Probing Mild-tempered Neutralino Dark Matter at the LHC

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Based on, arxiv:2103:09810
M. Guchait, A. Roy, S. Sharma

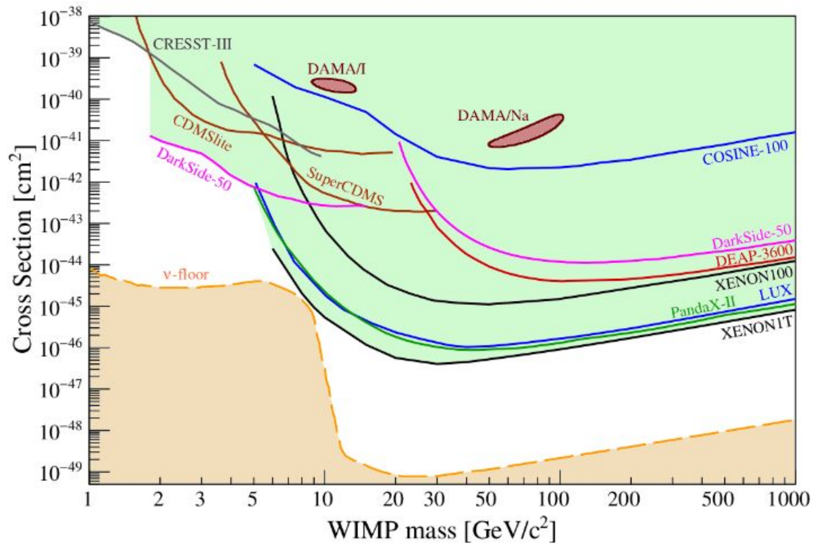
WIMP, status and exclusion

Different evidences from astrophysics and cosmology → **DM exists..**

Thermal DM

$\Omega h^2 = 0.12 \pm 0.001$ → Natural for **WIMP** → strong exclusion from different experiments

(arXiv:1807.06209, PLANCK Expt.)



Marc Schumann, J. Phys. G46 (2019) no.10, 103003

MSSM neutralino is not a preferred option anymore

- Need **extended SUSY models**
- e.g. Phys. Rev. D 102, 075023 (2020), M.Guchait, AR

MSSM neutralino may still be a viable option

- **Highly restricted**
- What is the current status?
- We focus on **50-500 GeV**

Tempered Neutralino

- ❖ A pure **Higgsino/Wino** of mass ~100 GeV leads to under-abundance of relic density
- ❖ Unless sfermions are light, pure **bino** leads to overabundance

N. Arkani-Hamed et. al.
arXiv:hep-ph/0601041

Tempered neutralino is the solution to achieve right relic density !!

- The **gaugino-higgsino-Higgs coupling** plays important role

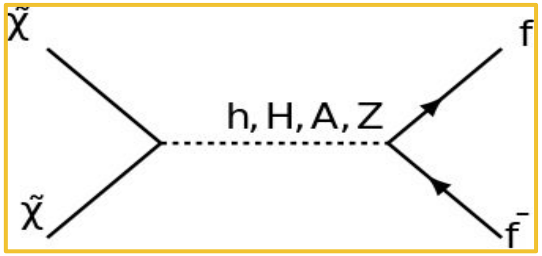
$$\boxed{g_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} \sim g(N_{12} - \tan\theta_W N_{11})(\cos\alpha N_{13} + \sin\alpha N_{14})}$$

$$\boxed{g_{H\tilde{\chi}_1^0\tilde{\chi}_1^0} \sim g(N_{12} - \tan\theta_W N_{11})(\cos\alpha N_{14} - \sin\alpha N_{13})}$$

$$\boxed{g_{A\tilde{\chi}_1^0\tilde{\chi}_1^0} \sim g(N_{12} - \tan\theta_W N_{11})(\sin\beta N_{13} - \cos\beta N_{14})}$$

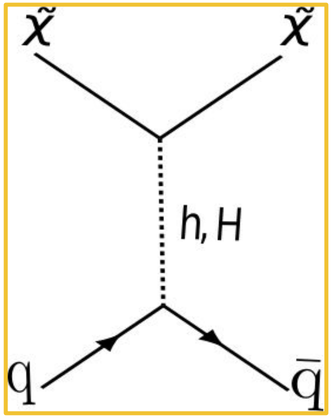
$$(\tilde{\chi}_i^0 = N_{i1}\tilde{B} + N_{i2}\widetilde{W}_3 + N_{i3}\tilde{H}_d^0 + N_{i4}\tilde{H}_u^0)$$

Annihilation



- To get right relic density **Higgsino component** has to be moderate to small

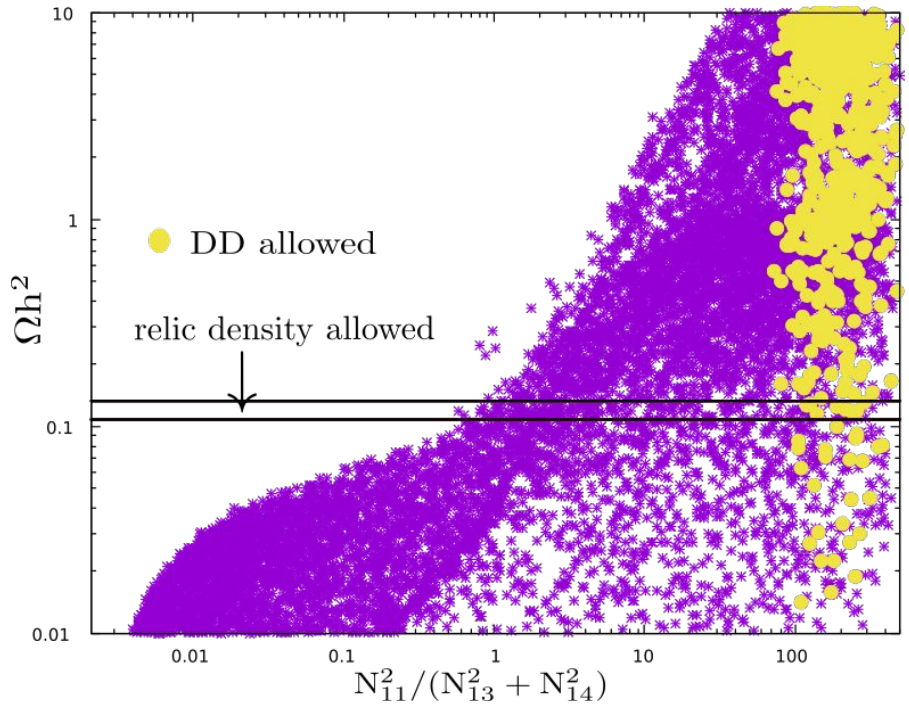
➔ Further **restricted from DD limits**, mainly SI scattering cross-section



SI-Scattering

Q. How much Higgsino fraction is compatible with limits from direct detection experiments?

Mild-tempered Neutralino



- Large **Higgsino** component → **Under-abundance** of relic density
- Large **Bino** component → Mostly **over-abundance**
  - But often right relic-density can be met
  - **Resonance annihilation** through Higgs, due to small Higgsino component

- To satisfy DD limits :

$$N_{13}^2 + N_{14}^2 \sim 1\% \text{ or less}$$ → **Mild-tempered neutralino**

Q. **Is it the only possibility?**

Blind Spot in Dark Matter Direct Detection

Light Higgs exchange **Heavy Higgs exchange** (Wagner et. al., Phys. Rev. D 90, 015018 (2014))

$$\sigma_p^{SI} \sim \left[\left(F_d^{(p)} + F_u^{(p)}\right)\left(m_{\tilde{\chi}_1^0} + \mu \sin 2\beta\right)\frac{1}{m_h^2} + \mu \tan\beta \cos 2\beta \left(-F_d^{(p)} + F_u^{(p)} / \tan^2\beta\right)\frac{1}{m_H^2}\right]^2$$

$$F_d^{(p)} \sim 0.15,\ F_u^{(p)} \sim 0.14$$

Decoupling limit

$$m_h << m_H$$

$$\left(m_{\tilde{\chi}_1^0} + \mu \sin 2\beta\right) = 0$$

Intermediate m_H

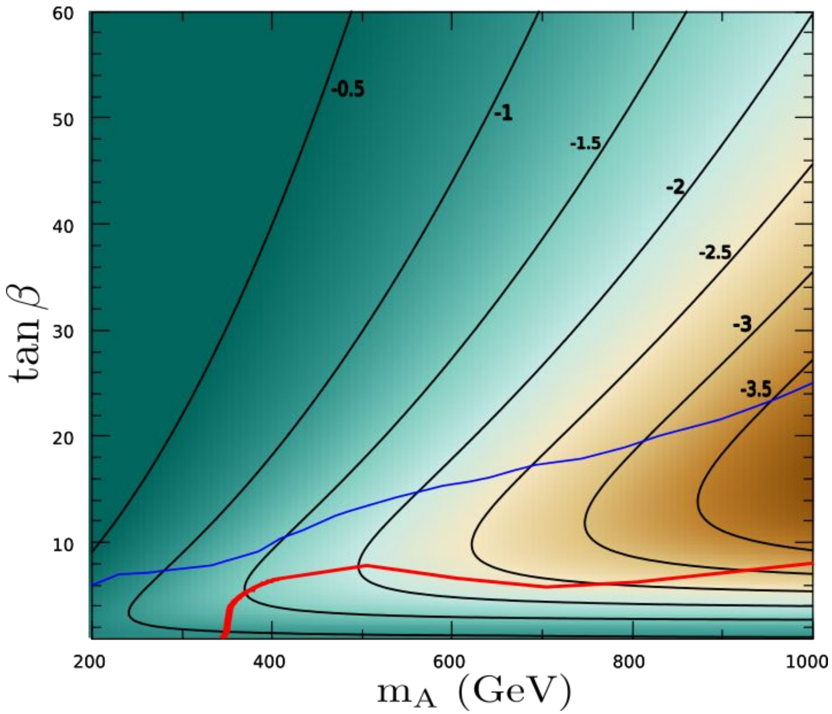
$$\frac{M_1}{\mu} \sim -\left(\sin 2\beta + \tan\beta \frac{m_h^2}{2m_H^2}\right)$$

- For decoupling limit, reduced Higgs coupling to lightest neutralino
- For intermediate m_H , **destructive interference between light and heavy Higgs exchange**

Higgsino mass μ <0, for M1>0

- Need to check exclusion from h,A $\rightarrow \tau\tau$ analyses

Blind spot for intermediate mH



$$\boxed{\frac{M_1}{\mu} \sim -(\sin 2\beta + \tan\beta \frac{m_h^2}{2m_H^2})}$$

contours of μ/M_1 show blind spots
for given values of $m_A = m_H$ and $\tan\beta$

- **Blue(red)** line presents exclusion from **h,A → ττ** analysis by **CMS** (**ATLAS**) experiment
- Indicates $\mu > M_1$
- Favorably $-1.5 < \mu/M_1 < -3.5$
- Higgsino component ~10-20% is allowed

Again, the **bino-dominated**, small Higgsino tempered region

Allowed parameter spaces and features

- Scanned the parameters in the following range

$$\boxed{\begin{array}{l}1.5 \leq \tan\beta \leq 60, 30 \leq \mathrm{M_1} \leq 1000, 100 \leq \mathrm{M_2} \leq 3000, \\ 100 \leq |\mu| \leq 1000, 100 \leq \mathrm{M_A} \leq 1500, 600 \leq \mathrm{M_{Q_3}} \leq 2500, 600 \leq \mathrm{M_{t_R}} \leq 2500,\end{array}}$$

- **SUSPECT+SUSYHIT** for mass spectra and decays
- Absolute **LEP constraints** are checked
- DM constraints are calculated and checked using **Micromegas**
- Higgs boson related constraints are checked using **Higgsbounds**
- SUSY particles exclusions are checked by **SModelS**

Key Features

- **Bino-dominated LSP with non-negligible Higgsino component**
  - **Higgsino-like** $\tilde{\chi}^0_{2,3}$
  - The gaugino-Higgsino type $g_{h\tilde{\chi}^0_i\tilde{\chi}^0_j}$ coupling gets enhanced

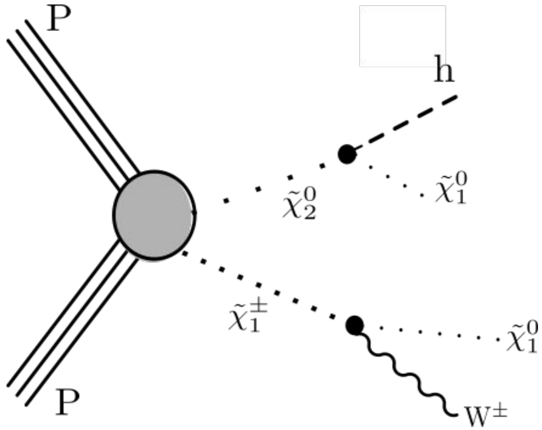
- **Top-squark dominantly decays to Higgsinos**

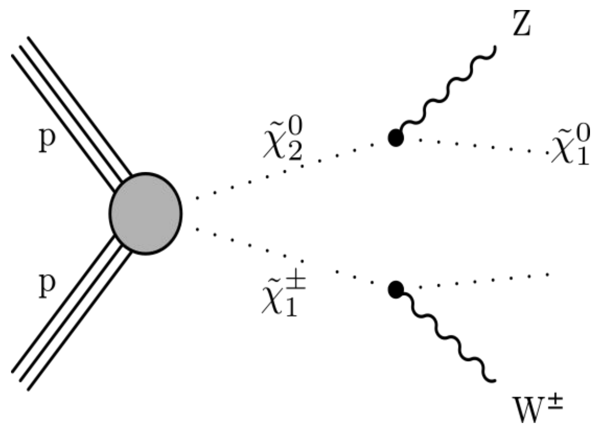
$\boxed{\mathrm{BR}(\tilde{t}_1 \to \tilde{\chi}^0_{2,3} + t)}$ **&** $\boxed{\mathrm{BR}(\tilde{\chi}^0_{2,3} \to h + \tilde{\chi}^0_1)}$ **dominates**

whereas $\boxed{\mathrm{BR}(\tilde{t}_1 \to \tilde{\chi}^0_1 + t)}$ **Very less**

➔ A **characteristic feature** of mild-tempered scenario.

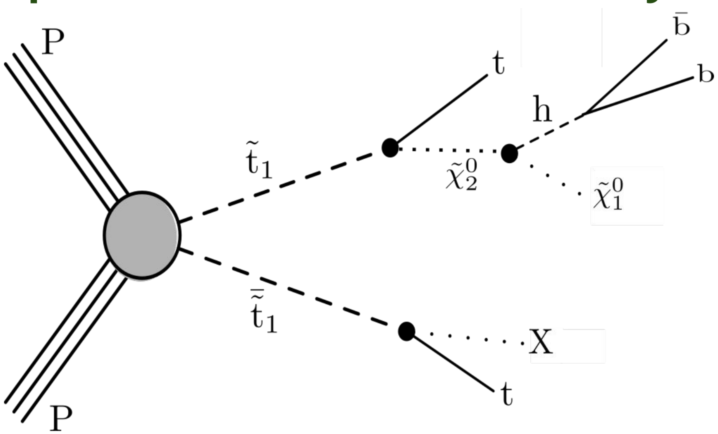
❖ **Chargino-neutralino production**





➔ **EW production**

❖ **Top-squark pair production and cascade decays (This work)**



$$X = \tilde{\chi}_1^0, \tilde{\chi}_{2,3}^0$$

➔ **Strong production**

❖ The combined rate for the final state with one higgs boson turns out to be greater in the 2nd case.

Signal & backgrounds

Signal

$$\boxed{h_{b\bar{b}} + \ell + \not{E}_T + (\geq 1)\ b - \text{jets};\quad \ell = e, \mu}$$

Dominating backgrounds

$$\boxed{p\,p \to t\bar{t}(1\ell),\ t\bar{t}(2\ell),\ t\bar{t}h,\ t\bar{t}Z,\ t\bar{t}b\bar{b}}$$

➔ Combination of two b's coming from the top, h, Z, or gluon splitting may mimic the signal h-jet

➔ MET and lepton from leptonic decay of top

❑ **Primary signal categories: Mild-tempered neutralino & BS**

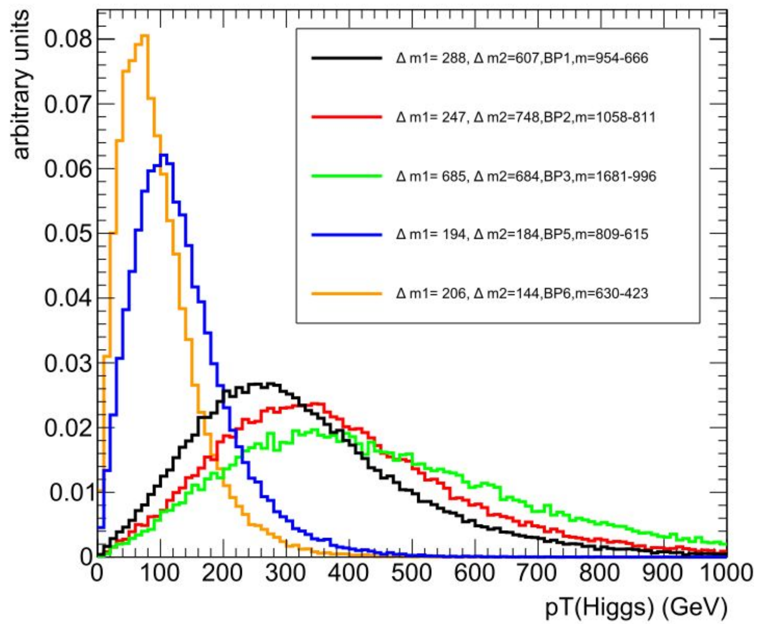
❑ The **boost of Higgs boson** depends on

$$\boxed{\begin{aligned} \Delta m_1 &= m_{\tilde{t}_1} - (m_t + m_{\tilde{\chi}^0_{2,3}}) \\ \Delta m_2 &= m_{\tilde{\chi}^0_{2,3}} - (h + m_{\tilde{\chi}^0_1}) \end{aligned}}$$

❑ Two categories depending on the boost of Higgs boson:

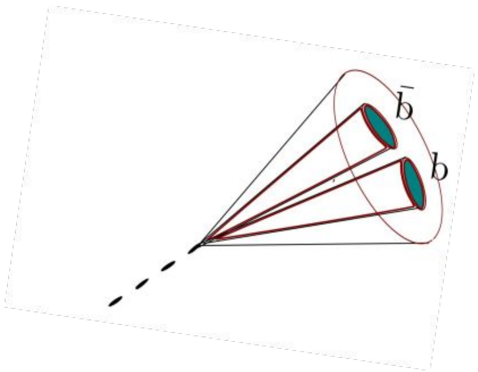
❖ **Resolved category** : Higgs not boosted, **b-jets are separated**

❖ **Non-resolved category**: Higgs is boosted, **b-jets are collimated**



HJ reconstruction & Mass distribution

- For the **non-resolved category**, Higgs bosons can be reconstructed as a fat jet



Higgs Fat Jet

- Used **MDTagger** to get tagged fat jet with two subjets
- Subjets are matched with b-quarks of the event

- In **resolved category**, pair of b-jets giving invariant mass closest to 125 GeV are identified
- If **100 GeV < m(bb) <150 GeV**, assign the resultant 4-momentum to Higgs-Jet

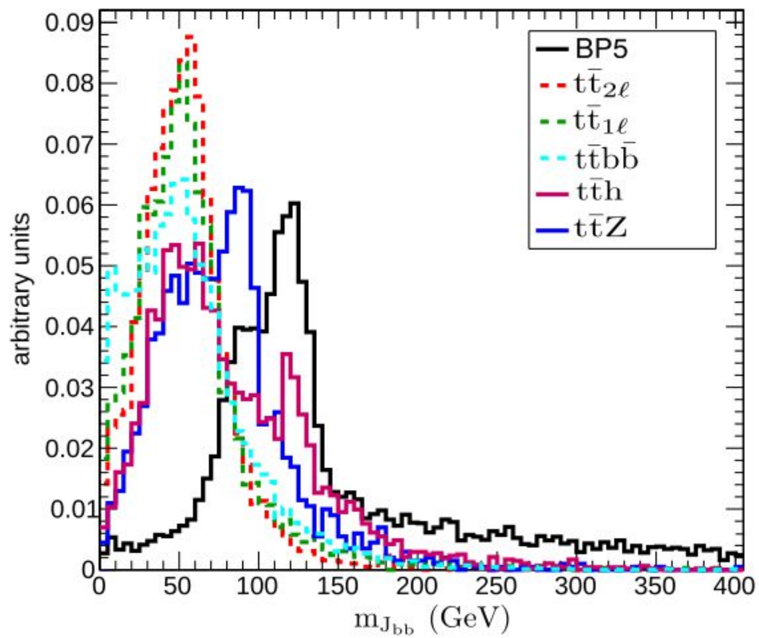
❖ **HJ with a specific mass requirement is a very important feature of our signal**

❖ Substantially different for backgrounds and signal processes

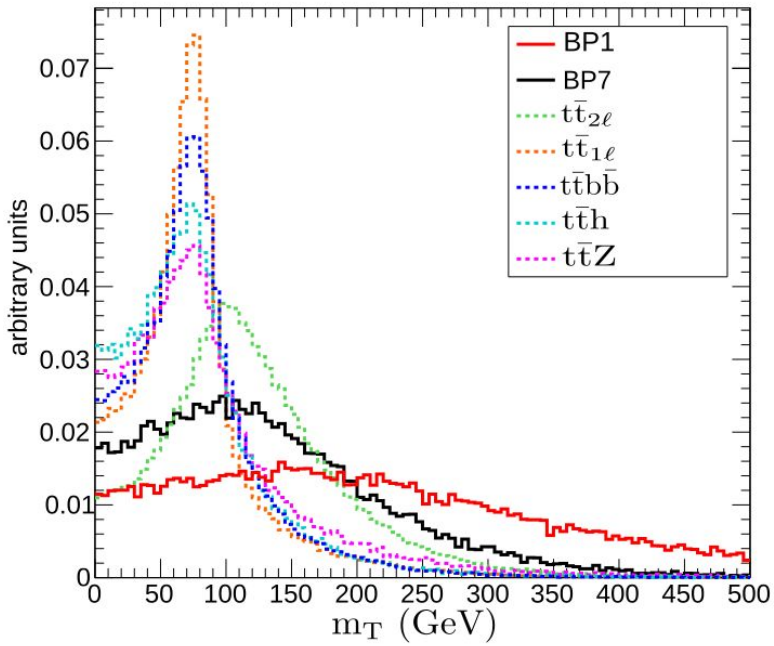
❖ Less effective only for tth background

$$\boxed{m_{J_{b\bar{b}}} \geq 100 \text{ GeV}}$$

HJ Mass for non-resolved category



Transverse Mass and HT



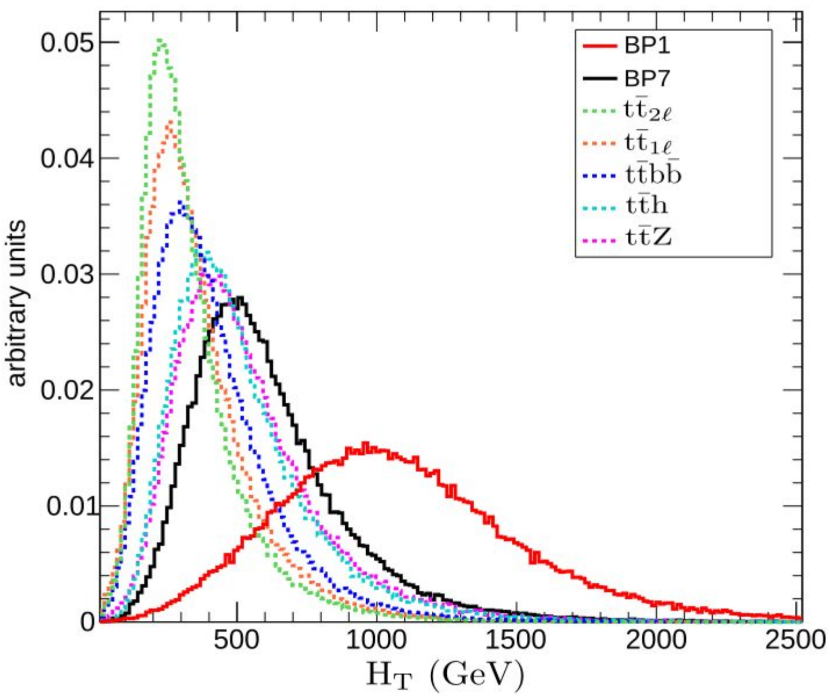
- **Transverse mass between lepton and MET**

$$m_T(\ell, \not{E}_T) = \sqrt{2 \times p_T^\ell \times \not{E}_T \times (1 - \cos\phi(\ell, \not{E}_T))}$$

$$\boxed{m_T(\ell, \not{E}_T) \geq 110 \text{ GeV}}$$

- HT : scalar sum of pT of all jets except those constitute HJ

$$\boxed{H_T \geq 500 \text{ GeV}}$$



Signal significances

	Non-resolved category					Resolved category			
Luminosity (fb^{-1})	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8	BP9
300	3.5	2.0	0.035	1.8	0.14	7	2.9	8.5	5.0
3000	11	6	0.1	6	0.44	22	9	27	16

Blind Spot **Blind Spot**

Signal significances using cut-based analysis

- BP3 and BP5 have tiny sensitivity mainly because of smaller production cross-section due to high top-squark masses
- Similar argument stands for lesser significance of non-resolved category

Multivariate analysis

- Several kinematical variables are constructed
- Sensitivity is found to be increased 4-5 times

	Non-resolved category					Resolved category			
Luminosity (fb^{-1})	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8	BP9
300	6	4.6	0.15	3.5	0.35	16	9	22	15
3000	19	14	0.47	11	1.1	50	28	69	47

Blind Spot **Blind Spot**

Signal significances using MVA

Summary

- MSSM can still provide a viable DM candidate of mass ~100 GeV.
- This DM has to be **bino-dominated**, but **little Higgsino component** is necessary → **Mild tempered neutralino**
- Another possible scenario is the **Blind-spot** w.r.t DD experiment.
  - Allowed blind spots also indicate bino-dominated nature of LSP
  - Amount of allowed Higgsino component in the LSP can be somewhat more in BS scenario

- $\mathrm{BR}(\tilde{\chi}^0_{2,3} \rightarrow \mathrm{h} + \tilde{\chi}^0_1)$ gets enhanced due to gaugino-higgsino coupling
  - An important feature of these scenarios

- **Top-squark pair production** and its **subsequent decay** turns out to be an interesting channel to search the mild-tempered neutralino and BS scenario
- **SM-like Higgs boson in the final state** adds an important handle for signal
- Cut-based analysis is performed
- Significant improvement was seen applying MVA technique
- **Detectable signal significance can be achieved** for high luminosity options at LHC