WIMP Searches at the International Linear Collider

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Particles, Strings, and the Early Universe
The Structure of Matter and Space-Time

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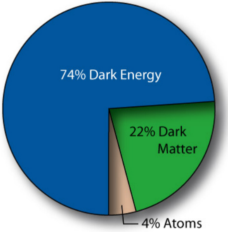
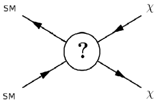
DESY

How well can the ILC explore the WIMP paradigm ?



- 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



Theoretical Framework: Effective Operators

1. classify WIMP based on its quantum numbers (spin and weak isospin)
2. construct minimal effective Lagrangian
   $\Rightarrow$ general approach

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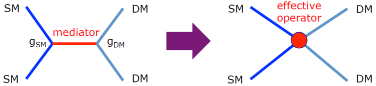
examples:

- vector-like fermion WIMP
  e.g.: vector-like operator



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

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

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

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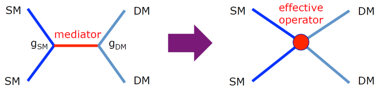

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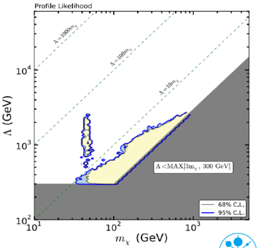
- singlet-like fermion WIMP
  full minimal Lagrangian

[arxiv:1604.02230]

- likelihood analysis of Planck, PICO-2L, LUX, XENON100, LEP, LHC plus LZ, PICO250 projections
- surviving region assuming no WIMP signals are detected



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validity:
- $M_{mediator} \gg \sqrt{s}$
- $g_f, g_\chi \lesssim \sqrt{4\pi}$ (pertubativity)

$\Rightarrow \Lambda > 3\ m_\chi$

$\Rightarrow \Lambda > 300$ GeV

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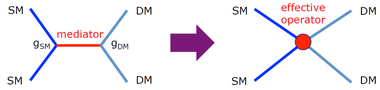

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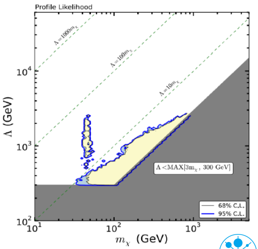
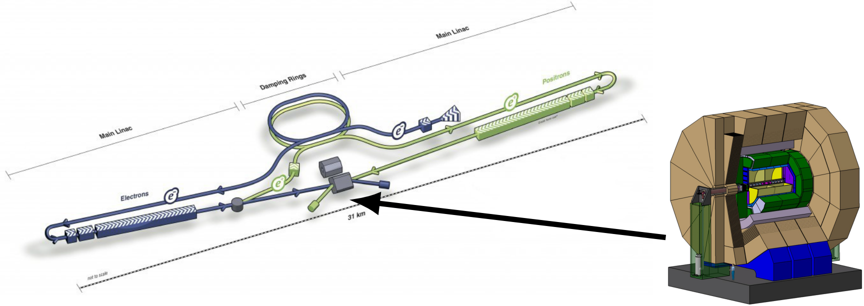


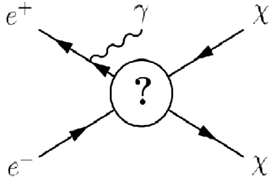
The International Linear Collider

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

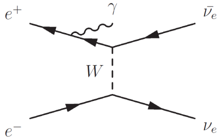


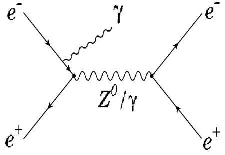
WIMPs Detection at ILC

- **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

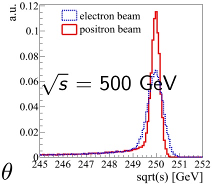


- **Main Background Processes**
  - **Neutrino pairs** $e^+e^- \to \nu\bar{\nu}\gamma$
    - irreducible
    - polarisation: enhance or suppress
  - **Bhabha scattering** $e^+e^- \to e^+e^-\gamma$
    - huge cross section
    - mimics signal if leptons are undetected $\Rightarrow$ requires best possible hermeticity in the forward region of the detector



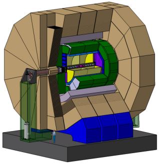


Modelling of Signal and Background



- generated using WHIZARD 2.2.8
  - polarised beams
  - beam spectrum
  - photon modelling:
    - in **matrix element** "$\nu\bar{\nu}\gamma$" $\Rightarrow$ correct E, θ
    - as dedicated **ISR parametrisation**
      ISR implementation: all orders of soft-collinear photons, first three orders of hard-collinear photons $\Rightarrow$ best cross-section

  $\Rightarrow$ no double counting
- signal: $\chi\chi\gamma$
  - reweight $\nu\bar{\nu}\gamma$ according to WIMP mass, spin, ...
- background:
  - $\nu\bar{\nu}$ + nγ
  - e^+e^- + nγ (Bhabha scattering)
- full Geant4 based ILD simulation



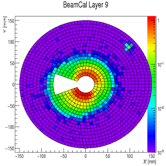
Signal Definition and Background Rejection

- signal definition (single photon plus missing energy)
  - $E_\gamma > 10$ GeV
  - $E_\gamma < 220$ GeV (Z return at 242 GeV: avoid large background)
  - $|\cos\theta_\gamma| < 0.98$ (tracking needed to distinguish γ from $e^{-/+}$)

  $\Rightarrow$ Bhabhas: hard photon boosts leptons in detector
- empty detector
  - veto events with track with $p_T > 3$ GeV
  - additional visible energy < 20 GeV
  - no e^+/e^- in forward region $\Rightarrow$ no cluster in BeamCal

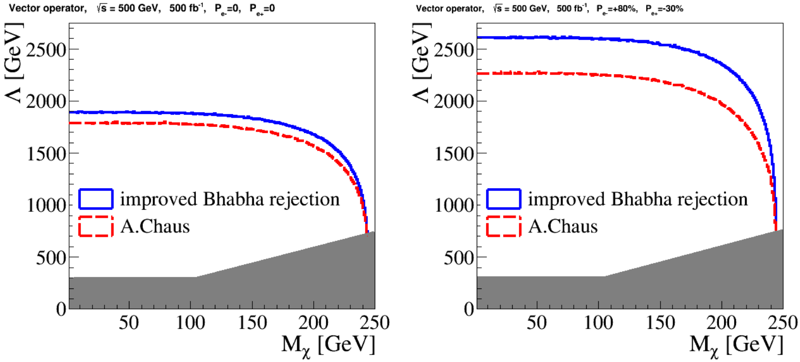
$\Rightarrow$ retains 90% of signal

$\Rightarrow$ Bhabha background rejection improved by factor 15



$e^+e^-\gamma$	A.Chaus	new analysis
p_T	21.1%	26.1%
E_{vis}	16.0%	1.9%
BeamCal	0.29%	0.02%

Higher Sensitivity with Improved Bhabha Rejection



lower Bhabha background than in previous ILD analysis by A.Chaus

sensitivity is improved by 6%
without polarisation of beams

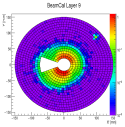
... by 15%
for right-handed electrons
and left-handed positron

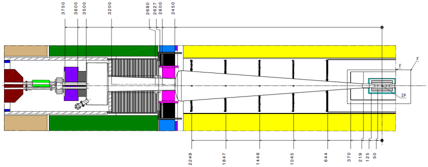
for "vector" operator, $\sqrt{s} = 500$ GeV, 500 fb^{-1}

Sensitivity Depends on Forward Detector Design

- forward region is currently being redesigned
  (as favoured by accelerator design)

⇒ BeamCal has to be moved closer to interaction point by 40 cm





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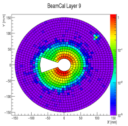
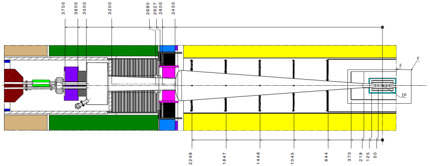
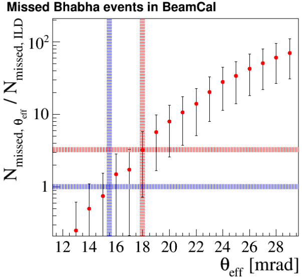




- hermeticity is crucial for Bhabha events
- simplified approach:
  assume that hermeticity depends purely geometrically on the distance of BeamCal to IP
- if ILD decides to move BeamCal in
  - 3-4 times more Bhabhas remain
  - partial loss of improvement

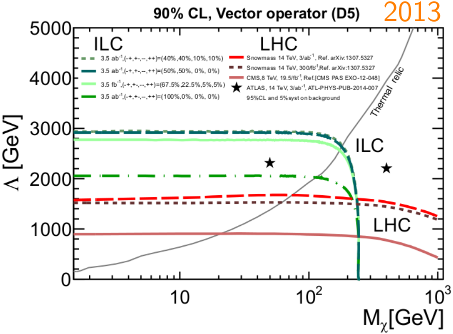
$\Rightarrow$ a full ILD update is underway



LHC vs. ILC

- LHC
  - tests couplings to quarks/gluons
  - sensitive to higher M_χ

A.Chaus 2013



- ILC
  - tests coupling to leptons
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  - low systematic uncertainties of BG
  - no pile-up, no beam remnants

  - polarisation

  $\Rightarrow$ signal can be enhanced

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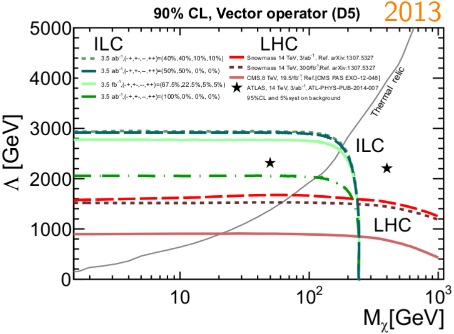

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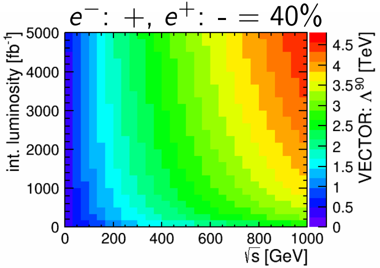
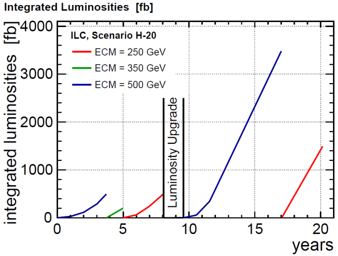
  type of interaction can be tested

  - well known initial state

  $\Rightarrow$ allows to calculate M_χ

Sensitivity in Different Operation Scenarios





- extrapolation of sensitivity from full simulation
  - 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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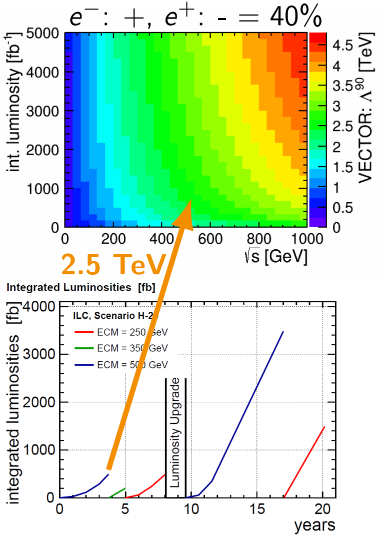

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  - after first four years: **$\Lambda \approx$ 2.5 TeV**

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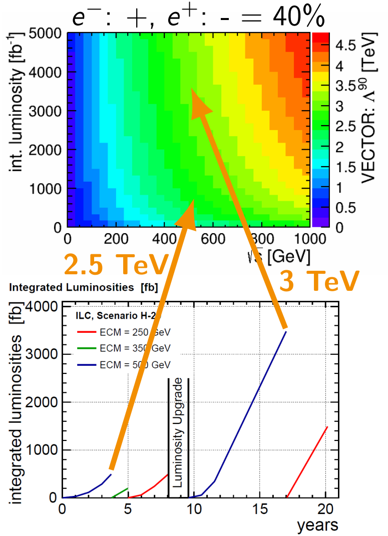

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  - after full ILC programme: **Λ ≈ 3 TeV**

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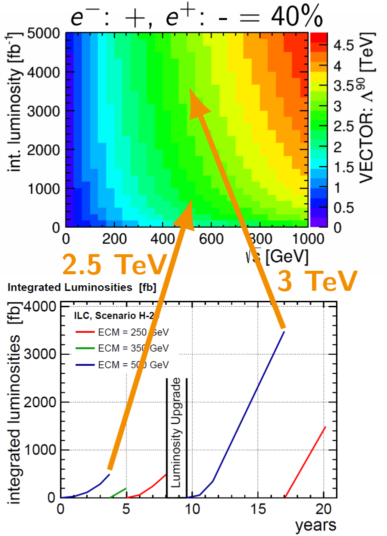

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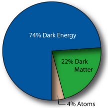
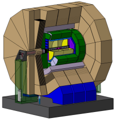
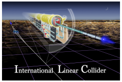
  - after first four years: **$\Lambda \approx$ 2.5 TeV**
  - after full ILC programme: **$\Lambda \approx$ 3 TeV**
- for upgrade to $\sqrt{s} = 1$ TeV: **$\Lambda \approx$ 4.5 TeV**

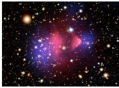
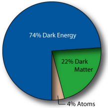
Summary: WIMP searches at the International Linear Collider

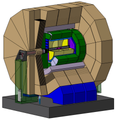
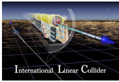




- WIMPs are still among favorite candidates for dark matter
- ILC covers unique parameter space
- ILC sensitivity complementary to LHC searches
  - coupling to leptons instead of quarks/gluons
  - $m_\chi < \sqrt{s}/2$
  - but sensitive to smaller couplings
    $\Rightarrow \Lambda$ up to 3-4 TeV
- detector design has crucial impact
  $\Rightarrow$ maintain hermeticity in forward region down to few mrad
- update of simulation study underway
  $\Rightarrow$ input for the likelihood analysis

References

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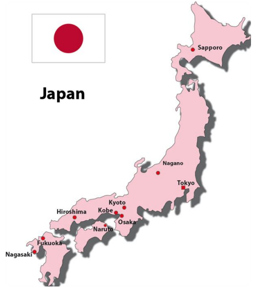
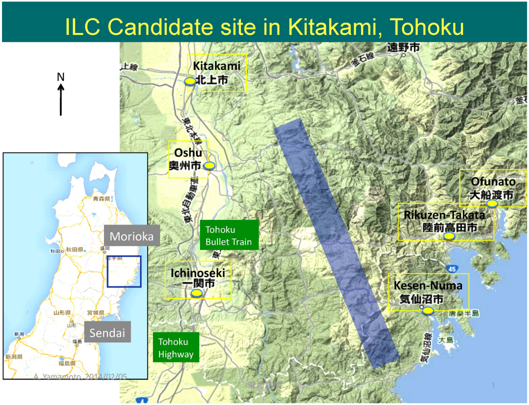
  - Technical Design Report: arXiv:1306.6327
  - Operating Scenarios: arXiv:1506.07830
- Simulation Study
  - EFT interpretation, vector-like mediator:
    PhD thesis of Andrii Chaus, Université Paris-sud 11, 2014PA112300
  - Cosmological interpretation: arXiv:1206.6639
- Likelihood analysis
  - arXiv:1604.02230
  - arXiv:1603.07387
  - arXiv:1407.1859

ILC Candidate Site: Kitakami





Likelihood Analysis (Shigeki Matsumoto

How well can the ILC explore the WIMP paradigm?

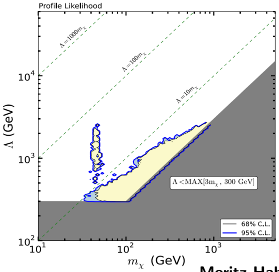
In order to make the discussion quantitative, we first classify WIMP based on its quantum number (spin and weak isospin) and construct a minimal effective Lagrangian in each case.
(e.g. singlet-like scaler WIMP, doublet-triplet vector WIMP, triplet-like fermion WIMP, etc.)

Ex. For the singlet-like fermion WIMP, the minimal effective Lagrangian is

$$\mathcal{L}_{\rm EFT} \supset \frac{c_S}{2\Lambda}(\bar{\chi}\chi)|H|^2 + \frac{c_P}{2\Lambda}(\bar{\chi}i\gamma_5\chi)|H|^2 + \sum_f \frac{c_f}{2\Lambda^2}(\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{f}\gamma_\mu f) + \frac{c_H}{2\Lambda^2}(\bar{\chi}\gamma^\mu\gamma_5\chi)(H^\dagger i\overleftrightarrow{D}_\mu H)$$

Scanning parameter space (m_χ, Λ, c_S, c_U, c_D, c_Q, c_L, c_E, c_H) via Likelihood (MCMC) analysis.

(CP invariance, $c_P = 0$, is assumed.)

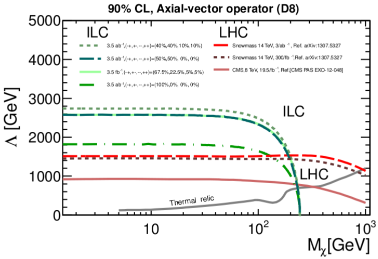


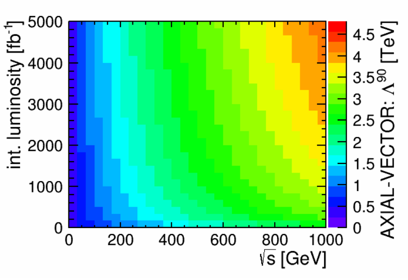
← Would-be parameter region survived assuming no WIMP signals are detected before the ILC .

An important question is how well the ILC can explore the parameter region via the mono-γ process, etc.

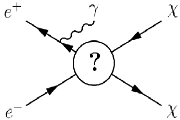
A careful study involving a realistic detector simulation is now on-going!

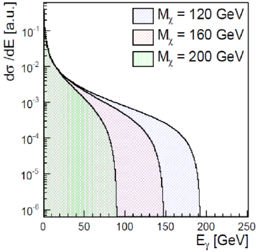
Results for an "Axial-Vector" Mediator

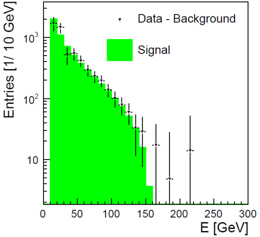




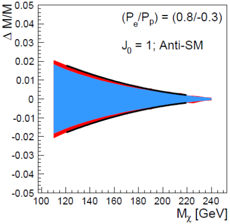
Measuring the WIMP Mass







- E_γ: shape information is used
- range depends on M_χ and $\sqrt{s}$
- lepton collider $\rightarrow$ initial state is known
- $\sqrt{s}$ known $\rightarrow M_\chi$
- uncertainty on $\sqrt{s}$ dominates accuracy of M_χ



systematical uncertainty

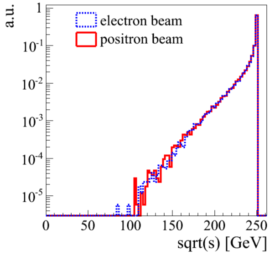
statistical uncertainty

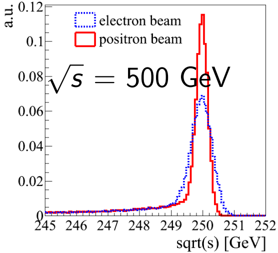
over-simplified approach

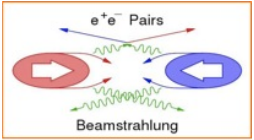
Luminosity Spectrum: "our PDF"

lepton collider: requirement of high instantaneous luminosity

- ⇒ beams are highly collimated
- ⇒ strong electro-magnetic fields
- ⇒ both bunches are focussed in the field of the other beam
- ⇒ e^+/e^- emit synchrotron radiation ("beamstrahlung")
- ⇒ ... and on average lose a few percent of their energy
- ⇒ this energy distribution leads to systematic uncertainy on M_χ
- ⇒ beamstrahlung photons generate e^+/e^- pairs







Bhabha Scattering Background and the BeamCal

- if leptons are not detected
  $\rightarrow$ mimics mono-photon signal
- forward region of detector important: BeamCal
  (6 mrad $< \theta <$ 40 mrad $\Leftrightarrow$ $3.91 < \eta < 5.85$)
- beamstrahlung photons generate e^+/e^- pairs
  $\rightarrow$ energy deposition in detector
  $\rightarrow$ $\epsilon \ll 1$ at very low angles
- reconstruction of Bhabha leptons in BeamCal reduces background by factor 60 - 100