Light $\tilde{\tau}$, Dark Matter and EWkinos in the MSSM

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A. Pierce, N. R. Shah and K. Freese, **arXiv:1309.7351 [hep-ph]**

Outline

- Motivation:
  - 125 GeV (almost?) SM-like Higgs
  - As yet Null results for BSM at the LHC
  - Light EW states could be hiding
- MSSM Neutralino DM
  - *t*-channel exchange of light staus
  - Probe structure of staus and Neutralinos
- EWikinos
- Direct Detection
- Conclusions and Outlook

Motivation

Higgs Boson and …

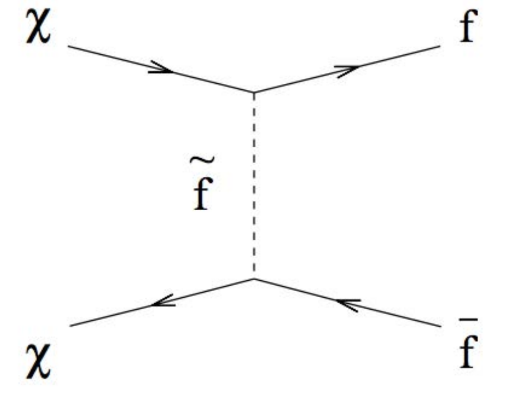
- Almost SM-like Higgs Boson
  - CMS: ~ SM h to $\gamma\gamma$ rate
  - ATLAS: Enhancement
    - Light STAUS ??
- So far NULL search results at LHC
- Light STAUS
  - Even if don't impact h to $\gamma\gamma$, hard to directly search for at the LHC
  - Before we give up on light states, TURN OVER EVERY STONE
    - DM Implications?

MSSM: Neutralino DM

Neutralino DM $\Omega h^2 \sim 0.1$

- $$\chi = \tilde{B}N_{11} + \tilde{W}N_{12} + \tilde{H}_d N_{13} + \tilde{H}_u N_{14}$$
- STAUS:
  - Not Co-annihilation region
  - *t*-channel exchange of stau: "BULK STAU"
  - LEP Limit for staus: ~ > 95 GeV
  - Light DM: ~ < 100 GeV
  - Recent pMSSM scans
- Qualitative understanding ?

Annihilation cross-section and $\chi\tilde{\tau}\tau$ Couplings



$$\langle \sigma v \rangle_x = a + 6\frac{b}{x} \,,$$

$$a = \frac{m_\chi^2}{8\pi}\left(\frac{g_{L_1}g_{R_1}}{(m_{\tilde{\tau}_1}^2 + m_\chi^2)} + \frac{g_{L_2}g_{R_2}}{(m_{\tilde{\tau}_2}^2 + m_\chi^2)}\right)^2 ,$$

$$b \approx \frac{m_\chi^2}{48\pi}\left[\frac{(g_{L_1}^4 + g_{R_1}^4)(m_{\tilde{\tau}_1}^4 + m_\chi^4)}{(m_{\tilde{\tau}_1}^2 + m_\chi^2)^4} + \frac{(g_{L_2}^4 + g_{R_2}^4)(m_{\tilde{\tau}_2}^4 + m_\chi^4)}{(m_{\tilde{\tau}_2}^2 + m_\chi^2)^4}\right] .$$

$$g_{\chi_1^0\tilde{\tau}_1\tau_L} \equiv g_{L_1} = \frac{\sqrt{2}}{v}\left(M_Z\cos\tau(N_{12}c_W + s_W N_{11}) - m_\tau\frac{\sin\tau}{\cos\beta}N_{13}\right)$$

$$g_{\chi_1^0\tilde{\tau}_1\tau_R} \equiv g_{R_1} = -\frac{\sqrt{2}}{v}\left(2M_Z\sin\tau s_W N_{11} + m_\tau\frac{\cos\tau}{\cos\beta}N_{13}\right) ,$$

Pure Bino + Stau Mixing

- Possible to realize $\Omega h^2 \sim 0.1$
- Could have implications for h to $\gamma\gamma$.
- Heavy stau could be less than ~ 500 GeV
- No Direct Detection constraints

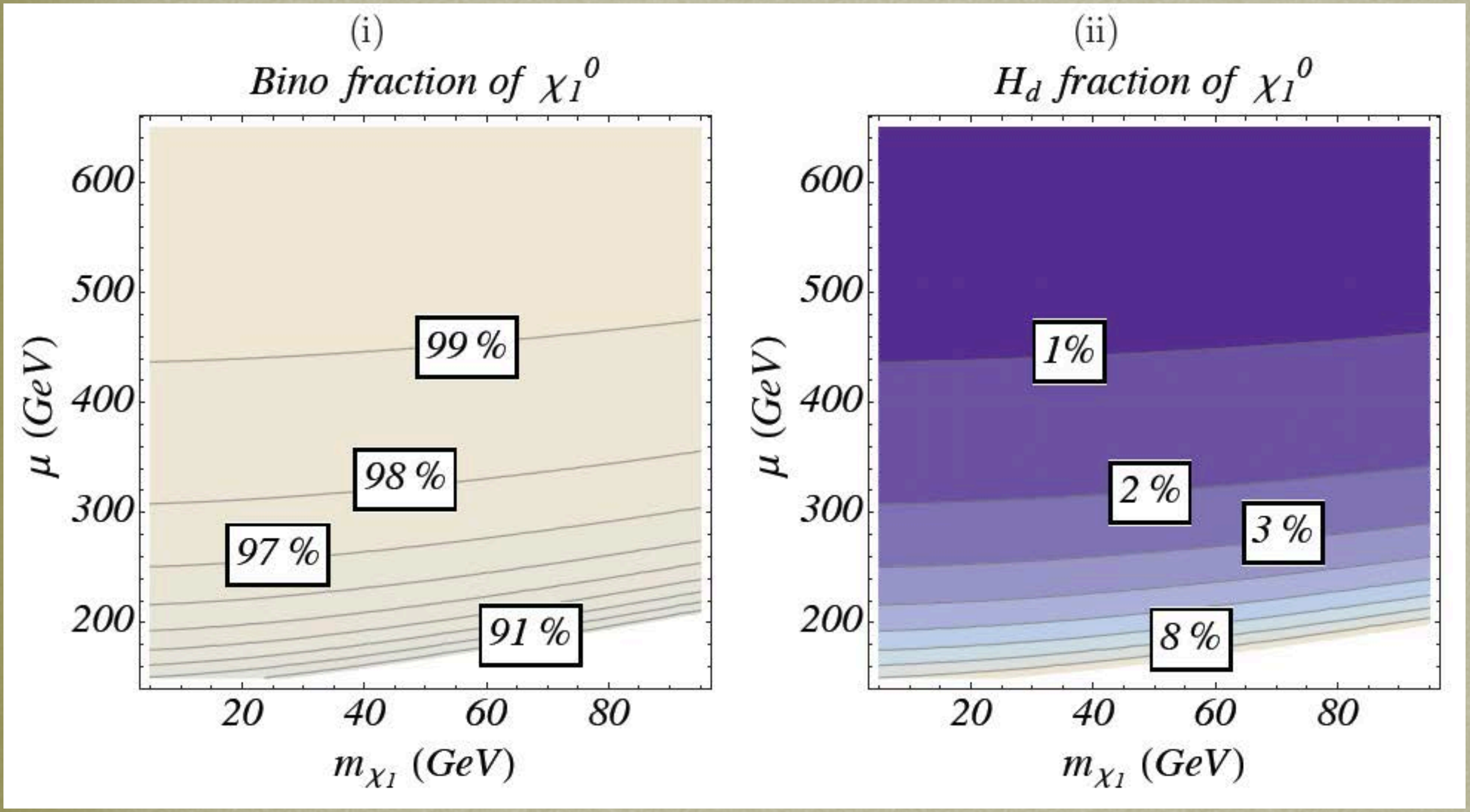
- Will not focus on this scenario

$$g_{L_1} \approx \frac{\sqrt{2}}{v} M_Z s_W \cos\tau,$$
$$g_{R_1} \approx -\frac{2\sqrt{2}}{v} M_Z s_W \sin\tau.$$

Higgsino Doping

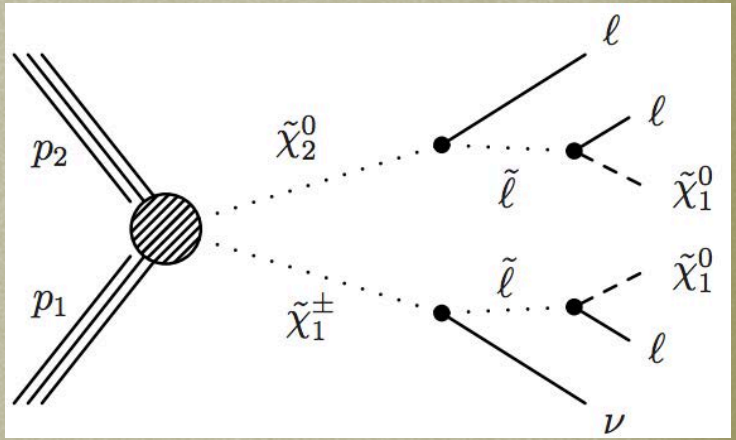
$$g_{L_1} \approx \frac{\sqrt{2}}{v} M_Z s_W \left(\frac{m_\tau \tan\beta}{\mu} \right)$$

$$g_{R_1} \approx -\frac{2\sqrt{2}}{v} M_Z s_W .$$



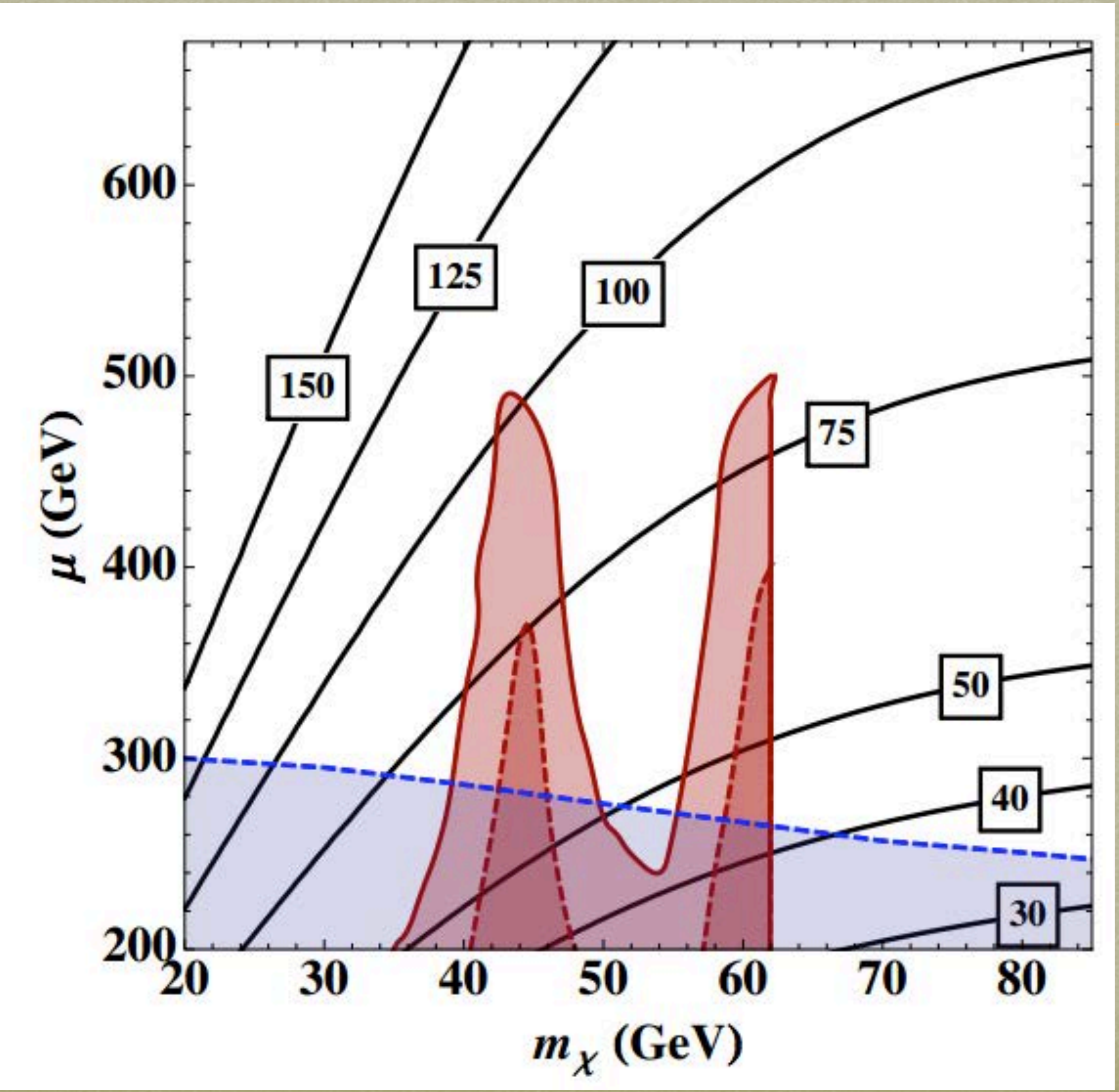
Constraints on μ

- Invisible Z decays:
  - $\mu > 150$ GeV
- ATLAS and CMS trilepton searches
  - Assume ~ degenerate wino-like chargino/neutralino2.
  - τ dominated scenario.
- Instead our scenario consists of ~ degenerate Higgsino-like chargino/ neutralino2 and 3.



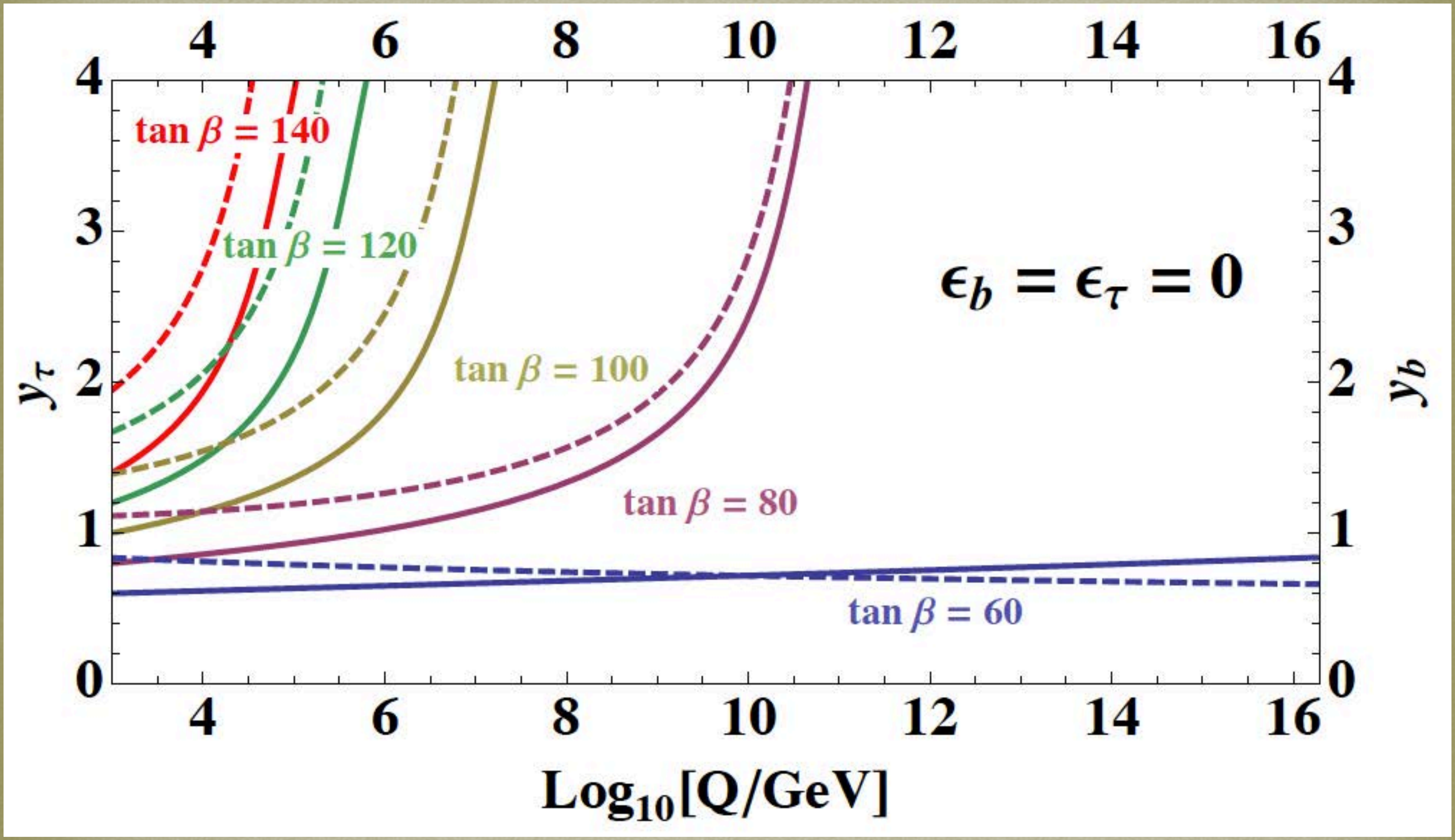
- We don't do a detailed recasting of the results
- We estimate:
  - Production cross-section for higgsino-like chargino/neutralino decreases by factor 4 compared to wino-like.
    - However we have both $\chi 2$ and $\chi 3$ almost degenerate.
    - BR into τ
  - For each $m_{\chi 0}$, find μ such that σ x BR into τ is at the CMS limit.
  - Our derived approximate bounds are in agreement with those presented by ATLAS for their pMSSM interpretation.

Tan β in the μ - m_χ plane for Ωh^2=0.12

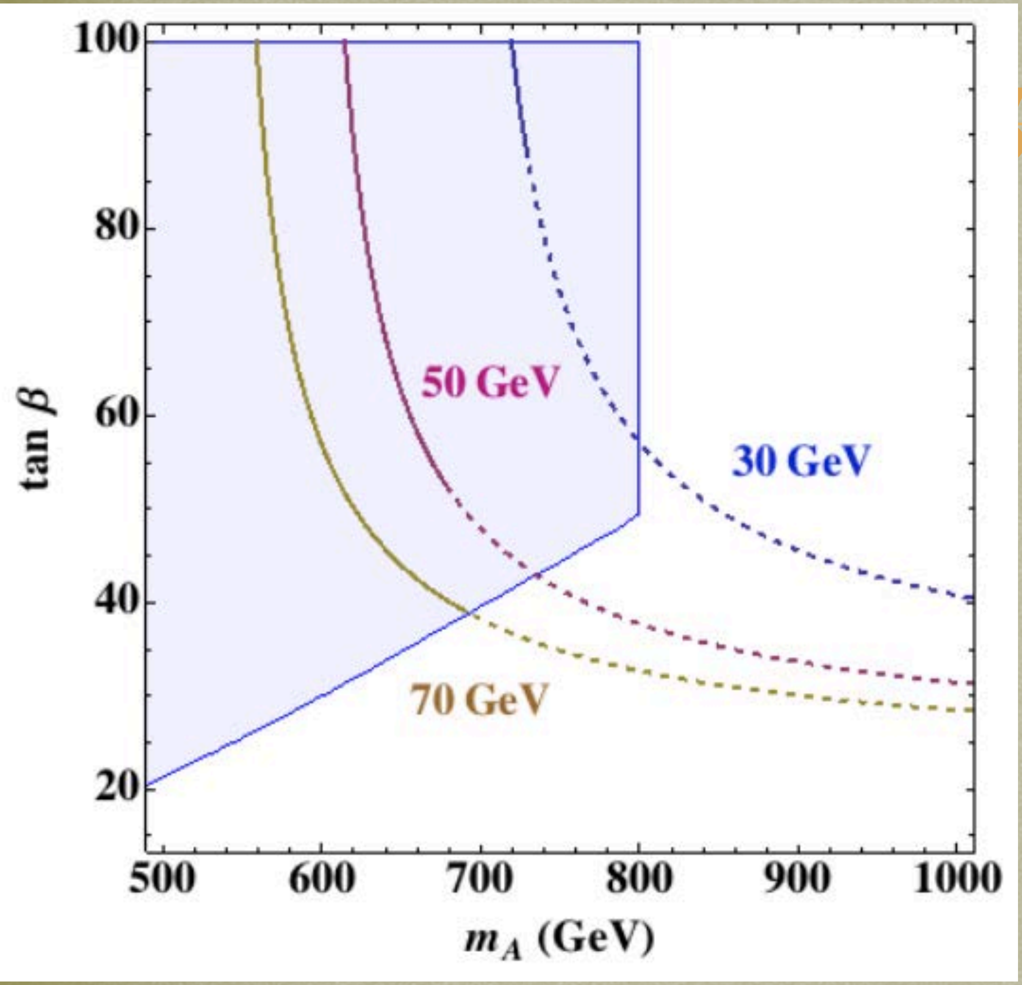


$m_{\tau 1}$ = 95 GeV

Bottom and tau Yukawas

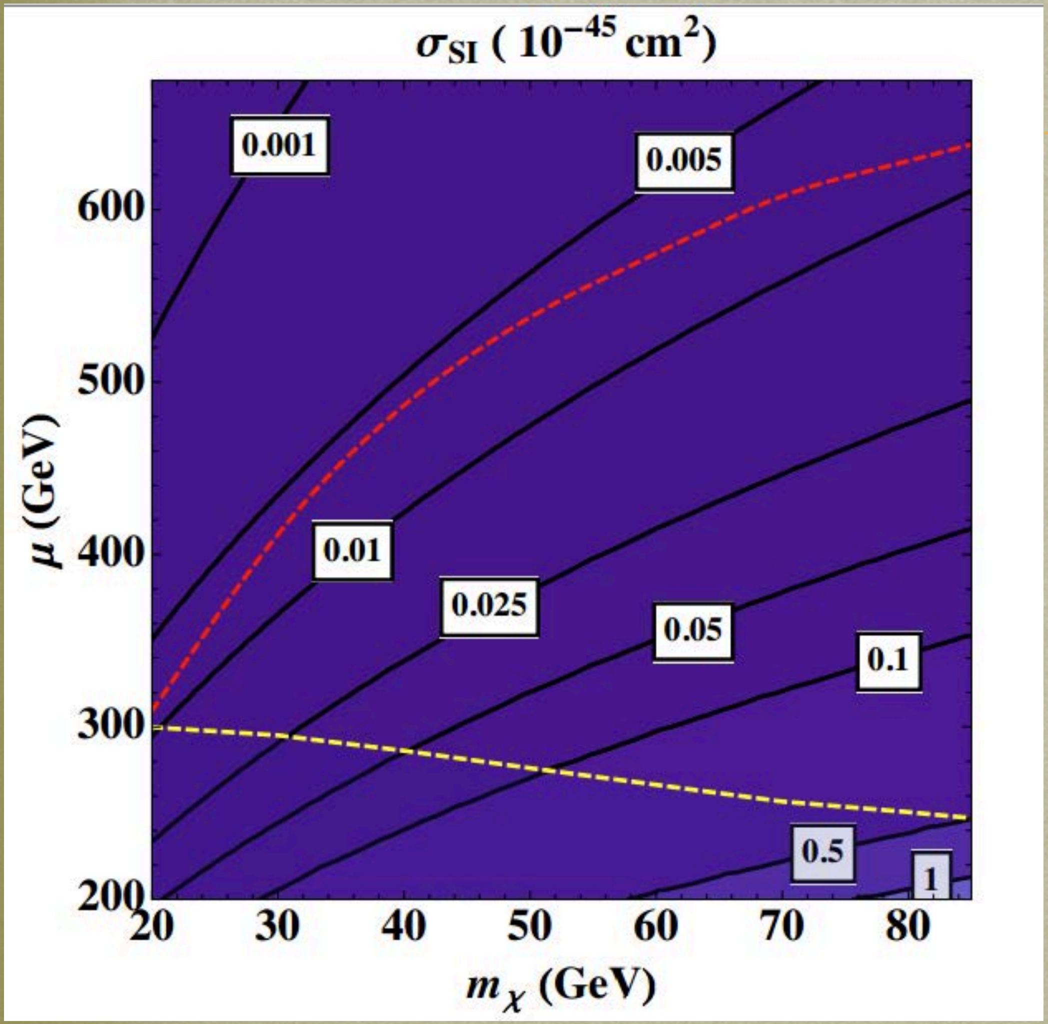


Direct Detection



- Dominated by Heavy Higgs exchange.
- Xenon100 bounds:
  - m_χ:
    - ($\tan\beta$, μ) such that Ωh^2=0.12
  - m_A:
    - Direct detection bounds evaded
- Left of contour excluded by Xe100
- Dashed lines signify values of μ disfavored by CMS/ATLAS
- Shaded region signifies exclusion by LHC direct searches.
- New LUX results a factor of a few stronger
  - m_A scaled by ~< 1.3

Projected Limits



- Projected Xe-1T Limits
- ~3 orders of magnitude stronger
- Sensitive to light Higgs only contribution to SI cross-section.
  - Everything below RED curve probed.
  - Above red curve, even few TeV scale super partners could give observable contributions.

Conclusions and Outlook

- Pure Bino LSP and heavily mixed Light Staus can realize consistent relic density.
  - May have a significant impact on *h* to γγ.
  - Heavy Stau expected to be ~< 500 GeV.

- Bino-Higgsino LSP and Purely right-handed Light Staus can also give rise to a consistent relic density
  - Significant Higgsino LSP component implies light/degenerate chargino/neutralinos (2,3).
  - Large tan β required
  - Direct Detection constraints from Xenon100 on the m_A- tan β already competitive with direct searches
  - Projected limits from Xe-1T will be sensitive to the light Higgs only contribution to SI cross section
  - Maybe sensitive to contributions from few TeV scale super partners.

Backup Slides

SI Cross section

$$\sigma_{SI} = \frac{4m_r^2}{\pi}\left[Zf_p + (A-Z)f_n\right]^2$$

$$f_{p,n} = \left(\sum_{q=u,d,s} f_{T_q}^{(p,n)}\frac{a_q}{m_q} + \frac{2}{27}f_{TG}^{(p,n)}\sum_{q=c,b,t}\frac{a_q}{m_q}\right)m_{(p,n)},$$

$$a_u = -\frac{g_2 m_u}{4m_W s_\beta}(g_2N_{12} - g_1N_{11})\left[N_{13}s_\alpha c_\alpha\left(\frac{1}{m_h^2} - \frac{1}{m_H^2}\right) + N_{14}\left(\frac{c_\alpha^2}{m_h^2} + \frac{s_\alpha^2}{m_H^2}\right)\right],$$

$$a_d = \frac{g_2\bar{m}_d}{4m_W c_\beta}(g_2N_{12} - g_1N_{11})\left\{N_{13}\left[\frac{s_\alpha^2(1-\epsilon_d/t_\alpha)}{m_h^2} + \frac{c_\alpha^2(1+\epsilon_d t_\alpha)}{m_H^2}\right]\right.$$
$$\left. + N_{14}s_\alpha c_\alpha\left[\frac{(1-\epsilon_d/t_\alpha)}{m_h^2} - \frac{(1+\epsilon_d t_\alpha)}{m_H^2}\right]\right\}.$$

$$\sigma_{SI}^h \approx \frac{g_2^2 m_r^2 m_{(p,n)}^2}{4\pi m_W^2 m_h^4}(g_1N_{11} - g_2N_{12})^2(c_\beta N_{13} - s_\beta N_{14})^2(1 - \frac{7}{9}f_{TG}^{(p,n)})^2.$$

Probing Light Staus:

Direct weak production of a **stau + tau sneutrino** through the s-channel exchange of a *W*.

- **Quite model independent:**
  - Depends only on masses and mixings of staus and sneutrinos.
  - Would be open even in scenario with very heavy squarks/gluinos.
- **Typical signature:**
  - Multi-taus,
  - Missing energy and
  - Weak gauge bosons, giving rise to additional leptons.

- **We used parton level results from** Madgraph 5.
- **A more realistic simulation should include:**
  - Parton showering,
  - Hadronization, and
  - Detector simulation.

- Properly matched matrix element + parton shower simulation particularly important for estimation of *W+jets* background.
- However, our analysis sufficient to obtain a rough order of magnitude estimate of the discovery reach.

Current LHC Search Status

- Final states containing taus, leptons, hard jets and large missing energy, arising from (relatively light) squarks/gluinos decaying directly or through cascades into the stau NLSP.
  - This channel complementary to the ones we investigate, but more model dependent.
- Final states similar to the ones we analyze have been investigated in the context of searches for charginos and neutralinos.
  - Comparing the cross sections of the LHC searches, we note that the multilepton searches are still not sensitive to our scenario.

Most stringent constraint on the stau mass given by LEP bound ~ 85-90 GeV for the case of the split stau-neutralino spectrum.

$m_{L3} = m_{e3}$ = 280 GeV, tan β = 60, μ = 650 GeV, M_1 = 35 GeV, giving a light stau, $m_{\tau 1} \sim$ 95 GeV, a very light LSP, $m_{\chi 1} \sim$ 35 GeV and a light sneutrino, $m_{\nu\tau} \sim$ 270 GeV for 8 TeV LHC.

$$pp \to \tilde{\tau}_1 \tilde{\nu}_\tau \to \tilde{\tau}_1 (W \tilde{\tau}_1) \to \tau \chi_1 W \tau \chi_1$$

- $\tilde{\tau}_1 \tilde{\tau}_1$ production overwhelmed by background.
- Better situation: $\tilde{\tau}_1 \tilde{\nu}_\tau$ with leptonically decaying *W*.
- 2 loose τ tags:
  - 60% τ identification
  - Jet Background rejection factor: 20-50

- Background: $pp \to W \tau \bar{\tau}$
  - *l* from *W* in signal more boosted:
    - Large missing E_T, => E_T > 70 GeV
    - p_T > 70 GeV
  - τ mostly from Z^*/γ^*,
    - exclude 80 GeV < $m_{\tau\tau}$ <120 GeV
    - low statistics => marginal improvement.
  - Fake τ from *Wjj*
    - Veto hard jets recoiling from *W*
    - p_T^j < 75 GeV

	Total (fb)	Basic (fb)	Hard Tau (fb)
Signal	1.6	0.26	0.11
Physical background, $W + Z/\gamma^*$	27	0.32	$\lesssim 10^{-3}$
$W+$ jets background	10^4	39	0.25

Cross sections for the signal and the physical and fake background after τ-tags at the 14 TeV LHC: after imposing $p_T^{\tau(j)} > 10$ GeV, $\Delta R > 0.4$ and and $|\eta| < 2.5$ (second column); with the additional requirement $p_T^\ell > 85$ GeV and $\not{E}_T > 85$ (third column); imposing that the τ is not too boosted $p_T^\tau < 80$ GeV (fourth column).

Similar cuts for 14 TeV LHC: Can get S/B ~ 1 with σ ~ 1 fb (low statistics)

p_T Distribution

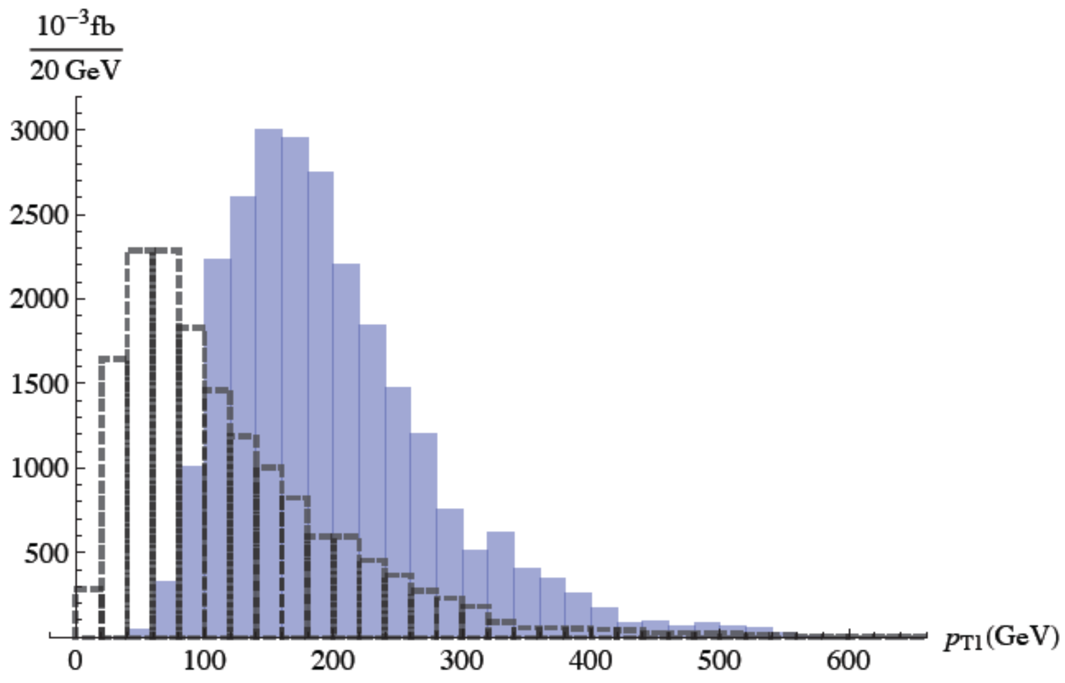


Figure 9: p_T distribution for the leading jet faking a tau of the $W+$ jets background (in blue) and for the leading tau of the signal (black dashed) at the 8 TeV LHC. The events shown satisfy the basic set of cuts ($p_T^\ell > 70$ GeV and $\not{E}_T > 70$ GeV). The signal has been scaled by a factor of 100 for visibility.

	Signature	8 TeV LHC (fb)	14 TeV LHC (fb)
$pp \to \tilde{\tau}_1\tilde{\tau}_1$	$2\tau, \not{E}_T$	55.3	124.6
$pp \to \tilde{\tau}_1\tilde{\tau}_2$	$2\tau, Z, \not{E}_T$	1.0	3.2
$pp \to \tilde{\tau}_2\tilde{\tau}_2$	$2\tau, 2Z, \not{E}_T$	0.15	0.6
$pp \to \tilde{\tau}_1\tilde{\nu}_\tau$	$2\tau, W, \not{E}_T$	14.3	38.8
$pp \to \tilde{\tau}_2\tilde{\nu}_\tau$	$2\tau, W, Z, \not{E}_T$	0.9	3.1
$pp \to \tilde{\nu}_\tau\tilde{\nu}_\tau$	$2\tau, 2W, \not{E}_T$	1.6	5.3

Table 1: Possible stau and sneutrino direct production channels with their signatures at the LHC. The cross sections shown are computed for $m_{L_3} = m_{e_3} = 280$ GeV, $\tan\beta = 60$, $\mu = 650$ GeV and $M_1 = 35$ GeV.

	Total (fb)	Basic (fb)	Hard Tau (fb)
Signal	0.6	0.16	0.07
Physical background, $W + Z/\gamma^*$	15	0.25	$\lesssim 10^{-3}$
$W+$ jets background	4×10^3	26	0.3

Table 2: Cross sections for the signal and the physical and fake backgrounds after τ-tags at the 8 TeV LHC: after imposing acceptance cuts $p_T^{\tau(j)} > 10$ GeV, $\Delta R > 0.4$ and and $|\eta| < 2.5$ (second column); with the additional requirement $p_T^\ell > 70$ GeV and $\not{E}_T > 70$ (third column); imposing that the τ is not too boosted $p_T^\tau < 75$ GeV (fourth column).

	Total (fb)	Basic (fb)	Hard Tau (fb)
Signal	1.6	0.26	0.11
Physical background, $W + Z/\gamma^*$	27	0.32	$\lesssim 10^{-3}$
$W+$ jets background	10^4	39	0.25

Table 3: Cross sections for the signal and the physical and fake background after τ-tags at the 14 TeV LHC: after imposing $p_T^{\tau(j)} > 10$ GeV, $\Delta R > 0.4$ and and $|\eta| < 2.5$ (second column); with the additional requirement $p_T^\ell > 85$ GeV and $\not{E}_T > 85$ (third column); imposing that the τ is not too boosted $p_T^\tau < 80$ GeV (fourth column).

Loop induced gluon and gamma widths

$$\Gamma_{H\to gg} = \frac{G_\mu \alpha_s^2 m_H^3}{36\sqrt{2}\pi^3} \left| \frac{3}{4} \sum_f A_f(\tau_f) \right|^2$$

$$\Gamma_{H\to\gamma\gamma} = \frac{G_\mu \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 A_f(\tau_f) + A_W(\tau_W) \right|^2$$

$$A_f(\tau) = 2\left[\tau + (\tau - 1) f(\tau)\right] \tau^{-2}$$

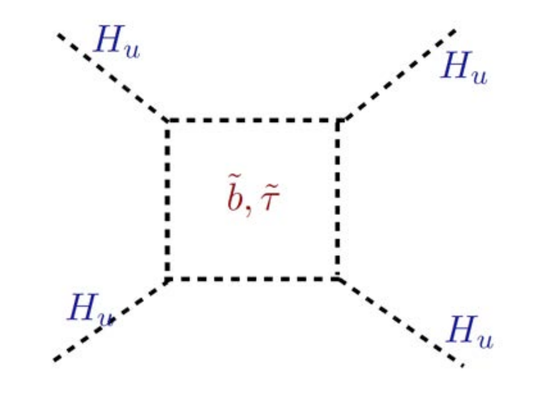
$$A_W(\tau) = -\left[2\tau^2 + 3\tau + 3(2\tau - 1) f(\tau)\right] \tau^{-2}$$

$$f(\tau) = \begin{cases} \arcsin^2\sqrt{\tau} & \tau \le 1 \\ -\frac{1}{4}\left[\ln \frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right]^2 & \tau > 1 \end{cases}$$

Additional Affects at Large tan β

- Sbottoms: $\Delta m_h^2 \simeq -\frac{h_b^4 v^2}{16\pi^2}\frac{\mu^4}{M_{\rm SUSY}^4}\left(1+\frac{t}{16\pi^2}(9h_b^2 - 5\frac{m_t^2}{v^2} - 64\pi\alpha_3)\right)$
  - h_b recieves 1-loop corrections that depend on sign of $\mu M_{\tilde{g}}$

$$h_b \simeq \frac{m_b}{v\cos\beta(1+\tan\beta\Delta h_b)}$$



- Staus: $\Delta m_h^2 \simeq -\frac{h_\tau^4 v^2}{48\pi^2}\frac{\mu^4}{M_{\tilde{\tau}}^4}$
  - h_τ corrections depend on the sign of μM_2

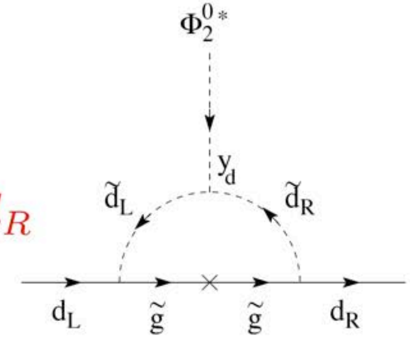
$$h_\tau \simeq \frac{m_\tau}{v\cos\beta(1+\tan\beta\Delta h_\tau)}$$

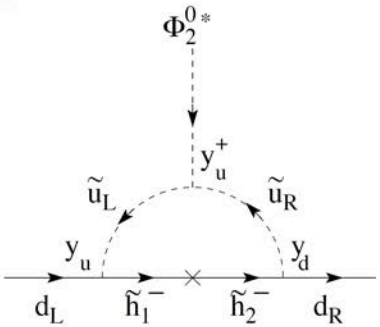
- Both corrections give negative contributions to the Higgs mass
  - Positive values of $\mu M_{\tilde{g}}$ and μM_2 enhance the value of the Higgs mass.

Radiative Corrections to Flavor Conserving Higgs Couplings

- Couplings of down and up quark fermions to both Higgs fields arise after radiative corrections.

$$\mathcal{L} = \bar{d}_L(h_d H_1^0 + \Delta h_d H_2^0) d_R$$





- The radiatively induced coupling depends on ratios of supersymmetry breaking parameters

$$m_b = h_b v_1 \left(1 + \frac{\Delta h_b}{h_b} \tan\beta\right)$$

$$\boxed{\tan\beta = \frac{v_2}{v_1}}$$

$$\frac{\Delta_b}{\tan\beta} = \frac{\Delta h_b}{h_b} \simeq \frac{2\alpha_s}{3\pi} \frac{\mu M_{\tilde{g}}}{\max(m_{\tilde{b}_i}^2, M_{\tilde{g}}^2)} + \frac{h_t^2}{16\pi^2} \frac{\mu A_t}{\max(m_{\tilde{t}_i}^2, \mu^2)}$$

$$X_t = A_t - \mu/\tan\beta \simeq A_t \qquad \Delta_b = (E_g + E_t h_t^2) \tan\beta$$

Resummation : Carena, Garcia, Nierste, C.W.'00