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

Teresa Núñez - DESY

- Motivation of $\tilde{\tau}$ studies
- Limits at LEP and LHC
- $\tilde{\tau}$ analysis
  - Signal and SM background
  - Worst mixing
  - General cuts
  - Beam induced backgrounds
  - Limits
- Outlook and conclusions

Basically completed analysis

We plan to turn it into an ILD topic paper (we will ask the PSB to get referees)

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ILD General Meeting, 7 March 2023

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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:

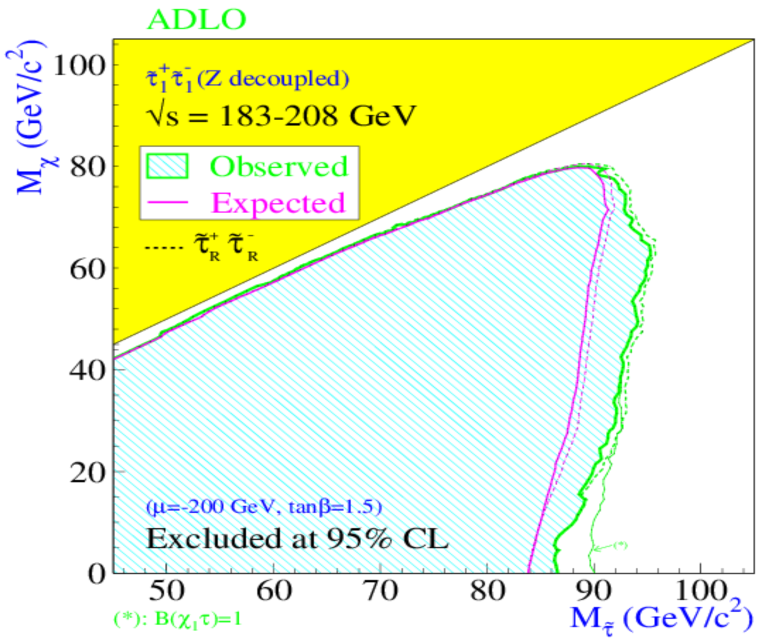
  - pair produced (s-channel via Z^0/γ exchange, low σ since $\tilde{\tau}$-mixing suppresses coupling to the Z^0)

  - 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 ($\tilde{\tau}$ - neutralino coannihilation)

Limits at LEP and LHC

$\tilde{\tau}$ searches at LEP



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

LEPSUSYWG/04-01.1

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

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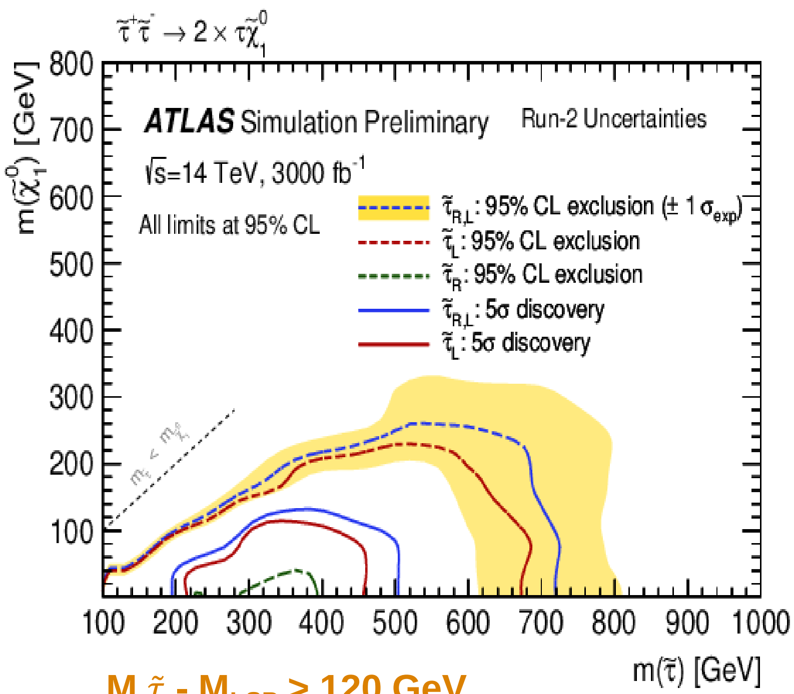
Limits at LEP and LHC (ctd.)

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



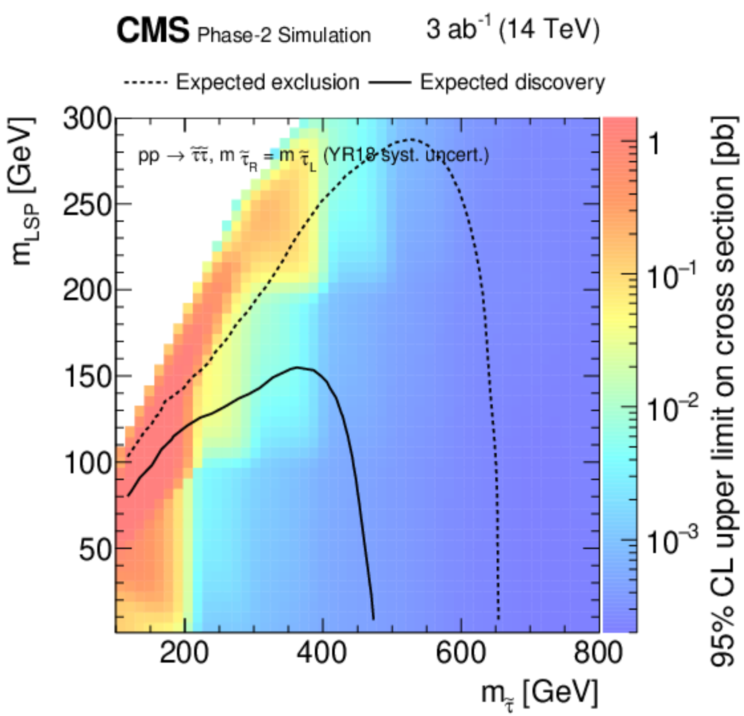
$M_{\tilde{\tau}} - M_{LSP} > 120$ GeV

ATL-PHYS-PUB-2018-048

Expected gain in sensitivity to direct $\tilde{\tau}$ production

- Two models: $\tilde{\tau}_R$ *and* $\tilde{\tau}_L$
- No mixing

- Two $\tilde{\tau}$ assumed to be mass-degenerate
- No mixing



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

CMS PAS FTR-18-010

Profits in future e^+e^- Higgs/EW/Tops factories

Wrt. previous electron-positron colliders:

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

Wrt. hadron colliders:

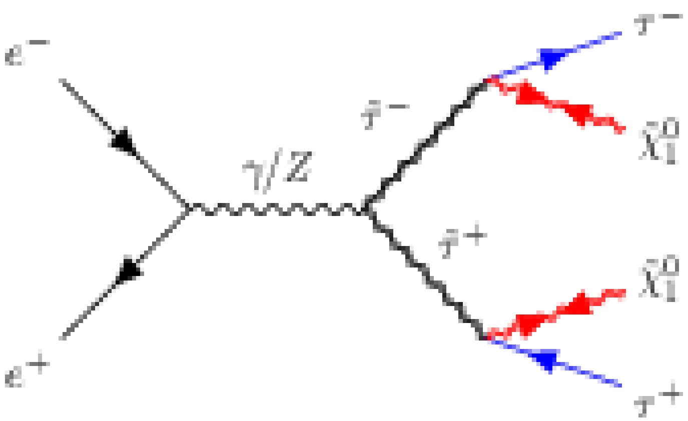
- cleaner environment
- known initial state
- triggerless operation of the detectors

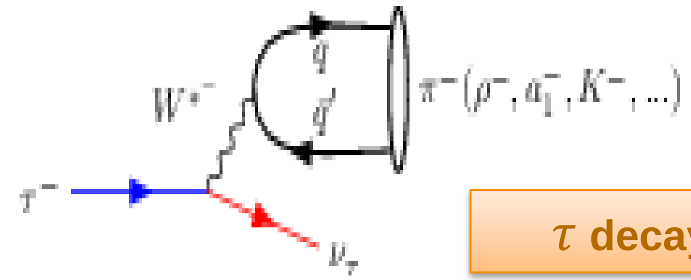
Studies using the full detector simulation and reconstruction procedures of the International Large Detector concept (ILD) at the International Linear Collider (ILC)

- electron-positron collider at $\sqrt{s}$ = 250-500 GeV with upgradability (1TeV)
- electrons (80%) and positrons (30%) polarised
- clean and reconstructable final state (near absence of pile-up)
- hermetic detectors (almost 4π coverage)

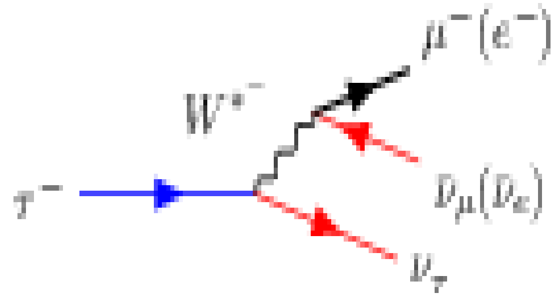
Signal characterization

s-channel production





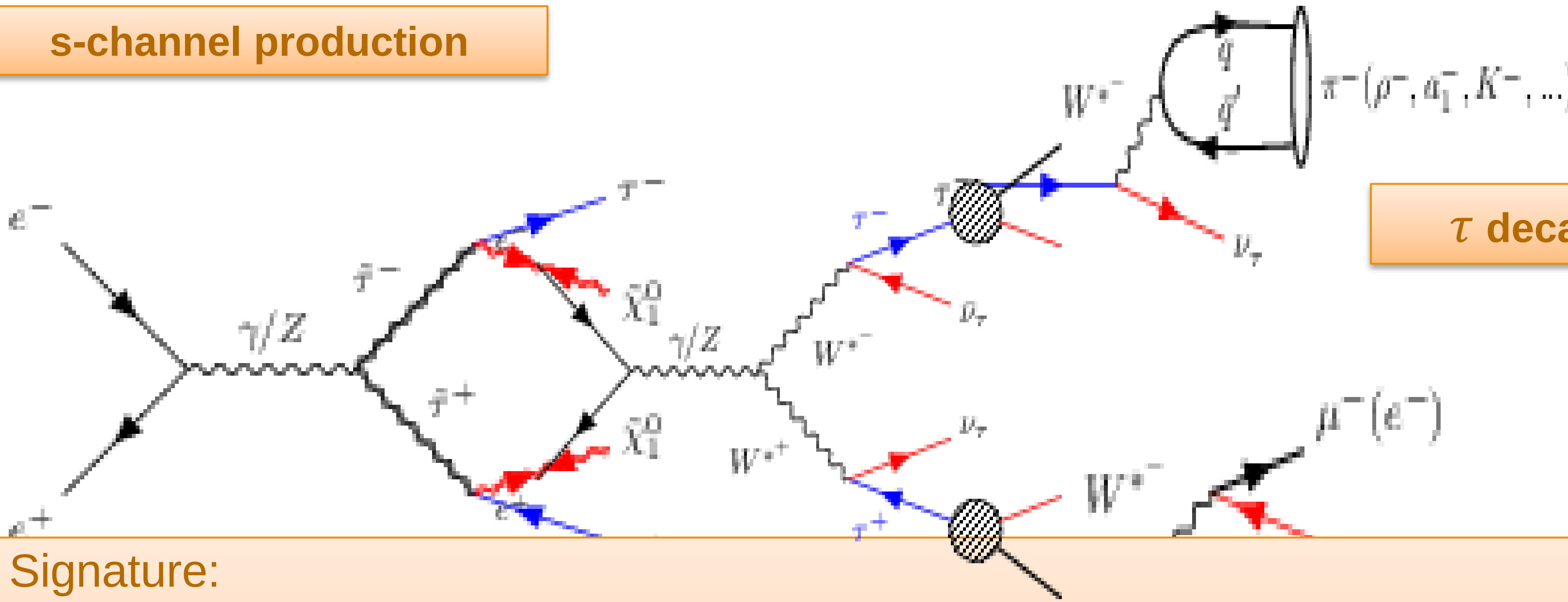
τ decays



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

Signal characterization

s-channel production



τ decays

Signature:

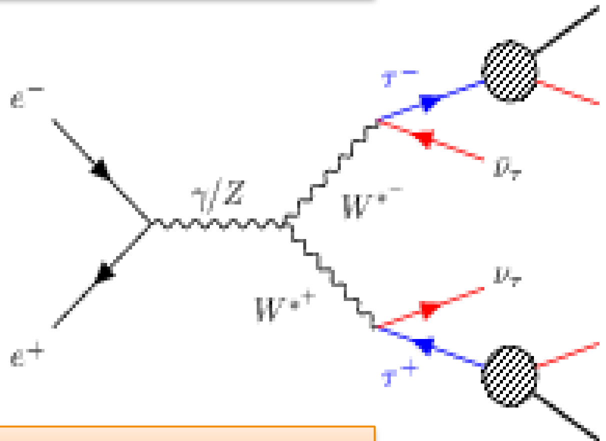
- large missing energy and momentum
- large fraction of detected activity in central detector (isotropic production of scalar particles)
- large angle between the two τ-lepton directions
- unbalanced transverse momentum
- zero forward-backward asymmetry

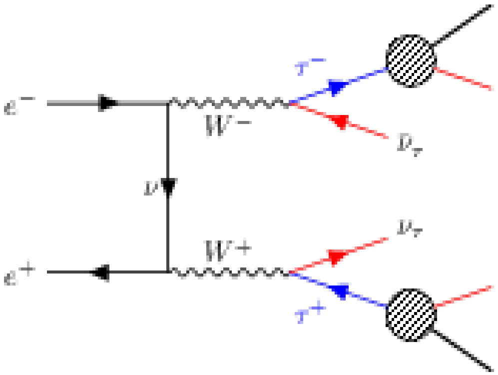
SM background

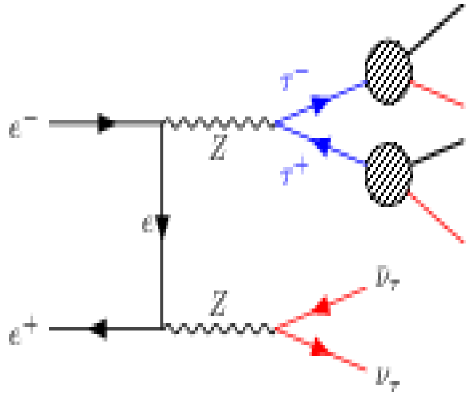
SM processes with real or fake missing energy

Irreducible

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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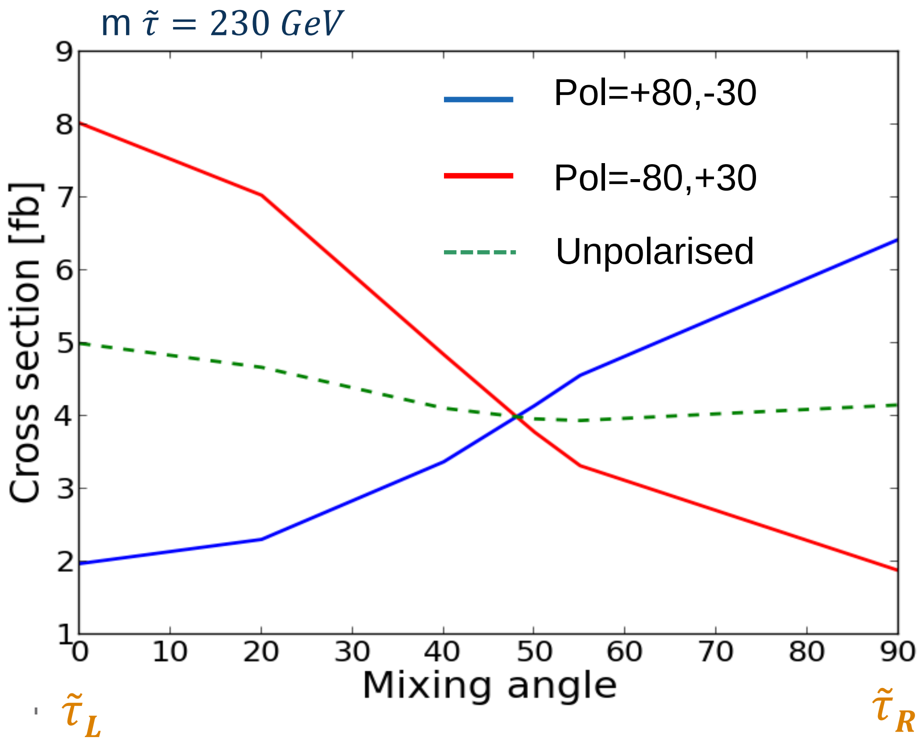
Analysis of worst mixing

Search for "worst" mixing angle

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



Use ILC conditions weighting contribution of both polarisations

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

- Signal: Whizard 2.8.5 + Tauola
- Background: Whizard 1.95

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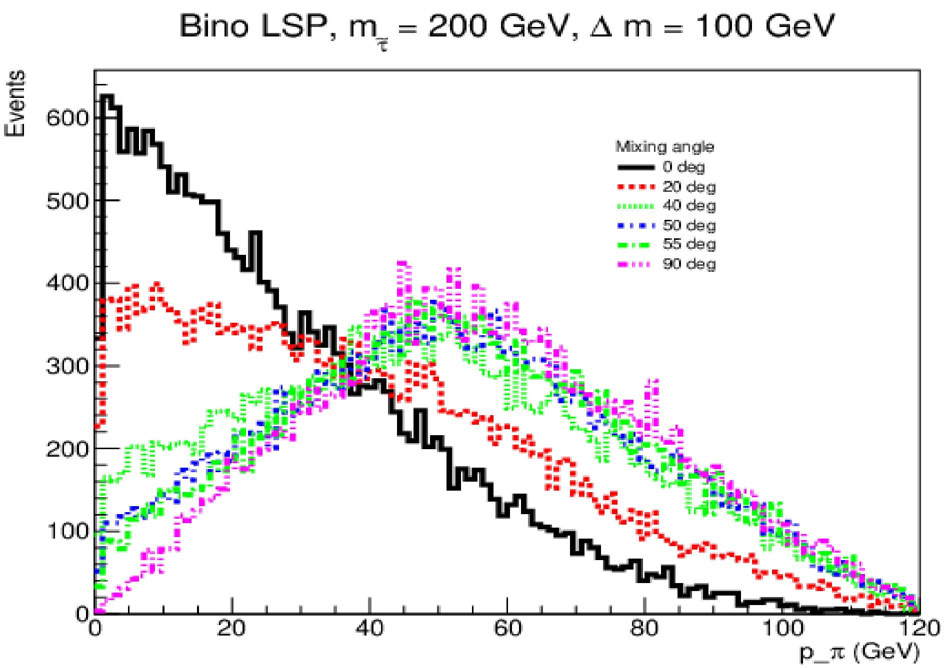
Analysis of worst mixing (ctd.)

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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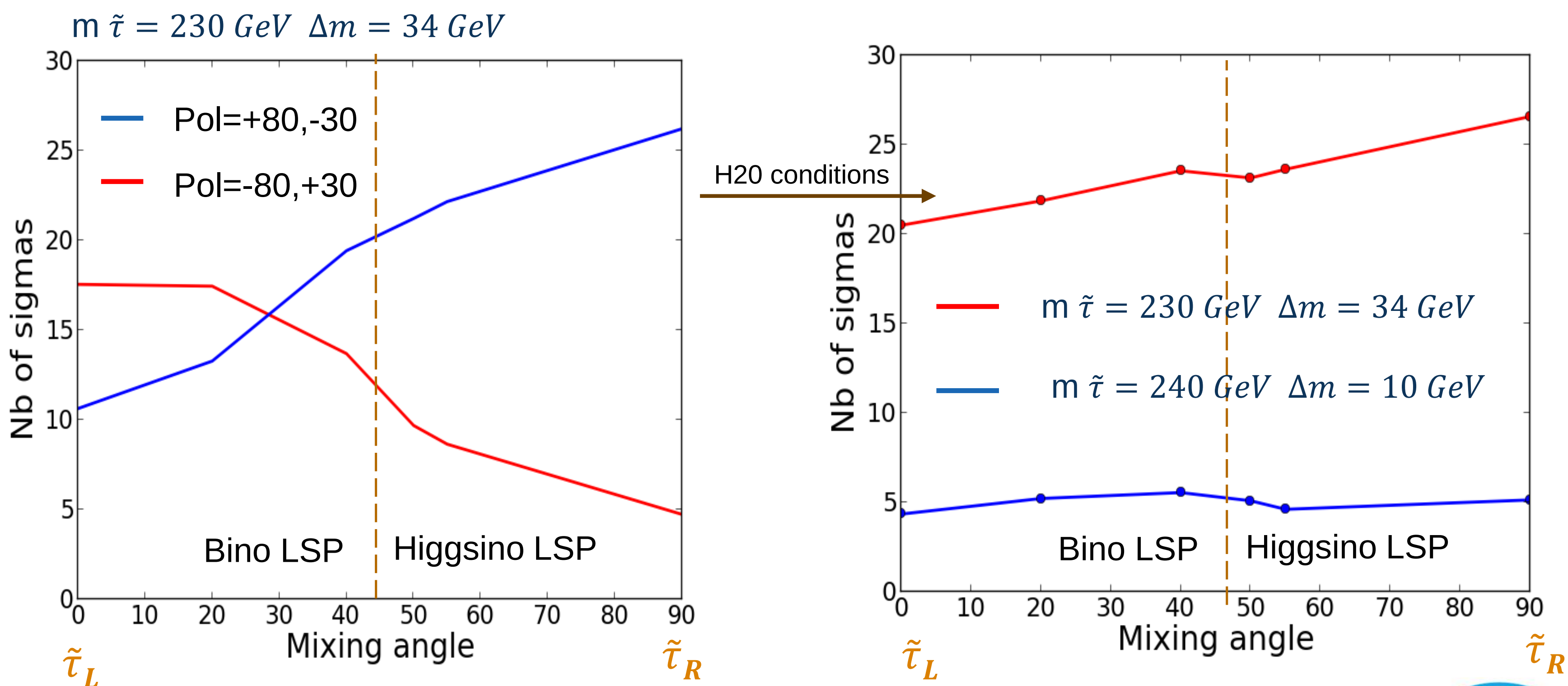
Analysis of worst mixing (ctd.)

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

General cuts

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)

- 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:

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

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

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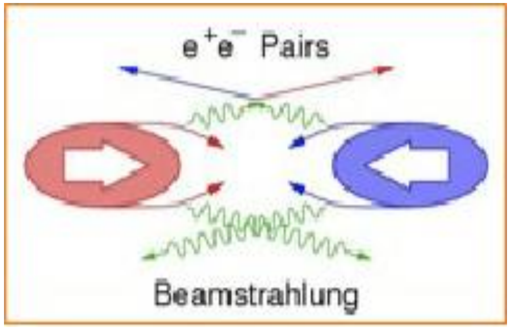
Beam induced backgrounds in e^+e^- colliders

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



Interactions between real and/or virtual photons produce:

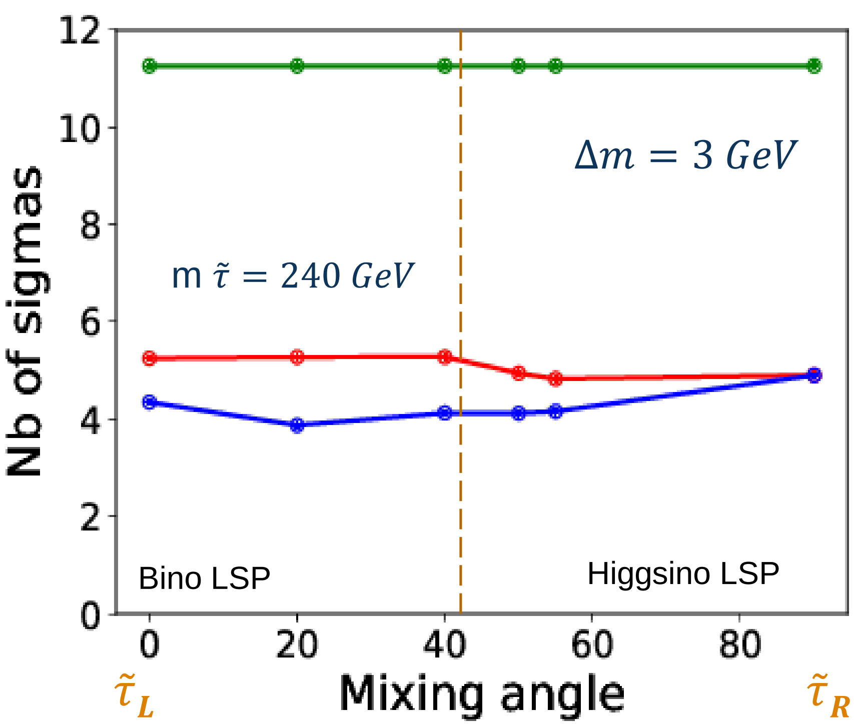
- e^+e^- pairs
  - produced by scattering of two real photons
  - 10^5 pairs per bunch crossing
  - very low p_T (< 1GeV), curl up in magnetic field, interesting for BeamCal studies
- low p_T hadrons
  - produced by vector meson fluctuations of real or virtual photons
  - <1.05> events per bunch crossing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

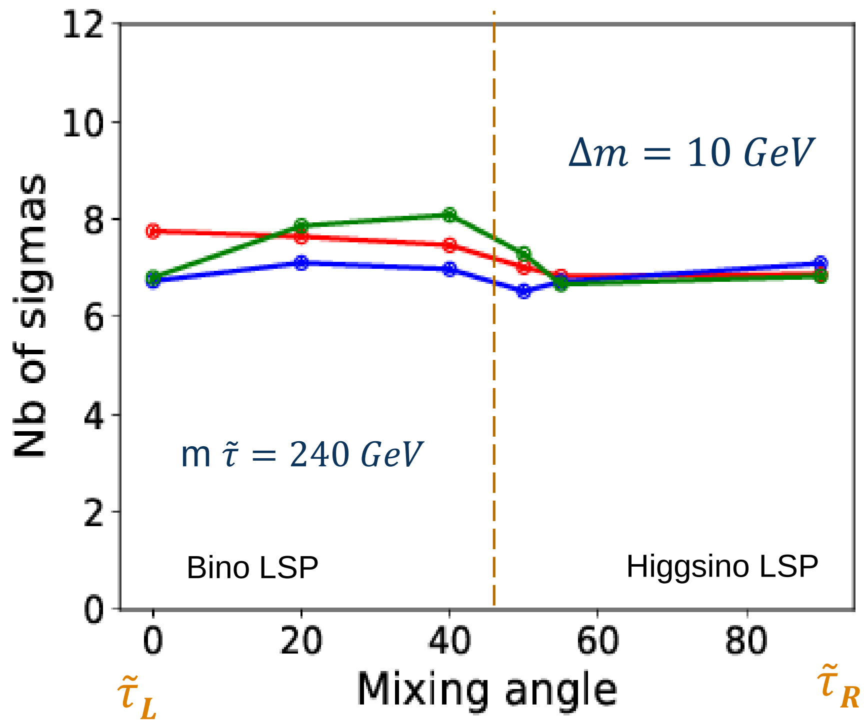
$\gamma\gamma$ interactions are independent of the e^+e^- process, but can happen simultaneously to it (overlay-on-physics events) or not (overlay-only events)

Effect of overlay-on-physics events

Full simulation

- 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

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

A suppression stronger than 10^{-9} is needed to make the background from overlay-only events negligible

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

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Only-overlay analysis strategy

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
- study of two different mass differences between $\tilde{\tau}$ and LSP masses (2 and 10 GeV)

Sample overlay-only events:

- extracted from the standard “IDR” production
- $\gamma\gamma$ interactions generated by Pythia 6.442 ($M_{\gamma\gamma}$ > 2 GeV) or a dedicated generator (arxiv: hep−ph/9305247) ($M_{\gamma\gamma} \leq$ 2 GeV)

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Effect of cuts on overlay-only events

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)

Main differences between 2GeV and 10 GeV cuts:

- Multiplicity and τ-identification cuts are similar
- Missing energy cuts more for DM = 2 GeV
- Missing transverse momentum cuts drastically for DM = 10 GeV
- $\cos(\theta_{P_{tot}})$ important cut for DM = 2GeV

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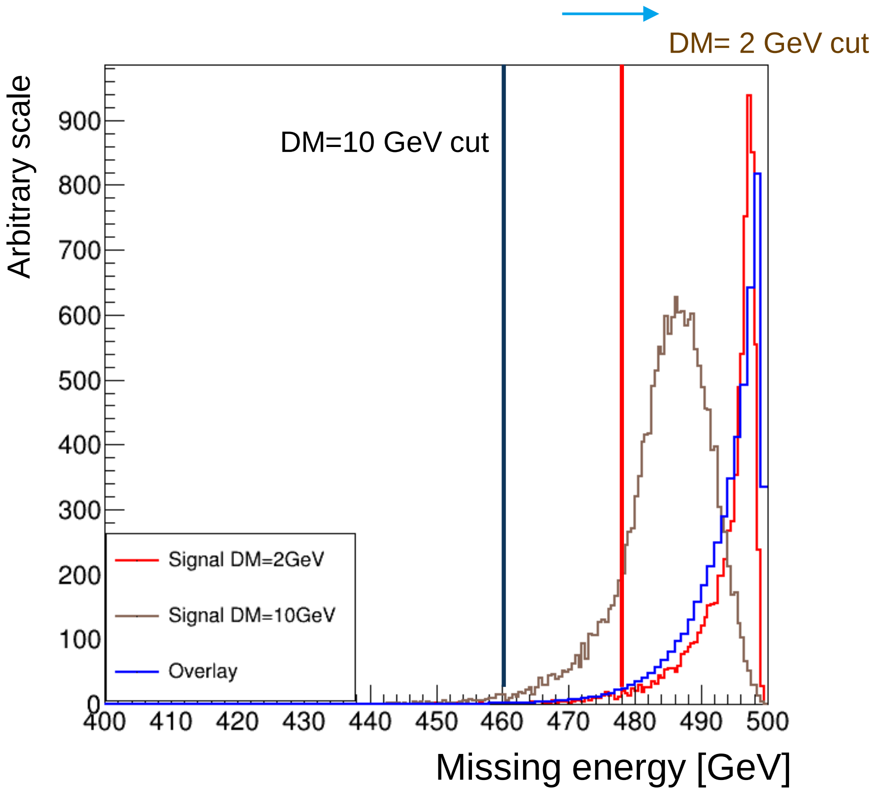
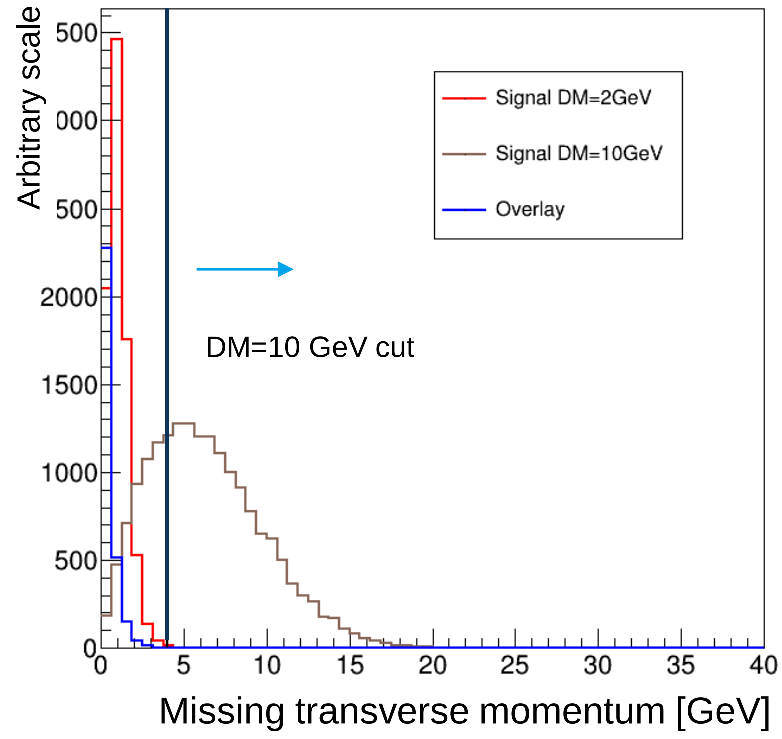
Effect of cuts on overlay-only events (ctd.)





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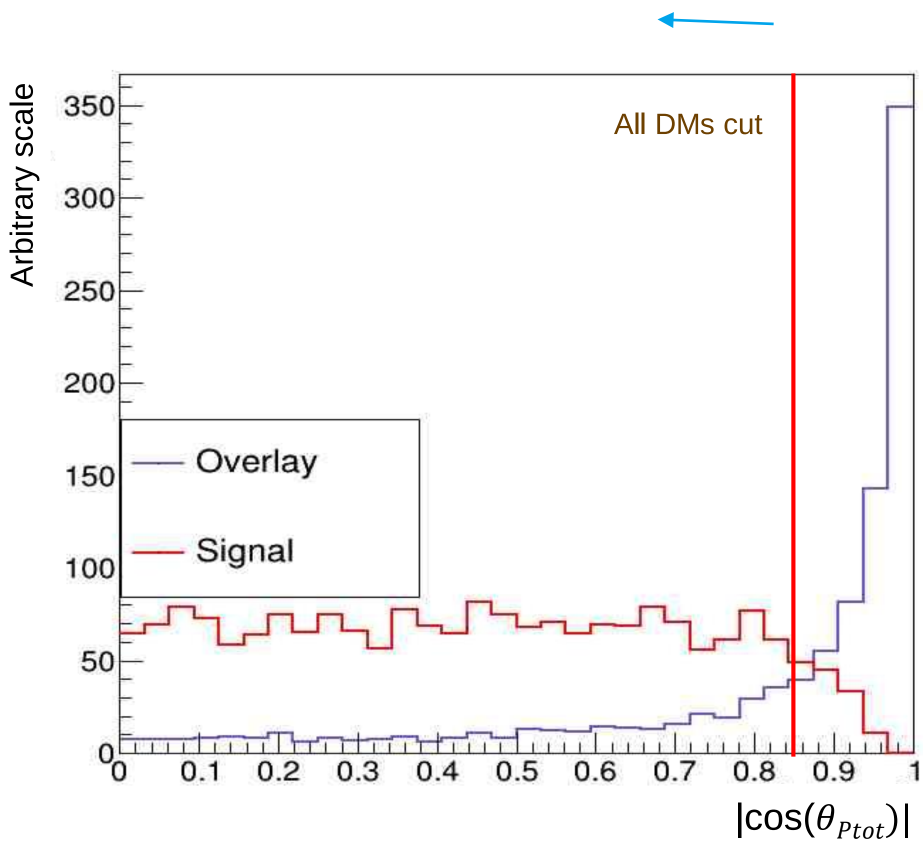
Effect of cuts on overlay-only events (ctd.)



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Independent and additional cuts

Independent set of cuts from the “standard” ones:

- missed $p_T + \rho$[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 thurst axis

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

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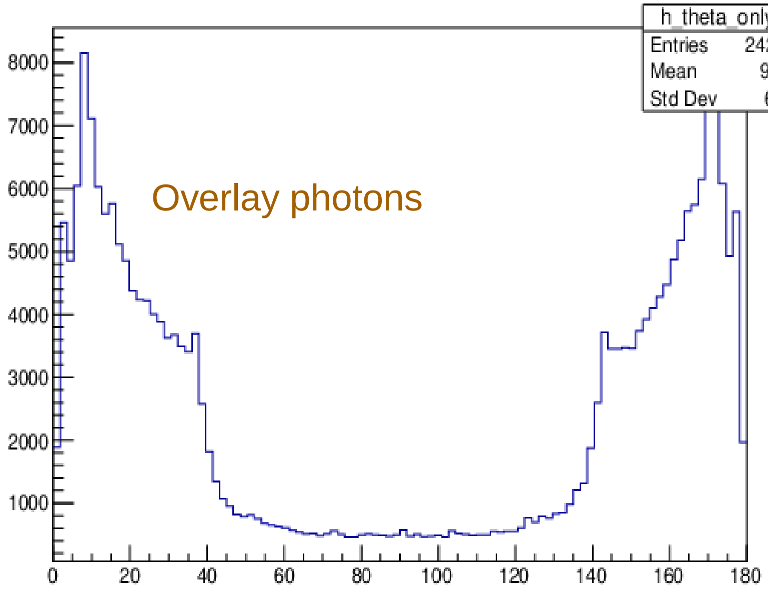
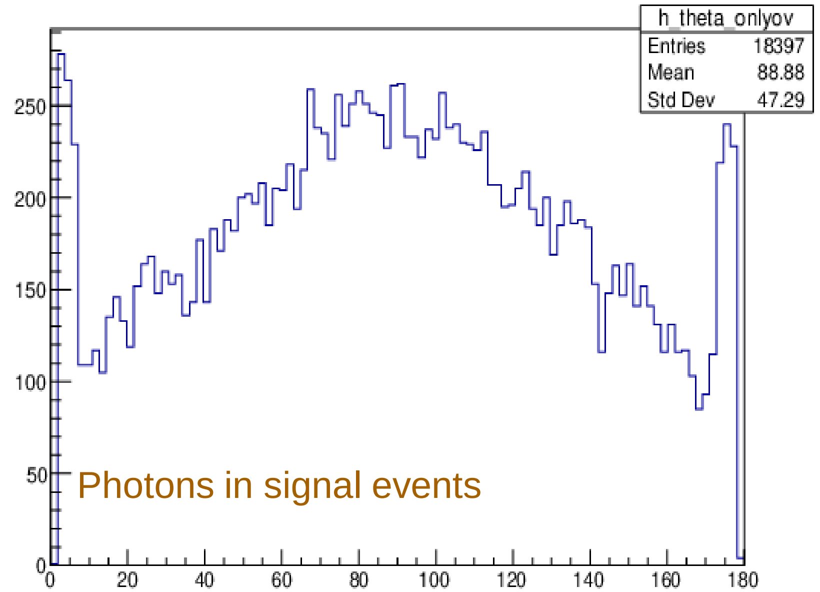
ISR requirement

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 [degrees]



θ [degrees]

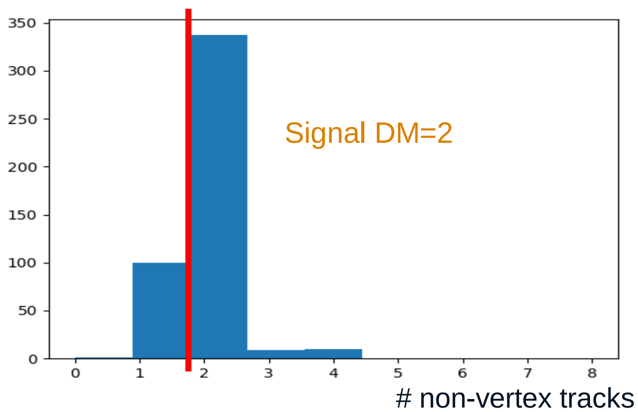
θ *cut tuned from* $\theta >$ 7 *degrees (lower edge tracking system) to*

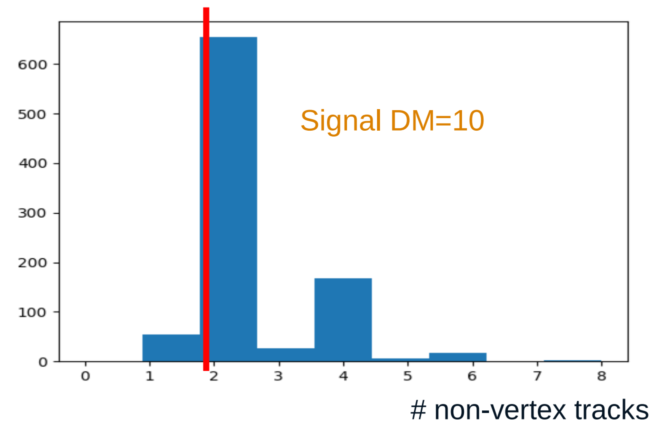
$45 < \theta < 135$ *(no background)*

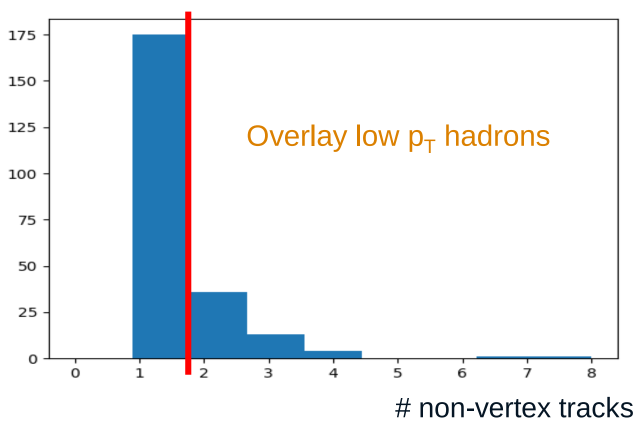
Vertex requirement

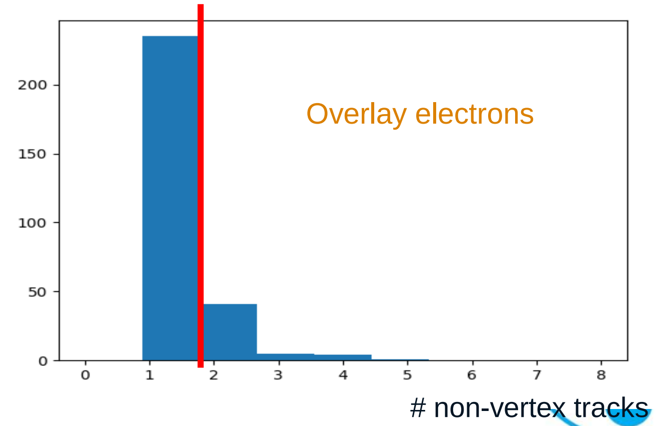
Events with at least two “non-vertex” tracks

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}

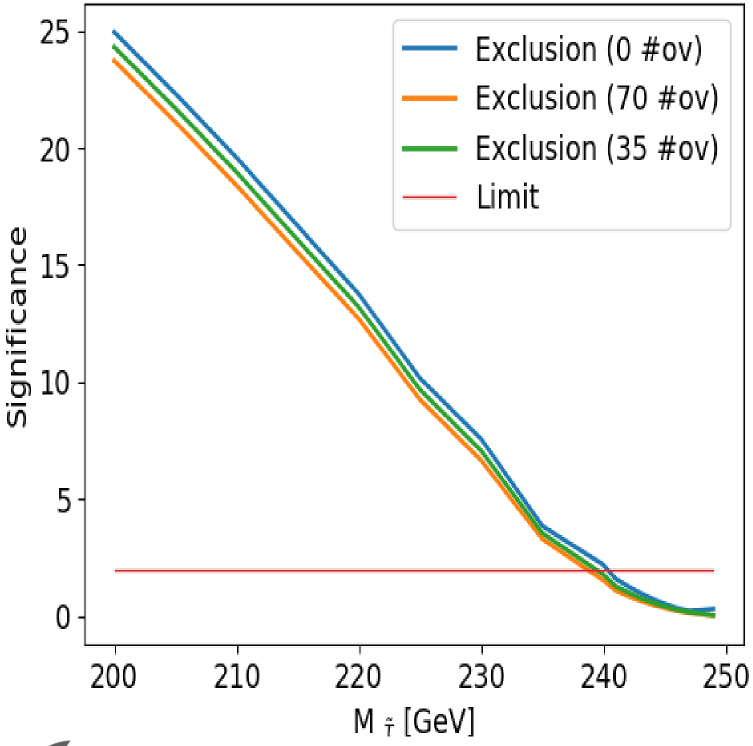
red.	alone	combined w/ vertex
standard cuts	2.6×10^{-3}	5.0×10^{-5}
standard cuts + ISR ($7< \theta$)	1.8×10^{-7}	3.5×10^{-9}
Standard cuts + ISR ($30< \theta <150$)	9.5×10^{-9}	1.8×10^{-10}

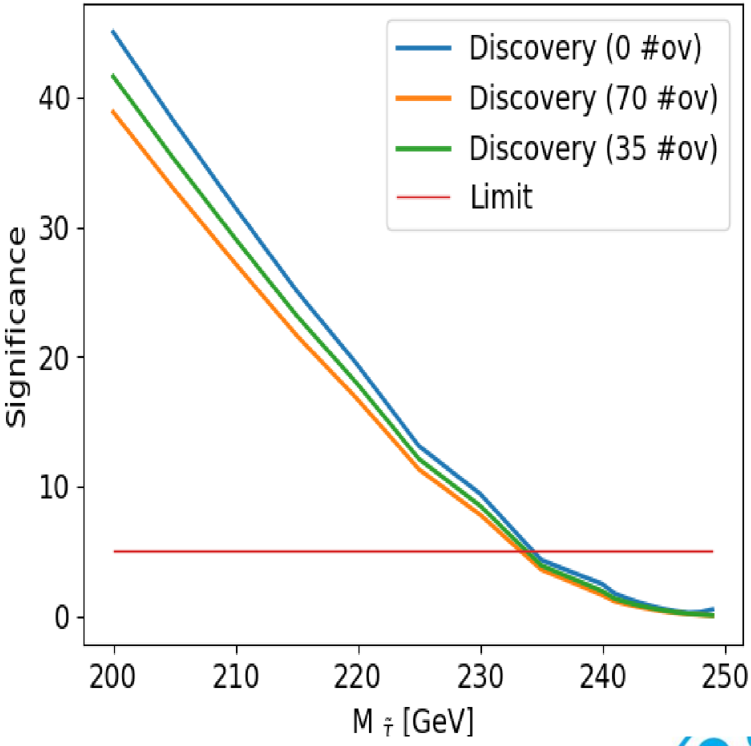
Signal efficiency: ~10% with no requirement on detecting an ISR. It goes to ~5% if a detected ISR is required (for any θ)

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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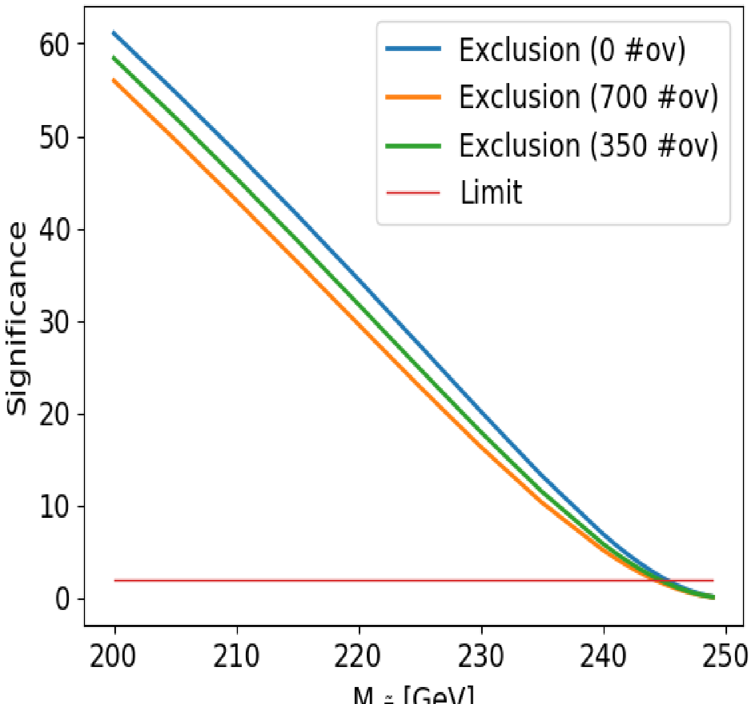
Adding overlay-only events to SM background

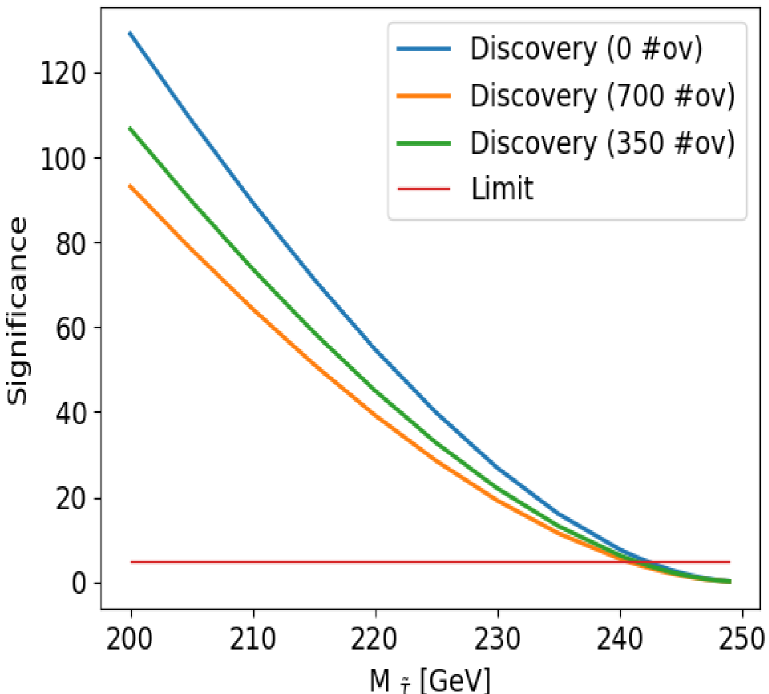
Significance with/wo overlay-only events

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)

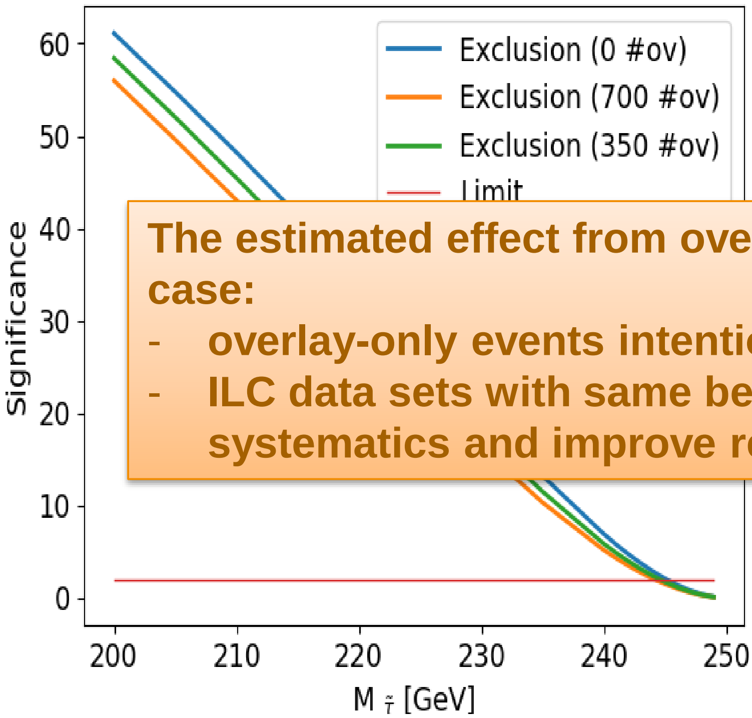
Adding overlay-only events to SM background

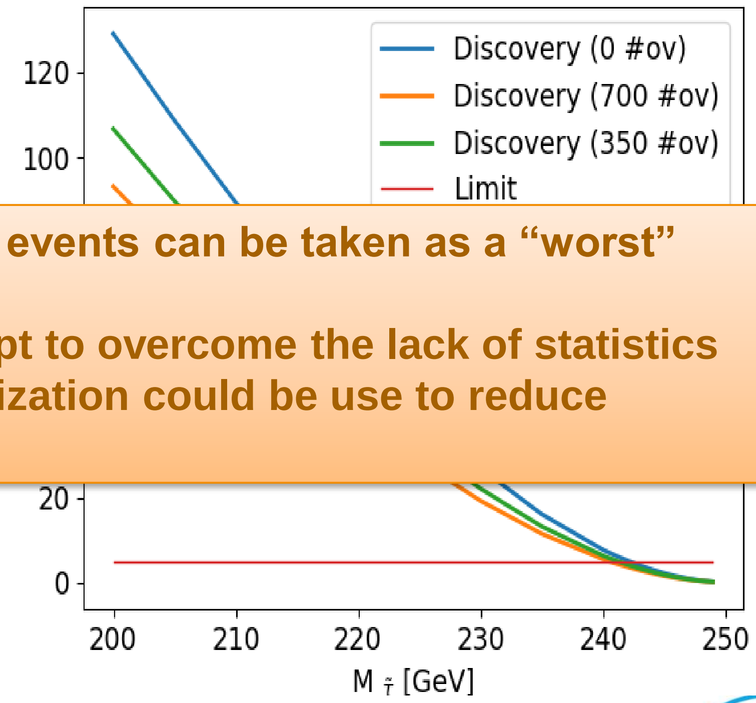
Significance with/wo overlay-only events

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 polarization could be use to reduce systematics and improve results**

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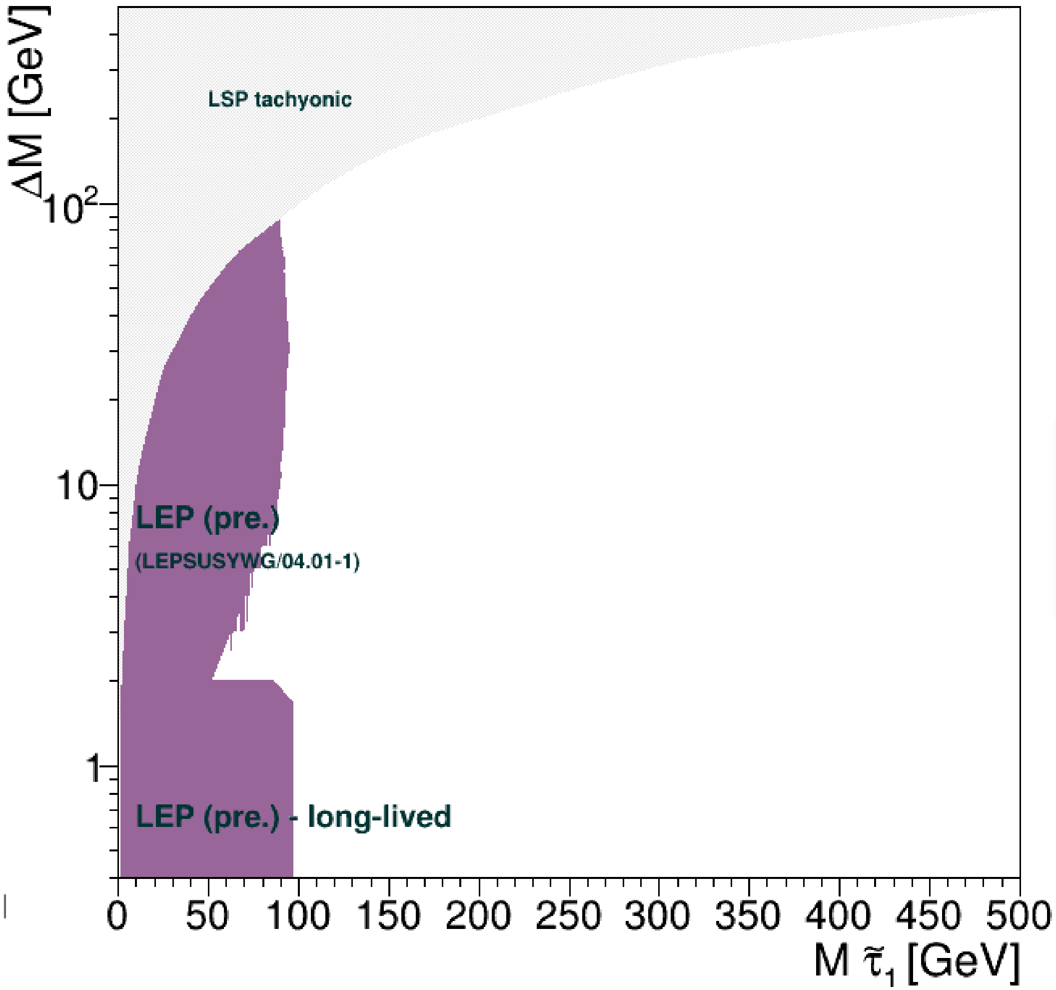
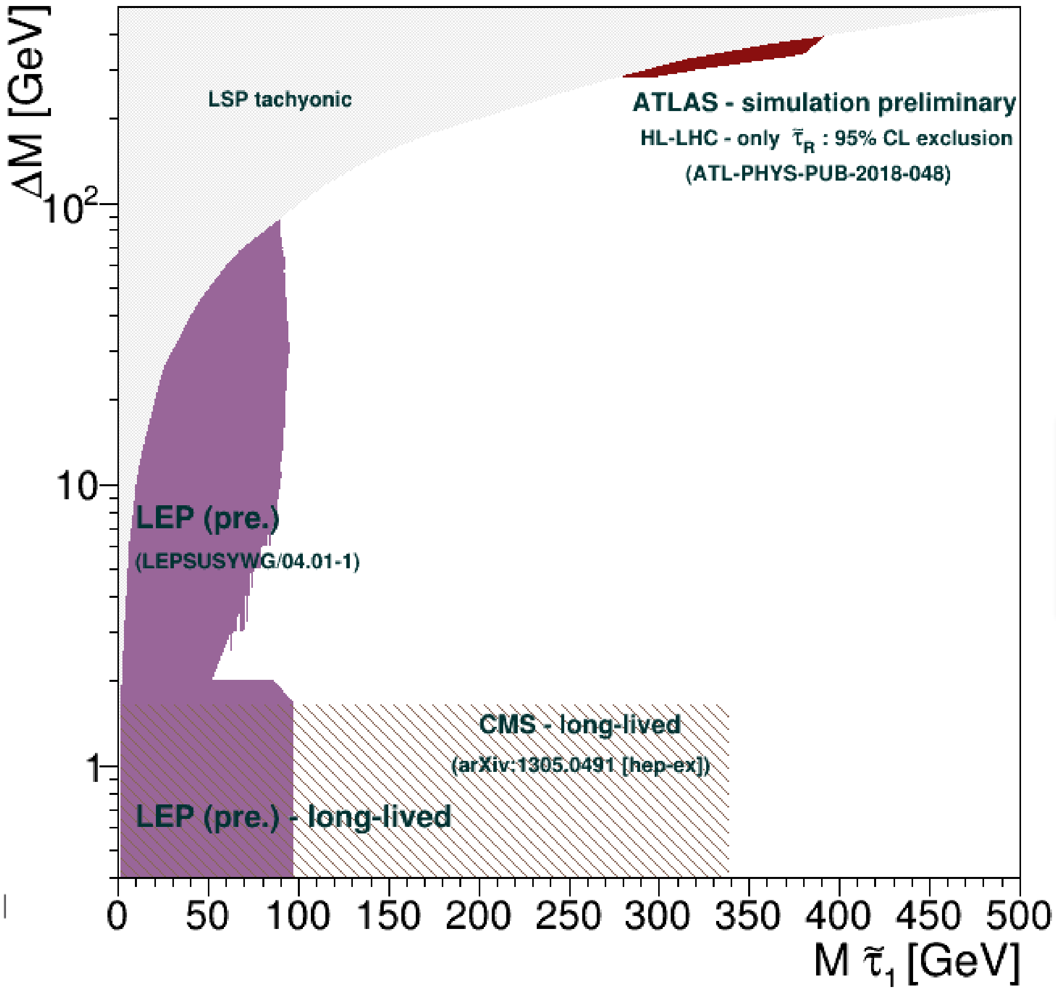
ILC expected limits



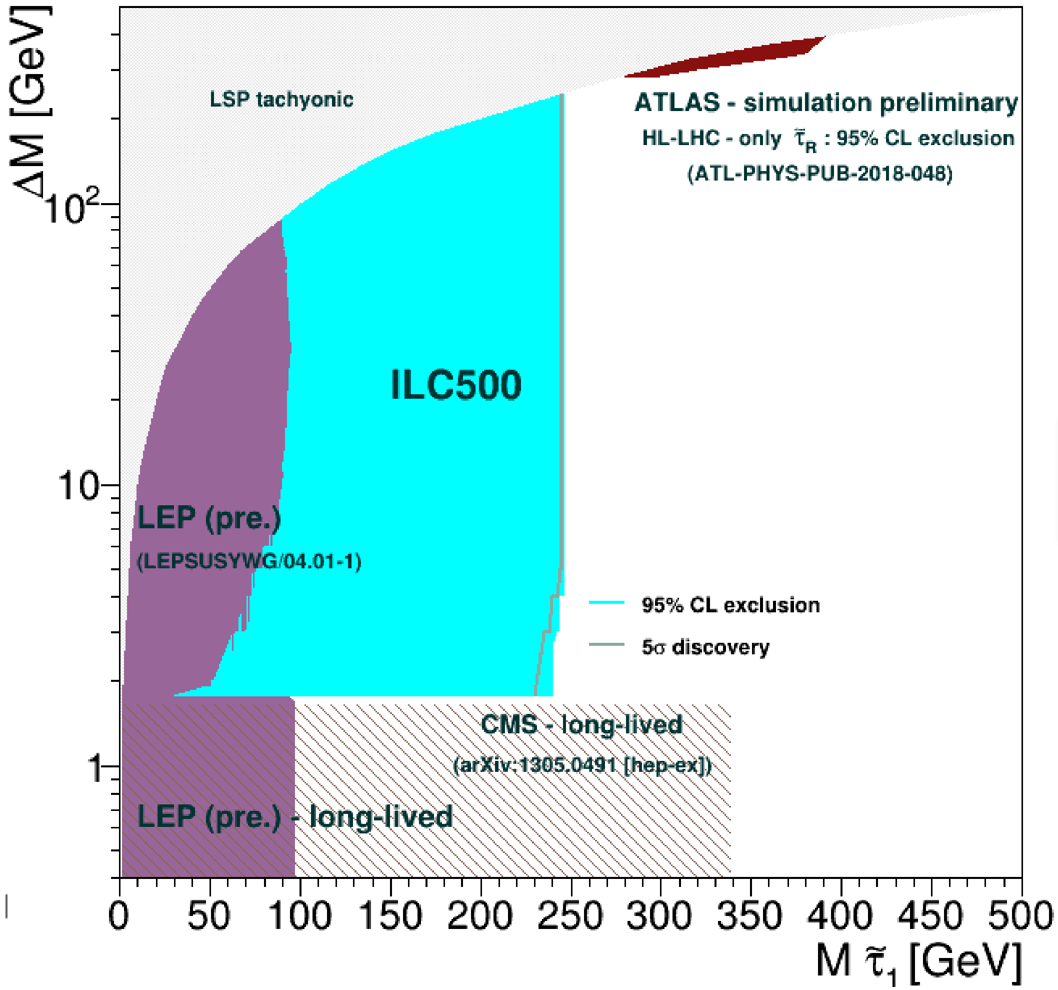
Current model-independent limits for ΔM > τ mass come from LEP

ILC expected limits



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

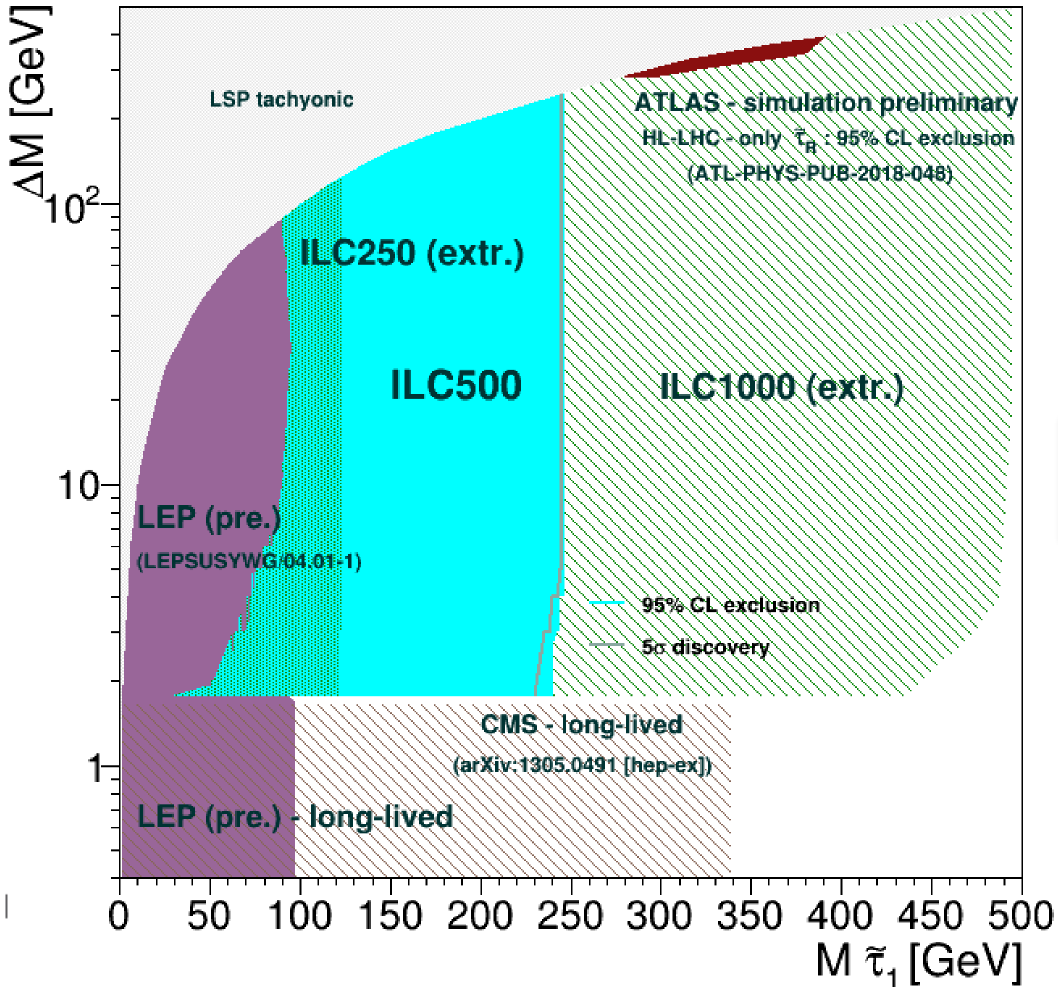
ILC expected limits



At ILC discovery and exclusion are almost the same

arXiv:2105.08616

ILC expected limits



At ILC discovery and exclusion are almost the same

arXiv:2105.08616

Outlook/Conclusions

- Even after HL-LHC large parts of the $\tilde{\tau}$-LSP mass plane will remain 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 limits

Draft for turning the study into an ILD topic paper is on preparation

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