Stau searches at future e^+e^- colliders

Teresa Núñez - DESY

- SUSY at future e^+e^- colliders
- Motivation for $\tilde{\tau}$ searches
- ILD full simulation analysis
- Impact of ILD/ILC specific features
- Evaluating impact of FCCee-like MDI in $\tilde{\tau}$ sensitivity
- Conclusions

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SUSY at future e^+e^- colliders

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

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

- 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

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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 (due to $\tilde{\tau}$-neutralino coannihilation, possible for $\Delta M \leq 10$ GeV)

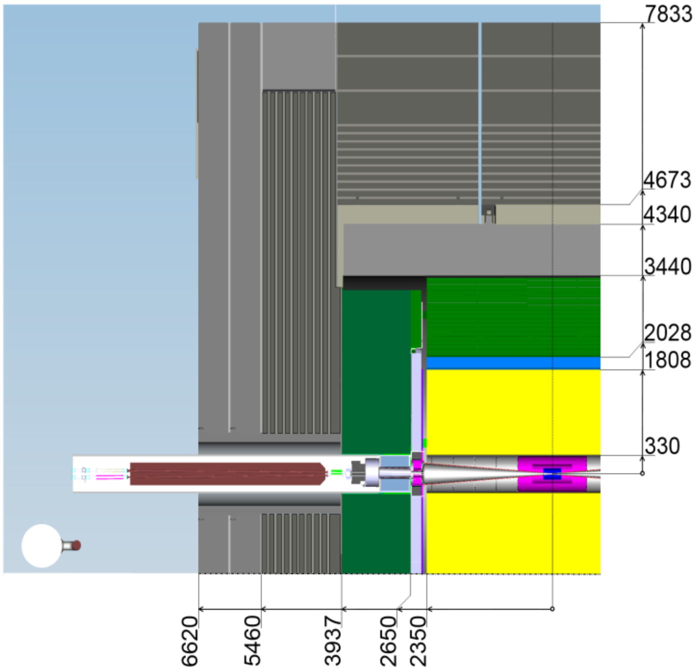
ILD full simulation analysis

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 $\sigma(1/p_{\perp}) = 2\text{x}10^{-5}$ 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

Full SM and beam induced backgrounds with all $e^+e^-/e^{+/-}\gamma/\gamma\gamma$ processes ($>10^7$ events)

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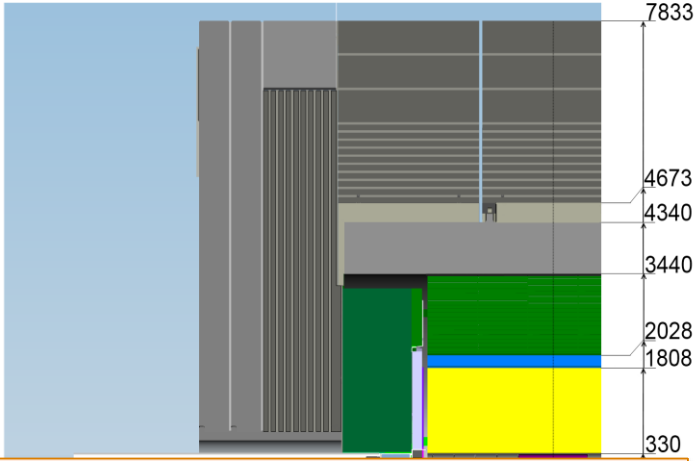

Effect of beam induced backgrounds for $\tilde{\tau}$ searches was analysed (as overlay-on-physics and overlay-only events – not in previous studies)

Both beams polarised: study done for $P(e^-, e^+) = (+/-80\%, +/-30\%)$

Studies using the full Geant4 simulation of the ILC version of the ILD and the existing 500GeV MC samples

Full SM and beam induced backgrounds with all $e^+e^-/e^{+/-}\gamma/\gamma\gamma$ processes (>10^7 events)

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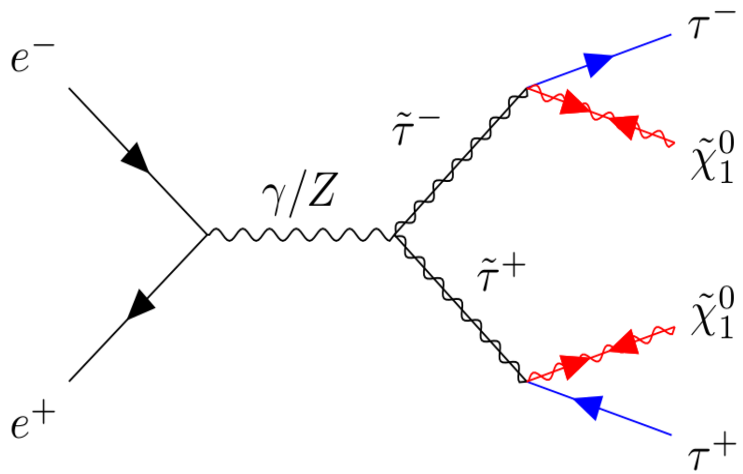
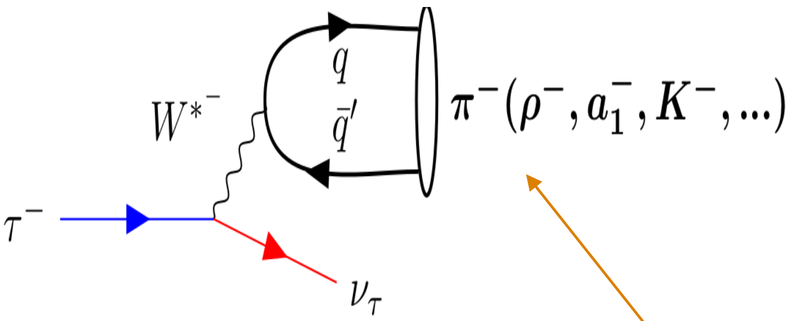
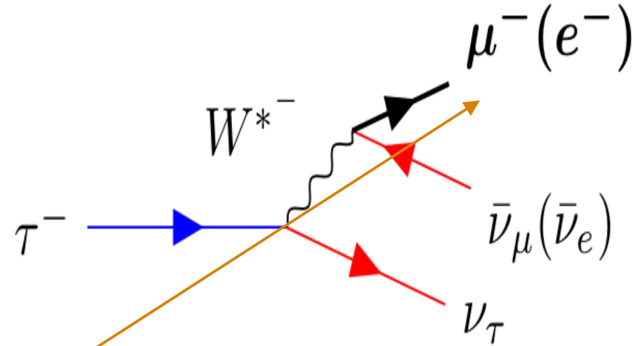
ILD full simulation analysis:

$\tilde{\tau}$ pair production and decay







Detectable final states
(thick black lines)

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Red lines: undetectable final states

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ILD full simulation analysis:

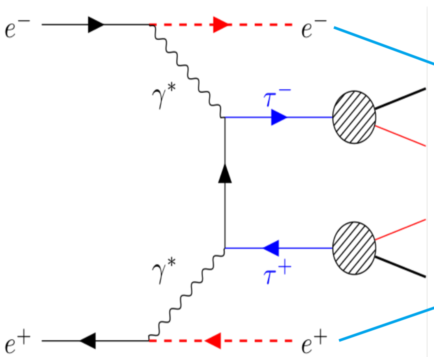
Event selection

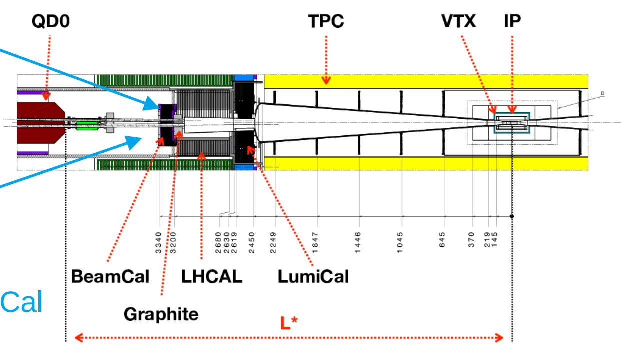
Veto beamCal

Hermeticity

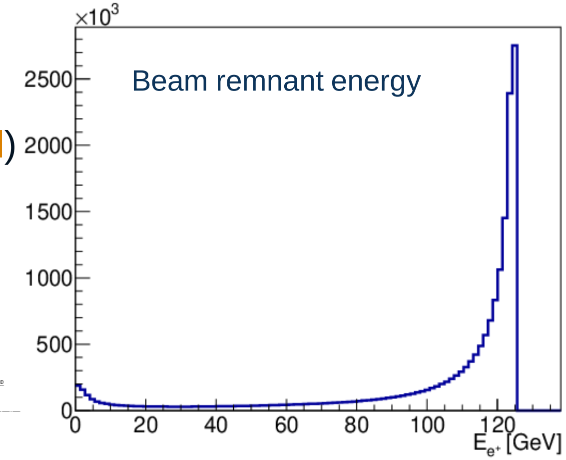
- Absence of signal in the calorimeter close to the beam pipe (beamCal)

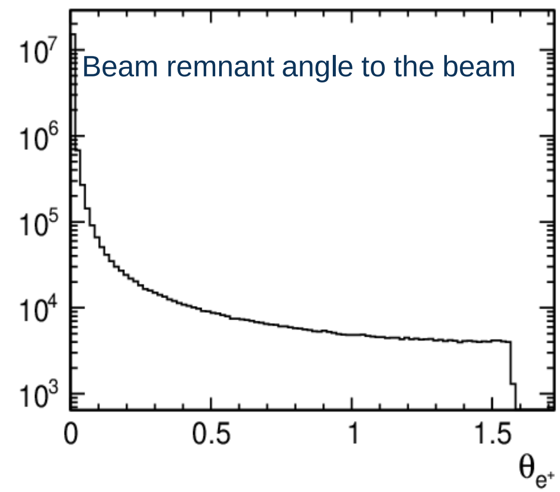
$\gamma\gamma$ events …





Detected in BeamCal





… contributes to the background in case remnant electron or positron escape detection by going down beam pipe, fake missing energy

Strong suppression of $\gamma\gamma$ events, main source of background specially for small mass differences

ILD full simulation analysis:

Event selection

Veto beamCal

Hermeticity

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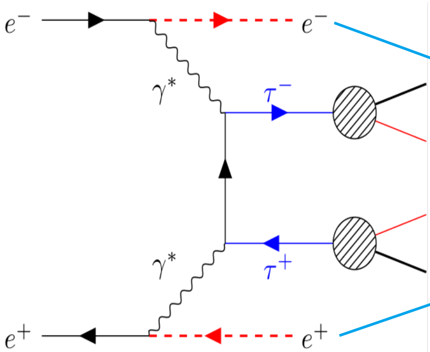
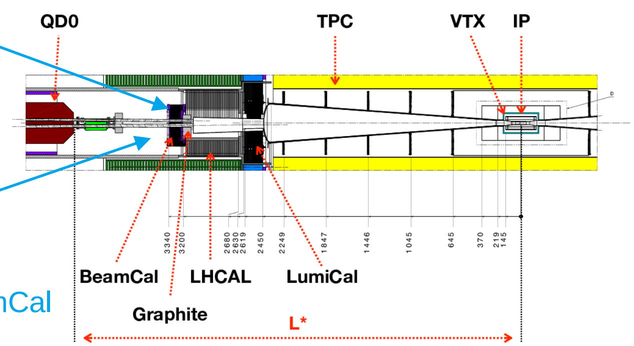
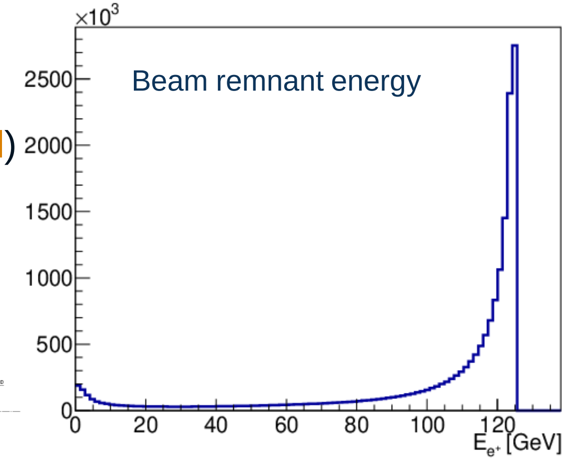
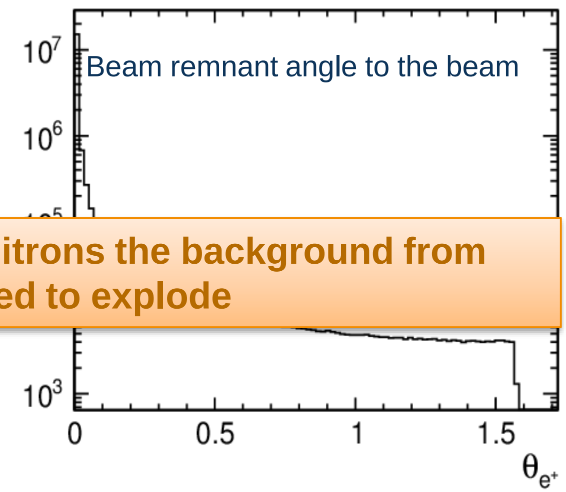
$\gamma\gamma$ events …



Detected in BeamCal







Without the ability to veto forward-scattered electrons and positrons the background from interactions for real or virtual photons is expected to explode

Strong suppression of $\gamma\gamma$ events, main source of background specially for small mass differences

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ILD full simulation analysis:

Event selection (ctd.)

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

Well known initial state
Hermeticity

- Missing energy (E_{miss}). E_{miss} > 2 x M_{LSP} GeV
- Visible mass (m_{vis}). m_{vis} < 2 x ($M_{\tilde{\tau}}$ - 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:

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

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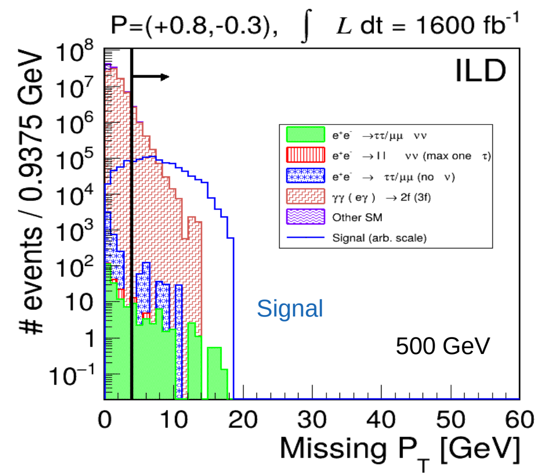
ILD full simulation analysis: Event selection (ctd.)

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

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

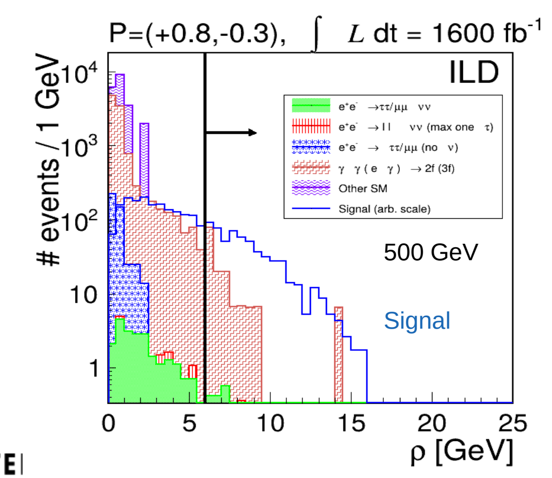


Cuts against properties of irreducible sources of background

- 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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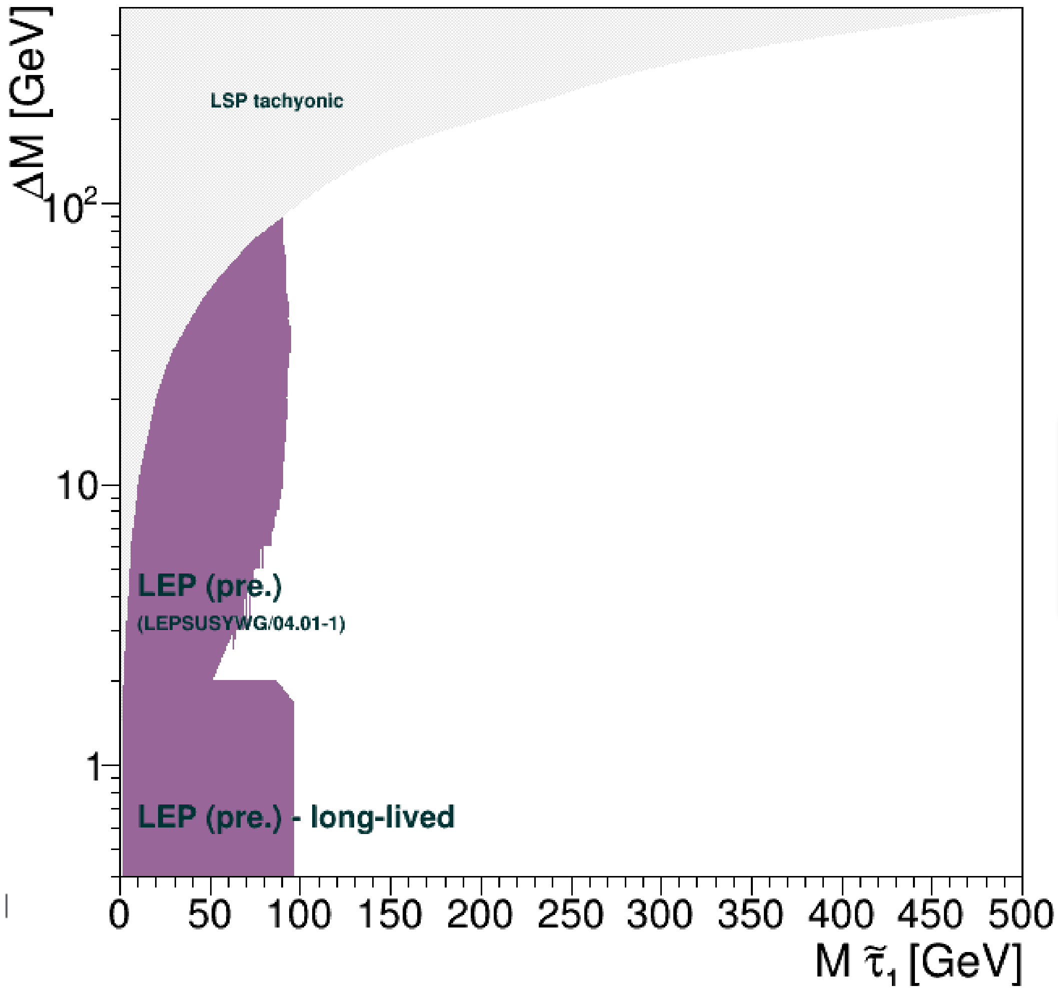
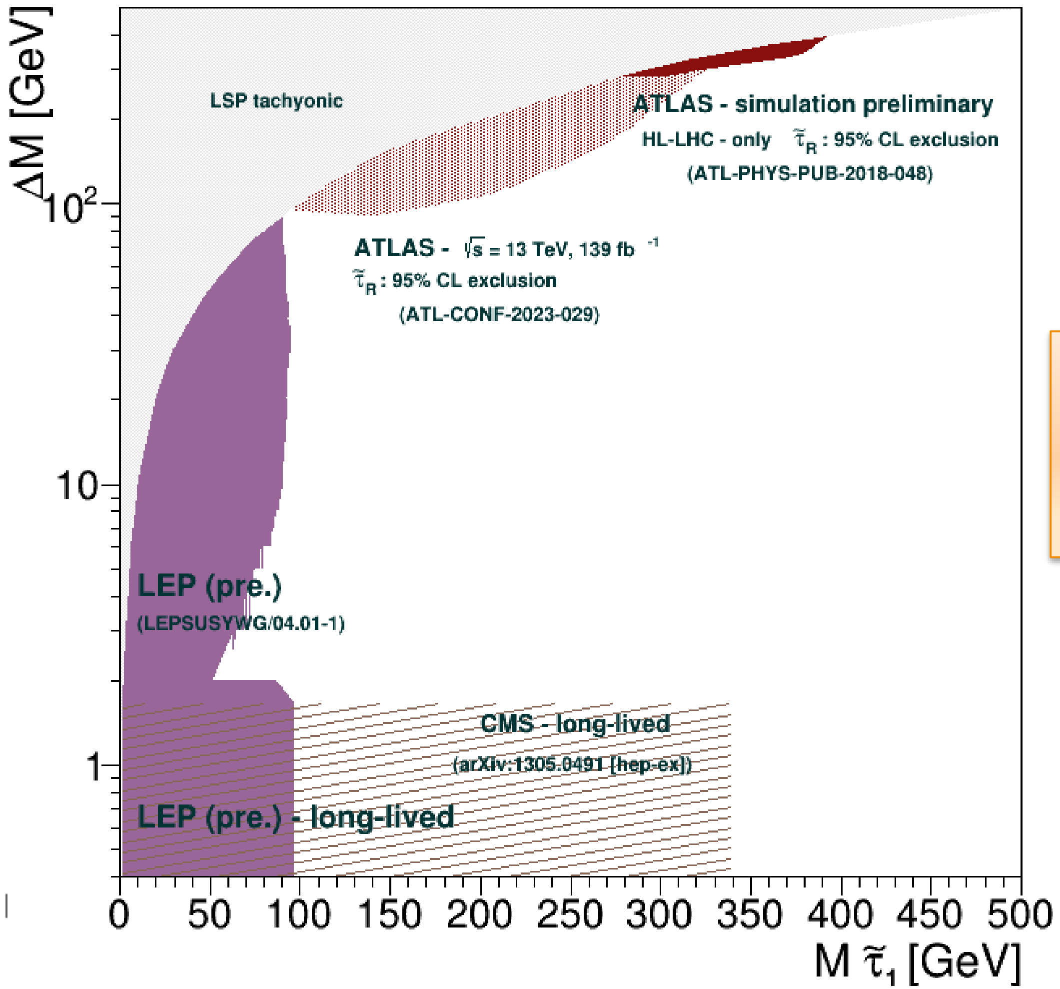
$M_{\tilde{\tau}}$=245GeV ΔM=10 GeV

ILD full simulation analysis: limits



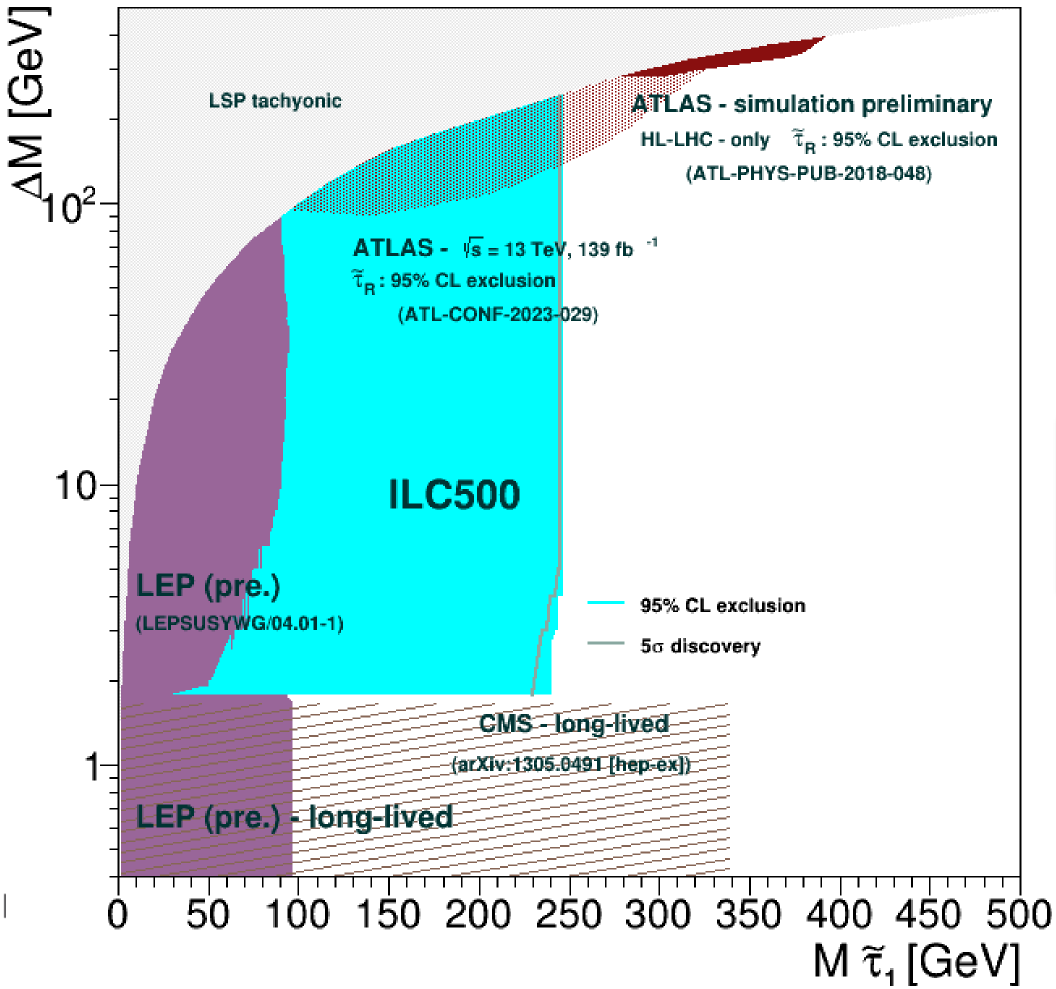
Current model-independent limits for ΔM > τ mass come from LEP

ILD full simulation analysis: limits



LHC/HL-LHC limits, highly model dependent, do not have discovery potential for the best motivated scenarios

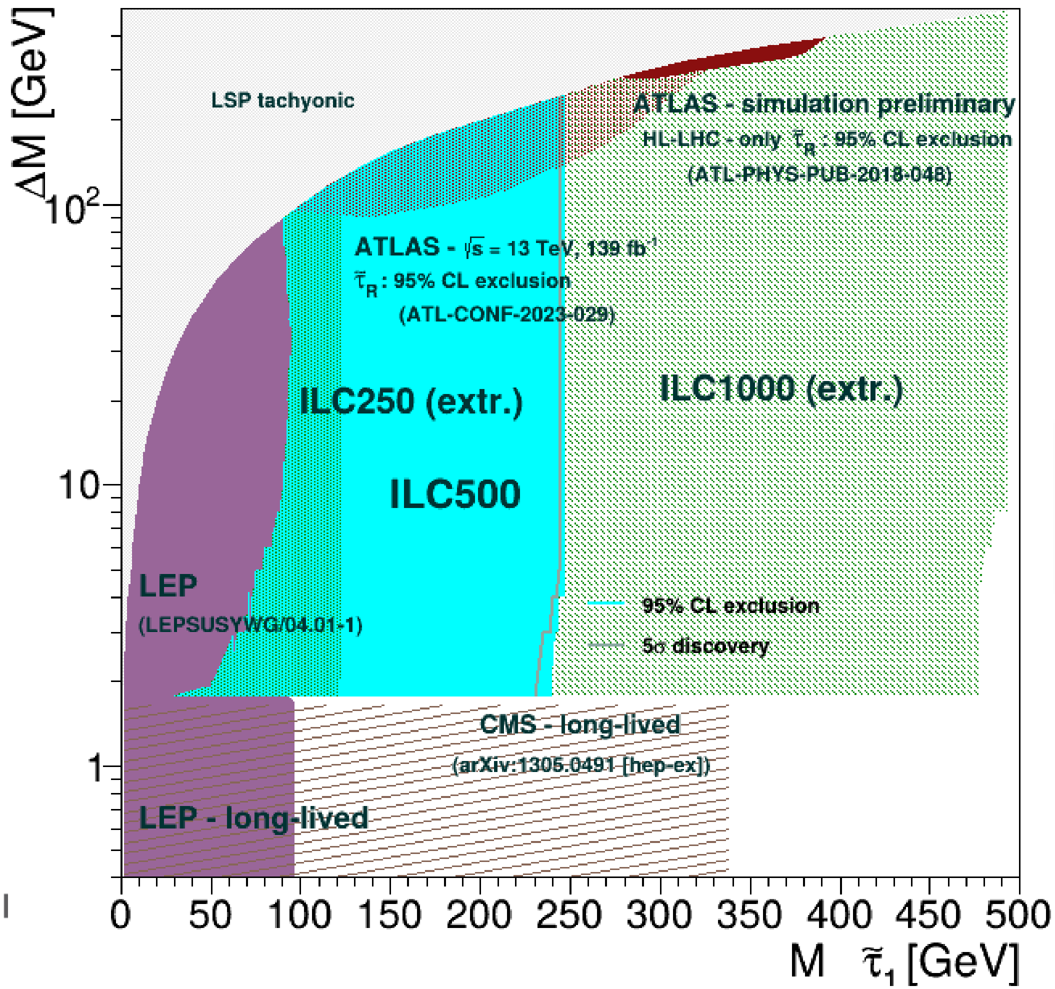
ILD full simulation analysis: limits



At ILC discovery and exclusion are almost the same and close to the kinematic limit

arXiv:2105.08616

ILD full simulation analysis: limits



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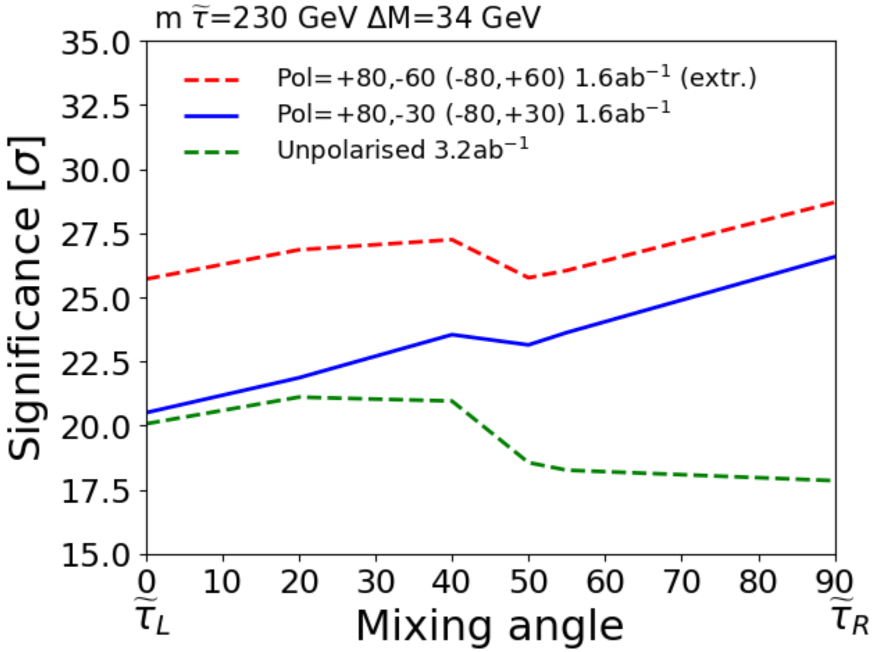
Impact of specific ILD/ILC features: polarisation

General e+e- future colliders features:

- 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, η ~ 5.81), still good for others (down to ~50 mrad, η ~ 3.69)

Polarisation:

- polarisation of both beams provides higher sensitivity than one beam or none: Likelihood ratio weighting
- polarisation of both beams increases the effective luminosity of s-channel processes, 24% ILC wrt. FCCee
- polarisation helps to reduce systematics



Clear edge for ILC (both beams polarised)

FCCee does not foresee longitudinal polarisation of the beams

Impact of specific ILD/ILC features:

Luminosity, energy, triggerless operation

Luminosity:

The strong point 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 112 to 117 (117) GeV, negligible for ΔM = 10 GeV

Energy:

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

Main advantage of any linear option

Triggerless operation:

- big advantage when searching for unexpected signatures

Possible at linear colliders due to low collision frequency, very challenging at circular colliders

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Impact of specific ILD/ILC features:

beam-induced backgrounds, hermeticity

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)

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

Smaller beam-spot, triggerless operation, thinner beam-pipe and vertex detector, polarisation, timing information, all makes the linear options not suffering on that

Impact, estimated at ILC500, smaller at ILC250, of less than 1 GeV for highest reachable masses and smallest mass differences, negligible for the rest of the parameter space

Hermeticity:

- crucial when searching for missing momentum signatures

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

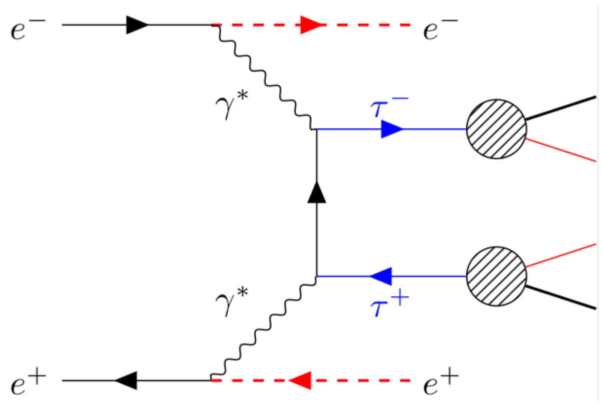
Evaluating impact of FCCee-like MDI in $\tilde{\tau}$ sensitivity

Main FCCee features considered:

- Hermeticity: 50 mrad (vs 6 mrad)
- Luminosity: 12 ab^{-1} (vs 3.2 ab^{-1})
- Energy: 240 GeV (vs 500 GeV)
- Beam-induced backgrounds: ~none (vs 10^6 /BX)
- Beam polarisation: none (vs both beams)

Conditions:

- Generator level samples at $\sqrt{s}$ = 250 GeV
- Kinematic cuts down by a factor 2 (ILC study done at $\sqrt{s}$ = 500 GeV)
- Unpolarised beams
- Focus on $\gamma\gamma$ backgrounds and the effect of hermeticity



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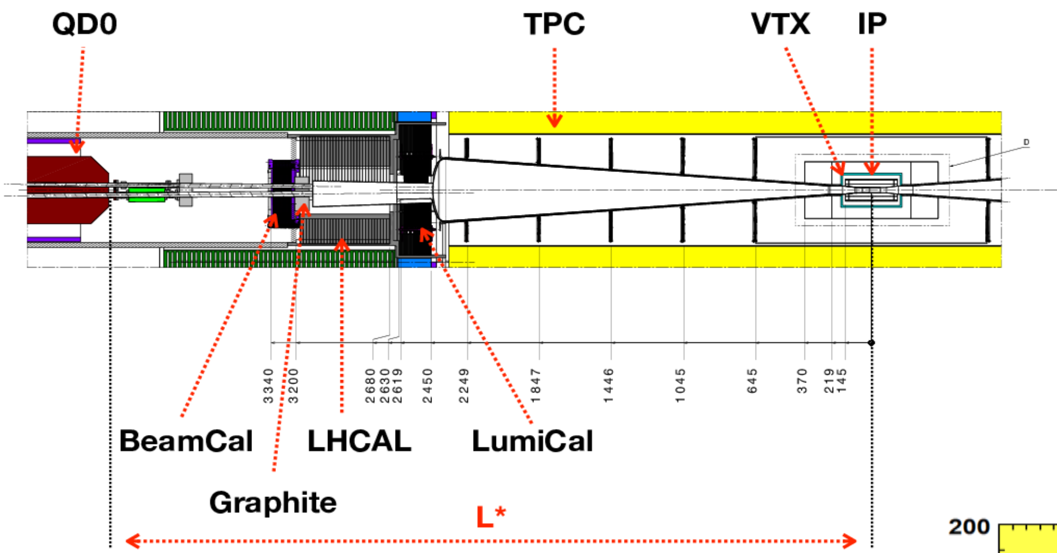
Evaluating impact of FCCee-like MDI in $\tilde{\tau}$ sensitivity (ctd.)



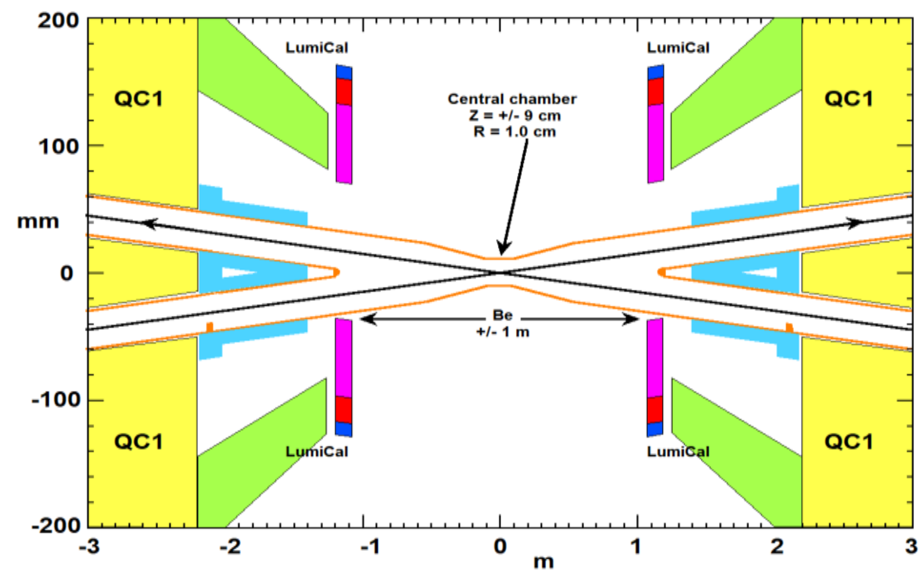
Effect of hermeticity on vetoing $\gamma\gamma$ events

ILD@ILC

ILD@FCCee

BeamCal 6 mrad , η ~ 5.81, down to the beam pipe

No beamCal



LumiCal 50 mrad, , η ~ 3.69, down to the beam pipe

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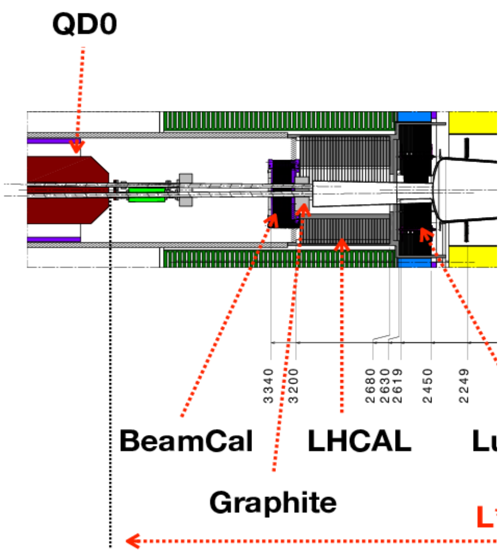
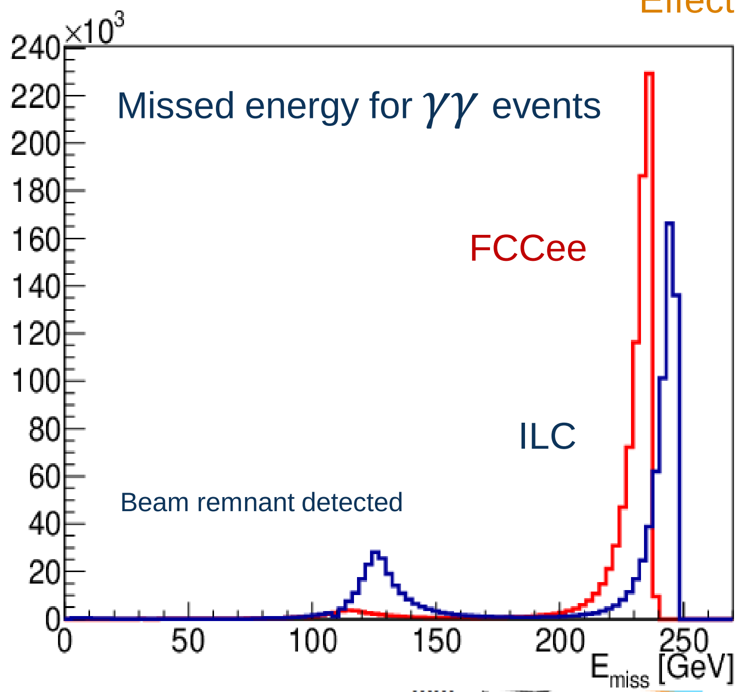
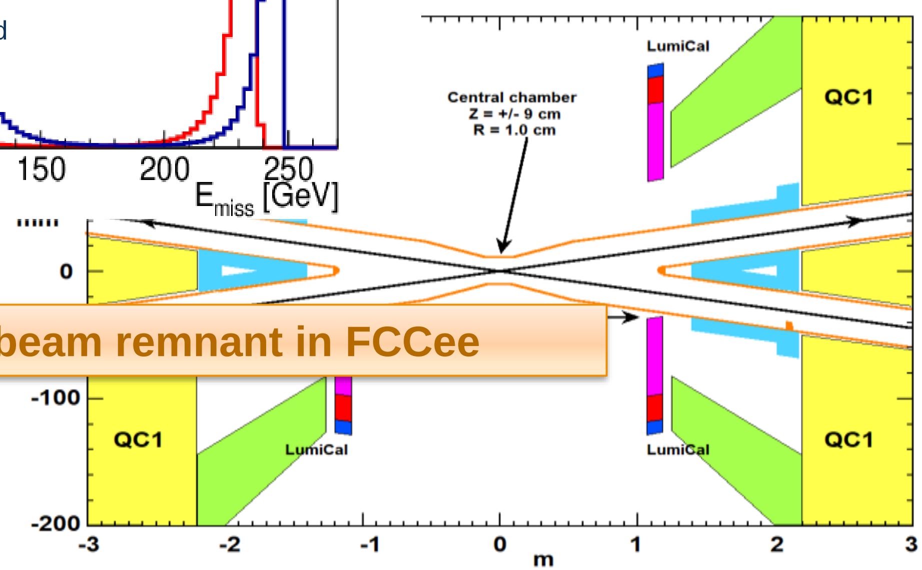




BeamCal 6 mrad , η ~ 5.81, (
the beam pipe

ILD@FCCee



Almost not detection of beam remnant in FCCee

LumiCal 50 mrad, , η ~ 3.69, down to the beam pipe

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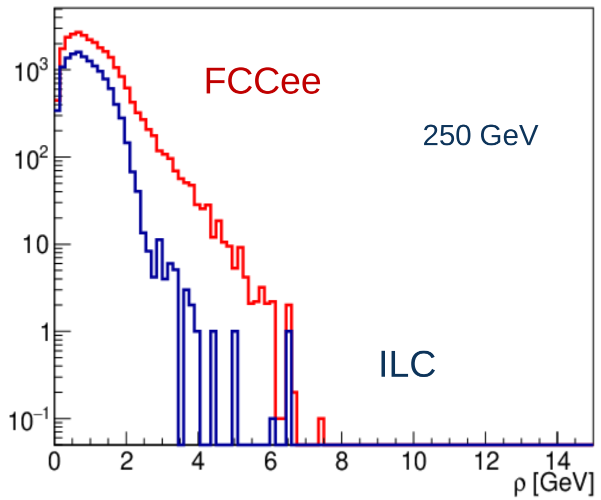
Evaluating impact of FCCee-like MDI in $\tilde{\tau}$ sensitivity (ctd.)

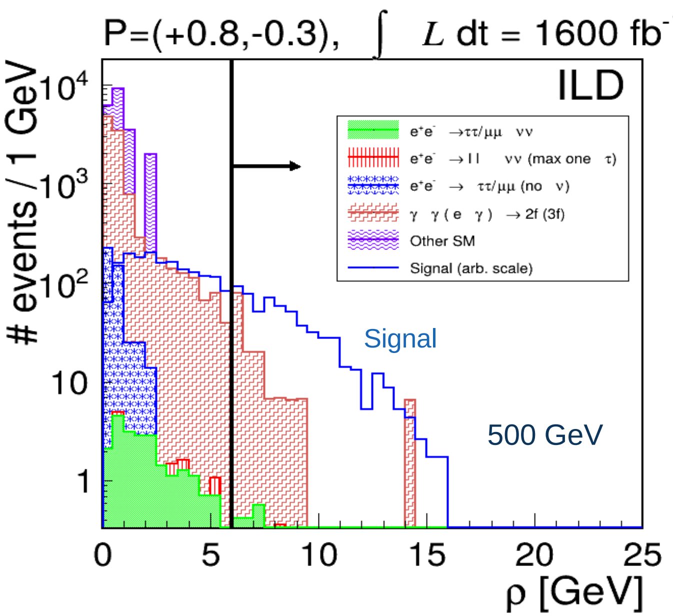
Effect of hermeticity on ρ cut

Designed to cut against back-to-back τ´s



ρ distribution from $\gamma\gamma$ background just before the cut on this variable

ρ cut should be increased by about 75% to keep the same level of background, but this would remove about 82% of the signal



$M_{\tilde{\tau}}$=245GeV ΔM=10 GeV

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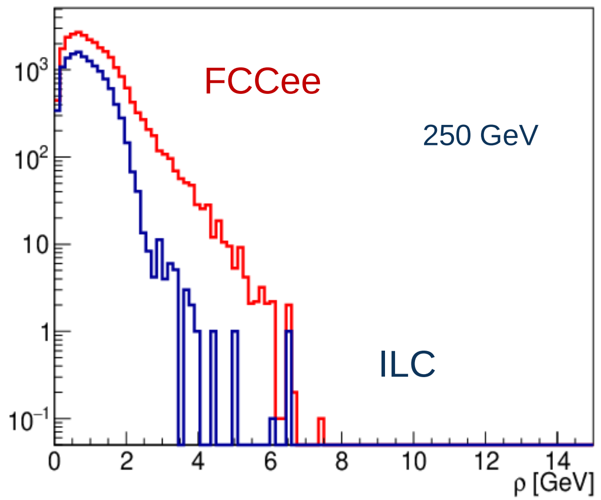

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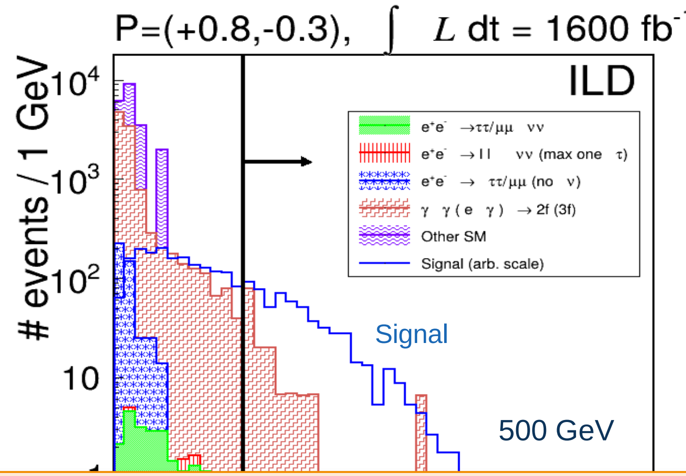

$M_{\tilde{\tau}}$=245GeV ΔM=10 GeV

Increase of kinematic cuts (missed P_T , ρ) by 75% needed to low down FCCee backgrounds to ILC level

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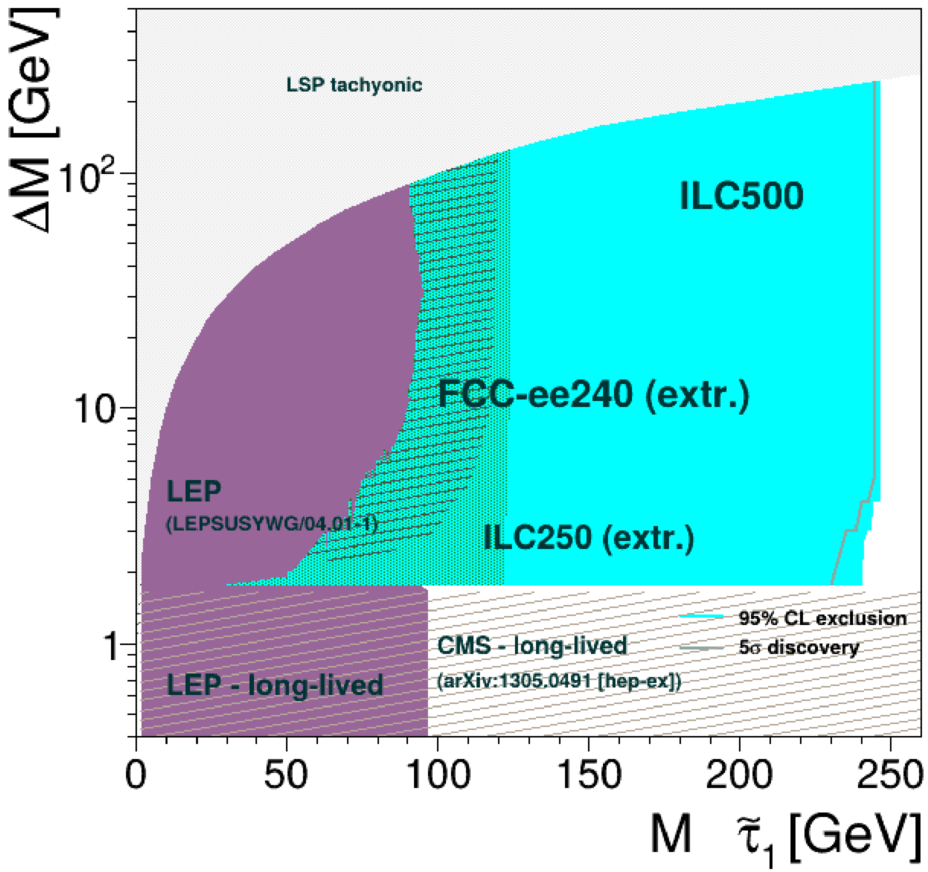
Evaluating impact of FCCee-like MDI in $\tilde{\tau}$ sensitivity (ctd.)



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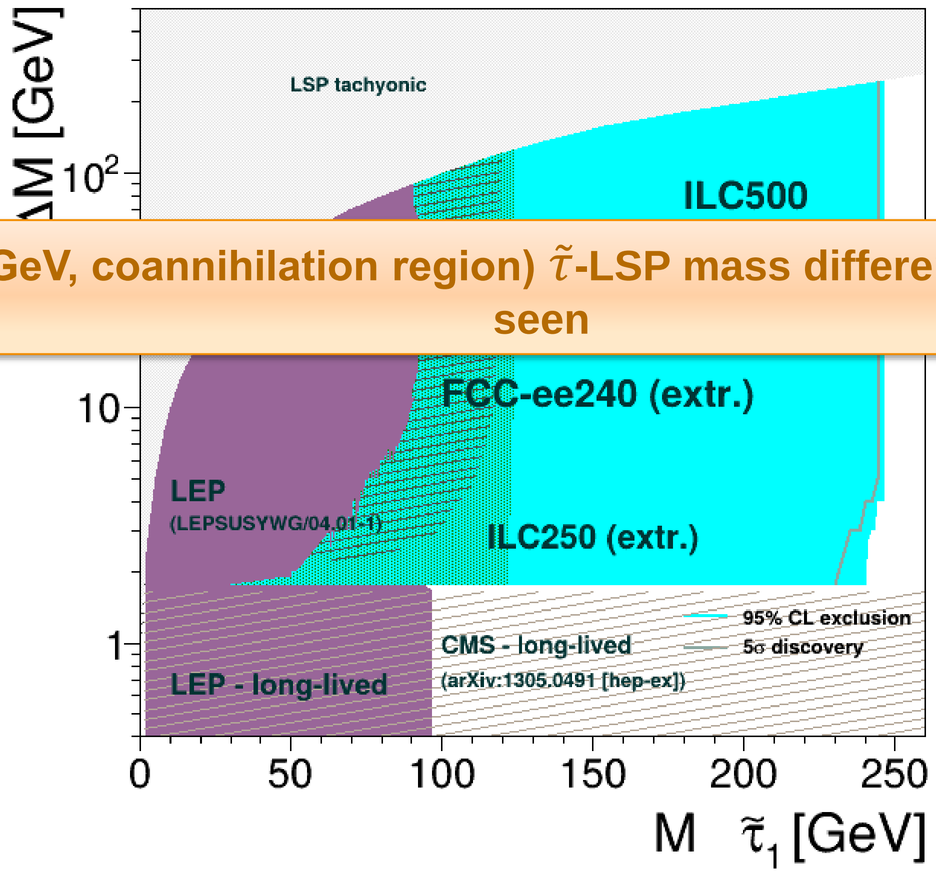

Small (≤ 5 GeV, coannihilation region) $\tilde{\tau}$-LSP mass differences not able to be seen

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
- Polarised beams: provides higher sensitivity, increasing the effective luminosity for s-channel processes
- Beam-induced backgrounds at Linear Colliders can be mitigated up to small residual impact of ~1GeV on highest reachable mass for lowest ΔM
- Higher center-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, with an MDI region as currently discussed for FCCee detectors, mass differences below 5 GeV very likely can not be probed

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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