Search for Hidden Valley at future colliders

Marcin Kucharczyk
(on behalf of CLICdp collaboration)
IFJ PAN Kraków

Epiphany 2024
Kraków

08.01 - 12.01 2024

Outline

- Physics motivation
- Compact Linear Collider
- Analysis strategy
- Sensitivity
- Upper limits

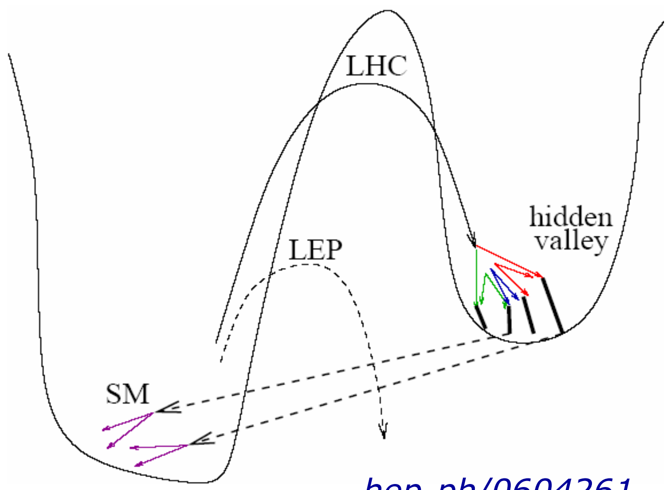
Analysis partially supported by Prof. Jadach's grant NCN 2015/18/M/ST2/00123

Hidden sector – generic possibility for NP

Consequence of string-theory

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

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



hep-ph/0604261

BARRIER

communicator's high mass, weak couplings, small mixing angles, …

→ weakens interaction between sectors

→ production of new particles rare at low energy

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

→ all SM particles neutral within G_v

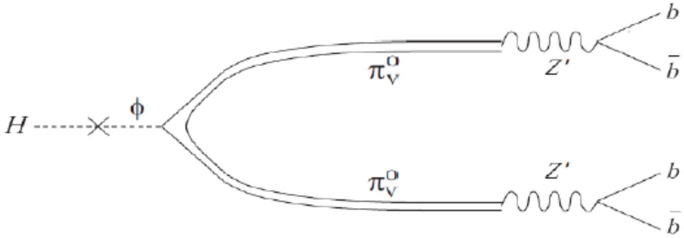
→ if energy sufficient → ***v-particle*** charged within G_v, neutral under G_{SM}

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

Direct production and SM Higgs

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

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



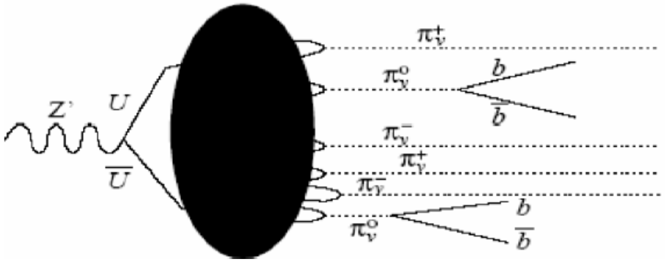
- scalar decaying to the heaviest particles it has access to in order to defeat natural helicity suppression

Phys. Lett. B651 (2007) 374

- **Direct multi-π_v production**

$Z' \rightarrow \pi_v^0 + \pi_v^+$

└► $b\bar{b}$ └► *missing energy*



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

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

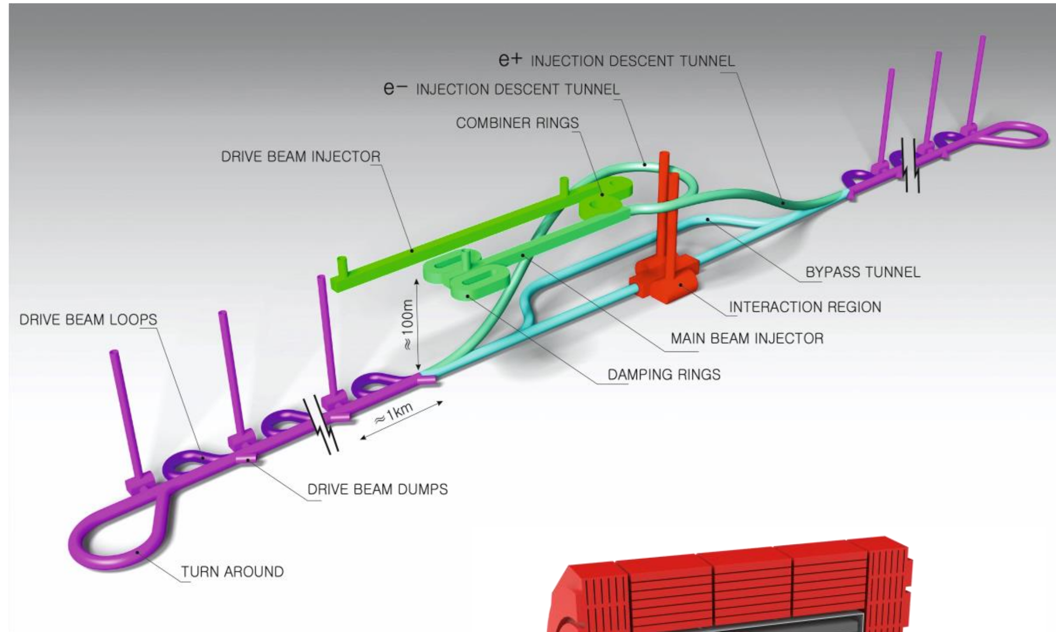
if lifetime between 1 ps and 1 ns *(characteristic for weak decays)*

can be identified in tracking systems by displaced vertices!

Compact Linear Collider

- Electron-positron linear collider at CERN for the era beyond HL-LHC
- Planned for construction in three energy stages:
  - → 350 GeV (Higgs/top)
  - → 1.5 TeV (expanding Higgs/top)
  - → 3 TeV (energy frontier)
- Nominal physics program lasts for 25-30 years
- Benefit of linear machine:
  - → length/energy staging plan
  - → can be updated in response to developing physics landscape
- Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities

  ~11km in its initial phase



[LCD-Note-2011-002]

SM Higgs decay into 2 Hidden Valley pions

[MK, M. Goncerz, JHEP 03 (2023) 131]

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

Analysis for two energy stages:

- $\sqrt{s}$ = 350 GeV

  → dominant production in Higgsstrahlung ($e^+e^- \rightarrow Z\,H$)

  → assumed integrated luminosity = 1 ab^{-1}

- $\sqrt{s}$ = 3 TeV

  → dominant production in *WW*-fusion

  → assumed integrated luminosity = 3 ab^{-1}

Generation / simulation

- WHIZARD 1.95 + PYTHIA 6.4
- interaction with CLIC_ILD

  → Geant4 + MOKKA

Signal & background samples

[MK, M. Goncerz, JHEP 03 (2023) 131]

		$\sqrt{s} = 350$ GeV			$\sqrt{s} = 3$ TeV		
$m_{\pi^0_v}$[GeV/c^2]	$\tau_{\pi^0_v}$[ps]	σ[pb]	sample size	Eff.$^{presel.}$ [%]	σ[pb]	sample size	Eff.$^{presel.}$ [%]
25	1	0.93	~240K	78	0.42	~200K	68
25	10	0.93	~240K	94	0.42	~200K	86
25	100	0.93	~240K	99	0.42	~200K	93
25	300	0.93	~240K	97	0.42	~200K	80
35	1	0.93	~240K	76	0.42	~200K	70
35	10	0.93	~240K	93	0.42	~200K	86
35	100	0.93	~240K	99	0.42	~200K	94
35	300	0.93	~240K	98	0.42	~200K	82
50	1	0.93	~240K	72	0.42	~200K	72
50	10	0.93	~240K	89	0.42	~200K	89
50	100	0.93	~240K	99	0.42	~200K	90
50	300	0.93	~240K	99	0.42	~200K	86
$q\bar{q}$		24.41	~2M	12	2.95	~200K	6
$q\bar{q}\nu\bar{\nu}$		0.32	~306K	12	1.32	~200K	8
$q\bar{q}q\bar{q}$		5.85	~1.44M	8	0.55	~750K	9
$q\bar{q}q\bar{q}\nu\bar{\nu}$			—		0.07	~300K	11
$t\bar{t}$		0.45	~241K	12		—	
WWZ		0.01	~40K	14		—	

Eff.$^{presel.}$

- ≥ 2 DVs
- *b*-tag prob. > 0.95

- for every signal sample x-section of 0.93 pb ($\sqrt{s}$ = 350 GeV) and 0.42 pb ($\sqrt{s}$ = 3 TeV) with BR($\pi_v \to bb(bar)$) = 100%
- in each case samples without pileup of $\gamma\gamma \to$ hadrons were also produced

Hidden Valley pions

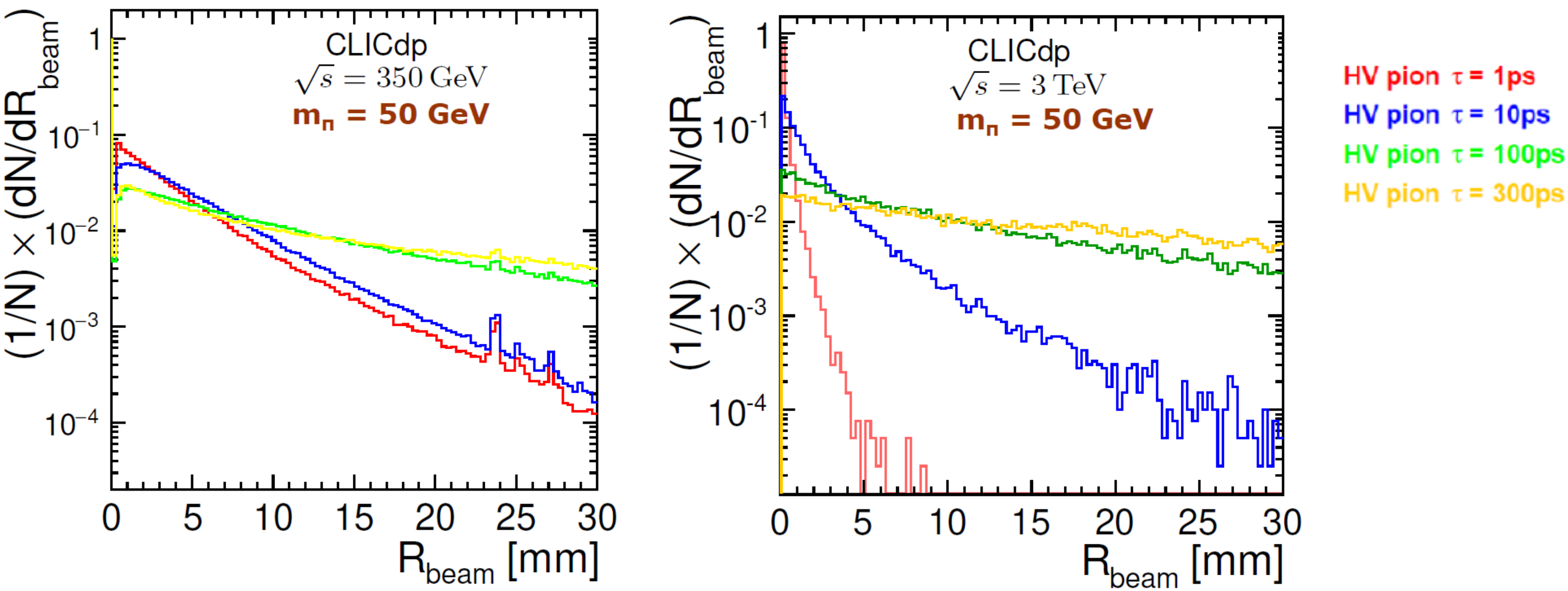
[MK, M. Goncerz, JHEP 03 (2023) 131]

v-particles have non-zero lifetime

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

→ displaced vertices *(DV)* – *more PV-like*

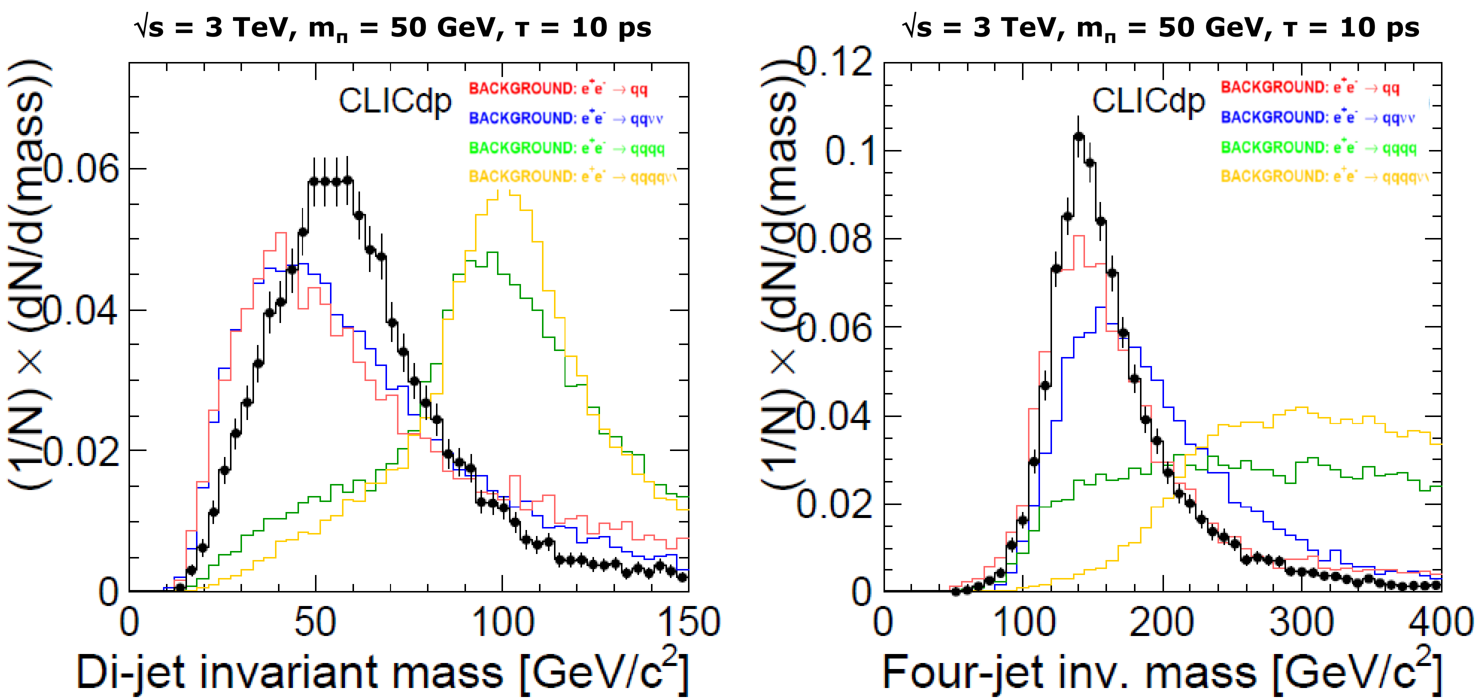
Generated π_v's



Jet reconstruction and tagging

[MK, T. Wojtoń, CLICdp-Note-2018-001]

- k_t algorithm *(FastJet)*
- *b*-tag and *c*-tag probability found through a Boosted Decision Tree based procedure
- *R(=1.0)* parameter optimized by looking at RMS/Mean of the di-jet and four-jet mass



- assign two *b*-jets to a single displaced vertex
  → *nr of common charged particles jet-DV is max. (second max.)*

Displaced vertex reconstruction

[MK, M. Goncerz, JHEP 03 (2023) 131]

Displaced vertices are rather PV-like objects

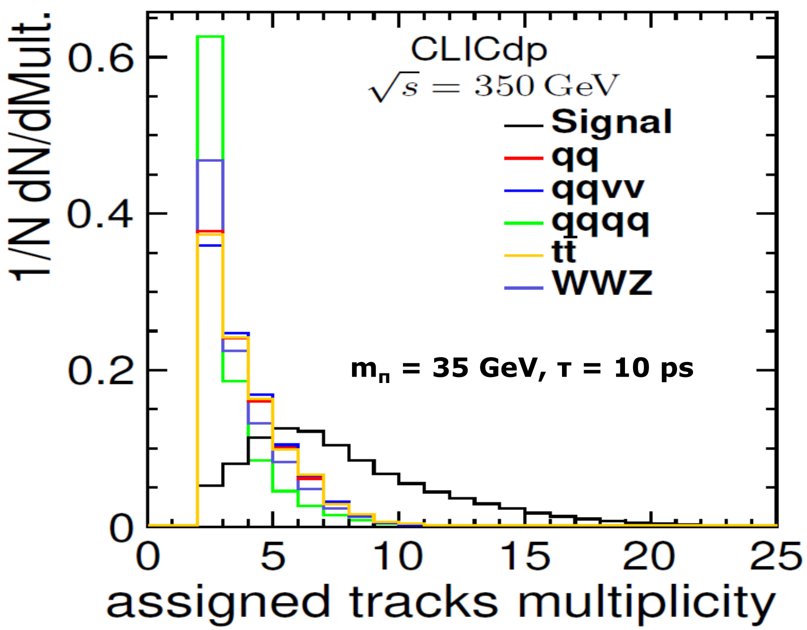
- accumulate as many tracks as possible from Hidden Valley pions
- nr of tracks > 4 $\rightarrow$ *eliminate background from b-hadrons*

Dedicated two step procedure to reconstruct DV's

(1) seeding: *search for space points with accumulation of tracks*

(2) fitting: *weighted least-square*

$\rightarrow$ developed and optimised for the Hidden Valley



Multi-variate analysis

[MK, M. Goncerz, JHEP 03 (2023) 131]

Multi-variate analysis for events with at least 2 DV's

→ 7 variables with good separation of signal wrt background *(m_π = 25, 35, 50 GeV)*

1) nr of tracks assigned to DV
2) DV multiplicity in the event
3) DV invariant mass
4) mass of di-jet assigned to the DV
5) mass of four-jet assigned to 2 DVs

if reconstruct events with 4 jets

6) $\log(y_{n-1,n})$ - *distance at which transition from three-jet event to two-jet event takes place*
   → effective against backgrounds with 2 or 3 jets

if reconstruct events with 2 jets

7) $\log(y_{n+1,n})$ - *distance at which transition from four-jet event to three-jet event takes place*
   → effective against backgrounds with 3 or 4 jets

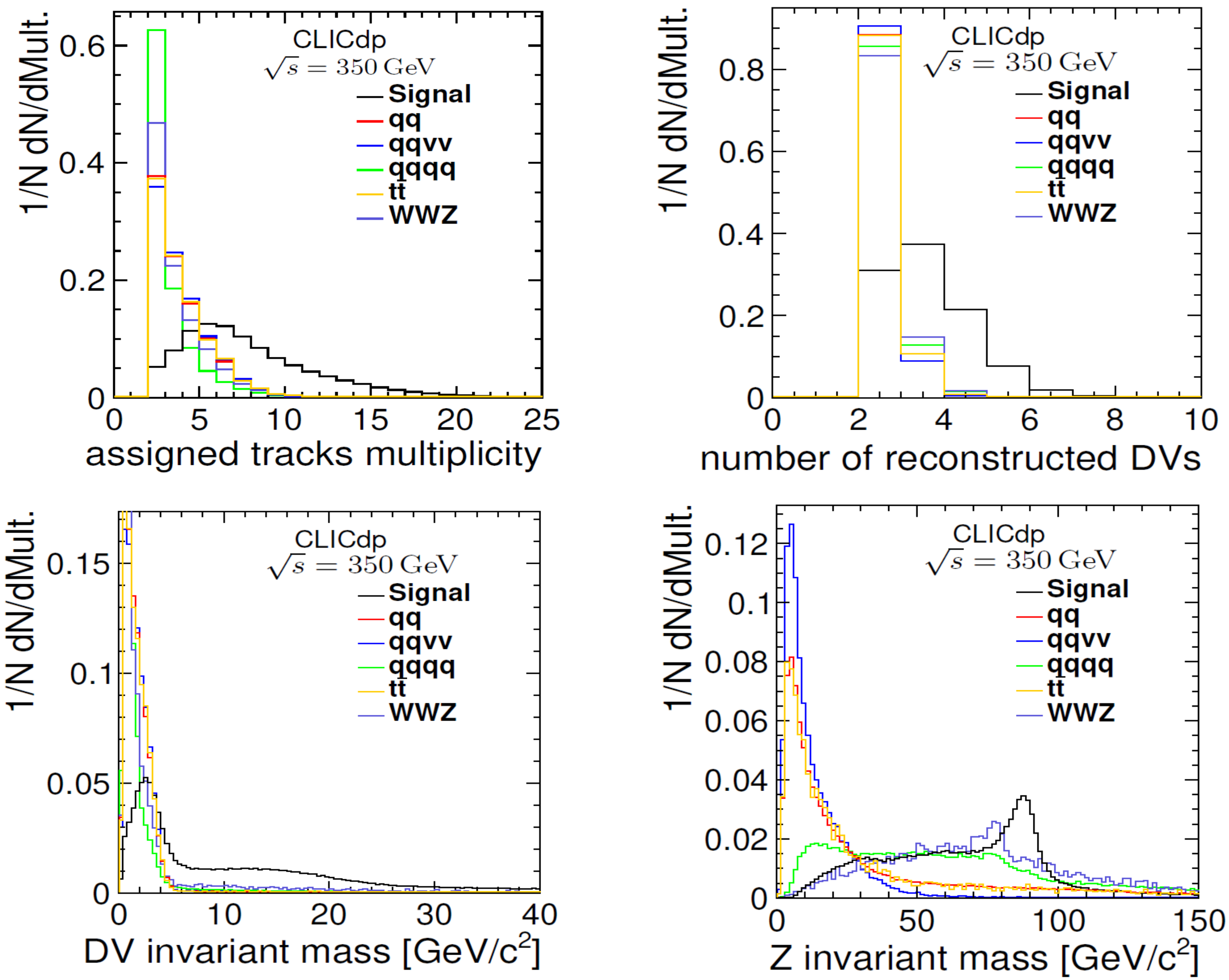
only for $\sqrt{s}$ = 350 GeV

8) *Z* invariant mass

Separation

$\sqrt{s}$ = 350 GeV, m_{π} = 35 GeV, τ = 10 ps

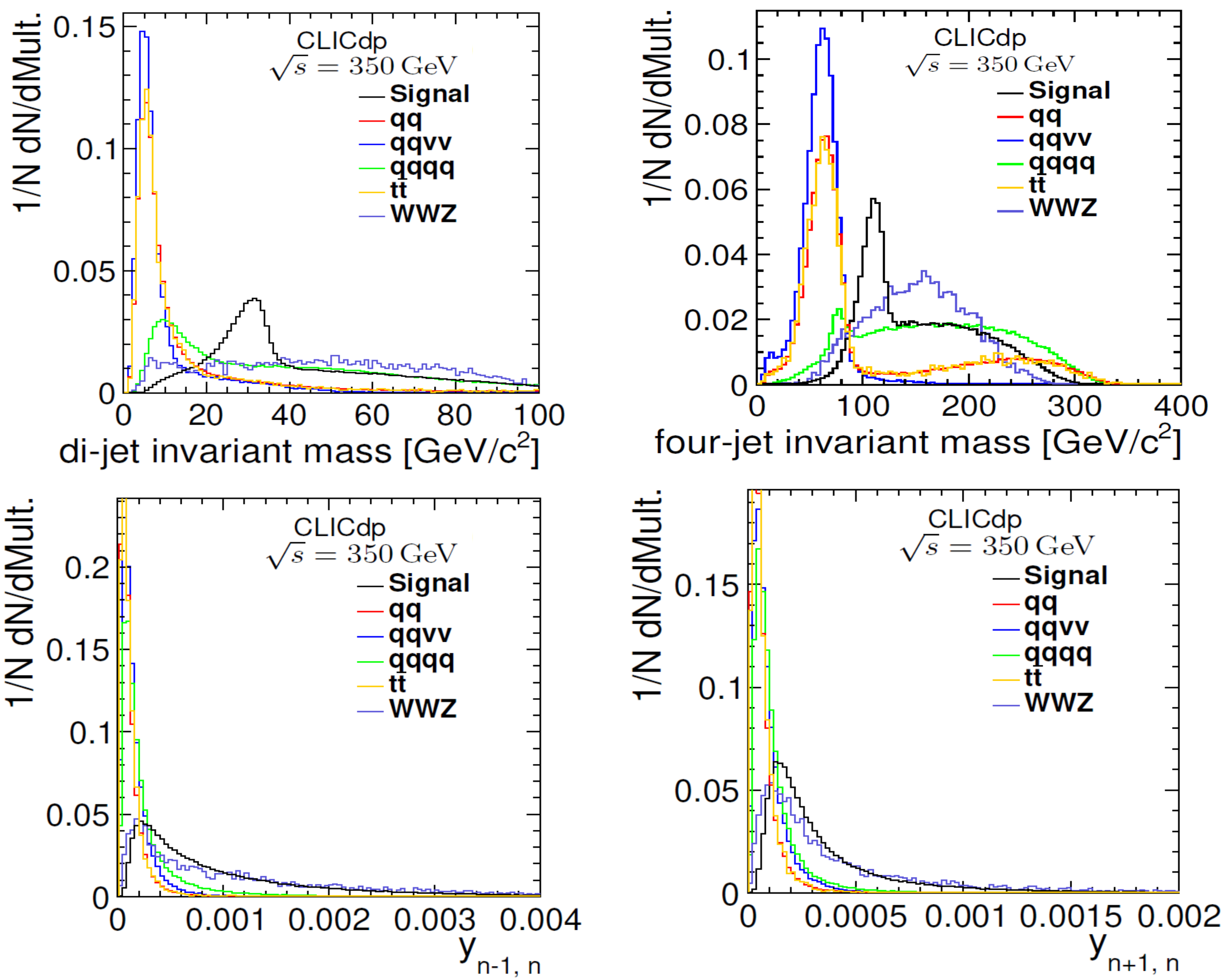
[MK, M. Goncerz, JHEP 03 (2023) 131]



Separation

$\sqrt{s}$ = 350 GeV, m_{π} = 35 GeV, τ = 10 ps

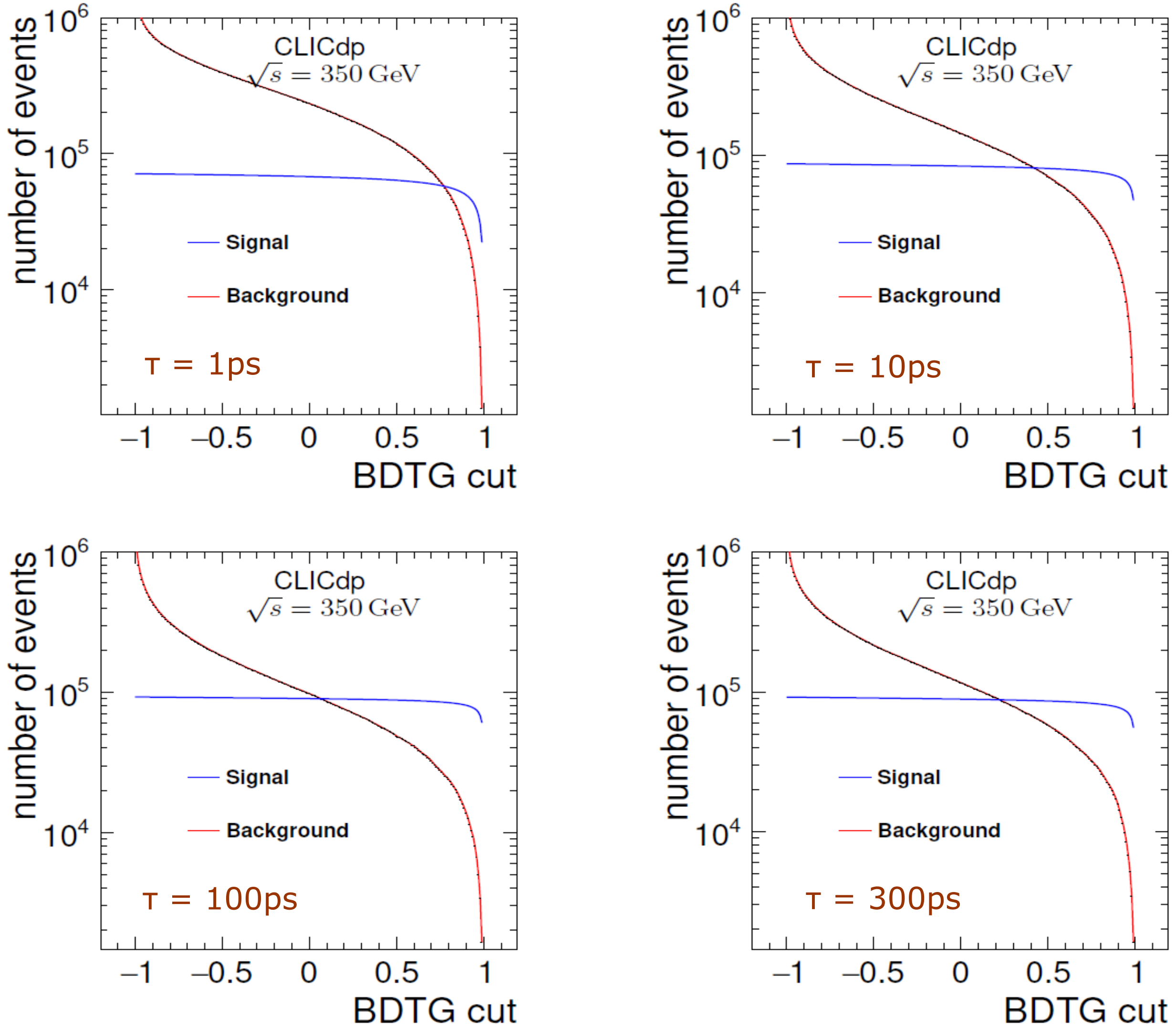
[MK, M. Goncerz, JHEP 03 (2023) 131]



BDT response

√s = 350 GeV, m_π = 35 GeV *vs* combined background

[MK, M. Goncerz, JHEP 03 (2023) 131]



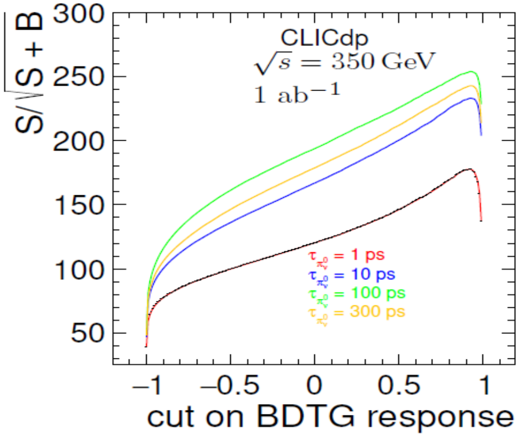
Sensitivity: √s = 350 GeV

[MK, M. Goncerz, JHEP 03 (2023) 131]

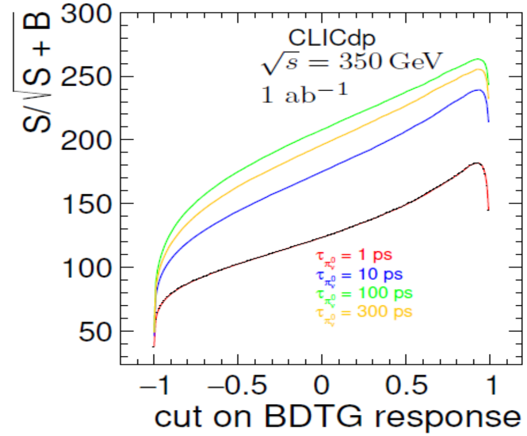
Sensitivity S / √(S + B) as a function of the cut on BDTG response

→ to optimize the cut on BDTG discriminator

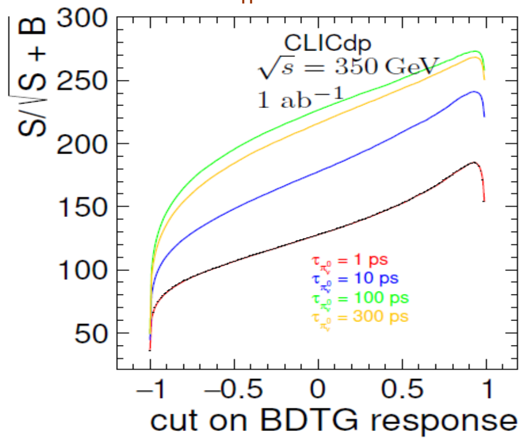
m_{π} = 25 GeV



m_{π} = 35 GeV



m_{π} = 50 GeV



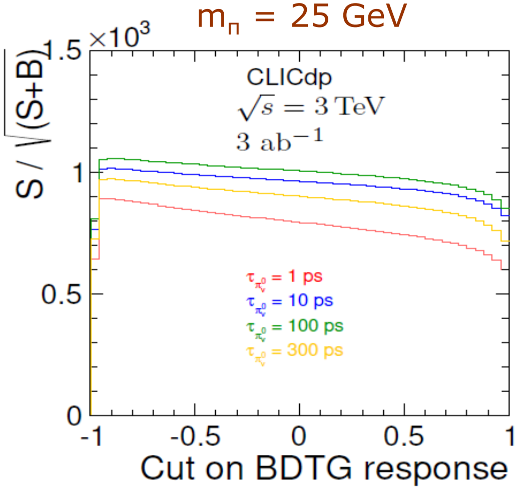
Sensitivity: √s = 3 TeV

[MK, M. Goncerz, JHEP 03 (2023) 131]

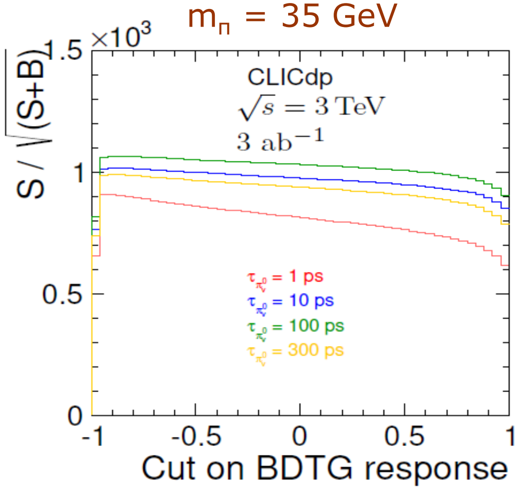
Sensitivity S / √(S + B) as a function of the cut on BDTG response

→ to optimize the cut on BDTG discriminator

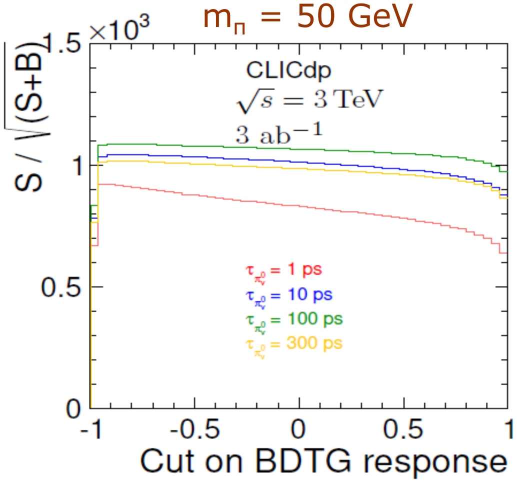
m_η = 25 GeV



m_η = 35 GeV



m_η = 50 GeV



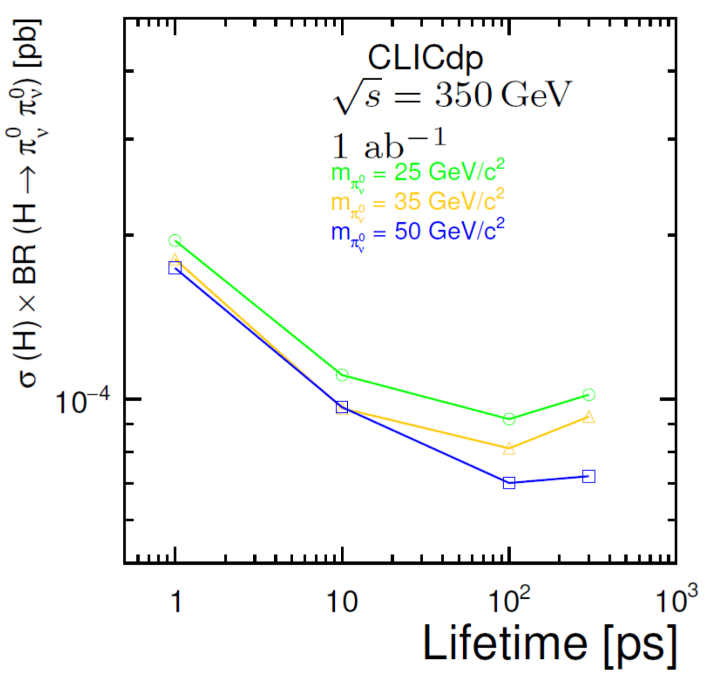
Upper limits

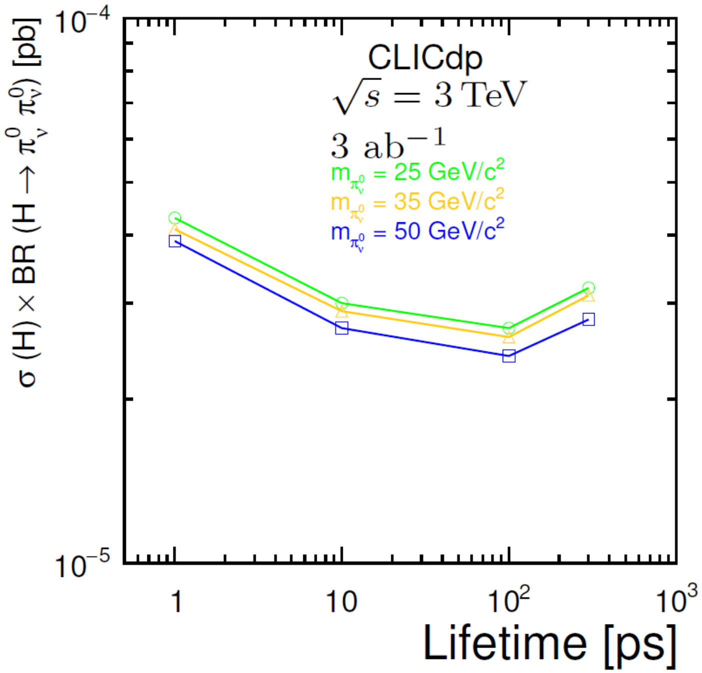
[MK, M. Goncerz, JHEP 03 (2023) 131]

Upper limits on x-section × BF at 95% CL for using CLs *(cut on BDTG > 0.95)*

→ direct comparison to *pp* results not straightforward

→ much better limits as compared to ATLAS, CMS and LHCb results *(even after upgrades planned for HL-LHC)*



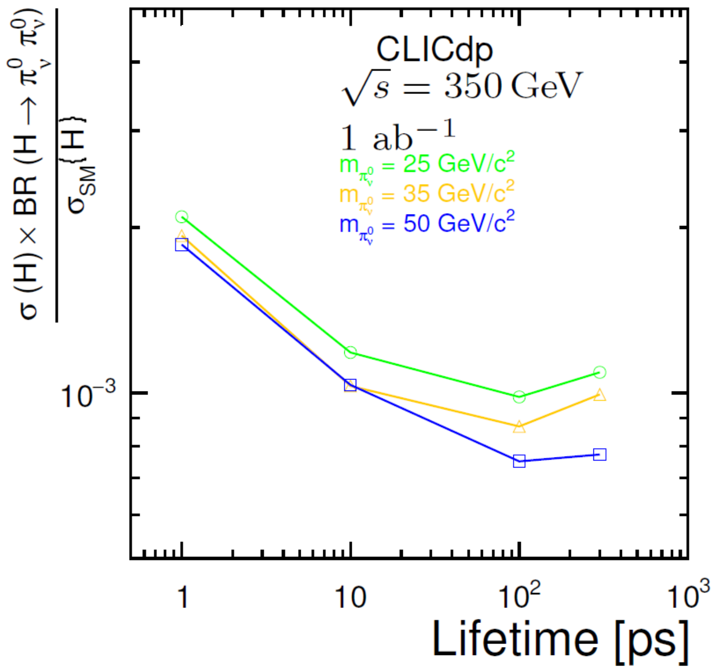


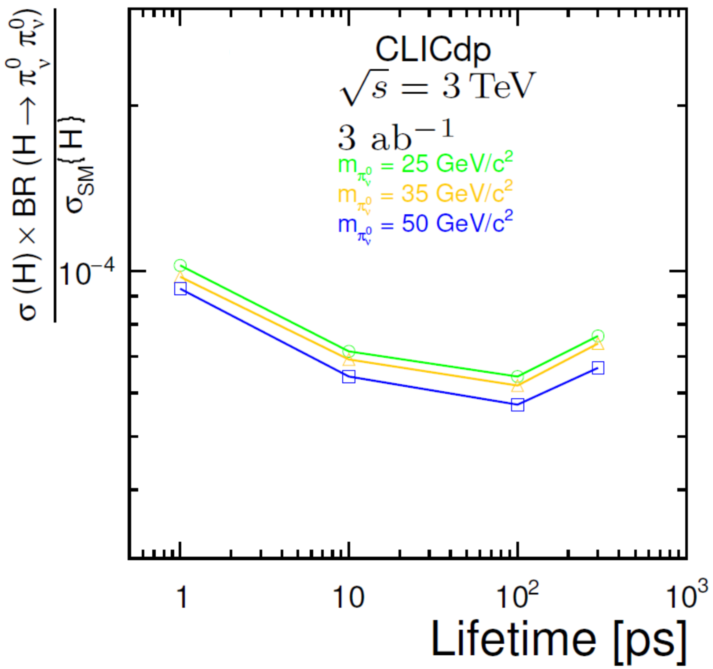
expected upper limits obtained in the absence of signal observation

Upper limits

[MK, M. Goncerz, JHEP 03 (2023) 131]

Upper limits normalized to the Standard Model production cross-section of the Higgs boson





expected upper limits obtained in the absence of signal observation

Systematics

[MK, M. Goncerz, JHEP 03 (2023) 131]

Main purpose of analysis → estimate the sensitivities and upper limits

- main limitation dominated by the statistics rather than systematics
- total luminosity expected to be measured at the level of a few permille at CLIC
- estimation of systematics related to reconstruction not meaningful now
  → final detector configuration not yet fully established
- initial studies of systematics
  → leading contribution identified as related to secondary vertices originating from detector material
  → minor influence on the results

Conclusions

- Hidden sector: generic possibility for BSM physics
- Sensitivity of CLIC_ILD detector model to long-lived particles from Higgs decays for 350 GeV and 3 TeV

  $\rightarrow$ respective integrated lumi. of 1 ab^{-1} and 3 ab^{-1}
- Signal samples for 4 different HV pion lifetimes and 3 different masses
- Analysis based on displaced vertices assigned to *b*-jets
- Expected upper limits in absence of signal much more stringent compared to currently operating detectors
- Ongoing analysis for FCCee (356 GeV) with CLIC-like detector model

  $\rightarrow$ not published yet