Searches for dark matter at future high energy lepton colliders

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Deutsches Elektronen-Synchrotron DESY

13th Rencontres du Vietnam

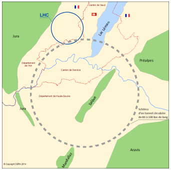
Exploring the Dark Universe

25 July 2017

Future lepton colliders

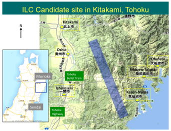
CEPC - Circular e^-e^+ Collider

- $\sqrt{s} = 240\text{-}250$ GeV
- 50-70 km ring



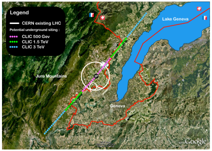
FCC-ee - Future Circular Collider

- $\sqrt{s}$: 90 - 350 GeV
- 100 km ring



ILC - International Linear Collider

- $\sqrt{s}$: 250 GeV - 1 TeV
- L = 34 km for 500 GeV



CLIC - Compact Linear Collider

- $\sqrt{s}$: 380 GeV - 1.4 - 3 TeV
- L = 50 km

Future lepton colliders

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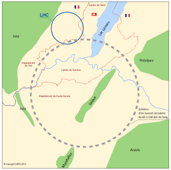

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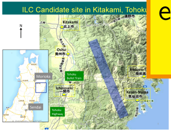

most studies exist for ILC
everything shown applies to all lepton colliders
with sufficient $\sqrt{s}$ and beam polarisation

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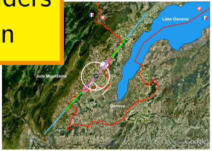

CLIC - Compact Linear Collider

- $\sqrt{s}$: 380 GeV - 1.4 - 3 TeV
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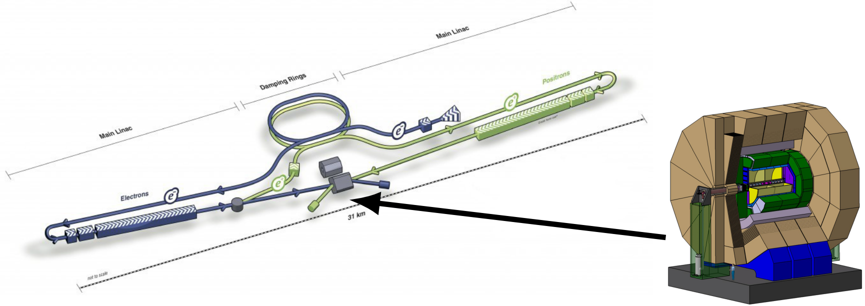
The International Linear Collider

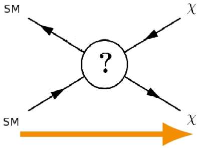
- a future electron positron collider
  - mature technology
  - waiting for political decision in Japan
- centre-of-mass energy: 250 - 500 GeV (upgrade: 1 TeV)
- $\mathcal{L} = 1.8 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}$ (upgrade: $3.6 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}$)
- polarised beams: $\text{P}(\text{e}^-) = \pm 80\%$, $\text{P}(\text{e}^+) = \pm 30\%$
- 2 detectors: SiD and International Large Detector (ILD)



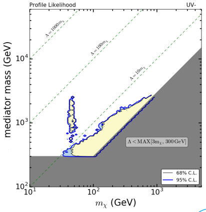
Introduction

- Weakly Interacting Massive Particles (WIMPs) are candidates for dark matter
- WIMPs can be searched for
  - directly
  - indirectly
  - **at colliders**

    $\Rightarrow$ idea: SM particles $\rightarrow$ WIMP pair production



- singlet-like fermion WIMP
  (Shigeki Matsumoto et al., arxiv:1604.02230)
- likelihood analysis of
  - Planck, PICO-2L, LUX, XENON100
  - LEP, LHC
  - plus LZ, PICO250 projections
- Can lepton colliders help to probe the surviving region?



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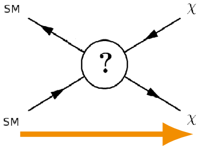

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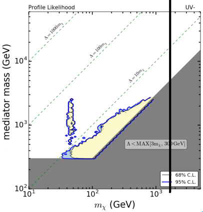
$\sqrt{s} = 3\,\text{TeV}$



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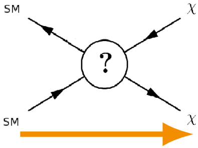

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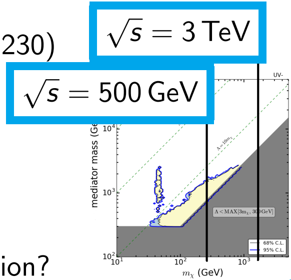

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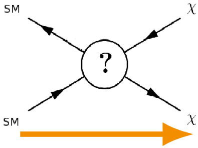

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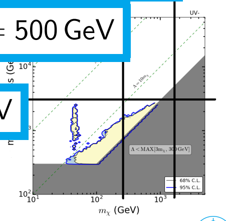
$\sqrt{s} = 3$ TeV

$\sqrt{s} = 500$ GeV

$M_{med} \approx 3$ TeV



Outline

- General search: mono-photon channel
- Limits in the framework of effective operators
- Comparison to LHC
- Assuming detection: parameter extraction
- Identifying the nature of DM: e.g. SUSY

General search: mono-photon

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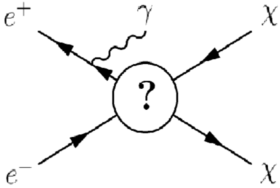
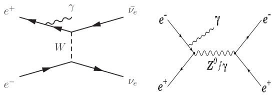
- **Signal**
  - **WIMP pair production**
    with a photon from initial state radiation
    $e^+e^- \to \chi\chi\gamma$
  - quasi model-independent
  - single photon in an "empty" detector
    $\to$ missing four-momentum
  - observables: E_γ, θ_γ



- **Main Background Processes**
  - **Neutrino pairs** $e^+e^- \to \nu\bar{\nu}\gamma$
    - irreducible
    - polarisation: enhance or suppress
  - **Bhabha scattering** $e^+e^- \to e^+e^-\gamma$
    - huge cross section
    - cross section rises for low polar angles
    - mimics signal if leptons in forward region are undetected



General search: mono-photon

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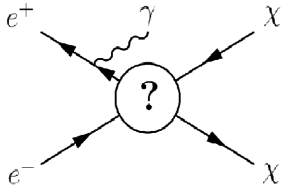

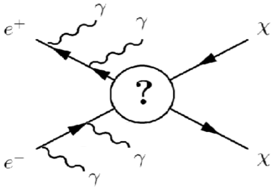

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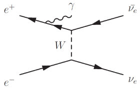
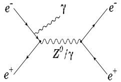
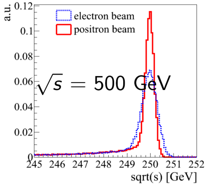
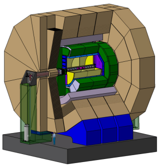




Modelling of signal and background

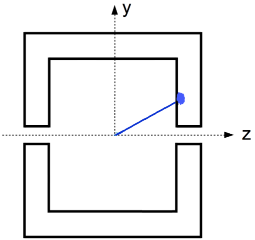


- generated using WHIZARD 2.2.8
  - $\sqrt{s} = 500$ GeV
  - polarised beams
  - beam spectrum: ILC, TDR
- background:
  - $\nu\bar{\nu} + n\gamma$
  - $e^+e^- + n\gamma$ (Bhabha scattering)
- signal: $\chi\chi\gamma$
  - reweight $\nu\bar{\nu}\gamma$ according to WIMP mass, spin, ...
- full Geant4 based ILD simulation



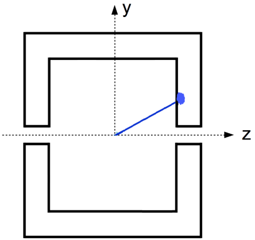
Event selection

- signal definition (mono-photon)



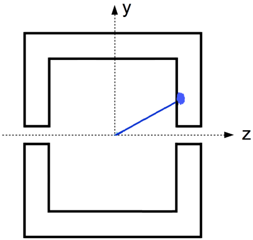
Event selection

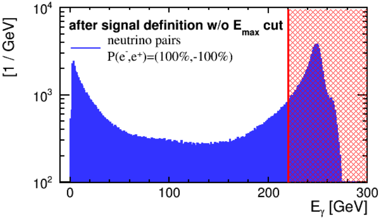
- signal definition (mono-photon)
  - **minimum polar angle**
    need tracker to distinguish photon from electron ($|\cos\theta_\gamma| < 0.996$)



Event selection

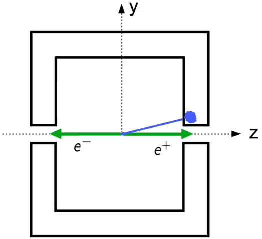
- signal definition (mono-photon)
  - minimum polar angle
  - **maximum energy**
    avoid large background at Z return ($E_\gamma < 220$ GeV)





Event selection

- signal definition (mono-photon)
  - minimum polar angle
  - maximum energy
  - **minimum transverse momentum**
    ensure Bhabha lepton hits detector ($p_{T,\gamma} >$2-5 GeV)



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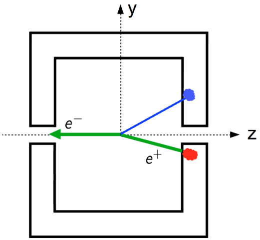

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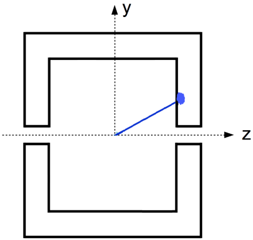
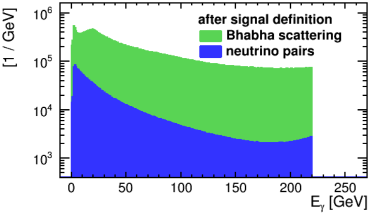
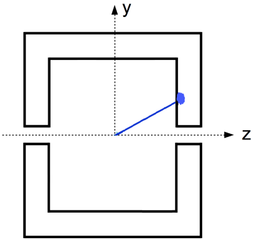
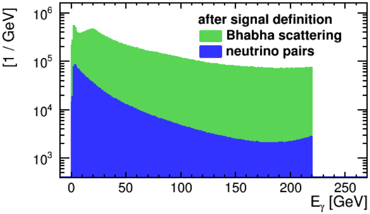




- signal definition (mono-photon)
  - minimum polar angle
  - maximum energy
  - minimum transverse momentum
- selection criteria (empty detector)
  - → suppress Bhabhas
  - → keep neutrinos





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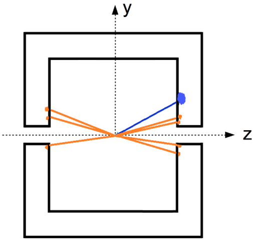

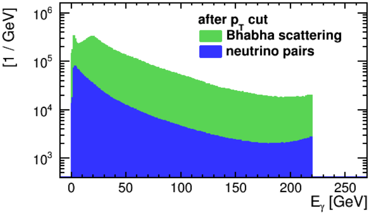

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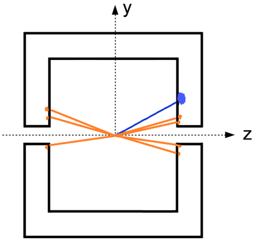

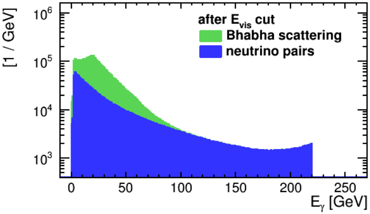

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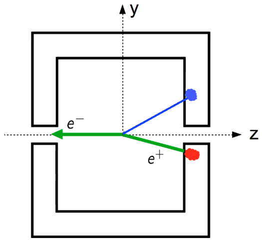
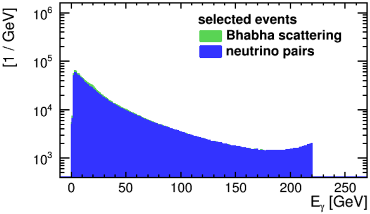
  - very forward region: no reconstructed clusters





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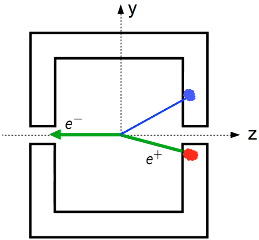
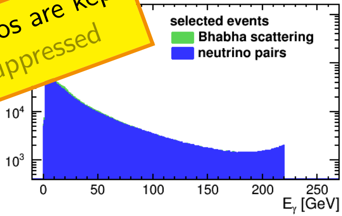
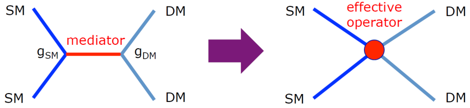


signal-like neutrinos are kept
Bhabhas are suppressed



Effective operators

Theoretical framework: effective operators



$$\left(\frac{g_f g_\chi}{q^2 - M^2}\right)(\overline{f}\gamma_\mu f)(\overline{\chi}\gamma^\mu \chi) \qquad \frac{1}{\Lambda^2}(\overline{f}\gamma_\mu f)(\overline{\chi}\gamma^\mu \chi)$$

OK for lepton colliders since $\Lambda \gg \sqrt{s}$

1. classify WIMP based on its quantum numbers

   (example: vector-like fermion WIMP and vector-like operator)

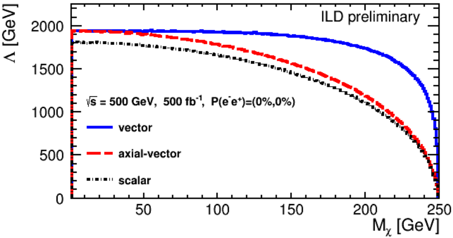
2. construct minimal effective Lagrangian
   - assumption:
     new physics interaction is mediated by a **heavy** particle
   - interaction can be integrated out
   - four-point contact interaction

   $\Rightarrow$ general approach

   $\Rightarrow$ only one parameter ("energy scale of new physics")

$\Lambda = M_{mediator} / \sqrt{g_f g_\chi}$ and $\sigma \propto 1/\Lambda^4$

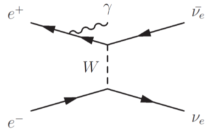
Sensitivities for effective operators



- setup and cross-sections formulas from JHEP05(2013)138
- "vector" $\Leftrightarrow (\bar{f}\gamma^\mu f)(\overline{\chi}\gamma_\mu\chi)$
  $\rightarrow \sigma_{LL} = \sigma_{RR} = 0$
- "axial-vector"$\Leftrightarrow (\bar{f}\gamma^\mu\gamma^5 f)(\overline{\chi}\gamma_\mu\gamma_5\chi)$
  $\rightarrow \sigma_{LR} = \sigma_{RL} = 0$
- "scalar" (s-channel) $\Leftrightarrow (\bar{f}f)(\overline{\chi}\chi)$
  $\rightarrow \sigma_{LR} = \sigma_{RL} = 0$

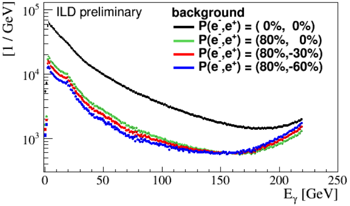
Role of polarisation

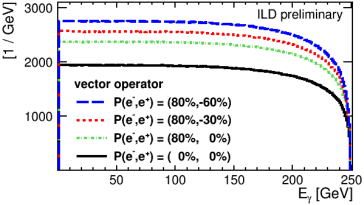
- background
  - neutrinos can be suppressed for right-handed e^- and left-handed e^+



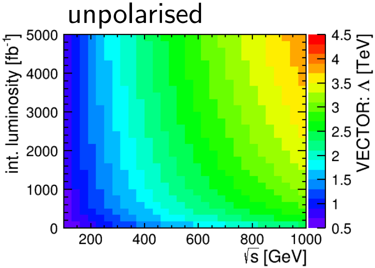
$N_{500 fb^{-1}}$	unpolarised	P_{e-}= +80% P_{e+}= −30%
$\nu\nu\gamma$	2479.19	483.51
$e^+e^-\gamma$	84.74	83.06

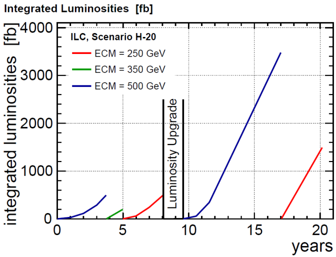
- WIMPs
  - production can be enhanced





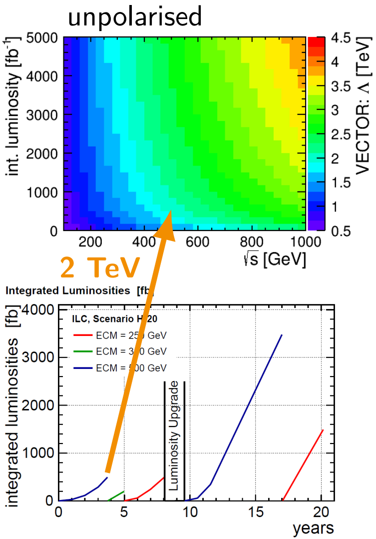
Sensitivity in different operation scenarios





- extrapolation of sensitivity from full simulation at 500 GeV
  - reachable Λ at different $\sqrt{s}$ and integrated luminosities
  - for small M_χ ($<$ 100 GeV)
- allows to give estimates for sensitivity
  - for different time scales
  - for different running scenarios
- already at 240/250 GeV new phase space can be explored
  - centre-of mass energy (slightly) higher than at LEP
  - more luminosity
  - polarisation

Sensitivity in different operation scenarios



- extrapolation of sensitivity from full simulation at 500 GeV
  - reachable Λ at different $\sqrt{s}$ and integrated luminosities
  - for small M_χ ($<$ 100 GeV)
- allows to give estimates for sensitivity
  - for different time scales
  - for different running scenarios
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  - centre-of mass energy (slightly) higher than at LEP
  - more luminosity
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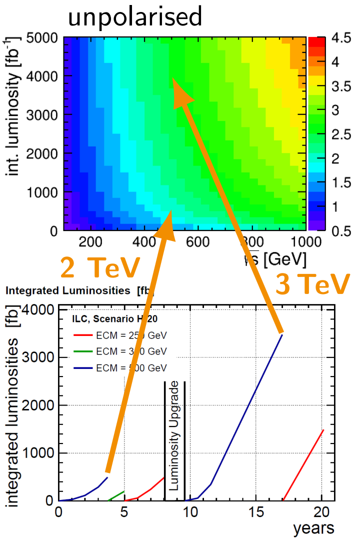

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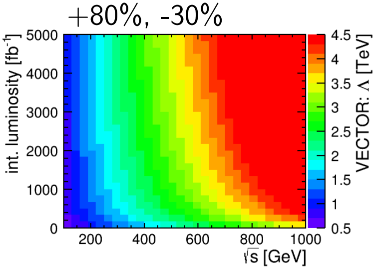

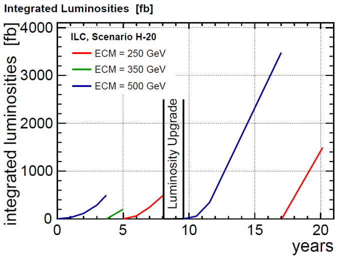

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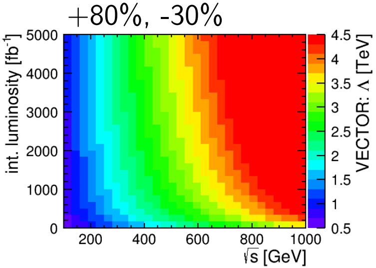

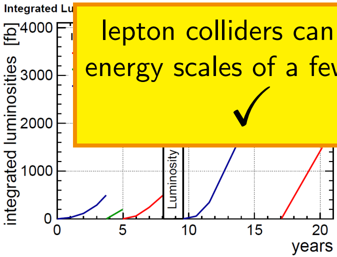

lepton colliders can test energy scales of a few TeV ✓

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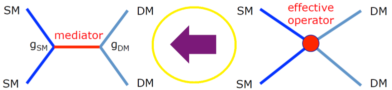
lepton colliders vs. LHC

Lepton colliders vs. LHC

- mono-X searches
  $\Rightarrow$ mono-photon, mono-jet (gluon), ...
- complementary
  $\Rightarrow$ LHC tests couplings to quarks/gluons
  $\Rightarrow$ e^-e^+ colliders test couplings to leptons
- assumptions need to be made to compare results

Simplified models and effective operators

- at lepton colliders: OK to use effective operators
- at LHC: simplified models



$$\left(\frac{g_f g_\chi}{q^2 - M^2}\right)(\overline{f}\gamma_\mu f)(\overline{\chi}\gamma^\mu \chi) \qquad \frac{1}{\Lambda^2}(\overline{f}\gamma_\mu f)(\overline{\chi}\gamma^\mu \chi)$$

- 3 free parameters
  - mediator mass
  - coupling to SM
  - coupling to DM
- instead of $\Lambda = \frac{M_{med}}{\sqrt{g_{SM} \cdot g_{DM}}}$

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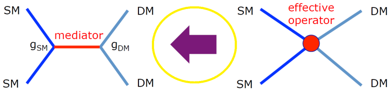
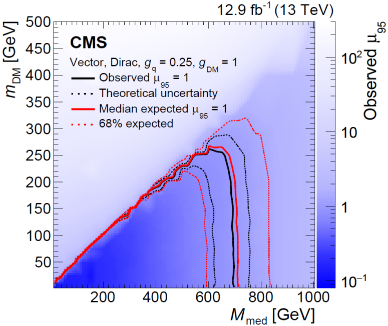


$\left(\frac{g_f g_\chi}{q^2 - M^2}\right)(\overline{f}\gamma_\mu f)(\overline{\chi}\gamma^\mu\chi)$ $\quad\quad$ $\frac{1}{\Lambda^2}(\overline{f}\gamma_\mu f)(\overline{\chi}\gamma^\mu\chi)$

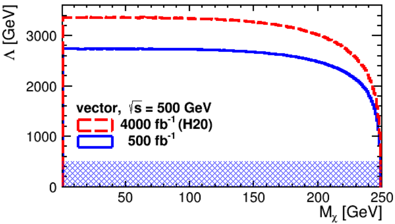
- 3 free parameters $\Rightarrow$ present limits for M_{med} & fix couplings
  - mediator mass
  - coupling to SM $\Rightarrow$ **0.25** $\rightarrow$ avoid sizeable di-jet production
  - coupling to DM $\Rightarrow$ **1**
- instead of $\Lambda = \frac{M_{med}}{\sqrt{g_{SM} \cdot g_{DM}}}$

Comparing LHC and lepton collider limits

- recent CMS results for mono-photon WIMP search: arxiv:1706.03794
- vector operator



- ILC limits
- assumption: $g^q_{sm} = g^l_{sm}$
- translate into simplified models: $M_{med} = \sqrt{g_{SM} \cdot g_{DM}} \cdot \Lambda = 0.5 \cdot \Lambda$



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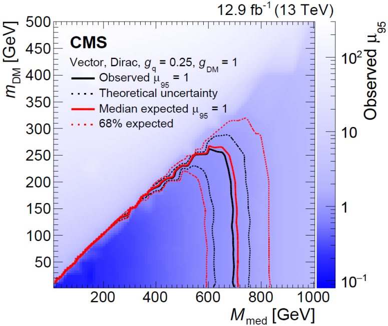

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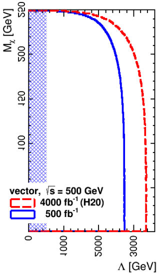

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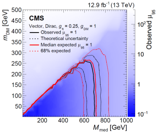

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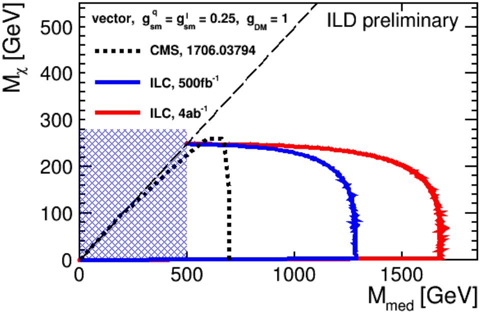
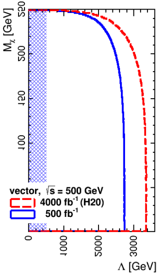




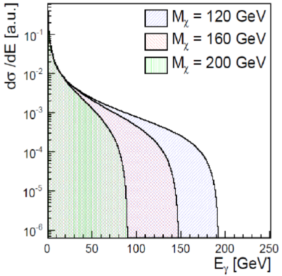
In case of a signal...

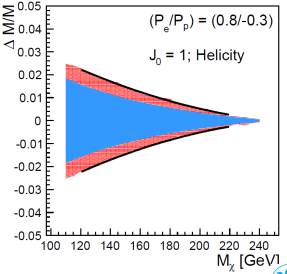
In case of a signal...

- so far: exclusion limits
- if a lepton collider discovers new particle...
  $\Rightarrow$ measure its mass
  $\Rightarrow$ measure the chirality of its production
- is it dark matter?
  $\Rightarrow$ can it explain the cosmological relic density?

WIMP mass measurement

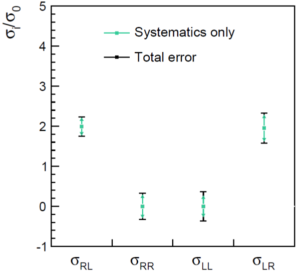
- at a lepton collider initial state is known
- shape of photon energy spectrum depends on WIMP mass
  - clear endpoint: the higher M_χ the lower $E_{\gamma,max}$
  - endpoint buried in the fluctuation of the background
  - template photon energy spectra with different M_χ are compared to the data...
  - ... and χ^2-minimised
- with $500\,\text{fb}^{-1}$, $(P_{e^-},P_{e^+})=(+80\%,-30\%)$: precision of a few GeV to sub-GeV
  - dominated by systematic uncertainties
  - conservative: no information on beam spectrum assumed





Measurement of polarised cross-sections

- experiment: polarisation <100%→ $(P_{e^-}, P_{e^+}) = (80\%, 30\%)$
  → measurement is combination of all polarised cross-sections:
  $\sigma_{measured} = A \cdot \sigma_{LL} + B \cdot \sigma_{LR} + C \cdot \sigma_{RL} + D \cdot \sigma_{RR}$
  e.g.: $$\sigma_{-+} = (1+|P_{e-}|)(1-|P_{e+}|)\sigma_{LL} + (1+|P_{e-}|)(1+|P_{e+}|)\sigma_{LR} + (1-|P_{e-}|)(1-|P_{e+}|)\sigma_{RL} + (1-|P_{e-}|)(1+|P_{e+}|)\sigma_{RR}$$
- fully polarised cross-sections can be extracted
- e.g. vector-like operator: $\sigma_{LL} = \sigma_{RR} = 0$



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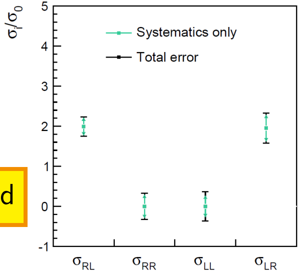
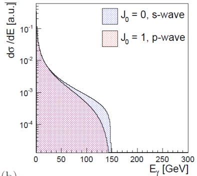


chirality of interaction can be tested

Partial wave determination

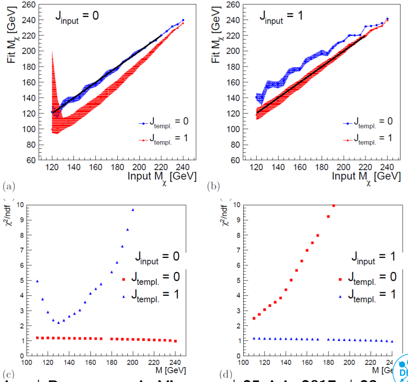
- dominant partial wave (s or p)
- leads to different shape of photon spectrum



(b)

- the wrong assumption leads to wrong M_χ

- can be distinguished with χ^2-minimisation



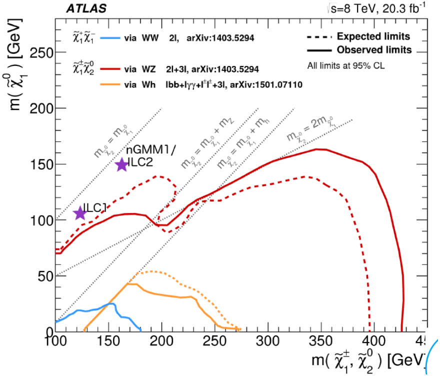
Identifying the nature of DM

Identifying the nature of dark matter

- Does WIMP candidate really explain dark matter ?
  $\Rightarrow$ predict relic density from collider measurements
  $\Rightarrow$ compare to cosmological observation (Planck)
- need UV-complete theory
- e.g. supersymmetry: lightest supersymmetric particle (LSP) candidate for dark matter
  - with a (small) number of new particles
  - fitting supersymmetry parameters to observables

Scenario 1: natural supersymmetry

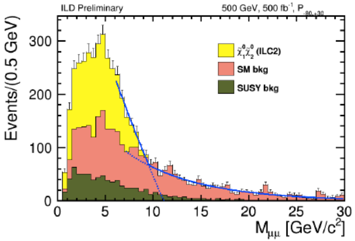
- naturalness and small fine tuning requires higgsino mass parameter μ at the EW scale: $m_Z^2 = 2\frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - 2\mu^2$
- μ small $\rightarrow$ light higgsinos

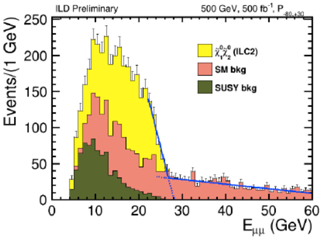


- several benchmarks studied
  - $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$ observed
  - cross-section for production at e^-e^+: several hundred fb

1) Natural SUSY: mass extraction

- $e^+e^- \to \widetilde{\chi}_1^0\widetilde{\chi}_2^0$; $\widetilde{\chi}_2^0 \to \mu^+\mu^-\widetilde{\chi}_1^0$
- kinematics
  - maximum invariant mass gives the mass splitting
  - maximum of di-muon energy gives masses (since initial state is known)





- mass precisions 0.2% with $4\,\mathrm{ab}^{-1}$

1) Natural SUSY: relic density fit

- fitting dark matter relic density
  - with observables as input
  - using micrOMEGAs (arxiv1305.0237)
- $\Omega_{fit}/\Omega_{Planck} = 0.054 \pm 0.001$
  $\Rightarrow$ natural SUSY: no good DM candidate
  (can be clearly seen - and very precisely!)
  $\Rightarrow$ strong hint that non-SUSY DM
  or non-thermal production exists

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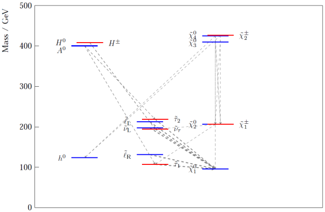
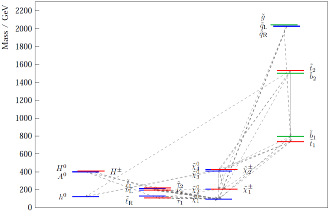
$\Rightarrow$ found a WIMP -
but it's not the dark matter
we're looking for

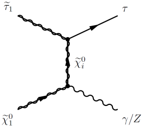
Scenario 2: SUSY with LSP as DM

- study model with lightest supersymmetric particle (LSP) that matches observed density
  $\Rightarrow$ Can the relic density be determined
  if only a few particles are accessible?
  $\Rightarrow$ Can Planck's precision be reached?



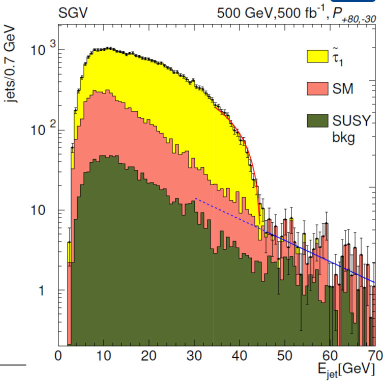


- $m_{\widetilde{\chi}_1^0} = 96\,\text{GeV}$ (bino), $m_{\widetilde{\tau}_1} = 107\,\text{GeV}$ (RH)
- $\Rightarrow$ stau coannihilation



2) DM SUSY: measurements

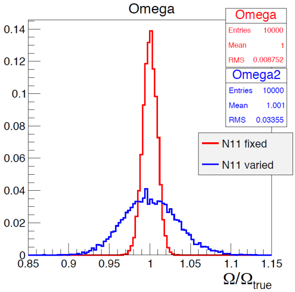
- analysis at $\sqrt{s} = 500\,\text{GeV}$ (arxiv:1508.04383)
- $\widetilde{\tau}_1 \to \tau \widetilde{\chi}^0_1$ endpoint
  $\to \Delta\ m_{\widetilde{\tau}_1} = 0.15\%$
- discovery of all sleptons, sneutrinos, $\widetilde{\chi}^0_1$, $\widetilde{\chi}^0_2$, $\widetilde{\chi}^{\pm}_1$
- permille mass precisions



$m_{\widetilde{\chi}^0_1}$	0.15%	$m_{\widetilde{\chi}^0_2}$	0.5%
$m_{\widetilde{\tau}_1}$	0.16%	$m_{\widetilde{\tau}_2}$	2.5%
$m_{\widetilde{e}_R}$	0.17%	$m_{\widetilde{\mu}_R}$	0.40%

2) DM SUSY: relic density precision

- several assumptions were tested (arXiv:1602.08439 [hep-ph])
  - observation of different particles tested
  - precision on observables varied
  - varied vs. fixed binoness N11 (neutralino mixing known or not)
- conclusions
  - crucial: $m_{\tilde{\chi}_1^0}$ (LSP) and $m_{\tilde{\tau}_1}$
  - 1 TeV particles help (elektroweakino & Higgs sector)
  - higher masses (squarks) irrelevant
  - need 1% precision on LSP mixings and $\tilde{\tau}$ mixing



- with this → precision from fit: 2%
  → same precision as Planck
- Planck: $\Omega_{CDM} h^2 = 0.1197 \pm 0.0022 \Rightarrow \Delta = 2\%$

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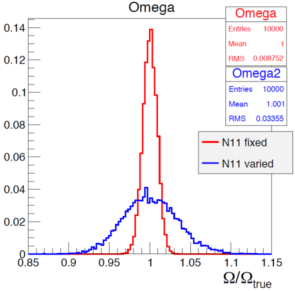

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Identified WIMP as dark matter constituent

Conclusions

- high-energy lepton colliders can explore new phase space
  - testing of couplings to leptons $\rightarrow$ complementary to LHC and direct detection searches
- polarised beams
  - suppression of background and enhancement of WIMP production
  - allow to test the chirality of the interaction
- in the case of a discovery
  - high precision on: mass, cross-section, chirality of the interaction
  - model fits allow determination of relic density with percent precision
  - lepton colliders can contribute to the verification or falsification of WIMP as thermal dark matter