$H \rightarrow ZZ \rightarrow llqq$ Higgs Approval

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(on behalf of $H \rightarrow ZZ \rightarrow llqq$ group)

16th December 2014
Higgs Meeting

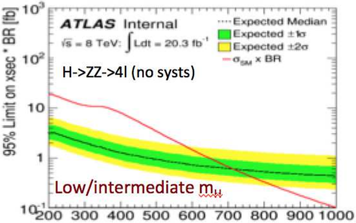
Outline

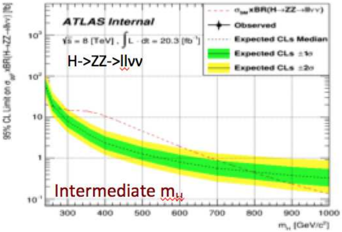
Introduction

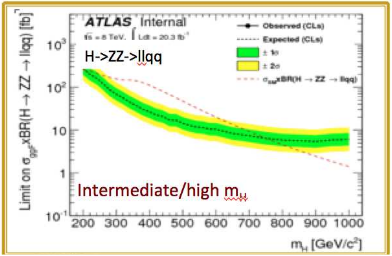
- Update of published 7 TeV result using full 2012 dataset
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2012-15/
  - Based heavily on SM $Zh \rightarrow llbb$ and very similar to $A \rightarrow Zh \rightarrow llbb$
- Many improvements (above lumi increase) $\rightarrow \times 15$ @ 600 GeV :
  - Increased acceptance + reoptimised cuts
  - Add explicit VBF category + merged category for highest m_H
    - Merged jet channel being finalised (backup) $\rightarrow$ only resolved here
  - Improved b-tagging ($\mathrm{MV1C}$) and reduced uncertainties ($t\bar{t}$ calib)
  - Extended m_{lljj} range up to 1 TeV
- Split into b-tag categories and use m_{lljj} (m_{llJ}) as discriminant
- Set limits in several models:
  - Model-independent $\sigma \times$BR for ggF and VBF channels in NWA
  - 2HDM NWA (tan β vs cos($\beta - \alpha$); cos($\beta - \alpha$) or tan β vs m_H)
  - EW singlet (varying H width and taking into account ZZ interference)
  - First two shown here; EWS in progress

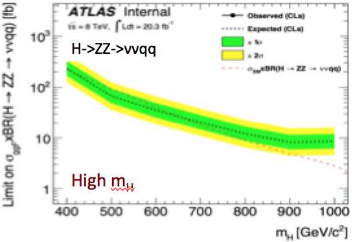
$H \to ZZ$ Sensitivity Comparison

- Includes ZZ decay BR but can compare to "SM-like" line









Datasets

- Muon/Egamma streams: 20.3 fb^{-1} @ $\sqrt{s} = 8$ TeV
- Signal: Powheg ggF and VBF
  - From 200–1000 GeV in 20 (50) GeV steps below (above) 600 GeV
  - Both narrow width approx (NWA) and complex-pole scheme (CPS)
  - Reweight CPS to BW + ZZ interference (ggF:gg2VV/VBF: REPOLO)
  - Plots currently show "SM-like" but will be updated to given σ and/or 2HDM point (to be agreed amongst channels)
- Background MC:
  - Z/W+jets (dominant):
    - ggf: Inclusive + boosted Sherpa l/c/b samples
    - Make most of stats for b/c by truth tagging for 1/2-tag case
    - VBF: Alpgen+Pythia (better describes VBF vars due to N_p samples)
  - $t\bar{t}$: Powheg
  - Single top: Powheg (Wt/s-chan) / Acer (t-chan)
  - Diboson ($ZZ/WZ/WW$): Powheg
  - QCD multijet from data in ee (negligible in $\mu\mu$)
    - SR: Reversed track isolation; TopCR: SS $e\mu$ events

Event Selection

Based closely on HSG5 selection and very similar to $A \to Zh$

- Preselection + recommended single/dilepton triggers
  - GRL, LAr/tile error veto, jet cleaning, LAr hole veto, $N_{trk}(PV) > 2$
- Exactly 2 electrons/muons (no additional lepton with $p_T > 7$ GeV)

Electron

- VeryLooseLH
- $p_T > 25/7$ GeV
- $|\eta| < 2.47$
- $\sum p_T(\Delta R = 0.2)/p_T < 0.10$
- OQ cuts
- Trigger matched

Muon

- CB/ST + CB/ST/SA/Calo
- $p_T > 25/7$ GeV
- $|\eta| < 2.7$
- $\sum p_T(\Delta R = 0.2)/p_T < 0.10$
- MCP + IP cuts
- Trigger matched

- $83 < m_{ll} < 99$ GeV
- $E_T^{\text{miss}}/\sqrt{H_T} < 6\ (3.5)\ \text{GeV}^{0.5}$ in untagged/tagged
  - H_T from sum of selected leptons + jets
- Separate ggF and VBF categories ...
  - Final discriminant is m_{lljj} with m_{jj} constrained to m_Z
  - Simple scaling of jet four vec by m_Z/m_{jj}

Event Selection (2)

Based closely on HSG5 selection and very similar to $A \to Zh$

VBF

- ≥ 4 jets (EM+GSC)
  - $p_T > 20/30$ GeV
  - $|\eta| < 4.5$
- $\eta_1 \times \eta_2 < 0$
- Pick highest m_{jj} pair
  - Non b-tagged
- $m_{jj} > 500$ GeV
- $\Delta\eta > 4$
- Follow ggF cuts

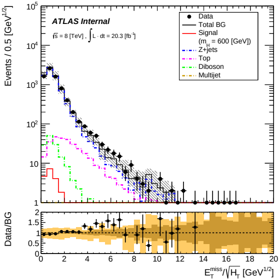
- Continuous b-tagging using MV1c @ 70%
- Pick highest b-weight jets, then highest p_T

ggF

- Veto VBF events
- ≥ 2 signal jets
  - $p_T > 45/20$ GeV and $|\eta| < 2.5$
- $70 < m_{jj} < 105$ GeV
- Untagged/tagged channels
- Optimised cuts (untagged/VBF)
  - $p_T^{ll} > \min[-54 + 0.46 m_{lljj}, 275]$
  - $P_T^{\text{jet}} > 0.1 m_{llqq}$
  - $\Delta\phi_{ll} > 3.2e8/m_{llqq}^{3.5} + 1$
- Optimised cuts (tagged)
  - $p_T^{ll} > \min[-79 + 0.44 m_{lljj}, 275]$

VBF Bug

- Since circulating, found 2 bugs in the VBF analysis (ggF unaffected):
- METSig cut not being applied due to mistake in units
  - Will be a very small effect ($< 1\%$) for VBF as inclusive in N_{jet}
- Old optimised p_T^Z cut was being applied
  - Will change limits by up to $\approx 10\%$
  - Effects both ggF and VBF model-indep limits as profile VBF for ggF git

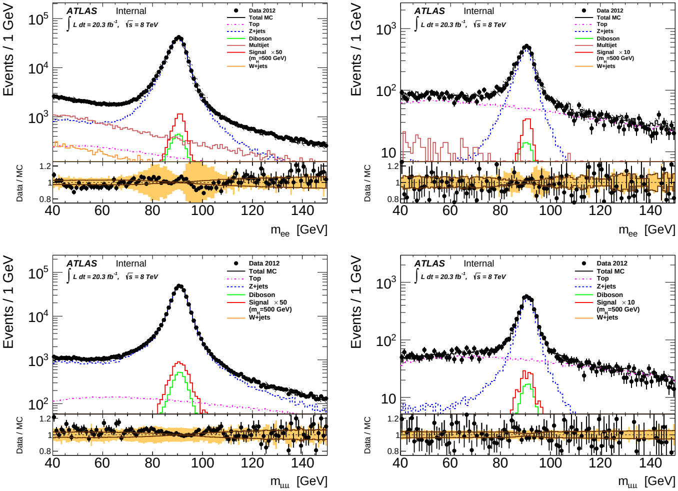


- Results in talk updated except rankings (pull are) and 2HDM limits (little effect from VBF here)

m_{ll}

- Small QCD in electron channel, well described by data-driven method

0/1 *b*-tag 2 *b*-tag

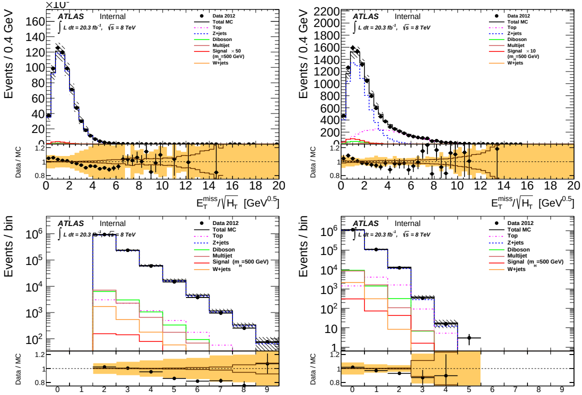


Jet + E_T^{miss}

- E_T^{miss} reasonably described with systs but some slope
- Slope in Data/MC for N_{jet} but 2/3 jet OK and few events in tail
  - Similar slope of $\sim 20\%$ seen in ongoing SM 8 TeV Z+jets analysis
    - Checked no effect on limits if reweight (backup)

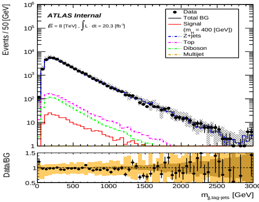
0/1 b-tag

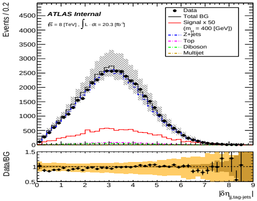
2 b-tag



VBF + m_{jj}

- VBF vars and m_{jj} (ggF after opt cuts; VBF before) well described
  - b-jets corrected for semi-lep μs and $p_T^{\rm reco}/p_T^{\rm true}$ when forming m_{bb}

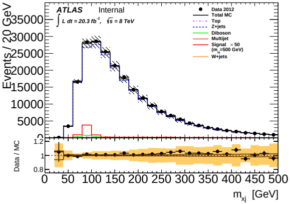


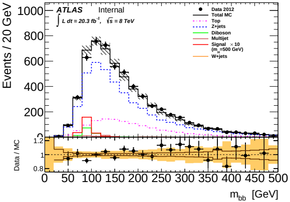


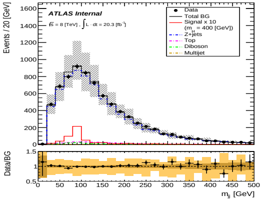
0+1 b-tag

2 b-tag

VBF





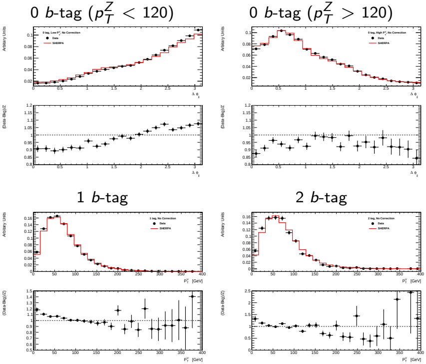


Background Modelling

Based on procedure used by HSG5/$A \rightarrow Zh$ result

- Norm: extract Z & top SF using CRs in final PL fit (see later)
  - "Flavour fit" as MC won't necessarily get ratio of flavours correct
  - Diboson from MC; QCD from data-driven method shown earlier
- Shape: taken from MC but checked/corrected using CRs
  - m_{jj} SB for Z and $e\mu$ events for top

- Sherpa Z+jets corrections (ggF)
- $\Delta\phi_{jj}$ mismodelled in 0/1 tag
  - Only at low p_T^{ll} (<120 GeV)
  - Linear correction from 0 b-tag SB applied to $Z+l$ jets
- p_T^{ll} mismodelled in 1/2 tag
  - Correction from 1+2 b-tag SB using $a + b\log(p_T^{ll})$ fit to Z+hf
  - $Z+l$ and non-Z bkg subtracted

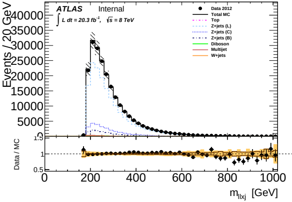


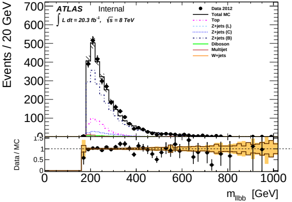
- In VBF channel use alpgen Z+jets and m_{lljj} reweighed instead

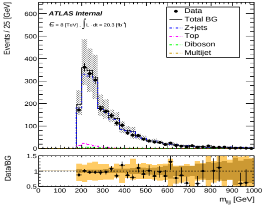
Z+jets CR: m_{lljj}

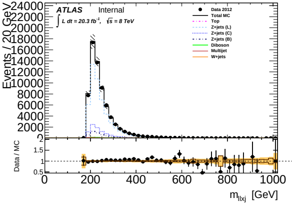
- m_{jj} SBs: before (top) and after (bottom) optimised cuts
  - $50 < m_{jj} < 70$ GeV or $105 < m_{jj} < 150$ GeV (kinematics similar to SR)

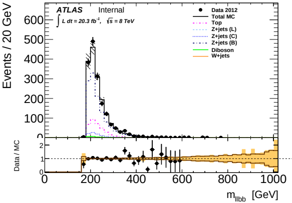
0/1 *b*-tag | 2 *b*-tag | VBF

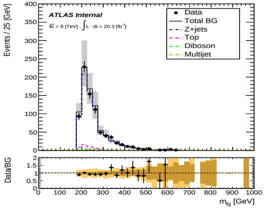








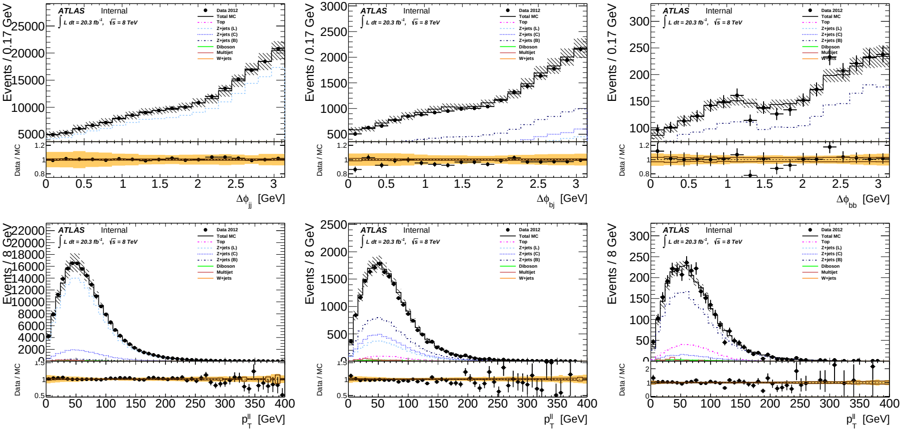




Z+jets CR: $\Delta\phi_{jj} + p_T^{ll}$

- Good description of $\Delta\phi_{jj}$ (top) and p_T^{ll} (bottom) in SB after reweight

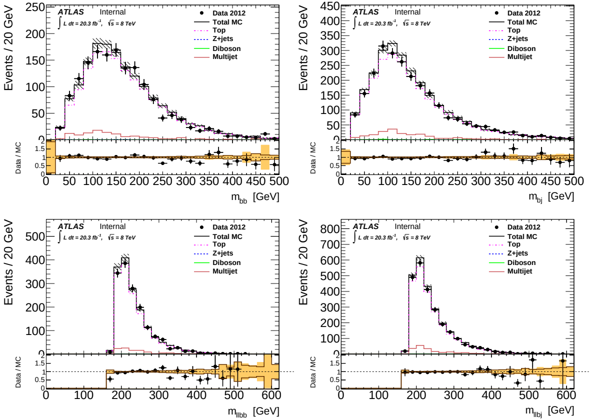
0 b-tag | 1 b-tag | 2 b-tag



Top CR ($e\mu$)

- ggF $e\mu$ events with $83 < m_{ll} < 99$ GeV (similar kinematics to SR)
  - Opposite charge only (remove QCD)
  - 1 b-tag with $E_T^{\mathrm{miss}}/\sqrt{H_T}$ reversed as VR

2 b-tag CR | 1 b-tag VR



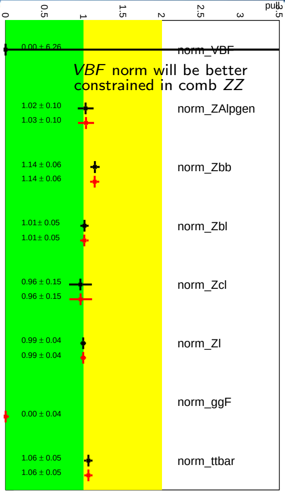
Fit Configuration

ggF (black) and VBF (red)

- Simultaneous fit to ggF +VBF SR +CRs:
  - ggF 0/1 and 2 tag SR (m_{lljj})
  - ggF 0/1 and 2 tag ZCR (MV1cSum)
  - ggF 2 tag TopCR (m_{lljj})
  - VBF SR + ZCR (m_{lljj})

$N_{b\text{-tag}}$	Categories						
	ggF			~~Merged~~		VBF	
	m_{jj} SR	m_{jj} CR	$e\mu$ CR	~~m_j SR~~	~~m_j CR~~	m_{jj} SR	m_{jj} CR
0 b-tag	$m_{\ell\ell jj}$	MV1c	—	~~$m_{\ell\ell j}$~~	~~$m_{\ell\ell j}$~~	$m_{\ell\ell jj}$	$m_{\ell\ell jj}$
1 b-tag			—				
2 b-tag	$m_{\ell\ell jj}$	MV1c	$m_{\ell\ell jj}$				

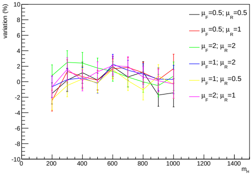
- Floating (all plots use SFs from fit)
  - μ(ggF) / μ(VBF) or μ(ggF+VBF)
    - For model-indep, fit 1 & profile other; for 2HDM, fit μ(ggF+VBF) with correct ratio
  - Sherpa Zl, Zbl, Zbc, Zhf(=bb,bc,cc)
  - Alpgen Z (uncorrelated to ggF)
  - Top (correlated between ggF/VBF)

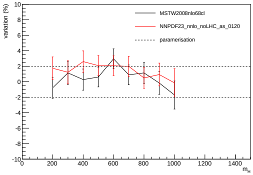


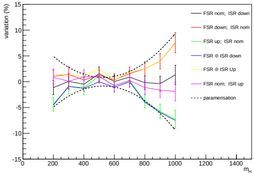
- Zbb same as public VHbb
- Agrees with 7 TeV Z+jets

Systematics: Experiment/Signal

- Experimental
  - **Lepton:** energy scale/resolution + efficiency
  - **Jet:** JES (14 NP + multijes) + JER + ptreco syst + JVF syst
  - *b*-**tag:**
    - 10 EV variations for l/b SFs; 15 for c SFs
    - Uncertainty on MC-to-MC b/c SF correction comparing sherpa to pythia8
    - Uncertainty on truth-tagging correction in ΔR_{jj} (from HSG5 *VHbb*)
  - $E_T^{\rm miss}$**:** Propagate object uncertainties to $E_T^{\rm miss}$ + soft scale/resol
  - **Lumi + pileup:** 2.8% lumi uncertainty + vary μ scale
- Signal: ISR/FSR, μ_F/μ_R, PDF + error on interference for EWS
  - ggF **untagged** below







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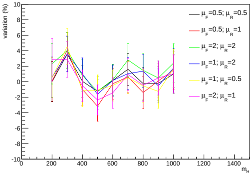

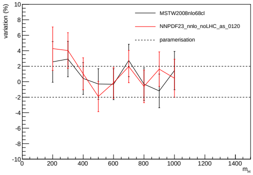

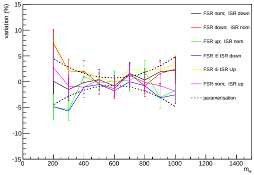

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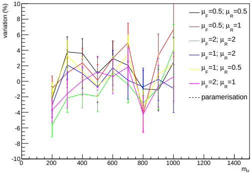
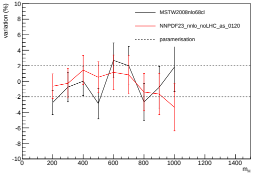
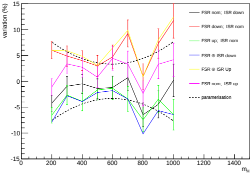
  - **VBF** below





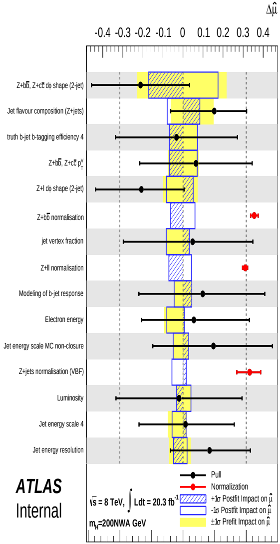


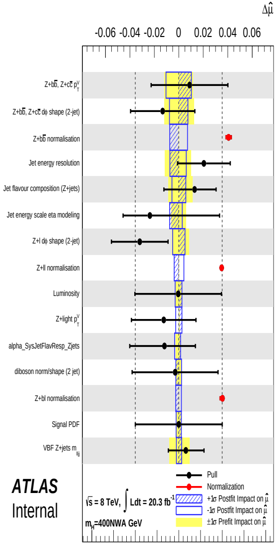
Systematics: Bkg Modelling

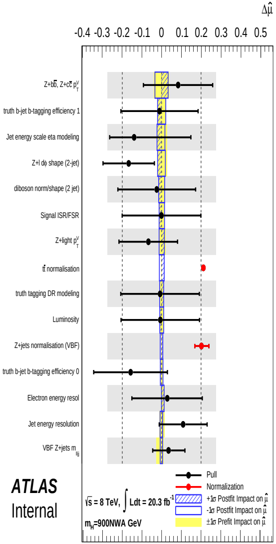
- **Z+jets:**
  - m_{jj} shape uncertainty from comparing data/MC in SB
  - ggF: Uncertainty on $\Delta\phi_{jj}$ & p_T^{ll} reweights (50/100%; $l/b+c$ uncorr)
  - VBF: Uncertainty on m_{lljj} reweight (100%)
- **$t\bar{t}$:**
  - m_{jj} shape uncertainty from comparing different generators/PDFs
  - $p_T^{t\bar{t}}$ shape uncertainty by reweighting to ATLAS 7 TeV result
- **Single top (Wt dominates):**
  - m_{jj} shape uncertainty from comparing Herwig/AcerMC
  - Norm uncertainty by varying μ_F/μ_R, α_s, PDF (7%)
- **Diboson:**
  - m_{jj} shape uncertainty from comparing Powheg and Herwig
  - Uncertainty on p_T^{ll} by comparing MC and NLO MCFM prediction via S-T
  - Norm uncertainty from varying α_s, PDF (3/4%)
- **QCD:** 50% norm uncertainty
- **MC Stats:** 1% threshold
- NP smoothed and small/noisy NP pruned using HSG5 *VHbb* method

NP Ranking

ggF at $m_H = 2/4/900$ GeV left/centre/right

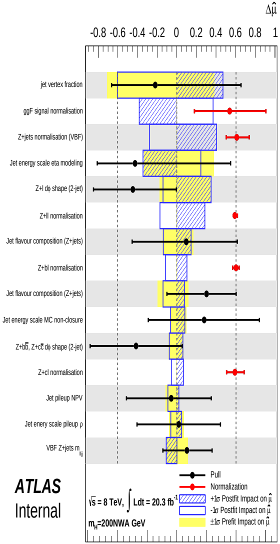


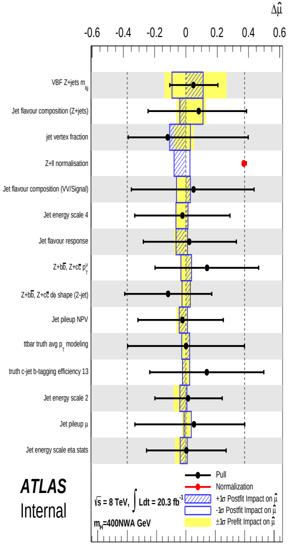


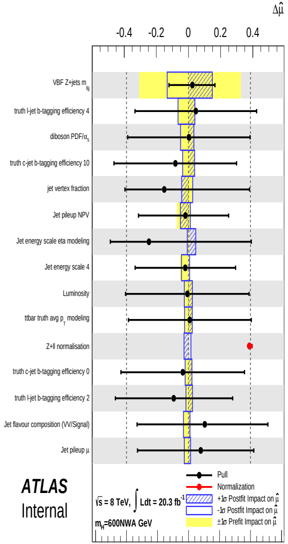


NP Ranking

VBF at $m_H = 2/4/600$ GeV left/centre/right



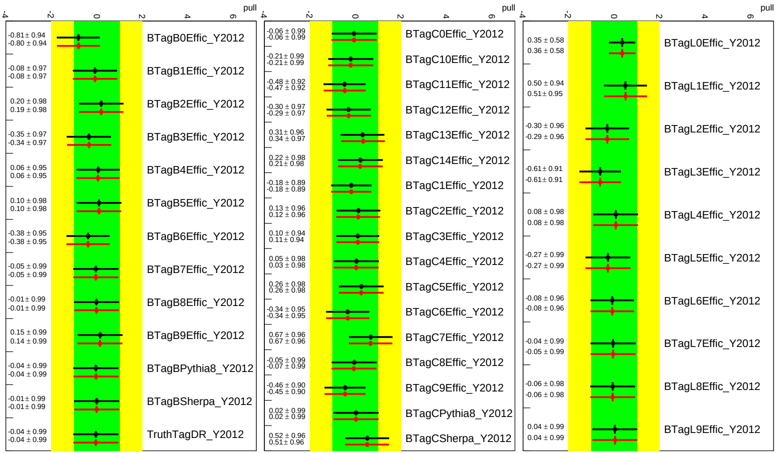




NP Pulls: *b*-tagging

ggF (black) and VBF (red) @ 400 GeV - pulls vs Asimov in backup

- Some small pulls/constraints in b-tagging but expected since fit MV1c so have power in analysis. Similar seen in HSG5 fits.

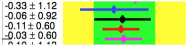


NP Pulls: Jets

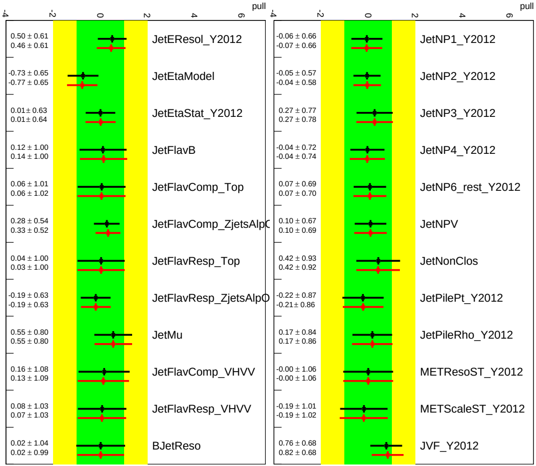
ggF (black) and VBF (red) @ 400 GeV - pulls vs Asimov in backup

- JER constrained
  - Not surprising as large stats in 0/1 tag and know overestimated
  - Also seen in Asimov fit

- JetFlavComp for Z+jets constrained a bit
  - Unsurprising as input is 50% g/q fraction with 100% error



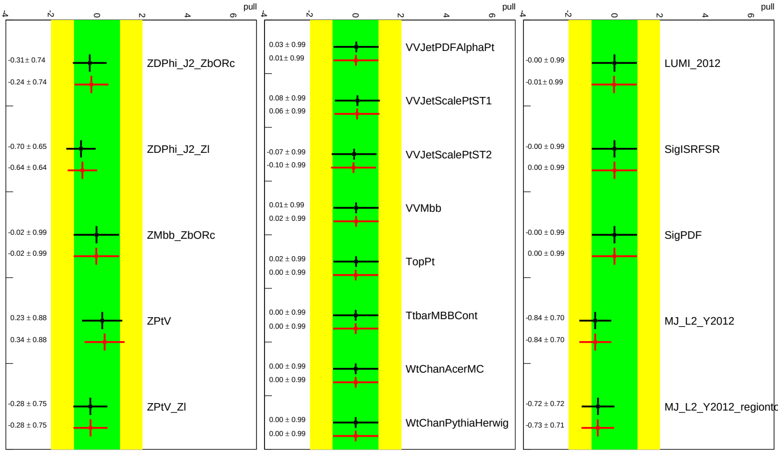
- JetNonClos pulled
  - Syst plots look OK



NP Pulls: Modelling

ggF (black) and VBF (red) @ 400 GeV - pulls vs Asimov in backup

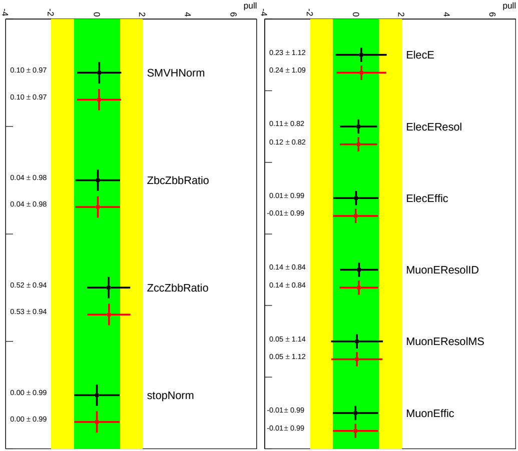
- Only significant constraint is on VBF m_{lljj} systematic
  - Comes from removing/doubling syst derived from SB so conservative



NP Pulls: Modelling/Leptons

ggF (black) and VBF (red) @ 400 GeV - pulls vs Asimov in backup

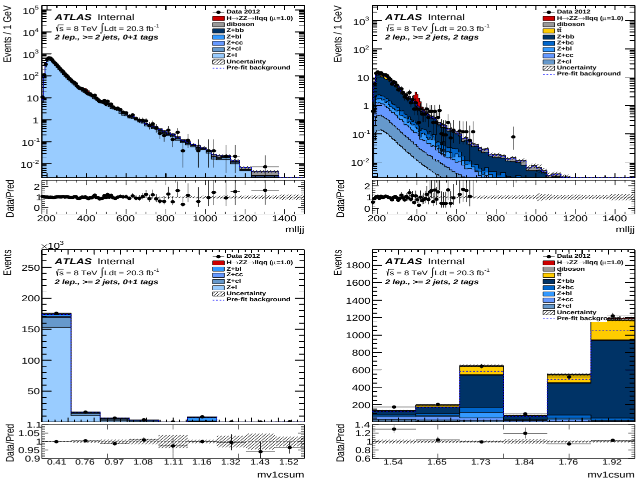
- Ratios are priors on flavour comps within $Zhf = (Zbb + Zbc + Zcc)$, from comparing generators



Post-fit plots (in fit binning)

Other variables in backup

- m_{lljj} in ggF SR (top) and MV1c sum in ZCR (bottom)
  - 0/1 tag (L) & 2 tag (R); signal for NWA with $m_H = 400$ GeV



Post-fit plots (in fit binning)

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- m_{lljj} in ggF Top CR (top) and VBF SR (bottom)
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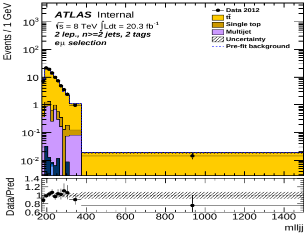
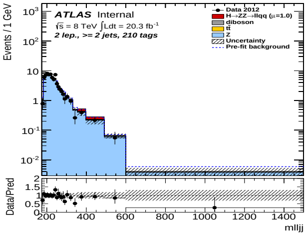
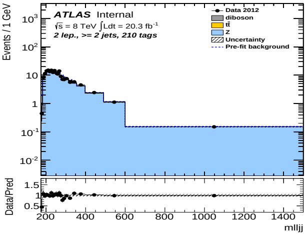


VBF SR

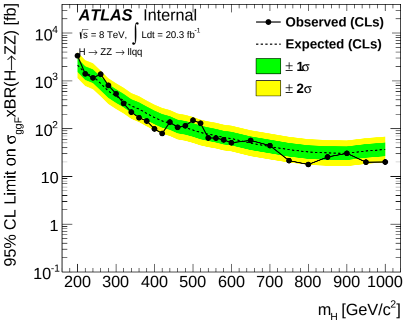


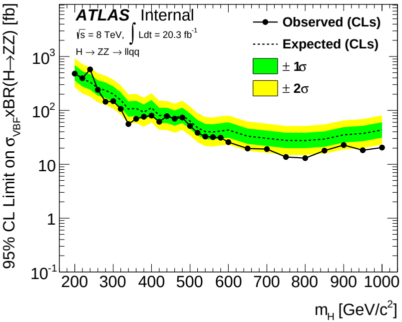
VBF ZCR



Model-independent Limits (bug)

- Limit on $\sigma \times$BR for NWA in both ggF and VBF channels





$\sigma_{ggF} \times \mathrm{BR}(H \to ZZ)$

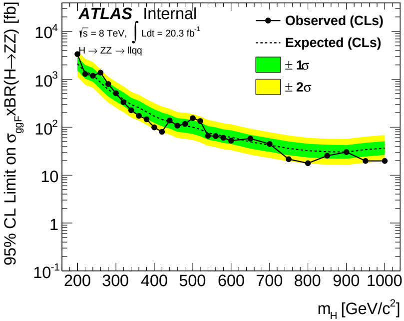
- 3347 fb (2215 fb) @ $m_H = 200$ GeV
- 19.9 fb (36.6 fb) @ $m_H = 1$ TeV

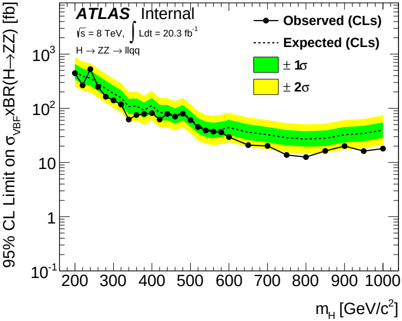
$\sigma_{VBF} \times \mathrm{BR}(H \to ZZ)$

- 443 fb (472 fb) @ $m_H = 200$ GeV
- 18.1 fb (39.7 fb) @ $m_H = 1$ TeV

Model-independent Limits (fixed)

- Limit on $\sigma \times$BR for NWA in both ggF and VBF channels





$\sigma_{ggF} \times \mathrm{BR}(H \rightarrow ZZ)$

- 3347 fb (2215 fb) @ $m_H = 200$ GeV
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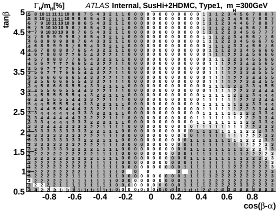
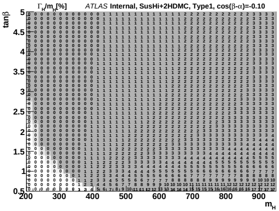
$\sigma_{VBF} \times \mathrm{BR}(H \rightarrow ZZ)$

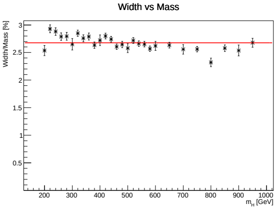
- 443 fb (472 fb) @ $m_H = 200$ GeV
- 18.1 fb (39.7 fb) @ $m_H = 1$ TeV

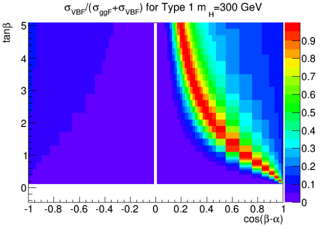
2HDM: Width & ggF:VBF

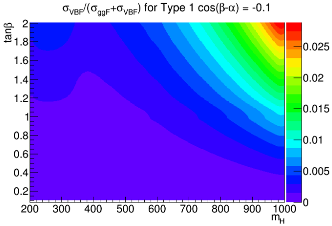
- Both width (T) and ggF:VBF ratio (B) vary across the 2HDM plane
  - Width is not negligible compared to experimental resolution ($\approx 3\%$)





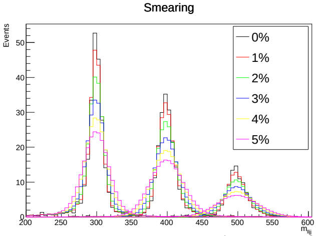






2HDM: Width procedure

- Cannot use CPS samples since are relatively small % width at low mH. Instead perform a BW smearing of NWA signals to account for non-zero natural width
  - Loop over each bin of signal hist and redistributing events according to BW, centred on bin centre with $\Gamma_H = m_H \times s$, where s=smearing factor and m_H=generated H mass
  - Doesn't account for interference but negligible if keep $\Gamma_H/m_H < 5\%$
    - Estimate using CPS samples at $m_H = 440 - 460$ GeV, where $\Gamma_H/m_H \approx 5\%$
    - Not fully correct as interference depends on m_H



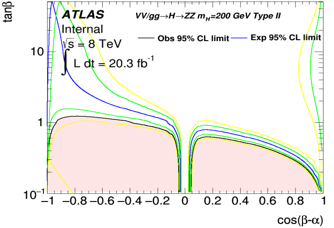
m_H	Interf	obs	-2σ	-1σ	exp	$+1\sigma$	$+2\sigma$
440	no	0.073	0.047	0.062	0.088	0.122	0.164
GeV	yes	0.073	0.047	0.065	0.088	0.126	0.166
460	no	0.098	0.052	0.070	00960	0.132	0.179
GeV	yes	0.098	0.052	0.070	00960	0.135	0.181

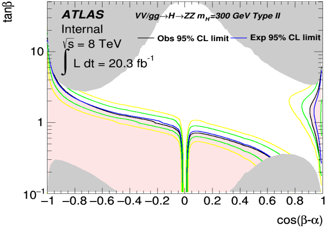
2HDM: Implementation

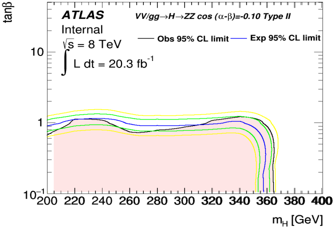
- To avoid computationally-intensive limit fits for each point in the 2HDM parameter space, instead do the following ...
- First extract limit as function of width/m_H and $\sigma_{VBF}/(\sigma_{ggF}+\sigma_{VBF})$
  - Smear m_{lljjj} with 0, 1, 2, 3, 4, 5, 6% (last to have a point beyond end)
  - For each of these the VBF fraction is varied from 0 to 1 in 0.1 steps
    - Need to divide out SM cross-section of course
  - Results in 77 fits for a given mass but won't do 2HDM $\tan\beta$ vs $\cos(\beta-\alpha)$ for many masses
    - Can ignore VBF for $\tan\beta$ vs m_H where sensitive (reduce fits)
- Use limits to construct TGraph2D of limit vs width & VBF fraction
- When draw 2HDM plot, find width/m_H & VBF fraction for each point & use this to look up limit in TGraph2D via Interpolate(x,y)
- Currently neglect bbH prod, which can be large at high $\tan\beta$
  - But $\sigma_{\mathrm{tot}} \times \mathrm{BR}(H \to ZZ)$ small $\to$ little effect on limit at $m_H = 200$ GeV, but completely dominated by 4l here; no effect at 300 GeV
  - Can add to ggF with diff in acceptance via gen-level study if needed

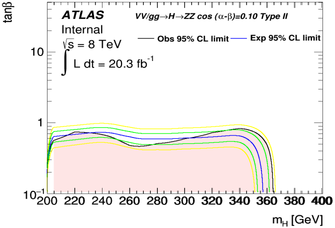
2HDM: Limits

- Results in $\tan\beta$ vs $\cos(\beta-\alpha)$ for 2/300 GeV and $\tan\beta$ vs m_H planes
  - Grey region is $\Gamma_H/m_H > 5\%$ where limit not valid (to add to m_H plot)





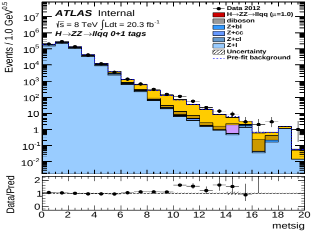


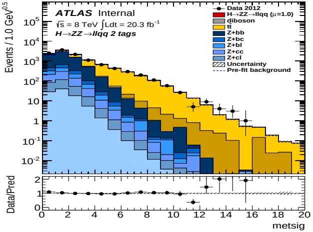


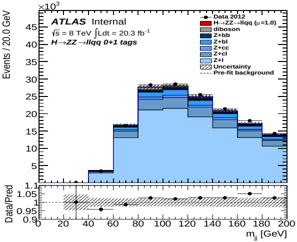
Summary

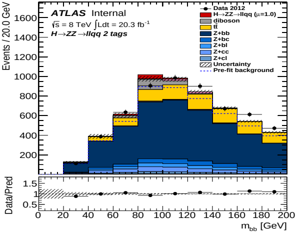
- Search for high-mass $H \to ZZ \to llqq$ in ggF and VBF very mature
  - Based on lots of work in HSG5 VHbb
  - Very similar to approved $A \to Zh \to llbb$
- Cuts and background modelling have been finalised for quite a while
- Main work recently on limit interpretations
  - Procedure fully setup up to incorperate width and ggf:VBF fraction
    - Common with $A \to Zh$
  - bbH can be added to ggF if needed but depends what done in 4l
  - EWS in progress in parallel but don't want to hold up the paper
- To do
  - EWS interpretation (in parallel)
  - Merged regime
  - Combination
    - Have first model-indep results and 2HDM in progress
  - Paper
    - Aim for good first draft in $\sim$ mid-January

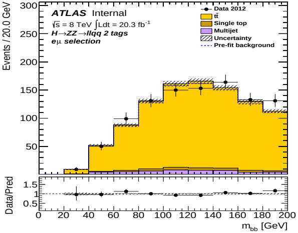
ggF Post-fit plots: METSig, m_{jj}



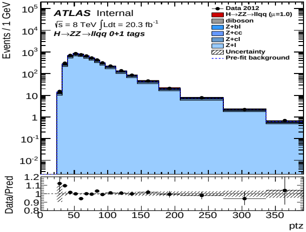


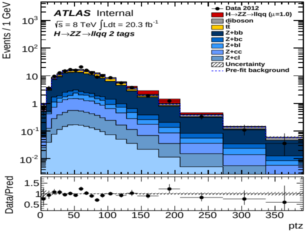


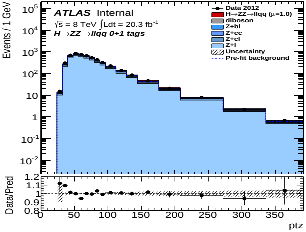


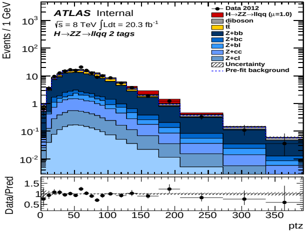


ggF Post-fit plots: p_T^{ll}

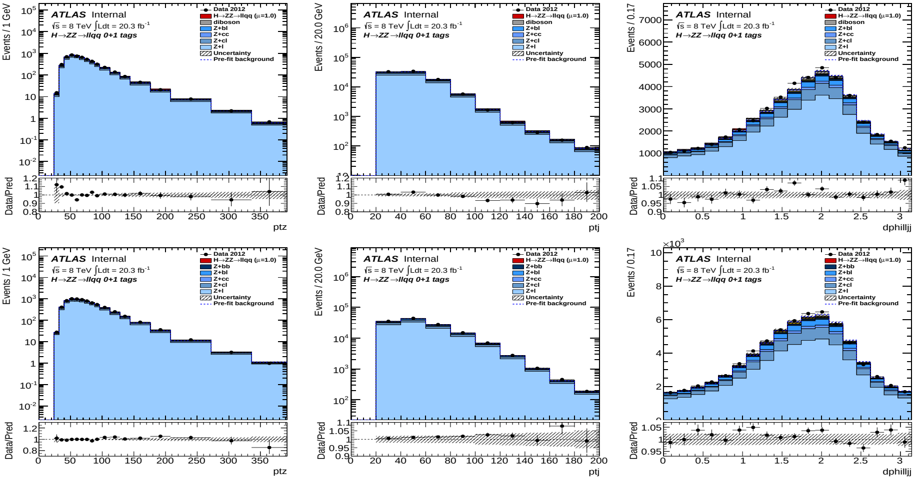




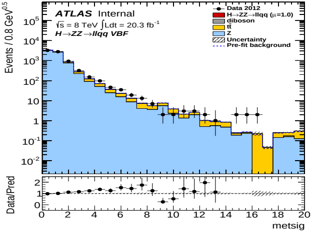


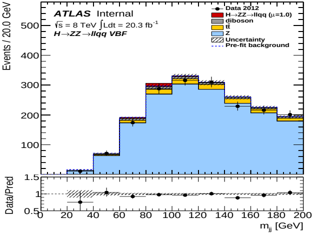


ggF Post-fit plots: $p_T^J, \Delta\phi_{ll}$

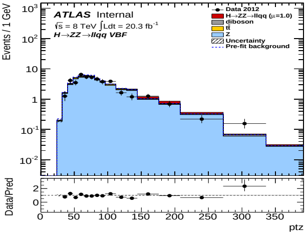


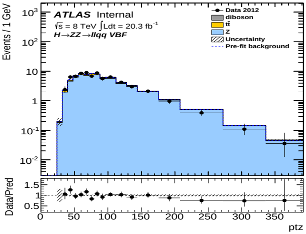
VBF Post-fit plots: METSig,m_{jj}



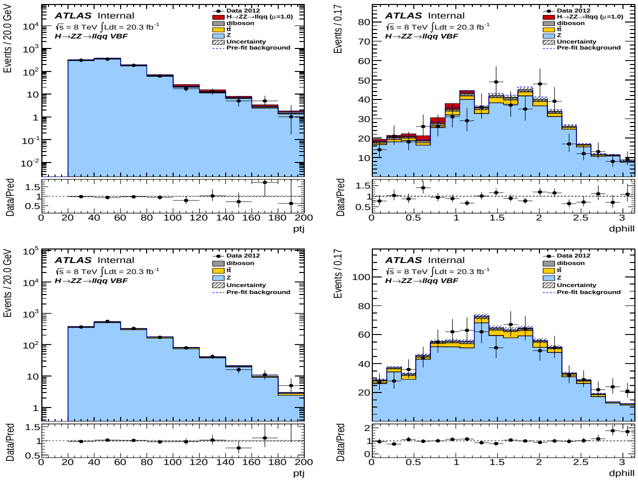


VBF Post-fit plots: p_T^{ll}

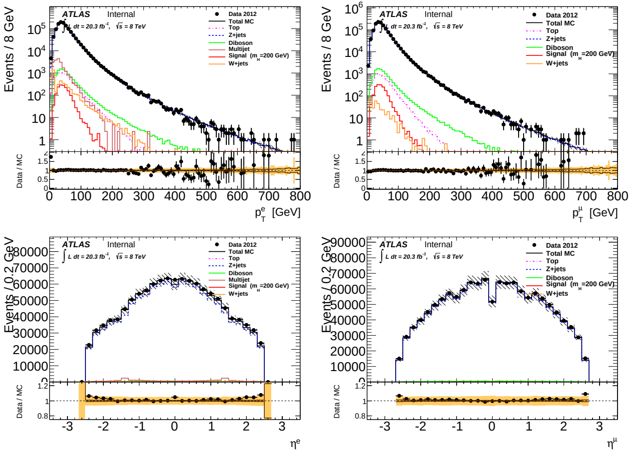




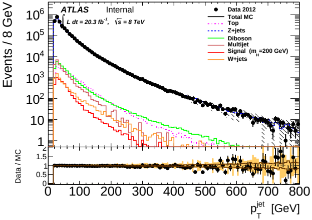
VBF Post-fit plots: $p_T^J, \Delta\phi_{ll}$

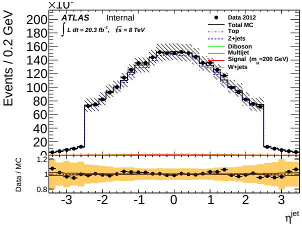


Kinematics: leptons



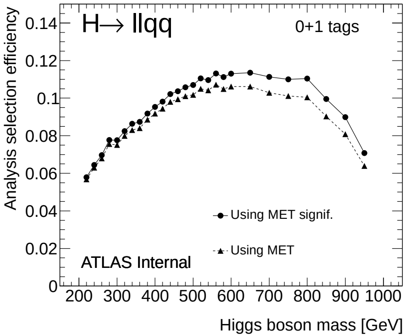
Kinematics: jets

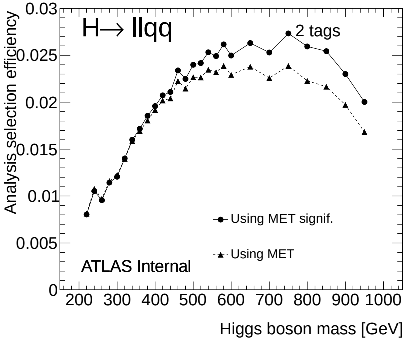




E_T^{miss} significance

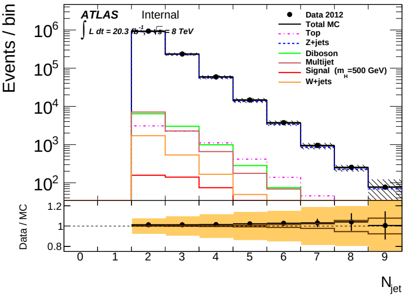
- Improves signal efficiency at high m_H without affecting bkg rejection

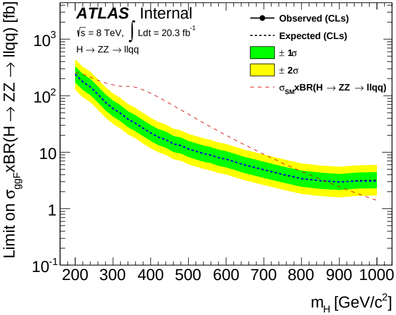




$N_{\rm jet}$

- Check effect of $N_{\rm jet}$ description on exp limit by reweighting MC to match data
  - Compare blue deashed line to black dashed line
  - Very small effect ($\sim 1\%$) at lowest/highest m_H





ggF/VBF Efficiency

- No apriori ratio of ggF to VBF cross-section (except 2HDM)
- Efficiency for each channel and ratio below:

m_H (GeV)	ggF channel			VBF channel		
	ϵ_{ggF}	ϵ_{VBF}	$\epsilon_{ggF}/\epsilon_{VBF}$	ϵ_{ggF}	ϵ_{VBF}	$\epsilon_{VBF}/\epsilon_{ggF}$
200	4.06	2.09	1.94	0.11	1.66	14.95
400	11.56	5.52	2.09	0.20	3.12	15.48
600	13.44	7.45	1.80	0.32	4.36	13.63
800	12.35	7.55	1.64	0.40	4.12	10.30
1000	7.49	4.92	1.52	0.27	2.24	8.21

$h(125)$ + Real EW Singlet Model

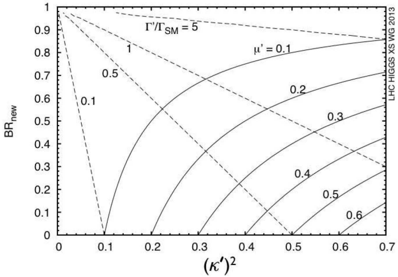
- Heavy real singlet couplings rescaled from SM CPS signal
- Scan in two parameters for each m_H and set upper limit on $\sigma \times \mathrm{BR}$
  - H_{new} **coupling:** κ' ($\kappa = h_{125}$ coupling)
    - Constrained by: $\kappa_V'^2 + \kappa_V^2 = 1$ where $\kappa \equiv \kappa_V = \kappa_f = \sqrt{\mu}$
  - $\mathrm{BR}_{\mathrm{new}}$: new decay modes, e.g. to additional Higgses

$$\mu' = \frac{\sigma' \times \mathrm{BR}'}{\sigma_{\mathrm{SM}} \times \mathrm{BR}_{\mathrm{SM}}} = \kappa'^2(1 - \mathrm{BR}_{\mathrm{new}})$$

$$\sigma' = \kappa'^2 \sigma_{\mathrm{SM}}$$

$$\Gamma' = \frac{\kappa'^2}{1 - \mathrm{BR}_{\mathrm{new}}} \Gamma_{\mathrm{SM}}$$

$$\mathrm{BR}' = (1 - \mathrm{BR}_{\mathrm{new}})\mathrm{BR}_{\mathrm{SM}}$$



- Width may be narrower/wider than SM; restrict to $\Gamma'_{\mathrm{NWA}} \leq \Gamma' \leq \Gamma'_{\mathrm{SM}}$
- Some constraints already from experimental measurements of μ

EW Singlet Tools

- Need to scan width and account for interference
  - Natural width sizable contribution to $S + B$ interference
- Interference for nominal CPS SM width (also $H \to WW$)
  - **ggF:** HTO Passarino results (Gen)
  - **VBF:** Results from REPOLO in VBF@NLO (Rikard et al)
- Width reweight for EW singlet scan (also $H \to WW$)
  - Lineshape predictions from POWHEG (Sara)
- Interference reweight for width scan
  - As width changes, the amount of interference also changes
  - **ggF:**
    - Results from gg2VV (Scott)
    - ($H \to WW$ using MCFM but doesn't do ZZ final state)
  - **VBF:**
    - Results from REPOLO in VBF@NLO (Rikard et al)

2HDM Model

- Two identical complex scalar fields ($SU(2)$)
- The 2HDM scalar potential is a Z_2 broken symmetric 2HDM:

$$\begin{aligned} V(\Phi_1,\Phi_2) = {} & m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 + (m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c}) \\ & + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\ & + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c}] \end{aligned}$$

- We are interested in the CP-conserving case $\rightarrow$ parameters are:
  - 3 masses: $m_h, m_H, m_{H^\pm}, m_A,$
  - 2 angles: α, β
  - 1 potential parameter: m_{12}^2
- Each parameter set gives specific predictions for σ/BR for h/H
- Follow method for benchmark points setup by HSG6
  - Common with $H \rightarrow WW$

2HDM Benchmarks

Recipe compatible with current knowledge on h:

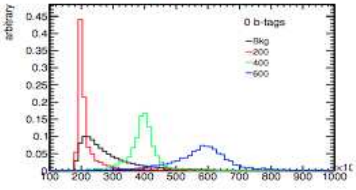
- Light Higgs is 125 GeV CP-even particle
- m_A and $m_H^{\pm}$ large, equal to m_H
  - Except very low m_H hypothesis where keep them above 300 GeV.
- Scan over m_H, $\cos(\beta - \alpha)$ and $tan\beta$ planes
  - Restrict $\cos(\beta - \alpha) \sim 0 \rightarrow h$ compatible with SM rates.
  - Explore both positive and negative quadrants
- Fix m_{12}^2
  - $m_{12}^2 = 0$ (exact Z_2 symmetry)
  - $m_{12}^2 = f(m_A, \tan\beta)$ (softly broken Z_2 symmetry e.g. MSSM)
- Do this for both Type I and II (no FCNC)

Optimisation: Cuts vs m_H

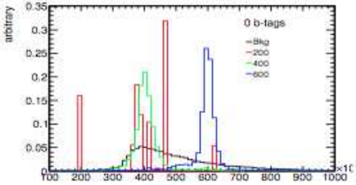
Applying kinematic selection makes $m(\ell\ell jj)$ distribution of background look more like signal.

Generally, applying cuts optimized for a given Higgs mass results in the background peaking around the same mass.

$m(\ell\ell jj)$, precuts only



$m(\ell\ell jj)$, after $m_H = 400$ GeV cuts



Optimisation: p_T^Z

- Calculate signif for 90% window arround m_{lljj} peak for sliding cut
- Fit optimal cut value vs m_{lljj}

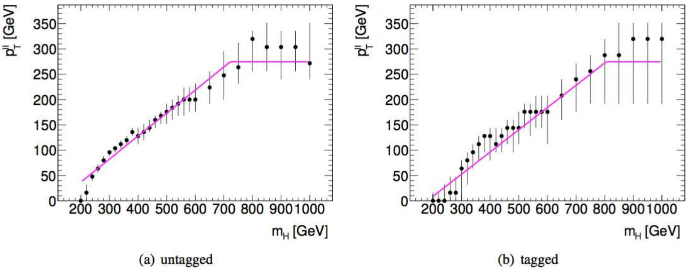
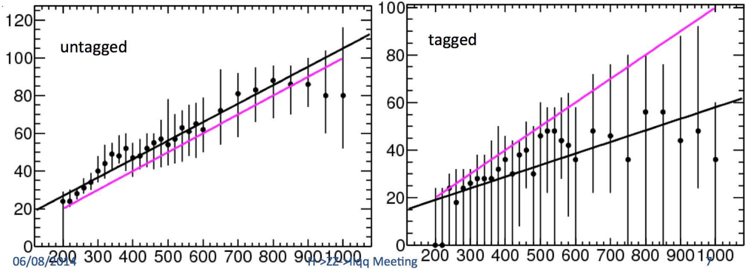


Figure 57: Results of the ${p_T}^{\ell\ell}$ selection optimization for the untagged and tagged cases. The points are the optimal cut values, as a function of m_H, and the error bars show the range in which the significance is the same within uncertainties. The magenta line is the result of a linear fit, which is then cut off at 275 GeV as inidcated.

Optimisation: p_T^j (after p_T^Z)

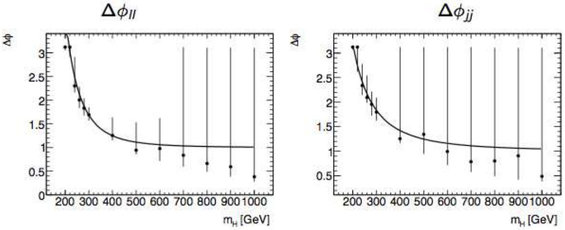
- Calculate signif for 90% window arround m_{lljj} peak for sliding cut
- Fit optimal cut value vs m_{lljj}



Optimisation: $\Delta\phi$

- Calculate signif for 90% window arround m_{lljj} peak for sliding cut
- Fit optimal cut value vs m_{lljj}

  - No gain in applying $\Delta\phi_{ll}$ ($\Delta\phi_{jj}$) from 700 (400) GeV
    - Reminder: point is max signif. but errors indicate where signif. same within uncertainty
  - Can apply funciton tending to 1 so no affect at high m_{llqq}



  - Can gain from $\Delta\phi_{ll}$ in intermediate m_H.

Optimisation: Shape-sensitive (1)

- Would like to fully take the shape of the mass peak into account in the significance calculation, rather than just doing a counting experiement in a window around the peak.
- If we imagine simultaneously normalizing the signal and background to the data, this will automatically penalize cuts that make the background look too much like the signal.
- Extend current aymptotic formula used for significance.
- Currently using eq. (97) from the asymptotic paper:

$$\mathrm{med}[Z_0] = \sqrt{q_{0,A}} = \sqrt{2((s+b)\ln(1+s/b)-s)} \tag{2}$$

- Comes from discovery significance

$$q_0 = -2\ln L(0)/L(\hat{\mu}); \qquad L(\mu) = \mathrm{pois}(n; \mu s + b) \tag{3}$$

evaluated at the Asimov value $n = s + b$. This can be done analytically and yields (97). (The asymptotic approximation is that the significance $Z_0 \approx \sqrt{q_0}$.)

Optimisation: Shape-sensitive (2)

- Extend likelihood for a binned histogram and add a nuisance parameter for the background strength:

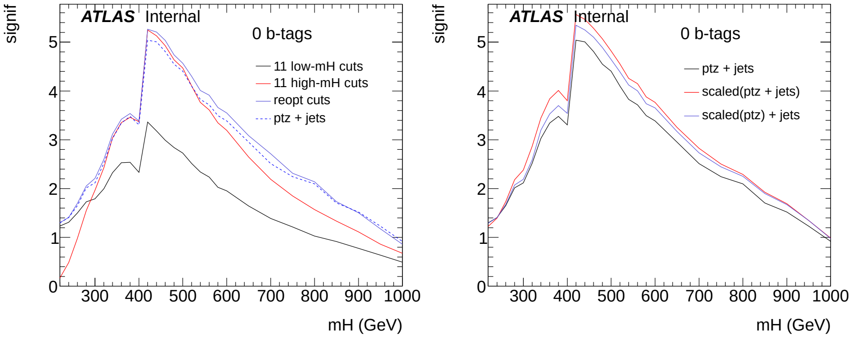
$$L(\mu, \theta) = \prod_i \text{pois}(n_i; \mu s_i + \theta b_i) \qquad (4)$$

- Then

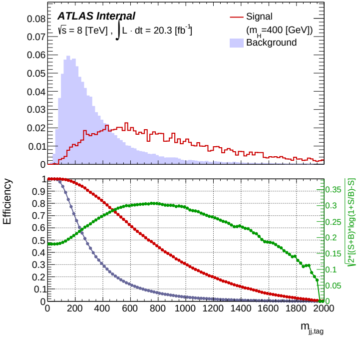
$$q_0 = -2 \ln L(0, \hat{\hat{\theta}})/L(\hat{\mu}, \hat{\theta}) \qquad (5)$$

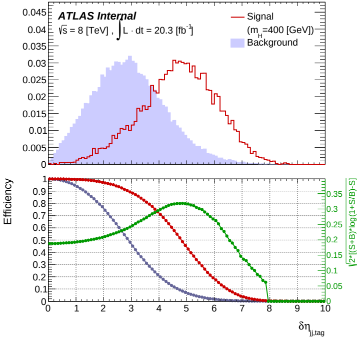
- Evaluate at $n_i = s_i + b_i$. Denominator is maximum of L; occurs at $\hat{\mu} = \hat{\theta} = 1$. Numerator is evaluated at the maximum in θ with $\mu = 0$; need to do this numerically.
- Difficulty: Bins with very low b_i (due to low background statistics) can give a large contribution to significance. Control by cutting off the high end of the mass distribution 3σ above the mean higgs signal mass, and by ignoring bins with unreasonably small backgrounds.

Optimisation: Results

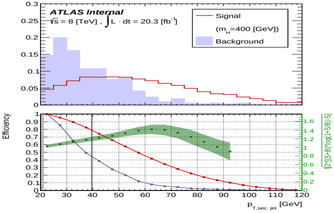


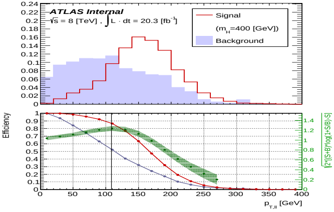
Optimisation: VBF m_{jj} and $\Delta\eta_{jj}$

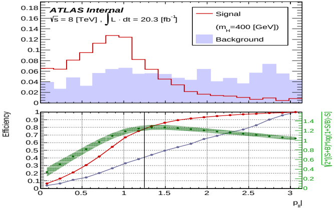




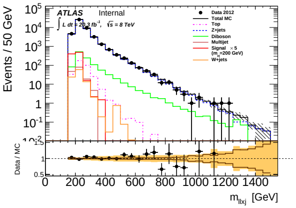
Optimisation: VBF $\Delta\phi_{jj}$, p_T^{ll}, p_T^j

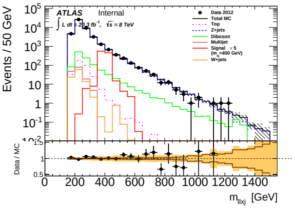


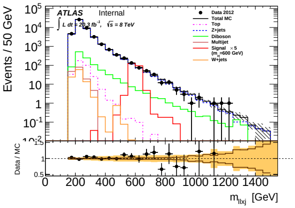


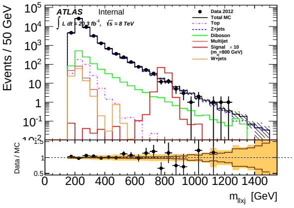


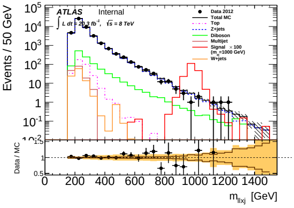
m_{lljj} ggF untagged



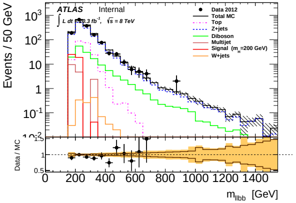


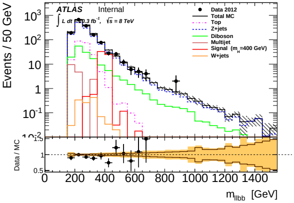


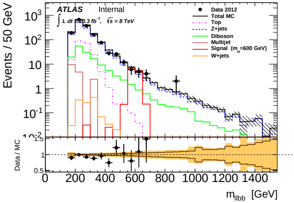


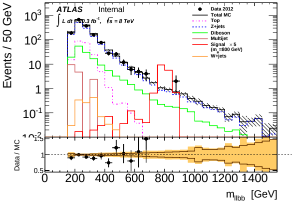


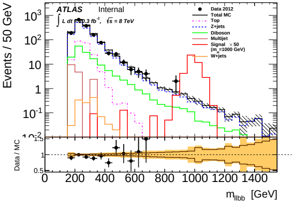
m_{lljj} ggF tagged



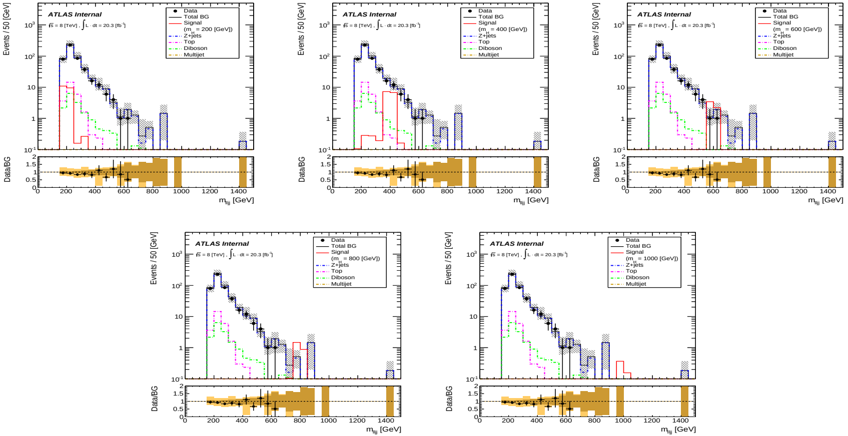






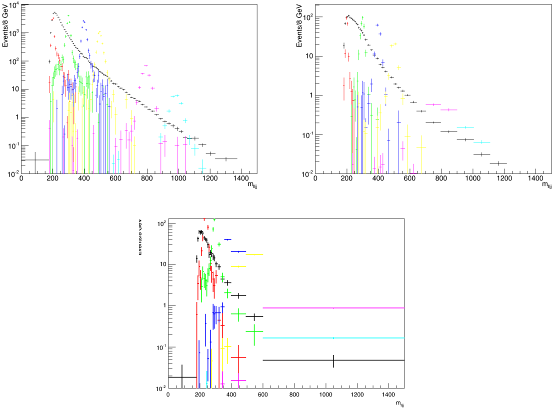


m_{lljj} VBF

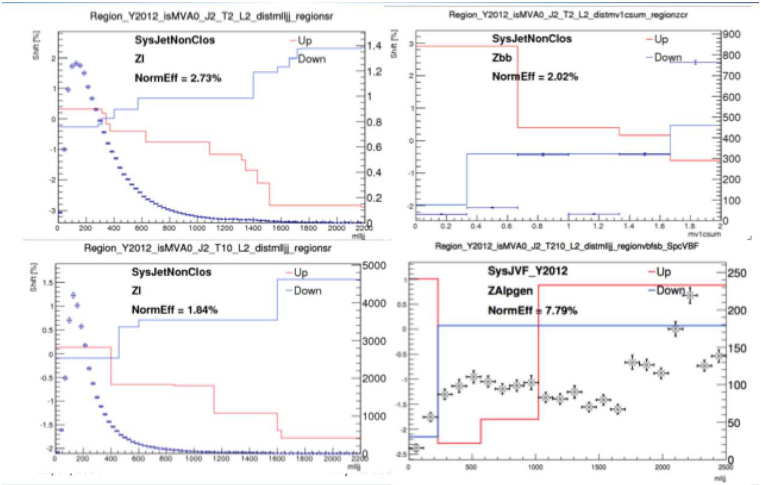

ATLAS Internal
$\sqrt{s}$ = 8 [TeV] , $\int L \cdot dt$ = 20.3 [fb^{-1}]
Data
Total BG
Signal
(m_H = 200 [GeV])
(m_H = 400 [GeV])
(m_H = 600 [GeV])
(m_H = 800 [GeV])
(m_H = 1000 [GeV])
Z+jets
Top
Diboson
Multijet
Events / 50 [GeV]
Data/BG
m_{lljj} [GeV]

m_{jj} binning

- Non-equidistant binning to keep backgroun uncertainties reasonable
  - ggF untagged (TL) and tagged (TR); VBF (bottom)



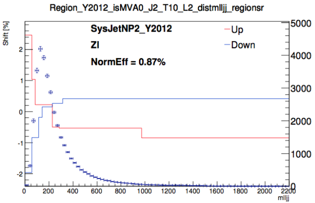
JetNonClosure



NP smoothing

To mitigate these effects, two so-called "smoothing" algorithms (developed by HSG5) are used to merge consecutive bins in the MC templates. First, bins from one extremum to the next are merged until at most one local extremum remains in the $m_{\ell\ell jj}$ distribution. If there are more than two extrema, merging is performed at each step of this iterative process where the difference between merged and unmerged templates is smallest. Second, the bins resulting from this first algorithm are sequentially merged, starting from the upper end of the distribution, until the statistical uncertainty in each of the merged bins, calculated in the nominal template, is smaller than 5%. In each of these sets of bins, the integrals of the nominal and systematically shifted distributions are compared to give the $\pm 1\sigma$ variation. This value is then used as the associated uncertainty for all the nominal bins in the set. Figure 31 shows such a rebinned distribution.

In the MV1c distribution, it does not make sense to merge neighbouring bins since the MV1c distribution is discrete and hence the smoothing procedure described above is not applied.

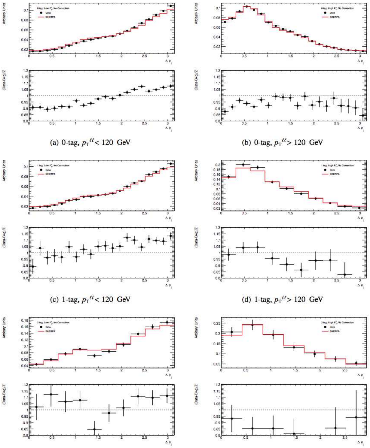


NP pruning

- Reduce statistical fluctuations by the smoothing procedure described in Section 8.1.7 only for those systematic which require a re-sampling of the events (i.e. JES and not b-tagging)
- Neglect the normalization uncertainty for a given sample in a region if either of the following is true:
  - the variation is less than 0.5%
  - both up and down variations have the same sign
- Neglect the shape uncertainty for a given sample in a given region if either of the following is true:
  - not one single bin has a deviation over 0.5% after the overall normalization is removed
  - if only up or the down variation is non-zero and passed the previous pruning steps
- Neglect the shape and normalization uncertainty for a given sample in a given region if the sample is less than 2% of the total background:
  - if the signal < 2% of the total background in all bins and the shape and normalization error are each < 0.5% of the total background
  - if at least one bin has a signal contribution > 2% of the total background, only in those bins where the shape and normalization error are each < 2% of the signal yield

In the ggF Z control region, where the MV1c distribution (which cannot be smoothed as mentioned in Section 8.1.7) is fitted, the only pruning performed is to remove one-sided systematics in a given MV1c bin.

$\Delta\phi_{jj}$ (before corrections)



(a) 0-tag, $p_T^{\ell\ell} < 120$ GeV

(b) 0-tag, $p_T^{\ell\ell} > 120$ GeV

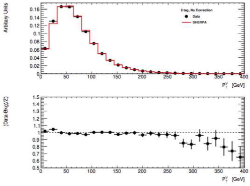
(c) 1-tag, $p_T^{\ell\ell} < 120$ GeV

(d) 1-tag, $p_T^{\ell\ell} > 120$ GeV

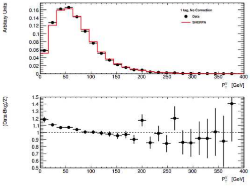
(e) 2-tag, $p_T^{\ell\ell} < 120$ GeV

(f) 2-tag, $p_T^{\ell\ell} > 120$ GeV

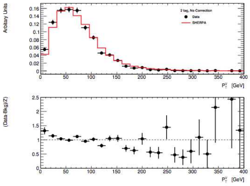
p_T^{ll} (after $\Delta\phi_{jj}$ corrections)



(a) 0-tag

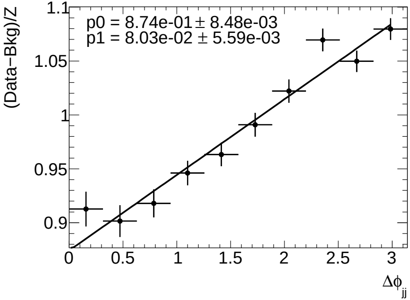


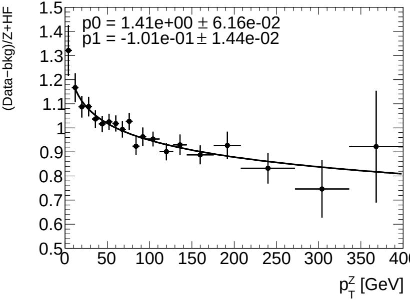
(b) 1-tag



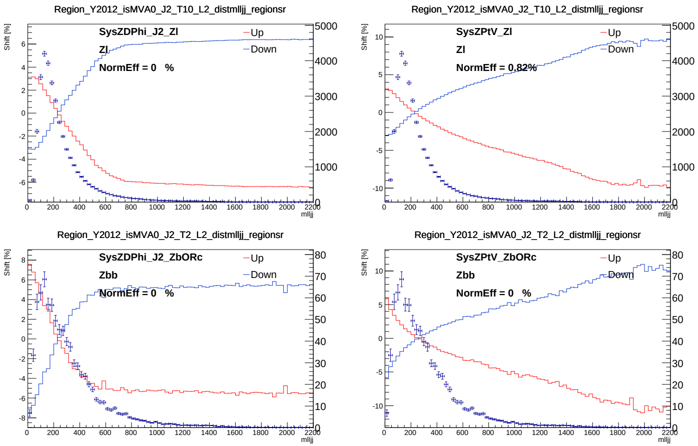
(c) 2-tag

$\Delta\phi_{jj}$ and p_T^{ll} reweight

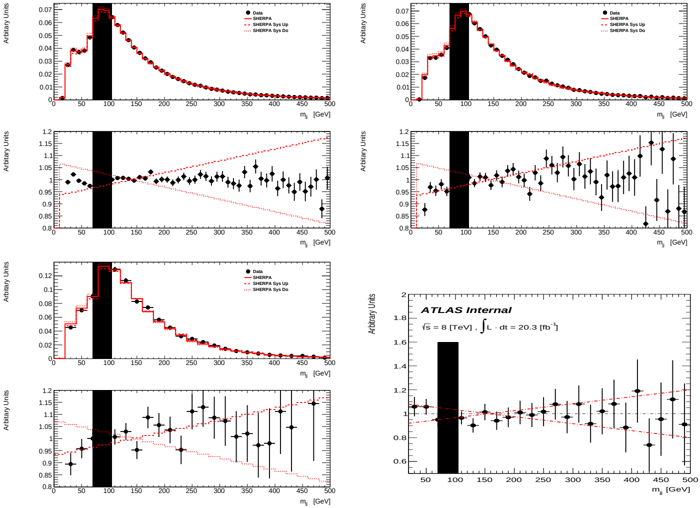




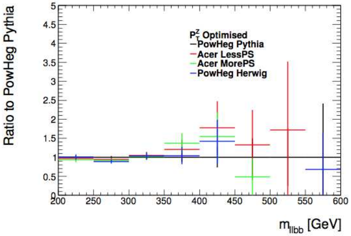
$\Delta\phi_{jj}$ and p_T^{ll} errors on m_{lljj}



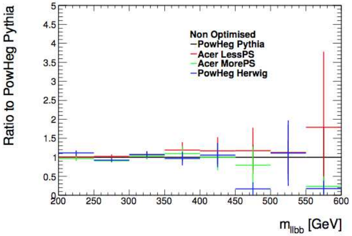
m_{jj} systematic



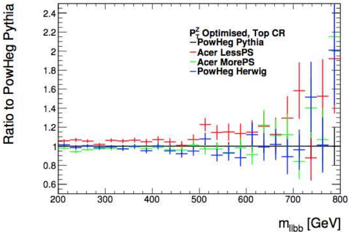
Top Systematics: MC comp



(a) p_T^Z Optimised



(b) Non-optimised



Top Systematics: Effect on m_{lljj}

- Effect of p_T & m_{jj} uncertainty on m_{bb} & m_{lljj} shape (from $A \to Zh$)

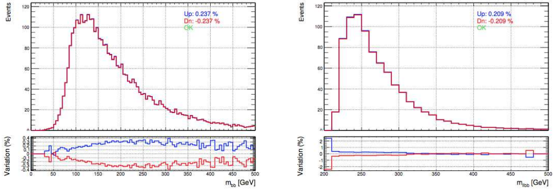


Figure 80: The effect on the total background of the systematic SysTopPt for the m_{bb} (m_{llbb}) distributions left(right).

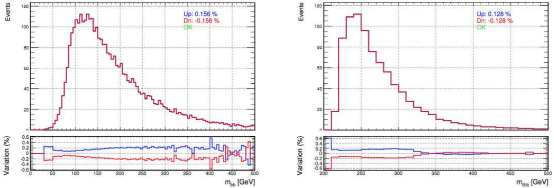


Figure 81: The effect on the total background of the systematic SysTtbarMBBCont for the m_{bb} (m_{llbb})

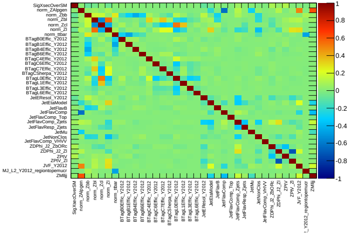
MC Statistical Errors

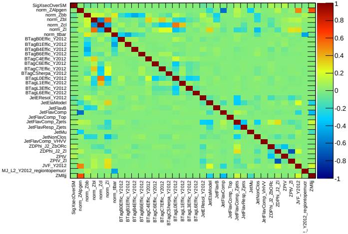
- Adding in the bin-by-bin MC statistical errors degraded the limit at low m_H but has lee effect at high m_H
  - As expected since have low stats for inclusive Z+jets MC but more for higher p_T^V slices
- Tried different thresholds fro including MC stats errors in a bin
  - Choose 1% threshold as negligible change to limit going lower

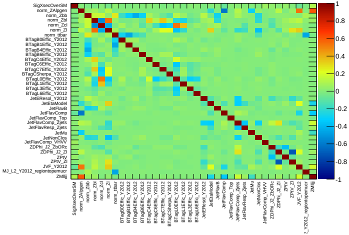
mass [GeV]	No stat	Stat 5%	Stat 1%	Stat 0%
200	245.79	253.93	272.81	272.83
300	59.33	59.43	62.78	62.78
400	22.31	22.44	23.03	23.03
500	12.07	12.17	12.35	12.35
600	8.11	8.25	8.26	8.26
700	5.62	5.65	5.65	5.65
800	4.29	4.29	4.30	4.30
900	4.08	4.09	4.09	4.09
1000	5.05	5.07	5.07	5.07

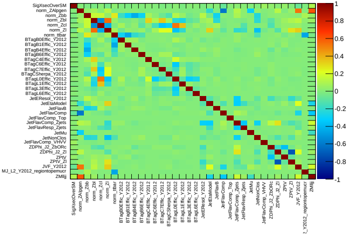
NP correlations ($> 25\%$)

- ggF (top) and VBF (bottom); Asimov (left) and data (right)



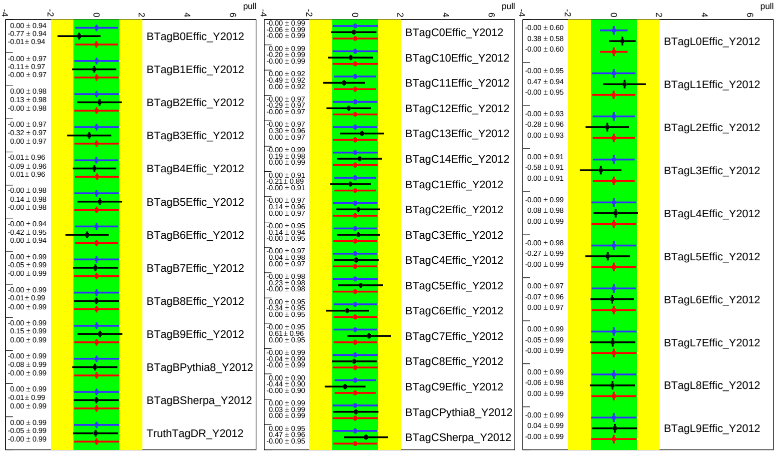






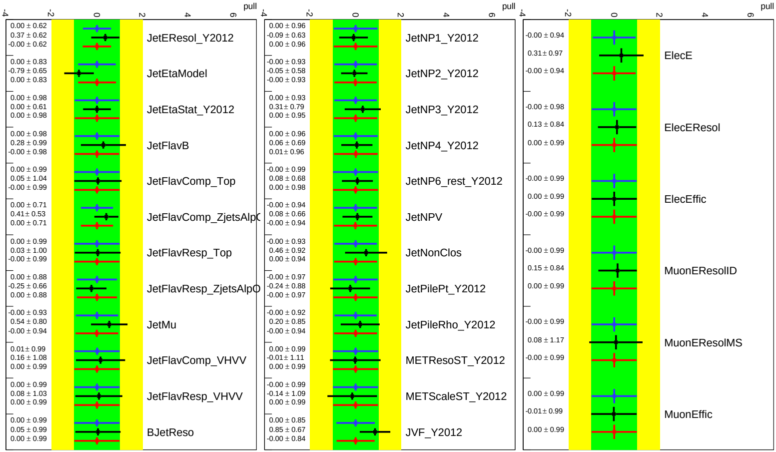
ggF pulls @ 200 GeV (1)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



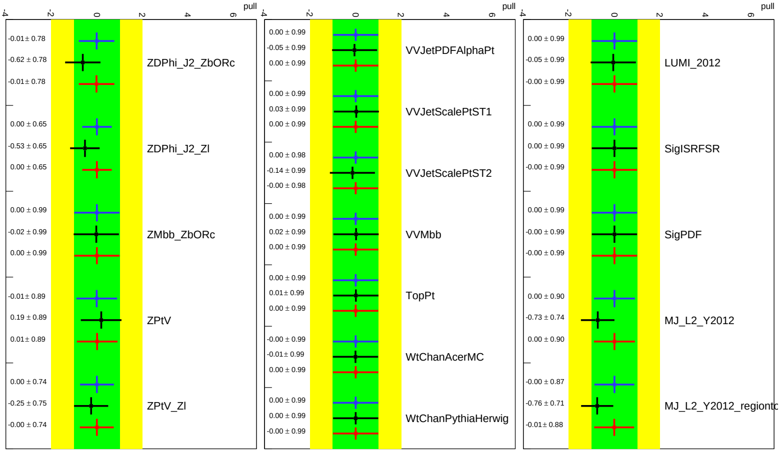
ggF pulls @ 200 GeV (2)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



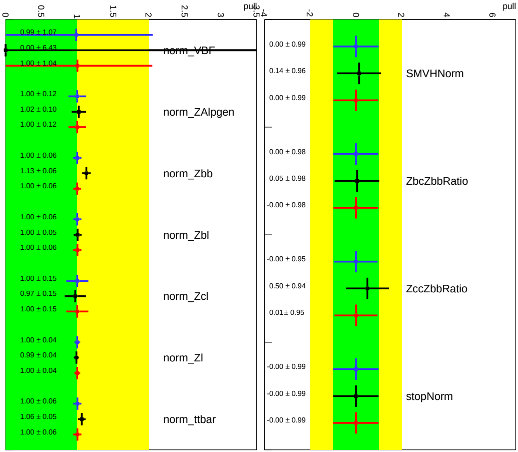
ggF pulls @ 200 GeV (3)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



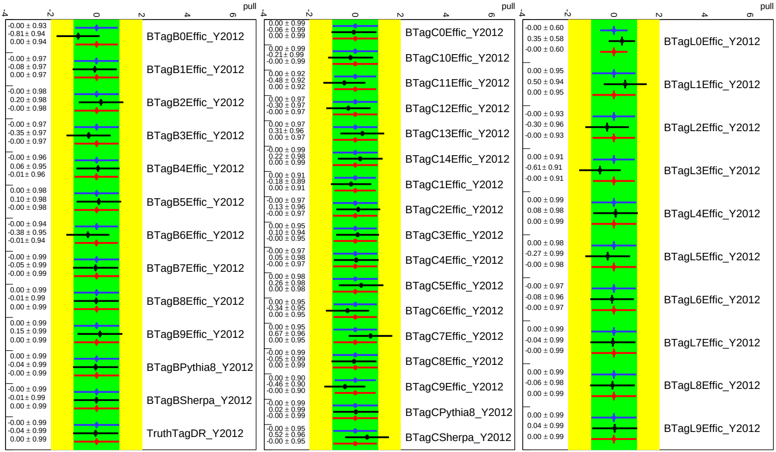
ggF pulls @ 200 GeV (4)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



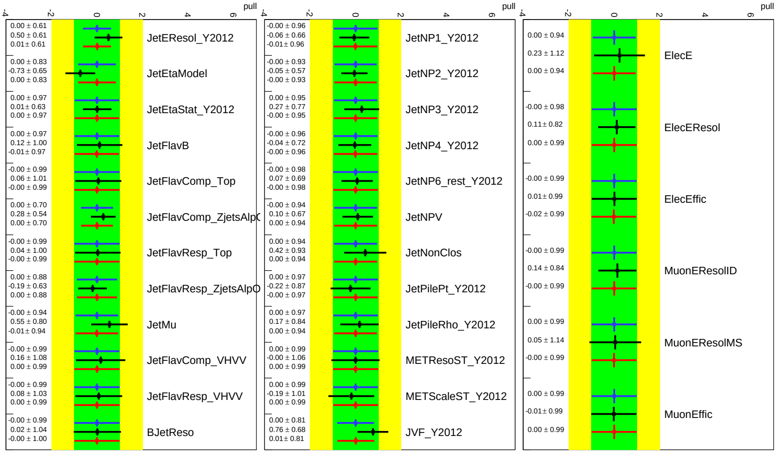
ggF pulls @ 400 GeV (1)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



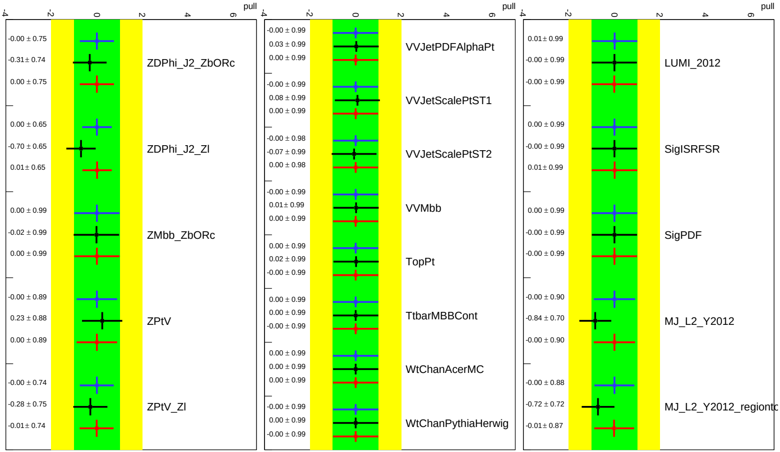
ggF pulls @ 400 GeV (2)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



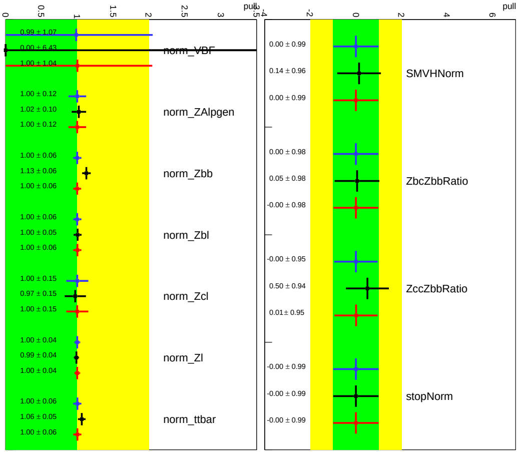
ggF pulls @ 400 GeV (3)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



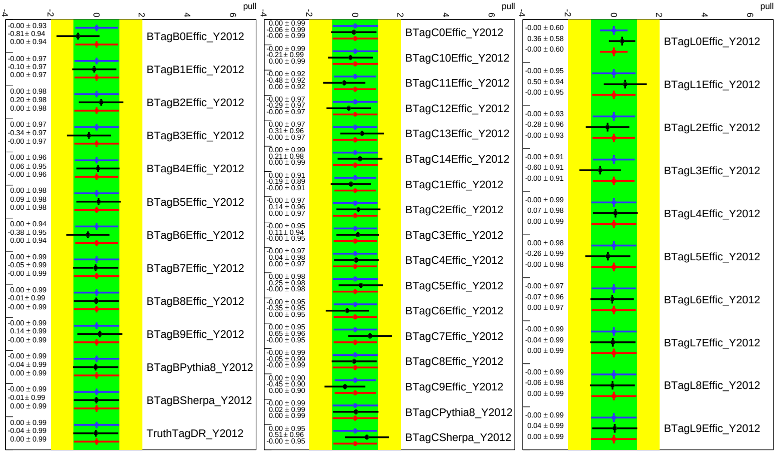
ggF pulls @ 400 GeV (4)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



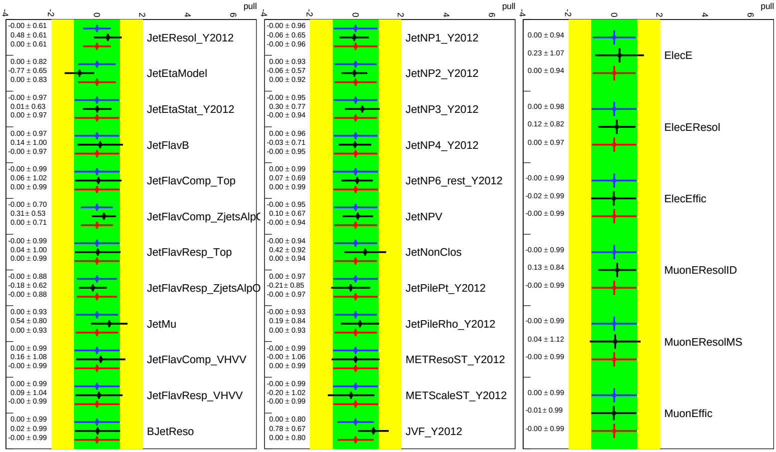
ggF pulls @ 900 GeV (1)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



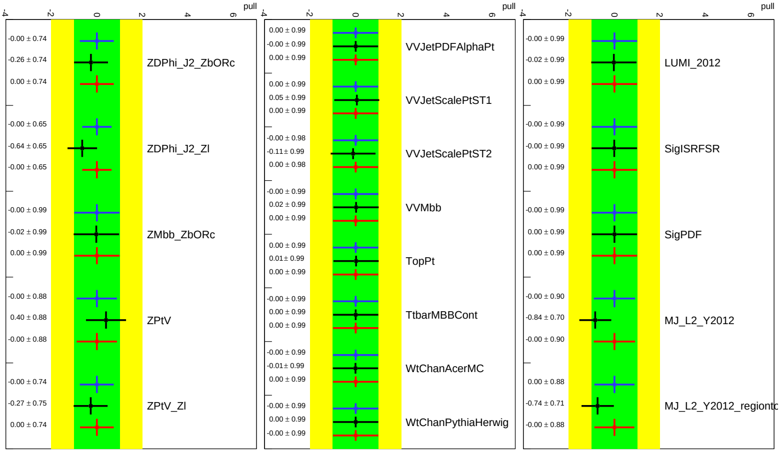
ggF pulls @ 900 GeV (2)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



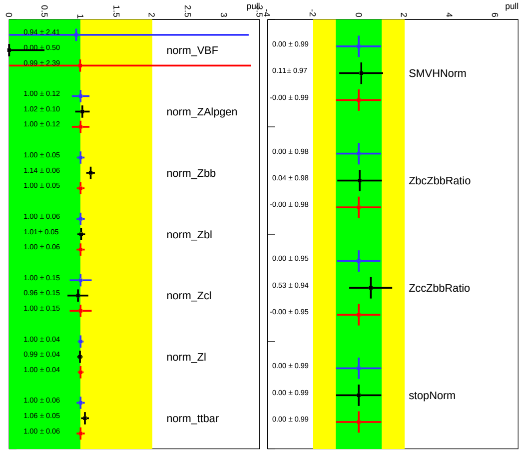
ggF pulls @ 900 GeV (3)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



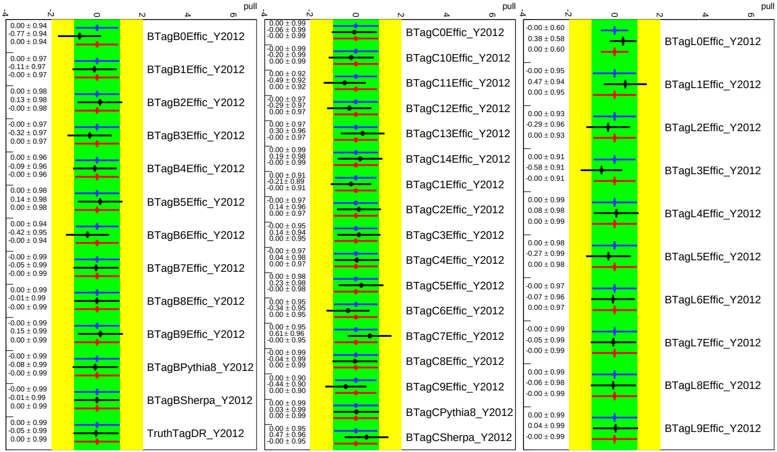
ggF pulls @ 900 GeV (4)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



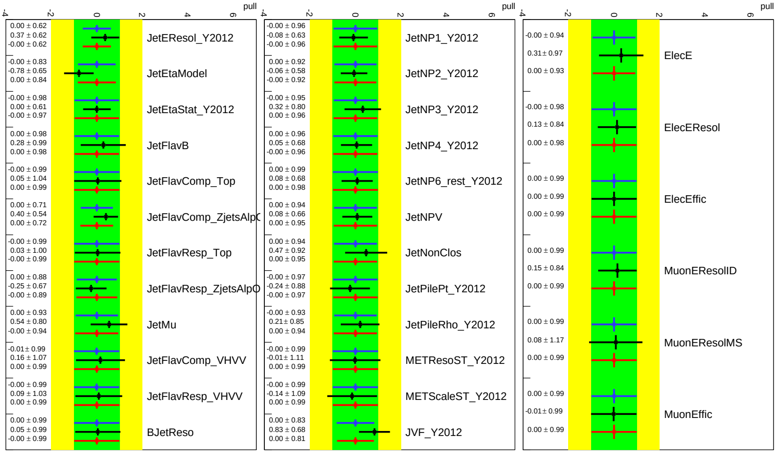
VBF pulls @ 200 GeV (1)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



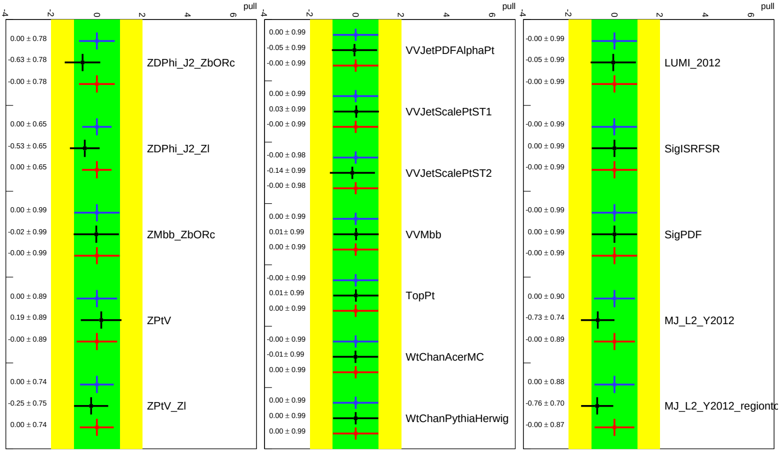
VBF pulls @ 200 GeV (2)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



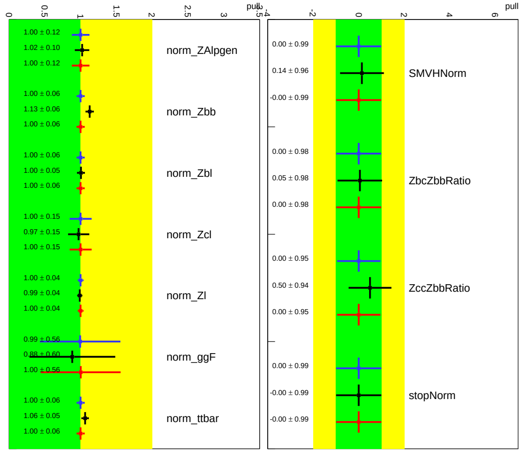
VBF pulls @ 200 GeV (3)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



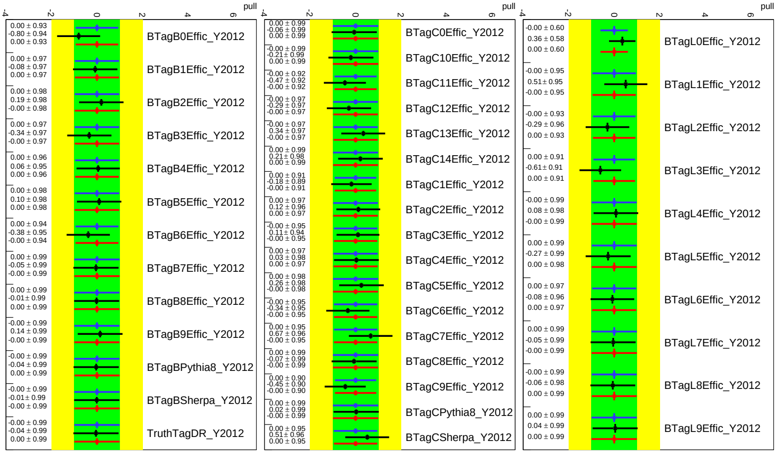
VBF pulls @ 200 GeV (4)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



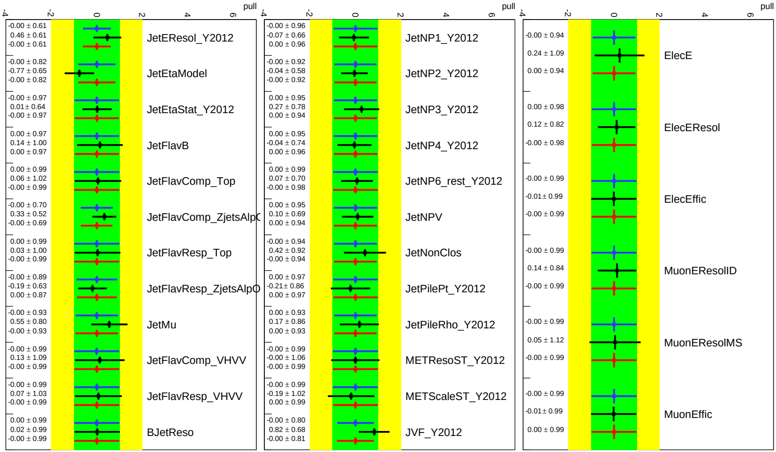
VBF pulls @ 400 GeV (1)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



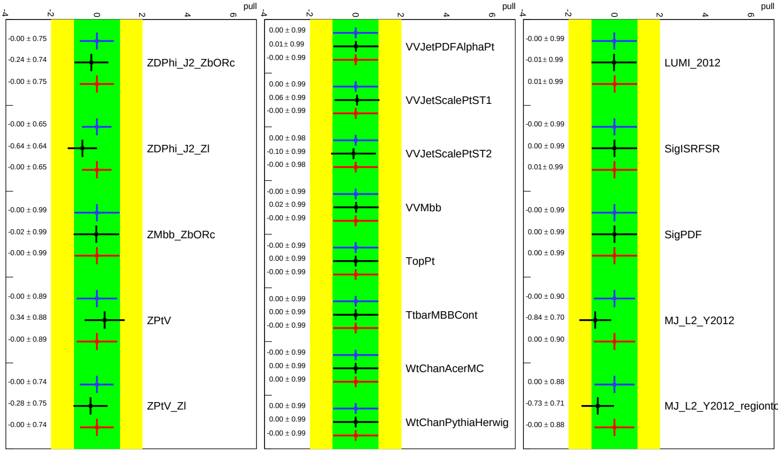
VBF pulls @ 400 GeV (2)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



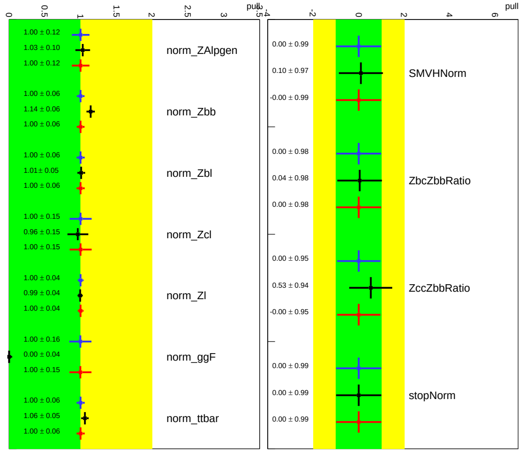
VBF pulls @ 400 GeV (3)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



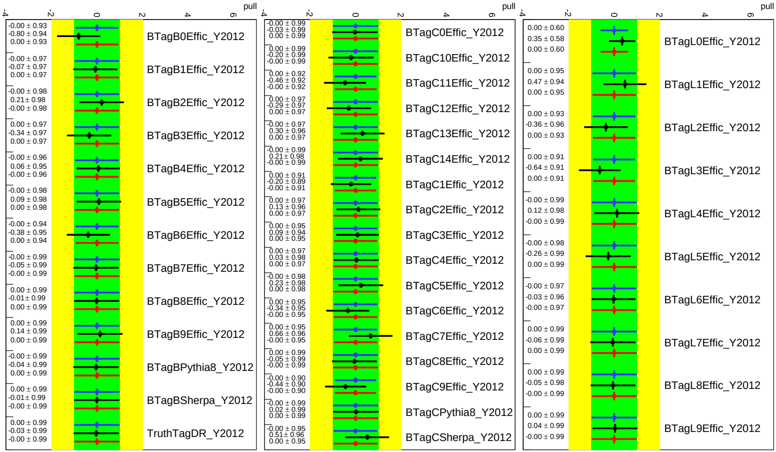
VBF pulls @ 400 GeV (4)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



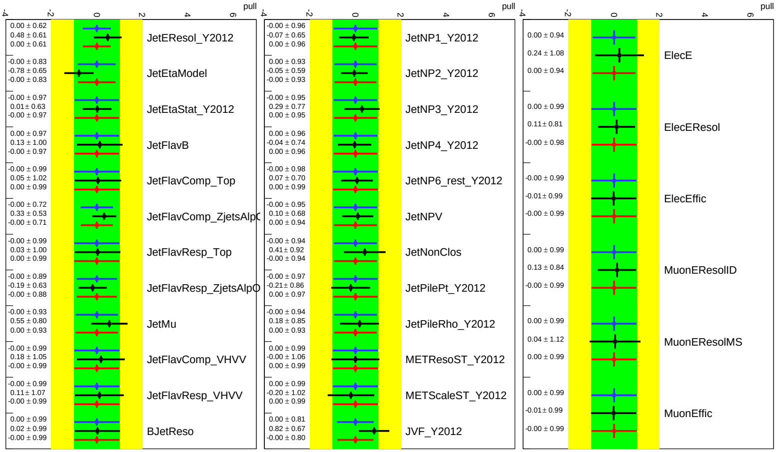
VBF pulls @ 900 GeV (1)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



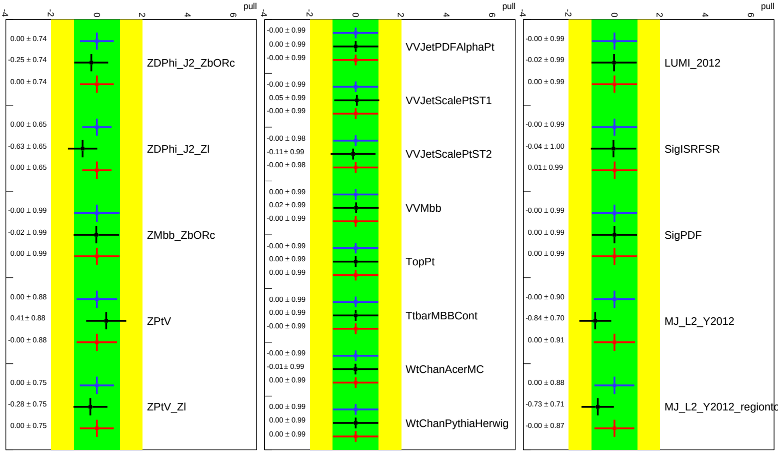
VBF pulls @ 900 GeV (2)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



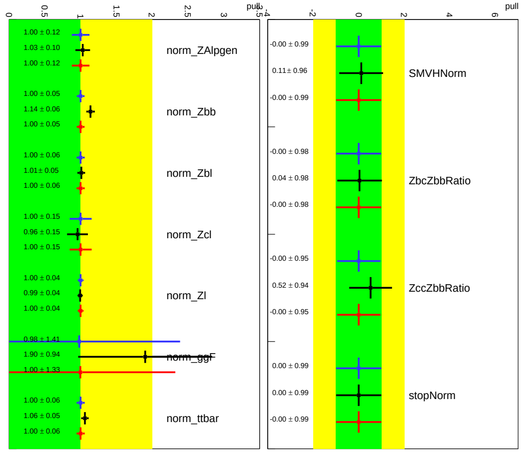
VBF pulls @ 900 GeV (3)

Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



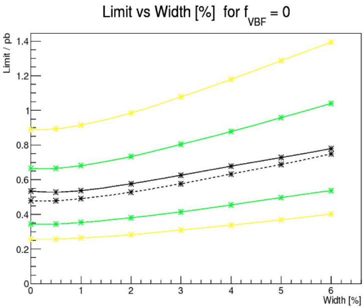
VBF pulls @ 900 GeV (4)

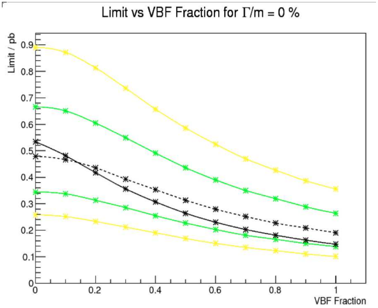
Data (black) and $\mu = 1$ (red)/$\mu = 0$ (blue) Asimov



2HDM: Variations in limit

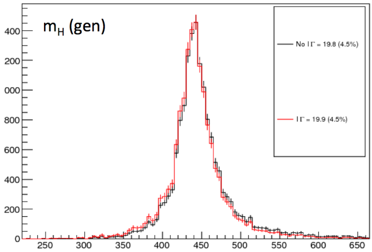
- Example variations for H->ZZ->llqq with width and vbf fraction
  - As expected limit gets worse as width increases
  - Limit gets “better” with increasing VBF fraction simply because VBF cross section is smaller

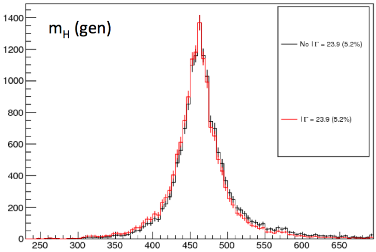




2HDM: Interference (1)

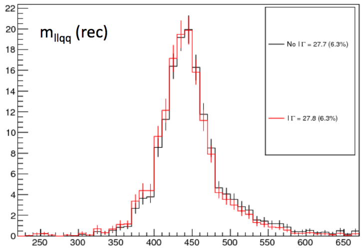
- Plan to stop at 5% as if get too wide the interference effect with ZZ continuum will be non-negligible (keep hashed band)
- Need to check when this becomes an issue
  - Run H->ZZ->llqq CPS samples for m_H where Γ/m ~ 5% with and w/o interference. Turns out this is somehwere between 440 and 460 GeV
  - Not completely correct as interference also depends on m_H

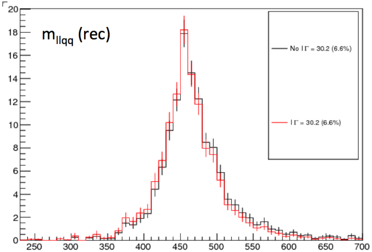




2HDM: Interference (2)

- Reconstructed m_{lljj} agrees within stat uncertainties:



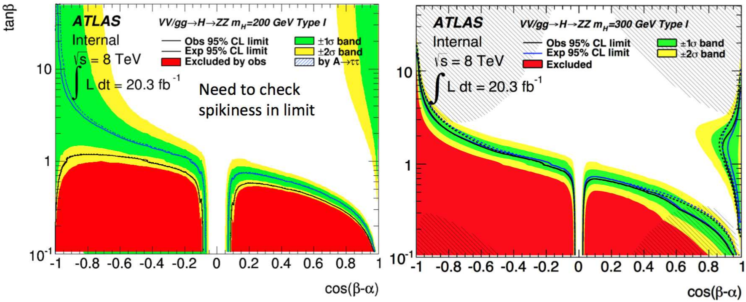


- Limits / pb
  - fVBF=0
  - Smear=0
- No change in obs/exp
  - 1% diff in bands

m_H	Inter	obs	-2σ	1σ	exp	+1σ	+2σ
440	w/o	**0.073**	0.047	0.062	**0.088**	0.122	0.164
	with	**0.073**	0.047	0.065	**0.088**	0.126	0.166
460	w/o	**0.098**	0.052	0.070	**0096**	0.132	0.179
	with	**0.098**	0.052	0.070	**0096**	0.135	0.181

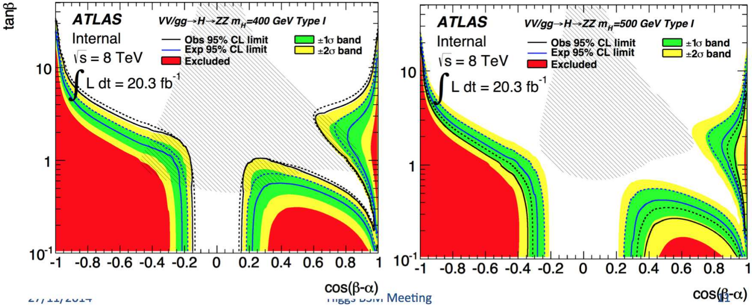
2HDM: Width Effect Limit (1)

- Solid (dashed) lines show H->ZZ->llqq results with (without) width taken into account
  - Small effect for 200 GeV; 1σ effect at some parts of plane for 300 GeV
  - Width only up to 5%, will completely cover (not just hash) outside this
    - For 200 GeV, width does not go above 5%



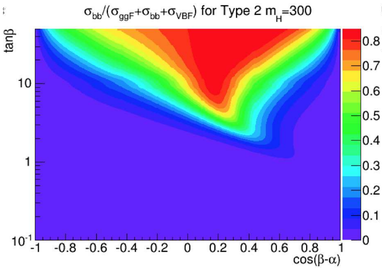
2HDM: Width Effect on Limit (2)

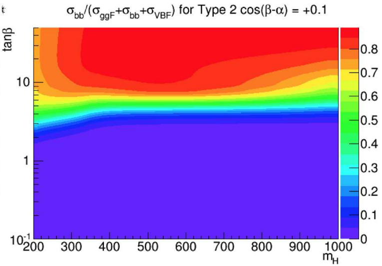
- For 400 GeV only a small fraction of the region is < 5% Γ_H/m_H
  - Hashed band should be inverted
  - Unlikely to change significantly when add other channles
- Propose to show for 200 & 300 GeV in paper + tanβ vs m_H plane
  - Possibly 350 GeV threshold region as aux material; nothing above that



2HDM: bbH (1)

- bbH prod can become significant for type II, esp at high tanβ

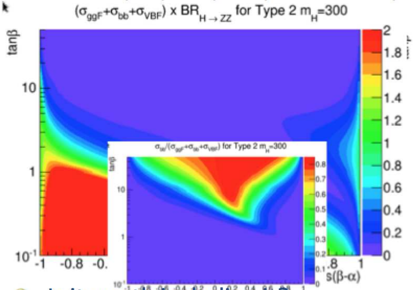


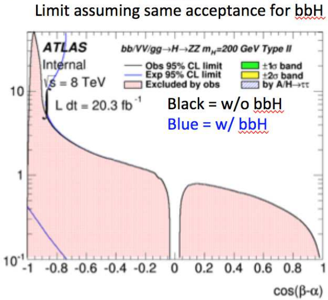


- Currently negelcting this, which makes limits consevative
  - But CMS recently put out A->Zh with this included and helps exlcusion significanlty at high tanβ. Planning to add it in for ATLAS A->Zh
- What about H->ZZ?

2HDM: bbH (2)

- However, if you look at total σin region where bbH is large you find it is very small: < 0.2 pb, while our limit is ~ 0.5 pb
  - Hence we are not so sensitive to this: small effect at 200 GeV (which is anyway completely dominated by 4l) and none at 300 GeV





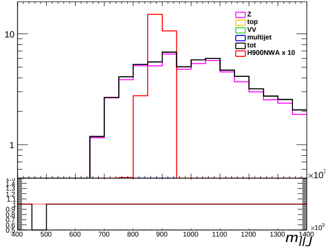
- Is it worth including it?
  - Can include as additional σ to ggF channel, taking into account diff in acceptance from gen-level study (simulated samples also being requested)

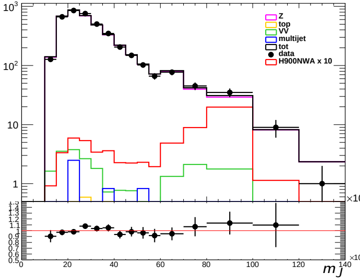
27/11/2014

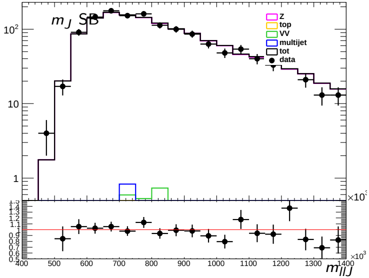
Status of Merged regime

Not unblinding yet (hopefully get final limits very soon)

- Select events w/ 1 jet or 2 outside m_{jj}
  - Anti-k_t 0.4 jet with $m_J > 70$ GeV
- m_J and m_{llJ} well described
  - m_{llJ} checked in $30 < m_J < 70$ SB
- Working on jet mass calib + systs
  - Jet group have approved results







Jet m response (pre-calib)

Jet mass response versus mass in bins of jet p_T