Motivation

- How to look for NP in view of hierarchy problem
  - High mass (~TeV)
  - Not seen in EWK precision tests
  - Coupling to massive SM particles (W,Z,t)

\[ X \rightarrow VV \]

- Experimental advantages:
  - W/Z with well known mass → suppress backgrounds
  - Good kinematic reconstruction → reconstruct resonance mass

- Disadvantages:
  - Many different final states → lots of work
  - Resolution suffers in final states with neutrinos
What are we looking for?

Extra Dimensions:
- RS1: traditional benchmark, small BR to VV
- Bulk G: localize SM particles in 5th dim (bulk)
- Bulk G: large BR to tt, V_LV_L and HH
- Radion → HH

New strong Sector:
- Technicolor
- Little Higgs
- Partial compositeness
- …

More Ideas Welcome
Want to have your model excluded (or found!)?
Talk to us!
All leptonic final states

- Look for:
  - $Z \rightarrow ee/\mu\mu$,  
  - $Z \rightarrow \nu\nu$,  
  - $W \rightarrow e\nu/\mu\nu$

- Advantages:
  - Low backgrounds, high purity  
  - Kinematic resolution for $ZZ \rightarrow 4l$

- Disadvantages:
  - Low branching fraction  
  - Kinematic reconstruction with more than one neutrino
WZ → llν

- All leptonic final state
  - Only one ν → decent mass resolution
  - very pure
  - Very low BR (~ 1.5%)

- Analysis strategy
  - Select three leptons
  - Compute \( M_{WZ} \) from MET and W mass constraint
  - Search for bump in \( M_{WZ} \) spectrum
**WZ → ℓℓν limits**

- Interpret limits in terms of
  - Sequential SM $W'$
  - Heavy vector triplet (weakly coupled resonance and composite Higgs)
  - Technicolor

$\pi_{TC}$ and $\rho_{TC}$ masses and BR related
**WW → 2l2ν**

- Compared to WZ:
  - Two ν → poor mass resolution
  - Only two leptons → increased background

- Strategy:
  - Select two leptons (Z veto!)
  - B-veto suppresses top
  - Requite MET
  - Study transverse mass of llMET system

- Sensitive to many neutral resonances:
  - RS and bulk Graviton used as benchmark
  - Can be reinterpreted as other narrow resonances
Hadronic Decays

- Look for:
  - Semi-leptonic
  - Fully hadronic

- Advantages:
  - Decent kinematic resolution
  - High branching fractions
  - Access to $H \rightarrow bb$

- Disadvantages:
  - Giant backgrounds
  - Somewhat less at very high masses
ZZ→2l2q

- **Reconstruct leptonic Z**
  - The easy part
  - Two leptons, opposite sign, same flavor
  - Compatible with Z mass

- **Reconstruct Hadronic Z**
  - Tricky: high $p_t$ Z reconstructed as single jet (“merged”)
  - Analyze 2 categories
    → dijet with Z mass
    → single massive jet

\[ \Delta R_{qq} \approx 2 \frac{M_Z}{p_{t,Z}} \]

\[ \Delta R > \text{jet radius} \]

\[ \Delta R < \text{jet radius} \]
**ZZ→2l2q**

- Background estimated from \( M_{jj/j} \) sidebands

- Most serious syst. Uncertainty from background estimate

- Two \(~\)independent results for dijet and monojet → joint at point of equal exclusion power
Jet sub-structure

- Recluster jet constituents, applying additional conditions at each recombination
  \[ z = \frac{\min(p_{T,i},p_{T,j})}{p_{T,jet}} > 0.1 \]
  \[ \Delta R < 0.5 \frac{M_{jet}}{p_{T,jet}} \]
- Filter out soft and large angle QCD emissions

Mass Drop (arXiv:0802.2470)
- de-cluster jet by stopping jet algo before last iteration
- \( \rightarrow \) two subjets
- jet is V-tagged if its mass drop \( \mu_D \) < (analysis dependent) cut value
  \[ \mu_D = \frac{M_1}{M_{jet}} \]

N-subjettiness (arXiv:1011.2268)
- Topological compatibility with hyp of N subjets
- Rescluster jet, halting when N subjets reached
- \( \tau_N : p_T \)-weighted sum over jet constituents of distances from closest subjet axis
  \[ \tau_N = \frac{1}{d_0} \sum_k p_{T,k} \cdot \min(\Delta R_{1,k},\Delta R_{2,k}, \ldots, \Delta R_{N,k}) \]

These are NOT THE ONLY POSSIBILITIES ! Plenty of alternatives available
check CMS EXO-13-006
Control Measurements

- Jet-substructure dependent on hadronization models
  - Depends on MC program
  - Decently but not perfectly modeled

- Get Control measurement from data
  - Select semileptonic \( t\bar{t}b\bar{t} \) events
  - Lepton, MET, bjet
  - Look at opposite hemisphere → high chance for W from t decay
  - Similar to “Tag & Probe” technique

- Extract & Apply correction factors
  - Still about 10% uncertainty
  - Application to Z justified by MC
Semileptonic with Substructure

- High $p_t$ lepton reco from $Z'$ searches
- Standard CMS W reconstruction
- Special treatment for leptons in $Z$
  - At high boosts, leptons in each others isolation cones → subtract!
- Only merged category
  - Using CA8 jets to catch lower $p_t$ W/Z
  - Jet pruning
  - N-subjettiness
- Backgrounds
  - Z+jets for Z channel
  - Also top, WW in W channel
  - Estimate from $M_j$ sideband
Analysis well synchronized
- Identical hadronic V treatment
- Will allow easy combination for improved limit / exclusion range
VV all hadronic

- No leptons, only jets
- Reduce large backgrounds with substructure variables
- Somewhat compensated by large signal branching ratio
- Trigger thresholds quite high

Analysis Flow:
- Select two CA8 jets
- Apply jet-substructure selection
- Scan $M_{jj}$ (smoothness test, MC free)

Results:
- Many possible final states implicit (WW/WZ/WZ)
  $\rightarrow$ many possible signals (W', Graviton…)

[ CMS EXO-12-024 ]
VV all hadronic

Jet resolution + efficiency depends on V flavor (W vs Z) and polarization

→ need to check different signal hypothesis separately, even if data remains the same
HH→4b

- All hadronic
  - Use btags to suppress QCD background
  - $M_{jj}$ to define signal and control regions

- Selection
  - 4 b-jets, $p_t > 40$ GeV, $|\eta| < 2.5$
  - 2 dijets with $\Delta R < 1.5$, $p_{t,dijet} > 200$ GeV
  - Top veto
  - Signal region in $M_{jj}$

[Atlas-Conf-2014-005]
HH→4b results

- Background
  - Multijet dominates
  - Use fewer btag samples
  - Use $M_{jj}$ control regions

- Systematic uncertainties dominated by btag

- Competitive limits on RS Graviton
  - Losing sensitivity to jet merging at high mass
Outlook: We are not done yet

- **Subjet b-tag**
  - Especially suitable for H
  - Huge reduction in background

- **Explore more final states**
  - VH of additional interest
  - Currently not all W/Z final states covered
  - Limit by manpower

- **Combine different channels**
  - More powerful limits
  - Increases model dependence
  - Requires coordination between analysis groups
Conclusion

- Searches for new physics in diboson push to higher masses
  - Low signal cross section → hadronic final states gain importance
  - developing new techniques to deal with high boosts

- No WW/ZZ/WZ resonance seen
  - SM still standing strong
  - Exclusion limits stronger than ever
  - Many final states probed, but some missing

- Expect more results in Run II
  - Greatly increased reach at 13 TeV
  - Jet-substructure may become more important