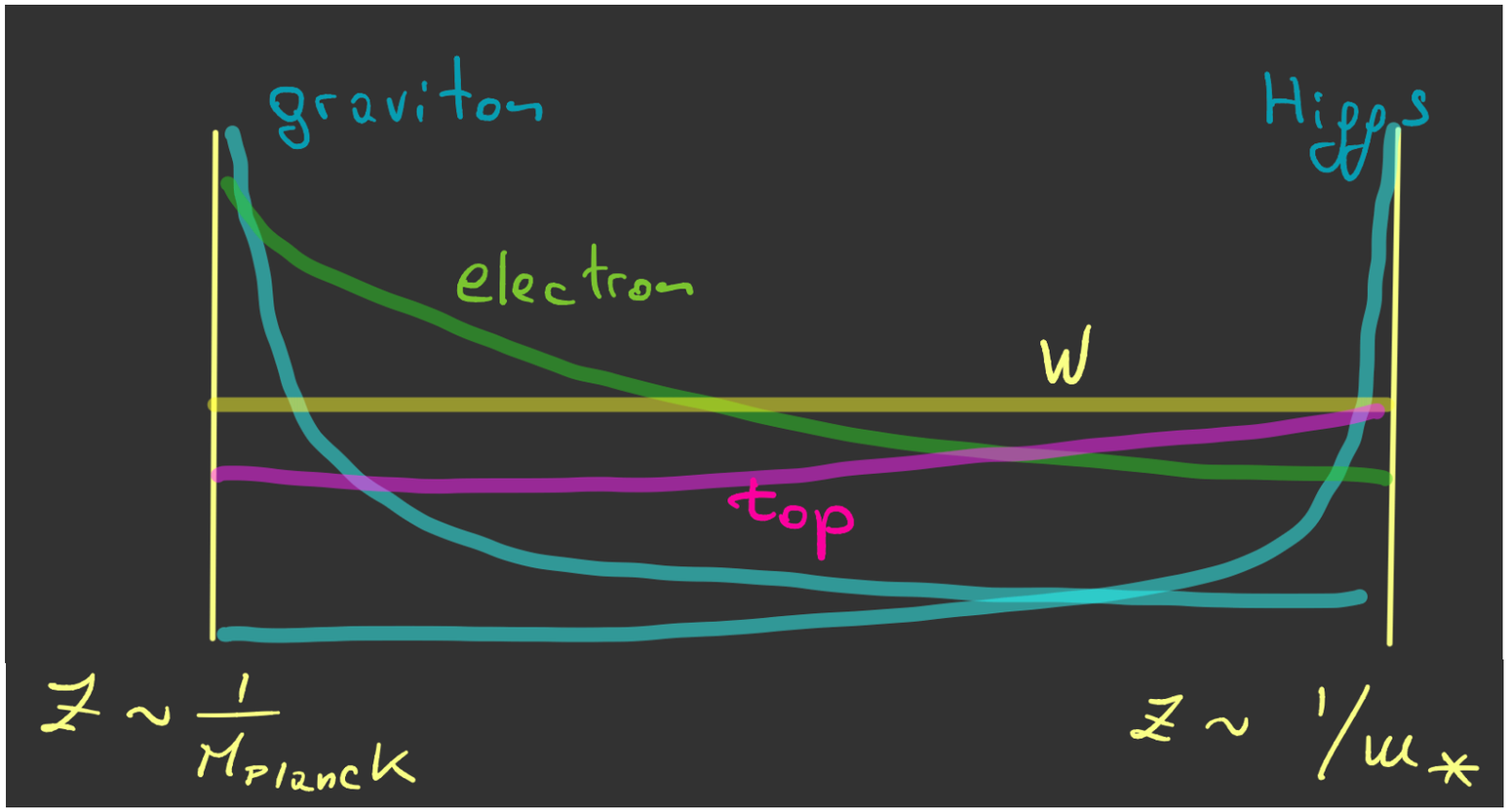
- q_i 

u_j $\qquad Y^u_{ij} \;\sim\; \dfrac{\bar{y}^q_{ia}\, \bar{y}^u_{jb}}{g_*}\, m_{ab}$

A full fledged CFT realizing all that?

... of course not

but we at least have 'holographic realizations'



Randall-Sundrum's slice of AdS5

$m_* \sim m_{KK}$

$g_* \sim g_{KK} \sim \frac{4\pi}{\sqrt{N}}$

RG-flow ∽ mode profile

Higgs potential & Naturalness

$m_h,\ m_*$ ——————

Higgs potential & Naturalness

m_* ——————

Higgs is a pseudo-Nambu-Goldstone boson

m_h ——————

Higgs potential & Naturalness

m_* ——————

Higgs is a pseudo-Nambu-Goldstone boson

m_h ——————

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

▲ $V(H)$ is 'calculable'

$$\lambda_h = \frac{\#g_*^2}{8\pi^2} y_t^2 + \cdots \qquad g_* \sim 2 \div 4$$

▲ Naturalness

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

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

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

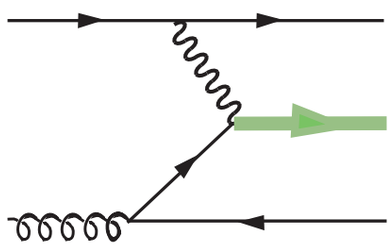
LHC

▲ Higgs non-linearities:  + ...

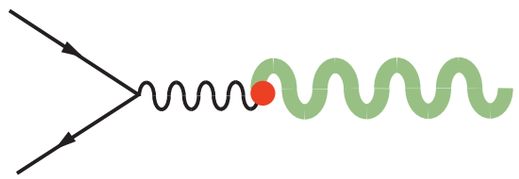
$$\frac{H^\dagger H}{f^2} \quad \Rightarrow \quad \frac{\delta g_h}{g_h|_{SM}} \sim \frac{v^2}{f^2} \sim \epsilon_{FT}$$

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

▲ Composite resonances:

top partners 

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

W/Z partners 

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

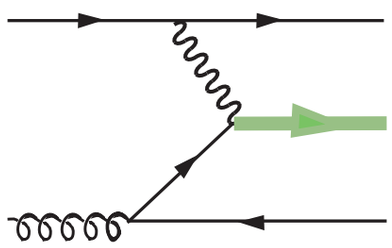
LHC

▲ Higgs non-linearities:  + ...

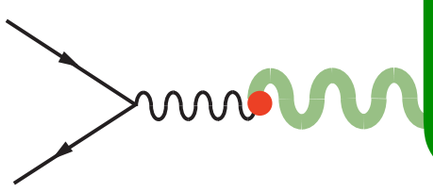
$$\frac{H^\dagger H}{f^2} \quad \Rightarrow \quad \frac{\delta g_h}{g_h|_{SM}} \sim \frac{v^2}{f^2} \sim \epsilon_{FT}$$

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

▲ Composite resonances:

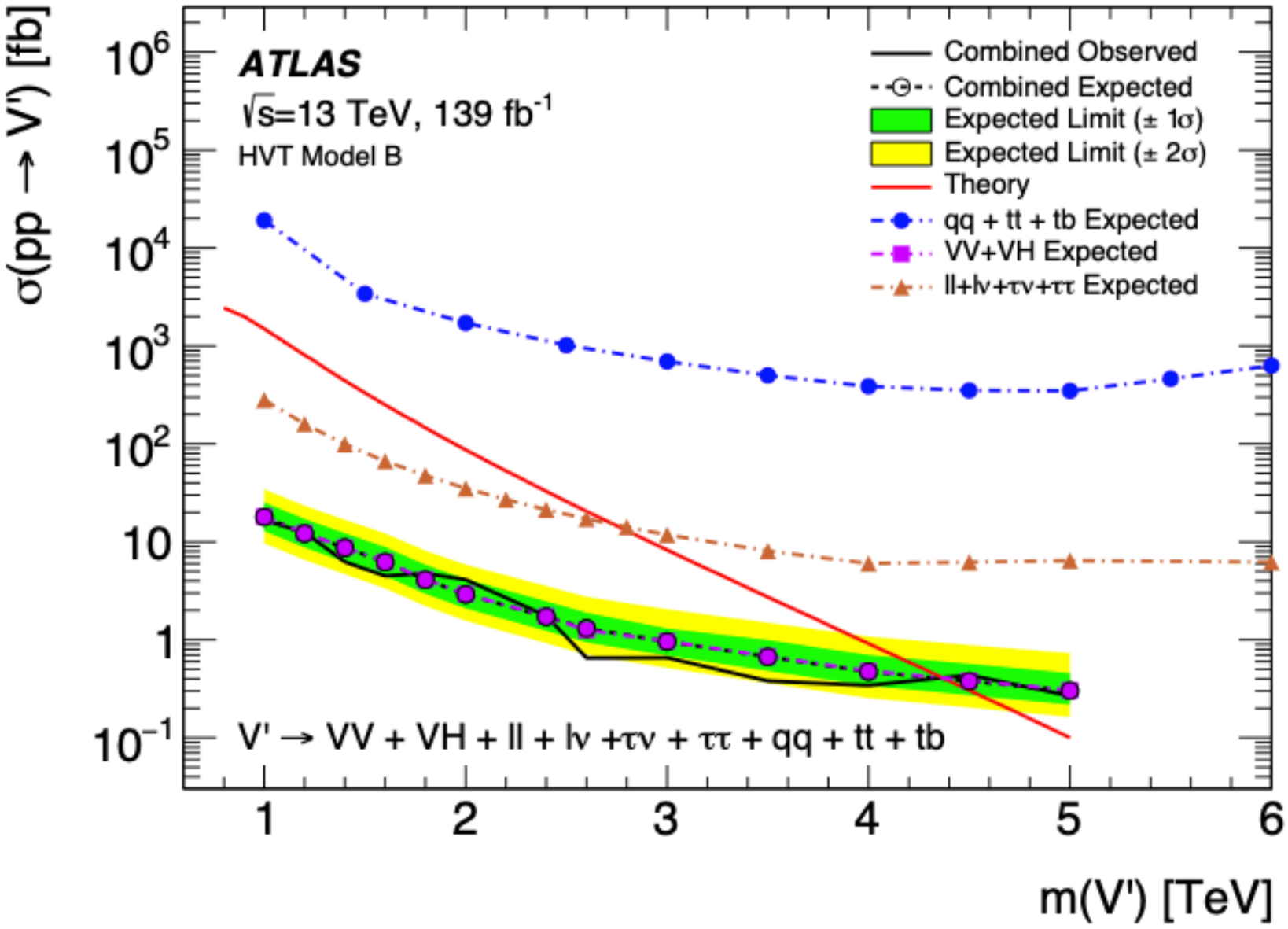
top partners 

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

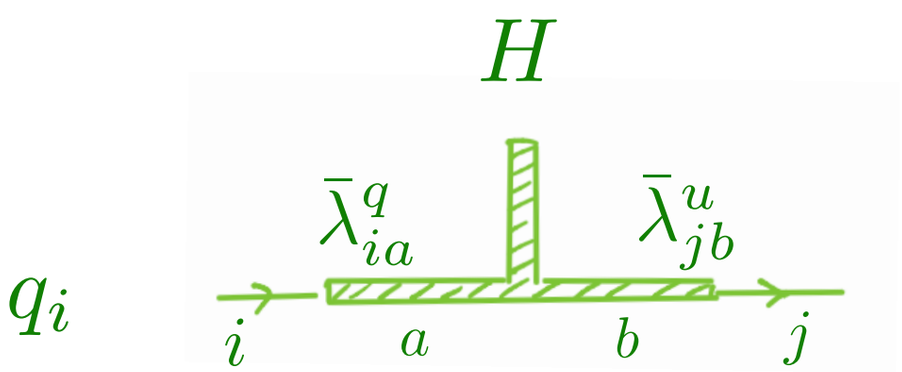
W/Z partners 

$$\epsilon_{FT} \lesssim 0.01$$

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

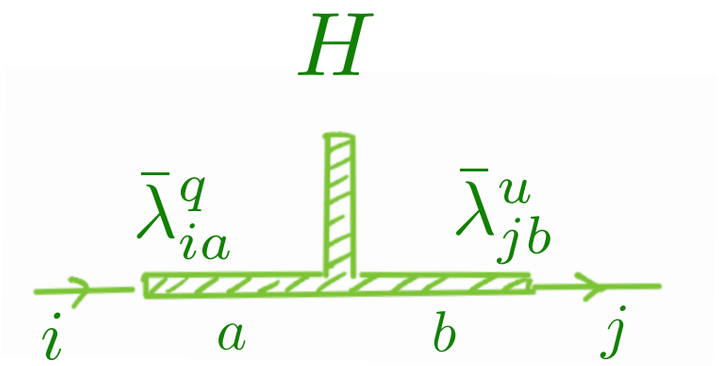

ATLAS
√s=13 TeV, 139 fb-1
HVT Model B
Combined Observed
Combined Expected
Expected Limit (± 1σ)
Expected Limit (± 2σ)
Theory
qq + tt + tb Expected
VV+VH Expected
ll+lν+τν+ττ Expected
V' → VV + VH + ll + lν +τν + ττ + qq + tt + tb
σ(pp → V') [fb]
m(V') [TeV]

... and then there came Flavor

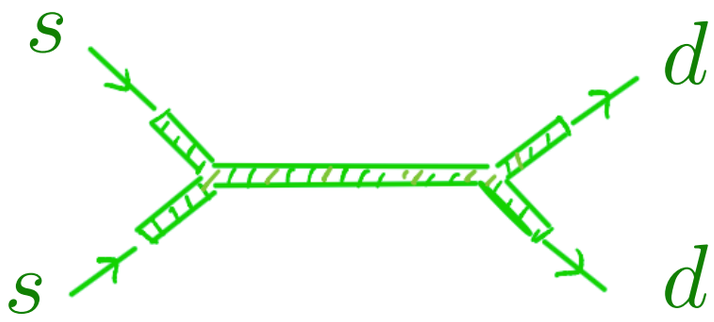


$$Y^u_{ij} \sim \frac{\bar{y}^q_{ia}\,\bar{y}^u_{jb}}{g_*}\, m_{ab}$$

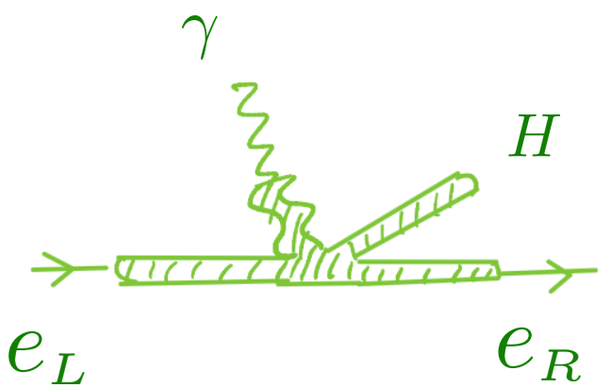
... and then there came Flavor



$$q_i \qquad u_j \qquad \longrightarrow \qquad Y^u_{ij} \sim \frac{\bar{y}^q_{ia}\,\bar{y}^u_{jb}}{g_*}\, m_{ab}$$



$$\longrightarrow \quad \epsilon_K \quad \longrightarrow \quad m_* \gtrsim 30\,\mathrm{TeV}$$

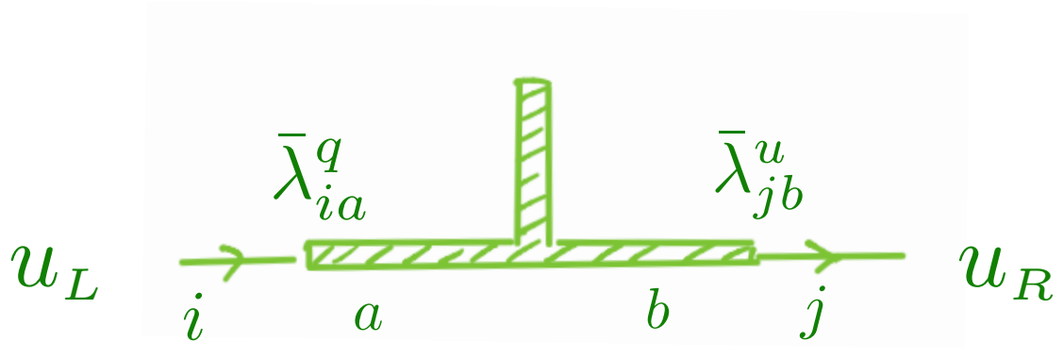


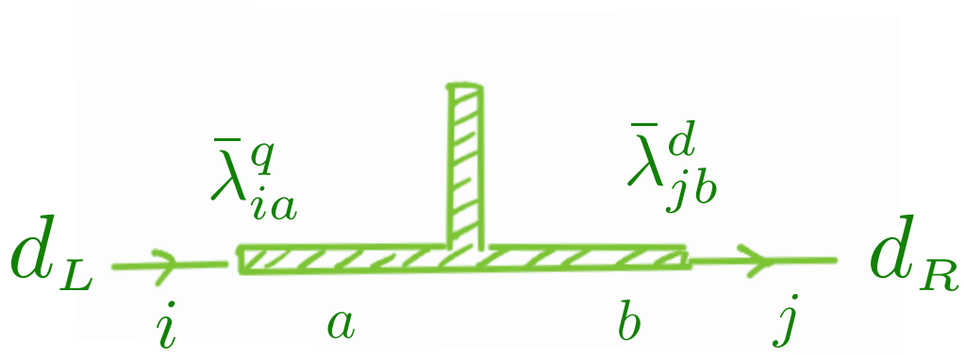
$$\longrightarrow \quad d_e \quad \longrightarrow \quad m_* \gtrsim 2 \times 10^3\,\mathrm{TeV}$$

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

→ explanation of fermion spectrum is lost

Redi, Weiler '11 Barbieri et al. '13 & '23 Glioti, RR, Ricci, Vecchi '24

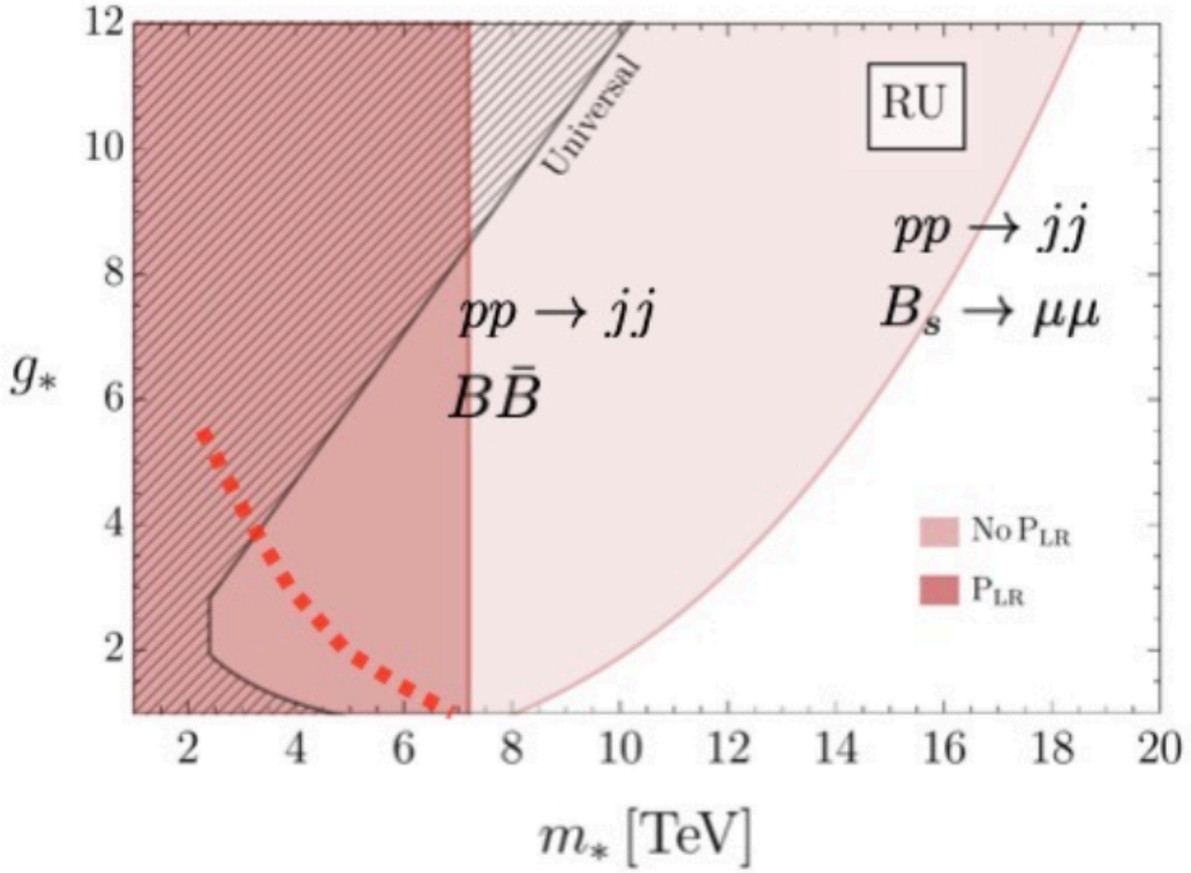


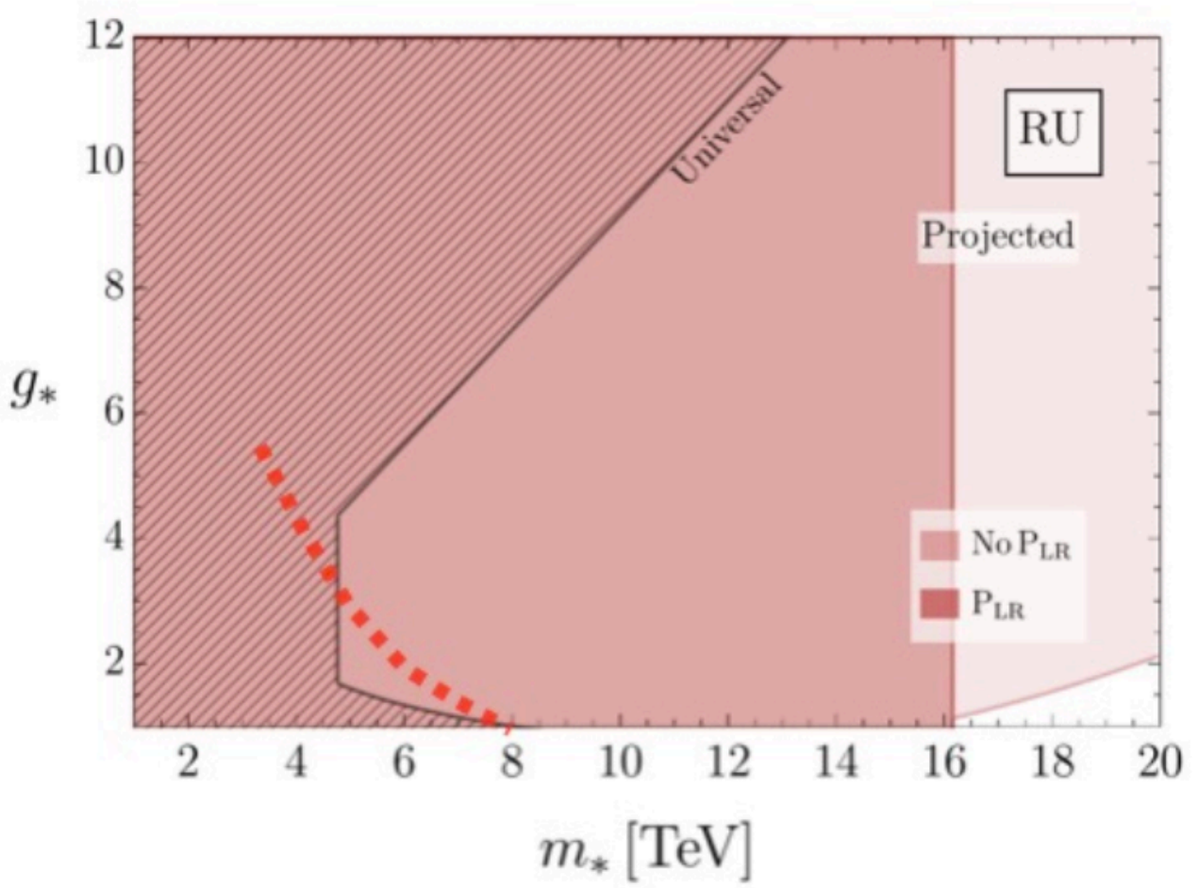


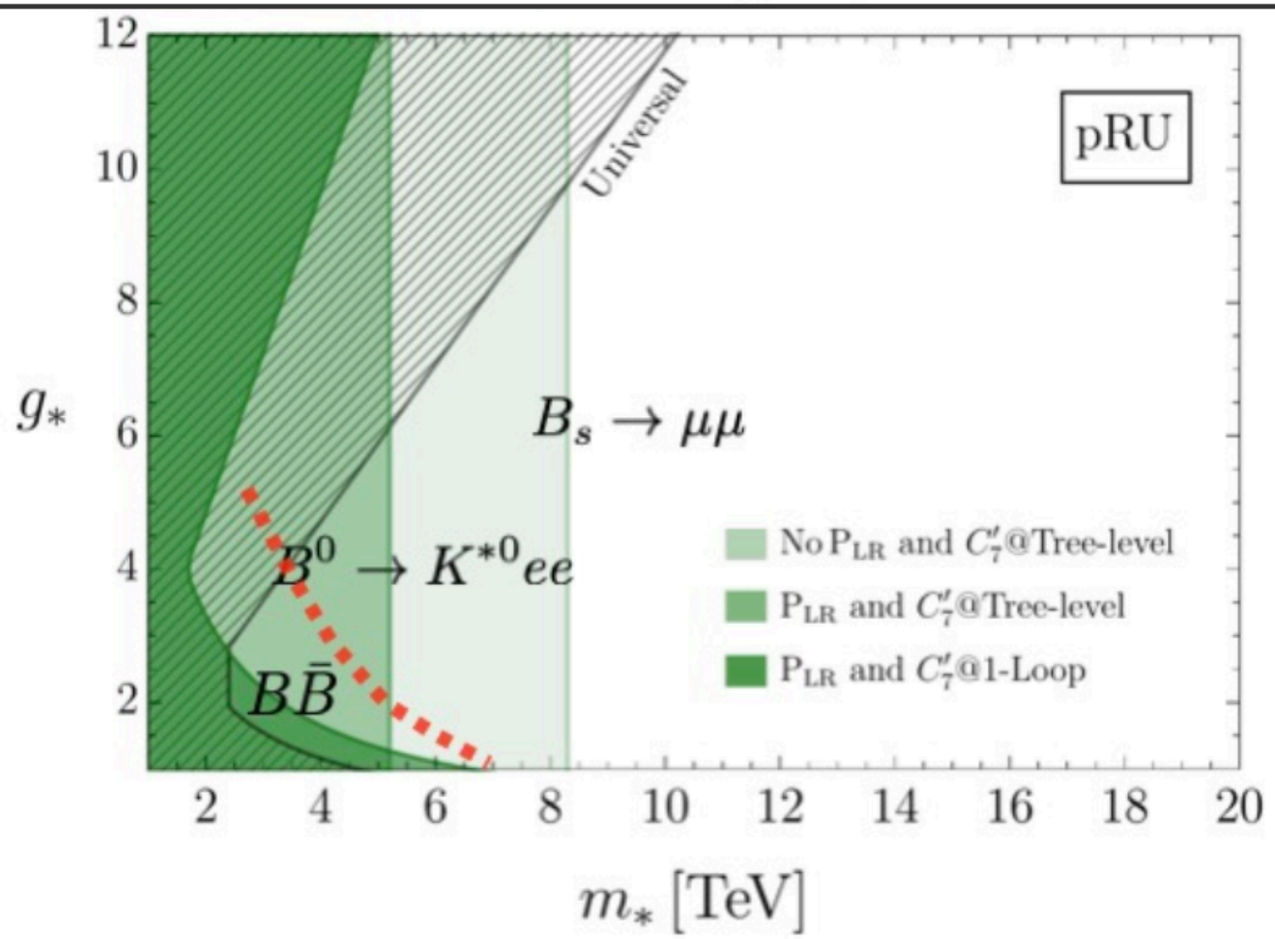
classify the possible symmetries of $\bar{\lambda}^q,\ \bar{\lambda}^u,\ \bar{\lambda}^d$

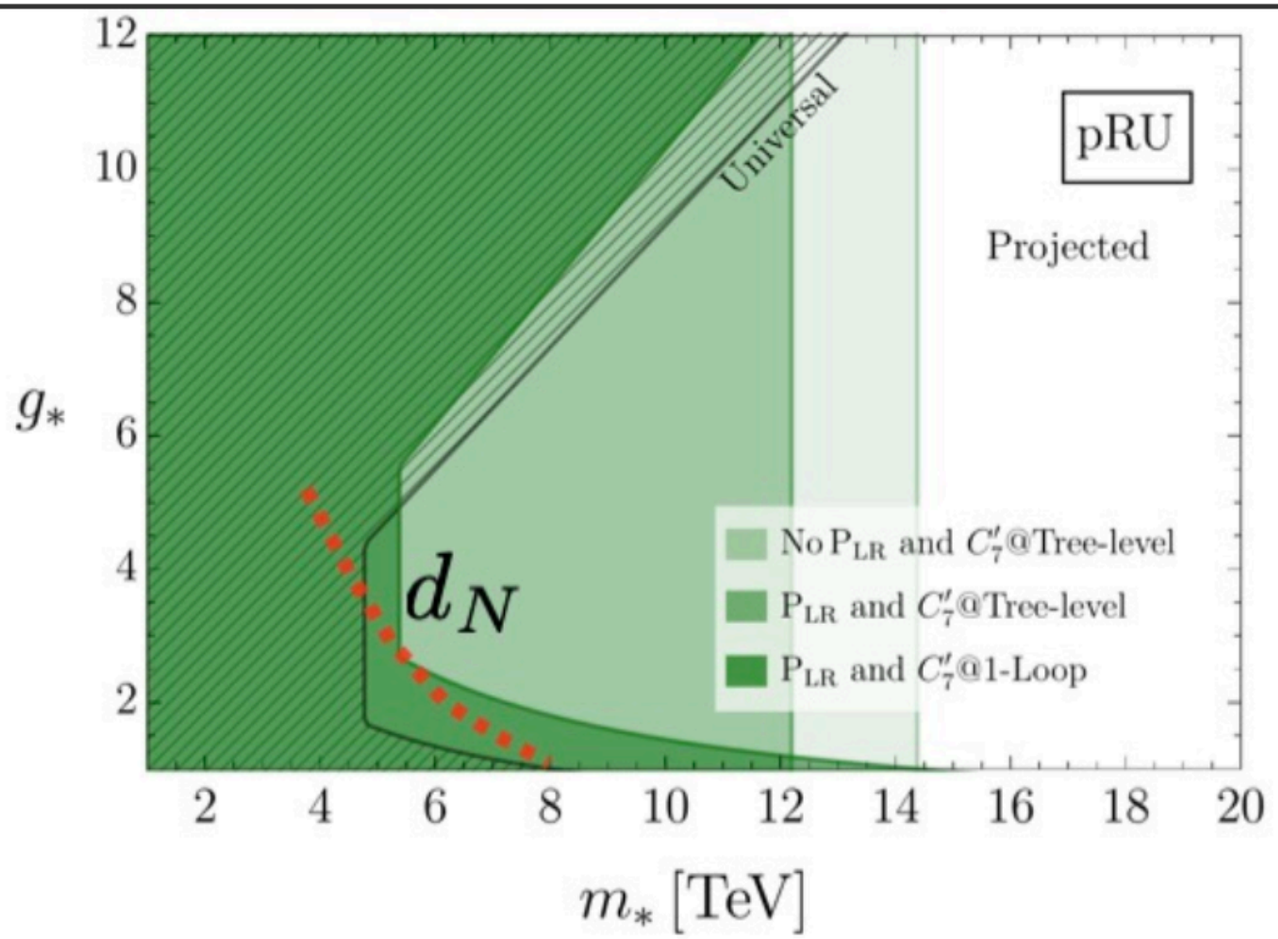
→ Scenarios

- 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
$pp \to jj$
$B\bar{B}$
$pp \to jj$
$B_s \to \mu\mu$
No P_{LR}
P_{LR}
g_*
m_* [TeV]

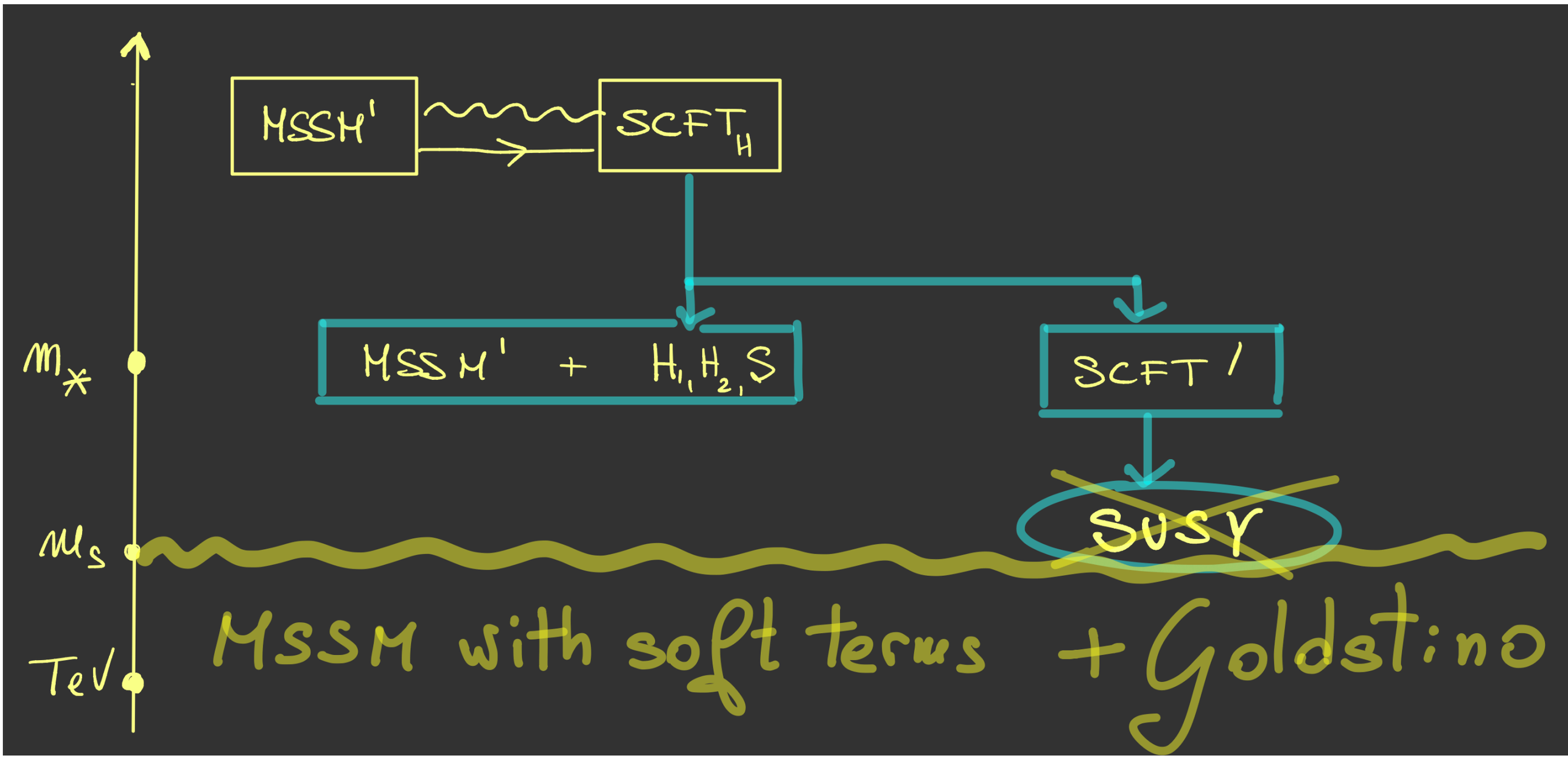

RU
Universal
Projected
No P_{LR}
P_{LR}
g_*
m_* [TeV]


pRU
Universal
$B_s \to \mu\mu$
$B^0 \to K^{*0}ee$
$B\bar{B}$
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

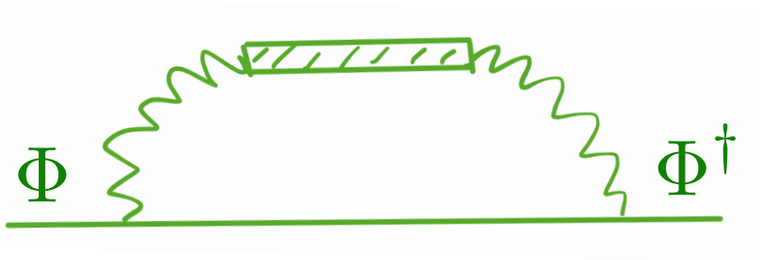
$$\mathcal{L} = \mathcal{L}_{MSSSM'} + \mathcal{L}_{SCFT_H} + \int d^4\theta\, g\, V_{SM}\, J_{SCFT_H} + \int d^2\theta\, y_{ia}\, \Phi_i\, \mathcal{O}_a$$



Nomura, Papucci, Stolarski '08 Okada, Yamada '11 ... Agashe, Giudice, RR, Sundrum, to appear

- gaugino and sfermions masses from SM gauge forces

$$m_{1/2} \sim \frac{g^2}{g_*^2}\, m_s \sim \frac{\alpha\, N}{4\pi}\, m_s$$



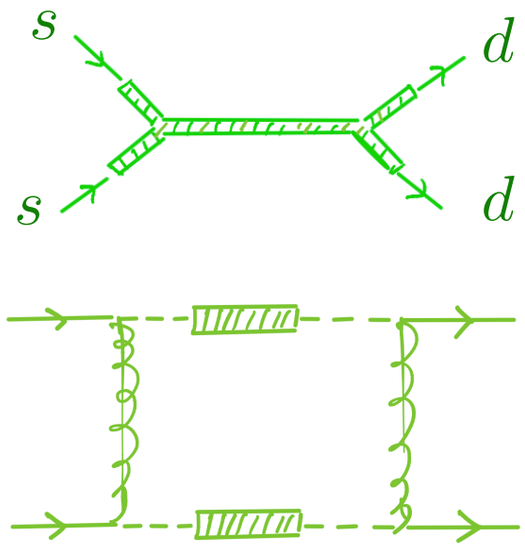
$$m^2_{sfermions} \sim \frac{m^2_{1/2}}{N}$$ = Flavor Universal

- Higgs mass parameters from compositeness

$$\int d^4\theta [H_1^\dagger H_1 + H_2^\dagger H_2 + H_1 H_2 + ...] \times \left(\frac{\mathcal{O}_{CFT'}}{m_*^{\Delta_\mathcal{O}}}\right) \qquad \mu \sim B \sim A \sim \left(\frac{m_s}{m_*}\right)^{\Delta_\mathcal{O}} m_s$$

$$\mu \sim m_{1/2} \quad \Longleftrightarrow \quad 100 \text{ TeV} \lesssim m_* \lesssim 2000 \text{ TeV}$$

ϵ_K



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

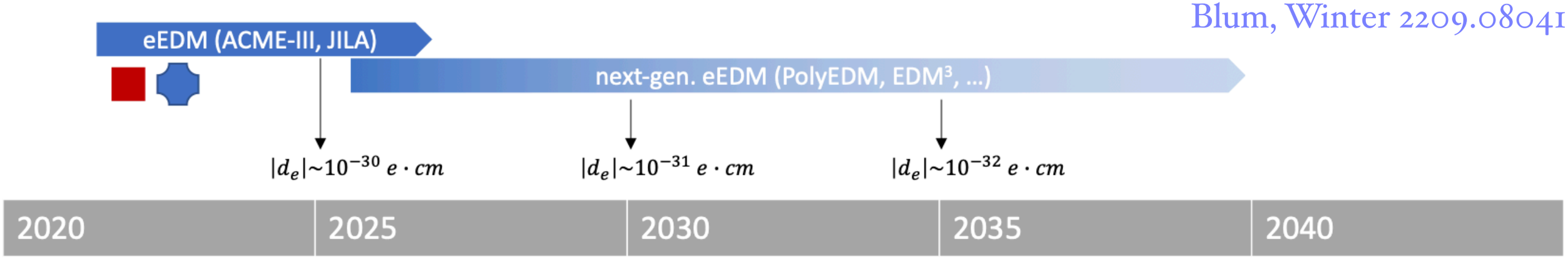
$$m_{\tilde{g},\tilde{q}} \gtrsim 1\,\text{TeV}$$

edm

$$\frac{d_e}{e} \sim 4\times10^{-30}\,\text{cm} \times \frac{100\,\text{TeV}}{m_*} \times \frac{\text{TeV}}{m_{\tilde{\ell},\tilde{w}}}$$

$$\frac{d_e}{e} \sim 4\times10^{-30}\,\text{cm} \times \frac{700\,\text{TeV}}{m_*} \times \frac{\tan\beta}{10} \times \frac{\text{TeV}}{m_{\tilde{\ell},\tilde{w}}}$$

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: $\dfrac{\delta\lambda_3}{\lambda_3} \sim \dfrac{\delta g_{hZZ}}{g_{hZZ}} \sim \epsilon_{FT}$ not competitive

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

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

■ possibly motivated by EW baryogenesis, but ...

■ standard scenarios ruled-out/borderline by electron-edm bound

■ scenarios evading edm bound all have small $\delta\lambda_3$

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

Back to the Strong CP problem

chatting with Luty, Luzio, Redi, Stelzl, Vecchi, ...

‘ θ_{QCD} is determined by vacuum dynamics, not by microphysics, hence it is futile to seek symmetry based solution à la Nelson-Barr ’

Dvali ’06
Kaplan, Melia, Rajendran ’24

... but global symmetries (ex P, CP) may just emerge

- 5D YM $\Rightarrow$ 4D $\quad -\frac{1}{4g_5^2}G^2 + k\,\Omega_{CS} + \dots$

local minimum at $\oint A_5 dx^5 = 0 \quad \Rightarrow \quad \theta = 0 + \text{loops} \ll 1$

- Banks-Zaks fixed point with real scalar $\quad \mathcal{L}_{BZ} + (\partial\phi)^2 + y\phi\bar{q}q + \lambda\phi^4$

either θ evolves (via instantons) or is exactly marginal (!?)

1-instanton $\Rightarrow \quad \beta_\theta = \kappa\, e^{-8\pi^2/g_*^2} \sin\theta$

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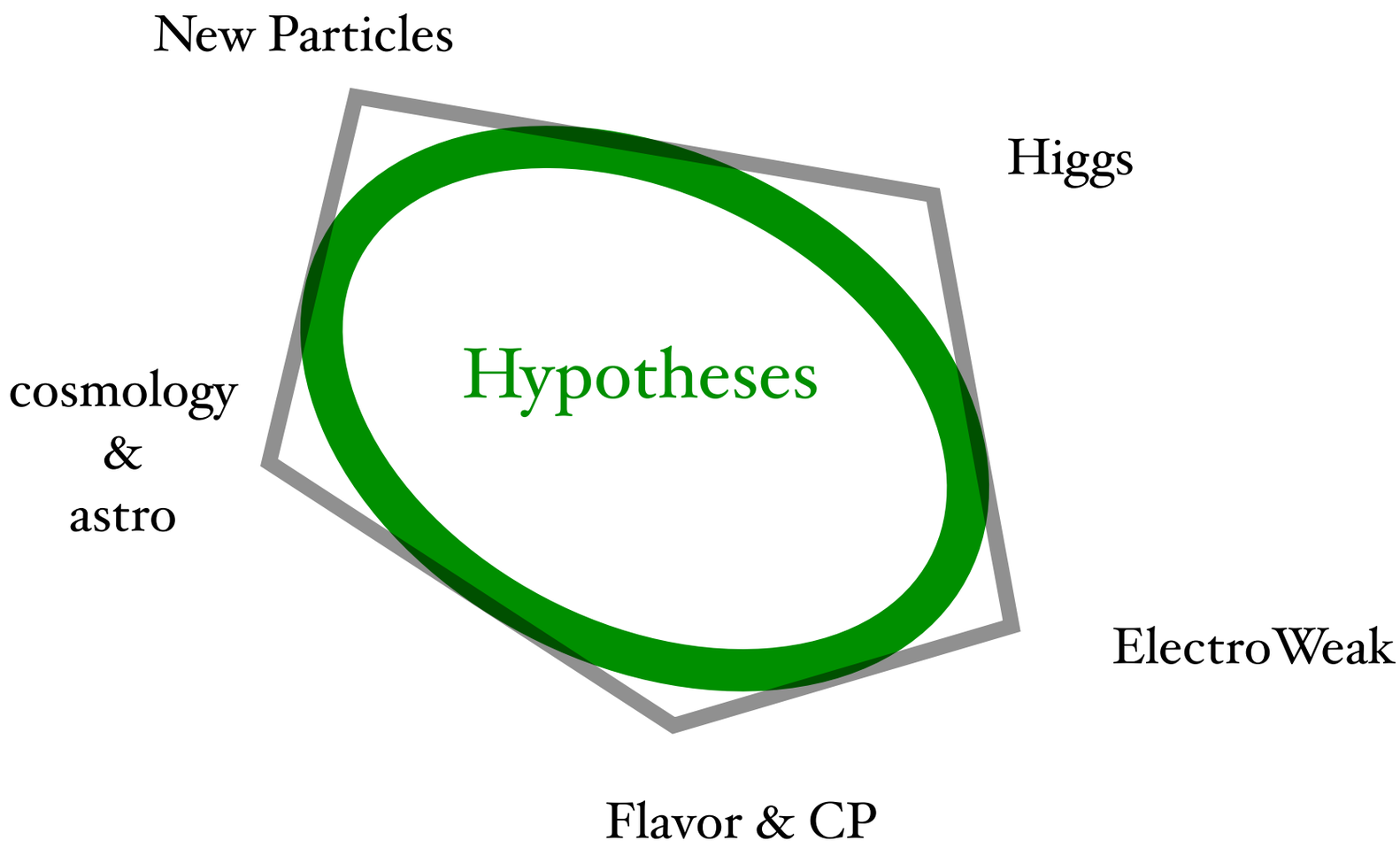
What is the origin of the weak scale?

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



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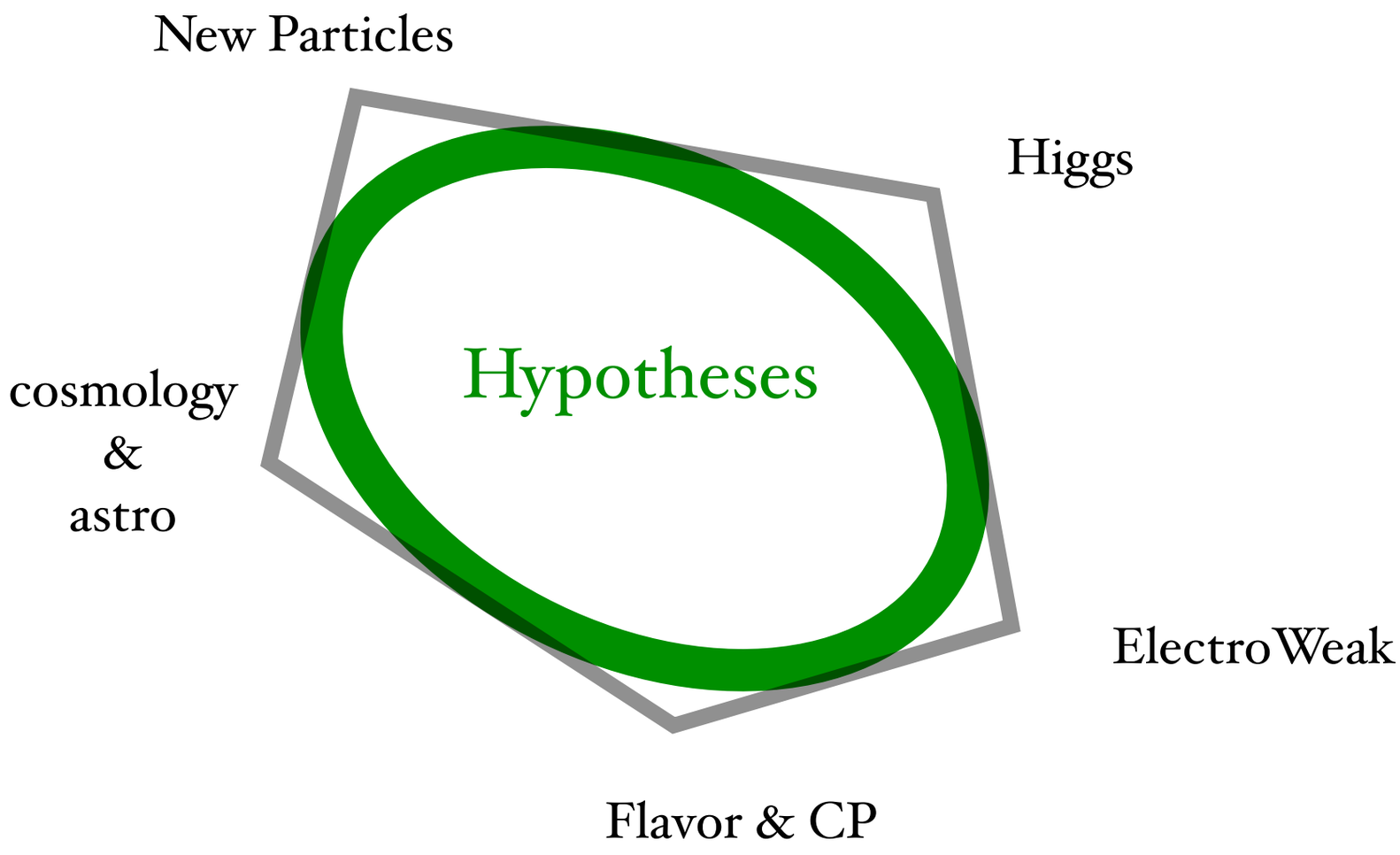

Let us all meet at GGI to discuss and be inspired!