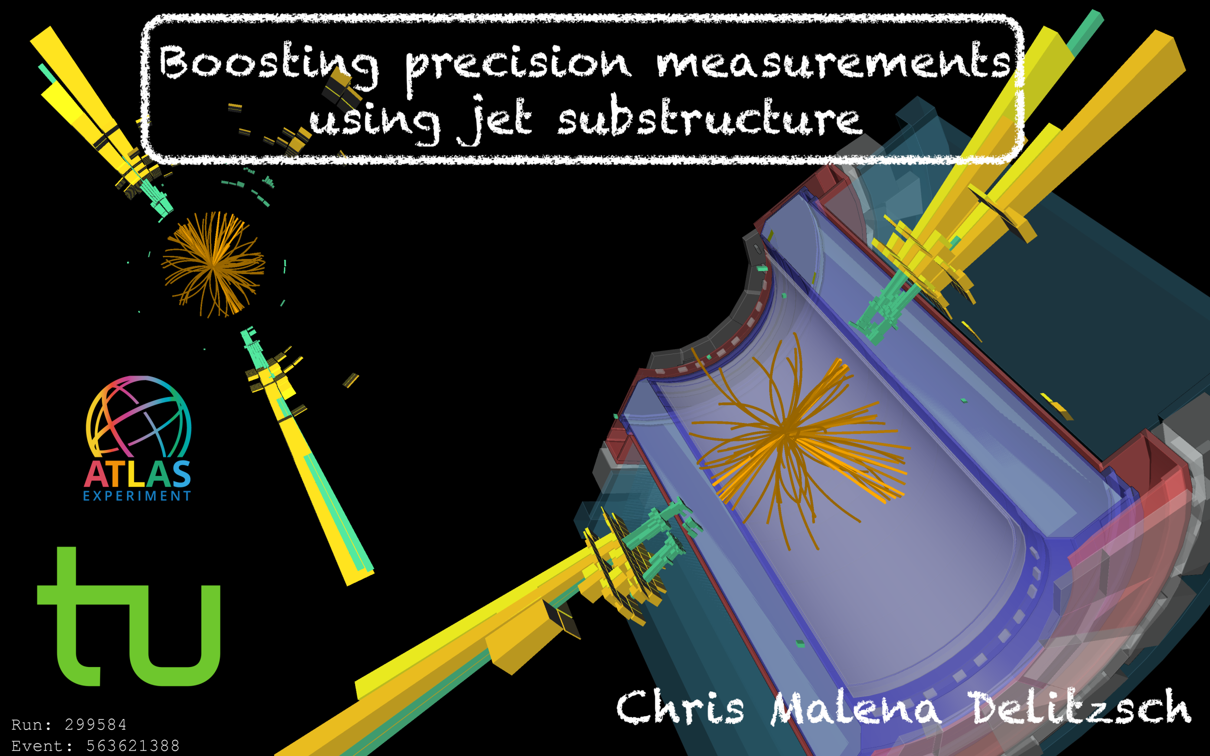
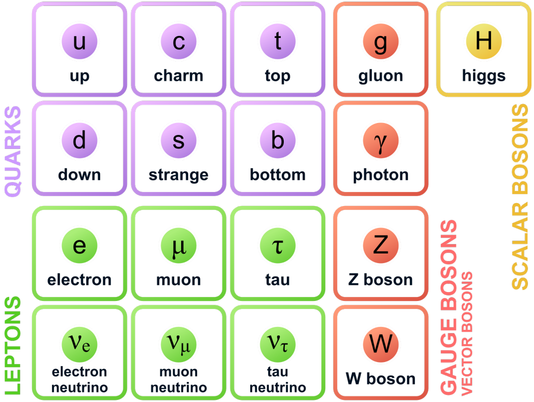
Boosting precision measurements using jet substructure

Chris Malena Delitzsch

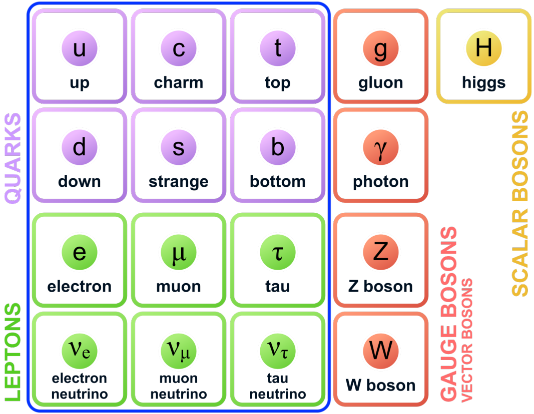


The Standard Model (SM) of Particle Physics



Particle content

The Standard Model (SM) of Particle Physics



Particle content

- *Fermions* (Quarks and leptons)
  - Spin 1/2 particles

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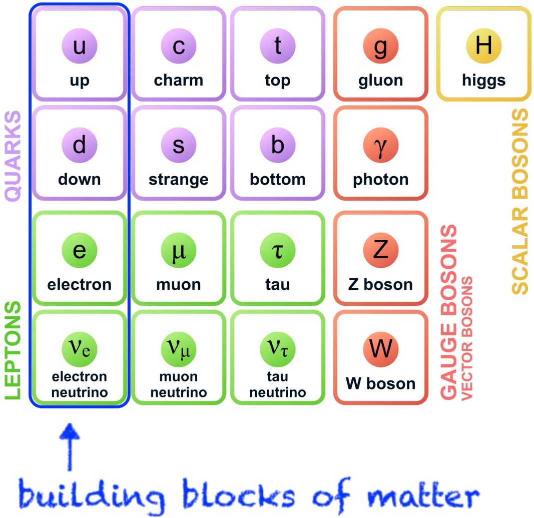

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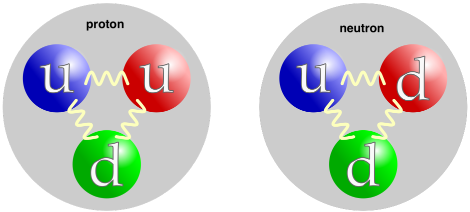

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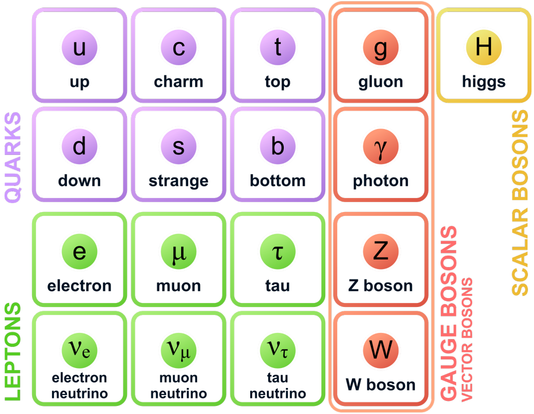

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- Interactions mediated via *gauge bosons*
  - Spin 1

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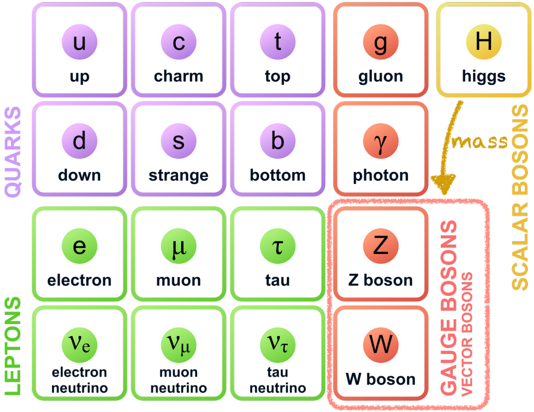


Particle content

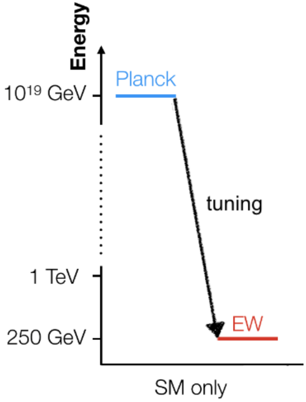
- *Fermions* (Quarks and leptons)
  - Spin 1/2 particles
- Interactions mediated via *gauge bosons*
  - Spin 1
- Masses included via Higgs mechanism
  - Higgs boson: Spin 0

Hierarchy problem - an open question of the SM

- Large differences between the Planck scale and the scale of electroweak SM sector

$$\underset{(125\ \text{GeV})^2}{\text{Higgs Boson}} = \underset{(10^{36}\ \text{GeV}^2)}{\text{raw mass}} - \underset{(10^{36}\ \text{GeV}^2)}{\text{quantum corrections}}$$

1234567890123456789012345678901234 56
-
1234567890123456789012345678901078 31
=
15625 = $(125)^2$



- Physics beyond the Standard Model will reduce these large corrections

How to search for physics beyond the SM?

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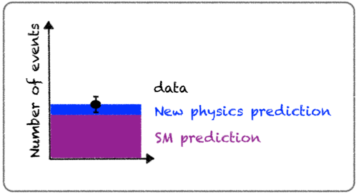
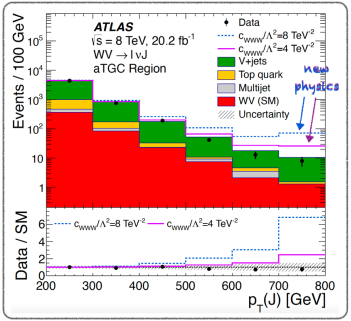
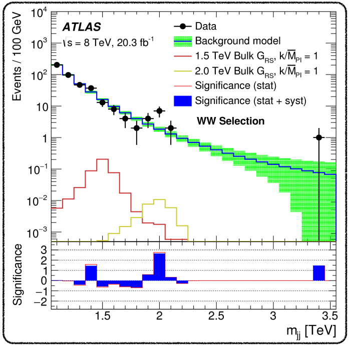
- Indirect and direct searches for BSM physics

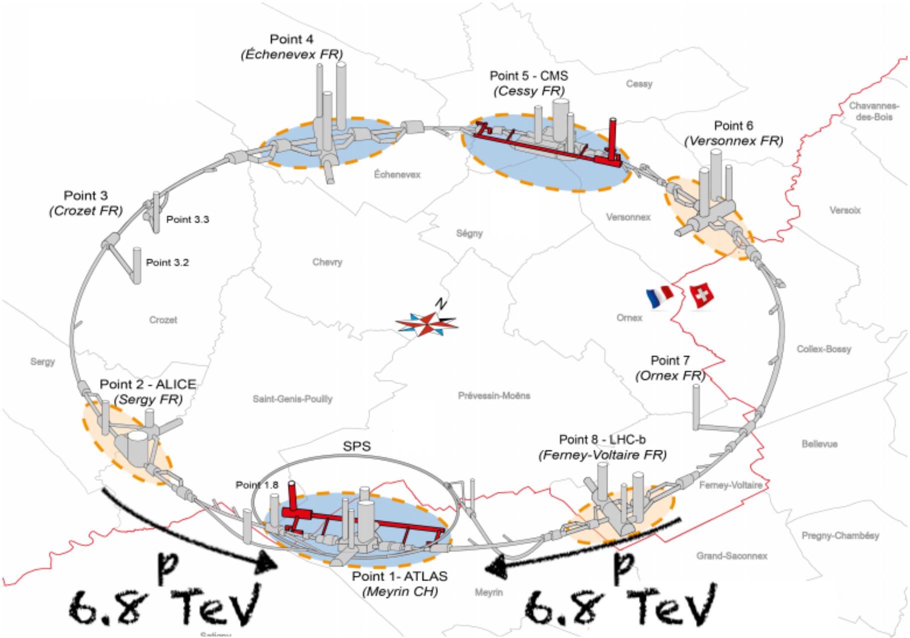




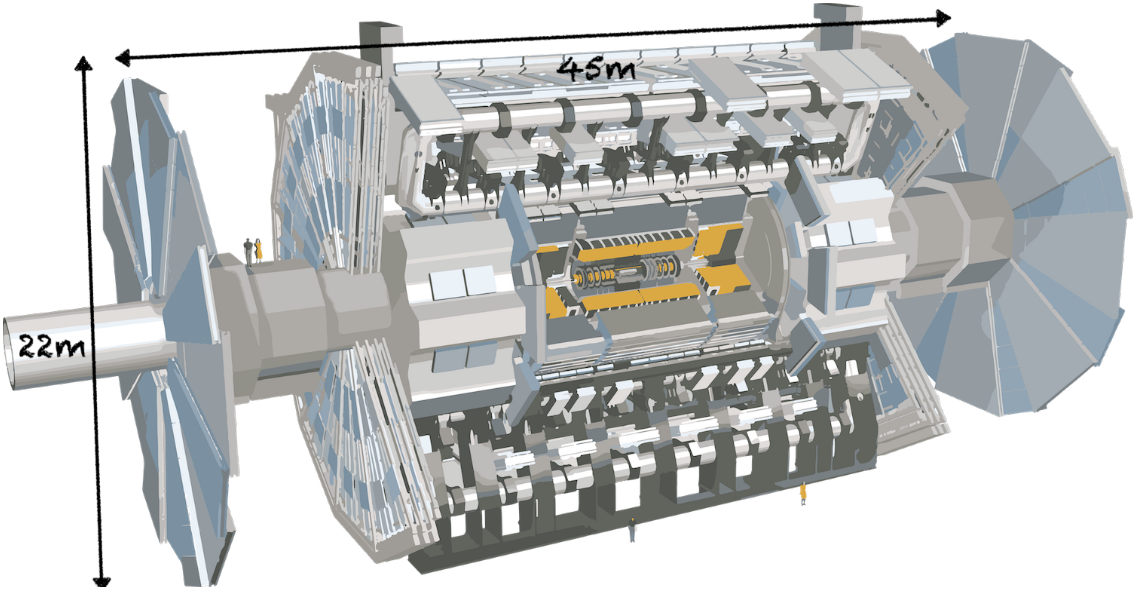


- We are specifically sensitive to BSM physics at high transverse momenta
  - Hadronic decays of interest due to their large branching ratio
  - I am particularly interested in processes involving top quarks and W/Z bosons
- We can only search for new physics if we understand the SM with utmost precision

Large Hadron Collider @ CERN



ATLAS Experiment

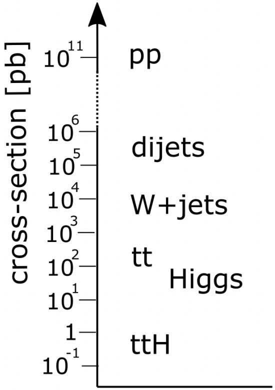


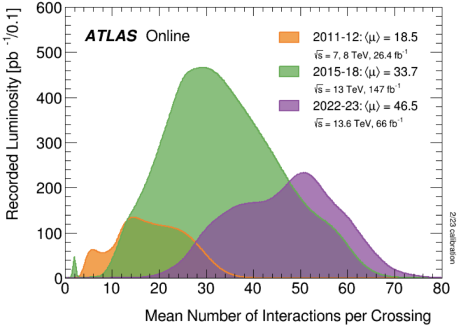
Challenge at the LHC - Pile-up

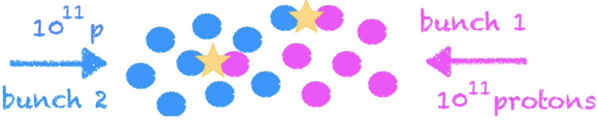
$$N = \mathcal{L} \cdot \sigma$$

- N: number of events of specific process
- $\mathcal{L}$: integrated luminosity
- σ: cross-section

theory →

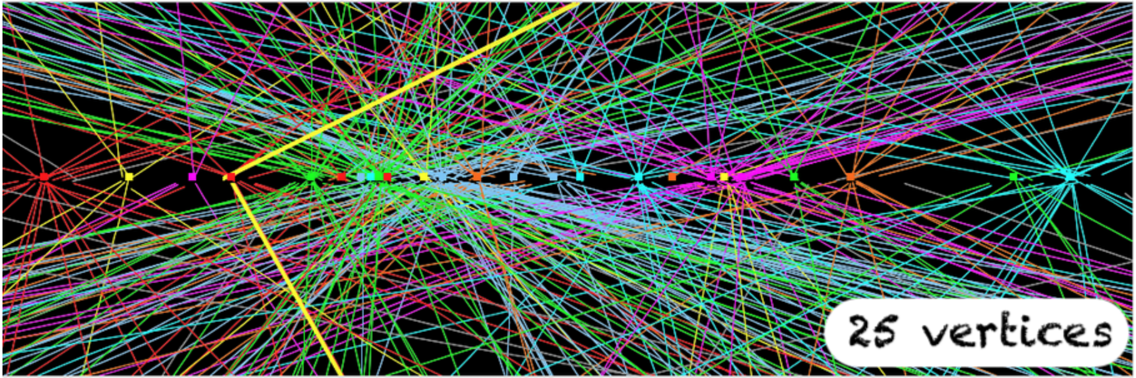






LuminosityPublicResultsRun3

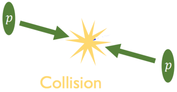
How does this look like in our detector?



- We’re only interested in one of these collisions and the associated particles

How to reconstruct hadronically decaying objects

- We cannot directly measure quarks from the decay of heavy objects
  - $W \to q\bar{q}'$, $Z \to q\bar{q}$, $t \to q\bar{q}'b$



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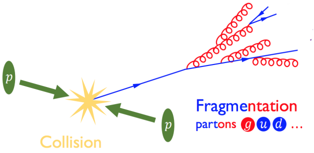

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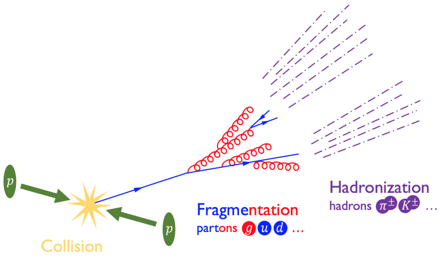

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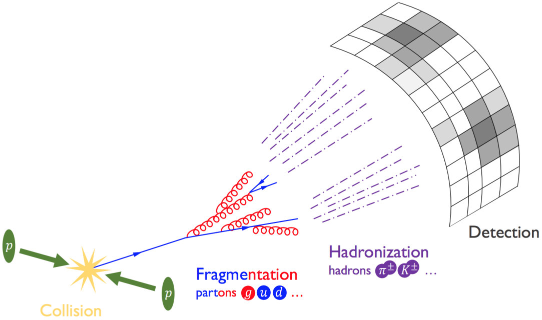

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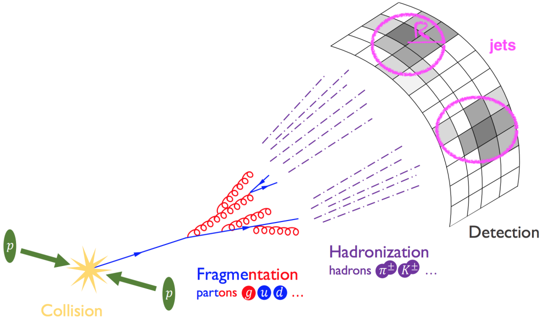
- Instead define proxy for quarks - *jet*
  - Collimated spray of hadrons (cone)
  - Clustering based on distance parameter



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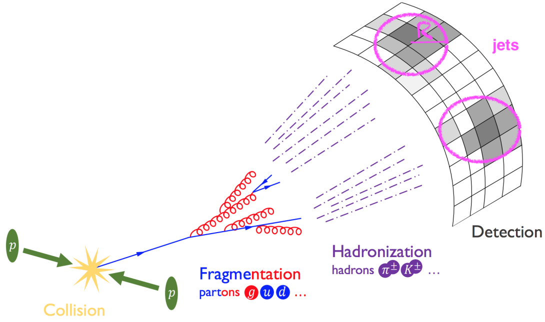
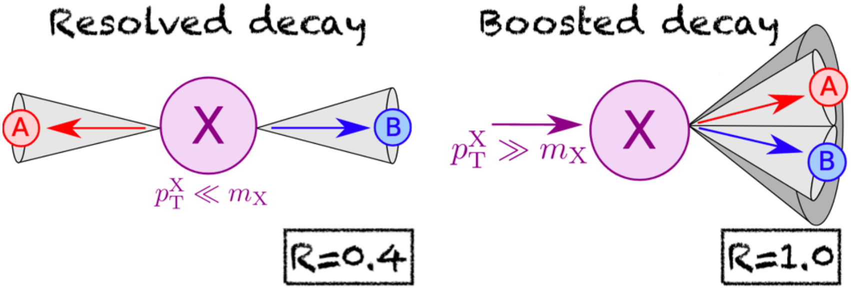


- We would expect e.g. two (three) jets for the decay of a W/Z boson (top quark)
  - Jets have distance parameter of $R = 0.4$

Boosted object reconstruction

- What happens at high p_T with decay products?
  - Decay products are collimated such that hadrons from quarks start overlapping
    - Reconstruct decay products instead as single $R = 1.0$ jet



Rule of thumb

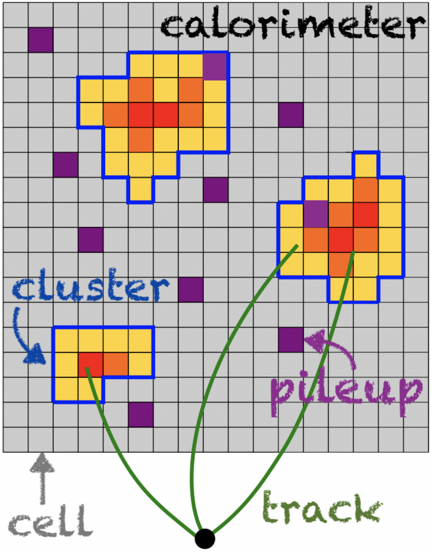
$$\Delta R \approx \frac{2 \cdot m_X}{p_\mathrm{T}}$$

- Resolved W boson decay: two small-R jets with $m^2 = (p_1 + p_2)^2$
- Boosted W boson decay: one large-R jet with mass close to m_W

What are the inputs to jet reconstruction?

- Jets are comprised of 2/3 charged particles and 1/3 neutral particles
  - Tracker only sees charged particles, while the calorimeter sees both types
  - Energy deposits in the calorimeter are thus the key to jet reconstruction
- Deposits in EM calorimeter from e.g. $\pi^0 \rightarrow \gamma\gamma$
- *Topo-clusters* constructed to suppress pile-up
  - Group of topologically connected cells
  - Pile-up creates add. energy or clusters

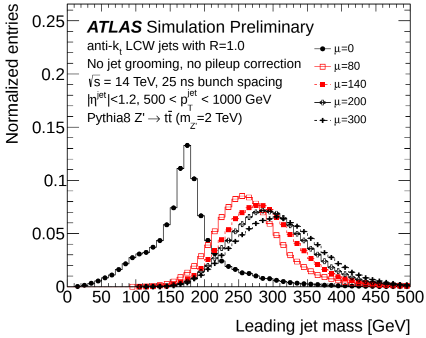
arXiv:1603.02934



Pileup: major challenge for large-R jets

link to figure

- The larger catchment area results in a larger pile-up susceptibility
  - Energy deposits from other simultaneous collisions pollute large-R jet
- Need to groom jet before studying its substructure



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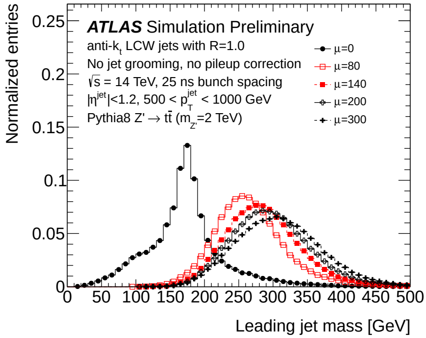
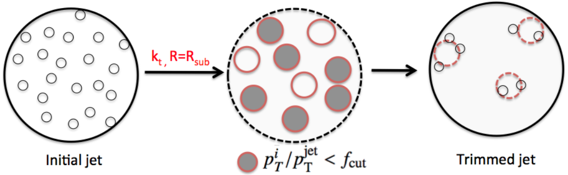
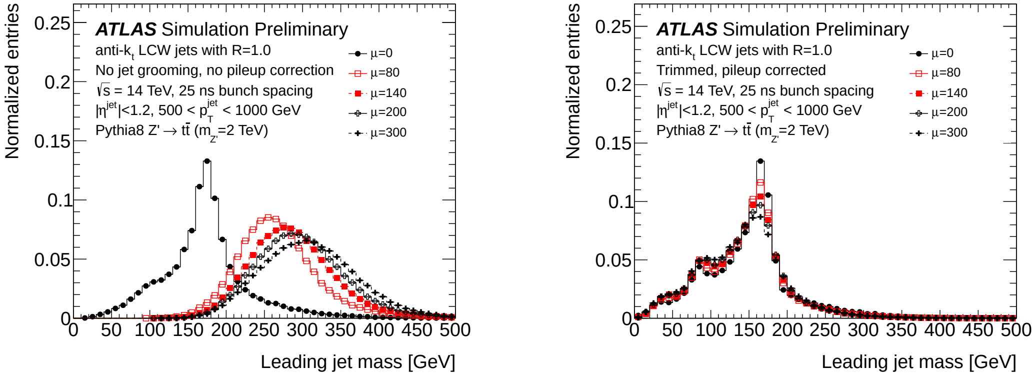


Trimming (arXiv:0912.1342)



Impact of jet grooming

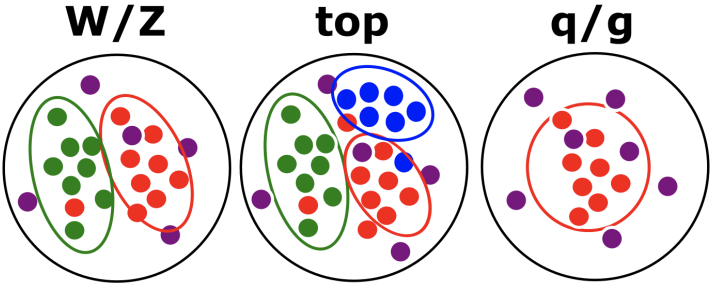
link to figures



- Pileup removal works even for pileup scenarios expected for the HL-LHC!

Jet substructure

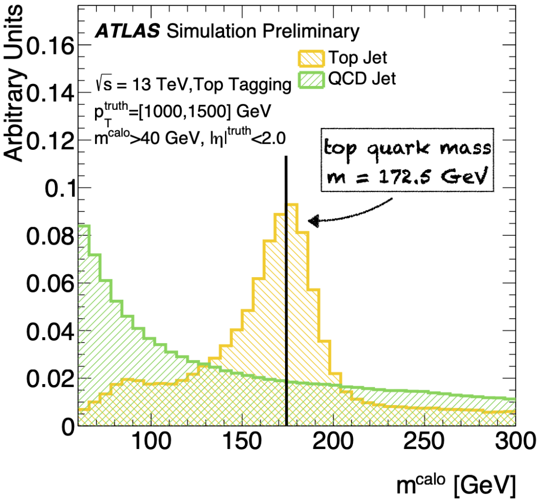
- The number of background events significantly exceeds that of signal events
- Background jets: jets initiated by one quark or gluon
- Study the jet's inner structure for signal vs. background separation: jet substructure



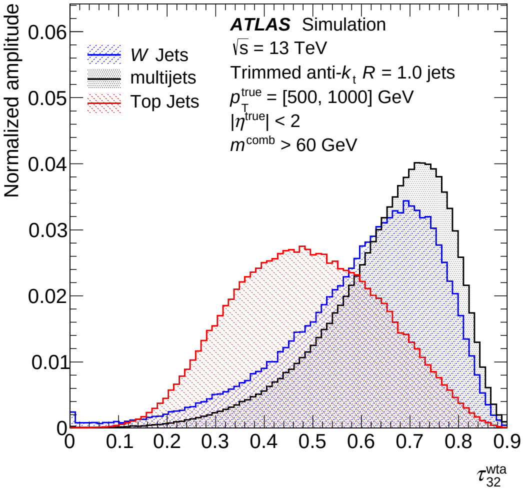
Jet substructure - II

arXiv:1808.07858

Jet mass



N-Subjettiness



- τ_{32} is trying to determine if the jet is composed out of 3 or 2 subjets

$VV \rightarrow JJ$ candidate

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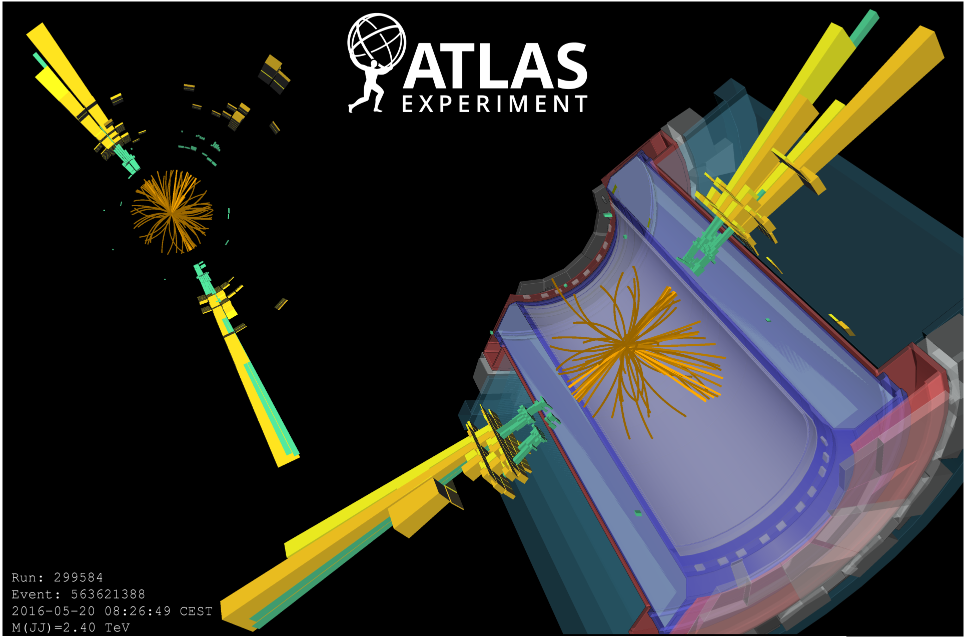

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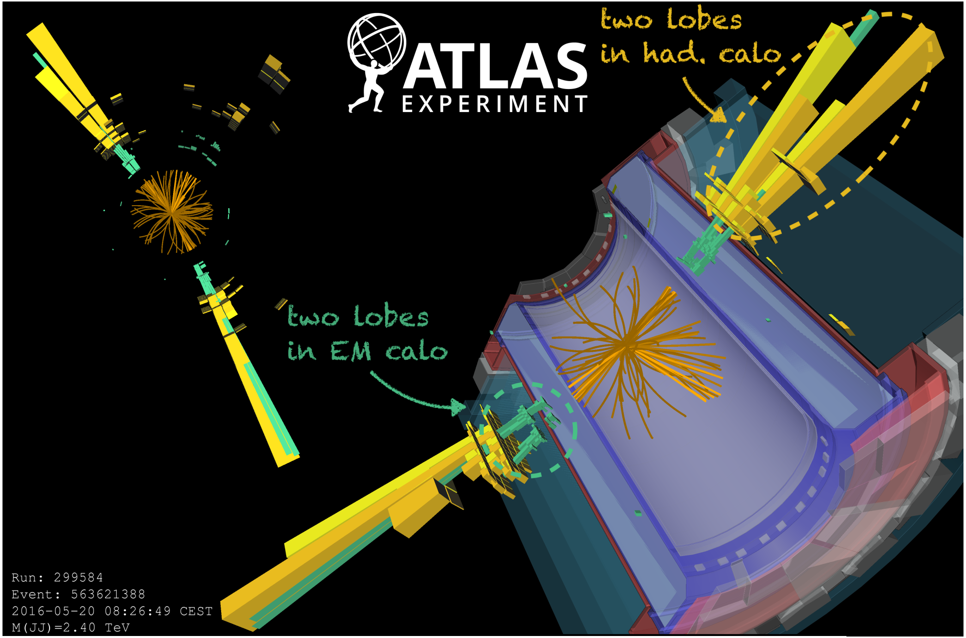
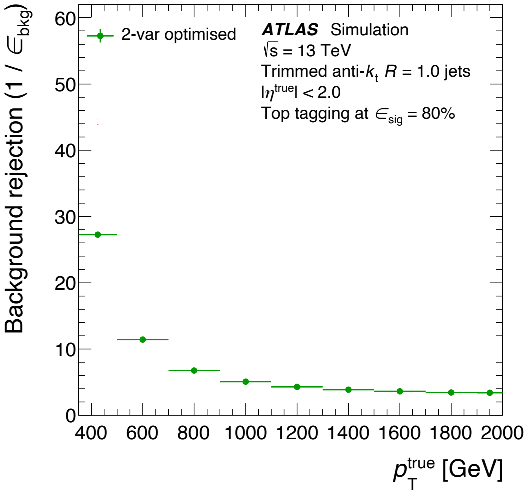


The machine learning era

- Need powerful tools to distinguish signal from background

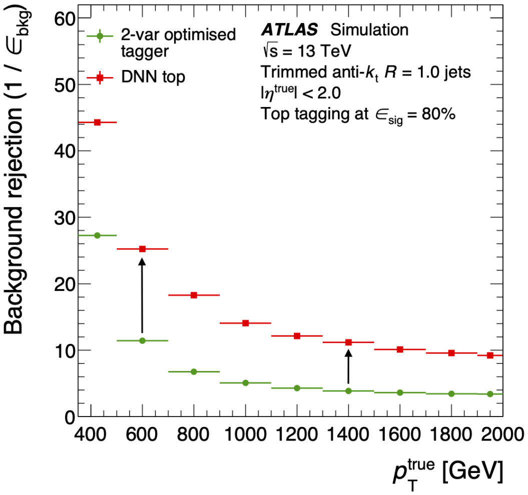
arXiv:1808.07858



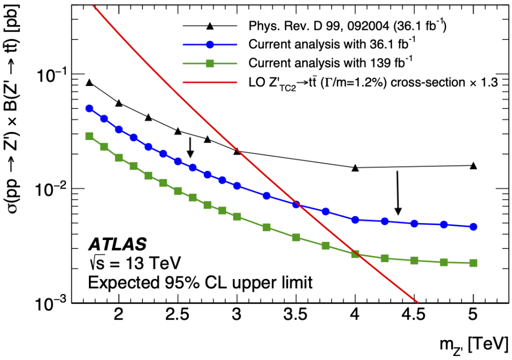
The machine learning era

- Need powerful tools to distinguish signal from background
  - ML-based taggers (using various substructure variables), improved inputs to jet reco

[arXiv:1808.07858]

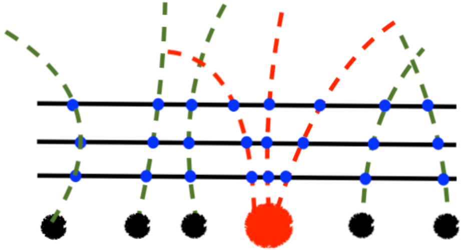


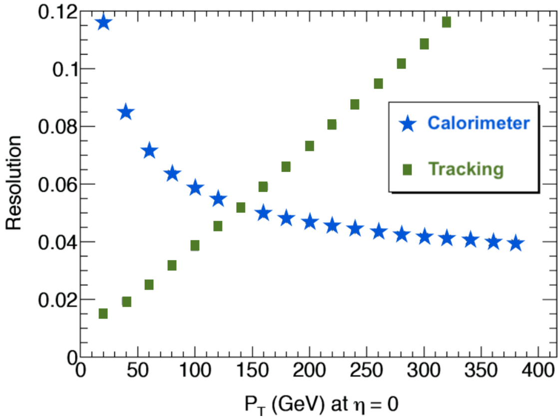
- Search for new heavy particle $Z' \to t\bar{t}$
- [arXiv:2005.05138]



Adding tracks to the mix

- The tracker is less susceptible to pile-up and has a better p_{T} resolution at low momenta
- Combine information from tracker and calorimeter to form inputs for jet reconstruction
  $\Rightarrow$ *Particle-Flow Algorithm* (arXiv:1703.10485)
- Better angular resolution of tracks





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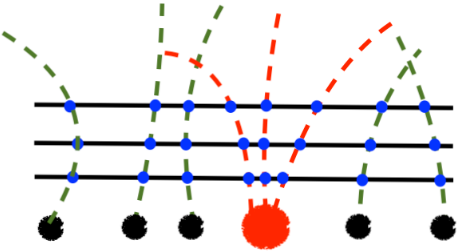
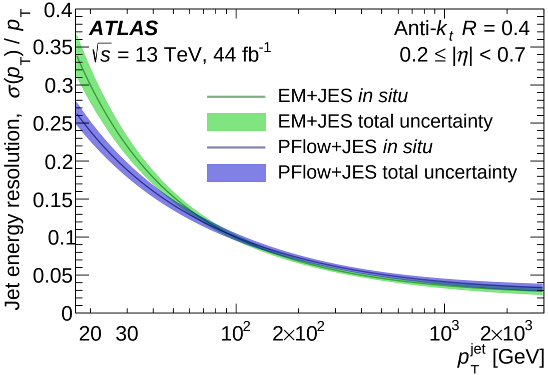


arXiv:2007.02645



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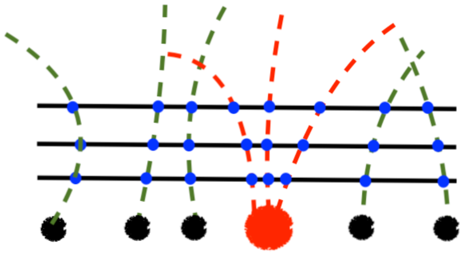

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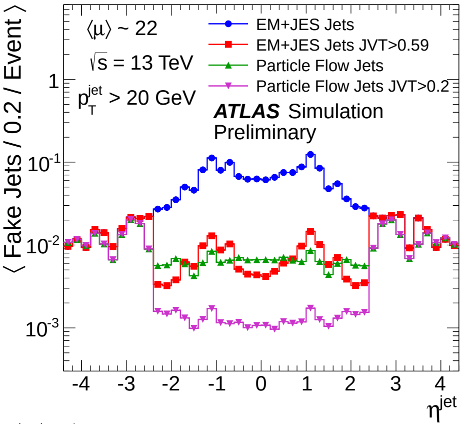
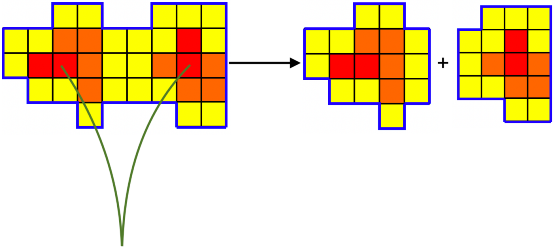


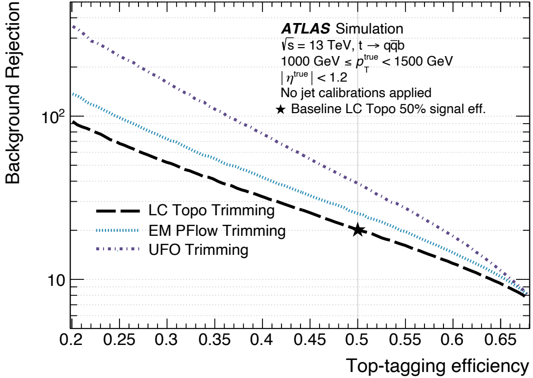
Another set of UFOs at the LHC

- At very high p_T, decay products could be reconstructed in only one cluster
  $\rightarrow$ loss of substructure information

- Split cluster based on tracks and replace angular position with track measurement
  - UFOs: Unified Flow Objects

arXiv:2009.04986





- This does not work for clusters purely from neutral hadrons
  $\rightarrow$ **development of new splitting algorithms**

The machine learning era - the good

- Community is moving towards constituent-based taggers with improved performance
    - More sophisticated neural networks being developed

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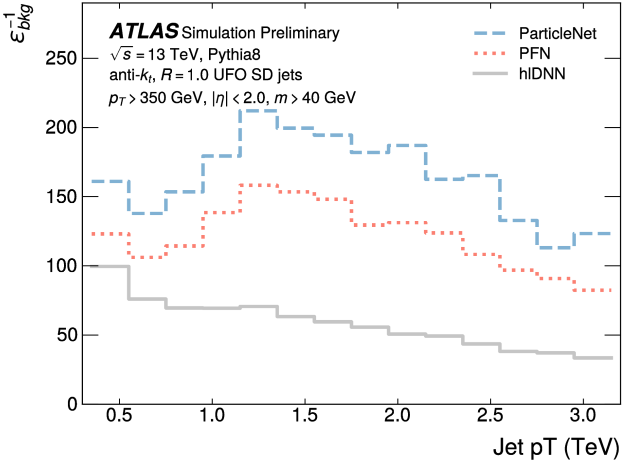

The machine learning era - the bad

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- Community is moving towards constituent-based taggers with improved performance
  - More sophisticated neural networks being developed
- But new taggers show increase in modelling differences

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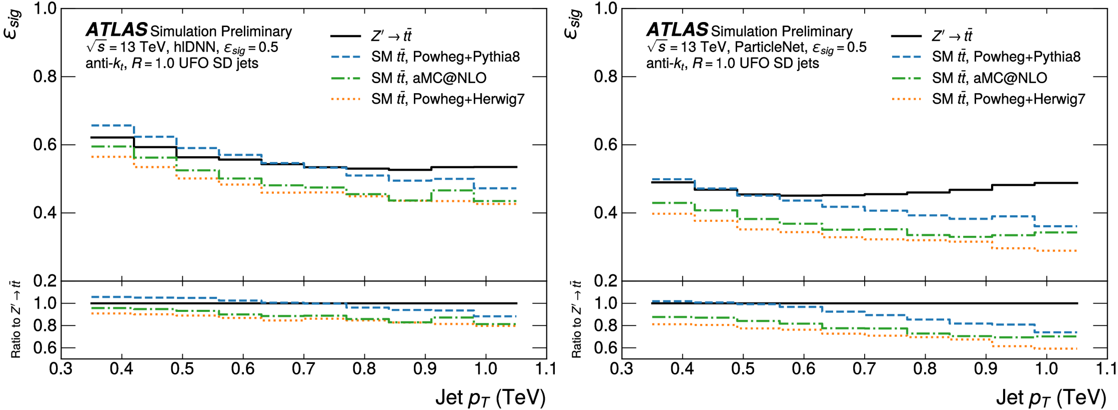


Calibration chain of large-R jets

Reconstructed jets → **Grooming algorithm** → **MC-based calibration**

Jet algorithm applied to track & calorimeter-based inputs

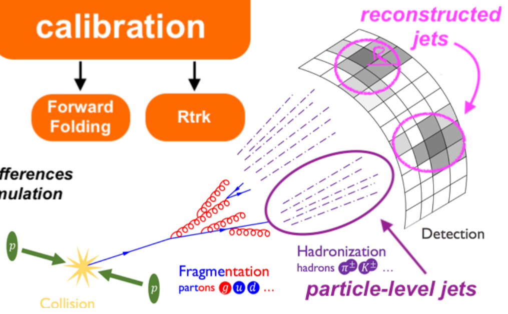
pile-up suppression

calibration of 4-vector to the particle-level

→ ***in situ* JES calibration** → ***in situ* JMS calibration**

- *in situ* JES calibration:
  - η - inter-calibration
  - γ + jets
  - Z+jets
  - Multijet balance
- *in situ* JMS calibration:
  - Forward Folding
  - Rtrk

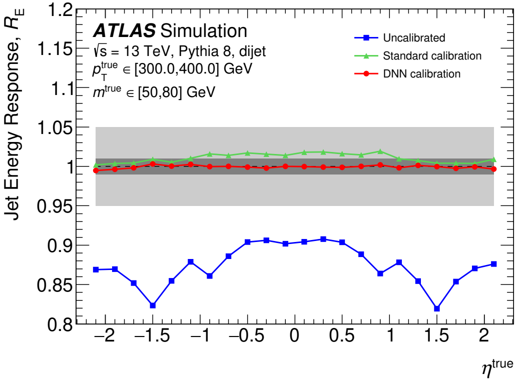
in situ correction of differences between data and simulation

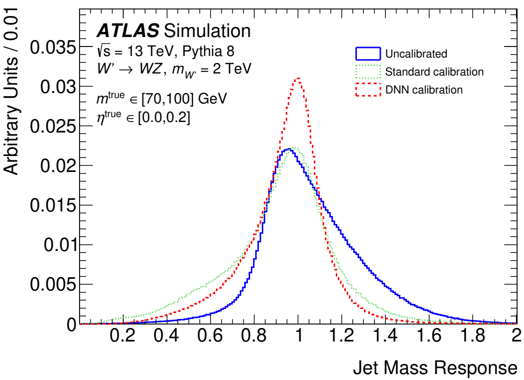


MC-based calibration of large-R jets

- Correct the reconstructed jet energy on average to the truth jet energy
- Energy lost due to non-compensating calorimeter, inactive material, noise thresholds, …
- Previously, energy and mass (despite their correlation) were calibrated individually
- Improved closure with DNN taking into account shower evolution, substructure
- Accounts for differences between jet types, e.g. quark vs. gluon or q/g vs. W/Z/H/top

arXiv:2311.08885





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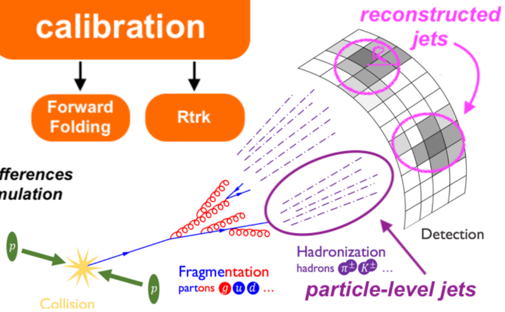
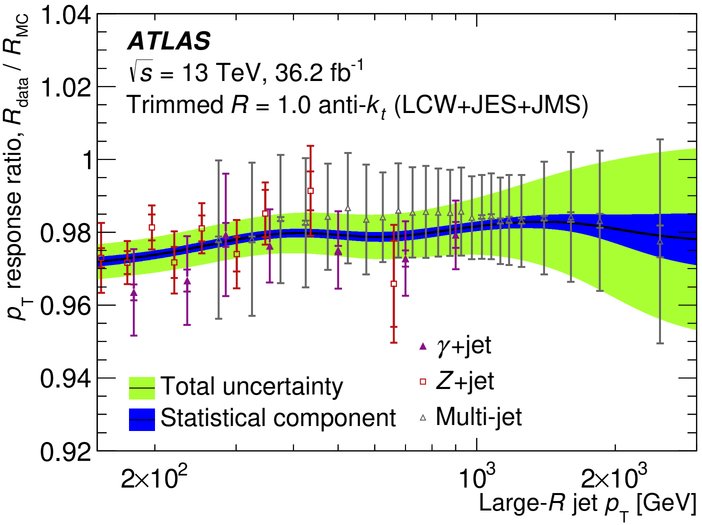


In situ calibration of large-R jets

arXiv:1807.09477



Large-R jet mass in $t\bar{t}$ events

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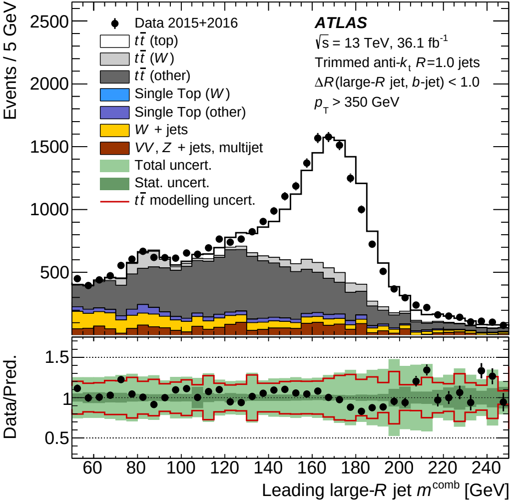
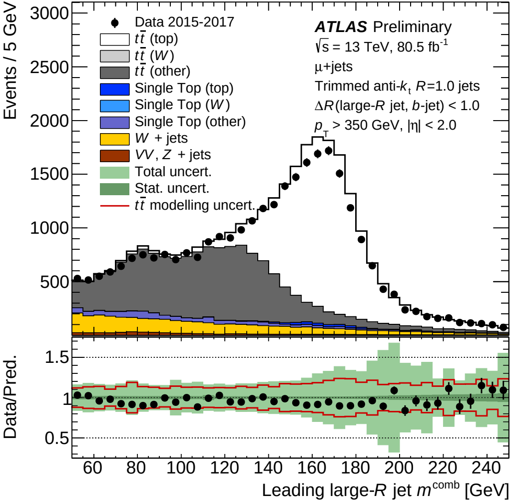
without *in situ* JES correction

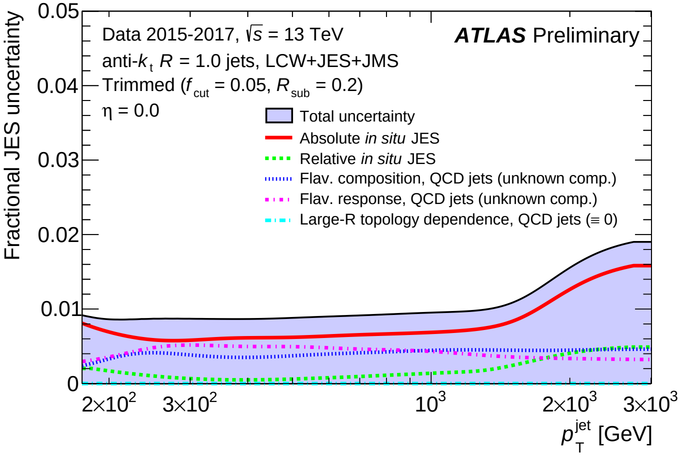


with *in situ* JES correction



Uncertainties on large-R jet energy scale

JETM-2019-05



- Achieved already high precision of large-R jets
  - Compatible with small-R jets in same p_{T} regime
  - Reduced from an uncertainty of approx. 5% initially

Precision measurements using jet substructure

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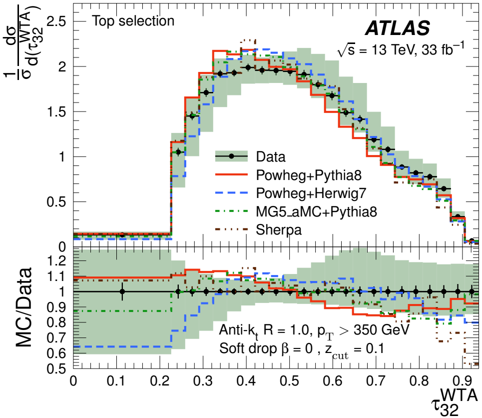
- Tools shown before are fantastic for e.g BSM searches or to select objects in measurements

arXiv:1903.0294

- But we can use them for much more
  $\Rightarrow$ e.g. tuning of simulation

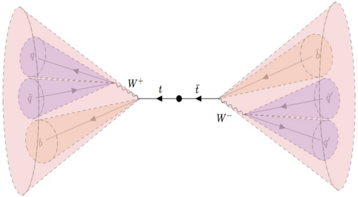
- Comparison to diff. generators to disentangle effects like parton shower vs. hadronization

- Grooming algorithms reduce sensitivity of observables to soft physics
  $\rightarrow$ less affected by non-perturbative effects



Jet substructure in $t\bar{t}$ events

- Provide unfolded data to test analytic predictions and tune MC generators in $t\bar{t}$ events
- Measurement performed using full Run 2 data in lepton+jets and all-had channel
- arXiv:2312.03797



2nd large-R jet	1st large-R jet: t0b0	t1b0	t0b1	t1b1
t1b1	J	K	L	S
t0b1	B	D	H	N
t1b0	E	F	G	M
t0b0	A	C	I	O

- Require two b-tagged jets matched to large-R jet
  - Suppresses large multi-jet background
- Non-probe jet has to be top tagged
- Extended ABCD method for bkg estimation
- Only charged-particle tracks used to measure substructure

Jet substructure in $t\bar{t}$ events - yields

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Category	Event yields ℓ+jets selection	Number of large-R jets all-hadronic selection
Data	**83 069**	**30 524**
Predictions	**97 200 ± 3 700**	**36 500 ± 1 400**
$t\bar{t}$ (ℓ+jets)	90 600 ± 3 400	1 610 ± 140
$t\bar{t}$ (all-hadronic)	–	25 700 ± 1 400
Multijet	–	8 100 ± 300
Single-top quark	2 200 ± 300	710 ± 70
NP/Misid. leptons	1 500 ± 600	
W+jets	1 500 ± 700	–
$t\bar{t}V$ ($t\bar{t}Z$+ $t\bar{t}W$+ $t\bar{t}H$)	920 ± 120	310 ± 40
Other	400 ± 200	–
Data/Predictions	0.85 ± 0.03	0.84 ± 0.03
(Data – Background)/Signal	0.84 ± 0.03	0.77 ± 0.05

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Jet substructure in $t\bar{t}$ events - τ_{32}

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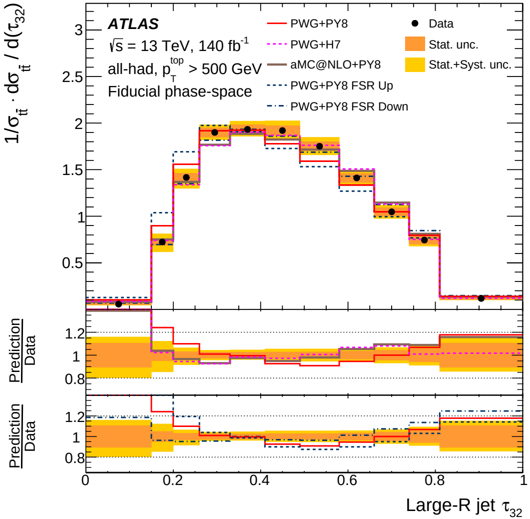
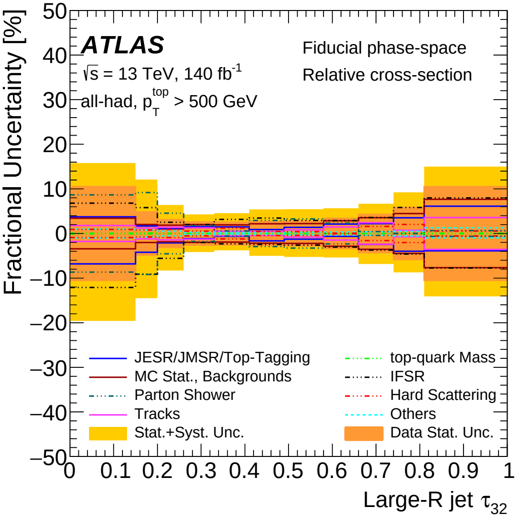
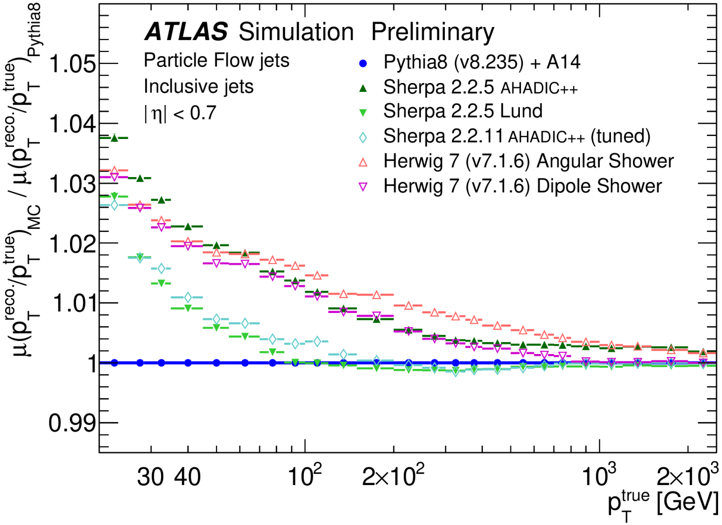




- Largest uncertainties coming from the comparison of different Monte Carlo generators
- Jet-related uncertainties can be also large in some regions of phase space
  - Some double-counting of uncertainties related to modelling → MC-to-MC scale factors

Small interlude - why tuning is important

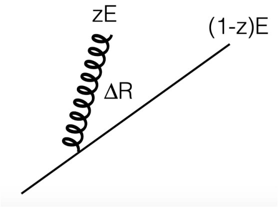
ATL-PHYS-PUB-2022-021



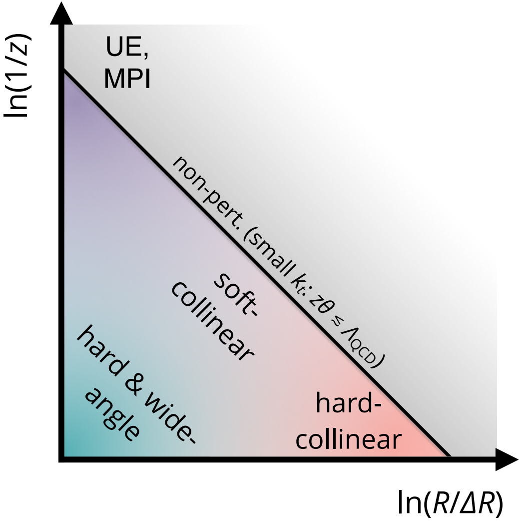
- New AHADIC tune from Sherpa authors using LEP data (hadron fractions within jet)

The Lund plane - introduction

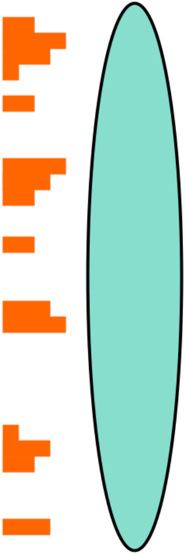
- Lund plane is a useful tool to display emissions



- Expect uniform emission pattern in $\ln(1/z)$ and $\ln(1/\theta)$
- However not directly usable because we don't observe quarks/gluons
- arXiv:2004.03540



Re-clustering with the Cambridge/Aachen algorithm



- Cluster jet constituents with C/A alg
  - Based on angular separation
- Reverse of parton shower

Re-clustering with the Cambridge/Aachen algorithm

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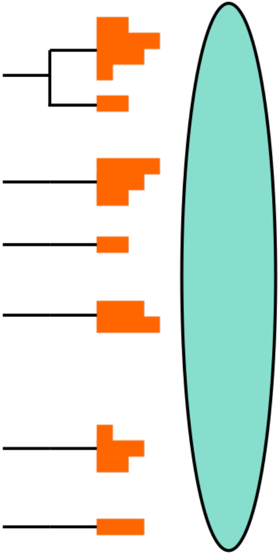

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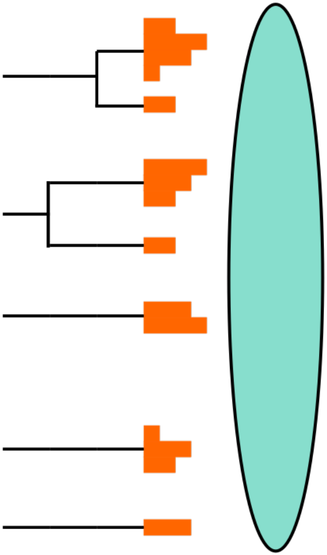

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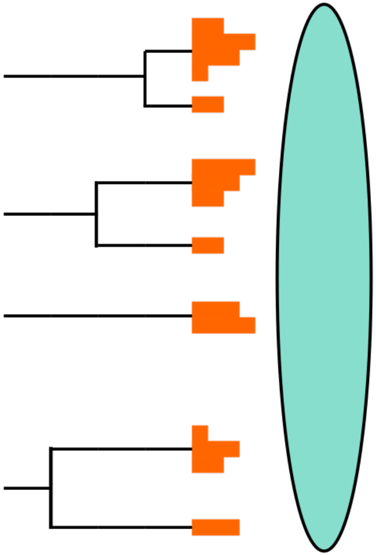

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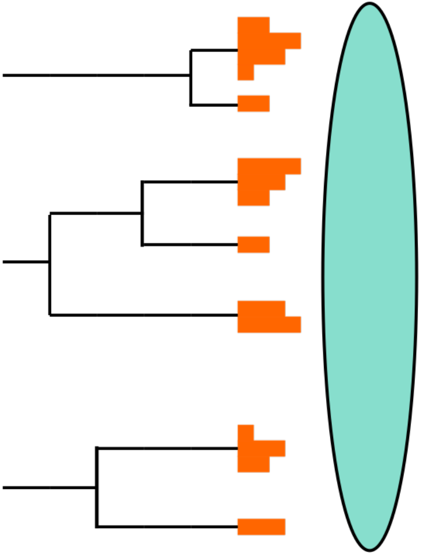

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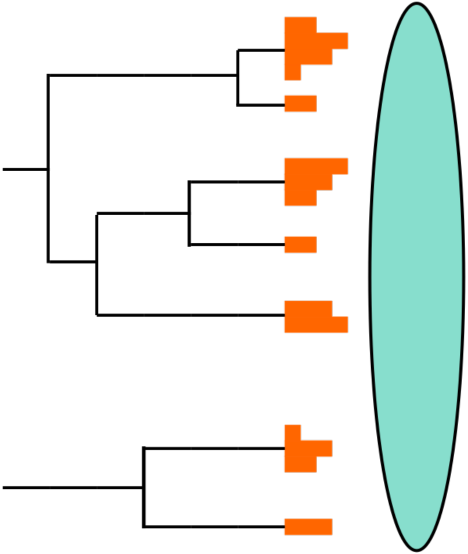

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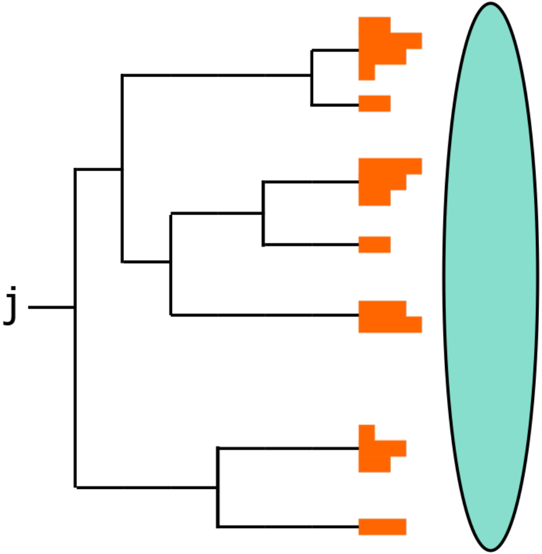

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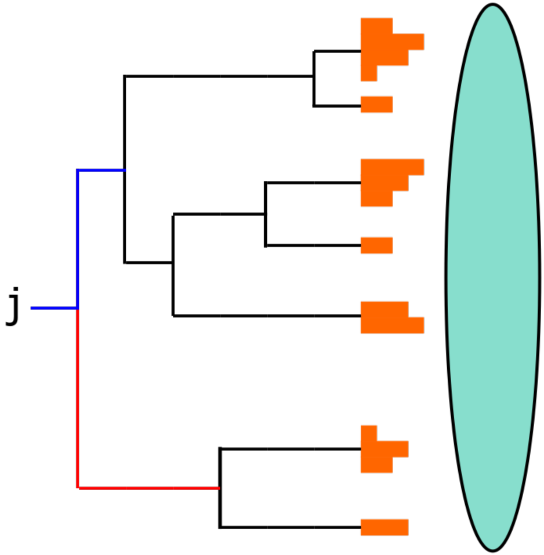

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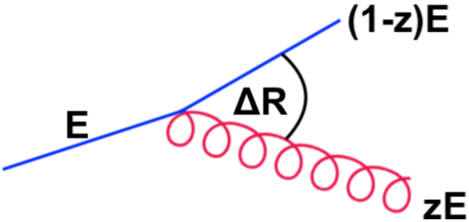
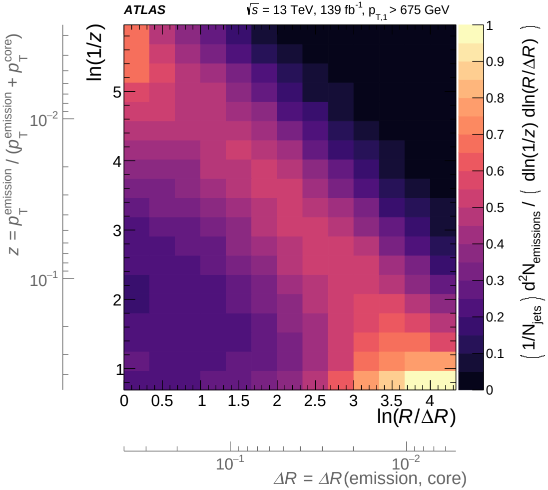


The Lund jet plane - arXiv:2004.03540

- Measured Lund Jet Plane in dijet events using $R = 0.4$ jets
- Only tracks are used here to allow for precise measurement of small splittings



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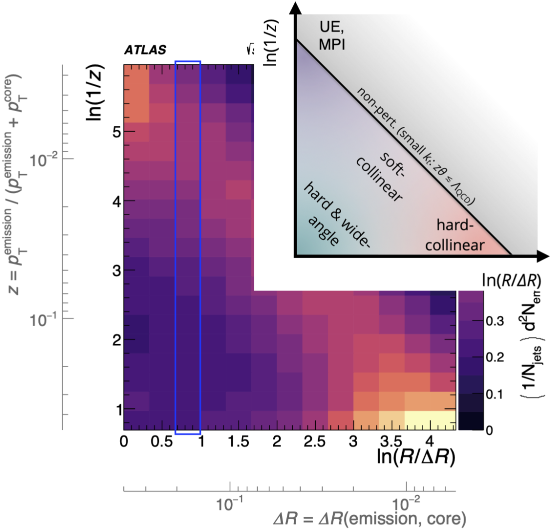

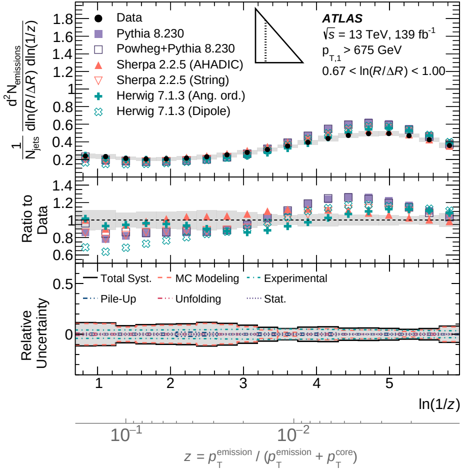

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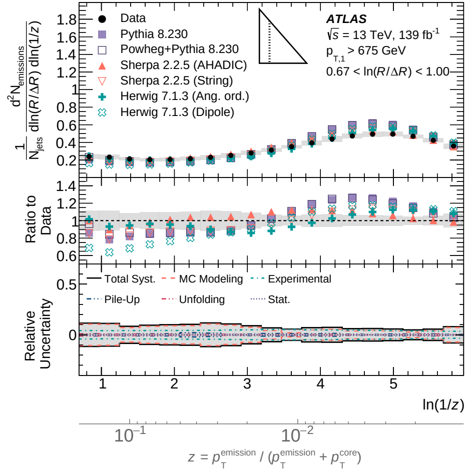

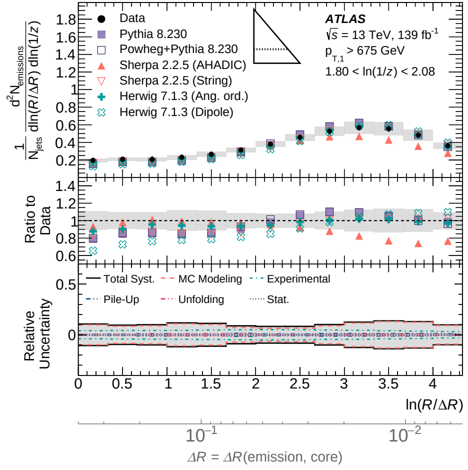

Improvements for future measurements

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- Lately, precision jet substructure measurements have been only performed with tracks
- Uncertainties associated with topoclusters are relatively large compared to tracks
  - We could be missing important discrepancies stemming from neutral particles

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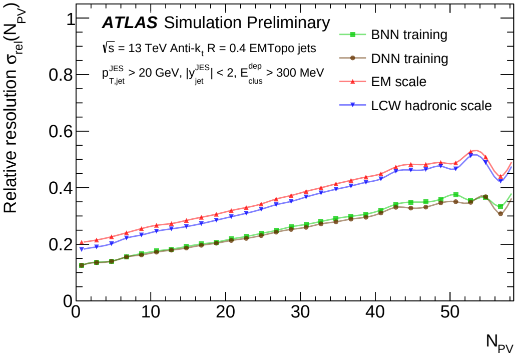

- ML-based calibrations for topoclusters
  - Response for hadronic clusters lower than for electromagnetic ones
- Efforts on-going to reduce pile-up dependence, e.g. cell-level timing cuts

Summary

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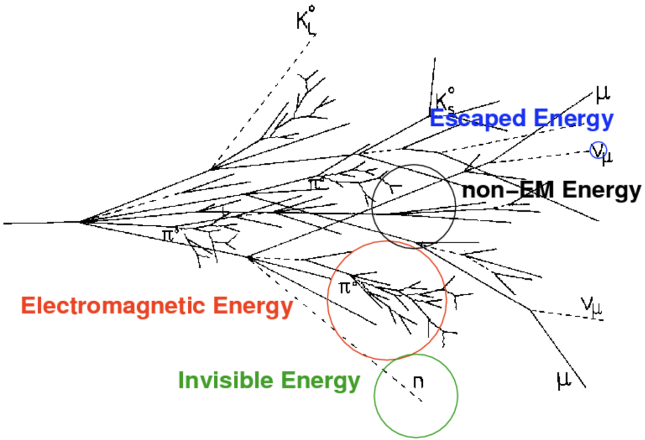
- **Jet substructure is a versatile tool to probe the SM**
  - Tuning of the simulation, α_s determination, jet quenching, searches for BSM ...
- **Large-R reconstruction has significantly improved over the past 10 years**
  - We can determine the jet energy scale with 1% precision, same level as for small-R jets
- **There is much more that I couldn't show here today ...**
  - e.g. quark vs. gluon tagging, multijet event isotropies, mass measurements, ...
- **Interested? Join us at BOOST in Genova**
  - Annual meeting on jet reconstruction, tagging, pileup mitigation, QCD calculations, ...
  - Agenda: link

Backup

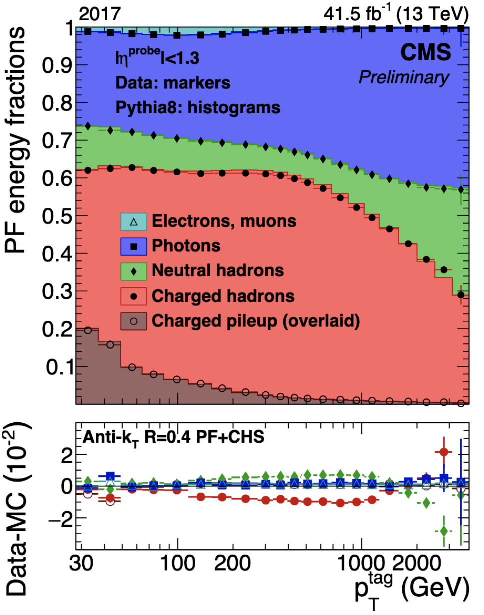
Hadronic shower



- A hadronic shower has two components: a hadronic and an electromagnetic one
- Escaped energy: e.g. muons and/or neutrinos (from hadron decays)
- Electromagnetic component: $\pi^0 \to \gamma\gamma$

Jet composition

- Jets are not only composed of charged & neutral hadrons but also of e, μ, γ
  - e.g. hadron decays, soft photon emissions
- $\approx 2/3$ charged and $1/3$ neutral particles
- Tracker
  - Reconstructs only charged particles
- Calorimeter:
  - Reconstructs neutral + charged particles

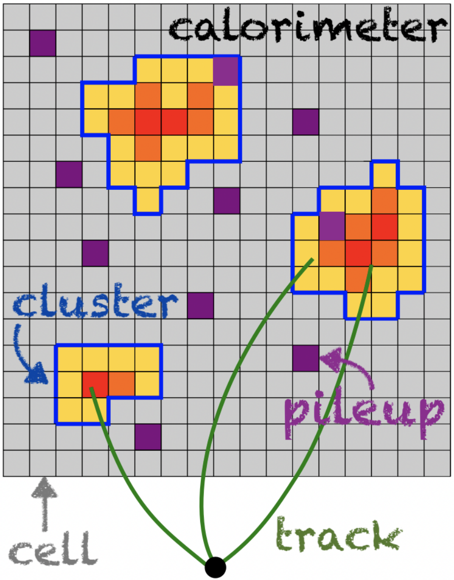


Topological clusters

- Cells are grouped together in topoclusters based on the cell significance ς (4-2-0)
- Cell significance: ratio of signal to noise

$$\varsigma_{\text{cell}}^{\text{EM}} = \frac{E_{\text{cell}}^{\text{EM}}}{\sigma_{\text{noise, cell}}^{\text{EM}}} = \frac{E_{\text{cell}}^{\text{EM}}}{\sqrt{\left(\sigma_{\text{noise}}^{\text{electronic}}\right)^2 + \left(\sigma_{\text{noise}}^{\text{pile-up}}\right)^2}}$$

- seed cells, $\varsigma > 4$
- growth cells, $\varsigma > 2$
- boundary cells, $\varsigma > 0$
- cells from pile-up vertices



Calorimeter noise

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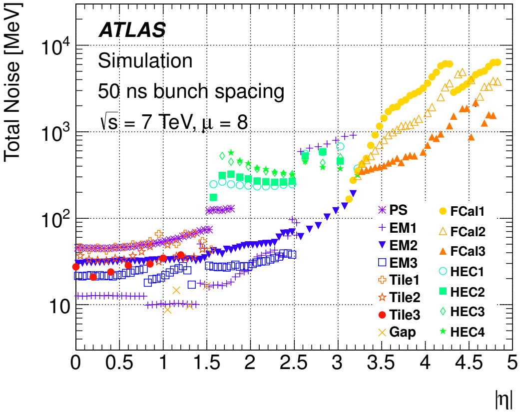
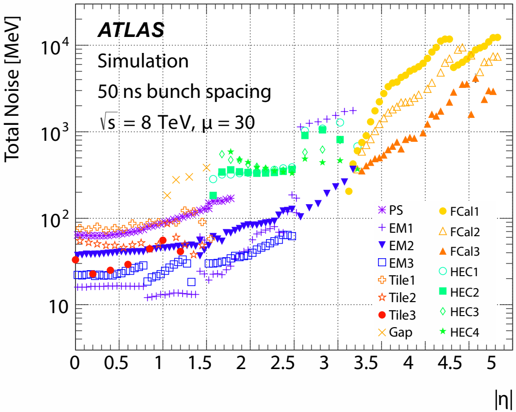
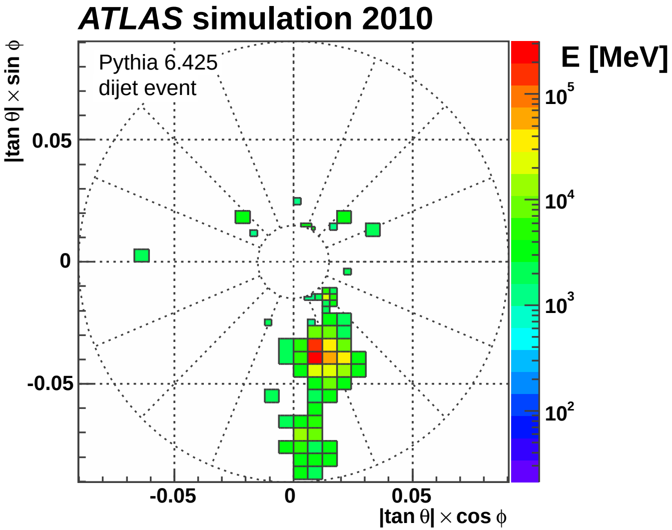
- Topo-cluster formation depends on the cell noise which is dominated by pile-up noise
- Noise from pile-up needs to be determined prior to data-taking and well tuned



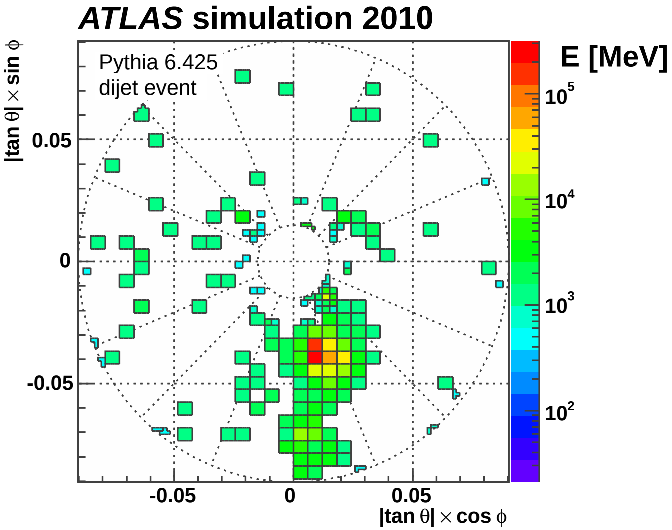


Cluster formation



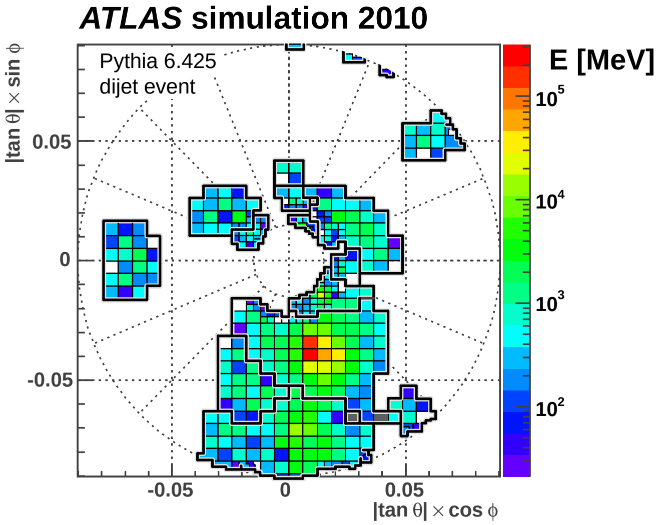
■ Seed cells

Cluster formation



- Seed cells
- Growth cells

Cluster formation



- Seed cells
- Growth cells
- Cluster formation

- Cluster splitting in case of two local maxima

EM vs. LCW scale

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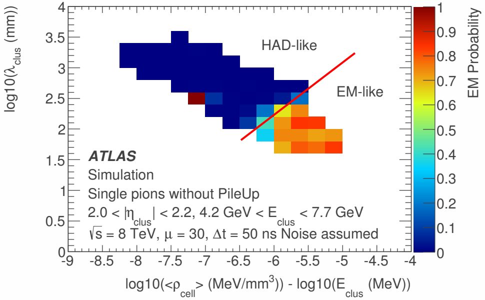
- The hadronic calorimeter is a non-compensating calorimeter:
  - i.e. smaller signal for hadrons than e, γ of the same incident energy
  - caused by invisible energy: energy used to release nucleons from nuclei + μ + ν_x

- We measure the hadronic signal at the electromagnetic (EM) scale
- **Local Cell Weighted** scale: extra calibration for hadronic signals to account for:
  - Non-compensating character of the calorimeter
  - Signal losses due to inactive material
  - Energy falling in unclustered cells

- Clusters first have to be identified as either hadronic or electromagnetic

- LCW used only for large-R jets in Run-2
- Small-R jets showed larger pile-up dependence
- New efforts on-going to improve LCW using ML



Particle Flow - continued

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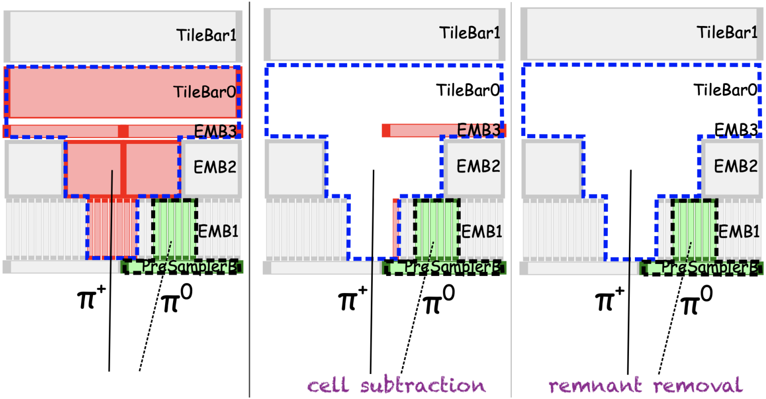
1. Match charged-particle tracks to topo-clusters in the calorimeter
2. Subtract energy deposited in the calorimeter by charged particles from matched clusters
3. Add only tracks associated with hard-scatter vertex to list of inputs to jet reconstruction (**C**harged **H**adron **S**ubtraction)

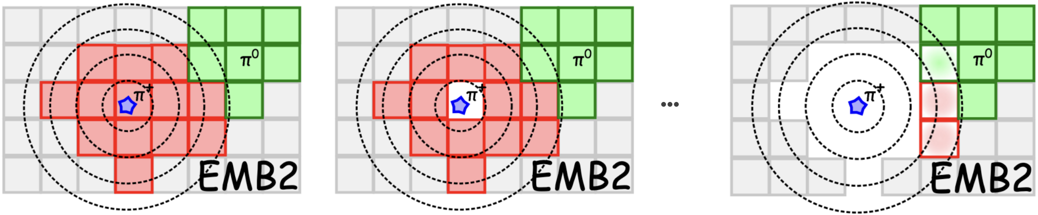


E/p

- Need to know how much energy a particle with p_{trk} deposits on average in the calorimeter

$$\langle E_{\mathrm{dep}} \rangle = p_{\mathrm{trk}} \left\langle \frac{E_{\mathrm{clus}}}{p_{\mathrm{trk}}^{\mathrm{ref}}} \right\rangle$$

- $\langle E_{\mathrm{dep}} \rangle$ is determined in single-particle simulations without pile-up
- $\langle E_{\mathrm{dep}} \rangle$ provided as a function of p_{trk}, η and the layer of highest energy density (LHED)
  - Shower core has a well-defined ellipsoidal shape in $\eta - \phi$
  - First perform subtraction in LHED before progressing to less regular shower periphery
- If $\langle E_{\mathrm{dep}} \rangle > E_{\mathrm{clus}}$: remove cluster, else cell-by-cell subtraction



p_{T} balance techniques

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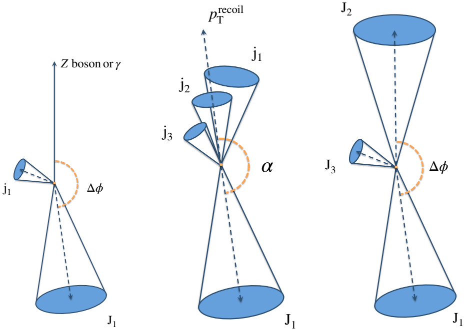
- Need to measure the jet response in data and simulation, correction factor defined as

$$c = \mathcal{R}^{in\ situ}_{\mathrm{MC}} / \mathcal{R}^{in\ situ}_{\mathrm{data}}$$

- Response is calculated by balancing the jet p_{T} against a well-calibrated reference object with approx. no other hadronic activity

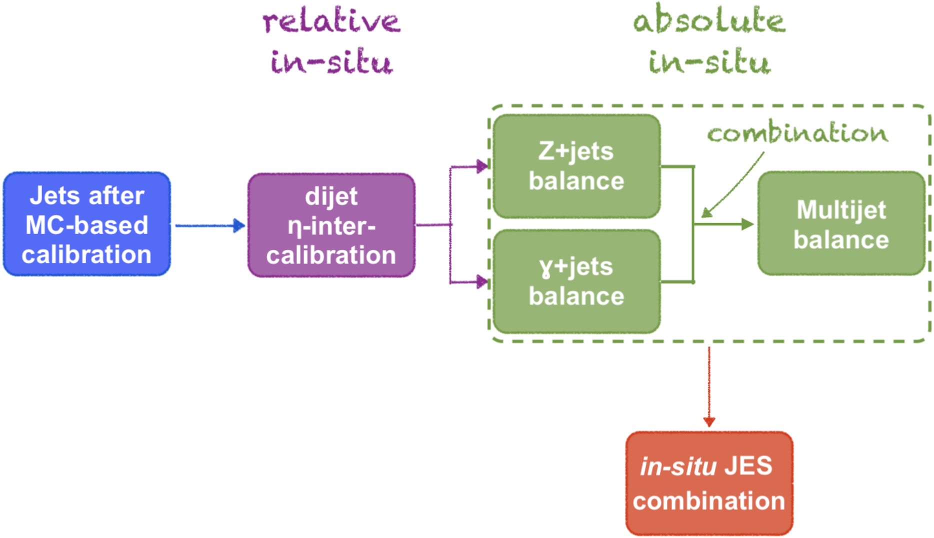
$$\mathcal{R}^{in\ situ}_{\mathrm{MC,data}} = \left\langle \frac{p_{\mathrm{T}}^{\mathrm{jet}}}{p_{\mathrm{T}}^{\mathrm{ref}}} \right\rangle$$

  - Distribution fitted in bins of $p_{\mathrm{T}}^{\mathrm{ref}}$ with Gaus $\rightarrow$ extract mean



- Uncertainties of ref. object are propagated, thus use objects with high precision, e.g. $Z \rightarrow \mu\mu$, $Z \rightarrow ee$, γ or system of well-calibrated low p_{T} jets

The small-R JES calibration chain



- Relative *in-situ* JES: correct jets with $|\eta| > 0.8$ to the same energy scale as $|\eta| < 0.8$
- Absolute *in-situ* JES: correct jets with $|\eta| < 0.8$ to a precise reference object

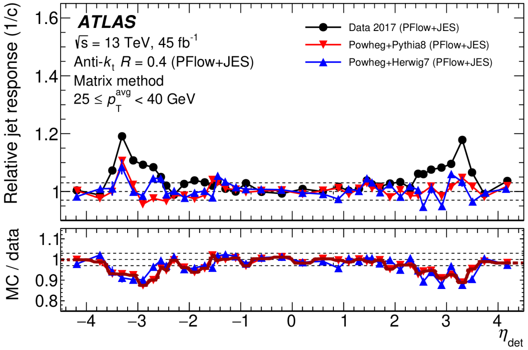
- Aim: flatten the JES across the detector
- Matrix method used to increase stat.: neither of the jets needs to be within $|\eta| < 0.8$
  - Multiple reference regions are defined which are calibrated against each other
  - Calibration derived using dijet events

- Response difference between two regions

$$\mathcal{A} = \frac{p_T^{\text{left}} - p_T^{\text{right}}}{p_T^{\text{avg}}}$$

- Response ratio $\mathcal{R}$ of the two jets defines the calib factor c for each jet

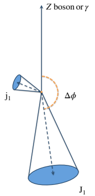
$$\mathcal{R} = \frac{c_{\text{left}}}{c_{\text{right}}} = \frac{2 + \langle \mathcal{A} \rangle}{2 + \langle \mathcal{A} \rangle} \simeq \frac{p_T^{\text{left}}}{p_T^{\text{right}}}$$



- Dominating uncertainties are Monte Carlo generator differences and the third jet veto

Absolute *in situ* JES - V+jet calibration - direct balance

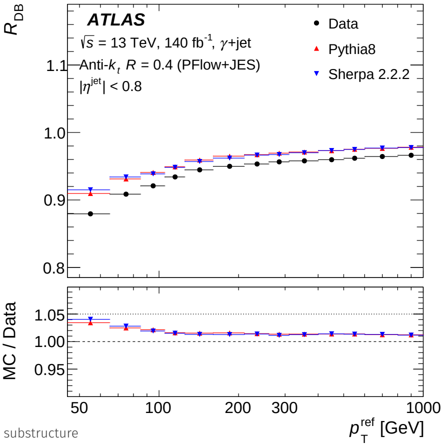
- Reference objects are either $Z(\rightarrow \mu\mu)$, $Z(\rightarrow ee)$ or γ
- Z+jets covers lowest p_{T} range ($p_{\mathrm{T}} > 17$ GeV), γ+jets starting at $\approx$ 25 GeV
- Jets required to be calibrated with η-intercalibration for second jet veto



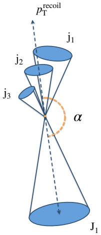
$$\mathcal{R}_{\mathrm{DB}} = \left\langle \frac{p_{\mathrm{T}}^{\mathrm{jet}}}{p_{\mathrm{T}}^{\mathrm{ref}}} \right\rangle$$

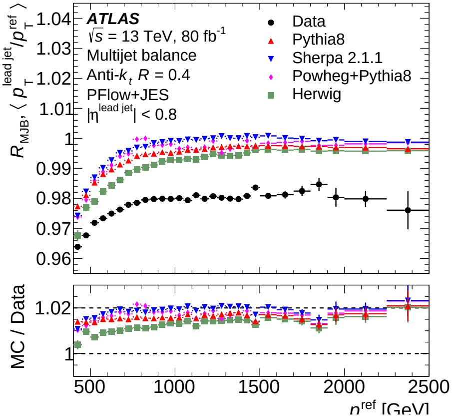
$$\text{with} \;\; p_{\mathrm{T}}^{\mathrm{ref}} = p_{\mathrm{T}}^{Z/\gamma} |\cos(\Delta\phi(X, \mathrm{jet}))|$$

- p_{T} imbalance may be introduced by out-of-cone (OOC) effects, pile-up or ISR/FSR
  $\rightarrow$ MPF technique
- Technique also used to derive JES for b-jets, see e.g. JETM-2022-01



- Reference object: system of low-p_{T} small-R jets
  - Those jets are calibrated with combination of Z+jets & γ+jets calib
  - Uncertainties from low-p_{T} calibration are propagated through the MJB
- MJB covers roughly the range $p_{\mathrm{T}} > 400$ GeV up to 2.5 TeV





$$\mathcal{R}_{\mathrm{DB}} = \left\langle \frac{p_{\mathrm{T}}^{\mathrm{lead.\ jet}}}{p_{\mathrm{T}}^{\mathrm{ref}}} \right\rangle$$

- $p_{\mathrm{T}}^{\mathrm{ref}}$ is the vectorial sum of the recoil system
- Multiple iterations to extend the reach of the technique
- Dominating uncertainties are the flavour uncertainties, propagated γ+jets uncertainties and MC generator differences