Disappearing tracks at CLIC

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Searching for long-lived particles at the LHC: Seventh workshop of the LHC LLP Community - 26th May 2020
Long-lived particles at CLIC

- Various new physics models predict particles with macroscopic lifetimes
- CLIC = Compact Linear Collider
- High-luminosity linear $e^+e^-$ collider
- Three centre-of-mass energy stages: 380 GeV, 1.5 TeV, 3 TeV
- **Clean collision environment** compared to hadron colliders
  - Although some beam-induced background present
  - Possibility of triggerless readout
Experimental conditions @ 3TeV

- High luminosities achieved by using extremely small beam sizes
  → CLIC bunch size: 40 nm (x) x 1 nm (y) x 44 μm (z)
  → very high EM-fields → beam-beam interactions

- Main backgrounds:
  ○ Incoherent e^+e^- pairs
  ○ γγ → hadrons

- Linear colliders operate in bunch trains:
  ○ 312 bunches within train separated by 0.5 ns
  ○ Low duty cycle
  ○ Possibility of power pulsing of detectors
  ○ Possibility of triggerless readout
  ○ Bunch separation → Impact on detector design (timing, granularity)
Degenerate Higgsino Dark Matter

- Example of disappearing tracks signature
- Higgsino as WIMP **dark matter candidate**
- Dark matter relic abundance
  → Thermal higgsino DM mass ~ 1 TeV
- Higgsino multiplet as SU(2)-doublet Dirac fermion
  \( (\chi_1^\pm, \chi_1^0) \)
- **Decay process:** \( \chi_1^\pm \rightarrow \pi^\pm \chi_1^0 \)
  with **small mass splitting** between charged and neutral components → long-lived chargino
- Model parameters:

<table>
<thead>
<tr>
<th>chargino mixing</th>
<th>thermal limit mass</th>
<th>mass difference</th>
<th>lifetime</th>
<th>( cT )</th>
<th>( \Gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>pure higgsino</td>
<td>1050 GeV</td>
<td>355 MeV</td>
<td>0.023 ns</td>
<td>6.9 mm</td>
<td>( 2.86 \times 10^{-14} ) eV</td>
</tr>
</tbody>
</table>

**CLIC @ 3 TeV:**

\( E_e = 1.5 \) TeV, \( m_\chi \sim 1.05 \) TeV → \( p_\chi = 1.07 \) TeV

→ **pion very soft, difficult to detect**

→ **chargino very straight and short track**
Studies at generator level

- Analysis with 1 or 2 identifiable stub tracks and possibly additional photon at 3 TeV
  - Taking into account the geometrical acceptance and requiring a minimum length of the stub tracks to provide 4 hits
  - Background not included

- 95% exclusion reach
  - stub only and stub + ISR photon
  - different cuts on photon energy (50, 100, 200 GeV)

- All analyses cover large range of masses
- Most optimistic strategies up to thermal dark matter target \( m_\chi \sim 1 \text{ TeV} \)
- Results very promising
- Full simulation study on-going

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N. Craig and S. Alipour-Fard in *The CLIC Potential for New Physics*
The CLICdet tracker

- Superconducting solenoid with 4T magnetic field

- Vertex detector
  - $25 \times 25 \, \mu m^2$ pixels
    - 3 double layers in barrel
    - Spiral arrangement in forward region
  - Single point resolution = 3 $\mu m$
  - Material Budget < 0.2 % $X_0$ per layer

- Silicon Tracker
  - Large pixels/strips
  - Outer $R \sim 1.5$ m
  - Single point resolution = 7 $\mu m \times 90 \, \mu m$
  - Precise timing for background rejection:
    - < 10 ns hit time-stamping in tracking

- Full simulation with DD4hep geometry
Conformal Tracking

- Cellular Automaton-based track finding in conformal space
- The **conformal mapping** method is based on the fact that circles passing through the origin of a coordinate system can be translated onto straight lines in a new coordinate system (slide in backup)
- Tracking fully efficient in the entire tracker volume and at any transverse momentum more than 0.1 GeV
- Similar performance w/ and w/o background

Comprehensive article published recently:
How does an “event” look like?

Event display
\[ e^+e^- \rightarrow \chi^\pm \chi^\pm \rightarrow \pi^\pm \chi^0 \pi^\pm \chi^0 \@ 3 \text{ TeV} \]
without any background overlaid
How does an “event” look like?

Event display
\[ e^+e^- \rightarrow \chi^\pm\chi^\mp \rightarrow \pi^\pm\chi^0 \pi^\pm\chi^0 @ 3 \text{ TeV} \]

with \( \gamma\gamma \rightarrow \text{had background overlaid} \)

Full simulation used to overlay the simulated hits from \( \gamma\gamma \rightarrow \text{had background to the signal ones} \)

- impose timing cuts \( \rightarrow 30 \) bunch crossings integrated (10 before, 20 after hard interaction)

\( p_T \) and timing cuts are usually used to mitigate the background
Analysis strategy

- **Signal:**
  - Stub track candidate definition:
    - At least **four hits** in the tracking system
    - **Prompt, isolated** track
    - Minimum **transverse** momentum
    - **Disappearing** within the tracking system volume
    - No energy deposition in the **calorimeter**
    - Additional: dE/dx requirement
  - At least one stub candidate per event
  - Additional: soft displaced pion(s) and additional photons
  - Samples generated:
    - $c_\tau = 6.9 \text{ mm}$
    - $c_\tau = 180 \text{ mm}$
    - $c_\tau = 600 \text{ mm}$
    - (Default: $c_\tau = 600 \text{ mm}$ to increase statistics)

- **Background:**
  - Beam-induced $\gamma\gamma \rightarrow$ hadrons:
    - random combination of hits
    - split tracks
    - conversion
Chargino tracking efficiency

- Challenges for chargino tracks reconstruction:
  - Short
  - Straight
- $p_T$ reconstruction of short, straight tracks is limited by the single point resolution and length of the track ($\sim n_{\text{Hits}}$), but can still be powerful

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Long-Lived particles at CLIC

(1) Arbitrary normalisation
Chargino tracking efficiency

- Challenges for chargino tracks reconstruction:
  - Short
  - Straight
- Reconstruction is more difficult for short charginos
- Performance are similar if background is included

Reconstruction of short, straight tracks is limited by the single point resolution and length of the track ($\sim n_{\text{Hits}}$), but can still be powerful.
Pion tracking efficiency

- Challenges for pion tracks reconstruction:
  - Displaced
  - Very soft
- Soft displaced pions are well reconstructed
- Duplicate tracks in central region due to loopers

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Challenges for pion tracks reconstruction:
- Displaced
- Very soft
- Soft displaced pions are well reconstructed
- Duplicate tracks in central region due to loopers

Reconstruction is more difficult for displaced pions
Performance are similar if background is included
Stub track properties

- Min $n_{\text{Hits}} = 4$
- **Prompt** track
  - Promptness $= \sqrt{d_0^2 + z_0^2}$
  - Possible cut at 0.5 mm

![Graph](image)
Stub track properties

- Min \( n_{\text{Hits}} = 4 \)
- Prompt track
  - Promptness = \( \sqrt{d_0^2 + z_0^2} \)
  - Possible cut at 0.5
- **Isolated** track
  - Isolation = \( \Delta R_{\text{nearest track}} \)
  - Possible cut at 0.1
  - Other isolation criteria are under investigation, e.g. \( p_T \) sum in a cone.

Reconstructed
- other tracks
- \( \chi_1^{\pm} \)
Stub track properties

- Min $n_{\text{Hits}} = 4$
- Prompt track
  - Promptness = $\sqrt{d_0^2 + z_0^2}$
  - Possible cut at 0.5
- Isolated track
  - Isolation = $\Delta \mathcal{R}_{\text{nearest track}}$
  - Possible cut at 0.1
- Transverse momentum requirement
  - Possible cut at 10 GeV
  - Preliminary with low background statistics
  - Effect on shorter stub under investigation

(*) Arbitrary normalisation
Stub track properties

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- Transverse momentum requirement
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  - Effect on shorter stub under investigation
- No **energy deposition** in the calorimeter (PFO)
  - Charginos associated to PFO (14.1 %) include:
    - standalone tracks below 1.5 GeV
      (assigned as PFO)
    - overestimate of the lifetime
Preliminary background study

- $\gamma\gamma \rightarrow \text{hadrons-only sample is used to study the main background}$
- By requiring at least on stub candidate with:
  - Promptness < 0.5 mm
  - $p_T > 10$ GeV
  - No PFO association
  $\rightarrow$ Fakerate $\sim 0.32\%$
  $\rightarrow$ Efficiency $\sim 82.7\%$
- Ongoing study to further understand and suppress the background:
  - Additional cut could be on $<dE/dx>$
    - $dE/dx$ resolution
  - Optimise analysis selection
  - Additional requirement on pions
  - Possibility to add photons

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Long-Lived particles at CLIC

26th May 2020
Conclusions and outlook

- Long-lived particles signatures = **unexplored avenues** for searches for new physics
- Charged long-lived particles at **CLIC** benefit from clean environment and high precision of the track reconstruction

- Investigated a sample of long-lived chargino pair production ($e^+e^- \rightarrow \chi^+\chi^- \rightarrow \pi^+\pi^-\chi^0\chi^0$)
- Track reconstruction of stub tracks quite **efficient** but...
  - $p_T$ reconstruction limited by length of the track (still useful!)
- Additional **soft pion** can increase detectability

- Preliminary background study shows handle on $\gamma\gamma \rightarrow$ hadrons by optimizing stub track definition and dE/dx criterion
Backup
CLIC input to European Strategy Update

- Yellow Reports:
  - CLIC 2018 Summary Report
  - CLIC Project Implementation Plan
  - The CLIC Potential for New Physics
  - Detector technologies for CLIC

- Two formal ESU submissions:
  - Physics Potential
  - Accelerator and Detector

- Many more Journal publications and CLICdp Notes

- Full list can be found in: http://clic.cern/european-strategy
The conformal mapping method is based on the fact that circles passing through the origin of a coordinate system \( xy \) can be translated onto straight lines in a new coordinate system \( uv \):

\[
\begin{align*}
  u &= \frac{x}{x^2 + y^2} \\
  v &= \frac{y}{x^2 + y^2}
\end{align*}
\]
Conformal tracking in CLICdet

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Hit collection</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build tracks</td>
<td>Vertex barrel</td>
<td>Standard cuts</td>
</tr>
<tr>
<td>Extend tracks</td>
<td>Vertex endcap</td>
<td>Standard cuts</td>
</tr>
<tr>
<td>Build tracks</td>
<td>Vertex</td>
<td>Looser cuts (angle x 5)</td>
</tr>
<tr>
<td>Build tracks</td>
<td>Vertex</td>
<td>Looser cuts (angle x 10; $\chi^2$ x 20)</td>
</tr>
<tr>
<td>Extend tracks</td>
<td>Tracker</td>
<td>Looser cuts (angle x 10; $\chi^2$ x 20)</td>
</tr>
<tr>
<td>Build tracks</td>
<td>Vertex + Tracker</td>
<td>Displaced cuts</td>
</tr>
</tbody>
</table>

- **5 steps targeting prompt-tracks:**
  - From vertex detector to silicon tracker
  - Min number of hits = 4
  - Standard or looser (angle or $\chi^2$) cuts

- **1 step targeting displaced tracks:**
  - Quadratic terms in conformal space fit added
  - Inverted order search: from silicon tracker to vertex detector
  - Broader search angle than for prompt tracks
  - Min number of hits = 5
Definitions

**Associated** particle = Simulated MC particle from which the majority of track hits are originated

**Reconstructable** particle = stable MC particle with following requirements:
- \( p_T > 0.1 \text{ GeV} \)
- \(|\cos\theta| < 0.99\)
- unique hits \( \geq 4 \)

**Purity** = Number of track hits associated to the same MC particle
- *Pure track* if purity \( \geq 75 \% \)
- *Fake track* if purity \(< 75 \%\)

\[ \text{Efficiency} = \frac{\# \text{pure tracks associated to MC particle}}{\# \text{reconstructable MC particles}} \]

\[ \text{Fake rate} = \frac{\# \text{fake reconstructed tracks}}{\# \text{reconstructed tracks}} \]