Long-lived particles at CLIC

Erica Brondolin (CERN), Emilia Leogrande (CERN), Ulrike Schnoor (CERN) on behalf of the CLICdp Collaboration

Searching for long-lived particles at the LHC:
5th Workshop of the LHC LLP Community
28 May 2019
Introduction

- signatures of new physics may be very diverse
- detectors at future colliders should be able to assess the broadest possible spectrum
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- signatures of new physics may be very diverse
- detectors at future colliders should be able to assess the broadest possible spectrum

- **CLIC** (Compact Linear Collider): promising to probe long-lived particles
  - 3 centre-of-mass energy stages: 380 GeV, 1.5 TeV, 3 TeV
  - clean collision environment
    - although some beam-induced background present (e.g. $\gamma\gamma \rightarrow$ hadrons)
  - no trigger
Outline

- Two long-lived particle studies performed in the framework of CLIC

1. **Degenerate Higgsino Dark Matter** analysis
   
   => *disappearing tracks*
   
   - generator level (CLICdet acceptance) \([CERN-2018-009-M, Sec 5.2]\)
   - full simulation study with CLICdet [new]

2. **Hidden valley searches in Higgs boson decays**

   => *displaced multitrack vertices*
   
   - full simulation study with CLIC_ILD \([CERN-2018-009-M, Sec 8.1]\)

Both searches need full simulation studies to assess the impact of beam-induced background

- **iLCSoft** framework to perform simulation, reconstruction and analysis
Degenerate Higgsino DM at CLIC

- Higgsino as WIMP dark mat
- dark matter relic abundance => thermal higgsino DM mass ~ O(TeV)
  - @ CLIC 3 TeV: E = 1.5 TeV, m ~ 1.05 TeV => $p^2 = E^2 - m^2$ => $p = 1.07$ TeV
- higgsino multiplet as SU(2)-doublet Dirac fermion (small mass splitting between charged and neutral components) => chargino travels ~ O(cm) before decaying into neutralino and soft pion
  - masses of chargino and neutralino very similar => pion too soft to be detected

=> chargino very straight and short track
a.k.a. ‘stub’ track
Degenerate Higgsino DM at CLIC

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- masses of chargino and neutralino very similar $\Rightarrow$ pion too soft to be detected

$\Rightarrow$ chargino very straight and short track a.k.a. ‘stub’ track

- CLIC (Compact Linear Collider) @ 3 TeV: promising to probe signature from thermal higgsino DM
Chargino at CLICdet

- CLICdet acceptance and tracking algorithm determine the capabilities of reconstructing tracks with $O(\text{cm})$ length

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<thead>
<tr>
<th>Barrel Radii [cm]</th>
<th>Endcap Z [cm]</th>
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<td>1 - 2</td>
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<td>5.8 - 6.0</td>
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(0,0) 6 cm 116 mm 130
Chargino at CLICdet

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- Minimum distance $d_{\text{min}}$ the chargino must travel to be reconstructable:
  - given minimum number of hits = 4 for tracking algorithm
  - given the geometric acceptance

\[
d_{\text{min}}(\theta) = \begin{cases} 
\frac{4.4 \text{ cm}}{\sin \theta} & 19^\circ < \theta < 90^\circ \\
\frac{22 \text{ cm}}{\cos \theta} & 13^\circ < \theta < 19^\circ \\
\frac{29 \text{ cm}}{\cos \theta} & 8^\circ < \theta < 13^\circ 
\end{cases}
\]
Charged stub - generator level

- Methods to count expected number of events with at least one (or two) identifiable stub tracks:
  - 100% efficiency assumed
  - background not included
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    - 50, 100, 200 GeV

N. Craig and S. Alipour-Fard
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All analyses cover large range of masses

- most optimistic strategies up to thermal dark matter target $m_X \sim 1.1$ TeV
- Results very promising, but need to be confirmed by full simulation and reconstruction

N. Craig and S. Alipour-Fard

[Graph showing 95% Exclusion Reach vs. $m_X$ (GeV)]
Charged stub - full simulation study

1. artificial short track sample

- No chargino sample was available at the time of this preliminary study
  => CLICdet reduced to the vertex detector only (workaround to produce artificially short tracks, i.e. ~ 6 hits on track)

  - [particle type] muons
  - [momentum] p = 1.0 TeV
  - [angular distribution] cos(theta)
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CLICdp work in progress

Flag for reconstructed

MonteCarlo tracks

Number of hits on track

- Efficiency larger than 90%
- Reconstructed tracks have correct number of hits in most of the cases
Charged stub - full simulation study

1. artificial short track sample

\[ \frac{(p_T,\text{rec} - p_T,\text{true})}{p_T,\text{true}} \]

- CLICdp work in progress
- Entries: 9325
- Mean: -0.8163
- Std Dev: 0.2824

\[ \text{reconstructed } p_T \text{ does not match the simulated one} \]
Charged stub - full simulation study

1. artificial short track sample

- In the presented study:
  - [length (d)] given that the IP is not a measurement* (i.e. a hit on the track), the track length has to be calculated as the difference between the outermost and innermost hit radii
  - CLIC beam spot smaller than LHC (@ 3 TeV: $\sigma_x = 40$ nm, $\sigma_y = 1$ nm)
    => this information can be used in a future refined study
  - [sagitta (s)] The smallest measurable sagitta is approximately equal to the single point resolution (divided by $\sqrt{2}$).

\[ p_T = 0.3B \left( \frac{d}{2} \right)^2 + \frac{s^2}{2s} \]

* CLIC beam spot smaller than LHC (@ 3 TeV: $\sigma_x = 40$ nm, $\sigma_y = 1$ nm)

reconstructed $p_T$ does not match the simulated one

- The sensitivity to the curvature of a particle in a given magnetic field depends on the length of the track (d) and on the sagitta (s)
Charged stub - full simulation study

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- **[sagitta (s)]** The smallest measurable sagitta is approximately equal to the single point resolution (divided by sqrt(2)).

- To be able to reconstruct properly the \( p_T \) of a 1 TeV track in the barrel
  - [single point resolution 3μm] stub length should be at least 12 cm

\[
\left(\frac{p_T,\text{rec} - p_T,\text{true}}{p_T,\text{true}}\right)
\]

\[
\begin{align*}
\text{CLICdp work in progress} & \\
\text{ptRes} & \\
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\text{Std Dev} & 0.2824 \\
\end{align*}
\]

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p_T = 0.3B \frac{(d/2)^2 + s^2}{2s}
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Charged stub - full simulation study

2. chargino samples $e^+ e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \pi^+ \tilde{\chi}_1^0 \pi^-$

- 10k events produced with WHIZARD(*) => 20k charginos
- chargino decays produced with PYTHIA and GEANT for correct decay vertex assignment (*)
- chargino mass 1050 GeV, neutralino mass 1049.8 GeV
- $c\tau = 20$ mm

(*) more details in back-up
Charged stub - full simulation study

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Efficiency 100%

reconstructed $p_T$ distribution compatible with preliminary study with artificially short muons

Study currently in progress

(*) more details in back-up
Charged stub - full simulation study
3. chargino samples with $\gamma\gamma \rightarrow$ hadron overlay

![Diagram showing bunch trains]
Charged stub - full simulation study
3. chargino samples with $\gamma\gamma \rightarrow \text{hadron overlay}$

- entire bunch train available for offline reconstruction (no trigger)
- ~ one hard interaction per bunch train, all other bunch crossings background only

**Diagram:**
- CLIC Beam
- $T = 20[ms]$
- 312 x 500ps
- 156ns
- bunch trains
- $t$
Charged stub - full simulation study

3. chargino samples with $\gamma \gamma \rightarrow $hadron overlay

- Main source of background in the barrel: beam-induced $\gamma \gamma \rightarrow $hadrons
- Full simulation used to overlay the simulated hits from background to simulated hits from signal
  - time stamp hits from detectors (central detectors $\leftrightarrow$ hard interaction)
  - impose timing cuts $\Rightarrow$ 30 bunch crossings integrated (10 before, 20 after hard interaction)
  - reconstruction window in silicon detectors: 10 ns
  - much better timing resolution for particles reaching the calorimeters

- entire bunch train available for offline reconstruction (no trigger)
- $\sim$ one hard interaction per bunch train, all other bunch crossings background only
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Charged stub - full simulation study

3. Charged stub - full simulation study

- Efficiency ~95%
- pT cut to reject beam-induced background

Study currently in progress
Hidden valley searches in Higgs decays

- hidden gauge sector coupling to SM particles at high energies
- models contain new massive long lived particles
- search for these LLP through displaced vertices reconstruction

- dominant production channel: VBF @ CLIC 3 TeV
- dominant decay mode: \( h \rightarrow \pi_v^0\pi_v^0 \rightarrow b\bar{b}b\bar{b} \)
- search for these LLP through displaced vertices reconstruction

- Observed 95% CL cross-section upper limits on the \( \sigma(H) \times \text{BR}(H\rightarrow\pi_v^0\pi_v^0) \) for three different \( \pi_v^0 \) masses as a function of \( \pi_v^0 \) lifetime

  - results from full simulation for CLIC_ILD
  - 100% branching fraction of decay into b quarks

- this analysis has been recast for heavy Higgs boson search (neutral naturalness theories)

\[ \frac{\sigma}{[\text{pb}]} \]

\[ \times \frac{\text{BR}(H\rightarrow\pi_v^0\pi_v^0)}{[\text{ps}]} \]

\[ \sigma(H) \times \text{BR}(H\rightarrow\pi_v^0\pi_v^0) \]

\[ \text{Lifetime [ps]} \]

\[ \text{CLICdp} \]

\[ m_{\chi^0} = 25 \text{ GeV/c}^2 \]

\[ m_{\chi^0} = 35 \text{ GeV/c}^2 \]

\[ m_{\chi^0} = 50 \text{ GeV/c}^2 \]

\[ \text{M. Kucharczyk and T. Woiton} \]

[https://cds.cern.ch/record/2625054/](https://cds.cern.ch/record/2625054/)
Conclusions

- **Long-lived particles** occur in many New Physics models
- **CLIC** is **well suited** to investigate signatures from long-lived particles
  - e+e- => clean environment
  - high energy => probe high mass states
  - linear collider => no trigger
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- Two analyses performed in CLIC, which underline the importance of **full simulation**:
  - **Higgsino DM**: chargino leaves short straight track (stub) in the vertex detector
    - study at the reconstruction level (both with artificially short muons and realistic chargino sample) shows **very good efficiency** but biased $p_T$ reconstruction
    - nevertheless: **reconstructed $p_T$ still valuable to reject most of the beam-induced background** already from presented preliminary results
    - **background rejection to be further studied and understood**
    - **scan in chargino masses to be performed**
    - **further investigation required with additional photon**
    - **possibility to profit from dE/dx from silicon layers**

- **Hidden valley in Higgs decays**
  - full simulation study to evaluate the sensitivity to masses and lifetimes
  - recast to heavier Higgs bosons
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  - dedicated studies required
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Idea/discussions with LLP community welcome!
Extra slides
Charged stub - generator level

- Two methods to count expected number of events with at least one (or two) identifiable stub tracks:
  - for both: no efficiency factor applied, no background included

- a) purely analytical method based on survival probability

\[
P_s(d_{\text{min}}) = e^{-m \chi d_{\text{min}}} \Gamma / |\vec{P}_x| \]

- b) Monte Carlo (MadGraph 5)
  - random decay length from lifetime distribution

\[
\Gamma(\chi^{\pm} \to \chi^0 \pi^{\pm}) = \frac{G_F^2}{\pi} \cos^2 \theta_c f_\pi^2 \delta m^3 \sqrt{1 - \frac{m_{\pi}^2}{\delta m^2}}
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- All analyses cover large range of masses
  - most optimistic strategies up to thermal dark matter target \( m_X \sim 1.1 \) TeV
Charged stub - full simulation study

2. artificial short track sample with $\gamma\gamma \rightarrow \text{hadron overlay}$

- 100 physics events: “short” muons with $p = 1$ TeV, distribution flat in $\cos \theta$

CLICdp work in progress

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reconstructed $p_T$ distribution
Charged stub - full simulation study

2. artificial short track sample with $\gamma\gamma \rightarrow$ hadron overlay

- 100 physics events: "short" muons with $p = 1$ TeV, distribution flat in $\cos \theta$

In spite of the limit on the $p_T$ sensitivity, the signal sample is well separated from the reconstructed tracks from background particles

✓ $p_T$ cut can be used to reject most of the background

NB: with the artificially short muons, most of the tracks have 6 hits

- real stub signal may be characterized by fewer hits on tracks $\rightarrow$ background and signal distributions may be less separated
- normalization to be investigated
- background from artificially short tracks with $n=6$ also to be estimated
Charged stub - generator level

- Purely analytical method based on survival probability
- no efficiency factor applied
- no background included

\[ P_s(d_{\text{min}}) = e^{-m_X d_{\text{min}} \Gamma_X / |\vec{p}_X|} \]

\[ N_{\text{evts}}^{1\text{-stub}} = L_{\text{int}} \times \int_{-1}^{1} \frac{d\sigma(e^+e^- \rightarrow \chi^+\chi^-)}{d\cos \theta} \left[ 2P_s(d_{\text{min}}) - P_s(d_{\text{min}})^2 \right] d\cos \theta \]

\[ N_{\text{evts}}^{2\text{-stub}} = L_{\text{int}} \times \int_{-1}^{1} \frac{d\sigma(e^+e^- \rightarrow \chi^+\chi^-)}{d\cos \theta} P_s(d_{\text{min}})^2 d\cos \theta. \]

- Monte Carlo validation (MadGraph 5)
- 5x10^4 events at each m_X interval
  - 100-180 GeV @CLIC 380 GeV
  - 100-800 @CLIC 1.5 TeV
  - 100-1600 GeV @CLIC 3 TeV
- random decay length from lifetime distribution
- counted if d > d_{\text{min}}
Charged stub - generator level

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  - counted if \( d > d_{\text{min}} \)

- charged stub only

- charged stub + photon
Charged stub - reconstruction level

1. artificial short track sample

- The hard limit on the maximum reconstructed $p_T$ is given by a combination of magnetic field, stub track length and single point resolution.

- For stub tracks of $p = 1$ TeV in the barrel ($\theta = 89$ deg) and length $d$:
  - From analytical estimate:
    - [max hits = 6] $d = r_{\text{max}} - r_{\text{min}} = 2.9$ cm $\Rightarrow p_T \sim 60$ GeV/c
    - [min hits = 4] $d = r_{\text{max}} - r_{\text{min}} = 1.5$ cm $\Rightarrow p_T \sim 16$ GeV/c
  - From analytical estimate and IP included as innermost hit on track:
    - [max hits = 6] $d = 6.0$ cm $\Rightarrow p_T \sim 254$ GeV/c
    - [min hits = 4] $d = 4.6$ cm $\Rightarrow p_T \sim 150$ GeV/c
  - From full simulation results [# hits = max hits = 6]:
    - [single point resolution 3$\mu$m (default)] mode of the reco $p_T$ distribution $\sim 35$ GeV/c
    - [single point resolution 1$\mu$m] mode $\sim 110$ GeV/c

\[ p_T = 0.3B \frac{\left(\frac{d}{2}\right)^2 + s^2}{2s} \]

- To be able to reconstruct properly the $p_T$ of a 1 TeV track in the barrel:
  - [single point resolution 3$\mu$m] stub length should be at least 12 cm
  - [single point resolution 1$\mu$m] stub length should be at least 7 cm
Monte Carlo generation for long-lived chargino pair production

- Process: chargino pair production where the charginos decay to a neutralino and a pion:
  \[ e^+ e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \pi^+ \tilde{\chi}_1^0 \pi^- \]

- Chargino mass \( m_{\tilde{\chi}_1^\pm} = 1050 \text{ GeV (PDGID = 1000024)} \),
  neutralino mass \( m_{\tilde{\chi}_1^0} = 1049.8 \text{ GeV (PDGID = 1000022)} \)

- Chargino lifetime \( c\tau = 60 \text{ mm (to be varied)} \)

- Whizard-2.7.0 used for generation of the hard process, Pythia6 for the parton shower
  - Full chain in Whizard up to neutralino and pion final state, with Pythia used for parton shower,
    OR:
  - Pythia can also do the chargino decay, passing the relevant parameters to the Whizard-Pythia interface:
    $\text{ps_PYTHIA_PYGIVE} = \"IMSS(1)=1;PMAS(312,1)=1050.;PMAS(312,4)=60.;MDCY(312,2)=2601;MDCY(312,3)=1;PMAS(310,1)=1049.8;MDCY(310,1)=0;KFDP(2601,1)=1000022;KFDP(2601,2)=211;KFDP(2601,3)=0;KFDP(2601,4)=0;KFDP(2601,5)=0;BRAT(2601)=1.0\"$

- Event record from Whizard does not contain the displacement (authors contacted)

- Workaround: Use Geant4 to obtain the displaced decay by setting the chargino lifetime in the Geant4 particle table\(^1\)
  - In ddsim, this is done via the option --physics.pdgfile particle.tbl

---

\(^1\)https://github.com/AIDASoft/DD4hep/blob/master/DDG4/examples/particle.tbl
Hidden valley searches in Higgs decays

- this analysis has been recast for heavy Higgs boson search (neutral naturalness theories)

- $m_H = 125 \text{ GeV}$

- $m_H = 600 \text{ GeV}$

- $m_H = 1000 \text{ GeV}$