Review of ICHEP VV/VH Results (+ some future plans)





15th September 2016 Higgs Plenary Meeting

Introduction

Review of ATLAS/CMS VV/VH analyses presented at ICHEP

- Try to compare and contrast, not going through analysis details
- Highlight differences
- Compare results

Will not cover:

- Any 8 TeV results
- Leptonic VV
 - Covered by HZZ/WW later
- All-hadronic VV \rightarrow JJ
 - Not so relevant for Higgs

Boosted Methodology

CMS

- Anti-k_t 1.0 jets with trimming
 - Recluster with R=0.2 and remove subjets with p_T^{jet}/p_T^{sub} < 0.05</p>

W (Z): m_J within ±15 GeV of m_{W(Z)}

- 2-prong substructure using $D_2^{(\beta=1)}$
 - Low/high purity pass/fails cut
 - LP: 50% efficiency



H: 75 < m_j < 145 GeV
 Ghost match to R=0.2 track-jets for b-tagging

- Anti-k_t 0.8 jets with prnning
 - Remove protojets typical of soft,
 wide-angle radiation → pruned m_{jet}
- W (Z): 65(75) < m_J < 95(105) GeV
 - 2-prong substructure using $\tau_{21} = \tau_2 / \tau_1$
 - Low/high purity based on cut value
 - HP: ~ 60% efficient



H: 105 < m_i < 135 GeV</p>

 b-tagging on 2 R=0.4 subjets from reversing last step of pruning

VV resonance

WV → Ivqq

- ATLAS-CONF-2016-062
- CMS-PAS-B2G-16-020

SV → Ildd

- ATLAS-CONF-2016-082
- CMS-PAS-B2G-16-010

SV → vvqq

- ATLAS-CONF-2016-082
- (No CMS result)

$X \rightarrow WV \rightarrow Ivqq$

ATLAS: 13.2/fb CMS : 12.9/fb

- Lepton + E_T^{miss} and boosted qq pair for ~13 / fb in ggF channel only
 - Split into low/high purity categories (CMS for low/high (>1 TeV) m respectively)
 - m_{wv} as discriminant

Main diff is W+jet modelling

- ATLAS: MC shape, norm using m_i SB in LH fit
- CMS: functional form for m_{wv} in low m_J SB data

$$F(m_{\mathrm{WV}}) = N_0 \cdot \exp\left(am_{\mathrm{WV}} + \frac{b}{m_{\mathrm{WV}}}\right),$$

norm to data in both $\rm m_{J}\,SB$ using analytic MC param

Extrapolated to SR using TF





$X \rightarrow WV \rightarrow Vvqq(2)$

ATLAS: 13.2/fb CMS : 12.9/fb

Both WW and WZ interpretations over same range with very similar limits ۲



$X \rightarrow ZV \rightarrow IIqq$

- ATLAS: 13.2/fb CMS : 2.7/fb
- 2 leptons + resolved or booosted qq pair split into categories with m_{zz} discrim.
 - <u>ATLAS (2015+16)</u>
- Boosted
 - Low/high purity
- Resolved
 - Untagged
 - ggF & VBF
 - Tagged

<u>CMS (only 2015)</u>

- Low mass
 - Low Purity Boosted
 - Untagged/tagged based on
 ≥1 medium b-tag subjet
 - Resolved
 - Untagged/tagged based on loose + tight b-tags

- High mass
 - Boosted
 - LP/HP

Similar high-m efficiency but CMS seem higher at low m (but diff signals)







$X \rightarrow ZV \rightarrow IIqq(2)$

ATLAS: 13.2/fb CMS : 2.7/fb

Similar bkg models for ATLAS + low-m CMS: MC normalised to CR in LH fit

CMS also corrects Z+jets shape from fit to $m_{j(j)}$ SB using $1 + s(M_X - 500)/500$, with s then treated at NP in LH fit

High-mass CMS uses functional form

Param m_J for leading and subleading bkgs

| Category | Parametric model | | |
|----------|------------------|----------|---------------------|
| MLP | (ErfExp) | \oplus | (ErfExp + Gaussian) |
| ELP | (ErfExp) | \oplus | (ErfExp + Gaussian) |
| MHP | (ErfExp) | \oplus | (ErfExp) |
| EHP | (ErfExp) | \oplus | (ErfExp) |

and fit to m_J SB to get # events in SR

Fit m_{WV} shape in SB and use MC TF to SR







$X \rightarrow ZV \rightarrow IIqq(3)$

ATLAS: 13.2/fb CMS : 2.7/fb

- Both ATLAS/CMS have limits in terms of Graviton from 500 GeV
 - ATLAS: RS up to 5 TeV; CMS: RS only up to 1.4 TeV and bulk up to 2.5



In addition, ATLAS has model-independent ggF/VBF scalar and HVT W' \rightarrow WZ



ATLAS $X \rightarrow ZV \rightarrow vvqq$

ATLAS only: 13.2/fb

- No leptons, $E_{T}^{miss} > 250 \text{ GeV} + \text{boosted } qq \text{ pair from ATLAS only}$
 - Split into LP/HP categories
 - No resolved or VBF cats
 - m_{τ} as discriminant
- Like llqq, backgrounds taken from MC, normalised to CRs in LH fit



Model-indep scalar limits + G (HVT) interpretation for ZZ (WZ) up to 4.5 TeV



Future VV plans

Updates

- Switch to combined jet mass
 - Linear combo of calo and track-assisted mass
- Add resolved for lvqq
 - Not clear will add for vvqq given trigger threshold
- Add VBF for missing channels
- Include GM triplet H⁺ interpretation

Publication plans

- 2 separate papers for Moriond (llqq+vvqq, lvqq)
- Combine with eath other and other diboson channels for summer
 - Can add interpretations then so can maybe minimise for Moriond papers
 - Would be nice to include leptonic channels if possible but needs discussion



VH resonance

See Strain S

- CMS-PAS-B2G-16-003
- (ATLAS-CONF-2016-015 already presented at Moriond)

⊌ VH → qqbb

- ATLAS-CONF-2016-083
- (No CMS result)

A \rightarrow ZH \rightarrow llbb (H \neq h₁₂₅)

- CMS-PAS-HIG-16-010
- (No ATLAS result)

CMS Vh \rightarrow vvqq/lvqq/llqq

CMS only: 2.17-2.52/fb

- CMS analysis of Vh in boosted-only regime for 0,1,2 lepton channels using 2015 data only
 - Split into 1+2 b-tags based on tagging subjets
- Unlike ATLAS, bkgs again modelled with funcl forms following similar method to llqq analysis



- Model m_j for each bkg with functional form and fit to SB to get V+jets norm
- Param V+jets m_{vh} shape in SB data and apply MC TF to SR (others param to MC)



$CMS \rightarrow vvqq/lvqq/llqq(2)$

CMS only: 2.17-2.52/fb

HVT interpretation for Zh/Wh up to 3/4TeV

Similar exclusion limits to previous ATLAS 2015 results (ATLAS also had A \rightarrow Zh)



ATLAS $X \rightarrow Vh \rightarrow qqbb$

ATLAS only: 13.3/fb

ATLAS analysis for $m_x > 1$ TeV, requiring ≥ 2 boosted fatjets and no leptons

≥

- Benefits from large BF of V \rightarrow qq at high m
- Assign lower/higher m₁ jet to V/H (99% efficient), apply mass cuts and split into 4 categories:
 - "V-jet" consistent with m_w/m_z
 - D₂ substructure cut (no low purity category)
 - 1 or \geq 2 b-tagged track jets associated to "H-jet"

Background modelling follows hh \rightarrow 4b:

- MJ from 0 b-tag data, corrected for kinematic diff, normalised in high m_{J.H} SB
- Fit with functional form (checked in VR) $f(x) = p_a (1-x)^{p_b} (x)^{p_c}$ $x = m_{\rm VH} / \sqrt{s}$

Limits on Z'/W' in HVT up to 3.5 TeV

Better than semi-lep Vh already at 2 TeV from simple lumi scaling



$\mathsf{CMS}\,\mathsf{H}\, \xrightarrow{}\, \mathsf{ZA} \xrightarrow{}\, \mathsf{IIbb}$

CMS only: 2.3/fb

• CMS-only 2015 analysis, for $H \rightarrow ZA$ ($H \neq h_{125}$) in 2HDM

- Unlike 8 TeV result, only "inverted" hierarchy with m_H > m_A
- Large BR at low tanβ in alignment limit
- Consider m_A = 300, 500, 800 GeV
 - With m_H = 50, 100, 200, 400 GeV for each

Strategy: define SR box in (m_{bb}, m_{llbb}) centred on (m_A, m_H)

- Width set to 3 x detector resolution (typically 15% $m_{A/H}$)
- Main Z+jets/ttbar bkg normalised by fit to m_{II} outside SR







Model indep limits vs m_A for each $m_H \rightarrow$ just reaching 2HDM

Future VH plans

Updates

- Again, switch to combined jet mass
- Semi-leptonic Vh
 - Switch to recycling of resolved/merged
 - Gains ~10-20% in sensitivity
- Vh \rightarrow qqbb
 - Add low purity category
 - Try direct functional parameterisation of bkg
 - Seeing some limitations of 0 tag to model SR

Add missing A/H \rightarrow Z H/A analysis

- Kick-off meeting planned for Weds 28th @ 10am
 - https://indico.cern.ch/event/569540/
- Interested manpower identified and samples already requested
 - https://twiki.cern.ch/twiki/bin/view/AtlasProtected/AZH_run_2

Publication plans

- 2 separate papers for Moriond (vvqq+lvqq+llqq, qqbb)
- Again, combine with eath other and other VV channels for summer
- A/H \rightarrow Z H/A paper for summer



Combination

- CMS performed full combination of both VV and VH in HVT for 8 + 13 TeV
 - Interpreted in HVT Z'/W' for VV+Vh; Bulk G for VV

ATLAS only 13 TeV summary plot of W' \rightarrow VV in HVT; no combination



Summary

- ATLAS presented a lot of new VV/Vh results at ICHEP
 - Many more results with 2016 data than CMS
- Generally, analyses similar between two experiments
 - CMS seem more willing to use complicated functional forms for bkgs
 - Less reliance on MC but choice/validation of function not easy
- Exclusion limits generally similar where can be compared
- Plan several updates for EOY/Moriond papers
 - Fill in missing $A \rightarrow ZH$ analysis
 - Aim for combinations for summer in EYETS