Search for a very light pseudoscalar boson produced in decays of the 125 GeV Higgs boson in final state with two muons and two tau leptons

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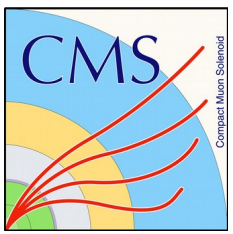


HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Motivation:

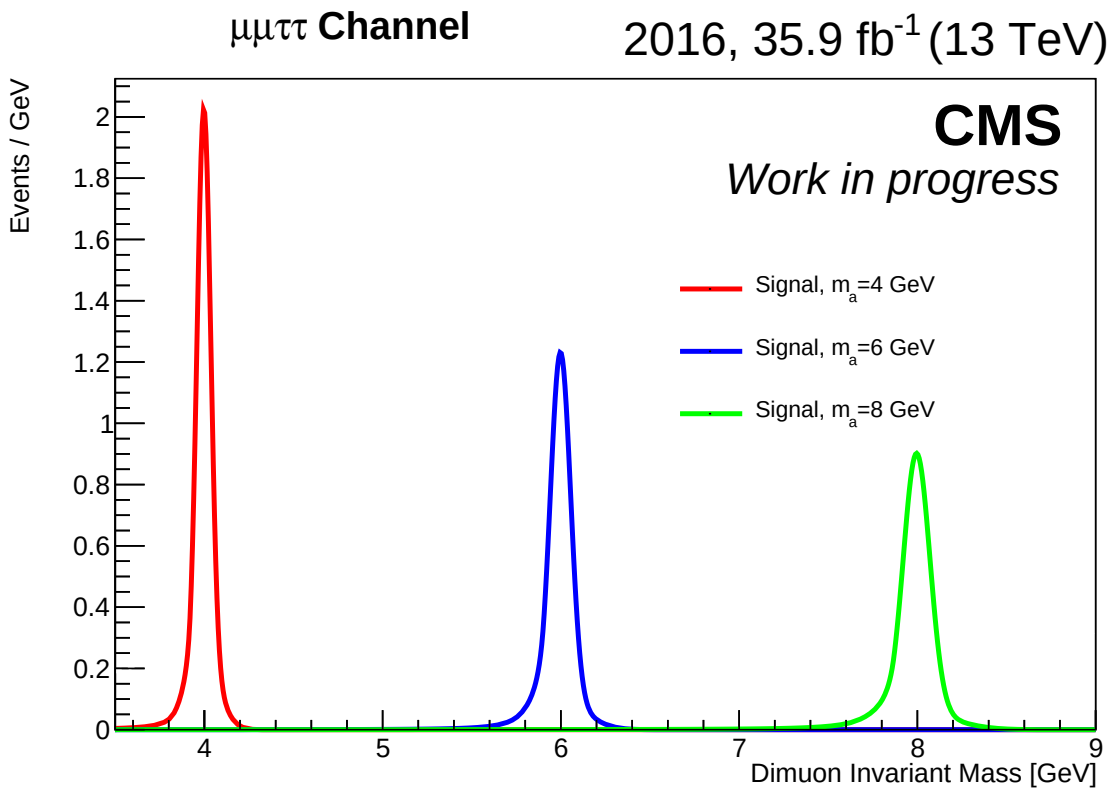
- Higgs sector of 2HD+1S Models: three CP-even ($h_{1,2,3}$), two CP-odd ($a_{1,2}$), and two charged Higgs states

- 2HD+1S Models scenarios might have a very light a_1 state

- $a_1 a_1 \to \mu\mu\tau\tau$ channel more accessible with full Run2 dataset

  Pros: Clean final state with narrow dimuon mass peak

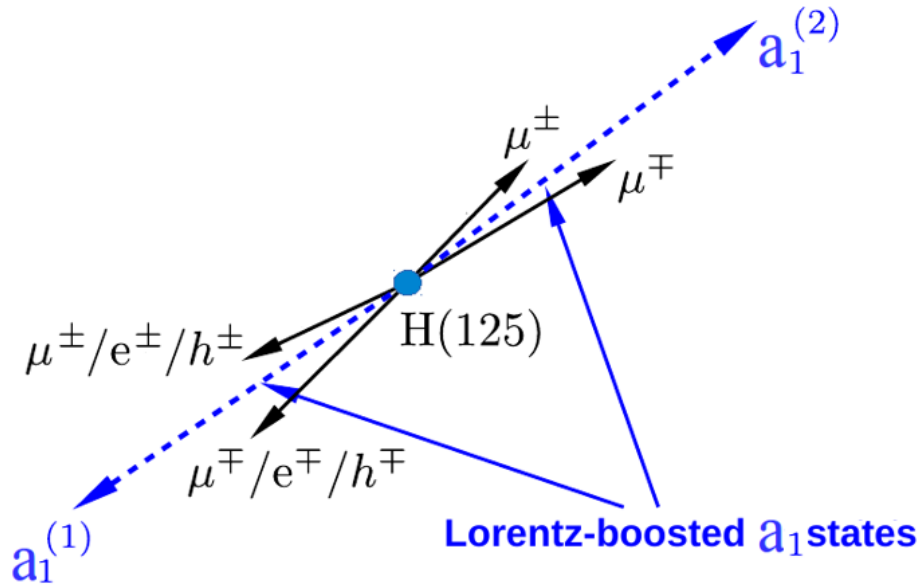
  Cons: Low branching fraction within the analysed mass range



Signal signature and analysis strategy:

- Probe low m_{a_1} region: $4 < m_{a_1} < 19$ GeV
- Exploit $a_1 \to \mu\mu$ and $a_1 \to \tau_{1-prong}\tau_{1-prong}$, 1-prong (muon, electron or hadron reconstructed as track)
- gg $\to$ H(125)$\to a_1 a_1 \to (\mu\mu)(\tau_{1-prong}\tau_{1-prong})$

- Highly boosted a_1 bosons
  $\to$ collimated decay products
  $\to$ non-isolated leptons in final state



Dimuon Pair:

- Opposite sign pair of muons
- Muons of pair with the highest sum of p_T identified as the $a_1 \to \mu\mu$ candidates

Ditrack Pair:

- Opposite sign high purity tracks
- Track-track pair with the highest sum of p_T identified as $a_1 \to \tau\tau$ candidate

Signal region:

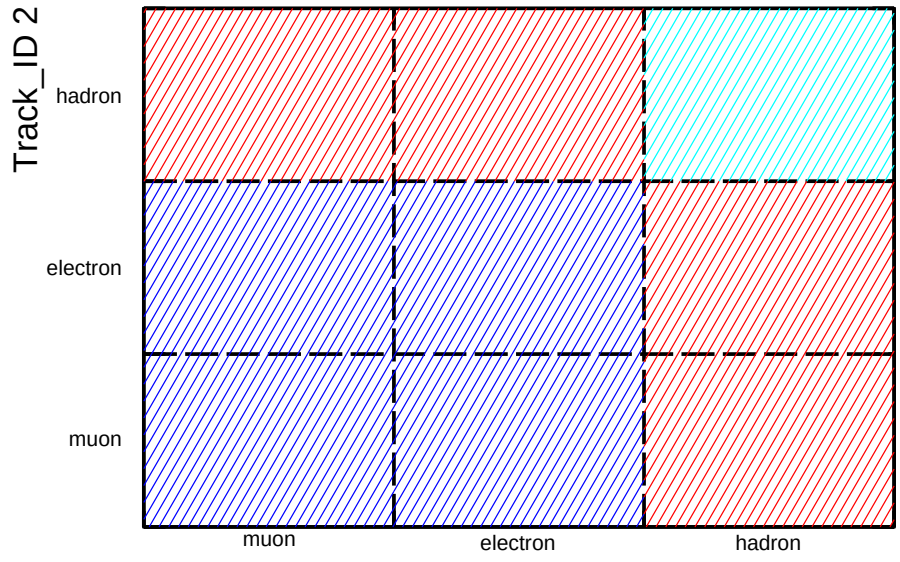
Dimuon+ditrack system (each of the muons and the tracks isolated within ΔR cone of 0.2)

Categorization according to the track identification as muon, electron or hadronic tau decay:

-**lepton-lepton** (it includes: muon-muon, muon-electron, electron-electron)

-**lepton-hadron** (it includes: muon-hadron, electron-hadron)

-**hadron-hadron**



> **Additional cuts:**

-Cut on visible mass (invariant mass of the 4 objects): $M_{vis} < 125$ GeV

-Mass window around the mass of the system: [dimuon + ditau] of 75 GeV (Ditau reconstructed via Kinematic Fit using collinear approximation)

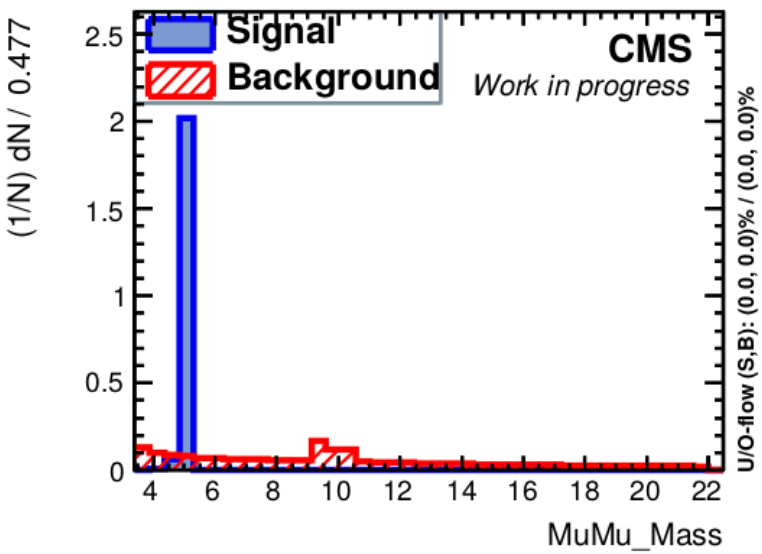
-$m_{\mu\mu} > m_{track-track}$

Signal extraction:

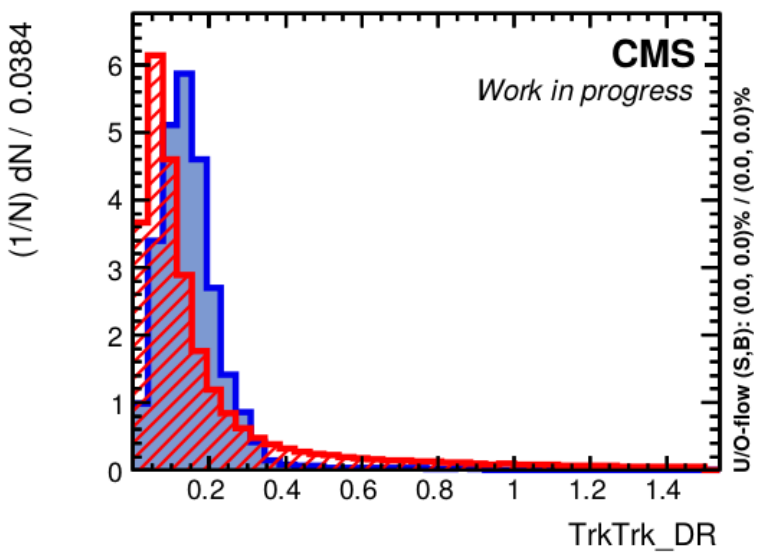
Extraction of the signal through: Binned Max-likelihood fit applied to the BDT classification distribution

- Training of the BDT performed with signal samples (signal region) and background from a data control region (defined in next slide)
- 2 of the variables introduced to the BDT with high discriminating power:

mass of the dimuon system



△R of the ditrack system



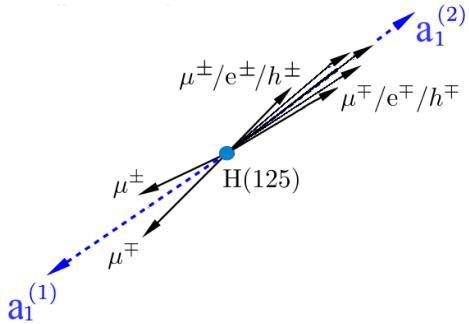
- Final discriminant: BDT classification distribution

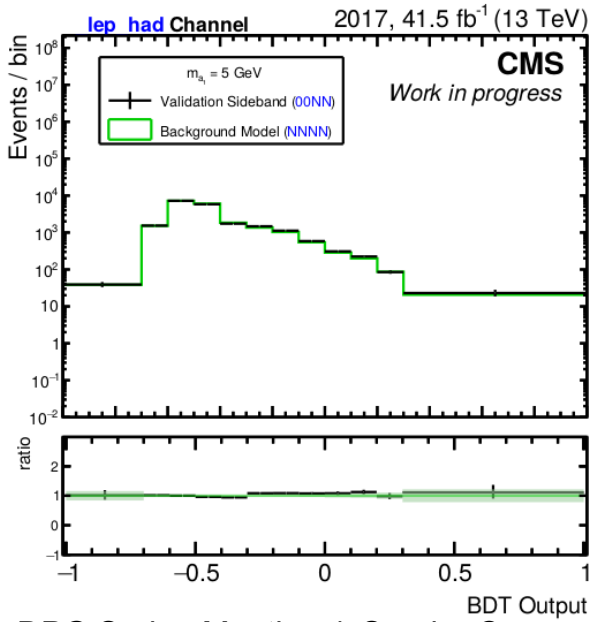
  Background shape derived from control region in data, background and signal normalizations kept freely floating

Background estimation:

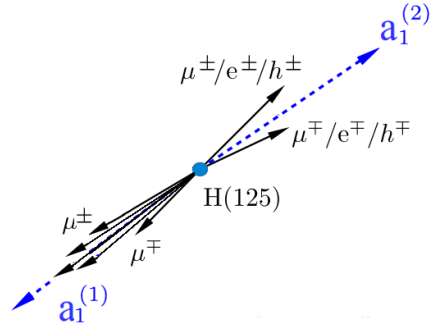
- **Data driven:** Shape from control region NNNN: At least one of the muons ore one of the tracks is anti-isolated
- **Validation of background model:** Shape on control region NNNN compared with shape in sideband regions 00NN and NN00

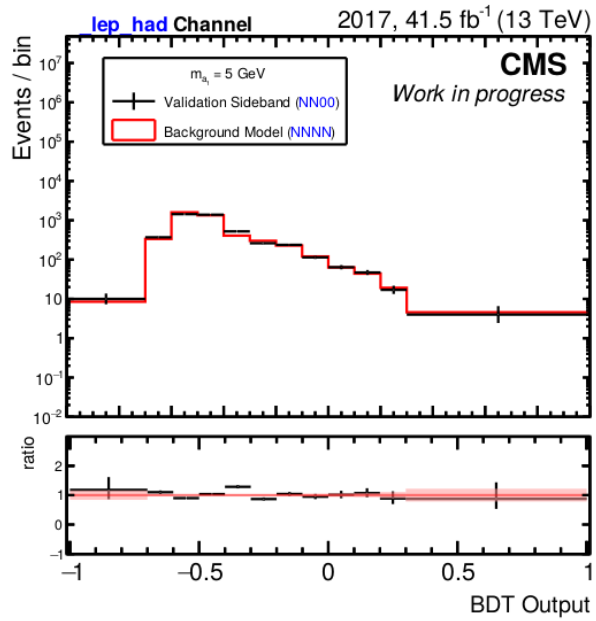
Control region for the dimuon system (00NN):





Control region for the ditrack system (NN00):





Systematic uncertainties:

> **Signal:**

-Statistical uncertainty on signal acceptance

-Luminosity: 2016 (2.5%), 2017 (2.3%)

-Trigger efficiency ($\sim 2\%$)

-B tagging efficiency ($\sim 1\%$)

-Theory uncertainties:

Uncertainty from renormalization/factorization scales: 0.8−2%

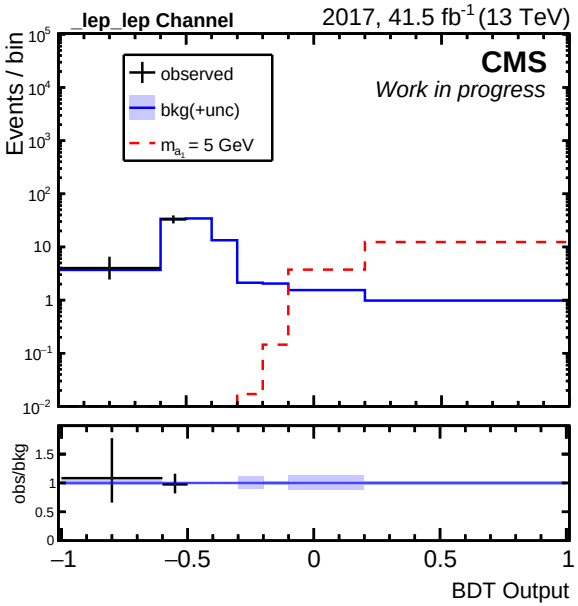
PDF uncertainties: 1−2%

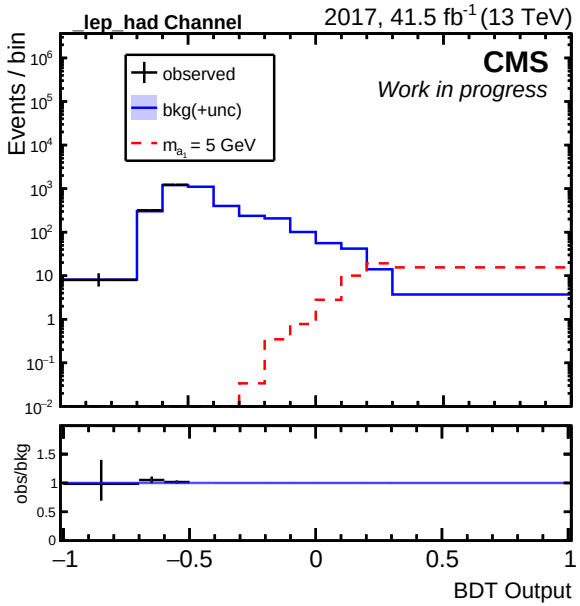
> **Background:**

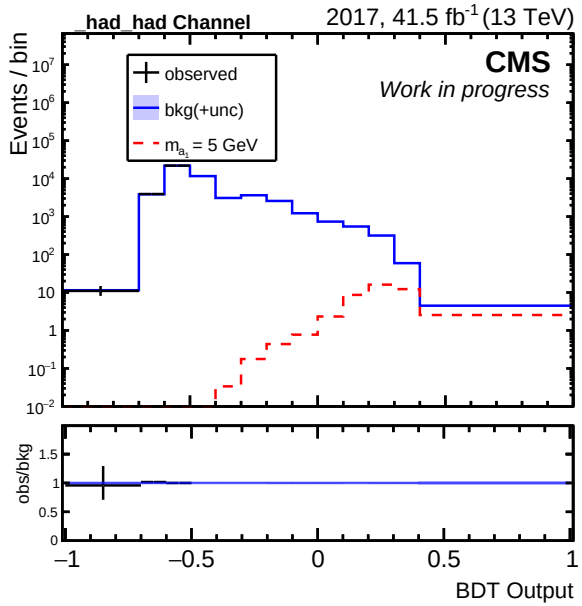
-Difference on shape of BDT output between CR NNNN and SR regarded as shape uncertainty (estimation done in sideband regions NN00 and 00NN)

Results:

- **BDT Output:** Taken as a binned discriminator to extract the signal
- Background distribution obtained after performing fit to data under the background-only hypothesis





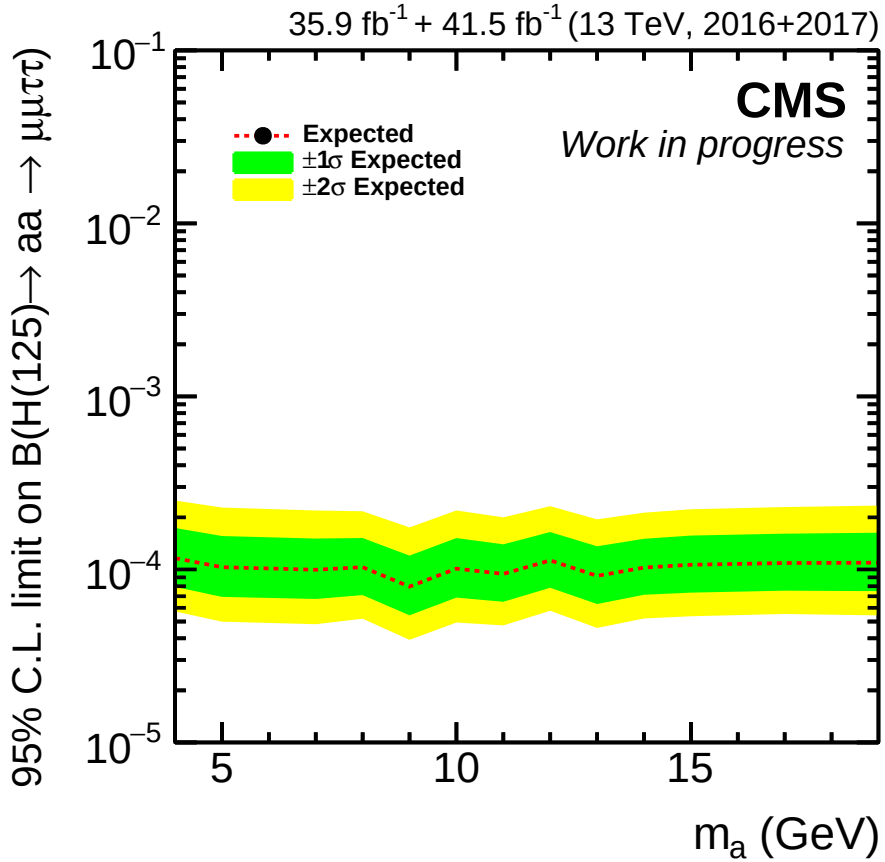


- Benchmarking signal normalization events

Branching ratio : $B(H(125) \rightarrow a_1 a_1 \rightarrow \mu\mu\tau\tau) = 0.1\%$

Expected Sensitivity:

- Evaluated in terms of expected 95% CL limits on: $B(H(125) \rightarrow a_1 a_1 \rightarrow \mu\mu\tau\tau)$
- Combination of all channels for 2016 and 2017 datasets:



Summary H(125) $\rightarrow a_1 a_1 \rightarrow$ 2μ2τ analysis:

- **Search for very light pseudoscalar Higgs boson in H(125) $\rightarrow a_1 a_1 \rightarrow$ 2μ2τ channel presented**

- Search currently covers the range of m_{a_1} between 4 and 19 GeV, with 2016+2017 dataset. The plan is to add 2018 dataset (full Run2 analysis)

- **Signal extraction:** binned maximum-likelihood fit applied to the BDT classification distribution

- Sensitivity of the analysis evaluated in terms of expected limit on BR($H(125) \rightarrow a_1 a_1 \rightarrow 2\mu 2\tau$)

  - Upper 95% CL limit ranges from:
    $0.80 * 10^{-4}$ (m_{a_1} = 9 GeV) to $1.16 * 10^{-4}$ (m_{a_1} = 4 GeV)

Thank you!

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Backup

> Additional material

Triggers:

- Analysed luminosity:

  Run 2016 $\simeq$ 35.9 fb^{-1}

  Run 2017 $\simeq$ 41.5 fb^{-1}

- Overview of the triggers used in this analysis and the corresponding integrated luminosities:

  2016: HLT_IsoTkMu24_v (35.9 fb^{-1})

  2017: HLT_IsoMu27 (41.5 fb^{-1})

MC Samples. Data / MC corrections:

- MC event generator PYTHIA 8.2 was used to model the Higgs boson signal produced via ggF for mass points between 4 and 19 GeV with 1 GeV step

- **Corrections to simulation to account for differences between data and MC:**

- Pileup reweighting:

  -The MC distribution of the number of primary vertices is reweighted to match the number of pile-up interactions in data

- Trigger efficiency

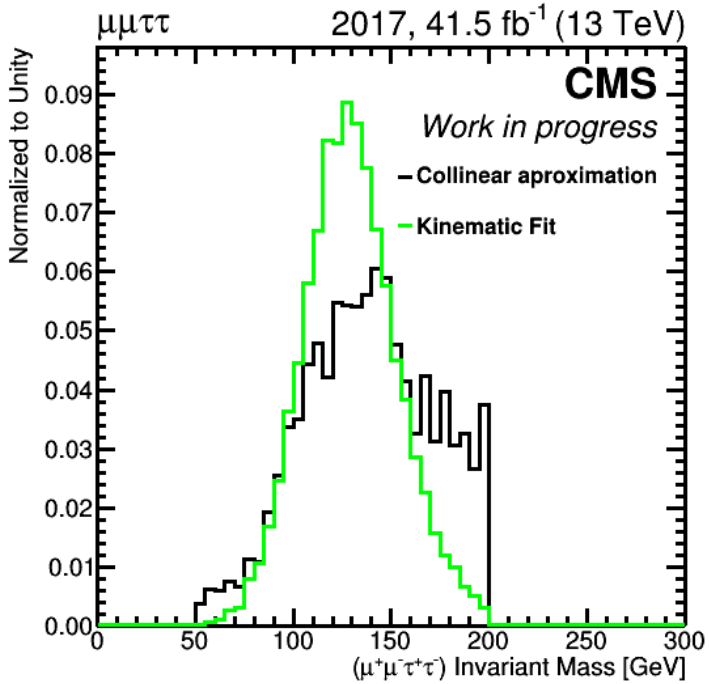
- Higgs p_T reweighting

- B tagging efficiency

- A very conservative Scale Factor of 0.9 is applied to account for relative isolation in $\Delta R = 0.2$ of the 2 muons and the two 1-prong-tracks

Kinematic fit:

- The kinematic fit insures that the measured as well as unmeasured quantities fulfill the kinematic constraints deduced from the event hypothesis, improving the estimators of the underlying kinematics for a given event.
- The reconstructed mass of the 125 GeV Higgs boson for $m_{a_1} = 5$ GeV is shown hereafter:

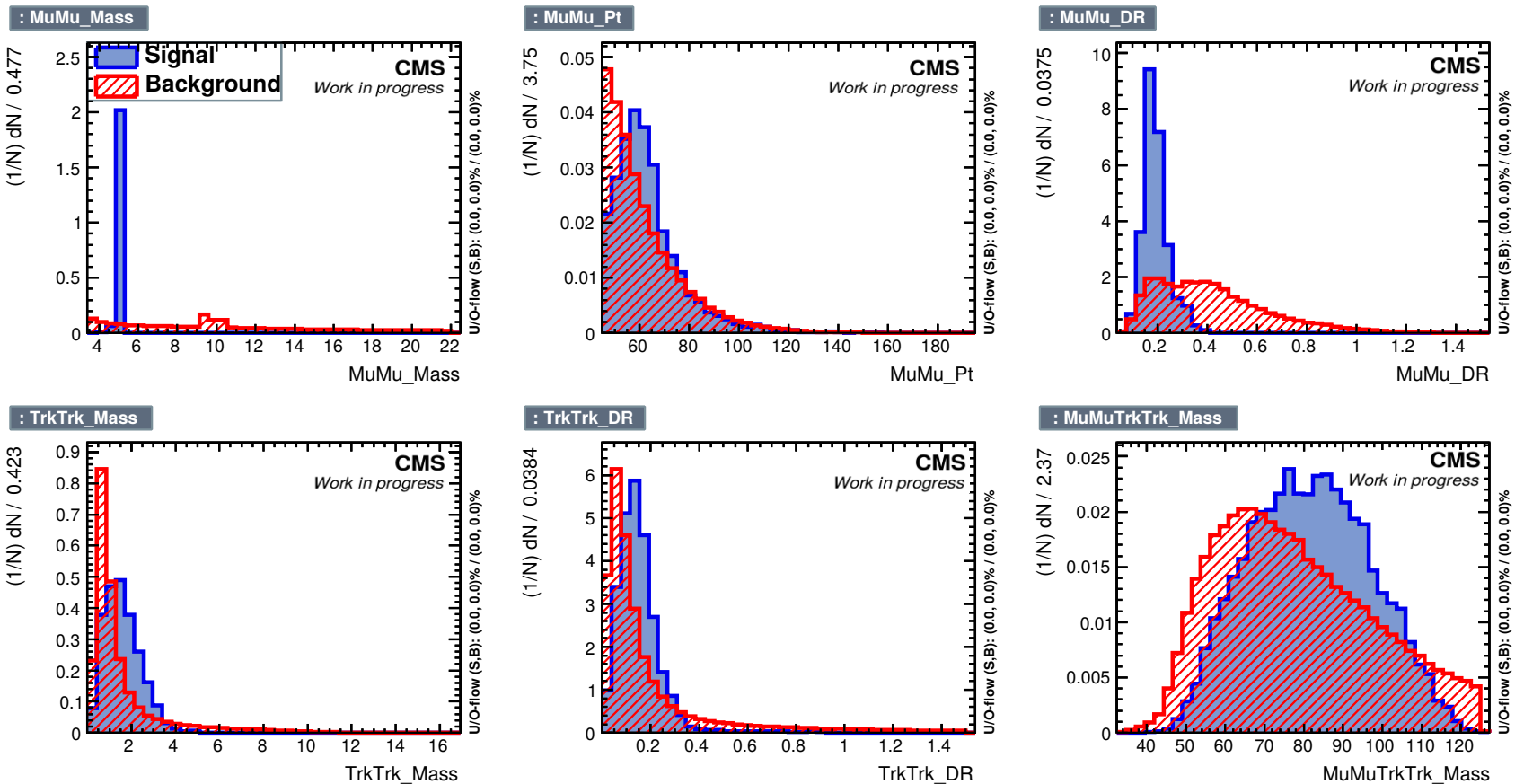


Complete input of BDT:

- **Variables introduced to the BDT (11 in total):**

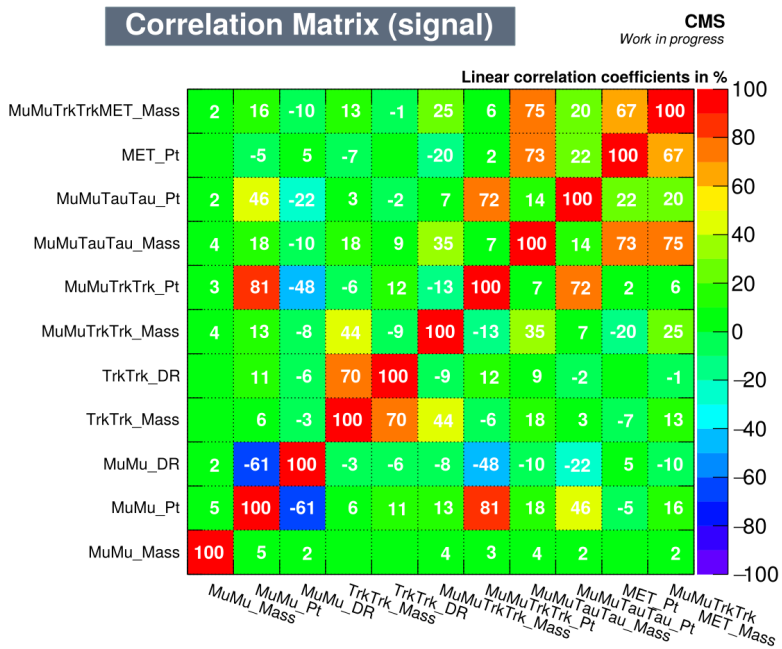
  $m_{\mu,\mu}$, $p_{T_{\mu,\mu}}$, $\Delta R(\mu,\mu)$, $m_{trk,trk}$, $\Delta R(trk,trk)$, $m_{\mu,\mu,trk,trk}$, $p_{T_{\mu,\mu,trk,trk}}$, $m_{\mu,\mu,\tau,\tau}$, $p_{T_{\mu,\mu,\tau,\tau}}$, MET_{p_T} and $m_{\mu,\mu,trk,trk,MET}$

- Checking signal from background separation of input variables



Correlation matrix:

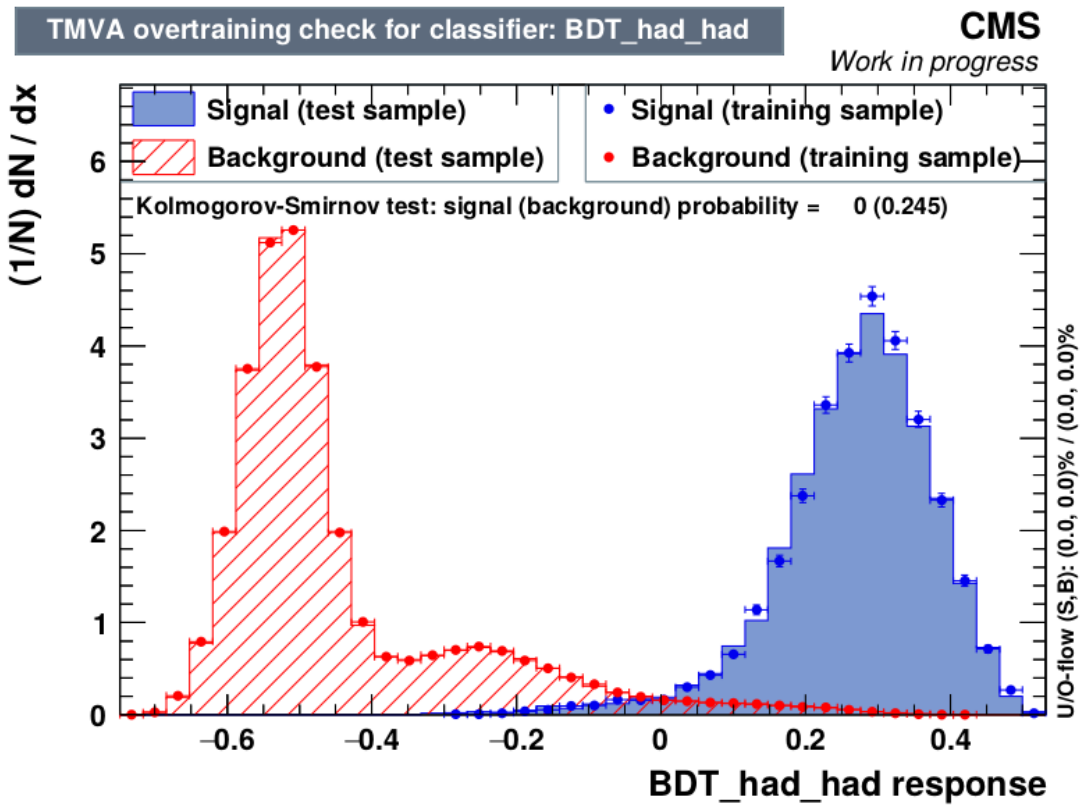
> Linear correlation coefficients between the input variables for signal and background training samples



Overtraining check:

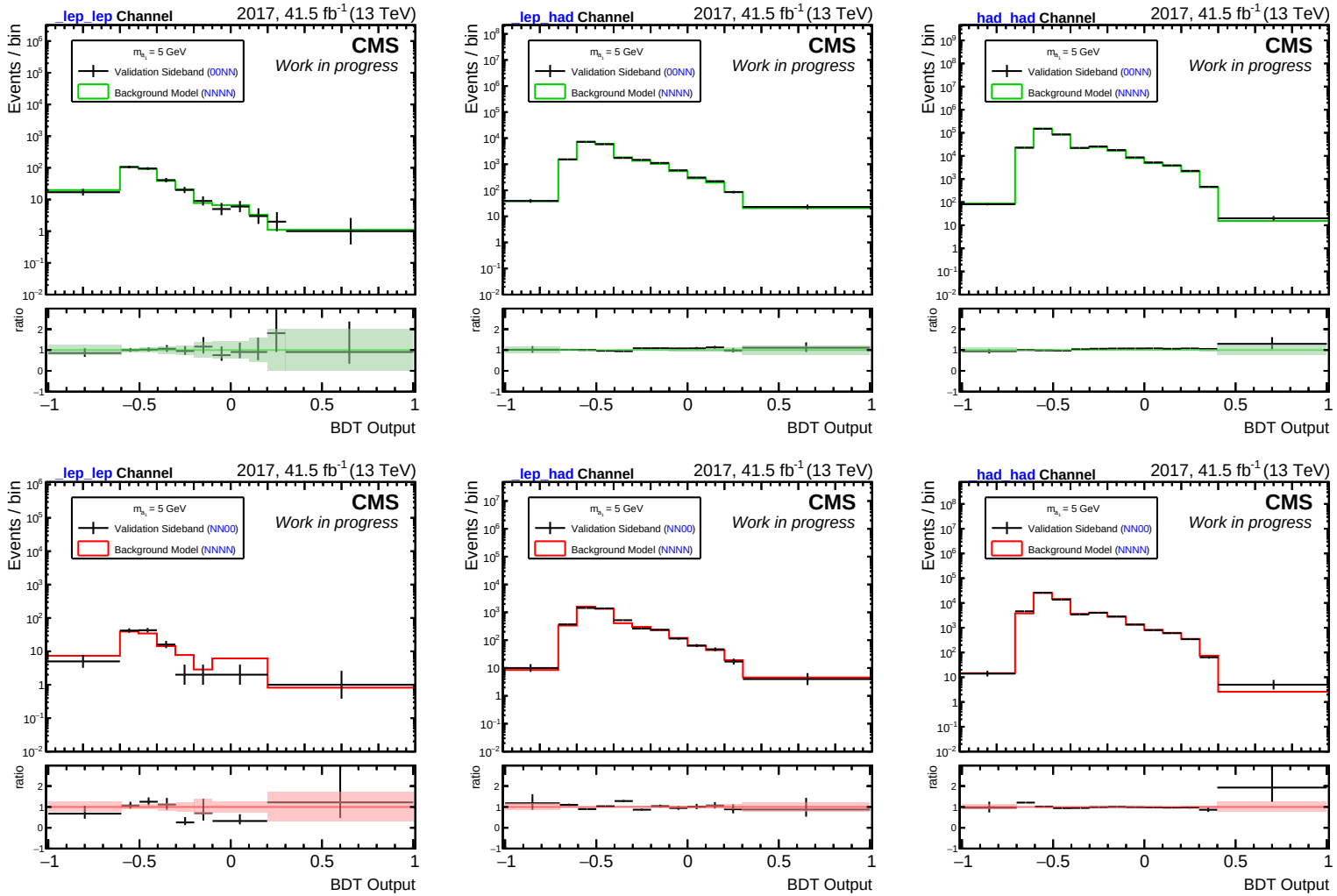
- Overtraining leads to an increase in the classification performance if measured on the training sample, and to an effective performance decrease when measured with an independent test sample

- Its impact on the analysis was checked comparing the performance results between the training samples and the test samples (the training and test samples are subsets of control region NNNN and signal region)



Validation of Background Model:

- Shape on control region NNNN is compared with shape in sideband regions 00NN and NN00



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