$\tilde{\tau}$ searches at the ILC

Teresa Núñez - DESY

- Why still SUSY?
- Motivation of $\tilde{\tau}$ studies
- $\tilde{\tau}$ analysis
  - Signal and SM background
  - Worst mixing
  - General cuts
  - Beam induced backgrounds
  - Limits
- Outlook and conclusions

International Workshop in Future Linear Colliders
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Why still SUSY?

Future electron-positron colliders offer excellent facilities for SUSY searches,

wrt. previous electron-positron colliders:

- increased luminosity and centre-of-mass energy
- improved technologies

wrt. hadron colliders:

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

… being, in contrast to hadron colliders, well adapted to colour neutral SUSY sector:

- one of the most relevant for SUSY as explanation of the main problems of the SM
- expected to have a sufficiently light mass to be observable in these future colliders, for theoretical reasons and from the results of the global fits

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Motivation for $\tilde{\tau}$ searches to have guarantees of discovery or exclusion

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:

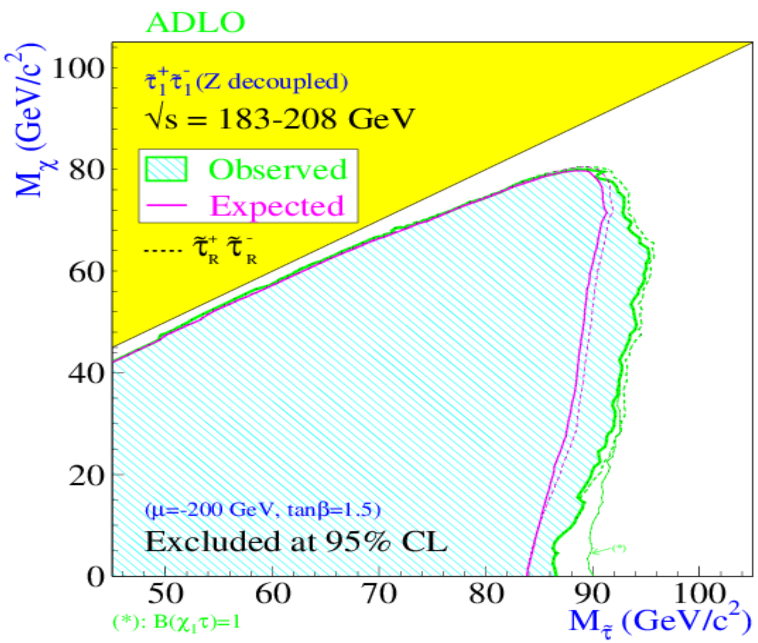
  - pair produced (s-channel via Z^0/γ exchange, low σ since $\tilde{\tau}$-mixing suppresses coupling to the Z^0)

  - 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)

Current limits (LEP) and HL-LHC prospects

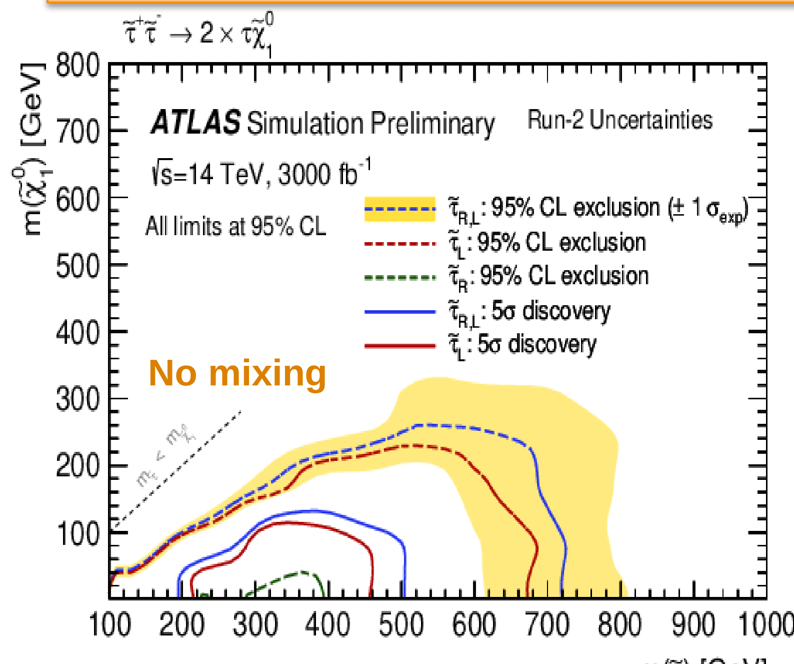
Current $\tilde{\tau}$ limits (combining data from four LEP experiments)



LEPSUSYWG/04-01.1

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

$\tilde{\tau}$ prospects at HL-LHC (same conclusions for ATLAS and CMS limits)



M $\tilde{\tau}$ - M$_{LSP}$ > 120 GeV

ATL-PHYS-PUB-2018-048

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

Conditions ILC searches

Studies using the full detector simulation and reconstruction procedures of the International Large Detector concept (ILD) at the International Linear Collider (ILC)

- $\sqrt{s}$ = 500 GeV (extrapolated to 250 GeV and 1 TeV)
- Both main polarisations, P(+80%, -30%) and P(-80%, +30%), with $\mathcal{L}$ = 1.6 ab^{-1} each (H20 scenario)
- Including all SM and beam-induced backgrounds

Detector simulation and reconstruction for the signal done using the SGV fast simulation with beam-spectrum and photons in the beam added from the full simulated background samples

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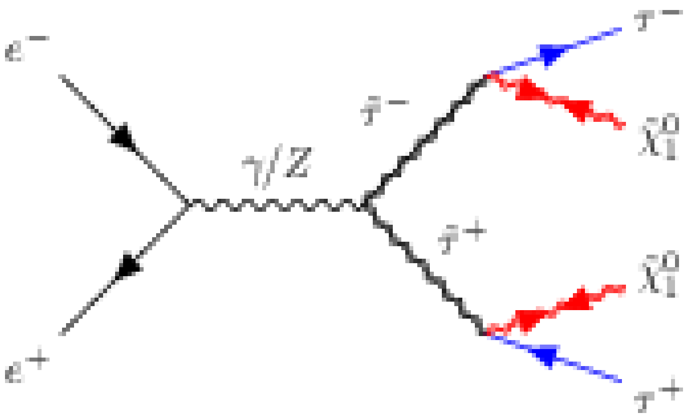
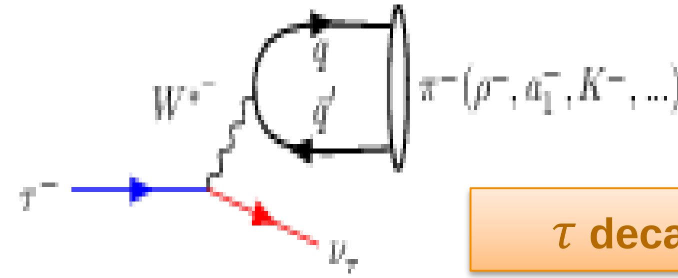
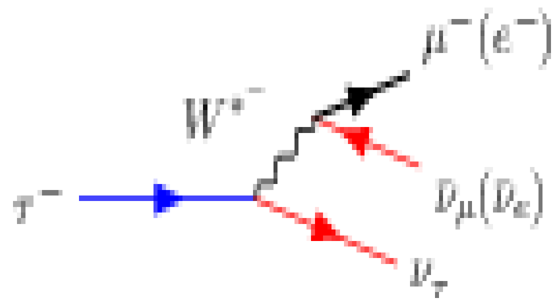
Signal characterization

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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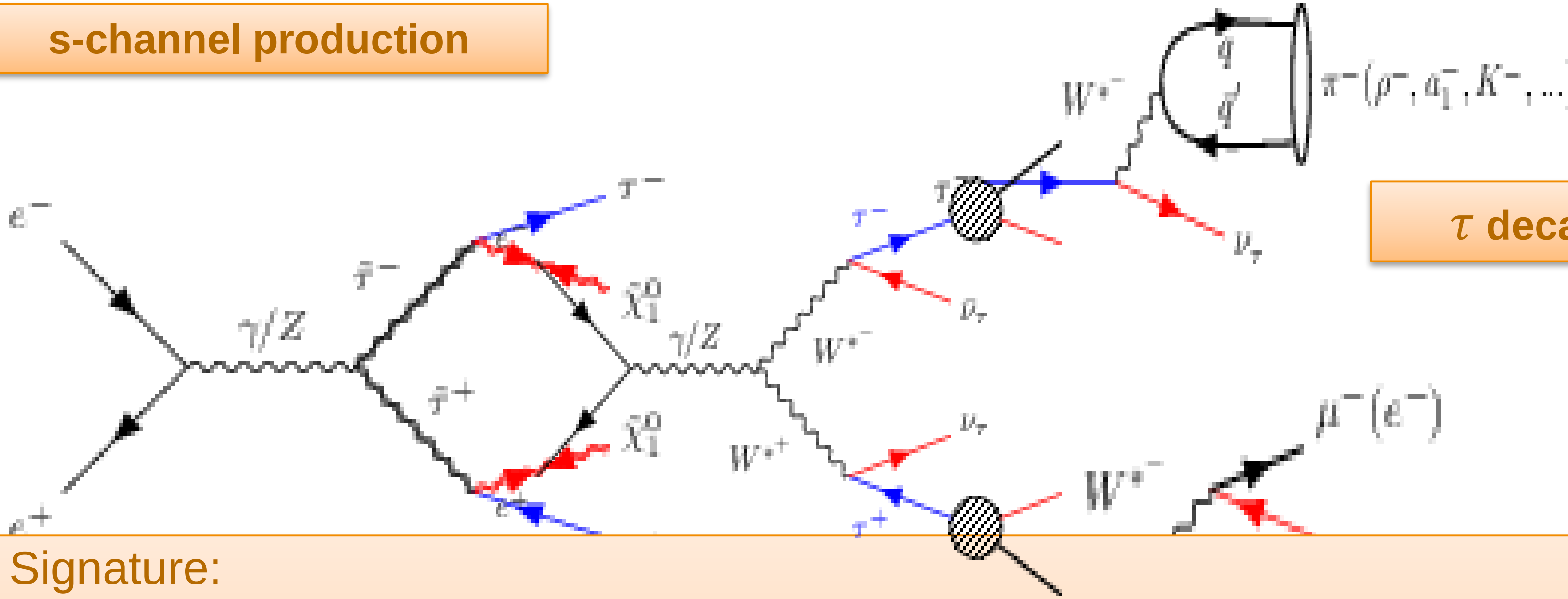
Signal characterization

s-channel production



τ decays

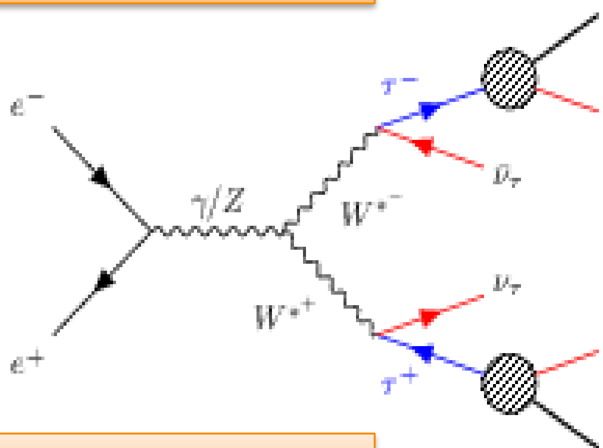
Signature:

- 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

SM background

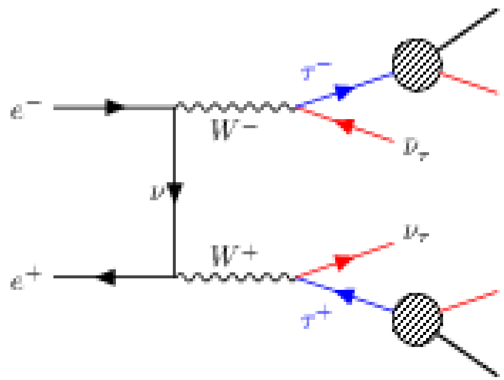
SM processes with real or fake missing energy

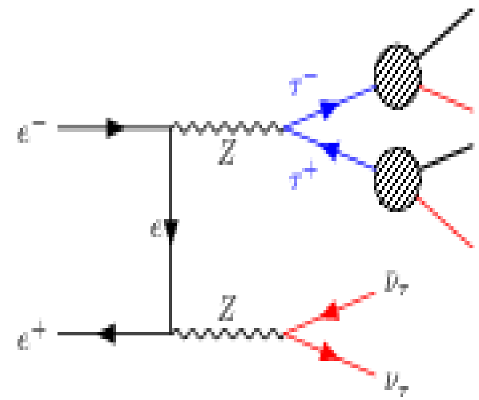
Irreducible



Almost irreducible

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





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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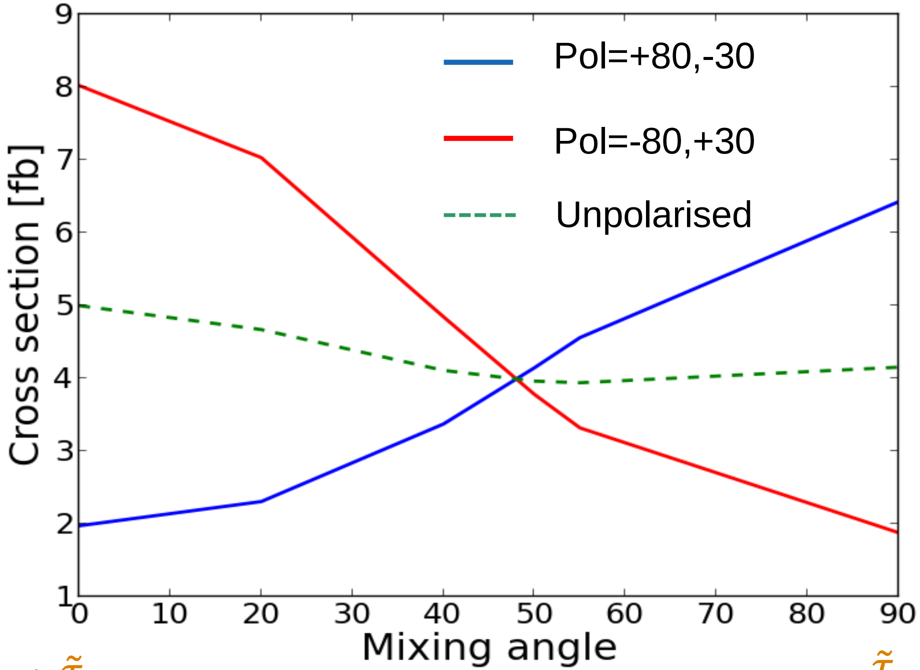
Analysis of worst mixing

Search for “worst” mixing angle

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

m $\tilde{\tau} = 230\ GeV$



$\tilde{\tau}_L$ $\tilde{\tau}_R$

Use ILC conditions weighting contribution of both polarisations

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

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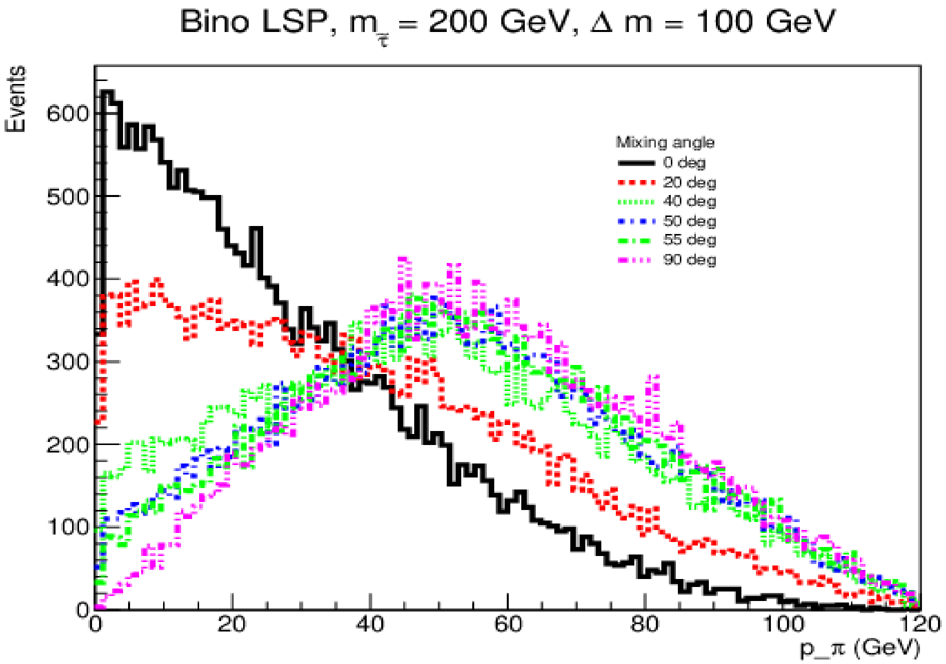
Analysis of worst mixing (ctd.)

Dependence of signal efficiency on $\tilde{\tau}$ mixing



- 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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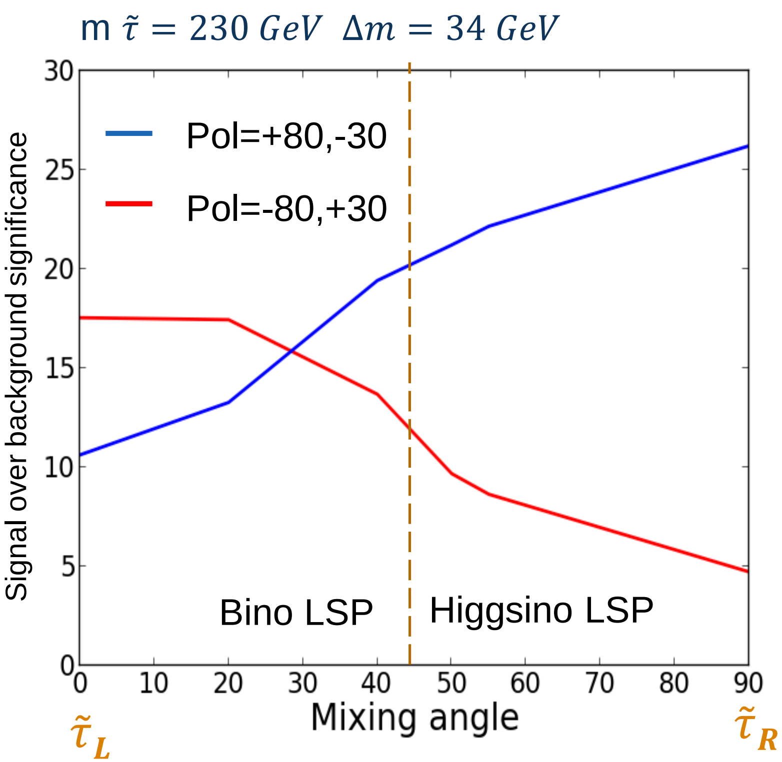
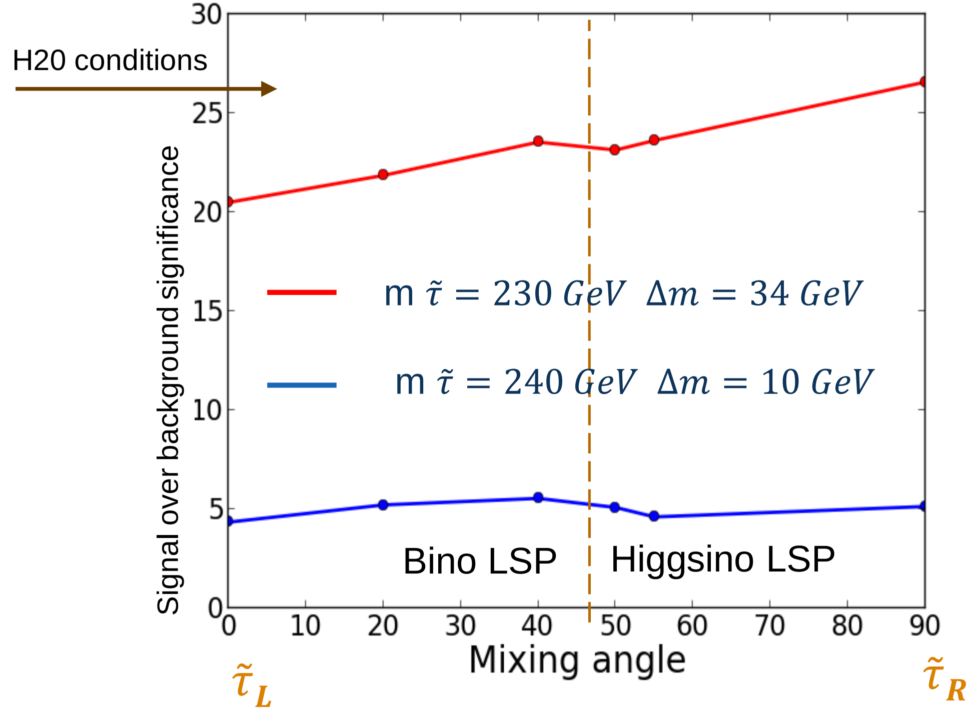
Analysis of worst mixing (ctd.)

Likelihood-ratio statistic used to weight both polarisations





Equal sharing of P(+80,-30) and P(-80,+30) forseen in H20 ensures an uniform sensitivity to all mixing angles

Mixing angle of 53 degrees selected

General cuts

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

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)

- Two well identified τ's and little other activity

Clean final state
('no' pile-up)

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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Triggerless operation

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General cuts (ctd.)

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

- Missing transverse momentum
- Large acoplanarity
- Large transverse momentum wrt. thrust-axis
- 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

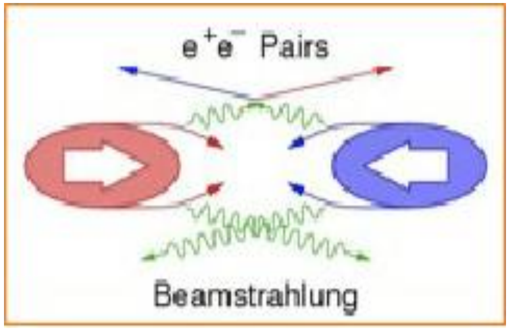
High polarised beams

Properties that the background often "does not" have

- Low energy in small angles
- Low energy of isolated neutral clusters

Beam induced backgrounds in e^+e^- colliders

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



Interactions between real and/or virtual photons produce:

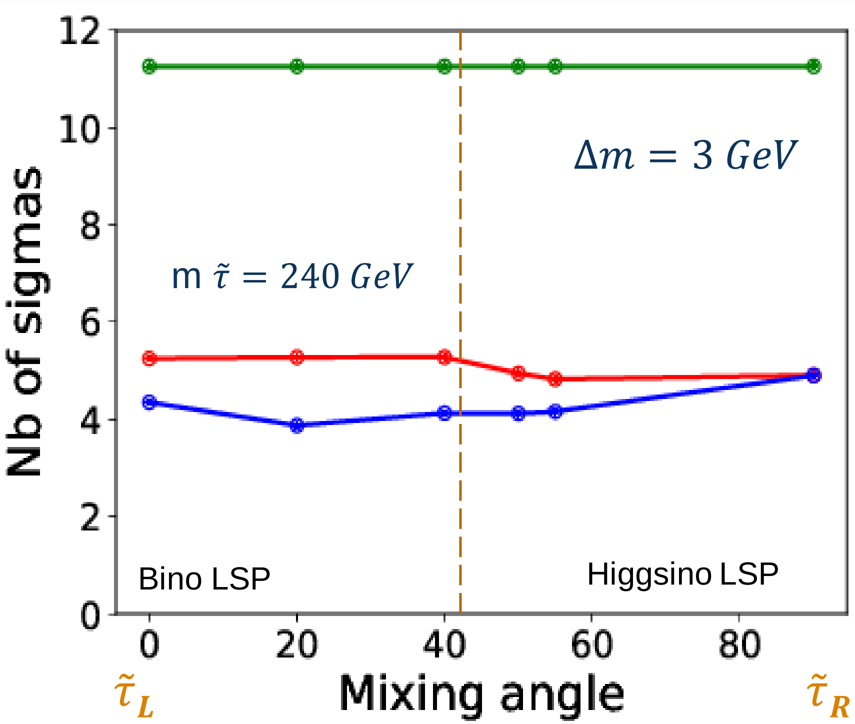
- e^+e^- pairs
  - produced by scattering of two real photons
  - 10^5 pairs per bunch crossing
  - very low p_T (< 1GeV), curl up in magnetic field, interesting for BeamCal studies
- low p_T hadrons
  - produced by vector meson fluctuations of real or virtual photons
  - <1.05> events per bunch crossing at $\sqrt{s}$ = 500 GeV
  - low p_T, travelling through the detector

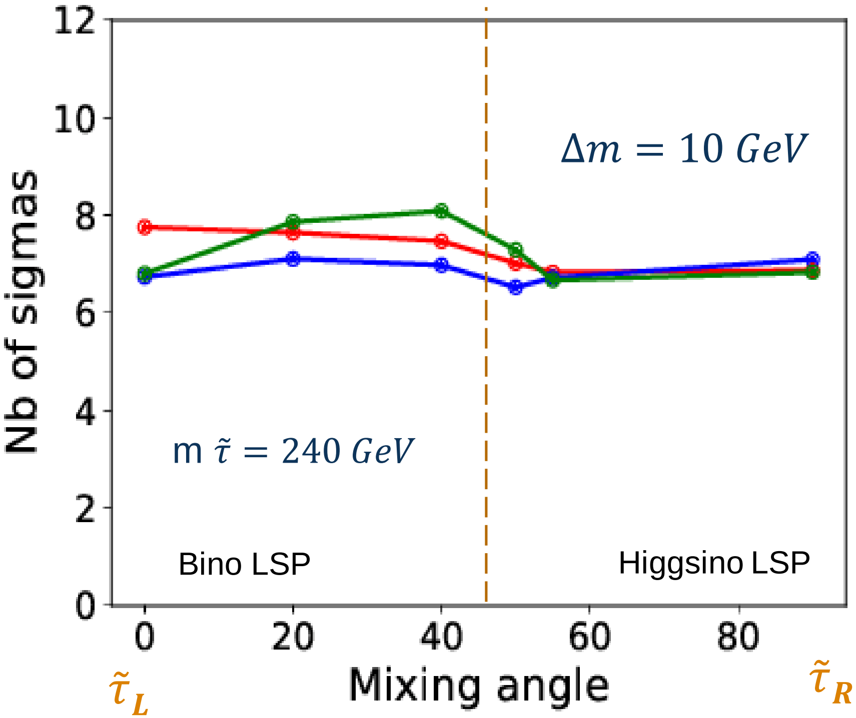
$\gamma\gamma$ interactions are independent of the e^+e^- process, but can happen simultaneously to it (overlay-on-physics events) or not (overlay-only events)

Effect of overlay-on-physics events

Full simulation

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





Larger effect of overlay tracks in low DM case since they are more similar to the signal ones: strong reduction of significance

Motivation for only-overlay events analysis

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

$\gamma\gamma \rightarrow low\ pT\ hadrons$ 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

Only-overlay analysis strategy

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

Rejection "standard" cuts alone:

$M_{\tilde{\tau}} - M_{LSP}$ (DM)	2 GeV	10 GeV
	2.6×10^{-3}	$< 2.7 \times 10^{-6}$ (95% CL)

(All surviving events with $\gamma\gamma \rightarrow low\ pT\ hadrons$ interactions)

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

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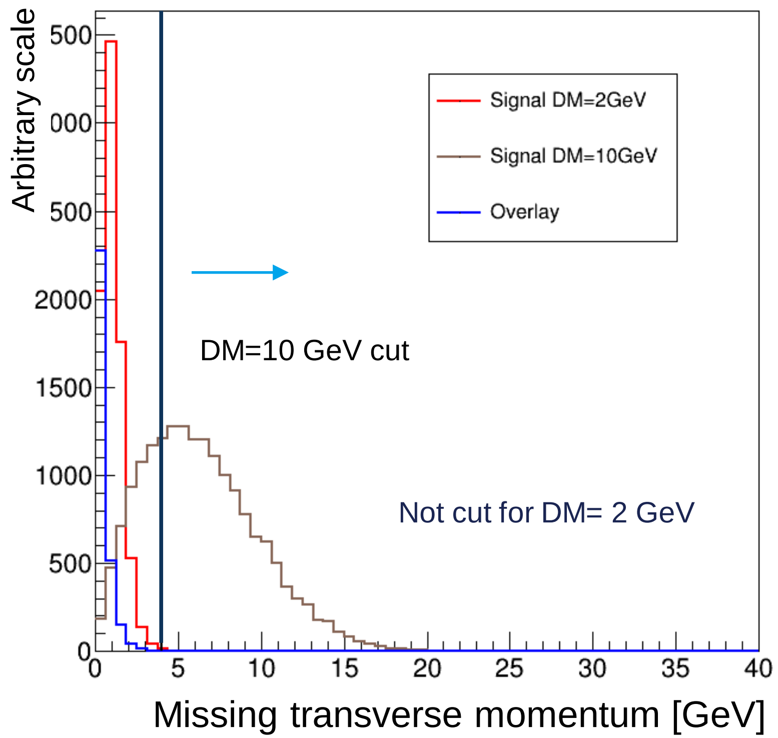
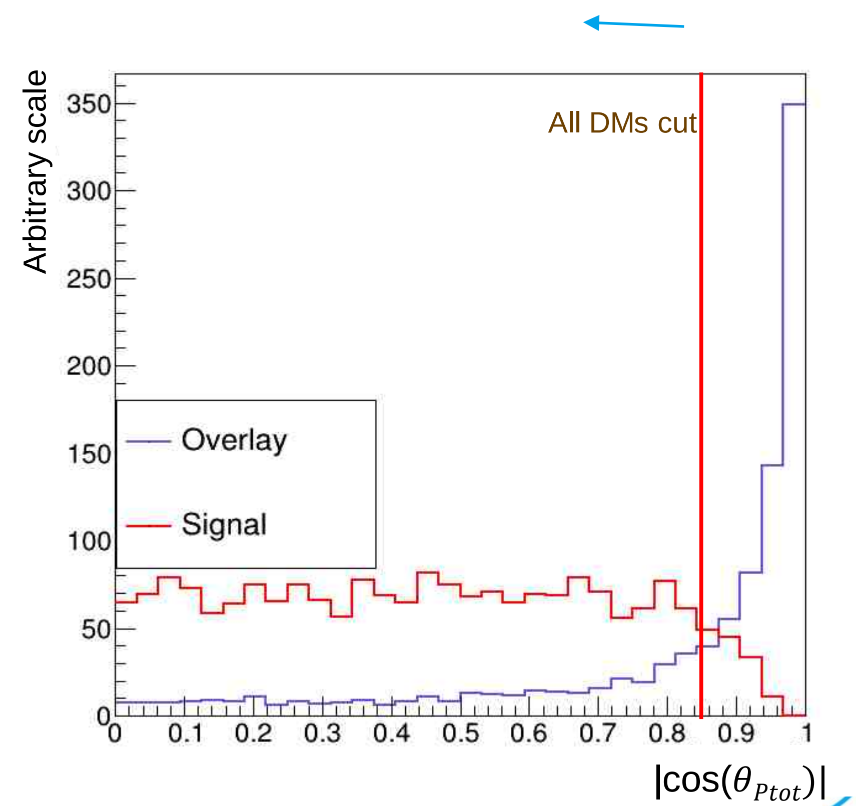
Examples general cuts on overlay-only events

Main difference between DM= 2 GeV and DM = 10 GeV rejections



Main difference between tracks in signal and overlay-only events
(main rejection for DM= 2 GeV)



Independent and additional cuts

Independent set of cuts from the "standard" ones:

- missed p_T+ ρ[1]
- remaining cuts[2]

(several cuts among the "standard" ones depend on the exact model-point)

Additional independent requirements based on:

- Initial State Radiation photons (ISR)
- vertex

(1) Tranverse momentum (in the plane) with respect to the thrust axis

(2) Multiplicity, energy, angular distributions, τ identification

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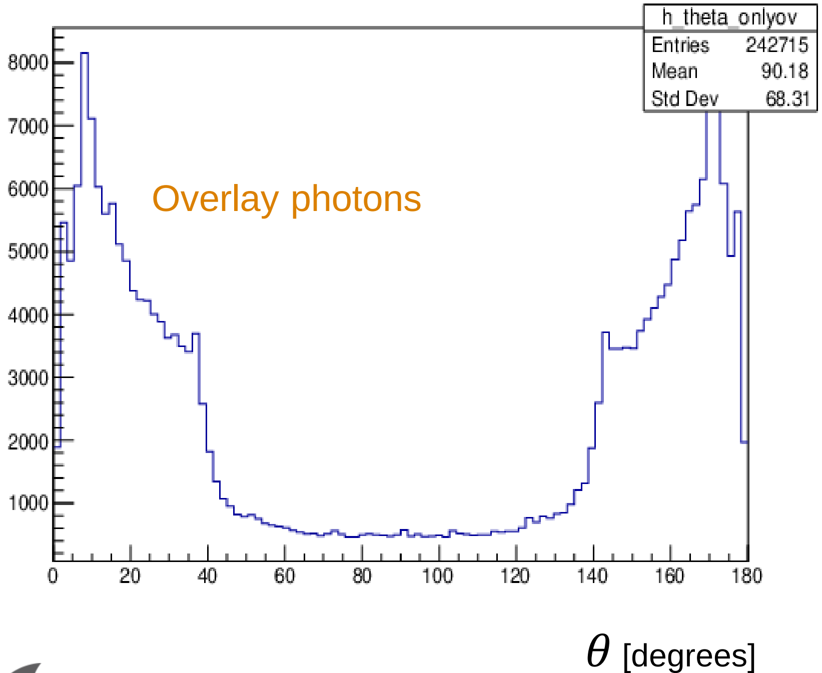
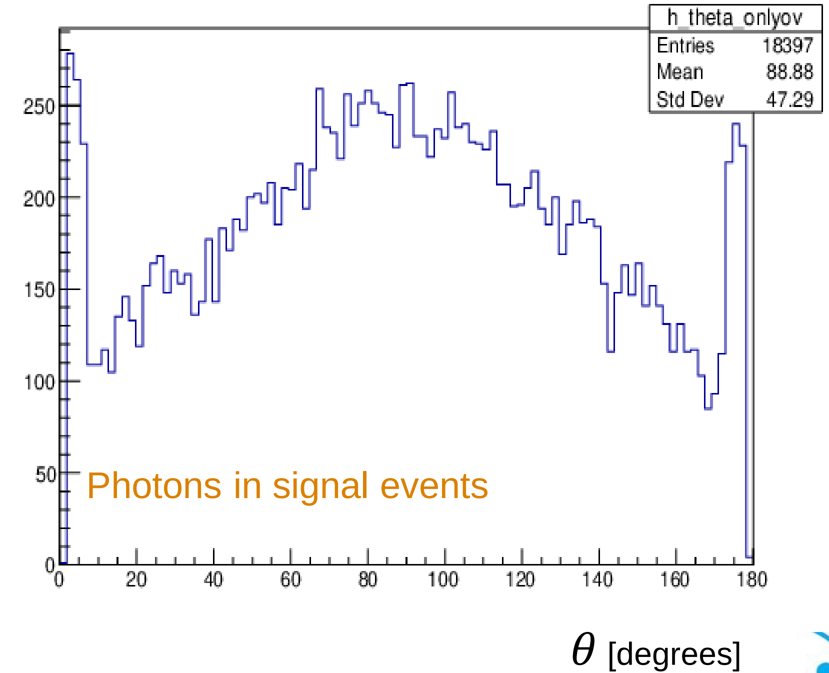
ISR requirement

Events with isolated photons with sizeable energy and angle to the beam above the lower edge of the tracking system

- Energy > 1.1 GeV
- Angle optimized for getting enough rejection without killing all events



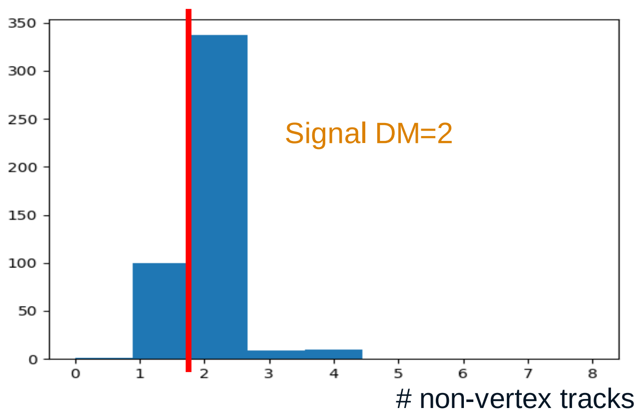


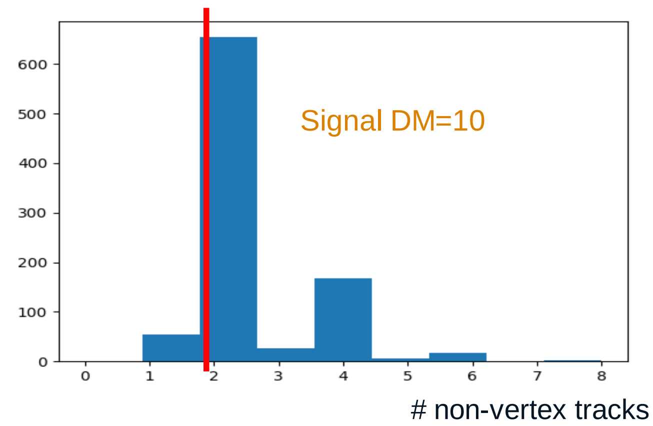
θ *cut tuned from* $\theta > 7$ *degrees (lower edge tracking system) to* $45 < \theta < 135$ *(no background)*

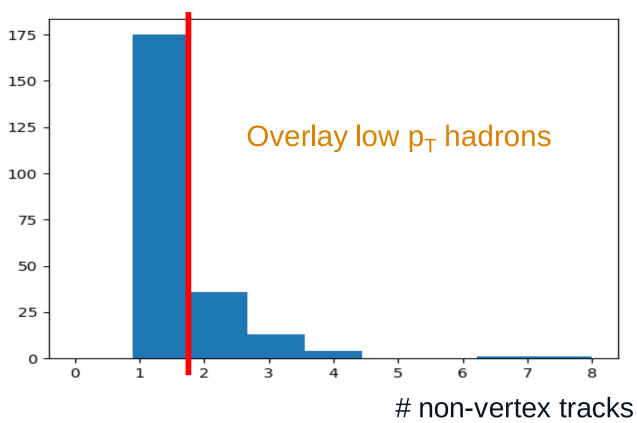
Vertex requirement

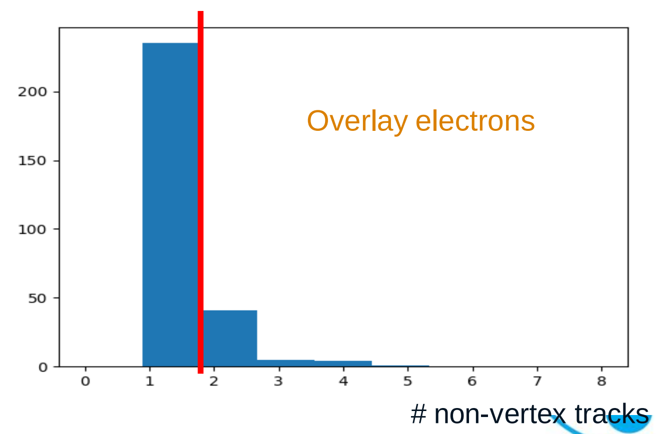
Events with at least two “non-vertex” tracks

Main vertex fitted with beam-spot as a constraint, effectively meaning that it will have at least two tracks
Tracks that are not included in any vertex (too high x^2) are “non-vertex” tracks









Rejection on overlay-only events

DM = 10 GeV

	red. missed $P_T + \rho$
	1.3×10^{-3}

	red. alone	combined w/ missed $P_T + \rho$
remaining cuts	6.0×10^{-3}	7.8×10^{-6}
remaining cuts + ISR ($7 < \theta$)	1.4×10^{-4}	1.8×10^{-7}
remaining cuts + ISR ($35 < \theta < 145$)	1.7×10^{-5}	2.2×10^{-9}

DM = 2 GeV

	red. vertex
	1.9×10^{-2}

	red. alone	combined w/ vertex
standard cuts	2.6×10^{-3}	5.0×10^{-5}
standard cuts + ISR ($7 < \theta$)	1.8×10^{-7}	3.5×10^{-9}
standard cuts + ISR ($30 < \theta < 150$)	9.5×10^{-9}	1.8×10^{-10}

Signal efficiency: ~10% with no requirement on detecting an ISR. It goes to ~5% if a detected ISR is required (for any θ)

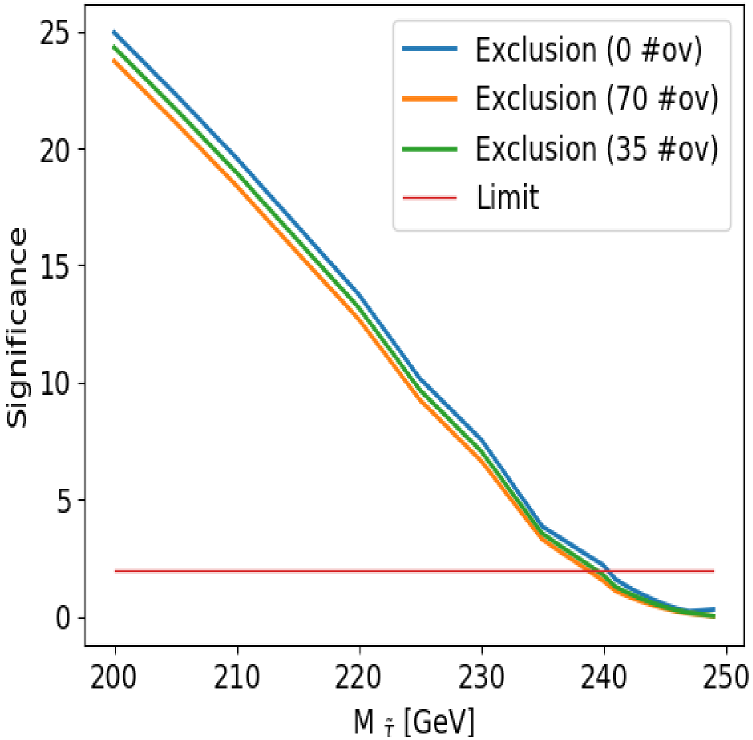
Adding overlay-only events to SM background

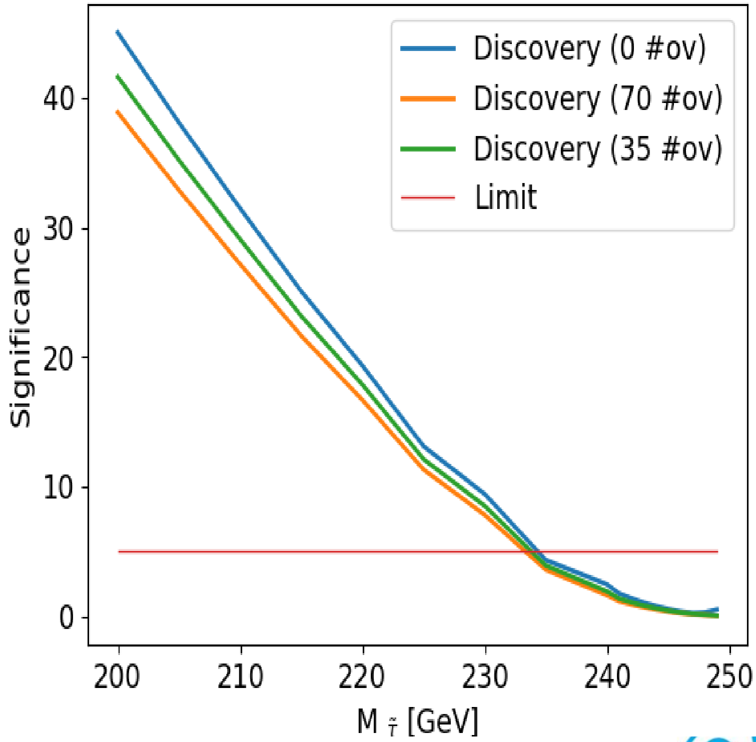
Significance with/wo overlay-only events

DM = 2 GeV

#overlay-only events ~70 per polarisation

(complete running time, both polarisations)





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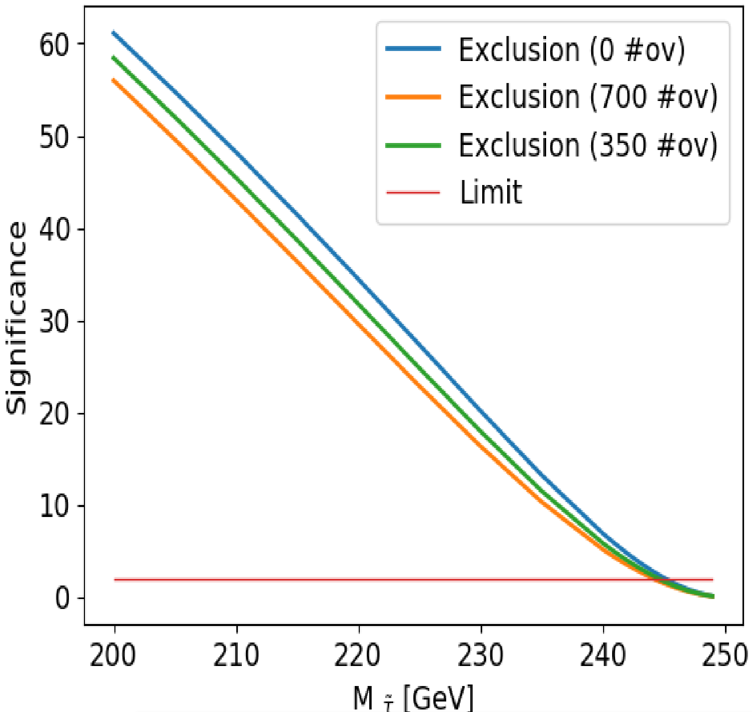
Adding overlay-only events to SM background

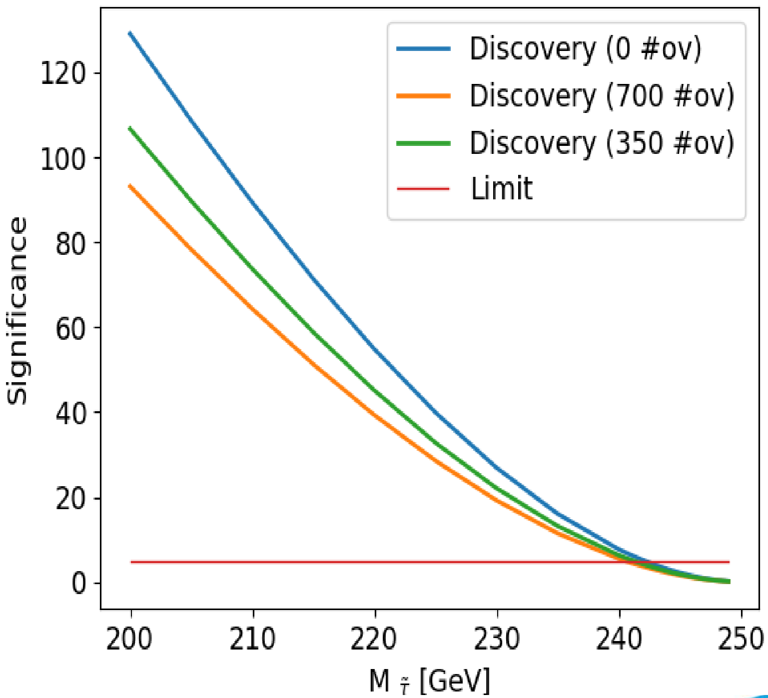
Significance with/wo overlay-only events

DM = 10 GeV

#overlay-only events ~700 per polarisation

(complete running time, both polarisations)





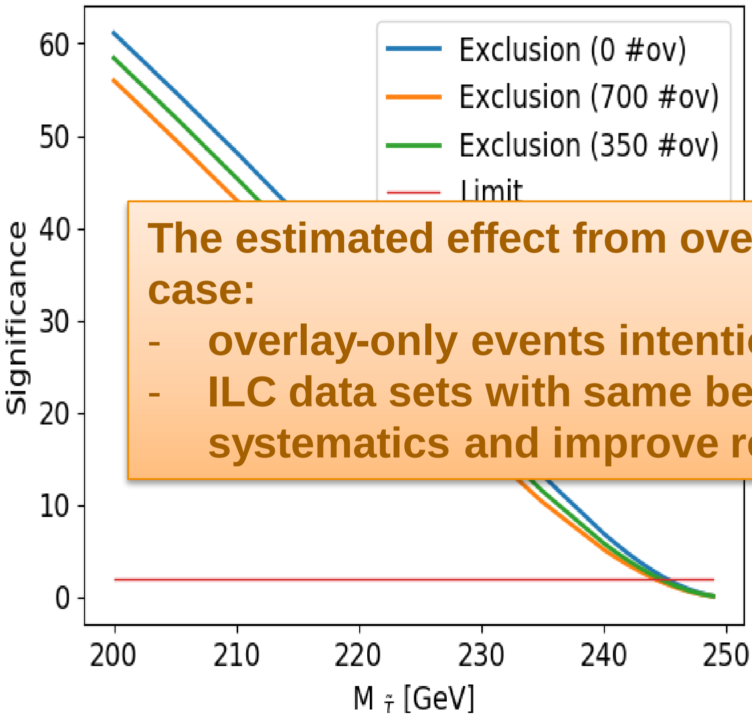
Less effect for DM = 10 GeV since remaining SM background is higher than the ones from overlay-only events (opposite to DM= 2)

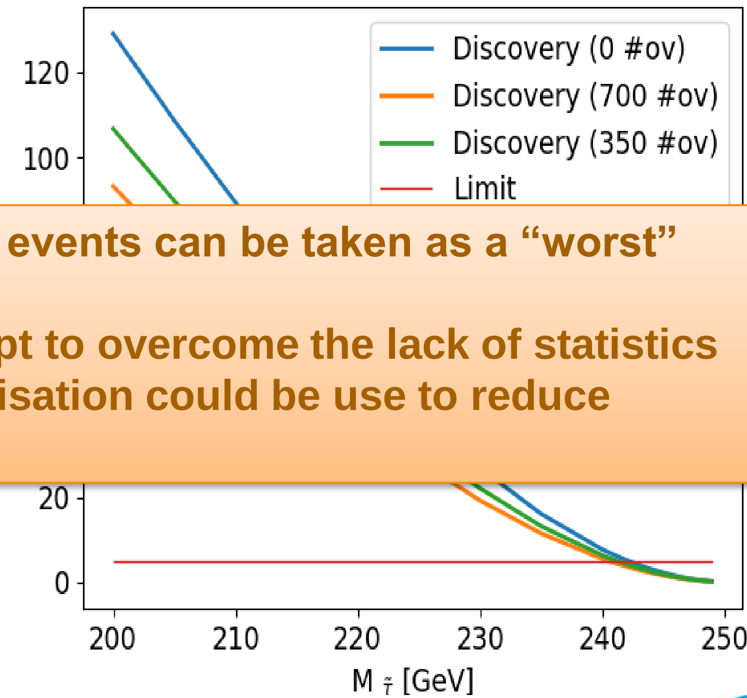
Adding overlay-only events to SM background

Significance with/wo overlay-only events

DM = 10 GeV

#overlay-only events ~700 per polarisation
(complete running time, both polarisations)





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**

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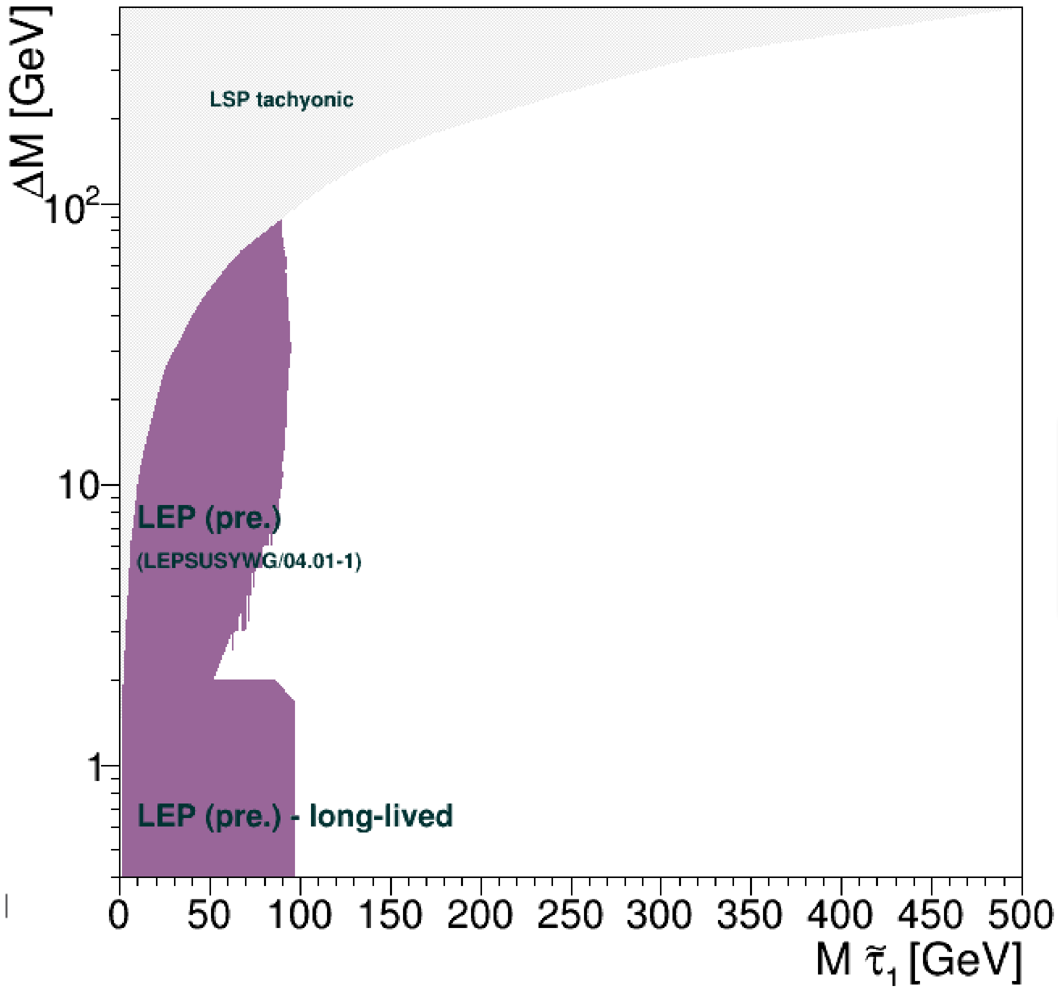
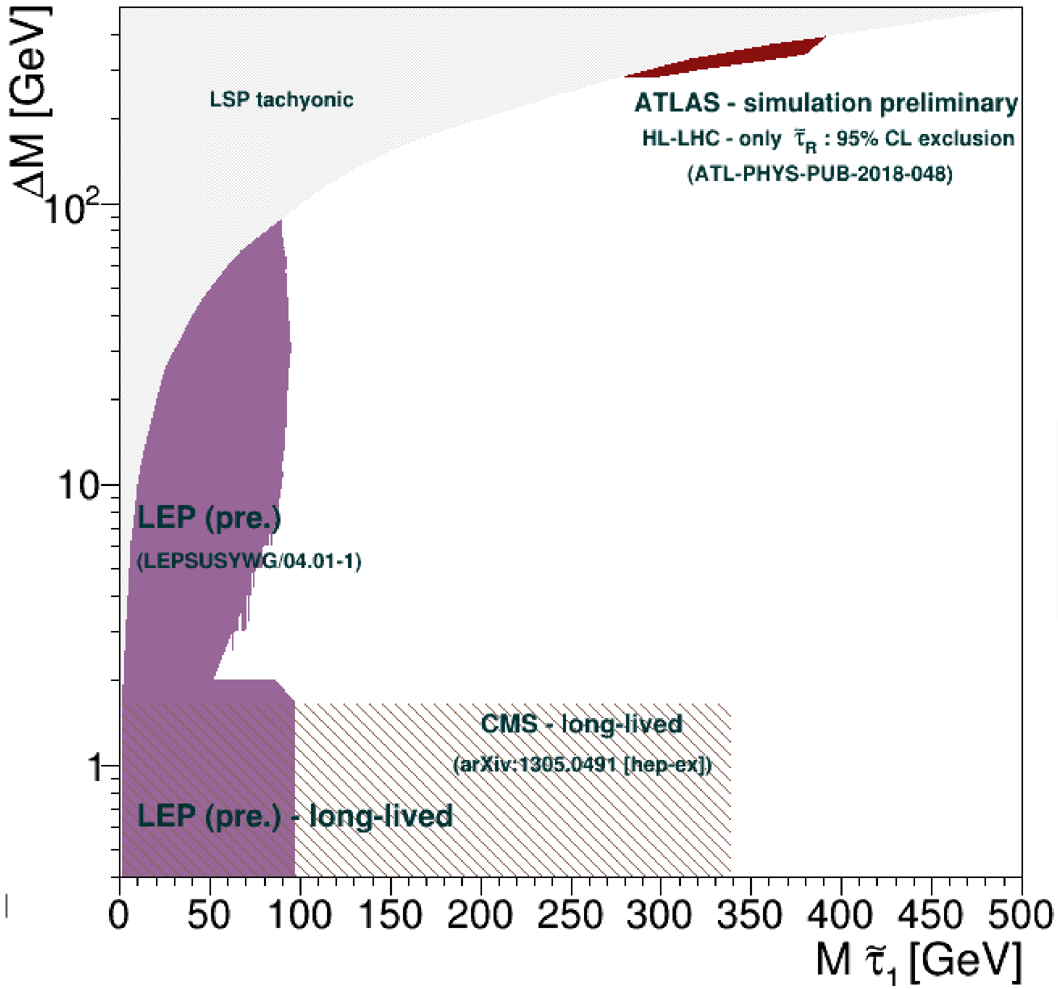
ILC expected limits



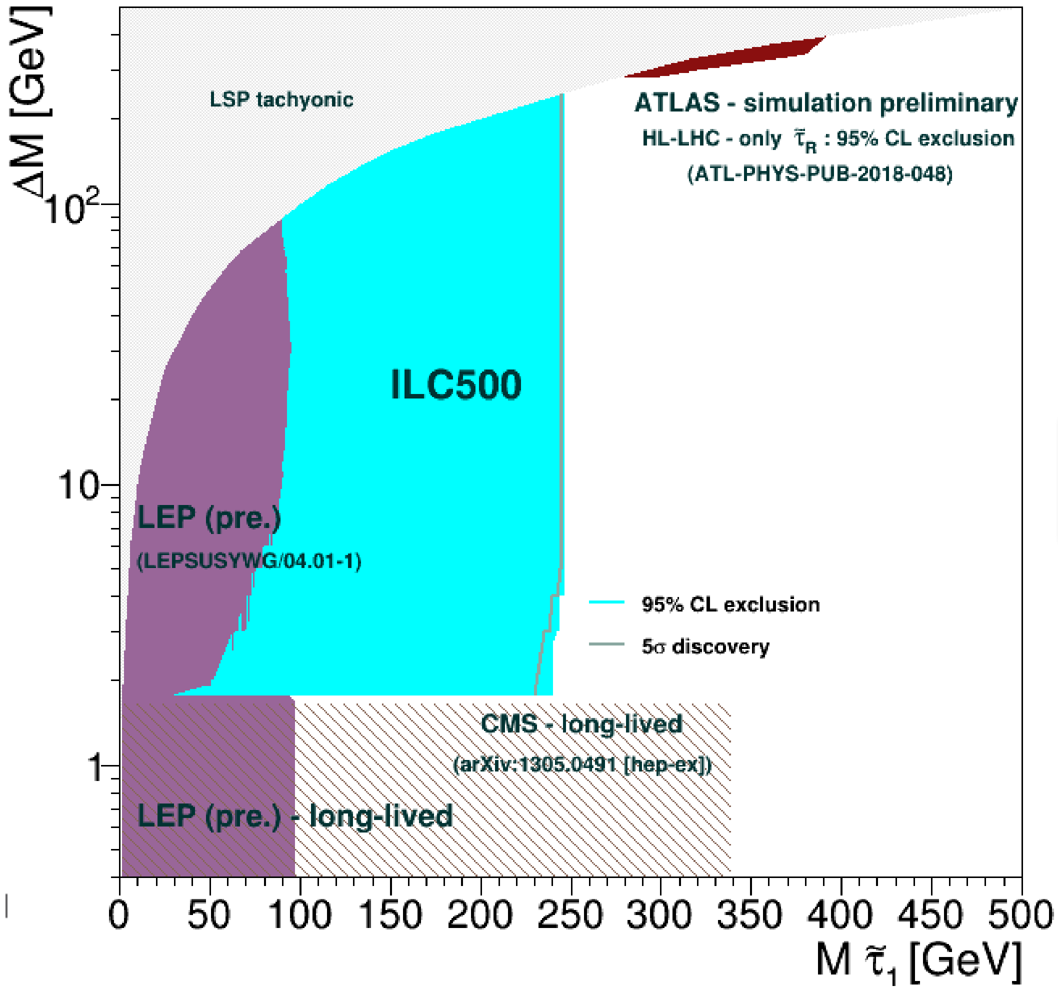
Current model-independent limits for ΔM > τ mass come from LEP

ILC expected limits



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

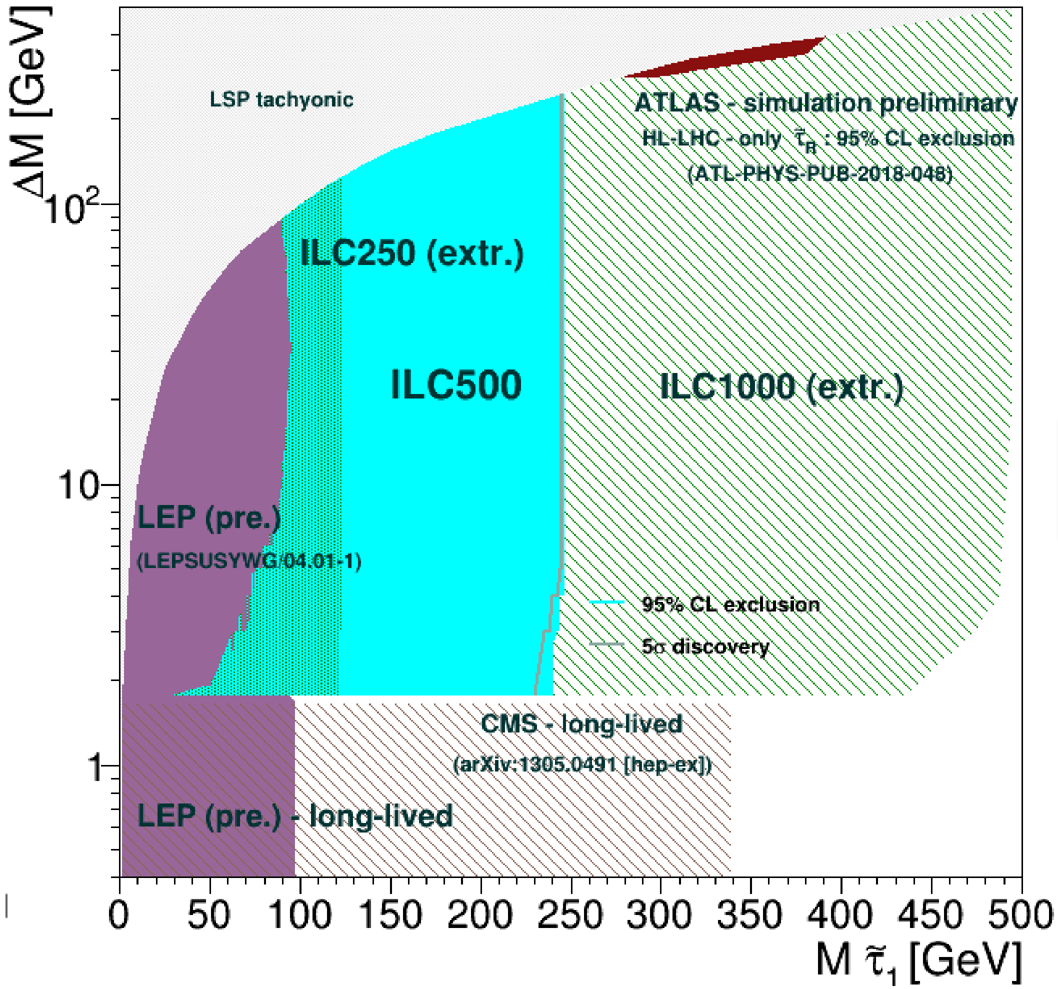
ILC expected limits



At ILC discovery and exclusion are almost the same

arXiv:2203.15729

ILC expected limits



At ILC discovery and exclusion are almost the same

arXiv:2203.15729

Outlook/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
- Worst scenario for $\tilde{\tau}$ production at the ILC was reviewed taking into account ILC beam polarisation conditions
- Effect of beam induced backgrounds for $\tilde{\tau}$ searches was analysed (as overlay-on-physics and overlay-only events)

ILC will discover/exclude $\tilde{\tau}$'s for any $\tilde{\tau}$-LSP mass difference and any $\tilde{\tau}$-mixing nearly up to the kinematic limit

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