Status of constraints on SUSY

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1. **SUSY models**
2. **High energy colliders**
3. **Electroweak precision data**
4. **Flavor and Higgs physics**
5. **Cosmology**

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Apologies for the very incomplete references!

Introduction: SUSY models

"Minimal MSSM":

Spin 0	Spin 1/2	Spin 1
Neutral Higgses h_0, H_0, A_0	Neutralinos $\tilde{\chi}_1^0 \dots \tilde{\chi}_4^0$	photon γ
Charged Higgs $H^\pm$	Chargino $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	Z boson
	Gluino $\tilde{g}$	$W^\pm$ bosons
		gluon g
sleptons $\tilde{e}$, $\tilde{\mu}$, $\tilde{\nu}$,...	leptons e, μ, ν, ...	
squarks $\tilde{u}$, $\tilde{d}$, ...	quarks u, d, ...	

- R-parity conservation: $R_p = \pm 1$ for SM/SUSY particles
- CP conservation
- Minimal flavor violation: CKM matrix is only source of flavor violation

SUSY breaking

mSUGRA/CMSSM:

- Gaugino masses, scalar masses and triple-scalar couplings (A-terms) unify at $M_{\mathrm{GUT}} \sim 10^{16}$ GeV
- Lightest SUSY particle (LSP) is $\tilde{\chi}_1^0$, $m_{\tilde{\chi}_1^0} \sim \mathcal{O}(100 \text{ GeV})$

GMSB:

- Gaugino masses unify at $M_{\mathrm{GUT}} \sim 10^{16}$ GeV
- Scalar masses do not unify
- Triple-scalar couplings ≈ 0 at $\Lambda_{\mathrm{mess}} \sim 100$ TeV
- LSP is gravitino $m_{\tilde{G}} \sim 100 \text{ eV} \ldots 1 \text{ GeV}$

MSSM with additional singlet

- μ-problem in MSSM:

Superpotential has term $W_{\text{MSSM}} \supset -\mu\, \hat{H}_1 \cdot \hat{H}_2$

$\longrightarrow$ Why is $\mu \ll M_{\text{Planck}}$?

- Solve μ-problem with new singlet superfield S:

$$W = \lambda\, \hat{S} \hat{H}_1 \cdot \hat{H}_2 + \kappa\, \hat{S}^3 + m_S\, \hat{S}^2 + \tau_S\, \hat{S} + \text{ Yukawa terms}$$

Effective μ-term through VEV of S: $\mu_{\text{eff}} = -\lambda \langle S \rangle$

a) NMSSM: $\mathbb{Z}_3$ global symmetry $\longrightarrow m_S = 0,\ \tau_S = 0$

b) nMSSM: $\mathbb{Z}_{5,7}$ global symmetry $\longrightarrow m_S = 0,\ \kappa = 0,\ \tau_S = \mathcal{O}(\text{TeV})$

c) UMSSM: $U(1)$ gauge symmetry $\longrightarrow m_S = 0,\ \kappa = 0,\ \tau_S = 0$
(has also Z' gauge boson)

SUSY constraints from high energy colliders

Scenario-independent results from LEP2:

Sparticle	lower limit [GeV]
$\tilde{\chi}_2^0$	62.4
$\tilde{\chi}_3^0$	99.9
$\tilde{\chi}_4^0$	116.0
$\tilde{\chi}_1^\pm$	94.0

Sparticle	lower limit [GeV]
$\tilde{\nu}$	94.0
$\tilde{e}_L$	107.0
$\tilde{\mu}_R$	91.0
$\tilde{\tau}_1$	81.9
$\tilde{q}$	97.0
$\tilde{t}_1$	92.6

Some of the limits require

$m_{\tilde{X}} - m_{LSP} >$ 3–15 GeV

Constraints from Tevatron:

CMSSM/mSUGRA	
$\tilde{g}$	308
$\tilde{q}$	380
$\tilde{\chi}_1^\pm$	140

more general	
$\tilde{g}$	$\sim$150
$\tilde{q}$	—
$\tilde{\chi}_1^\pm$	—

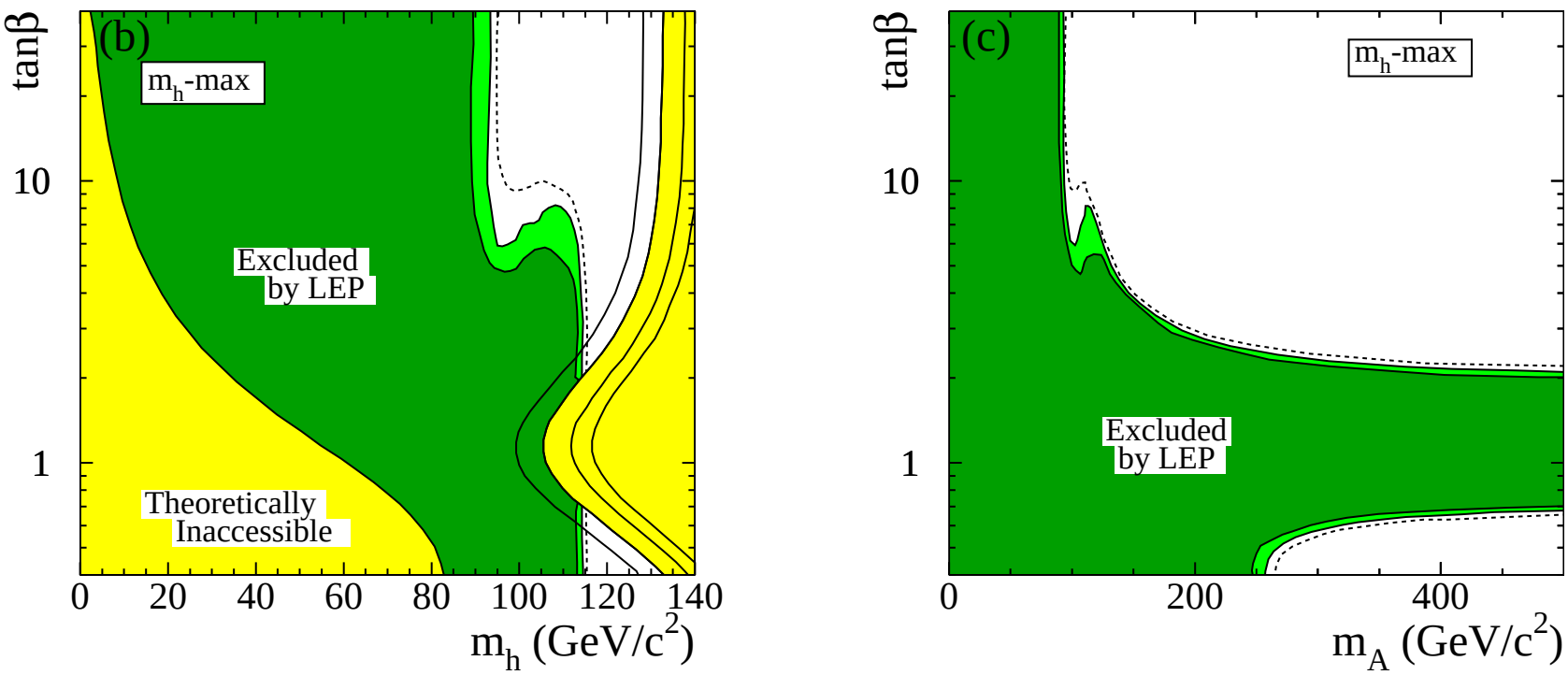
more in following talks...

Higgs searches at LEP2

LEP searched for Higgs production in $e^+e^- \to h\,Z$

$\longrightarrow \quad m_h^{\mathrm{SM}} > 114.4$ GeV

LEP Higgs WG '06



$$m_h \lesssim M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t} + \frac{X_t^2}{m_{\tilde{t}}^2} + \ldots\right] \qquad X_t = A_t - \frac{\mu}{\tan\beta}$$

Higgs searches at LEP2

MSSM parameter space has to fulfill at least one of the following:

- $\tan\beta \gg 1$ because of $M_Z^2 \cos^2 2\beta$ term
- Heavy stops $m_{\tilde{t}}^2 = m_{\tilde{t}_1} m_{\tilde{t}_2} \gtrsim (1\ \text{TeV})^2$
- Large stop mixing because of $X_t^2/m_{\tilde{t}}^2$ term

Constraints on models with extra singlets (NMSSM) or gauge groups are relaxed due to new tree-level contributions

Batra, Delgado, Kaplan, Tait '04

Electroweak precision data

SUSY loop corrections affect predictions for electroweak precision observables

Current state of the art:

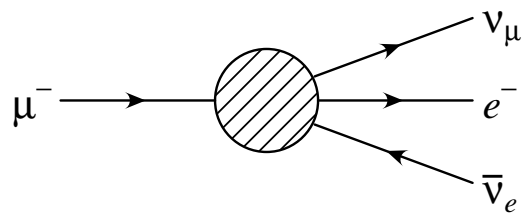
- Complete MSSM one-loop corrections — Chankowski et al. '94
- Leading two-loop corrections $\mathcal{O}(\alpha\alpha_s)$ and $\mathcal{O}(\alpha y_{t,b}^2)$ — Djouadi et al. '98, Haestier et al. '05
- Only partial one-loop results for NMSSM

Important quantities:

- W-boson mass M_{W}
- Effective weak mixing angle of Z-boson $\sin\theta_{\mathrm{eff}} = \frac{1}{4}\left(1 - \mathrm{Re}\frac{v_{\mathrm{eff}}}{a_{\mathrm{eff}}}\right)$
- Z-boson width Γ_{Z} and total cross section $\sigma[e^+e^- \to Z \to f\bar{f}]$
- Muon anomalous magnetic moment $a_\mu = (g_\mu - 2)/2$

Electroweak precision data

- W-boson mass M_W (from muon decay)



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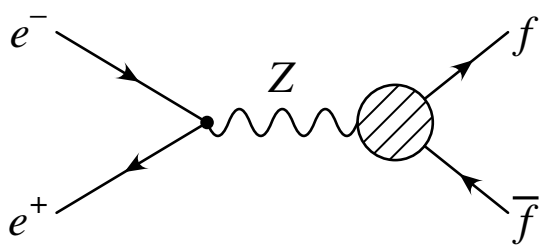

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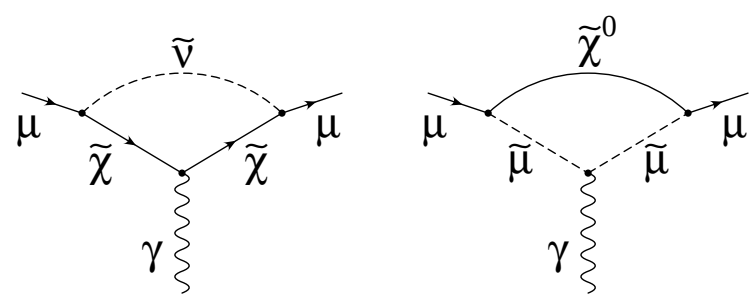
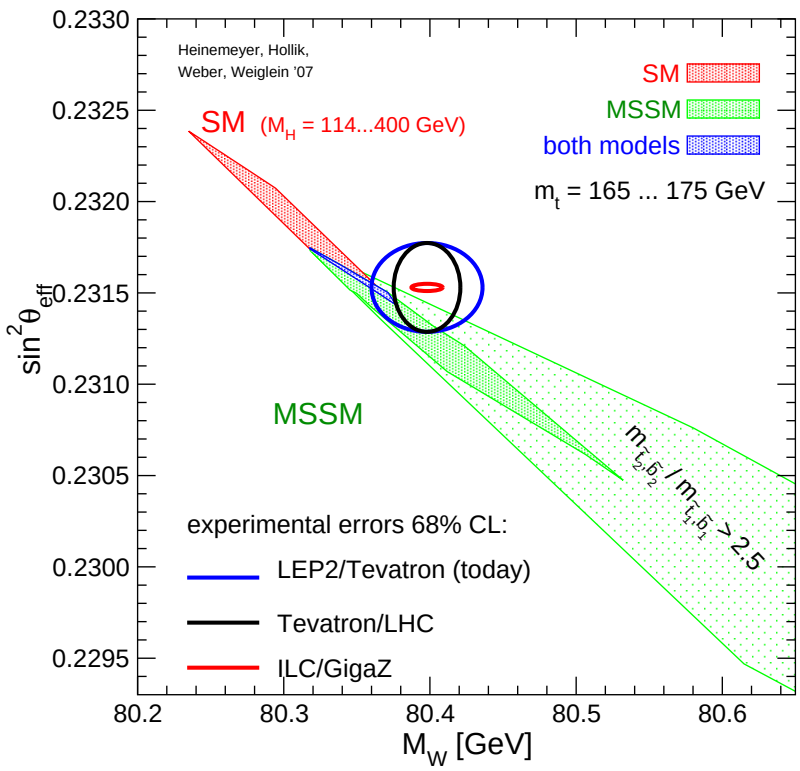


Electroweak precision data

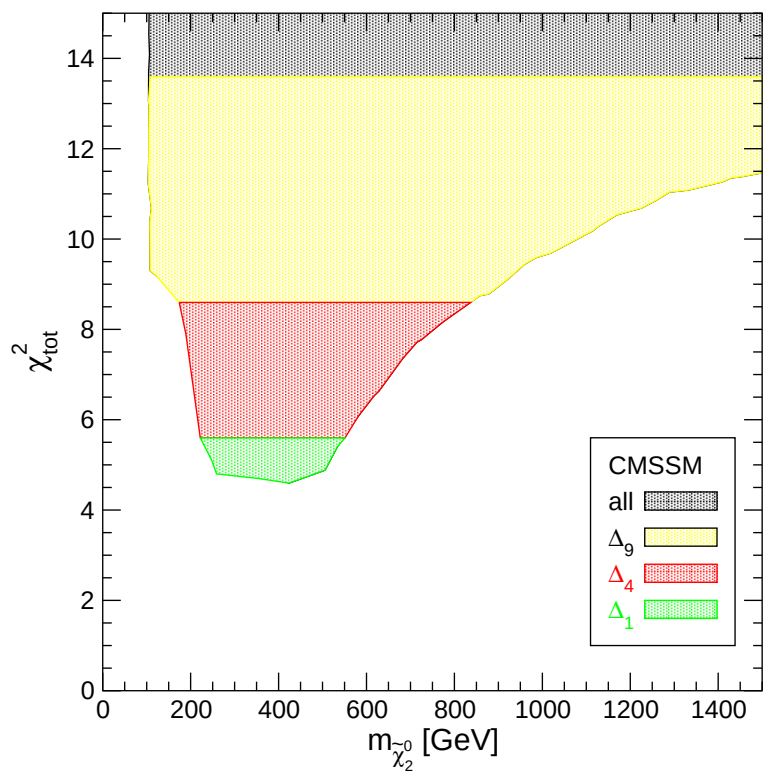
EWPO prefer relatively light sleptons and gauginos:

→ Best fit to EWPO in SM gives $m_h \approx 87$ GeV
Can be pushed to $m_h > 100$ GeV by SUSY effects

→ SUSY can account for 3.3σ discrepancy
$a_\mu^{\text{exp}} - a_\mu^{\text{theo}} = (27.5 \pm 8.4) \times 10^{-10}$



Heinemeyer, Hollik, Weber, Weiglein '07



Heinemeyer, Miao, Su, Weiglein '08

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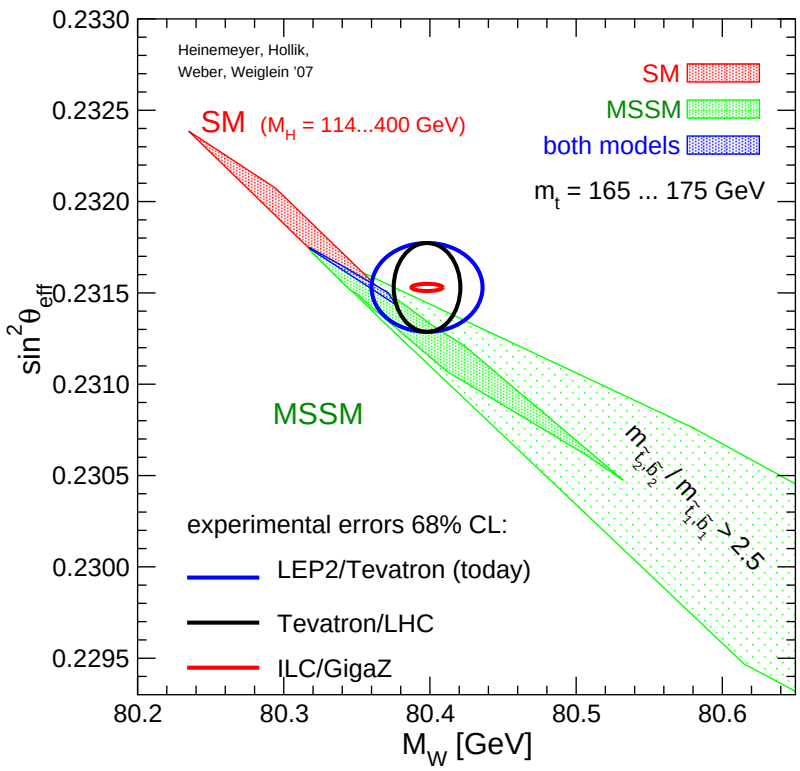

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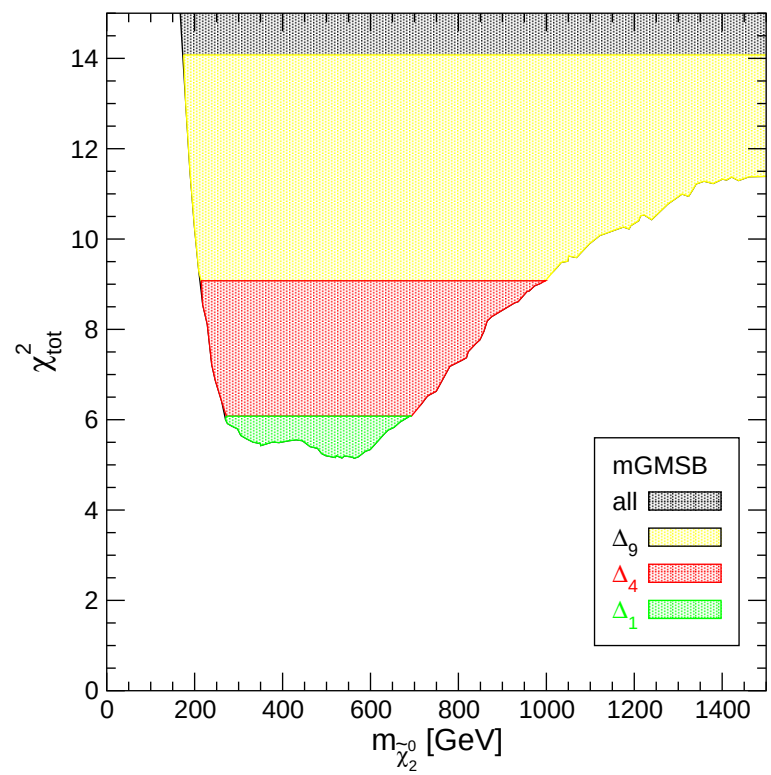

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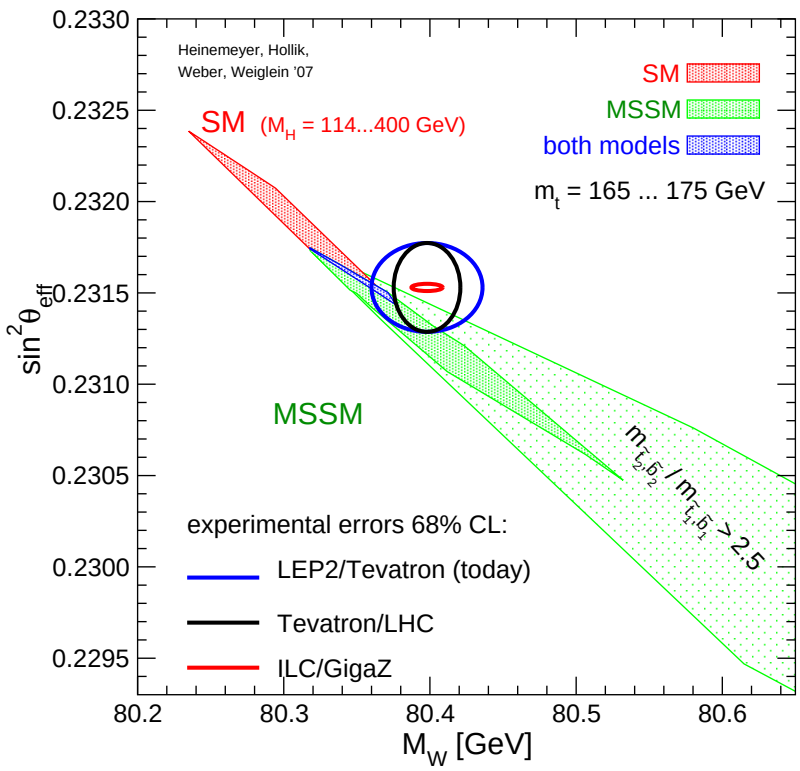

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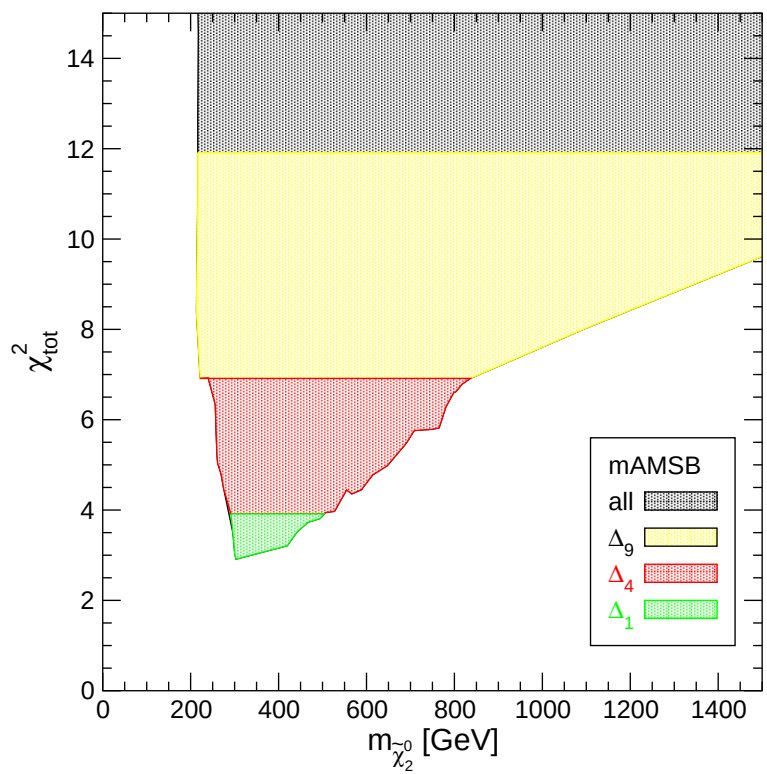


Heinemeyer, Miao, Su, Weiglein '08

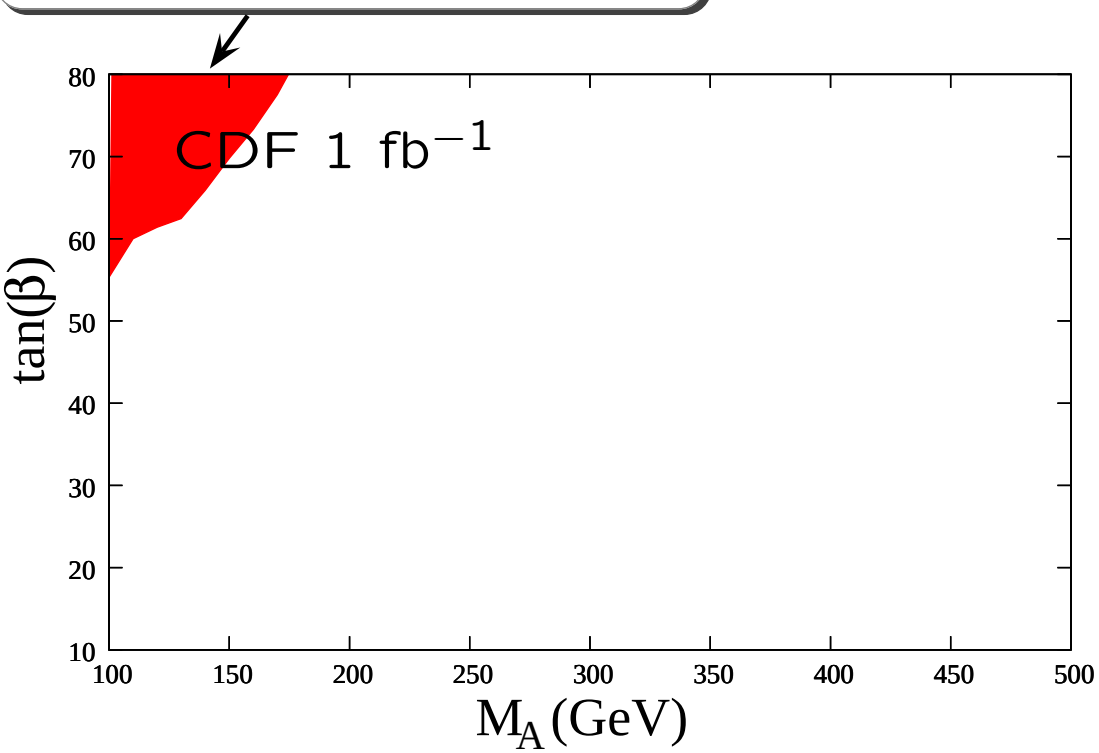
Flavor and Higgs physics

For large $\tan\beta$ enhancement for

Carena, Menon, Wagner '07

- production of non-standard Higgs bosons
- effects in B physics observables

$$\sigma[pp \to A \to \tau\tau] \sim \tan^2\beta$$



$$\mathrm{BR}[B_s \to \mu\mu] \sim \tan^6\beta$$
$$\mathrm{BR}[B_u \to \tau\nu] \sim 1 - \frac{\tan^2\beta}{M_A^2}$$

$$\mathrm{BR}[b \to s\gamma] \sim 1 + A\tan\beta + B\tan\beta/M_A^2$$

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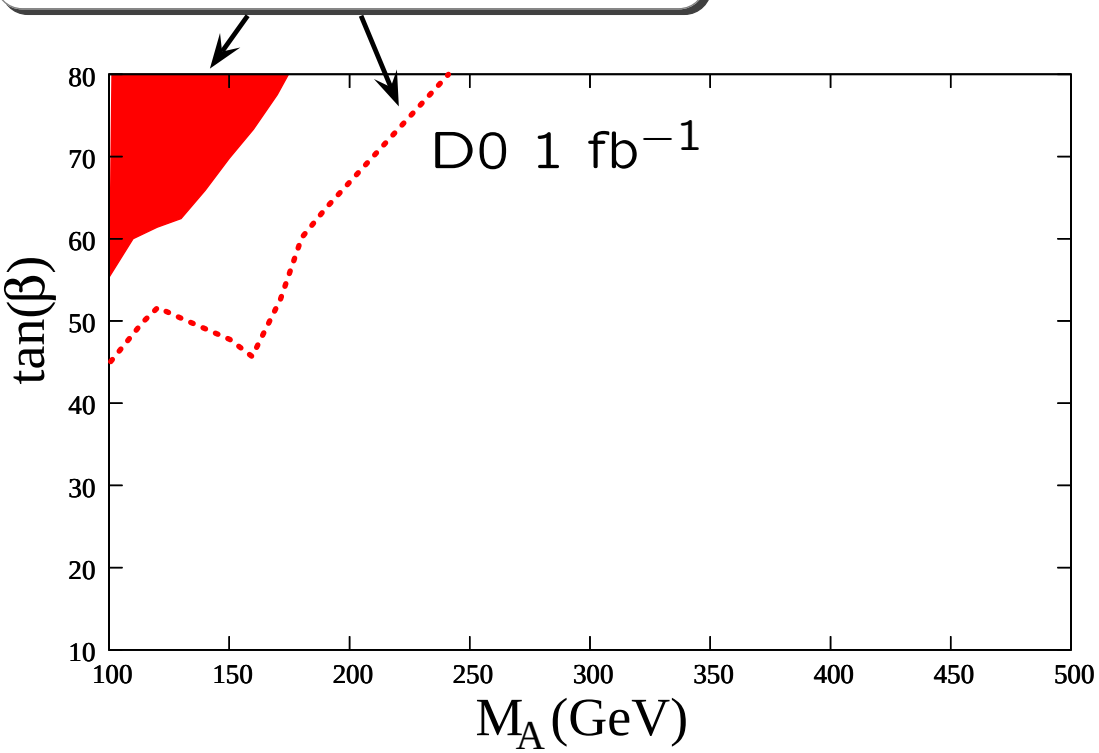

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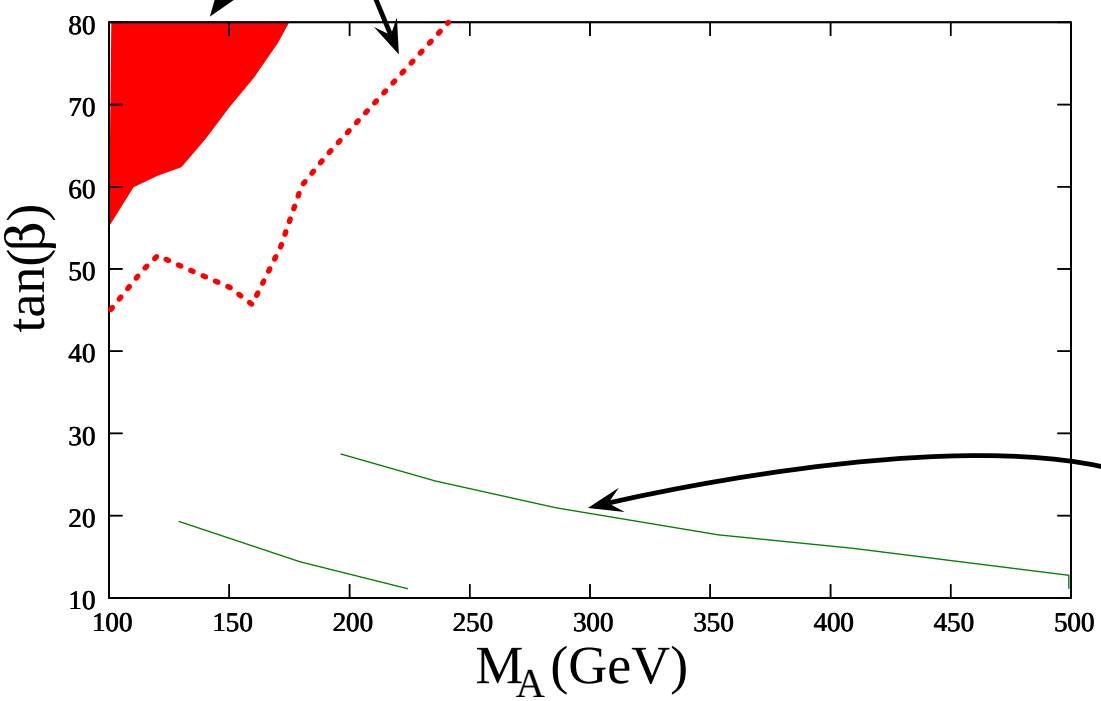

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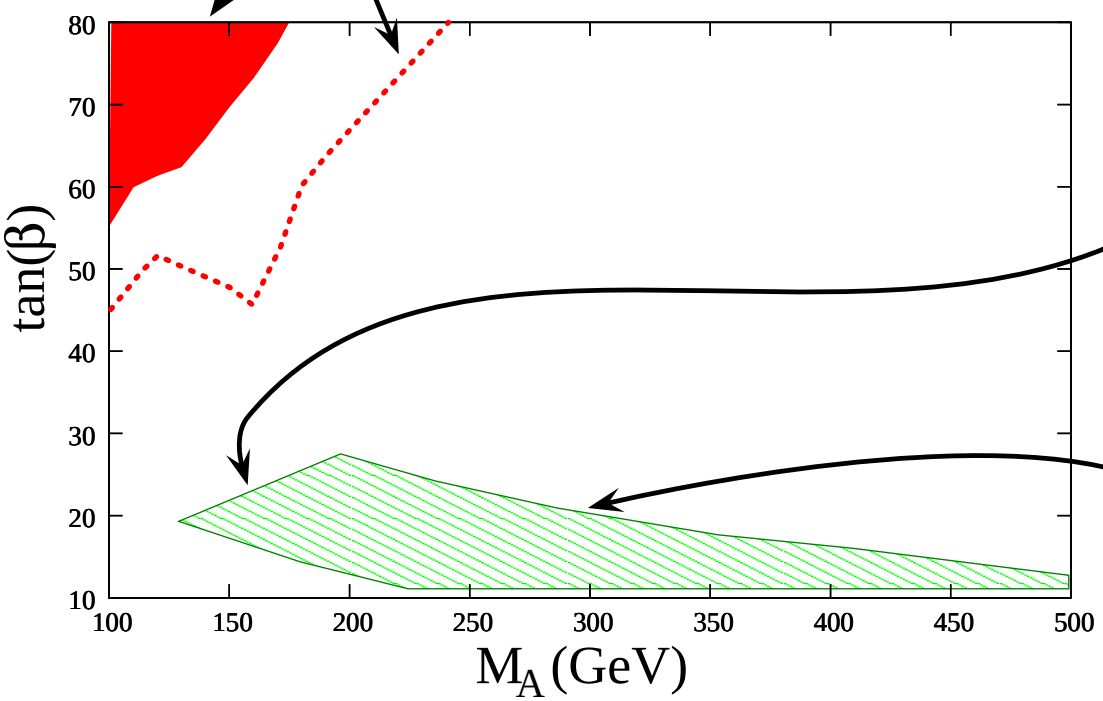
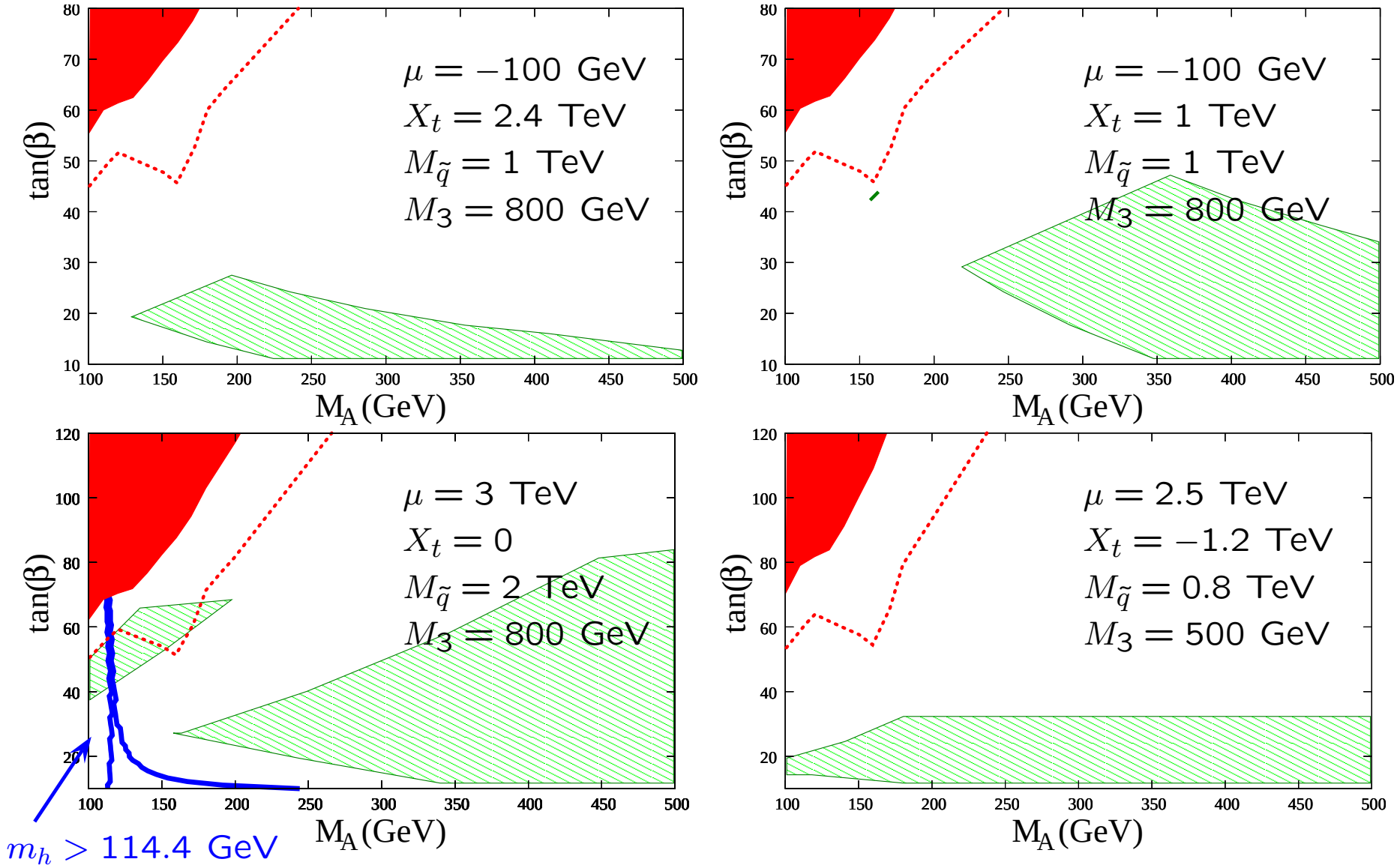


$\mathrm{BR}[b \to s\gamma] \sim 1 + A\tan\beta + B\tan\beta/M_A^2$

Flavor and Higgs physics

Carena, Menon, Wagner '07

Dependence on parameters: $(M_1 = 250 \text{ GeV}, M_2 = 500 \text{ GeV})$



Flavor and Higgs physics: General picture

- Robust constraints on region of **large** $\tan\beta$ and **small** M_A from A_0 searches, $B_s \to \mu\mu$ and $B_u \to \tau\nu$

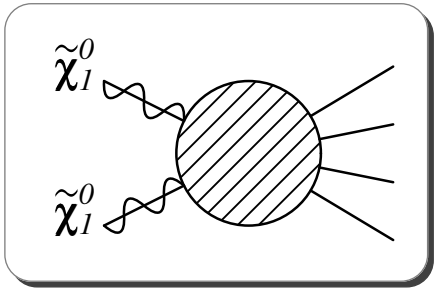
- **Large** $\tan\beta$ is also constrained for $M_A \gtrsim 250$ GeV, but depends on other parameters

Cosmology: dark matter

$\Omega_{\rm DM} h^2 = 0.110 \pm 0.006$ WMAP '08

If R-parity is conserved, the LSP is stable and a **dark matter** candidate

$\longrightarrow$ Must be neutral and weakly interacting



Relic density calculation depends on many model parameters

- Lightest neutralino $\tilde{\chi}_1^0$:

a) $\tilde{\chi}_1^0$ is mainly bino

a1) $m_{\tilde{\chi}_1^0} < 100$ GeV, $m_{\tilde{l}} \approx 100$ GeV ("bulk")

a2) $m_{\tilde{X}} - m_{\tilde{\chi}_1^0} \ll m_{\tilde{\chi}_1^0}$ (co-annihilation)

a3) $2m_{\tilde{\chi}_1^0} \approx M_Z, m_h, m_A$ (resonant annihilation)

b) $\tilde{\chi}_1^0$ is mixed bino/wino/higgsino

$m_{\tilde{\chi}_1^0} \sim \mathcal{O}$(few 100 GeV) is natural

Cosmology: dark matter

- Sneutrino $\tilde{\nu}$:

L-Sneutrinos $\tilde{\nu}_L$ cannot be dominant source of DM
$\longrightarrow$ too large direct detection cross section

Dominantly R-sneutrinos $\tilde{\nu}_R$ can give correct $\Omega_{\rm DM}$ in agreement with other constraints for 10 GeV $\lesssim m_{\tilde{\nu}_R} \lesssim$ 1 TeV Arina, Fornengo '07

- Gravitino $\tilde{G}$: Steffen '06

a) $\tilde{G}$ DM from NLSP decays

Constraints for NLSP $\tilde{\tau}$: $m_{\tilde{\tau}} \gtrsim 0.5$ TeV to avoid hot DM
1 GeV $\lesssim m_{\tilde{G}} \lesssim$ 700 GeV due to $\Omega_{\rm DM}$

b) Thermal $\tilde{G}$ production

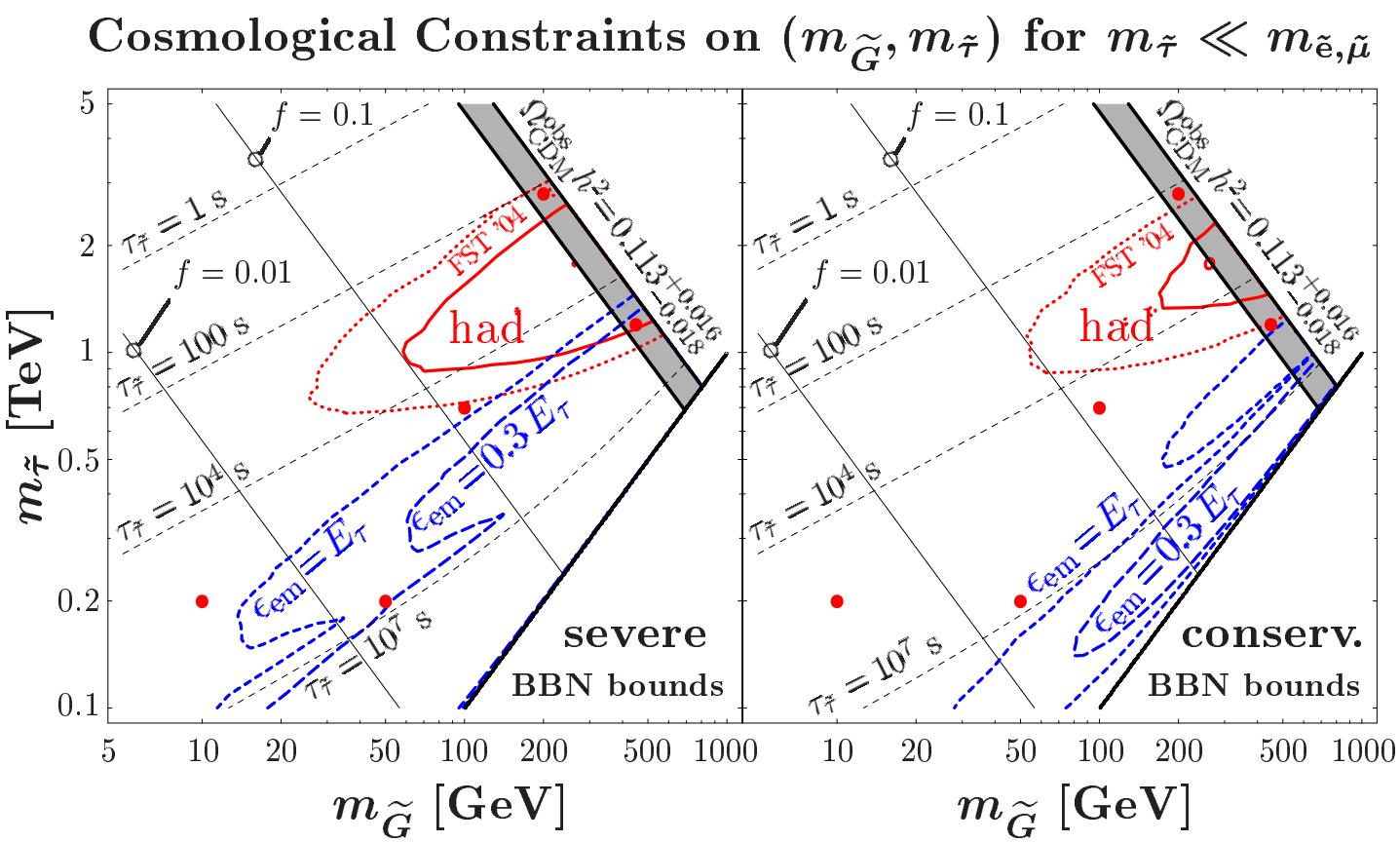
b1) Production from thermal equilibrium gives too large $\Omega_{\rm DM}$
$\longrightarrow T_{\rm R} \ll T_{\rm eq}$

b2) Non-equilibrium production viable for 1 keV $\lesssim m_{\tilde{G}} \lesssim$ 1 TeV, depending on $T_{\rm R}$

Cosmology: BBN

For gravitino LSP the energy released in NLSP decays can be problematic for Big-Bang **nucleosynthesis**

For $\tau_{\rm NLSP} \gtrsim 100$ s, hadro- and photon-dissociation can destroy light elements



$\rightarrow$ $m_{\tilde{G}} \lesssim$ 100–500 GeV

Steffen '06

Cosmology: Baryogenesis

- Leptogenesis: Particle-Antiparticle asymmetry generated by decay of long-lived heavy (s)neutrinos
$\longrightarrow$ No constraint on low-energy spectrum

- Electroweak baryogenesis:

a) Electroweak phase transition needs to be strongly **first order**

In MSSM: Correction to Higgs effective potential from stops
$\longrightarrow$ $m_{\tilde{t}_1} < 140$ GeV, $m_{\tilde{t}_2} > 3$ TeV Carena, Quirós, Wagner '97,98
Laine, Losada, Rummukainen '98,00
Cirigliano, Profumo, Ramsey-Musolf '06

In NMSSM: Contributions from (tree-level) Higgs-singlet coupling
Pietroni '93; Davies, Froggatt, Moorhouse '96

b) **CP-violationg currents** active during electroweak phase transition

In MSSM: Complex phase in neutralino/chargino sector
$\longrightarrow$ EDM constraints require $m_{\tilde{e}}, m_{\tilde{q}} \gtrsim 10$ TeV

In NMSSM: CP phase can also be in Higgs sector
(weaker constraints) Huber et al. '06

Cosmology: ultra-light neutralinos

Dreiner et al. '07

Bino-like $\tilde{\chi}_1^0$ is not constrained by collider data

Constraints from astrophysics/cosmology:

- $m_{\tilde{\chi}_1^0} > 3$ GeV to avoid DM overproduction (R-parity conservation)
- $m_{\tilde{\chi}_1^0} > 200$ MeV from supernova cooling ($m_{\tilde{e}} \lesssim 500$ GeV)
  $\longrightarrow$ No constraint for $m_{\tilde{e}} \gtrsim 1200$ GeV
- $m_{\tilde{\chi}_1^0} \gtrsim 1$ keV or $m_{\tilde{\chi}_1^0} \lesssim 1$ eV due to structure formation

Constraints on $\tilde{\chi}_1^0$ are very weak

More general SUSY breaking

Flavor violation

Sfermion mass parameters can introduce new sources of flavor violation (FV)

$\longrightarrow$ Strongly constrained by K^0, D^0 mixing, B decays, $\mu \to e\gamma$, $\mu \to e$ conversion, *etc.*

However, in 2nd and 3rd generation only, $\mathcal{O}(M_{\text{SUSY}})$ FV terms are still allowed Ciuchini et al. '07

CP violation

Strongly constrained for gauginos and 1st generation sfermions from electron and neutron electric dipole moments (EDMs)

Sizeable CP violation allowed in Higgs sector and 3rd generation sfermions

R-parity violation

$$W_{\not{R}_p\text{MSSM}} = W_{\text{MSSM}} + \frac{1}{2}\lambda_{ijk} L_i \cdot L_j E^c_k + \frac{1}{2}\lambda'_{ijk} L_i \cdot Q_j D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i \cdot D^c_j D^c_k$$

- Product of L- and B-number violating couplings is strongly constrained by proton decay:
  $|\lambda''_{ijk}\lambda_{ijk}|, |\lambda''_{ijk}\lambda'_{ijk}| \ll 1$
  $\longrightarrow$ Could be explained by discrete symmetries

- L-number violating couplings constrained by ν masses:
  $|\lambda_{ijk}|, |\lambda'_{ijk}| \lesssim 10^{-5} \ldots 0.6$ Allanach, Dedes, Dreiner '03

- Some experimental (s)particle mass bounds get relaxed:

  $m_{\tilde{g}} > 6.3$ GeV, $m_{\tilde{b}_1} > 7.5$ GeV, $m_{\tilde{\tau}_1} > 11$ GeV Janot '03,04
  $m_h > 82$ GeV Carpenter, Kaplan, Rhee '08

Summary: rough ideas

MSSM + R_p	MSSM + $\not{R}_p$	NMSSM & other ext.
$m_{\tilde{l}}$, $m_{\tilde{q}}$, $m_{\tilde{\chi}_1^\pm} \gtrsim 100$ GeV, $m_{H^\pm} \gtrsim 100$ GeV		
$m_{\tilde{g}} \gtrsim 150$ GeV	$m_{\tilde{g}} \gtrsim 6.3$ GeV	$m_{\tilde{g}} \gtrsim 150$ GeV
$m_{\tilde{\tau}_1} \gtrsim 82$ GeV	$m_{\tilde{\tau}_1} \gtrsim 11$ GeV	$m_{\tilde{\tau}_1} \gtrsim 82$ GeV
$m_{\tilde{\mu}}$, $m_{\tilde{\chi}_2^0} < 1$ TeV		
$m_{\tilde{\chi}_1^0} > 3$ GeV	—	?
$\tan\beta \gtrsim 3$	—	—
$\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \gtrsim 1$ TeV and/or large A_t	($\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \gtrsim 300$ GeV)	
$M_A/\tan\beta \gtrsim 3$ GeV		—