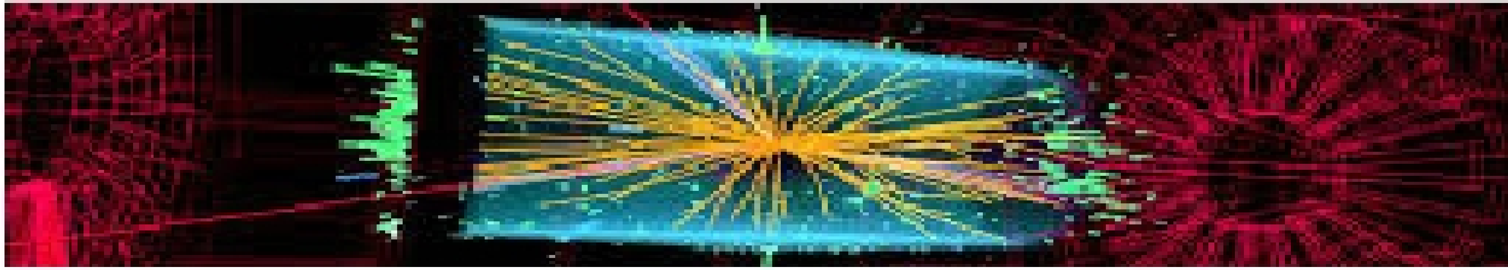
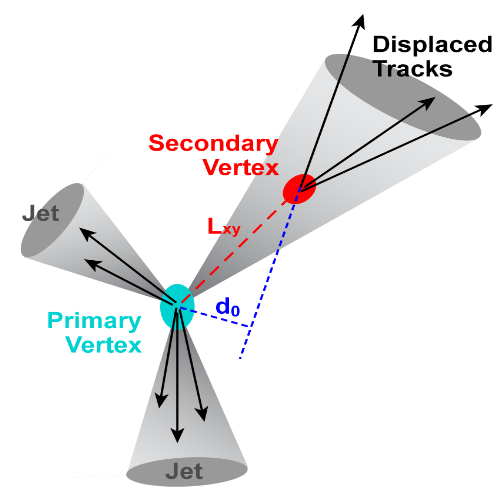


Search for Higgs boson decaying to a pair of new light bosons in the final state with pair of muons and b-quarks at √s = 13 TeV

($h \rightarrow aa \rightarrow \mu\mu bb$)



By

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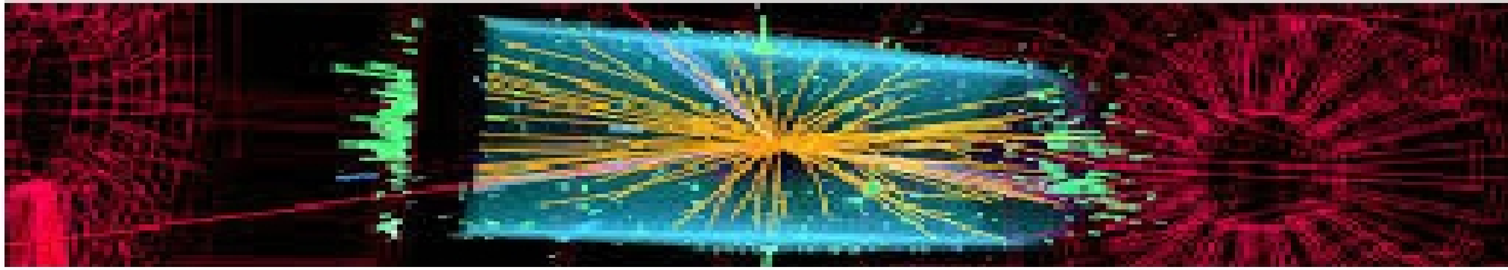
University of Delhi, India

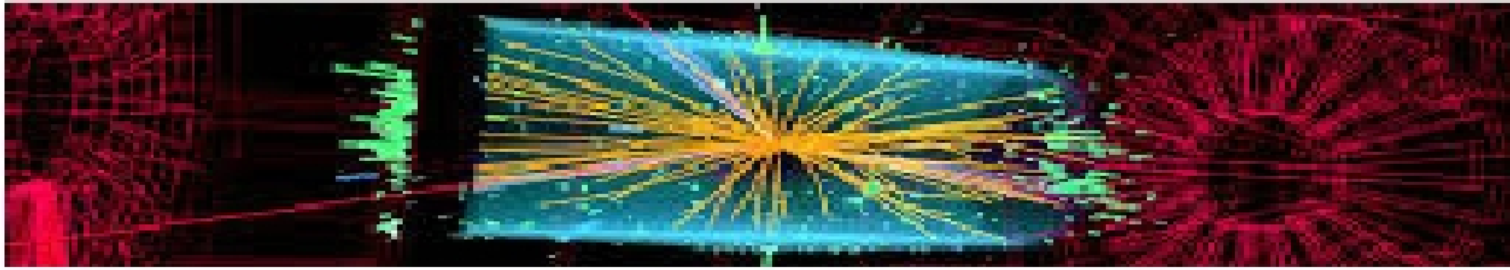
On behalf of the CMS Collaboration

XXIII DAE-BRNS High Energy Physics Symposium, IIT Madras, Dec 10-14,. 2018



Outline

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



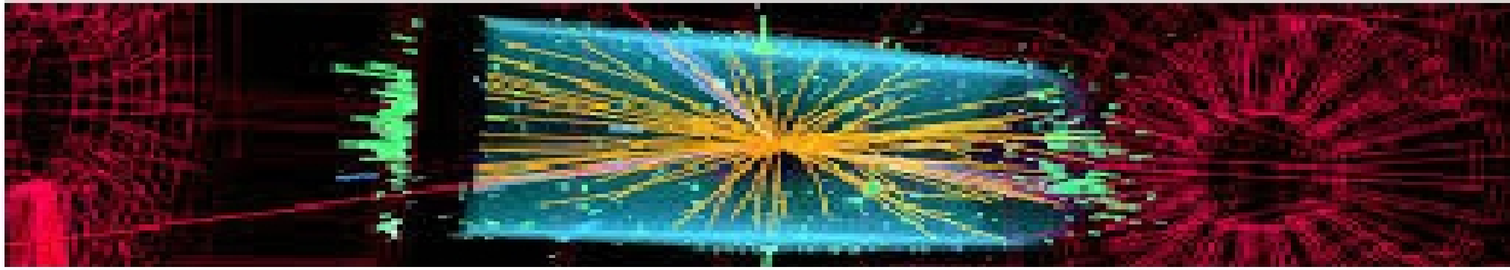
Why low mass?

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, $H^{\pm}$**
  - **compatible with a 125 GeV SM-like scalar (h or H) + a light Higgs Boson (a)**

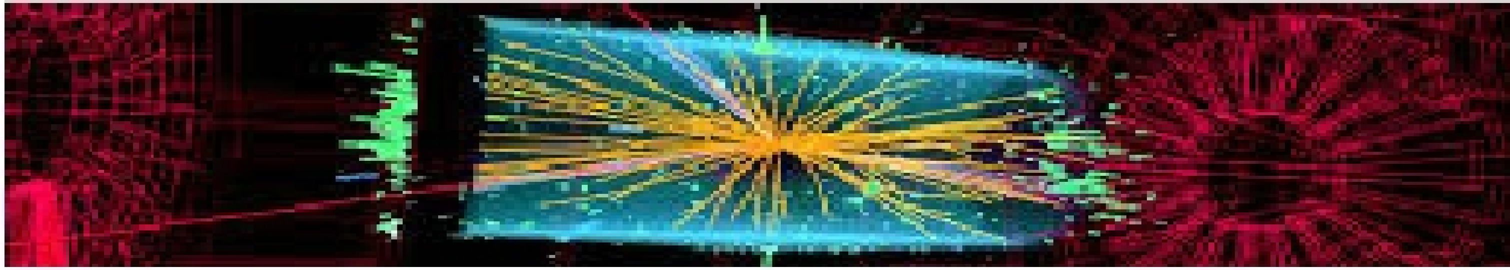
- **2HDM+S:**
  - **Special case NMSSM**
  - **2Higgs doublets + 1 singlet → 7 Higgs bosons : h_1 , h_2 , h_3 , a_1 , a_2 , $H^{\pm}$**
  - **Compatible with a 125 GeV SM-like scalar (h_1 or h_2) + a mostly "singlet-like" light Higgs Boson (a_1 or h_1)**



CMS low-mass searches

Exotic decays of Higgs Boson, $h \rightarrow aa$ are searched in various final states:

- **$\mu\mu\tau\tau$, $bb\tau\tau$, (CMS PAS HIG-17-029, CMS PAS HIG-17-024)**
- **$\mu\mu\mu\mu$, bbbb, $\tau\tau\tau\tau$ (Ongoing)**
- **$\mu\mu$bb, CMS PAS HIG-18-003**

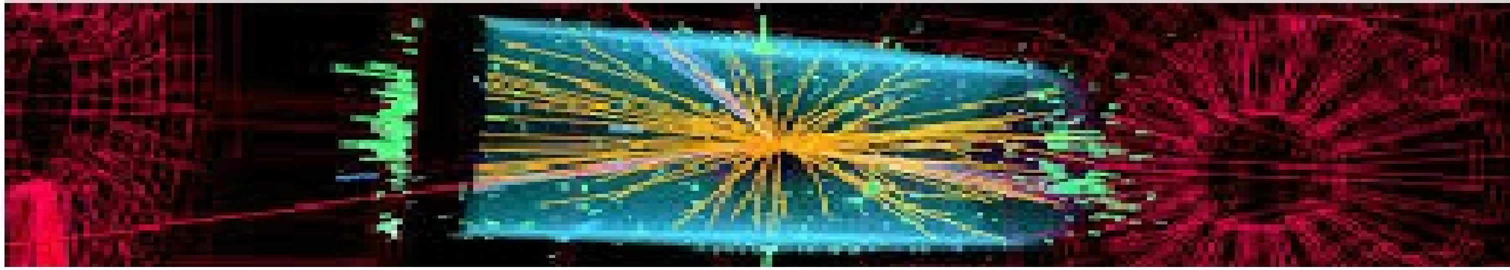


CMS low-mass searches

why μμbb final state?

- 4b final state expected to occur with higher number of events but has challenging backgrounds
- 4μ final state clean but very rare
- μμbb final state compromise between bbbb and μμμμ states
    - a→μμ has a clear peak
    - a→bb: large BR in many parts of the parameter space
- Particularly very large in the context of the NMSSM [1]
- Search may provide better sensitivity in the long run [2]

[1] Phy. Rev. D 90, 075004 (2014)
[2] JHEP 1308 (2013) 019, [arXiv:1303.2113]



Simulated Signal Samples

Mass range, $20 < m_a < 62.5$ GeV

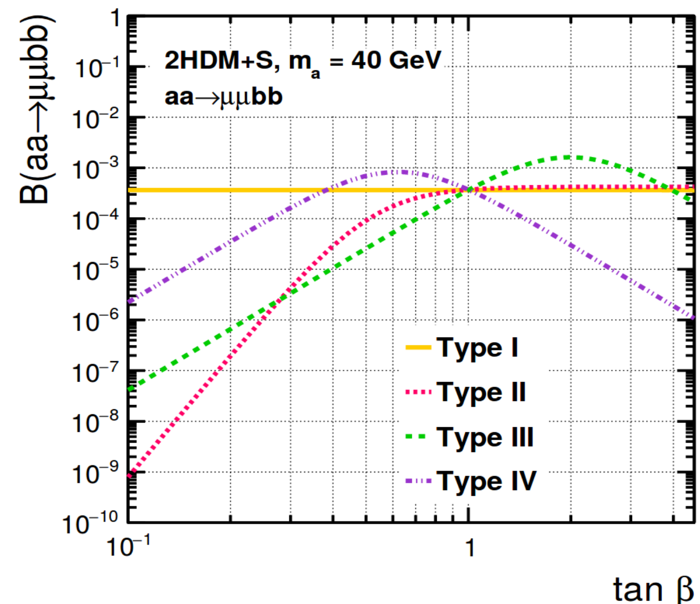
Model Used

- 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($h \rightarrow aa$) = 10%
- BR($aa \rightarrow \mu\mu bb$) = 1.7×10^{-3} in 2HDM+S Type 3 *{Predicted as per [Ref]}*

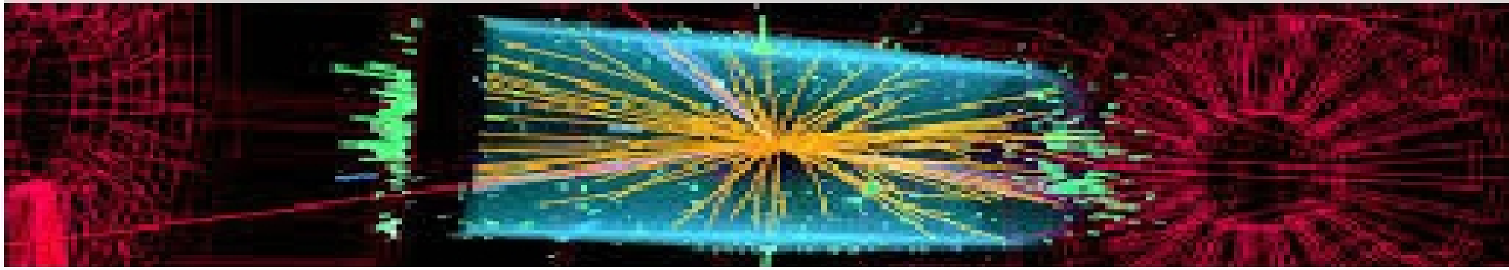
To estimate the contribution from $\mu\mu\tau\tau$ and $\tau\tau bb$, samples with $\mu\mu\tau\tau$ and $\tau\tau bb$ final state were also generated



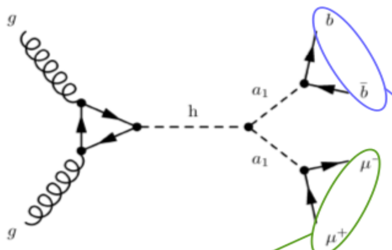
[Ref] D. Curtin et al., Phys. Rev. D 90 (2014) 075004

Sample name (Process)	"a" mass (GeV) points Simulated
$h \rightarrow aa \rightarrow 2\mu 2b$ (ggF)	20, 25, 30, 35, 40, 45, 50, 55, 60
$h \rightarrow aa \rightarrow 2\mu 2b$ (VBF)	20, 30, 40, 60
$h \rightarrow aa \rightarrow 2b 2\tau$ (ggF)	20, 30, 60
$h \rightarrow aa \rightarrow 2\mu 2\tau$ (ggF)	20, 30, 60

Dataset-2016



Preselection and Optimization



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

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

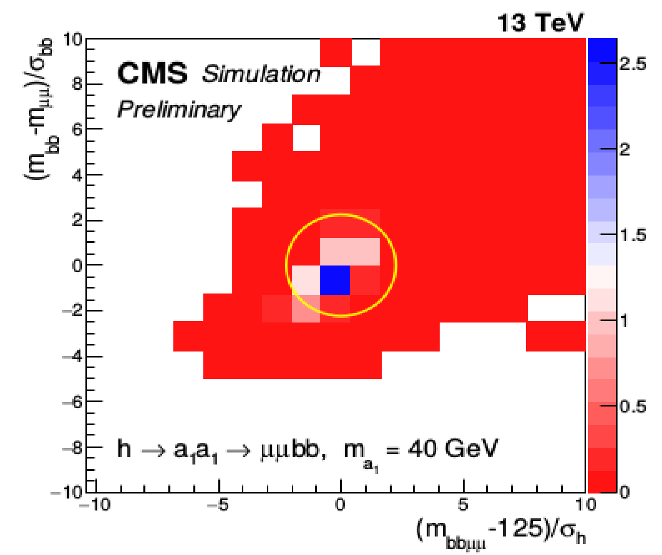
At least one good primary vertex

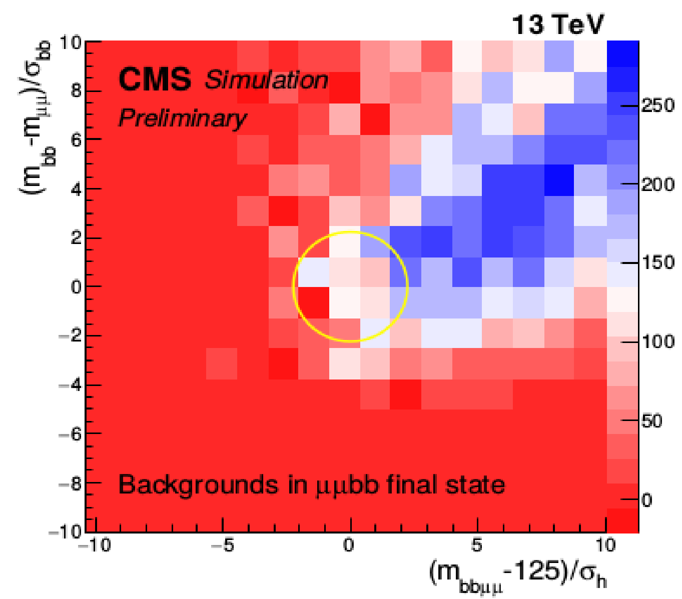
At least two jets :
- Pt > 20/15 GeV (Optimized)
- |η| < 2.5
- ΔR(μ, jet) > 0.4
- b-tagging CSVv2 :
  - One loose/One tight(Optimized)

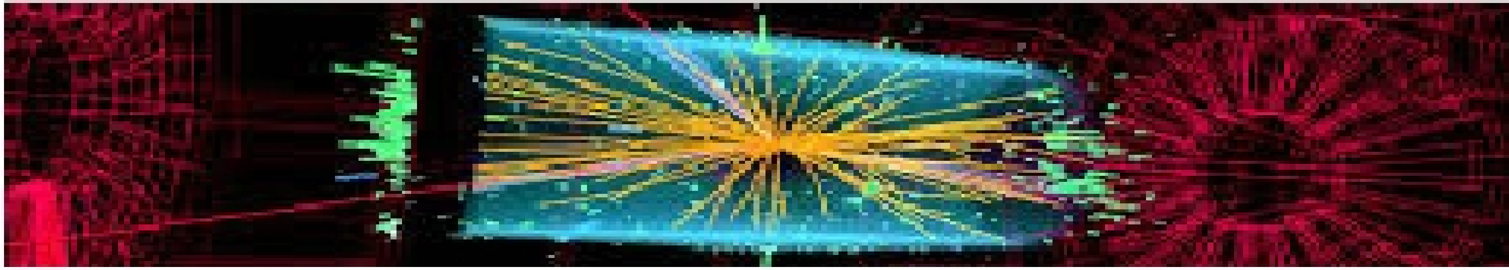
Additional Optimization:

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

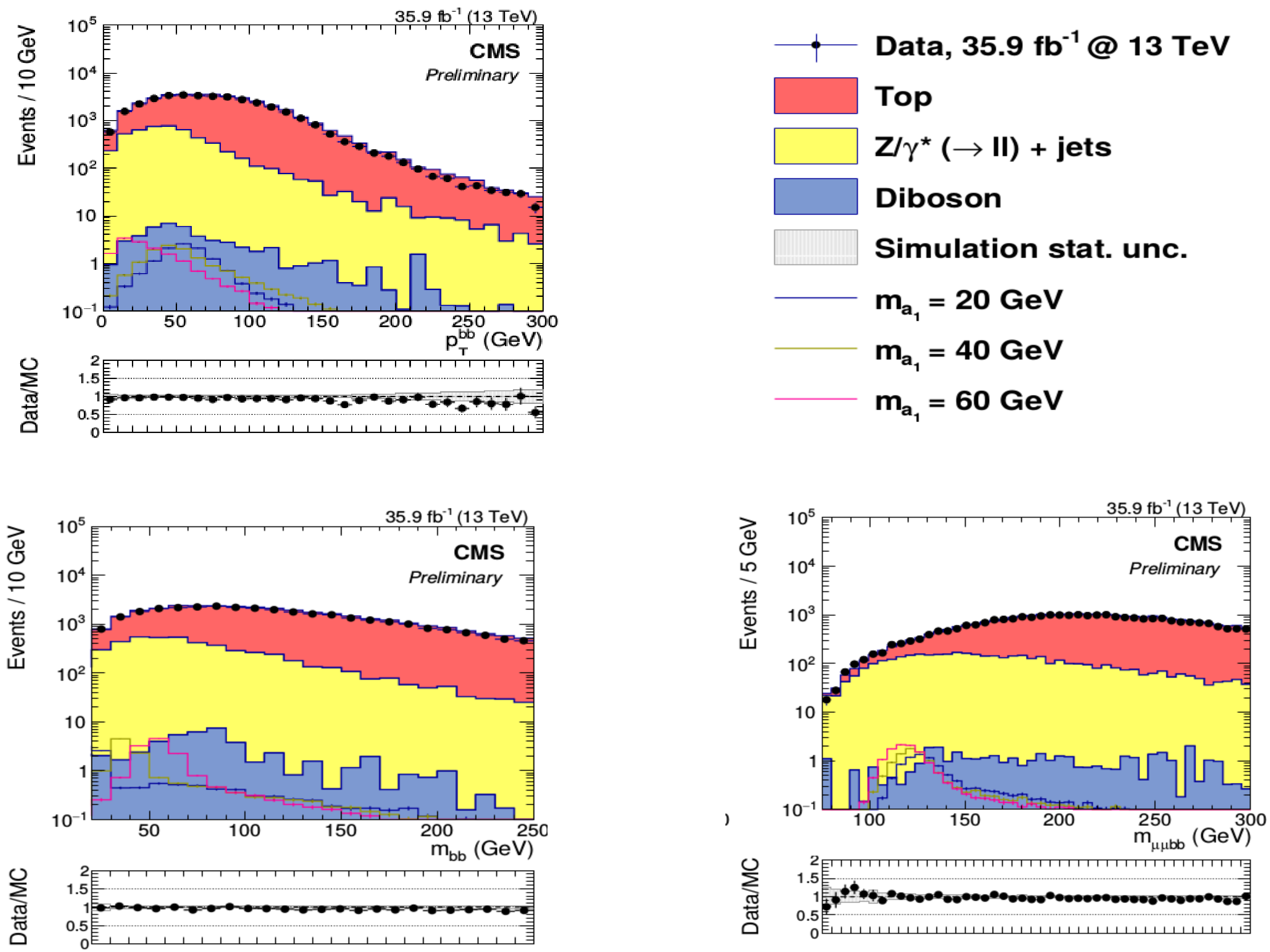
$$\chi^2_{total} = \frac{(m_{bb} - m_{\mu\mu})^2}{\sigma^2_{bb}} + \frac{(m_{\mu\mu bb} - 125)^2}{\sigma^2_h}$$

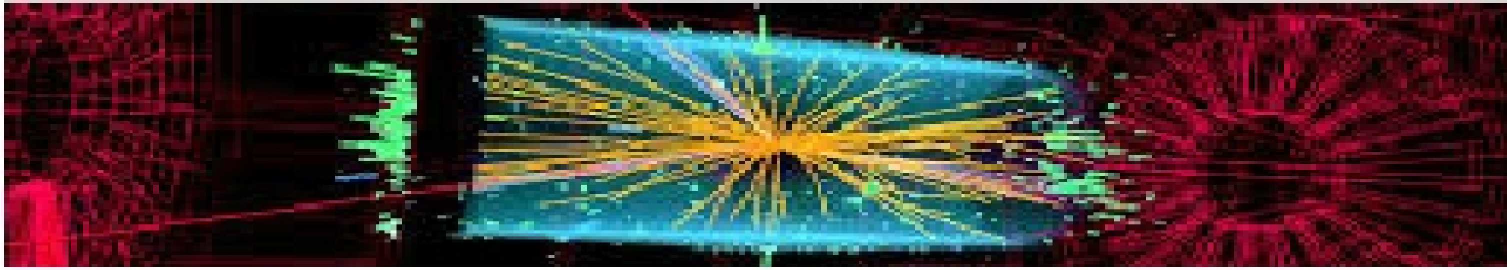






Distributions at Preselection





Signal and Background Yields

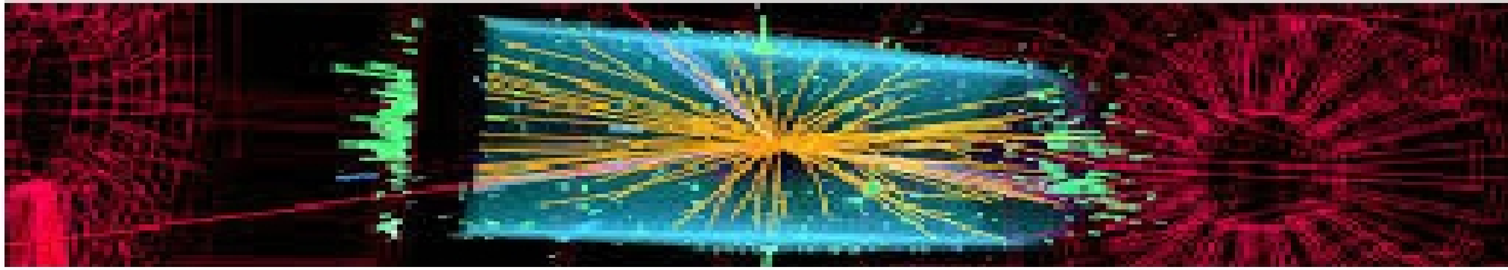
Process	$\mu^+\mu^-b\bar{b}$ selection	Final selection
Top ($t\bar{t}$, single top quark)	33730 ± 120	198 ± 9
Drell–Yan	5237 ± 77	399 ± 21
Diboson	51 ± 4	1 ± 0.1
Total expected background	39015 ± 140	598 ± 23
Data	36360	610
Signal for $\sigma_h \times \mathcal{B} \approx 8$ fb		
$m_{a_1} = 20$ GeV	14.0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



Signal Model

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

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

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

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

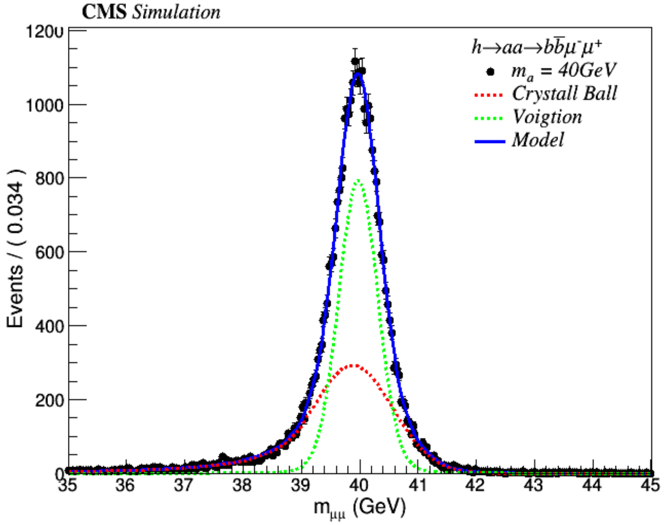
$$L(m_{\mu\mu},\gamma,m_a) = \frac{\gamma}{\pi\left((m_{\mu\mu}-m_a)^2+\gamma^2\right)}$$

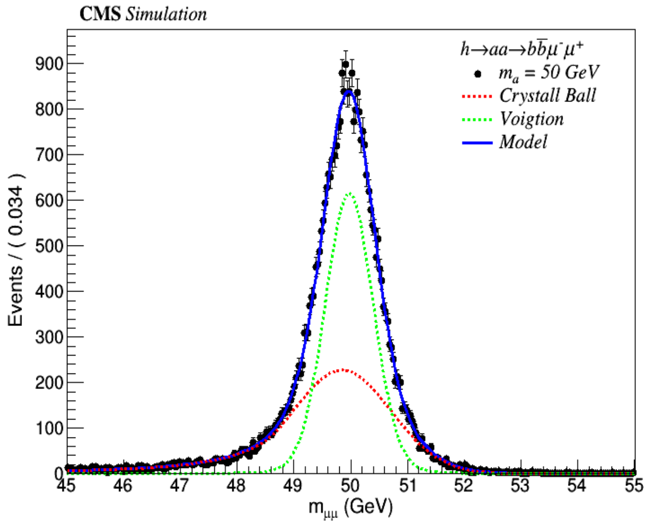
$$\textit{CrystallBallFunction}\quad CB(m_{\mu\mu}|p_{CB}) \equiv CB(m_{\mu\mu},n,\sigma_{CB},\alpha,m_a) = N.e^{-(m_{\mu\mu}-m_a)^2/2\sigma_{CB}^2}\quad \textit{for}\quad \frac{m_{\mu\mu}-m_a}{\sigma_{CB}} > -\alpha$$

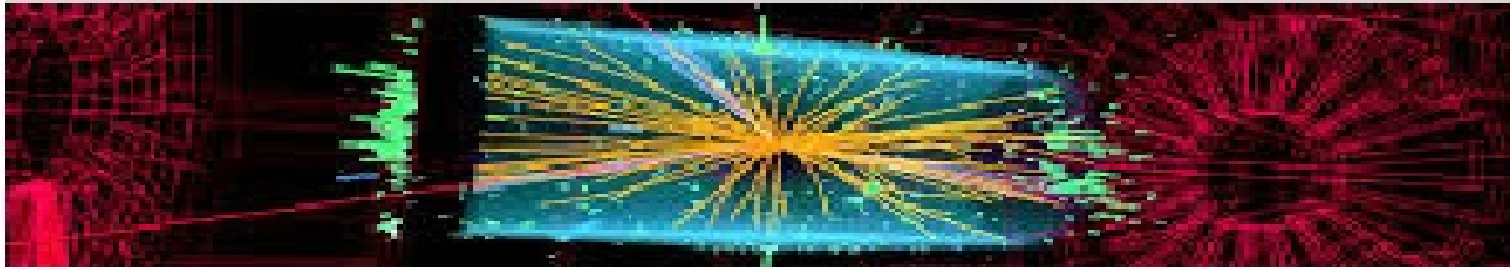
$$N.\left(A.\left(B-\frac{m_{\mu\mu}-m_a}{\sigma_{CB}}\right)^{-n}\right)\quad \textit{for}\quad \frac{m_{\mu\mu}-m_a}{\sigma_{CB}} \leqslant -\alpha$$

Resolutions have been expressed as:

$$\sigma_V = \sigma_{V,0} + \alpha\, m_{\mu\mu},$$
$$\sigma_{cb} = \sigma_{cb,0} + \beta\, m_{\mu\mu}.$$



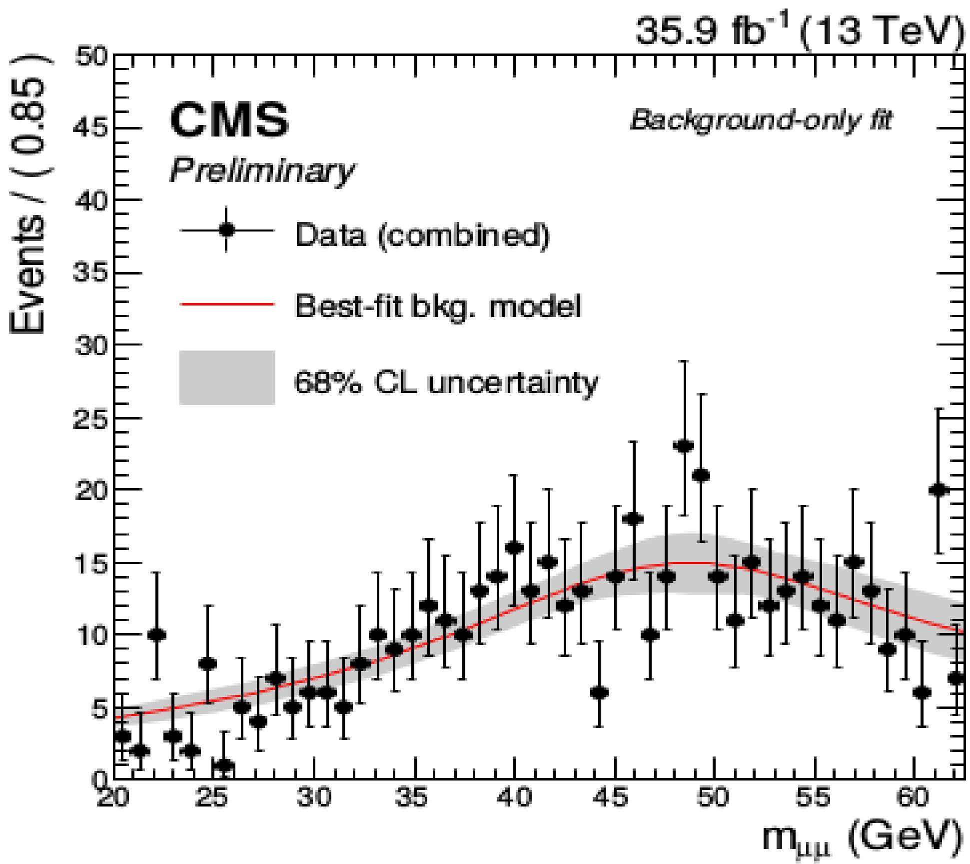


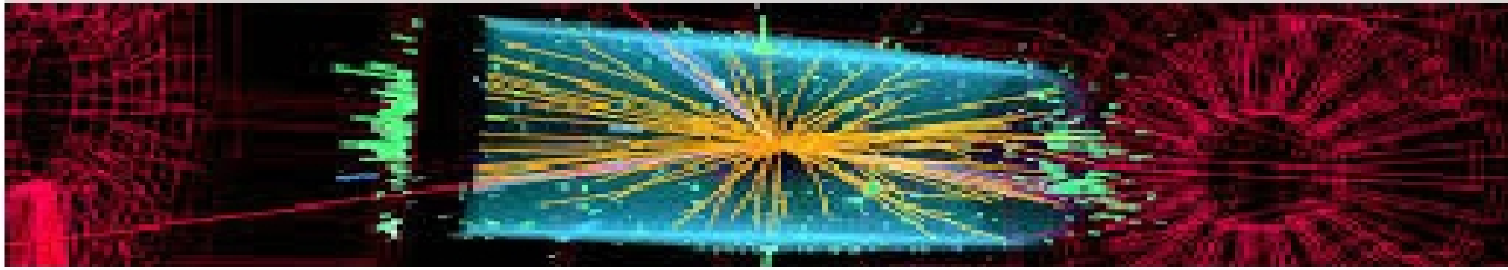


Background Model

Trial functions to model background

The TLexc category			
Model	χ^2/ndf	F-test probability (> 0.05)	Decision
Polynomial III	0.95	–	✓
Polynomial IV	0.91	0.15	✓
Polynomial V	0.80	0.15	✓
Polynomial VI	0.77	0.03	×
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	×





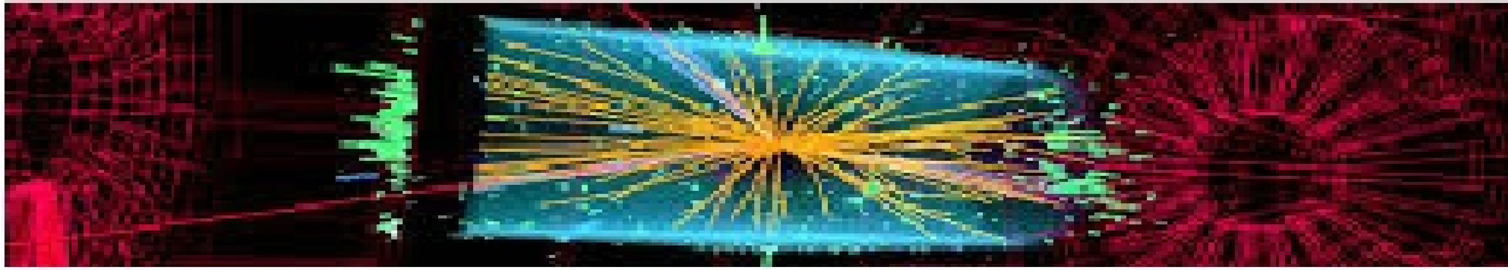
Systematics Uncertainties

Background

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

Signal

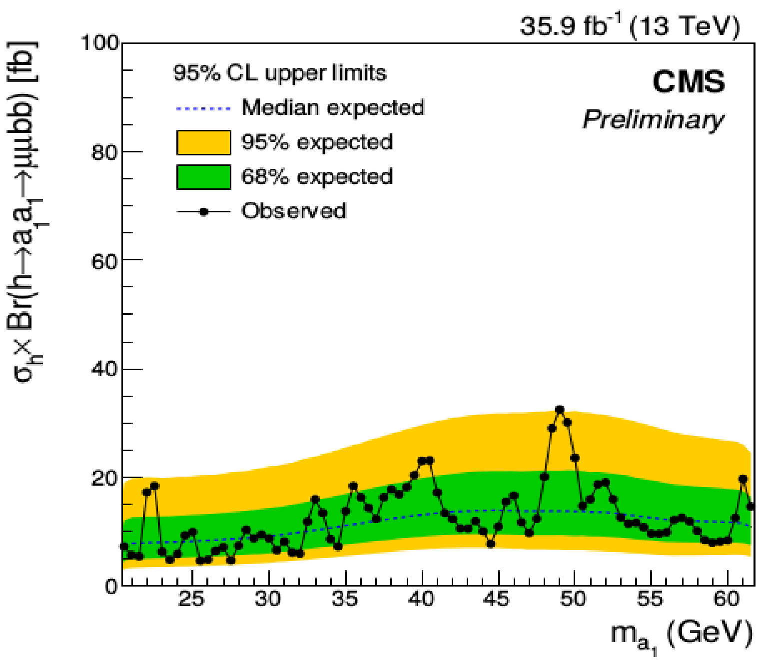
- Signal normalization is affected by various sources of systematic uncertainties:
  - σ_h : ±3.6%, considered for the limit on BR
  - Luminosity: ±2.5%
  - Pileup: ±4.6% on the $\sigma_{pp}^{inelastic}$
  - μ, ID, Iso, HLT scale factors: doubled for p_T < 20 GeV
  - JES: p_T and η dependent corrections applied on jets and propagated to E_t^{miss}
  - JER
- b-tagging: different sources affecting the shape calibration are considered and are doubled for low p_T jets

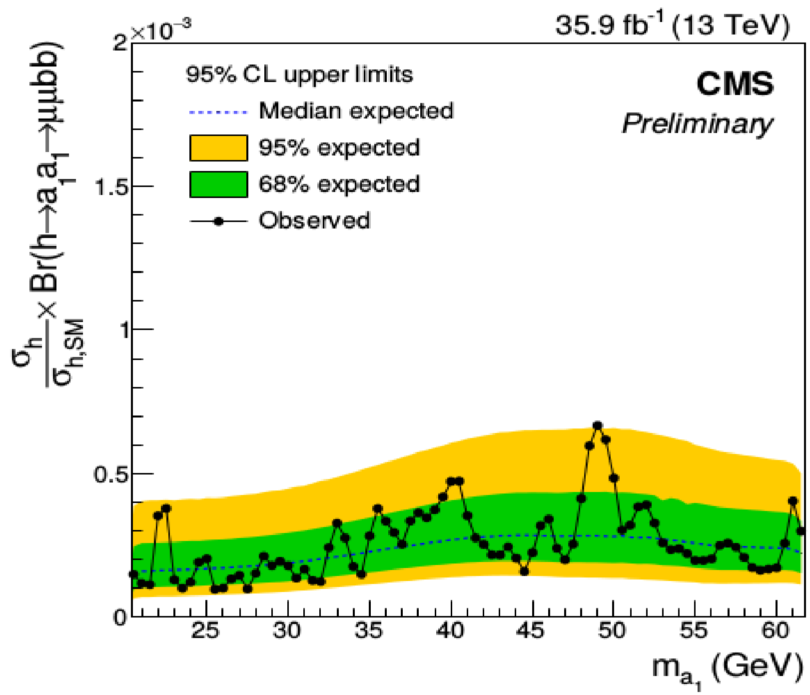


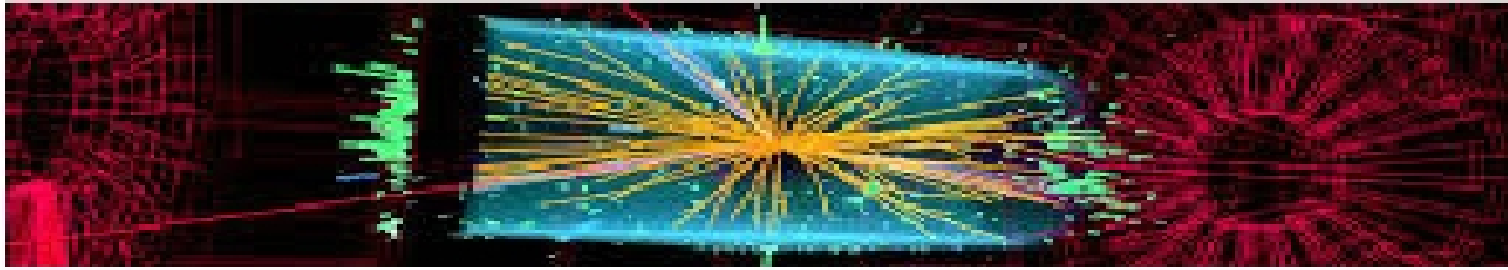
Results

Expected and observed limits

- **Assuming the SM prediction of σ_h**
- **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**







Summary

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

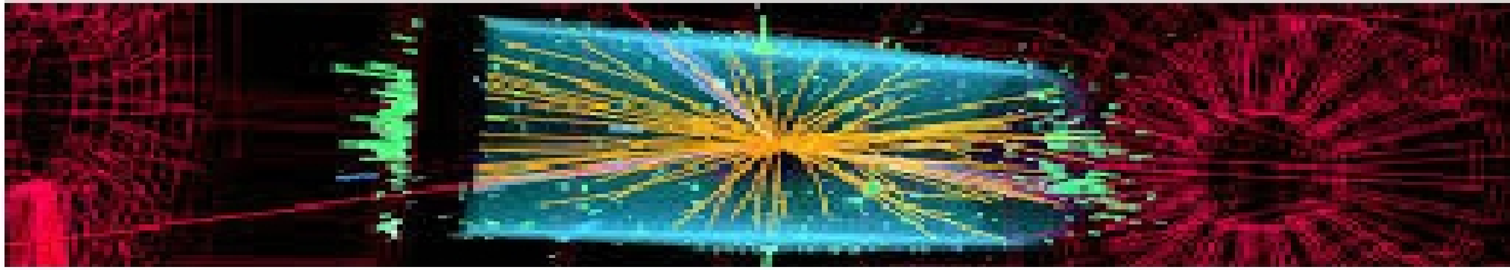
Search for exotic Higgs decay in μμbb final state has been presented

- **Present talk covered only 2016 data set**
- **The VBF μμbb signal is also included and does not have much impact on significance**
- **Contribution from μμττ and bbττ signals is observed to be very small.**
- **No excess is found over the SM backgrounds**
- **Upper limits are reported on BR(h→aa→μμbb)**

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



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Present and future Work:

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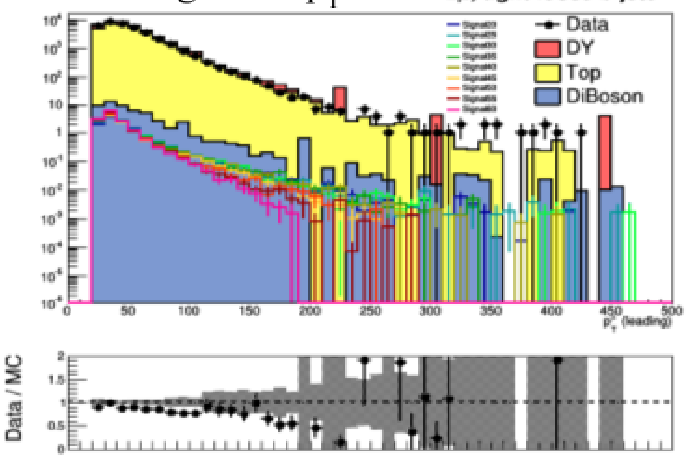
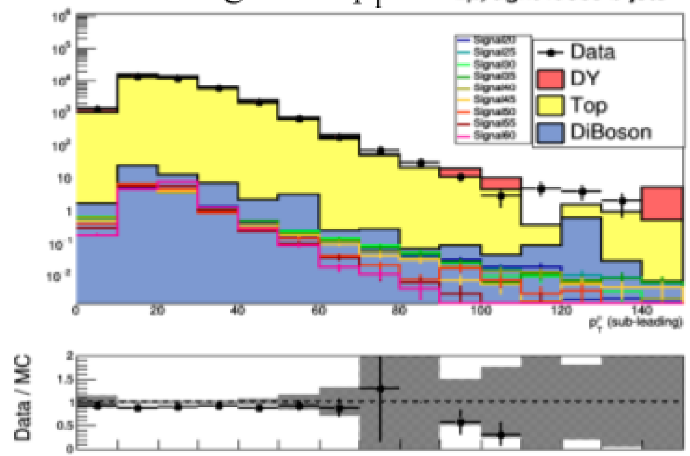
Thank You

Distributions at preselection

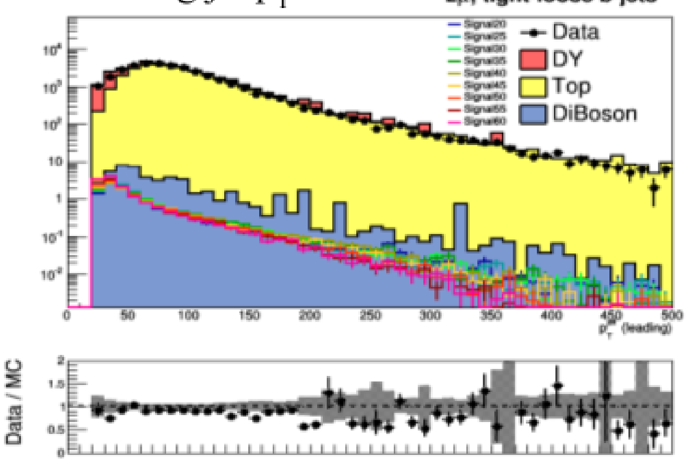
Leading muon p_T



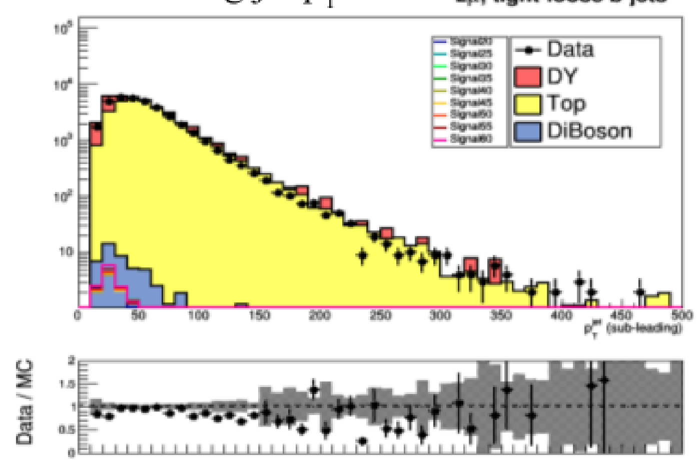
Subleading muon p_T

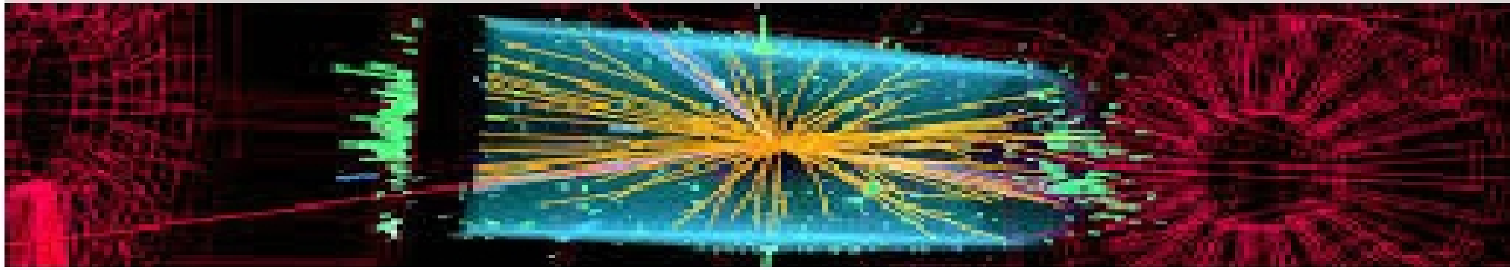


Leading jet p_T



Subleading jet p_T

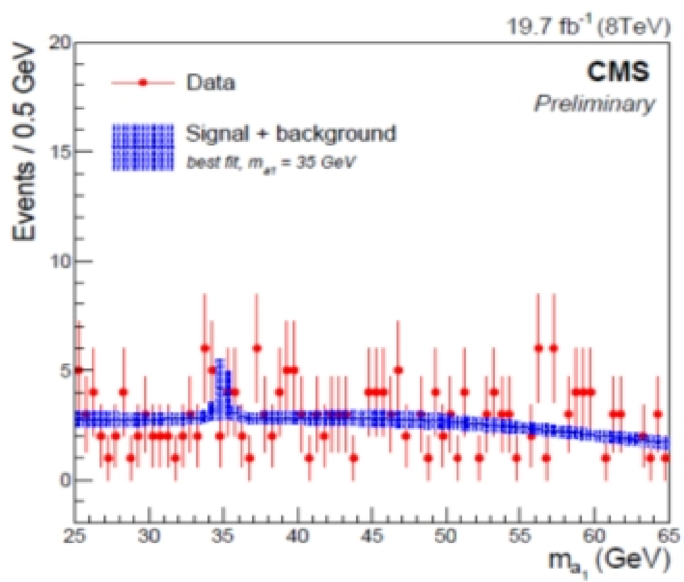


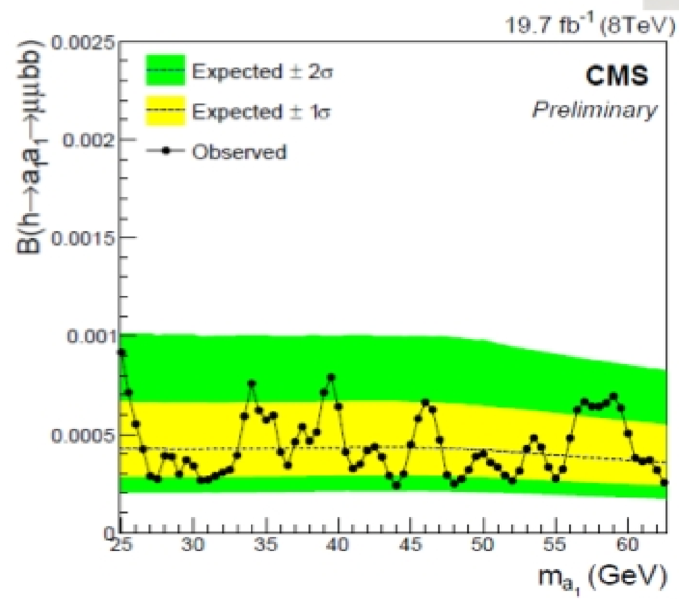


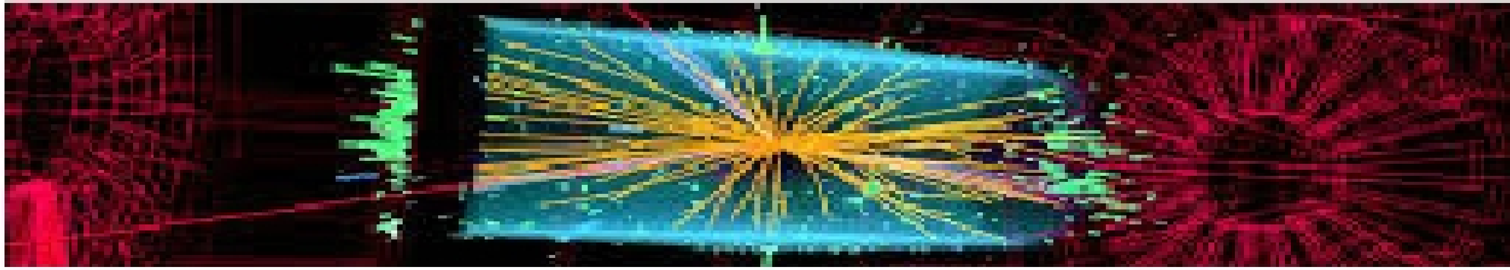
Back-Up

$h_{125} \to aa \to \mu\mu b\bar{b}$ CMS-HIG-14-041

- NMSSM : $BR(h_1 \to a_1 a_1 \to \mu\mu b\bar{b})$ up to $\sim 2.10^{-3}$
- Range [25,65] GeV
- Fit in $m_{\mu\mu}$ distribution
- Exclude pseudoscalars with $BR(h \to a_1 a_1 \to \mu\mu b\bar{b})$ above 10^{-3}

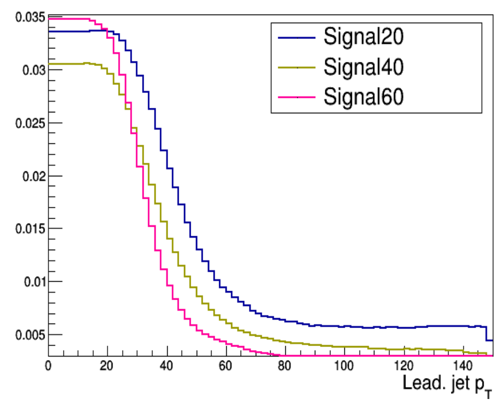


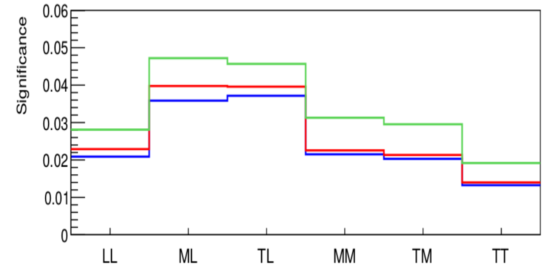


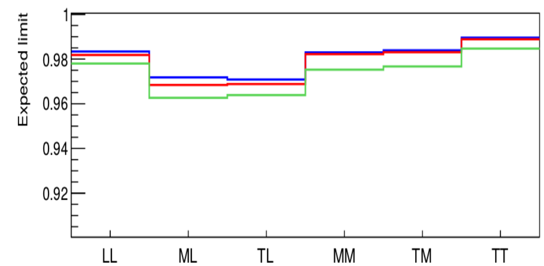


Optimization procedure

- 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



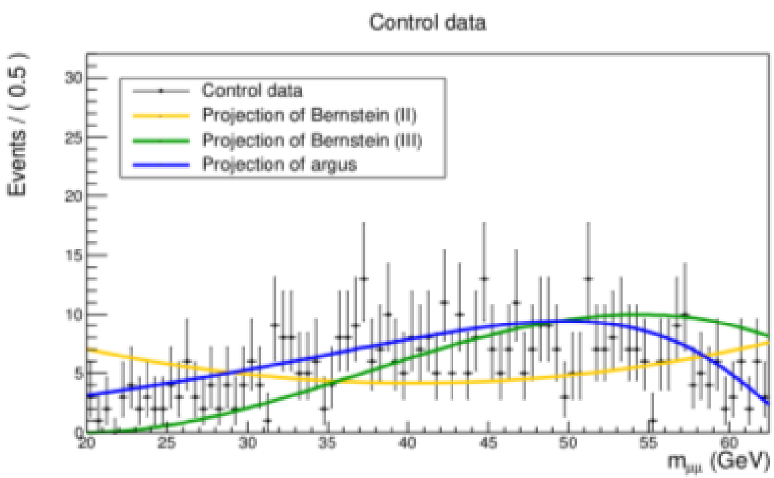




Functions for multipdf

- 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

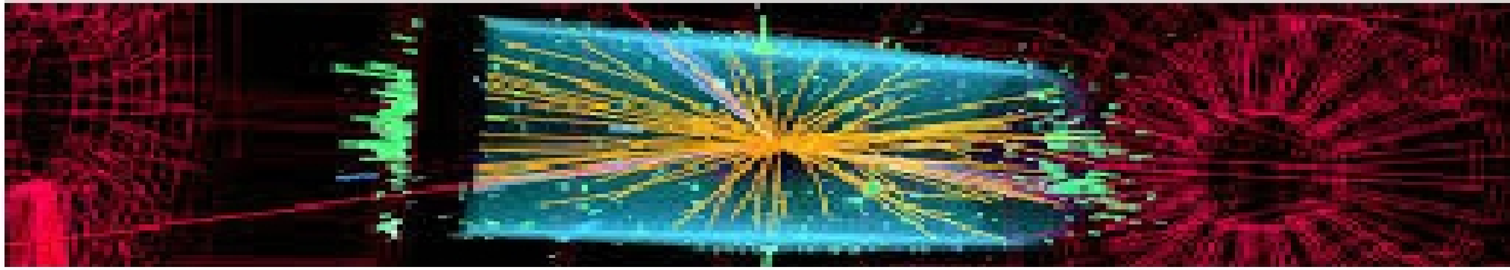
General strategy

- **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)

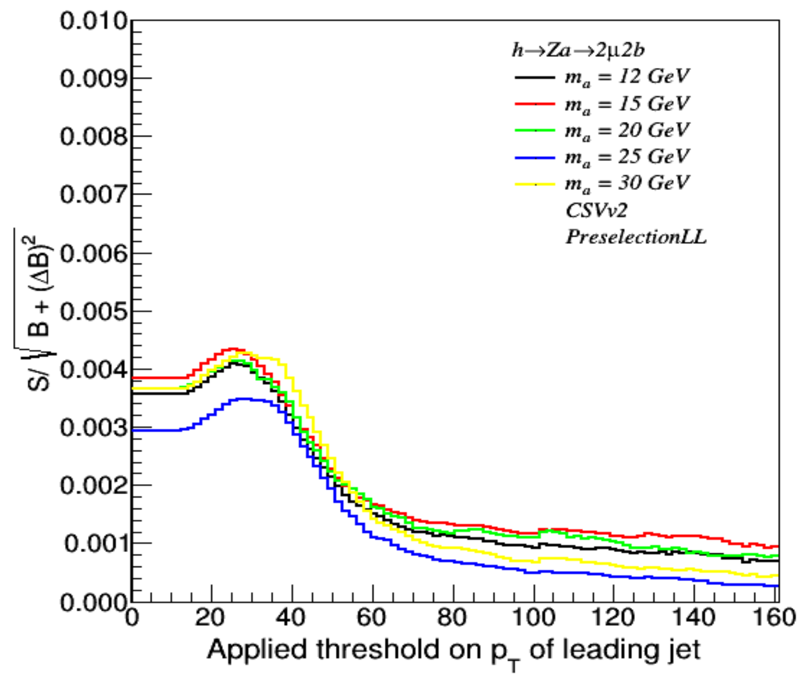
- **Expected limits** are evaluated and compared



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**

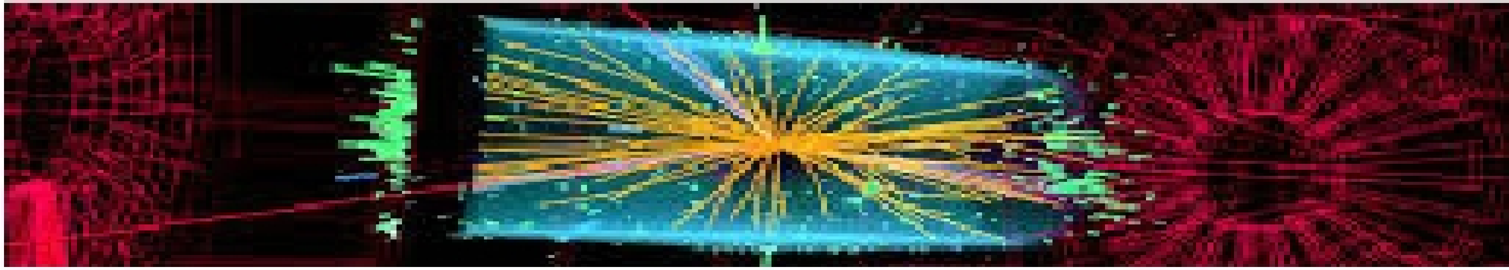
- **B-tag working points are used**

- **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