$h \rightarrow bb$ kinematical fit for $A \rightarrow Zh \rightarrow \ell\ell bb$

Paolo Checchia, Tommaso Dorigo, **Stefano Lacaprara**, Mia Tosi, Alberto Zucchetta

INFN Padova

Hbb meeting,
CERN, 12 December 2013

Introduction

Motivation

- We are searching for a resonant decay $A \to Zh \to \ell\ell bb$;
- the signal sensitivity depends on the 4-body ($\ell\ell bb$) mass resolution;
- which is dominated by the b-jets resolution;
- we can try b-jet energy regression, or
- let's use the fact that the bb system is resonant for signal $h \to bb$
- and we know $M_h = 125.8 \pm 0.4 \pm 0.4$;

Two ways

- Brutally force $M_{bb} = M_h$;
- Kinematical fit M_{bb} to M_h, varying jets energy according to their resolution;

Analysis overview

- Preselection
  - either HLT_Mu17_Mu8 or HLT_Ele17[...]Ele8[...] trigger fired;
  - $N_\ell \geq 2$: $p_T > 20(10)$ GeV, $\pm$, same flavour, isolated ($PF^{rel}_{iso} < 0.15$);
  - $N_{jets} \geq 2$: $p_T > 20$ GeV, $\Delta R_{jet,\ell} > 0.5$;
- Analysis cuts
  - Z Selection: $80 < m_{\ell\ell} < 100$ GeV;
  - b-tagging (CSV): jet$_1$ is CSVT, jet$_2$ CSVL;
  - ~~h selection: $90 < m_{bb} < 140$ GeV~~; today's topic!
  - Final selection is m_A dependent.

M_{250}

- $MET < 50$ GeV
- $HT > 100$ GeV
- $1 < \Delta R_{bb} < 3.25$

M_{300}

- $MET < 50$ GeV
- $HT > 100$ GeV
- $1 < \Delta R_{bb} < 3.25$
- $p_T^Z > 60$ GeV

M_{350}

- $MET < 50$ GeV
- $HT > 125$ GeV
- $1 < \Delta R_{bb} < 2.5$
- $p_T^Z > 80$ GeV

Force $M_{bb} = M_h$

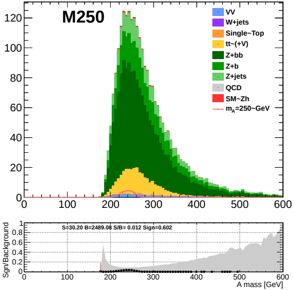
What it is about:

- Force the 4-momentum of bb system to have mass: $M_{bb} = M_h$ scaling p_T and E, while η and ϕ stays fixed;
- Problem: should we force all bb pairs to M_h?
  - or only those which are already "close"?
  - next slides will show results w/o and w/ selection $90 < m_{bb} < 140\ GeV$
  - in next section a better approach.
- Look at expected limit (CLs) using $M_A = M_{\ell\ell bb}$ shape, with reasonable assumption for syst (will show our work on syst soon);
- Focus on changes between the three methods
  1. no constraint;
  2. constraint for all bb pairs;
  3. constraint for bb pairs which pass: $90 < m_{bb} < 140\ GeV$.

$M_A = 250\ GeV$ $\sigma_{signal} = 25\ fb$

Other M_A in backup

M_{bb} not forced

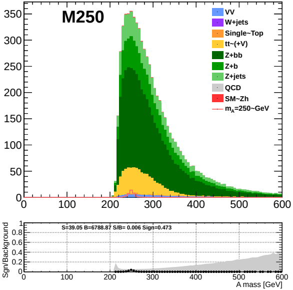


$M_A = 239.2 \pm 0.1\ GeV$

$\sigma_{M_A} = 14.5 \pm 0.1\ GeV$

$S = 30.20 \quad B = 2500$

$M_{bb} = M_h$

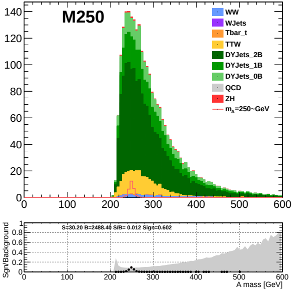


$M_A = 249.01 \pm 0.05\ GeV$

$\sigma_{M_A} = 7.23 \pm 0.05\ GeV$

$S = 39.20 \quad B = 6800$

$M_{bb} = M_h$ if $90 < M_{bb} < 140\ GeV$



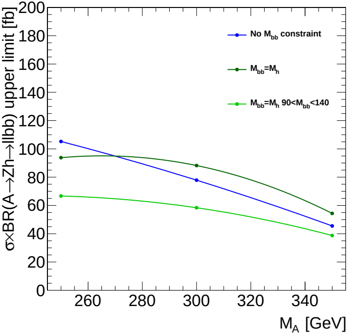
$M_A = 249.11 \pm 0.05\ GeV$

$\sigma_{M_A} = 6.18 \pm 0.04\ GeV$

$S = 30.20 \quad B = 2500$

M_A width, expected limit and Conclusion I

M_A	σ_{M_A} GeV original	σ_{M_A} GeV $M_{bb} = M_h$
250	14.5 ± 0.1	6.18 ± 0.04
300	18.9 ± 0.1	10.50 ± 0.08
350	21.5 ± 0.1	17.25 ± 0.13



- Forcing M_{bb} to M_h reduces significantly the width of the 4-body invariant mass $M_A = M_{\ell\ell bb}$;
- If it is applied to all events, the S/B worsen a lot since we cannot select events with M_{bb};
- If it is applied only to events passing a selection on M_{bb}: $90 < M_{bb} < 140$ GeV, the S/N is the same (by construction) but the reduced width improves the expected limit.

Kinematical fit of M_{bb} to M_h

Idea

- Try a better constraint for M_{bb} than just force it to M_h;
- Change jets E **within jet resolution** to get M_{bb} closer to M_h;
  1. Get jet resolution on p_T as a function of p_t and η (we neglect resolution on ϕ and η, supposedly less important);
  2. Build a 4-momentum for jets starting from the measured one and varying the p_T, E;
  3. Apply a Gaussian constraint on p_T, E using jet resolution as width;
  4. Get as close as possible to M_h.

Formulas

- B-jets$_i$ 4-momentum: $p_{b_i}(\alpha_i) = \{p_T + \alpha_i \sigma_{p_T},\ \eta,\ \phi,\ E + \alpha_i \sigma_E\}$
- Minimize χ^2

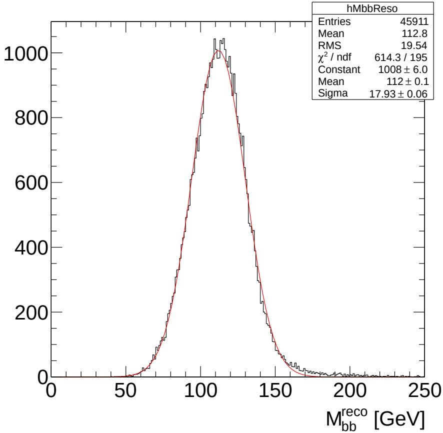
  $$\chi^2(\alpha_1, \alpha_2) = \left(\frac{M_{bb}(\alpha_1,\alpha_2) - M_h}{\sigma_{M_h}}\right)^2 + {\alpha_1}^2 + {\alpha_2}^2$$

  - $\sigma_{p_T,E}$ is jet resolution
    - Assume $\sigma_{p_T}/p_T = \sigma_E/E$
    - depend on p_T, η[a]
    - $\sigma_{p_T,E} \sim \mathcal{O}(10 - 20\%)$ (some plots in backup)
    - $\sigma_{p_T,E}$ is different between jet$_1$ and jet$_2$
  - $M_h = 125.8\ GeV$;
  - which σ_{M_h}?
    - M_{bb} resolution for $h \to bb$ from MC or uncertainty on M_h?
    - Try both.
- Use α_1, α_2 to redefine b-jets (b'_i), and **look at** $M_{b'b'}$ **and** $M_{b'b'll}$

[a] from AN 2010 371

Di-jet Mass resolution

M_{bb} reco, with both jet matched to the b-jets from $h_{125} \to bb$ decay.

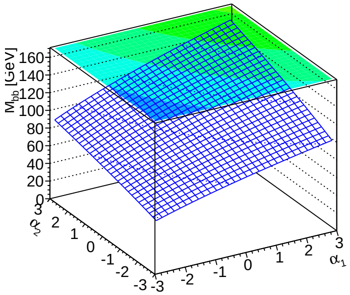


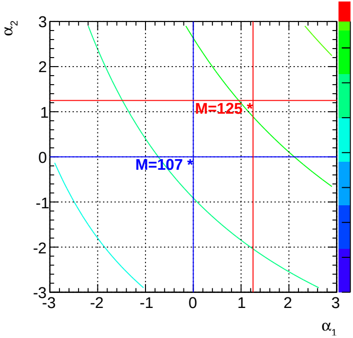
- $\sigma_{M_h} = 18 GeV$
- but the uncertainty on M_h is much smaller! $\sim 0.8\ GeV$
- Try and see the effect to use $\sigma_{M_h} = 18/10/1\ GeV$

An example

Consider two jets, $J_{1,2}$ with $p_{T,1} = 39.9\ GeV$, $p_{T,2} = 35.1\ GeV$, and $M_{jj} = 107\ GeV$

Let vary $P_{T,i} = p_T \cdot (1. + \alpha_i \cdot \sigma_{p_T})$, and E_i likewise. Look at $M_{jj}(\alpha_1, \alpha_2)$

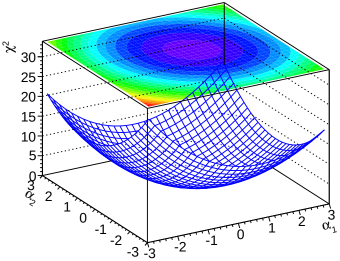


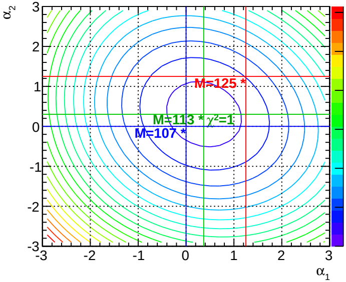


To force $M_{jj} = M_h$ we would need to stretch the jet p_T by $\sim 1.25 \cdot \sigma_{p_T}$

Minimimization

Build and minimize the χ^2 as defined above with $\sigma_{M_{bb}} = 18\ GeV$



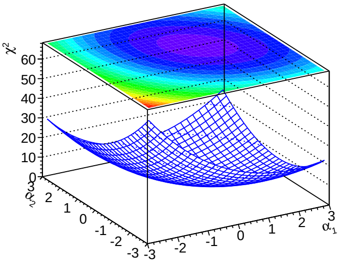


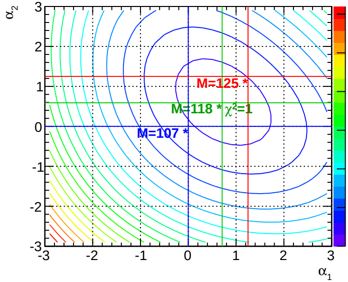
Results

χ^2 minimized correspond to $M_{jj} = 112.6\ GeV$ with $\chi^2 = 0.75$

Minimimization

Build and minimize the χ^2 as defined above with $\sigma_{M_{bb}} = 10\ GeV$



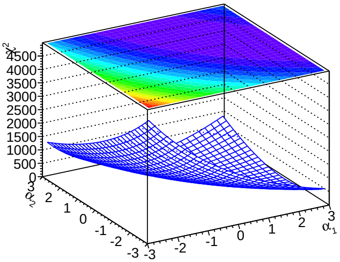


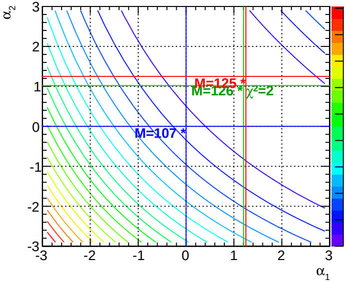
Results

χ^2 minimized correspond to $M_{jj} = 117.9\ GeV$ with $\chi^2 = 1.46$

Minimimization

Build and minimize the χ^2 as defined above with $\sigma_{M_{bb}} = 1\ GeV$



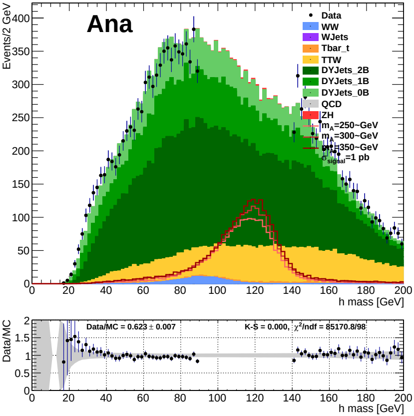


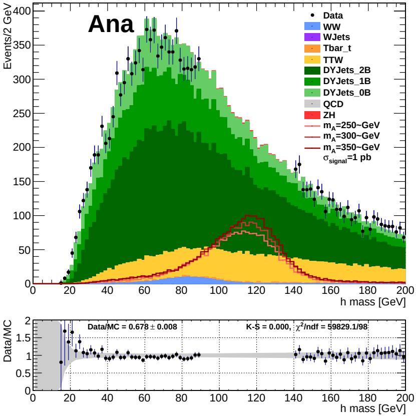
Results

χ^2 minimized correspond to $M_{jj} = 125.6\ GeV$ with $\chi^2 = 2.50$

M_{bb} distribution

Z mass cut + 1 CVST + 1 CVSL - $\sigma_{signal} = 1pb \sim (40x)$





M_{bb} w/ kin fit with $\sigma_{M_{bb}} = 18\ GeV$

$M_h = 115.98 \pm 0.11\ GeV$

$\sigma_{M_h} = 14.52 \pm 0.12\ GeV$

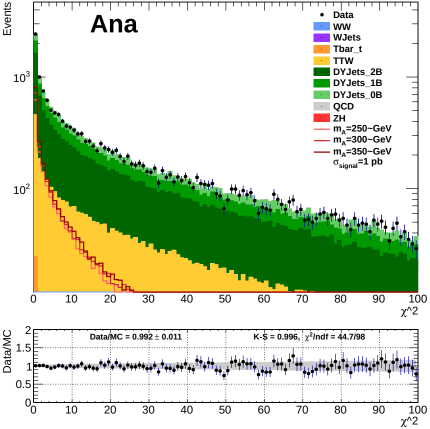
Likewise w/o kin fit

$M_h = 113.47 \pm 0.16\ GeV$

$\sigma_{M_h} = 17.66 \pm 0.21\ GeV$

χ^2 distributions

Z mass cut + 1 CVST + 1 CVSL - $\sigma_{signal} = 1pb \sim (40x)$

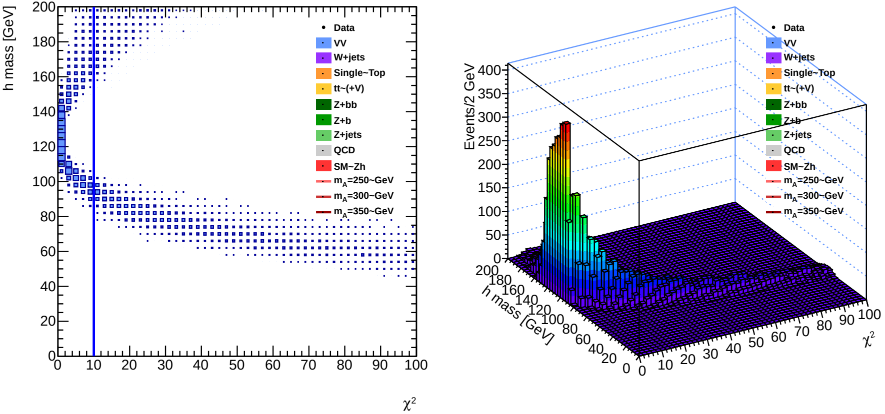


Kinematical fit χ^2 distribution for data and MC, with $\sigma_{M_h} = 18\ GeV$

NB: $\sigma_{signal} = 1pb$, enhanced by a factor $\sim (40x)$ with respect to a typical 2HDM $\sigma_{signal} = 25\ fb$

χ^2 distributions (II)

Z mass cut + 1 CVST + 1 CVSL



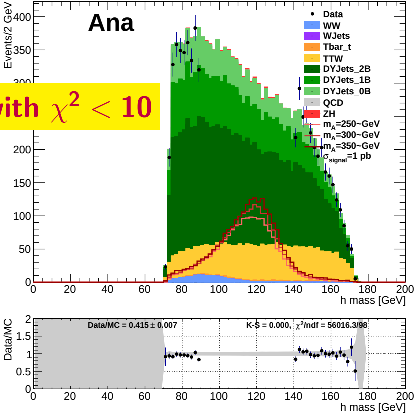
M_{bb} vs kinematical fit χ^2 distribution for data and MC

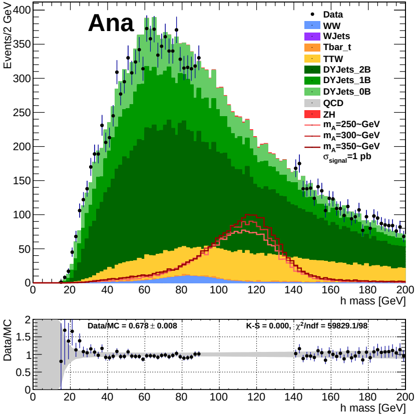
A cut on χ^2 (*e.g.* $\chi^2 < 10$) acts as an effective cut on M_{bb}

M_{bb} distribution

Z mass cut + 1 CVST + 1 CVSL - $\sigma_{signal} = 1pb \sim (40x)$

with $\chi^2 < 10$





M_{bb} w/ kin fit with $\sigma_{M_{bb}} = 18\ GeV$

$M_h = 115.97 \pm 0.11\ GeV$

$\sigma_{M_h} = 14.50 \pm 0.12\ GeV$

Likewise w/o kin fit

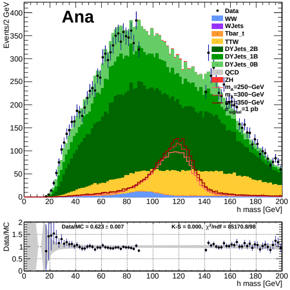
$M_h = 113.47 \pm 0.16\ GeV$

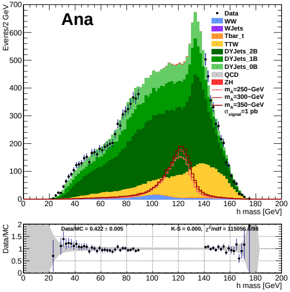
$\sigma_{M_h} = 17.66 \pm 0.21\ GeV$

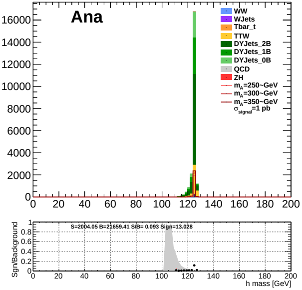
M_{bb} distribution

Z mass cut + 1 CVST + 1 CVSL ($\sigma_{signal} = 1pb$)

M_{bb} kinematical fit with :





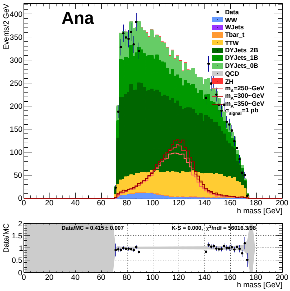


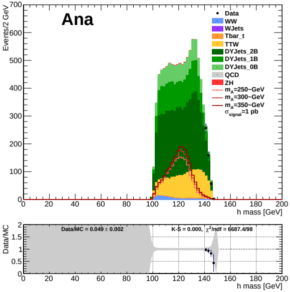
$\sigma_{M_{bb}} = 18\ GeV$	$\sigma_{M_{bb}} = 10\ GeV$	$\sigma_{M_{bb}} = 1\ GeV$
$M_h = 115.98 \pm 0.11\ GeV$	$M_h = 118.93 \pm 0.07\ GeV$	$M_h = 124.91 \pm 0.01\ GeV$
$\sigma_{M_h} = 14.52 \pm 0.12\ GeV$	$\sigma_{M_h} = 10.61 \pm 0.07\ GeV$	$\sigma_{M_h} = 0.71 \pm 0.00\ GeV$

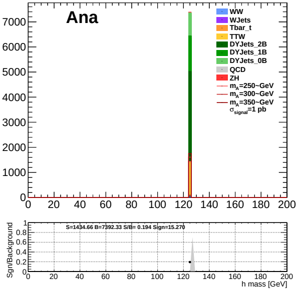
M_{bb} distribution

Z mass cut + 1 CVST + 1 CVSL ($\sigma_{signal} = 1pb$)

M_{bb} kinematical fit with $\chi^2 < \mathbf{10}$ and:







$\sigma_{M_{bb}} = 18\ GeV$	$\sigma_{M_{bb}} = 10\ GeV$	$\sigma_{M_{bb}} = 1\ GeV$
$M_h = 115.98 \pm 0.11\ GeV$	$M_h = 118.93 \pm 0.07\ GeV$	$M_h = 124.91 \pm 0.01\ GeV$
$\sigma_{M_h} = 14.52 \pm 0.12\ GeV$	$\sigma_{M_h} = 10.61 \pm 0.07\ GeV$	$\sigma_{M_h} = 0.71 \pm 0.00\ GeV$

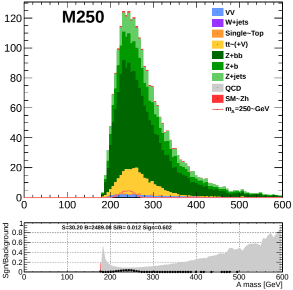
What is the impact on 4-body $M_{\ell\ell bb}$

- Apply the method described above and look at the 4-body $M_{\ell\ell bb}$ invariant mass distribution;
- For the three available M_A (250, 300, and 350 GeV);
- Compute the expected limit (CLs) with the kinematical fit, and compare with that using the mass constraint $M_{bb} = M_h$ as well as to the standard analysis (no mass constraint).

$M_A = 250\ GeV$

More "realistic" $\sigma_{signal} = 25\ fb$: other M_A in backup

M_{bb} not forced

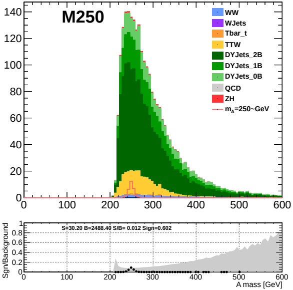


$M_A = 239.2 \pm 0.1\ GeV$

$\sigma_{M_A} = 14.5 \pm 0.1\ \ GeV$

$S = 30 \quad B = 2490$

$M_{bb} = M_h$ if $90 < M_{bb} < 140\ GeV$

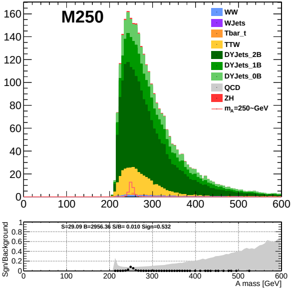


$M_A = 249.11 \pm 0.05\ GeV$

$\sigma_{M_A} = 6.18 \pm 0.04\ GeV$

$S = 30.20 \quad B = 2500$

Kin fit M_{bb} to M_h $\sigma_M = 1\ GeV$

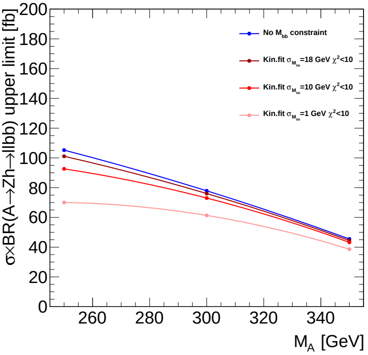


$M_A = 250.89 \pm 0.04\ GeV$

$\sigma_{M_A} = 5.69 \pm 0.04\ GeV$

$S = 29 \quad B = 2960$

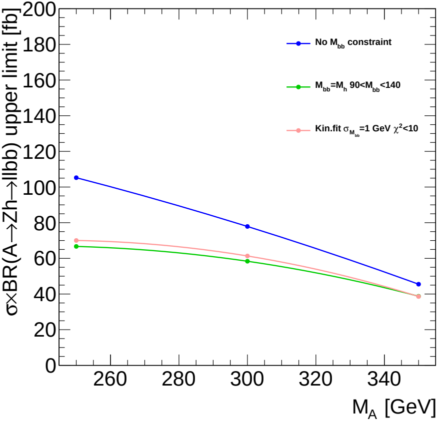
Conclusion II



	σ_{M_A} GeV		
	$\sigma_{M_{bb}} = 18$ GeV	$\sigma_{M_{bb}} = 10$ GeV	$\sigma_{M_{bb}} = 1$ GeV
250	13.38	9.90	5.69
300	17.30	13.00	9.42
350	19.32	15.38	12.46

- Kinematical Fit improves the expected limits;
- The smaller $\sigma_{M_{bb}}$, the better the limit

Comparison of the two methods



M_A	σ_{M_A} GeV original	$M_{bb} = M_h$	kin fit
250	14.5	6.18	5.69
300	18.9	10.50	9.42
350	21.5	17.25	12.46

- Forcing $M_{bb} = M_h$ gives results as good as kinematical fit with $\sigma_{M_{bb}} = 1\ GeV$
- provided the former is applied only to those events with $90 < M_{bb} < 140\ GeV$.

Summary

Force $M_{bb} = M_h$

- Background is not peaked as much as Signal;
- If we cut on M_{bb} before forcing $M_{bb} = M_h$: expected limit is significantly better
- If not, Background is significantly higher!!

Kinematical fit

- M_A peak can be narrowed by M_h kinematical fit
- A cut on M_{bb} can be replaced by a cut in χ^2
- With small $\sigma_{M_{bb}} = 1\ GeV$, the results are similar to that of forcing the mass with a prior cut on M_{bb}

Backup

Backup

Guess what?

Yep, backup slides ahead!

2HDM Scan

- Rui Santos kindly provided the 2HDM (type-I [left] and type-II [center]) scans for $\sigma \times \mathcal{B}$ for $A \to Zh$ modes.
- https://twiki.cern.ch/twiki/bin/view/CMS/Higgs/HiggsExotics2HDM
  - $\sigma \times \mathcal{B}(A \to Zh) \times \mathcal{B}(h \to bb) \sim \mathcal{O}(1\ pb)$
  - $\times \mathcal{B}(Z \to \ell\ell) \approx 0.07$ not included in 2DHM plots!
  - $\sigma \times \mathcal{B}(A \to Zh \to \ell\ell bb) \sim \mathcal{O}(100\ fb)$
- [right] expected sensitivity (from feasiblity studies) for this analysis
- We are in the correct ballpark (limits overlayed by hand!)
- It could be worth to look at wider m_A range: $m_A = 200 \div 500$

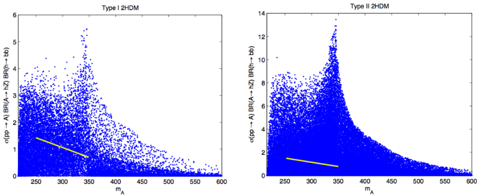
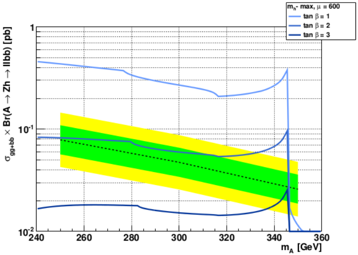
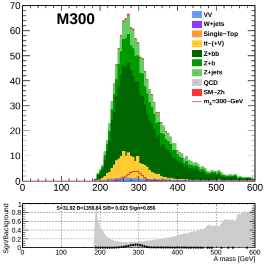


FIG. 7: The pseudoscalar scalar mass *versus* $\sigma(pp \to A)BR(A \to hZ)BR(h \to bb)$. Left - type I and right - type II. Cross sections in pbarn and masses in GeV. The peak at ~ 375 GeV, corresponding to the "opening" of the $t\bar{t}$ channel in the gluon-gluon production of A



$M_A = 300\ GeV$ $\sigma_{signal} = 25\ fb$

M_{bb} not forced

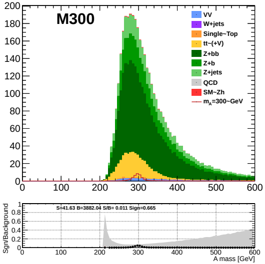


$M_A = 288.6 \pm 0.1\ GeV$

$\sigma_{M_A} = 18.9 \pm 0.1\ GeV$

$S = 32 \quad B = 1350$

$M_{bb} = M_h$

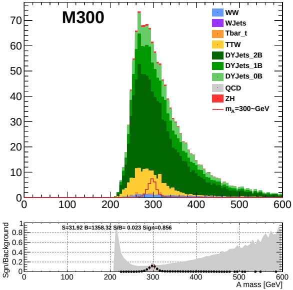


$M_A = 296.60 \pm 0.09\ GeV$

$\sigma_{M_A} = 12.59 \pm 0.09\ GeV$

$S = 42 \quad B = 3880$

$M_{bb} = M_h$ if $90 < M_{bb} < 140\ GeV$



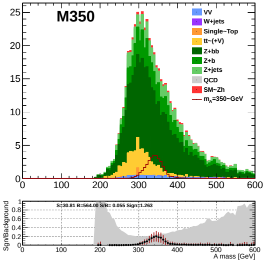
$M_A = 297.00 \pm 0.08\ GeV$

$\sigma_{M_A} = 10.50 \pm 0.08\ GeV$

$S = 32 \quad B = 1350$

$M_A = 350\ GeV$ $\sigma_{signal} = 25\ fb$

M_{bb} not forced

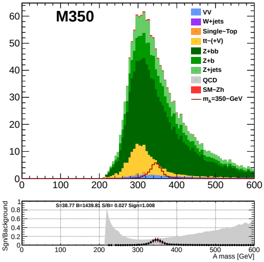


$M_A = 339.1 \pm 0.2\ GeV$

$\sigma_{M_A} = 21.5 \pm 0.1\ \ GeV$

$S = 31 \quad B = 560$

$M_{bb} = M_h$

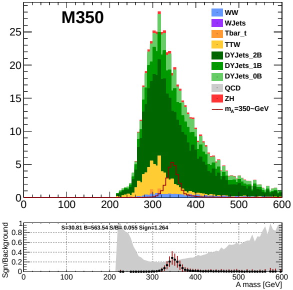


$M_A = 345.21 \pm 0.12\ GeV$

$\sigma_{M_A} = 17.25 \pm 0.13\ GeV$

$S = 39 \quad B = 1440$

$M_{bb} = M_h$ if $90 < M_{bb} < 140\ GeV$



$M_A = 345.72 \pm 0.11\ GeV$

$\sigma_{M_A} = 14.50 \pm 0.10\ GeV$

$S = 31 \quad B = 560$

Jet resolution

AN 2010 371: Jet resolution vs p_T for various $|\eta|$ bins.

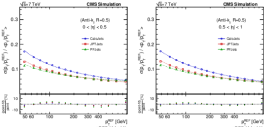


Figure 9: MC truth resolution for $0.0 \leq |\eta| < 0.5$ (*left*) and $0.5 \leq |\eta| < 1.0$ (*right*)

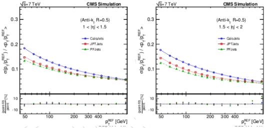


Figure 10: MC truth resolution for $1.0 \leq |\eta| < 1.5$ (*left*) and $1.5 \leq |\eta| < 2.0$ (*right*)

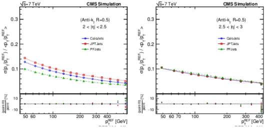
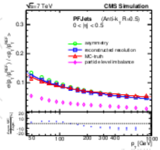
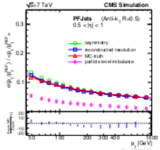


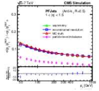
Figure 11: MC truth resolution for $2.0 \leq |\eta| < 2.5$ (*left*) and $2.5 \leq |\eta| < 3.0$ (*right*)



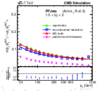
d CaloJets (*left*), JPTJets (*middle*)
rticle-level (magenta) results are
parison to the MC truth derived
netry resolution measurements
Collaboration).



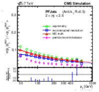
PFJets (*right*) at $0.5 \leq |\eta| < 1.0$.



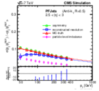
PFJets (*right*) at $1.0 \leq |\eta| < 1.5$.



PFJets (*right*) at $1.5 \leq |\eta| < 2.0$.



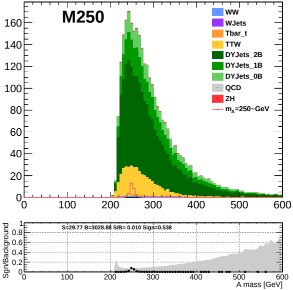
PFJets (*right*) at $2.0 \leq |\eta| < 2.5$.



PFJets (*right*) at $2.5 \leq |\eta| < 3.0$.

$M_A = 250\ GeV$

Kin fit M_{bb} to M_h $\sigma_M = 1\ GeV$

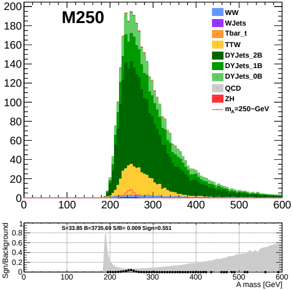


$M_A = 250.89 \pm 0.04\ GeV$

$\sigma_{M_A} = 5.69 \pm 0.04\ GeV$

$S = 30 \quad B = 3030$

Kin fit M_{bb} to M_h $\sigma_M = 10\ GeV$

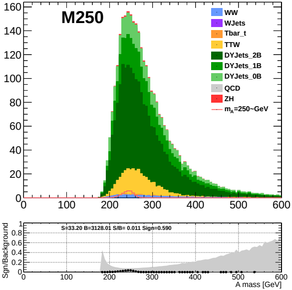


$M_A = 245.44 \pm 0.07\ GeV$

$\sigma_{M_A} = 9.90 \pm 0.06\ GeV$

$S = 34 \quad B = 3730$

Kin fit M_{bb} to M_h $\sigma_M = 18\ GeV$



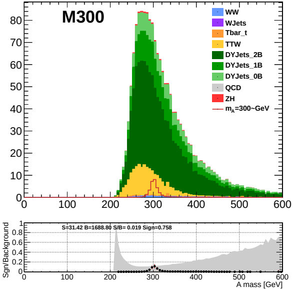
$M_A = 241.54 \pm 0.10\ GeV$

$\sigma_{M_A} = 13.38 \pm 0.08\ GeV$

$S = 33 \quad B = 3130$

$M_A = 300\ GeV$

Kin fit M_{bb} to M_h $\sigma_M = 1\ GeV$

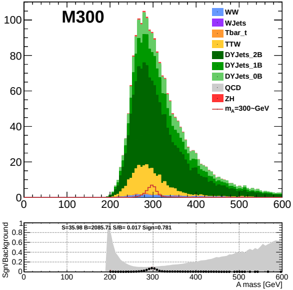


$M_A = 301.44 \pm 0.07\ GeV$

$\sigma_{M_A} = 9.42 \pm 0.08\ GeV$

$S = 31 \quad B = 1690$

Kin fit M_{bb} to M_h $\sigma_M = 10\ GeV$

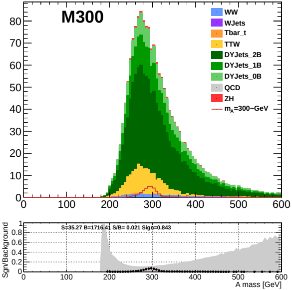


$M_A = 295.39 \pm 0.09\ GeV$

$\sigma_{M_A} = 13.00 \pm 0.10\ GeV$

$S = 36 \quad B = 2085$

Kin fit M_{bb} to M_h $\sigma_M = 18\ GeV$



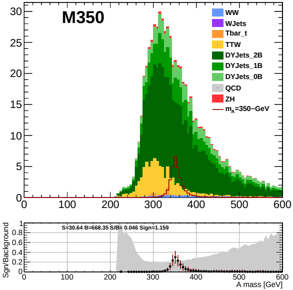
$M_A = 291.24 \pm 0.13\ GeV$

$\sigma_{M_A} = 17.30 \pm 0.12\ GeV$

$S = 35 \quad B = 1716$

$M_A = 350\ GeV$

Kin fit M_{bb} to M_h $\sigma_M = 1\ GeV$

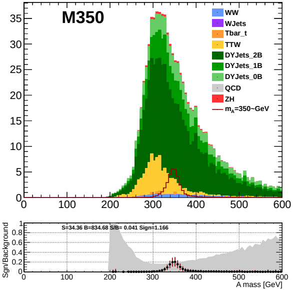


$M_A = 352.37 \pm 0.10\ GeV$

$\sigma_{M_A} = 12.46 \pm 0.10\ GeV$

$S = 31 \quad B = 670$

Kin fit M_{bb} to M_h $\sigma_M = 10\ GeV$

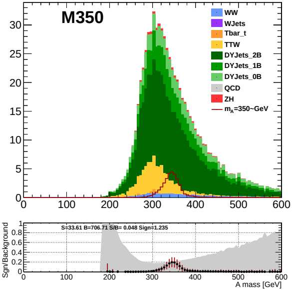


$M_A = 346.43 \pm 0.11\ GeV$

$\sigma_{M_A} = 15.38 \pm 0.12\ GeV$

$S = 35 \quad B = 834$

Kin fit M_{bb} to M_h $\sigma_M = 18\ GeV$



$M_A = 342.13 \pm 0.14\ GeV$

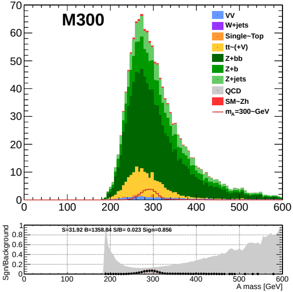
$\sigma_{M_A} = 19.32 \pm 0.14\ GeV$

$S = 34 B = 706$

$M_A = 300\ GeV$

More "realistic" $\sigma_{signal} = 25\ fb$

M_{bb} not forced

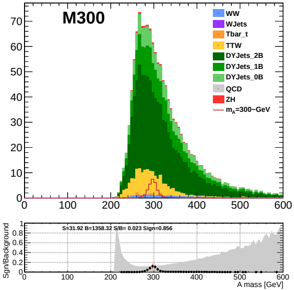


$M_A = 288.6 \pm 0.1\ GeV$

$\sigma_{M_A} = 18.9 \pm 0.1\ GeV$

$S = 32 \quad B = 1350$

$M_{bb} = M_h$ if $90 < M_{bb} < 140\ GeV$

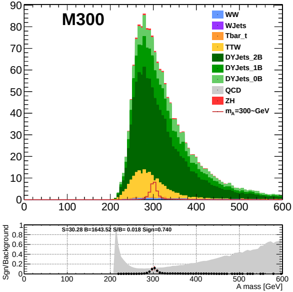


$M_A = 297.00 \pm 0.08\ GeV$

$\sigma_{M_A} = 10.50 \pm 0.08\ GeV$

$S = 32 \quad B = 1350$

Kin fit M_{bb} to M_h $\sigma_M = 1\ GeV$



$M_A = 301.44 \pm 0.07\ GeV$

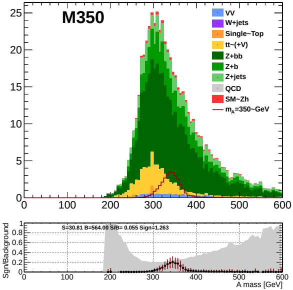
$\sigma_{M_A} = 9.42 \pm 0.08\ GeV$

$S = 30.3 \quad B = 1640$

$M_A = 350\ GeV$

More "realistic" $\sigma_{signal} = 25\ fb$

M_{bb} not forced



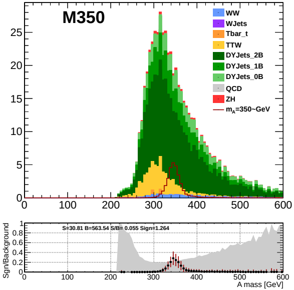
$M_A = 339.1 \pm 0.2\ GeV$

$\sigma_{M_A} = 21.5 \pm 0.1\ \ GeV$

$S = 31 \quad B = 564$

$M_{bb} = M_h$ if

$90 < M_{bb} < 140\ GeV$



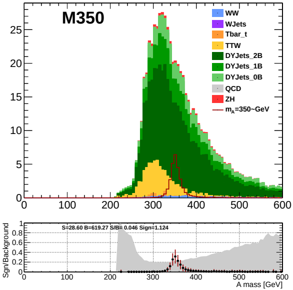
$M_A = 345.72 \pm 0.11\ GeV$

$\sigma_{M_A} = 14.50 \pm 0.10\ GeV$

$S = 31 \quad B = 560$

Kin fit M_{bb} to M_h

$\sigma_M = 1\ GeV$

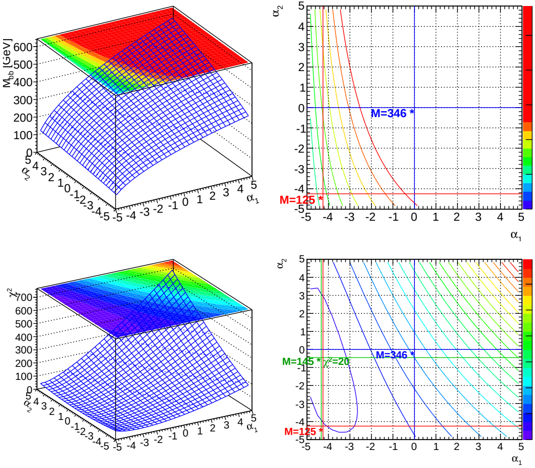


$M_A = 352.37 \pm 0.10\ GeV$

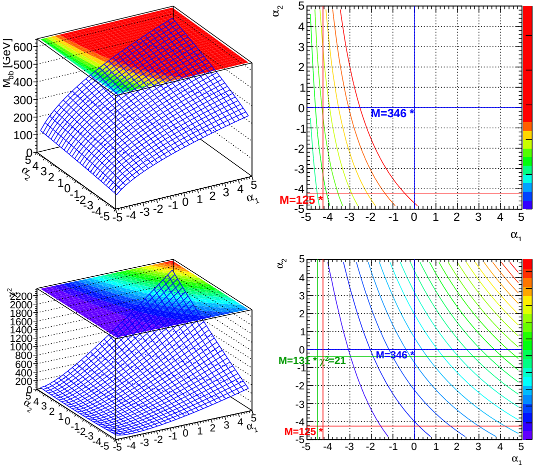
$\sigma_{M_A} = 12.46 \pm 0.10\ GeV$

$S = 28.6 \quad B = 620$

A bad example: $M_{bb} = 345\ GeV$ with $\sigma_{M_{bb}} = 18\ GeV$



A bad example: $M_{bb} = 345\ GeV$ with $\sigma_{M_{bb}} = 10\ GeV$



A bad example: $M_{bb} = 345$ GeV with $\sigma_{M_{bb}} = 1$ GeV