$\tilde{\tau}$ searches at future e^+e^- colliders

Teresa Núñez - DESY

- Introduction
- $\tilde{\tau}$ ´s at future e^+e^- colliders
- ILD full simulation analysis
- Impact of ILD/ILC specific features
- Conclusions

Second ECFA Worshop on e+e- Higgs/Top/EW Factories
Paestum, October, 11-13, 2023

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Introduction:

SUSY at future e^+e^- Higgs/EW/Tops factories

Supersymmetry is the most complete BSM theory, and …

… boilerplate for BSM (almost any new topology can be obtained in SUSY)

Excellent scenarios for SUSY searches

Wrt. previous electron-positron colliders:

- increased luminosity and centre-of-mass energy
- beam polarisation
- improved detector technologies
- microscopic beam-spot

Wrt. hadron colliders:

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

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Introduction:

SUSY at future e^+e^- Higgs/EW/Tops factories (ctd.)

- Naturalness, the hierarchy problem, the nature of DM, or the measured magnetic moment of the muon prefer a light electroweak sector of SUSY
- Many models and the global set of constraints from observation point to a compressed spectrum

Future e^+e^- colliders are well adapted to well motivated, and very challenging for hadron colliders, SUSY scenarios

- energies from 90 GeV to 3 TeV, with typically a first run at 240/250 GeV
- both/one/none of the beams polarised
- clean or very clean conditions
- hermeticity excellent for some (down to ~6 mrad), still good for others (down to ~50 mrad)

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Introduction: Motivation for $\tilde{\tau}$ searches

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

$\tilde{\tau}$ satisfies both conditions

Scalar superpartner of τ-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/γ exchange, low σ since $\tilde{\tau}$-mixing suppresses coupling to the Z^0)

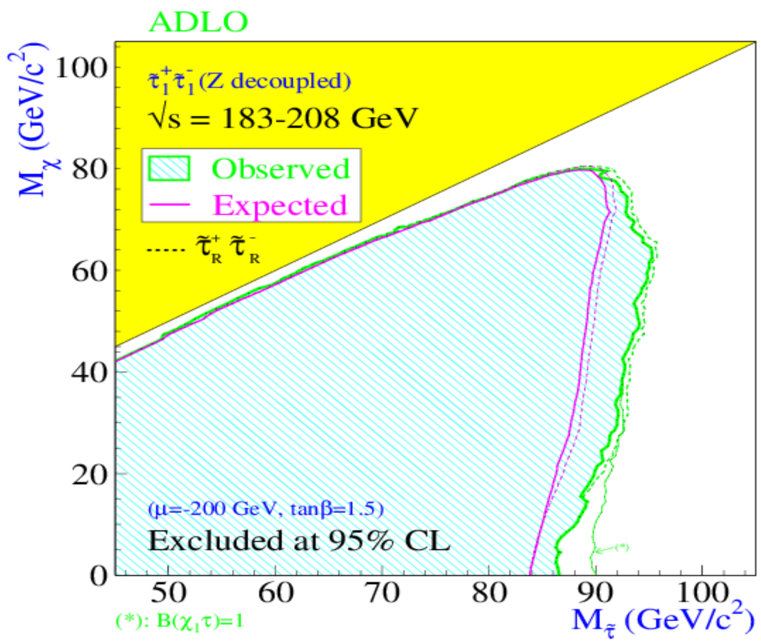
  - decay to LSP and τ, implying more difficult signal identification than the other sfermions

SUSY models with a light $\tilde{\tau}$ can accommodate the observed relic density ($\tilde{\tau}$ - neutralino coannihilation)

Introduction: Limits at LEP and LHC/HL-LHC

$\tilde{\tau}$ searches at LEP

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



- **$\sqrt{s}$ = 183-208 GeV**
- **Combined four LEP experiments data**

LEPSUSYWG/04-01.1

Main limitations for LEP searches are energy, luminosity and trigger

According to PDG, most solid limit on $\tilde{\tau}$ mass comes from DELPHI and is set to 81.9 GeV (valid for any mixing if DM > 15 GeV)

DELPHI suppresses $\tilde{\tau}$ masses below 26.3 for any mixing and mass difference

arXiv:hep-ex/0311019

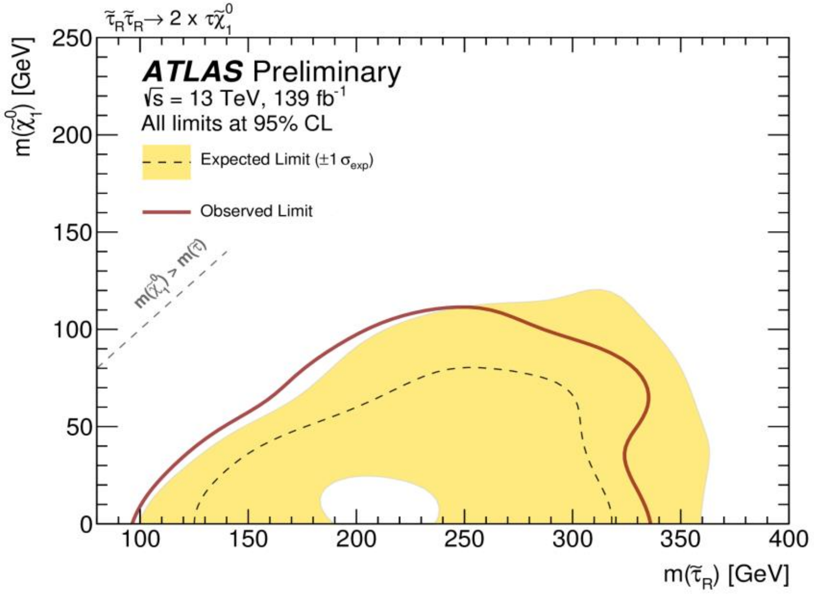
Introduction: Limits at LEP and LHC/HL-LHC (ctd.)

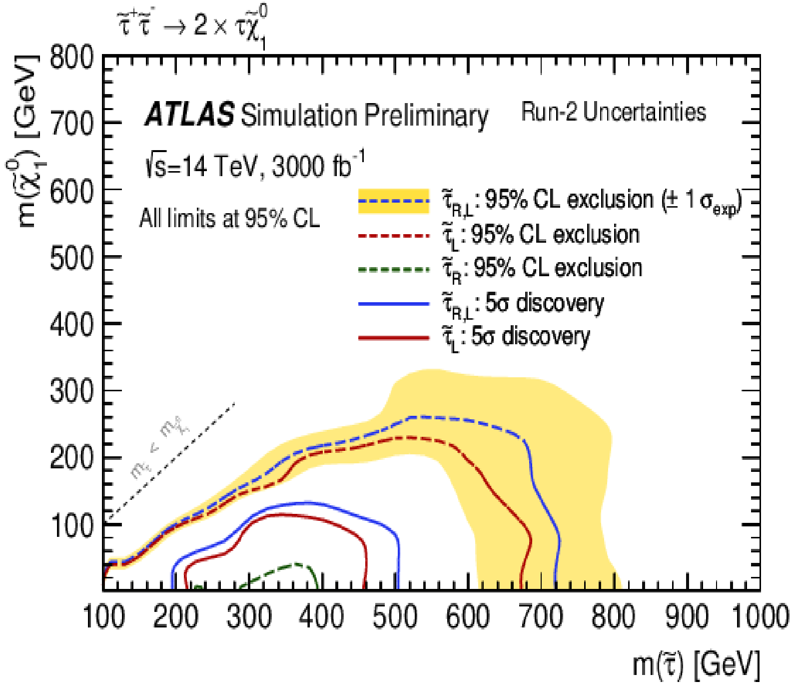
Assume $\tilde{\tau}_R$ and $\tilde{\tau}_L$ to be mass degenerated and not mixing

$\tilde{\tau}$ prospects at HL-LHC

First $\tilde{\tau}_R$ limits at LHC

ATLAS-CONF-2023-029





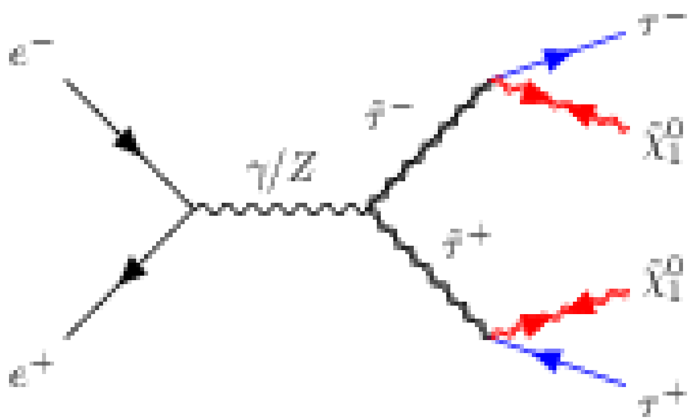
$M_{\tilde{\tau}} - M_{LSP} > 120$ GeV

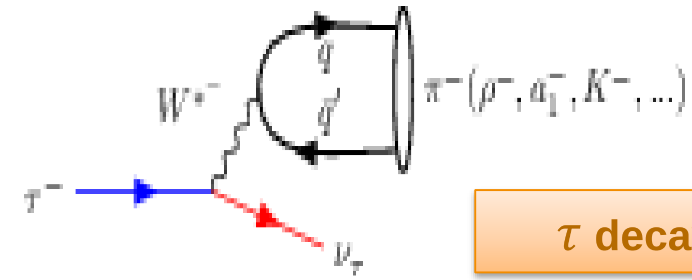
No discovery potential for $\tilde{\tau}$ coannihilation scenarios or $\tilde{\tau}_R$ pair production

ATL-PHYS-PUB-2018-048

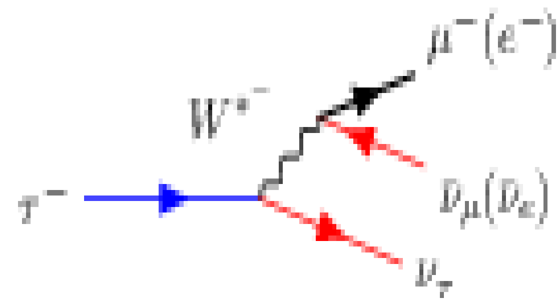
$\tilde{\tau}$´s at future e^+e^- colliders:production & decay

s-channel production





τ decays



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

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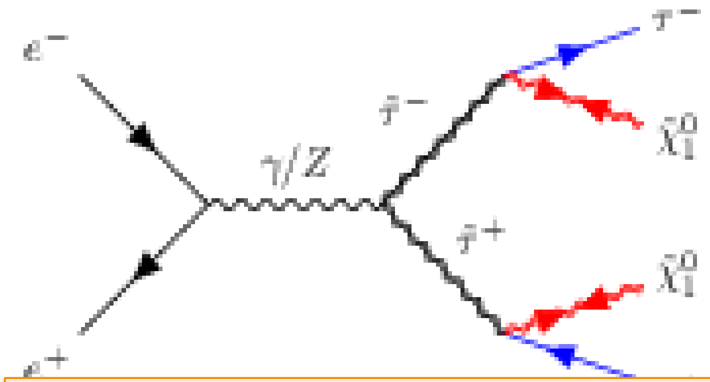
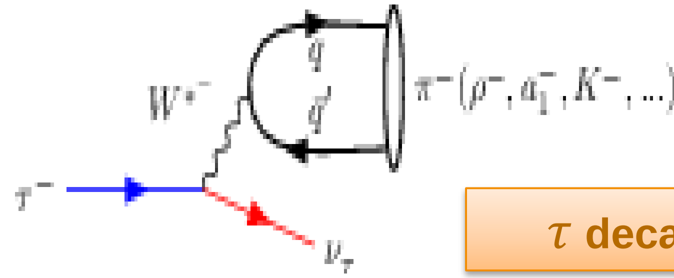
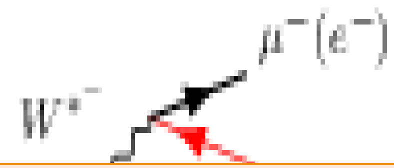
$\tilde{\tau}$ ´s at future e^+e^- colliders:production & decay(ctd.)

s-channel production





τ decays



Signature:

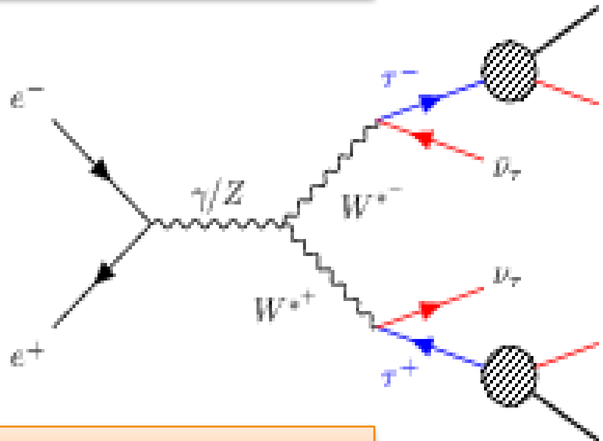
- large missing energy and momentum
- large fraction of detected activity in central detector (isotropic production of scalar particles)
- large angle between the two τ-lepton directions
- unbalanced transverse momentum
- zero forward-backward asymmetry

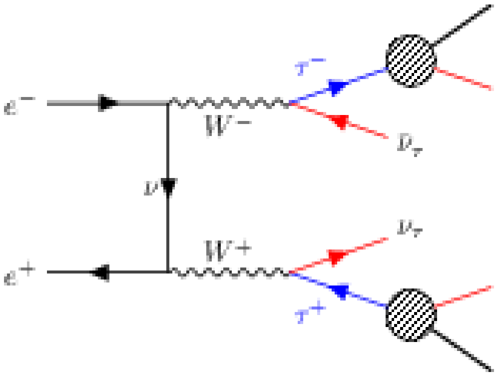
$\tilde{\tau}$´s at future e⁺e⁻ colliders: backgrounds

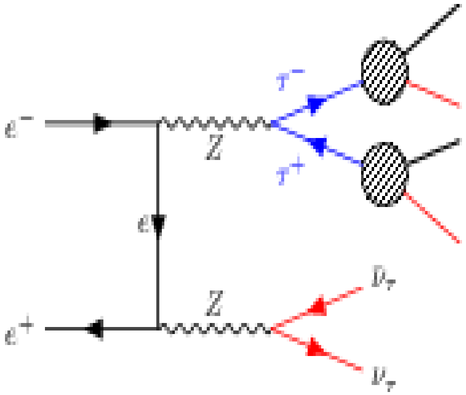
SM processes with real or fake missing energy

Irreducible

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







Almost irreducible

Mis-identification of τ´s or of missing momentum

- *ee* -> $\tau\tau$, *ZZ* -> $\nu\nu\ ll$, *WW* -> $l\nu\ l\nu$ (l = e or μ)
- *ee* -> $\tau\tau$ + ISR, *ee* -> $\tau\tau$ *ee*, $\gamma\gamma$ -> $\tau\tau$

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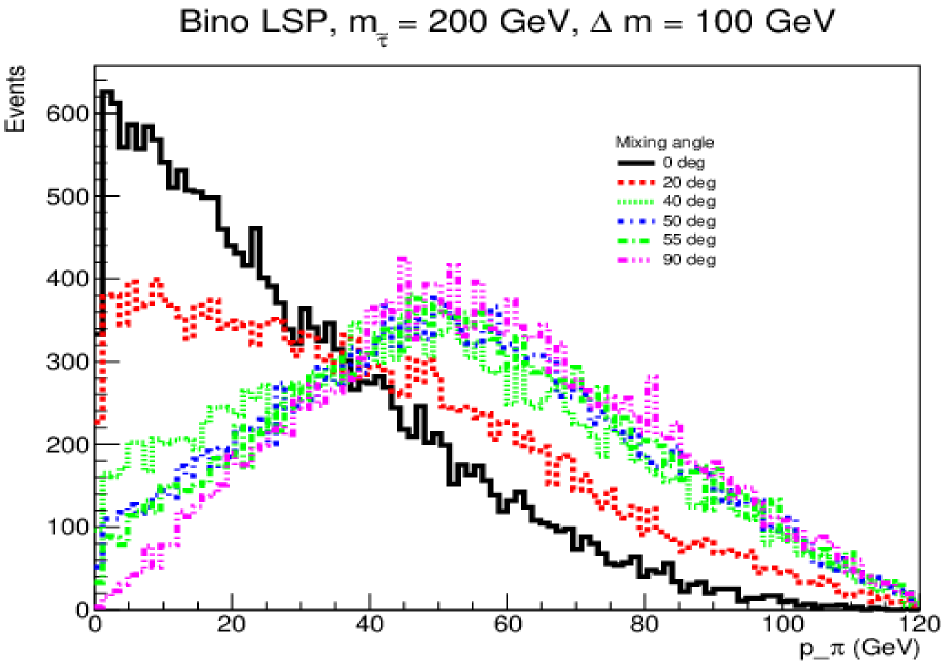
$\tilde{\tau}$'s at future e⁺e⁻ colliders: impact of mixing and LSP nature

Impact on signal efficiency



- Signal efficiency depends on spectrum of detectable τ decays
- Spectrum of τ decay products depends on τ polarisation
- τ 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

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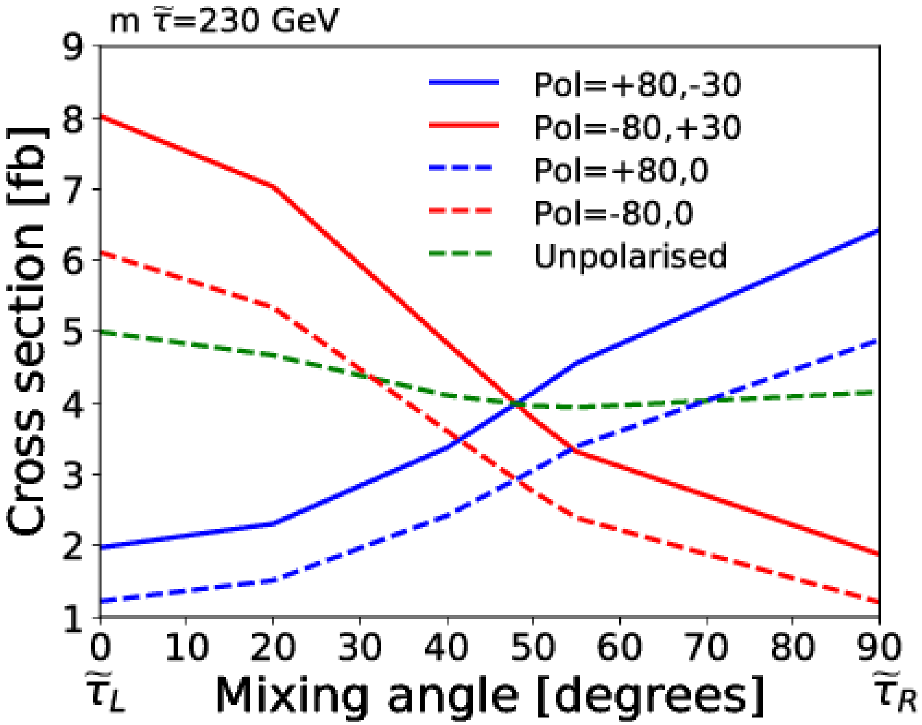
$\tilde{\tau}$ ´s at future e⁺e⁻ colliders:

impact of mixing and LSP nature (ctd.)

Search for "worst" scenario

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



When using polarised beams the contribution of the different polarisation configurations should be weighted

Take into account effect of mixing on cross-section and signal efficiency

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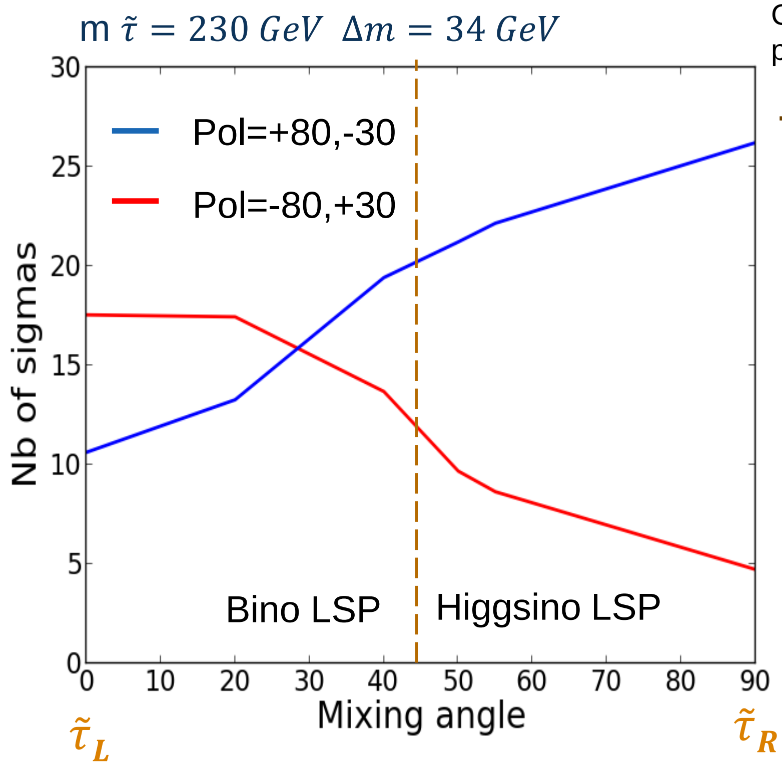
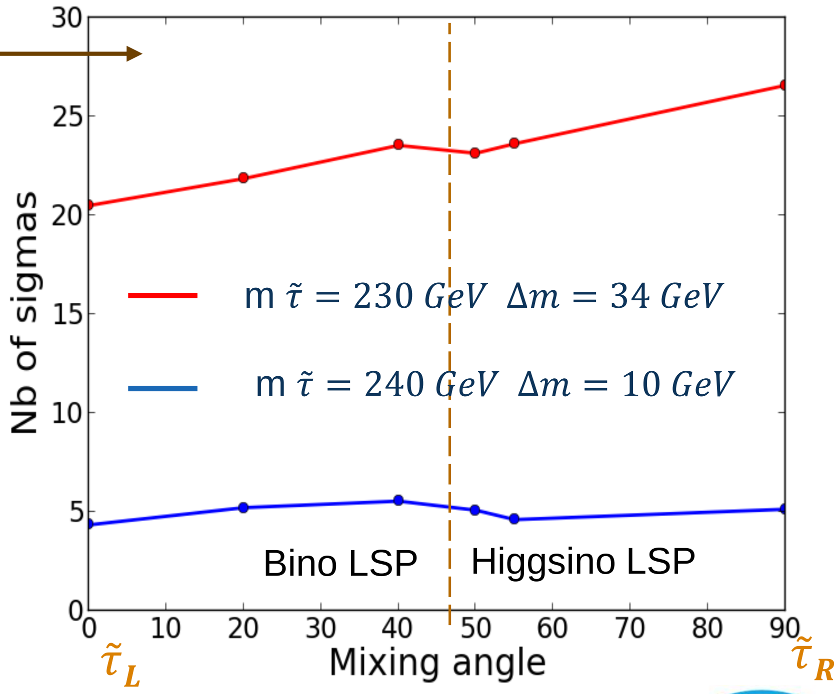
$\tilde{\tau}$´s at future e$^+$e$^-$ colliders: impact of mixing and LSP nature (ctd.)

Likelihood-ratio statistic used to weight both polarisations



Combination for polarised case



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

ILD full simulation analysis:

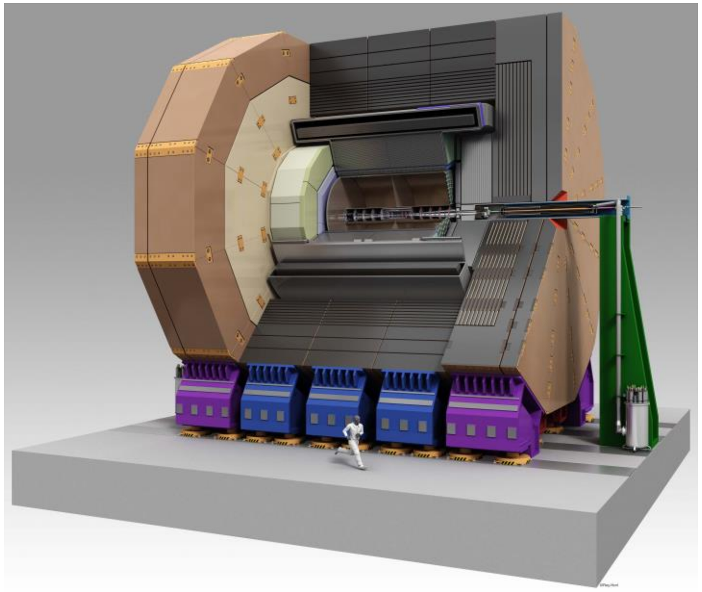
MC samples and event selection

ILD concept …

- High granularity calorimeters optimised for particle flow
- Power-pulsing for low material

… satisfying Physics requirements for BSM …

- Jet energy resolution 3-4%
- Asymptotic momentum resolution $\sigma(1/p_\perp) = 2\times10^{-5}$ GeV^{-1}
- Impact parameter resolution $\sigma(d_0) < 5$ µm
- Hermeticity down to 6 mrad
- Triggerless operation



… developed for the ILC, now studying adjustments for other colliders, esp. FCCee.

Studies using the full Geant4 simulation of the ILC version of the ILD and the existing 500GeV MC samples covering the full SM background with all $e^+e^-/e^{+/-}$ gamma/gammagamma processes ($>10^7$ events)

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ILD full simulation analysis:

MC samples and event selection (ctd.)

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

Event selection

Well known initial state
Hermeticity

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

Clean final state
('no' pile-up)

- Two well identified τ's and little other activity

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

- Maximum jet momentum:

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

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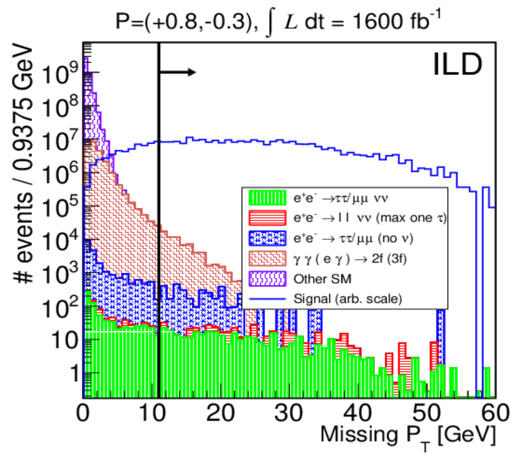
ILD full simulation analysis:

MC samples and event selection (ctd.)

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

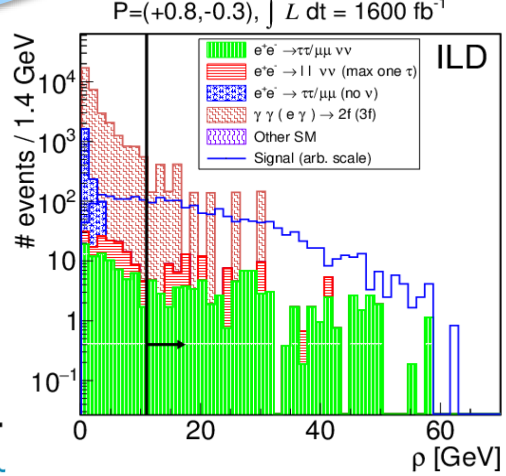
- Missing transverse momentum
- Large acoplanarity
- Large transverse momentum wrt. thrust-axis (ρ)
- High angles to beam



Cuts against properties of irreducible sources of background

High polarised beams

- Charge asymmetry ($\Sigma charge * \cos(polar\_angle)$)
- 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

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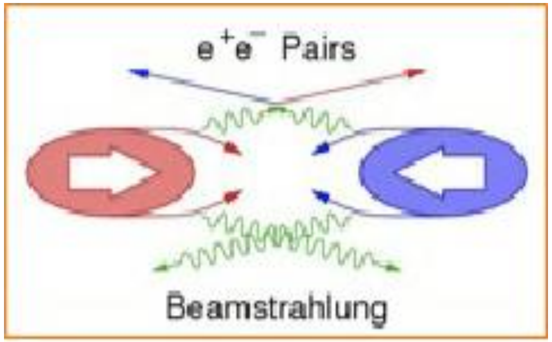
ILD full simulation analysis:

beam induced backgrounds

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



Interactions between real and/or virtual photons produce:

- low p_T hadrons
  - produced by vector meson fluctuations of real or virtual photons
  - e.g. at ILC500 <N>=1.05/BX, CLIC380(3000) <N>=0.17(3.1)/BX, FCCee <N>~=0/BX
  - low p_T, travelling through the detector

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

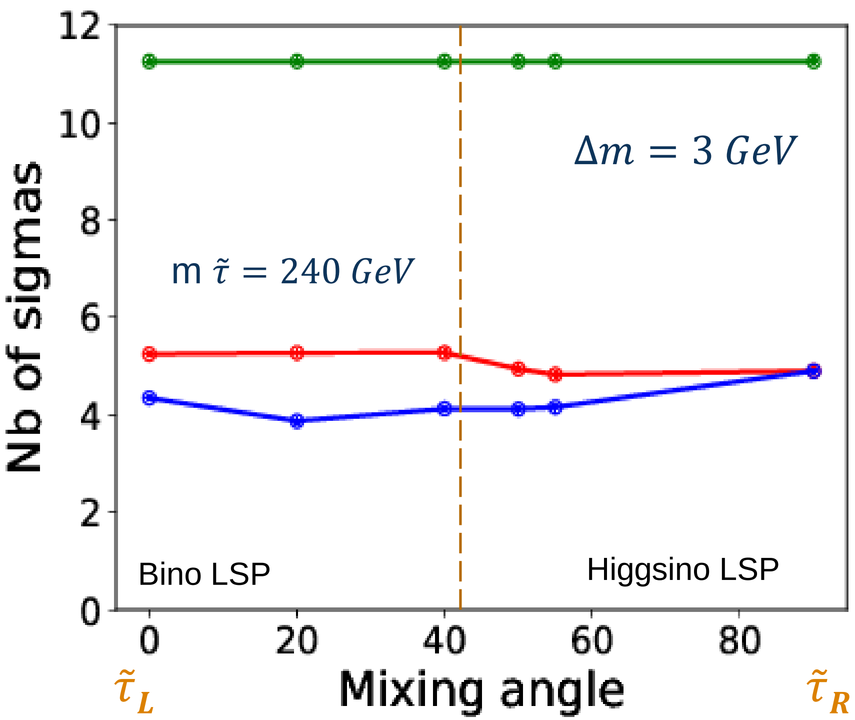
$\gamma\gamma$ interactions are independent of the e^+e^- process, but can happen simultaneously to it (overlay-on-physics events) or not (overlay-only events)

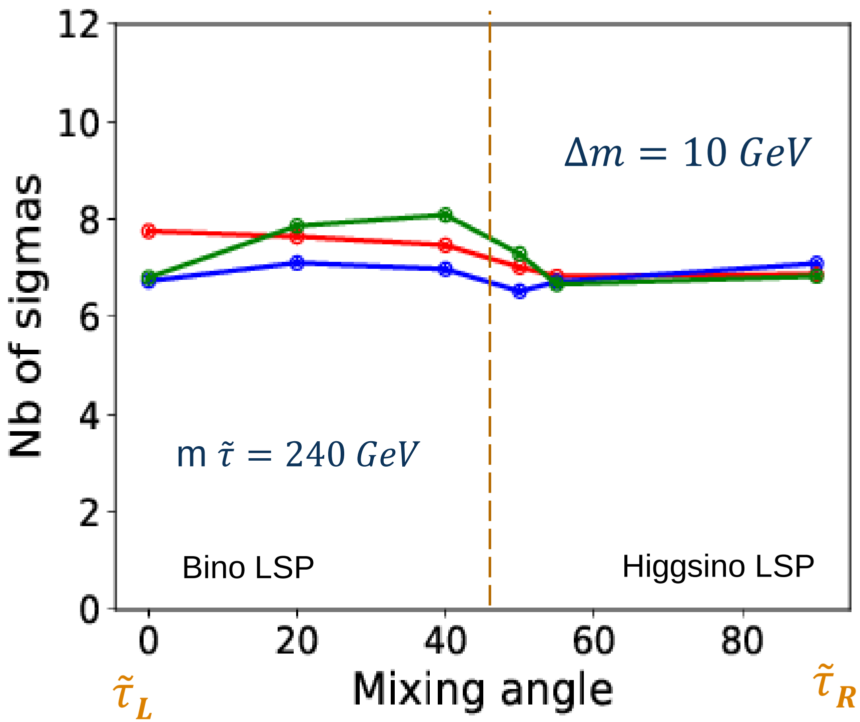
ILD full simulation analysis: beam induced backgrounds

ILC500: effect of overlay-on-physics events

Full simulation

- (blue line) Not cut on overlay tracks
- (red line) Cut on tracks based on transverse momentum, angular distribution and input parameter significance
- (green line) 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

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ILD full simulation analysis:

beam induced backgrounds

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

Motivation for only-overlay analysis

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

ILC500 conditions

$\gamma\gamma \rightarrow low\ pT\ hadrons$ similar to visible products from $\tilde{\tau}$ production for small (≤ 10 GeV) LSP- $\tilde{\tau}$ 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

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ILD full simulation analysis:

beam induced backgrounds

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

Independent set of cuts from the “standard” ones, based on kinematics:

- missed $p_T + \rho^1$
- remaining cuts[2]

Overlay-only analysis strategy

Additional independent requirements based on:

- Initial State Radiation photons (ISR)
- vertex

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

ILD full simulation analysis:

beam induced backgrounds

Identify a set of independent cuts (not enough Monte Carlo statistics to get the suppression by sequential cuts)

Com ... ther of

Achieved rejection factor: 8.2×10^{-11} (1.8×10^{-10}) at the DM = 2 (DM= 10) GeV model point

Indep

70 (30) overlay-only events expected for each polarisation at the DM = 2 (DM= 10) GeV model point

- remaining cuts[2]

Additional independent requirements based on:

- In
- v

For Δ M = 2 (Δ M = 10) GeV, remaining SM background of the order of (two orders of magnitude larger than) the remaining overlay-only events

Negligible effect for Δ M = 10

(2 and 10 GeV) since general cuts depend on space point

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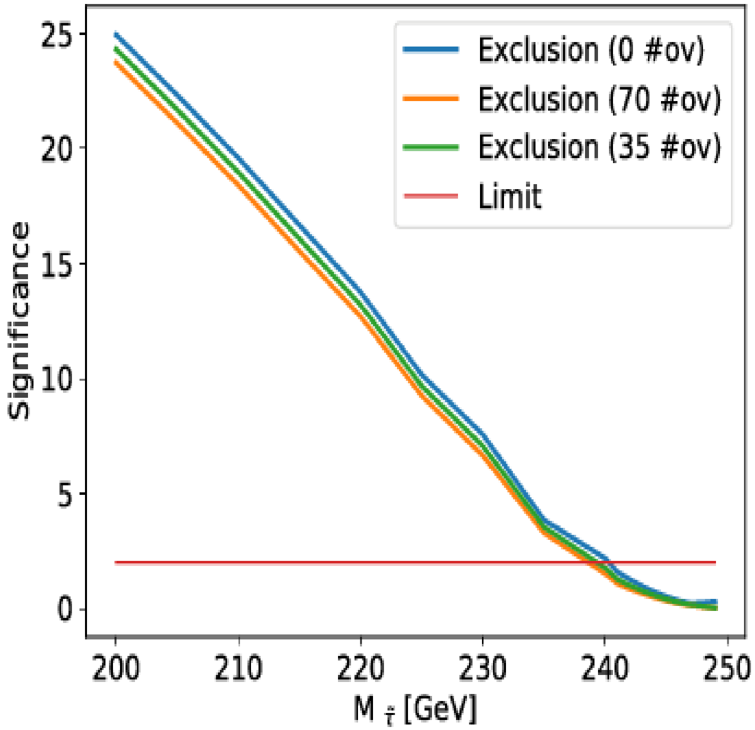
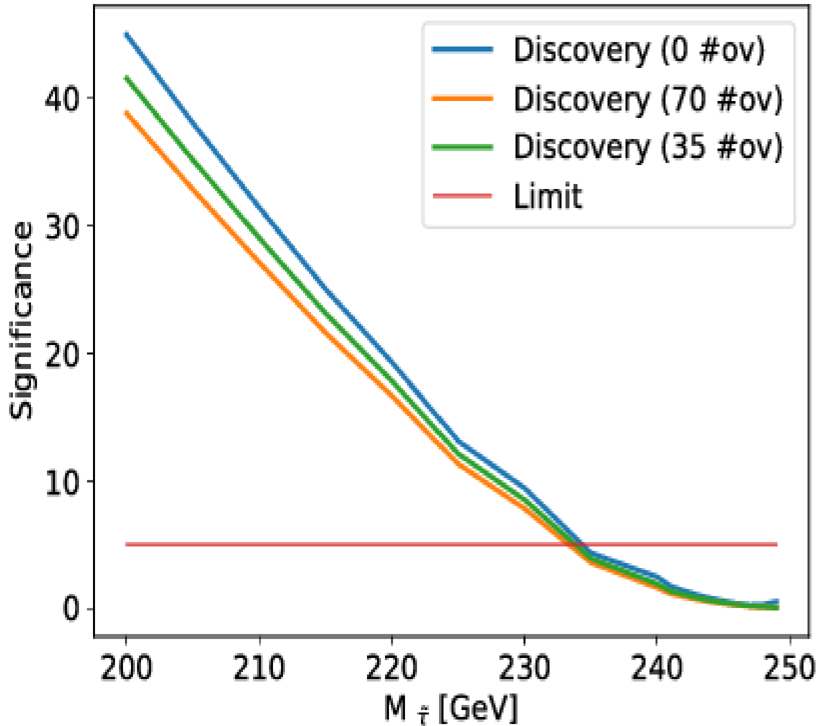
ILD full simulation analysis:

beam induced backgrounds

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

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





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Effect of overlay-only events on limits

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ILD full simulation analysis:

beam induced backgrounds

Significance with/wo overlay-only events

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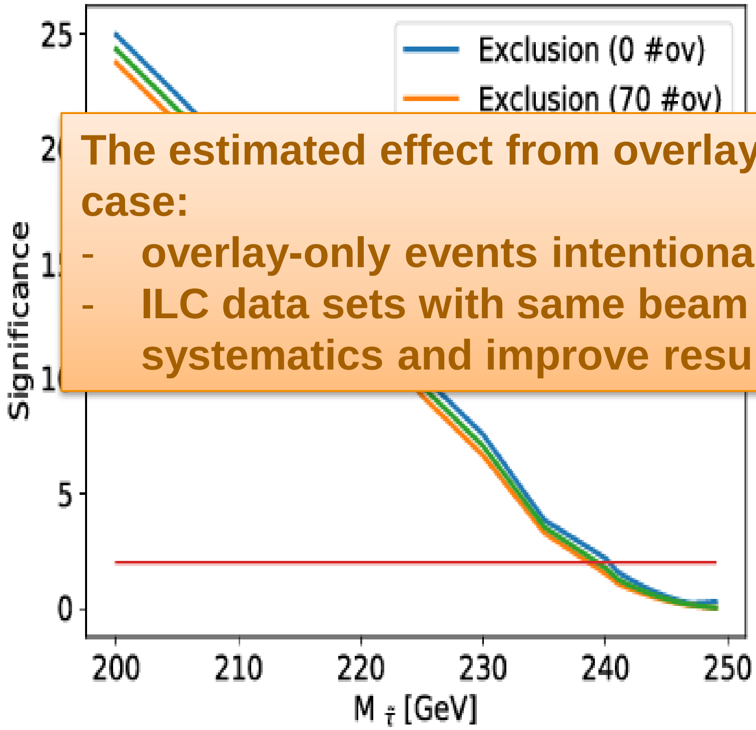

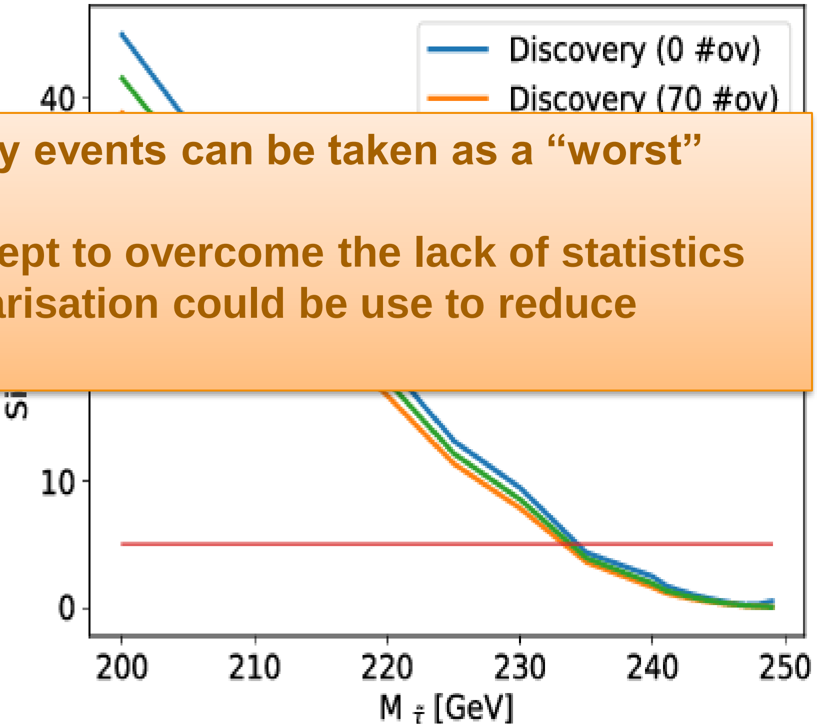

The estimated effect from overlay-only events can be taken as a "worst" case:

- **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**

Effect of overlay-only events on limits

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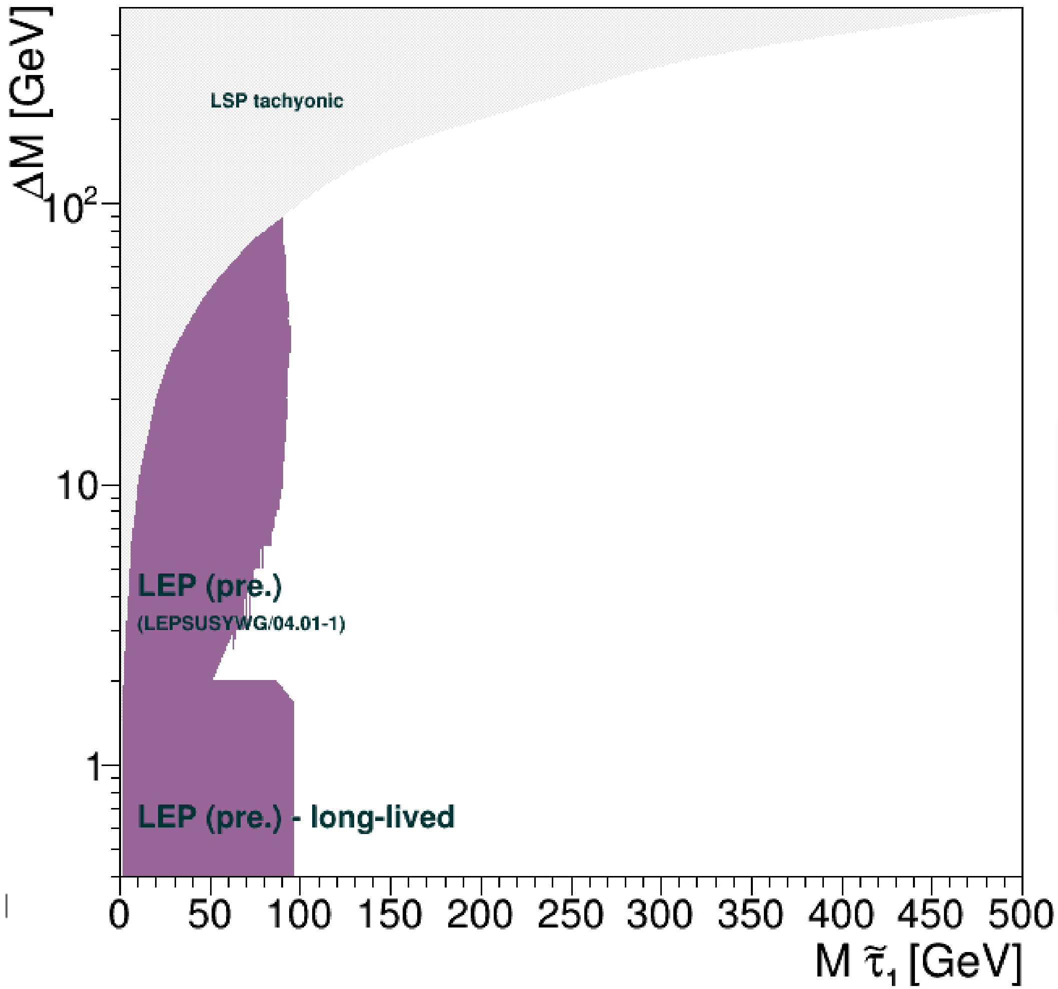
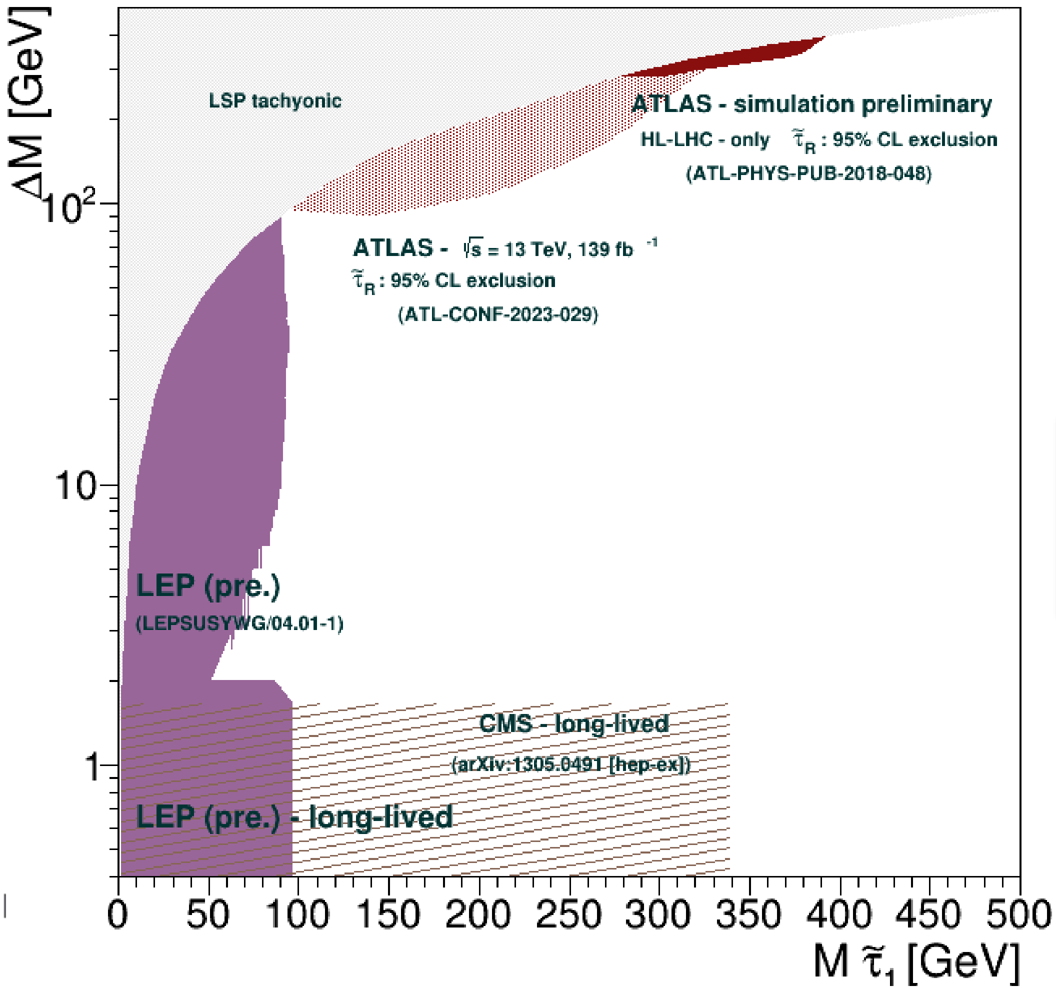
ILD full simulation analysis:results



Current model-independent limits for ΔM > τ mass come from LEP

ILD full simulation analysis:results



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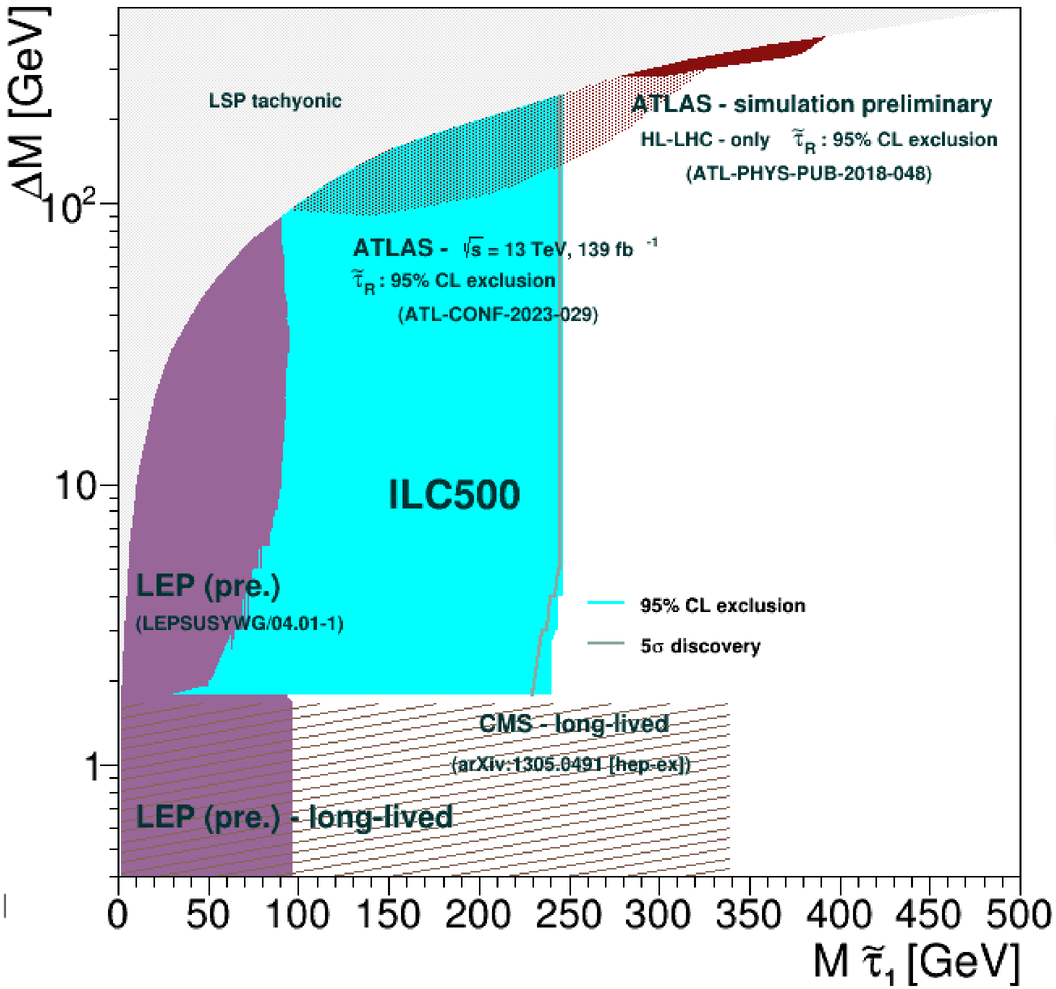
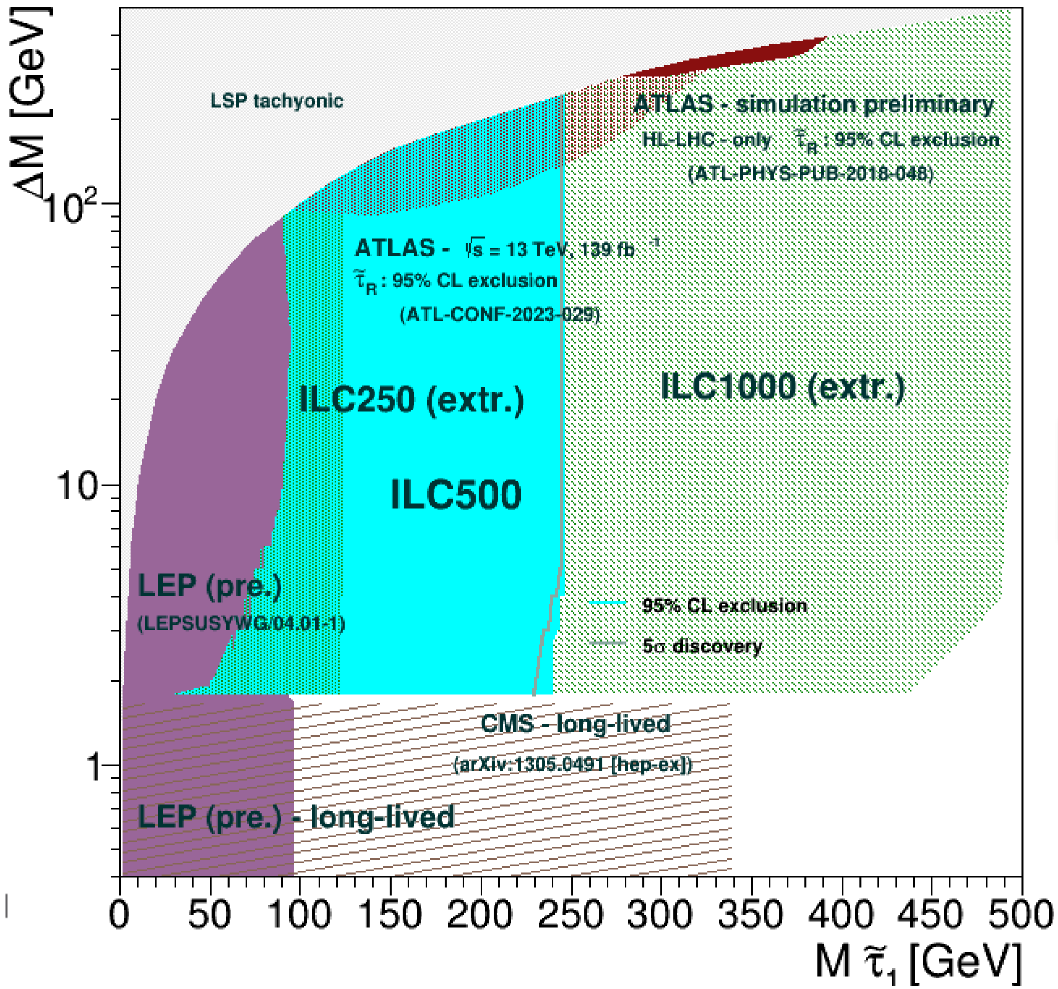
ILD full simulation analysis:results



At ILC discovery and exclusion are almost the same

arXiv:2105.08616

ILD full simulation analysis:results



At ILC discovery and exclusion are almost the same

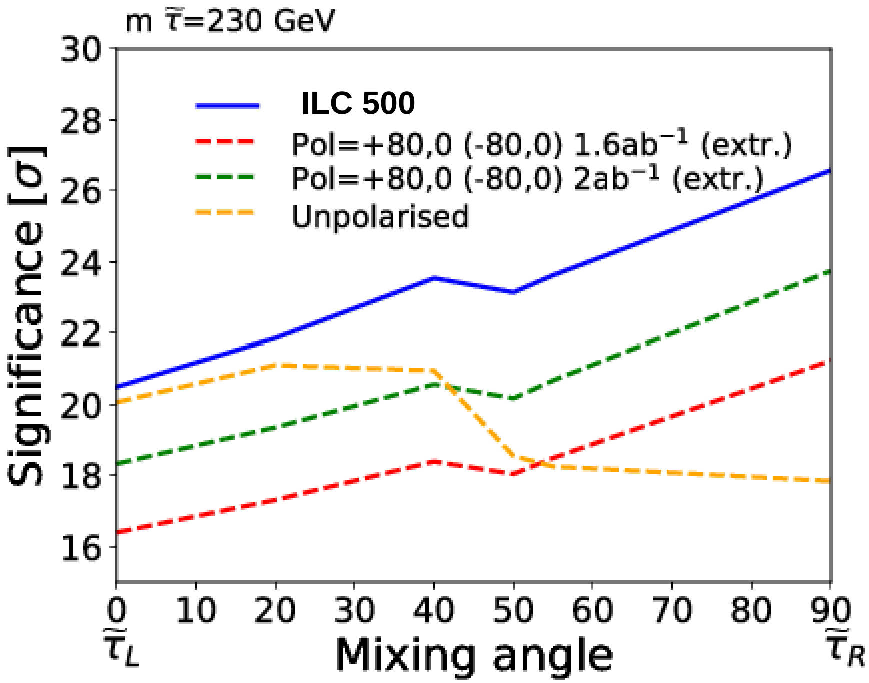
arXiv:2105.08616

Impact of specific ILD/ILC features: polarisation, luminosity, energy

Polarisation:

- combination of data-taking with different polarisation signs enables equal sensitivity to all mixing angles
- polarisation of both beams provides higher sensitivity than one beam or none

CLIC, C3, foresee only the electron beam to be polarised, FCCee does not foresee longitudinal polarisation of the beams, CEPC studies the possibility of electron polarization.



Luminosity:

- higher luminosity gives only very little improvement

Ex. 2 to 5 (10) ab^{-1} at 250 GeV for DM = 2 GeV changes excl. limit on M$\tilde{\tau}$ from 122 to 117 (117) GeV, negligible for DM = 10 GeV

Energy:

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

Impact of specific ILD/ILC features : beam-induced backgrounds

Beam-induced backgrounds:

- possible lost of significance mitigated applying cuts based on transverse momentum and transverse parameter significance (overlay-on-physics) and on vertex (overlay-only)

Impact of less than 1 GeV for highest reachable masses and smallest mass differences, negligible for the rest of the parameter space

Mitigation makes profit of the microscopic beam-spot: similar order of magnitude at CLIC and C3; larger in circular colliders, but no-existent beam-induced backgrounds.

Estimated impact apply to ILC500, smaller at ILC250. No-existent at FCCee, CEPC. CLIC, where the detector needs to integrate over many BX, suffers for more overlay events, but provides timing information that can reduce them substantially

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

Hermeticity:

- crucial when searching for missing momentum signatures

Ex. 50 mrad instead of 6 mrad (ILC) decreases the significance from …

… 34.9 to 10.7 for $M\tilde{\tau}$ = 230 GeV DM = 34 GeV
… 2.08 to 0.7 for $M\tilde{\tau}$ = 245 GeV DM = 10 GeV

Similar order for other linear collider, ex. 10 mrad CLIC, but not for circular ones, ~50 mrad

Triggerless operation:

- big advantage when searching for unexpected signatures

Possible at linear colliders due to low collision frequency, not possible at circular colliders

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
- $\tilde{\tau}$ 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 ~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 $\tilde{\tau}$ mass limit only by 5 GeV
- Hermeticity of detector crucial

Future electron-positron colliders are well suited for discovering/excluding $\tilde{\tau}$'s for any $\tilde{\tau}$-LSP mass difference and any $\tilde{\tau}$-mixing nearly up to the kinematic limit – hermetic detector and ECM reach crucial

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