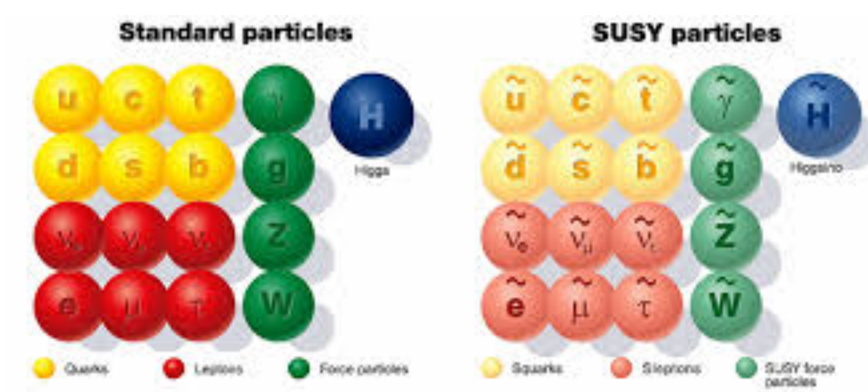
Multi-methods for multi-boson production in unnatural and natural SUSY*

Howie Baer
University of Oklahoma
MBI 2016, Madison, WI

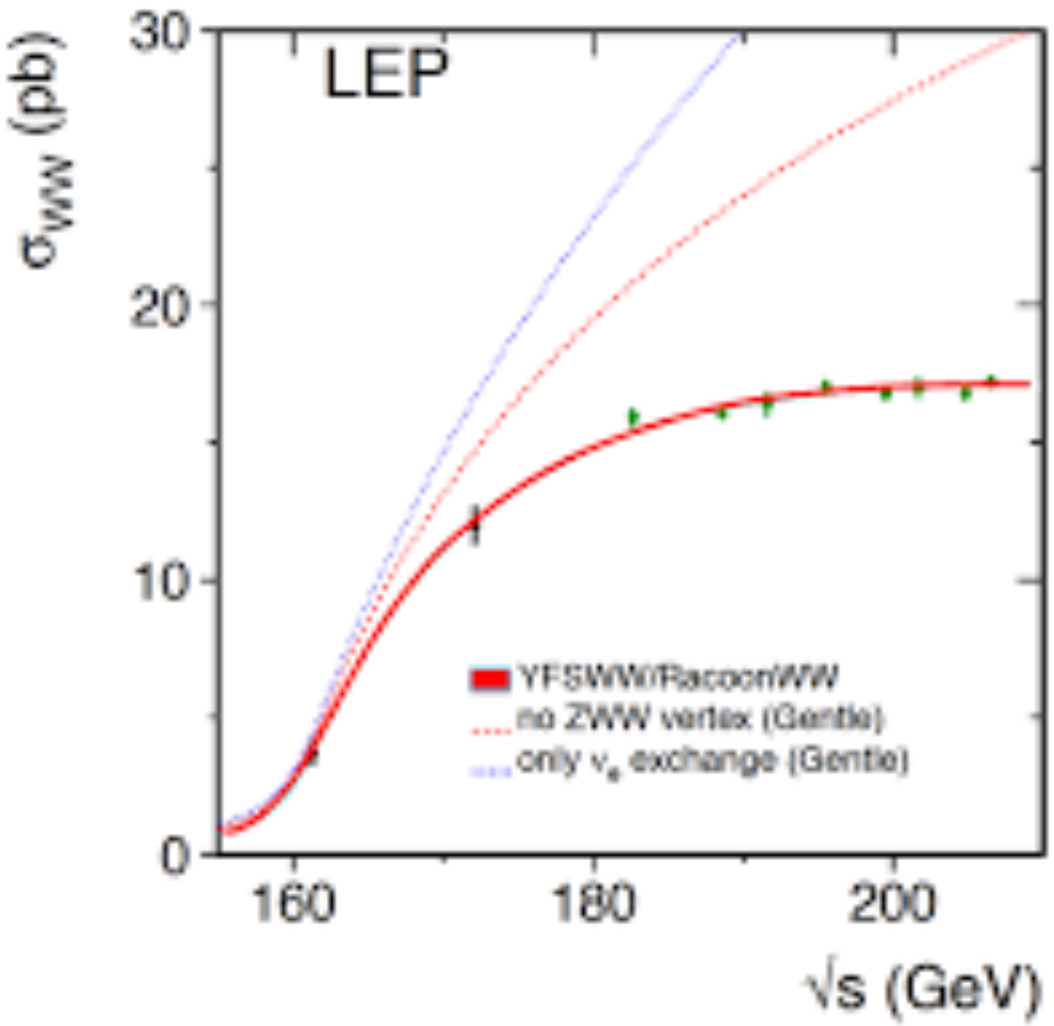




or why Buckminster Badger loves SUSY!

*this is first SUSY talk at this series of meetings

Let us recall some historical roots to MBI



Bad high energy behavior of $e^+e^- \to W^+W^-$ individual amplitudes (ν_e t-channel exchange vs. γ, Z s-channel exchange cancels due to gauge symmetry

Lesson: any single diagram gives large overestimate of total cross section (keep in mind for later use)

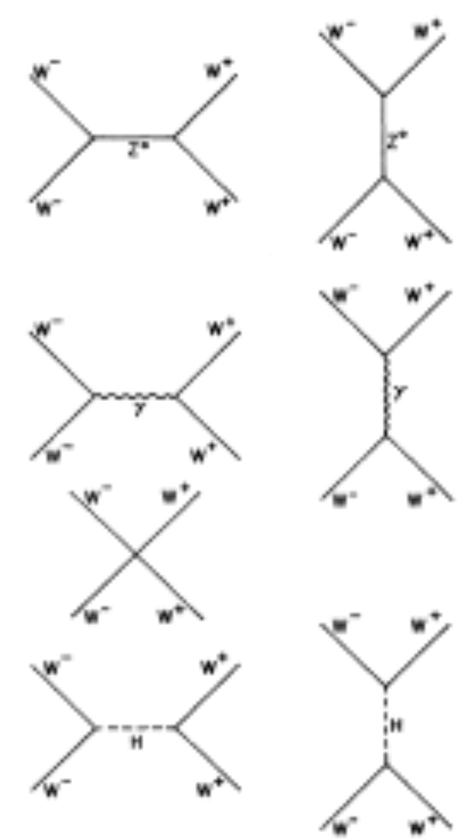
Subleading bad behavior due to EW symmetry breaking:

Strength of Weak Interactions at Very High Energies and the Higgs Boson Mass

Benjamin W. Lee, C. Quigg,* and H. B. Thacker
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
(Received 28 February 1977)

It is shown that if the Higgs boson mass exceeds $M_c = (8\pi\sqrt{2}/3G_F)^{1/2}$ partial-wave unitarity is not respected by the tree diagrams for two-body reactions of gauge bosons, and the weak interactions must become strong.

either light Higgs boson exists or
weak interactions
become strong around Q~1 TeV



At high energies, $WW \to WW$ becomes strong much like $\pi\pi \to \pi\pi \cdots$?

Historical aside:
strong VV scattering calculations by Chanowitz and Gaillard provided the motivation for construction of 40 TeV SSC

MULTIPLE PRODUCTION OF W AND Z AS A SIGNAL OF NEW STRONG INTERACTIONS

Michael S. CHANOWITZ
Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, USA

and

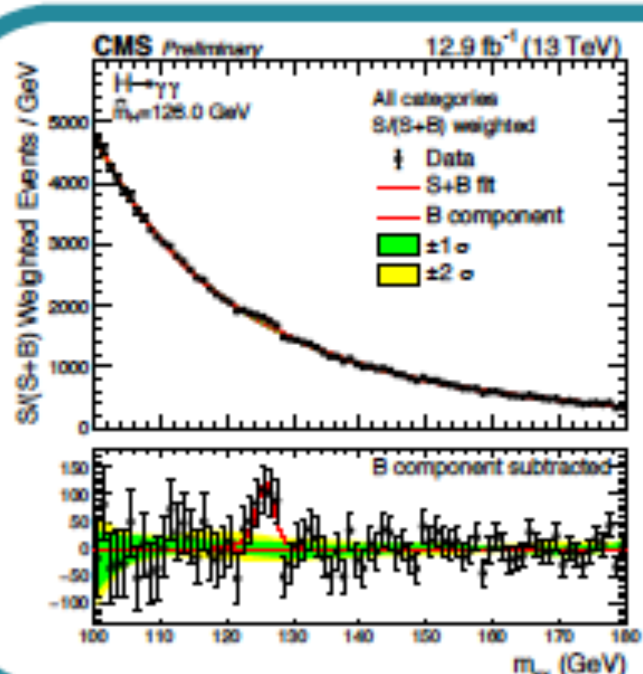
Mary K. GAILLARD
Lawrence Berkeley Laboratory, and Department of Physics, University of California, Berkeley, CA 94720, USA

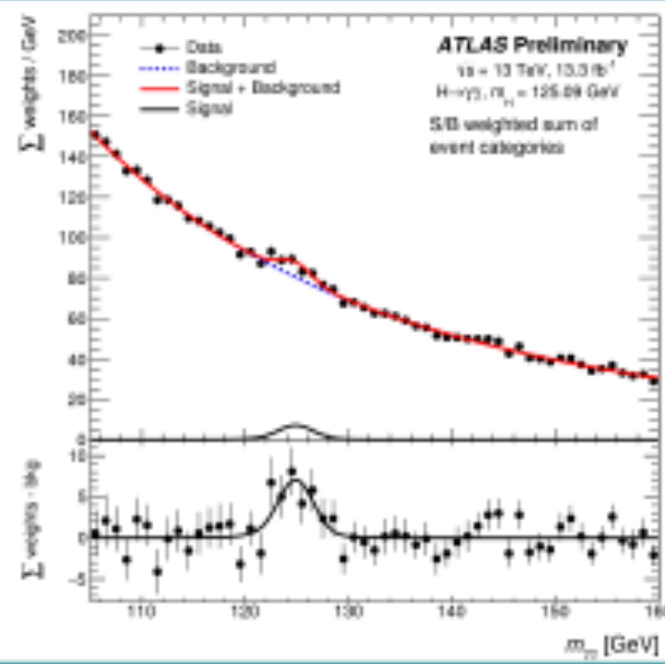
Received 2 April 1984

Anomalously large cross sections for multi W and Z final states will occur at SSC energies if electroweak symmetry breaking is due to new strong interactions.

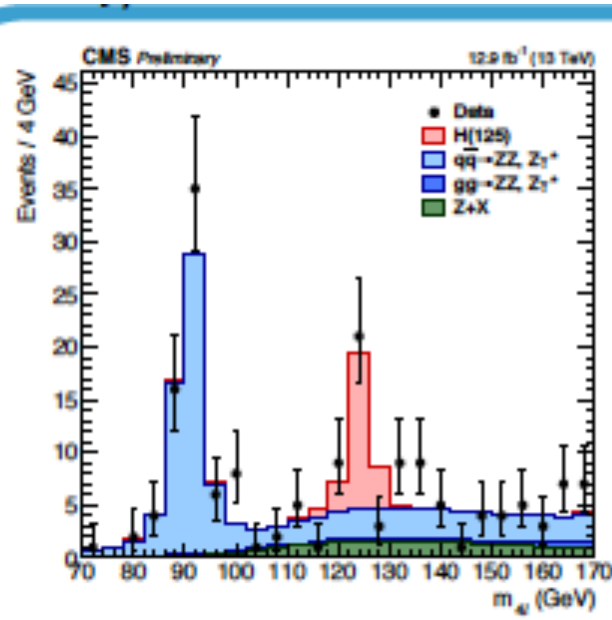
LHC was built at maximal energy possible for LEP tunnel but with ~10 times luminosity to try to be competitive with SSC for strong VV scattering

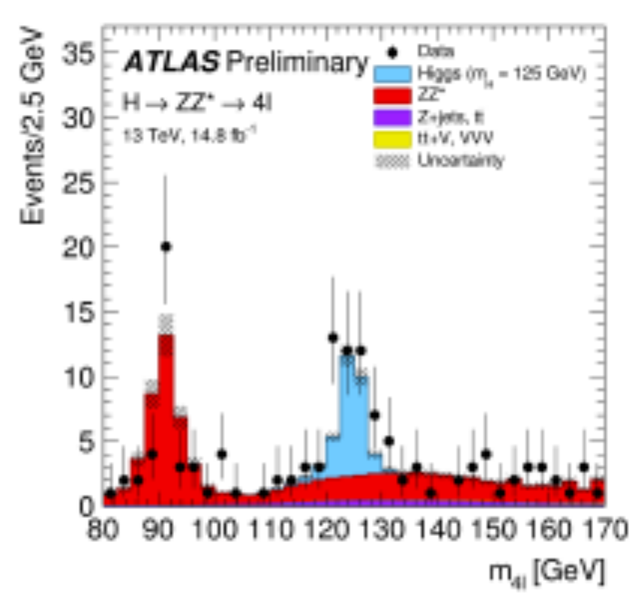
But $\cdots$, the Higgs is now discovered
with $m_h \simeq 125$ GeV
SM describes LHC data very well!



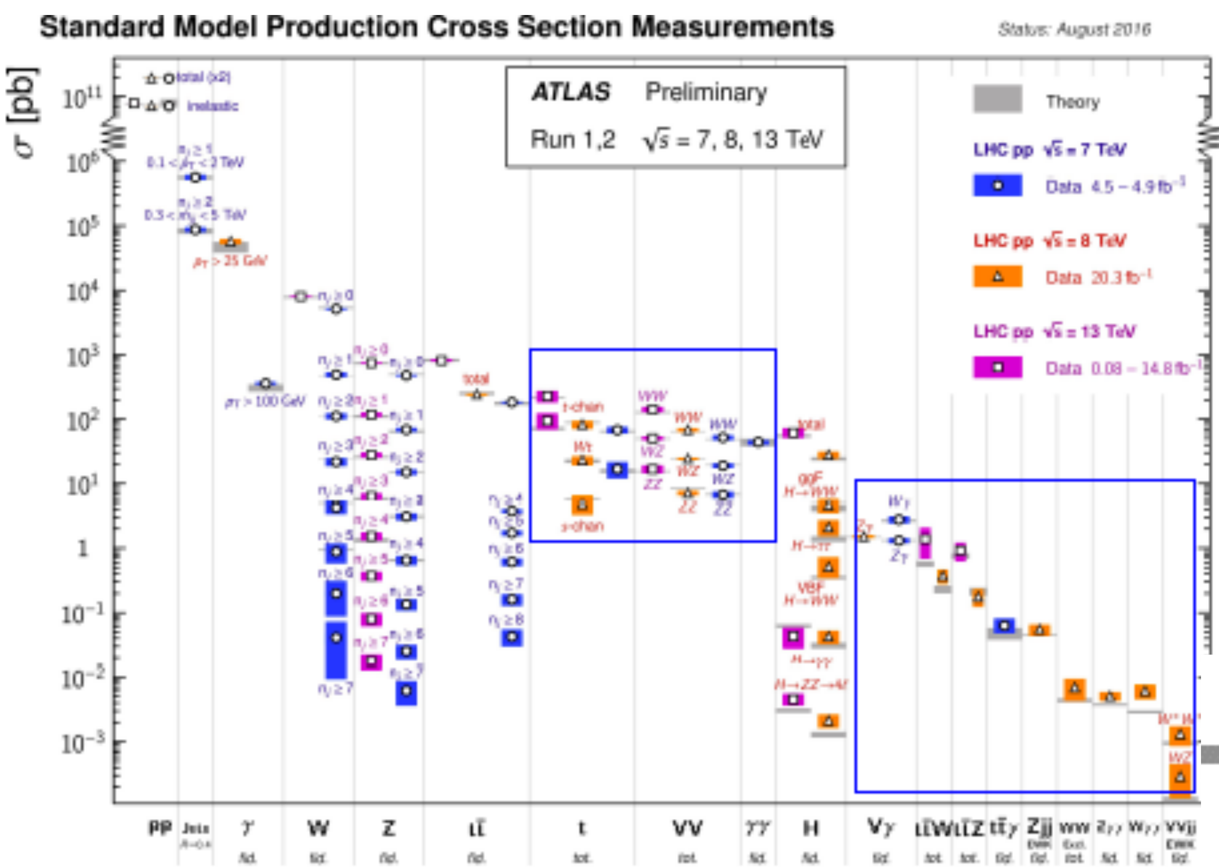


F. Canelli, ICHEP16



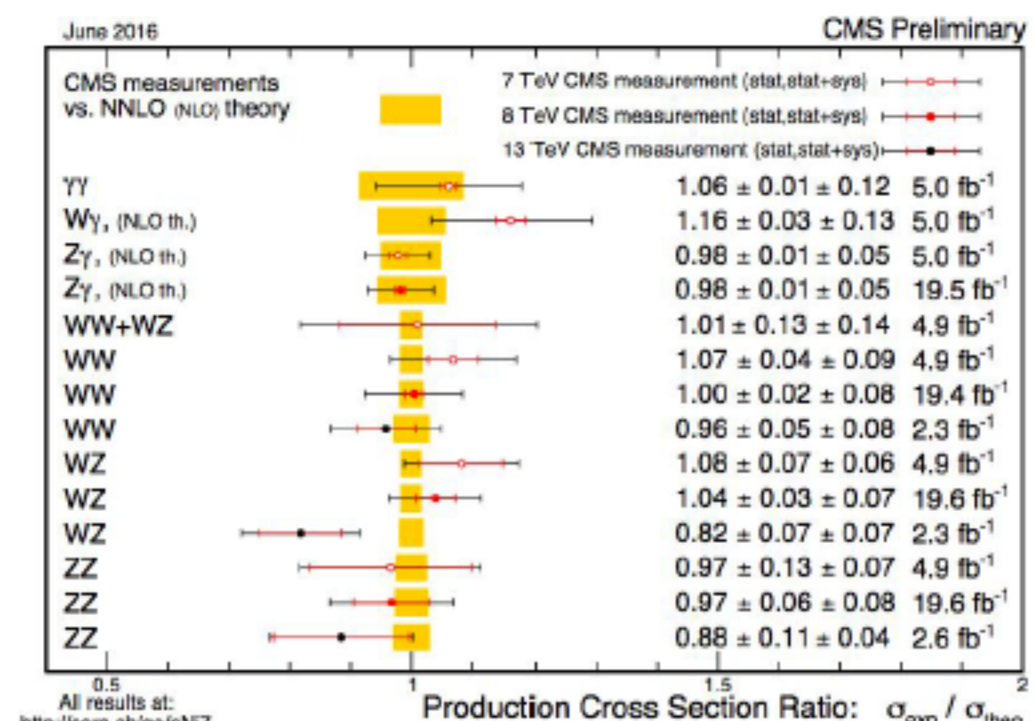


Previous diboson cross section excess now in accord with NNLO calculations!



Diboson cross section summary

Final precise 8TeV diboson cross sections, differential cross sections.
New 13TeV cross section, starting to go differential.
Measurements consistent with NNLO



What we learned from ICHEP2016:
MB data in exceptional agreement with SM!

750 GeV $\gamma\gamma$ bump gone

Is there any hope for discovery of BSM physics at LHC?
Many papers skeptical:
nature looks very SM-like and so far no SUSY either

Natural SUSY: Now or Never?

J. S. Kim*
Instituto de Física Teórica UAM/CSIC, Madrid, Spain

K. Rolbiecki†
Institute of Theoretical Physics, University of Warsaw, Poland

R. Ruiz‡
Instituto de Física Corpuscular, IFIC-UV/CSIC, Valencia, Spain

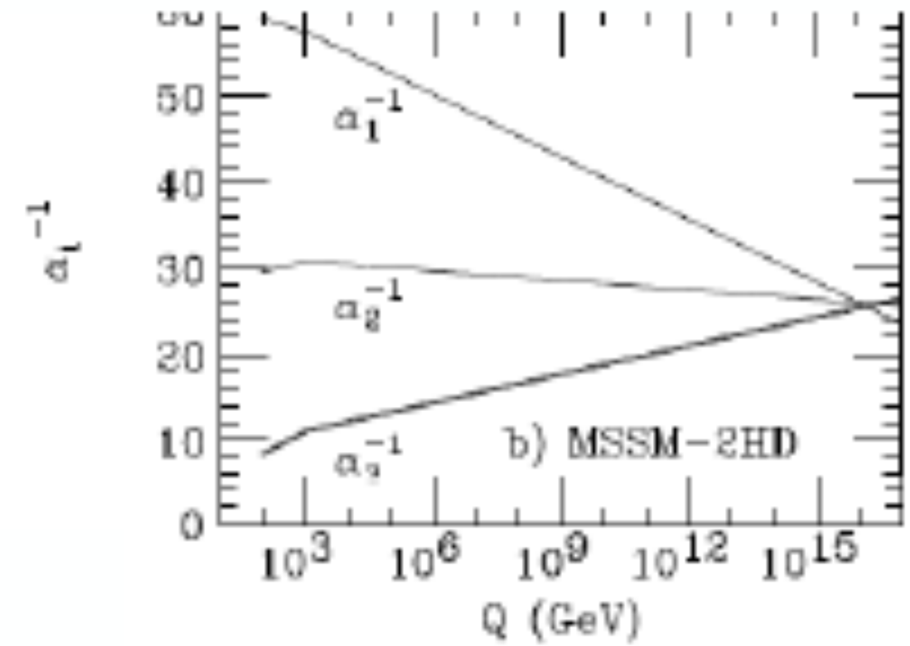
J. Tattersall§ and T. Weber¶
Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen, Germany

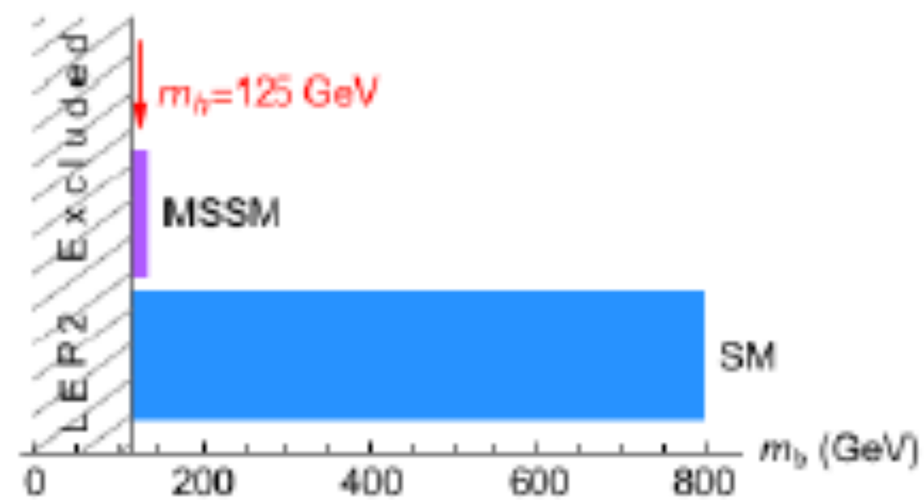
same time period. However, more pessimistically we find that if no signal begins to appear this summer only a very small region of parameter space can be discovered with 5-σ significance. For

We will refute this point of view;
prospects for SUSY at LHC quite bright!

Nature sure looks like SUSY

- stabilize Higgs mass
- measured gauge couplings
- m(t)~173 GeV for REWSB
- mh(125): squarely within SUSY window





Multi-boson production from gluino/squark production: already noted in first paper on SUSY cascade decays

Detecting gluinos at hadron supercolliders

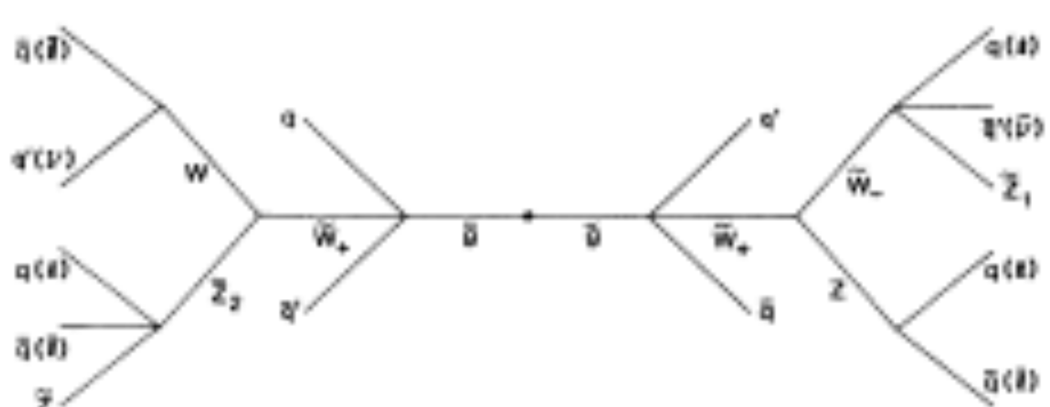
Howard Baer
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

V. Barger
Physics Department, University of Wisconsin, Madison, Wisconsin 53706

Debra Karatas
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439
and Physics Department, Illinois Institute of Technology, Chicago, Illinois 60616

Xerxes Tata
Physics Department, University of Wisconsin, Madison, Wisconsin 53706
(Received 5 December 1986)

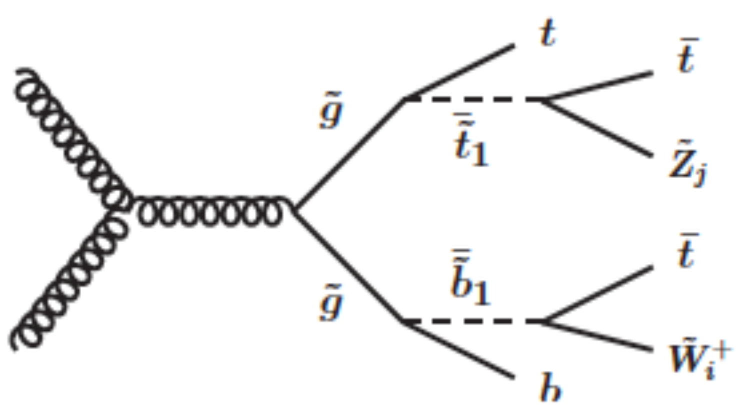
If the gluino mass exceeds 150–200 GeV, searches for gluinos will likely have to be made at multi-TeV hadron colliders. Unlike the case of light gluinos ($m_{\tilde{g}} \lesssim 60$ GeV), which dominantly decay via $\tilde{g} \to q\bar{q}\tilde{\gamma}$, heavy-gluino decays proceed via $\tilde{g} \to q\bar{q}\tilde{W}_i$ and $\tilde{g} \to q\bar{q}\tilde{Z}_j$ where $\tilde{W}_i$ and $\tilde{Z}_j$ are charged and neutral mass eigenstates in the gauge-Higgs-fermion sector. The usual missing-p_T signatures are altered and new strategies may be required for gluino detection. We analyze heavy-gluino and scalar-quark decays and estimate the production rates for $\tilde{W}_i\tilde{W}_j$, $\tilde{W}_i\tilde{Z}_j$, and $\tilde{Z}_i\tilde{Z}_j$ pairs at a 40-TeV pp collider. Since a heavy gluino decays dominantly into jets and the heavy chargino, which in turn decays into a Z^0 or W boson plus a lighter chargino or neutralino, a typical gluino-pair event contains several leptons and/or jets in the final state.



$$\tilde{g}\tilde{g} \to WZ + jets + MET$$

nowadays, expect enhanced multi-boson production from gluino/squark production

$$\tilde{g} \to t\bar{t}\tilde{\chi}_i^0$$
$$\tilde{g} \to t\bar{b}\tilde{\chi}_j^- + c.c.$$



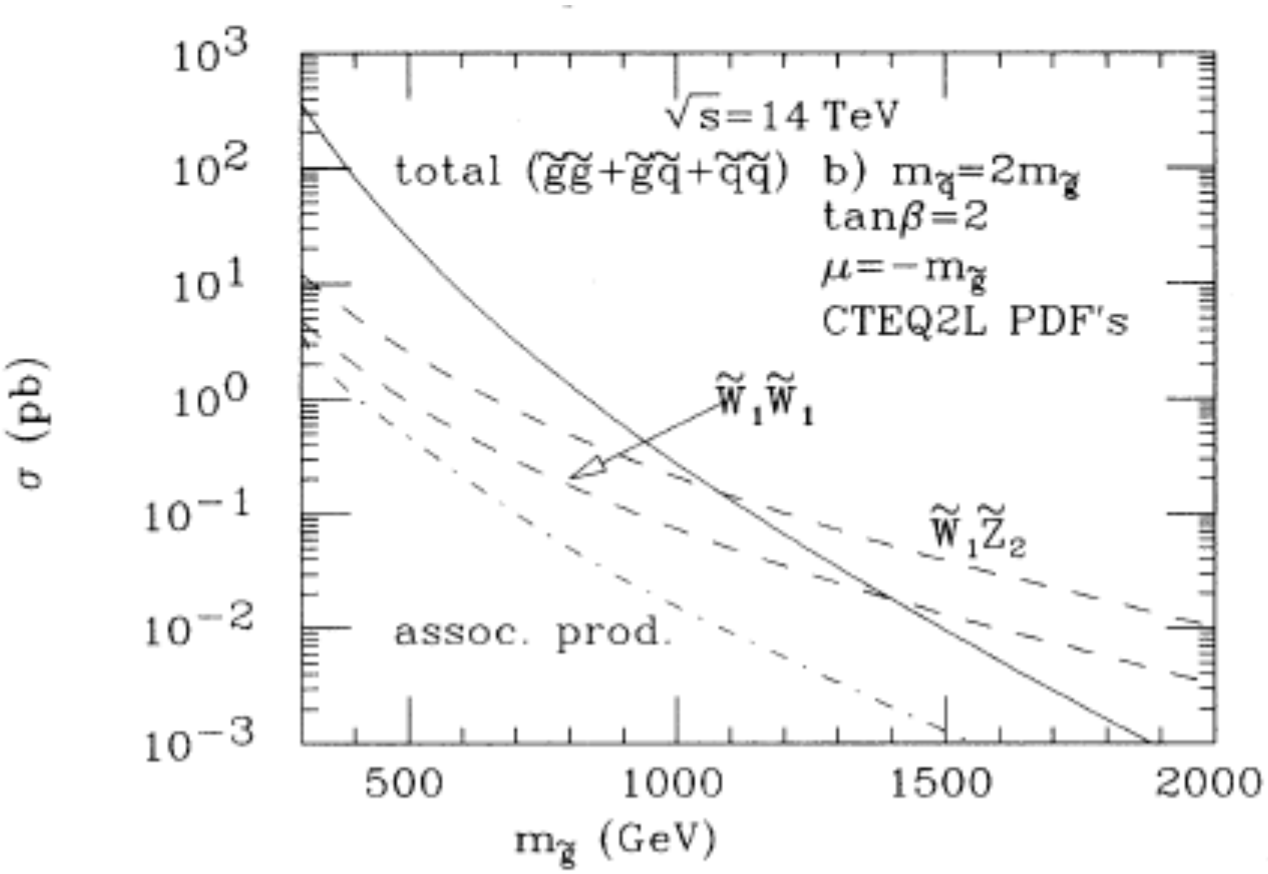
$\tilde{g} \to top$ enhanced by:

- large top Yukawa
- low mass stop mediator
- stop mass splitting due to mixing

HB, Tata, Woodside, PRD42 (1990) 1568; PRD45 (1992) 142

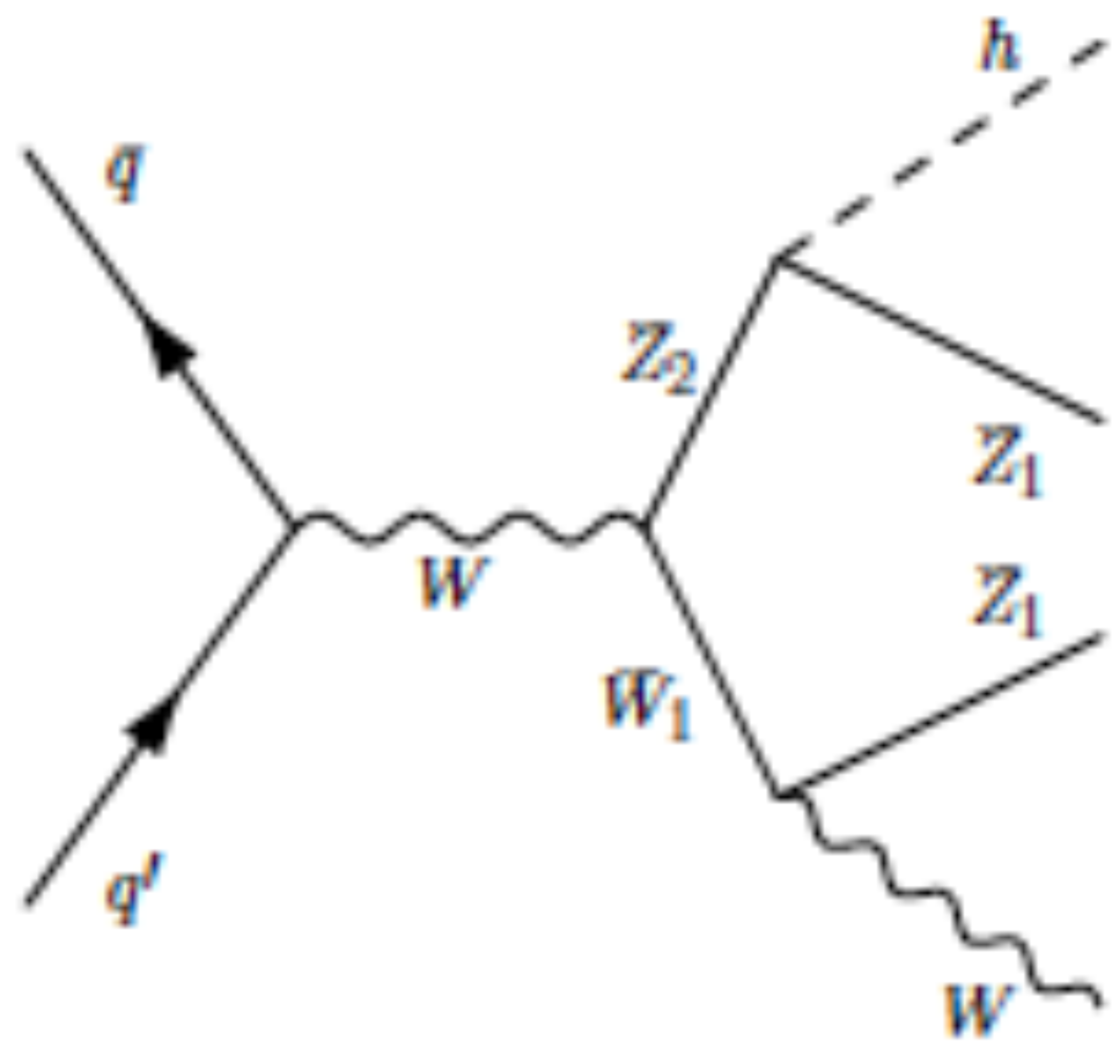
can lead to WWWW+jets+MET signatures
signals rich in top and b jets
multi-isolated leptons: 1l, OS, SS, 3l,4l…

It is often said that gluinos/squarks yield the largest SUSY production cross sections at LHC: this is true if all sparticles are equal mass; NOT true if e.g. gaugino mass unification: then expect M1:M2:M3~1:2:7



$$\sigma(EWinos) \gg \sigma(\tilde{g}\tilde{g})?$$

This provides new search possibilities especially for higher integrated luminosity LHC



This reaction was labelled ``spoiler mode'' for Tevatron SUSY searches since once it turned on, then clean trilepton signature was suppressed

But for LHC, it offers new search possibility:

$$pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to (W\tilde{\chi}_1^0) + (h\tilde{\chi}_1^0) \to Wh + MET$$

HB, Barger, Lessa, Sreethawong, Tata PRD85 (2012) 055022

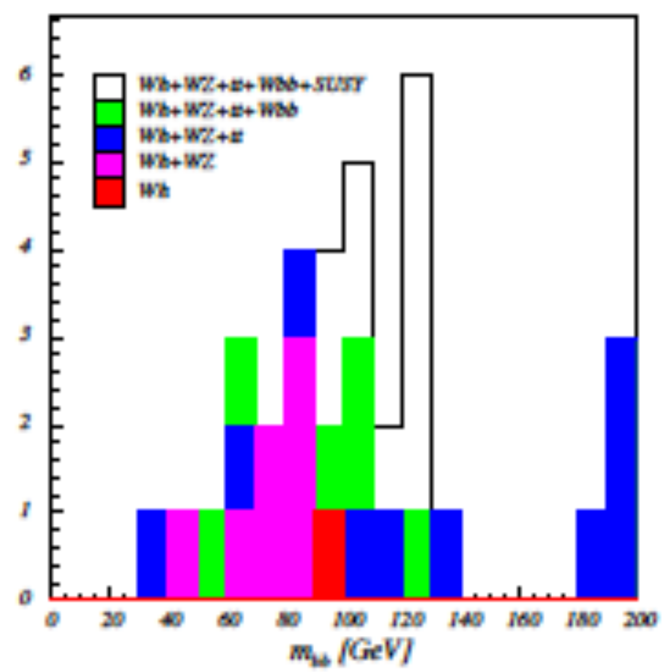
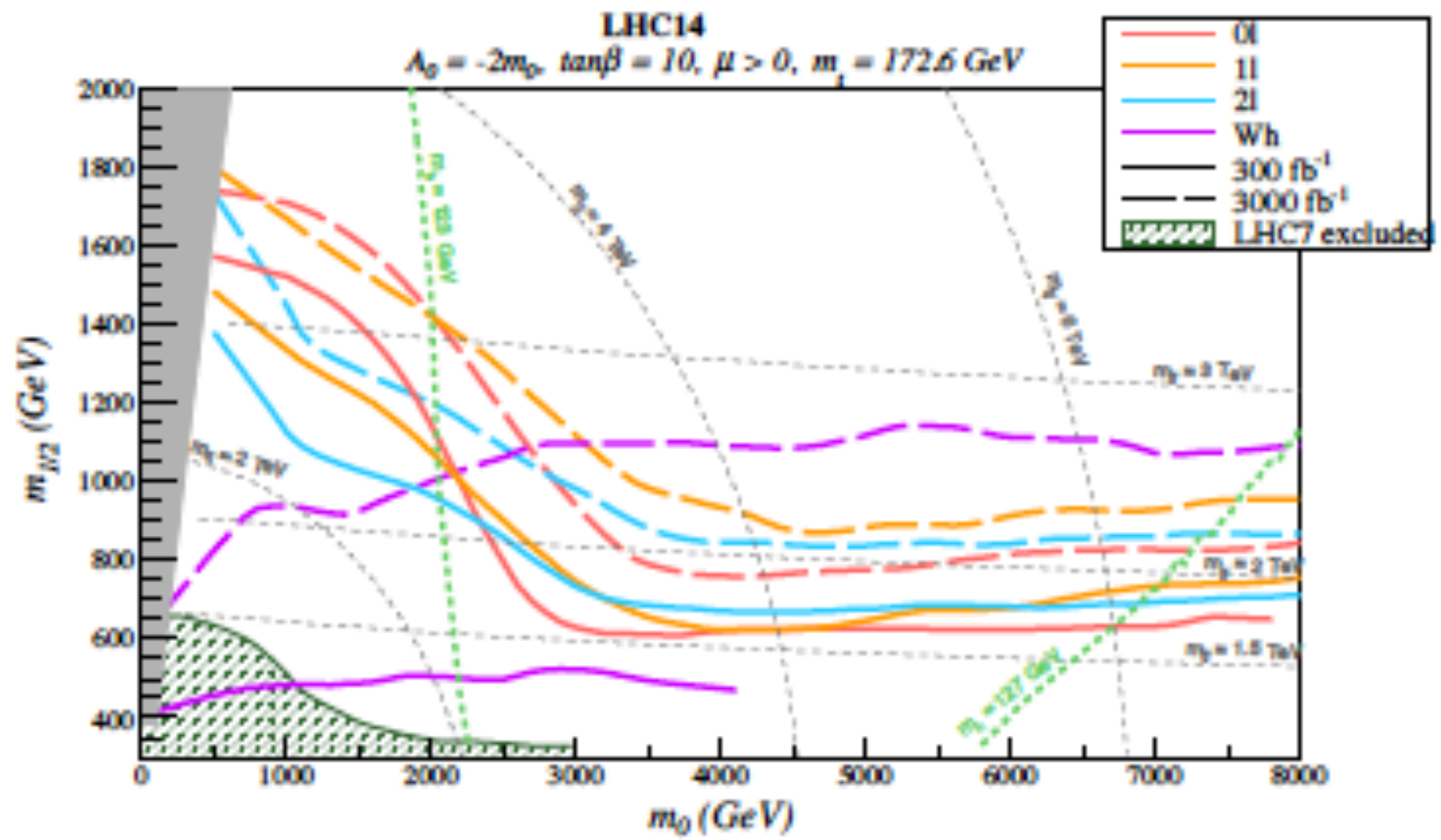
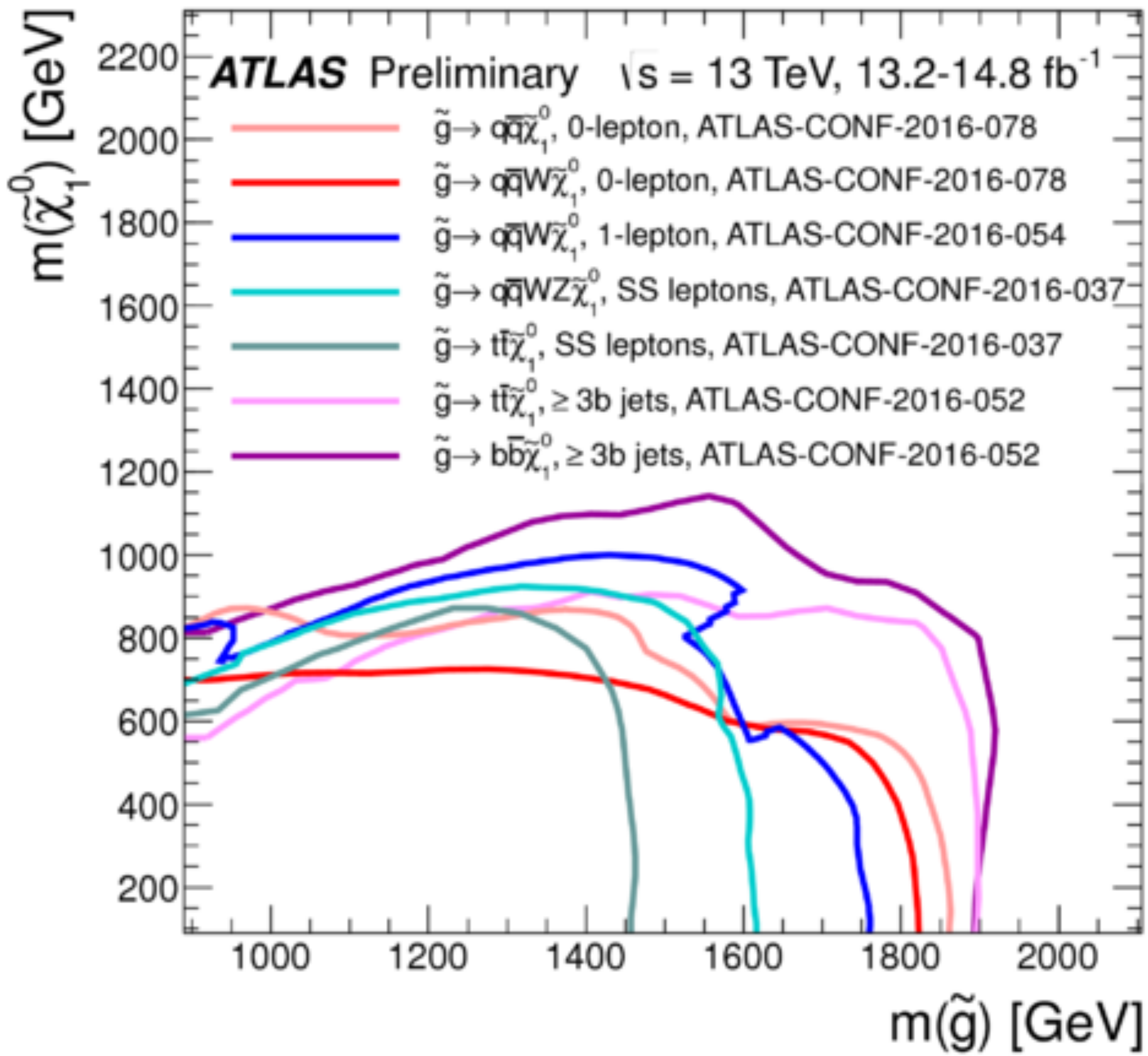


FIG. 3: Number of events expected in 100 fb^{-1} of LHC14 d
versus $m(b\bar{b})$ for various summed SM backgrounds (shad
and SUSY signal, with $m_{\tilde{W}_1} = 620$ GeV and $m_h = 125$ G



this channel gives best reach of HL-LHC for (unnatural) models like mSUGRA/CMSSM!

HB, Barger, Lessa, Tata, PRD86 (2012) 117701 recent search results from Atlas run 2 @ 13 TeV:



evidently $m_{\tilde{g}} > 1.9$ TeV

compare: BG naturalness (1987): $m_{\tilde{g}} < 0.35$ TeV

or is SUSY dead?
how to disprove SUSY?
when it becomes ``unnatural''?
this brings up naturalness issue

``…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!”

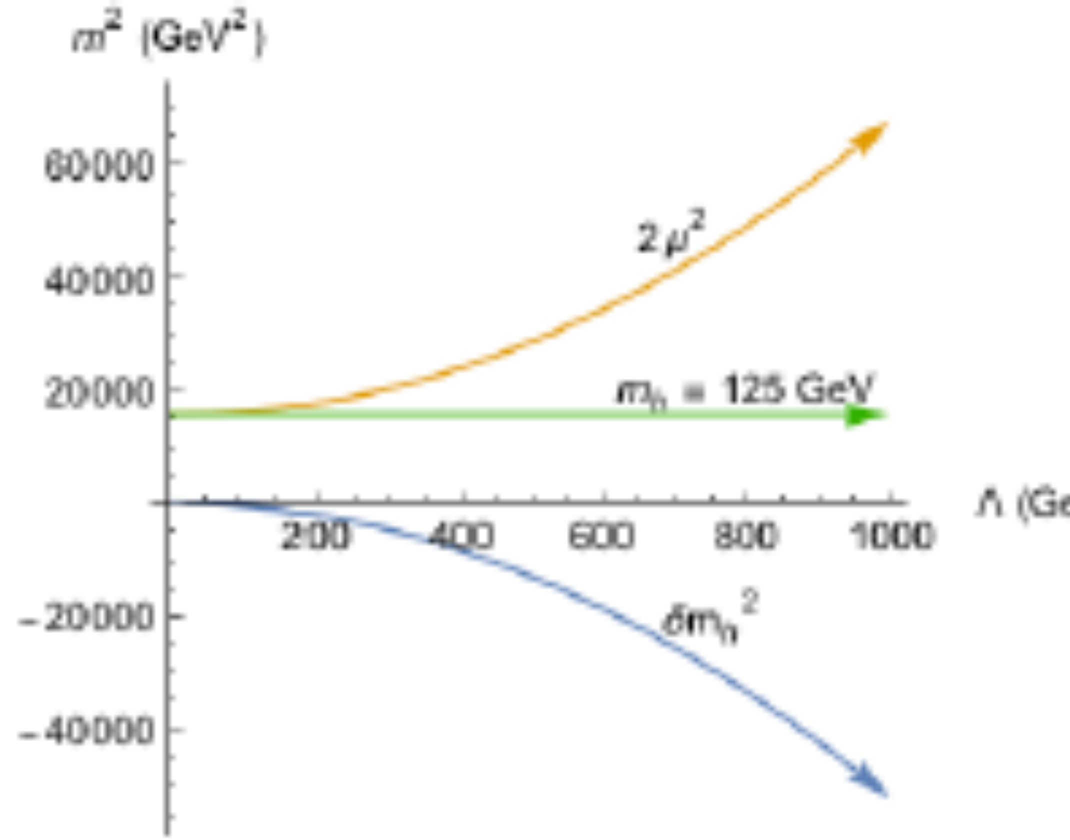
HB, Barger, Mickelson, Padeffke-Kirkland, arXiv:1404.2277

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:

#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)

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

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

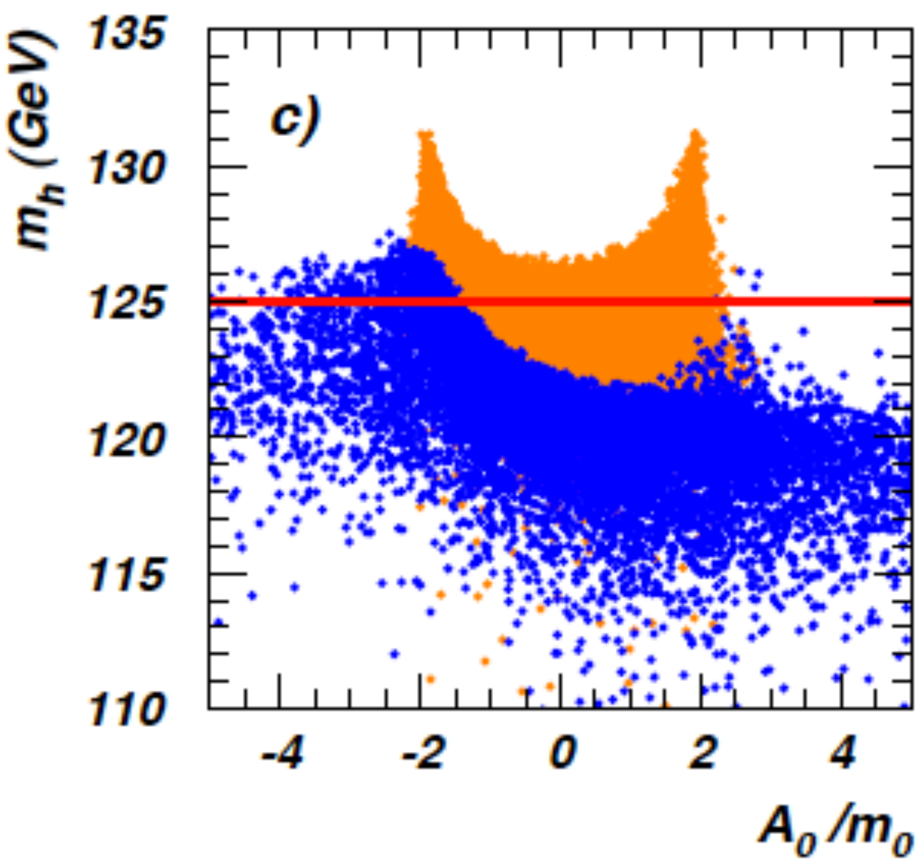
CETUP*-12/002, FTPI-MINN-12/22, UMN-TH-3109/12, UH-511-1195-12

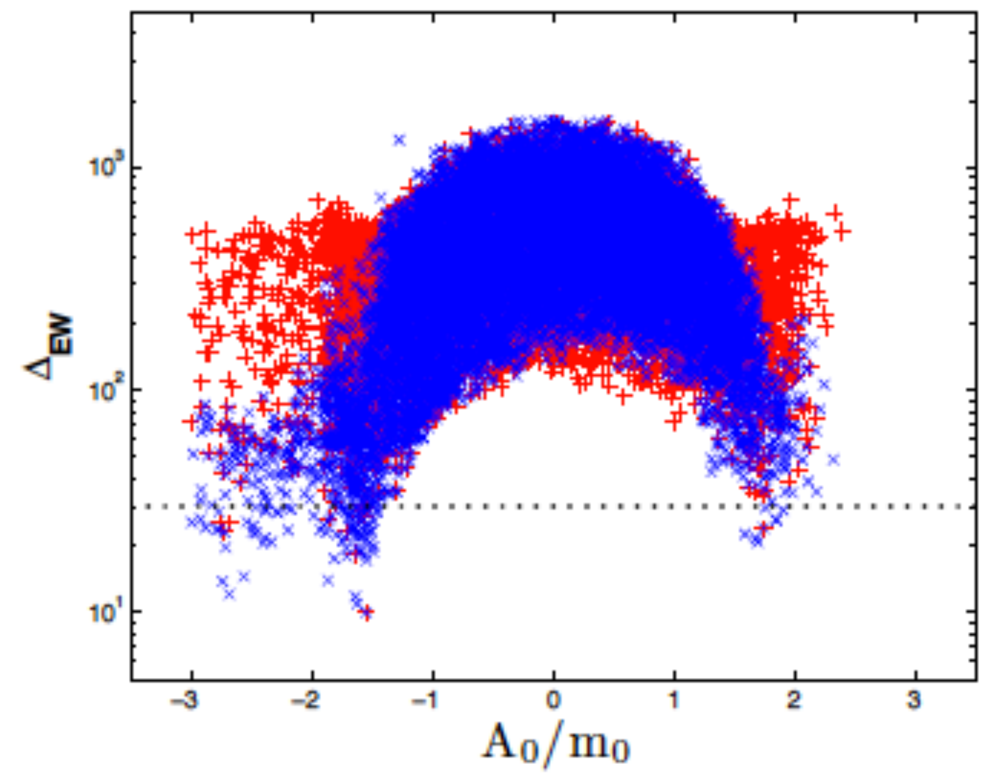
Radiative natural SUSY with a 125 GeV Higgs boson

Howard Baer,[1] Vernon Barger, Peisi Huang,[2] Azar Mustafayev,[3] and Xerxes Tata[4]
[1] Dept. of Physics and Astronomy, University of Oklahoma, Norman, OK, 73019, USA
[2] Dept. of Physics, University of Wisconsin, Madison, WI 53706, USA
[3] W. I. Fine Institute for Theoretical Physics, University of Minnesota, Minneapolis, MN 55455, USA

PRL109 (2012) 161802

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



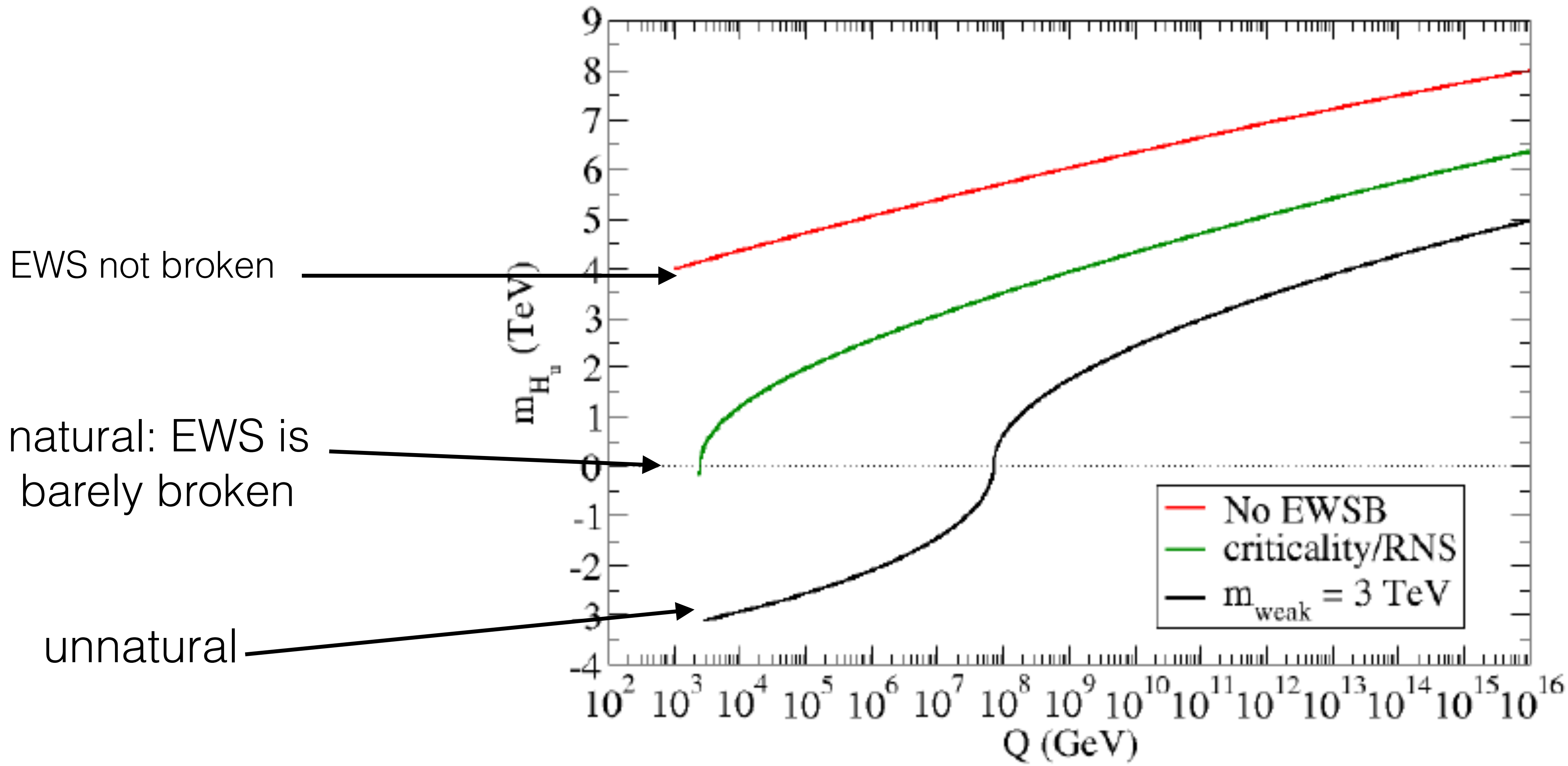


$$\Sigma_u^u(\tilde{t}_{1,2}) = \frac{3}{16\pi^2} F(m_{\tilde{t}_{1,2}}^2)\left[f_t^2 - g_Z^2 \mp \frac{f_t^2 A_t^2 - 8g_Z^2(\frac{1}{4}-\frac{2}{3}x_W)\Delta_t}{m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2}\right]$$

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

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

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



Evolution of the soft SUSY breaking mass squared term $sign(m^2_{H_u})\sqrt{|m^2_{H_u}|}$ 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

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

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

neglect gauge pieces, S, mHu and running;
then we can integrate from m(SUSY) to Lambda

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

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

$$m_{\tilde{t}_{1,2},\tilde{b}_1} < 500 \text{ GeV}$$

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

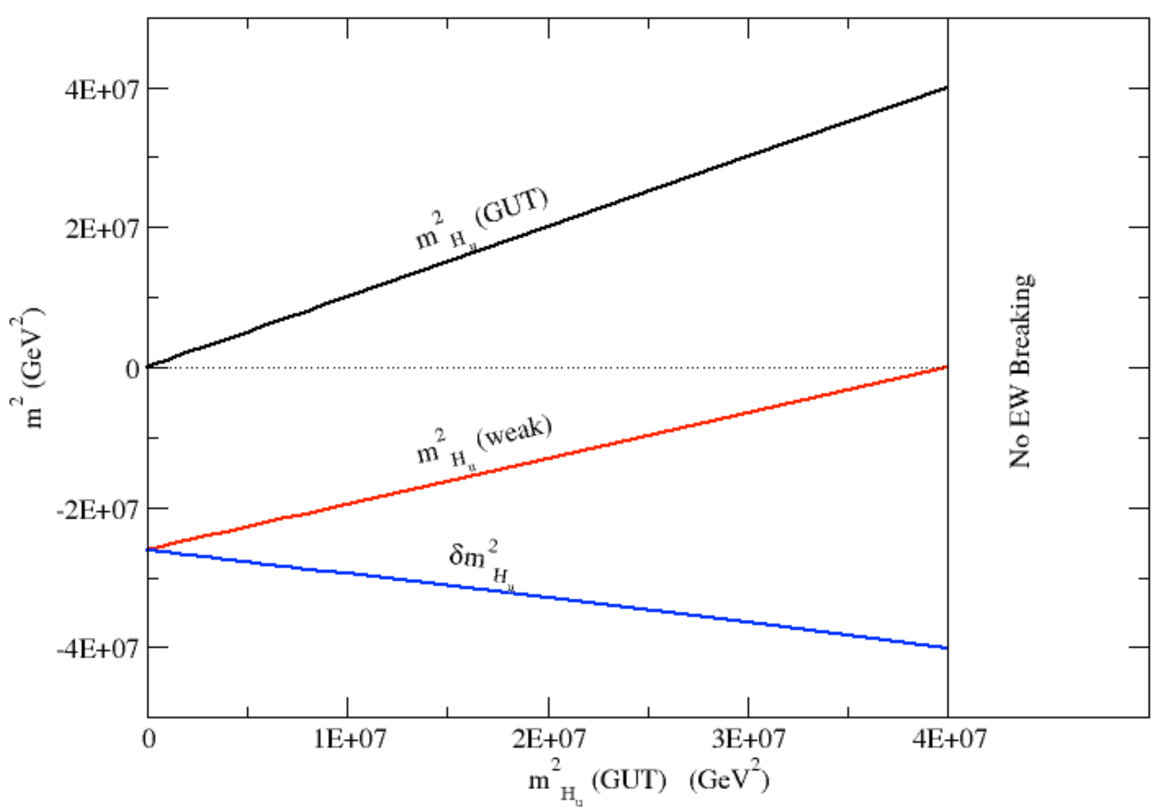
old natural SUSY then A_t can't be too big

What's wrong with this argument?

In zeal for simplicity, have made several simplifications: most egregious is that one sets m(Hu)^2=0 at beginning to simplify

$$m^2_{H_u}(\Lambda) \text{ and } \delta m^2_{H_u} \text{ are } \textit{not} \text{ independent!}$$

violates prime directive!



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

HB, Barger, Savoy

To fix: combine dependent terms:

$m_h^2 \simeq \mu^2 + \left(m_{H_u}^2(\Lambda) + \delta m_{H_u}^2\right)$ where now both μ^2 and $\left(m_{H_u}^2(\Lambda) + \delta m_{H_u}^2\right)$ 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 ?

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

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 $m_{1/2} = -A_0 = \sqrt{3} m_{3/2}$

$$\begin{aligned} m_{H_u}^2 &= a_{H_u} \cdot m_{3/2}^2, \\ m_{Q_3}^2 &= a_{Q_3} \cdot m_{3/2}^2, \\ A_t &= a_{A_t} \cdot m_{3/2}, \\ M_i &= a_i \cdot m_{3/2}, \\ &\cdots . \end{aligned}$$

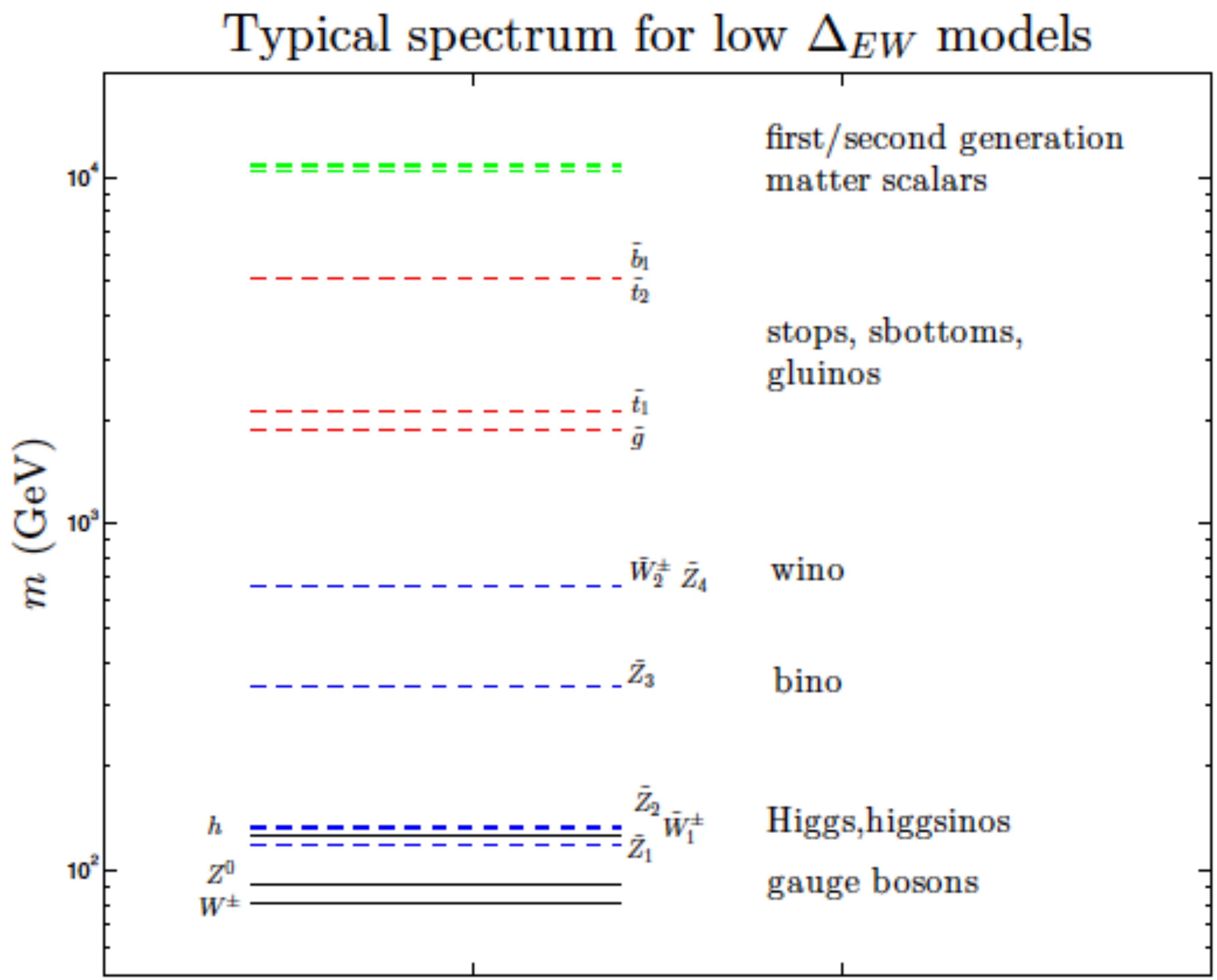
since μ hardly runs, then

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

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

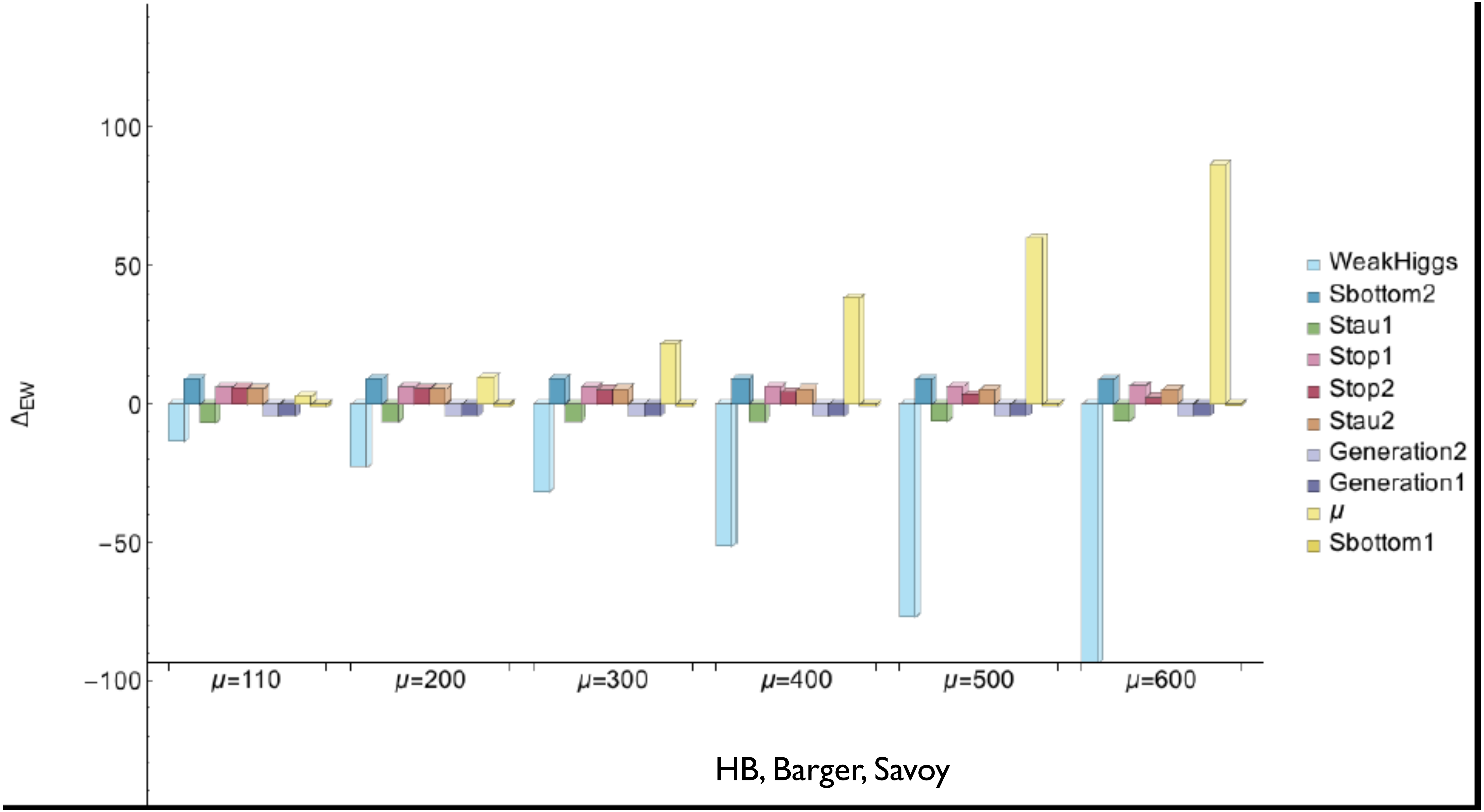
using μ^2 and $m_{3/2}^2$ as fundamental,
then $\Delta_{BG} \simeq \Delta_{EW}$ even using high scale parameters!

SUSY spectra with ~10% EW fine-tuning



easy to hide at LHC

How much is too much fine-tuning?



HB, Barger, Savoy

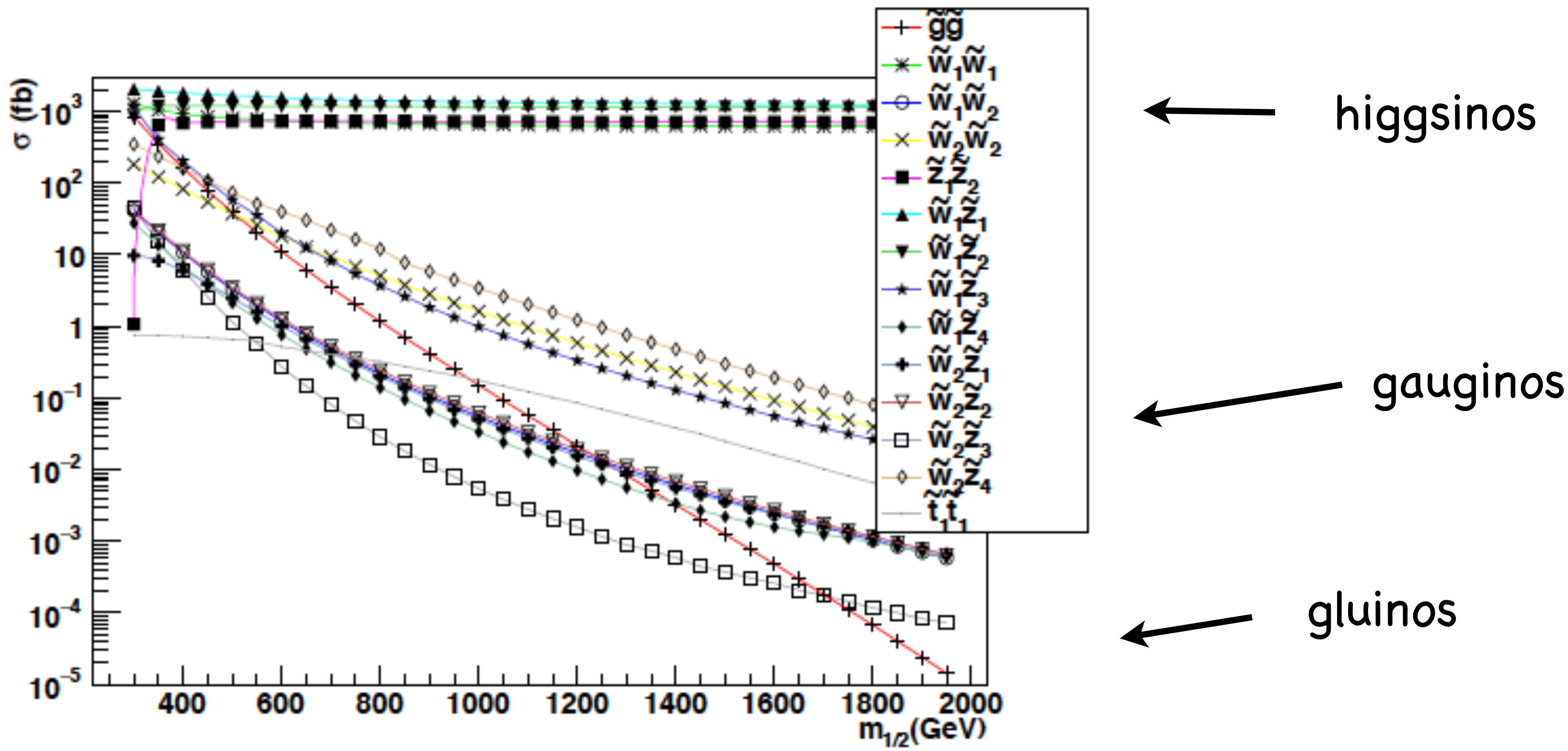
Visually, large fine-tuning has already developed by $\mu \sim 350$ or $\Delta_{EW} \sim 30$

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!

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

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

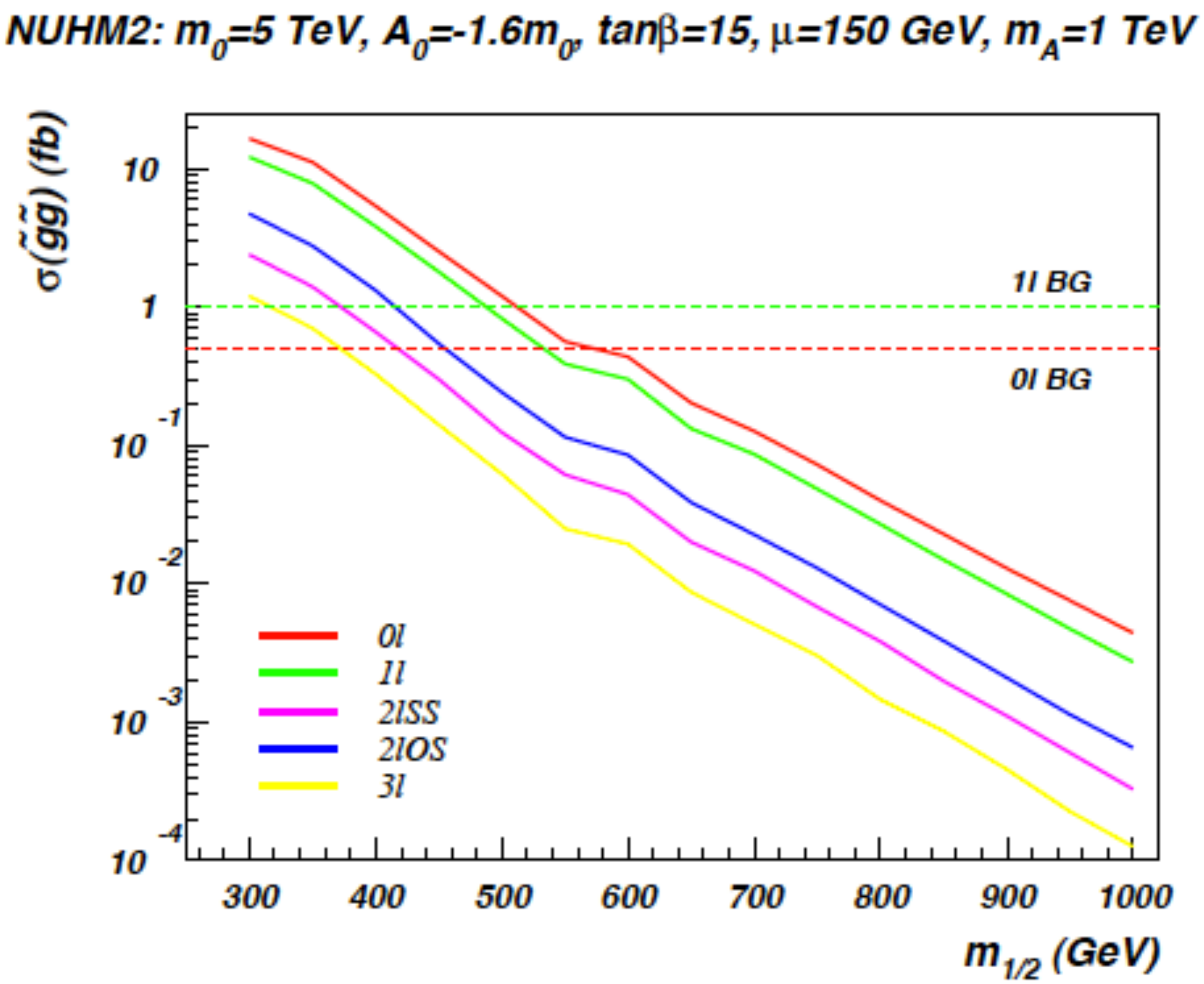


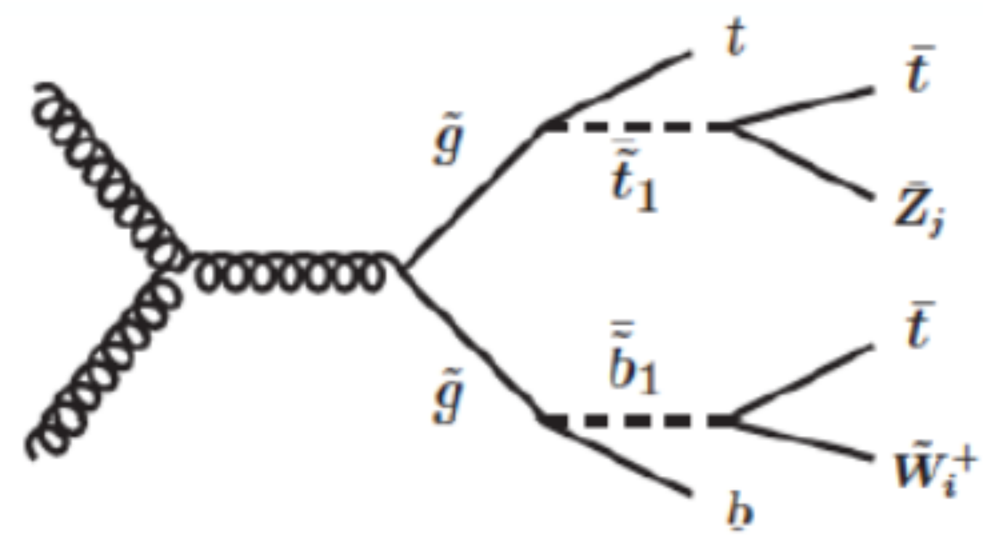
higgsino pair production dominant-but only soft visible energy release from higgsino decays

largest visible cross section: wino pairs

gluino pairs sharply dropping

gluino pair cascade decay signatures





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

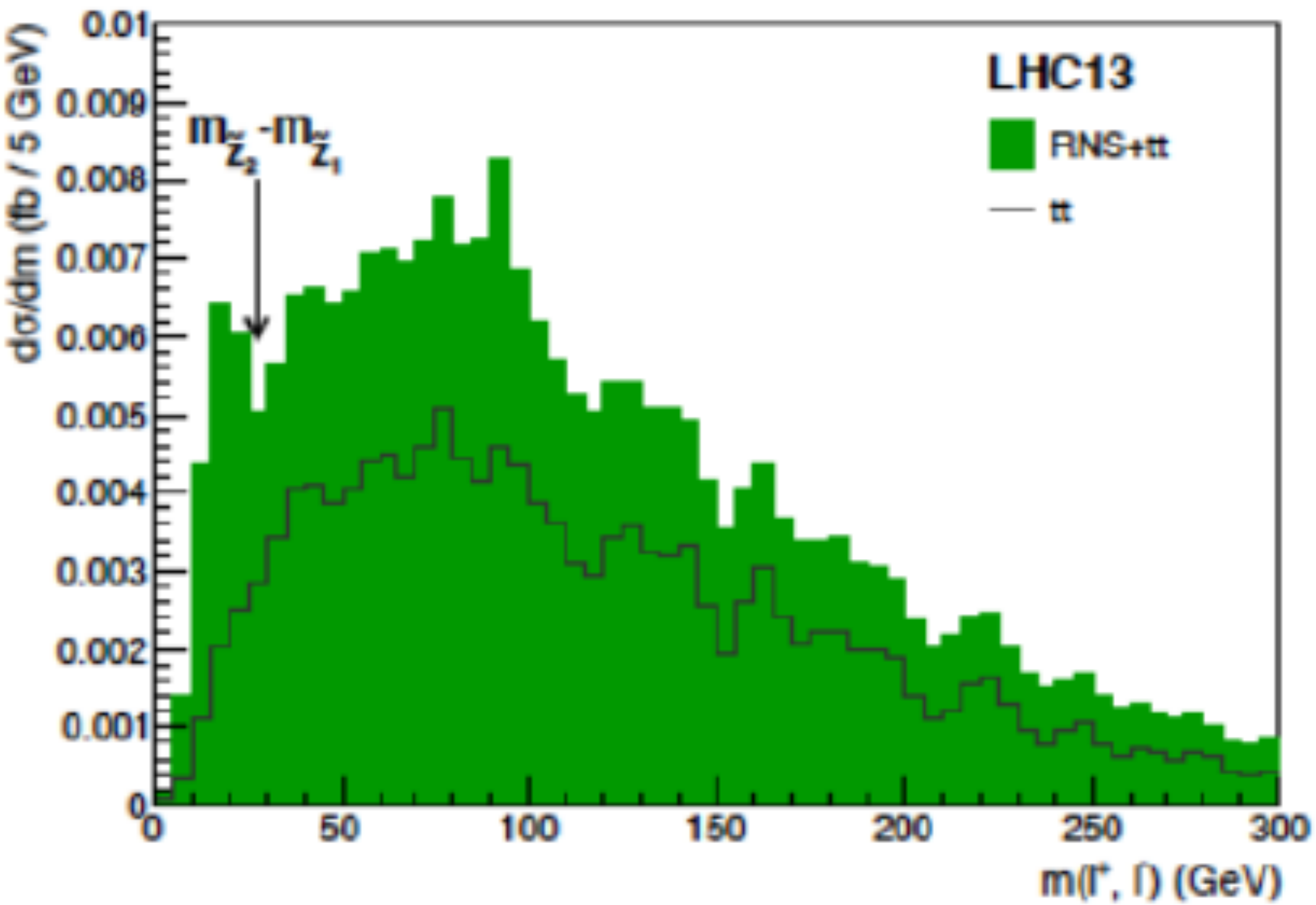
Table 1: Dominant branching fractions of various sparticles along the RNS model line for $m_{1/2} =$ 1 TeV.

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(gluino) (TeV)

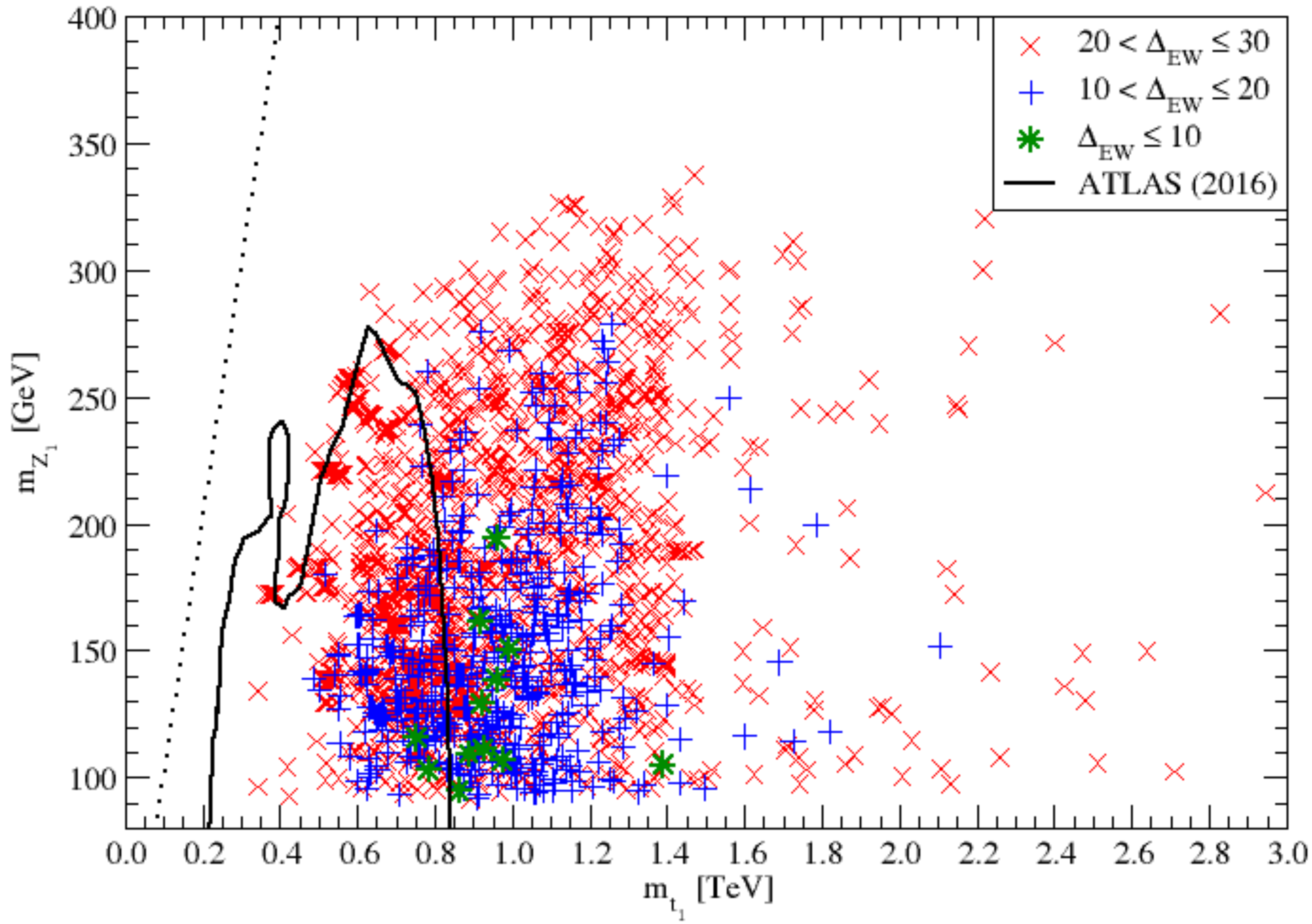
since m(gluino) extends to ~4 TeV, LHC14 can see about half the low EWFT parameter space in these modes

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

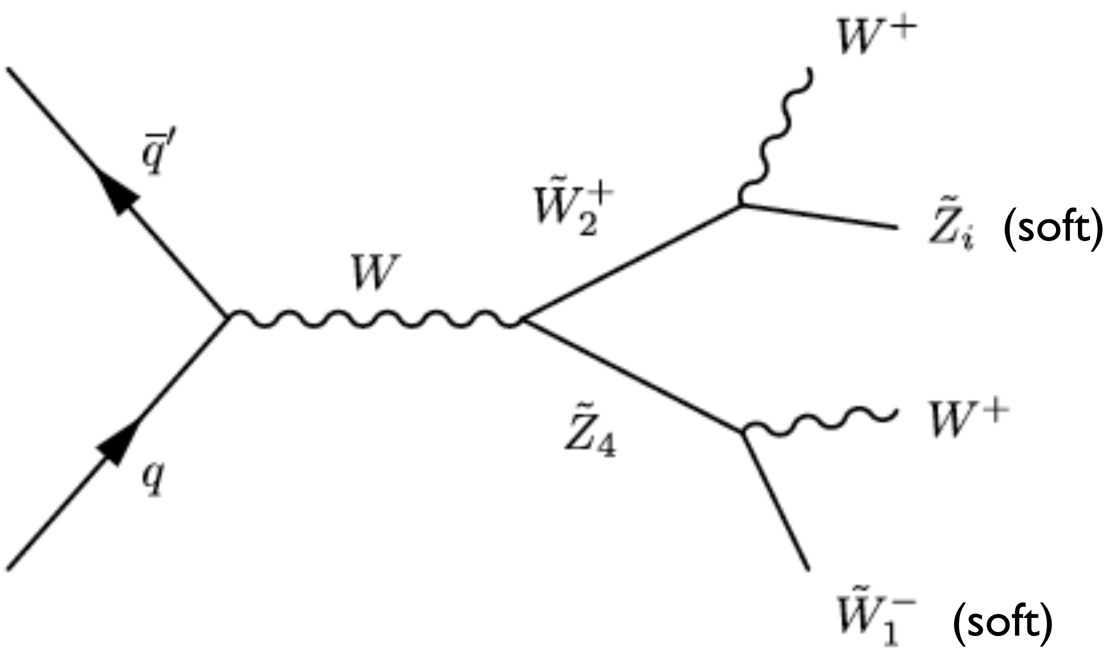


OS/SF dilepton mass edge apparent from cascade decays with z2->z1+l+lbar

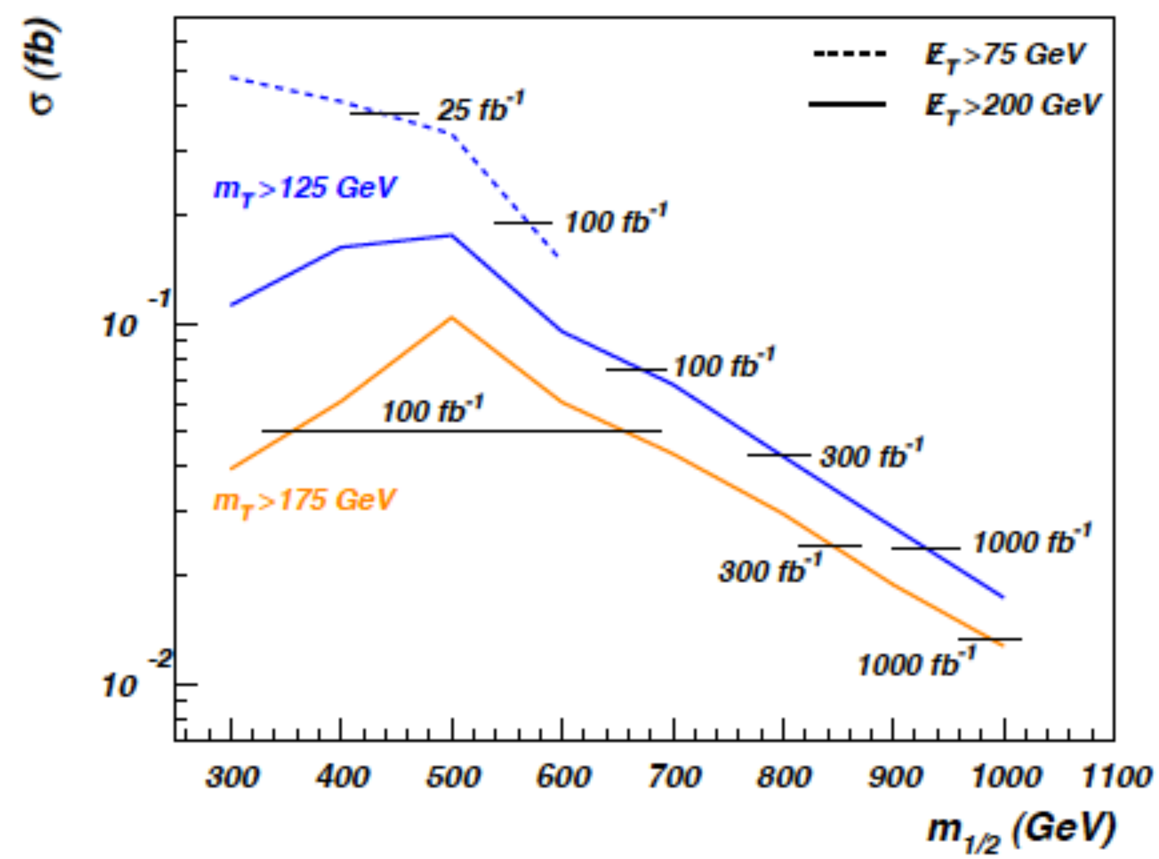
top squark pair searches: LHC has only begun…



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



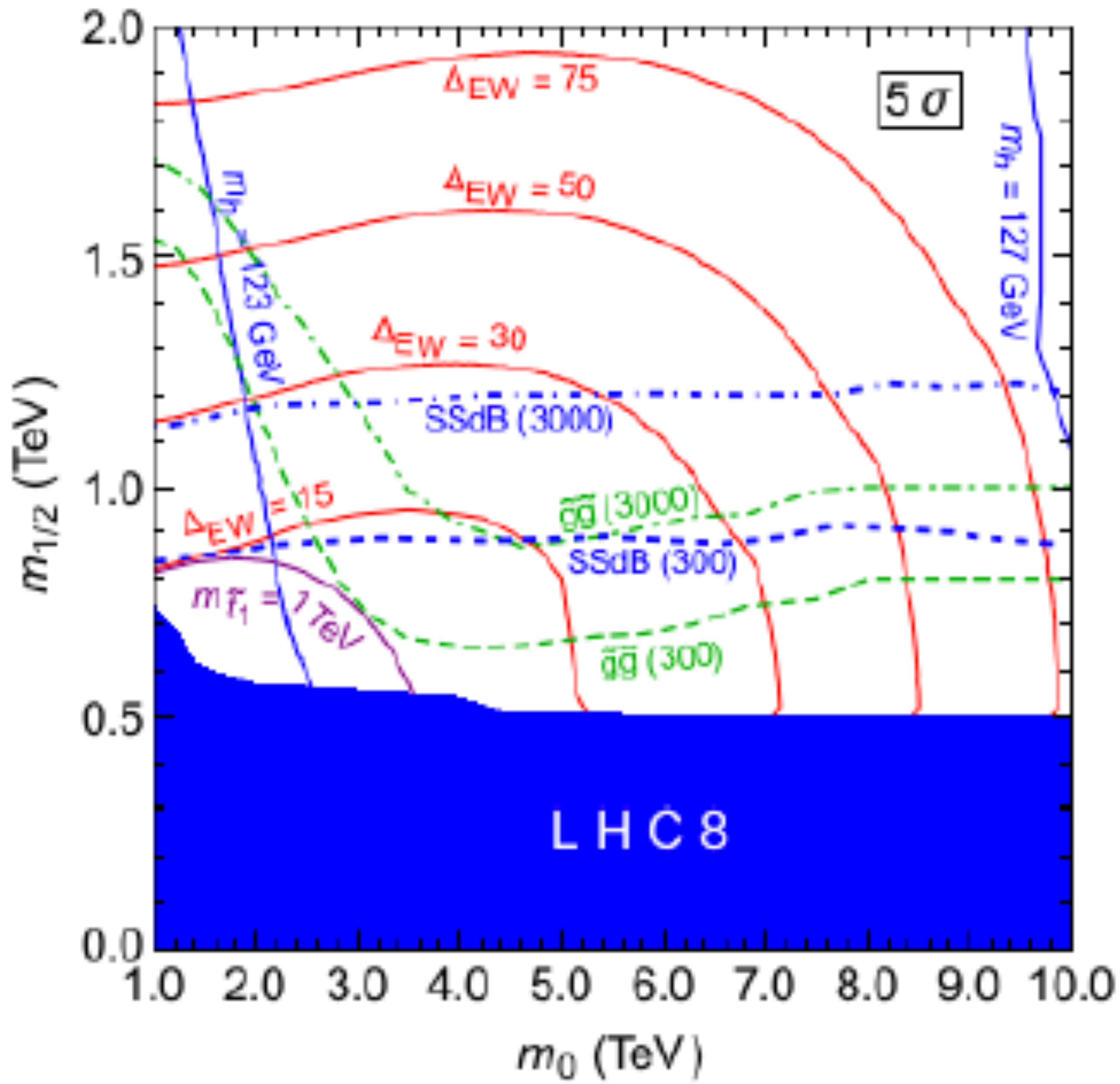
wino pair production



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

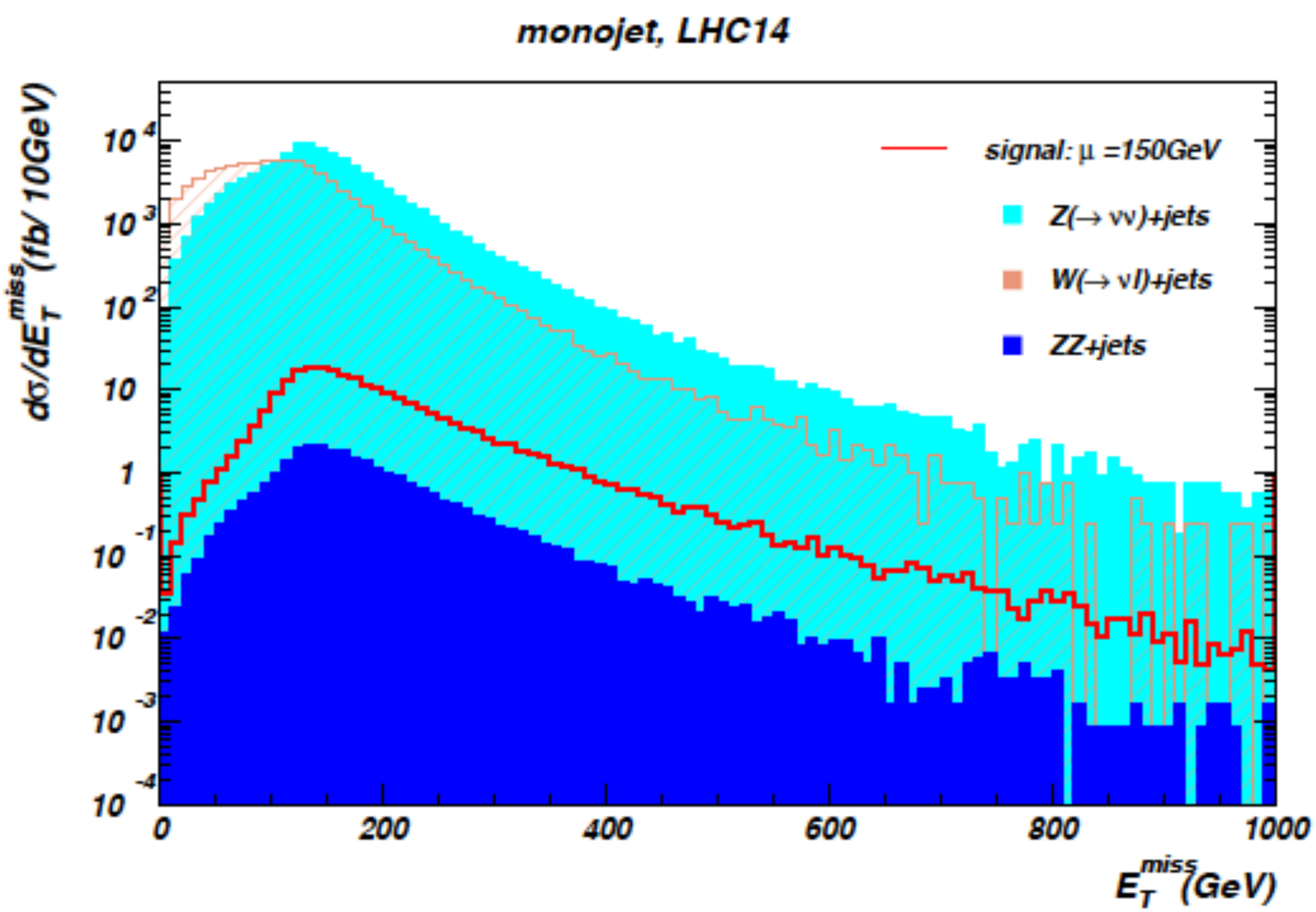
H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev, W. Sreethawong and X. Tata, *Phys. Rev. Lett.* **110** (2013) 151801.

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



HB,Barger,Savoy, Tata; arXiv:1604.07438

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

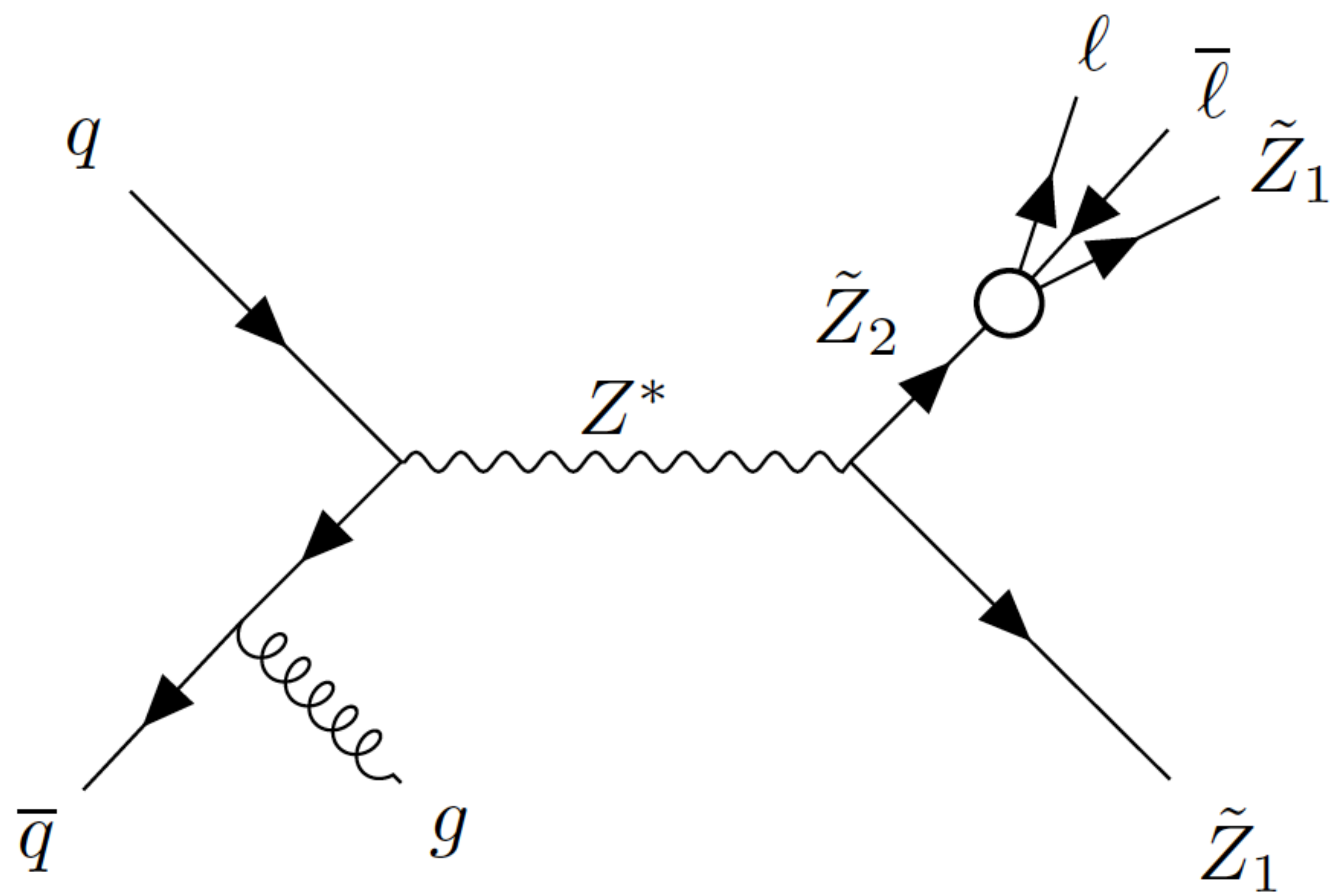


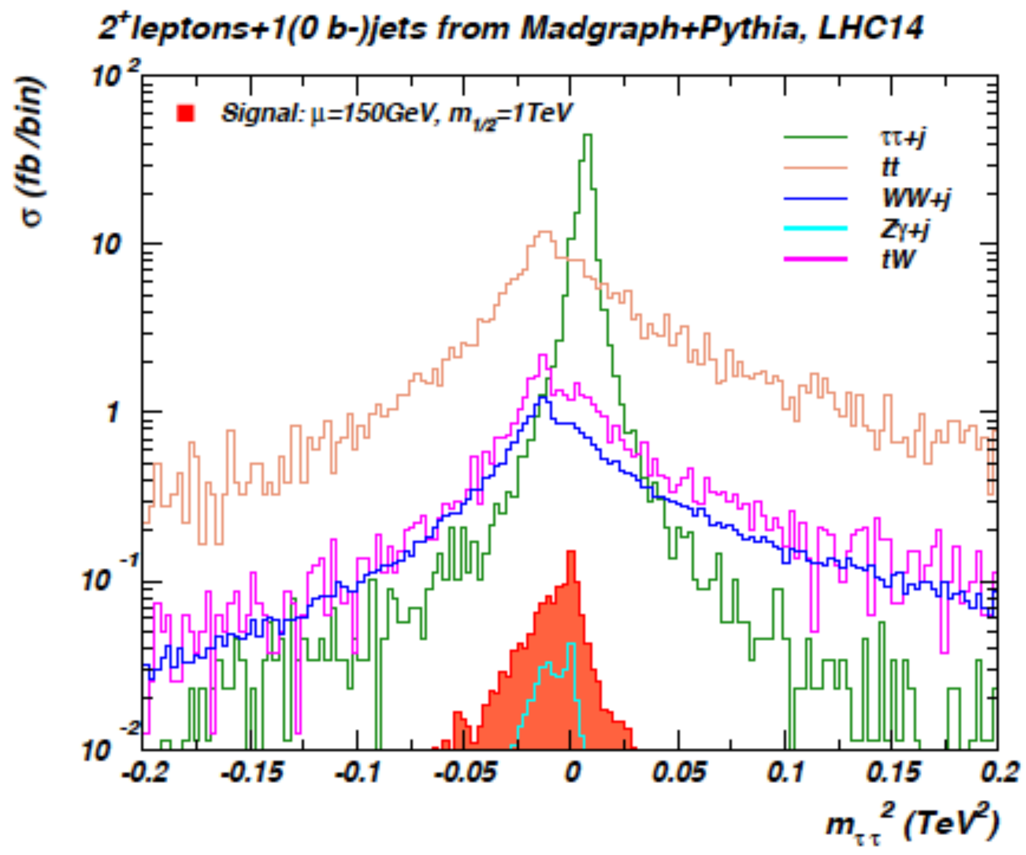
typically 1% S/BG after cuts:
very tough to do!

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

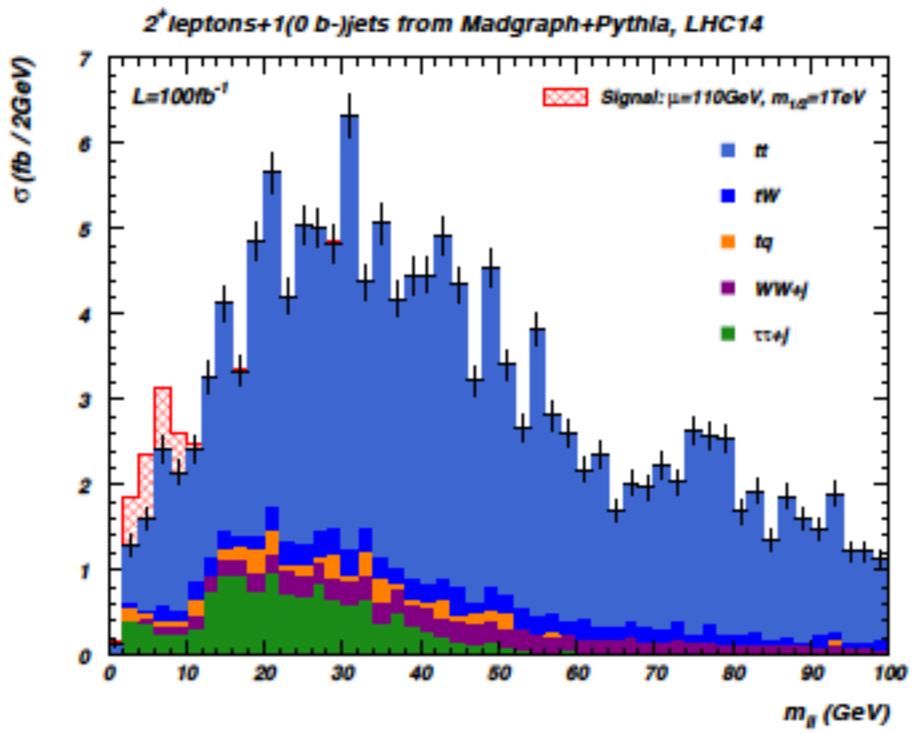
di-bosino production

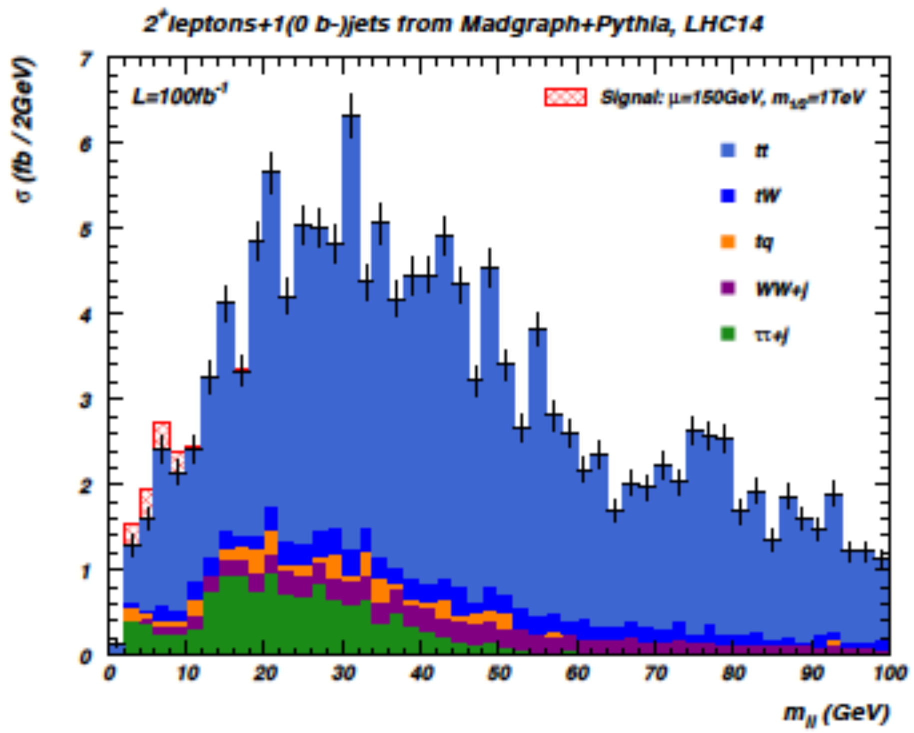
Giudice, T. Han, Wang, Wang, PRD81 (2010) 115011;
Han, Kribs, Martin, Menon, PRD89 (2014) 075007;
HB, Mustafayev, Tata, PRD90 (2014) 115007;



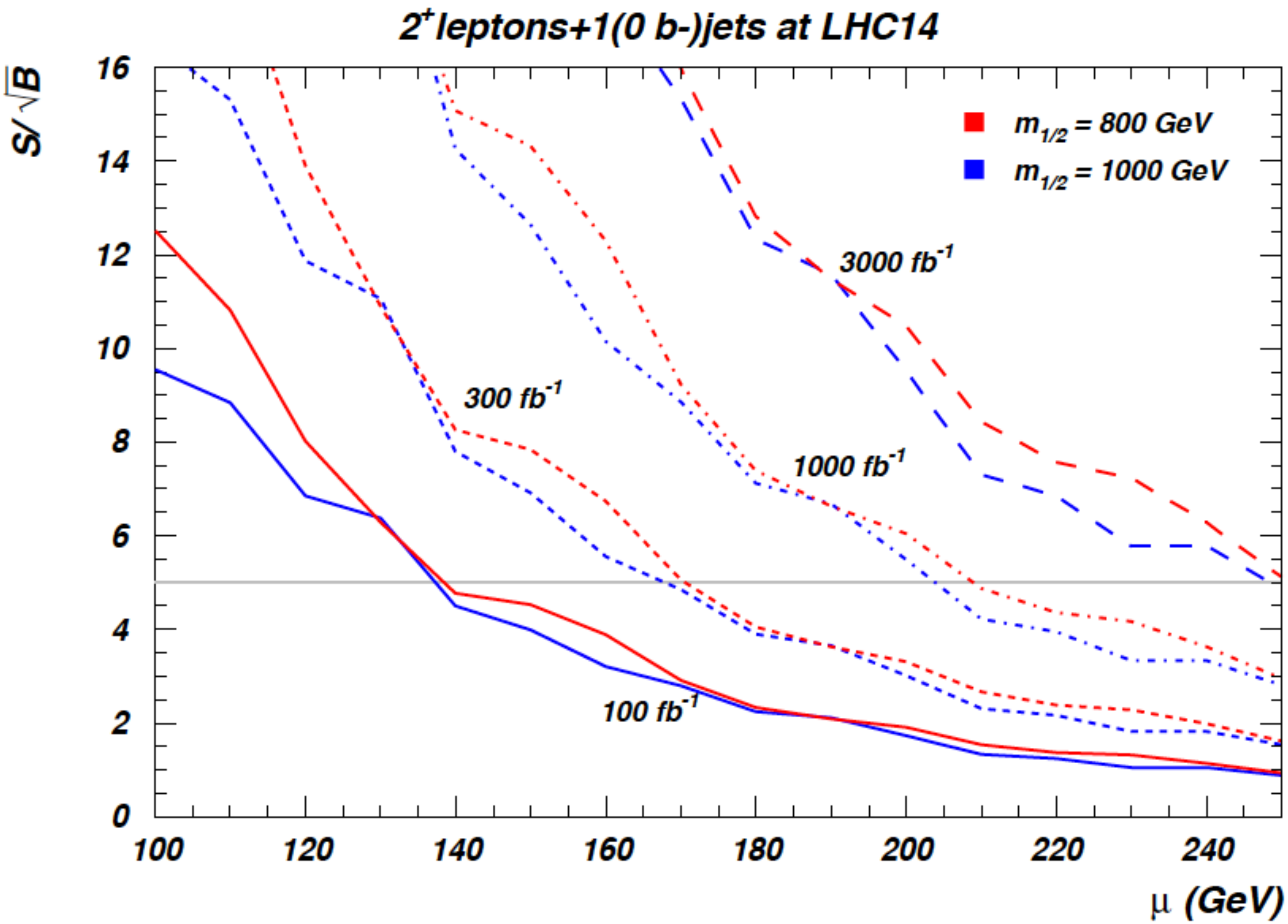


use MET to construct m^2(tau-tau)



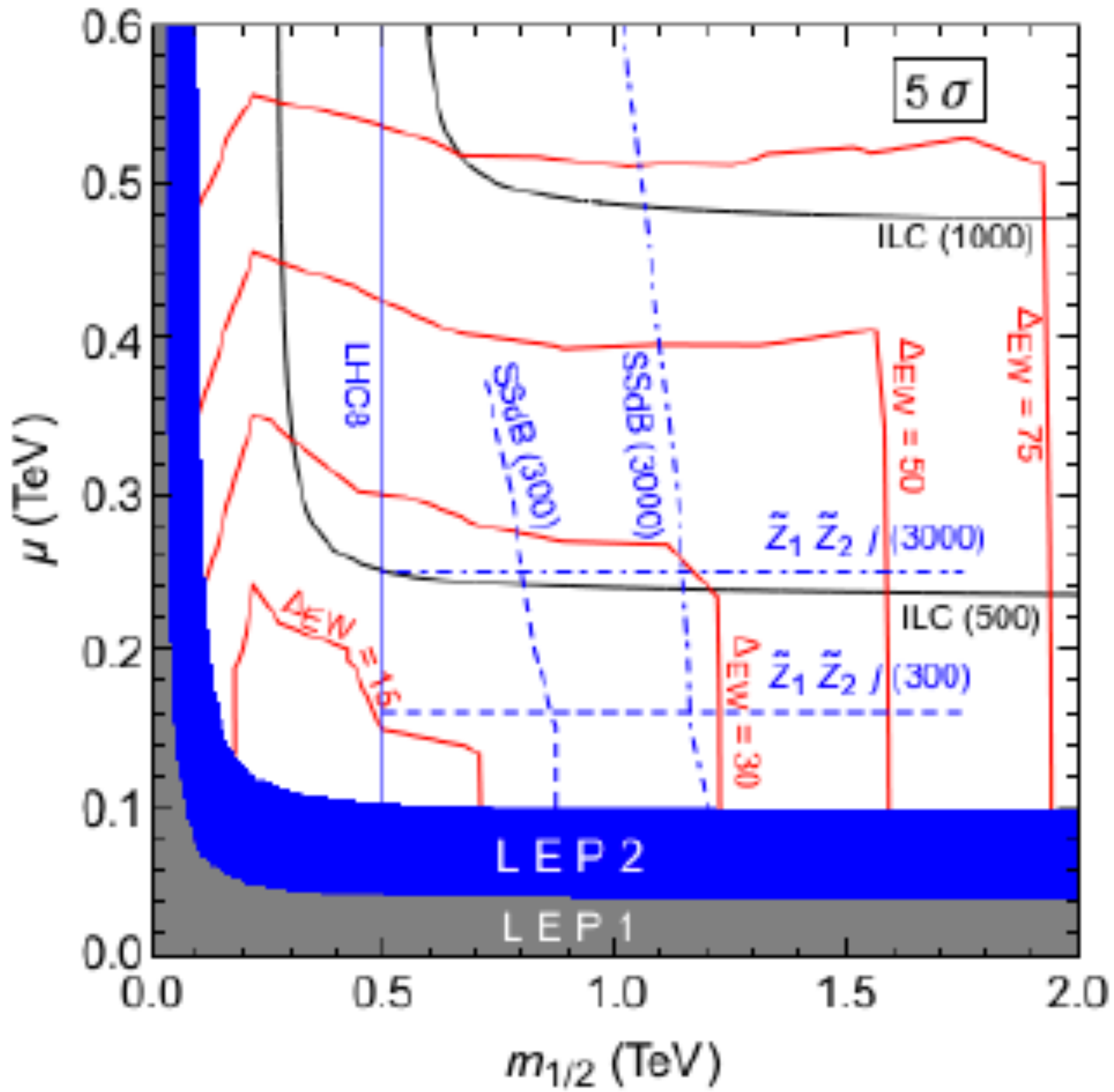


LHC reach for soft dilepton+jet+MET



HB, Mustafayev, Tata; PRD90 (2014) 115007

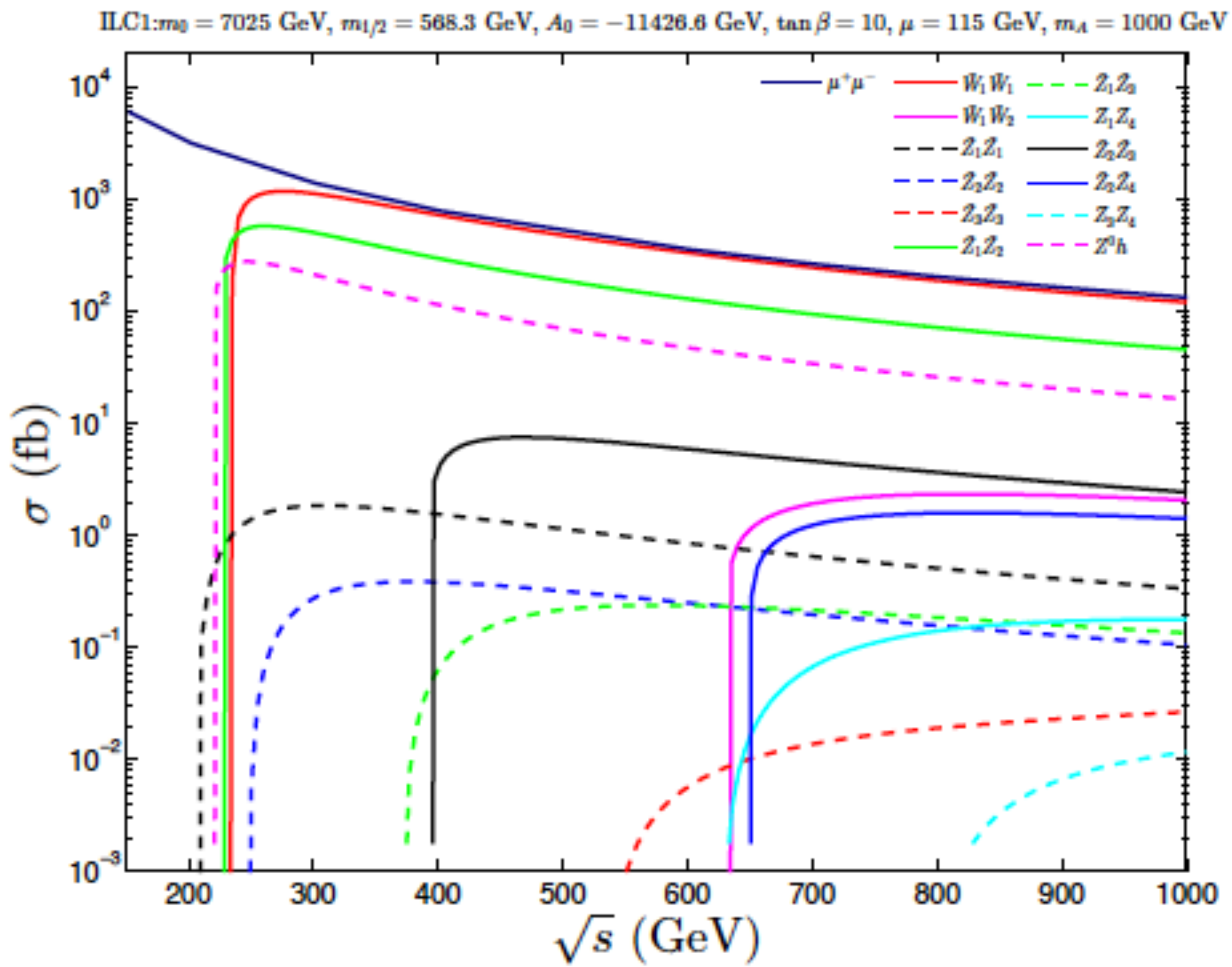
panoramic view of reach of HL-LHC for natural SUSY



LHC14 with 3000 fb¹ can cover essentially all parameter space with $\Delta_{EW} < 30$, usually with 2-3 distinct signals: $\tilde{g}\tilde{g}$, SSdB and $\tilde{Z}_1\tilde{Z}_2 j$

rich arena for ILC physics: Higgs factory => higgsino factory!

$$\sqrt{s} > 2m(higgsino)$$

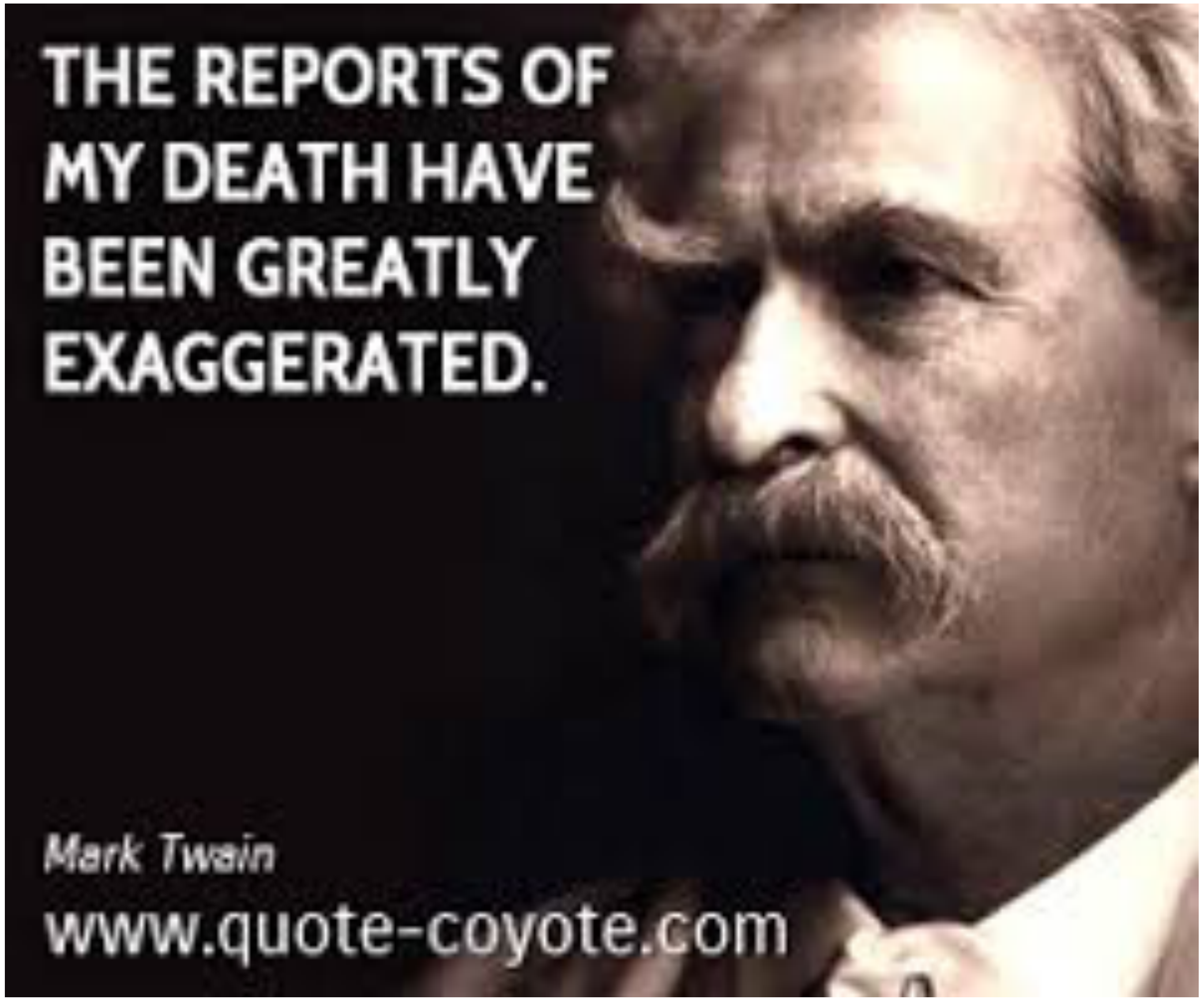


$\tilde{W}_1^{\pm}\tilde{W}_1^{\mp}$ and $\tilde{Z}_1\tilde{Z}_2$

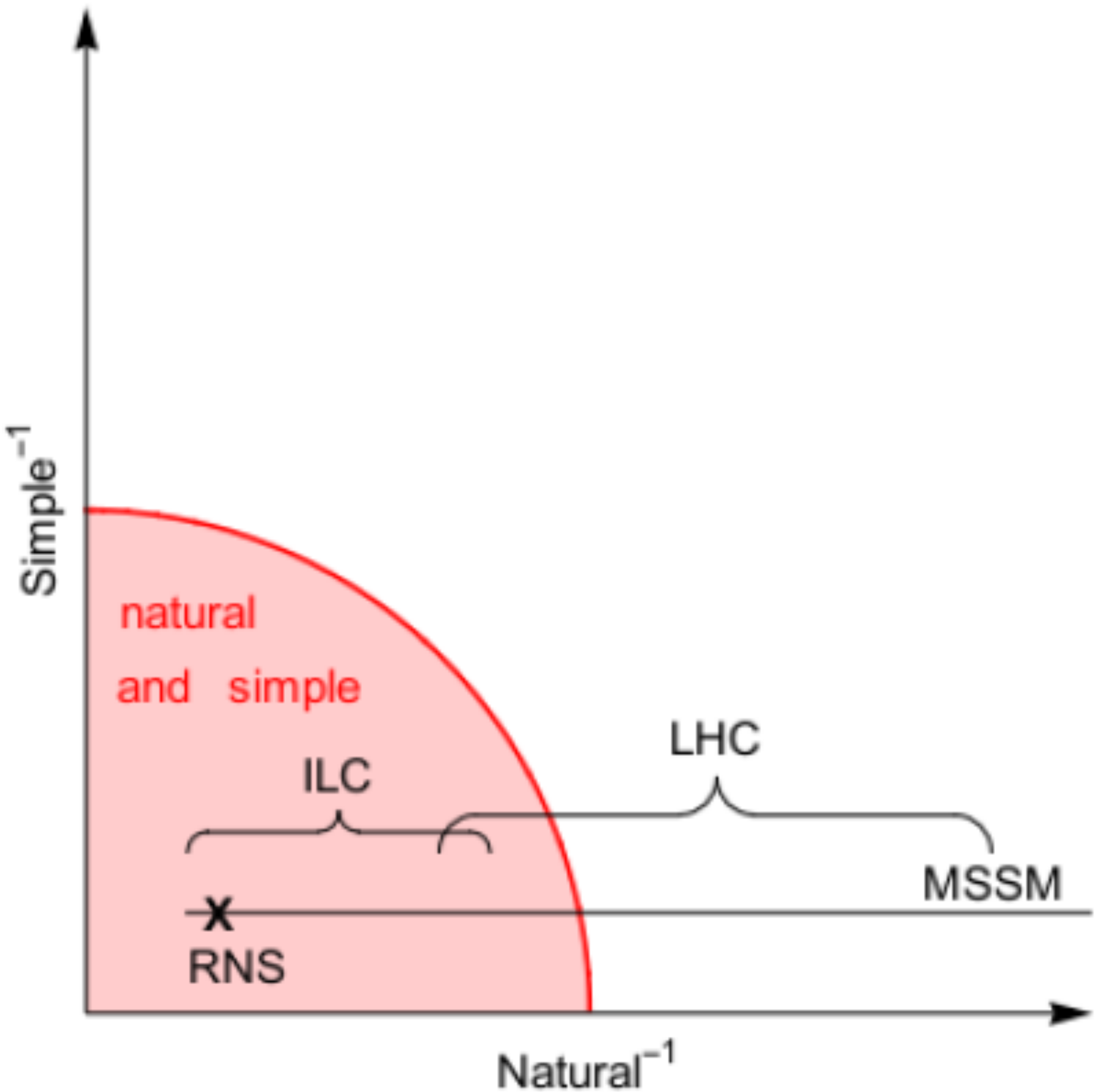
Conclusions: status of SUSY 2016

- nature looking like SUSY: but where are sparticles?
- naturalness: why a Little Hierarchy mu<< m(3/2)?
- radiatively-driven naturalness: mu~100-200 GeV, m(t1)<3 TeV, m(gluino)<4 TeV
- multi-boson production from gluino/squark cascade decays
- W1Z2->Wh+MET ultimate search channel in unnatural SUSY like CMSSM/mSUGRA
- natural SUSY: HL-LHC can cover via SSdB+Z1Z2j channels
- expect ILC as higgsino factory
- DM= axion+higgsino-like WIMP admixture ?

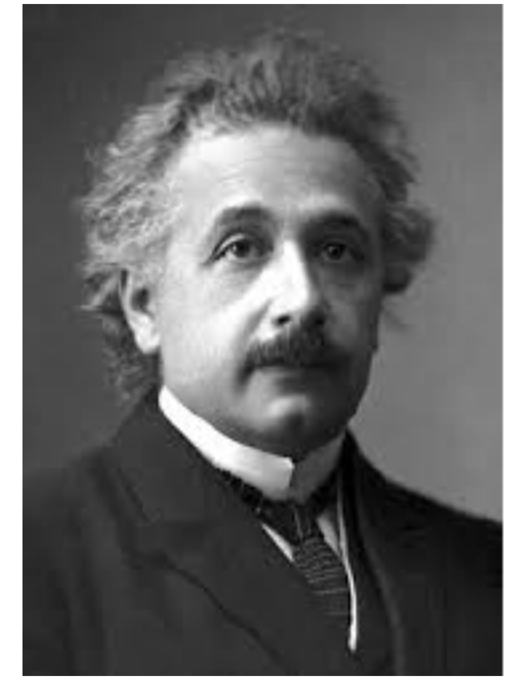
Mark Twain, 1835-1910 (or SUSY)



1897


Simple^{-1}
natural
and simple
ILC
LHC
MSSM
RNS
Natural^{-1}

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

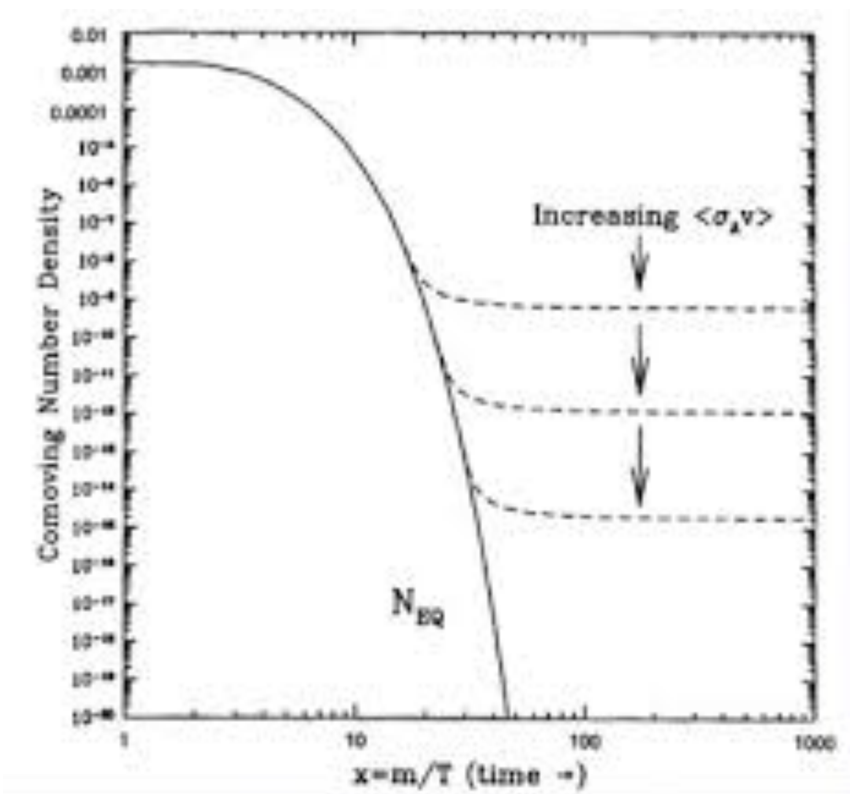
unnatural theory is likely wrong theory

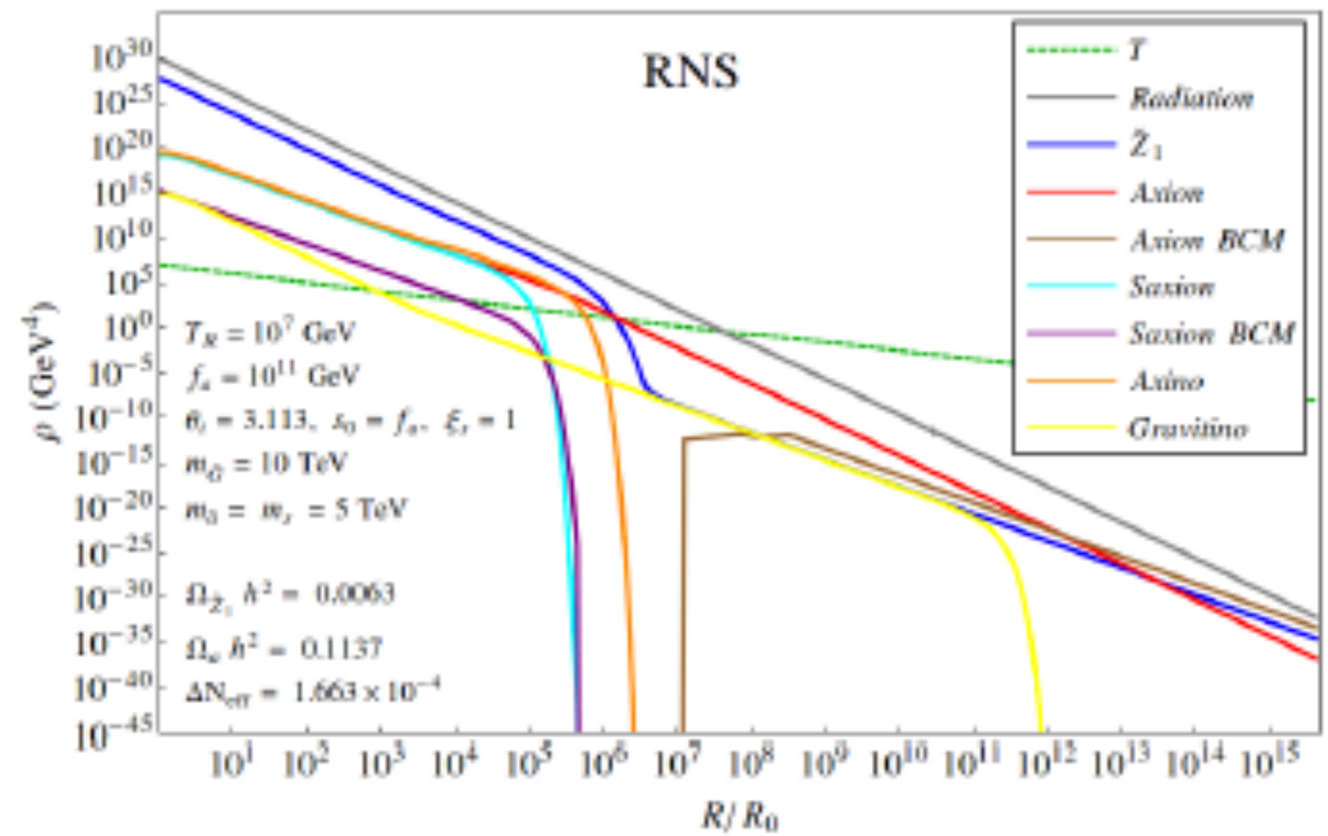
the further one strays from the SM (without good reason), the more likely one is to be wrong

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<< m_3/2!
- ultimately detect both WIMP and axion!

usual picture => mixed axion/WIMP

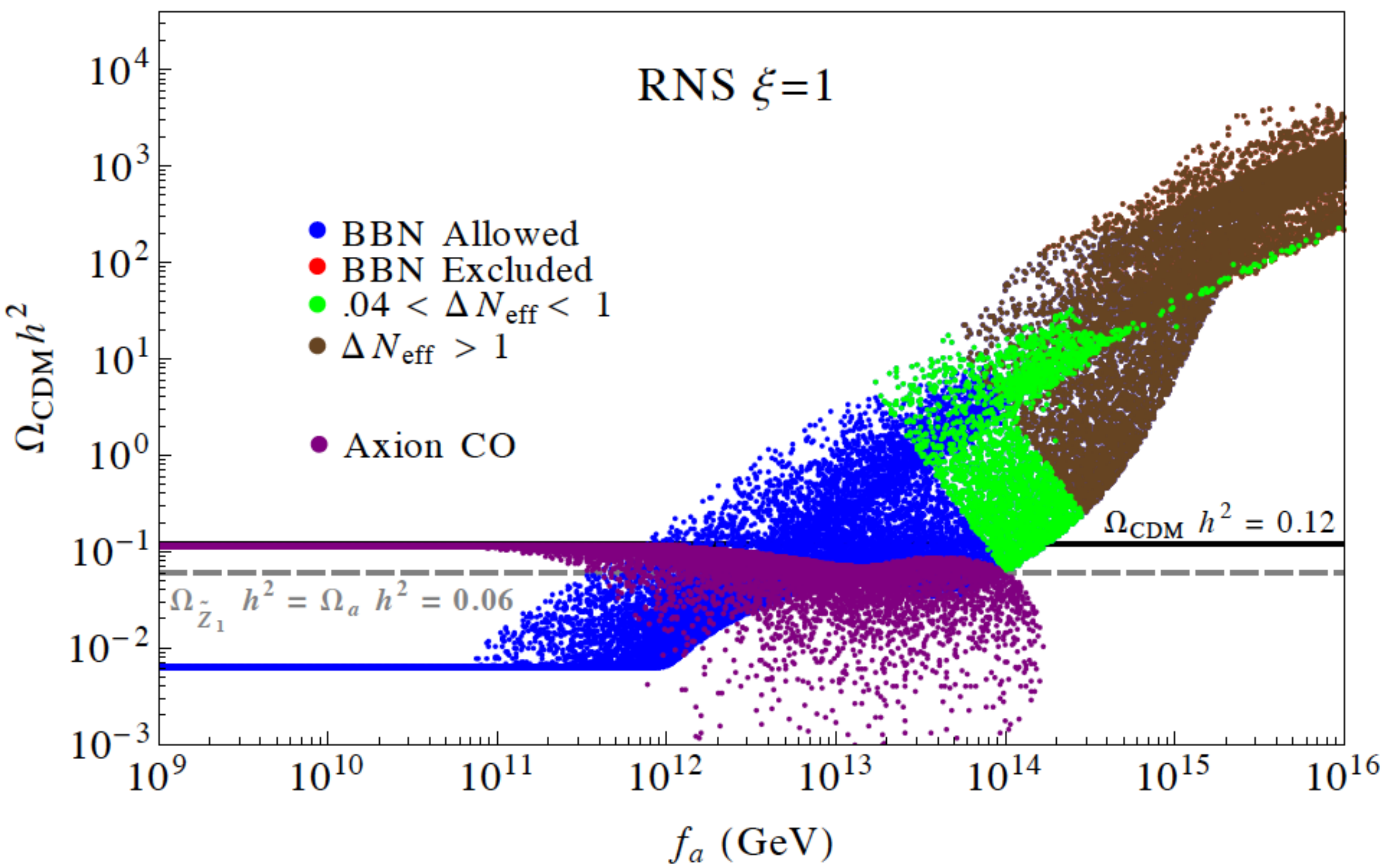




KJ Bae, HB, Lessa, Serce

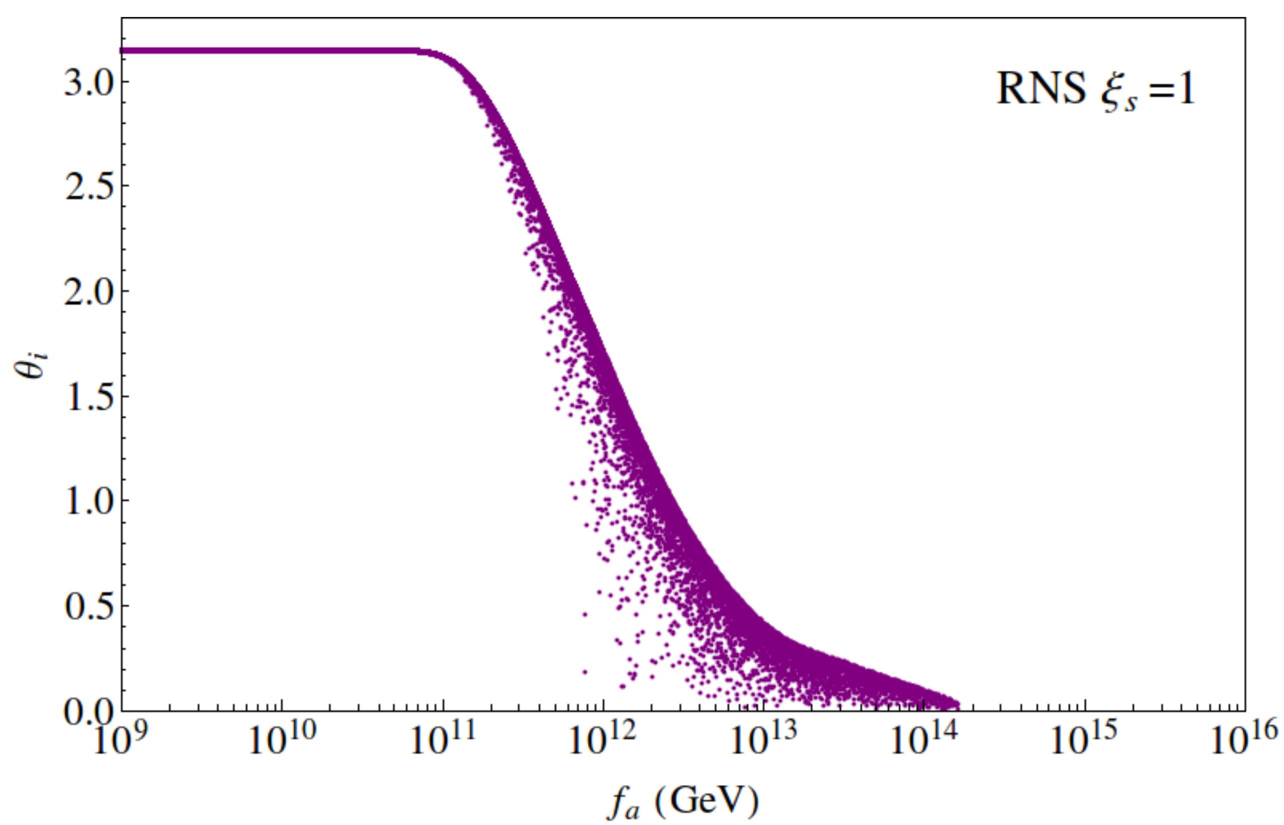
much of parameter space is axion-dominated
with 10-15% WIMPs

=>



higgsino abundance

axion abundance



mainly axion CDM for fa<~10^12 GeV; for higher fa, then get increasing wimp abundance

Bae, HB,Lessa,Serce

Why might mu << m(3/2)?

- Kim-Nilles solution to SUSY mu problem
- SUSY DFSZ axion model: mu forbidden by PQ symmetry
- mu 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)

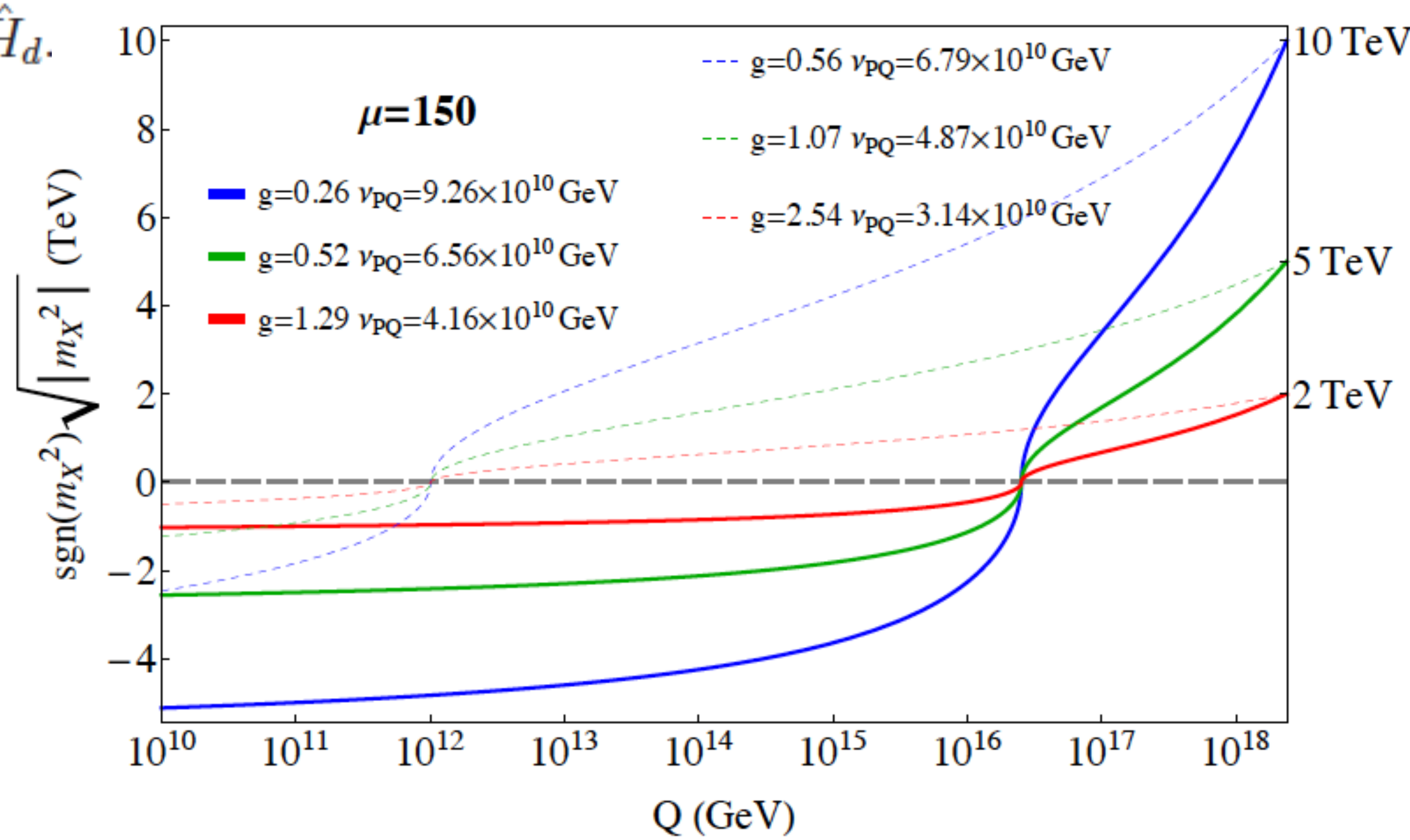
Bae, HB, Serce, PRD91 (2015) 015003

augment MSSM with PQ charges/fields:

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

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

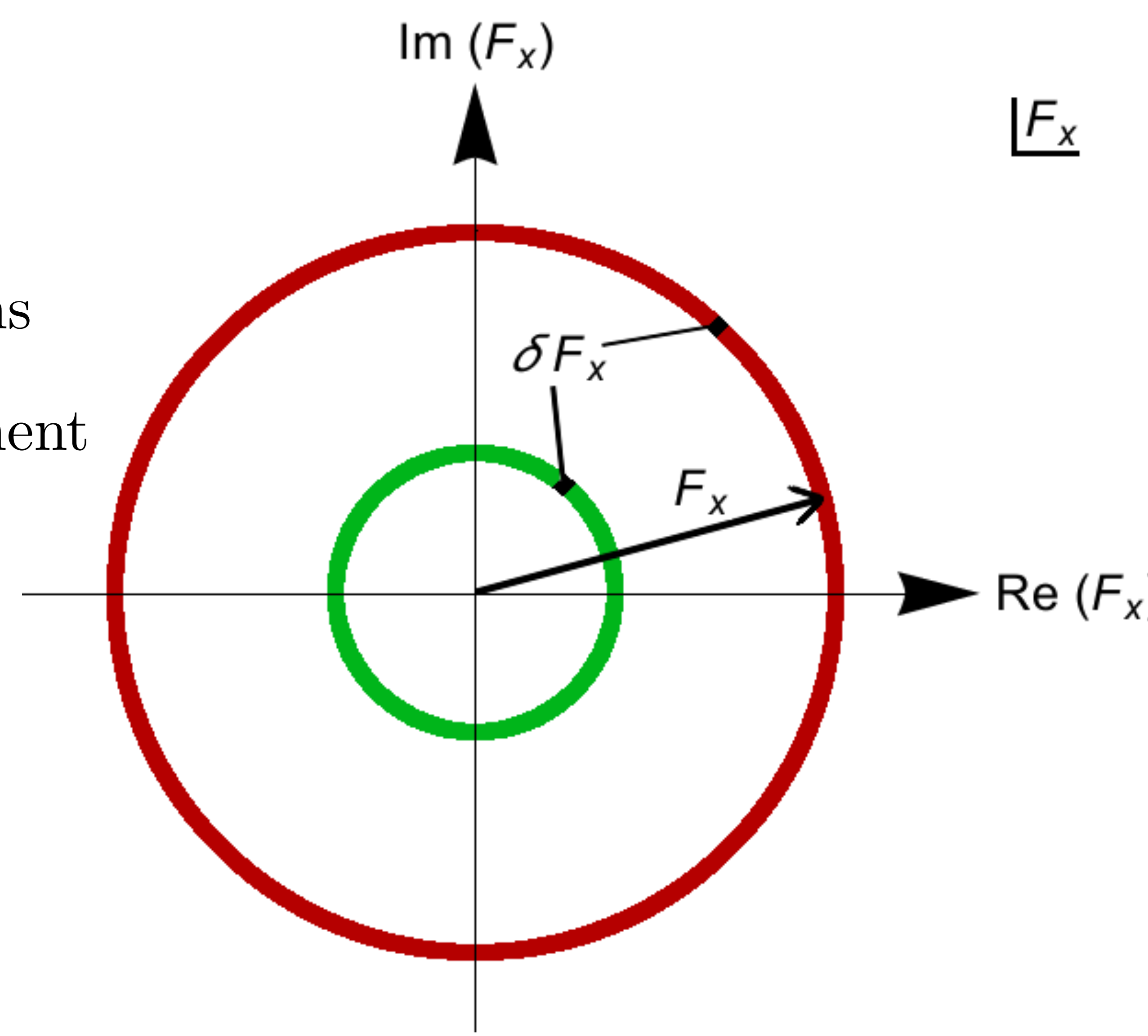
$$\mu = g\frac{v_X v_Y}{M_P}\ .$$



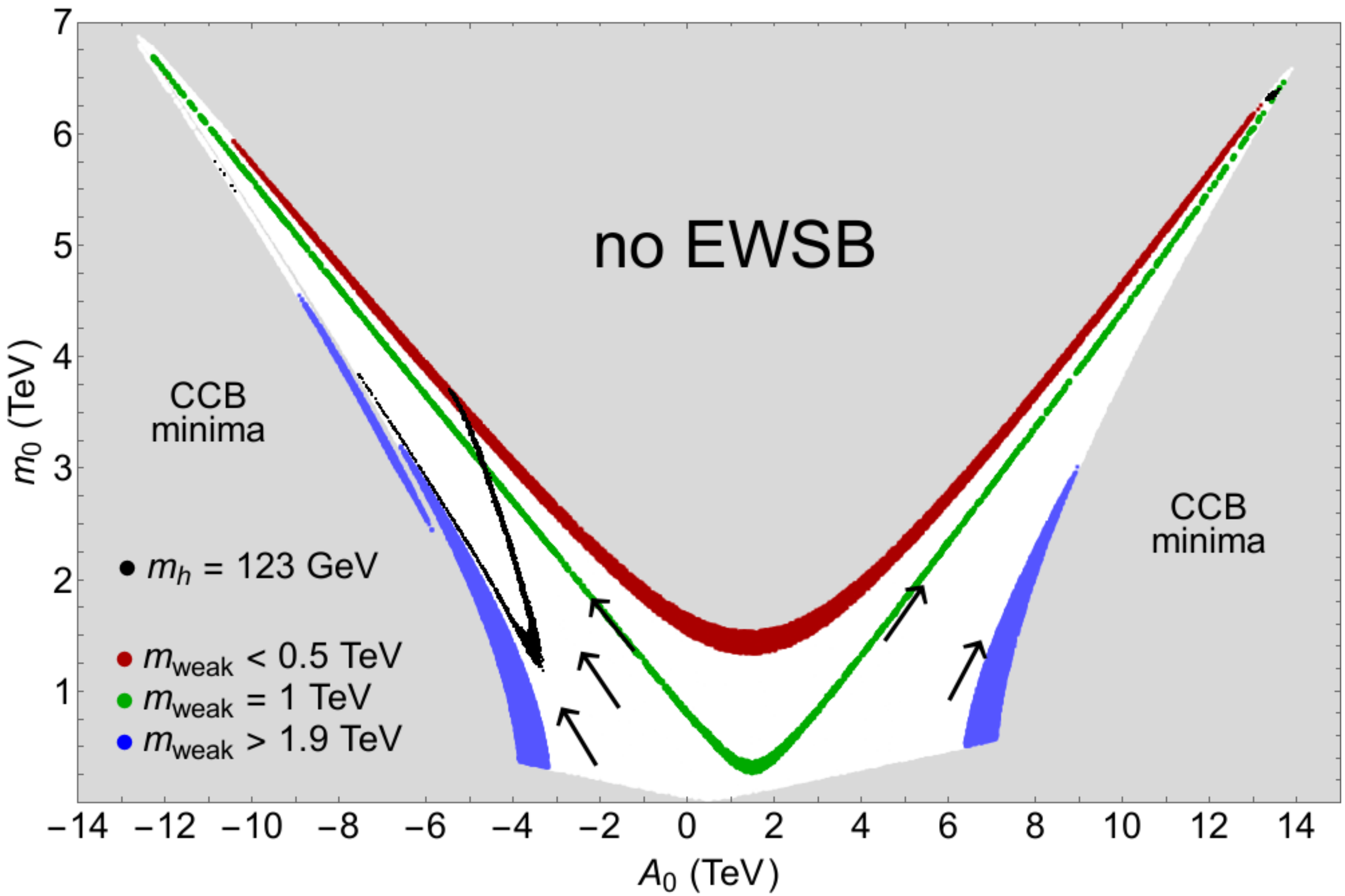
Large $m_{3/2}$ generates small $\mu \sim 100 - 200$ GeV!

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 $m(weak)^2 \sim |m^2_{H_u}|$
- 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 $m_{weak} \sim 100$ GEV



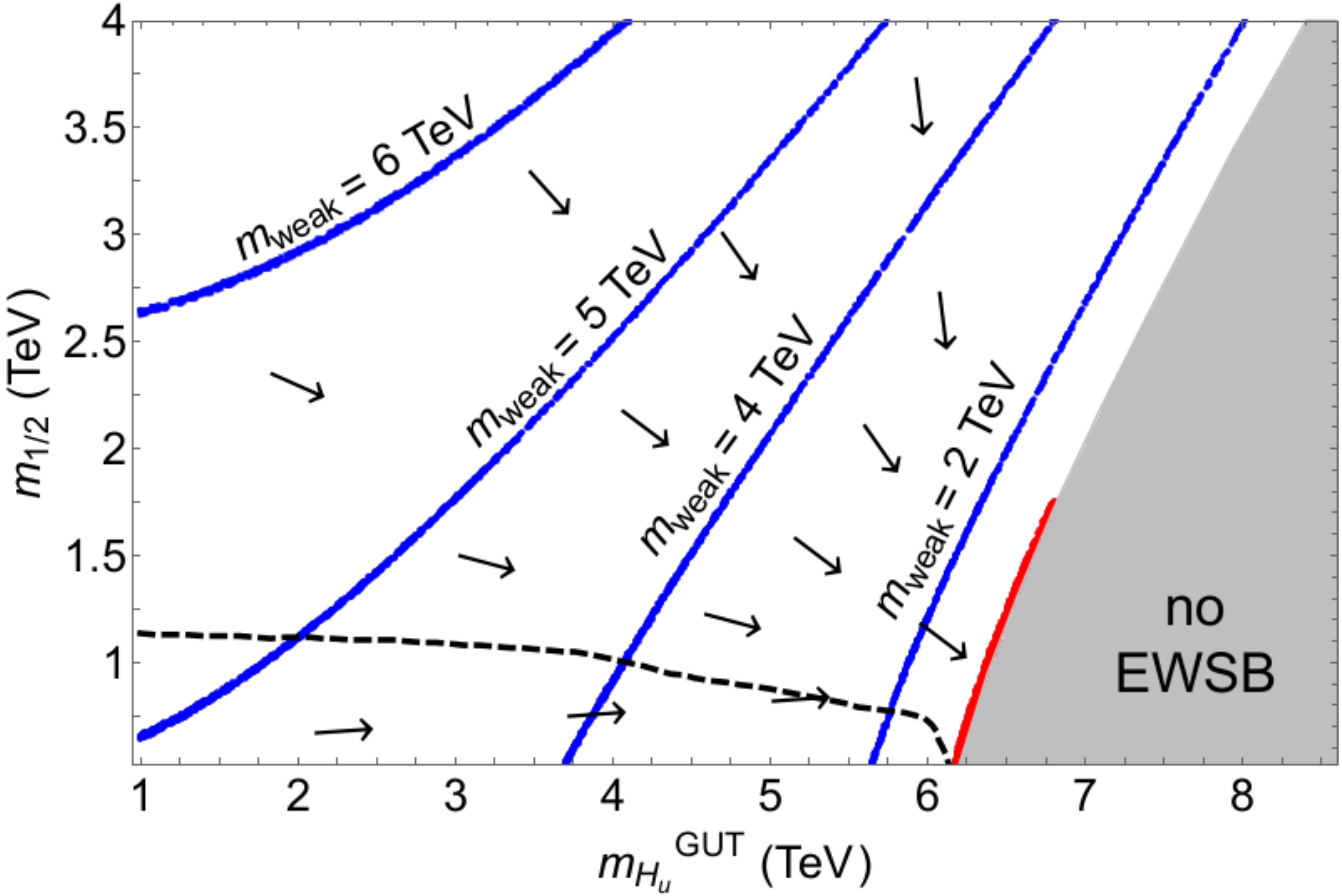
Anthropic selection of $m_{weak} \sim 100\ GeV$:
If m_W too large, then weak interactions $\sim (1/m_W^4)$ too weak
weak decays, fusion reactions suppressed
elements not as we know them



statistical draw to large soft terms balanced by anthropic draw toward red (m(weak)~100 GeV: then m(Higgs)~125 GeV and natural SUSY spectrum!

Giudice, Rattazzi, 2006

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



statistical/anthropic draw toward FP-like region