

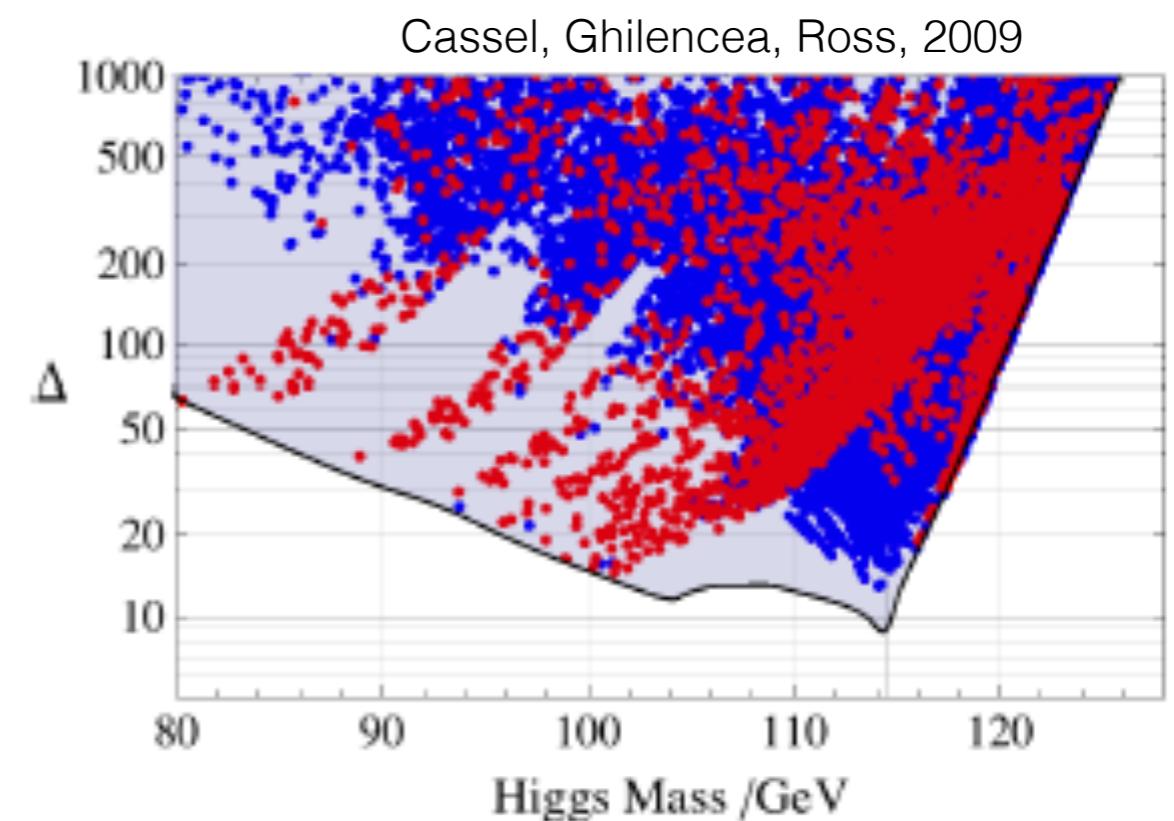
SUSY: crisis, or no crisis? radiatively -driven naturalness: implications for LHC, ILC, WIMP and axion searches

Howard Baer
University of Oklahoma



SUSY partners sighted in AU?

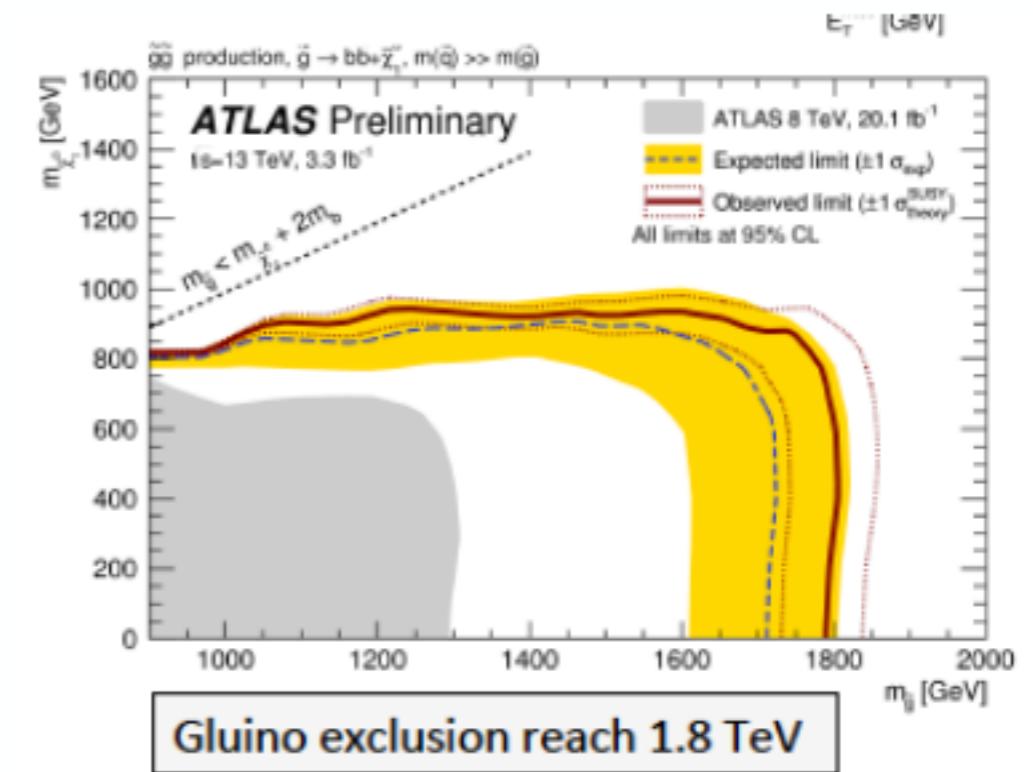
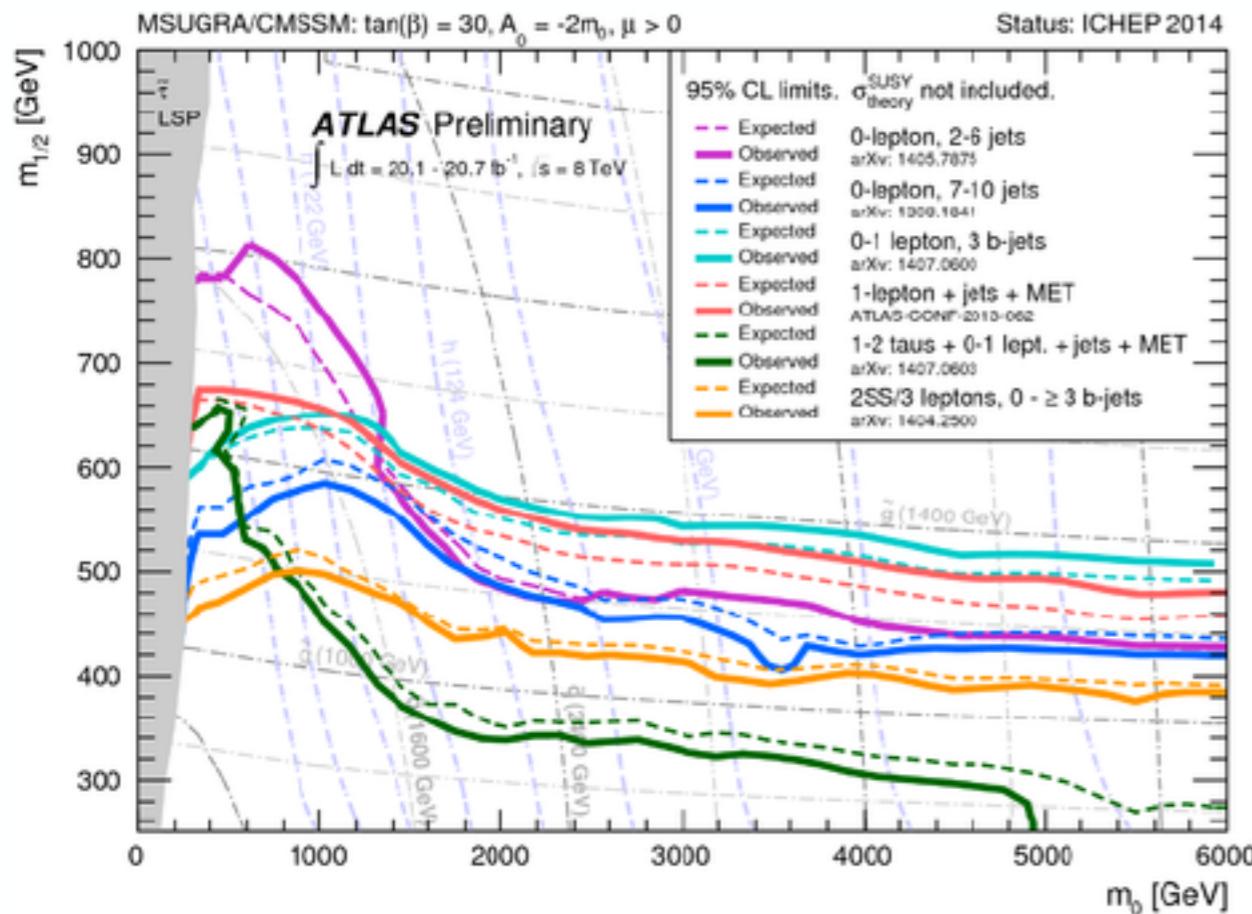
A naturalness crisis has been brewing in our field!



$m_h \simeq 125 \text{ GeV} \Rightarrow \Delta_{BG} \sim 1000$
 $\Rightarrow 0.1\% \text{ fine-tuning?}$

$$\Delta_{BG} = 10 \Rightarrow \Delta_{BG}^{-1} = 0.1 \equiv 10\%$$

But where are the sparticles?



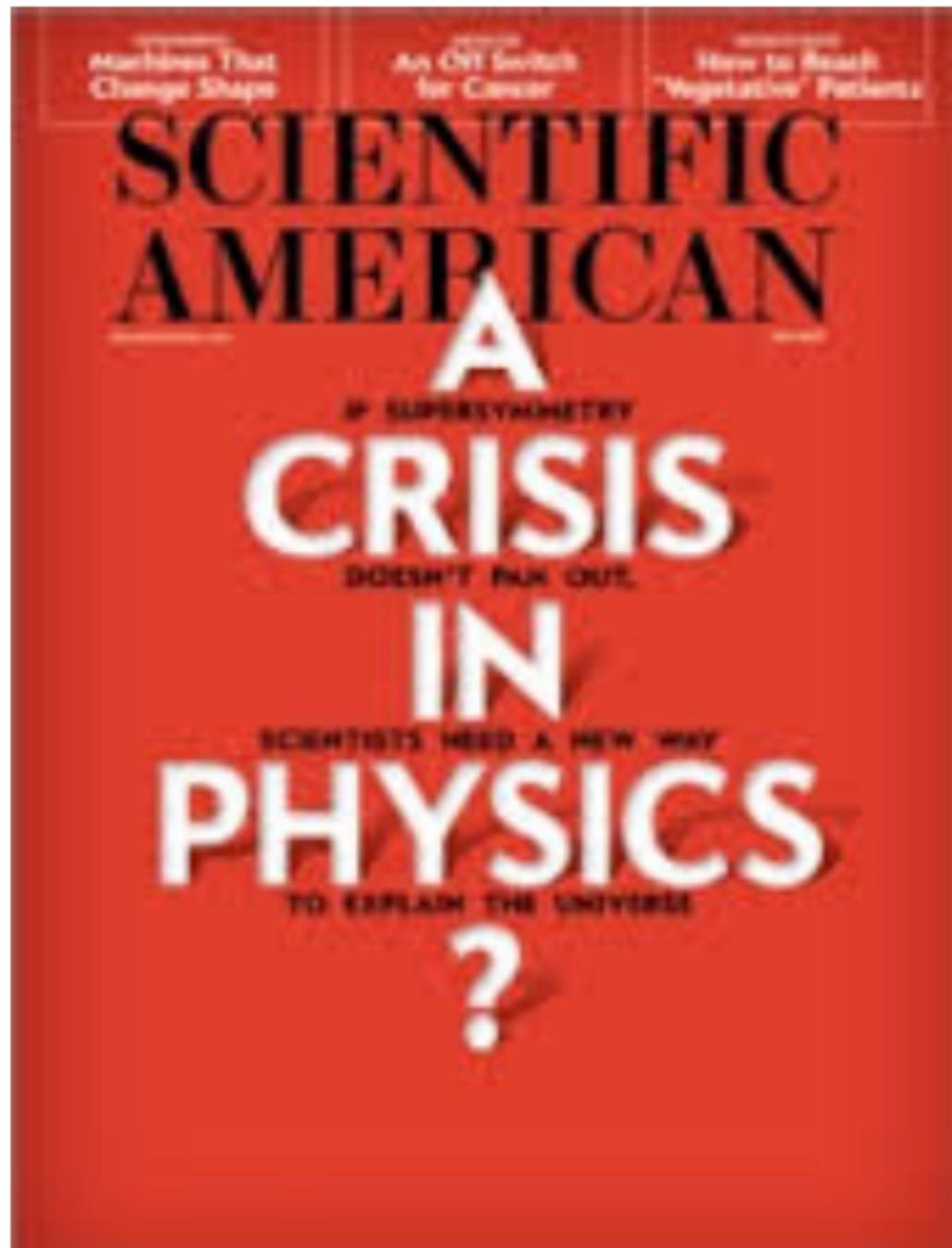
$m_{\tilde{g}} > 1.3 \text{ TeV}$ for $m_{\tilde{q}} \gg m_{\tilde{g}}$

$m_{\tilde{g}} > 1.8 \text{ TeV}$

$m_{\tilde{g}} > 1.8 \text{ TeV}$ for $m_{\tilde{q}} \sim m_{\tilde{g}}$

$m_{\tilde{t}_1} \sim \text{multi - TeV}$ for $m_h \simeq 125 \text{ GeV}$

Is there a crisis in physics?

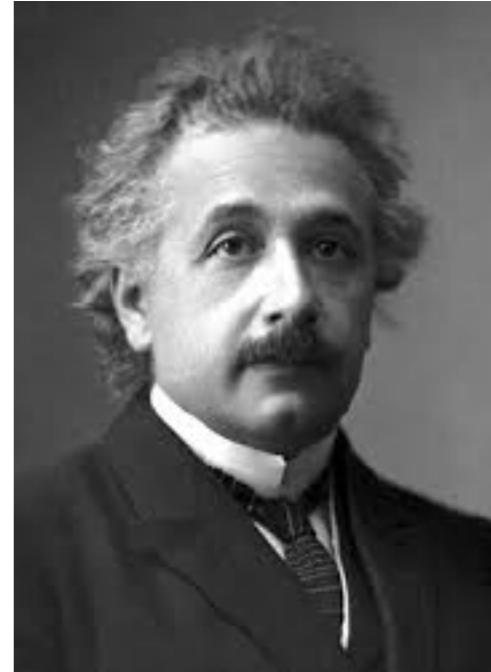


short answer:
No! but there may be a crisis
in how theorists
calculate naturalness

This unshakable fidelity to supersymmetry is widely shared. Particle theorists do admit, however, that the idea of natural supersymmetry is already in trouble and is headed for the dustbin of history unless superpartners are discovered soon...



twin pillars of guidance:
naturalness & simplicity



“The appearance of fine-tuning
in a scientific theory is like a
cry of distress from nature,
complaining that something
needs to be better explained”

S. Weinberg

“Everything should be
made as simple as
possible, but not
simpler”

A. Einstein

unnatural theory is
likely wrong theory

the further one strays from the
SM (without good reason),
the more likely one is to be wrong

``...settling the ultimate fate of naturalness is perhaps the most profound theoretical question of our time”



Arkani-Hamed et al.,
arXiv:1511.06495

“Given the magnitude of the stakes involved,
it is vital to get a clear verdict on naturalness from experiment”

This should be matched by theoretical scrutiny of what we mean by naturalness

Most claims against SUSY stem from
overestimates of EW fine-tuning.

These arise from violations of the

Prime directive on fine-tuning:

“Thou shalt not claim fine-tuning of
dependent quantities one against another!”

HB, Barger, Mickelson, Padeffke-Kirkland, arXiv:1404.2277

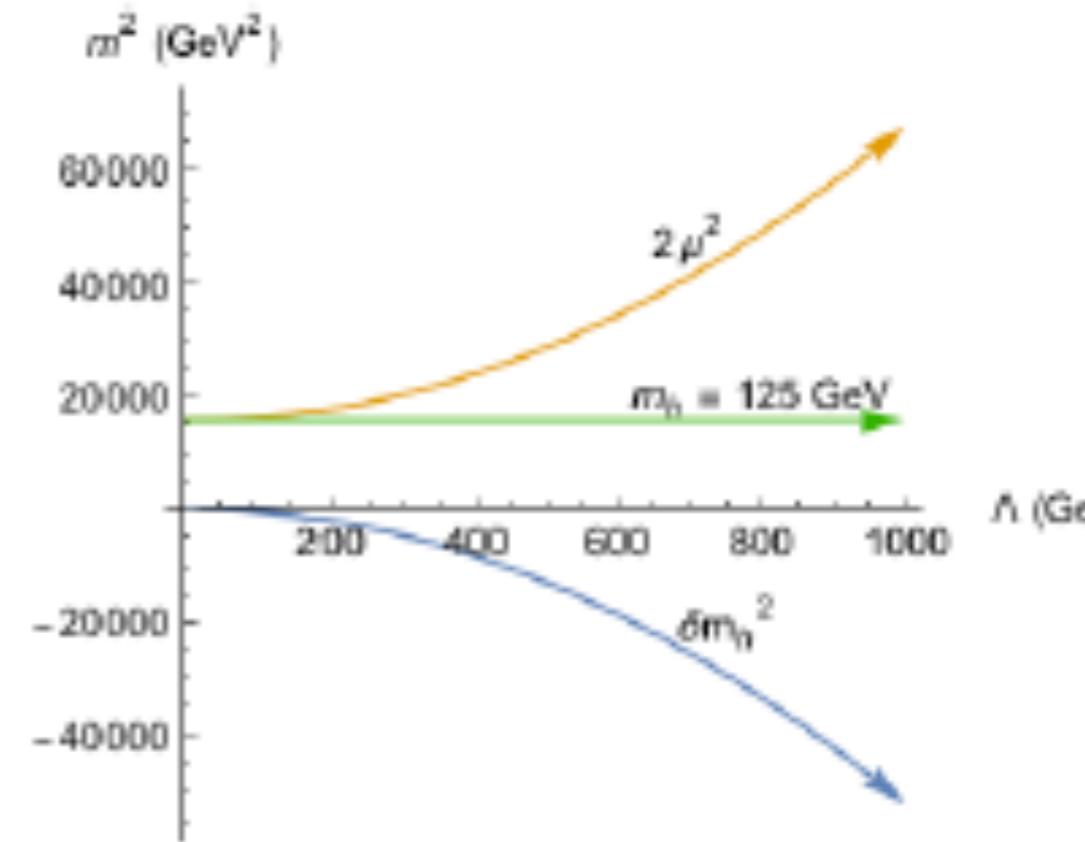


Is $\mathcal{O} = \mathcal{O} + b - b$ fine-tuned for $b > \mathcal{O}$?

Reminder: why we are here

Higgs sector of SM is ``natural'' only up to cutoff

$$\begin{aligned} V &= -\mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2 \\ m_h^2 &\simeq 2\mu^2 + \delta m_h^2 \\ \delta m_h^2 &\simeq \frac{3}{4\pi^2} \left(-\lambda_t^2 + \frac{g^2}{4} + \frac{g^2}{8\cos^2\theta_W} + \lambda \right) \Lambda^2 \end{aligned}$$

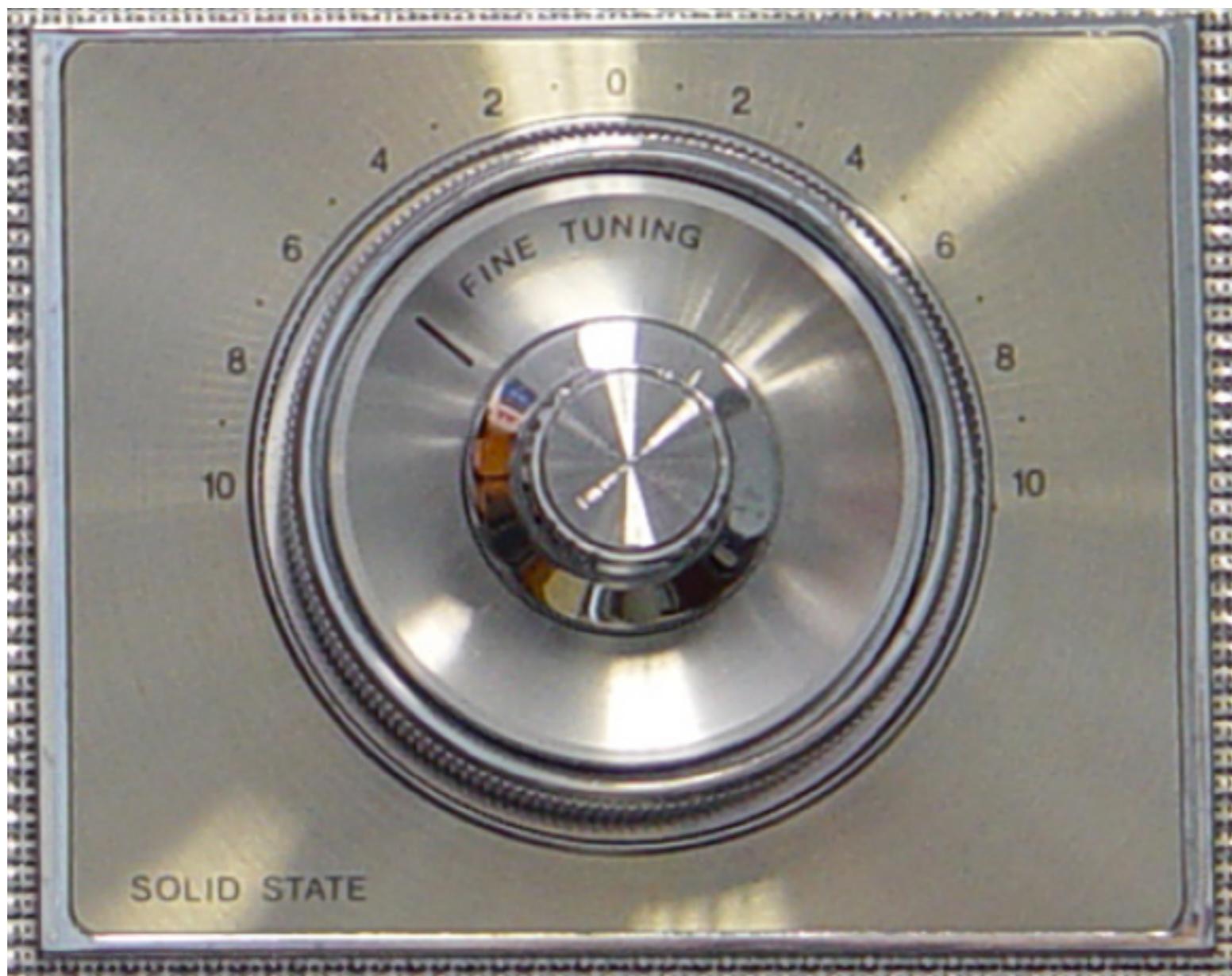


Since δm_h^2 is *independent* of μ^2 ,
can freely dial (fine-tune) μ^2 to maintain $m_h = 125$ GeV

Naturalness: $\delta m_h^2 < m_h^2 \Rightarrow \Lambda < 1$ TeV!

New physics at or around the TeV scale!

Three measures of fine-tuning:



related work:
Kim, Athron, Balazs, Farmer, Hutchison
PRD90 (2014)055008

#1: Simplest SUSY measure: Δ_{EW}

Working only at the weak scale, minimize scalar potential: calculate $m(Z)$ or $m(h)$

No large uncorrelated cancellations in $m(Z)$ or $m(h)$

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u) \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2 \sim -m_{H_u}^2 - \Sigma_u^u - \mu^2$$

$$\Delta_{EW} \equiv \max_i |C_i| / (m_Z^2/2) \quad \text{with} \quad C_{H_u} = -m_{H_u}^2 \tan^2 \beta / (\tan^2 \beta - 1) \quad \text{etc.}$$

simple, direct, unambiguous interpretation:

- $|\mu| \sim m_Z \sim 100 - 200$ GeV
- $m_{H_u}^2$ should be driven to small negative values such that $-m_{H_u}^2 \sim 100 - 200$ GeV at the weak scale and
- that the radiative corrections are not too large: $\Sigma_u^u \lesssim 100 - 200$ GeV

CETUP*-12/002, FTPI-MINN-12/22, UMN-TH-3109/12, UH-511-1195-12

Radiative natural SUSY with a 125 GeV Higgs boson

Howard Baer,¹ Vernon Barger, Peisi Huang,² Azar Mustafayev,³ and Xerxes Tata⁴

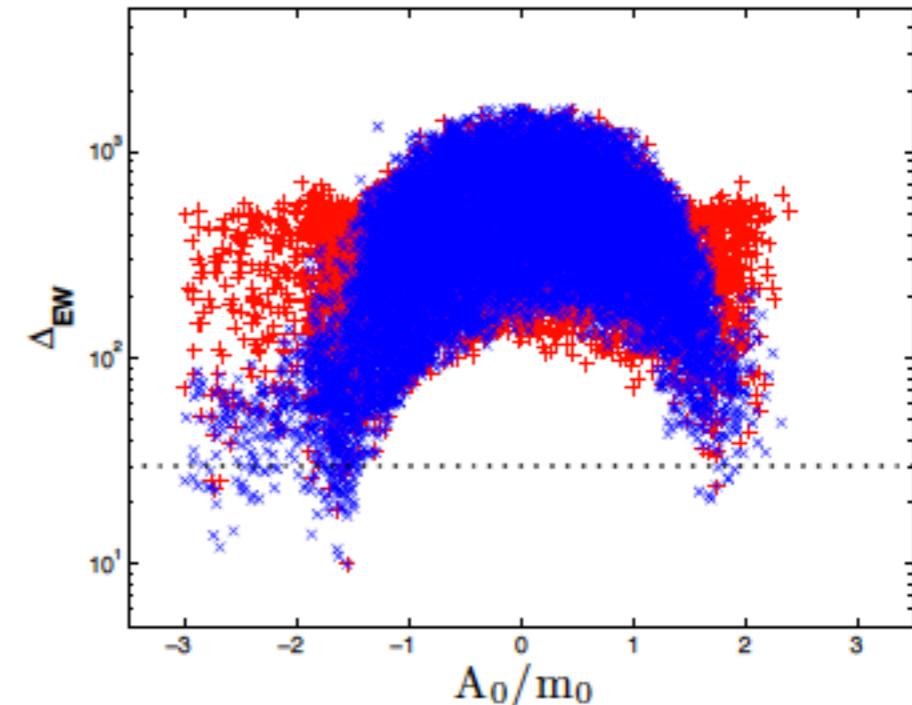
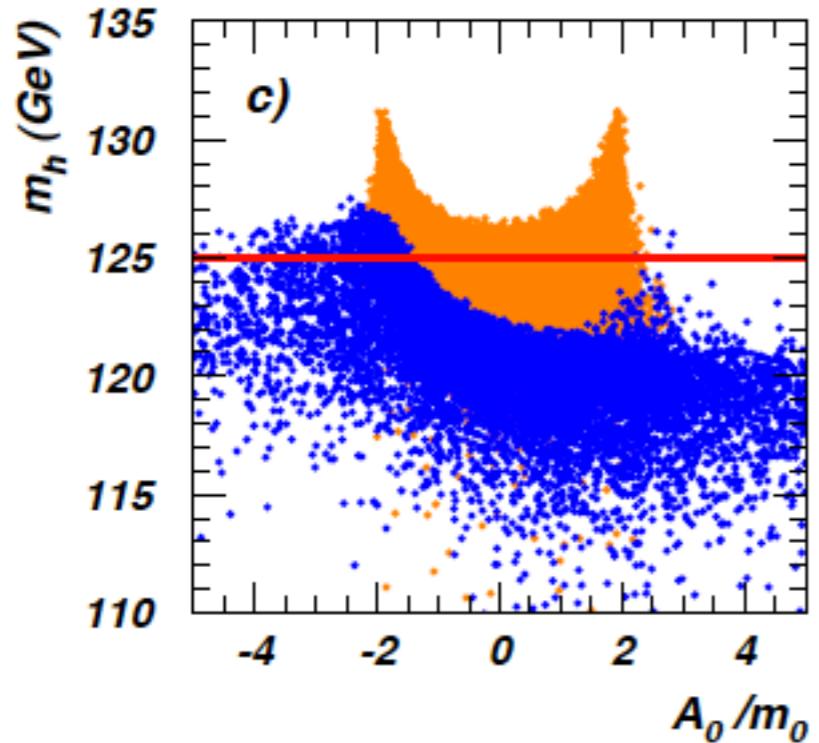
PRL109 (2012) 161802

¹Dept. of Physics and Astronomy, University of Oklahoma, Norman, OK, 73019, USA

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³W. L. Fine Institute for Theoretical Physics, University of Minnesota, Minneapolis, MN 55455, USA

Large value of A_t reduces $\Sigma_u^u(\tilde{t}_{1,2})$ contributions to Δ_{EW} while uplifting m_h to ~ 125 GeV

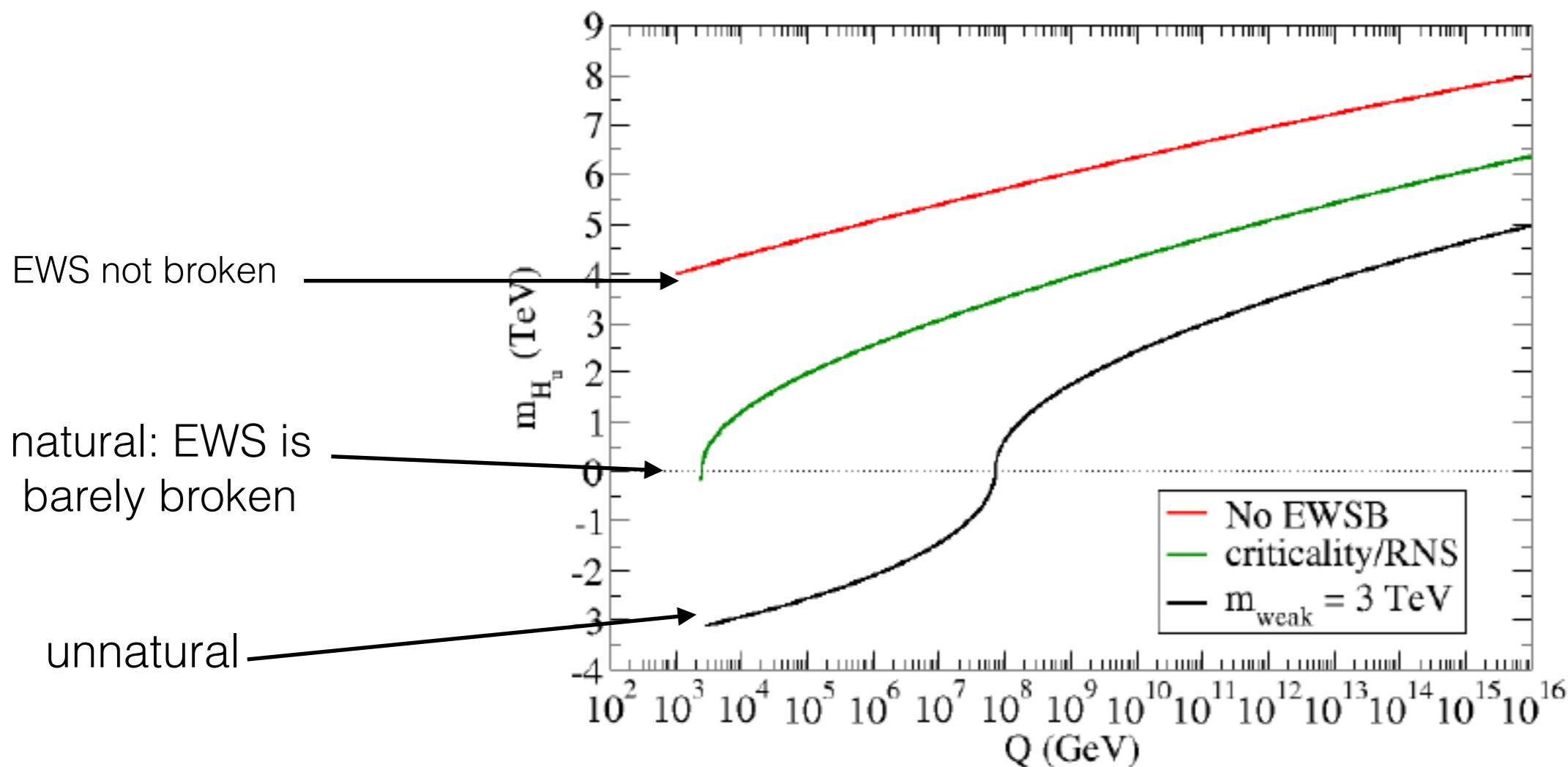


$$\Sigma_u^u(\tilde{t}_{1,2}) = \frac{3}{16\pi^2} F(m_{\tilde{t}_{1,2}}^2) \left[f_t^2 - g_Z^2 \mp \frac{f_t^2 A_t^2 - 8g_Z^2 (\frac{1}{4} - \frac{2}{3}x_W) \Delta_t}{m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2} \right]$$

$$\Delta_t = (m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2)/2 + M_Z^2 \cos 2\beta (\frac{1}{4} - \frac{2}{3}x_W)$$

$$F(m^2) = m^2 \left(\log \frac{m^2}{Q^2} - 1 \right) \quad Q^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}$$

radiative corrections drive $m_{H_u}^2$ from unnatural GUT scale values to naturalness at weak scale:
radiatively-driven naturalness



Evolution of the soft SUSY breaking mass squared term $\text{sign}(m_{H_u}^2)\sqrt{|m_{H_u}^2|}$ vs. Q

#2: Higgs mass or large-log fine-tuning Δ_{HS}

It is tempting to pick out one-by-one quantum fluctuations **but** must combine log divergences before taking any limit

$$m_h^2 \simeq \mu^2 + m_{H_u}^2 + \delta m_{H_u}^2|_{rad}$$

$$\frac{dm_{H_u}^2}{dt} = \frac{1}{8\pi^2} \left(-\frac{3}{5}g_1^2 M_1^2 - 3g_2^2 M_2^2 + \frac{3}{10}g_1^2 S + 3f_t^2 X_t \right) \quad X_t = m_{Q_3}^2 + m_{U_3}^2 + m_{H_u}^2 + A_t^2$$

neglect gauge pieces, S , m_{Hu} and running; then we can integrate from m(SUSY) to Lambda

$$\delta m_{H_u}^2 \sim -\frac{3f_t^2}{8\pi^2} (m_{Q_3}^2 + m_{U_3}^2 + A_t^2) \ln(\Lambda/m_{SUSY})$$

$$\Delta_{HS} \sim \delta m_h^2 / (m_h^2/2) < 10$$

$$m_{\tilde{t}_1, 2, \tilde{b}_1} < 500 \text{ GeV}$$

$$m_{\tilde{g}} < 1.5 \text{ TeV}$$

old natural SUSY

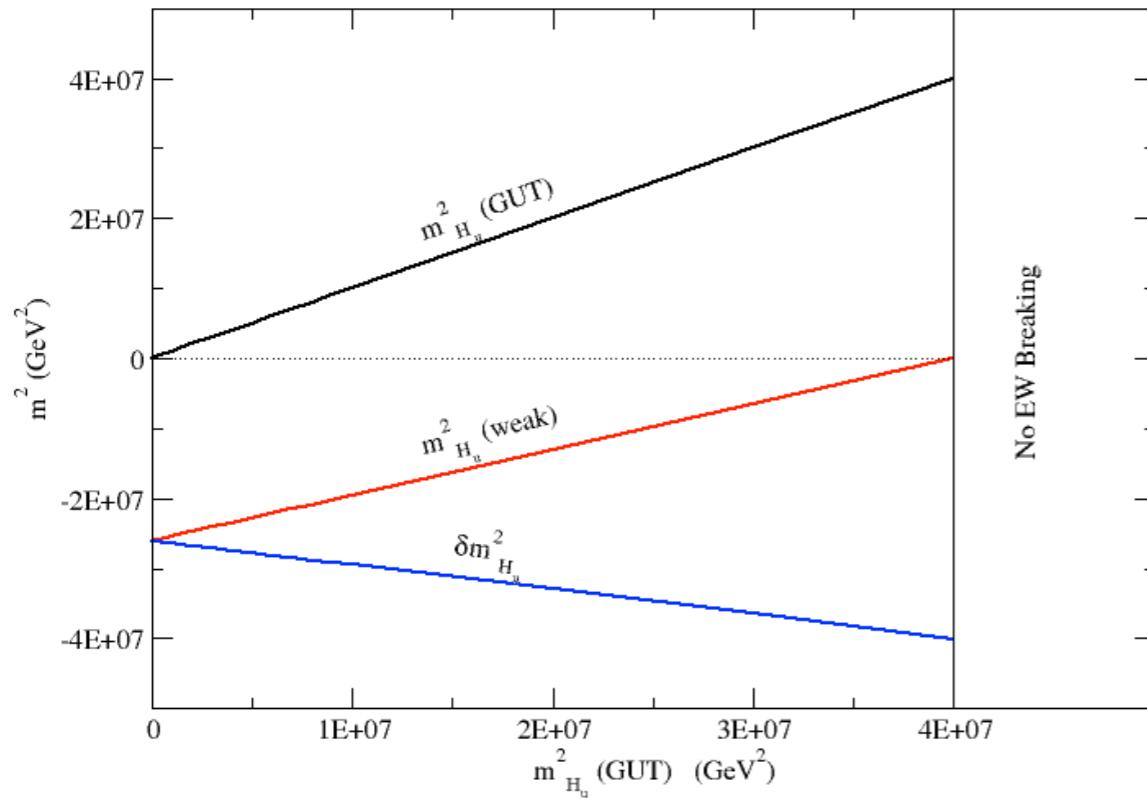
then

A_t can't be too big

What's wrong with this argument?
In zeal for simplicity, have made several
simplifications: most **egregious** is that one
sets $m(H_u)^2=0$ at beginning to simplify

$m_{H_u}^2(\Lambda)$ and $\delta m_{H_u}^2$ are *not* independent!

violates prime directive!



The larger $m_{H_u}^2(\Lambda)$ becomes, then the larger becomes the cancelling correction!

HB, Barger, Savoy

To fix: combine dependent terms:

$m_h^2 \simeq \mu^2 + (m_{H_u}^2(\Lambda) + \delta m_{H_u}^2)$ where now both
 μ^2 and $(m_{H_u}^2(\Lambda) + \delta m_{H_u}^2)$ are $\sim m_Z^2$

After re-grouping: $\Delta_{HS} \simeq \Delta_{EW}$

Instead of: the radiative correction $\delta m_{H_u}^2 \sim m_Z^2$
we now have: the radiatively-corrected $m_{H_u}^2 \sim m_Z^2$

#3. What about EENZ/BG measure?

$$\Delta_{BG} = \max_i \left| \frac{\partial \log m_Z^2}{\partial \log p_i} \right| = \max_i \left| \frac{p_i}{m_Z^2} \frac{\partial m_Z^2}{\partial p_i} \right|$$

applied to pMSSM, then $\Delta_{BG} \simeq \Delta_{EW}$

What if we apply to high (e.g. GUT) scale parameters ?

$$\begin{aligned} m_Z^2 \simeq & -2.18\mu^2 + 3.84M_3^2 + 0.32M_3M_2 + 0.047M_1M_3 - 0.42M_2^2 \\ & + 0.011M_2M_1 - 0.012M_1^2 - 0.65M_3A_t - 0.15M_2A_t \\ & - 0.025M_1A_t + 0.22A_t^2 + 0.004M_3A_b \\ & - 1.27m_{H_u}^2 - 0.053m_{H_d}^2 \\ \hline & + 0.73m_{Q_3}^2 + 0.57m_{U_3}^2 + 0.049m_{D_3}^2 - 0.052m_{L_3}^2 + 0.053m_{E_3}^2 \\ \hline & + 0.051m_{Q_2}^2 - 0.11m_{U_2}^2 + 0.051m_{D_2}^2 - 0.052m_{L_2}^2 + 0.053m_{E_2}^2 \\ & + 0.051m_{Q_1}^2 - 0.11m_{U_1}^2 + 0.051m_{D_1}^2 - 0.052m_{L_1}^2 + 0.053m_{E_1}^2, \end{aligned}$$

For correlated scalar masses $\equiv m_0$,

scalar contribution collapses:

what looks fine-tuned isn't: *focus point SUSY*
multi-TeV scalars are *natural*

Feng, Matchev, Moroi

What about EENZ/BG measure?

$$\Delta_{BG} = \max_i \left| \frac{\partial \log m_Z^2}{\partial \log p_i} \right| = \max_i \left| \frac{p_i}{m_Z^2} \frac{\partial m_Z^2}{\partial p_i} \right|$$

applied to pMSSM, then $\Delta_{BG} \simeq \Delta_{EW}$

apply to high (e.g. GUT) scale parameters

$$\begin{aligned} m_Z^2 \simeq & -2.18\mu^2 + 3.84M_3^2 + 0.32M_3M_2 + 0.047M_1M_3 - 0.42M_2^2 \\ & + 0.011M_2M_1 - 0.012M_1^2 - 0.65M_3A_t - 0.15M_2A_t \\ & - 0.025M_1A_t + 0.22A_t^2 + 0.004M_3A_b \\ & - 1.27m_{H_u}^2 - 0.053m_{H_d}^2 \\ & + 0.73m_{Q_3}^2 + 0.57m_{U_3}^2 + 0.049m_{D_3}^2 - 0.052m_{L_3}^2 + 0.053m_{E_3}^2 \\ & + 0.051m_{Q_2}^2 - 0.11m_{U_2}^2 + 0.051m_{D_2}^2 - 0.052m_{L_2}^2 + 0.053m_{E_2}^2 \\ & + 0.051m_{Q_1}^2 - 0.11m_{U_1}^2 + 0.051m_{D_1}^2 - 0.052m_{L_1}^2 + 0.053m_{E_1}^2, \end{aligned}$$

applied to most parameters,

Δ_{BG} large, looks fine-tuned for *e.g.* $m_{\tilde{g}} \simeq M_3 > 1.8$ TeV

$$\Delta_{BG}(M_3^2) = 3.84 \frac{M_3^2}{m_z^2} \simeq 1500$$

But wait! in more complete models,
soft terms not independent

violates prime directive!

e.g. in SUGRA, for well-specified hidden sector,
each soft term calculated as multiple of $m_{3/2}$;
soft terms must be combined!

e.g. dilaton-dominated SUSY breaking: $m_0^2 = m_{3/2}^2$ with $m_{1/2} = -A_0 = \sqrt{3}m_{3/2}$

$$m_{H_u}^2 = a_{H_u} \cdot m_{3/2}^2,$$

$$m_{Q_3}^2 = a_{Q_3} \cdot m_{3/2}^2,$$

$$A_t = a_{A_t} \cdot m_{3/2},$$

$$M_i = a_i \cdot m_{3/2},$$

...

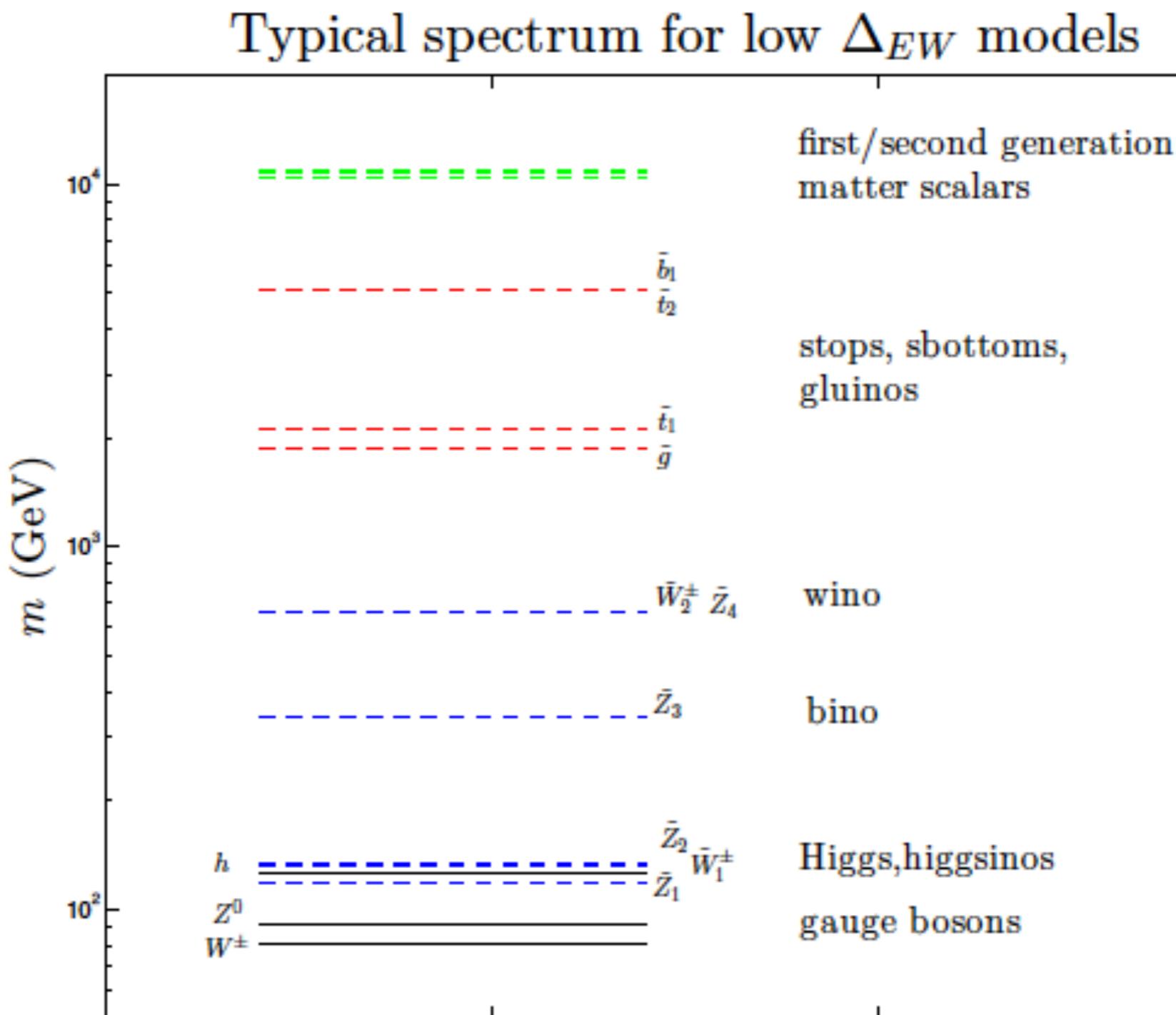
since μ hardly runs, then

$$\begin{aligned} m_Z^2 &\simeq -2\mu^2 + a \cdot m_{3/2}^2 \\ &\simeq -2\mu^2 - 2m_{H_u}^2 \text{ (weak)} \end{aligned}$$

$$m_{H_u}^2 \text{ (weak)} \sim -(100 - 200)^2 \text{ GeV}^2 \sim -a \cdot m_{3/2}^2 / 2$$

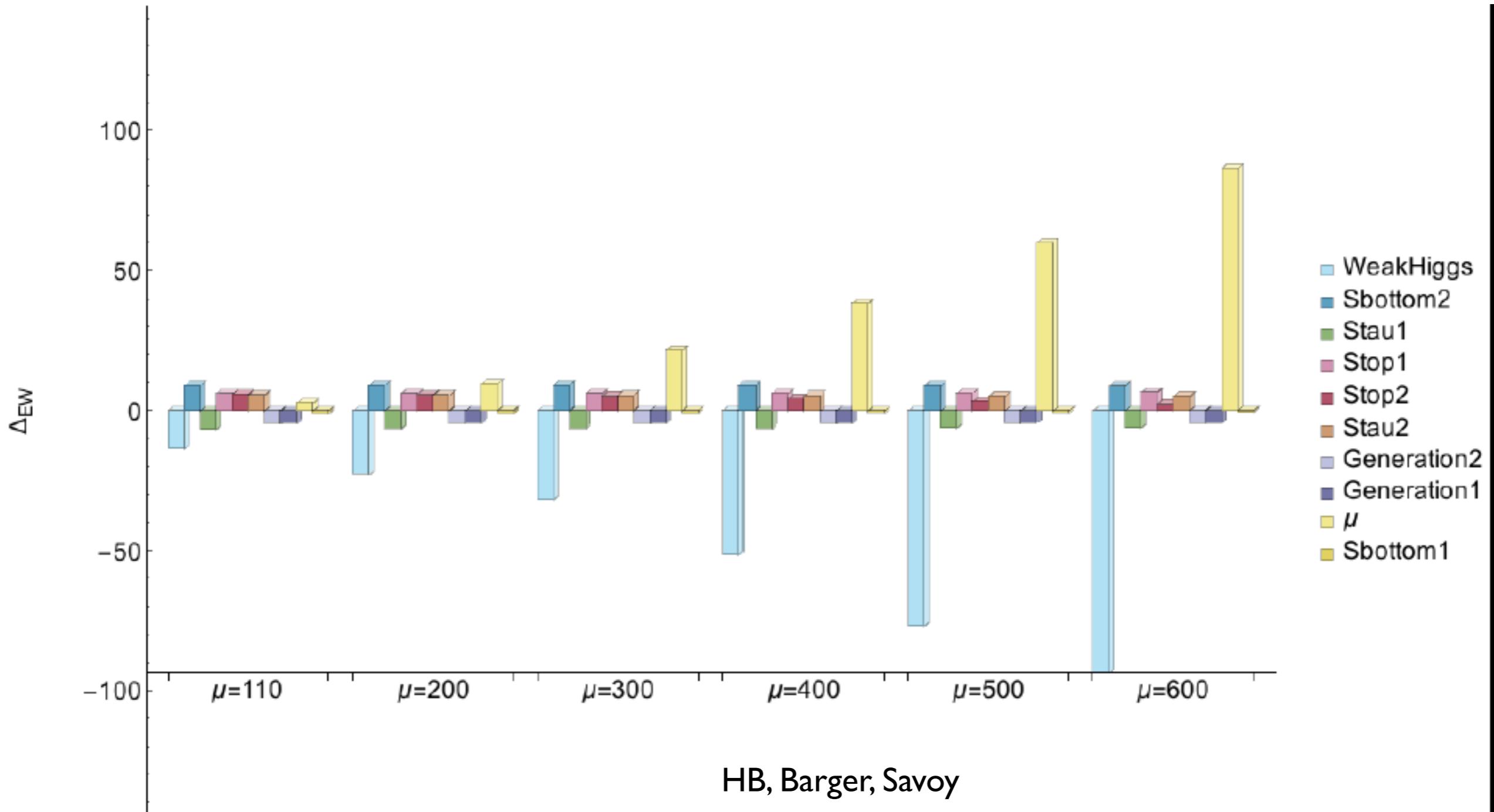
using μ^2 and $m_{3/2}^2$ as fundamental,
then $\Delta_{BG} \simeq \Delta_{EW}$ even using high scale parameters!

SUSY spectra with $\sim 10\%$ EW fine-tuning



easy to hide at LHC

How much is too much fine-tuning?

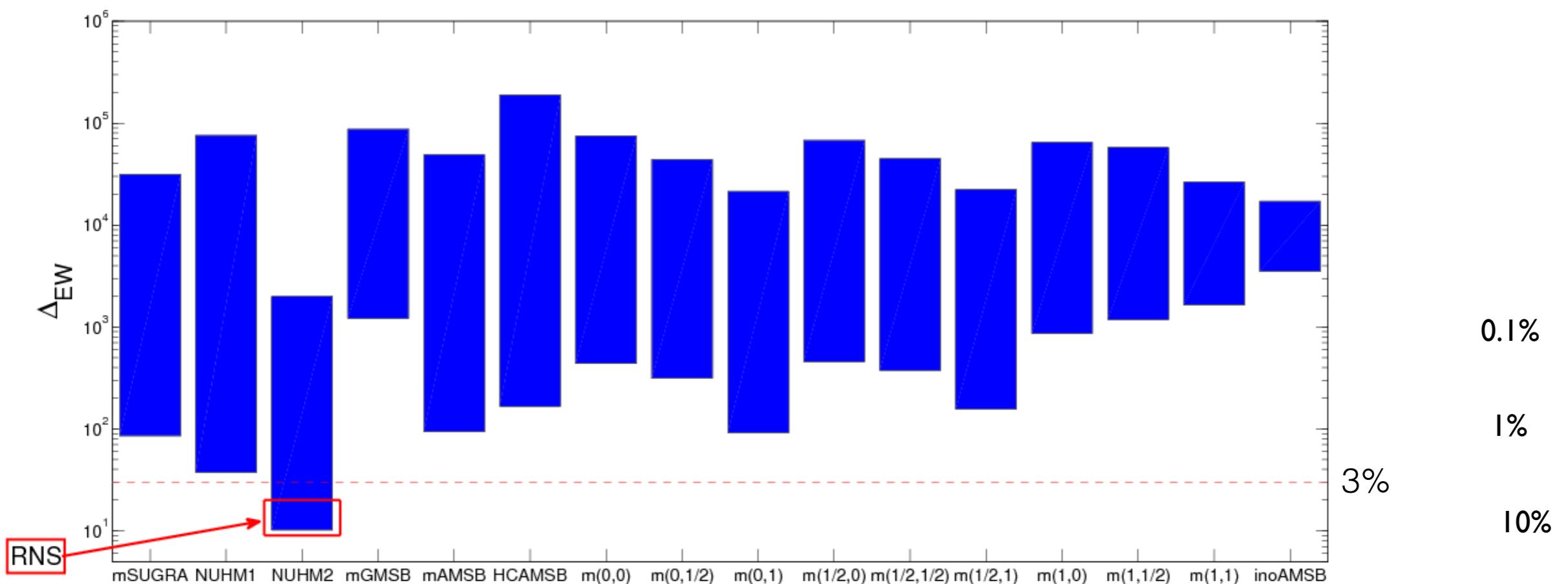


Visually, large fine-tuning has already developed by $\mu \sim 350$ or $\Delta_{EW} \sim 30$

Δ_{EW} is highly selective:
 most constrained models are ruled out
 except NUHM2 and its generalizations:

J. Ellis, K. Olive and Y. Santoso, *Phys. Lett. B* **539** (2002) 107; J. Ellis, T. Falk, K. Olive and Y. Santoso, *Nucl. Phys. B* **652** (2003) 259; H. Baer, A. Mustafayev, S. Profumo, A. Belyaev and X. Tata, *J. High Energy Phys.* **0507** (2005) 065.

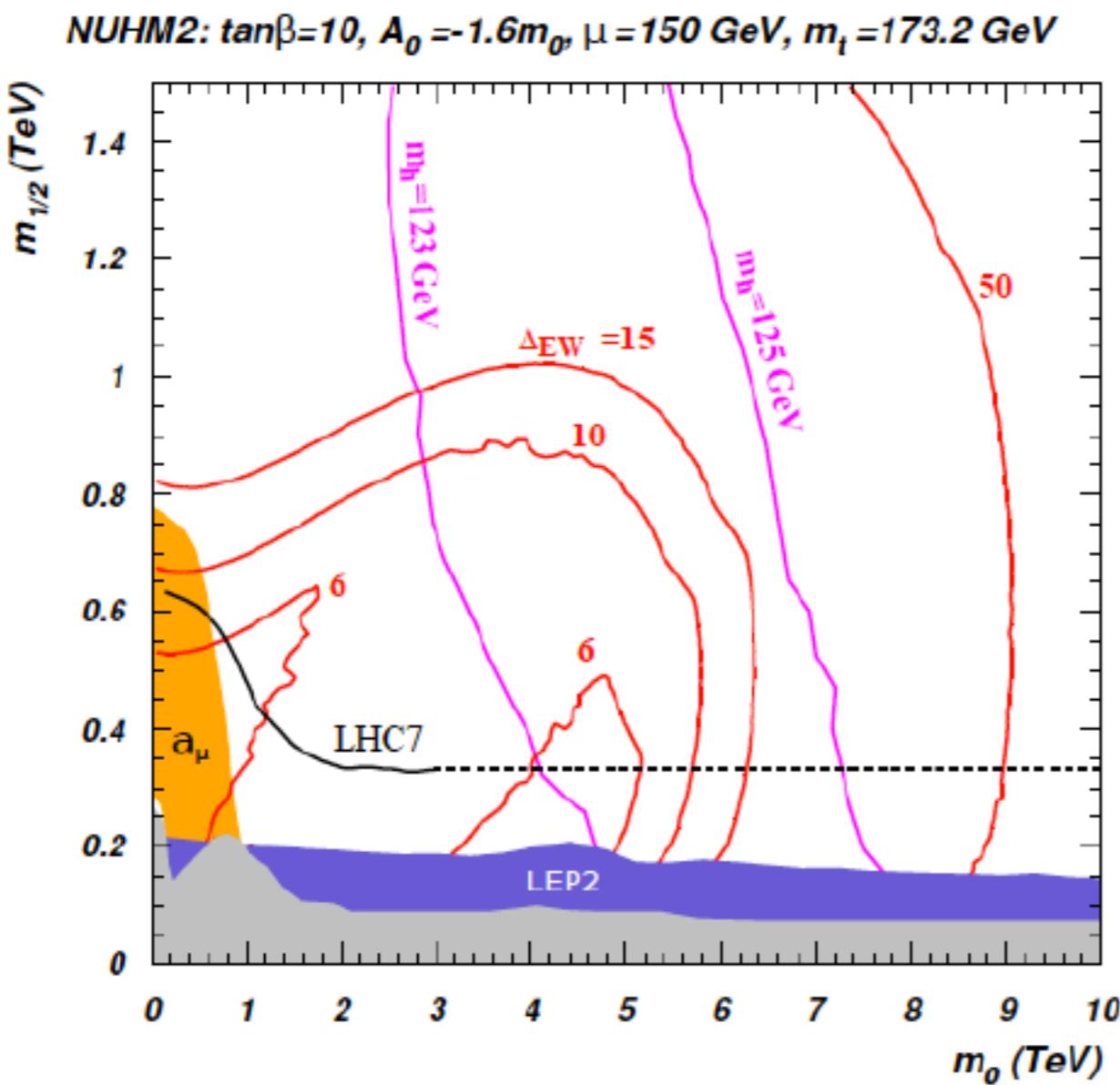
scan over p-space with $m(h)=125.5\pm 2.5$ GeV:



bounds from naturalness (3%)	BG/DG	Delta_EW
mu	350 GeV	350 GeV
gluino	400-600 GeV	4000 GeV
t1	450 GeV	3000 GeV
sq/sl	550-700 GeV	10-20 TeV

$h(125)$ and LHC limits are perfectly compatible
with 3-10% naturalness: no crisis!

Good old m₀ vs. m_{hf} plane still viable, but require low mu (NUHM2)



$\mu = 150 \text{ GeV}$ throughout
which is allowed for NUHM2

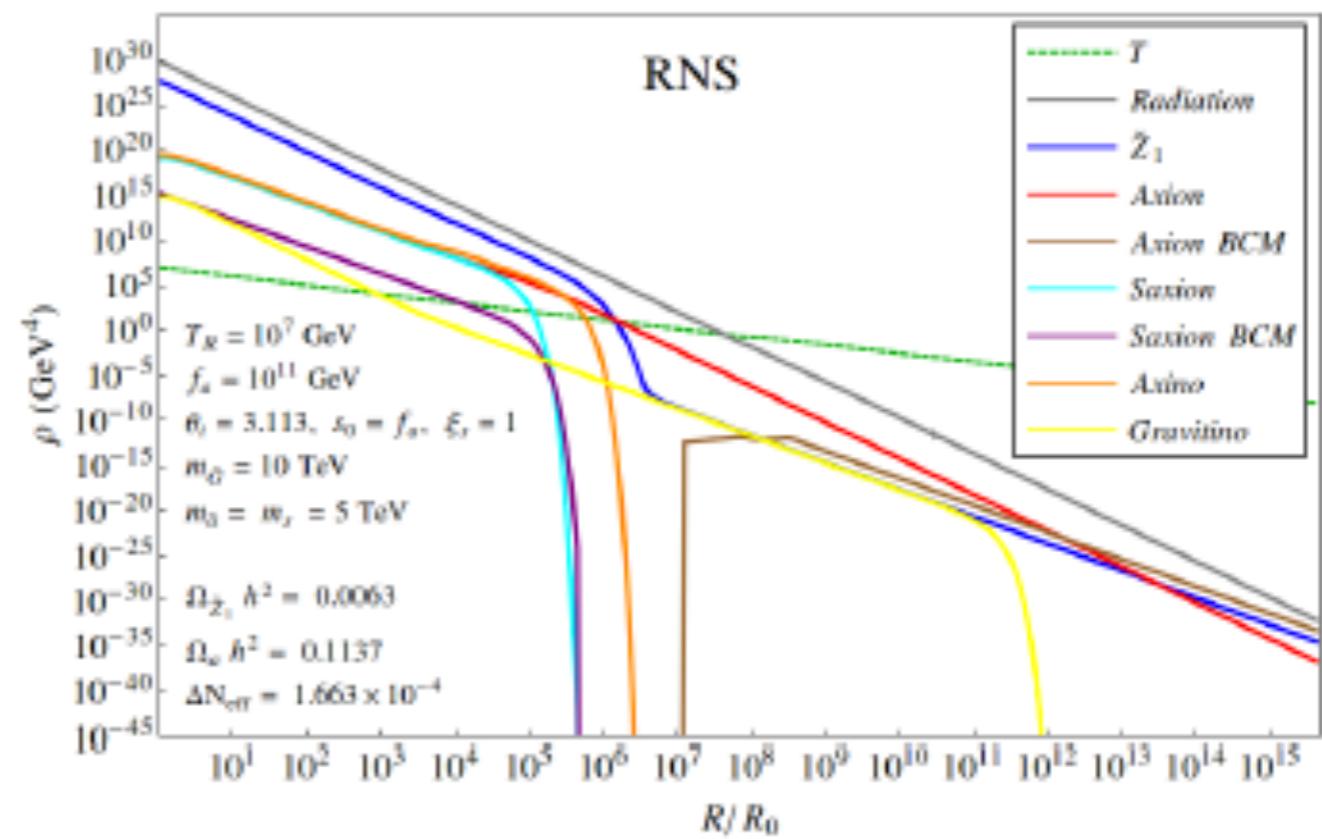
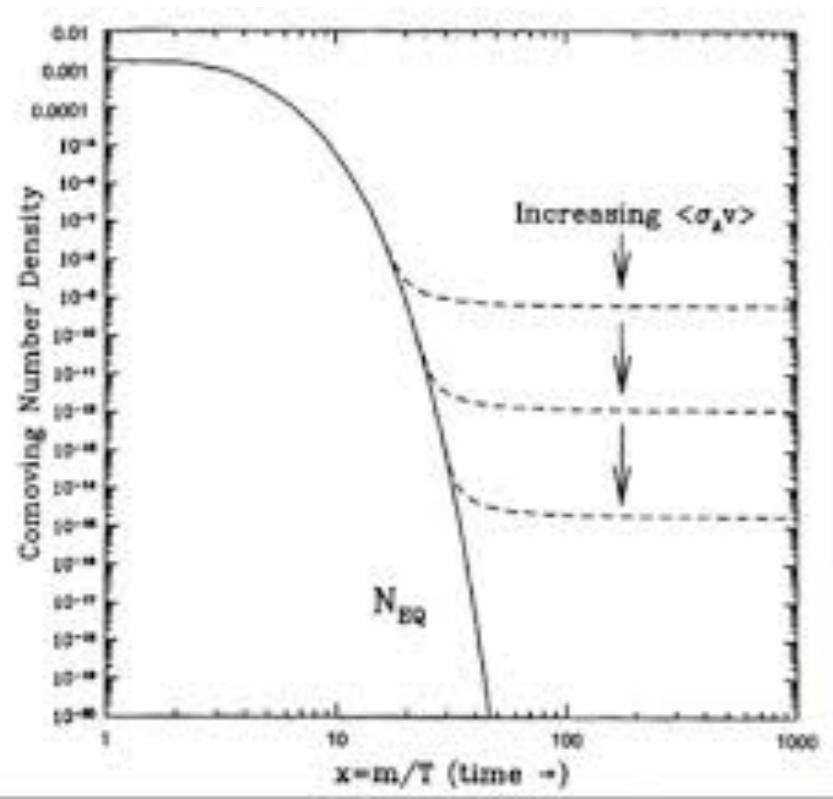
What happens to SUSY WIMP dark matter?

- higgsino-like WIMPs thermally underproduced
- 3 not four light pions => QCD theta vacuum
- EDM(neutron) => axions: no fine-tuning in QCD sector
- SUSY context: axion superfield, axinos and saxions
- DM= axion+higgsino-like WIMP admixture
- DFSZ SUSY axion: solves mu problem with $\mu \ll m_3/2$!
- ultimately detect both WIMP and axion!

usual picture

=>

mixed axion/WIMP

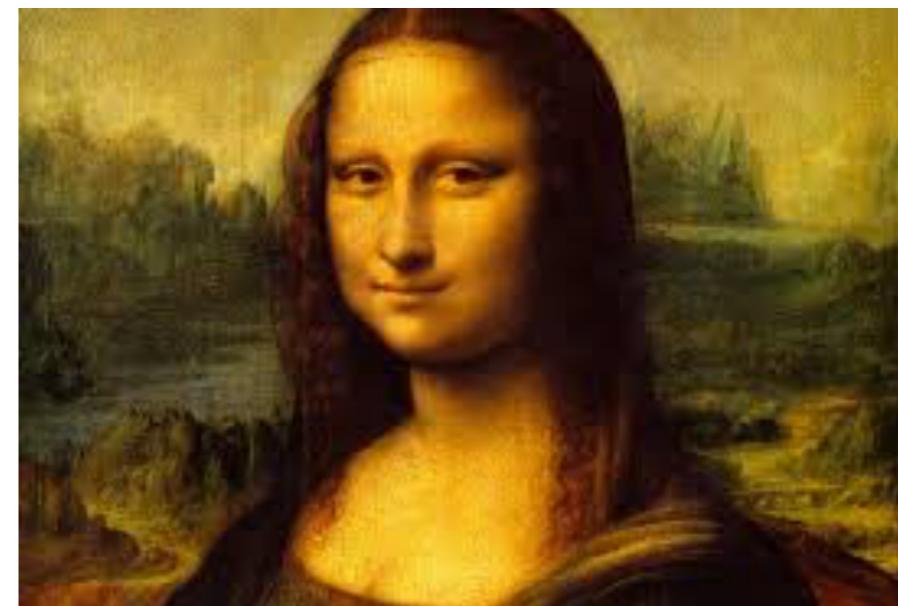


KJ Bae, HB, Lessa, Serce

much of parameter space is axion-dominated
with 10-15% WIMPs



=>



Why might $\mu \ll m_{3/2}$?

- Kim-Nilles solution to SUSY μ problem
- SUSY DFSZ axion model: μ forbidden by PQ symmetry
- μ and axion generated via PQ breaking
- $\mu \sim f_a^2/M_P$
- $m_{3/2} \sim m_{hidden}^2/M_P$
- $\mu \ll m_{3/2} \Rightarrow f_a \ll m_{hidden}?$
- models with radiative PQ breaking (MSY, CCK, Y^2) typically generate $\mu \sim 100$ GeV from $m_{3/2} \sim 10$ TeV
- PQ scale f_a sets axion mass, Higgs and higgsino masses!

Little Hierarchy from radiative PQ breaking? exhibited within context of MSY model

Murayama, Suzuki, Yanagida (1992);
 Gherghetta, Kane (1995)
 Choi, Chun, Kim (1996)

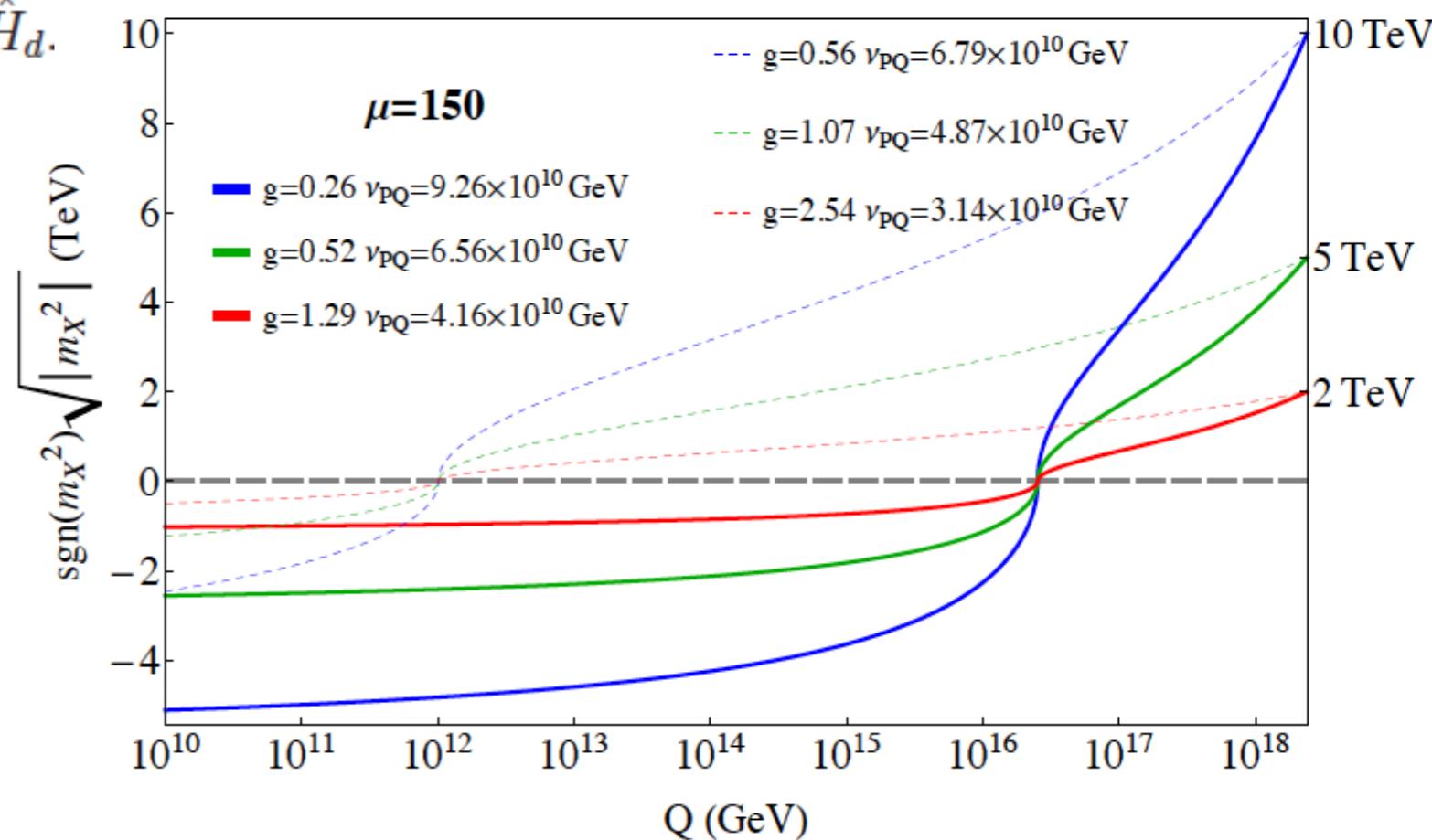
Bae, HB, Serce, PRD91 (2015) 015003

augment MSSM with PQ charges/fields:

$$\hat{f}' = \frac{1}{2} h_{ij} \hat{X} \hat{N}_i^c \hat{N}_j^c + \frac{f}{M_P} \hat{X}^3 \hat{Y} + \frac{g}{M_P} \hat{X} \hat{Y} \hat{H}_u \hat{H}_d.$$

$$M_{N_i^c} = v_X h_i|_{Q=v_X}$$

$$\mu = g \frac{v_X v_Y}{M_P} .$$



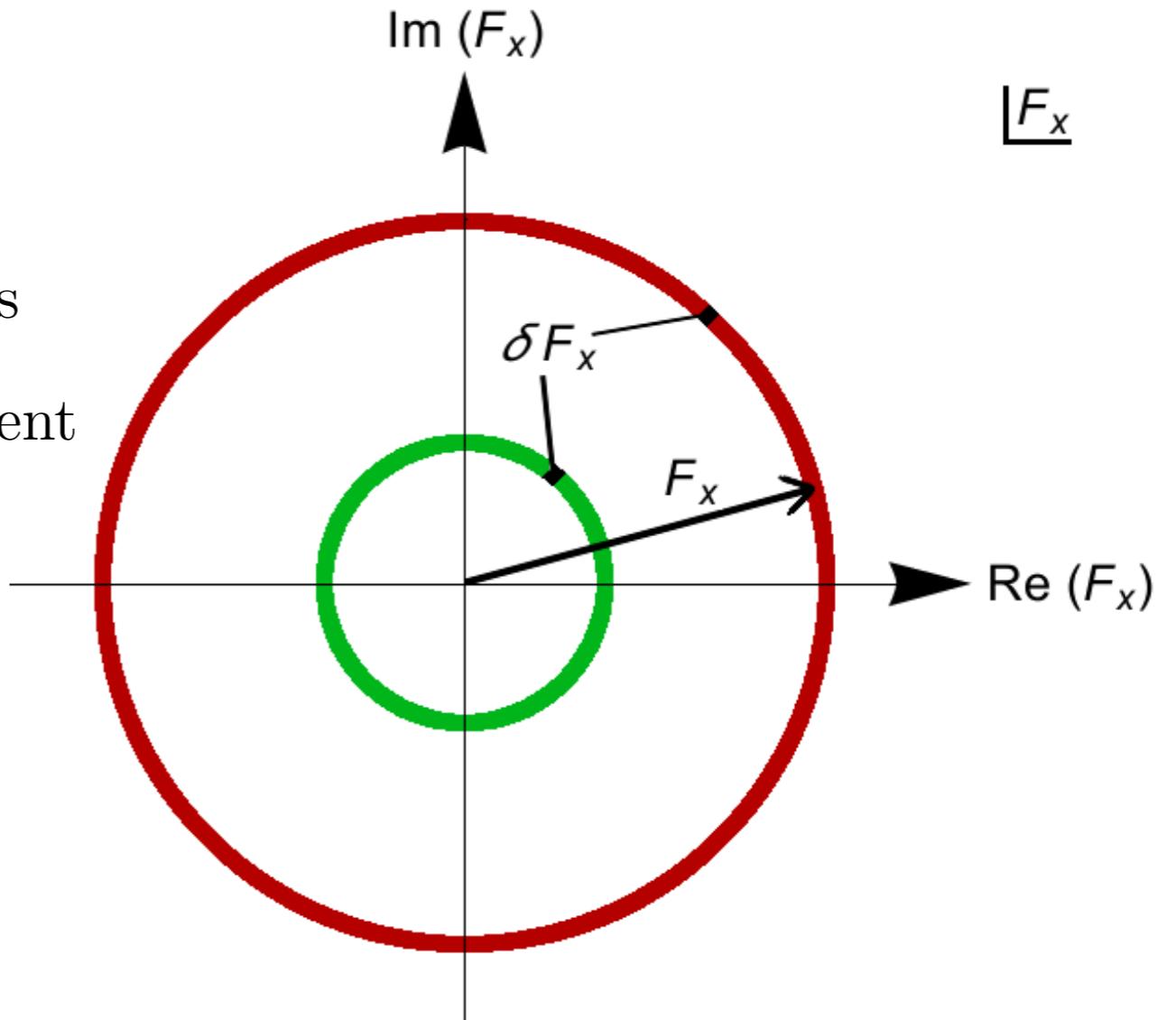
Large $m_{3/2}$ generates small $\mu \sim 100 - 200$ GeV!

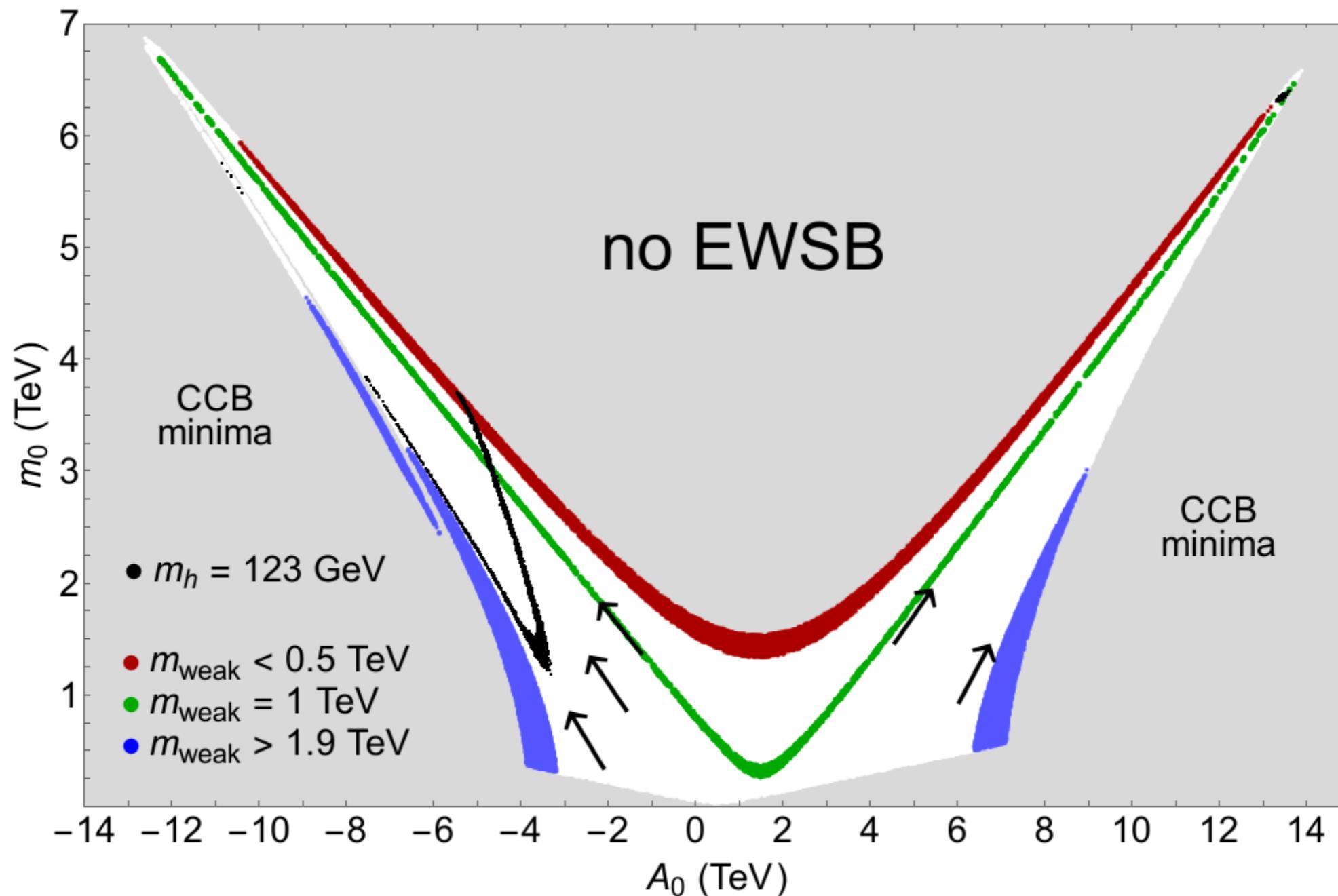
why soft terms take on values needed for natural (barely-broken) EWSB? string theory landscape?

- assume model like MSY/CCK where $\mu \sim 100$ GeV
- then $m(\text{weak})^2 \sim |m_{H_u}^2|$
- If all values of SUSY breaking field $\langle F_X \rangle$ equally likely, then mild (linear) statistical draw towards large soft terms
- This is balanced by anthropic requirement of weak scale $m_{\text{weak}} \sim 100$ GEV

Anthropic selection of $m_{\text{weak}} \sim 100$ GeV:

If m_W too large, then weak interactions $\sim (1/m_W^4)$ too weak
weak decays, fusion reactions suppressed
elements not as we know them

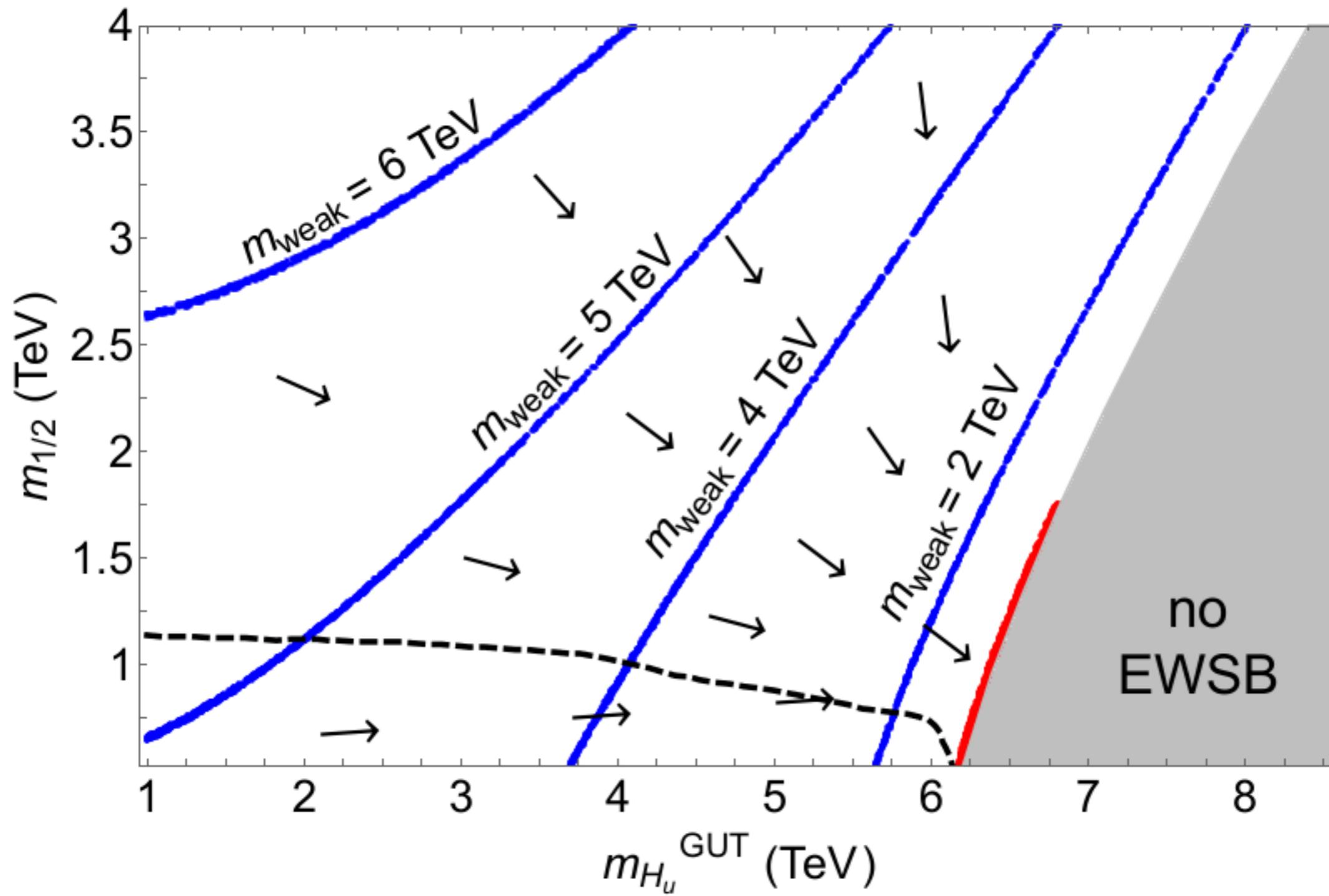




statistical draw to large soft terms balanced by
anthropic draw toward red ($m(\text{weak}) \sim 100 \text{ GeV}$):
then $m(\text{Higgs}) \sim 125 \text{ GeV}$ and natural SUSY spectrum!

Giudice, Rattazzi, 2006

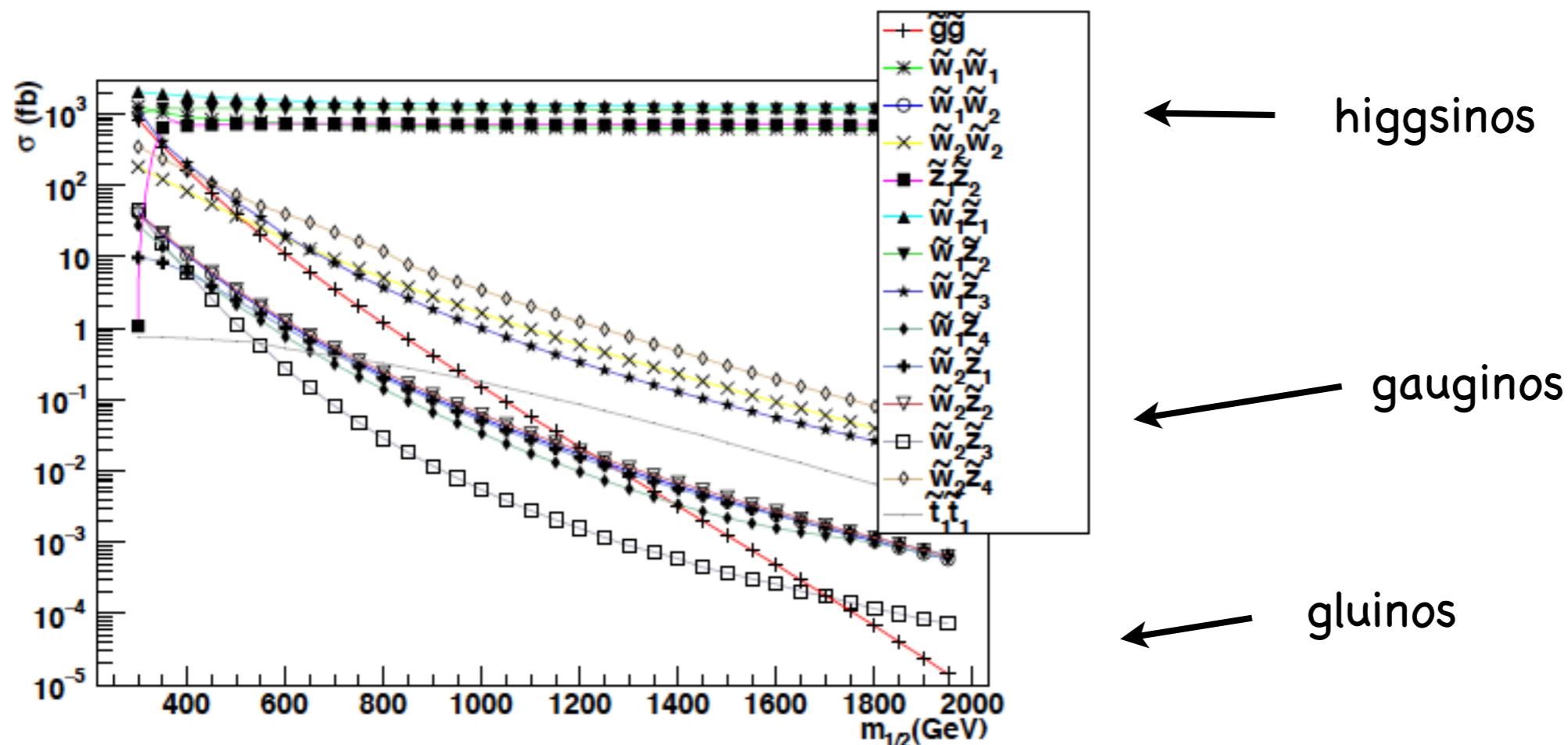
HB, Barger, Savoy, Serce, PLB758 (2016) 113



statistical/anthropic draw toward FP-like region

Prospects for discovering
SUSY
with radiatively-driven naturalness
at LHC and ILC

Sparticle prod'n along RNS model-line at LHC14:

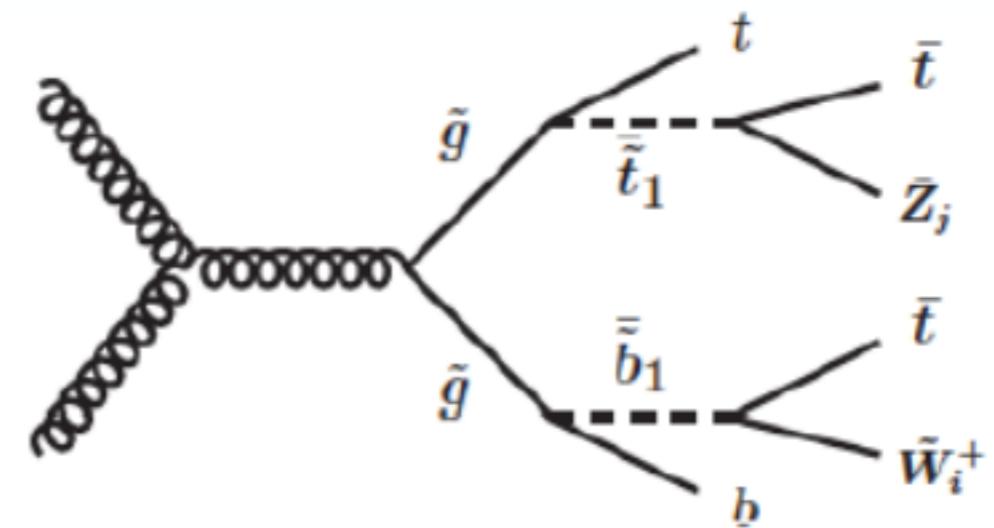
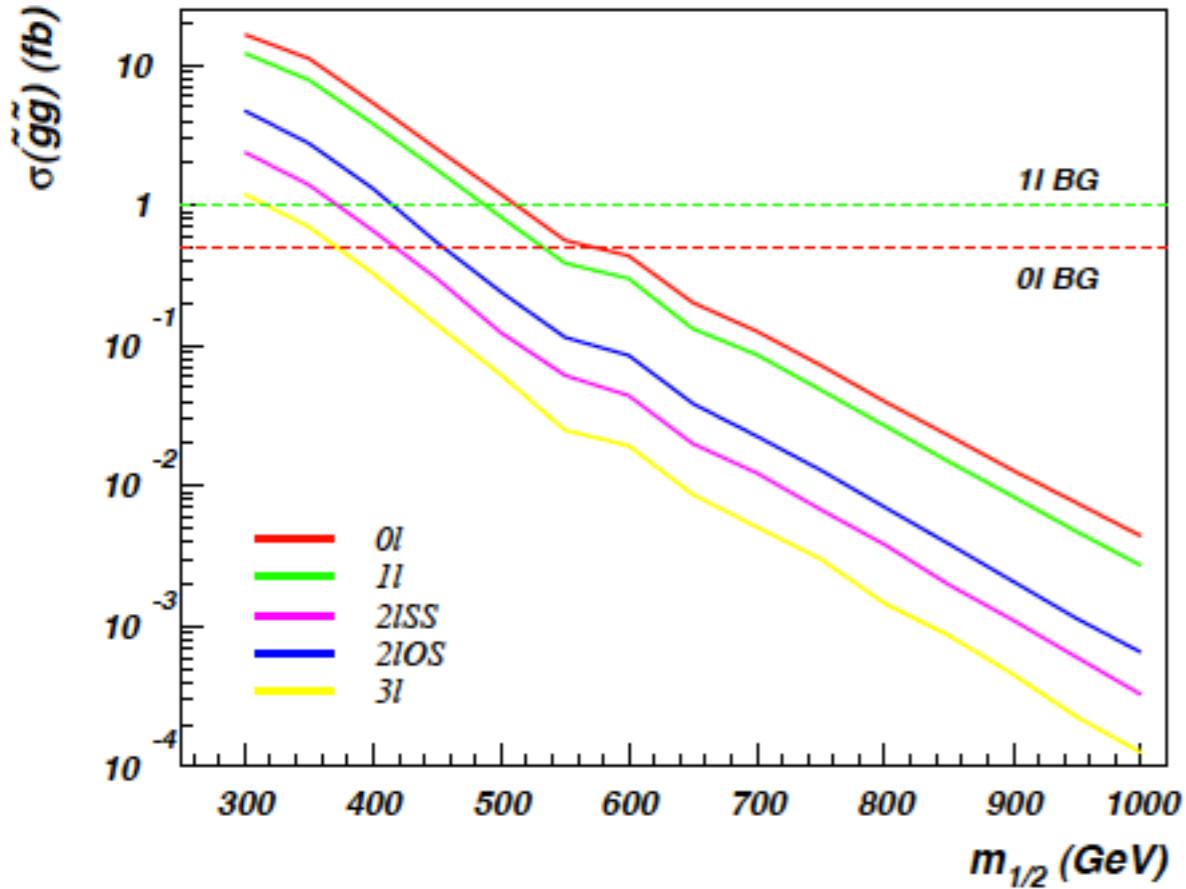


higgsino pair production dominant—but only soft visible energy release from higgsino decays

largest visible cross section: **wino pairs**
gluino pairs sharply dropping

gluino pair cascade decay signatures

NUHM2: $m_0 = 5 \text{ TeV}$, $A_0 = -1.6m_0$, $\tan\beta = 15$, $\mu = 150 \text{ GeV}$, $m_A = 1 \text{ TeV}$



Particle	dom. mode	BF
\tilde{g}	$\tilde{t}_1 t$	$\sim 100\%$
\tilde{t}_1	$b\tilde{W}_1$	$\sim 50\%$
\tilde{Z}_2	$\tilde{Z}_1 f\bar{f}$	$\sim 100\%$
\tilde{Z}_3	$\tilde{W}_1^\pm W^\mp$	$\sim 50\%$
\tilde{Z}_4	$\tilde{W}_1^\pm W^\mp$	$\sim 50\%$
\tilde{W}_1	$\tilde{Z}_1 f\bar{f}'$	$\sim 100\%$
\tilde{W}_2	$\tilde{Z}_i W$	$\sim 50\%$

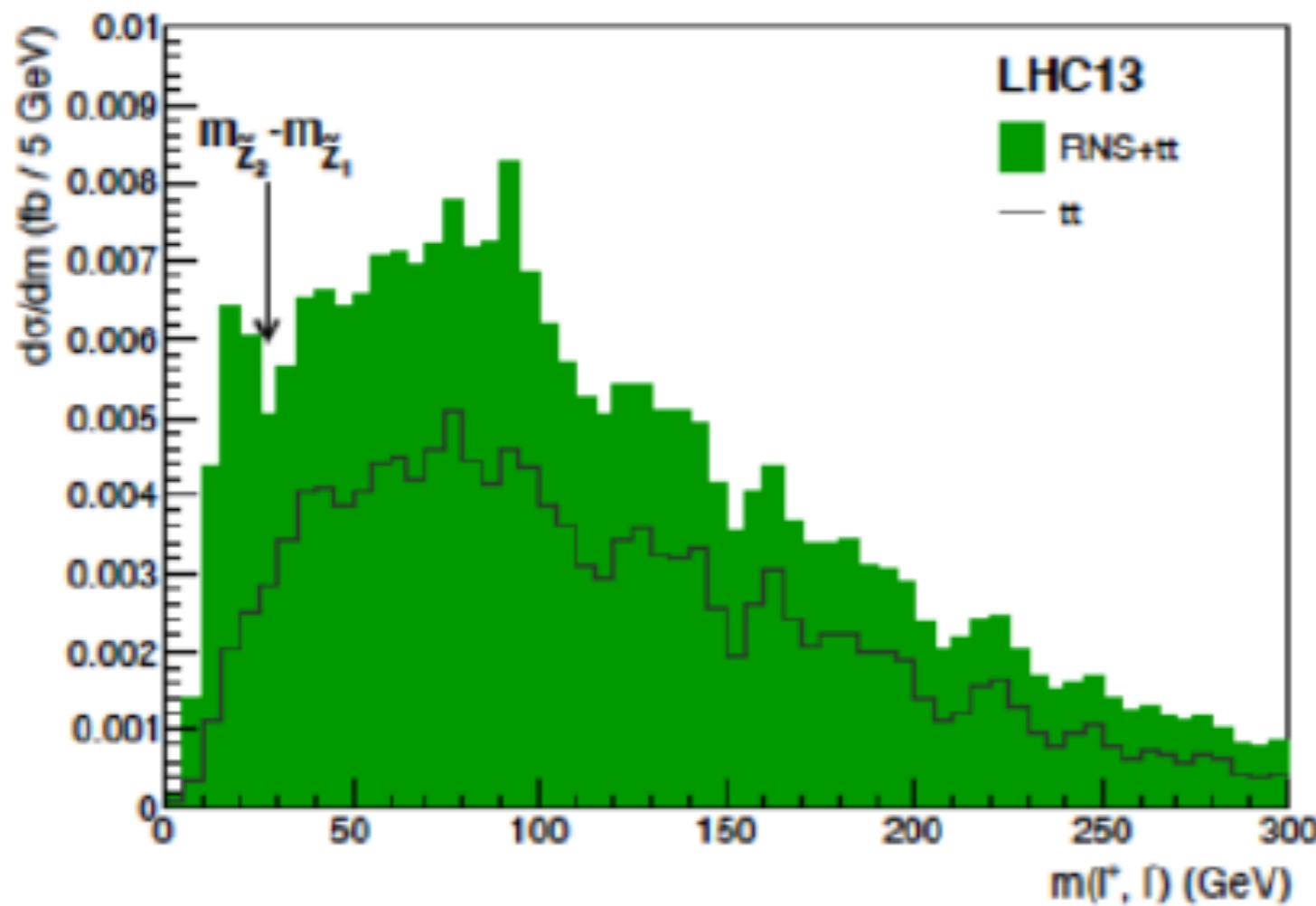
Table 1: Dominant branching fractions of various sparticles along the RNS model line for $m_{1/2} = 1 \text{ TeV}$.

Int. lum. (fb $^{-1}$)	$\tilde{g}\tilde{g}$
10	1.4
100	1.6
300	1.7
1000	1.9

LHC14 5sigma reach
in $m(\text{gluino})$ (TeV)

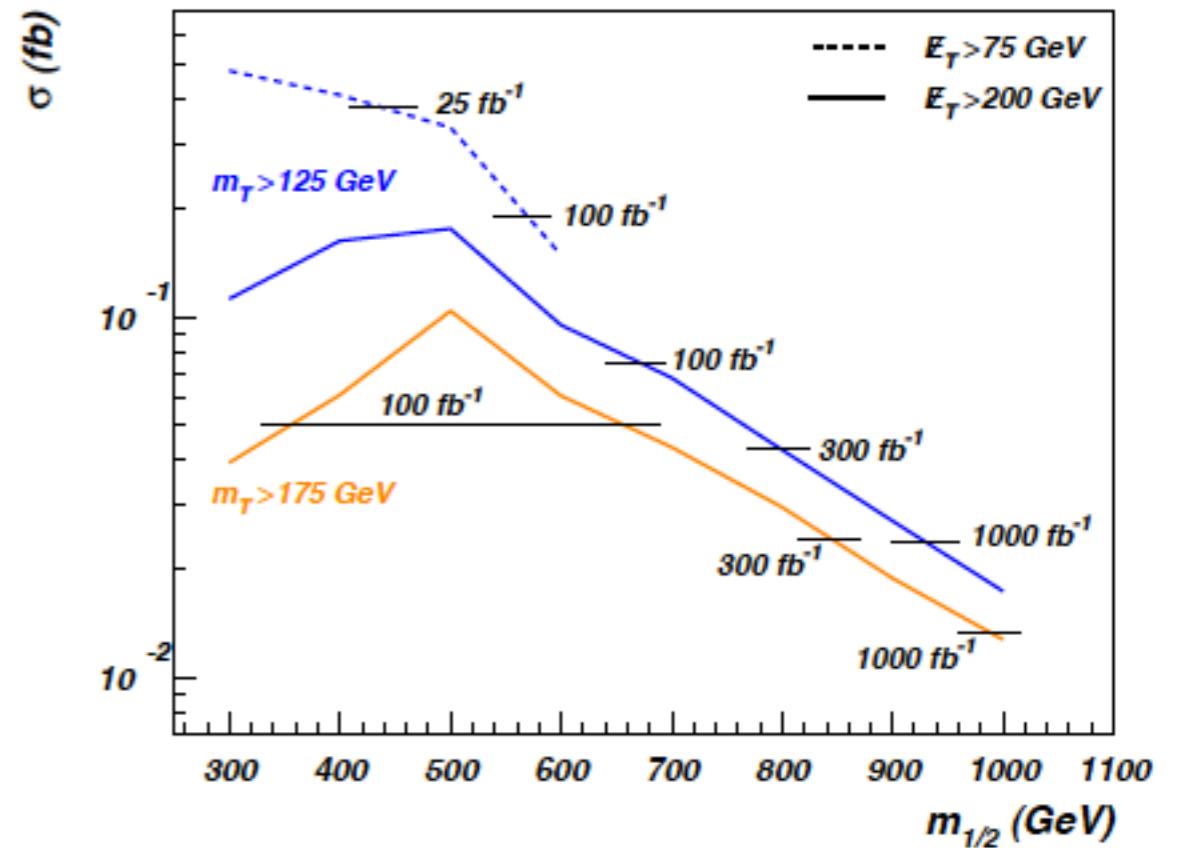
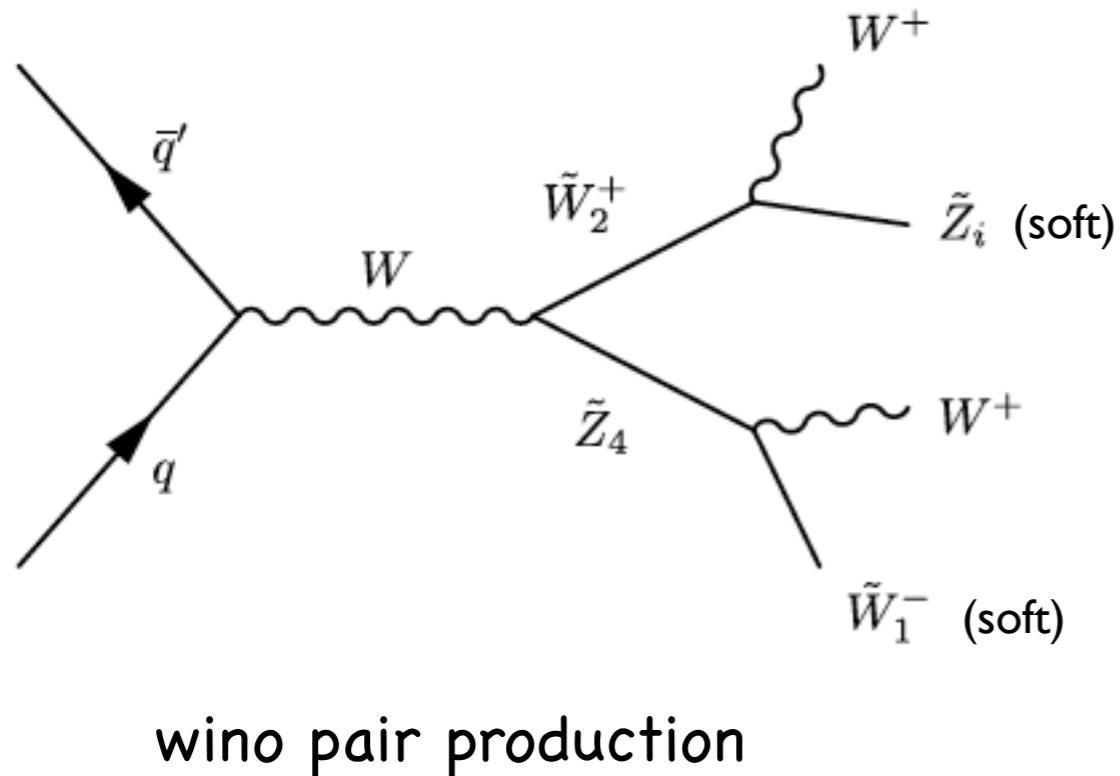
since $m(\text{gluino})$ extends to $\sim 4 \text{ TeV}$,
LHC14 can see about half the low EWFT
parameter space in these modes

LHC14 has some reach for
gluino pair production in RNS;
if a signal is seen,
should be distinctive



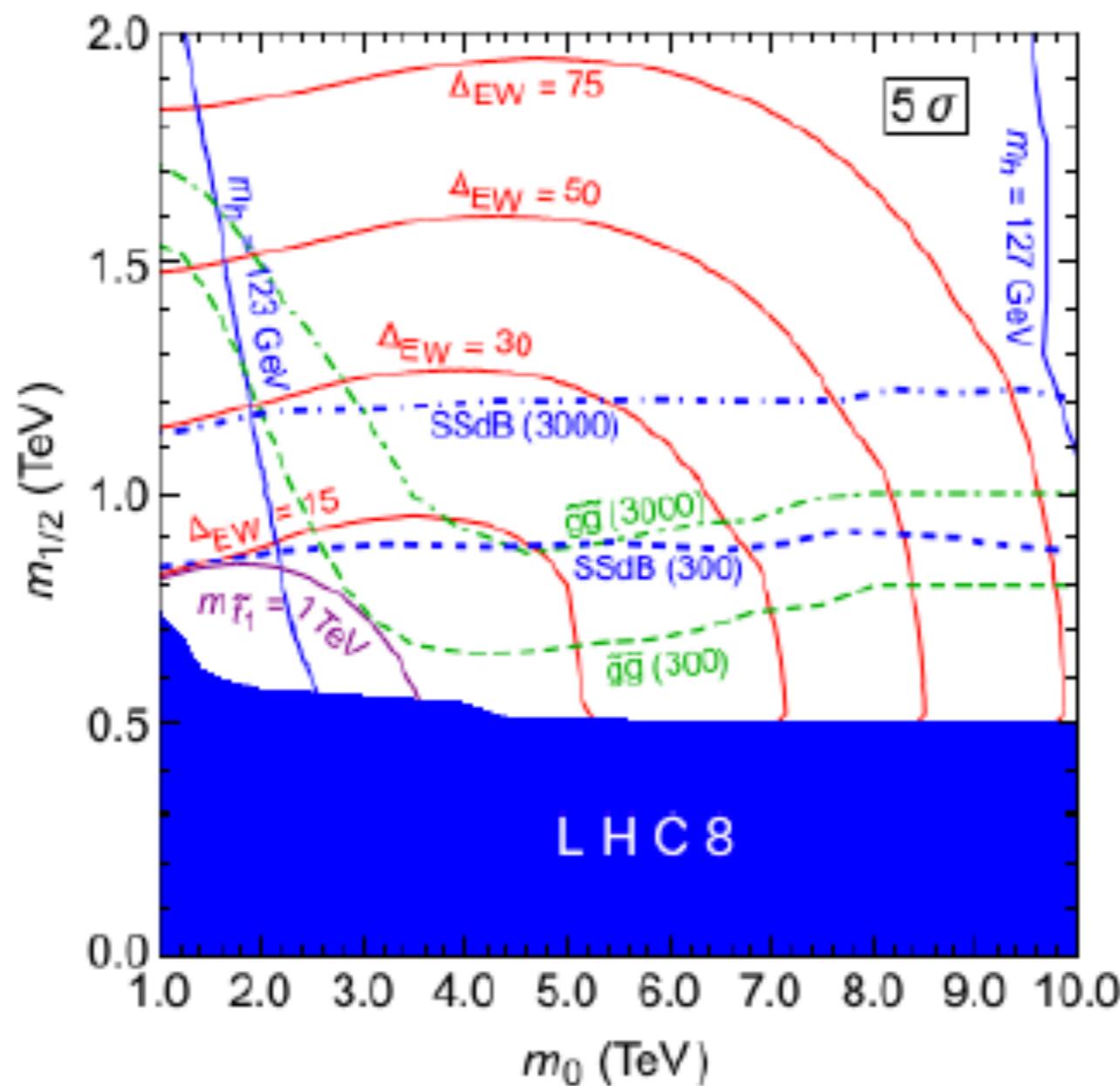
OS/SF dilepton mass
edge apparent from
cascade decays
with $Z_2 \rightarrow Z_1 + l + l\bar{b}$

Distinctive same-sign diboson (SSdB) signature from SUSY models with light higgsinos!

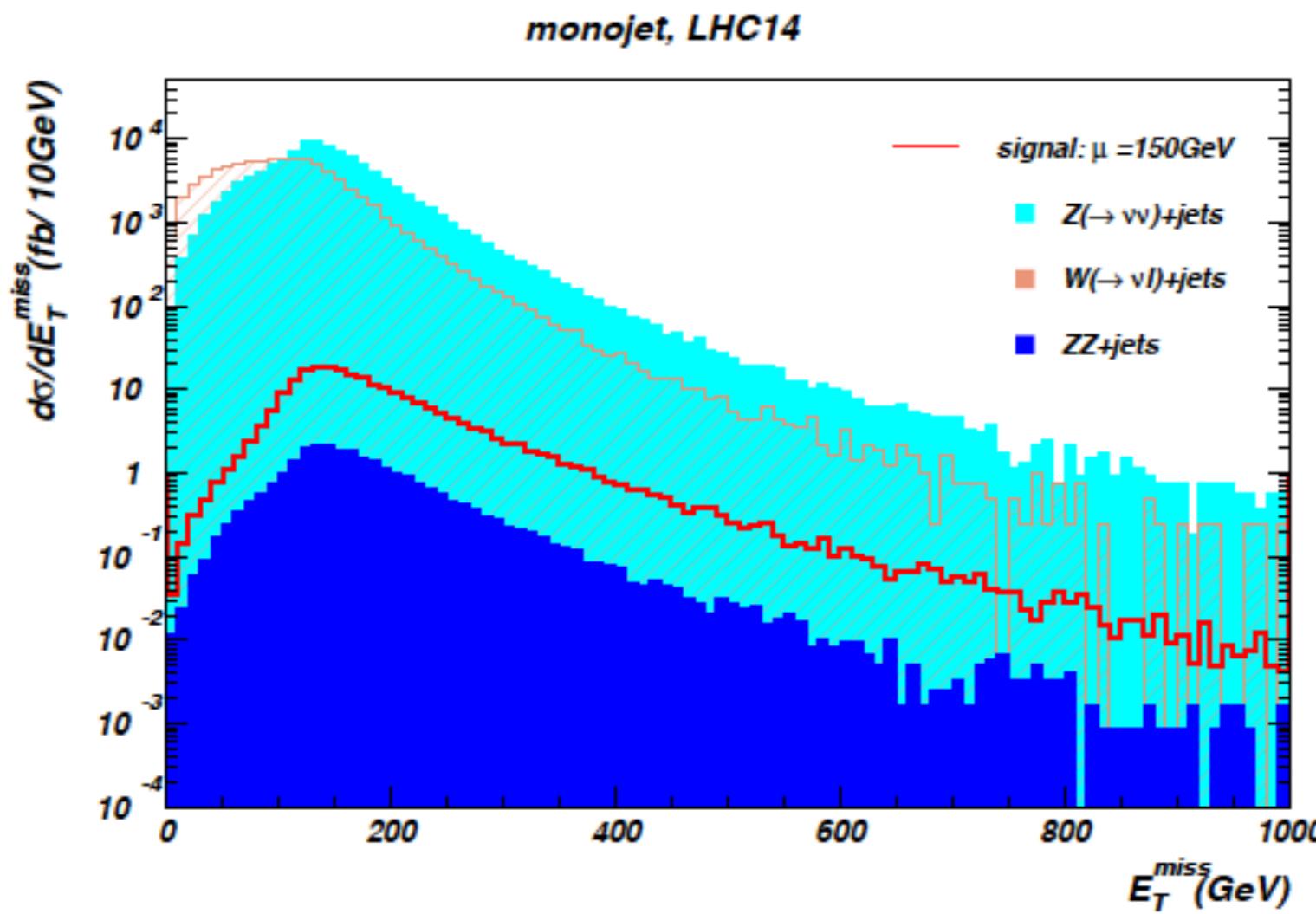


This channel offers best reach of LHC14 for RNS;
it is also indicative of wino-pair prod'n
followed by decay to higgsinos

HL-LHC reach for radiative natural SUSY via
SSdB and $\tilde{g}\tilde{g}$ channels
completely covers $\Delta_{EW} < 30$ at 5σ level!



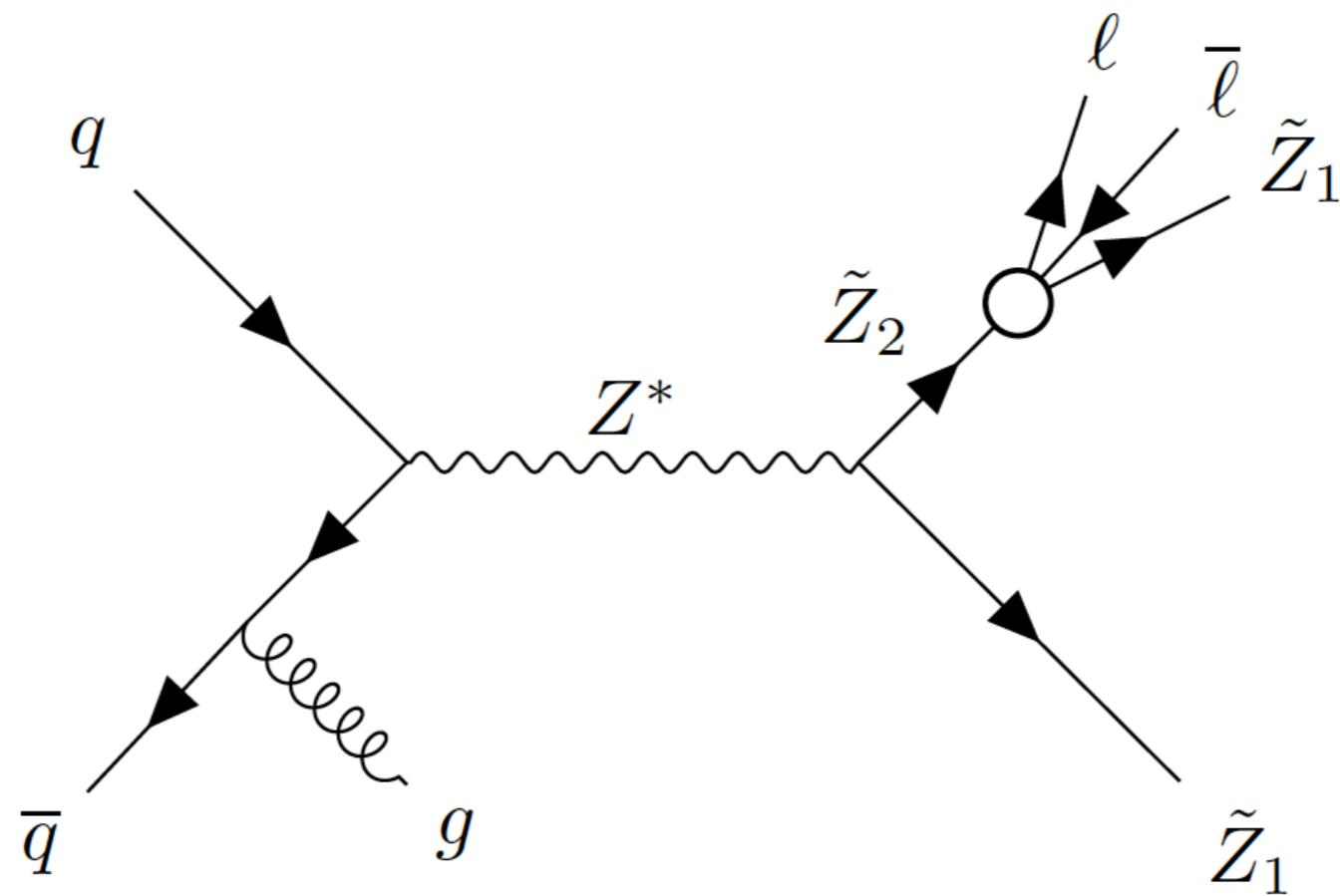
See direct higgsino pair production
recoiling from ISR (monojet signal)?

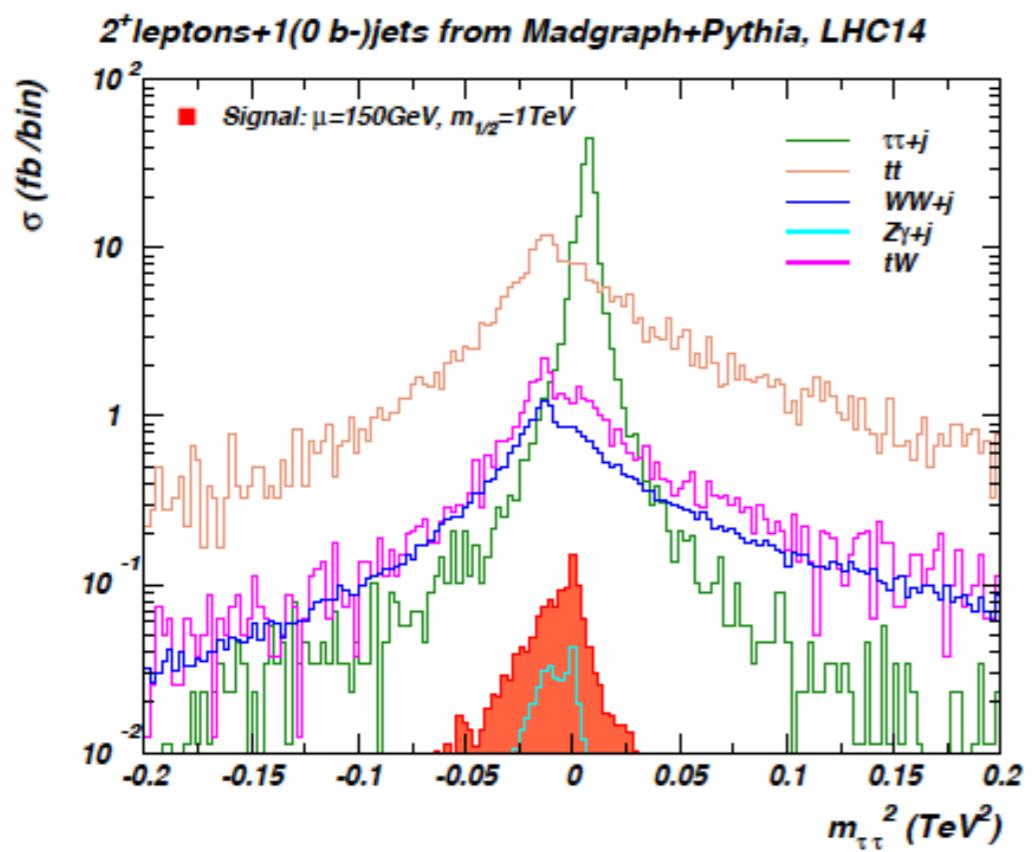


typically 1% S/BG after cuts:
very tough to do!

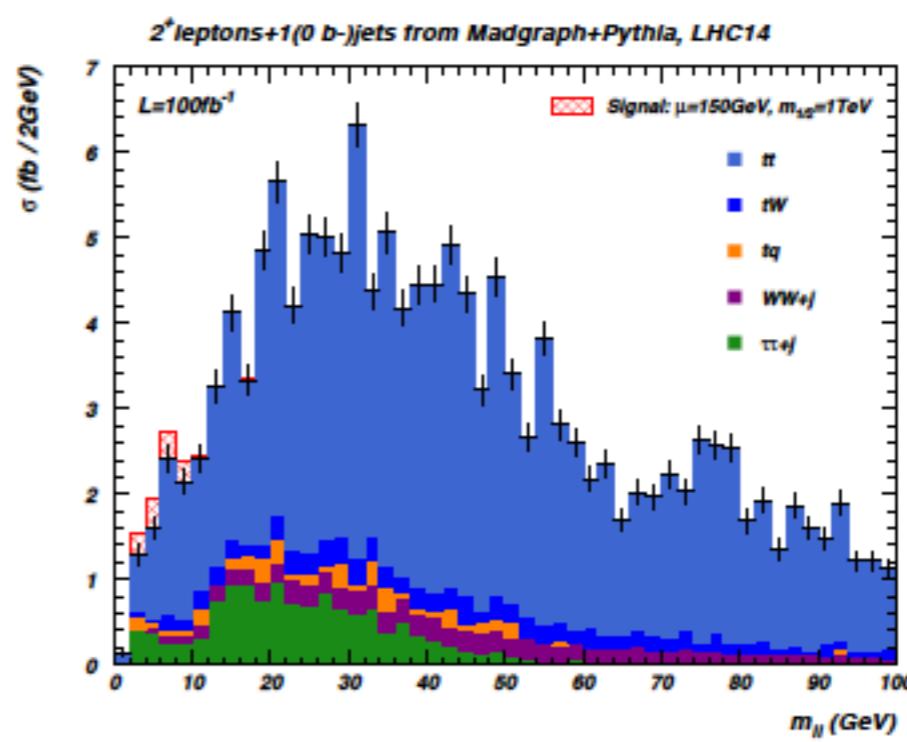
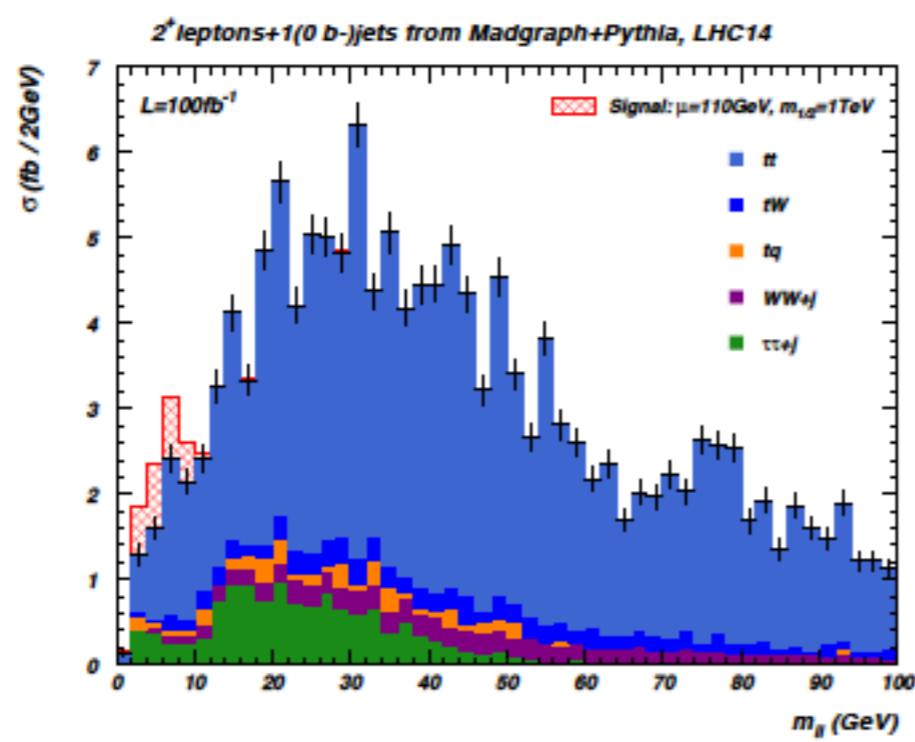
What about $pp \rightarrow \tilde{Z}_1 \tilde{Z}_2 j$ with $\tilde{Z}_2 \rightarrow \tilde{Z}_1 \ell^+ \ell^-$?

Han, Kribs, Martin, Menon, PRD89 (2014) 075007;
HB, Mustafayev, Tata, PRD90 (2014) 115007;

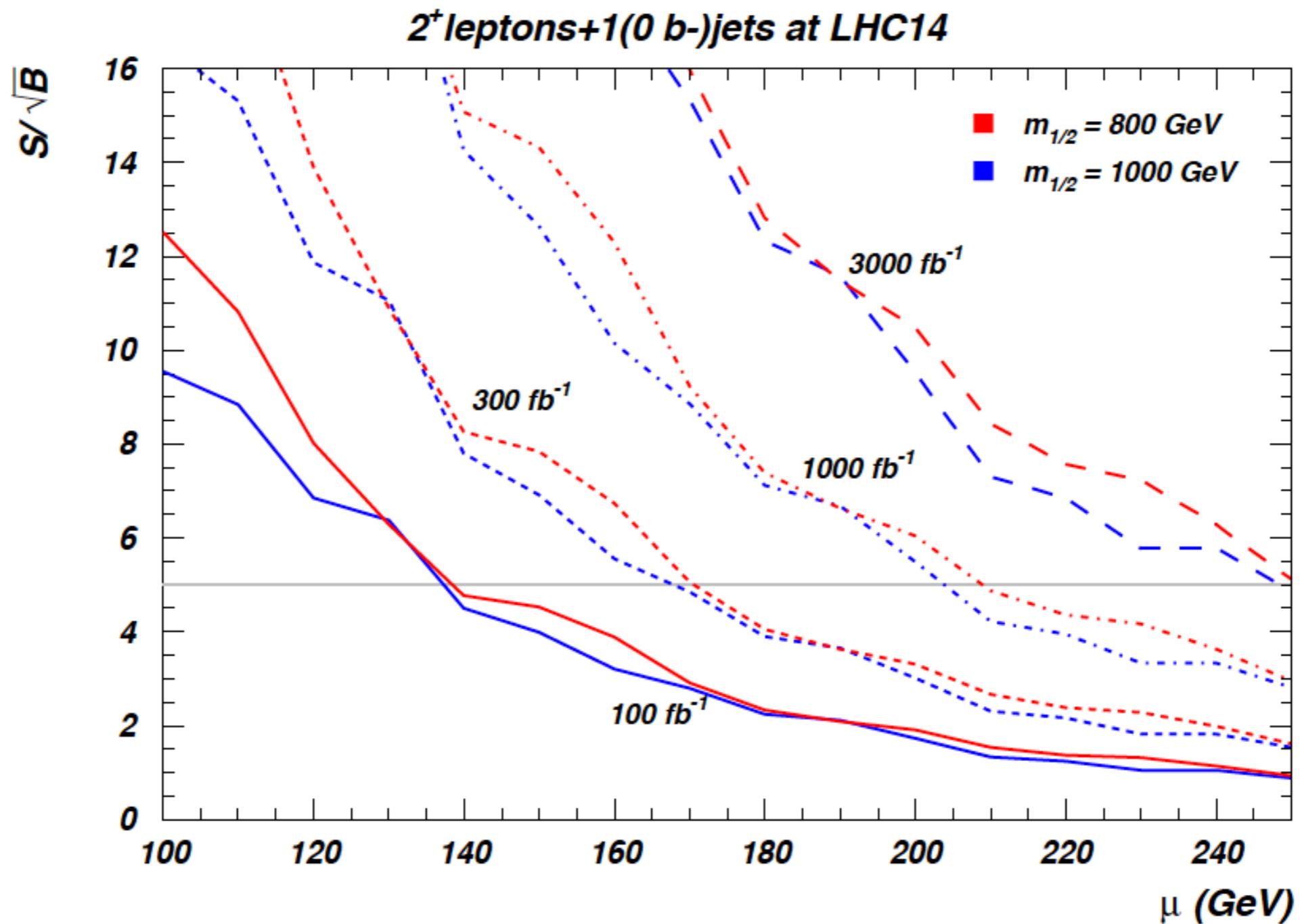




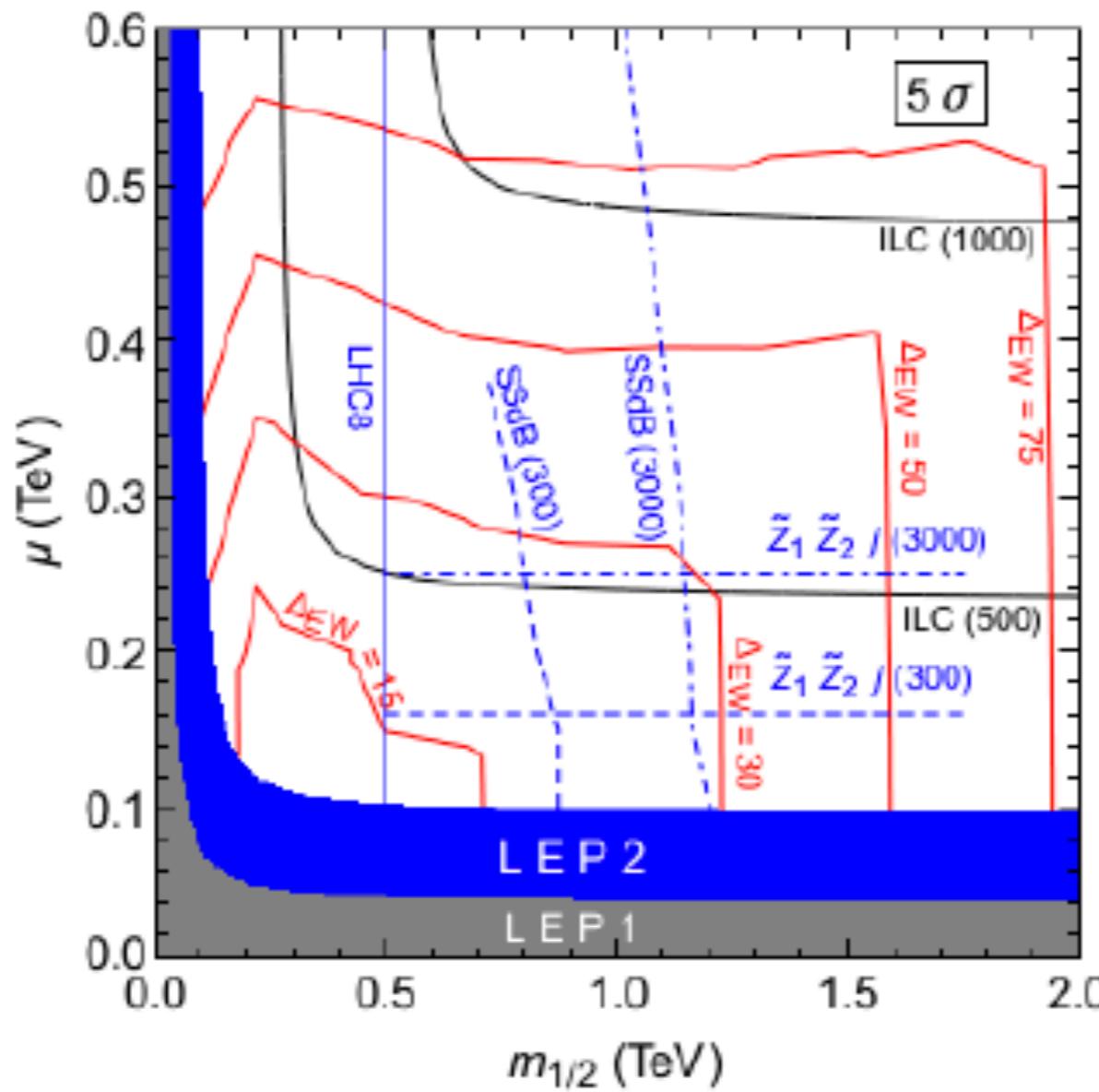
use MET to construct
 $m^2(\tau\tau)$



LHC reach for soft dilepton+jet+MET

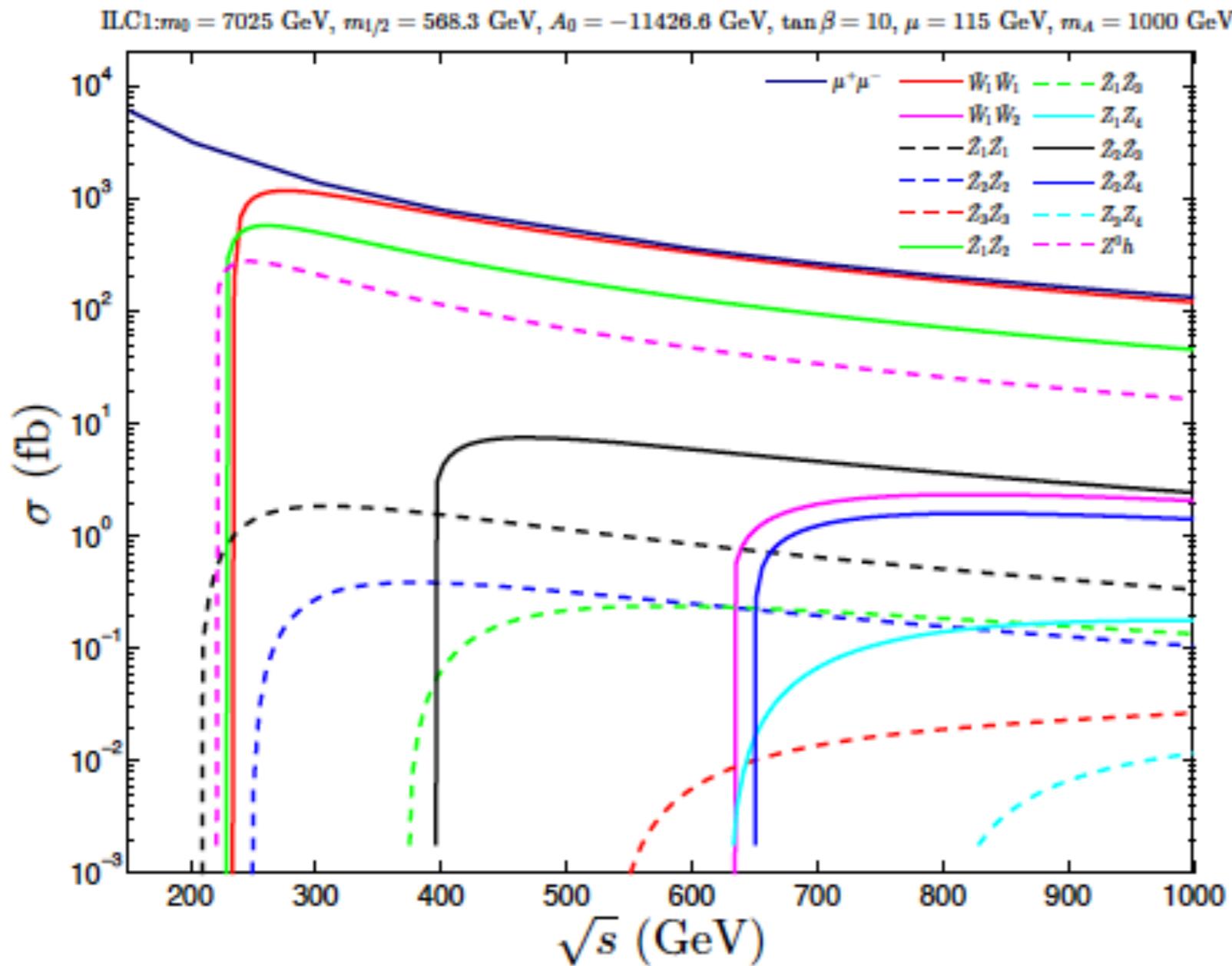


panoramic view of reach of HL-LHC for natural SUSY



LHC14 with 3000 fb^{-1} can cover essentially all parameter space with $\Delta_{EW} < 30$, usually with 2-3 distinct signals:
 $\tilde{g}\tilde{g}$, SSdB and $\tilde{Z}_1\tilde{Z}_2j$

rich arena for ILC physics:
 Higgs factory => higgsino factory!
 $\sqrt{s} > 2m(\text{higgsino})$



$\tilde{W}_1^\pm \tilde{W}_1^\mp$ and $\tilde{Z}_1 \tilde{Z}_2$

see talk by Suvi-Leena Lehtinen

Conclusions: status of SUSY post LHC8

- SUSY EWFT **non-crisis**: EWFT allowed at 10% level in radiatively-driven natural SUSY: SUGRA GUT paradigm is just fine in NUHM2 but CMSSM/others fine-tuned
- naturalness maintained for $\mu \sim 100\text{-}200 \text{ GeV}$; $t_1 \sim 1\text{-}3 \text{ TeV}$, $t_2 \sim 3\text{-}8 \text{ TeV}$, highly mixed; $m(\text{glino}) \sim 1\text{-}4 \text{ TeV}$
- LHC14 w/ 3000 fb^{-1} can see all $\text{DEW} < 30$ RNS parameter space
- e^+e^- collider with $\sqrt{s} \sim 500\text{-}600 \text{ GeV}$ needed to find predicted light higgsino states
- Discovery of and precision measurements of light higgsinos at **ILC**!
- SUSY DFSZ/MSY invisible axion model: solves strong CP and SUSY μ problems while allowing for $\mu \sim m(Z) \ll m(\text{SUSY})$
- soft terms pulled to natural SUSY/barely broken EWS values, landscape?
- RNS spectra characterized by mainly higgsino-like WIMP: standard relic underabundance
- Expect mainly axion CDM with 5-10% higgsino-like WIMPs over much of p-space
- Ultimately detect **both axion and higgsino-like WIMP**

