Top squark searches at 100 TeV

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**Physics motivation**

- **SUSY**: One of the most extensively studied BSM theories
  - An excellent answer to hierarchy problem, dark matter and unification of couplings
- “Natural SUSY” models: attract a lot of attention at the LHC
  - Particularly relevant to address the hierarchy problem / understanding of naturalness of the EWK scale

**Recent articles relax these conditions:** $M_{\text{stop}} < \sim 3 \text{ TeV}$
- Baer et. al. 1602.0769, 1611.08511
- Ross et. al. 1110.6926

- **Natural SUSY spectrum**: higgsinos, stops/sbottoms and gluinos, $\sim \text{ TeV}$ Scale [maybe within LHC reach]
- All other sparticles can be very heavy [decoupled]

This talk: Focus on the search for top squarks in models with R-parity conservation
Setting the stage

- **Simplified model spectra [SMS]:** used for design & result interpretation
  - Minimal set of free parameters to describe a particular set of decay chains
  - More generic description -> results applicable to other scenarios

- But.. there are some simplifications:
  - eg. full SUSY spectrum not provided; particle properties, (usually) BR=100% for the sparticle decays

![ CMS Supplementary 35.9 fb⁻¹ (13 TeV) ]

- Region kinematically forbidden
  \( m[\text{prod. sparticle}] < m[\text{LSP}] \)

- Excluded parameter space

- Set Upper Limits in cross-section

- Observed & Expected mass limits based on the nominal production cross-section

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No hints of SUSY after the first years of LHC operation

Models with $m_{\text{stop}}$ up to $\sim 1$ TeV and light LSP are excluded
Results should be interpreted as indicative of the expected performance

[e.g. no detector aging vs time considered]

- End of HL-LHC Physics program: Exclude top squarks $\sim 2$ TeV
End of HL-LHC program: What’s next?

- **Optimistic scenario [or scenario 1]:**
  - Discovery/Observation top squarks at the LHC [~TeV scale]:
    - mechanism for the “hierarchy problem” [and for dark matter if $R_p$ is conserved]
  - Need a SUSY-factory to study the properties [mass spectrum, BR, etc.]
  - 100 TeV pp collider is a **SUSY-factory** [e.g. $m_{\text{stop}} = 2$ TeV $\rightarrow \sigma_{100\text{TeV}}/\sigma_{13\text{TeV}} \sim 10^4$]

- **Pessimistic scenario [or scenario 2]:**
  - No hints from SUSY after HL-LHC
    - Natural-SUSY in trouble [though not dead]
    - Other SUSY models alive [i.e. split-SUSY] / SUSY mass spectrum very high [?]
  - Need a powerful hadronic collider to really explore the naturalness issue and the viability of SUSY in general
    - SUSY is to this day on the most appealing BSM theories
Motivation for FCC-hh @100 TeV

- Theory motivations for superpartner mass upper bounds and the reach of a 100 TeV pp collider:
  - Measured Higgs mass [FCC-hh Yellow report]:
    - Top squarks have the largest contributions to the Higgs mass
    - $1 \text{ TeV} < m_{\text{stop}} < 10 \text{ TeV}$ seem to be favored in many models
  - Gauge coupling unification [FCC-hh Yellow report]:
    - Predict superpartners with $m_{\text{stop}} < 10 \text{ TeV}$
  - Understanding the naturalness of the EWK state:
    - “Never seen fine-tuning of $10^{-4}$ in HEP”: $\text{FT } 10^{-4} \Rightarrow \sim 10 \text{ TeV}$ top squarks

Mostly outside the HL-LHC reach; Need for a powerful hadron collider
Theory motivations for superpartner mass upper bounds and the reach of a 100 TeV pp collider:

- Measured Higgs mass [FCC-hh Yellow report]:
  - Top squarks have the largest contributions to the Higgs mass
  - $1 \text{ TeV} < m_{\text{stop}} < 10 \text{ TeV}$ seem to be favored

**GOAL: Probe up to the $\sim10 \text{ TeV}$ regime in $m_{\text{stop}}$ with FCC-hh @ 100 TeV**

- Never seen fine-tuning of $10^{-4}$ in HEP? FT $10^{-4}$ -> $\sim10 \text{ TeV}$ top squarks
- Gauge coupling unification [FCC-hh Yellow report]:
  - Predict superpartners with $m_{\text{stop}} < 10 \text{ TeV}$

Mostly outside the HL-LHC reach; Need for an FCC-hh @ 100 TeV
Search design
Signal characteristics

- Design a search for top squarks in the all hadronic channel
  - Largest branching fraction (~45%)
  - Very distinct signature

- Baseline selection:
  - Veto leptons with $p_T > 30$ GeV
  - $N_j = 2$ with $p_T > 1000$ GeV; $N_b = 1$ with $p_T > 50$ GeV
  - $M_{E_T} > 2$ TeV
  - $\Delta \phi (j_{1,2} ; M_{E_T}) > 0.5$ ; $\Delta \phi (j_3 ; M_{E_T}) > 0.3$ [QCD killers]

- Multiple jets
- 2 b-jets
- On-shell top quarks
- Large $M_{E_T}$ [from the two LSPs]
Background processes

- Relevant backgrounds:
  - "Lost Lepton" (LL) backgrounds:
    - Stemming from leptonic decays of W with the lepton escaping detection -> large MET
    - ttbar dominates, important contributions from ttW/ttH
  - ttZ(Z->vv) background:
    - Similar characteristics with signal
    - $\sigma(100\ TeV)/\sigma(14\ TeV) \sim 50$
  - "Rare" backgrounds:
    - ttVV, tttt, ...
    - Largely irreducible background [but small $\sigma$]
    - Very small contribution from V+jets

- Technical details:
  - BKG and signal generated using MadGraph
  - NLO k-factors applied
  - Events simulated using FCC detector & Delphes

$\sigma(m_{\text{stop}} \sim 7\ TeV) \sim 10^{-4}$ [NLO]
Top tagging in top squark searches

- **Key player for top squark searches:** *Identification of hadronic top quarks*
  - Provides a powerful handle to suppress many of the SM backgrounds
    - NB: 2 hadronic top quarks in signal
- **Top quarks are typically boosted in signal**
  - Top decay products merged into a single jet \([\Delta R \sim 2m_{\text{top}}/p_T(\text{top})]\)
  - Boost of the top depends on characteristics of the signal model
  - Need top tagging over a wide range of \(p_T\) [challenging]

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**Signals with moderate \(\Delta m\)**
- Top quarks with moderate \(p_T\)
- \(\sim\) TeV [similar to LHC]

**Signals with large \(\Delta m\)**
- Top quarks with very high \(p_T\)
- \(\sim 5\)-10 TeV

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*Top squark searches at 100 TeV*

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**Hadronic top tagging**

- **In theory:** A top quark decays to a W boson and a b quark
  - $\rightarrow 3$ quarks in total
    - **Substructure:** identify the 3-prong structure
    - **Flavor:** Identify the b quark [or even $W\rightarrow cX$]

- **In practice:** Jet is a cone of reconstructed particles in the detector
  - With a mass and kinematics consistent with the top decay

Top decay in real life

BKG [gluon/quark]

Challenging..
Choice of the jet distance parameter ($R$)

- Large enough to contain the top decay products
- But not too large...
  - Contributions from the underlying event, pile-up, ISR lead to increased jet mass.

There is not a single choice: Optimal $R$ depends on $p_T$[top]
Top tagging at 100 TeV: Challenge 2

- Spatial separation of the decay products of ultra-boosted top quarks
  - $\Delta R$ (ECAL) $\sim 0.02$, $\Delta R$ (HCAL) $\sim 0.1$
    4x better wrt CMS/ATLAS
  - CALO granularity not sufficient for efficient identification of ultra-boosted tops
- Inspired from 1503.03347:
  - Exploit tracking for jet substructure

Putting pieces together
- top candidate: anti-kT PF-Jets with $R=0.8$
- iteratively reduce $R$ and exploit jet substructure
- Repeat using jets made solely from tracks
- Utilize Multivariate methods [i.e. BDT] to suppress fake rate

“Multi-R + Tracks” top tagging algorithm
Multi-R + tracks tagger: performance

Work in progress: Study performance with improved calorimeters [e.g. HGC]

- modest improvement wrt cut-based tagger
- “Multi-R+Tracks”: Similar performance to Multi-R version [as expected in this $p_T$ regime]

- significant gain wrt to the cut based tagger
- Addition of track-based variables recovers loss of performance in the high-$p_T$ regime
Highlights from the search design

- “Multi-R + Tracks” provides a powerful handle to suppress many backgrounds:

FCC Simulation
$\sqrt{s} = 100$ TeV, 30 $\text{ab}^{-1}$

SIG scaled to BKG

Working point:
$\sim 5\%$ mistagging rate

Powerful observable:
[up to 90% BKG for <10% SIG]
Highlights from the search design (2)

- On top of the baseline, categorize events based on $N_t$ and $N_b$

- $M_{E_T}$ traditionally powerful variable to separate signal from background

- $M_{E_T}$ spectrum depends strongly on the signal model:
  - Fit $M_{E_T}$ shape

![Graph showing $M_{E_T}$ spectrum with $N_t \geq 2, N_b \geq 2$]
Challenge: Background estimation

- We will enter in the regime of very small SUSY production $\times$-sections [very massive sparticles]
  - $\sigma$(SUSY) orders of magnitude smaller wrt $\sigma$(SM)

- SUSY signal is mainly searched for in the tails of the distributions
  - BKG: very good control of the tails needed

- Strategy:
  - Main backgrounds [LL & ttZ] estimated using data-driven methods:
    - Use dedicated “data” control samples [with kinematics similar to the signal] to measure each process
    - Translate the measurement to a BKG prediction with the aid of simulation
  - Rare backgrounds:
    - Estimated from simulation with generous uncertainties [100%]
**FCC Simulation**

- **LL BKG: 1L control sample**
  - \(N_L = 1\) with \(p_T(L) \geq 30\) GeV
  - \(M_T(L, ME_T) < 100\) GeV:
    - suppress potential signal contamination

- **ttZ BKG: 3L control sample**
  - \(N_L = 3\) with \(p_T(L) \geq 30\) GeV
  - OSSF pair consistent with \(M_Z\)
  - \(p_T(Z) > 2\) TeV:

**Systematics**

- Dominant uncertainty from the stats of the control regions
  [propagated to the final results]
- Two scenarios to account for additional sources:
  - "nominal": 20% (*)
  - "conservative": 40% (*)
  - Uncorrelated across all regions/processes
Results
Results @ 3 ab$^{-1}$

Expected limit @95% CL

- Discovery potential (5σ)
  - FCC Simulation
  - $\sqrt{s} = 100$ TeV, 3 ab$^{-1}$
  - Nominal
  - Conservative

- Expected limit @95% CL
  - ~2 TeV
  - HL-LHC

- Discovery potential (5σ)
  - ~1.4 TeV
  - HL-LHC
Results @ 30 ab\(^{-1}\)

**Expected limit @95% CL**

- FCC Simulation\(\sqrt{s} = 100\) TeV, 30 ab\(^{-1}\)
  - Nominal
  - Conservative

- ~2 TeV
  - HL-LHC
- ~8.5 TeV
  - FCC-hh (3ab\(^{-1}\))

**Discovery potential (5\(\sigma\))**

- FCC Simulation\(\sqrt{s} = 100\) TeV, 30 ab\(^{-1}\)
  - Nominal
  - Conservative

- ~1.4 TeV
  - HL-LHC
- ~4.5 TeV
  - FCC-hh (3ab\(^{-1}\))

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Summary

- We have designed a search for top squarks for the FCC-hh at 100 TeV
  - Focus on all hadronic channel -> take advantage of the largest BR
- Tagging ultra-boosted top quarks @ 100 TeV needs detector granularity and improved methods:
  - Multi-R approach
  - Track-based substructure variables

"Multi-R+Tracks"

5-10x improved background rejection wrt to existing approaches

[Still lots of room for improvement]

Conclusion:

- We can reach the $m_{\text{stop}} \sim 8.5$ TeV barrier already with 3 ab$^{-1}$
- Additional luminosity [i.e. 30 ab$^{-1}$] is important for SUSY hunt:
  - discover top squarks with $m_{\text{stop}} \sim 9.5$ TeV & exclusion up to $\sim 11$ TeV

The FCC-hh physics program will be critical in our discovery or abandonment of SUSY
Back-ups