Ideas to search for Hidden Valley

Marcin Kucharczyk *(HNI Krakow)*

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Theoretical models

Hidden sector – generic possibility for NP

„Sectors with non-abelian gauge group with a new quantum number „v" (analogous to charge →v = 0, ±1), which couple weakly to the Standard Model via higher dimension operators, and which has a mass gap."

Strassler & Zurek

Consequence of string-theory

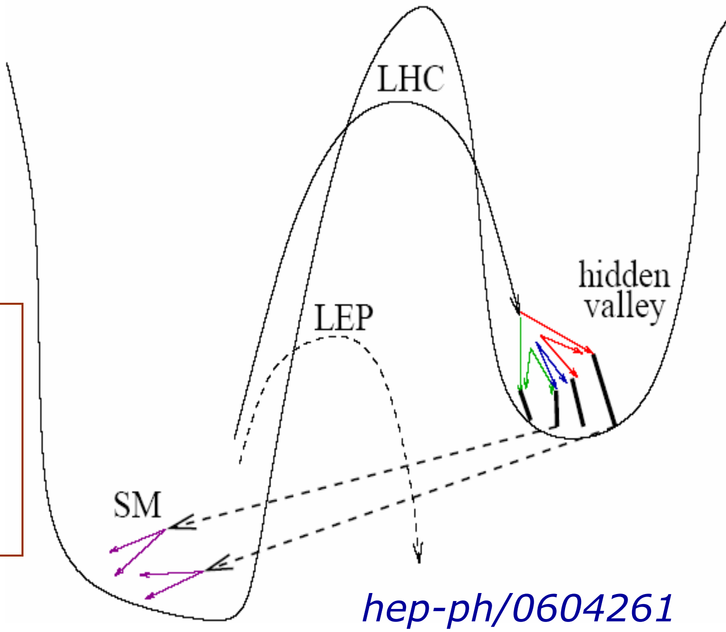
→ additional gauge sectors may be introduced to SM, SUSY, TeV-ED

- hidden sector - „v-sector"
- communicator - interacts with both sectors

BARRIER *(communicator's high mass, weak couplings, small mixing angles, ...)*

→ weakens the interactions between sectors

→ production of new particles rare at low energy



hep-ph/0604261

Hidden sectors and communicators

SM group G_{SM} extended with non-abelian group G_v

→ all SM particles neutral within G_v

→ if energy sufficient → ***v-particle*** charged within G_v, neutral under G_{SM}

Possible bridges to the hidden sector

- *W, Z*
- *Higgs*
- *LSP*
- *Z′*
- *neutrino*
- *graviton*

…

→ *gauge invariant operator to connect SM and HV sector*

At TeV scale high dimension operators (Z′, Higgs) make possible interactions
SM ↔ v-particles

How to find the hidden sector

- **Connector** - particle charged under both sectors

  $\rightarrow$ higher dimensional operator *(e.g. Higgs - 2-dim)*

- ***v*-hadrons** *(π_v^0)*

  $\rightarrow$ neutral under G_{SM}

  $\rightarrow$ weakly coupled to SM

  $\rightarrow$ can decay into combinations of SM particles *(quark or lepton pairs)*

  $\rightarrow$ macroscopic decay lengths

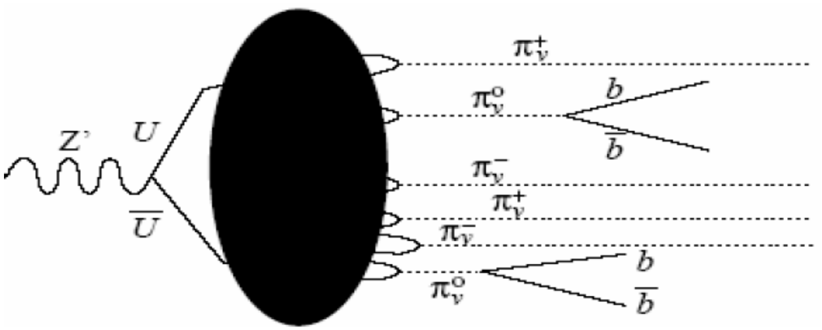
LOOKING FOR: long-lived particles *(LLP's)*

if lifetime between 1 ps and 1 ns *(characteristic for weak decays)*
can be identified in tracking systems by displaced vertices!

Direct production via Z'

Direct multi-π_v production

- $Z' \rightarrow \pi_v^0 + \pi_v^+$
  - $\pi_v^0 \rightarrow b\bar{b}$
  - $\pi_v^+ \rightarrow$ *missing energy*



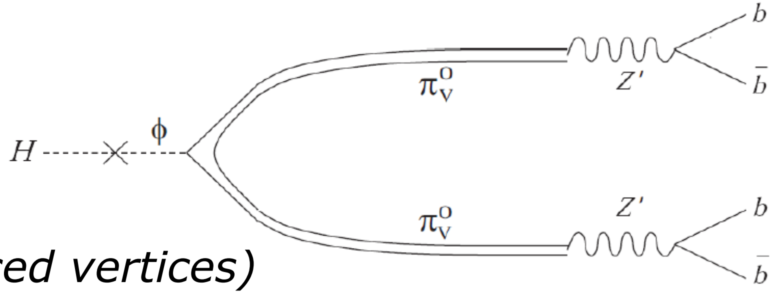
- π_v^0 and $\pi_v^\pm$ are **electrically neutral!**
- *v*-quark production results in multiple *v*-hadron production with ratio *$m(Z')/\Lambda_v$* *(Λ_v : v-confinement scale)*

v-hadron production multiplicities could be **large if Λ_v << *1TeV***

Higgs decays into *v*-particles

- **SM Higgs may decay into 2 *v*-particles, each decaying to *bb(bar)***

$$h^0 \rightarrow \pi_V^0 \pi_V^0 \rightarrow b\bar{b}b\bar{b}$$



- 4 *b*-jets in the final state *(2 displaced vertices)*

- **distant from PV and beam axis**

Scalar decaying to the heaviest particles it has access to in order to defeat natural helicity suppression

- **Hidden Valley $\rho_v^0 \rightarrow$ di-lepton**

$$h^0 \rightarrow \rho_v^0\, \rho_v^0, \quad \text{both} \quad \rho_v^0\text{'s} \rightarrow \mu^+\mu^-$$

- *4 muons in the final state*

- *search for v-particles in muon chambers (lifetimes >> 1ns)*

Phys. Lett. B651 (2007) 374

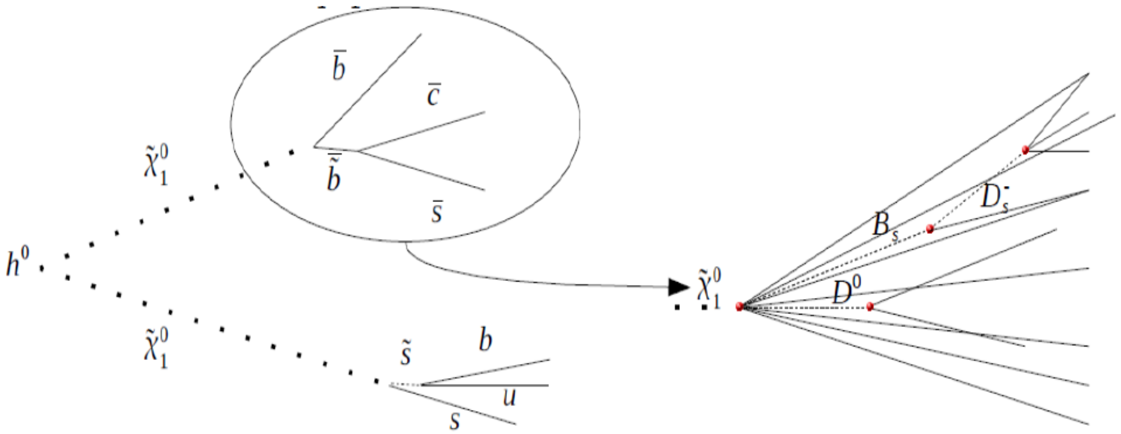
mSUGRA with baryon number violation

Similar signatures *(displaced vertices)* have other models like mSUGRA with BNV

„Six-Quark decays of the Higgs Boson in Supersymmetry with R-Parity Violation"

Kaplan model

- LSP in MSSM *(neutralino)* may decay because of baryon number violation
- neutralino decays into 3 quarks via virtual squark
- within this model light Higgs may decay into 2 neutralinos



6 (*b*)-jets in the final state *(3 displaced vertices)*

Phys. Rev. Lett. 99 (2007) 211801

If there is a hidden valley sector…

What states?

How many?

How do we know these states are SM gauge singlets?

Masses/spins of states

Symmetries of the hidden sector

How does it communicate to SM?

What communicator?

Experimental challenges

Analysis strategy

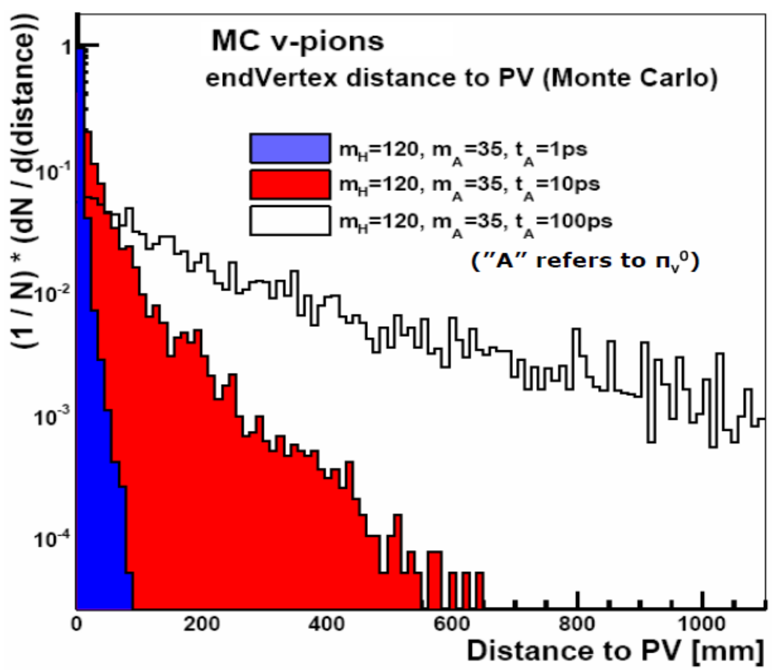
v-paricles have non-zero lifetime

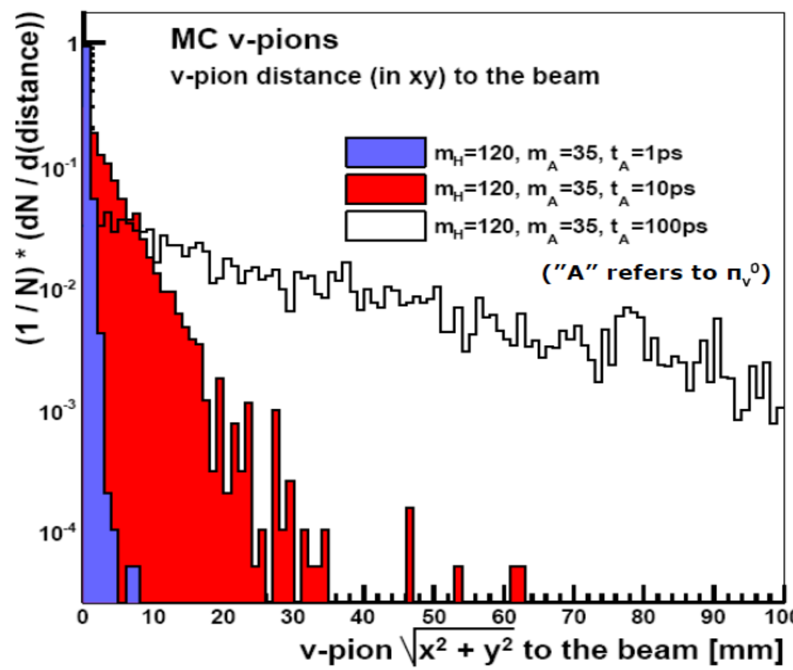
→ analysis based on reconstruction of SV's „far" from PV and beam axis

→ displaced vertices *(DV)*

- at least 2 displaced vertices
- distant from beam axis
- nr of tracks assigned to DV > 5
  (to eliminate the background from b-hadron decays)
- cut on inv. mass of the DV

Signal samples generated using Pythia 6.4 for pp collisions





Background

Main sources of background at hadron colliders

- Displaced vertices from secondary interactions with detector material
  → eliminate by MATTER VETO
- **QCD background**
  → inclusive *bb(bar)* production
  (4b's produced because of NLO effects, like gluon splitting)
  → 4b's
  → 4c's
  → 2b+2c

Hadron colliders

- high background levels
- high particle multiplicities
- unknown initial state
- complex trigger

Limits from hadron colliders

Limits from hadron colliders for $H \to \pi_v^0\, \pi_v^0,\quad \pi_v^0 \to bb(bar)$

CDF
Phys. Rev. D85 (2012) 012007

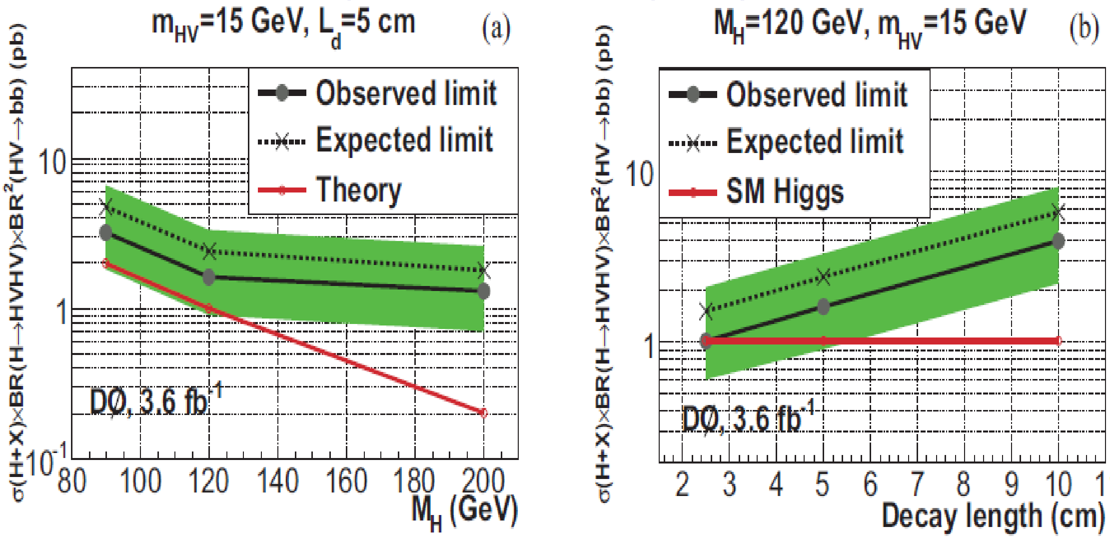
D0
Phys. Rev. Lett. 103 (2009) 071801

ATLAS
Phys. Rev. Lett. 108 (2012) 251801
(7 TeV, 2 fb^{-1})

CMS
CMS-PAS-EXO-12-038
(8 TeV, 19 fb^{-1})

LHCb
LHCb-CONF-2012-014
(7 TeV, 37 pb^{-1})

Phys. Rev. Lett. 103 (2009) 071801



LHCb-CONF-2012-014

LLP lifetime = 10 ps @ 95% CL

m_{LLP} / m_{h^0}	30	35	40	48	55
100	101	58	44	58	
105	100	75	44	39	
110	132	75	56	34	
114	128	91	47	32	46
120	148	93	58	34	31
125	179	90	61	41	29

Upper limits *(in pb)*

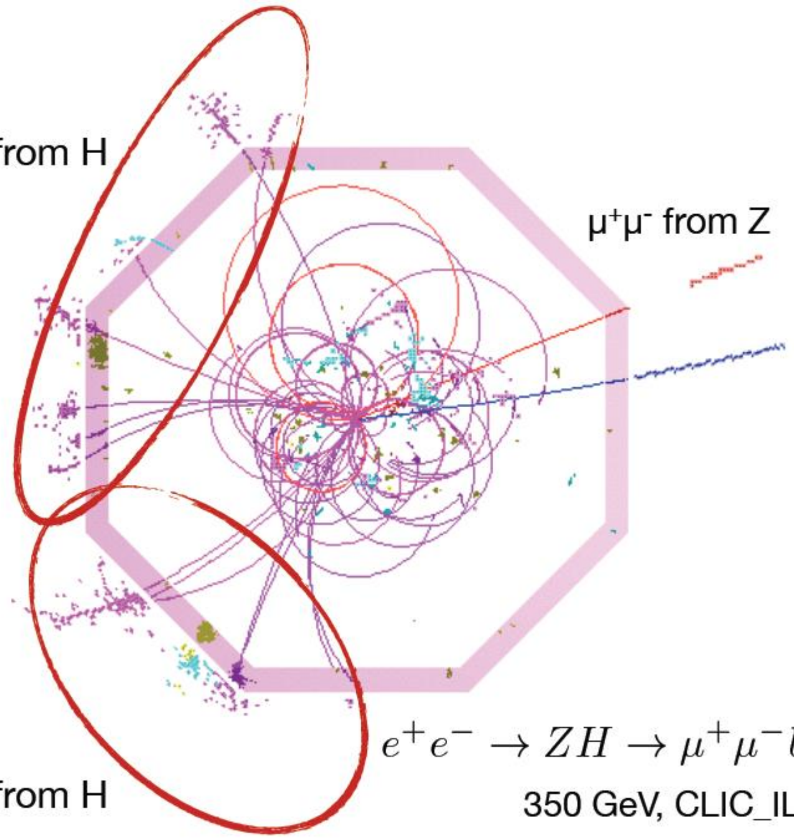
σ(h⁰) × BR(h⁰ → 2 LLP's) < 90 pb

σ(h⁰) × BR(h⁰ → 2 LLP's) < 93 pb

Prospects at CLIC

Idea of Hidden Valley searches at CLIC

- ***Clean experimental environment in e^+e^-***



e^+e^- collisions
e^+/e^- are point-like → Initial state well defined (√s / polarization) → High-precision measurements
Linear Colliders (avoid synchrotron rad.)
Cleaner experimental environment → trigger-less readout → Low radiation levels
Superior sensitivity for electro-weak states

from Frank Simon's slides

Idea of Hidden Valley searches at CLIC

- ***High energy and integrated lumi***

CLIC: e^+e^- collider, staged approach

- 500 fb^{-1} @ 350 – 375 GeV : precision Higgs and top physics
- 1.5 ab^{-1} @ ~1.5 TeV : precision Higgs, precision SUSY, BSM reach, …
- 2 ab^{-1} @ ~ 3 TeV : Higgs self-coupling, precision SUSY, BSM reach,

Exact energies of TeV stages would depend on LHC results

- ***No trigger***

$\rightarrow$ *long-lived states cannot be missed!*

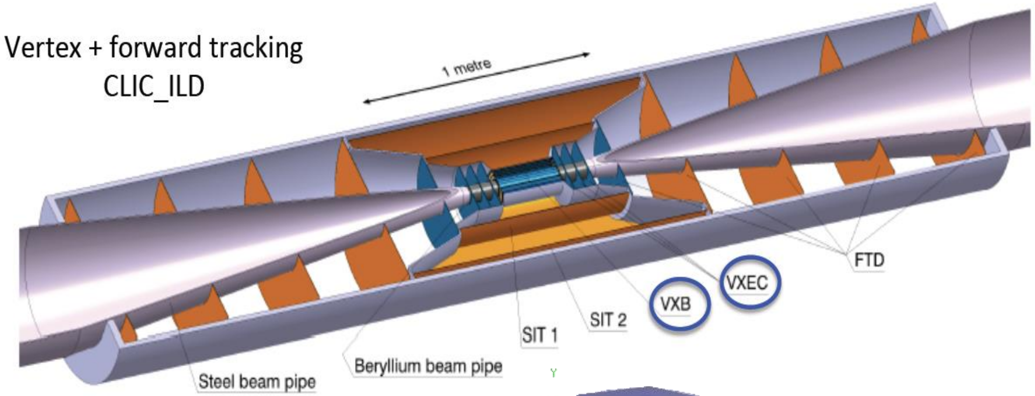
- ***Jet reconstruction based on particle flow***

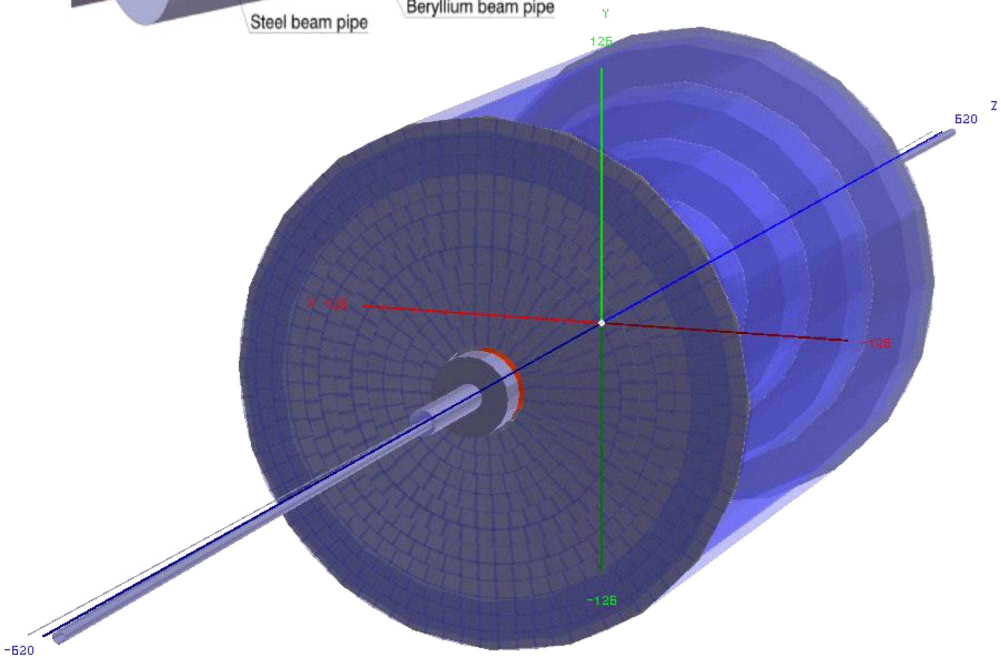
$\rightarrow$ *fine-grain calorimetry*

$\rightarrow$ *complex forward calorimeter*

Long and precise vertexing + tracking

Vertex + forward tracking
CLIC_ILD





- ~25×25 µm pixel size => ~2 Giga-pixels
- 0.2% X_0 material per layer <= very thin !
  - Very thin materials/sensors
  - Low-power design, power pulsing, air cooling
  - Aim: 50 mW/cm^2
- Time stamping 10 ns
- Radiation level <10^{11} $n_{eq}cm^{-2}year^{-1}$ <= 10^4 lower than LHC

A long main tracker is crucial for the forward tracking performance:

- momentum resolution depends even stronger on the lever arm at lower angles
- **do not want a tracker shorter than the one of ILD *(2.3 m)***

from Frank Simon's slides

- **Possible to reconstruct displaced SV's**
- **Ability to measure π_v^0 lifetimes up to 300-500 ps (?)**

CLIC – detector requirements

- **momentum resolution:**

from Lucie Linssen's talk

e.g. Smuon endpoint

Higgs recoil mass, Higgs coupling to muons

$$\sigma_{p_T}/p_T^2 \sim 2\times 10^{-5}\ \mathrm{GeV}^{-1}$$

- **jet energy resolution:**

e.g. W/Z/h di-jet mass separation

$$\frac{\sigma_E}{E} \sim 3.5 - 5\ \%$$

(for high-E jets)

- **impact parameter resolution:**

e.g. c/b-tagging, Higgs BR

$$\sigma_{r\phi} = 5 \oplus 15/(p[\mathrm{GeV}]\sin^{\frac{3}{2}}\theta)\ \mu\mathrm{m}$$

- **angular coverage, very forward electron tagging**

LHC vs CLIC

- **discovery** *(energy reach, larger cross sections)*
  vs. precision *(mass, spin measurements)*

- **data acquisition / trigger**
  (LHC e.g. 40 MHZ $\rightarrow$ 100 Hz $\Rightarrow$ possibility to miss long-lived states)

- **less of a challenge at CLIC**
  (event rate smaller, though more information in each event)

- LHC might only provide guidance
  $\rightarrow$ energy scale of the bridge to hidden sector
  (light LSP, or heavy Z0?)

- **discovery of HV may only be possible at linear colliders like CLIC**
  (e.g. if Higgs has rare decays into v-particles, will not be seen at LHC)

Summary and plans

- Hidden sector generic possibility for BSM physics
- Motivated by dark matter
- Good prospects for e^+e^- colliders

  $\rightarrow$ clean experimental environment

  $\rightarrow$ high energy and statistics to be collected

  $\rightarrow$ long vertexing + tracking

Plans

- Implement new particles to the CLIC generating software
- Sensitivity studies for different energies
- *Learn CLIC software first*