Dark matter searches with mono-photon signature at future $e^+e^-$ colliders

Aleksander Filip Žarnecki

Covering results from:

Research supported by

Dark Matter 2021: From the Smallest to the Largest Scales
September 15, 2021
**Probing Dark Matter with $e^+e^-$**

Many hints for existence of Dark Matter (DM), but its nature is unknown. Many possible scenarios, wide range of masses and couplings to consider.

High energy $e^+e^-$ machines offer many options for DM searches:

- **Higgs Frontier**
  - New Tool for Discovery

- **Energy Frontier**
  - Extendible to Multi-TeV

- **Luminosity Frontier**
  - ~1000x LEP

For more general picture see my presentation at [SUSY’2021](https://example.com/susy2021)
Introduction

**Mono-photon signature**

The mono-photon signature is considered to be the most general way to look for **DM particle production** in future $e^+e^-$ colliders.

DM can be pair produced in the $e^+e^-$ collisions via exchange of a new mediator particle, which couples to both electrons (SM) and DM states.

This process can be detected, if additional hard photon radiation from the initial state is observed in the detector...
Outline

1. Introduction
2. Colliders
3. Simulating mono-photon events
4. Mono-photon results
   - Heavy mediator approximation (CLICdp and ILD studies)
   - Light mediator exchange
5. Conclusions
International Linear Collider

Technical Design (TDR) completed in 2013

- superconducting accelerating cavities
- 250 – 500 GeV c.m.s. energy (baseline), 1 TeV upgrade possible
- footprint 31 km
- polarisation for both e\(^-\) and e\(^+\) (80%/30%)
Colliders

Compact Linear Collider

Conceptual Design (CDR) presented in 2012
- high gradient, two-beam acceleration scheme
- staged implementation plan with energy from 380 GeV to 3 TeV
- footprint of 11 to 50 km
- $e^-$ polarisation (80%)

For details refer to arXiv:1812.07987
Running scenarios

Staged construction assumed for both ILC and CLIC. Results presented in this talk focus on the highest energy stages.

**ILC**

Total of \(4000 \text{ fb}^{-1}\) assumed at 500 GeV (H-20 scenario)

- \(2 \times 1600 \text{ fb}^{-1}\) for LR and RL beam polarisation combinations
- \(2 \times 400 \text{ fb}^{-1}\) for RR and LL beam polarisation combinations

assuming polarisation of \(\pm 80\%\) for electrons and \(\pm 30\%\) for positrons

**CLIC**

Total of \(5000 \text{ fb}^{-1}\) assumed at 3 TeV

- \(4000 \text{ fb}^{-1}\) for negative electron beam polarisation
- \(1000 \text{ fb}^{-1}\) for positive electron beam polarisation

assuming polarisation of \(\pm 80\%\) for electrons
Simulating mono-photon events

For proper estimate of the mono-photon signature sensitivity consistent simulation of BSM processes and of the SM backgrounds is crucial.

“Irreducible” background comes from radiative neutrino pair-production

\[
\begin{align*}
e & \rightarrow e + \nu_i + \nu_i + \gamma \\
e & \rightarrow e + e + \nu_i + \gamma \\
e & \rightarrow e + e + \nu_i + \gamma
\end{align*}
\]

Detector acceptance & reconstruction efficiency

⇒ significant contribution from radiative Bhabha scattering

WHIZARD provides the ISR structure function option that includes all orders of soft and soft-collinear photons as well as up to the third order in high-energy collinear photons.

However, WHIZARD ISR photons are not ordinary final state photons: they represent all photons radiated in the event from a given lepton line.
Simulating mono-photon events

ISR structure function can not account for hard non-collinear photons
⇒ all “detectable” photons generated on Matrix Element level

Dedicated procedure developed to avoid double-counting of ISR and ME

Two variables, calculated separately for each emitted photon:

\[ q_- = \sqrt{4E_0E_\gamma} \cdot \sin \frac{\theta_\gamma}{2}, \]
\[ q_+ = \sqrt{4E_0E_\gamma} \cdot \cos \frac{\theta_\gamma}{2}, \]

are used to separate “soft ISR” emission region from the region described by ME calculations.
Simulating mono-photon events

ISR structure function can not account for hard non-collinear photons
\[ \Rightarrow \text{all “detectable” photons generated on Matrix Element level} \]

Dedicated procedure developed to avoid double-counting of ISR and ME

Two variables, calculated separately for each emitted photon:
\[
q_- = \sqrt{4E_0 E_\gamma} \cdot \sin \frac{\theta_\gamma}{2},
\]
\[
q_+ = \sqrt{4E_0 E_\gamma} \cdot \cos \frac{\theta_\gamma}{2},
\]
are used to separate “soft ISR” emission region from the region described by ME calculations.

Detector acceptance \( \sqrt{s} = 3 \text{ TeV} \)
Dark Matter searches at 3 TeV CLIC

Heavy mediator approximation, generator level

Signature:

- high energy, isolated photon
- no other “hard” activity in the detector

Highest sensitivity to DM production from the ratio of the photon energy distributions measured for the two electron beam polarisations

\[
\frac{\gamma}{E_0} \text{ (GeV)}, \quad P_t^{\gamma} \leq 170 \text{ GeV}, \quad \theta \geq 3 \text{ TeV}, \quad 10^2 \text{s}
\]

\[
\text{with systematic errors}
\]

\[
\sigma (95\%) \text{ [fb]}
\]

\[
\text{Data PeL/PeR, B+S S:Yv} \quad m_X = 1 \text{ TeV}
\]

\[
\text{Temp PeL/PeR, B}
\]

\[
\text{CLICdp 3 TeV, with systematic errors}
\]

\[
\text{PeL, L=4 ab}^{-1}
\]

\[
\text{PeR, L=1 ab}^{-1}
\]

\[
\text{PeL/PeR, L=1 ab}^{-1}
\]

\[
\text{PeNo, L=5 ab}^{-1}
\]

\[
\text{Ratio} \Rightarrow \text{cancellation of systematic uncertainties, but results model-dependent}
\]
Heavy mediator approximation, generator level

Limits on the mono-photon cross section can be translated to the expected exclusion range in the DM-mediator mass space.

For a light WIMP mass the exclusion range extends up to 9 TeV.

If significant excess of mono-photon events is observed, WIMP mass in a TeV range can be extracted with a 1% accuracy.
WIMP Dark Matter at the 500 GeV ILC

Heavy mediator (EFT limit), full simulation


Signature:

- single photon in the central region (high tracking efficiency)

Signal photon spectrum

- $\chi_M = 140\text{GeV}$
- $\chi_M = 220\text{GeV}$

"Irreducible" background from radiative neutrino pair-production events $e^+e^- \rightarrow \nu\nu + N$ dominates after selection and bg suppression cuts

A.F. Žarnecki (University of Warsaw)
Heavy mediator (EFT limit), full simulation

Signature:
- single photon in the central region (high tracking efficiency)
- no other activity in the detector
- veto in BeamCal (forward region)

"Irreducible" background from radiative neutrino pair-production events $e^+e^- \rightarrow \nu\nu + N\gamma$ dominates after selection and bg suppression cuts
WIMP Dark Matter at the 500 GeV ILC

Heavy mediator (EFT limit), full simulation

Different polarisation combinations help to reduce the systematics
⇒ significant improvement of mass scale limits

Sensitivity to the BSM mass scales up to $\Lambda \sim 3$ TeV

$$\Lambda^2 = \frac{M_Y^2}{|g_{ee}\gamma g_{\chi\chi\gamma}|}$$
Heavy mediator approximation

Comparison of mass scale limits calculated in the EFT framework

$e^+e^-$ mass reach comparable with that of FCC-hh !!!
New analysis approach

DM production via light mediator exchange **still not excluded**
for scenarios with very small mediator couplings to SM, $\Gamma_{SM} \ll \Gamma_{tot}$

“Experimental-like” approach
⇒ focus on cross section limits as a function of mediator mass and width

Detector response simulated in the **Delphes** framework (fast simulation).

**Whizard** level selection:
- 1, 2 or 3 ME photons
- at least one ME photon with $p_T^\gamma > 2\text{ GeV} \ \& \ 5^\circ < \theta^\gamma < 175^\circ$ (ILC 500 GeV)
- $p_T^\gamma > 5\text{ GeV} \ \& \ 7^\circ < \theta^\gamma < 173^\circ$ (CLIC 3 TeV)

**Delphes** level selection:
- single photon with $p_T^\gamma > 3\text{ GeV} \ \& \ |\eta^\gamma| < 2.8$ (ILC)
- $p_T^\gamma > 10\text{ GeV} \ \& \ |\eta^\gamma| < 2.6$ (CLIC)
- no other activity in the detector
- other reconstructed objects
Light mediator exchange

**Background vs Signal distributions**  

For mono-photon events, two variables fully describe event kinematics.  
⇒ use 2D distribution of \((p_T^\gamma, \eta)\) to constrain DM production

**Background**  

**Signal**

\[
\begin{align*}
\eta \gamma & \\
f_T^\gamma & \\
0 & 0.2 0.4 0.6 0.8 1
\end{align*}
\]

- **ILC 500 GeV** (-80%/+30%) 1600 fb\(^{-1}\)
- **Signal normalised** to unpolarised DM pair-production cross section of 1 fb

\[
M_\gamma = 400 \text{ GeV}, \Gamma/M = 0.03
\]
Cross section limits for radiative events (with tagged photon)

Vector Mediator $\Gamma / M = 0.03$

with and without systematics

ILC @ 500 GeV

CLIC @ 3 TeV

Systematic effects reduced for on-shell production of narrow mediator
Light mediator exchange

Cross section limits for radiative events (with tagged photon)

Vector Mediator $\Gamma/M = 0.5$ with and without systematics

ILC @ 500 GeV

CLIC @ 3 TeV

Systematic effects reduced for on-shell production of narrow mediator
Light mediator exchange

Cross section limits for total DM production cross section
Corrected for probability of hard photon tagging!

Combined limits for Vector mediator

ILC @ 500 GeV

CLIC @ 3 TeV

Radiation suppressed for narrow mediator with \( M_Y \sim \sqrt{s} \Rightarrow \) weaker limits
**Light mediator exchange**

**Cross section limits** for total DM production cross section
Corrected for probability of hard photon tagging!

Combined limits for mediators with $\Gamma/M = 0.03$

**ILC @ 500 GeV**

- Vector
- Pseudo-Vector
- Scalar
- Pseudo-Scalar
- $V$-$A$ coupling
- $V$+$A$ coupling

**CLIC @ 3 TeV**

- Vector
- Pseudo-Vector
- Scalar
- Pseudo-Scalar
- $V$-$A$ coupling
- $V$+$A$ coupling

Radiation suppressed for narrow mediator with $M_Y \sim \sqrt{s} \Rightarrow$ weaker limits
Light mediator exchange

**Coupling limits**

Combined limits for Vector mediator

**ILC @ 500 GeV**

**CLIC @ 3 TeV**

Almost uniform sensitivity to mediator coupling \( g_{eeY} \) up to kinematic limit.
Coupling limits

Combined limits for mediators with $\Gamma/M = 0.03$

Almost uniform sensitivity to mediator coupling $g_{eeY}$ up to kinematic limit.
Conclusions

**Dark matter searches with mono-photon signature at future e^+e^- colliders**

Future e^+e^- colliders: **many complementary options** for DM searches.

Mono-photon signature: the most general way to look for DM production, EFT sensitivity extending to the $\mathcal{O}(10)$ TeV mass scales

New framework for **mono-photon analysis** developed
focus on light mediator exchange and very small mediator couplings to SM

- $\mathcal{O}(1 \text{ fb})$ limits on the radiative production $e^+e^- \rightarrow \chi\chi\gamma_{\text{tag}}$
- $\mathcal{O}(10 \text{ fb})$ limits on the DM pair-production $e^+e^- \rightarrow \chi\chi(\gamma)$
  except for the resonance region $M_Y \sim \sqrt{s}$
- $\mathcal{O}(10^{-3} – 10^{-2})$ limits on the mediator coupling to electrons up to the kinematic limit $M_Y \leq \sqrt{s}$

For light mediators limits more stringent than those expected from direct resonance search in SM decay channels
Thank you!
Validation of the Whizard simulation procedure

Whizard predictions were compared to the results from the KKMC code for $e^+e^- \rightarrow \nu \bar{\nu} + N\gamma$

$3\text{ TeV CLIC}$

⇒ very good agreement observed (both for shape and normalisation)

For more details:

Simplified DM model

UFO model covering most popular scenarios of DM pair-production

Possible mediators:
- scalar
- pseudo-scalar
- vector
- pseudo-vector
- $V-A$ coupling
- $V+A$ coupling

Possible DM candidates:
- real or complex scalar
- Majorana or Dirac fermion
- real vector

Cross section for $e^+ e^- \rightarrow \chi \chi$ for $M_{\chi} = 50$ GeV and $M_Y = 300$ GeV
ISR rejection probability

Fraction of events generated by \texttt{WHIZARD} removed in merging procedure (ISR photons emitted in the phase-space region covered by ME)

ILC @ 500 GeV

CLIC @ 3 TeV

\begin{align*}
\frac{f_{\text{ISR rej.}}}{\%} & \text{ vs. } M_\gamma \text{ [GeV]} \\
\end{align*}
Tagging efficiency

based on Delphes simulation

Mono-photons reconstructed only in a fraction of generated signal event

\[ \sigma (e^+ e^- \rightarrow \chi \chi \gamma_{\text{tag}}) = f_{\text{mono-photon}} \cdot \sigma (e^+ e^- \rightarrow \chi \chi (\gamma)) \]

ILC @ 500 GeV

CLIC @ 3 TeV

Emission strongly suppressed for narrow mediator with \( M_Y \sim \sqrt{s} \)
Systematic uncertainties


Considered sources of uncertainties:

- Integrated luminosity uncertainty of 0.26% uncorrelated between polarisations
- Luminosity spectra shape uncertainty correlated between polarisations
- Uncertainty in neutrino background normalisation of 0.2% (th+exp) correlated between polarisations
- Uncertainty in Bhabha background normalisation of 1% (th+exp) correlated between polarisations
- Uncertainty on beam polarisation of 0.02–0.08% (ILC)/0.2% (CLIC) correlated for runs with same beam polarisation at ILC

⇒ nuisance parameters in the model fit (11 for ILC, 7 for CLIC)
Comparison of new analysis with ILD study

Effective mass scale limits: \[ \Lambda^2 = \frac{M_Y^2}{|g_{ee\gamma}g_{\chi\chi\gamma}|} \]

Limits from fast simulation (points) vs limits from full simulation (lines)

Very good agreement between full simulation and fast simulation results!
\( \Rightarrow \) reliable extrapolation to low mediator mass domain...