#### Searches for Supersymmetry Cristóvão B. da Cruz e Silva



LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS



### Outline

- **Overview of last lecture**
- Simplified Susy Models
- Other searches

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#### • Search for supersymmetric top quarks decaying via the 4-body mode

## Supersymmetry

- Compared to the SM, Supersymmetry introduces a new symmetry between fermions and bosons
- The new symmetry implies the existence of new particles
  - New particles cancel, by construction, quadratically divergent terms to the one loop corrections to the Higgs mass squared → Elegant solution to the Hierarchy Problem
  - Lightest supersymmetric particle can be a good dark matter candidate
- Supersymmetry must be a broken symmetry or the supersymmetric particles would have same mass as SM particles and would already be discovered
- Introduce minimal, but complete, set of terms to the Lagrangian to construct the MSSM
  - 124 free parameters

# Supersymmetry Particle Spectra

- The parameters of the model are chosen, then the supersymmetric particle masses can be computed and the spectra is drawn  $\rightarrow$
- It is possible that not all particles are within reach of an experiment: LHC  $\rightarrow \sqrt{s} = 14$  TeV
  - From an experimental point of view, we only care about the particles we can reach
  - If working on an analysis searching for the selectron, assume the selectron is in reach and its decay chain products as well
- Vast parameter phase space of MSSM is challenging  $\rightarrow$  use simplified models for setting limits

$H^{\pm}$	~	~	ĝ	$rac{ ilde{d}_L ilde{u}_L}{ ilde{u}_R ilde{d}_R}$	$\frac{\tilde{t}_2  \tilde{b}_2}{\tilde{b}_1}$
$H^0 A^0$	$\frac{N_4}{\tilde{N}_3}$	$C_2$			$ ilde{t}_1$
	$\tilde{N}_2$	$ ilde{C_1}$		$rac{ ilde{e}_L}{ ilde{ u}_e}$	$rac{ ilde{ au}_2}{ ilde{ u}_ au}$
$h^0$	$N_1$			$\tilde{e}_R$	$ ilde{ au}_1$

Taken from "Supersymmetry Primer"



# Simplified SuSy Models

- Phenomenological MSSM: ullet
  - MSSM with some assumptions:
    - R-parity is conserved  $\rightarrow$  LSP is stable
    - No new CP violation term beyond the SM CKM matrix
    - No flavour changing neutral currents at tree level
    - are negligible
  - pMSSM has 19 additional parameters compared to the SM
- Effective Field Theory and Simplified Model Spectra: ullet
  - Take SM Lagrangian and expand it with minimal terms to only introduce particles of interest
  - Minimum amount of parameters for a specific scenario
  - May not correctly account for interference and loop effects
  - Care must be taken when interpreting results  $\rightarrow$  Limits are typically set on  $\sigma \times BR$
- desired point in the parameter phase space)

• For the first and second generation, the left and right handed sparticles are degenerate and tri-linear couplings

#### Not SuSy Specific

• With simplified models, it is easier to produce MC signal samples scanning the parameter space (i.e. one sample for each

# Supersymmetric Top Quark

- We are interested in models that provide a Dark Matter candidate so the lightest supersymmetric particle (LSP) must be neutral
- neutralino is the LSP
  - Stop decays to a top and a neutralino (R-parity conservation and baryon number conservation)

$$\tilde{t}_1 \to \tilde{\chi}_1^0 + t$$

Cosmological data seems to favour stops in a compressed region, i.e. where the mass lacksquarethe relic density of dark matter

• Search for stop is an interesting avenue because the high top mass leads to a potentially large splitting between the mass of the two stop particles  $\rightarrow$  lightest stop could be the lightest squark

• Focus on the situation where stop is next-to-lightest supersymmetric particle (NLSP) and





difference between the lightest stop and the LSP is small. These models are compatible with https://arxiv.org/abs/hep-ph/9911496 https://arxiv.org/abs/hep-ph/0403224

## **Compressed Stop Scenario**

- $\bullet$ neutralino is not kinematically allowed
  - decay:

$$\tilde{t}_1 \to \tilde{\chi}_1^0 + b + W^{\pm}$$

- If mass difference is smaller than the W boson mass, the 3-body decay is also not  $\bullet$ kinematically allowed
  - Stop must undergo a "4-body" decay:

$$\tilde{t}_1 \to \tilde{\chi}_1^0 + b + l^{\pm} + \nu_l \tilde{t}_1 \to \tilde{\chi}_1^0 + b + q + q$$

If mass difference is smaller than the top quark mass, the decay of the stop to a top and a  $\Delta m \equiv m\left(\tilde{t}_{1}\right) - m\left(\tilde{\chi}_{1}^{0}\right) \leq m\left(t\right) \approx 170 \,\text{GeV}$ 

• The decay is only allowed if the top quark is a "virtual particle" and immediately decays to a W boson and a lighter quark (normally b quark)  $\rightarrow$  Stop must undergo a "3-body"



 $\Delta m \equiv m\left(\tilde{t}_1\right) - m\left(\tilde{\chi}_1^0\right) \le m\left(W\right) \approx 80 \,\text{GeV}$ 

Both the top quark and W boson decay products are virtual and immediately decay  $\rightarrow$ 



### Phase Space of Stop as NLSP



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#### Search for 4-body Stop Decay @CMS If one stop decays to a lepton and the other to hadrons: 1 lepton $\bullet$ MET ll • 4 jets, 2 of which are b-jets m $W^{\pm}$ $\sim$ Choose semi-leptonic channel because few processes producing leptons at LHC $\rightarrow$ less background at the cost of lower cross section $Z^0$ 9

- Experimental Signature:

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- Initial State Radiation (ISR) Jet balanced against the stop pair  $\rightarrow$  boosts the stop pair
- Ultimately boosts decay products, particularly neutralinos → Increased MET
- Increased MET has better reconstruction

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#### Initial State Radiation Jet



## Stop 4-body Preselection

#### 2017 Data/MC



- Require exactly 1 lepton → reduce multilepton ttbar background
- HT > 200 GeV  $\rightarrow$  reduce W+Jets background
- p<sub>T</sub>(Jet<sub>1</sub>) > 110 GeV → preferentially select events which boost against an ISR jet
- Δφ(Jet<sub>1</sub>,Jet<sub>2</sub>) < 2.5 if p<sub>T</sub>(Jet<sub>2</sub>) > 60 GeV → reduce multijet background
- MET > 280 GeV → Since Neutralinos should not be detected
   Where is b-jet requirement?

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### **Stop 4-body Kinematics**



- Signal points with different Δm have different kinematic distributions

Exploit this to reduce the parameter space and aggregate the signal samples into  $\Delta m$  bins, then train one MVA for each bin b-Jet variables fed to the MVA

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#### Signal points with the same $\Delta m$ have similar kinematic distributions

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# **Stop 4-body Final Selection**

- The final selection is defined as a cut on the MVA (in this case a BDT) output
  - i.e. one selection for each  $\Delta m$  (for each year)
- Cut value is defined through minimization of the expected upper limit on the  $\sigma$
- Main backgrounds are estimated through DD methods, to not depend on MC in extreme corners of the phase space where MC statistics may not be sufficient or modelling may have limitations

## **Stop 4-body Final Selection**



nb: Even though all selections are shown in a single plot, the selections are not mutually exclusive so a single event may end up in multiple "bins". In other words, do not treat all bins together as a single signal region, each  $\Delta m$  must be treated on its own

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## Stop 4-body Final Result

The yields across the 3 years of Run II (2016, 2017 and 2018) are interpreted ulletstop decay channels)



together and a limit on the  $\sigma$  is set (or  $\sigma \times BR$  for models where there are competing

Excluded top squark masses up to:

- 480 GeV at  $\Delta m = 10$  GeV
- 700 GeV at  $\Delta m = 80$  GeV

Disagreement at  $\Delta m = 10$  GeV (local significance of  $2.5\sigma$ ) was scrutinized and no issues found, Run III data will tell whether statistical fluctuation or something interesting...



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# **Result on Stop 4-body**

- Same process\*, different analysis approach
- Traditional Cut&Count/Shape-Fit instead of ML
  - Several signal regions, with different selections, each for a non-overlapping range of  $\Delta m$
- Both approaches have a similar performance
- Only at very low  $\Delta m$  does the ML approach exhibit significantly higher sensitivity



**@Atlas** 



#### **Fully Hadronic Compressed Stop Decay**





#### • Covers the search for several scenarios, all with fully hadronic final states, such as:



# **Two Lepton Stop Decay**

Covers the search for several scenarios, all with two leptons in the final state, such as: ullet









Selection not optimized for the varying  $\Delta m$ 

### **Supersymmetric Tau Searches**

- Similar to the stop, the stau has the largest splitting of the lepton superpartners  $\rightarrow$  stau is often the lightest supersymmetric lepton
- independent of colour sector
- dark matter density hep-ph/9905481 JHEP08(2011)151
- So search for events where stau is the NLSP

Does not depend on QCD, so limits set on stau impose limits on MSSM

• Light stau with low  $\Delta m$  also compatible with cosmology results and relic

#### **Direct Stau Pair Decaying to Hadrons**

- decay are "cleaner" but low branching ratio  $\rightarrow$  even more challenging)
- Results depend on stau helicity
- Challenging low cross section  $\rightarrow$

 Use embedding technique to estimate τ backgrounds from SM

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• Hadronic Decay considered due to the higher branching ratio (semi-leptonic/leptonic)

 $\cdots \widetilde{\chi}^0_1$ 



#### **Direct Stau Pair Decaying to Hadrons**

Cut&Count approach:

- For an LSP of 1 GeV:
  - Mass degenerate: stau masses
     90 400 GeV excluded.
  - Left-handed: stau masses 115 340 GeV excluded.
  - Right-handed: stau masses 140
     240 GeV excluded.



# **Chargino Searches**



# **MSSM Higgs Sector Searches**

- - bosons and 2 additional parameters; normally take:
- All three contribute to the "Higgs to tau tau" channel:



• Two  $3\sigma$  excesses observed  $\rightarrow$ 

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• Remember MSSM requires 2 Higgs superfields  $\rightarrow$  several neutral Higgs (h, H, A)

 Masses of all 5 Higgs bosons are set by the masses of the known gauge  $m_A, \tan\beta$ 



### **MSSM Higgs Sector Searches**



8 tan

#### Conclusion

- Vast amount of physics analyses in search of Supersymmetry
- Cover many different scenarios (choose your favorite)
- No evidence of SuSy yet

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