BSM Hidden Valley searches

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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

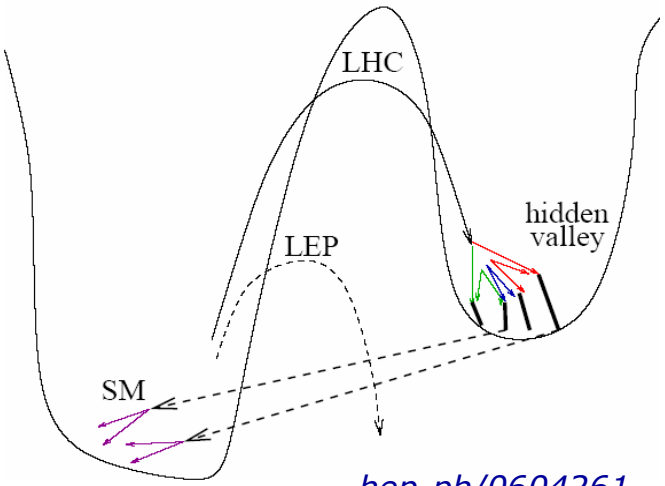
- hidden sector - „*v*-sector"
- communicator - interacts with both sectors

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

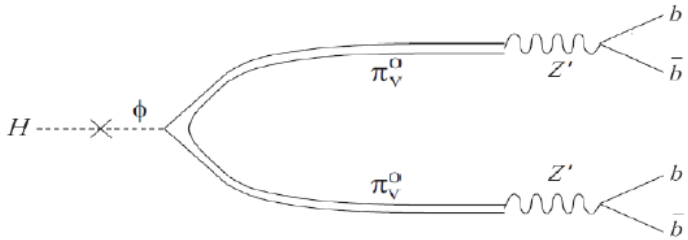
→ if energy sufficient → ***v-particle*** charged within G_v, neutral under G_{SM}

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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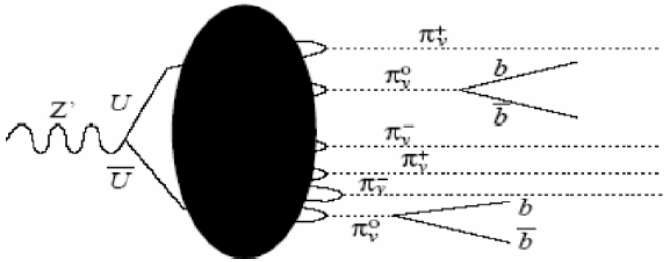
- **Direct multi-π_v production**

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

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

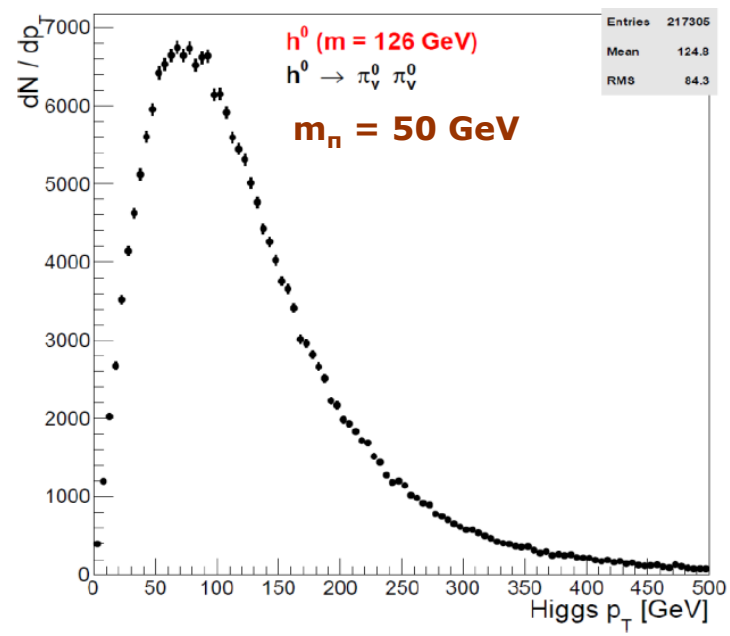
if lifetime between 1 ps and 1 ns *(characteristic for weak decays)*

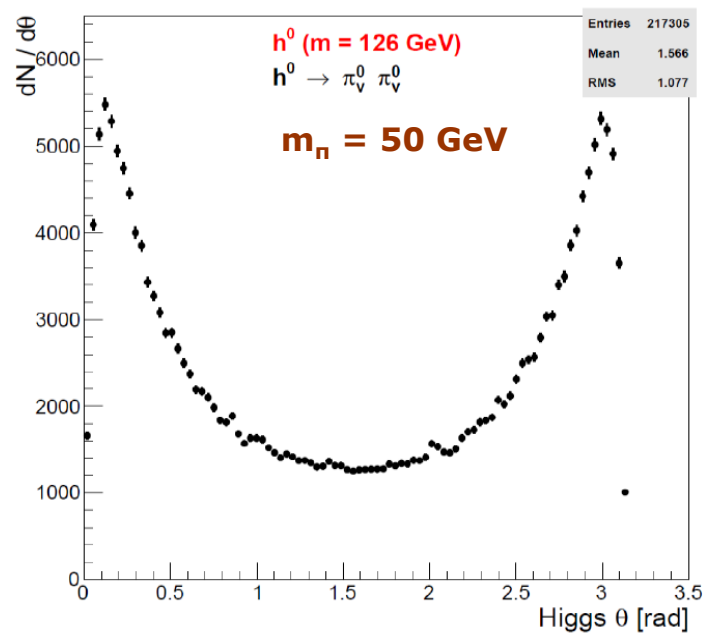
can be identified in tracking systems by displaced vertices!

Generated samples

Signal $h^0 \to \pi_v^0 \pi_v^0$ ***(at 3TeV)*** 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 ***(at 3TeV)***	
$e^+e^- \to qq$	*(bb(bar))*
$e^+e^- \to qqvv$	*(bb(bar))*
$e^+e^- \to qqqq$	*(4b, 4c, 2b2c)*
$e^+e^- \to qqqqvv$	*(4b, 4c, 2b2c)*

Thanks to Philipp!



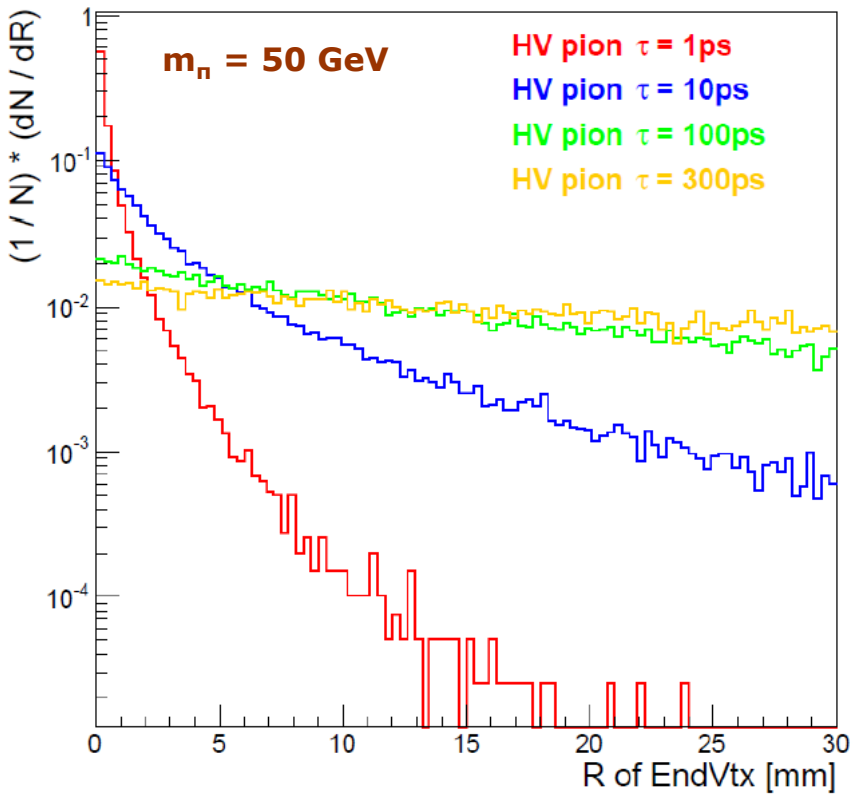


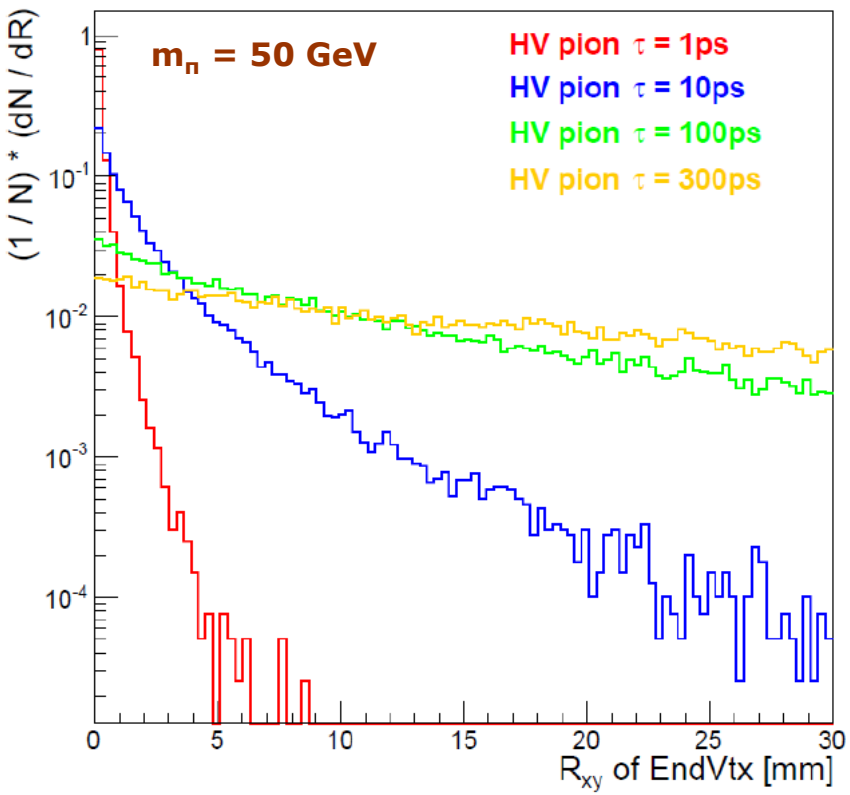
Generated Hidden Valley pions

***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*

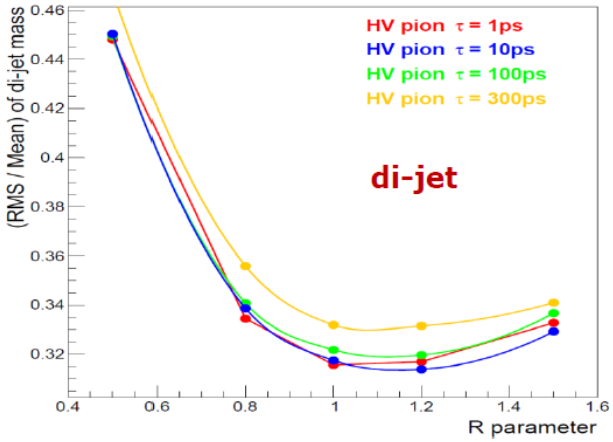


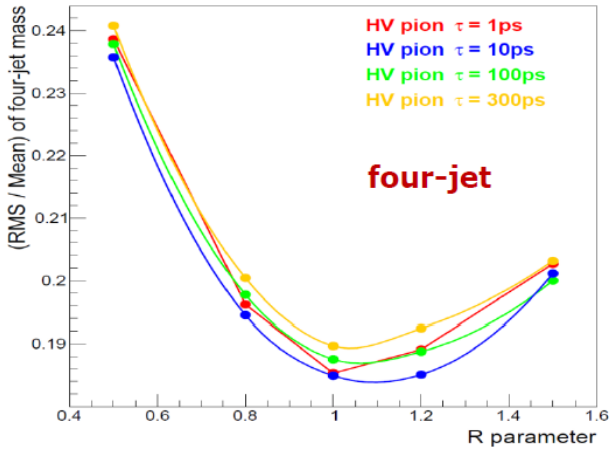


Di-jet and four-jet mass – *R* optimization

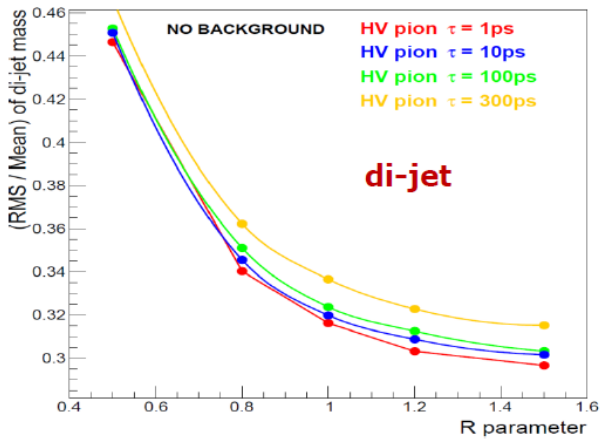
- fastjet k_T algorithm
- nr of required exclusively reconstructed jets = 4

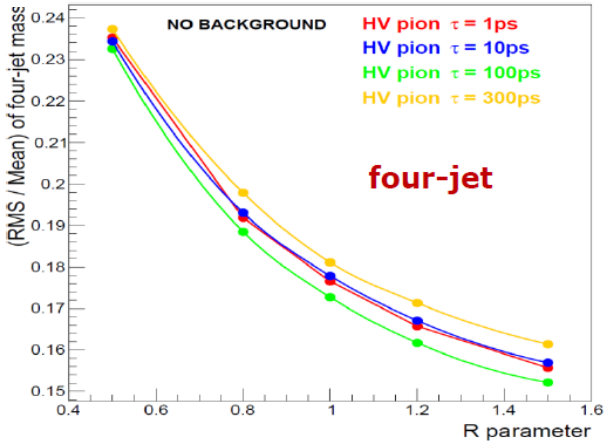
$\gamma\gamma \rightarrow$ hadrons background





NO background

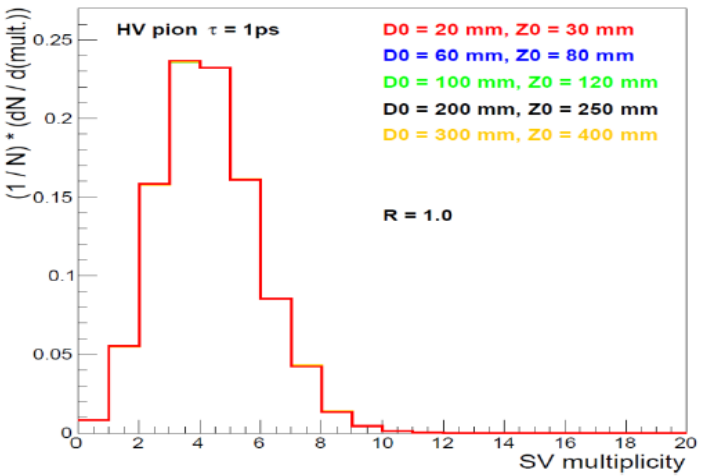


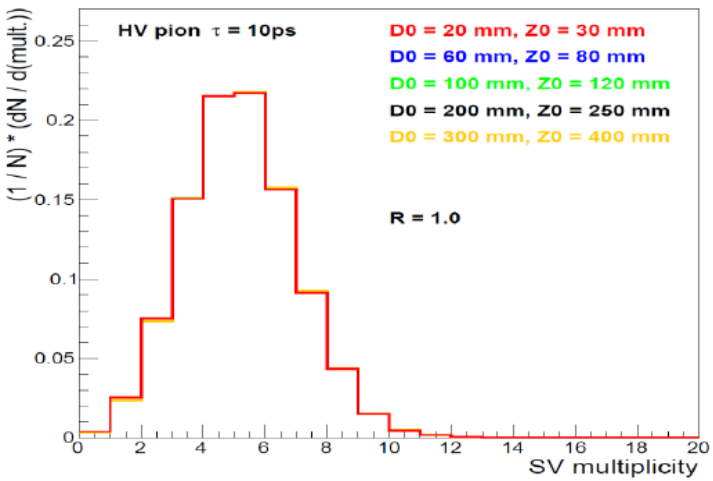


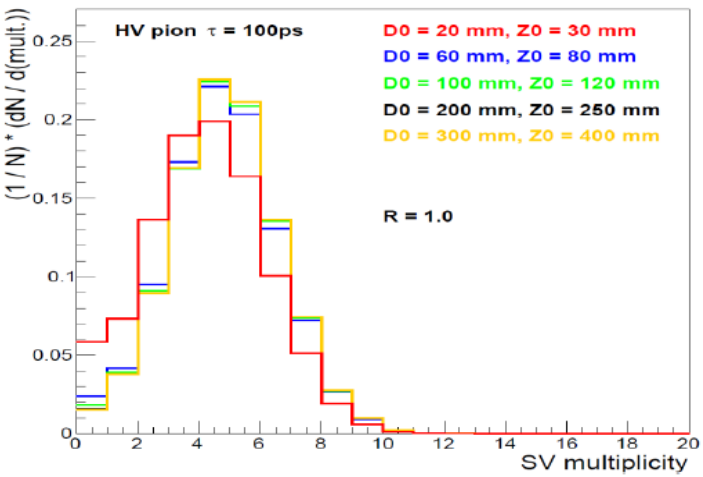
jet *R* parameter chosen to be = 1.0

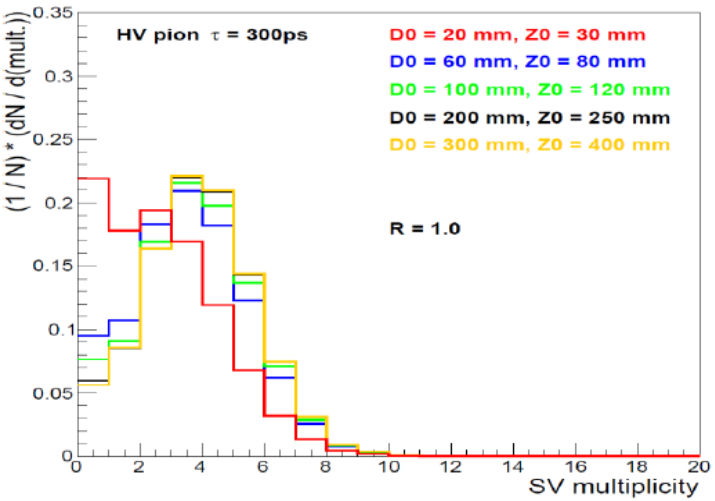
Track *D0* and *Z0* cuts - optimization

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









DVs: 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

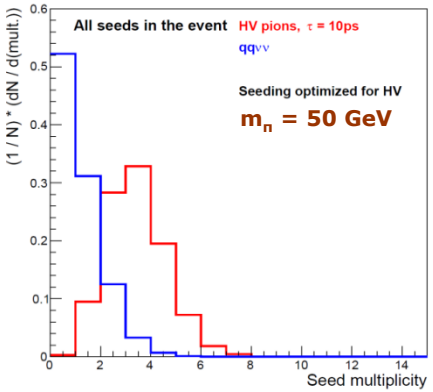
→ loose SV reconstruction → DV's

Seeding procedure

- select charged tracks with high IP wrt PV
- for each track *(base track)* a set of close tracks is determined
- track defined as close if distance of closest approach *(DOCA)* to the base track < 1 mm
- for such a track pair the point of closest approach *(POCA)* is calculated - **seed**
- all tracks close enough to the POCA are marked as used
- loop over tracks is continued, and the tracks marked as used are skept *(fast saturation)*
- loose SV fit around seeds → **reconstructed displaced vertices**

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

Selection



- loose SV reconstruction based on seeding optimized for Hidden Valley
- cut on nr of displaced vertices in the event
- multi-variate analysis

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	
$e^+e^- \rightarrow qq$	6 %
$e^+e^- \rightarrow qq\nu\nu$	8 %
$e^+e^- \rightarrow qqqq$	9 %
$e^+e^- \rightarrow qqqq\nu\nu$	11 %

In the next step: assign two jets to one displaced vertex

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

TMVA: variables

Multi-variate analysis for events with at least 2 DV's *(seeds)*

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

(1) nr of tracks in DV (seed)

(2) DV (seed) multiplicity in the event

(3) DV (seed) 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

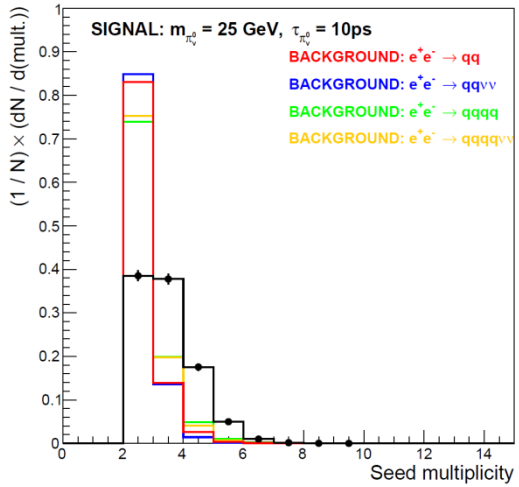
(6) $\log(y_{n-1,n})$ effective against backgrounds with 2 or 3 jets

if reconstruct events with 2 jets

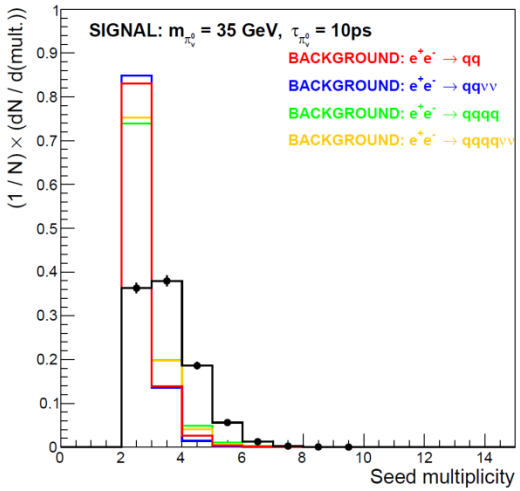
(7) $\log(y_{n+1,n})$ effective against backgrounds with 3 or 4 jets

TMVA: variables *(m = 25, 35, 50 GeV)*

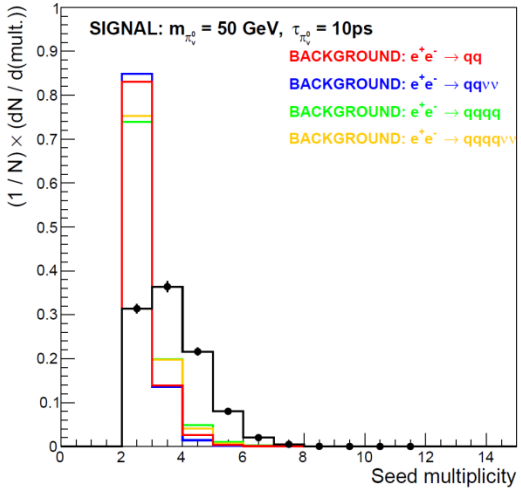
m_π = 25 GeV



m_π = 35 GeV



m_π = 50 GeV



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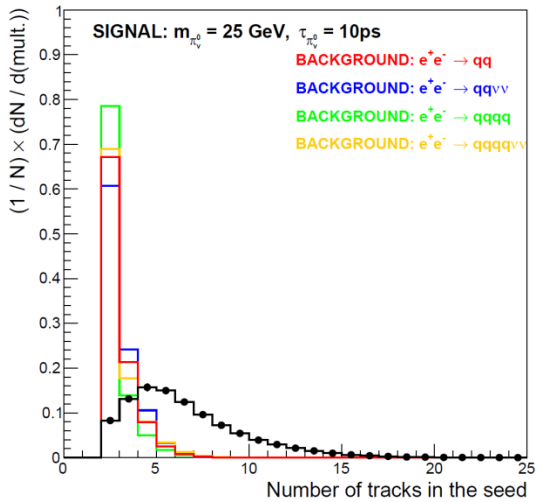

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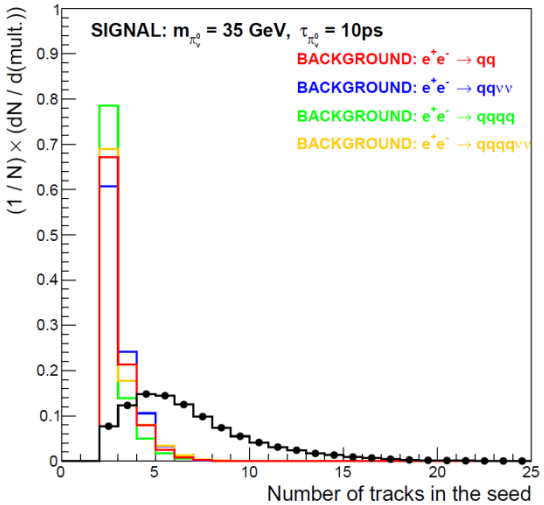

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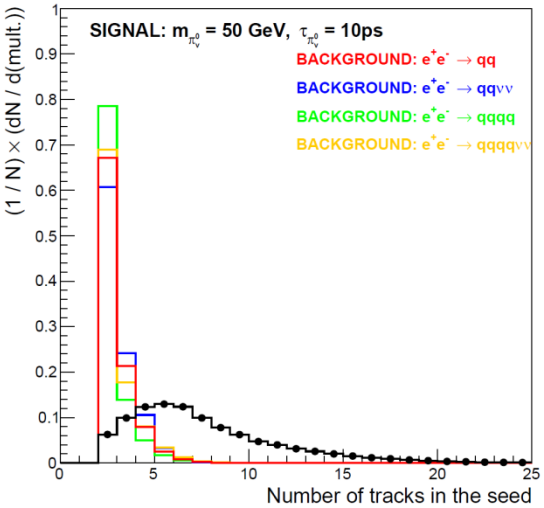

TMVA: variables *(m = 25, 35, 50 GeV)*

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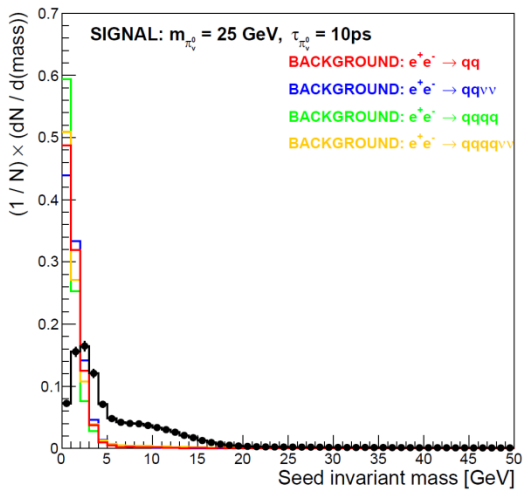

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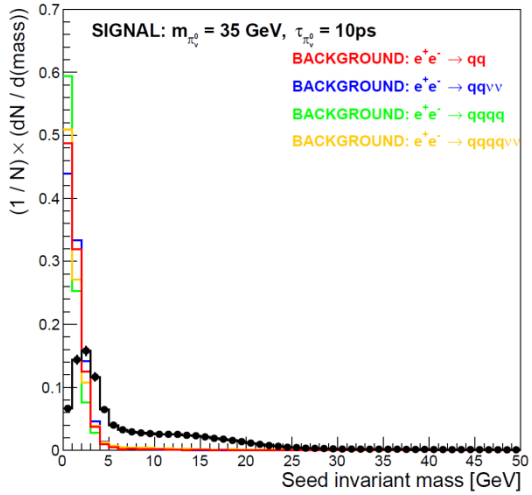

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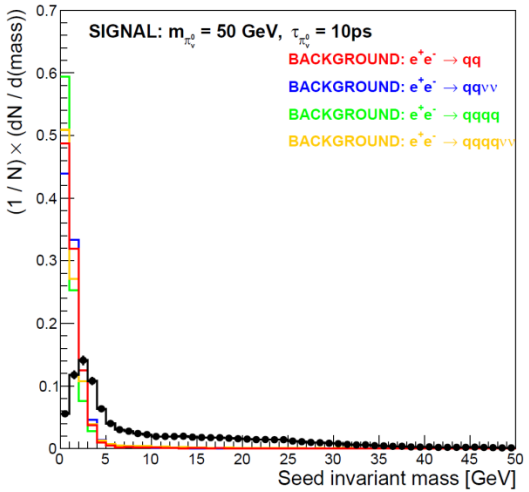
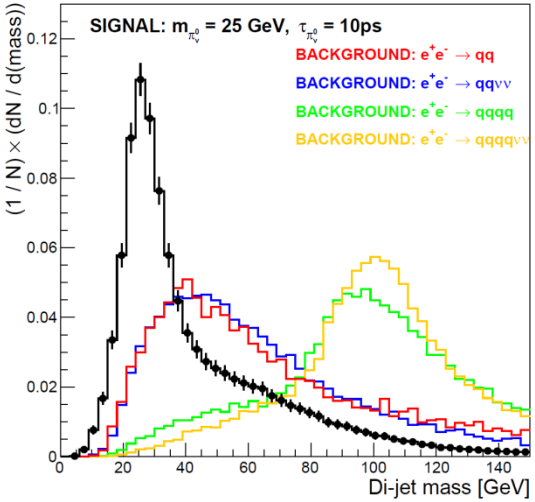
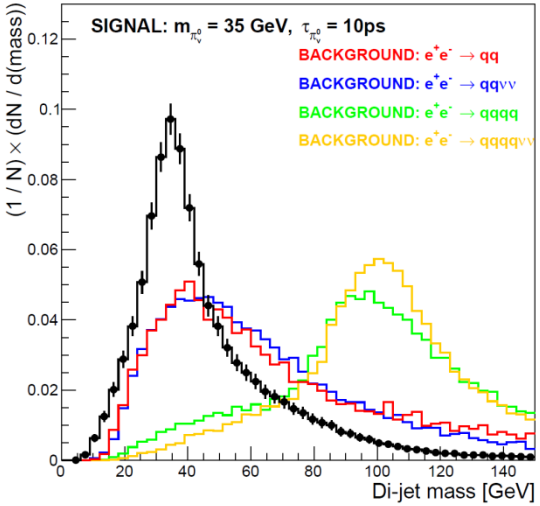


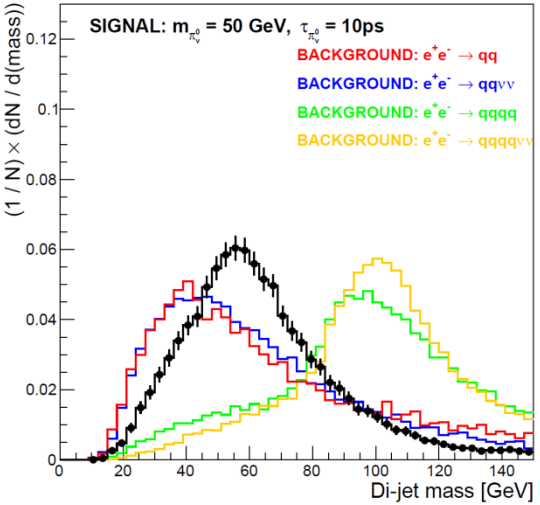
m_π = 25 GeV



m_π = 35 GeV

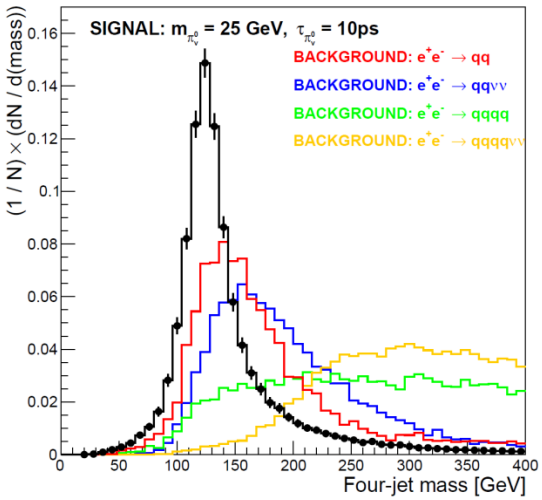


m_π = 50 GeV



TMVA: variables *(m = 25, 35, 50 GeV)*

m_π = 25 GeV



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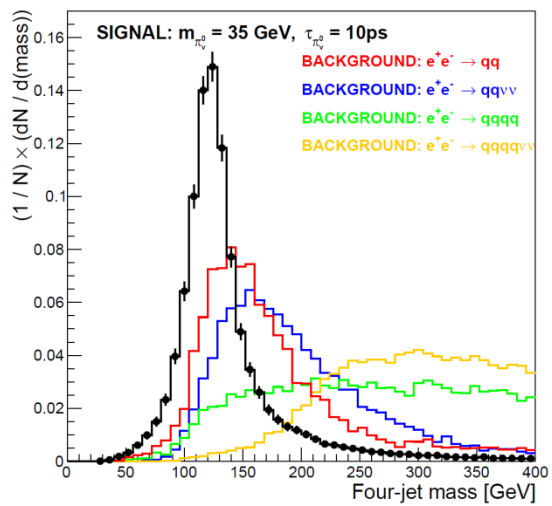
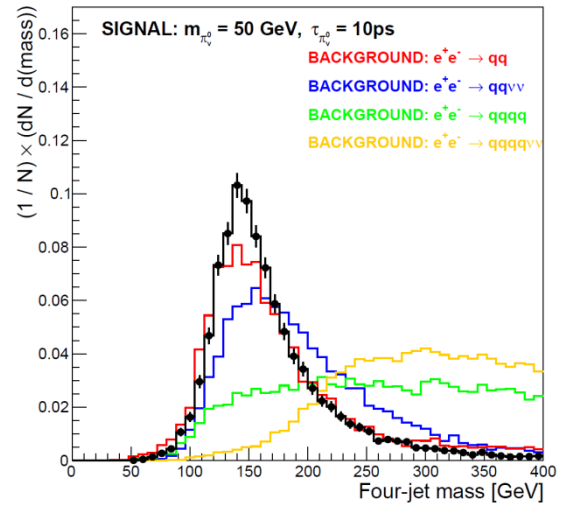


m_π = 50 GeV



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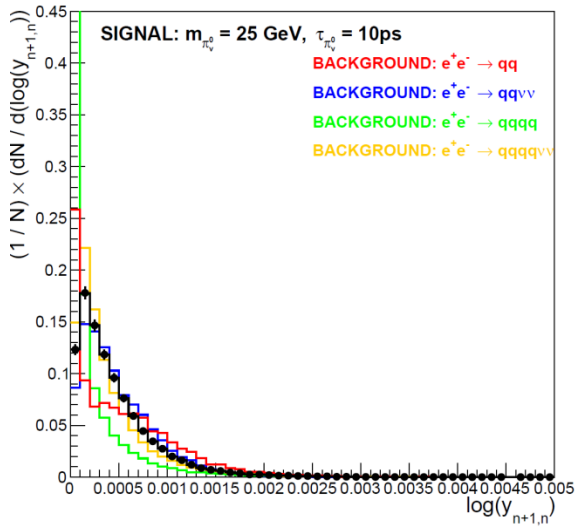

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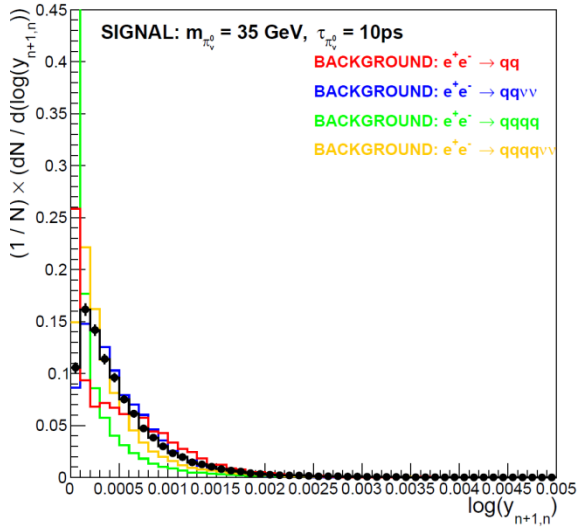

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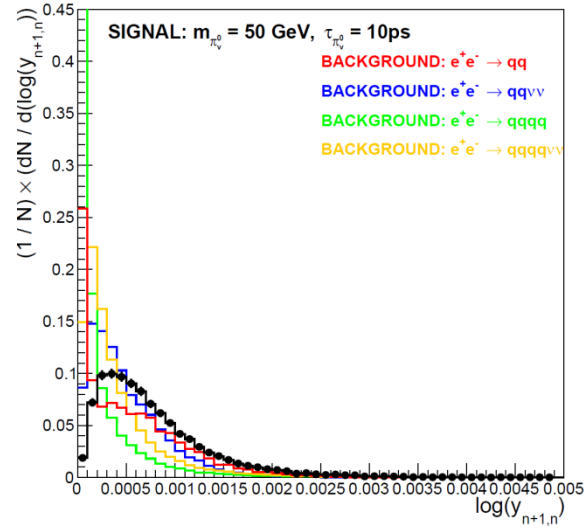
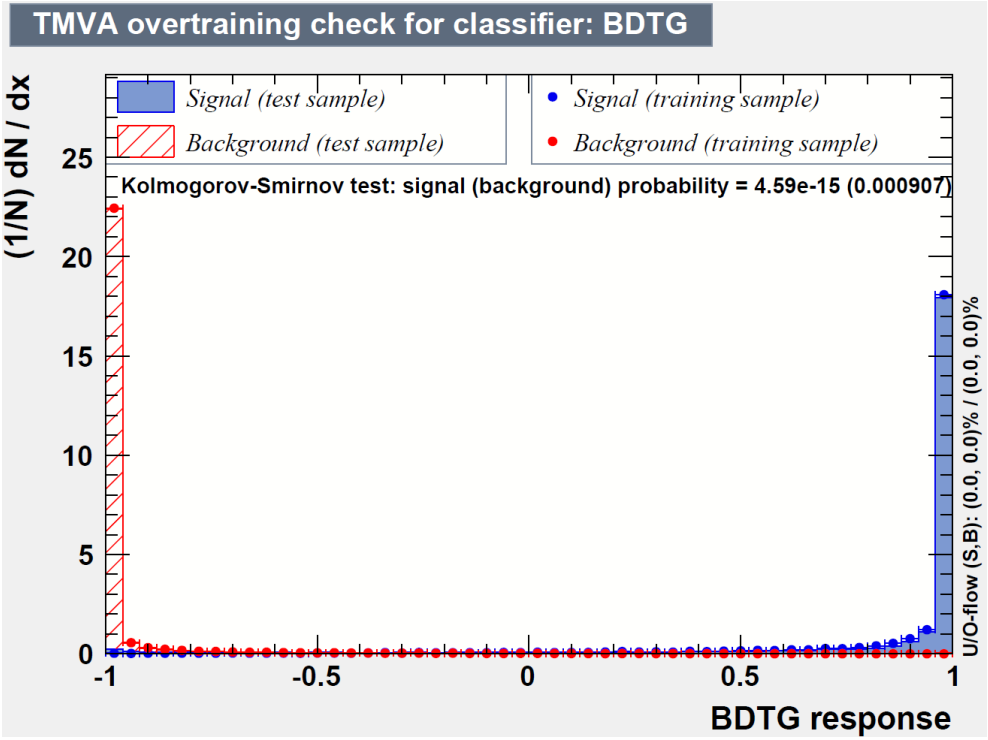
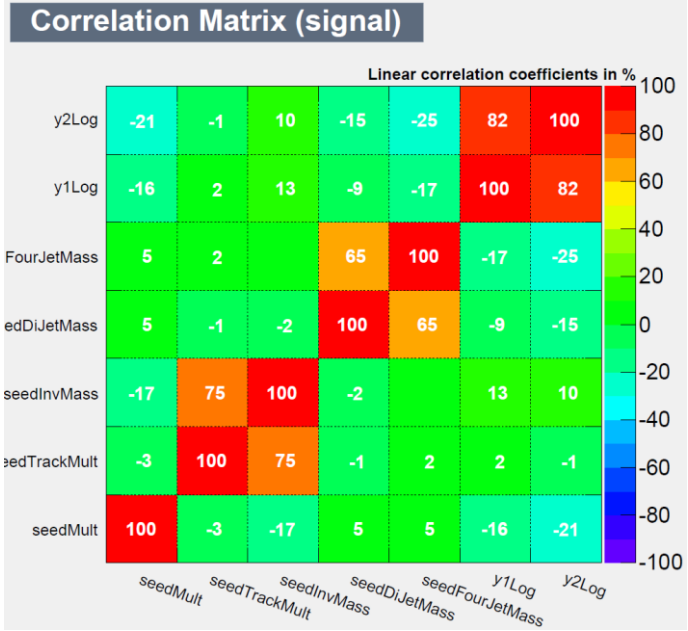
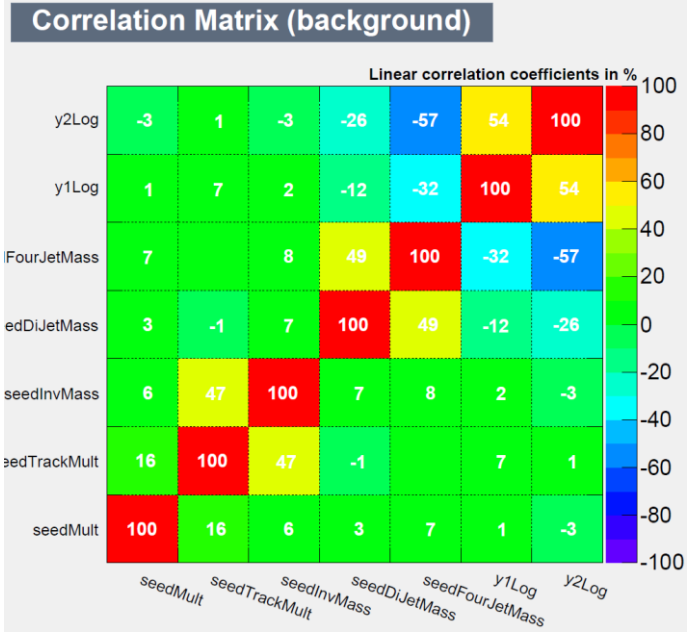


TMVA: response

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



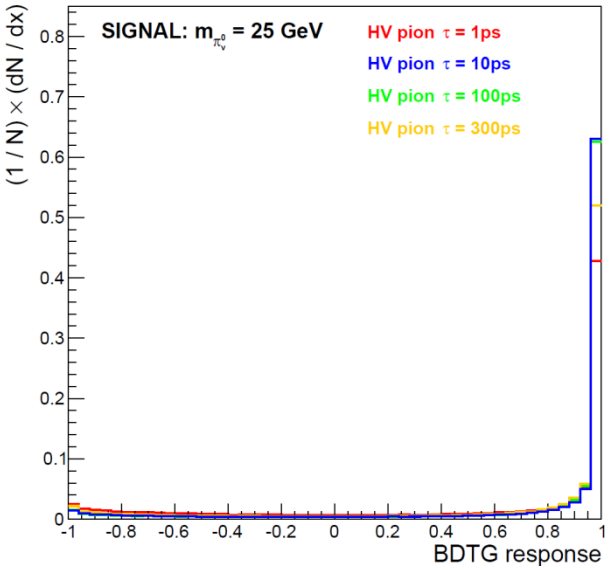




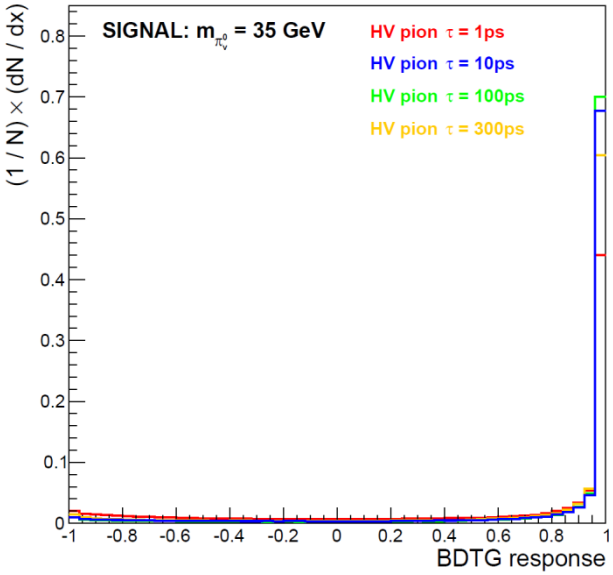
TMVA weights applied to signal *(m = 25, 35, 50 GeV)*

- TMVA weights applied to the signal MC samples

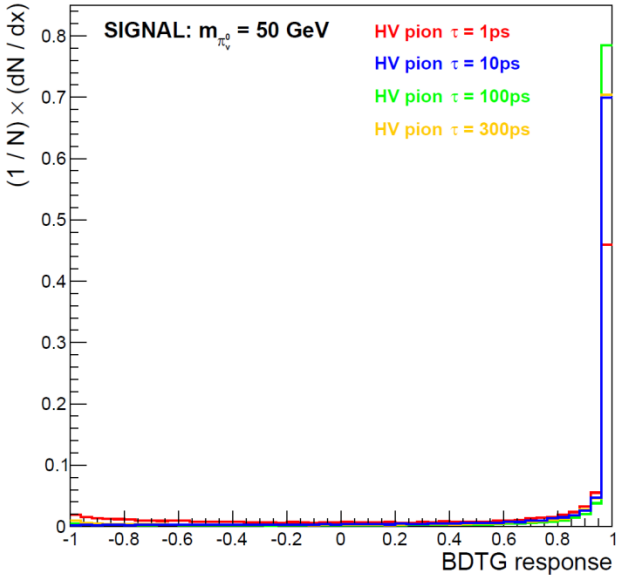
m_π = 25 GeV



m_π = 35 GeV

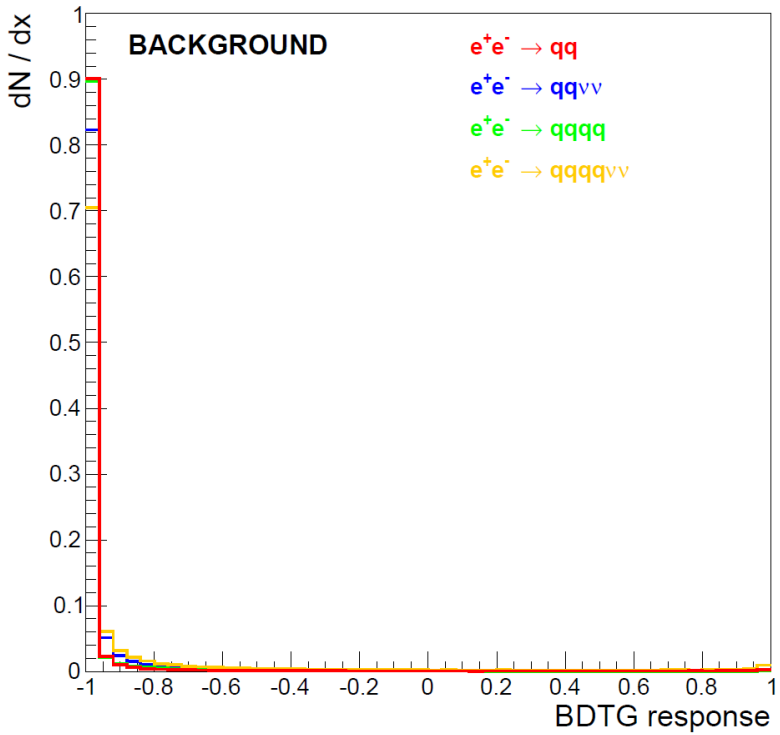


m_π = 50 GeV



TMVA weights applied to background

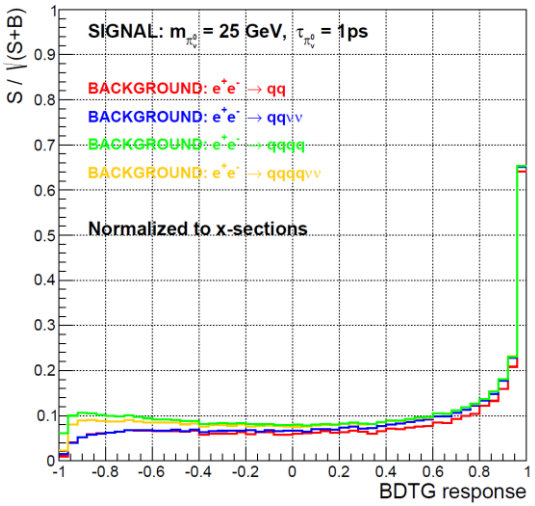
- TMVA weights applied to the background MC samples



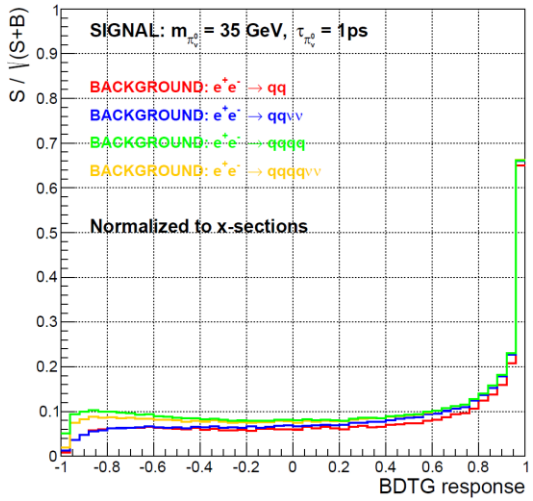
Sensitivity for CLIC 2 ab^{-1} at 3 TeV *(τ = 1, 10 ps)*

- S / √(S + B) with normalization to the x-sections for m_{π} = 25, 35, 50 GeV

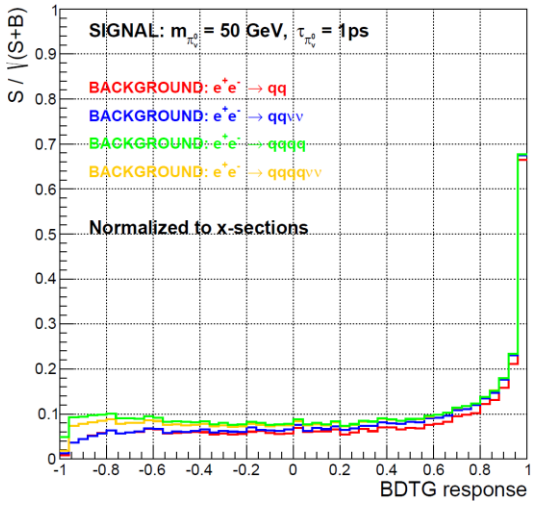
m_{π} = 25 GeV



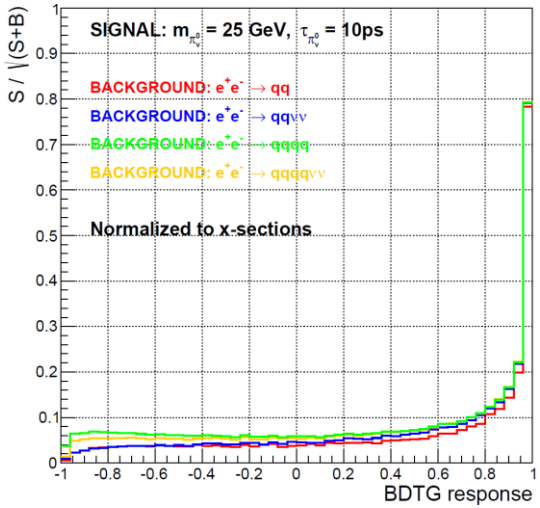
m_{π} = 35 GeV



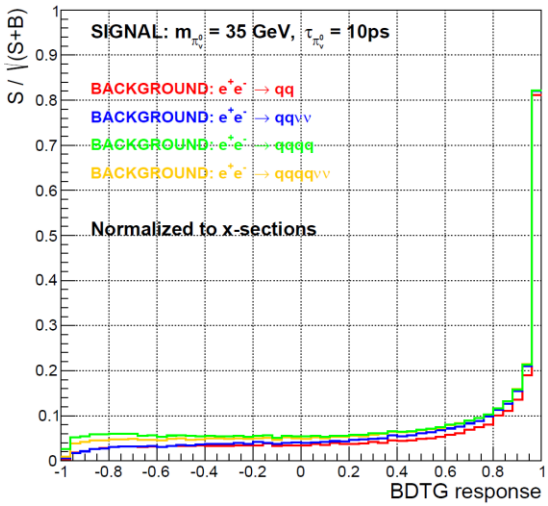
m_{π} = 50 GeV



m_{π} = 25 GeV



m_{π} = 35 GeV



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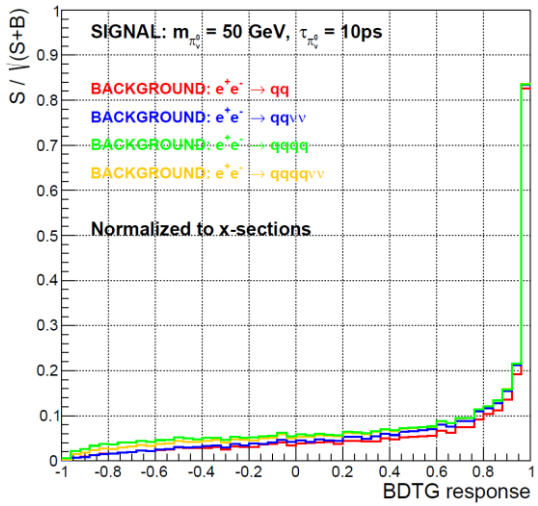
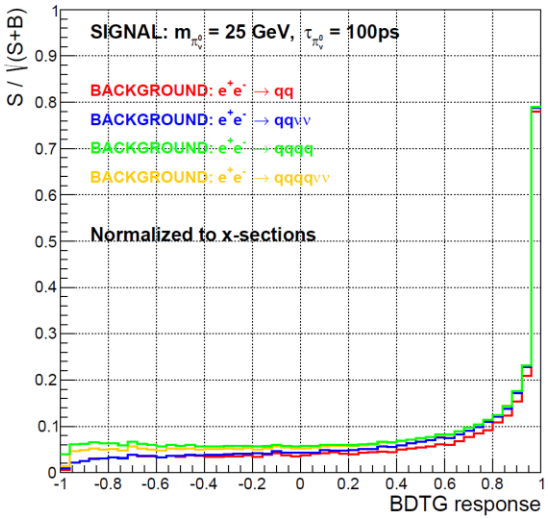
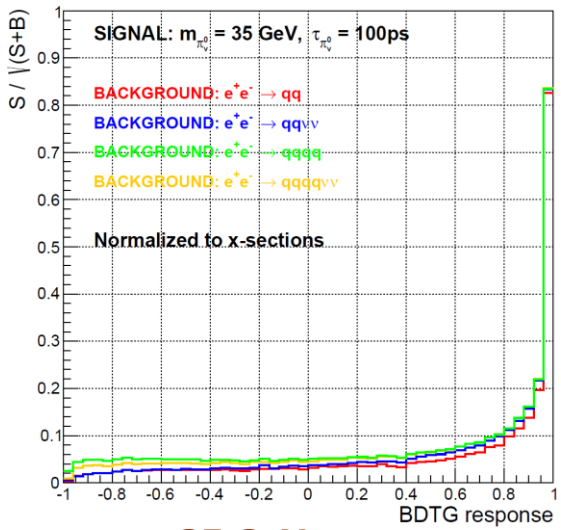


Sensitivity for CLIC 2 ab^{-1} at 3 TeV *(τ = 100, 300 ps)*

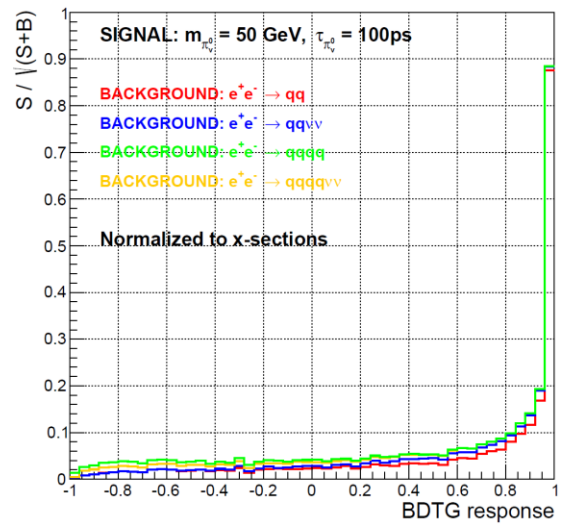
m_π = 25 GeV



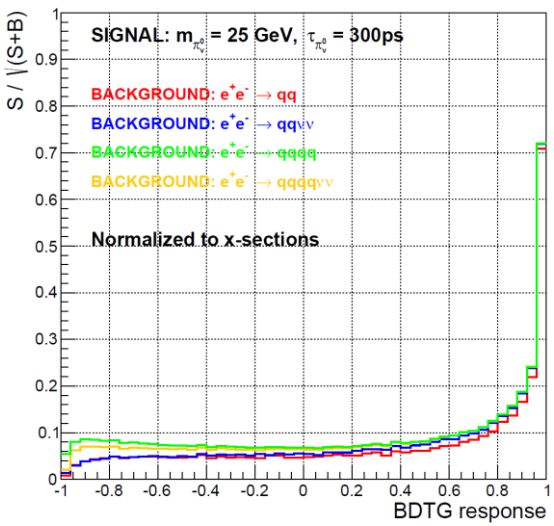
m_π = 35 GeV



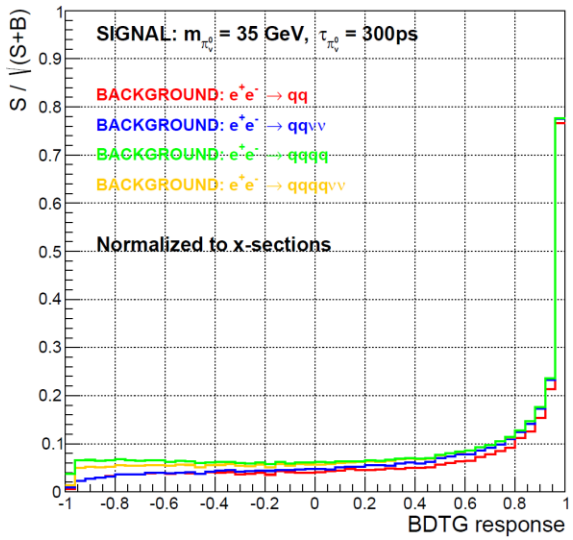
m_π = 50 GeV



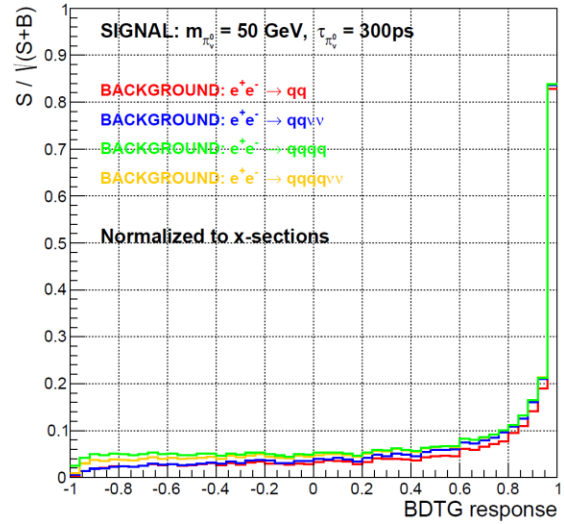
m_π = 25 GeV



m_π = 35 GeV



m_π = 50 GeV

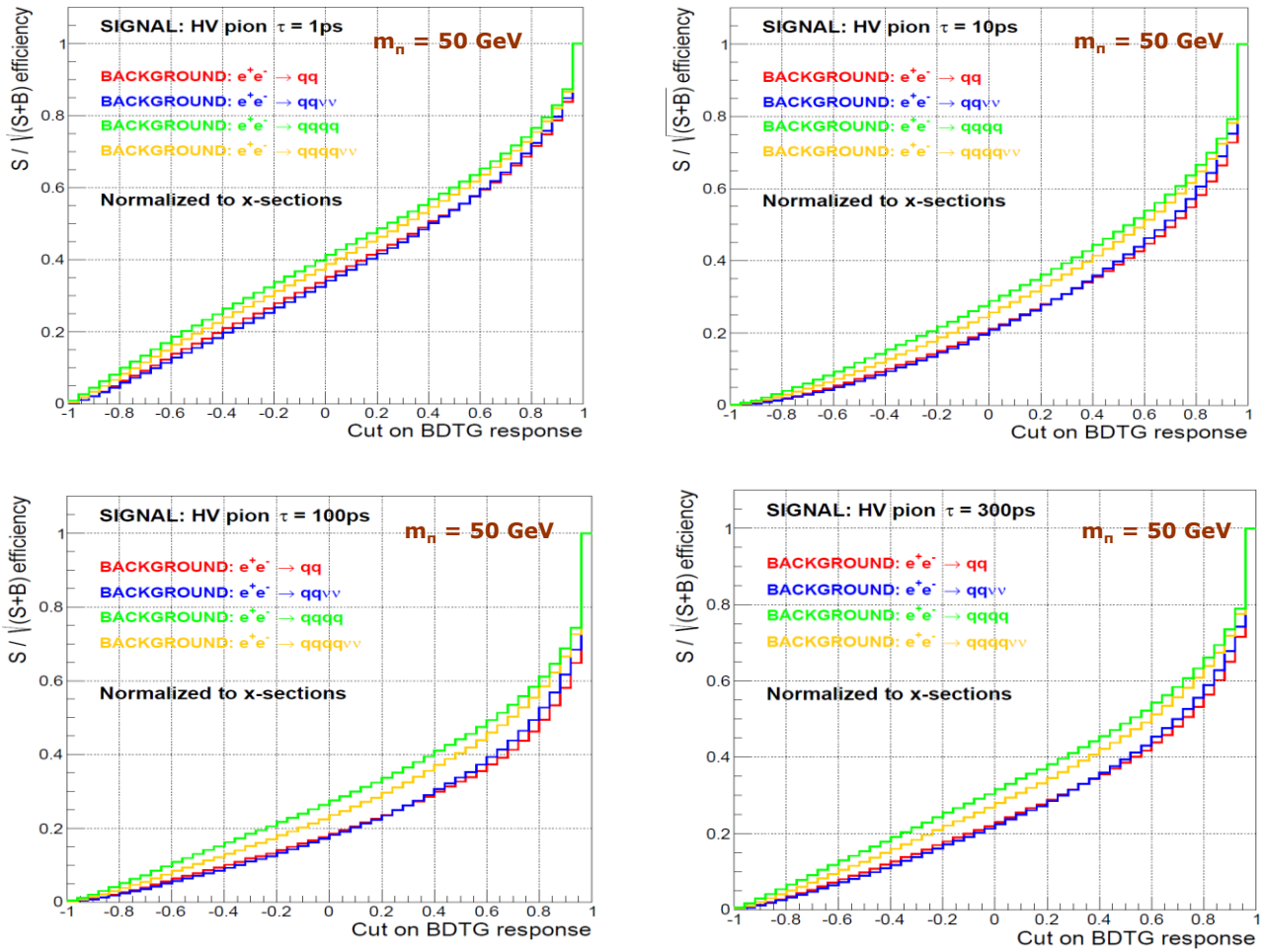


S/√(S+B) efficiency vs cut on BDTG

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

- to choose the cut on BDTG discriminator

- **example plots for m_π = 50 GeV**



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 DV reconstruction + jetting
- Sensitivities for CLIC 2 ab^{-1} at 3 TeV

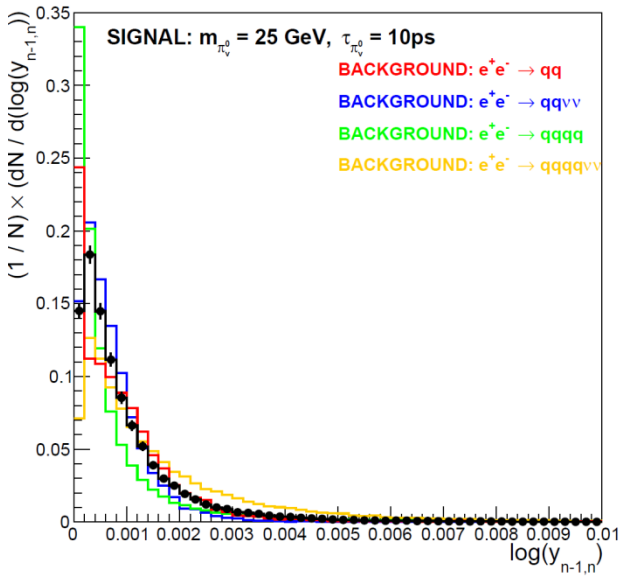
- **PLANS:** Upper limits for different HV pion parameters for CLIC 2 ab^{-1} at 3 TeV

Analysis note started!

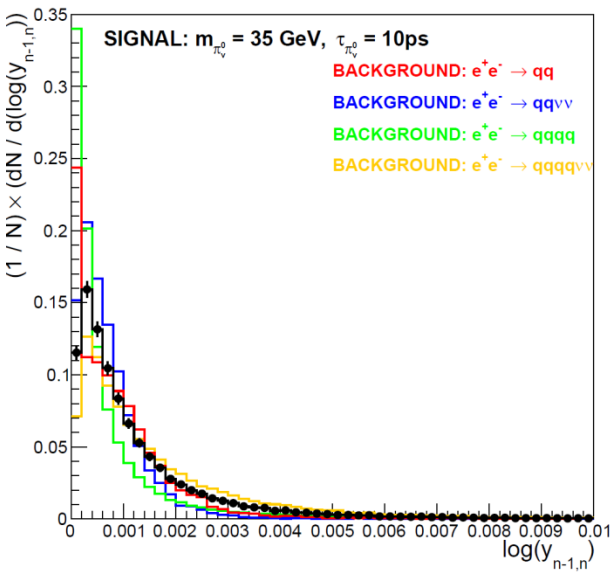
Backup

TMVA: variables *(m = 25, 35, 50 GeV)*

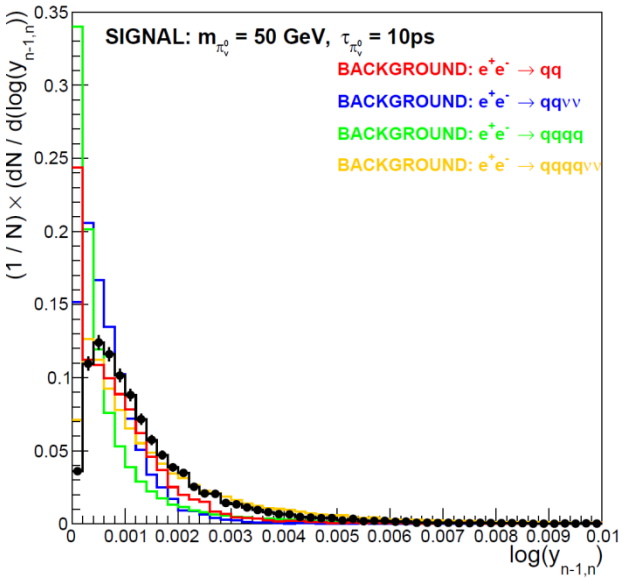
m_{π} = 25 GeV



m_{π} = 35 GeV



m_{π} = 50 GeV



Expected number of events

EXAMPLE: Expected number of events after selection

- BDT response > 0.95
- m_{π} = 50 GeV

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			
$e^+e^- \to qq$	2.95	0.09	5 K
$e^+e^- \to qq\nu\nu$	0.55	0.19	2 K
$e^+e^- \to qqqq$	1.32	0.20	5 K
$e^+e^- \to qqqq\nu\nu$	0.07	0.22	0.3 K

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