Unification and supersymmetric Extensions of the Standard Model

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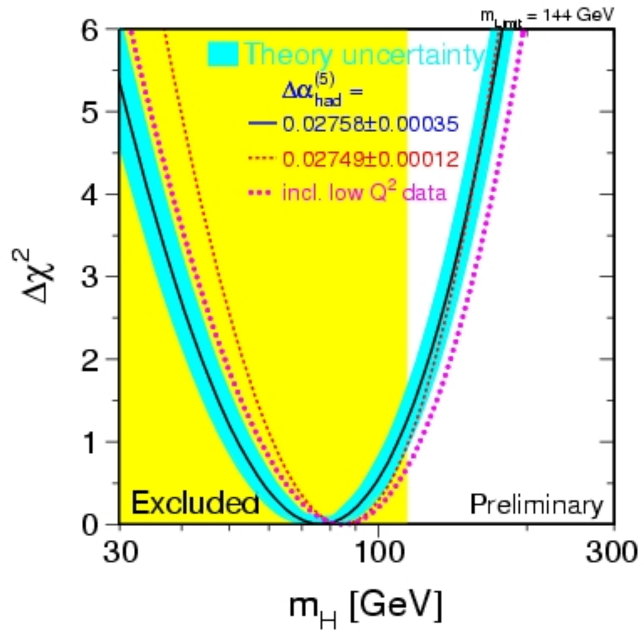
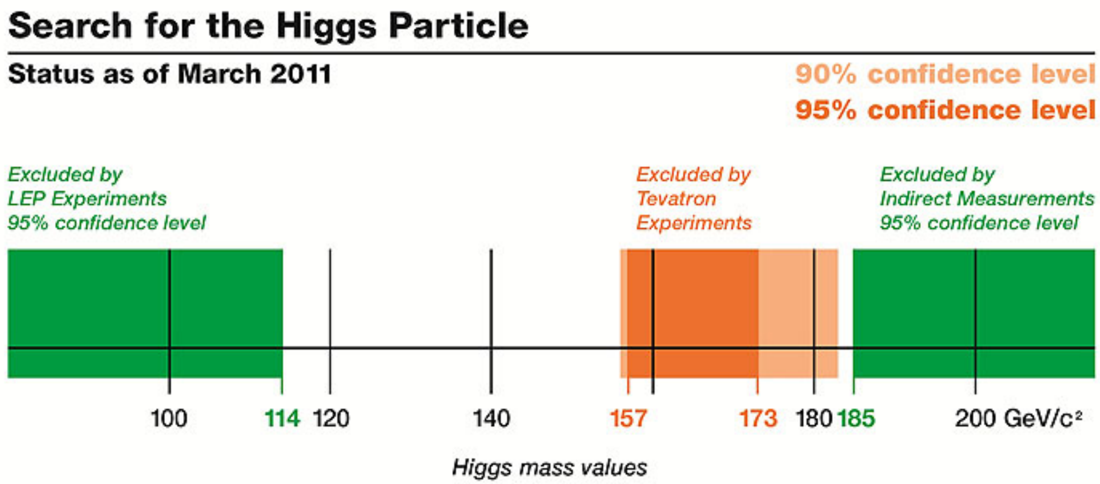
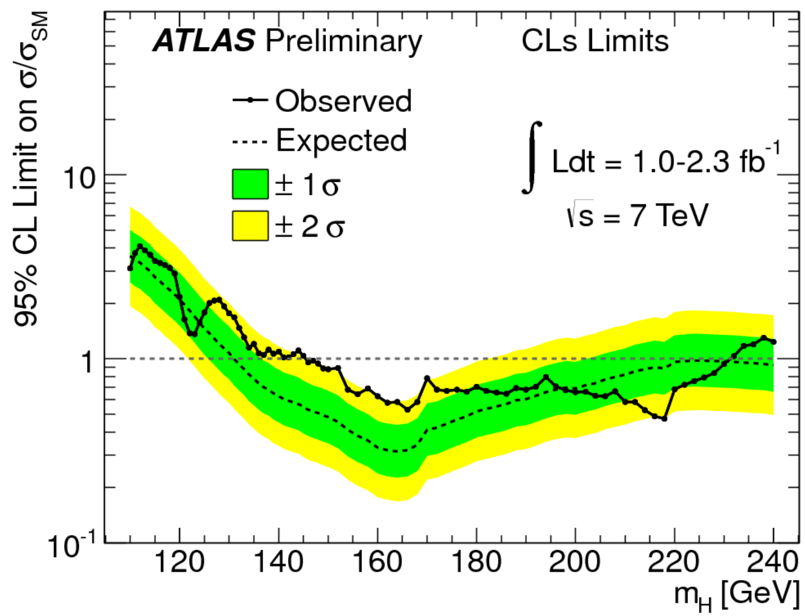
The Higgs Mass Range is converging

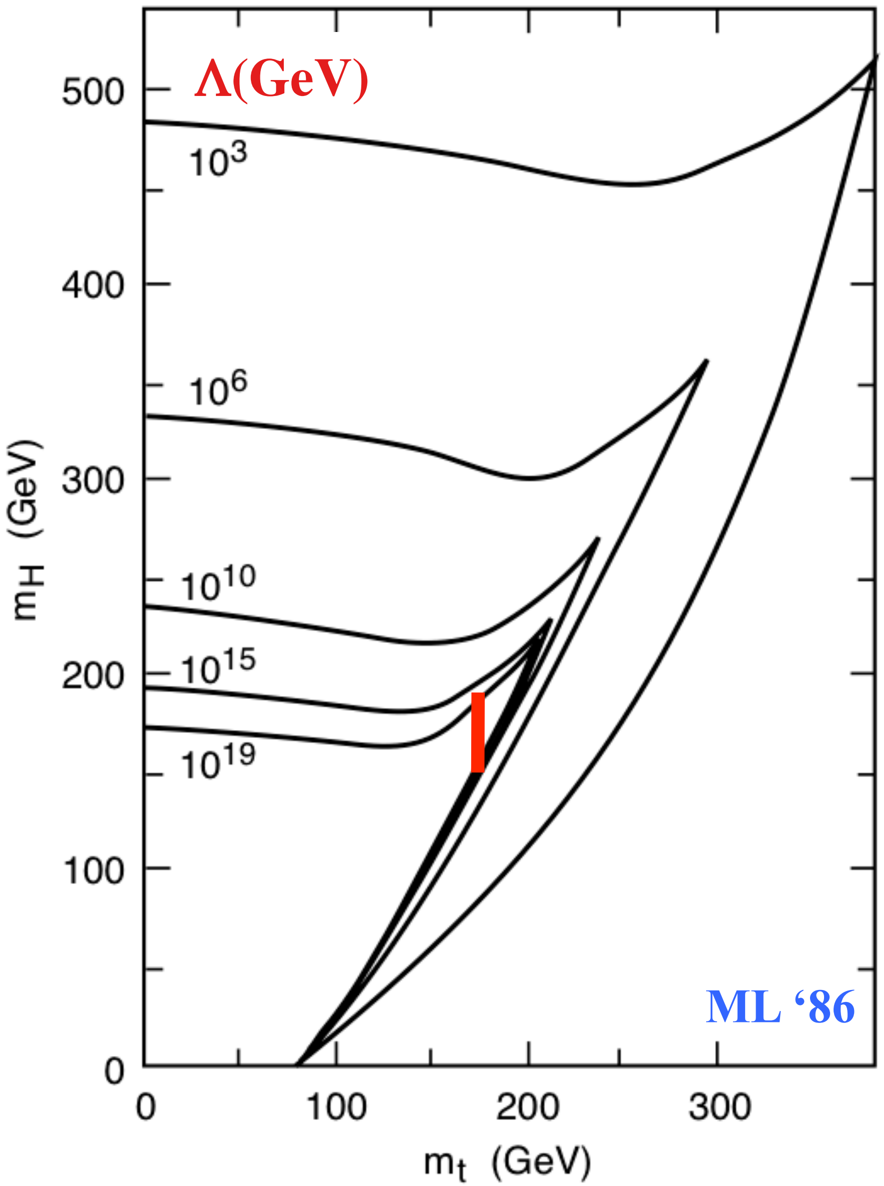






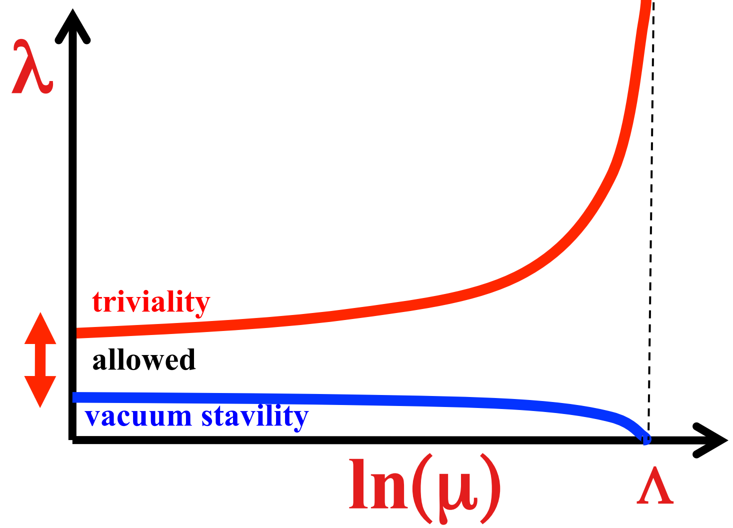
- allowed mass range is shrinking…
- if Higgs exists → light
- no (clear) signs for anything else
→ just the SM?

Why we must extend the SM: Triviality



126 GeV < m_H < 174 GeV

SM does not exist w/o embedding
- U(1) copling , Higgs self-coupling



➔ RGE arguments seem to work
➔ we need some embedding

The allowed Range ←→ Experiment

Theory:

$$m_{\rm min} = [126.3 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 1.5]\ \mathrm{GeV}$$

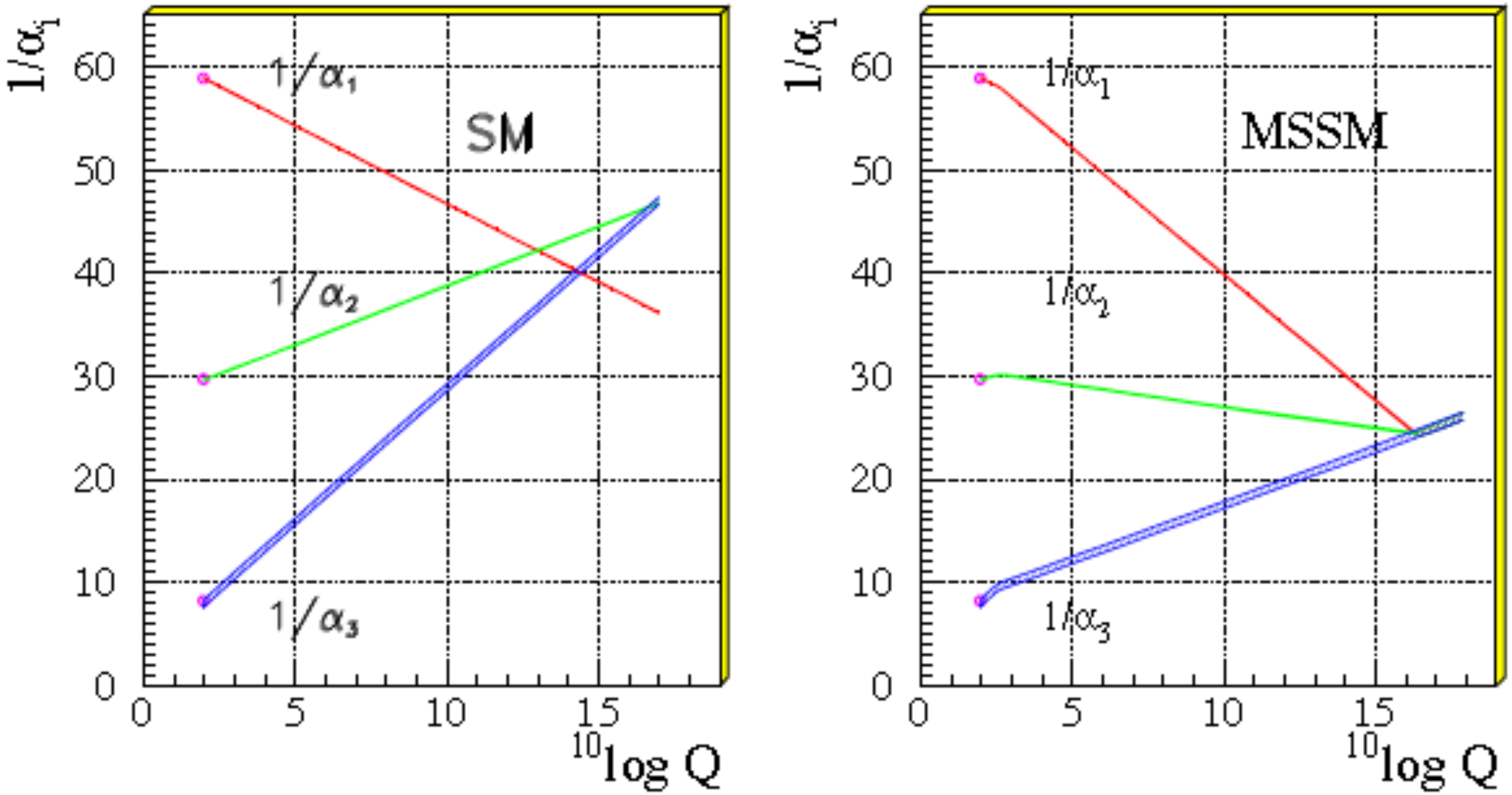
$$m_{\rm max} = [173.5 + \frac{m_t - 171.2}{2.1} \times 1.1 - \frac{\alpha_s - 0.1176}{0.002} \times 0.3]\ \mathrm{GeV}$$

→ interesting experimental ranges:

1) **below 126 GeV → instability → new physics (or disaster)**
2) **126 GeV – 135 GeV perfect SM + MSSM range, …**
3) **135 GeV – 157 GeV perfectly SM , non-minimal SUSY, …**
4) **above 157 GeV – BSM**

BUT: We need to solve anyway the hierarchy problem… → SUSY

Weak Scale SUSY works very good



SM: couplings do not unify

MSSM: perfect!➔ luck?

➔what happens in other models?

EW Symmetry Breaking Options

EW symmetry breaking scenarios:

- Just SM up to high scale ➔ hierarchy problems unsolved

a) why is $v = 246$ GeV $<< M_{Planck} = 10^{19}$ GeV?

b) how can $v << M_{planck}$ be stabelized ?

- Dynamical symmetry breaking ➔ ~ effective Higgs

- Protective symmetry ➔ Supersymmetry, ?

➔ new Physics in TeV range…
➔ LHC will see new physics
… but what if not?

alternative scenarios:
➔ SUSY later
➔ other protective symmetry

Alternative Routes

- What the LHC could find beyond what is known…

  - nothing ➔ unitarity violation! ⟵➔ hidden stuff
  - just a SM Higgs!
  - extension w/o immediate solution of the hierarchy problem
  - …

➔ Maybe we should think about gauge extensions which are super-symmetrized later (or vice versa)

- e.g. left-right symmetric extensions
- add SUSY at Λ_{LR} or close by ➔ … to avoid hierarchies…
- scenarios where one scalar (=SM Higgs) is lighter
- unification should occur $\tau_p \sim \frac{M_{\rm GUT}^4}{m_p^5}$
  - ➔ above proton decay scale
  - ➔ below or at M_{Pl} – unification at M_{Pl} would be even nice…

Left-Right Extensions

all quarks and leptons fit nicely into L, R doublets

$$Q(3,2,1,\tfrac{1}{3}) = \begin{pmatrix} u \\ d \end{pmatrix} \qquad Q^c(3^*,1,2,-\tfrac{1}{3}) = \begin{pmatrix} d^c \\ -u^c \end{pmatrix}$$

$$L(1,2,1,-1) = \begin{pmatrix} \nu_e \\ e \end{pmatrix} \qquad L^c(1,1,2,1) = \begin{pmatrix} e \\ -\nu_e \end{pmatrix}$$

symmetry breaking $SU(2)_R \times U(1)_{B-L} \xrightarrow{M_{\rm LR}} U(1)_Y$

nice: U(1) carries B-L charge

scalars for SB: $\Delta(1,3,1,2)$ and $\Delta^c(1,1,3,-2)$

$\Phi(1,2,2,0)$ **→ non-SUSY LR model with triplets**

add SUSY $\bar{\Delta}(1,3,1,-2)$ and $\bar{\Delta}^c(1,1,3,2)$

→superfields Φ_1 and Φ_2

R-parity cons. $S(1,1,1,0)$ **→ minimal SUSY LR model**

Other Models

S replaced by triplets $\Omega(1,3,1,0)$ and $\Omega^c(1,1,3,0)$

➔ non-minimal SUSY LR model with triplets

➔staged SB $SU(2)_R \times U(1)_{B-L} \xrightarrow{M_{\rm LR}} U(1)_R \times U(1)_{B-L} \xrightarrow{M_{B-L}} U(1)_Y$

Pati-Salam group

$$SU(2)_L \times SU(2)_R \times SU(4)$$

➔ SUSY Pati-Salam model

$$\xrightarrow{M_{\rm PS}} SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\xrightarrow{M_{\rm LR}} SU(3)_c \times SU(2)_L \times U(1)_Y \ ,$$

matter $\psi(2,1,4)$ and $\psi^c(1,2,4^*)$

Higges $\Phi(2,2,1)$ and $\Phi(2,2,15)$

RGEs

$$16\pi^2 \frac{dg_i(t)}{dt} = b_i \left[g_i(t)\right]^3 \rightarrow \boxed{\alpha_i^{-1}(t) = \alpha_i^{-1}(t_0) - \frac{1}{2\pi} b_i \left(t - t_0\right)}$$

$$b_i = \sum_R s(R)\, T_i(R) - \frac{11}{3} C_{2i}\,. \qquad \text{(non-SUSY models)}$$

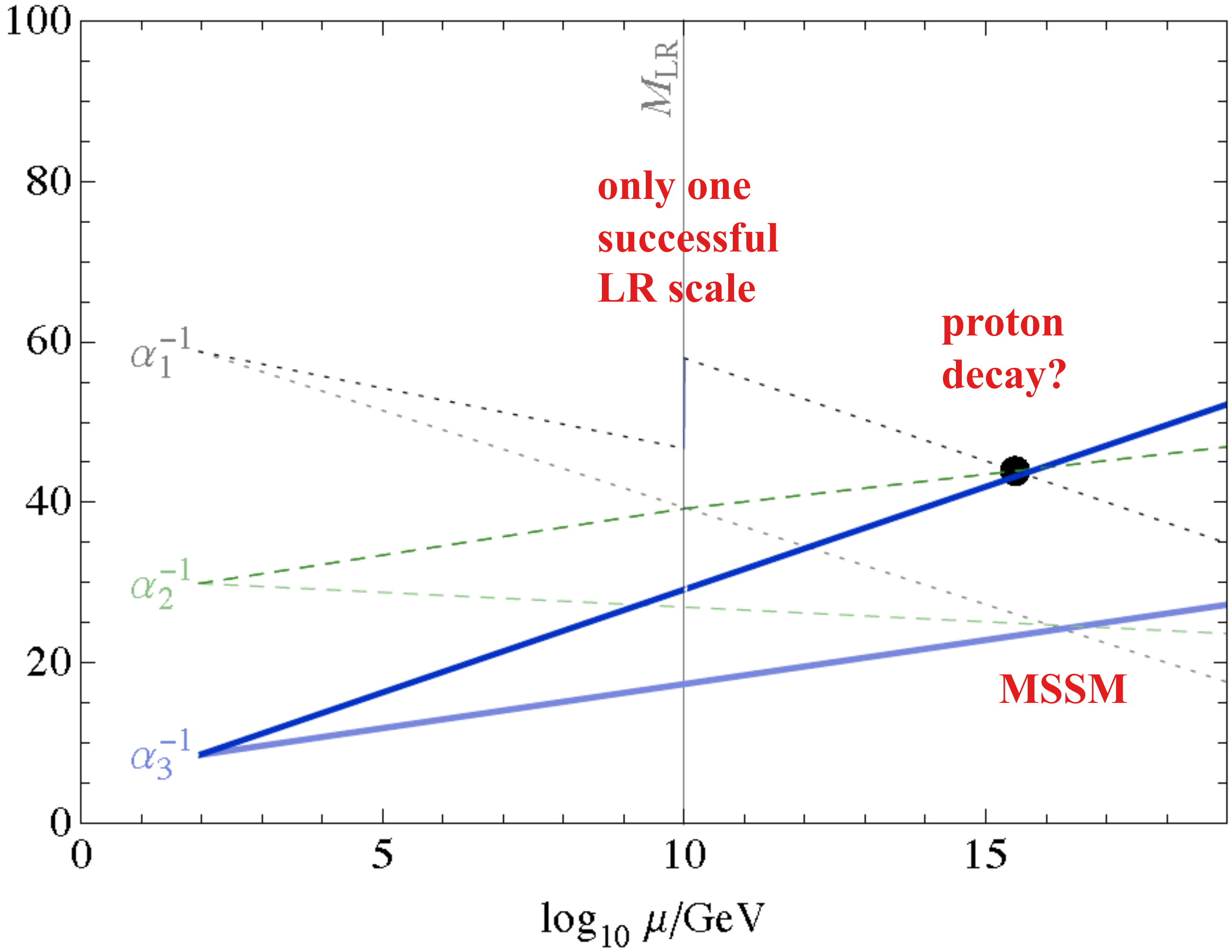
$$b_i = \sum_R T_i(R) - 3\, C_{2i}\,. \qquad \text{(SUSY models)}$$

1-loop, no thresholds, no detailed spectrum

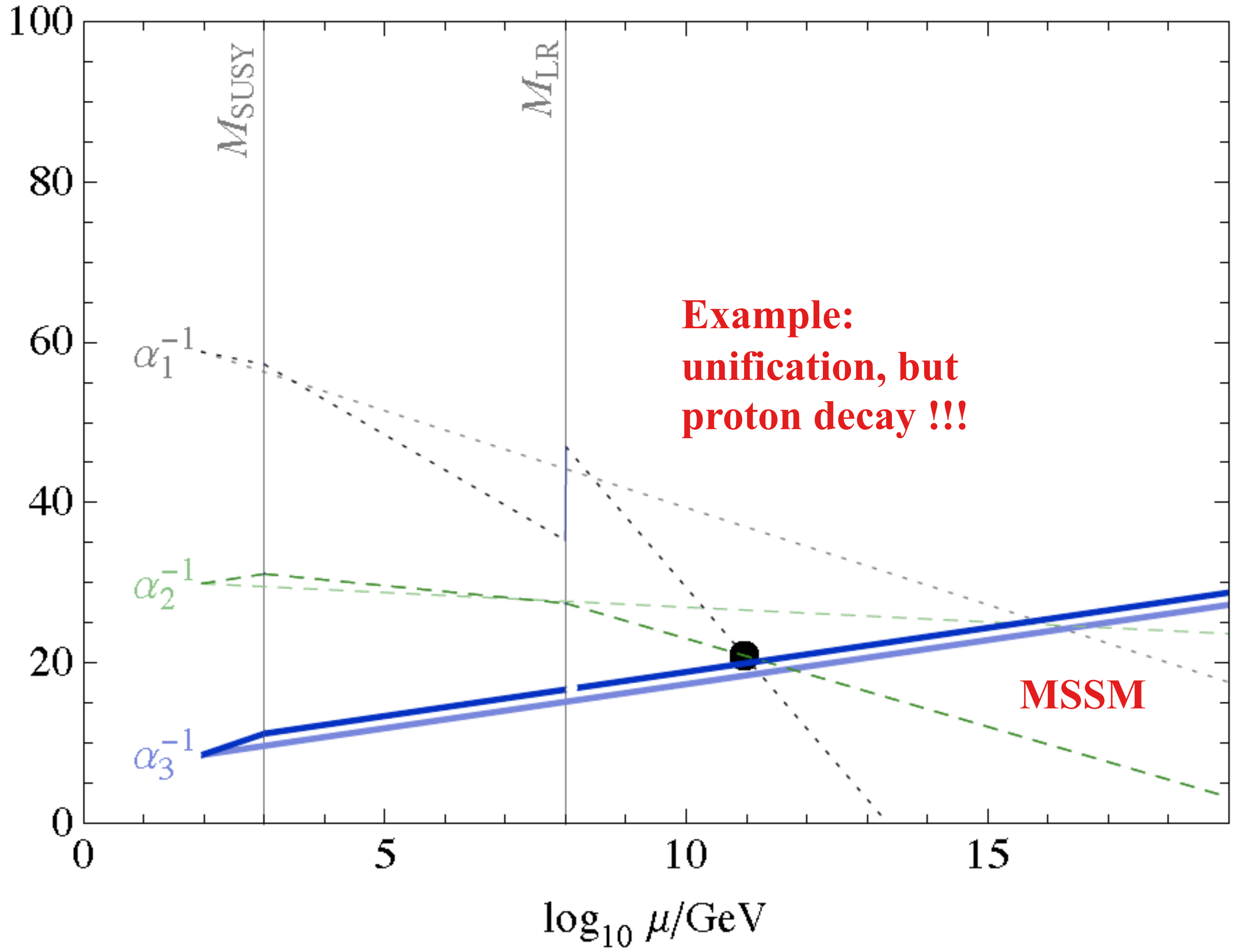
GUT - U(1) normalization: SM, MSSM→GUT =20/3 LR=8/3
→ matching at LR-scale

$$\alpha_{1,\mathrm{LR}}(M_{\mathrm{LR}}) = \frac{2}{5} \frac{\alpha_{1,\mathrm{SM}}(M_{\mathrm{LR}})\, \alpha_2(M_{\mathrm{LR}})}{\alpha_2(M_{\mathrm{LR}}) - \frac{3}{5}\alpha_{1,\mathrm{SM}}(M_{\mathrm{LR}})}$$

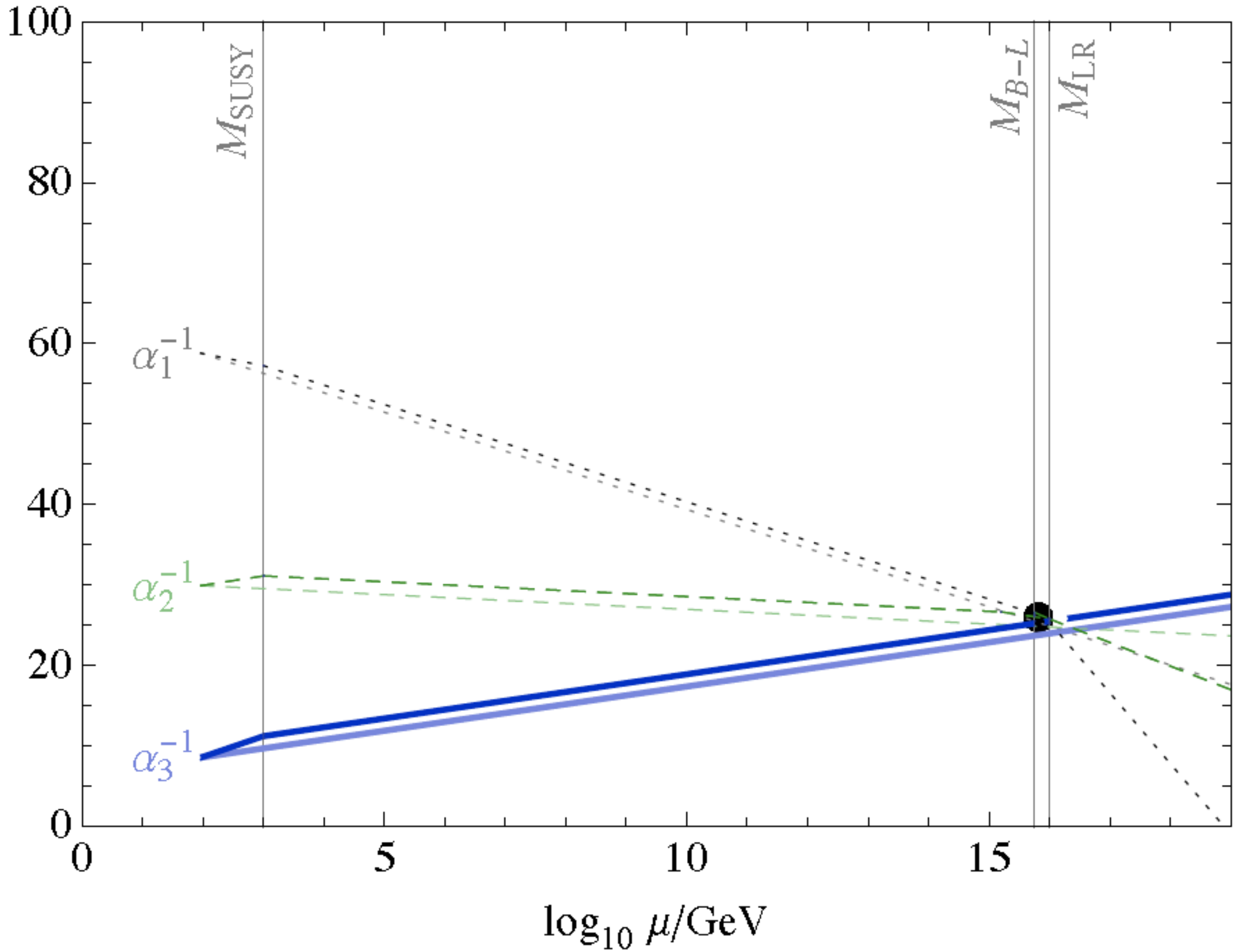
Non-SUSY LR model with Higgs Triplets



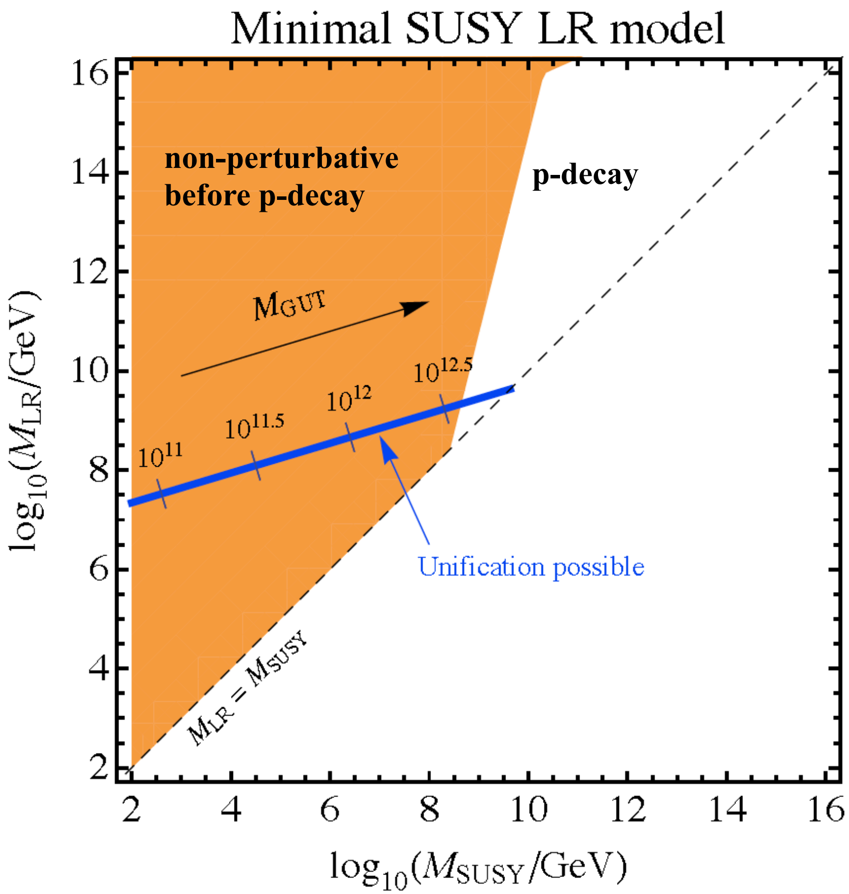
Minimal SUSY-LR Model

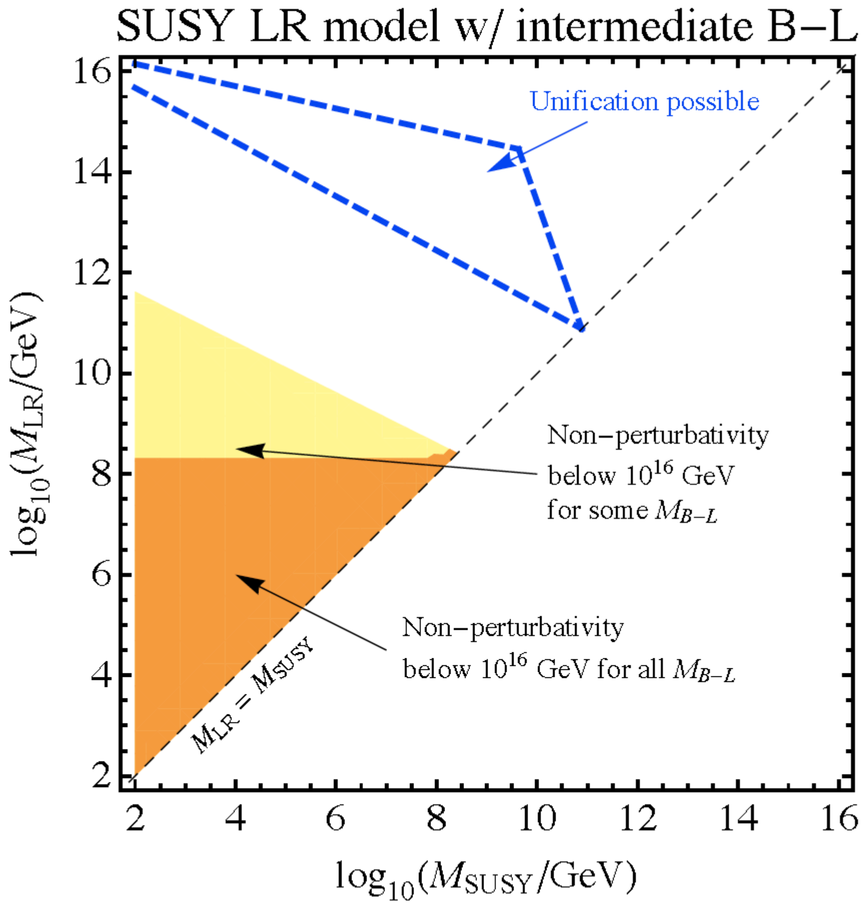


SUSY-LR Model with intermediate B-L



Coupling Unification & Perturbativity

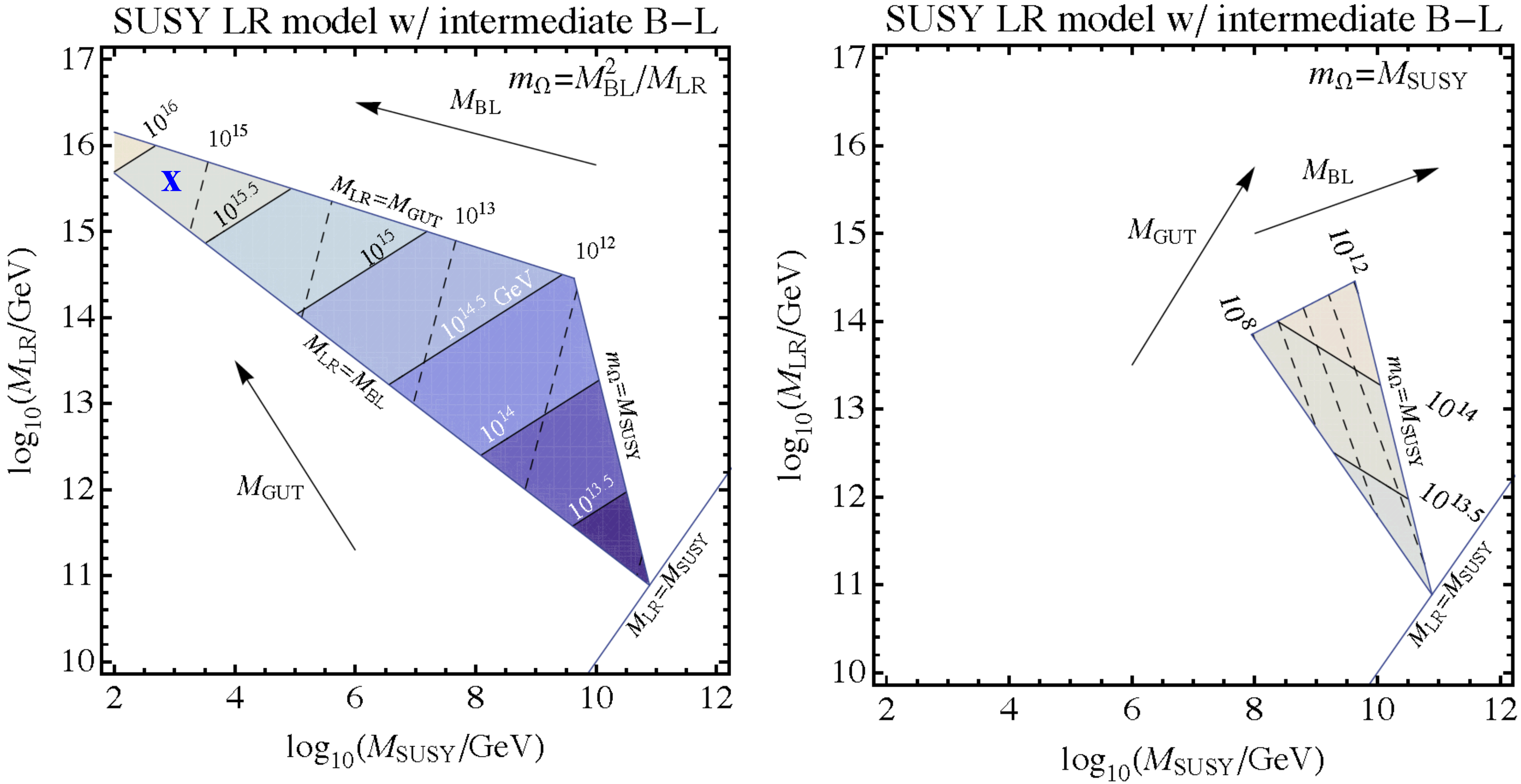




➔ **no low scale solutions**

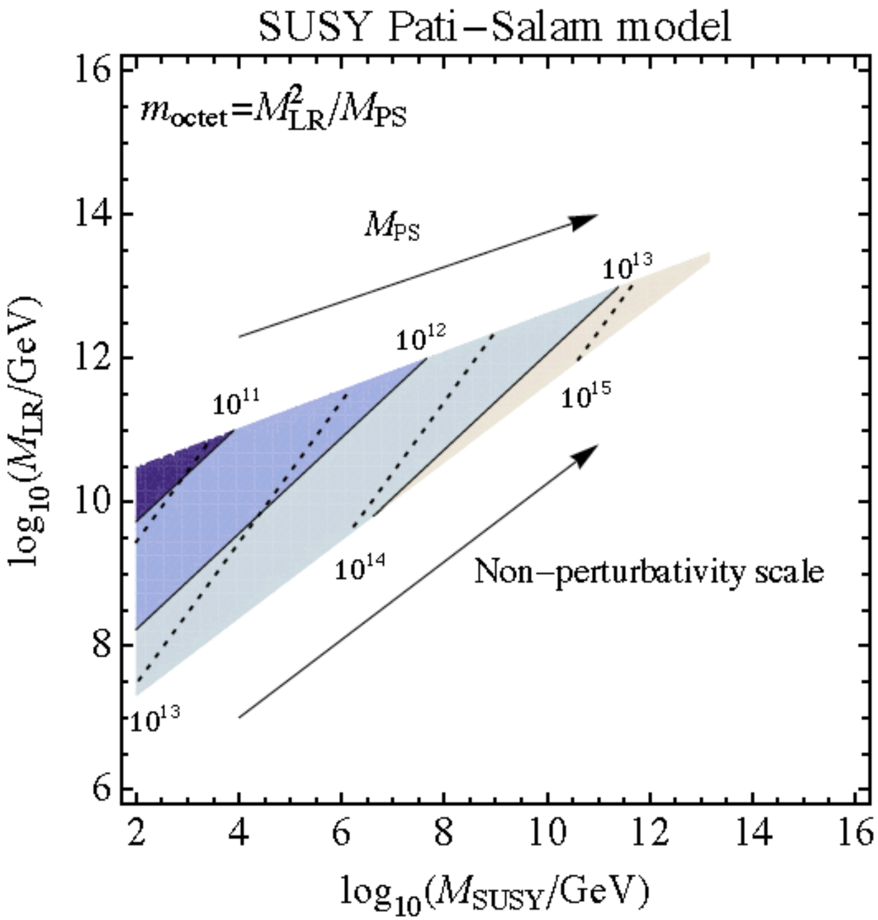
➔ **solutions: MSSM + intermediate B-L + late LR extension**

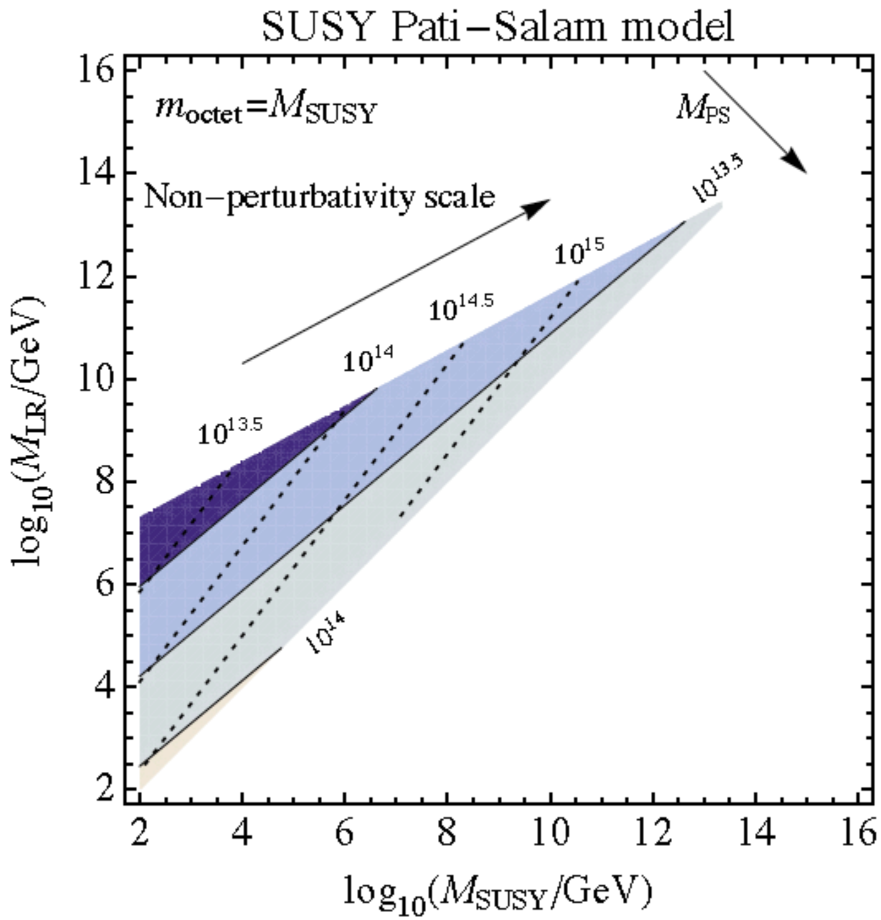
GUT scale (solid lines) and B-L breaking scale (dashed)



proton decay ➔ only highes scales ➔ low SUSY scale and high LR scale

PS scale (solid lines) and non-perturbativity (dashed)



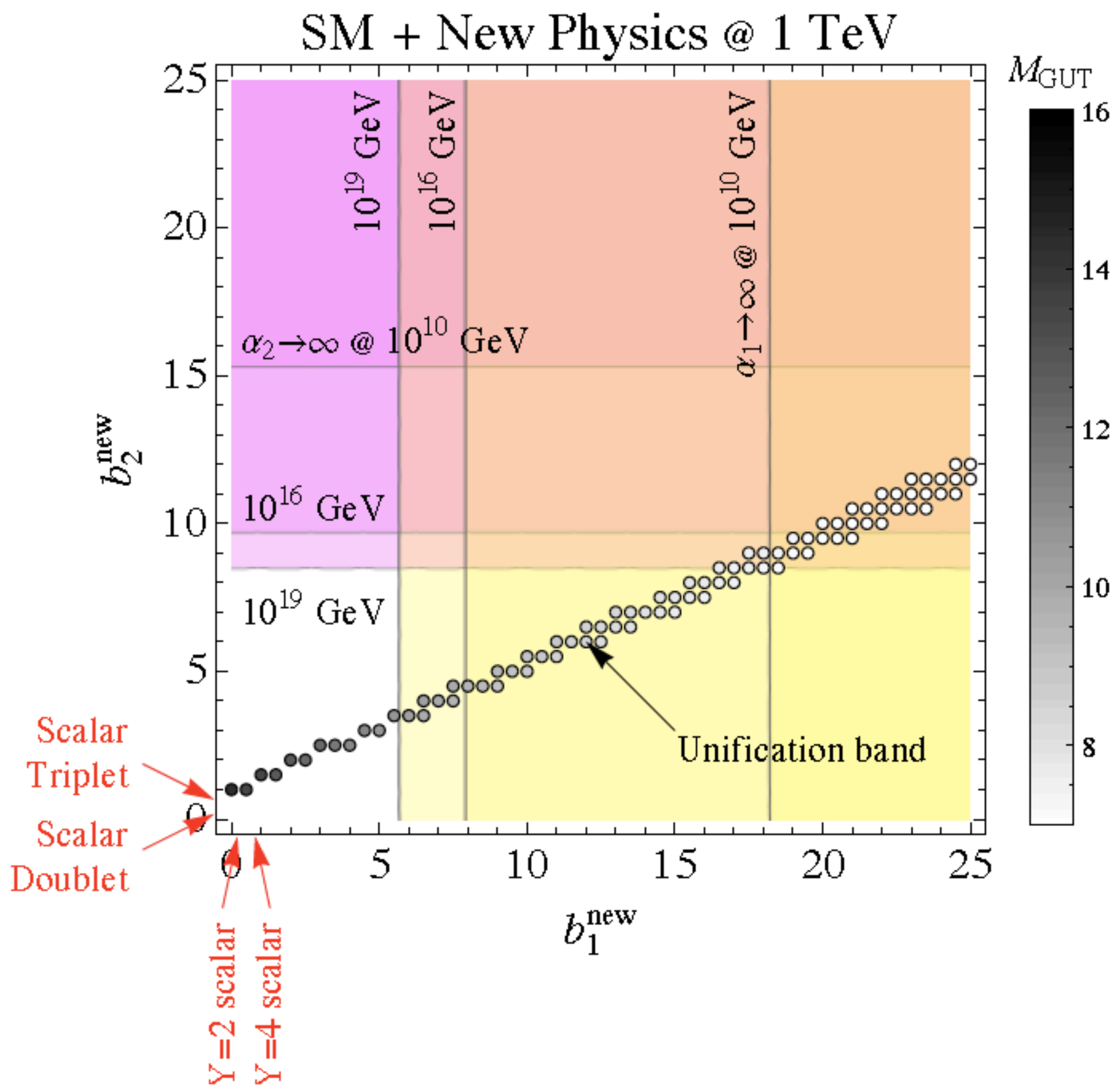


Contributions of arbitrary new Particles

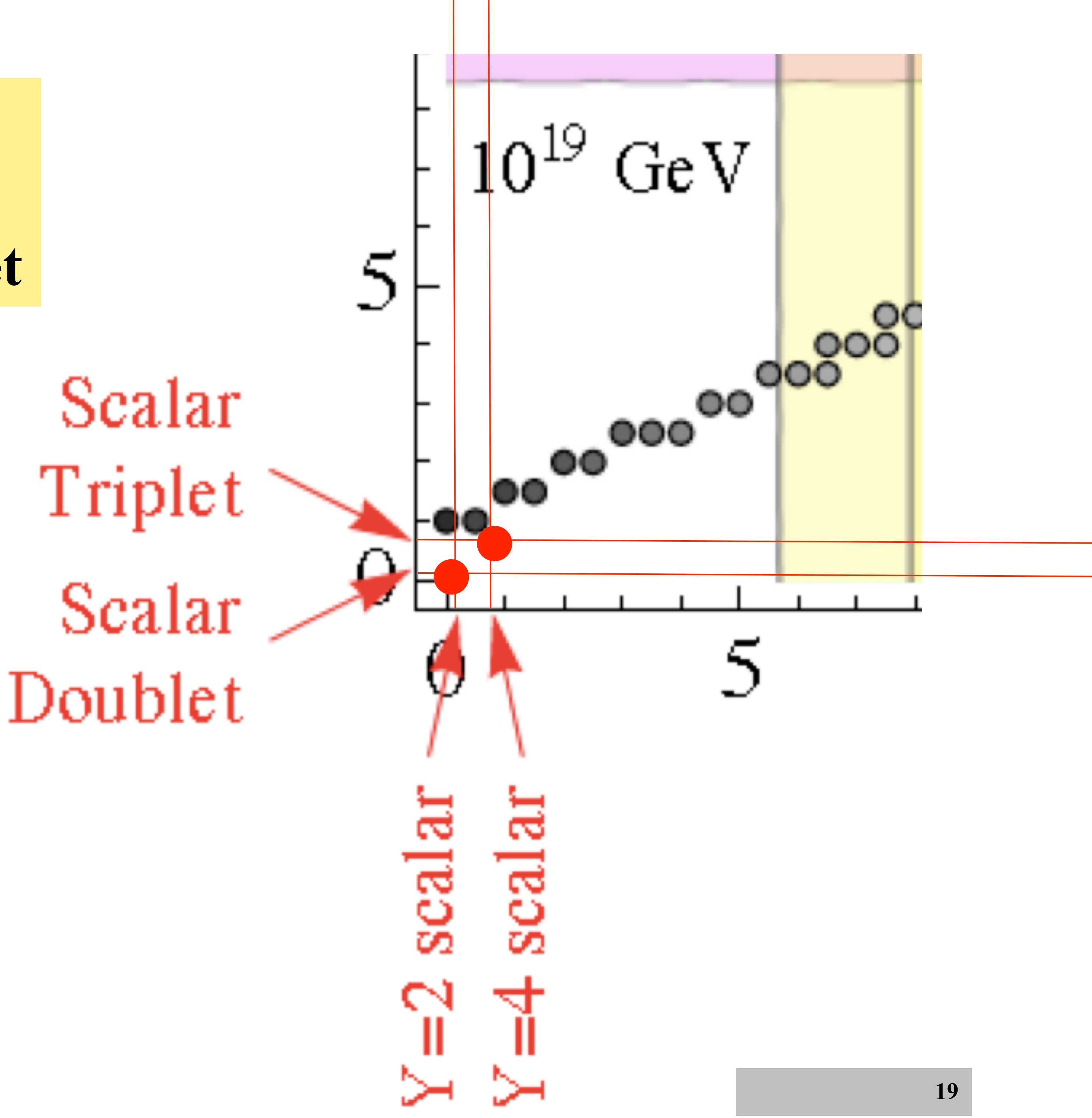
MSSM rep.	b_1^{new}	b_2^{new}	b_3^{new}
$(Y,1,1)$	$0.15Y^2$	0	0
$(Y,2,1)$	$0.3Y^2$	0.5	0
$(Y,3,1)$	$0.45Y^2$	2	0
$(Y,4,1)$	$0.6Y^2$	5	0
$(Y,5,1)$	$0.75Y^2$	10	0
$(Y,6,1)$	$0.9Y^2$	17.5	0
$(Y,7,1)$	$1.05Y^2$	28	0
$(Y,1,3)$	$0.45Y^2$	0	0.5
$(Y,2,3)$	$0.9Y^2$	1.5	1
$(Y,3,3)$	$1.35Y^2$	6	1.5
$(Y,4,3)$	$1.8Y^2$	15	2
$(Y,5,3)$	$2.25Y^2$	30	2.5
$(Y,6,3)$	$2.7Y^2$	52.5	3
$(Y,7,3)$	$3.15Y^2$	84	3.5
$(Y,1,6)$	$0.9Y^2$	0	2.5
$(Y,2,6)$	$1.8Y^2$	3	5
$(Y,3,6)$	$2.7Y^2$	12	7.5
$(Y,4,6)$	$3.6Y^2$	30	10
$(Y,5,6)$	$4.5Y^2$	60	12.5
$(Y,6,6)$	$5.4Y^2$	105	15
$(Y,7,6)$	$6.3Y^2$	168	17.5
$(Y,1,8)$	$1.2Y^2$	0	3
$(Y,2,8)$	$2.4Y^2$	4	6
$(Y,3,8)$	$3.6Y^2$	16	9
$(Y,4,8)$	$4.8Y^2$	40	12
$(Y,5,8)$	$6Y^2$	80	15
$(Y,6,8)$	$7.2Y^2$	140	18
$(Y,7,8)$	$8.4Y^2$	224	21

- numbers for chiral super fields → non-SUSY x1/3 or x2/3 for scalars/fermions
- b_1 includes GUT normalization factor 3/20
- new physics at 1 TeV

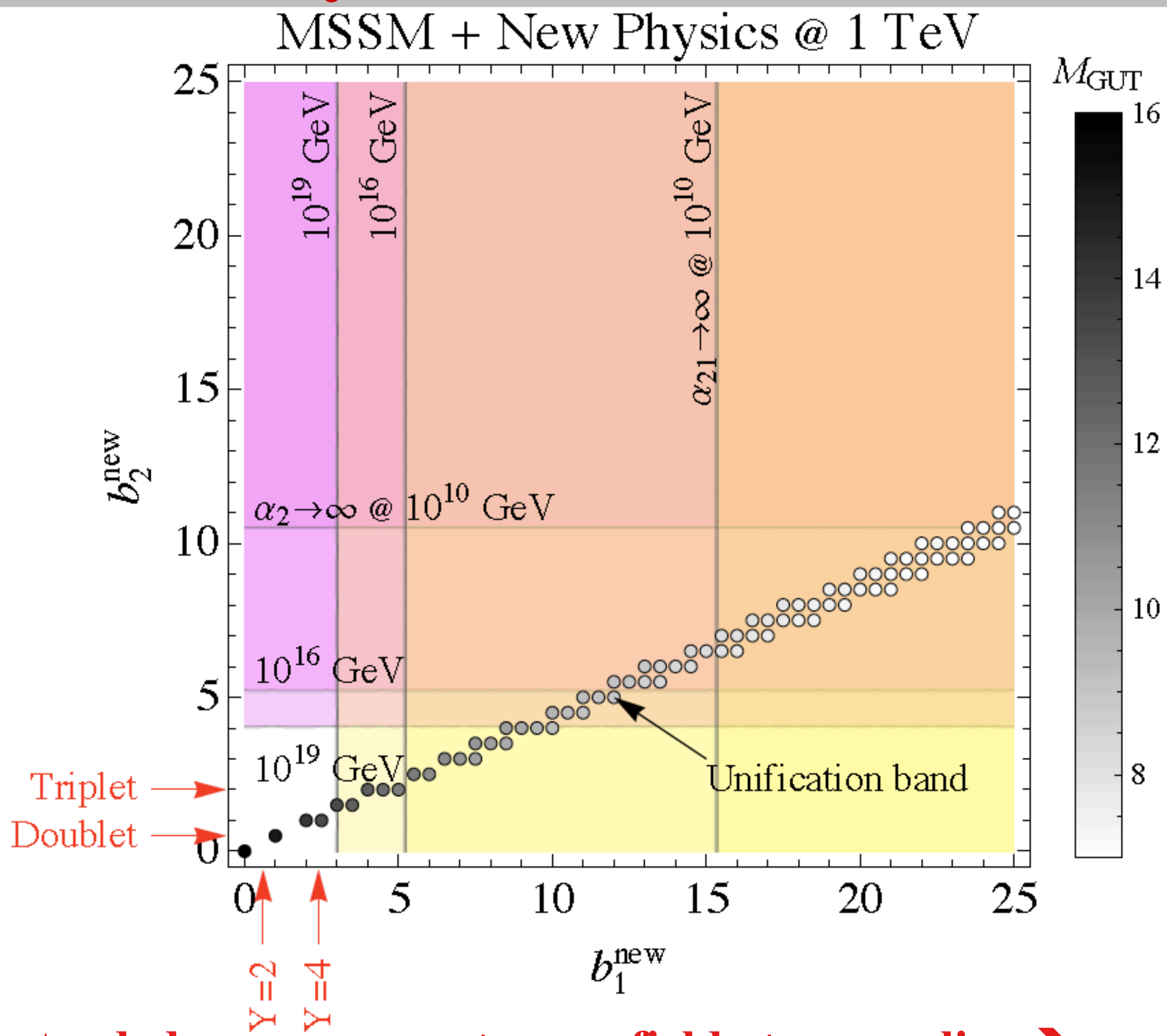
Perturbativity & Unification w/o SUSY



<u>Without</u> SUSY: adding one doublet or triplet

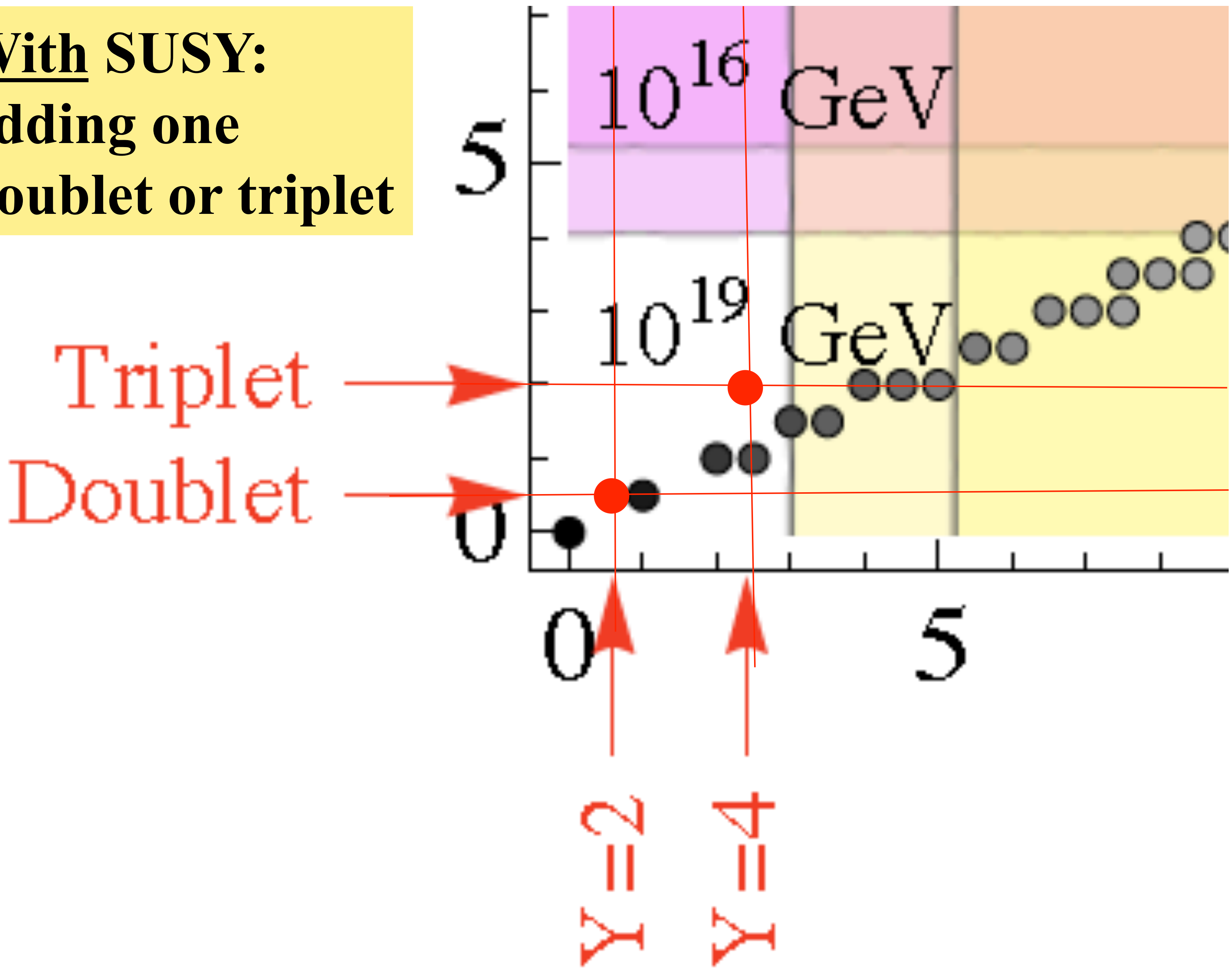


Perturbativity & Unification with SUSY



➔ **problem: extended gauge group + superfields + anomalies ➔ many particles**
⬄ less parameter space available

With SUSY:
adding one
doublet or triplet



Conformal Symmetry & Hierarchy Problem

Are there other protective symmetries…?

➔ conformal symmetry

Exact (unbroken) CS

- ➔ absence of Λ^2 and $\ln(\Lambda)$ divergences
- ➔ no preferred scale

Conformal anomaly

- ➔ explicit breaking of CS!
- ➔ breaking ←→ β-functions ←→ $\ln(\Lambda)$ divergences
- ➔ BUT: Maybe CS still forbids Λ^2 divergences Bardeen, …

Simplest Realization (under this assumption):

➔Coleman-Weinberg effective potential of SM for $\mu^2=0$

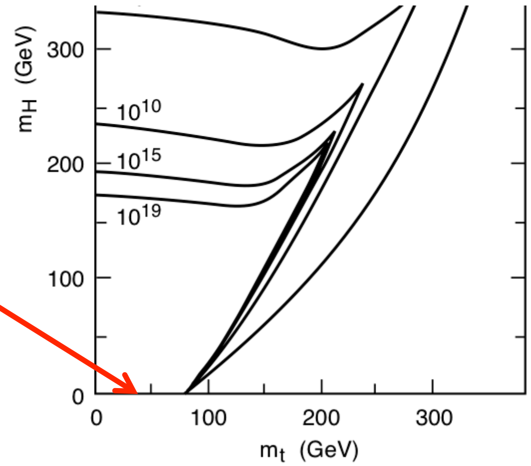
$$V_{eff} = (\mu^2=0)\Phi^2 + \lambda\Phi^4 + C\,\Phi^4 \ln(\Phi^2/\Lambda^2)$$

with C ←→ β-functions ←→ $\ln(\Lambda)$

Realizing this Idea

Standard Model

➔ does not work: m_H too light and does not exist for m_t>80 GeV



Other realizations

R. Foot, A. Kobakhidze, R. Volkas
H. Nicolai, U. Meissner
M. Holthausen, ML, M. Schmidt ➔

Conformal LR-extension of SM

➔ choose suitable particle content←→ breaking of V_{eff}
➔ use Gildner Weinberg formalism
➔symmetry breaking $SU(2)_R \times U(1)_{B-L} \xrightarrow{M_{LR}} U(1)_Y$

➔works, but requires some parameter adjustments
Λ_{LR} & FCNC ←→ Λ_{LR} high enough & SM Higgs must be choosen

Summary

SM extensions with larger gauge groups and low lying SUSY:

- breaking of extended symmetries → additional scalars
- SUSY → superpartners of new scalars (and other new particles)
- anomaly cancellation of superpartners of new scalars → more fields

→ many new fields → generic feature for many extensions

- drives running couplings bigger (destroys asymptotic freedom, non-perturbative)
- often leads to divergent couplings ←→ trivial?
- especially U(1)

→ extended models with low lying SUSY ←→ hierarchy problem adding gauge groups or representations →

- leads systematically to problems with perturbativity
- destroys gauge unification
- problems with proton decay scale

→ low lying SUSY in its minimal form (MSSM) works best

→ argument in favour of SUSY at weak scale in ~ minimal form

→ or something else → conformal symmetry?

The Unification/Perturbativity/p-Decay Roadmap