$ilde{ au}$ searches at future e⁺e⁻ colliders

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FC@DESY, March 2025



CLUSTER OF EXCELLENCE QUANTUM UNIVERSE



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Motivation for $\tilde{\tau}$ searches

For SUSY searches it is a Good Idea (TM):

- To search for well motivated and maximally difficult NLSPs
- Since, if one can find this, then one can find any other NLSP

The $\tilde{\tau}$, the scalar super-partner of τ -lepton, satisfies both conditions.

• Well motivated:

- Due to mixing, likely to be the lightest sfermion.
- Can do co-annihilation.
- Least constrained from data.

• Difficult:

- Due to mixing, has lower cross-section than other sleptons and squarks
- Decays partially invisibly.
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The $\tilde{\tau}$...

- 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 likely to be the lightest sfermion (stronger trilinear couplings)
- With assumed R-parity conservation:
 - Pair produced in s-channel via Z^0/γ exchange. Low σ since $\tilde{\tau}$ -mixing suppresses coupling to the Z^0 .
 - Decay to LSP and $\tau,$ implying more difficult signal identification than the other sfermions

Limits at LEP and LHC/HL-LHC

• Unpublished LEP combination, LEPSUSYWG/04-01.1

- PDG: Best published limit (DELPHI) 81.9 GeV (any mixing if ΔM > 15 GeV), 26.3 for any mixing and ΔM
- Limited by energy, luminosity and trigger
- LHC : ATLAS modeldependent (only for τ̃_R), excludes only very high ΔM. No discovery potential..
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 $\tilde{\tau}$ properties at e⁺e⁻ colliders

$\tilde{\tau}$ properties at e⁺e⁻ colliders: Production & decay



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$\tilde{\tau}$ properties at e⁺e⁻ colliders: Backgrounds

SM processes with real or fake missing energy

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SM processes with real or fake missing energy Irreducible

• 4-fermion production with two of the fermions being neutrinos and two τ 's



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Almost Irreducible

- $e^+e^- \rightarrow \tau \tau$, $ZZ \rightarrow \nu \nu II$, $WW \rightarrow I \nu I \nu$ $(I = e \text{ or } \mu)$
- $e^+e^- \rightarrow \tau \tau + ISR$, $e^+e^- \rightarrow \tau \tau ee$, $\gamma \gamma \rightarrow \tau \tau$
- Mis-identification of *τ*'s or of missing momentum

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- Production cross-section depends on mixing.
- Visibility depends on the τ polarisation, and τ polarisation depends on both τ̃ and neutralino nature.
- So, to get the worst case, the combination of low cross-section and low visibility should be found.



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- Use Likelihood-ratio statistic to weight both polarisations.
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- At ILC, both beams are polarised, and same luminosity LR and R
 Neyman-Pearson's lemma applied to a counting experiment
- Use Likeli weight bo • Then, the \sim uniform with a slic $N_{\sigma} = \frac{\sum_{i=1}^{n_{samp}} s_i \ln (1 + s_i/b_i)}{\sqrt{\sum_{i=1}^{n_{samp}} n_i [\ln (1 + s_i/b_i)]^2}}$ (n_i is either $s_i + b_i$ (exclusion), or b_i (discovery))

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ILD full simulation analysis: MC samples

- Use the IDR 500 GeV FullSim samples
- Covering the full SM background with all $e^+e^-/e^{+/-}\gamma/\gamma\gamma$ processes (> 10⁷ events)
- Beam-spectrum and pairs background from GuineaPig, low P_T hadrons from Barklow generator.
- Signal
 - Spectrum obtained with Spheno.
 - Generated with Whizard
 - Simulated with SGV, with pairs and low P_T hadrons extracted from full-sim
 - 10000 events per point and polarisation,
 - 1867 mass-points, 37×10^6 events.

ILD full simulation analysis: Event selection

Properties $\tilde{\tau}$ -events "must" have

- Missing energy: *E_{miss}* > 2 × *M_{LSP}* GeV
- Visible mass: $M_{vis} < 2 \times (M_{\widetilde{\tau}} M_{LSP})$ GeV

Well-known initial state and hermeticity !

- Two well identified τ 's and little other activity
- Maximum jet momentum:

$$P_{max} = \frac{\sqrt{s}}{4} \left(1 - \left(\frac{M_{LSP}}{M_{\tilde{\tau}}} \right)^2 \right) \left(1 + \sqrt{1 - \frac{4M_{\tilde{\tau}}^2}{s}} \right)$$

Clean final state with no pile-up.

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Well-known ir Above 95 % signal efficiency after these

- Two well cuts (excluding for the τ -identification)
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ILD full simulation analysis: Event selection

Properties $\tilde{\tau}$'s "might" have, but background "rarely" has

- Missing P_T
- Large acoplanarity
- Large P_T wrt. thrust-axis (ρ)
- High angles to beam

properties of irreducible sources of background

- Charge asymmetry $(q_{jet} \cos \theta_{jet})$
- Difference between visible mass and Z mass
- Properties that background often "does not" have
 - Low energy in small angles
 - Low energy of isolated neutral clusters



 e^+e^- beams are accompanied by real and virtual photon Interactions between these produce:

- Low p_T hadrons
 - At ILC500 $\langle N\rangle{=}1.05/BX,$ CLIC380(3000) $\langle N\rangle{=}0.17(3.1)/BX,$ FCCee $\langle N\rangle$ =0/BX
 - Low p_{T} hadrons are "physics": the total number collected scale with $\int \mathcal{L}$
- e⁺e⁻pairs
 - At ILC, 10^5 pairs per bunch crossing, but only \sim 10 will hit any tracking detector.
 - Much reduced at FCCee, assumed absent in our recast.

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

Overlay-on-physics events: Not an issue at FCCee, due to low per-BX luminosity.

Green: No overlay, Red,Blue: with overlay with or w/o mitigation. $M_{\tilde{\tau}}$ =240 GeV.

- $\Delta M = 3 \text{ GeV}$
- $\Delta M = 10 \text{ GeV}$
- Larger effect for low △M, hardly any for △M > 10 GeV.

Overlay-only events: Similar for ILC and FCCee.

- Need reduction-factor ~ 10⁻¹⁰, which can be achieved.
- Some slight effect at $\Delta M = 2$, completely negligible wrt. other backgrounds at $\Delta M = 10$.



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Impact of specific ILD/ILC features: Energy, triggerless operation

Energy, the main advantage for any linear option, a no-brainer:

 increase in centre-of-mass energy covers much more parameter space, up to close to kinematic limit

Triggerless operation:

• Big advantage when searching for unexpected signatures Possible at linear colliders due to low collision frequency, might not possible at circular colliders, but we will assume it will.

Impact of specific ILD/ILC features: Polarisation

Polarisation:

- Combination different polarisation samples allows for equal sensitivity to all mixing angles
- Polarisation provides higher sensitivity: Likelihood ratio weighting.
- Both beams polarised: Effective luminosity for s-channel processes increased, +24 % for ILC wrt. FCCee.

Clear edge for ILC - CLIC/C3 only e⁻ polarisation, FCCee has no polarisation. CepC studies if polarisation *might* be possible.



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Impact of specific ILD/ILC features: Luminousiy, Beam-induced backgrounds

Luminosity, the strong points for FCCee and CepC.

- But: higher luminosity gives only very little improvement
 - Ex. 2 to 5 (10) ab^{-1} at 250 GeV for $\Delta M = 2$ GeV changes excl. limit on $M_{\tilde{\tau}}$ from 112 to 117 (117) GeV, negligible for $\Delta M = 10$ GeV

Beam-induced backgrounds:

- Overlay-on-physics: Due to low per-BX-luminosity this is not an issue for the circular colliders.
- Overlay-only: to first order, similar for both options (goes with total luminosity)
- The details enter: Smaller beam-spot, triggerless operation, thinner beam-pipe and vertex detector, polarisation, all makes the linear options more powerful

Hermeticity: The issue is can you see the beam-remnant $e^{+/-}$ in $\gamma\gamma$ processes ? If not, false missing P_T will be seen ...

 ILD at ILC: hermetic to 6 mrad - Any detector at FCCee; hermetic to 50 mrad.

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- ... but less so for τ̃: Much missing P_T is from the neutrinos.
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Conclusions

- Even after HL-LHC τ̃-LSP mass plane will remain almost completely unexplored
- Future electron-positron colliders are ideally suited for $\tilde{\tau}$ searches
- *τ* mixing and LSP nature influence production cross-sections and decay kinematics ⇒ picked "worst scenario" for actual analysis
- Polarised beams: combination of data-taking with different signs enables equal sensitivity to all mixing angles
- Beam-induced backgrounds at Linear Colliders can be mitigated up to small residual impact of \sim 1GeV on highest reachable mass for lowest ΔM
- Higher centre-of-mass energies cover much more parameter space, higher luminosity gives only very little improvement, ex. increase of ILC250 luminosity from 2 to 10 ab⁻¹ affects the τ mass limit only by 5 GeV
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BACKUP SLIDES

Mikael Berggren (DESY)

 $\tilde{\tau}$ searches

FC@DESY, March 2025 21/22

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ILD full simulation analysis: Beam-induced backgrounds

- Overlay-only events are $\sim 10^3$ more than any other SM background, and $\sim 10^6$ times higher than the signal !
- $\gamma\gamma \rightarrow \text{low } p_T$ hadrons looks like $\tilde{\tau}$ production for $\Delta M \leq 10 \text{ GeV}$).
- Similar for ILC and FCCee

Not enough MC statistics to estimate the suppression from single set of cuts!

Identify a set of independent cuts: total rejection factor as the product of the factors obtained with either.

- Achieved rejection factor factor: $\sim 8.2 \times 10^{-11}$ for $\Delta M = 2$; 1.8×10^{-10}) for $\Delta M = 10$.
- In total, 70 or 30 additional background events expected from overlay-only.
- Some slight effect at $\Delta M = 2$, completely negligible wrt. other backgrounds at $\Delta M = 10$.

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