Dark Matter at the ILC: Mono-Photon and SUSY Searches

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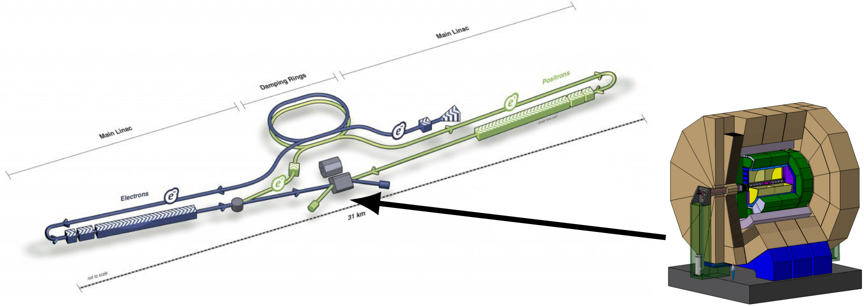
The International Linear Collider

- 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)



Outline

1. General search: mono-photon channel
   - Limits in the framework of effective operators
   - Comparison to LHC
2. Supersymmetry
   - fitting SUSY parameters to observables
   - does WIMP candidate really explain dark matter ?

General search: mono-photon

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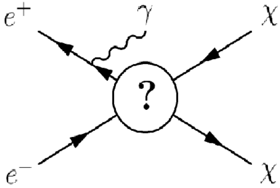
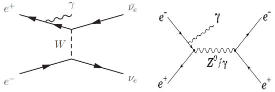
- **Signal**
  - **WIMP pair production with a photon from initial state radiation** $e^+e^- \to \chi\chi\gamma$
  - quasi model-independent
  - single photon in an "empty" detector $\to$ missing four-momentum
  - observables: E_γ, θ_γ



- **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



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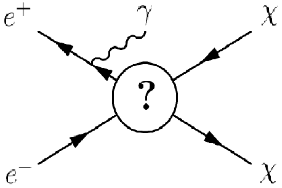

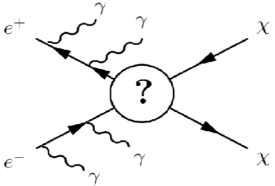

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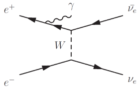
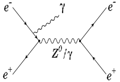
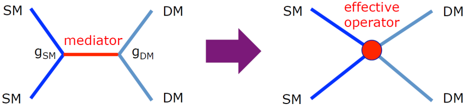




Effective operators

Theoretical Framework: Effective Operators



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

$\boxed{\text{OK at ILC since } \Lambda \gg \sqrt{s}}$

construct minimal effective Lagrangian

- assumption:
  new physics interaction is mediated by a **heavy** particle
- interaction can be integrated out
- four-point contact interaction

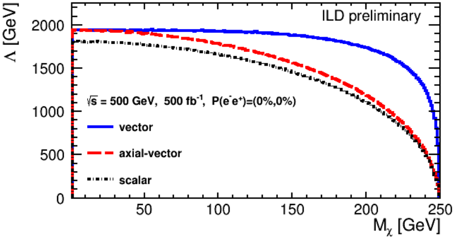
$\Rightarrow$ general approach

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

$$\boxed{\Lambda = M_{mediator} / \sqrt{g_f g_\chi}}$$

Sensitivities for effective operators

- 3σ exclusion limits
- Λ as a function of M_χ
- M_χ up to $\sqrt{s}/2$ can be tested
- $\sigma \propto 1/\Lambda^4$

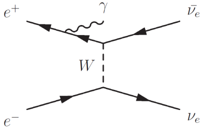


setup and cross-sections formulas from Chae and Perelstein JHEP05(2013)138

vector	$(\bar{f}\gamma^\mu f)(\overline{\chi}\gamma_\mu\chi)$	$\sigma_{LR} = \sigma_{RL}$	$\sigma_{LL} = \sigma_{RR} = 0$
axial-vector	$(\bar{f}\gamma^\mu\gamma^5 f)(\overline{\chi}\gamma_\mu\gamma_5\chi)$	$\sigma_{LL} = \sigma_{RR}$	$\sigma_{LR} = \sigma_{RL} = 0$
scalar (s-channel)	$(\bar{f}f)(\overline{\chi}\chi)$	$\sigma_{LL} = \sigma_{RR}$	$\sigma_{LR} = \sigma_{RL} = 0$

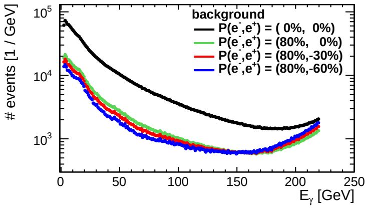
Role of polarisation

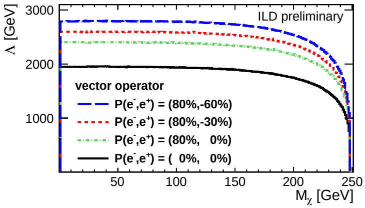
- background
  - neutrinos can be suppressed for right-handed e^- and left-handed e^+



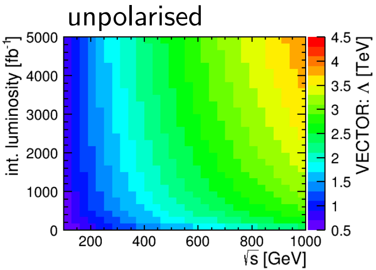
$N_{500 fb^{-1}}$	**unpolarised**	$P_{e-} = +80\%$ $P_{e+} = -30\%$
$\nu\nu\gamma$	3761	820
$e^+e^-\gamma$	187	187

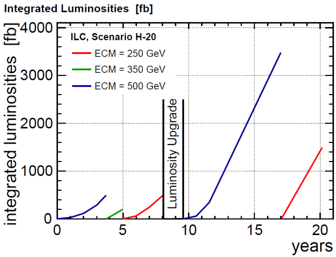
- WIMPs
  - production can be enhanced
  - chirality of interaction can be tested





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 250 GeV new phase space can be explored
  - centre-of mass energy (slightly) higher than at LEP
  - more luminosity
  - polarisation

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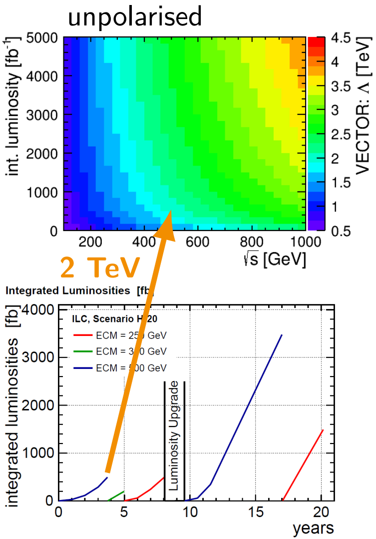

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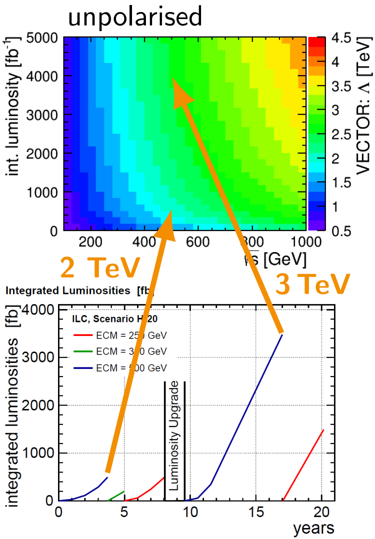

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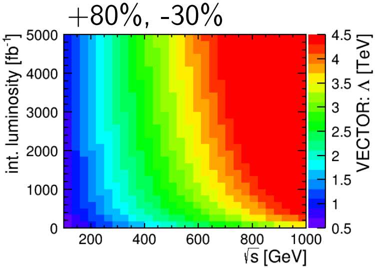

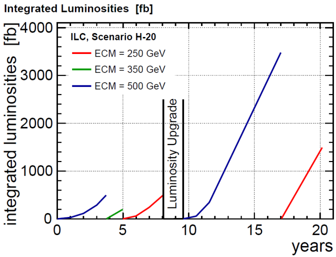

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ILC vs. LHC

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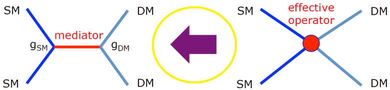
- mono-X searches
  ⇒ mono-photon, mono-jet (gluon), ...
- complementary
  ⇒ LHC tests couplings to quarks/gluons
  ⇒ ILC tests couplings to leptons
- assumptions need to be made to compare results

Simplified models and effective operators

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



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- 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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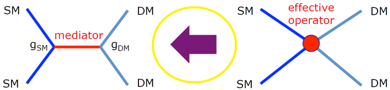

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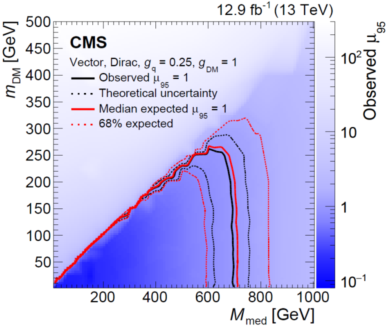
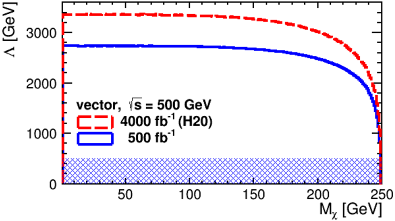
- 3 free parameters $\Rightarrow$ present limits for M_{med} & fix couplings
  - mediator mass
  - coupling to SM $\Rightarrow$ **0.25** $\rightarrow$ avoid sizeable di-jet production
  - coupling to DM $\Rightarrow$ **1**
- instead of $\Lambda = \frac{M_{med}}{\sqrt{g_{SM} \cdot g_{DM}}}$

Comparing LHC and ILC 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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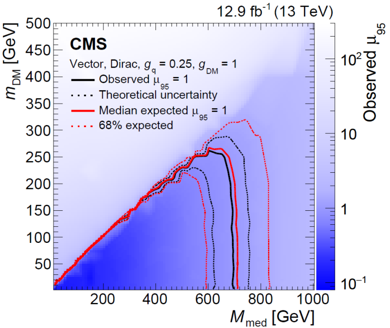

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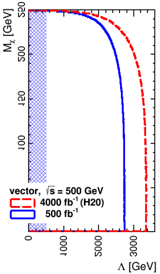

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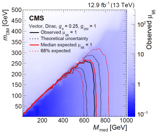

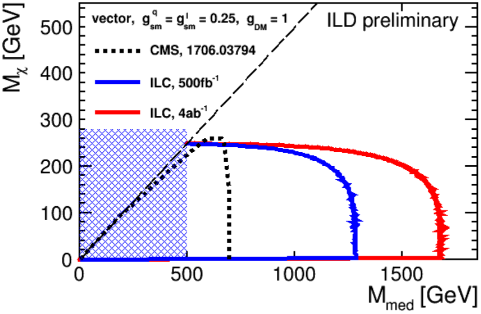

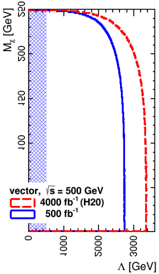

In case of a signal...

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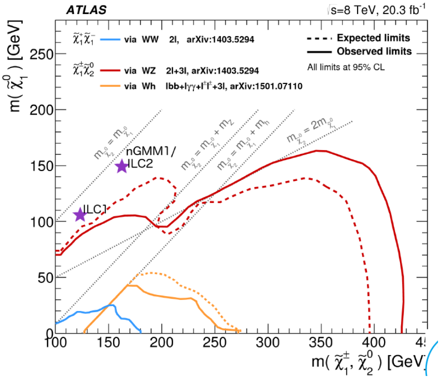
- so far: exclusion limits
- if ILC discovers new particle...
  $\Rightarrow$ measure parameters: mass, chirality of its production
- Does WIMP candidate really explain dark matter ?
  $\Rightarrow$ predict relic density from collider measurements
  $\Rightarrow$ compare to cosmological observation (Planck)
- 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

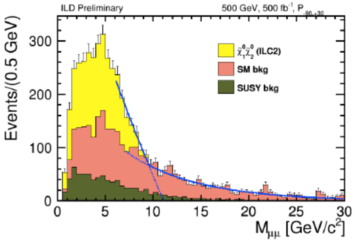
- naturalness and small fine tuning requires higgsino mass parameter μ at the EW scale: $m_Z^2 = 2\frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - 2\mu^2$
- μ small $\rightarrow$ light higgsinos

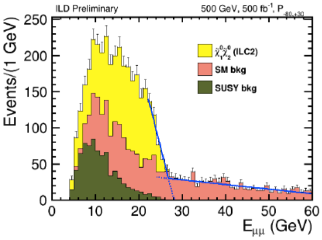


- several benchmarks studied
  - $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$ observed
  - cross-section for production at e^-e^+: several hundred fb

1) Natural SUSY: mass extraction

- $e^+e^- \to \widetilde{\chi}_1^0\widetilde{\chi}_2^0; \qquad \widetilde{\chi}_2^0 \to \mu^+\mu^-\widetilde{\chi}_1^0$
- 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
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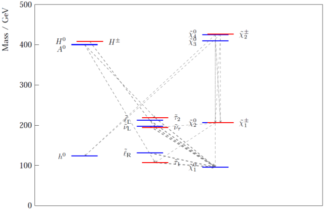
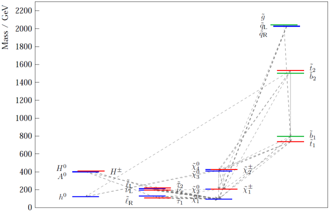
$\Rightarrow$ found a WIMP -
but it's not the dark matter
we're looking for

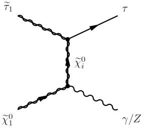
Scenario 2: SUSY with LSP as DM

- 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?





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



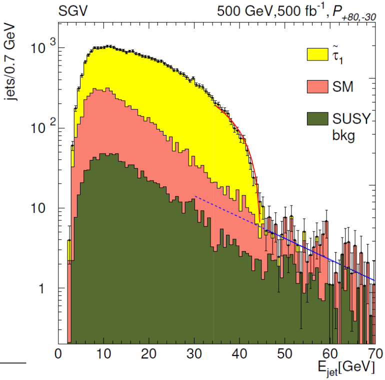
2) DM SUSY: measurements

- analysis at $\sqrt{s} = 500\,\text{GeV}$ (arxiv:1508.04383)

- $\widetilde{\tau}_1 \to \tau \widetilde{\chi}_1^0$ endpoint
  $\to \Delta\ \text{m}_{\widetilde{\tau}_1} = 0.15\%$

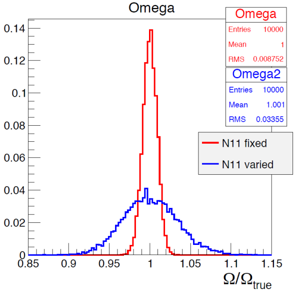
- discovery of all sleptons, sneutrinos, $\widetilde{\chi}_1^0$, $\widetilde{\chi}_2^0$, $\widetilde{\chi}_1^\pm$
- permille mass precisions

$m_{\widetilde{\chi}_1^0}$	0.15%	$m_{\widetilde{\chi}_2^0}$	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 bininess N11 (neutralino mixing known or not)
- conclusions
  - crucial: $m_{\tilde{\chi}^0_1}$ (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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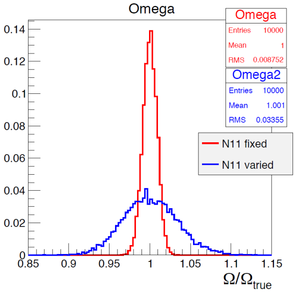

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Identified WIMP as dark matter constituent

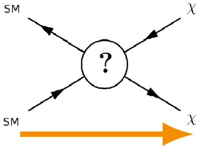
Conclusions

- ILC 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
  - the ILC can contribute to the verification or falsification of WIMP as thermal dark matter

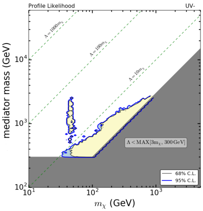
Mono-Photon Dark Matter Search: Overview

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

  ⇒ idea: SM particles → WIMP pair production

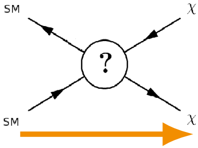


- singlet-like fermion WIMP
  (Shigeki Matsumoto et al., arxiv:1604.02230)
- likelihood analysis of
  - Planck, PICO-2L, LUX, XENON100
  - LEP, LHC
  - plus LZ, PICO250 projections
- Can lepton colliders help to probe the surviving region?



Mono-Photon Dark Matter Search: Overview

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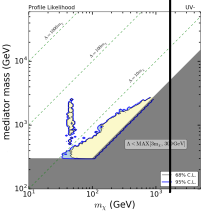
$\boxed{\sqrt{s} = 3\,\text{TeV}}$



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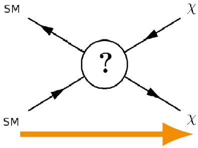

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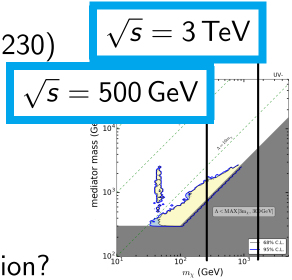

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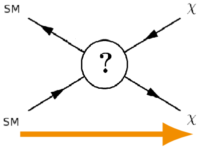

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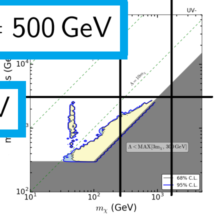
$\sqrt{s} = 3$ TeV

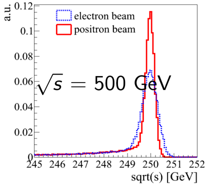
$\sqrt{s} = 500$ GeV

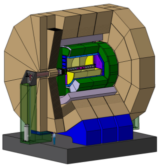
$M_{med} \approx 3$ TeV



Modelling of signal and background

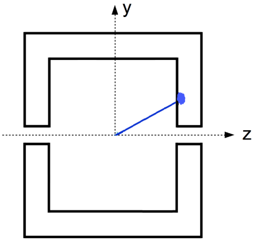
- generated using WHIZARD 2.2.8
  - $\sqrt{s} = 500\,\text{GeV}$
  - polarised beams
  - beam spectrum: ILC, TDR
- background:
  - $\nu\bar{\nu}$ + nγ
  - e^+e^- + nγ (Bhabha scattering)
- signal: $\chi\chi\gamma$
  - reweight $\nu\bar{\nu}\gamma$ according to WIMP mass, spin, ...
- full Geant4 based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





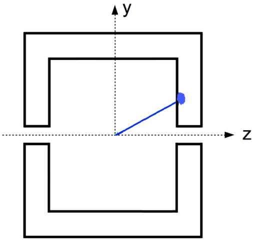
Event selection: single photon in an empty detector

- signal definition (mono-photon)



Event selection: single photon in an empty detector

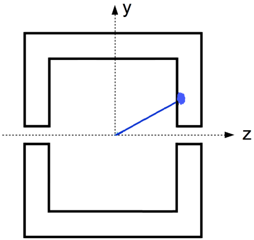
- signal definition (mono-photon)
  - **minimum polar angle: $\theta_\gamma > 7^\circ$**
    need tracker to distinguish photon from electron

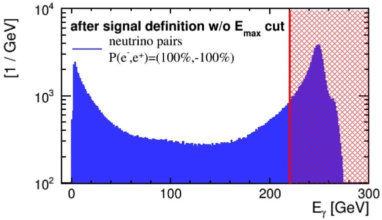


Event selection: single photon in an empty detector

- signal definition (mono-photon)
  - minimum polar angle: $\theta_\gamma > 7°$
  - **minimum energy: 2 GeV**
  - **maximum energy: 220 GeV**

    avoid large background at Z return





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- signal definition (mono-photon)
  - minimum polar angle: $\theta_\gamma > 7^\circ$
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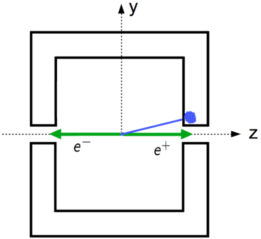
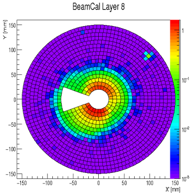
  - **minimum transverse momentum**
    - ensure Bhabha lepton hits detector
    - follows inner rim of BCal ($\Leftrightarrow$ ϕ-dependent)
    - $p_{T,\gamma} > 5.71$ GeV for $|\phi| \leq 35$
    - $p_{T,\gamma} > 1.97$ GeV for $|\phi| > 35$
    - in BCal coordinates (7° tilted)





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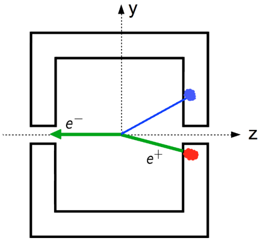

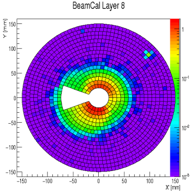

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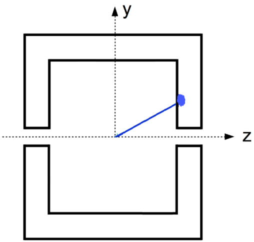

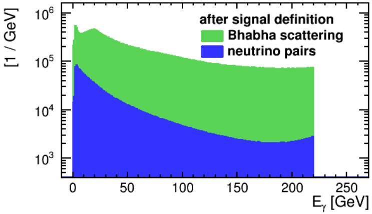

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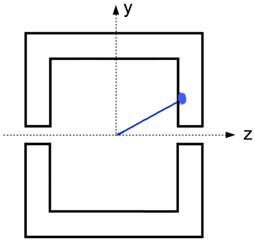
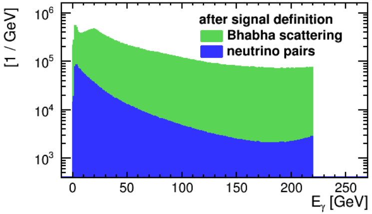
  - $\rightarrow$ keep neutrinos





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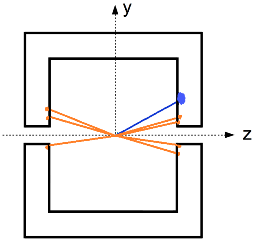
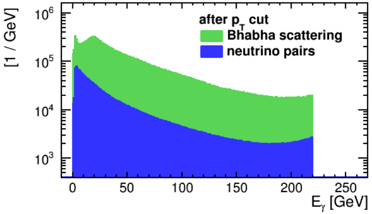
  - **veto events with track with $p_T > 3\,\text{GeV}$**





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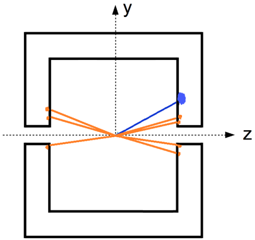
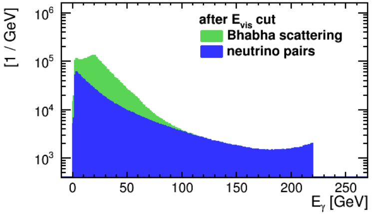
  - minimum transverse momentum
- selection criteria (empty detector)

  $\rightarrow$ suppress Bhabhas

  $\rightarrow$ keep neutrinos
  - veto events with track with $p_T > 3$ GeV
  - **max. additional visible energy**
    - add up all PFO energies
    - only consider particles if E $>$ 5 GeV
    - allow a max. energy sum of 10 GeV
    - or 30 GeV, if the extra energy is from reconstructed neutrons or pions





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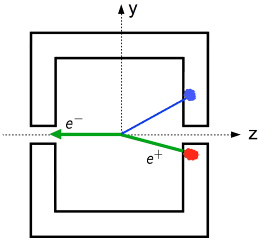
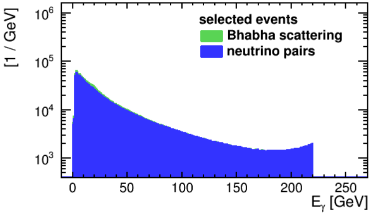
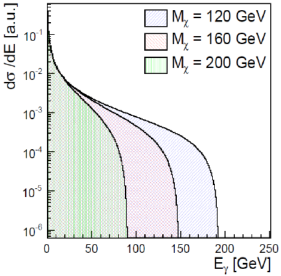
  - max. additional visible energy
  - **no reconstructed clusters in forward calorimeter BeamCal**

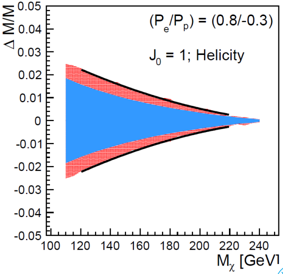




WIMP mass measurement

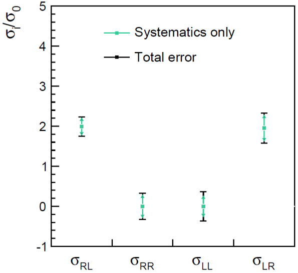
- at a lepton collider initial state is known
- shape of photon energy spectrum depends on WIMP mass
  - clear endpoint: the higher M_χ the lower $E_{\gamma,max}$
  - endpoint buried in the fluctuation of the background
  - template photon energy spectra with different M_χ are compared to the data...
  - ... and χ^2-minimised
- with 500 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%$\rightarrow$ (P_{e^-},P_{e^+})=(80%, 30%)
  $\rightarrow$ 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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  $\sigma_{measured} = A \cdot \sigma_{LL} + B \cdot \sigma_{LR} + C \cdot \sigma_{RL} + D \cdot \sigma_{RR}$
  e.g.: $$\begin{aligned}\sigma_{-+} &= (1+|P_{e-}|)(1-|P_{e^+}|)\sigma_{LL}\\ &+ (1+|P_{e-}|)(1+|P_{e^+}|)\sigma_{LR}\\ &+ (1-|P_{e-}|)(1-|P_{e^+}|)\sigma_{RL}\\ &+ (1-|P_{e-}|)(1+|P_{e^+}|)\sigma_{RR}\end{aligned}$$
- fully polarised cross-sections can be extracted
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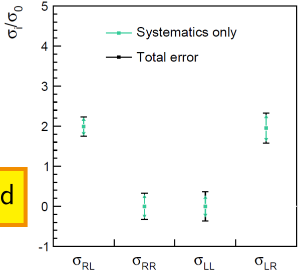
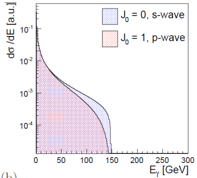
chirality of interaction can be tested



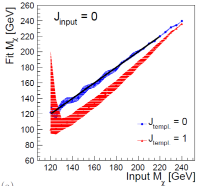
Partial wave determination

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

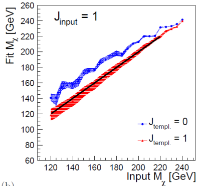


(b)

- the wrong assumption leads to wrong M_χ

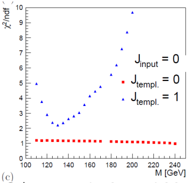


(a)

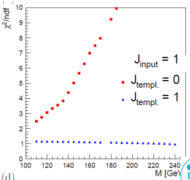


(b)

- can be distinguished with χ^2-minimisation



(c)



(d)