LHC 2010 - Jets and Relevance for VBF

Higgs Hunting - Orsay

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for the ATLAS and CMS Collaborations
Outline

I. ATLAS & CMS

II. Vector Boson Fusion and Prospects

III. Jet and MET Performance

IV. Inclusive Jet Cross Section

A list of references can be found in the back-up.
I. The ATLAS Detector

Calorimeters:

- **Non-compensating:**
  Response to hadrons lower than to EM objects, correct for e/γ, but jet energy underestimated

- **Dead Material before and between calos**

  ⇒ Need jet energy correction by calibration

Components:

| LAr     | EM Barrel |  | (EM & had) end-caps |  | (EM & had) Forward calo |  | (had) Tile Barrel |  | (had) Tile Ext. Barrel |
|---------|-----------|  | 1.5 < |η| < 3.2 |  | 3.2 < |η| < 4.9 |  | |η| < 0.7 |  | 0.8 < |η| < 1.7 |
| Scintillator |  |  |  |  |  |  |  |  |  |  |  |  |

Resolutions:

- **EM:**
  \[ \frac{\sigma}{E} = 10\% \sqrt{E} \text{ [GeV]} \oplus 0.7\% \oplus \frac{0.3 \text{ GeV}}{E} \]

- **Hadronic:**
  \[ \frac{\sigma}{E} = 50\% \sqrt{E} \text{ [GeV]} \oplus 1.7\% \oplus \frac{3 \text{ GeV}}{E} \]
The CMS Detector

Calorimeters:

- Calibration of hadronic energy deposits required due to non-linear and non-compensating response

Components:

- ECAL: Lead-tungstate crystals
- HCAL: Brass absorber and plastic tile scintillators
- HF: Iron/quartz-fibre based Cherenkov detector

| Component               | $|\eta| < 3.0$ | $3.0 < |\eta| < 5.0$ |
|-------------------------|-------------|------------------------|
| ECAL Barrel + End-caps  |             |                        |
| Central HCAL            |             |                        |
| Forward HCAL            |             |                        |

Resolutions:

EM: $\sigma / E = 3 \% \quad / \sqrt{E}$ [GeV]

Had: $\sigma / E = 100 \% \quad / \sqrt{E}$ [GeV]
SM Higgs Boson Production

Cross sections

Branching ratios

Vector Boson Fusion (VBF):

- 2nd largest cross section after gluon fusion (10 times below ggH)
- Provides special topology used to suppress (QCD) backgrounds
- Studied in $\tau\tau$ (115-145 GeV), WW ($\geq 140$ GeV)
  and $\gamma\gamma$ (110-140 GeV) final states
II. VBF Topology

General signal signature:

- Two jets in opposite direction ('tagging jets') with large $\eta$ gap
- Higgs boson decay products in central region
- No color flow between quarks
  \[\Rightarrow\] Central Jet Veto (CJV)
- Large invariant dijet mass

Example: $H \rightarrow \tau\tau$
II. Prospects for VBF $H \rightarrow \tau\tau$

Challenges:

- MET resolution crucial:
  - Higgs mass reconstruction
  - Discriminant variable

- Influence by pile-up:
  - CJV
  - Higgs mass resolution
  - tau ID

Dominant systematic uncertainties:

<table>
<thead>
<tr>
<th>Expected uncertainty ($\approx 10$ fb$^{-1}$)</th>
<th>Impact on signal efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS $\Delta E/E = 7%$ all jets</td>
<td>$\pm 10%$</td>
</tr>
<tr>
<td>ATLAS $\Delta E/E = 7%$ (15%) central (forward) jets</td>
<td>$+16% / -20%$</td>
</tr>
<tr>
<td>ATLAS &amp; CMS Jet resol. $\sigma(E) = 0.45 (0.63) \sqrt{E}$</td>
<td>$\pm 1%$</td>
</tr>
<tr>
<td>ATLAS &amp; CMS Tagging and CJV efficiency</td>
<td>each $\pm 2%$</td>
</tr>
</tbody>
</table>

Little sensitivity with 1 fb$^{-1}$ at 7 TeV

14 TeV

$\int L \, dt = 1$ fb$^{-1}$

$H \rightarrow \tau\tau \rightarrow l \nu\nu + \tau_{\text{had}} \nu$

$\sqrt{s} = 14$ TeV, 30 fb$^{-1}$

$\tau\tau \rightarrow ll 4\nu$

$\tau\tau \rightarrow \pi\ell 3\nu$

Expected Significance ($\sigma$)

Systematics included

LHC 2010 - Jets and Relevance for VBF

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II. Prospects for $H \rightarrow WW$ (VBF and Gluon Fusion)

- ee/µµ/µµ + MET final states considered
- Impact of jet uncertainties on backgrounds:
  - ATLAS (H+2j study @ 10 TeV) up to 15 %
  - CMS (14 TeV study) overall 10 %

Prospects for 2011: ATLAS

- Sensitivity to SM Higgs starts with 250 pb$^{-1}$
- Discovery of $m_H=160$ GeV with 5 fb$^{-1}$
  (full systematics)

DOMINANT BACKGROUNDs: WW, ttbar, W/Z
- CMS: 0 jet strategy $\Rightarrow$ ggH dominant
- ATLAS: 0/1/2 jet bins $\Rightarrow$ VBF relevant in 2 jet analysis

Hope to confirm and improve Tevatron limits with 1 fb$^{-1}$
• ATLAS: Topological clusters as inputs to the anti-$k_t$ algorithm with $R = 0.6$ or $R=0.4$

  TopoCluster:
  - Seeded by calorimeter cells with energy deposit $E_{\text{cell}} > 4 \times \text{noise}$
  + Neighbouring cells with $E_{\text{cell}} > 2 \times \text{noise}$ iteratively added
  + All nearest neighbours around cluster to accumulate shower tail

• CMS: Three types of jets

  1) Calorimeter jets (Calo)

    Calorimeter towers as inputs to the anti-$k_t$ jet finder with $R=0.5$ or $R=0.7$

    Calo Tower:
    - Built from HCAL cells + corresponding ECAL crystals
    - For $|\eta| > 3.0$ each tower corresponds to one HCAL cell

  2) Jet plus Track jets (JPT): Calo towers replaced by tracks if matched

  3) Particle Flow Jets (PF)

    Coherent combination of all subdetectors for reconstruction and ID of all particles. Jets are computed out of these calibrated particles

• Track Jets (ATLAS and CMS)  Reconstructed from tracks alone, independent from calos
Kinematic Distributions

III. ATLAS

ATLAS Preliminary
\( \sqrt{s} = 7 \text{ TeV} \)

anti-\( k_t \) jets R=0.6
\( p_T^{\text{jet}} > 30 \text{ GeV} \) \( |\eta^{\text{jet}}| < 2.8 \)

- Data \( \int \mathcal{L} dt = 1 \text{ nb}^{-1} \)
- PYTHIA

inclusive

\( \frac{1}{N_{\text{events}}} \times N_{\text{events}} \)

\( N_{\text{Jet}} \)

1 nb\(^{-1}\)

CMS (Calorimeter jets only)

CMS preliminary 2010
\( \sqrt{s} = 7 \text{ TeV} \)
\( P_T^{\text{jet}} > 25 \text{ GeV} \)
\( |\eta^{\text{jet}}| < 3 \)

- Data
- Simulation

back-to-back
topology

\( 1/\mathcal{N}_{\text{Jet}} \times dN/d\Phi^{\text{di-jet}} \)

\( \Delta \Phi^{\text{di-jet}} \)

0.2 nb\(^{-1}\)

Higgs Hunting - Orsay
Jet Energy Scale (JES) and Uncertainty - ATLAS

Calibration factors $C(p_T, \eta)$ from MC:

- Anti-$K_T$, $R=0.6$ jets
  - $0.3 < |\eta| < 0.8$
  - $2.1 < |\eta| < 2.8$

Summary for anti-$k_t$ jets $R=0.6$:

<table>
<thead>
<tr>
<th>$\eta$ region</th>
<th>Maximum relative JES Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^{jet} &gt; 20$ GeV</td>
<td>$p_T^{jet} &gt; 60$ GeV</td>
</tr>
<tr>
<td>$0 &lt;</td>
<td>\eta</td>
</tr>
<tr>
<td>$0.3 &lt;</td>
<td>\eta</td>
</tr>
<tr>
<td>$0.8 &lt;</td>
<td>\eta</td>
</tr>
<tr>
<td>$1.2 &lt;</td>
<td>\eta</td>
</tr>
<tr>
<td>$2.1 &lt;</td>
<td>\eta</td>
</tr>
</tbody>
</table>

Dominant contributions:

- Detector geometry
- Noise description
- Hadronic shower model
+ Additional 2% from pile-up
- Cross checked by single particle response
- JES uncertainty for forward jets not yet evaluated
JES and Uncertainty

JES correction depends on jet type

⇒ JES uncertainty depends on jet type

Conservative estimates:
- Calo jets: 10 %
- JPT and PF jets: 5 %

+ 2 % \cdot |\eta|

From single particle responses, eg. PF jets:
- EM scale: 1-2 %
- low pT: JES uncertainty of charged hadrons < 1 %
- JES uncertainty of neutral hadrons 3-5 %

Cross checks between jet types to evaluate JES uncertainty:

- Matching of calo, JPT and PF jets in ΔR < 0.25
- Relative response: $p_{T}^{\text{type1}} / p_{T}^{\text{type2}}$ (after calibration)
- Mean values of responses of data and MC agree well

$\text{CaloJet } p_{T} / \text{JPTJet } p_{T}$

$\langle \text{PF Jet } p_{T} \rangle$ (GeV)
III. In-situ Jet Calibration - ATLAS

Eta Inter-calibration with dijet $p_T$ balance

- **Before**: Calibration factors $C(p_T,\eta)$ derived from MC
- **Now**: Use central calorimeter as reference region and quantify calorimeter response by the $p_T$ balance between central (reference) jet and a forward (probe) jet

- Asymmetry of dijet system: $$A = \frac{p_T^\text{probe} - p_T^\text{ref}}{p_T^\text{avg}}$$ $p_T^\text{avg} = \frac{1}{2} (p_T^{j1} + p_T^{j2})$

- **Selection**: MinBias or L1_J5 trigger, 2 jets with $p_T^\text{avg} > 20$ GeV, $\Delta \Phi > 2.6$ and $p_T^{j3} < 0.25 p_T^\text{avg}$
Eta Inter-calibration - Results

Mean value of asymmetry in each \((p_T, \eta)\) bin used to calculate \(1/c\)

\[
\frac{p_T^{\text{probe}}}{p_T^{\text{ref}}} = \frac{2 + A}{2 - A} = 1/c
\]

MC and data agree to
- 2% in \(|\eta| < 1.8\)
- 5% in \(1.8 < |\eta| < 2.8\)
- 10% in \(|\eta| > 2.8\)

Larger discrepancies in forward regions

Re-calibration of data:
- First MC based \(C(p_T, \eta)\) applied, then data re-calibrated using factors \(c\) obtained insitu
- Excess of foward jets in data compared to MC is improved with eta inter-calibration

\(\Leftarrow\) After re-calibration, data and MC match.
Jet resolution from dijet asymmetry

This method was also applied in ATLAS

- Event selection:
  - Trigger: MinBias, dijet $p_T$ average 15 GeV and 30 GeV
  - Dijets: $\Delta \Phi > 2.7$, $|\eta| < 1.4$, veto on third jet with $p_T < p_T^{j3,max}$

- Asymmetry: $A = \frac{p_T^{jet1} - p_T^{jet2}}{p_T^{jet1} + p_T^{jet2}}$

  For $p_T^{jet1} \approx p_T^{jet2}$: $\frac{\sigma(p_T)}{p_T} = \sqrt{2} \sigma_A$

- Underlying event and out of cone particles by showering broaden $p_T$ resolution already at truth level $\Rightarrow$ (Small) correction necessary.
Jet resolution from dijet asymmetry

- Jet $p_T$ resolution over-estimated due to additional soft radiations spoiling the $p_T$ balance
- Jets not reconstructed below $p_T$ threshold, instead extrapolation to $p_T^{jet3} \rightarrow 0$ GeV

Results:

- Use of tracking info improves $p_T$ resolution
- Jet resolution for PF jets very similar to JPT jets

<table>
<thead>
<tr>
<th>$p_T^{max}$ (GeV)</th>
<th>In situ Jet Resolution</th>
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Uncertainties within 10%
Jet width $w = \frac{\sum R_i \times E_{T_i}}{\sum E_{T_i}}$

with distance $R$ of cluster $i$ to jet center:

Fraction of energy deposited in EM layers:

Discrepancies smaller with $\eta$ inter-calibration applied.

Comparisons to different shower models. Details:
CERN-LCGAPP-2010-02
Forward Jet Performance - CMS

35 GeV < $p_T$ < 120 GeV
3.2 < $|\eta|$ < 4.7

- Calorimeter jets only
- JES calibration from MC only
- No systematics, no unfolding

⇒ Reasonable MC description

Jet $p_T$ resolution estimated from MC:
15 % for $p_T = 20$ GeV
12 % for $p_T > 100$ GeV

Jet $p_T$ resolution, 3.2 < $|\eta|$ < 4.7

Jet $p_T$ resolution estimated from MC:
15 % for $p_T = 20$ GeV
12 % for $p_T > 100$ GeV

CMS Preliminary

Data

Simulation
III. MET Performance - ATLAS

- MET Calibration:
  - GCW: Global cell energy weighting
  - LCW: Local cluster energy weighting
  - ReFined: Association to reconstructed objects

- MET resolution measured in MinBias data:

\[
\sigma_{EM} = 0.41 \sqrt{\sum E_T} \quad \sigma_{GCW} = 0.39 \sqrt{\sum E_T} \\
\sigma_{LCW} = 0.37 \sqrt{\sum E_T} \approx \sigma_{refined}
\]

At least one jet with \( p_T^{EM} > 20 \text{ GeV} \):

\[
E_{\text{miss}}^{\text{Final}} = E_{\text{miss}}^{\text{calo}} + E_{\text{miss}}^{\text{muon}} + E_{\text{miss}}^{\text{cryo}}
\]
MET Performance - CMS

III.

Calo based MET

Track corrected MET

Particle Flow MET

• Cleaning cuts applied to reject anomalous signals and beam induced backgrounds

• MET better described in Dijet than in MinBias data

• MET resolution comparison among three algorithms
  Same calibration determined in-situ from γ+jets events
  ⇒ Pf MET best resolution, before TcMET and CaloMET

• Fraction of pile-up events: 1%
  Higher $\Sigma E_T$ and MET expected
IV. Inclusive Jet Cross Section - ATLAS

**Jet cross section in p_T:**

- Systematics: JES, jet resolution, pile-up
- 11 % luminosity uncertainty (not included)
- Theory uncertainty: Renormalization & factorisation scales, PDFs, $\alpha_s$ and effects from soft QCD modelling

**Dijet mass cross section:**

- Bin-by-bin data correction: Correction factor from ratio of MC truth to simulation applied to data in each bin
  - Corrections < 20 %

**ATLAS Preliminary**

- $L dt = 17 \text{ nb}^{-1}$, \( \sqrt{s} = 7 \text{ TeV} \)
- $p_T^{\text{jet}} > 60 \text{ GeV}$, $|y| < 2.8$
- $p_T^{\text{sub-leading jet}} > 30 \text{ GeV}$
- $m_{12}$ [GeV]

**ATLAS Preliminary**

- $L dt = 17 \text{ nb}^{-1}$, \( \sqrt{s} = 7 \text{ TeV} \)
- $p_T^{\text{jet}} > 60 \text{ GeV}$, $|y| < 2.8$
- $p_T^{\text{sub-leading jet}} > 30 \text{ GeV}$
- $m_{12}$ [GeV]
Inclusive Jet Cross Section

Jet cross section in $p_T$, calo jets:

- JES correction from MC,
in addition $y$ dependent relative calibration correction in-situ from dijets

- Systematics:
- JES uncertainty: 10% for calo jets
- 10% jet resolution uncertainty
- 11% luminosity uncertainty

- Bin-by-bin migration correction:
ansatz for truth $p_T$ spectrum $f(p_T)$ smear $f(p_T)$ to data $\Rightarrow F(p_T)$
$\Rightarrow$ unsmearing correction $C_{\text{res}} = f(p_T) / F(p_T)$

- Theory uncertainties:
- soft QCD modelling
- PDFs
- renormalization & factorization scales
**Inclusive Jet Cross Section - CMS**

Jet cross section in $p_T$, JPT jets:

Jet cross section in $p_T$, PF jets:

**JES uncertainty:** 5 % for JPT and PF jets
Conclusions and Outlook

• Jet/MET reconstruction and control of uncertainties crucial for upcoming Higgs searches

• Energy calibration of jets and MET based on MC and/or in-situ

• JES uncertainty: ATLAS: 7-10 % (central jets)
  CMS: 10 % (calo jets), 5 % (JPT and PF jets) + 2% $|\eta|$  

Prospects:

• Further performance checks, understanding of small discrepancies between data and MC, testing of other MC tunes

• With 1 pb$^{-1}$: Expect $W \rightarrow \tau \nu$ and $Z \rightarrow \tau \tau$ events ⇒ Study real taus
  Approaching $t\bar{t}$ production with 1 pb$^{-1}$
  Jet calibration with $Z/W$ events

• With 250 pb$^{-1}$: Sensitivity to exclusion of SM $H \rightarrow WW$ begins

• With 1 fb$^{-1}$: Improve exclusion limits, Background studies to various SM and MSSM Higgs analyses
References

First Data Performances:

ATLAS:

- Jet production cross section (ATL-CONF-2010-049)
- Jets and input to calibration (ATL-CONF-2010-052)
- Eta inter-calibration and forward jets (ATL-CONF-2010-053)
- In-situ jet efficiency and resolution (ATL-CONF-2010-054)
- Single particle reponse and JES (ATL-CONF-2010-050)
- JES and JES uncertainty (ATL-CONF-2010-056)
- MET Performance (ATL-CONF-2010-055)
- Energetic jets at 7 TeV (ATL-CONF-2010-043)
- Jet cleaning cuts (ATL-CONF-2010-038)

CMS:

- Inclusive jet cross section (CMS-PAS-QCD-10-011)
- Jet performance (CMS-PAS-JME-10-003)
- Forward jet performance (CMS-DPS-2010-026)
- Single particle response (CMS-PAS-JME-10-008)
- MET performance (CMS-PAS-JME-10-004)
- Tau reconstruction (CMS-PAS-PFT-10-004)
- Jet cleaning cuts (CMS-PAS-JME-09-008)


Sensitivity Studies:

- ATLAS CERN-OPEN-2008-20
- 10 TeV $H \rightarrow WW$ Atlas (ATL-PHYS-PUB-2010-006)
- $H \rightarrow WW$ CMS (CMS-PAS-HIG-07-001)
- CMS TDR Vol II (CERN/LHCC 2007-021)
- 7 TeV Sensitivity ATLAS (ATL-PHYS-PUB-2010-009)
- 7 TeV Sensitivity CMS (CERN-CMS-NOTE-2010-008)
- CMS $H \rightarrow \tau \tau$ with 1 fb$^{-1}$ (CMS-PAS-HIG-08-008)

Misc:

- Cacciari, Salam: anti-$k_t$ jet algorithm (arXiv:0802.1189)
- ATLAS Topocluster algorithm (ATL-LARG-PUB-2008-002)
**Trigger & Event Selection**

**ATLAS**
- Minimum Bias events triggered by MBTS and/or signal from BPTX
- QCD events triggered by L1 jet trigger L1_J5 (jet with 5 GeV, unprescaled)
- Primary vertex with at least 5 tracks

**CMS**
- Minimum Bias triggered by Beam Scintillator Counter in coincidence with BPTX
- QCD triggered by high level jet triggers with different thresholds and prescales
- Veto on beam-halo events
- Primary vertex with at least 4 or 5 tracks

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**ATLAS** Preliminary

\[ \sqrt{s} = 7 \text{ TeV} \]
anti-\( k_T \) jets, \( R = 0.6, |y^{\text{jet}}| < 2.8 \)

- Data
- Pythia 6

\[ \begin{array}{c}
\text{L1 Efficiency} \\
\hline
0.0 & 0.2 & 0.4 & 0.6 & 0.8 & 1.0 \\
0 & 50 & 100 & 150 & 200 & 250 & 300 \end{array} \]

**CMS**

\[ \begin{array}{c}
\text{Trigger Efficiency} \\
\hline
0.0 & 0.2 & 0.4 & 0.6 & 0.8 & 1.0 \\
20 & 30 & 100 & 200 & 1000 \end{array} \]

\[ \sqrt{s} = 7 \text{ TeV} \]
\[ |y| < 0.5 \]

- MinBias
- Jet6u
- Jet15u
- Jet30u

Anti-\( k_T \) \( R=0.5 \) PF

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**LHC 2010 - Jets and Relevance for VBF**

**Higgs Hunting - Orsay**

**Backup 2**
Jet and MET Cleaning (ATLAS & CMS)

- **Detector level:** Only high quality data flagged as valuable for physics analysis ('good runs') with stable beam condition

- **Object level:**
  - Certain fraction of energy deposit distributed among certain number of channels to reject spurious (sporadic) signals
  - Jet timing within small difference to average event time, to suppress non-collision backgrounds: Cosmics, beam-gas, beam-halo, cavern background.

- **Details:** ATL-CONF-2010-038, CMS-PAS-JME-09-008