Long-lived particles at CLIC

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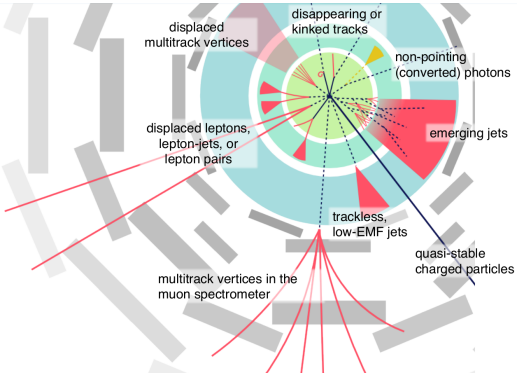
CLICdp Meeting 2020

Introduction to long-lived particles (LLP)

- Various new physics models predict particles with macroscopic lifetimes
- Example: Small mass splitting/compressed spectra
- "Standard" analyses lack sensitivity
- Variety of signatures in detectors depending on the model (mass, lifetime, boost)
- Long-lived particles at LHC:
  - LHC LLP overview report: 1903.04497
  - Many ongoing analyses
  - Proposed dedicated experiments (e.g. FASER)
- Physics beyond colliders: 1901.09966

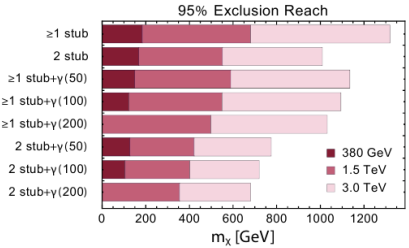


from https://indico.cern.ch/event/607314/contributions/2542309

Long-lived particles at CLIC

1. Hidden valley searches in Higgs boson decay
   - displaced multi-track vertices
   - full simulation study with CLIC_ILD CLICdp-Note-2018-001
2. Degenerate Higgsino Dark Matter
   - Theory-level study for the CLIC Potential for New Physics yellow report [1812.02093] by N. Craig and S. Alipour-Fard
   - Process: chargino pair production
   - Stub tracks from charged Higgsino with a lifetime of 6.9 mm
   - Decay to pion and neutralino
   - Using geometrical detector acceptance and minimum reconstructable length for the efficiency of reconstructing the stub tracks

- Analysis with 1 or 2 stubs and possibly additional photon at 3 TeV
- Resulting exclusion limits assuming no background:

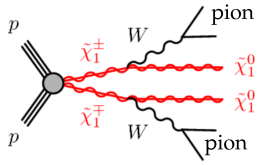


(Fig. 74 from the YR)

- Reach thermal DM mass of ≈ 1 TeV

Full simulation of LLP chargino pair production

- Process: chargino pair production where the $\chi_1^\pm$ decay to a neutralino and a pion: $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\pi^+\tilde{\chi}_1^0\pi^-$
- CLICdet at 3 TeV, with ISR and Beamspectrum included
- Small mass difference between chargino and neutralino: Chargino mass $m_{\tilde{\chi}_1^\pm} = 1050\,\text{GeV}$, neutralino mass $m_{\tilde{\chi}_1^0} = 1049.645\,\text{GeV}$
- Production chain:
  - Chargino pair production and decay in Whizard
  - Parton shower and hadronization in Pythia
  - Displacement of the decay vertex in Geant4



chargino mixing	thermal limit mass	mass difference	lifetime	$c\tau$	Γ
pure higgsino	1050 GeV	355 MeV	0.023 ns	6.9 mm	2.86×10^{-14} eV

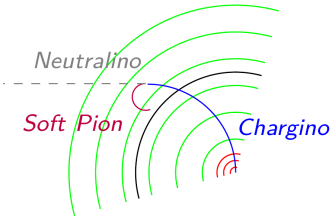
- Sample produced for the studies shown here uses lifetime of 600 mm in order to increase the statistics of reconstructable charginos

Analysis strategy

Stub track analysis at 3 TeV with CLICdet

Signal selection

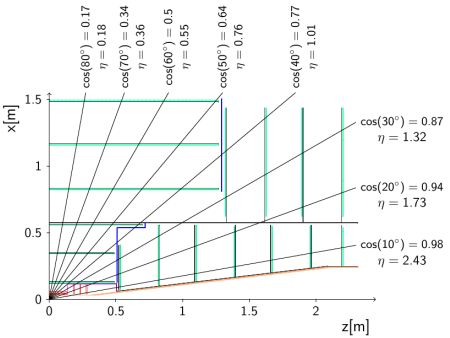
- Stub track candidate definition:
  - at least four hits in the tracking system
  - disappearing within the tracking system volume
  - no energy deposition in the calorimeter
  - prompt, isolated track
  - minimum transverse momentum
  - dE/dx requirement
- At least one stub candidate per event
- Additional: Requirements on soft displaced pion(s)
- Additional: Requirements on additional photons



Backgrounds:

- Beam-induced $\gamma\gamma \rightarrow$ hadrons:
  - algorithmic
  - split tracks
  - conversion
- final states with low multiplicity of isolated leptons

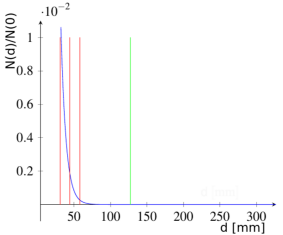
Track reconstruction for the analysis



CLICdet vertex & tracker

2 challenging types of objects for track reconstruction with conformal tracking:

- Stub track reconstruction
  - in many cases too short to be reconstructable
  - at CLIC 3 TeV: $E_{max} = 1.5$ TeV, m = 1.05 TeV $\Rightarrow p_{max} \approx 1.07$ TeV
  - $\Rightarrow$ chargino gives very straight and short track $\Rightarrow$ difficult to reconstruct track parameters
- Displaced pions
  - very soft
  - displaced

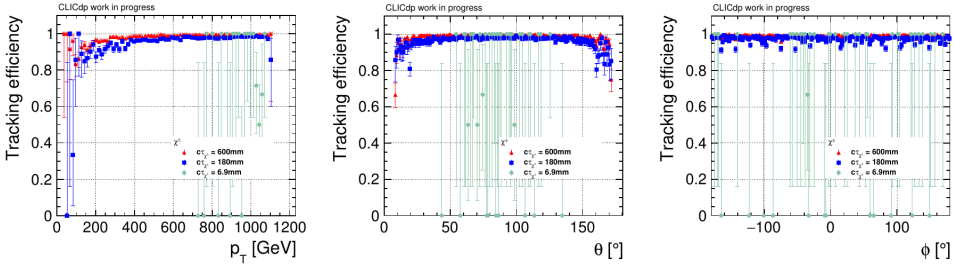


chargino lifetime distribution at $\theta = 90°$ for $c\tau = 6.9$ mm:

– vertex barrel double layers

Tracking performance

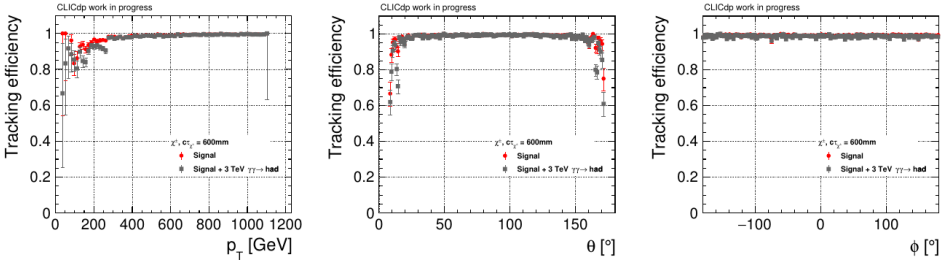
- Customized tracking validation code in place
- More details: *see Erica's slides from 01-09-2020*
- Chargino tracking efficiency for different lifetimes without overlay:



- Low statistics for the sample with short lifetime (6.9 mm)
- Consistent behaviour, higher tracking efficiencies for longer tracks

Chargino reconstruction with overlay

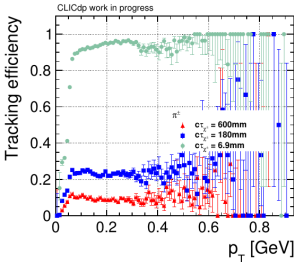
- Comparison with and without overlay shows very similar performance:

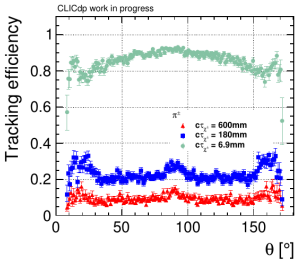


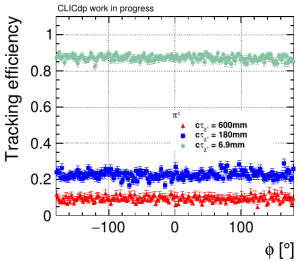
for the 600 mm sample

Pion reconstruction and tracking performance

- Very soft pions *could* be used as an additional signature to the stub track
- Tracking efficiency highly depends on the lifetime of the chargino, i.e. the displacement of the vertex of origin of the pion







Lifetime reweighting for the signal

- The samples were produced with a longer lifetime than in the model
  - to ensure efficient Monte Carlo generation
  - to allow lifetime-dependent limit setting
- Use the survival probability for the chargino to travel at least the distance d_{min}:

$$P_s(d_{\text{min}}) = \frac{1}{k} e^{(-m_{\tilde{\chi}} d_{min} \Gamma_{\tilde{\chi}})/p_{\tilde{\chi}}}$$

  - chargino mass $m_{\tilde{\chi}}$
  - chargino momentum $p_{\tilde{\chi}}$
  - decay width $\Gamma_{\tilde{\chi}}$
  - normalization constant $k = \frac{pc\tau}{m}$

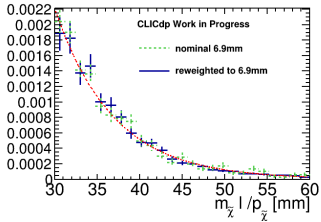
- Resulting weights for each chargino:

$$w(\ell) = \frac{P_{target}(\ell)}{P_{MC}(\ell)} = \frac{c\tau_{MC}}{c\tau_{target}} \exp\left(-m_{\tilde{\chi}} \frac{\ell}{p_{\tilde{\chi}}} \left[\frac{1}{c\tau_{target}} - \frac{1}{c\tau_{MC}}\right]\right)$$

applied to each event for both charginos based on truth trajectory ℓ

Validation of reweighting

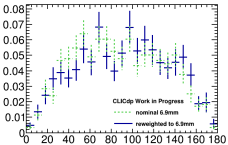
- Validate the lifetime distribution:

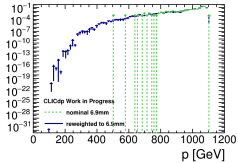


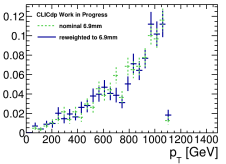
(both normalized to 1.0)

- statistical errors smaller for the reweighted sample for values above 30 mmm (relevant range for our detector)

- Validate kinematic properties:
  ($\ell > 30$ mm to mimic detector acceptance)







- good agreement between nominal and reweighted
- validation of event-wise and pion variables good agreement as well

Chargino candidate preselection

Charginos are pre-selected from `SiTracks_Refitted` tracks with the following criteria now:

- $p_T > 1\,\text{GeV}$,
- $\sqrt{d_0^2 + z_0^2} < 0.5\,\text{mm}$
- if $p_T > 1.5\,\text{GeV}$, they should not be associated with a PFO
- isolation: the sum of the pTs of the tracks surrounding the chargino candidate track in a cone of R=0.1 must not be more than 10 % of the chargino candidate track pT, i.e.

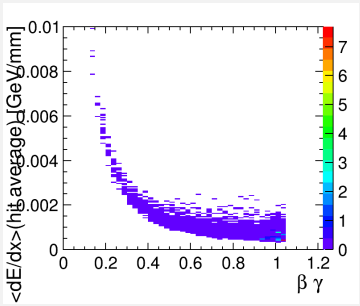
$$\frac{\sum_{tracks} p_T(R \leq 0.1)}{p_T(track)} < 0.1$$

The 2 preselected tracks with highest reconstructed pT are considered as chargino candidates in the event

dE/dx as a discriminating variable

- Study whether dE/dx can be used as a discriminating variable, possibly compensating part of the loss of sensitivity due to the limited reconstruction of pT from tracking
- dE/dx is related to $\beta\gamma = p/m$ which is around 1 for the signal but larger for some of the backgrounds as they have smaller mass $\rightarrow$ potential discrimination

Average dE/dx vs. $\beta\gamma$ (truth) for the highest pT chargino (after preselection):



- Cutoff at 1.02 due to the restriction of the energy to $\sqrt{s}/2 = 1500\,\text{GeV} \Rightarrow$ momentum $p < 1071\,\text{GeV} \Rightarrow \beta\gamma = \frac{p}{m} < 1.02$
- Compare to: (PDG)

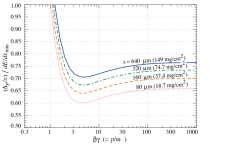


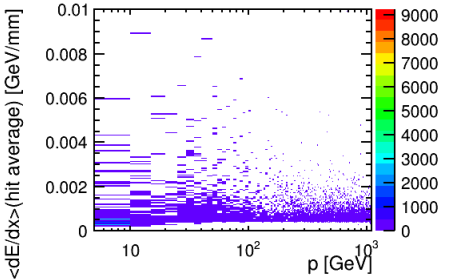
Figure 34.9: Most probable energy loss in silicon, scaled to the mean loss of a minimum ionizing particle, 388 eV/μm (1.66 MeV g^{-1}cm^2).

- Agreement with prediction

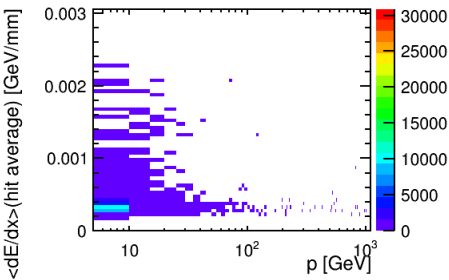
dE/dx vs reco momentum

- Average dE/dx vs reco momentum for the signal and background chargino candidates (after preselection)

ch1 (highest pT) in signal



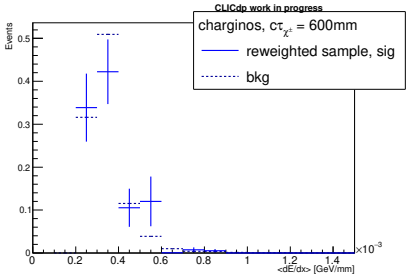
ch1 (highest pT) in background



- Difference between the distributions, note that the y axis ranges are quite different
- However the maximum is for both cases at low pT and low dE/dx

dE/dx comparison and conclusions

Comparison between Signal and Background for average dE/dx:



- Fluctuations, but no clear shape difference that would allow using a cut
- The detector acceptance introduces a bias towards more boosted particles: if $\ell^{LF} > 30\,\text{mm}$ cut is applied, this implies a cut on γ: $\gamma > \frac{\ell^{RF}}{30\,\text{mm}}$ (especially for low $c\tau$)

$\Rightarrow$ low dE/dx

- This would be different for larger p/m, i.e. smaller mass or higher $\sqrt{s}$

$\Rightarrow$ dE/dx can still be useful for disappearing tracks in other models/parameter points

Conclusions & Outlook

- Reweighting the 600mm sample to 6.9mm works
- New isolation variable
- Investigated dE/dx as a discriminating variable

Outlook

- Background estimate from $\gamma\gamma \rightarrow$ hadrons-only samples
  - shapes of distributions
  - normalization/extrapolation of total number
- Estimate sensitivity, potentially in dependence of lifetime and chargino (Higgsino) mass

Additional Material

Available samples

- **production v2**
  - signal only: lifetime 600mm, neg. e^- beam pol, 50k events
  - signal + $\gamma\gamma \rightarrow$ hadrons background
  - only $\gamma\gamma \rightarrow$ hadrons background
- **production v3**
  - signal only: lifetime 180mm, no e^- beam pol, 50k events
- **production v4**
  - signal only: lifetime 6.9mm, neg. e^- polarisation, 50k events
  - signal + $\gamma\gamma \rightarrow$ hadrons background