



### Reconstruction of Physics Objects at CMS

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#### Introduction



- The reconstruction and identification of physics objects in CMS detector will be discussed in the order of importance to the charged Higgs search analyses.
- Tau, Jets, MET, b-tagging, Muon and Electron
- Most of the reconstruction / identification methods employ Particle Flow technique
- Particle Flow : Aimed at reconstructing and identifying all stable particles by combining measurements in all CMS sub-detectors.
- Better energy resolution, more robust against pileup.





#### Hadronic Tau Identification



#### Tau Decay Signature

- 65% of tau decays
- 1 or 3 π<sup>+</sup>
- 0, 1, or 2  $\pi^0$
- Via  $\rho$  or a<sub>1</sub> decay

#### **Challenges**

- Reject huge jet  $\rightarrow \tau_{h}$  background
- Reject  $e \rightarrow \tau_h$  fakes
  - Appears as isolated track + calo, like one prong  $\tau_h$
- Reject  $\mu \rightarrow \tau_h$  fakes(relatively easier )
- $\tau_h$  candidates are collimated:
  - $\circ$   $\;$  A few overlapping  $\;\pi^{\scriptscriptstyle +}$  and  $\gamma s$  from  $\pi^0$  decays
- PFlow is used to resolve objects

Decay Mode	Resonance	$Mass(MeV/c^2)$	Branching Fraction $(\%)$
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$			17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$			17.4
$\tau^- \rightarrow h^- \nu_{\tau}$			11.6
$ au^-  ightarrow h^- \pi^0  u_ au$	$\rho(770)$	775	25.9
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	1230	9.5
$ au^-  ightarrow h^- h^- h^+  u_{ au}$	$a_1(1260)$	1230	9.8
$\tau^- \rightarrow h^- h^- h^+ \pi^0 \nu_{\tau}$			4.8
Other hadronic decays			3.2



#### Hadronic Tau Identification

#### Hadron Plus Strips Algorithm







### **Decay Mode Reconstruction**



### Mass cut around given tau decay resonances : $\pi(140)$ , $\rho(770)$ OR a<sub>1</sub>(1220)





#### **Cut Based Isolation**



- > Isolation cone of  $\Delta R = 0.5 : \Sigma P_T$  (charged and neutral candidates not belonging to tau candidate).
- > Avoid PU particles in the isolation cone.
  - Only use charged hadrons in the isolation cone with  $\Delta z < 2mm$  from highest P<sub>T</sub> Tau track.
- Corrections for the neutral component of pileup in the isolation cone :
  - $\circ \quad \Delta\beta \text{ correction}: \text{ Estimate PU contribution of neutrals in the isolation cone as } \left[ \sum p_T \text{ of charged hadrons in iso cone times charged to neutral ratio} \right].$

Subtract estimated neutral PU contribution from isolation  $p_{T}$ .

working points :

wp	threshold
Loose	2 GeV
Medium	1 Gev
Tight	0.8 GeV



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#### **MVA Based Isolation**



➢ Isolation p<sub>T</sub> summed in rings around tau
 ❖ Use same PF particles as cut based
 ➢ BDT trained against jet → τ fake rates
 ➢ Improved performance than cut based
 ○ lower fake rate at same efficiency
 ➢ Loose, Medium, Tight WPs (cut on BDT output)



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# Tau ID Efficiency

- Efficiency computed using Tag and Probe technique, using Z->ττ->μτ events
- Fit mass distribution for passing and failing TauID probes.
- Uncertainty on Tau ID efficiency : 6%
- □ Tau Efficiency mostly flat vs pt above 25 GeV

Loose MVA has better efficiency wrt Loose Δβ (tuned to provide same fake rate)









#### Efficiency vs Pileup



#### • Only small dependency on pileup





#### Jet $\rightarrow$ tau fake rate



- Measured in  $W \rightarrow \mu v$  + jets events from data.
- Fake Rate = N(jets passing TauID)/N(jets Pt>20, |η|< 2.3, passing AntiMuon and AntiElectron discriminator).
- Fake Rate ~3% for 70% efficiency
- Slightly higher in 2012 compared to 2011





#### **Discrimination Against Electron**



- Electrons (1track + EM deposit) can fake a 1 prong Tau ( $\pi^{\pm}$  and  $\pi^{0}$ s)
- Require low electron compatibility
- Multiple working points : cut based, MVA (BDT)
- $\Box e \rightarrow \tau \text{ Fake Rates}:$
- Measured using Tag and Probe technique with Z->ee events.
- Probe electron reconstructed as an isolated Tau.
- Fit the mass distribution for probes passing or failing different AntiE WPs.
- Simultaneous fit of signal + background.





# **Discrimination Against Muon**



CMS Preliminary 2012 √s=8 TeV L ~ 500 pb<sup>-1</sup>: passing probe

 Working points based on compatibility of being identified as a muon

 $\Box$  Measure  $\mu \rightarrow \tau$  fake rate :

- Tag and Probe technique using Z->μμ events.
- Similar FR for 2011 and 2012.



### Tau Energy Scale



- Data/MC agreement within 2% for all decay modes.
- Systematic uncertainty ~3%

• Insensitive to pileup







tracks



# Jet Energy Correction

Factorized approach for jet calibration in CMS





- Corrections for pile-up : Average offset correction(Npv), L1FastJet (ρ) (energy density from pileup in event [arXiv:0707.1378v2])
   Correction for detector
- 2. Correction for detector response : MC truth (using QCD MC)
- Relative residual corrections for η dependence : using dijet balance
- 4. Residual corrections to absolute  $p_T : \gamma$ +jets, Z+jets





### Jet Energy Scale Uncertainty





- The contribution of different uncertainty sources depends on  $\textbf{p}_{\text{T}}$  and  $\eta$
- Total uncertainty of the jet energy scale is close to 1% for  $|\eta|$  < 2.4
- Pileup uncertainties increasing due to higher average pile-up



# Missing Transverse Energy



- ★ MET calculated using Particle flow is commonly used in CMS  $E_{T(x,y)}^{miss} = -\sum \overrightarrow{p}_{T(x,y)}$  (all PF candidates
- $\begin{array}{ll} \bigstar \quad \text{Correction:} \\ E_{x,y}^{miss,corr} &= E_{x,y}^{miss,raw} + \Delta_{x,y} \\ \Delta_i &= \sum P_i^{calibrated} P_i \end{array}$
- Type-0 : Correction for pileup (not mandatory)
- Type-1 : corrections using JEC
  - Apply L1Fastjet, L2 and L3 corrections
  - PFJets with corrected p<sub>T</sub>>10 GeV for pfMET
  - Brings the MET response to unity
- Type-2: correct unclustered energies (not associated with jets and other high P<sub>T</sub> objects) (not mandatory)





### **MET Scale and Resolution**



- MET response and resolution measured using Z+jets (and γ+jets ) events
- Transverse momentum sum of all particles, except the boson:  $u_T$
- In perfectly measured event u<sub>T</sub> balances transverse momentum of the Z (q<sub>T</sub>)



- The mean of the distribution of --  $u_{11}/q_T$  is a measure of response
- The RMS widths of  $-u_{||}, -q_T$  and  $u_{\perp}$  are used to measure resolution



u<sub>1</sub>/GeV



- Resolution for fixed NVtx is better in 2012A due to improved the ECAL and HCAL energy reconstruction to reduce the effects of out-of-time pileup interactions
  - HCAL: 100ns time window in 2011, 50ns time window in 2012.
  - ECAL: Reject out-of-time energy deposits not only in the barrel but also in the endcap
- PU introduces an additional smearing of ~2.5-3.5 GeV on MET resolution (in quadrature)



# **b-Jet Tagging**



- $\circ$   $\,$  Many algorithms deployed at CMS  $\,$
- Best separation from light jets and c-jets
- Rely on long lifetime and high mass of B-hadrons
- Track Counting : Tracks are ordered in IP significance
   Discriminator : IP/σ of 2nd (High Efficiency, TCHE) or 3rd highest (High Purity, TCHP) track
- Jet Probability (JP): Likelihood combining all IP/σ tracks
- Jet B Probability : More weights to highest IP/σ tracks
- Simple secondary Vertex: decay length ΔL/σ with ≥2 tracks (SSVHE) and ≥3 tracks (SSVHP)
- Combined secondary vertex (CSV): likelihood from SSV + track based lifetime info



Operating points: tuned at jet pT~80 GeV (from QCD MC in pT hat 80-120)

- Loose: 10% mistag
- Medium: 1% mistag
- Tight: 0.1% mistag



# **b**-Tagging Performance



#### Expected performance predicted by simulation

#### CSV algorithm has highest b-efficiency when light-flavor efficiency is ~1%.



- IP3D Ο
- System8 : simultaneous use of
  - pTrel, away jet, muon jet tagging efficiencies
- Using reference lifetime tagger :
  - Use JP tagger to measure fraction of b-jets obtained in the sub-sample tagged by an independent algorithm.
  - Efficiency is measured with fitting JP discriminant templates to data
- Efficiency measured using ttbar events [CMS-PAS-BTV-11-003]

# Efficiency Measurements

- CMS-PAS-BTV-11-004 Using kinematics of muons in jets :
- Efficiency is measured with a tag and probe like method using dijet events
- Select heavy flavor enriched sample by tagging one jet with TCHPM tagger.
- Fit muon observables on the second jet:
  - $p_{T}$  relative to the jet axis Ο









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### Mistag rates







- Use tracks with negative impact parameter or secondary vertices with negative decay length to measure the negative tag rate
- The track IP or secondary vertex ΔL can be defined as positive (negative) if its angle w.r.t the jet axis is smaller (larger) than 90°
- The QCD MC is used to compute a ratio  $R_{light} = \epsilon_{MC}^{mistag} (udsg) / \epsilon_{MC}^{neg.tag} (udsg+c+b)$
- From which one can infer the light tag efficiency in real data :  $\varepsilon_{data}^{mistag} = \varepsilon_{data}^{neg.tag} * R_{light}$
- or a data/MC scale factor:

SF =  $\varepsilon_{data}$  mistag /  $\varepsilon_{MC}$  mistag

#### Mistag rates





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#### Muon



- Reconstruction approaches : Global Muon, Tracker Muon, Particle Flow muon
- Muon ID : Several Categories of muon identification algorithms based on track quality cuts, compatibility of the calorimeter response with the muon hypothesis and the presence of matched segments in the muon system : cut based , Likelihood based
- Baseline selection categories : Loose Muon, Soft Muon, Tight Muon, High Pt muon
- Muon isolation : sub-detector based (tracker relative iso), PF based (combined relative)
- **PF Cut based Isolation** : The charged hadrons only from primary vertex, Correction for neutral pileup using  $\Delta\beta$  or  $\rho$  correction.
- PF based MVA isolation





### Electron



- Electrons reconstructed using Gaussian Sum Filter (GsfElectron), seeded by tracker, Ecal cluster
- Identification :
  - Cut based & MVA methods using ECAL cluster shape, tracker and track-cluster matching variables
  - Rejection of converted photons
  - Several working points according to id-efficiency

> Isolation :

- PF based isolation
- Charged hadrons from pileup vertices are removed
- ρ\*EA (effective area) correction
   for neutral pileup in isolation cone



 $Z \rightarrow$  ee measured in 8 TeV data



#### Summary



- The biggest challenge in 2012 is the high pileup
- Particle Flow technique used in CMS provides good handle to deal with high pileup
- Most analyses use physics objects reconstructed using Pflow method
- CMS developed an excellent "decay mode based" tau identification method
  - Robust against pileup
  - Reasonably high efficiency with substantially low fake rate









# Discriminating Against Leptons



Electrons (1track + EM deposit) can fake a 1 prong Tau ( $\pi$ ± and  $\pi$ 0s). AntiElectron uses PFElectron ID MVA

Electron Rejection	
Loose	PFElectronMVA < 0.6
Medium	PFElectronMVA < -0.1 & η-Crack Veto
Tight	Medium & not (1 prong & mass < 0.55 GeV & EHCAL/Ptrack < 0.1 & 99% of PFGamma energy within Dh < 0.03 of leading PF candidate)
MVA	Medium & BDT (see AN-11/390)

Muon Rejection	
Loose	No segments matched to leading PF Charged Hadron
Medium	No muon chamber hits matched to leading PF Charged Hadron
Tight	Medium & (EECAL + EHCAL)/Ptrack < 0.2 if 1 prong



### Additional MET correction



#### Type 0 MET Correction

- For each PU vertex calculate expected missing neutral part and add it vectorially
  - Using PFCandidate to vertex association (PFNoPU)
  - o Improved association of tracks from NI, V0 decay or a photon conversion
- Parameterize MET imbalance as function of  $\Sigma P_T^{charged}$  using MinBias MC
  - Improves pfMET resolution by ~10% in Z $\rightarrow$ µµ (8.7 GeV in quad.)
- Recommended to be used in analysis sensitive to core MET resolution
- $\blacktriangleright$  MET  $\Phi$  correction
  - MET  $\Phi$  modulation has been observed since long ago
    - Observed in both Calo and Track based objects
  - The modulation depends on overall activity in the event
    - $\circ$   $\;$  The dependence is parameterized as a function of NVtx  $\;$
  - MET  $\Phi$  modulation are effectively shifts in MEx, MEy
    - $\circ$   $\,$  Derive the shifts from data and MC separately



#### **MET Systematics**



- We propagate each object systematic uncertainties to MET:
  - Jet energy scale (from the JEC group)
  - Jet energy resolution
  - Unclustered energy scale (±10%)
  - Tau PT scale (±3%)
  - Muon PT scale (±0.2%)
  - Egamma PT scale (±0.6% for EB, ±1.5% for EE)



# MVA MET (PU mitigation)



- Train MVA to separate PU VS hard scatter jets
- Combine different types of MET into an MVA (regression)
- Train with targeting unit MET response:  $p_T/U_{||}$
- Train on Z→µµ events, using MET types (charged /neutrals from PV and PU, unclustered energy), jets 3-vector, NVtx
- Improves MET dependence on PU and MET resolution (30 40%)



### **B-tag Pileup dependency**



Small dependency on pileup





### **Efficiency Measurements**



#### Using kinematics of muons in jets

- Efficiency is measured with a tag and probe like method using dijet events
- Select heavy flavor enriched sample by tagging one jet with TCHPM tagger.
- Fit muon observables on the second jet:
  - pT relative to the jet axis
  - IP3D
- Distributions are fit for fractions of b, c and light jets
  - Assume templates from simulation
  - Apply correction for light jet templates using tracks in inclusive jet events
- B-tagging efficiency is measured as

$$\varepsilon_{b}^{\text{tag}} = \frac{f_{b}^{tag} \cdot N_{data}^{tag}}{f_{b}^{tag} \cdot N_{data}^{tag} + f_{b}^{untag} \cdot N_{data}^{untag}}$$







#### Efficiency Measurements Using reference lifetime tagger



- Use JP tagger to measure fraction of b-jets obtained in the sub-sample tagged by an independent algorithm.
- The method performed in both inclusive and muon-jet samples.
- The JP tagger can be calibrated from data using tracks with –ve impact parameter.
- high b fraction with JP information (Cb): 90% (>98%) at 20 (>50) GeV
- Efficiency is measured with fitting JP discriminant templates to data
- The templates for b,c and light jets assumed from MC, with constraint fb + fc + fl = 1





#### Efficiency Measured using ttbar events



- Top quarks decay in Wb final states almost 100% of the times
- Can use the different channels to probe b-tag efficiency
- Different methods are currently being pursued:
  - Profile Likelihood Ratio method using dilepton events
  - The Flavor Tag Consistency Method (I + jets events)
  - The flavour Tag Matching Method (dilepton events)
  - from a b-enriched jet sample



