Fenomenologia oltre il Modello Standard

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SISSA

- Indirect experimental hints and the weak/strong dicotomy

- Model-independent effective approaches to EWSB

- One example of a (new) explicit model

Indirect experimental information on physics beyond the EW scale before LHC

- Strongest and most precise hints presumably associated to E » TeV: *grand-unification* and *neutrino masses*

  not **directly** relevant to TeV, still

  - best friends with physics that can be extrapolated to high scale
  - gauge coupling unification precisely PREDICTED in very few models, but accounted for in many

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L_i	1	2	-1/2
$e^c{}_i$	1	1	1
Q_i	3	2	1/6
$u^c{}_i$	3^*	1	-2/3
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			Y

	SU(3)	SU(2)	U(1)		SO(10)
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⇒

SO(10)
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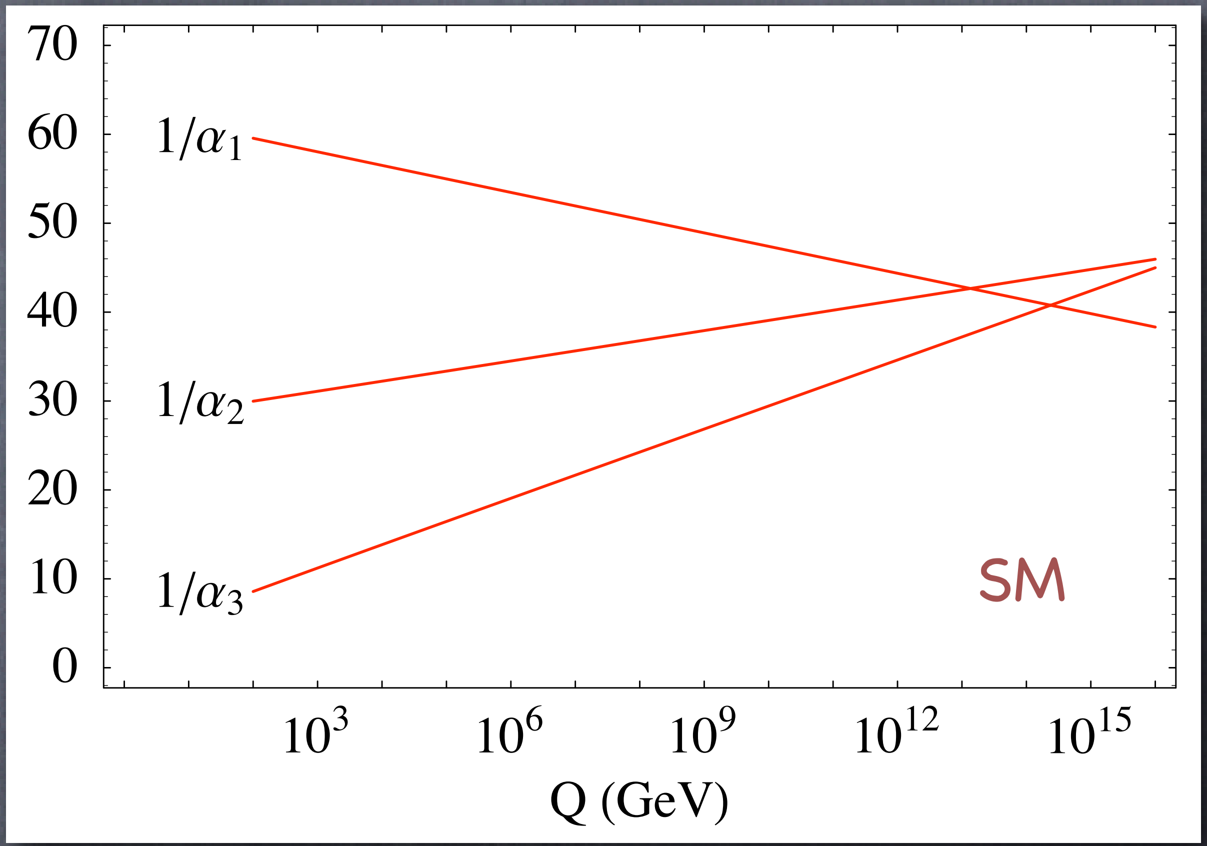

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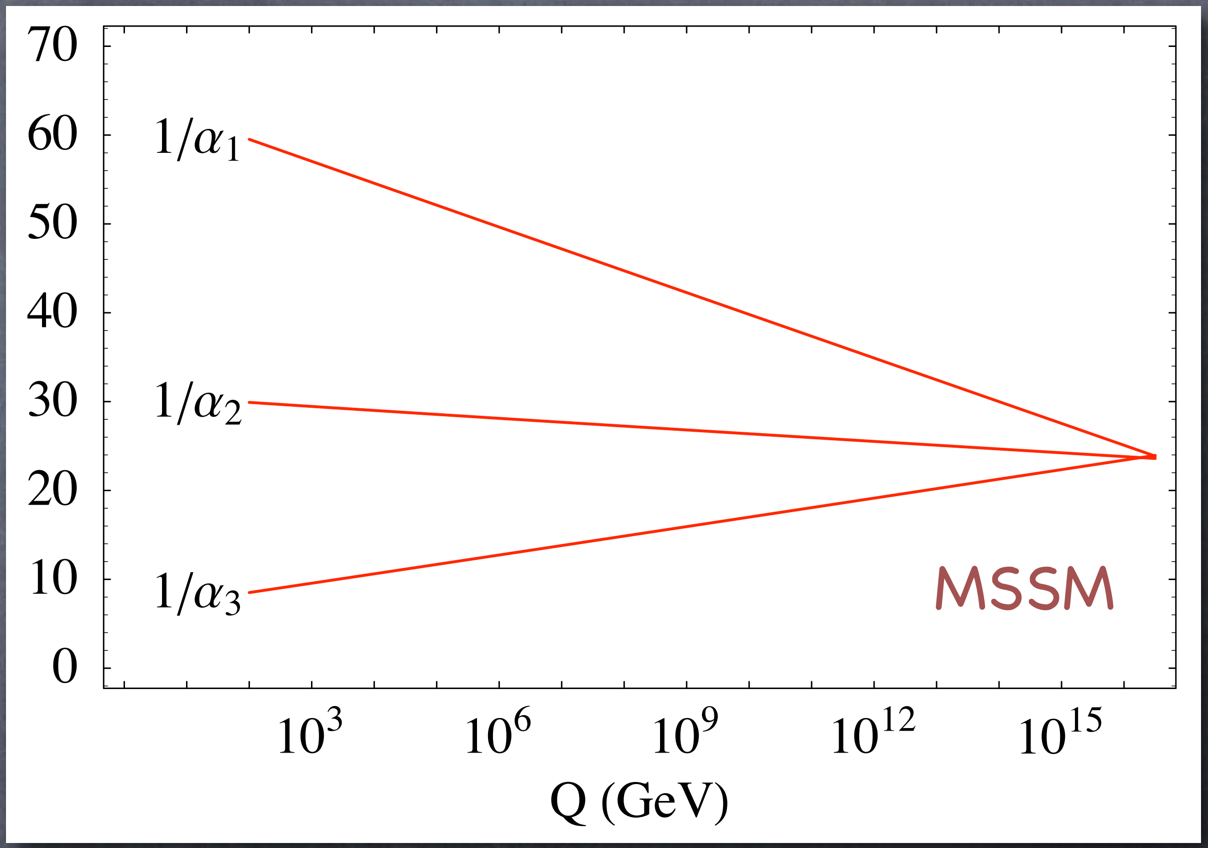

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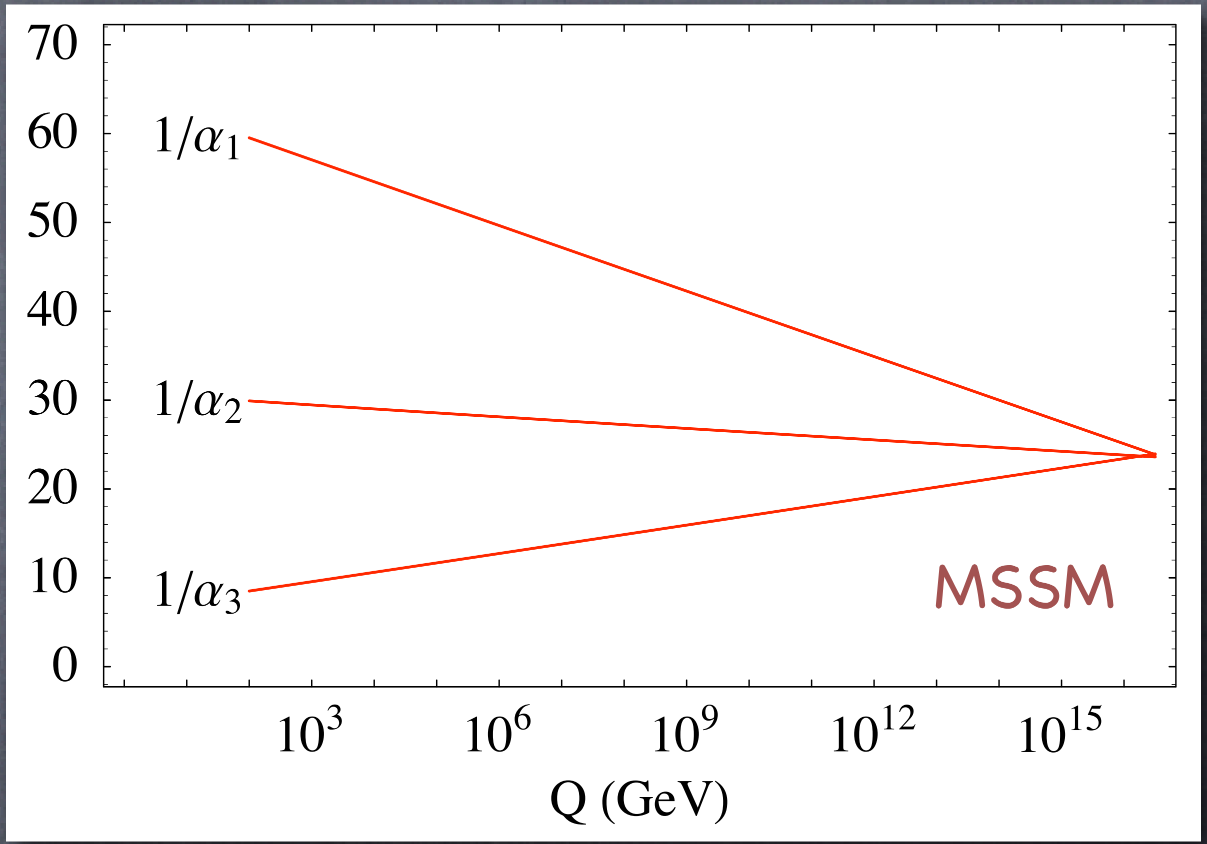

+ M_{GUT} prediction: $\Lambda_B < M_{GUT} < M_{Pl}$

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- Hints from cosmology and astroparticle physics: *dark matter, baryon asymmetry, inflation, dark energy*

  not **necessarily** relevant to TeV, still

  - relic-abundance prediction from EW-scale WIMP DM
  - but does not point at a single model

EW-scale WIMP Dark Matter

$$\Omega_\chi h^2 = \frac{688\pi^{5/2} T_\gamma^3 x_f}{99\sqrt{5g_*}(H_0/h)^2 M_{\rm Pl}^3 \sigma} = 0.1\,\frac{\rm pb}{\sigma}$$

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Too good *not* to be true?

No lack of candidates

- $s = 0$: little higgs, stable by T-parity
- $s = 1/2$: supersymmetry, stable by R-parity
- $s = 1$: extra dimensions, stable by KK-parity

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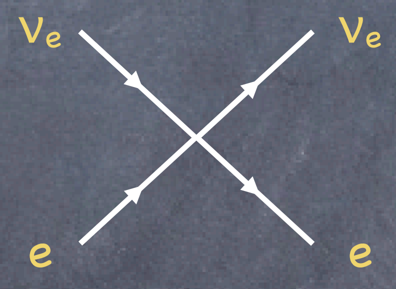
- "nσ" hints in precision and flavour observables: g-2, A^{0b}_{fb}, $B_s \to J/\psi\, \varphi$, ...

  possibly relevant, not conclusive

Indirect experimental information on the EW scale before SPS

$$\mathcal{L}^{\rm eff}_{\rm weak} = \frac{G_F}{\sqrt{2}} j^\mu_c j^\dagger_{c\mu} + \ldots \qquad G_F^{-1/2} \equiv \Lambda \sim 250\,{\rm GeV}$$

$$j^\mu_c = \frac{1}{2}\bar{\nu}_e\gamma^\mu(1-\gamma_5)e + \frac{1}{2}\bar{u}\gamma^\mu(1-\gamma_5)d = \overline{\nu_L}\gamma^\mu e_L + \overline{u_L}\gamma^\mu d_L$$



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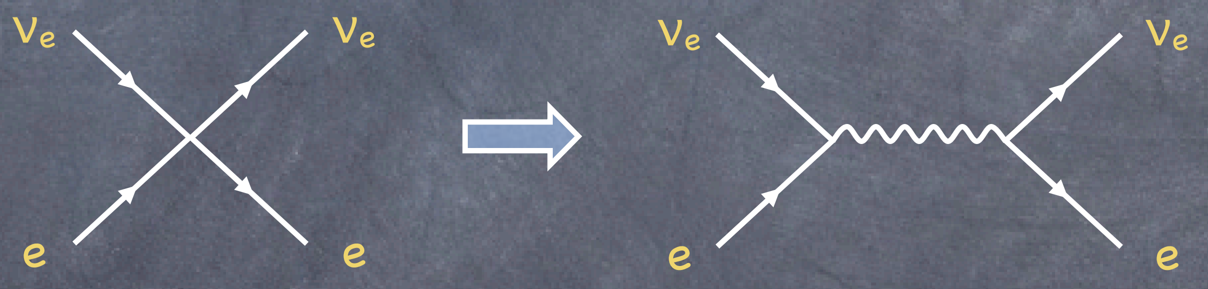
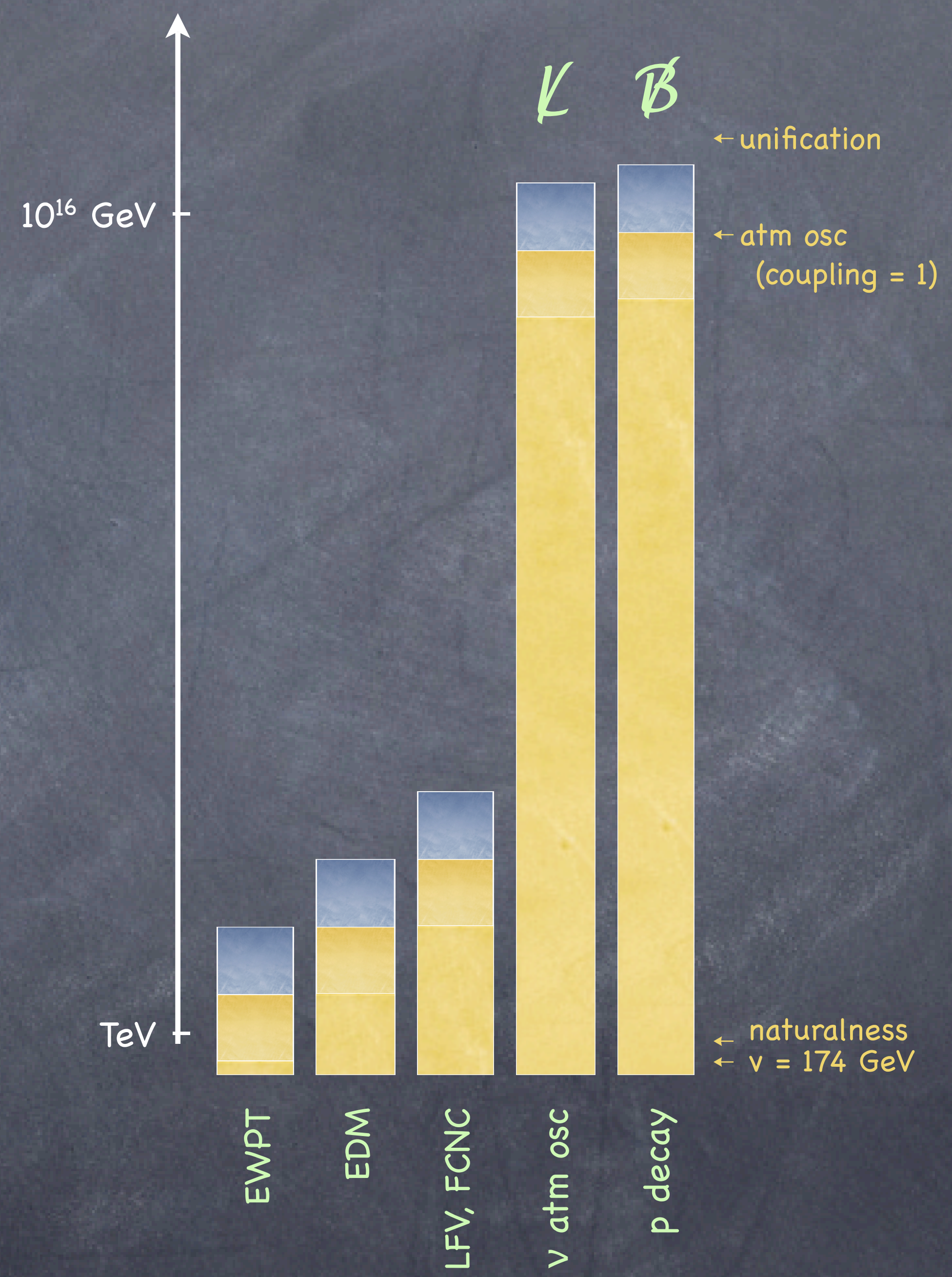


W_μ coupling with L-fermions

Limits from lack of new effective interactions



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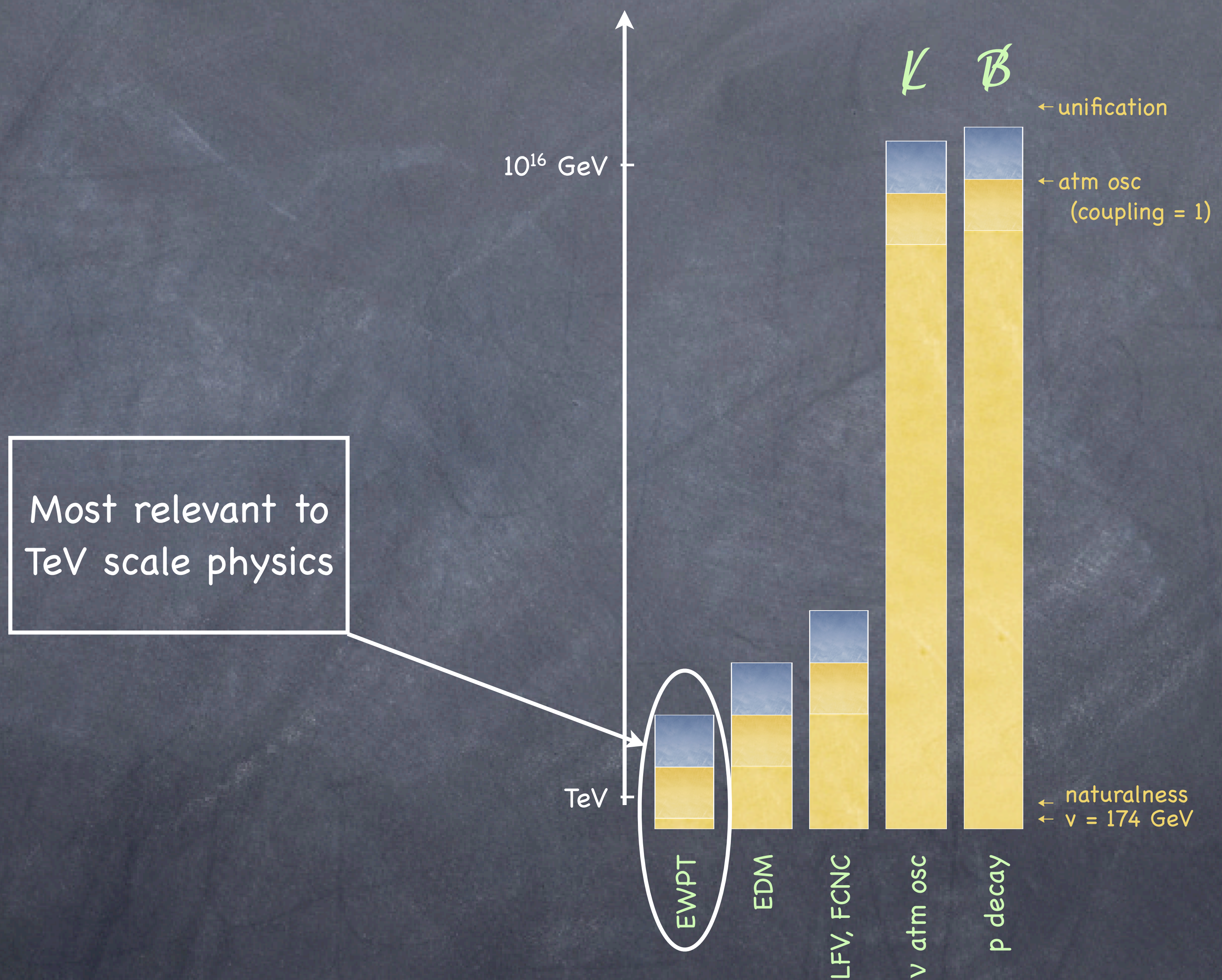

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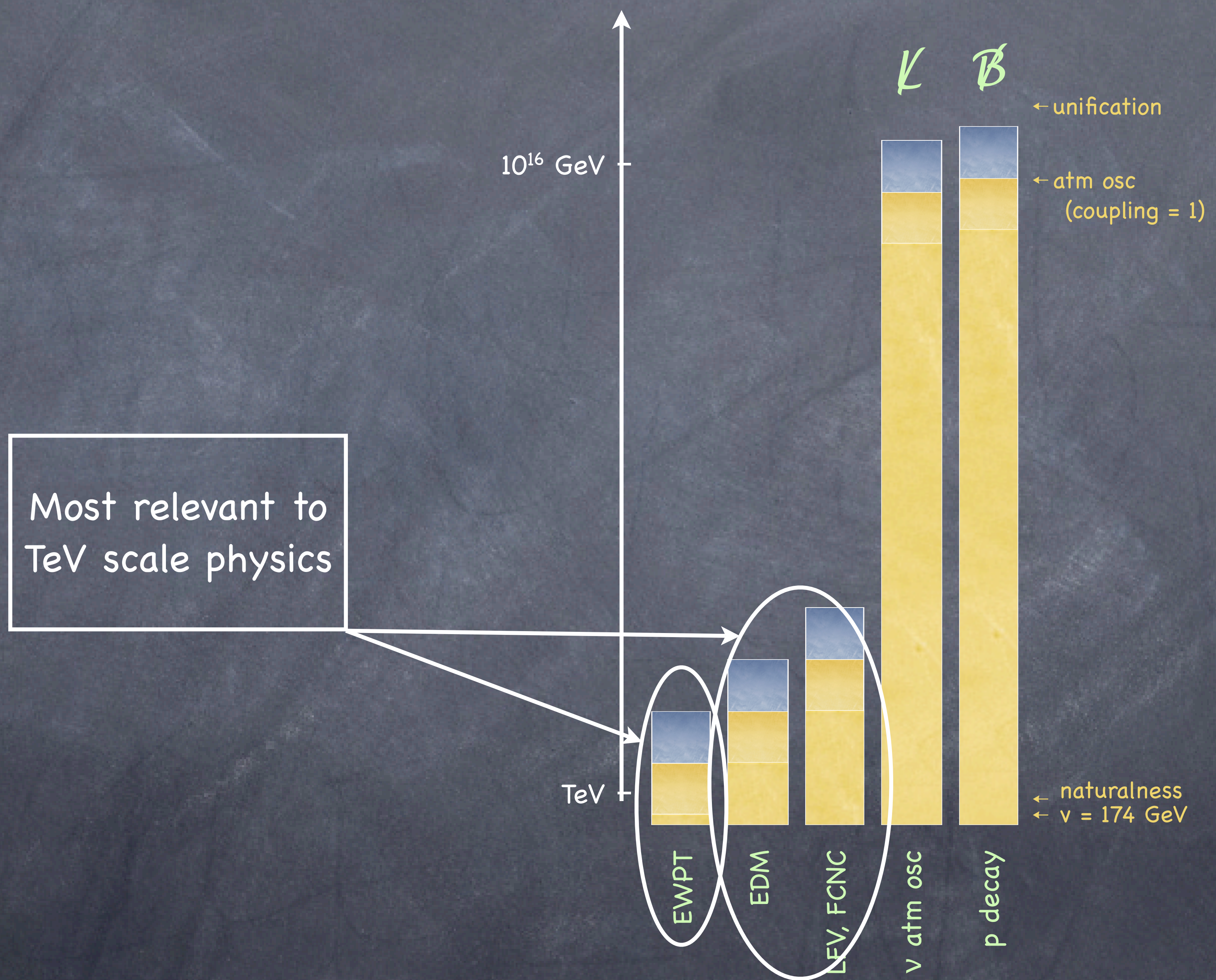

The landscape of theory models

- Indirect information does not single out a model
  → proliferation of theory models addressing the "naturalness/unitarity" problem:
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- Higgsless: TC, ETC, walking-TC, EWSB in 5D or more, etc
- TeV cutoff for δm^2_h:
  - Fundamental scale (large, TeV, susy, flat, warped, etc)
  - Higgs compositeness (plain, Little, see-above, etc)
  - Supersymmetry breaking scale (MSSM, xMSSM, etc)
- Fine-tuned models (SM, SpS, SuperSpS, etc)

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Weakly interacting at Λ » TeV

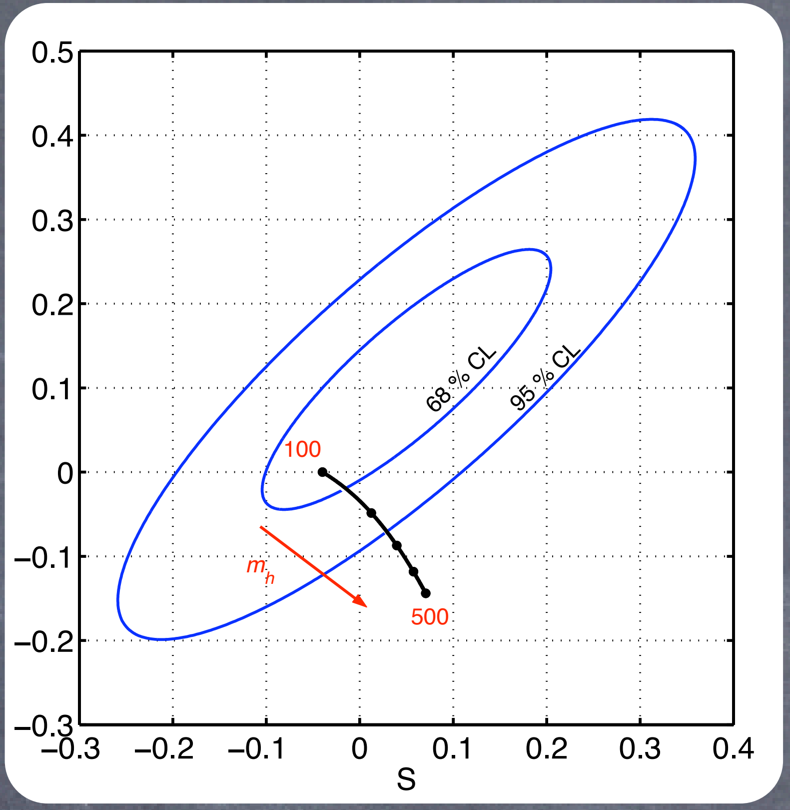
A minimal, model independent approach

- Known fields: $g_A^\mu \quad W_a^\mu \quad B^\mu \quad Q_i \quad u_i^c \quad d_i^c \quad L_i \quad e_i^c \qquad G_a$
- General lagrangian: [Callan Coleman Wess Zumino] $U = e^{i\frac{G_a \sigma_a}{2v}} \qquad v = 246\,\mathrm{GeV}$

$$\mathcal{L} = \mathcal{L}^{\mathrm{SM}}_{\mathrm{gauge}} + \frac{v^2}{4}\mathrm{Tr}[(D_\mu U)^\dagger (D^\mu U)] - \left[\frac{v}{\sqrt{2}}\overline{Q_{Li}} U \begin{pmatrix} \lambda^U_{ij} u^R_j \\ \lambda^D_{ij} d^R_j \end{pmatrix} + \mathrm{h.c.}\right]$$
$$+ a_0 \frac{v^2}{4}[\mathrm{Tr}(U^\dagger D_\mu U T_3)]^2 + \ldots + \mathcal{O}\left(p^4\right)$$

- $\rho = \dfrac{M_W^2}{M_Z^2 \cos^2\theta_W} \approx 1 \Rightarrow a_0 \ll 1$, or approximate global $SU(2)_L \times SU(2)_R$
- Reliable up to $\Lambda \sim 4\pi v \sim$ few TeV
  - anything else below Λ?
  - what goes on at $E \gg \Lambda$?

- Electroweak precision observables (EWPOs) need new ingredients



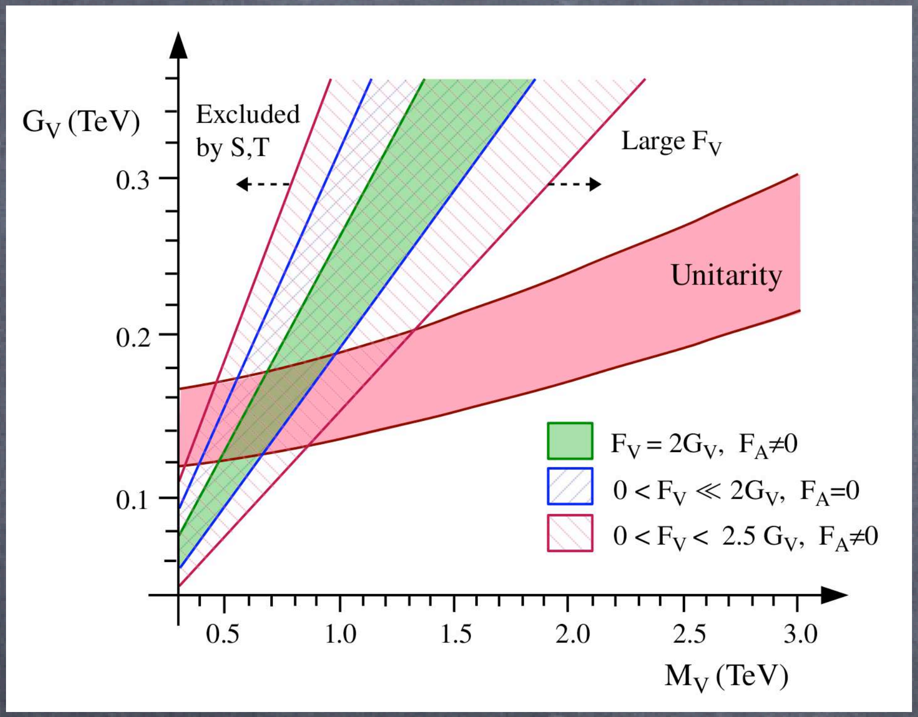
[Barbieri arXiv:0706.0684]

- Effect of s = 0, 1/2, 1 states below Λ revisited in a model independent way

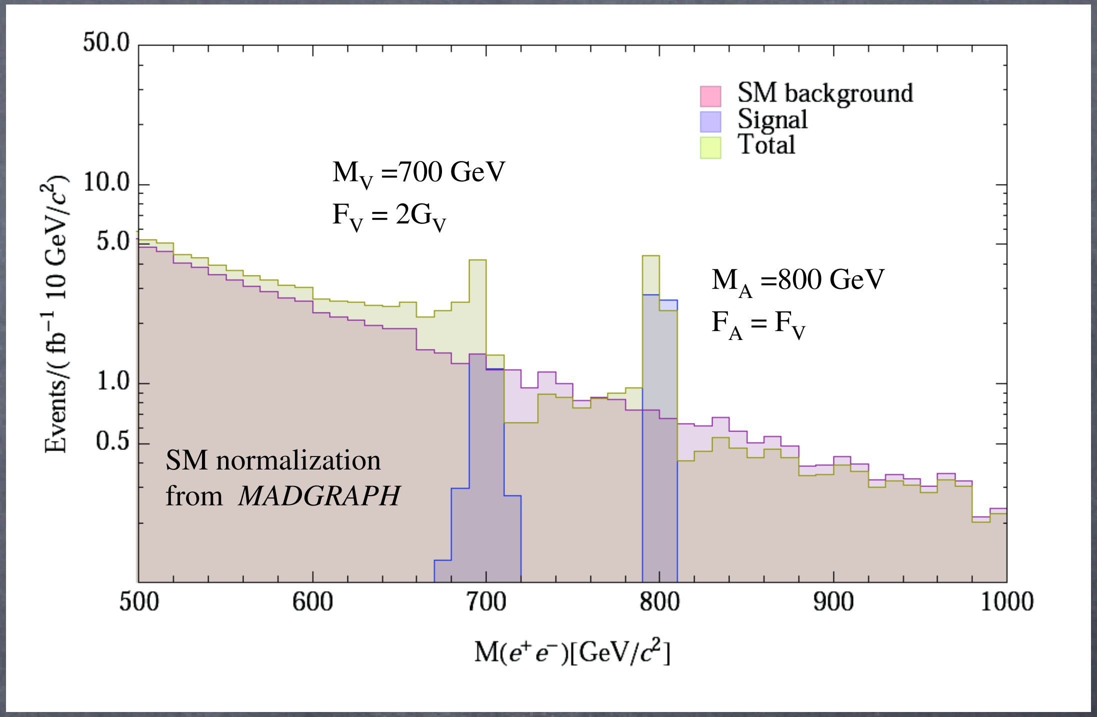
New vectors

Bagger 94
Chivukula Dicus He 02
Fabbrichesi Vecchi 07
Belayev 08
Accomando De Curtis Dominici Fedeli 08
Barbieri Isidori Rychkov Trincherini 08
Cata Isidori Kamenik
Barbieri Carcamo Corcella Torre Trincherini 09

- $V_\mu + A_\mu$ (vector + axial vector)
- Adjoint of $SU(2)_{L+R}$, coupled to SM gauge sector only (safe), L-R parity
- Parameters: M_V, F_V, G_F, M_A, F_A



Barbieri Isidori Rychkov Trincherini 08



Cata Isidori Kamenik

EWPOs

Signals
for M_V < 800 GeV
Drell-Yan production
clean l^+l^- signal

A light, possibly composite scalar

Kaplan Georgi 84
Arkani-Hamed Cohen Katz Nelson 02
Contino Nomura Pomarol 03
Agashe Contino Pomarol 05
Giudice Grojean Pomarol Rattazzi 07
Contino Grojean Moretti Piccinini Rattazzi 10
De Rujula Lykken Pierini Rogan Spiropulu 10

- $\mathcal{L} = (D_\mu H)^\dagger (D^\mu H) + \frac{c_H}{2f^2}[D_\mu(H^\dagger H)]^2 + \dots$
- f interpolates between
  - composite Higgs from strong dynamics at $\Lambda \sim f \sim$ few TeV (PGB, Little Higgs, holographic Higgs)
  - weakly interacting EW sector at $f \sim \Lambda$ » TeV, needing a cutoff to radiative corrections to the Higgs mass
- the scalar fixes EWPO in the large f light m_H limit
- $$\mathcal{L} = \mathcal{L}^{\rm SM}_{\rm gauge} + \frac{v^2}{4}{\rm Tr}[(D_\mu U)^\dagger (D^\mu U)]\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - \left[\frac{v}{\sqrt{2}}\overline{Q_{Li}}U\left(1 + c\frac{h}{v}\right)\begin{pmatrix}\lambda^U_{ij}u^R_j \\ \lambda^D_{ij}d^R_j\end{pmatrix} + {\rm h.c.}\right] + \dots$$

$$a = 1 - \frac{c_H}{2}\frac{v^2}{f^2}$$

$$b = 1 - 2c_H\frac{v^2}{f^2}$$

$$c = 1 - \frac{c_H}{2}\frac{v^2}{f^2}$$

- a: VV → VV constrained by EWPTs [Barbieri Bellazzini Rychkov Varagnolo]
  b: VV → hh chance of a signal at high L [Contino Grojean Moretti Piccinini Rattazzi]
  c: VV → ff

What goes on above Λ?

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Weakly interacting up to MPl
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Higgs mass stable under rad corr
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Supersymmetry

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Supersymmetry

issue: not seen so far..
or FT (due to the extrapolation)

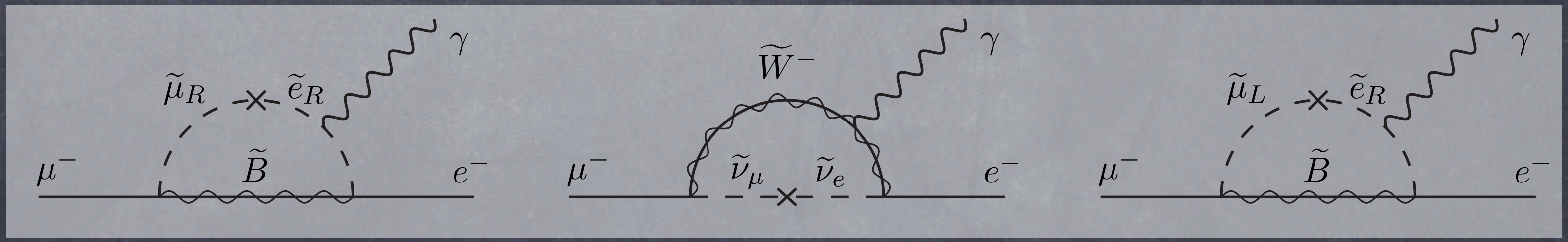
Supersymmetry breaking

- The supersymmetrization of the SM is straightforward, essentially unique, and does not introduce new parameters (it actually predicts one)
- Breaking supersymmetry is non-obvious, the mechanism is unknown (spontaneous?), a model-independent effective description is useful

$$\begin{aligned}-\mathcal{L}_{\rm soft} = &(\tilde m^2_q)_{ij}\tilde q^\dagger_i \tilde q_j + (\tilde m^2_{u^c})_{ij}(\tilde u^c_i)^\dagger \tilde u^c_j + (\tilde m^2_{d^c})_{ij}(\tilde d^c_i)^\dagger \tilde d^c_j + (\tilde m^2_l)_{ij}\tilde l^\dagger_i \tilde l_j \\ &+ (\tilde m^2_{e^c})_{ij}(\tilde e^c_i)^\dagger \tilde e^c_j + m^2_{h_u} h^\dagger_u h_u + m^2_{h_d} h^\dagger_d h_d \\ &+ \frac{M_3}{2}\tilde g_A \tilde g_A + \frac{M_2}{2}\tilde W_a \tilde W_a + \frac{M_1}{2}\tilde B \tilde B + \text{h.c.} \\ &+ A^U_{ij}\tilde u^c_i \tilde q_j h_u + A^D_{ij}\tilde d^c_i \tilde q_j h_d + A^E_{ij}\tilde e^c_i \tilde l_j h_d + m^2_{ud} h_u h_d + \text{h.c.}\end{aligned}$$

(MSSM)

- But about 100 new physical parameters



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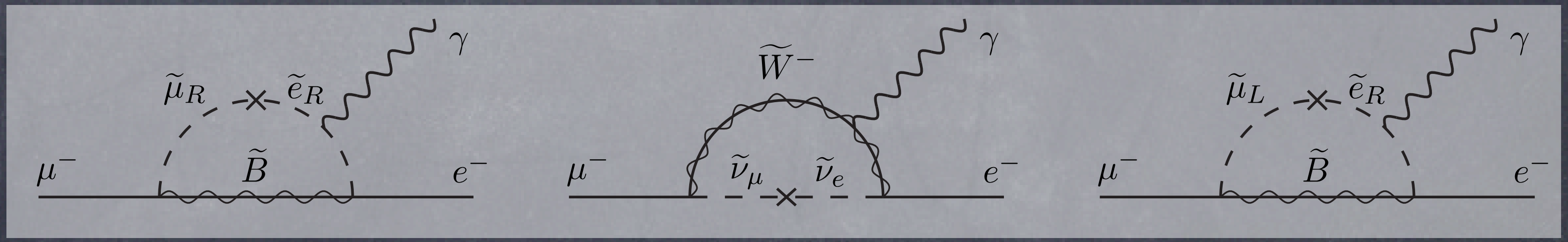

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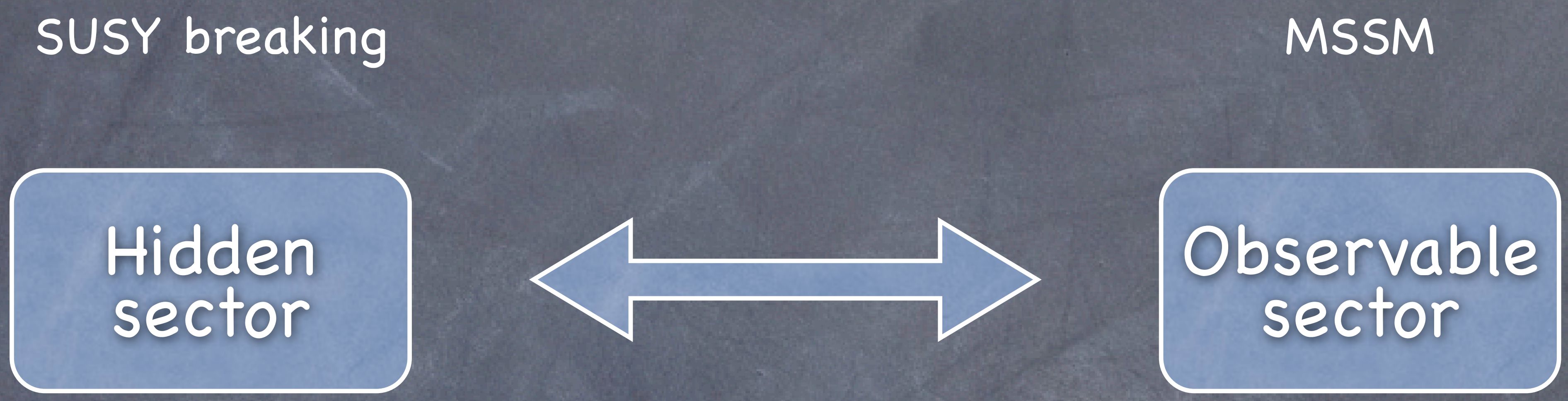
- One solution of SUSY flavour problem: $m^2_{ij} = m^2_0\, \delta_{ij}$ + rad corr

A wide class of models of supersymmetry breaking



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SUSY breaking

MSSM

Z chiral superfield

$\langle Z \rangle = F\theta^2$

$F \gg (M_Z)^2$

SM singlet

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$$\int d^4\theta \, \frac{Z^\dagger Z \, Q^\dagger Q}{M^2}$$

A wide class of models of supersymmetry breaking

SUSY breaking

Hidden sector

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MSSM

Observable sector

Q chiral superfield
(MSSM)

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Examples: gravity mediation, gauge mediation, gaugino mediation…

Tree level gauge mediation

Nardecchia, R, Ziegler
arXiv:0909.3058 (JHEP)
arXiv:0912.5482 (JHEP)

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$$\int d^4\theta \, \frac{Z^\dagger Z \, Q^\dagger Q}{M^2}$$

Z Q

Tree level gauge mediation

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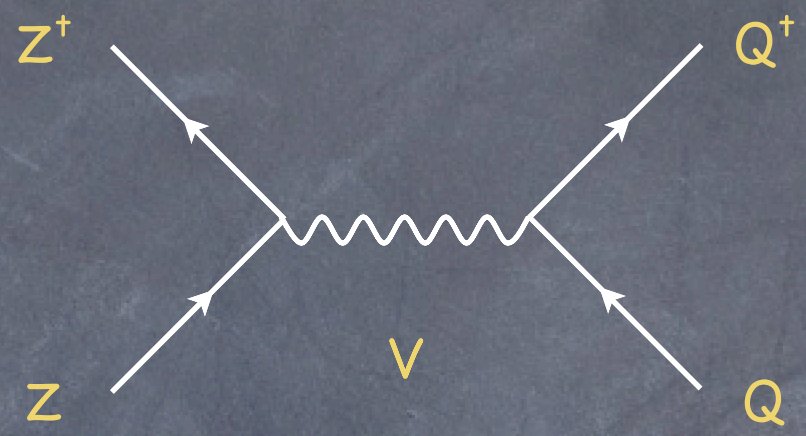

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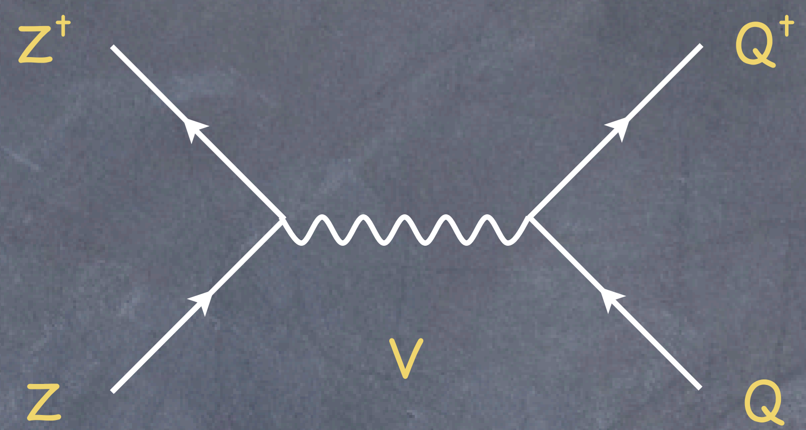


↑

heavy vector superfield
SM singlet
non-anomalous
assumed to part of a GUT

"Dietrologia"

- Supersymmetry breaking masses (Z*ZQ*Q) are obtained at the tree level from spontaneous SUSY breaking in a renormalizable theory

- Two arguments seem to prevent this possibility

1. what about the supertrace formula? > 0 contribution from MSSM fields compensated by < 0 contribution by superheavy fields

2. what about gaugino masses? loop factor suppression partially compensated by O(10) unavoidable enhancement + model-dependent enhancement

A concrete example

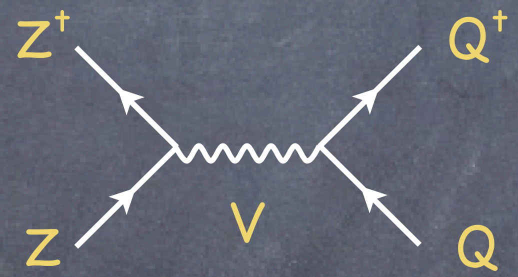
- G = SO(10) "minimal" GUT (V heavy SM singlet means rank ≥ 5)

- V associated to the SU(5)-invariant generator "X"

-

SO(10)		SU(5)				
16	=	$\bar{5}$	+	10	+	1
X		-3		1		5

SO(10)		SU(5)		
10	=	$\bar{5}$	+	5
X		2		-2

- 

gives $\tilde{m}_Q^2 \propto X_Q X_Z$

- The (usual) embedding of a MSSM family in a single 16 does not work (whatever the sign of X_Z)

- The three MSSM families are embedded in $16_i + 10_i$, i=1,2,3 (needs $X_Z > 0$)

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- Let us only consider SO(10) reps with d < 120

- SO(10) breaking to the SM needs $16 + \overline{16} + 45$

  $16 + \overline{16}$ needed to reduce the rank

  $16 = \bar{5} + 10 + 1$ $\quad \overline{16} = 5 + \overline{10} + \bar{1}$ $\quad \langle 1 \rangle = \langle \bar{1} \rangle = M \approx M_{GUT}$ (or larger)

- SUSY breaking: sfermion masses need Z SM singlet with $X_Z > 0$

  only option: Z is the singlet of a 16′

  gauge invariance: 16′ ≠ 16

  $16' = \bar{5}' + 10' + Z$ $\quad \overline{16}' = 5' + \overline{10}' + \bar{Z}$ $\quad \langle Z \rangle = F\,\theta^2$ $\quad$ ($\langle \bar{Z} \rangle = 0$ for simplicity)

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$$\tilde{m}_Q^2 = \frac{X_Q}{2X_Z}\frac{F^2}{M^2}$$

- Then $\tilde{m}^2_q = \tilde{m}^2_{u^c} = \tilde{m}^2_{e^c} = \tilde{m}^2_{10} = \frac{1}{10} m^2, \quad \tilde{m}^2_l = \tilde{m}^2_{d^c} = \tilde{m}^2_{\bar{5}} = \frac{1}{5} m^2, \quad m = \frac{F}{M}$

- In particular

  - all sfermion masses are positive

  - sfermion masses are flavour universal, thus solving the supersymmetric flavour problem

  - $\boxed{\tilde{m}^2_{q,u^c,e^c} = \frac{1}{2}\tilde{m}^2_{l,d^c}}$ (at M)

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- Splitting the SO(10) multiplets

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must be made heavy

- Automatic!
    - R_P-invariant superpotential interaction involving $16_i\ 10_i$:
    - $h_{ij}\ 16_i\ 10_j\ 16 \to M_{ij}\ 5_i\ \bar{5}_j$ when $16 \to \langle 16 \rangle$
    - $M_{ij} = M\ h_{ij}$ ($M = \langle 1_{16} \rangle$) ($h_{ij}$ may be related to light fermion masses)
    - (note also $h'_{ij}\ 16i\ 10_j\ 16'$ coupling 5_i, $\bar{5}_j$ to supersymmetry breaking)

- Reinforces the theoretical consistency of the framework

Gaugino masses

- Vanish at the tree level
- Arise at one-loop because of a built-in ordinary gauge mediation structure
- Consider for example the $16_i + 10_i$ model

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- ($W = h_{ij}\, 16_i\, 10_j\, 16 + h'_{ij}\, 16_i\, 10_j\, 16'$)
- $M_g = \frac{\alpha}{4\pi} \mathrm{Tr}(h' h^{-1})\, m, \quad \tilde{m}_t = \frac{m}{\sqrt{10}} \quad \left(m = \frac{F}{M} \right)$
- $\left.\frac{M_2}{\tilde{m}_t}\right|_{M_{\mathrm{GUT}}} = \frac{3\sqrt{10}}{(4\pi)^2}\lambda, \quad \lambda = \frac{g^2\, \mathrm{Tr}(h' h^{-1})}{3}$
- O(100) hierarchy → O(10): $\tilde{m}_t$ > O(10 TeV) → O(1 TeV) + model dep factor λ
- (model dependent; the three messengers contribute at different scales; the enhancement also enhances two loop contributions to sfermion masses)

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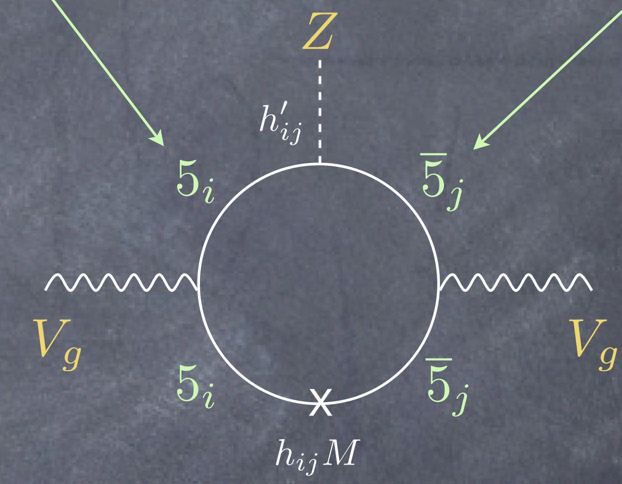

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- Also: a new solution to the μ-problem

Conclusions

- We enter the LHC era
  - confident, as LHC is crossing for the first time the energy territory where EWSB has its roots
  - prepared, with a background of strongly motivated theoretical ideas
  - aware that we might have not yet found the solution to the EWSB puzzle
    - do not give up looking for new ideas
    - develop model-independent approaches
  - ready to surprises

Spare slides

Cosmology

- LSP is the gravitino (in the regime in which sugra FCNC effects are under control), as in loop gauge mediation

$$m_{3/2} = \frac{F}{\sqrt{3}M_{\rm P}} \approx 15\,\text{GeV}\left(\frac{\tilde{m}_{10}}{\text{TeV}}\,\frac{M}{2\cdot 10^{16}\,\text{GeV}}\right)$$

- Stable gravitino: a dilution mechanism is necessary not to overclose the universe, $T_R < 2\ 10^9$ GeV
- NLSP decay can spoil BBN
  - If the NLSP is a neutralino (typical case) a decay channel much faster than the Goldstino one is needed in order not to spoil BBN (e.g. a tiny amount of R_P-violation; consistent with thermal leptogenesis and gravitino DM)

    [Buchmuller, Covi, Hamaguchi, Ibarra, Yanagida, arXiv:hep-ph/0702184 (JHEP)]
  - If the NLSP is a stau (the other possibility) BBN not a problem but the peculiar predictions of TGM are hidden by large loop gauge mediation contributions
  - (work in progress)

An example of spectrum

Higgs:	m_{h^0}	114
	m_{H^0}	1543
	m_A	1543
	$m_{H^\pm}$	1545
Gluinos:	$M_{\tilde{g}}$	448
Neutralinos:	$m_{\chi_1^0}$	62
	$m_{\chi_2^0}$	124
	$m_{\chi_3^0}$	1414
	$m_{\chi_4^0}$	1415
Charginos:	$m_{\chi_1^\pm}$	124
	$m_{\chi_2^\pm}$	1416
Squarks:	$m_{\tilde{u}_L}$	1092
	$m_{\tilde{u}_R}$	1027
	$m_{\tilde{d}_L}$	1095
	$m_{\tilde{d}_R}$	1494
	$m_{\tilde{t}_1}$	1007
	$m_{\tilde{t}_2}$	1038
	$m_{\tilde{b}_1}$	1069
	$m_{\tilde{b}_2}$	1435
Sleptons:	$m_{\tilde{e}_L}$	1420
	$m_{\tilde{e}_R}$	1091
	$m_{\tilde{\tau}_1}$	992
	$m_{\tilde{\tau}_2}$	1387
	$m_{\tilde{\nu}_e}$	1418
	$m_{\tilde{\nu}_\tau}$	1382

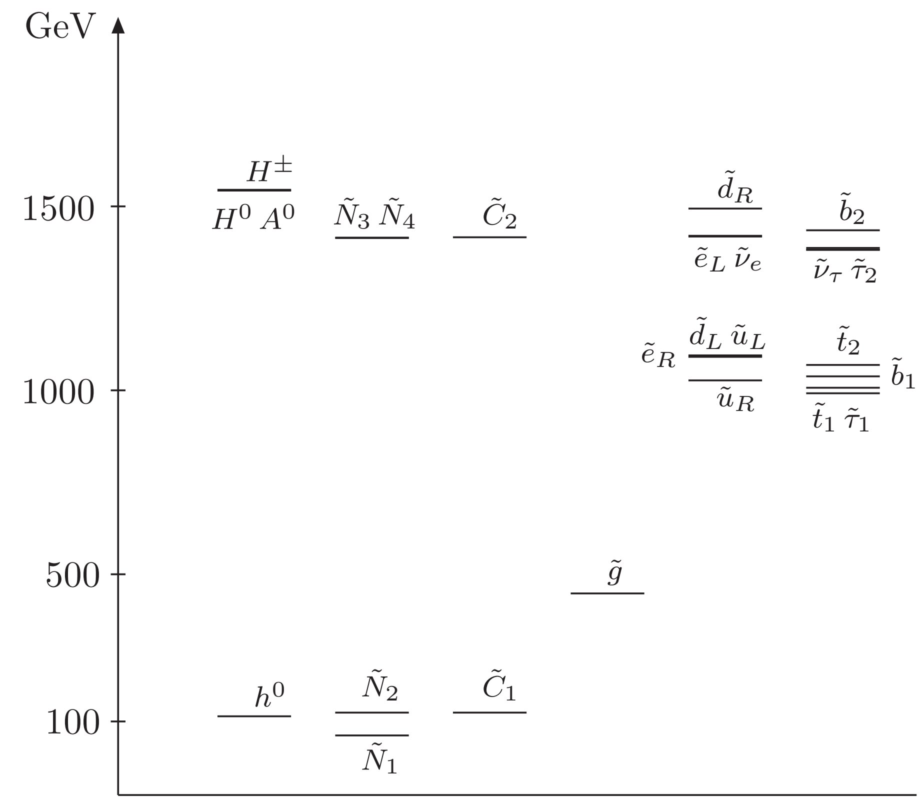

Figure 2: An example of spectrum, corresponding to $m = 3.2\,\text{TeV}$, $M_{1/2} = 150\,\text{GeV}$, $\theta_d = \pi/6$, $\tan\beta = 30$ and $\text{sign}(\mu) = +$, $A = 0$, $\eta = 1$. All the masses are in GeV, the first two families have an approximately equal mass.