WIMP Search: Update

Moritz Habermehl

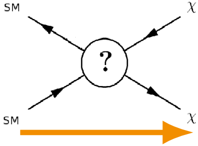
ILD Software / Analysis Meeting

19 July 2017

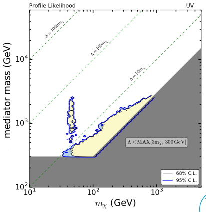
The Physics Case

- 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
- Is the ILC sensitive in the surviving region?



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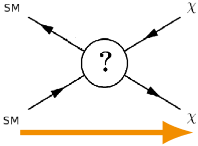

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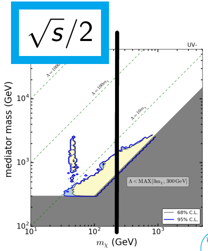

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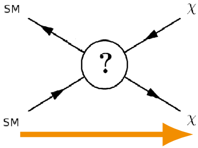

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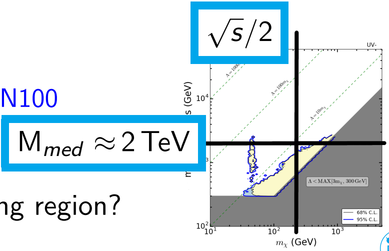
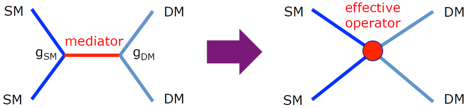


Theoretical Framework: Effective Operators



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

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

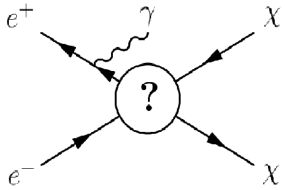
   ⇒ general approach

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

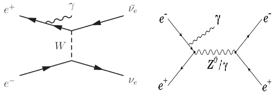
$\Lambda = M_{mediator}/\sqrt{g_f g_\chi}$ and $\sigma \propto 1/\Lambda^4$

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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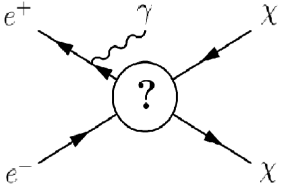

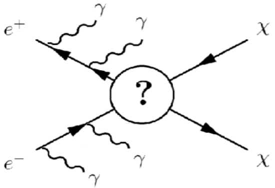

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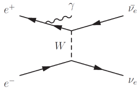
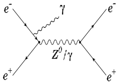


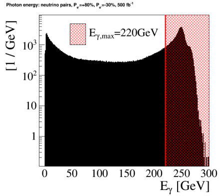


New Monte Carlo Samples

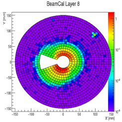
- generated with WHIZARD: completely new setup
  - new signal definition → different preselection cuts
  - gap in Bhabha phase space filled
  - ISR treatment: double-counting avoided
- centrally produced by ILD
  - detector simulation: Mokka, ILD_o1_v05 (TDR)
  - reconstruction: Marlin, 17-11

	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

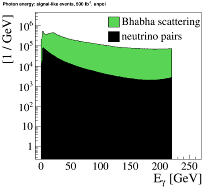
Event Selection: Criteria

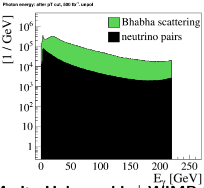


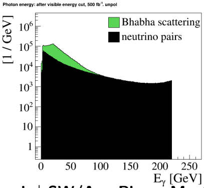
- signal definition (monophoton)
  - distinguish photon from electron
    $\rightarrow$ need tracker $\rightarrow$ $|\cos\theta_\gamma| < 0.996$
  - avoid large background at Z return $\rightarrow$ $E_\gamma < 220$ GeV
  - ensure Bhabha lepton hits detector $\rightarrow$ minimum $p_{T,\gamma}$
    (ϕ-dependent to follow inner rim of BeamCal)

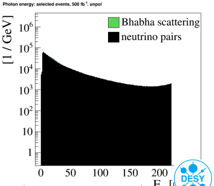


- selection criteria (**empty detector** apart from signal photon)
  - veto events with track with $p_T > 3$ GeV
  - additional visible energy < 20 GeV (PFOs)
  - no cluster in BeamCal









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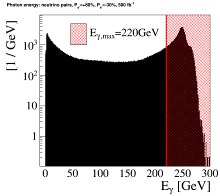

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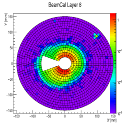

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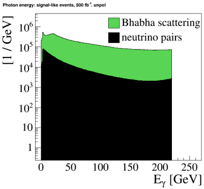
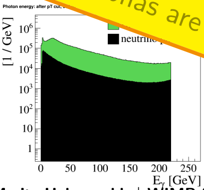
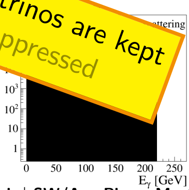
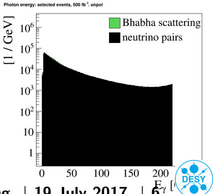
signal-like neutrinos are kept
Bhabhas are suppressed









Selection Efficiencies: Neutrinos

events per fb^{-1}

	sig. def.	no $p_T > 3$ GeV	no $E_{vis} > 20$ GeV	no BCal cluster
neutrino pair production				
$\nu\bar{\nu}\gamma$	3770.1	3639.6	2977.4	2967.9
		96.54%	78.97%	78.72%
previously		97.68%	91.60%	89.83%
$\nu\bar{\nu}\gamma\gamma$	863.2	822.7	512.8	465.2
		95.31%	59.40%	53.89%
previously		94.52%	69.28%	66.37%
$\nu\bar{\nu}\gamma\gamma\gamma$	99.8	93.9	42.5	34.9
		94.13%	42.58%	35.00%
previously		92.13%	46.54%	43.50%
$\nu\bar{\nu}\gamma\gamma\gamma\gamma$	7.7	7.2	2.2	1.7
		92.70%	29.12%	21.80%

- efficiency goes down for increasing number of photons
- overall level OK
- too many events lost due to low p_T overlay $\rightarrow$ visible energy cut will be adjusted

Selection Efficiencies: Bhabhas

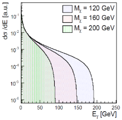
events per fb^{-1}

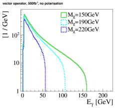
	sig. def.	no $p_T > 3$ GeV	no $E_{vis} > 20$ GeV	no BCal cluster
Bhabha scattering				
$e^- e^+ \gamma$				
	59081.4	30562.7	5856.0	204.6
		51.73%	9.91%	0.35%
previously		21.10%	15.99%	0.29%
$e^- e^+ \gamma\gamma$				
	6930.9	2345.7	207.9	5.2
		33.84%	3.00%	0.07%
$e^- e^+ \gamma\gamma\gamma$				
	450.8	96.4	5.3	0.1
		21.38%	1.17%	0.02%

- per mill level suppression
- BeamCalClusterReco works
- despite different setup: overall suppression similar to previous analysis (Christoph Bartels)

Limit Calculation

1. reweigh $\nu\bar{\nu}$ events to WIMP events
   - different effective operators: vector, axial-vector, scalar
   - weight: $d\sigma(e^+e^- \rightarrow \chi\chi\gamma)/dE_\gamma$ / $d\sigma(e^+e^- \rightarrow \nu\bar{\nu}\gamma)/dE_\gamma$
2. signal input: photon energy distribution for different M_χ





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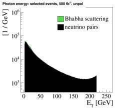

4. limit calculation
   - shape information is used
   - remember: $\sigma \propto 1/\Lambda^4$

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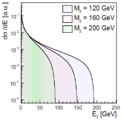

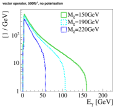

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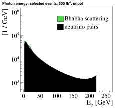

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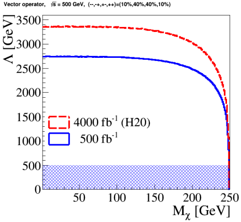
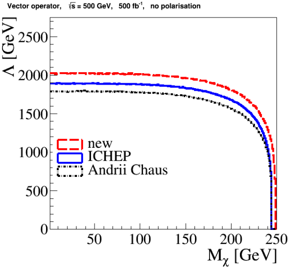
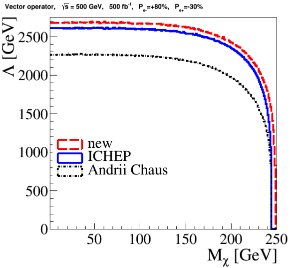


Comparison to Previous Results

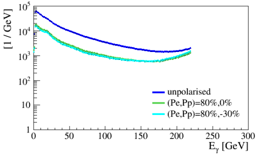




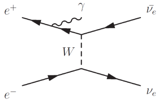
- improvement from "Andrii Chaus" to "ICHEP"
  - improved reconstruction (especially BeamCalClusterReco)
- improvement to "new"
  - new signal definitino has larger signal phase space
  - improvement despite larger Bhabha phase space

no beam polarisation	**neutrino pairs**
signal definition	2863.0 → 4741
selected events	2479.2 → 3470

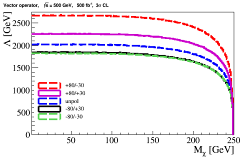
Role of Polarisation

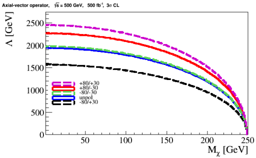


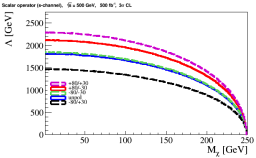
$N_{500fb^{-1}}$	**unpolarised**	$\mathbf{P_{e-}= +80\%}$ $\mathbf{P_{e+}= -30\%}$
$\nu\nu\gamma$	2479.19	483.51
$e^+e^-\gamma$	84.74	83.06



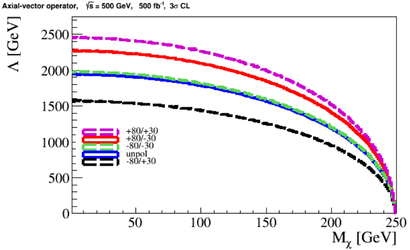
- background
  - neutrinos can be suppressed for right-handed e^- and left-handed e^+
- WIMPs
  - production can be enhanced
  - chirality of interaction can be tested

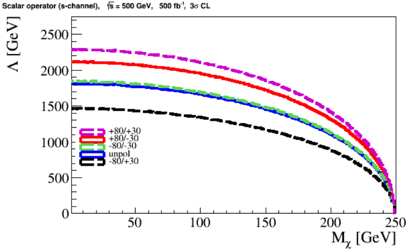


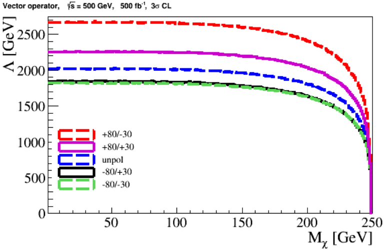




The Different Effective Operators

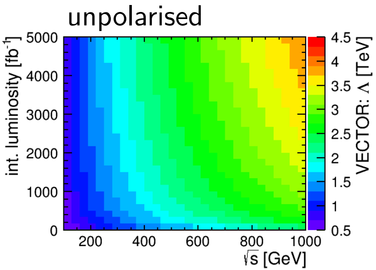


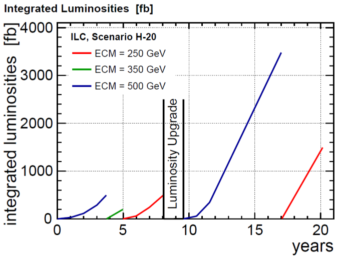




- polarised cross sections
  - vector operator: $\sigma_{LL} = \sigma_{RR} = 0$
  - axial-vector and scalar operators: $\sigma_{LR} = \sigma_{RL} = 0$

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
- one of the few BSM channels for which new phase space can be explored also at 250 GeV
  - centre-of mass energy (slightly) higher than at LEP
  - more luminosity
  - polarisation

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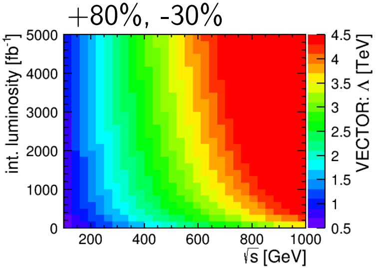

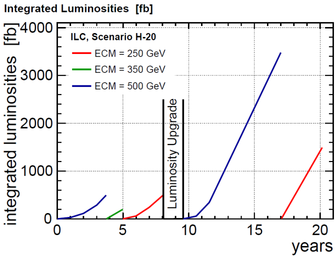

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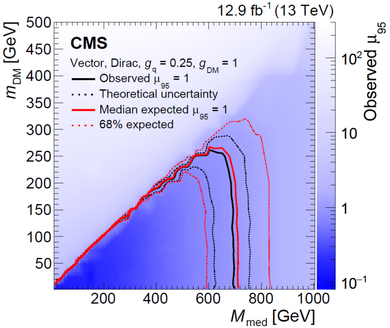
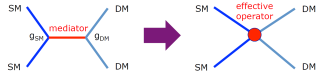
  - polarisation

CMS vs ILC I



- latest CMS results for mono-photon WIMP search: arxiv:1706.03794
- figure: vector operator in the framework of **simplified models**

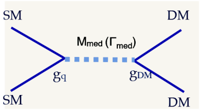
effective operators:



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

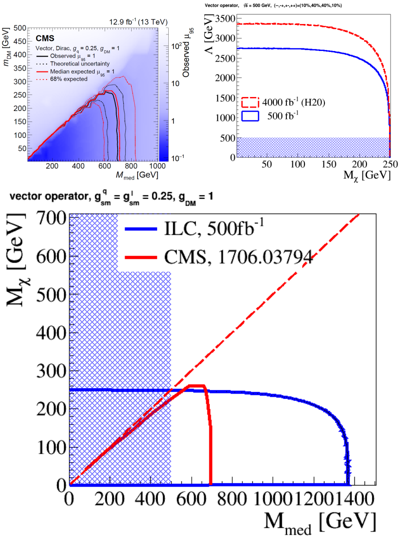
- $\Lambda = \frac{M_{med}}{\sqrt{g_{SM} \cdot g_{DM}}}$

simplified models:



- approach: fix couplings, present limits for M_{med}

CMS vs ILC II

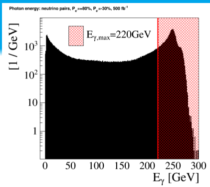


- LHC DM working group recommends
  - g_{SM}=**0.25** → small → avoid sizeable di-jet production: qq→new mediator→qq
  - g_{DM}=**1** → big completely arbitrary, leads to best exclusion limits
- assumption: $g^q_{sm} = g^l_{sm}$
- from EFT to simplified models: $M_{med} = \sqrt{g_{SM} \cdot g_{DM}} \cdot \Lambda = 0.5 \cdot \Lambda$
- blue shaded area: EFT only valid for $M_{med} > \sqrt{s}$
- red dashed line: $M_{med} = 2M_\chi$

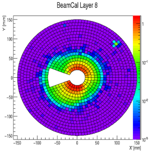
Summary: WIMP Search

- limits could be improved with new samples
- ILC is still more sensitive than LHC
  - now even compatible WIMP masses
  - depends on assumptions
- what remains to be done
  - update systematic uncertainties in limit calculation
  - improve cuts
  - few technicalities
- I'm going to attend the *Rencontres du Vietnam* conference *Exploring the Dark Universe*

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: minimum E_γ or $p_{T,\gamma}$
  - 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 $p_{T,\gamma}$

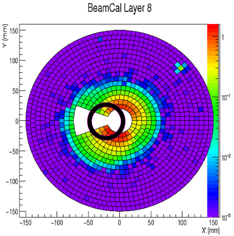


- in order to describe BeamCal hole best: ϕ dependent sig. def.
  - $p_{T,e} > 5.7$ GeV for $|\phi| \geq 141.5$
    $\Leftrightarrow$ $p_{T,\gamma} > 5.7$ GeV for $|\phi| \leq 38.5$
  - $p_{T,e} > 2.0$ GeV for $|\phi| < 141.5$
    $\Leftrightarrow$ $p_{T,\gamma} > 2.0$ GeV for $|\phi| > 38.5$

Signal Definition: Why New Samples?

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

$\rightarrow$ e^-e^+ from Bhabha events could escape detection



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

$\rightarrow$ leads to larger phase space of signal definition

$\Rightarrow$ pre-selection cuts adjusted to new signal definition