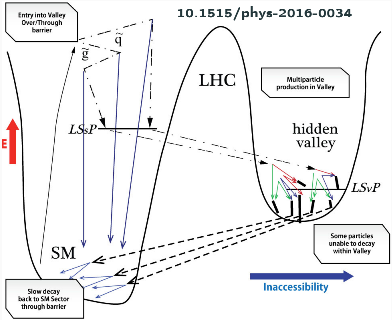
Search for exotic long-lived particles at CLIC

Mateusz Goncerz
Marcin Kucharczyk

motivation

- additional long-lived particles emerge in many BSM models
- Hidden Valley (HV) framework introduces them via *hidden* gauge sector
  - motivated by, among others, String Theory
  - communication either by overcoming the barrier in high-energy collisions or via massive messenger particles (ex. Z', Higgs)
  - decays of HV particles produce displaced vertices (DV)
  - ideal search for detectors like CLIC



introduction

- initial study performed by Marcin Kucharczyk and Tomasz Wojtoń for $\sqrt{s} = 3$ TeV (CLICdp-Note-2018-001)
- current one adds results for $\sqrt{s} = 350$ GeV and provides a comparison (arXiv:2212.04147)
- focus on sensitivity of *CLIC_ILD* detector model to decays of HV pions with Higgs boson as the messenger – $H \to \pi_v^0 \pi_v^0 \to b\bar{b}b\bar{b}$, assuming:
    - $m_{\pi_v^0} \in (25, 35, 50)$ GeV, $\tau_{\pi_v^0} \in (1, 10, 100, 300)$ ps
    - $BR(\pi_v^0 \to b\bar{b}) = 100\%$
    - $m_H = 126$ GeV
- the dominant Higgs production mechanism assumed
    - $e^+e^- \to H\nu_e\bar{\nu}_e$, $\sigma = 0.42$ pb at $\sqrt{s} = 3$ TeV
    - $e^+e^- \to HZ(\to q\bar{q})$, $\sigma = 0.93$ pb at $\sqrt{s} = 350$ GeV
- assumed integrated luminosities
    - 3 ab^{-1} at $\sqrt{s} = 3$ TeV
    - 1 ab^{-1} at $\sqrt{s} = 350$ GeV
- custom seeding algorithm to improve signal-background separation combined with multivariate analysis

samples – signal

		$\sqrt{s} = 350$ GeV		$\sqrt{s} = 3$ TeV	
$m_{\pi_v^0}$[GeV]	$\tau_{\pi_v^0}$[ps]	σ[pb]	sample size	σ[pb]	sample size
25	1	0.93	$\sim$ 240K	0.42	$\sim$ 200K
25	10	0.93	$\sim$ 240K	0.42	$\sim$ 200K
25	100	0.93	$\sim$ 240K	0.42	$\sim$ 200K
25	300	0.93	$\sim$ 240K	0.42	$\sim$ 200K
35	1	0.93	$\sim$ 240K	0.42	$\sim$ 200K
35	10	0.93	$\sim$ 240K	0.42	$\sim$ 200K
35	100	0.93	$\sim$ 240K	0.42	$\sim$ 200K
35	300	0.93	$\sim$ 240K	0.42	$\sim$ 200K
50	1	0.93	$\sim$ 240K	0.42	$\sim$ 200K
50	10	0.93	$\sim$ 240K	0.42	$\sim$ 200K
50	100	0.93	$\sim$ 240K	0.42	$\sim$ 200K
50	300	0.93	$\sim$ 240K	0.42	$\sim$ 200K

- beam induced $\gamma\gamma \to$ hadrons overlayed for each event

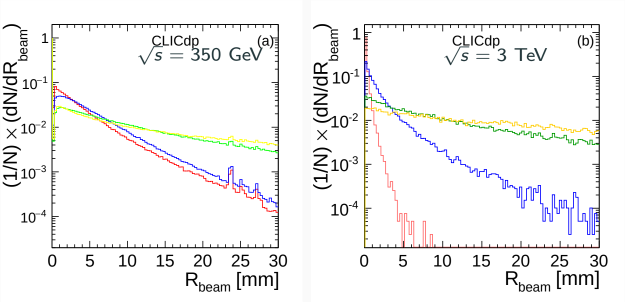
samples – background

	$\sqrt{s} = 350$ GeV		$\sqrt{s} = 3$ TeV	
background process	σ[pb]	sample size	σ[pb]	sample size
$q\bar{q}$	24.41	~ 2M	2.95	~ 200K
$q\bar{q}\nu\bar{\nu}$	0.32	~ 306K	1.32	~ 200K
$q\bar{q}q\bar{q}$	5.85	~ 1.44M	0.55	~ 750K
$q\bar{q}q\bar{q}\nu\bar{\nu}$		-	0.07	~ 300K
$t\bar{t}$	0.45	~ 241K		-
WWZ	0.01	~ 40K		-

- more than 4 jets omitted due to low cross-section
- beam induced $\gamma\gamma \to$ hadrons overlayed for each event

reconstruction of DVs

- vertices of π_v^0 decays are displaced from the beam axis

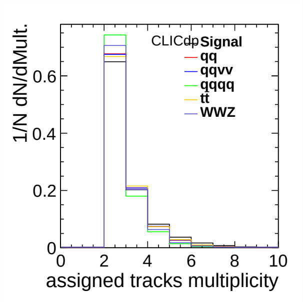


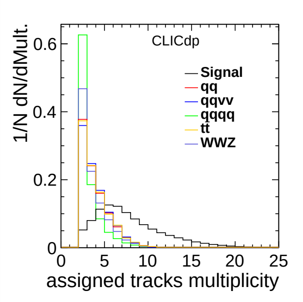
$m_{\pi_v^0} = 50$ GeV, $\tau_{\pi_v^0} = 1$ (red), 10 (blue), 100 (green), 300 (yellow) ps

- LCFI+ (Linear Collider Flavour Identification) algorithms for SV reconstruction were found to be inefficient
  - designed primarily for B and D hadron decays
  - too few charged tracks assigned to displaced vertices
  - hindering signal-background separation, especially in 1 ps samples

reconstruction of DVs – modified approach

- reconstruct tracks and jets (6 for $\sqrt{s} = 350$ GeV and 4 for $\sqrt{s} = 3$ TeV) using standard methods
    - longitudinally invariant k_t (FastJet), tagging based on BDT
    - optimized for HV particles (jet radius, requirements on impact parameter components etc.)
    - see CLICdp-Note-2018-001 for details
- perform manual seeding to find $\pi_v^0 \to b\bar{b}$ vertex candidates
    - consider good quality charged tracks not coming from PV
        - IP/$\sigma_{IP} > 16$
    - find base track with at least 4 close tracks assigned
        - DOCA < 1 mm
    - for each pair of tracks in this set, calculate their POCA
    - assign additional tracks with DOCA to POCA less than 1 mm
    - look for new base track and repeat untill no tracks left
- perform a standard SV reconstruction based on the impact parameter wrt. the seed positions determined in previous step





$m_{\pi_v^0} = 35$ GeV, $\tau_{\pi_v^0} = 10$ ps

- number of charged tracks assigned to SVs using standard algorithms (left) and our modified approach (right)
- clear signal-background separation introduced

SV-jet matching

- to match signal signature, we require events to have
    - at least two DVs
    - at least 4 jets with b-tag probability of at least 0.95
- as the jet reconstruction algorithm does not provide any information on position, they are assigned to vertices in a way that maximizes the number of common charged tracks
- this matching is used to reconstruct di-jets (π_v^0) and four-jet (Higgs)
- at $\sqrt{s} = 350$ GeV, the two remaining jets are used to reconstruct Z boson candidate

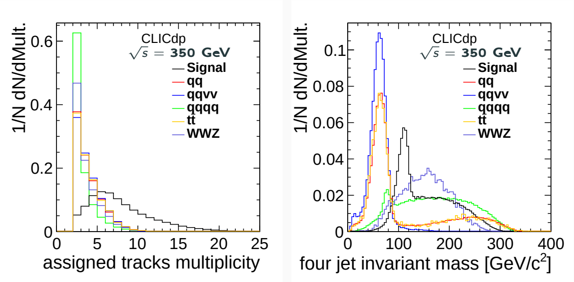
signal-background separation

- the pre-selection requirements are very effective at suppressing the backgrounds

		$\sqrt{s} = 350$ GeV	$\sqrt{s} = 3$ TeV
$m_{\pi_V^0}$ [GeV]	$\tau_{\pi_V^0}$ [ps]	Eff.$^{presel.}$ [%]	Eff.$^{presel.}$ [%]
25	1	78	68
25	10	94	86
25	100	99	93
25	300	97	80
35	1	76	70
35	10	93	86
35	100	99	94
35	300	98	82
50	1	72	72
50	10	89	89
50	100	99	90
50	300	99	86

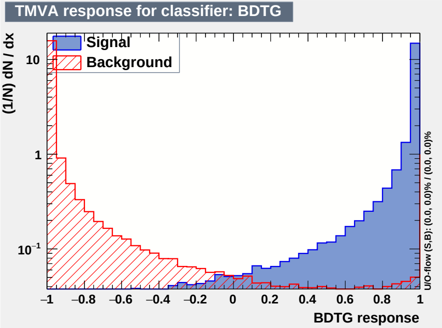
	$\sqrt{s} = 350$ GeV	$\sqrt{s} = 3$ TeV
background process	Eff.$^{presel.}$ [%]	Eff.$^{presel.}$ [%]
$q\bar{q}$	12	6
$q\bar{q}\nu\bar{\nu}$	12	8
$q\bar{q}q\bar{q}$	8	9
$q\bar{q}q\bar{q}\nu\bar{\nu}$	-	11
$t\bar{t}$	12	-
WWZ	14	-

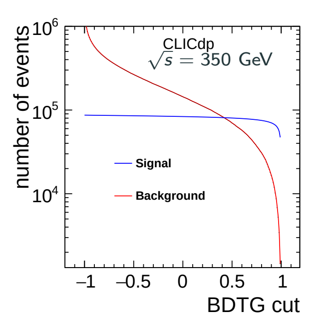
- further separation is achieved using a multivariate analysis
- a decision tree (BDTG) is trained to distinguish between signal and background events using physical variables with good separation:
  - DV, di-jet and four-jet mass
  - DV and their assigned tracks multiplicity
  - distance at which the transitions from 3 to 2-jet and from 4 to 3-jet event takes place
    - effective against backgrounds with different jet number
  - Z candidate mass (at $\sqrt{s} = 350$ GeV)



$m_{\pi_v^0} = 35$ GeV, $\tau_{\pi_v^0} = 10$ ps

- each signal sample is treated independently
- backgrounds are combined with weights based on their cross-section and pre-selection efficiency



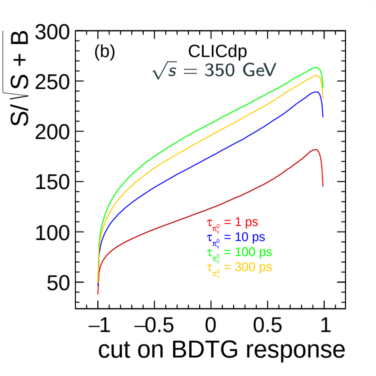


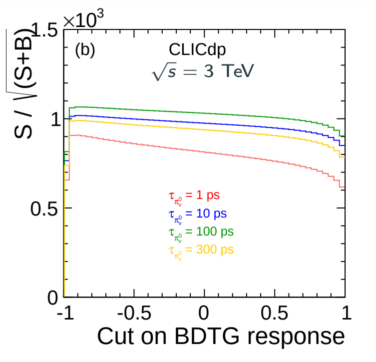
$m_{\pi_v^0} = 35$ GeV, $\tau_{\pi_v^0} = 10$ ps

- number of events normalized to assumed total luminosity

sensitivity

- the threshold value is chosen to maximize sensitivity $S/\sqrt{S+B}$



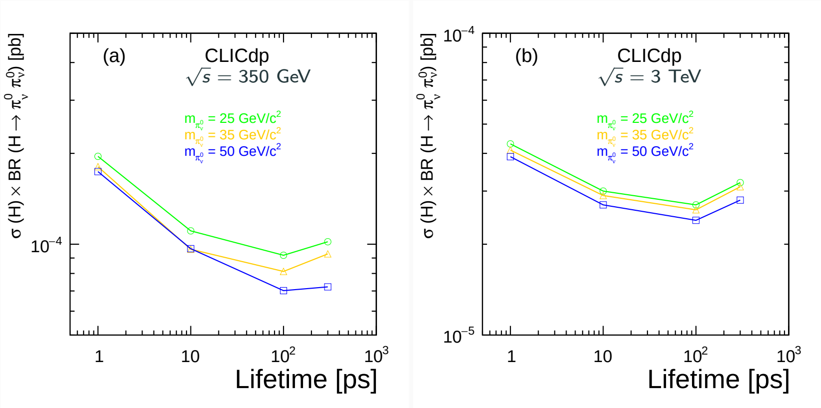


$m_{\pi_v^0} = 35$ GeV

- sensitivity roughly 4-6 times larger at $\sqrt{s} = 3$ TeV
  - bear in mind different luminosities
  - consistent across all $m_{\pi_v^0}$ masses

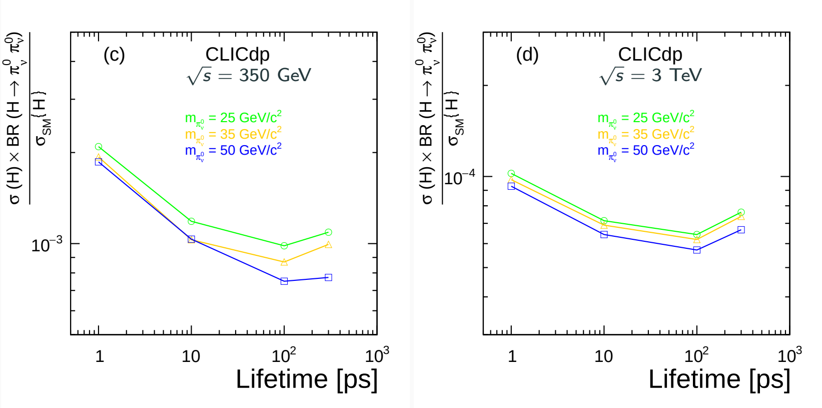
upper limits

- derived using CL(s) at 95% CL
- assuming absence of signal observation



- slightly higher at $\sqrt{s} = 350$ GeV, but same order of magnitude
- much better than existing experiments (orders of $10^0 - 10^2$)

- normalized to Higgs production cross-section



- an order of magnitude higher at $\sqrt{s} = 350$ GeV

summary

- the sensitivity of CLIC_ILD detector to long-lived HV particles was studied for the first ($\sqrt{s} = 350$ GeV) and last ($\sqrt{s} = 3$ TeV) stage of CLIC operation, assuming 1 and 3 inverse attobarns of collected data respectively
- the standard algorithm is not efficient enough in assigning charged tracks to vertices displaced from the beam axis
- the proposed modified approach mitigates these problems and allows for very good signal-background separation, when combined with multivariate analysis methods
- the resulting upper limits on Higgs production cross-section times the branching ratio to HV pions are many orders of magnitude better than achievable in current experiments