Neutralinos, 1

Matthew Low

Institute for Advanced Study

mostly based on

arXiv:1404.0682 *with* Lian-Tao Wang

arXiv:1502.05044 *with* Asher Berlin *and* Tongyan Lin *and* Lian-Tao Wang

Outline

- Brief review of results
  - Winos
  - Higgsinos
  - Mixed
  - Bino + colored coannihilator
- Will try to focus discussion on
  - where we were optimistic/pessimistic
  - possible future directions

Outline

- Brief review of results
  - Considered a variety of simplified SUSY spectra
  - Computed mass reach at 14 TeV and 100 TeV with 3 ab^{-1}
  - Generated Monte Carlo with Madgraph / Pythia / Delphes
  - Calculated significance as

$$\text{significance} = \frac{S}{\sqrt{B + \lambda^2 B^2 + \gamma^2 S^2}}$$

  - Checked different channels
    (monojet, soft leptons, vector boson fusion, disappearing tracks)

Neutralinos

- Neutralinos: $\tilde{B}$, $\tilde{W}$, $\tilde{H}_u$, $\tilde{H}_d$

$$\mathcal{L} \sim \mathcal{L}_{\text{kin}} + gh\tilde{H}_{u,d}\tilde{W} + g'h\tilde{H}_{u,d}\tilde{B}$$

- Mixing matrix

$$\begin{pmatrix} M_1 & 0 & -c_\beta s_w M_Z & s_\beta s_w M_Z \\ 0 & M_2 & c_\beta c_w M_Z & -s_\beta c_w M_Z \\ -c_\beta s_w M_Z & c_\beta c_w M_Z & 0 & -\mu \\ s_\beta s_w M_Z & -s_\beta c_w M_Z & -\mu & 0 \end{pmatrix}$$

- Squarks couple as

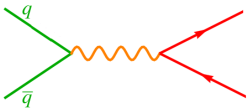
$$\mathcal{L} \sim g' q\tilde{q}\tilde{B} + gq\tilde{q}\tilde{W}$$

Wino

- *First case:* wino (triplet)

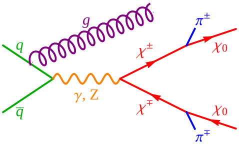
$$N_1,\ C_1^{\pm} \qquad\qquad \text{(all else decoupled)}$$

- Almost degenerate, $m_N \approx m_C$
- Small splitting, $\Delta m \approx 166$ MeV
- Interacts with SM, $W^{\pm}NC^{\mp}$ and $ZC^{\pm}C^{\mp}$

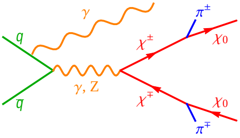


- For thermal relic, need $m = 3$ TeV

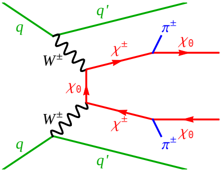
- Possible channels
  - Monojet



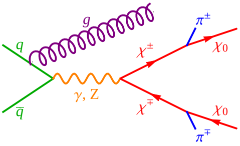
  - Monophoton



  - Vector boson fusion

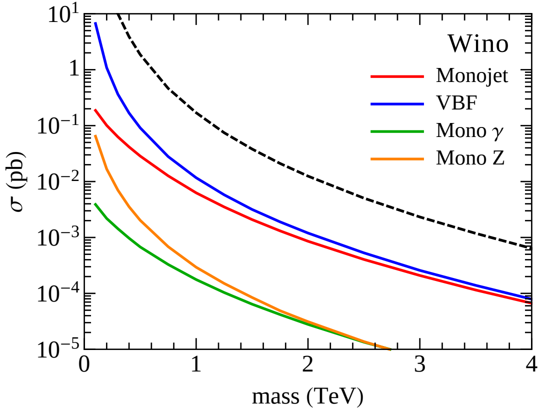


  - Disappearing tracks



(See also Cirelli, Sala, Taoso, 1407.7058)

- Possible channels
  - Rough rate comparison (parton-level Madgraph)

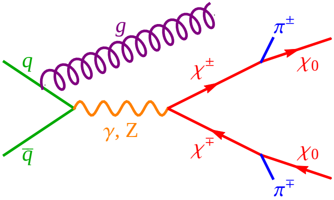


- Monojet: $p_T > 1$ TeV
- VBF: $p_T > 40$ GeV, $|\eta| < 4$
- Mono γ: $p_T > 500$ GeV
- Mono Z: $p_T > 30$ GeV

Wino

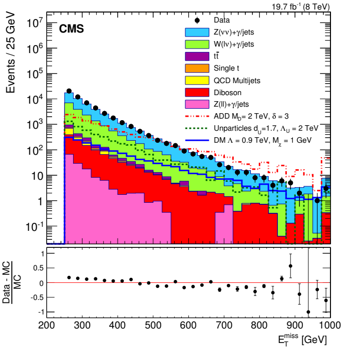
- **Monojet** search
  - Tag a hard jet (allow for a second jet also)
  - Require large missing energy
  - Jet and missing energy should be opposite
  - Veto other objects (leptons, additional jets, etc.)

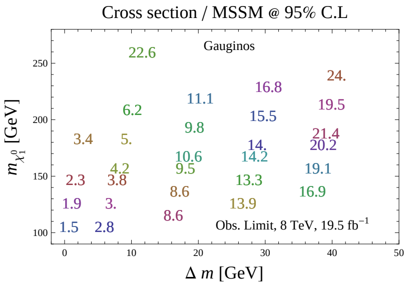
- Main backgrounds:
  - $Z(\nu\nu)$ + jets
  - $W(\ell\nu)$ + jets
  - $t\bar{t}$ + jets



Wino

- **Monojet** searches at the LHC
  - First studies, systematics $\simeq 4 - 12\%$ *(CMS, 1408.3583)*
  - Current studies, lowered to $\simeq 2.7 - 3.2\%$ *(CMS PAS EXO-12-055)* *(ATLAS, 1502.01518)*
  - Not sensitive to MSSM neutralinos

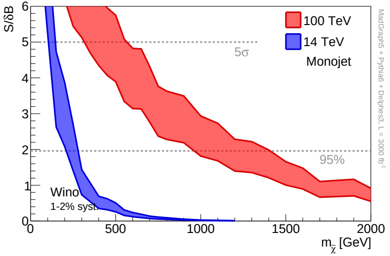




(Schwaller, Zurita, 1312.7350)

Wino

- **Monojet** searches at 100 TeV
  - Increase cuts on jets and missing energy
  - Highly dependent on assumed systematics
  - Varied systematics between 1 – 2 %



Exclusion

950 GeV – 1.4 TeV

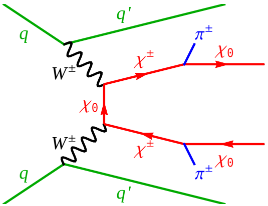
Discovery

300 GeV – 550 GeV

Wino

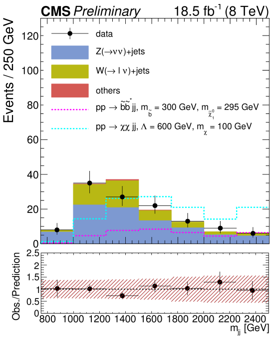
- **Vector boson fusion** search
  - Tag two forward jets
  - Require missing energy
  - Jet should be opposite (in η)
  - Veto other objects (leptons, additional jets, etc.)

- Main backgrounds:
  - $Z(\nu\nu)$ + jets ("QCD" and "EW")
  - $W(\ell\nu)$ + jets ("QCD" and "EW")



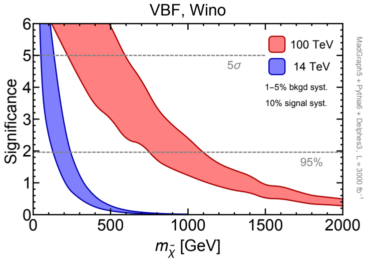
Wino

- **Vector boson fusion** searches at the LHC
  - Systematics $\simeq 6.5\%$ *(CMS PAS SUS-14-019)*
  - Systematics $\simeq 4 - 10\%$ (ATLAS, *1508.07869*)
  - Not sensitive to winos



Wino

- **Vector boson fusion** searches at 100 TeV
  - Increase cuts on jets and missing energy
  - Highly dependent on assumed systematics
  - Varied systematics between 1 – 5 %



Exclusion

750 GeV – 1.1 TeV

Discovery

200 GeV – 600 GeV

Wino

- **Vector boson fusion** searches at 100 TeV
  - Contrast to "traditional" VBF signals (i.e., addressing perturbative unitarity)
  - *Example:* pNGB Higgs with new resonances coupling to Z_L, W_L
    - V_L produced at lower p_T
    - Allowing forward jets to $|\eta| \simeq 6 - 7$ increases acceptance
  - Winos couple to transverse modes

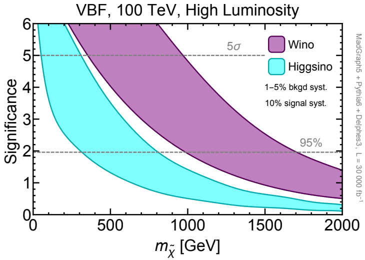
$$\mathcal{L} \supset {}^{i}/_{2} \tilde{W}^{a\dagger} \bar{\sigma}^{\mu} D_{\mu} \tilde{W}^{a}$$

    - $|\eta| \lesssim 5.5$ sufficient
    - Can raise forward jet p_T cut

(For V_L example: Kotwal, Chekanov, ML, 1504.08042)

Wino

- **Vector boson fusion** searches at 100 TeV
  - Looked at gain from additional luminosity
  - Avoided generating more Monte Carlo by extrapolating MET distributions
  - Kept other cuts fixed



Exclusion, 3 ab^{-1}

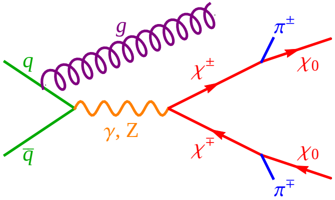
750 GeV – 1.1 TeV

Exclusion, 30 ab^{-1}

1.0 TeV – 1.7 TeV

Wino

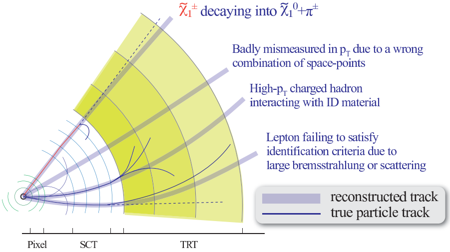
- **Disappearing tracks** search
  - Trigger on a hard jet
  - Require missing energy
  - Look for a track that ends before the end of the tracker
  - Veto other objects (leptons, additional jets, etc.)
- Main backgrounds:
  - track mismeasurement
  - interactions with detector
  - leptons

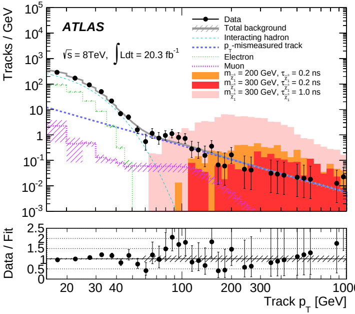


Wino

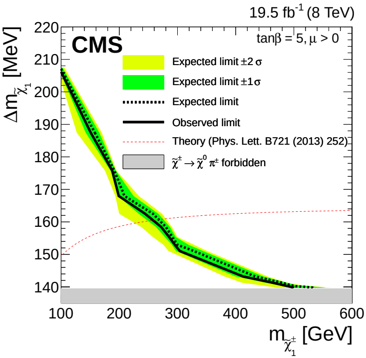
- **Disappearing track** searches at the LHC
  - No "physics" backgrounds
  - At high track p_T, track mismeasurement primary background

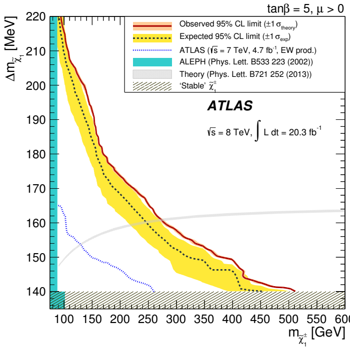
(ATLAS, 1310.3675)





- **Disappearing track** searches at the LHC
  - ATLAS: $m_\chi > 270$ GeV (ATLAS, 1310.3675)
  - CMS: $m_\chi > 270$ GeV (CMS, 1411.6006)
  - Same limit $\rightarrow$ reliable extrapolation?



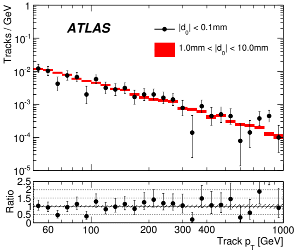


Wino

- Extrapolation procedure (background)
  - Use ATLAS's power law fit, $a = 1.78$

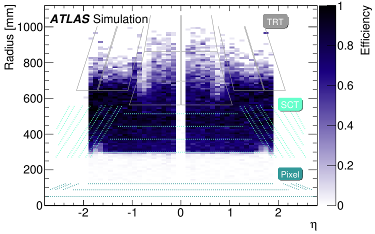
$$\frac{d\sigma}{dp_T} \propto p_T^{-a}$$

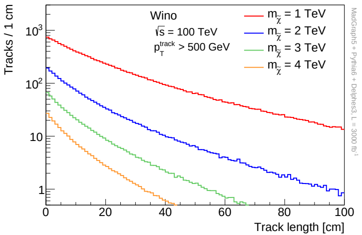
  - Scale by $Z(\nu\nu) +$ jets rate
  - Normalize using 8 TeV ATLAS rate



Wino

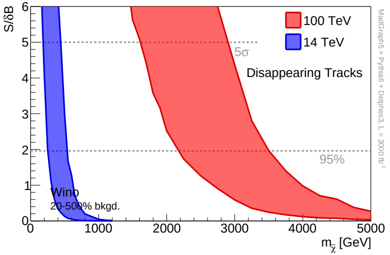
- Extrapolation procedure (signal)
  - Generate signal Monte Carlo
  - Compute $\gamma\beta c\tau$ for each chargino
  - Require track length d inside $0.1 < |\eta| < 1.9$ and 30 cm $< d <$ 80 cm
  - Match to ATLAS event count for remaining efficiency
  - Used Snowmass detector card





Wino

- **Disappearing tracks** searches at 100 TeV
  - Extrapolated background from track mismeasurement
  - Computed track lengths
  - Varied background normalization by factor of 5
  - Crucial for thermal wino!



Exclusion

$\sim$ 2.9 TeV

Discovery

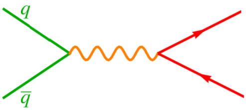
$\sim$ 2.2 TeV

Higgsino

- Higgsino (doublet)

$$N_1,\ N_2,\ C_1^\pm \qquad\qquad \text{(all else decoupled)}$$

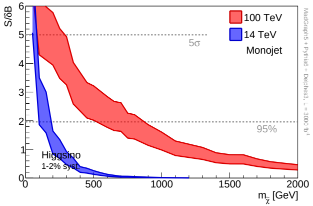
- Almost degenerate, $m_{N_1} \approx m_{N_2} \approx m_C$
- Small splitting, $\Delta m \approx 355$ MeV
- Interacts with SM, $W^\pm N C^\mp$ and $Z C^\pm C^\mp$



- For thermal relic, need $m = 1$ TeV
- Same search channels as for wino

Higgsino

- **Monojet** and **Vector boson fusion** searches at 100 TeV

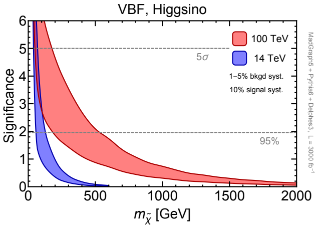


Exclusion

250 GeV – 850 GeV

Discovery

80 GeV – 250 GeV



Exclusion

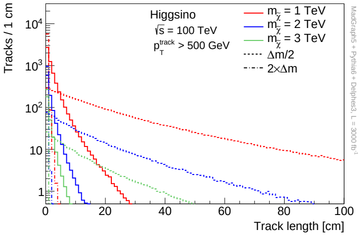
150 GeV – 500 GeV

Discovery

50 GeV – 150 GeV

Higgsino

- Disappearing tracks no longer effective, $c\tau \sim 6$ mm



- Splitting depends on multiplet

Quantum numbers SU(2)$_L$	U(1)$_Y$	Spin	DM can decay into	DM mass in TeV	$m_{DM^\pm} - m_{DM}$ in MeV	Events at LHC $\int \mathcal{L}\,dt$ =100/fb	σ_{SI} in 10^{-45} cm^2
2	1/2	0	EL	0.54 ± 0.01	350	$320 \div 510$	0.2
2	1/2	1/2	EH	1.1 ± 0.03	341	$160 \div 330$	0.2
3	0	0	HH^*	2.0 ± 0.05	166	$0.2 \div 1.0$	1.3
3	0	1/2	LH	2.4 ± 0.06	166	$0.8 \div 4.0$	1.3
3	1	0	HH, LL	1.6 ± 0.04	540	$3.0 \div 10$	1.7
3	1	1/2	LH	1.8 ± 0.05	525	$27 \div 90$	1.7
4	1/2	0	HHH^*	2.4 ± 0.06	353	$0.10 \div 0.6$	1.6
4	1/2	1/2	(LHH^*)	2.4 ± 0.06	347	$5.3 \div 25$	1.6
4	3/2	0	HHH	2.9 ± 0.07	729	$0.01 \div 0.10$	7.5
4	3/2	1/2	(LHH)	2.6 ± 0.07	712	$1.7 \div 9.5$	7.5
5	0	0	(HHH^*H^*)	5.0 ± 0.1	166	$\ll 1$	12
5	0	1/2	–	4.4 ± 0.1	166	$\ll 1$	12
7	0	0	–	8.5 ± 0.2	166	$\ll 1$	46

(Cirelli, Fornengo, Strumia, hep-ph/0512090)
(Example: fiveplet, Ostdiek, 1506.03445)

Higgsino

- Reach is $\sim$ 850 GeV (with 1% systematics), can get to 1 TeV?
  - No systematics $\rightarrow$ 1.1 TeV
  - Allow mixing $\rightarrow$ direct detection (see Joe Bramante's talk)
  - Other particles in the spectrum?
  - Modifications to Δm splitting?

Mixed Neutralinos

- Allow combinations of states:
  - $\tilde{B}/\tilde{H}$, $\tilde{B}/\tilde{W}$, etc.
- Kinematics depend on mass splittings
  - Broadly speaking, have
  - Large $\Delta m \to$ multilepton searches

    (e.g., Gori, Jung, Wang, Wells, 1410.6287)

    Hard leptons

    Large missing energy

    Production $\sim \sigma(\text{NLSP})$
  - Small $\Delta m \to$ soft lepton searches

    (e.g., Schwaller, Zurita, 1312.7350)

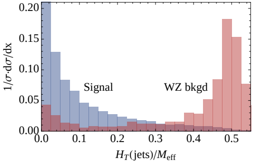
    Lepton $p_T \sim \Delta m$

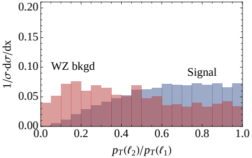
    Depends on how soft one can look

Mixed Neutralinos

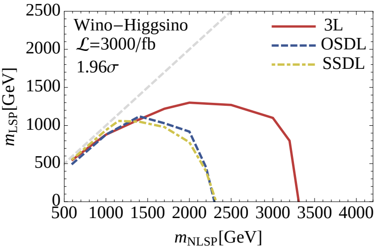
(Gori, Jung, Wang, Wells, 1410.6287)

- **Multilepton** searches at 100 TeV
  - Different signal/background kinematics





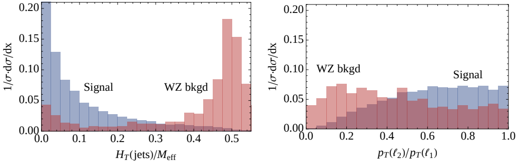
  - Example: Wino NLSP, Higgsino LSP



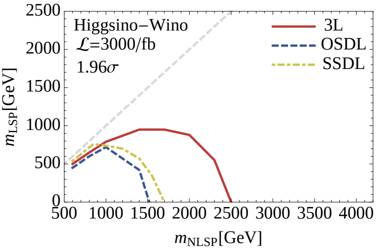
Mixed Neutralinos

(Gori, Jung, Wang, Wells, 1410.6287)

- **Multilepton** searches at 100 TeV
  - Different signal/background kinematics



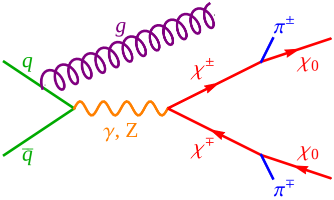
  - Example: Higgsino NLSP, Wino LSP



Mixed Neutralinos

- **Soft lepton** searches at 100 TeV
  - Trigger on a hard jet (e.g., Gori, Jung, Wang, 1307.5952)
  - Large missing energy
  - Low p_T lepton(s)

- Main backgrounds:
  - $W(\ell\nu)W(\ell\nu)$
  - $W(\ell\nu) + \text{jets}$
  - $t\bar{t}$

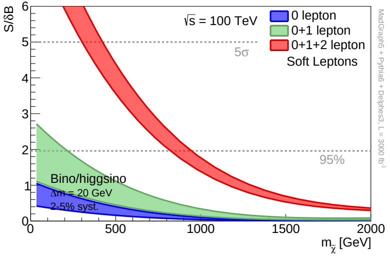


Mixed Neutralinos

- **Soft lepton** searches at 100 TeV
  - We looked at $\Delta m \simeq 20$ GeV and 30 GeV
  - Leptons with 10 GeV $< p_T <$ 30 GeV
  - Used *Snowmass* lepton efficiencies
    - 90 - 99% electrons
    - 98 - 99% muons
  - *FCC detector card*
    - 90 - 85% electrons (but up to $\eta = 6$)
    - 95 - 99% muons (but up to $\eta = 6$)

Mixed Neutralinos

- **Soft lepton** searches at 100 TeV
  - n_{lepton} has a big impact
  - Varied systematics 2 - 5%



Exclusion

800 GeV – 900 GeV

Discovery

300 GeV – 400 GeV

Co-Annihilation

- Gluino/bino

$$N_1,\ \tilde{g} \qquad\qquad \text{(all else decoupled)}$$

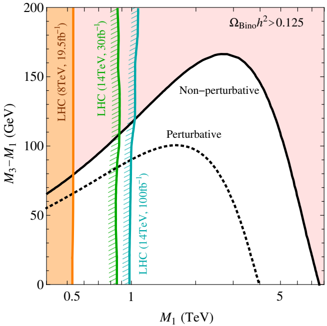
- Use $m_{\tilde{g}} = 1.05\ m_N$ as benchmark
- Rate $\propto$ gluino production
- Assume decays as

$$\tilde{g} \to N + \text{undetected}$$

- Minimum reach in monojet channel

Co-Annihilation

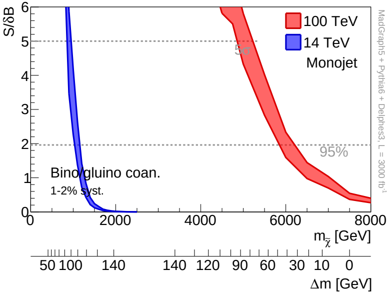
- Gluino/bino
  - Preferred mass (by relic density) varies by splitting
  - Upper end is $\simeq$ 7.5 TeV



(De Simone, Giudice, Strumia, 1402.6287)
(Harigaya, Kaneta, Matsumoto, 1403.0715)

Co-Annihilation

- Gluino/bino
  - Upper x-axis: bino mass using $m_{\tilde{g}} = 1.05\ m_N$
  - Lower x-axis: splitting to satisfy relic density



Exclusion

5.8 TeV – 6.2 TeV

Discovery

4.8 GeV – 5.2 GeV

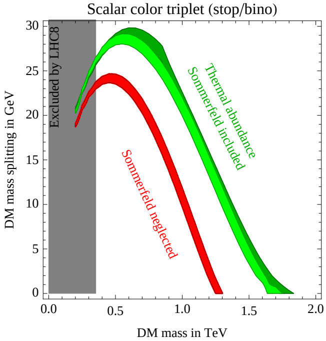
Co-Annihilation

(De Simone, Giudice, Strumia, 1402.6287)

- Stop/bino

$$N_1, \ \tilde{t}_R \qquad \text{(all else decoupled)}$$

- Use $m_{\tilde{t}} = 1.05\ m_N$ as benchmark



Exclusion

2.4 TeV – 2.8 TeV

Discovery

1.7 TeV – 2.1 TeV

Co-Annihilation

- Reach improved by colored cross-section
- 100 TeV (almost) covers thermal region
  - Look for $\tilde{g}$ decay products?

    $$\tilde{g} \to Njj$$

  - Look for $\tilde{t}$ decay products?

    $$\tilde{t} \to Nbjj$$

    $$\tilde{t} \to Nb\ell\nu$$

Conclusions

- Given thermal neutralino dark matter, 100 TeV is a crucial tool
- Should probe pure *winos*, *stop* co-annihilation
- Pure *higgsinos* come close, room for improvements?
- Tagging of soft leptons/jets useful for mixed states