Search for a heavy Higgs boson decaying into a Z boson and another heavy Higgs boson in the $\ell\ell bb$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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Reasons for BSM Physics

Unanswered questions:

1. Supersymmetry
2. Dark matter
3. Axions and the Strong CP Problem
4. Electroweak baryogenesis
5. Neutrino masses and mixings
6. Hierarchy problem

indicate that physics beyond SM must exist.
The Two-Higgs-doublet model (2HDM) is one of the simplest extensions of the SM.

Higgs Field (SM)

The Higgs field is a four-component scalar field, with two neutral and two electrically charged components that form a complex doublet of the weak isospin $SU(2)$ symmetry.

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^1 + i\phi^2 \\ \phi^0 + i\phi^3 \end{pmatrix} \tag{1}$$

SM uses only 2 parameters:

- $m_h \approx (125.18 \pm 0.16)\,\mathrm{GeV}/c^2$, the higgson mass
- $v \approx 246.22\,\mathrm{GeV}$, its vacuum expectation value

and the potential is:

$$V = \mu^2\phi^\dagger + \frac{1}{2}\lambda(\phi^\dagger\phi)^2 \tag{2}$$

Two Higgs Double Model (2HDM)

It contains two Higgs doublets instead of just one, with five physical scalar states:

- the CP even neutral Higgs bosons h and H (with $m_H > m_h$)
- the CP odd pseudoscalar A
- two charged Higgs bosons $H^{\pm}$

The discovered higgson is strongly hinted to be CP even so it is likely they can be mapped either h or H.
This leads to a richer phenomenology.

2HDM Parameter Space

The 2HDM potential can be generically writen as:

$$V = m_{11}^2\phi_1^\dagger\phi_1 + m_{22}^2\phi_2^\dagger\phi_2 - (m_{12}^2\phi_1^\dagger\phi_2 + H.C.) + V_{model}$$

where V_{model} depends on the specific 2HDM type and the m_{12} factor is called the 2HDM parameter.

Such a model can be described via six physical parameters:

- $m_h, m_H, m_A, m_{H^\pm}$: four Higgs masses
- $\tan\beta = \frac{v_1}{v_2}$: the ratio of the two doublets vacuum expectation values; it also represents rotation angle which diagonalizes the mass-squared matrices of the charged scalars and of the pseudoscalars
- α: the mixing angle which diagonalizes the mass matrix of the neutral CP even Higgses.

Special cases

The two parameters α and β determine the interactions of the various Higgs fields with the vector bosons and (given the fermion masses) with the fermions:

1. $\cos(\beta - \alpha) \to 0$, the *alignment limit*:
   - the lighter CP even Higgs boson h has couplings exactly like the SM-Higgs boson
   - the heavier H couples to just fermions ("gauge-phobic")
2. $\sin(\beta - \alpha) \to 0$:
   - the heavier CP even boson, and H is SM-like
   - leaving h to be the lighter than the discovered Higgs, and it couples just to gauge bosons ("fermio-phobic")

but not both.

2HDM solutions for (some of) the unanswered questions

- Supersimmetry requires at least two Higgs doublets:
  eg. the Minimal Supersymmetric Standard Model (MSSM)
- Axion models: possible CP-violating term in the QCD Lagrangian, can be rotated away if the Lagrangian contains a global U(1) symmetry.
  Imposing this symmetry requires two Higgs doublets.
- Baryon asymmetry: 2HDM has a scalar mass spectrum flexibility and additional sources of CP violation, either explicit or spontaneous

Guiding principles

The key method to distinguish between these different models involves a study of:

- particles' interactions ("coupling")
- exact decay processes ("branching ratios")

which can be measured and tested experimentally in particle collisions.

LHC Searches

There have been many searches for the heavy neutral Higgs bosons of the 2HDM at the LHC:

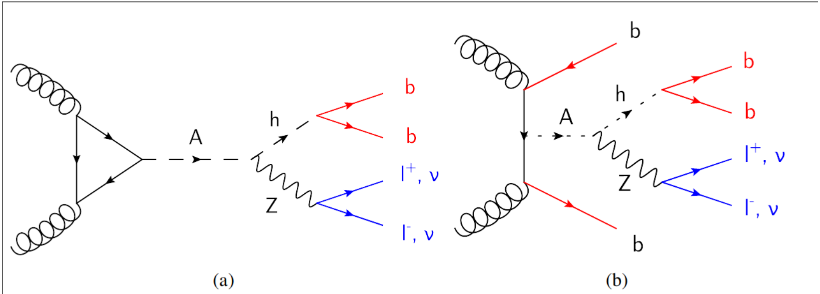
1. $H \to WW/ZZ$
2. $A \to ZH$
3. $H \to hh$
4. $A/H \to \tau\tau/bb$ [14–16]

Production channels (1)

- For large parts of the 2HDM parameter space, the dominant CP-odd Higgs boson decay channel is $A \to ZH$.
- This search for $A \to ZH$ decays uses proton–proton collision data at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 36.1 fb^{1} recorded by the ATLAS detector at the LHC.

Production channels (2)

The production of the A boson in the relevant 2HDM parameter space proceeds mainly through:



Channel selection

The search considers only:

- $Z \to \ell\ell$, where $\ell = e, \mu$, for the clean leptonic final state $\ell\ell bb$
- $H \to bb$, because of its large branching ratio.

This final state:

- is fully constrained: allows full reconstruction of the A boson decay kinematics.
- has less background noise
- has smallest Higgs signal

Jets and flavour tagging

Jets

A jet is a narrow cone of hadrons and other particles produced by the hadronization of a quark or gluon

- Particles carrying a color charge (quarks) cannot exist in free form because of QCD confinement.
- When an object containing color charge fragments, each fragment carries away some of the color charge.
- In order to obey confinement, these fragments create other colored objects around them to form colorless objects.
- The ensemble of these objects is called a jet, since the fragments all tend to travel in the same direction, forming a narrow "jet" of particles.

b-tagging

Tagging

It is the identification (or "tagging") of jets originating from the same quark flavor, e.g. bottom quarks (or b quarks, hence the name).

Importance of b-tagging:

- The physics of bottom quarks is quite interesting; in particular, it sheds light on CP violation.
- Some important high-mass particles (both recently discovered and hypothetical) decay into bottom quarks:
  - Top quarks very nearly always do so
  - the Higgs boson is expected to decay into bottom quarks more than any other particle
- Identifying bottom quarks helps to identify the decays of these particles.

ATLAS Coordinat System

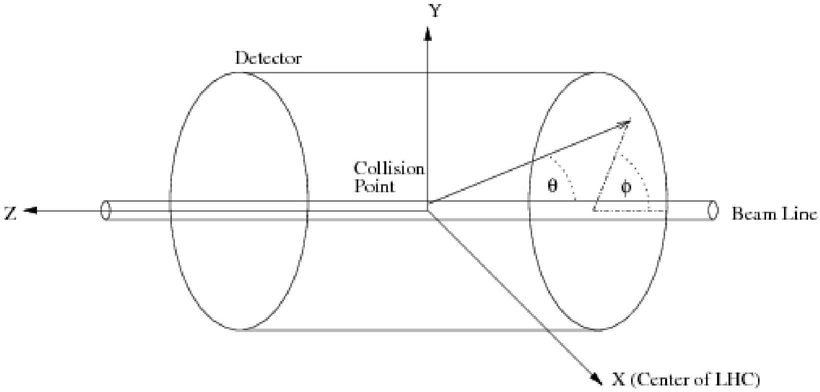
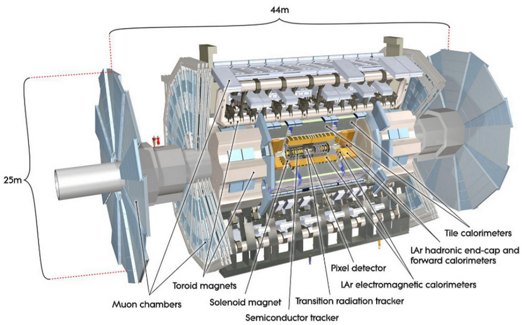


Figure 1: Atlas coordinate system

ATLAS detector



Definitions

Pseudorapidity

In terms of the polar angle θ, as $\eta = -\ln\tan(\theta/2)$

Transverse momenta p_T

Computed from the three-momenta $\vec{p}$ as $p_T = |\vec{p}|\sin\theta$

Reconstructed particles

Electrons

- Detected in the electromagnetic calorimeter
- Effciency to be reconsructed and meet criteria: 85% for $p_T > 7$ GeV and 90% for $p_T > 27$ GeV

Muons

- Detected in muon spectrometer
- Efficiency 97% for $|\eta| < 2.5$ and $p_T > 7$ GeV

Jets

- Detected in calorimeter system
- Candidates are required to have: $p_T > 20$ GeV at $|\eta| < 2.5$ and $p_T > 30$ GeV at $2.5 < |\eta| < 4.5$

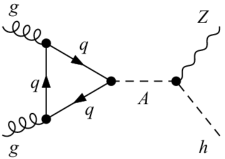
Resonance of interest

Resonance

The peak located around a certain energy found in differential cross sections of scattering experiments. In common usage, "resonance" only describes particles with very short lifetimes, mostly high-energy hadrons existing for 10^{-23} seconds or less.

The pseudoscalar boson resonance

$$A \to ZH \to \ell\ell bb$$



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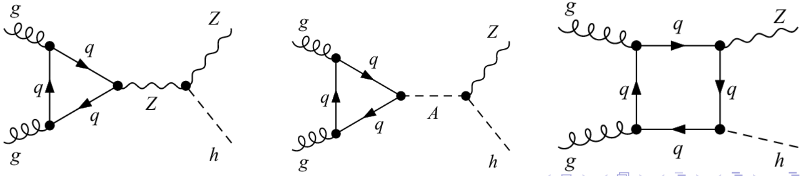
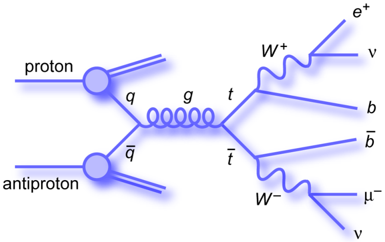
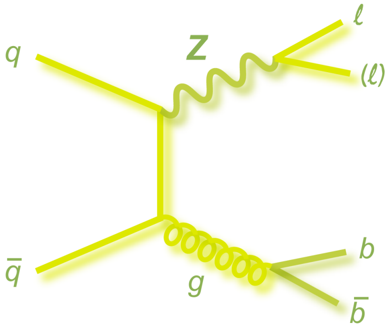


Most Relevant Background Resonances



$t\bar{t}$



Z+jets

Control regions

- The $t\bar{t}$ and $Z+$ jets control regions are included in the likelihood calculation, to help constrain their respective contribution in the signal region
- Achieved via two free normalisation scale factors $\vec{\alpha}$.
- Values estimated from the simulation and determined from the fit. Typical values are close to unity, e.g.:
  for $(m_A, M_H) = (700, 200)$ GeV:
  - $\alpha_{Z+jets} = 1.12 \pm 0.09$
  - $\alpha_{t\bar{t}} = 0.96 \pm 0.06$

Missing transverse energy

Primary vertex

Taken to be the reconstructed vertex with the highest p_T^2 of the associated tracks.

Missing Transverse Energy E_T^{miss}

Computed using *reconstructed* and *calibrated* leptons, photons and jets tracks from primary vertex.
It is used to infer the presence of non-detectable particles (e.g. neutrinos)

Possible resonances

Several resonances leading to an $\ell\ell bb$ final state, hence several cuts to focus on the A decay:

- $H \to bb$ reconstructed by requiring at least two b-jets with highest p_T one having $p_T > 45$ GeV.
  Reduce by requiring $E_T^{miss}/\sqrt{p_T} < 3.5$ GeV
- reduce the Z+jets background: $\sqrt{p_T^2}/m_{\ell\ell bb} > 0.4$, where $m_{\ell\ell bb}$ is the four body invariant mass
- the invariant mass of the two leading b-jets must be compatible with the assumed H boson mass:

$$0.85 \cdot m_H - 20GeV < m_{bb} < m_H + 20GeV \tag{3}$$

Analysis Strategy

The $m_{\ell\ell bb}$ distribution after the m_{bb} requirement is used to discriminate between signal and background.

- To improve resolution:
  - the $\ell\ell$ system's four momentum are scaled to match the Z boson mass
  - the bb system's four momentum components are scaled to match the assumed H boson mass
- This procedure improves the $m_{\ell\ell bb}$ resolution by a factor of 2 without significantly distorting the background distribution.

Fit models

- The following fits are done in order to interpolate between various discrete mass points that are put through the full detector and reconstruction chain.
- Distributions of interest: Gaussian, EGE, DCSB, Breit-Wigner

Distributions

- If the decay with is negligible compared to the detector resolution: EGE and DCSB.
- Both functions consist of a Gaussian core with mean a and variance σ, while the rest of the parameters describe the tails.
- The small differences in the tails of some distributions between the functional forms and the simulations:
  - have only negligible effects on the final results
  - are included as source of systematic uncertainty.

Distributions: EGE

i) ExpGaussExp (EGE):

$$f_{EGE}(m; a, \sigma, k_L, k_H) = \begin{cases} \exp\left\{\frac{1}{2}k_L^2 + k_L\frac{m-a}{\sigma}\right\}, \mathit{for}\, \frac{m-a}{\sigma} \leq -k_L \\ \exp\left\{-\frac{1}{2}\left(\frac{m-a}{\sigma}\right)^2\right\}, \mathit{for} - k_L < \frac{m-a}{\sigma} \leq k_H \\ \exp\left\{\frac{1}{2}k_H^2 - k_H\frac{m-a}{\sigma}\right\}, \mathit{for}\, \frac{m-a}{\sigma} > k_H \end{cases} \tag{4}$$

Distributions: DCSB

ii) double Gaussian Crystal Ball (DCSB):

$$f_{DCSB}(m; a, \sigma, k_L, k_H, n_1, n_2) =$$

$$= \begin{cases} g(m; a, -\sigma, k_L, n_1) \cdot \exp\left\{-\frac{1}{2}k_L^2\right\}, \mathit{for}\ \frac{m-a}{\sigma} \leq -k_L \\ \exp\left\{-\frac{1}{2}\left(\frac{m-a}{\sigma}\right)^2\right\}, \mathit{for} - k_L < \frac{m-a}{\sigma} \leq k_H \\ g(m; a, \sigma, k_H, n_2) \cdot \exp\left\{\frac{1}{2}k_H^2\right\}, \mathit{for}\ \frac{m-a}{\sigma} > k_H \end{cases}$$

where $g(m; a, \sigma, k, n) = \left[\frac{|k|}{n}\left(\frac{n}{|k|} - |k| + \frac{m-a}{\sigma}\right)\right]^{-n}$

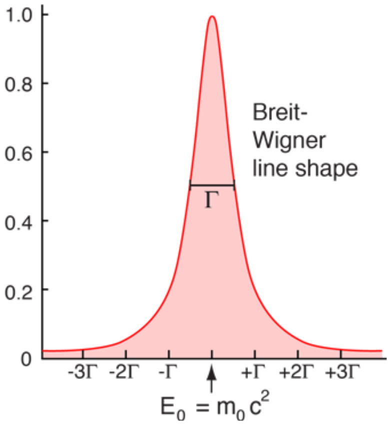
Breit-Wigner distribution

- Used for the case when the A boson's width is significant compared with the detector resolution while the H boson's width remains negligible.
- The relativistic Breit–Wigner distribution (after the 1936 nuclear resonance formula of Gregory Breit and Eugene Wigner) is a continuous probability distribution with the following probability density function:

$$f(E) = \frac{k}{\left(E^2 - M^2\right)^2 + M^2\Gamma^2} \tag{5}$$

where the constant of proportionality is $k = \frac{2\sqrt{2}M\Gamma\gamma}{\pi\sqrt{M^2+\gamma}}$ with $\gamma = \sqrt{M^2\left(M^2+\Gamma^2\right)}$

Breit-Wigner distribution (2)

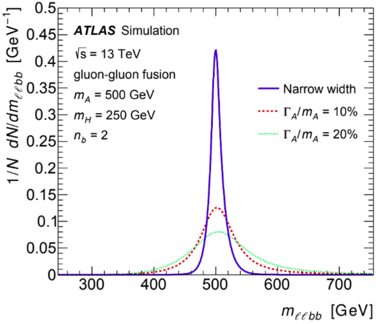


$$f(E) = \frac{k}{\left(E^2 - M^2\right)^2 + M^2\Gamma^2} \quad (6)$$

It is most often used to model resonances (unstable particles) in high-energy physics:

- E is the center-of-mass energy that produces the resonance
- M is the mass of the resonance
- Γ is the resonance width (or decay width), related to its mean lifetime according to $\tau = 1/\Gamma$.

Fit Model



- In order to model the $m_{\ell\ell bb}$ shape of A bosons with large natural widths, a modified Breit–Wigner distribution is convolved with the EGE and DSCB functions.
- The procedure is validated by comparing the results of the convolution with those of the simulated samples of A bosons with large natural widths. Widths of up to 20% of the A boson mass are considered.

Fit model

- The $m_{\ell\ell bb}$ distribution is expected to exhibit:
  - a resonant structure if signal events are present
  - a smooth shape from background events
- The shape difference in the $m_{\ell\ell bb}$ distribution between the signal and the background contributions are exploited through binned maximum-likelihood fits of the signal-plus-background hypotheses.

Fit parameters

For a given mass hypothesis of (m_A, m_H), the likelihood is constructed as the product of Poisson statistics in $m_{\ell\ell bb}$ bins:

$$L(\mu, \vec{\alpha}, \vec{\theta} | m_A, m_H) = \prod_{i=bins} Poisson\left(N_i \middle| \left(\mu \times S_i(m_A, m_H, \vec{\theta}) + B_i(\vec{\alpha}, \vec{\theta})\right)\right) \cdot G(\vec{\theta}) \tag{7}$$

- N_i is the number of observed events
- $S_i(m_A, m_H, \vec{\theta}$ and $B_i(\vec{\alpha}, \vec{\theta})$ are signal and background in bin i
- $\vec{\alpha}$ is the free background normalisation scale factors
- μ multiplicative factor to the expected signal rate and is called the signal-strength parameter (from systematic uncertainties)
- $\vec{\theta}$ denotes all explicitly non-listed parameters of the likelihood function

Signal strength parameter μ

- The effect of the systematic uncertainties on the search is studied using the signal-strength parameter μ for hypothesised signal production.
- Systematic Uncertainties are incorporated in the likelihood as nuisance parameters with either Gaussian or log-normal constraint terms.

Systematic Uncertainties

A) Experimental Uncertainties

- luminosity measurement
- trigger
- object identification
- energy/momentum scale
- resolution
- underlying event and pile-up

B) Theoretical Uncertainties

Modelling for:

- signal:
  - factorisation and renormalisation scale choice
  - the initial- and final-state radiation treatment
  - PDF choice
- background: modelling of the m_{bb} mass and the $p_T^{\ell\ell}$ distribution of Z+jets.

Uncertainties Contributions

Gluon–gluon fusion production				b-associated production			
(230, 130) GeV		(700, 200) GeV		(230, 130) GeV		(700, 200) GeV	
Source	$\Delta\mu/\mu$ [%]	Source	$\Delta\mu/\mu$ [%]	Source	$\Delta\mu/\mu$ [%]	Source	$\Delta\mu/\mu$ [%]
Data stat.	32	Data stat.	49	Data stat.	35	Data stat.	46
Total syst.	36	Total syst.	22	Total syst.	38	Total syst.	26
Sim. stat.	22	Sim. stat.	10	Sim. stat.	26	Sim. stat.	12
Bkg. model.	16	Bkg. model.	10	b-tagging	14	Bkg. model.	11
JES/JER	12	Theory	9.1	JES/JER	11	b-tagging	10
b-tagging	9.9	b-tagging	8.5	Bkg. model.	9.8	Theory	6.8
Theory	7.5	Leptons	4.2	Theory	7.0	JES/JER	6.2

Results

Step size

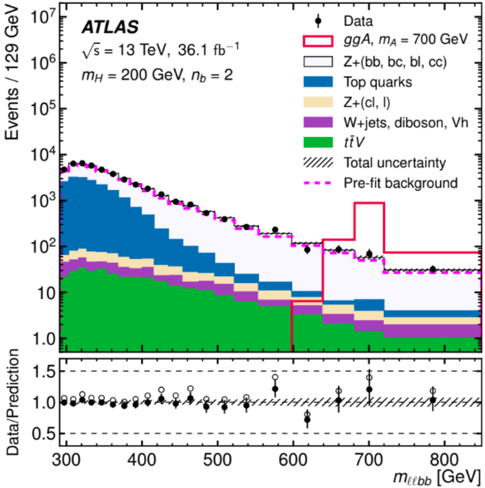
The scan is performed in steps of 10 GeV for:

- m_A range 230-800 GeV
- m_H range 130-700 Gev

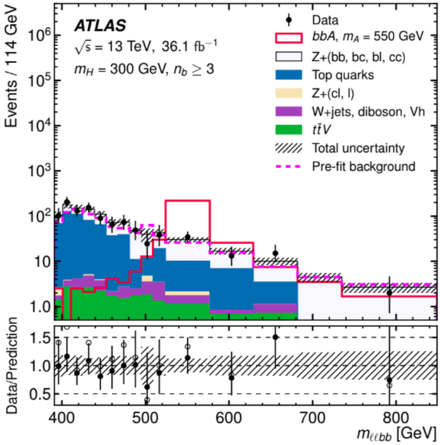
such that $m_A - m_H \geq 100$ GeV

Step size chosen to be compatible with the detector resolution.

$m_{\ell\ell bb}$ distribution: gluon-gluon fusion



$m_{\ell\ell bb}$ distribution: b jets associates



Background model comparison

Measured data is found to be well described by the background model. Some excesses are present at:

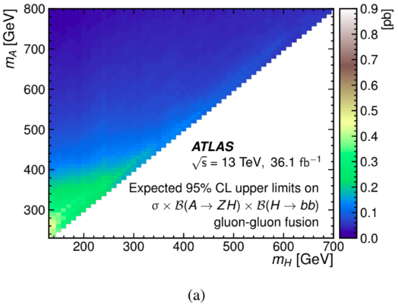
- gluon-gluon fusion production at $(m_A, m_H) = (750, 610)$ GeV with significance 3.5 (2.0)
- b-associated production at $(m_A, m_H) = (510, 310)$ GeV with significance 3.0 (1.2)

Assumptions

Results are interpreted in the context of 2HDM, with the assumptions:

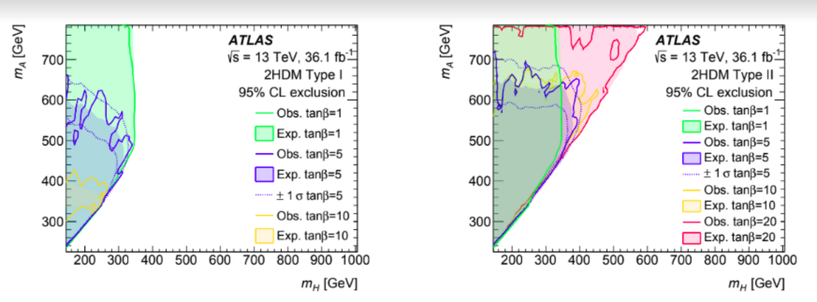
- $m_{H^\pm} = m_A$
- lightest Higgs h assumed to be the discovered one at $m_h = 125$ GeV with SM couplings as $\cos(\beta - \alpha) = 0$
- the 2HDM parameter fixed to: $m_{12}^2 = m_A^2 \dfrac{\tan\beta}{1 + \tan^2\beta}$

Confidence Levels (1)



Upper bounds at 95% CL on the production cross-section times the branching ratio $B(A \to ZH) \times B(H \to bb)$ in a pb for gluon-gluon fusion.

Confidence Levels (2)

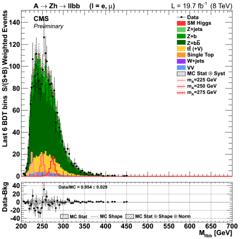


(a) (b)

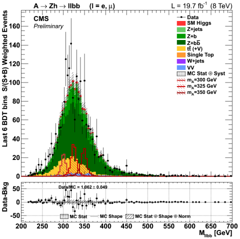
Observed and expected 95% CL exclusion regions in the (m_A, m_H) plane for various $\tan\beta$ values for (a) Type I, (b) Type II.

Similar CMS search

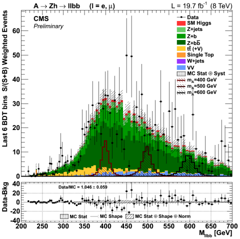
Four-body invariant mass distribution in the region of:



(a) low mass



(b) intermediate mass



(c) high mass

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- A is assumed to be assumed to be produced via either gluon-gluon fusion or b-associated production
- No significant deviation from the SM background predictions are observed in the $ZH \to \ell\ell bb$ final state
- However, this search tightens the constraints on the 2HDM in the case of large mass splitting between its heavier neutral Higgs bosons