Jets@ATLAS

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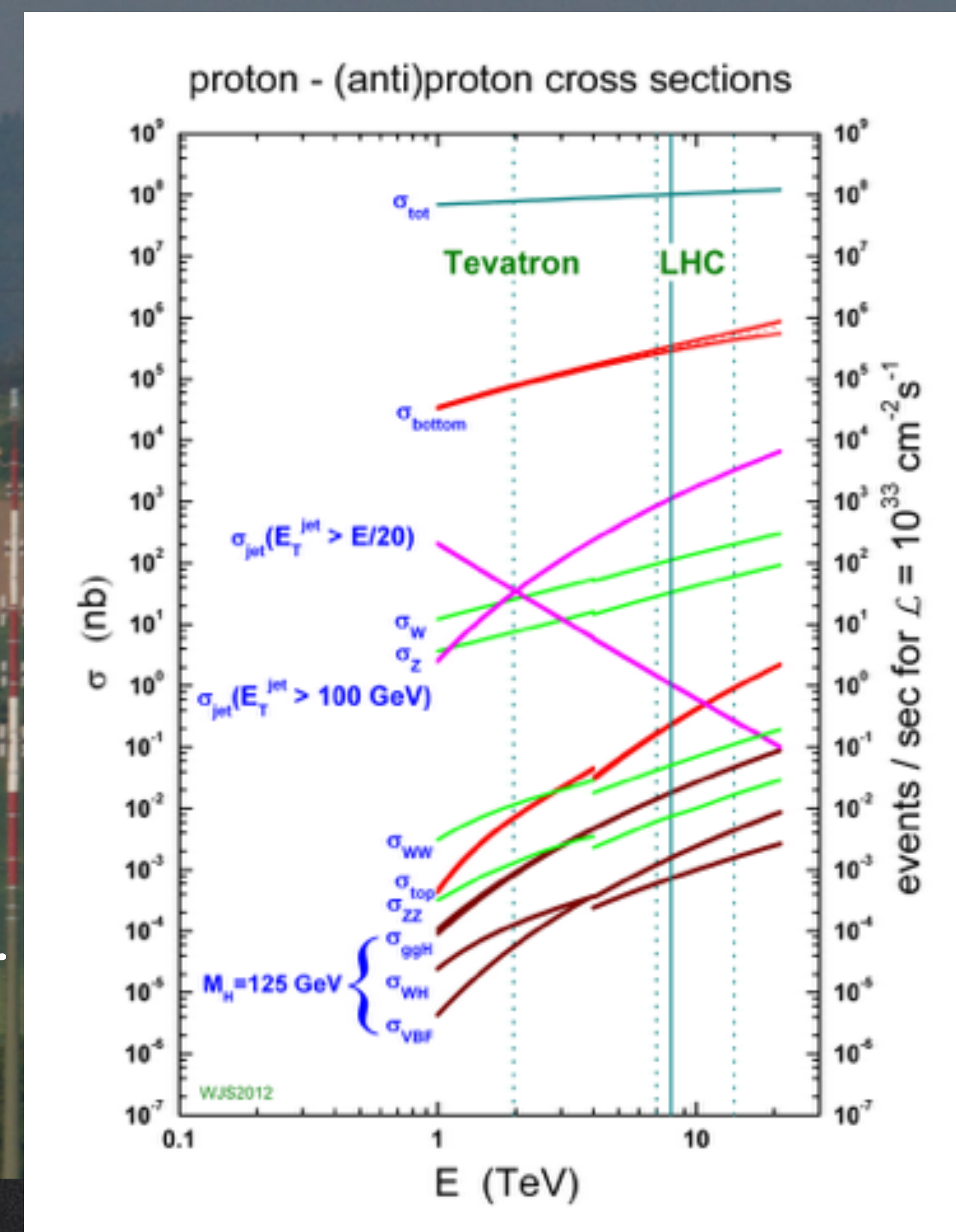
National Research Foundation NRF
UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG
ATLAS EXPERIMENT

LHC is a jet factory!

As a signal, test of QCD predictions

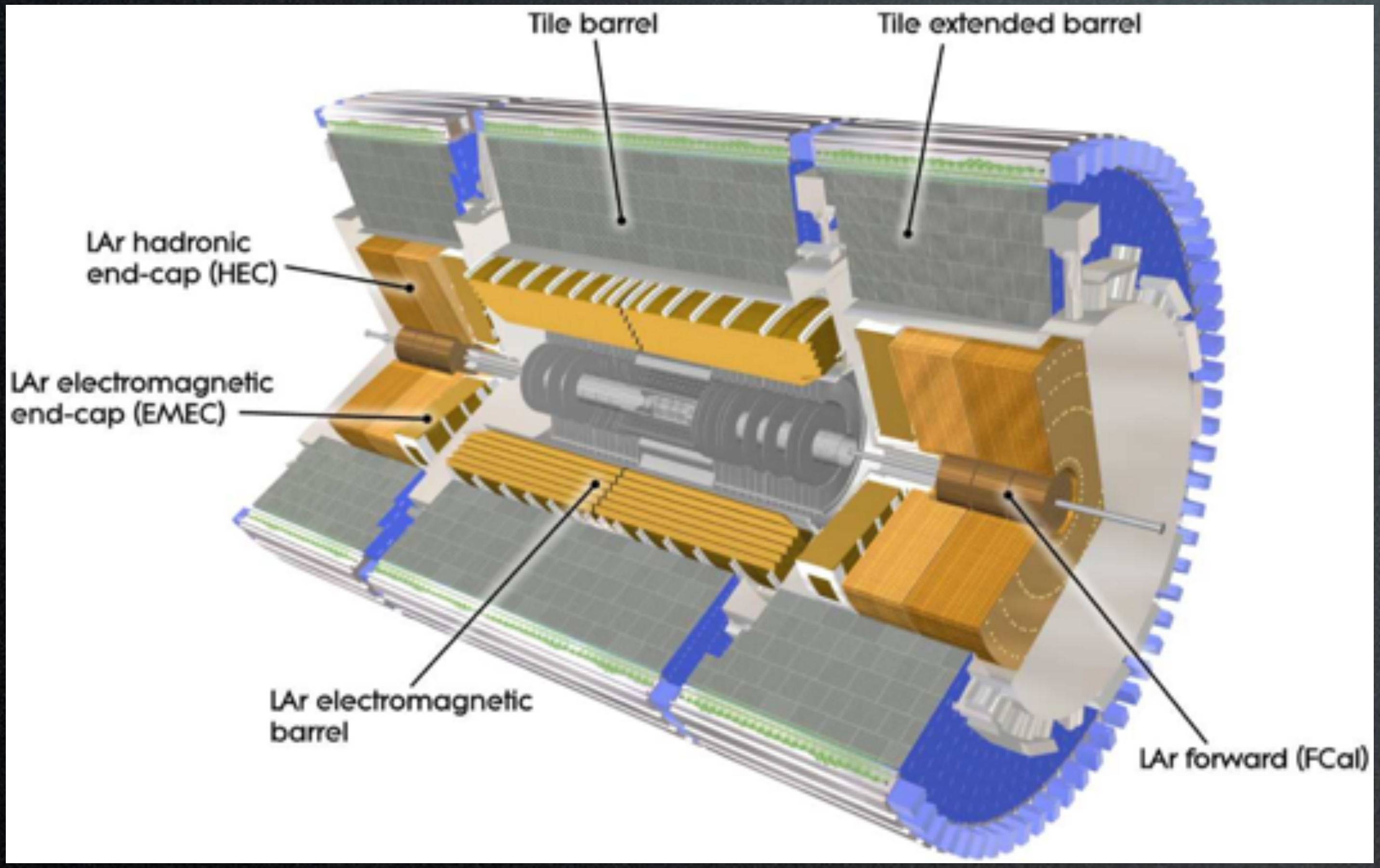
Background for most analyses

Large-radius jets offer a powerful way to identify boosted hadronically decaying particles



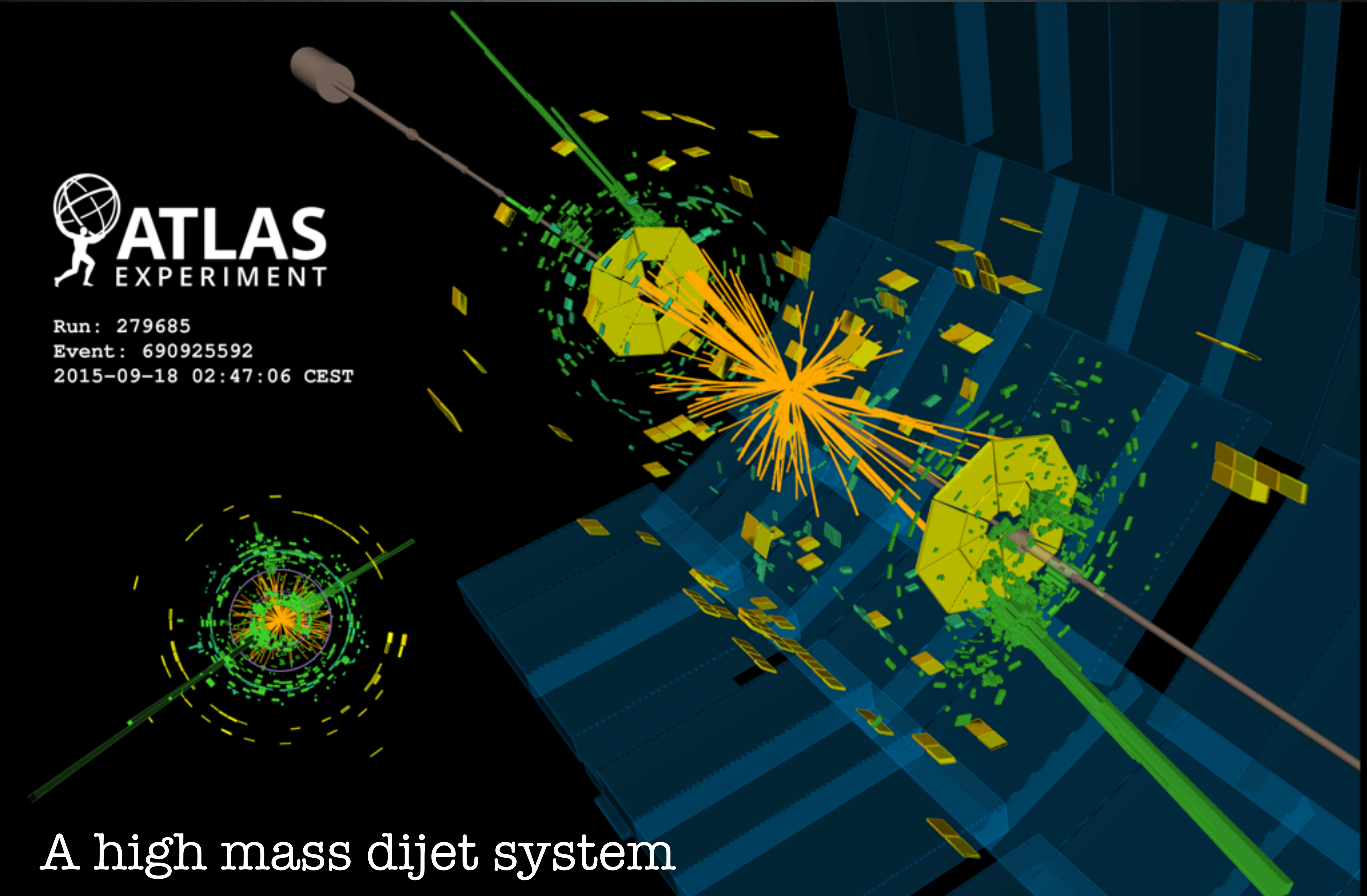
Part 1: Jet making and Performance

ATLAS Calorimeters



- High precision calorimetry
  - Highly granular electromagnetic calorimeter up to $|\eta| < 3.2$
  - Hadronic tile calorimeter barrel and endcaps up to $|\eta| < 3.2$
  - Forward calorimeters for $3.2 < |\eta| < 4.9$, granularity of $\Delta\eta \times \Delta\varphi \approx 0.2 \times 0.2$

Better jet energy resolution than CMS (worse momentum resolution in tracking)



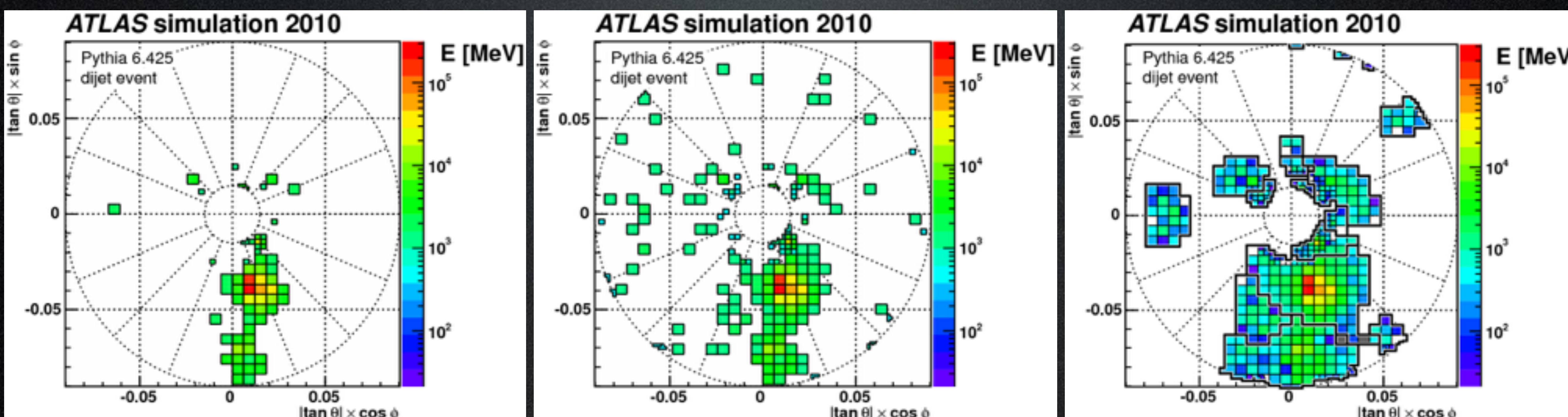
A high mass dijet system

Inputs

- 3 dimensional clusters of calorimeter cells, or topoclusters (treated massless)
- Attempt to reconstruct hadronic showers while suppressing noise (electronic+pileup)

Seeded by:

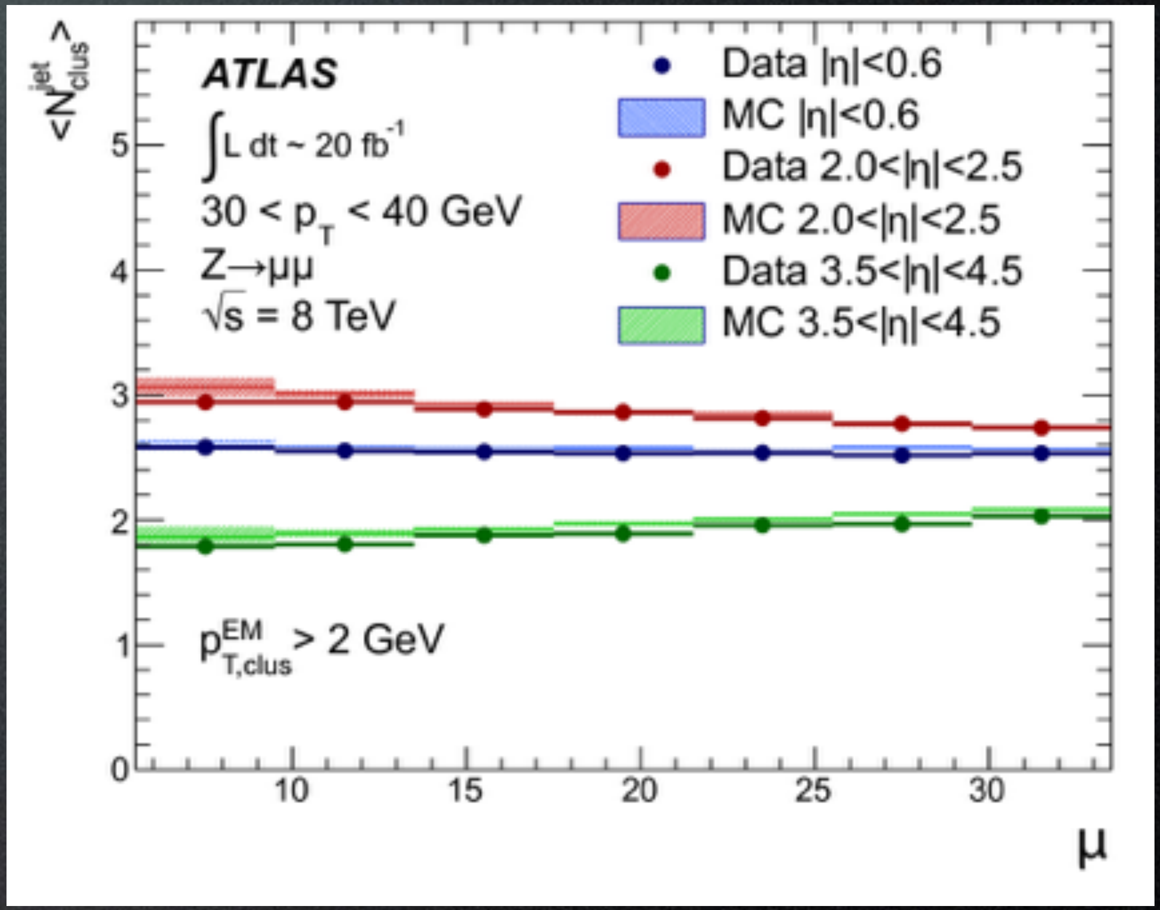
Built from all surrounding+ single layer of all adjacent cell (in 3D)



$E > 4\sigma_{noise}$ $E > 2\sigma_{noise}$ All

Topoclusters

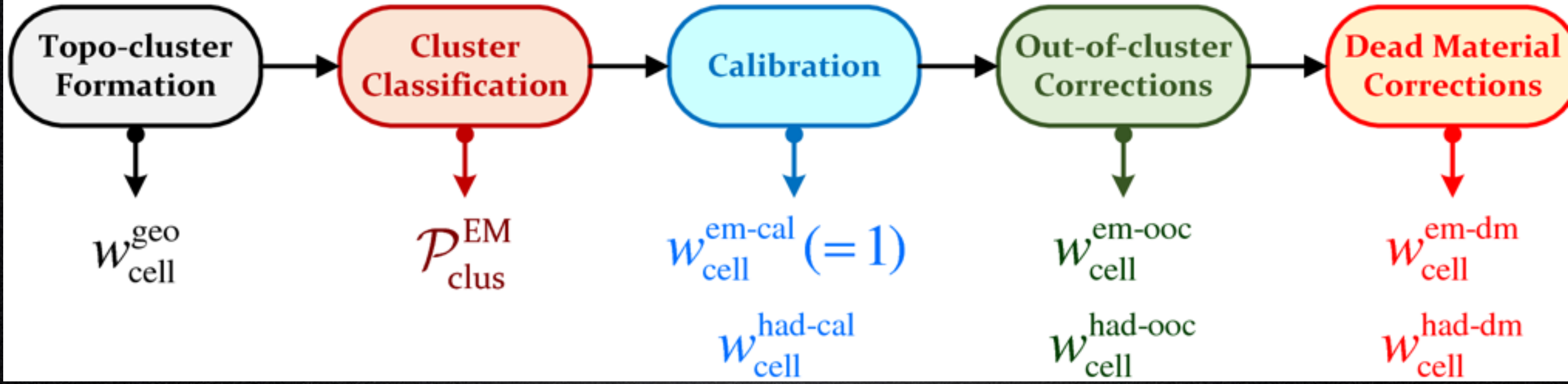
- Robust against pileup
- Topoclusters initially reconstructed at EM scale.



Local Hadronic Cell Weighting

Then calibrate them to account for hadron response.

From charged hadron and neutral pion MC.



Tracks

- Inner detector tracks can be ghost associated to jets, for pileup suppression and improving jet energy resolution (for ghost matching, tracks are treated as 4-vectors with infinitesimal magnitudes)
- Particle flow

Jets Need Calibration

1. **Calorimeter non-compensation:** correction for the different scales of the energy measured from hadronic and electromagnetic showers.

2. **Dead material:** energy lost in inactive areas of the detector.

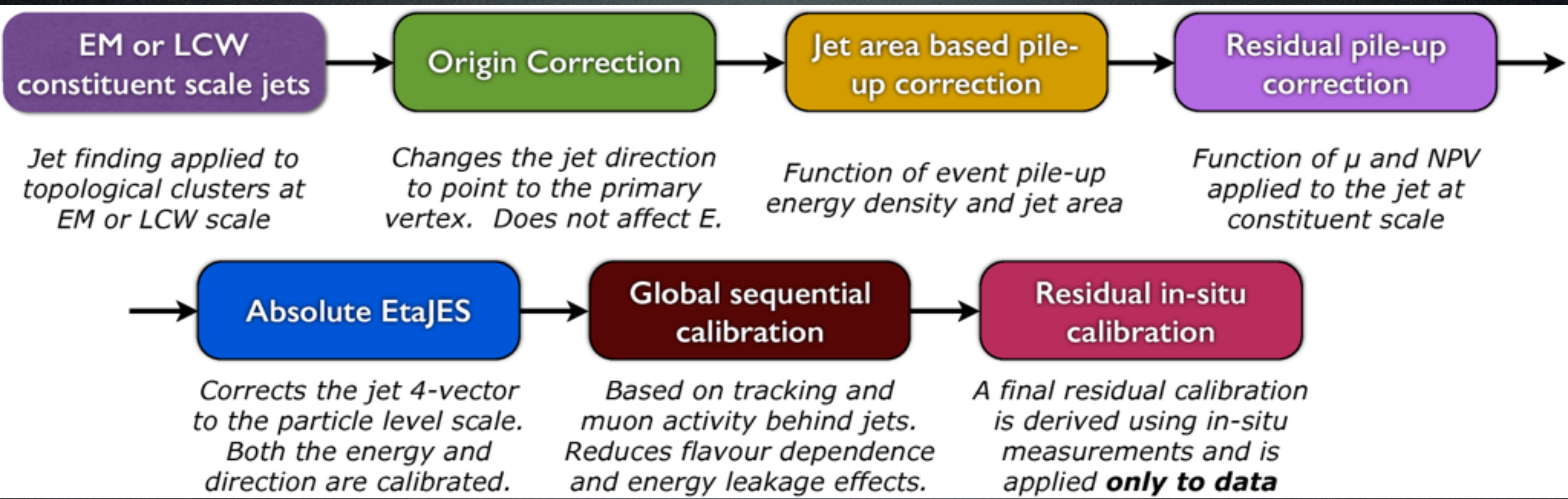
3. **Leakage:** showers reaching the outer edge of the calorimeters.

4. **Out of calorimeter jet:** energy of particles which are included in the truth jet but which are not included in the reconstructed jet.

5. **Energy deposits below noise thresholds:** clusters are only formed by energy deposits which are well above the background noise. Therefore the correction is required to correct for particles that do not form clusters. Additionally some part of a shower may fall outside of the topological clusters such that this also needs to be corrected for.

6. **Pile-up:** energy deposition in jets is affected by the presence of multiple *pp* collisions in the same bunch crossing as well as residual signals from other bunch crossings.

Jet Calibration



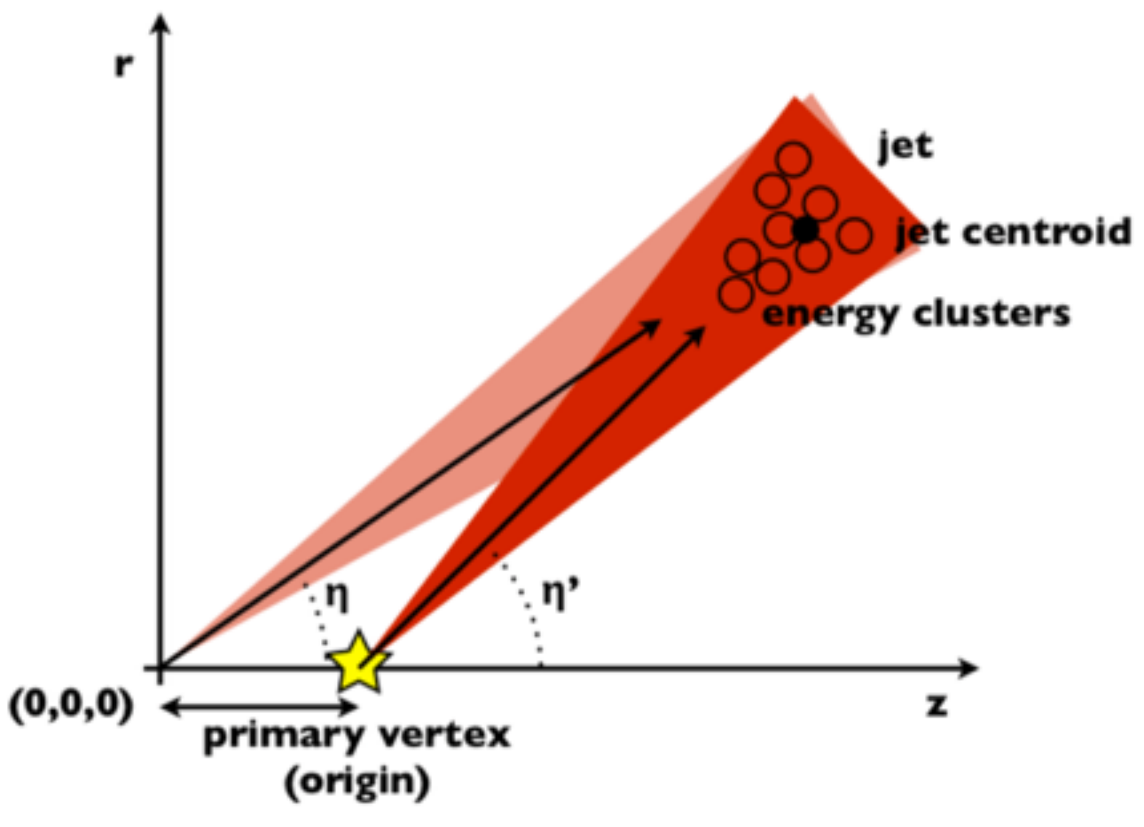
Reference is (stable) particle jets, without muon or neutrino

Definitions

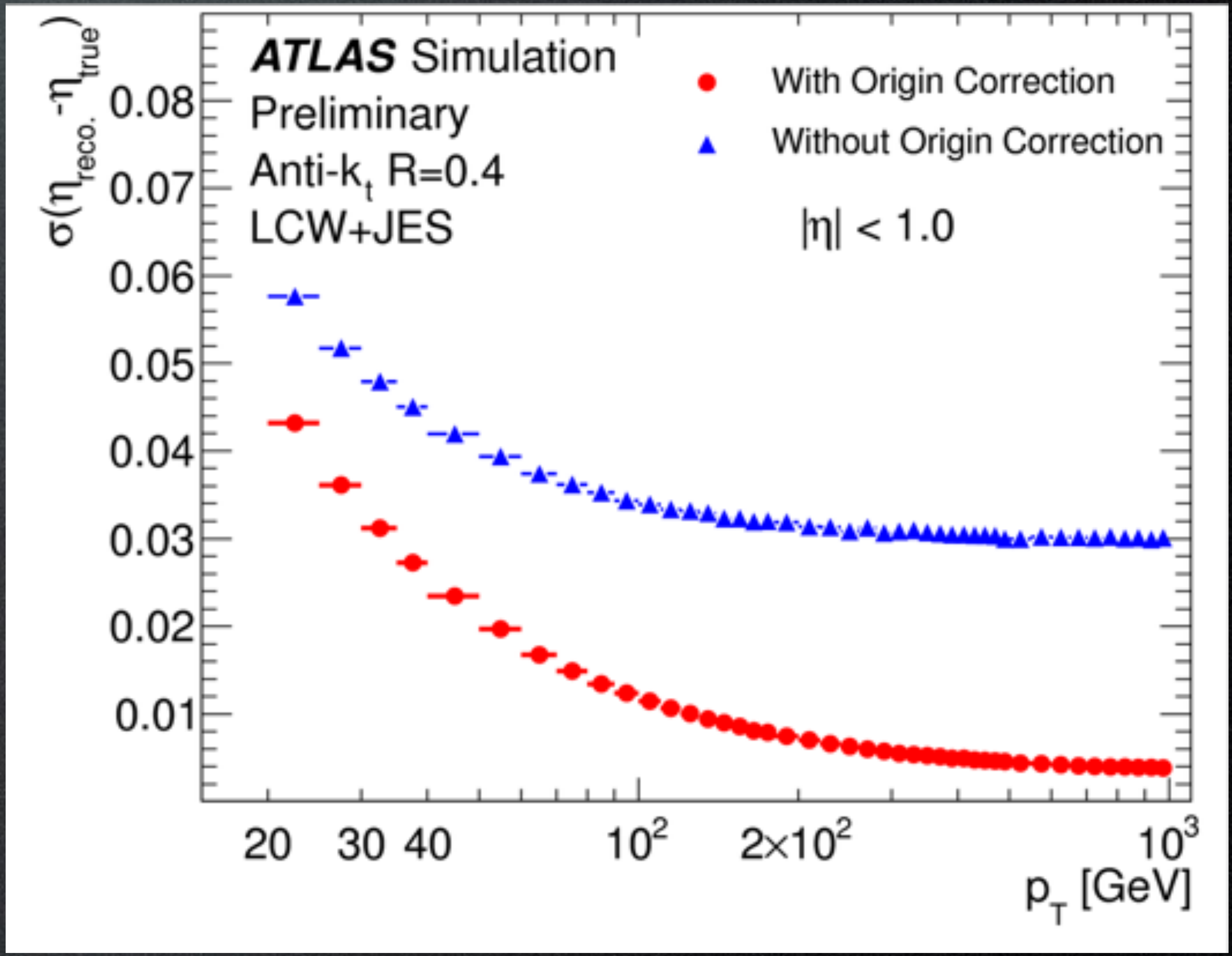
- Calculate $p_T^{jet}/p_T^{matched\text{-}truth\text{-}jet}$
- Fit a Gaussian
- Mean of the Gaussian: R or jet response.
- Standard deviation of the Gaussian: σ/R or jet resolution.

Origin Correction

(to point back to hard-scatter PV)



Accounts for the hard scattering primary vertex.



Changes the jet direction and improves η resolution

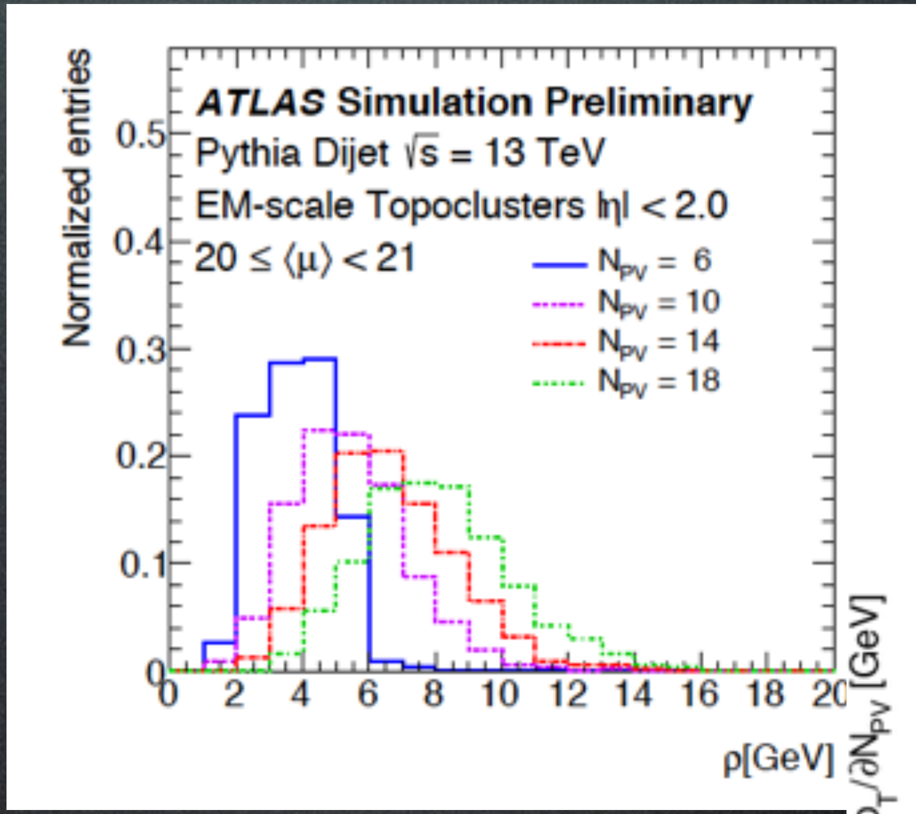
No change in energy

(Jet-area based) Pileup Correction

A uniform population of infinitesimally soft ghost particles are spread ...

Pileup p_T density:

$$\rho = \text{median}\left\{\frac{p_{T,i}^{\text{jet}}}{A_i^{\text{jet}}}\right\}$$



Takes into account event-by-event fluctuations

First step:

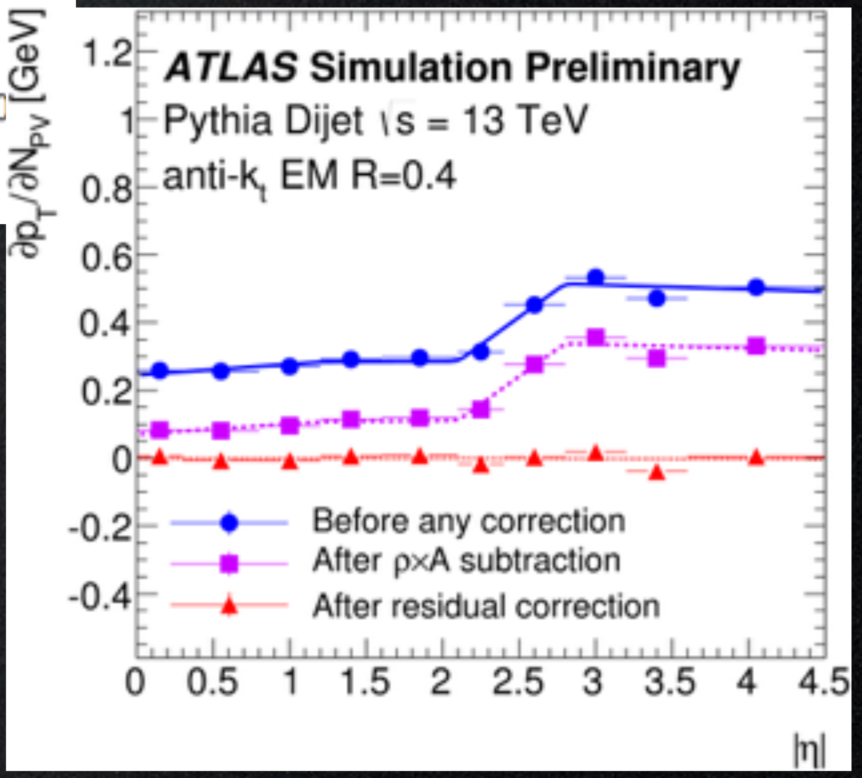
$$p_T^{\text{jet,corr}} = p_T^{\text{jet}} - \rho \cdot A$$

Residual correction:

$$\alpha \times (N_{PV} - 1) - \beta \times \langle\mu\rangle$$

In time pu Out of time pu

Simulation based



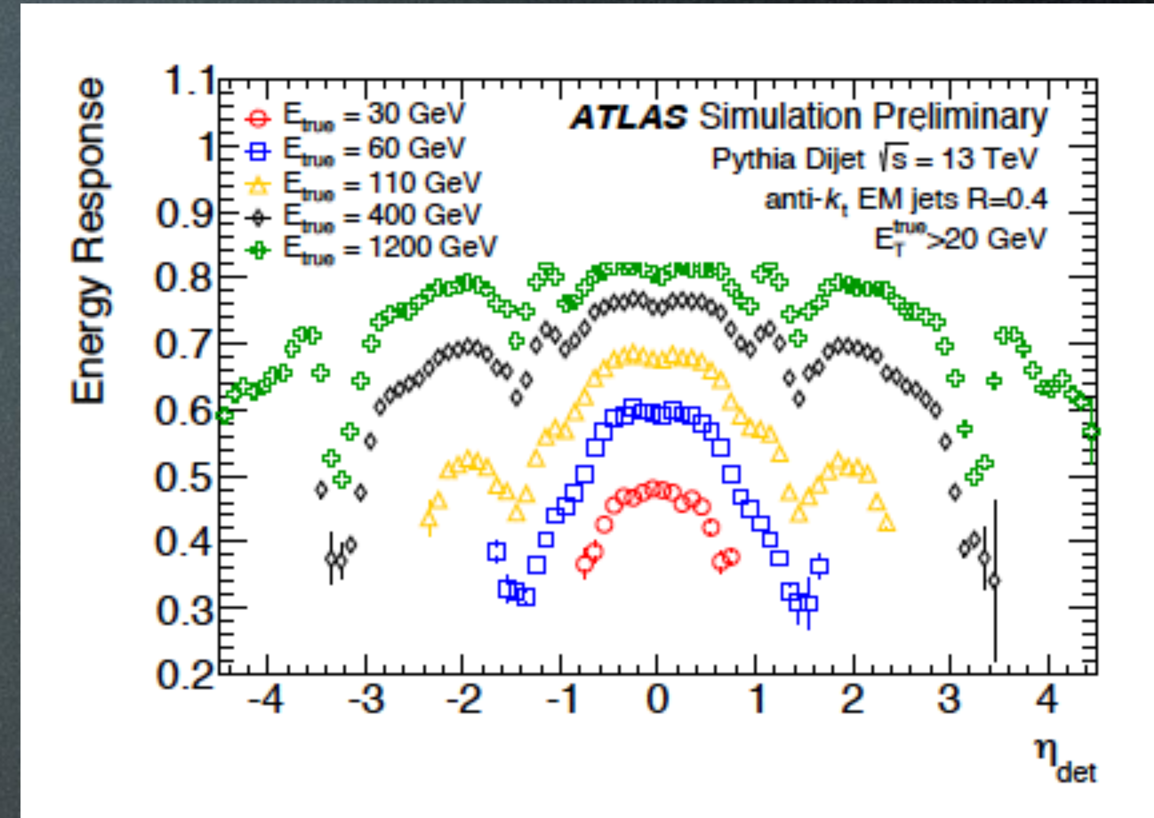
(MC-based) Jet Energy Scale

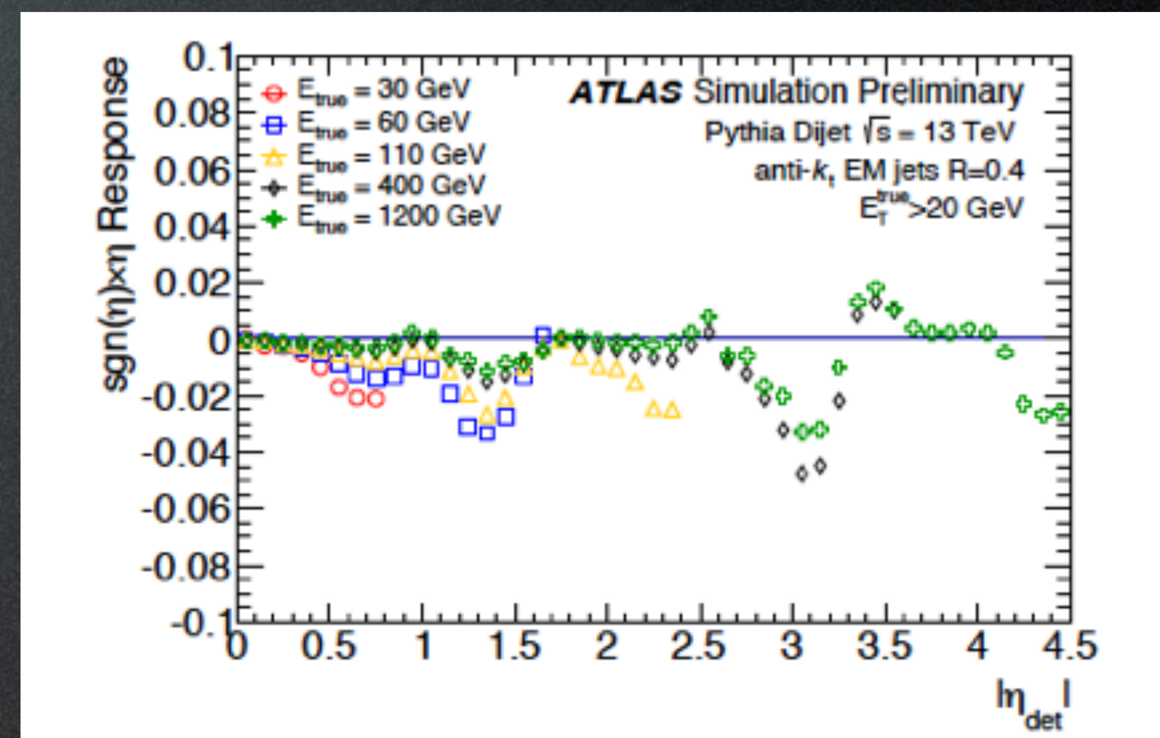
Jet response: p_T and η dependant

$$\mathcal{R} = \langle p_{\mathrm{T}}^{\mathrm{jet}} / p_{\mathrm{T}}^{\mathrm{truth}} \rangle.$$

In particular regions of the detector there is a bias in the η distribution (different calorimeter type) with respect to the truth jets.

Therefore, an additional correction in purely the angle of the jet is applied to resolve this bias.





Using dijet MC

Global Sequential Calibration

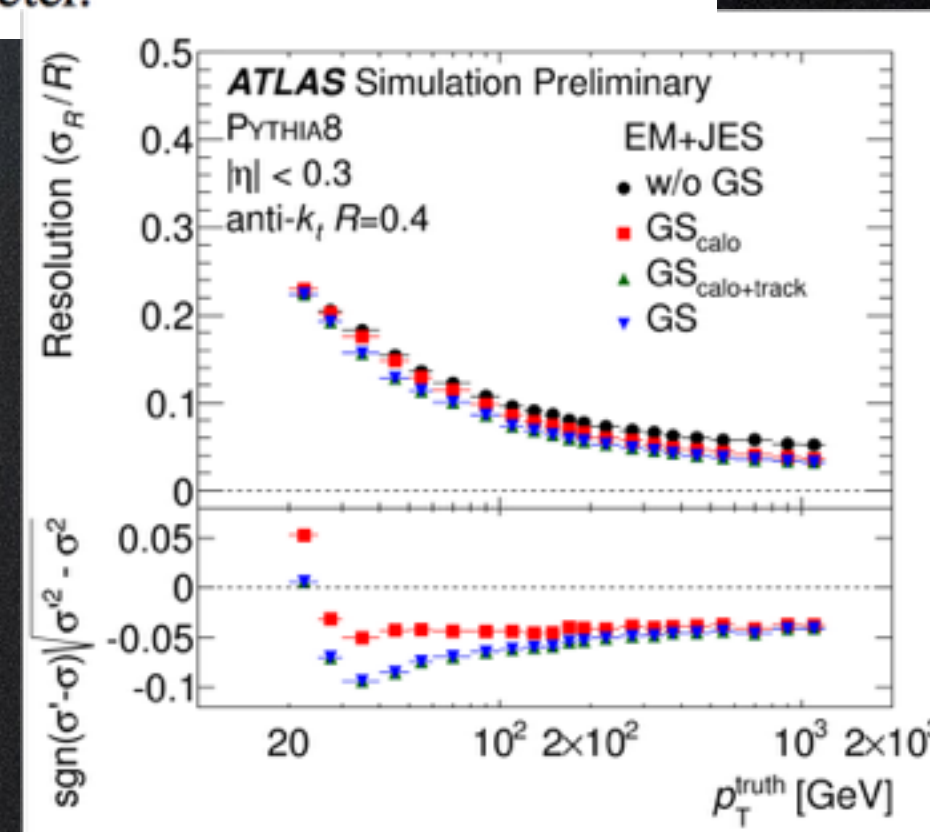
Observed difference between q/g initiated jets (closure, response), leads to large uncertainty on JES.

1. The fraction of energy deposited in the first layer of the tile calorimeter.
2. The fraction of energy deposited in the third layer of the electromagnetic calorimeter.
3. The number of tracks with $p_T > 1$ GeV associated to the jet.
4. The p_T-weighted transverse width of the jet measured using tracks with $p_T > 1$ GeV associated to the jet.
5. The amount of activity behind the jet as measured in the muon spectrometer.

for LCW last two steps only

Finally, correct for jets that are not fully contained in the calorimeter.

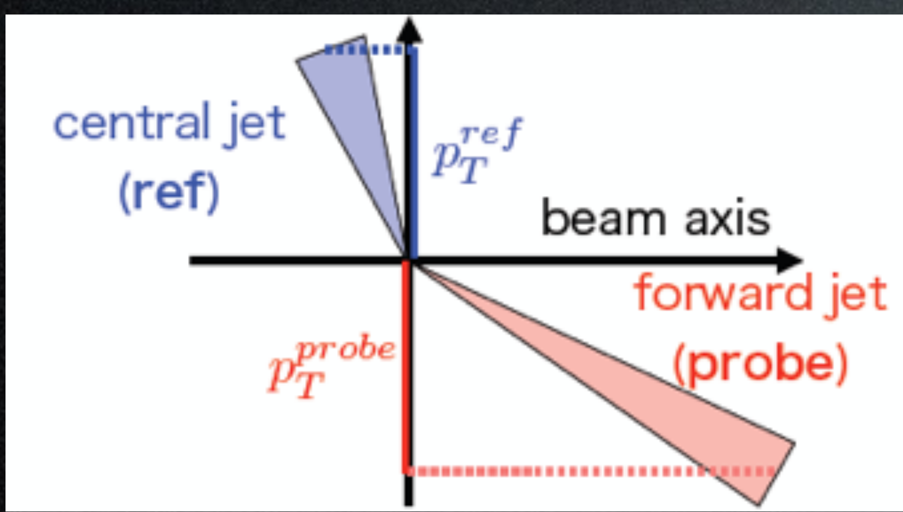
Mean response not affected



Residual In situ Corrections

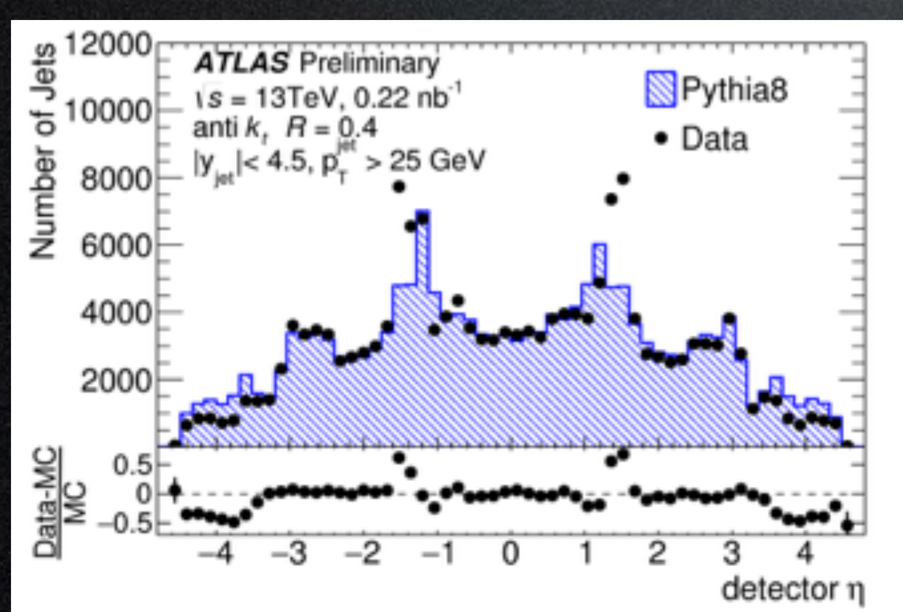
To account for difference in data and simulation
(applied to data only)

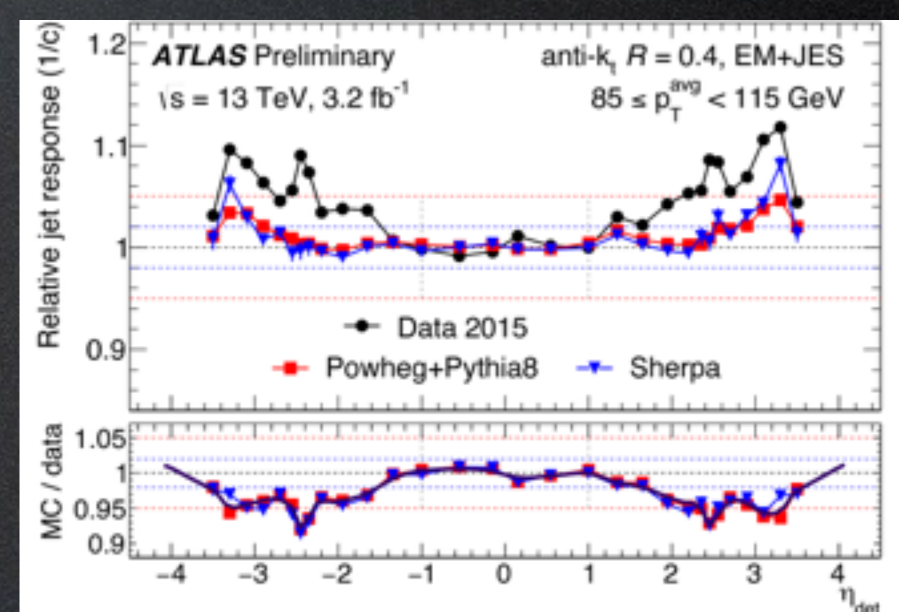
1. Relative (inter)-calibration in eta, derived from dijet events
2. Absolute scale correction from y/Z+jet and multijet events



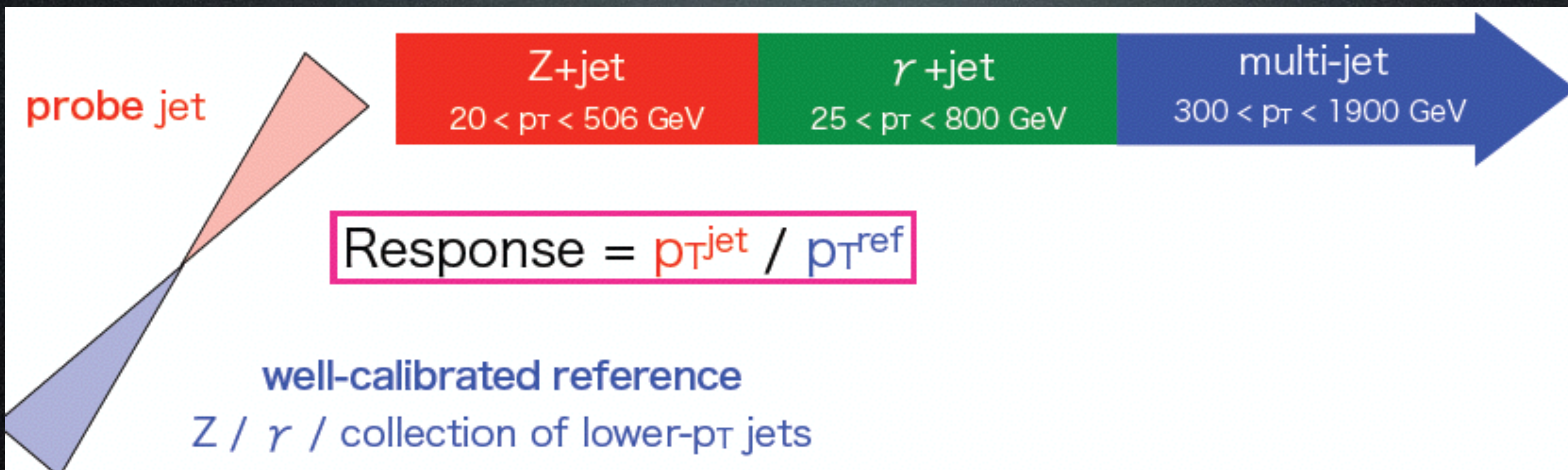
$$\frac{1}{c} = \frac{p_T^{probe}}{p_T^{ref}} = \frac{2 + \langle \mathcal{A} \rangle}{2 - \langle \mathcal{A} \rangle}$$

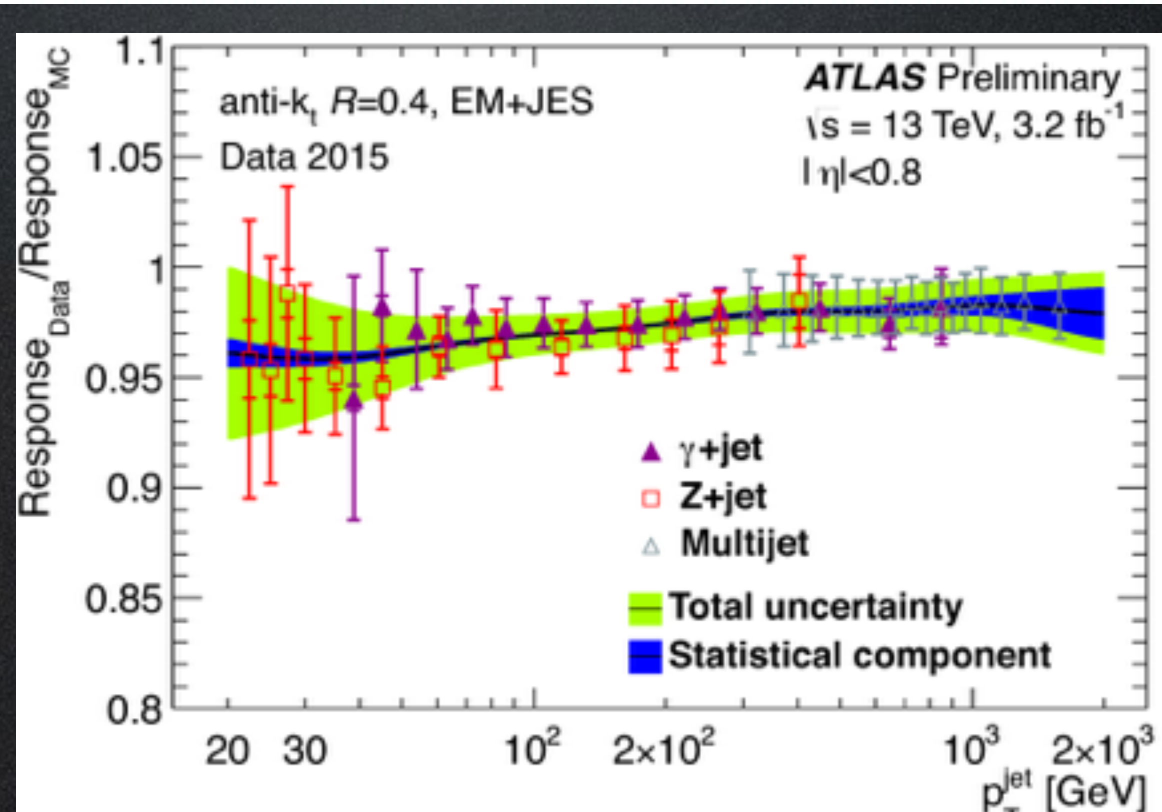
$$\mathcal{A} = \frac{p_T^{probe} - p_T^{ref}}{p_T^{avg}} \quad , \quad p_T^{avg} = \frac{p_T^{probe} + p_T^{ref}}{2}$$



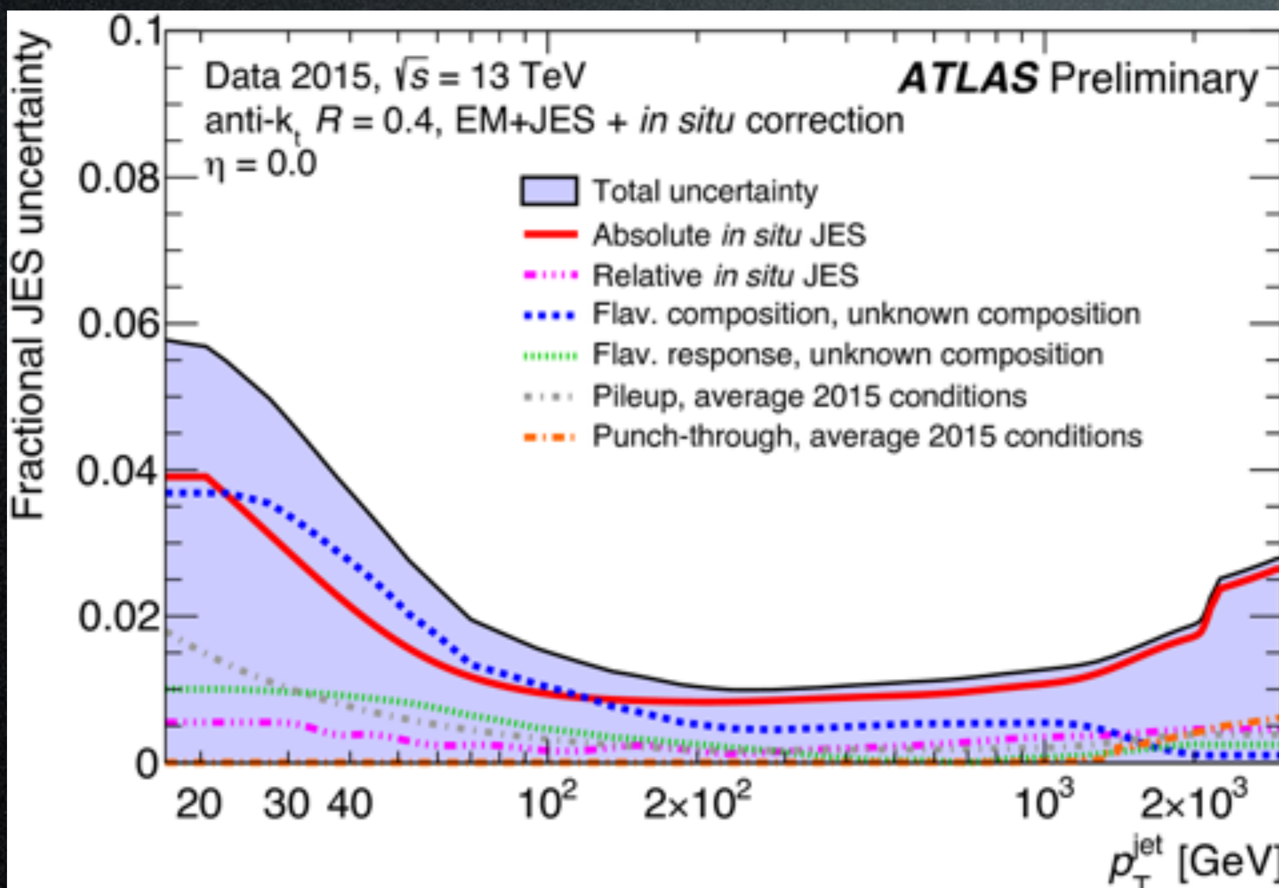


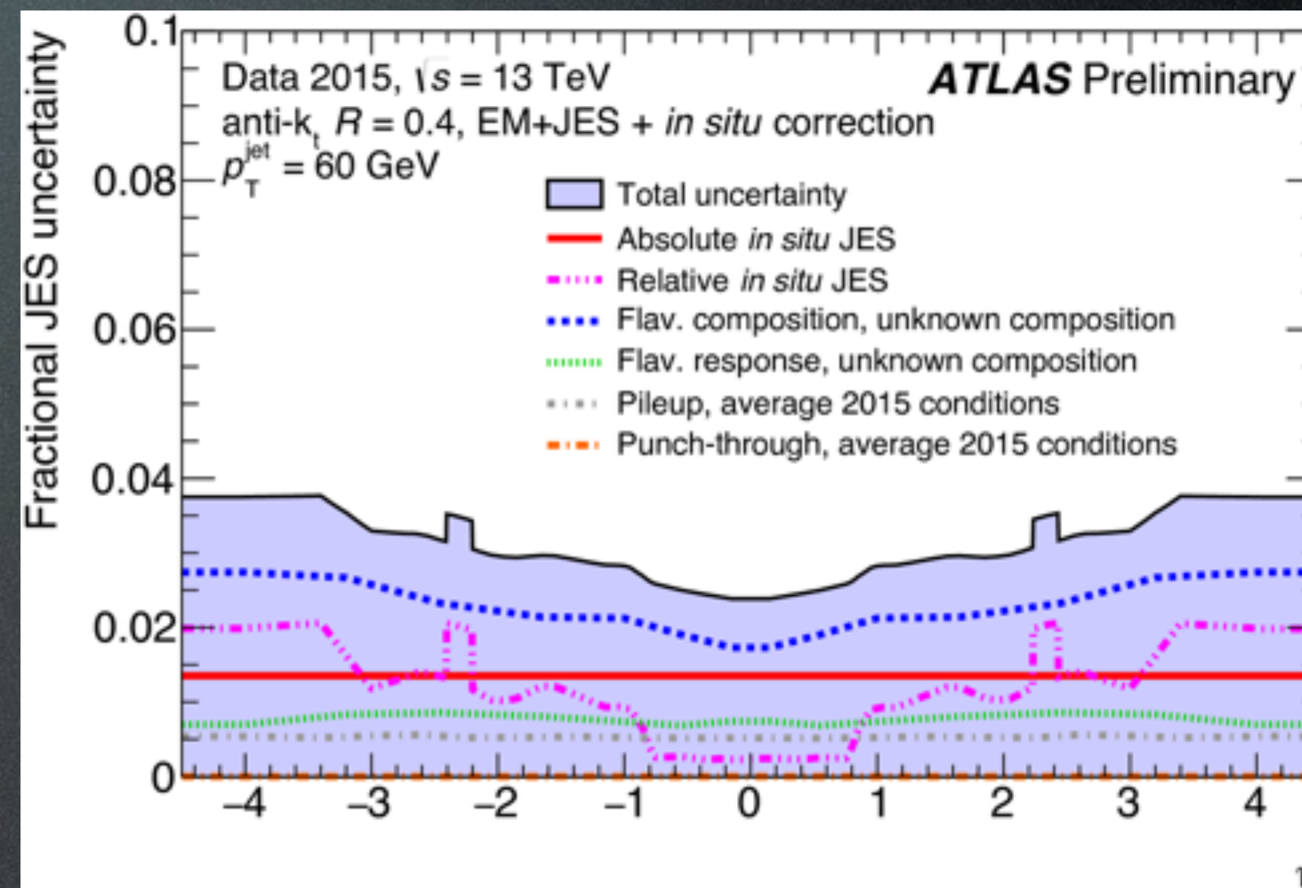
Jet Energy Calibration





JES uncertainty





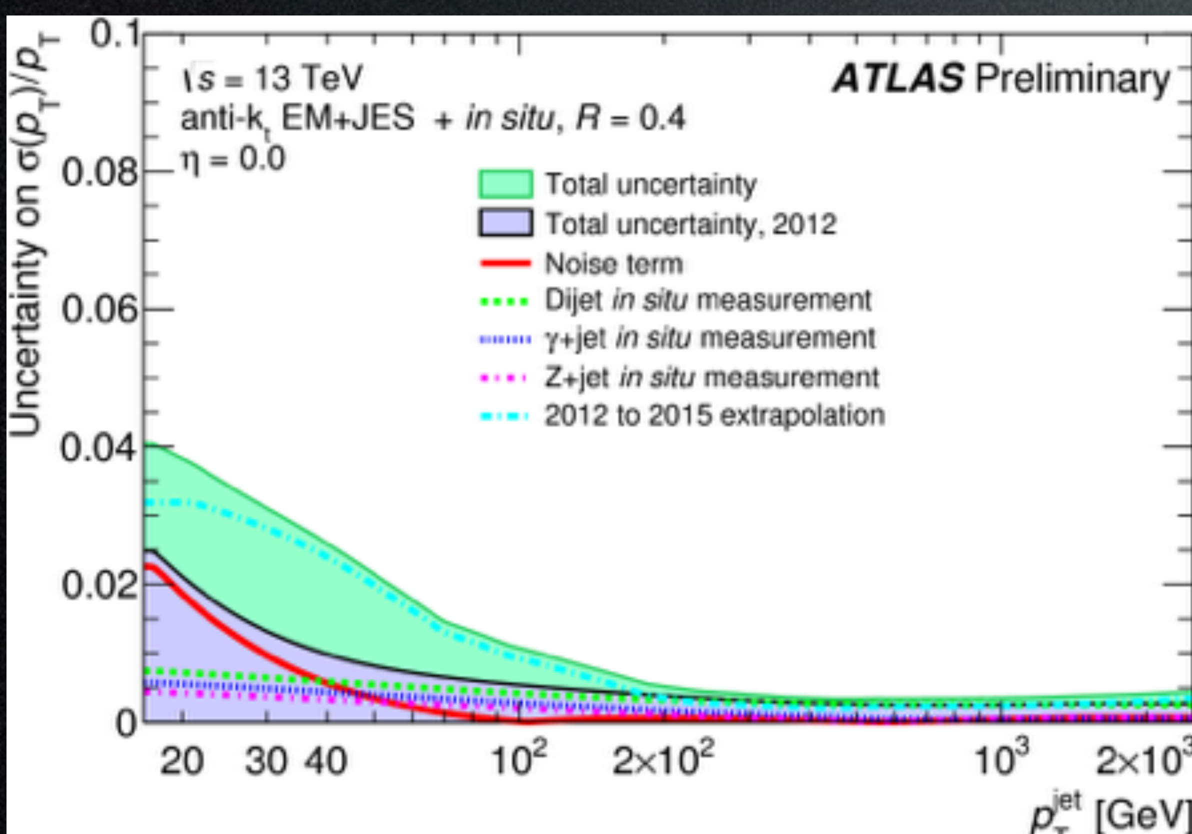
70 correlated components

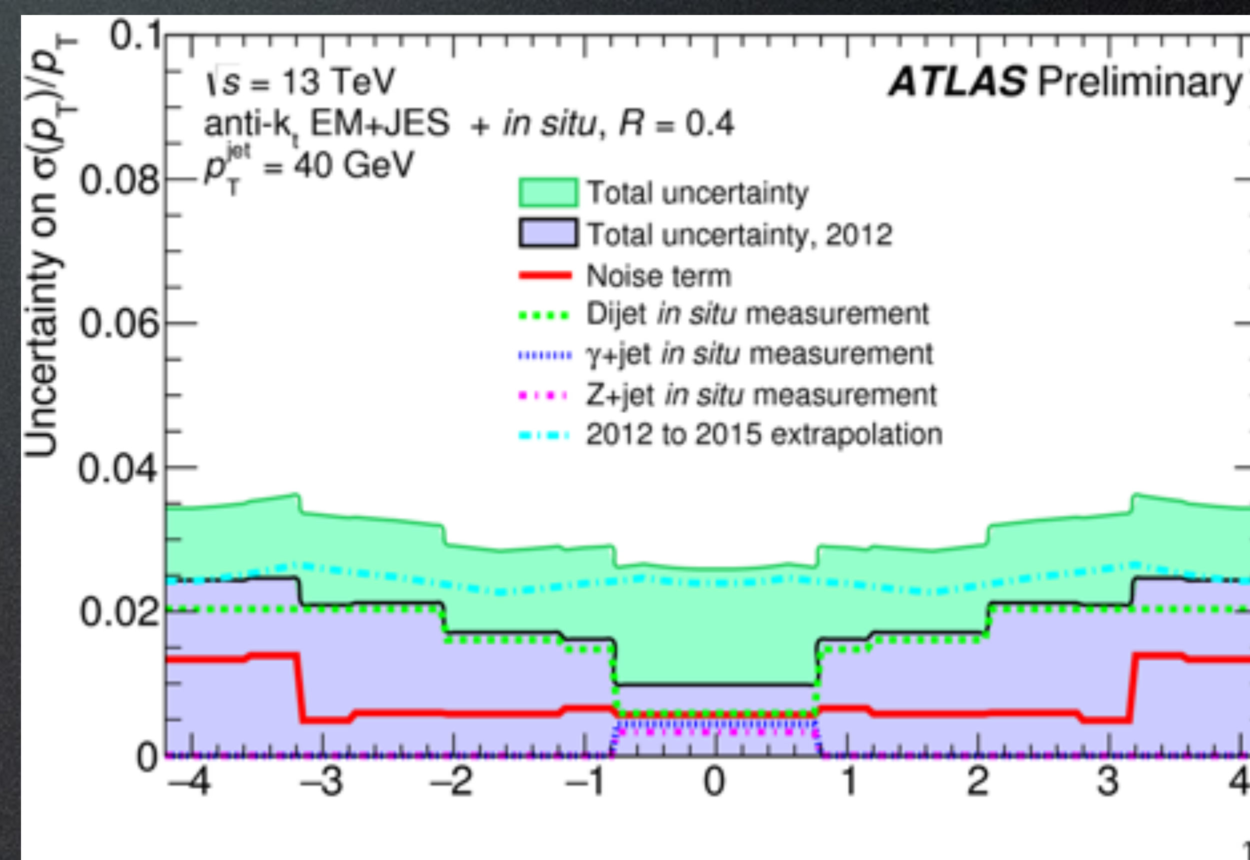
Reduced to smaller number in analyses

Jet Energy Resolution

$$\sigma(\mathcal{A}) = \frac{\sqrt{\sigma(p_T^{ref})^2 + \sigma(p_T^{probe})^2}}{p_T^{avg}}$$

All uncertainties are combined into one nuisance parameter in a correlated way





Large-R Jet

- No explicit pileup removal or origin correction.
- After MC based JES, data-MC double ratio for residual correction:

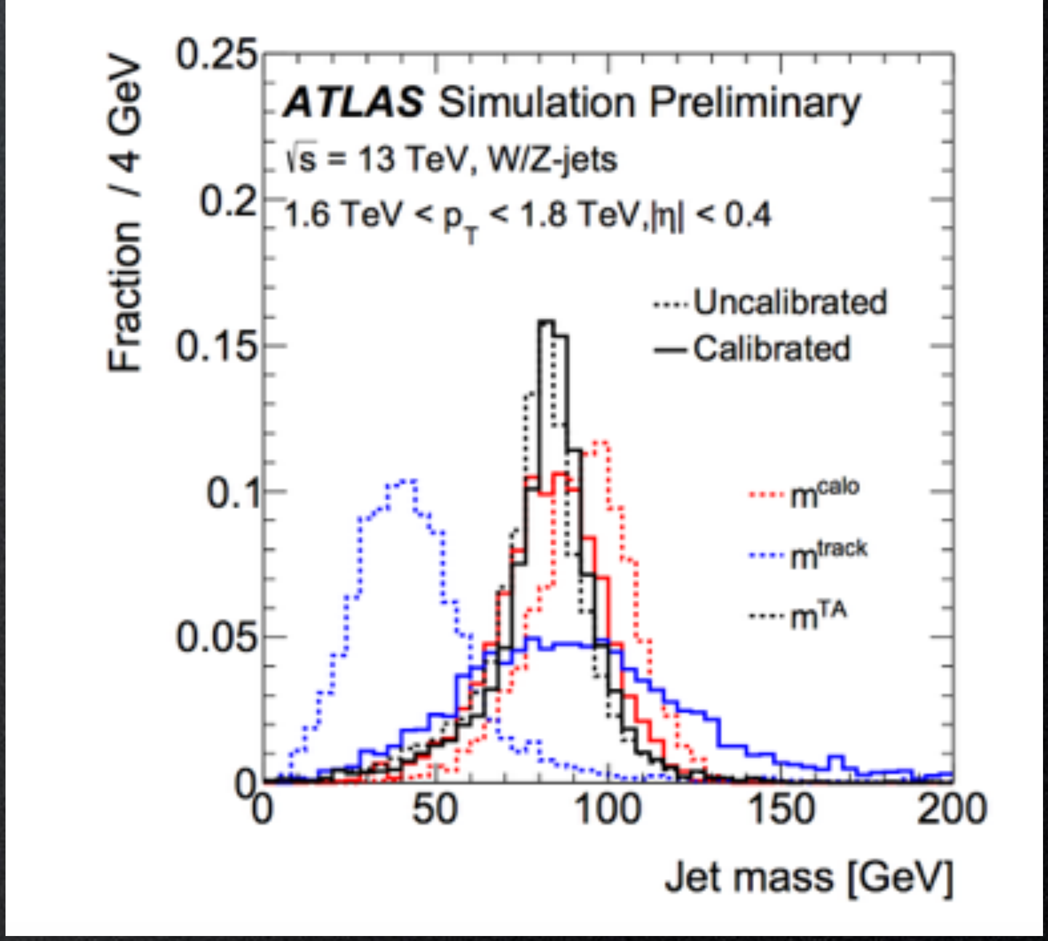
$$\frac{\mathcal{R}_{\mathrm{data}}}{\mathcal{R}_{\mathrm{MC}}} = \frac{\langle p_{\mathrm{T}}^{\mathrm{jet}} / p_{\mathrm{T}}^{\mathrm{ref}} \rangle_{\mathrm{data}}}{\langle p_{\mathrm{T}}^{\mathrm{jet}} / p_{\mathrm{T}}^{\mathrm{ref}} \rangle_{\mathrm{MC}}}$$

- More important: mass calibration.

(Large-R) Jet Mass

$$m^{\mathrm{TA}} = \frac{p_{\mathrm{T}}^{\mathrm{calo}}}{p_{\mathrm{T}}^{\mathrm{track}}} \times m^{\mathrm{track}},$$

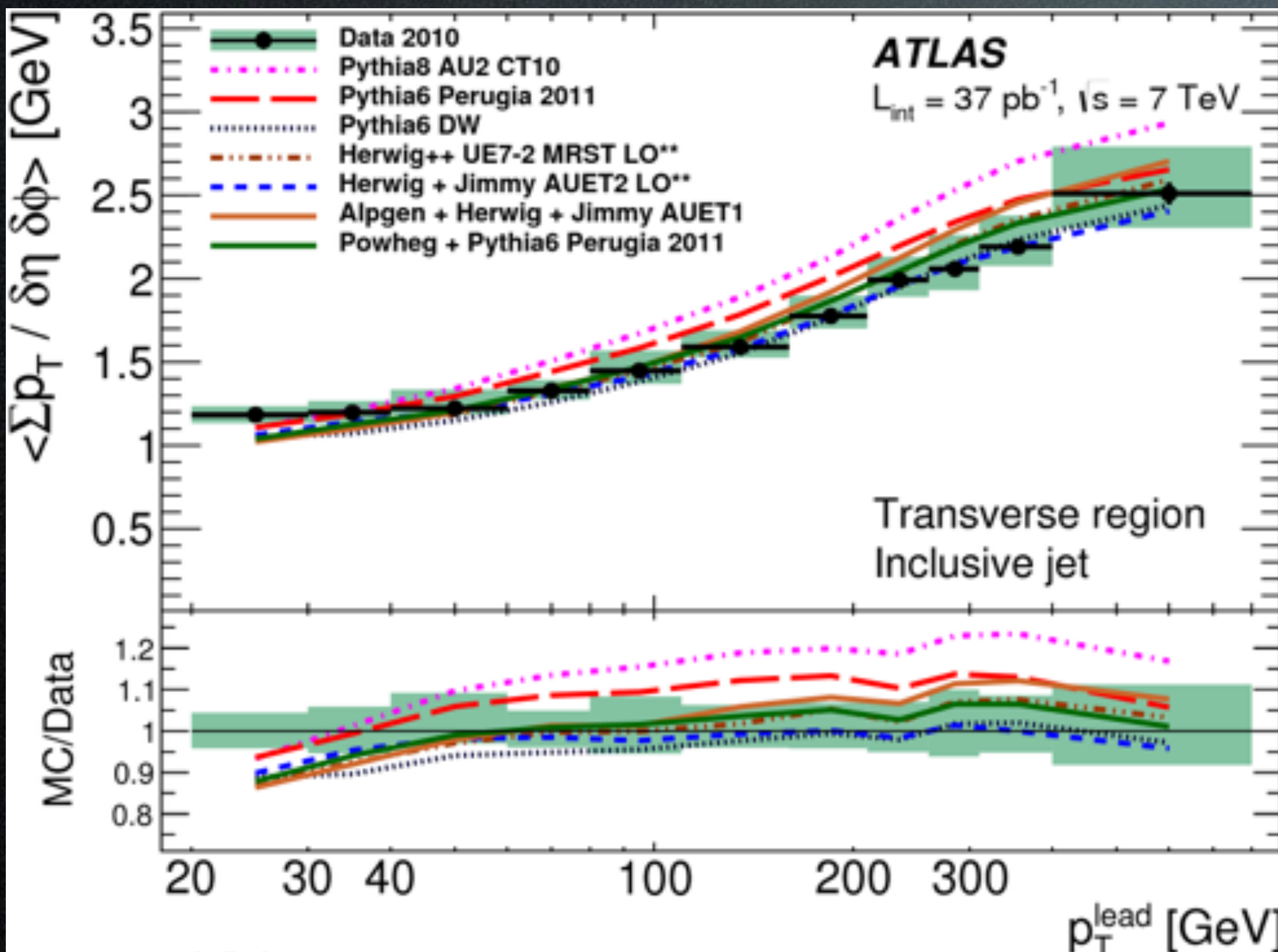
- m^{calo}: from constituent four vectors
- m^{TA}: track-assisted-mass, ratio corrects for charge to neutral fluctuations. Better control of uncertainties.

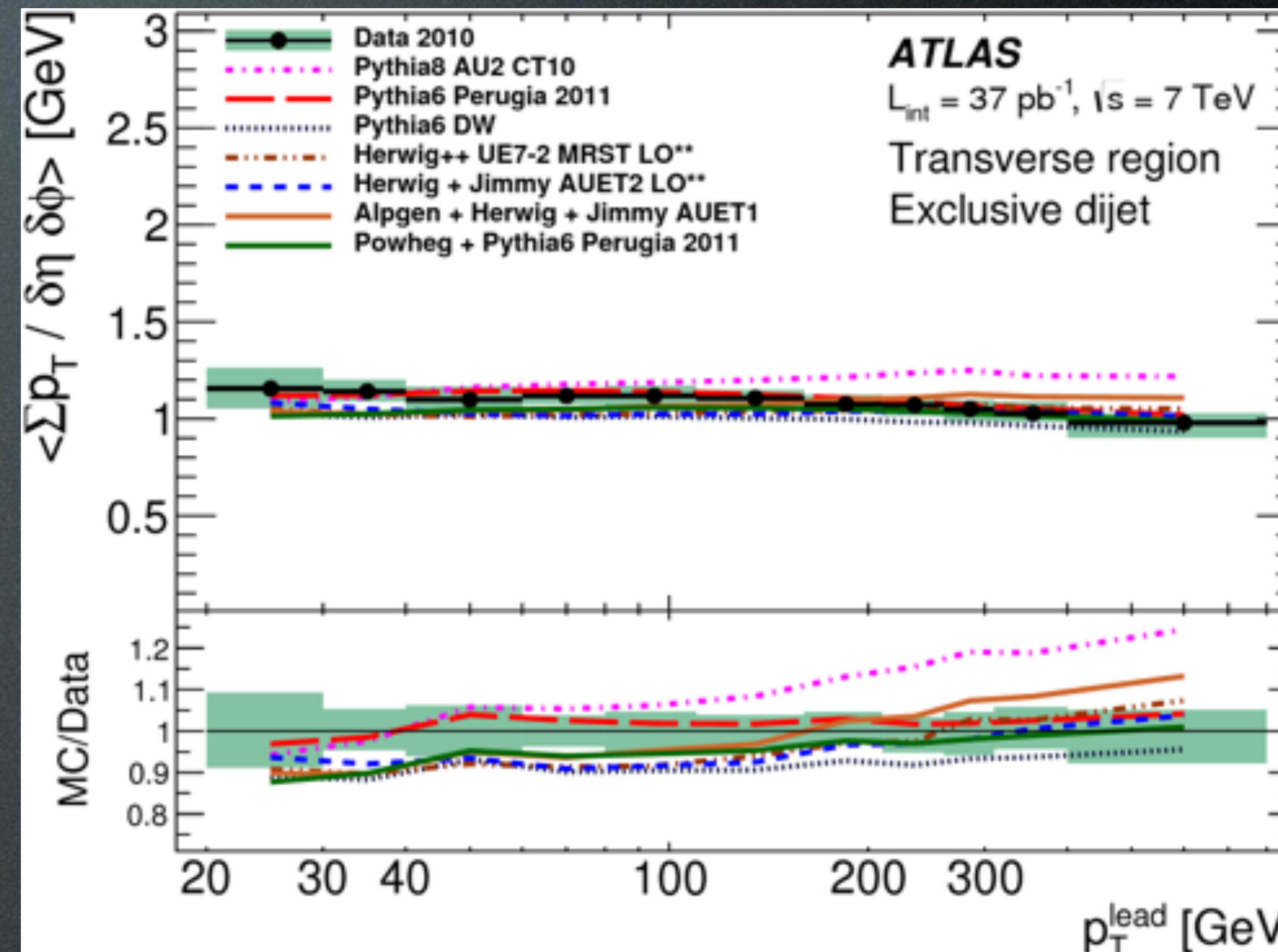


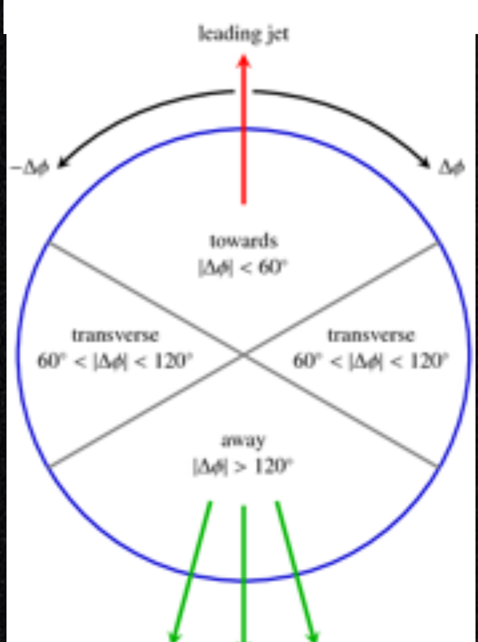
Jet Measurements

- Many interesting physics results
- Only a very small number covered in this talk

UE in Jet Events

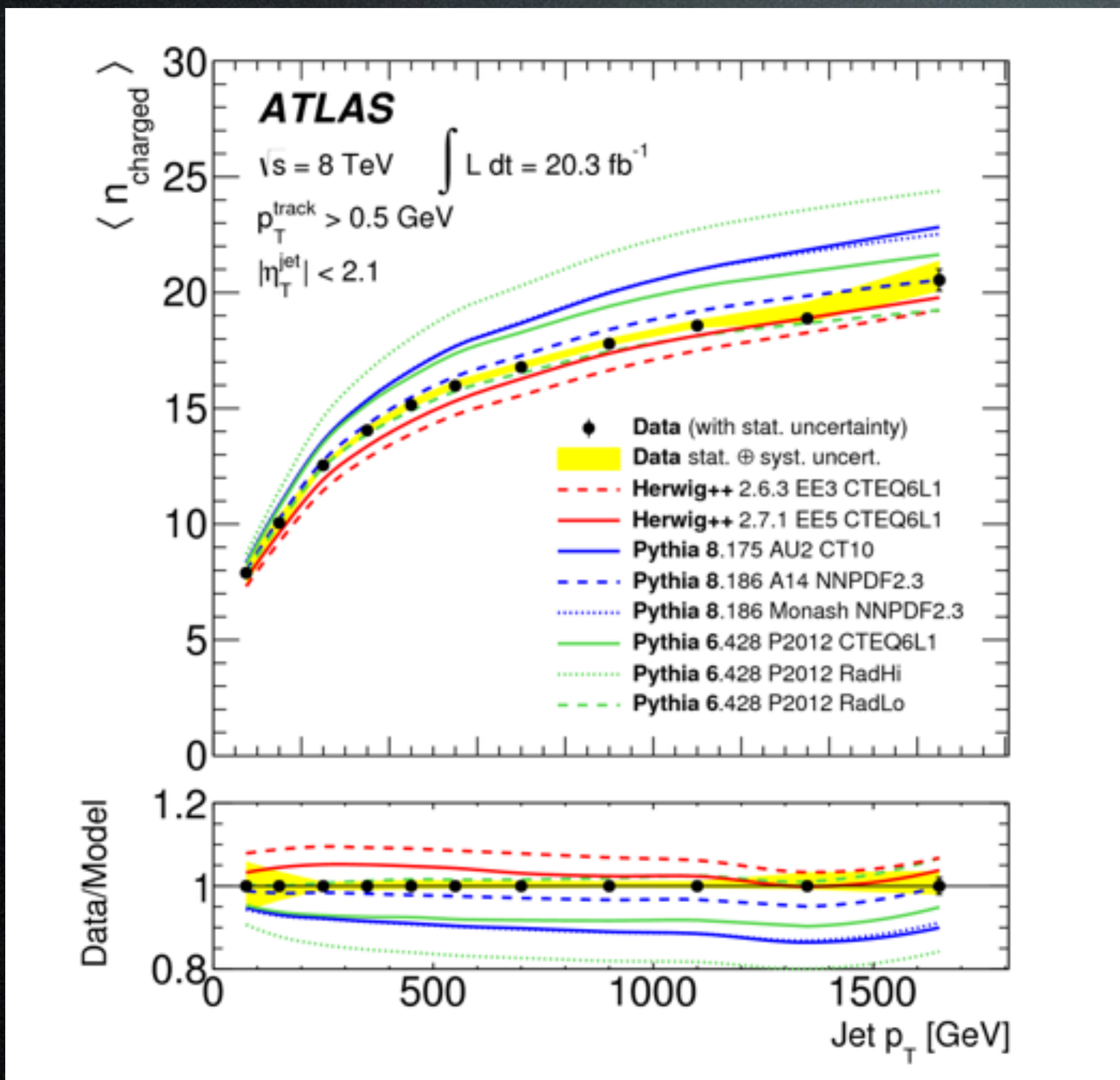






Exclusive topology more sensitive to MPI, modelled better

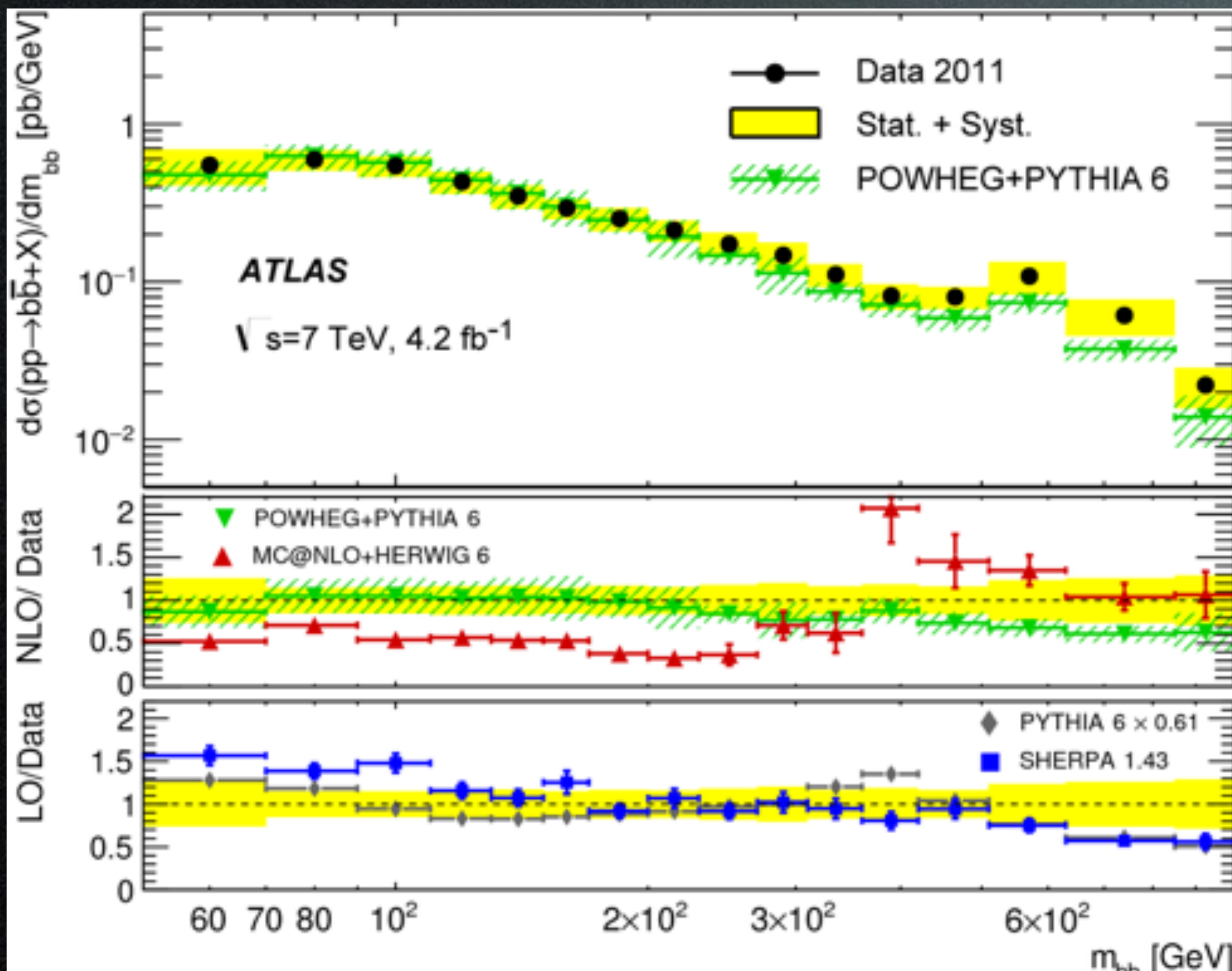
Charged Multiplicity inside Jets

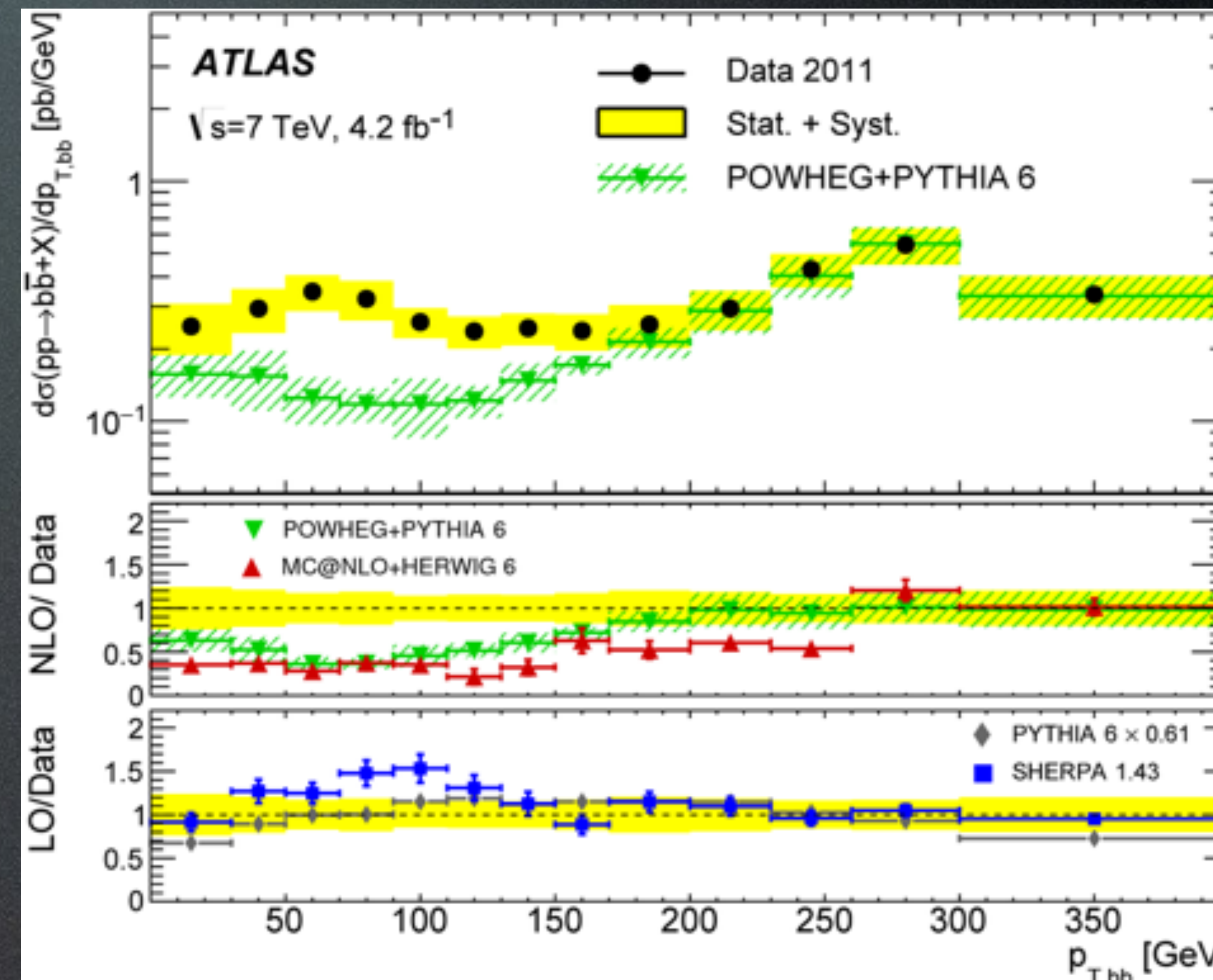


Sensitive to q/g tagging

Significant differences between generator predictions.

bbbar-dijet Production

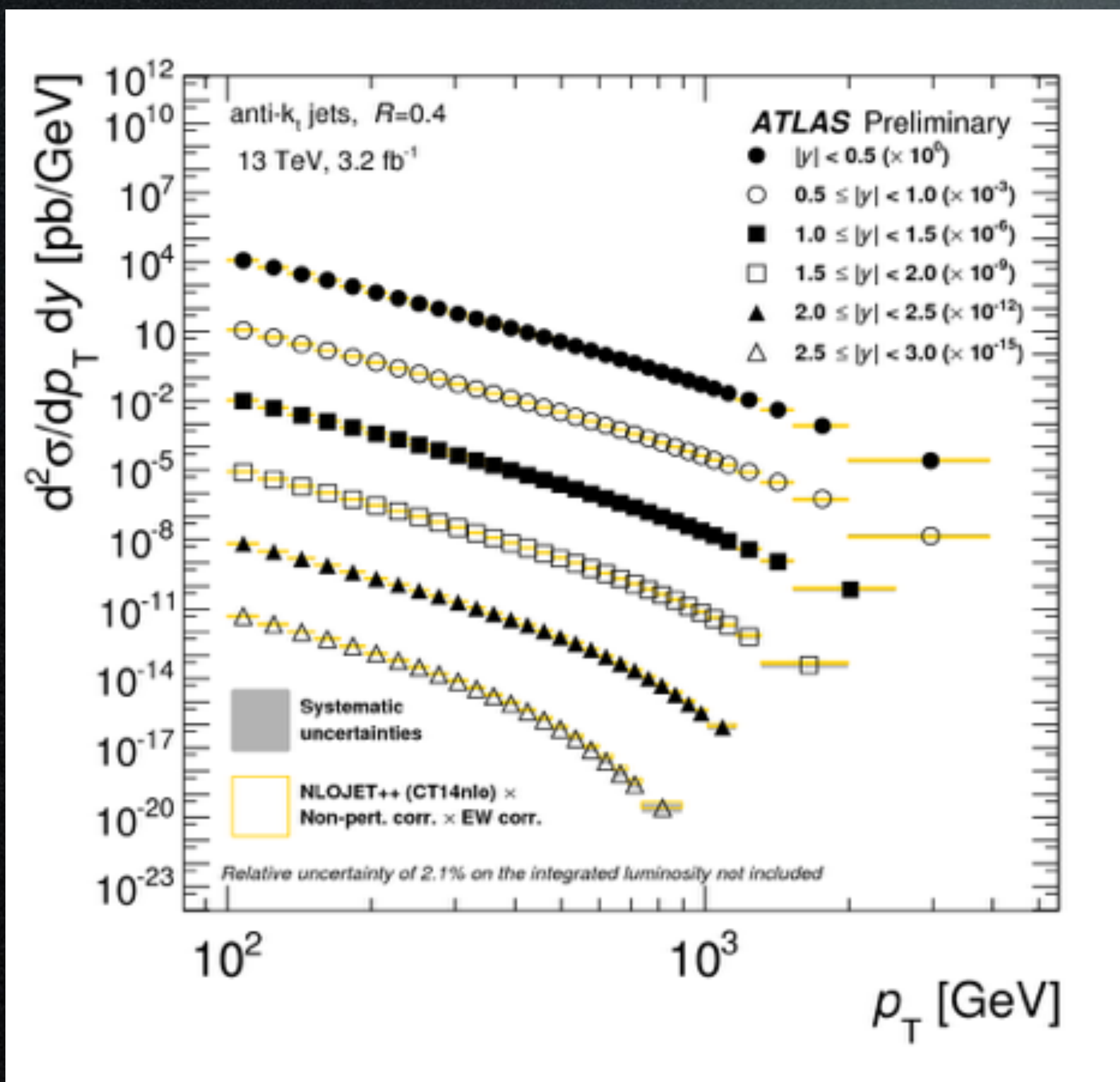


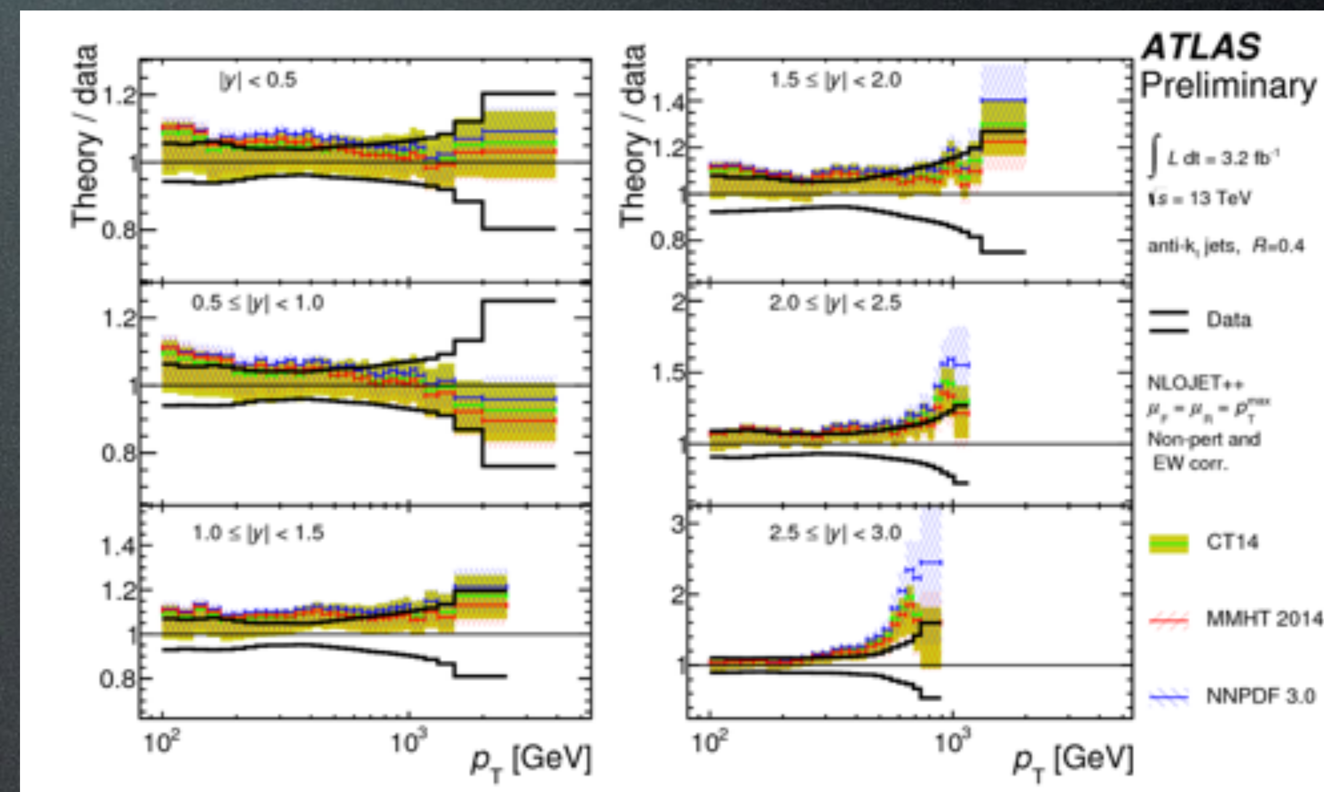


b-tagged by vertex and track information in a neural network, 70% efficiency

Difference in data and predictions

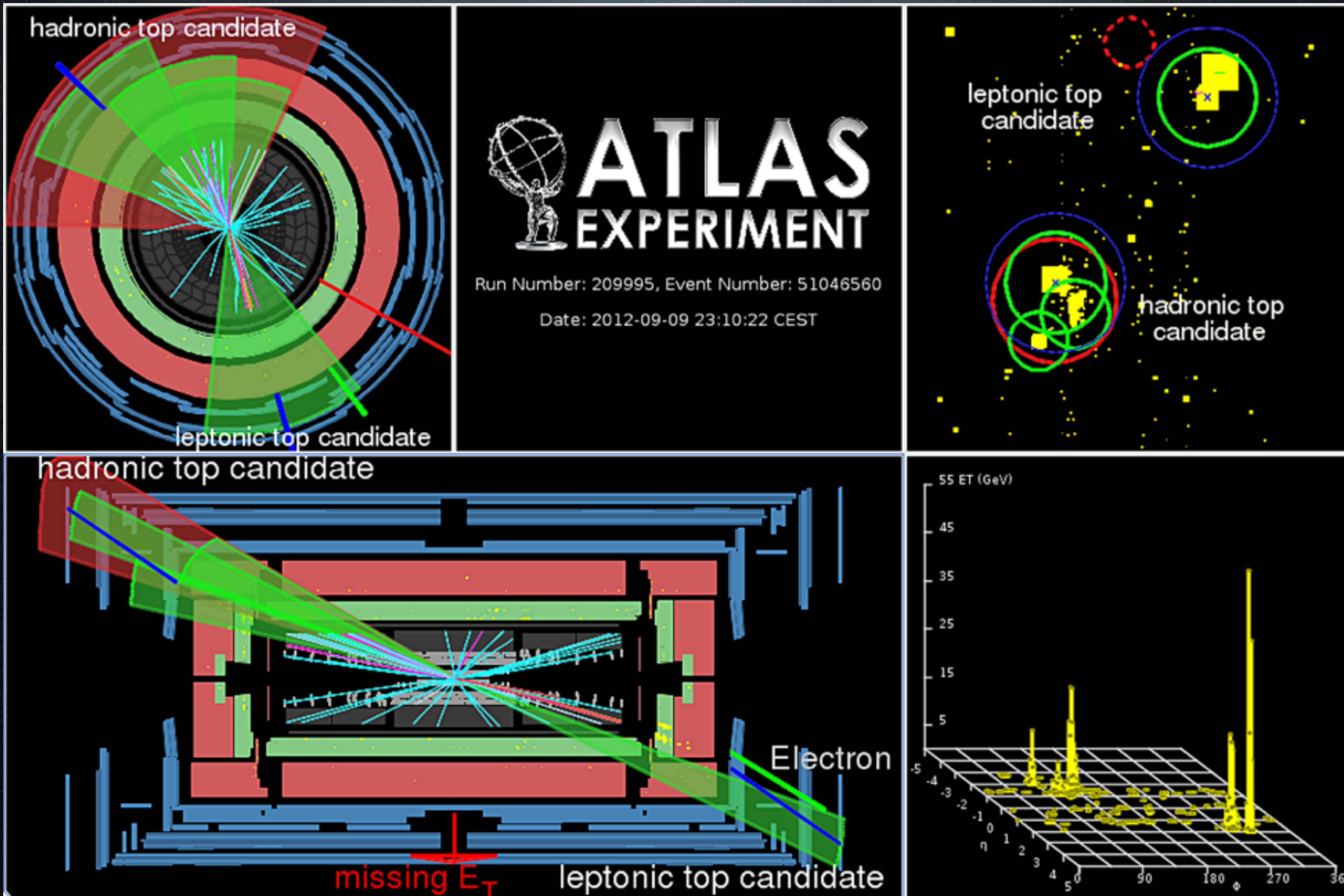
Inclusive Jet Cross-section at 13 TeV





100 GeV to 3.2 TeV!

Part 2: Jet Substructure, techniques and uses


hadronic top candidate
leptonic top candidate
ATLAS EXPERIMENT
Run Number: 209995, Event Number: 51046560
Date: 2012-09-09 23:10:22 CEST
leptonic top candidate
hadronic top candidate
hadronic top candidate
Electron
missing E_T
leptonic top candidate
55 ET (GeV)
45
35
25
15
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η
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0
90
180
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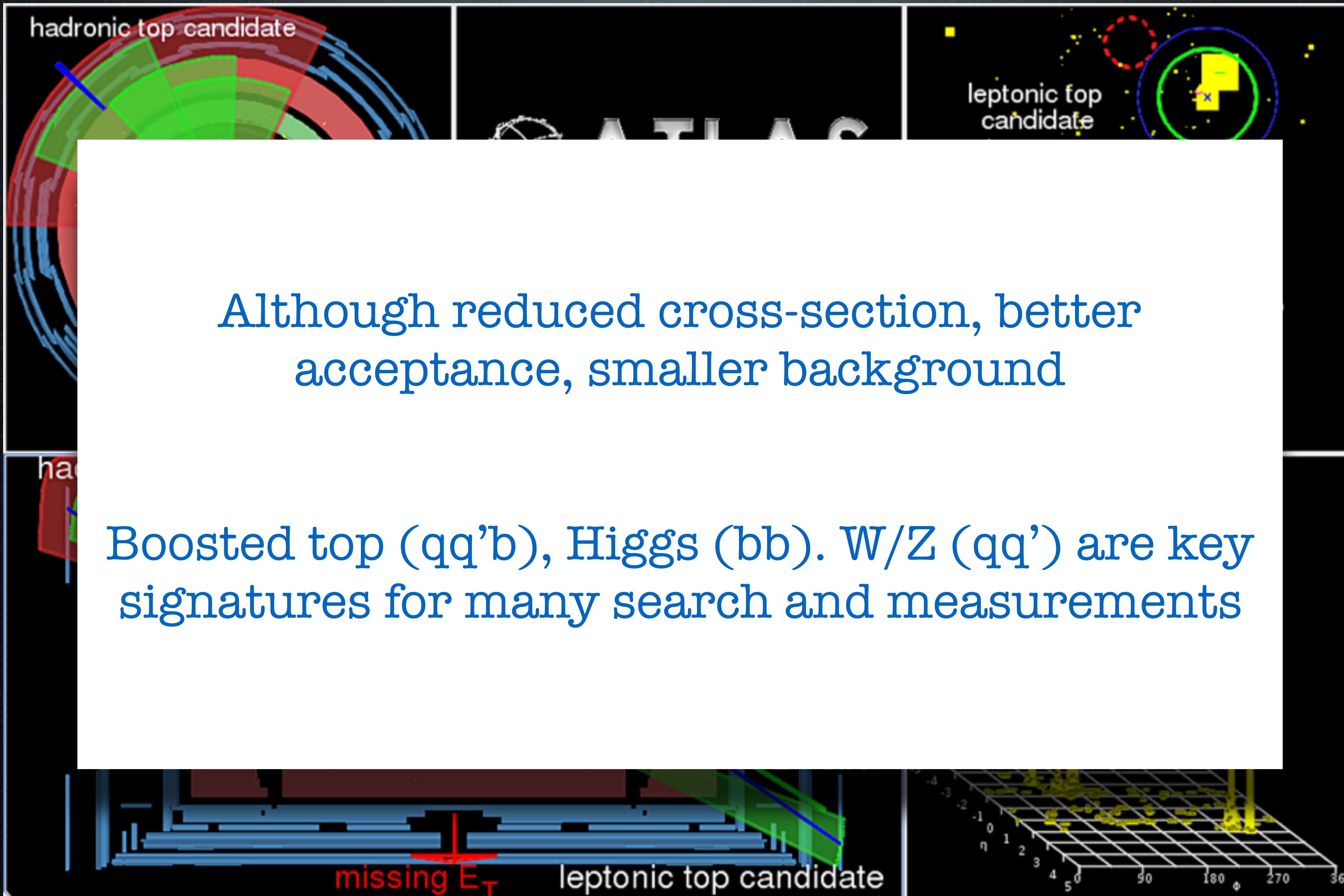
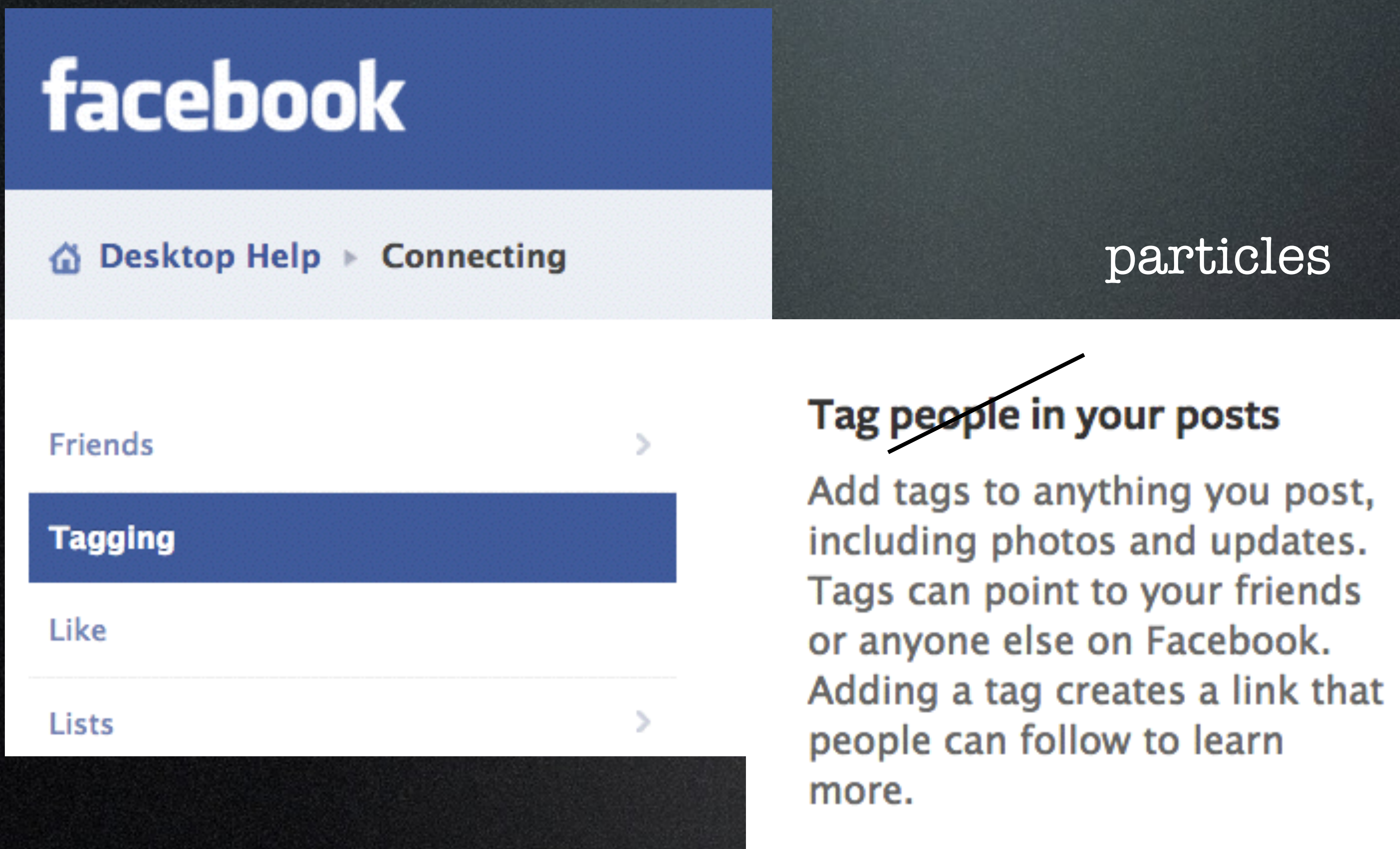


Although reduced cross-section, better acceptance, smaller background

Boosted top (qq'b), Higgs (bb). W/Z (qq') are key signatures for many search and measurements

Tagging Boosted Objects: observables and taggers

particles



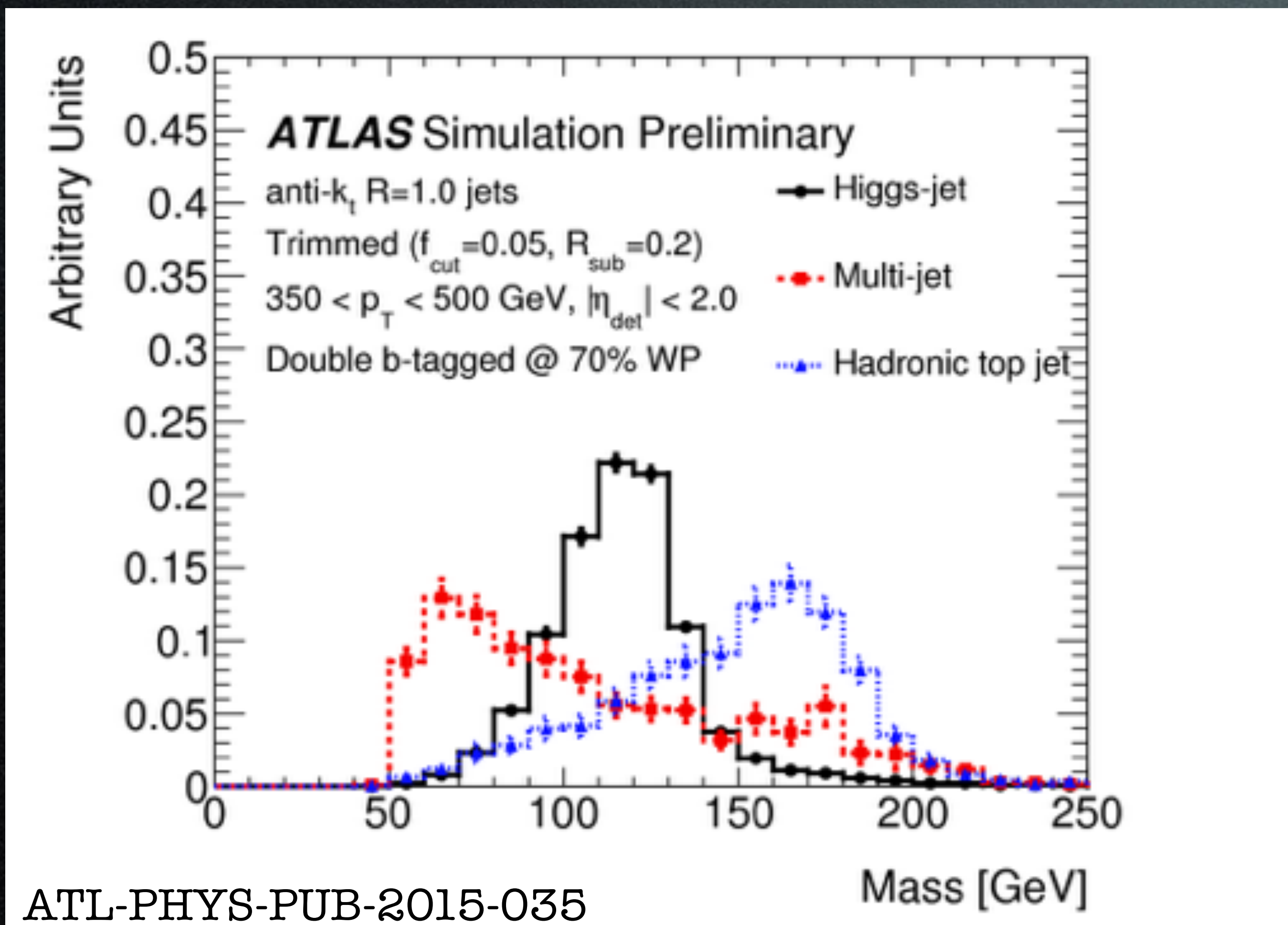
Target is to identify jets resulting from the decay of top quark or Higgs against jets coming from light quark/gluons.

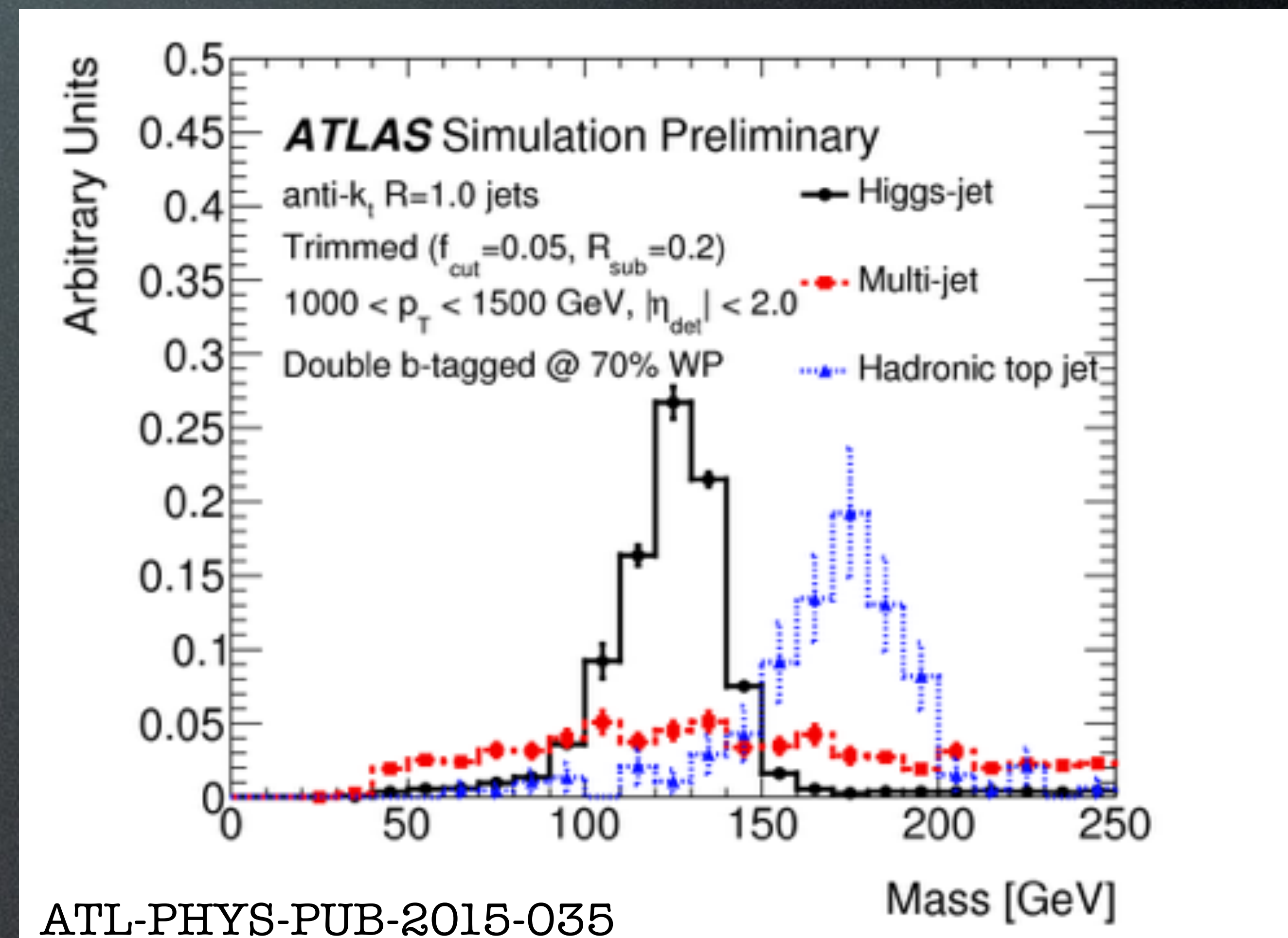
What we use in ATLAS

Typical starting point: Trimmed (f_{cut} = 5%, R_{sub} =0.2)
antik_t R=1.0 jet with p_T > 200 GeV, |eta| < 2.0

- Jet mass
- Splitting Scale
- Nsubjettiness (discussed yesterday)
- Energy Correlation
- HEPTopTagger (discussed yesterday)
- Shower Deconstruction

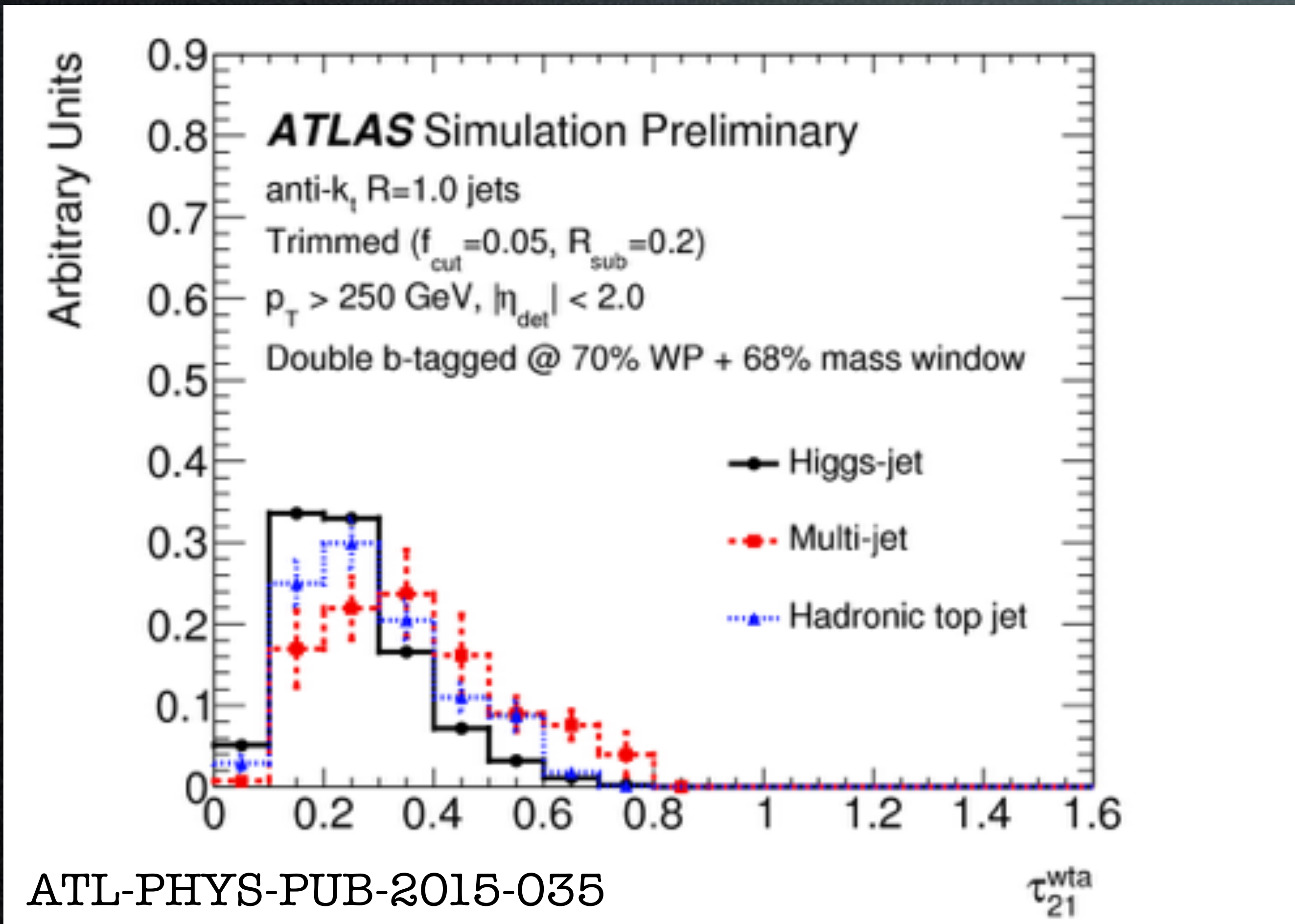
Boosted (tt)Higgs to (tt)bbbar

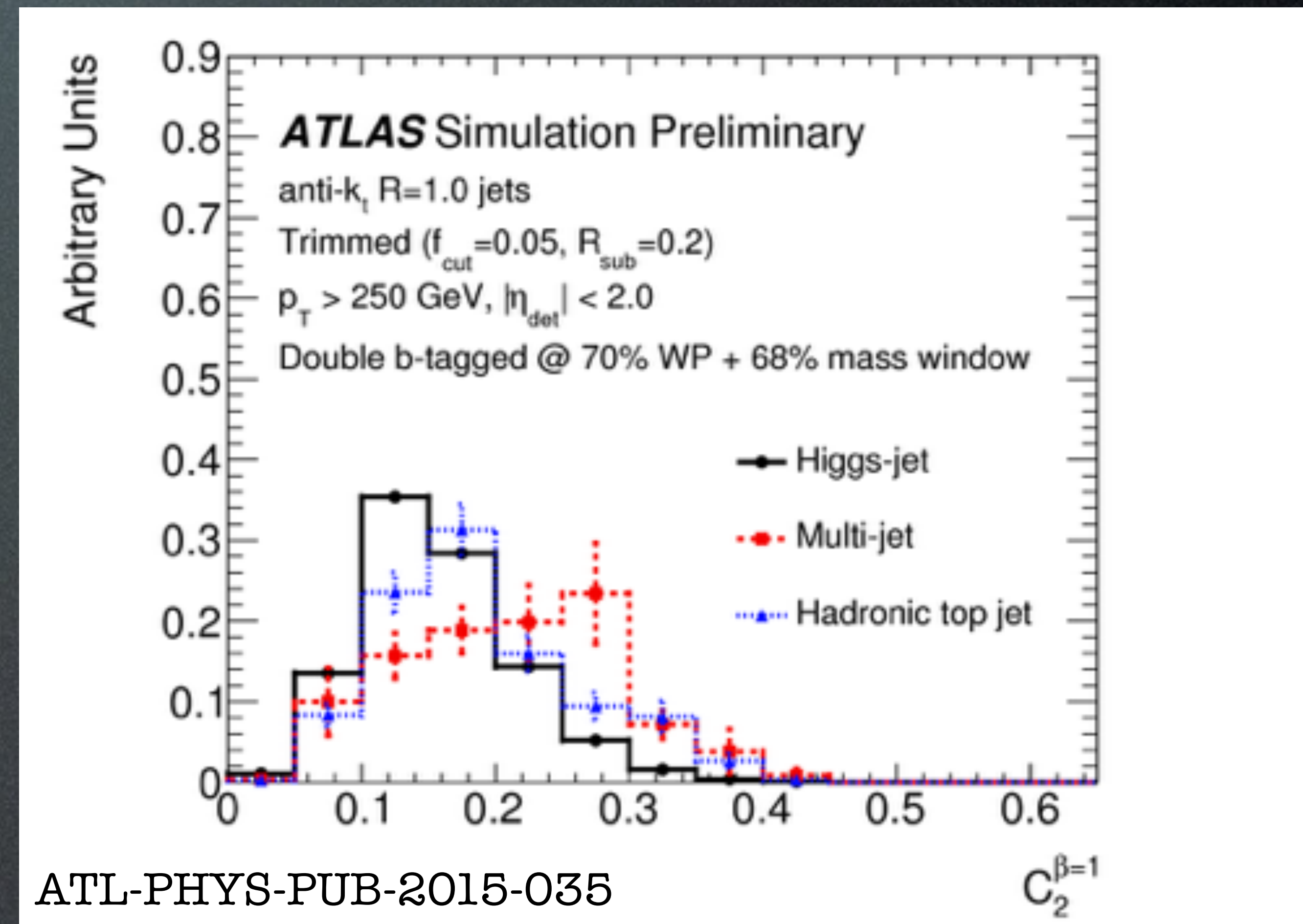




Fatjet mass can be a useful discriminating variable

Boosted (tt)Higgs to (tt)bbbar



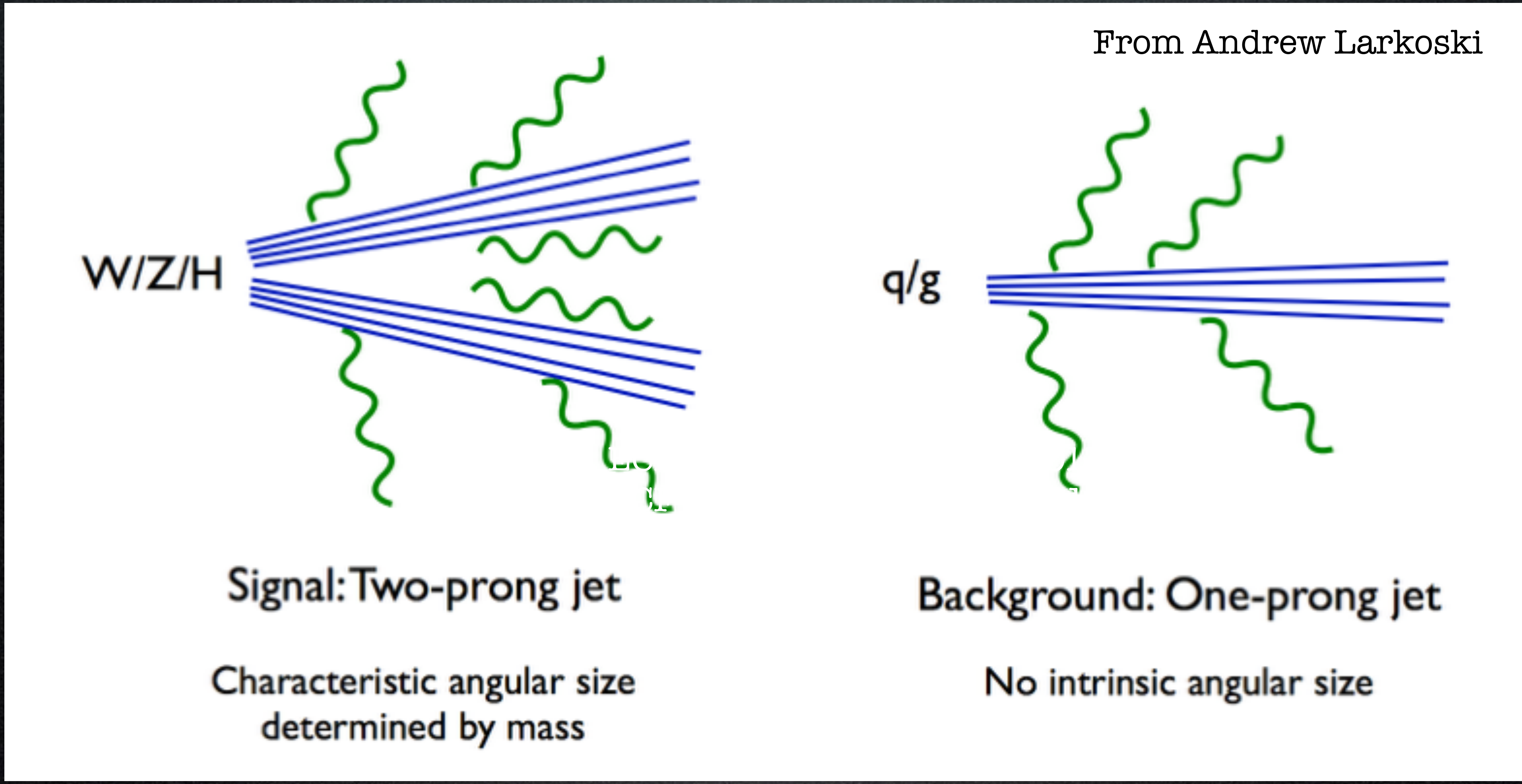


Mass can be combined with other substructure variables

Depends on specific analysis what efficiency/rejection working point is needed

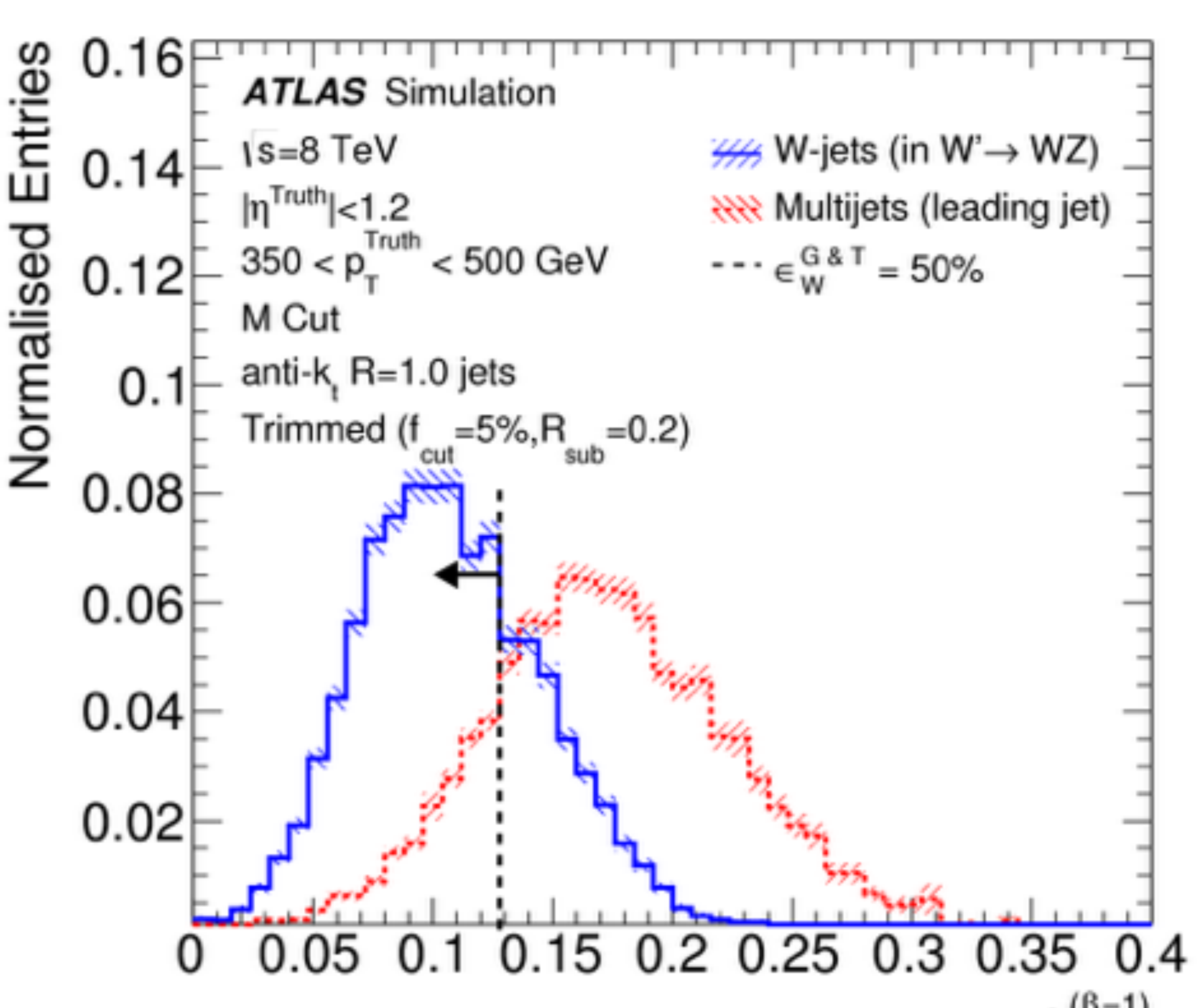
Energy Correlation Function
(or jet substructure without trees)

Discriminate between:



Larkoski, Salam, Thaler; JHEP 1306, 108 (2013), JHEP 1412, 009 (2014)

ECF Results



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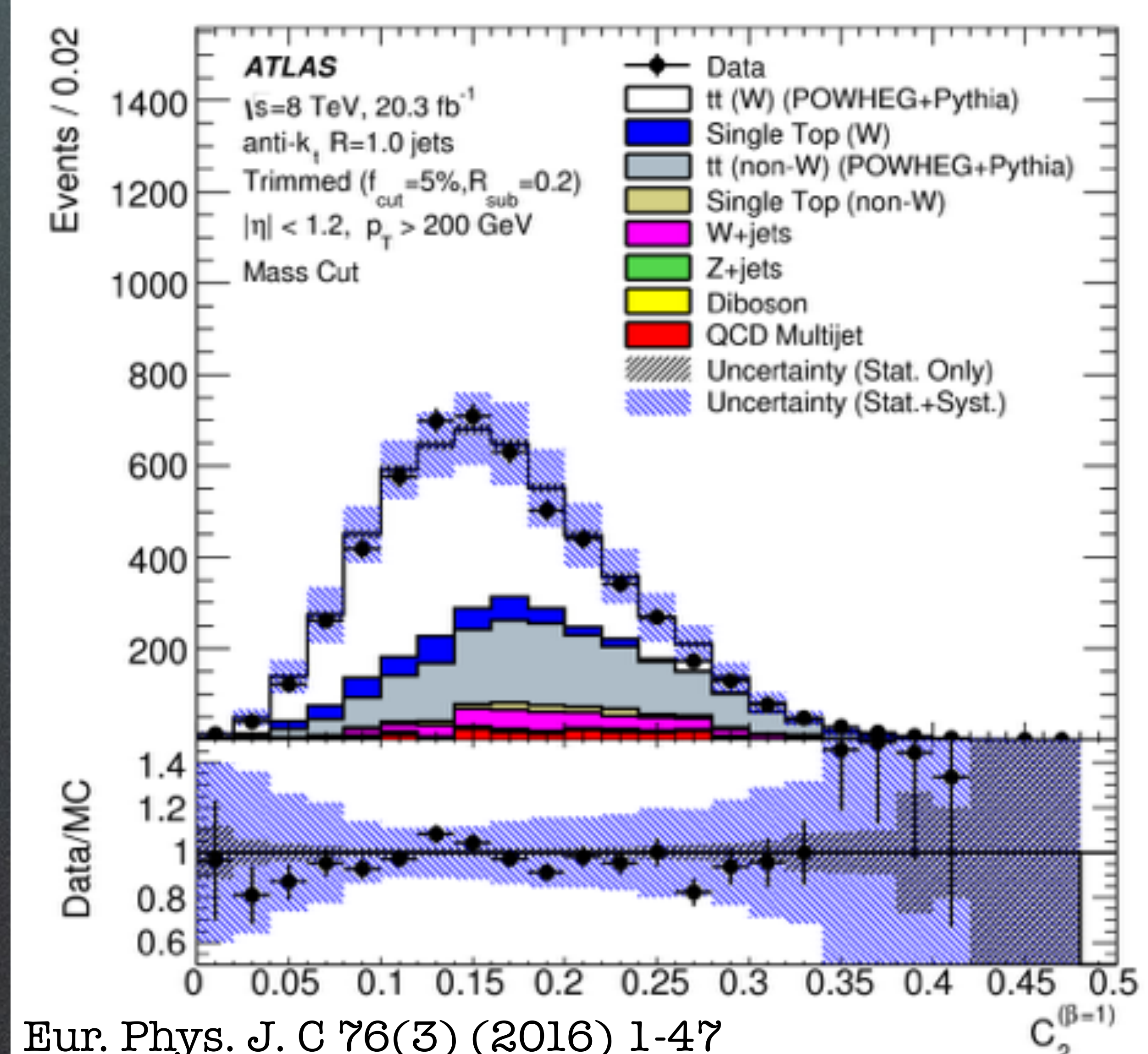

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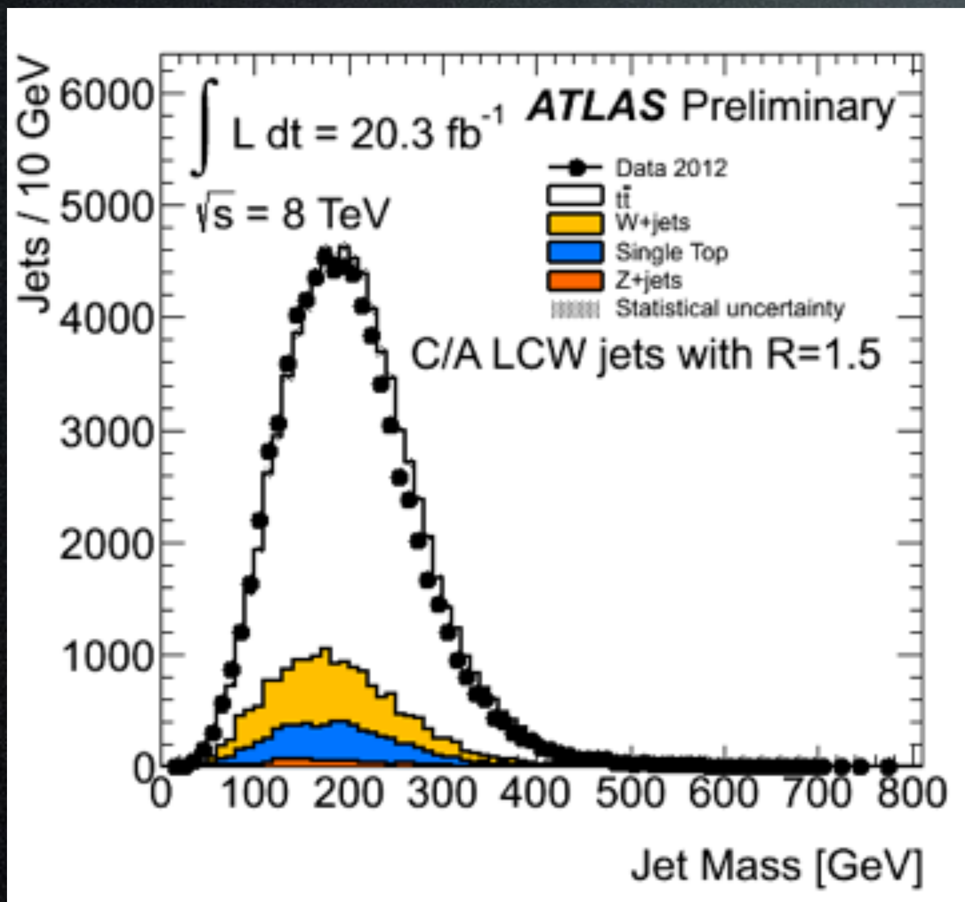
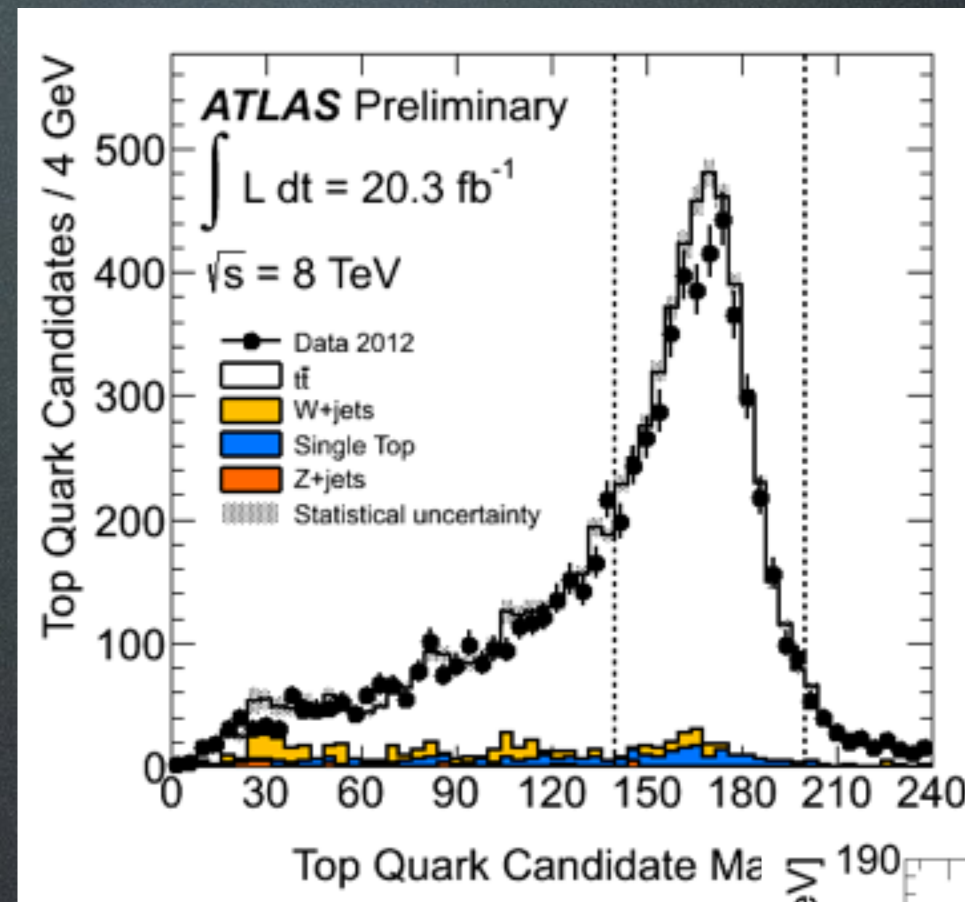
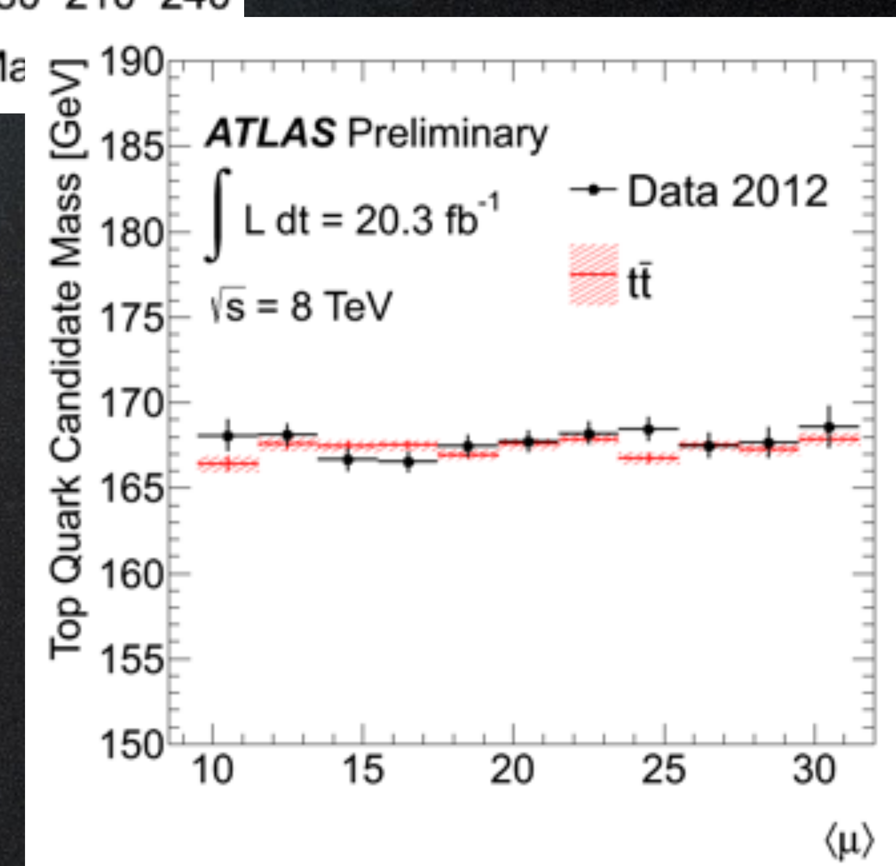
HEPTopTagger Performance





Before and after tagging by HepTopTagger

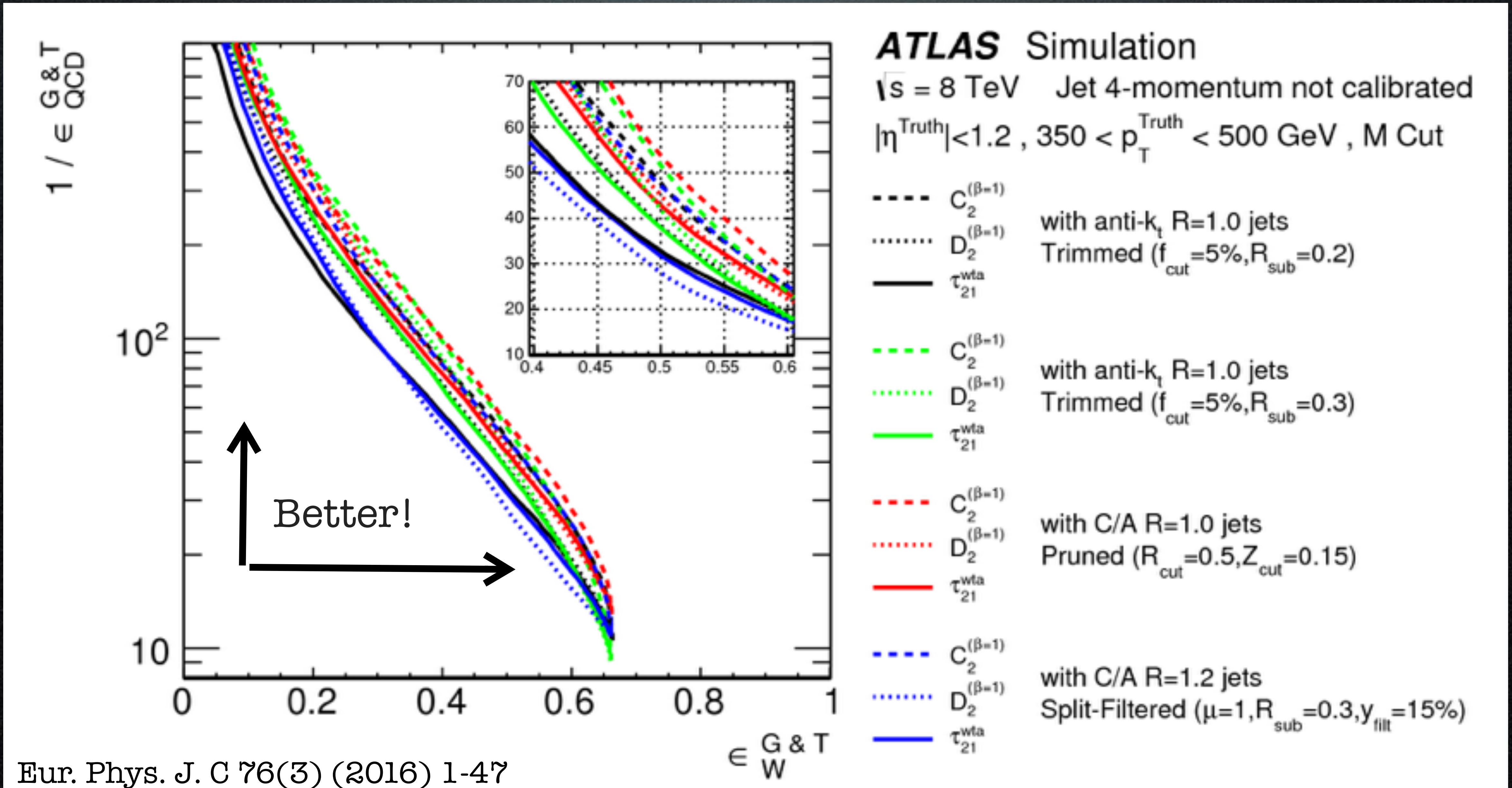


Pileup resilience

ATLAS-CONF-2013-084

Tagger Comparisons

W tagging Summary



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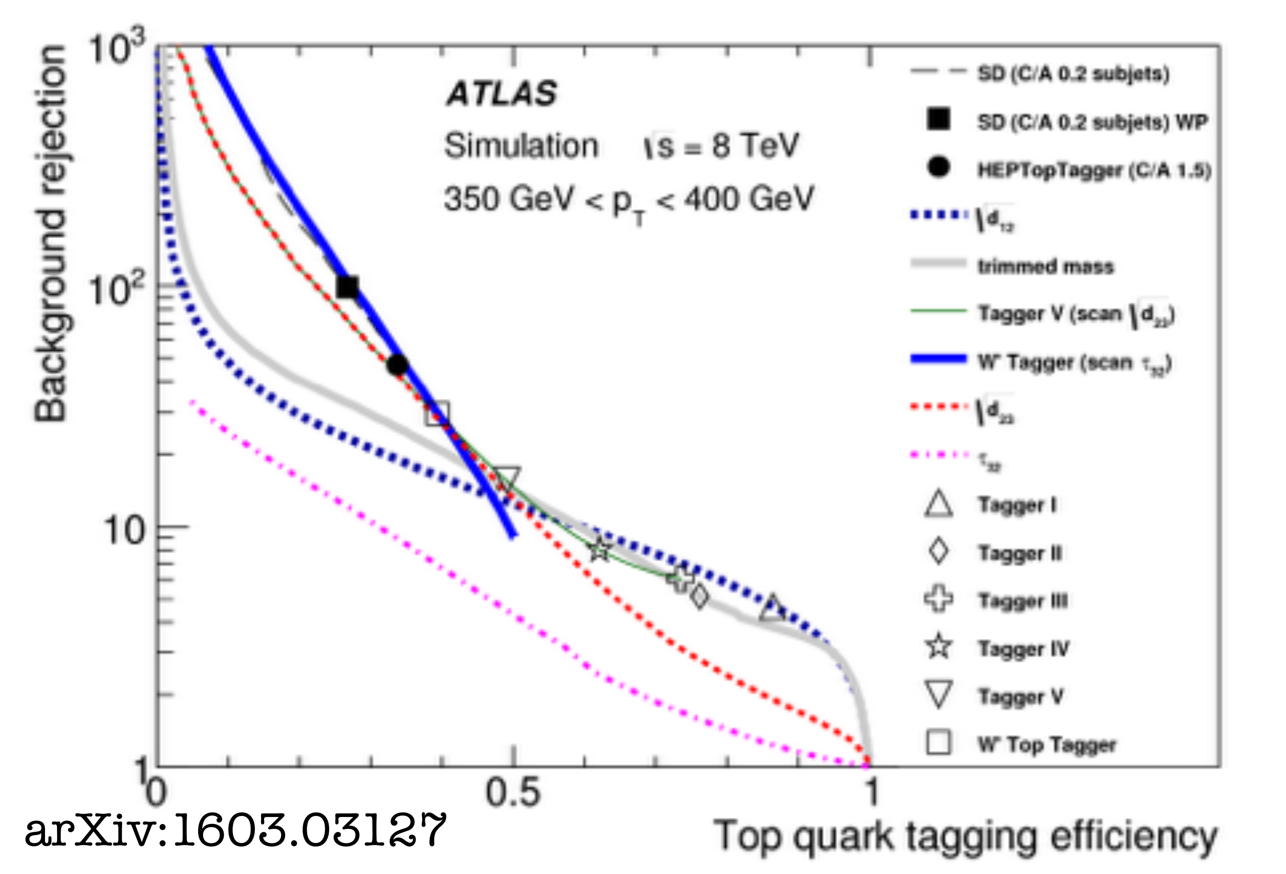
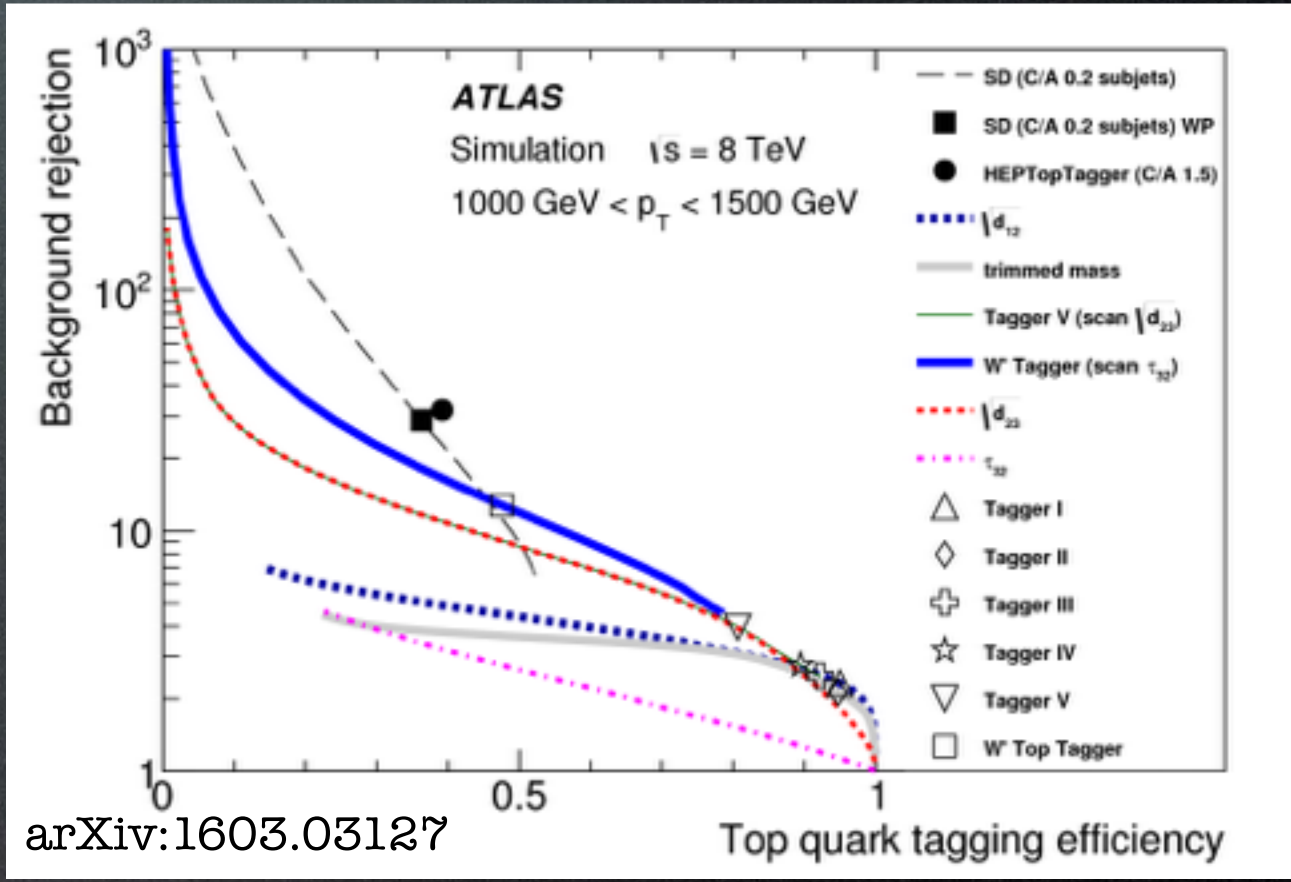
Top tagging Summary

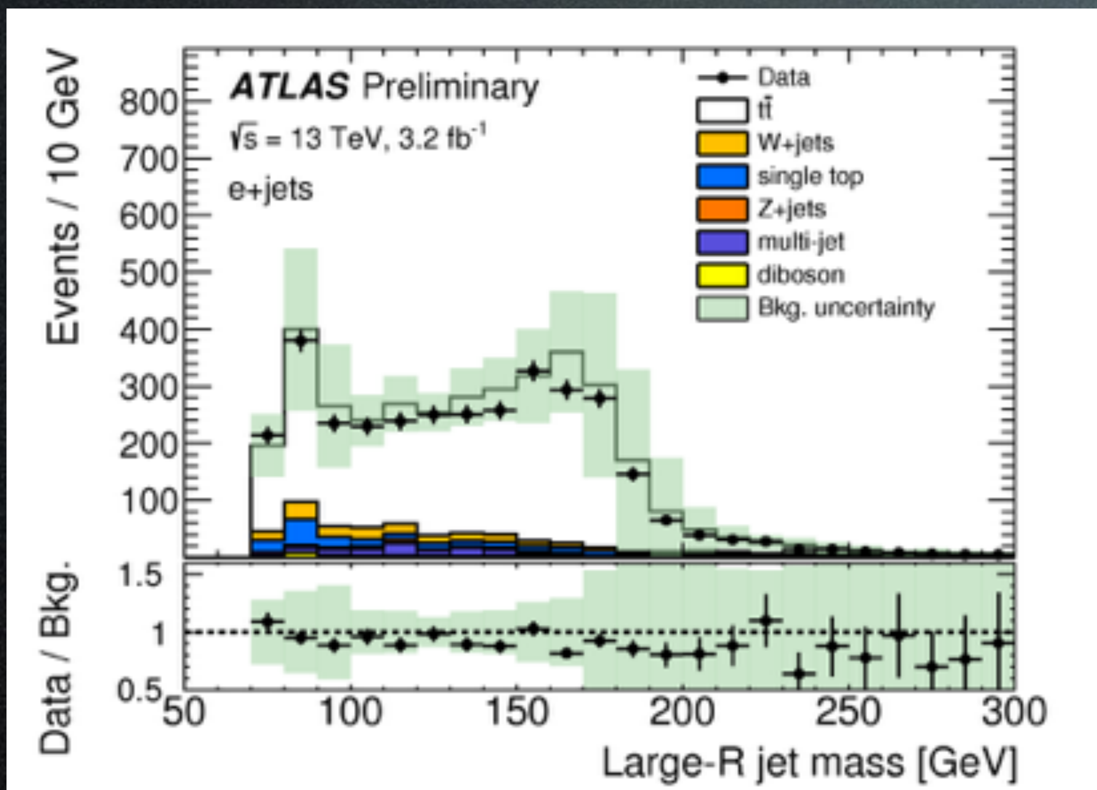


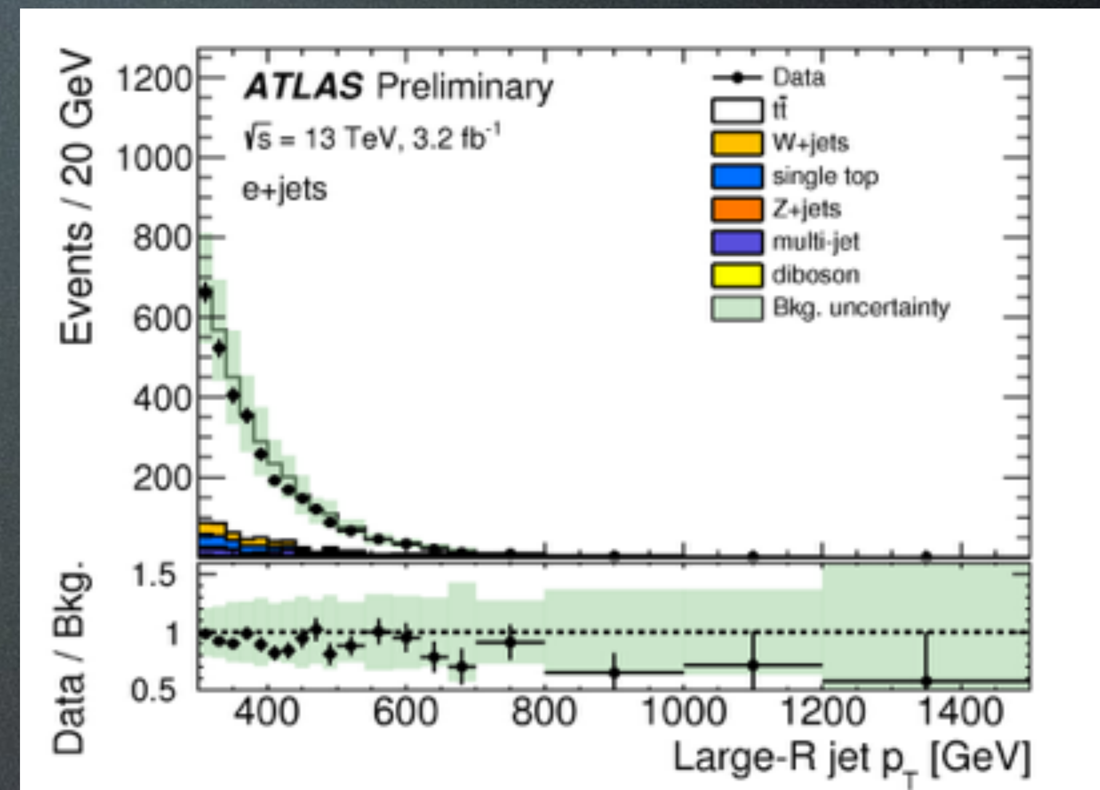


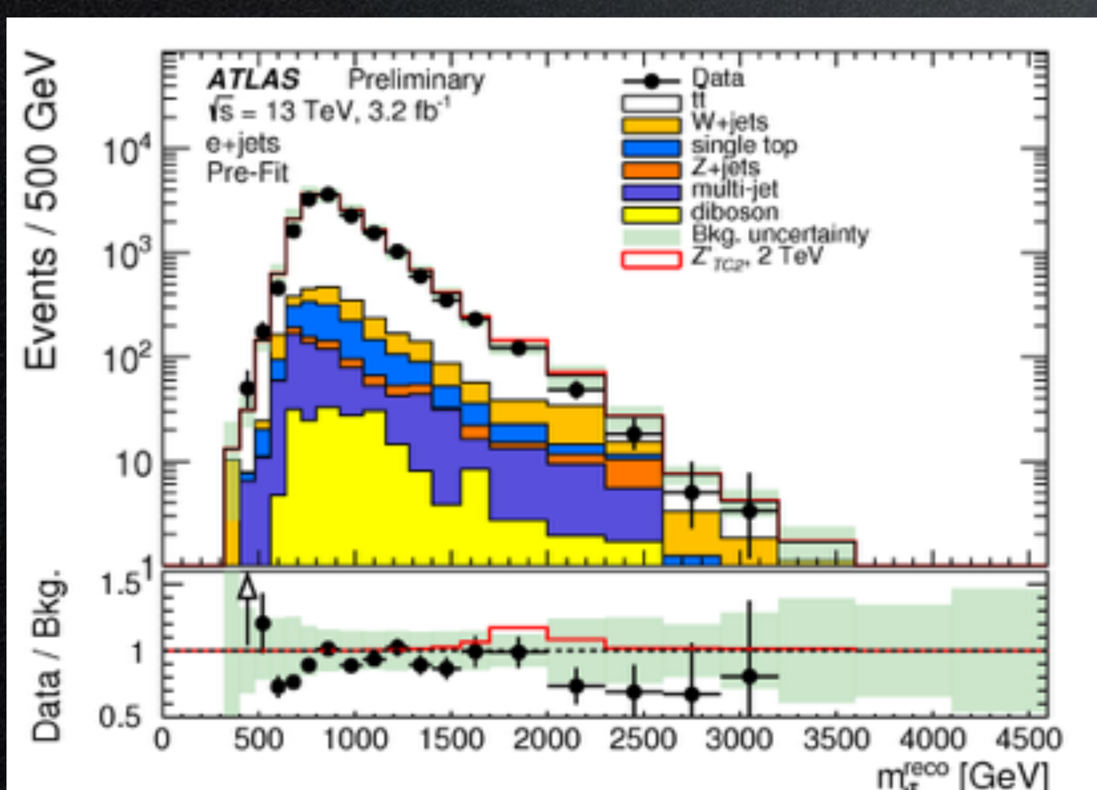
Better top quark finding efficiency with SD at the same rejection of multijets when compared to other taggers

Example Test Cases

ttbar Resonance







Top tagged by using mass+τ_{32}

80% efficiency working point

Used R=0.2 track jets for b-tagging

ATLAS-CONF-2016-55

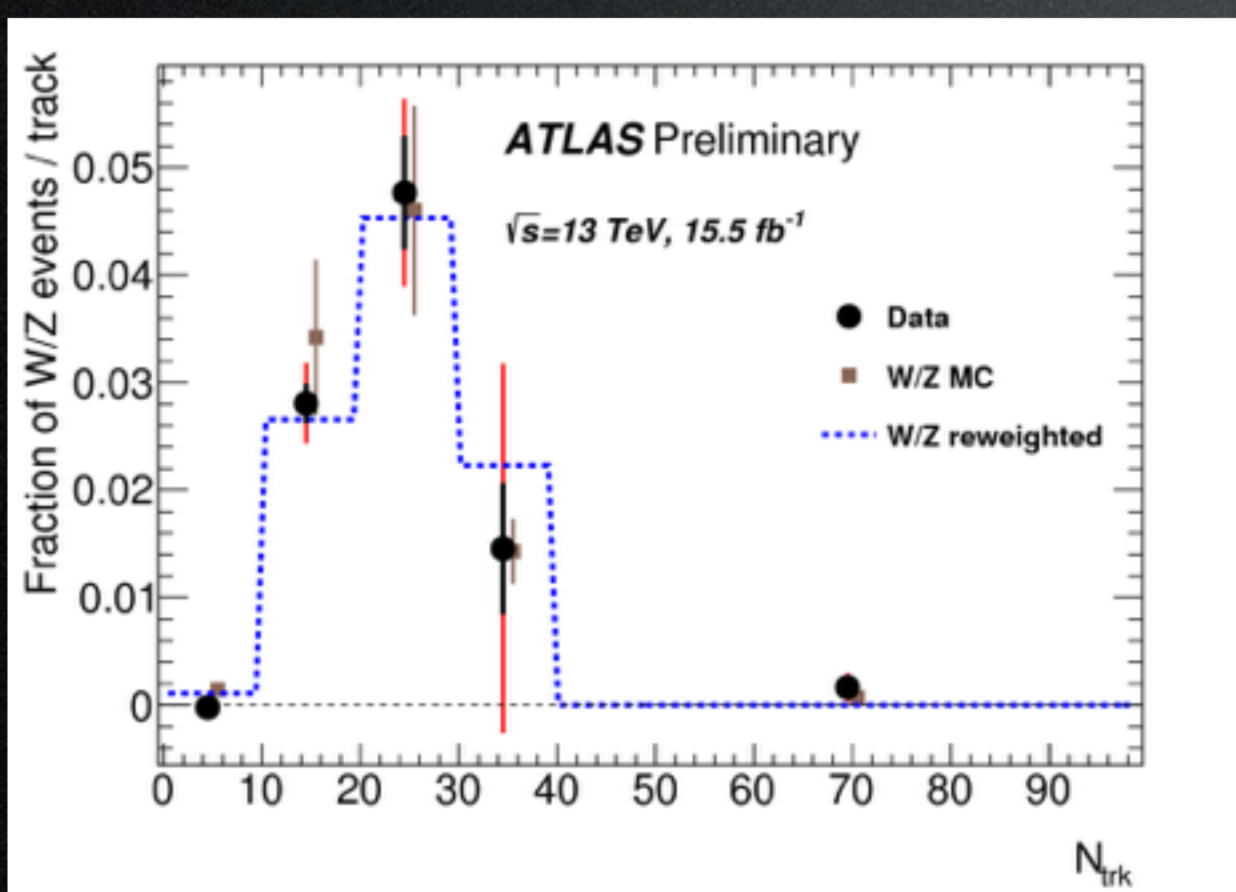
Vector Boson Pair Production

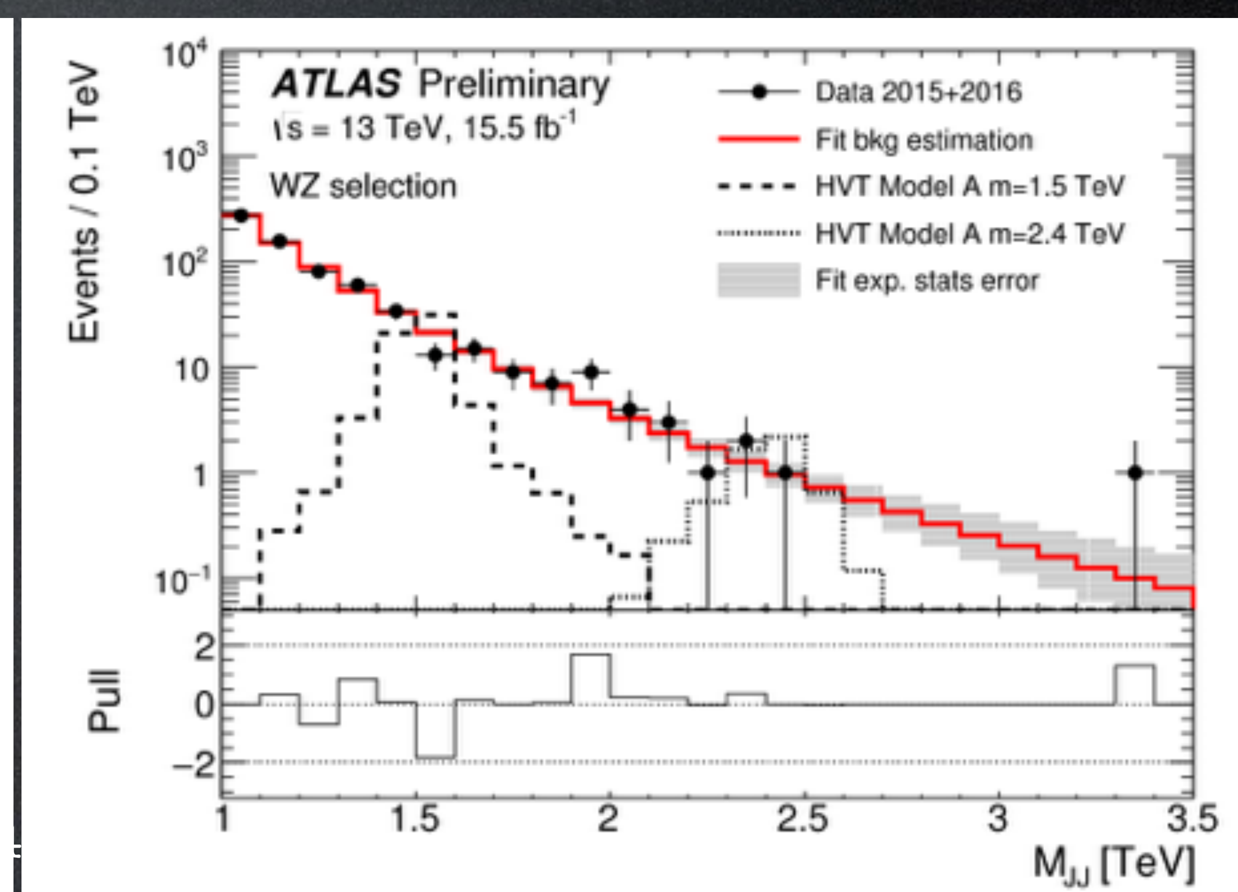
Event Selection: pair of fatjets, leading p_T> 450 GeV, m_{JJ} > 1 TeV, Δy_{12} < 1.2 (t-channel bg, s-channel signal)

Boson tagged by using mass (±15 GeV around W/Z peak) + D2 (β=1)

50% efficiency working point (p_T dependent)

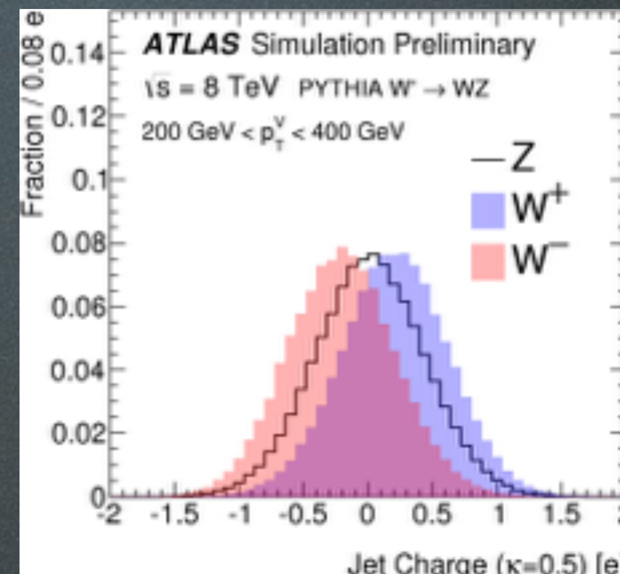
Additional requirement: N_{trk} < 30 (higher fraction of gluon jets in background, different fragmentation)

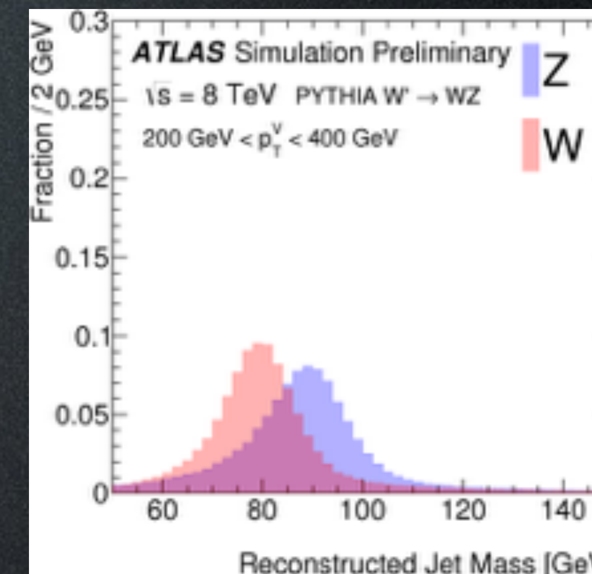


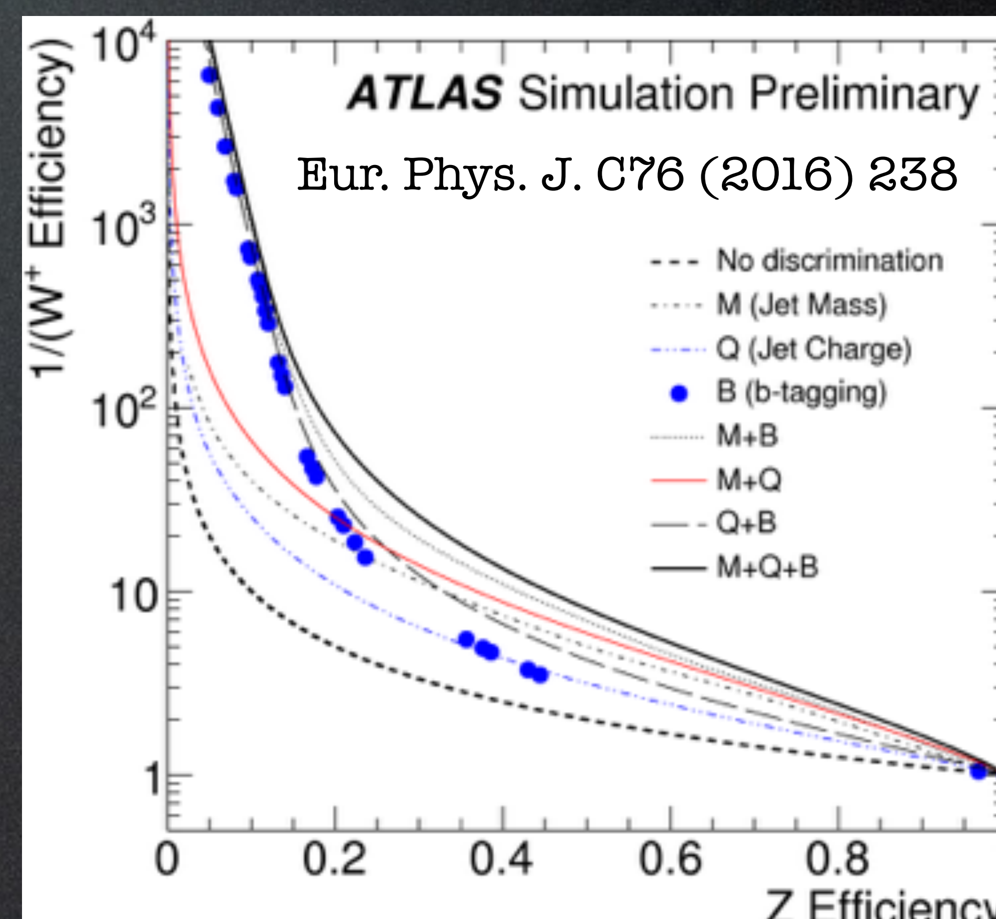


W/Z Discrimination

- Jet mass, charge and b-tagging used to construct a discriminant
- Only in simulation, although data models the observables well.







Summary

- Many signatures of new physics involve hadronically decaying boosted top quark or Higgs/W/Z boson(s), either by itself or adding sensitivity to the resolved channel.
- Higher kinematic reach at LHC Run 2 (and beyond) for such boosted objects.
- Pileup remains a significant challenge.
- Many theoretical tools, but commissioning them in experiment takes a lot of effort.

Supporting Material

What is a Quark Jet?

From lunch/dinner discussions

Ill-Defined ↓ Well-Defined	What people sometimes think we mean ↑ What we mean	
Ill-Defined	What people sometimes think we mean	A quark parton
		A Born-level quark parton
		The initiating quark parton in a final state shower
		An eikonal line with baryon number 1/3 and carrying triplet color charge
		A quark operator appearing in a hard matrix element in the context of a factorization theorem
		A parton-level jet object that has been quark-tagged using a soft-safe flavored jet algorithm (automatically collinear safe if you sum constituent flavors)
Well-Defined	What we mean	A phase space region (as defined by an unambiguous hadronic fiducial cross section measurement) that yields an enriched sample of quarks (as interpreted by some suitable, though fundamentally ambiguous, criterion)

Jesse Thaler — Report of the Les Houches Quark/Gluon Subgroup 3

What is a Quark Jet?

From lunch/dinner discussions

Ignores additional radiation

Ill-Defined ↓ Well-Defined	What people sometimes think we mean ↑ What we mean	
		A quark parton
		A Born-level quark parton
		The initiating quark parton in a final state shower
		An eikonal line with baryon number 1/3 and carrying triplet color charge
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What is a Quark Jet?

From lunch/dinner discussions

Ill-Defined ↓ **Well-Defined**

What people sometimes think we mean ↑ **What we mean**

A quark parton

A Born-level quark parton

The initiating q

How to define the born process?

An eikonal line
and carrying triplet color charge

A quark operator appearing in a hard matrix element in the context of a factorization theorem

A parton-level jet object that has been quark-tagged using a soft-safe flavored jet algorithm (automatically collinear safe if you sum constituent flavors)

A phase space region (as defined by an unambiguous hadronic fiducial cross section measurement) that yields an enriched sample of quarks (as interpreted by some suitable, though fundamentally ambiguous, criterion)

What is a Quark Jet?

From lunch/dinner discussions

Ill-Defined	What people sometimes think we mean	
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Well-Defined	What we mean	A phase space region (as defined by an unambiguous hadronic fiducial cross section measurement) that yields an enriched sample of quarks (as interpreted by some suitable, though fundamentally ambiguous, criterion)

Parton Shower history is meaningful only in LL

What is a Quark Jet?

From lunch/dinner discussions

Ill-Defined	What people sometimes think we mean	
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		A phase spac… hadronic fidu… an enriched … suitable, though fundamentally ambiguous, criterion)
Well-Defined	What we mean	

Ignores hadronisation effects

What is a Quark Jet?

From lunch/dinner discussions

Ill-Defined	What people sometimes think we mean	
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		An eikonal line with baryon number 1/3 and carrying triplet color charge
		A quark operator appearing in a hard matrix element in the context of a factorization theorem
		A parton- … using a so… collinear …
Well-Defined	What we mean	A phase space region (as defined by an unambiguous hadronic fiducial cross section measurement) that yields an enriched sample of quarks (as interpreted by some suitable, though fundamentally ambiguous, criterion)

Used here!

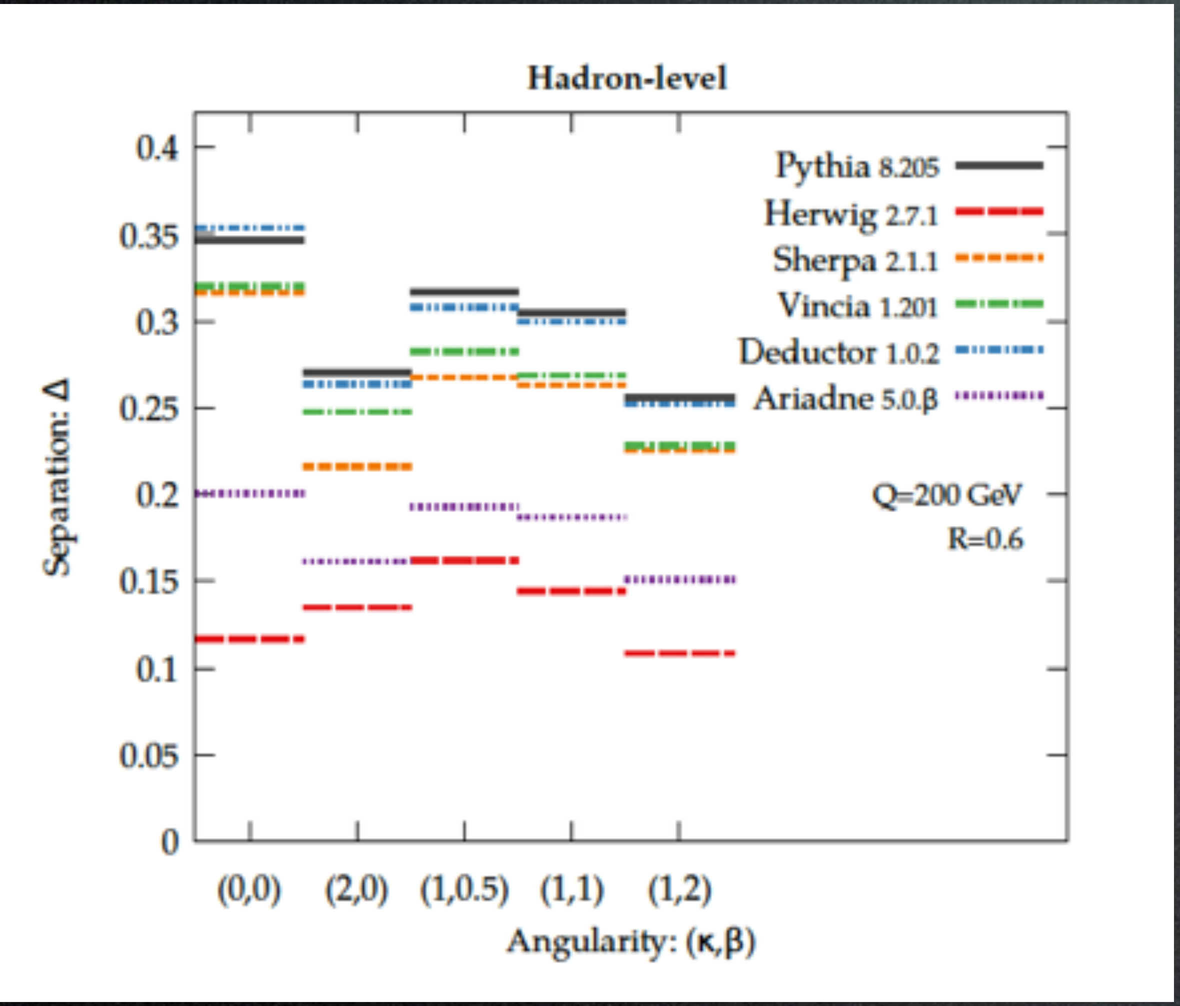
Les Houches Study

Generalised angularities:

$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \theta_i^\beta,$$

Discriminator:

$$\Delta = \frac{1}{2}\int \mathrm{d}\lambda \, \frac{\left(p_q(\lambda) - p_g(\lambda)\right)^2}{p_q(\lambda) + p_g(\lambda)},$$



Precise radiation pattern is very model dependent

Need more measurements

arXiv:1605.04692

ECF

Over all constituents (beta: angular exponent):

$$\mathrm{ECF}(1,\beta) = \sum_i p_{Ti}$$

$$\mathrm{ECF}(2,\beta) = \sum_{i<j} p_{Ti}\, p_{Tj}\, (R_{ij})^\beta \leftarrow \text{[see Banfi, Salam, Zanderighi; Jankowiak, Larkoski]}$$

$$\mathrm{ECF}(3,\beta) = \sum_{i<j<k} p_{Ti}\, p_{Tj}\, p_{Tk}\, (R_{ij} R_{jk} R_{ki})^\beta$$

$$\mathrm{ECF}(N,\beta) = \sum_{\text{sets of } N} (N \text{ energies}) \times \left(\binom{N}{2} \text{ angles}\right)^\beta$$

ECF(N+1) << ECF(N) for N subjets

Define (double) ratio = [ECF(N+1)/ECF(N)]/[ECF(N)/ECF(N-1)]

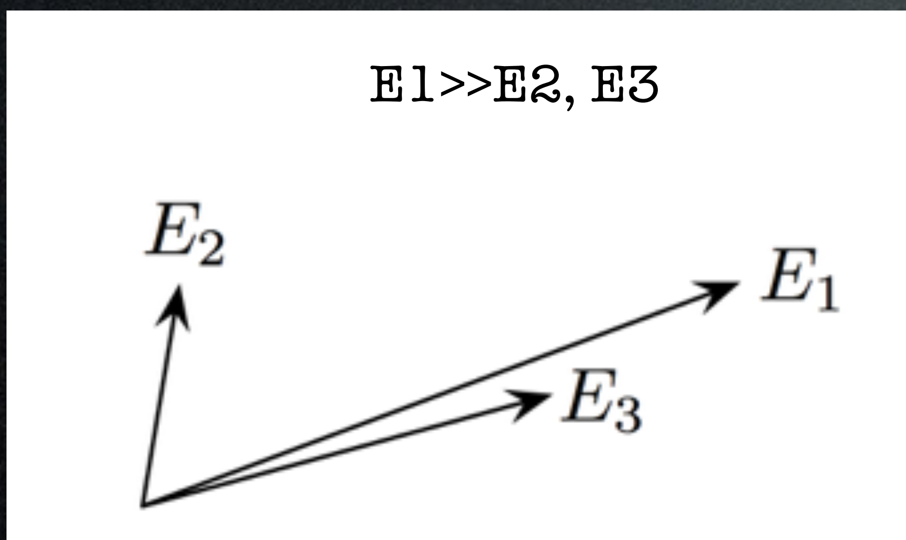
$$C_N^{(\beta)} = \frac{\mathrm{ECF}(N+1,\beta)\,\mathrm{ECF}(N-1,\beta)}{\mathrm{ECF}(N,\beta)^2}$$

Analogous to Nsubjettiness ratio

Large C_N: more than N subjets, extra radiation is not correlated with leading order N subjets.

For small C_N: the additional radiation is soft/collinear

ECF Discussion



For this multiple soft radiation case, with only 1 **real** subjet

$C_2 > \tau_{21}$

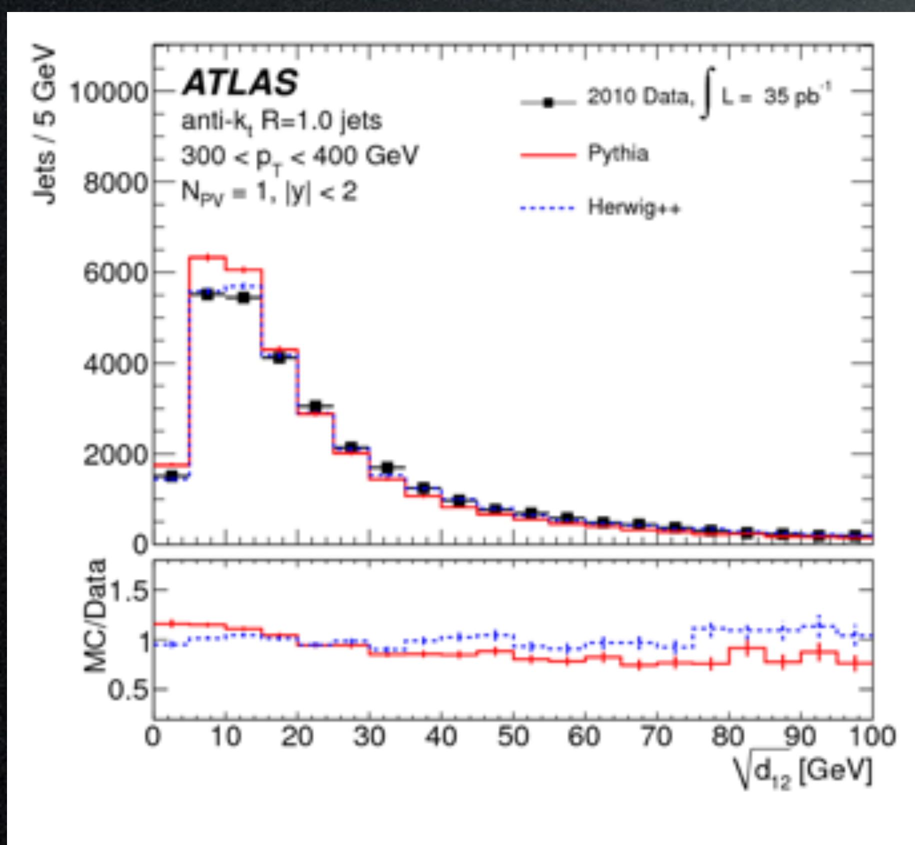
Nsubjettiness will identify this as more 2 subjet-like while ECF will identify more as 1 subjet-like

D-observables are further optimised by exploiting boost-invariance of the difference of one and two prong

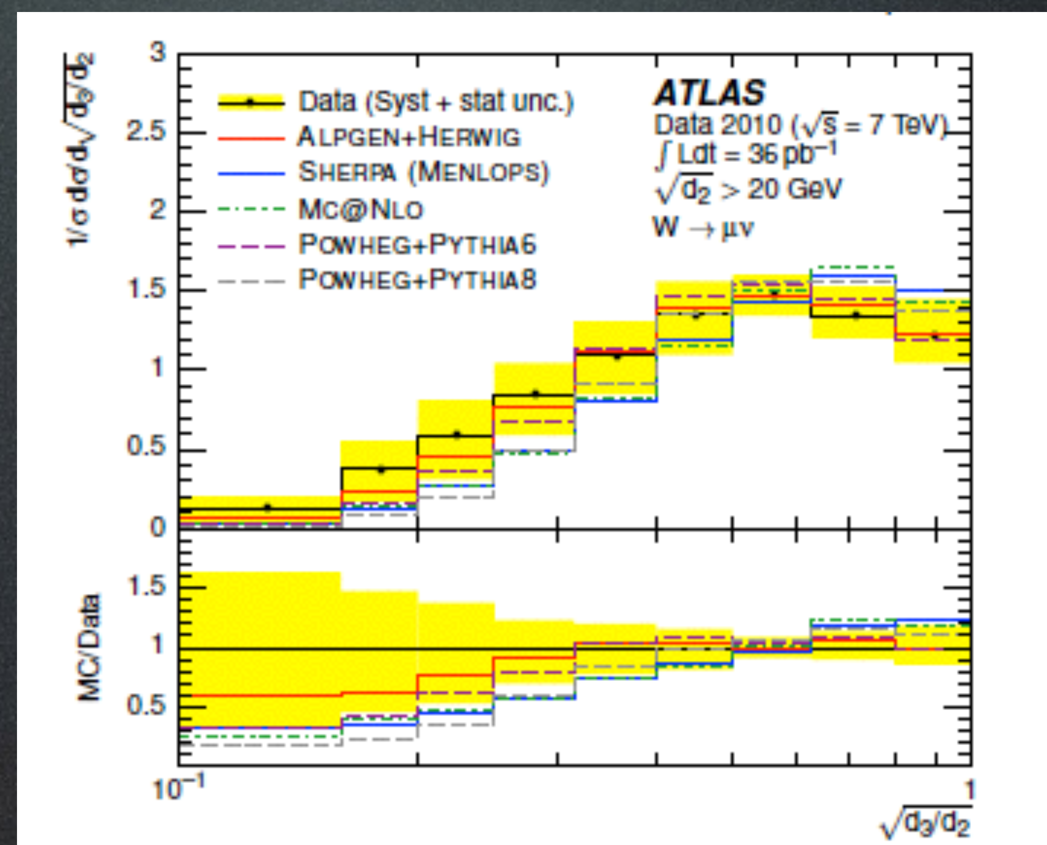
k_t Splitting Scale

$$\sqrt{d_{ij}} = \min(p_{\mathrm{T}i}, p_{\mathrm{T}j}) \times \Delta R_{ij}$$

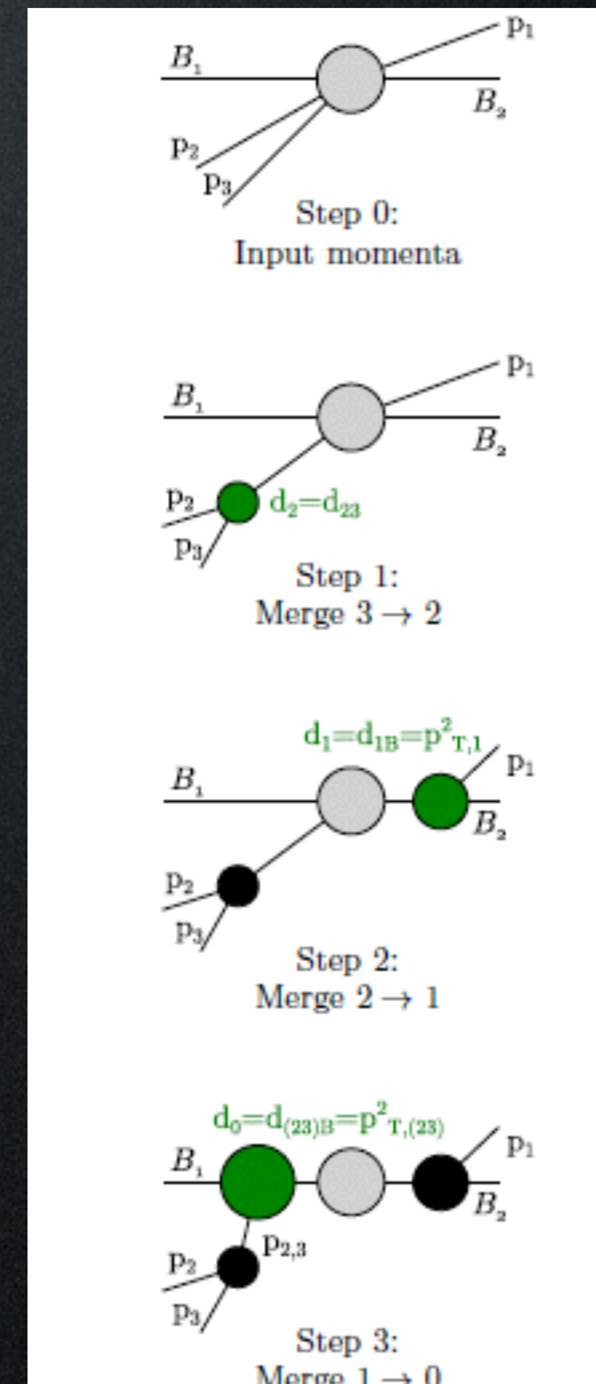
When combining two subjets with k_t algorithm:



arXiv:1203.4606



arXiv:1302.1415



arXiv:1302.1415

Symmetric for heavy particle two body decay

N-Subjettiness

Quantify the degree to which jet radiation is aligned along specific subjet axes.

$$\tau_N \equiv \frac{1}{d_0} \sum_{k=1}^{M} \left(p_{\mathrm{T},k} \times \underbrace{\Delta R_{\min,k}}_{\text{distance to nearest subjet}} \right)$$

$d_0 = R \times$ sum of p_T of all constituents

Smaller values: N or less energy deposits

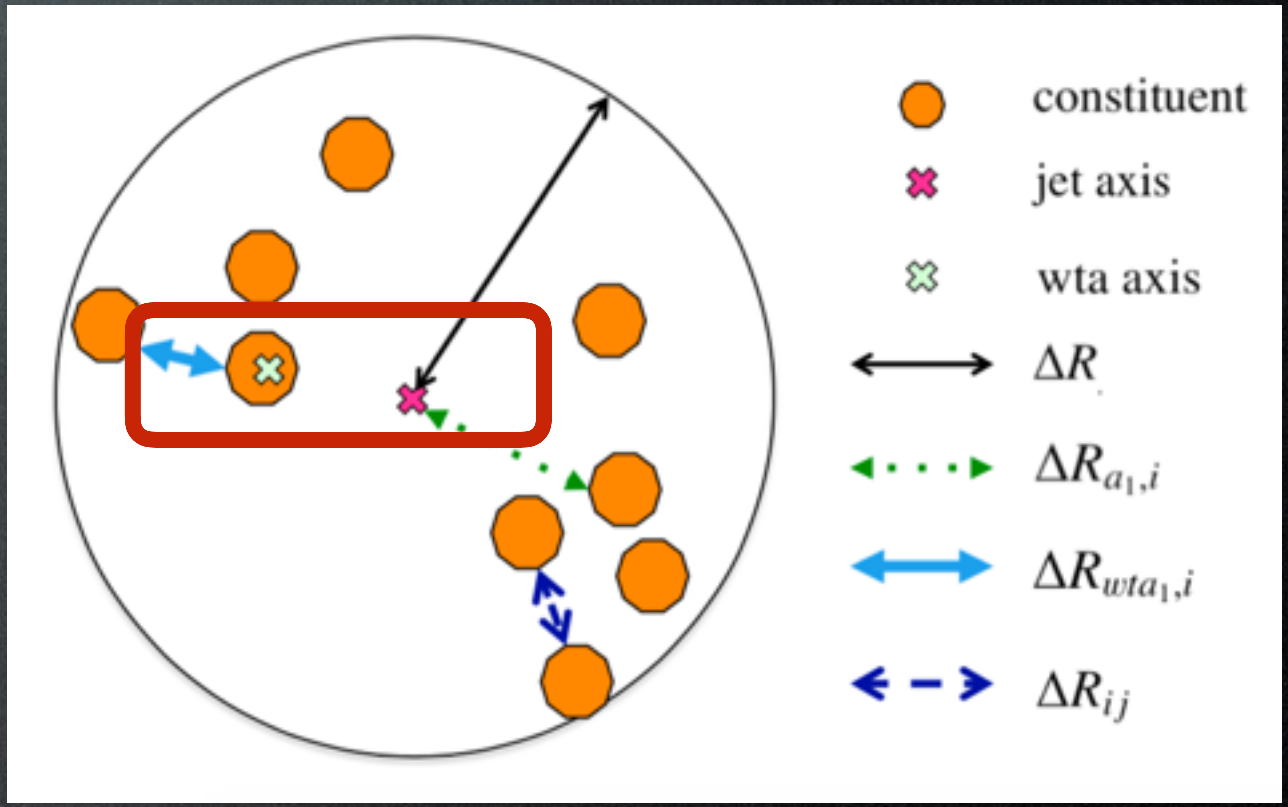
Larger values: more than N energy deposits

$\tau_{N-1} > \tau_N$ for N prong substructure

Calculated by k_t clustering the constituents, and requiring exactly N subjets

Winner Takes All

- Choice of subjet directions introduces an inherent ambiguity
- Sum the constituents, but p_T given by hardest
- Less number of subjets
- Minimize over all possible candidate subjet directions

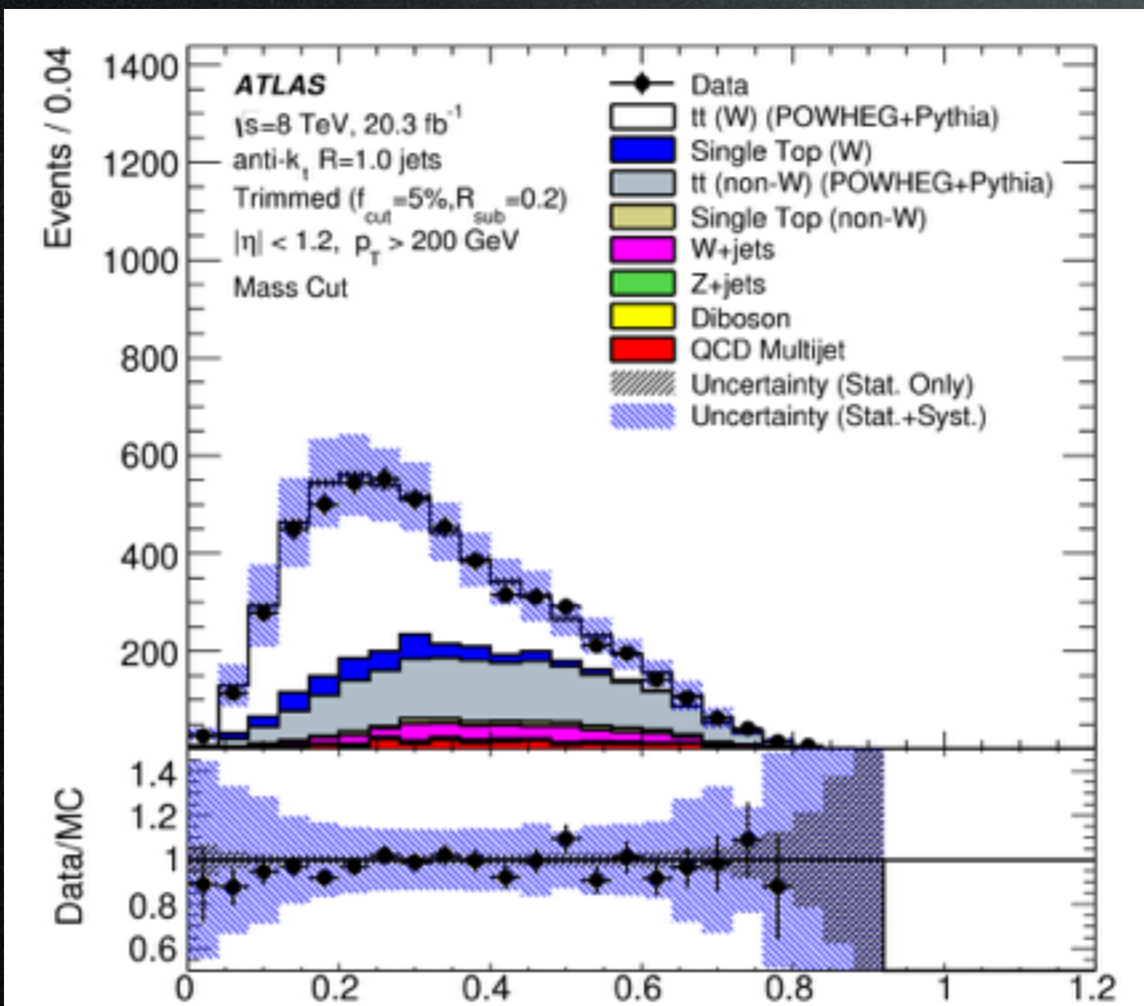


N-Subjettiness

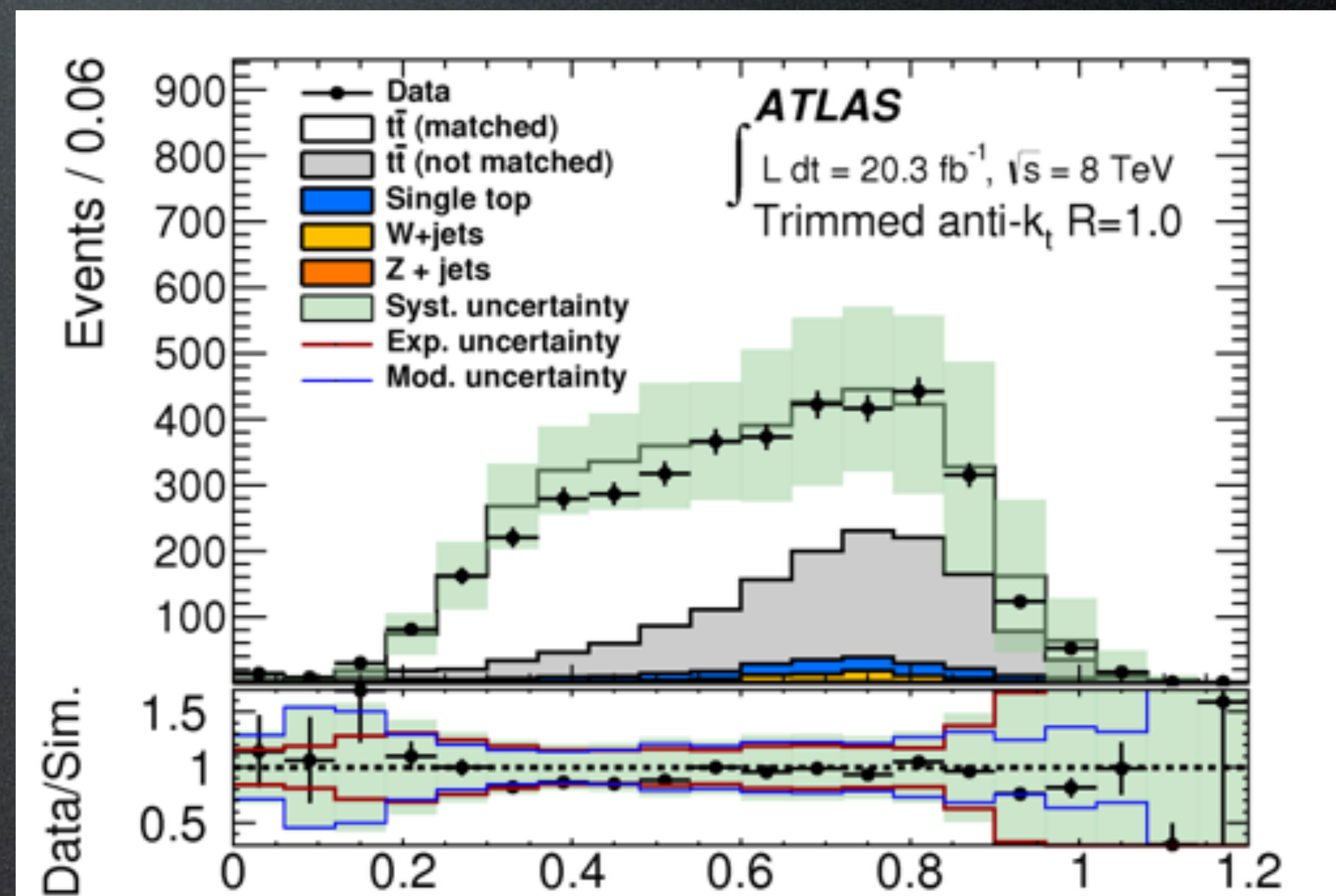
The ratio of τ_N/τ_{N-1} is used as discriminant

More like 2 subjets than 1

More like 3 subjets than 2



Eur. Phys. J. C 76(3) (2016) 1-47



arXiv:1603.03127

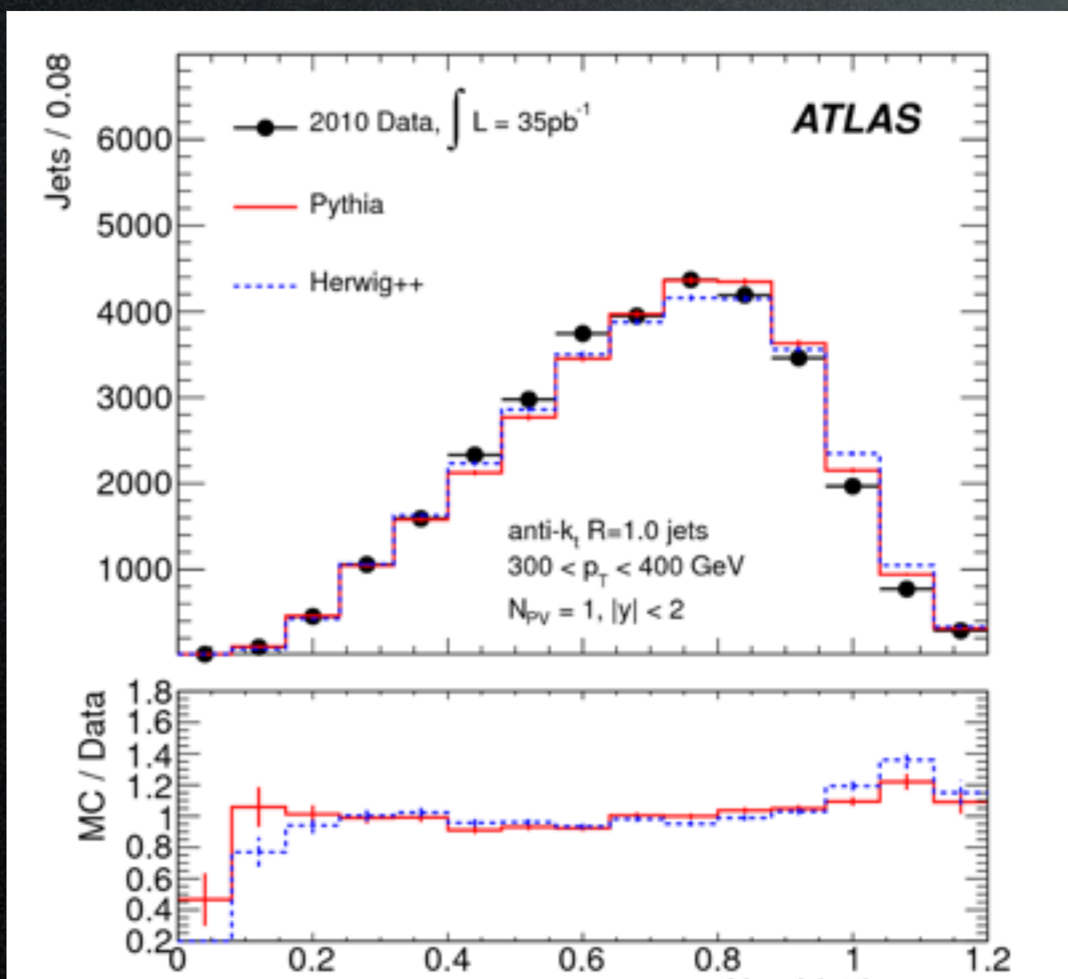
W-like ⟷ MJ-like

Top-like ⟷ MJ-like

N-Subjettiness

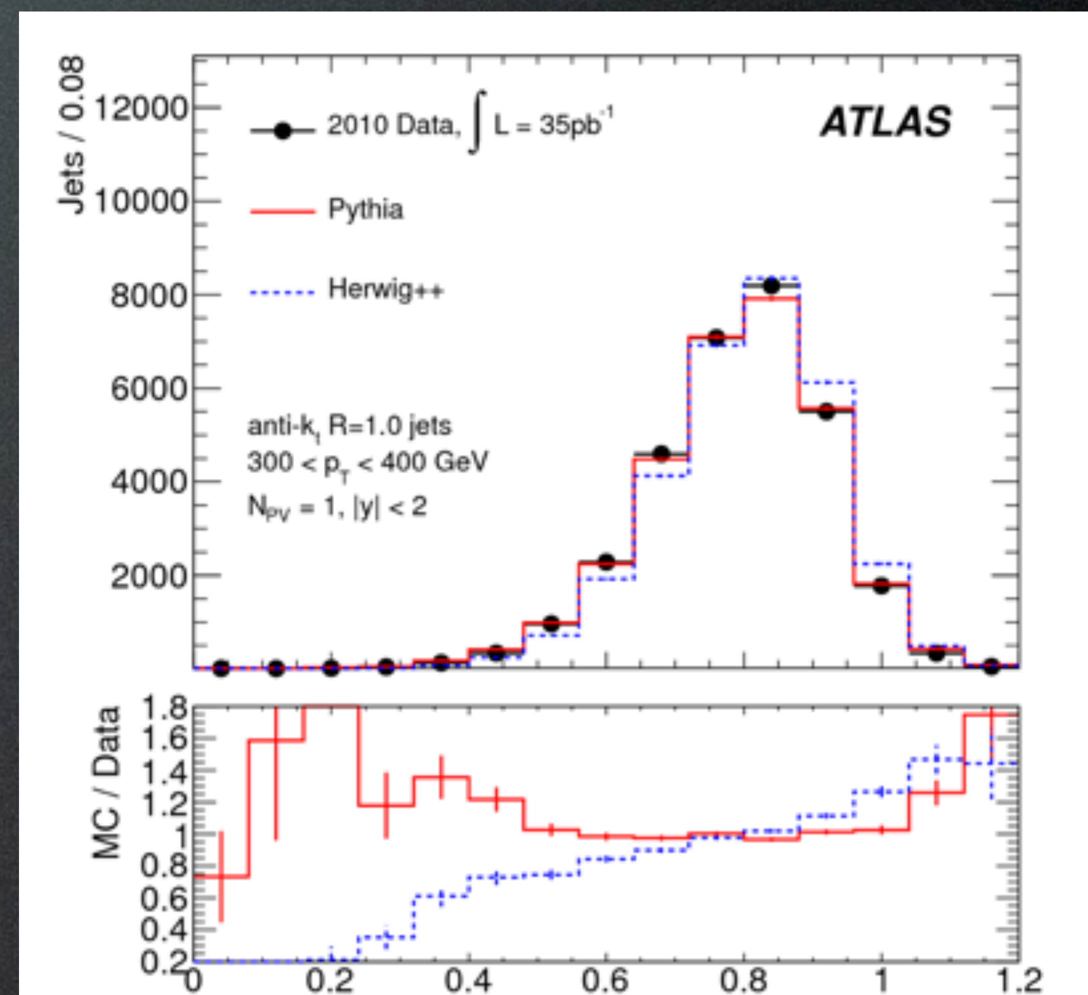
The ratio τ_N/τ_{N-1} is used as discriminant

More like 2 subjets than 1



JHEP 1205 (2012) 128

More like 3 subjets than 2



JHEP 1205 (2012) 128

W-like ⟷ MJ-like

Top-like ⟷ MJ-like

Tilman Plehn, Michael Spannowsky, Michihisa Takeuchi, Dirk Zerwas; arXiv:1006.2833

HEPTopTagger

Browsing through all the branches of jet recombination history

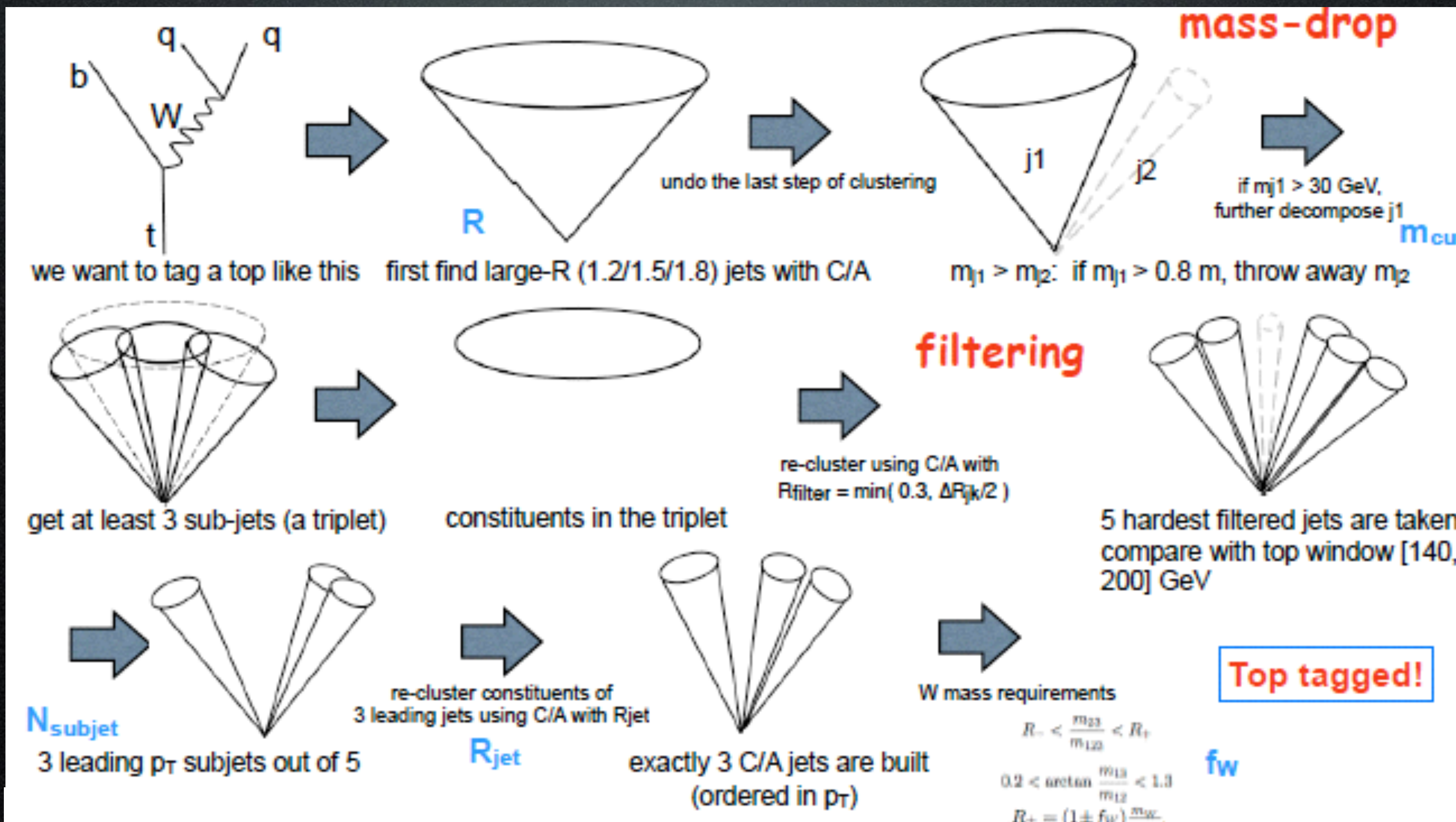


Figure by Xiaoxiao Wang

Ghost association provides a more correct matching of tracks to calorimeter jets. In this technique, tracks are treated as infinitesimally soft, low-pT particles by scaling their pT by a very small number, such as 10–100. These tracks are then added to the list of inputs to the jet algorithm. The low scale means the tracks do not affect the reconstruction of calorimeter jets. However, after the jet algorithm, it is possible to identify which tracks were clustered into which jets. This approach properly accounts for jets with irregular cross-sectional shapes, which would lead to incorrect association in the case of simple ΔR matching.