BSM searches at the ILC

Teresa Núñez - DESY

On behalf of the ICFA-IDT-WG3 BSM group

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

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Why ILC for BSM searches?

The International Linear Collider (ILC) provides an excellent scenario for BSM searches

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

ILC will profit from :

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

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Wrt. previous electron-positron colliders:

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Many BSM scenarios are difficult to address at a hadron collider and still not excluded by the existing experimental data

- microscopic beam-spot

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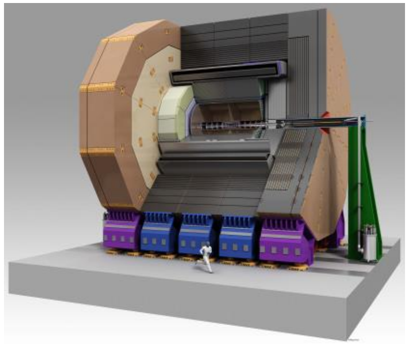
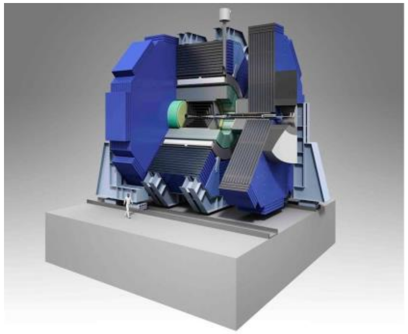
ILC detectors: ILD & SiD concepts



Physics requirements for SM and BSM:

- Jet energy resolution 3-4%
- Asymptotic momentum resolution $\sigma(1/p_\perp) = 2\times10^{-5}\ \mathrm{GeV}^{-1}$
- Impact parameter resolution $\sigma(d_0) < 5\ \mu m$
- 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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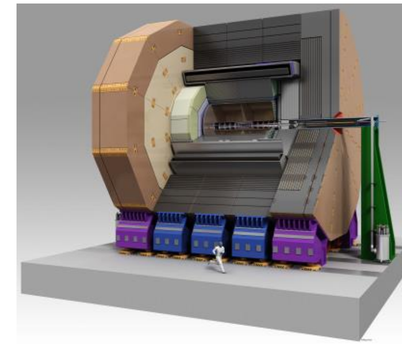

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Studies using the full/fast detector simulation and reconstruction procedures of the International Large Detector concept (ILD) at the International Linear Collider (ILC)

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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

SUSY: $\tilde{\tau}$ searches

Motivated NLSP candidate and most difficult scenario

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

- Searches include all SM and beam induced backgrounds (full simulation)
- Effect of beam induced backgrounds for $\tilde{\tau}$ searches was analysed (as overlay-on-physics and overlay-only events – not in previous studies)
- Detector simulation and event reconstruction for signal events performed by the SGV fast simulation adapted to the ILD

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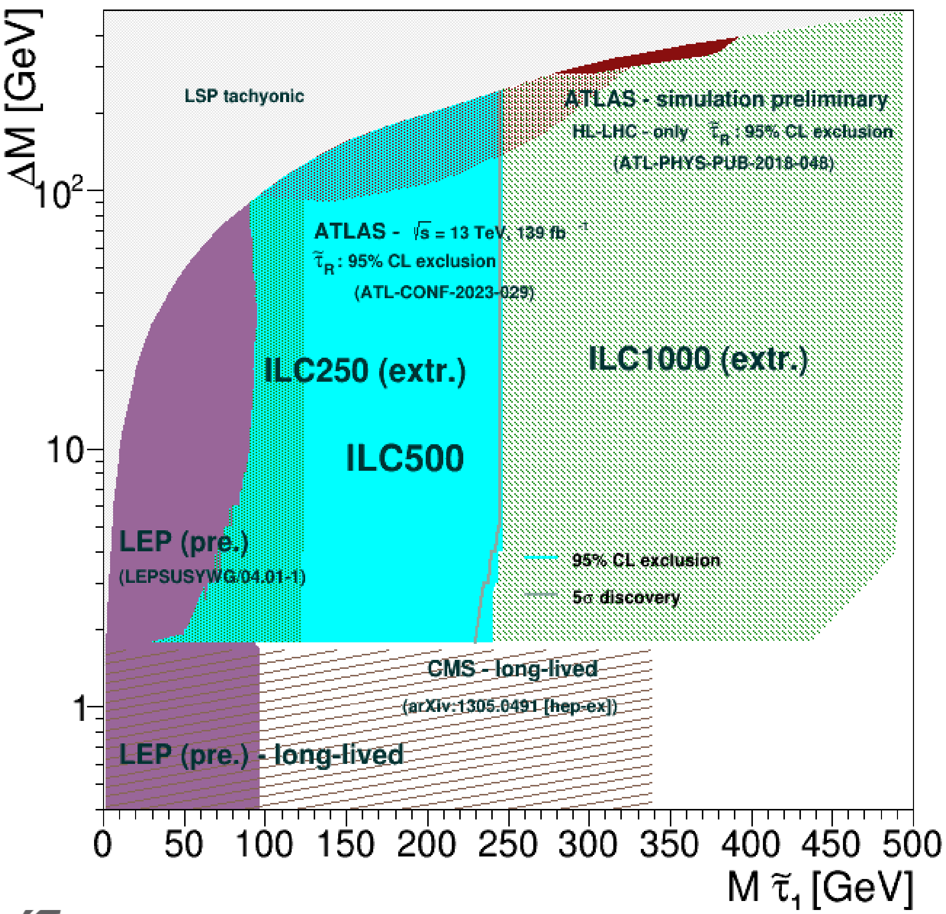
SUSY: $\tilde{\tau}$ searches (ctd.)



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

Poster contribution:

Stau searches at future e+e- colliders

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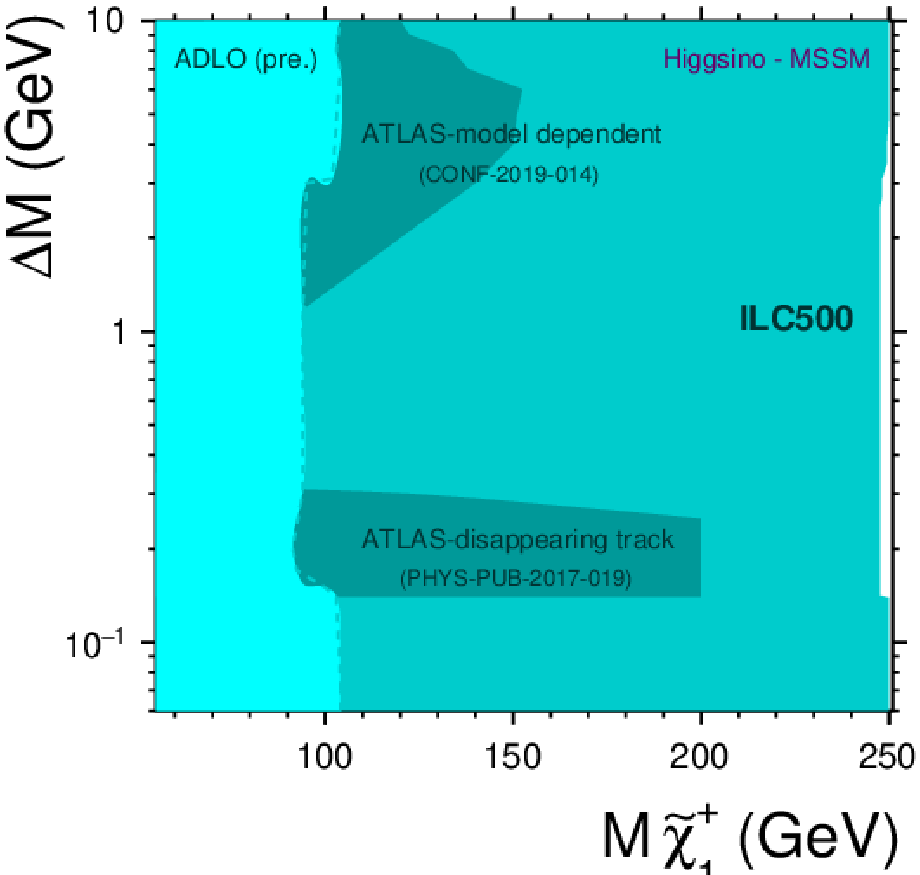
SUSY: Higgsino searches

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 exotic scalars

Predicted by many BSM models

Higgs factories are specially suited for searching at new scalars in the process $e^+e^- \to ZS^0$:

- independent of the S^0 decay mode (based on recoil mass)
- S^0 decaying to $\tau\bar{\tau}$, $b\bar{b}$ or invisible

Searches for scalar production in (exotic) Higgs decays also performed:

- invisible decays

Independent searches:

- Studies using the full detector simulation and reconstruction procedures of the ILD at the ILC ($\sqrt{s}$ = 250/500 GeV)
- Searches done for any mass and based on the recoil of the scalar against the Z

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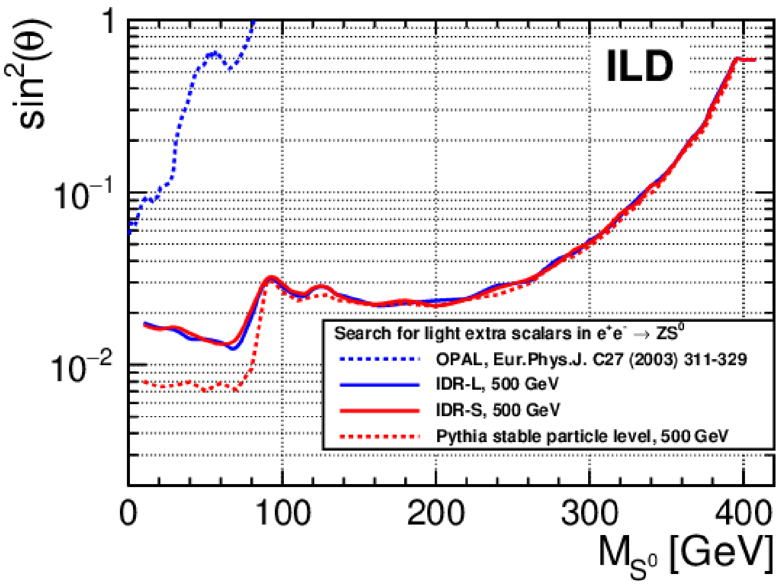
Exotic scalar in association with a Z boson: independent searches

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

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



- Two detector models were considered in the analysis, differing in radius of tracking volume and aspect ratio and strength of magnetic field
- Important detector performance aspects are:
  - di-muon identification and momentum reconstruction
  - ISR identification and energy reconstrucion

Most important limitation comes from ISR identification

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

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

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arxiv:2005.06265

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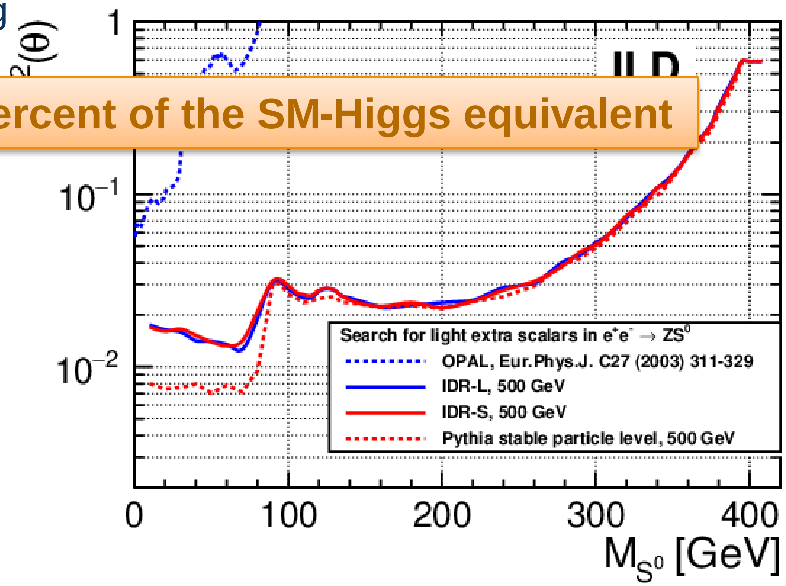

ILC can exclude couplings down to a few percent of the SM-Higgs equivalent

Most important limitation comes from ISR identification

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

Compar ... nes)

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

arxiv:2005.06265

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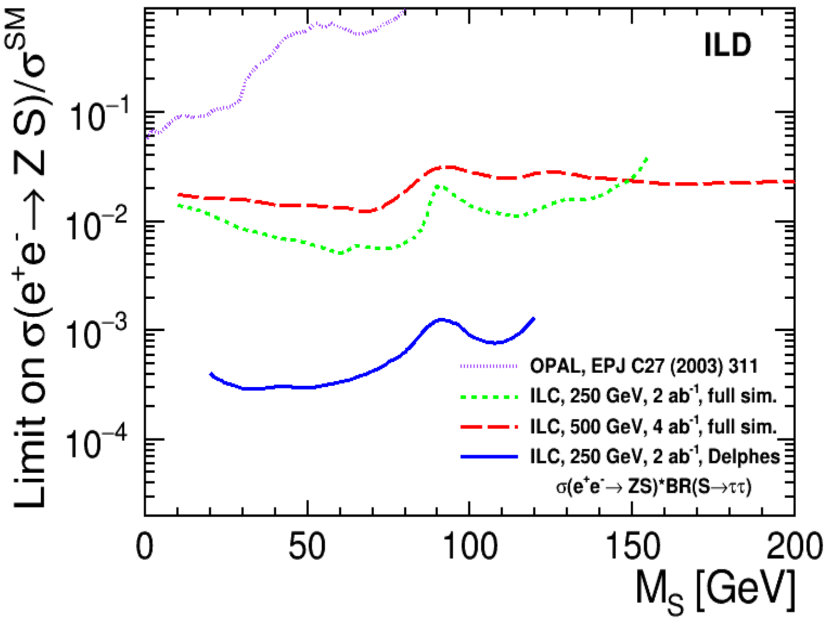
Exotic scalar in association with a Z boson: S^0 decays to $\tau\bar{\tau}$

$e^+e^- \longrightarrow Z' \longrightarrow ZS^0 \rightarrow q\bar{q}\ \tau\bar{\tau}$



- Detector response using DELPHES fast simulation
- ILC scenario at $\sqrt{s}$ = 250 GeV
- Looking for hadronic, semi-leptonic and leptonic τ decays in final state

Scalar search in the di-τ final state expected to result in more stringent limits than the decay independent search provided this branching ratio is of the order of 10% or above

Limits should improve further combining results from different decay channels

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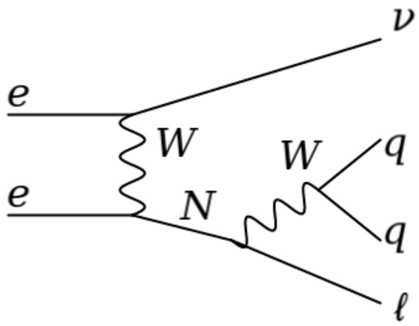
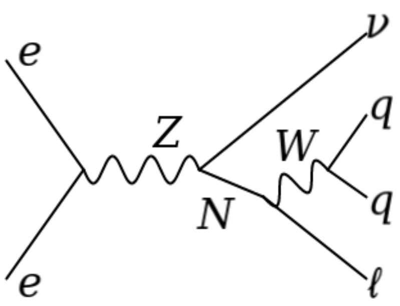
Heavy neutrinos

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

- Observing production and decay of heavy DIRAC and Majorana neutrinos
- Discriminating DIRAC and Majorana nature





Mostly model independent

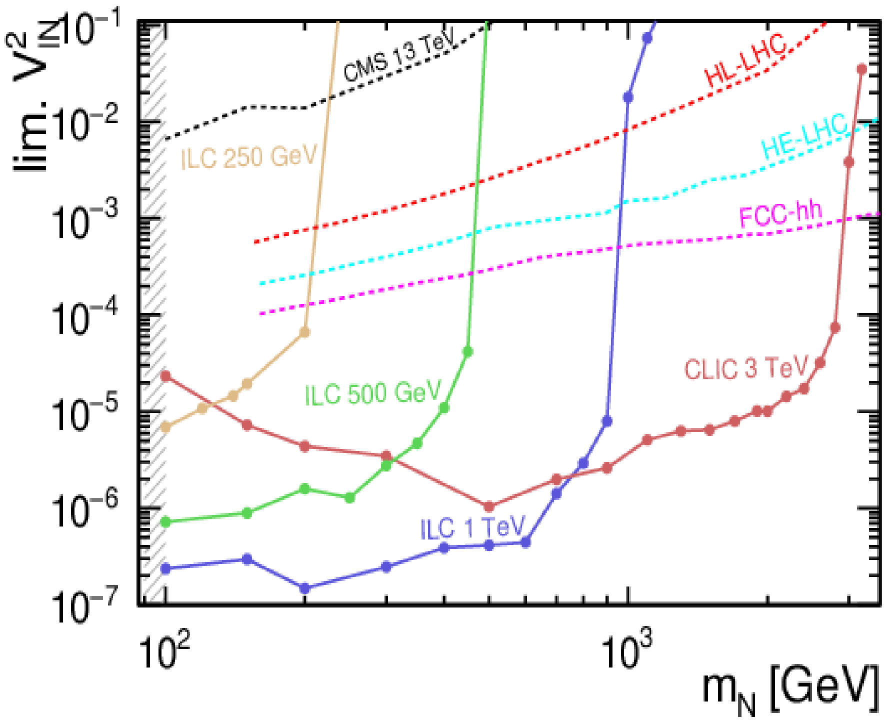
Only one heavy neutrino kinematically accessible - allowing for flavour mixing for all three generations – and not additional gauge bosons at any energy scale

Heavy neutrinos (ctd.)

- Studies focused on heavy neutrino masses above EW scale
- Detector response simulated with DELPHES (fast simulation)

Searches:

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



arxiv:2202.06703

Exclusion reach for the neutrino mixing parameter

(V^2_{lN} :effective weak coupling for the heavy neutrinos)

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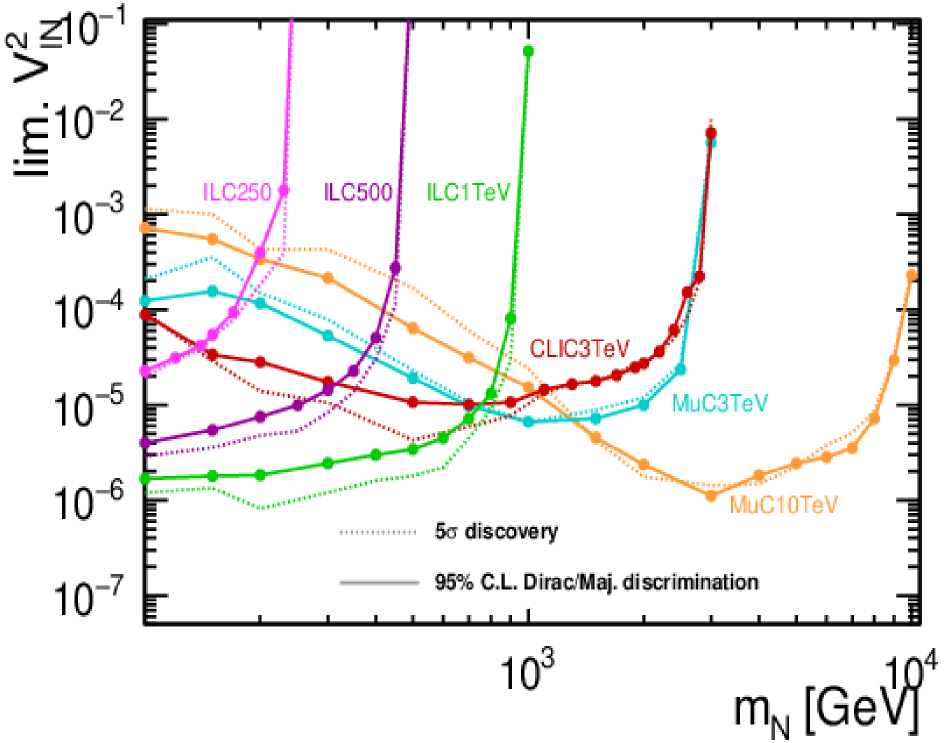
Heavy neutrinos (ctd.)

Discriminating:

- Extension of previous analysis combining kinematic information, like decay angles, with CP information, like charge of the decay lepton

ILC can effectively discriminate between Dirac or Majorana nature of heavy neutrinos simultaneously with their discovery



arxiv:2312.05223

Discovery reach and Dirac/Majorana discrimination

(V^2_{lN} :effective weak coupling for the heavy neutrinos)

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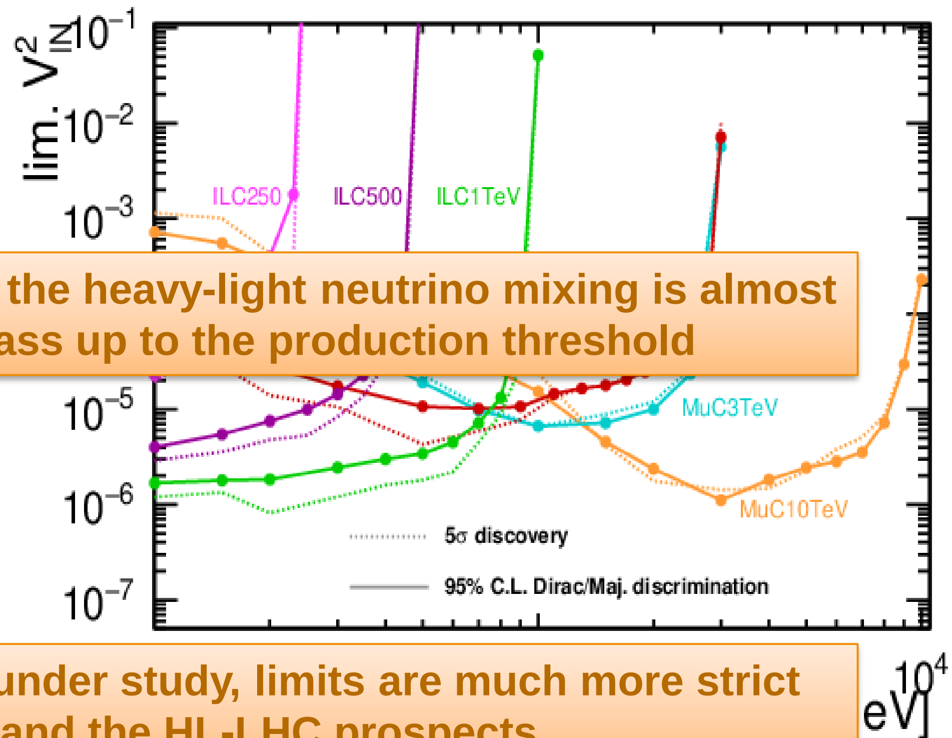

Sensitivity of future e^+e^- colliders to the heavy-light neutrino mixing is almost insensitive to the neutrino mass up to the production threshold

ILC can effectively discriminate between Dirac or Majorana nature of heavy neutrinos simultaneously with their discovery

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

[arxiv:2312.05223](https://arxiv.org/abs/2312.05223)

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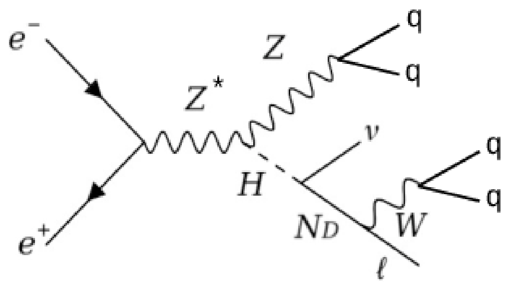
Dark neutrinos from exotic Higgs decays

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

Region under study: $m_Z < m_N < m_H$



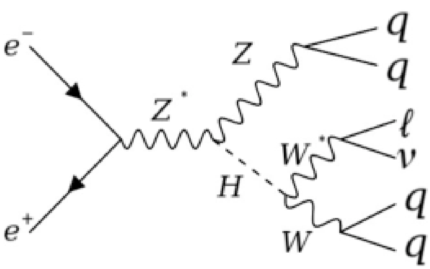
Signal

Based on the leading Higgs production channel and the exotic decay

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



Main background

arxiv:2309.11254

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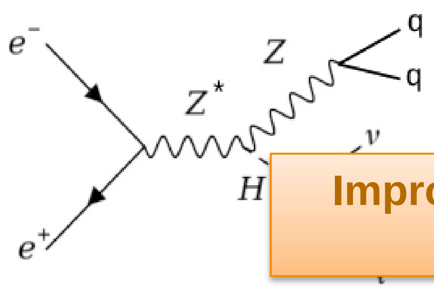
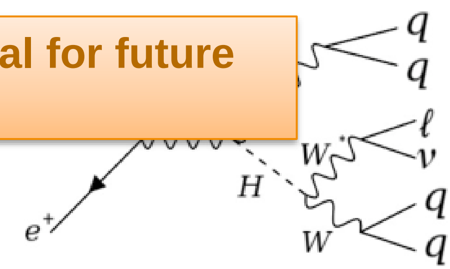


Signal

Improved jet clustering algorithms crucial for future collider experiments



Main background

Based on the leading Higgs production channel and the exotic decay

[arxiv:2309.11254](https://arxiv.org/abs/2309.11254)

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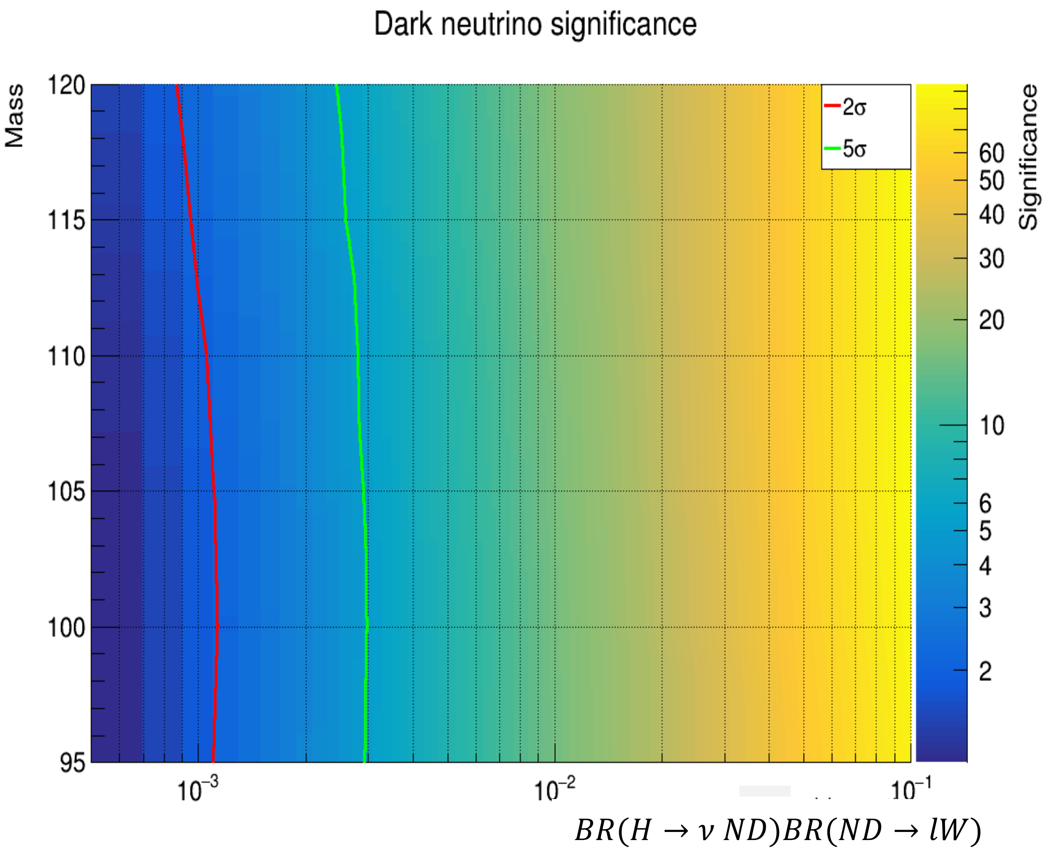
Dark neutrinos from exotic Higgs decays (ctd.)

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



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

[arxiv:2309.11254](https://arxiv.org/abs/2309.11254)

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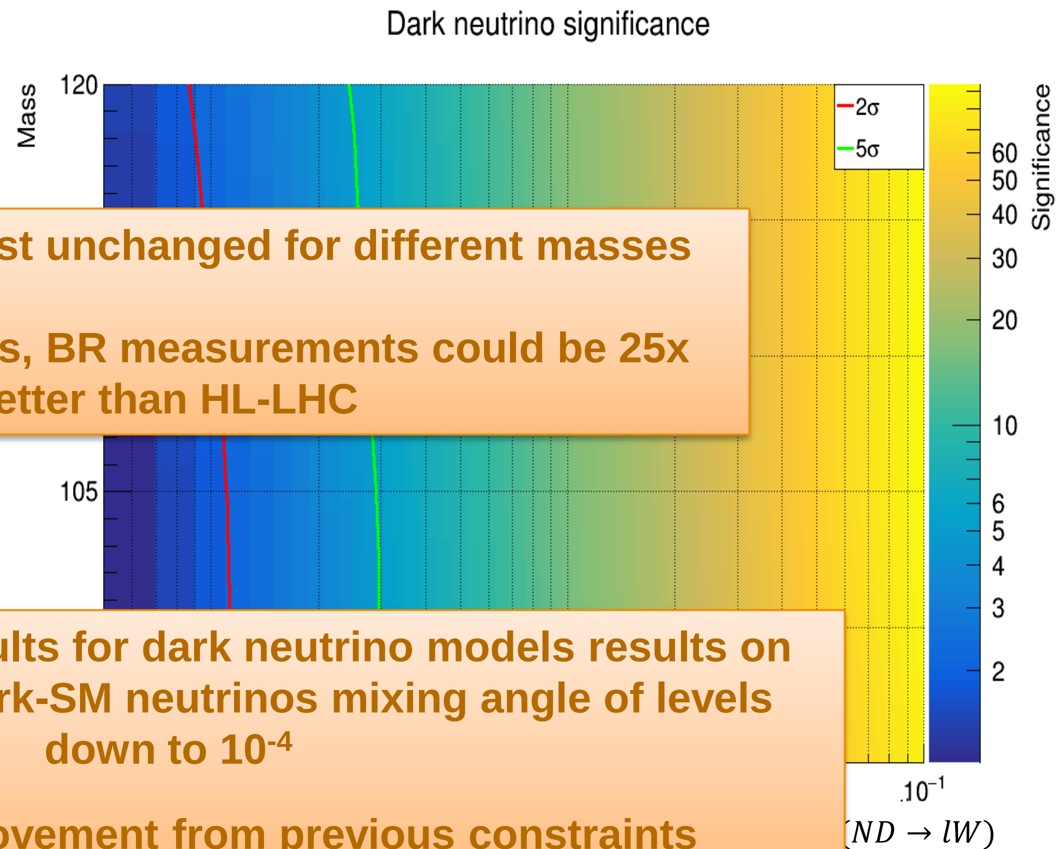

Significance almost unchanged for different masses

By some estimates, BR measurements could be 25x better than HL-LHC

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

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

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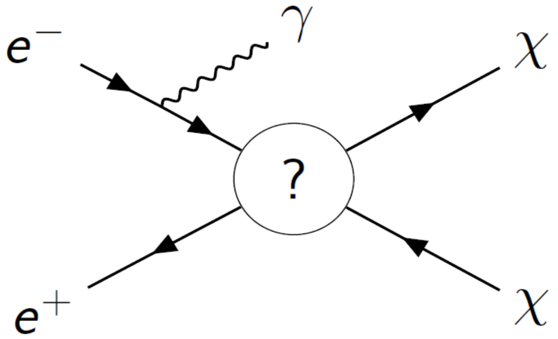
WIMP Dark Matter

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



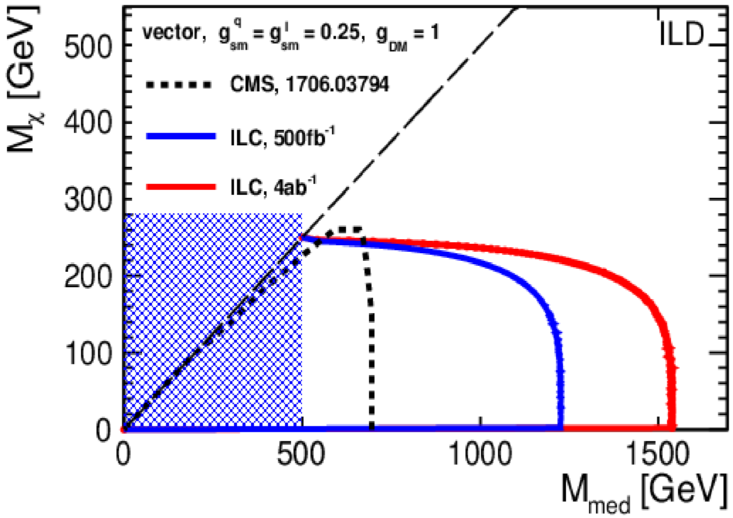
Current WIMP limits based on mono-photon signatures were derived from LEP results
Limits ~100fb

Studies complementary to those performed at the LHC

WIMP Dark Matter (ctd.)

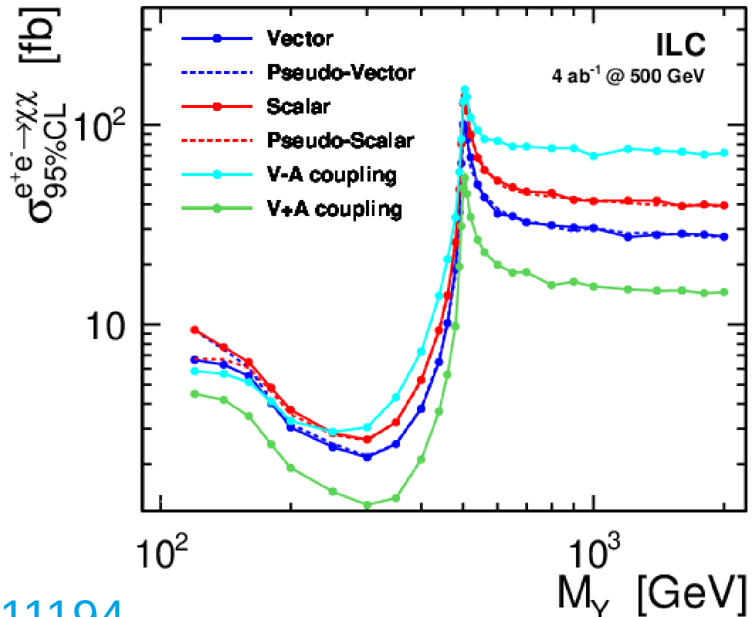
Two simplified model approaches:
- heavy mediator: model independent EFT approach
- arbitrary mediator: sensitivity depends on mediator properties. Limits given as a function of the light DM cross section expected to be least dependent on model details

Heavy mediator



arxiv:2001.03011

Arbitrary mediator



arxiv:2107.11194

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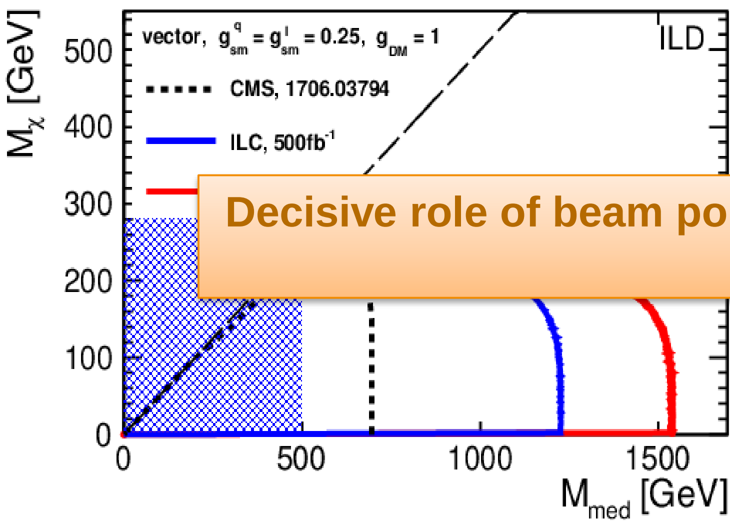
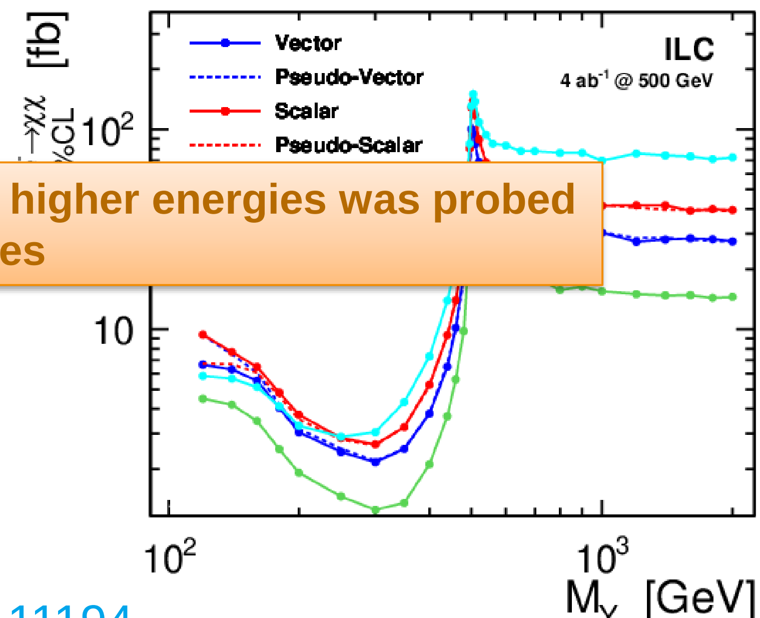


Arbitrary mediator



Decisive role of beam polarisations and higher energies was probed in these studies

arxiv:2001.03011

arxiv:2107.11194

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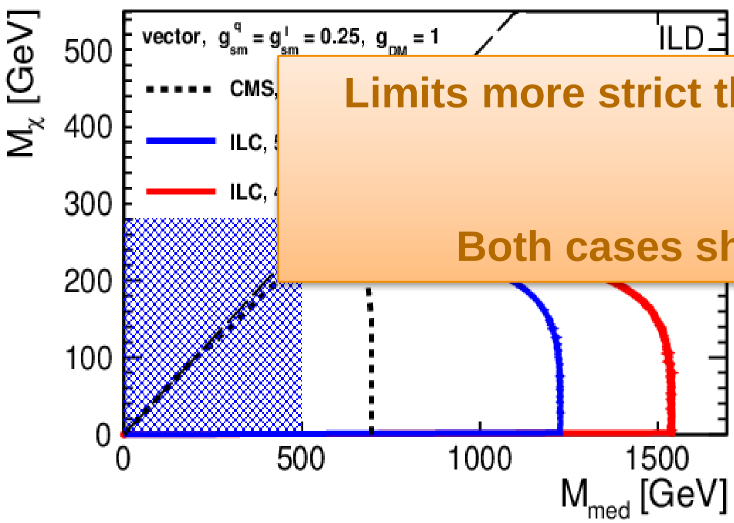
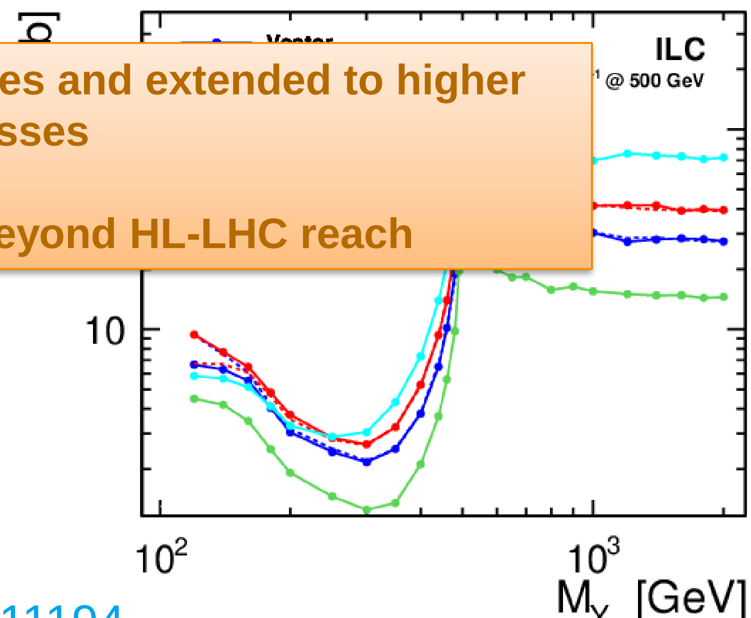


Arbitrary mediator



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

Both cases show potential beyond HL-LHC reach

arxiv:2001.03011

arxiv:2107.11194

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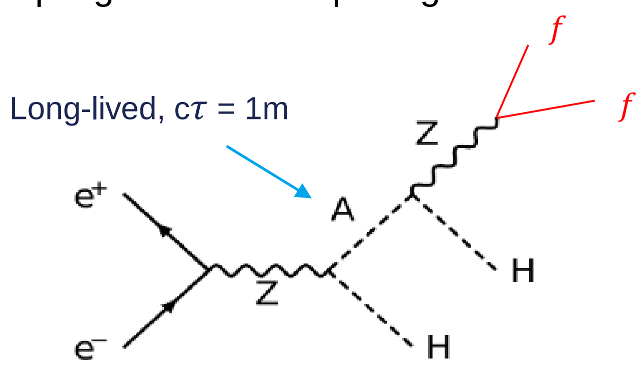
Long-lived particles

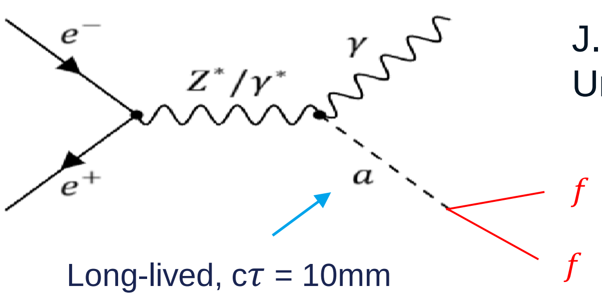
LLPs are widely considered in many BSM scenarios and searches for new particles

(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 splitting

- Two opposite extreme cases were studied: challenging signatures
- Focus on generic case: two tracks from a displaced vertex
- No other assumptions about final state (as general as possible)





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

Heavy scalar LLP (A) and DM (H) pair production with small mass splitting: small boost, low-P_T final state, not pointing towards IP

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

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[Long-lived particle searches with the ILD experiment](#)

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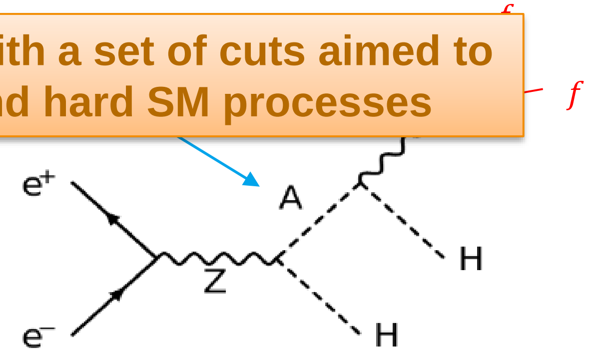
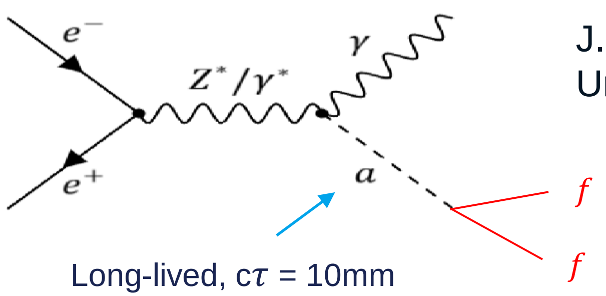
A simple vertex finding algorithm was developed, with a set of cuts aimed to suppress background from the overlay events and hard SM processes

- Two o
- Focus
- No other assumptions about final state (as general as possible)





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

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Long-lived particle searches with the ILD experiment

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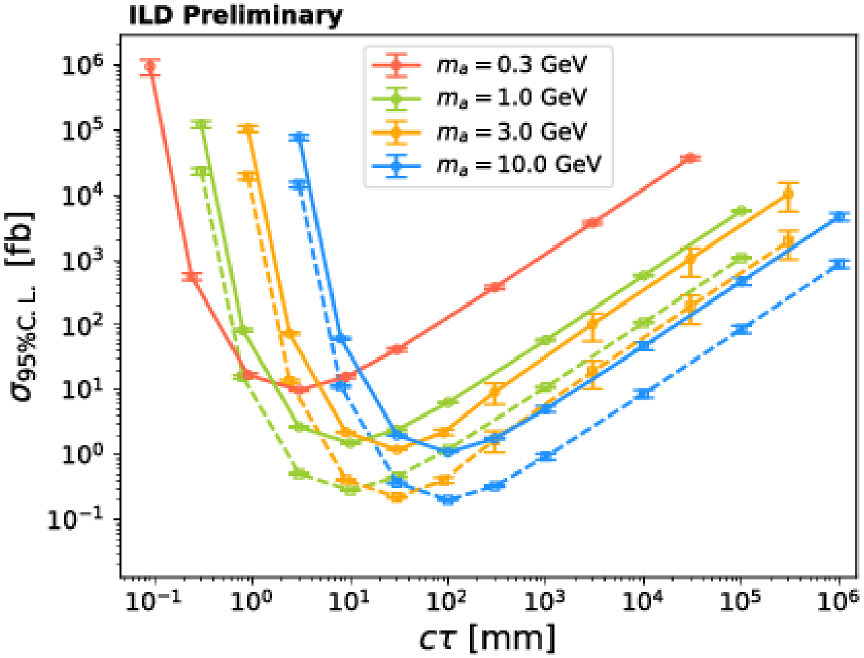
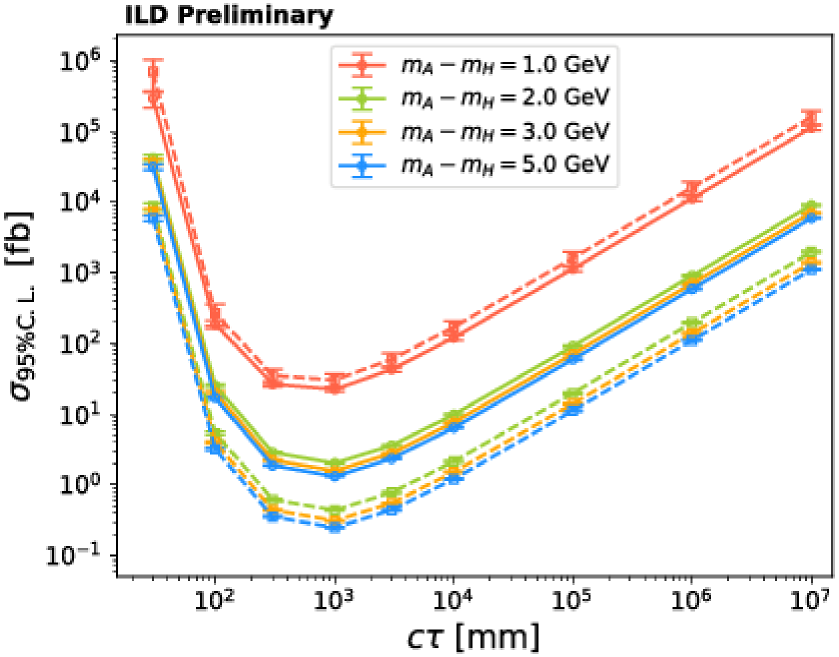
Long-lived particles (ctd.)

Light pseudoscalar



Heavy scalar



- Selection based on vertex position. Additional cut based on invariant mass is applied (two working points: standard – solid lines, and tight – dashed lines). Tight selection includes isolation criterium.
- Signal efficiency strongly dependent on the light pseudoscalar mass, m_a, and mass splitting, $m_A - m_H$
- Dedicated approach could enhance sensitivity for m_a = 300 MeV and $m_A - m_H$ = 1 GeV

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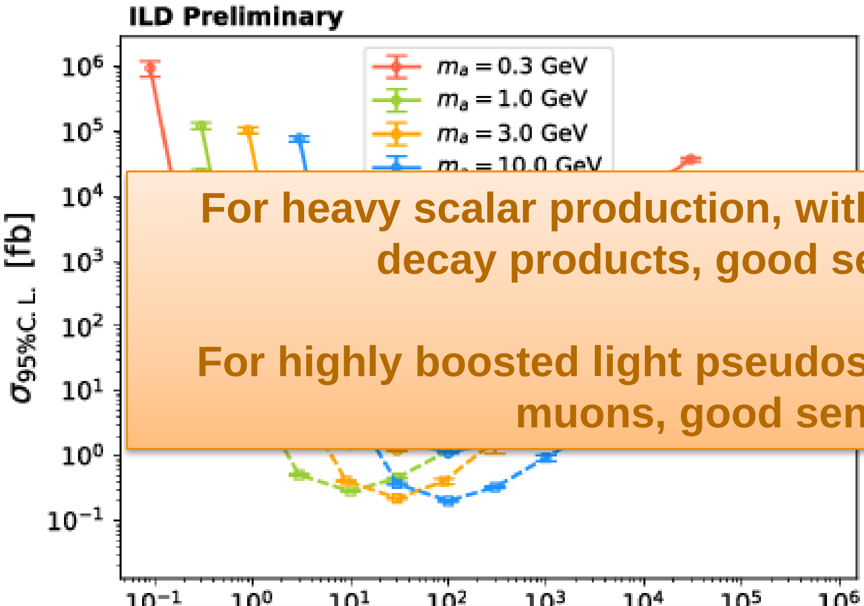
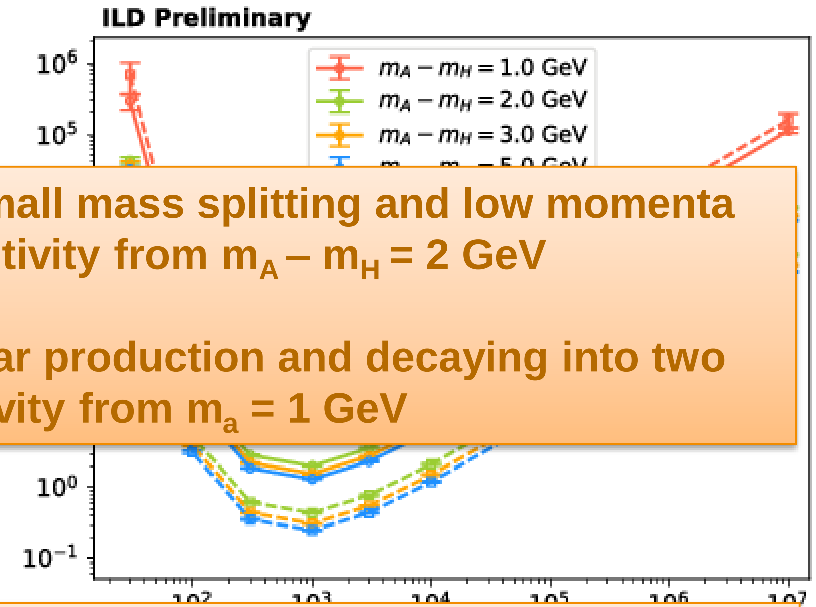
Long-lived particles (ctd.)

Light pseudoscalar



Heavy scalar



For heavy scalar production, with small mass splitting and low momenta decay products, good sensitivity from $m_A - m_H = 2$ GeV

For highly boosted light pseudoscalar production and decaying into two muons, good sensitivity from $m_a = 1$ GeV

Estimated 95% CL limits on signal cross section indicates high reach at the ILC for a wide range of lifetimes (0.003-10 m, depending on scenario)

- Selection based on vertex position. Additional cut based on invariant mass is applied (two working points: standard – solid lines, and tight – dashed lines)
- Signal efficiency strongly dependent on the light pseudoscalar mass, m_a, and mass splitting, $m_A - m_H$
- Dedicated approach could enhance sensitivity for m_a = 300 MeV and $m_A - m_H = 1$ GeV

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[Long-lived particle searches with the ILD experiment]

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DESY.

Indirect BSM searches

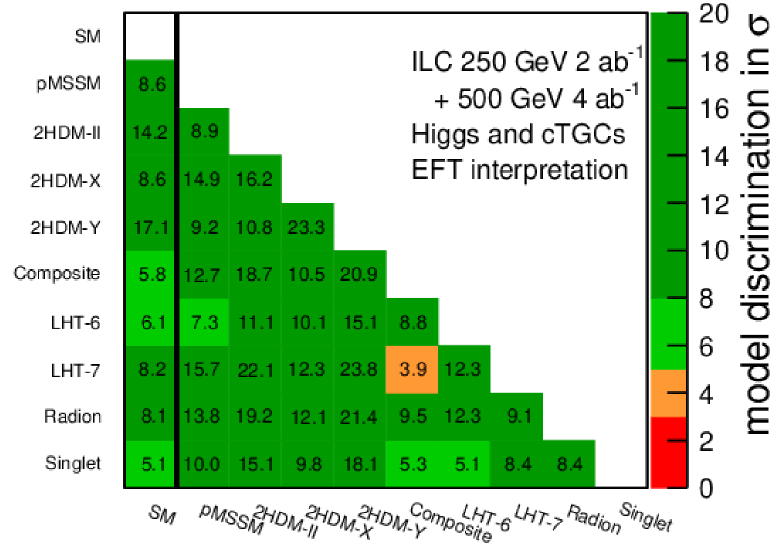
Detecting BSM by observing deviations from the behavior predicted by the SM

Standard Model Effective Field Theory, SMEFT, to study the implications of new physics through the introduction of modifications to the SM at very high energies

Separating BSM models based on Higgs properties and triple gauge couplings (TGCs)

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

High experimental precision is required for probing different scenarios



arxiv:1708.08912

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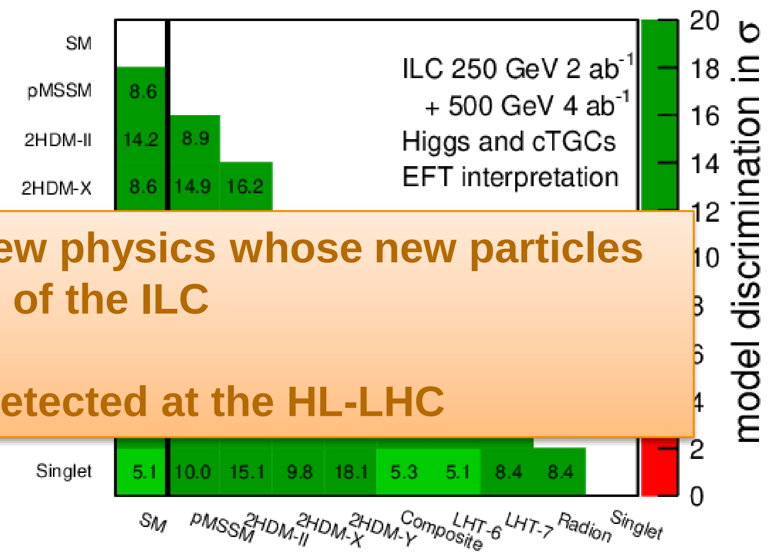

Separating BSM models based on Higgs

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

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

arxiv:1708.08912

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DESY.

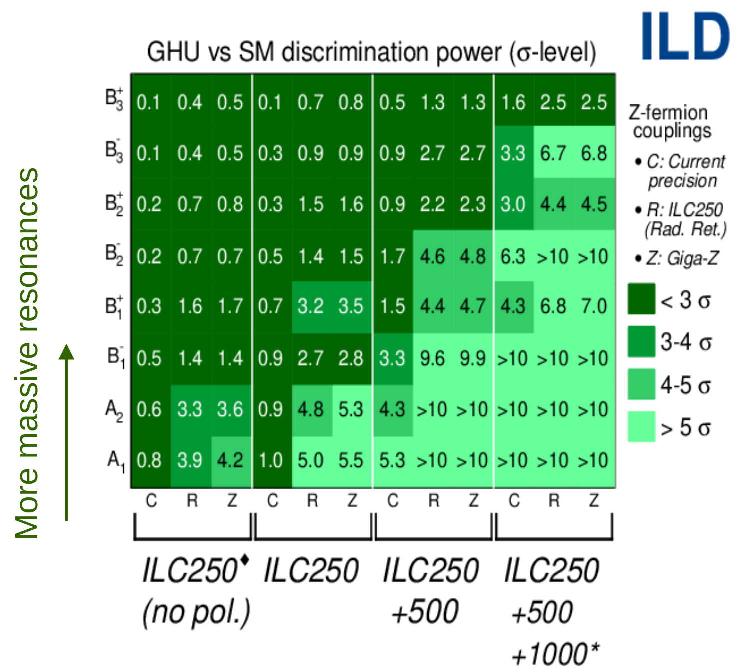
Indirect BSM searches (ctd.)

Probing Gauge-Higgs Unification models via high-precision measurements of the forward-backward asymmetry

arxiv:2403.09144

- Precise study of $e^+e^- \to c\bar{c}$ and $e^+e^- \to b\bar{b}$ interaccions
- Different center-of-mass energies
- Two gauge-Higgs unification models, A/B, predicting new BSM high resonances
- Based on full simulation and reconstruction of the ILD concept

- Testing statistical significance of each model with respect to a reference one
- Assuming different precisions for the SM Z boson couplings:
  current precision, ILC250 and Giga-Z (ILC run at Z-pole)



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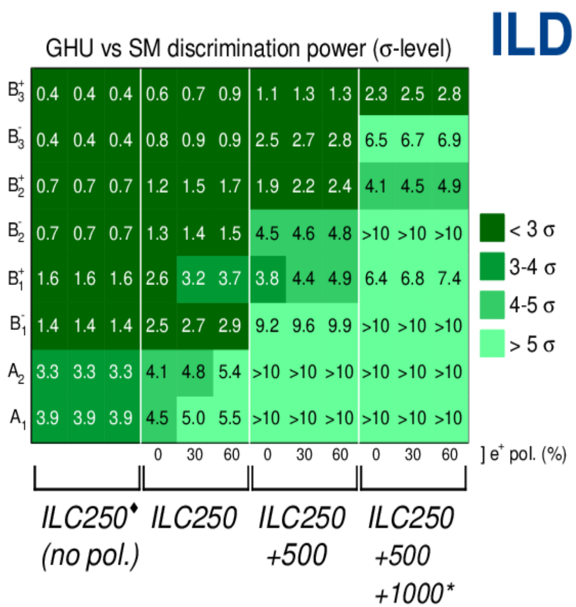
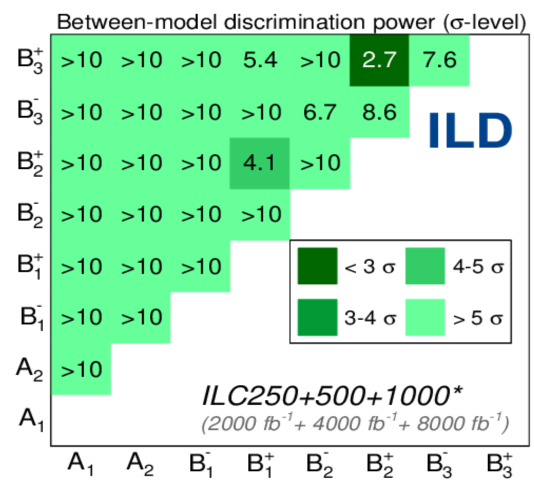
DESY.

Indirect BSM searches (ctd.)

Analysis of the effect of beam polarisation



Discrimination between different GHU models



Polarisation enhances sensitivity and allows combination of measurements with different SM sensitivity to control systematics

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DESY.

Indirect BSM searches (ctd.)

Analysis of the effect of beam polarisation

ILD

GHU vs SM discrimination power (σ-level)

B_3^+	0.4	0.4	0.4	0.6	0.7	0.9	1.1	1.3	1.3	2.3	2.5	2.8
B_3^-	0.4	0.4	0.4	0.8	0.9	0.9	2.5	2.7	2.8	6.5	6.7	6.9
B_2^+	0.7	0.7	0.7	1.2	1.5	1.7	1.9	2.2	2.4	4.1	4.5	4.9
B_2^-	0.7	0.7	0.7	1.3	1.4	1.5	4.5	4.6	4.8	>10	>10	>10
B_1^+	1.6	1.6	1.6	2.6	3.2	3.7	3.8	4.4	4.9	6.4	6.8	7.4
B_1^-	1.4	1.4	1.4	2.5	2.7	2.9	9.2	9.6	9.9	>10	>10	>10

< 3 σ
3-4 σ
4-5 σ
> 5 σ

Discrimination between different GHU models

Between-model discrimination power (σ-level)

B_3^+	>10	>10	>10	5.4	>10	2.7	7.6
B_3^-	>10	>10	>10	>10	6.7	8.6	
B_2^+	>10	>10	>10	4.1	>10		
B_2^-	>10	>10	>10	>10			

ILD

Full discrimination of almost all the proposed models and within models is possible at the baseline run plan for ILC

ILC offers unique capabilities to discriminate GHU vs SM: high energy reach & electron and positron polarisation

Polarisation enhances sensitivity and allows combination of measurements with different SM sensitivity to control systematics

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DESY.

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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