# Jet Energy Corrections in CMS

## Multiple Cone Sizes

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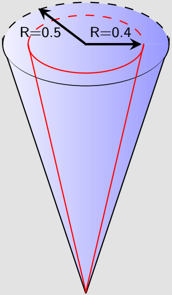
Tuesday 19$^{th}$ August, 2014

**BOOST2014** - University College London

# Motivation

## Multiple cone size studies

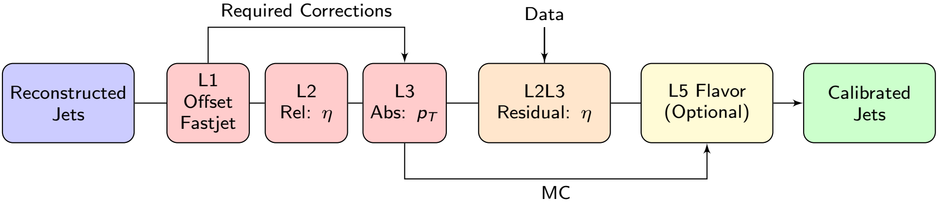
- Study was done to identify the optimal cone sizes to store in our datasets
  - i.e. the cone size which has the best jet response and resolution after correction
- In the past we stored $R = 0.5$ and $R = 0.7$ jets
  - Note: We now use $R = 0.4$ instead of $R = 0.5$
- **This is what motivated that switch!**
- CMS analyses have used cone sizes $R = 0.4, 0.5, 0.6, 0.7, 0.8, 1.0, 1.2, 1.5$




### Future

- New studies being done to take advantage of jets with many cone sizes [3, 4]
  - i.e. Look at same event many times, each time looking for jets with different $R$
- Use this additional information to improve signal to background discrimination

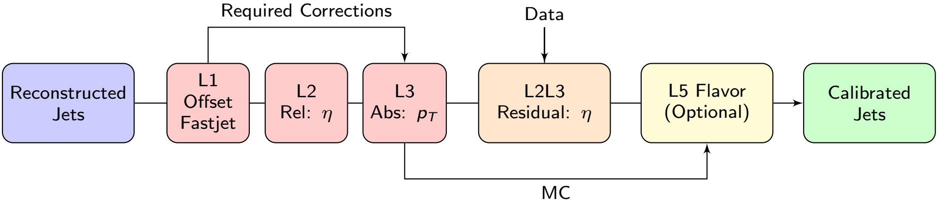
# Jets and Jet Energy Corrections at CMS

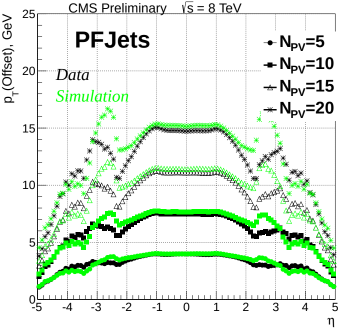


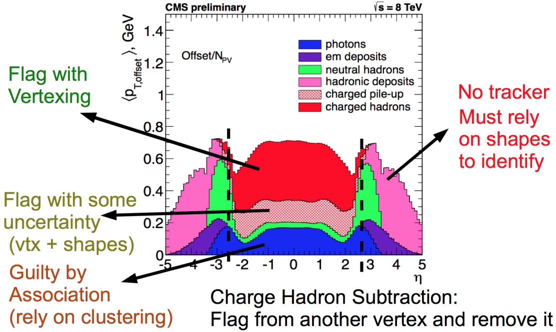

## Corrections (Factorized Approach)

- Factorized approach to jet energy corrections
- Anti-k$_T$ jets with $R = 0.4$ used by default, clustered from Particle Flow (PF) candidates
- Corrections for jets with and without charged hadron subtraction (CHS) available
  - CHS: Remove charged hadrons that can be traced back to pileup vertices, then recluster the jets
  - **There will be a talk on Thursday which will provide more details on CHS**

# CMS JEC Stages: Pileup corrections

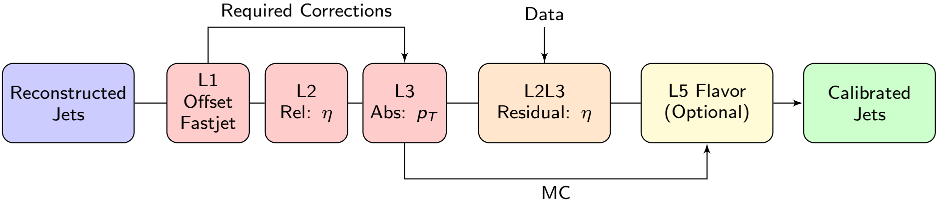


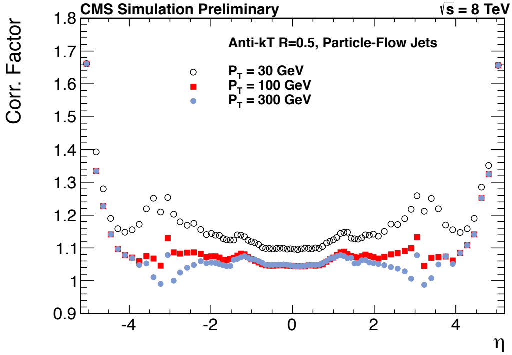




- Left: Additional energy due to pileup as a function of $\eta$ (AK5 PFJets)
- Right: Pileup composition in CMS

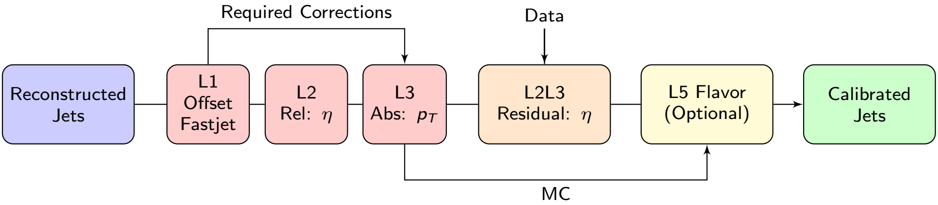
# CMS JEC Stages: $\eta$ and $p_T$ corrections

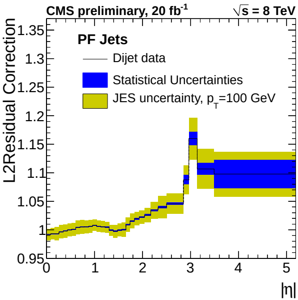


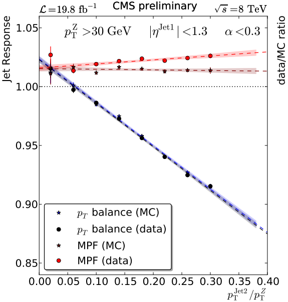



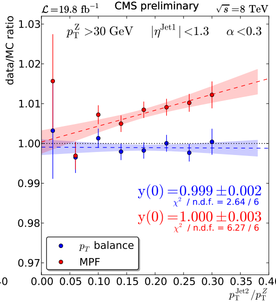

- $\eta$ and $p_T$-dependent scaling factor fully derived from MC after applying pileup corrections
- Multiplicative scale factors shown for three $p_T$ values
- Final correction stage for MC

# CMS JEC Stages: $\eta$ and $p_T$ residual corrections



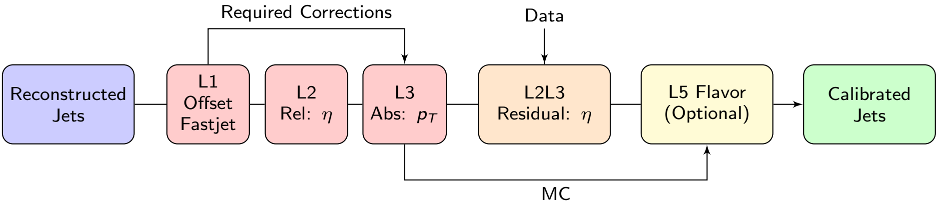



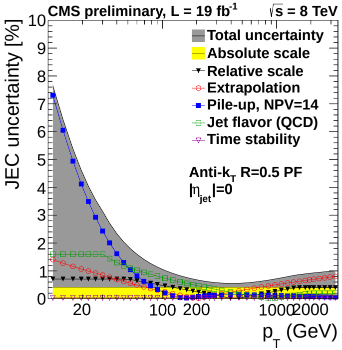



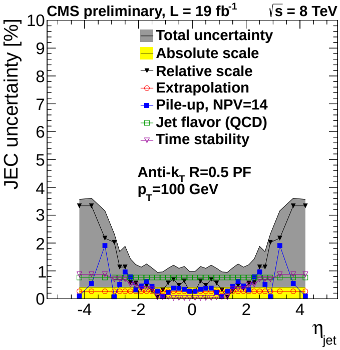




- Left: Correction factor for AK5 PFJets derived from dijet balancing using the Missing-$E_T$ Projection Fraction (MPF) method. Below 5% within the tracker region.
- Center/Right: Absolute correction factor in barrel derived from $Z \to \mu\mu + jet$

# CMS JEC Uncertainties

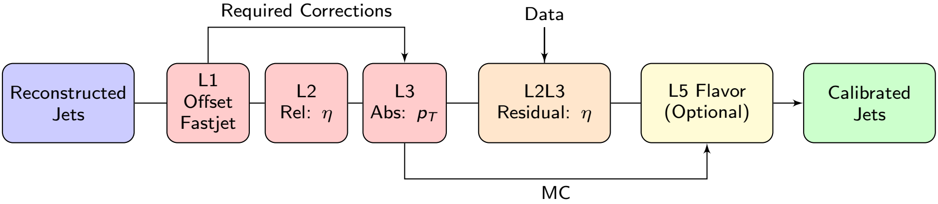



- Total uncertainty and sources for AK5 PFJets as a function of (left) $p_T$ and (right) $\eta$
- Sub-percent uncertainty with central jet $p_T > 100\,\mathrm{GeV}$

# Overview




## In this talk

- Jet energy corrections:
  - Pileup removal
  - Relative and absolute corrections
- Closure of fully corrected jets (MC)
- Resolution and optimization of cone sizes

# Technical Details

## Samples

- Used 2 QCD MC samples, one with pileup and one without
  - Same generator level events in each sample
  - Only difference is the pileup mixing step

## Cone Sizes

- $R = 0.2$ through $R = 1.0$ in steps of 0.1

## These are the things we get for "free" when we move from a large to a small cone size

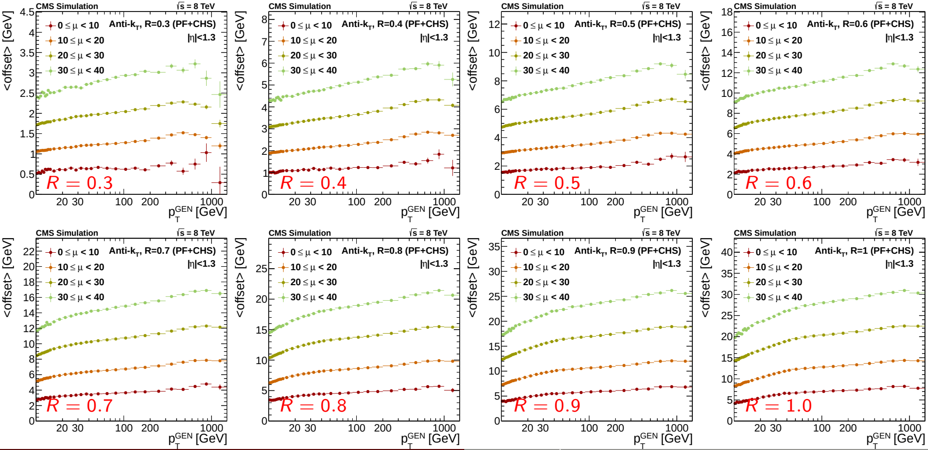
1. offset$= p_T^{PU} - p_T^{noPU}$ scales with $\mu \cdot a_{jet}$ and $a_{jet}$ scales with $R^2$
   - $R = 0.5 \Rightarrow R = 0.4$: We reduce the offset by $\sim \frac{1}{3}$
2. JER noise term scales with $\sqrt{\mu \cdot a_{jet}}$
   - $R = 0.5 \Rightarrow R = 0.4$: At low $p_T$ we can improve jet energy resolution (JER) by up to 20%

- The question is if other figures of merit degrade to compensate (e.g. JEC closure, offset $p_T$ dependence, matching efficiencies, Q/G tagging, etc.)

# Pileup Subtraction

## Offset **Before** Pileup Corrections ($|\eta| < 1.3$)

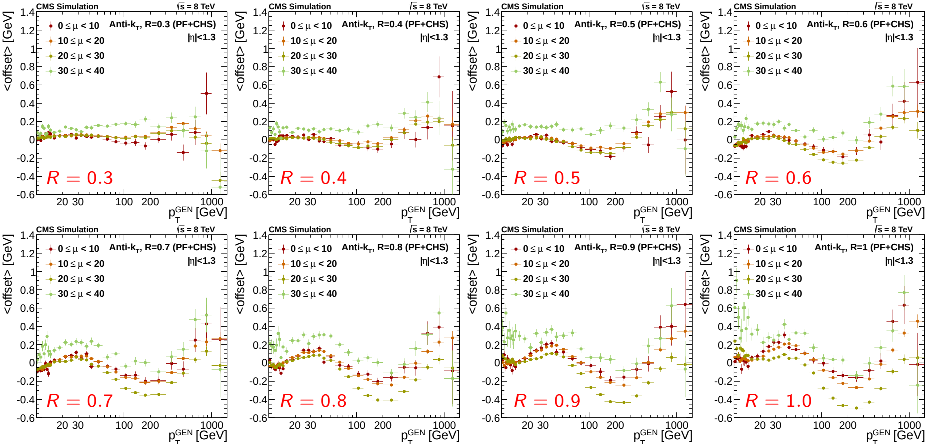
- $\mu$ is defined as the true number of pileup interaction
- Offset is defined as the average difference between PU jet $p_T$ and no PU jet $p_T$
- The average offset increases as jet $p_T$ goes higher due to jet reconstruction non-linearities
- Higher average offset for larger cone sizes (offset is directly proportional to jet area)



# Pileup Subtraction

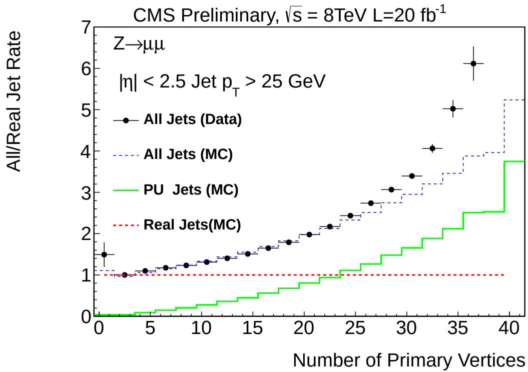
## Offset **After** Pileup Corrections ($|\eta| < 1.3$)

- Average difference between $p_T^{jet}$ **with** PU added (PU sample) and $p_T^{jet}$ **without** PU added (no PU sample)
- Residual average offsets are smaller for smaller cone sizes
  - This is expected since the amount of pileup you have to remove goes with $R^2$
  - There is $\left(\frac{1.0}{0.3}\right)^2 = 11$ times more pileup in a cone of $R = 1.0$ than there is in a cone of $R = 0.3$



# Number of Pileup Jets

- Rate of data and MC pileup jets relative to the rate of real (MC) jets [8]
- The rate of overlapping jets increases quadratically with $N_{PV}$
  - This rate increases even more if you consider more than two overlapping jets
- The probability of two overlapping jets with a given total $p_T$ (i.e. merged real and PU jets) is given by $p\left(overlap|p_T\right) \approx N_{pu}^2 \mathbf{a_{jet}^2} \frac{A^2}{p_T^{6.2}}$
  - A change in the cone size will have a significant effect on the number of pileup jets ($R^4$ dependence)

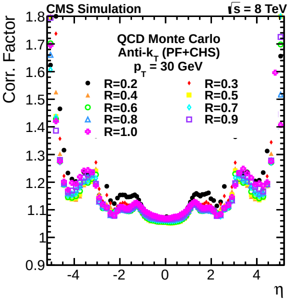


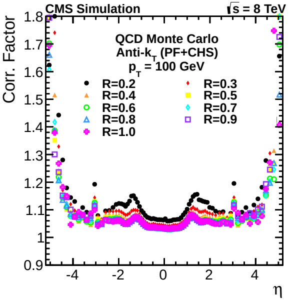

- $R = 0.5 \Rightarrow R = 0.4$: With an $R^4$ dependence we actually decrease PU jet rate by 60%
- The data and MC do not match in the high $N_{PV}$ region due to pileup reweighting
  - The pileup is poorly modeled in this region
  - It is more important that we have proper reweighting in the region of $N_{PV}$ representing the majority of our events

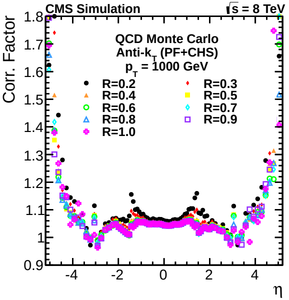
# Relative and Absolute MC-Truth Corrections

## Corrections Vs. $\eta$ in bins of $p_T$

- These JEC compensate for changing jet responses due to $\eta$ and $p_T$ dependencies
- Very similar corrections for *most* cone sizes
- The average corrections are on the order of 10% for $|\eta| < 1.3$ and up to 40% in the high $\eta$ regions
- More variation at low $p_T$, especially fo $R = 0.2$

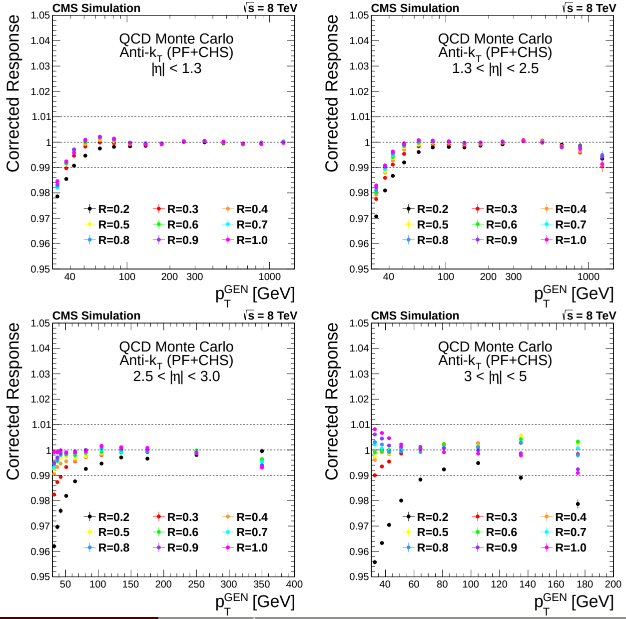


# Closure Vs. $p_T$

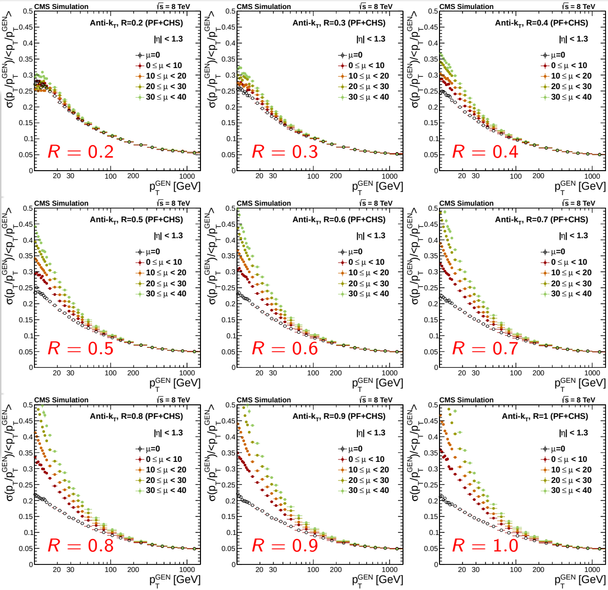
- The response ($p_T^{RECO}/p_T^{GEN}$) of the jets after being fully corrected
- Better closure for larger $R$ cones, especially at low $p_T$
- All cone sizes equivalently good at high $p_T$
- Response mostly contained within $\pm 1\%$
- Closure is decent even for a cone size of $R = 0.2$



# Resolution Due to Detector & Reco Effects

**After** Pileup Removal ($|\eta| < 1.3$)

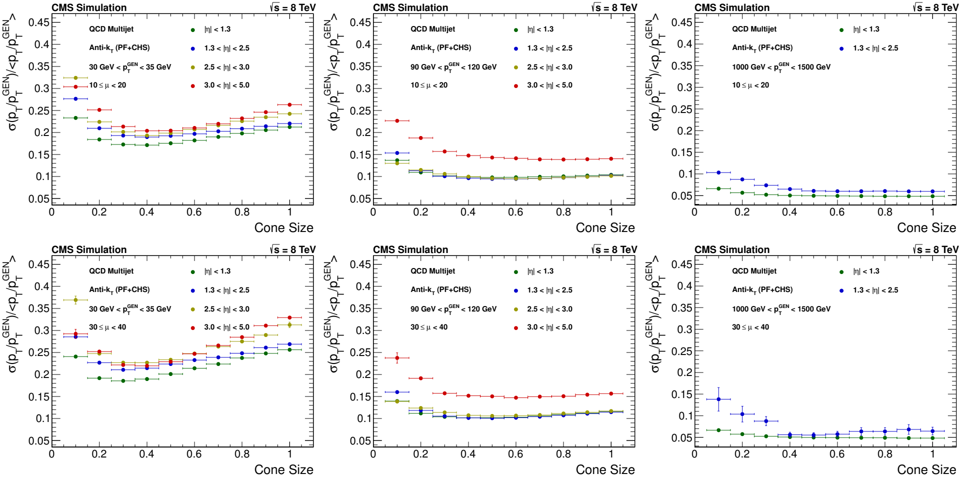
- The resolution of the response of the jets for various $\mu$ bins
- The resolution degrades with larger cone size at low $p_T^{GEN}$ and with higher $\mu$
- At high $p_T^{GEN}$ the resolution of the jets is the same for all cone sizes and all $\mu$



# Optimal Cone Size - Detector & Reco Effects

## **After** Pileup Removal

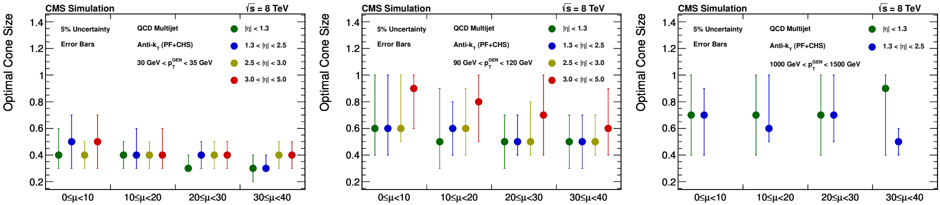
- The response resolution as a function of cone size for a given $p_T^{GEN}$ and $\mu$ bin
- The optimal cone size (for each detector region) is chosen as the one with the smallest response resolution
- With increasing pileup the optimal cone size becomes smaller, but the more you go forward in the detector, the more you want larger cones



# Optimal Cone Size - Detector & Reco Effects

## After Pileup Removal

- These are summary plots of the information from the last slide
  - These include all $\mu$ bins for a given $p_T^{GEN}$
  - Each point represents the cone size with the best resolution
- The more you go forward in the detector, the more you want larger cones
- Note: The error bars include cone sizes whose resolution is within 5% of the optimal size



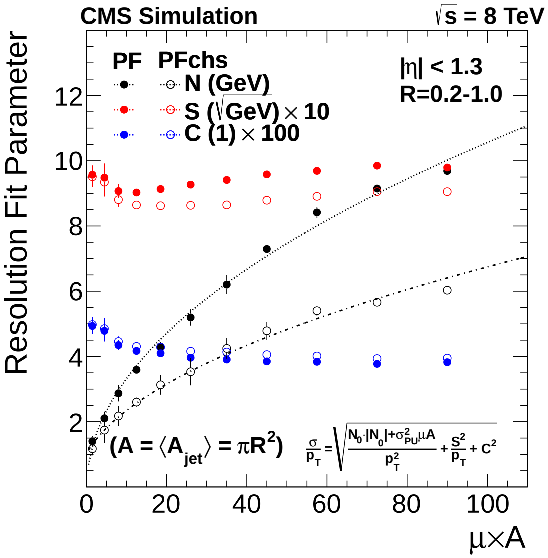
# Resolution Fits

## After Pileup Removal

- Equation parameterizing the resolution

$$\frac{\sigma}{p_T} = \sqrt{\frac{N_0\cdot|N_0| + \sigma_{PU}^2 \mu A}{p_T^2} + \frac{S^2}{p_T} + C^2}$$

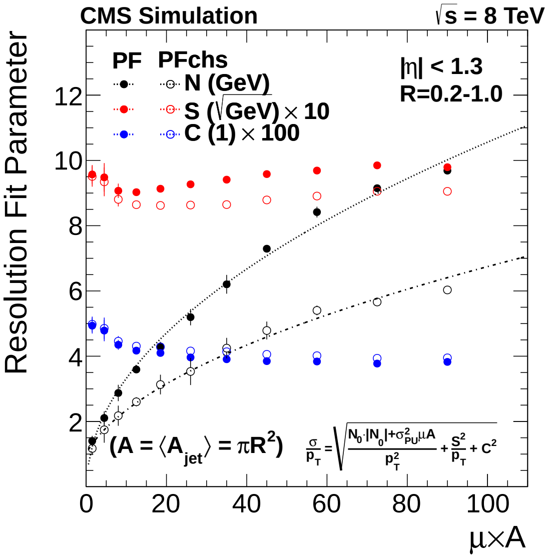
- Three terms:
  - Noise
    - $\sqrt{\mu \cdot a_{jet}}$ dependence
  - Stochastic
    - Constant in $\mu \cdot a_{jet}$
  - Constant
    - Constant in $\mu \cdot a_{jet}$



# Resolution Fits

## After Pileup Removal

- The stochastic and constant terms do not significantly change with pileup or R
- The stochastic term show a slight benefit when using PFchs
- The noise term can be effectively parameterized by simple square-root dependence on $\mu \times A$
  - PFchs is significantly better at reducing the noise term at high $\mu \times A$
  - This improvement is not as pronounced for smaller cone sizes, especially at small $\mu \times A$



# Summary

- **We have validated the performance of the jet energy corrections over a wide range of cone sizes**

- The performance of the JEC for all cone sizes is very good
- Rate of PU jets increases rapidly for larger cone sizes
- Smaller cone sizes provides a benefit in removing PU
  - More stable residual offset left for smaller cone sizes after the pileup corrections
  - Better low $p_T$ resolution
- Relative and absolute corrections have a minimal dependence on jet radius
- MC has the expected JER dependence on $\mu$ and jet area
  - Resolution increases with $\mu$ and with cone size
  - At high $p_T^{GEN}$ resolution is independent of cone size
  - Optimal resolution for all $p_T$ and $\mu$ bins found at $R = 0.4$

- Look for analyses to start using more cone sizes very soon!
  - See the benefit of using more cone sizes [3, 4]

# References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Pileup subtraction using jet areas.
*Physics Letters B*, 2008.
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[2] Matteo Cacciari, Gavin P. Salam, and Gregory Soyez.
The catchment area of jets.
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[3] Y.-T. Chien.
Telescoping Jets: Multiple Event Interpretations with Multiple R's.
arXiv:1304.5240 [hep-ph], April 2013.

[4] Y.-T. Chien, D. Farhi, D. Krohn, A. Marantan, D. Lopez Mateos, and M. Schwartz.
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[6] The CMS Collaboration.
Determination of jet energy calibration and transverse momentum resolution in cms.
*Journal of Instrumentation*, 2011.
arXiv:1107.4277v1 [physics.ins-det].

[7] The CMS Collaboration.
Jet energy scale performance in 2011.
*CMS Performance Note*, 2012.
CMS DP-2012/006.

[8] The CMS Collaboration.
Pileup Jet Identification.
Technical Report CMS-PAS-JME-13-005, CERN, Geneva, 2013.

# Backup Slides

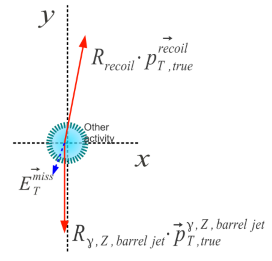
# Missing-$E_T$ Projection Fraction

- Missing transverse energy projection fraction (MPF) is based on the fact that Z+Jets events have no intrinsic $\not{E}_T$
  - At the parton level, the Z is balanced by the hadronic recoil in the transverse plane

$$\vec{p}_T^{Z} + \vec{p}_T^{recoil} = 0$$

- For reconstructed objects we need to add the detector responses

$$R_Z \vec{p}_T^{Z} + R_{recoil} \vec{p}_T^{recoil} = -\vec{\not{E}}_T$$



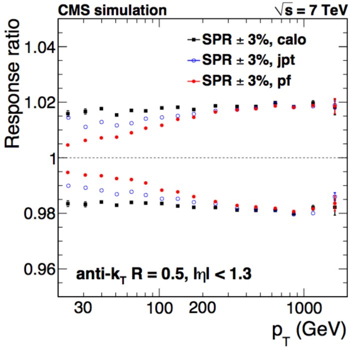

- Response given by the projection of $\vec{\not{E}}_T$ along the axis of the Z

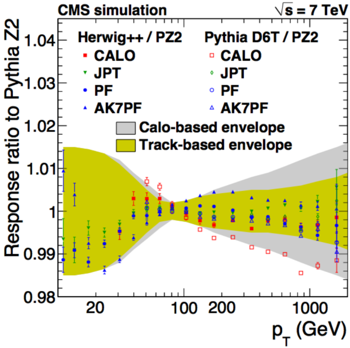
$$R_{recoil} = R_Z + \frac{\vec{\not{E}}_T \cdot \vec{p}_T^{Z}}{\left(p_T^{Z}\right)^2} \equiv R_{MPF}$$

- We also saw $\alpha = \frac{p_T^{jet2}}{p_T^{Z}}$, which makes sure that we veto on second jet activity
  - Removes the influence of soft radiation
- More details found in [6]

# Extrapolation Uncertainties

- Single particle response (SPR) for hadrons:
  - Measured in data by using isolated tracks and comparing the energy deposited in the calorimeters to the momentum as measured by the tracker
  - data/MC disagreement is less than $\pm 3\%$
  - SPR for PF is less than 2% and is better at low $p_T$ where the tracker measurement is dominant. When $p_T$ is high, the calorimeter measure is dominant in the PF algorithm.
- Fragmentation properties of the generators:
  - Ratio negligible at $p_T \sim 80\ \mathrm{GeV}$ and grows to $\sim 1.5\%$ at low and high $p_T$
- More information can be found at [6]



# Flavor Uncertainties

- Flavor uncertainties based on the PYTHIA/Herwig++ differences in uds/c/b-quark and gluon responses
- Default: extrapolate from Z+Jet mixture to the dijet QCD mixture
- Access to individual sources also given
    - i.e. can make a mixture specific to your signal or background
- More information found at [5]