Yukawa-unified SUSY

– dark matter and the LHC –

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Based on a series of papers in collaboration with
H. Baer, A. Lessa, S. Sekmen and H. Summy

0801.1831, 0809.0710, 0812.2693, 0908.0134, 0910.2988, 0911.4739

The Galileo Galilei Institute for Theoretical Physics
Arcetri, Florence

"The Dark Matter Connection: Theory & Experiment"
17–21 May 2010

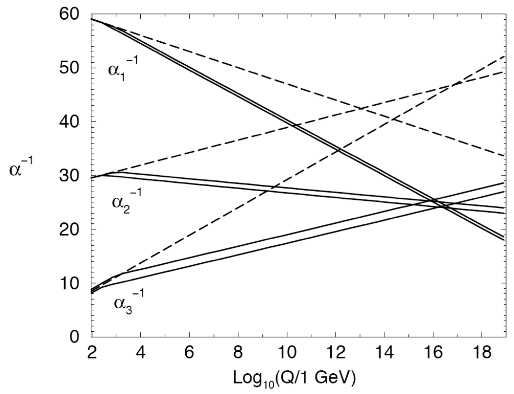
Ananthanarayan, Lazarides and Shafi, 1991
(and a long list to follow)

Framework: SUSY SO(10)

- SUSY GUTs based on SO(10) are particularly compelling
  - unify all matter of one generation in a 16-plet (incl. r.h. neutrino!)
  - automatic anomaly cancellation

- The simplest realizations (Higgs in a10-plet) require, in addition to gauge coupling unification, unification of t-b-tau Yukawa couplings at M_{GUT}.

$$\hat{f} \ni f \hat{\psi}_{16} \hat{\psi}_{16} \hat{\phi}_{10}$$

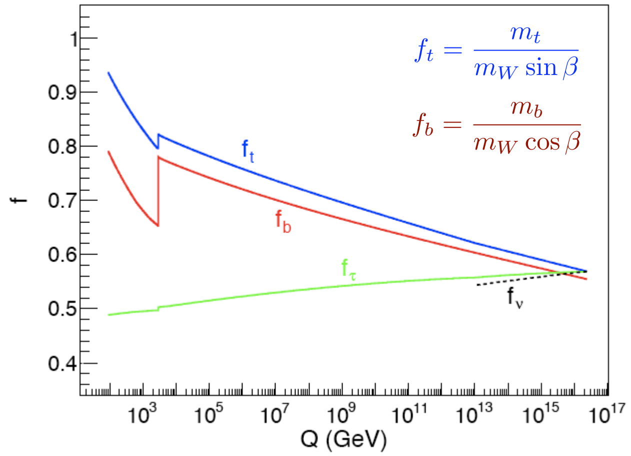


- Particle content below M_{GUT} = MSSM (+RHN)

- Parameters: $m_{1/2}$, m_{16}, m_{10}, M_D^2, A_0, tanβ, sign μ

$$m^2_{H_{u,d}} = m^2_{10} \mp M^2_D$$

c.f. NUHM: $m_{1/2}$, m_0, $m_{H_{1,2}}$, A_0, tanβ, sign μ.



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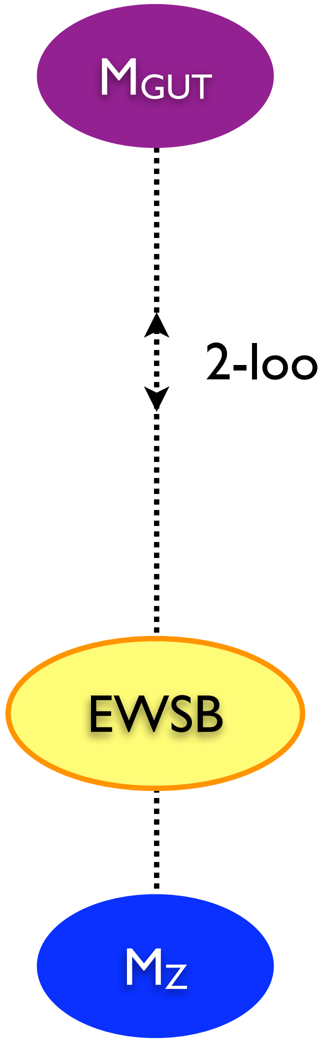


M_{GUT}

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

2-loop RGEs

EWSB

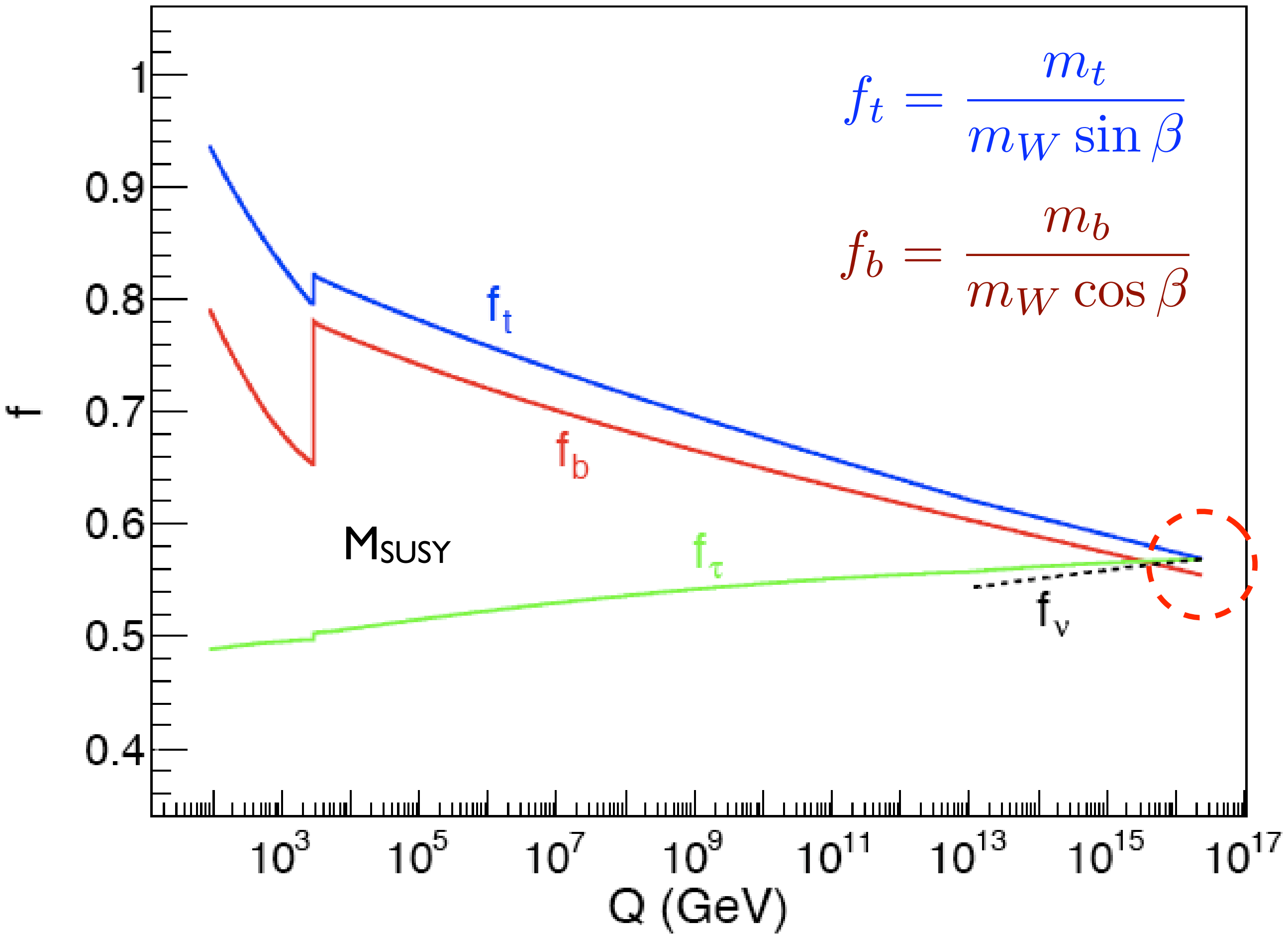
$$\mu^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{(\tan^2\beta - 1)} - \frac{M_Z^2}{2}$$

M_Z

gauge & Yukawa
couplings

we use Isajet
(bottom-up approach to YU)

$$R = \frac{max(f_t,\ f_b,\ f_\tau)}{min(f_t,\ f_b,\ f_\tau)} \longrightarrow 1$$



$$\tan\beta \sim m_t/m_b$$

$$\left(\frac{\delta m_b}{m_b}\right)^{\tilde{g}} \sim \frac{2\alpha_3}{3\pi}\,\mu \tan\beta\,\frac{m_{\tilde{g}}}{M^2_{SUSY}}$$

$$\left(\frac{\delta m_b}{m_b}\right)^{\tilde{\chi}^\pm} \sim \frac{\lambda_t^2}{16\pi^2} A_t \tan\beta\,\frac{\mu}{M^2_{SUSY}}$$

unification to few %

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

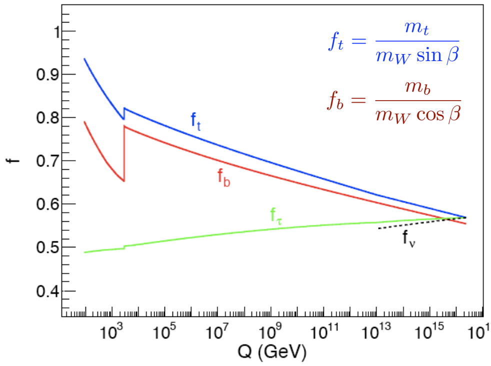
Large δm_b → important constraints from B physics

Blazek, Dermisek, Raby, hep-ph/0201081
Auto, Baer, et al., hep-ph/0302155

Conditions for Yukawa unification

★ For μ>0, as preferred by b→sγ, Yukawa unification (YU) can only be realized for very particular parameter relations

- $m_{16} \sim 5 - 15$ TeV,
- $A_0^2 \simeq 2m_{10}^2 \simeq 4m_{16}^2, \quad (A_0 < 0)$
- $m_{1/2} \ll m_{16}$,
- $\tan\beta \sim 50$.



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

★ D-term splitting

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

"just-so" Higgs splitting (HS) case

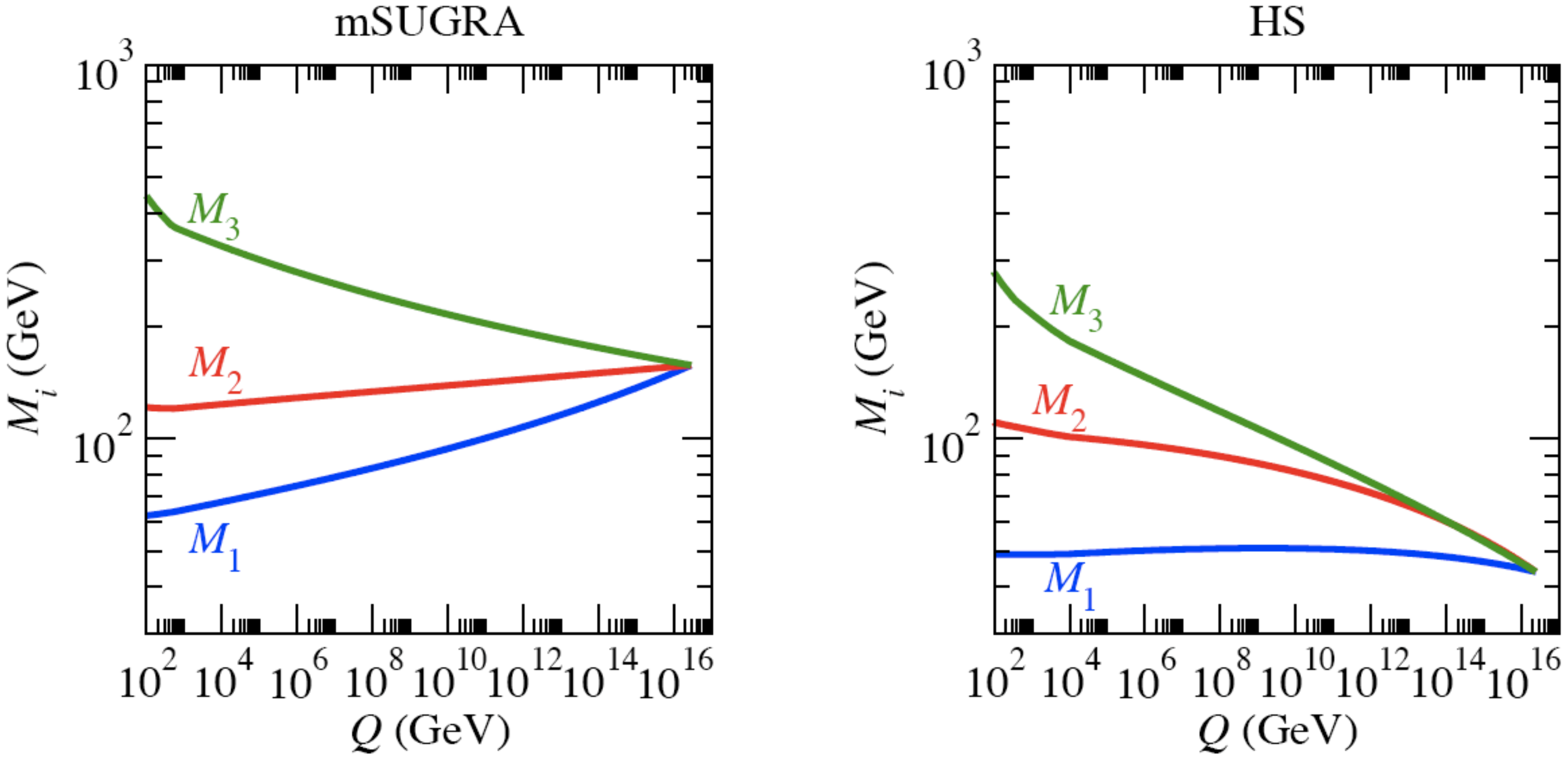
NB: we need $m_{H_u}^2 < m_{H_d}^2$ at $M_{\rm GUT}$, so $M_D^2 > 0$.

- 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

Baer et al., 0908.0134

Typical mass spectra

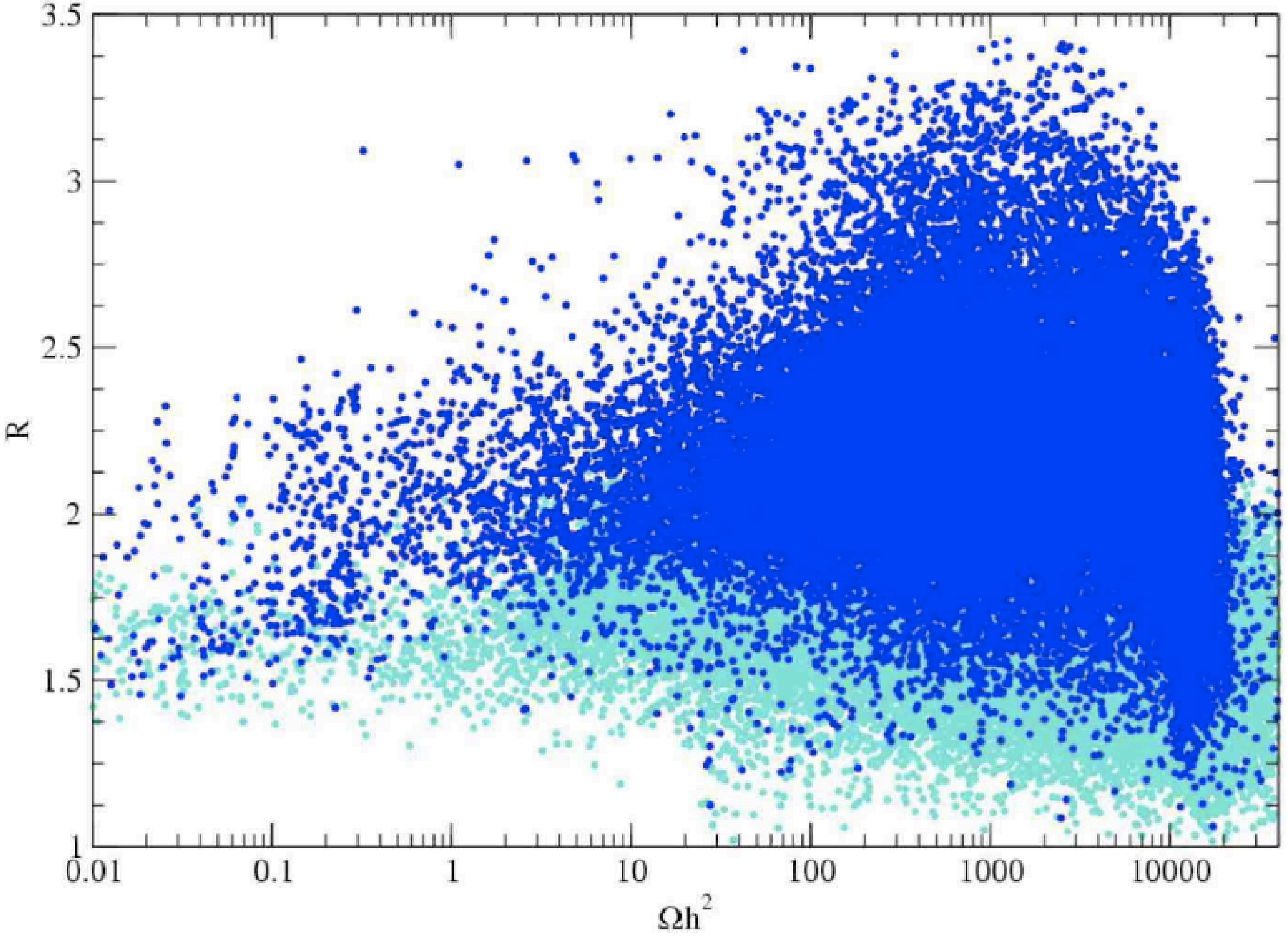
- 1st/2nd generation scalars in the multi-TeV range (5-15 TeV)
- 3rd gen. scalars, heavy Higgses and higgsinos in the 1-3 TeV range
- light gauginos: LSP ~ 50-80 GeV, gluino ~ 300-500 GeV
- c.f "effective SUSY" by Cohen, Kaplan, Nelson '1996



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

Relic density

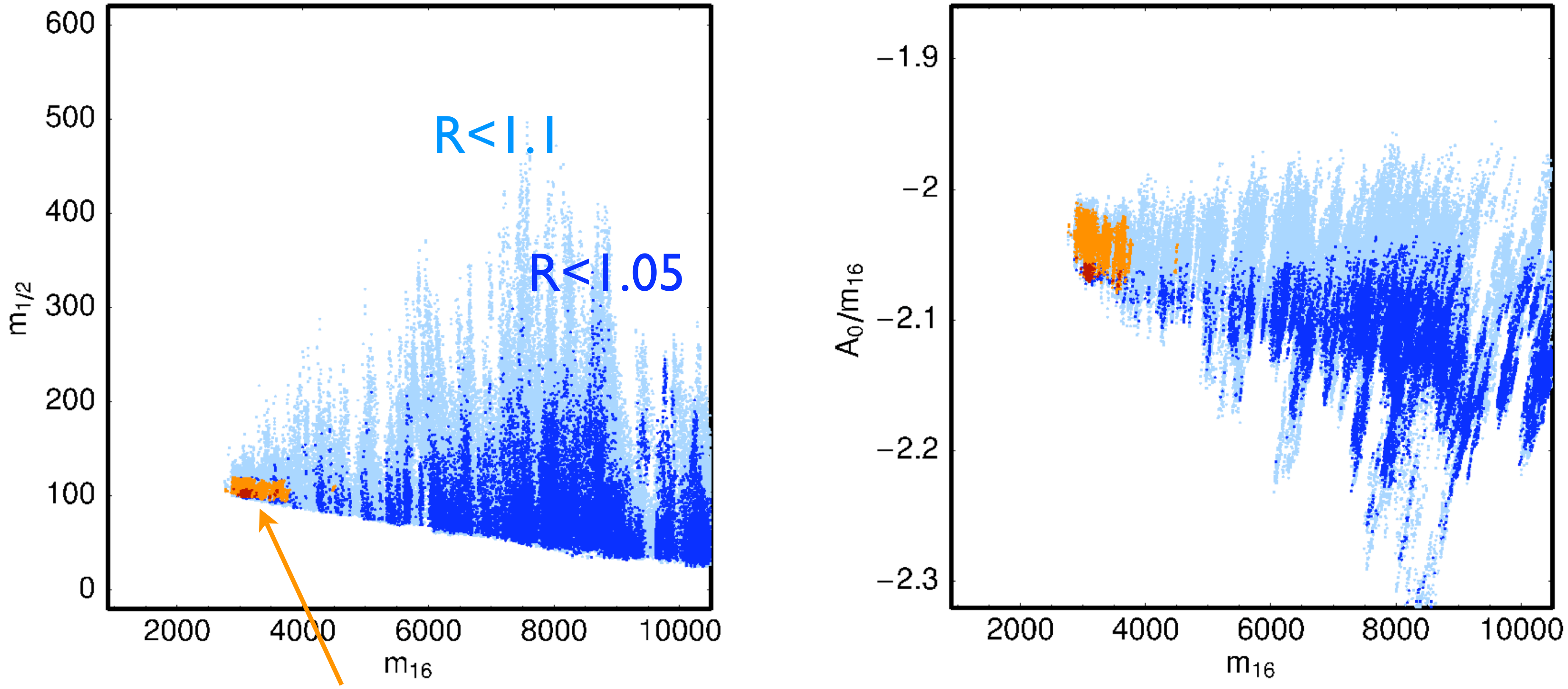
- Yukawa-unified solutions typically feature a bino-like neutralino LSP whose relic density is way too large



Random scan

Baer et al, 0801.1831

- MCMC scan over $m_{1/2}$, m_{16}, m_{10}, M_D^2, A_0, tanβ for small R (and $\Omega h^2 = 0.115 \pm 0.021$)

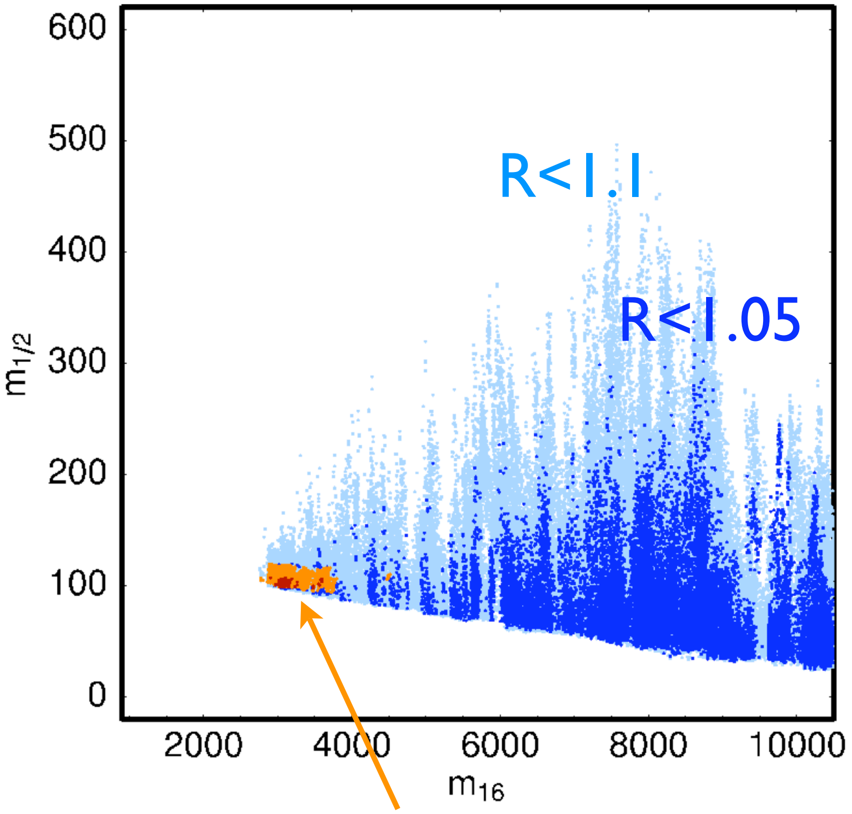


R<1.1 + Ωh^2<0.136

R<1.05 + Ωh^2<0.136

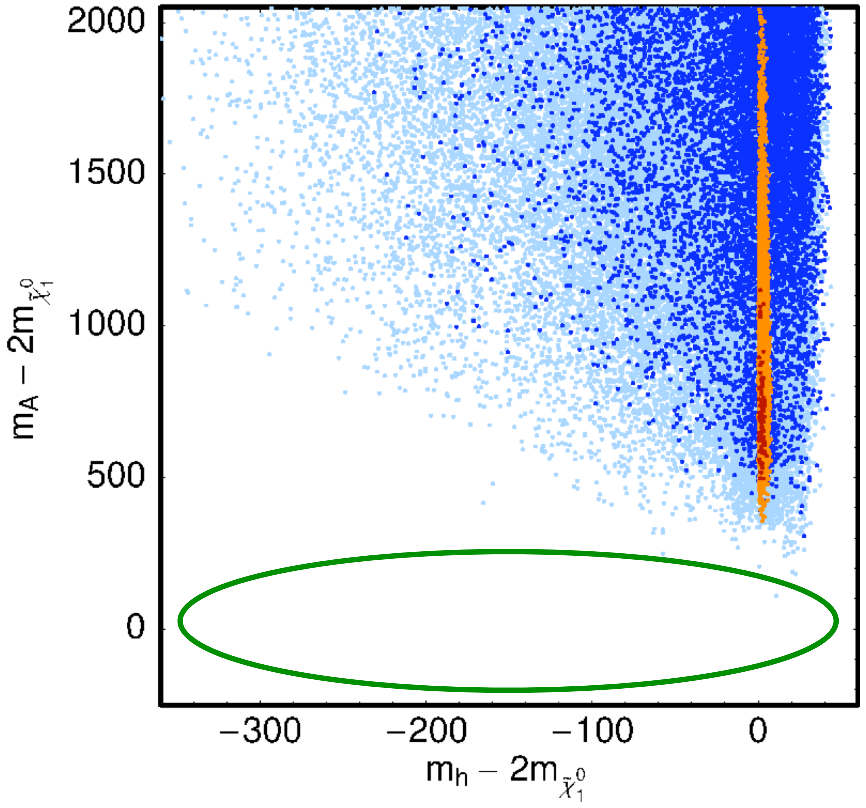
Baer et al, 0801.1831

- MCMC scan over $m_{1/2}$, m_{16}, m_{10}, M_D^2, A_0, $\tan\beta$ for small R (and $\Omega h^2 = 0.115 \pm 0.021$)



$R<1.1 + \Omega h^2<0.136$

$R<1.05 + \Omega h^2<0.136$

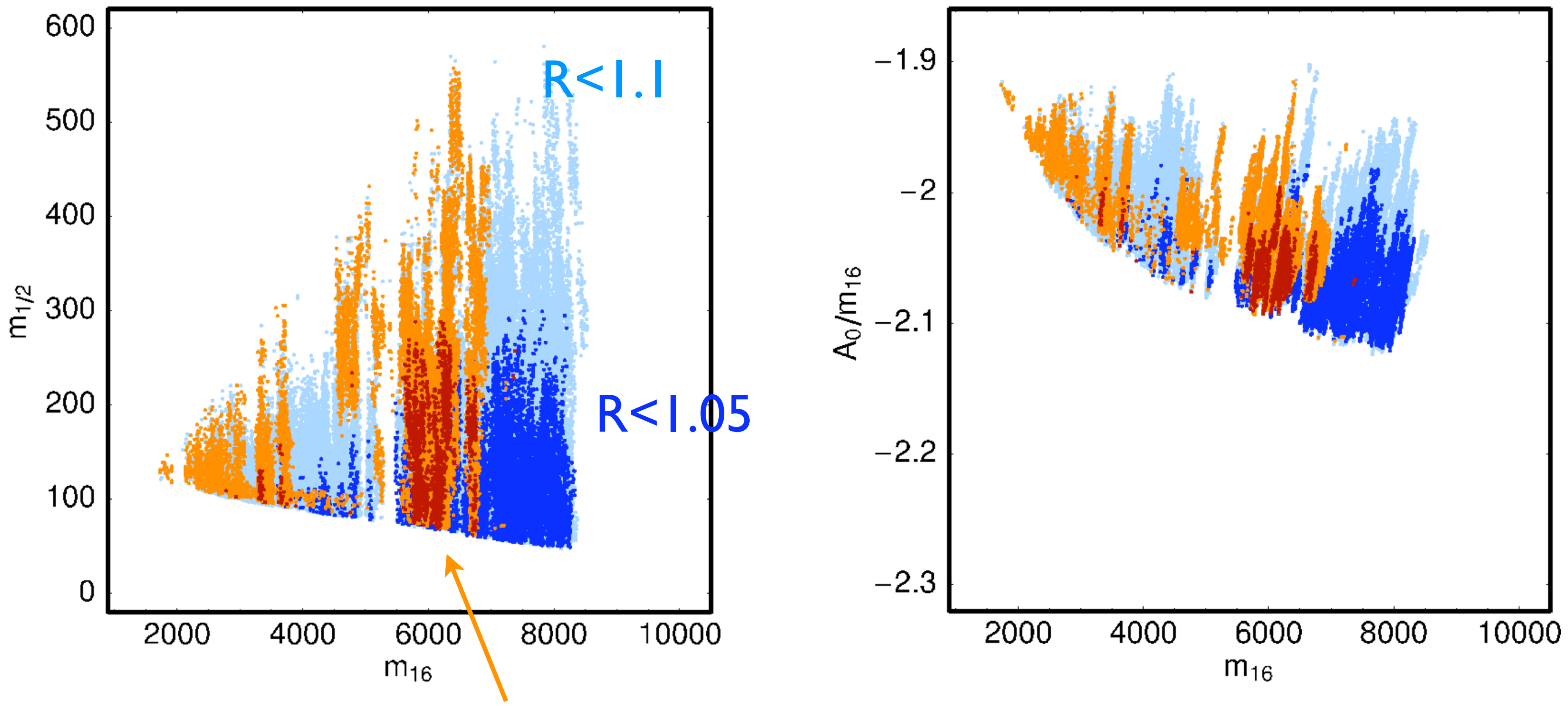


NB: we find neither the A-funnel nor the higgsino region of BDR

mechanism:
annihilation through h !

Baer et al, 0801.1831

- MCMC scan over $m_{1/2}$, m_{16}, m_A, μ, A_0, $\tan\beta$ for small R (and $\Omega h^2 = 0.115 \pm 0.021$)



R<1.1

R<1.05

R<1.1 + Ωh^2<0.136

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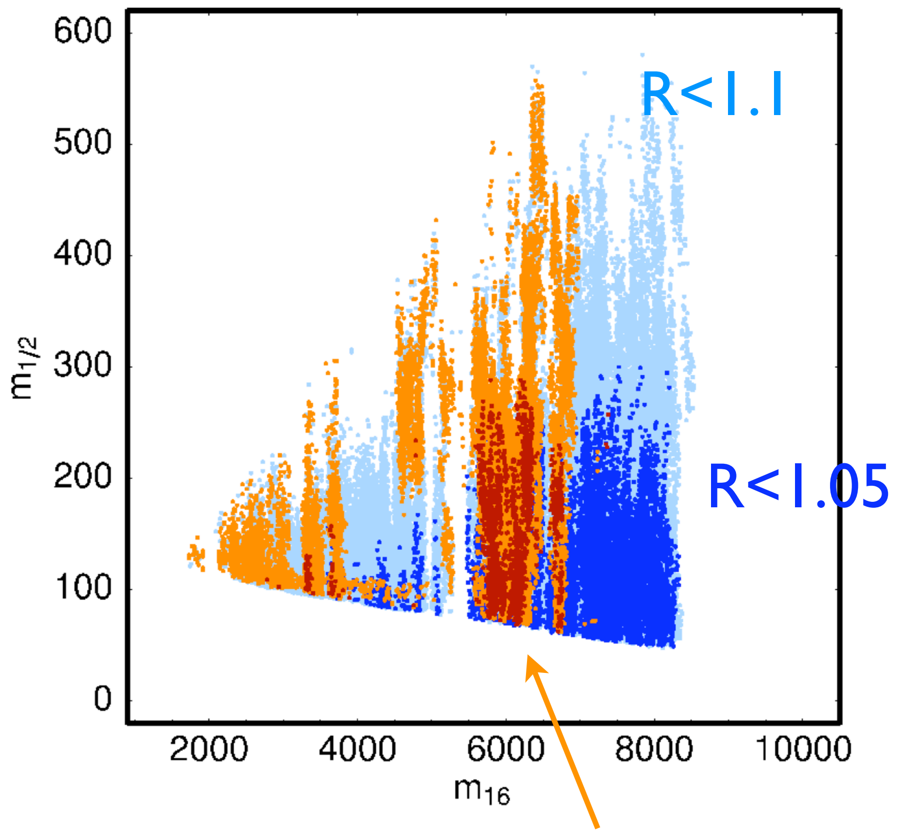
- MCMC scan over $m_{1/2}$, m_{16}, m_A, μ, A_0, $\tan\beta$ for small R (and $\Omega h^2 = 0.115 \pm 0.021$)



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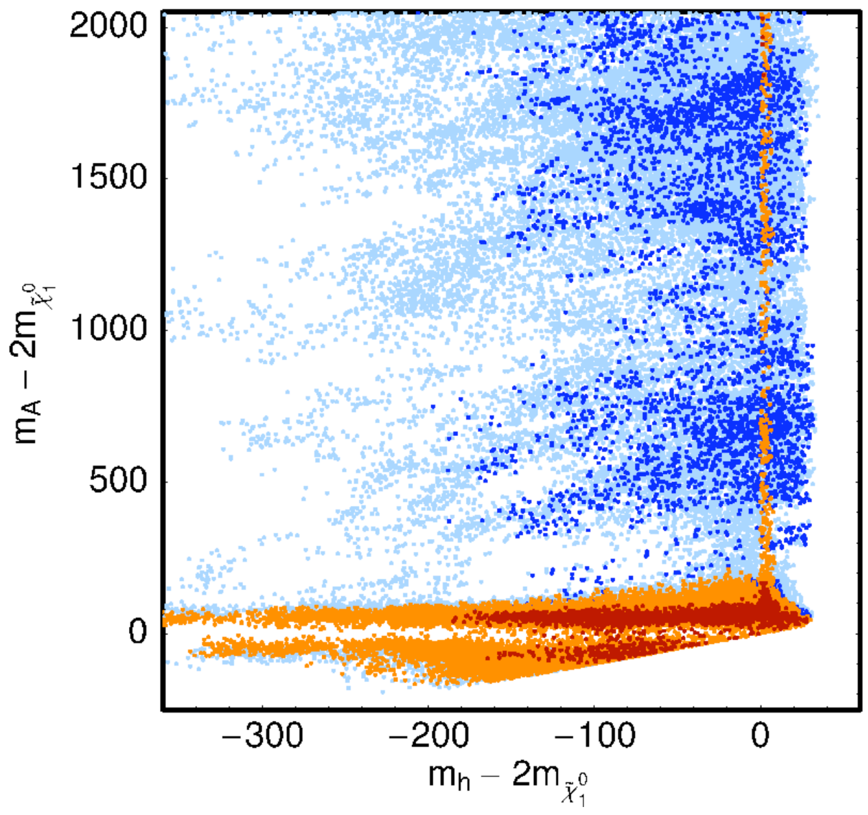
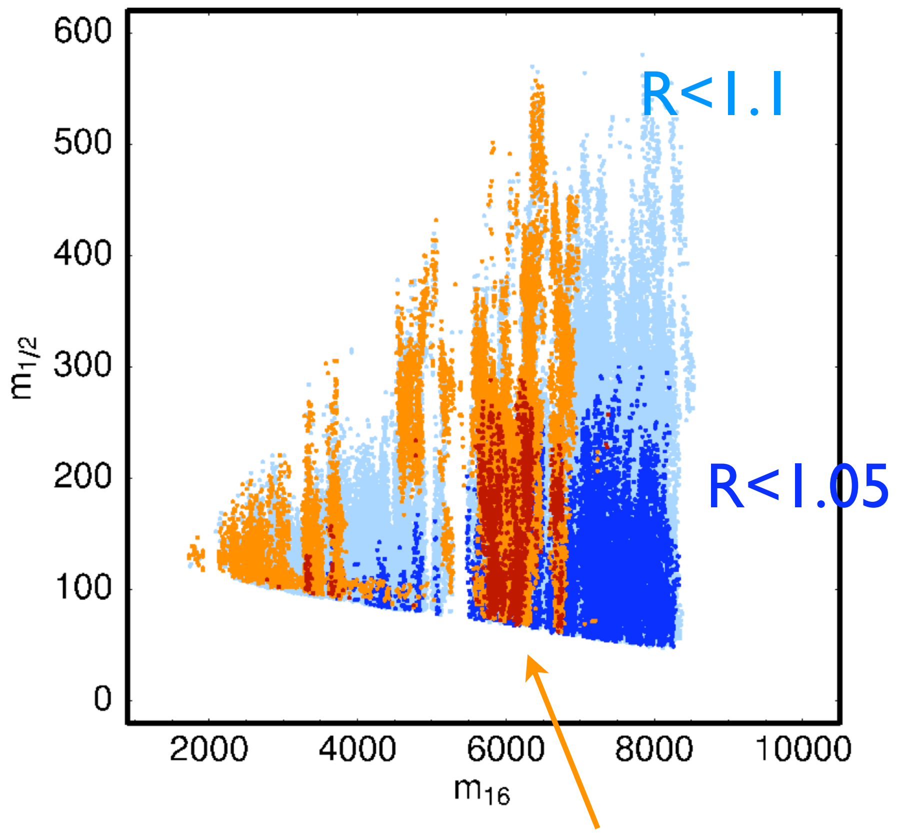


mechanism:
annihilation through A !

Baer et al, 0801.1831

- MCMC scan over $m_{1/2}$, m_{16}, m_A, μ, A_0, $\tan\beta$ for small R (and $\Omega h^2 = 0.115 \pm 0.021$)

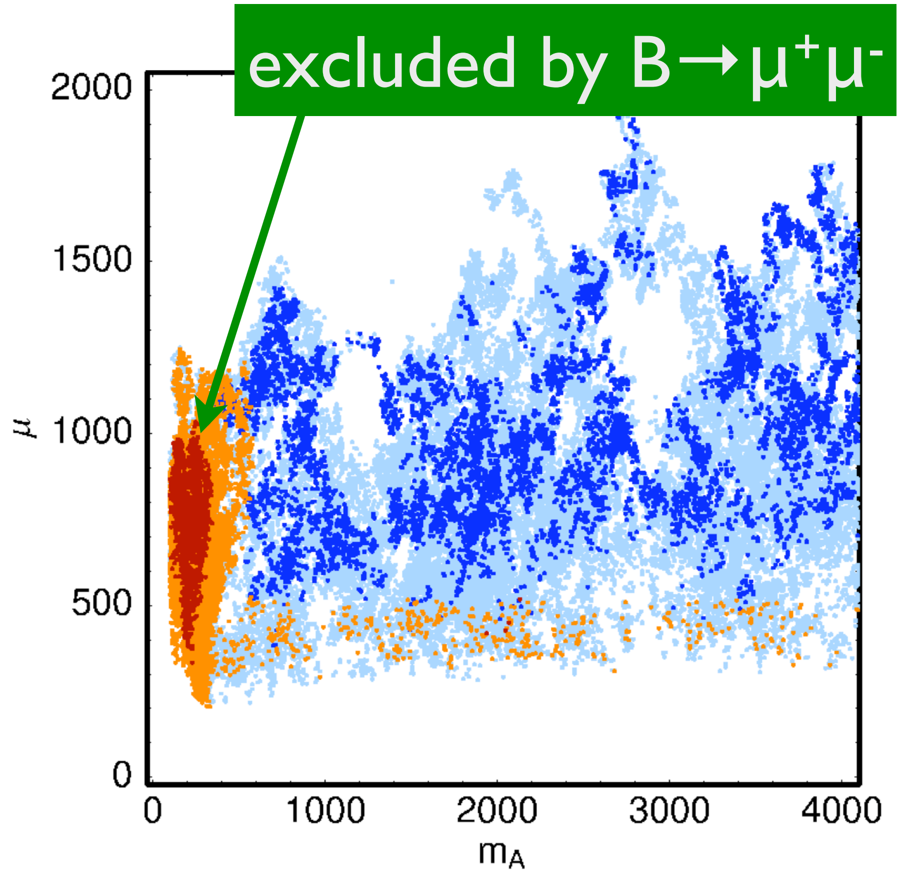


R<1.1

R<1.05

R<1.1 + $\Omega h^2 < 0.136$

R<1.05 + $\Omega h^2 < 0.136$

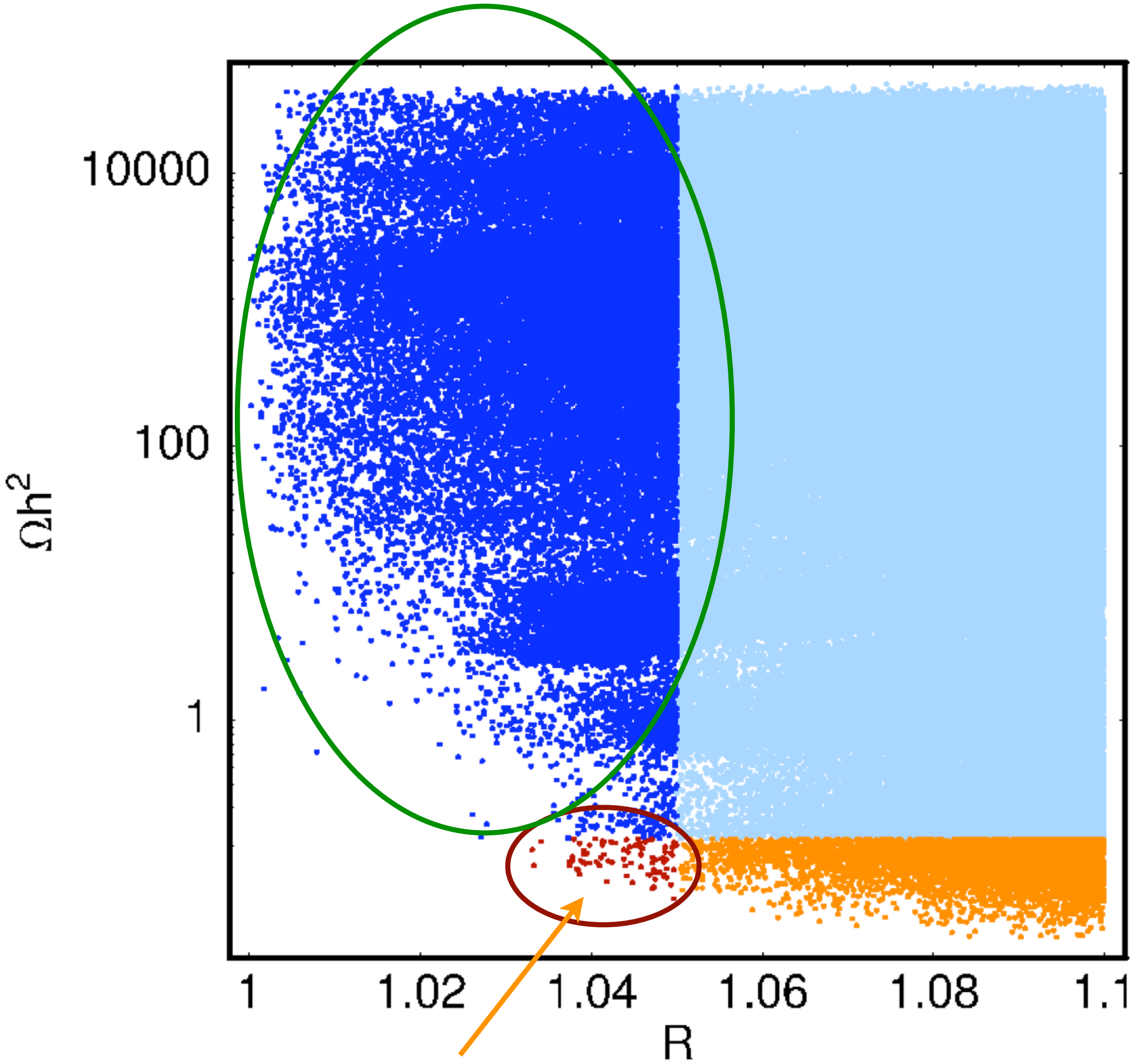


excluded by $B \to \mu^+\mu^-$

mechanism:
annihilation through A !

Analogous conclusions by Altmannshofer et el.

what about all the rest (bulk!) of the Yukawa-unified parameter space?



h funnel

Covi, Kim, Roszkowski, 1999

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

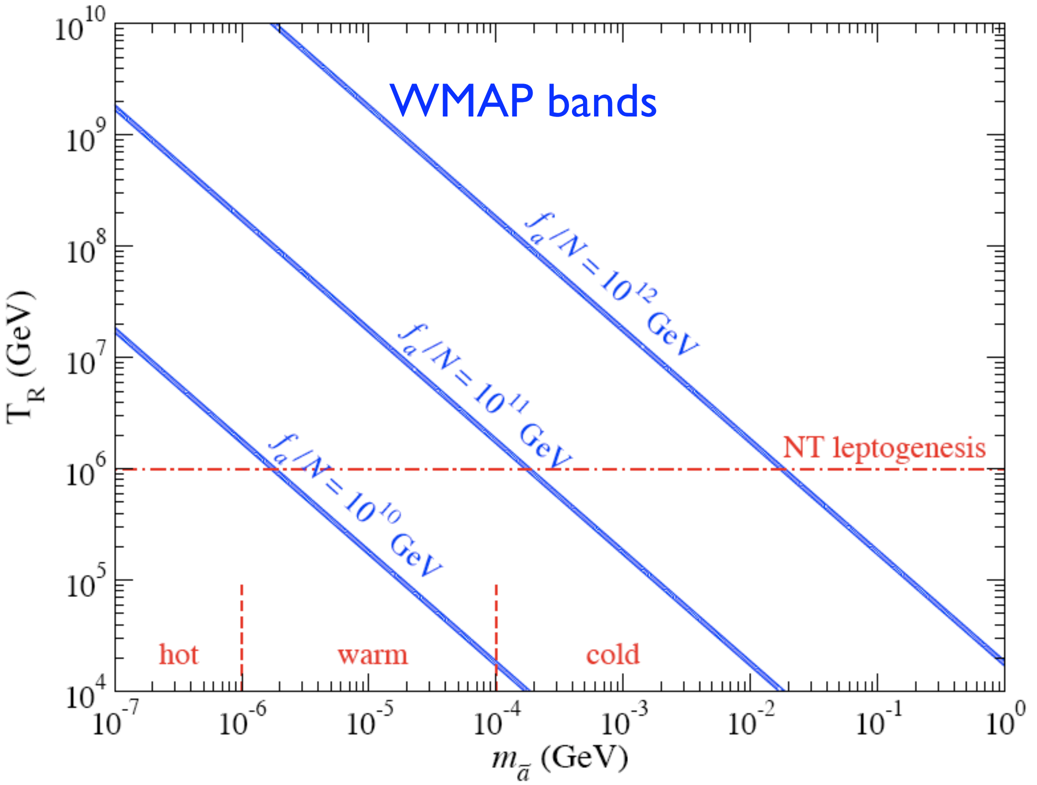
- Axion contribution to CDM

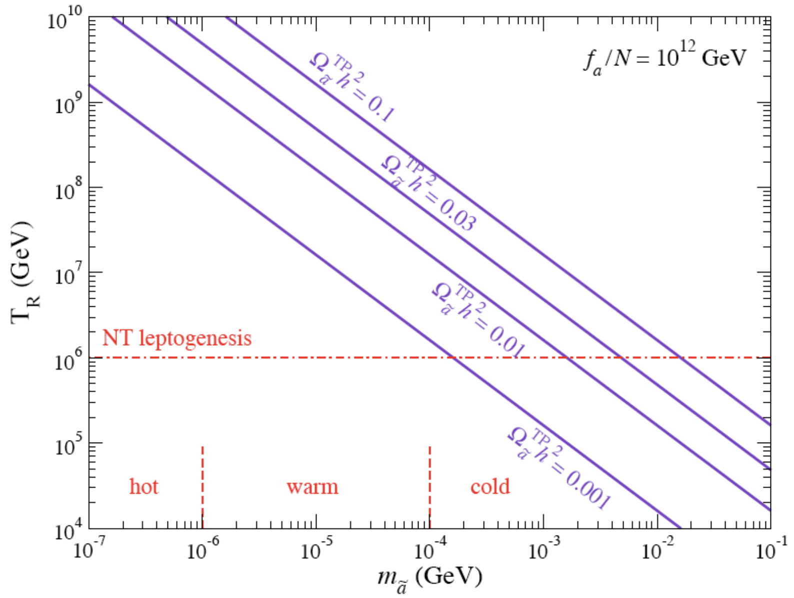
$$m_a \simeq 6\,{\rm eV}\,\frac{10^6\ {\rm GeV}}{f_a/N}, \quad n_a(t) \sim \frac{1}{2} m_a(t) \langle a^2(t) \rangle, \quad \Omega_a h^2 \simeq \frac{1}{4}\left(\frac{6\times10^{-6}\ {\rm eV}}{m_a}\right)^{7/6}$$

vacuum mis-alignment

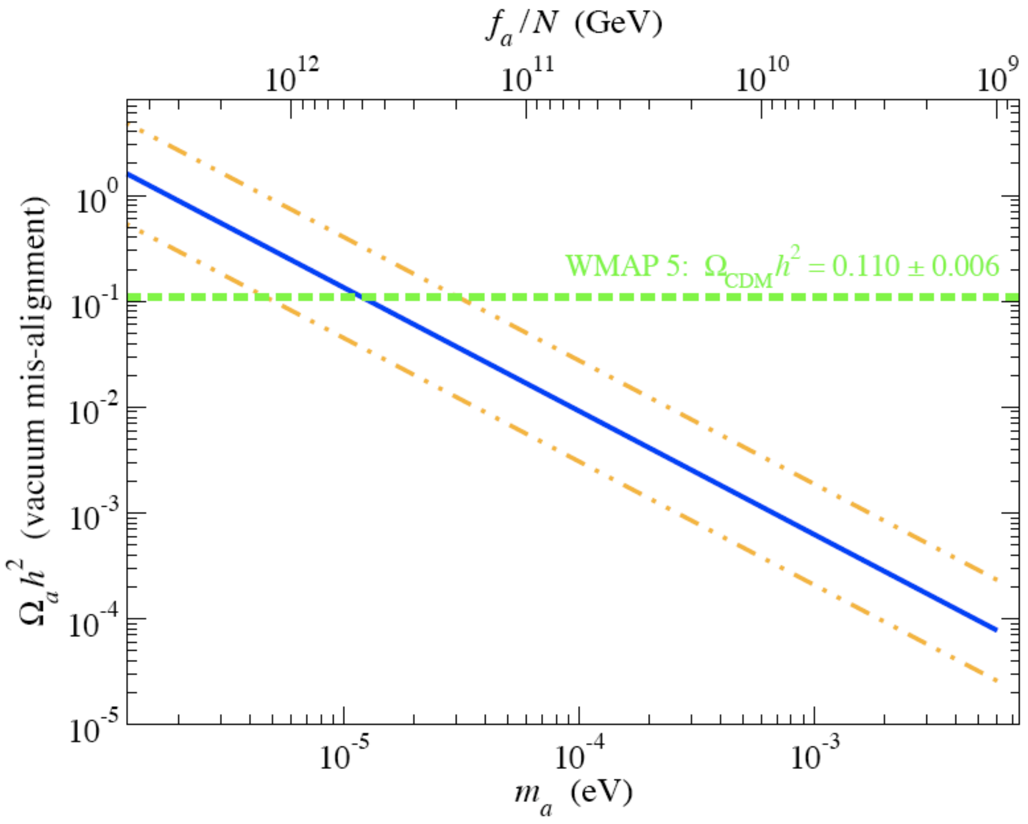
Abbott, Sikivie; Preskill, Wise, Wilczek;
Dine, Fischler; Turner (1983-86)

Thermally produced axino relic density

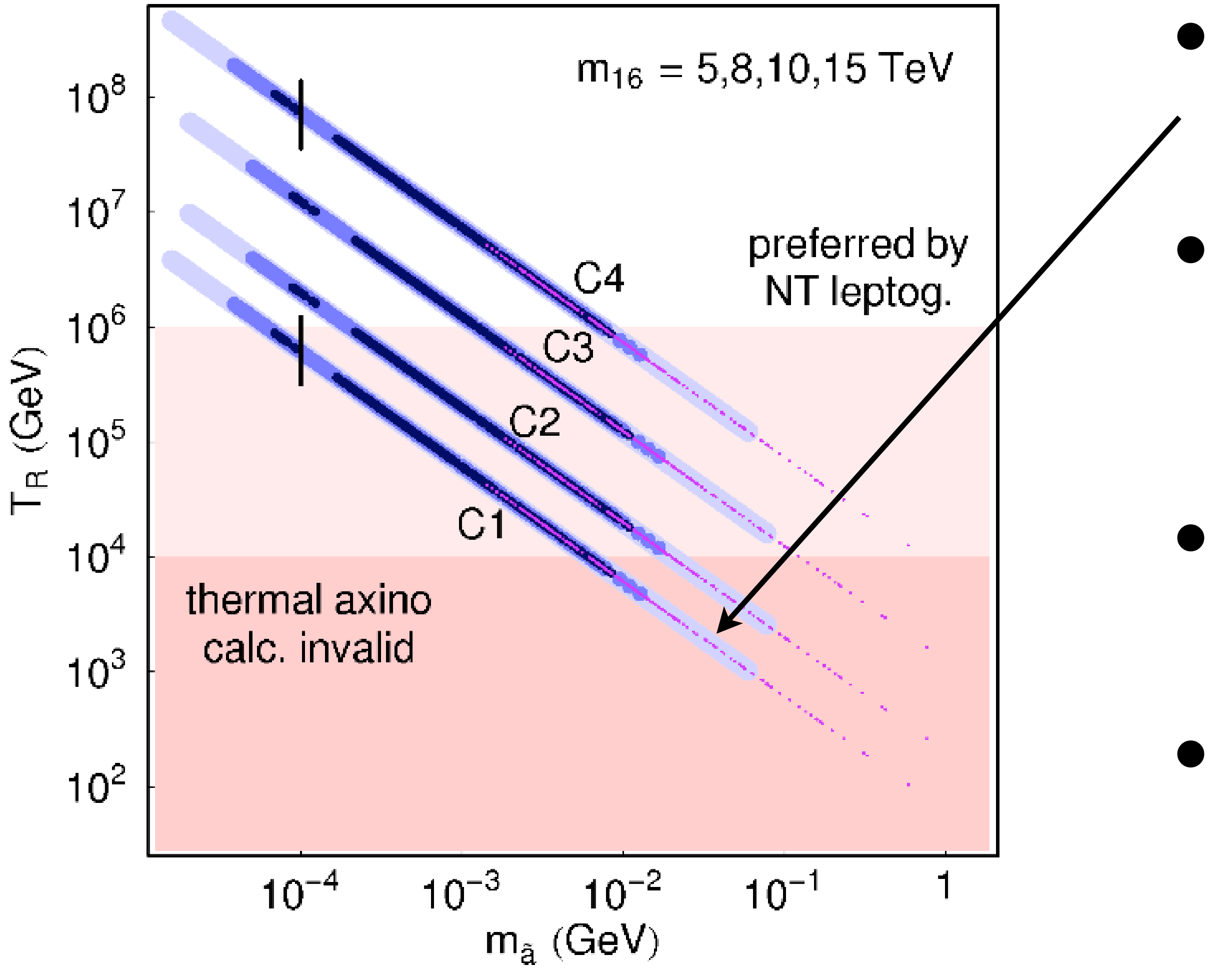




Axion relic density
due to vacuum mis-alignment



Yukawa-unified scenarios with mixed axion/axino dark matter

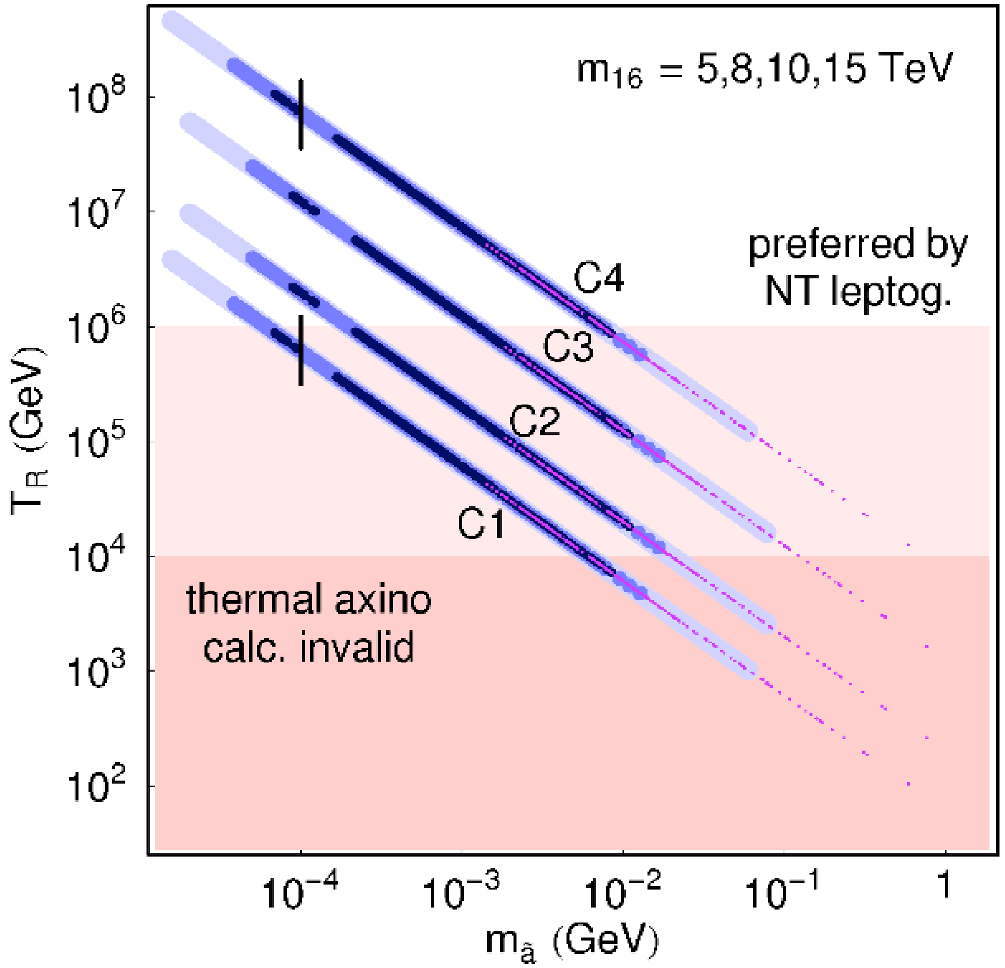


Case C1

- $f_a/N = 10^{11}$ 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 $\Omega_{DM}h^2=0.11$

Baer et al, 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.

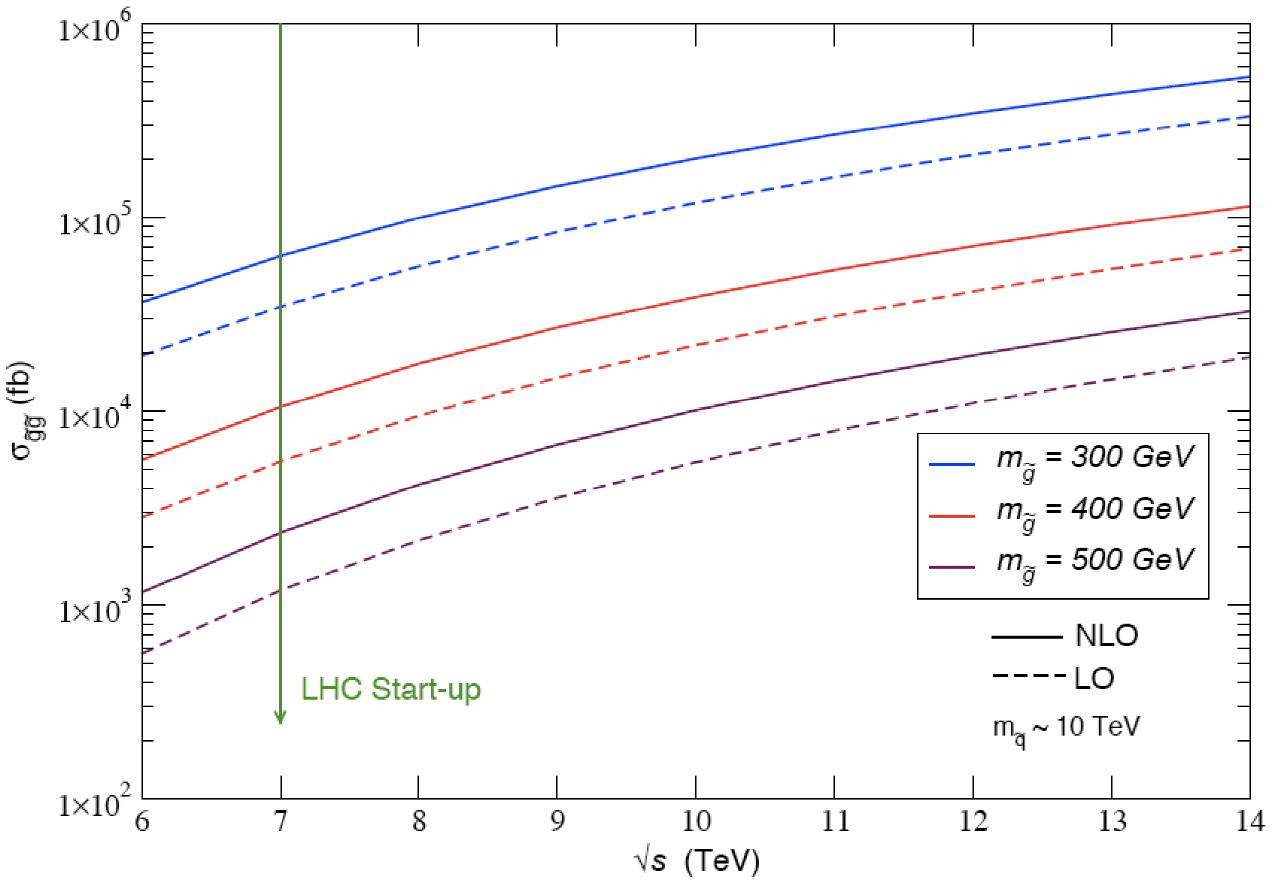
C3: $f_a/N = 10^{12}$ GeV, $\Omega_{axion}h^2 \sim 0.084$;
DM dominantly axions + some mixed cold and warm axinos.

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 $(\Omega_{axino}h^2)^{NTP}=0.01$

Message: can achieve consistent cosmology for Yukawa-unified SUSY

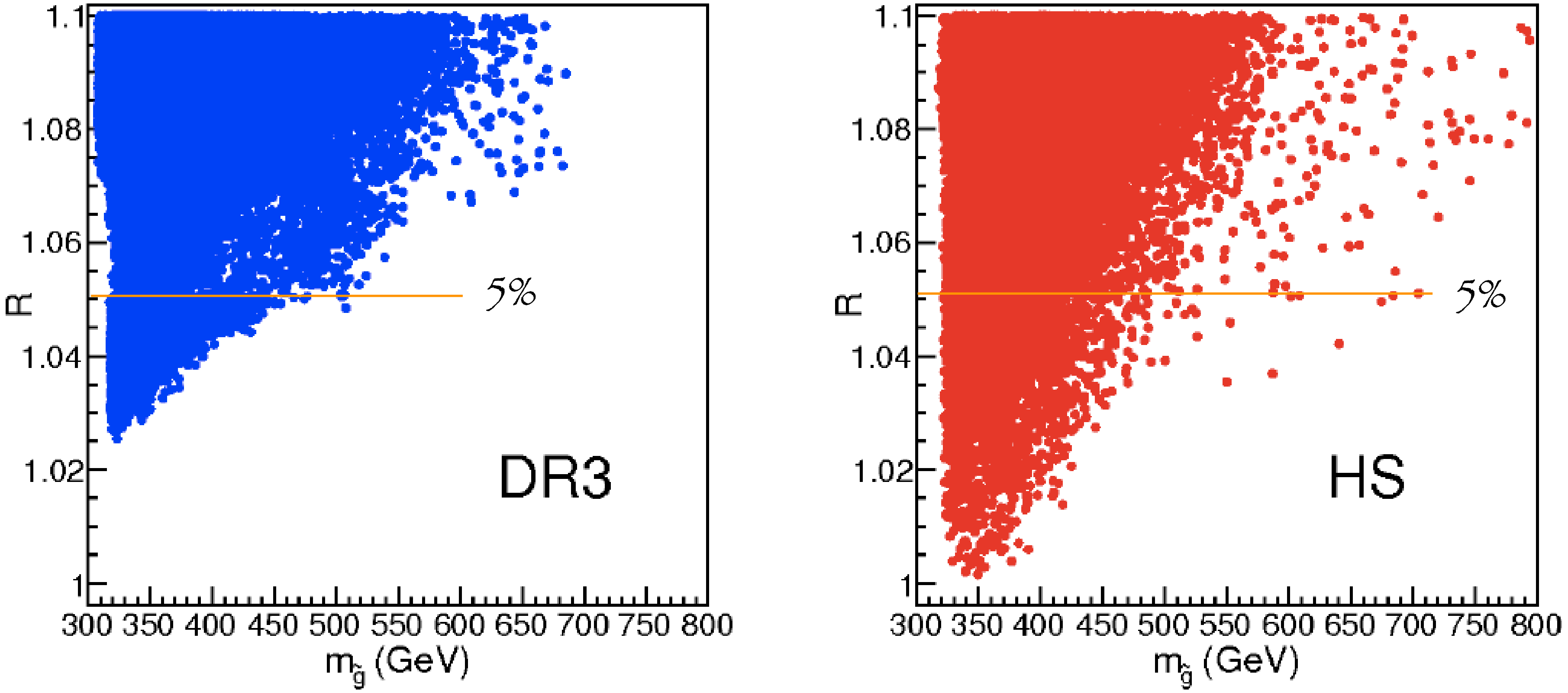
Baer et al, arXiv:0812.2693

LHC potential at 7 TeV



Recall: Typical mass spectra

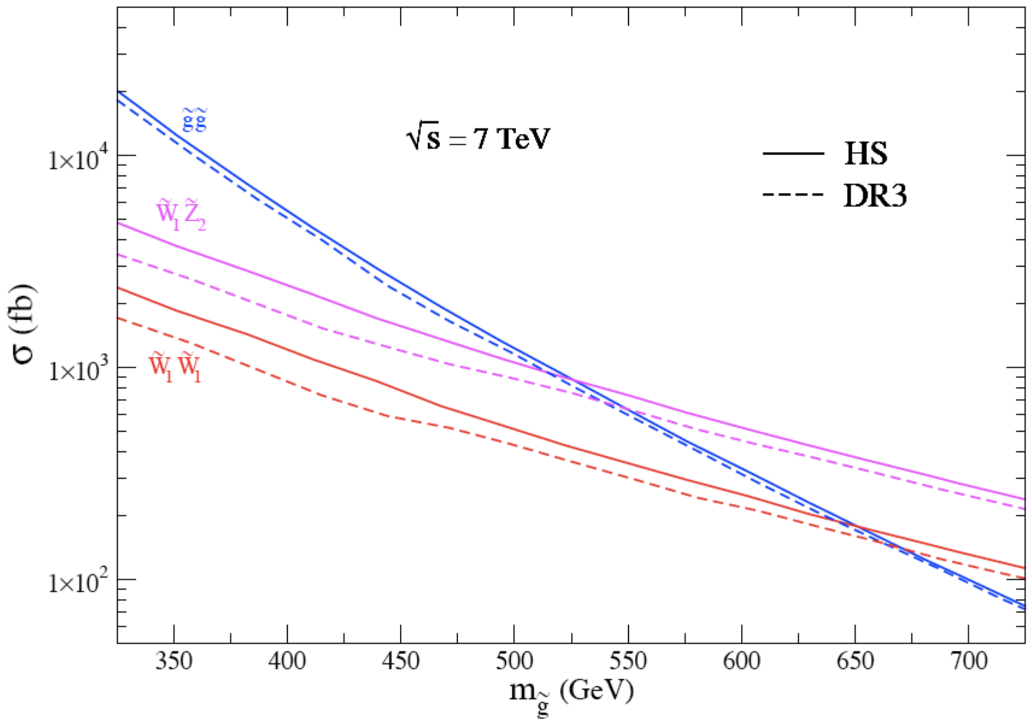
- 1st/2nd generation scalars in the multi-TeV range (5-15 TeV)
- 3rd gen. scalars, heavy Higgses and higgsinos in the 1-3 TeV range
- light gauginos: LSP ~ 50-80 GeV, gluino ~ 300-500 GeV



Points from a MCMC scan for small R

Baer et al, arXiv:0911.4739

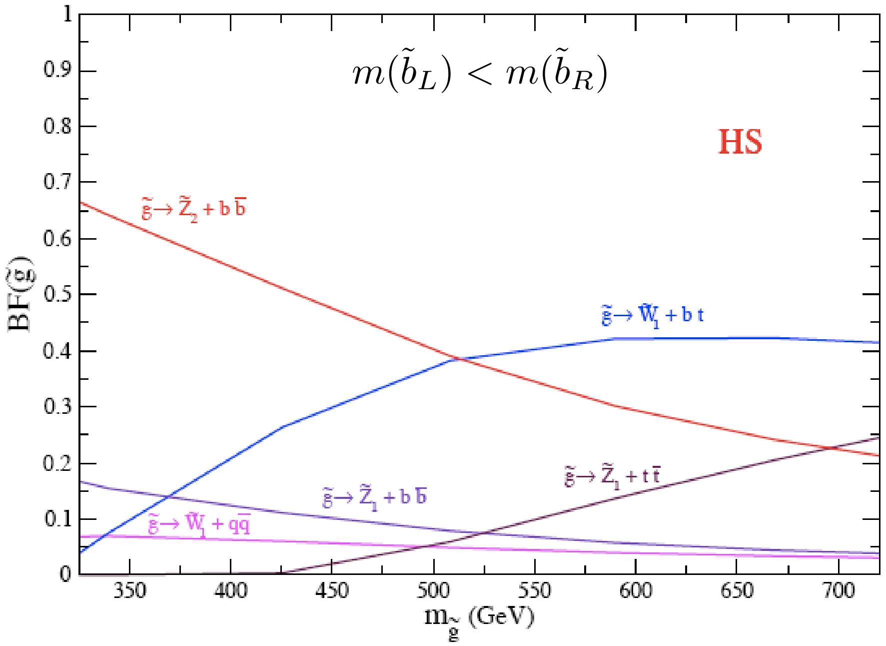
LHC reach at 7 TeV

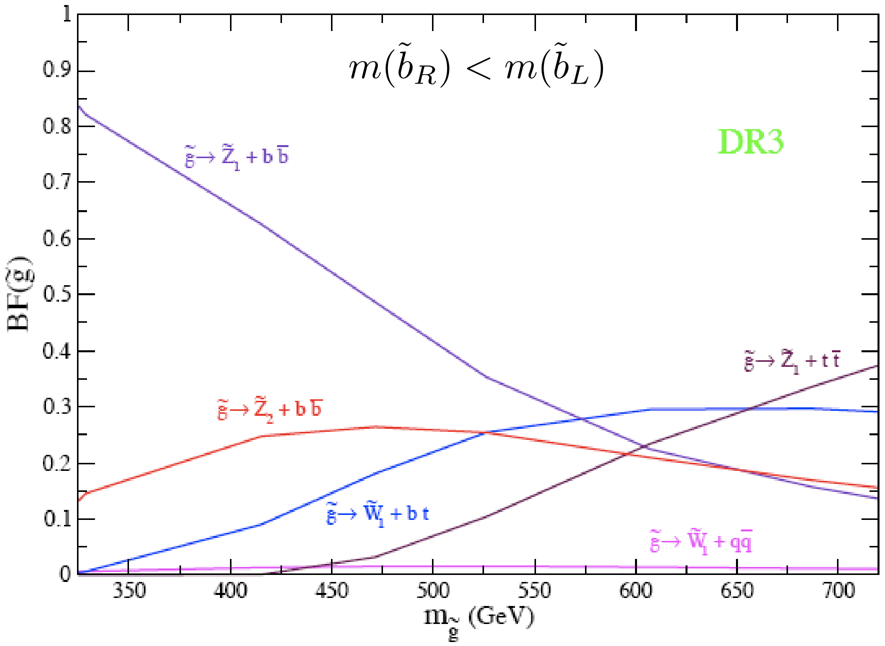


We consider model lines for HS and DR3 cases as function of m(gluino) up to 700 GeV.

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

Gluinos decays are dominanted by heavy flavours: $\tilde{g} \to \tilde{\chi}^0_{1,2} b\bar{b},\ \tilde{\chi}^\pm_1 tb$





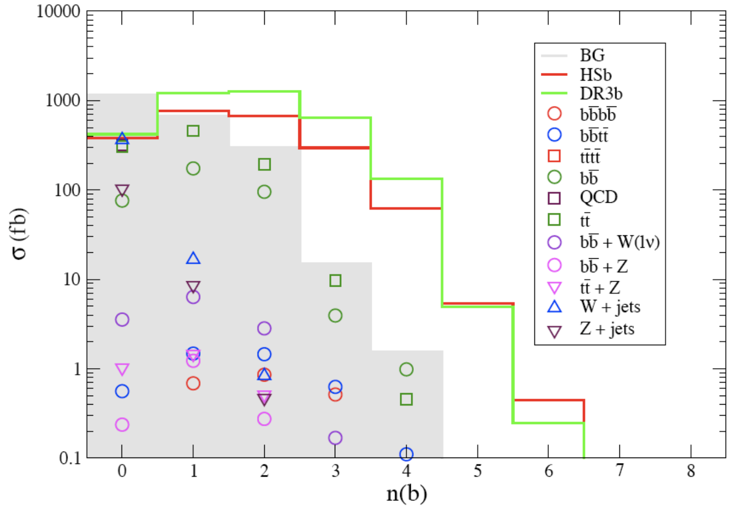
Baer et al, arXiv:0911.4739

LHC reach at 7 TeV

Event simulation:

- 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

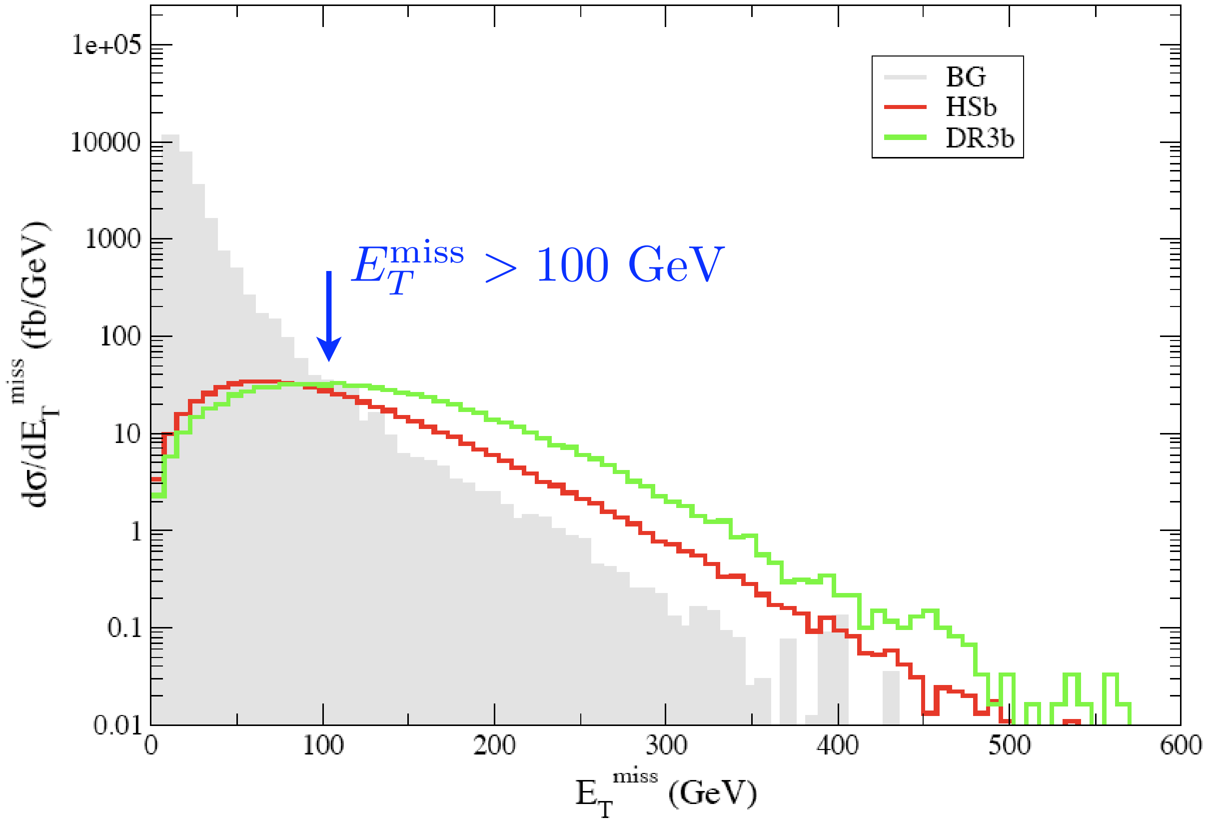
with cut on E_T^{miss}



Basic Cuts "C0":

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

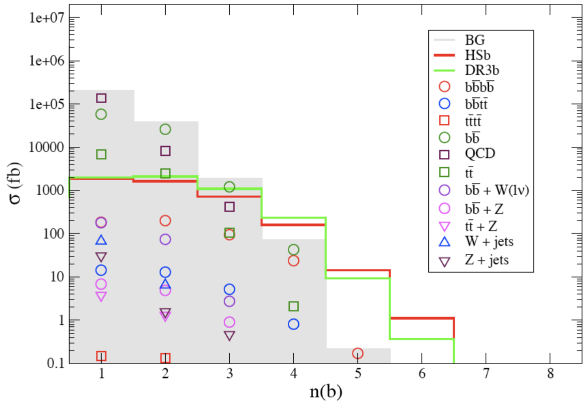
Results after C1-based selection			
	$\sigma(n(b) \geq 3)$	$\sigma(n(b) \geq 4)$	$\sigma(OS)$
HSb	364 fb	68 fb	81 fb
DR3b	782 fb	139 fb	23 fb
BG	16 fb	2 fb	9 fb

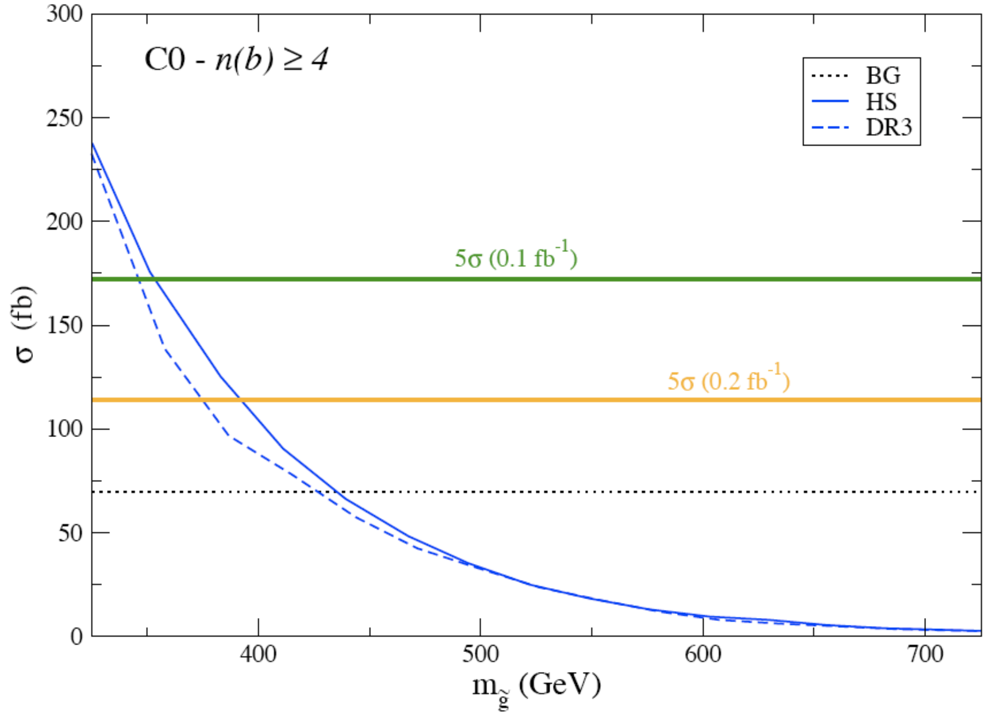


Baer et al, arXiv:0911.4739

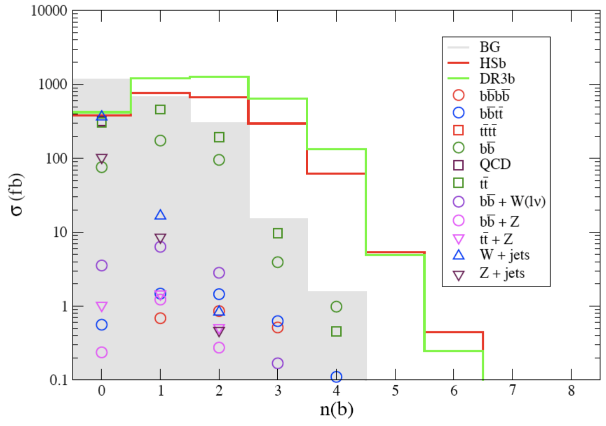
LHC reach at 7 TeV

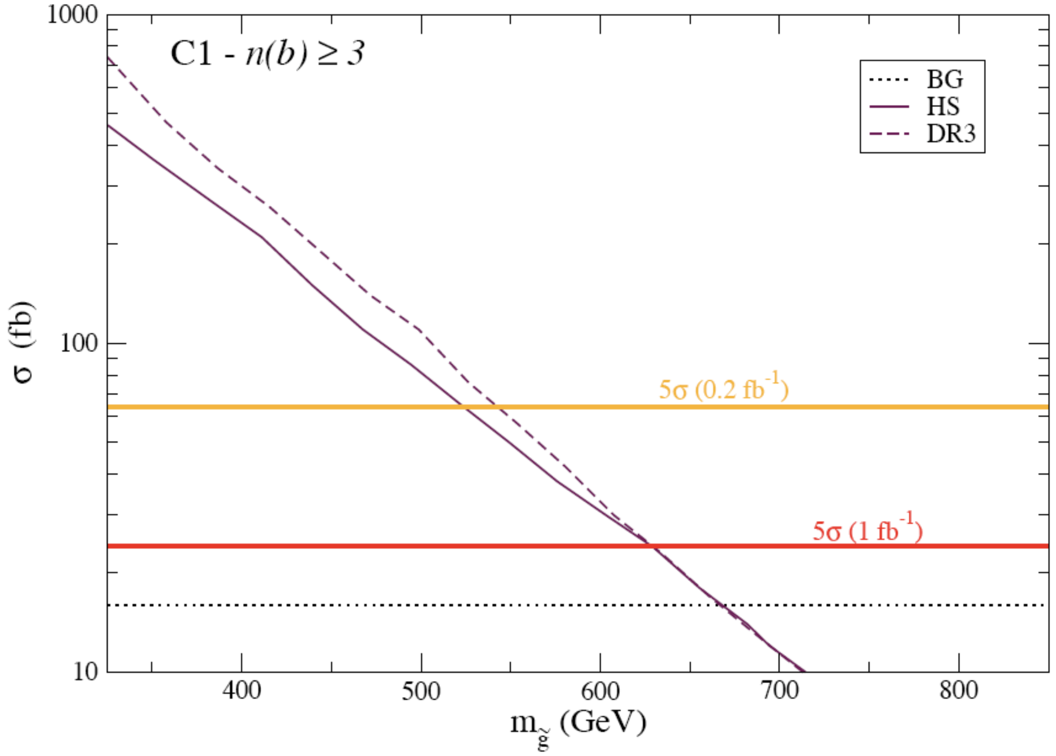
Without missing energy measurement:
up to m(gluino)=400 GeV with 0.2 fb^{-1} of data
requiring 4 b-jets



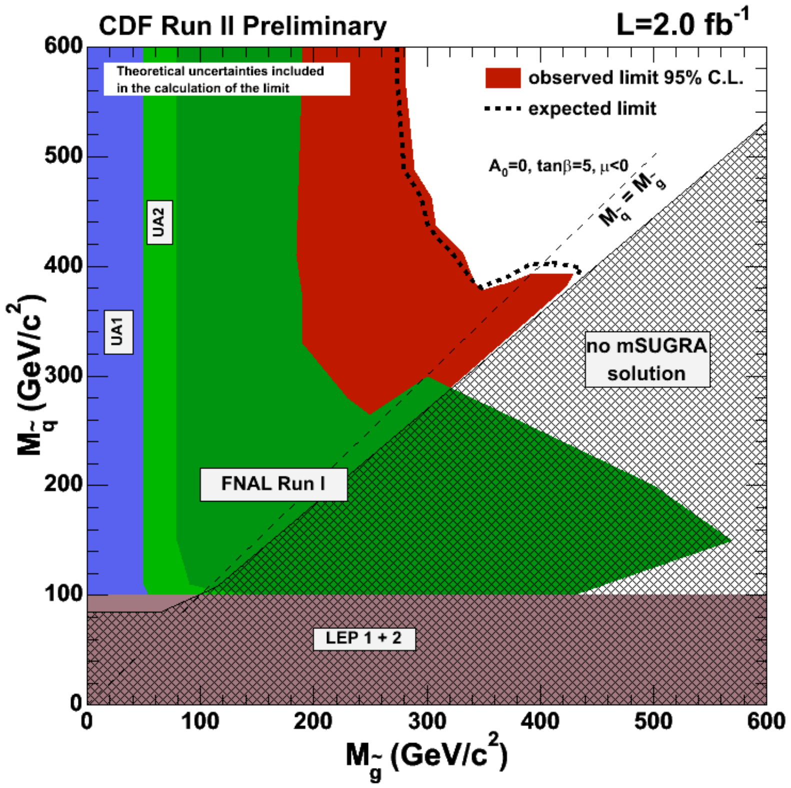


With reliable missing energy measurement:
reach up to m(gluino)=540-630 GeV
with 0.2-1 fb^{-1} of data,
n(b) ≥ 3





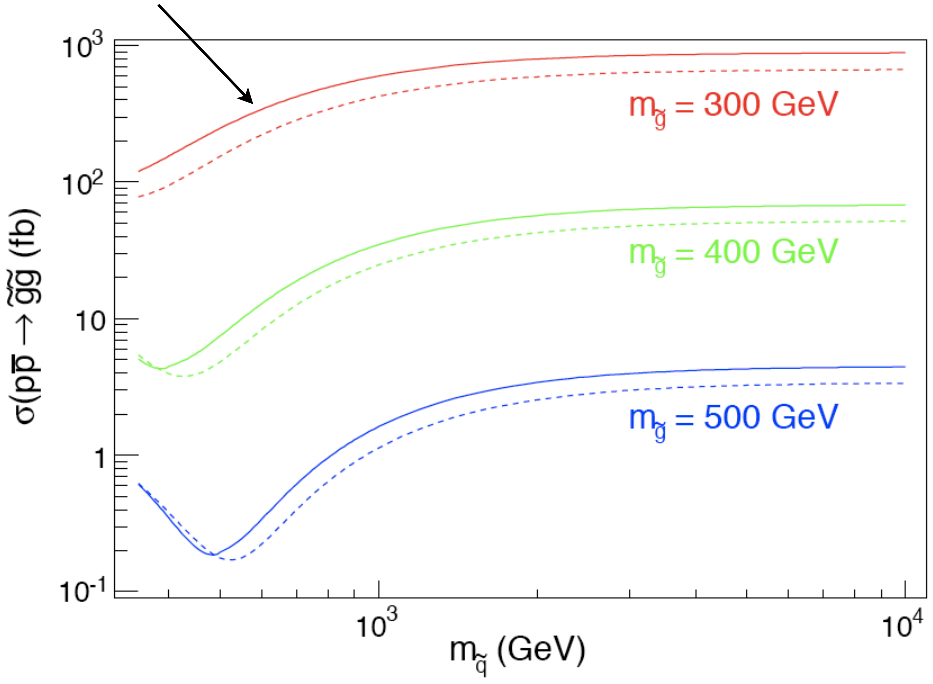
What about the Tevatron?



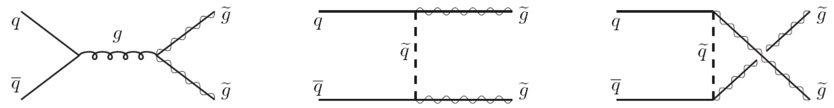
Baer et al, arXiv:0910.2988

Tevatron reach

current mSUGRA limit
for heavy squarks (2fb^{-2})



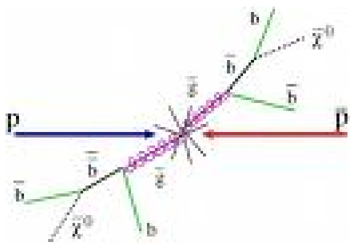
Gluino-pair prod. dominated by qq̄ fusion.
Negative interference of s-, t-, u-channels
for m(squark)~m(gluino)!

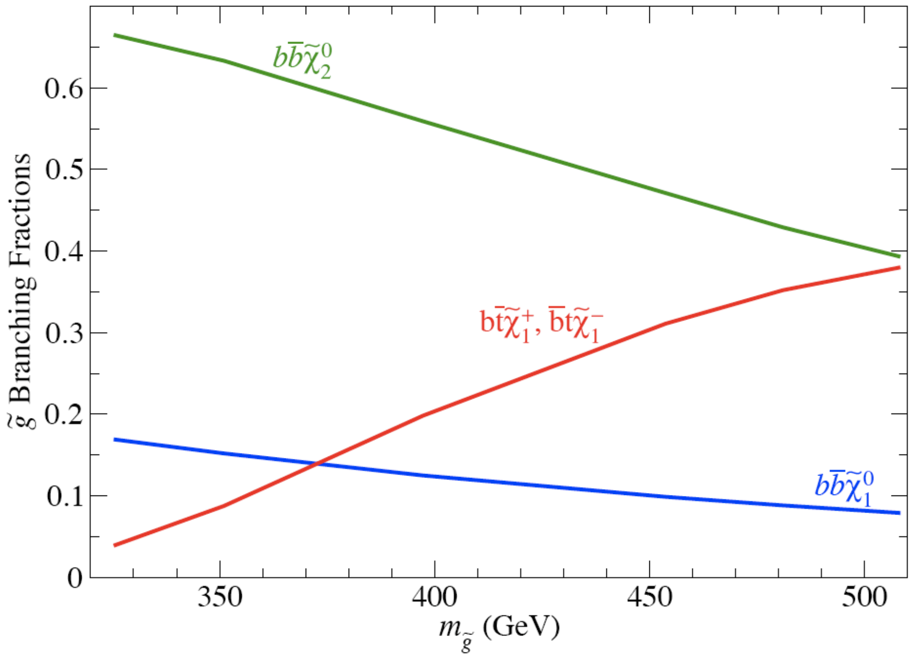


Xsection grows with increasing squark mass!

Gluino decays dominated by $\tilde{\chi}_2^0 b\bar{b}$ channel.
We adopt a YU model line by starting from
a HS point with m$_{16}$=10 TeV and R~1.02
and varying m$_{1/2}$.

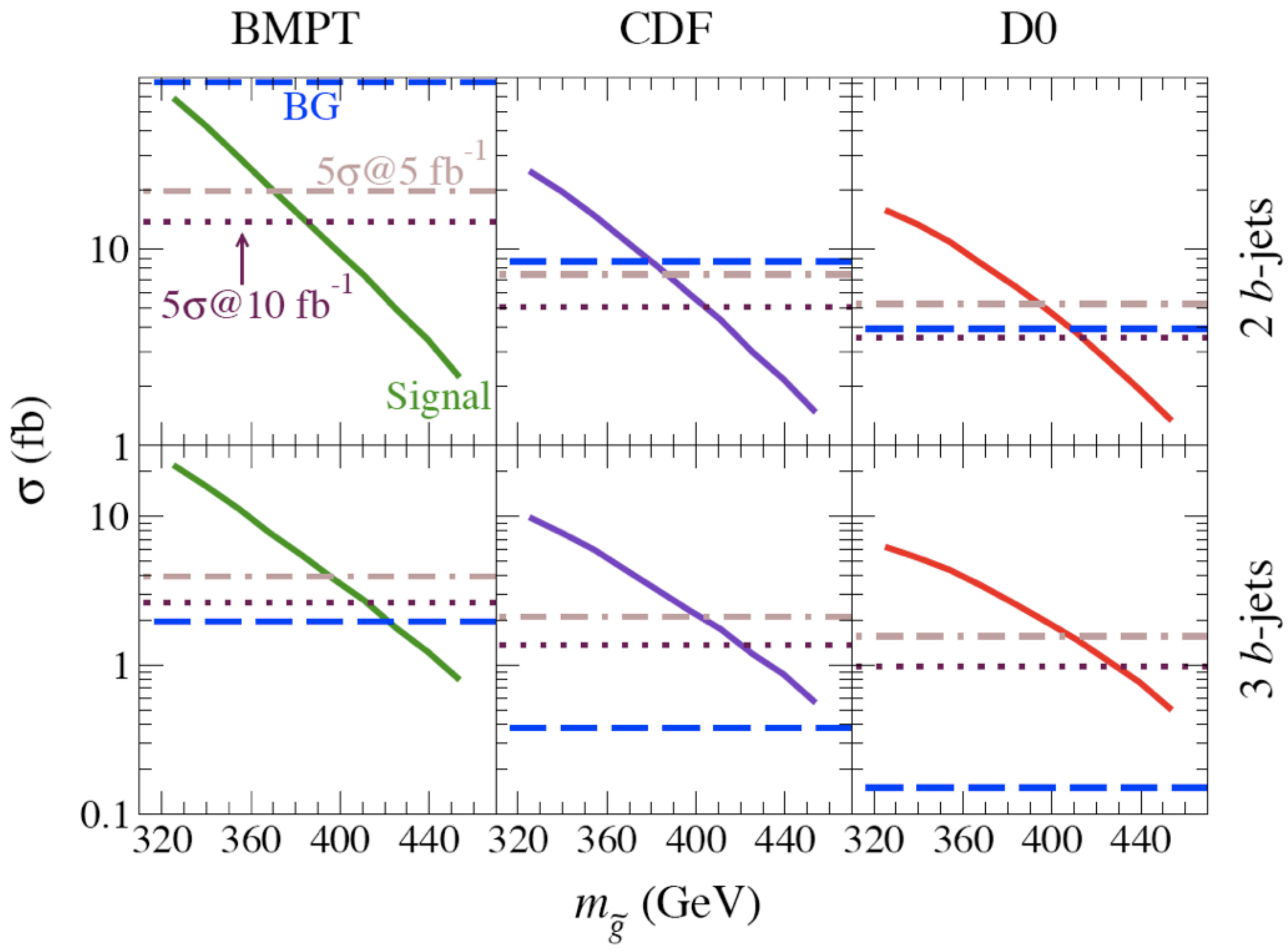
$$m_{1/2} = 35 - 100 \text{ GeV},$$
$$m_{\tilde{g}} = 325 - 508 \text{ GeV},$$
$$R \to 1.07$$

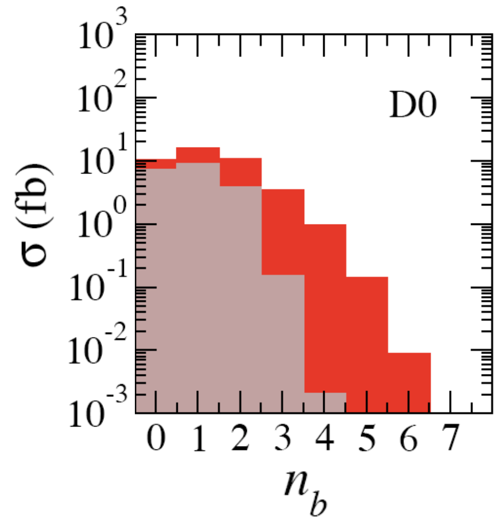




Baer et al, arXiv:0910.2988

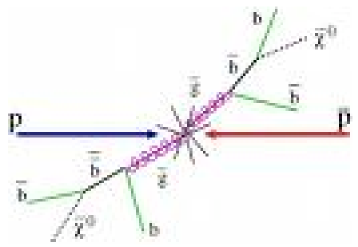
Tevatron reach





With "D0" cuts and requiring ≥3 b-jets, 5σ discovery reach with 10 fb^{-1} about m(gluino)=430 GeV!

cuts	E_T^{miss}	H_T	$E_T(j1)$	$E_T(j2)$	$E_T(j3)$	$E_T(j4)$
BMPT	≥ 75 GeV	–	15	15	15	15
CDF	≥ 90 GeV	280	95	55	55	25
D0	≥ 100 GeV	400	35	35	35	20



Conclusions

- Yukawa-unified SUSY GUT based on SO(10) is quite compelling.
- Typical mass spectrum: light gluino of 300-500 GeV mass, TeV-scale 3rd generation, multi-TeV 1st/2nd generation. (c.f. "effective SUSY")
- 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.
- Tevatron and/or LHC may soon discover or rule out the simplest case of a SO(10) SUSY GUT.
- Dark matter issue: neutralino LSP annihilating through h-funnel or mixed axion/axino DM