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

42nd international Conference on High Energy Physics
ICHEP2024, Prague - 19th July 2024

HELMHOLTZ GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

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

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY.

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

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

- microscopic beam-spot

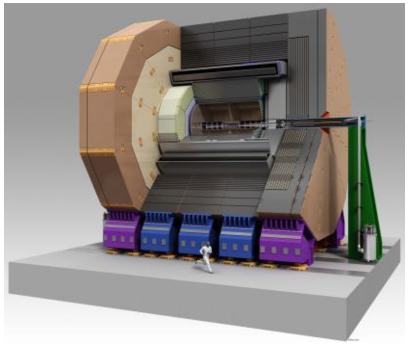
Wrt. hadron colliders:

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

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

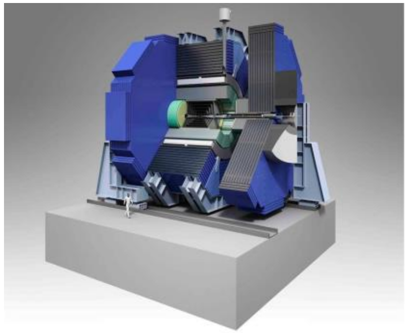
ILC detectors: ILD & SiD concepts

Physics requirements for SM and BSM:



- Jet energy resolution ~ LHC/2
- Asymptotic momentum resolution $\sigma(1/p_{\perp})$ ~ LHC/10
- Impact parameter resolution $\sigma(d_0)$ ~ LHC/2
- Hermeticity down to 5 mrad ~LHC/3
- Triggerless operation

leads to key features for the detectors:



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

Talk by A. Laundrai (20.07, 17:19):

The International Large Detector as Detector Concept for Linear and Circular e+e- Colliders

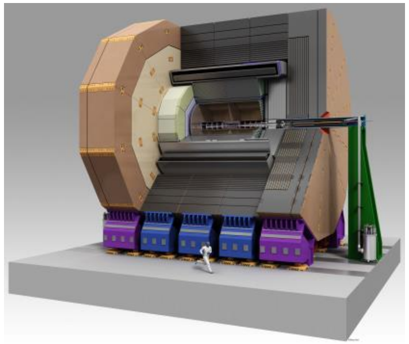
Both ILC detector concepts, ILD and SiD, designed to satisfy the requirements

HELMHOLTZ GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

DESY.

ILC detectors: ILD & SiD concepts



Physics requirements for SM and BSM:

- Jet energy resolution ~ LHC/2
- Asymptotic momentum resolution $\sigma(1/p_\perp)$ ~ LHC/10
- Impact parameter resolution $\sigma(d_0)$ ~ LHC/2
- Hermeticity down to 5 mrad ~LHC/3
- Triggerless operation

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

le

- Power-pulsing for low material

Talk by A. Laundrai (20.07, 17:19):

The International Large Detector as Detector Concept for Linear and Circular e+e- Colliders

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

HELMHOLTZ GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

DESY.

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)

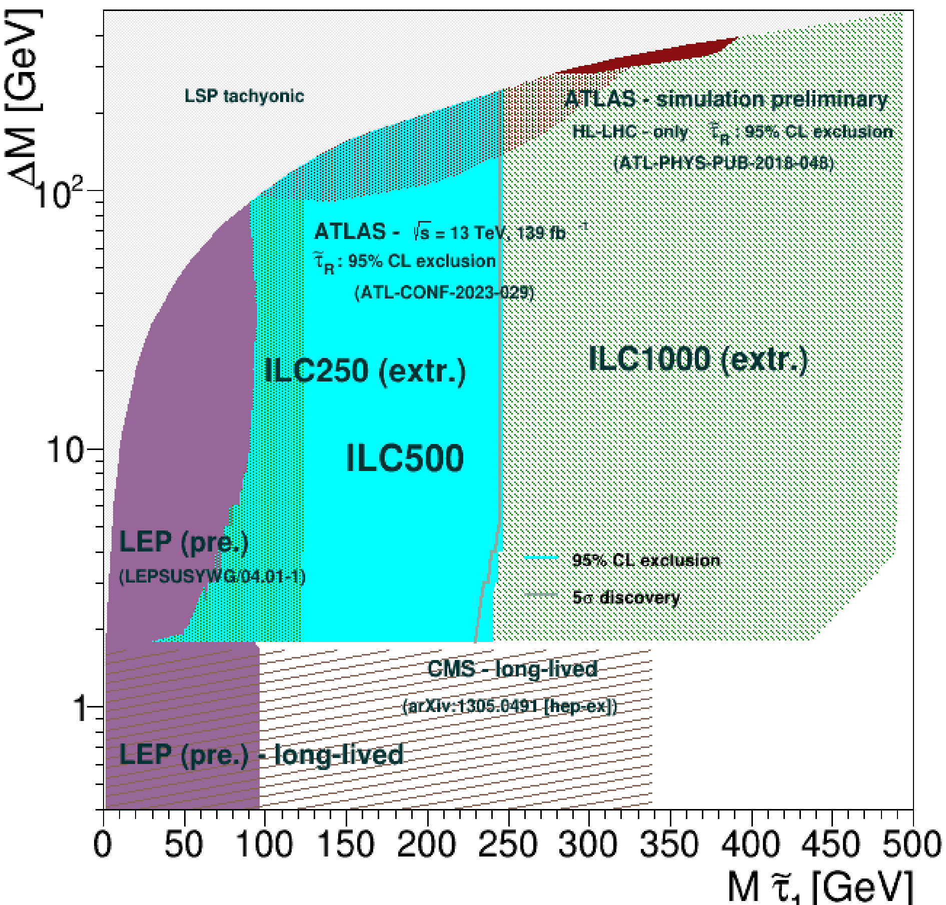
- Searches include all SM and beam induced backgrounds (full simulation)
- Effect of beam induced backgrounds for $\tilde{\tau}$ searches was analysed (as overlay-on-physics and overlay-only events – not in previous studies)
- Detector simulation and event reconstruction for signal events performed by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

HELMHOLTZ GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

DESY.

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 by myself:

[Stau searches at future e+e- colliders]()

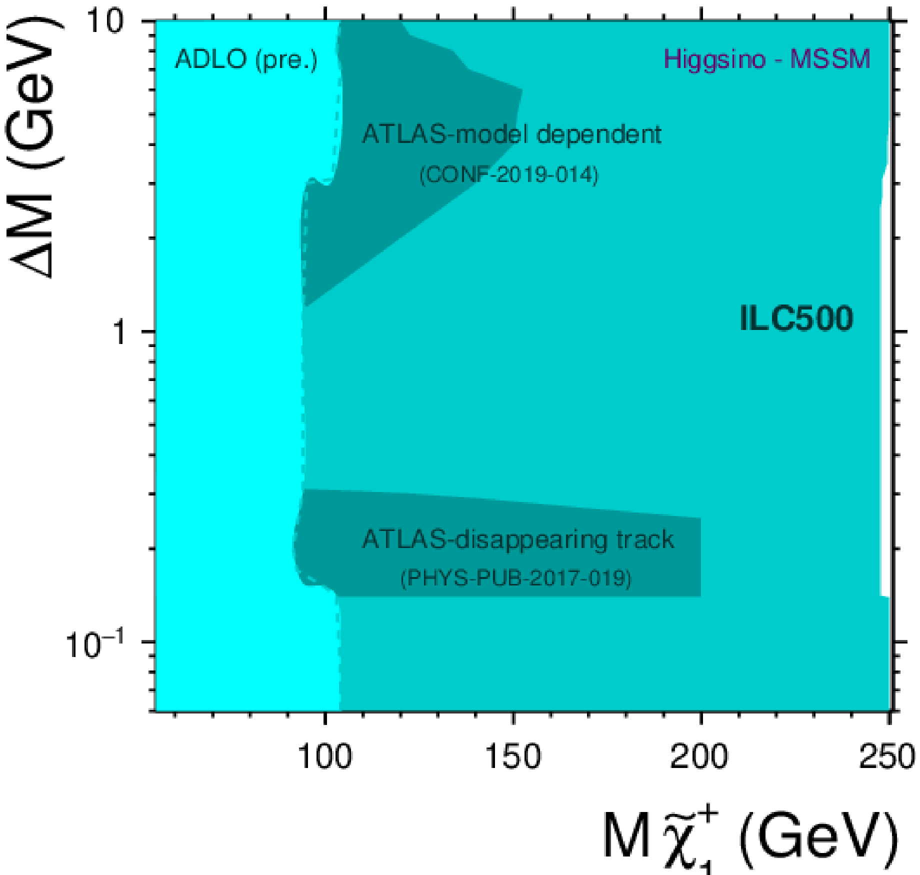
HELMHOLTZ GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

DESY.

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

New exotic scalars

Predicted by many BSM models

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

- 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

HELMHOLTZ
GEMEINSCHAFT

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

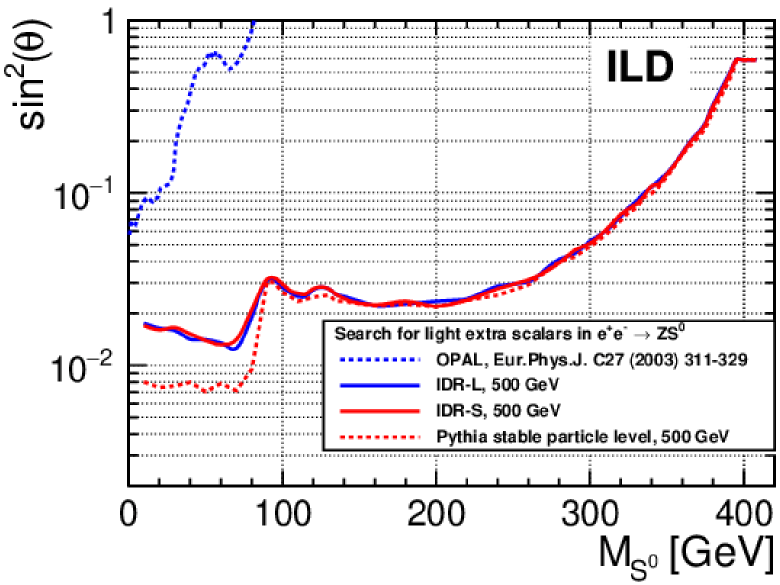
DESY.

Exotic scalar in association with a Z boson: independent searches

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

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)

HELMHOLTZ GEMEINSCHAFT

arxiv:2005.06265

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

DESY.

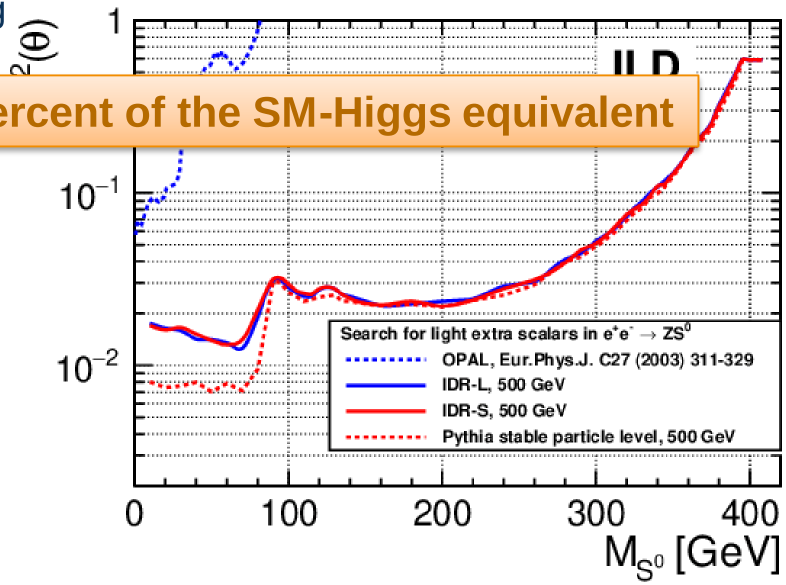
Exotic scalar in association with a Z boson: independent searches

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

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 magne
- Important detector performance aspects are:

  - di-muon identification and momentum reconstruction
  - ISR identification and energy reconstrucion



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

HELMHOLTZ GEMEINSCHAFT

[arxiv:2005.06265](https://arxiv.org/abs/2005.06265)

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

DESY.

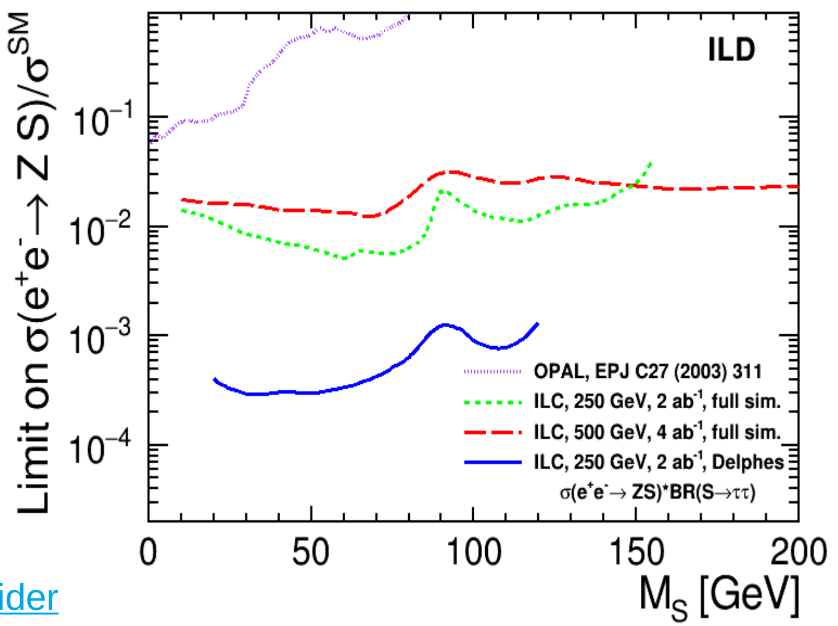
Exotic scalar in association with a Z boson: S^0 decays to $\tau\bar{\tau}$

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

- 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

Talk by A. F. Zarnecki (20.07, 18:10):

[Search for Exotic Scalars at the International Linear Collider]



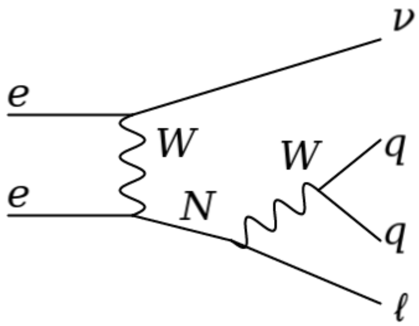
Scalar search in the di-τ final state expected to result in more stringent limits than the decay independent search provided this branching ratio is of the order of 10% or above

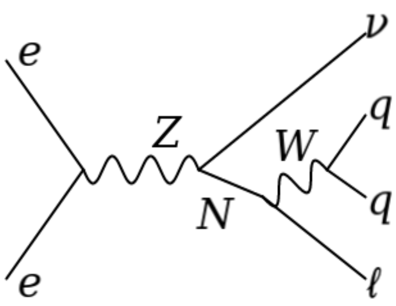
Limits should improve further combining results from different decay channels

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

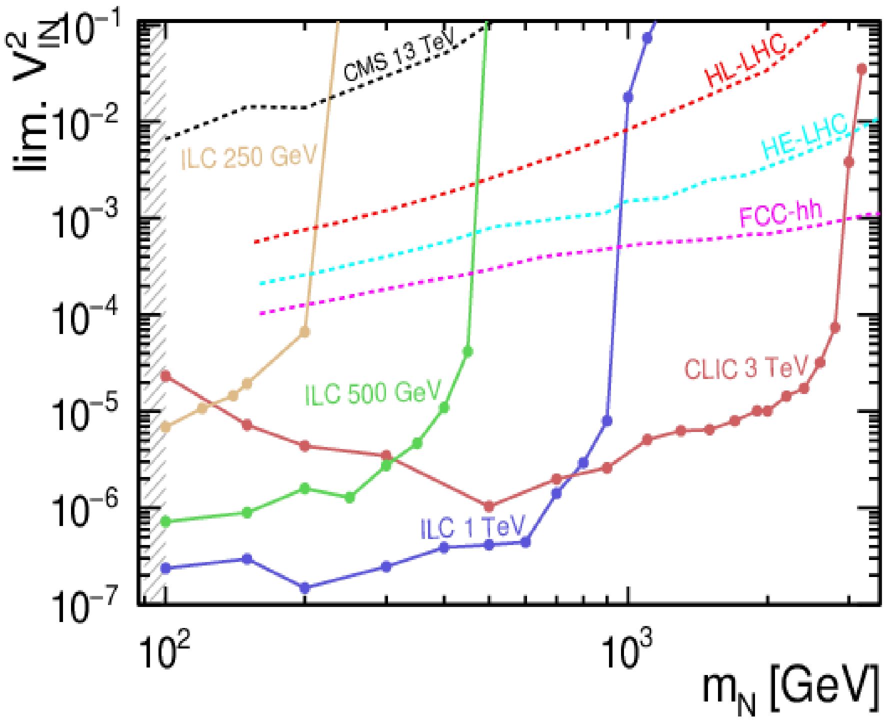
Only one heavy neutrino kinematically accessible - allowing for flavour mixing for all three generations – and not additional gauge bosons at any energy scale

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)

HELMHOLTZ GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

DESY.

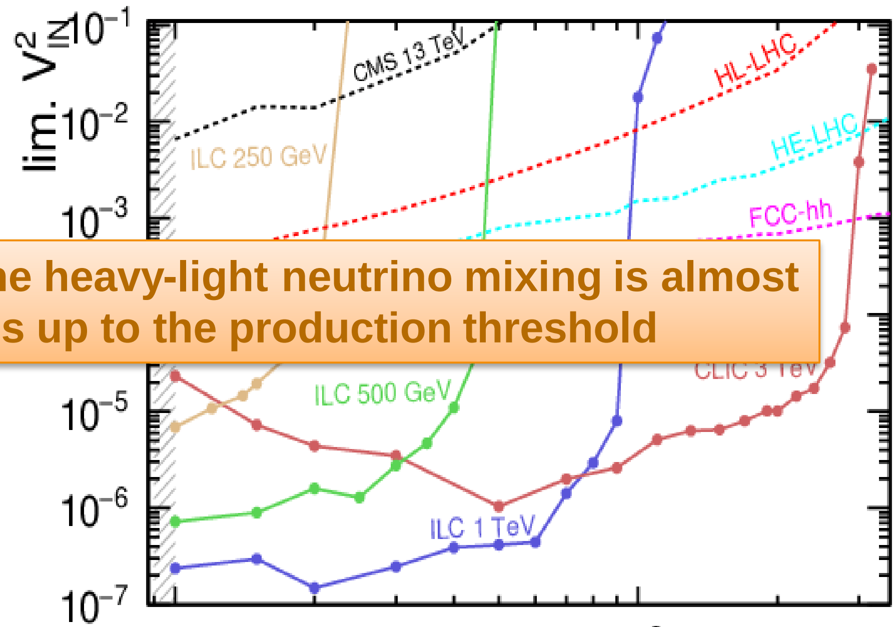
Heavy neutrinos (ctd.)

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

Sea...

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

- Ana... between DIRAC and Majorana hypotheses)
- For on-shell production of heavy neutrinos, almost the same expected limits for Dirac and Majorana particles



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

arxiv.2202.06703

Exclusion reach for the neutrino mixing parameter

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

HELMHOLTZ GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

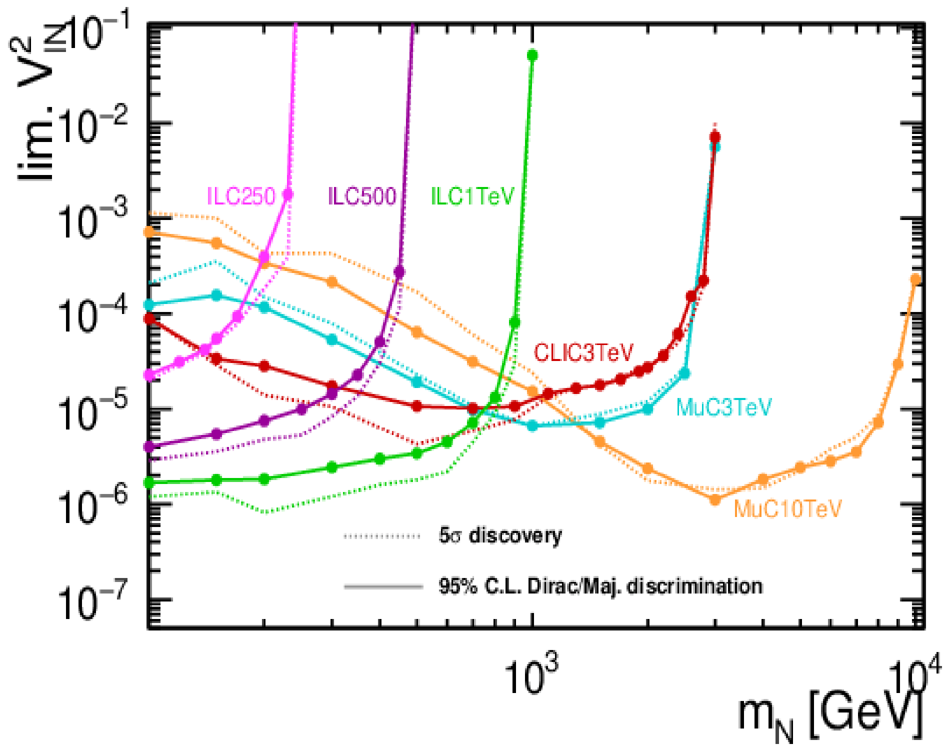
DESY.

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)

HELMHOLTZ GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

DESY.

Dark neutrinos from exotic Higgs decays

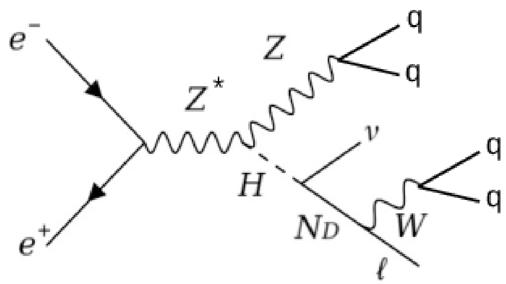
Dark neutrinos from exotics Higgs decays as explanation of matter-antimatter asymmetry

Region under study: $m_Z < m_N < m_H$

Model independent observable:

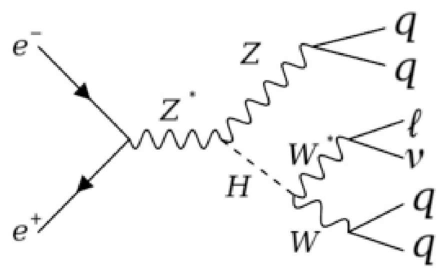
$$BR(H \to \nu\, N_D) BR(N_D \to lW)$$

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

arxiv:2309.11254

HELMHOLTZ GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

DESY.

Dark neutrinos from exotic Higgs decays

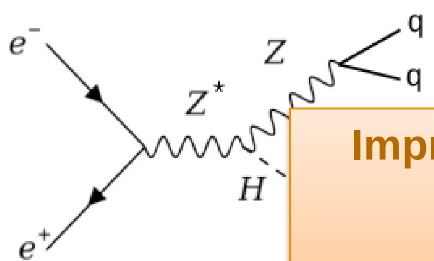
Dark neutrinos from exotics Higgs decays as explanation of matter-antimatter asymmetry

Region under study: $m_Z < m_N < m_H$

Model independent observable:

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

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

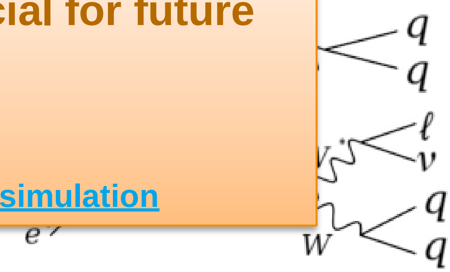


Signal

Based on the leading Higgs production channel and the exotic decay

Improved jet clustering algorithms crucial for future collider experiments

Talk by T. Suehara (20.07, 09:04):
[High level reconstruction with deep learning at ILD full simulation]



Main background

HELMHOLTZ GEMEINSCHAFT

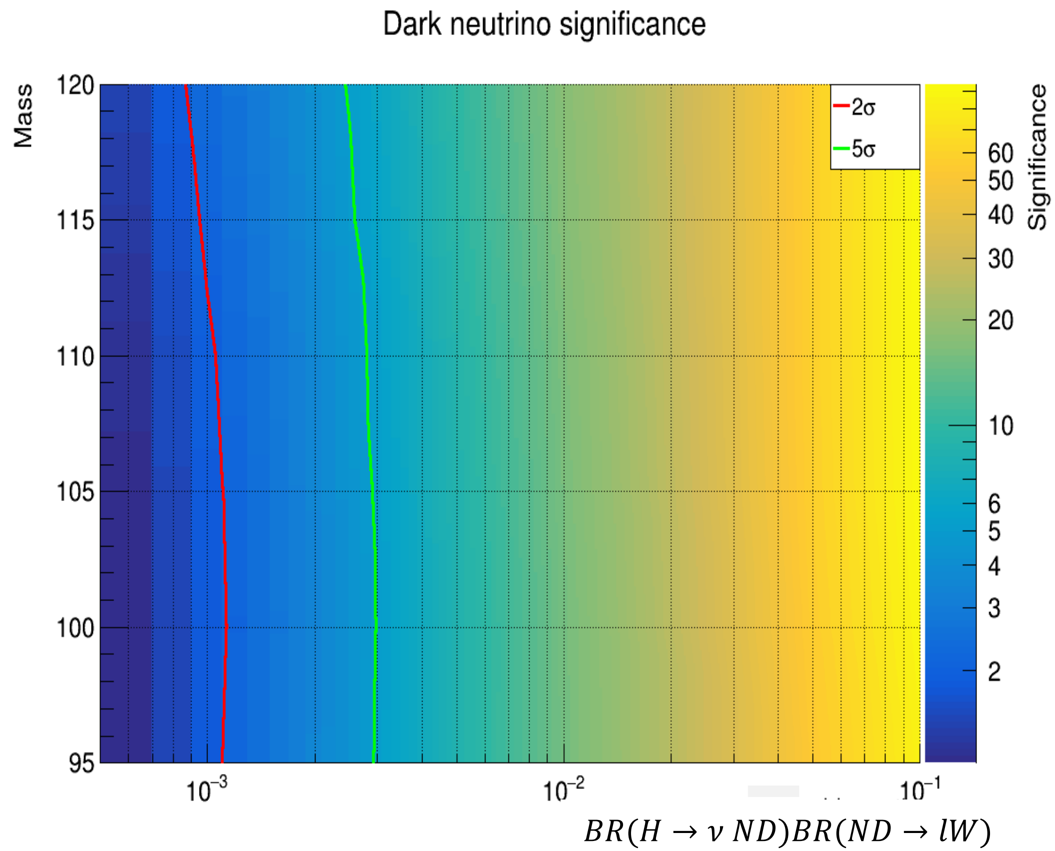
[arxiv:2309.11254]

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

DESY.

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

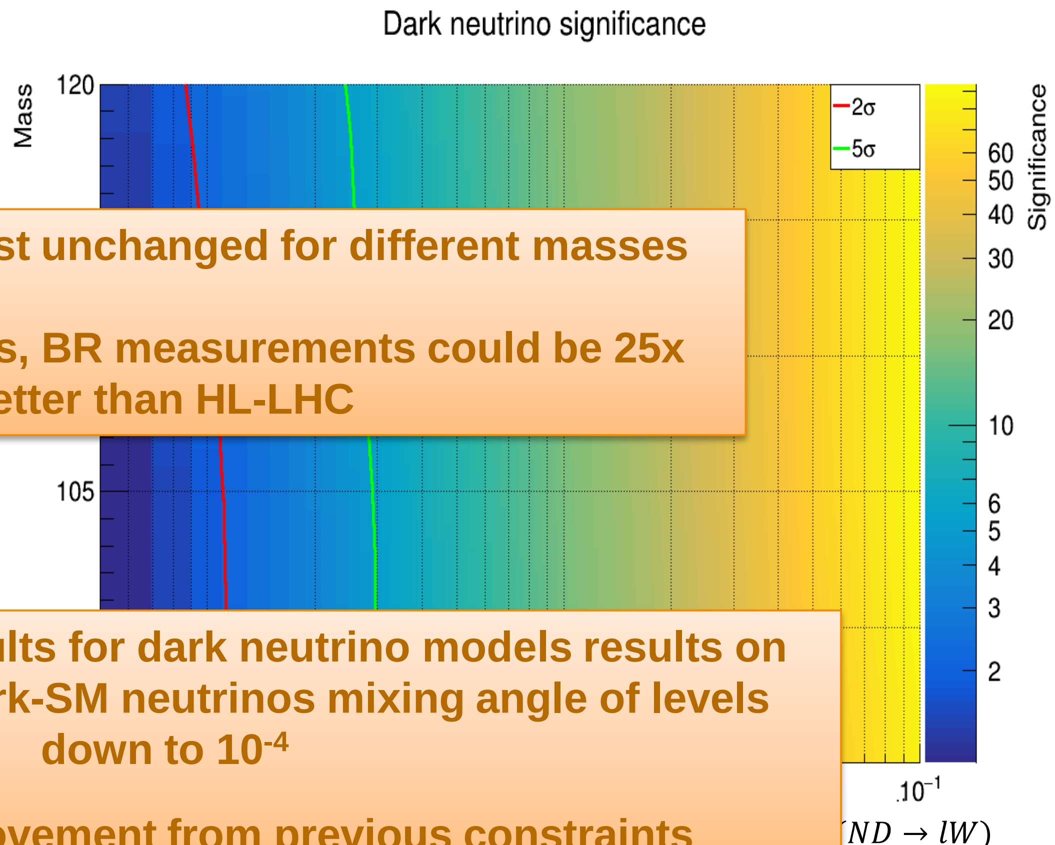
HELMHOLTZ GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

DESY.

Dark neutrinos from exotic Higgs decays (ctd.)

Significance abo
and 5σ fo



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

HELMHOLTZ GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

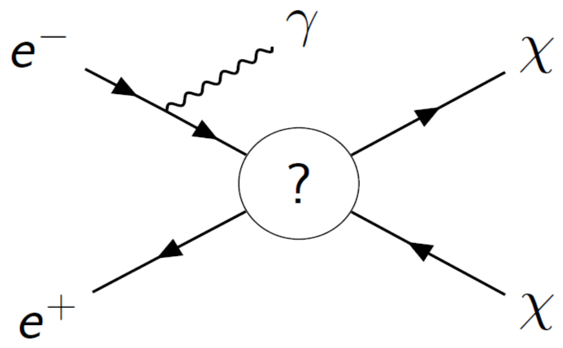
DESY.

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

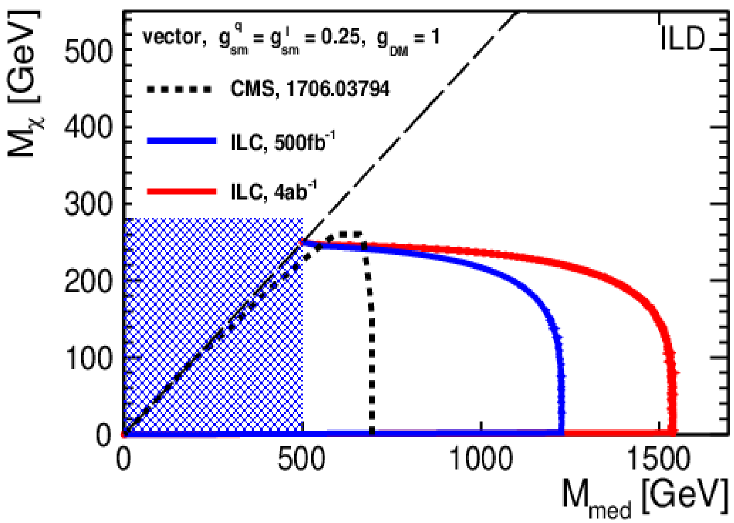
HELMHOLTZ | GEMEINSCHAFT

DESY.

WIMP Dark Matter (ctd.)

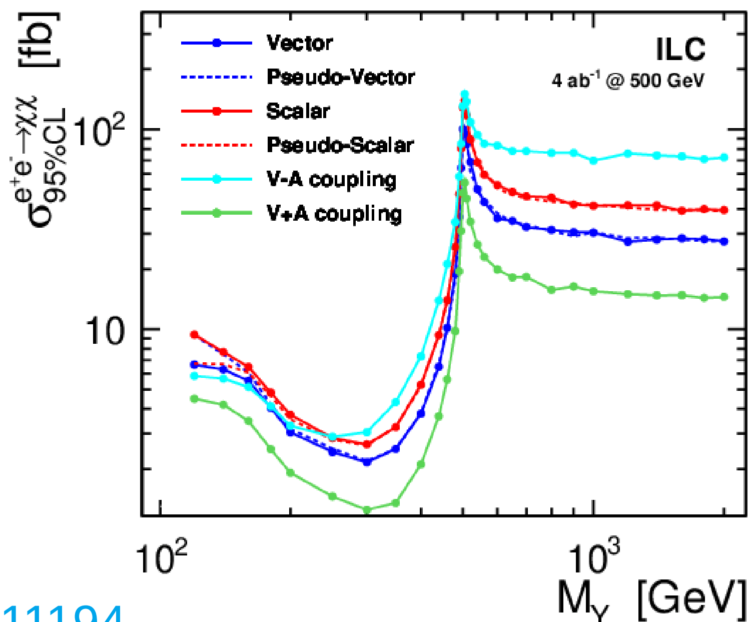
Two simplified model approaches:
- heavy mediator: model independent EFT approach
- arbitrary mediator: sensitivity depends on mediator properties. Limits given as a function of the light DM cross section expected to be least dependent on model details

Heavy mediator



arxiv:2001.03011

Arbitrary mediator



arxiv:2107.11194

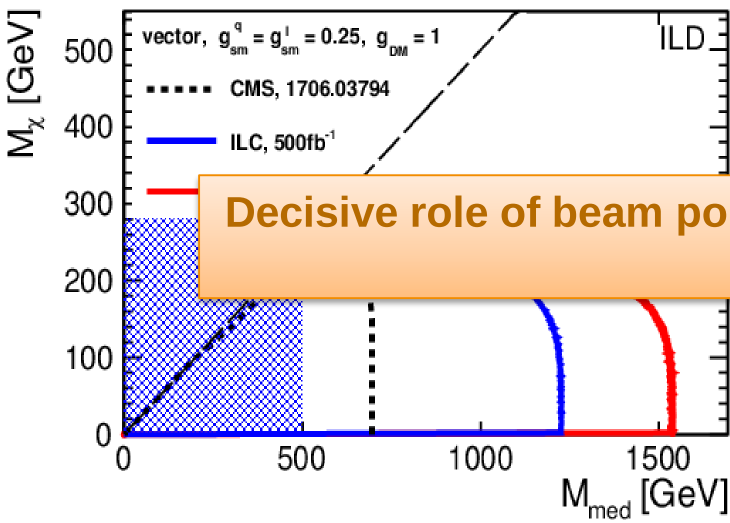
HELMHOLTZ GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

WIMP Dark Matter (ctd.)

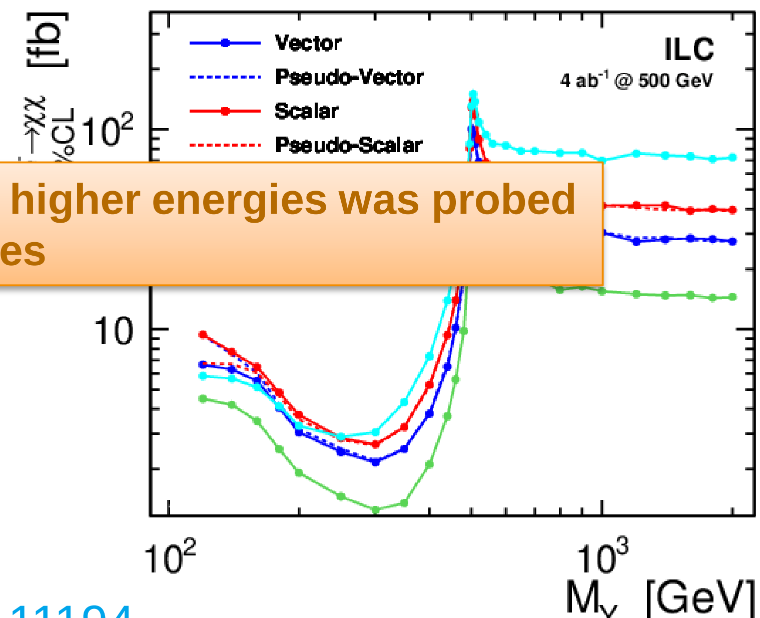
Two simplified model approaches:
- heavy mediator: model independent EFT approach
- arbitrary mediator: sensitivity depends on mediator properties. Limits given as a function of the light DM cross section expected to be least dependent on model details

Heavy mediator



arxiv:2001.03011

Arbitrary mediator



arxiv:2107.11194

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

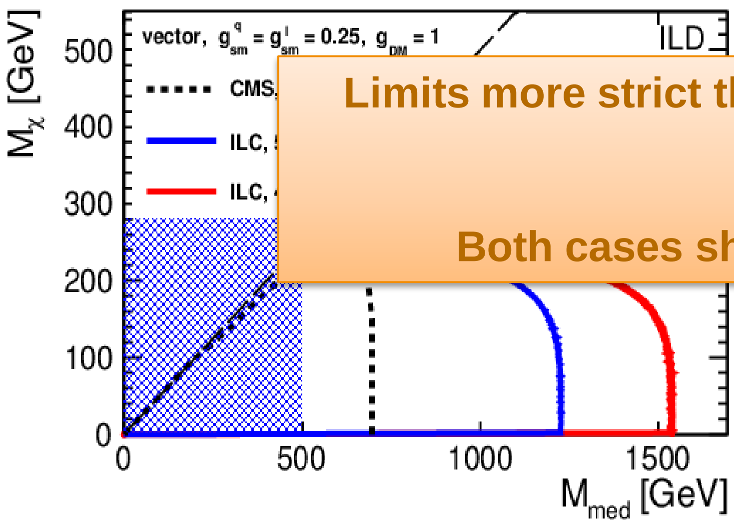
HELMHOLTZ GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

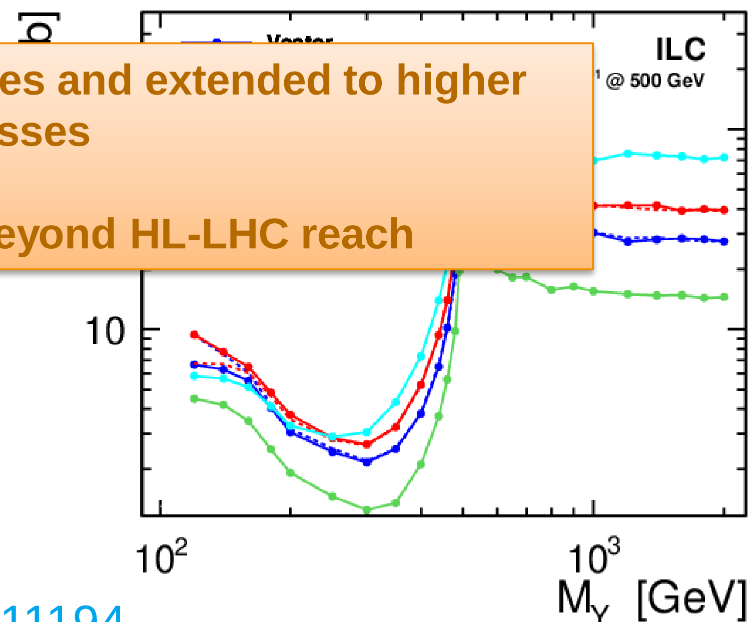
WIMP Dark Matter (ctd.)

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



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

HELMHOLTZ | GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

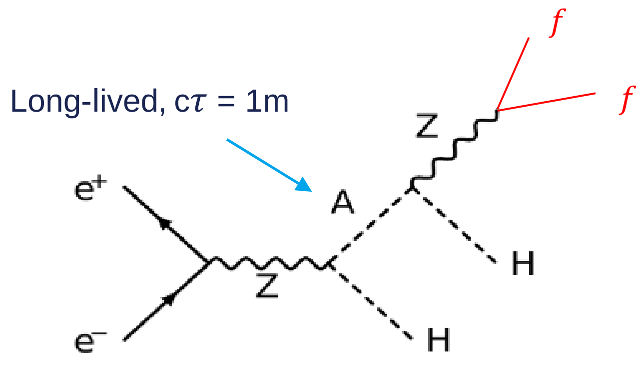
Long-lived particles

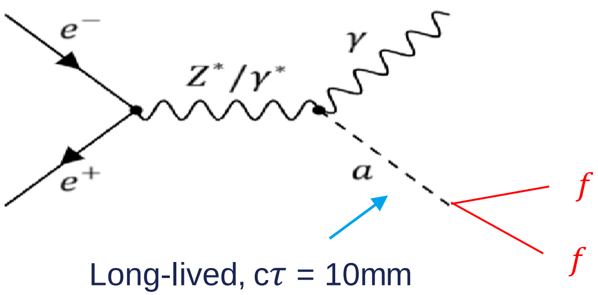
LLPs are widely considered in many BSM scenarios and searches for new particles

(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)





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

HELMHOLTZ GEMEINSCHAFT

Poster by F. A. Zarnecki:
Long-lived particle searches with the ILD experiment

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

DESY.

Long-lived particles

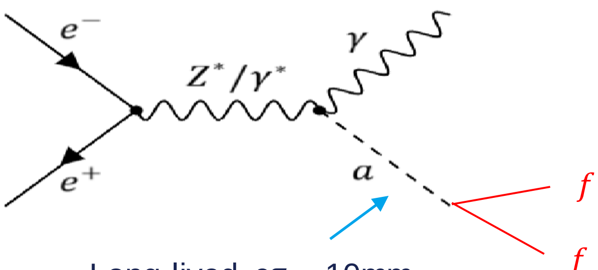
LLPs are widely considered in many BSM scenarios and searches for new particles

(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

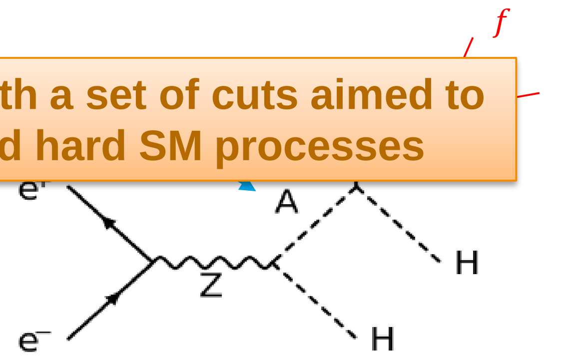
- Two o
- Focus
- No oth... assumptions about final state (as general as possible)

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



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

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



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

HELMHOLTZ GEMEINSCHAFT

Poster by F. A. Zarnecki:

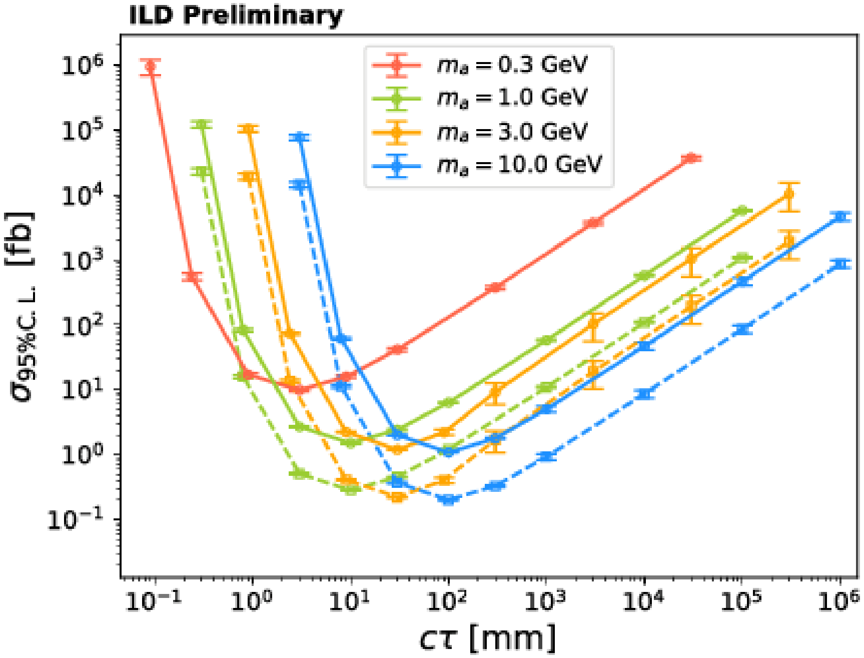
Long-lived particle searches with the ILD experiment

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

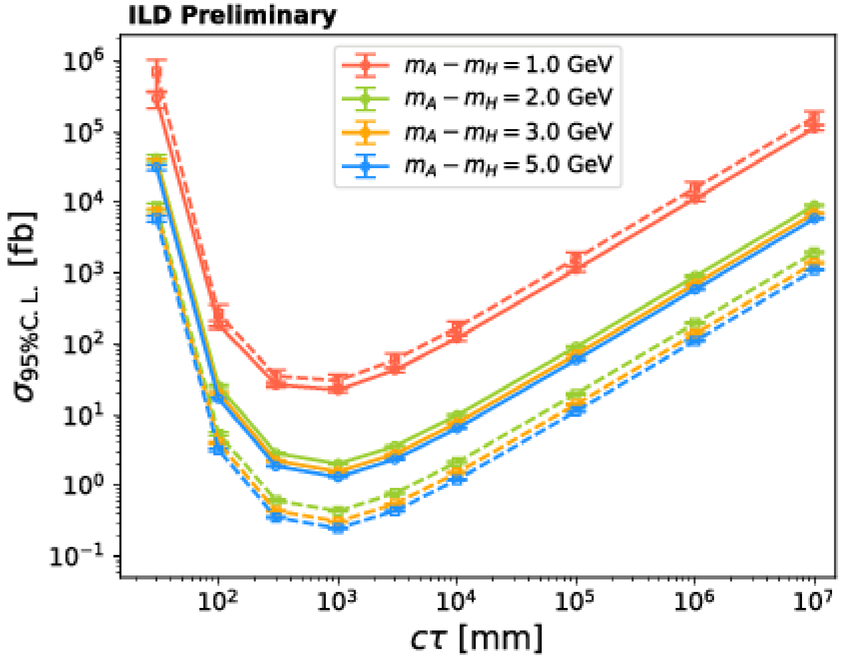
DESY.

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

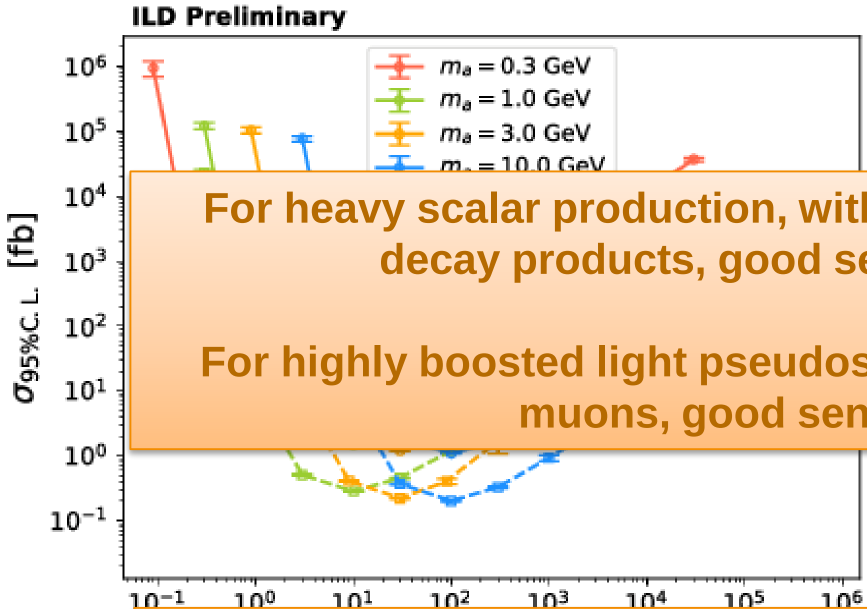
HELMHOLTZ GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

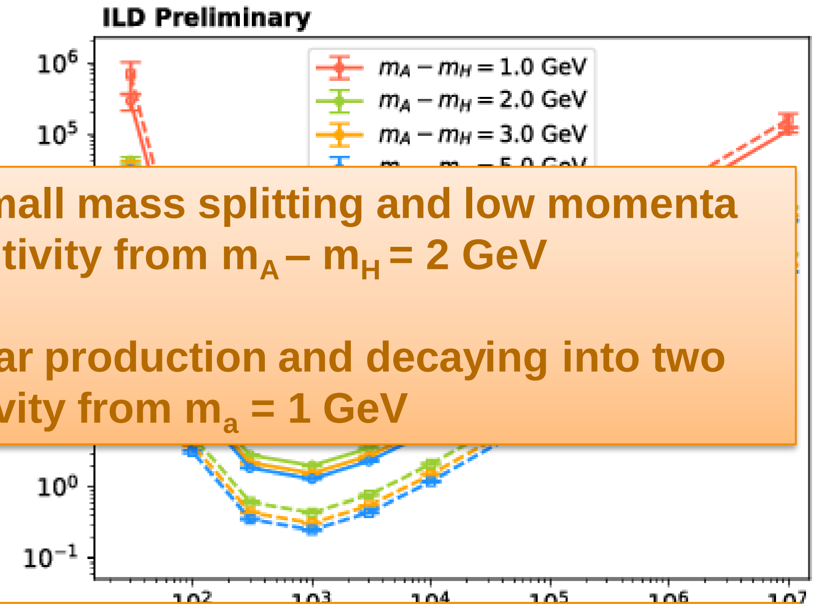
DESY.

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

HELMHOLTZ GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

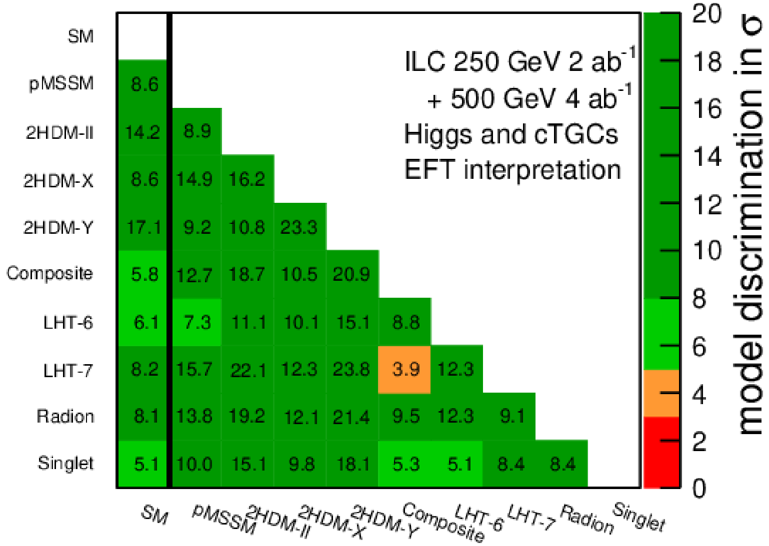
DESY.

Indirect BSM searches

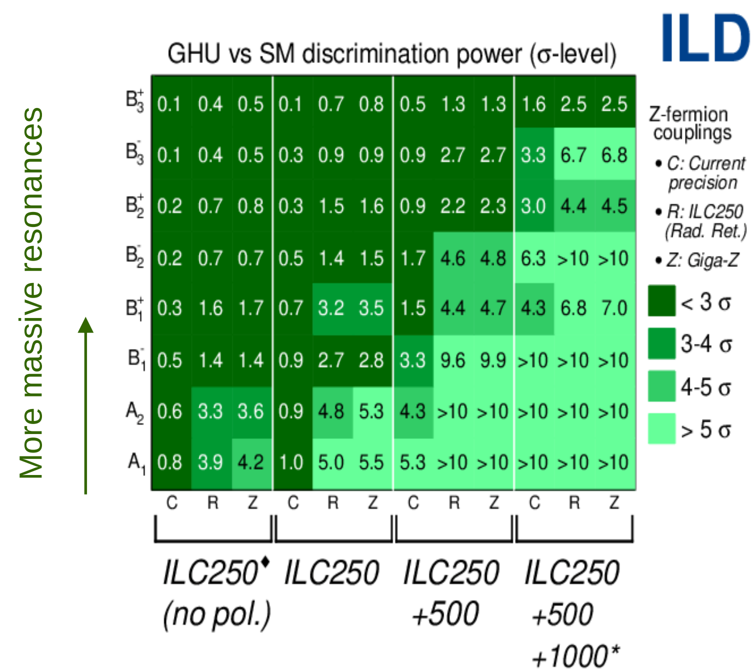
Detecting BSM by observing deviations from the behavior predicted by the SM

High experimental precision at the ILC allows this kind of searches

Unique capabilities due to electron and positron polarisation



arxiv:1708.08912



arxiv:2403.09144

HELMHOLTZ GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

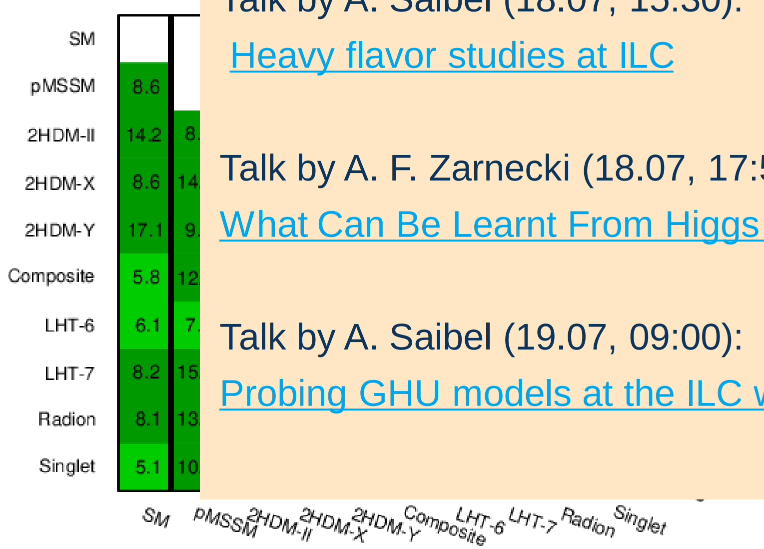
DESY.

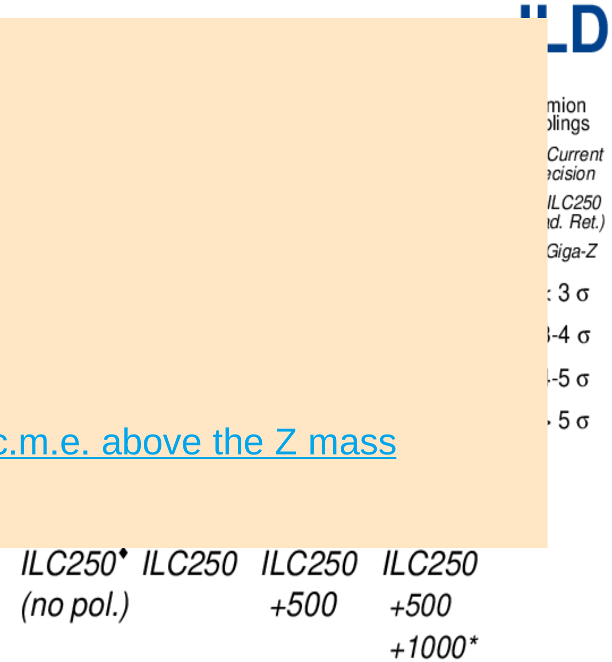
Indirect BSM searches

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

High experimental precision at the ILC allows this kind of searches

Unique capabilities due to electron and positron polarisation





Talk by A. Saibel (18.07, 15:30):

[Heavy flavor studies at ILC]

Talk by A. F. Zarnecki (18.07, 17:53):

[What Can Be Learnt From Higgs Studies at ILC]

Talk by A. Saibel (19.07, 09:00):

[Probing GHU models at the ILC with di-quark AFB at c.m.e. above the Z mass]

arxiv:1708.08912

arxiv:2403.09144

HELMHOLTZ GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

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

Complementary discovery reach at ILC and LHC is expected

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

HELMHOLTZ GEMEINSCHAFT

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

DESY.