New particle searches at the ILC

Teresa Núñez - DESY

On behalf of the ICFA-IDT-WG3 BSM group

- Introduction
- SUSY
- New Higgs-like scalars
- Heavy neutrinos
- Dark neutrinos from exotic Higgs decays
- WIMP Dark Matter
- Long-lived particles
- Indirect BSM searches
- Outlook and conclusions

European Physical Society Conference on High Energy Physics
EPS-HEP2023, 23rd August 2023

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Why ILC for new particle searches?

The International Linear Collider (ILC) offer excellent facilities for new particle searches

Wrt. previous electron-positron colliders:

- increased luminosity and centre-of-mass energy
- beam polarisation
- improved detector technologies
- microscopic beam-spot

Wrt. hadron colliders:

- EW-production then low background:
  - Hermetic detectors (almost 4π coverage)
  - No trigger
- colliding point-like objects then known initial state

ILC will profit from :

e+e- collisions with $\sqrt{s}$ = 250-500(-1000) GeV and polarised beams

22 year running → 2 ab^{-1} @ 250 GeV + 4 ab^{-1} @ 500 GeV

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ILC detectors: ILD & SiD concepts

Physics requirements for SM and BSM:

- Jet energy resolution 3-4%
- Asymptotic momentum resolution $\sigma(1/p_{\perp}) = 2x10^{-5}$ GeV^{-1}
- Impact parameter resolution $\sigma(d_0)$ < 5 µm
- Hermeticity down to 5 mrad
- Triggerless operation

leads to key features for the detectors:

- High granularity calorimeters optimised for particle flow
- Power-pulsing for low material

Both ILC detector concepts, ILD and SiD, designed to satisfy the requirements

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

- High granularity calorimeters optimised for particle flow
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Both ILC detector concepts, ILD and SiD, designed to satisfy the requirements

SUSY

Supersymmetry is the most complete BSM theory, and …

… boilerplate for BSM (almost any new topology can be obtained in SUSY)

Why SUSY searches at ILC?

- 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

In contrast to hadron colliders, ILC is well adapted to the colourless and compressed SUSY spectra, offering loop-hole free searches

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SUSY: $\tilde{\tau}$ searches

Motivated NLSP candidate and most difficult scenario

- 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)

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Searches include all SM and beam induced backgrounds

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

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

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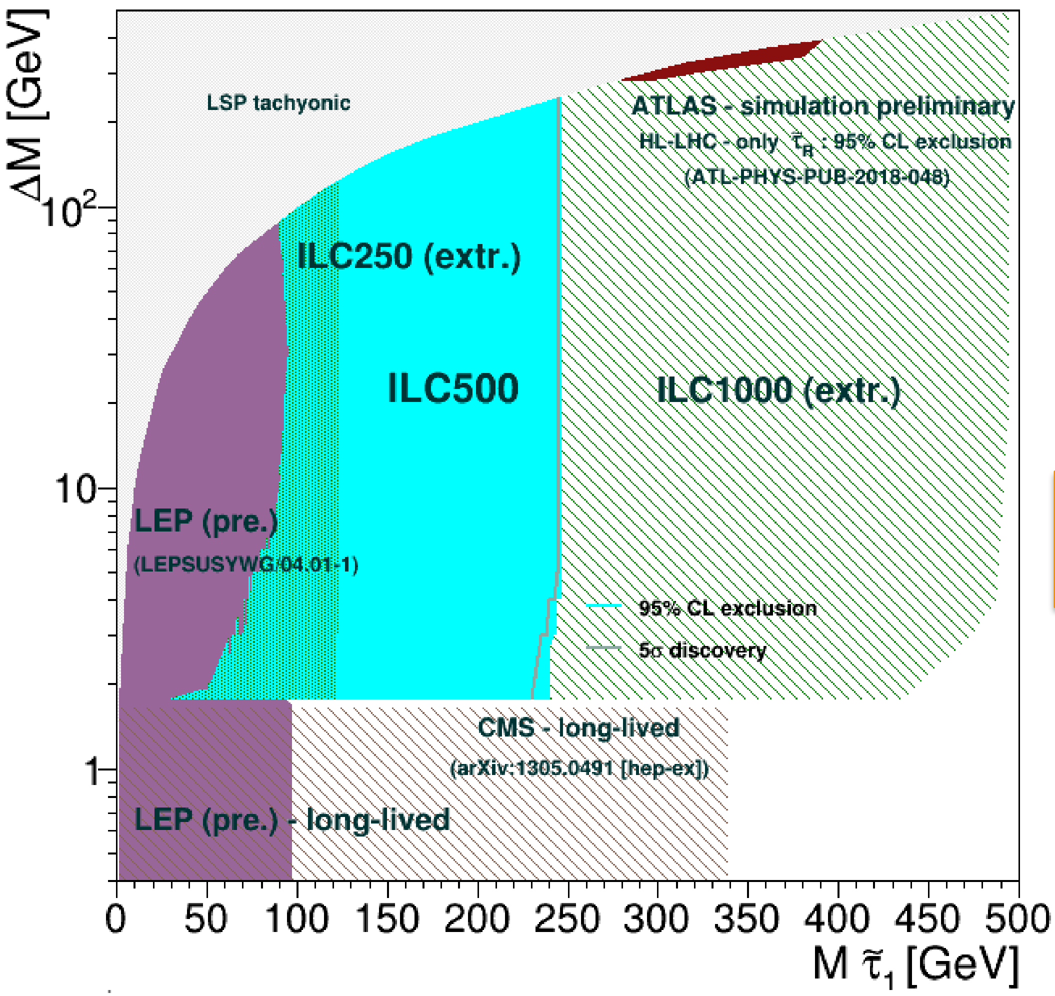
SUSY: $\tilde{\tau}$ searches (ctd.)



Model independent limits come from LEP

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

At ILC discovery and exclusion are almost the same

[arXiv:2203.15729](https://arxiv.org/abs/2203.15729)

$\tilde{\tau}$ searches at the ILC (poster contribution)

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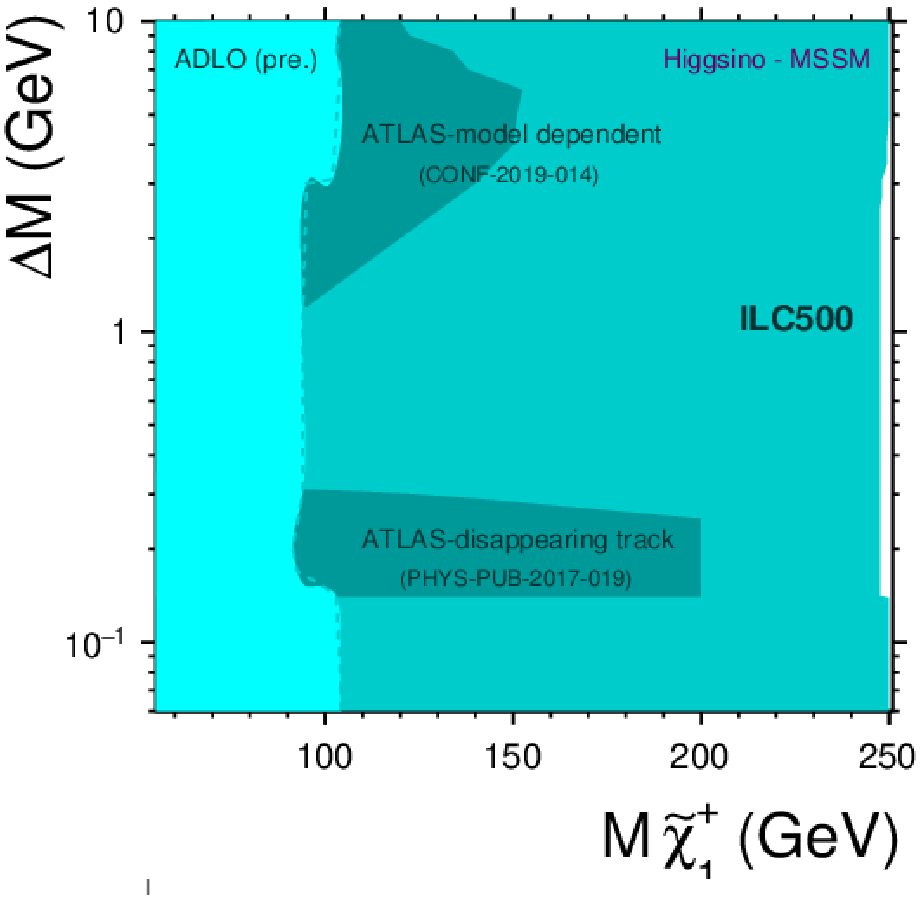
SUSY: Higgsino searches

ILC exclusion limits extrapolated from LEP results



Electroweak naturalness in simple SUSY models requires a cluster of four light Higgsinos

$\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0, \tilde{\chi}_2^0$ compressed spectrum (10-20 GeV) around ~ 100-300 GeV

Challenging for LHC if other sparticles are heavy … but not for ILC

arxiv:2002.01239

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New Higgs-like scalar in association with a Z boson

Predicted by many BSM models

$e^+e^- \rightarrow Z' \rightarrow ZS^0$

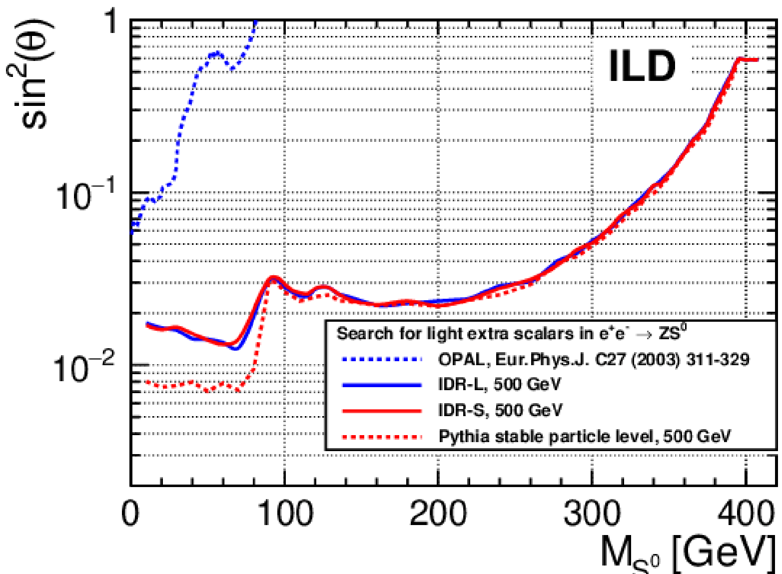
Searches done for any mass and independent of the S^0 decay mode

(recoil of the scalar against the Z)

Most LHC/LEP searches depend on model-specific S^0 properties

OPAL searches also based on recoil against the Z (most model-independent ones)

arxiv:2005.06265



Expected sensitivities at 95% CL for the cross section scale factor with respect to the SM Higgs, $\sin^2(\theta)$, for scalars masses between 10 and 410 GeV

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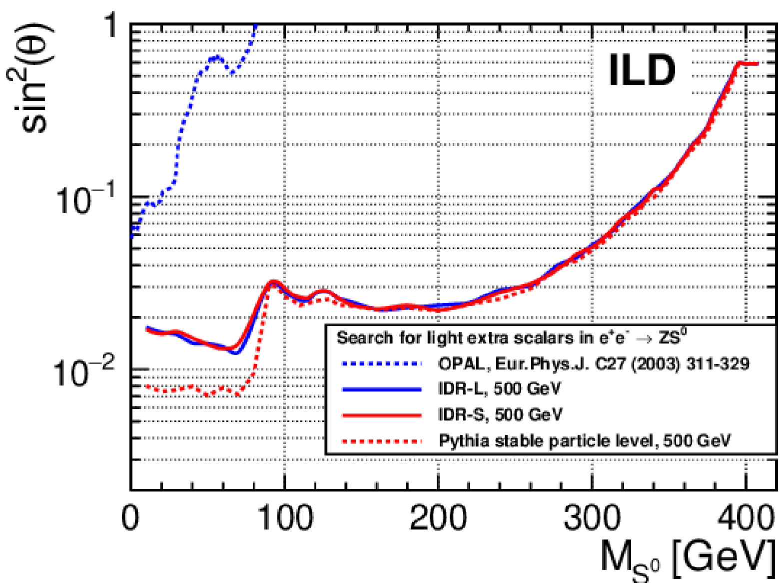
$e^+e^- \rightarrow Z' \rightarrow ZS^0 \rightarrow \mu^+\mu^- S^0$

Important detector performance aspects are identification and momentum reconstruction of the two muons and identification and energy reconstruction of ISR photons

Most important limitation comes from the ISR identification

arxiv:2005.06265



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$$e^+e^- \rightarrow Z' \rightarrow ZS^0$$

ILC can exclude couplings down to a few percent of the SM-Higgs equivalent

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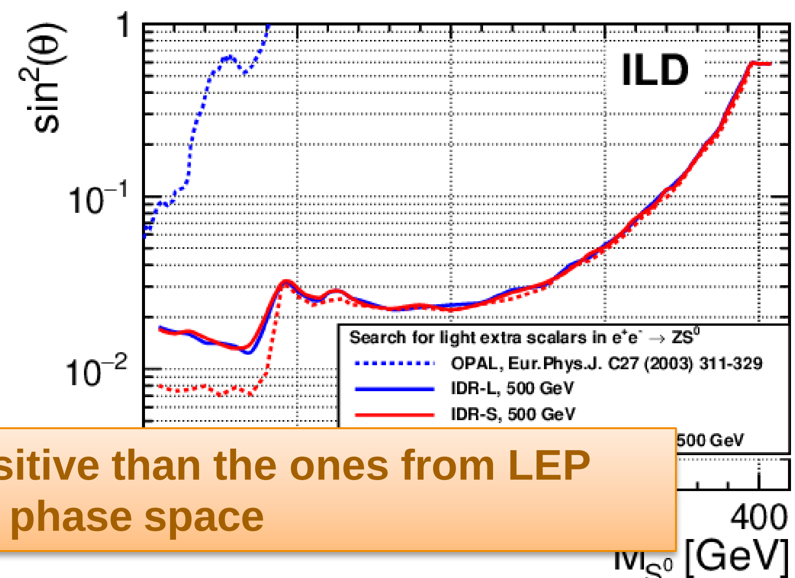
OPAL searches also based on recoil against the Z (most model-independent ones)



Limits two orders of magnitude more sensitive than the ones from LEP
Covering substantial new phase space

Expected sensitivities at 95% CL for the cross section scale factor with respect to the SM Higgs, $\sin^2(\theta)$, for scalars masses between 10 and 410 GeV

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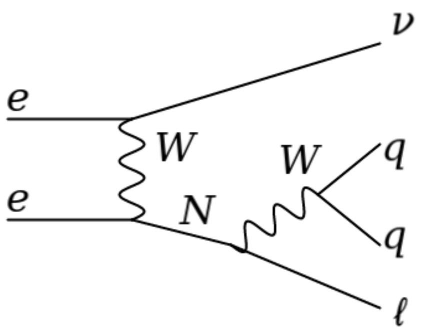
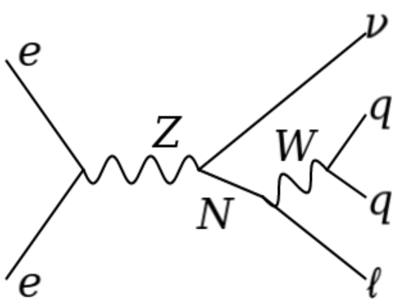
Heavy neutrinos

Many BSM models explain SM open problems (baryon asymmetry, flavor pluzze, nature of DM, …) introducing new species of neutrinos (DIRAC or Majorana)

Possibility of observing production and decay of heavy DIRAC and Majorana neutrinos





Mostly model independent

Only one heavy neutrino kinematically accessible - allowing for flavor mixing for all three generations – and not additional gauge bosons at any energy scale

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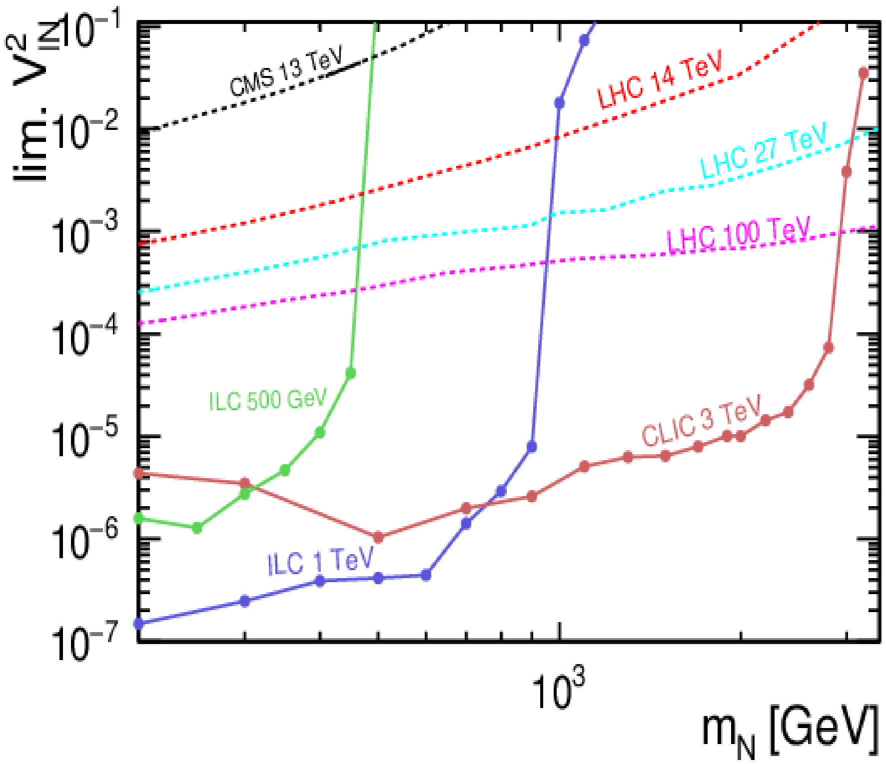
Heavy neutrinos (ctd.)

Study focused on heavy neutrino masses above EW scale

For on-shell production of heavy neutrinos, almost the same expected limits for Dirac and Majorana particles (variables used are not optimized for distinguishing between DIRAC and Majorana hypotheses)

arxiv:2005.06703



Exclusion reach for the neutrino mixing parameter, V^2_{lN} (effective weak coupling for the heavy neutrinos)

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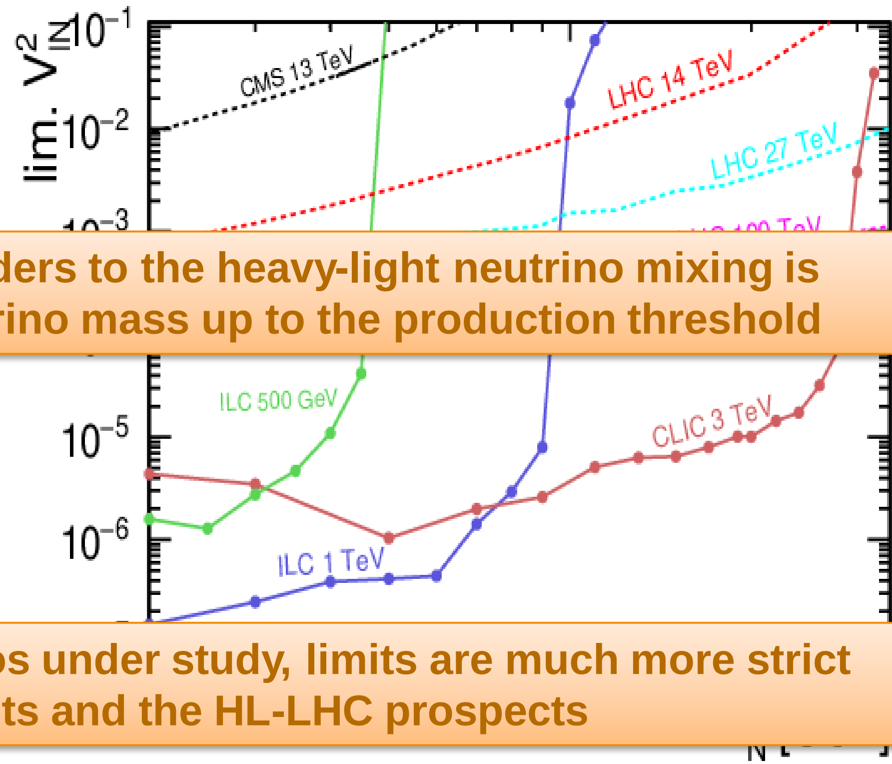

Sensitivity of future e+e- colliders to the heavy-light neutrino mixing is almost insensitive to the neutrino mass up to the production threshold

For the heavy neutrino scenarios under study, limits are much more strict than the LHC results and the HL-LHC prospects

[arxiv:2005.06703](https://arxiv.org/abs/2005.06703)

Exclusion reach for the neutrino mixing parameter, V^2_{lN} (effective weak coupling for the heavy neutrinos)

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Dark neutrinos from exotic Higgs decays

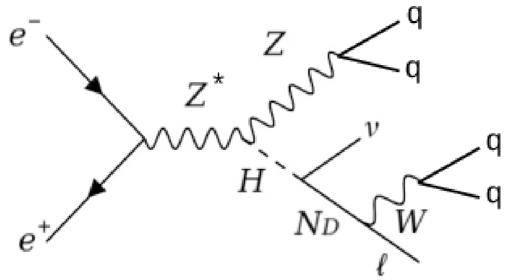
Dark neutrinos from exotics Higgs decays as explanation of matter-antimatter asymmetry

Region under study: $m_Z < m_N < m_H$

Model independent observable:

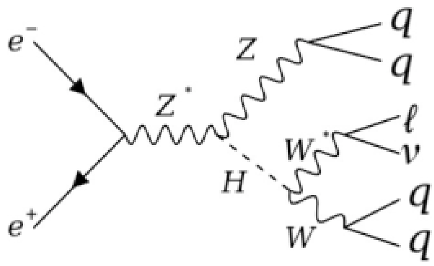
$$BR(H \rightarrow \nu \, Nd) BR(Nd \rightarrow lW)$$

Used to extract relevant model free parameters: dark neutrino mass and mixing between SM and dark neutrinos



Signal

Based on the leading Higgs production channel and the exotic decay



Main background

S. Thor – KTH Royal Institute of Technology
M. Ishino, J. Thian – University of Tokyo

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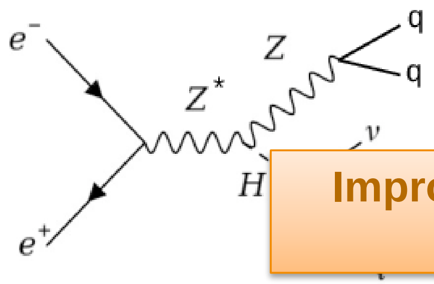
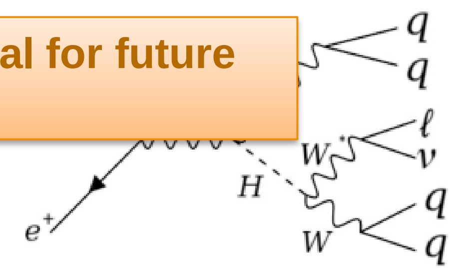


Signal

Improved jet clustering algorithms crucial for future collider experiments



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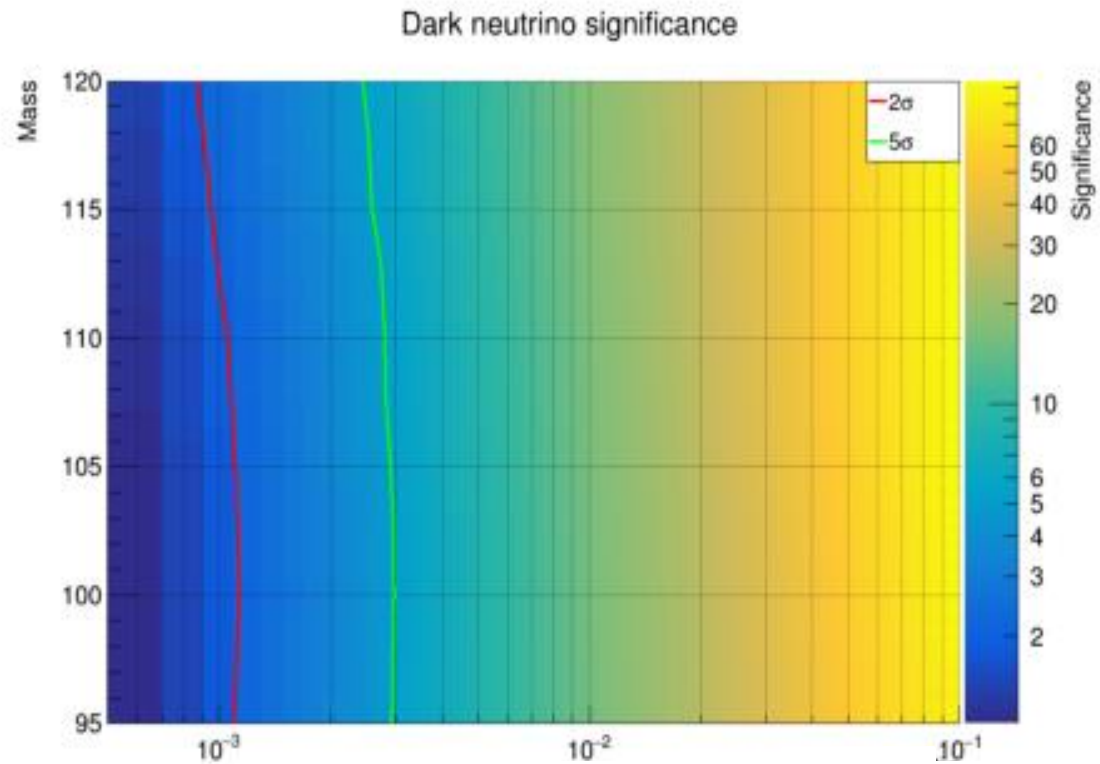
Dark neutrinos from exotic Higgs decays (ctd.)

Significance about 2σ for BR = 0.1% and 5σ for BR = 0.3%



$BR(H \rightarrow \nu\ Nd)BR(Nd \rightarrow lW)$

$\sqrt{s} = 250 GeV$, both main polarisations

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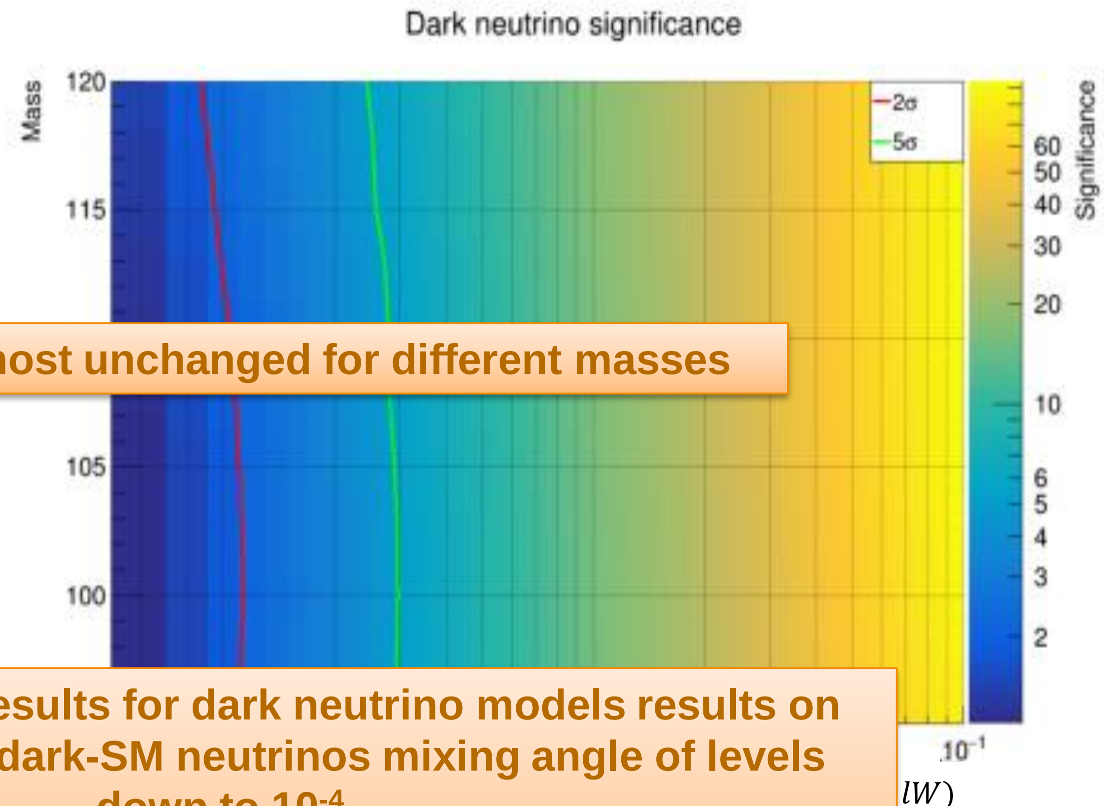


Significance about 2σ for BR = 0.1% and 5σ for BR = 0.3%

Significance almost unchanged for different masses

Interpreting these results for dark neutrino models results on constraints on the dark-SM neutrinos mixing angle of levels down to 10^{-4}

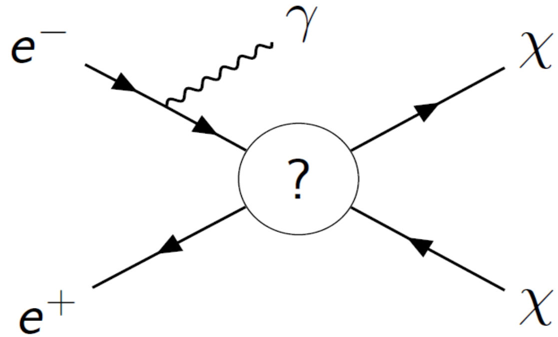
Factor of 10 improvement from previous constraints

WIMP Dark Matter

Weakly Interacting Massive Particles are among the primary candidates for Dark Matter

Searches based on simplified signatures: excess of mono-photon events

ISR can be described within the SM and depends only indirectly on the DM production mechanism



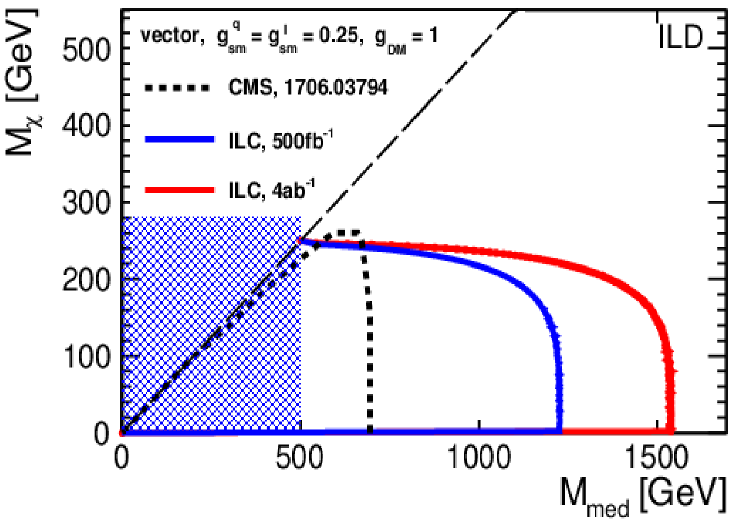
Current WIMP limits based on mono-photon signatures were derived from LEP results
Limits ~100fb

No possible direct comparison to LHC results without model assumptions on the relative strengths on the coupling to lepton and quarks.

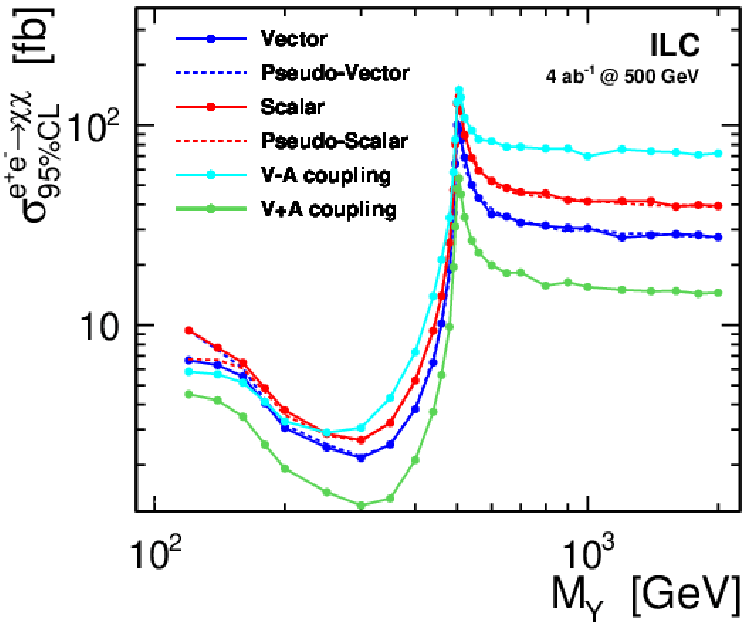
Constraining the couplings of the WIMP and the mediator to the SM particles based on the observed DM relic density and using EFT for singlet-like Majorana fermion WIMP, it has been shown that there is significant areas not covered by the LHC that can be covered by future e+e- colliders

WIMP Dark Matter (ctd.)

Two simplified model approaches:
- heavy mediator: model independent EFT approach
- arbitrary mediator: sensitivity depends on mediator properties



Heavy mediator



Arbitrary mediator

arxiv:2001.03011

arxiv:2107.11194

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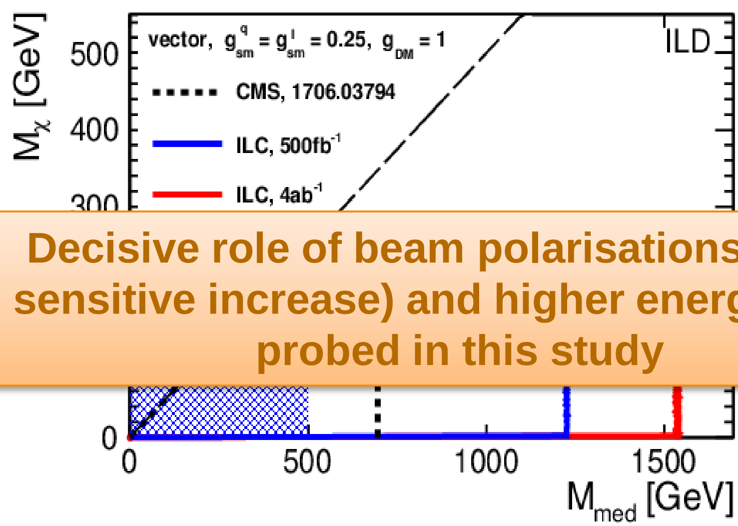
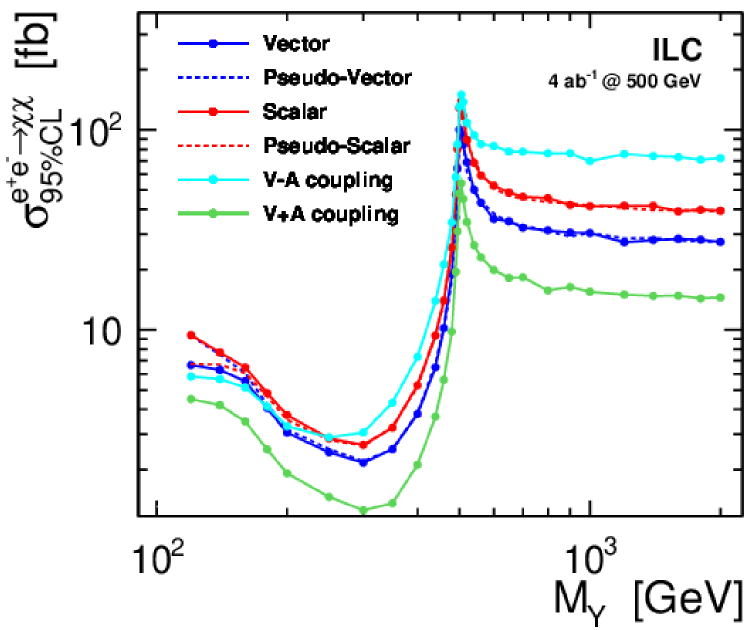


Decisive role of beam polarisations (>50 % sensitive increase) and higher energies was probed in this study

Heavy mediator



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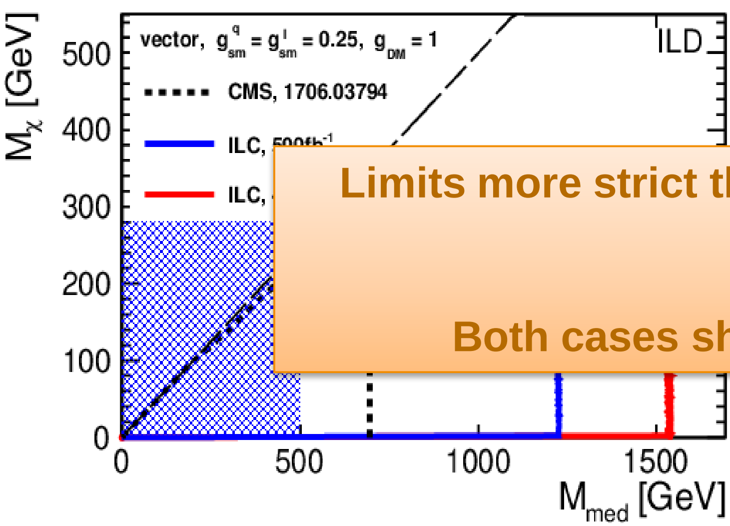

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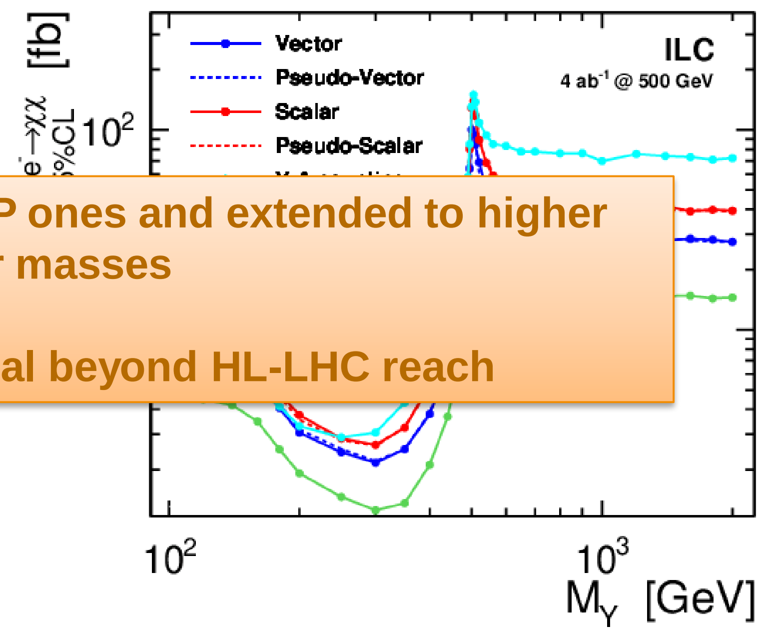

Limits more strict than the LEP ones and extended to higher mediator masses

Both cases show potential beyond HL-LHC reach

Arbitrary mediator

arxiv:2107.11194

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Long-lived particles

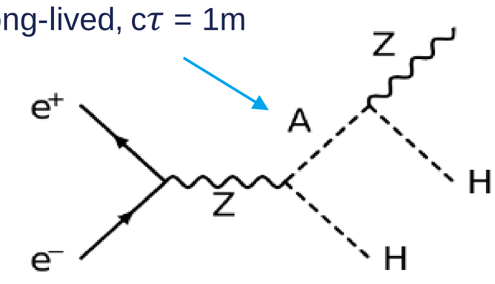
LLPs are widely considered in many BSM scenarios and searches for new particles

(SUSY particles, axion-like particles, heavy neutral leptons, dark photons, exotic scalar …)

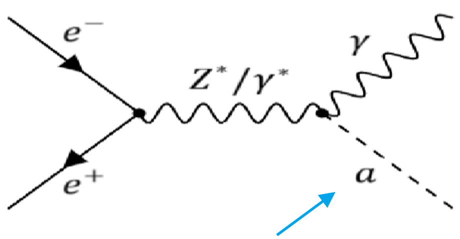
LHC searches mainly sensitive to high masses and couplings
ILC could probe complementary region: small masses, couplings and mass splittings

- Challenging signatures studies from experimental perspective
- Focus on generic case: two tracks from a displaced vertex
- No other assumptions about final state (as general as possible)

Long-lived, $c\tau$ = 1m



Heavy scalars (IDM): small boost, low-P_T track pair, not pointing towards IP



Long-lived, $c\tau$ = 10mm

Highly boosted light LLP (axion-like particle): small LLP mass, very high P_T , collinear tracks

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J. Klamka, A.F. Żarnecki
University of Warsaw

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A simple algorithm was developed offering high sensitivity for both extreme signatures

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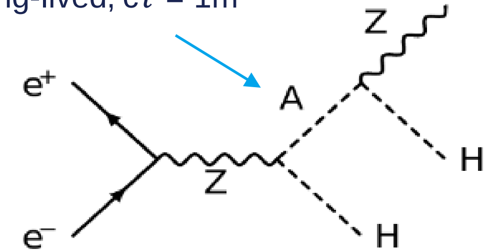

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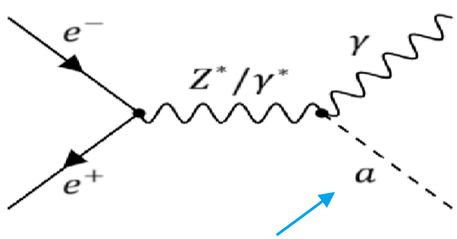

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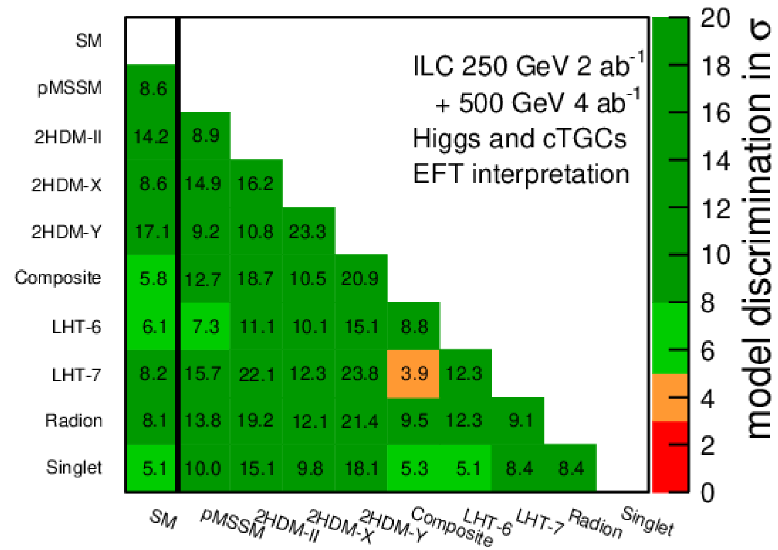
Indirect BSM searches

Detecting BSM by observing deviations from the behavior predicted by the SM

Standard Model Effective Field Theory, SMEFT, using ILC results on Higgs properties and triple gauge couplings (TGCs)

ILC can determine Higgs properties with high precision and in a model-independent way



Useful to separate BSM models

arxiv:1708.08912

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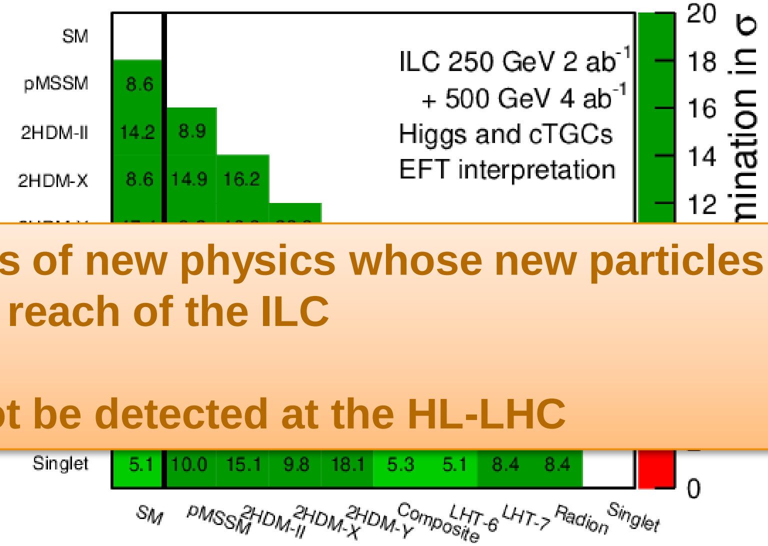

Observing and discriminating models of new physics whose new particles are beyond the reach of the ILC

The studied models can not be detected at the HL-LHC

Useful to separate BSM models

arxiv:1708.08912

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Outlook/Conclusions

The potential for direct discovery of new particles at the ILC have been proved

It could exceed that of the LHC in well-founded scenarios

- ILC offers clean environment without QCD backgrounds and well defined initial state
- ILC detectors will be more precise, hermetic and will not need to be triggered

Synenergies between ILC and LHC are expected

LHC have higher energy-reach, while ILC more sensitivity to subtle signals

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