WIMP Searches at the International Linear Collider

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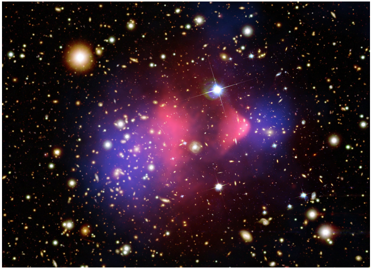
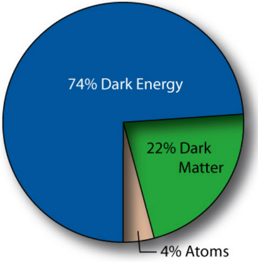
WIMP Dark Matter

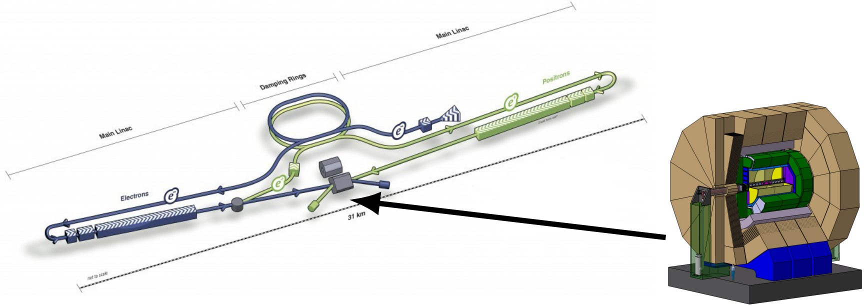




- Weakly Interacting Massive Particles (WIMPs) are candidates for dark matter
- WIMPs can be searched for directly and indirectly and at colliders
  $\Rightarrow$ idea: SM particles $\rightarrow$ WIMP pair production

The International Linear Collider

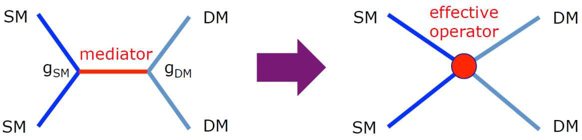
- a future electron positron collider
  - mature technology
  - waiting for political decision in Japan
- centre-of-mass energy: 250 - 500 GeV (upgrade: 1 TeV)
- $\mathcal{L} = 1.8 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$ (upgrade: $3.6 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$)
- polarised beams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



Theoretical Framework

- effective operators (general approach)
- assumption:
  "SM $\rightarrow$ DM" interaction is mediated by a **heavy** particle
- interaction can be integrated out

for example:
"vector" operator



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

$$\frac{1}{\Lambda^2}(\overline{f}\gamma_\mu f)(\overline{\chi}\gamma^\mu \chi)$$

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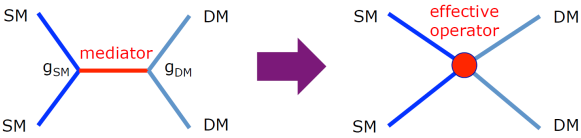

$$\left(\frac{g_f g_\chi}{q^2 - M^2}\right)(\bar{f}\gamma_\mu f) \ldots \chi)$$

$$\frac{1}{\Lambda^2}(\bar{f}\gamma_\mu f)(\bar{\chi}\gamma^\mu \chi)$$

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

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

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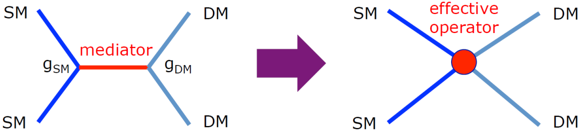


$$\left(\frac{g_f g_\chi}{q^2 - M^2}\right)(\bar{f}\gamma_\mu f) \quad \chi)$$

$$\frac{1}{\Lambda^2}(\bar{f}\gamma_\mu f)(\bar{\chi}\gamma^\mu \chi)$$

only one parameter
⇒ energy scale of new physics

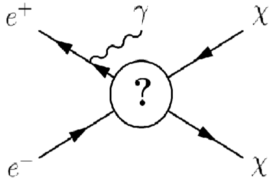
$$\Lambda = M_{mediator} / \sqrt{g_f g_\chi}$$

- validity
  - $M_{mediator} \gg \sqrt{s} \Rightarrow \Lambda > 3\ m_\chi$
  - pertubativity: $g_f,\ g_\chi \lesssim \sqrt{4\pi} \Rightarrow \Lambda >$ 300 GeV

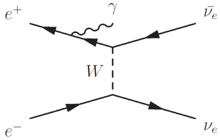
⇒ both can be fulfilled under ILC conditions

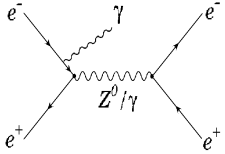
WIMPs in the Mono-Photon Channel

- **Signal**
  - **WIMP pair production with a photon from initial state radiation** $e^+e^- \to \chi\chi\gamma$
  - quasi model-independent / general approach
  - 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
    - mimicks signal if leptons are undetected $\Rightarrow$ requires best possible hermiticity 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** "$\nu\nu\gamma$" $\Rightarrow$ correct E, θ
      ISR implementation: all orders of soft-collinear photons, first three orders of hard-collinear photons
    - as dedicated **ISR parametrisation** $\Rightarrow$ best cross-section

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

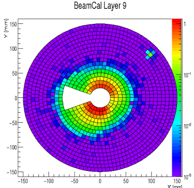
Signal Definition and Background Rejection

- signal definition ($\chi\chi\gamma$: 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 for photon identification)

  $\Rightarrow$ Bhabhas: hard photon boosts leptons in detector
- transverse momentum: $p_T > 3$ GeV rejected
  - allow for beam-induced background with low p_T
- empty detector: visible energy of > 20 GeV rejected
- e^+/e^- in forward region: BeamCal cluster $\rightarrow$ rejected

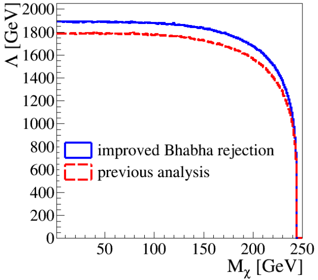
$\Rightarrow$ retains 90% of signal

$\Rightarrow$ Bhabha background rejection improved by factor 15



$e^+e^-\gamma$	new sample	old analysis
p_T	26.1%	21.1%
E_{vis}	1.9%	16.0%
BeamCal	**0.02%**	**0.29%**

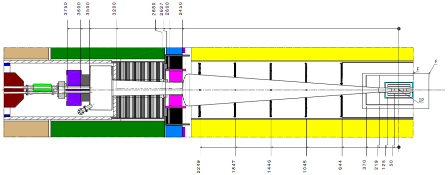
Higher Sensitivity with Improved Bhabha Rejection



- better reconstruction algorithm for BeamCal in forward region of the detector
- lower Bhabha background than in previous analysis
- sensitivity is improved by 100 GeV (for "vector" operator, $\sqrt{s} = 500$ GeV, 500 fb^{-1}, no polarisation of beams)
- for right-handed electrons and left-handed positron: expect improvement of 350 GeV

Sensitivity Depends on Forward Detector Design

- length of ILD currently under discussion
- efficiency to reconstruct Bhabha events depends on hermiticity
- hermiticity depends on the distance of forward detectors to interaction point



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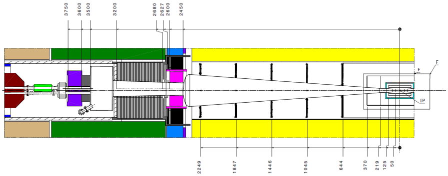
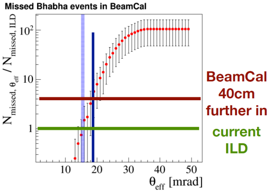
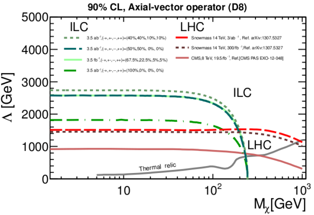




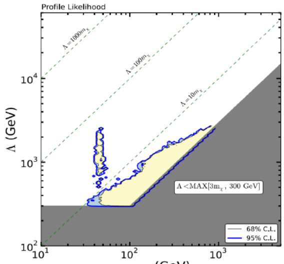
- simplified approach:
  - assume purely geometrical dependence (i.e. ignore shape of Beamstrahlung pair cone)
- if ILD decides to make the detector shorter
  - 3-4 times more Bhabhas are missed for shorter detector
    $\Rightarrow$ few 100 GeV loss in sensitivity

LHC vs. ILC

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



2013



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

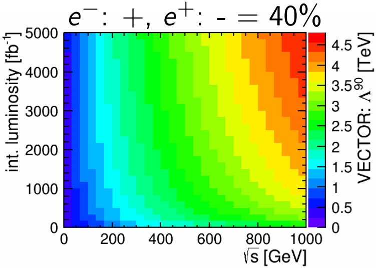
  $\Rightarrow$ signal can be enhanced

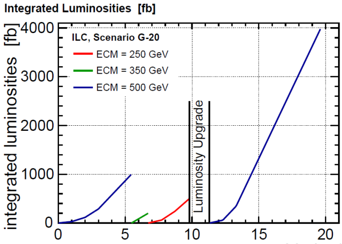
  $\Rightarrow$ background can be suppressed

  - well known initial state

  $\Rightarrow$ allows to calculate M_χ

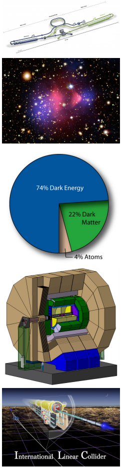
Sensitivity in Different Operation Scenarios



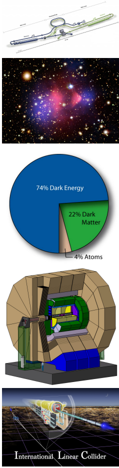


- extrapolation of sensitivity from full simulation
- reachable Λ at different $\sqrt{s}$ and integrated luminosities
- allows to give estimates for sensitivity
  - for different time scales
  - for different running scenarios
    - center-of-mass energies
      → higher values are favored
    - polarisation
      → $\nu\bar{\nu}\gamma$ suppression

Summary: WIMP searches at the International Linear Collider



- WIMP are still among favorite candidates for dark matter
- 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 hermiticity in forward region down to few mrad



Slide sent by Shigeki

How well can the ILC explore the WIMP paradigm?

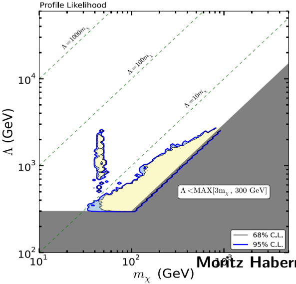
In order to make the discussion quantitative, we first classify WIMP based on its quantum number (spin and weak isospin) and construct a minimal effective Lagrangian in each case.
(e.g. singlet-like scaler WIMP, doublet-triplet vector WIMP, triplet-like fermion WIMP, etc.)

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.)

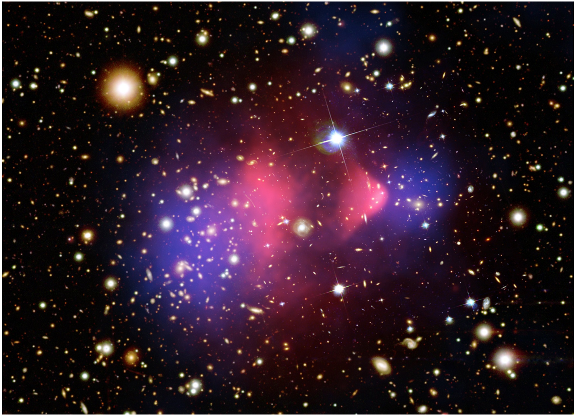


← Would-be parameter region survived assuming no WIMP signals are detected before the ILC .

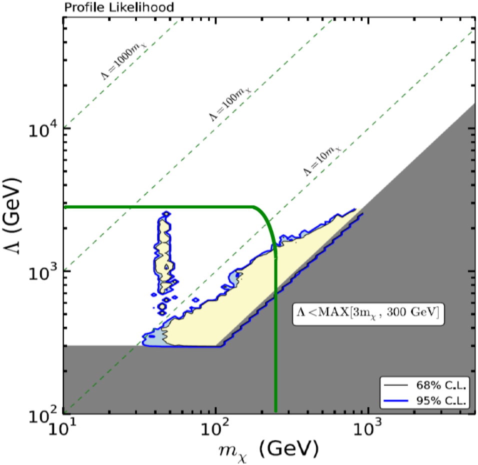
An important question is how well the ILC can explore the parameter region via the mono-γ process, etc.

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

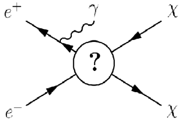
Backup

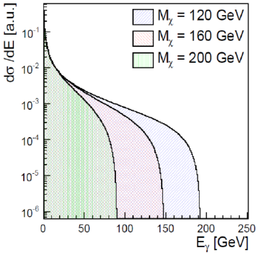


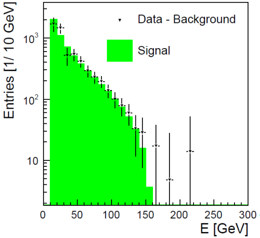
test


Profile Likelihood
Λ=1000mχ
Λ=100mχ
Λ=10mχ
Λ <MAX[3mχ, 300 GeV]
68% C.L.
95% C.L.
Λ (GeV)
mχ (GeV)
10^4
10^3
10^2
10^1
10^2
10^3

Measuring the WIMP mass



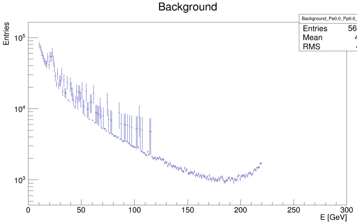


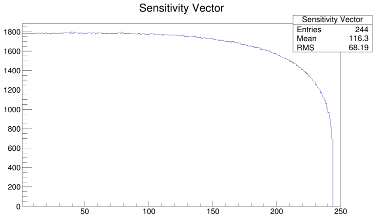


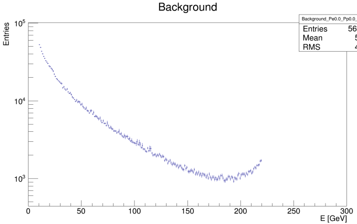
- E_γ: shape information is used
- range depends on M_χ and $\sqrt{s}$
- lepton collider $\rightarrow$ initial state is known
- $\sqrt{s}$ known $\rightarrow$ M_χ

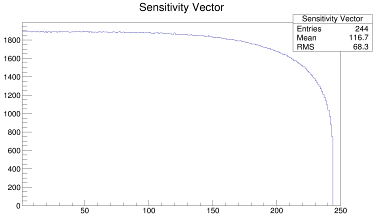
Input for Detecor Design

- design of forward region crucial to suppress Bhabha background

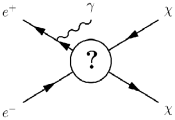








Effective operator approach



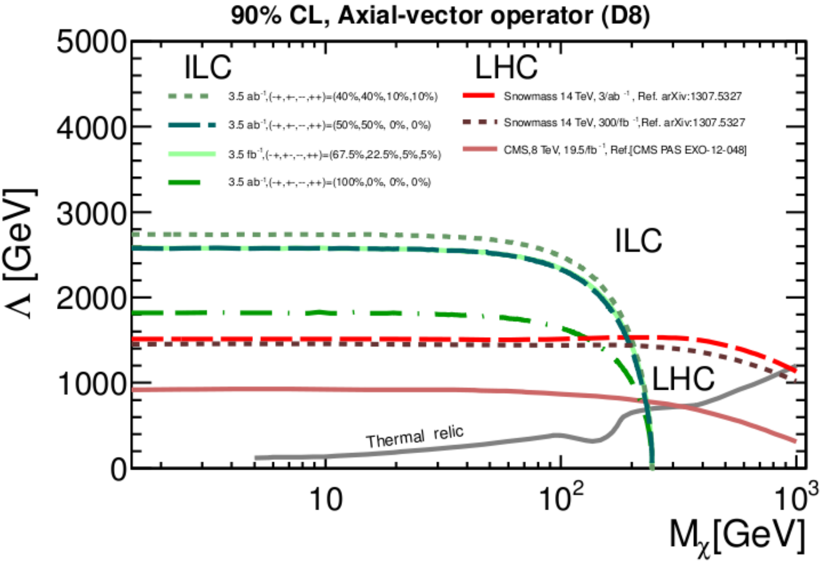
- $M_{mediator} \gg \sqrt{s}$
  $\Rightarrow$ interaction can be described by a few parameters
- Λ: energy scale of new physics ($\sigma \propto 1/\Lambda^4$)
- types of mediator: vector, axial-vector,...

$$\frac{d^2\sigma}{dzd\cos\theta} \approx \frac{\alpha}{12\pi^2}\frac{s}{\Lambda^4}\frac{1}{z\sin^2\theta}(1-z)[4(1-z)+z^2(1+\cos^2\theta)]$$

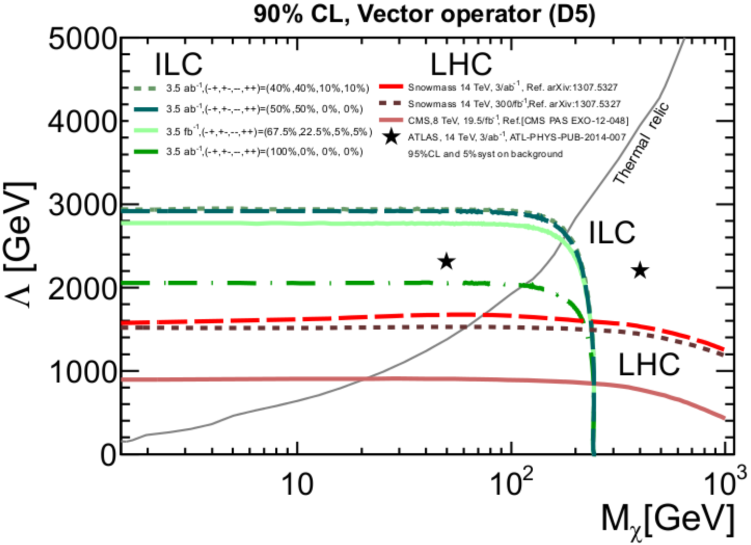
Chae and Perelstein 2013

$$(z = \frac{2E_\gamma}{\sqrt{s}},\ M_\chi \ll \sqrt{s})$$

LHC vs. ILC


90% CL, Axial-vector operator (D8)
ILC
LHC
3.5 ab⁻¹,(-+,+-,--,++)=(40%,40%,10%,10%)
3.5 ab⁻¹,(-+,+-,--,++)=(50%,50%, 0%, 0%)
3.5 fb⁻¹,(-+,+-,--,++)=(67.5%,22.5%,5%,5%)
3.5 ab⁻¹,(-+,+-,--,++)=(100%,0%, 0%, 0%)
Snowmass 14 TeV, 3/ab ⁻¹, Ref. arXiv:1307.5327
Snowmass 14 TeV, 300/fb ⁻¹,Ref. arXiv:1307.5327
CMS,8 TeV, 19.5/fb⁻¹, Ref.[CMS PAS EXO-12-048]
ILC
LHC
Thermal relic
Λ [GeV]
5000
4000
3000
2000
1000
0
10
10²
10³
Mχ[GeV]

LHC vs. ILC



90% CL, Vector operator (D5)
ILC
LHC
3.5 ab-1,(-+,+-,--,++)=(40%,40%,10%,10%)
3.5 ab-1,(-+,+-,--,++)=(50%,50%, 0%, 0%)
3.5 fb-1,(-+,+-,--,++)=(67.5%,22.5%,5%,5%)
3.5 ab-1,(-+,+-,--,++)=(100%,0%, 0%, 0%)
Snowmass 14 TeV, 3/ab-1, Ref. arXiv:1307.5327
Snowmass 14 TeV, 300/fb-1,Ref. arXiv:1307.5327
CMS,8 TeV, 19.5/fb-1, Ref.[CMS PAS EXO-12-048]
ATLAS, 14 TeV, 3/ab-1, ATL-PHYS-PUB-2014-007
95%CL and 5% syst on background
Thermal relic
ILC
LHC
Λ [GeV]
5000
4000
3000
2000
1000
0
10
10^2
10^3
Mχ[GeV]

EFT: validity