NMSSM H(125) $\rightarrow aa \rightarrow 2\mu 2\tau$

NMSSM H(125) $\rightarrow aa \rightarrow 4\tau$

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Outline:

- NMSSM H(125) $\rightarrow aa \rightarrow 4\tau$ analysis [HIG-18-006]

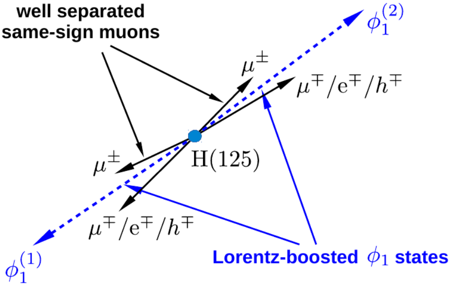
- Status of NMSSM H(125) $\rightarrow aa \rightarrow 2\mu 2\tau$ analysis
  - Motivation
  - Signal Signature and Selection
  - Signal and Background Model
  - Systematic uncertainties
  - Results

- Plans of DESY group for the legacy Run 2 results in the context of the Higgs EXO group

- gg $\rightarrow$ H(125)$\rightarrow$ aa $\rightarrow$ $(\tau_\mu \tau_{1-prong})(\tau_\mu \tau_{1-prong})$
- highly boosted a_1 bosons

  $\rightarrow$ collimated decay products

  $\rightarrow$ non-isolated leptons in final state

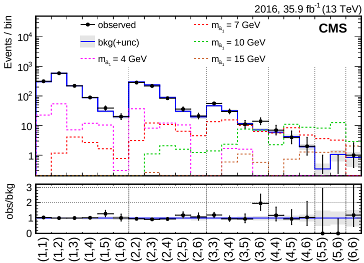


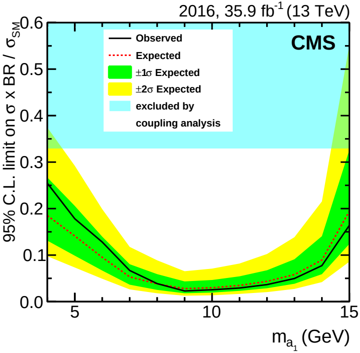
- probe low m_a region $2m_\tau < m_a < 2m_b$
- exploit $a \rightarrow \tau_\mu \tau_{1-prong}$ decays
- Select two muon track-pairs

Results

- Main Background: QCD-multijet events
- Final discriminant: 2D-distributions in the inv. masses of muon-track pairs
- Limits are set in terms of 95% CL on $B(H(125) \to a_1 a_1) \cdot B^2(a_1 \to \tau\tau)$

PAPER





- Sensitivity of the 8TeV analysis (HIG-14-019) largely superseded
- Observed limit ranges from 2.3% at $m_{a_1} = 9$ GeV to 26% at $m_{a_1} = 4$ GeV
- Expected limit ranges from 2.8% at $m_{a_1} = 9$ GeV to 19% at $m_{a_1} = 15$ GeV

H(125) $\to aa \to \mu\mu\tau\tau$ channel. Motivation:

- Higgs sector of NMSSM: three CP-even ($h_{1,2,3}$), two CP-odd ($a_{1,2}$), and two charged Higgs states
- NMSSM scenarios might have a very light a_1 state with mass in the range $2m_\tau < m_{a_1} < 2m_b$
- The aa $\to \mu\mu\tau\tau$ channel has become more accessible as the LHC reaches the end of Run2

  Pros: Clean final state with narrow dimuon mass peak

  Cons: Low branching fraction

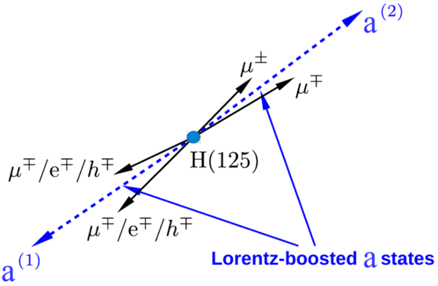
- Present analysis is a search for light Higgs boson in the decay channel H (125) $\to a_1 a_1$, with subsequent decay of light bosons into 2 muons and 2 τ leptons at $\sqrt{s} = 13 TeV$

Signal Signature and Analysis Strategy

- probe low m_a region $2m_\tau < m_a < 2m_b$
- exploit $a \to \mu\mu$ and $a \to \tau_{1-prong}\tau_{1-prong}$ decays
- gg $\to$ H(125)$\to$ aa $\to$ $(\mu\mu)(\tau_{1-prong}\tau_{1-prong})$
- highly boosted a_1 bosons

  $\to$ collimated decay products

  $\to$ non-isolated leptons in final state



- Analyzed luminosity of Run 2016 $\simeq 35.9\ fb^{-1}$
- Trigger used in this analysis:
  - *HLT_IsoTkMu24_v*

Selection:

Dimuon Pair:

- A dimuon pair is selected requiring them ($a_1 \to \mu\mu$ candidate):
  - to have opposite charge respect to each other
  - to pass a pTSumCut > 45 GeV: $pTSum = (\vec{p}_{\mu_1} + \vec{p}_{\mu_2})_T$
  - cuts on impact parameter
  - to be within a distance of $\Delta R < 1.5$ in η vs ϕ plane
  - the muons of the pair with the highest pTSum are identified as the $a_1 \to \mu\mu$ candidates
  - one of muons have to have $p_T > 25$ GeV and match the single muon trigger object

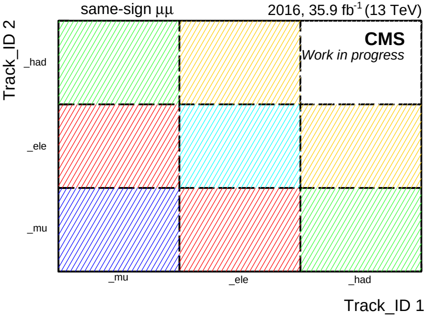
Ditrack Pair:

- Two 1-prong (muon, electron or hadron) high purity track candidates are selected requiring them ($a_1 \to \tau\tau$ candidates):
  - to have opposite charge respect to each other
  - to pass a pTSumCut > 10 GeV: $pTSum = (\vec{p}_{trk_1} + \vec{p}_{trk_2})_T$
  - cuts on impact parameter
  - to be within a distance of $\Delta R < 1.5$ in η vs ϕ plane
  - the track-track pair with the highest pTSum is identified as the $a_1 \to \tau\tau$ candidate

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

Categorization according to the track ID:
-muon-muon
-mu-electron
-muon-hadron
-electron-electron
-electron-hadron

8 = 3x3-1 categories considered:
-First track ID (muon, electron or hadron) and second track ID (muon, electron or hadron)
-Hadron-Hadron channel not included



- Additional cuts:

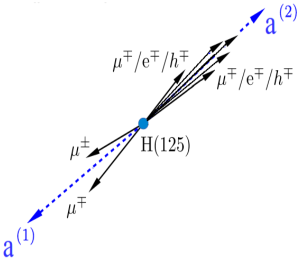
-Cut on visible mass (invariant mass of the 4 objects): $M_{vis} < 125\text{GeV}$

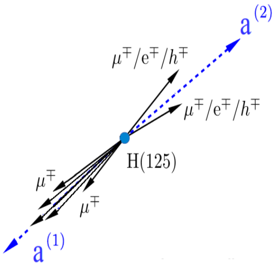
-Mass window around the mass of the system: [dimuon + ditau] of 75 GeV (Ditau reconstructed via Kinematic Fit using collinear approximation)

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

Control regions:

- Control region for the dimuon system (00NN):
  - Both muons of the $a \to \mu\mu$ candidate required to be isolated within ΔR cone of 0.2
  - No additional requirements are imposed to $a \to \tau\tau$ candidate (no isolation requirement applied)
- Control region for the ditrack system (NN00):
  - Both tracks of the ditrack system required to be isolated within ΔR cone of 0.2
  - No additional requirements are imposed to dimuon system (no isolation requirement applied)





- Control Region NNNN: The 4 objects non-isolated (N tracks around each of them)

Final discriminant

Two options tested:

- Two-dimensional (2D) spectrum of dimuon invariant mass vs. ditrack invariant mass
- BDT classification distribution

Extraction of the signal through:

- Unbinned maximum-likelihood fit applied to the two-dimensional (2D) spectrum of dimuon invariant mass vs. ditrack invariant mass
- Binned Max-likelihood fit applied to the BDT classification distribution

Background and signal normalizations floating freely $\rightarrow$ pure shape analysis

Working with Bidimensional Final Discriminant:

Signal Model:

- Double sided crystal ball (for the dimuon system): [x= $m_{\mu\mu}$]

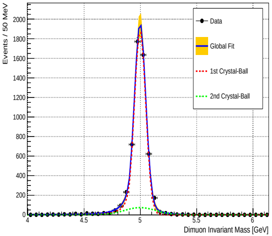
$$CB(x; m_0, \sigma, \alpha, n) = \frac{1}{N} \times \exp[-(x - m_0)^2/(2\sigma^2)]; \qquad x > m_0 - \alpha\sigma$$
$$CB(x; m_0, \sigma, \alpha, n) = \frac{1}{N} \times \frac{(n/\alpha)^n \exp[-\alpha^2/2]}{((m_0 - x)/\sigma + n/\alpha - \alpha)^n}; \qquad x < m_0 - \alpha\sigma \tag{1}$$

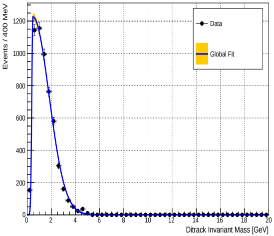
- Bifurcated Gaussian (for the ditrack system): [y= $m_{trk-trk}$]

$$BG(y; m_{bg}, \sigma_{bg}) = \frac{1}{\sqrt{2\pi\sigma_{bg}^2}} \times \exp[-(y - m_{bg})^2/(2\sigma_{bg}^2)]; \qquad y > m_{bg} \quad \sigma_{bg} = \sigma_R; \qquad y < m_{bg} \quad \sigma_{bg} = \sigma_L \tag{2}$$

- Assuming that the masses of the dimuon and ditrack system are uncorrelated:

$$PDF_{signal}(x, y; m_0, \sigma, \alpha_1, \alpha_2, n, f, m_{bg}, \sigma_{bg}) = [f \times CB(x; m_0, \sigma, \alpha_1, n) + (1 - f) \times CB(x; m_0, \sigma, \alpha_2, n)] \times BG(y; m_{bg}, \sigma_{bg}) \tag{3}$$





Background Model

- 2 exponential decay functions for the continuum background and Breit Wigner functions for the resonances (dimuon system:) [x= $m_{\mu\mu}$]

$$Exp(x;\lambda_0) = \exp[\lambda_0 x];$$

$$Exp(x;\lambda_1) = \exp[\lambda_1 x]; \tag{4}$$

$$BG(x;m_0,\Gamma) = \frac{1}{(x-m_0)^2+(\frac{\Gamma}{2})^2}; \qquad m_0 = m_{\Psi_{2S}}, m_{\Upsilon_{1S}}, m_{\Upsilon_{2S}}, m_{\Upsilon_{3S}}, \qquad \Gamma = \Gamma_1, \Gamma_2, \Gamma_3, \Gamma_4$$

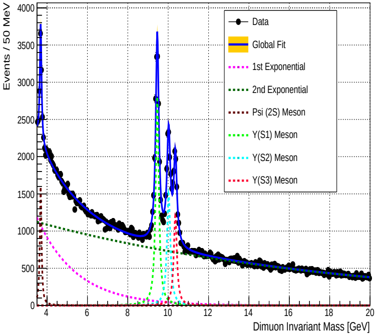
- Landau+gaussian function (for the ditrack system): [y= $m_{trk-trk}$]

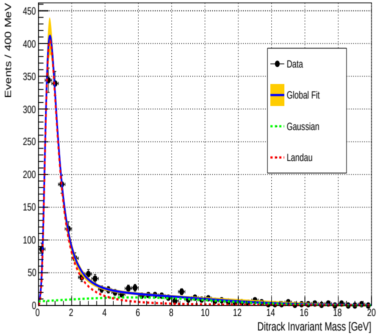
$$L(y;m_1,\xi) = \frac{1}{\xi}\phi(\lambda); \qquad \phi(\lambda) = \frac{1}{2\pi i}\int_{c-\infty}^{c+\infty} \exp\left[\lambda s + s\log s\right]ds \qquad \lambda = \frac{y-m_1}{\xi};$$

$$G(y;m_1,\sigma_1) = \frac{1}{\sqrt{2\pi\sigma_1^2}} \times \exp[-(y-m_1)^2/(2\sigma_1^2)] \tag{5}$$

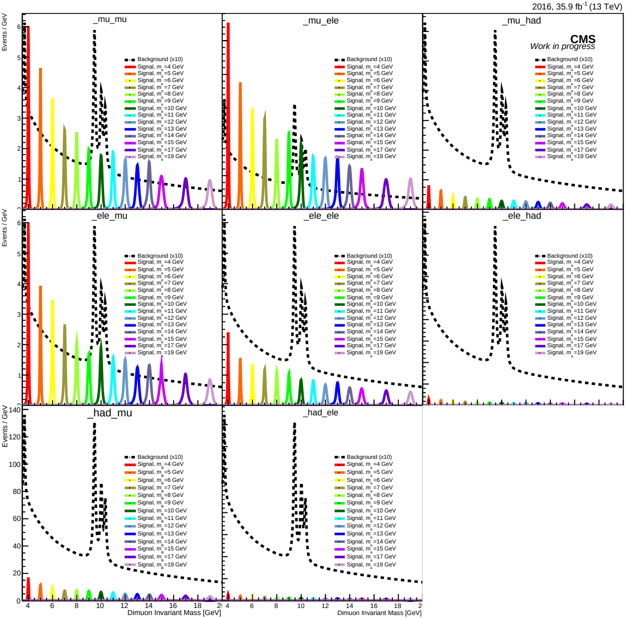
- The pdf is the cartesian product of both 1 dimensional functions:

$$PDF_{bkg}(x, y; \lambda_0, \lambda_1, m_{\Psi_{2S}}, m_{\Upsilon_{1S}}, m_{\Upsilon_{2S}}, m_{\Upsilon_{3S}}, \Gamma_1, \Gamma_2, \Gamma_3, \Gamma_4, f_1, f_2, f_3, f_4, f_5, f_6, m_1, \xi, \sigma_1) =$$
$$[(1 - f_1 - f_2 - f_3 - f_4 - f_5) \times Exp(\lambda_0) + f_1 \times Exp(\lambda_1) + f_2 \times BG(x; m_{\Psi_{1S}}, \Gamma_1)$$
$$+f_3 \times BG(x; m_{\Psi_{2S}}, \Gamma_2) + f_4 \times BG(x; m_{\Psi_{3S}}, \Gamma_3) + f_5 \times BG(x; m_{\Psi_{2S}}, \Gamma_4)] \times [(1 - f_6)\times$$
$$L(y; m_1, \xi) + f_6 \times G(y; m_1, \sigma_1)] \quad (6)$$

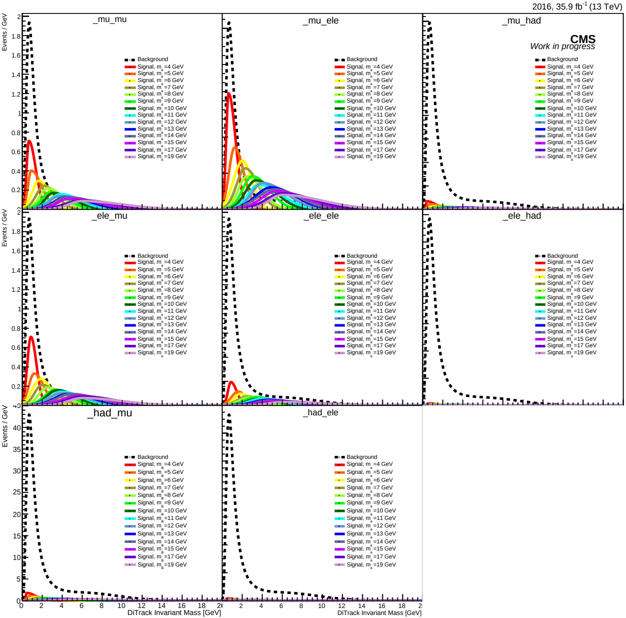




Final 2D discriminant, x coordinate (dimuon system):



Final 2D discriminant, y coordinate (ditrack system):



Systematic uncertainties

- Signal:
  - Statistical uncertainty on signal acceptance
  - Luminosity: 2.5%
  - Muon ID and trigger efficiency: 2% per muon
  - Muon and track momentum scale uncertainties: $< 0.3\%$, and have a negligible effect on the analysis
  - Theory uncertainties:

    -0.8 – 2% uncertainty from renormalization/factorization scales

    -1 – 2% from PDF uncertainties
- Background:
  - Shape uncertainty

Setting Up the BDT:

- Only the Background Shape is beeing derived form data driven method

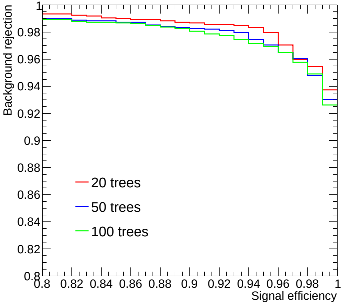
- Variables introduced (6 in total):

  $m_{\mu,\mu}$, $m_{trk,trk}$, $\Delta R(\mu,\mu)$, $\Delta R(trk,trk)$, $m_{\mu,\mu,trk,trk}$ and $\Delta\phi(a_1 \to \tau\tau, MET)$

- BDTs probed: 20, 50 and 100 trees

- Training performed with signal samples (signal region) vs Data (control region NNNN)

- Around 13K to 17K events to do training



- BDT Output: taken as a binned discriminator to extract the signal

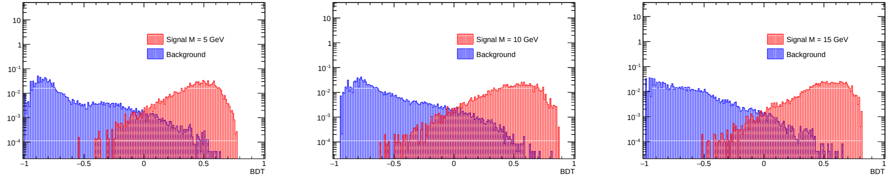


Figure: Showing the BDT output for Signal and Background normalized to the unity. All the 8 categories are added up for each of the mass point (5, 10 and 15 GeV). Mind the log scale!

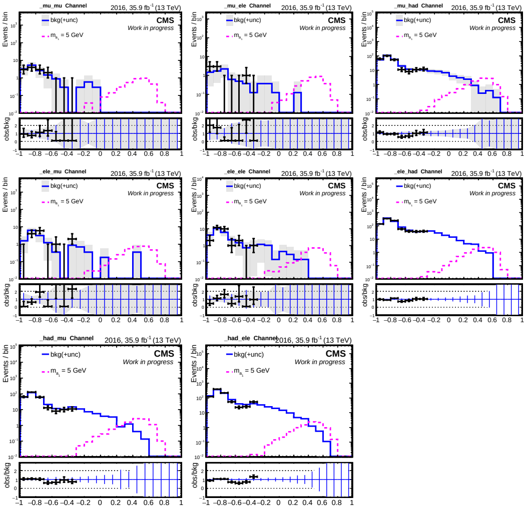
Uncertainties:

- All the previously considered relevant systematics in the case of unbinned discriminator + 2 additional shape uncertainties accounting for extrapolation of BDT output from CR NNNN to SR:
  - 1 - Shape difference between BDT in CR NN00 and in CR NNNN (accounts for isolation of objects coming from the $a_1 \to \tau\tau$ leg)
  - 2 - Shape difference between BDT in CR 00NN and in CR NNNN (accounts for isolation of objects coming from the $a_1 \to \mu\mu$ leg)

Results

- Showing final distributions for mass point 5 GeV in the 8 categories
- Benchmarking signal normalization events

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



Expected Sensitivity for 2016 dataset

- Evaluated in terms of expected 95% CL limits on: $B(H(125) \to aa \to \mu\mu\tau\tau)$

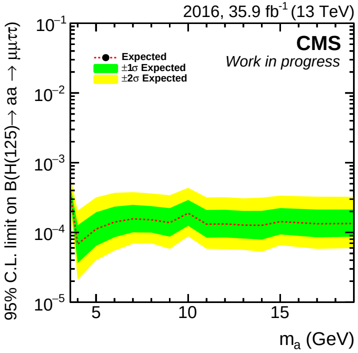


Figure: Bidimensional discriminator based

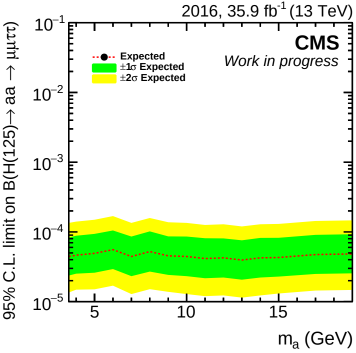


Figure: MVA (BDT) discriminator based

Summary $H(125) \to aa \to 2\mu 2\tau$ analysis

- Search for very light NMSSM pseudoscalar Higgs boson in $H(125) \to aa \to 2\mu 2\tau$ channel presented
- Search covers the range of m_a between 3.6 and 19 GeV, performed with full 2016 dataset
- Signal extraction: unbinned maximum-likelihood fit applied to the two-dimensional (2D) spectrum of dimuon invariant mass vs. track-track invariant mass/binned maximum-likelihood fit applied to the BDT classification distribution
- Sensitivity of the analysis evaluated in terms of expected limit on BR($H(125) \to aa \to 2\mu 2\tau$)
  - Upper 95% CL limit ranges from:

    Bidimensional discriminator based: $0.68 * 10^{-4}$ ($m_a = 4$ GeV) to $1.89 * 10^{-4}$ ($m_a = 10$ GeV)

    MVA (BDT) discriminator based: $0.40 * 10^{-4}$ ($m_a = 14$ GeV) to $0.56 * 10^{-4}$ ($m_a = 6$ GeV)

Summary

- $H(125) \to aa \to 4\tau$ analysis (HIG-18-006) entered CWR

- Timescale for $H(125) \to aa \to \mu\mu\tau\tau$ analysis:
  - Search with 2016 dataset is almost finished, analysis with 2017 data will start as soon as we have the MC samples
  - Depends on availability of MC samples for 2017
  - Personpower: 7

- Plans of DESY group for the legacy Run 2 results in the context of the Higgs EXO group:
  - Prepare a preliminary 2016+2017 paper if possible
  - A legacy Run2 paper (might include optimization and new DeepPF isolation)
  - Willing to make a combined paper with non-overlapping categories with the other $H(125) \to aa \to \mu\mu\tau\tau$ analysis in the same mass range

Thank you for your attention!!! 🙂

MC Samples

- MC event generator PYTHIA 8.2 used to model the NMSSM Higgs boson signal produced via ggF for mass points between 3.6 and 19 with 1 GeV step
- MC background samples not used for the final estimation of the background, but for validation of the background model
- QCD multijet background:
  - Simulated with PYTHIA8
  - Inclusive and p_T-binned samples used
- W/Z + Jets production:
  - Simulated using the MADGRAPH event generator interfaced to PYTHIA to account for the QCD initial and final state radiation
- Inclusive $t\bar{t}$ and single top production:
  - Simulated using the POWHEG event generator interfaced to PYTHIA
- Inclusive diboson production:
  - Inclusive WW, WZ and ZZ background processes generated using PYTHIA

- 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
  - Tracking efficiency
    - Scale factors, provided by the POGs applied to electrons and muons
  - Muon ID and trigger efficiency
  - A very conservative Scale Factor of 0.9 is applied to account for relative Iso in $\Delta R = 0.2$ of the 2 muons and the two 1-prong-tracks
  - Higgs p_T reweighting

Background shape per category for mu-trk (Bidimensional discriminator)

- Three shapes considered depending on track's flavor