Mono-photon WIMP search at 500 GeV

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ILD Software / Analysis Meeting

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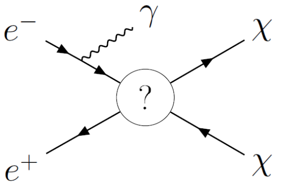
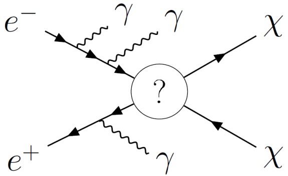
Mono-photon WIMP search at 500 GeV

- PhD thesis is planned to be submitted in the following weeks
- this talk gives an update of the WIMP analysis
  - new selection criterion
  - improved approach to produce signal events
  - study of detector effects
  - revisited systematic uncertainties
  - results for all ILC energies

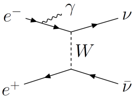
WIMP Detection at the ILC

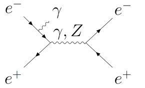
- **Signal**
  - **WIMP pair production with a photon from initial state radiation** $e^+e^- \rightarrow \chi\chi\gamma$
  - quasi model-independent
  - single photon in an "empty" detector $\rightarrow$ missing four-momentum
  - observables: E_γ, θ_γ





- **Main Background Processes**
  - **Neutrino pairs** $e^+e^- \rightarrow \nu\bar{\nu}\gamma$
    - irreducible
    - polarisation: enhance or suppress
  - **Bhabha scattering** $e^+e^- \rightarrow e^+e^-\gamma$
    - huge cross section
    - cross section rises for low polar angles
    - mimics signal if leptons in forward region are undetected





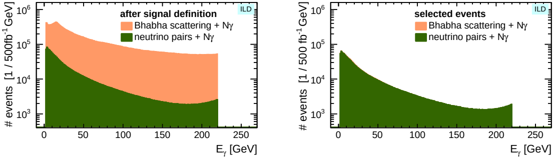
Background events: Neutrinos and Bhabhas

The data samples

- 500 GeV
- event generation: Whizard 2 with circe2 beam spectrum (dedicated samples for WIMP study with several ISR photons)
- simulation: Mokka (DBD style, old L*)
- reconstruction: ilcsoft v01-17-11 with updated Pandora photon reconstruction and `BeamCalClusterReco` (tuned for ILD)

Event selection

- 70%-80% of irreducible neutrino background kept
- suppression of Bhabhas to 0.2%



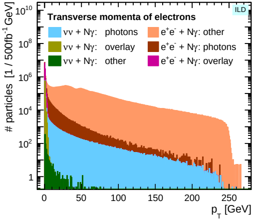
Signal definition and event selection

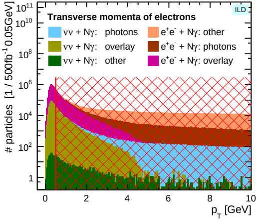
Single photon...

- $\theta_\gamma > 7°$: no tracker in forward region
- minimum $p_{T,\gamma}$: Bhabha lepton outside BeamCal openings
- $2 < E_\gamma < 220\,\text{GeV}$: avoid radiative return to Z

...in an empty detector

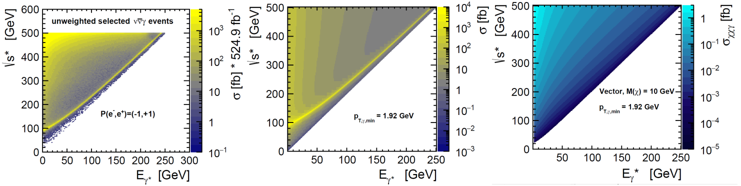
- allow low-p_T overlay: no charged $p_T > 3\,\text{GeV}$
  - new selection criterion: no $p_{T,e} > 0.5\,\text{GeV}$ in event
- maximum visible energy
- no reconstructed cluster in BeamCal





The signal events

- $\nu\bar{\nu}\gamma$ looks like $\chi\chi\gamma$ on an event-by-event basis
- reweigh neutrino events instead of producing WIMP samples for each tested model
- weight $w_{signal,pol} = \frac{d\sigma_{\chi\chi\gamma,pol}/dE_\gamma}{d\sigma_{\nu\bar{\nu}\gamma}/dE_\gamma}$ (with 1 photon)
- but MC events have several photons and luminosity spectrum: $\Phi(n\gamma, E_{beam}; \sqrt{s^*}) \times \sigma(\nu\bar{\nu}\gamma; \sqrt{s^*})$
- WIMP events = "neutrino Monte Carlo" $\times \frac{\sigma(\chi\chi\gamma, E^*_\gamma, \sqrt{s^*}, M_\chi, ...)}{\sigma(\nu\bar{\nu}\gamma, E^*_\gamma, \sqrt{s^*})}$



- with $\sqrt{s^*}$, E^*_γ measured in $\nu\bar{\nu}\gamma$ frame

The signal events

E_γ range depends on M_χ

- $\nu\bar{\nu}\gamma$ looks like $\chi\chi\gamma$ on an event-by-event basis
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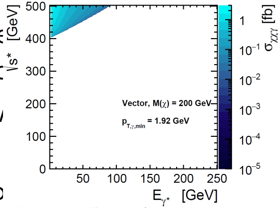
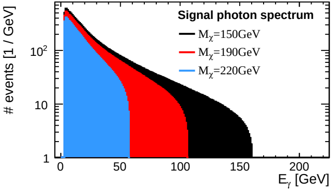
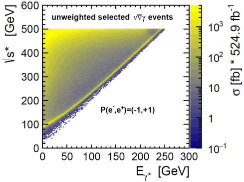
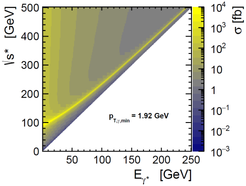
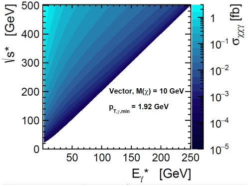




- WIMP events = "neutrino Monte Carlo" $\times \dfrac{\sigma(\chi\chi\gamma, E^*_\gamma, \sqrt{s^*}, M_\chi, \ldots)}{\sigma(\nu\bar{\nu}\gamma, E^*_\gamma, \sqrt{s^*})}$

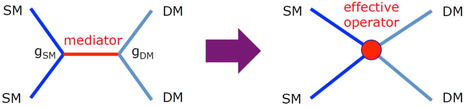






- with $\sqrt{s^*}$, E^*_γ measured in $\nu\bar{\nu}\gamma$ frame

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

$\Rightarrow$ general approach

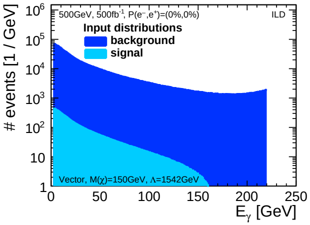
$\Rightarrow$ only one parameter ("energy scale of new physics")

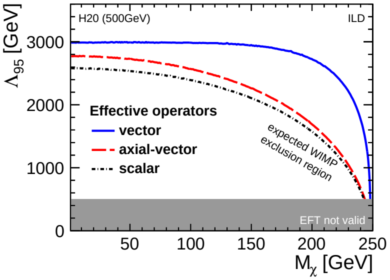
$$\Lambda = M_{mediator} / \sqrt{g_f g_\chi}$$

Sensitivities for effective operators

WIMP cross-section formulas from Chae & 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)	$(\bar{f}f)(\bar{\chi}\chi)$	$\sigma_{LL}=\sigma_{RR}$	$\sigma_{LR}=\sigma_{RL}=0$





- 2σ exclusion limits: Λ_{95} for different M_{χ}
  - Λ up to 3 TeV for H20 ($\sqrt{s}=500$ GeV)
  - M_{χ} up to $\sqrt{s}/2$ can be tested

Sensitivities for effective operators

WIMP cross-section formulas from Chae & Perelstein JHEP05(2013)138

vector	$(\bar{f}\gamma^\mu f)(\bar{\chi}\gamma_\mu\chi)$	$\sigma_{LR} = \sigma_{RL}$	$\sigma_{LL} = \sigma_{RR} = 0$
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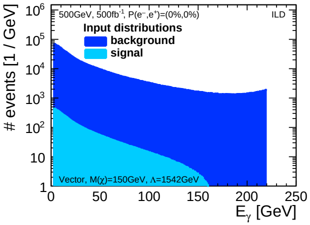
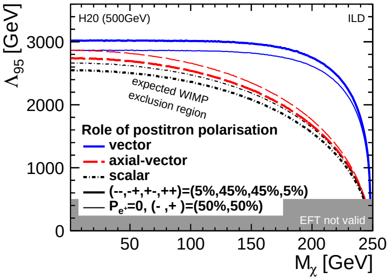
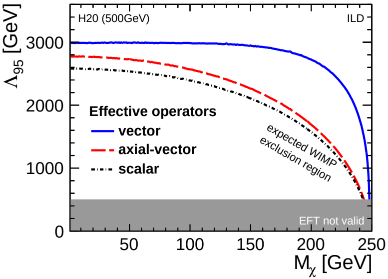


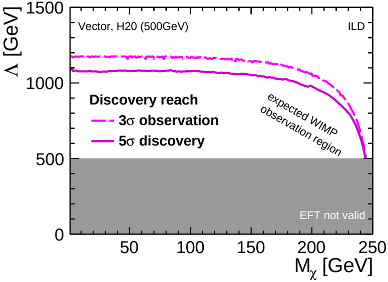


- 2σ exclusion limits: Λ_{95} for different M_χ
  - effect of polarisation sharing: $\Delta\Lambda \approx 100\,\text{GeV}$
  - different pol. combinations help to reduce the systematics

Observation of WIMPs

- signal with Λ in TeV range could be discovered

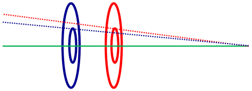


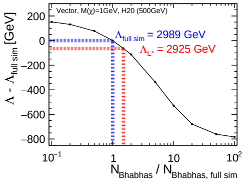


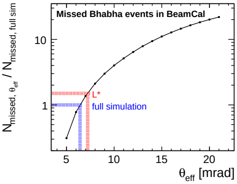
Detector effects

Detector effects: hermeticity

- suppress Bhabha background → need to detect lepton(s)
- hermeticity (in forward region) crucial
- simple setup to test influence of smaller L*
  1. effective polar angle θ_{eff}:
     - above every lepton can be reconstructed
     - blind below
  2. blind region is anti-proportional to L*



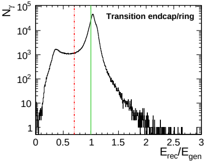


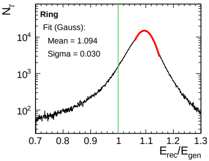


- with new L*: 50% more Bhabha background, 2% smaller sensitivity ⇒ acceptable

Detector effects: photon reconstruction

- photon reconstruction imperfections (energy shifts, issues at transition endcap/ring)
- test impact: smear MC true energy with ECal resolution
  $\rightarrow$ sensitivity affected only at percent level
- influence of ECal resolution: smear energy according to $\sigma_E/E = 1\%/\sqrt{E}$
  $\rightarrow$ negligible effect





	Λ_{95} [GeV] (vector, H20)			
	$M_\chi = 1\,\text{GeV}$		$M_\chi = 200\,\text{GeV}$	
full simulation	2989		2728	
MC true energies smeared	3076	(+3.0%)	2792	(+2.3%)
optimal ECal σ_E/E	3074	(+2.9%)	2804	(+2.8%)

Systematic uncertainties

Systematic uncertainty of the luminosity spectrum

- largest source of uncertainties in previous studies (Christoph Bartels, Andrii Chaus)
- new approach: use beam parameter fits
  - Grah and Sapronov JINST 3 (2008) P10004: *Beam parameter determination using beamstrahlung photons* (measured in GamCal) *and incoherent pairs* (measured in BeamCal)
  - 200 simulations of beam-beam interaction with GuineaPig
  - vary beam parameters N, σ_x and ϵ_x within fit uncertainties

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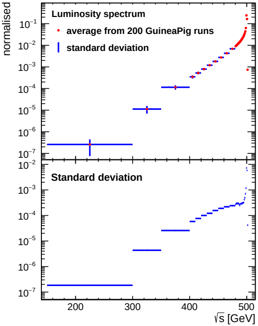
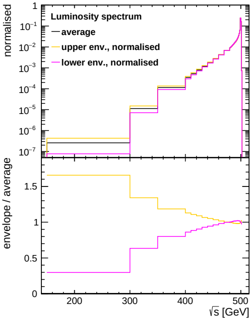
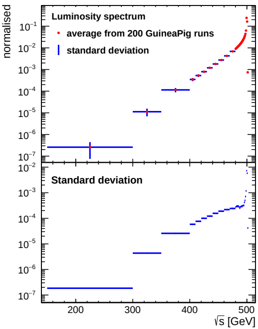
$\Rightarrow$ beam spectrum with uncertainties



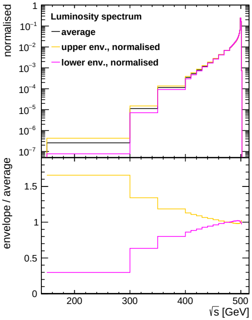
Translate systematics from LS to E_γ

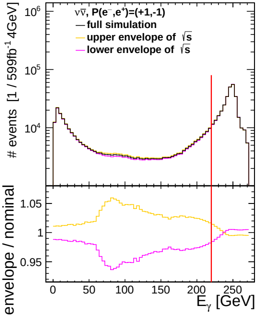




⇒ take upper and lower 1σ envelopes as 2 spectra with maximally different shape
⇒ normalise (overall luminosity is known from LumiCal)

Translate systematics from LS to E_γ





$\Rightarrow$ take upper and lower 1σ envelopes as 2 spectra with maximally different shape

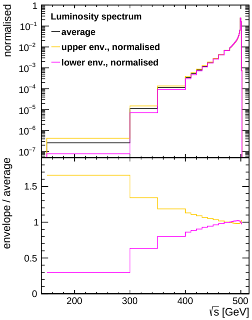
$\Rightarrow$ normalise (overall luminosity is known from LumiCal)

$\Rightarrow$ take MC true $\sqrt{s}$ of background events

$\Rightarrow$ apply weight $= \frac{\text{envelope}}{\text{nominal}}$

$\Rightarrow$ done: uncertainty on input to limit calculation

Translate systematics from LS to E_γ



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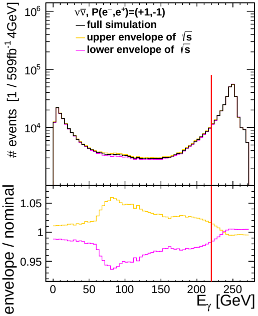

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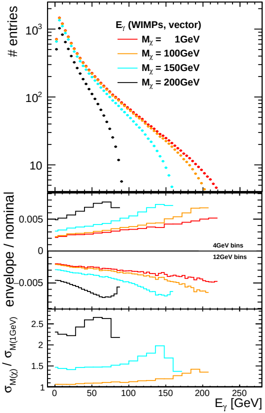
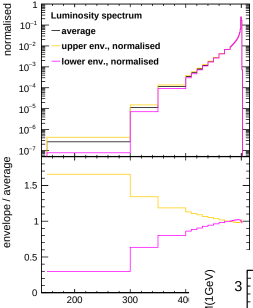
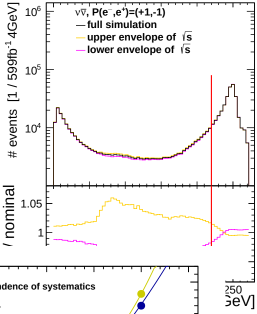
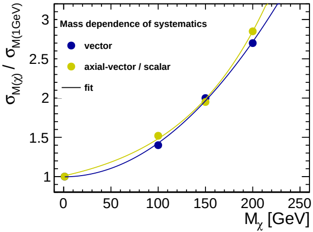


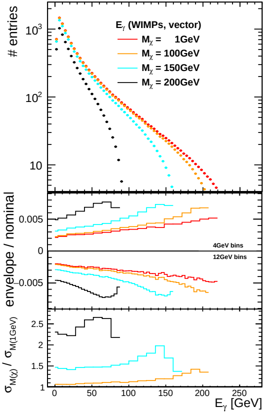
$\Rightarrow$ same for signal: apply envelope weights
$\Rightarrow$ uncertainties increases with WIMP mass

Translate systematics from LS to E_γ









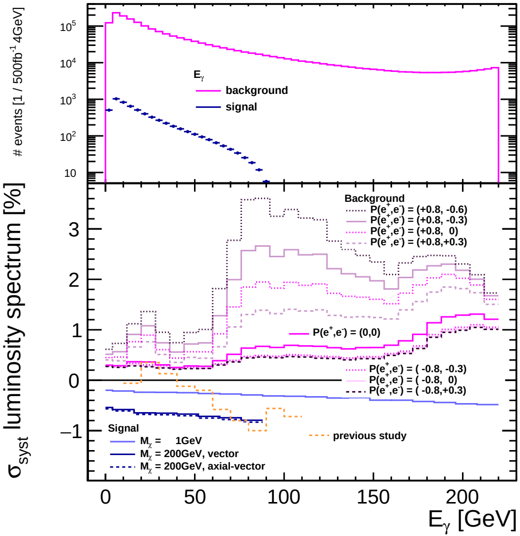
⇒ take upper anc ... of 1σ envelopes as 2 ... spectra with maxi ... different shape

⇒ normalise (ove ... on luminosity is known from ... input to limit calculation LumiCal)

⇒ same for signal: apply envelope weights

⇒ uncertainties increases with WIMP mass ⇒ fit

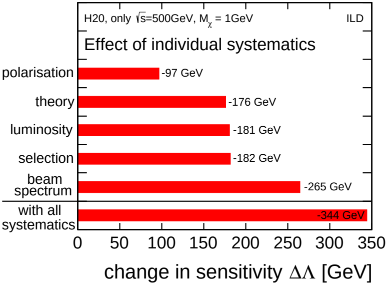
Systematics on the luminosity spectrum III

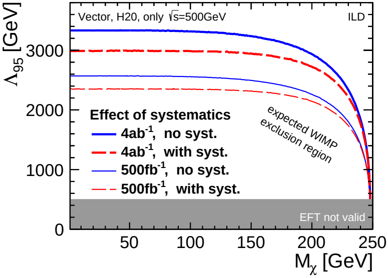


- uncertainties depend on polarisation
- in percent range
- larger than oversimplified approach in previous studies

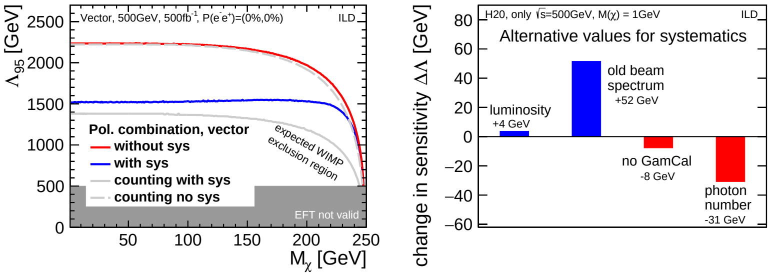
Effect of systematic uncertainties

source of systematics	value in standard setting	
luminosity spectrum	$\lesssim 3\%$	(previous slide)
luminosity	2.6‰	
polarisation	$0.2 - 2.5$‰	(Robert Karl)
event selection	2.0‰	
theory	1.3‰	(Whizard σ)





Test of alternative settings



- E_γ bins as single channels better than counting experiment
- if luminosity uncertainty anticipated 1‰ (instead of 2.6‰): tiny improvement
- beam spectrum of old study was too optimistic
- negligible importance of GamCal
- decreased sensitivity for full uncertainty on ISR treatment in Whizard

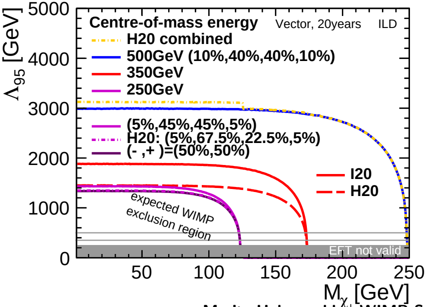
Sensitivity estimates for other $\sqrt{s}$

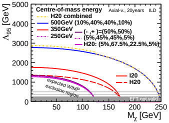
Sensitivity estimates for other $\sqrt{s}$

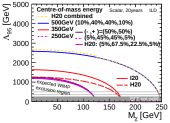
- full simulation at 500 GeV
- two approaches to obtain results for other centre-of-mass energies
  1. modify signal and background photon spectra
  2. extrapolate result (Λ)

Sensitivity estimates for other $\sqrt{s}$: 1st approach

- modify background photon spectrum
  - shape: compress spectrum with $\sqrt{s}_{new}/500\,\text{GeV}$
  - integral: calculate σ_{BG} at different $\sqrt{s}$ with Whizard
- signal photon spectrum
  - scale $\sqrt{s^*}$ with (nominal) centre-of-mass energy
  - too high E_γ get zero weight







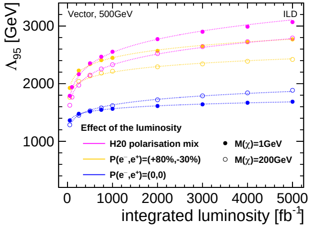
Sensitivity estimates for other $\sqrt{s}$: 2nd approach

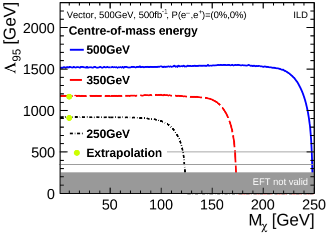
Extrapolation of sensitivity Λ with $\sqrt{s}$ and $\mathcal{L}$

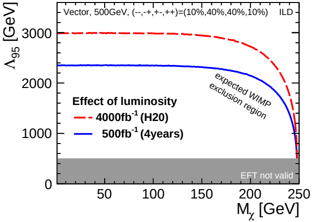
1. $\sigma = \sigma(\Lambda, \sqrt{s})$ and $S = \sigma\mathcal{L}$
2. $S \propto \sqrt{B}$
3. $B = B(\sqrt{s}, \text{pol.})$ from Whizard

$\Rightarrow$ approximate relation between Λ and $\sqrt{s}$, $\mathcal{L}$

- correct with empirical $\mathcal{L}$ dependence
- nice agreement with 1st approach

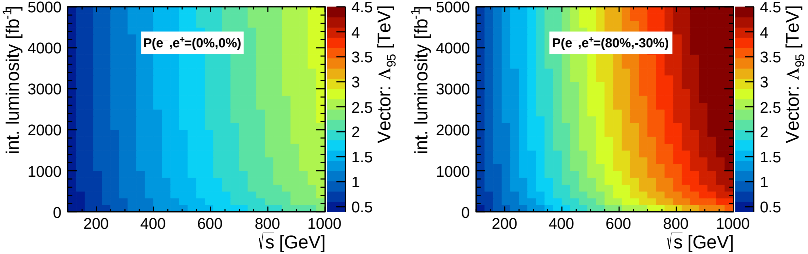






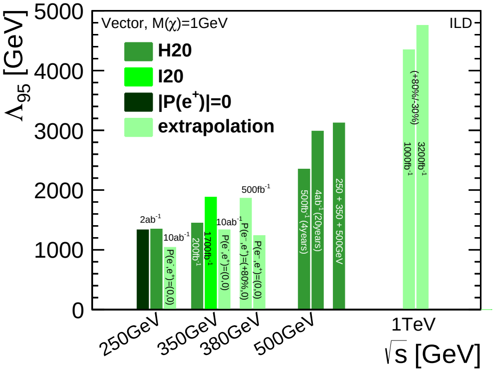
Extrapolation: results

Exclusion limits as a function of $\sqrt{s}$ and $\mathcal{L}$



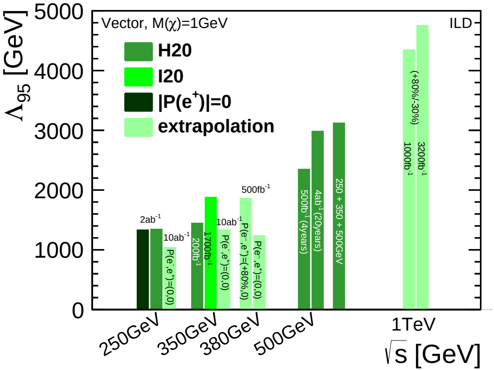
- higher energies are favored over high integrated luminosities
  $\Rightarrow$ linear colliders
- polarisation important
  $\Rightarrow$ ILC

Summary



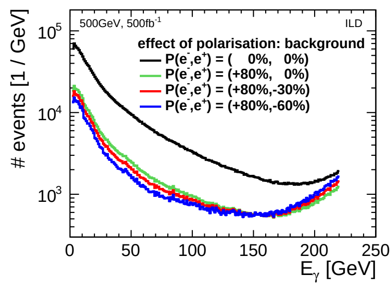
- 1 TeV results for the first time
- energy more important than luminosity
- polarisation crucial to decrease systematics (and to test chirality of new process)

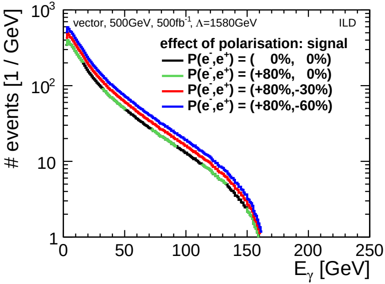
Summary

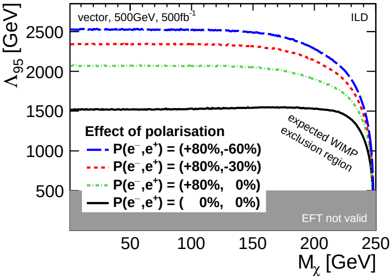


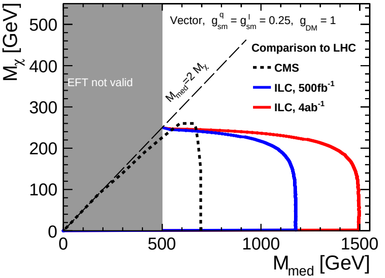
- 1 TeV results for the first time
- energy more important than luminosity
- polarisation crucial to decrease systematics (and to test chirality of new process)

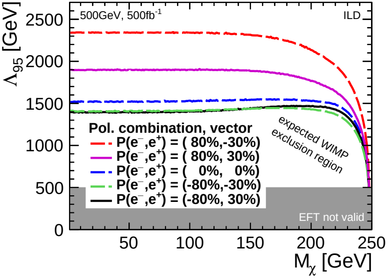
- WIMP study completed, thesis ready soon


500GeV, 500fb-1
ILD
effect of polarisation: background
P(e-,e+) = (0%, 0%)
P(e-,e+) = (+80%, 0%)
P(e-,e+) = (+80%,-30%)
P(e-,e+) = (+80%,-60%)
# events [1 / GeV]
Eγ [GeV]

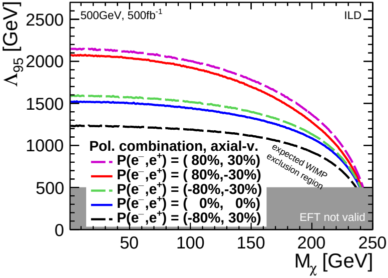

vector, 500GeV, 500fb-1, Λ=1580GeV
ILD
effect of polarisation: signal
P(e-,e+) = (0%, 0%)
P(e-,e+) = (+80%, 0%)
P(e-,e+) = (+80%,-30%)
P(e-,e+) = (+80%,-60%)
# events [1 / GeV]
Eγ [GeV]


vector, 500GeV, 500fb-1
ILD
Λ95 [GeV]
Effect of polarisation
P(e−,e+) = (+80%,-60%)
P(e−,e+) = (+80%,-30%)
P(e−,e+) = (+80%, 0%)
P(e−,e+) = (0%, 0%)
expected WIMP
exclusion region
EFT not valid
Mχ [GeV]

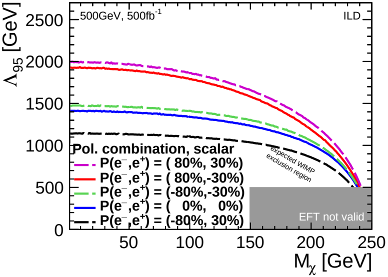

Vector, gsm q = gsm l = 0.25, gDM = 1
Comparison to LHC
CMS
ILC, 500fb-1
ILC, 4ab-1
EFT not valid
Mmed=2 Mχ
Mχ [GeV]
Mmed [GeV]



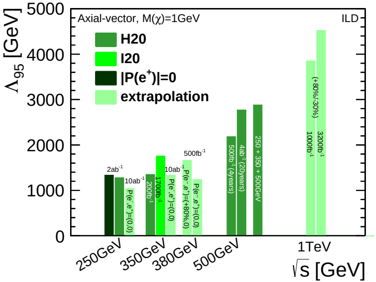
500GeV, 500fb⁻¹
ILD
Pol. combination, vector
P(e⁻,e⁺) = (80%,-30%)
P(e⁻,e⁺) = (80%, 30%)
P(e⁻,e⁺) = (0%, 0%)
P(e⁻,e⁺) = (-80%,-30%)
P(e⁻,e⁺) = (-80%, 30%)
expected WIMP exclusion region
EFT not valid
Λ95 [GeV]
Mχ [GeV]



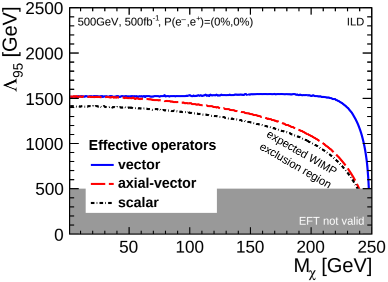
500GeV, 500fb⁻¹
ILD
Pol. combination, axial-v.
P(e⁻,e⁺) = (80%, 30%)
P(e⁻,e⁺) = (80%,-30%)
P(e⁻,e⁺) = (-80%,-30%)
P(e⁻,e⁺) = (0%, 0%)
P(e⁻,e⁺) = (-80%, 30%)
expected WIMP exclusion region
EFT not valid
Λ95 [GeV]
Mχ [GeV]

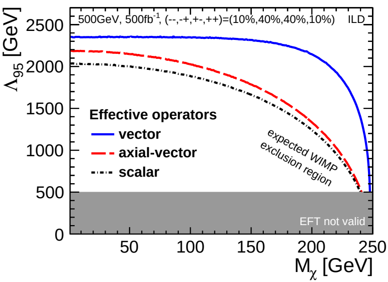


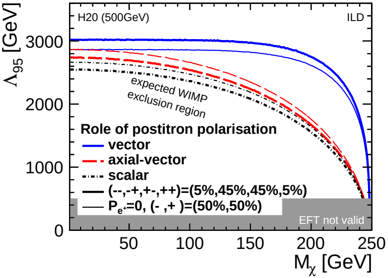
500GeV, 500fb⁻¹
ILD
Pol. combination, scalar
P(e⁻,e⁺) = (80%, 30%)
P(e⁻,e⁺) = (80%,-30%)
P(e⁻,e⁺) = (-80%,-30%)
P(e⁻,e⁺) = (0%, 0%)
P(e⁻,e⁺) = (-80%, 30%)
expected WIMP exclusion region
EFT not valid
Λ95 [GeV]
Mχ [GeV]

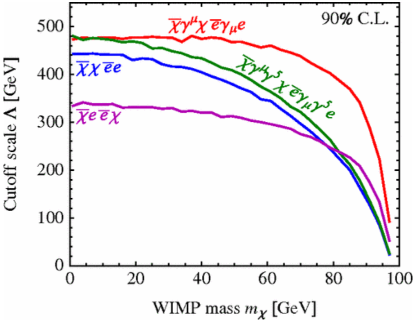


Axial-vector, M(χ)=1GeV
ILD
H20
I20
|P(e⁺)|=0
extrapolation
2ab⁻¹
10ab⁻¹
200fb⁻¹
1700fb⁻¹
500fb⁻¹
4ab⁻¹ (20years)
500fb⁻¹ (4years)
250 + 350 + 500GeV
1000fb⁻¹
3200fb⁻¹
(+80%/-30%)
250GeV
350GeV
380GeV
500GeV
1TeV
Λ95 [GeV]
√s [GeV]


500GeV, 500fb^{-1}, P(e$^-$,e$^+$)=(0%,0%)
ILD
Λ_{95} [GeV]
Effective operators
vector
axial-vector
scalar
expected WIMP exclusion region
EFT not valid
M_χ [GeV]


500GeV, 500fb^{-1}, (--,-+,+-,++)=(10%,40%,40%,10%)
ILD
Λ_{95} [GeV]
Effective operators
vector
axial-vector
scalar
expected WIMP exclusion region
EFT not valid
M_χ [GeV]


H20 (500GeV)
ILD
Λ_{95} [GeV]
expected WIMP exclusion region
Role of postitron polarisation
vector
axial-vector
scalar
(--,-+,+-,++)=(5%,45%,45%,5%)
P_{e^+}=0, (- ,+)=(50%,50%)
EFT not valid
M_χ [GeV]


90% C.L.
$\bar{\chi}\gamma^\mu\chi\bar{e}\gamma_\mu e$
$\bar{\chi}\chi\bar{e}e$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{e}\gamma_\mu\gamma^5 e$
$\bar{\chi}e\bar{e}\chi$
Cutoff scale Λ [GeV]
WIMP mass m_χ [GeV]