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

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ILD meeting, CERN, Jan 2023

Outline

Problems with the standard model

The standard model works excellently - but there are problems:

- Theory-experiment discrepancies
  - g-2 of the muon
  - Flavour anomalies
  - Maybe M_W
- Lack of explanations
  - What is dark matter and dark energy?
  - Naturalness and the hierarchy problem: Why is the Higgs mass so small, and why does it remains so?
  - Why do the coupling constants not unify?
  - Neutrinos are weird...
  - Why is charge quantised?
  - The SM gets the cosmological constant wrong by 120 orders of magnitude?!
  - Fermi-Dirac statistics and infinitely dense black holes?

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The need for BSM

So we need models beyond the SM. Two types:

- Well defined, but incomplete models tailored to address some of the issues
  - Simplified models
  - Portal models
- Complete self-consistent models. Not so many on the market:
  - Extra dimensions
  - Compositness
  - Leptoquarks
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SUSY offers solutions and/or hints to solutions to

- Naturalness, the hierarchy problem
- ature of Dark Matter
- g-2
- Lightness and stability of the Higgs
- Coupling constant unification
- Quantisation of charge
- Fermi-Dirac statistics in black holes
- Smallness of the cosmological constant
- ... but probably not DE, flavour

SUSY

Also, apart from this, SUSY is a boilerplate for BSM in general: almost any new topology can be obtained in SUSY.
To note:

- Naturalness, the hierarchy problem, the nature of Dark Matter, and g-2 prefer a light electroweak sector of SUSY.
- Many models and the global set of constraints from observations point to a compressed spectrum, i.e. the lightest (stable) SUSY particle (the LSP), and the next one (the NLSP) are close in mass.

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

Wrt. LEP/SLC:

- Any Higgs factory
  - Increased luminosity
  - Improved detector technologies
- For linear Higgs factories
  - Centre-of-mass energy
  - Beam polarisation
  - More hermetic
  - Trigger-less operation of the detectors

Wrt. hadron colliders:

- Microscopic beam-spot
- Cleaner environment
- Known initial state
- Trigger-less operation of the detectors
- Hermetic detectors

Motivation for $\tilde{\tau}$ searches

For SUSY seraches it is a Good Idea:

- 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
  - Mixing can further reduce detectability.

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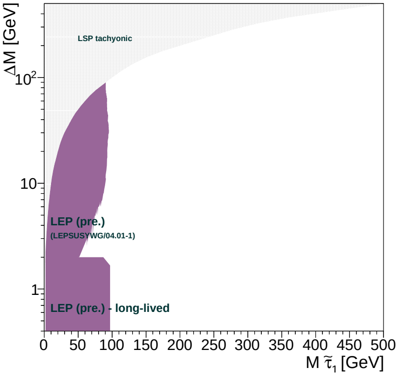
The $\tilde{\tau}$...

- 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 τ, 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 $\Delta M > 15$ GeV), 26.3 for any mixing and ΔM
- Limited by energy, luminosity and trigger
- LHC : ATLAS model-dependent (only for $\tilde{\tau}_R$), excludes only very high ΔM. No discovery potential..
- HiLumi: exclude somewhat higher $\tilde{\tau}_R$ masses for very high ΔM. No discovery potential..



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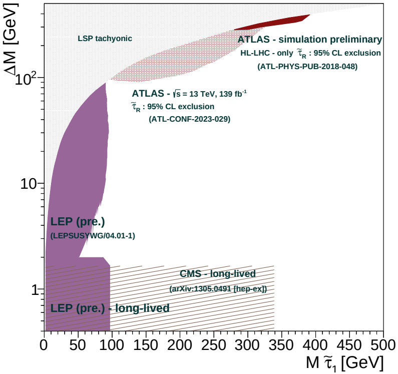
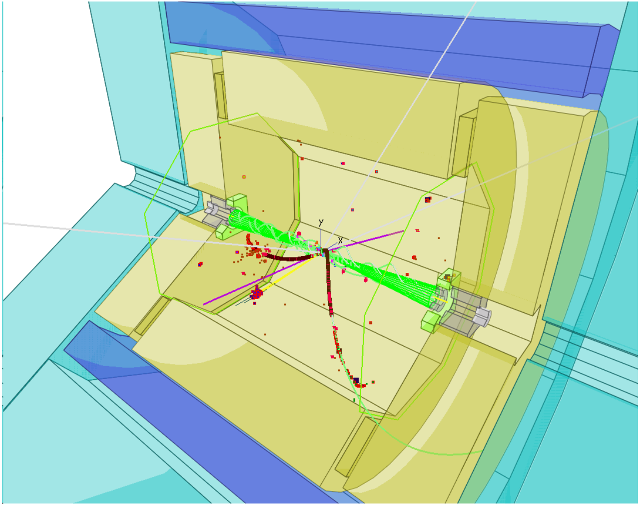


$\tilde{\tau}$ properties at e^+e^- colliders: Production & decay



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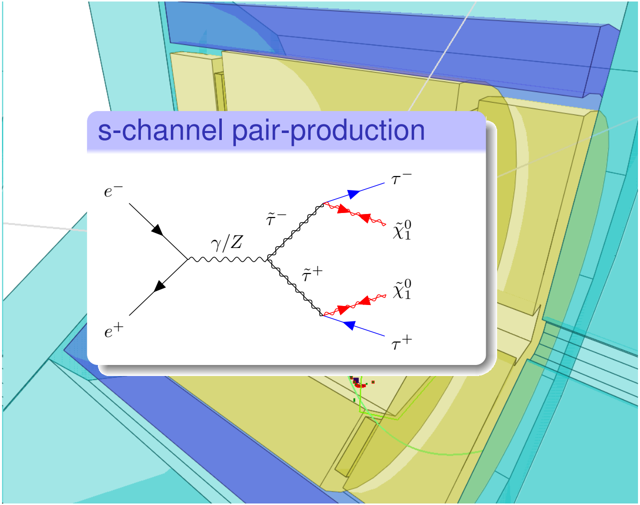

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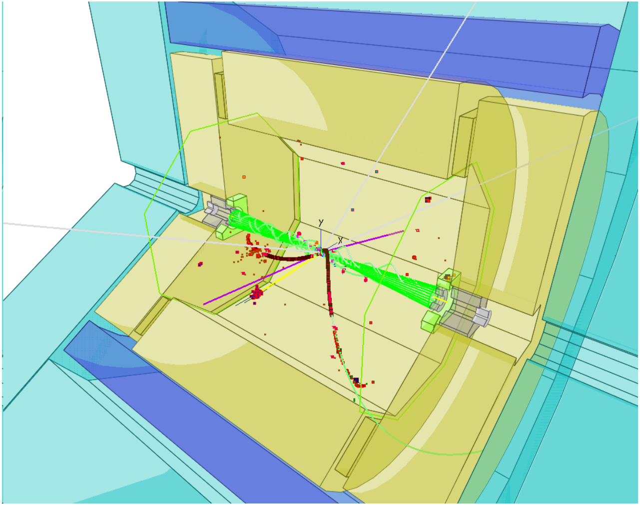

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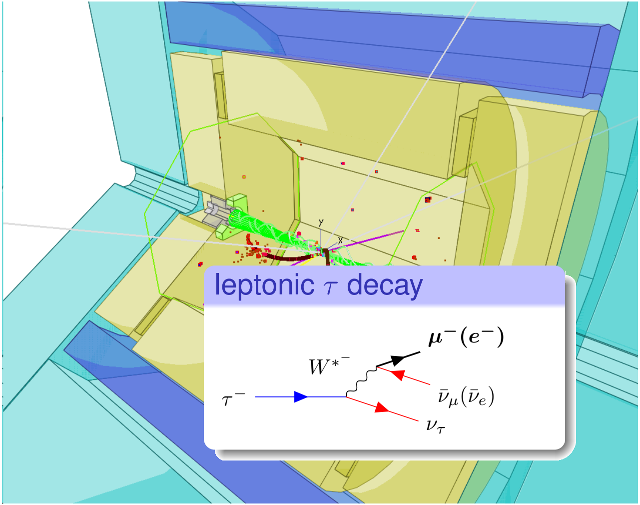

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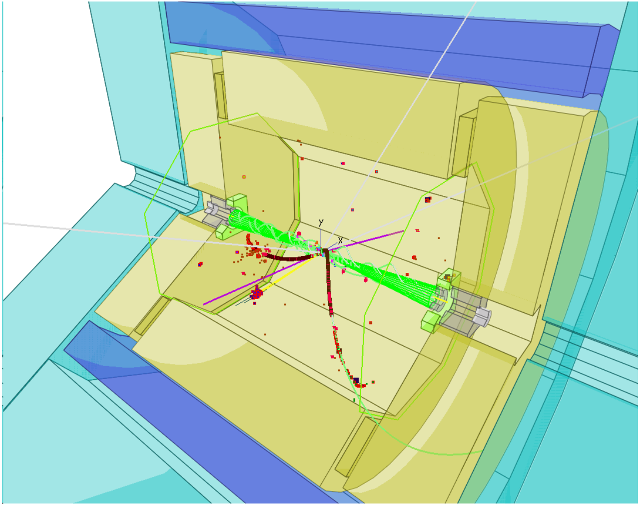

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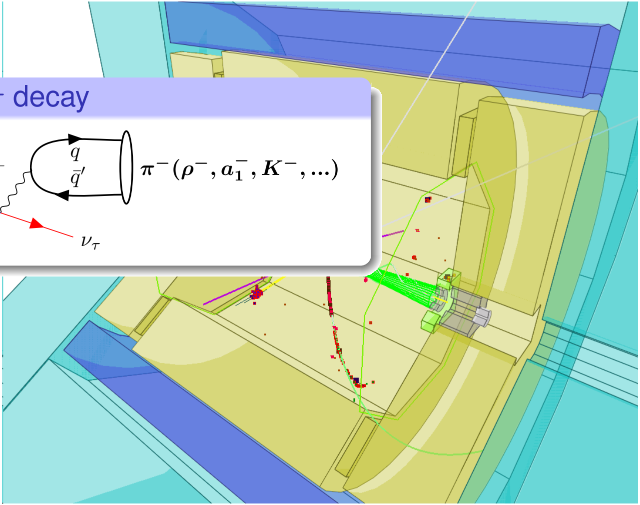
hadronic τ decay



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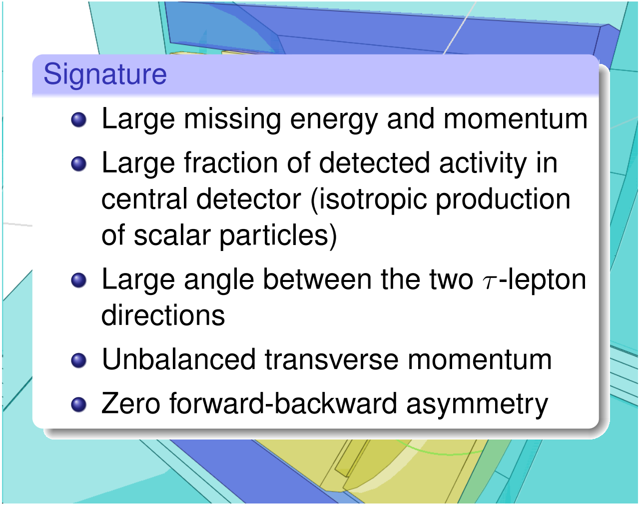

Signature

- 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

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

SM processes with real or fake missing energy

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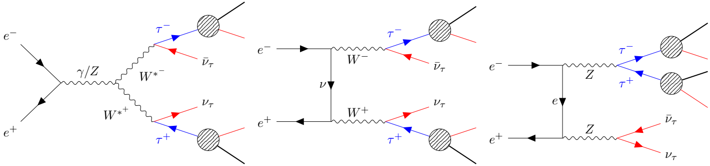
SM processes with real or fake missing energy

Irreducible

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



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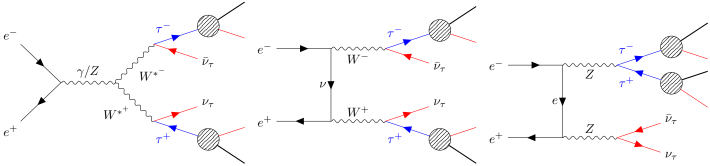
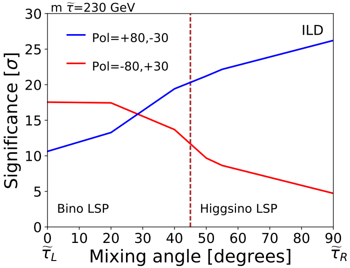


Almost Irreducible

- $e^+e^- \to \tau\tau$, $ZZ \to \nu\nu ll$, $WW \to l\nu l\nu$ ($l = e$ or μ)
- $e^+e^- \to \tau\tau + ISR$, $e^+e^- \to \tau\tau ee$, $\gamma\gamma \to \tau\tau$
- Mis-identification of τ's or of missing momentum

$\tilde{\tau}$ properties at e^+e^- colliders : impact of mixing and LSP nature

- Production cross-section depends on mixing.
- Visibility depends on the τ polarisation, and τ polarisation depends on both $\tilde{\tau}$ 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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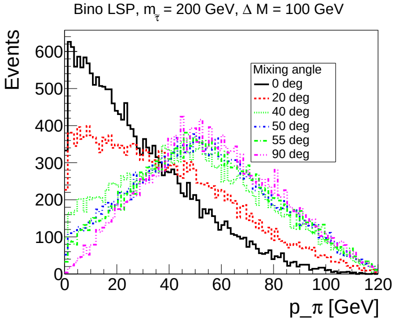

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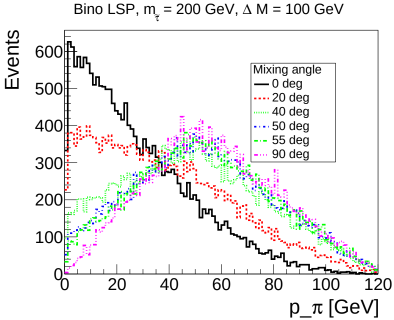

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- At ILC, both beams are polarised, and same luminosity will be collected for LR and RL beams. so:
- Use Likelihood-ratio statistic to weight both polarisations.
- Then, the sensitivity becomes $\sim$ uniform wrt. mixing angles, with a slight minimum at $\sim 55°$

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Neyman-Pearson's lemma applied to a counting experiment

$$N_\sigma = \frac{\sum_{i=1}^{n_{samp}} s_i \ln\left(1 + s_i/b_i\right)}{\sqrt{\sum_{i=1}^{n_{samp}} n_i \left[\ln\left(1 + s_i/b_i\right)\right]^2}}$$

(n_i is either $s_i + b_i$ (exclusion), or b_i (discovery))

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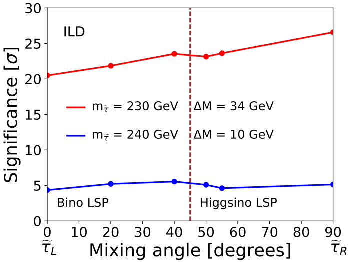

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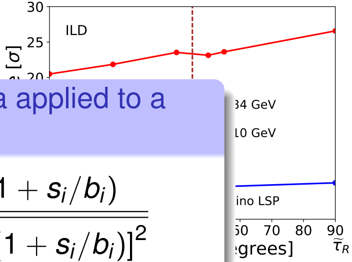

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Bookmark this formula !

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 ($> 10^7$ 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 $\times 10^6$ events.

ILD full simulation analysis: Event selection

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

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

Well-known initial stat 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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Clean final state with no pile-up.

> Above 95 % signal efficiency after these cuts (excluding for the τ-identification)

ILD full simulation analysis: Event selection

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

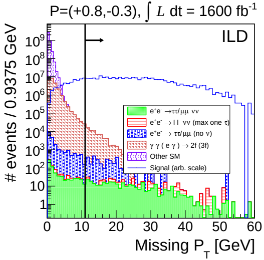
- Missing P_T
- Large acoplanarity
- Large P_T wrt. thrust-axis (ρ)
- High angles to beam

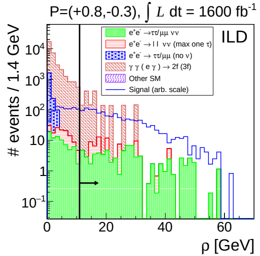
properties of irreducible sources of background

- 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





ILD full simulation analysis: Beam-induced backgrounds

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.
  - Absent at FCCee

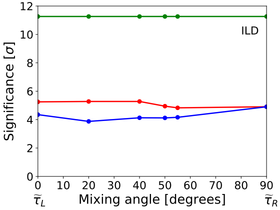
$\gamma\gamma$ interactions are independent of the e^+e^- process, but can happen simultaneously to it (overlay-on-physics events) or not (overlay-only events)

ILD full simulation analysis: Beam-induced backgrounds

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.

- ΔM = 3 GeV
- ΔM = 10 GeV
- Larger effect for low ΔM, hardly any for $\Delta M > 10$ GeV.



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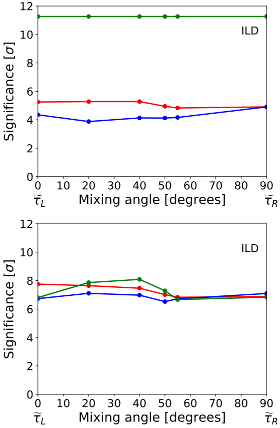

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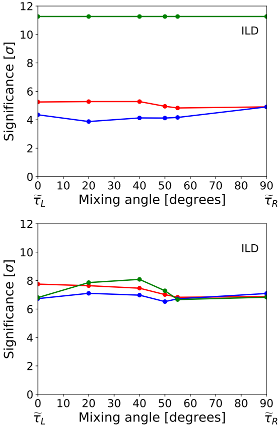

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- $\gamma\gamma \rightarrow$ low p_T hadrons looks like $\tilde{\tau}$ production for $\Delta M \leq 10$ GeV).
- Similar for ILC and FCCee

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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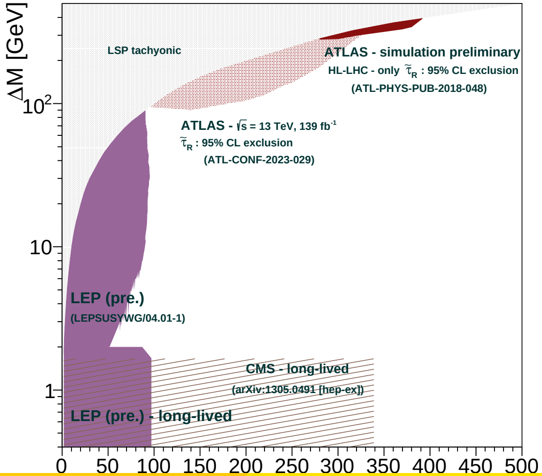
- Current model-independent limits for $\Delta M > \tau$ mass come from LEP
- Final result of our study arXiv:2105.08616
- At ILC discovery and exclusion are almost the same.
- Extra treat: Extrapolations to 250 GeV and 1 TeV



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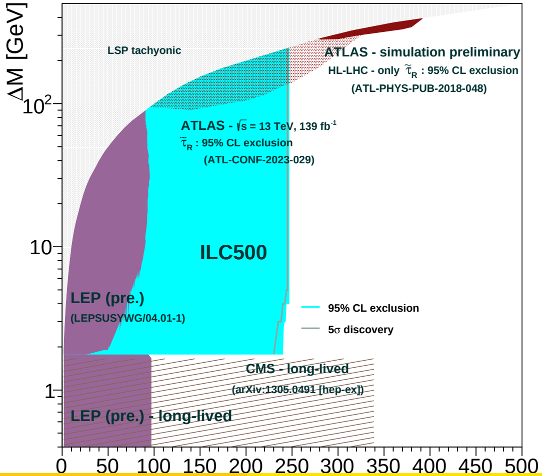

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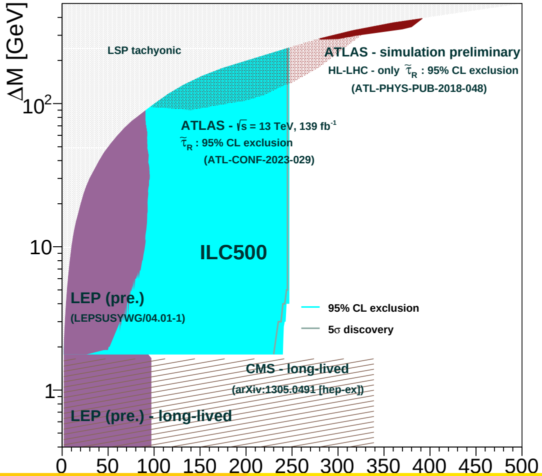

ILD full simulation analysis: Results

- Current model-independent limits for $\Delta M > \tau$ mass come from LEP
- Final result of our study arXiv:2105.08616
- At ILC discovery and exclusion are almost the same.
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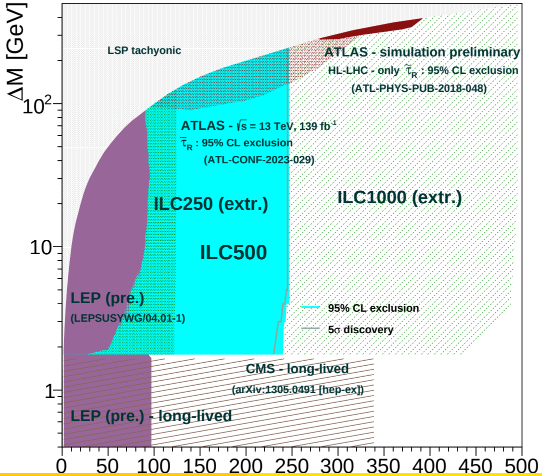
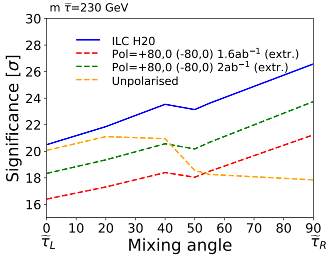


WIP: Impact of specific ILD/ILC features: Polarisation

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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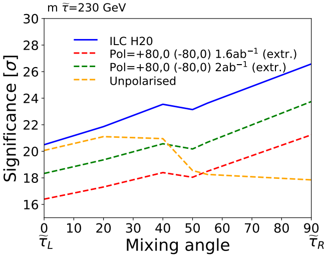

WIP: Impact of specific ILD/ILC features: Luminosity, Energy

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 ΔM = 2 GeV changes excl. limit on $M_{\tilde{\tau}}$ from 122 to 117 (117) GeV, negligible for ΔM = 10 GeV

Energy, the main advantage for any linear option:

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

WIP: Impact of specific ILD/ILC features: Beam-induced backgrounds, triggerless operation

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

Triggerless operation:

- Big advantage when searching for unexpected signatures

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

WIP: Impact of specific ILD/ILC features: Hermeticity

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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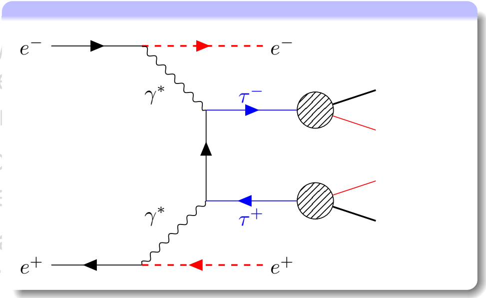

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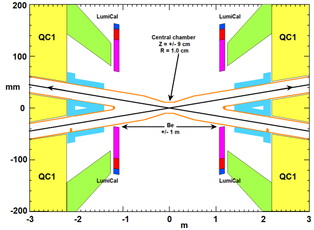

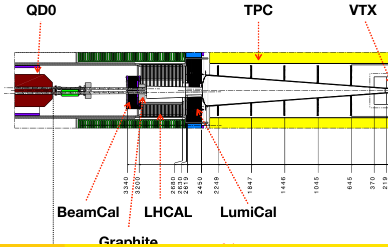

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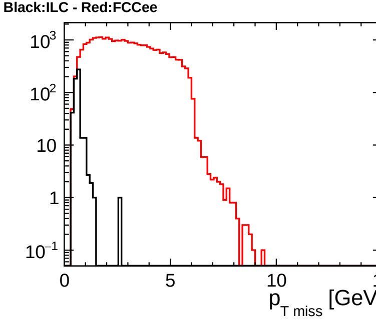

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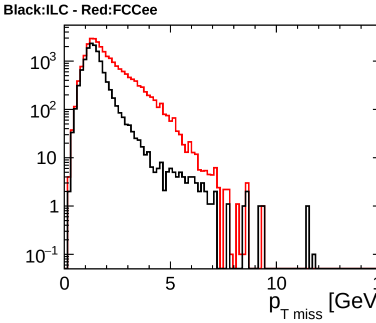

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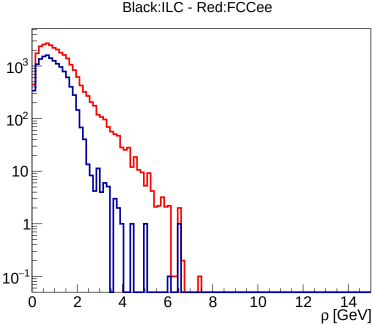

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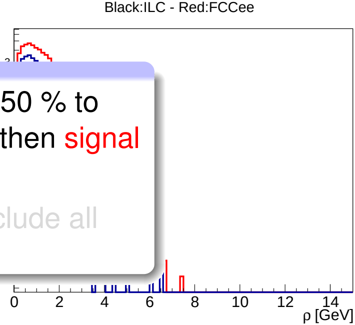

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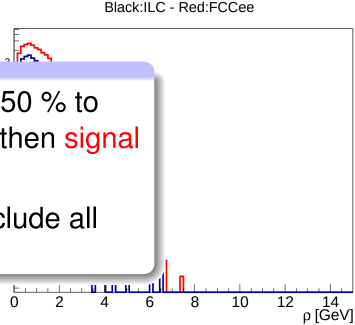

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Conclusions

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- Future electron-positron colliders are ideally suited for $\tilde{\tau}$ searches
- $\tilde{\tau}$ mixing and LSP nature influence production cross-sections and decay kinematics $\Rightarrow$ 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 $\tilde{\tau}$ mass limit only by 5 GeV
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Future linear 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 energy reach crucial.

At circular colliders, at most some modest amelioration of the limits from LEP can be expected.