Aspects of HI jet reconstruction in ATLAS

Jet quenching: the interface between theory and experiment
Characterizing jet quenching: experimental issues
Tuesday, February 12, 2013

Background subtraction

$$E_{\mathrm{T}}^{\mathrm{subtr}} = E_{\mathrm{T}}^{\mathrm{unsubtr}} - \rho A$$

- **This formula is used near universally in subtracting the UE**

- **How do you estimate the background?**
- **Must respect the experimental definition of a jet**
  - ➡ **Energy clustered in a jet reconstruction algorithm above the uncorrelated underlying event**
    - **May include medium response (correlated)**
- **Cannot use region containing jet to estimate background, at least not initially**
- **Use dE_{T}/dηdϕ distribution outside of jet region to characterize background beneath jet**

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Background ansatz

- **UE consists of:**
  - **Average underlying event (can be *η*-dependent)**
  - **Global event correlations (e.g. flow)**
  - **Local uncorrelated fluctuations (anything else)**
    - **Have no way to estimate on per jet basis, since by construction these are uncorrelated with anything else in the UE**
    - **Upshot is that this also means they should only contribute to the resolution**

$$\frac{\mathrm{d}E_{\mathrm{T}}^{\mathrm{UE}}}{\mathrm{d}\eta\mathrm{d}\phi} = \rho(\eta) f(\eta,\phi) + \delta E_{\mathrm{T}}^{\mathrm{fluct}}$$

$$1 + 2\sum_{n} v_{n}^{\mathrm{UE}}(\eta)\cos[n(\phi-\Psi_{n})])$$

Express as Fourier series (without loss of generality) and use what we know about flow to help in the determine the coefficients

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Background ansatz: ATLAS details

- **All of the details *are* in the ATLAS jet suppression paper**

  hep-ex/1208.1967

$$\rho^{\mathrm{ATLAS}}(\eta,\phi) = \rho(\eta)(1 + 2v_2^{\mathrm{UE}}\cos[2(\phi - \Psi_2)])$$

- **Use η-averaged v_n^{UE}**
  - **Difficult to obtain unbiased η-dependent v_n^{UE} in regions containing jet**
- **Currently use n=2 only, since elliptic flow is known to be dominant global event correlation in most centrality bins**
  - **Omission of other harmonics contributes to JER**
  - **Also introduces bias in** $$\frac{\mathrm{d}N_{\mathrm{jet}}}{\mathrm{d}(\phi_{\mathrm{jet}} - \Psi_n)}$$
- **Background computed in η bins of size 0.1.**

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Background ansatz: ATLAS fine print

- **Ψ_2 determined from FCal**

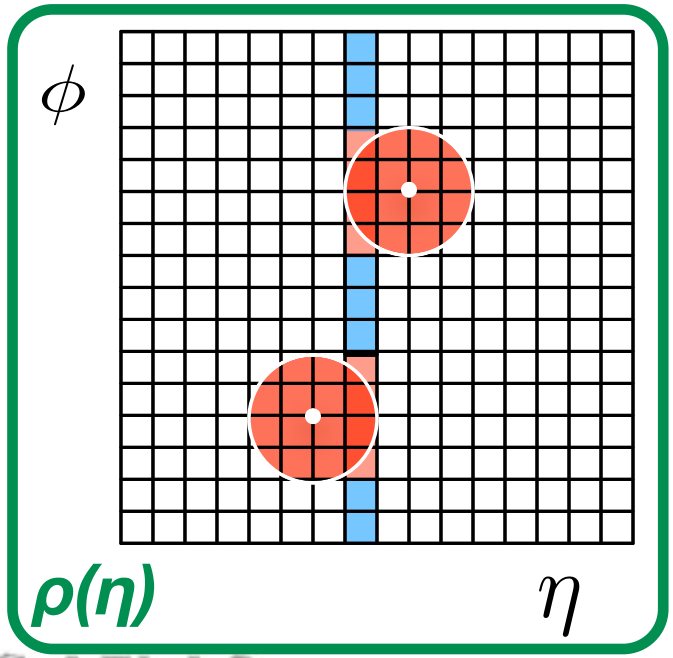
$$\Psi_2 = \frac{1}{2}\tan^{-1}\left[\frac{\sum_{i\in\mathrm{FCal}} E_\mathrm{T}^i \cos 2\phi^i}{\sum_{i\in\mathrm{FCal}} E_\mathrm{T}^i \sin 2\phi^i}\right]$$

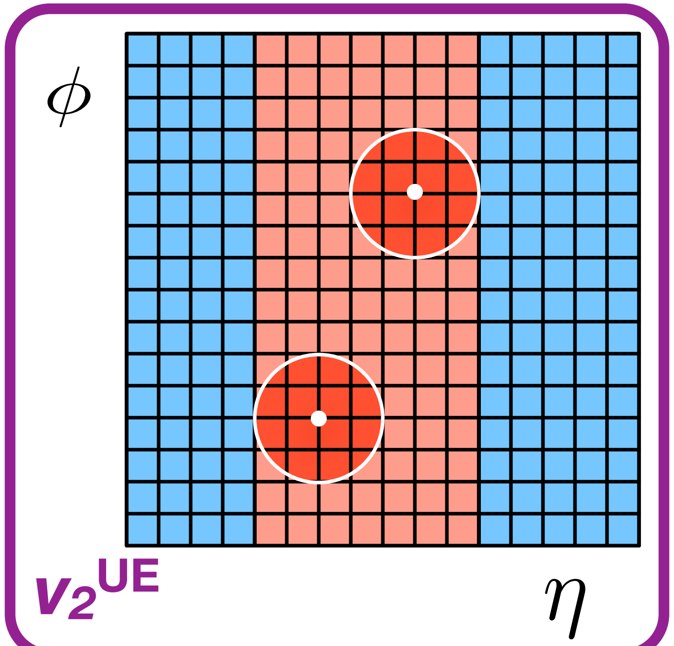
- **Jets excluded from estimates of and ρ and v_2^{UE}**

$$\rho(\eta) = \left\langle \frac{E_\mathrm{T}^i}{\Delta\eta^i \Delta\phi^i} \right\rangle_{i\notin\mathrm{jet},\, |\eta^i-\eta|<0.05}$$

$$v_2^{\mathrm{UE}} = \langle E_\mathrm{T}^i \cos[2(\phi^i - \Psi_2)]\rangle_{i\notin\mathrm{jet}}$$

- **Compute both $\rho(\eta)$ and v_2^{UE} per calorimeter sampling layer**





- **Only blue cells included in $\rho(\eta)$ and v_2^{UE} calculation**
- **Red cells excluded due to jets**

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Background subtraction

- If this is your definition of a jet
  - ➡ Energy clustered in a jet reconstruction algorithm above the uncorrelated underlying event
- Then all jets appearing the final measurement should be excluded from the background and anything not in a jet should be included in the background
  - This is hard to get exactly right
  - ➡ Goal should be to minimize the bias in the background determination
- Two scenarios
  I. A jet is mistakenly included in the background
  II. Something that is not a jet is excluded from the background

Scenario I: energy bias

- **Jet with energy E_T included in background**
- **ρ is biased by an amount:**

$$\rho^{B} = \frac{A^{UE}\rho^{U} + A^{jet}\rho^{U} + E_{T}^{jet}}{A^{UE} + A^{jet}} = \rho^{U} + \frac{E_{T}^{jet}}{A^{UE} + A^{jet}}$$

- **Jets are oversubtracted by** $\Delta E_T = -\frac{A^{jet}}{A^{UE} + A^{jet}} E_{T}^{jet}$
- **Jet suffers a *self energy bias* which is ~10% for *R*=0.4 jets**
  - **➡ Subset of jets in analysis have 10% JES error!**
- **Other jets which use the same background (in ATLAS same η slice) receive a *mutual energy bias***
  - **➡ Hard to estimate impact on jets in analysis**

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Scenario II: fluctuation bias

- **Mistakenly include upward UE fluctuation in spectrum**
  - **Only excluding upward fluctuations, not downward**
  - **Will bias the mean!**
- ***ρ* is biased by an amount:**

$$\rho^{\mathrm{B}} = \frac{A^{\mathrm{UE}}\rho^{\mathrm{U}} + A^{\mathrm{fluct}}\rho^{\mathrm{U}} + E_{\mathrm{T}}^{\mathrm{fluct}}}{A^{\mathrm{UE}} + A^{\mathrm{fluct}}}$$

- **Jets under-subtracted :** $\Delta E_{\mathrm{T}} = -\frac{A^{\mathrm{fluct}}}{A^{\mathrm{UE}} + A^{\mathrm{fluct}}} E_{\mathrm{T}}^{\mathrm{fluct}}$
- **Other jets may suffer *mutual energy anti-bias***
- **Also fluctuations are under-subtracted by ~10% due to opposite of self energy bias**

➡ Pushes up the fake rate in analysis!

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ATLAS solution: iterative procedure

- Jet seed: an object (jet) whose constituents are excluded from the background determination
- Make jet seed definition as close as possible to jet definition in analysis to minimize biases
  - Including fake rejection
- How to identify seeds?
  - Can't use E_T threshold, need seeds to determine background!
- Iterative procedure: determine using a seed criteria
  - Can be applied to unsubtracted jets
  - Has minimal sensitivity to UE fluctuations
- Determine background and subtract
  - Now have jets with (potentially biased) subtracted E_T

ATLAS solution: iterative procedure

- Re-determine background with new jet seeds
  - Use subtracted jet kinematics (ATLAS uses p_T threshold)
  - Add objects to seed list (ATLAS uses track jets)
  - Apply fake rejection
    - In past, ATLAS hasn't done this in reconstruction but in analysis, now explicitly part of reconstruction
    - ➡ Iterative approach makes SEB correction easy to implement at analysis stage
- Background is only biased to the extent to which the initial bias in the subtracted jet kinematics causes a jet to not be considered a seed
  - e.g. in ATLAS this can happen if initial SEB pushes a jet below seed threshold in second step
    - Has been studied and is not a significant effect

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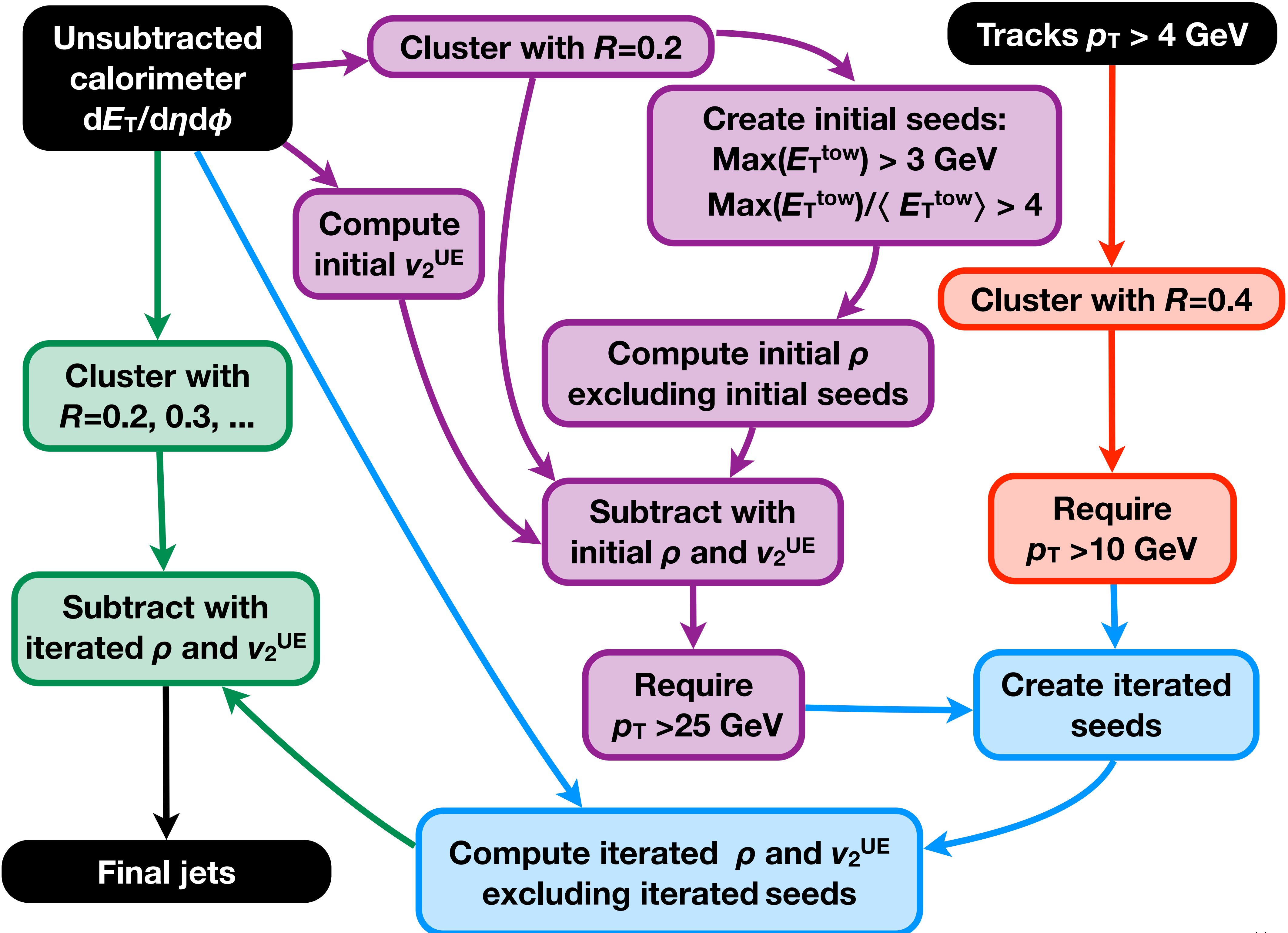
Unsubtracted calorimeter $dE_T/d\eta d\phi$
Cluster with R=0.2
Tracks p_T > 4 GeV
Create initial seeds:
Max(E_T^{tow}) > 3 GeV
Max(E_T^{tow})/⟨ E_T^{tow}⟩ > 4
Compute initial v_2^{UE}
Cluster with R=0.4
Compute initial ρ excluding initial seeds
Cluster with R=0.2, 0.3, ...
Subtract with initial ρ and v_2^{UE}
Require p_T >10 GeV
Subtract with iterated ρ and v_2^{UE}
Require p_T >25 GeV
Create iterated seeds
Final jets
Compute iterated ρ and v_2^{UE} excluding iterated seeds

Jet energy scale calibration

- Use "numerical inversion" procedure standard in ATLAS
- Measure energy at "EM scale"
  - Response calibrated assuming EM showers
- Correct to full hadronic scale using calibration
  - Fit points ($\langle E_T^{uncalib}/E_T^{truth}\rangle$,$\langle E_T^{uncalib}\rangle$)

➡ **Fit determined in peripheral collisions only**

  - Due to conflate subtraction effects with energy scale calibration effects

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Jet performance in ATLAS

- Measured jet (response) differs from true jet due to
  - underlying event fluctuations
  - variations in detector response and incomplete measurement of jet's energy
  - pathologies in the subtraction procedure
- Characterized by $\Delta E_T = E_T^{truth} - E_T^{reco}$ distribution
  - $\langle \Delta E_T \rangle / E_T^{truth}$ sensitive to jet energy scale (JES)
  - width of $\Delta E_T / E_T^{truth}$ is jet energy resolution (JER)
- All effects result in bin migration
  - Significant problem for steeply falling jet spectrum
  - Typically solved by unfolding
    - Better performance ↔ more controlled unfolding

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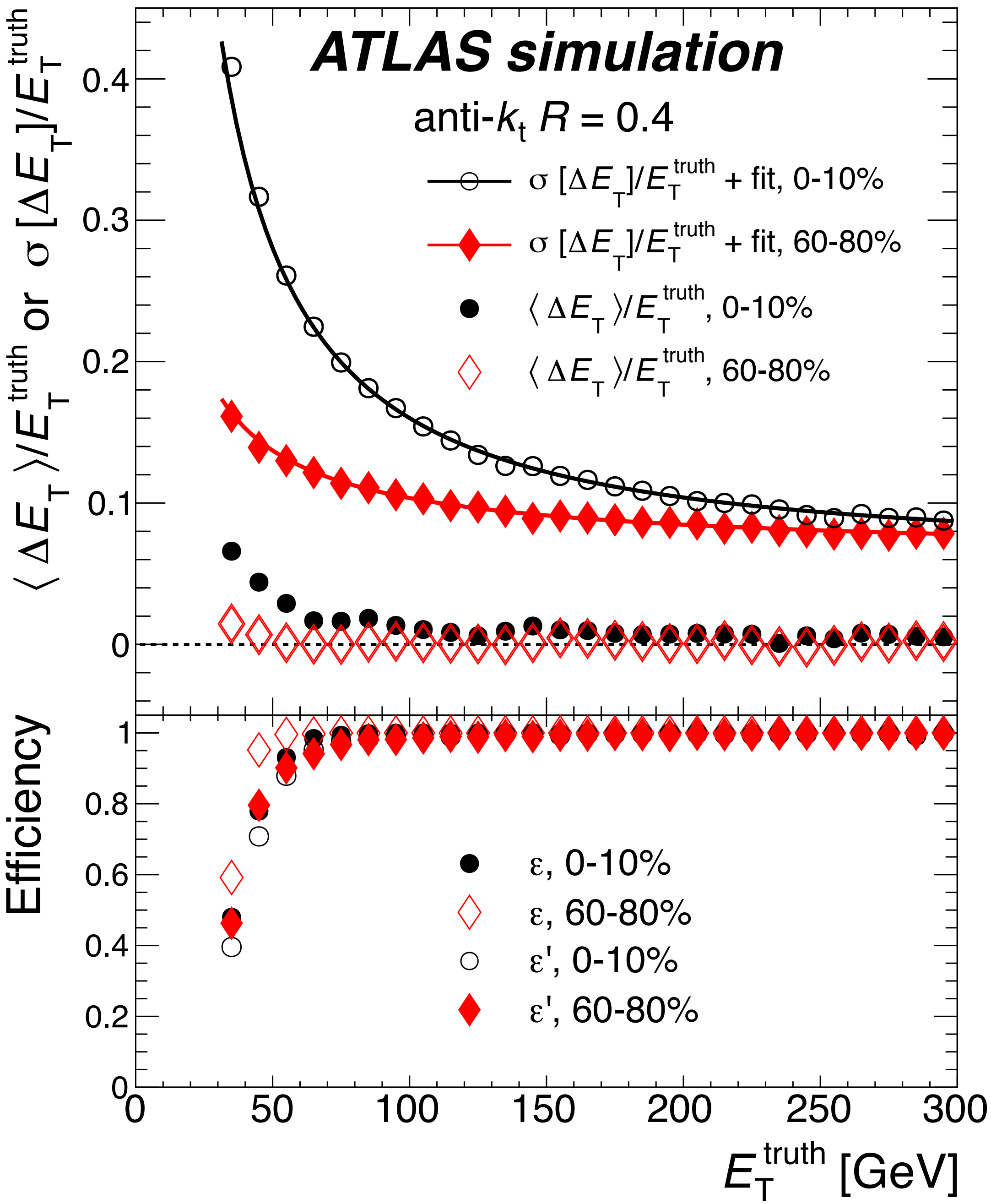
Jet performance in ATLAS R=0.4 jets



- For 2010 results (e.g. jet R_{CP} paper)
- Using HIJING+PYTHIA
- Complete performance available in thesis nucl-ex:1208:5043

- For E_T > 50 GeV JES closure and centrality variation < 1%
  - Systematic in R_{CP} measurement
- JER behavior understood (fit)
- Efficiency before and after fake rejection shown

- 2011 results using MB data+PYTHIA
  - performance generally better (JES closure < 0.5%)
  - no public results available

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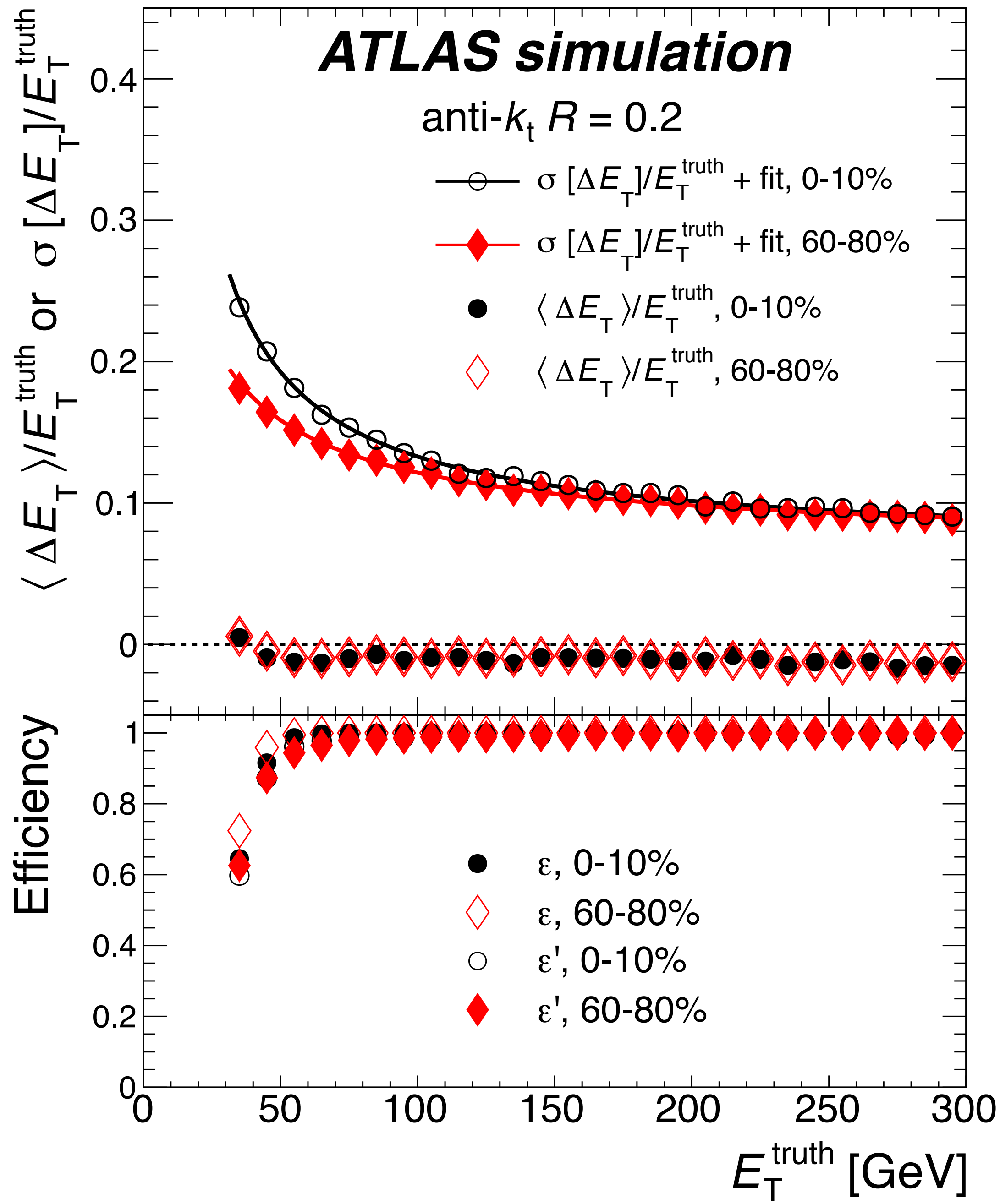
Jet performance in ATLAS *R*=0.2 jets

- For 2010 results (e.g. jet R_{CP} paper)
- Using HIJING+PYTHIA
- Complete performance available in thesis nucl-ex:1208:5043

- Smaller *R* value less sensitivity to UE effects
- Slightly better JES closure
- Better JER at low E_T where dominated by UE
- Better efficiency in central collisions



Performance and unfolding

- Fundamental ingredient in unfolding is response matrix
  - Performance does not enter directly but response and performance derived from same sample
- Do data driven evaluations of performance quantities and determine uncertainties
- Generate new response matricies reflecting systematic variation consistent with derived uncertainty
- Unfold with systematically varied response for each systematic

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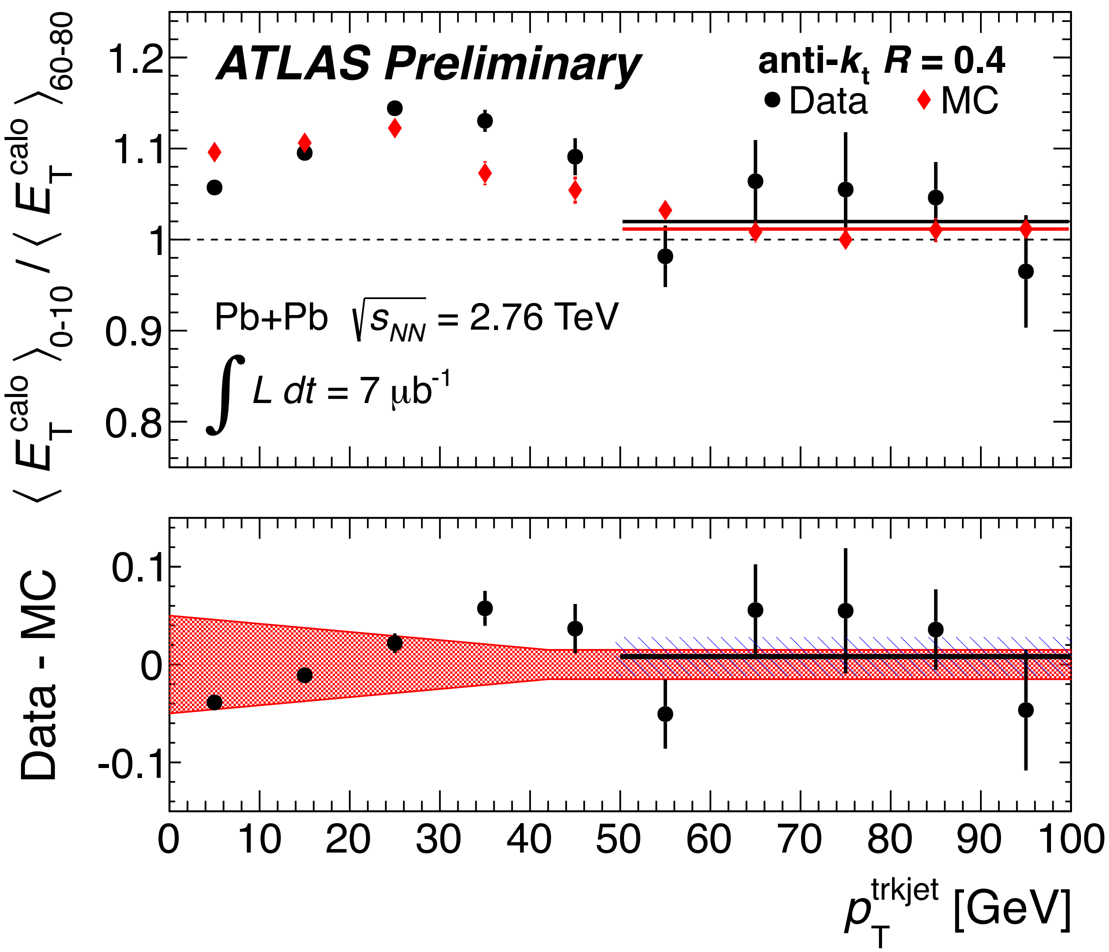
Data driven evaluation of JES

- **Track jets provide independent check on calorimetric energy scale**
- **Matching between track jets and calo jets to study calorimetric response in MC and data**
- **Compute mean calo jet E_T as function of track jet p_T**
- **Compare data and MC**
- **Limits effects of possible medium-modified**



- **JES uncertainty constant above 70 GeV (table)**
- **Grows linearly, doubling from its nominal value at 30 GeV**

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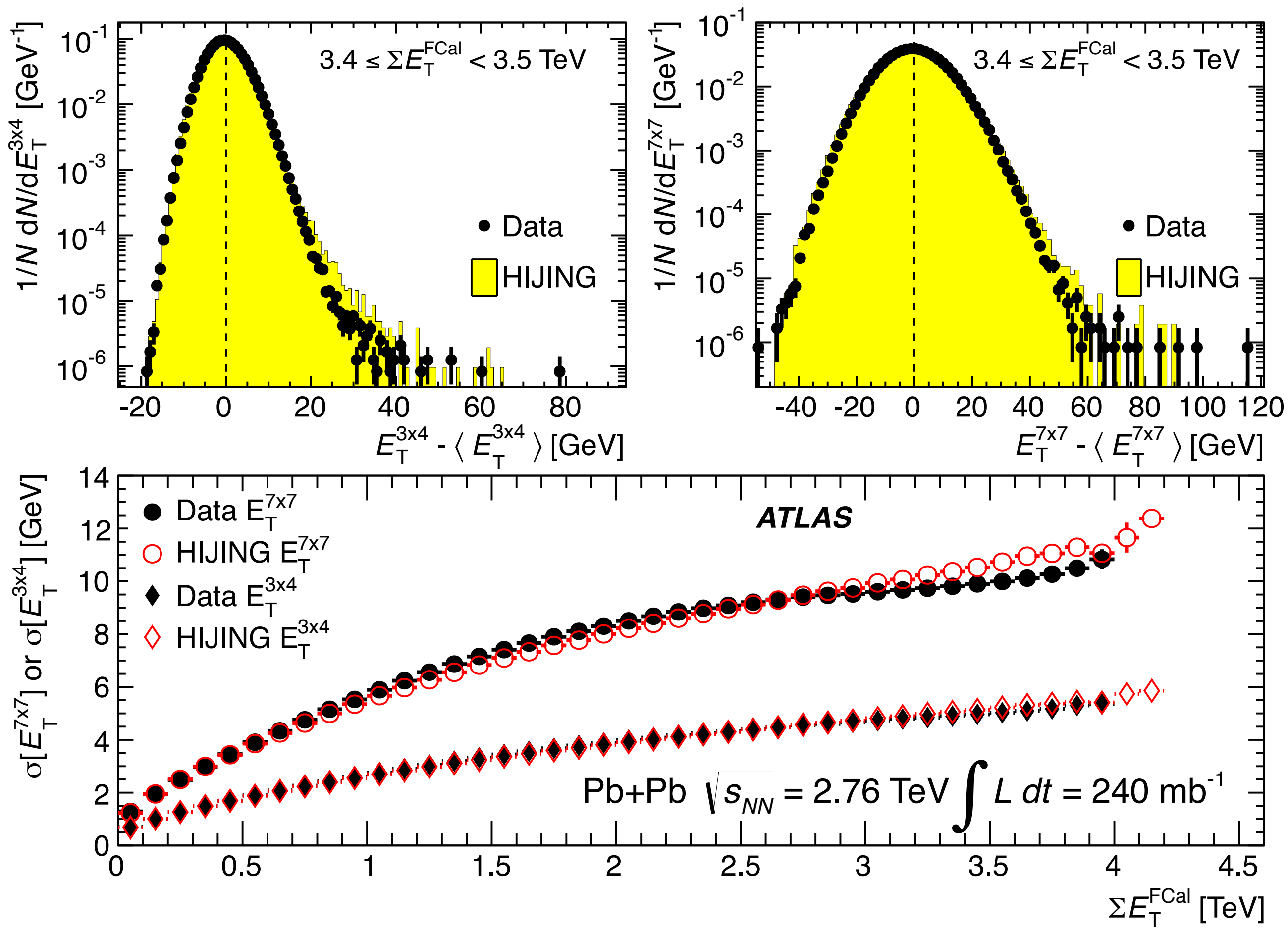
Data driven evaluation of JER

- **In 2010 MC sample background is HIJING plus elliptic flow afterburner**
- **Study deviations in fluctuation spectrum between data and HIJING**
- **Not at issue in 2011 since background is MB data**
- **Measure E_T distribution of sliding windows that are the size of a typical jet**



- **Characterize typical fluctuation by width**
- **Study width vs centrality and take difference as systematic uncertainty on fluctuation contribution to JER**

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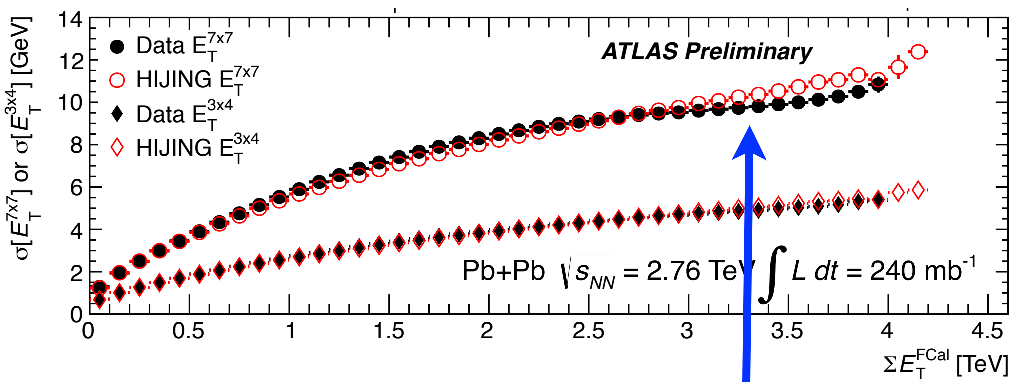
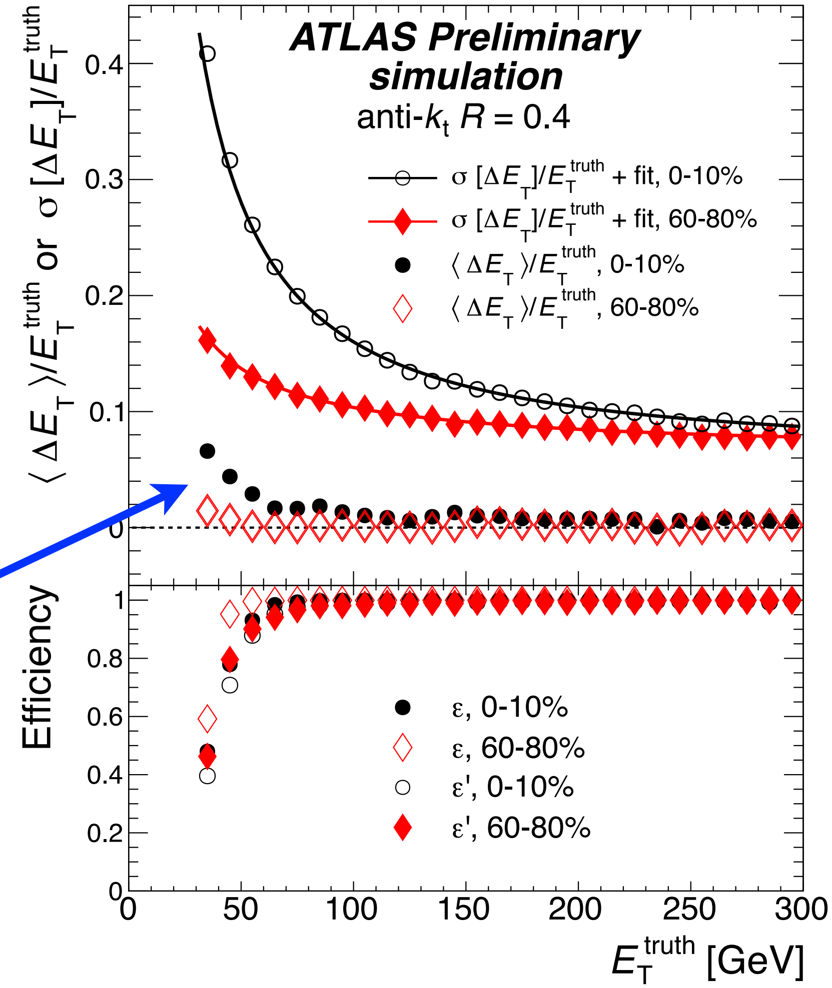
Relationship between JER and UE



Fixed by fluctuation analysis

$$\frac{\sigma(\Delta E_{\mathrm{T}})}{E_{\mathrm{T}}} = \frac{1}{E_{\mathrm{T}}}\left(a\sqrt{E_{\mathrm{T}}} \oplus b \oplus cE_{\mathrm{T}}\right)$$

Free parameters in fit



- **Fit results give a and c values in agreement for all centralities**
- **Establishes quantitative relationship between UE fluctuations and ΔE_T fluctuations (JER)**

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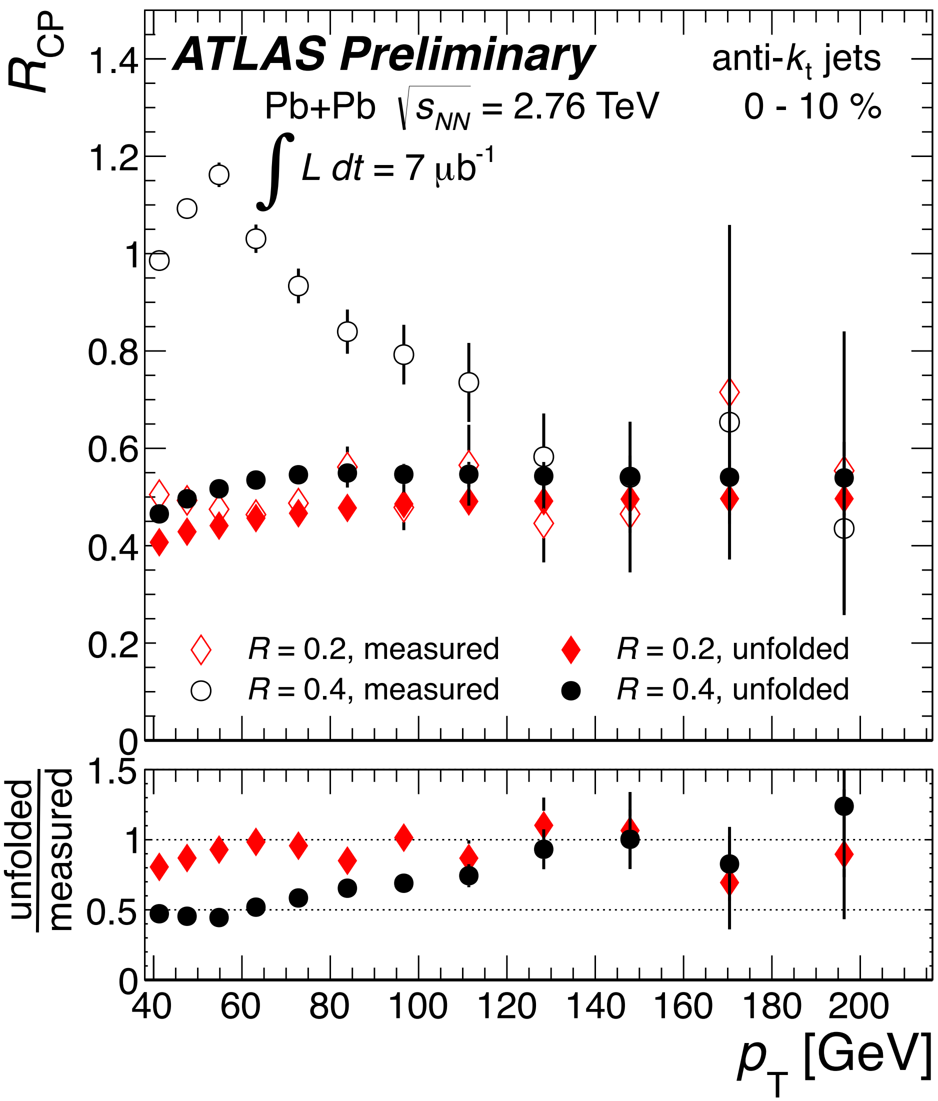
Unfolding



- **UE and detector effects result in finite JER**
  - **Jet spectrum is steeply falling**
  - **Result is significant bin migration**
- **Use MC to generate response matrix**
  - **Contains information about bin migration**
- **SVD unfolding**

Hocker and Kartvelishvili: hep-ph/9509307

  - **Invert response using curvature constraint on result to regularize unfolding**
- **Unfolding checks**
  - **Apply to MC, look for bias**
  - **"Refold" data, check refolded looks like input**

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Additional Slides

ATLAS details

- **In first determination of background clustering is run using anti-k_t with R=0.2 on unsubtracted calorimeter $dE_T/d\eta d\phi$**
  - **Define initial jet seeds to be jets for which**
    - **$\mathrm{Max}(E_T^{\mathrm{tower}}) > 3$ GeV**
    - **$\mathrm{Max}(E_T^{\mathrm{tower}})/\mathrm{Mean}(E_T^{\mathrm{tower}}) > 4$**
- **Determine initial background**
  - **Exclude cells within seeds from ρ**
  - **Do not exclude any cells from v_2 calculation**
- **Apply subtraction to get subtracted R=0.2 jets**
- **Separately build track jets**
- **Create new seeds using R=0.2 jets $p_T > 25$ GeV and track jets $p_T > 10$ GeV**

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ATLAS details

- Determine new background
  - Exclude cells with ΔR < 0.4 of new seeds from ρ and v_2
- Run anti-k_t with multiple R values on unsubtracted calorimeter $dE_T/d\eta d\phi$
- Apply same subtraction using the new background
- Issues:
  - For R > 0.4 , entire jet is not excluded
  - Fake rejection applied at analysis stage
    - Requires correction to jet energy to account for this (typically few % at low p_T, < 1 at high p_T)
  - New procedure will build this into the reconstruction
    - Second iteration using fake rejection
      - Excludes all cells in jets that pass rejection
- No plots shown use the new procedure

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ATLAS details

- New procedure will build this into the reconstruction
  - Second iteration using fake rejection
    - Excludes all cells in jets that pass rejection
  - No plots shown use the new procedure
- In principle, could define initial seeds to simply be those jets that pass fake rejection
  - In ATLAS fake rejection we use information dependent on initial background subtraction so this isn’t possible at present
    - Final background from jet reconstruction used to produce subtracted calorimeter distribution on which photon reconstruction is run