Searching for supersymmetry using hadronically decaying tau leptons

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What is supersymmetry?

- Standard model of particle physics
  - Describes the known matter
    + 3 interactions
  - to very high precision
  
  \[
  \begin{align*}
  \text{u} & \quad \text{c} & \quad \text{t} & \quad \text{g} & \quad \text{H} \\
  \text{d} & \quad \text{s} & \quad \text{b} & \quad \gamma \\
  \nu_e & \quad \nu_\mu & \quad \nu_\tau & \quad Z \\
  \text{e} & \quad \mu & \quad \tau & \quad W 
  \end{align*}
  \]
  
  - Unfortunately some open issues, e.g. what is dark matter?
What is supersymmetry?

• Standard model of particle physics
  – Describes the known matter + 3 interactions to very high precision
  – Unfortunately some open issues, e.g. what is dark matter?

 Maybe adding a new symmetry helps

SUPERSYMMETRY (SUSY)

Squarks

Sleptons

Gauginos

Higgsino
What is supersymmetry?

- **Standard model of particle physics**
  - Describes the known matter + 3 interactions to very high precision
    - Unfortunately some open issues, e.g. what is dark matter?

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\text{e} & \quad \text{\mu} & \quad \text{\tau} & \quad \text{W}
\end{align*}\]

- **Supersymmetry (SUSY)**
  - Dark matter candidate!
  - Neutralinos
  - Charginos

Un fortunately, not that simple
How could we see SUSY @ LHC?

- SUSY production

→ Squark/Gluino production via strong interaction

\[ \sigma_{\text{tot} \, [\text{pb}]}: \, pp \rightarrow \text{SUSY} \]
How could we see SUSY @ LHC?

- SUSY production
  - SUSY production $\rightarrow$ colliding protons
    - Squark/Gluino production via strong interaction
      - Excluded up to $O(\text{TeV})$

$\sigma_{\text{tot}}[\text{pb}]: pp \rightarrow \text{SUSY}$

$\sqrt{s} = 7 \text{ TeV}$

$m_{\text{average}} [\text{GeV}]$

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How could we see SUSY @ LHC?

- SUSY production → colliding protons
  - Squark/Gluino production via strong interaction
  - Direct electroweak production of chargino, neutralino and sleptons
  - Final state with τ's, $E_T^{miss}$ and O(0) jets
What do we measure?

• ATLAS detector

Multipurpose detector
→ Onion shell structure
  ▪ Inner detector – tracking
  ▪ Calorimeters
  ▪ Muon system
What do we measure?

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**Multipurpose detector**
- Onion shell structure
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**Tau leptons**
- $m_\tau = 1.78\text{GeV}$
- $\tau_\tau = 2.9 \times 10^{-13}\text{s}$
- decay length 87.1\(\mu\text{m}\)
- inside beam pipe
- $BR_{\text{hadrons}} = 65\%$
What do we measure?

• ATLAS detector

Final state signature
• ≥ 2 $\tau_{\text{had}}$
• Large $E_T^{\text{miss}}$
• Not much else

Multipurpose detector
→ Onion shell structure
  ▪ Inner detector – tracking
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Tau leptons
• $m_{\tau} = 1.78\text{GeV}$
• $\tau_{\tau} = 2.9 \times 10^{-13}\text{s}$
  → decay length 87.1$\mu$m
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• $BR_{\text{hadrons}} = 65\%$
How do we quantify our signature?

• Cut-and-Count Analysis

Cut
• Define electrons, muons, taus and jets
• Compute variables like $E_T^{\text{miss}}$, $m_{T2}$, etc
• Select events according to criteria e.g. $\geq 2 \tau$'s
How do we quantify our signature?

• Cut-and-Count Analysis

Cut
• Define electrons, muons, taus and jets
• Compute variables like $E_T^{\text{miss}}$, $m_T^2$, etc
• Select events according to criteria e.g. $\geq 2 \tau$'s

Count
• Count events passing the criteria

→ Compare
• Compare expectation from standard model to measured data
What do we need $m_{T2}$ for?

- “Invariant mass” of invisible particles (partially) decaying to invisible particles

Consider decay with 1 invisible particle: $\tilde{\tau}^+ \rightarrow \chi_1^0 \tau^+

\Rightarrow m_{\tilde{\tau}}^2 = m_{\tilde{\tau}}^2 + m_{\chi_1^0}^2 + 2[E_T^{\tilde{\tau}}E_T^{\chi_1^0} \cosh(\Delta y) - p_T^{\tilde{\tau}} \cdot p_T^{\chi_1^0}]$

\Rightarrow Transverse mass $m_T^2$: leave out $\cosh(\Delta y)$.

\Rightarrow Since $\cosh(\Delta y) \geq 1 \Rightarrow m_T^2 \leq m_{\tilde{\tau}}^2$


\( (*) \) rapidity $y = \frac{1}{2} \ln\left(\frac{E+p_z}{E-p_z}\right)$
What do we need $m_{T2}$ for?

- "Invariant mass" of invisible particles (partially) decaying to invisible particles

Consider decay with 1 invisible particle: $\tilde{\tau}^+ \rightarrow \chi^0_1 \tau^+$

$\rightarrow m^2_\tilde{\tau} = m^2_\tau + m^2_\chi_1 + 2[E_T^\tau E_T^{\chi^0_1} \cosh(\Delta y) - p_T^\tau \cdot p_T^{\chi^0_1}]$ with $\Delta y =$ rapidity(*)

- Transverse mass $m^2_T$: leave out $\cosh(\Delta y)$.
- Since $\cosh(\Delta y) \geq 1 \rightarrow m^2_T \leq m^2_\tilde{\tau}$

$\rightarrow 2$ decay $\rightarrow \tilde{\tau}^+ \tilde{\tau}^- \rightarrow \tau^+ \tau^- \chi^0_1 \chi^0_1$

$\rightarrow 2 \chi^0_1$ contribute to $E_T^{\text{miss}}$

$\rightarrow$ Split $E_T^{\text{miss}}$ into $E_T^{\text{miss}} = q_T^{(1)} + q_T^{(2)}$ such that

$$m^2_{T2}(\chi) = \min_{q_T^{(1)} + q_T^{(2)} = E_T^{\text{miss}}} \left[ \max \left\{ m^2_T(p_T^{(1)}, q_T^{(1)}; \chi), m^2_T(p_T^{(2)}, q_T^{(2)}; \chi) \right\} \right]$$

(*) rapidity $y = \frac{1}{2} \ln \left( \frac{E+p_z}{E-p_z} \right)$

How many events do we expect from standard model processes?

• Processes which look like our signal

**QCD multijet and W+jet**

\[ \text{tau} = \text{misidentified jet} \]

\[ E_{T}^{\text{miss}} = \text{additional artefact from instrumental effects or W-decay} \]

→ Largest background (30-80%)
→ Use data to estimate due to incorrect fake tau modelling in simulation
→ ABCD method
How many events do we expect from standard model processes?

- Processes which look like our signal

**QCD multijet and W+jet**
- tau = misidentified jet
- jet
- misidentified as tau
- \( E_T^{\text{miss}} = \) additional artefact from instrumental effects or W-decay

**Diboson, Z+jet, top**
- tau = real tau from particle decay
- \( E_T^{\text{miss}} = \) neutrinos e.g. from W-decay

- Largest background (30-80%)
- Use data to estimate due to incorrect fake tau modelling in simulation
- ABCD method

\[ \text{Diboson} = 2\text{nd largest (15-35%)} \]
- Estimate from simulation \( \rightarrow \) many systematics sources to be considered
- Validation of simulation in specific phase space regions with data
How does the ABCD method work?

- Divide phase space into 3 background A, B, C + 1 signal region D

• Pair of uncorrelated variables: tau ID and e.g. $m_{T2}$
• Regions A, B, C dominated by background which is to be estimated
• Events in region D via rule of proportion
How does the ABCD method work?

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$D = A \times C/B$

$\Rightarrow$ Other backgrounds to be subtracted
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  - Events in region D via rule of proportion

- $m_{T2} > 100\text{GeV}$
- $m_{T2} < 40\text{GeV}$

- Loose tau ID
- Tight tau ID

- Other backgrounds to be subtracted
- Signal contamination take into account
How does the ABCD method work?

- Divide phase space into 3 background A,B,C + 1 signal region D

\[ D = \frac{A \times C}{B} \]

\( m_{T_2} \)

\( m_{T_2} > 100 \text{GeV} \)

\( m_{T_2} < 40 \text{GeV} \)

Loose tau ID

Tight tau ID

\( \rightarrow \) Agreement between data and estimates in intermediate validation region

\( \rightarrow \) Compare obtained number of expected standard model events in signal region to data
How do the Monte Carlo estimates work, e.g. for diboson?

• Principle idea
  – Use number of events predicted in the signal regions
  – **But** signal regions = extreme phase space for diboson processes → range of very low Monte Carlo statistics
  → Produce as much Monte Carlo as possible
  → Statistically combine existing Monte Carlo to reduce statistical uncertainties
How do the Monte Carlo estimates work, e.g. for diboson?

- **Principle idea**
  - Use number of events predicted in the signal regions
  - **But** signal regions = extreme phase space for diboson processes \(\rightarrow\) range of very low Monte Carlo statistics

\(\rightarrow\) Produce as much Monte Carlo as possible

\(\rightarrow\) Statistically combine existing Monte Carlo to reduce statistical uncertainties

\(\rightarrow\) **Systematic uncertainties**

- Experimental uncertainties from reconstruction, e.g. tau energy scale
- Theoretical uncertainties from simulation, e.g. scales for separation of hard process, showering & radiation
What if we don’t see a difference between our expectation and data?

• Results from March 2013

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<td>9.2 ± 1.2</td>
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Observation

→ Probably no SUSY

→ But up to which parameter values are we sure we don’t see SUSY?
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**Observation**

→ Probably no SUSY

→ But up to which parameter values are we sure we don’t see SUSY?
Where is SUSY?

- Different analyses searching for SUSY electroweak production

**ATLAS** Preliminary $L_{\text{int}} = 20.3-20.7 \, \text{fb}^{-1}$, $\sqrt{s}=8$ TeV  Status: SUSY 2013

- Large part of the haystack is searched, but so far no SUSY found
- Continue with the remaining part