COLORLESS WAY BEYOND THE SM

LHC 7-8 TeV

A GREAT TRIUMPH: 125 GeV HIGGS DISCOVERY

A PARTICLE APPARENTLY JUST AS THE ELEMENTARY HIGGS BOSON PREDICTED BY THE SM IS DISCOVERED!

„APPARENTLY JUST" IS VERY IMPORTANT!

Mh=125 GeV AND ITS COUPLINGS WITHIN ~20% CONSISTENT WITH THE SM→ NOT SUCH A BIG SURPRISE

PRE-LHC LANDSCAPE

- PRECISION FITS IN THE SM
- LEP LIMIT

HIGGS SELF-COUPLING

$$\lambda|H|^4 \qquad v = 246GeV \qquad \rightarrow \lambda = 0.12$$

WELL WITHIN PERTURBATIVE REGIME

AT LEAST AT THE ELECTROWEAK SCALE, THE SM IS A CORRECT EFFECTIVE THEORY OF ELECTROWEAK INTERACTIONS

IS THE SM A CONSISTENT THEORY UP TO THE PLANCK SCALE ?

YES!

RENORMALISABLE

NO LANDAU POLE UP TO Mp

(ALMOST) STABLE VACUUM UP TO Mp

THOSE CONCLUSIONS STRONGLY DEPEND ON

$$m_t = 173GeV, \qquad m_h = 125GeV$$

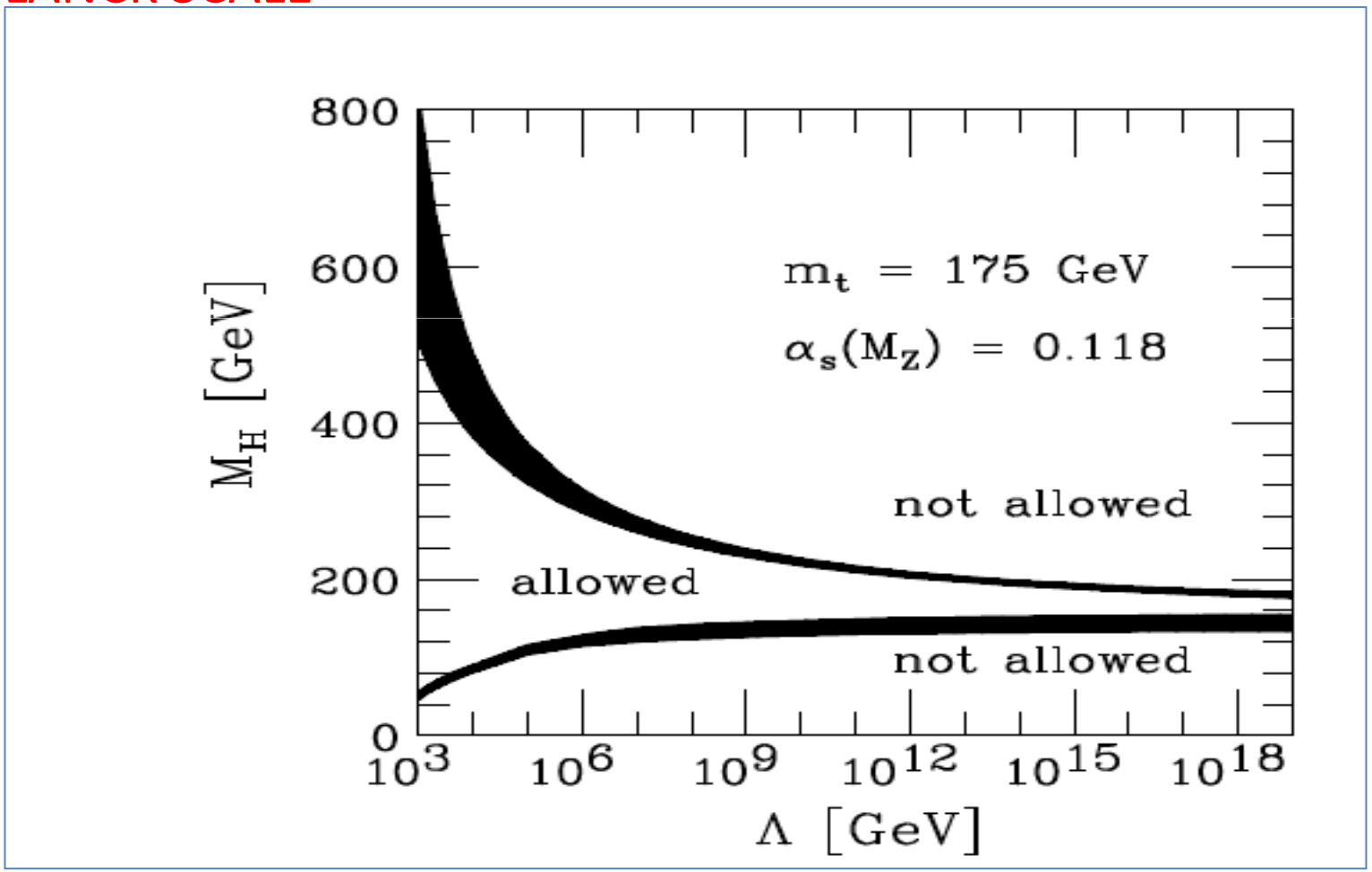
TWO THEORIES THAT PREDICT THE HIGGS MASS IN A CERTAIN NARROW RANGE, AS A FUNCTION OF THE TOP MASS

- SM EXTRAPOLATED TO THE PLANCK MASS
- MINIMAL SUPERSYMMETRIC MODEL

$$(\lambda \sim g)$$

m_h^{MAX} AS A FUNCTION OF THE TOP AND STOP MASS

THE HIGGS MASS HAPPENS TO BE WELL BELOW THE PERTURBATIVITY LIMIT AND AT THE EDGE OF THE VACUUM STABILITY BOUND (FOR THE TOP MASS AROUND 173 GeV) UP TO THE PLANCK SCALE



MSSM

$$m_h = M_Z^2 \cos^2(2\beta) + (\delta m_h^2)^{\rm rad}$$

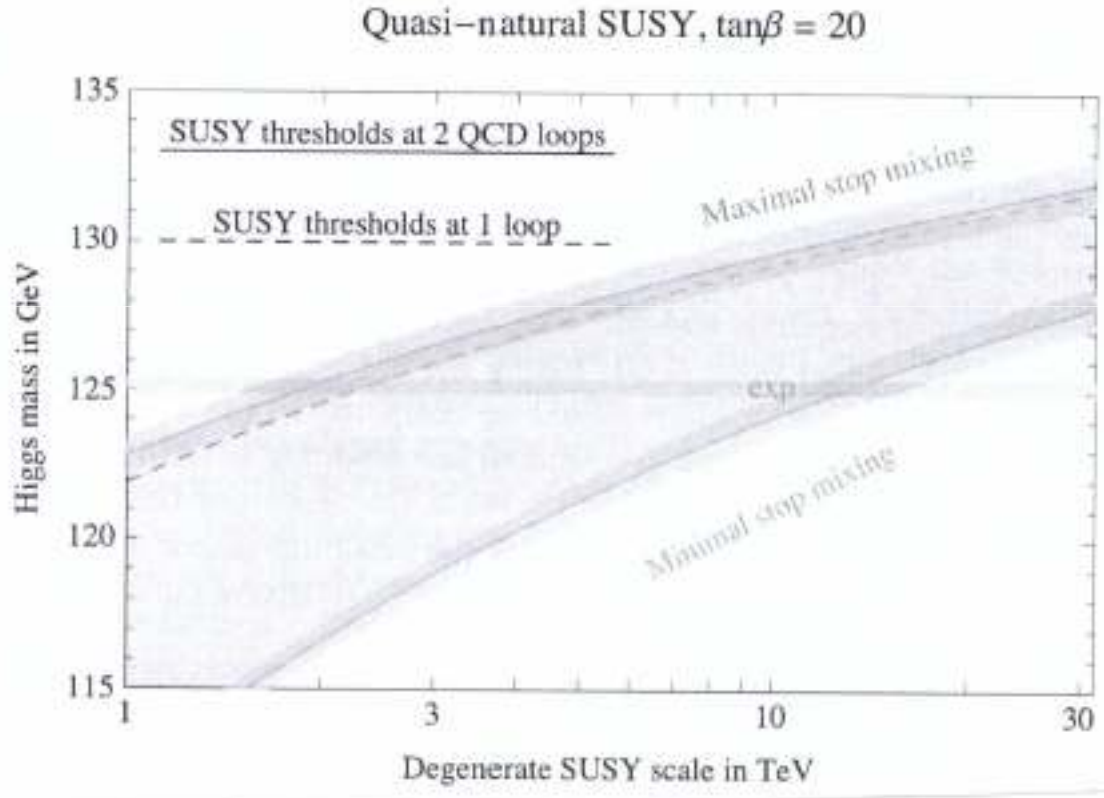
$$(\delta m_h^2)^{\rm rad} \approx \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{\rm SUSY}^2}\right)\right]$$

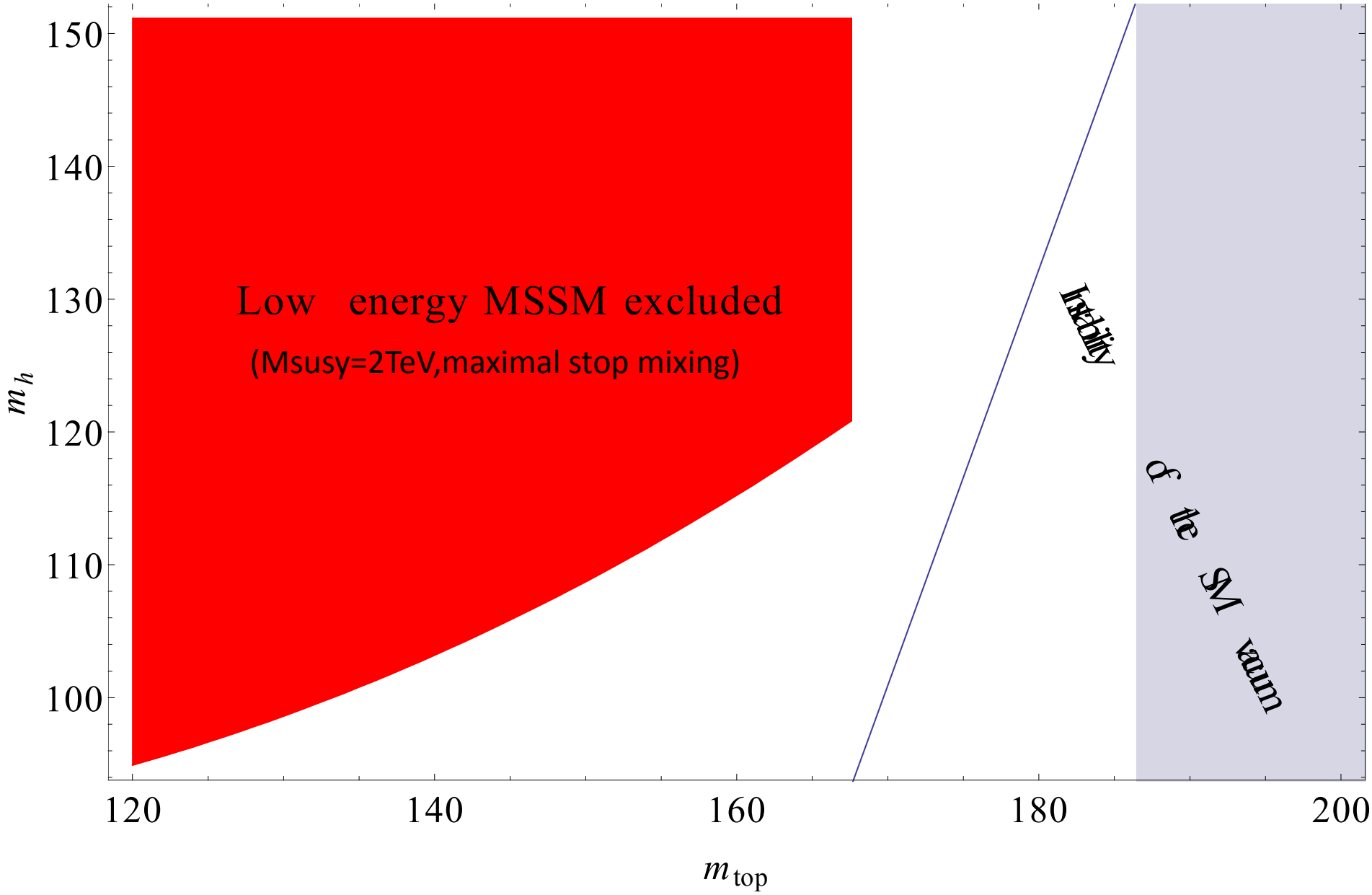
$$M_{\rm SUSY} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

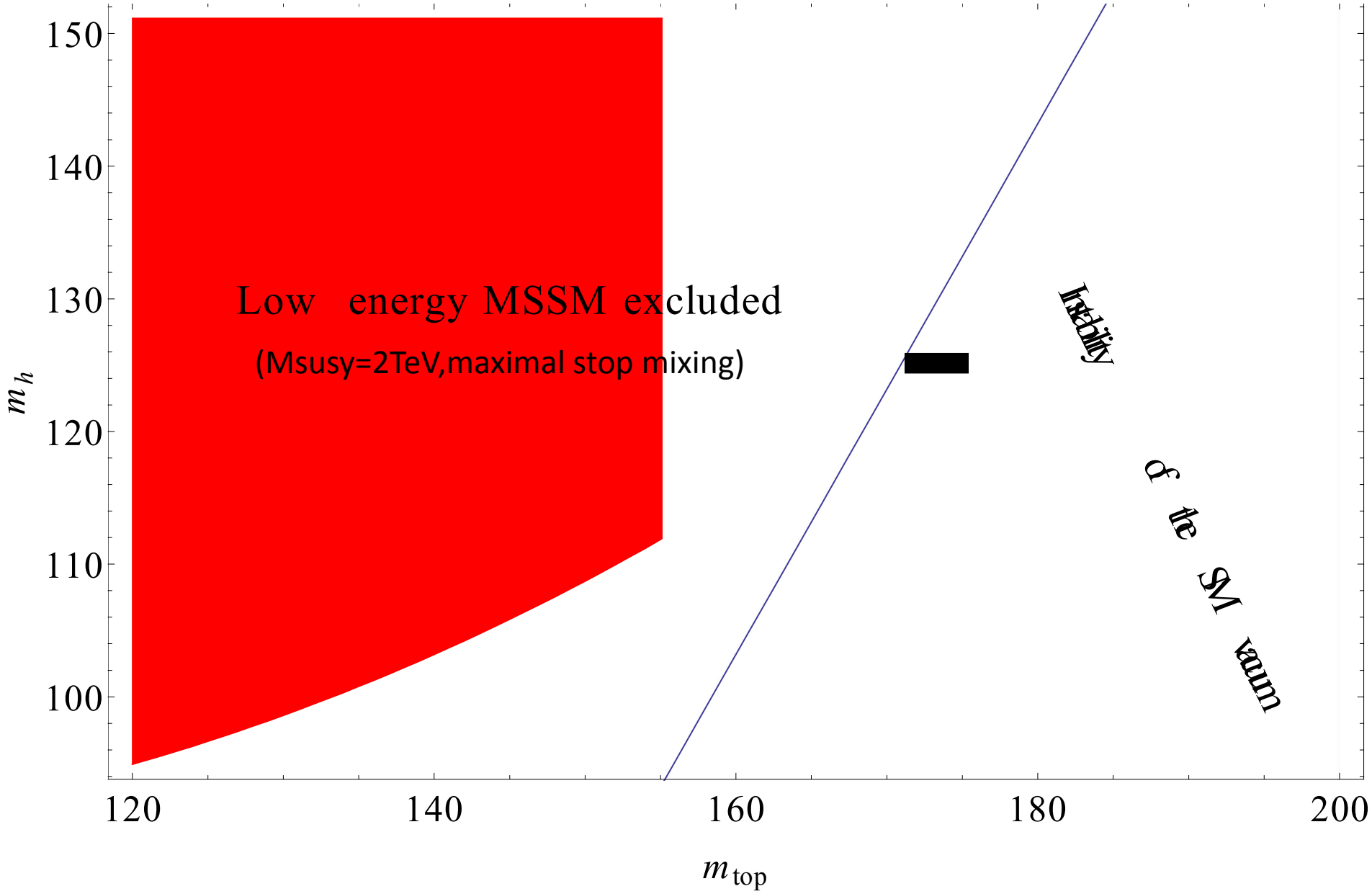
$$X_t \equiv A_t - \mu/\tan\beta$$

Summing $\ln(Msusy/M_Z)$ = MATCHING SM TO MSSM AT Msusy

Bagnaschi, Giudice, Slavich, Strumia (2014)




Low energy MSSM excluded
(Msusy=2TeV,maximal stop mixing)
Instability
of the SM vaum
150
140
130
120
110
100
120
140
160
180
200
m_h
m_{top}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STATUS OF THE SM

Simplest dynamical sector (considered by many as a toy model) with global chiral symmetry (to be spontaneously broken) – self interacting scalar field, a doublet of SU(2)- IS NOW PROMOTED TO A REAL THING

$$V = m_H^2 H H^+ + \tfrac{1}{2}\lambda (H H^+)^2$$

$$v^2 = -m_H^2/\lambda$$

$$m_h^2 = 2\lambda v^2$$

IS THE SM A CONSISTENT THEORY UP TO THE PLANCK SCALE?

YES BUT….

ISNT IT INDEED JUST AN EFFECTIVE THEORY, AN APPROXIMATION TO A DEEPER ONE
(SIMILARLY AS QED, ALTHOUGH CONSITENT UP TO Mp, IS ONLY LOW ENERGY APPROXIMATION TO SM)?

BY THE WAY, RENORMALISABILITY IS A GREAT VIRTUE OF EFFECTIVE THEORIES

WELL KNOWN ARGUMENTS FOR BSM PHYSICS
(EMPIRICAL AND THEORETICAL)

THE (UN)NATURALNESS OF THE SM HIGGS POTENTIAL - A SERIOUS ISSUE

ANY SHORT DISTANCE PHYSICS THAT COUPLES TO THE HIGGS (RH NEUTRINO, GUT PARTICLES..) WOULD INTRODUCE
QUADRATIC SENSITIVITY OF VEV TO THOSE SCALES

NATURALNESS PROBLEM OF THE SM: $\delta m_h^2 \sim M^2$

CONSPIRACY OF DIFFERENT MASS SCALES

UNNATURAL SM- NEW PARADIGM?

NO PRECISE CRITERION BUT….

WITH THE ABOVE GUIDELINE, THERE ARE TWO MAIN DIRECTIONS:

SUPERSYMMETRY

COMPOSITE HIGGS MODELS (HIGGS DOUBLET AS A NAMBU- GOLDSTONE BOSON OF A NEW STRONG SECTOR WITH A SUFFICIENTLY BIG SPONTANEOUSLY BROKEN GLOBAL SYMMETRY E.G. SO(5)→SO(4)

BOTH PREDICT NEW COLORED TOP PARTNERS (SCALARS IN SUSY, FERMIONS IN COMPOSITE HIGGS)

AT WHAT MASS SCALE?

Pokazac ze susy wciąż eksperymentalnie
Aktualna, zwrocic uwage na to ze w composite
Gorna granica na fermiony a w susy dolna,
Wspomniec o korespondencji extra dim= composite

NON-OBSERVATION OF NEW COLORED PARTICLES UP TO 1 TeV IS PUTTING THE IDEA OF NATURALNESS UNDER CERTAIN PRESSURE (1:100 CANCELLATIONS IN THE HIGGS POTENTIAL ARE NEEDED)

IN MSSM, ADDITIONAL CONSTRAINT FROM THE HIGGS MASS, STOPS HEAVIER THAN 2 TeV

REVIVAL OF THE IDEAS OF HIDDEN (UNCOLORED) NATURALNESS WITH NEW COLORED PARTICLES ABSENT OR SIGNIFICANTLY HEAVIER

TWIN HIGGS

SM-LIKE HIGGS IS A PSEUDO-GOLDSTONE BOSON OF AN APPROXIMATE GLOBAL SU(4) SYMMETRY

Zaczac od Z2

$$\mathcal{H} = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$ SU(2), hidden SU(2)

$$V = \lambda\left(|\mathcal{H}|^2 - f^2/2\right)^2$$

$$\langle \mathcal{H} \rangle = f/\sqrt{2}$$

SU(4) broken to SU(3)

7 GOLDSTONE BOSONS: 3 + 3 + 1

eaten Higgs

SU(4) IS EXPLICITLY BROKEN BY GAUGE & YUKAWA COUPLINGS OF THE SM.

ADDITIONAL ASSUMPTIONS: SM GAUGE BOSONS AND FERMIONS ARE MIRRORED, SO THAT THE SPECTRUM IS SYMMETRIC (NOT A FULL REPRESENTATION OF SU(4)) Z_2

THE PARTNER PARTICLES ARE NOT RELATED TO SM STATES BY A CONTINOUS SYMMETRY AND SO NEED NOT CARRY SM GAUGE QUANTUM NUMBERS.

TWIN FERMIONS: Q_B → A DOUBLET OF TWIN SU(2) AND A TRIPLET OF TWIN SU(3) („HIDDEN QCD")

T_B --> A SINGLET OF TWIN SU(2) AND A TRIPLET OF TWIN SU(3)

NEW YUKAWA COUPLING $y_t^B \bar{Q}_B H_B T_B$

THE 1-LOOP RADIATIVE POTENTIAL FOR $H_A \& H_B$

$$16\pi^2 V^{1-loop} = -6\Lambda^2(y_t^{(A)2}|H_A|^2 + y_t^{(B)2}|H_B|^2)$$

$$+3y_t^{(A)4}|H_A|^4 ln(\Lambda^2/y^{(A)2}|A|^2) + (A \to B, y_t^A \to y_t^B)$$

$$Z_2 : y_t^A = y_t^B \to$$

THIS CONTRIBUTION RESPECTS THE GLOBAL SYMMETRY, SO CANNOT CONTRIBUTE TO THE MASS OF THE NGBs

Λ IS A CUT OFF OF 5-10 TeV
(SOLVING SMALL HIREARCHY PROBLEM)

QUADRATIC DIVERGENCES OF THE TOP QUARK LOOP ARE CANCELLED BY A TOP QUARK PARTNER WITH THE „HIDDEN” COLOR

Z_2 HAS TO BE SOFTLY BROKEN BECAUSE OTHERWISE

$$v_A^2 = v_B^2 = f^2/2$$

ADD SOFT BREAKING TERM: $\sigma |H_A|^2$

F.T. $= \dfrac{2v^2}{f^2}$ (A SHORT CALCULATION)

IT IS DETERMINED BY THE QUADRATIC TERMS IN THE POTENTIAL

CANCELLATION OF QUADRATIC DIVERGENCES IN NON-LINEAR PARAMETRIZATION, AFTER INTEGRATING OUT THE HEAVY RADIAL MODE:

Non - linear parametrization

$$\mathcal{H} = \begin{pmatrix} H \dfrac{f}{\sqrt{HH^\dagger}} \sin\left(\dfrac{\sqrt{HH^\dagger}}{f}\right) \\ 0 \\ f \cos\left(\dfrac{\sqrt{HH^\dagger}}{f}\right) \end{pmatrix} \equiv \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$

H - Higgs doublet of the SM

$$H_B = \begin{pmatrix} 0 \\ f - \frac{1}{2f} H^\dagger H \end{pmatrix}$$

Yukawa

$$y_t H Q t_R + y_t^B \left(f - \frac{1}{2f} H^\dagger H\right) Q T^B$$

EXPERIMENTAL SIGNATURES

HIGGS COUPLINGS

$$H_A = \begin{pmatrix} 0 \\ f \sin\left(\frac{v+h}{\sqrt{2}f}\right) \end{pmatrix} \qquad H_B = \begin{pmatrix} 0 \\ f \cos\left(\frac{v+h}{\sqrt{2}f}\right) \end{pmatrix}$$

COUPLINGS TO THE SM GAUGE BOSONS

$$|D^A_\mu H_A|^2 + |D^B_\mu H_B|^2 \quad \Rightarrow$$

$$\left[\frac{f^2 g^2}{2} W^+_{A\mu} W^{-\mu}_A + ZZ\right] \sin^2 \frac{v+h}{\sqrt{2}f} + [A \to B] \cos^2 \frac{v+h}{\sqrt{2}f}$$

$$m^2_{W_A} = \frac{f^2 g^2}{2} \sin^2 \frac{v}{\sqrt{2}f}, \qquad v_{EW} = \sqrt{2} f \sin \frac{v}{\sqrt{2}f}$$

AND FOR THE COUPLINGS

$$\frac{2m_{W_A}^2}{v_{EW}}\left(1-\frac{v_{EW}^2}{2f^2}\right)^{1/2} W_\mu^A W_A^\mu h$$

THE SAME RESULT FOR THE TOP YUKAWA

The LHC data put limits on $\frac{v_{EW}^2}{f^2}$

$$\sigma(pp\to h) = \left(1-\frac{v_{EW}^2}{2f^2}\right)\sigma_{SM}(pp\to h)$$

HIDDEN QCD WITH GLUEBALL

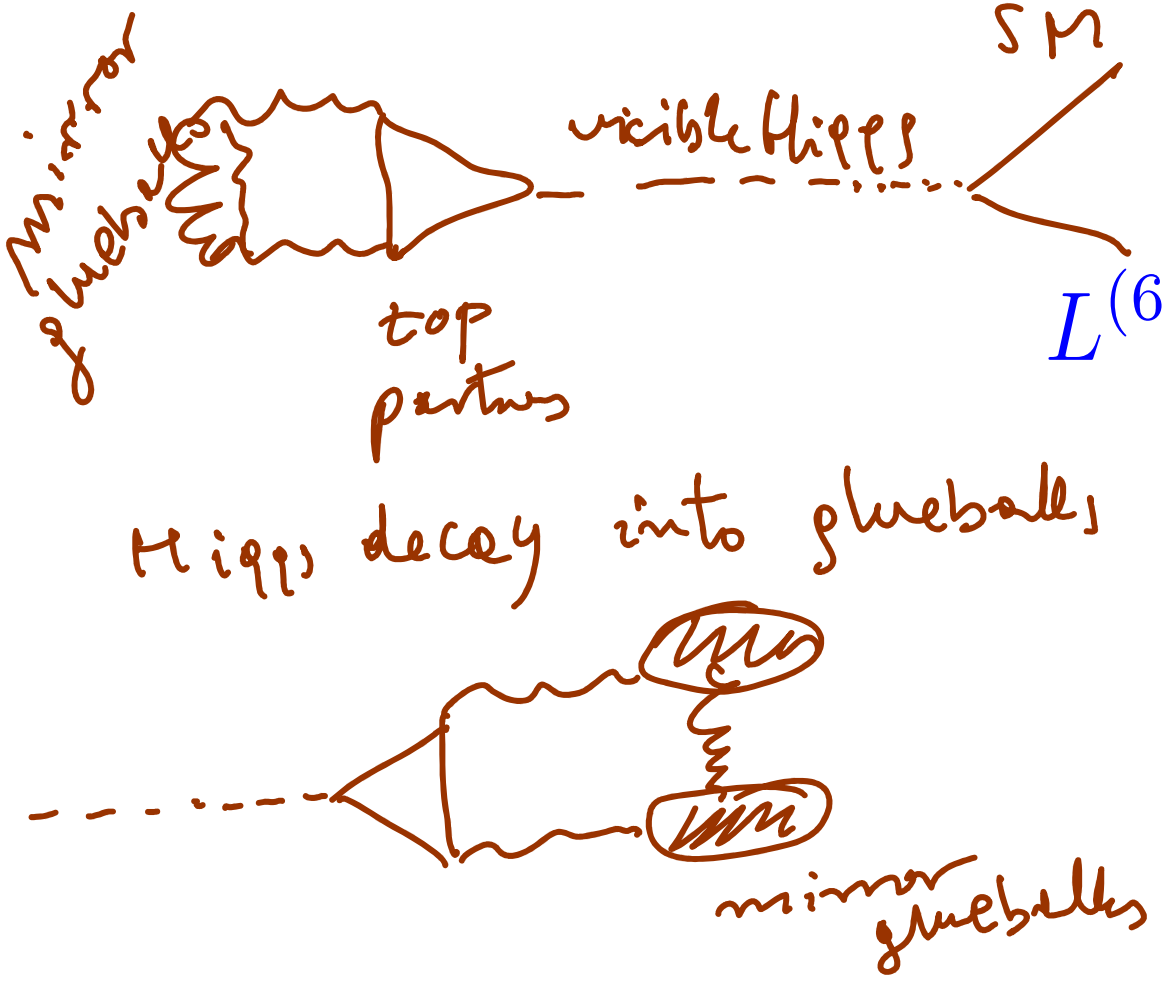
IF FERMIONS CARRYING TWIN SU(3) ARE MUCH HEAVIER THAN THE CONFINEMMENT SCALE → THE INFRARED PHYSICS IS THAT OF PURE SU(3) GAUGE FIELDS →

THE LIGHTEST STATES IN THE CONFINED TWIN SECTOR WILL BE GLUEBALLS.

FOR $g_3^B = g_3^A$ AT THE CUT-OFF Λ,

THE CONFINEMENT SCALE $\Lambda^B \approx 10\Lambda^A$ (RGE)

GLUEBALLS MIX WITH THE HIGGS VIA TOP PARTNER LOOP BECAUSE THE PHYSICAL HIGGS HAS A SMALL „DARK" COMPONENT



$$L^{(6)} = c H_A^\dagger H_A G_B^{\mu\nu} G_{\mu\nu}^B$$

$$c \approx \frac{\alpha_3}{6\pi} \frac{y_t^2}{m_T^2}$$

1) THE HIGGS CAN DECAY TO „HIDDEN” GLUEBALLS – EXOTIC DISPLACED DECAYS

2) HIGGS PORTAL TOP PARTNER PRODUCTION AND THEIR ANNIHILATION INTO GLUEBALLS – EMERGING JETS

Hidden QCD without glueballs:

Invisible Higgs decays, e.g.

$$h \to b_B \bar{b}_B \quad , \quad h \to g_B g_B$$

↳

$$\Gamma(h \to b_B \bar{b}_B) \approx \Gamma(h \to \text{invis}) \approx$$

$$\approx \Gamma(h \to b\bar{b}) \, tg^2\left(\frac{v}{2f}\right)$$

HIGGS DECAYS - A POWERFUL TOOL (IN PRINCIPLE),

IS SENSITIVE TO NEW PHYSICS THAT CANNOT BE

SEEN VIA NEW PARTICLE PRODUCTION

UV - completions:

Supersymmetric - double protection

Z_2 broken by soft mass terms of H_A, H_B

Main gain: cut-off Λ can be high

UNCOLORED WAY BEYOND THE SM: MOTIVATED ALSO INDEPENDENTLY OF UNCOLORED NATURALNESS.

EXAMPLES:

- ELECTROWEAK SECTOR IN SPLIT OR MINI-SPLIT SUPERSYMMETRY
- DARK MATTER SEARCHES OR, MORE GENERALLY, SEARCHES FOR STABLE PARTICLES WITH $\Omega \leq \Omega_{obs}$
- Z', MULTI-SCALAR MODELS FOR FLAVOR PHYSICS

COLLIDER SIGNATURES: MONOJETS, DISPLACED VERTICES, DISAPPEARING TRACKS, ….

CONCLUSION

NEW COLORED PARTICLES MAY BE HEAVY OR MAY NOT EXIST AT ALL;

IN PARALLEL TO SEARCHING FOR THEIR DIRECT PRODUCTION, TECHNIQUES ARE BEING DEVELOPED AND SHOULD BECOME MORE ADVANCED FOR DISCOVERING NEW UNCOLORED PARTICLES (OR THEIR INDIRECT EFFECTS), WITH MUCH SMALLER PRODUCTION RATES