Search for a pseudoscalar boson produced in decays of the 125 GeV Higgs boson and decaying into τ leptons

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Introduction:

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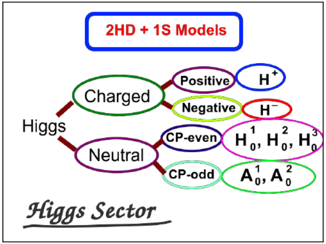
- This analysis focuses on 2HD+1S models
- Higgs sector composed by 7 physical states
- That is realized for example in the NMSSM



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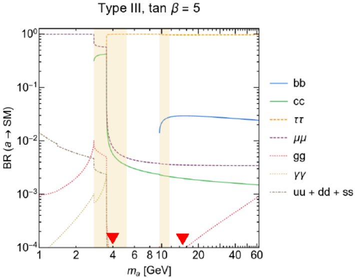
- There exist scenarios that can have a very light a_1 state
- Potentially accessible in $H(125) \to a_1 a_1 \to 4\tau$, especially for $2m_\tau < m_{a_1} < 2m_b$
- In case of fermion couplings of Type III (for $tan\beta > 1$) the decay to $\tau^+\tau^-$ even dominates above the $b\bar{b}$-threshold



[arXiv:1312.4992]

Signal Signature and Analysis Strategy

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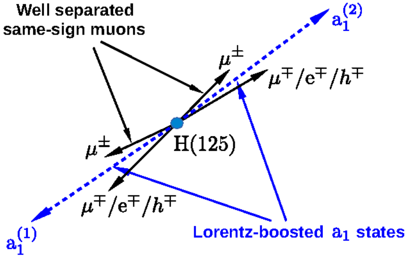
- Highly boosted a_1 bosons
  - Collimated decay products
  - Non-isolated leptons in final state
- Exploit $a_1 \to \tau_\mu \tau_{1-prong}$ decays
- Primarily targets ggH but other production modes are taken into account

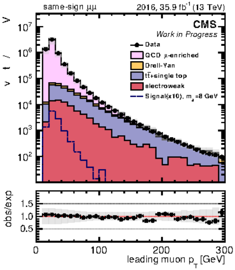


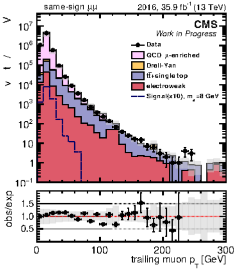
Dataset and Selection

- 35.9 fb^{-1} collected by the CMS experiment at $\sqrt{s} = 13$ TeV
- Same sign muons separated in $[\eta, \phi]$ plane
- Each muon is accompanied by one particle with charge opposite to the charge of muon

Same-sign-muons selection

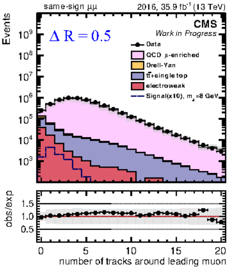
- Control plots: *(QCD scaled by 0.52)*

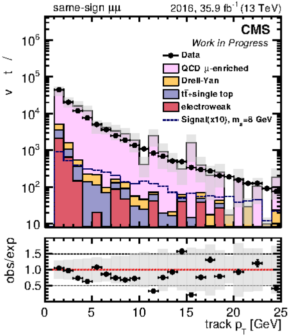




Isolation requirement

- Each muon required to have only one close-by track within predefined isolation cone ΔR_{Iso}
- Optimized value of isolation cone: $\Delta R_{Iso} = 0.5$





Selection of the 1-prong candidates

- Net charge of track and close-by muon: $q_{\mu} + q_{trk} = 0$
- $\Delta R(\mu, trk) < 0.5$
- $p_T(trk) > 2.5$ GeV

- Selection of two isolated muon-track pairs

Sample	Number of events
Data	2035
QCD multijet (MC)	1950±650
$t\bar{t}$ + single-top (MC)	12.0±2.2
Electroweak (MC)	10.0±1.2

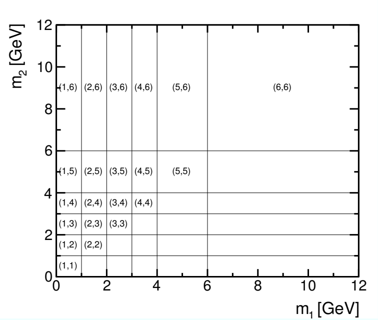
- Signal channels:
  - $a_1 a_1 \to 4\tau$: *ggH, VBF, VH, $t\bar{t}H$*
  - $a_1 a_1 \to 2\mu 2\tau$: *ggH*

$$\frac{\Gamma(a_1 \to \mu\mu)}{\Gamma(a_1 \to \tau\tau)} = \frac{m_{\mu}^2}{m_{\tau}^2 \sqrt{1 - \left(2m_{\tau}/m_{a_1}\right)^2}} \quad (1)$$

Signal Extraction

Constructing the final discriminant

- Reconstruct the invariant mass of each pair of selected muon and nearby track, $m_1 = m(\mu_1 - trk_1)$ and $m_2 = m(\mu_2 - trk_2)$
- 2D distribution filled with ordered values of masses, $m_2 > m_1$
- Unroll the 2D template into a 1D distribution



Procedure followed for signal extraction

- Extract signal by means of a binned Max-likelihood fit applied to the unrolled 2D (m_1, m_2) distribution
- Performed with background and signal normalizations freely floating

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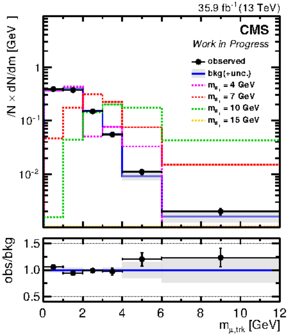
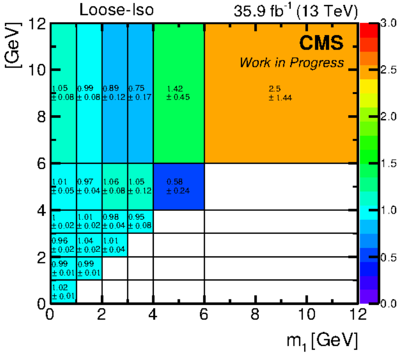
- Modeling of the background shape (2D probability density function) done with data
- Background model, constructed as:

$$f_{2D}(i,j) = C(i,j) \cdot (f_{1D}(i) \cdot f_{1D}(j)) \tag{2}$$

- f_{1D}: derived from sideband region N23 in data
- $C(i,j)$: calculated in Loose-Iso control region in data

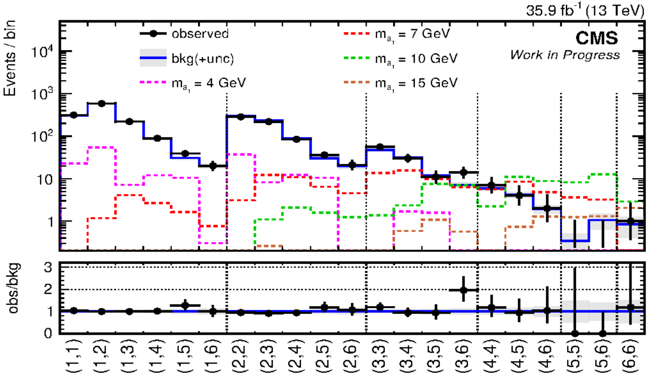




Final Discriminant : 2D (m_1, m_2) Distribution

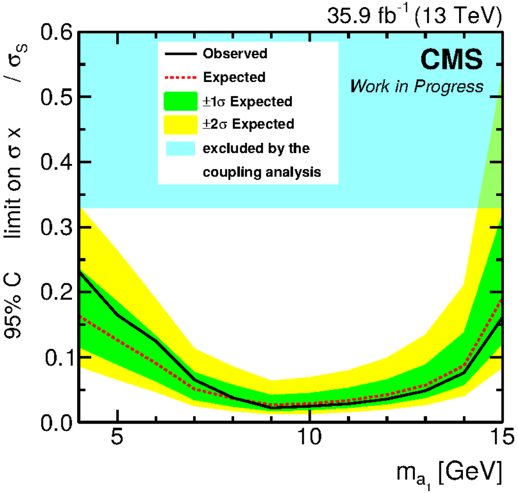
- Background distribution is obtained after performing fit to data under the background-only hypothesis

$$\text{Branching ratio}: \; B(H(125) \to a_1 a_1) \cdot B^2(a_1 \to \tau\tau) = 20\%$$



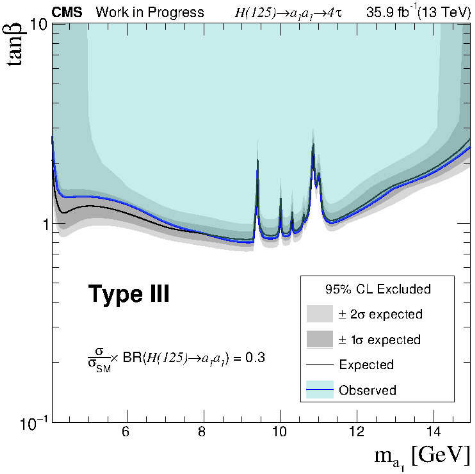
Expected and Observed limits with 2016 dataset

- Limits are set in terms of 95% CL on $\frac{\sigma}{\sigma_{SM}} \times B(H(125) \to a_1 a_1) \cdot B^2(a_1 \to \tau\tau)$
- Reference exclusion by coupling analysis: JHEP 08 (2016) 045



Constraints on 2HD+1S models

- Exclusion limits on $\tan\beta$ vs m_{a_1} for 2HD+1S model of type III.
- Benchmark value of $\frac{\sigma}{\sigma_{SM}} \times B(H(125) \to a_1 a_1) = 0.3$



Summary

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- A search for a very light pseudoscalar Higgs boson in $H(125) \to a_1 a_1 \to 4\tau$ channel was presented

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- Search covers the range of m_{a_1} between 4 and 15 GeV
- Performed with full 2016 dataset
- Signal extraction from 2D (m_1, m_2) distribution
- No significant deviations of data from the background expectation were observed
- Limits were set on $\mathrm{BR}(H(125) \to a_1 a_1 \to 4\tau)$
- Model dependent limits were set on the parameter phase space for different 2HD+1S scenarios

Thanks for your attention!

Backup

Dataset, objects and selection

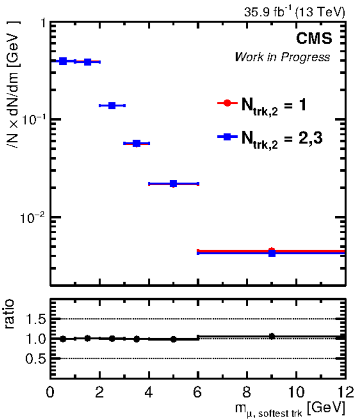
- Dataset:
  - Dataset corresponding to an integrated luminosity of 35.9 fb^{-1} collected by the CMS experiment during proton-proton collision at 13 TeV
- Objects and Selection:
  - MUONS:
    - Events are triggered if they contain two same sing muons. Those muons are required to pass the following offline selection:
    - $p_T > 9$ GeV, $|\eta| < 2.4$
    - $p_T > 18$ GeV, $|\eta| < 2.4$
    - no isolation requirement imposed
    - impact parameter w.r.t. primary vertex
      $|d_0| < 0.5$ mm $|d_Z| < 1.0$ mm
    - $\Delta R(\mu_1, \mu_2) > 2$
    - If # same-sign muon pair>1 $\rightarrow$ pair with the largest sum of muons p_T chosen
  - TRACKS:
    - Very good quality tracks are selected and the following requirements are imposed:
    - $p_T(trk) > 1$ GeV , $|\eta| < 2.4$
    - Loose impact parameter cuts: $|d_{xy}| < 1.0$ cm , $|d_z| < 1.0$ cm

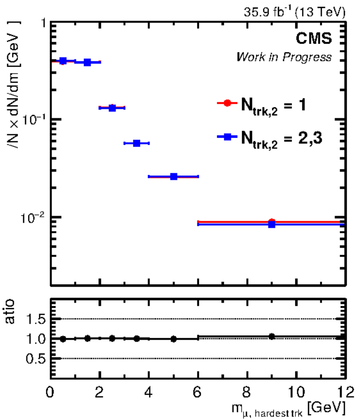
Data/MC corrections

- 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
  - Muon ID, tracking and trigger efficiency
    - Scale Factors (SF) are applied to simulated samples
  - Combined muon-track isolation and one-prong tau decay identification efficiency
    - Measurement is done with $Z \to \tau_\mu \tau_{1-prong}$ sample
    - SF are derived by fitting $m_{\mu+trk}$ distribution in bins of track p_T
  - Higgs p_T reweighting
    - Simulated samples (LO PYTHIA8) reweighted to match higher order predictions for H (125) p_T spectrum and, therefore, to improve estimate of signal acceptance

Validation of f_{1D}

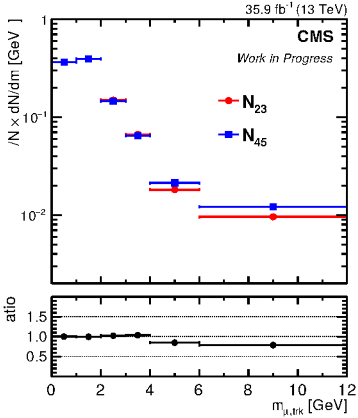
- Shapes of invariant mass distributions of the first muon and the softest or hardest accompanying track compared for the two different isolation requirements on the second muon
- Varying the # of tracks around μ_2 does not affect the shape of f_{1D} for μ_1, allowing use of N23 to derive f_{1D}





Validation of f_{1D}

- Potential dependence of the muon-track invariant mass on the isolation requirement imposed is verified
- Additional comparison of shapes in the control regions N23 and N45 (analogous to N23)
- Difference is taken as a shape uncertainty in the f_{1D} template



- This difference is related to the fact that the selected samples in N23 and N45 regions have different fractions of non-QCD contributions
  - Electroweak processes like W/Z + Jets and $t\bar{t}$ contribute mainly at higher values of the muon-track invariant mass

Validation of $C(i,j)$

- Direct validation impossible due to limited statistics of simulated muon-enriched QCD multijet samples
  - Difference in $C(i,j)$ between signal region and background sideband assessed with a dedicated simulation study
  - MC sample used to compute probability of parton of flavor f to yield the signal topology of $a_1 \rightarrow \tau_\mu \tau_{1-prong}$ decay with a given mass of muon-track pair

$$pdf = F(f, sign(q_\mu \cdot q_f), p_u/p_f, p_f, m_{\mu,trk})$$

$$f : \text{parton flavor (u, d, s, c, b, g)}$$

$$sign(q_\mu \cdot q_f) : \text{net charge of parton and muon in the associated jet}$$

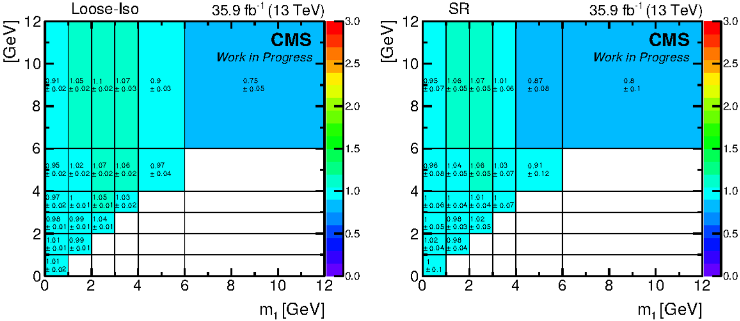
$$p_f : \text{momentum of parton}$$

$$p_u/p_f : \text{ratio of muon momentum and momentum of matched parton}$$

$$m_{\mu,trk} : \text{invariant mass of isolated muon-track pair in jet}$$

- Modeling of $f_{2D}(i,j)$ using MC sample:
  - Select QCD MC events with at least one isolated muon-track pair appearing as result of fragmentation/hadronization in one of jets
  - Model mass of the muon-track pair in the recoiling jet according to derived pdf

Validation of $C(i,j)$



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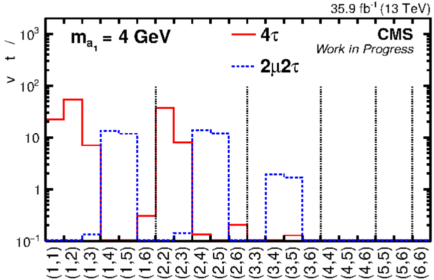
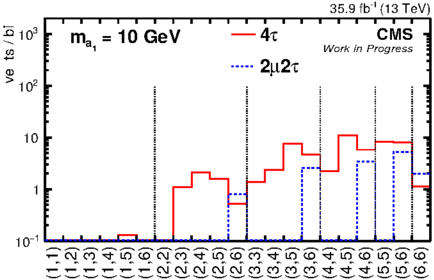
Good agreement observed between $C(i,j)$ obtained in Loose-Iso and in Signal region

- The signal templates are derived from the simulated samples of the $H(125) \rightarrow a_1 a_1 \rightarrow 4\tau$ decays in the ggH, VBF, VH and ttH production modes, and the $H(125) \rightarrow a_1 a_1 \rightarrow 2\mu 2\tau$ decays in the ggH (contribution from other production modes is expected to be less than 2%) production mode.



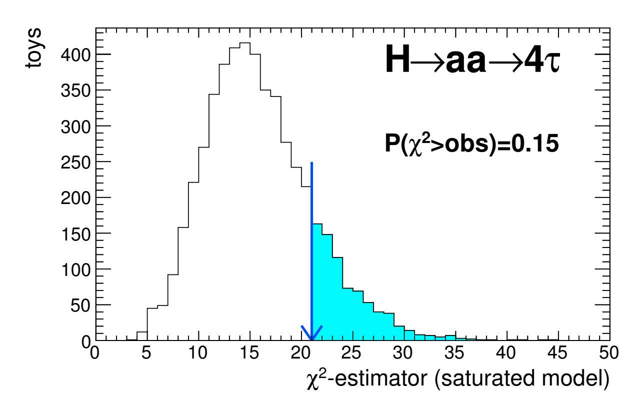


Summary of systematic uncertainties

Source	Value	Affected sample	Type	Effect on the total yield
Statistical uncertainties in $C(i,j)$	3–60%	bkg.	bin-by-bin	–
Extrapolation uncertainties in $C(i,j)$	–	bkg.	shape	–
Uncertainty in the 1D template $f_{1D}(i)$	–	bkg.	shape	–
Integrated luminosity	2.5%	signal	norm.	2.5%
Muon ID and trigger efficiency	2% per muon	signal	norm.	4%
Track selection and isolation efficiency	4–12% per track	signal	shape	10–18%
MC stat. uncertainties in signal yields	8-100%	signal	bin-by-bin	5–20%
Theory uncertainties in the signal acceptance				
μ_r and μ_f variations		signal	norm.	0.8–2%
PDF		signal	norm.	1–2%
Theory uncertainties in the signal cross sections				
μ_r and μ_f variations ($gg \to H(125)$)		signal	norm.	$^{+4.6\%}_{-6.7\%}$
μ_r and μ_f variations (VBF)		signal	norm.	$^{+0.4\%}_{-0.3\%}$
μ_r and μ_f variations (VH)		signal	norm.	$^{+1.8\%}_{-1.6\%}$
μ_r and μ_f variations ($t\bar{t}H$)		signal	norm.	$^{+5.8\%}_{-9.2\%}$
PDF ($gg \to H(125)$)		signal	norm.	3.1%
PDF (VBF)		signal	norm.	2.1%
PDF (VH)		signal	norm.	1.8%
PDF ($t\bar{t}H$)		signal	norm.	3.6%

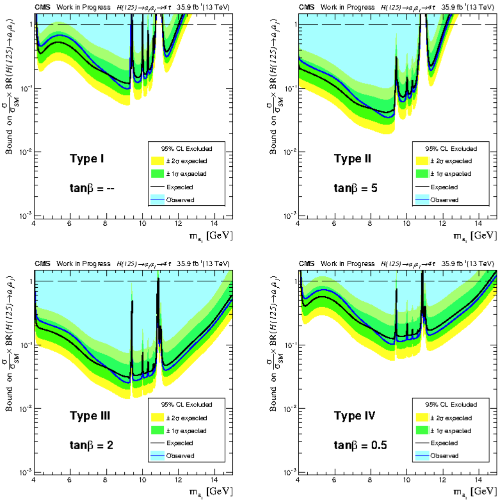
Goodness of fit test

- Goodness-of-fit test using the saturated model
- Observed value of χ^2 -like goodness-of-fit indicator compared to distribution of goodness-of-fit indicator in the ensemble of Monte Carlo toy experiments
- Probability of having in the ensemble of Monte Carlo toy experiments the value of goodness-of-fit indicator greater than that observed in data, is found to be $\sim 15\%$



Constraints on 2HD+1S models

- Exclusion limits on $\frac{\sigma}{\sigma_{SM}} \times B(H(125) \to a_1 a_1)$ vs m_{a_1} for different $\tan\beta$ scenarios in four types (I, II, III, and IV) of 2HD+1S models



Constraints on 2HD+1S models

- Exclusion limits on $\tan\beta$ vs m_{a_1} for a benchmark scenario of $\frac{\sigma}{\sigma_{SM}} \times B(H(125) \rightarrow a_1 a_1) = 0.3$ in two types (II and III) of 2HD+1S models