WIMP Search
in the Mono-Photon Channel

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WIMP Search in the Mono-Photon Channel

WIMP Search at the ILC

Event Selection

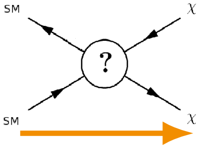
Exclusion Limits

Data Quality: Photon Reconstruction (in Mokka)

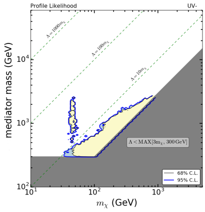
The Physics Case

- 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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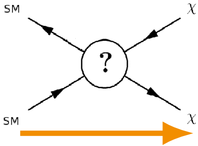

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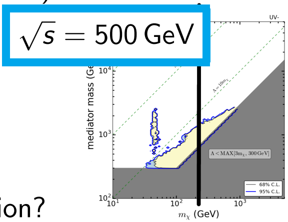

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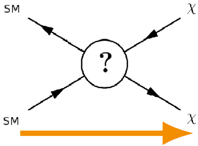

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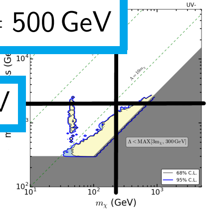
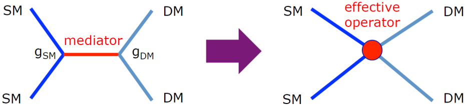
$\sqrt{s} = 500$ GeV

$M_{med} \approx 3$ TeV



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 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

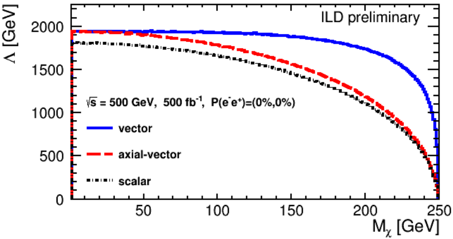
⇒ general approach

⇒ only one parameter ("energy scale of new physics")

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

Sensitivities for effective operators

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

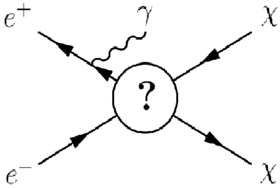


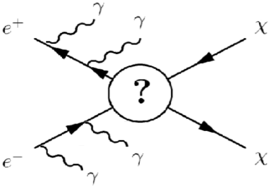
setup and cross-sections formulas from Chae and Perelstein JHEP05(2013)138

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

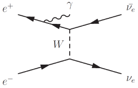
WIMP Detection at ILC

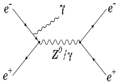
- **Signal**
  - **WIMP pair production with a photon from initial state radiation** $e^+e^- \to \chi\chi\gamma$
  - quasi model-independent
  - single photon in an "empty" detector $\to$ missing four-momentum
  - observables: E_γ, θ_γ





- **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
    - cross section rises for low polar angles
    - mimics signal if leptons in forward region are undetected





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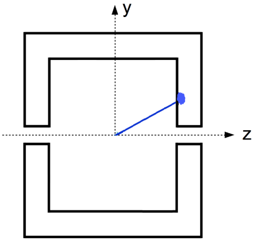
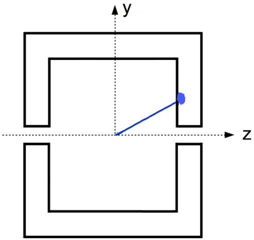
Event selection: single photon in an empty detector

- signal definition (mono-photon)



Event selection: single photon in an empty detector

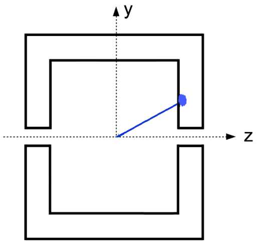
- signal definition (mono-photon)
  - **minimum polar angle:** $\theta_\gamma > 7°$
    need tracker to distinguish photon from electron

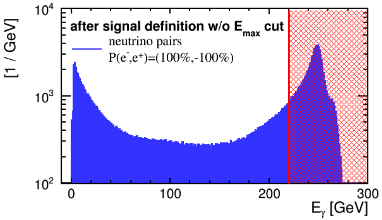


Event selection: single photon in an empty detector

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

    avoid large background at Z return





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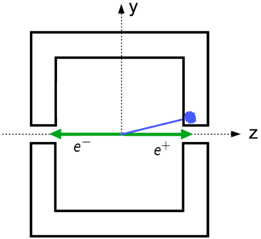
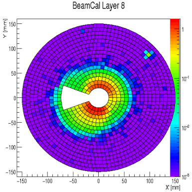
  - **minimum transverse momentum**
    - ensure Bhabha lepton hits detector
    - follows inner rim of BCal ($\Leftrightarrow$ ϕ-dependent)
    - $p_{T,\gamma} > 5.71$ GeV for $|\phi| \leq 35$
    - $p_{T,\gamma} > 1.97$ GeV for $|\phi| > 35$
    - in BCal coordinates (7° tilted)





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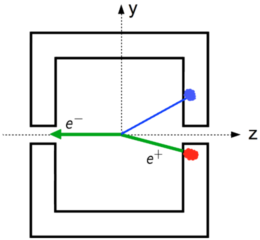

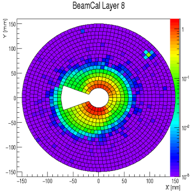

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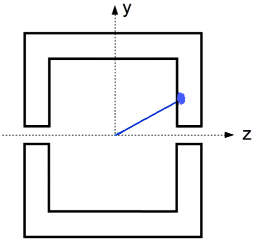

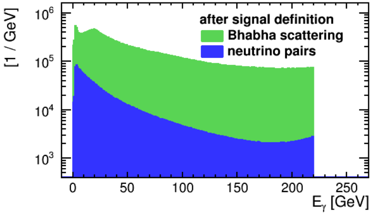

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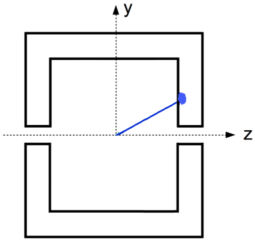
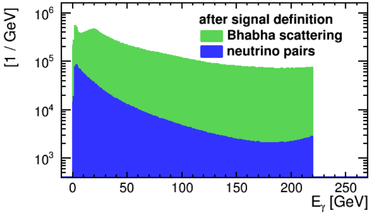
- selection criteria (empty detector)
  - $\rightarrow$ suppress Bhabhas
  - $\rightarrow$ keep neutrinos





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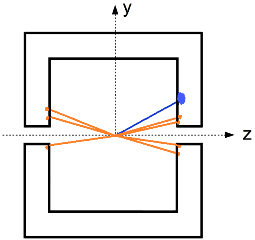
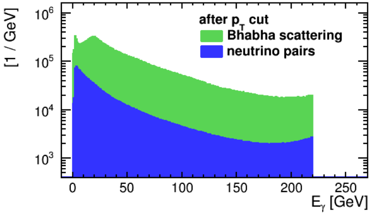
  - **veto events with track with $p_T > 3$ GeV**





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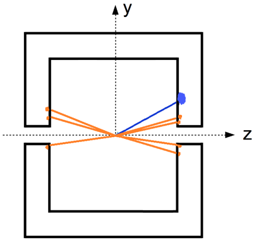
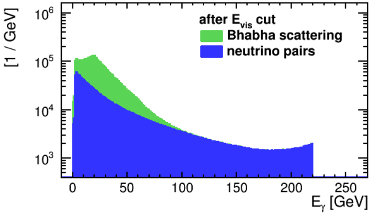
  - → suppress Bhabhas
  - → keep neutrinos
  - veto events with track with $p_T > 3$ GeV
  - **max. additional visible energy**
    - add up all PFO energies
    - only consider particles if E > 5 GeV
    - allow a max. energy sum of 10 GeV
    - or 30 GeV, if the extra energy is from reconstructed neutrons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





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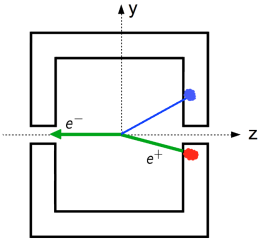
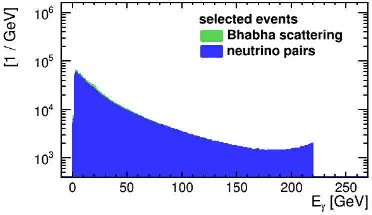
  - max. additional visible energy
  - **no reconstructed BCal clusters**

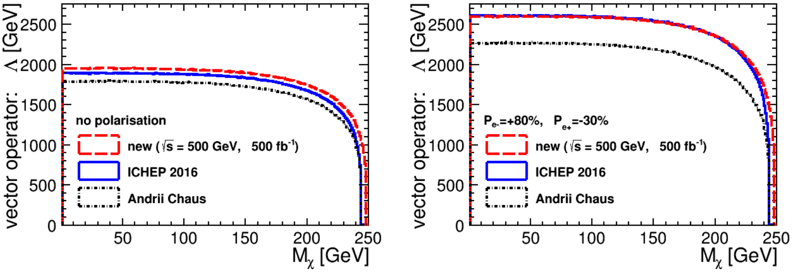




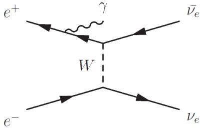
WIMP Search in the Mono-Photon Channel

Comparison to Previous Results

- 2016
  - latest reconstruction tools: e.g. BeamCalClusterReco
  - better background suppression
- 2017
  - more realistic (larger) Bhabha background
  - better signal definition → larger signal-to-noise ratio



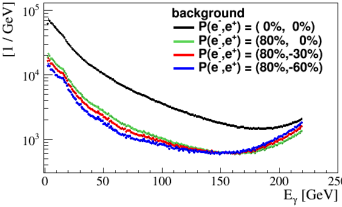
Role of polarisation

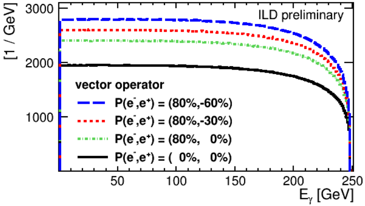


- background
  - neutrinos can be suppressed for right-handed e^- and left-handed e^+

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

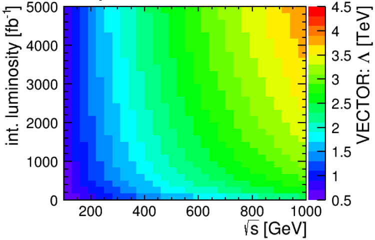
- WIMPs
  - production can be enhanced
  - chirality of interaction can be tested

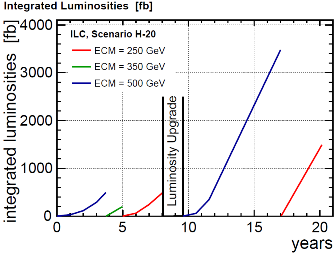




Sensitivity in different operation scenarios

unpolarised





- 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
  - $\sqrt{s}$ (slightly) higher than at LEP
  - more luminosity
  - polarisation
- ILC can test energy scales of a few TeV

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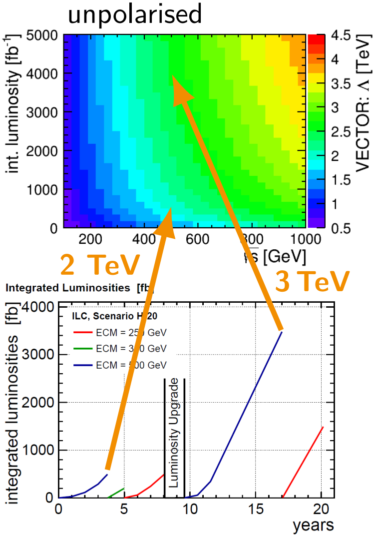

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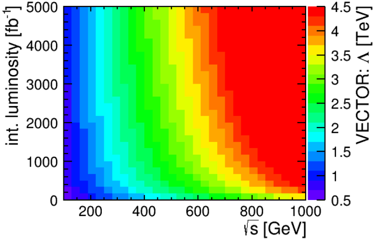
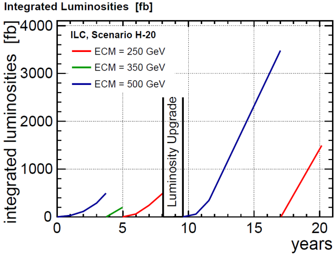
Sensitivity in different operation scenarios

"40,40,10,10"





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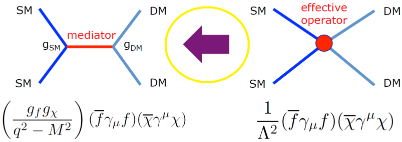
Simplified models and effective operators

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

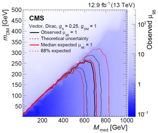


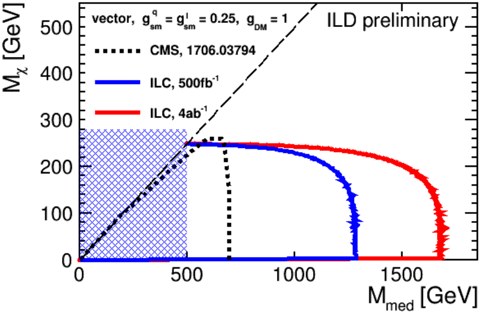
- 3 free parameters $\Rightarrow$ present limits for M_{med} & fix couplings
  - mediator mass
  - coupling to SM $\Rightarrow$ **0.25** $\rightarrow$ avoid sizeable di-jet production
  - coupling to DM $\Rightarrow$ **1**
- instead of $\Lambda = \frac{M_{med}}{\sqrt{g_{SM} \cdot g_{DM}}}$

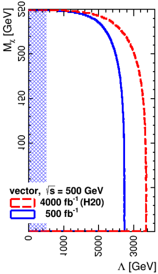
Comparing LHC and lepton collider limits

- 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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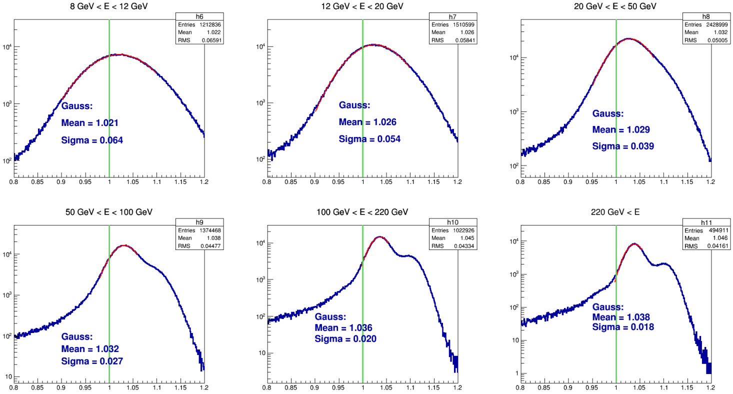
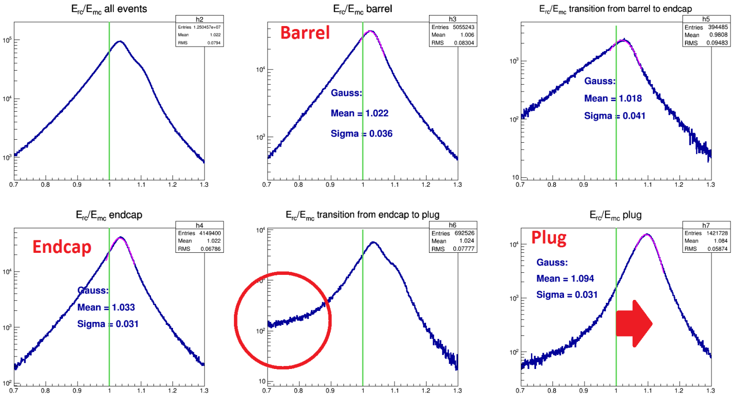
Reconstructed Energy as a Function of the Energy



- reconstructed energy ≈2-4% too high
- level rises with energy
- second peak around 110%

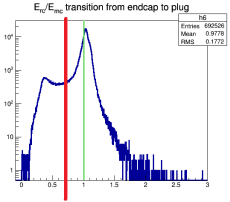
Reconstructed Energy as a Function of the Polar Angle

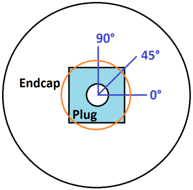


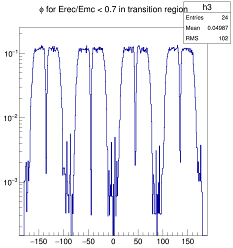
- barrel and endcap OK
- in plug reconstructed energy 10% too high
- transition region between endcap and plug: tail

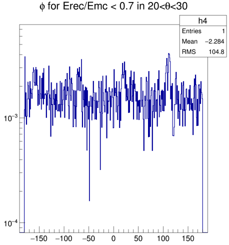
Transition region between endcap and plug

- peak at too low reconstructed energies
- square shape
  $\rightarrow$ look at ϕ-distribution
  - for $9.3^\circ < \theta < 12^\circ$ (transition region)
  - $E_{reco}/E_{MC} < 0.7$
- reconstruction fails for 10% of photon clusters
  - fine around 0,90,180,270 degrees (γ fully contained in endcap)
  - fine around 45,135,... degrees (γ fully contained in plug)







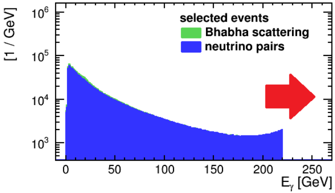


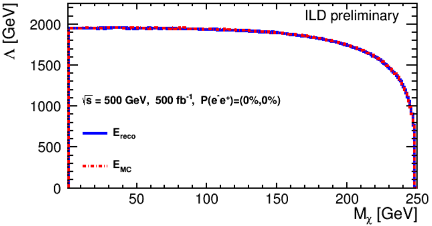
Using MC information I

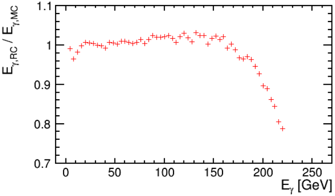
- How do photon reconstruction imperfections influence the WIMP limits ?
- idea
  - true MC energy and p_T of selected photons
  - smear with test beam ECal resolution: $16.53\%/\sqrt{E} + 1.07\%$
  - use information from full reconstruction to select events ("empty detector")

Using MC Information II

- similar number of selected events
  - 1.1% more with MC information
  - up to 25% in plug migrate to energies higher than E_{max}
- exclusion limits: few GeV better







⇒ effect of reconstruction imperfections can be neglected

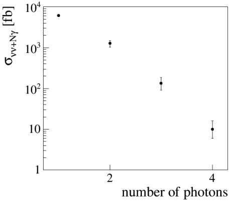
Summary: WIMP Search

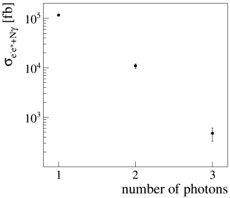
- ILC can explore new phase space
  - testing of coupling to leptons → complementary to LHC and direct detection searches
- with the new MC samples...
  - ... the limits are similar to previously
    - larger signal phase space
    - better reconstruction tools
  - ... the estimates are more realistic
    - Bhabha phase space is fully populated
    - signal definition ensure that Bhabhas are distinguished from signal-like events
- OK to use photons from full simulation despite the reconstruction imperfections

Event Generation with WHIZARD 2.4.4

- ISR treatment
  - "hard" photons are put in matrix element
    $\rightarrow$ gives correct E_γ and θ_γ
    $\rightarrow$ control over photon number
  - additionally: WHIZARD's ISR routine
    (all orders of soft-collinear photons,
    first three orders of hard-collinear photons)
    $\rightarrow$ correct cross-section
    photons are constraint to $\theta = 0$

  $\Rightarrow$ double counting is avoided
- theory uncertainty: arbitrary cuts
  - matrix element photons need minimum θ (collinear divergence) and minimum energy (infra-red divergence)$\rightarrow$ $p_{T,\gamma} < 0.1\,\text{GeV}$
  - at the moment, Whizard does not allow more realistic ISR treatment





Status of WIMP Analysis at ILD

- Christoph Bartels, 2011
  - full detector simulation at $\sqrt{s} = 500\,\text{GeV}$
  - Whizard 1.96 with RDR beam parameters
  - ILCSoft v01-06
  - detector models: ILD_00, partially LDC_PrimeSc_01
  - interpretation: cosmological approach
- Andrii Chaus, 2014: re-interpretation: effective operators (Λ)
- me, since 2014:
  - full detector simulation at $\sqrt{s} = 500\,\text{GeV}$ + extrapolation
  - Whizard 2.2.4 with TDR beam spectrum (Circe2)
  - improved reconstruction in ILCSoft v17-11
  - Bhabha phase space and new L*
- Shigeki Matsumoto et al.: likelihood analysis
- Daniel Dercks: uses WIMP search to test CheckMATE

Monte Carlo Samples

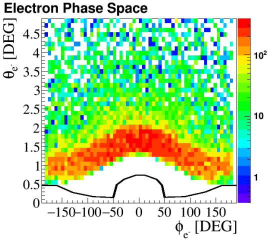
- generated with WHIZARD: completely new setup
- centrally produced by ILD
  - detector simulation: Mokka, ILD_o1_v05 (TDR)
  - reconstruction: Marlin, latest version

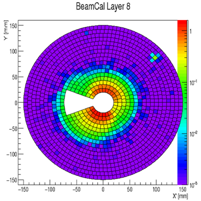
	cross-section	events	int. luminosity
neutrino pairs: $\nu\bar{\nu}$ + 1-4γ			
P(e$^-$)=L, P(e$^+$)=R	28093	14,745,059	524.9
P(e$^-$)=R, P(e$^+$)=L	1938	1,161,407	599.4
Bhabha scattering: e$^-$e$^+$ + 1-3γ			
P(e$^-$)=L, P(e$^+$)=L	123911	2,994,007	24.2
P(e$^-$)=L, P(e$^+$)=R	133071	2,994,006	22.5
P(e$^-$)=R, P(e$^+$)=L	130234	2,994,006	23.0
P(e$^-$)=R, P(e$^+$)=R	123917	2,994,007	24.2

- signal events
  - reweigh $\nu\bar{\nu}$ events according to WIMP mass, spin ...
  - weight: $d\sigma(e^+e^- \to \chi\chi\gamma)/dE_\gamma \cdot d\sigma(e^+e^- \to \nu\bar{\nu}\gamma)/dE_\gamma$

Event Generation: Why new Samples?

- Bhabha samples used before:
  WHIZARD (1) default cuts
  - invariant mass of all possible particle pairs $> 4\,\mathrm{GeV}$
  - $\rightarrow \theta_e \approx 1$ DEG (on MC level)
  - (ϕ dependence due to crossing angle)





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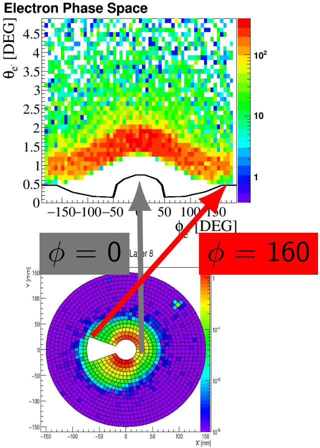

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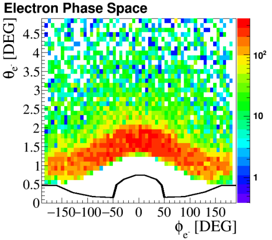
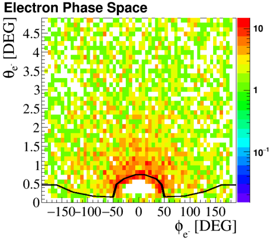
- new sample with $M_{inv} > 1\,\mathrm{GeV}$
  $\Rightarrow$ **gap is closed**





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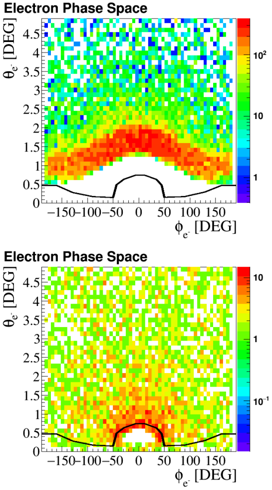
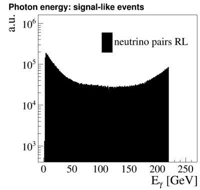
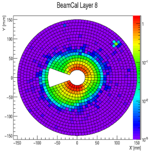
  - invariant mass of all possible particle pairs $> 4\,\mathrm{GeV}$
  - $\rightarrow \theta_e \approx 1$ DEG (on MC level)
  - (ϕ dependence due to crossing angle)
- new sample with $M_{inv} > 1\,\mathrm{GeV}$
  $\Rightarrow$ **gap is closed**
- only now: realistic estimate of Bhabha background possible



Signal Definition



- observables: E_γ, θ_γ
- motivations for signal defining conditions
  - distinguish photon from e^-/e^+
    $\rightarrow$ need tracker: maximum $\cos(\theta)$ — $|\cos\theta_\gamma| < 0.996$
  - avoid large backgrounds at Z return
    (242 GeV for $\sqrt{s} = 500$ GeV): maximum E_γ — $E_\gamma < 220$ GeV
  - distinguish photon from noise: $E_\gamma > 2$ GeV
  - ensure that one e^-/e^+ in Bhabha events is detected,
    i.e. does not go down the beam pipe $\rightarrow$ minimum $p_{T,e}$
    $\rightarrow$ counterbalanced by minimum $p_{T,\gamma}$

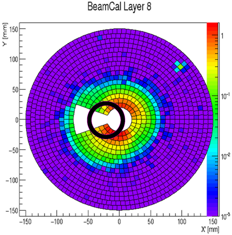


- in order to describe BeamCal hole best: ϕ dependent sig. def.
  - $p_{T,e} > 5.7$ GeV for $|\phi| \geq 141.5$
    $\Leftrightarrow$ $p_{T,\gamma} > 5.7$ GeV for $|\phi| \leq 38.5$
  - $p_{T,e} > 2.0$ GeV for $|\phi| < 141.5$
    $\Leftrightarrow$ $p_{T,\gamma} > 2.0$ GeV for $|\phi| > 38.5$

Signal Definition: Why New Samples?

1. old signal definition: $p_{T,min}$ was too small

→ e^-e^+ from Bhabha events could escape detection



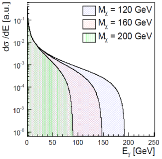
2. $p_{T,min}$ instead of $E_{\gamma,min}$ and $\theta_{\gamma,min}$

→ leads to larger phase space of signal definition

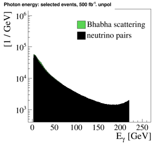
⇒ pre-selection cuts adjusted to new signal definition

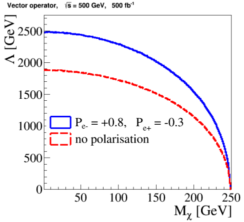
Limit Calculation

1. reweigh $\nu\bar{\nu}$ events to WIMP events
2. signal input: photon energy distribution for different M_χ



3. background input: photon energy distribution





4. limit calculation
   - shape information is used
   - remember: $\sigma \propto 1/\Lambda^4$