Jet Physics and Substructure in ATLAS

Dresden, November 2019

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Outline

- **Introduction**
  - Quantum Chromo Dynamics
  - Jets
  - Pile-up
- **Jet reconstruction**
  - Measuring jets with ATLAS
  - Jet inputs
  - Jet Algorithms
- **Jet calibration**
  - Jet Energy Scale
  - Jet Mass Scale
- **Jet Substructure**
  - "Prong-like" variables
    - Top-tagging
  - "Haze-like" variables
    - Quark/gluon-tagging

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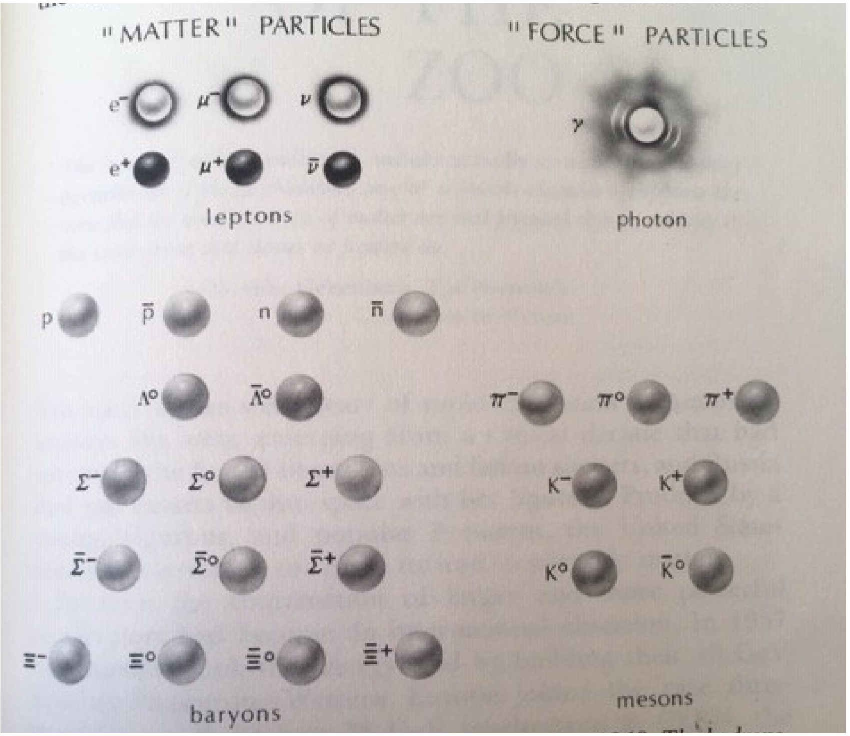
QCD – A very brief introduction

- In 1960 Particle Physics was a chaotic zoo of observations
  - Electrons, muons and neutrinos, called ***leptons***
  - Protons, neutrons, and a plethora of other ***hadrons***



Michael Riordan: *The Hunting of the Quark*

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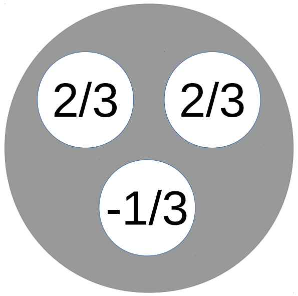
Proton:



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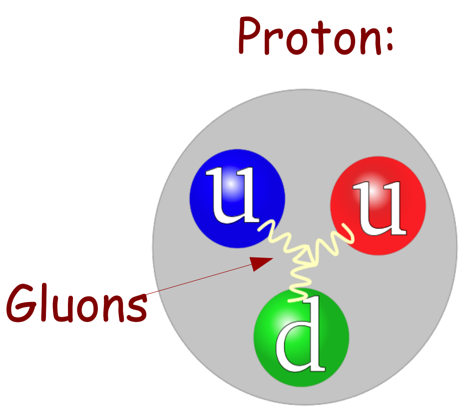
- The quark model had big implications:
  - Pauli exclusion principle demanded a new quantum number
    - ***Color charge***
  - And a new force, holding the quarks together:
    - The ***strong force*** carried by the ***gluon***
    - Weaker at small distances (***asymptotic freedom***)
    - Stronger at large distances (***confinement***)



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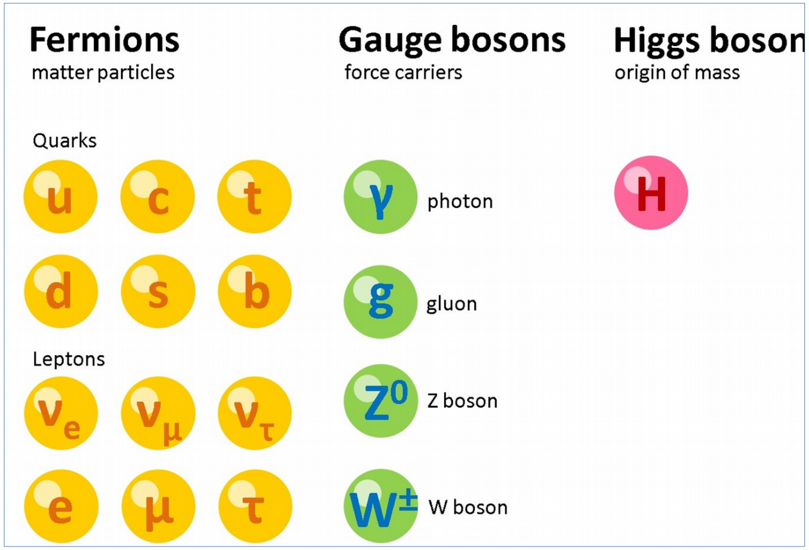
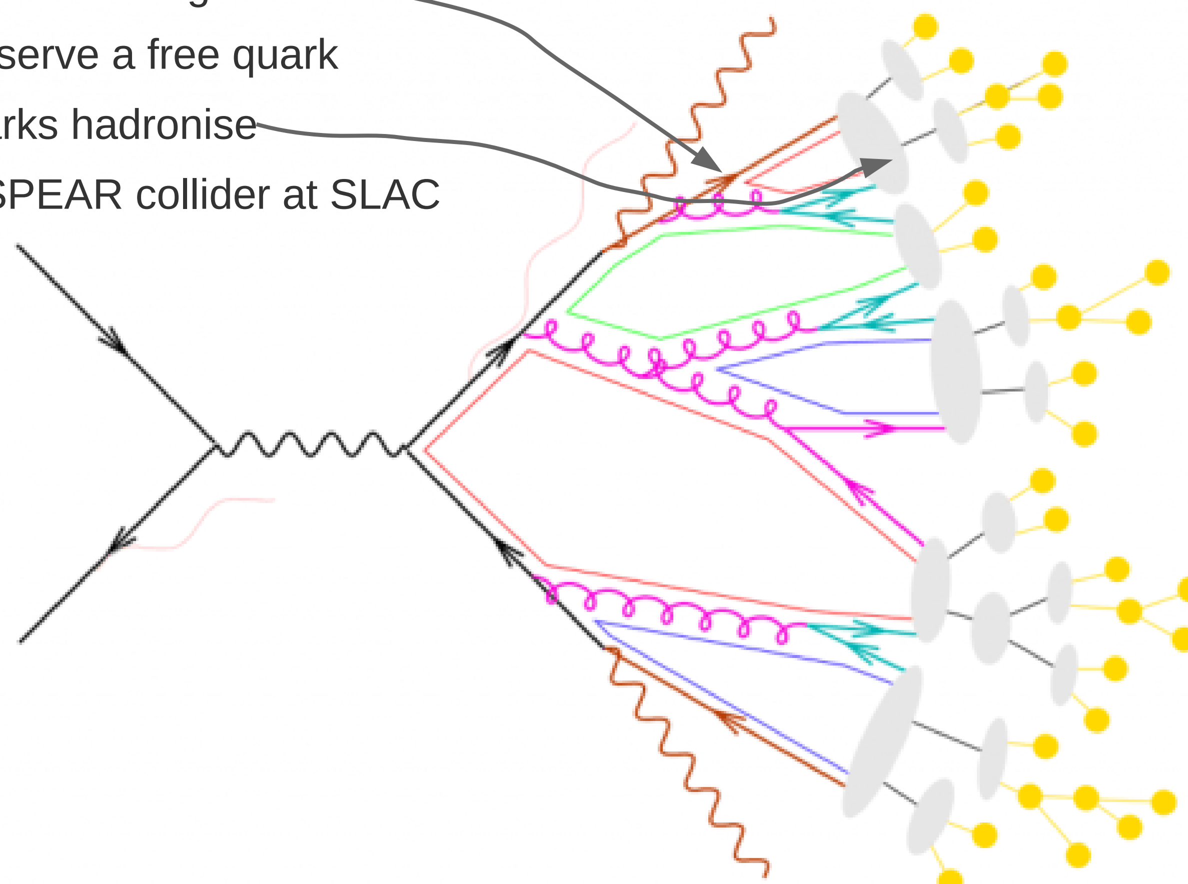
- The ***Standard Model*** of particle physics took form



Jets: Showering and hadronisation

- QCD predicted a detectable signature that was crucial for establishing the theory: ***Jets***!
- Asymptotic freedom: Quarks are ~free at small distances
  - Interact as individual particle at very high energy / short distance
  - Emit "Bremstrahlung" when accelerated in a hard scattering, forming a narrow shower of quarks and gluons
- Confinement: One can never observe a free quark
  - At distances of ~ 1 fm the quarks hadronise
- First evidence in 1975 with the SPEAR collider at SLAC



Jets: Showering and hadronisation

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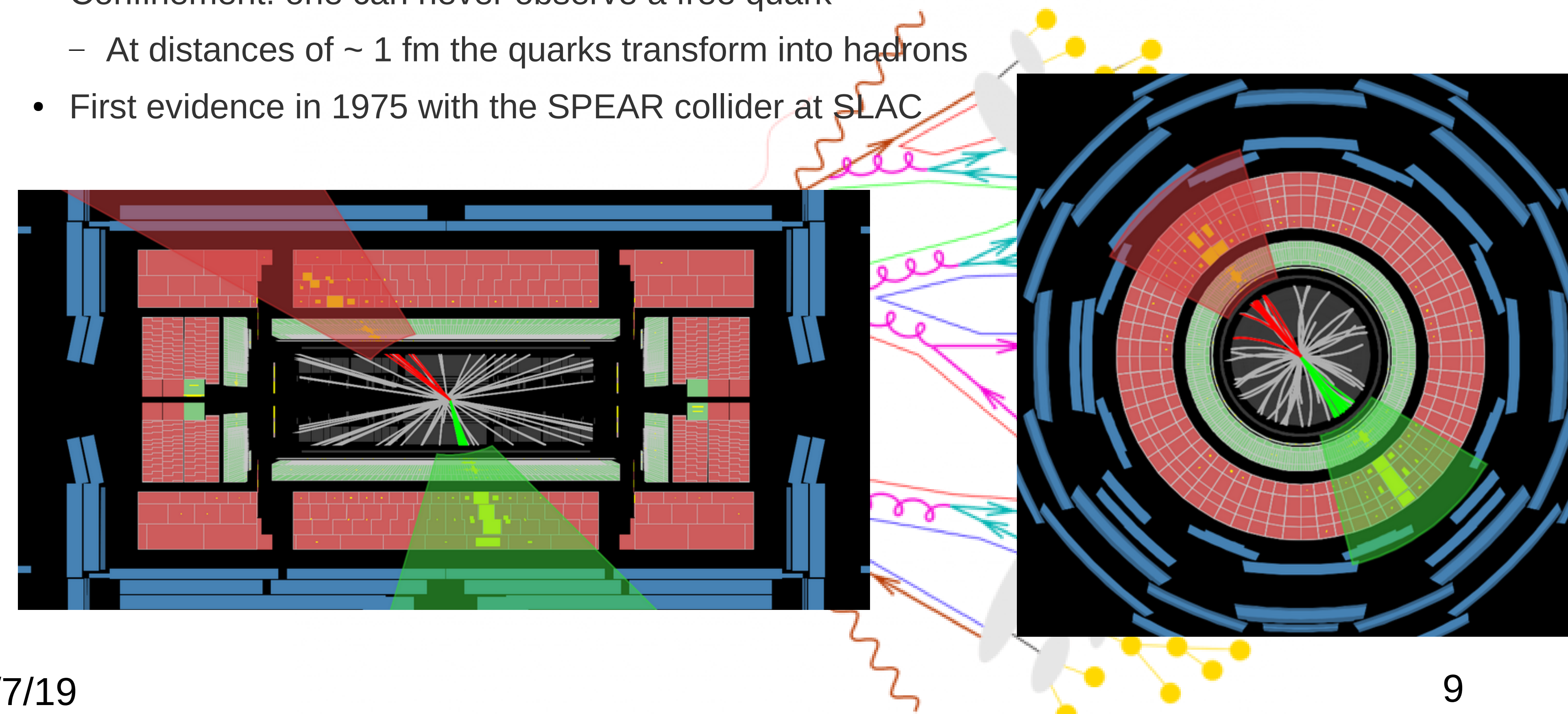
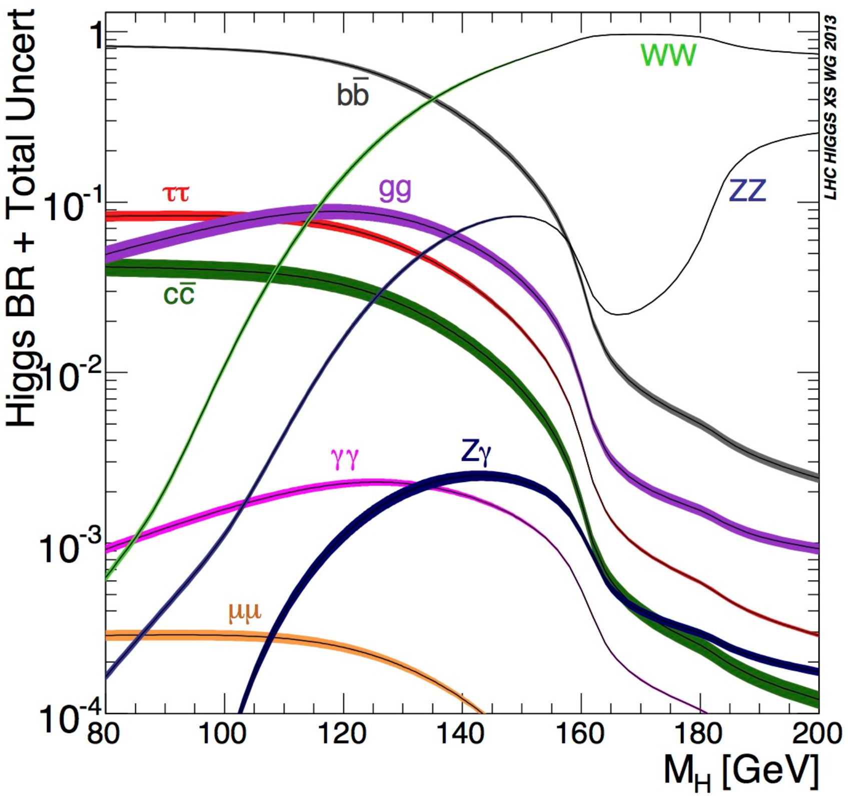
  - Interact as individual particle at very high energy / short distance
  - Emit “Bremstrahlung” like electrons when accelerated forming a narrow shower of quarks and gluons
- Confinement: one can never observe a free quark
  - At distances of ~ 1 fm the quarks transform into hadrons
- First evidence in 1975 with the SPEAR collider at SLAC



Jets: Pros and cons

- ✔ Useful probes of QCD at both soft and hard energy scales
- ✔ Probable final state for interesting processes at collider experiments
  - Higgs decay channels
  - New heavy particles in many SM extensions



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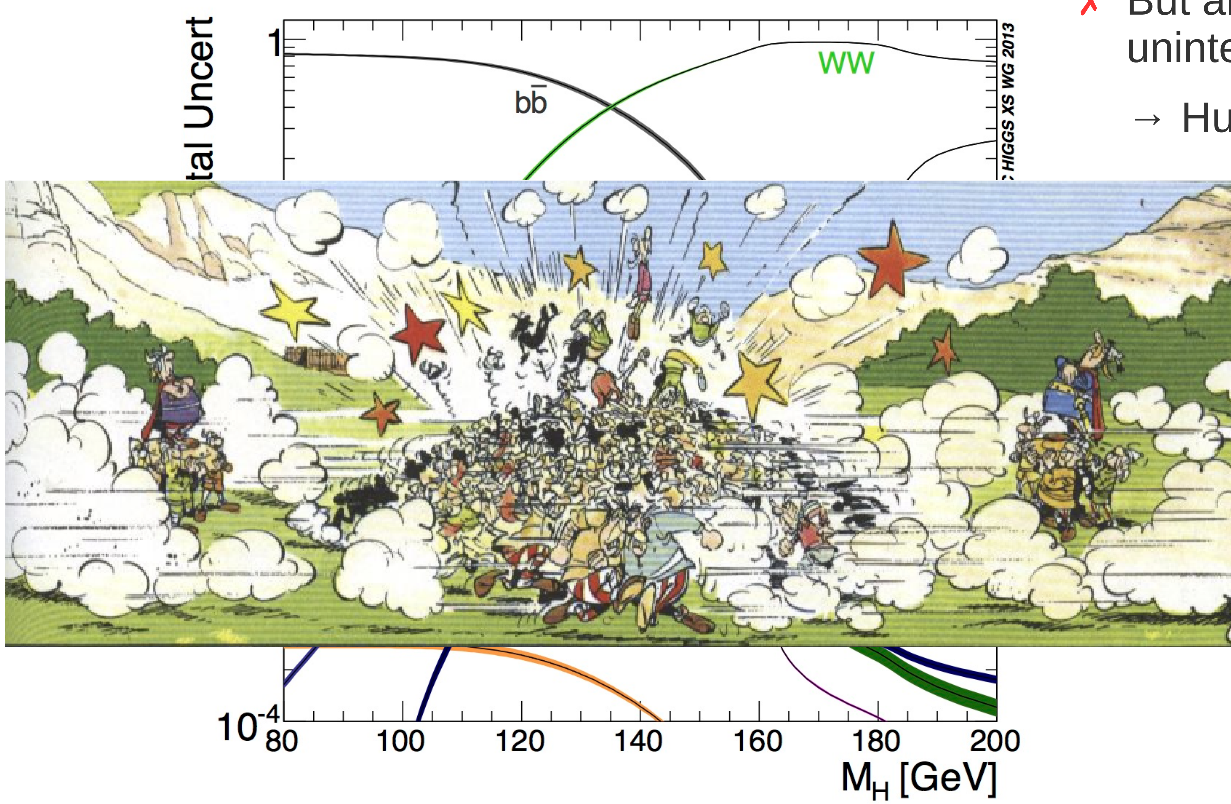


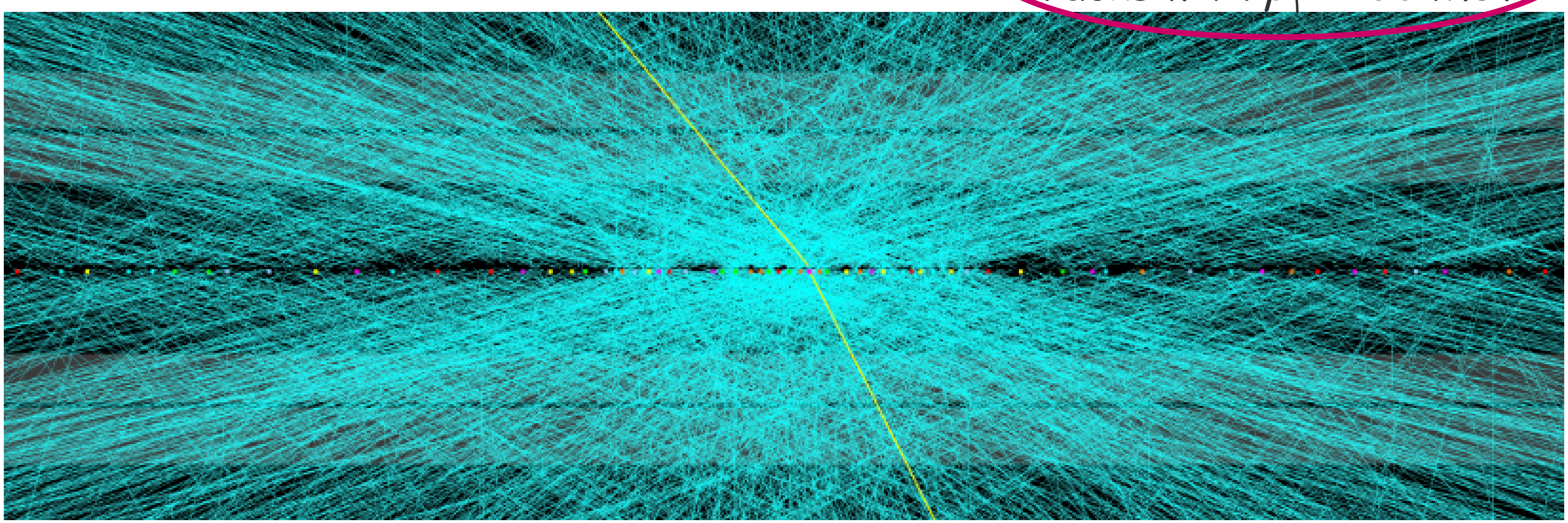
- ✗ But also very probable in uninteresting processes

  → Huge backgrounds!

Pile-up at the LHC

- Very high energy means a ~1:1 correspondence between jet and origin particle
- Protons are collided in bunches every 25 ns to increase luminosity
  - Many collisions per bunch crossing → (In-time) ***Pile-up***
  - Energy deposits from previous/future bunch crossings → (Out-of-time) ***Pile-up***
- Complicates event reconstruction and analyses

65 reconstructed vertices
Tracks with p_T > 100 MeV



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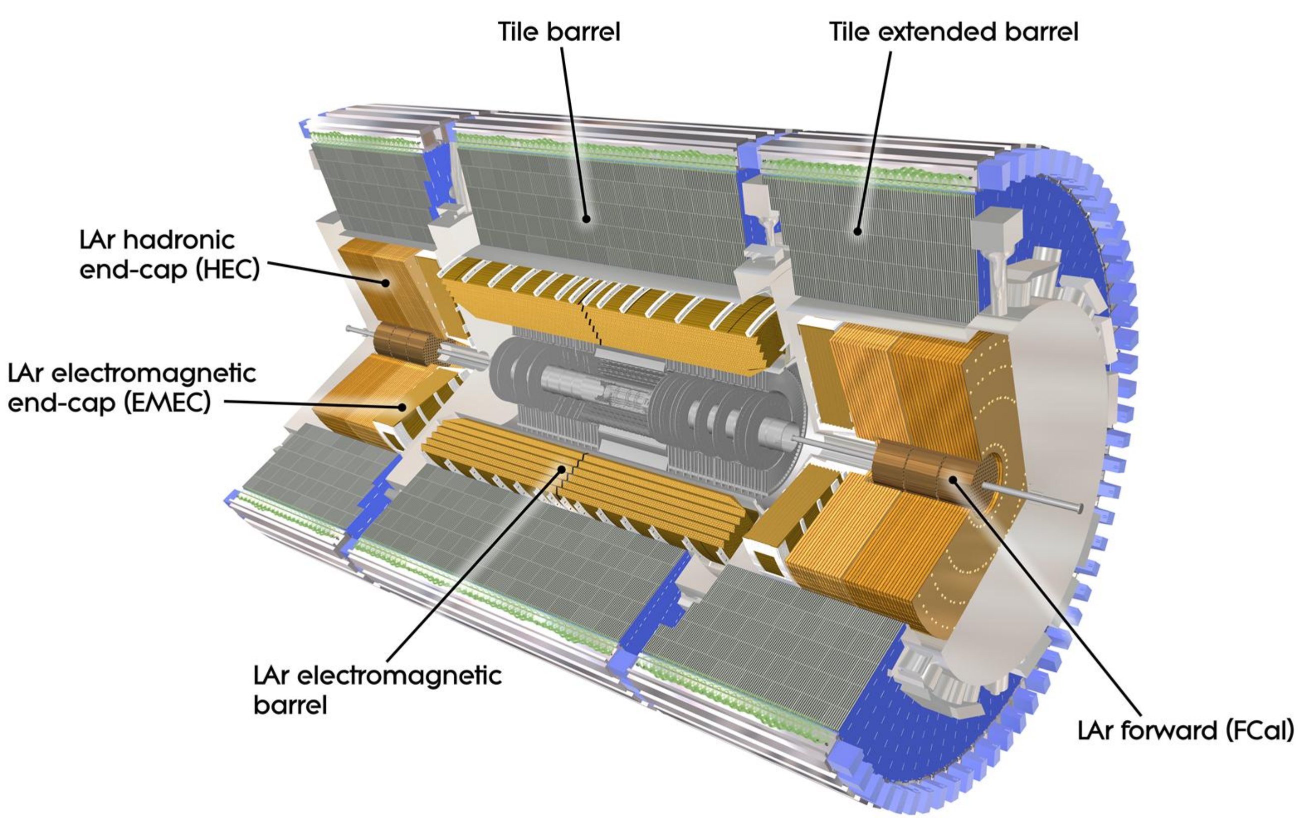
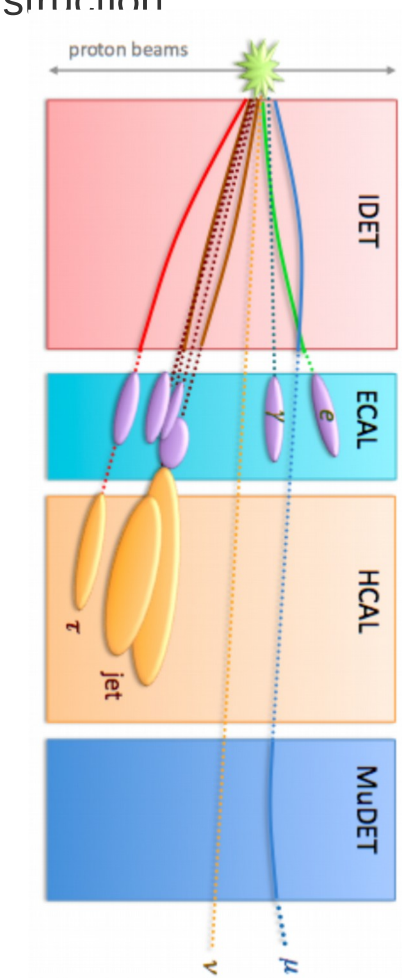
Measuring Jets with ATLAS

- Different subdetectors allow us to identify and reconstruct most particles efficiently
- Calorimeters provide the principal signals for jet measurement
  - Full coverage and fine segmentation
- The inner detector provides precision p_T and direction information of charged particles
  - Vertex reconstruction, pile-up mitigation, refinement of jet reconstruction

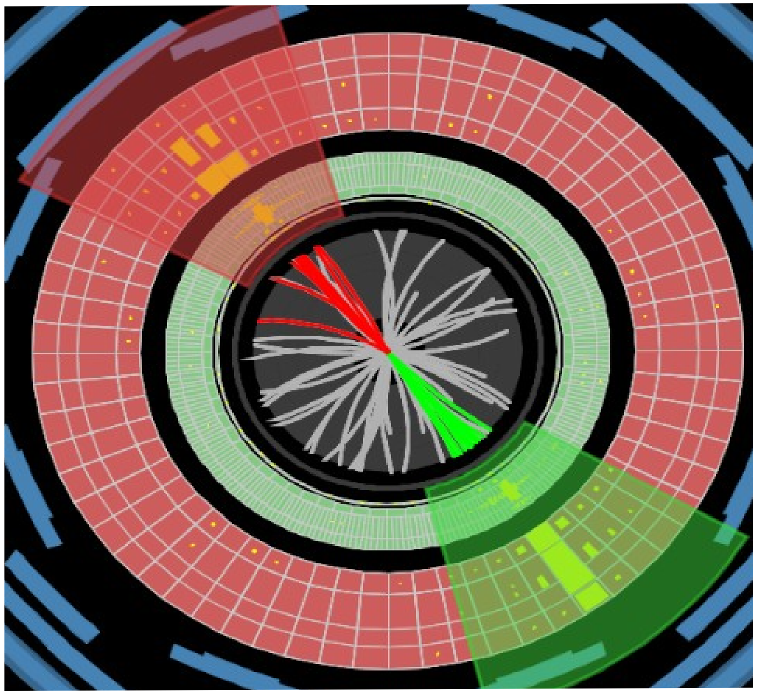




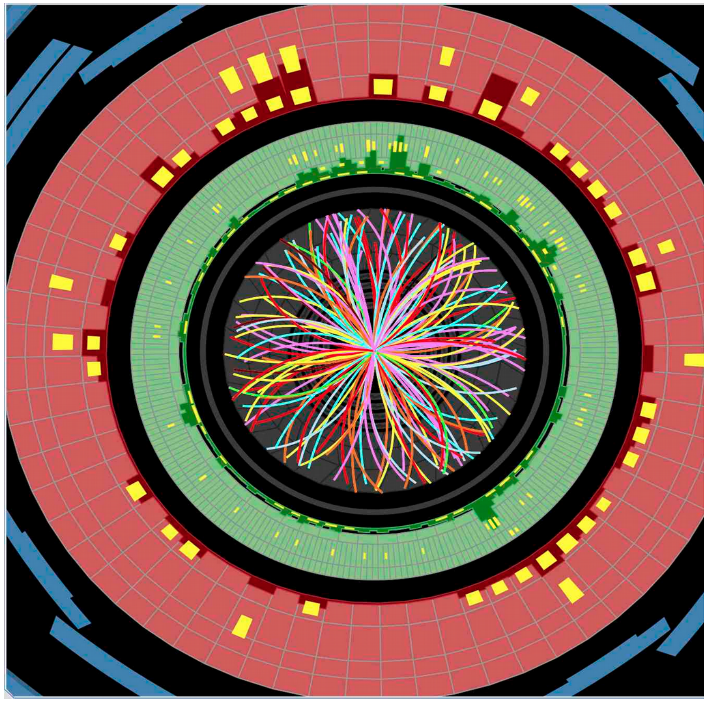
Jamie Boyd's slides

Defining jets

Clearly 2 jets



How many do
we see here?



Inputs to Jet Algorithms

Two main input definitions used in ATLAS:

"Traditional" ATLAS

Topoclusters

Clusters of topologically connected calorimeter signals

Two weighting schemes:

1) (Electomagnetic) EM-scale

2) (Local cell weighting) LCW

"New" to ATLAS

Particle flow (PFlow) objects

Combines information from inner detector and calorimeters:

Tracks from charged particles

Topoclusters not associated to tracks

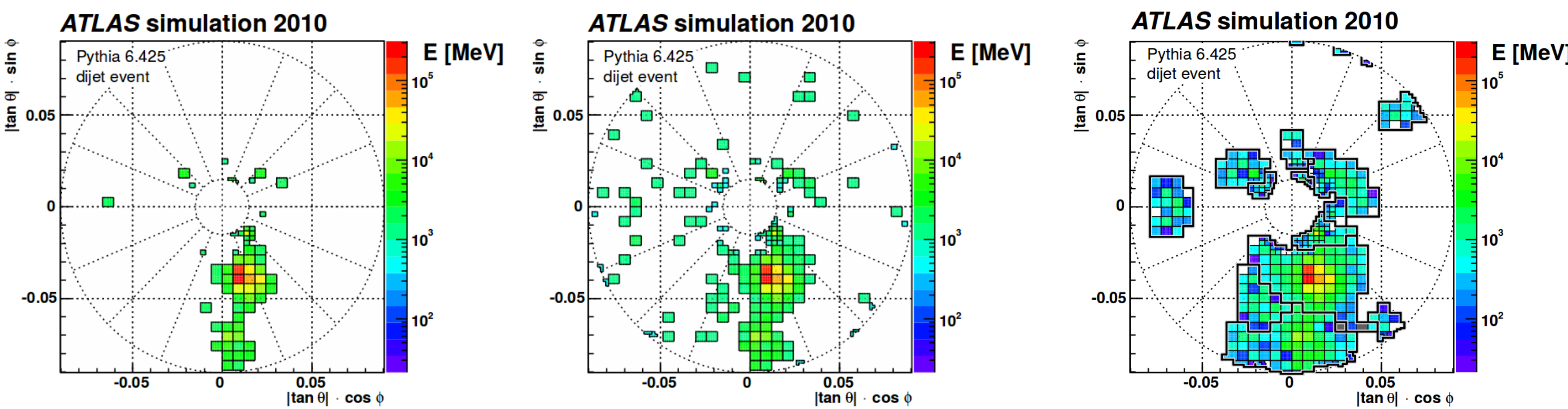
More jet inputs combining tracks and calorimeter cluster are being studied:

- Track Calo Cluster (TCC)
- Unified Flow Object (UFO)

Topological Clusters

1) Clustering: Initialised by high energy seeds and expanded in two steps:

a) $E > 4\sigma_{noise}$ b) $E > 2\sigma_{noise}$ c) $E > 0$



2) Origin correction: Modifies topocluster 4-momentum to point back at the primary vertex
   - Improves η-resolution without changing the energy

3) Rescaling:
   - ***EM-scale***: All cell energies are weighted according to the electromagnetic scale calibration
   - ***LCW***: Topoclusters are weighted depending them being electromagnetic or hadronic due to lower response in hadronic calorimeter

Particle Flow

Many benefits to combining information from trackers and calorimeter

- Tracking detectors:
  - Better resolution for low p_T particles
  - Better angular resolution
  - Can trace particle to either the hard-scatter interaction or pile-up
- Calorimeters:
  - Better resolution for high p_T particles
  - Captures neutral particles

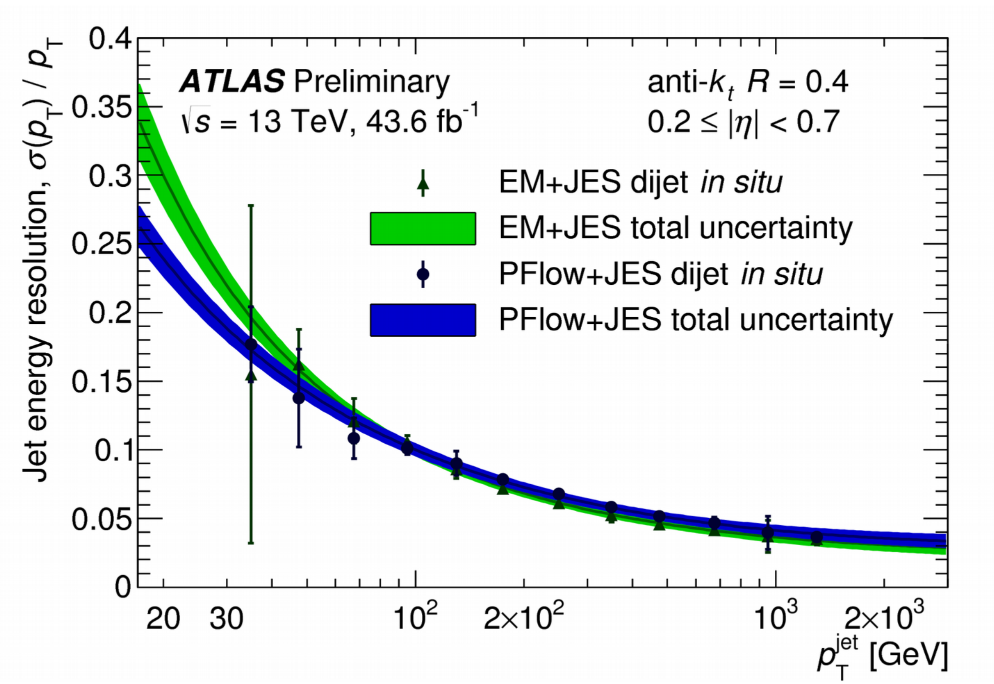
Rough sketch of the algorithm:

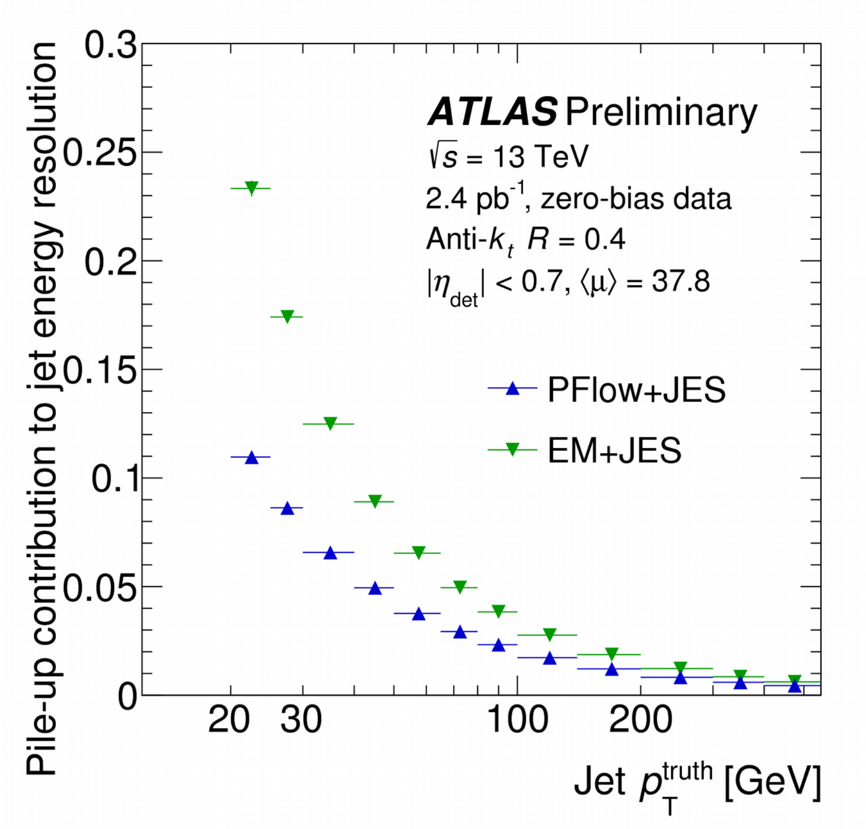
1) Select “high quality” tracks coming from the primary vertex $p_T < 40$ GeV
2) Match track to corresponding topocluster(s)
3) Subtract energy from the cluster depending on position and track p_T
4) Selected tracks and remaining topoclusters constitute PFlow objects passed to the jet algorithm

More PFlow

- Improved p_T resolution
- Improved angular resolution
- Less pile-up contribution

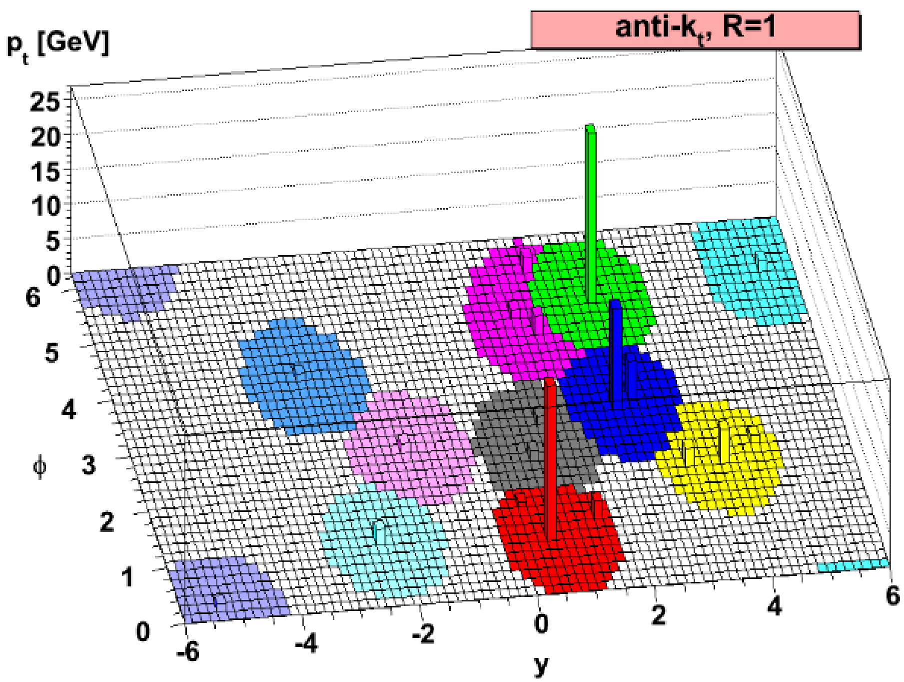
} Better E_t^{miss} !





Jet Finding Algorithms

- Intuitive way: Define a cone of fixed size and sum up all momenta inside
- **NB!** Jet algorithms must be insensitive to arbitrarily soft and collinear splittings in order to make theoretical predictions we can compare to data!
- Sequential algorithms to the rescue!



Anti-kt paper

- Generalised definition:
  1) Define the two distances, p={-1, 0, 1}:

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}, \quad d_{iB} = k_{ti}^{2p}$$

  2) If d_{ij} is smallest, combine *i* and *j*
  3) Else, declare *i* a jet and remove it
  4) Repeat until no more particles remain
- Most popular is p = -1: the **Anti-kt algorithm**
  - Clusters hardest constituents first
  - Gives nearly conical jets
- *R* is the radius parameter
  - Typically *R* = 0.2, 0.4, 0.6, 1.0, 1.2

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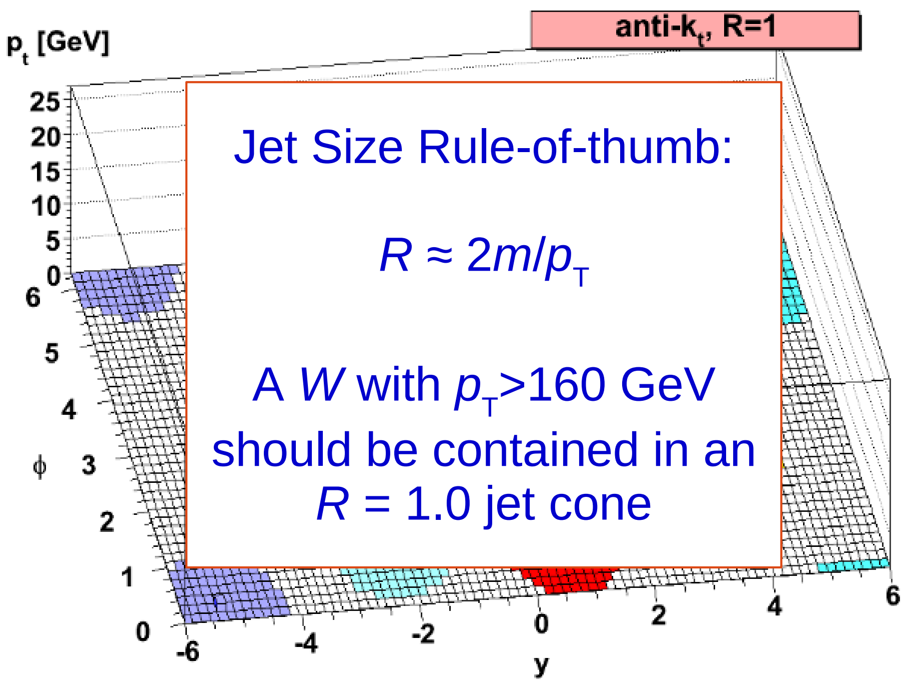

Jet Size Rule-of-thumb:

$R \approx 2m/p_T$

A W with p_T>160 GeV should be contained in an R = 1.0 jet cone

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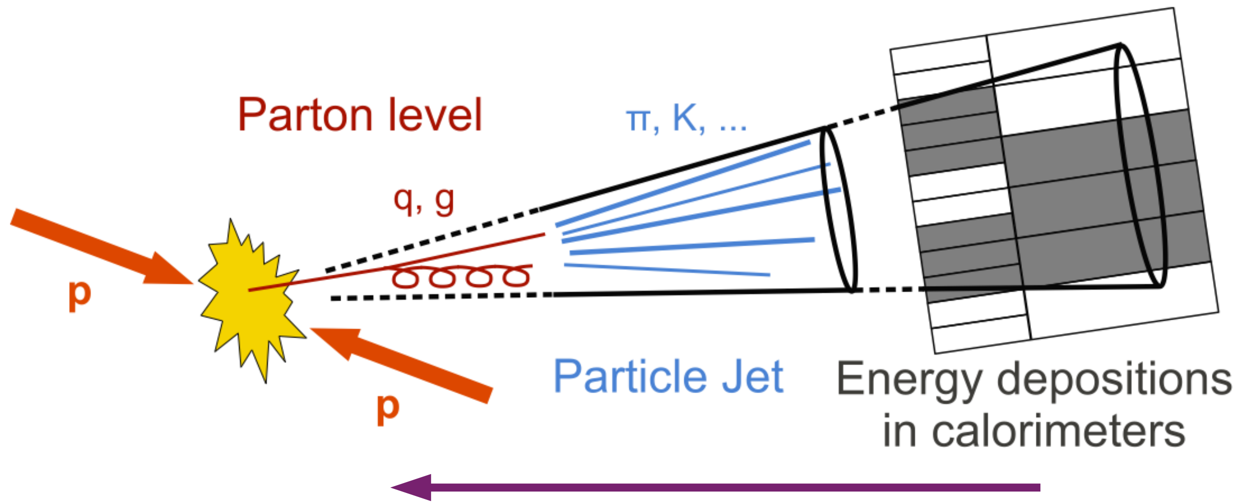
Why calibrate?



To correct the translation of calorimeter signal to original parton for detector effects:

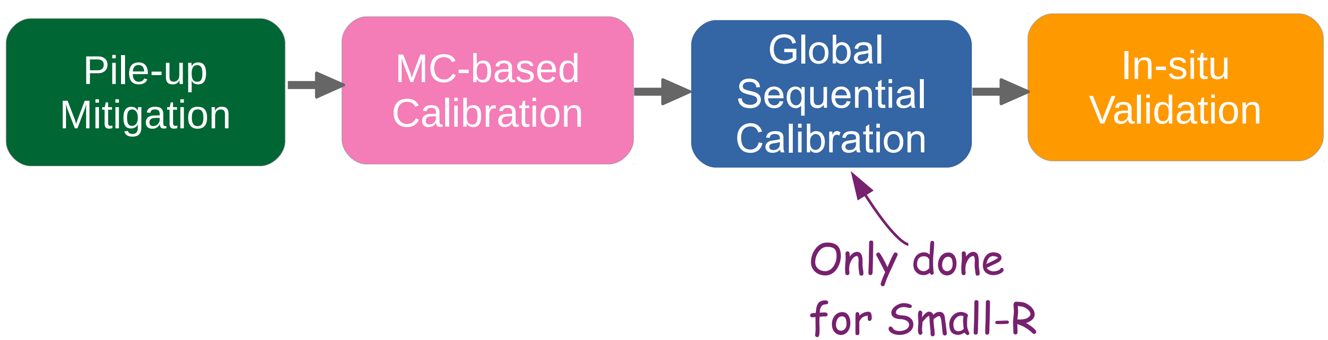
- Dead material
  - Energy deposited in non-sensitive regions of the detector
- Calorimeter non-compensation
  - Partial measurement of the energy deposited by hadrons
- Punch-through
  - Showers extending beyond the calorimeters
- Pile-up
  - Additional energy deposits from other particles
- Out-of-cone
  - Part of the particle shower not included in the jet cone
  - Worse for low p_T jets because of magnetic field
- Energy deposits below noise threshold

Jet Energy Scale

- Calibrations are provided for several jet definitions
  - "Small-R jets": **Anti-kt R=0.4,** based on **Particle Flow**
  - "Large-R jets": **Anti-kt R=1.0,** based on **Local Cell Weighting**
  - "R-Scan jets": Anti-kt R=0.2 and 0.6 LCW jets
  - Heavy Ion Jets

} Focus of this talk

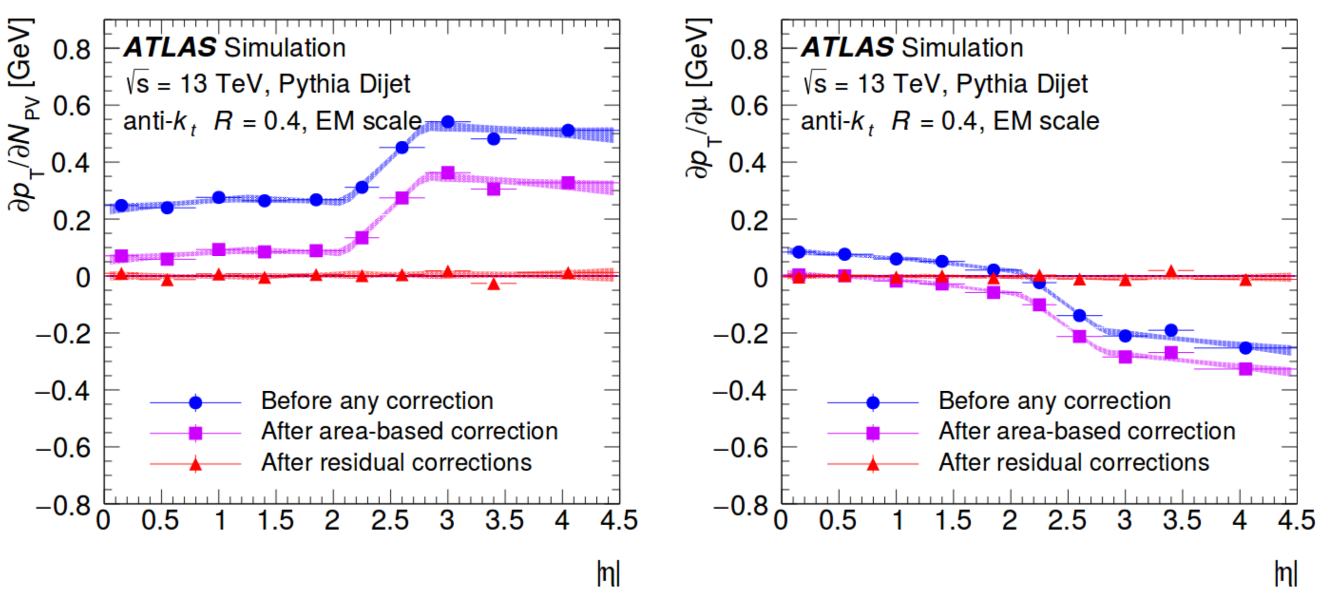
- Calibration differs slightly for the different definition, but principles are the same:



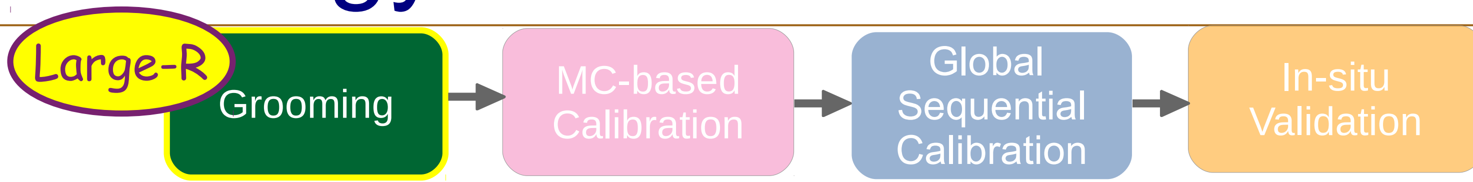
Jet Energy Scale

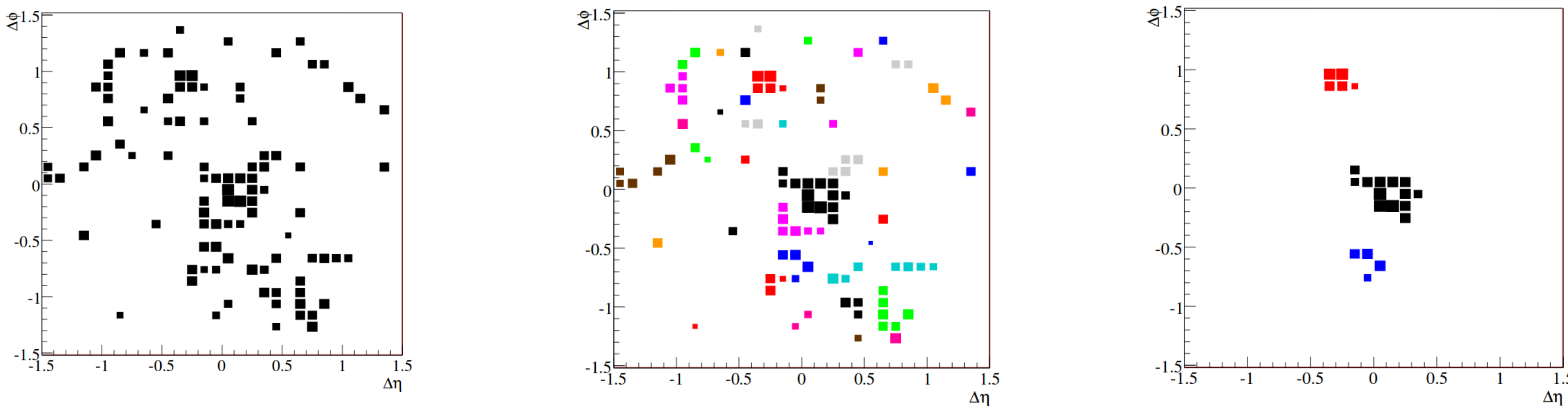
- Pile-up subtraction done in two steps
  - **Area based subtraction** of the per-event pile-up contribution to the p_T of each jet
  - **Residual N_{PV} and μ based subtraction**

$$p_T^{corr} = p_T^{reco} - \rho \times A - \alpha (N_{PV} - 1) - \beta \langle \mu \rangle$$



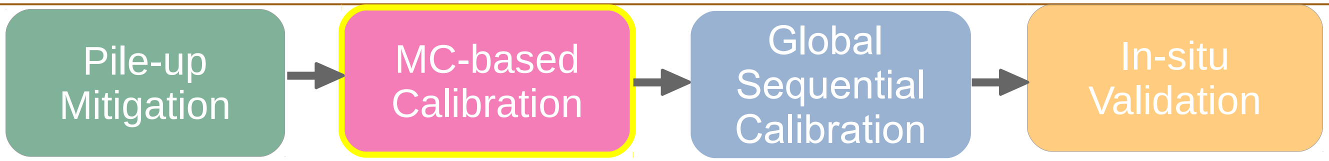
Jet Energy Scale



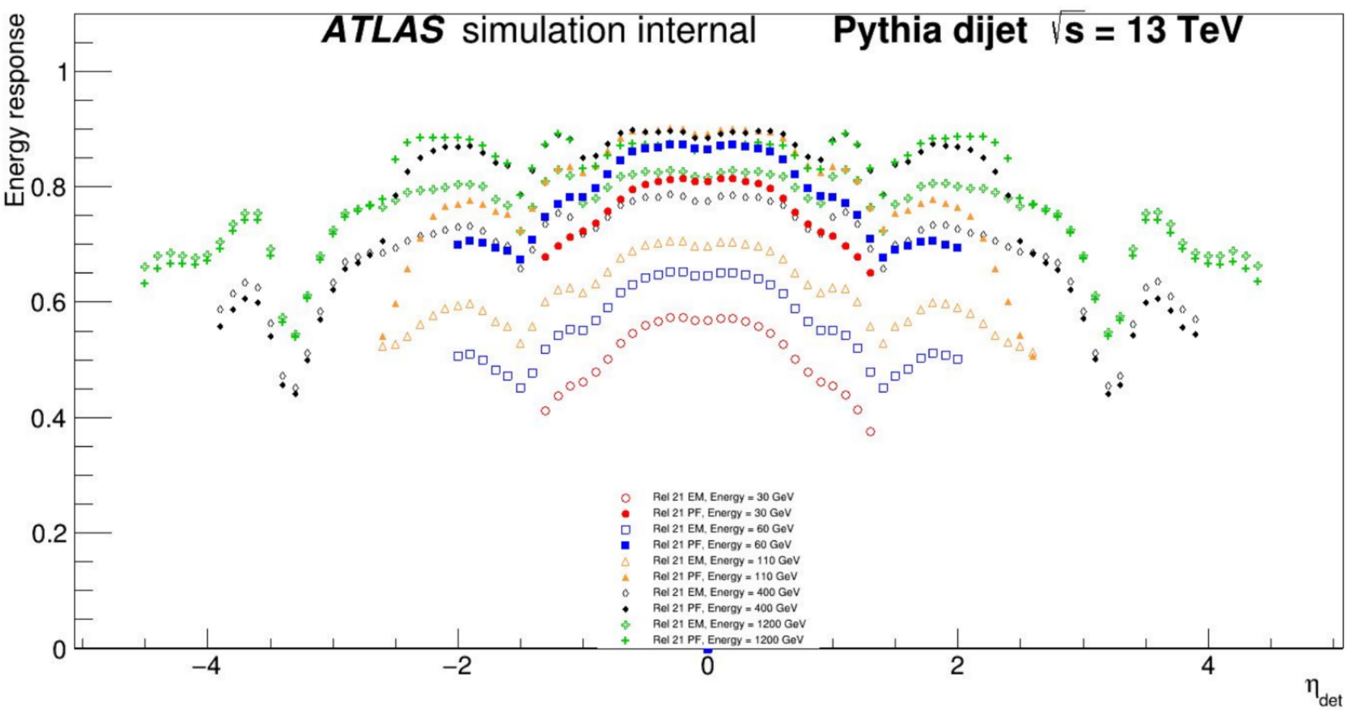


- **"Grooming" techniques reduce the contribution of pile-up and soft/wide-angle emissions**
- Improves the p_T and mass resolution
- Makes substructure variables less dependent on fragmentation
- Full calibration provided for **trimmed jets**
- Reclusters the R=1.0 jet into constituent subjets with R_{sub}= 0.2
  - Removes subjets with $p_T^{subjet} / p_T^{jet} < 0.05$
  - Recalculates the jet four-momentum from the remaining constituents

Jet Energy Scale



- Energy response differs across η
  - Especially at boundaries between different calorimeter technologies and granularities
- Isolated reco jets are matched to truth jets and compared



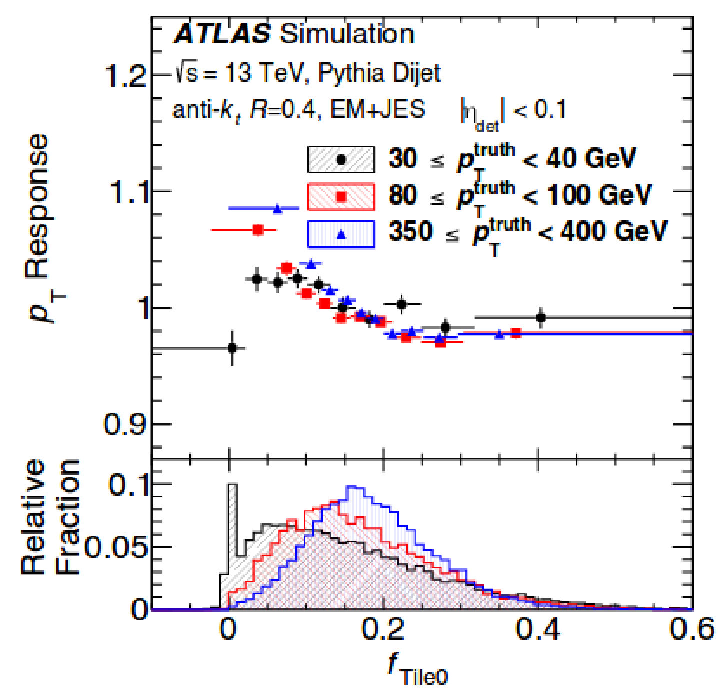
Two/three corrections are applied

1) **Absolute JES correction**
   - Response: Mean of a Gaussian fit to E^{reco}/E^{truth}
2) **Jet η correction**
   - Response: η^{reco}-η^{truth}
3) **Jet mass correction** (just for large-R)
   - Response: m^{reco}/m^{truth}

Jet Energy Scale

Pile-up Mitigation → MC-based Calibration → **Global Sequential Calibration** → In-situ Validation

- Only done for Small-R jets!
- The GSC is applied to adjust for:
  - **Non-compensation:** Difference in response to hadrons, leptons and photons
  - **Flavor dependence:** Difference in response to quarks and gluon
  - **Punch-through:** Jets extending beyond the calorimeters
- Calibration is done in five/six steps (LCW/PFlow)
- Uses observables related to
  - **Energy deposits in the calorimeter**
  - **Track information of jets**
  - **Activity in the muon segments**
- For each observable a 4-momentum correction is derived as a function of p_T^{truth} and $|\eta|$
- Does not change the average energy



Jet Energy Scale

Pile-up Mitigation → MC-based Calibration → Global Sequential Calibration → **In-situ Validation**

- Last step is the residual in-situ calibration
  - Corrects for potential differences between data and MC
  - Applied only to data
- The in-situ methods rely on a well-calibrated reference object in the event to constrain the true jet p_T

$$Response = R = \left\langle p_T^{jet} / p_T^{ref} \right\rangle$$

$$Correction\,factor = \frac{R_{MC}}{R_{data}}$$

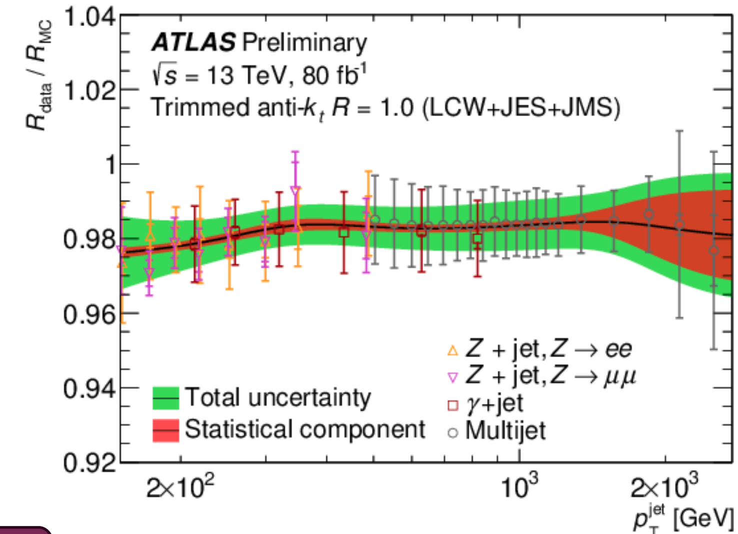
- Consists of a set of sub-steps:

η-intercalibration → *Z*+jet balance / *γ*+jet balance → Multijet balance

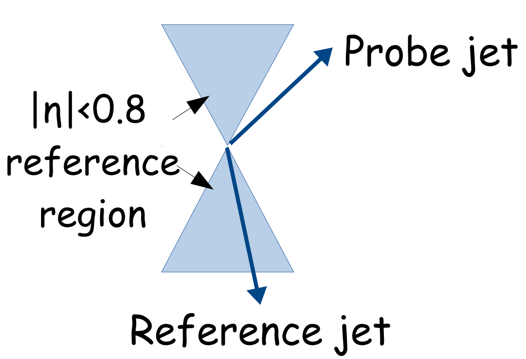
Jet Energy Scale

Pile-up Mitigation → MC-based Calibration → Global Sequential Calibration → In-situ Validation

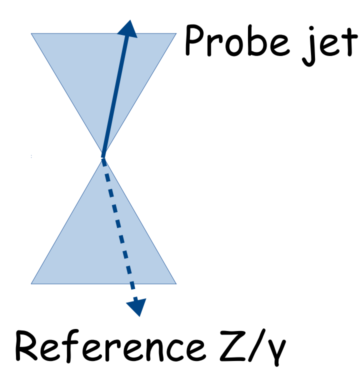
- The results of the three in-situ methods are combined to give a continuous and smooth calibration curve
- Each set of measurements is interpolated using splines
- Combined to a single curve by doing a weighted average in fine bins of p_T
  - Weights are determined by the uncertainties



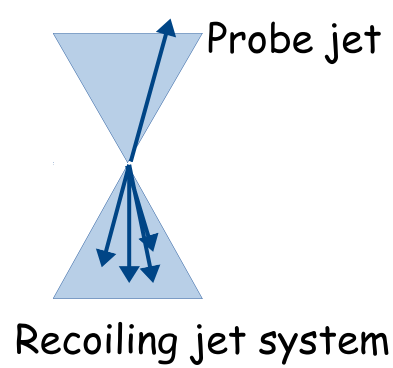
η-intercalibration



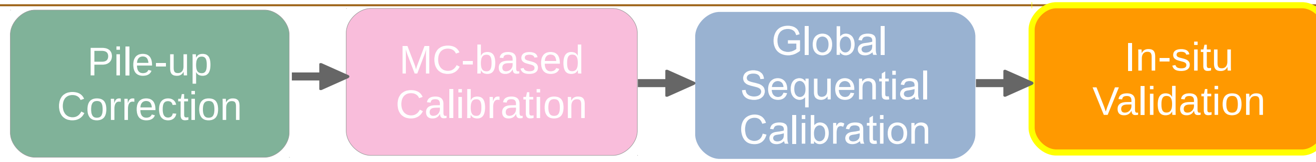
Z/γ+jet balance



Multijet balance



Jet Mass Scale



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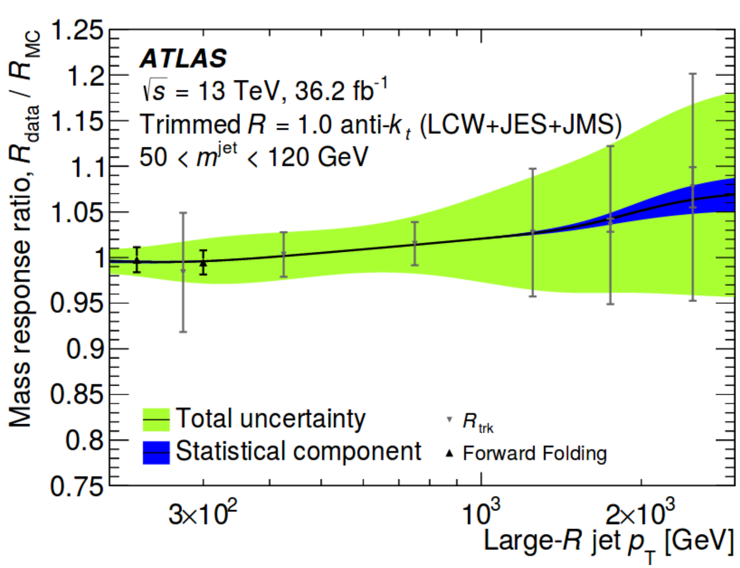
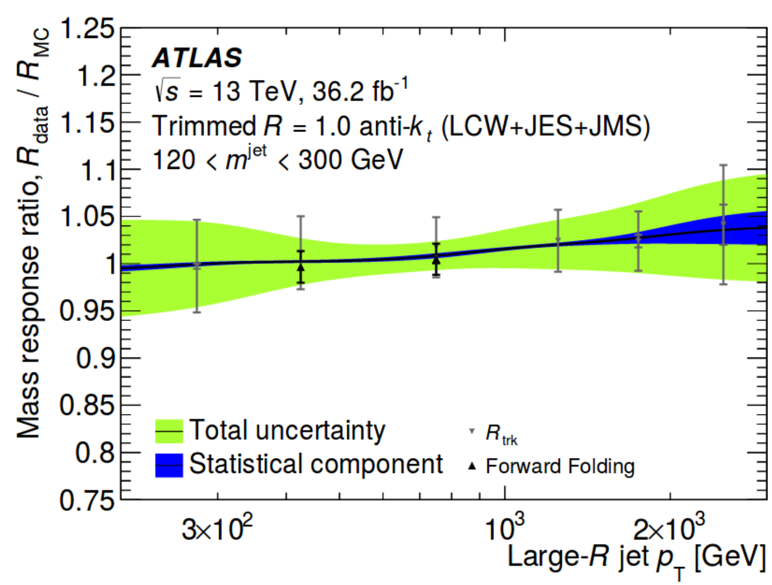
- Two in-situ methods are employed to correct the calorimeter mass response
  - **Forward folding**
    - Uses $t\bar{t}$ events with hadronically decaying boosted *W*s and tops
    - Fits the mass peaks and jet mass response of the *W* and top
  - **The R_{trk} method**
    - Uses track jets to provide an independent measurement of the jet mass scale
- The combination is done separately for each mass bin





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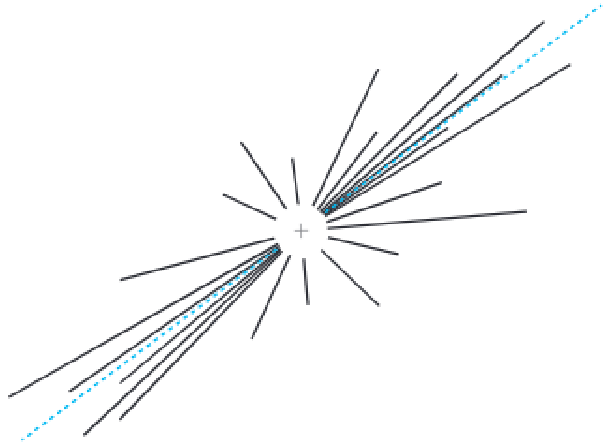
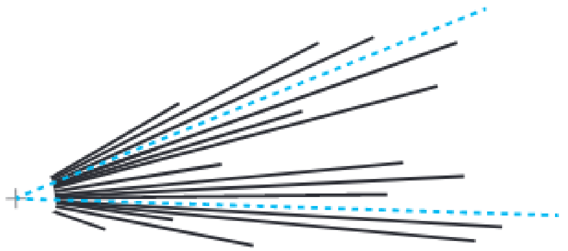
Why study substructure?

- To identify what kind of particle initiated the jet
  - Light quark, gluon, or something heavy?
- Measuring heavy SM particles (W/Z/top/H) as well as potential new heavy resonances is central for big parts of the ATLAS physics program
- At LHC energies, heavy particles are often produced with a large Lorentz boost
  - Leads to collimated decay products
  - Visible by the internal structure of jets
- Three main substructure variables: Mass, “Prong-ness” and “Hazy-ness”



Particle decaying at rest



Boosted particle decay

Combined Jet Mass

- Mass is the ID-card of particles
- Measuring jet mass requires granularity finer than the size of the jet
  - Depend on both energy and opening angle between decay products
- Two definitions are used
  - Calorimeter Mass:

$$m^{\text{calo}} = \sqrt{\left(\sum_{i \in J} E_i\right)^2 - \left(\sum_{i \in J} \vec{p}_i\right)^2}$$

  - Track-Assisted Mass:

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

- Best performance is obtained from a linear combination:

$$m^{\text{comb}} = w^{\text{calo}} \times m^{\text{calo}} + w^{\text{TA}} \times m^{\text{TA}}$$

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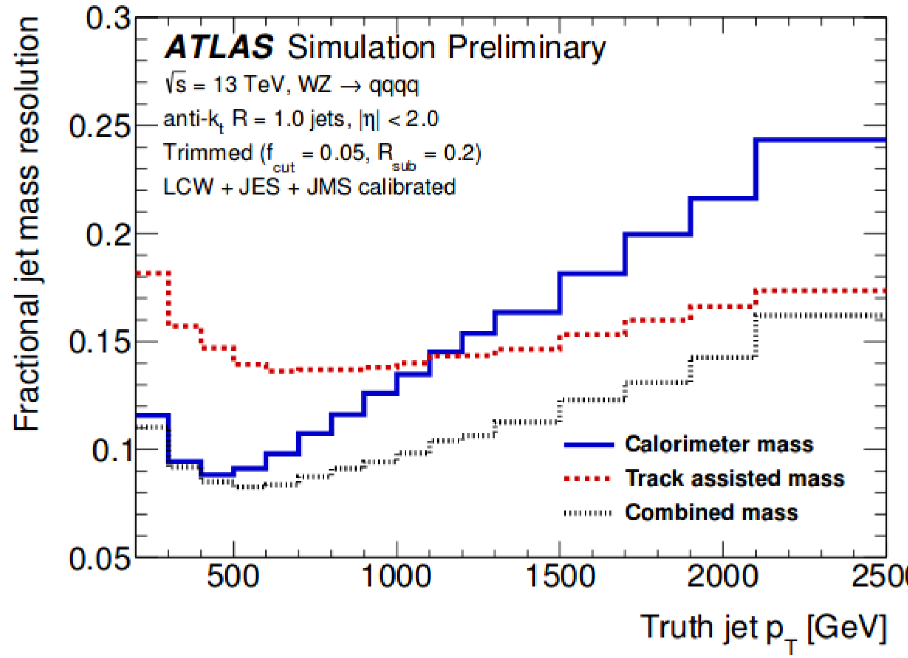


”Prong-like” Variables

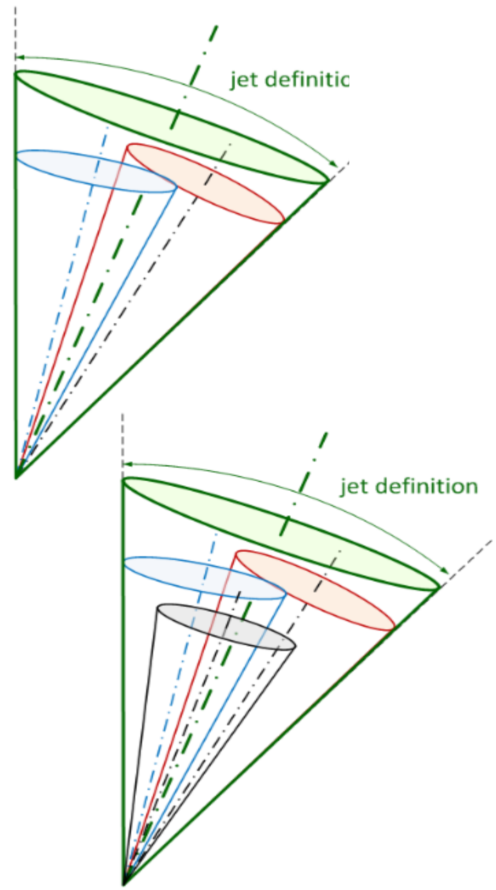
- Several options out there
- **N-subjettiness**:
  - Define a variable that quantifies how well the jet is described by *N* subjets:

$$\tau_N = \frac{1}{d_0} \sum_k p_{\mathrm{T}k} \times \min(\delta R_{1k}, \delta R_{2k}, ..., \delta R_{Nk}) \,, \text{ with } \; d_0 \equiv \sum_k p_{\mathrm{T}k} \times R$$

    - Typically use the ratio $\tau_{N,N-1} = \tau_N/\tau_{N-1}$ for tagging a jet as “*N*-prong”
    - τ_{32} found to perform best for top tagging
- **Energy correlation ratios**:
  - Takes ratios and double ratios of energy correlation functions:

$$\mathrm{ECF}(N,\beta) = \sum_{i_1<i_2<...<i_N\in J} \left(\prod_{a=1}^{N} p_{T i_a}\right) \left(\prod_{b=1}^{N-1} \prod_{c=b+1}^{N} R_{i_b i_c}\right)^{\beta}$$

  - Found to perform best for W tagging

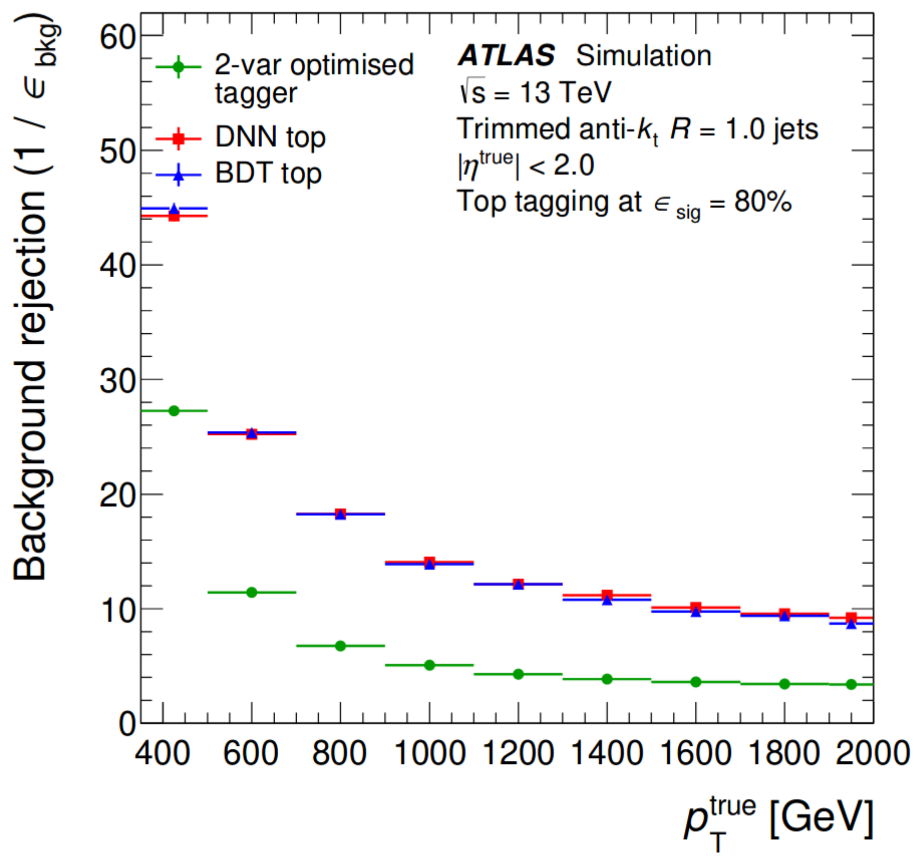


Top tagging

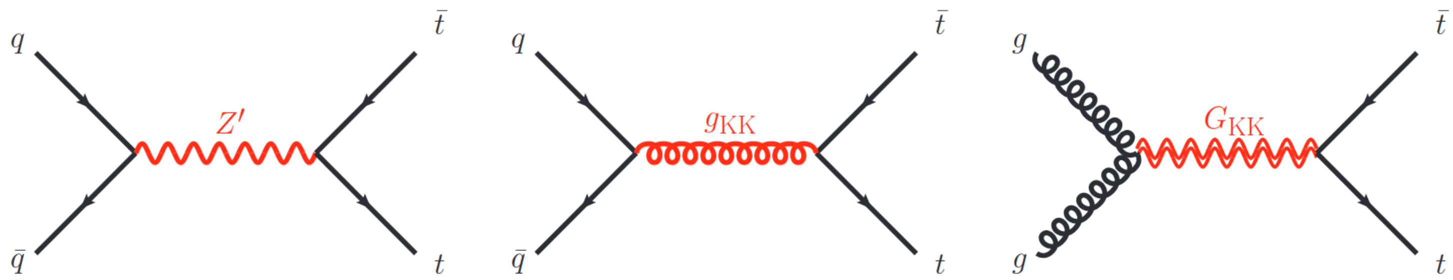
- Wishes: Discrimination, stability against pile-up, and understood systematics
- Simple cut on tau32 and combined mass give good overall performance
- Still be something to gain with more complex multivariate techniques
- ATLAS now has a new Neural Network-based tagger

CERN-EP-2018-192

Observable	Variable	Used for	References
Calibrated jet kinematics	p_T, m^{comb}	top, W	[44]
Energy correlation ratios	e_3, C_2, D_2	top, W	[50, 54]
N-subjettiness	$\tau_1, \tau_2, \tau_{21}$	top, W	[55, 56]
	τ_3, τ_{32}	top	
Fox–Wolfram moment	R_2^{FW}	W	[57, 58]
Splitting measures	z_{cut}	W	[59, 60]
	$\sqrt{d_{12}}$	top, W	
	$\sqrt{d_{23}}$	top	
Planar flow	$\mathcal{P}$	W	[61]
Angularity	a_3	W	[62]
Aplanarity	A	W	[58]
KtDR	$KtDR$	W	[63]
Qw	Q_w	top	[59]



Example of top-tagging use: $t\bar{t}$ resonance search



- Search for new heavy particles decaying to top pair
- Looking for deviations in the invariant mass spectrum of the $t\bar{t}$ system
- Using events where both tops decay hadronically ($t \rightarrow Wb \rightarrow qqb$)
- Different search strategies used to target different resonance mass ranges
  - M < 1.2 TeV: Top decay products are resolved
  - M > 1.2 TeV: Top is boosted and the decays merge into a single jet
- For the "boosted" analysis tops are tagged with straight cuts on the jet mass and τ_{32}

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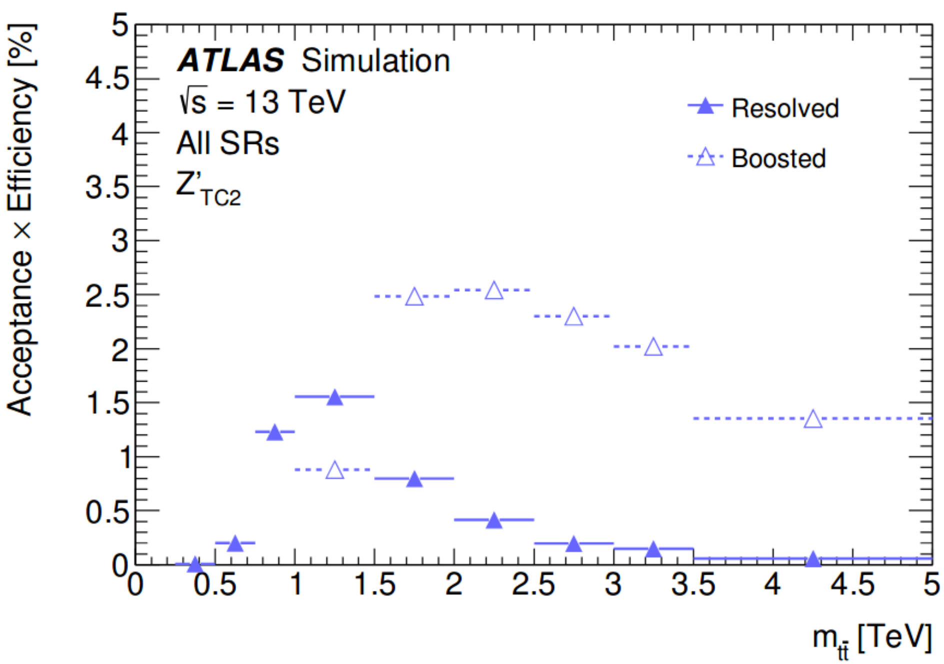
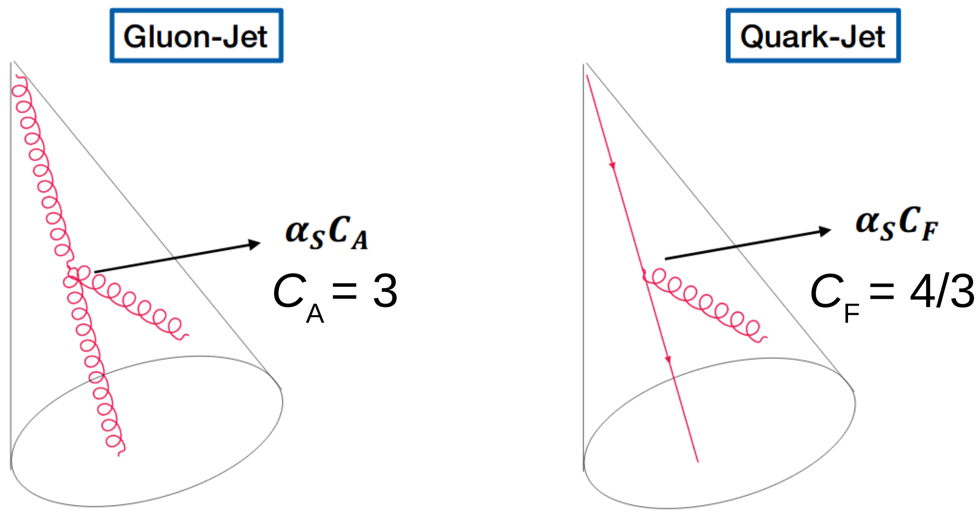


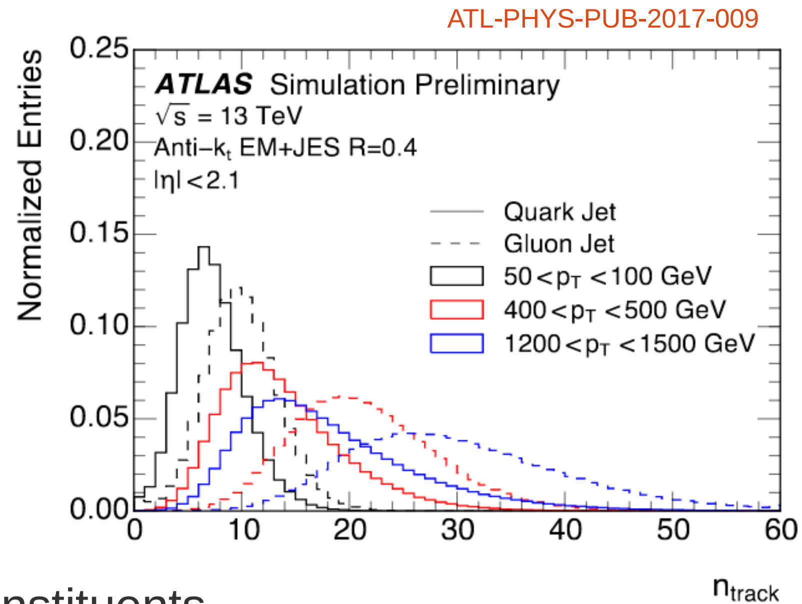
”Haze-like” Variables

- Used to characterise radiation pattern when not interested in the number of prongs
- Popular haze-variables include
  - Number of constituents
    - Often approximated by the track multiplicity n_{trk}
  - Width of the jet
    - Often defined by the sum of distances between tracks and jet axis weighted by p_{T}

$$w_{track} = \frac{\sum_i p_T^i \Delta R(i, jet)}{\sum_i p_T^i}$$

Quark/gluon tagging



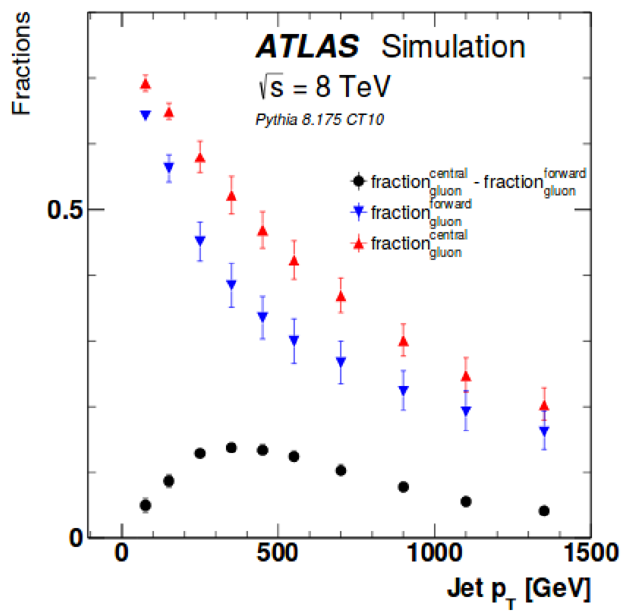


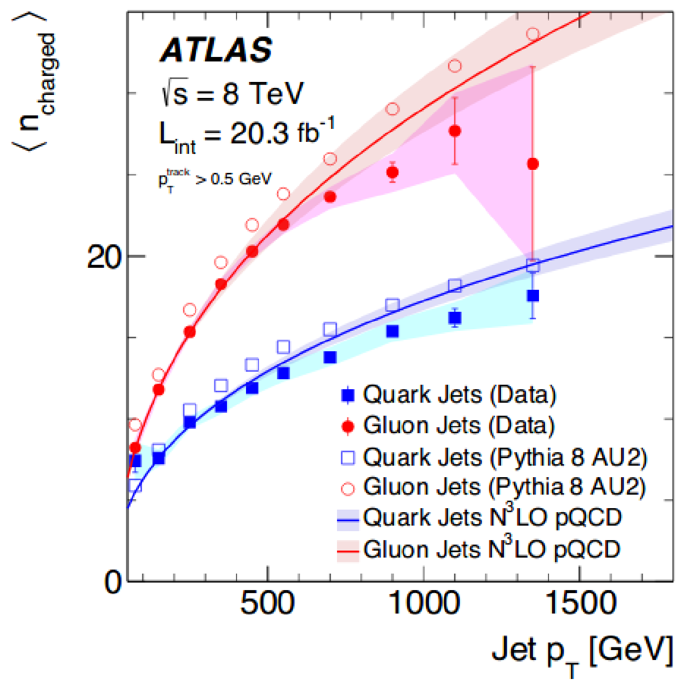
- Gluon jets tend to be broader and have more constituents
- Track multiplicity n_{trk} is strongest discriminating variable
- Challenges to quark/gluon tagging:
  1) No universal way of truth labeling in Monte Carlo
  2) n_{trk} is sensitive to fragmentation modeling
  3) Quark and gluon jets are rather alike...

Quark/gluon tagging

- Current recommendation based only on n_{trk}
- Data-driven technique used to estimate uncertainty
- For a given p_T, n_{trk} does not depend on eta, but the probability of a jet being q or g does

$$\langle n^{\mathrm{f}}_{\mathrm{charged}} \rangle = f^{\mathrm{f}}_{\mathrm{q}} \langle n^{q}_{\mathrm{charged}} \rangle + f^{\mathrm{f}}_{\mathrm{g}} \langle n^{g}_{\mathrm{charged}} \rangle$$
$$\langle n^{\mathrm{c}}_{\mathrm{charged}} \rangle = f^{\mathrm{c}}_{\mathrm{q}} \langle n^{q}_{\mathrm{charged}} \rangle + f^{\mathrm{c}}_{\mathrm{g}} \langle n^{g}_{\mathrm{charged}} \rangle,$$

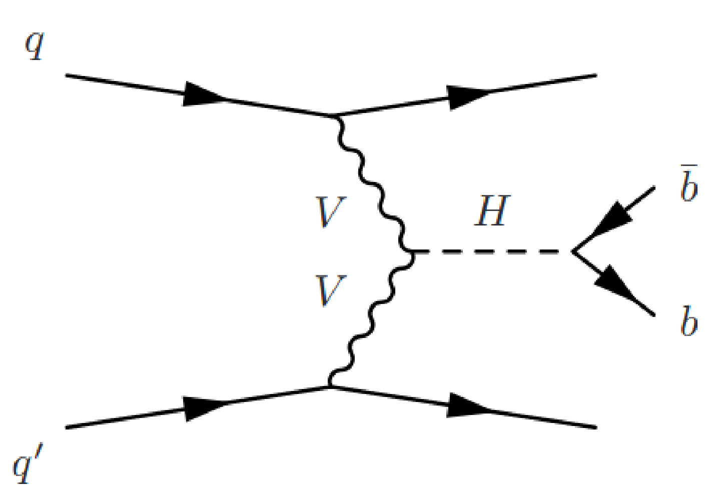


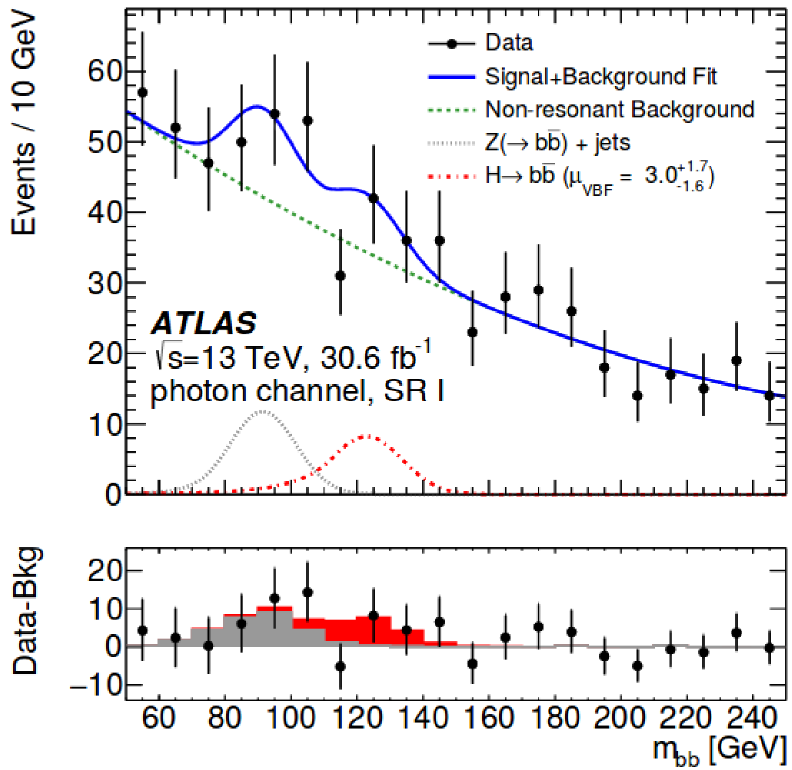


ATL-PHYS-PUB-2017-009

Example of quark/gluon-tagging use:
Vector-boson fusion Higgs

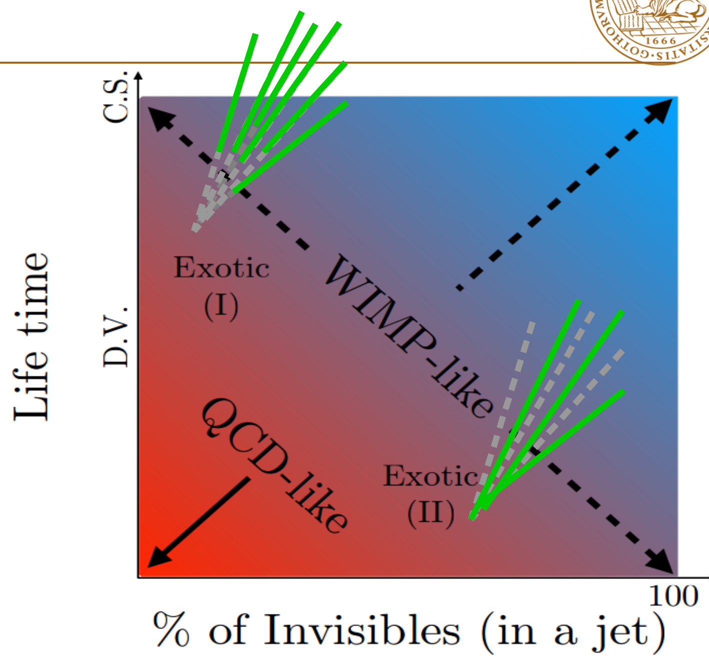
- A Higgs produced via VBF is accompanied by two light-flavor quarks
- Background processes are more rich on gluon jets
- Select events with four jets of which two are b-tagged
- N_{trk} is used as an input variable in a BDT to discriminate signal from background events
- The uncertainty on n_{trk} is propagated through to the limit setting



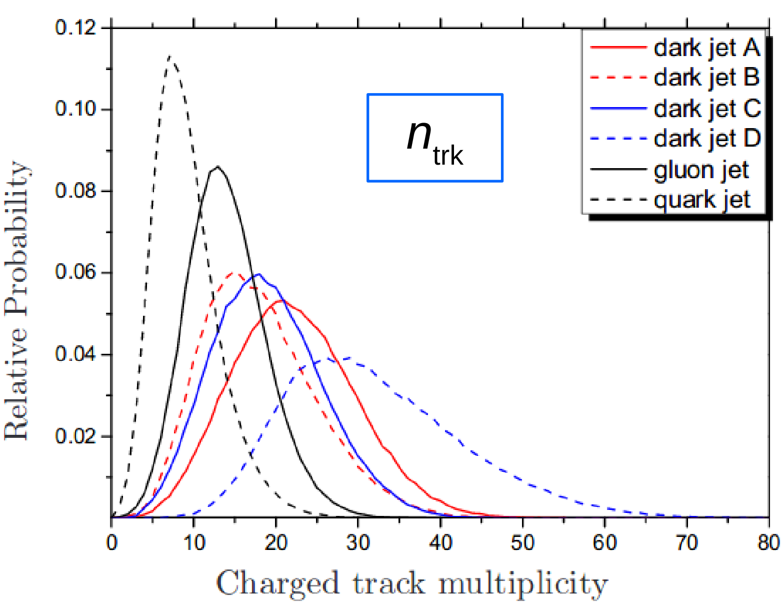


One more example:
Dark QCD-like sectors

- QCD-like hidden sector models can lead to jets with substructure than SM jets
- Composition of **visible** and **invisible** partons in the jet dependent on parameter choice:
  - Exotic I: Displaced vertices, emerging jets
  - Exotic II: Semi-visible jets
  - **We target SM QCD-like models**
    - With *s*-channel mediator decaying to two dark quarks



- Four models implemented in Pythia Hidden Valley process
  - **All have larger confinement scales than SM QCD!**
    - → Many more constituents!
  - Based on arXiv:1712.09279
- Strategy:
  - Select dijet events using **substructure variables**
  - Look for a bump in the dijet invariant mass spectrum



Conclusions

- Jets are
  - abundant in LHC experiments
  - interesting for both QCD studies and new physics
  - challenging because of large backgrounds and pile-up
- In the high-pile-up era we are entering, there is a lot to gain from combining track information with calorimeter signal
- Though the topic of jet substructure has existed for a long time, it is still a very vigorous field of study, which will only be more important as colliders go to higher energies

Backup

Calibration Chain: Global Sequential Calibration

Origin Correction → Reconstruction EM/PFlow Scale → Pile-up Correction → Absolute EtaJES Calibration → **Global Sequential Calibration** → In-situ Calibration

- Observables are related to
  - **Energy deposits in the calorimeter / Non-compensation**
  - **Track information of jets / Flavor dependence**
  - **Activity in the muon segments / Punch-through**

Step 0 Only PFlow	Step 1	Step 2	Step 3	Step 4	Step5
Charge fraction	f_{tile0}	f_{LAr3}	N_{trk}	w_{track}	N_{segments}

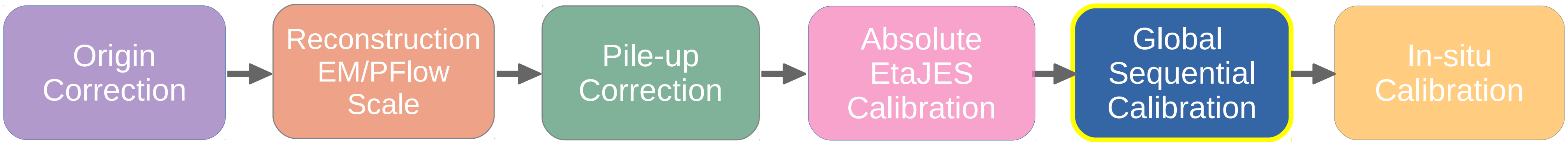
$$CF = \frac{p_T^{track}}{p_T^{jet}}$$

$$f_{layer} = \frac{E_{EM}^{Layer}}{E_{EM}^{jet}}$$

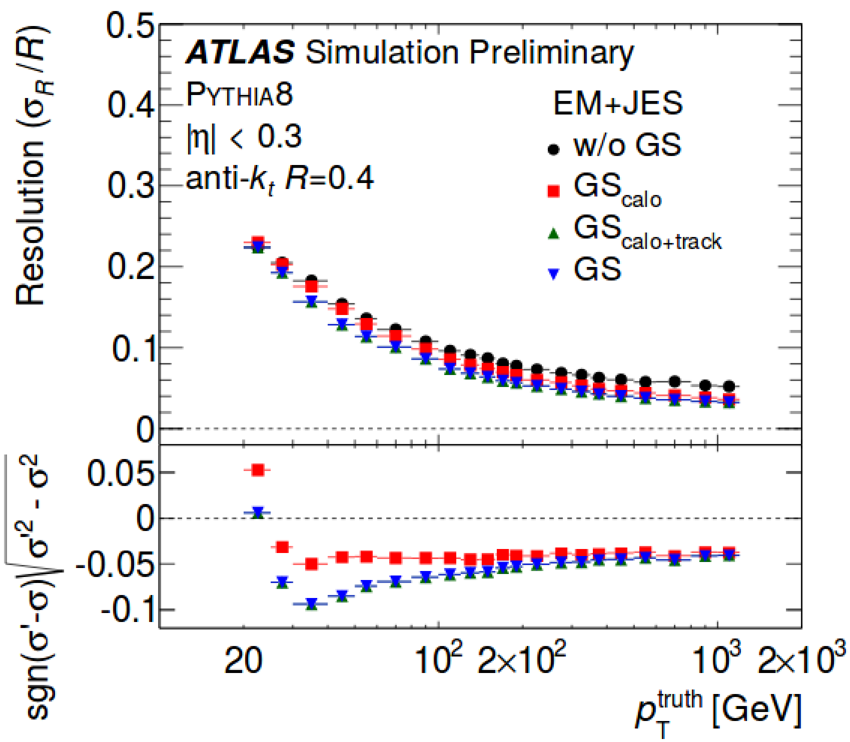
$$w_{track} = \frac{\sum_i p_T^i \Delta R(i, jet)}{\sum_i p_T^i}$$

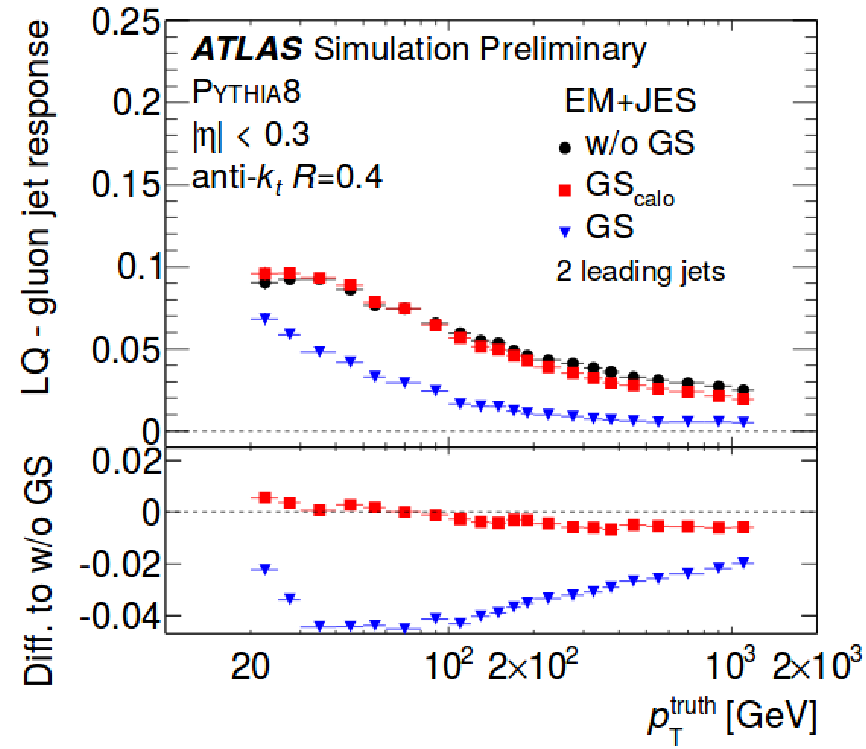
$N_{segments}$ = No. muon segments associated with the jet

Calibration Chain: Global Sequential Calibration

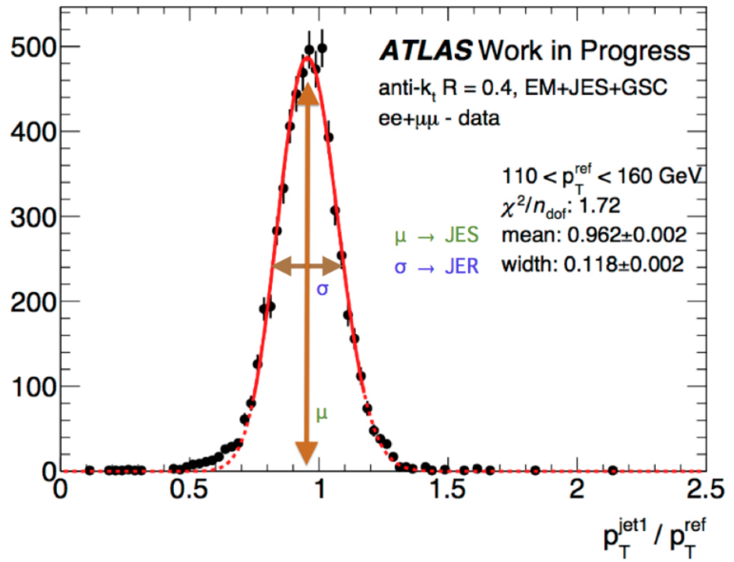


- Improvement on, for example, **resolution** and **flavor dependency**





- The Jet Energy Resolution (JER) is the width of the response distribution in a given bin



- Parameterised as

Noise term

Constant term

$$\frac{\sigma(p_T)}{p_T} = \frac{N}{p_T} \oplus \frac{S}{\sqrt{p_T}} \oplus C$$

Stochastic term

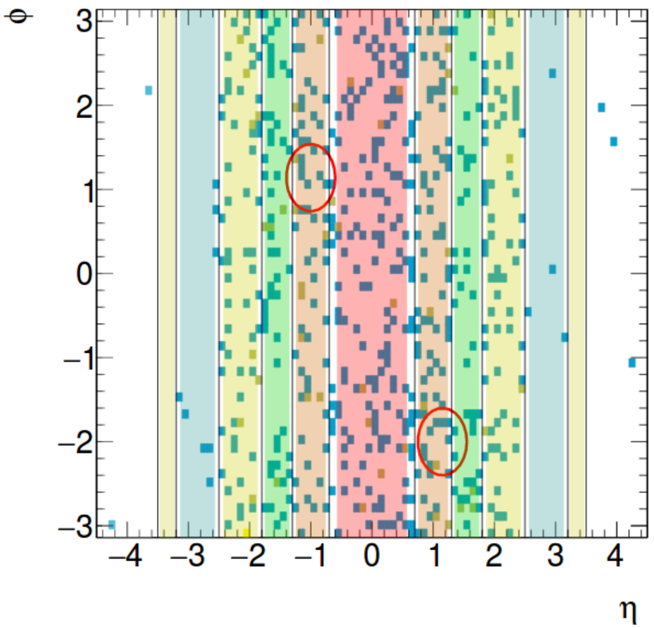
- **N**: Pile-up and electronic noise
- **S**: Statistical Poisson fluctuations
- **C**: Signal loss in passive material

- Noise term constrained using **Random Cone Method** and a ***μ*=0 MC sample**
- Other terms obtained by fitting in-situ measurements from **dijet** (and potentially Z/γ+jet) events with *N* held fixed

Small-R JER

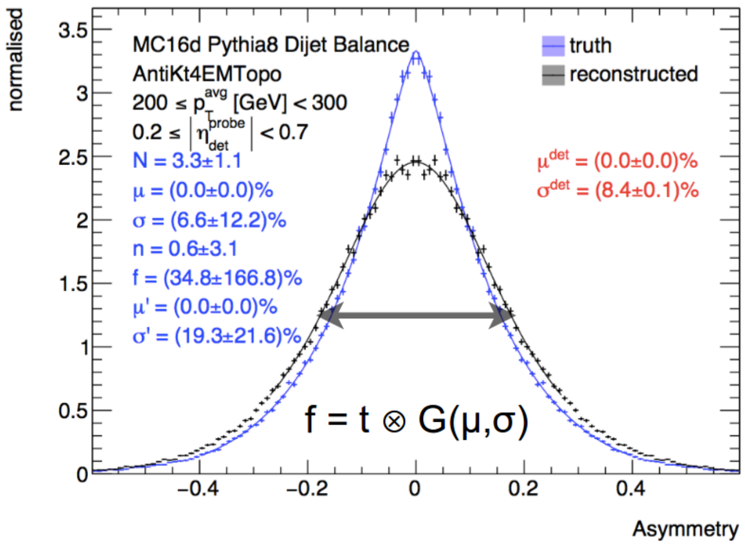
- **Noise term** includes pile-up and electronic noise

$$N_{\text{full}} = \underbrace{N_{\text{pile-up}}}_{\text{Random cones}} \oplus \underbrace{N_{\mu=0}}_{\mu=0\text{ sample}}$$



  - $N_{\text{pile-up}}$ is derived with the **Random Cone Method:**
    - Construct two random cones in zero-bias data sample
    - Sum energy clusters within the two cones
    - Fluctuations due to pile-up are taken as the width of the p_T difference distribution
  - $N_{\mu=0}$ is derived from a **MC sample with no pile-up**

- **Dijet method:**
  - Similar to the η-intercalibration
  - JER is the width of the asymmetry distribution



Small-R JER

- Fit performed to dijet measurements with constraint on noise term from Random Cones method
- JER measurements in Z/γ+jet events may be included to span more phase space
- Brand new recommendations out now

Noise term

$$\frac{\sigma(p_T)}{p_T} = \frac{N}{p_T} \oplus \frac{S}{\sqrt{p_T}} \oplus C$$

Stochastic term

Constant term