Searches for Third Generation Scalar Quarks with the ATLAS Detector

Experimental results at $\sqrt{s} = 8$ and 13 TeV

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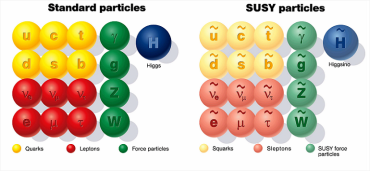
Introduction

- This talk presents an overview of the experimental searches for third generation squarks in ATLAS, in the context of natural SUSY models.
- Outline of the talk:
  1. Third generation squarks in the natural pMSSM.
  2. Experimental signatures and analysis strategies.
  3. Focus on the $tb + E_T^{miss}$ final state (8 TeV).
  4. Summary plot of the results from p-p collisions at $\sqrt{s} = 8$ TeV (Run 1).
  5. From 8 to 13 TeV: cross section improvements.
  6. Early results at $\sqrt{s} = 13$ TeV on the $bb + E_T^{miss}$ final state.
  7. Discovery prospects with more 13 TeV data.
- Useful link:
  - ATLAS Supersymmetry public results

The phenomelogical Minimal Supersymmetric Standard Model (pMSSM) and naturalness

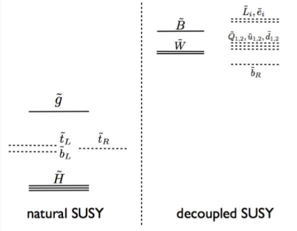
pMSSM

- Reduced number of free parameters after SUSY breaking.
- Conservation of R-parity:
  $\rightarrow$ Superpartners must be pair-produced.
  $\rightarrow$ The Lightest Supersymmetric Particle (LSP) is stable.
- Our focus: R-parity, neutral and weakly interacting LSP (possibly Dark Matter candidate).



Naturalness

- Fix divergent corrections to the Higgs boson mass.
- Constraints on the mass of gluinos, third generation squarks and Higgsinos.
- "Natural" mass spectrum:

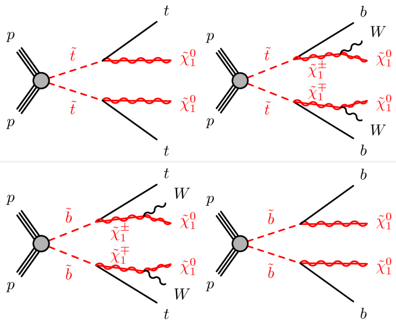


JHEP 1209 (2012) 035

Experimental signatures of third generation squarks

Direct $\tilde{t}$ and $\tilde{b}$ pair production

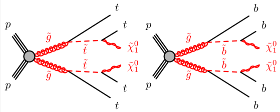
Final states with two third generation quarks and missing transverse momentum (E_T^{miss}):



Objects to reconstruct: 2 b-tagged jets (b-jets) and E_T^{miss}, plus leptons depending on the model.

Extra: gluino mediated $\tilde{t}$ and $\tilde{b}$ production

Many third gen quarks and E_T^{miss}

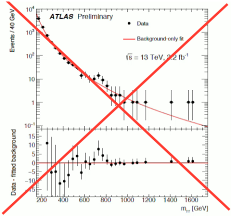


Larger b-jet multiplicity (≥ 3). Characteristic signature of gluino searches $\rightarrow$ not further developed in this talk.

Next: focus on $\tilde{t}$ and $\tilde{b}$ pair production

Analysis strategy for third generation SUSY searches

$\begin{cases} E_T^{miss} \text{in the final state} \\ \text{Pair produced particles} \end{cases} \rightarrow$ No invariant mass peak.



Reconstructing resonant signals isn't possible

$\rightarrow$ STANDARD APPROACH: CUT AND COUNT ANALYSIS

Analysis steps:

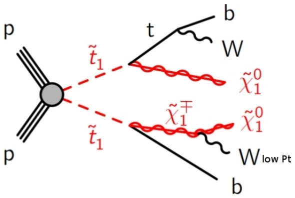
1. Select a subset of events according to the experimental signature of the targeted signal.
2. Make use of discriminating variables to separate the signal from the Standard Model background $\rightarrow$ Define Signal Regions (SR).
3. Estimate the number of expected background events in the SRs.
4. Open the box: count the observed events in the SRs and compare them with the "background only" or "signal+background" hypotheses.
5. Depending on the result, compute the statistical significance of the discovery or set exclusion limits on the signal model.

- The $tb + E_T^{miss}$ is one of the several analyses that were performed by the ATLAS Collaboration targeting direct pair production of third generation squarks.

Assumption on $\tilde{t}$ and $\tilde{b}$ decay modes:

$$\begin{cases} \tilde{t} \rightarrow t\tilde{\chi}_i^0 \text{ or } b\tilde{\chi}_1^+ \\ \tilde{b} \rightarrow b\tilde{\chi}_i^0 \text{ or } t\tilde{\chi}_1^+ \end{cases} \rightarrow \text{Mixed or symmetric decay legs}$$

OUR TARGET: MIXED DECAY (as in diagram)

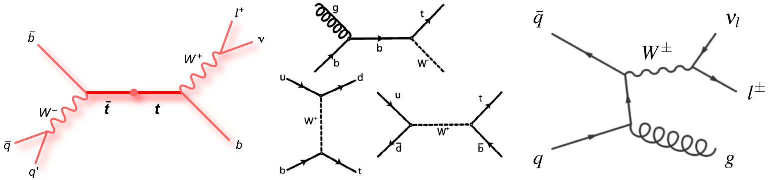


Preliminary event selection according to the signal model

- 2 b-tagged jets.
- Missing transverse momentum (E^T_{Miss}).
- 1 on shell W → Choose leptonic decay → Select exactly one lepton.
- 1 off shell W → Only low P_T objects from it (not observable).

Backgrounds and cross sections

$t\bar{t}$ | single top | $W(\ell,\nu)$ + jets



Minor contributions: $t\bar{t} + V$, diboson, $Z(\ell,\ell)$ + jets.

Cross sections of the relevant processes (more on this in slide 13)

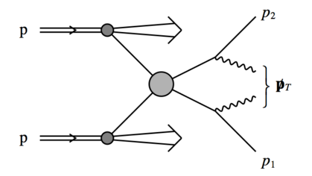
- The signal cross section at 8 TeV is of the order of the *pb*, strongly dependent on the mass of the sparticle.
  $\rightarrow$ The background cross sections are larger by several orders of magnitude!
- The preliminary selections do isolate the signal, but the background rate is dominant.
  $\rightarrow$ The discriminating variables are an essential ingredient for the analysis.

Discriminating variables

- $M_T(lep, E^T_{Miss}) = \sqrt{2P^T_{lep}E^T_{Miss}\left[1-\cos(\varphi^{lep}-\varphi^{E^T_{Miss}})\right]}$
  If lepton and E^T_{miss} are from a W decay, M_T is below the W mass.
- $aM_{T2}(b_1, b_2, lep, E^T_{Miss})$. Key variable related to the stransverse mass (M_{T2}).

Asymmetric stransverse mass (aM_{T2}) J.Phys. G29 (2003) 2343-2363

$$M^2_{T2}(P_1, P_2, E^T_{Miss}) = min\left[max\left[M^2_T(P_1, \nu_1), M^2_T(P_2, \nu_2)\right]\right].$$



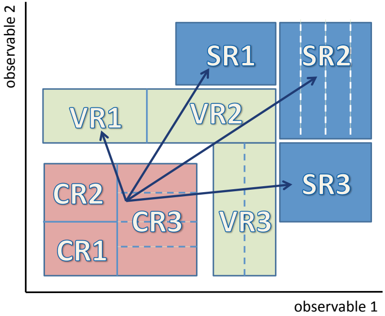
- E^T_{Miss} is decomposed in ν_1 and ν_2
  $\rightarrow$ The minimum is taken wrt all the possible directions.
- Asymmetric version for the $tb + E^{miss}_T$: the lepton is coupled to one of the two b-jets based on an invariant mass algorithm.

- For semi-invisibly decaying pair-produced particles, aM_{T2} has an endpoint driven by the mass of the decaying object $\rightarrow$ Key variable to suppress $t\bar{t}$.

Background estimation strategy: Control Regions (CR)

- Each step of the analysis relies heavily on Monte Carlo (MC) simulations.
- However the most relevant background processes are constrained in Control Regions (CRs), where they are fitted to the observed number of data events.
- The extrapolation from CRs to SRs relies again on MC simulation: its accuracy is tested in Validation Regions (VRs) as shown in the diagram.

HistFitter software: Eur.Phys.J. C75 (2015) 153

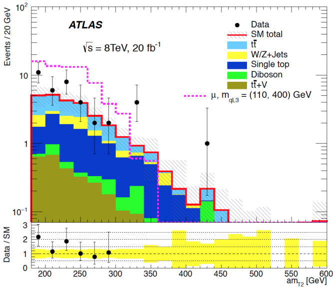


In the $tb + E_T^{miss}$ analysis, CRs and VRs are defined for the $t\bar{t}$ and $W + jets$ backgrounds.

Signal Regions and Results

- Two sets of SRs are defined:
  - Exclusive in N_{jets} (1 SR) : require low jet multiplicity, to target signals with small mass splitting between squarks and neutralinos/charginos.
  - Inclusive (3 SRs) : No jet veto, to cover signal models with larger mass splittings.
- No significant excess is observed in the four SRs: this lead us to set exclusion limits, both model independent (see table) and model dependent (next slide).

aM_{T2} distribution in SRinA:

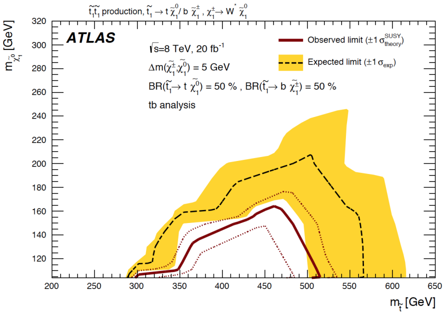


Signal channel	Obs	Exp	S^{95}_{obs}	S^{95}_{exp}	$\langle\epsilon\sigma\rangle^{95}_{obs}$ [fb]
SRinA	38	27 ± 7	28.5	$19.3^{+7.0}_{-6.1}$	1.41
SRinB	20	14.1 ± 2.8	16.3	$10.7^{+4.5}_{-2.6}$	0.81
SRinC	10	7.1 ± 2.9	11.9	$9.8^{+3.3}_{-2.4}$	0.58
SRexA	46	31 ± 7	32.1	$20.3^{+8.0}_{-3.6}$	1.58

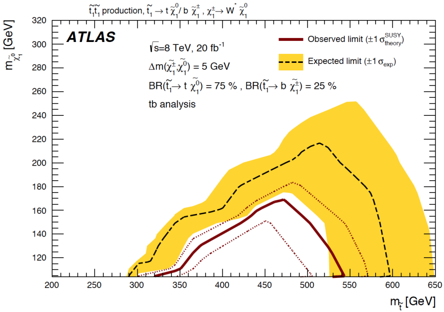
Model dependent exclusion limits

- Limits are set in a simplified model with the $\tilde{t}$ decaying in $t + \tilde{\chi}_1^0$ and $b + \tilde{\chi}_1^+$ with variable branching ratio.

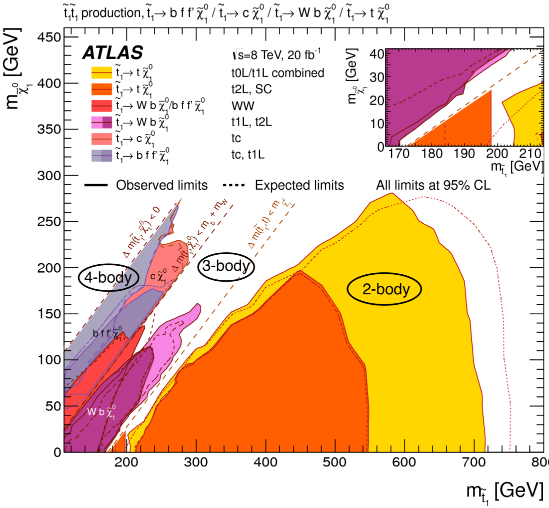
- Simplified model with 50% BR of $\tilde{t} \rightarrow t + \tilde{\chi}_1^0$



- Simplified model with 75% BR of $\tilde{t} \rightarrow t + \tilde{\chi}_1^0$



Summary plot of the ATLAS 8 TeV results in the $m_{\tilde{t}}$-$m_{\tilde{\chi}_1^0}$ mass plane



Physics process	cross section (pb) at 8 TeV	cross section (pb) at 13 TeV
$t\bar{t}$	252	831
W+jets	12087	20080
Z+jets	1122	1906
gluino pair production with $m_{\tilde{g}}$ of 1350 GeV	0.0013	0.034
gluino pair production with $m_{\tilde{g}}$ of 1500 GeV	0.00039	0.014
bottom-squark pair production with $m_{\tilde{b}_1}$ of 700 GeV	0.0081	0.067

- Huge gain in signal cross section.
- Also the background xsec grows, but less dramatically.
- Improvements in sensitivity to SUSY signals:
  $\rightarrow$ Huge gains in gluino analyses.
  $\rightarrow$ Significant gain also for third generation.
- At any energy, strong dependence of the xsec on the mass of the sparticle.

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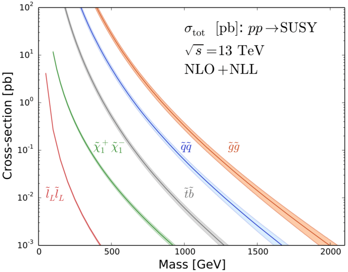
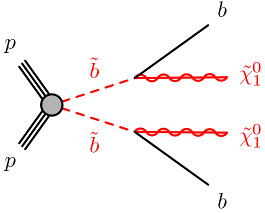


- Signal with 0 leptons, 2 b-jets with large P_T, low extra jet multiplicity, large E^T_{miss}.

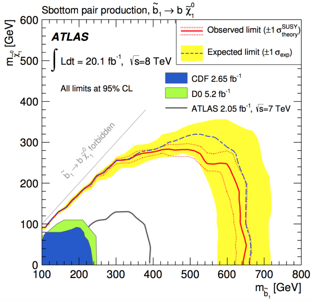


8 TeV

SRA → heavy sbottom, light neutralino.

SRB → diagonal region.

Sbottom masses up to 620 GeV are excluded for $m_{\tilde{\chi}_1^0} < 150$ GeV.



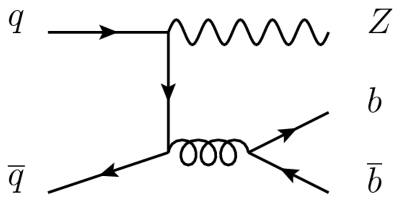
13 TeV

{ Simple experimental signature.
Large signal xsec gain compared to 8 TeV.

→ First ATLAS public result on third generation at $\sqrt{s} = 13$ TeV.

Backgrounds and discriminating variables

- Main background: $Z(\to \nu\nu) + b\bar{b}$.
- Other contributions: $t\bar{t}$, single top, $W+$jets, dibosons, $t\bar{t}V$.



Two useful variables

- m_{bb}, invariant mass of the two b-jets.
- M_{CT}: contransverse mass [JHEP 0804 (2008) 034] targeting semi-invisibly decaying pair-produced particles (as aM_{T2} for the $tb + E_T^{miss}$).

$$M_{CT}^2(v_1, v_2) = \left[E^T(v_1) + E^T(v_2)\right]^2 - \left[\vec{P}_T(v_1) + \vec{P}_T(v_2)\right]^2$$

$\to$ endpoint close to the mass of the parent particle.

$\to$ correlated with E_T^{miss}.

$\to$ useful to suppress $t\bar{t}$ background targeting signal models with large $\tilde{b}$ masses.

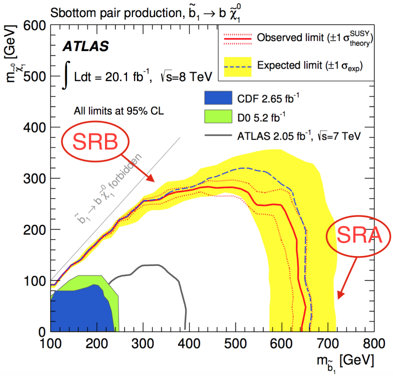
SRAs and SRB - following the 8 TeV analysis strategy

SRAs

- Target: Large ΔM between $\tilde{b}$ and $\tilde{\chi}_1^0$.
- Two leading jets b-tagged.
- Apply an M_{CT} cut with 3 different thresholds ($> 250, 350, 450$ GeV) to cover a wide area in the $\tilde{b}$-$\tilde{\chi}_1^0$ mass plane.
  $\rightarrow$ Define SRA250, SRA350, SRA450.

SRB

- Target: Small ΔM between $\tilde{b}$ and $\tilde{\chi}_1^0$ (diagonal region).
- Still two b-jets, but not leading.
- Require a leading light ISR jet that recoils against the sbottom system
  $\rightarrow$ large E_T^{miss}, $\Delta\varphi$ (jet$_1$, E_T^{miss}) > 2.5



Background estimate in $bb + E_T^{miss}$ analysis

SRA fit

- Control Regions:
  - $Z(\to \nu\nu) + b\bar{b}$: 2ℓ CR
  - $t\bar{t}$: 1ℓ CR
  - single top: 1ℓ CR
  - W+jets: 1ℓ CR
- 2 Validation Regions (0ℓ)
- 3 Signal Regions (0ℓ)

SRB fit

- Control Regions:
  - $Z(\to \nu\nu) + b\bar{b}$: 2ℓ CR
  - $t\bar{t}$: 1ℓ CR
- 1 Validation Region (0ℓ)
- 1 Signal Region (0ℓ)

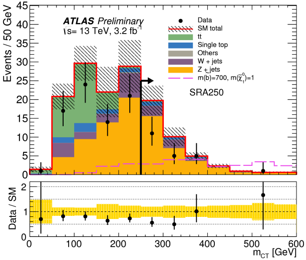
Alternative, data-driven estimate for Z background

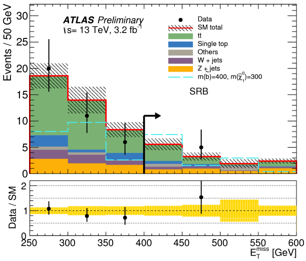
- Extract the shape of the kinematic distribution of M_{CT} from a $Z(\to \ell\ell)$+0b sample $\to$ Large statistics available.
- Normalise the background in a low M_{CT} region and extrapolate to the SRs using the data-driven shape.
- Useful to cross-check the baseline background estimation.

Results of the analysis

- Agreement between data and expected background in SRA350 and SRA450.
- Small ($< 2\sigma$) event deficit observed in SRA250 and SRB.
- No signal observed.

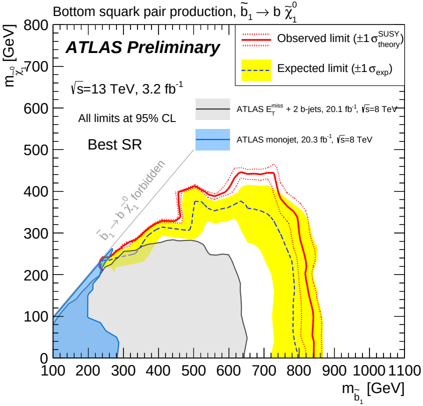
Signal region channels	SRA250	SRA350	SRA450	SRB
Observed events	22	6	1	5
Fitted bkg events	40 ± 8	9.5 ± 2.6	2.2 ± 0.6	13.1 ± 3.2
Fitted $t\bar{t}$ events	0.9 ± 0.4	0.37 ± 0.16	0.06 ± 0.03	5.9 ± 2.4
Fitted single top events	2.1 ± 1.3	0.54 ± 0.37	0.15 ± 0.10	1.2 ± 0.8
Fitted W+jets events	6.3 ± 2.4	1.3 ± 0.6	0.41 ± 0.23	1.2 ± 0.6
Fitted Z+jets events	30 ± 7	7.1 ± 2.4	1.5 ± 0.5	3.3 ± 1.4
(Alt. method Z+jets events)	*(33 ± 7)*	*(7.2 ± 1.9)*	*(2.7 ± 0.9)*	
Fitted "Other" events	0.7 ± 0.6	0.1 ± 0.1	0.02 ± 0.02	1.4 ± 0.4





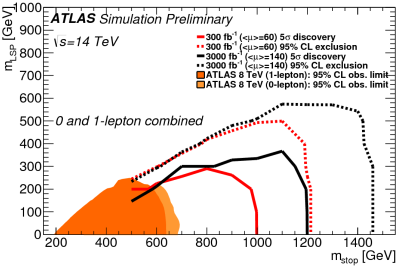
Interpretation of the results in the $\tilde{b}$-$\tilde{\chi}_1^0$ mass plane

- The results of the analysis are shown in terms of exclusion limits.
- With 3.2 fb^{-1} of data, the limits on the $\tilde{b}$ mass overcome the 8 TeV result by almost 200 GeV for light $\tilde{\chi}_1^0$.
- The small discrepancy between expected and observed limits in the bulk of the plane is due to the event deficit in SRA250 and SRB.



Discovery prospects for third generation squarks

- The reach of SUSY searches for $\tilde{t}$ and $\tilde{b}$ pair production is shown below for 300 fb^{-1} and 3000 fb^{-1} of data, combining 0ℓ and 1ℓ analyses and assuming an energy of 14 TeV.
- In the long term, the analyses are expected to be sensitive to mass values above the TeV.



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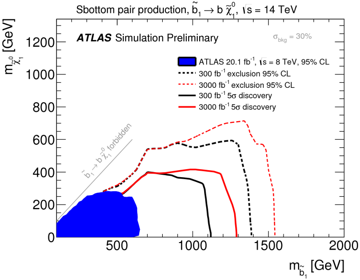

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Conclusions

- Third generation squarks are of particular interest because their mass is constrained in many BSM theories, in particular under the assumption of naturalness.
- The direct production of such squarks typically yields final states with two third generation SM quarks and missing transverse momentum (E_T^{miss}).
- The Supersymmetry group in ATLAS has a well developed analysis strategy to target a wide variety of third generation signals.
- Several searches were performed during Run 1, and preliminary results on the $bb + E_T^{miss}$ final state at 13 TeV were presented in this talk.
- No signal has been observed yet, but several new results and improvements are expected from the 13 TeV collisions $\rightarrow$ Possible room for future discoveries.

THANK YOU FOR YOUR ATTENTION!

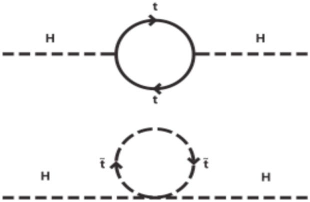
BACKUP

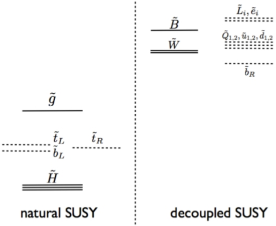
The hierarchy problem and the natural SUSY mass spectrum

- In the pMSSM, the loop corrections to the Higgs mass are cancelled by loops of scalar partners.
- But SUSY is broken → The cancellation isn't exact, and the corrections are given by:

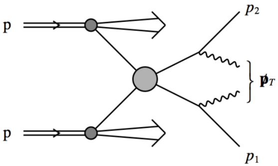
$$\Delta m_H^2 = \frac{\lambda}{16\pi^2}\left[m_f^2 \log\left(\frac{\Lambda}{m_f}\right) - m_S^2 \log\left(\frac{\Lambda}{m_S}\right)\right]$$

- Naturalness requires that Δm_H doesn't exceed $\sim$ 1 TeV.
- Higgs coupling proportional to the mass of the quark → Large corrections from third generation quarks → The mass of stop ($\tilde{t}$) and sbottom ($\tilde{b}$) is constrained to be below the TeV scale!
- Taking into account tree level and 2-loop constraints, one obtains the "natural SUSY mass spectrum" on the right.





aM_{T2} algorithm for $tb + E_T^{miss}$ analysis



1. Compute the invariant masses $M(b_1 + lep, b_2)$ and $M(b_1, b_2 + lep)$.
2. If both are $< 170\,GeV$ (compatible with a top decay), $aM_{T2} = min\left[M_{T2}(b_1 + lep, b_2), M_{T2}(b_1, b_2 + lep)\right]$.
3. If only one of them is $< 170\,GeV$, compute aM_{T2} using the corresponding b-lep coupling.
4. If both are $> 170\,GeV$, reject the event.

$tb + E_T^{miss}$ limits on natural pMSSM model