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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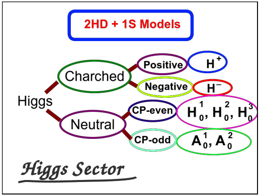
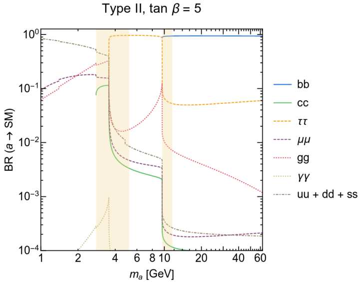
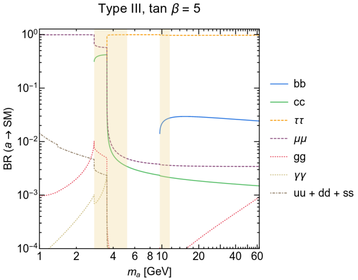
- This analysis focuses on 2HD+1S models, where the Higgs sector is extended by one additional singlet field
- That is realized for example in the NMSSM that solve the so-called μ-problem of the MSSM



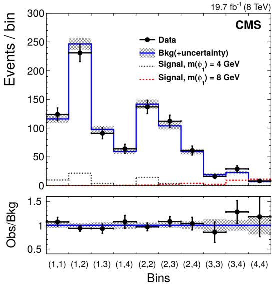
- There exist scenarios that can have a very light a_1 state with mass in the range $2m_\tau < m_{a_1} < 2m_b$, potentially accessible in H (125)$\rightarrow a_1 a_1 \rightarrow 4\tau$

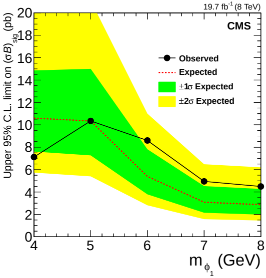




Previous Search and Differences:

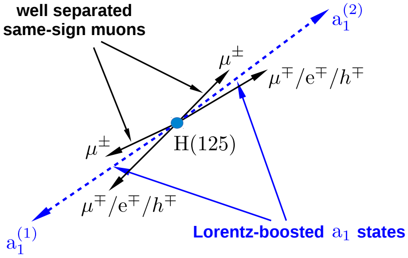
- (CMS Run I @ 8TeV), published on JHEP: doi:10.1007/JHEP01(2016)079
  - Focused on gluon-gluon fusion, mass range from 4 to 8 GeV
  - No significant excess, upper limits set on the signal production cross section times branching fraction





- Main differences:
  - 13 TeV & 35.9 fb^{-1}
  - Mass range extended up to 15 GeV
  - All production modes (ggH, VBF, VH, ttH) and $H(125) \rightarrow a_1 a_1 \rightarrow 2\mu 2\tau$ channel included
  - More robust and reliable background model

- probed mass range is $4 < m_{a_1} < 15$ GeV
- exploit $a_1 \to \tau_\mu \tau_{1-prong}$ decays (by 1-prong we mean 1-prong hadronicaly or leptonicaly)
- primarily targets ggH but other production modes are taken into account



- highly boosted a_1 bosons

  $\to$ collimated decay products

  $\to$ non-isolated leptons in final state
- selection of same sign (SS) muons separated in $[\eta, \phi]$ plane
- each muon is accompanied by one particle with charge opposite to the charge of muon

Dataset, objects and selection

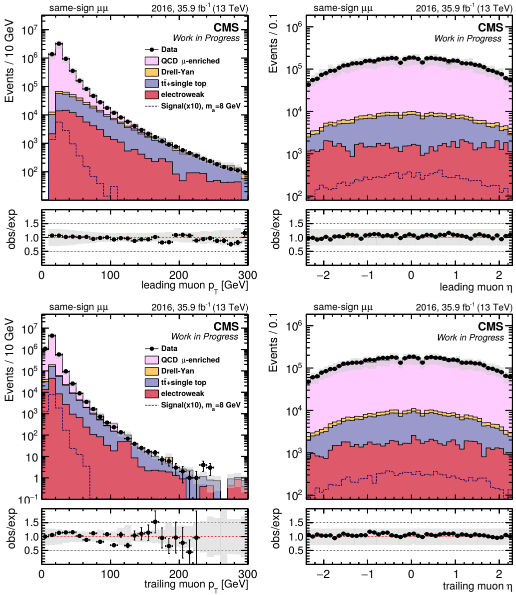
- Dataset:
  - Dataset corresponding to an integrated luminosity of 35.9 fb^{-1} collected by the CMS experiment during proton-proton collision at 13 TeV

- Objects and Selection:
  - MUONS:
    - Events are triggered if they contain two same sign 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

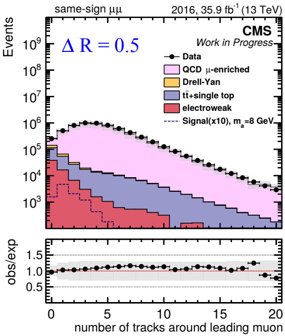
Same-sign-muons selection

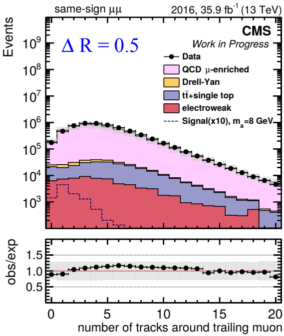
- Control plots: *(QCD scaled by 0.52)*



Isolation requirement

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

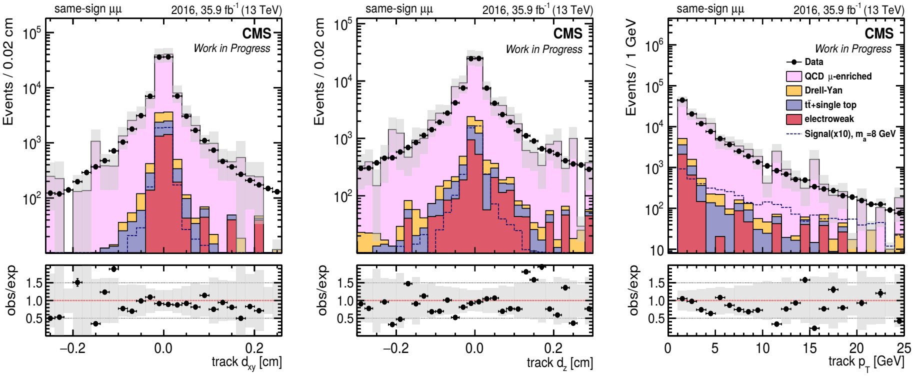




- Loose impact parameter requirements on the tracks designed to suppress background events in which a heavy-flavour hadron decays into a muon and several charged particles
- Background events with tracks displaced from the PV, but still satisfying the loose track impact parameter criteria, rejected by the requirement of exactly one track accompanying the muon

Selection of 1-prong tau decay candidate

- For the selection of the 1-prong tau-lepton decay candidates the single track around each muon must fulfill the additional selection criteria:
  - net charge of track and close-by muon $q_{\mu} + q_{trk} = 0$
  - $p_T(trk) > 2.5$ GeV, $|\eta| < 2.4$
  - $|d_{xy}| < 0.02$ cm , $|d_z| < 0.04$ cm



- 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

Selection in signal region

- 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

$$\frac{\Gamma(\mathrm{a}_1 \to \mu\mu)}{\Gamma(\mathrm{a}_1 \to \tau\tau)} = \frac{m_\mu^2}{m_\tau^2 \sqrt{1 - (2m_\tau / m_{\mathrm{a}_1})^2}} \quad (1)$$

Benchmark value of BR:
$B(H(125) \to a_1 a_1) \cdot B^2(a_1 \to \tau\tau) = 20\%$

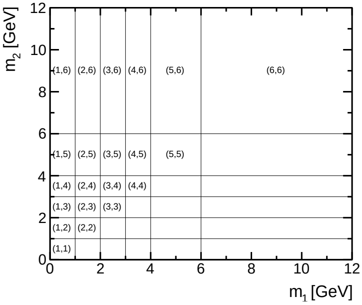
Signal acceptance $\times 10^3$ $\mathrm{pp} \to \mathrm{H(125)} + \mathrm{X}, \quad \mathrm{H(125)} \to \mathrm{a_1 a_1}$					
Signal process	$a_1 a_1 \to 4\tau$				$a_1 a_1 \to 2\mu 2\tau$
m_{a_1} [GeV]	ggH	VBF	VH	$\mathrm{t\bar{t}H}$	ggH
4	6.69 ± 0.35	5.23 ± 0.67	5.21 ± 0.92	4.48 ± 0.86	28.10 ± 0.45
7	5.11 ± 0.31	4.02 ± 0.57	3.85 ± 0.82	1.98 ± 0.56	21.72 ± 0.45
10	3.02 ± 0.24	1.66 ± 0.38	2.75 ± 0.68	1.44 ± 0.48	14.82 ± 0.38
15	0.44 ± 0.09	0.17 ± 0.13	0.34 ± 0.26	1.34 ± 0.48	1.09 ± 0.10
Number of signal events					
4	117.7±6.1	7.16±0.91	4.25±0.75	0.82±0.16	48.2 ± 0.8
7	89.8±5.4	5.50±0.79	3.14±0.67	0.36±0.10	19.9 ± 0.4
10	53.0±4.2	2.28±0.51	2.24±0.56	0.26±0.09	12.5 ± 0.3
15	7.7±1.5	0.23±0.18	0.28±0.21	0.25±0.09	0.88 ± 0.08

- Procedure followed for signal extraction:

  -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 containing in total $N \times (N+1)/2 = 6 \times (6+1)/2 = 21$ bins



- 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 floating freely $\rightarrow$ pure shape analysis

Background estimation

- QCD multijet events dominate the final selected sample (other backgrounds constitute $\sim 1\%$)
- Modeling of the background shape (2D probability density function) done with data
- Background model, constructed as:

$$f_{2D}(m_1, m_2) = C(m_1, m_2) \cdot (f_{1D}(m_1) \cdot f_{1D}(m_2))$$

  - translating it into binned 2D template filled with ordered values $m_2 > m_1$

$$m_1 \rightarrow i \qquad m_2 \rightarrow j$$

...

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

$$(f_{1D}(i) \cdot f_{1D}(j))^{sym} = \begin{cases} f_{1D}(i) \cdot f_{1D}(i) & j = i \\ f_{1D}(i) \cdot f_{1D}(j) + f_{1D}(j) \cdot f_{1D}(i) & j > i \end{cases}$$

- Background model, constructed as:

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

$$\swarrow \qquad \qquad \searrow$$

- $C(i,j)$: calculated in Loose-Iso control region in data
  - each of the muon-tracks pairs allowed to be accompanied by 2 or 3 soft tracks
  - $C(i,j) = \frac{f_{2D}(i,j)}{f_{1D}(i) f_{1D}(j)}$
- f_{1D}: derived from sideband region N23 in data
  - one of muon-track pairs passes nominal selection (isolation required)
  - the other pair is non-isolated (muon has 2 or 3 close-by soft tracks)

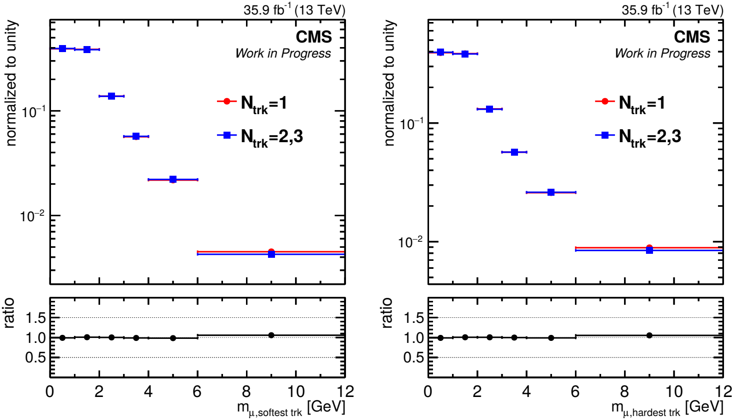
Verification of these assumptions with simulation not conclusive (limited size of MC samples)

$$\swarrow \qquad \qquad \searrow$$

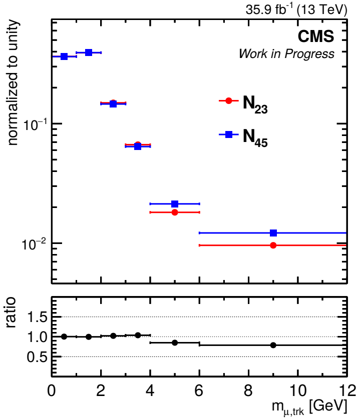
- $C(i,j)$:
  A dedicated MC study was performed
- f_{1D}:
  Test performed with an additional control sample

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}

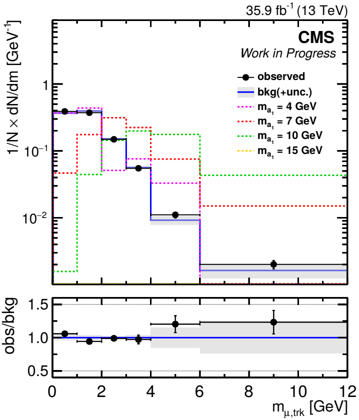


- Potential dependence of the muon-track invariant mass on the isolation requirement imposed is verified
- Additional comparison of shapes in the control regions N23 and N45 (analogous to N23)
- Difference is taken as a shape uncertainty in the f_{1D} template



- 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

$f_{1D}(i)$ template



- Normalized invariant mass distribution of the muon-track system for events passing the signal selection
- Showing signal simulations for four mass hypothesis, $m_{a_1} = 4$, $m_{a_1} = 7$, $m_{a_1} = 10$ and $m_{a_1} = 15$ GeV (dashed histograms)

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 $a_1 \to \tau_\mu \tau_{1-prong}$ 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 : parton flavor (u, d, s, c, b, g)

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

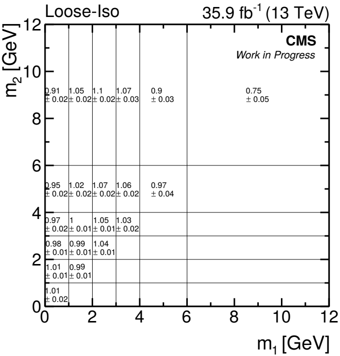
p_f : momentum of parton

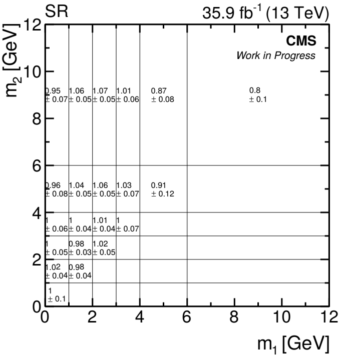
p_u/p_f : ratio of muon momentum and momentum of matched parton

$m_{\mu,trk}$: 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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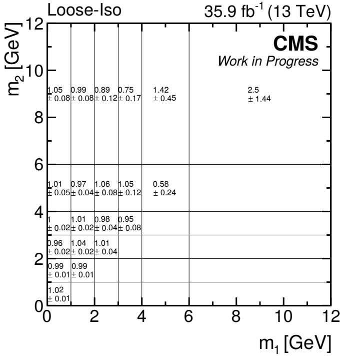
Good agreement observed between $C(i,j)$ obtained in Loose-Iso and in Signal region

$C(i,j)$



- The correlation factors in the signal region are computed as:

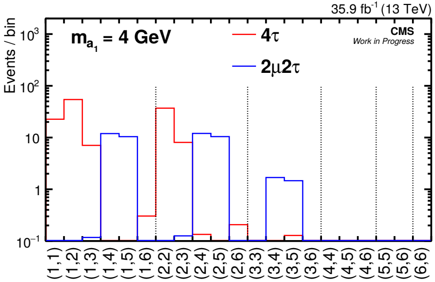
$$C(i,j) = C(i,j)^{CR}_{data} \frac{C(i,j)^{sig}_{MC}}{C(i,j)^{CR}_{MC}} \tag{3}$$

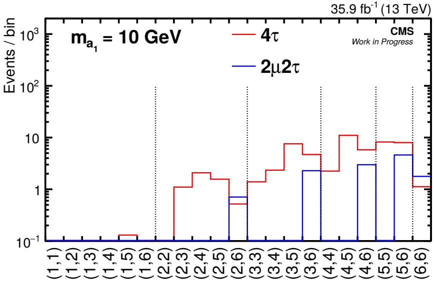
- The difference in correlation factors derived in the signal region and in the control region Loose-Iso is taken into account as an uncertainty in $C(i,j)$

- Quoted errors in $C(i,j)$ are statistical uncertainties

Signal Modeling

- The signal templates are derived from the simulated samples of the $H(125) \to a_1 a_1 \to 4\tau$ decays in the ggH, VBF, VH and ttH production modes, and the $H(125) \to a_1 a_1 \to 2\mu 2\tau$ decays in the ggH (contribution from other production modes is expected to be less than 2%) production mode.
- $H(125) \to a_1 a_1 \to 2\mu 2\tau$ signal samples have largely different shape of the $f_{2D}(i,j)$ distribution compared to the $H(125) \to a_1 a_1 \to 4\tau$ signal samples due to the peak structure in the $a_1 \to \mu\mu$ leg.





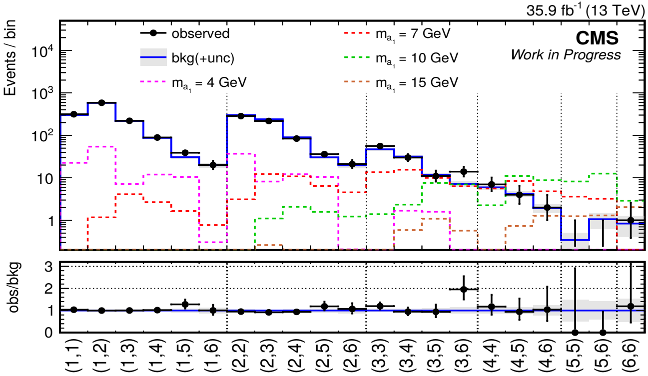
Summary of systematic uncertainties

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 $f_{\mathrm{1D}}(i)$	–	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 ($\mathrm{gg} \to \mathrm{H}(125)$)		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 ($\mathrm{t\bar{t}H}$)		signal	norm.	$^{+5.8\%}_{-9.2\%}$
PDF ($\mathrm{gg} \to \mathrm{H}(125)$)		signal	norm.	3.1%
PDF (VBF)		signal	norm.	2.1%
PDF (VH)		signal	norm.	1.8%
PDF ($\mathrm{t\bar{t}H}$)		signal	norm.	3.6%

Final Discriminant : 2D (m_1, m_2) Distribution

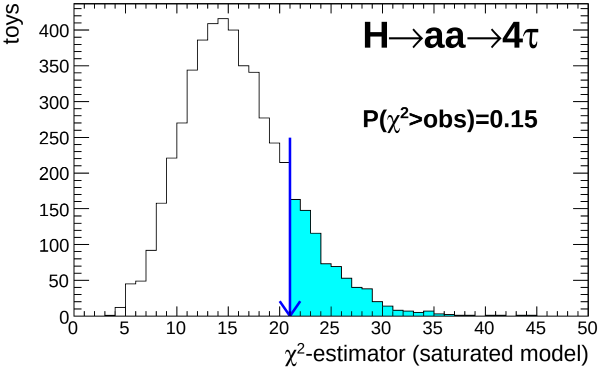
- Showing unrolled $f_{2D}(i,j)$ distribution
- Background distribution is obtained after performing fit to data under the background-only hypothesis
- Benchmarking signal normalization events

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



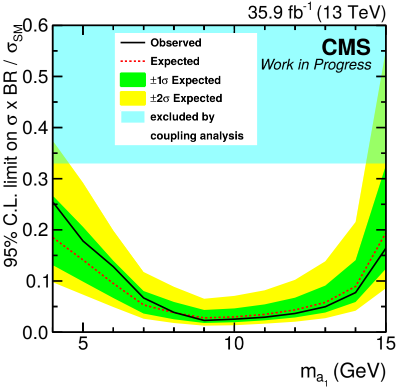
Goodness of fit test

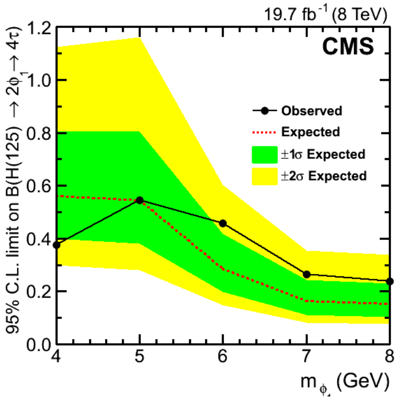
- Goodness-of-fit test using the saturated model
- Observed value of χ^2 -like goodness-of-fit indicator compared to distribution of goodness-of-fit indicator in the ensemble of Monte Carlo toy experiments
- Probability of having in the ensemble of Monte Carlo toy experiments the value of goodness-of-fit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



Expected and Observed limits with 2016 dataset

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





- Sensitivity of the 8TeV analysis 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

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 $\text{BR}(H(125) \to a_1 a_1 \to 4\tau)$
  - Upper 95% CL observed limit ranges from 2.3% at $m_{a_1} = 9$ GeV to 26% at $m_{a_1} = 4$ GeV
  - Upper 95% CL expected limit ranges from 2.8% at $m_{a_1} = 9$ GeV to 19% at $m_{a_1} = 15$ GeV

Thanks for your attention!