NATURAL SUSY - THEORY

Patrick Meade
Yang Institute for Theoretical Physics
Stony Brook University

Can it still exist?

NATURAL SUSY - ~~THEORY~~

Patrick Meade
Yang Institute for Theoretical Physics
Stony Brook University

OUTLINE

- The Hierarchy Problem and Naturalness
- Supersymmetry
- Natural Supersymmetry and the Little Hierarchy Problem
- What does Natural SUSY imply and is it bounded?

A MATTER OF "FUNDAMENTAL" SCALES IN GEV...

QCD	EW	Gravity/ cutoff of SM EFT?
Λ_{QCD}	v	M_{Pl}
10^{-1}	10^{2}	10^{18}

A MATTER OF "FUNDAMENTAL" SCALES IN GEV...

Why don't we care about this separation?

A MATTER OF "FUNDAMENTAL" SCALES IN GEV...

QCD — Λ_{QCD} — 10^{-1}

EW — v — 10^{2}

Gravity/ cutoff of SM EFT? — M_{Pl} — 10^{18}

Dimensional Transmutation

Why don't we care about this separation?

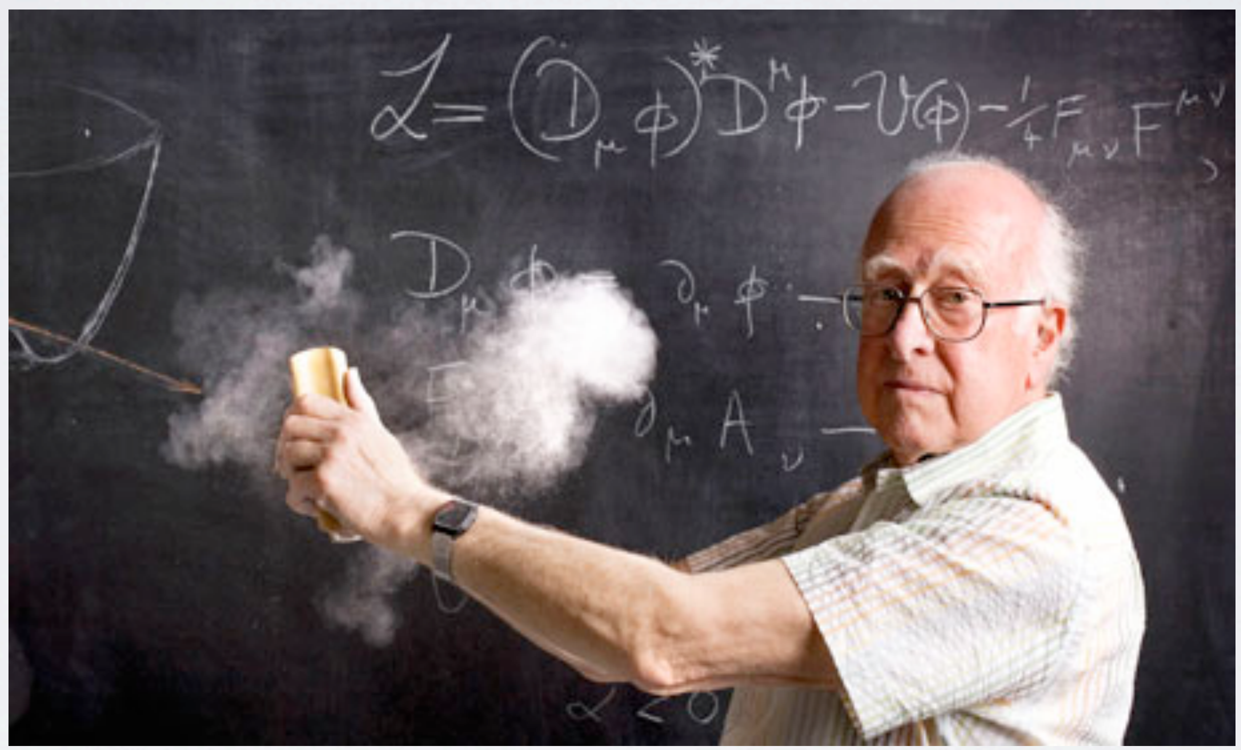
A MATTER OF "FUNDAMENTAL" SCALES IN GEV...

QCD	EW	Gravity/ cutoff of SM EFT?
Λ_{QCD}	v	M_{Pl}
10^{-1}	10^{2}	10^{18}

Why <u>do</u> we care about this separation?

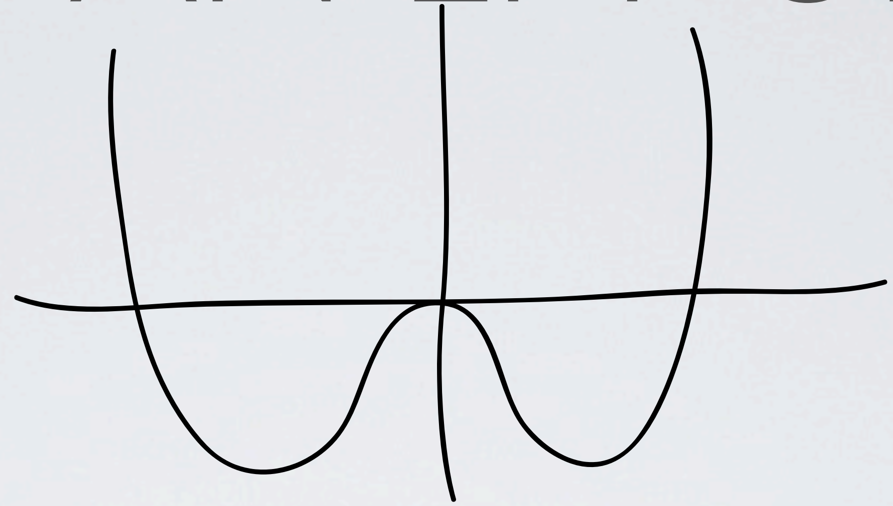
A MATTER OF "FUNDAMENTAL" SCALES IN GEV...

QCD	EW		Gravity/ cutoff of SM EFT?
Λ_{QCD}	v		M_{Pl}
10^{-1}	10^{2}		10^{18}



Why do we care about this separation?

VIEW SM AS AN EFT UP TO Λ



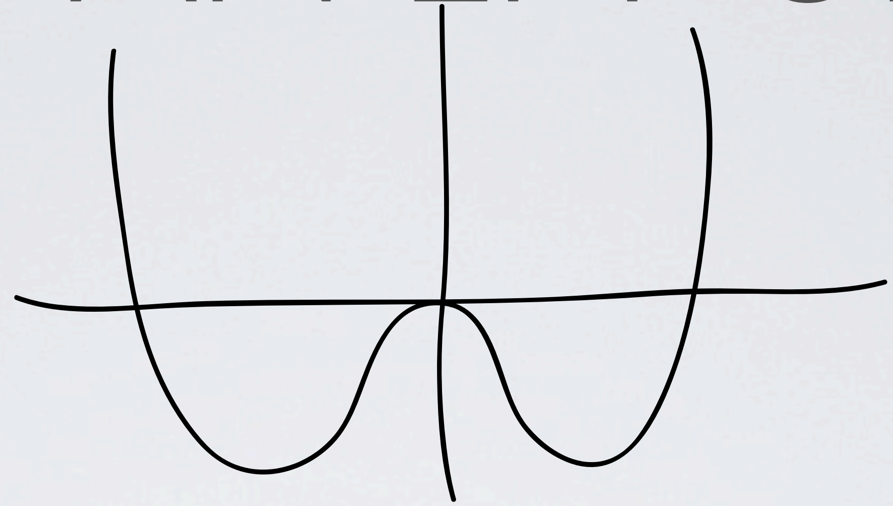
$$V(\phi) \sim \lambda \phi^4 - \mu^2 \phi^2$$

$$v \equiv \langle \phi \rangle \sim \sqrt{\frac{\mu^2}{\lambda}}$$

Tree-Level Relation

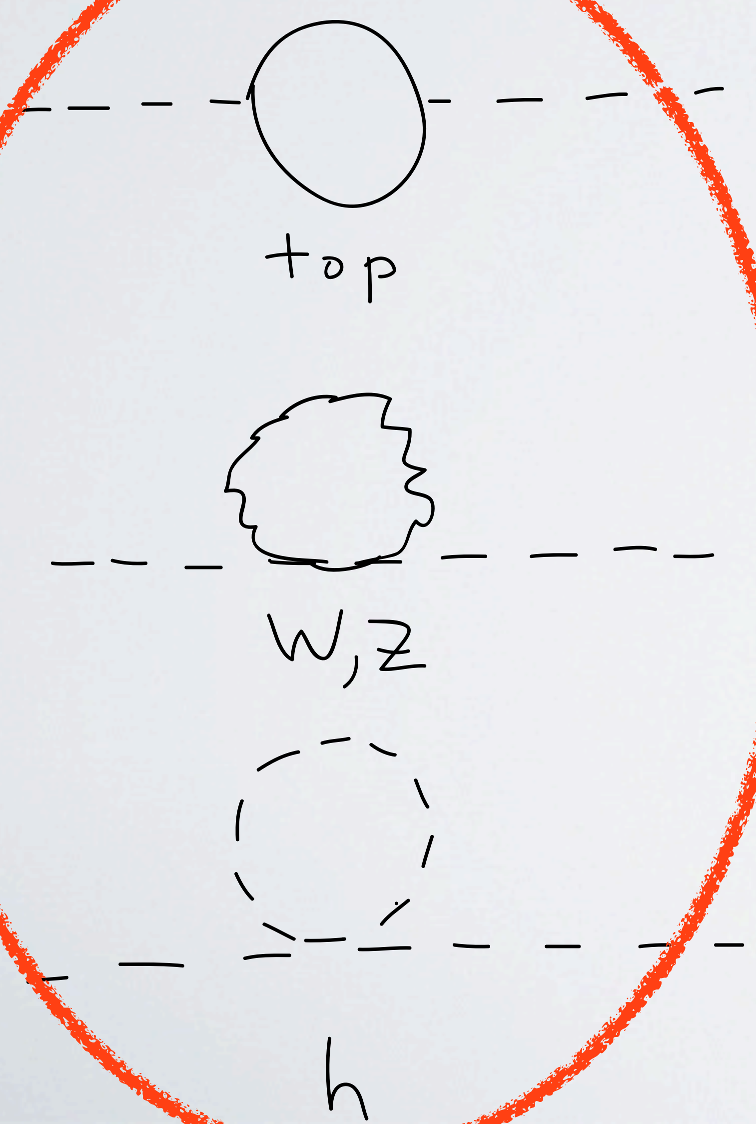
$$(100\,\mathrm{GeV})^2 \sim \mu^2$$

VIEW SM AS AN EFT UP TO Λ



$$V(\phi) \sim \lambda \phi^4 - \mu^2 \phi^2$$

$$v \equiv \langle \phi \rangle \sim \sqrt{\frac{\mu^2}{\lambda}}$$



bare term

quantum corrections

$$(100\,\mathrm{GeV})^2 \sim \mu^2 - \Lambda^2$$

Quantum corrected relation

FIXED by VEV

HIERARCHY PROBLEM!!!

Let's say there is no new physics below
Λ ~10^18 GeV...

$$(100\,\mathrm{GeV})^2 \sim \mu^2 - \Lambda^2$$

HIERARCHY PROBLEM!!!

Let's say there is no new physics below
Λ ***~10^18 GeV...***

$$(100\,\mathrm{GeV})^2 \sim \mu^2 - \Lambda^2$$

- SM is correct and we just have to tune to a part in 10^32
  - .0000000000000000000000000000000I **FINE TUNING**

HIERARCHY PROBLEM!!!

Let's say there is no new physics below
Λ ~10^18 GeV...

$$(100\,\mathrm{GeV})^2 \sim \mu^2 - \Lambda^2$$

- SM is correct and we just have to tune to a part in 10^32
  - .00000000000000000000000000000001 **FINE TUNING**

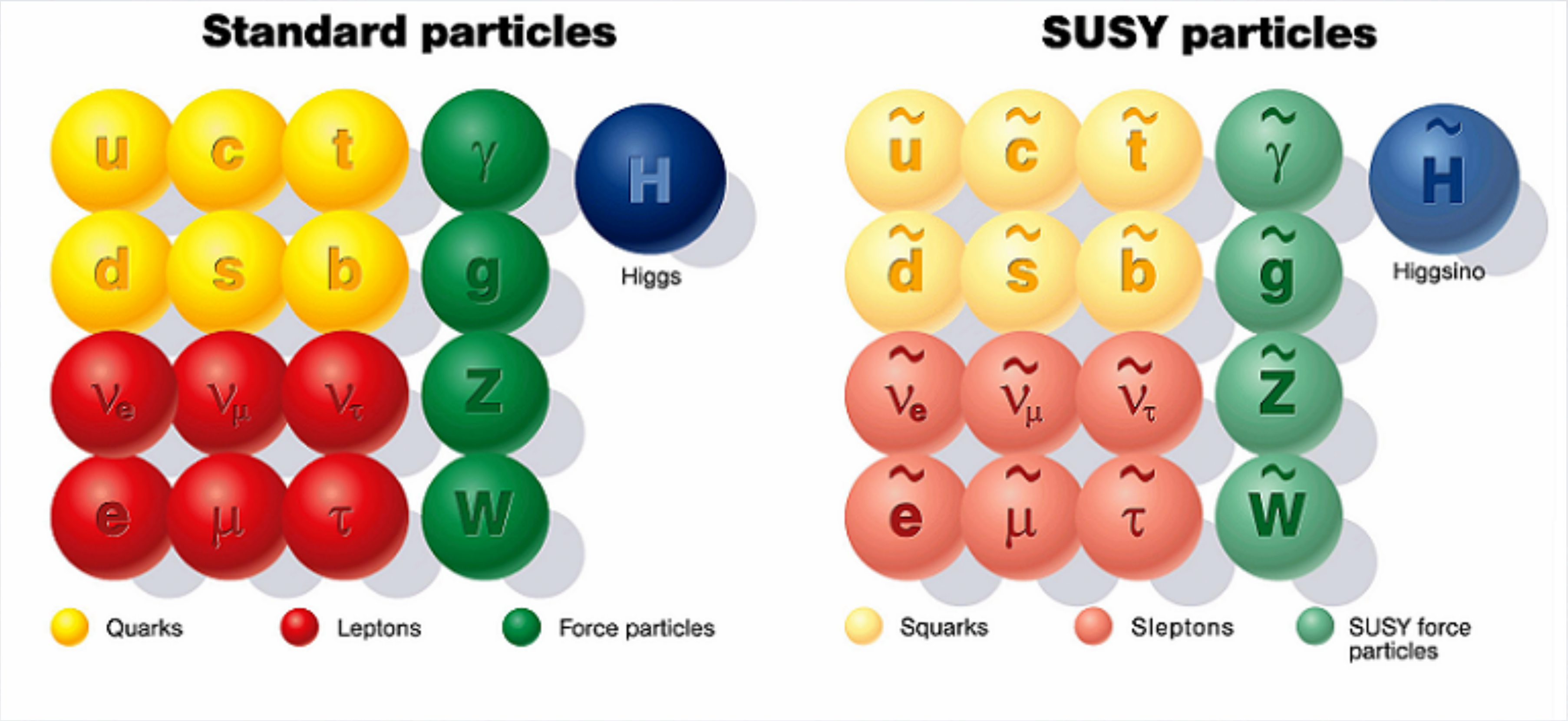
OR

- We need a MECHANISM/SYMMETRY to explain why we exist...

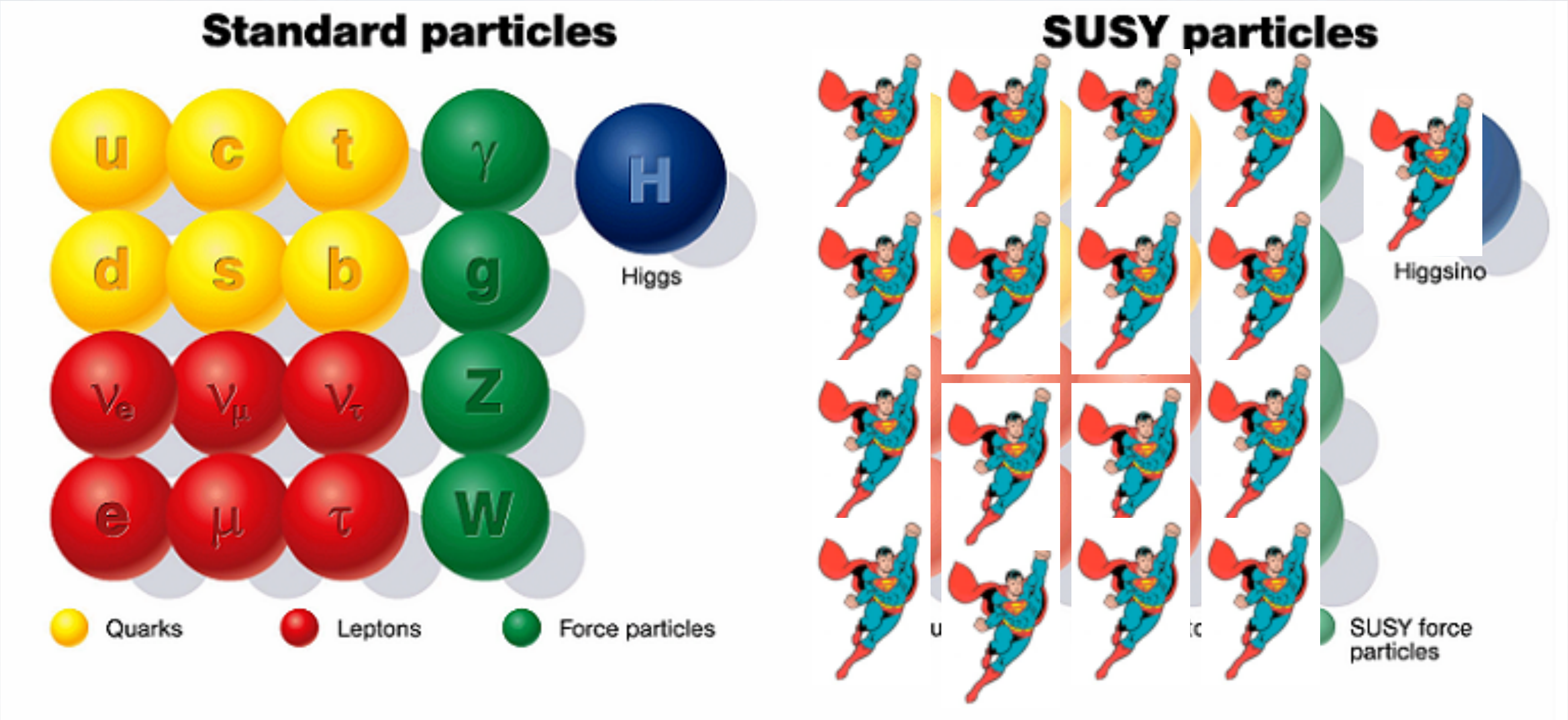

SUPERMAN

SYMMETRY

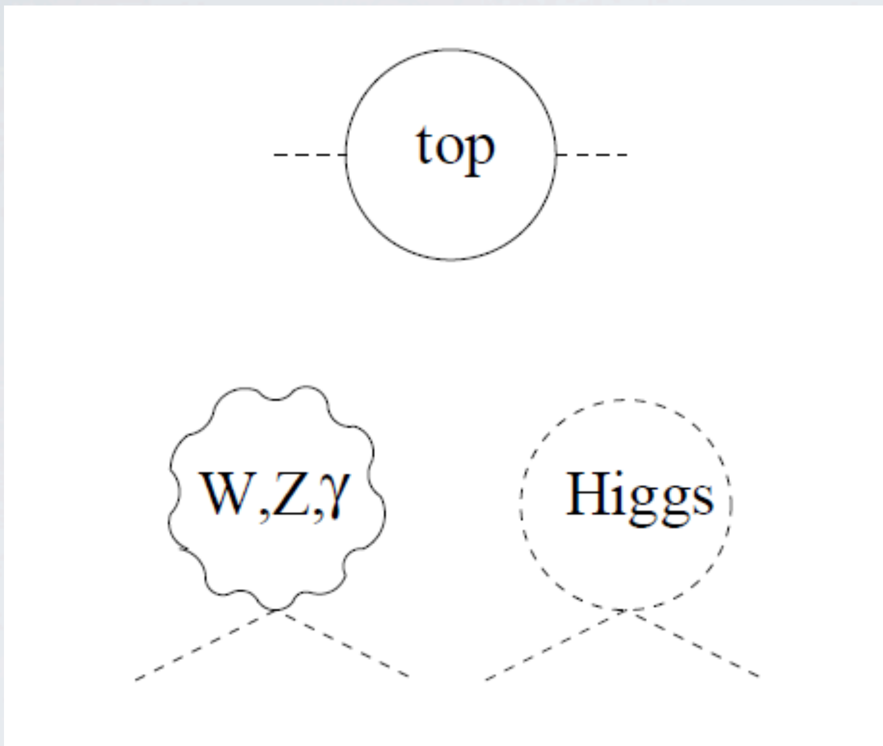
HOW DOES THIS HELP?



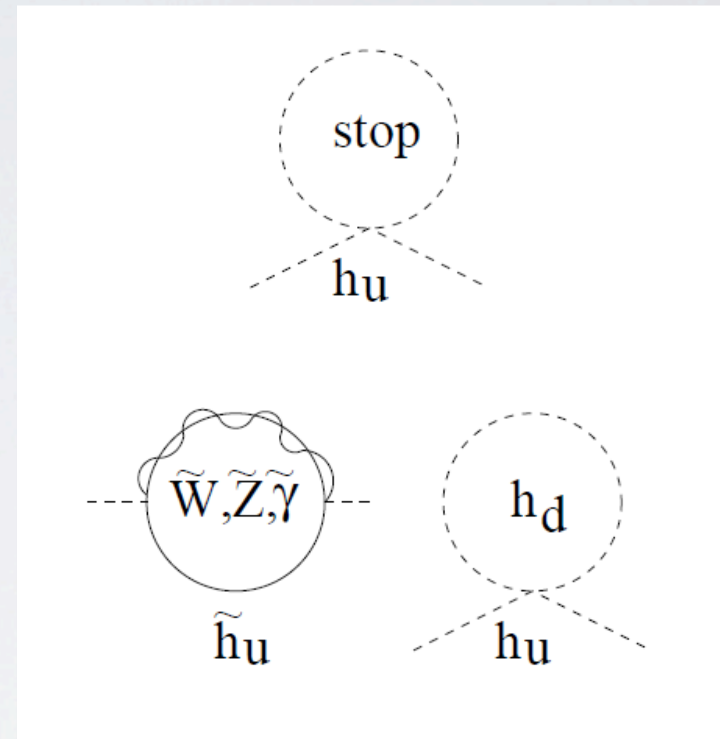
HOW DOES THIS HELP?



SUSY AND NATURALNESS

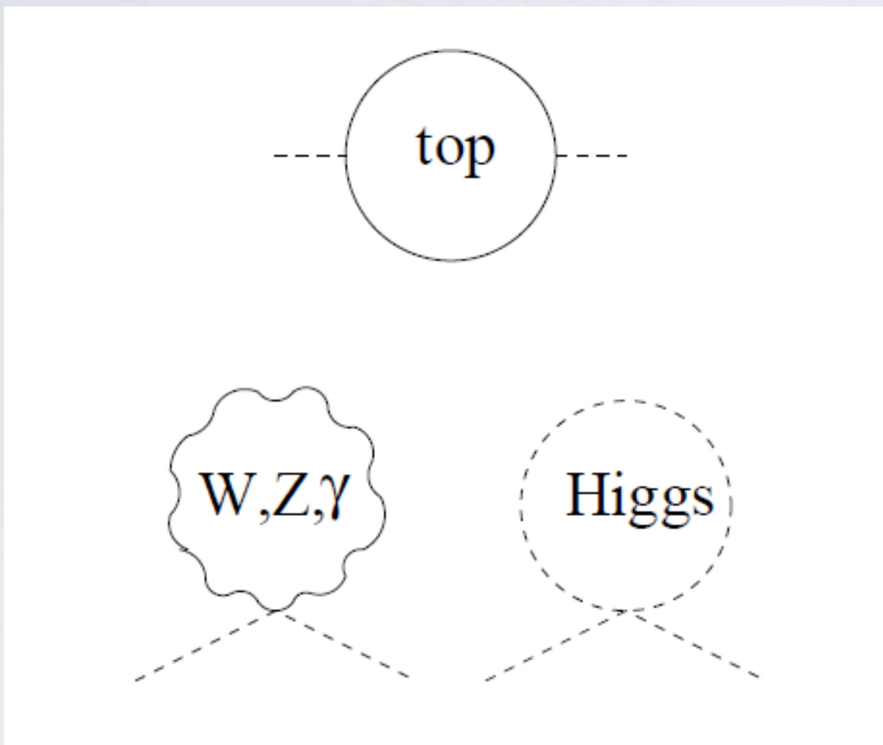


+

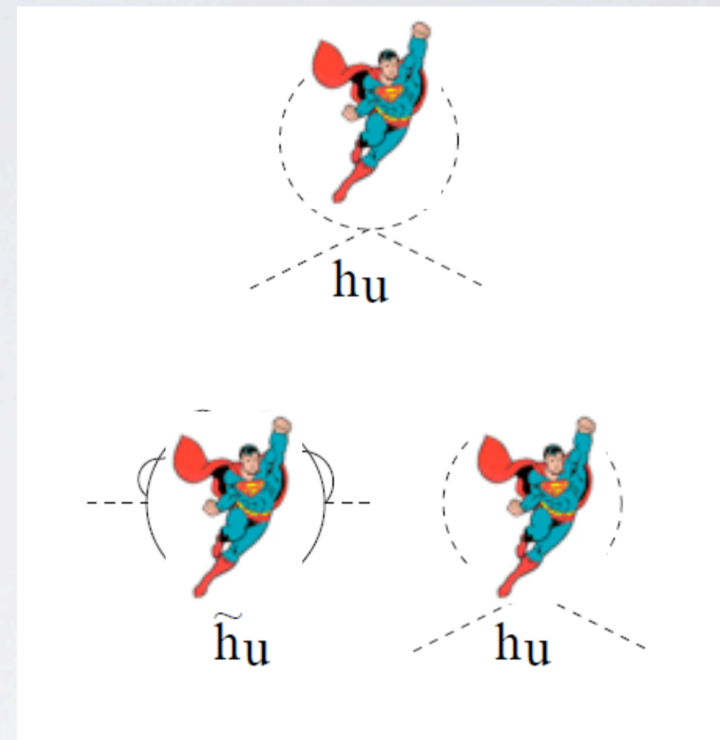


=

SUSY AND NATURALNESS

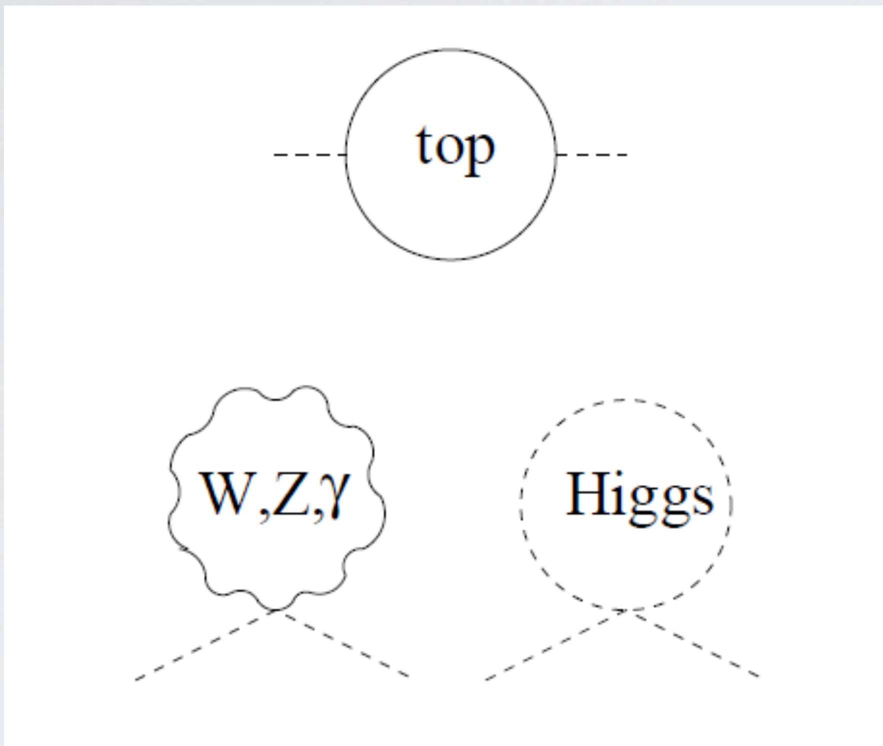


+

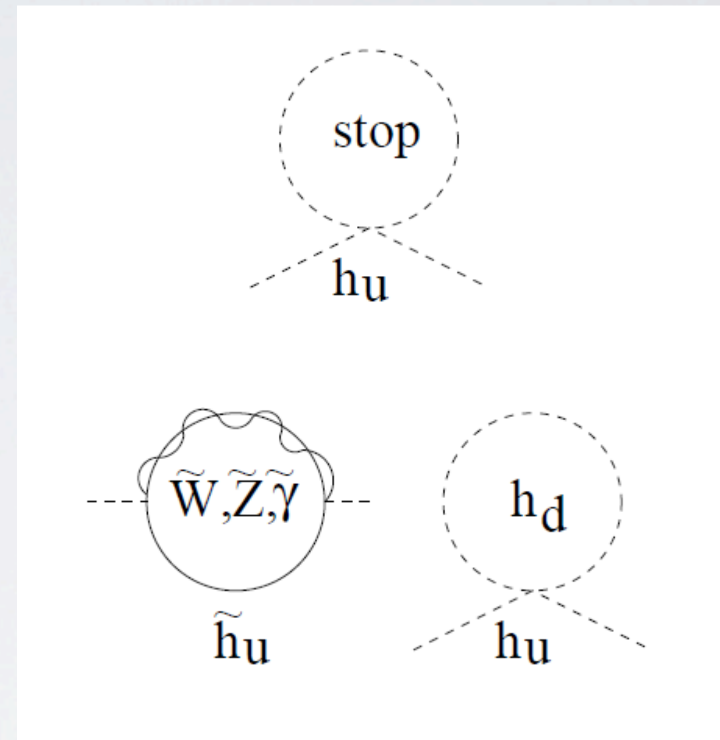


=

SUSY AND NATURALNESS



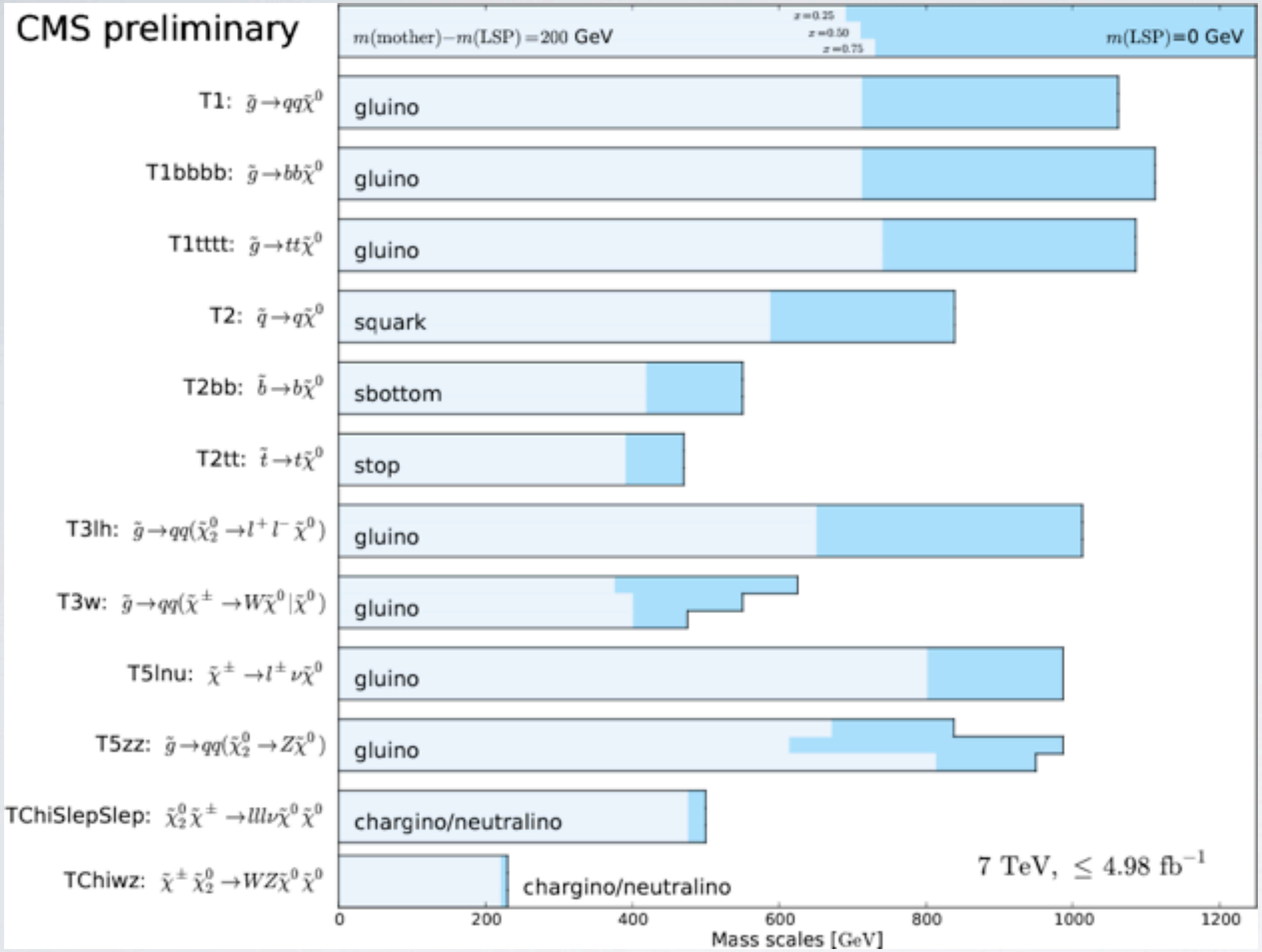
$+$

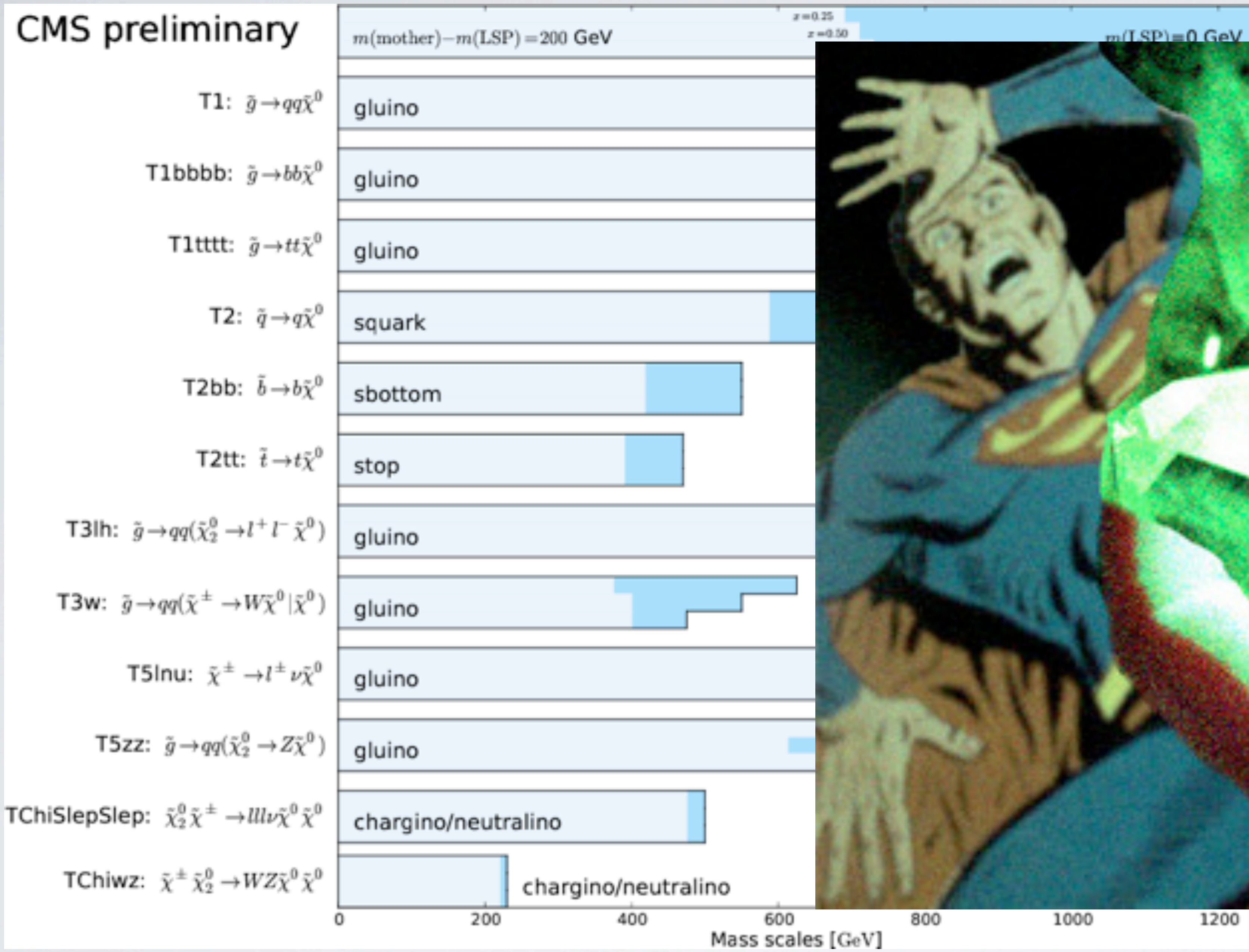


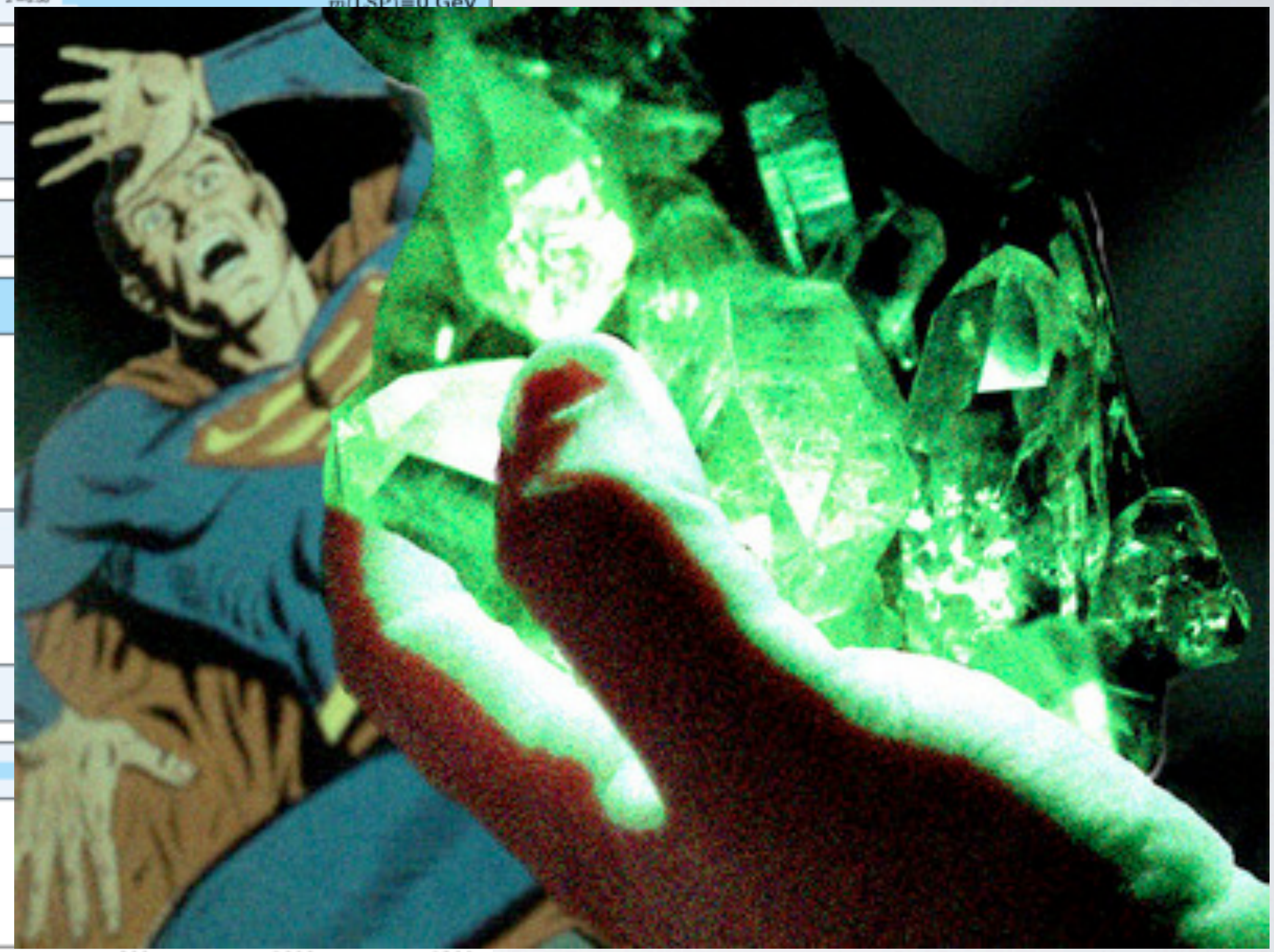
SUSY breaking mass

$$= \quad \delta m_H^2 \sim m_{SUSY}^2 \ln \frac{\Lambda}{m_{SUSY}}$$

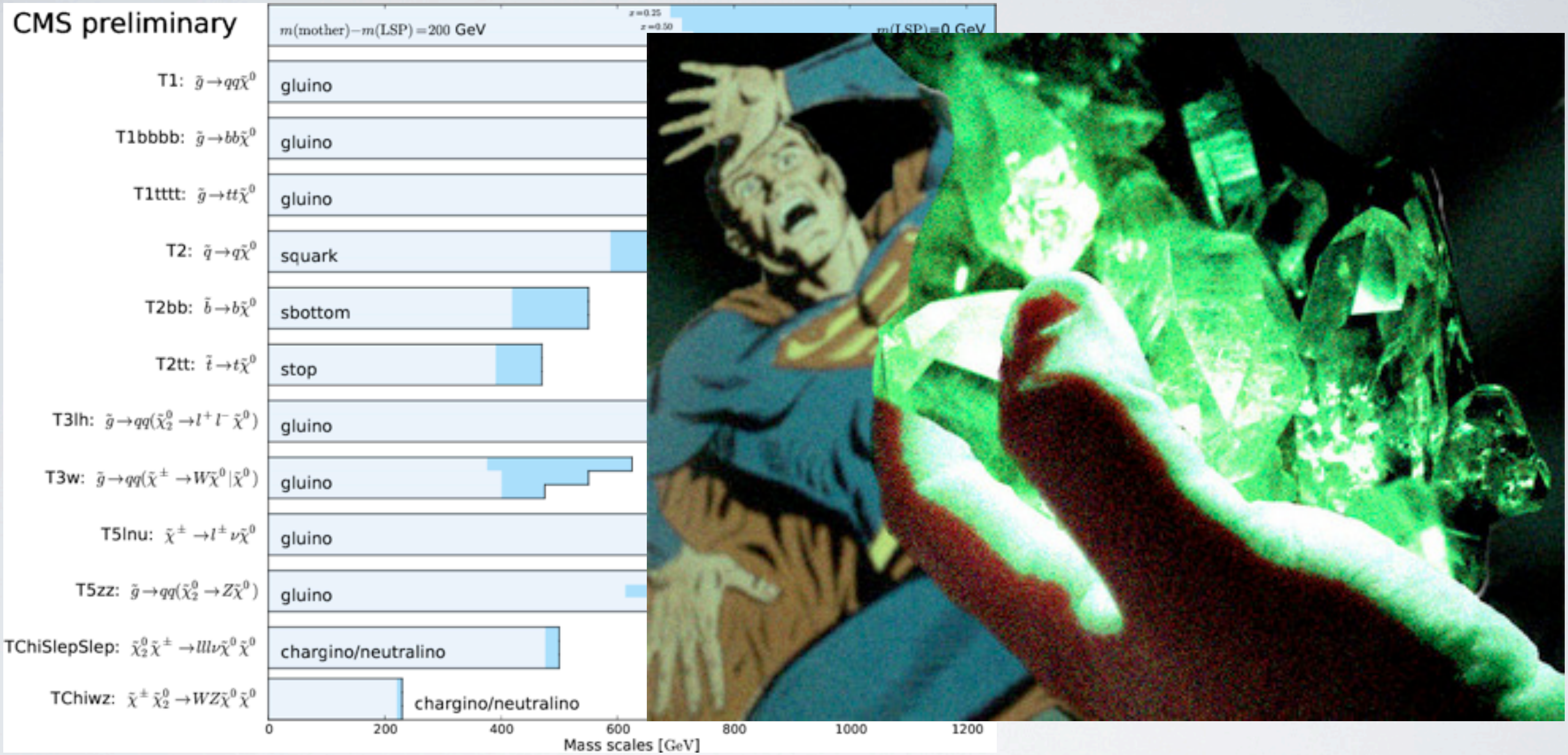
IF SUSY is ***light*** we have a solution to the hierarchy problem


CMS preliminary
m(mother)−m(LSP)=200 GeV
x=0.25
x=0.50
x=0.75
m(LSP)=0 GeV
T1: $\tilde{g}\to qq\tilde{\chi}^0$
gluino
T1bbbb: $\tilde{g}\to bb\tilde{\chi}^0$
gluino
T1tttt: $\tilde{g}\to tt\tilde{\chi}^0$
gluino
T2: $\tilde{q}\to q\tilde{\chi}^0$
squark
T2bb: $\tilde{b}\to b\tilde{\chi}^0$
sbottom
T2tt: $\tilde{t}\to t\tilde{\chi}^0$
stop
T3lh: $\tilde{g}\to qq(\tilde{\chi}^0_2\to l^+l^-\tilde{\chi}^0)$
gluino
T3w: $\tilde{g}\to qq(\tilde{\chi}^\pm\to W\tilde{\chi}^0|\tilde{\chi}^0)$
gluino
T5lnu: $\tilde{\chi}^\pm\to l^\pm\nu\tilde{\chi}^0$
gluino
T5zz: $\tilde{g}\to qq(\tilde{\chi}^0_2\to Z\tilde{\chi}^0)$
gluino
TChiSlepSlep: $\tilde{\chi}^0_2\tilde{\chi}^\pm\to lll\nu\tilde{\chi}^0\tilde{\chi}^0$
chargino/neutralino
TChiwz: $\tilde{\chi}^\pm\tilde{\chi}^0_2\to WZ\tilde{\chi}^0\tilde{\chi}^0$
chargino/neutralino
7 TeV, ≤ 4.98 fb^{-1}
0
200
400
600
800
1000
1200
Mass scales [GeV]





NO SUSY ANWHERE???



NO SUSY ANWHERE???

* can give an example where SUSY fits better than SM... not part of this talk...

Where should SUSY be???

Where should SUSY be???

SLAC–PUB–3551
LBL–18990
January 1985
(T/E)

IMPLICATIONS OF A SYSTEMATIC STUDY OF
THE CERN MONOJETS FOR SUPERSYMMETRY*

R. MICHAEL BARNETT

Lawrence Berkeley Laboratory, University of California
Berkeley, California 94720

HOWARD E. HABER

Division of Natural Sciences II
University of California, Santa Cruz, California 95064
and
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

G. L. KANE

Randall Laboratory of Physics, University of Michigan
Ann Arbor, Michigan 48109

ABSTRACT

We report on a comprehensive study of supersymmetric processes which could give events similar to those observed at the CERN $S\bar{p}pS$ collider. The present limited data seem to suggest a gluino mass $\lesssim$ 20 GeV and a scalar-quark mass of 100 – 120 GeV, although certain other supersymmetric masses are not yet excluded. With this choice of masses we also predict that other events with different characteristics should be observed. An essential ingredient of our analysis is the inclusion of events originating from a perturbatively generated gluino distribution function inside the proton.

Almost ***anywhere*** if you ask your neighborhood theorist
(integrated over time of course)

Where should SUSY be???

SLAC–PUB–3551
LBL–18990
January 1985
(T/E)

IMPLICATIONS OF A SYSTEMATIC STUDY OF
THE CERN MONOJETS FOR SUPERSYMMETRY*

R. MICHAEL BARNETT

Lawrence Berkeley Laboratory, University of California
Berkeley, California 94720

HOWARD E. HABER

Division of Natural Sciences II
University of California, Santa Cruz, California 95064
and
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

G. L. KANE

Randall Laboratory of Physics, University of Michigan
Ann Arbor, Michigan 48109

ABSTRACT

We report on a comprehensive study of supersymmetric processes which could give events similar to those observed at the CERN $S\bar{p}pS$ collider. The present limited data seem to suggest a gluino mass $\lesssim$ 20 GeV and a scalar-quark mass of 100 – 120 GeV, although certain other supersymmetric masses are not yet excluded. With this choice of masses we also predict that other events with different characteristics should be observed. An essential ingredient of our analysis is the inclusion of events originating from a perturbatively generated gluino distribution function inside the proton.

Almost ***anywhere*** if you ask your neighborhood theorist
(integrated over time of course)

NATURAL SUSY

- Basic premise, **if** nature *cares* about **naturalness**, spectrum should be guided **naturalness**, not by what your favorite theorist tells you the mediation mechanism should be :)

TEST OF NATURALNESS

Size of shift to Higgs mass in SM

$\delta m_h^2 \sim$

$y_t^2\Lambda^2$ New physics in top **first**

$g^2\Lambda^2$ NP in gauge bosons **next**

$\lambda^2\Lambda^2$ New physics in higgs sector **last**

NOT SO FAST SUSY!!

NOT SO FAST SUSY!!

$$m_h = 125\,\text{GeV}$$

HIGGS IN SUSY IN DETAIL

Two Higgs Doublet Model

$$
\begin{aligned}
V &= (|\mu|^2 + m^2_{H_u})(|H_u^0|^2 + |H_u^+|^2) + (|\mu|^2 + m^2_{H_d})(|H_d^0|^2 + |H_d^-|^2) \\
&\quad + [b\,(H_u^+ H_d^- - H_u^0 H_d^0) + \text{c.c.}] \\
&\quad + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 + |H_u^+|^2 - |H_d^0|^2 - |H_d^-|^2)^2 + \frac{1}{2}g^2|H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2.
\end{aligned}
$$

Quartic comes from D-terms and is DETERMINED

$$
\begin{aligned}
V &= (|\mu|^2 + m^2_{H_u})|H_u^0|^2 + (|\mu|^2 + m^2_{H_d})|H_d^0|^2 - (b\,H_u^0 H_d^0 + \text{c.c.}) \\
&\quad + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2.
\end{aligned}
$$

SOME GREAT AND NOT SO GREAT FEATURES

- Radiative Electroweak Symmetry Breaking!
  - Life isn't so arbitrary...

$$\begin{aligned} V &= (|\mu|^2 + m^2_{H_u})|H_u^0|^2 + (|\mu|^2 + m^2_{H_d})|H_d^0|^2 - (b\, H_u^0 H_d^0 + \text{c.c.}) \\ &\quad + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2. \end{aligned}$$

- Fixed relations after EWSB...

$$m_h^2 = m_Z^2 c_{2\beta}^2$$

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

NOT ALL IS LOST!

stop mixing

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

$$M_S^2 \equiv m_{\tilde{t}_1} m_{\tilde{t}_2}$$

stop masses

NOT ALL IS LOST!

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

$$\delta m_{H_u}^2|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2\right) \log\left(\frac{\Lambda}{\text{TeV}}\right)$$

NOT ALL IS LOST!

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

$$\delta m_{H_u}^2|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2\right) \log\left(\frac{\Lambda}{\text{TeV}}\right)$$

NOT ALL IS LOST!

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

SUSY LITTLE HIERARCHY PROBLEM

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

$$\downarrow$$

$$\delta m_{H_u}^2|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2\right) \log\left(\frac{\Lambda}{\text{TeV}}\right)$$

PHYSICAL STOP MASSES

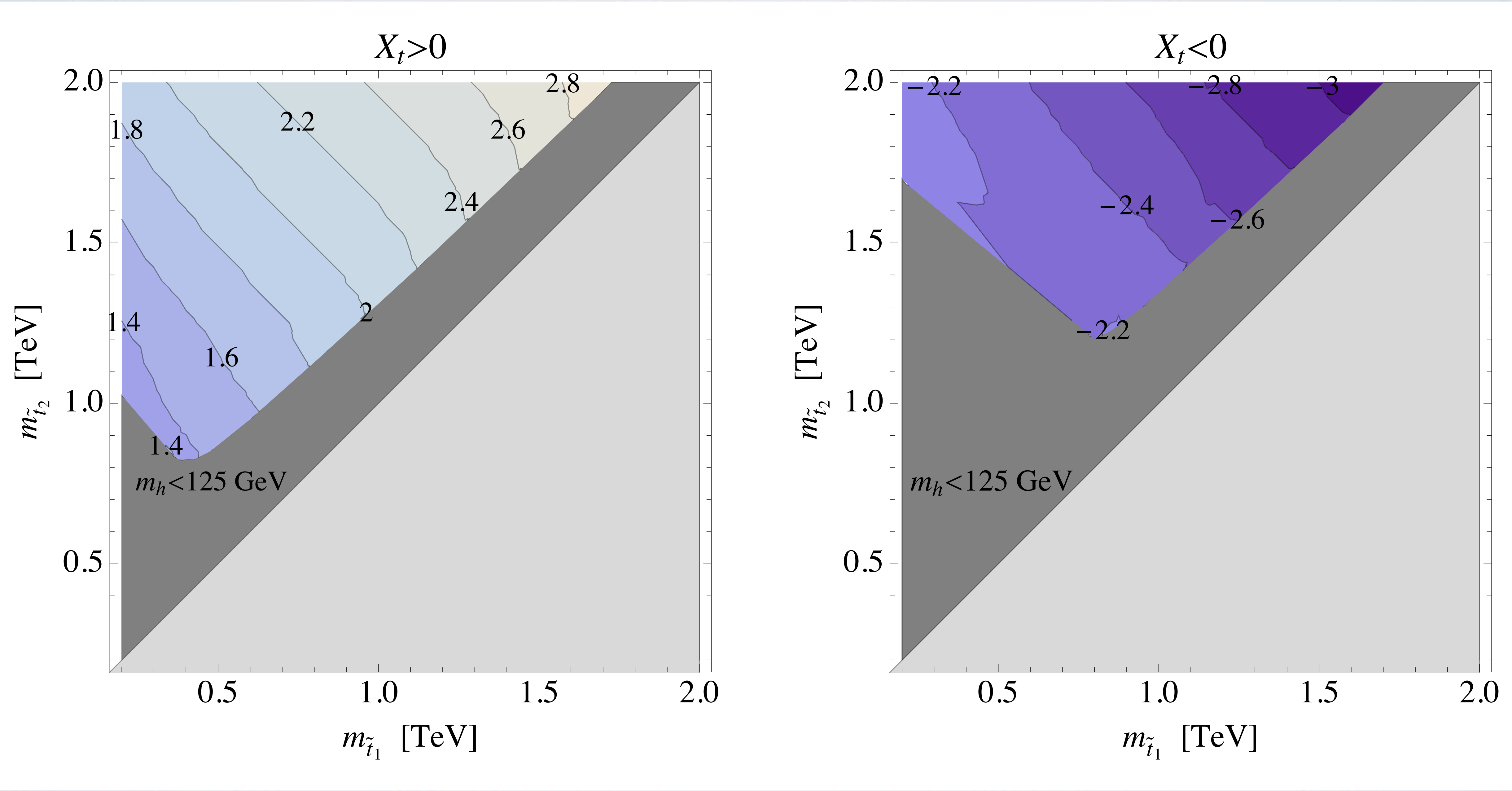


FIG. 3. Contour plot of X_t in the plane of physical stop masses $(m_{\tilde{t}_1}, m_{\tilde{t}_2})$. Here X_t is fixed to be the absolute minimum positive (left) or negative (right) solution to $m_h = 125$ GeV.

TUNING IN MSSM

- ***Independent*** of ***every*** other collider search, just from the Higgs mass the MSSM is tuned at a part in 100-1000

- What now?

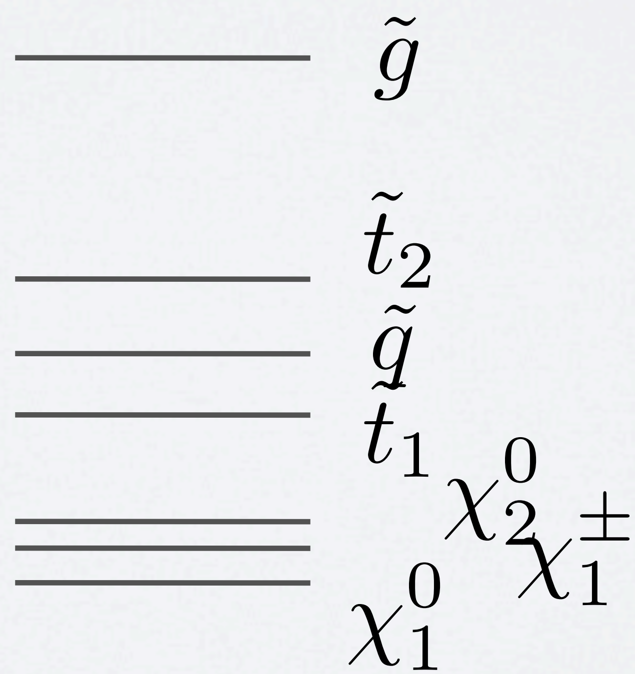
- Could be just a super fine tuned SM... There could be other options...

- Where can ***SUSY*** be with this Higgs mass?

PRE LHC GENERICITY?

$$\begin{aligned}
\mathcal{L}_{\rm soft}^{\rm MSSM} \;=\;& -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right) \\
& -\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right) \\
& -\widetilde{Q}^\dagger\,\mathbf{m_Q^2}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m_L^2}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m_{\overline{u}}^2}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m_{\overline{d}}^2}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m_{\overline{e}}^2}\,\widetilde{\overline{e}}^\dagger \\
& - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_uH_d + \text{c.c.})\,.
\end{aligned}$$

Rich sub-TeV spectrum



CURRENT POSSIBILITIES

MSSM+Higgs sector

"Natural" MSSM

Tuned MSSM

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

$$\delta M_{H_u}^2 \sim M_S^2 \log\frac{\Lambda}{M_S}$$

CURRENT POSSIBILITIES

MSSM+Higgs sector

"Natural" MSSM

Tuned MSSM

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

maximal

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

As small as possible

as small as possible (but big enough for 125 GeV)

$$\delta M_{H_u}^2 \sim M_S^2 \log\frac{\Lambda}{M_S}$$

CURRENT POSSIBILITIES

MSSM+Higgs sector

"Natural" MSSM

Tuned MSSM

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \delta m_h^2$$

$$+\frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

$$\delta M_{H_u}^2 \sim M_S^2 \log\frac{\Lambda}{M_S}$$

As small as possible

CURRENT POSSIBILITIES

MSSM+Higgs sector

"Natural" MSSM

Tuned MSSM

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right)$$

jack it up
no worries...

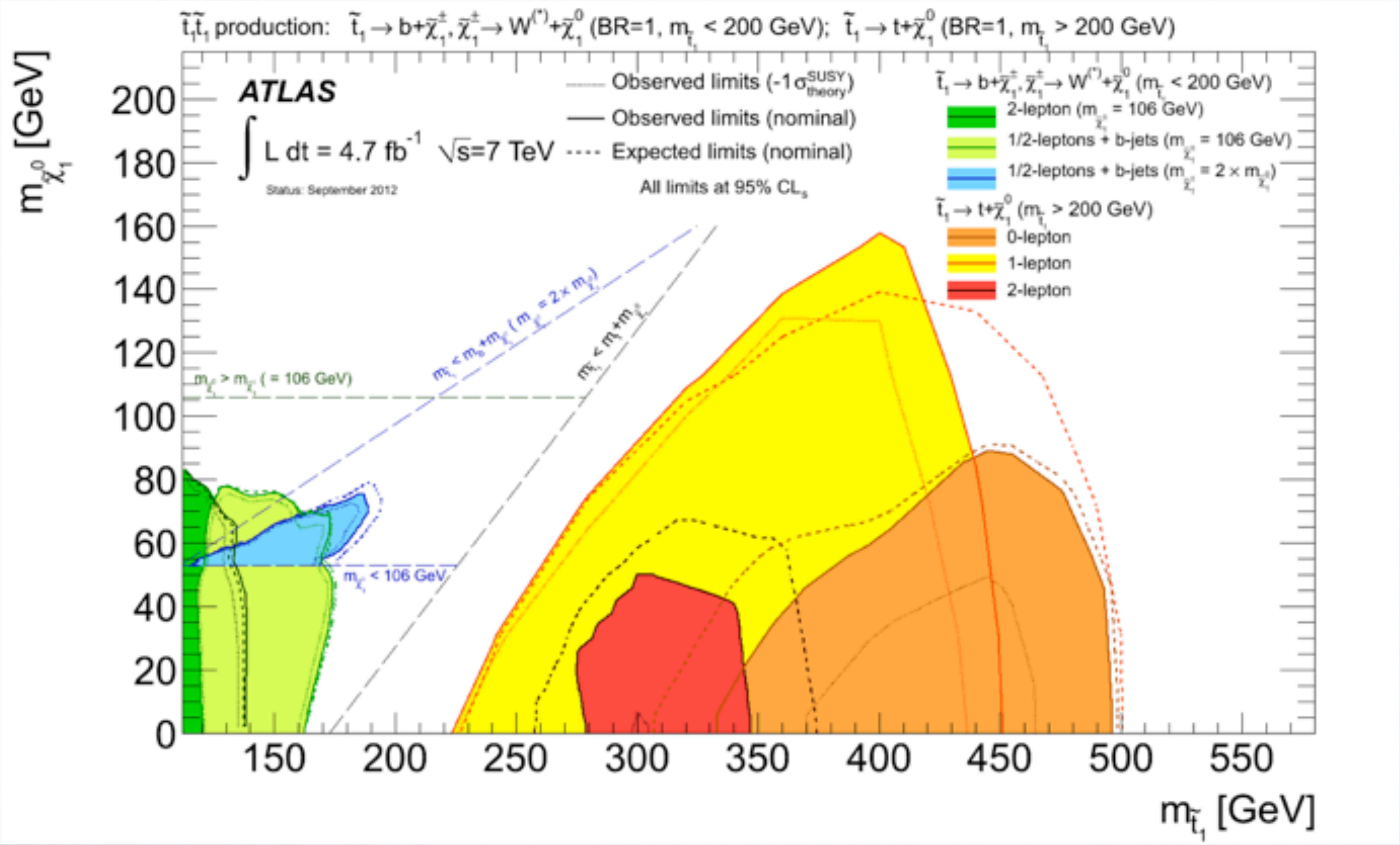
$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

$$\delta M_{H_u}^2 \sim M_S^2 \log\frac{\Lambda}{M_S}$$

NATURAL SUSY SPECTRUM

- One light stop (in MSSM), both if you can fix the Higgs mass
- Light Higgsinos
- Gluinos can't be **TOO** heavy...
- First two generation of squarks? not too worrying...
- Other gauginos as you please...

CONSISTENT MSSM MINIMALLY TUNED



Tied for 2nd most interesting 2012 result

$\tilde{q}, \tilde{g}$ $\tilde{t}_2$

TeV

few hundred GeV

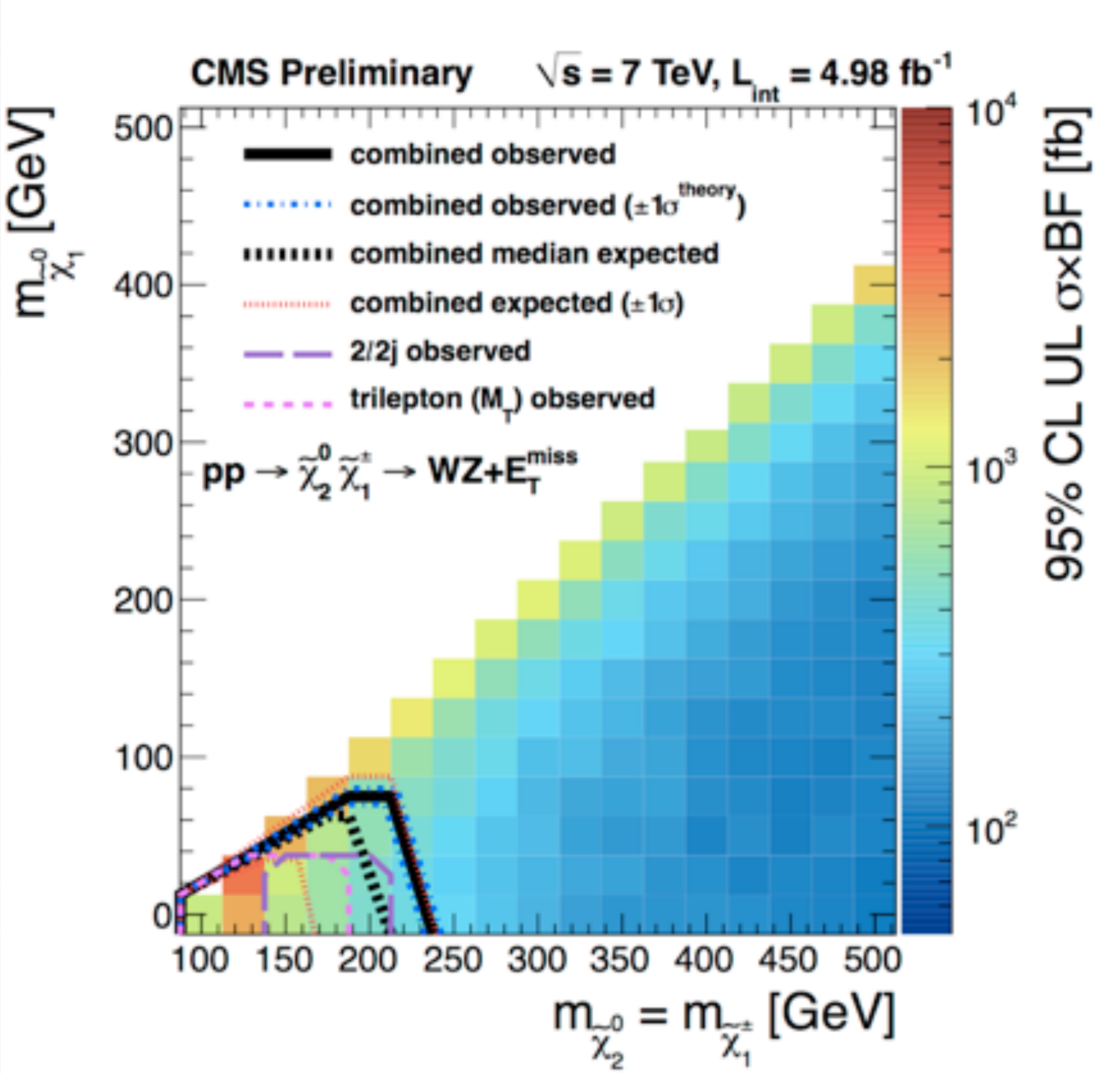
$\tilde{t}_1$

χ_2^0 $\chi_1^\pm$

χ_1^0

EW GAUGINO BOUNDS

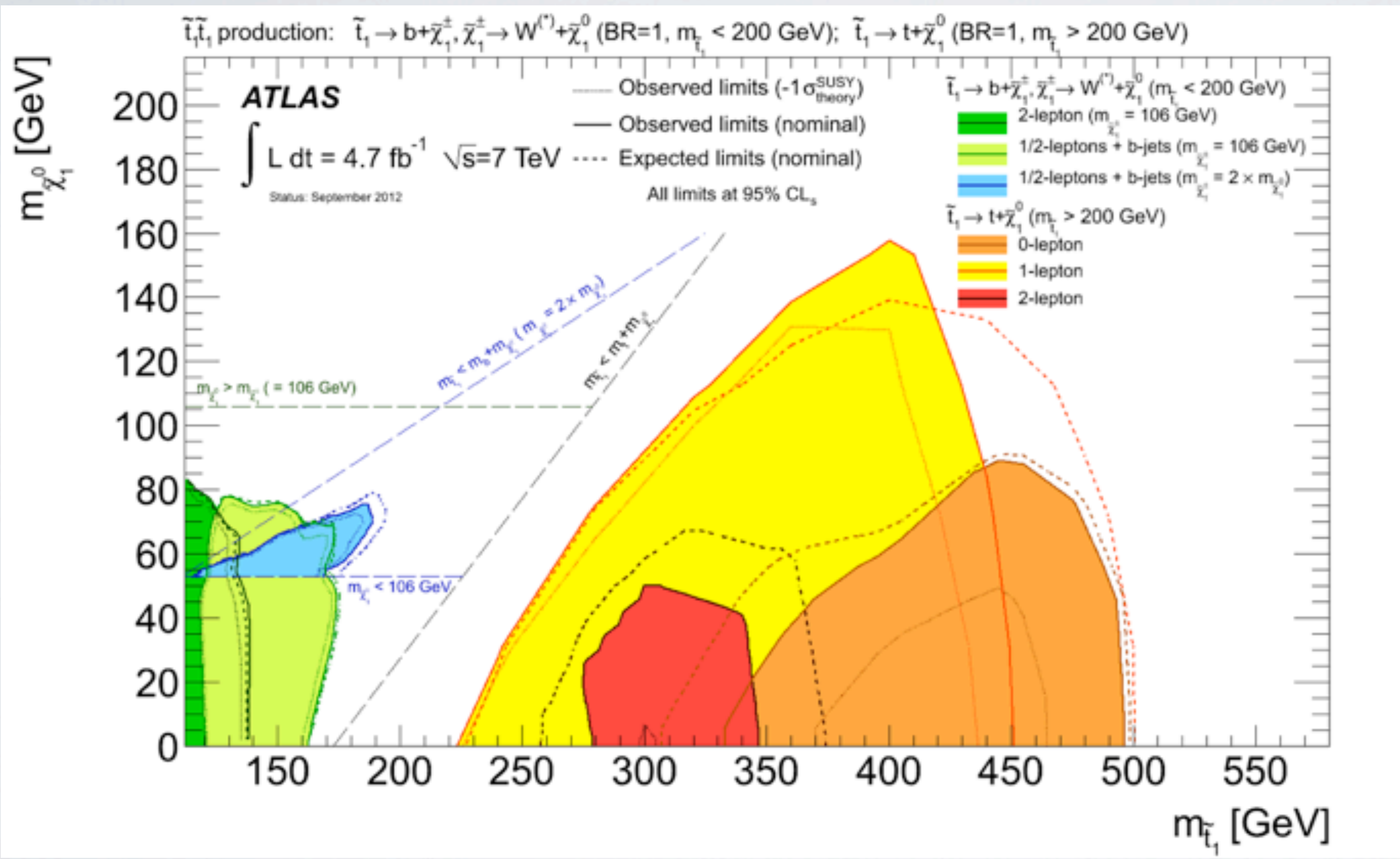
WZ final state ruled out well above LEP



Wh state also ruled out by ATLAS 7 TeV Wh search

~ 160 GeV Higgsinos

MSSM+EXTENDED HIGGS SECTOR



$\tilde{q}, \tilde{g}$

TeV

few hundred GeV

$\tilde{t}_1\ \tilde{t}_2$

EWinos

Possible modified Higgs properties

TUNED MSSM

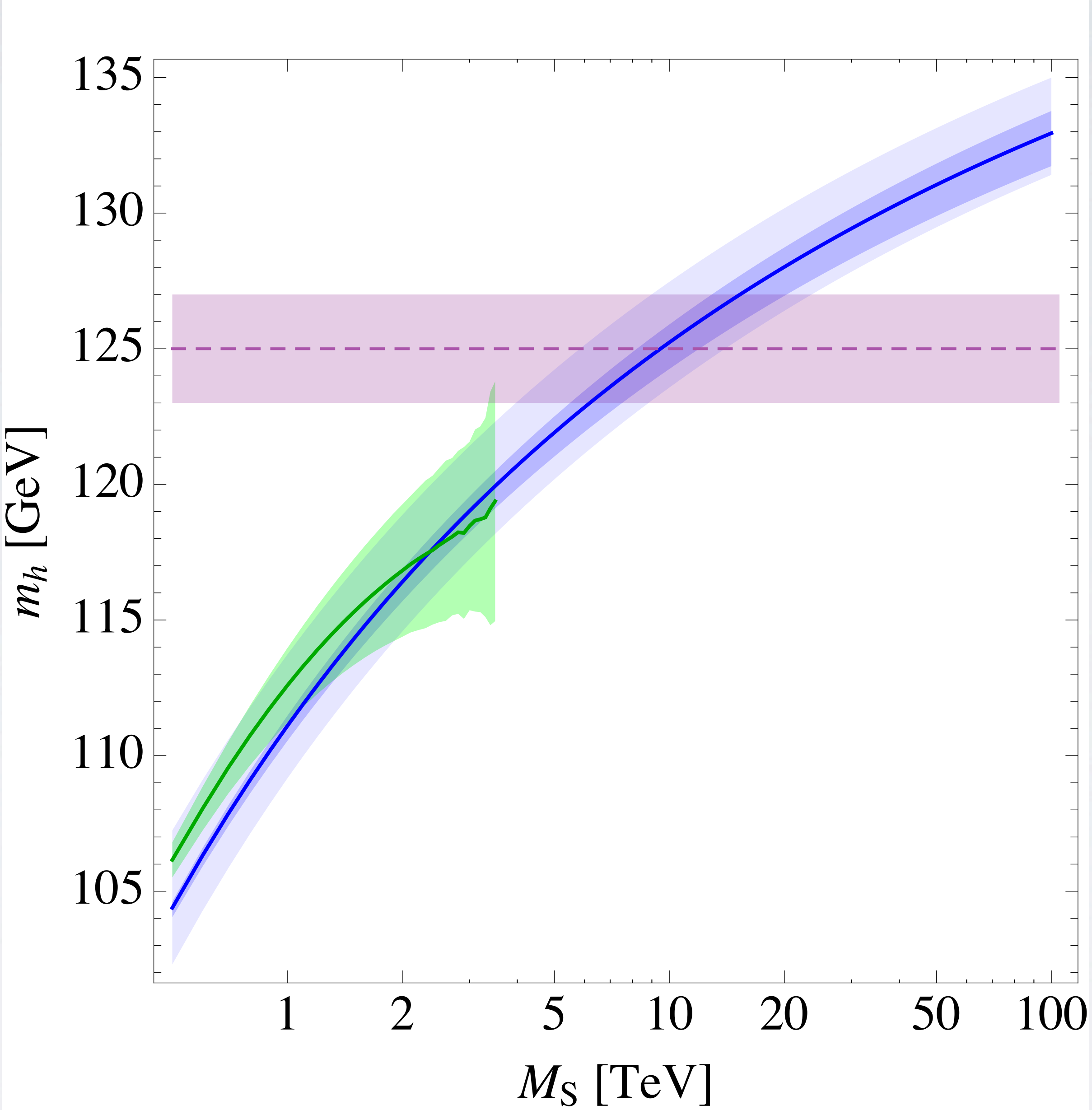


FIG. 6. Higgs mass as a function of M_S, with $X_t = 0$. The green band is the output of FeynHiggs together with its associated uncertainty. The blue line represents 1-loop renormalization group evolution in the Standard Model matched to the MSSM at M_S. The blue bands give estimates of errors from varying the top mass between 172 and 174 GeV (darker band) and the renormalization scale between $m_t/2$ and $2m_t$ (lighter band).

“MINI”-SPLIT SUSY

——— 100 TeV scalars

——— Sub-TeV gauginos

Higgs HAS to look SM
like or this is dead

Is a part in 10^6 better than a part in 10^32?

"MINI"-SPLIT SUSY

100 TeV scalars

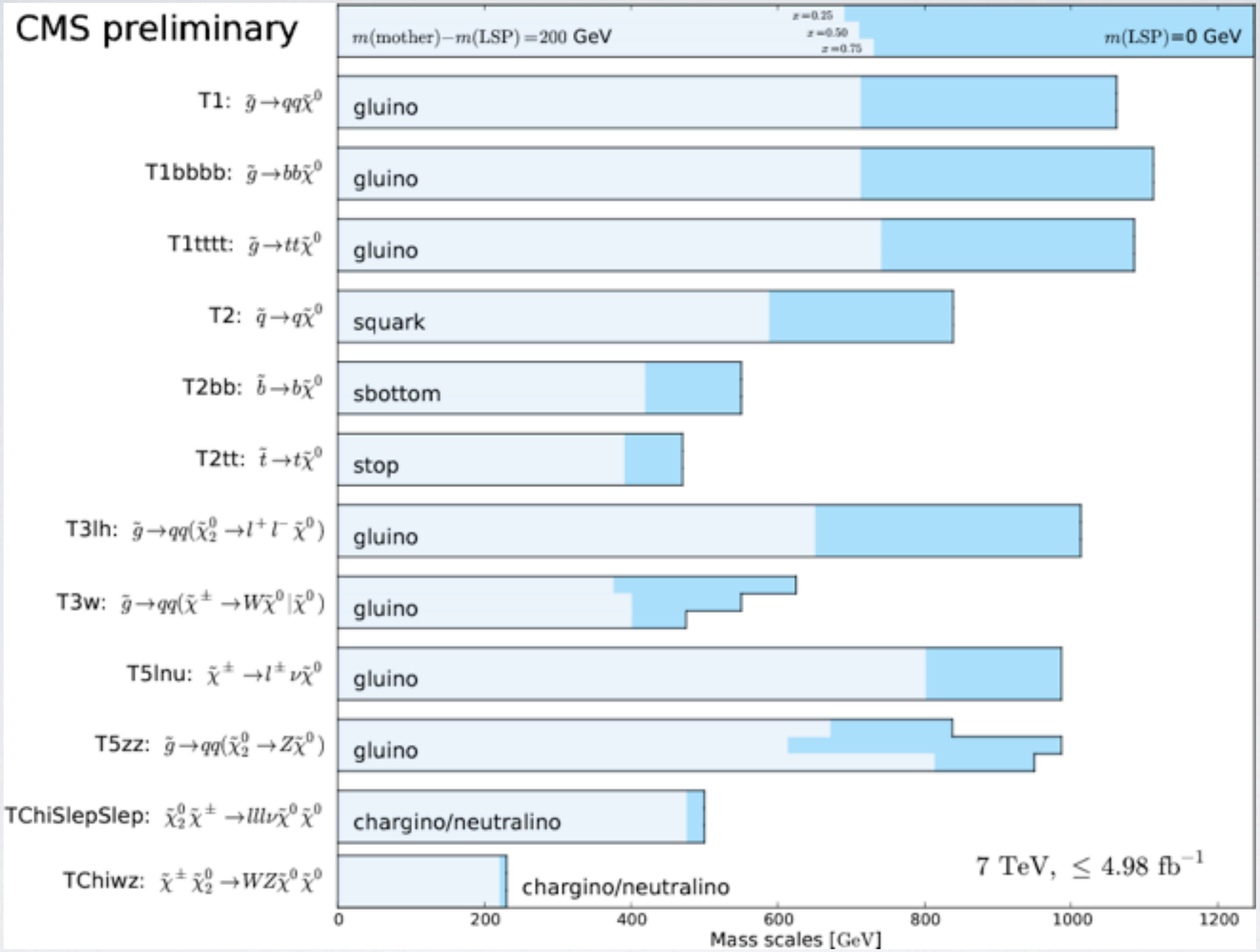
Sub-TeV gauginos?

Higgs HAS to look SM
like or this is dead

Is a part in 10^6 better than a part in 10^32?

FOX NEWS.com We Report. You Decide.

ANY OTHER WAYS OUT?



- RPV/no MET you can certainly make everything lighter
- Still have to accommodate 125 GeV Higgs!

NATURAL SUSY STATUS

- Is it **ALIVE?** Yes, but starting to get tuned... will it get more tuned than now? probably not for a long time...
- It can still be very light, and it can still improve the SM fits to data (see light charginos ;-))
- SUSY is the least tuned of new physics scenarios that explain hierarchy problem and the most robust
- Maybe new physics isn't related to the hierarchy problem, or nature is "unnatural"

CONCLUSIONS

- LHC is testing naturalness in EWSB

- Depending on the answer to the question: does nature care about naturalness? A lepton collider ***could*** be in a perfect position...

Natural

Unnatural

CONCLUSIONS

- LHC is testing naturalness in EWSB

- Depending on the answer to the question: does nature care about naturalness? A lepton collider ***could*** be in a perfect position...

Natural **Unnatural**

Maybe they are both just as good!

THE END

BACKUP SLIDES

PARAMETER DEPENDENCE

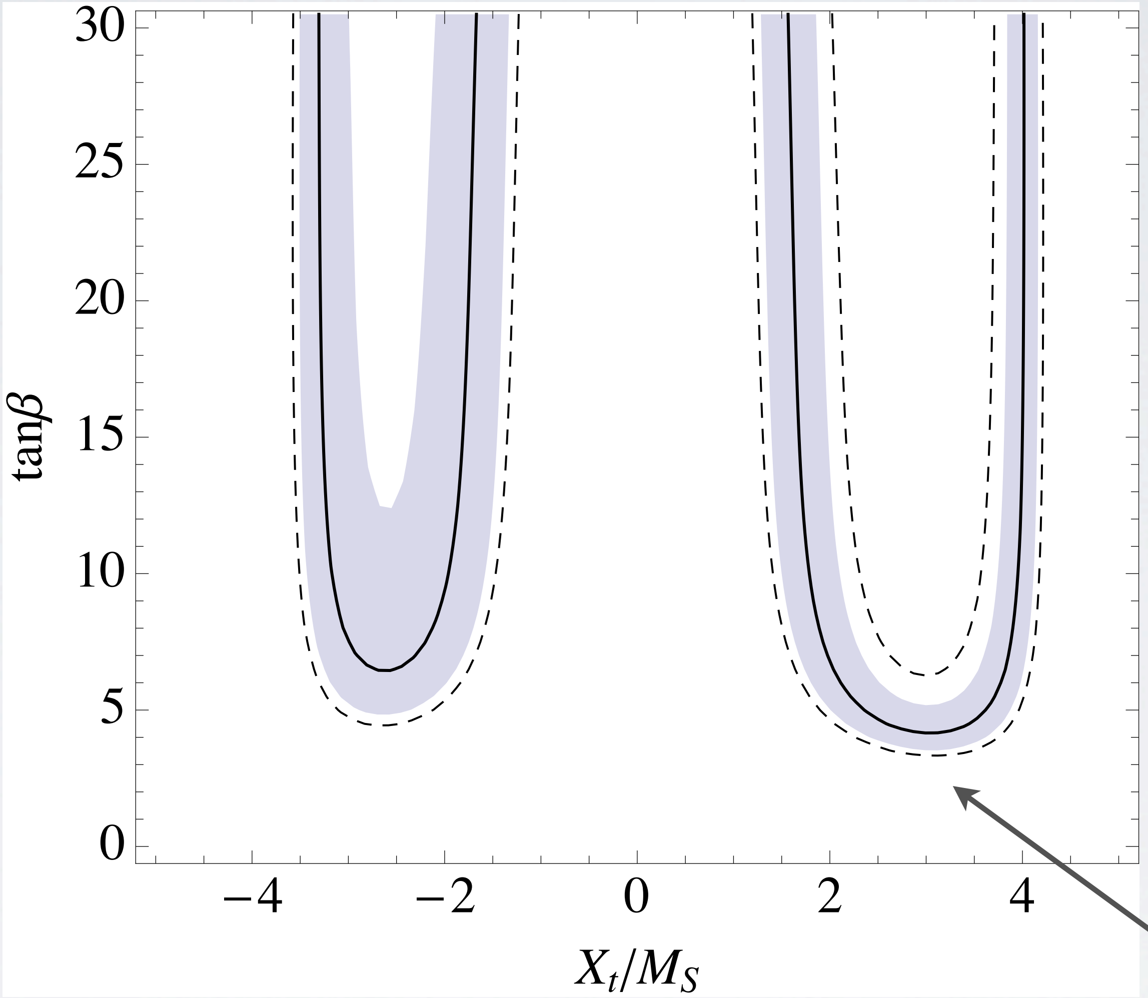


FIG. 1. Contour plot of m_h in the $\tan\beta$ vs. X_t/M_S plane. The stops were set at $m_Q = m_U = 2$ TeV, and the result is only weakly dependent on the stop mass up to ~ 5 TeV. The solid curve is $m_h = 125$ GeV with $m_t = 173.2$ GeV. The band around the curve corresponds to m_h =123-127 GeV. Finally, the dashed lines correspond to varying m_t from 172-174.

Maximal
Mixing

PARAMETER DEPENDENCE

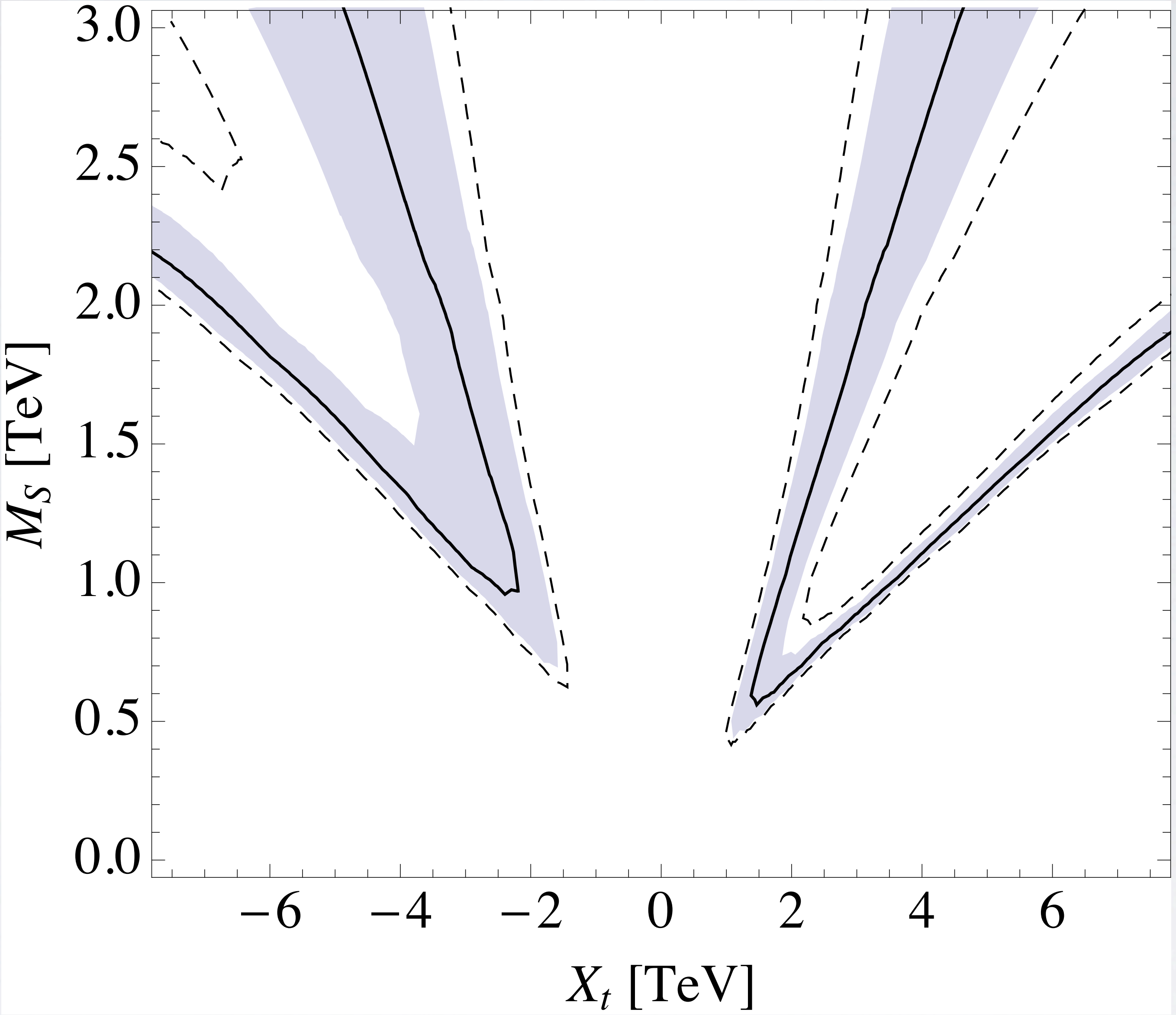


FIG. 2. Contours of constant m_h in the M_S vs. X_t plane, with $\tan\beta = 30$ and $m_Q = m_U$. The solid/dashed lines and gray bands are as in fig. 1.

A TERMS AND LOW SCALE SUSY

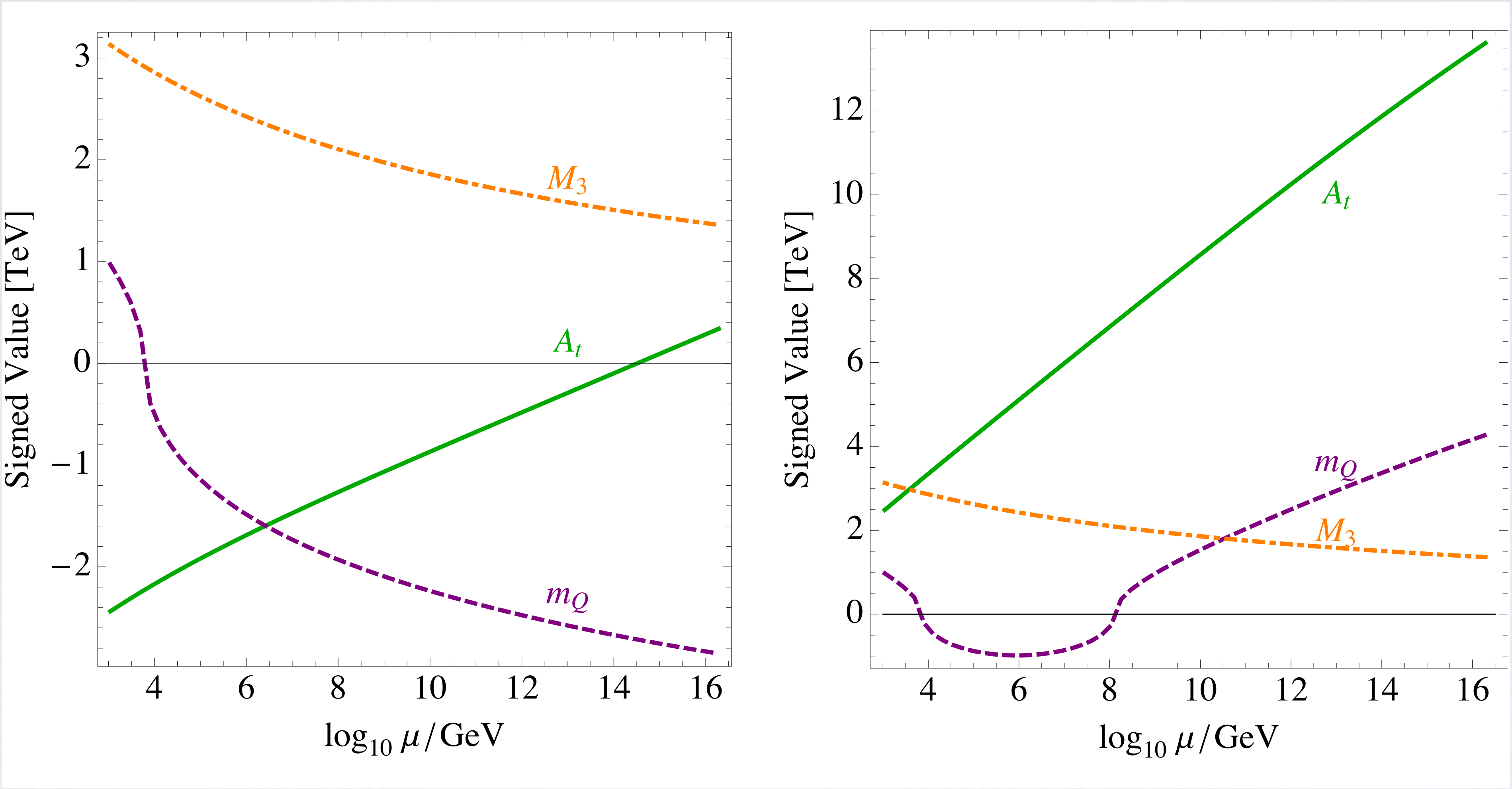


FIG. 4. Values of running parameters: at left, in a case where A_t is large and negative at low scales; at right, in a case where it is large and positive. The case $A_t < 0$ at low scales can be compatible with $A_t = 0$ from a high-scale mediation scheme, and in this case we expect that it is generally associated with tachyonic squarks at a high scale. Scalar masses are plotted as signed parameters, e.g. $m_Q^{(plotted)} \equiv m_Q^2/|m_Q|$.

GAUGE MEDIATION

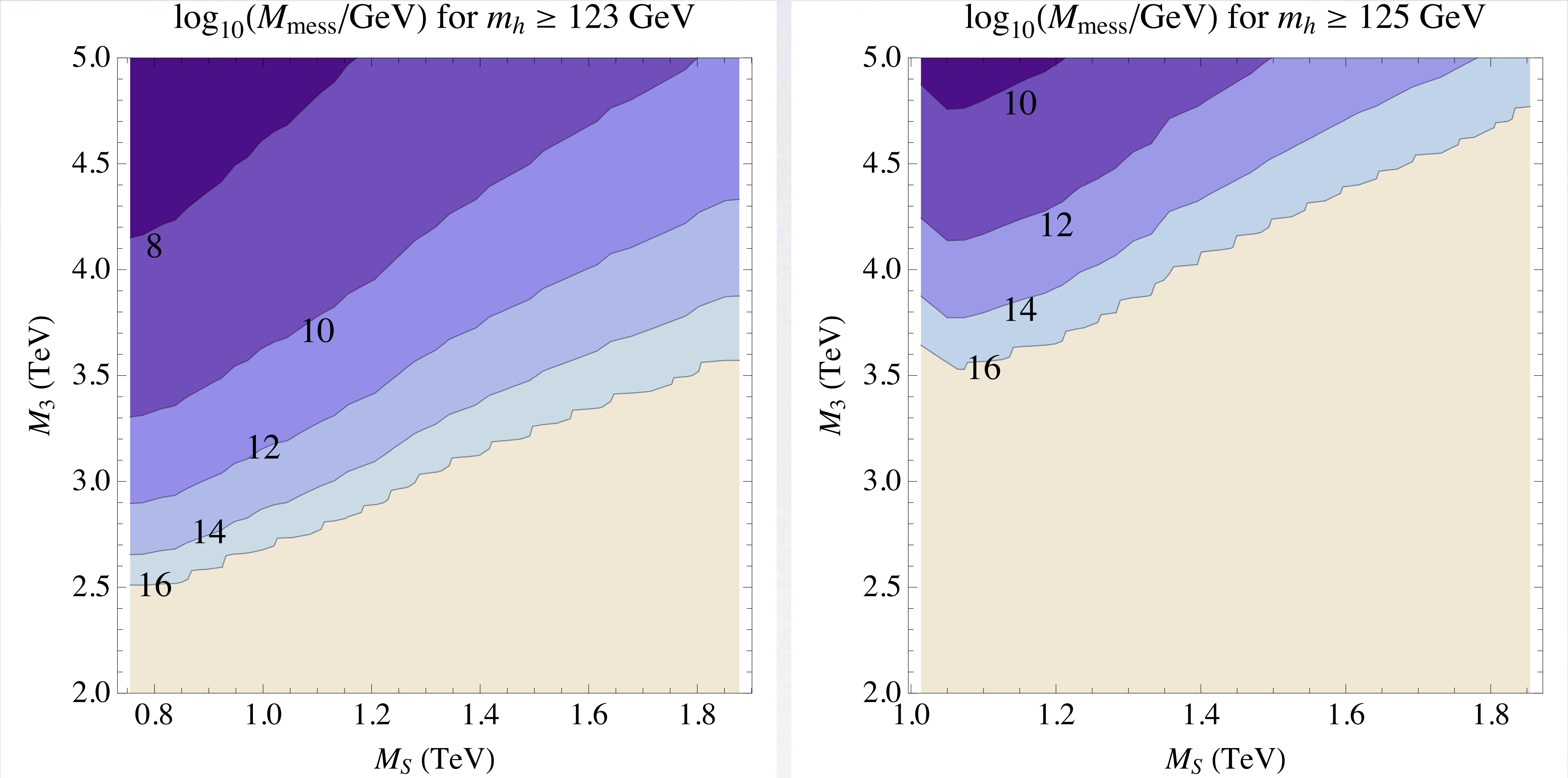
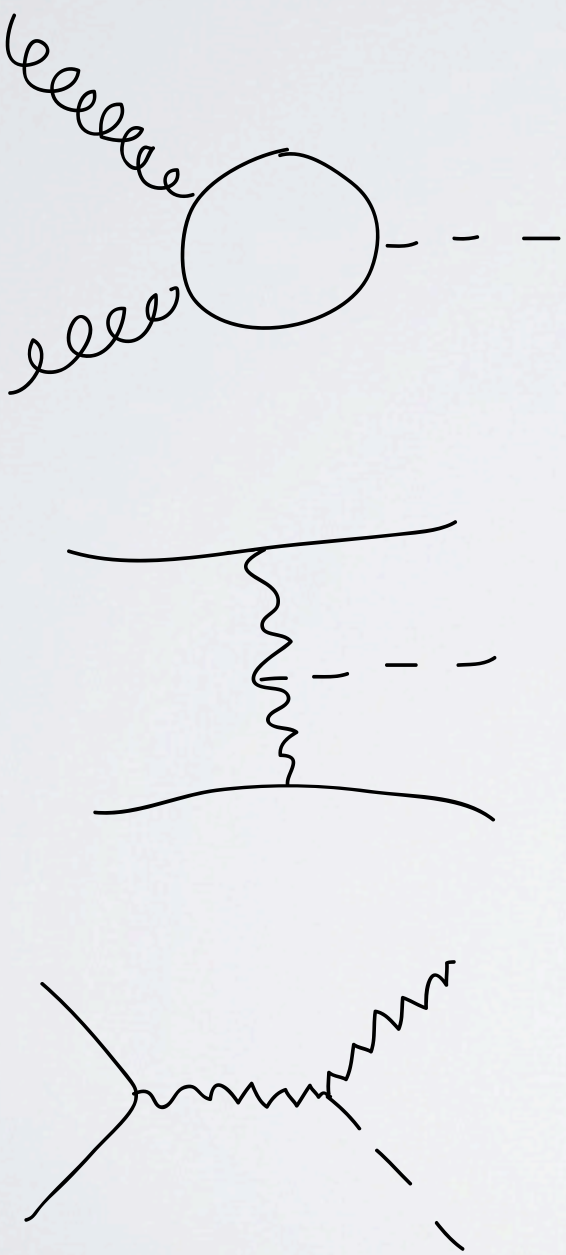


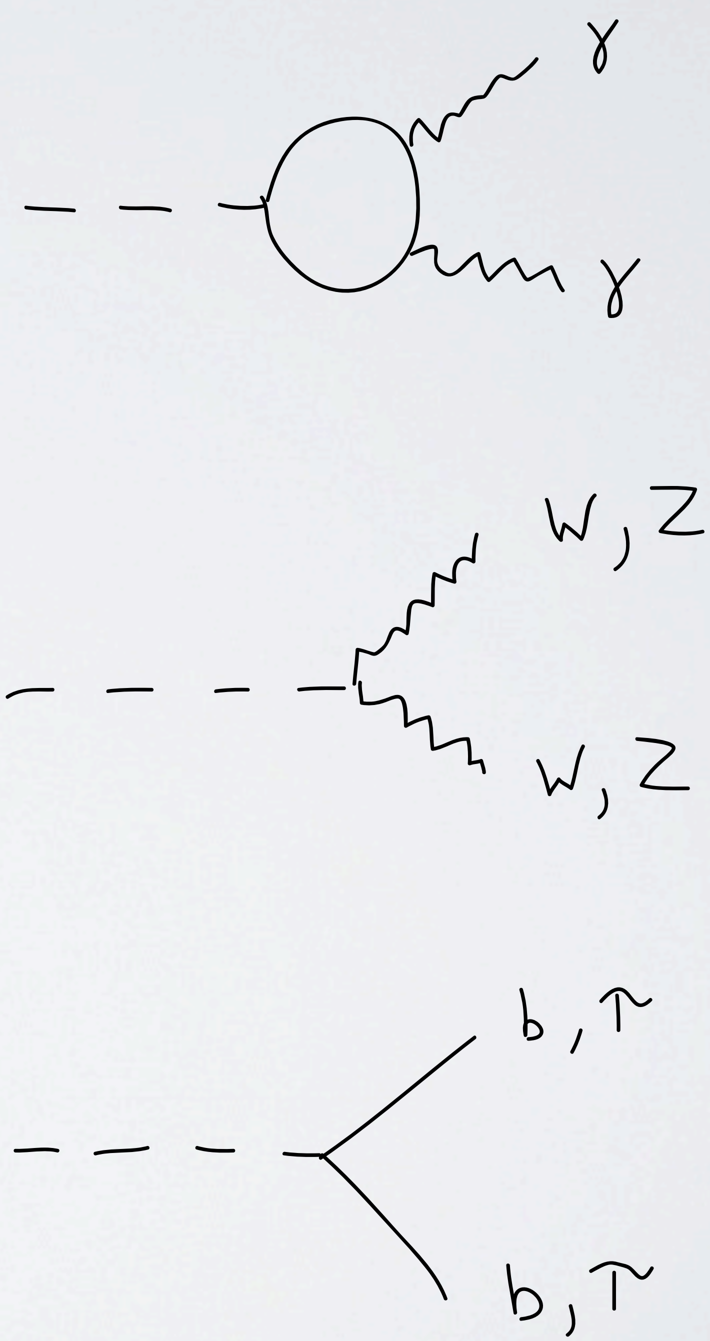
FIG. 5. Messenger scale required to produce sufficiently large $|A_t|$ for $m_h = 123$ GeV (left) and $m_h = 125$ GeV (right) through renormalization group evolution.

MSSM ALSO CHANGES HIGGS PHENOMENOLOGY

Production



Decay

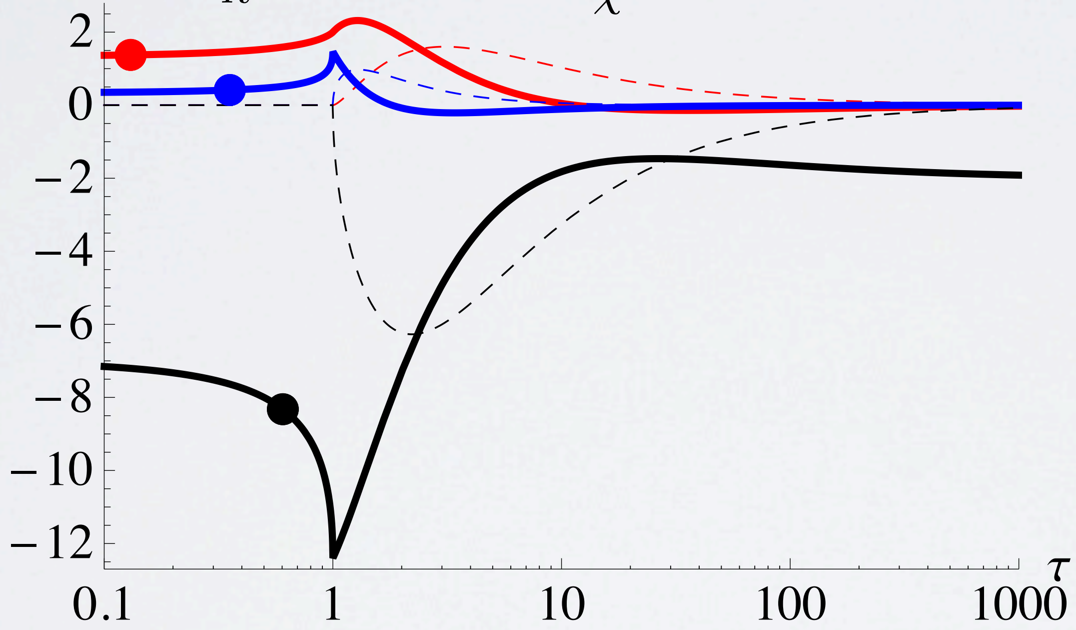


MSSM HIGGS PHENO

$$\Gamma(h \to gg) = \frac{G_\mu \alpha_s^2 m_h^3}{36\sqrt{2}\pi^3} \left| \frac{3}{4} \sum_f A_{1/2}(\tau_f) + \frac{3}{4} \frac{g_{h\tilde{t}_R\tilde{t}_R}}{m_{\tilde{t}_R}^2} A_0(\tau_{\tilde{t}_R}) \right|^2$$

$$\Gamma(\hat{h} \to \gamma\gamma) = \frac{G_\mu \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 A_{1/2}(\tau_f) + A_1(\tau_W) \right.$$

$$\left. + \frac{4}{3} \frac{g_{h\tilde{t}_R\tilde{t}_R}}{m_{\tilde{t}_R}^2} A_0(\tau_{\tilde{t}_R}) + \sum_{\chi^+} \frac{2m_W}{m_{\chi^+}} g_{h\chi^+\chi^-} A_{1/2}(\tau_{\chi^+}) \right|^2$$



$$\tau_i = m_h^2/4m_i^2$$

Figure 3: The solid (dashed) curves represent the real (imaginary) part of the functions $A_0(\tau)$ (blue), $A_{1/2}(\tau)$ (red) and $A_1(\tau)$ (black). The blue, red and the black points correspond to a 105 GeV stop, top quark and W boson respectively assuming a Higgs boson of mass 125 GeV.

MSSM ALSO CHANGES HIGGS PHENOMENOLOGY

Production

Decay