Boosting the Higgs boson

Higgs couplings 2018
Tokyo
Nov. 27, 2018

Ben Kilminster
Physik Institut

University of Zurich
Boosted Higgs bosons

- **Can improve sensitivity of SM Higgs measurements**
  - At high Higgs $P_T > 200$ GeV
    - $H \rightarrow bb, H \rightarrow \tau\tau$ can benefit from analysis of unresolved jets
    - At higher $P_T$, $H \rightarrow ZZ/WW \rightarrow qqqq$ can also benefit

- **Can be used as a tool to search for BSM physics**
  - Radions, RS Bulk Gravitons
  - Composite Higgs
  - New vector triplets ($W^\pm', Z'$)
  - Portal to dark matter (2HDM)
SM Higgs boson at high $P_T$

- SM theory shape is remarkably stable wrt higher orders at high $P_T$
- May provide a way to identify new physics that enters at high $P_T$

**SM predictions**

$pp \rightarrow H + j @ 13$ TeV

- $d\sigma/dp_{T,H}$ [fb/GeV]
- LO, NLO
- $p_{T}[\text{GeV}]$

**BSM example**: SMEFT with deviations in chromomagnetic operator

- $d\sigma/dp_{T}(H)$ [pb/GeV]
- $ggH@LHC 13$ TeV LO H+j
- $M_{h}=125$ GeV

PLB 1801.08226, and see Jonas Lindert’s talk yesterday

- See later slides on our experimental techniques to probe this …
Focus of this talk

- **Boosted Analyses and techniques used in**: 
  - BSM : \( X \rightarrow VV \rightarrow qqqq \) (ATLAS)
  - BSM : \( X \rightarrow HH \rightarrow \tau\tau bb \) (CMS)
  - BSM : \( H \rightarrow bb +\text{dark matter} \) (ATLAS)
  - SM : \( gg \rightarrow H \rightarrow bb \) (CMS)

- **Boosted boson techniques, mainly …**
  - \( V(qq)\)-tagging vs. \( H(bb)\)-tagging
  - Track+Calorimeter techniques (ATLAS)
  - Track jets for b-tagging (ATLAS)
  - Double-b tagging (CMS)
  - \( H \rightarrow \tau\tau \) tagging (CMS)

- **BSM searches currently driving experimental techniques at high \( P_T \)**
Measuring a boson-jet

• At low $P_T$, a boson (W,Z,H) decaying to two quarks looks like 2 jets
  • i.e., $W \rightarrow qq$
  • $\vec{P}_W \sim 0$
Measuring a boson-jet

- At low $P_T$, a boson ($W, Z, H$) decaying to two quarks looks like 2 jets
  - i.e., $W \rightarrow qq$
  - $\bar{P}_W \sim 0$
Measuring a boson-jet

- At low $P_T$, a boson (W,Z,H) decaying to two quarks looks like 2 jets
  - i.e., $W \rightarrow qq$
  - $\bar{P}_W \sim 0$

- But in heavy particle decays, two quarks become merged
  - i.e., $X \rightarrow WW \rightarrow qq+qq$
  - Mass of $X \rightarrow$ Momentum of $W$’s
  - $W$’s are said to be Lorentz “boosted”
  - Quarks are essentially massless
  - Merging when $M_X / M_W > 10$
    - i.e., somewhere around ~ 1 TeV
Quark-jets vs. boson-jets

- **Quark jets**:
  - Smaller cone

- **Boson-jets**:
  - Larger cone
Quark-jets vs. boson-jets

• Quark jets:
  • Smaller cone
  • Jet collimated over single axis

• Boson-jets:
  • Larger cone
  • Jet collimated over two axes
Quark-jets vs. boson-jets

- **Quark jets**:
  - Smaller cone
  - Jet collimated over single axis
  - Mass of jet ~ 0 GeV

- **Boson-jets**:
  - Larger cone
  - Jet collimated over two axes
  - Mass of jet ~ boson mass ~ 100 GeV

\[ M^2 \sim E_1 \cdot E_2 (1 - \cos \theta) \]
Grooming jets

Many algorithms used: trimming, pruning, soft drop ...

Goal:

Removing soft, high angle emissions
Grooming jets

Many algorithms used: trimming, pruning, soft drop …

Goal:

Removing soft, high angle emissions

![Diagram showing jet mass distributions for different processes, including SM Higgs, W+Jets, and ungroomed jet mass.]
Grooming jets

Many algorithms used: trimming, pruning, soft drop …

Goal:
Removing soft, high angle emissions

Improves discrimination between quark-jets and boson-jets
Sub-jet finding

We calculate a sum of:

\[(P_T \times \text{angular distance to axis})\]

for each energy deposit in cone

Then compare ratio of 2-axis sum to 1-axis sum

\[\tau_{21} = \tau_2 / \tau_1\]
Sub-jet finding

We calculate a sum of:

\((P_T \times \text{angular distance to axis})\)

for each energy deposit in cone

Then compare ratio of 2-axis sum to 1-axis sum

\(\tau_{21} = \tau_2 / \tau_1\)
Sub-jet finding

We calculate a sum of:

\[(P_T \ast \text{angular distance to axis})\]

for each energy deposit in cone

Then compare ratio of 2-axis sum to 1-axis sum

“\(\tau_{21} = \tau_2/\tau_1\)”

Helps further isolate boson-jets from background
Does this all work?

- Luckily, we have a way of testing these:
  - jet mass
  - pruning/trimming
  - sub-jet finding

- The standard model process of top quark decay gives standard candle

Example from ATLAS: Identifying boosted $W$ boson from top-quark decays
So we know we can disentangle W-jet, Z-jet, and H-jet through jet mass
Diboson resonances

- Extra dimensions
- Composite Higgs
- Extended gauge symmetry (more Z' and W' bosons)

Signature is TeV-mass diboson resonance $X$

$X$ is a new BSM particle at TeV-scale
$Y$ is a $W$, $Z$, or $H$ boson

Keep in mind for the rest of this talk:
The boson $P_T$ being probed in a diboson search is $\sim$ half the mass of $X$
ATLAS new particle flow for V-tagging

• **Standard : Locally calibrated (LC) topo-clusters**
  + Excellent jet energy resolution based on noise-suppressed calorimeter cell clustering
  - Granularity of calorimeter insufficient to resolve angular separation from highly-boosted hadronic decays

• **New : Track-Calor cluster (TCC) algorithm**
  - Combined TTCs (clusters matched to primary-vertex tracks)
    - Robust against pile-up (remove combined TTC if matched to PU vertex)
    - Yields improved angular resolution from tracks
  - Neutral TTCs (clusters not matched to tracks)
    - Not robust against pile-up

• **Followed by trimming procedure**
  - remove pile-up and soft radiation inside large cone


[JHEP 0912.1342]

12
ATLAS : new TCC jets

TCC : track-calor-clusters

Performance of new algorithm

- While jet mass resolution is not better below $P_T$ of 2 TeV, the resolution of variable $D_2$, useful for boson tagging does greatly improve

$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3} \text{ Ratio of 3 and 2-point energy correlation functions}$$
Results on VV search

Control region

Signal regions

Note: Data out to $P_T > 2$ TeV
Resonance interpretation

Note: Limits out to boson $P_T > 2 \text{ TeV}$

Huge gains with new TCC tagger
Higgs portal to DM

- Signature b-jet(s) opposite MET
ATLAS: variable-Radius track jets

- Difficult to identify boosted b-jet pairs that are merged
- Standard algorithm, Fixed-radius (FR) jets less effective at high PT
- New algorithm, Variable-radius (VR) track jets
  - Radius parameter decreases with jet PT

\[ R \rightarrow R_{\text{eff}}(p_T) \approx \frac{\rho}{p_T} \]

\( \rho \) determines how jet-radius scales with jet P_T

Optimized to get:
\( \rho = 30 \text{ GeV}, R_{\text{min}} = 0.02 \text{ and } R_{\text{max}} = 0.4 \)
Identifying B hadrons in fat jets

- VR track jets improve significantly the efficiency for high PT H → bb tagging (Mass above 2 TeV)
Reconstructing Higgs-jet

- Gain of using fat jets between 1 and 2 TeV

Jets groomed
Calibrated to particle level

Gain of using fat jets between 1 and 2 TeV

Changeover for boson $P_T$ 500-1000 GeV
Track-assisted jet mass

Improves jet mass resolution

→ Improves $S/\sqrt{B}$ for boson signal at high $P_T$
Results on H+DM

Higgs-Jet mass used to search for signal (and set limits)

Clear gain from VR jets clear Mass above 2 TeV, (boson $P_T > 1$ TeV)
boosted $HH \rightarrow b\bar{b} \tau \tau$

- Motivated by models:
  - $X = \text{Spin-2 Bulk graviton, Spin-0 radion}$
  - Heavy vector boson, $V' = Z', W'$
boosted $H \rightarrow \tau \tau$ identification

1. $\tau$ pair algorithm starts with CA8 jets

2. Reverses final step of clustering

3. Applies standard $\tau$ ID techniques (HPS) to identify hadronic taus with some modifications on isolation
HH → bbττ data

Jet mass

Diboson mass in sidebands

Note: Data out to Higgs $P_T \sim 2$ TeV
HH→bbττ results

Note: Data out to Higgs $P_T > 1$ TeV  → Set limits on new particles up to 4 TeV
boosted SM $H \rightarrow bb$
Conventional wisdom

• Largest sources of Higgs bosons

  • Leading Higgs boson branching ratios

    1. $H \rightarrow bb$ (57%)
    2. $H \rightarrow WW$ (22%)

  • Leading Higgs boson production mechanisms

    1. $ggH$ (44 pb)
    2. $VBF\ H$ (3.7 pb)

  ➤ Most signal comes from $gg \rightarrow H \rightarrow bb$ (25 pb)

  ➤ However, $bb$ background is large (560 ub : $10^7$ bigger !) \[1\]

  ➤ CW : despite being our biggest source of Higgs bosons, $gg \rightarrow H \rightarrow bb$ impossible !
But, is there a way to find $gg \rightarrow H \rightarrow bb$?

Perhaps by identifying high $P_T$ bosons, where S/B is more favorable.

Get inspiration from searches for new physics decaying to boosted Higgs bosons.
Ingredients to $gg+ISR \rightarrow$ boosted $H \rightarrow bb$

1. Start with AK8 jets

2. Apply PUPPI to remove pileup
   
   1. Fix $P_T$ and $\eta$ problems introduced

3. Trim jets & apply soft-drop to remove soft, wide-angle emissions to get jet mass - make corrections to get correct mass scale

4. Use $\rho$ variable to remove difficult events to model

5. Calculate $N_{2^1}$ variable from 2-point and 3-point energy correlation functions

6. Transform $N_{2^1} \rightarrow N_{2^1,DDT}$ to flatten effect of QCD, and make cut

7. Select events based on double-$b$ tagger
Soft-Drop

For $\beta = 0$, case corresponds to so-called modified mass-drop tagger" (mMDT) 

CMS: $z_{\text{cut}} = 0.1$, $\beta = 0$

For $\beta = 0$, case corresponds to so-called modified mass-drop tagger" (mMDT) 

[1307.0007, 0802.2470]
Double b-tagger

1. The two $\tau_2$ axes matched to secondary vertices using IVF algorithm (Inclusive Vertex Finder) runs on tracks, independent of jets

2. Then, combination of 2nd vtx info and impact parameters of tracks used to define MVA double-b tagger
Tagging jets with 2 b quarks

**CMS Simulation 13 TeV, 2016**

**Misid. probability (multijet)**

- AK8 jet
  - Subjet CSVv2, minimum among two subjets
  - AK8 jet CSVv2
  - R(AK4 jet, AK8 jet)<0.4
  - ∆AK4 jet CSVv2, double-b

- AK8 jet
  - T 300 < p 50 < m < 200 GeV

**Tagging efficiency (H)***

- AK8 jet
  - Subjet CSVv2, minimum among two subjets
  - AK8 jet CSVv2
  - R(AK4 jet, AK8 jet)<0.4
  - ∆AK4 jet CSVv2, double-b

- AK8 jet
  - T 1200 < p 50 < m < 200 GeV

---

[CMS PAS BTV-15-002 ]
Previously:
- poor modeling of jet mass
- many parameters to describe fit
- hard to model correctly for all boson $P_T$

Now: Better fit of mass, across $P_T$

(Can discuss from backups how better modeling is obtained at low and high $P_T$)
Modeling of jet mass

Previously:
• poor modeling of jet mass
• many parameters to describe fit
• hard to model correctly for all boson $P_T$

Now: Better fit of mass, across $P_T$

This could allow differential Higgs measurements vs. $P_T$

(Can discuss from backups how better modeling is obtained at low and high $P_T$)
First, consider events failing the double b-tagger

→ Mainly sensitive to $W+$jet
1) Measurement of $Z \rightarrow bb$
(for $Z \ p_T > 450$ GeV)
Expected $Z(bb)$ significance : $5.8\sigma$
Observed $H(bb)$ significance : $5.1\sigma$
1) **Measurement of Z→ bb**
   (for Z $p_T > 450$ GeV)
   Expected Z(bb) significance : $5.8\sigma$
   Observed H(bb) significance : $5.1\sigma$

2) **Search for H→bb**
   (for H $p_T > 450$ GeV)
   Expected H(bb) sig. : $0.7\sigma$
   Observed H(bb) sig. : $1.5\sigma$
   “Measurement” : $\sigma/SM = 2.3^{+1.8}_{-1.6}$
   $74 \pm 48 \text{(stat)}^{+17}_{-10} \text{(syst)} \text{ fb}$
Identifying bosons above QCD

For lead jet $P_T > 600$ GeV

Boson-tagging based on $D_2$ only

Results make us wonder, could we see $H \rightarrow bb$ this way also?
Summary

- Presented techniques for identifying high $P_T$ bosons
  - Boosted W-jet and Z-jet
  - Boosted jets of $H(bb)$ & $H(\tau\tau)$

- **Can be used to probe for new physics** (heavy vector bosons, radions, bulk gravitons, dark matter, 2HDM, etc.)

- **Can be a tool for SM measurements** (as in $gg+ISR\rightarrow H\rightarrow bb$) not previously thought possible …

  - Should we be recasting our boosted measurements and searches as differential wrt Higgs jet $P_T$?
Description of techniques and acronyms

- **Hadronic jets**
  - **AK**: Jets clustered with sequential anti-Kt algorithm [0802.1189]
  - **C/A jets**: jets sequentially clustered with Cambridge/Aachen algorithm only uses angular separation to build up successive jets [9907280]
  - **PF**: Particle Flow jets - technique at CMS to combined measurements from calorimeters, trackers, muon detectors to get particles, used for jet clustering [1706.04965]
  - **TCC**: Track-Calor Clusters - technique at ATLAS to combined tracking and calorimeter information, used for jet clustering [ATL-PHYS-PUB-2017-15]
  - **N_{12}**: variable with ratio of 2-point and 3-point energy correlations within jet, used to find boson-jets [1609.07483]
  - **SD (Soft-Drop)**: algorithm for removing soft wide-angle radiation from jet [1402.2657]
  - **jet trimming, pruning**: algorithms for removing small QCD-like emissions from within a jet [0912.1342]
  - **PUPPI**: pileup per particle identification algorithm (CMS) for removing particles likely to be pile-up from jets [1407.6013]
  - **\( \rho = \log(m^2/p_T^2) \)**: a variable for defining a dimensionless scale for QCD jets, whose distribution varies little over \( P_T \) [1307.0007]
  - **DDT**: Designed Decorrelated tagger - a transform of \( N_{12} \) that flattens out the efficiency for QCD jets, uses \( \rho \) & \( p_T \) [1603.00027]
  - **\( \tau_{21} \)**: N-subjettiness, \( \tau_1 \) represents how much a jet seems to have a 1-prong shape, \( \tau_2 \) is how much it has a 2-prong shape, etc. The variable \( \tau_{21} \) is the ratio \( \tau_2 \) to \( \tau_1 \) such that small \( \tau_{21} \) means a jet is more likely to have a 2-prong structure [1011.2268]
B-tagging Higgs jets

VR track jets: Variable-radius track jets (dependent on $P_T$) used at ATLAS for B-tagging within large-cone jets [theory 0903.0392, ATLAS implementation ATL-PHYS-PUB-2016-013]

Double B-tagger: MVA based tagger, used at CMS for tagging Higgs boson, starts with IVF (Inclusive Vertex Finder) that finds secondary vertices in tracks independent of jets, matches to sub-jets from $\tau_{21}$ algorithm, and considers variables like impact parameter [CMS-PAS-BTV-15-002]
Description of techniques and acronyms

• **Tau identification**

  • SVFit : algorithm for calculating di-tau invariant mass based on MET and visible products [1104.1619]

  • boosted tau lepton ID : CMS techniques for identifying tau leptons in sub-jets of large-R jets [CMS-DP-2016-038]
Backup
When do we need a boost?

\[ X \rightarrow V V \rightarrow q + q \]  (where \( V = W/Z \), applies to H)
When do we need a boost?

\[ X \rightarrow V V \rightarrow q + q \] (where \( V = W/Z \), applies to \( H \))

\[ dR(q,q) = 0.5 \Rightarrow M_X = 8M_V = 650 - 1000 \text{ GeV} \ (W - H) \]

\[ dR(q,q) = 0.2 \Rightarrow M_X = 12M_V = 950 - 1500 \text{ GeV} \ (W - H) \]
When do we need a boost?

\[ X \rightarrow V V \rightarrow q + q \]  (where \( V = W/Z \), applies to H)

\[ dR(q,q) = 0.5 \quad \Rightarrow \quad M_X = 8M_V = 650 - 1000 \text{ GeV} \quad (W - H) \]

\[ dR(q,q) = 0.2 \quad \Rightarrow \quad M_X = 12M_V = 950 - 1500 \text{ GeV} \quad (W - H) \]
When do we need a boost?

\[ X \rightarrow V V \rightarrow q + q \]  
(where \( V = W/Z \), applies to H)

\[ \Delta R_{\text{min}}^{qq} \approx \Delta \theta_{\text{min}}^{qq} \approx 2 \frac{M_V}{p_{T,V}} \approx 2 \frac{M_V}{2 M_X} \]

\[ M_X = \frac{4 M_V}{dR(q,q)} \]

\( dR(q,q) = 0.5 \rightarrow M_X = 8 M_V = 650 - 1000 \text{ GeV} \)  
\( (W - H) \)

\( dR(q,q) = 0.2 \rightarrow M_X = 12 M_V = 950 - 1500 \text{ GeV} \)  
\( (W - H) \)

\[ M_X < 600 \text{ GeV} : \text{two resolved cone 0.5 jets} \]

\[ 600 - 1000 \text{ GeV} : \text{wise to consider both boosted and resolved quarks} \]

\[ > 1000 \text{ GeV} : \text{cone of 0.8 captures sub-jets} \]
New physics in Higgs $P_T$
Improved background estimate for high-\(P_T\) Higgs with \(N_{2}^{1,\text{DDT}}\)

\[ N_{2}^{(\beta)} = \frac{2e_{3}^{(\beta)}}{(1e_{2}^{(\beta)})^2} \]

\(\text{DDT} = \text{Designed decorrelated tagger}\)

\(N_{2}^{1,\text{DDT}} = N_{2}^{1} - N_{2}^{(26\%)}\), where \(N_{2}^{(26\%)}\) is the 26th percentile of the \(N_{2}^{1}\) distribution in simulated QCD events as a function of \(\rho\) and \(P_T\). This ensures that the selection \(N_{2}^{1,\text{DDT}} < 0\) yields a constant QCD background efficiency of 26% across the entire \(\rho\) and \(P_T\) range considered in

Use QCD data to model signal region by selecting events which fail a cut on \(N_{2}^{1,\text{DDT}}\)

Better fit of mass, across \(P_T\)

Modeled vs. jet \(\rho, P_T\)

\[ p_{\text{pass}}^{\text{QCD}}(m_{SD}, P_T) = F(\rho(m_{SD}, P_T), P_T) \times p_{\text{fail}}^{\text{QCD}}(m_{SD}, P_T) \]

More info PRL 1709.05543
CMS particle flow
PUPPI+soft drop W-tagging in top events
Measuring a normal quark jet

Particles: $\pi, K, \ldots$

Parton level

$q, g$

Particle Jet

Energy depositions in calorimeters
Measuring a normal quark jet
Measuring a normal quark jet

- 2/3 of jet momentum from charged particles
  - Bend in 3.8 T B-field (CMS)
  - Produce ionization in tracker
    - determine momentum precisely from curvature >~1%
Measuring a normal quark jet

- 2/3 of jet momentum from charged particles
  - Bend in 3.8 T B-field (CMS)
  - Produce ionization in tracker
    - determine momentum precisely from curvature $\sim 1\%$

- 1/3 of jet momentum from neutral particles
  - 2/3 of which are photons that shower EM
    - Produce scintillation light within 20 cm crystal calorimeter (ECAL)
    - Precise energy measurement from light $\sim 1\%$
  - 1/3 of which are neutral hadrons
    - Produce extended nuclear shower in 100 cm brass-sampling scintillator hadronic calorimeter (HCAL)
    - Poor energy measurement $\sim 20\%$
Measuring a normal quark jet

- 2/3 of jet momentum from charged particles
  - Bend in 3.8 T B-field (CMS)
  - Produce ionization in tracker
    - determine momentum precisely from curvature $\geq 1\%$

- 1/3 of jet momentum from neutral particles
  - 2/3 of which are photons that shower EM
    - Produce scintillation light within 20 cm crystal calorimeter (ECAL)
    - Precise energy measurement from light $\sim 1\%$
  - 1/3 of which are neutral hadrons
    - Produce extended nuclear shower in 100 cm brass-sampling scintillator hadronic calorimeter (HCAL)
    - Poor energy measurement $\sim 20\%$

Using all 3 detectors, we measure quark-jet energies to 10%
4.1.3 Variable-radius track jets

The VR track jets are reconstructed from inner detector tracks using the anti-\(k_T\) algorithm. The considered tracks are required to have \(p_T^{\text{track}} > 0.5\) GeV and \(|\eta| < 2.5\). In addition, the tracks must have at least 7 hits in total in the SCT and pixel detectors, and no more than one hit shared by multiple tracks in the pixel detector. If no hit is observed in an active detector element where one is expected, this is referred to as a missing hit. Tracks are required to have no more than one missing hit in the pixel detector and no more than two missing hits in the SCT detector. The longitudinal impact parameter \(|z_0\sin(\theta)|\) is required to be less than 3 mm with respect to the primary vertex to reduce the pile-up contribution efficiency in selecting tracks from the hard-scatter vertex.

The main feature of the VR jet reconstruction is the \(p_T\) dependence of the jet radius:

\[
R \to R_{\text{eff}}(p_T) \approx \frac{R}{p_T}
\]

where the parameter \(\rho\) determines how the effective jet radius scales with the \(p_T\) in the jet finding procedure. Two additional parameters \(R_{\text{min}}\) and \(R_{\text{max}}\) are used and an upper cut on the jet radius. The optimal values of these three parameter double \(b\)-tagging over a wide mass range have been found to be: \(\rho = 30\) GeV, \(R = 0.7\) [69].

Below 2.5 TeV, a higher efficiency for identifying two \(b\)-jets is obtained with FR track jets. This is due to the fact that in this regime, often more than two jets are reconstructed with the VR jet algorithm, and the two highest-\(p_T\) jets are not always the \(b\)-jets [69]. Thus, when considering only the two highest-\(p_T\) track jets, the efficiency is smaller for VR compared to FR track jets. It is possible to recover this signal efficiency by considering the three highest-\(p_T\) jets [69], but in the search presented here this was found to also increase the background contamination to a level that led to an overall decrease in sensitivity. Therefore, only the two highest-\(p_T\) VR track jets are used in this analysis. Even though the signal efficiency is higher for FR track jets below 2.5 TeV, the use of the VR algorithm provides a better signal-to-background ratio. In particular, including events containing only one \(b\)-tagged jet leads only to a marginal improvement in sensitivity when using VR track jets. Since the background modelling in such events is more challenging, they are not included in the result presented here, but are shown for illustration in Figure 2. More detailed studies and the potential inclusion of such events in the search are left for future work.

In the resolved regions, events with at least two small-\(R\) jets are considered required to be \(b\)-tagged. The Higgs-boson candidate is reconstructed from at least one of these two jets to have a \(p_T\) above 45 GeV. The scalar sum of the highest-\(p_T\) additional jet, if present, has to be larger than 63% of the event to reject \(t\bar{t}\) events. In order to reduce backgrounds from multijet ev between the two jets forming the Higgs candidate is restricted to below 1 must be less than 1.8. The Higgs candidate has to be separated from the object-based \(E_T^{\text{miss}}\) significance has to fulfil \(S > 16\). For events with two (or sum of the first two) jets to be greater than 120 (150) GeV. In all central jets are considered, then forward jets, each set of jets order.

The merged-region selection requires the presence of at least one large-\(R\) jets associated with the leading large-\(R\) jet are required to be \(b\)-tagged at separation cut as described in Sec. 4.2. Events that contain one or more \(l\) the large-\(R\) jet are rejected. The \(p_T\) of the leading large-\(R\) jet is required scalar sum of the transverse momenta of the leading large-\(R\) jet and all sm the contribution from \(t\bar{t}\) events.

In Figure 2, the gain in sele illustrated. Figure 2(a) show for events with \(E_T^{\text{miss}} > 50\) that the mass of the Higgs candidate lies between 100 and 200 GeV, as a function of \(m_T^Z\). In particular selection requires at least two track jets associated to the large-\(R\) jet, and a minimum angular separa of the two leading track jets as described in Sec. 4.2. The efficiency is calculated only considering \(Z\) decays to \(b\)-quarks. Open symbols and dashed lines mark the efficiencies obtained when using fixed-\(R\) (FR) track jets with a radius parameter of 0.2, while filled symbols and solid lines correspond to the u VR track jets. The effect is shown separately for \(b\)-tag multiplicities of 1 (square markers) and 2 (triangular markers). In addition, the combined acceptance from events with 0, 1 or 2 \(b\)-tagged jets is drawn circular markers. It is considerably higher for VR track jets in the region above 2.5 TeV, as events \(t\) often fail the requirement of more than one track jet in the case of FR jets. The increase in accept for both 1- and 2-\(b\)-tag events is also most pronounced for \(m_T^Z\) above 2.5 TeV, corresponding to the la
two separated b-jets (R=0.4)

$\Delta R(b\bar{b}) \sim 2m_H/p_T$

one merged double b-jet (R=0.8)
Higgs PT modeling
Heavy resonances decaying to two bosons

- These two bosons $Y=\{W,Z,H\}$ each mostly decays to quarks

So we just need controlled way to make TeV-mass scale heavy resonances and then look for quarks in our detector
In spring 2015, while studying 2012 LHC data...
In spring 2015, while studying 2012 LHC data

But fluctuations like this are expected some times

UZH Jennifer Ngadiuba

2 TeV
In summer 2015, things got more interesting

- Another bump at 2 TeV found by ATLAS analyzing the 2012 data
ATLAS 2 TeV bump in 2012 data

\[ X \rightarrow VV \rightarrow JJ \]

![Plot of ATLAS 2 TeV bump in 2012 data with m_\parallel [TeV] on the x-axis and Events / 100 GeV on the y-axis, showing data, background model, and significance.](image.png)

**Events / 100 GeV**

- Data
- Background model
- 1.5 TeV EGM W', c = 1
- 2.0 TeV EGM W', c = 1
- 2.5 TeV EGM W', c = 1
- Significance (stat)
- Significance (stat + syst)

**Significance (stat)**
- 1.5 TeV EGM W', c = 1
- 2.0 TeV EGM W', c = 1
- 2.5 TeV EGM W', c = 1

**Significance (stat + syst)**
- 1.5 TeV EGM W', c = 1
- 2.0 TeV EGM W', c = 1
- 2.5 TeV EGM W', c = 1

**Local p_0**

- WZ Selection
- WW Selection
- ZZ Selection

**\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)**

**σ**
- 0
- 1
- 2
- 3
- 4

**m_\parallel [GeV]**

- 1400
- 1600
- 1800
- 2000
- 2200
- 2400
- 2600
- 2800
- 3000
protons

protons
protons

$E = mc^2$

&

QFT

protons
protons
protons
Other 2012-data diboson resonance searches

![Graphs showing CMS data and background estimation for ZZ resonances at 2 TeV.](image)

**UZH Dr. Andreas Hinzmann**

**2 TeV**

JHEP 08 (2014) 173

JHEP 08 (2014) 174
Other 2012-data diboson resonance searches

JHEP 08 (2014) 173
JHEP 08 (2014) 174

UZH Dr. Andreas Hinzmann

2 TeV

Extremely difficult boosted topology
ATLAS new 2015 data search results

- Nothing at 2 TeV
- Statistical fluctuations as expected
CMS 2015 data search results

CMS Data

Dijet invariant mass [GeV]

Events / (100 GeV)

100
200
300
400
500
600
700
800
900
1000

2.2 fb⁻¹ (13 TeV)

CMS Preliminary

Data-Fit

σ

3 par. background fit (default)

2 par. background fit (alt.)

G(2 TeV)→ZZ (σ = 0.019 pb)

ZZ, high-purity

h_j < 2.4, p_j > 200 GeV

M_j > 1 TeV, |η| < 1.3

CMS Preliminary

Uncertainty

CMS Data

W+jets

WW/WZ

Single Top

G_{bulk} M_{W} = 2 TeV (×100)

High-Purity, WW enriched

UZH Jennifer Ngadiuba

UZH Thea Årrestad
CMS 2015 data search results

- Nothing obvious at 2 TeV
- Statistical fluctuations as expected
- 3 TeV excess more interesting than 2 TeV
  - (combined ~2σ local fluctuation)
X $\rightarrow$ WH $\rightarrow$ lvbb

CMS EXO-14-010

MET = 185 GeV
Ele $P_T = 400$
Jet $P_T = 1.08$ TeV
$M_J = 124$
$M_X = 1.81$ TeV
X $\rightarrow$ WH $\rightarrow$ lvbb

CMS EXO-14-010

MET = 185 GeV
Ele $P_T = 400$
Jet $P_T = 1.08$ TeV
$M_J = 124$
$M_X = 1.81$ TeV
X $\rightarrow$ WH $\rightarrow$ lvbb

MET = 185 GeV
Ele $P_T = 400$
Jet $P_T = 1.08$ TeV
$M_J = 124$
$M_X = 1.81$ TeV

but not seen in muons