Yukawa-unified SUSY: cosmology and collider prospects

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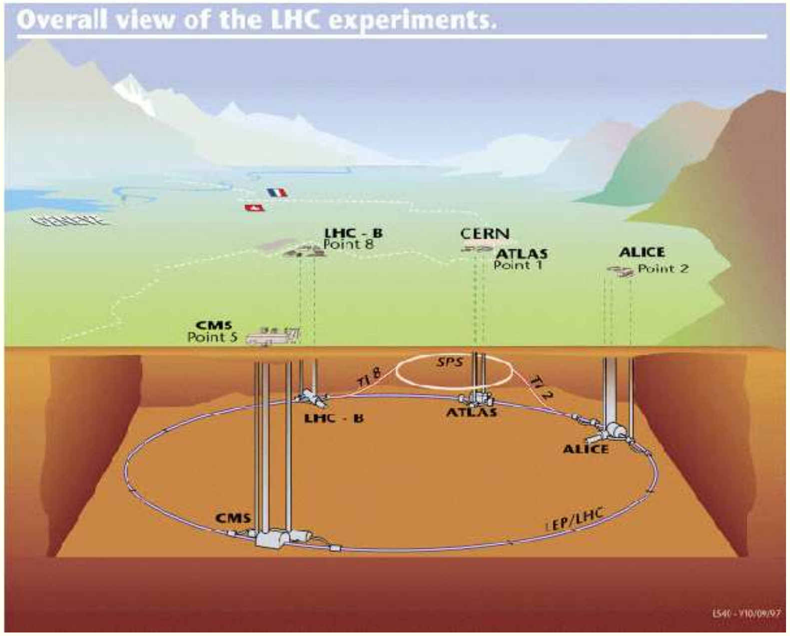
- ⋆ $SO(10)$ motivation
- ⋆ Yukawa unification
- ⋆ Sparticle mass calculation
- ⋆ Dark matter problem
  - Decay to axino
  - compromise sol'n
- ⋆ cosmology of SUSY $SO(10)$
- ⋆ $SO(10)$ at LHC
  - – can see with just 0.1 fb^{-1}!



SUSY is standard way beyond the SM

"if we consider the main classes of new physics that are currently being contemplated$\cdots$, it is clear that (supersymmetry) is the most directly related to GUTs. SUSY offers a well defined model computable up to the GUT scale and is actually supported by the quantitative success of coupling unification in SUSY GUTs.For the other examples$\cdots$, all contact with GUTs is lost or at least is much more remote. $\cdots$ the SUSY picture$\cdots$ remains the standard way beyond the Standard Model"

G. Altarelli and F. Feruglio, hep-ph/0306265

$SO(10)$: **synopsis**

⋆ $SO(10)$ is a rank-5 Lie group which contains the SM gauge symmetry. It has several important features:

- The $SO(2n)$ groups have *spinorial* representations of dim'n 2^{n-1}, in addition to the usual tensor reps
- The 16-dim'l spinor rep of $SO(10)$ is large enough to contain *all* the matter in a single generation of the SM, plus a right-handed neutrino state. This *unifies* matter as well as gauge groups.
- The right-hand neutrino state is contained in a superfield

$$\hat{N}_i^c = \tilde{\nu}_{Ri}^\dagger(\hat{x}) + i\sqrt{2}\bar{\theta}\psi_{N_i^c L}(\hat{x}) + i\bar{\theta}\theta_L \mathcal{F}_{N_i^c}(\hat{x}).$$

- Upon breaking $SO(10)$, the $\hat{N}_i^c$ fields become SM singlets, and can obtain a Majorana mass M_{Ni}. The superpotential obtains the form

$$\hat{f} = \hat{f}_{\mathrm{MSSM}} + (\mathbf{f}_\nu)_{ij}\epsilon_{ab}\hat{L}_i^a \hat{H}_u^b \hat{N}_j^c + \frac{1}{2}M_{Ni}\hat{N}_i^c\hat{N}_i^c \ . \qquad (1)$$

$SO(10)$: continued

- Upon EWSB, the neutrinos obtain masses via the *see-saw* mechanism, where the (dominantly) right-handed neutrino obtains a mass $m_{\nu R} \sim M_N$, while the (dominantly) left-handed neutrino obtains a mass $m_{\nu L} \sim \frac{(f_\nu v_u)^2}{M_{Ni}}$. For third generation, with $f_\nu \simeq f_t$, then $m_{\nu_\tau} \sim 0.03$ eV for $M_{N3} \sim 10^{15}$ GeV, very close to M_{GUT}!
- Further, the group $SO(n)$ (except $n = 6$) are naturally anomaly-free, thus explaining the seemingly fortuitous anomaly cancellation in the SM and in $SU(5)$.
- In the unbroken $SO(10)$ theory, the superpotential is expected to have the form

$$\hat{f} \ni f\hat{\psi}_{16}\hat{\psi}_{16}\hat{\phi}_{10} + \ldots \tag{2}$$

with f being the single Yukawa coupling per generation in the GUT scale theory. The ellipses represent terms including for instance higher dimensional Higgs representations and interactions responsible for the breaking of

$SO(10)$. Thus, naively, it is expected in $SO(10)$ theories that the various Yukawa couplings of each generation should unify as well. This should hold especially for the 3rd generation. Yukawa coupling unification puts a strong constraint on the phenomenology expected in SUSY models.

Yukawa unification in SUSY: assumptions

- some form of 4-d or x-d $SO(10)$ SUGRA-GUT valid at $Q > M_{GUT}$
- SUGRA breaking via superHiggs mechanism: $m_{\tilde{G}} \sim 1$ TeV and soft SUSY breaking terms ~ 1 TeV
- $SO(10)$ breaks to MSSM or MSSM plus gauge singlets at $Q = M_{GUT}$ either via Higgs mechanism (4-d) or x-d compactification
- MSSM (or MSSM plus $\hat{N}^c$) is correct effective theory between M_{SUSY} and M_{GUT}
- EWSB broken radiatively due to large m_t
- we will assume that $t - b - \tau$ Yukawa couplings unify at $Q = M_{GUT}$

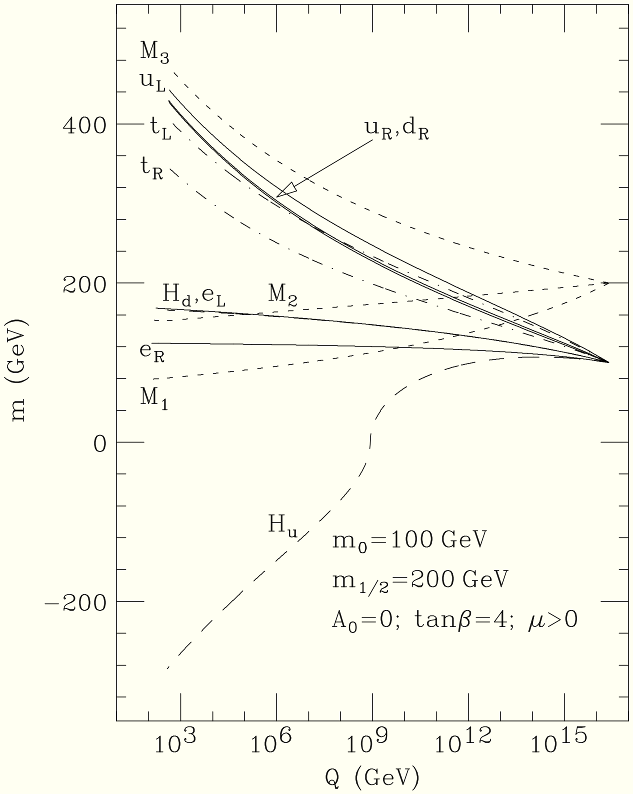
lots of previous work!

- B. Ananthanarayan, G. Lazarides and Q. Shafi, PRD44 (1991)1613 and PLB300 (1993)245;
- V. Barger, M. Berger and P. Ohmann, PRD49 (1994)4908;
- M. Carena, M. Olechowski, S. Pokorski and C. Wagner, NPB426 (1994)269;
- B. Ananthanarayan, Q. Shafi and X. Wang, PRD50 (1994)5980;
- L. Hall, R. Rattazzi and U. Sarid, PRD50 (1994)7048;
- R. Rattazzi and U. Sarid, PRD53 (1996)1553;
- T. Blazek, M. Carena, S. Raby and C. Wagner, PRD56 (1997)6919; T. Blazek and S. Raby, PLB392 (1997)371 and PRD59 (1999)095002; T. Blazek, S. Raby and K. Tobe, PRD60 (1999)113001 and PRD62 (2000)055001;

more recent work

- H. Baer, M. Diaz, J. Ferrandis and X. Tata, PRD61 (2000)111701
- H. Baer, M. Brhlik, M. Diaz, J. Ferrandis, P. Mercadante, P. Quintana and X. Tata, PRD63 (2001)015007;
- H. Baer and J. Ferrandis, PRL87 (2001)211803;
- T. Blazek, R. Dermisek and S. Raby, PRL88 (2002)111804 and PRD65 (2002)115004;
- D. Auto, H. Baer, C. Balazs, A. Belyaev, J. Ferrandis and X. Tata, JHEP0306 (2003)023
- D. Auto, H. Baer, A. Belyaev and T. Krupovnickas, JHEP0410 (2004)066;
- R. Dermisek, S. Raby, L. Roszkowski and R. Ruiz de Austri, JHEP0304 (2003)037 and JHEP0509 (2005)029
- H. Baer, S. Kraml, S.Sekmen and H. Summy, arXiv:0801.1831 (2008).

Sparticle mass spectra



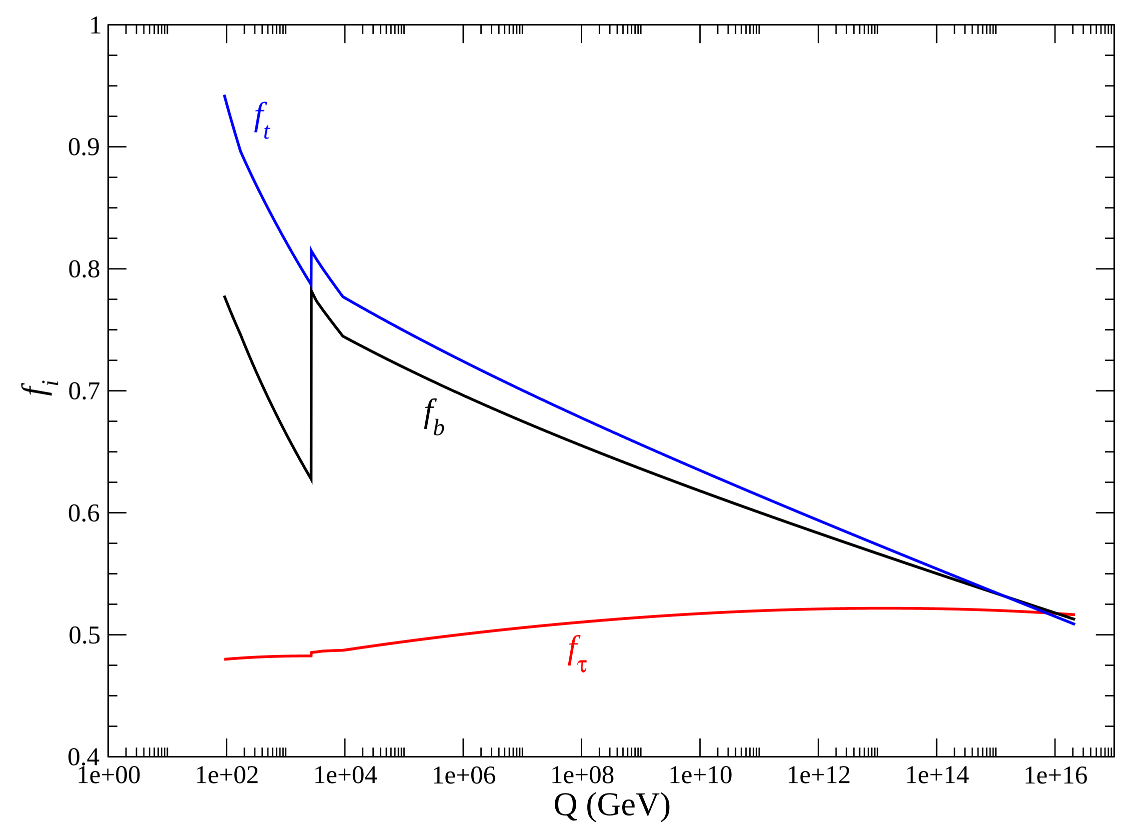
- ★ Mass spectra codes
- ★ RGE running: $M_{GUT} \to M_{weak}$
  - Isajet 7.75 (HB, Paige, Protopopescu, Tata)
    - ∗ $\geq$7.72: Isatools
  - SuSpect (Djouadi, Kneur, Moultaka)
  - SoftSUSY (Allanach)
  - Spheno (Porod)
- ★ Comparison (Belanger, Kraml, Pukhov)
- ★ Website: `http://kraml.home.cern.ch/kraml/comparison/`

YU requires precision calculation of SUSY spectrum:

Hall, Rattazzi, Sarid; Pierce *et al.* (PBMZ)

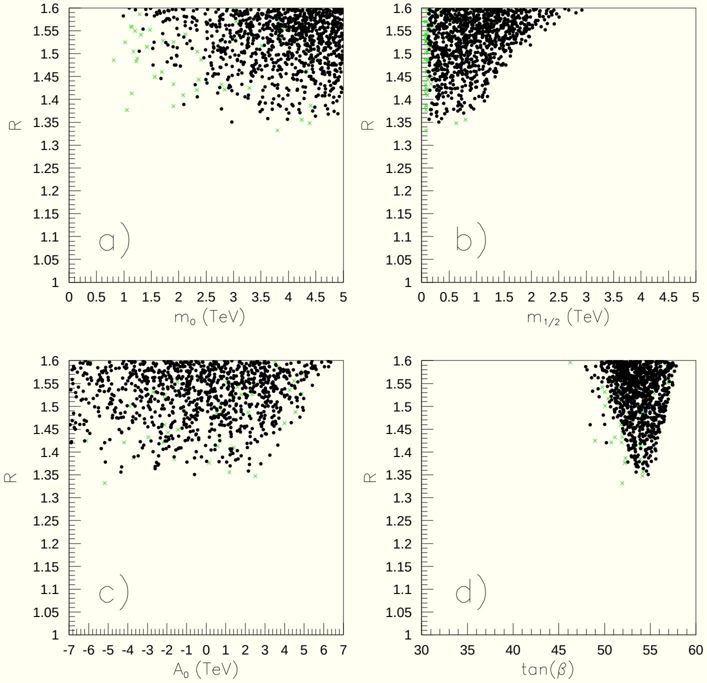
- need full 2-loop RGE running
- full threshold corrections calculated at optimized scale
  - applies especially to b-quark self-energy
  - $\tilde{g}\tilde{b}_i$, $\widetilde{W}_i\tilde{t}_j$, $\cdots$ loops included
- off-sets Yukawa coupling RG trajectory
- use Isajet/Isasugra spectrum generator

Yukawa unification in MSSM:

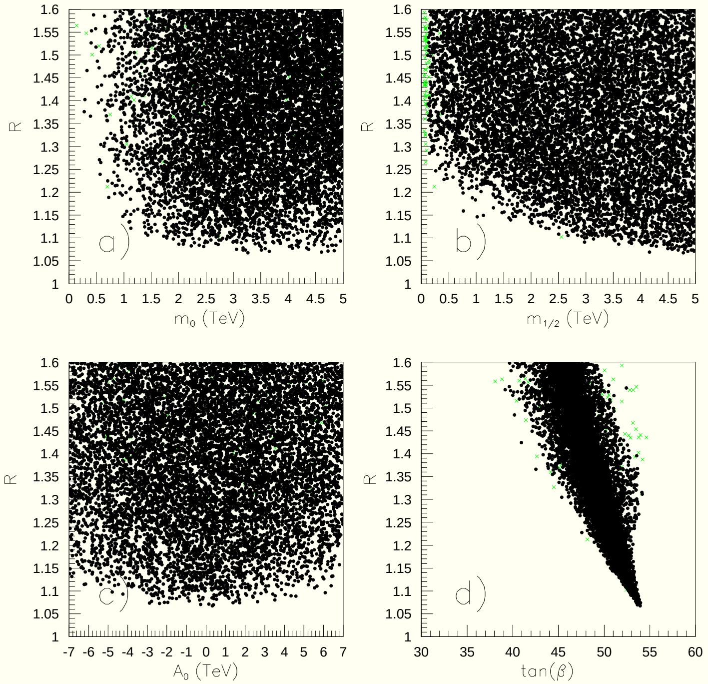


Yukawa unification in mSUGRA model? $\mu > 0$ scan

- $R = max(f_t, f_b, f_\tau)/min(f_t, f_b, f_\tau)$ at $Q = M_{GUT}$



Yukawa unification in mSUGRA model? $\mu < 0$ scan



Why Yukawa unification problematic in models with universality

For EWSB in MSSM (tree level), minimization condition:

$$B\mu = \frac{(m_{H_u}^2 + m_{H_d}^2 + 2\mu^2)\sin 2\beta}{2}, \quad \text{and}$$

$$\mu^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{(\tan^2\beta - 1)} - \frac{M_Z^2}{2}.$$

$$\frac{dm_{H_d}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 - \frac{3}{10}g_1^2S + 3f_b^2X_b + f_\tau^2X_\tau\right),$$

$$\frac{dm_{H_u}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 + \frac{3}{10}g_1^2S + 3f_t^2X_t\right),$$

- Unified YCs push $m_{H_d}^2$ more negative than $m_{H_u}^2$
- Solution: require $m_{H_u}^2 < m_{H_d}^2$ already at M_{GUT} so that $m_{H_u}^2$ gets head start in RG running

Higgs splitting: two approaches

- DT (D-term) model:

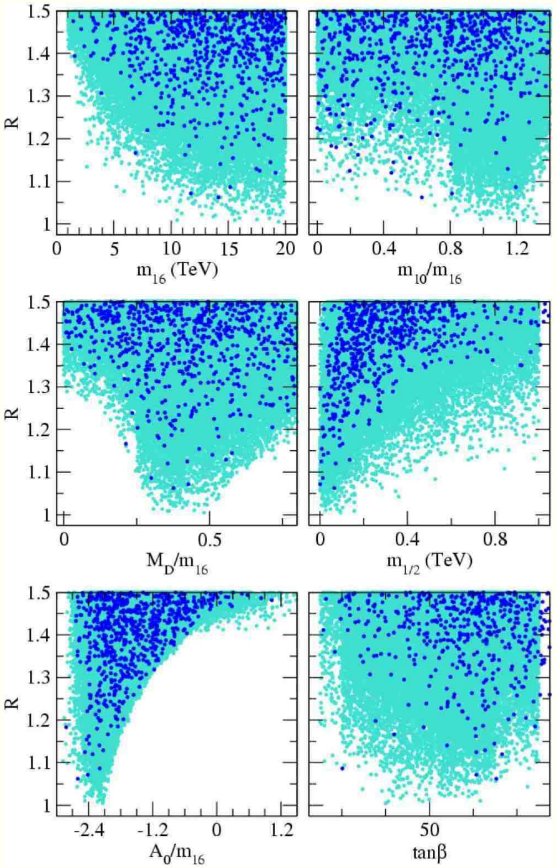
$$\begin{aligned} m_Q^2 &= m_E^2 = m_U^2 = m_{16}^2 + M_D^2 \\ m_D^2 &= m_L^2 = m_{16}^2 - 3M_D^2 \\ m_{H_{u,d}}^2 &= m_{10}^2 \mp 2M_D^2 \\ m_N^2 &= m_{16}^2 + 5M_D^2 \end{aligned}$$

- HS model: apply splitting only to Higgs SSB terms

⋆ The HS method gives better Yukawa unification than DT model for $\mu > 0$ and $m_{16} \gtrsim 2$ TeV

  – HS can arise at 10-15% level at GUT scale due to threshold corrections (BDR)

Top-down scan of HS model with $\mu > 0$



Auto, HB, Balazs, Belyaev, Ferrandis, Tata

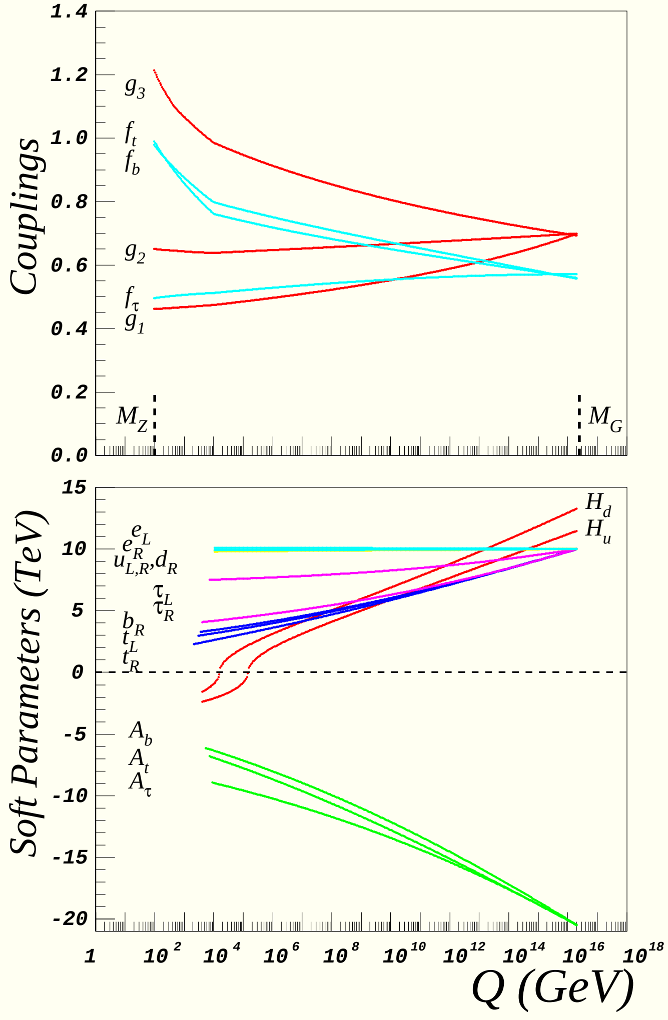
New analysis: HB, Kraml, Sekmen, Summy

Correlation of SSB terms for YU models

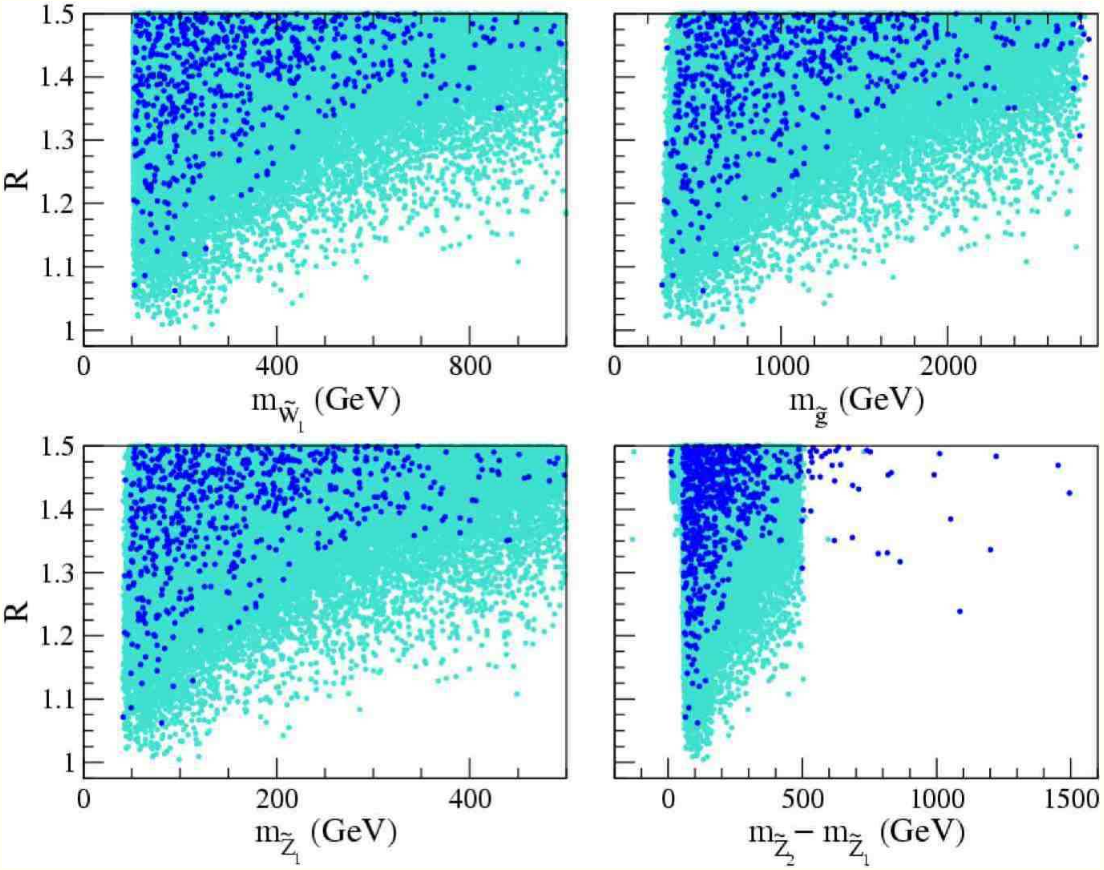
- ⋆ Note correlation amongst parameters:
  - $A_0 \sim -2m_{16}$
  - $m_{10} \sim 1.2m_{16}$
  - $\tan\beta \sim 50$
- ⋆ Earlier work: Bagger, Feng, Polonsky, Zhang derived $A_0^2 = 2m_{10}^2 = 4m_{16}^2$ with $m_{1/2}$ tiny and Yukawa unified couplings: in context of "radiatively induced inverted scalar mass hierarchy model"
  - – Meant to reconcile naturalness with FCNC suppression by having $m(third\ gen.\ scalars) \ll m(1st/2nd\ ge.\ scalars)$
  - – Original model needed to be reconciled with EWSB; get hierarchy, but much less than anticipated: HB, Balazs, Mercadante, Tata, Wang (2001)

$t-b-\tau$ Yukawa unification in HS model!

- need $m_{10} \simeq \sqrt{2} m_{16}$
- $A_0 \simeq -2m_{16}$
- inverted scalar mass hierarchy: Bagger et al.
- split Higgs: $m_{H_u}^2 < m_{H_d}^2$
- Auto, HB, Balazs, Belyaev, Ferrandis, Tata
  - $m_{\tilde{q},\tilde{\ell}}(1,2) \sim 10$ TeV
  - $m_{\tilde{t}_1},\ m_A,\ \mu \sim 1-2$ TeV
  - $m_{\tilde{g}} \sim 300-500$ GeV
- Blazek, Dermisek, Raby
  - small μ, $m_A \sim 100-200$ GeV

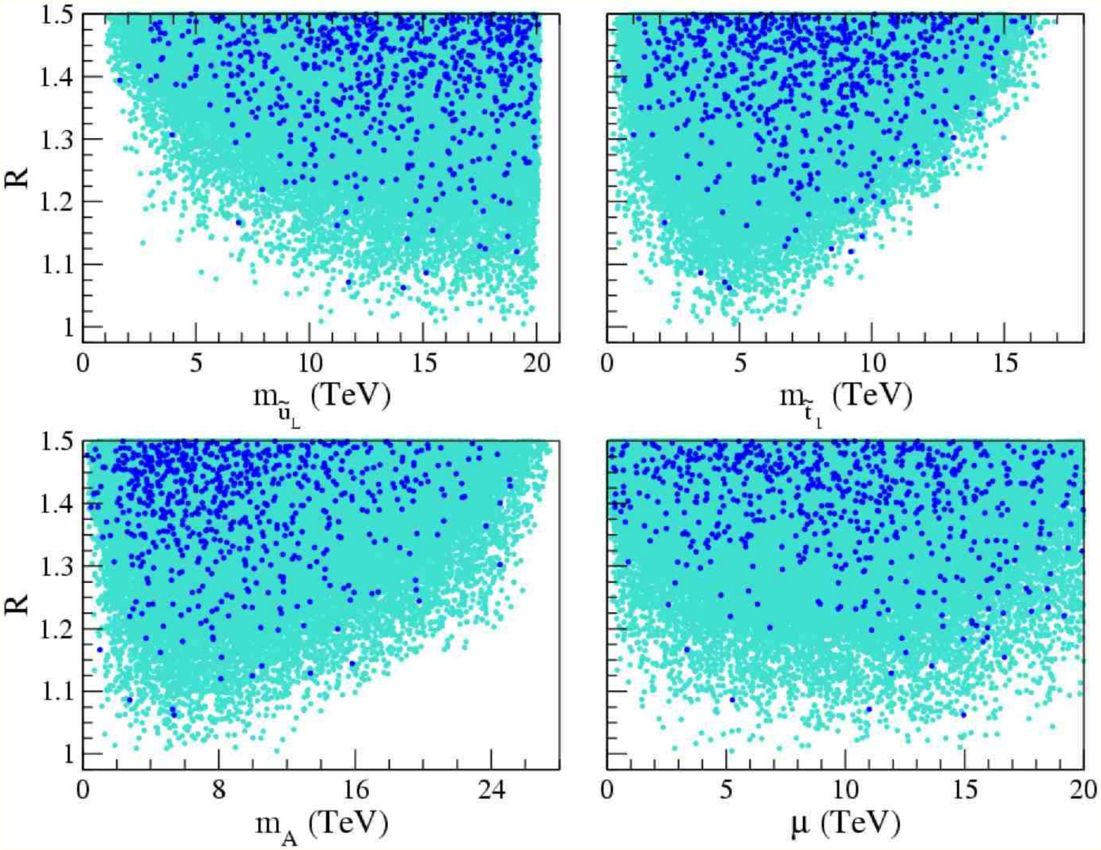


Sparticle masses for HS model with $\mu > 0$



HB, Kraml, Sekmen, Summy

Sparticle masses for HS model with $\mu > 0$

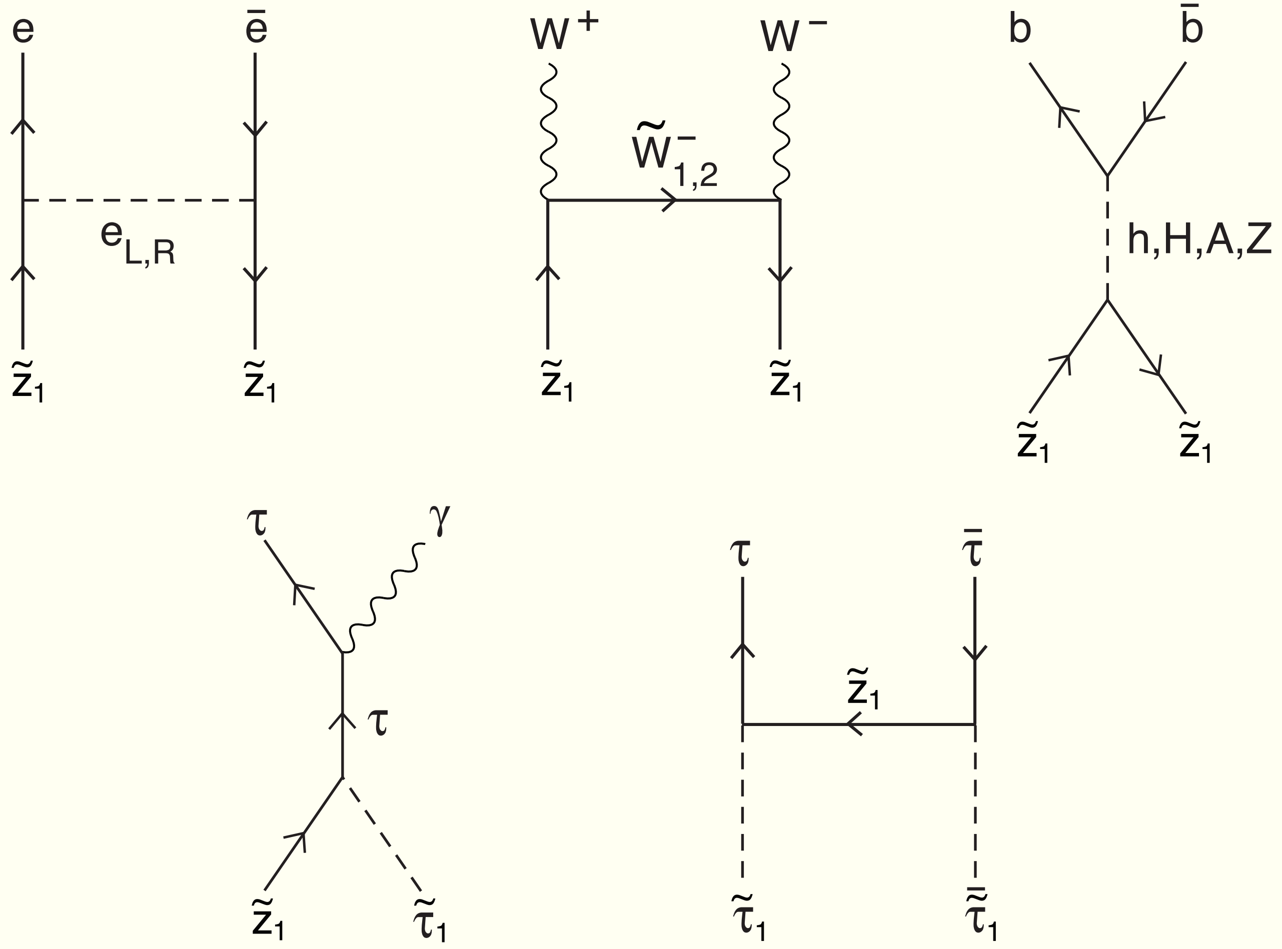


HB, Kraml, Sekmen, Summy

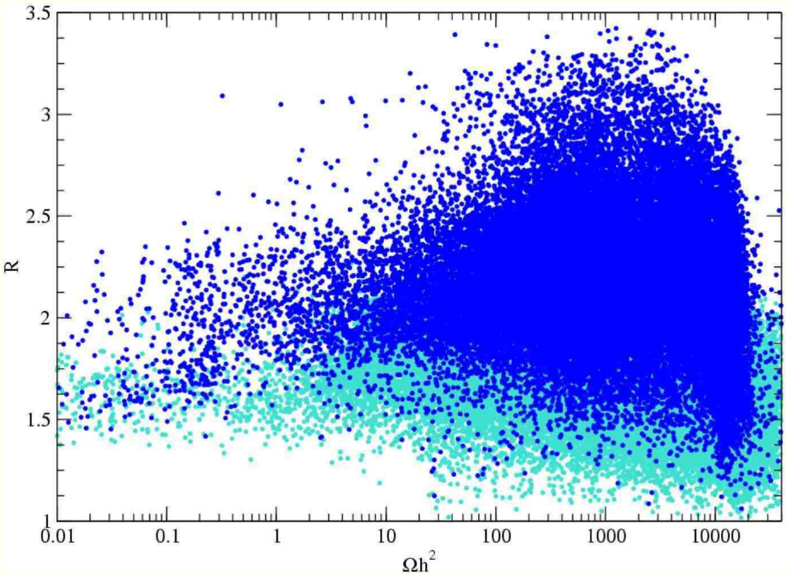
Neutralino dark matter

- ⋆ Why R-parity? natural in $SO(10)$ SUSYGUTS if properly broken, or broken via compactification (Mohapatra, Martin, Kawamura, $\cdots$)
- ⋆ In thermal equilibrium in early universe
- ⋆ As universe expands and cools, freeze out
- ⋆ Number density obtained from Boltzmann eq'n
  - $dn/dt = -3Hn - \langle\sigma v_{rel}\rangle(n^2 - n_0^2)$
  - depends critically on thermally averaged annihilation cross section times velocity
- ⋆ many thousands of annihilation/co-annihilation diagrams
- ⋆ several computer codes available
  - DarkSUSY, Micromegas, IsaReD (part of Isajet)

Some neutralino (co)annihilation processes



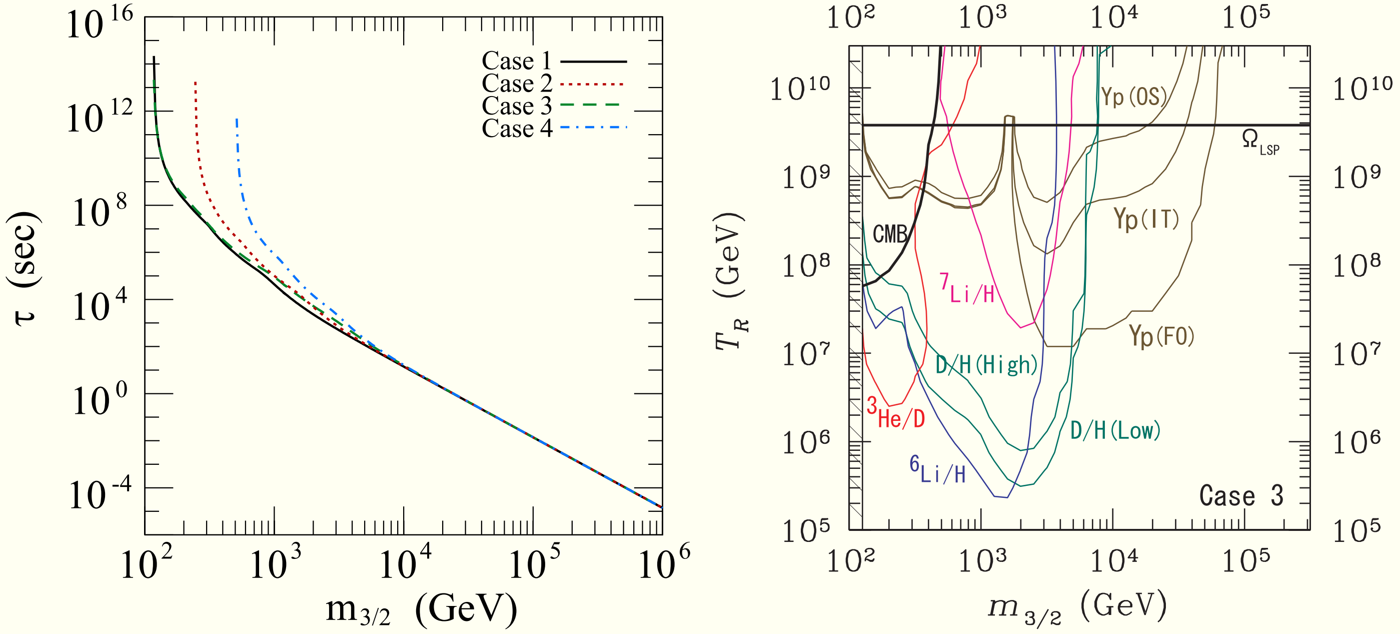
Problem reconciling DM with Yukawa unification



- one solution: axino DM instead of neutralino
- $\Omega_{\tilde{a}} h^2 \sim \frac{m_{\tilde{a}}}{m_{\widetilde{Z}_1}} \Omega_{\widetilde{Z}_1} h^2$: ⇒ warm DM
- also thermal component depending on T_R: ⇒ CDM

Consistent cosmology for SUSY $SO(10)$: gravitino problem

- gravitino problem in generic SUGRA models: overproduction of $\tilde{G}$ followed by late $\tilde{G}$ decay can destroy successful BBN predictons: upper bound on T_R



(see Kohri, Moroi, Yotsuyanagi; Cybert, Ellis, Fields, Olive)

Leptogenesis via inflaton decay

- Upper bound on T_R from BBN is below that for successful thermal leptogenesis: need $T_R \gtrsim 10^{10}$ GeV (Buchmuller, Plumacher)
- Alternatively, one may have non-thermal leptogenesis where inflaton $\phi \to N_i N_i$ decay
- additional source of N_i in early universe allows lower T_R:

$$\frac{n_B}{s} \simeq 8.2 \times 10^{-11} \times \left(\frac{T_R}{10^6\ \mathrm{GeV}}\right)\left(\frac{2m_{N_1}}{m_\phi}\right)\left(\frac{m_{\nu_3}}{0.05\ \mathrm{eV}}\right)\delta_{eff} \tag{3}$$

- WMAP observation: $n_b/s \sim 0.9 \times 10^{-10} \Rightarrow T_R \gtrsim 10^6$ GeV

Cold and warm axino DM in the universe

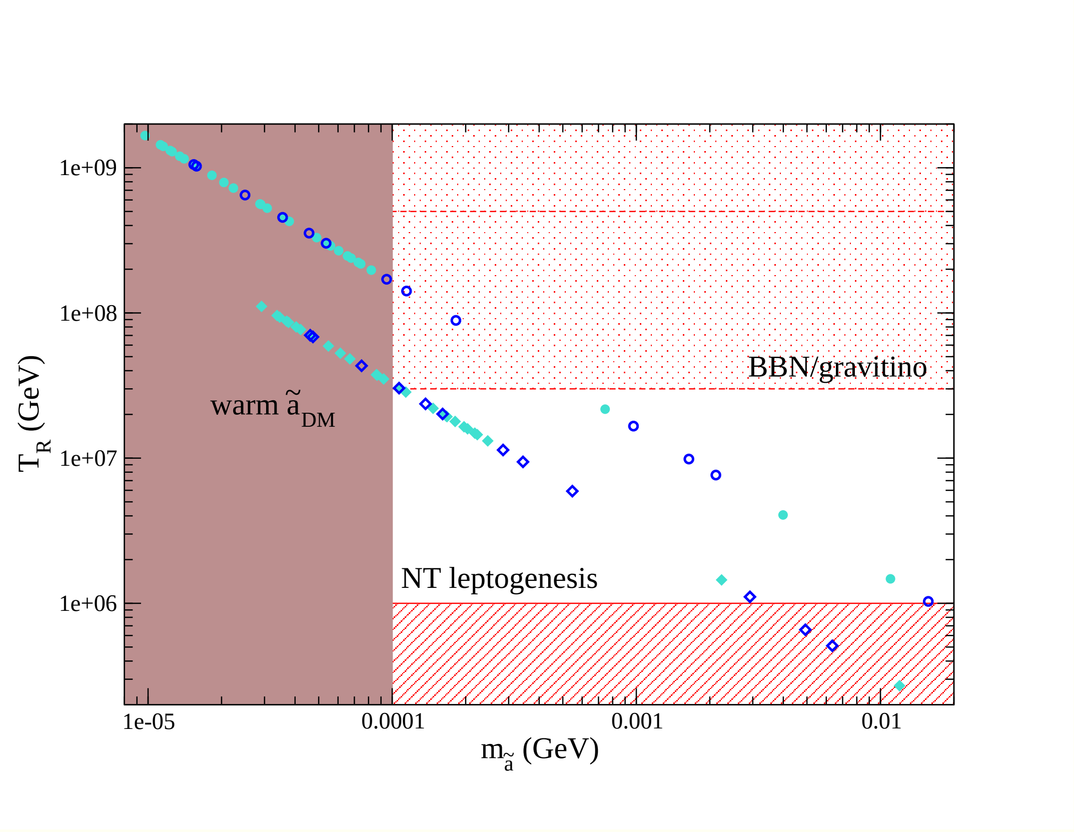
- Non-thermal axino production via $\widetilde{Z}_1 \to \tilde{a}\gamma$ decay:
  $\Rightarrow$ warm DM for $m_{\tilde{a}} \lesssim 1$ GeV (Jedamzik, Lemoine, Moultaka)
- thermal production of $\tilde{a}$: *cold* DM for $m_{\tilde{a}} > .1$ MeV (Brandenberg, Steffen)

$$\Omega_{\tilde{a}}^{TP} h^2 \simeq 5.5 g_s^6 \ln\left(\frac{1.108}{g_s}\right)\left(\frac{10^{11}\ \mathrm{GeV}}{f_a/N}\right)^2\left(\frac{m_{\tilde{a}}}{0.1\ \mathrm{GeV}}\right)\left(\frac{T_R}{10^4\ \mathrm{GeV}}\right) \qquad (4)$$

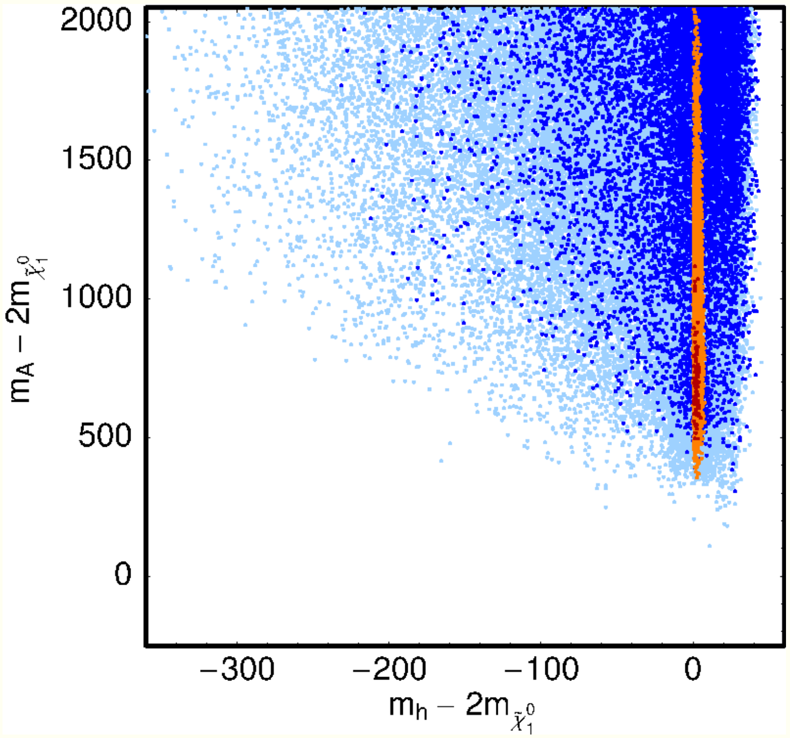
- with $0.1 \simeq \Omega_{\tilde{a}} h^2 = \Omega_{\tilde{a}}^{TP} h^2 + \frac{m_{\tilde{a}}}{m_{\widetilde{Z}_1}} \Omega_{\widetilde{Z}} h^2$, can calculate value of T_R needed given a PQ breaking scale $f_a/N \sim 10^{11}$ GeV

Consistent cosmology for $SO(10)$ SUSY GUTs with $\tilde{a}$ DM

- Happily, T_R falls into the right range to give *cold* axino DM with a small admixture of warm axino DM, preserve BBN predictions and have non-thermal leptogenesis!
- See HB and H. Summy, arXiv:0803.0510 (2008)



MCMC scan: compromise solution with $m_{16} \sim 3$ TeV

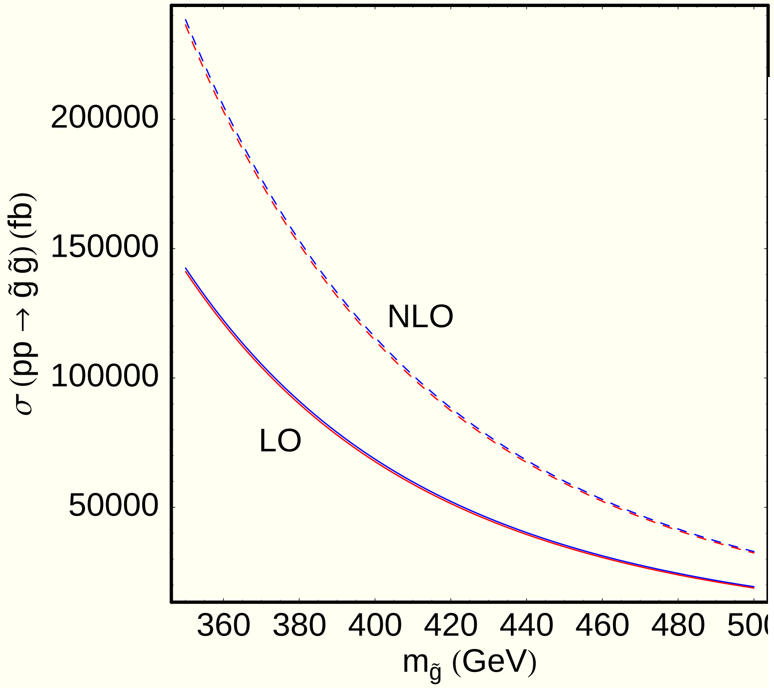


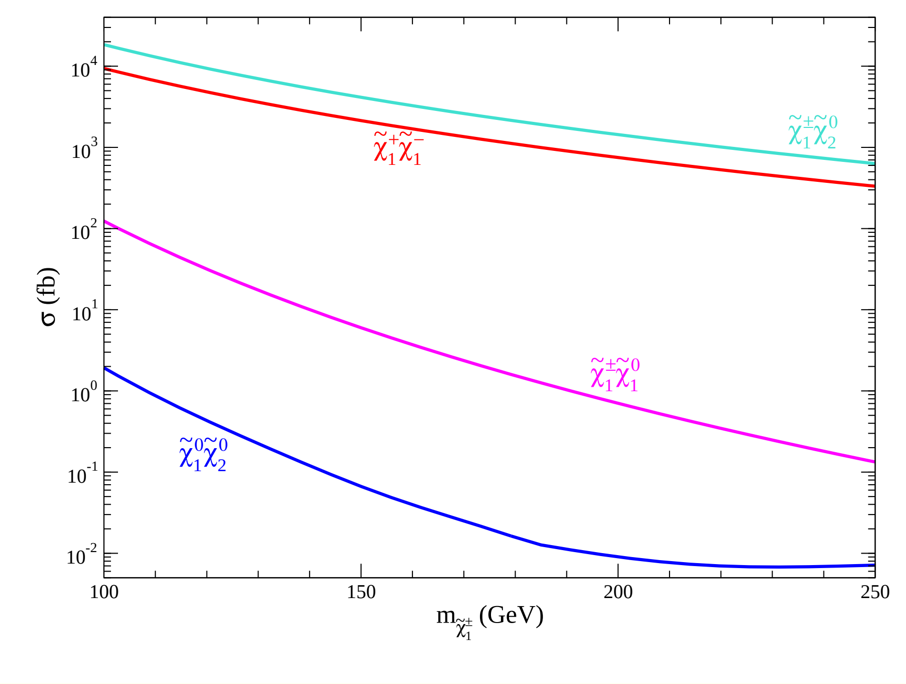
- can have $\widetilde{Z}_1 = LSP$ in this case
- $\widetilde{Z}_1\widetilde{Z}_1$ annihilate through h resonance
- lower m_{16} means $R \sim 1.09$

Prediction of new physics at LHC from $SO(10)$ SUSYGUTs:

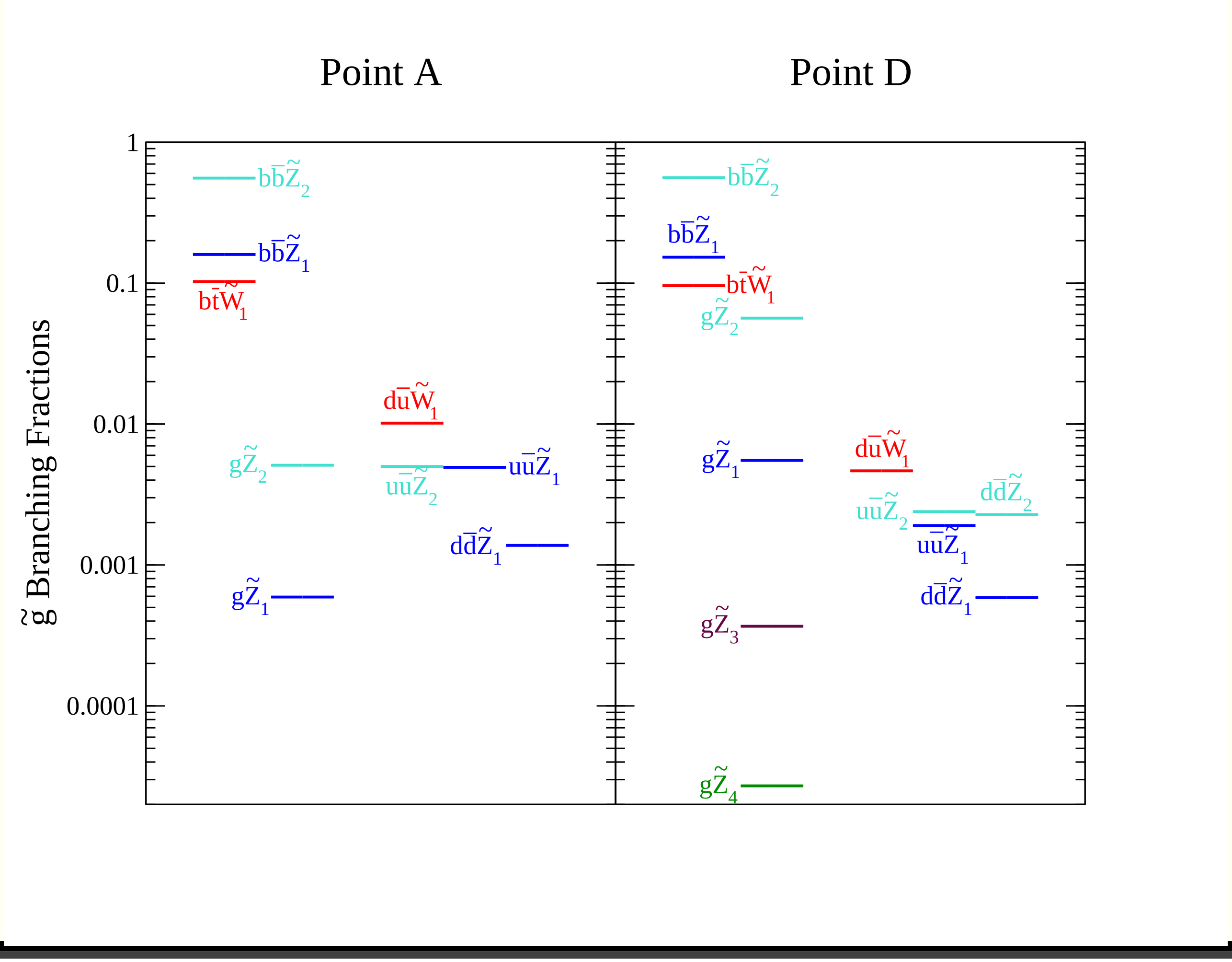
- gluino pair production with $m_{\tilde{g}} \sim 350-450$ GeV
- high b-jet multiplicity
- $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1} \sim 50-75$ GeV dilepton mass edge

Production of sparticles at LHC

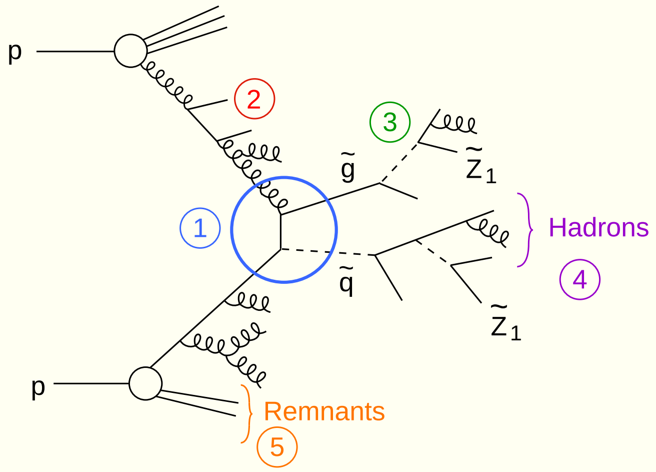




Sparticle cascade decays



Event generation for sparticles



Event generation in LL - QCD

1) Hard scattering / convolution with PDFs

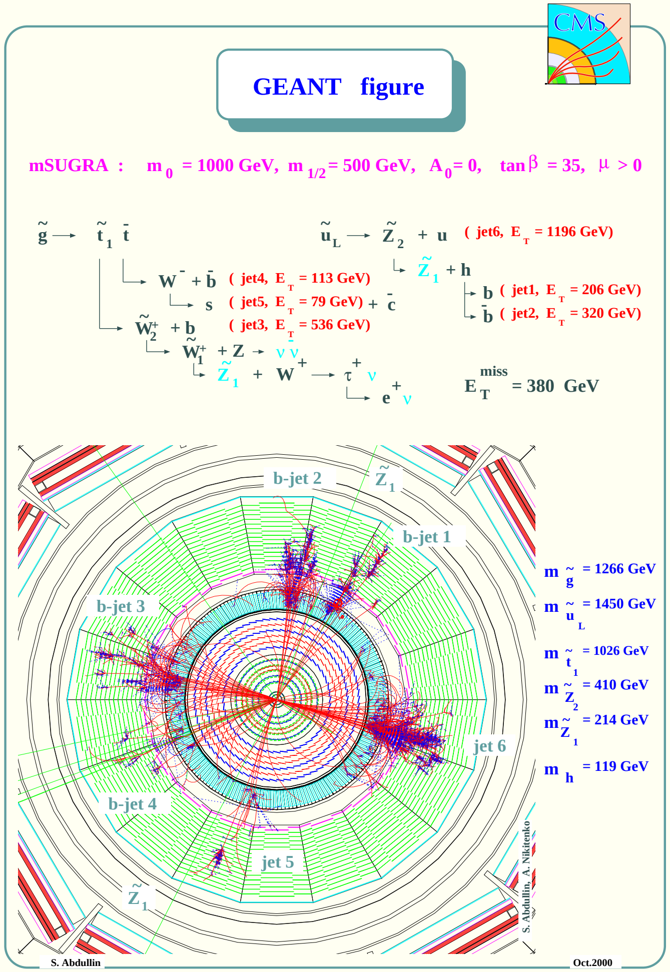
2) Intial / final state showers

3) Cascade decays

4) Hadronization

5) Beam remnants

Sparticle production at CMS (LHC)



GEANT figure

mSUGRA : $m_0 = 1000$ GeV, $m_{1/2} = 500$ GeV, $A_0 = 0$, $\tan\beta = 35$, $\mu > 0$

$\tilde{g} \longrightarrow \tilde{t}_1 \, \bar{t}$

$\quad \hookrightarrow W^- + \bar{b}$ (jet4, $E_T = 113$ GeV)

$\qquad \hookrightarrow s$ (jet5, $E_T = 79$ GeV) + $\bar{c}$

$\quad \hookrightarrow \tilde{W}_2^+ + b$ (jet3, $E_T = 536$ GeV)

$\qquad \hookrightarrow \tilde{W}_1^+ + Z \rightarrow \nu\,\bar{\nu}$

$\qquad\quad \hookrightarrow \tilde{Z}_1 + W^+ \longrightarrow \tau^+ \nu$

$\qquad\qquad \hookrightarrow e^+ \nu$

$\tilde{u}_L \longrightarrow \tilde{Z}_2 + u$ (jet6, $E_T = 1196$ GeV)

$\quad \hookrightarrow \tilde{Z}_1 + h$

$\qquad \hookrightarrow b$ (jet1, $E_T = 206$ GeV)

$\qquad \hookrightarrow \bar{b}$ (jet2, $E_T = 320$ GeV)

$E_T^{miss} = 380$ GeV

$m_{\tilde{g}} = 1266$ GeV

$m_{\tilde{u}_L} = 1450$ GeV

$m_{\tilde{t}_1} = 1026$ GeV

$m_{\tilde{Z}_2} = 410$ GeV

$m_{\tilde{Z}_1} = 214$ GeV

$m_h = 119$ GeV

S. Abdullin, A. Nikitenko

S. Abdullin

Oct.2000

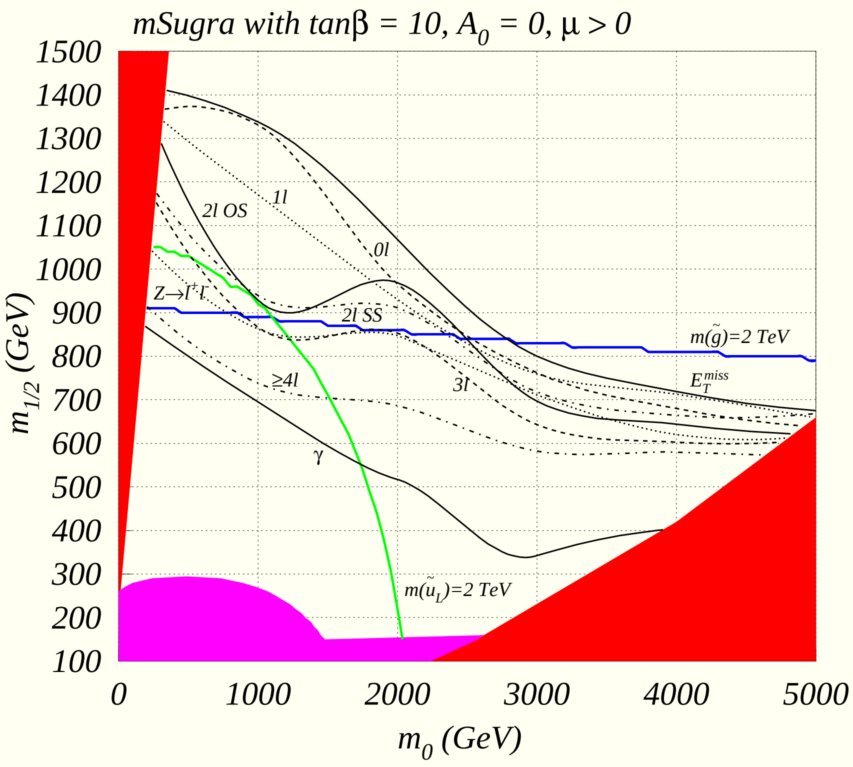
Search for SUSY at CERN LHC

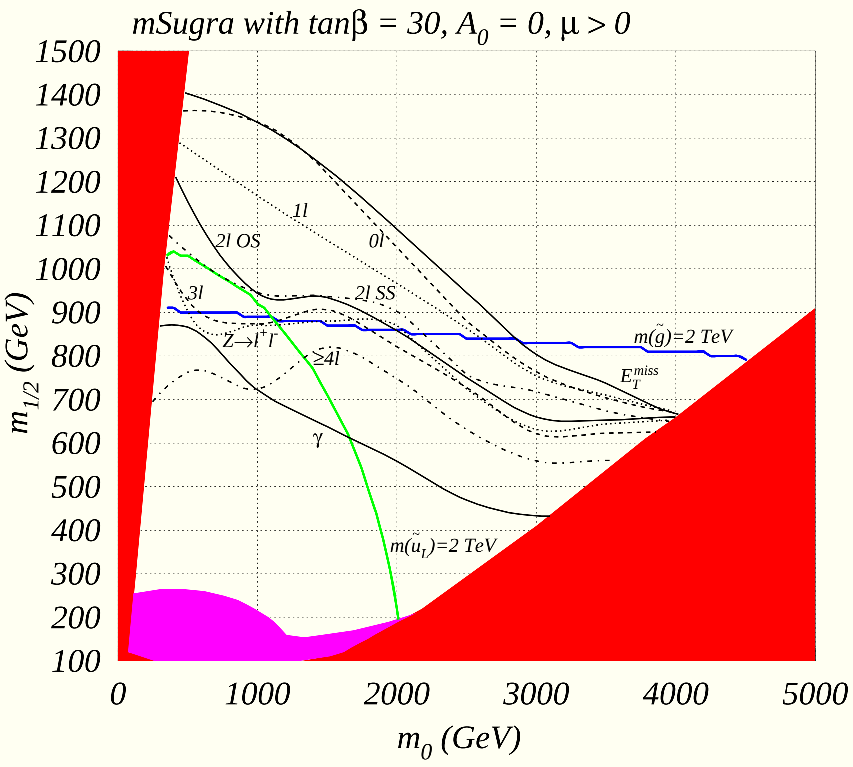
- ⋆ $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ production dominant for $m \lesssim 1$ TeV
- ⋆ lengthy cascade decays are likely
  - $\not{E}_T+$ jets
  - $1\ell+\not{E}_T+$ jets
  - $OS\ 2\ell+\not{E}_T+$ jets
  - $SS2\ell+\not{E}_T+$ jets
  - $3\ell+\not{E}_T+$ jets
  - $4\ell+\not{E}_T+$ jets
- ⋆ BG: $W+jets$, $Z+jets$, $t\bar{t}$, $b\bar{b}$, WW, $4t$, $\cdots$
- ⋆ Grid of cuts gives optimized S/B

Pre-cuts and cuts

- ⋆ $\not{E}_T > 200$ GeV
- ⋆ $N_j \geq 2$ (where $p_T(jet) > 40$ GeV and $|\eta(jet)| < 3$
- ⋆ Grid of cuts for optimized S/B:
  - $N_j \geq 2 - 10$
  - $\not{E}_T > 200 - 1400$ GeV
  - $E_T(j1) > 40 - 1000$ GeV
  - $E_T(j2) > 40 - 500$ GeV
  - $S_T > 0 - 0.2$
  - muon isolation
- ⋆ $S > 10$ events for 100 fb^{-1}
- ⋆ $S > 5\sqrt{B}$ for optimal set of cuts

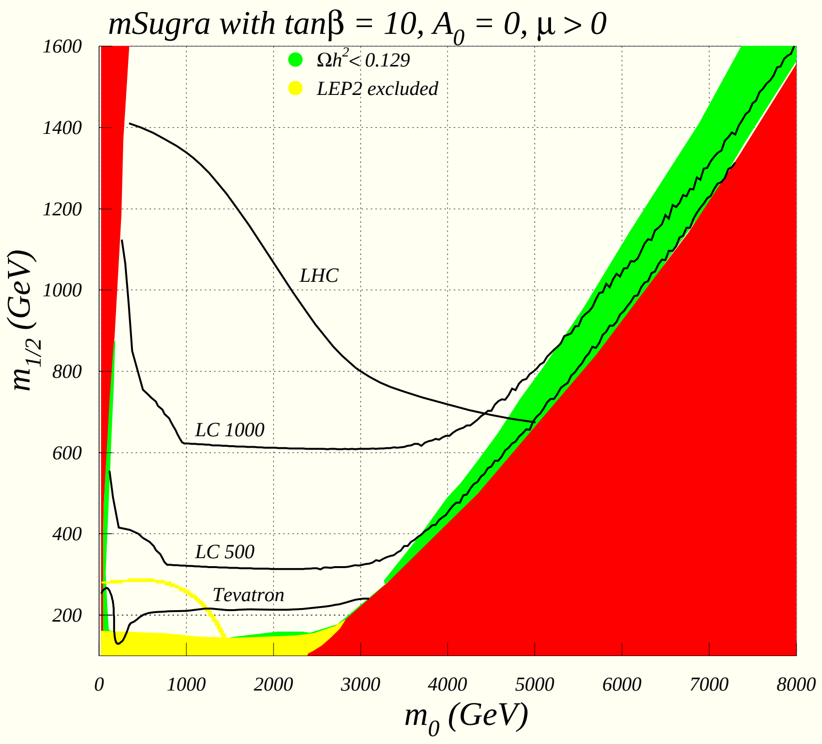
Sparticle reach of LHC for 100^{-1} fb

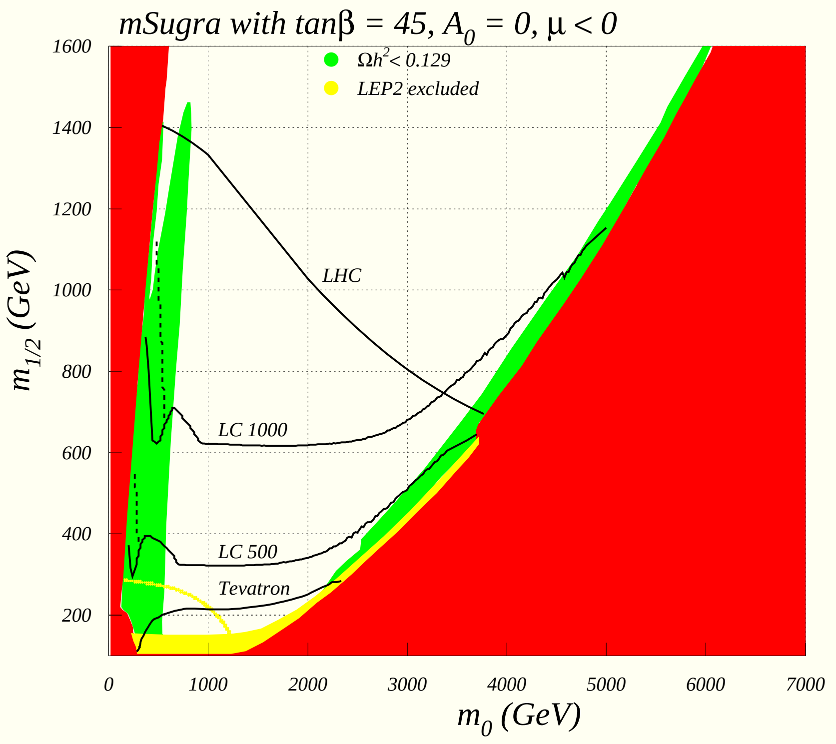




HB, Balazs, Belyaev, Krupovnickas, Tata: JHEP 0306, 054 (2003)

Sparticle reach of all colliders and relic density


mSugra with tanβ = 10, A_0 = 0, μ > 0


mSugra with tanβ = 45, A_0 = 0, μ < 0

HB, Belyaev, Krupovnickas, Tata: JHEP 0402, 007 (2004)

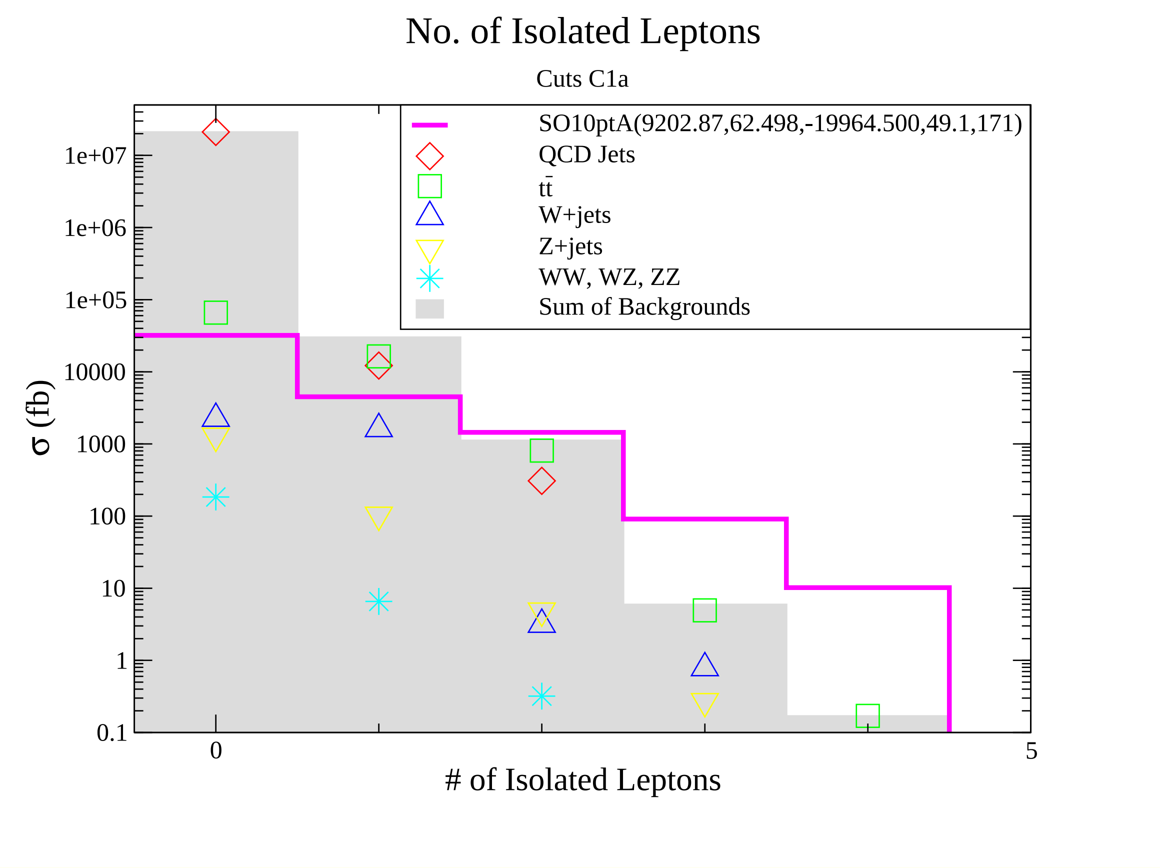
What $SO(10)$ SUSY GUTs look like at LHC

- with $m_{\tilde{g}} \sim 400$ GeV, expect $\sigma(pp \to \tilde{g}\tilde{g}X) \sim 10^5$ fb!
- LHC detectors would have LOTS of SUSY events!
- But, it will take time to measure many SM processes to reliably calibrate the entire detector for $jets + \not{E}_T$ search
- Could be a year or two if experience is similar to that of Tevatron D0 detector....

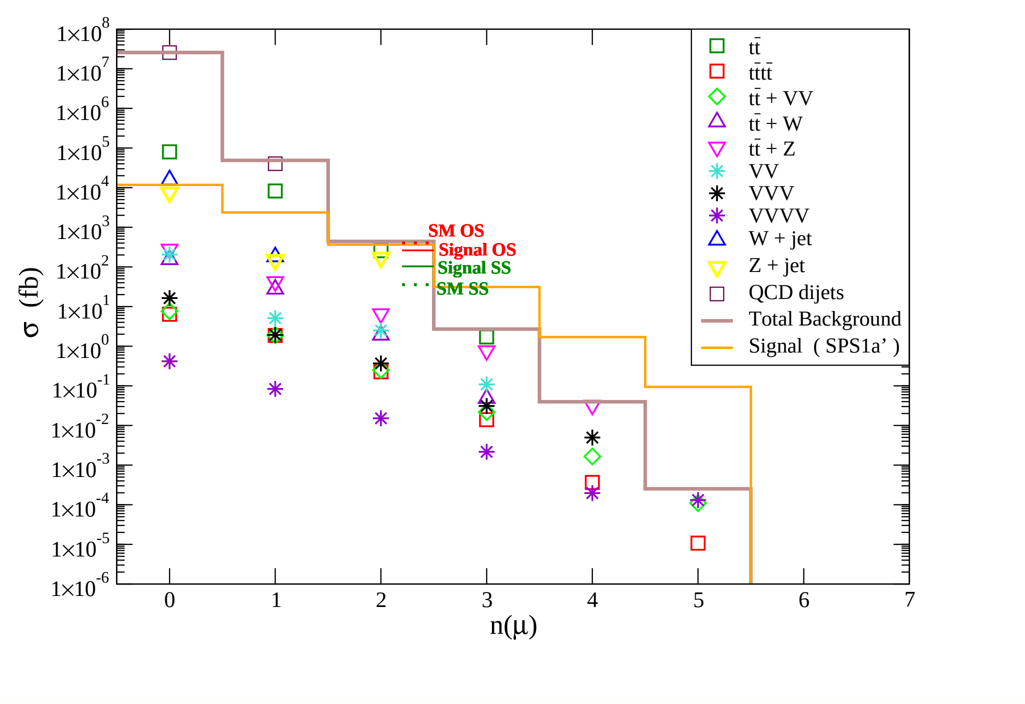
As theorists, we are an impatient bunch...

- Can we make early discovery of SUSY at LHC *without* $\not\!\!E_T$?
- Expect $\tilde{g}\tilde{g}$ events to be rich in jets, b-jets, isolated ℓs, τ-jets,....
- These are *detectable*, rather than inferred objects
- Inferred objects like $\not\!\!E_T$ require knowledge of complete detector performance
  - dead regions
  - "hot" cells
  - cosmic rays
  - calorimeter mis-measurement
- Answer: YES! See HB, Prosper, Summy, arXiv:0801.3799

Require simple cuts:

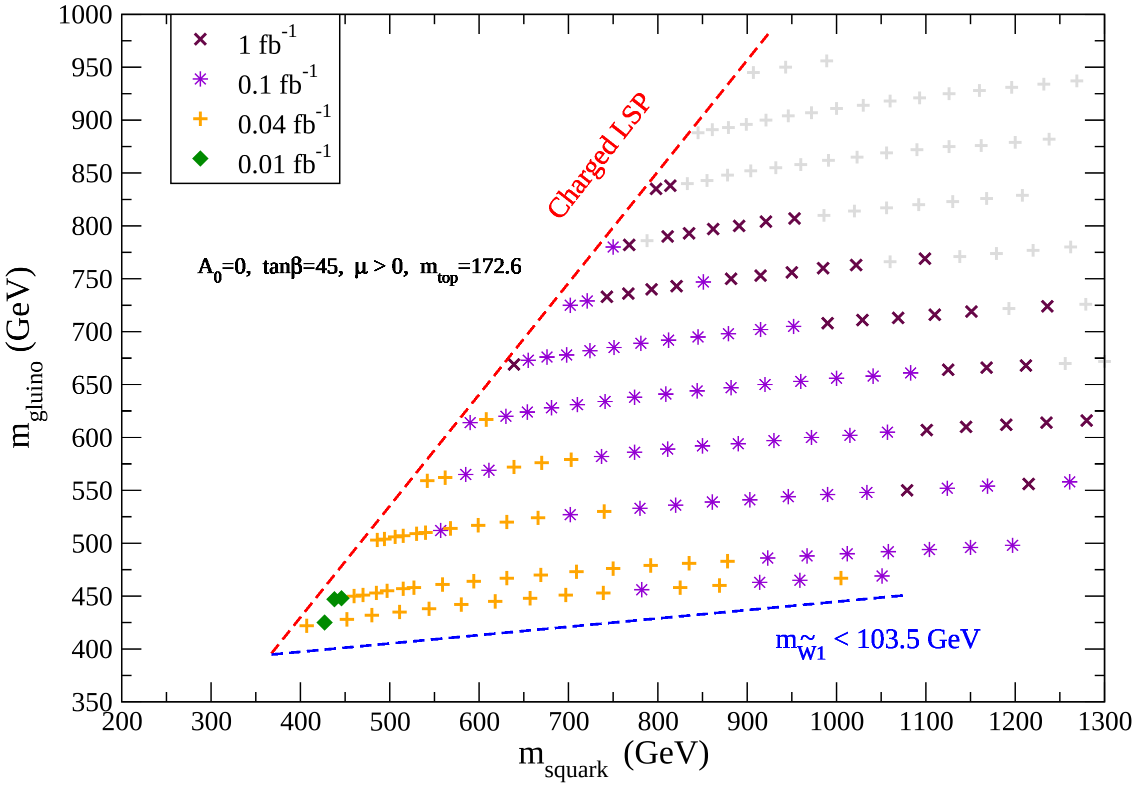


If early e ID problematic: focus on SS and multi-muons

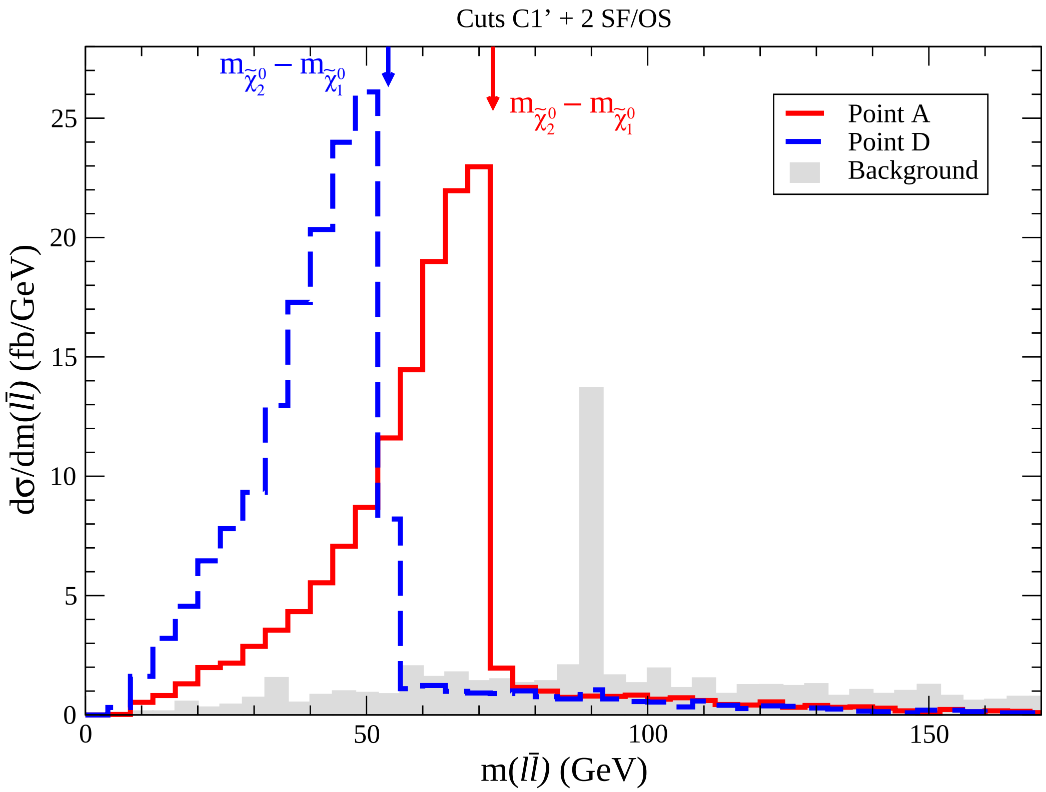


- HB, A. Lessa and H. Summy, arXiv:0809.4719

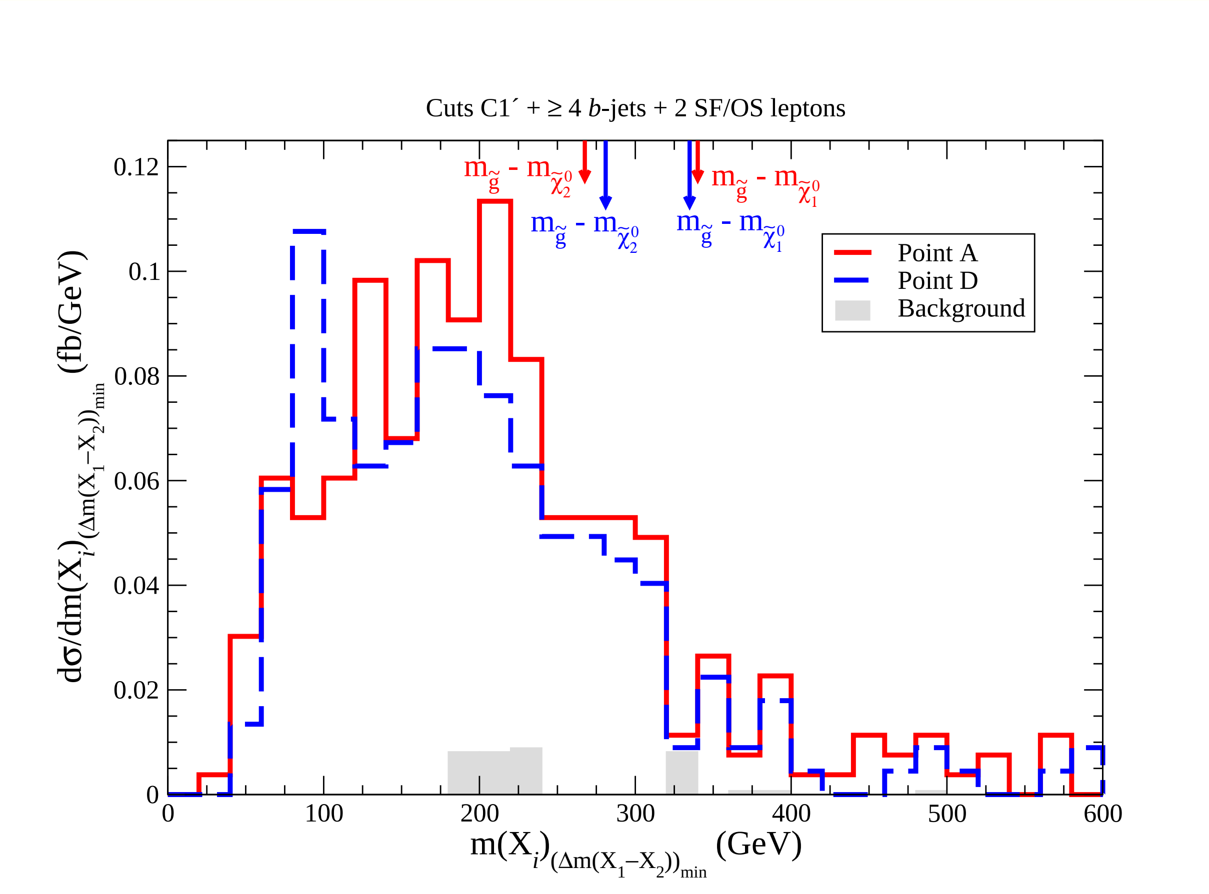
Require $\geq$ 4-jets plus SS isolated di-muons



Cuts C1′ plus $\geq 2\ OS/SF\ \ell$

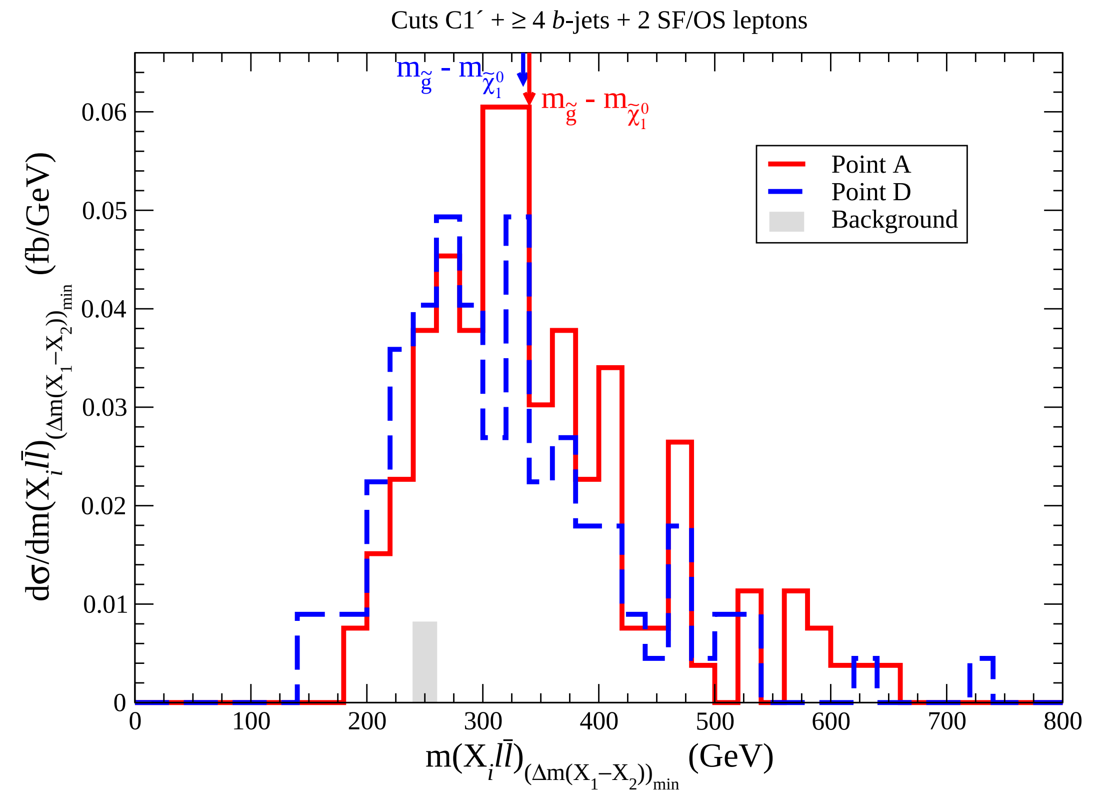


Cuts C1$'$ plus ≥ 4 b-jets+ $\ell^+\ell^-$



- Get $m(b\bar{b})$ from $\tilde{g} \to b\bar{b}\widetilde{Z}_2$ decay

Cuts C1$'$ plus ≥ 4 b-jets+ $\ell^+\ell^-$

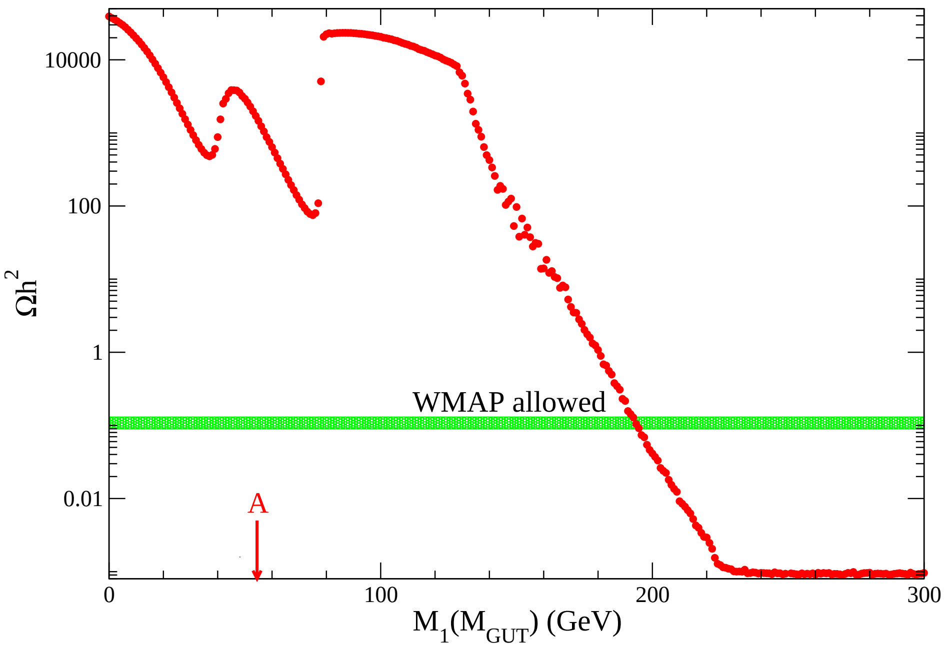


- Get $m(b\bar{b}\ell^+\ell^-)$ from $\tilde{g} \to b\bar{b}\widetilde{Z}_2$ decay

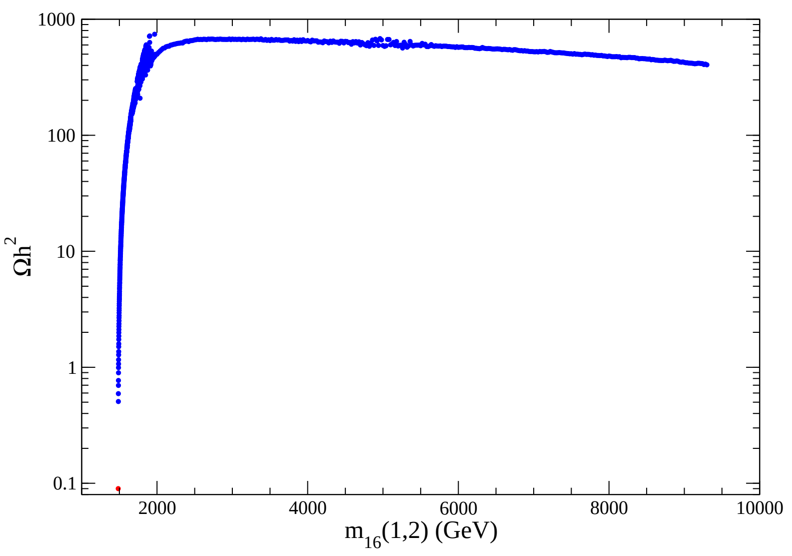
Conclusions

- ⋆ $SO(10)+SUSY$ is extremely compelling effective theory at $Q=M_{GUT}$
- ⋆ In simple $SO(10)$ SUSYGUTs, expect $t-b-\tau$ unification
- ⋆ For $\mu>0$, get YU for HS model with $A_0^2\sim 2m_{10}^2=4m_{16}^2$
- ⋆ Can reconcile with DM abundance: $\widetilde{Z}_1\to\tilde{a}\gamma$ or "compromise solution" or ...
- ⋆ Cosmology: axino DM solution gives consistent cosmology: gravitino problem and non-thermal leptogenesis
- ⋆ Predict $m_{\tilde{g}}\sim 400$ GeV, decoupled scalars: LHC awash in $\tilde{g}\tilde{g}$ events
- ⋆ Can see signal with only 0.1 fb^{-1} of integrated luminosity in jets $+OS/SF$ leptons or $\geq 3\ell$ channel
- ⋆ $m(\ell^+\ell^-)$ mass edge $\sim 50-75$ GeV; reconstruct $m_{\tilde{g}}$, $m_{\widetilde{Z}_2}$, $m_{\widetilde{Z}_1}$?
- ⋆ We will soon know if Yukawa unified SUSY is correct theory of weak scale physics! LHC turn-on in 2008!

Reconciling DM with YU: non-universal gaugino masses

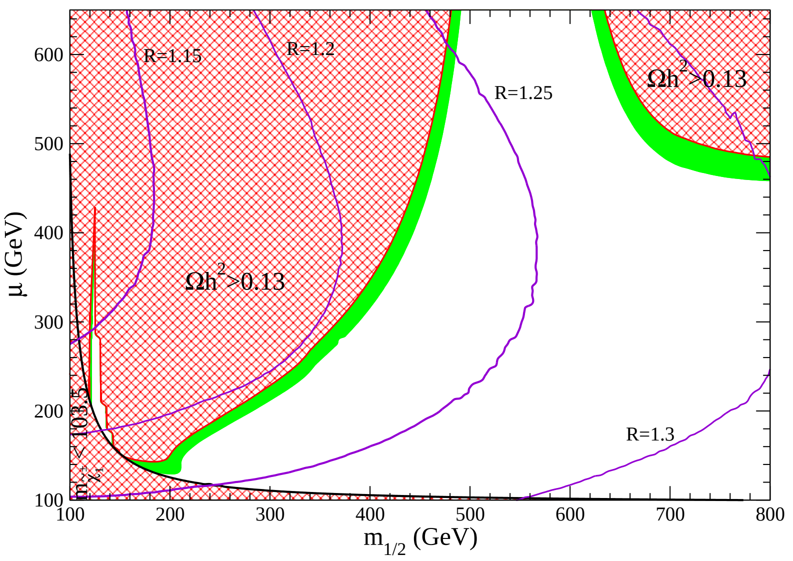


Reconciling DM with YU: non-universal m_{16}



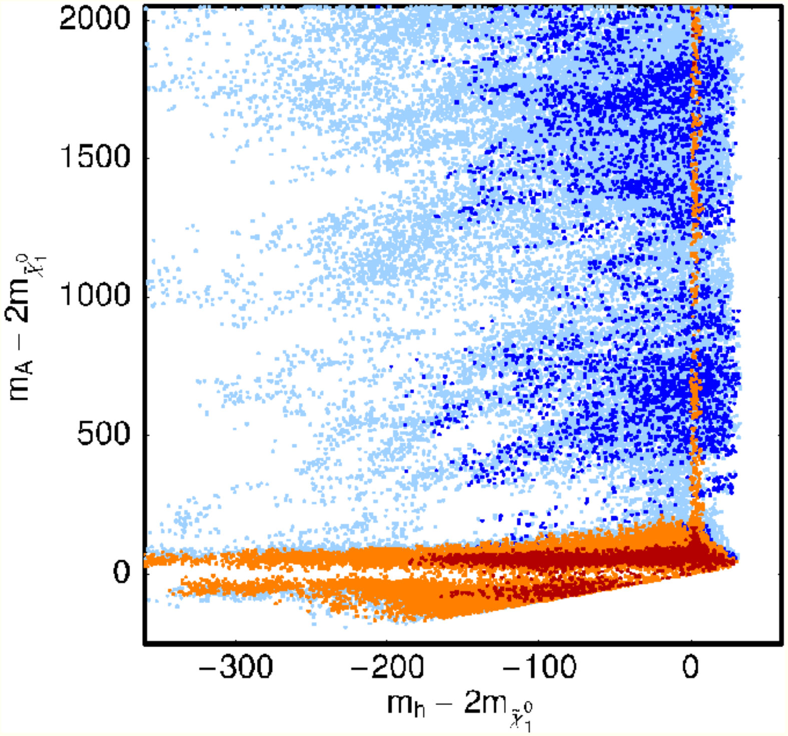
- gives extremely light $\tilde{u}_R,\ \tilde{c}_R \sim 130$ GeV due to HS in RGEs

Can generate BDR solutions with both WS/GS BCs



- Using top-down approach and exact Yukawa unification, BDR generate low $\mu,\ m_A$ solutions with low χ^2 fit to m_t, m_b, m_τ
- best fit for BFPZ BCs, HS model and $\tan\beta \sim 50$
- our numerical code differs sustantially from BDR

Can generate BDR-type solutions with low $m_A \sim 150$ GeV



- $\widetilde{Z}_1\widetilde{Z}_1$ annihilate through A resonance
- comb. large $\tan\beta \sim 50$ and low m_A: excluded by $B_s \to \mu^+\mu^-$