Hidden Valley searches at CLIC

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Outline

- Physics motivation
- Analysis strategy
- Multi-variate analysis
- Sensitivity
- Upper limits

Hidden sector – generic possibility for NP

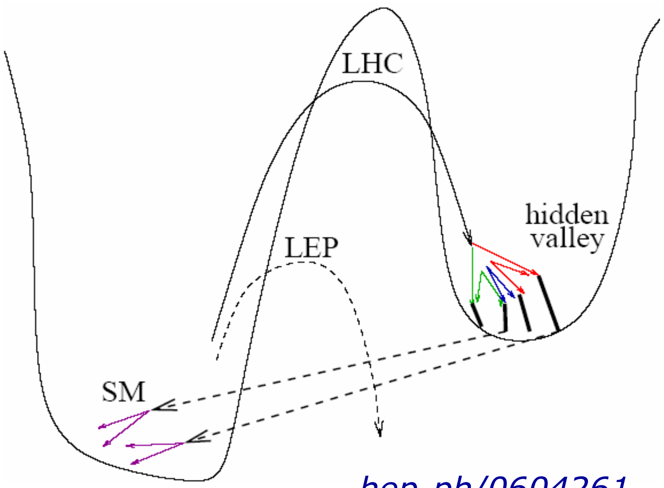
Consequence of string-theory

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

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

BARRIER

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



hep-ph/0604261

→ 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

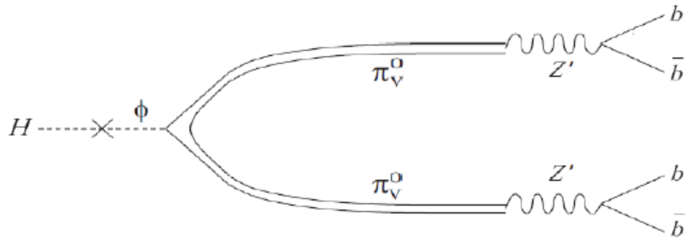
→ if energy sufficient → ***v-particle*** charged within G_v, neutral under G_{SM}

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)***

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



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

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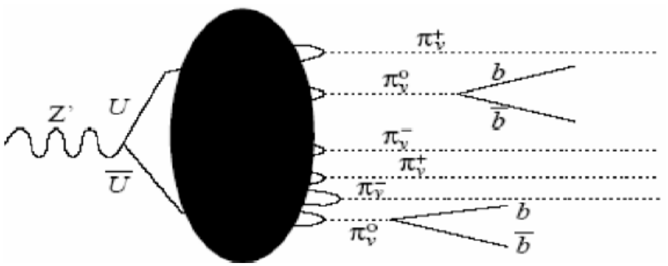
- **Direct multi-π_v production**

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

π_v^0 ↳ *$b\bar{b}$*, π_v^+ ↳ *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!

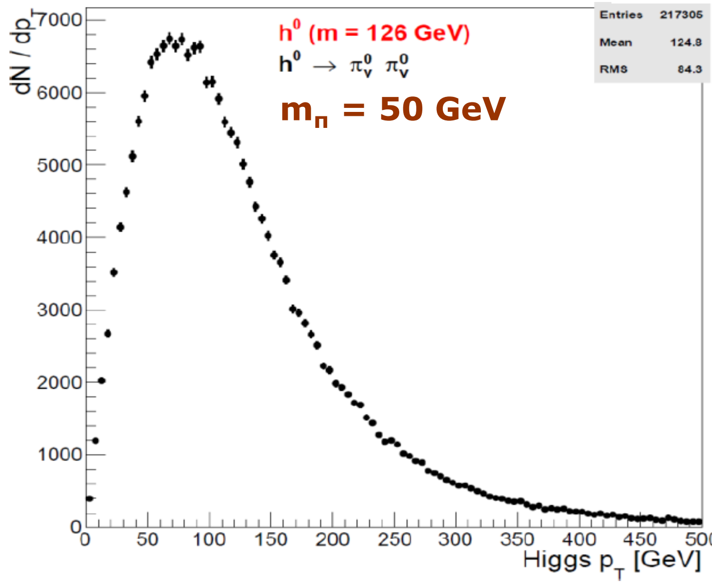
Signal & background samples

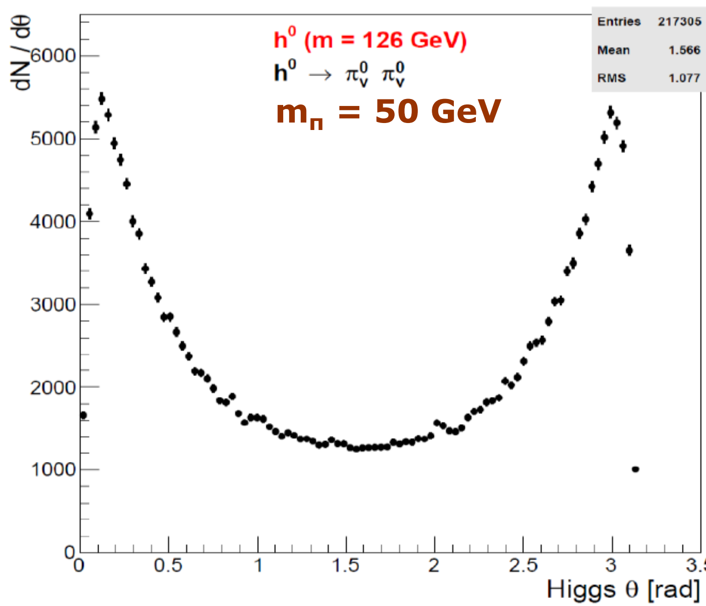
[CLICdp-Note-2018-001]

Signal $h^0 \to \pi_v^0 \pi_v^0$ (3 TeV) mass(h^0) = 126 GeV
HV pion τ = 1 ps m = 25, 35, 50 GeV
HV pion τ = 10 ps m = 25, 35, 50 GeV
HV pion τ = 100 ps m = 25, 35, 50 GeV
HV pion τ = 300 ps m = 25, 35, 50 GeV
HV pion τ = 1, 10, 100, 300 ps m = 50GeV *samples **without** pileup of $\gamma\gamma \to$ hadrons*
Background (3 TeV)
$e^+e^- \to$ qq *(bb)*
$e^+e^- \to$ qqvv *(bb)*
$e^+e^- \to$ qqqq *(4b, 4c, 2b2c)*
$e^+e^- \to$ qqqqvv *(4b, 4c, 2b2c)*

- WHIZARD 1.95 + PYTHIA 6
- interaction with CLIC_ILD

  → *Geant4 + MOKKA*



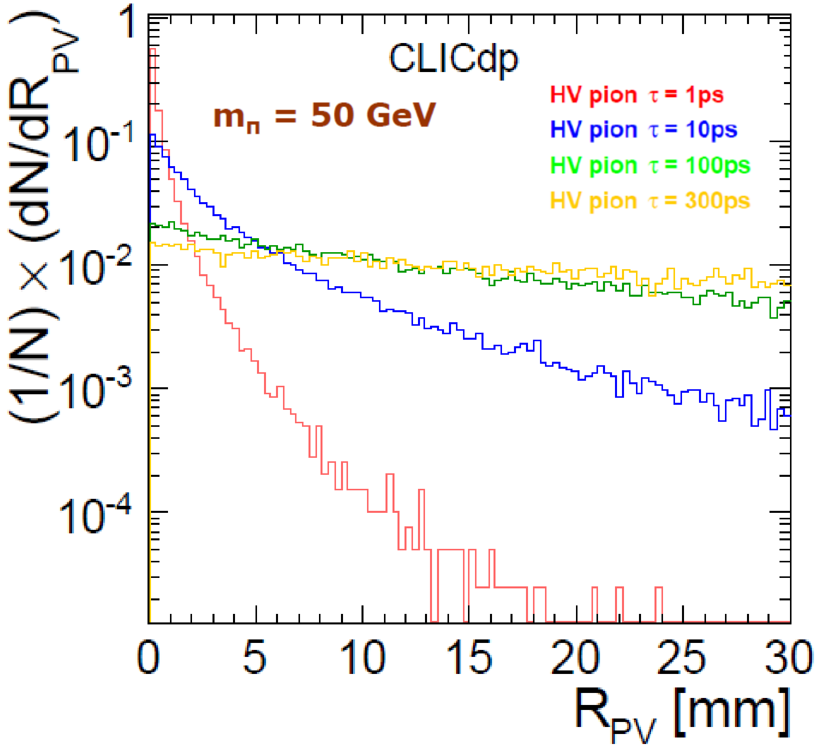


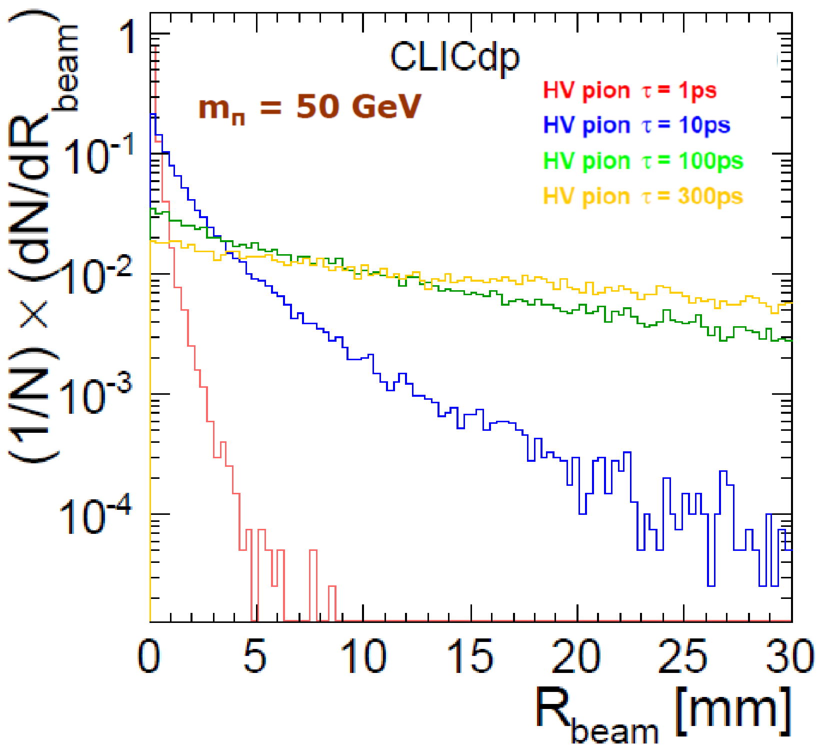
Hidden Valley pions

***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*

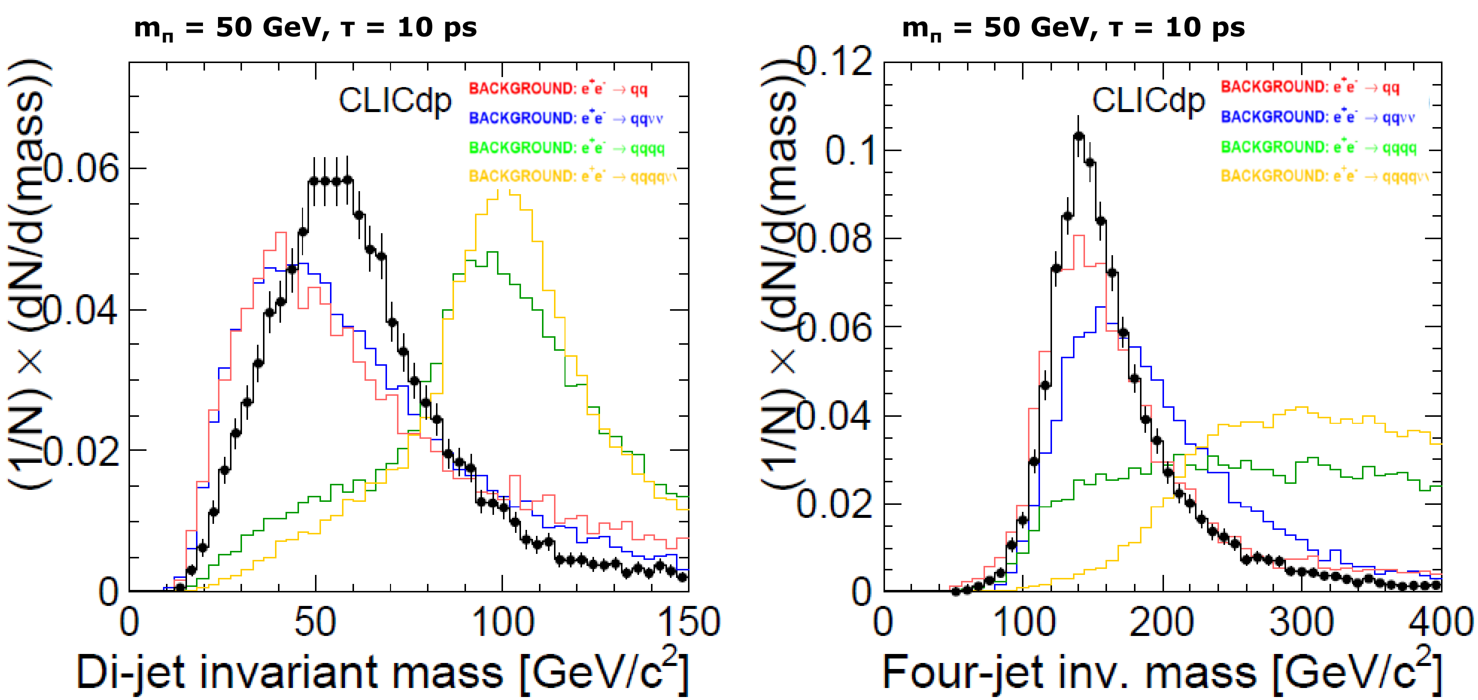




Jet reconstruction and tagging

[CLICdp-Note-2018-001]

- k_t algorithm *(FastJet)*
- *b*-tag and *c*-tag probability found using standard CLICdp BDT procedure
- *R* parameter optimized by looking at RMS/Mean of the di-jet and four-jet mass



Displaced vertex reconstruction

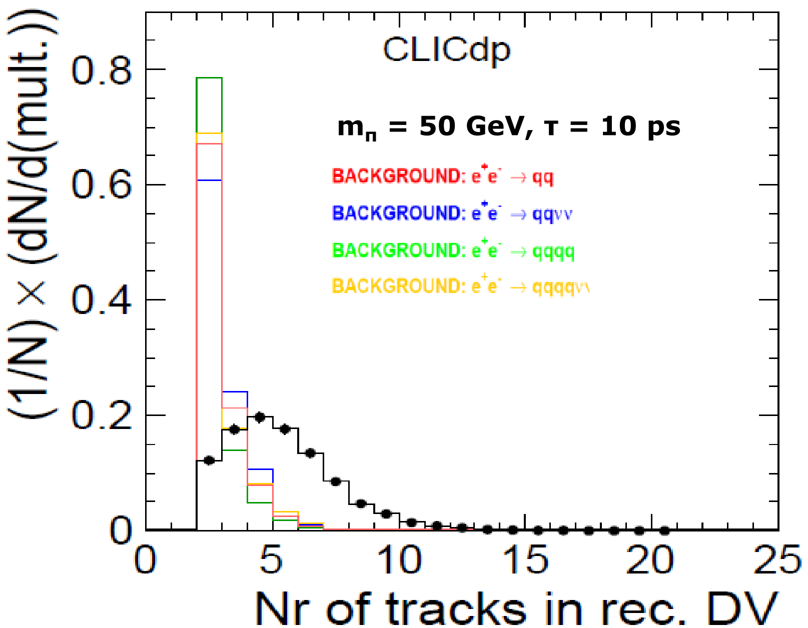
[CLICdp-Note-2018-001]

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*

Specific two step procedure to reconstruct DV's

- including seeding and fitting
- developed and optimised for the Hidden Valley analysis



Selection efficiency

[CLICdp-Note-2018-001]

- DV reconstruction based on seeding optimized for Hidden Valley
- cut on nr of displaced vertices in the event

Signal	Fraction of events with at least 2 DV's
HV pion, τ = 1 ps m = 50 *(25,35)* GeV	72 *(68,70)* %
HV pion, τ = 10 ps m = 50 *(25,35)* GeV	89 *(86,86)* %
HV pion, τ = 100 ps m = 50 *(25,35)* GeV	97 *(93,94)* %
HV pion, τ = 300 ps m = 50 *(25,35)* GeV	86 *(80,82)* %
Background	
$e^+e^- \to$ qq	6 %
$e^+e^- \to$ qqνν	8 %
$e^+e^- \to$ qqqq	9 %
$e^+e^- \to$ qqqqνν	11 %

- **assign two jets to one displaced vertex**

  → *nr of common charged particles jet-DV (seed) is max. (second max.)*

Multi-variate analysis

[CLICdp-Note-2018-001]

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)*

- *nr of tracks in DV*
- *DV multiplicity in the event*
- *DV invariant mass*
- *mass of di-jet assigned to the DV*
- *mass of four-jet assigned to 2 DVs*

if reconstruct events with 4 jets

- *$\log(y_{n-1,n})$ effective against backgrounds with 2 or 3 jets*

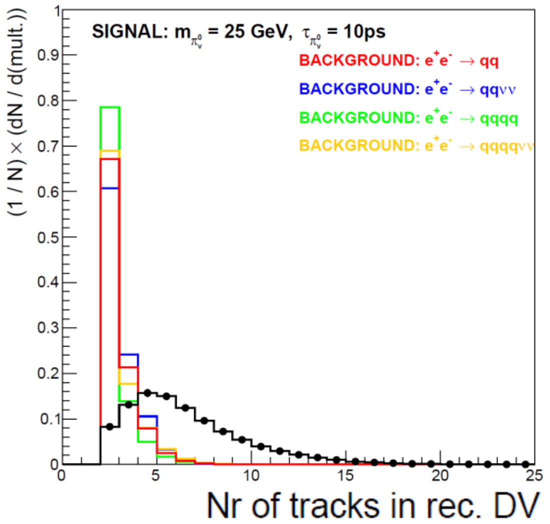
if reconstruct events with 2 jets

- *$\log(y_{n+1,n})$ effective against backgrounds with 3 or 4 jets*

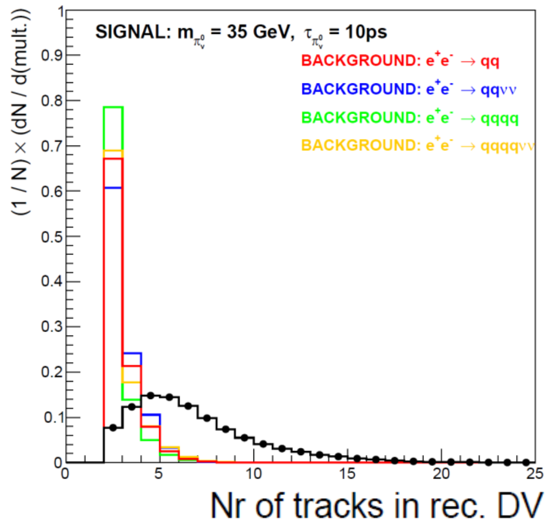
Example separation

[CLICdp-Note-2018-001]

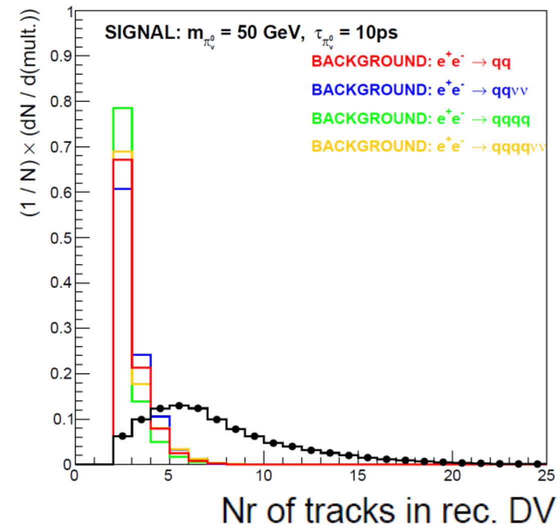
m_η = 25 GeV



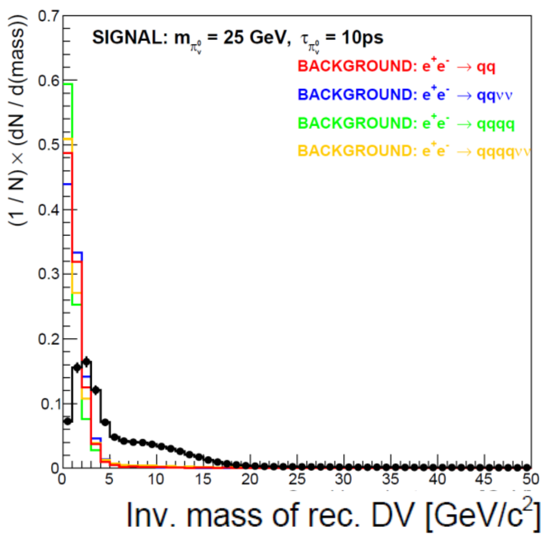
m_η = 35 GeV



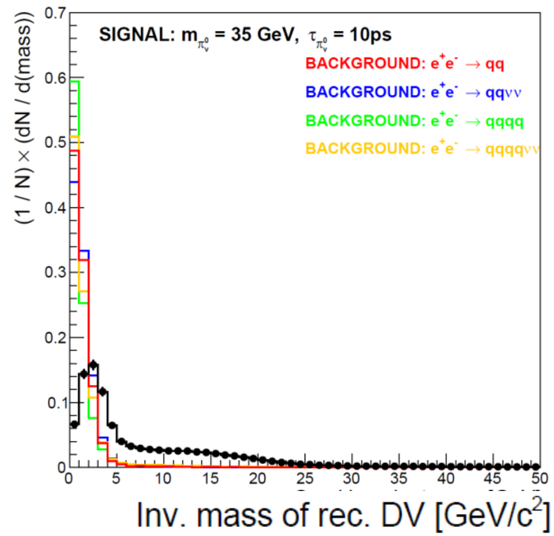
m_η = 50 GeV



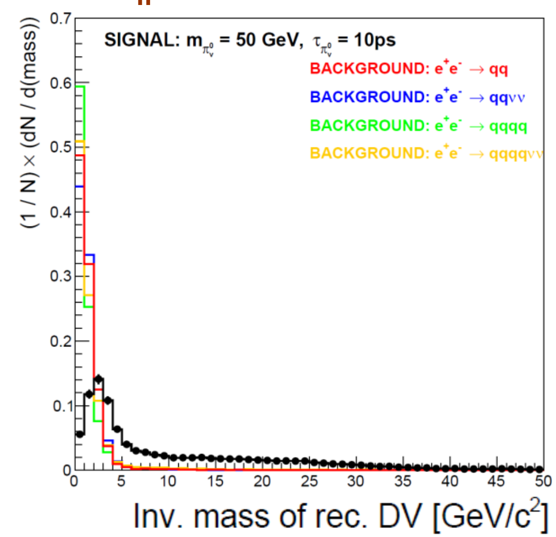
m_η = 25 GeV



m_η = 35 GeV

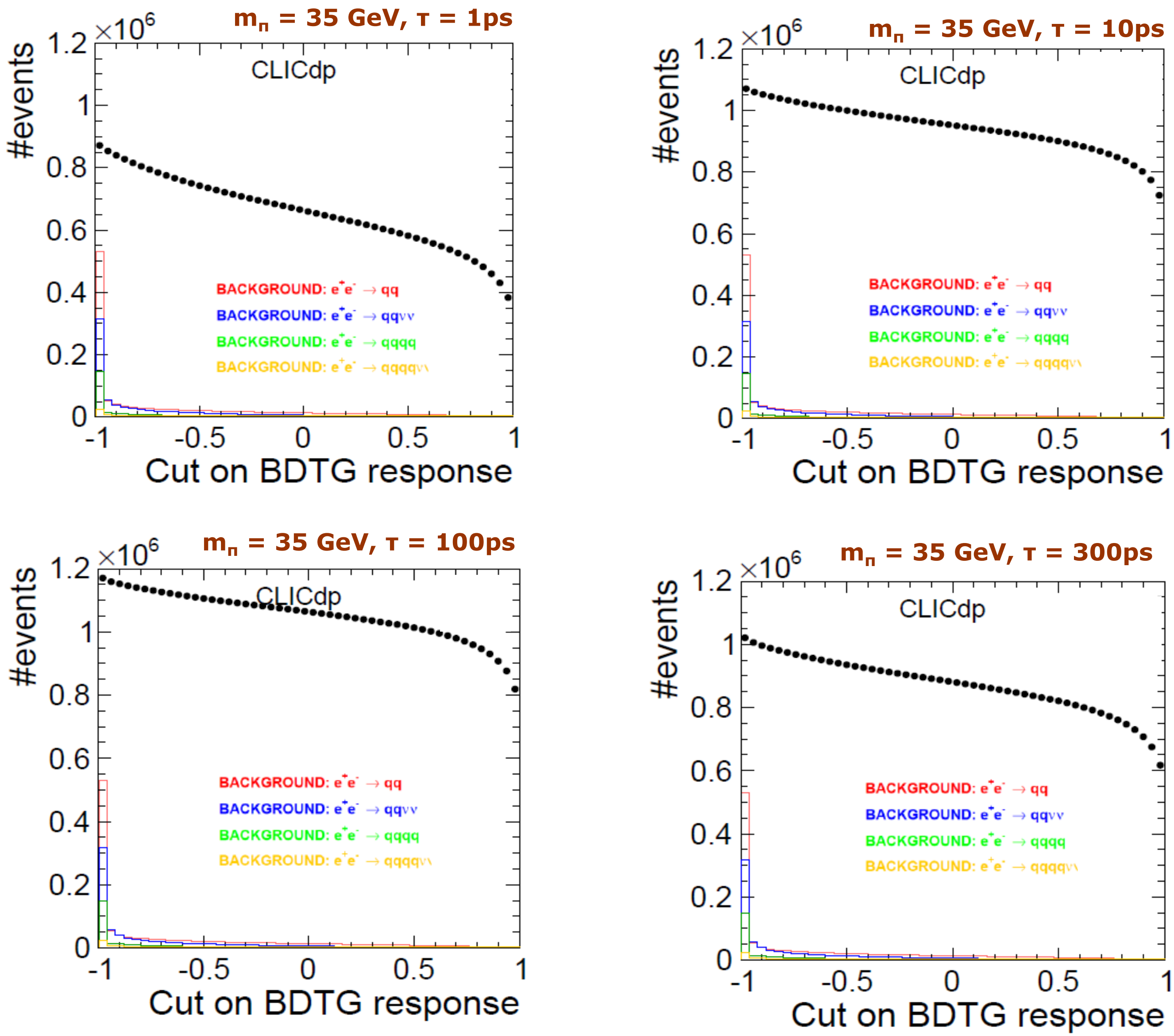


m_η = 50 GeV



BDT for CLIC 3 ab^{-1} at 3 TeV

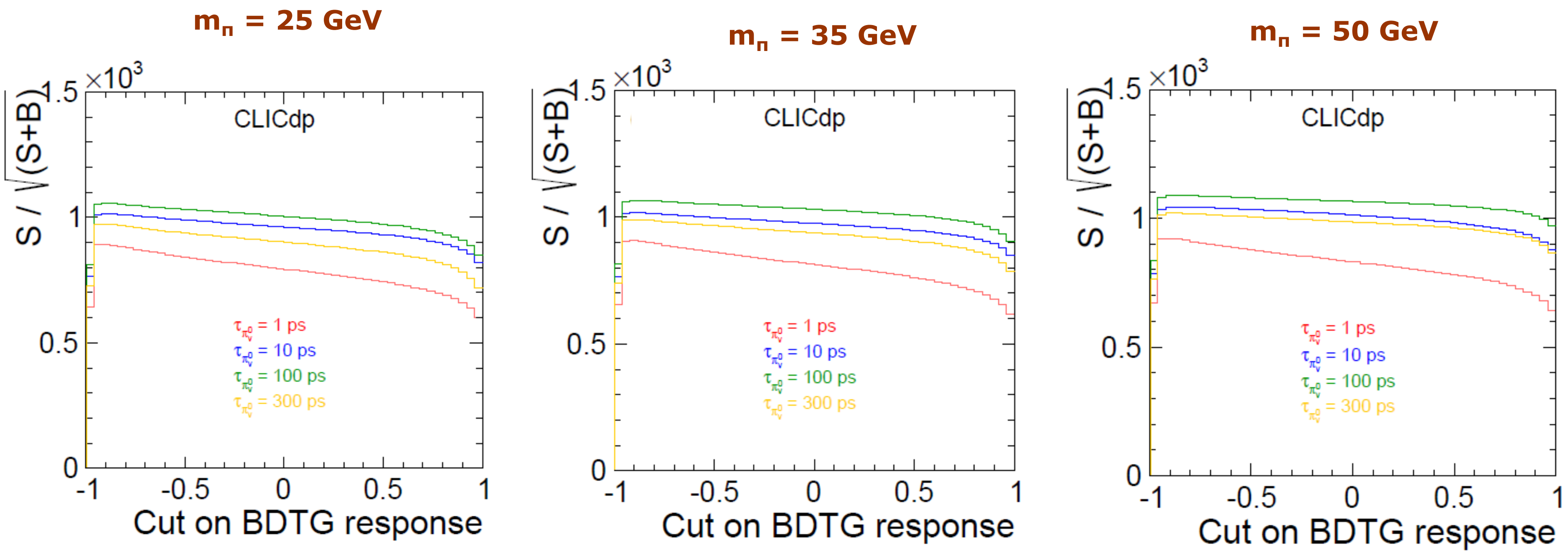
[CLICdp-Note-2018-001]



Significance

[CLICdp-Note-2018-001]

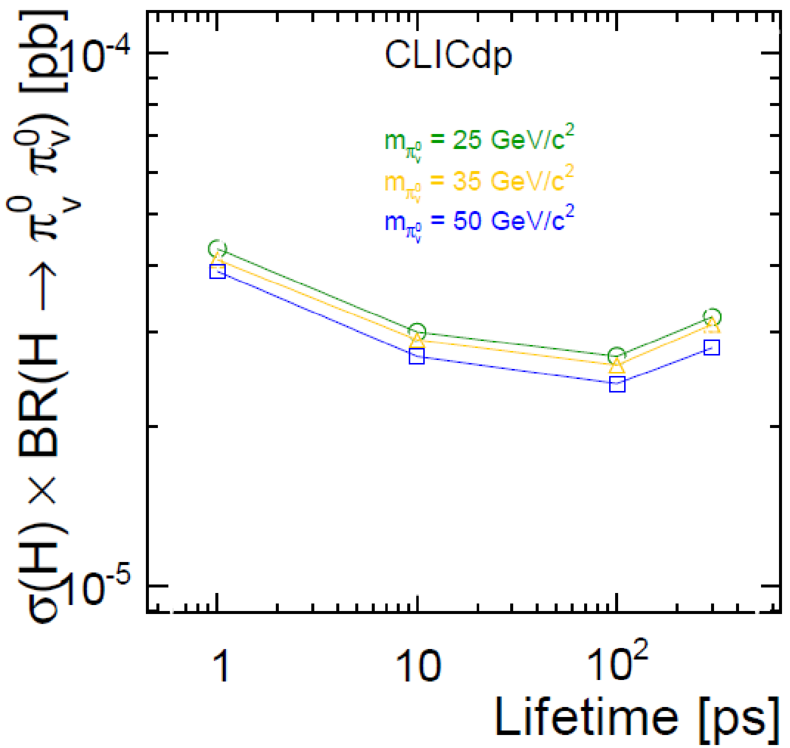
- Significance S / √(S + B) as a function of the cut on BDTG response
  - to choose the cut on BDTG discriminator



Upper limits

[CLICdp-Note-2018-001]

- Upper limits on x-section * BF at 95% CL for 3 ab^{-1} using CLs
  - *- direct comparison to pp results not straightforward*
  - *- but much better limits as compared to ATLAS, CMS and LHCb results!*



Conclusions

- Hidden sector: generic possibility for BSM physics
- Signal samples for 4 different HV pion lifetimes and 3 different masses
- Particle and jet reconstruction optimized
- Displaced vertices reonstructed using seeding procedure + loose SV finding
- Multivariate analysis based on reconstructed DVs & jets
- Sensitivities for CLIC 3 ab^{-1} at 3 TeV
- **Upper limits at 95% CL for 3 ab^{-1}**

much better results as compared to ATLAS, CMS and LHCb

- **PLANS:** - use new tracking for displaced tracks and $\sqrt{s}$ = 350 GeV
  - off-shell Higgs