Studies of jet shapes and substructure with ATLAS

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On behalf of the ATLAS Collaboration

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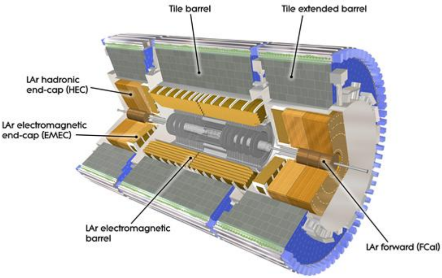
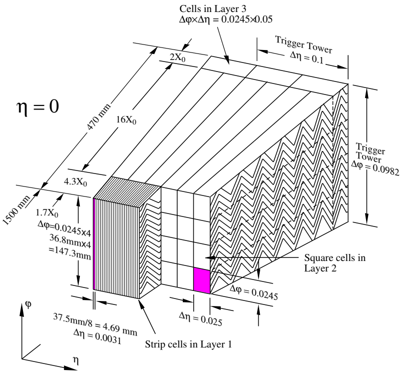
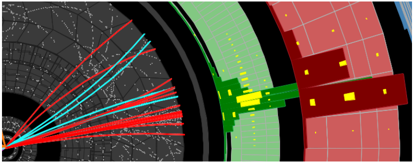
Jets at ATLAS





(Up↑) Highly granular EM calo, down to $\Delta\eta \times \Delta\phi \approx 0.025 \times 0.025$.

(Right→) ATLAS primarily uses anti-k_t jets with $R = 0.4$ and 0.6. Larger radii and different algorithms in specific cases.

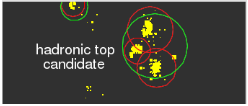


Jets - more than 4-vectors

Why look inside a jet?

- May contain massive particles (W, Z, top, etc.)
- Search for boosted BSM particles.
- Study non-perturbative effects (fragmentation, hadronization.)

- Measurements can bring insight and constrain models.
- A growing list of measurements performed at ATLAS.



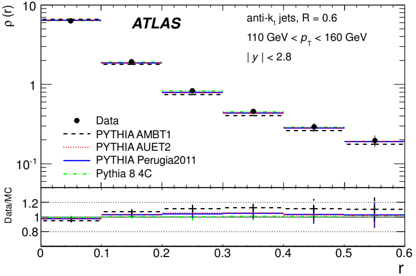
- **Study of jet shapes in inclusive jet production in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector** (Phys. Rev. **D83**, 052003 (2011))
- **Jet Shapes in ATLAS and MC modeling** (ATL-PHYS-PUB-2011-010)
- **Measurement of the jet fragmentation function and transverse profile in proton-proton collisions at a center-of-mass energy of 7 TeV with the ATLAS detector** (Eur. Phys. J. C **71** (2011) 1795)
- **ATLAS measurements of the properties of jets for boosted particle searches** (Phys. Rev. **D86**, 072006 (2012))
- **Jet mass and substructure of inclusive jets in $\sqrt{s} = 7$ TeV pp collisions with the ATLAS experiment** (JHEP **1205** (2012) 128)
- **Performance of large-R jets and jet substructure reconstruction with the ATLAS detector** (ATLAS-CONF-2012-065)
- **Studies of the impact and mitigation of pile-up on large-R and groomed jets in ATLAS at $\sqrt{s} = 7$ TeV** (ATLAS-CONF-2012-066)

Phys. Rev. **D83**, 052003 (2011)
ATL-PHYS-PUB-2011-010

Jet Shapes

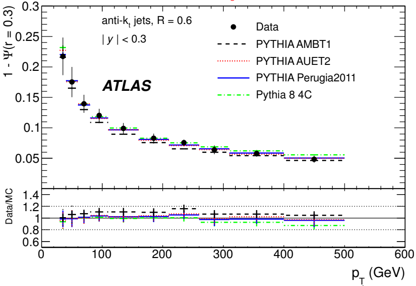
Differential jet shape

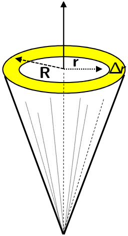
$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N^{\mathrm{jet}}}\sum_{\mathrm{jets}}\frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)}$$



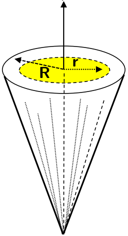
Integrated jet shape

$$\Psi(r) = \frac{1}{N^{\mathrm{jet}}}\sum_{\mathrm{jets}}\frac{p_T(0,r)}{p_T(0,R)}$$





- Most of the jet momentum is in the core.
- After tuning, PYTHIA describes data well.
- **Jets become narrower with p_T.**

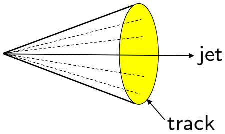


See also talk later today on b-quark jet shapes with ATLAS by Javier Llorente

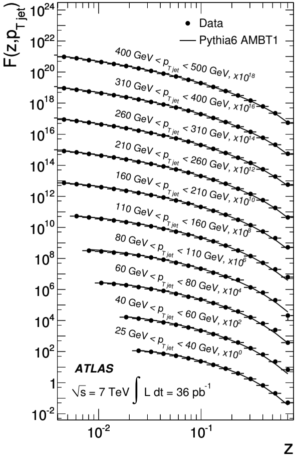
Eur. Phys. J. C **71** (2011) 1795

Fragmentation

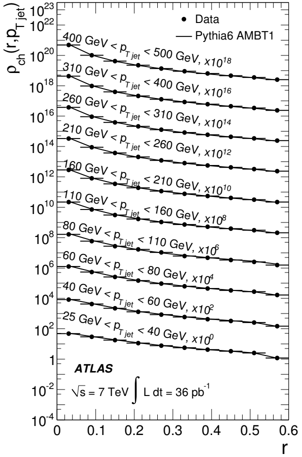
Structure of a jet studied using charged particles (tracks).



- $p_{T\,\text{track}} > 0.5$ GeV.
- Relative momentum parallel to jet axis, $z = \frac{\vec{p}_{\text{jet}} \cdot \vec{p}_{ch}}{|\vec{p}_{\text{jet}}|^2}$.
- Relative momentum transverse to jet axis.
- Density of charged particles in the jet.



$$F(z, p_{\mathrm{T\,jet}}) \equiv \frac{1}{N^{\mathrm{jet}}} \frac{dN_{ch}}{dz}$$



$$\rho_{ch}(r, p_{\mathrm{T\,jet}}) \equiv \frac{1}{N^{\mathrm{jet}}} \frac{dN_{ch}}{2\pi r dr}$$

Conclusions

⇒ PYTHIA describes the data well.

⇒ Longitudinal momentum scales with $p_{T\,\text{jet}}$.

⇒ Jets become denser with $p_{T\,\text{jet}}$.

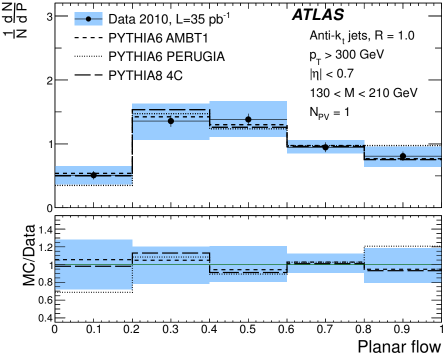
Phys. Rev. **D86**, 072006 (2012)

Jet properties for boosted particle searches

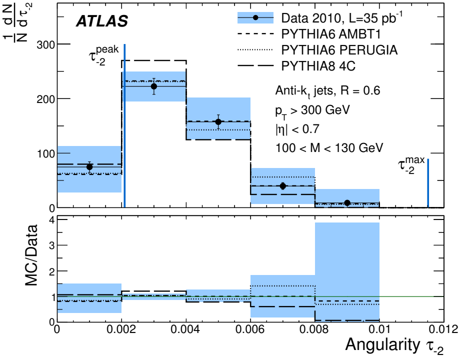
Jets produced by massive boosted particles are different from QCD jets. Can we distinguish using substructure of jets?

- Planar flow - distribution of energy across the face of the jet.
- Angularity - degree of symmetry in energy flow inside the jet.

QCD jets peak at higher values →



Broader tail in QCD jets →

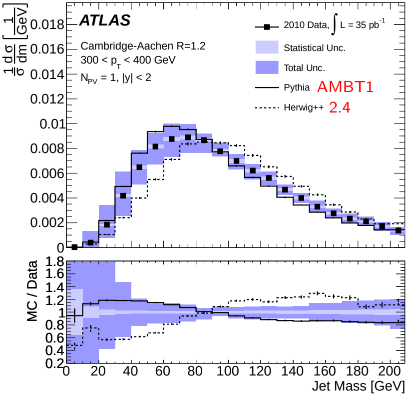


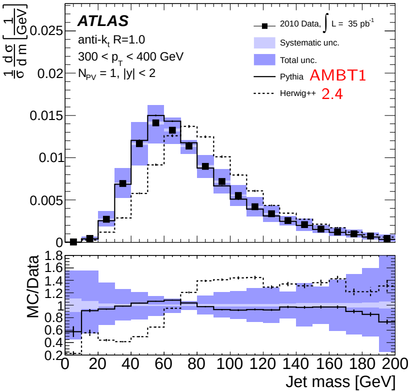
$\Rightarrow$ **Energy flow inside a jet modelled well in PYTHIA.**

Jet mass

- Jet mass - $M^2 = \left(\sum_i E_i\right)^2 - \left(\sum_i \vec{p}_i\right)^2$.
- Compare two jet algorithms (anti-k_t and C/A).

- C/A clusters objects based solely on angular distance
- anti-k_t clusters highest p_T objects first





⇒ PYTHIA jet mass is too soft;

⇒ Herwig++ jet mass is too hard.

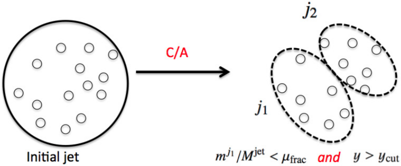
⇒ PYTHIA shows good agreement;

⇒ Herwig++ jet mass is too hard.

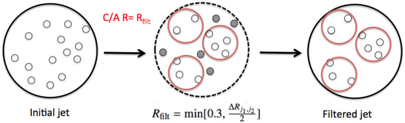
Jet mass

Decrease sensitivity to soft physics with jet grooming algorithms.

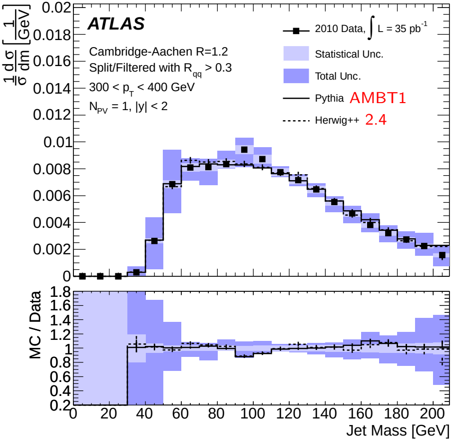
- "Splitting and filtering" procedure:



  - Undo last clustering step, require mass drop and symmetry.
  - Require $\delta R_{j1,j2} > 0.3$.



  - Re-cluster and filter.

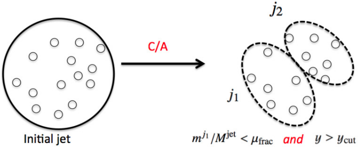


After grooming

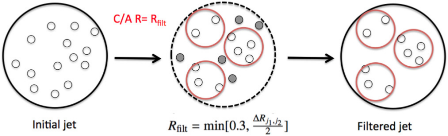
Observe better agreement than plain jet mass

ATLAS-CONF-2012-065

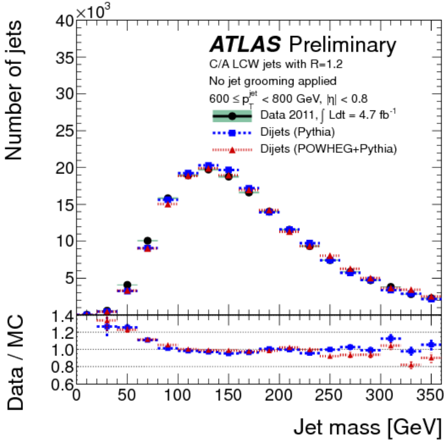
Jet mass - data 2011

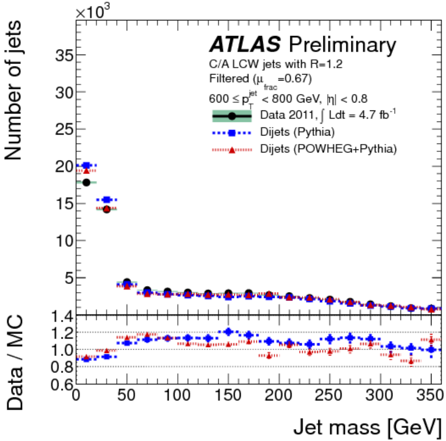


- Undo last clustering step.



- Re-cluster and filter.





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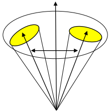
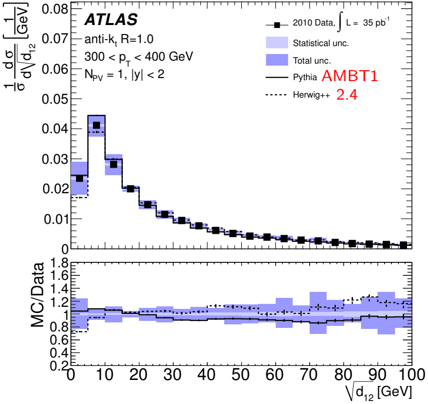
Jet substructure - k_t splitting scales

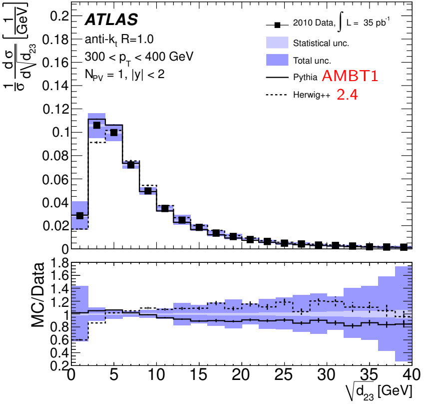


Distinguish heavy particles jets from QCD jets.

- Re-cluster jet constituents with k_t algorithm.
- $\sqrt{d_{12}} = \min(p_{Ti1}, p_{Ti2}) \times \delta R_{i1,i2}$.

- Heavy particle decay, $\Rightarrow \sqrt{d_{12}} \sim \frac{m}{2}$.
- Inclusive jets, $\Rightarrow \sqrt{d_{12}} \sim \frac{p_T}{10}$.





$\Rightarrow$ **Better agreement than plain jet mass.**

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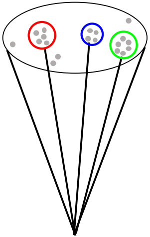
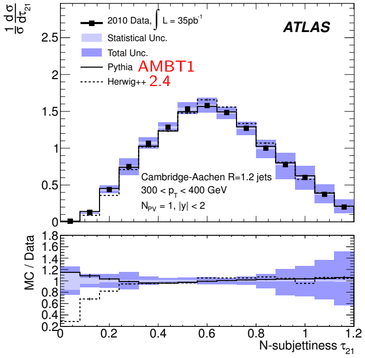
Jet substructure - N-subjettiness

"How much does this jet look like N different subjets?"

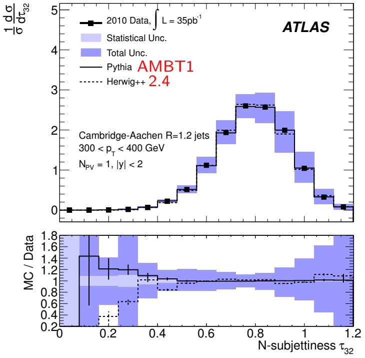
- Re-cluster jet with k_t, requiring N subjets.
- $\tau_3 = \frac{1}{d_0} \sum_k p_{T,k} \times \min(\delta R_{1,k}, \delta R_{2,k}, \delta R_{3,k})$.
- $d_0 = \sum_k p_{T,k} \times R$, $\tau_{32} = \frac{\tau_3}{\tau_2}$.



More like 2 subjets than one big jet



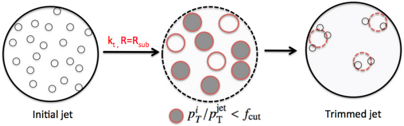
More like 3 subjets than 2 subjets

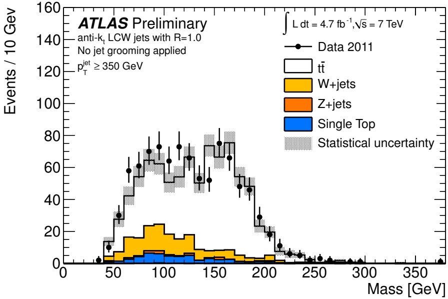


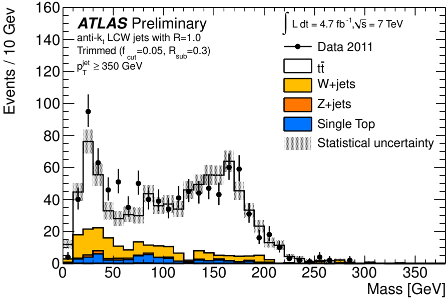
Jet grooming performance

Trimming in $t\bar{t}$ events:

- select $t\bar{t} \to (Wb)(Wb) \to (\mu\nu b)(q\bar{q}b)$;
- Find hadronic top candidate with anti-k_t $R = 1.0$ jet.







After grooming

- Enhanced mass resolution.
- Better separation between signal and background.

Jet grooming performance

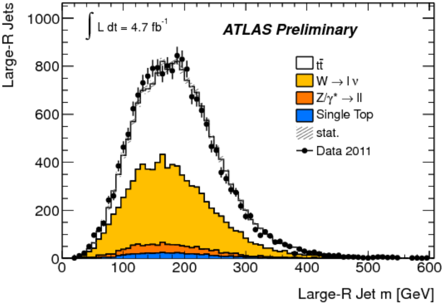
HEPTopTagger, (Tilman *et al.*), tool based on jet grooming techniques to select boosted object.

- Select $t\bar{t} \rightarrow (Wb)(Wb) \rightarrow (\mu\nu b)(q\bar{q}b)$.
- HEPTopTagger applied on C/A, $R = 1.5$, jets.

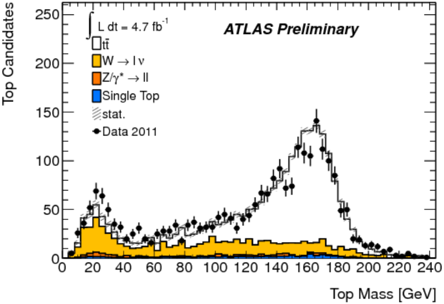
HEPTopTagger algorithm

- Use a variant on "Splitting and filtering".
- Subjets required to be in top and W mass window.

Before



After



After HEPTopTagger

$\Rightarrow$ Relatively pure $t\bar{t}$ selection for $m_{\text{top}} > 120$ GeV.

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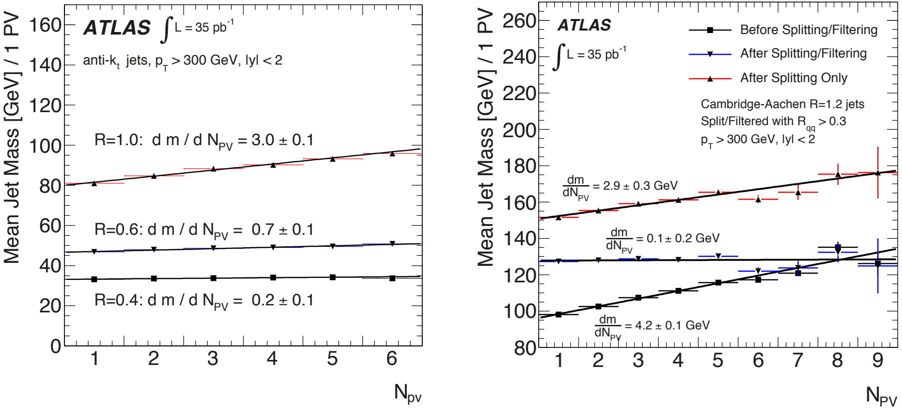
Pile-up and jet mass - data 2010

$\langle N_{PV} \rangle \approx 2.2$

Jet mass especially sensitive to multiple *pp* interactions (pile-up).

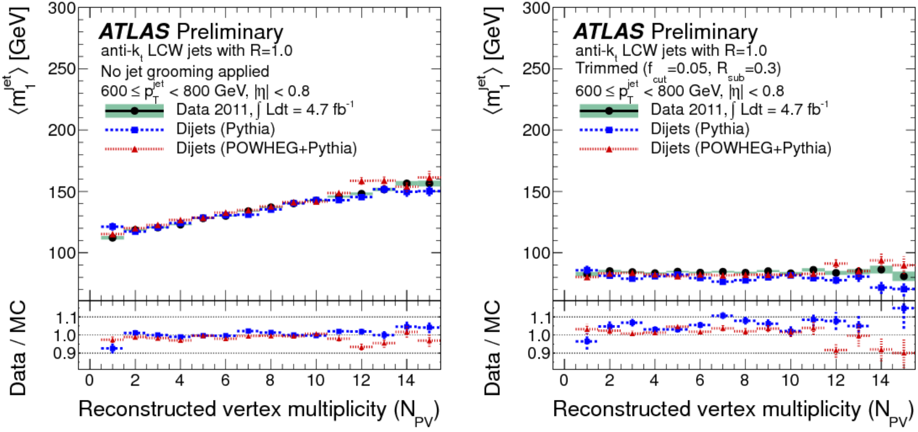


- Mean invariant mass grows as $\sim R^3$.
- "Splitting and filtering" reduce dependence on N_{PV} significantly.

Pile-up and jet mass - data 2011

$<N_{PV}> \approx$ **6**

Invariant mass of large jets especially sensitive to pile-up.

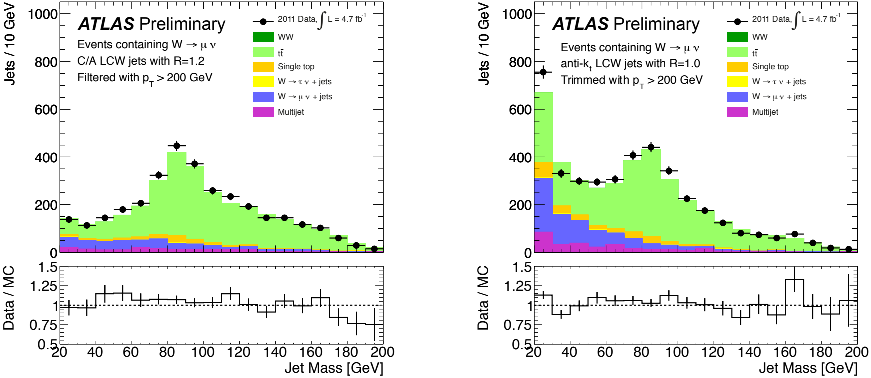


- "Trimming" reduces dependence on N_{PV} significantly.
- Good agreement between data and MC.

Jet mass calibration validation

Jet grooming ⇒ data driven jet mass calibration!

- Select $t\bar{t} \to (Wb)(Wb) \to (\mu\nu b)(q\bar{q}b)$ events.
- Find hadronic W-boson candidates with C/A and anti-k_t.
- Groom jets to reduce background.



⇒ **Signal and background well separated.**

⇒ **Distributions can be used to validate jet mass calibration.**

Summary

Jet substructure and grooming is a growing field.

Conclusions

- Jet grooming reduces sensitivity to soft physics.
- Jet grooming mitigates effects of pile-up.
- Successful in selecting massive boosted particles!

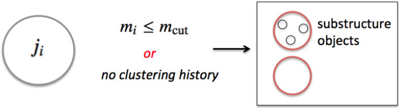
Recent ATLAS paper - JHEP **1301** (2013) 116

Search for resonances decaying into top-quark pairs using fully hadronic decays in *pp* collisions with ATLAS at $\sqrt{s} = 7$ TeV

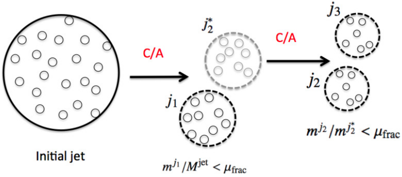
Backup Slides

HEPTopTagger

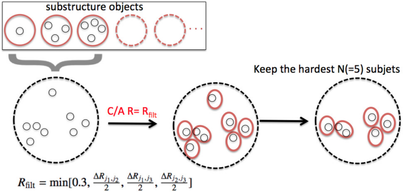
The **HEPTopTagger** procedure,



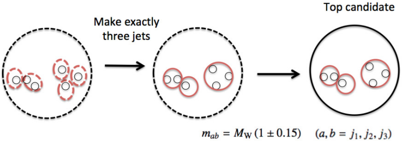
- De-cluster the jet.



- Apply mass-drop iteratively - n_i substructure objects left.



- Filter in triplets and re-cluster into N_i subjets. Require $140 < m_{N_i}^{jet} < 200$ GeV.



- Require W mass window.