## Jet and ET<sup>Miss</sup> Performance for *hh* Searches

Double Higgs Production at Colliders Workshop

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Why Care About Jet/E<sup>TMiss</sup>?

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- So why do we bother?
  - And why are hadronic topics the only performance talks at this workshop?

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- Almost any final state you can use involves jets and/or ET<sup>Miss</sup>!
- The discovery will happen with jets and E<sub>T</sub><sup>Miss</sup>!

#### CMS-DP-2017-028



 $\mu$ =100, today

• Jets and  $E_T^{Miss}$  already have worse resolution than leptons and photons



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  - We need high-performance hadronic reconstruction to keep up with pileup



#### CMS-DP-2017-028



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- Jets and E<sub>T</sub><sup>Miss</sup> already have worse resolution than leptons and photons
- The problem is going to get even worse!
  - We need high-performance hadronic reconstruction to keep up with pileup
  - The discovery of di-Higgs won't happen without this!

#### Mapping Hadronic Observables









#### CMS-PRF-14-001

- CMS generally uses "particle flow" reconstruction
  - Match calorimeter and track information, use the "best" measurement
  - Can remove contributions from pileup: tracker gives vertex info





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#### ATLAS-PERF-2014-07

- ATLAS calorimeter is highly segmented: reconstruct with 3D topological clusters
  - Cluster shape information can be used to calibrate
  - Can suppress pileup with noise thresholds
- ATLAS also now has PFlow: new standard for Run2!

#### Particle Flow: Ups and Downs





- Particle flow uses the "best measurement" available: calorimeter at high pT, tracker at low pT
  - PFlow can remove energy from pileup, while calorimeters don't have the resolution
- Relies on good matching between calorimeter and tracker
  - "Confusion term" can increase resolution if matches are poor
  - This is the challenge at high pileup!
- NB: CMS's larger magnet and worse HCal make it ideally suited for PFlow, but ATLAS can benefit as well, especially at low pT

## Pileup Mitigation

ATLAS

-2 -1.5

Pvthia Dijet vs= 14 Te

Voronoi + SoftKiller 0.(

Simul

events

180

160

140

120

100

80

60

40

20

0<sup>L</sup>0

CMS

Preliminary

20

10

30



ATLAS Simulation Preliminary Pythia Dijet  $\sqrt{s}$ = 13 TeV 0.6 Anti-k<sub>T</sub> LCW, R=0.4 No Pileup Correction Jet-Area subtraction In<sup>true</sup>l<0.8, <u>=200 Vor. Spread. • Vor. Spread. + CVF 5 GeV-0.5 Vor. Supp. + SK 0.6
CS, ΔR<sup>max</sup>=0.25 + SK 0.6 0.4 0.2 Ratio to Uncorrected 55 40 45 50 60 p\_rtrue [GeV]

0.5

0

1.5

ATLAS-CONF-2017-065

uthiets R-04

ATLAS Simulation Preliminary

Pythia Dijet  $\sqrt{s}$ = 14 TeV,  $\mu$  = 200

-2

-1.5 -1 -0.5

- Huge number of techniques to address this and remove residual effects of pileup
- PUPPI used in CMS, several methods in ATLAS

#### Jet Reconstruction and Calibration









• Naively, jet algorithms are the inverse of the parton shower:



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• The standard at the LHC is anti- $k_T$ : cluster hard particles first, and soft around them

## Calibration Sequence





- When we measure a muon, the "reconstructed" object has essentially the same  $p_T$  as the true particle
- But because of pileup, and our sampling and non-compensating calorimeters, measured jets aren't at the same p<sub>T</sub> as true jets
- Calibrations correct for this, and then use measurements to ensure data and MC are at the same scale
  - And constrain the systematics along the way

## Pileup "Area Subtraction"





- To first order, pileup contributions to jets can be viewed as isotropic
- Measure the ambient energy density, ρ, then correct the jet energy by ρ x Area
- Some residual dependences can be addressed with on-average corrections
- This removes the pileup energy from jets: now we can continue to calibrate

## Jet Energy Scale (Correction)



- Calorimeters are sampling and non-compensating: hadrons won't deposit their "full" energy
- Use MC to correct measured jet energies to "particle scale"

#### Global Sequential Calibration



- Jets are now calibrated on average: but depending on flavor (quark/gluon/c/b...) and specific hadronization, true energy can still be offset from calibrated energy
- Many of these effects have measurable impact on jet properties: can use these to correct energies
  - Iteratively correct for several different variables for best performance
- This can dramatically improve resolution: even for PFlow jets!

### **Eta-Intercalibration**



- First step of using data: equalize response across detector
  - Detector cracks, material can be poorly modeled in simulation
- Use well measured central jets as reference, and normalize other jets to the center
  - Dijet events should be balanced: select this topology to ensure good reference

## In-Situ Calibration





## JER Determination





- Resolution (and its uncertainties) set how well we reconstruct our Higgs's
- Want this as low as possible, but also want data and MC resolutions to agree!
- Improved inputs, pileup corrections, calibrations can reduce the JER
  - This will be critical to our success in Run 3/4

### Pileup Tagging

# Pileup Tagging





- Even after pileup corrections for energy, can have entirely new jets from pileup vertices
  - Even after charged-hadron subtraction, neutral components can create new jets
- Can tag whether jets are coming from the primary vertex
  - ATLAS and CMS both use pileup taggers to remove these extra jets
  - PFlow removes huge number of pileup jets just by removing tracks from non-primary vertex!

fJVT



<u>ATLAS-PERF-2016-06</u>



- Forward region has no tracking: can't tell which vertex jets are originating from
  - But we can balance forward jets against central jets, and the use vertex information from there!
  - This (along with jet shape information) is enough to reject some amount of forward pileup jets
- Run4 will improve η coverage of ID, but performance will still degrade at high η: techniques like this can help!

#### ET<sup>Miss</sup> Reconstruction and Performance

### E<sub>T</sub>Miss Calculation



- Add up the event!
- Everything that's not part of a reconstructed object gets summed as the "soft term"
  - In CMS, use raw PFlow objects
  - In ATLAS, use tracks (or now PFlow)
    - No forward region and no neutrals with track, but performance gain relative to clusters because of pileup robustness
- Critical to reconstruct leptonic W: one of the important sub-channels for di-Higgs!



#### ATLAS ET Miss Performance





- Here, compare:
  - E<sub>T</sub><sup>Miss</sup> with track soft term
  - E<sub>T</sub><sup>Miss</sup> with calorimeter soft term,
  - pT<sup>Miss</sup> built with only tracks
- Track soft term improves pileup robustness, maintains good resolution
  - Scale can be degraded slightly wrt calorimeter measurement, but is more robust

## CMS E<sub>T</sub>Miss Performance



- CMS uses PFlow: robust to pileup, but still some dependence at highest luminosities
- New methods like PUPPI can correct for this, but these can overcorrect the scale: care needed at low  $E_T^{Miss}$

## E<sub>T</sub>Miss Significance





- Instead of just using the raw value of E<sub>T</sub><sup>Miss</sup>, weight by the resolution
  - Often fake E<sub>T</sub><sup>Miss</sup> comes from mismeasured jets: if you know the resolution is bad, don't count it in the significance calculation so high
- Especially in our hh systems, with low p<sub>T</sub> jets, E<sub>T</sub><sup>Miss</sup> significance can improve reconstruction!

## Looking Forward

# ATLAS Improvements





- ATLAS's version of PFlow including GSC improvements to resolution— is now the standard for final Run2 analyses
- Large gains in resolution and E<sub>T</sub><sup>Miss</sup> stability!
- Many important steps (e.g. btagging) remain, but large improvements at low p<sub>T</sub> now standard for ATLAS

# Highlights in Higgs Analyses





- Jet resolution matters— and our work can improve it!
  - Can make the Higgs peak 30% narrower with b-jet regression and kinematic fit (using event ET<sup>Miss</sup>)
  - This is a huge improvement for the analysis!
- Can we do similar things to other jet categories?
  - ATLAS's GSC already does this to some extent, but can be further improved

### Dealing with High Luminosity





- Lots of effort to estimate resolutions and performance for the HL-LHC
  - Forward tracking will bring improved pileup suppression
  - Constituent-level corrections with tracking information improve resolution by 30%
- These are the objects that will make up our Higgses: resolutions are degrading, but new ideas may recover this

30

35

40

45

50

55

p\_true [GeV]

60

# CMS Upgrades





- CMS upgrades also present a huge opportunity to improve reconstruction at high pileup
- New detectors will call for entirely new reconstruction
  - How can 4D reconstruction from the timing detector improve jet and E<sub>T</sub><sup>Miss</sup> resolution?
  - Can the high granularity calorimeter remove the effects of pileup?



#### M. Swiatlowski (UC)

### Conclusions

- We could get away without using jets and  $E_T^{Miss}$  for the Higgs boson discovery
- But with the branching ratios and crosssections we're facing for hh, we don't get to choose the "golden channels" anymore
- Anything we discover will need to use jets and/or ET<sup>Miss</sup>
  - When we improve our objects, we improve our analyses
  - We need these tools to make these discoveries!





### Backup

## Noise Thresholds



JetEtmissApprovedBOOST2014EventDisplays