Why still SUSY?
Motivation of \( \tilde{\tau} \) studies
\( \tilde{\tau} \) analysis
- Signal and SM background
- Worst mixing
- General cuts
- Beam induced backgrounds
- Limits
Outlook and conclusions

International Workshop in Future Linear Colliders
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Why still SUSY?

Future electron-positron colliders offer excellent facilities for SUSY searches, wrt. previous electron-positron colliders:

- increased luminosity and centre-of-mass energy
- improved technologies

wrt. hadron colliders:

- cleaner environment
- known initial state
- triggerless operation of the detectors

... being, in contrast to hadron colliders, well adapted to colour neutral SUSY sector:

- one of the most relevant for SUSY as explanation of the main problems of the SM
- expected to have a sufficiently light mass to be observable in these future colliders, for theoretical reasons and from the results of the global fits
Motivation for $\tilde{\tau}$ searches to have guarantees of discovery or exclusion

Searching SUSY focused on best motivated NLSP candidates and most difficult scenarios

$\tilde{\tau}$ satisfies both conditions

Scalar superpartner of $\tau$-lepton

- Two weak hypercharge eigenstates ($\tilde{\tau}_R$, $\tilde{\tau}_L$) not mass degenerate
- Mixing yields to the physical states ($\tilde{\tau}_1$, $\tilde{\tau}_2$), the lightest one being with high probability the lightest sfermion (stronger trilinear couplings)
- With assumed R-parity conservation:
  - pair produced (s-channel via $Z^0/\gamma$ exchange, low $\sigma$ since $\tilde{\tau}$-mixing suppresses coupling to the $Z^0$)
  - decay to LSP and $\tau$, implying more difficult signal identification than the other sfermions

SUSY models with a light $\tilde{\tau}$ can accommodate the observed relic density ($\tilde{\tau}$ - neutralino coannihilation)
Current limits (LEP) and HL-LHC prospects

Current $\tilde{\tau}$ limits (combining data from four LEP experiments)

- $\tau^+_1 \tau^-_1$ (Z decoupled)
- $\sqrt{s} = 183-208$ GeV
- $\tau^+_R \tau^-_R$

$\tilde{\tau}$ prospects at HL-LHC (same conclusions for ATLAS and CMS limits)

- No discovery potential for $\tilde{\tau}$ coannihilation scenarios or $\tilde{\tau}_R$ pair production

Valid for any mixing and any values of the not shown parameters

LEPSUSYWG/04-01.1

ATL-PHYS-PUB-2018-048
Conditions ILC searches

- $\sqrt{s} = 500$ GeV (extrapolated to 250 GeV and 1 TeV)
- Both main polarisations, $P(+80\%, -30\%)$ and $P(-80\%, +30\%)$, with $\mathcal{L} = 1.6$ ab$^{-1}$ each (H20 scenario)
- Including all SM and beam-induced backgrounds

Detector simulation and reconstruction for the signal done using the SGV fast simulation with beam-spectrum and photons in the beam added from the full simulated background samples.
Signal characterization

- **s-channel production**

- **τ decays**

Signal events with the (visible) decay products of two τ’s being the only detectable activity
Signal characterization

**s-channel production**

**τ decays**

**Signature:**
- large missing energy and momentum
- large fraction of detected activity in central detector (isotropic production of scalar particles)
- large angle between the two τ-lepton directions
- unbalanced transverse momentum
- zero forward-backward asymmetry
SM background

**SM processes with real or fake missing energy**

**Irreducible**

**Almost irreducible**

**4-fermion production with two of the fermions being neutrinos and two $\tau$’s**

**Mis-identification of $\tau$’s or of missing momentum**

- $ee \rightarrow \tau \tau$, $ZZ \rightarrow \nu \nu \; ll$, $WW \rightarrow lv \; lv \; (l = e \; or \; \mu)$
- $ee \rightarrow \tau \tau \; + \; \text{ISR}$, $ee \rightarrow \tau \tau \; ee$, $\gamma \gamma \rightarrow \tau \tau$
Analysis of worst mixing

Search for “worst” mixing angle

53 degrees $\tilde{\tau}$ mixing angle corresponds to the worst case for (unpolarized ) LEP conditions

$m\tilde{\tau} = 230\ GeV$

Use ILC conditions weighting contribution of both polarisations

Take into account effect of mixing in cross-section and signal efficiency
Analysis of worst mixing (ctd.)

Dependence of signal efficiency on $\tilde{\tau}$ mixing

- Signal efficiency depends on spectrum of detectable $\tau$ decays
- Spectrum of $\tau$ decay products depends on $\tau$ polarisation
- $\tau$ polarisation depends on $\tilde{\tau}$ and LSP mixing angles

Higgsino changes chirality but Bino does not

$\tilde{\tau}_L + $ Bino LSP ($\tilde{\tau}_R + $ Higgsino LSP) softer visible decay products
Analysis of worst mixing (ctd.)

Likelihood-ratio statistic used to weight both polarisations

$m \tilde{\tau} = 230 \text{ GeV} \quad \Delta m = 34 \text{ GeV}$

Equal sharing of $P(+80,-30)$ and $P(-80,+30)$ forseen in H20 ensures an uniform sensitivity to all mixing angles

Mixing angle of 53 degrees selected
General cuts

Properties $\tilde{\tau}$ -events “must” have

- Missing energy ($E_{\text{miss}}$). $E_{\text{miss}} > 2 \times M_{\text{LSP}}$ GeV
- Visible mass ($m_{\text{vis}}$). $m_{\text{vis}} < 2 \times (M_{\tilde{\tau}} - M_{\text{LSP}})$ GeV
- Momentum of all jets ($p_{\text{jet}}$). $p_{\text{jet}} < 70\%$ Beam Momentum (or $M_{\tilde{\tau}}/M_{\text{LSP}}$ dependent)

- Two well identified $\tau$’s and little other activity

- Maximum jet momentum:
  \[ P_{\text{max}} = \frac{\sqrt{s}}{4} \left(1 - \left(\frac{M_{\text{LSP}}}{M_{\tilde{\tau}}}ight)^2\right) \left(1 + \sqrt{1 - \frac{4M_{\tilde{\tau}}^2}{s}}\right) \]

Above 95 % signal efficiency for each of these cuts (excluding for the $\tau$-identification)

Well known initial state Hermeticity

Clean final state (‘no’ pile-up)

Triggerless operation
General cuts (ctd.)

Properties $\tilde{\tau}$-events “might” have, but background “rarely” has

- Missing transverse momentum
- Large acoplanarity
- Large transverse momentum wrt. thrust-axis
- High angles to beam

Cuts against properties of irreducible sources of background

- Charge asymmetry ($\sum \text{charge} \times \cos(\text{polar\_angle})$)
- Difference between visible mass and $Z$ mass

Properties that the background often “does not” have

- Low energy in small angles
- Low energy of isolated neutral clusters
Beam induced backgrounds in $e^+e^-$ colliders

$e^+e^-$ beams are accompanied by real (beamstrahlung) and virtual (Weizsäcker-Williams process) photons

Interactions between real and/or virtual photons produce:

- **$e^+e^-$ pairs**
  - produced by scattering of two real photons
  - $10^5$ pairs per bunch crossing
  - very low $p_T$ ($< 1 \text{GeV}$), curl up in magnetic field, interesting for BeamCal studies

- **low $p_T$ hadrons**
  - produced by vector meson fluctuations of real or virtual photons
  - $<1.05>$ events per bunch crossing at $\sqrt{s} = 500 \text{ GeV}$
  - low $p_T$, travelling through the detector

**$\gamma\gamma$ interactions are independent of the $e^+e^-$ process**, but can happen simultaneously to it (overlay-on-physics events) or not (overlay-only events)
Effect of overlay-on-physics events

Full simulation
- Not cut on overlay tracks
- Cut on tracks based on transverse momentum, angular distribution and input parameter significance

Fast simulation (SGV) – not overlay tracks

Larger effect of overlay tracks in low DM case since they are more similar to the signal ones: strong reduction of significance

\[ \Delta m = 3 \text{ GeV} \]

\[ m \tilde{\tau} = 240 \text{ GeV} \]

\[ \Delta m = 10 \text{ GeV} \]

\[ m \tilde{\tau} = 240 \text{ GeV} \]
Motivation for only-overlay events analysis

Overlay-only events are $\sim 10^3$ times higher than any SM background included in the analysis

- Overlay-only events: $\sim 10^3$ per train
  - ($<1.05> \text{ low } p_T \text{ hadrons } + \sim 1 \text{ seeable } e^+e^- \text{ pair})/BX$
- SM background: $\sim 1$ per train
- Signal: $\sim 10^{-6}$ per train

$\gamma\gamma \rightarrow \text{low } p_T \text{ hadrons} \quad \text{similar to visible products from } \tilde{\tau} \text{ production for small } (\leq 10 \text{ GeV}) \text{ LSP- } \tilde{\tau} \text{ mass differences}$

Overlay-only events can be misidentified as signal events

A suppression stronger than $10^{-9}$ is needed to make the background from overlay-only events negligible
Only-overlay analysis strategy

Identify a set of independent cuts (not enough Monte Carlo statistics to get the suppression by sequential cuts)
Compute total rejection factor as the product of the factors obtained with either of these cuts

Rejection “standard” cuts alone:

\[ M_{\tilde{\tau}} - M_{\text{LSP}} \text{ (DM)} \]

- 2 GeV: 2.6 x 10^{-3}
- 10 GeV: < 2.7 x 10^{-6} (95% CL)

(All surviving events with \( \gamma\gamma \rightarrow \text{low pT hadrons} \) interactions)

Study of two different mass differences between \( \tilde{\tau} \) and LSP masses (2 and 10 GeV) since general cuts depend on space point
Examples general cuts on overlay-only events

Main difference between DM= 2 GeV and DM = 10 GeV rejections

Main difference between tracks in signal and overlay-only events (main rejection for DM= 2 GeV)
Independent set of cuts from the “standard” ones:
- missed $p_T + \rho^1$
- remaining cuts$^2$

(several cuts among the “standard” ones depend on the exact model-point)

Additional independent requirements based on:
- Initial State Radiation photons (ISR)
- vertex

(1) Tranverse momentum (in the plane) with respect to the thrust axis
(2) Multiplicity, energy, angular distributions, $\tau$ identification
ISR requirement

Events with isolated photons with sizeable energy and angle to the beam above the lower edge of the tracking system

- Energy > 1.1 GeV
- Angle optimized for getting enough rejection without killing all events

\[ \theta \text{ cut tuned from } \theta > 7 \text{ degrees (lower edge tracking system) to } 45 < \theta < 135 \text{ (no background)} \]
Vertex requirement

Events with at least two “non-vertex” tracks

Main vertex fitted with beam-spot as a constraint, effectively meaning that it will have at least two tracks

Tracks that are not included in any vertex (too high $x^2$) are “non-vertex” tracks

- Signal DM=2
- Signal DM=10
- Overlay low $p_T$ hadrons
- Overlay electrons
Rejection on overlay-only events

DM = 10 GeV

<table>
<thead>
<tr>
<th>Condition</th>
<th>red. missed $P_T + \rho$</th>
<th>combined w/ missed $P_T + \rho$</th>
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<tr>
<td>red. alone</td>
<td>1.3x10^{-3}</td>
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<td>remaining cuts</td>
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<tr>
<td>remaining cuts</td>
<td>6.0x10^{-3}</td>
<td>7.8x10^{-6}</td>
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<tr>
<td>remaining cuts + ISR ($7 &lt; \theta$)</td>
<td>1.4x10^{-4}</td>
<td>1.8x10^{-7}</td>
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<tr>
<td>remaining cuts + ISR ($35 &lt; \theta &lt; 145$)</td>
<td>1.7x10^{-5}</td>
<td>2.2x10^{-9}</td>
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DM = 2 GeV

<table>
<thead>
<tr>
<th>Condition</th>
<th>red. vertex</th>
<th>combined w/ vertex</th>
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<tr>
<td>standard cuts</td>
<td>2.6x10^{-3}</td>
<td>5.0x10^{-5}</td>
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<tr>
<td>standard cuts + ISR ($7 &lt; \theta$)</td>
<td>1.8x10^{-7}</td>
<td>3.5x10^{-9}</td>
</tr>
<tr>
<td>standard cuts + ISR ($30 &lt; \theta &lt; 150$)</td>
<td>9.5x10^{-9}</td>
<td>1.8x10^{-10}</td>
</tr>
</tbody>
</table>

Signal efficiency: ~10% with no requirement on detecting an ISR. It goes to ~5% if a detected ISR is required (for any $\theta$)
Adding overlay-only events to SM background

Significance with/wo overlay-only events
DM = 2 GeV

#overlay-only events ~70 per polarisation
(complete running time, both polarisations)
Adding overlay-only events to SM background

Significance with/wo overlay-only events
DM = 10 GeV

#overlay-only events ~700 per polarisation
(complete running time, both polarisations)

Less effect for DM = 10 GeV since remaining SM background is higher than the ones from overlay-only events (opposite to DM= 2)
Adding overlay-only events to SM background

Significance with/wo overlay-only events
DM = 10 GeV

#overlay-only events ~700 per polarisation (complete running time, both polarisations)

The estimated effect from overlay-only events can be taken as a “worst” case:
- overlay-only events intentionally kept to overcome the lack of statistics
- ILC data sets with same beam polarisation could be use to reduce systematics and improve results
ILC expected limits

Current model-independent limits for $\Delta M > \tau$ mass come from LEP
ILC expected limits

Current model-independent limits for $\Delta M > \tau$ mass come from LEP

ATLAS - simulation preliminary
HL-LHC - only $\tau_R$ : 95% CL exclusion
(ATL-PHYS-PUB-2018-048)
ILC expected limits

At ILC discovery and exclusion are almost the same

arXiv:2203.15729
ILC expected limits

At ILC discovery and exclusion are almost the same

arXiv:2203.15729
Outlook/Conclusions

• Even after HL-LHC \( \tilde{\tau} \)-LSP mass plane will remain almost completely unexplored

• Future electron-positron colliders are ideally suited for \( \tilde{\tau} \) searches

• Worst scenario for \( \tilde{\tau} \) production at the ILC was reviewed taking into account ILC beam polarisation conditions

• Effect of beam induced backgrounds for \( \tilde{\tau} \) searches was analysed (as overlay-on-physics and overlay-only events)

ILC will discover/exclude \( \tilde{\tau} \)‘s for any \( \tilde{\tau} \)-LSP mass difference and any \( \tilde{\tau} \)-mixing nearly up to the kinematic limit