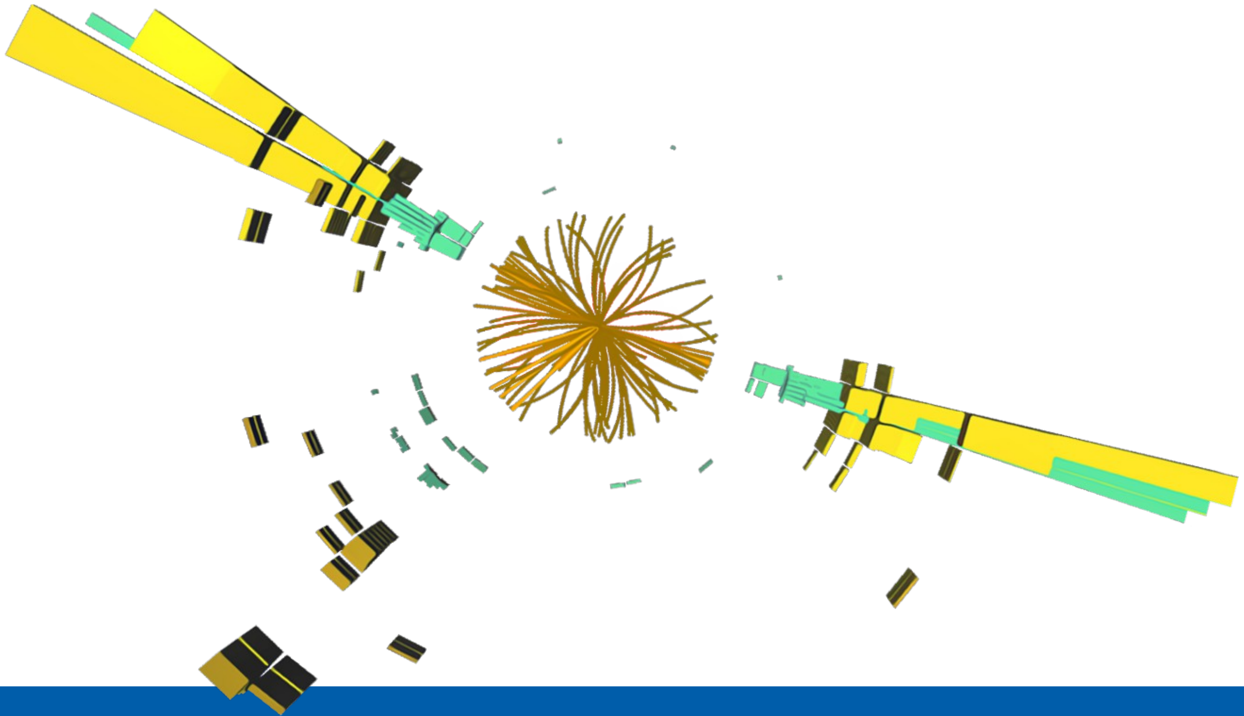

Improving Jet Substructure Performance in ATLAS with Unified Tracking and Calorimeter Inputs

Connecting The Dots 2018

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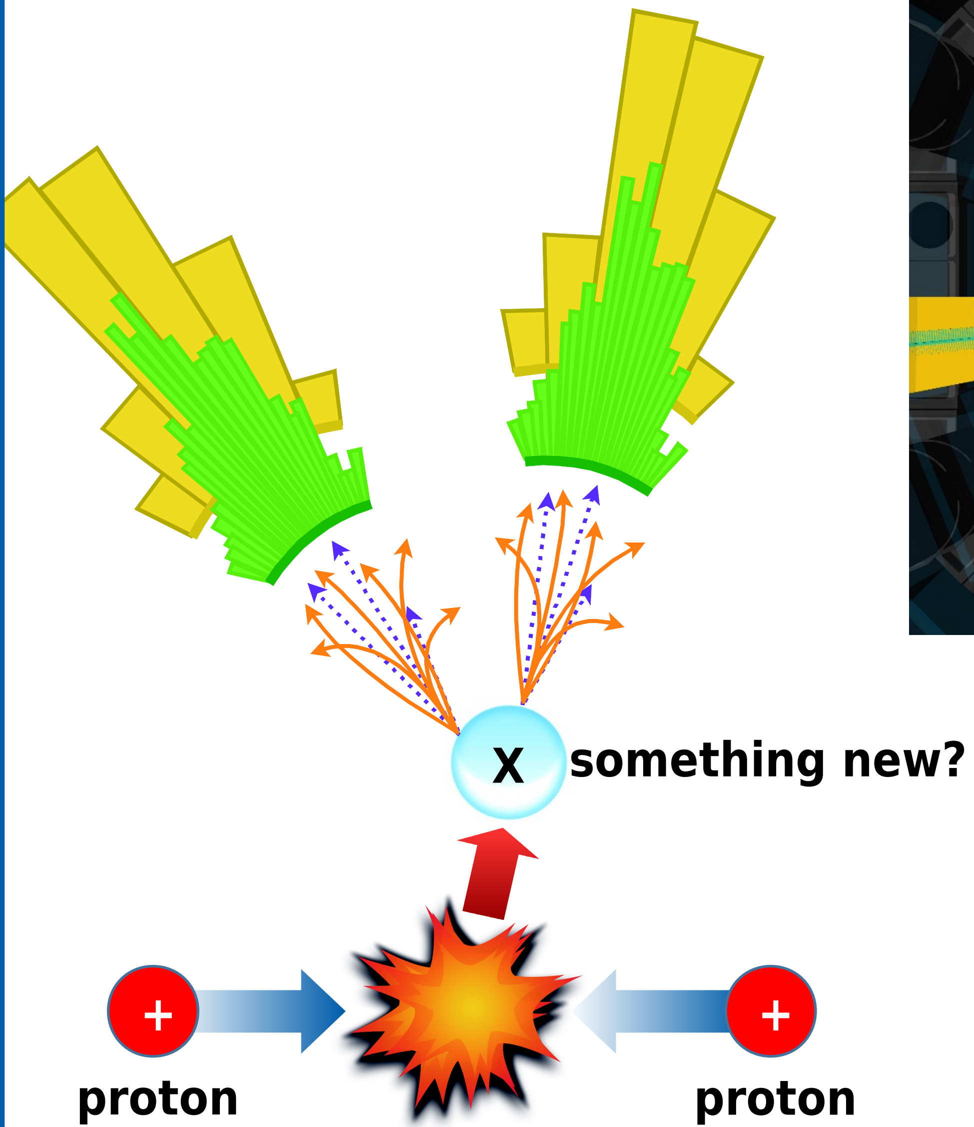
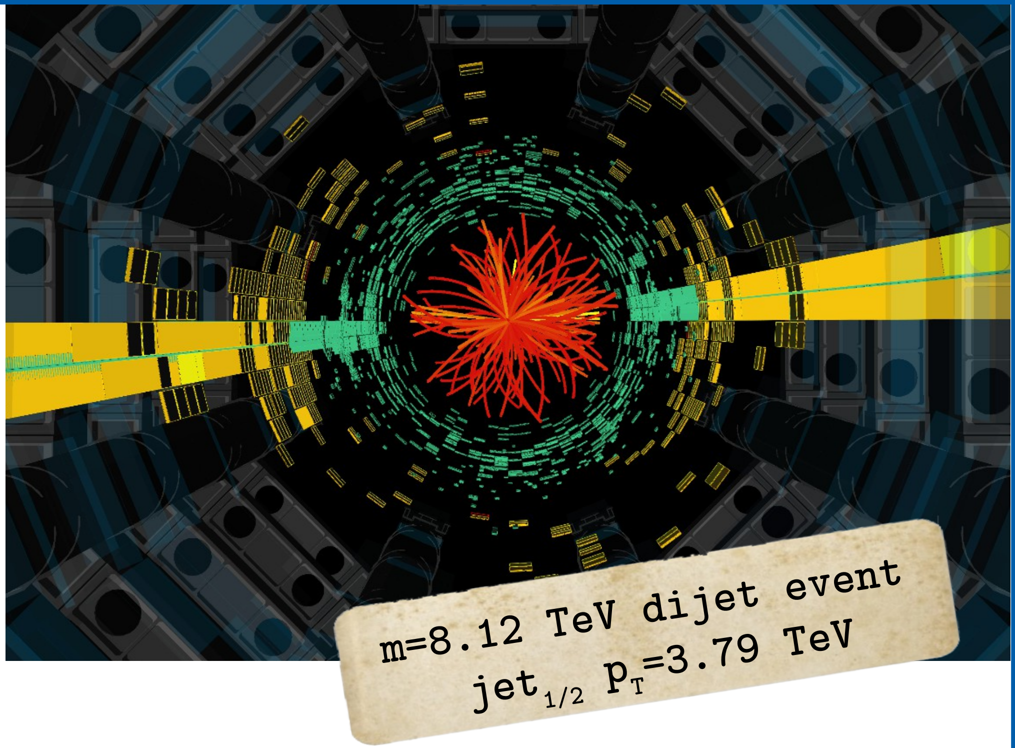
University of Geneva

21st March 2018

Jets at the Energy Frontier



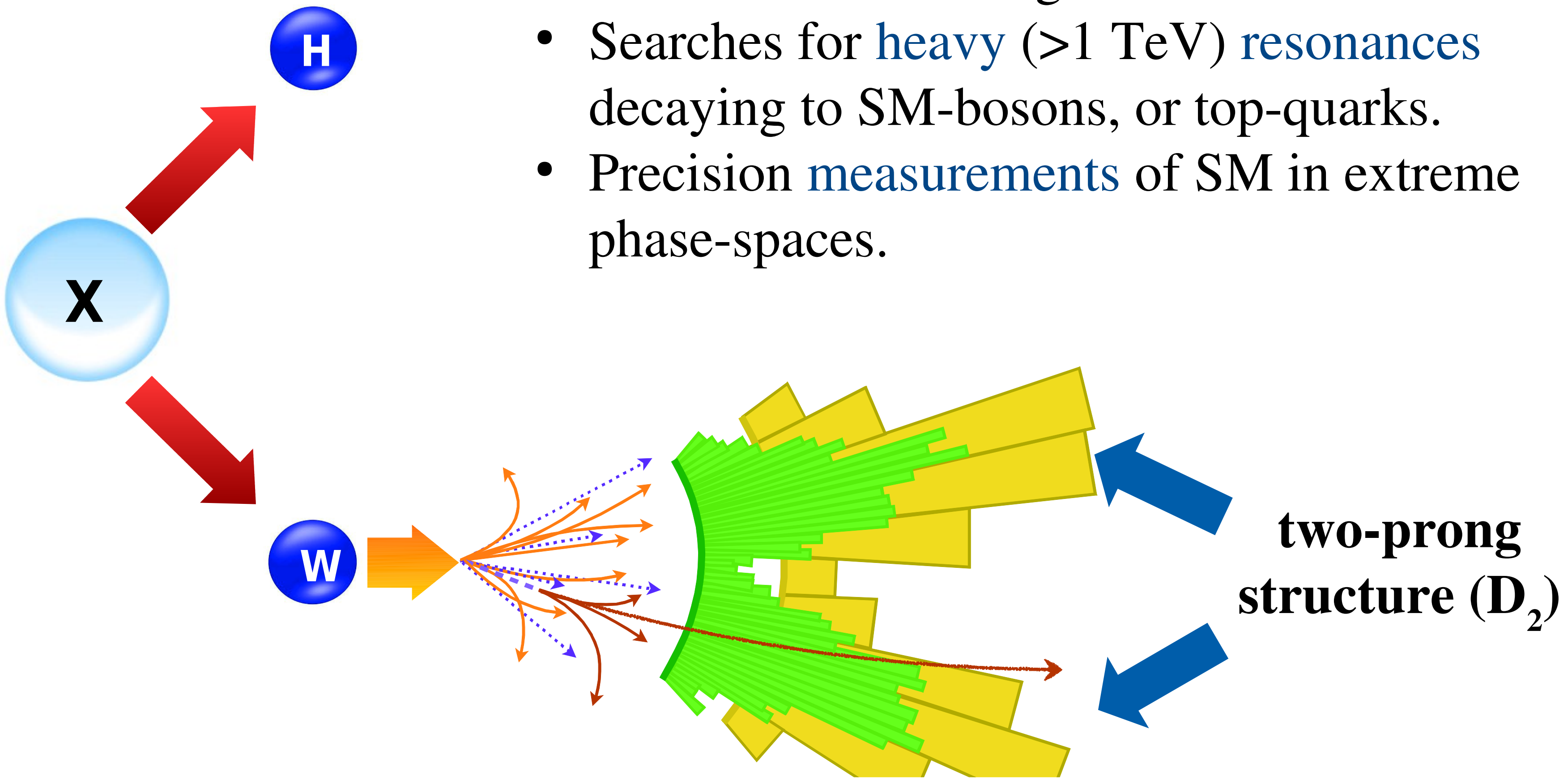


- LHC: $\sqrt{s} = 13$ TeV.

Jet Substructure (1/2)

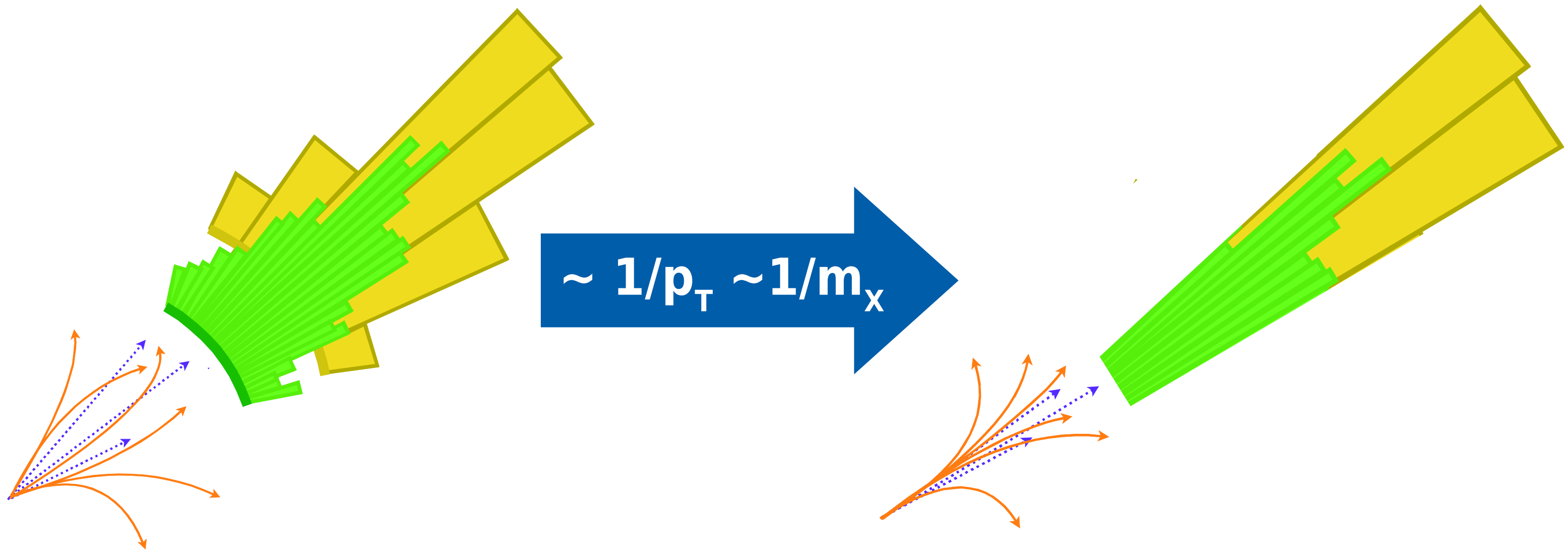
Jet substructure crucial tool for:

- Inclusive search for and measurement of $H \rightarrow bb$ in boosted regime.
- Searches for heavy (>1 TeV) resonances decaying to SM-bosons, or top-quarks.
- Precision measurements of SM in extreme phase-spaces.



Jet Substructure (2/2)

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



- Tracker granularity superior to calorimeter.
  → **Use tracker in reconstruction of jet substructure.**

Motivation for TrackCaloClusters

ATL-PHYS-PUB-2017-015

- Track-CaloClusters (TCC) are our **approach to track-assisting jets**
  - Basic idea is simple: **match tracks to clusters**
  - As usual, the details can be a bit more complex
- **Track-assisting has had great success** in m_{TA}(ATLAS-CONF-2016-035), integrated into m_{comb}
  - Provides better mass resolution at high p_T
  - Particularly important when $m/p_T \ll 1$
- However, **TA assumes that the charge/neutral fraction is uniform**
  - A large-R jet can have sizable local fluctuations
  - Fluctuations should be important for substructure variables
- **TCC is a step further**
  - Is aimed at accounting for these local fluctuations
  - Work at the level of individual tracks and clusters

$$m_{\text{calo}} = \sqrt{\left(\sum_{c\,\in\,C} E_c\right)^2 - \left(\sum_{c\,\in\,C} \vec{p}_c\right)^2}$$

$$m_{\text{trk}} = \sqrt{\left(\sum_{t\,\in\,T} E_t\right)^2 - \left(\sum_{t\,\in\,T} \vec{p}_t\right)^2}$$

$$m_{\text{TA}} = \frac{p_{\text{T}}^{\text{calo}}}{p_{\text{T}}^{\text{trk}}} \times m_{\text{trk}}$$

$$m_{\text{comb}} = \frac{\sigma_{\text{calo}}^{-2}}{\sigma_{\text{calo}}^{-2} + \sigma_{\text{TA}}^{-2}} \times m_{\text{calo}} + \frac{\sigma_{\text{calo}}^{-2}}{\sigma_{\text{calo}}^{-2} + \sigma_{\text{TA}}^{-2}} \times m_{\text{TA}}$$

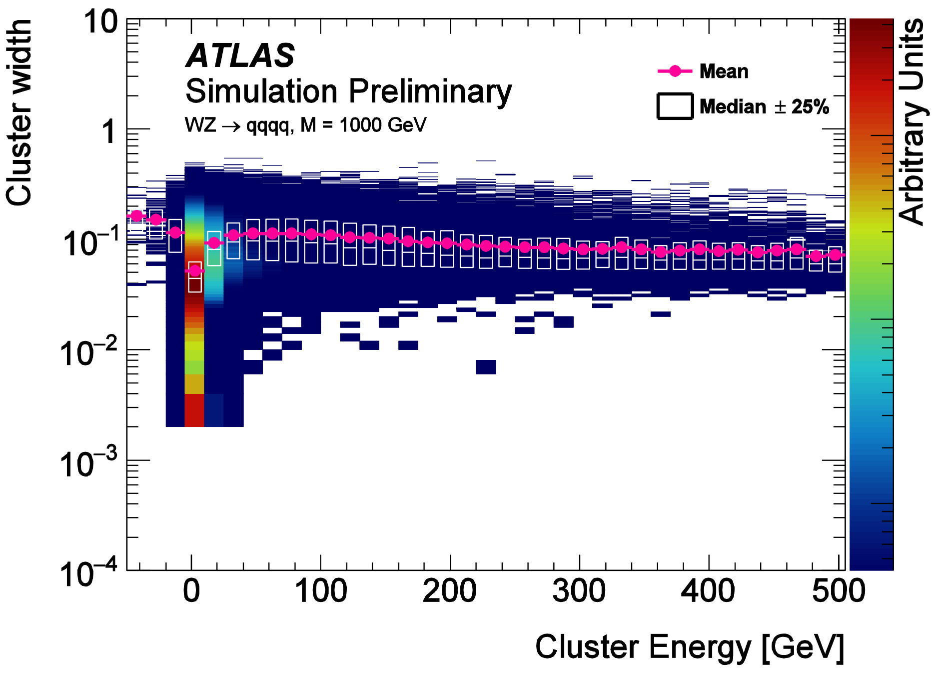
Motivation for TrackCaloClusters

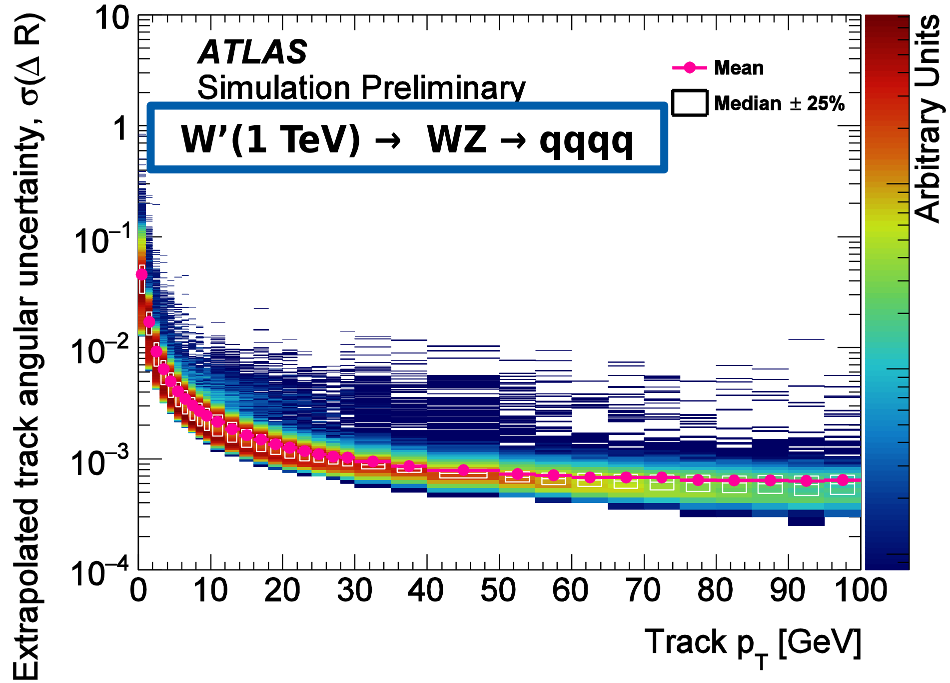
- The next logical question is how this compares to particle flow
  → **They have very different use cases and intentions!**
- Particle flow:
  - **At low p_T:** the tracker has a better energy resolution
  - Use it to improve the performance/pileup stability of low p_T jets
- Track-caloclusters:
  - **At high p_T:** the calorimeter has the better energy resolution
  - However, the tracker has the better spatial resolution
  - Use the tracker to better understand the structure of the jet
- **The method of application is also very different**
  - PFlow: subtract energies to avoid double-counting
  - TCC: use calorimeter energy scale and tracker spatial coordinates

Motivation for TrackCaloClusters

ATL-PHYS-PUB-2017-015

- At **high p_T**:
  - Calorimeter provides good energy resolution, but poor granularity.
  - Tracker provides good angular resolution, but degraded p_T resolution.
- Extrapolation uncertainty of tracks to calorimeter smaller than average angular width of topological-clusters in calorimeter.





Idea of TrackCaloClusters

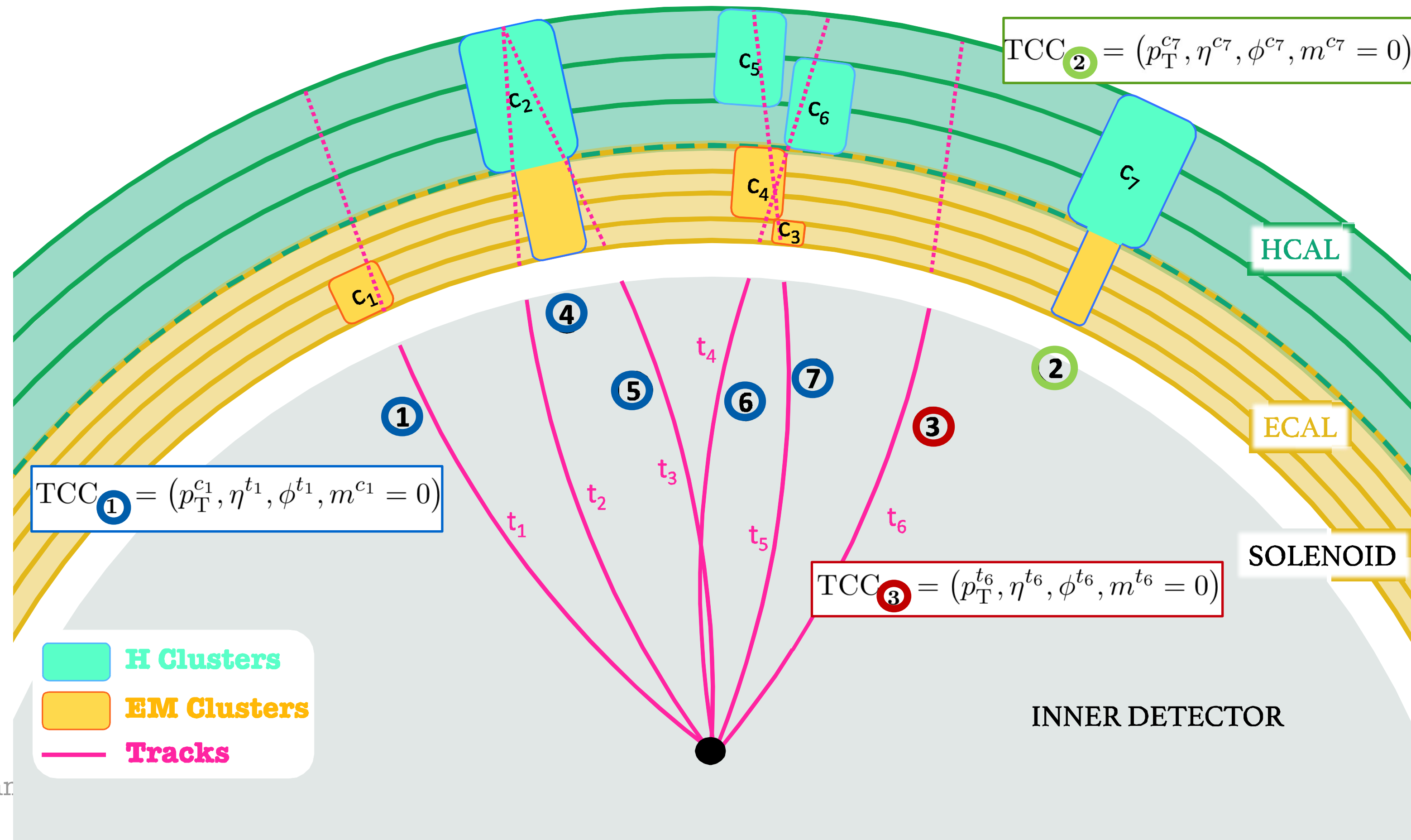
- **TrackCaloClusters (TCCs) are a way to profit from the complementary behaviour of the two detectors at high p_T.**

- **Basic idea:**
  - **Match <u>all</u> tracks to <u>all</u> clusters.**
    - Tracks are extrapolated to the calorimeter with uncertainty σ_{track}.
    - Topo-clusters in calorimeter have angular dimension $\sigma_{cluster}$.
    - Check if $\sigma_{track} < \sigma_{cluster}$. If it is:
    - Match track to cluster if $\Delta R < \sqrt{\sigma_{track}^2 + \sigma_{cluster}^2}$.
  - **Build 4-vector from matched objects.**
    - Use the spatial information from the tracker (η, ϕ).
    - Use the energy measurements of the calorimeter (p_T, m).

Tastes of TrackCaloClusters

Distinguish three interesting tastes:

- **Combined**: track from hard scatter vertex matched to topo-cluster.
- **Charged**: unmatched track from hard scatter vertex.
- **Neutral**: unmatched topo-cluster - not matched to any (pile-up) track.



Energy Reshuffling (1/2)

- **Calorimeter energy and mass reshuffled, using all relevant clusters and tracks via three p_T ratios.**
  - Each matched cluster c contributes to TCC τ proportionally to its p_T out of all matched clusters k.
  - Cluster c matched to multiple tracks contributes to TCC τ proportional to track τ p_T compared to other matched tracks t.
  - Contribution of each of these tracks weighted by fraction of energy cluster c represents compared to all clusters k matched to the track t.

$$f_\tau^c = \frac{p_T^c}{p_T\left[\sum_{k\in C_\tau} \mathbf{p}^k\right]}$$

$$\mathcal{F}_{c,t}^\tau = \frac{p_T^\tau}{p_T\left[\sum_{t\in T_c} \mathbf{p}^t f_t^c\right]}$$

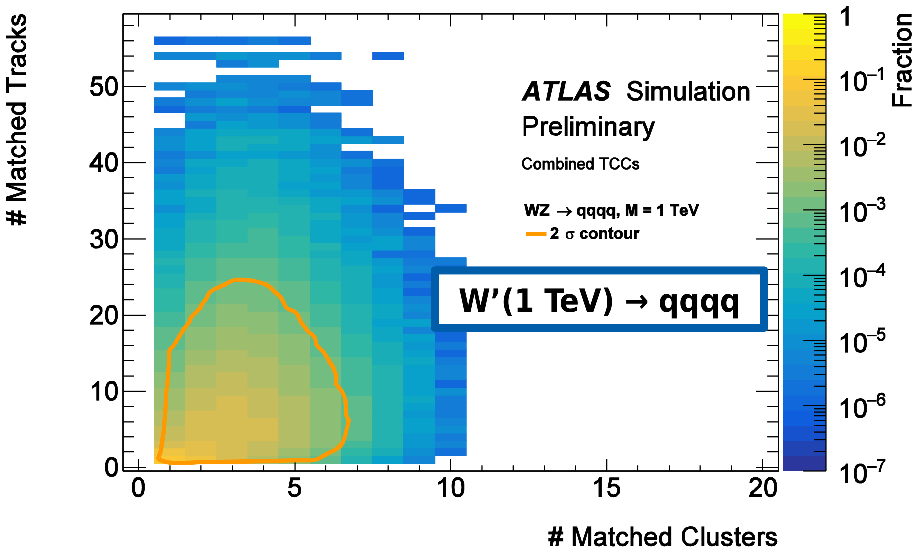
$$f_t^c = \frac{p_T^c}{p_T\left[\sum_{k\in C_t} \mathbf{p}^k\right]}$$

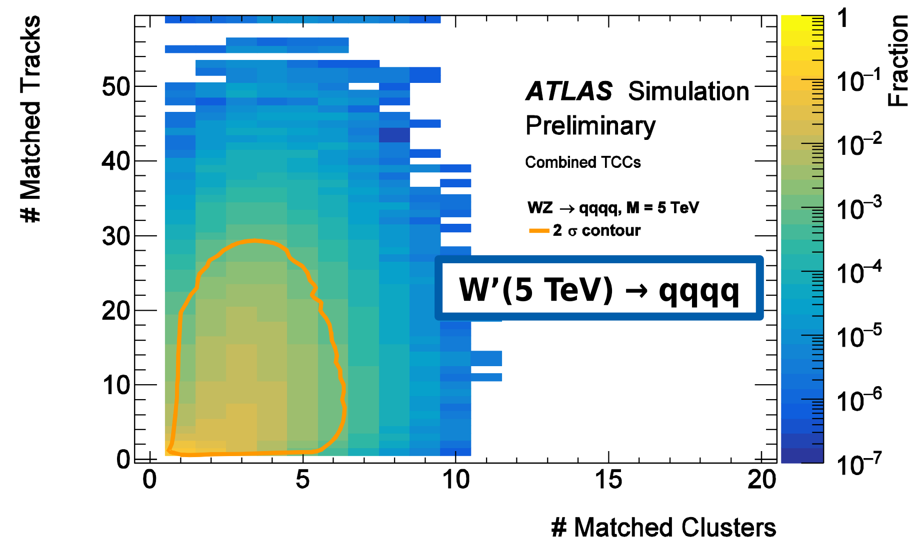
Energy Reshuffling (2/2)

- Calorimeter energy and mass reshuffled, using all relevant clusters and tracks.

$$\mathrm{TCC}_\tau = (p_\mathrm{T}[\mathbf{M}_\tau], \eta^\tau, \phi^\tau, m[\mathbf{M}_\tau])$$

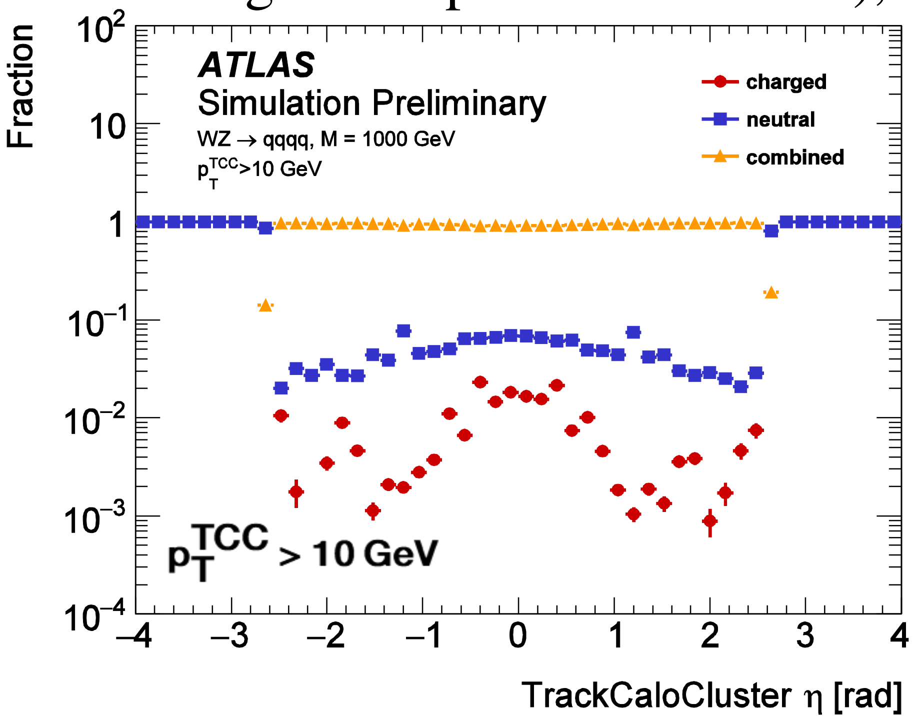
$$\mathbf{M}_\tau = \sum_{c \in C_\tau} \mathbf{p}^c \, f^c_\tau \, \mathcal{F}^\tau_{c,t} = \sum_{c \in C_\tau} \mathbf{p}^c \, \frac{p_\mathrm{T}^c}{p_\mathrm{T}\left[\sum_{k \in C_\tau} \mathbf{p}^k\right]} \, \frac{p_\mathrm{T}^\tau}{p_\mathrm{T}\left[\sum_{t \in T_c} \mathbf{p}^t \frac{p_\mathrm{T}^c}{p_\mathrm{T}\left[\sum_{k \in C_t} \mathbf{p}^k\right]}\right]}$$

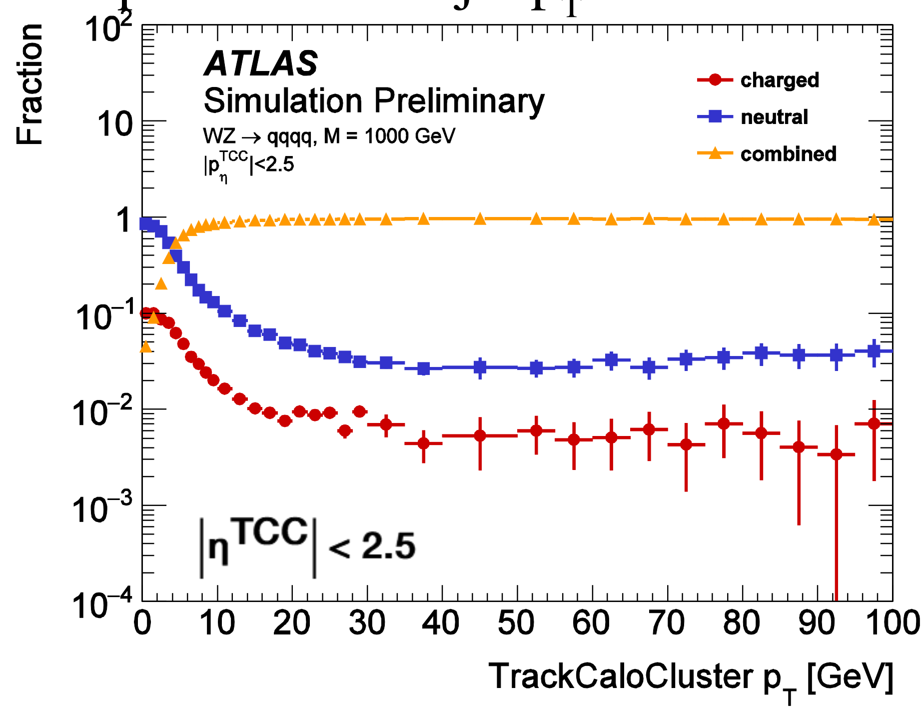




Matching Efficiencies

- **Algorithm matches all tracks in inner detector acceptance and p_T >10 GeV.**
- <1% high p_T charged TCCs mostly mis-measured tracks (and few muons) → don't use in jet substructure reconstruction.
- Neutral TCCs rare at high jet p_T (due to collimation of neutral & charged component of shower), but important at low jet p_T.

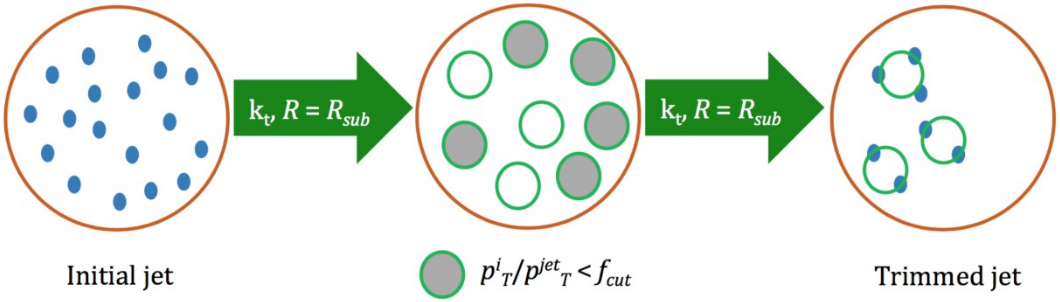




ª And Then There Were Jetsº

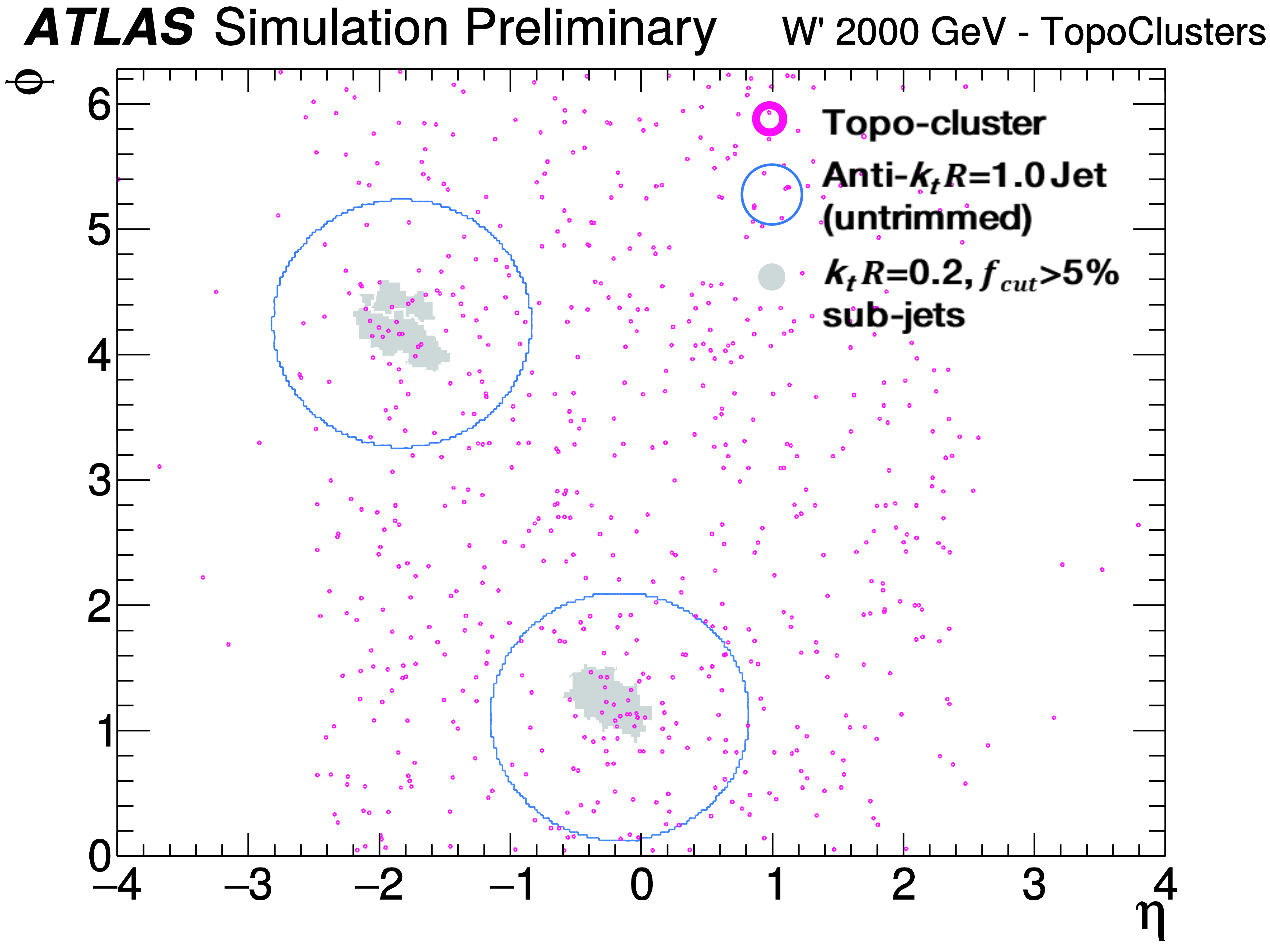
Jet Trimming

- Build large-radius jets using ATLAS default algorithm: anti-k_t with distance parameter R=1.0 & trimming applied (f_{cut}=5% and R_{sub}=0.2).



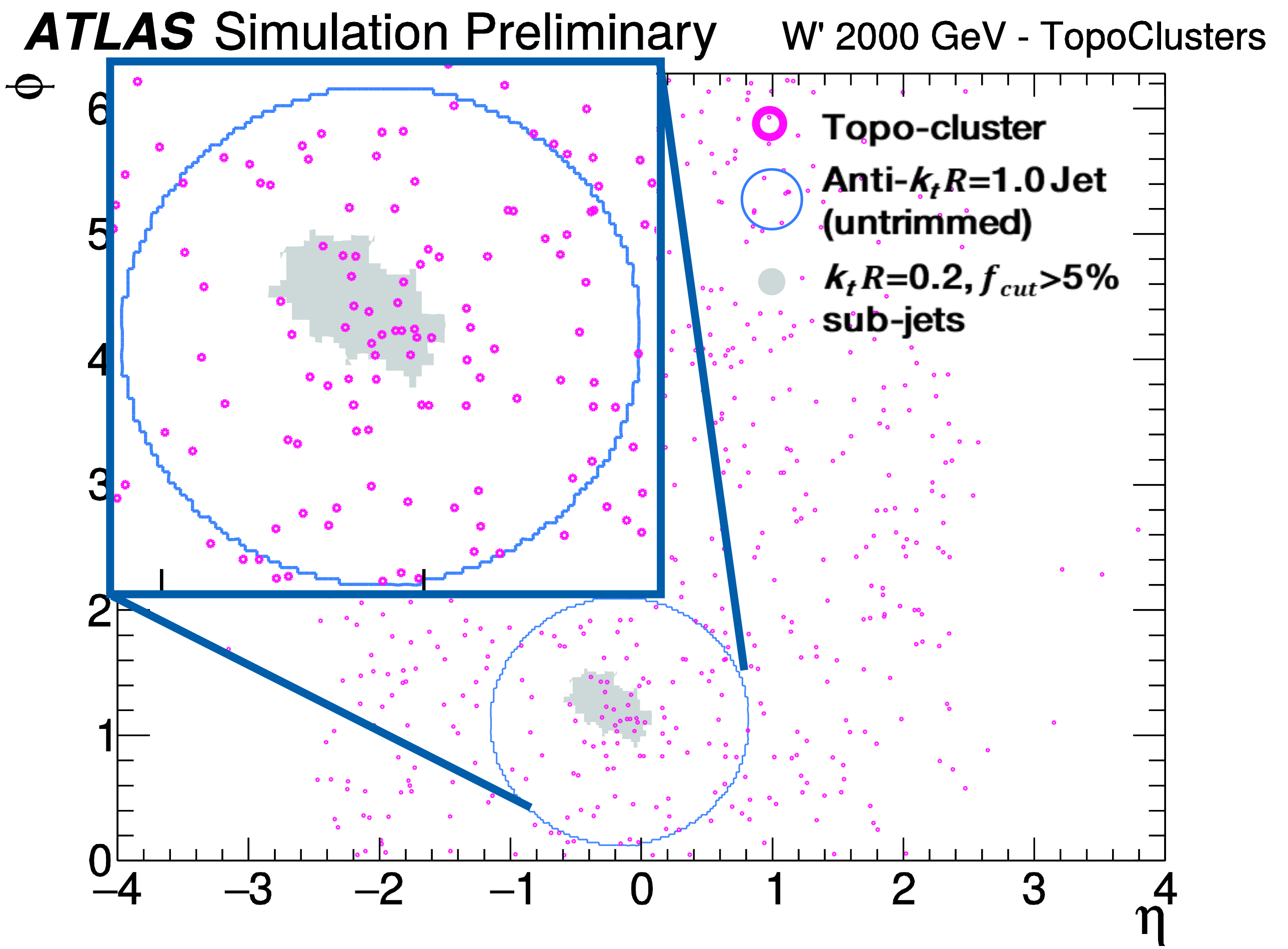
“And Then There Were Jets”

- Build large-radius jets using ATLAS default algorithm: anti-k_t with distance parameter R=1.0 & trimming applied (f_{cut}=5% and R_{sub}=0.2).



[a] And Then There Were Jets[o]

- Build large-radius jets using ATLAS default algorithm: anti-k_t with distance parameter R=1.0 & trimming applied (f_{cut}=5% and R_{sub}=0.2).



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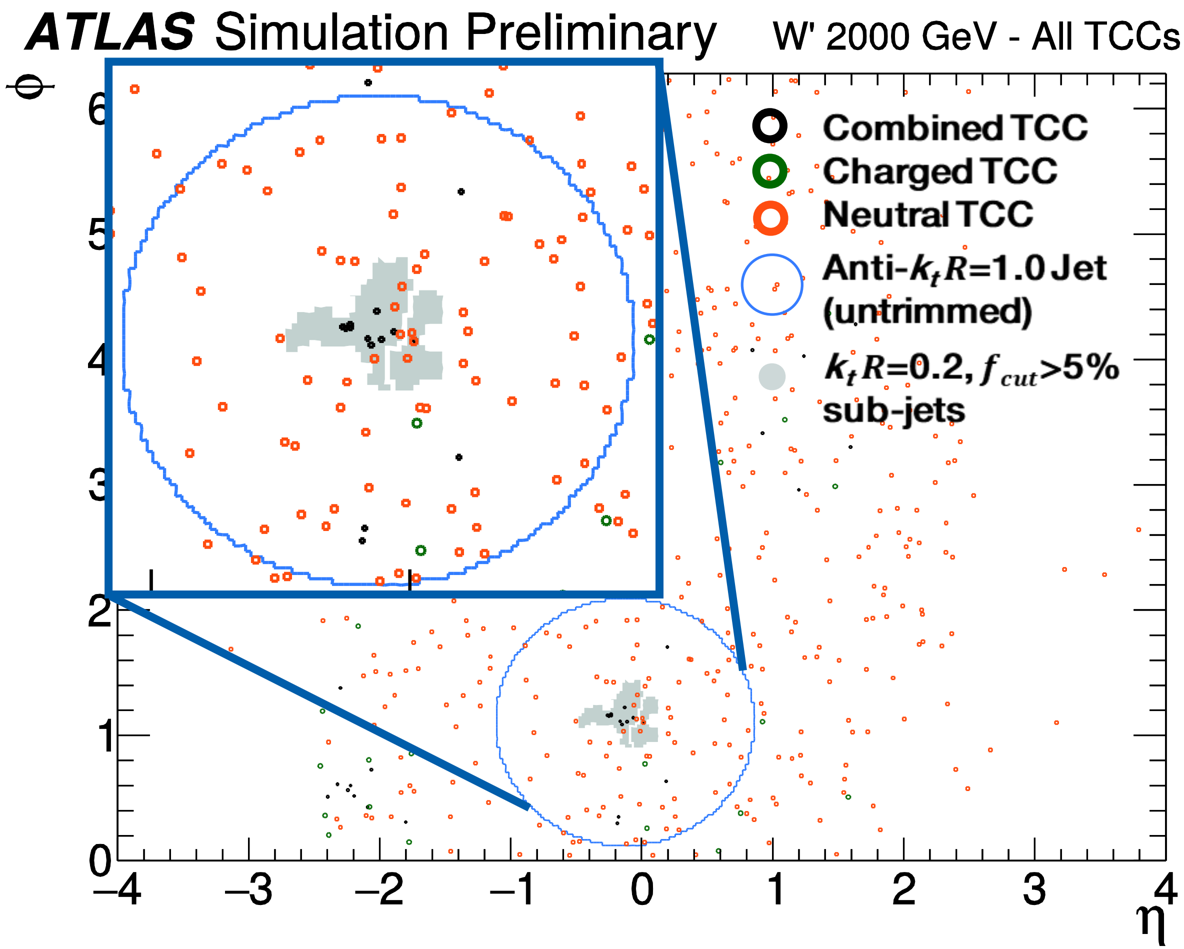

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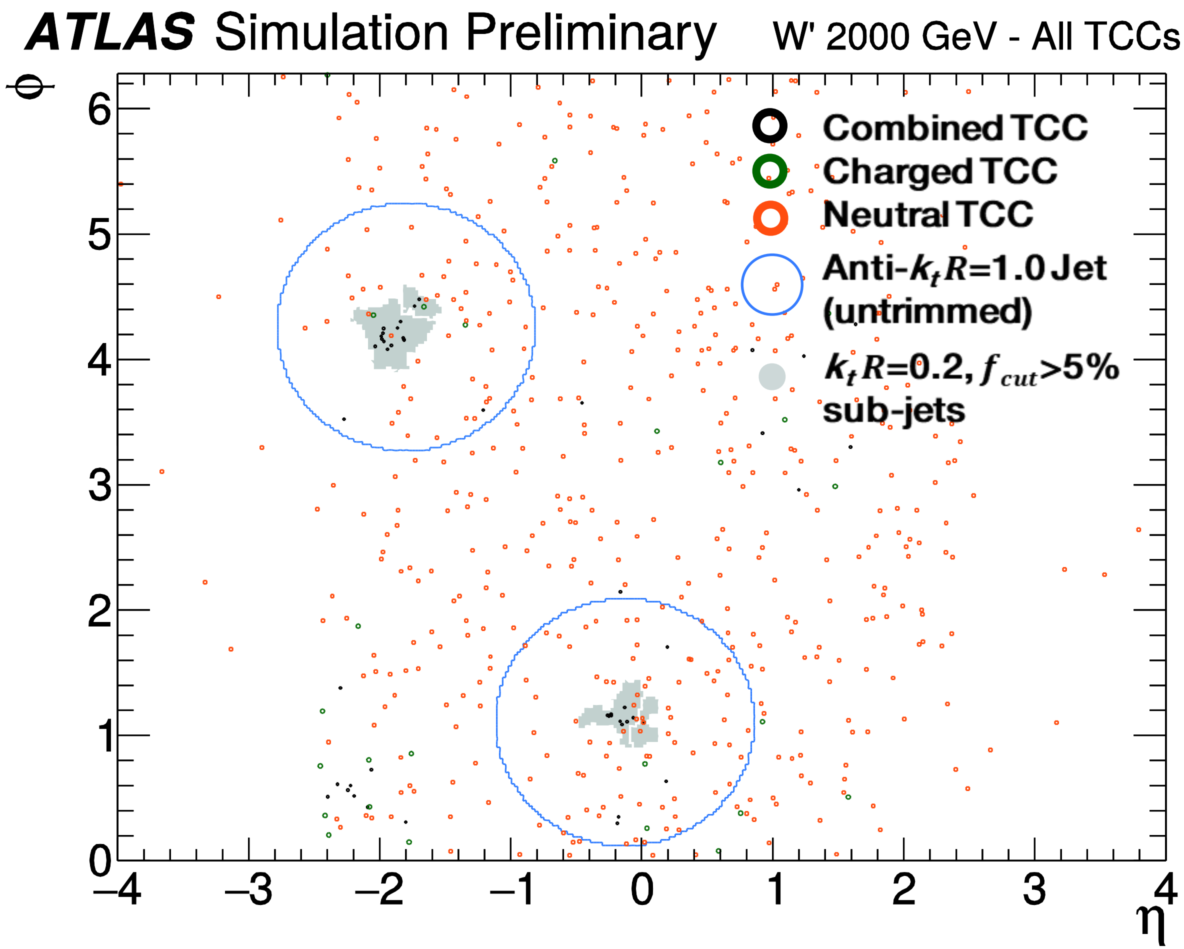
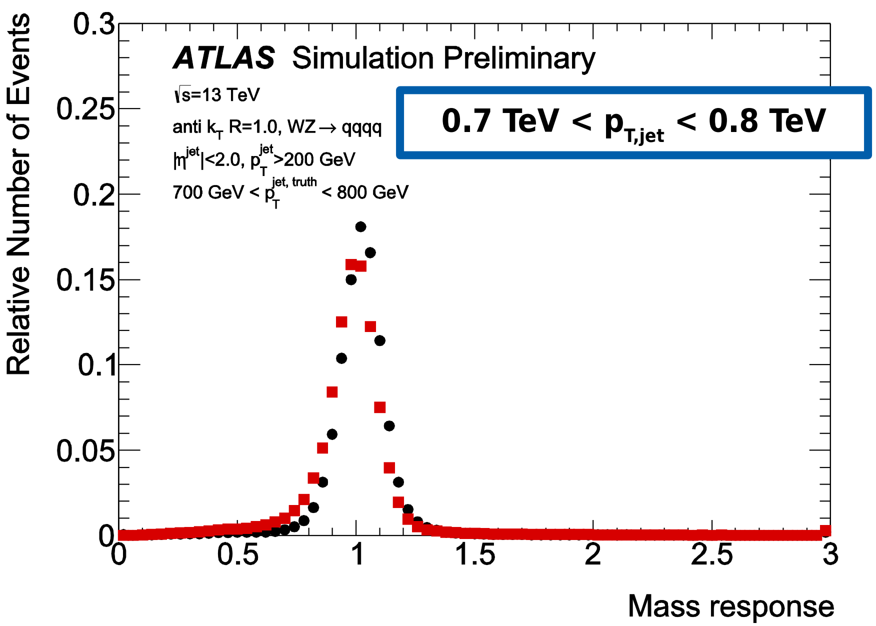
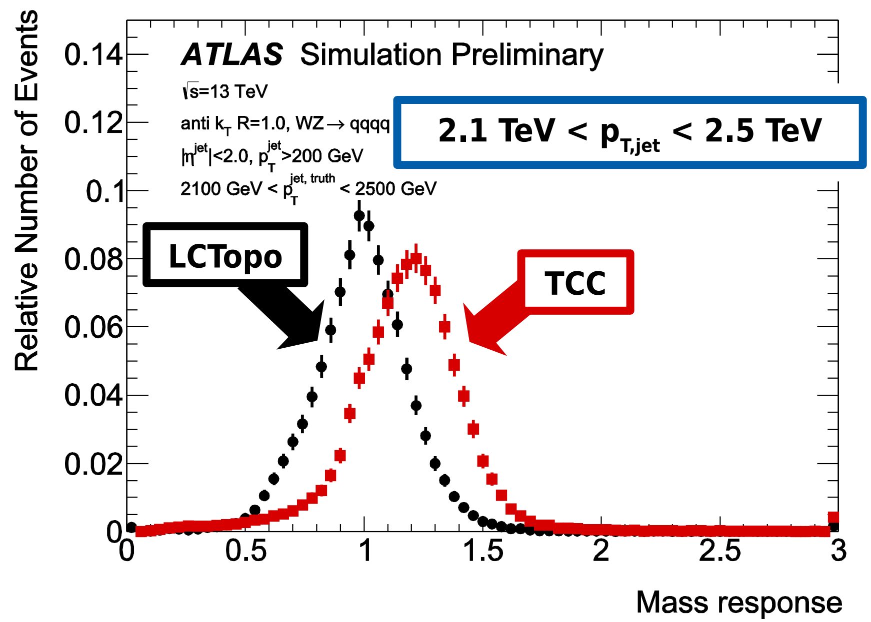


Mass Performance (1/2)

- Mass ratio ($\mathcal{R}^r = m^{\text{reco}}/m^{\text{true}}$) reflects accuracy and precision of reconstructed variable.
- **LCTopo mass calibrated for these results, TCC mass not.**

→ **TCC jets provide similar performance across full studied p_T range.**

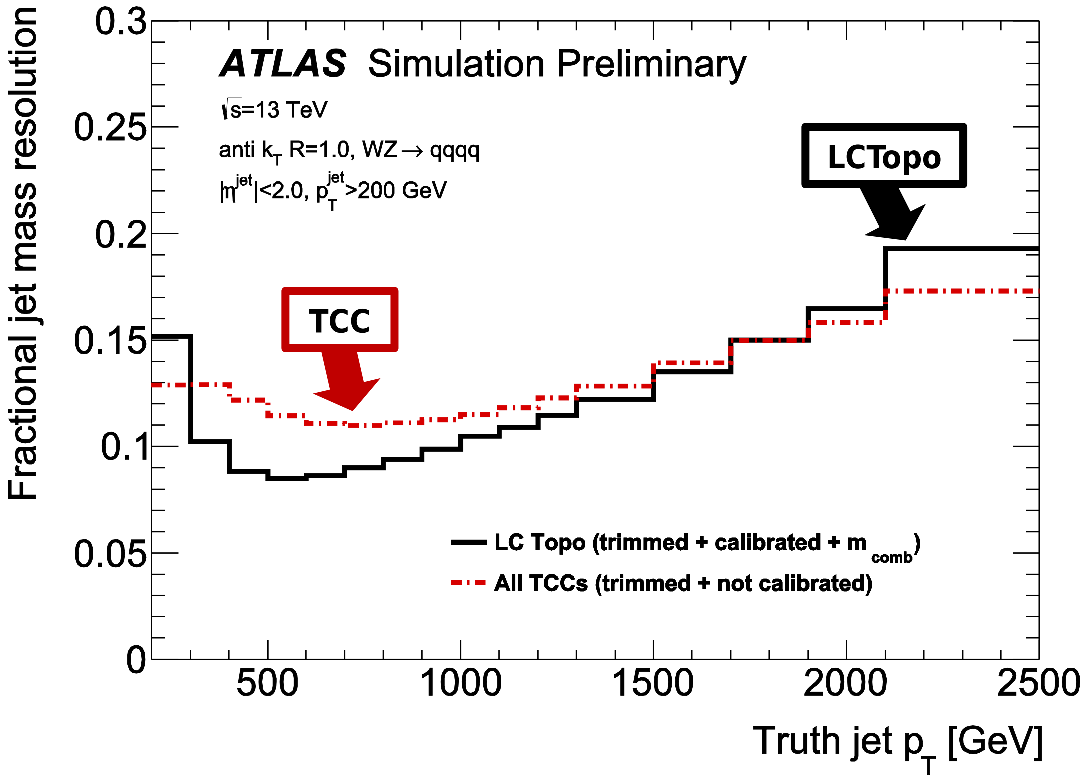




Mass Performance (2/2)

- Measure quantitative mass resolution as inter-quantile range:
  $\mathrm{IQR}^r = \frac{1}{2}\frac{Q_{75}(\mathcal{R}^r) - Q_{25}(\mathcal{R}^r)}{Q_{50}(\mathcal{R}^r)}$, where Q_x is the x% quantile boundary.

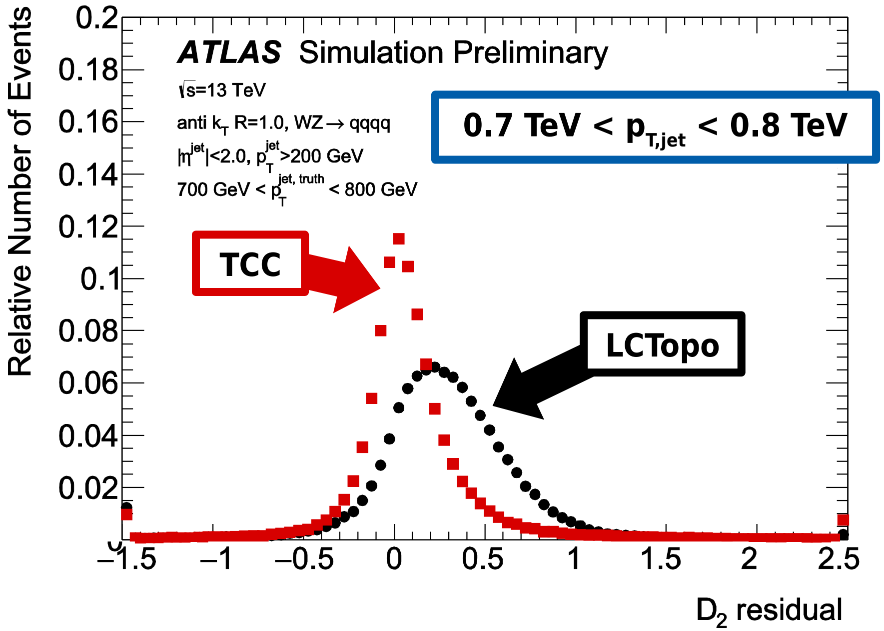
- **TCC jets give good improvement in resolution above 2000 GeV with respect to combined mass**

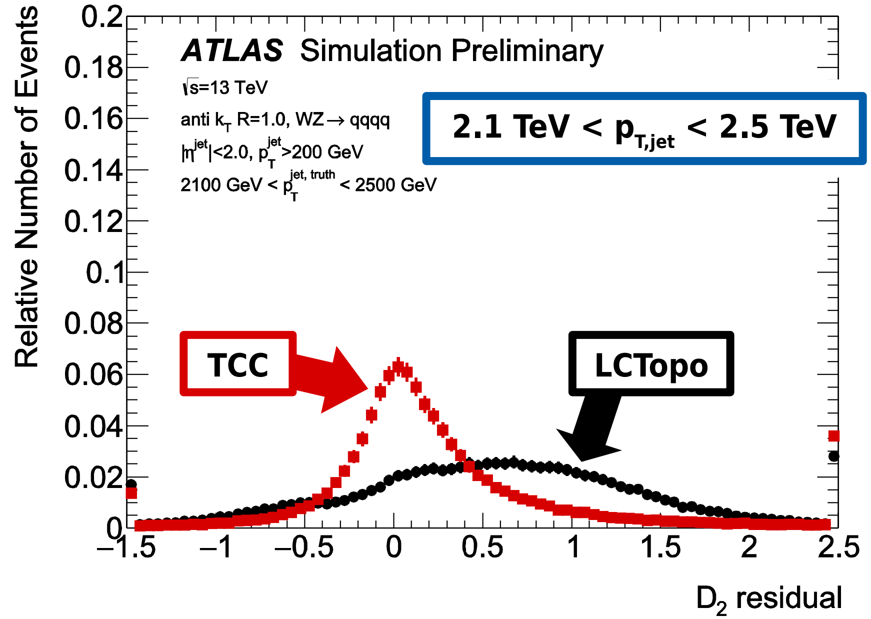


D_2 Performance (1/2)

- Reminder: D_2 measure of how two-prong-like the jet is.
- Residual ($\mathcal{R}^d = D_2^{\text{reco}} - D_2^{\text{true}}$) reflects accuracy and precision of reconstructed variable.
- **At high p_T, calorimeter-only jet substructure breaks down.**

TCC jets provide superior performance also in extreme topologies.

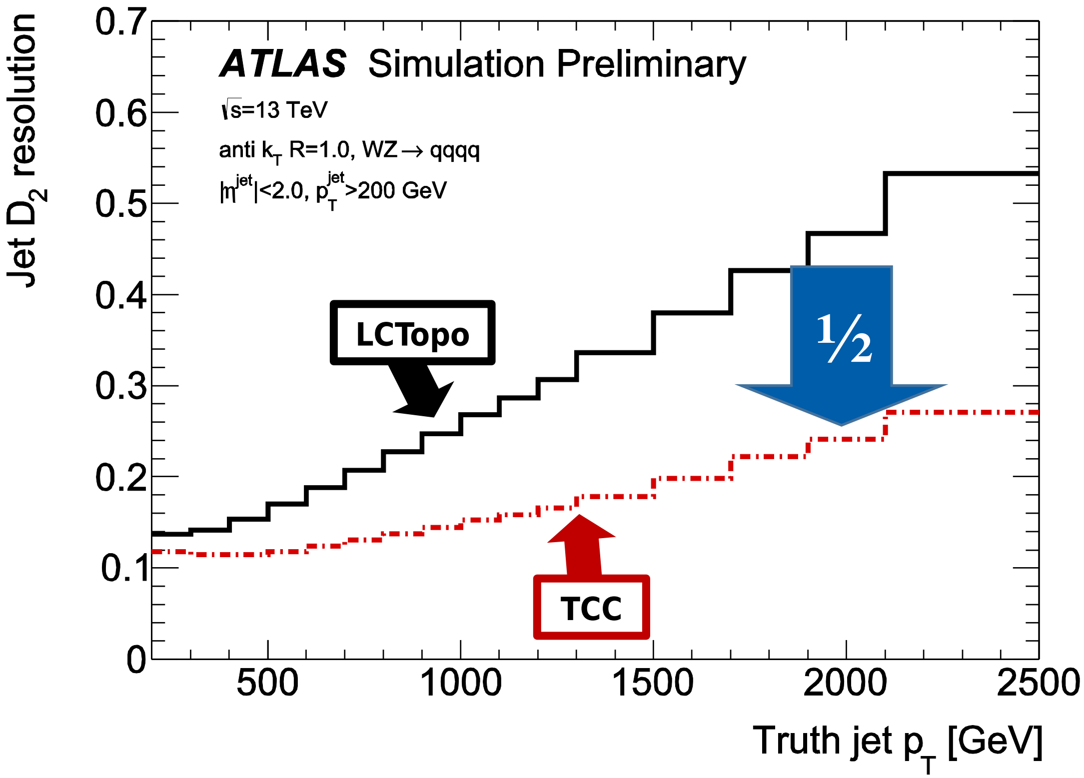




D_2 Performance (2/2)

- Measure quantitative D_2 resolution as inter-quantile range: $\mathrm{IQR}^d = \frac{1}{2}\left[Q_{75}(\mathcal{R}^d) - Q_{25}(\mathcal{R}^d)\right]$, where Q_x is the $x\%$ quantile boundary.

- **TCC jets give factor of two improvement in resolution for 2000 GeV jets.**
- Also superior for all other jet p_T.



Summary

- **Jet substructure crucial** for SM measurements (including $H \rightarrow bb$) and searches for new physics with boosted objects.
- **Calorimeter** provides good energy resolution, but **poor angular resolution** at high jet p_T

  → Use **superior angular resolution of tracker** as complementary information.
- Algorithms tries matching all tracks to all clusters, ~100% efficient for track p_T >10 GeV
- Reshuffling calorimeter energy and mass, using all relevant clusters and tracks via three p_T ratios = TrackCaloClusters.
- Provides **excellent jet substructure resolution**.
- Currently becoming new standard for large-radius jet reconstruction in several ATLAS analyses.

  → First search results using TCCs expected by this summer.