Discovery prospects with jets @ LHC

Debarati Roy
Post Doctoral Research Fellow
University of the Witwatersrand

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Outline of my Talk

• Where are we standing?
• Current objective in LHC
• What is a jet in LHC?
• Some distinct features of jets
• Measurements of jets
• Jets as a tool in new Physics search
• Summary & Outlook
Where are we standing?

Matterhorn at Zermatt, Alps

We have covered a lot but a lot still remains!
Our Wonderful Standard Model (SM)
A remarkable insight into fundamental structure of matter & their interactions.

- Validated with series of new particle discoveries at LEP, Tevatron, LHC.
- Last missing piece found in 2012!
What Next : Looking Beyond SM (BSM)

• SM cannot be the whole story : New Physics 🌟👻🌟
  
  • What’s the origin of neutrino masses ?
  • What’s the origin of dark matter/energy ?
  • What’s the origin of matter-antimatter asymmetry ?
  • What’s the solution to the hierarchy problem ?
  • ...

Everything is a BSM search in the end ....

• Delve into unknowns ..
What we do @ LHC?
1. Search for signatures of New Physics

Completed Run2 in 2018 end at 13 TeV, with 160 fb$^{-1}$ integrated luminosity.
1. Search for signatures of New Physics

How?
1. Search for signatures of New Physics

How?

Bump Hunting!

Klipriviersberg Nature Reserve, SA
1. Search for signatures of New Physics

How?

Bump Hunting!

=> Looking for excess over background.
1. Search for signatures of New Physics

2. Measure SM processes at every new energy regime LHC runs
1. Search for signatures of New Physics

2. Measure SM processes at every new energy regime LHC runs

Why?
1. Search for signatures of New Physics
2. Measure SM processes at every new energy regime LHC runs

Why?
To estimate background

Klipriviersberg Nature Reserve, SA
1. Search for signatures of New Physics
2. Measure SM processes at every new energy regime LHC runs

Both can be studied with Jets : Most common candidate in LHC
Jets

A bunches of collimated stable hadrons called a jet in LHC.

LHC is a Jet factory!

A typical jet event with reconstructed initiating partons!

SM particles decay to jets with largest Branching fraction.
A jet is reconstructed

Particle Flow (PF) jet:
Optimised combination** from all sub-detectors to identify a particle.
e.g. A set of track + clusters constitute a charged hadron.

Identified particles fed to jet reconstruction algorithm to build jets.

**a) Track reconstruction  b) Calorimeter clustering  c) Extrapolation of tracks and linking the deposits of each particle.

Calorimeter jet: Energy topo-clusters in calorimeters used as input to a jet reconstruction algorithm.
Jet Reconstruction Algorithm

- Jets can be built from any set of 4-vectors: Topoclusters, tracks, particles..

Jet Reconstruction:
Sequential Recombination Algorithm (in LHC)

What is $k_T$?

- Intrinsic transverse momentum
- Fixed “radius” parameter

Distance between two input objects Distance between each input object and beam

- Find the smallest of all $\{d_{ij}, d_{IB}\}$
- If this is one of the $d_{ij}$ values, inputs $i$ and $j$ are merged. & Iterate.
- If it is one of the $d_{IB}$ values, $i^{th}$ input is considered a jet.

$R = 0.4, 0.5, ..1.0$
Event Simulation: Vital for data to theory comparison

- Monte Carlo (MC) event generators (based on theory calculations & data-driven models) used.

- Output fed to Geant4 for particle through detector simulation.

- Leading Order (LO) MC with 2 -> 2 hard scattering, then builds up a complex 2 -> N final state by parton shower. Examples: Pythia, Herwig family.

- Higher Order/Multileg generators: Powheg, Madgraph.

**Underlying Event (UE)**

- Background to events with an identified hard scatter.
- UE not well predicted as analytically cannot be solved.

- Strategy: Test UE with parametrised models to “Tune” MC to have best description of data.
Tuning

• Ultimate goal: models need to describe real data.

• “Free” parameters control all these aspects of the models, which cannot be derived analytically.

• A bunch of correlated (or anti-correlated) parameters describe one aspect, so have to change them simultaneously.

Tune: A particular optimized parameter setting in a particular MC generator to match the simulation with available data. Differ according to which datasets are included.

Taken from Deepak Kar’s talk @TIFR
Event-shape variables : Useful input for Tuning

- Performed at early phase of LHC with 5 fb\(^{-1}\) of CMS data.
- At start of LHC understanding MC model performance was crucial.
- Event shapes explore the geometry of hadronic energy flow.
- Sensitive to both soft (e.g. hadronization) & hard (e.g. multijet radiation) aspects of hadron interaction.
- Expressed in terms of the ratio of the jets momenta.

- **Transverse thrust**: Event thrust defined as

\[
\tau_\perp \equiv 1 - \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_T|}{\sum_i p_{T,i}}
\]

\[
\tau_\perp, c = 1 - \frac{2}{\pi}
\]

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Unfolded Measurements Compared with MC Predictions

- Computed with at least 2 PF jets.
- D’Agostini unfolding method used.

- Thrust: Sensitive to hadronization, parton shower, less sensitive to Multijet radiation.
- Multileg Madgraph generator performs well except in dijet dominated phase space.
• Computed with at least 3 jets.
• Sensitive to hard parton emission, less sensitive to hadronization model or parton shower.
• Madgraph performs best.
• Rivet routine provided to compare with theory/experiment.
Jet Charge: Estimator of electric charge of a jet

Useful tool to probe charge of particle/parton initiating the jet:
Discriminator between quarks/anti-quarks/gluons/any two particles with different electric charges.

Useful tool for determining charge of hadronically decaying particles.

Measurement can lead to improve MC simulation (& promote its new applications.)

This was the first unfolded jet charge measurement in CMS (different definitions studied)!
Higher the energy more quark jet fraction dominates

Jet charge definitions

**Default**

\[ Q_{\kappa} = \frac{1}{(p_T)^{\kappa}} \sum_i Q_i (p_T^i)^{\kappa} \]

**Parallel**

\[ Q_{L}^{\kappa} = \sum_i Q_i \left( p_{||}^i \right)^{\kappa} / \sum_i \left( p_{||}^i \right)^{\kappa} \]

**Perpendicular**

\[ Q_{T}^{\kappa} = \sum_i Q_i \left( p_{\perp}^i \right)^{\kappa} / \sum_i \left( p_{\perp}^i \right)^{\kappa} \]

Compared to \( Q_{\kappa} \), the quantity \( Q_{L}^{\kappa} \) is more directly related to the fragmentation function \( F(z) \) of a quark or a gluon, which reflects the probability to find particle \( i \) with momentum fraction \( z = p_{||}^i / |p_{\text{jet}}| \) in a quark jet or a gluon jet [1]. We study all three variables \( Q_{\kappa} \), \( Q_{L}^{\kappa} \), and \( Q_{T}^{\kappa} \) to elucidate the fragmentation of partons into hadrons.
Different features of jet charge

- Discriminating power of jet charge for initiating parton: Up(0.166e), Down(-0.088e), Gluon(0.013e).

- $k$ leads to different sensitivity to low & hard $p_T$ jet constituents (lower $k$ lower $p_T$ particles dominate).
- Detector effect causing more impact as lower $k$ values approached.
More sensitive to parton shower, hadronization than parton distribution function.

Each definition has different sensitivity than other between PH+P8 & PH+HPP.

T reflects maximum experimental uncertainty as larger weights given to low $p_T$ particles (similarly for low $k \sim 0.3$).
Jet charge value rises with $p_T \Rightarrow$ More quark jets than gluon jets in high $p_T$ range: More underlying hard partons can be probed!

Agreement between unfolded measurement & MC generators improve with higher $p_T$ (exhibits model robustness in quark dominated regime than gluon). Rivet routine provided.
Not a familiar jet all the way!
Not a familiar jet all the way!

• The way we treat jets is evolving.

• We are pulling them apart, looking at their (sub)structure, shapes and properties!

• Necessary for the physics program at the LHC.
More energy → boost

As LHC energy increases, objects are produced with more $p_T$.

• In high $p_T$ regime difference between daughter & mother particles is sufficient to provide a boost to the daughter particle: boosted daughter decay then forms a “fatjet” or “large-R jet” e.g. $\text{top}(\rightarrow q\bar{q}, 'b), \text{Higgs}(\rightarrow b\bar{b}), \text{W/Z}(\rightarrow q\bar{q})$: Leads to subjets inside a fatjet!

![Diagram showing normal analyses and high-$p_T$ regime with boosted objects](image)

Normal analyses: two quarks from $X \rightarrow q\bar{q}$ reconstructed as two jets

High-$p_T$ regime: EW object $X$ is boosted, decay is collimated, $q\bar{q}$ both in same jet

Happens for $p_t \gtrsim 2m/R$

$p_t \gtrsim 320$ GeV for $m = m_W, R = 0.5$

more luminosity → pile-up

We are inundated with additional pp interactions on top of our process of interest -> fatjet reduces combinatorial nightmare!
jet phase space

$p_T$

20 GeV  100 GeV  300 GeV  2 TeV

pileup jets

quark/gluon jets

W/Z/H jets

top jets

???

New Physics?

as a general rule, the boosted regime: $\Delta R \sim 2m/p_T$

[From Nhan Tran’s talk @Fermilab]
• More energetic $X$ ($X \rightarrow ab$), more collimated decay products ($\text{top} \rightarrow q\bar{q}^\prime b$, $W \rightarrow q\bar{q}$)

Boosted characteristics in LHC

• We exploit the “substructure” of the fatjet to identify original particles.

• Fatjet not only includes particles coming from interesting decay, but also from pile-up, UE $\Rightarrow$ needs to be Groomed!
Fatjet Grooming & Calibration

Softdrop

Trimming

In situ Calibration

Softdrop ($\beta = 0$, $Z_{cut} = 0.1$)

- Cluster together constituents using the C/A algorithm
- undo last clustering step to get resulting subjets $j_1$ and $j_2$
- If the subjets pass the soft drop condition: $\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > Z_{cut} \left( \frac{\Delta R_{12}}{R_0} \right) ^ \beta$
- Otherwise, discard lowest $p_T$ subjet and iterate.
In situ calibration of large radius jet at 13 TeV in ATLAS

- Sensitivity of searches/measurements with a fatjet depend on precision of its mass & $p_T$ responses.
- In situ calibration measures fatjet mass, $p_T$ responses from several physics processes where a fatjet balances against a reference object (e.g. a Z boson).
- It is based on a data-to-mc ratio of response measurement & applied only to data (typically 2–3%).
- Correction applied as a four-momentum scale factor to jets in data.

**Strategy & Result**

- A direct balance ($R_{DB}$ or $R_{bal}$) approach followed in momentum between fatjet and Z boson.

$$R_{bal} = \frac{p_T^{jet}}{p_T^{ref}}, \text{ where } p_T^{ref} = p_T^Z|\cos\Delta\phi(jet, Z)|$$

where $\Delta\phi$ is the angle between fatjet jet axis and Z boson.

- Both $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ decays studied.

- Mis-modelling estimated with $R_{DB}$ double ratio between data & MC.

- Extra energetic radiation is vetoed to prevail balancing topology.

- $Z +$ jet calibration valid till $p_T$ range $\sim 500$ GeV.
A search with unusual topology: Electron in a fatjet

Motivation:

- What’s the origin of neutrino masses?
- What’s the origin of dark matter/energy?
- What’s the origin of matter-antimatter asymmetry?
- What’s the solution to the hierarchy problem?
- ...

Several searches performed in LHC to explain origin of a very small neutrino ($\nu$) mass.

- Existence of small $\nu$ mass explained in BSM by introducing right-handed gauge boson ($W_R$) & right-handed neutrino ($N_R$).
- $\nu$ obtained its mass via coupling to $N_R$ by mass mixing matrix.

Usual final state consists of 2 small jets ($q\bar{q}$) & 2 leptons ($2\ell$)

Resolved Topology
Extending phase space with boosted topology

Latest ATLAS result with resolved topology

$m_{NR} << m_{WR}$:

- Least explored phase space as sensitivity drops with resolved topology.
- More efficient to consider boosted scenario!

$m_{NR} << m_{WR}$

- First time in LHC we looked at possibility for boosted $N_R$ in ATLAS with 80 fb$^{-1}$ of data at 13 TeV (Accepted in Phys. Lett. B.).

arXiv:1904.12679

Fatjet
Extending phase space with boosted topology

Latest ATLAS result with resolved topology

\[ m_{N_R} \ll m_{W_R} : \]
- Least explored phase space as sensitivity drops with resolved topology.
- More efficient to consider boosted scenario!

Fatjet is the proxy for \( N_R \)!
(distinguishing feature of this search)

\[ m_{N_R} \ll m_{W_R} \]

- First time in LHC we looked at possibility for boosted \( N_R \) in ATLAS with 80 fb\(^{-1}\) of data at 13 TeV (Accepted in Phys. Lett. B.).
• Final state consists of a fatjet & 2ℓ.
• Electron (e) & muon (μ) final states looked at separately with no flavour mixing.
• A balancing topology between hardest e (e₁) or μ (μ₁) & highest mass fatjet (j) along with 2nd hardest e (e₂) or μ (μ₂) inside it gives well shaped detector level variables. =>>
• Different NR mass computation performed between e & μ final states due to nature of jet reconstruction:
  - m_{NR} in e channel : Mass of j (as e energy is a part of j
  - m_{NR} in μ channel : Invariant mass of j & μ₂.
**\( m_{WR} \) : The discriminating variable for region definition**

- **\( m_{WR} \) Computation in e final state**: Invariant mass of \( j + e_1 \).
- **\( m_{WR} \) Computation in \( \mu \) final state**: Invariant mass of \( j + \mu_1 + \mu_2 \).
- **Control Region (CR : \( m_{WR} < 2 \) TeV)** shows reasonable data-mc agreement including statistical uncertainty.
- **Signal Region (SR : \( m_{WR} > 2 \) TeV)**.
- **A Validation Region (VR)** studied with a hard e inside j balanced by a \( \mu \) to conclude that data can be well predicted by mc (when a hard e inside j).
Performance of large radius jet with a hard e inside

- Jet Mass Scale (JMS) as a function of generator level fatjet mass shows reasonable behaviour:

- Effect of a non-negligible fraction of EM clusters in jet investigated in terms of jet energy & jet mass scales as a function of ratio of energy of $e$ to the energy of $j$.

- A weak dependence (within scale expected uncertainty range) concludes no additional correction factor needs to be implemented.

Events mostly concentrated at the JMS expected value equal to unity.
Overlap Removal (OR) Strategy for e close to hadronic activity

- In signal topology e2 always close to a real jet
  - => Standard OR in ATLAS removes jet or e if within $\Delta R < 0.4$:
    - Thus signal efficiency drops off!
  - => A modified OR approach followed for e2:
    - Within $\Delta R \sim 0.04$ of e & jet, events dominated with a true e mis-reconstructed as a jet. Thus events with $\Delta R > 0.04$ selected.
    - => Further standard e efficiency correction factor cannot be used.

Thus in VR additional criterion applied: a b-tagged jet & data-mc comparison done within $0.04 < \Delta R < 0.4$.

Residual disagreement quantified as an additional efficiency correction factor uncertainty.

arXiv:1904.12679
Background Estimation & lower limits in \( m_{WR} - m_{NR} \) plane

- No significant excess observed.
- Slight excess will be studied with Full Run2.

A data-driven fit performed & extrapolated to SR.
- Different steeply falling functional forms tested in CR, best taken with respect to mc closure (in CR & VR) & GOF.
- As Zjets dominates in higher mass range, a Zjets mc fit parameters used in resultant fit to data.
- Fitted uncertainty includes extreme variations in SR yield using different fit ranges in CR as well as modelling uncertainty in Zjets mc & statistical uncertainty of fit.
Measurement of jet substructure at 13 TeV in ATLAS

- Most comprehensive jet substructure measurement at LHC.

Most widely used substructure observables

**dijet selection**
- Events with 2 large R jets with a \( p_T > 200 \) GeV
- Leading jet \( p_T > 450 \) GeV (trigger plateau)
- Veto on leptons
- Consider central \( |\eta| < 1.5 \) leading jet from each event

**w/top selection**
- Tag leptonic top and consider recoiling fatjet, basic selection:
  - \( E_T^{miss} > 20 \) GeV and \( E_T^{miss} + M_T^W > 60 \) GeV
  - 1 muon with \( p_T > 25 \) GeV
  - \( \geq 1 \) b-tagged jet at a 70% WP
  - \( \geq 1 \) jet with \( p_T > 25 \) GeV that is within \( \Delta R < 1.5 \) of the selected lepton
  - Select leading large R jet with \( \Delta \phi > 2.3 \) with lepton and \( \Delta R > 1.5 \) with leading selected small R jet

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Measurement of jet substructure at 13 TeV in ATLAS

- Most comprehensive jet substructure measurement at LHC.

Most widely used substructure observables

\[ \text{N-Subjets LHA} \]
\[ \text{N-Subjettiness EnergyCorrelation function} \]

**dijet selection**
- Events with 2 large R jets with a \( p_T > 200 \text{ GeV} \)
- Leading jet \( p_T > 450 \text{ GeV} \) (trigger plateau)
- Veto on leptons
- Consider central \( |\eta| < 1.5 \) leading jet from each event

**w/top final selection**
- Lower \( p_T \) cut of 200 (350) GeV for \( W \) (top) selection to ensure boosted jet
- Consider closest b-tag track-jet to the selected large R jet:
  - Selected as top jet if \( \Delta R(J^R=1.0, J^{btag}) < 1.0 \)
  - Selected as W jet if \( 1.0 < \Delta R(J^R=1.0, J^{btag}) < 1.8 \)

Additional cuts on jet mass:
- \( m_{jet} > 140 \text{ GeV} \) for top selection
- \( m_{jet} = [60, 100] \text{ GeV} \) for W selection

JHEP 08 (2019) 033
Stunning features of Substructure measurements!

- Number of subjets with $p_T > 10$ GeV, reconstructed from the fatjet constituents with $k_T$ algorithm with $R = 0.2$.

$\Rightarrow$ Dijet : 1, $W : 2$, Top : 3 subjets dominated.

- LHA:

$$\chi^\kappa_\beta = \sum_{i \in \text{jet}} z_i^\kappa \theta_i^\beta, \quad \kappa=1, \beta=0.5$$

where $z_i$ is the transverse momentum fraction $p_T^i/p_T^{\text{jet}}$ of the constituent, and $\theta_i$ is the angle of the $i$th constituent of the jet relative to the jet axis, normalised by the jet radius. The exponents $\kappa$ and $\beta^{\text{LHA}}$ probe different aspects of the jet fragmentation. The ($\kappa = 1, \beta^{\text{LHA}} = 0.5$) variant is termed the Les Houches angularity (LHA) [65] and used in this analysis.

- Softer/centralised radiation in Dijet.
Stunning features of Substructure measurements!

- **N-Subjettiness**: Quantify the degree to which jet radiation aligned along specific subjet axes.

\[
\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{ \Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k} \}
\]

\[
d_0 = R \times \text{sum of } p_T \text{ of all constituents}
\]

\[\tau_N \to 0 \text{ for } N \text{ prong substructure}\]

Visible difference in two & three-prong substructures
Summary & Outlook

- As LHC energy & luminosity increase extended phase space becoming more suitable to explore massive resonances & thus more crucial to study boosted topologies (& performing thorough measurements of SM in such topologies).

- Till now as no new physics can be reached in LHC with standard topologies we need to focus more on unusual topologies & objects which present a challenge to standard reconstruction/identification => a fatjet with a hard electron inside an example that also results into small background.

- Further tuning for this search in order to gain more signal efficiency for near future is underway => a Wits student working on to bring up a lepton identification in dense hadronic environment & in high $p_T$ regime.

Stay Tuned!
• Extra material
Right handed coordinate system: Same convention in ATLAS & CMS.

- Origin => Interaction point, +x => towards centre of LHC ring, +y => points upward, +z => points parallel to the anticlockwise beam direction.
- $\phi$ => Measured with respect to x axis in xy plane. $\eta$ => $-\ln(\tan(\theta / 2))$, $\theta$ => Measured with respect to the z axis.
Jet Detection in LHC

- Coaxial cylindrical layers of sub-detectors
- Strong magnet to bend high $p_T$ particles
- ATLAS: 2 times larger in size than CMS!
- Overall similar cylindrical structure
Jet Needs Calibration

- To compensate nonlinear response of calorimeters.
- To reduce pile-up (effect from other pp collisions from same/preceding/subsequent bunch crossings), detector noise, data-MC mismatch.

Jet response: Ratio of energy of reconstructed jet with truth-particle jet (jets built from all stable MC particles from hard interaction & UE activity.

\[ R(E, \eta) = \frac{E_{\text{reco}}}{E_{\text{truth}}} \]

- Calibrated jets are used as inputs for analysis purpose.
Calorimeters

• Calorimeters: Blocks of instrumented material in which particles to be measured are fully absorbed.

• Interaction of the incident particle with the detector (absorber), through electromagnetic or strong processes, produces a shower of secondary particles with progressively degraded energy.

• Energy deposited by charged particles of the shower in the active part (scintillator) of the calorimeter can be detected with photo detectors that convert light into an electric signal.

• The more energy the incoming particle has, the more secondary particles it produces.
Event Shape Analysis Event Selection

• Inclusive Jet Events : Events selected with at least 2 PF jets with anti-$k_T$ algorithm $R = 0.5$.

• Each event has all jets with $p_T > 30$ GeV & $|\eta| < 2.4$.

• Events should pass at least one single jet trigger (keep interesting events by matching object requirement!).

• Events are divided into five sectors in terms of leading jet $p_T$ range, each sector utilised data from corresponding trigger.
• Inclusive Jet Events: Events selected with at least 2 jets with anti-$k_T$ algorithm $R = 0.5$.

<table>
<thead>
<tr>
<th>Trigger $p_T,th$ (GeV)</th>
<th>Range of $p_T,1$ (GeV)</th>
<th>Luminosity</th>
<th>Number of events</th>
<th>Fraction of events (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$N_{jet} = 2$</td>
</tr>
<tr>
<td>60</td>
<td>110–170</td>
<td>0.403 pb$^{-1}$</td>
<td>96833</td>
<td>57.9</td>
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<tr>
<td>110</td>
<td>170–250</td>
<td>7.15 pb$^{-1}$</td>
<td>228854</td>
<td>43.0</td>
</tr>
<tr>
<td>190</td>
<td>250–320</td>
<td>153 pb$^{-1}$</td>
<td>601554</td>
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<tr>
<td>240</td>
<td>320–390</td>
<td>521 pb$^{-1}$</td>
<td>497827</td>
<td>31.0</td>
</tr>
<tr>
<td>300</td>
<td>$&gt;390$</td>
<td>4.98 fb$^{-1}$</td>
<td>2234304</td>
<td>28.4</td>
</tr>
</tbody>
</table>

• Events are divided into five sectors in terms of leading jet $p_T$ range, each sector utilised data from corresponding trigger (keep interesting events by matching object requirement!).
Measurements with jets

Study of hadronic event-shape variables in CMS with 7TeV data

- Sensitive to pQCD & Non-pQCD.
- Describe energy flow of final state.
- Expressed in terms of the ratio of the jets momenta (reduce JES uncertainty).
- Aim: Understand MC model constraint to improve MC prediction.

- **Total Jet Broadening:**
  \[ B_X \equiv \frac{1}{2 P_T} \sum_{i \in C_X} p_{T,i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2} \]
  \[ B_{tot} \equiv B_U + B_L \]

- **Transverse plane divided as up C_U (p_T \cdot n_T > 0) & down, C_D (with p_T \cdot n_T < 0):**
  - **Transverse thrust:** Event thrust defined as (in the transverse plane wrt beam axis),
    \[ \tau_1 \equiv 1 - \max_n \frac{\sum_i [p_{T,i} \cdot \hat{n}_T]}{\sum_i p_{T,i}} \]
  - **Jet Mass:** Normalized squared invariant jet mass,
    \[ \rho_x \equiv \frac{M_X^2}{P^2} \]
  - **Third Jet Resolution Parameter:** Estimates relative strength of \( p_T \) of third jet with respect to other two jets,
    \[ Y_{23} \equiv \min(p_{T,3}^2, \min(p_{T,i}, p_{T,j})^2 \times (\Delta R_{ij})^2 / R^2)] \]
Madgraph generates parton level events.

In jet $p_T$ distribution with official Madgraph sample, significant deviation observed.

Thus private samples are produced with different recipes.

MadEvent samples are then showered with parton shower generator Pythia6.

Basic jet objects and event shapes are compared with private/official samples, as well as with unfolded data.

**Table 1: Recipes of the privately produced MADGRAPH samples**

<table>
<thead>
<tr>
<th>Tag</th>
<th>$x_{\text{qcut}}$ (GeV)</th>
<th>$p_{\text{Tj}}$ (GeV)</th>
<th>$Q_{\text{cut}}$ (GeV)</th>
<th>$H_T$ bins (in GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1</td>
<td>10</td>
<td>10</td>
<td>15</td>
<td>100−250, 250−500, 500−1000, &gt;1000</td>
</tr>
<tr>
<td>Set 2</td>
<td>20</td>
<td>20</td>
<td>25</td>
<td>100−250, 250−500, 500−1000, &gt;1000</td>
</tr>
<tr>
<td>Set 3</td>
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<td>100−250, 250−500, 500−1000, &gt;1000</td>
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<tr>
<td>Set 4</td>
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<td>100−250, 250−500, 500−1000, &gt;1000</td>
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<tr>
<td>Set 6</td>
<td>20</td>
<td>20</td>
<td>30</td>
<td>100−250, 250−500, 500−1000, &gt;1000</td>
</tr>
</tbody>
</table>

**Table 2: Recipes of the officially produced MADGRAPH samples**

<table>
<thead>
<tr>
<th>Tag</th>
<th>$x_{\text{qcut}}$ (GeV)</th>
<th>$p_{\text{Tj}}$ (GeV)</th>
<th>$Q_{\text{cut}}$ (GeV)</th>
<th>$H_T$ bins (in GeV)</th>
</tr>
</thead>
<tbody>
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<td>Official</td>
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<td>20</td>
<td>100−250</td>
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<tr>
<td></td>
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<td>60</td>
<td>500−1000</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>40</td>
<td>60</td>
<td>&gt;1000</td>
</tr>
</tbody>
</table>

$x_{\text{qcut}}$ : Minimum $k_T$ of the hard jets should be above this value.

$p_{\text{Tj}}$ : The jet $p_T$ threshold at hard interaction.

$Q_{\text{cut}}$ : The same as $x_{\text{qcut}}$ but at the parton shower level.
Unfolding

- In other fields known as “deconvolution” or “unsmearing”

- Given a “true” PDF in $\mu$ that is corrupted by detector effects, described by a response function, $R$, we measure a distribution in $v$. For a binned distribution:

$$v_i = \sum_{j=1}^{M} R_{ij} \mu_j \quad i = 1..N$$

- This may involve
  1. inefficiencies: lost events
  2. bias and smearing: events moving between bins (off-diagonal $R_{ij}$)

- With infinite statistics, it would be possible to recover the original PDF by inverting the response matrix

$$\mu = R^{-1}v$$
Privately generated Madgraph sample used (where jet $p_T$ threshold made independent of HT slices) which solves jet $p_T$ discontinuity (first solved in this work).

**Thrust:** Sensitive to hadronization, parton shower, less sensitive to ME calculation.

### Unfolded Measurements Compared with MC Predictions

<table>
<thead>
<tr>
<th>MC Model</th>
<th>Tune</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pythia6.426</td>
<td>D6T</td>
<td>Virtuality ordered parton showering (PS) based on Tevatron data.</td>
</tr>
<tr>
<td></td>
<td>PERUGIA-P0</td>
<td>$p_T$ ordered PS based on LEP and Tevatron data.</td>
</tr>
<tr>
<td></td>
<td>Z2</td>
<td>$p_T$ ordered PS based on CMS data.</td>
</tr>
<tr>
<td>Pythia8.153</td>
<td>TUNE4C</td>
<td>$p_T$ ordered PS and Underlying Event (UE) based on the Multi Parton Interaction (MPI) model of Pythia6 interleaved with initial and final state radiations.</td>
</tr>
<tr>
<td>Herwig++ 2.5.0</td>
<td>TUNE23</td>
<td>PS evolution based on angular ordering, eikonal MPI model is used to generate the UE.</td>
</tr>
<tr>
<td>Madgraph 5.1.5.7</td>
<td></td>
<td>Matrix element generator, showered with Pythia6 Tune Z2.</td>
</tr>
</tbody>
</table>
Jet Charge Analysis Event Selection

• Events selected with 8 TeV CMS data corresponding to 19.7 fb\(^{-1}\) integrated luminosity.

• All jets are reconstructed with PF algorithm, with anti-\(k_T\) jet clustering algorithm with R= 0.5.

• Each event should have leading jet \(p_T > 400\) GeV, sub leading jet \(p_T > 100\) GeV, both should lie within \(|\eta| < 1.5\).

• Jet constituents \(p_T > 1\) GeV (both at generator level and reconstructed level).

• Measurement is corrected for detector effect (i.e. unfolded) and compared with LO, NLO(Powheg) event generators.
Measurements with jets

- Jet charge FSR sensitive. Significant improvement with low FSR $\alpha_S$.
Object & Event selection:

- **LargeR jet selection (J1):**
  AntiKt10LCTopoTrimmedPtFrac5SmallR20Jets, \( p_T > 100 \text{ GeV} \), |\( \eta \) < 0.8
  JES_MC16recommendation_FatJet_JMS_calo_29Nov2017.config (2015, 2016)

- **Z boson selection:**
  2 Opposite Sign leptons (electrons or muons)
  Dilepton invariant mass window > 80 GeV & < 116 GeV

- **Small jet (j2, used to veto subleading jet):**
  AntiKt4EMTopoJets
  \( p_T < \max(0.1*p_T^{\text{Ref}}, 15\text{GeV}) \), JVT > 0.59 for \( p_T < 60 \text{ GeV} \) & |\( \eta \) < 2.4,
  \( dR(J1,j2) > 1.4 \)

- **Lepton:**
  - **Electron:** Trigger: HLT_2e15_lhvloose_nod0_L12EM13VH, HLT_2e17_lhvloose_nod0 (2015, 2016)
    HLT_2e17_lhvloose_nod0_L12EM15VHI (2017)
    Medium ID & loose isolation, \( p_T > 20 \text{ GeV} \), |\( \eta \) < 2.47, \( dR(\text{Electron},j2) > 0.4 \), \( dR(\text{Electron},J1) > 1.0 \)

  - **Muon:** Trigger: HLT_2mu10, HLT_2mu14
    Loose quality & loose isolation, \( p_T > 20 \text{ GeV} \), |\( \eta \) < 2.4, \( dR(\text{Muon},j2) > 0.4 \), \( dR(\text{Muon},J1) > 1.0 \)

- **Additional balancing cut:** \( d\Phi(\text{lepton, J1}) > 2.8 \).
With data1516 & mc16a combining electron & muon channels

Mean $R_{\text{DB}} / R_{\text{bal}}$ in data as a function of reference object $p_T$ representing balancing topology throughout ref. $p_T$ values.

A Gaussian fit performed with $R_{\text{DB}}$ in ref. $p_T$ bins. Each bin average response for best fitted poisson form is further used.
With data1516 & mc16a combining electron & muon channels

Response as a function of ref. $p_T$ is mapped to response as a function of largeR jet $p_T$.

From each ref. $p_T$ bin (above) mean largeR jet $p_T$ value is used. Mapping

$\Rightarrow$

$\Rightarrow$ Combining all
Searches with many jets

W prime (all hadronic)

tth(bb)
Boosted heavy neutrino search: Analysis Selection

Object Selection:
- Exactly 2 leptons & at least 1 fat trimmed jet.
- Isolated $e_1/\mu_1$ & non-isolated $e_2/\mu_2$ ($2^{\text{nd}}$ hardest leptons allowed to be close to fatjet).
- Highest mass fat ($R = 1.0$) jet (j) used with $p_T > 200$ GeV, $|\eta| < 2.0$ ($m_j > 50$ GeV in e final state).
- $p_{T,e_1/e_2} > 26$ GeV, $|\eta| < 2.47$. $p_{T,\mu_1/\mu_2} > 28$ GeV, $|\eta| < 2.5$.

Topological Cuts:
- Azimuthal separation ($d\Phi$) between $e_1/\mu_1$ & $j > 2.0$.
- $\Delta R$ between $e_2/\mu_2$ & $j < 1.0$.

Further Background Reduction Cuts:
- Dilepton invariant mass ($m_{ll}$) > 200 GeV.
- $d\Phi$ between $e_1(\mu_1)$ & $e_2(\mu_2) > 1.5$.

Selection results in almost negligible background!
• Large radius jet reconstruction in ATLAS based on energy clusters calibrated at hadronic scale.

• Effect of a non-negligible fraction of EM clusters in j investigated in terms of jet energy scale (JES) & jet mass scale (JMS) as a function of ratio of energy of e to the energy of j.

• A weak dependence (within scale expected uncertainty range) concludes no additional correction factor needs to be implemented.

arXiv:1904.12679
Performance of large radius jet with a hard e inside

- Large radius jet reconstruction in ATLAS based on energy clusters calibrated at hadronic scale.

- Effect of a non-negligible fraction of EM clusters in j investigated in terms of jet energy scale (JES) & jet mass scale (JMS) as a function of ratio of energy of e to the energy of j.

- A weak dependence (within scale expected uncertainty range) concludes no additional correction factor needs to be implemented.

arXiv:1904.12679
Background Estimation: A fit extrapolation from CR to SR

- A data-driven CR fit (range 600-1800GeV) performed & extrapolated to SR.
- Different steeply falling functional forms tested in CR, best taken with respect to mc closure (in CR & VR) & GOF.
- As Zjets dominates in higher mass range, a Zjets mc fit (range 400-4000GeV) parameters used in resultant fit to data.
- Fitted uncertainty includes extreme variations in SR yield using different fit ranges in CR as well as modelling uncertainty in Zjets mc & statistical uncertainty of fit.

arXiv:1904.12679
Estimation of Limit

\begin{tabular}{|c|c|}
\hline
Electron Channel & Muon Channel \\
\hline
\text{Signal (}m_{WR} = 3 \text{ TeV}, m_{NR} = 150 \text{ GeV)} & 346_{-75}^{+48} \quad 411_{-48}^{+36} \\
\text{Signal (}m_{WR} = 3 \text{ TeV}, m_{NR} = 300 \text{ GeV)} & 471_{-40}^{+42} \quad 429_{-40}^{+29} \\
\text{Signal (}m_{WR} = 4 \text{ TeV}, m_{NR} = 400 \text{ GeV)} & 66_{-10}^{+6} \quad 57_{-4}^{+4} \\
\text{Expected background} & 2.8_{-0.7}^{+0.5} \quad 1.9_{-0.7}^{+0.5} \\
\text{Observed background} & 8 \quad 4 \\
\text{Significance} & 2.4\sigma \quad 1.2\sigma \\
\text{P-value} & 0.0082 \quad 0.12 \\
\hline
\end{tabular}

- SR yields from signal, background & systematic uncertainties as a set of nuisance parameters used for likelihood fit to data as a single bin.
- Lower limits on masses of \(N_R\) & \(W_R\) determined by profiled likelihood test statistic with CLs method.
- Excluded region extends upto \(m_{WR} \sim 4.8 \text{ TeV in } e \& 5 \text{ TeV in } \mu\) (\(m_{NR} \sim 0.4-0.5 \text{ TeV}\)).

Assumptions: \(g_{WR} = g_{WL}\)
\(N^e_R, N^\mu_R, N^\tau_R\) at same mass

arXiv:1904.12679
Tools to deal “fatjet” : Trimming widely used in ATLAS

- **Trimming**
  - $k_t, R = R_{sub}$
  - $p_T^{i}/p_T^{jet} < f_{cut}$
  - Comparison with $p_T$(constituents) with $p_T$(jet) – removes soft components which are primarily from UI & PU

- **Filtering**
  - $C/A = R_{filt}$
  - $R_{filt} = \min(0.3, \Delta R_{ij}/2)$
  - Remove constituents that are outside of subjets

- **Pruning**
  - $k_t$ or $C/A$
  - $p_T^{ij}/p_T^{j+1,j} > z_{cut}$ and $\Delta R_{ij} < R_{cut}$
  - Similar to trimming but occurs during jet reconstruction ⇒ does not require subjet reconstruction

- Resolution improves with grooming
- Significant shift for small jets : Bkg reg.
- Much robust with pileup
Tools to deal “fatjet” : Several discriminating variables used

Jet mass : Performed with jet constituents

\[
(m_{\text{jet}})^2 = \left( \sum_i E_i \right)^2 - \left( \sum_i \vec{p}_i \right)^2
\]

N-subjetting : N-subjetty of a fatjet

\[
\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}\}
\]

\[
d_0 = \sum_k p_{T,k} R_0
\]

Powerful discriminator!

arXiv:1011.2268
As written, Eq. (2.1) is most appropriate for $e^+e^-$ colliders where energies and angles are the usual experimental observables. For hadron colliders, it is more natural to define $\text{ECF}(N, \beta)$ as a transverse momentum correlation function:

$$\text{ECF}(N, \beta) = \sum_{i_1 < i_2 < \ldots < i_N \in J} \left( \prod_{a=1}^{N} p_{Ti_a} \right) \left( \prod_{b=1}^{N-1} \prod_{c=b+1}^{N} R_{i_b,i_c} \right)^{\beta},$$  \hspace{1cm} (2.2)

where $R_{ij}$ is the Euclidean distance between $i$ and $j$ in the rapidity-azimuth angle plane, $R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$, with $y_i = \frac{1}{2} \ln \frac{E_i + p_{zi}}{E_i - p_{zi}}$. In this paper, we will only consider up to 4-point correlation functions:

$$\text{ECF}(0, \beta) = 1,$$ \hspace{1cm} (2.3)

$$\text{ECF}(1, \beta) = \sum_{i \in J} p_{Ti},$$ \hspace{1cm} (2.4)

$$\text{ECF}(2, \beta) = \sum_{i < j \in J} p_{Ti} p_{Tj} (R_{ij})^{\beta},$$ \hspace{1cm} (2.5)

$$\text{ECF}(3, \beta) = \sum_{i < j < k \in J} p_{Ti} p_{Tj} p_{Tk} (R_{ij} R_{ik} R_{jk})^{\beta},$$ \hspace{1cm} (2.6)

$$\text{ECF}(4, \beta) = \sum_{i < j < k < \ell \in J} p_{Ti} p_{Tj} p_{Tk} p_{T\ell} (R_{ij} R_{ik} R_{i\ell} R_{jk} R_{j\ell} R_{k\ell})^{\beta}.$$ \hspace{1cm} (2.7)

If a jet has fewer than $N$ constituents then $\text{ECF}(N, \beta) = 0$. Note that the computational cost for $\text{ECF}(N, \beta)$ with $k$ particles scales like $k^N/N!$.

From the $\text{ECF}(N, \beta)$, we would like to define a dimensionless observable that can be used to determine if a system has $N$ subjets. The key observation is that the $(N + 1)$-point correlators go to zero if there are only $N$ particles. More generally, if a system has $N$ subjets, then $\text{ECF}(N + 1, \beta)$ should be significantly smaller than $\text{ECF}(N, \beta)$. One potentially interesting ratio is

$$\tau_N^{(\beta)} \equiv \frac{\text{ECF}(N + 1, \beta)}{\text{ECF}(N, \beta)},$$ \hspace{1cm} (2.8)

which behaves much like $N$-subjettiness $\tau_N$ in that for a system of $N$ partons plus soft radiation, the observable is linear in the energy of the soft radiation.\(^4\) Of course, this is but one choice for an interesting combination of the energy correlation functions, and one can imagine using the whole set of energy correlation functions in a multivariate analysis.
Stunning features of Substructure measurements!

**ATLAS**

$\sqrt{s} = 13$ TeV, $33$ fb$^{-1}$

Top selection

$\text{MC/Data}$

**ATLAS**

$\sqrt{s} = 13$ TeV, $33$ fb$^{-1}$

W selection

**ATLAS**

$\sqrt{s} = 13$ TeV, $33$ fb$^{-1}$

$\text{MC/Data}$

A subjet independent way

Large $D_2$: more than having $N$ prong structure, extra radiation not correlated with leading order $N$.

Small $D_2$: More tends to have $N$ prong structure with additional radiation soft.
• N-point Energy Correlation function (ECF(N)) : Describes with energies, pair-wise angles of jet constituents [arXiv:1305.0007]

\[ C_N^{(\beta)} = \frac{ECF(N + 1, \beta) ECF(N - 1, \beta)}{ECF(N, \beta)^2} \quad D_N^{(\beta)} = \frac{ECF(N-1, \beta)^3 ECF(N+1, \beta)}{ECF(N, \beta)^2} \]

• ECF(N+1) << ECF(N) for N-prong fatjet
• Distinguished features wrt N-subjects
• Experiment used for 2-prong fatjet

[Graphs showing distributions for QCD jets and Z jets]
What is $k_T$?

**Why the name?**

$$d_{ij} = \min(p_{T,i}^2, p_{T,j}^2) \cdot [(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2]/R^2$$

is essentially

$$d_{i,j} = k_T^2/R^2$$

$$k_T = |\vec{p}_T| \Delta \theta$$
CMS (Compact Muon Solenoid)

- Cylinder structure
- Coaxial layers of sub-detectors
- Strong magnet to bend high pT particles
- Jets signature in Tracker, Electromagnetic Calorimeter (ECAL), Hadron Calorimeter (HCAL)

ATLAS (A Toroidal LHC ApparatuS)

- ATLAS (42m long, 7000 tons weight) twice as large as CMS (21.6m long, 12500 tons)
- ATLAS (Toroidal magnetic field +solenoidal magnetic field), CMS (Solenoidal magnetic field)
• High precision calorimetry
  • Highly granular electromagnetic calorimeter up to $|\eta| < 3.2$
  • Hadronic tile calorimeter barrel and endcaps up to $|\eta| < 3.2$
  • Forward calorimeters for $3.2 < |\eta| < 4.9$, granularity of $\Delta\eta \times \Delta\phi \approx 0.2 \times 0.2$
A simulation example of hard scatter and jet production:

**Hard Scatter**: Hard interaction with large momentum transfer.

**Underlying Event**: All contributions that are not associated to a hard interaction.

**PDF (Parton Distribution Function)**: Probability of finding a parton with a momentum fraction within a proton depending on the energy scale.

The final state partons produce showers with successively low energy. After parton showering partons combine to colourless hadrons.

Fragmentation functions model parton showering and hadronization.