Yukawa-unified SUSY

– minimal SUSY SO(10) GUT –

Sabine Kraml
LPSC Grenoble

based on a series of papers with
H. Baer, A. Lessa, S. Sekmen, H. Summy
arXiv: 0801.1831, 0809.0710, 0812.2693, 0908.0134, 0910.2988, 0911.4739

SUSY10
18th International Conference on Supersymmetry and Unification of Fundamental Interactions
23-28 Aug 2010, Physikalisches Institut, Bonn, Germany

Overview

1. Introduction and motivation
2. Conditions for Yukawa unification
3. Typical mass spectra
4. LHC phenomenology
5. Dark matter

See also S. Raby's preSUSY lecture!

Introduction

Georgi, 1974; Fritzsch, Minkowski, 1975; Gell-Mann, Ramond, Slansky, 1978.

SUSY GUTs based on SO(10) are very compelling:

- All three forces of the SM are unified by a simple Lie group, hierarchy between weak and GUT scales stabilized by SUSY.
- All matter fermions of one generation, including a RH neutrino, sit in one irreducible **16**-dimensional representation.
  → neutrino see-saw
  → leptogenesis
- The group SO(10) is anomaly-free, and provides an explanation for cancellation of triangle anomalies.
- The MSSM weak hypercharge assignments can be derived from broken SO(10) using only the lowest-dim Higgs multiplets.
  → group-theoretic evidence for SO(10) ? Lykken, Montroy, Willenbrock, 1998
- R-parity conservation quite natural.

Hall, Suzuki, 1984; Mohapatra, 1986; Font, Ibanez, Quevedo, 1989; Martin, 1996; Aulakh, Melfo, Rasin, Senjanovic, 1999.

Ananthanarayan, Lazarides and Shafi, 1991
(and a long list to follow)

Yukawa coupling unification

- The two Higgs doublets of the MSSM sit in the **10** dim. representation of SO(10).

- In the simplest version of the model, the 3rd generation Yukawa couplings are given by a single term in the superpotential:

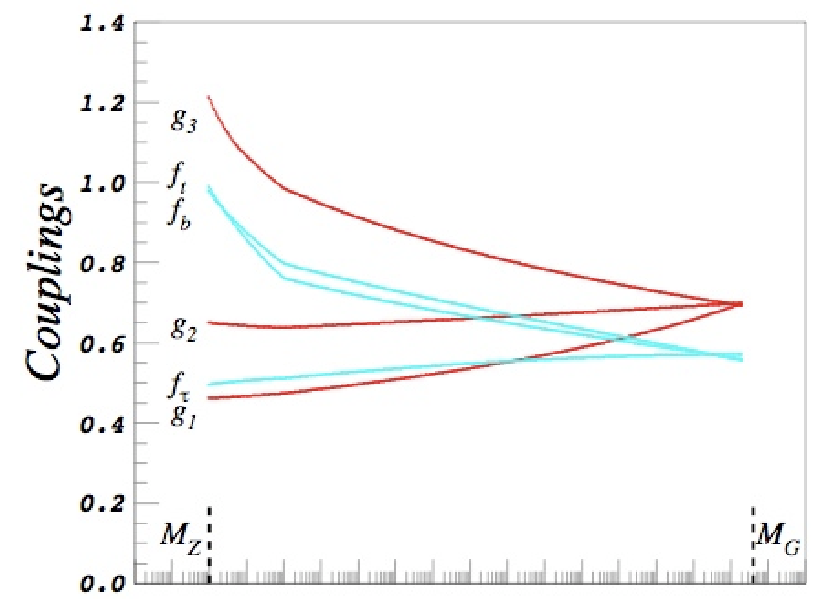
  W = f **16 10 16**

  resulting in Yukawa unification at M_{GUT} :

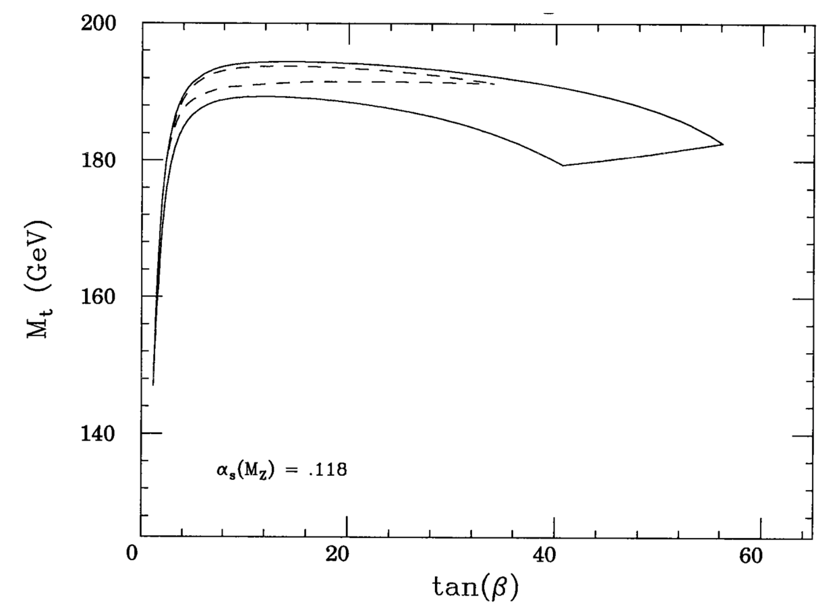
$$f_t = f_b = f_\tau = f_\nu$$

- Like for gauge coupling unification there is a definite prediction but now for a heavy top and tanβ ≈ 50 !

For fermion masses of the lighter generations see, e.g., Dimopouplos, Hall, Raby, 1984; Anderson et al., 1994; Carena et al. 1995; Babu, Barr, 1997; Albright, Barr, 1998; Babu, Pati, Wiczek, 2000; Demisek, Raby, 2005.



Anderson et al, 1993



$\tan\beta = 60.6 \pm 3$, $m_t = 179 \pm 4$ GeV, $\alpha_s \geq 0.123$ and $|V_{cb}| \geq .052$.

20 years of Yukawa unification

B. Ananthanarayan, G. Lazarides and Q. Shafi, PRD44, 1613 (1991) and PLB300, 245 (1993); L.J. Hall, R. Rattazzi and U. Sarid, PRD50, 7048 (1994); G. Anderson et al., PRD47, 3702 (1993) and PRD49, 3660 (1994); V. Barger, M. Berger and P. Ohmann, PRD49, 4908 (1994); M. Carena, M. Olechowski, S. Pokorski and C. Wagner, NPB426, 269 (1994); B. Ananthanarayan, Q. Shafi and X. Wang, PRD50, 5980 (1994); R. Rattazzi and U. Sarid, PRD53, 1553 (1996); H. Murayama, M. Olechowski and S. Pokorski, PLB371, 57 (1996), T. Blazek, M. Carena, S. Raby and C. Wagner, PRD56, 6919 (1997); T. Blazek, S. Raby, PLB392, 371 (1997) and PRD59, 095002 (1999); T. Blazek, S. Raby and K. Tobe, PRD60, 113001 (1999) and PRD62, 055001 (2000); H. Baer, M. Diaz, J. Ferrandis and X. Tata, Phys. Rev. D61, 111701 (2000);

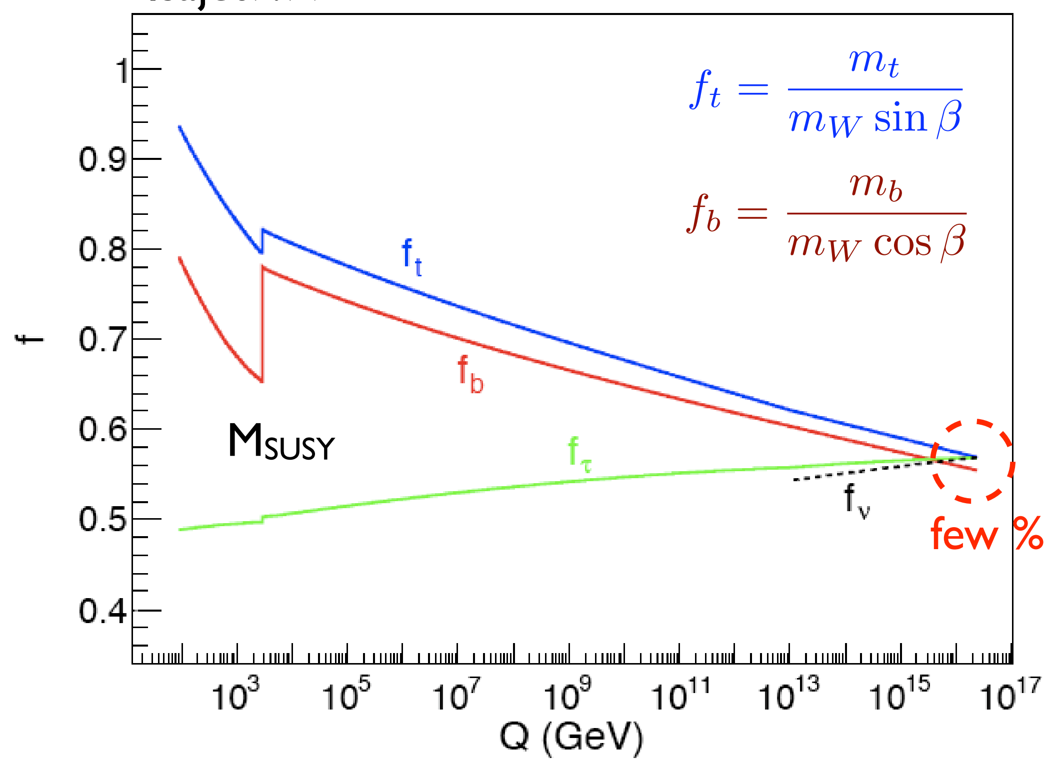
H. Baer, M. Brhlik, M. Diaz, J. Ferrandis, P. Mercadante, P. Quintana and X. Tata, Phys. Rev. D63, 015007 (2001); H. Baer and J. Ferrandis, PRL87, 211803 (2001); T. Blazek, R. Dermisek and S. Raby, PRL88, 111804 (2002) and PRD65, 115004 (2002); M. Gomez, G. Lazarides and C. Pallis, PRD61, 123512 (2000), NPB638, 165 (2002) and PRD67, 097701 (2003); U. Chattopadhyay, A. Corsetti and P. Nath, PRD66, 035003 (2002); I. Gogoladze, Y. Mimura, S. Nandi and K. Tobe, PLB575, 66 (2003); S. Profumo, PRD68, 015006 (2003); C. Balazs and R. Dermisek, JHEP0803, 024 (2003); K. Tobe and J.D. Wells, NPB663, 123 (2003); D. Auto, H. Baer, C. Balazs, A. Belyaev, J. Ferrandis and X. Tata, JHEP0306, 023 (2003); C. Pallis, NPB678, 398 (2004); R. Dermisek, S. Raby, L. Roszkowski and R. Ruiz de Austri, JHEP0304, 037 (2003) and JHEP0509, 029 (2005); M. Gomez, T. Ibrahim, P. Nath and S. Skadhauge, PRD72, 095008 (2005);

M. Albrecht, W. Altmannshofer, A.J. Buras, D. Guadagnoli and D. Straub, JHEP0710, 055 (2007); H. Baer, S. Kraml, S. Sekmen and H. Summy, JHEP0803, 056 (2008) and JHEP0810, 079 (2008) 079; W. Altmannshofer, D. Guadagnoli, S. Raby and D. Straub, PLB668, 385 (2008); I. Gogoladze, R. Khalid and Q. Shafi, PRD79, 115004 (2009); H. Baer, M. Haider, S. Kraml, S. Sekmen and H. Summy, JCAP0902, 002 (2009); D. Guadagnoli, S. Raby and D.M. Straub, JHEP0910, 059 (2009); H. Baer, S. Kraml and S. Sekmen, JHEP0909, 005 (2009); H. Baer, S. Kraml, A. Lessa, S. Sekmen and H. Summy, PLB685, 72 (2010); H. Baer, S. Kraml, A. Lessa and S. Sekmen, JHEP1002, 055 (2010); I. Gogoladze, R. Khalid, S. Raza and Q. Shafi, arXiv:1008.2765;

NB: this list is incomplete, let me know if your paper is missing ....

Large δm_b corrections

Isajet7.79



At large $\tan\beta$, the bottom Yukawa is subject to large SUSY loop corrections

$$m_b^{\mathrm{MSSM}} = m_b^{\mathrm{SM}} \left[1 + \left(\frac{\delta m_b}{m_b} \right) \right]^{-1}$$

so that the Yukawa unification (YU) depends on the whole SUSY spectrum.

Hall, Rattazzi, Sarid, 1994;
Carena, Olechowski, Pokorski, Wagner, 1994.

$$\left(\frac{\delta m_b}{m_b} \right) \approx \frac{g_3^2}{12\pi^2} \frac{\mu M_3}{m_{\tilde{b}}^2} \tan\beta + \frac{f_t^2}{32\pi^2} \frac{\mu A_t}{m_{\tilde{t}}^2} \tan\beta + \mathrm{logs} + \ldots$$

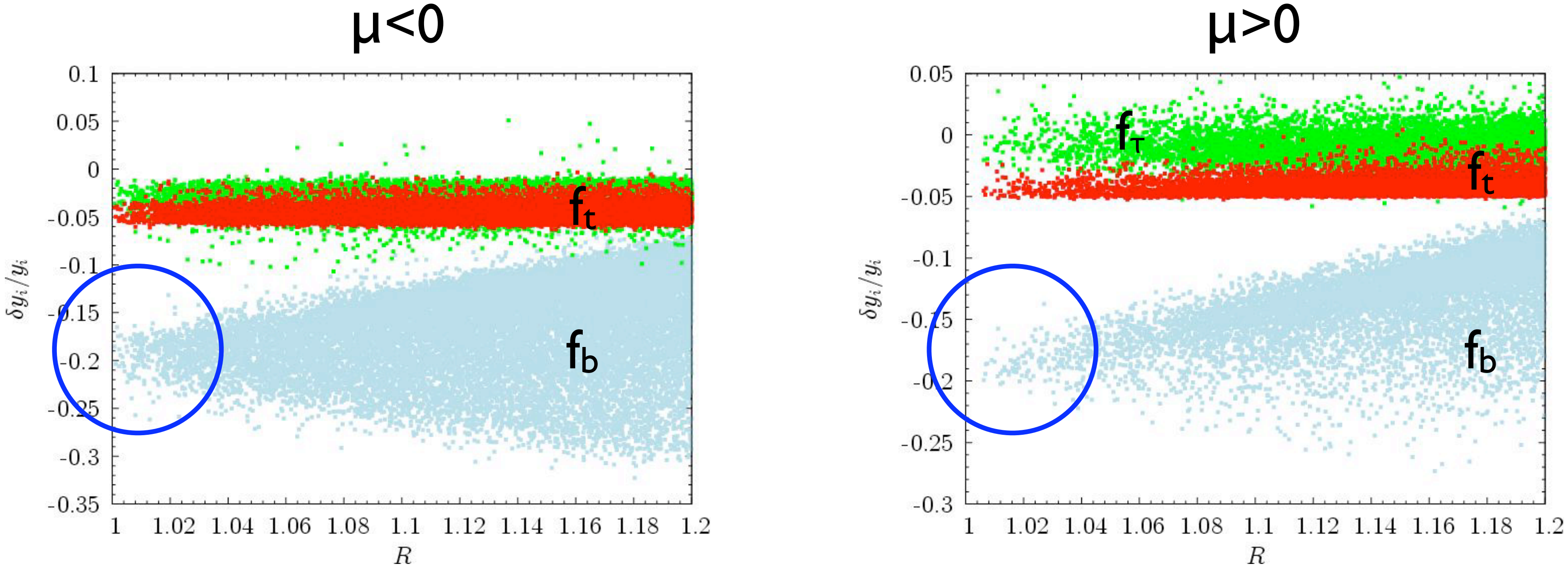
$M_3 > 0$

Gluino-loop correction: dominant over most of the parameter space. Positive for μ>0. ☹

Chargino-loop correction: negative for μ>0 (since A_t<0 !), but small unless very large $|A_t|$ and fairly light stop.

- Consequence: t-b-τ Yukawa unification is easier to achieve for μ<0.

$$\frac{\delta f_i}{f_i}$$



plots from Gogoladze et al., arXiv:1008.2765;

$$R = \frac{\max(f_t, f_b, f_\tau)}{\min(f_t, f_b, f_\tau)}$$

Flavour constraints

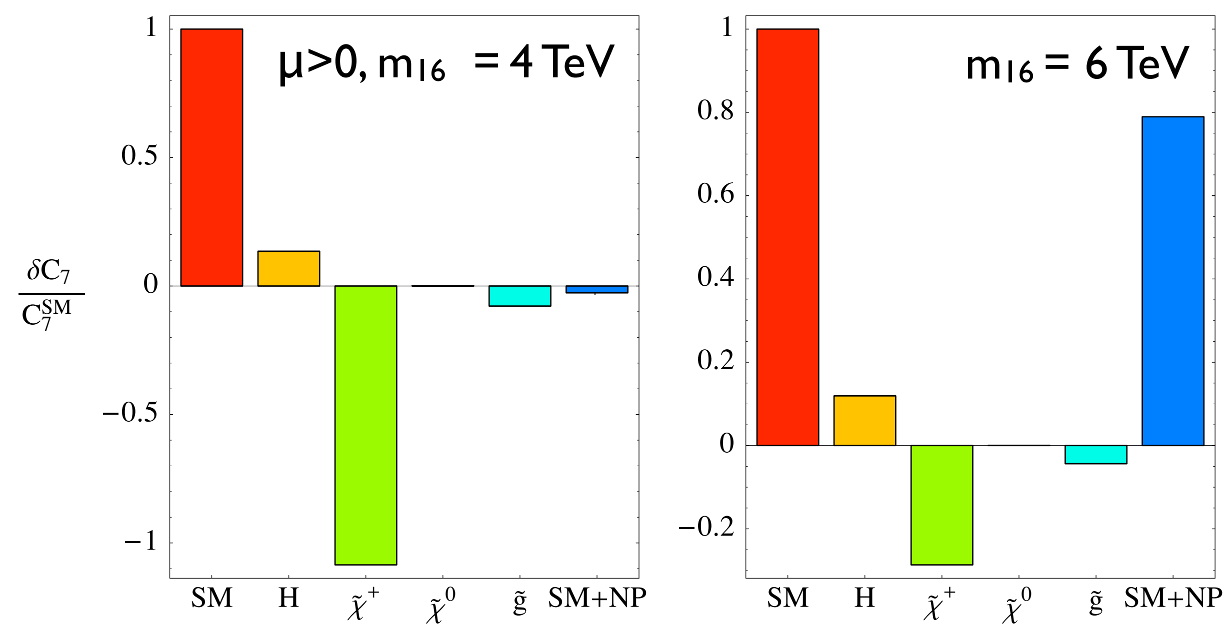
- $BR(B_s \to \mu^+\mu^-) \approx \tan\beta^6/m_A^4$ .... pushes m_A to ~ TeV.
- $BR(B \to X_s\gamma)$: charged and neutral Higgs contributions are strictly positive, chargino contribution is

$$C_7^{\tilde{\chi}^+} \propto \mu A_t \tan\beta \times \mathrm{sign}(C_7^{\mathrm{SM}})$$

Typically need to decouple SUSY contributions, more so for $\mu>0$.

- $B \to X_s l^+l^-$: favours $C_7 = C_7^{SM}$
- (g-2) : favours $\mu>0$

Tough for YU!



Detailed discussion of flavour constraints in
M. Albrecht, W. Altmannshofer, A.J. Buras, D. Guadagnoli and D. Straub, arXiv: 0707.3954
see also talk by D. Straub on Monday

Soft terms and RGEs

- Sparticles in the same multiplet should pick up the same soft mass. So we expect universal soft terms for the scalars in each the **16** and the **10** at M_{GUT}. Breaking SO(10) through SU(5)xU(1) also motivates a common gaugino mass.

$$m_{1/2},\ m_{16},\ m_{10},\ A_0, \tan\beta, \mathrm{sign}(\mu)$$

- Higgs RGEs and REWSB:

$$16\pi^2 \frac{\mathrm{d}}{\mathrm{d}t} m^2_{H_u} = 3X_t - 6g_2^2\,|M_2|^2 - \dots, \quad X_t = 2|f_t|^2\,(m^2_{H_u} + M^2_{\tilde{Q}_3} + M^2_{\tilde{U}_3} + |A_t|^2)$$

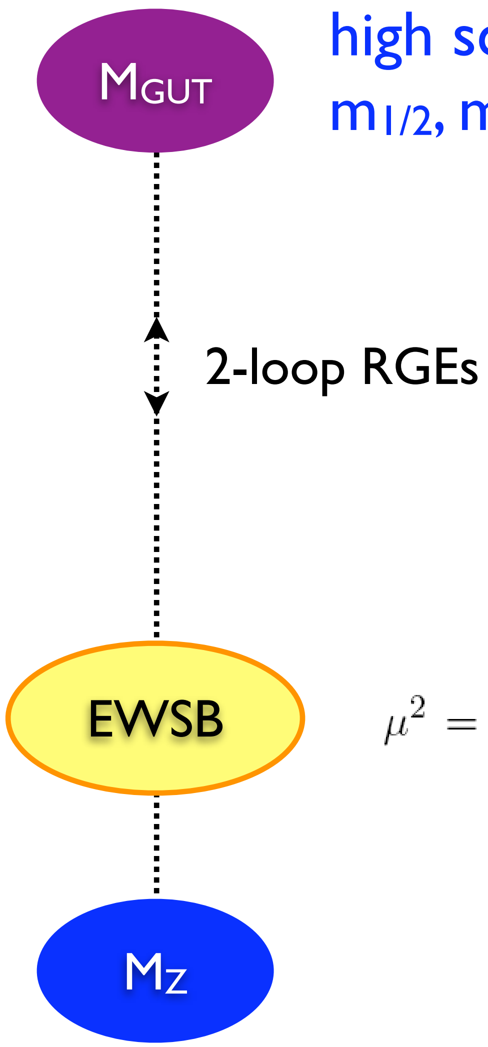
$$16\pi^2 \frac{\mathrm{d}}{\mathrm{d}t} m^2_{H_d} = 3X_b + X_\tau - 6g_2^2\,|M_2|^2 - \dots, \quad X_b = 2|f_b|^2\,(m^2_{H_d} + M^2_{\tilde{Q}_3} + M^2_{\tilde{D}_3} + |A_b|^2)$$

- To achieve proper REWSB, Higgs mass parameters need to be split at M_{GUT} :

$$m^2_{H_u} < m^2_{H_d} \quad \Rightarrow \quad m^2_{H_{u,d}} = m_{10} \mp 2M_D^2$$

Murayama, Olechowski and Pokorski, 1996

high scale parameters
$m_{1/2}$, m_{16}, m_{10}, M_D^2, A_0



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

gauge & Yukawa couplings

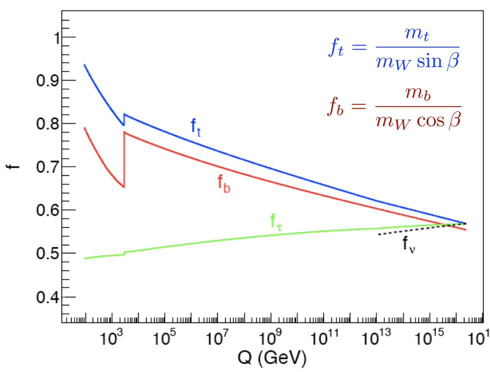
We take a bottom-up approach, fixing EW parameters and searching for good Yukawa unification.

Raby et al.: impose exact YU and do a top-down fit of weak-scale parameters (M_Z, m_b, ...)

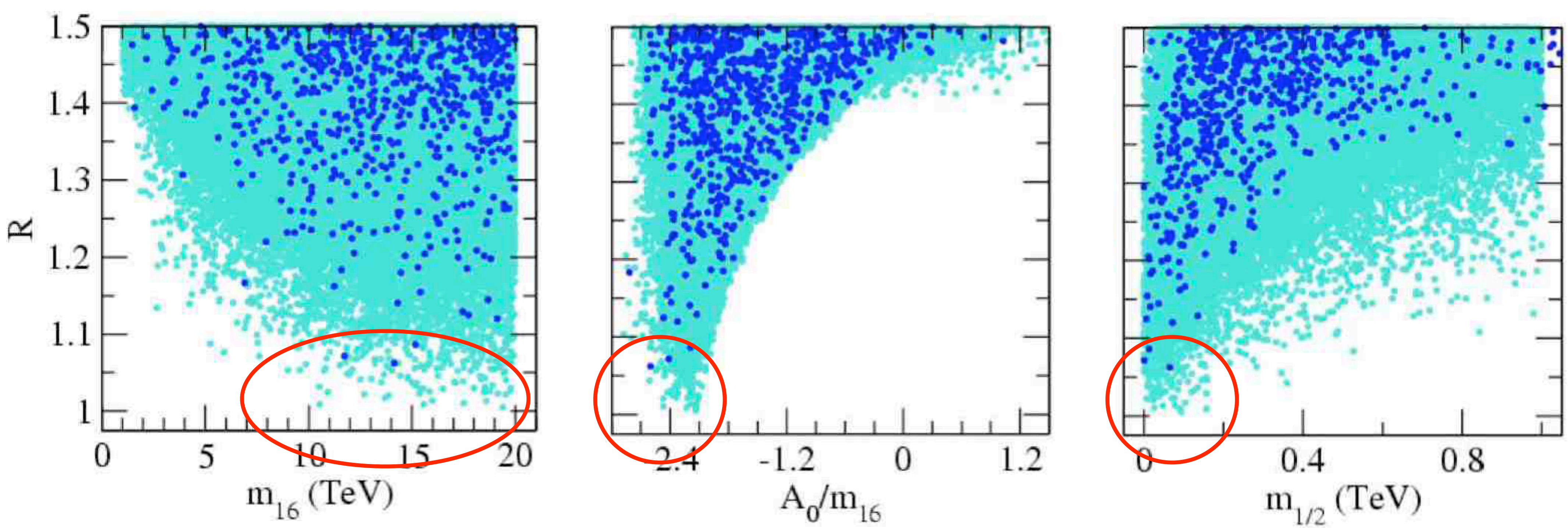
Conditions for Yukawa unification

★ For μ>0, as preferred by low-energy constraints, Yukawa unification can only be realized for very particular parameter relations

- $m_{16} \sim 5 - 15$ TeV ,
- $m_{10} \sim 1.3 m_{10}$,
- $A_0 \sim -2 m_{16}$,
- $m_{1/2} \ll m_{16}$.



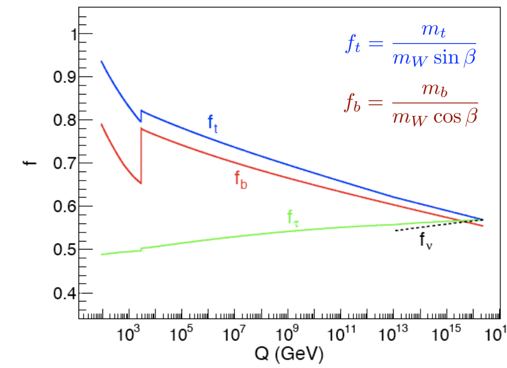
$$R = \frac{max(f_t,\ f_b,\ f_\tau)}{min(f_t,\ f_b,\ f_\tau)}$$



Conditions for Yukawa unification

★ For μ>0, as preferred by low-energy constraints, Yukawa unification can only be realized for very particular parameter relations

- $m_{16} \sim 5 - 15$ TeV ,
- $m_{10} \sim 1.3 m_{16}$,
- $A_0 \sim -2 m_{16}$,
- $m_{1/2} \ll m_{16}$.



$$R = \frac{max(f_t,\ f_b,\ f_\tau)}{min(f_t,\ f_b,\ f_\tau)}$$

★ HS vs D-term splitting

$$m_Q^2 = m_E^2 = m_U^2 = m_{16}^2 + M_D^2$$
$$m_D^2 = m_L^2 = m_{16}^2 - 3M_D^2$$
$$m_{\tilde{\nu}_R}^2 = m_{16}^2 + 5M_D^2$$
$$m_{H_{u,d}}^2 = m_{10}^2 \mp 2M_D^2 .$$

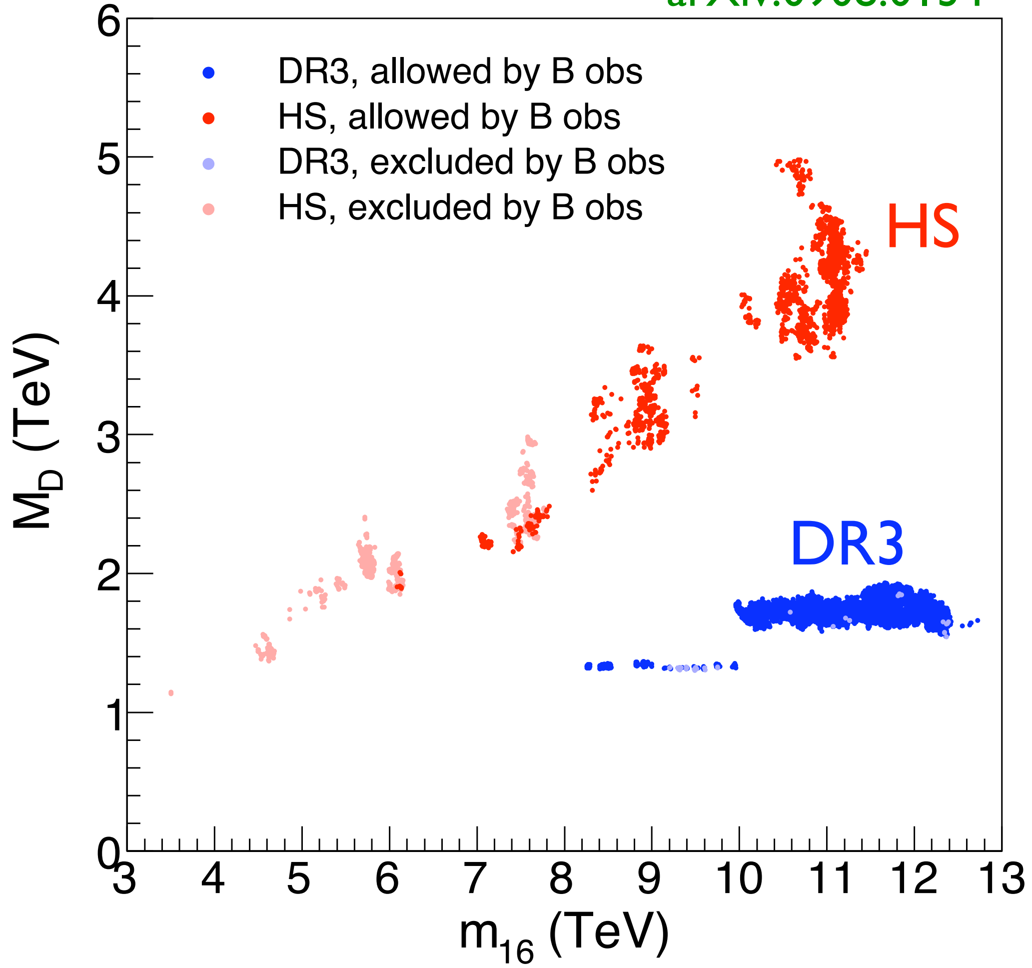
"just-so" Higgs splitting (HS) case

NB: we need $m_{H_u}^2 < m_{H_d}^2$ at $M_{\rm GUT}$, so $M_D^2 > 0$.

- D-term splitting w/o RHN gives R~1.08 (i.e. 8% unification)
- Splitting of only m_H's ("just-so HS") allows for R~1.01
- D-term splitting with RHN gives R~1.04, ...
- ... but if we allow in addition small non-degeneracy of 3rd vs. 1st/2nd generation, we get R~1.02 ("DR3")

Baer et al., 0908.0134

arXiv:0908.0134



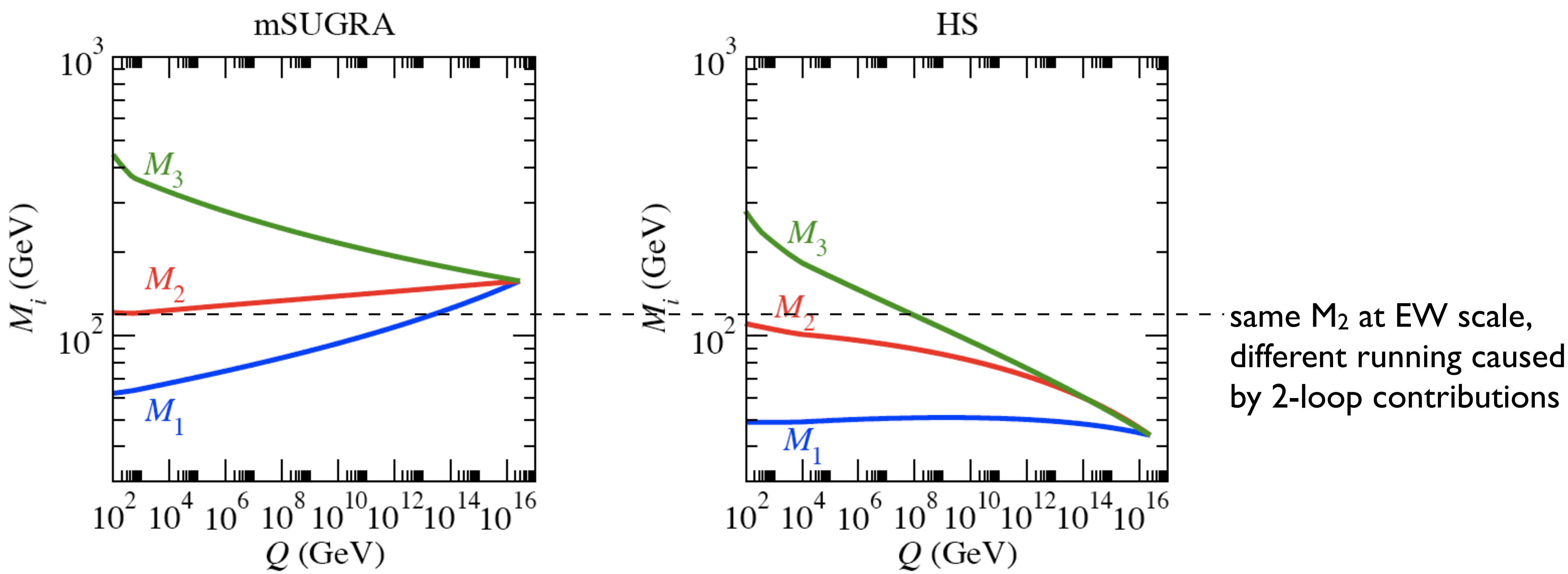
m_D versus m_{16} for HS and DR3 cases: points from MCMC scans for small R.

Typical mass spectra

- Radiatively driven inverted scalar mass hierarchy: 1st/2nd generation in 10 TeV range, while 3rd generation, mA and μ at O(1) TeV.

Bagger, Feng, Polonsky, Zhang, 2000

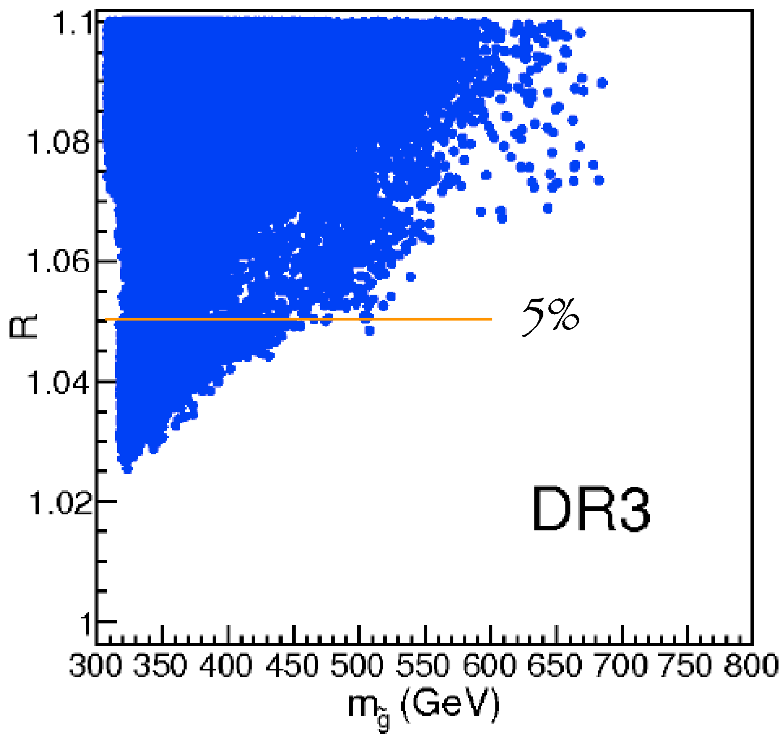
- Lightest sfermion in HS case: stop-right, in DR3 case: sbottom-right.
- Light gauginos: LSP ~ 50-80 GeV, gluino ~ 300-500 GeV

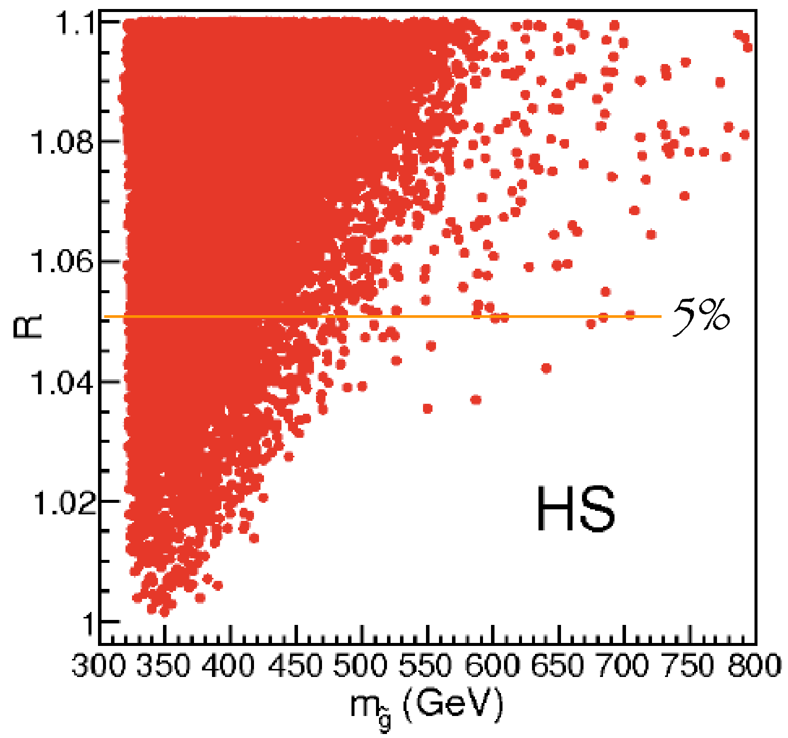


Evolution of gaugino masses in mSUGRA and Yukawa-unified SO(10) HS model

Typical mass spectra

- Inverted scalar mass hierarchy (c.f. "Effective SUSY", talk by A. Lessa)
- Stop/sbottom masses reflect D-term contributions
- Light gauginos: bino LSP ~ 50-80 GeV, gluino ~ 300-500 GeV

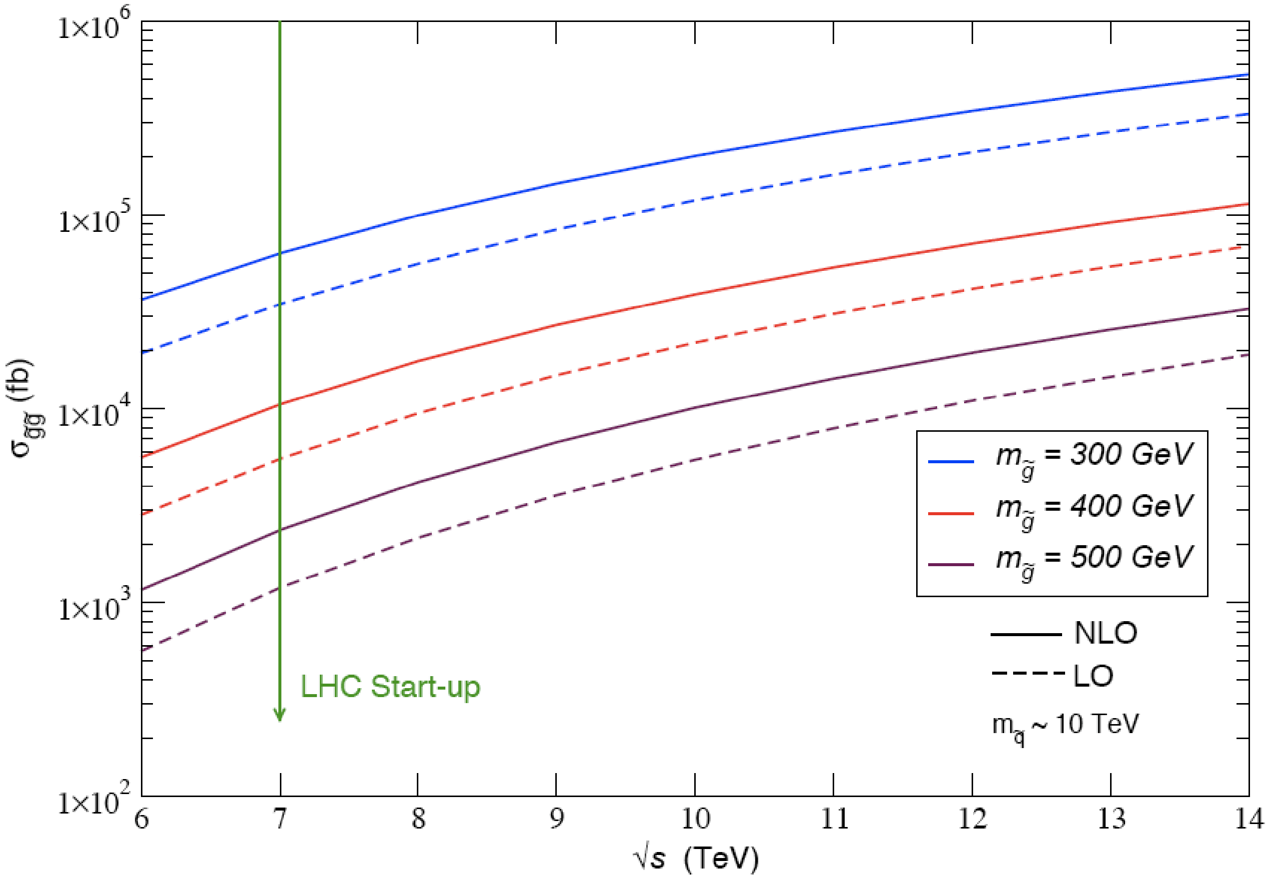




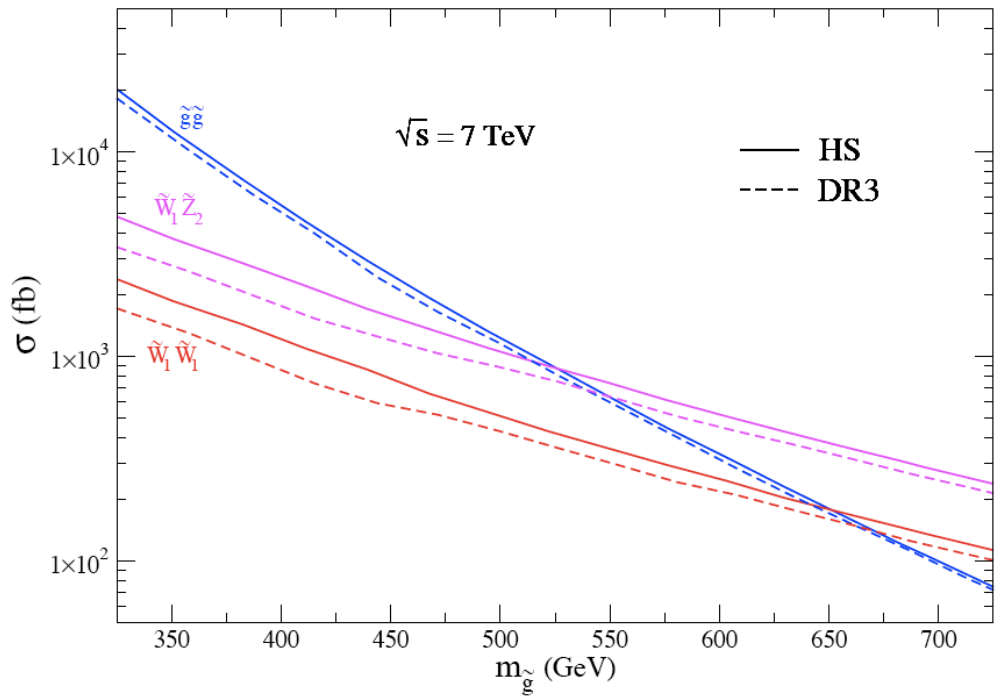
R versus gluino mass:
points from MCMC scans for small R.

parameter	HSb	DR3b
$m_{16}(1,2)$	10000	11805.6
$m_{16}(3)$	10000	10840.1
m_{10}	12053.5	13903.3
M_D	3287.1	1850.6
$m_{1/2}$	43.9442	27.414
A_0	-19947.3	-22786.2
$\tan\beta$	50.398	50.002
R	1.025	1.027
μ	3132.6	2183.4
$m_{\tilde{g}}$	351.2	321.4
$m_{\tilde{u}_L}$	9972.1	11914.2
$m_{\tilde{t}_1}$	2756.5	2421.6
$m_{\tilde{b}_1}$	3377.1	1359.5
$m_{\tilde{e}_R}$	10094.7	11968.5
$m_{\widetilde{W}_1}$	116.4	114.5
$m_{\widetilde{Z}_2}$	113.8	114.2
$m_{\widetilde{Z}_1}$	49.2	46.5
m_A	1825.9	668.3
m_h	127.8	128.6

Light gluino
↓
LHC potential at 7 TeV ?



LHC reach at 7 TeV

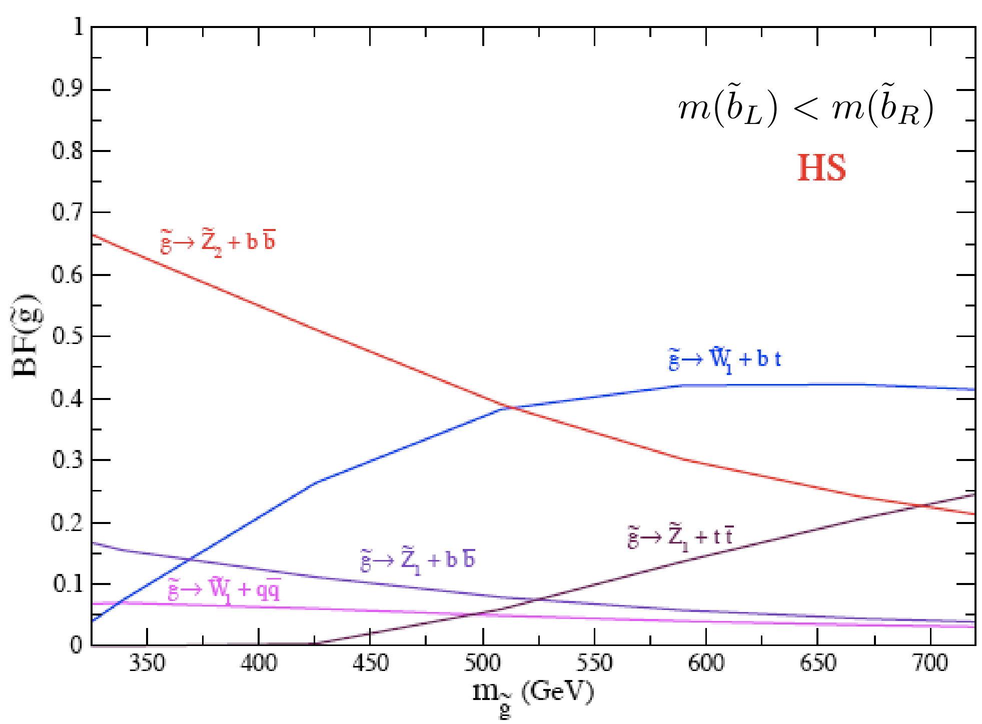


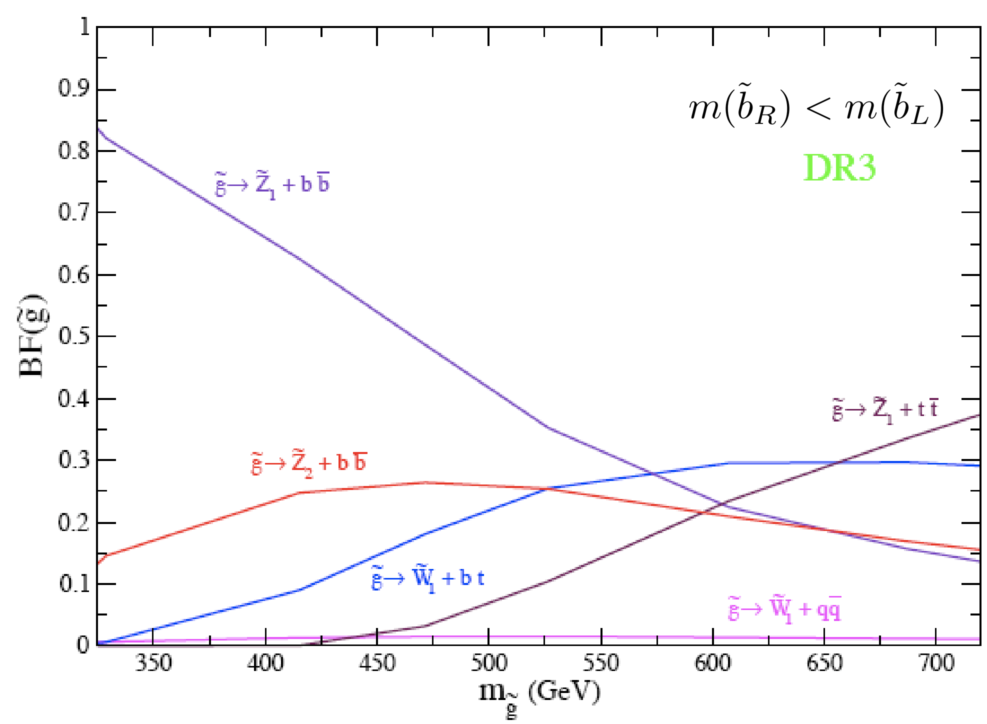
We consider model lines for HS and DR3 cases as function of m(gluino) up to 700 GeV.

Gluino-pair prod. dominated by gg fusion, σ(LO)~1 pb at m(gluino)~525 GeV.

Gluino signatures are dominanted by 3-body decays into heavy flavours:

$$\tilde{g} \to \tilde{\chi}^0_{1,2} b\bar{b},\ \tilde{\chi}^\pm_1 tb$$



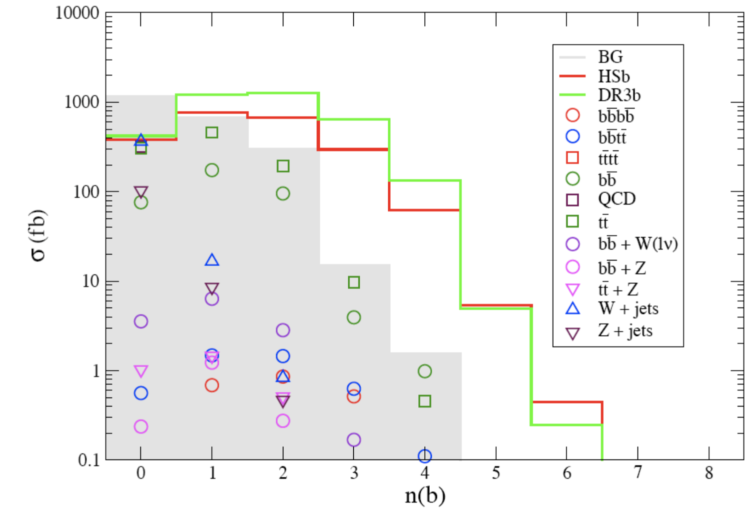


LHC reach at 7 TeV

Event simulation for HS and DR3 model lines:

- Isajet 7.79 for the signal
- QCD, 2- and 3-bdy BGs with Alpgen
- 4t, 4b, 2t2b BGs with Madgraph
- Phythia for showering and hadronization
- Generic toy detector simulation

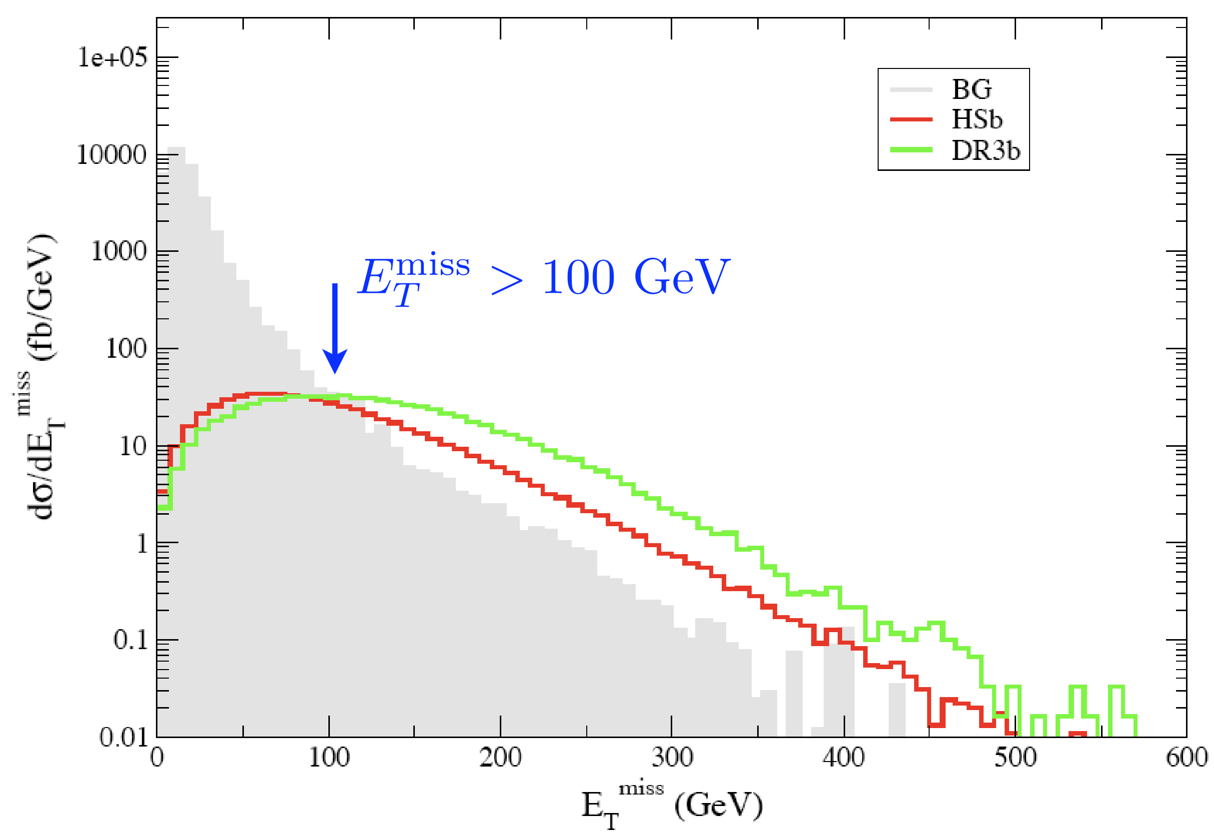
with cut on E_T^{miss}



Basic Cuts "C0":

- n(jets)≥4 with p_T > 50GeV
- hardest jet p_T >100 GeV
- S_T ≥ 0.2 (transv sphericity)
- n(b) ≥ 1 (b-eff. 60%)

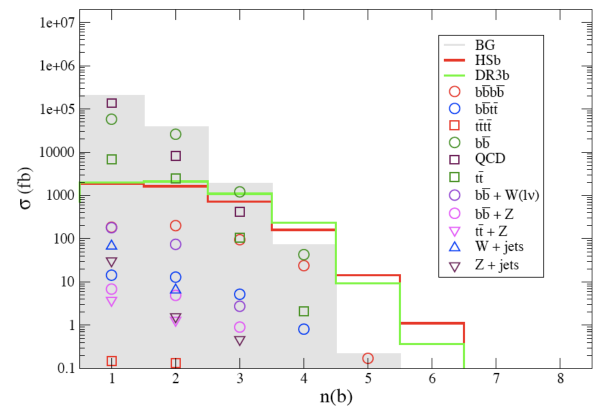
Results after C1-based selection			
	$\sigma(n(b) \geq 3)$	$\sigma(n(b) \geq 4)$	$\sigma(\mathrm{OS})$
HSb	364 fb	68 fb	81 fb
DR3b	782 fb	139 fb	23 fb
BG	16 fb	2 fb	9 fb

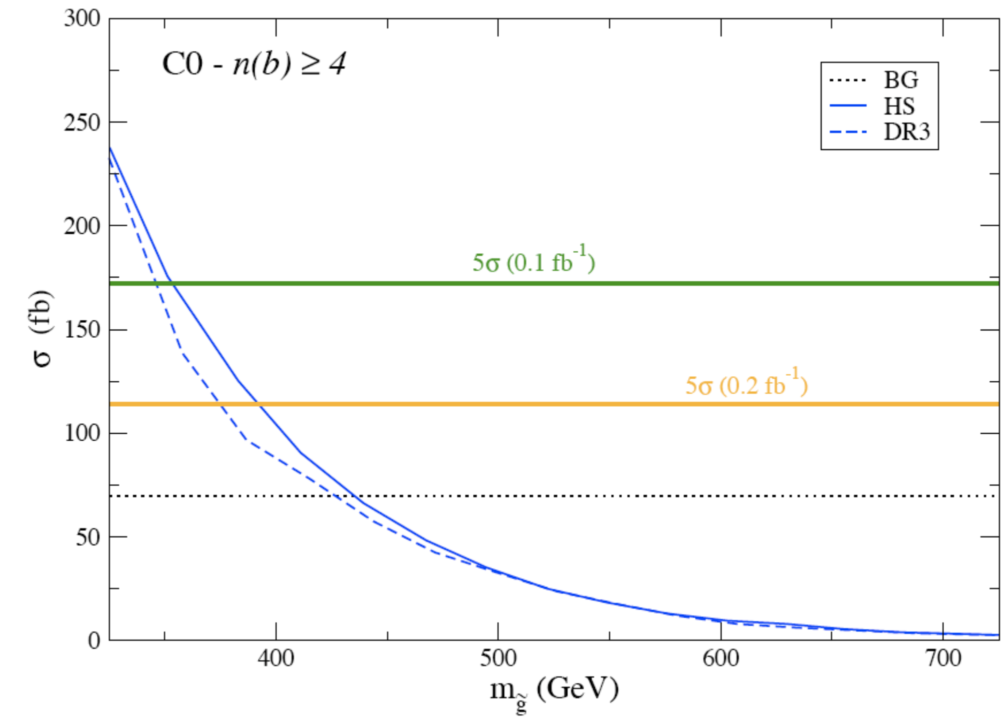


arXiv:0911.4739

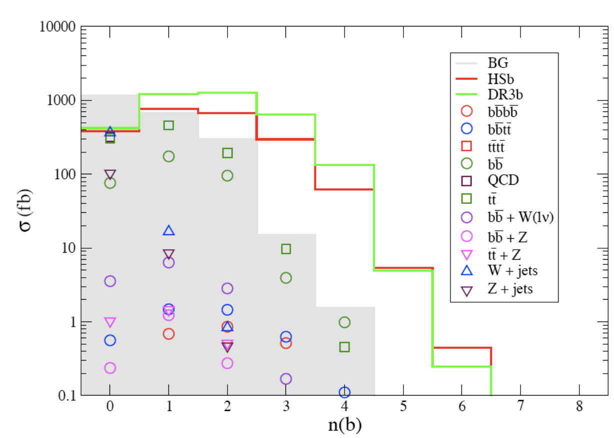
LHC reach at 7 TeV

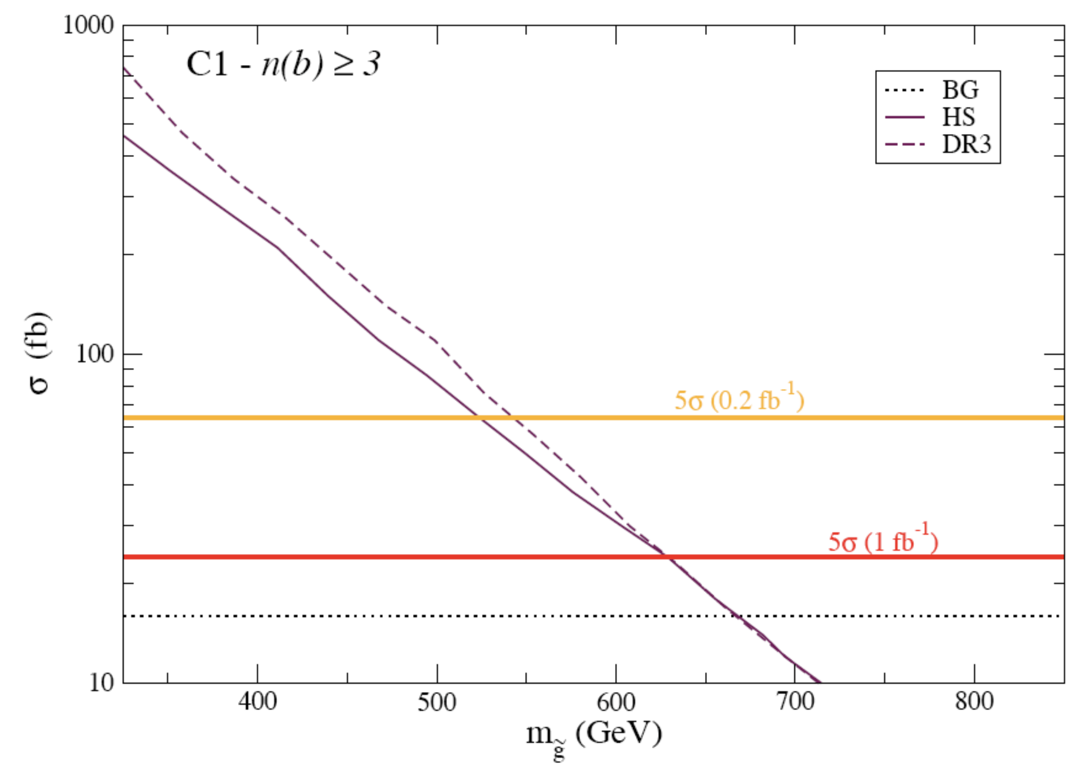
Without missing energy measurement:
up to m(gluino)=400 GeV with 0.2 fb^{-1} of data
requiring 4 b-jets





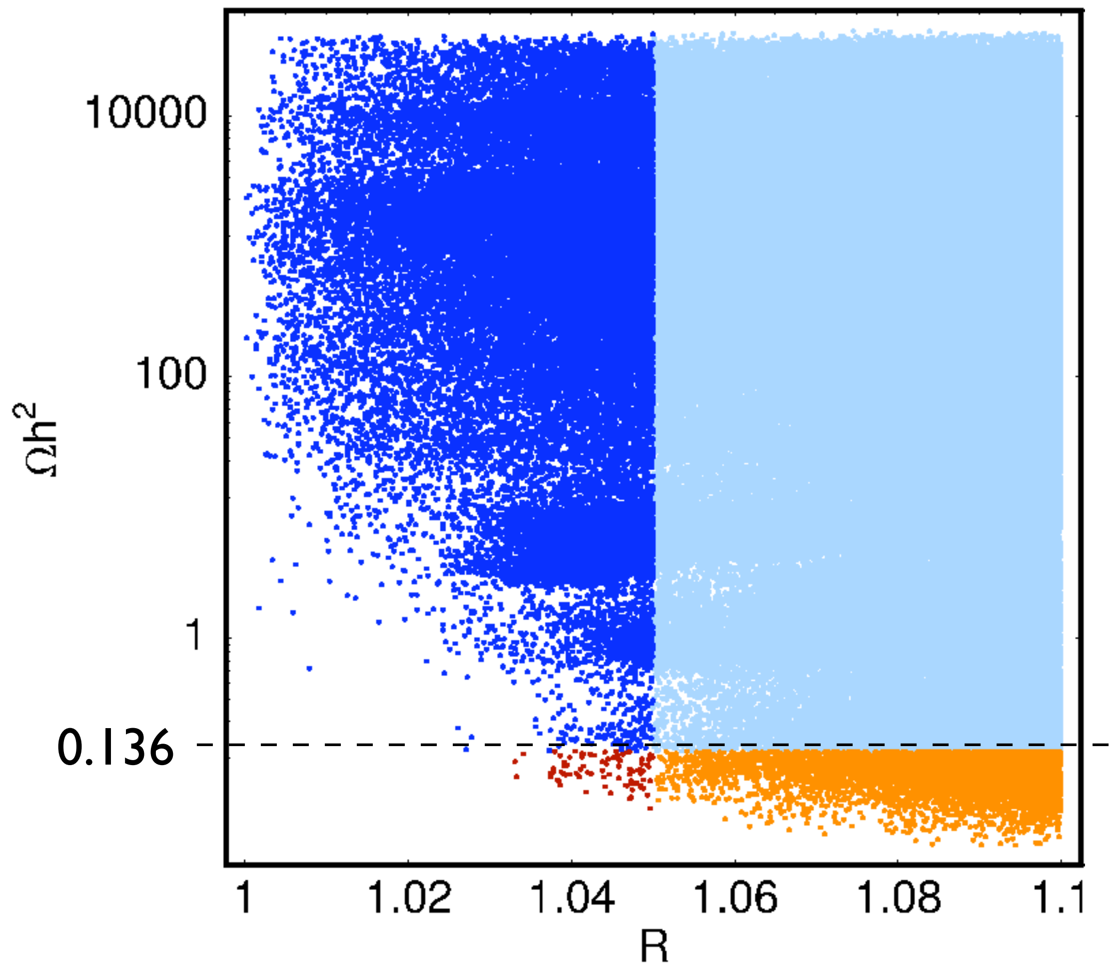
With reliable missing energy measurement:
reach up to m(gluino)=540-630 GeV
with 0.2-1 fb^{-1} of data,
n(b) ≥ 3





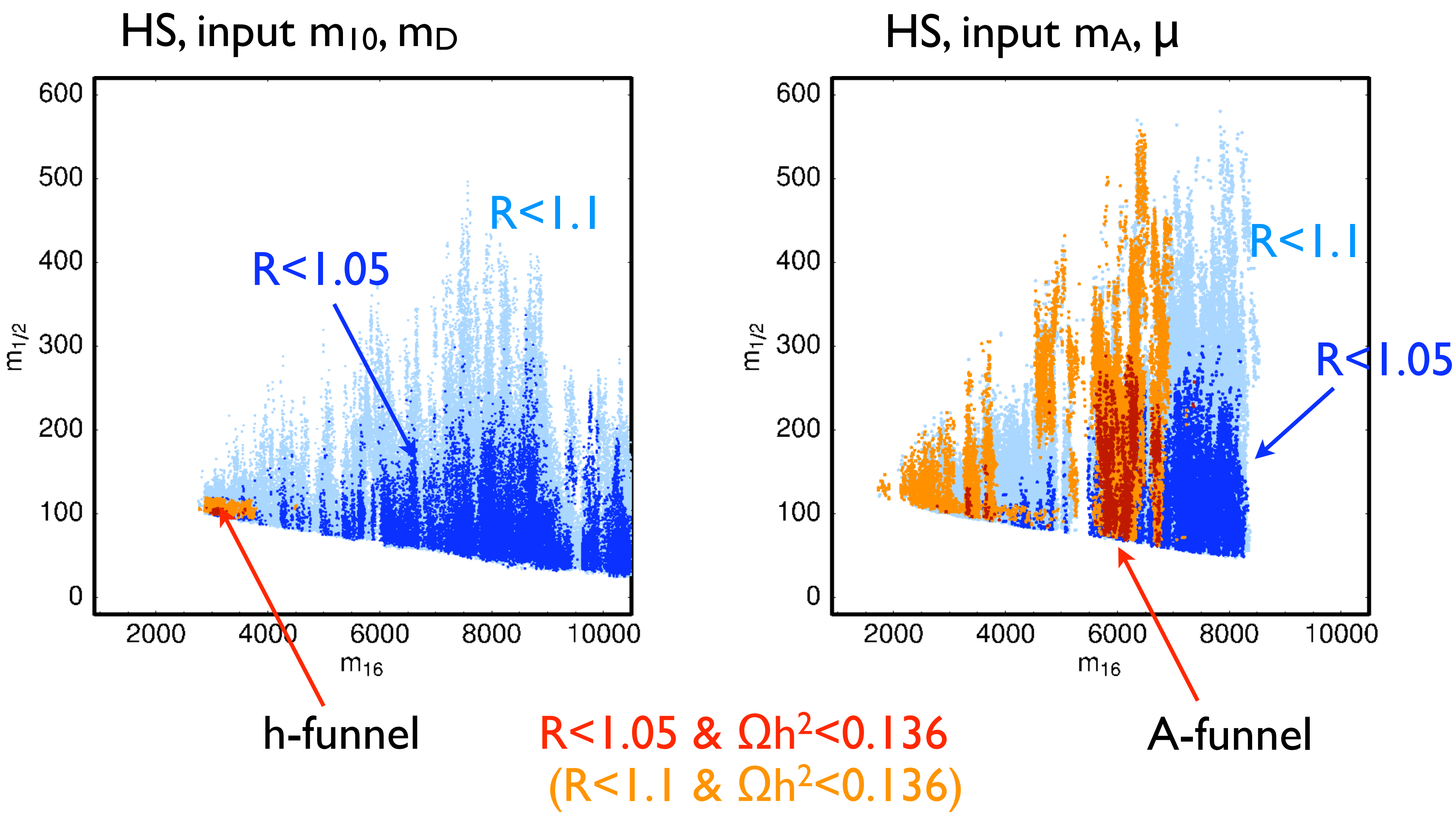
Dark Matter?

arXiv: 0801.1831



Points from a MCMC scan for R→1 in the HS case.

Neutralino DM ?



However, the A-funnel region is completely excluded by $B_s \to \mu\mu$!

Covi, Kim, Roszkowski, 1999

Talks by Laura Covi
and Howie Baer

Axion/axino dark matter?

- If the true LSP is an axino rather than the neutralino

$$\Omega_{\tilde{a}}^{\rm NTP} h^2 = \frac{m_{\tilde{a}}}{m_{\tilde{\chi}_1^0}} \Omega_{\tilde{\chi}_1^0} h^2$$

warm dark matter
for $m_{\tilde{a}} \lesssim 1$ GeV
(Jedamzik *et al.*)

- Thermal axino production

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

f_a: PQ breaking scale,
N: model-dependent color anomaly O(1),
$f_a/N \gtrsim 10^9$ GeV

cold dark matter for $m_{\tilde{a}} \gtrsim 100$ keV

Covi, Kim, Kim, Roszkowski, 2001
Brandenburg, Steffen, 2004

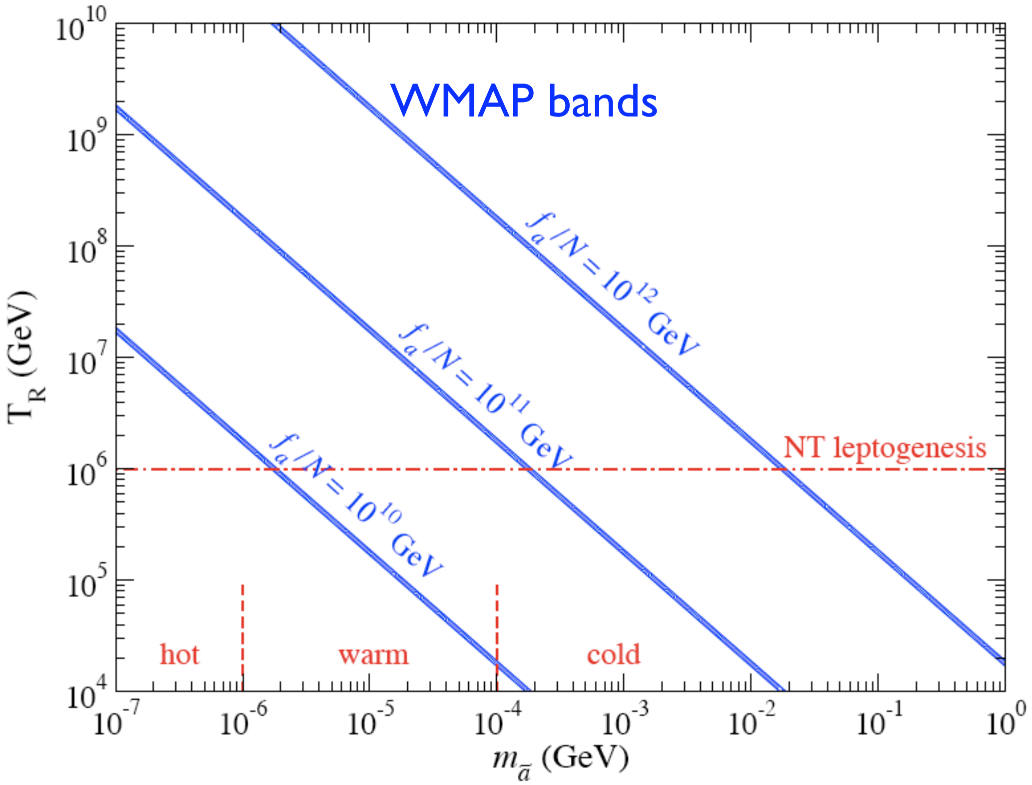
- Axion contribution to CDM

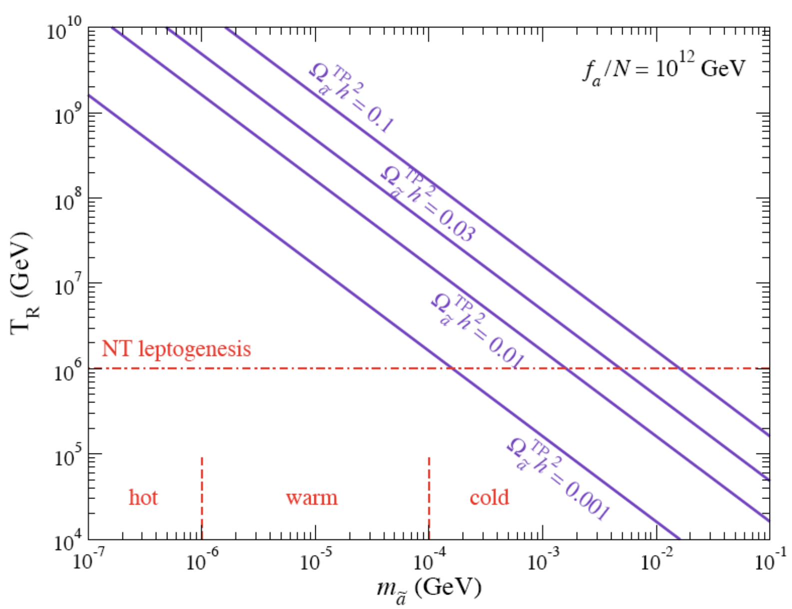
$$m_a \simeq 6\,{\rm eV}\,\frac{10^6\ {\rm GeV}}{f_a/N}, \quad n_a(t) \sim \frac{1}{2} m_a(t)\langle a^2(t)\rangle, \quad \Omega_a h^2 \simeq \frac{1}{4}\left(\frac{6\times 10^{-6}\ {\rm eV}}{m_a}\right)^{7/6}$$

vacuum mis-alignment

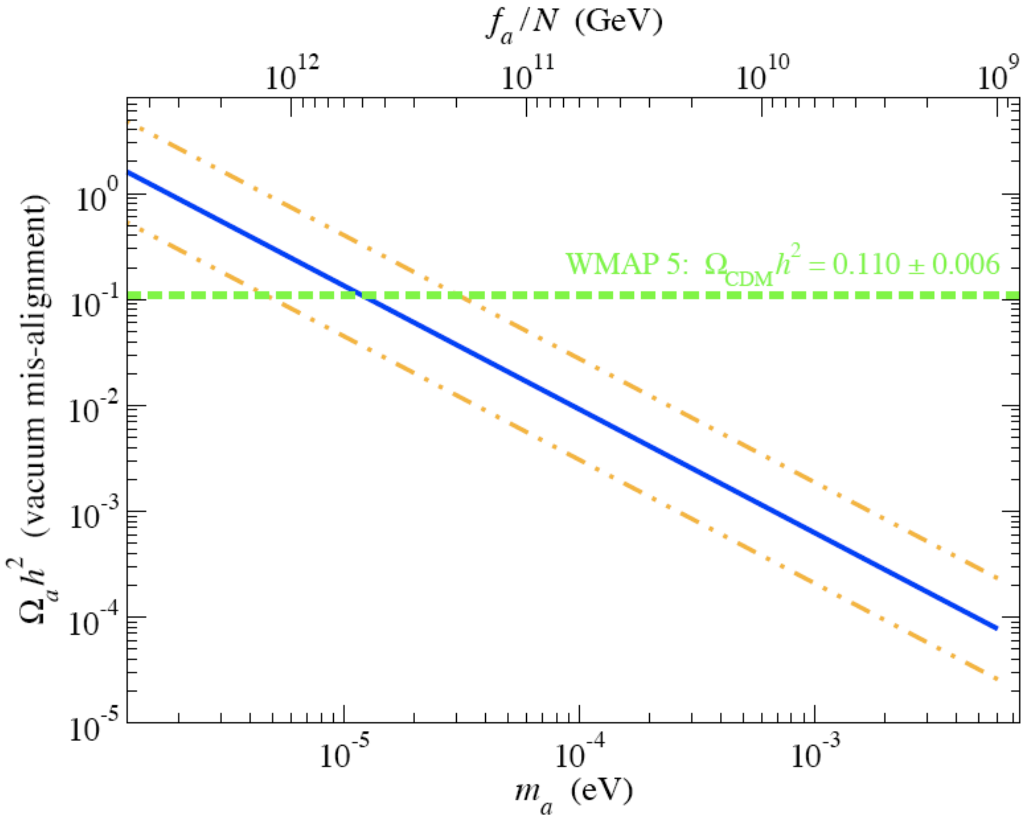
Abbott, Sikivie; Preskill, Wise, Wilczek;
Dine, Fischler; Turner (1983-86)

Thermally produced axino relic density

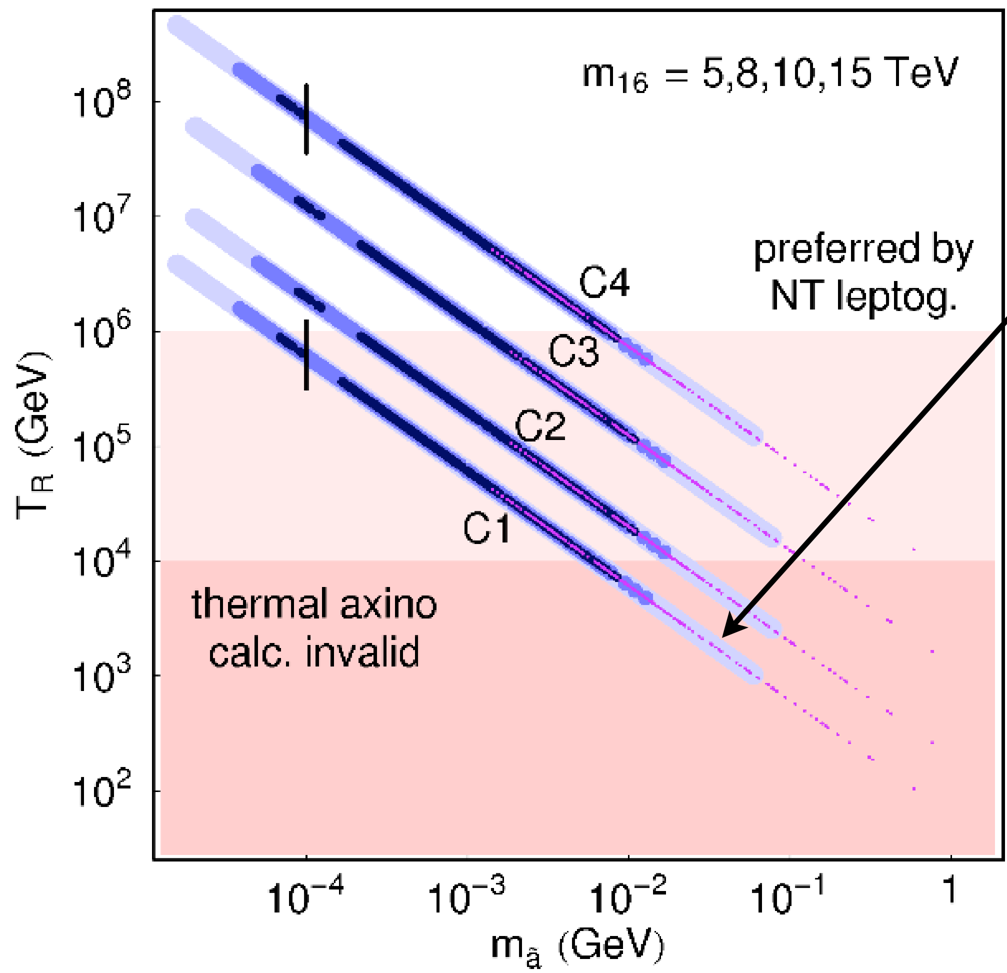




Axion relic density due to vacuum mis-alignment



Yukawa-unified scenarios with mixed axion/axino dark matter

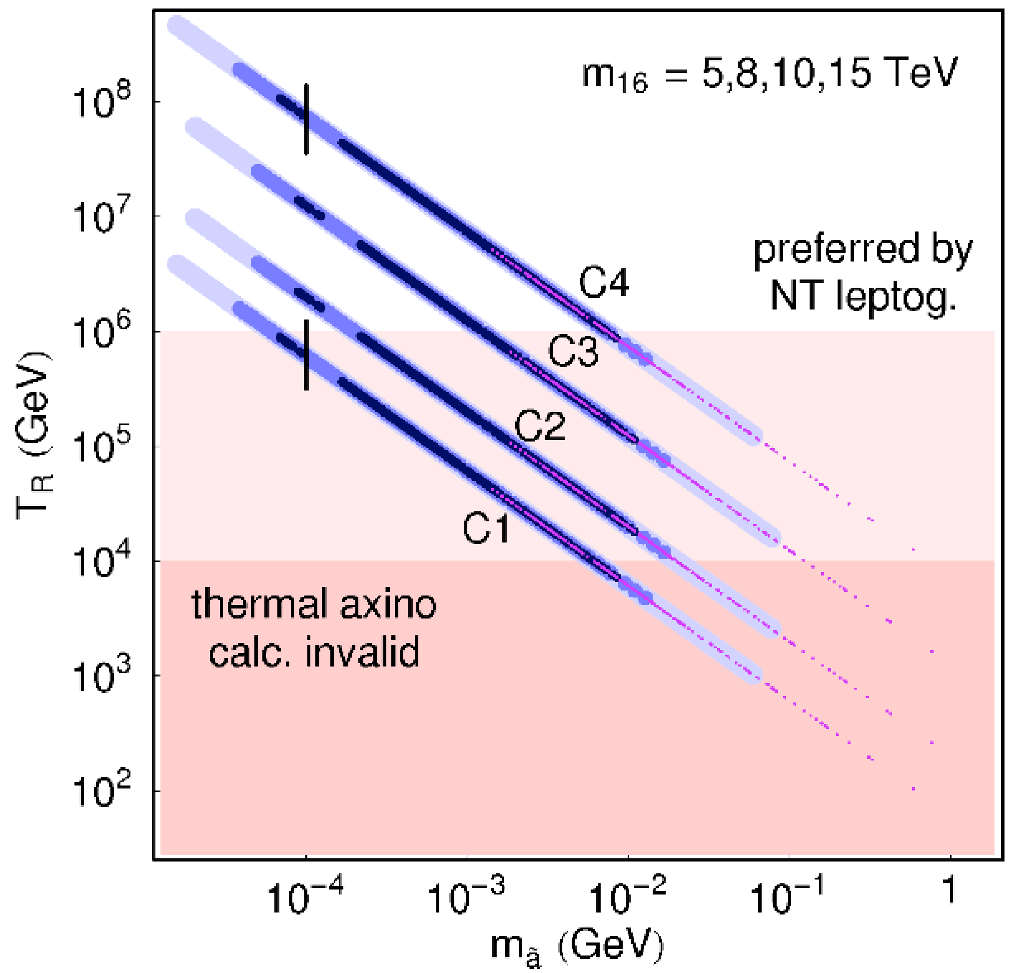


Case C1

- $f_a/N = 10^{11}$ GeV: small fraction of axion CDM: $\Omega_{axion}h^2 \sim 0.017$.
- The bulk of CDM must then be composed of something else: in our case, thermally produced axinos.
- We choose $(\Omega_{axino}h^2)^{TP}$=0.083 and $(\Omega_{axino}h^2)^{NTP}$=0.01 → gives m_{axino}.
- Compute T_R necessary to match WMAP-measured $\Omega_{DM}h^2$=0.11

arXiv:0812.2693

Yukawa-unified scenarios with mixed axion/axino dark matter



C1: $f_a/N = 10^{11}$ GeV, $\Omega_{axion}h^2 \sim 0.017$; DM dominantly therm. produced axinos.

C2: $f_a/N = 4\times10^{11}$ GeV, $\Omega_{axion}h^2 \sim 0.084$; DM dominantly axions + some mixed cold and warm axinos.

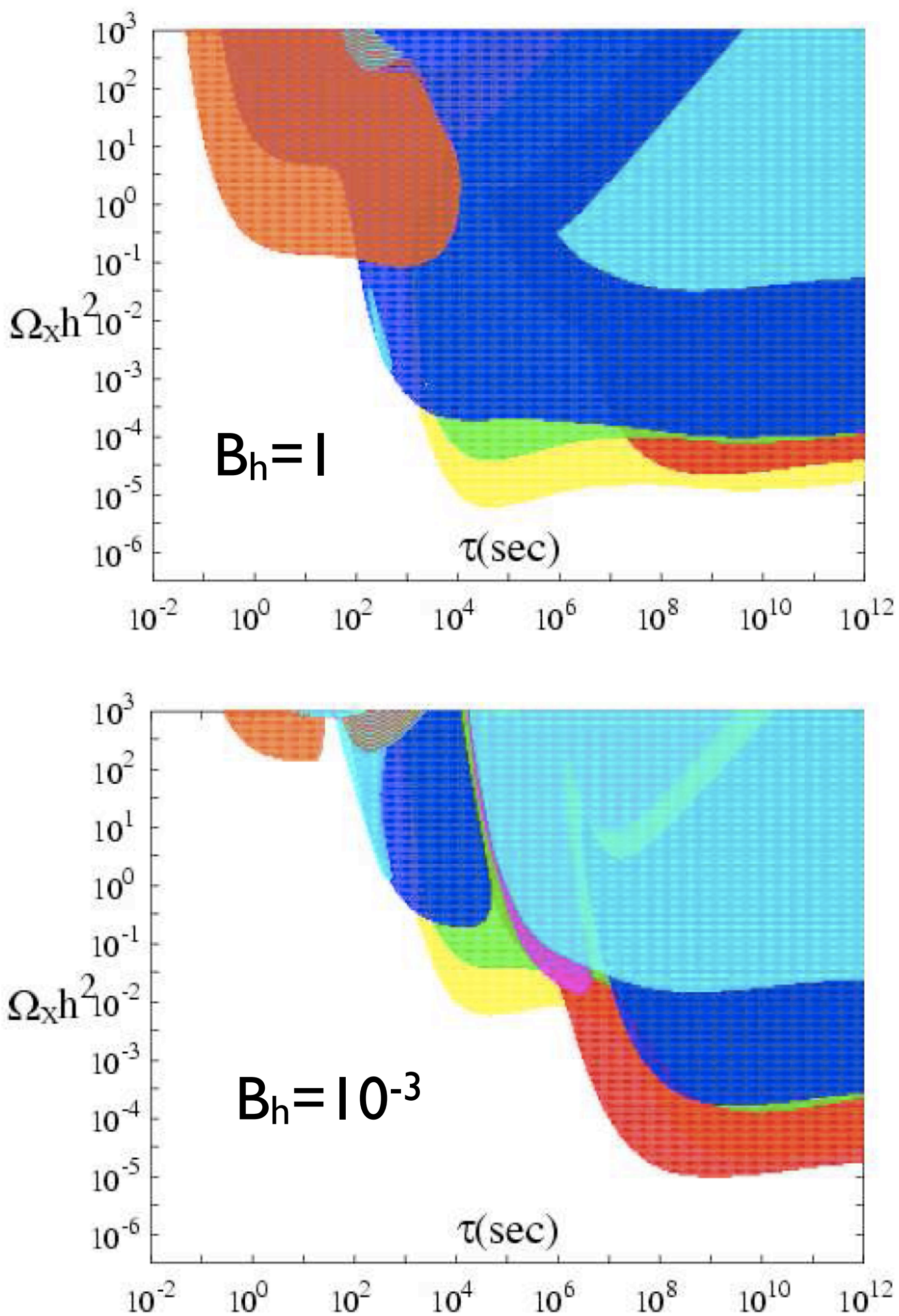
C3: $f_a/N = 10^{12}$ GeV, $\Omega_{axion}h^2 \sim 0.084$; DM dominantly axions + some mixed cold and warm axinos.

C4: $f_a/N = 10^{12}$ GeV, $\langle a \rangle \sim 0$, $\Omega_{axion}h^2 \sim 0$; DM dominantly axinos, we choose $(\Omega_{axino}h^2)^{TP}=0.1$ and $(\Omega_{axino}h^2)^{NTP}=0.01$

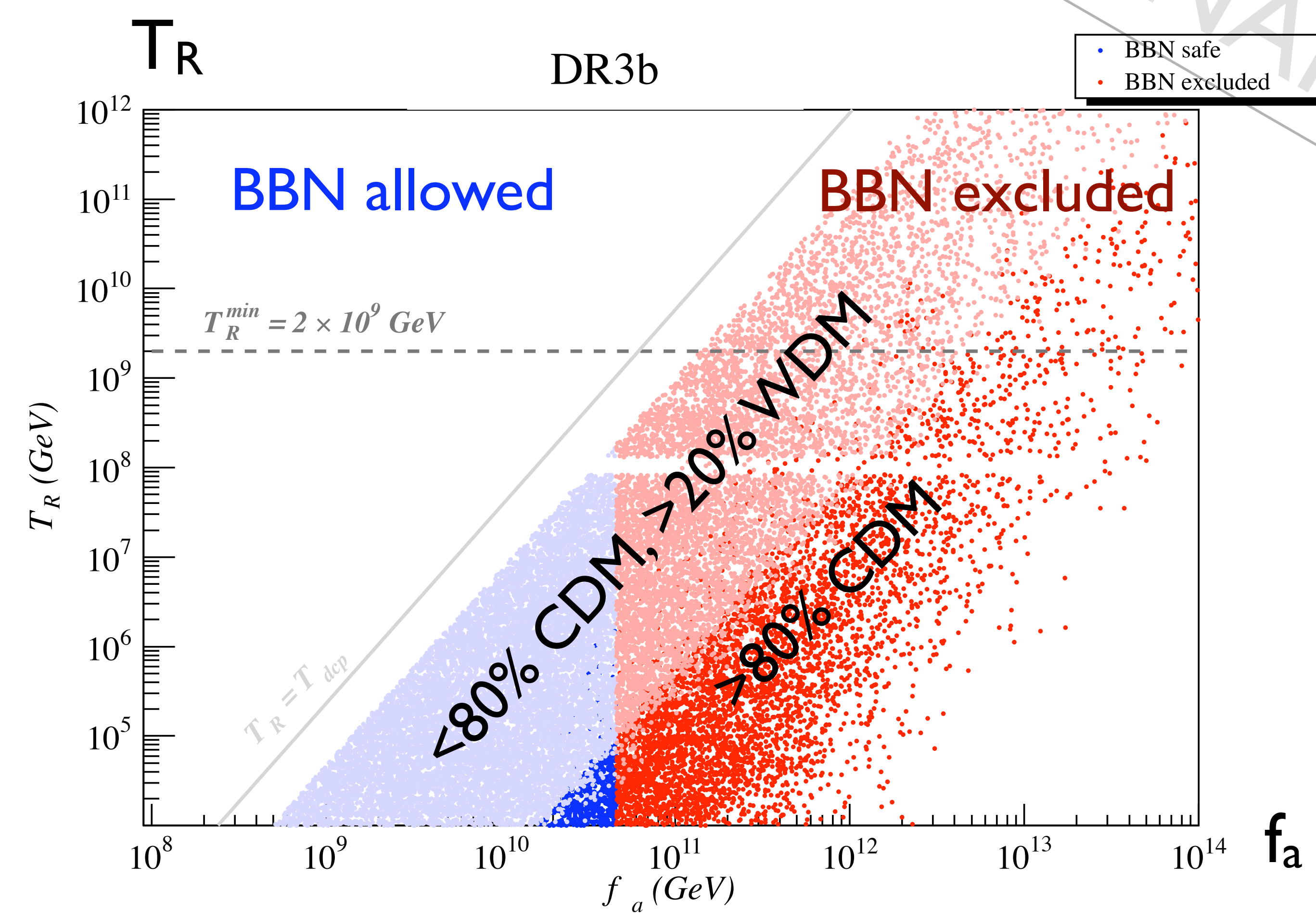
arXiv:0812.2693

BBN constraints

PRELIMINARY



Jedamzik, 2006



$$\Omega h^2(\tilde{\chi}_1^0) = 194$$

May be modified by additional entropy production e.g. from s-axion decay.

Talk by J. Hasenkamp

Conclusions

- Yukawa-unified SUSY based on SO(10) is highly compelling.
- Typical mass spectrum for μ>0: inverted scalar mass hierarchy with multi-TeV 1st/2nd generation and TeV-scale 3rd generation, light gauginos, gluino mass 300-700 GeV !
- Quite good discovery potentials for such scenarios:
  - ★ Tevatron: m(gluino)~430 GeV with 10 fb^{-1}
  - ★ LHC@7TeV: m(gluino)~630 GeV with 1 fb^{-1}
- Search in multi-b channels is essential for early discovery.
- Neutralino relic density typically far too high, except h-funnel. Mixed axion/axino DM interesting alternative. Constrained by BBN and allowed WDM (HDM) components.
- Not covered: split trilinears, Pati-Salam group, etc. ....