Light singlino in the Next-to-Minimal Supersymmetric SM: Challenges for Susy Searches at the LHC

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Outline:

— The Next-to-Minimal Supersymmetric SM

— "Missing" missing transverse energy

— New signatures for searches for supersymmetry

The Next-to-Minimal Supersymmetric SM

Generally, supersymmetric extensions of the Standard Model require an extended Higgs sector, at least two Higgs doublets

MSSM: Just two doublets, but:

– The quartic Higgs self couplings, which determine the mass of the SM-like Higgs boson H_{SM} given its known VEV, are given by electroweak gauge couplings + radiative corrections $\longrightarrow M_{H_{SM}} \leq M_Z$ + rad. corrs.

$\longrightarrow$ In order to explain the mass of $\sim$ 126 GeV of the SM-like Higgs boson, the radiative corrections (and hence the top-squark masses) must be large, $\gtrsim$ 1.5 TeV for at least one of them, which is unnatural

– Since charged higgsinos Ψ_{H_u}, Ψ_{H_d} have not been observed at LEP (must have masses $\gtrsim 100$ GeV), a supersymmetric mass term "μ" for the Higgs superfields is necessary;
generates $\mu \Psi_{H_u} \Psi_{H_d}$ as desired, but also $|\mu^2|(H_u^2 + H_d^2)$ in the scalar Higgs potential; should NOT be much larger than the weak scale

$\longrightarrow$ How can a supersymmetric mass term accidentally be of the order of the weak scale ($\sim$ the scale of Susy breaking mass terms)? "μ-problem"

NMSSM: An additional gauge singlet superfield S
— with Yukawa coupling $\lambda S \Psi_{H_u} \Psi_{H_d}$ and a VEV v_s generated by Susy breaking terms;
$\longrightarrow$ an effective μ-term $\lambda v_s \Psi_{H_u} \Psi_{H_d}$ which has automatically the required order of magnitude;
$\longrightarrow$ generates automatically an additional quartic Higgs doublet self coupling proportional to λ^2
$\longrightarrow$ additional contributions to the mass of the SM-like Higgs boson!

$\longrightarrow$ The NMSSM is more "natural", less fine-tuning of its parameters is required

Extended Higgs sector:

3 CP-even, 2 CP-odd neutral and 1 charged Higgs states $H_{1,2,3}$, $A_{1,2}$, $H^{\pm}$

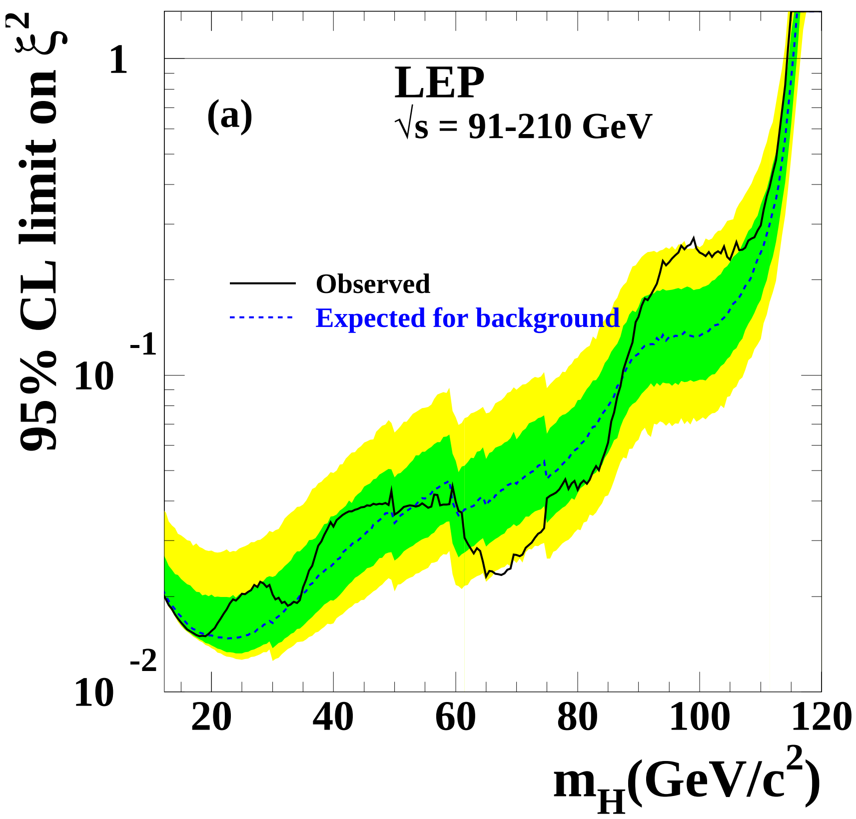
The observed Higgs boson $H_{126\text{ GeV}}$ can be H_1 or H_2

If $H_{126\text{ GeV}} = H_2$: H_1 is mostly singlet-like
(but not completely due to mixing)

Extended neutralino sector:

Bino (partner of the $U(1)_Y$ gauge boson B), wino, 2 higgsinos, singlino
$\longrightarrow$ 5 neutralinos

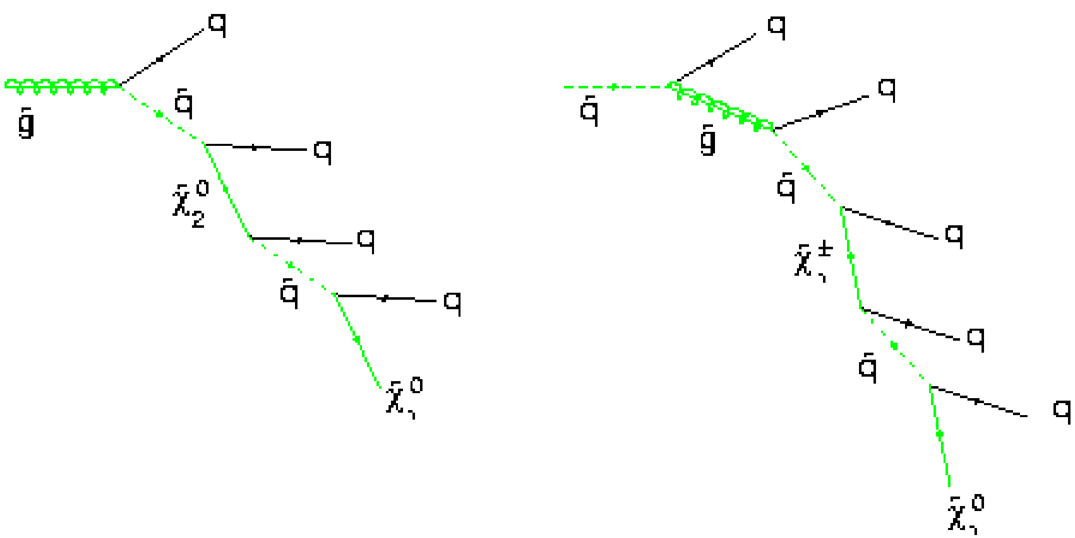
Note: A mostly singlet-like Higgs boson can be light!
Allowed by LEP provided its coupling ξ^2 to the Z boson (relative to the SM) is small enough:
Constraints from LEP in the $M_H - \xi^2$ plane (only the region below the black line is allowed):



The role of neutralinos in Searches for Susy

— The lightest among them is typically the "lightest Susy particle" (LSP), stable since odd under R-parity!
— A welcome candidate for DM (its annihilation cross section in the early universe should give the correct relic density, its direct detection cross section should comply with present bounds from LUX etc.)

— All Susy particle decay cascades will end up in the LSP which is invisible (like neutrinos)
→ Susy particle (pair-) production leads to missing transverse momentum/energy!



— In the MSSM, the LSP is typically mostly bino-like (can be mixed with higgsinos/neutral wino)

— In the NMSSM, the LSP can be dominantly singlino-like and light (a few GeV), typically with small DM direct detection cross section; annihilation in the early universe through additional Higgs bosons in the s-channel

Early days of Susy (1980's): $M_{squark}, M_{gluino} \lesssim$ 100 GeV?

Tevatron: $M_{squark}, M_{gluino} \gtrsim$ 300...600 GeV

Searches for Susy at the LHC

Dominant production cross sections:
coloured partners of quarks, "squarks", and gluon, "gluino"

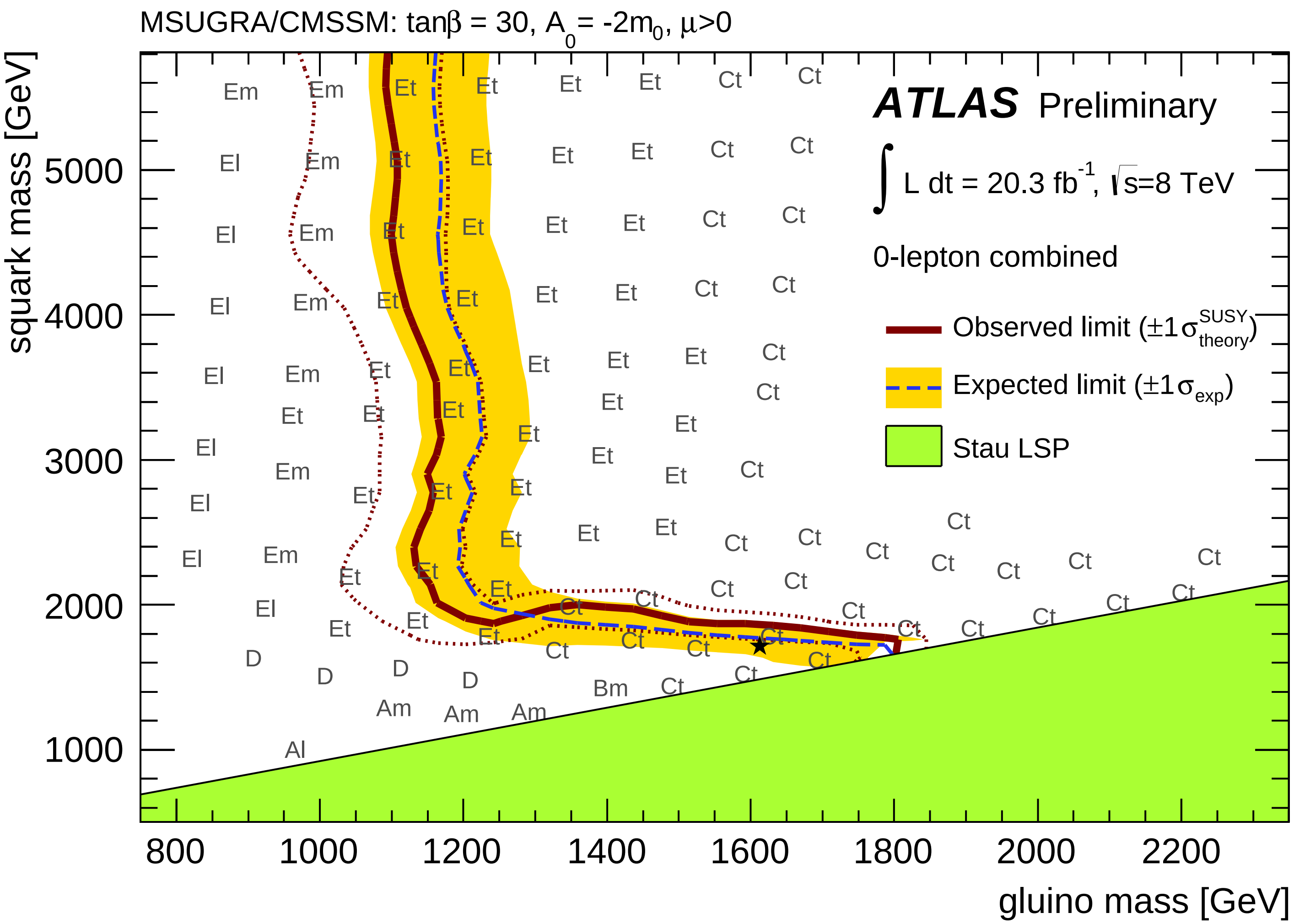
Decay into quarks, gluons, ... + LSP

$\longrightarrow$ Signatures: many jets with large P_T,
missing transverse momentum/energy E_T^{miss}, typically $\gtrsim$ 160 GeV
(transverse to the beam axis)

After $\sim 20\ fb^{-1}$ at 8 TeV at the LHC: no excesses of events

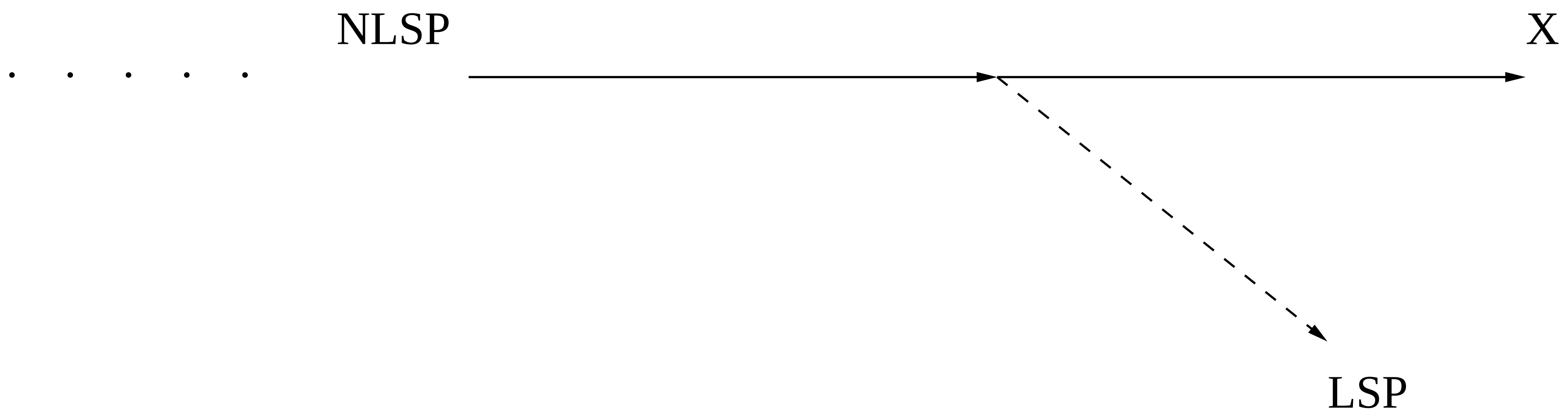
$\longrightarrow$ lower bounds on u/d-squark masses $\sim$ 2 TeV, on gluino masses $\sim$ 1.1 TeV (cascades and bounds are model dependent!)

E.g. within the MSSM with universal soft Susy breaking terms at the GUT scale:



“Missing” missing transverse energy

Consider a (possible) last step in a Susy particle decay cascade from a next-to-lightest Susy particle (NLSP) into the LSP + X,



where ”X” decays into SM particles (X = Higgs boson, Z,...)

If the available phase space is narrow, $M_{NLSP}-(M_{LSP}+M_X) \ll M_{NLSP}$, the energy (momentum) E_{LSP} transferred from the NLSP to the LSP is proportional to the ratio of masses:

$$\frac{E_{LSP}}{E_{NLSP}} \simeq \frac{M_{LSP}}{M_{NLSP}}$$

$\longrightarrow$ If the LSP is light and $M_X \sim M_{NLSP}-M_{LSP}$, little (missing transverse) energy is transferred to the LSP; the transverse energy is carried away by X

$\longrightarrow$ If X decays do not give rise to E_T^{miss}, the E_T^{miss} signature disappears!

Possible in the MSSM? A light ($\sim$ few GeV) LSP has to be bino-like (higgsinos/winos have charged SU(2) partners)
$\longrightarrow$ Squarks (with hypercharge!) etc. would prefer to decay directly into the LSP, without the NLSP in the decay cascade
$\longrightarrow$ The effect would be rare

In the NMSSM, a light singlino-like LSP Ψ_S is natural:

Its mass originates from a Yukawa coupling $2\kappa S \Psi_S \Psi_S$

$\longrightarrow$ $M_{singlino} \sim 2\kappa v_s \sim$ a few GeV if κ is small, $\kappa \sim 10^{-5}...10^{-4}$

A light singlino has very small couplings to squarks, gluinos and all other Susy particles

$\longrightarrow$ all decay cascades end "provisionally" in the NLSP, typically the bino; only subsequently the NLSP decays into the singlino-like LSP + X
(But typically not with measurable decay lengths)

Possible states X:

Z, W: Have leptonic decays (incl. neutrinos), lead to some E_T^{miss}

H_{SM}: Has leptonic decays $H_{SM} \to WW/ZZ \to$ ... which lead to some E_T^{miss}

Worst case with little E_T^{miss}:

— $X = H_1$, a NMSSM specific light Higgs boson with $M_{H_1} < M_Z$
(Just occasionnaly: $H_1 \to \tau^+\tau^- \to$ ... + neutrinos)

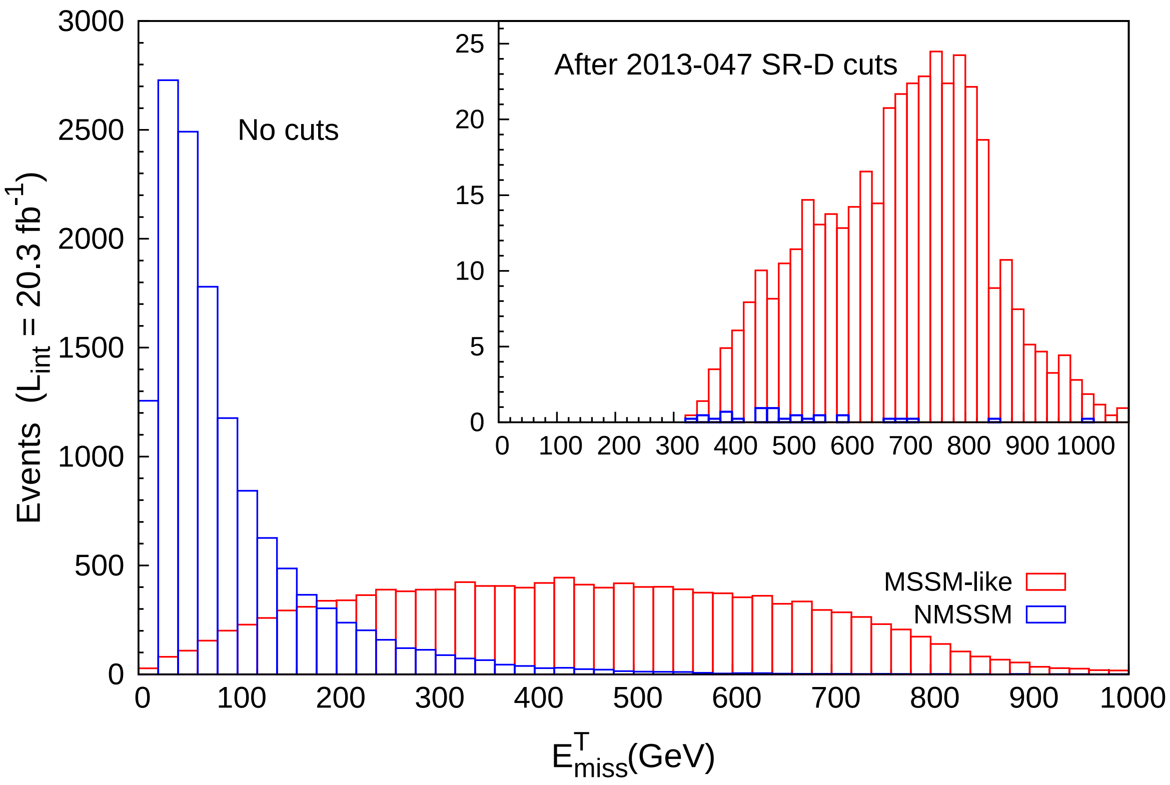
— no Zs/Ws (decaying possibly into neutrinos) in squark decay cascades;
if wino/higgsino masses $\gtrsim$ squark masses:

$$\tilde{q} \to q + bino \to q + singlino + H_1,$$
$$\tilde{g} \to q + \tilde{q} \to ...$$

Benchmark point: $M_{NLSP} \sim M_{bino} \sim 89$ GeV, $M_{H_1} \sim 83$ GeV,
$M_{LSP} \sim M_{singlino} \sim 5$ GeV

Simulation with MadGraph5+1j, Pythia, Delphes;
LHC constraints from CheckMATE-1.1.2, M. Drees et al., 1206.5001;
(dominant constraints from ATLAS-CONF-2013-047, channel D)

Spectrum of E_T^{miss} from squark/gluino production at 8 TeV:



— in the MSSM with a 89 GeV bino as LSP, would be ruled out!

— in the NMSSM with the additional bino $\to H_1+$ singlino cascade

Inlet: after Cuts on P_T of 5 jets, $E_T^{miss}/m_{eff} > 0.2$ where $m_{eff} \sim \sum |p_T|_{jets}$

$\longrightarrow$ few events survive the cuts!

$\longrightarrow$ Dramatic reduction of the number of events with large E_T^{miss}

Where does the remaining E_T^{miss} come from in the NMSSM?
H_1 has branching fractions similar to H_{SM} of the same mass:
$\sim$ 8% into $\tau^+\tau^-$ leading to neutrinos in the final state;
$\sim$ 85% into $b\bar{b}$ with partially leptonic decays

Still: The benchmark point with $M_{squarks} \sim 830$ GeV, $M_{gluino} \sim 860$ GeV, $M_{stops,sbottoms} \sim 810 - 1060$, $M_{charginos} \sim 830 - 950$ GeV passes all LHC constraints

The only LHC allowed scenario with all sparticle masses below ~ 1 TeV!

(Lower limits within "Squeezed" spectra with $M_{LSP} \sim M_{squark}, M_{gluino}$ assume $M_{gluino} \gg M_{squark}$ or $M_{squark} \gg M_{gluino}$, respectively)

Existing potentially sensitive search channels?

CMS-PAS-SUS-13-019: gluino pair production,
NLSP $\to$ LSP + SM Higgs boson ($M_{NLSP} = M_{LSP} + 200$ GeV):
"M_{T2}" analysis (invariant masses in two hemispheres, corrected for E_T^{miss}),
≥ 2 b-jets, simplified model, some E_T^{miss} required $\longrightarrow$ $M_{gluino} \gtrsim 900$ GeV

Remarks on dark matter:

Good relic density of the singlino-like LSP possible through a light A_1 with $M_{A_1} \sim 2M_{LSP}$ allowing for LSP+LSP $\to A_1 \to$ ...
(requires some tuning due to the small coupling $\sim \kappa$)
Or: gauge mediated Susy breaking: the singlino-like LSP deacys into a lighter gravitino (outside the detector)

Which NMSSM?

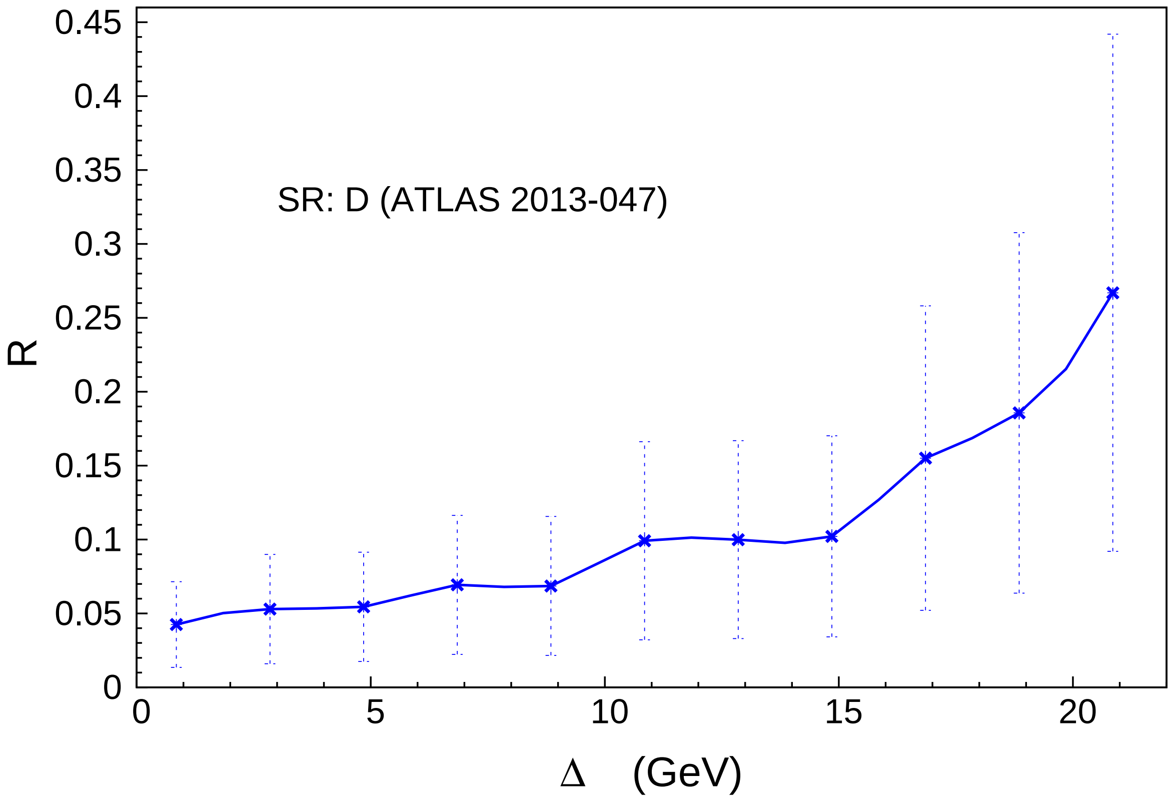
Actually: $M_{H_1} \gg M_{singlino}$ does require Z_3 violating terms in the NMSSM Lagrangian like a soft Susy breaking tadpole term $\xi_S S$ which appears naturally within GMSB and a coupling of the singlet to the messengers, see U.E. et al., 0803.2962

Do the NLSP-, LSP- and H_1 masses have to be tuned for a suppression of the "standard" signal based on E_T^{miss}?

$R =$ ratio of the number of events passing the cuts (NMSSM/MSSM) from the most constraining channel D (5 jets) in ATLAS-CONF-2013-047, as function of the available phase space

$$\Delta = M_{NLSP} - (M_{H_1} + M_{LSP})$$

$$R(\Delta) = \frac{\text{bino} \rightarrow \text{singlino} + H_1}{\text{bino LSP (MSSM)}}$$



→ The reduction of acceptance is below $\sim 10\%$ as long as $\Delta \lesssim 15$ GeV (Benchmark point: $\Delta \simeq 6$ GeV)

If E_T^{miss} is no longer the dominant signature for sparticle production, what are the properties of the final states from squark/gluino production?

Jets + two H_1 states (like in SM Higgs pair production), but

— Larger cross section:
$\gtrsim$ 6000 fb at 14 TeV for the previous benchmark point;
decreases towards the SM Higgs pair production cross section $\sim$ 28 fb for $M_{squark} \sim M_{gluino} \sim$ 2 TeV

— M_{H_1} not known, e.g. $M_{H_1} \sim 50 - 90$ GeV

— Events accompagnied by hard jets

Possible search strategy at the LHC at 13/14 TeV (preliminary):

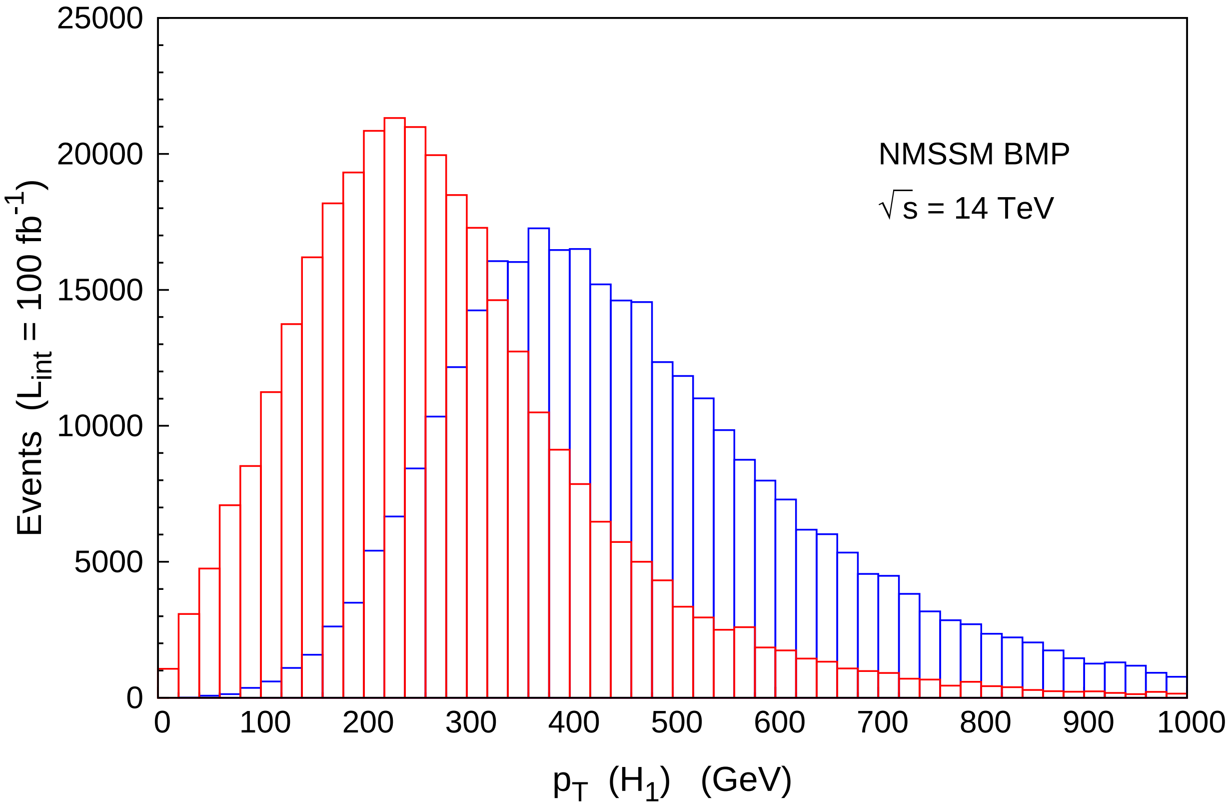
Simulations of squark/gluino production (+ 1 jet) of the previous benchmark point with MadGraph $\to$ Pythia6 $\to$ detector simulation DELPHES

— Require hard jets, e.g. with $P_T \geq 400,\ 200,\ 80,\ 80$ GeV

— Instead of E_T^{miss}, have to look for remnants of two H_1 Higgs bosons: These decay, similar to H_{SM}, dominantly ($\sim$ 85%) into $b\bar{b}$ and ($\sim$ 8%) into $\tau^+\tau^-$
(less into ZZ^*, WW^* since too light; $BR(H_1 \to \gamma\gamma) \sim 10^{-4}$ only)

— b-jets are also produced by QCD; compromise: ask for two b-jets and two τs ($M_{2\tau} < 120$ GeV); try to reconstruct the H_1 mass from two b-jets

Both H_1 Higgs bosons are typically boosted, large P_T:
(Before H_1 decay)



blue: Leading H_1
red: Second H_1

Analyse the final state twice:

First:

— look for two "slim" b-jets using anti-k_T jet-finding algorithm with small cone size $R = \Delta\varphi \times \Delta\eta = 0.1 - 0.15$
(ATLAS hadronic calorimeter cells $\Delta\varphi \times \Delta\eta = 0.1$)
Assumed b-tag efficiency: 70%
Define a $2b$ pseudo-jet $2bPJ$ as the sum

— Low cut on $|E_T^{miss}| > 30$ GeV (which may be due to τ decays), but require $\Delta\varphi(E_T^{miss}, 2bPJ) > 0.3$ to suppress E_T^{miss} from leptonic b-decays which reduce the visible bb invariant mass

Second:

— Apply the anti-k_T jet-finding algorithm again, with $R = 0.5$

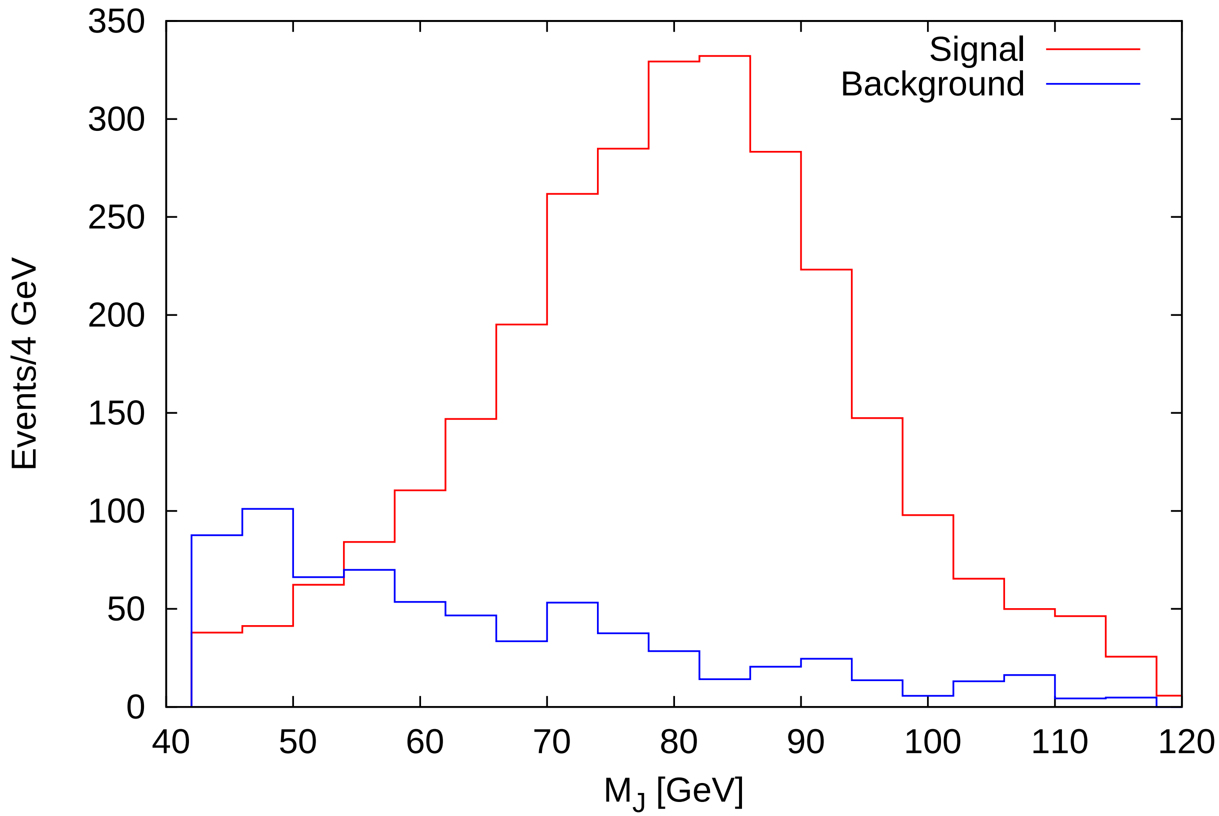
$\longrightarrow$ The two b-jets will merge into a single fatter jet $\hat{J}$;
look for the jet $\hat{J}$ closest in φ, η to the previously found $2bPJ$:
Require its direction very close to the one of $2bPJ$: $\Delta R(\hat{J}, 2bPJ) < 0.1$
($\hat{J}$ will usually be b-tagged, but no longer required)

— Require $P_T(\hat{J}) > 400$ GeV (cf. the previous plot)

— Require the $\hat{J}$ mass above the inv. mass of $2bPJ$; require its inv. mass in the 40-120 GeV window

(Refined constraints allow to suppress $b\bar{b}$ from QCD or $t\bar{t}$ which are typically NOT in a colour singlet state, and hadronise differently: QCD or $t\bar{t}$ b-quarks are connected by "colour strings" to partons outside the $b\bar{b}$ system, which subsequently contribute to $\hat{J}$ changing its direction and inv. mass.)

Invariant mass of $\hat{J}$ (event numbers after $100 fb^{-1}$ at 14 TeV):

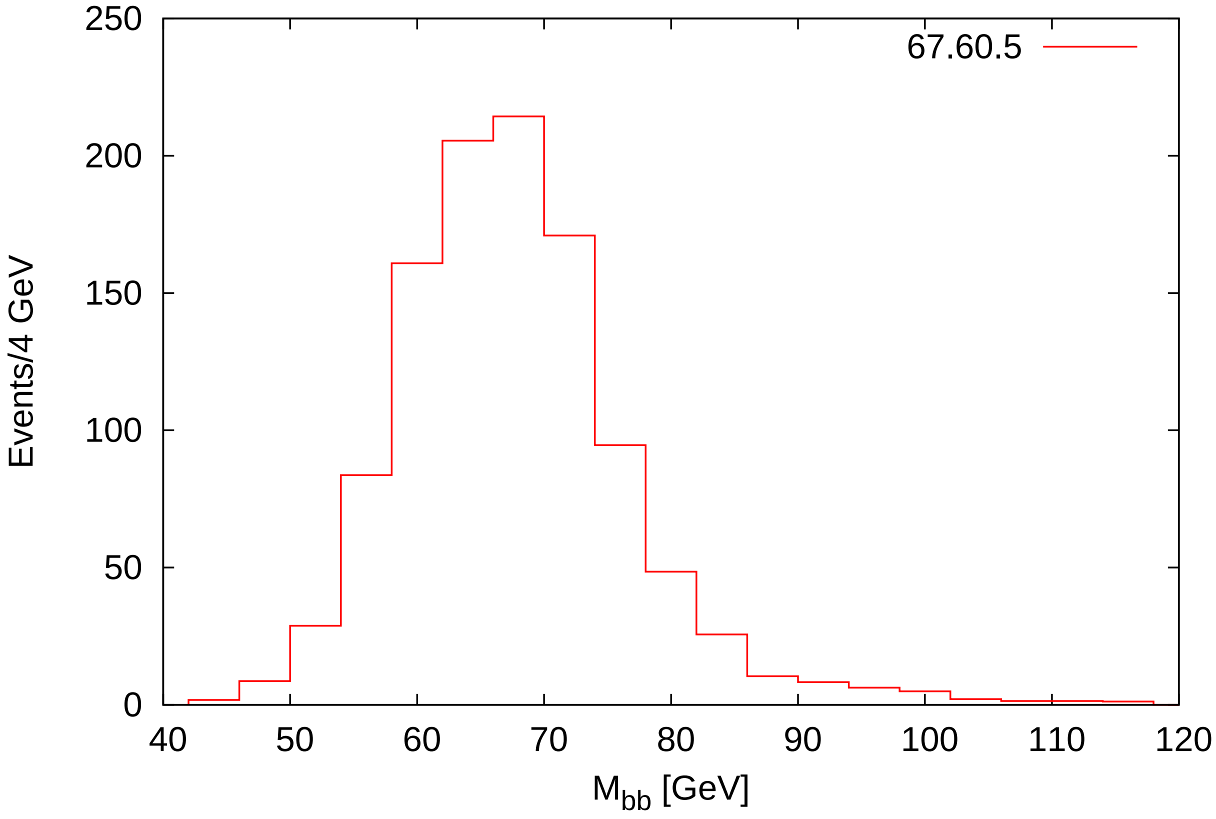


$\rightarrow$ The signal is there! Recall: $M_{H1} = 83$ GeV

(Dominant background from QCD: 2 jets + $b\bar{b}$ + 2 fake τ's)

And if M_{H1} is not 83 GeV, but 60 GeV?

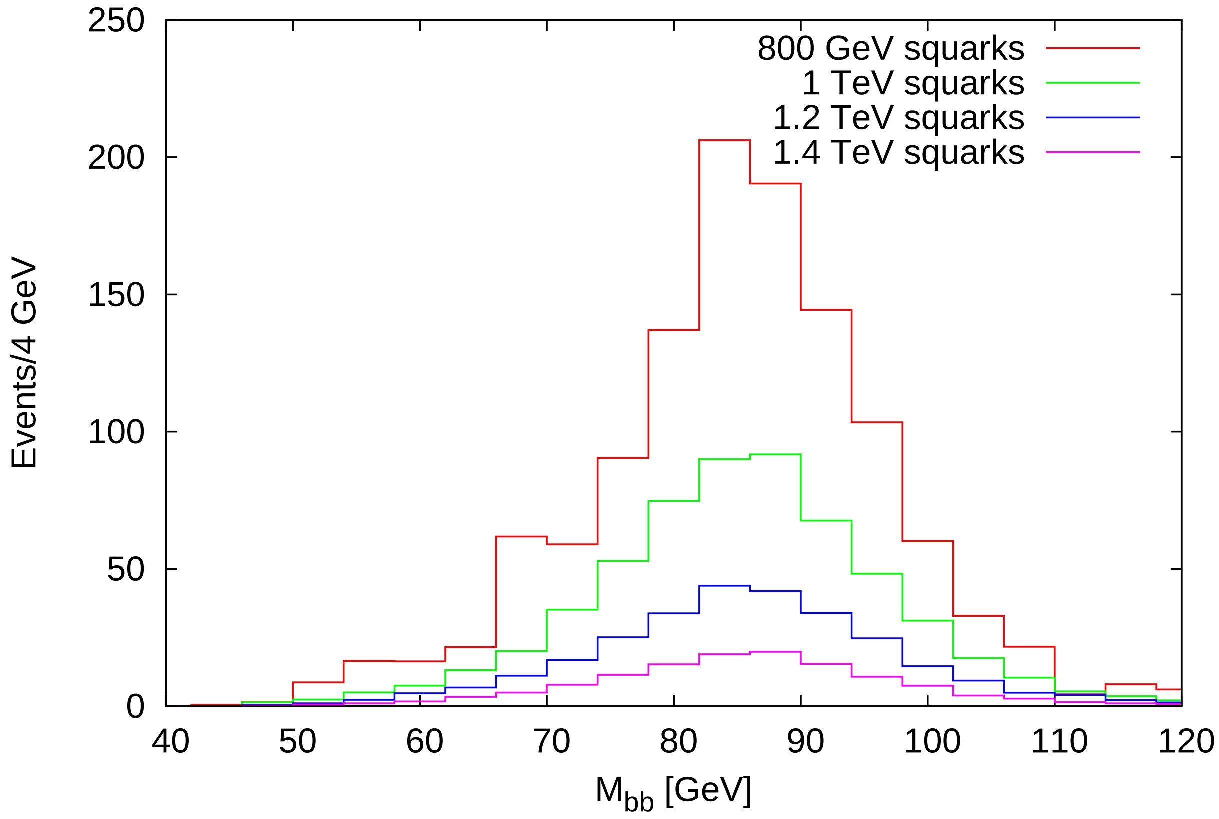
Here: 67 GeV bino, 5 GeV singlino:



$\longrightarrow$ Also visible, but a precise mass measurement will be difficult

(See the Standard Model Higgs in the $b\bar{b}$ channel ...)

And if squarks/gluinos are heavier than 830/860 GeV as assumed here?



$\rightarrow$ reduced production cross sections, reduced signal rates, but similar signal shapes; harder cuts on jet p_T are possible to suppress background

Conclusions

(Very) light singlinos can pose serious challenges for Susy searches at the LHC:

— "Missing" missing transverse energy, if the bino NLSP decays into a Higgs with similar mass and a light singlino
(and no other sources for missing energy like neutrinos)

Worst case: bino decays into a NMSSM-specific lighter Higgs
$\longrightarrow$
Scenarios with all sparticles below $\sim$ 1 TeV are allowed by present bounds!

$\longrightarrow$ squark/gluino production looks like (non-SM) Higgs pair production, but with additional jets and (hopefully) larger cross section

$\longrightarrow$ new search strategies may discover supersymmetry together with an additional Higgs boson; the presented analysis can be refined using jet-substructure techniques