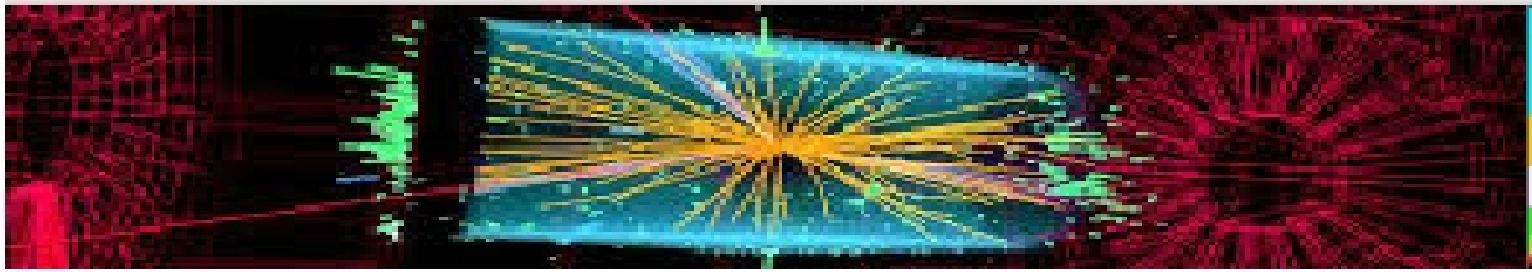

Searches for Higgs boson exotic decays at CMS

By

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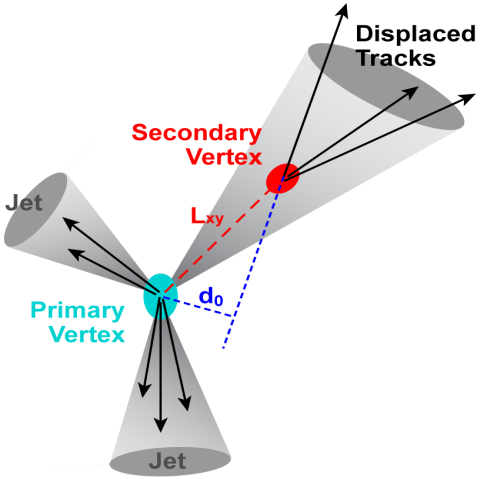
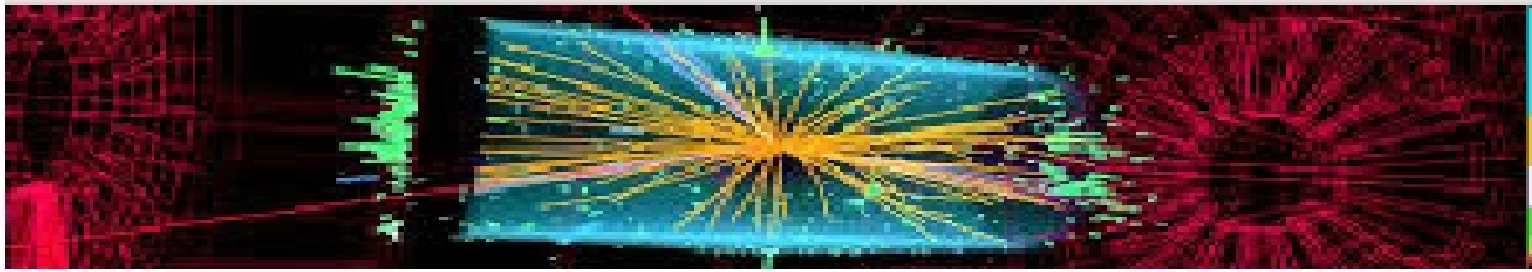
On behalf of the CMS Collaboration

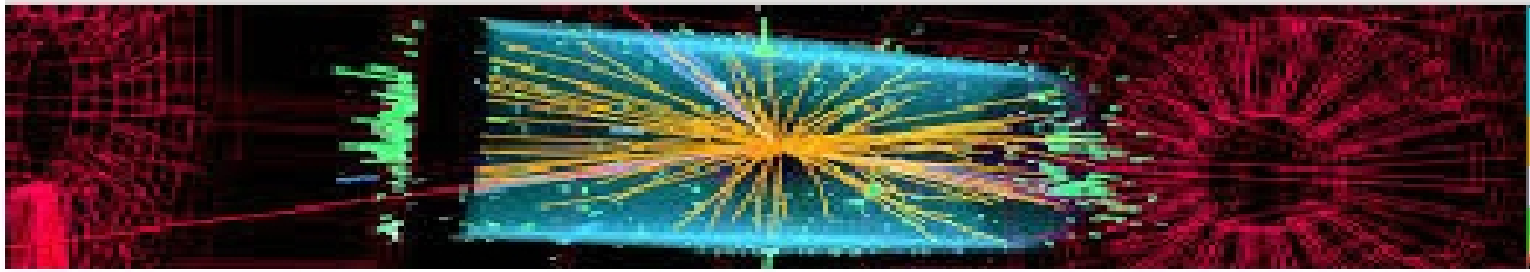


Phenomenology 2019 Symposium, University of Pittsburgh, USA, 6-8 May 2019



Outline

- Motivation
- MC Simulations and Data
- Signal and Background Models
- Systematics
- Results and Summary



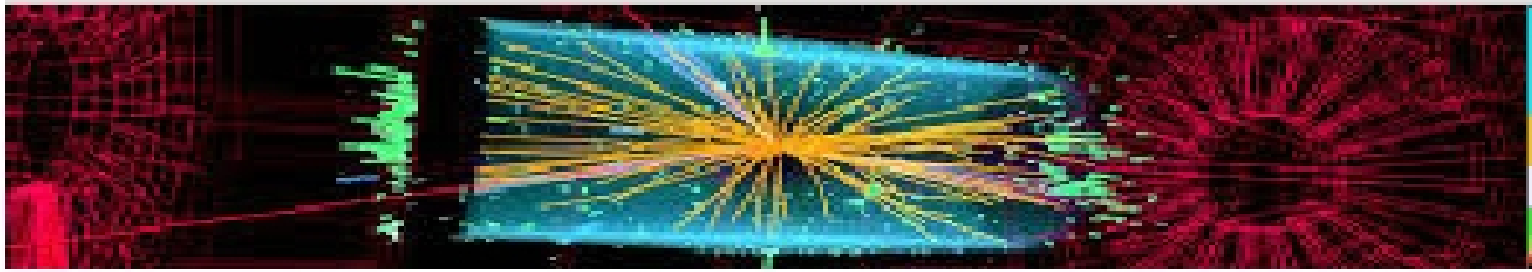
Why low mass?

Is the h (125 GeV) really a SM Higgs boson?

Some BSM theories predict additional low-mass (< 125 GeV) scalars/pseudoscalars:

- **General 2HDM :**
  - **2 Higgs doublets (4 types) → 5 Higgs bosons: h, H, a, $H^{\pm}$**
  - **In the alignment limit, allows h→ aa decay**
  - **h is compatible with a 125 GeV SM-like scalar (h or H) + a light Higgs Boson (a)**

- **2HDM+S:**
  - **2 Higgs doublets + 1 singlet → 7 Higgs bosons: h_1, h_2, h_3 , a_1, a_2, $H^{\pm}$**
  - **Allows direct production for h→ a_1a_1**
  - **Special case NMSSM allowing enhanced coupling to leptons at higher values of tanβ**
  - **Compatible with a 125 GeV SM-like scalar (h_1 or h_2) + a mostly "singlet-like" light Higgs Boson (a_1 or h_1)**



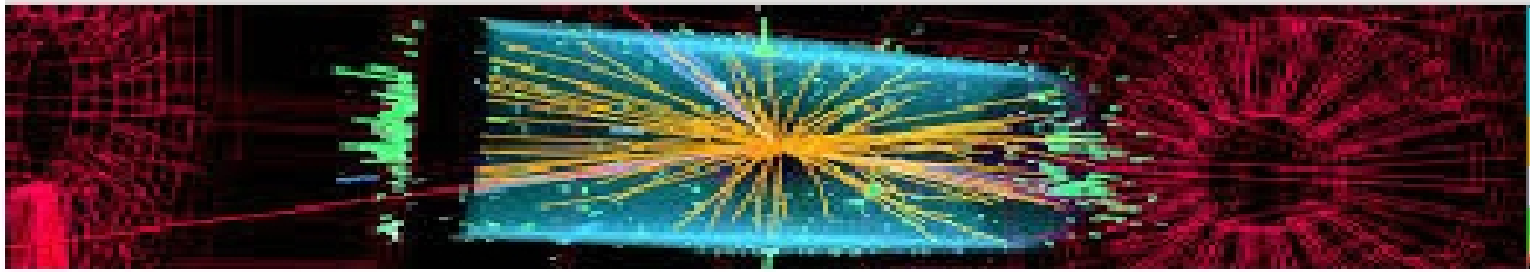
CMS low-mass searches

Exotic decays of Higgs Boson, h (125) → aa are searched in various final states

Recent results with 2016 dataset at 35.9 fb^{-1}:

- **μμbb (20 – 62.5 GeV), CMS PAS HIG-18-003**
- **μμττ (15 – 62.5 GeV), CMS PAS HIG-17-029**
- **bbττ (15 – 60 GeV), CMS PAS HIG-17-024**
- **μμμμ (0.25 - 8.5 GeV), CMS PAS HIG-18-003**
- **ττττ, ττμμ (4 - 15 GeV), CMS HIG-18-006**
- **bbbb (Ongoing)**

Talk covers results of μμbb and μμττ final states

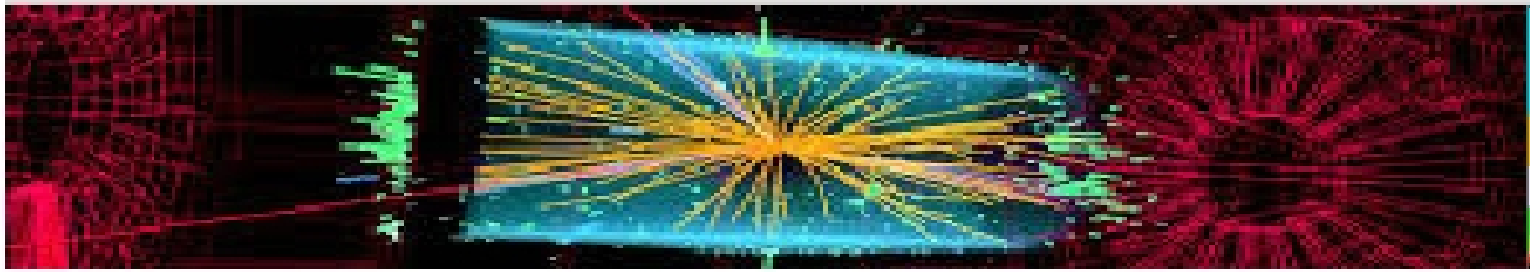


CMS low-mass searches

Why $\mu\mu bb$ and $\mu\mu\tau\tau$ final states?

- 4b final state expected to occur with higher number of events but has challenging backgrounds
- 4μ final state clean but very rare
- $\mu\mu bb$ final state is considered a compromise between 4b and 4μ states
- Same stands true for $\mu\mu\tau\tau$
- Both the decay channels are expected to provide better sensitivity in the long run [Ref. 01]:
  - $a \rightarrow \mu\mu$ has a clear peak
  - Br depend on the model and model parameters
  - $a \rightarrow bb$ and $a \rightarrow \tau\tau$ have large BR in many parts of the parameter space
  - Particularly very large in the context of the NMSSM [Ref. 02]

[Ref. 01] JHEP 1308 (2013) 019, [arXiv:1303.2113]
[Ref. 02] Phy. Rev. D 90, 075004 (2014)



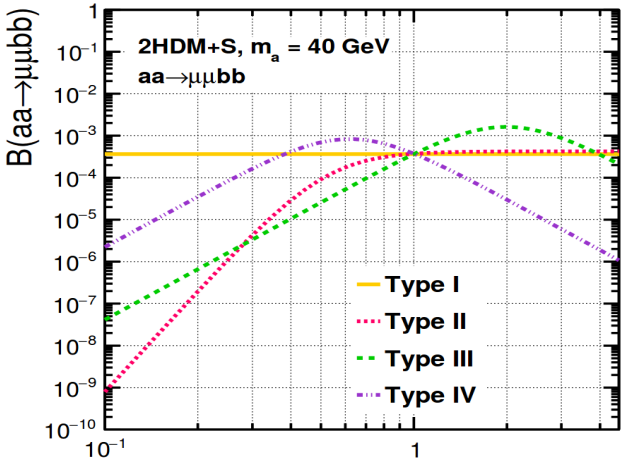
Simulated Signal Samples

Model Used

- NMSSMHET used in MadGraph_aMCatNLO, generated signal at LO Mechanism
- Mechanism
  - ggF with σ_{ggF} = 48.58 pb
  - VBF with σ_{VBF} = 3.78 pb

Benchmark for the expected yield

- BR(h → aa) = 10%
- BR(h→aa→μμbb) = 1.7×10^{-3} in 2HDM+S Type 3 *{Predicted as per [Ref. 03]}*
- Br(h→aa→μμττ) = 1 x 10^{-3}



[Ref. 03.] D. Curtin et al., Phys. Rev. D 90 (2014) 075004

h→a a→μμbb:

Mass range 20 < m_a < 62.5 GeV

To estimate the contribution from μμττ and ττbb, samples with μμττ and ττbb final state were also generated

Sample name (Process)	"a" mass (GeV) points Simulated
h→aa→2μ2b (ggF)	20, 25, 30, 35, 40, 45, 50, 55, 60
h→aa→2μ2b (VBF)	20, 30, 40, 60
h→aa→2b2τ (ggF)	20, 30, 60
h→aa→2μ2τ (ggF)	20, 30, 60

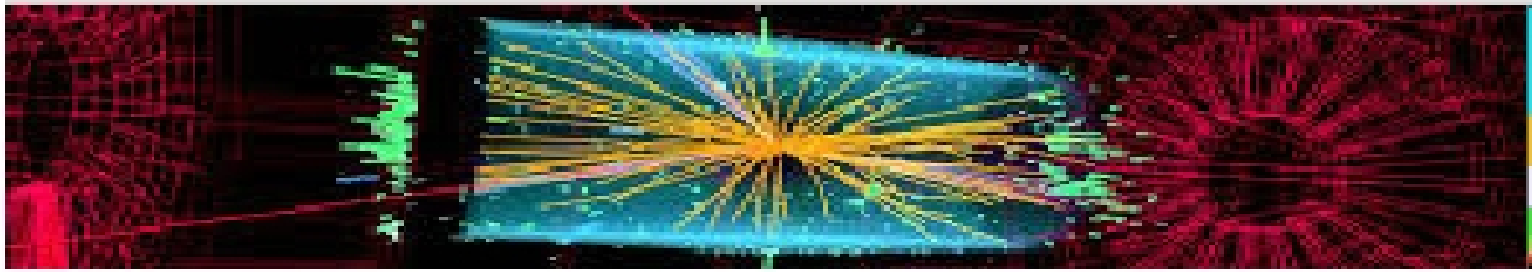
Similarly simulated signal samples for h→a a→μμττ where generated

Mass range 15 < m_a < 62.5 GeV

Four final states are considered:
μμ + eμ, μμ + eτ_h , μμ + μτ_h and μμ + $\tau_h\tau_h$

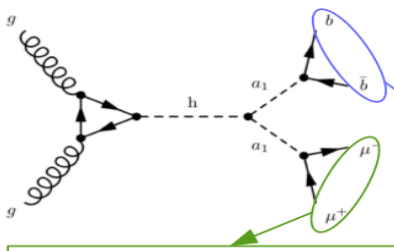
The μμ + ee and μμ + μμ final states are not considered

- Smaller branching fractions
- large contribution from the irreducible backgroundof Z boson pair production.



Preselection and Optimization

$h \rightarrow aa \rightarrow \mu\mu bb$

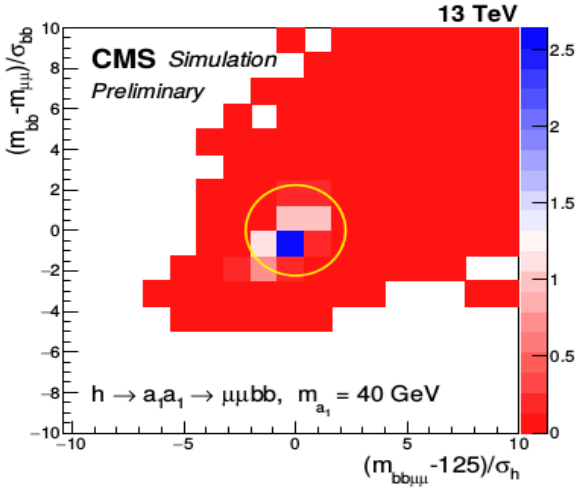


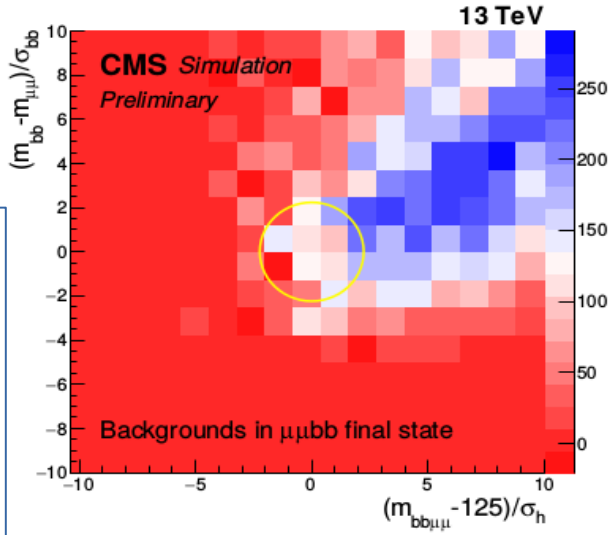
2 Opposite sign Muons :
- Pt > 20/9 GeV (Optimized)
- $|\eta| < 2.4$
- Tight ID
- Rel. Iso. < 0.15

$15\ \text{GeV} < m_{\mu\mu} < 70\ \text{GeV}$

At least one good primary vertex

At least two jets :
- Pt > 20/15 GeV (Optimized)
- $|\eta| < 2.5$
- $\Delta R(\mu, \text{jet}) > 0.4$
- b-tagging CSVv2 :
  - One loose/One tight(Optimized)





Look for improvements in sensitivity applying optimization cuts on MET and χ^2

Additional Optimization:

- E_T^{miss} < 60 GeV
- Exploit features in signal such as χ^2 with χ^2 < 5

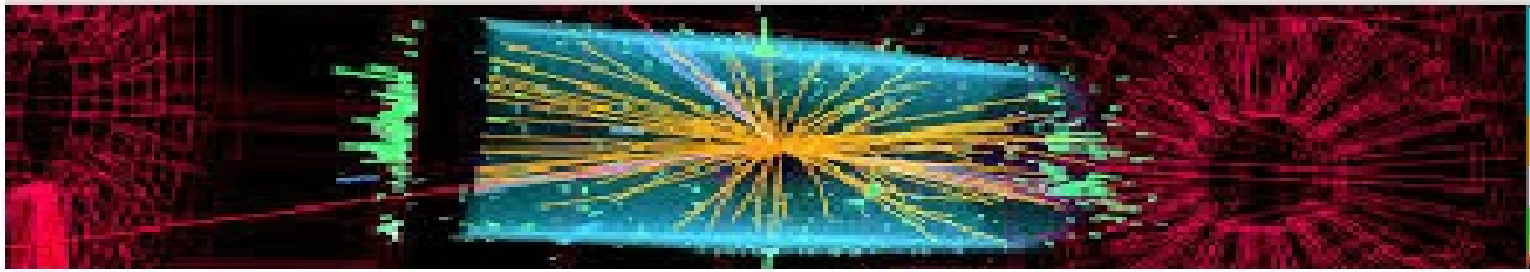
$$\chi^2_{total} = \frac{(m_{bb} - m_{\mu\mu})^2}{\sigma^2_{bb}} + \frac{(m_{\mu\mu bb} - 125)^2}{\sigma^2_h}$$

$h \rightarrow aa \rightarrow \mu\mu\tau\tau$

Muons p_T > 18/ 9 GeV

Electrons from τ lepton decays are required to have p_T > 7 GeV

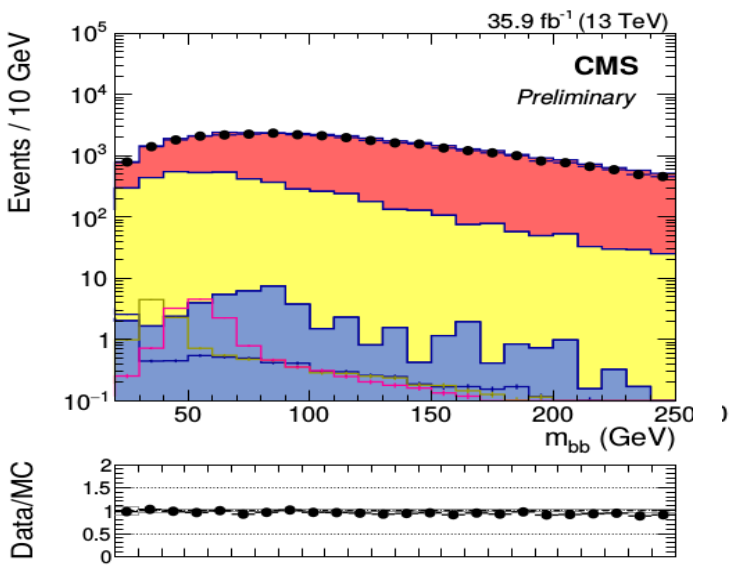
τ_h candidates are required to satisfy p_T > 18.5 GeV

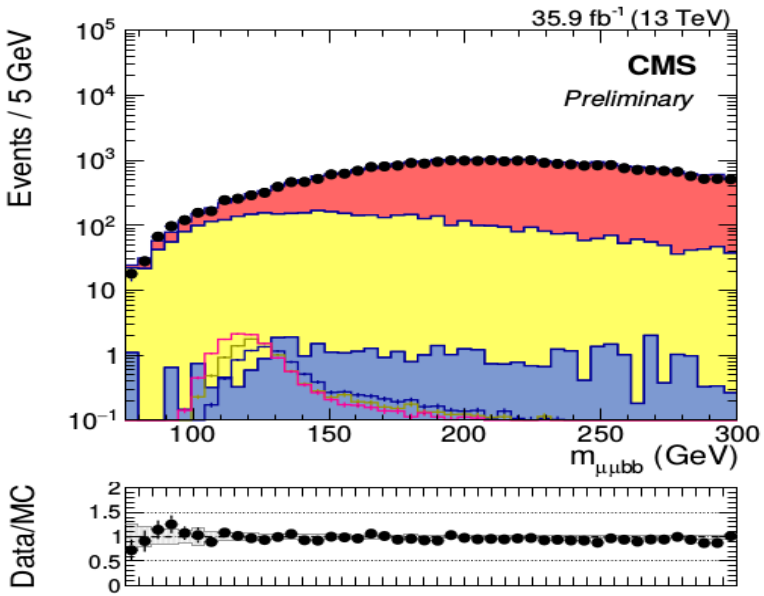


Data-MC Distributions and yeilds

$h \to a\,a \to \mu\mu bb$

- Data, 35.9 fb^{-1} @ 13 TeV
- Top
- Z/γ* (→ ll) + jets
- Diboson
- Simulation stat. unc.
- m_{a_1} = 20 GeV
- m_{a_1} = 40 GeV
- m_{a_1} = 60 GeV





Signal and backgroung yields

Process	$\mu^+\mu^-b\bar{b}$ selection	Final selection
Top ($t\bar{t}$, single top quark)	33730 ± 120	198 ± 9
Drell–Yan	5237 ± 77	399 ± 21
Diboson	51 ± 4	1 ± 0.1
Total expected background	39015 ± 140	598 ± 23
Data	36360	610
Signal for $\sigma_h \times \mathcal{B} \approx 8$ fb		
m_{a_1} = 20 GeV	14.0± 0.1	6.0 ± 0.1
m_{a_1} = 40 GeV	14.8± 0.1	7.5 ± 0.1
m_{a_1} = 60 GeV	16.7± 0.1	10.1 ± 0.1

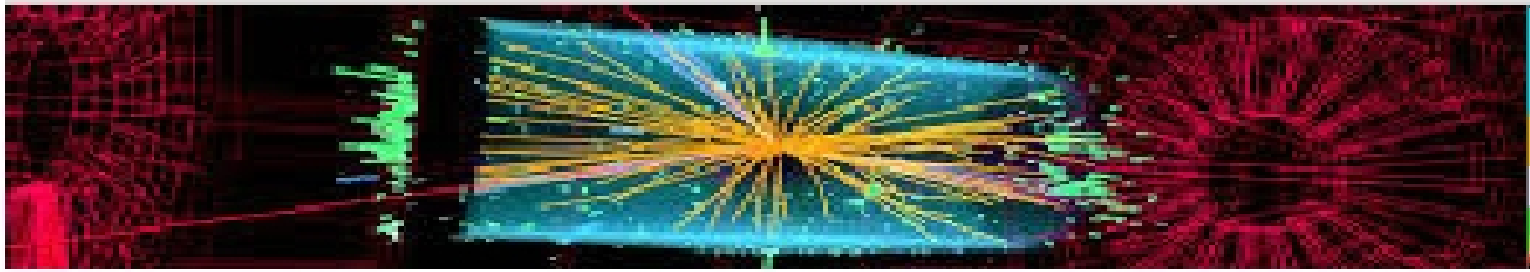
Contribution from other signals

The μμττ and ττbb signals can contribute in our selection

- ττbb with τ→μ decays
  - Leads to a displaced μμ mass w.r.t the μμbb signal : negligible effect on signal yield
- μμττ with a possibility for τ-b misidentification
  - The contribution is small at the benchmark

Process	m_{a_1} = 20 GeV	m_{a_1} = 40 GeV	m_{a_1} = 60 GeV
$\mu\mu\tau\tau$	0.017± 0.005	0.051 ± 0.009	0.084 ± 0.011
$\tau\tau bb$	0.304 ± 0.103	0.280 ± 0.086	0.448 ± 0.114

For μμττ final state, 14% of the h→aa→4τ events have at least two muons in the final state



Signal Model

- **Signal Shape derived from simulation**

- **Combination of Voigtion and a Crystal ball profiles**

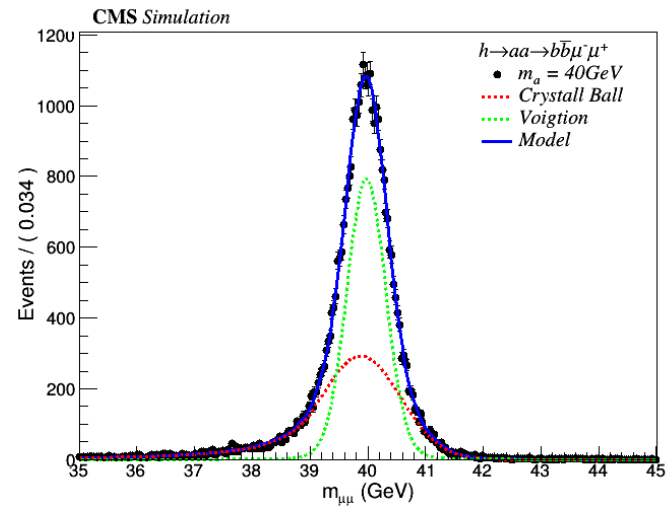
$$S(m_{\mu\mu}|f, p_V, p_{cb}) \equiv f \cdot V(m_{\mu\mu}|p_V) + (1-f) \cdot CB(m_{\mu\mu}|p_{cb})$$

- **The Voigt profile function is a convolution of Lorentz and Gaussian profiles**

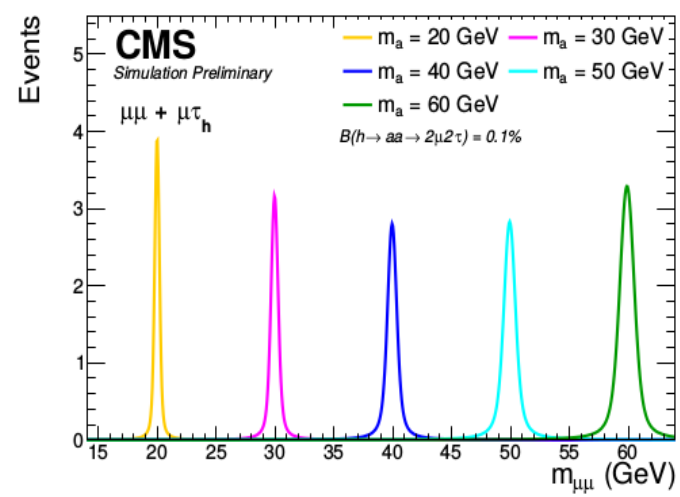
- **The Crystal ball function has a Gaussian core and a power-law low-end tail**

- **Resolutions are modelled linearly as a function of dimuon invariant mass:**

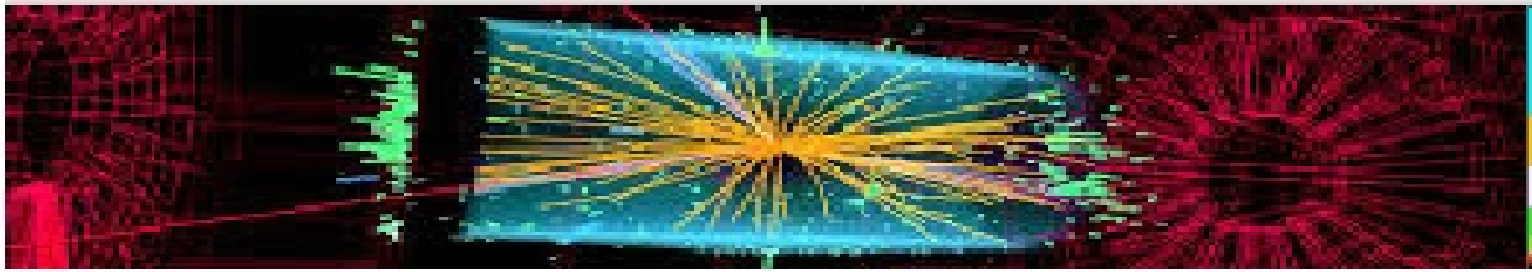
$$\sigma_{\rm v} = \sigma_{\rm v,0} + \alpha\, m_{\mu\mu},$$
$$\sigma_{\rm cb} = \sigma_{\rm cb,0} + \beta\, m_{\mu\mu}.$$



The constructed signal model



Parameterized dimuon invariant mass distributions of the h → aa → 2μ2τ

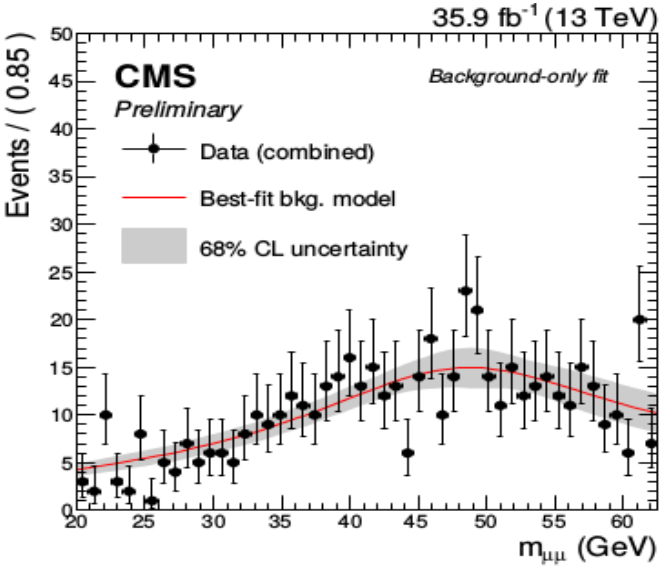


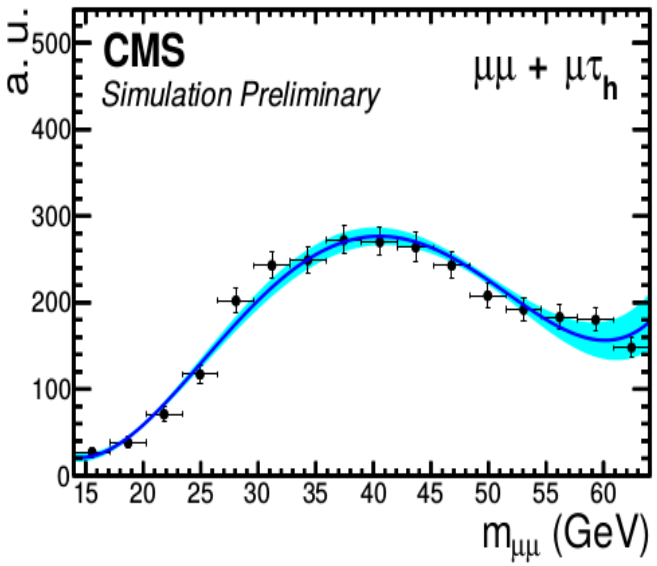
Background Model

The dimuon mass distributions are parameterized with different polynomials

The number of degrees of the polynomial required to describethe background in each channel is determined with a Fisher F-test

The TLexc category			
Model	χ^2/ndf	F-test probability (> 0.05)	Decision
Inv. Poly II	0.87	–	✓
Inv. Poly III	0.86	0.32	✓
Inv. Poly IV	0.83	0.90	✓
Inv. Poly V	0.81	0.03	×

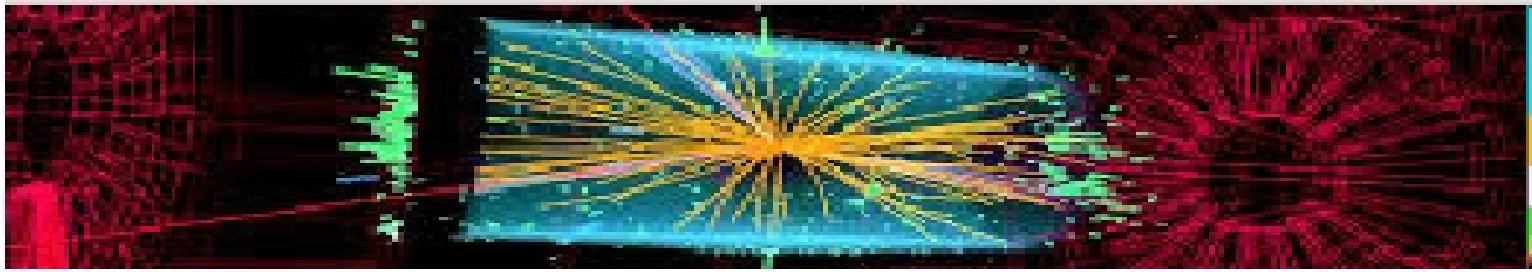




The best fit output to the data under the background-only hypothesis

Parameterization of the irreducible backgrounds

Dark grey and green bands are the 68% CL uncertainty bands for the background model



Systematics Uncertainties

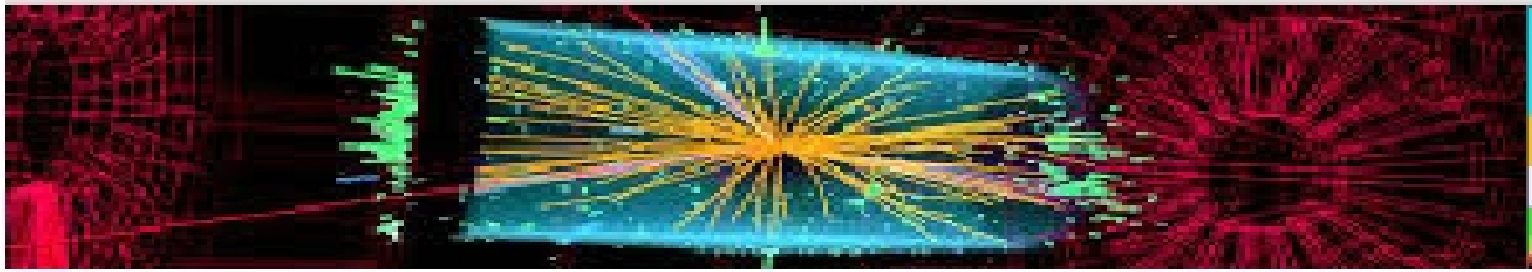
Background

- Uncertainties on the background model are taken into account with the discrete profiling method

Signal

- Signal normalization is affected by various sources of systematic uncertainties:
  - σ_h : ±3.6%, considered for the limit on BR
  - Luminosity: ±2.5%
  - Trigger efficiency: 2%
  - Pileup: ±4.6% on the $\sigma_{pp}^{inelastic}$
  - μ, ID, Iso, HLT scale factors: doubled for p_T < 20 GeV
  - JES: p_T and η dependent corrections applied on jets and propagated to E_T^{miss}
  - JER
  - identification, isolation, and reconstruction uncertainties amount to 2% per muon, 2% per electron, and 5% per τ_h candidate.

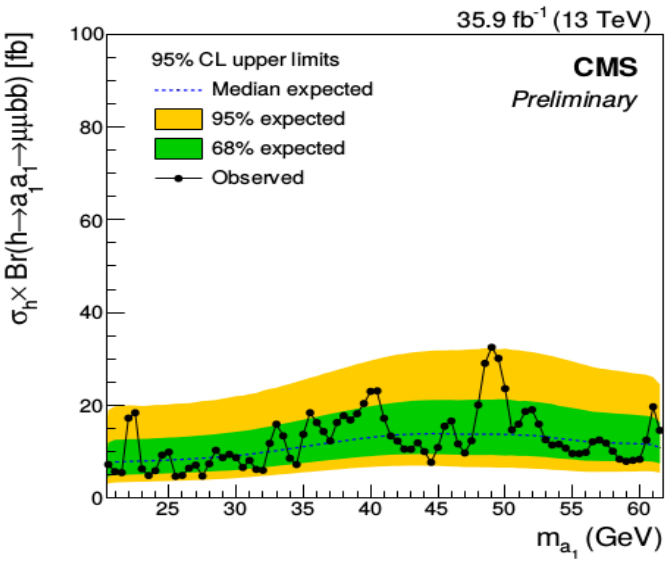
- b-tagging: different sources affecting the shape calibration are considered and are doubled for low p_T jets

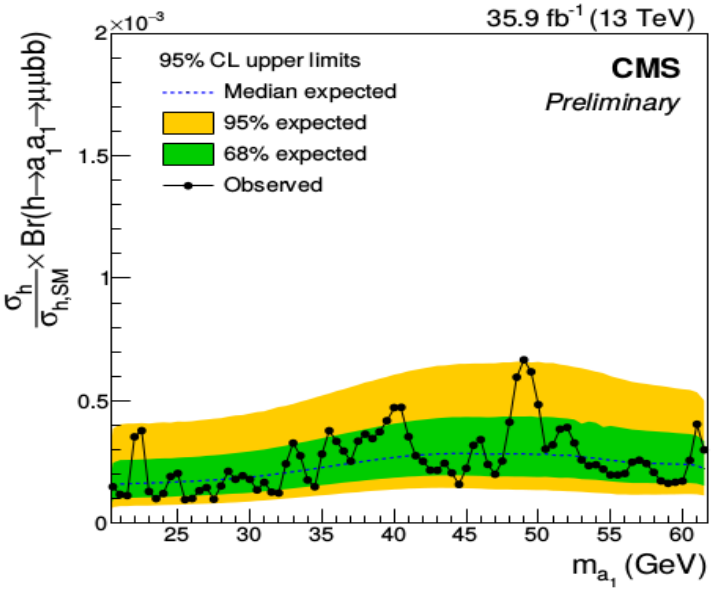


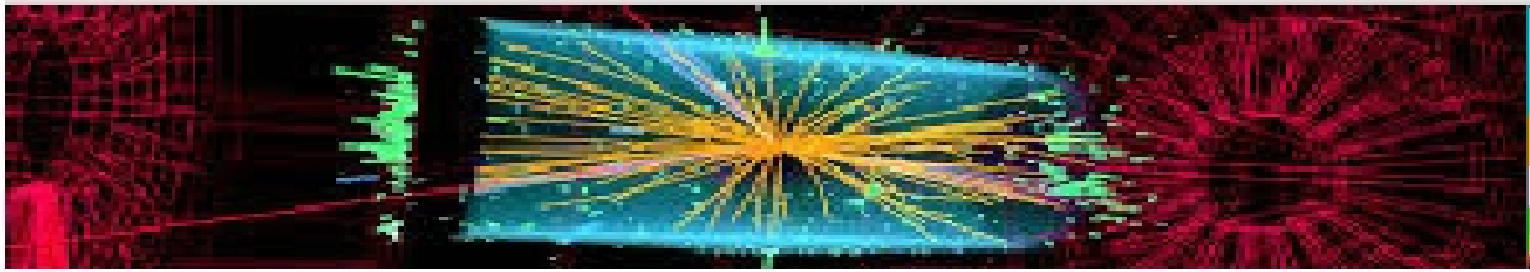
Results (h→a a→μμbb)

Expected and observed limits

- Assuming the SM prediction of σ_h, the results are extracted by fitting the reconstructed dimuon mass distributions
- Upper limits at 95% CL on the Higgs boson production cross section times branching ratio on $\sigma_h \times B(h \to a\,a \to \mu\mu bb)$ as well as on the Higgs boson branching ratio
- Limits are improved by a factor of 2 with respect to Run-I analysis
- The limits on the branching fraction are reported as $(2-6) \times 10^{-4}$







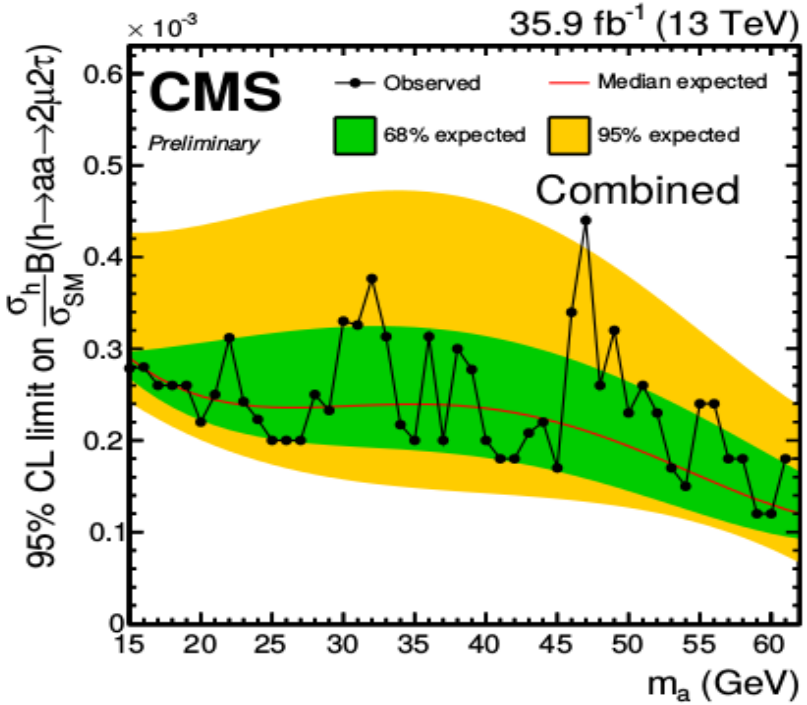
Results ($h \to a\,a \to \mu\mu\tau\tau$)

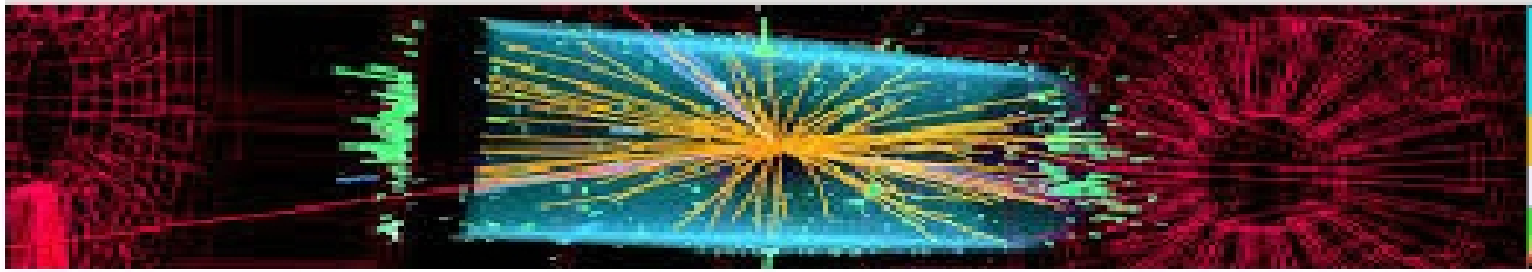
- **Expected and observed limits**

  - **Upper limits at 95% CL on $(\sigma_h / \sigma_{SM}) \times B(h \to a\,a \to \mu\mu\tau\tau)$ for the combined final states: $\mu\mu + e\mu$, $\mu\mu + e\tau_h$, mm + $\mu\tau_h$, and $\mu\mu + \tau_h\tau_h$**

  - **Upper limits are set at the 95% confidence level on the branching fraction $B(h \to aa \to 2\mu 2\tau)$ for masses of the light pseudoscalar between 15 and 62.5 GeV, and are as low as 1.2×10^{-4} for a mass of 60 GeV**

  - **These are the most stringent limits so far fo such a decay channel**





Summary

We have just started to extract the physics potential of the 13 TeV dataset!

Extensive program for exotic decays of Higgs boson at CMS is already underway

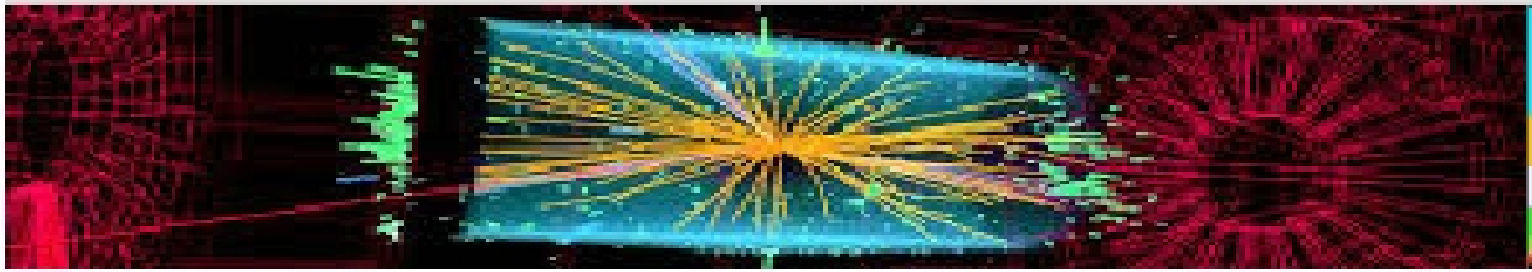
Search for exotic Higgs decay in $\mu\mu bb$ and $\mu\mu\tau\tau$ final state with 2016 dataset has been presented

- **The VBF contribution to the signal is also included and does not have much impact on significance**
- **For $\mu\mu bb$ final state, contribution from $\mu\mu\tau\tau$ and $bb\tau\tau$ signals is observed to be very small**
- **No excess is found over the SM backgrounds**
- **Upper limits are reported on BR($h \rightarrow aa \rightarrow \mu\mu bb$) and BR($h \rightarrow aa \rightarrow \mu\mu\tau\tau$)**

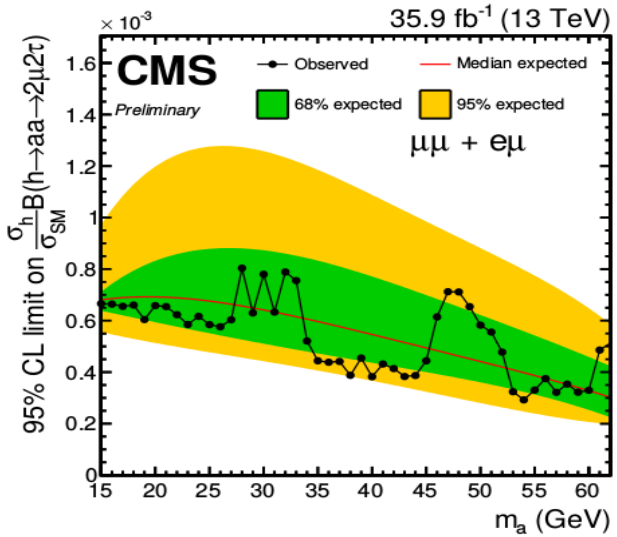
Present and future Work:

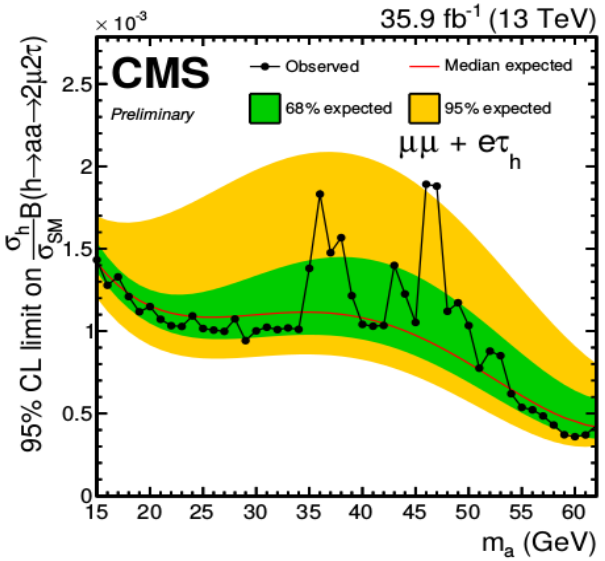
- **Whole Run-II data-set analysis in progress**
- **Improve sensitivity below 20 GeV and to use dedicated tools for low p_T searches**

Thank You



Back-Up


35.9 fb^{-1} (13 TeV)
CMS
Preliminary
Observed
Median expected
68% expected
95% expected
$\mu\mu + e\mu$
95% CL limit on $\frac{\sigma_h}{\sigma_{SM}}B(h\to aa\to 2\mu 2\tau)$
m_a (GeV)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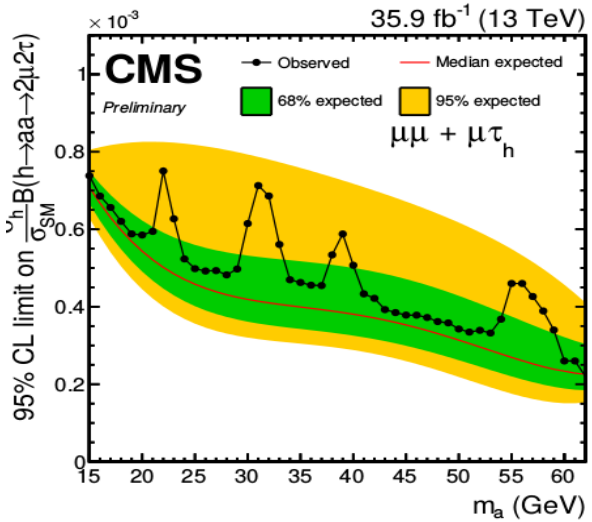
35.9 fb^{-1} (13 TeV)
CMS
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Observed
Median expected
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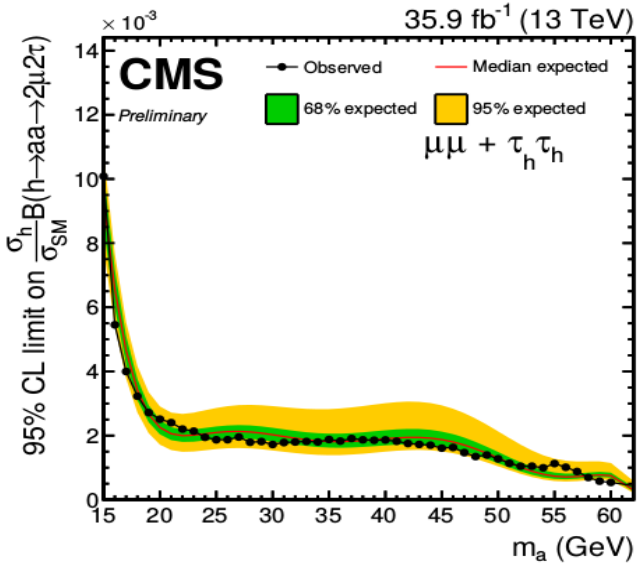
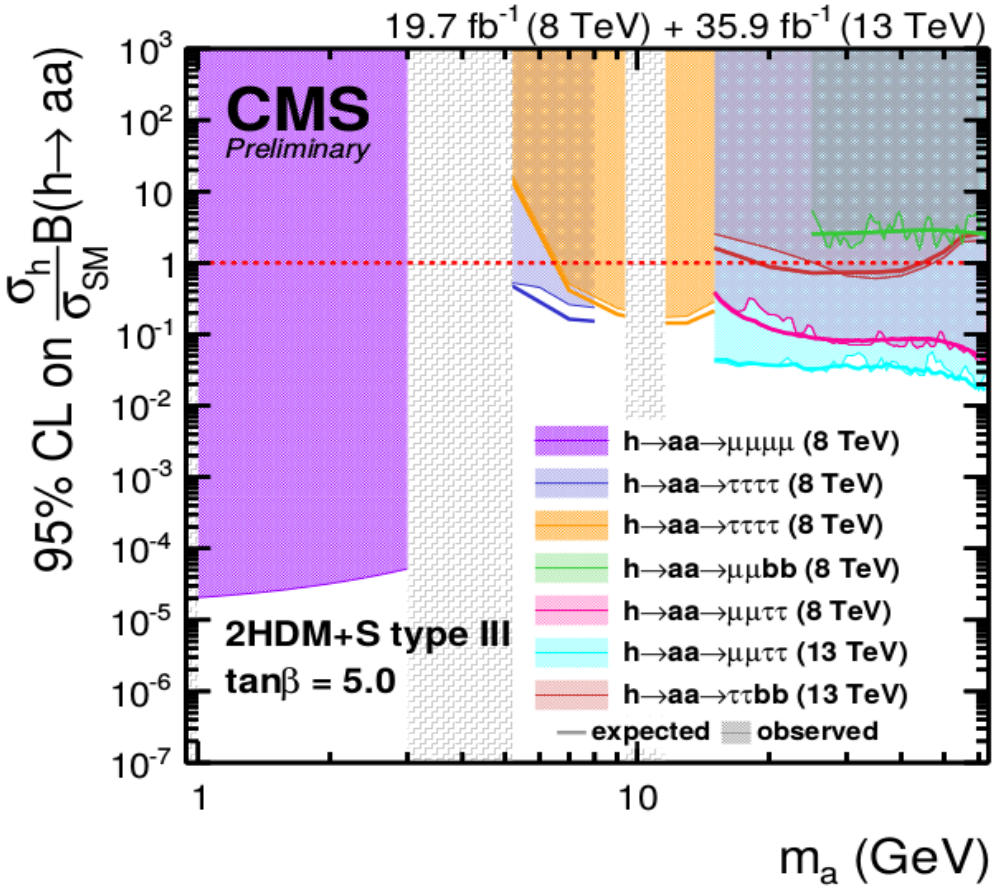
m_a (GeV)

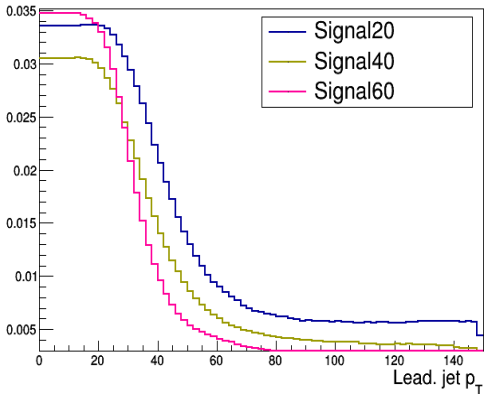

35.9 fb^{-1} (13 TeV)
CMS
Preliminary
Observed
Median expected
68% expected
95% expected
$\mu\mu + \tau_h\tau_h$
95% CL limit on $\frac{\sigma_h}{\sigma_{SM}}B(h\to aa\to 2\mu 2\tau)$
m_a (GeV)

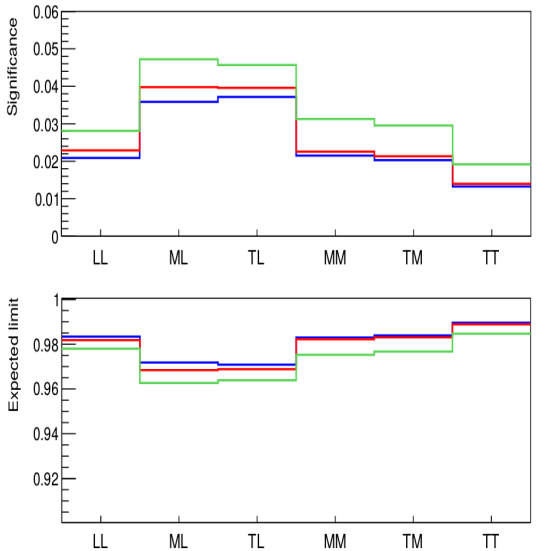
Back-Up


19.7 fb^{-1} (8 TeV) + 35.9 fb^{-1} (13 TeV)
CMS
Preliminary
95% CL on $\frac{\sigma_h}{\sigma_{SM}}$B(h→ aa)
2HDM+S type III
tanβ = 5.0
h→aa→μμμμ (8 TeV)
h→aa→ττττ (8 TeV)
h→aa→ττττ (8 TeV)
h→aa→μμbb (8 TeV)
h→aa→μμττ (8 TeV)
h→aa→μμττ (13 TeV)
h→aa→ττbb (13 TeV)
expected
observed
m_a (GeV)

Optimization procedure

- Based on *simulated background samples*
- Started with a *loosely* selected sample :
  - $p_T^{\mu} > 17(8)$ GeV,
  - $p_T^{jet} > 10$ GeV,
  - >= 2 loose b-jets
- Different FOM's used to cross check :
  - $s/\sqrt{(b)}, s/\sqrt{b+(\delta b)^2}, \sqrt{2((s+b)\ln(1+s/b)-s)}$
  - Expected limit based on counting signal and background yields in $|m_{\mu\mu}-m_a| < 5$ GeV
- Tried to have a uniform selection vs. m_a

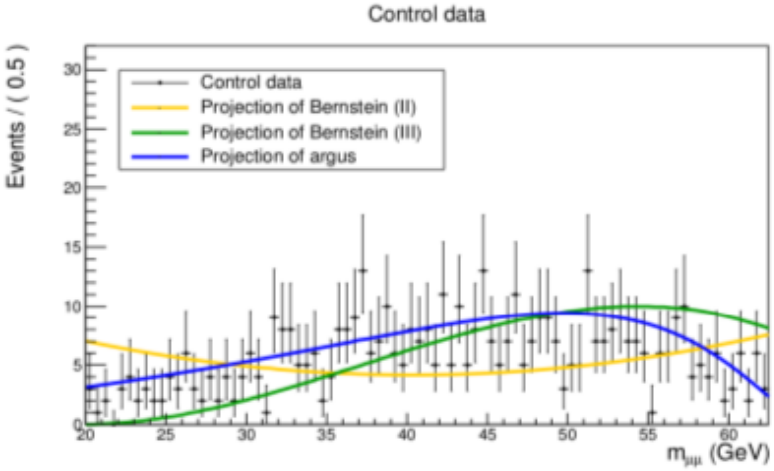




Functions for multipdf

- Different types of polynomials are checked on data in CR
  - RooPolynomial
  - RooBernstein (a particular polynomial with positive definite coefficients)
  - RooArgus
- An inverse polynomial is also introduced ($1/P_n$, *a la* Run I)
- An F-test is used to determine the collection of pdfs for each family
- The lowest degree is where the χ^2 / ndf is close to 1
  - Degrees are increased until Prob(-2ΔNLL, 1) < 0.05

Model	χ^2/ndf	F-test probability (> 0.05)	Decision
Bernstein II	1.001	–	✓
Bernstein III	0.948	0.149	✓
Bernstein IV	0.859	0.017	×



- RooPolynomial and $1/P_n$ never gave χ^2 / ndf ~1

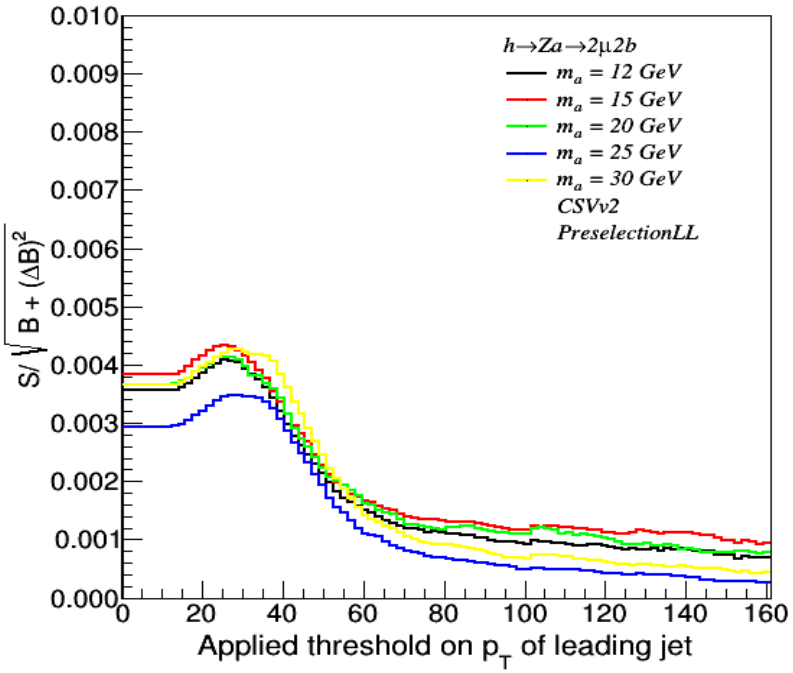
General strategy

- **Signal:**
  - Shape is assumed to remain unchanged
- **Background:**
  - Shape is taken from CR, assuming no change in categories
- **Two type of categorizations in signal region:**
  - MET < 30 & 30 < MET < 60 → *bkg yield from MC*
  - B-tagging criterion on Loose b-tagged jet → *bkg yield from CR (no MC stat.)*
    - TT, TMexc (medium, not tight), Tlexc (loose, not medium)
- **Expected limits** are evaluated and compared

Optimization

- **Based on simulated background samples**

- **Initially selected loose cuts on signal sample :**
  - **p_T^{μ} (leading) > 17 GeV**
  - **p_T^{μ} (sub-leading) > 8 GeV**
  - **p_T^{jet} (leading/sub-leading) > 10 GeV**
  - **both jets selected with loose b-tag discriminant**



- **Variable $s/\sqrt{b+(\delta b)^2}$ used, where δb is the statistical uncertainty from MC**

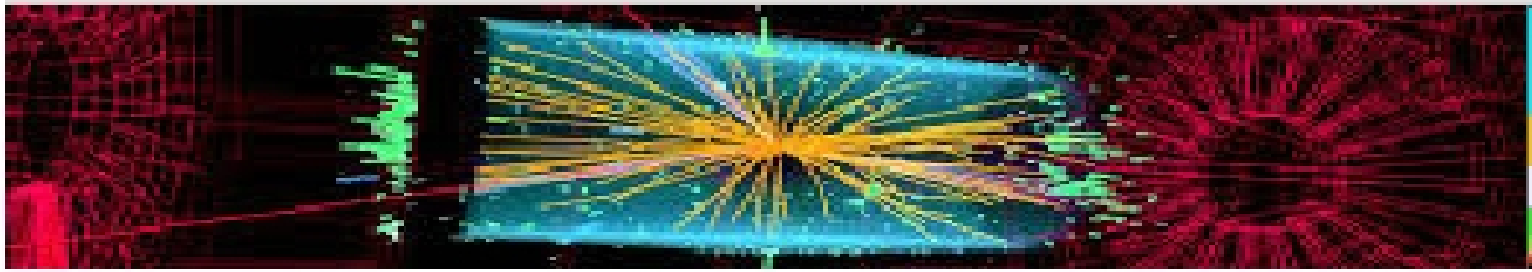
- **B-tag working points are used**

- **Pair of jets in the final state**

Various possible permutations

1) **Loose-Loose**
2) **Medium-Loose**
3) **Tight-Loose**
4) **Medium-Medium**
5) **Tight-Medium**
6) **Tight-Tight**

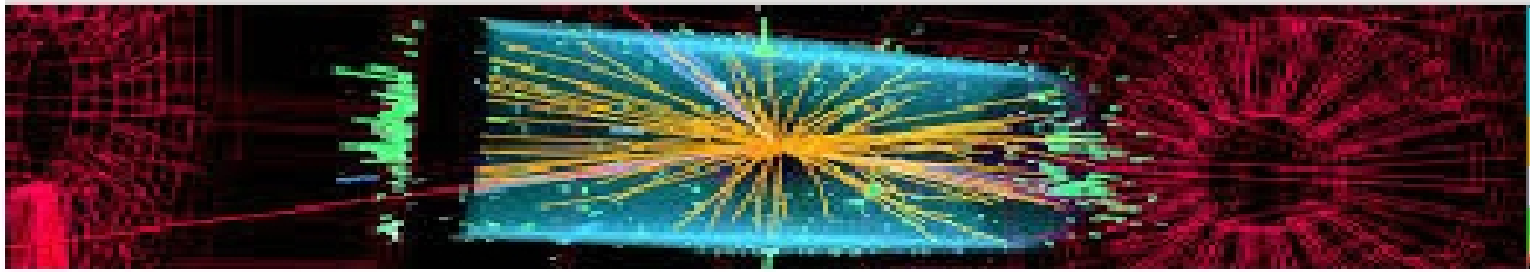
Significance estimated for each permutation for both the taggers (CSVv2 and DeepCSV)



ATLAS Summary

Table 1: Summary of the event selection of the different analyses described in this paper. The quarkonia resonance masses $m_{J/\Psi}$, $m_{\Psi(2S)}$, $m_{\Upsilon(1S)}$, and $m_{\Upsilon(3S)}$ are taken from Ref. [73].

	$H \to ZX \to 4\ell$ (15 GeV $< m_X <$ 55 GeV)	$H \to XX \to 4\ell$ (15 GeV $< m_X <$ 60 GeV)	$H \to XX \to 4\mu$ (1 GeV $< m_X <$ 15 GeV)
Quadruplet selection	- Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-sign leptons - Three leading-p_T leptons satisfying $p_T >$ 20 GeV, 15 GeV, 10 GeV - At least three muons are required to be reconstructed by combining ID and MS tracks in the 4μ channel		
	- Select best quadruplet (per channel) to be the one with the (sub)leading dilepton mass (second) closest to the Z mass - 50 GeV $< m_{12} <$ 106 GeV - 12 GeV $< m_{34} <$ 115 GeV - $m_{12,34,14,32} >$ 5 GeV	Leptons in the quadruplet are responsible for firing at least one trigger. In the case of multi-lepton triggers, all leptons of the trigger must match to leptons in the quadruplet	
	$\Delta R(\ell, \ell') > 0.10$ (0.20) for same-flavour (different-flavour) leptons in the quadruplet		-
Quadruplet ranking	Select first surviving quadruplet from channels, in the order: 4μ, $2e2\mu$, $2\mu2e$, $4e$	Select quadruplet with smallest $\Delta m_{\ell\ell} = \lvert m_{12} - m_{34} \rvert$	
Event selection	115 GeV $< m_{4\ell} <$ 130 GeV		120 GeV $< m_{4\ell} <$ 130 GeV
		$m_{34}/m_{12} > 0.85$ Reject event if: $(m_{J/\Psi} - 0.25$ GeV$) < m_{12,34,14,32} < (m_{\Psi(2S)} + 0.30$ GeV$)$, or $(m_{\Upsilon(1S)} - 0.70$ GeV$) < m_{12,34,14,32} < (m_{\Upsilon(3S)} + 0.75$ GeV$)$	
		10 GeV $< m_{12,34} <$ 64 GeV $4e$ and 4μ channels: 5 GeV $< m_{14,32} <$ 75 GeV	0.88 GeV $< m_{12,34} <$ 20 GeV No restriction on alternative pairing



Signal Model

- **Signal Shape derived from simulation**
- **Combination of Voigtion and a Crystal ball profiles**

$$SignalModel \quad S\left(m_{\mu\mu}|f,p_V,p_{CB}\right) \equiv f.V\left(m_{\mu\mu}|p_V + (1-f).CB\left(m_{\mu\mu}|p_{CB}\right)\right)$$

$$Where, \quad VoigtionFunction \quad V\left(m_{\mu\mu}|p_V\right) \equiv V\left(m_{\mu\mu},\sigma,\gamma\right) = G\left(m_{\mu\mu},\sigma,m_a\right) * L\left(m_{\mu\mu},\gamma,m_a\right)$$

$$Where \quad G\left(m_{\mu\mu},\sigma,m_a\right) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{\left(m_{\mu\mu}-a\right)^2}{2\sigma^2}}$$

$$L\left(m_{\mu\mu},\gamma,m_a\right) = \frac{\gamma}{\pi\left(\left(m_{\mu\mu}-m_a\right)^2+\gamma^2\right)}$$

$$CrystallBallFunction \quad CB\left(m_{\mu\mu}|p_{CB}\right) \equiv CB\left(m_{\mu\mu},n,\sigma_{CB},\alpha,m_a\right) = N.e^{-\left(m_{\mu\mu}-m_a\right)^2/2\sigma_{CB}^2} \quad for \quad \frac{m_{\mu\mu}-m_a}{\sigma_{CB}} > -\alpha$$

$$N.\left(A.\left(B-\frac{m_{\mu\mu}-m_a}{\sigma_{CB}}\right)^{-n}\right) \quad for \quad \frac{m_{\mu\mu}-m_a}{\sigma_{CB}} \leqslant -\alpha$$