Hidden Valley particles search in e^+e^- future linear colliders

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Hidden sector – generic possibility for NP

Consequence of string-theory

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

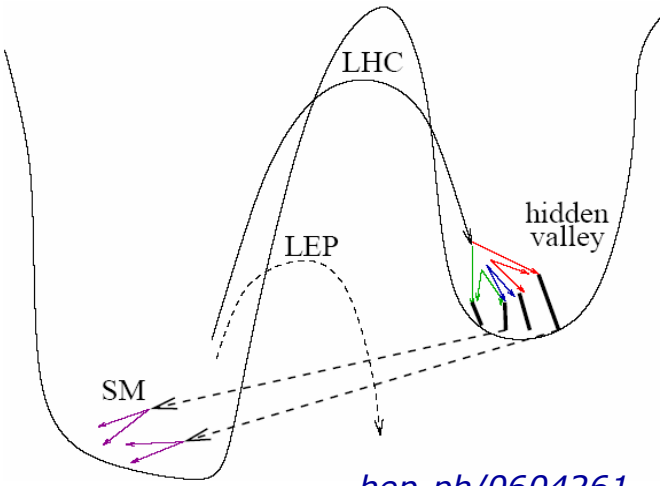
- hidden sector - „*v*-sector"
- communicator - interacts with both sectors

BARRIER

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

→ weakens interaction between sectors

→ production of new particles rare at low energy



hep-ph/0604261

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

→ all SM particles neutral within G_v

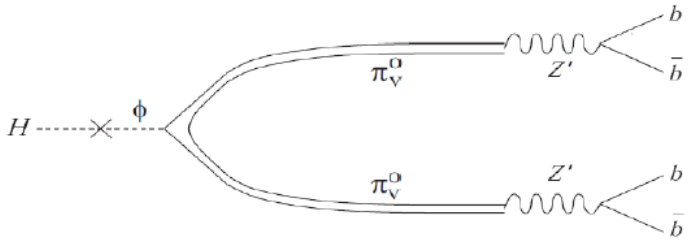
→ if energy sufficient → ***v-particle*** charged within G_v, neutral under G_{SM}

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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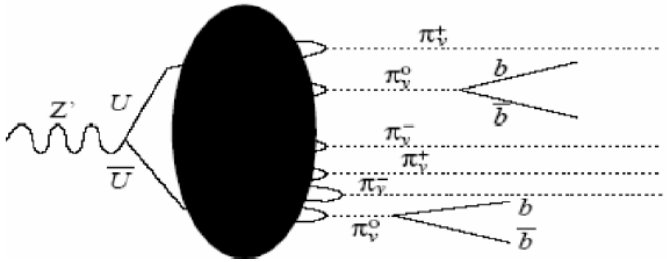
- **Direct multi-π_v production**

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

$\pi_v^0 \to b\bar{b}$, $\pi_v^+ \to$ *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!

Generated samples

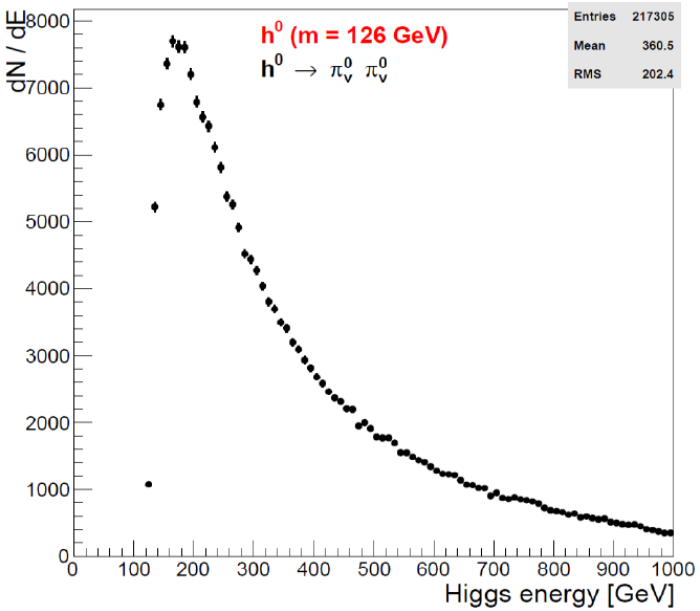
Higgs → $\pi_v^0\pi_v^0$ (at 3TeV)

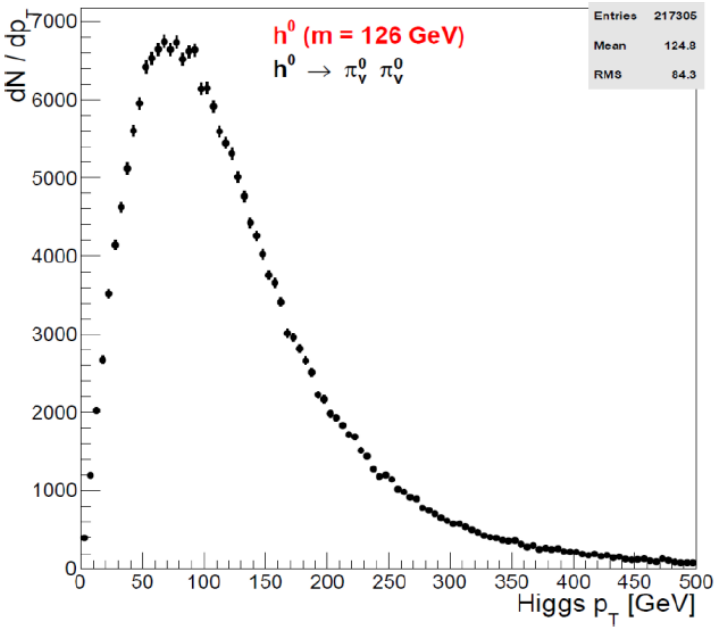
- mass(h^0) = 126 GeV
- mass(π_v^0) = 50 GeV
- π_v^0 lifetimes: 1, 10, 100, 300 ps

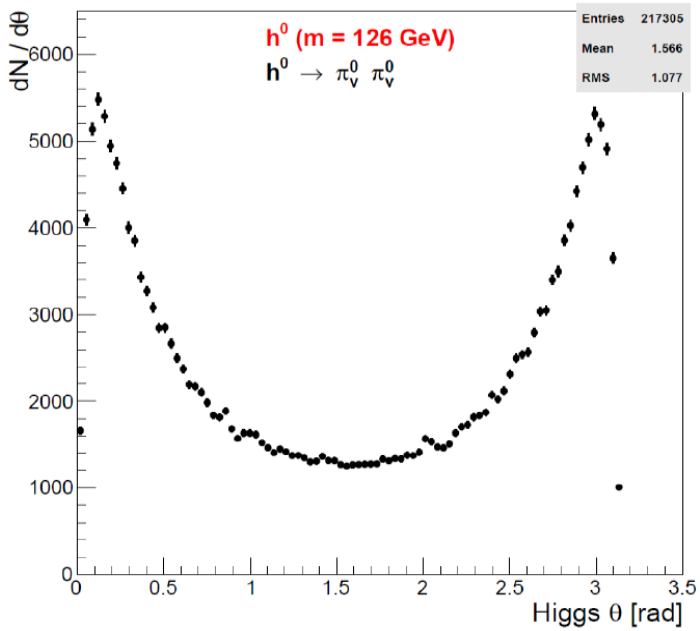
samples **with and without** pileup of $\gamma\gamma \rightarrow$ hadrons

Background (at 3 TeV)

- ee → qqvv *(qq)* *(bb(bar))*
- ee → qqqqvv *(qqqq)* *(4b, 4c, 2b2c)*





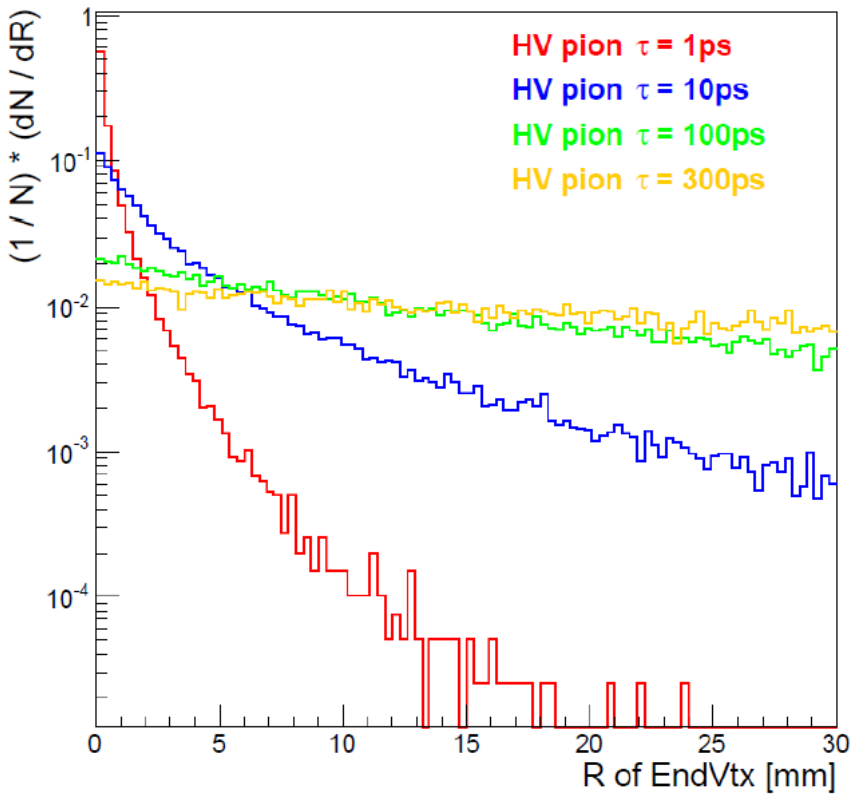


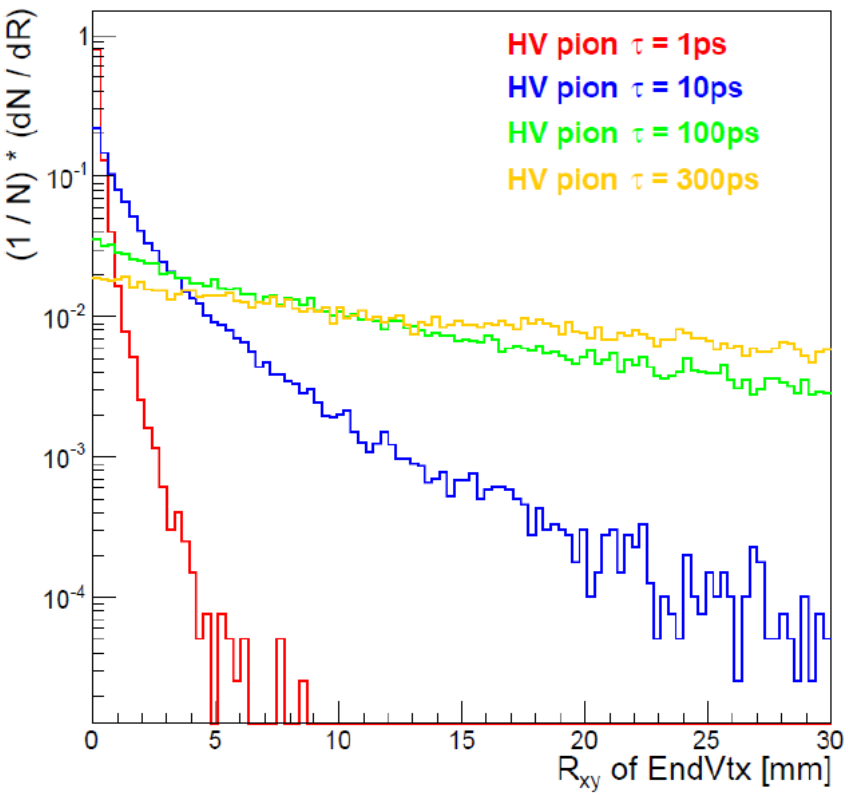
Generated Hidden Valley pions

v-paricles have non-zero lifetime

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

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

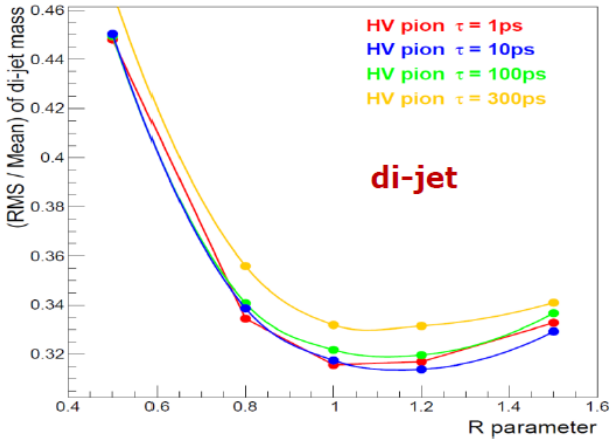


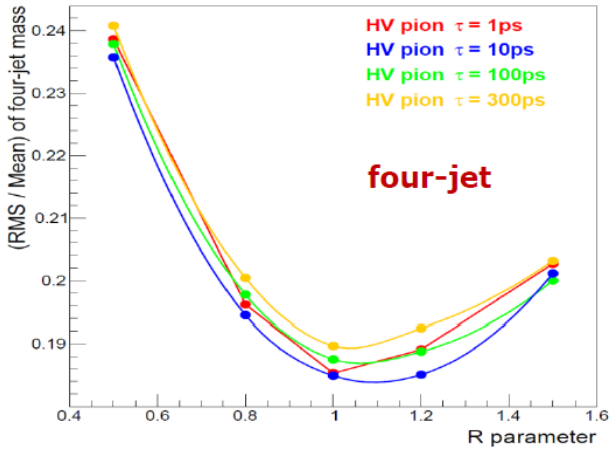


Di-jet and four-jet mass – *R* optimization

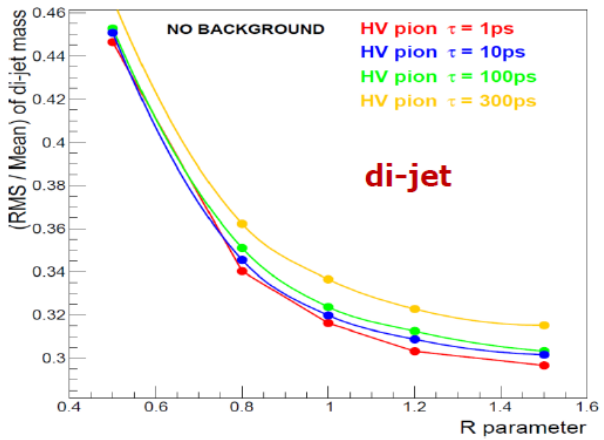
- fastjet k_T algorithm
- nr of required exclusively reconstructed jets = 4

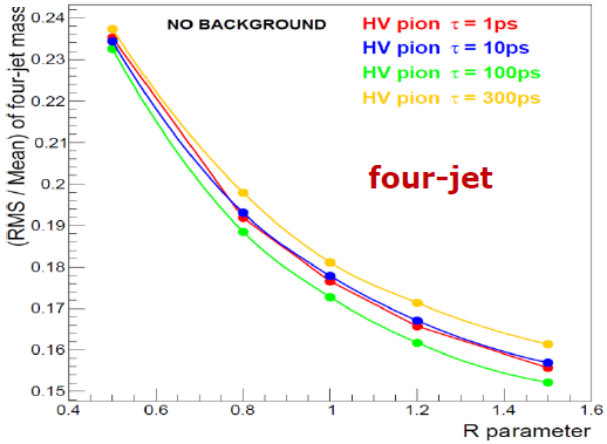
$\gamma\gamma \rightarrow$ hadrons background





NO background

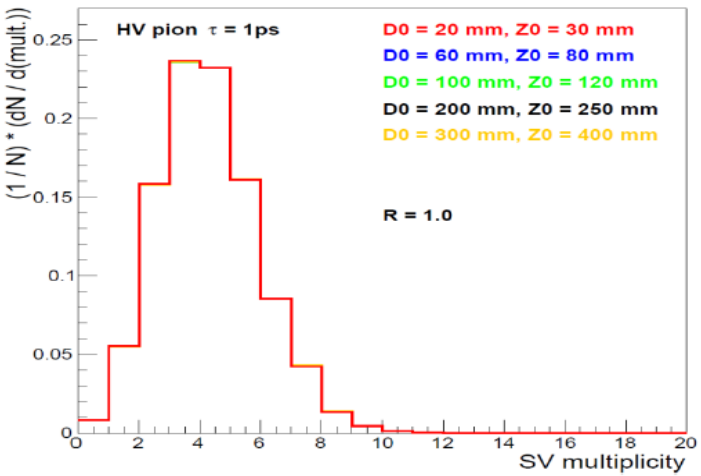


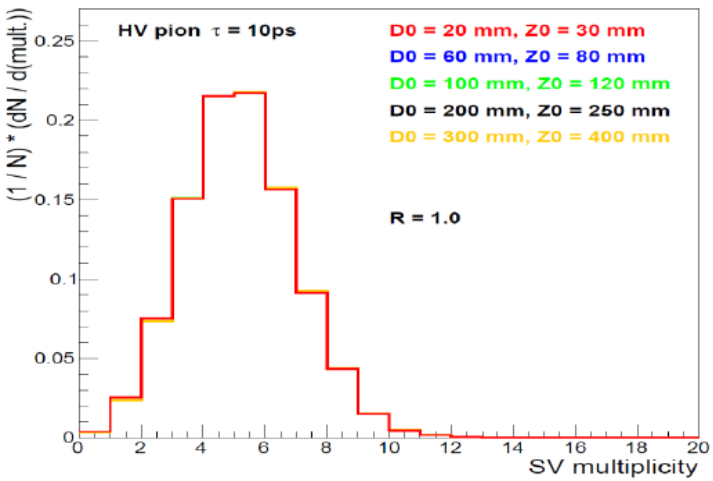


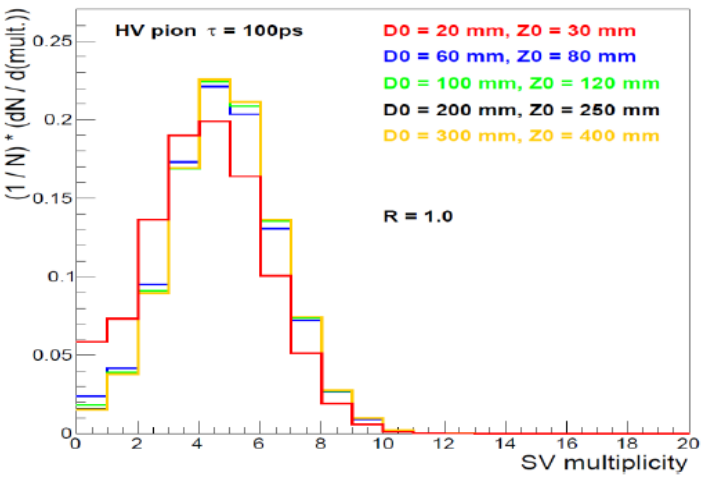
jet *R* parameter chosen to be = 1.0

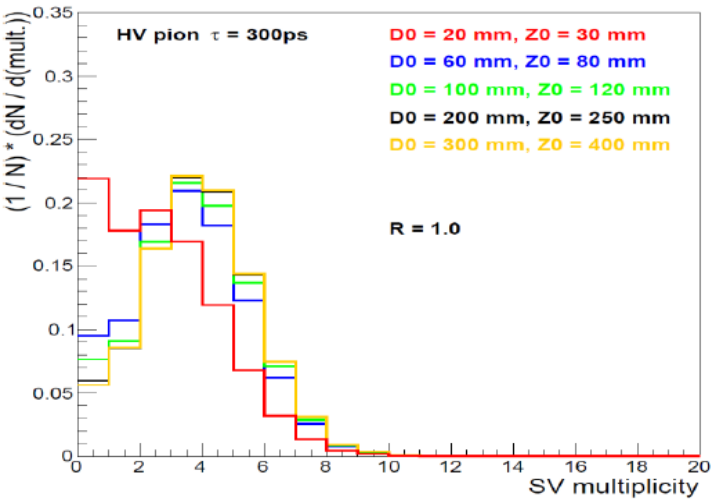
Track *D0* and *Z0* cuts - optimization

- 5 different D0 values tried: *20, 60, 100, **200**, 300 mm*
- with 5 different values of Z0: *30, 80, 120, **250**, 400 mm*









SVs: Loose SV finding strategy

Displaced vertices *(DVs)*

→ rather PV-like objects to cumulate as many as possible tracks from Hidden Valley pions

→ DV track multiplicity should be > 4 *(to remove b-hadron background)*

DV reconstruction based on loose SV reconstruction (seeding)

Seeds: candidates for displaced vertices

→ points at which a sufficient number of tracks pass close to each other

→ loose SV reconstruction

Loose SV reconstruction (seeding procedure):

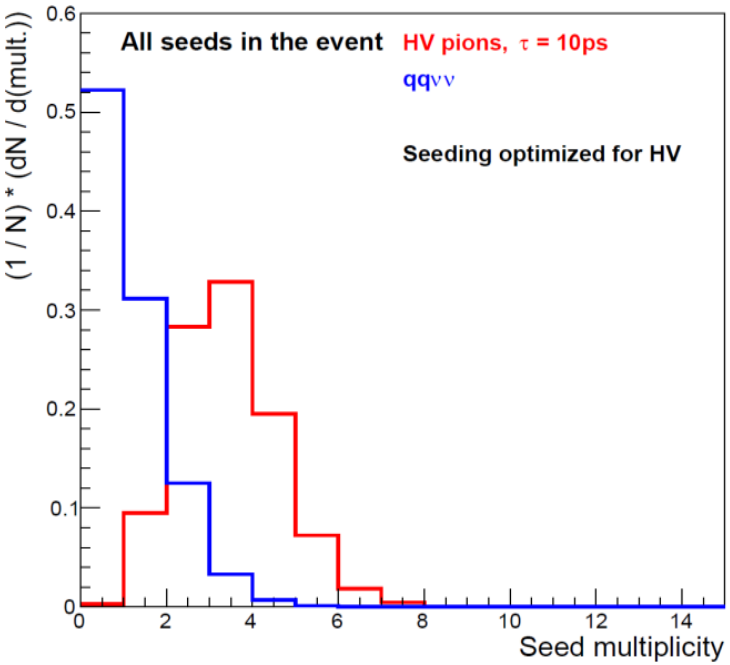
- select charged tracks with high IP wrt PV
- for each track *(base track)* a set of close tracks is determined
- track is defined as close if its distance of closest approach *(DOCA)* to the base track is less than 1 mm
- for such a track pair the point of closest approach *(POCA)* is calculated - **seed**
- all tracks close enough to this POCA are marked as used
- loop over tracks is continued and the tracks marked as used are skept

Re-assignement of tracks to the SVs starting from initial set of charged tracks with cut on IP_{PV}

Selection

- loose SV reconstruction (seeding) optimized for Hidden Valley
- cut on nr of seeds in the event
- multi-variate analysis

Signal	Fraction of events with at least 2 seeds
HV pion, τ = 1 ps	72 %
HV pion, τ = 10 ps	89 %
HV pion, τ = 100 ps	97 %
HV pion, τ = 300 ps	86 %
Background	
$e^+e^- \rightarrow qq$	6 %
$e^+e^- \rightarrow qqvv$	8 %
$e^+e^- \rightarrow qqqq$	9 %
$e^+e^- \rightarrow qqqqvv$	11 %



IN NEXT STEP: assign two jets to one displaced vertex

- *nr of common tracks jet-SV (seed) is max. (second max.)*

TMVA: variables

Multi-variate analysis for events with at least 2 seeds

→ 7 variables with good separation: signal wrt background

1) nr of tracks in SV (seed)

2) SV (seed) multiplicity in the event

3) SV (seed) invariant mass

4) mass of di-jet assigned to the SV

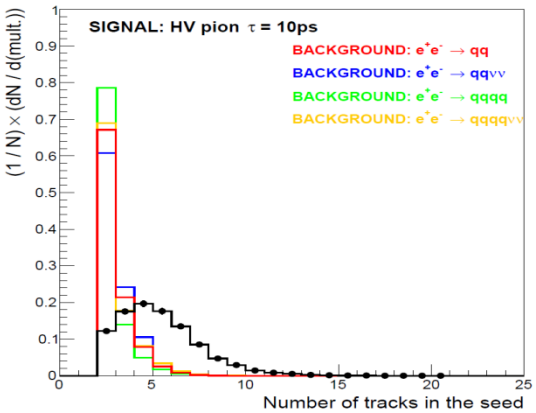
5) mass of four-jet assigned to 2 SVs

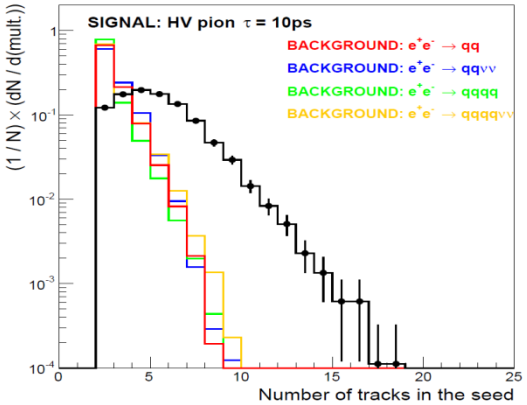
if reconstruct events with 4 jets

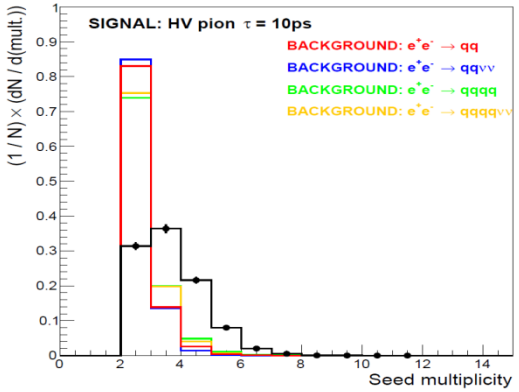
6) $\log(y_{n-1,n})$ effective against backgrounds with 2 or 3 jets

if reconstruct events with 2 jets

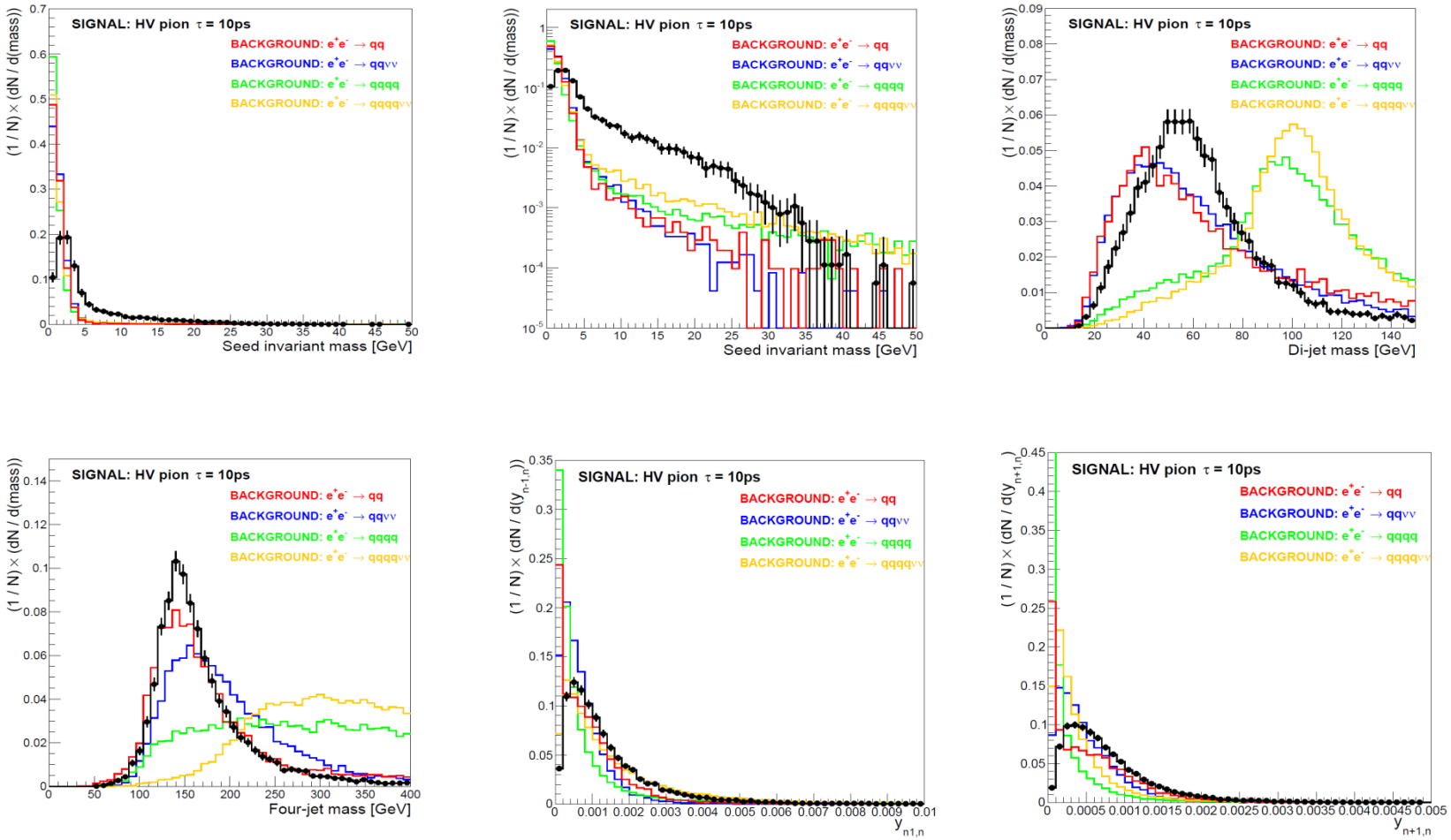
7) $\log(y_{n+1,n})$ effective against backgrounds with 3 or 4 jets





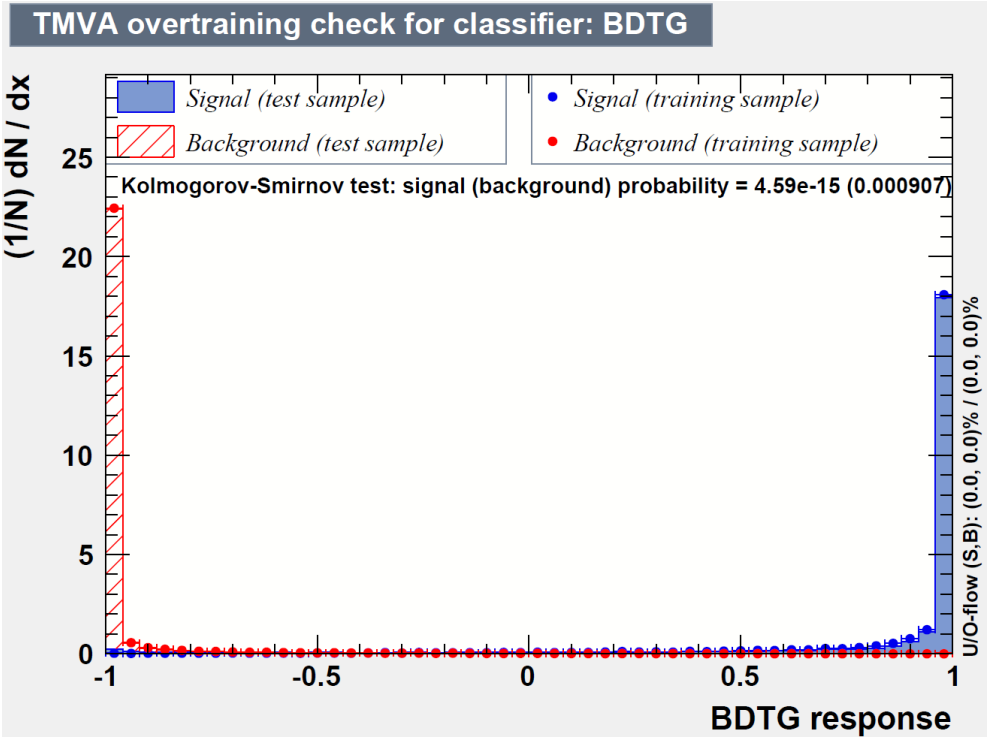


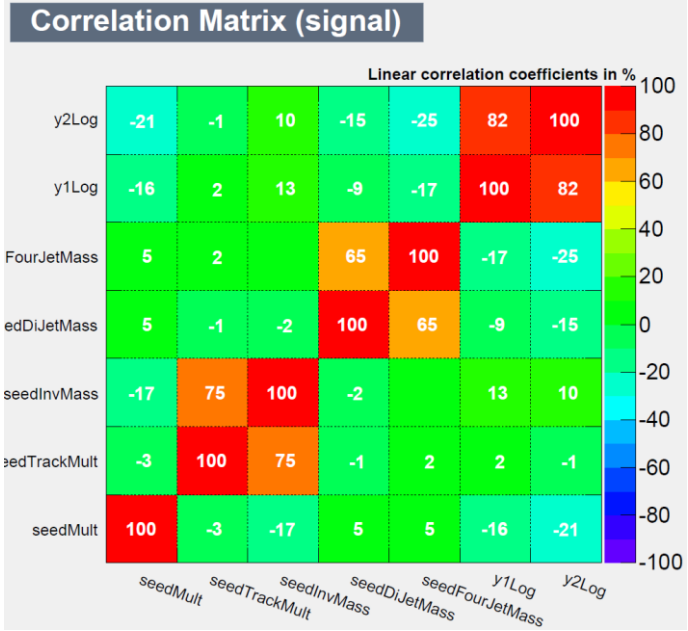
TMVA: variables

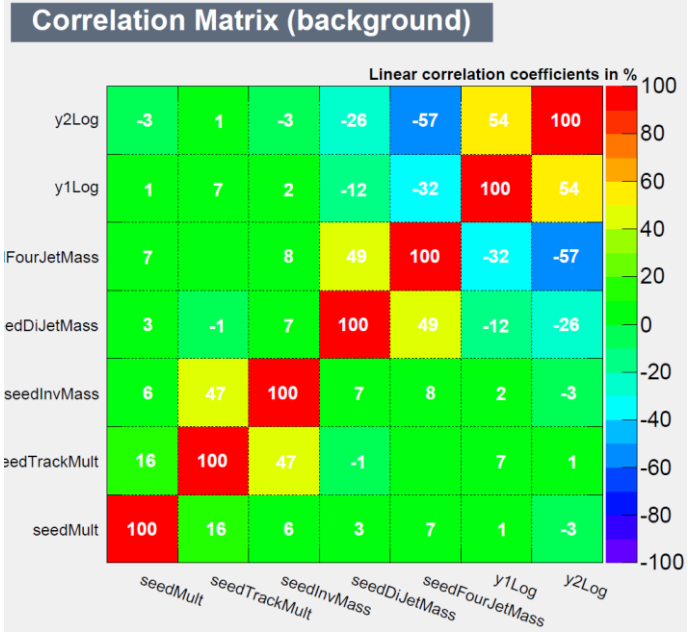


TMVA: response

- several methods tested
- BDTG method chosen as most effective
  - signal: *HV, mass = 50 GeV, τ = 10 ps*
  - background: *$e^+e^- \rightarrow qqvv$*

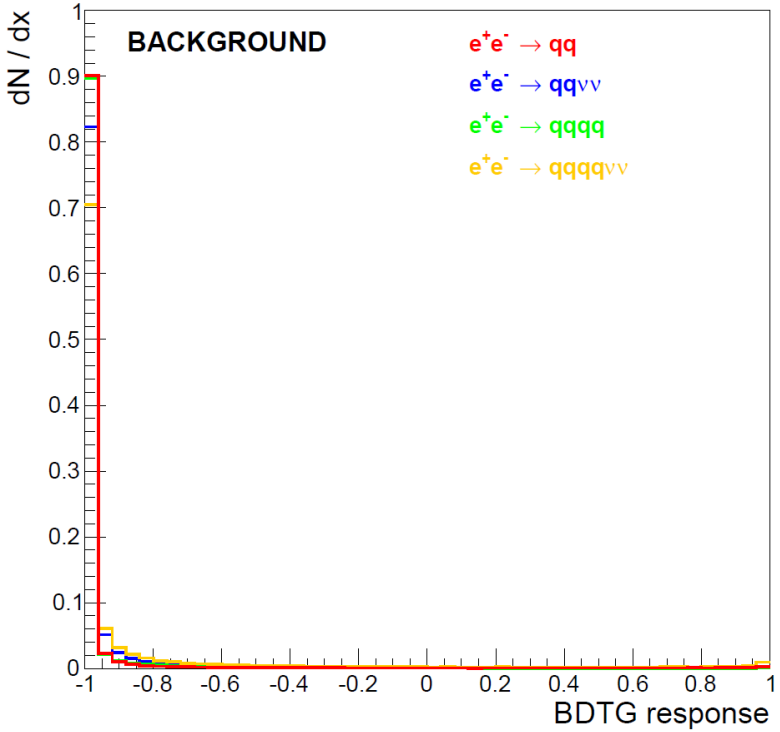


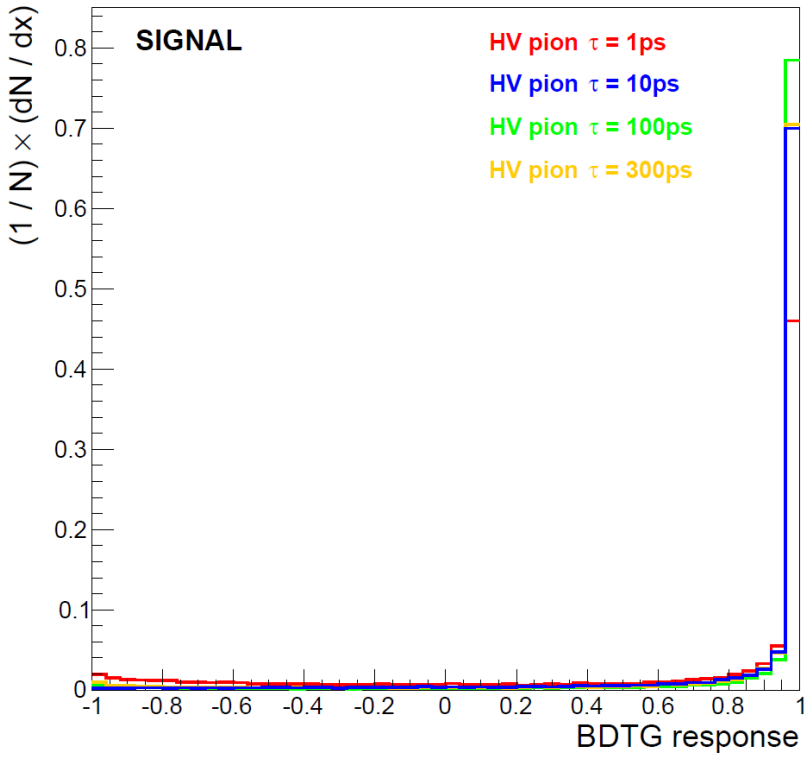




TMVA weights applied to signal and background

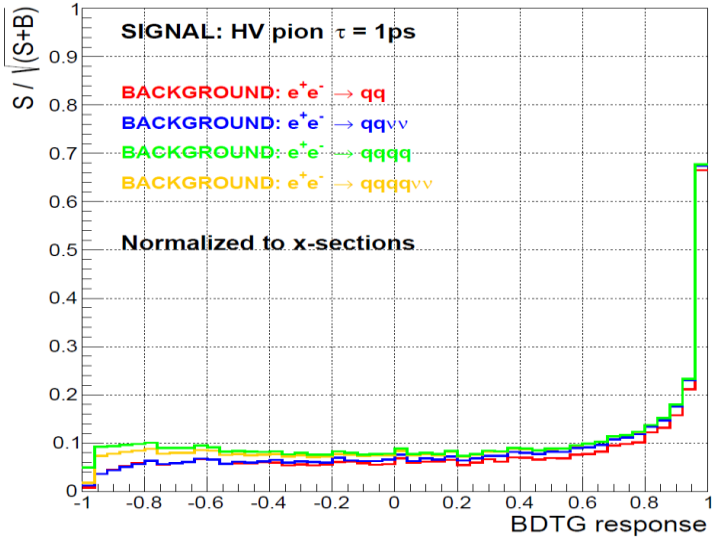
- TMVA weights applied to the MC samples

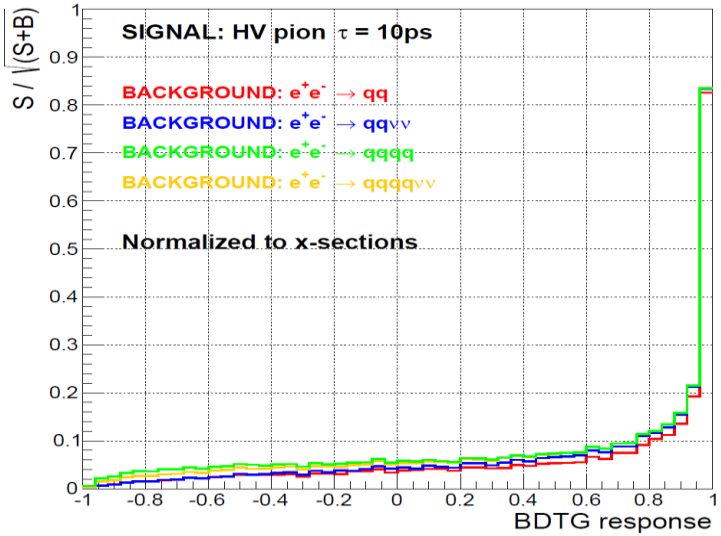


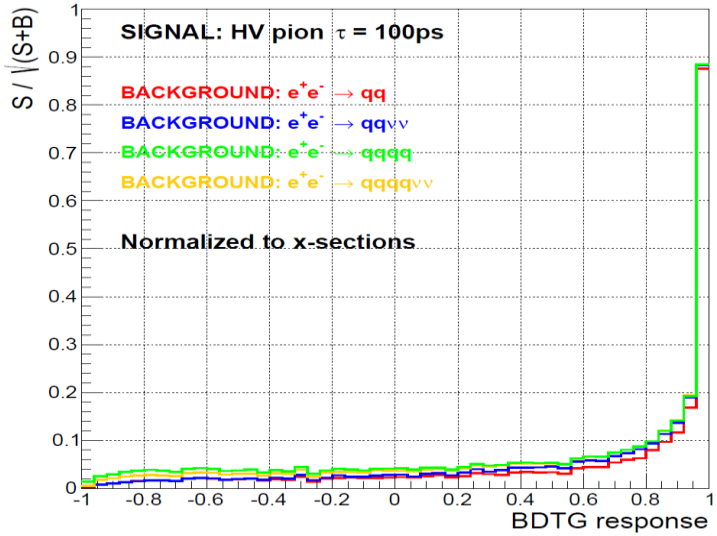


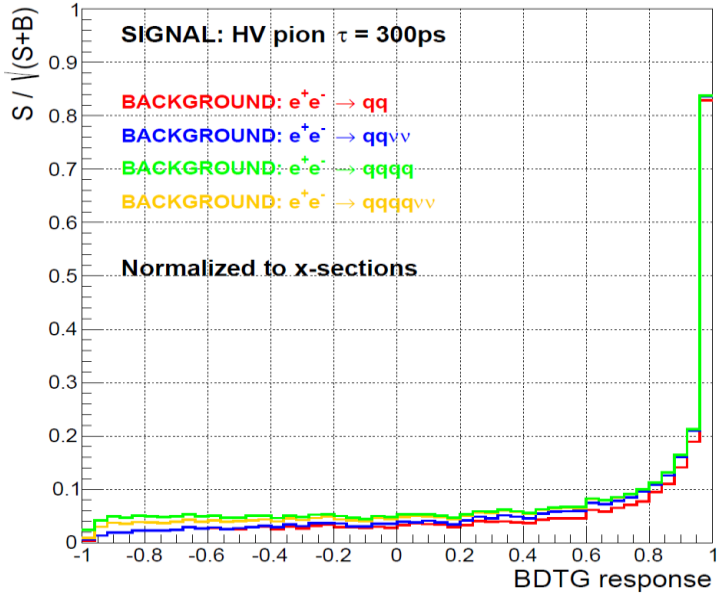
Sensitivity for CLIC 2 ab^{-1} at 3 TeV vs BDT resp.

- $S / \sqrt{(S + B)}$ with normalization to the x-sections

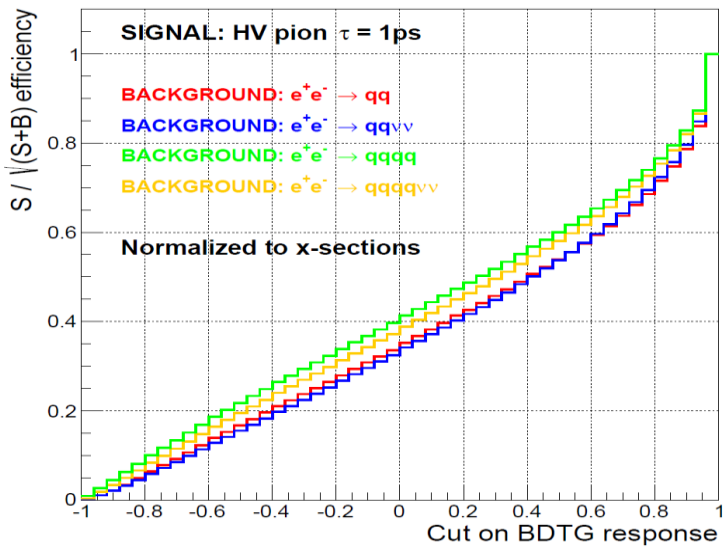


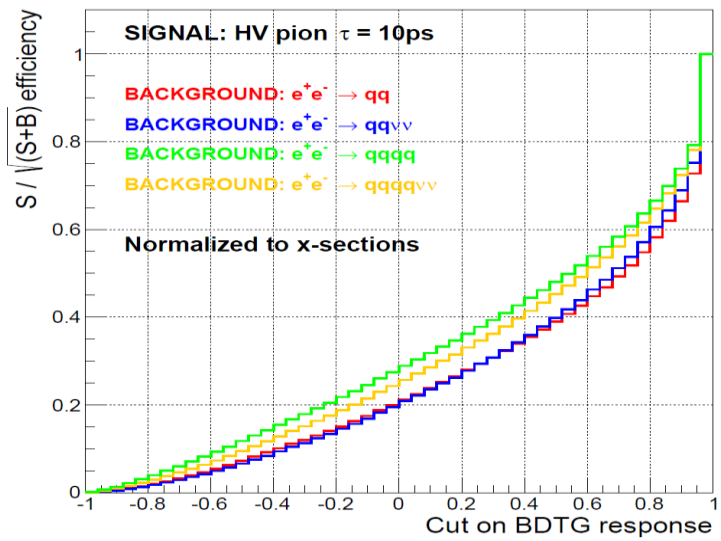


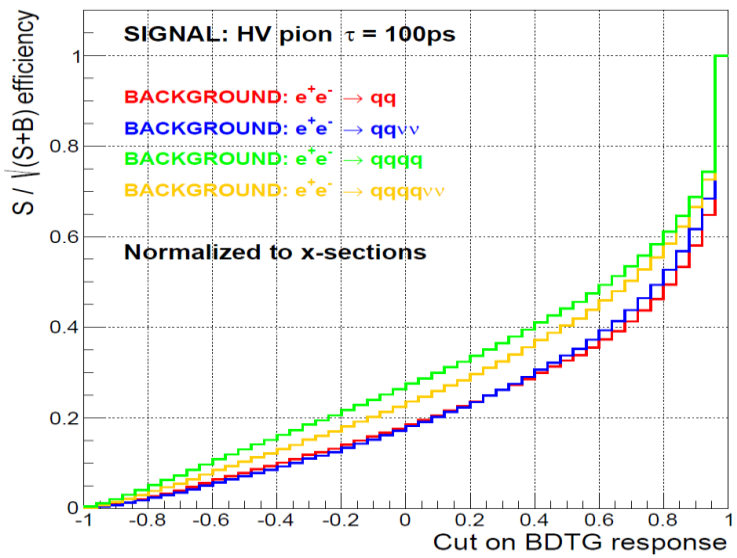


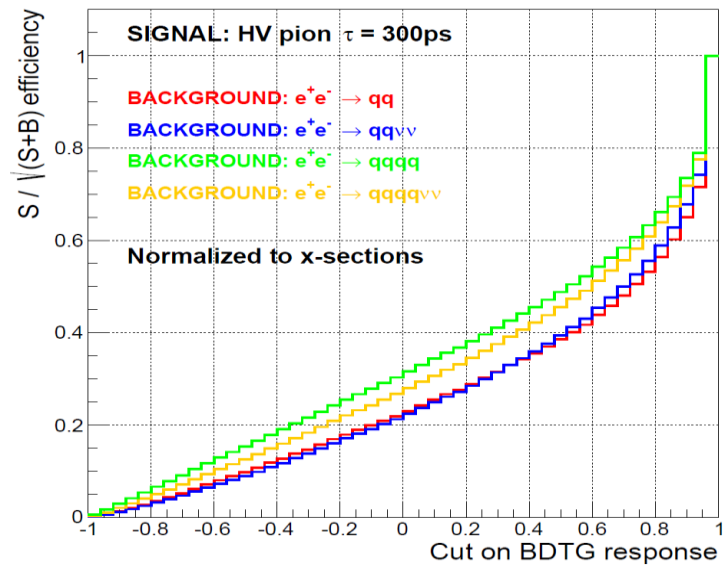


S/√(S+B) efficiency vs cut on BDTG









Conclusions

Expected number of events after selection *(with BDT response > 0.95)*

Signal	**Cross section** [pb]	**Selection eff.** (%)	**Expected events for 2 ab^{-1}**
HV pion, τ = 1 ps	10.6 (*)	36.7	7780 K
HV pion, τ = 10 ps	3.8 (*)	60.5	4598 K
HV pion, τ = 100 ps	16.2 (*)	75.7	24527 K
Background			
$e^+e^- \rightarrow qq$	2.95	0.09	5 K
$e^+e^- \rightarrow qq\nu\nu$	0.55	0.19	2 K
$e^+e^- \rightarrow qqqq$	1.32	0.20	5 K
$e^+e^- \rightarrow qqqq\nu\nu$	0.07	0.22	0.3 K

* *LHCb upper limits at 7 TeV with 95% CL taken from LHCb-PAPER-2014-062*

- Hidden sector: generic possibility for BSM physics
- Jetting and loose SV finding parameters optimized
- Sensitivities for CLIC 2 ab^{-1} at 3 TeV

- **PLANS:** analysis for different HV masses & HV pions from Z'