Jets and Missing Transverse Energy Reconstruction With CMS

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Outline

- A brief definition of Jets
- Jet Algorithms used in CMS
- Jet Algorithm performances; Timing, Efficiency
- Jet Energy corrections; MC based & Data-driven
- Track-based Jets
- Missing ET reconstruction & its calibrations
- Summary
What are Jets:

Footprints of partons that cannot be observed directly: color confinement \(\rightarrow\) hadrons \(\rightarrow\) detector signals

Identifying Jets (accurately) is an important issue in collider physics, many physics topologies involve jets

- Our knowledge on QCD is based on Jet measurements: gluon was discovered in 3-jet event (PETRA), determination of \(\alpha_s\) ...

- Most of the searches for physics beyond the SM relies on Jet measurements: SUSY, high pT di-jets
- SM processes, top, W/Z+jets

Jet Production cross section is HUGE at the LHC!

\[ \sigma(\text{Jet } p_T > 100 \text{ GeV}) \sim 10^3 \text{ nb} \sim 1000 \text{ events/s} \]
Several Jet clustering algorithms available desired properties are:

- **Measurable & Calculable & Accurate:**
  - Good correspondence between parton-, particle-, detector-level
  - Insensitivity to detector details, PileUp, underlying event
  - Reliable calibration
  - Fast execution
  - Infrared and collinear safe

Two classes of jet algorithms:

1) Cone-Based
2) Sequential Recombination ($k_T$)

With MC simulate every step after the collision and study jets at each level.
Jet Algorithms in CMS

**IterativeCone Algorithm**
- Input: CaloTowers, particles with $E_T > 1$ GeV
- Iterative search for stable cones of radius $R$
  $$ R = \sqrt{\Delta \eta^2 + \Delta \phi^2} $$
- Particles assigned to a stable cone are removed from the input list and iterate...
- No split&Merge conflict
- Not infrared & collinear safe

**MidPoint Cone Algorithm**
- Similar to IterativeCone Algorithm
- Infrared safety introduced considering "mid-points" of proto-Jets closer than $2R$.
  IR safe only up to NLO.
- Split&Merge necessary
- May leave unclustered energy
- Not any more part of standard reconstruction in CMS
Jet Algorithms in CMS

* (Fast-) $k_T$ Algorithm
- Faster implementation of standard $k_T$
- combines 4-vectors according to their relative transverse momentum
  \[ d_{i,j} = \min \{ k_T^i, k_T^j \} \sqrt{\Delta \eta_{i,j}^2 + \Delta \phi_{i,j}^2} \]
  \[ d_i = k_T^i \]
- Infrared & Collinear Safe
- No unclustered energy

\[ d_{i,j} = \min \{ k_T^i, k_T^j \} \sqrt{\Delta \eta_{i,j}^2 + \Delta \phi_{i,j}^2} \]
\[ d_i = k_T^i \]

If $d_{\text{min}} = d_{ij} \rightarrow$ merge
if $d_{\text{min}} = d_i$ object $i$ is excluded from the next iteration

* SisCone Algorithm
- "Seedless Infrared Safe Cone" algorithm
- searches for ALL stable cones
- applies Split&Merge procedure
- Infrared and Collinear safe
- No dark energy

Recombination scheme: "E-Scheme" for all jet algorithms
Jet Algorithms: Timing

- Jet reconstruction takes ~0.5% of CPU time necessary for full event reconstruction, Jet algo choice does not have significant impact.
- IterativeCone algorithm is simple and fast: will be used at HLT.
- Execution time for $k_T$ algorithm, as implemented in the FastJet package, is improved dramatically w.r.t. earlier implementations.
Jet matching efficiency

Matching efficiency: fraction of GenJets which matches to a Calorimeter jet with a distance $\Delta R(\text{GenJet}, \text{CaloJet})<0.5$

- ~100% efficiency for $p_T > 30$ GeV
- KT and SiScone algo yields better efficiencies
- Data driven methods to measure the efficiency under development
Jet energy corrections

CMS develops a factorized multi-level jet correction

**Required Corrections**
- Reconstructed Jets
- Offset
- Rel: $\eta$
- Abs: $p_T$

**Optional Corrections**
- EMF
- Flavor
- UE
- Parton
- Calibrated Jets

**Offset**: for Pile Up and electronic noise in the detector (measure in zero-bias data)

**Relative ($\eta$)**: variations in jet response with $\eta$ relative to a control region

**Absolute ($p_T$)**: correcting the $p_T$ of a measured jet to particle level jet $p_T$

**EMF**: variations in jet response with electromagnetic energy fraction

**Flavor**: variations in jet response to different jet flavor (light quark, c,b, gluon)

**Underlying Event**

**Parton**: correcting measured jet $p_T$ to the parton level

derive from MC simulation tuned on test-beam data at start-up, data driven when available, on the long term from simulation tuned on collision data
Jet energy corrections: relative(\(\eta\))

**Goal:** Flatten the jet response versus \(\eta\)

**MC based:**
- QCD di-jet events
- study \(\Delta p_T(\eta) = p_T^{\text{CaloJet}} - p_T^{\text{GenJet}}\)
- most probable val of \(\Delta p_T(\eta)\) is compared to most probable val of \(\Delta p_T(\eta)\) \(|\eta|<1.3\) (reference point is the response at \(|\eta|<1.3\))

**Data driven**
- di-jet balance in QCD events \(\Delta \Phi(\text{jet1, jet2})>2.5\)
- any 3rd jet \(p_T < 0.25p_T^{\text{dijet}}\)

\[
p_T^{\text{dijet}} = \frac{p_T^{\text{probe}} + p_T^{\text{barrel}}}{2}
\]

\[
B = \frac{p_T^{\text{probe}} - p_T^{\text{barrel}}}{p_T^{\text{dijet}}}
\]

\[
r = \frac{2+ < B >}{2- < B >}
\]

Response = \(p_T^{\text{CaloJet}}/p_T^{\text{GenJet}}\)

Relative Response = \(r(\eta)/r(|\eta|<1.3)\)

Response values from MC & dijet balance tech. are in agreement within
- 1\% (\(|\eta|<1.3\)),
- 2-3\%(1.3<\(|\eta|<3\)),
- 5-10\% (3<\(|\eta|<5\))
Jet energy corrections: absolute $p_T$

MC based

- Flatten the absolute jet response of calorimeter vs. $p_T$
- Corrects energy of jet back to the particle level in control region ($|\eta|<1.3$)
- Use Calorimeter jets within $|\eta|<1.3$ which are matched to GenJet $\Delta R<0.25$

$$\Delta p_T = p_T^{CaloJet} - p_T^{GenJet}$$

**Absolute Jet Response vs. $p_T$(GenJet)**

![Graph showing the absolute jet response vs. $p_T$](image1)

$$R(\text{GenJet}) = 1 + \frac{<\Delta p_T>}{p_T^{GenJet}}$$

**Absolute Jet Correction vs. $p_T$(CaloJet)**

![Graph showing the absolute jet correction vs. $p_T$](image2)
Jet energy corrections: absolute $p_T$

**Data driven $\gamma$+jet:** $p_T$ balance in events with the jet in the control region

- consider clean events with $\Delta \Phi (\text{jets}) > \pi - 0.2$
- NO extra jet with $p_T > 0.1 p_T(\gamma)$
- isolated (ECAL, Tracker, HCAL) photons to reduce QCD bgr.

**$\gamma$+jet & Background Rate**

- QCD background
- $\gamma$ + jet

**$\gamma$ + jet balance**

- calibration constants can be obtained for $p_T < 600$ GeV with a data of 100 pb$^{-1}$. 
Data driven (Z→μμ)+jet: $P_T$ balance in events with the jet in the control region

- muons reconstructed in the tracker (independent from calorimeter)
- clean events with well separated Jet-Z
- $p_T(\mu)>15$ GeV, opposite charge, $m_{\mu\mu}$ within $m(Z)\pm20$ GeV
- NO extra jet with $P_T > 0.2P_T(Z)$.
- negligible background

✓ measure jet correction up to 400 GeV with 100 pb$^{-1}$.
✓ correction factors from MC dijet & Z+jet consistent within 5%
✓ combine jet calibration constants from Z+jet and MC truth, extrapolate to higher $p_T$
✓ consistent results with $\gamma$+jet calibrations
Jet energy corrections: (optional)

- **EMF dependent corrections**
  - correct for variations in jet response versus EM energy fraction of Jets
  - improves jet energy resolution up to 10%

- **Flavor dependent corrections**
  - Gluon, c and b quark jets all have lower response than light quark jets

**Corrections to parton level**

- correcting jet pT to the parton level
- gluons radiate more → lower response due to out-of-cone effect
- process dependent
Performance in ttbar events

- hadronic/semi-leptonic decays in ttbar ALPGEN sample
- select uniquely matched jets to top(W) decay products
- Apply MC based jet calib & flavor dependent corrections
- $m_{\text{top}}=m_{\text{three-Jet}}, m_{W}=m_{\text{di-Jet}}$

![Graphs showing performance metrics for different jet calibration and flavor corrections.](image)

**Figure:**
- Left: Resolution from dijet asymmetry as a function of the $p_T$ threshold applied to the third jet in the event for Iterative Cone $R=0.5$. The red and green lines correspond to detector and particle level, respectively. The plots are taken from the average $p_T$ bin with $0.8 < p_T < 1.0$ GeV.
- Right: Resolution obtained with the Asymmetry Method and from Monte Carlo Truth for Iterative Cone $R=0.5$ jets.

**Tables:**

| GEN | Mean: 80.6 | RMS: 8.04 |
|-----|------------|-----------|
| CALO Mean: 53.4 | RMS: 10.2 |
| L5(CORR+FLV) Mean: 85.4 | RMS: 12.1 |
| CORR Mean: 92 | RMS: 12.6 |

| GEN | Mean: 175.9 | RMS: 14.1 |
|-----|------------|-----------|
| CALO Mean: 110.9 | RMS: 18.7 |
| L5(CORR+FLV) Mean: 177.7 | RMS: 21.6 |
| CORR Mean: 187.2 | RMS: 22.2 |

**Jet Calibration and Flavor Corrections:**
- GEN: at GenJet Level
- CALO: uncalibrated CaloJets
- CORR: MC based jet calibrations applied
- L5: calibrations + flavor dependent corrections

**Diagram Notes:**
- Fast $k_T$, $D=0.4$
- $p_T \geq 0$ GeV and $|\eta| \leq 1.4$
- Only jets with uncorrected $p_T \geq 0$ GeV and $|\eta| \leq 1.4$ are considered.
- The generated W boson and top quark masses are indicated by the black vertical lines.

**Jet Selection Criteria:**
- hadronic/semi-leptonic decays in ttbar
- select uniquely matched jets to top(W) decay products
- Apply MC based jet calib & flavor dependent corrections
- $m_{\text{top}}=m_{\text{three-Jet}}, m_{W}=m_{\text{di-Jet}}$
Jet energy resolution: Data-Driven

Asymmetry method
- select the back-to-back ($\Delta \Phi > 2.7$) jets in the barrel region
- relate resolution to Asymmetry variable $A$

\[ A = \frac{p_T^{Jet1} - p_T^{Jet2}}{p_T^{Jet1} + p_T^{Jet2}} \]

\[ \frac{\sigma(p_T)}{p_T} = \sqrt{2\sigma_A} \]

- Good agreement between data-driven and MC-driven resolutions

Resolution as a function of the $p_T$ threshold on the third jet

![Graph showing resolution as a function of $p_T$ threshold](image)

CMS Preliminary
ICone, R=0.5, $|\eta| < 1.4$, 150 < $p_T$ < 210

- CaloJet Asymmetry Resol.
- GenJet Asymmetry Resol.
Study Mass resolution in $Z' \rightarrow q\bar{q}$ → both position & energy resolution participates

- MC Samples miss-calibrated according to expectations of 100/pb data, $m(Z') = 700, 2000, 5000$ GeV
- Two leading jets in the barrel region of HCAL $\eta < 1.3$

- $m(Z') = m(\text{jet1, jet2})$

☑ Similar resolutions from SISCone & MidPoint

![Graph](image-url)
Jet Reconstruction with Tracks (1)

- CMS can profit from excellent tracker measurements also for measuring Jets
- Reconstruct jets using charged tracks only, independent from calorimeter
  - independent systematics
  - can be used to cross check Calorimeter Jets
  - data driven efficiencies, tag&prob
- charged fraction of hadronic jets is about 60% (large fluctuations: bad Jet energy resolution)

Jet Matching efficiency
\( \Delta R < 0.3 \)

- good jet matching efficiencies: better angular resolution (\( \Phi \))
- stable jet energy response up to \( \sim 1\) TeV
Jet Reconstruction with Tracks (2)

- Performance in Z+jets + PileUp (average 5 interaction per bunch crossing)
  - Tracks are measured at the IP origin: tracks coming from other vertices can be rejected a priori to jet clustering
  - Tracks compatible with muon vertex are selected

Fraction of reconstructed Jets which are not matched to a GenJet $\Delta R<0.3$

**Figure (Jet mismatched rate as a function of the reconstructed jet $p_T$)***

TrackJets are transparent to PU effects
Jet Reconstruction with Tracks (3)

- Performance in “crowded” events: fully hadronic decays of \( t\bar{t} \)

Select hadronic decays \( t\bar{t} \rightarrow b\bar{b}q\bar{q}q\bar{q} \) (45% of total) with all six quarks within \( |\eta|<2 \). (15% of total)

Averaged number of Matched Jets

![Graph showing averaged number of matched jets](image)

efficiency of matching 6 quarks to a reco Jet

![Graph showing efficiency of matching 6 quarks to a reco Jet](image)
* Imbalanced transverse energy in the event
* signature of only weakly or non-interacting particles
* Crucial object for many measurements

Medium/low MET (~20-100 GeV)
- SM measurements (top, W, Higgs, τ, ...)
- Large MET (>200 GeV)
  - SUSY (gluino searches: jets + MET, ...)
  - Extra Dimension searches (monojets)

**Challenges:**
- MET triggering
- Corrections on MET:
  - jet energy corrections
  - μ/e/τ corrections
  - hot/dead channels
  - ...
Finally we will use \( \vec{E}_T \) which is somewhat confusing as it commonly refers to either the "D2 vector of missing transverse momentum" or to Missing Transverse Energy. Historically, missing transverse momentum is often referred to as Missing Transverse Energy by the detector and to ensure that it's a trustworthy variable for searches. Consequently, great care is required to understand the distribution in missing transverse momentum as measured. The Missing Transverse Energy is an important variable for electroweak measurements and for searches for new physics with CMS.

\[
\vec{E}_T = - \sum_n \left( E_n \sin \theta_n \cos \phi_n \hat{i} + E_n \sin \theta_n \sin \phi_n \hat{j} \right) = E_x \hat{i} + E_y \hat{j}
\]

**Resolution**

\[ \sigma(E_T) = A \oplus B \sqrt{\sum E_T} - D \oplus C(\sum E_T) - D \]

- **Noise (A):** electronic, underlying event, Pile Up
- **Stochastic (B):** sampling effects, e/π
- **Constant (C):** non-linearities, cracks, hot/dead channels
- **Offset (D):** effects of Pile Up, underlying event on \( \sum E_T \), anti-correlated with noise term

![Graph](image-url)
MET is calculated from un-calibrated CaloTowers, needs to be corrected for non-linearities in response versus $P_T$ and $\eta$.

- standard jet calibrations for jets can be used to correct MET
- CMS has a non-compensating calorimeter system, $e/h \neq 1$
- Use calibrated jets with EMF < threshold, i.e. 90%, & $P_T^{\text{jet (Uncor)}} > 10$ GeV

$$ \vec{E}_T^{\text{corr}} = \vec{E}_T - \sum_{i=1}^{N_{\text{jets}}} \left[ \vec{p}_{T_i}^{\text{corr}} - \vec{p}_{T_i}^{\text{raw}} \right] $$

Bias and relative resolution on $MET_{||}$ for $(W \rightarrow e\nu)+\text{jets}$
Muon corrections on missing $E_T$

- Muon leaves a small fraction of its energy in calorimeter

$$\vec{E}_T = - \sum_{i=1}^{\text{towers}} \vec{E}_T^i - \sum_{\text{muons}} \vec{p}_T^\mu + \sum_{i=1}^{\text{towers}} \vec{E}_T^i.$$  

Muons are identified in the Tracker and muon system, well separated in $\eta$-$\phi$ with jets & $p_T^\mu > 10$ GeV are used

- Further study for selection criteria for high $p_T$ muons underway

MET component parallel to $Z$ for different correction levels

Raw MET ||
+ Muon Corr
+ Corr for muon Energy dep. in CAL
+ Jet calibtarions
Tau corrections on missing $E_T$

- Tau jets are different from ordinary QCD jets, typically less constituents with fairly high energy, so applying standard jet corrections to hadronic tau jets will result in significant overcorrection on $ME_T$.

- Tau-specific corrections have been derived using Particle-flow algorithm and propagated into $ME_T$ corrections.

**Very accurate $\tau$ energy with Particle-Flow**

\[
\Delta \overrightarrow{E}_T = \sum \overrightarrow{E}_{\text{jet}}^{\text{cal}} 0.5 - \overrightarrow{E}_T^{\text{PF}} \tau
\]

* Particle Flow is an algorithm that uses Tracking & Calorimeter information for particle id and energy measurement, not covered here.
MET in $W \rightarrow e^\pm \nu$

- Single Isolated electron HLT
- A high $E_T$ electron ($E_T > 30$ GeV) within $|\eta|<2.5$
- Isolated: no tracks with $P_T > 1.5$ GeV in a cone of $\Delta R < 0.6$ around the electron.
- Electron Id: $H/E$, $\Delta \eta$, $\Delta \varphi$, $\sigma_{\eta\eta}$
- Reject events with a 2$^{nd}$ electron having $E_T > 20$ GeV.

- MET shows clear separation of signal from Background
- QCD is the major background and methods to estimate it from data are developed, while EWK background estimation is based on MC

Assuming cross sections at 14 TeV and 10pb$^{-1}$ of $\int Ldt$ we expect:

- $\sim 28K$ $W \rightarrow e\nu$ events and $\sim 6K$ QCD events
Jets & MET in SUSY events

Signature:
- Cascade decay of primarily produced SUSY particles
- R-Parity conserving models $\rightarrow$ LSP $\rightarrow$ MET
- Many jets, jet-pair mass comparable with W or Z

In the Fully Hadronic Decay Mode

Example diagram:

Signature:
- Cascade decay of primarily produced SUSY particles
- R-Parity conserving models $\rightarrow$ LSP $\rightarrow$ MET
- Many jets, jet-pair mass comparable with W or Z

Jets & MET in SUSY events

- lepton veto
- $E_T > 200$ GeV
- $P_T$ of 1st jet > 180 GeV
- 2nd jet > 110 GeV
- 3rd jet > 30 GeV
- HT > 500 GeV
- Further MET clean-up and QCD rejection cuts are applied
Most of the results that I presented are being updated

CMS explores excellent tracker measurement also for jets and MET

- Only Calorimeter/Track-only based Jets/MET is presented
- Many new results with a lot of improvement in resolutions coming soon
- Jets and MET using ParticleFlow objects
- Corrections on Jets (JetPlusTrack) and MET (tcMET) using tracks
CMS exercises several jet algorithms and their parameters, recent developments on algorithmic side, timing, IRC safety...

A lot of effort on Jet calibrations

- A multi-level factorized correction
- MC based as well as data driven techniques

Jets reconstructed using using different/combined detectors are well under study: Tracks-only; Particle-Flow Objects; Jets corrected precisely measured tracks

- Missing $E_T$ is a complicated object but it is important
- Calibrations to improve resolutions are promising
- biggest problems with MET will be known when beams collide (beam effects, dead/hot channels are important)

First collision data will be crucial to understand both objects and their calibrations