Impact of detector and accelerator conditions on the $\tilde{\tau}$-pair production sensitivity at future Higgs factories

Teresa Núñez - DESY

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

Third ECFA Worshop on e+e- Higgs/Top/EW Factories
Paris, October 2024

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SUSY and $\tilde{\tau}$'s at future e^+e^- Higgs/EW/Tops factories

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

The direct $\tilde{\tau}$ pair production is one of the most interesting channels to search for SUSY

- Motivated NLSP candidate
- Most difficult scenario

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

ILD full simulation analysis:

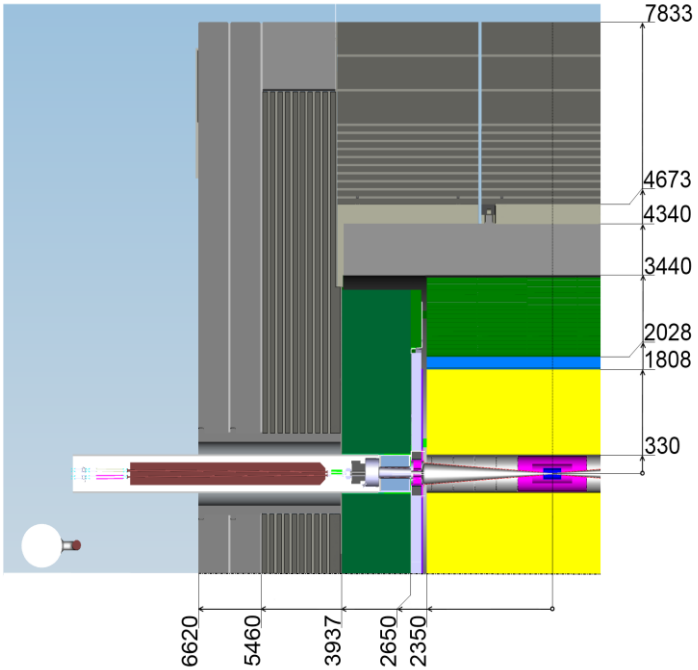
MC samples and event selection

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 $\sigma(1/p_\perp) = 2\text{x}10^{-5}$ 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 covering the full SM and beam induced backgrounds with all $e^+e^-/e^{+/-}\gamma/\gamma\gamma$ processes (>10^7 events)

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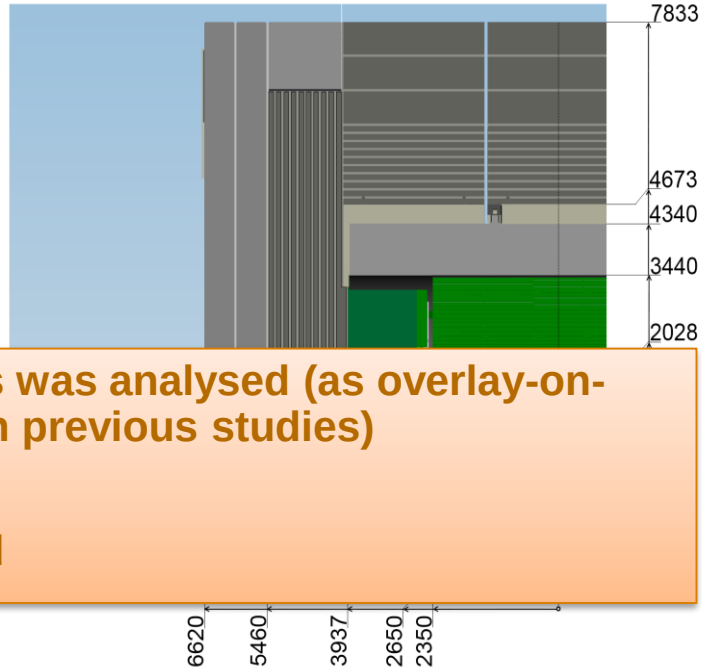


… satisfying Physics requirements for BSM …

- Triggerless operation

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

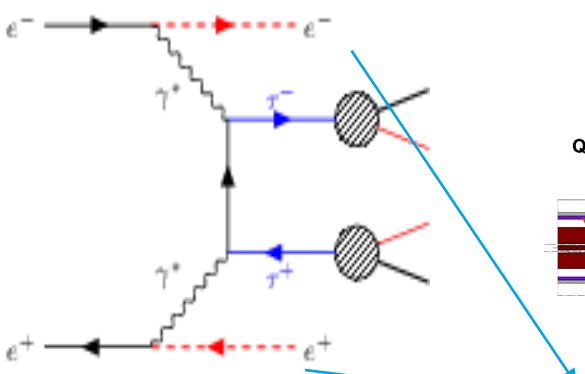
Both beams polarised

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

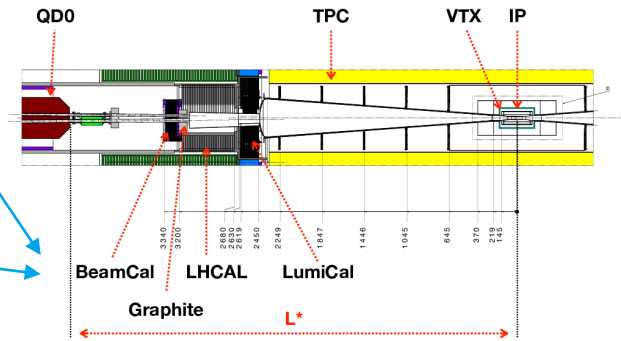
Studies using the full Geant4 simulation of the ILC version of the ILD and the existing 500GeV MC samples covering the full SM and beam induced backgrounds with all $e^+e^-/e^{+/-}\gamma/\gamma\gamma$ processes (>10^7 events)

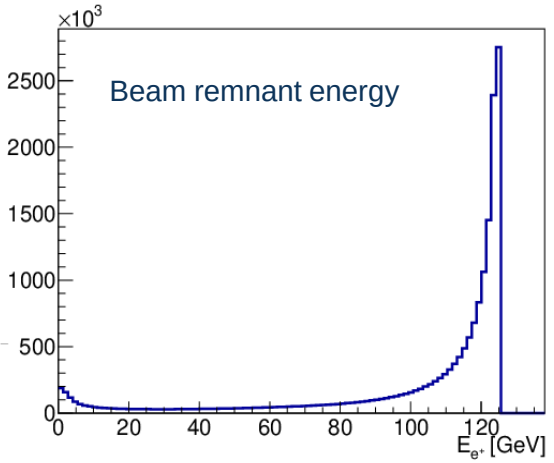
ILD full simulation analysis:

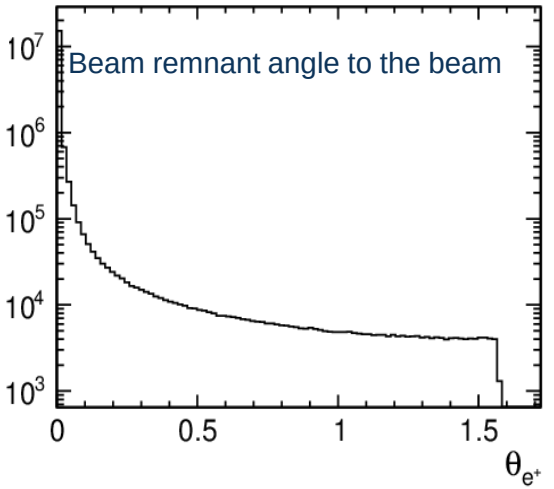
Veto BeamCal



Detected in BeamCal







- Main source of background, specially for small mass differences
- Contributes to the background in case remnant electron or positron escape detection by going down beam pipe, fake missing energy

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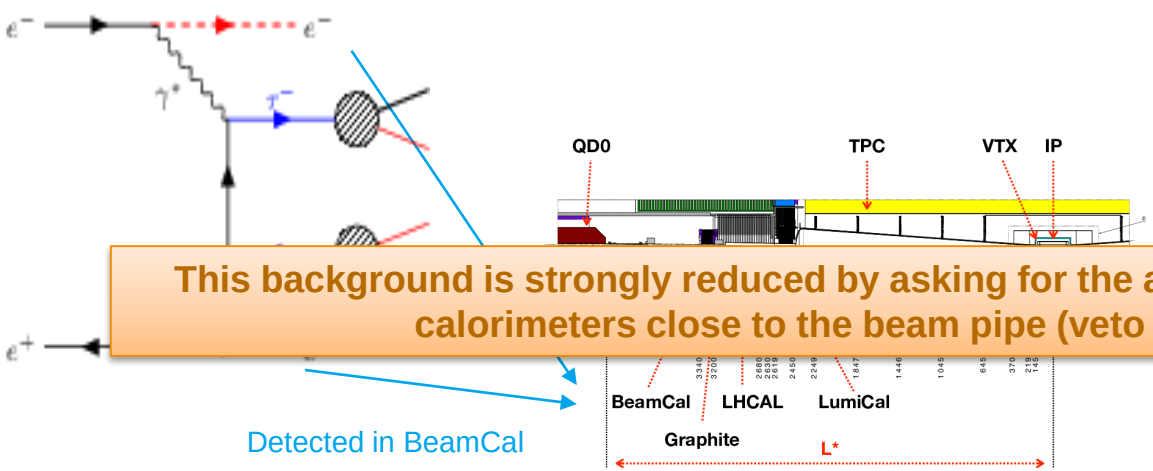
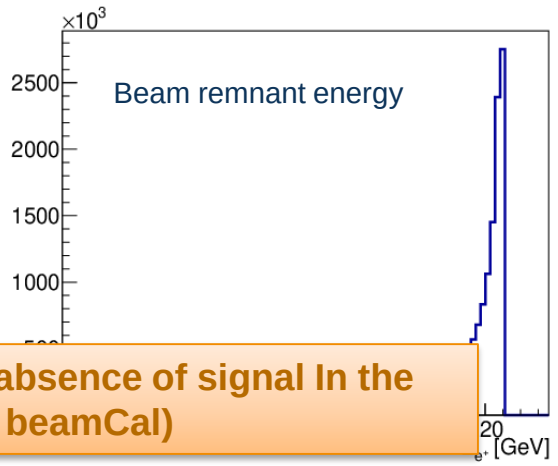
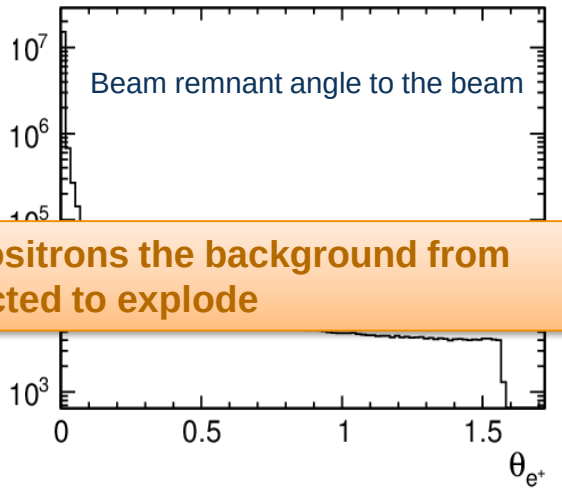
ILD full simulation analysis:

Veto BeamCal





This background is strongly reduced by asking for the absence of signal In the calorimeters close to the beam pipe (veto beamCal)



- Main source of background, specially for small mass differences
- **Without the ability to veto forward-scattered electrons and positrons the background from interactions for real or virtual photons is expected to explode**

missing energy

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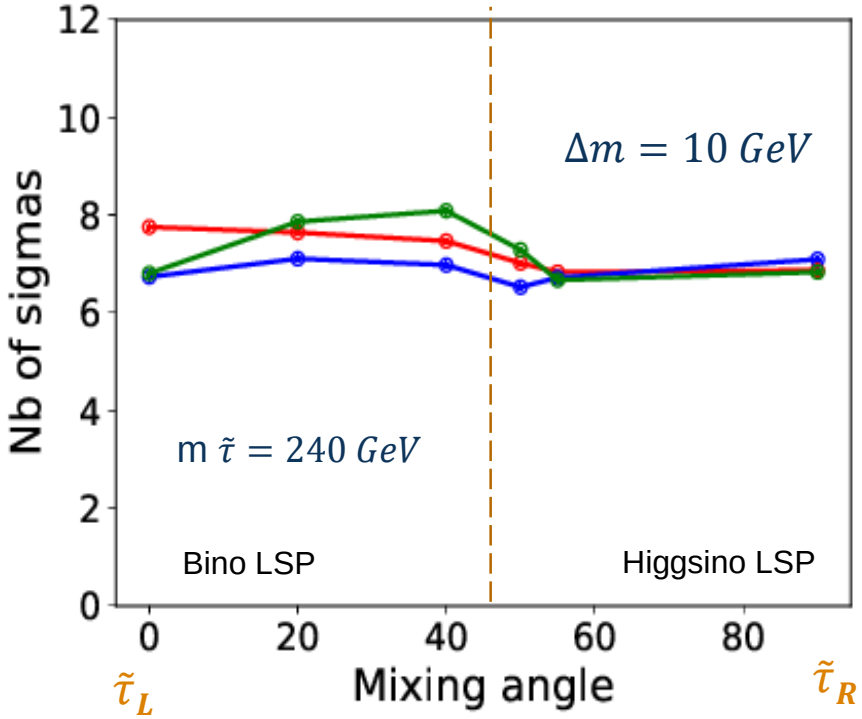
ILD full simulation analysis:

beam induced backgrounds

Full simulation

ILC500: effect of overlay-on-physics events

- Not cut on overlay tracks
- Cut on tracks based on transverse momentum, angular distribution and input parameter significance
- Fast simulation (SGV) – not overlay tracks



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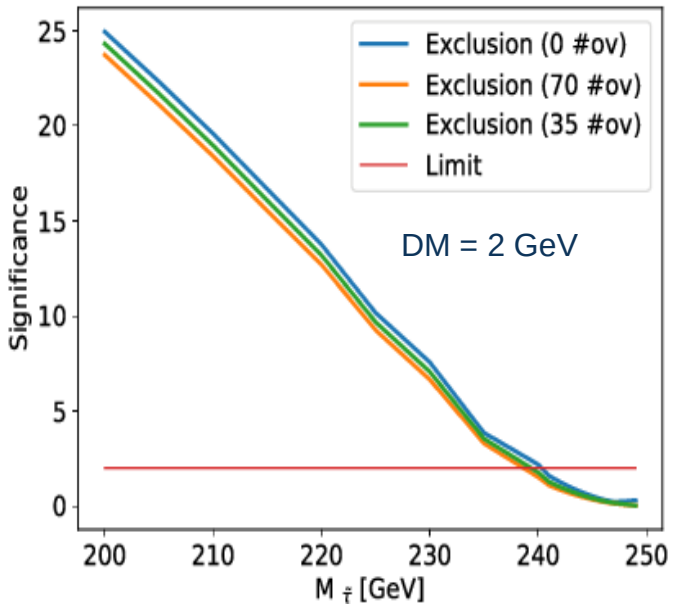
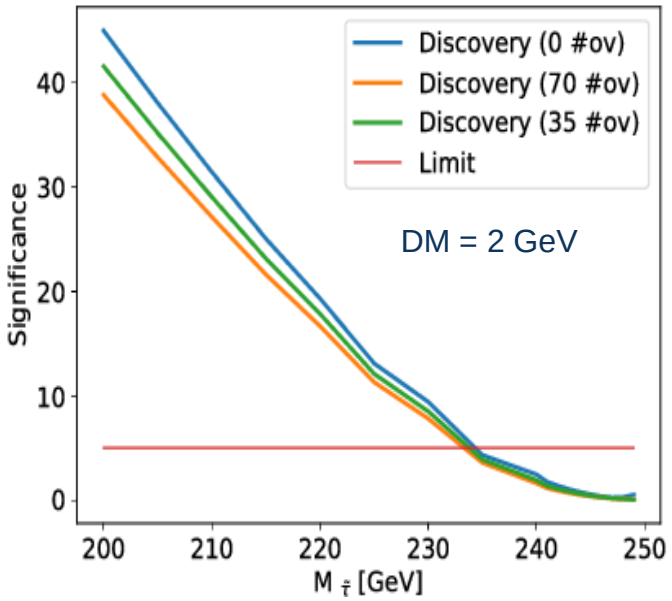
beam induced backgrounds

ILC500: effect of overlay-only events

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

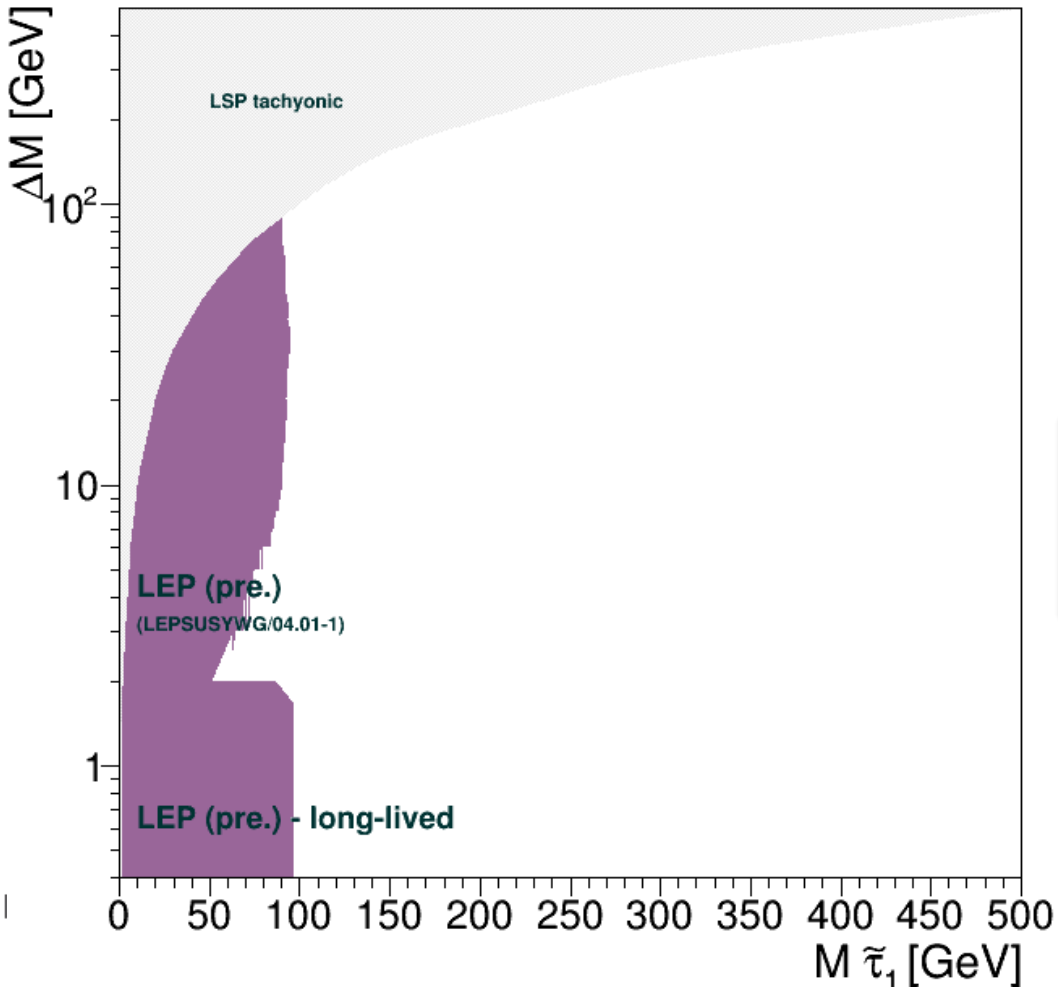
.. effect only appreciable for $\tilde{\tau}$ masses close to kinematic limit and smallest (~ 2 GeV) LSP- $\tilde{\tau}$ mass differences





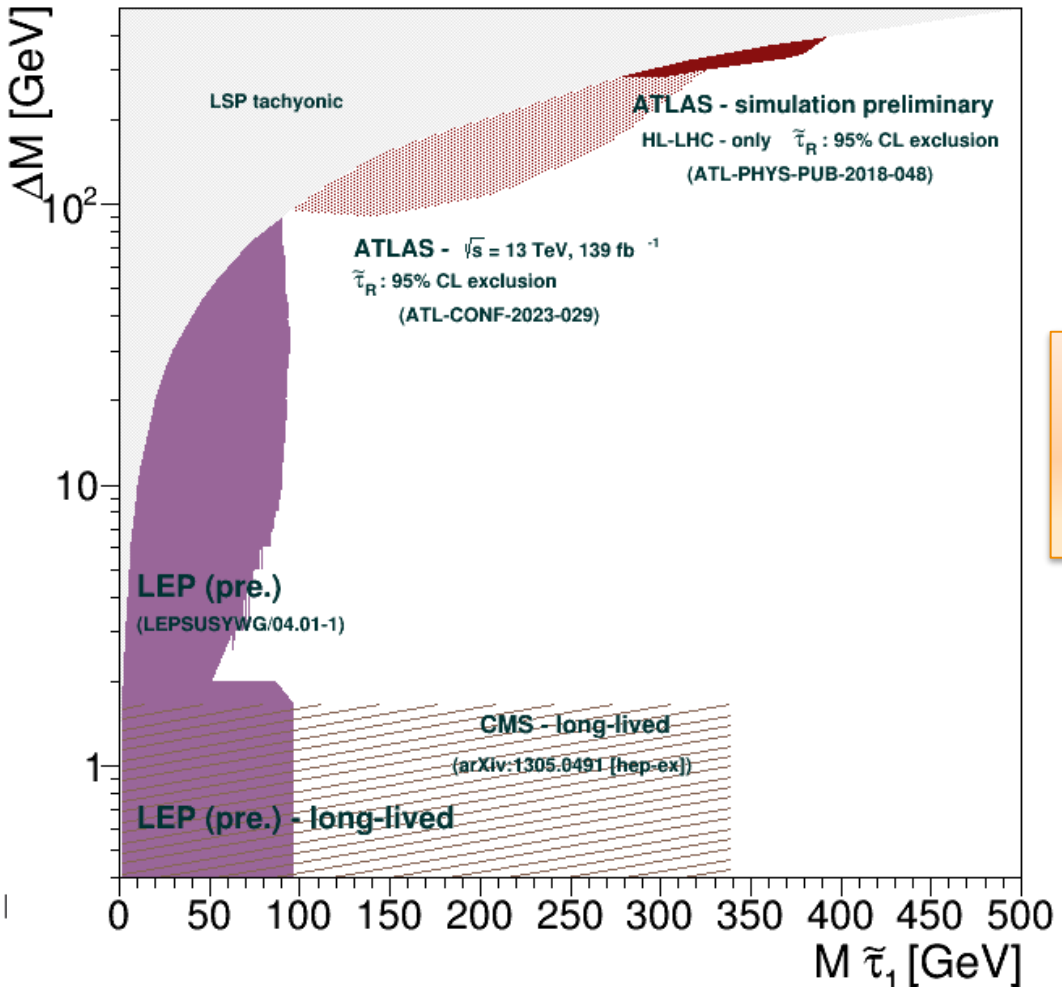
Impact of overlay-only events can be mitigated to negligible levels (additional ISR and vertex information can be used)

ILD full simulation analysis:results



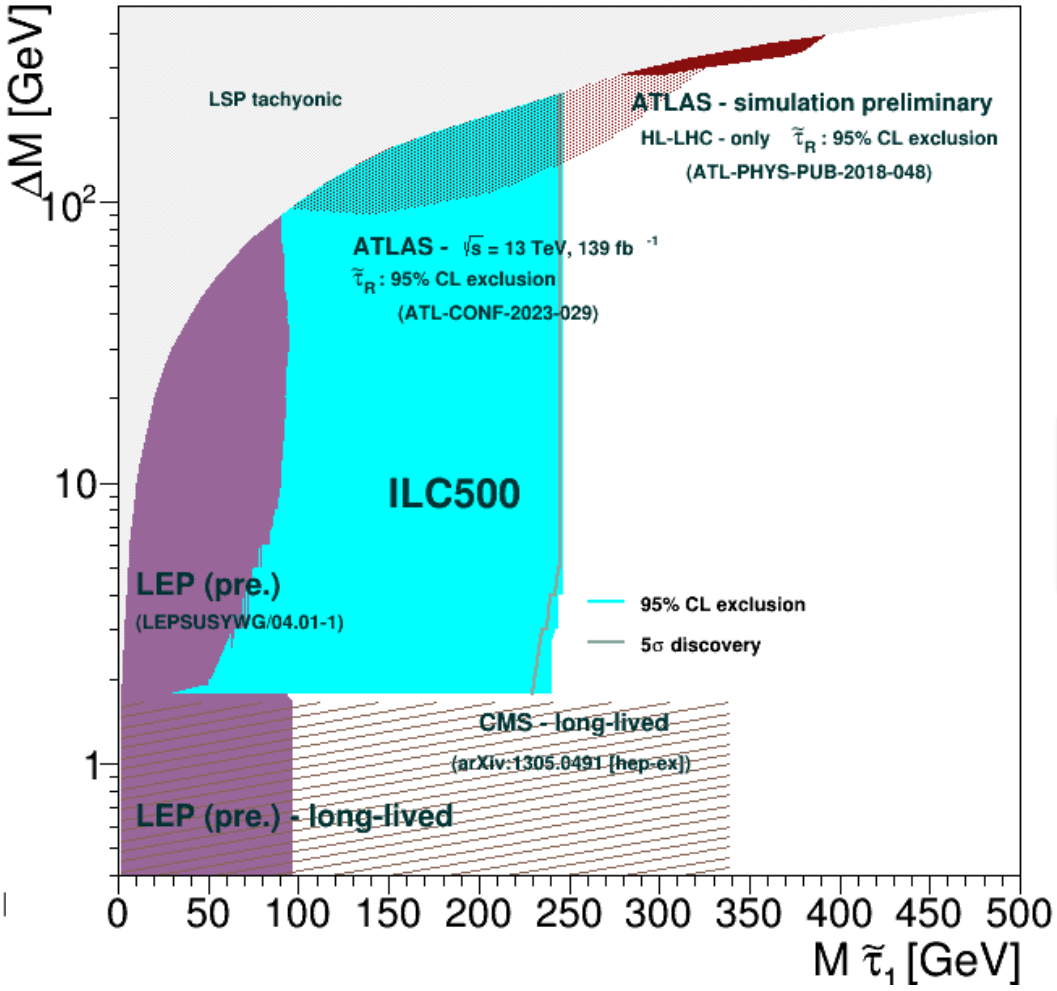
Current model-independent limits for $\Delta M > \tau$ mass come from LEP

ILD full simulation analysis:results



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

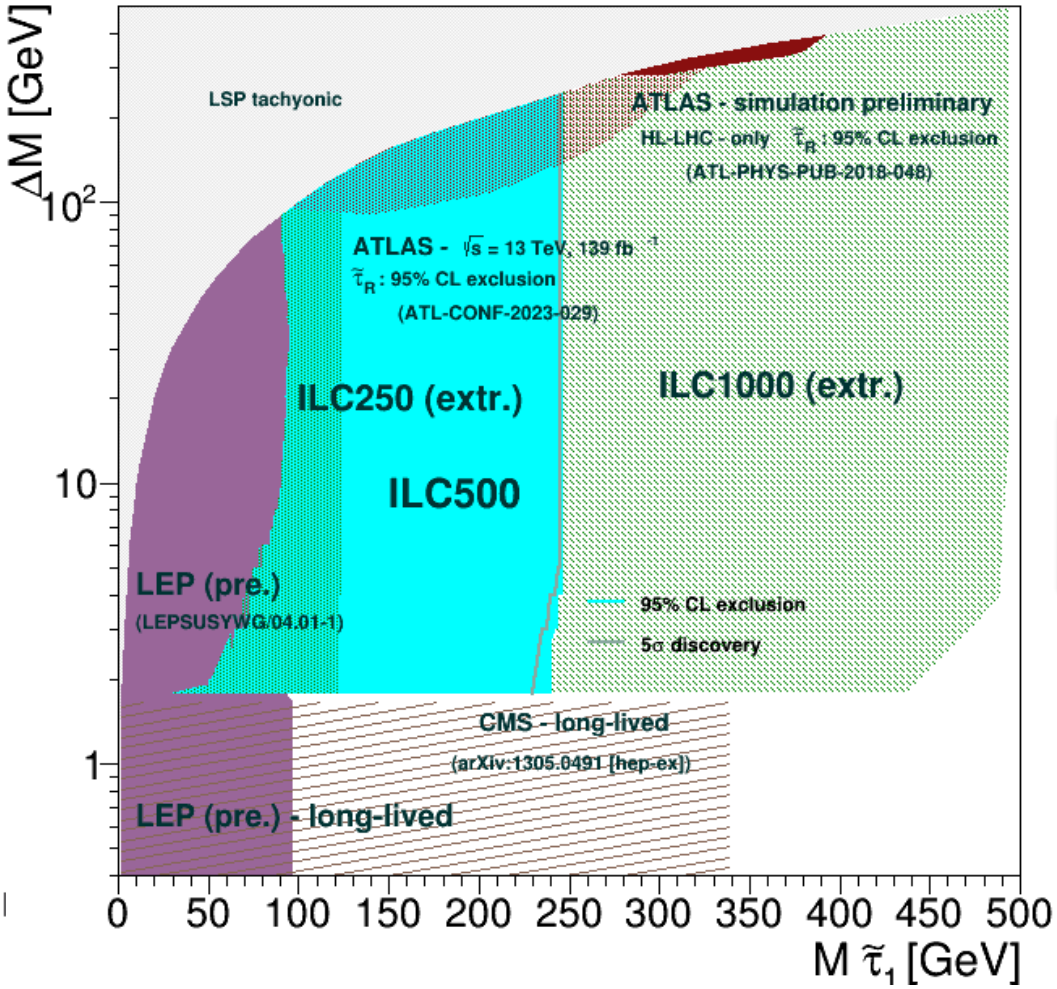
ILD full simulation analysis:results



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

arXiv:2105.08616

ILD full simulation analysis:results



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

arXiv:2105.08616

Impact of specific ILD/ILC features: polarisation

General e+e- future colliders features:

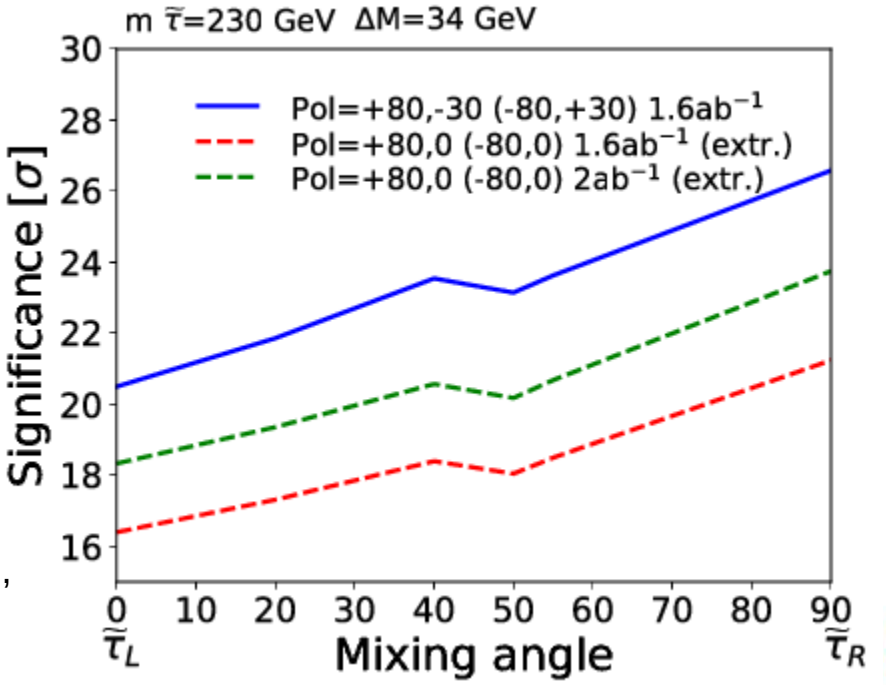
- energies from 90 GeV to 3 TeV, with typically a first run at 240/250 GeV
- both/one/none of the beams polarised
- clean or very clean conditions
- hermeticity excellent for some (down to ~6 mrad), still good for others (down to ~50 mrad)

Polarisation:

- combination different polarisation samples allows for equal sensitivity to all mixing angles
- 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

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 polarisation



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 DM = 2 GeV changes excl. limit on $M\tilde{\tau}$ from 112 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

Main advantage of any linear option

Triggerless operation:

- big advantage when searching for unexpected signatures

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

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Impact of specific ILD/ILC features:

beam-induced backgrounds, hemerticity

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 transverse 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

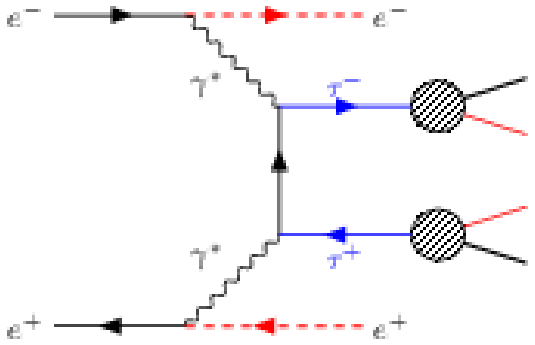
Evaluating impact of FCCee-like MDI in $\tilde{\tau}$ sensitivity

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 (preliminary estimation):

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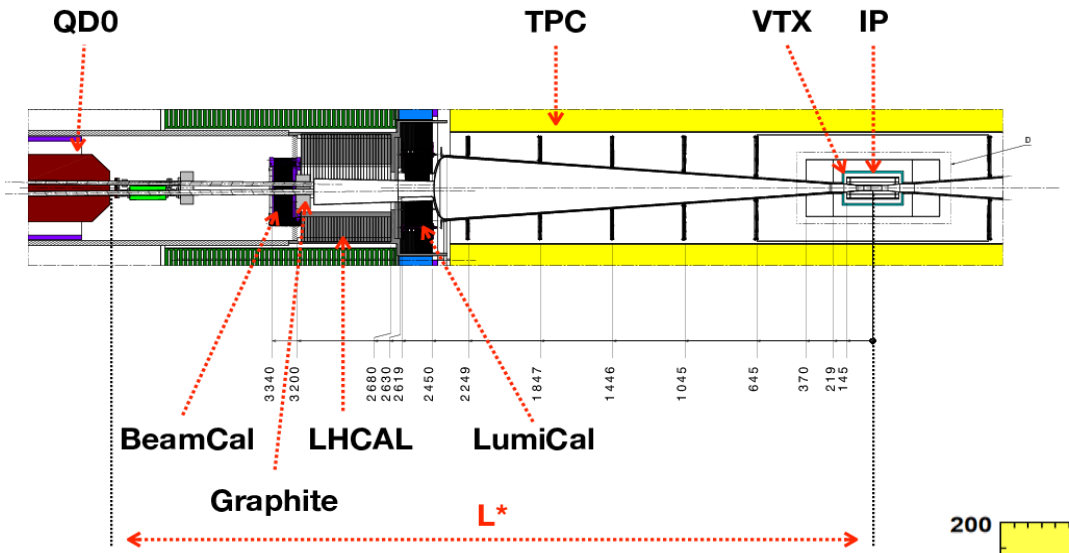
Evaluating impact of FCCee-like MDI in $\tilde{\tau}$ sensitivity (ctd.)



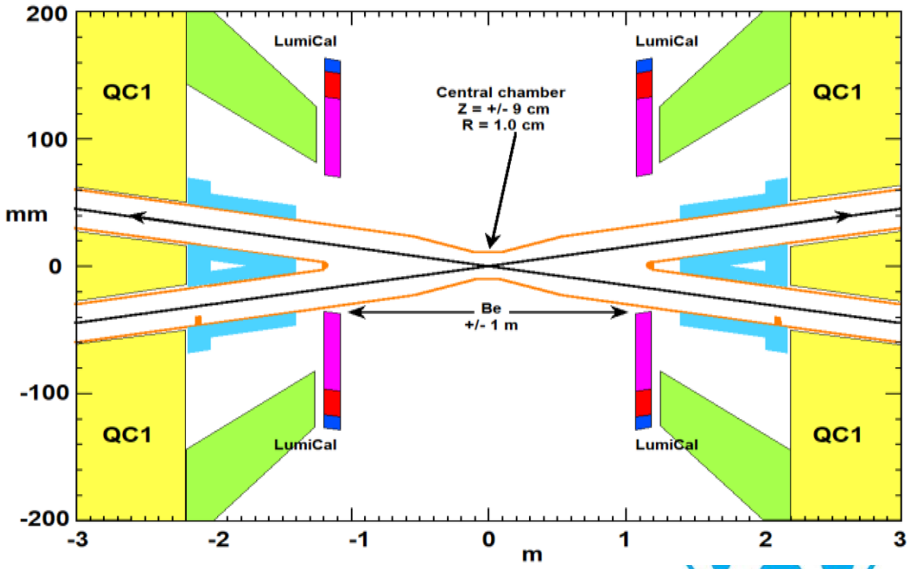
ILD@ILC

FCCee

BeamCal 6 mrad down to the beam pipe

No BeamCal

LumiCal 50 mrad down to the beam pipe



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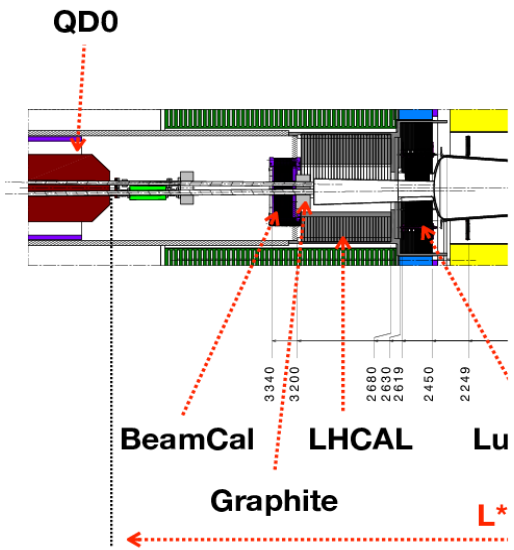
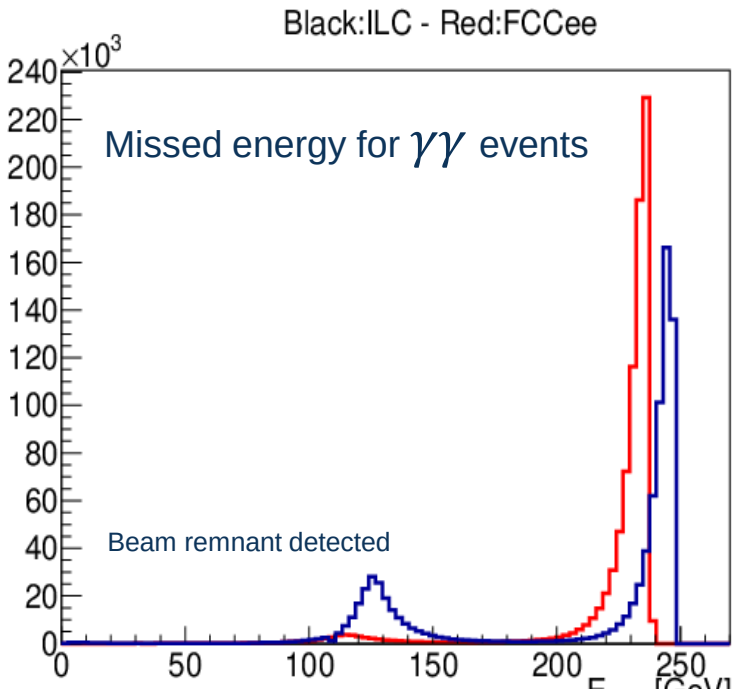
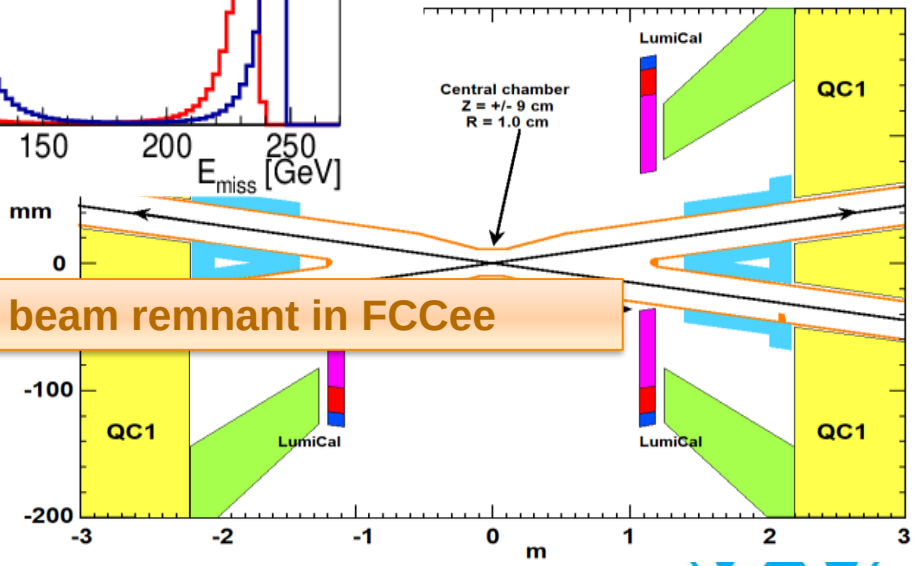


BeamCal 6 mrad down to the



FCCee



Almost not detection of beam remnant in FCCee

LumiCal 50 mrad down to the beam pipe

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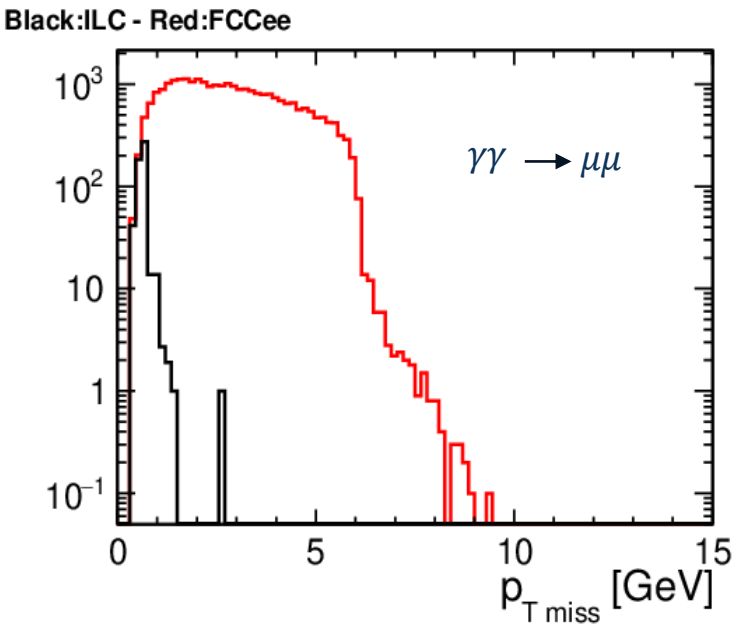
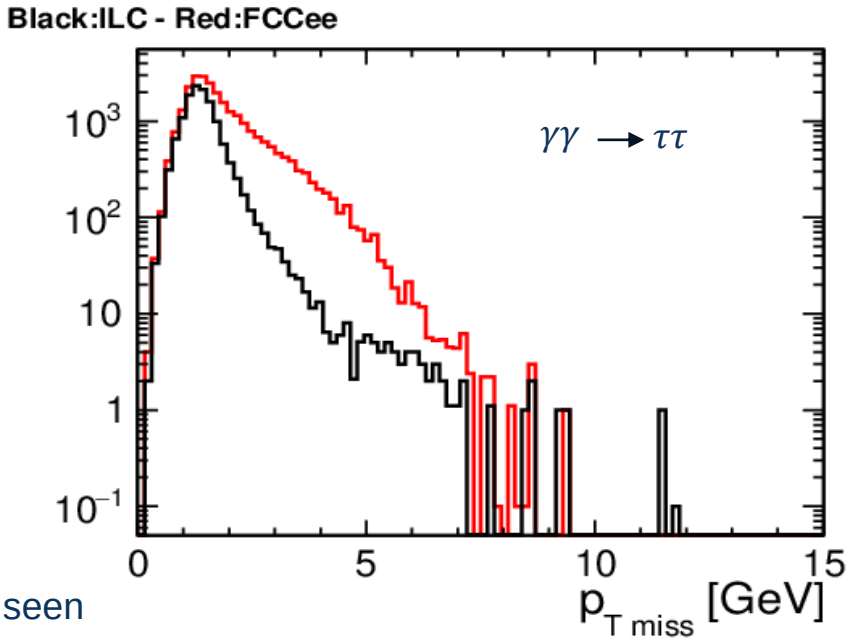
Evaluating impact of FCCee-like MDI in $\tilde{\tau}$ sensitivity (ctd.)

Effect of hermeticity on p_{Tmiss}

p_{Tmiss} distributions from $\gamma\gamma$ background just before the cut on this variable





Dramatic effect in the $\mu\mu$ case, where all the p_T of the pair is seen
Cut in p_{Tmiss} 10 times higher for getting the same rejection

Difference washed up in the $\tau\tau$ case due to the extra missing p_T of the neutrinos in the τ decays

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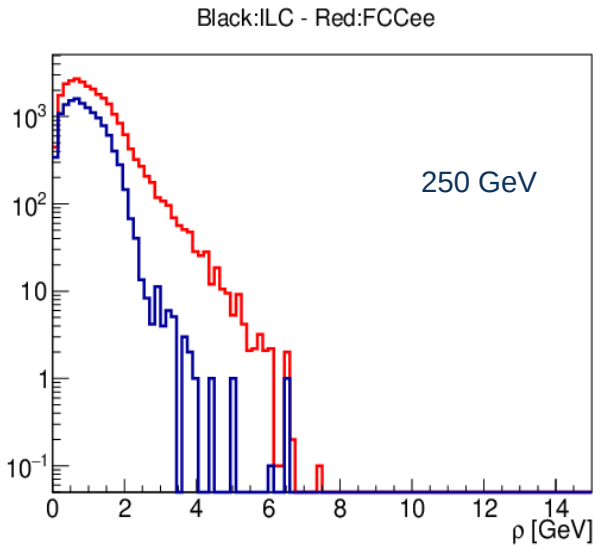
Evaluating impact of FCCee-like MDI in $\tilde{\tau}$ sensitivity (ctd.)

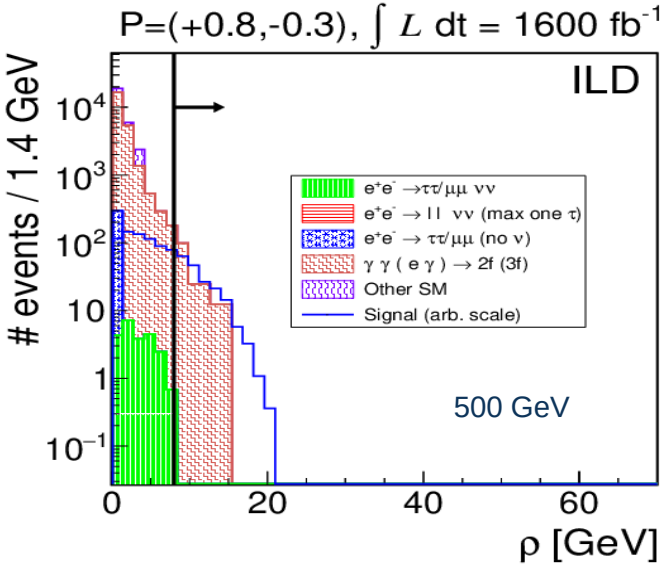
Effect of hermeticity on ρ cut



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

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

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



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

Extrapolating ILC-500 results to FCCee-240 conditions

- Re-scaling the results from $\sqrt{s}$ = 500 GeV to $\sqrt{s}$ = 240 GeV
- Taking the different beam conditions into account, mainly polarisation and luminosity (beam-induced backgrounds can be neglected)
- Changing the detector acceptance from 6 mrad to 50 mrad

Energy

- Kinematical variables scale with the energy
- Ratio S/B stays the same
- Ratio S/$\sqrt{B}$ 2.08 times better at 240 GeV

Polarisation and beam-induced backgrounds

No polarisation means:

- no increase of effective luminosity (24% in ILC-500 conditions)
- no possibility to do Likelihood ratio weighting

Ex. M$\tilde{\tau}$ = 245 GeV ΔM= 8 GeV significance 2.54σ in ILC-500 conditions, 1.8σ for unpolarized beams.

Absence of overlay-on-physics events at FCCee is an advantage at very low mass differences, but no longer present for ΔM= 8 GeV

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

Hermeticity

Estimate the increase in background modifying acceptance of forward calorimeter at generator level for $\gamma\gamma$ background (dominant at mass differences around/below 10 GeV)

Ex. M$\tilde{\tau}$ = 245 GeV ΔM= 10 GeV

- $\gamma\gamma$ background represents 93% of total one at ILC-500 with unpolarized beams
- ρ cut needs to be increased by 75% to keep the same level of this background, implying 82% signal lost
- Significance goes down to 0.4σ and S/B to 2.6%

Putting all together …

- M$\tilde{\tau}$ = 245 GeV ΔM= 10 GeV at ILC-500 would be M$\tilde{\tau}$ = 118 GeV ΔM= 4.8 GeV at FCCee-240
- Significance would be 2.08 times better, that means 0.8σ
- 2σ would not be reached even with the increase in luminosity

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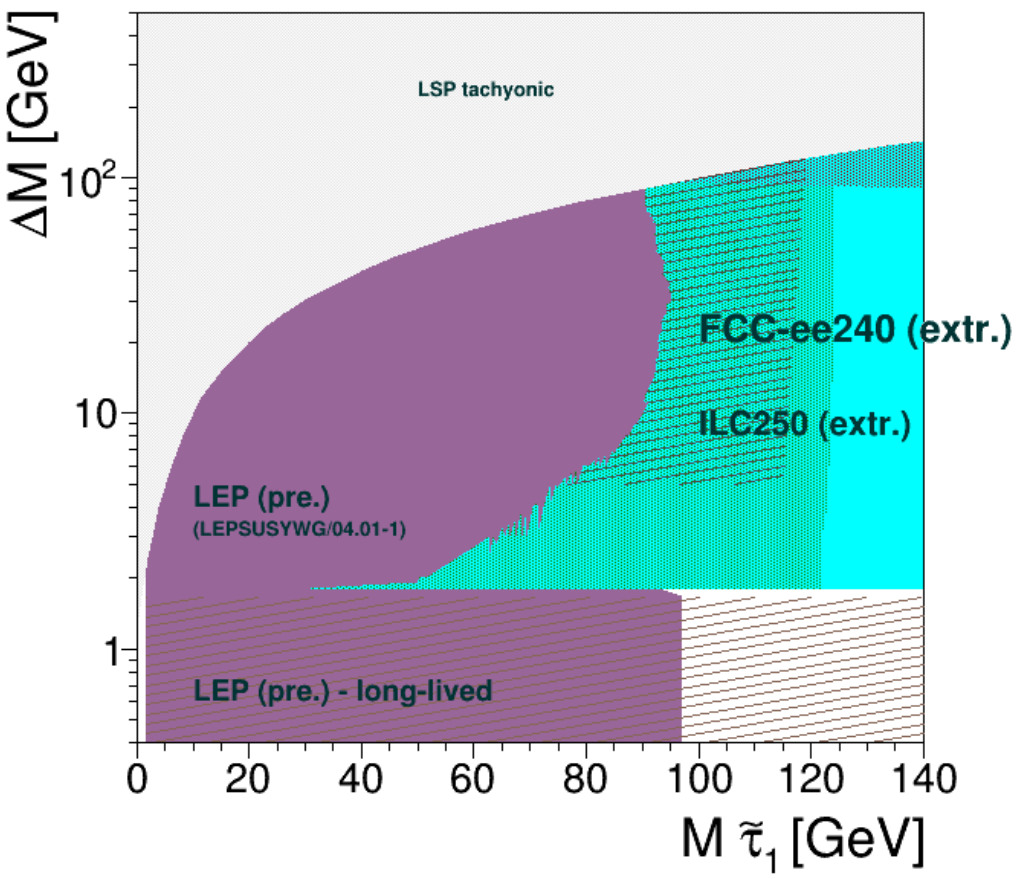
Evaluating impact of FCCee-like MDI in $\tilde{\tau}$ sensitivity (ctd.)

Rude extrapolation …



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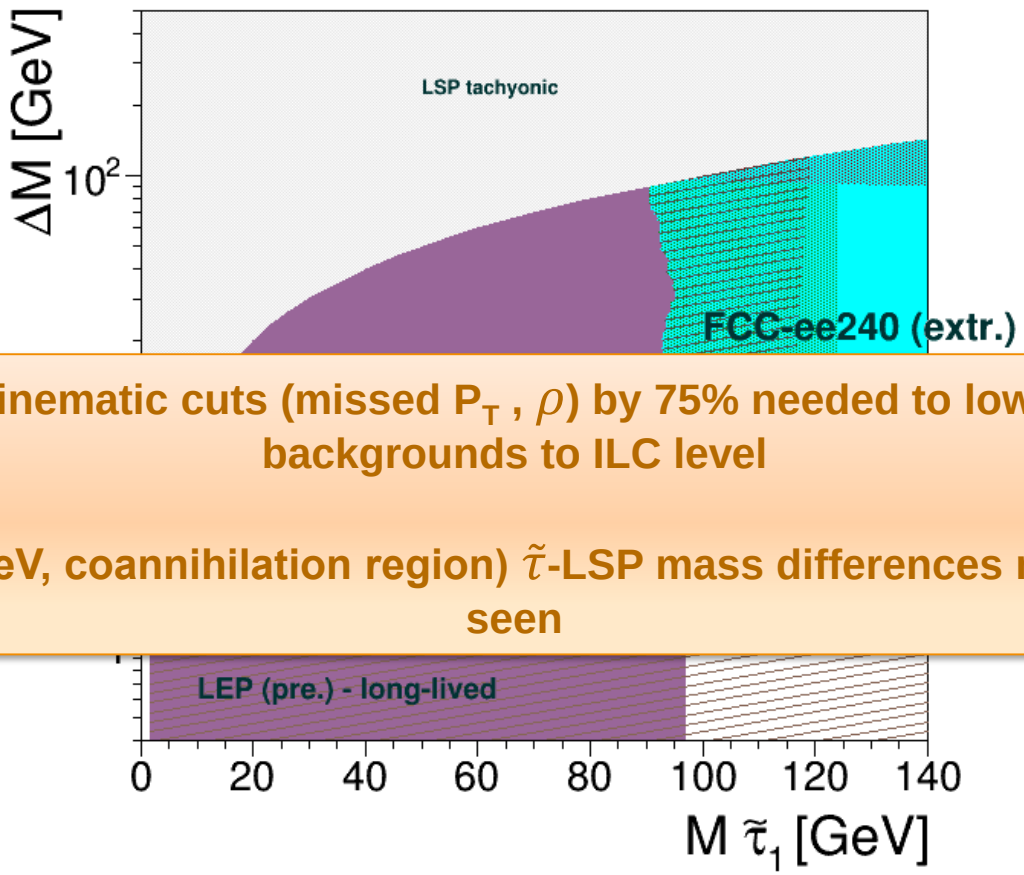

Increase of kinematic cuts (missed P_T , ρ) by 75% needed to low down FCCee backgrounds to ILC level

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

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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: 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, 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