Introduction to jets

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BROWN

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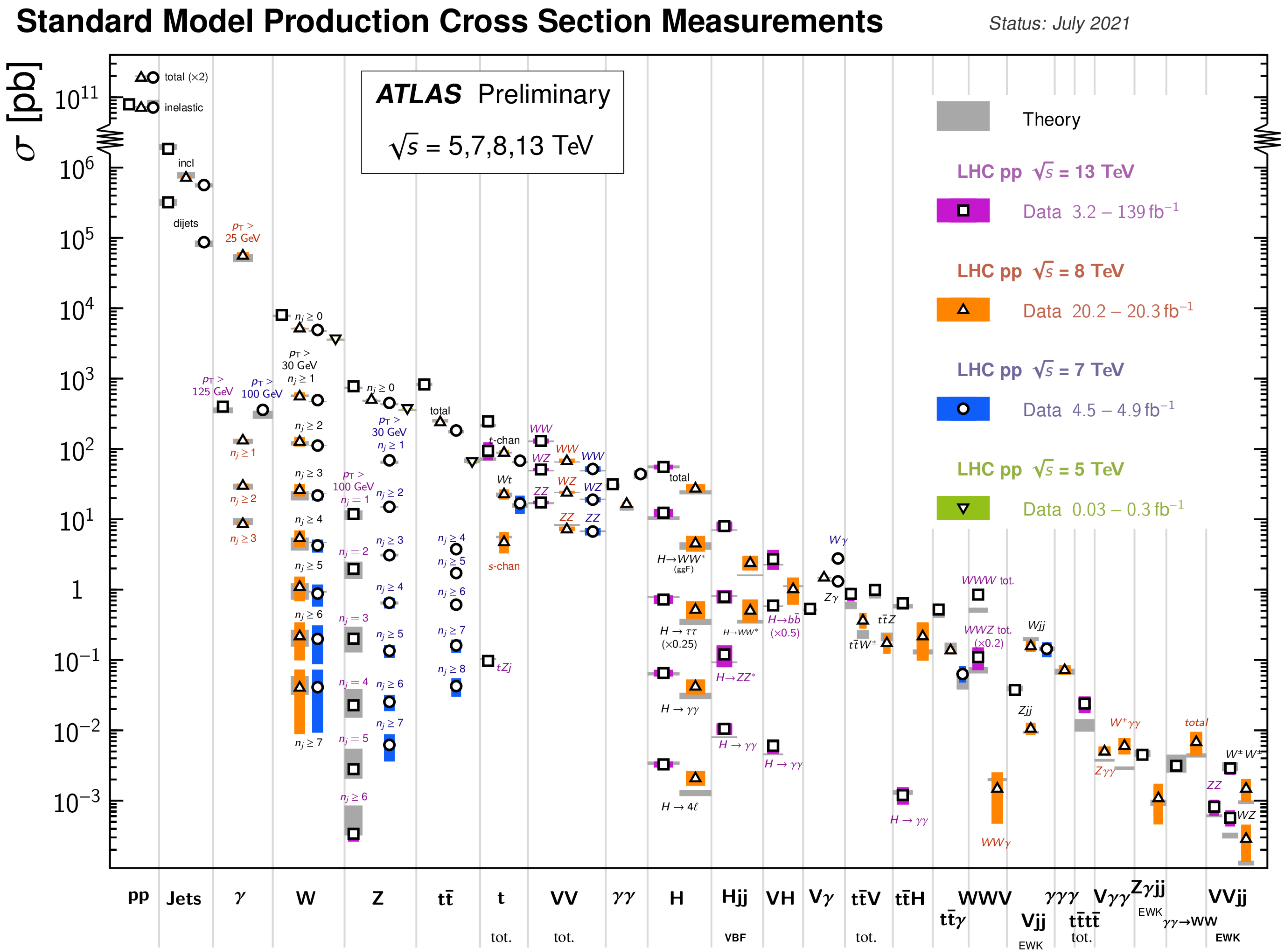
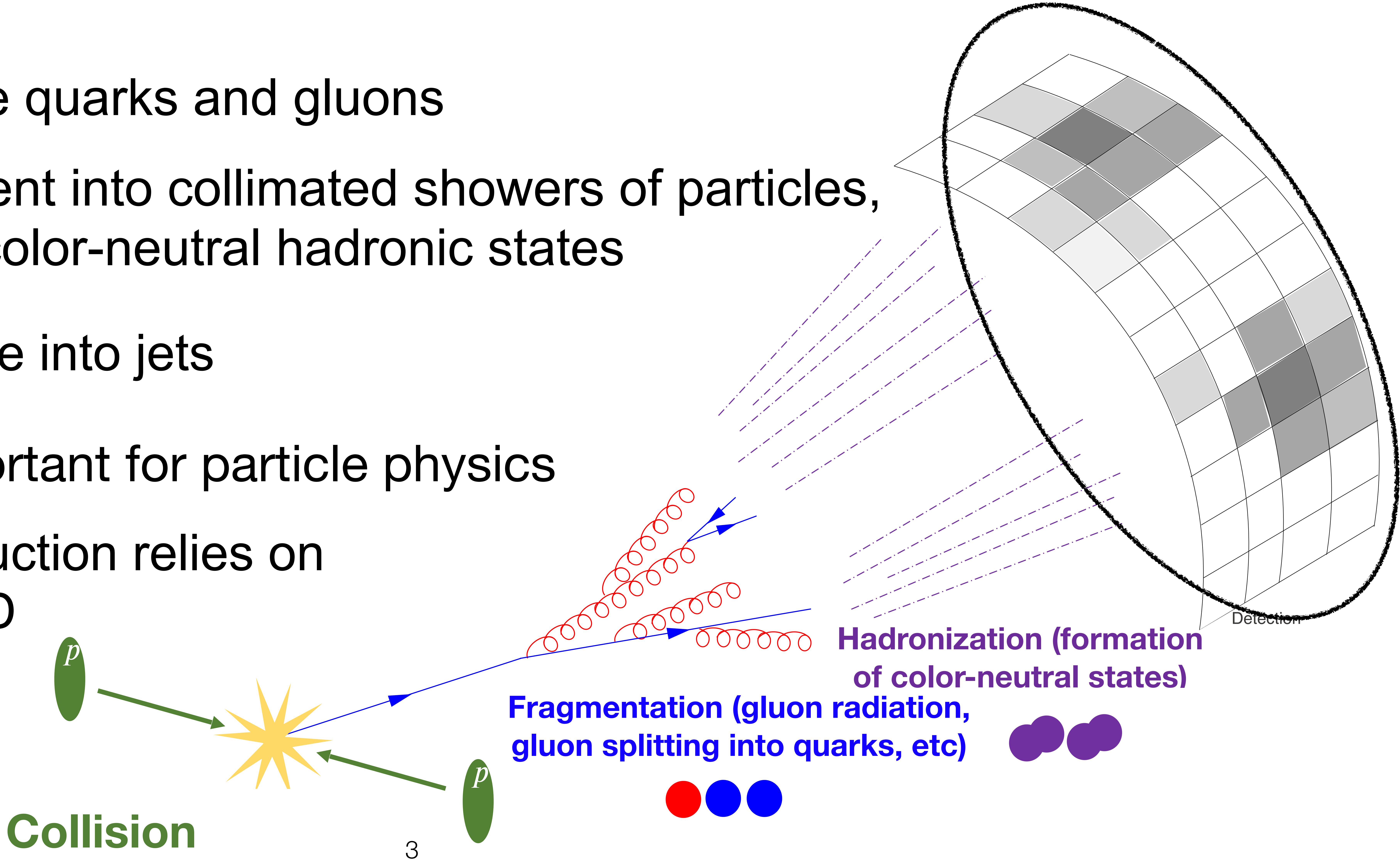


- Studying a wide range of processes, with cross-sections spanning many orders of magnitude
- Precision often limited by our understanding of QCD and jets!
  - Top mass measurement, vector-boson production, certain Higgs processes and more
- Better precision requires both experimental and theoretical improvements to our understanding of QCD

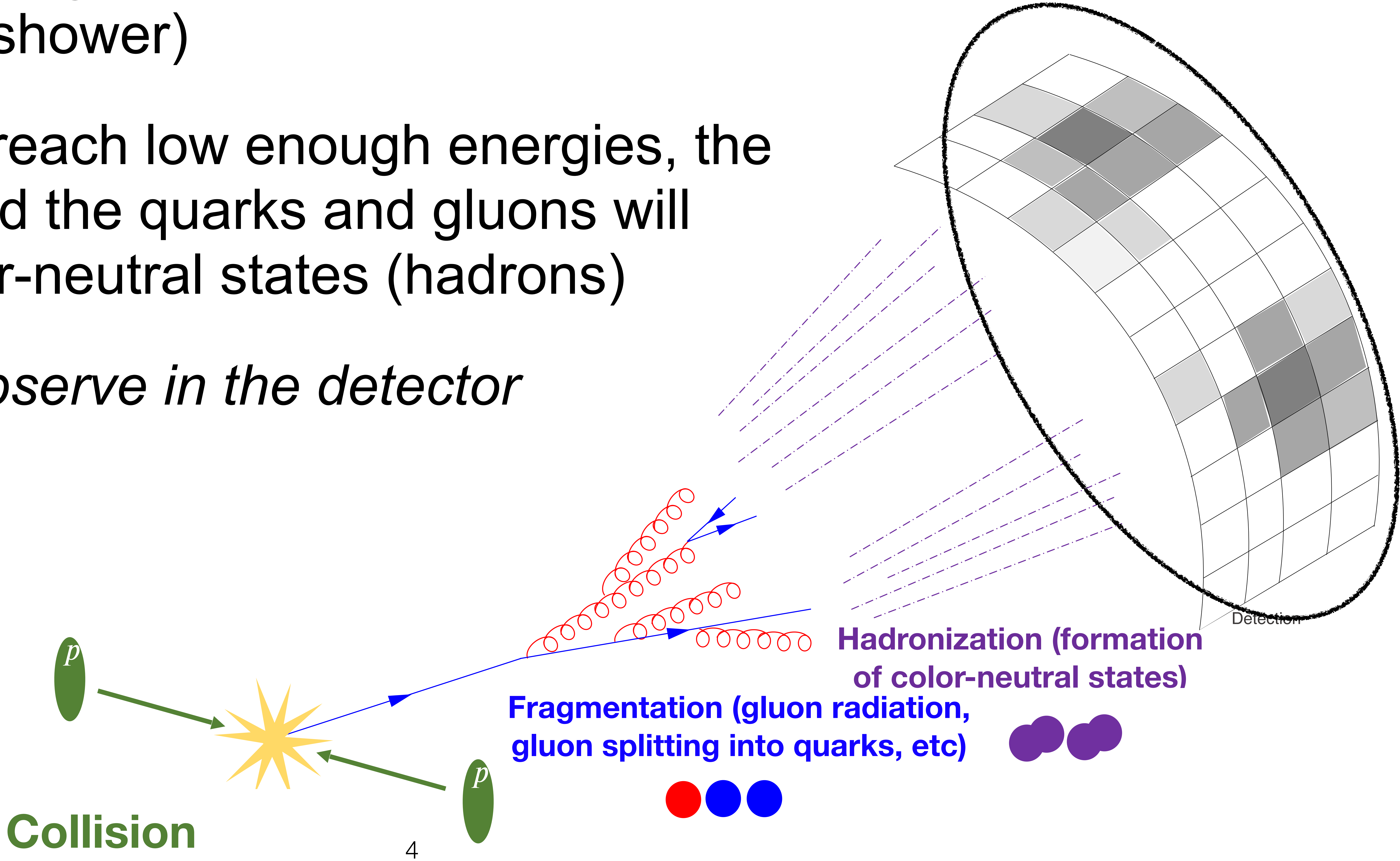
qcd at the lhc

- The strong force is unusual — its strength increases with distance
  - Cannot observe free quarks and gluons
  - Instead, they fragment into collimated showers of particles, eventually forming color-neutral hadronic states
  - We reconstruct these into jets
- Jets are broadly important for particle physics
  - … and jet reconstruction relies on understanding QCD



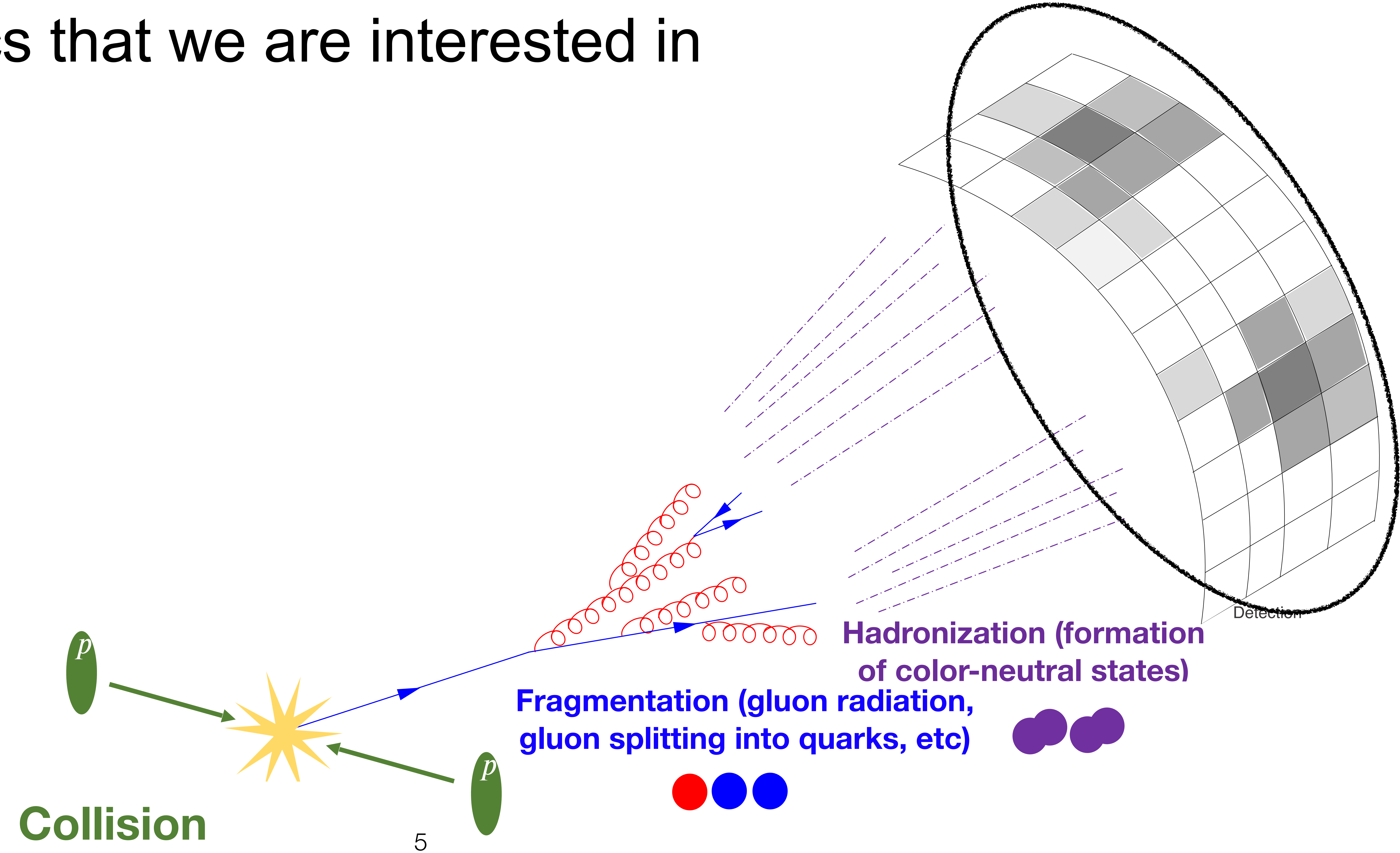
what is a jet?

- Quarks and gluons fragment into collimated showers of particles (parton shower)
- When the particles reach low enough energies, the shower will stop, and the quarks and gluons will recombine into color-neutral states (hadrons)
  - *This is what we observe in the detector*



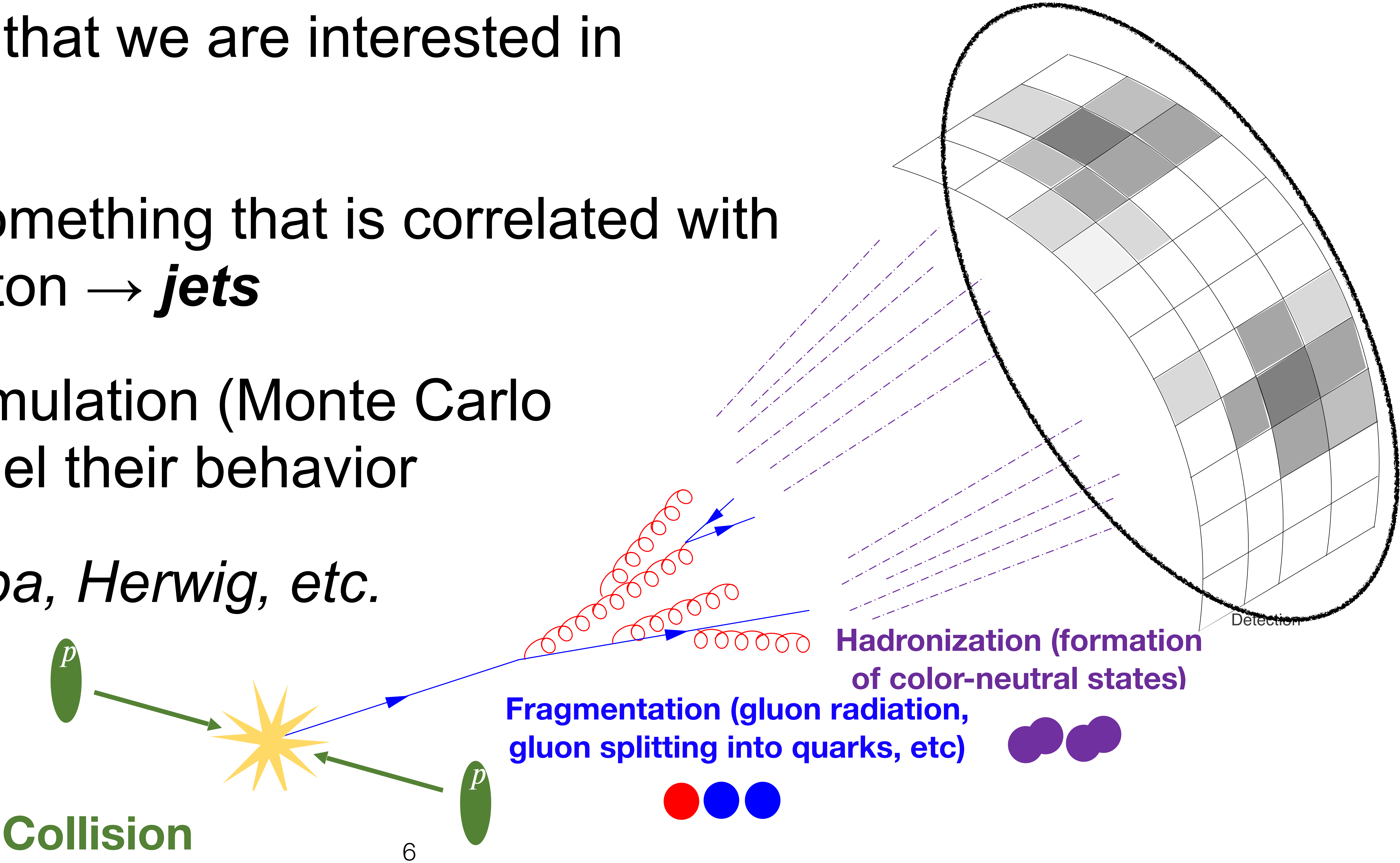
what is a jet?

- Difficult to translate individual hadrons into the underlying physics that we are interested in studying



what is a jet?

- Difficult to translate individual hadrons into the underlying physics that we are interested in studying
  - Need to create something that is correlated with the individual parton → ***jets***
- Typically rely on simulation (Monte Carlo predictions) to model their behavior
  - *e.g. Pythia, Sherpa, Herwig, etc.*

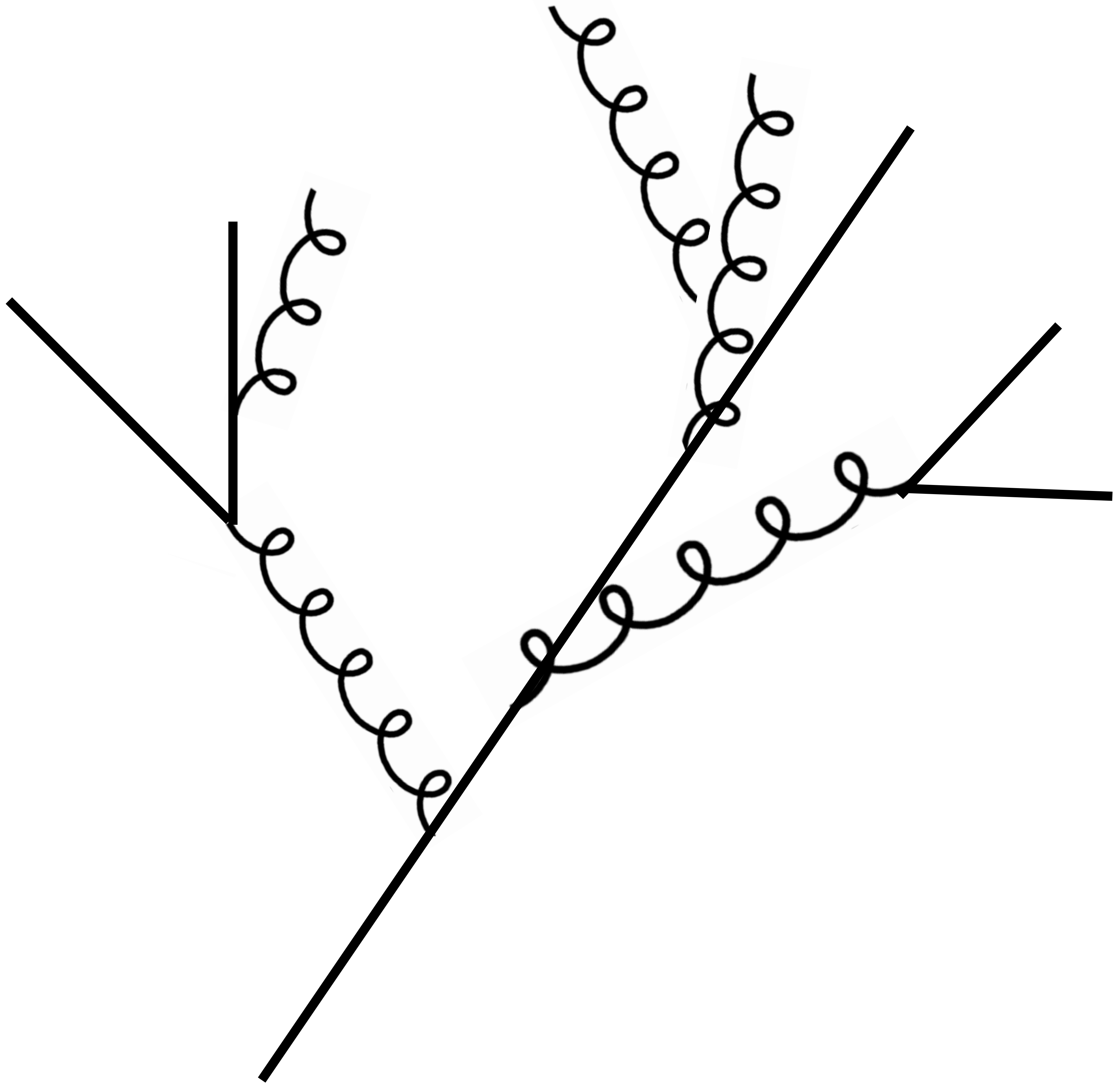


why study jets?

- Jets are used for a wide variety of physics analyses
  - *Way too many to list in one place…*
  - **Higgs and electroweak physics**, especially for certain types of production (vector boson scattering / fusion)
  - Searches for physics **beyond the Standard Model**, including dark matter searches
  - Direct link to **quantum chromodynamics** → used to study parton distribution functions and the strong coupling constant
- Since they are used for so many things, it's very important to understand them well and to be able to reconstruct them experimentally!
  - Giving an (incomplete) overview of many important aspects of jets at the LHC

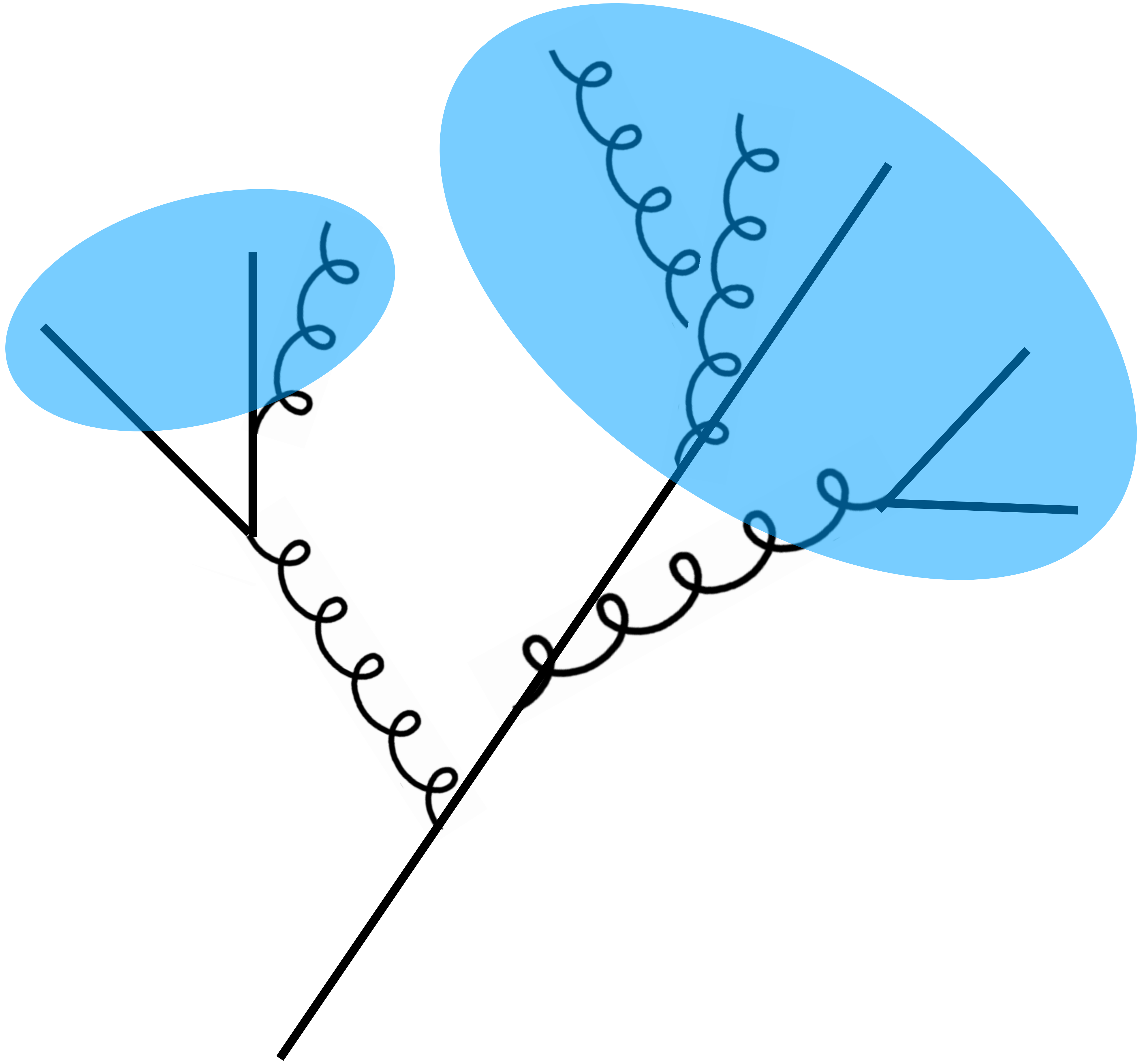

ATLAS
EXPERIMENT

what is a jet?



- There is no single way to define a jet
- Instead, a *jet is defined by its algorithm*
- Choice of jet definition depends on the relevant physics being studied

what is a jet?



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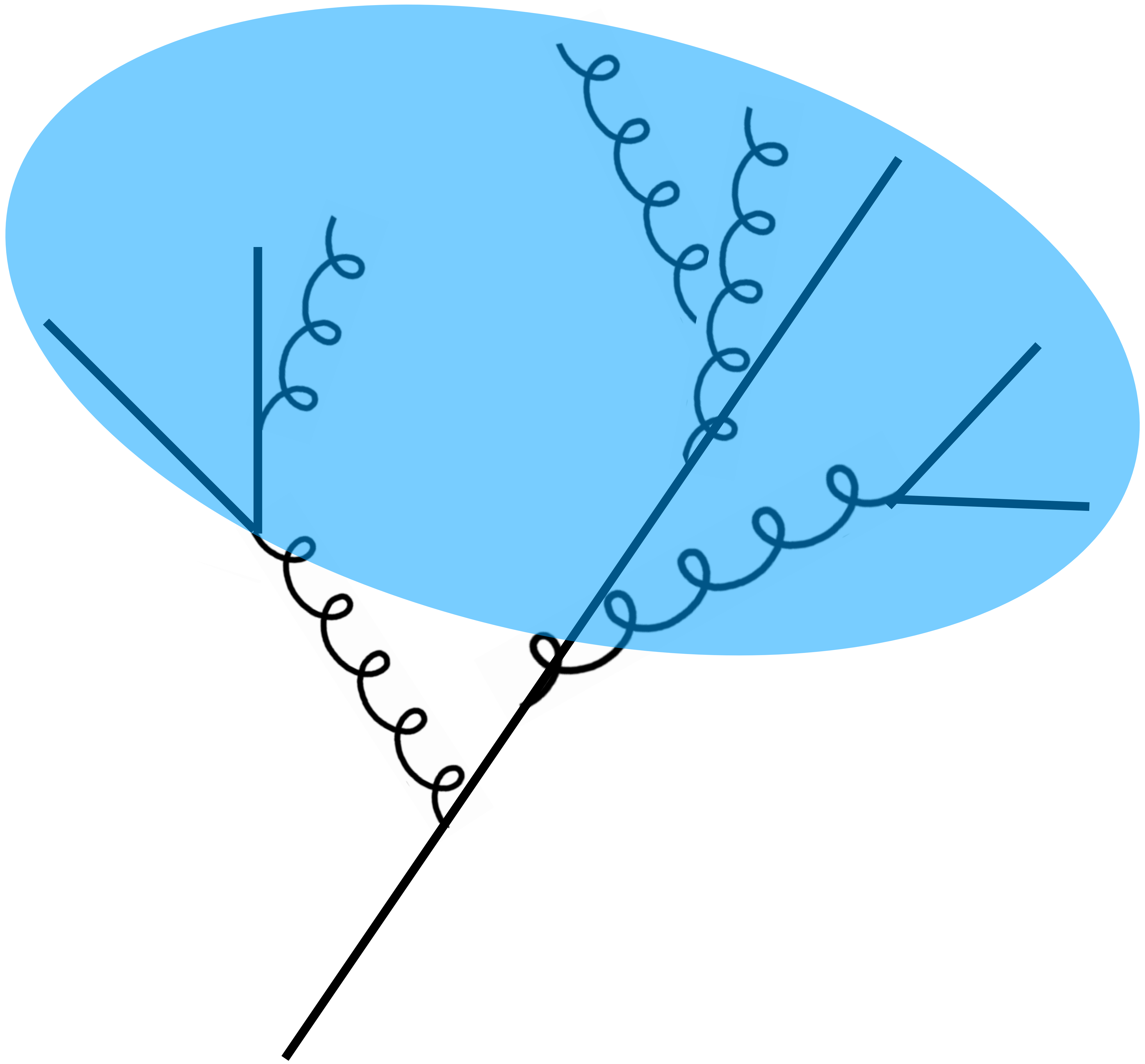
- Instead, a *jet is defined by its algorithm*
- Choice of jet definition depends on the relevant physics being studied
  - **Small radius**: less affected by contamination from pileup and underlying event, good for resolving individual partons

what is a jet?



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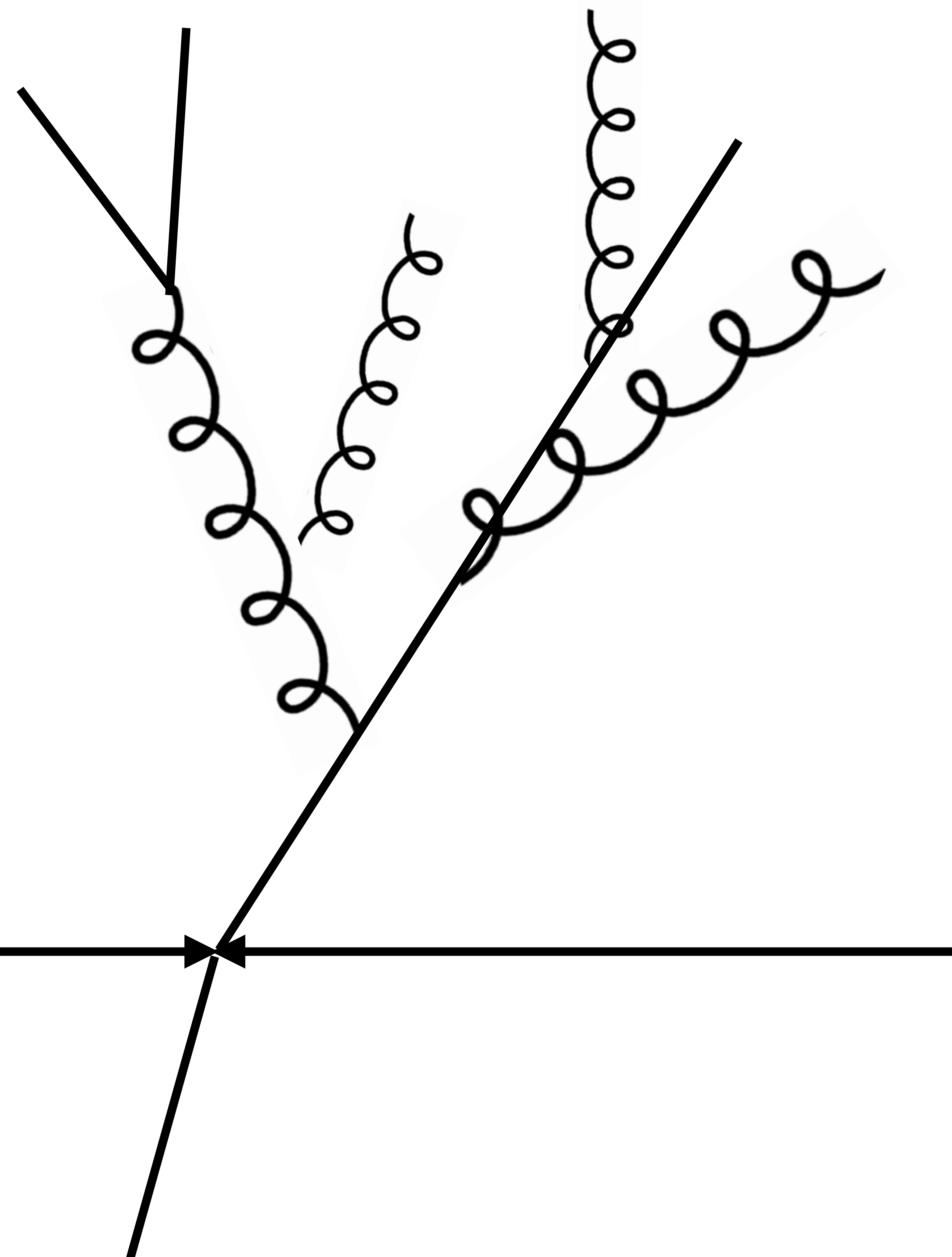
- Instead, a *jet is defined by its algorithm*
- Choice of jet definition depends on the relevant physics being studied
  - **Small radius**: less affected by contamination from pileup and underlying event, good for resolving individual partons
  - **Large radius**: captures more perturbative fragmentation

what is a jet?

- Typically use *sequential recombination algorithms* to form jets
  - Use some distance metric to determine closest pair of particles
  - Cluster the closest pair of particles together into a “pseudo-jet”
  - Continue doing this until ΔR* between any pair of constituents is larger some maximum value *R* (the jet radius)



* $\Delta R^2 = \Delta\eta^2 + \Delta\phi^2$

This is an angular distance metric commonly used at hadron colliders

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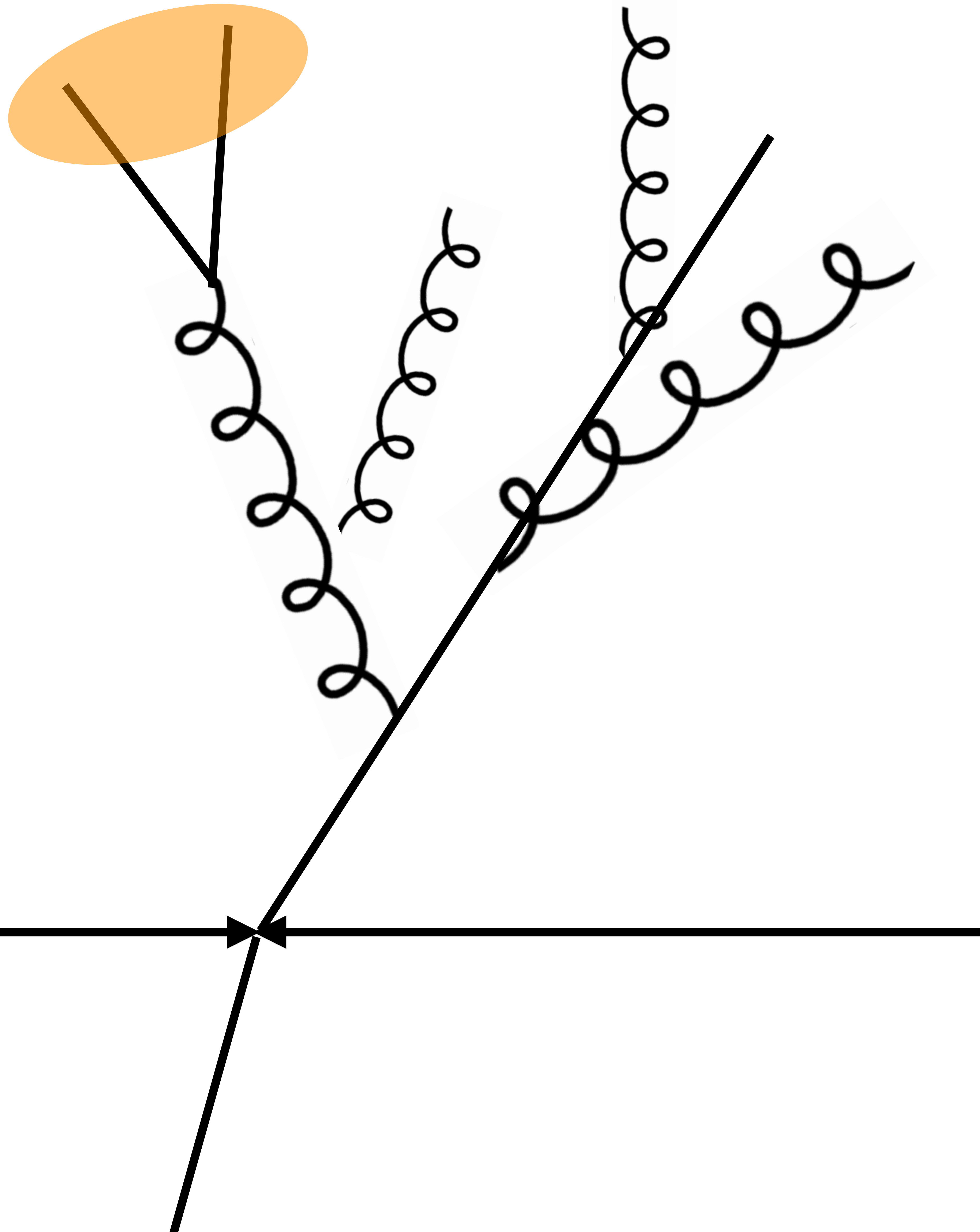

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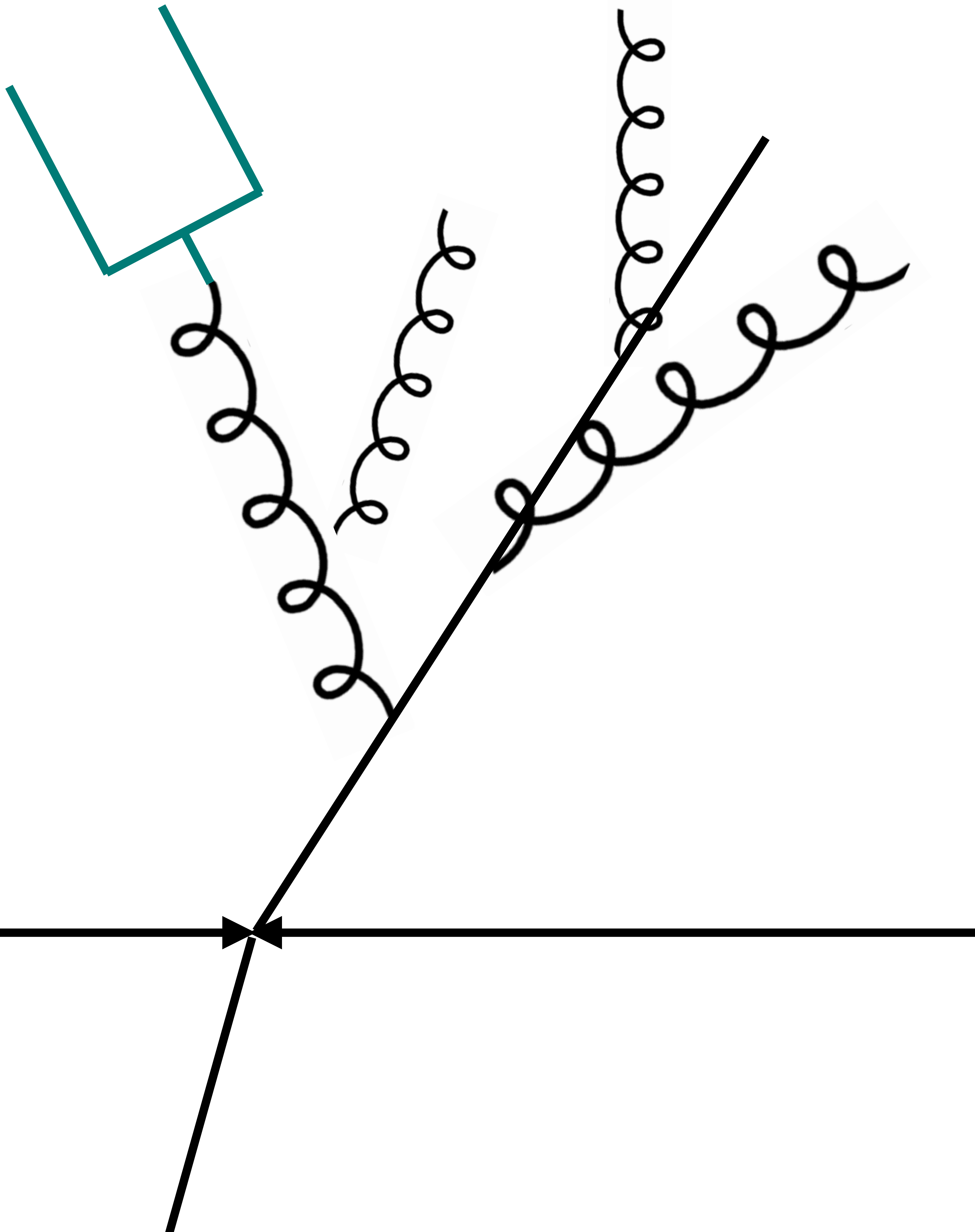

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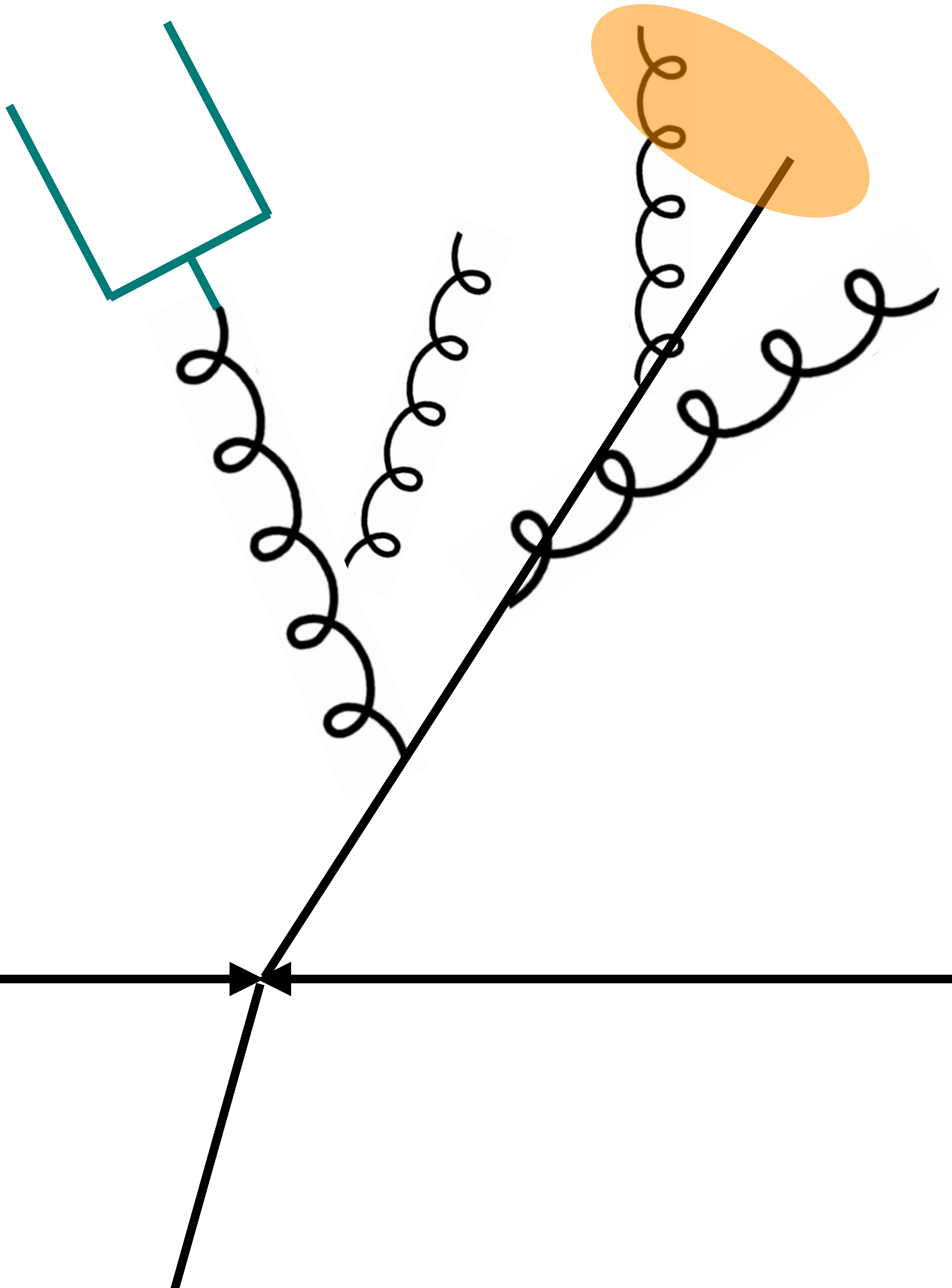

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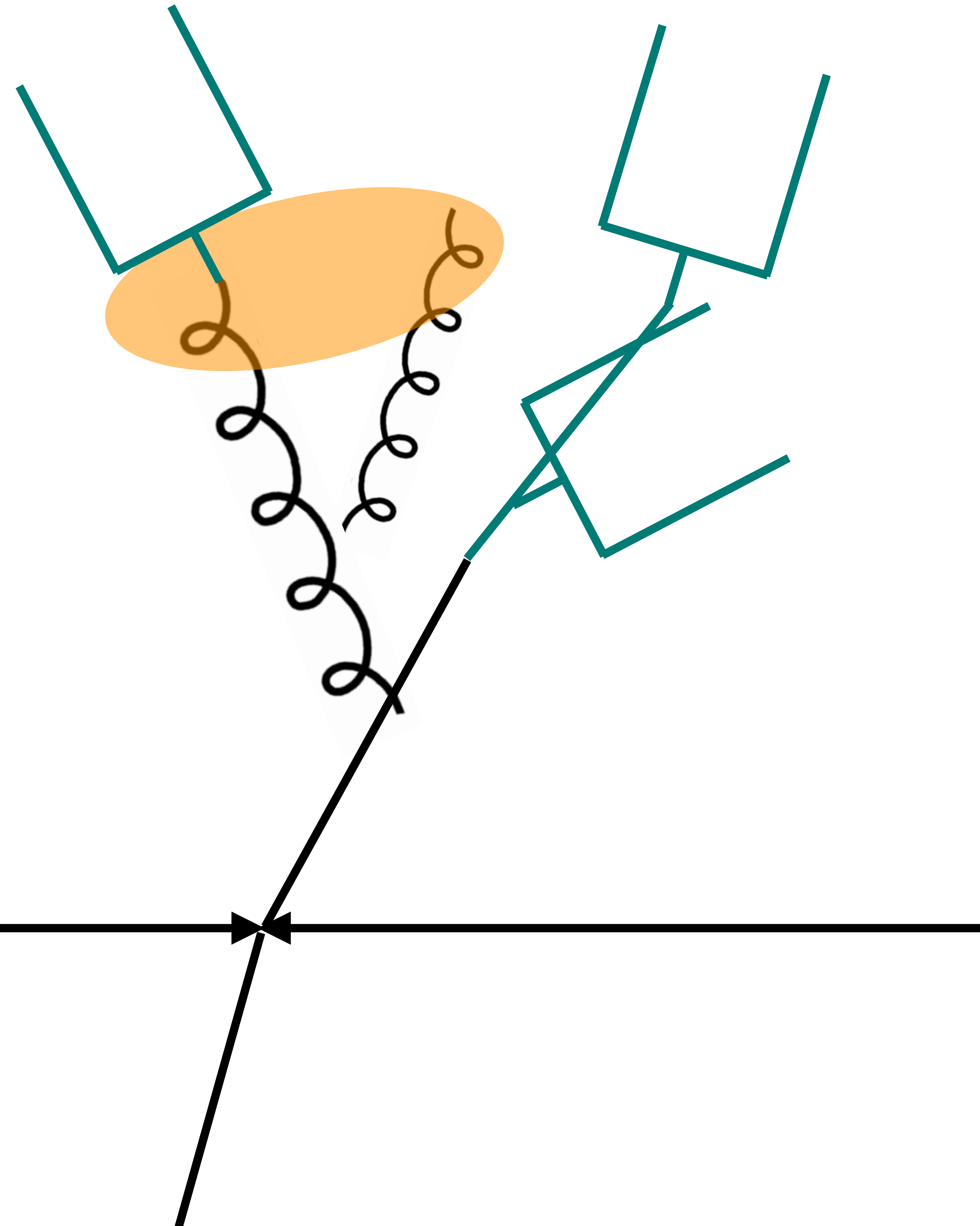

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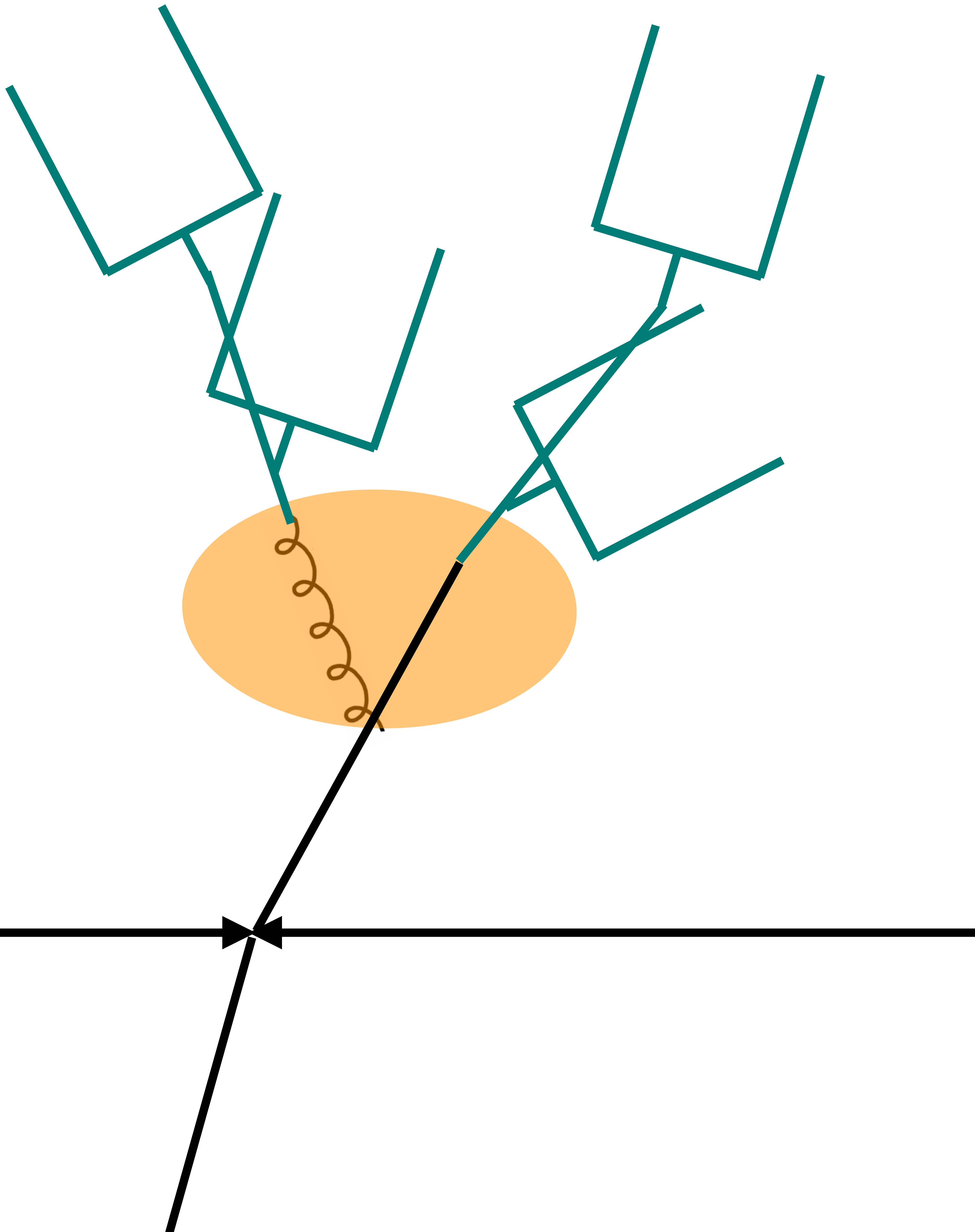
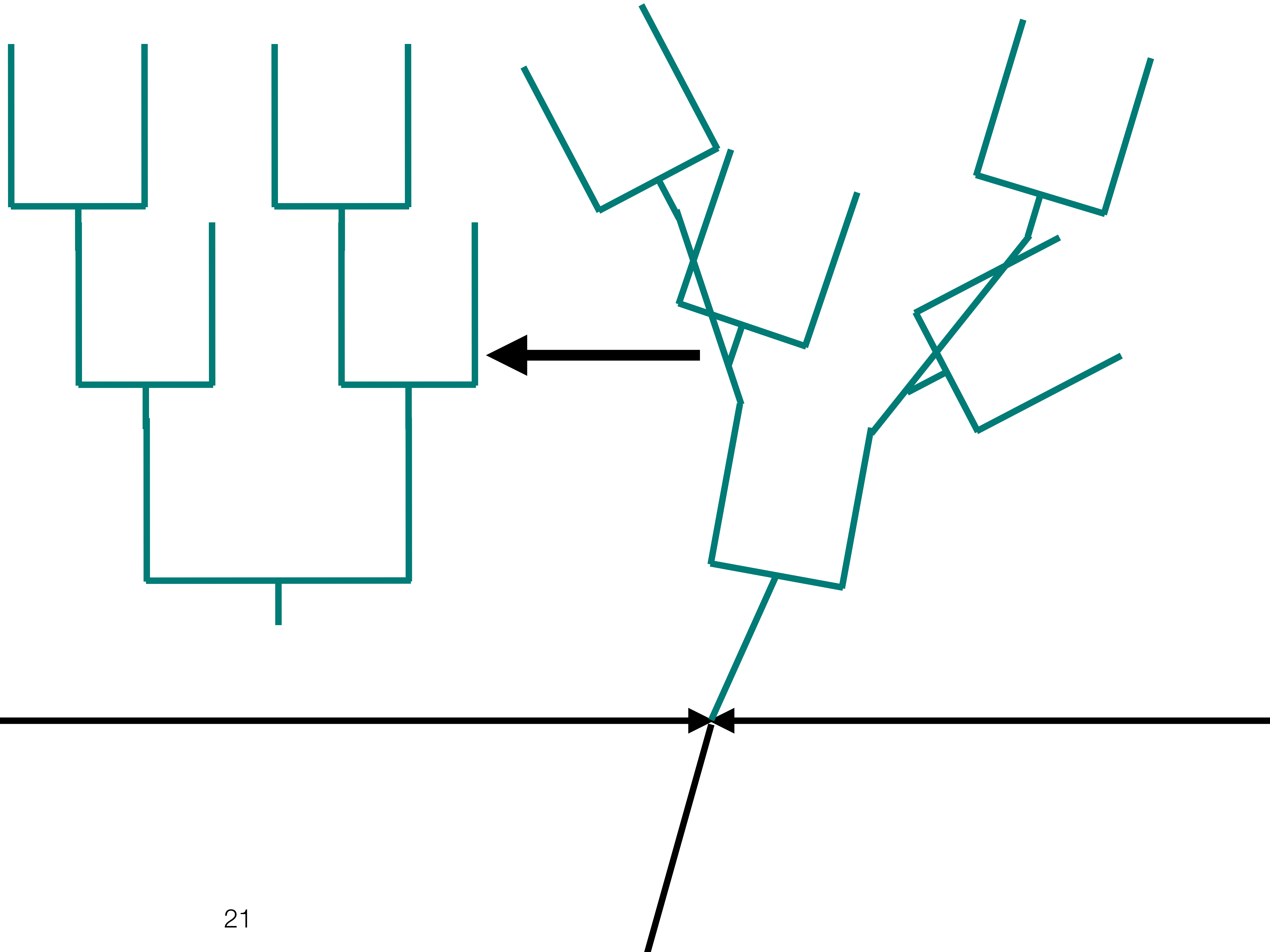


what is a jet?

what is a jet?

what is a jet?

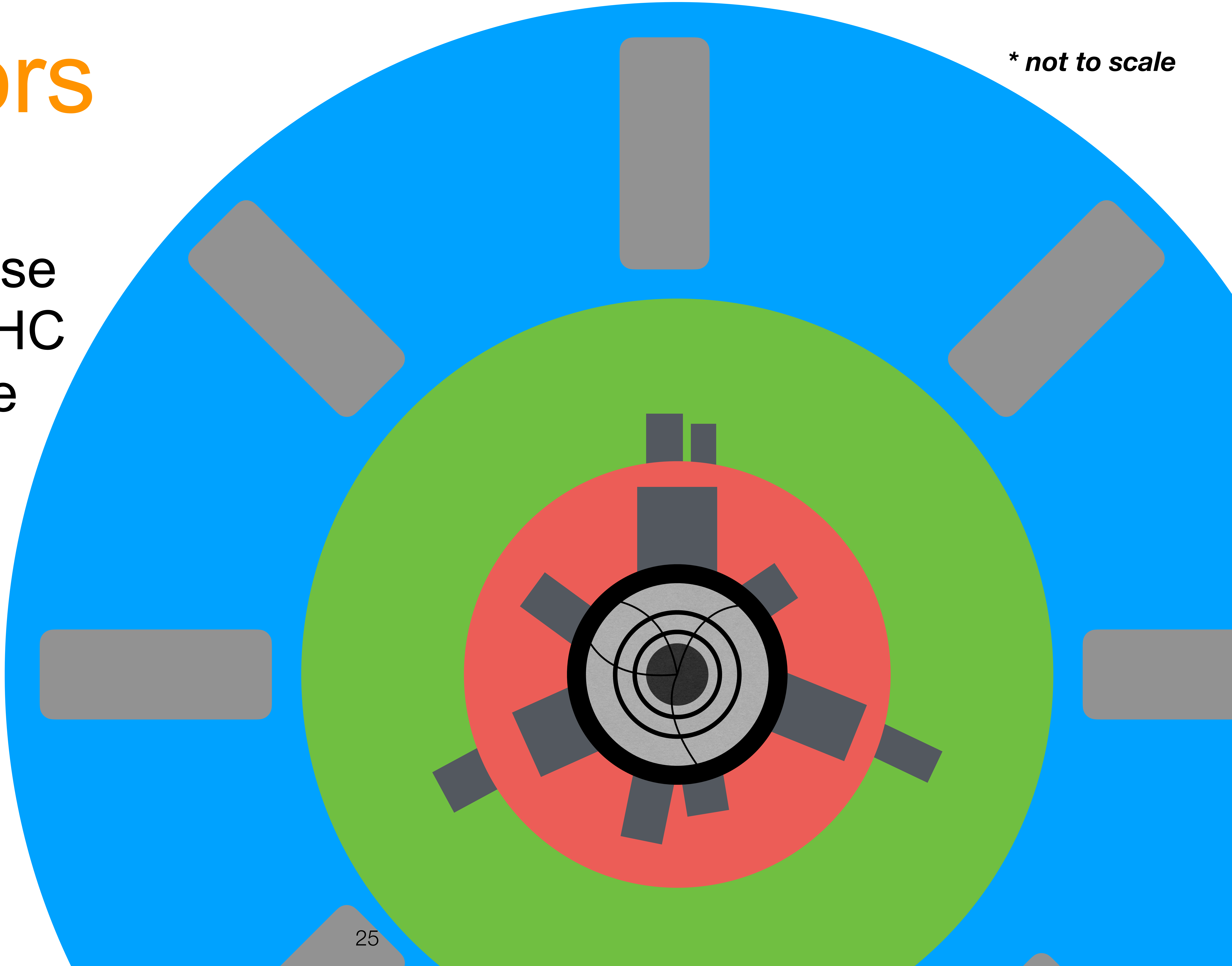
- Different clustering algorithms produce different jets
  - Jets with the same constituents will have different clustering histories
  - The constituents and clustering of a jet *can* tell you a lot about QCD
- No single correct jet definition!
  - Strategic choices can lead to better sensitivity



jet reconstruction

the detectors

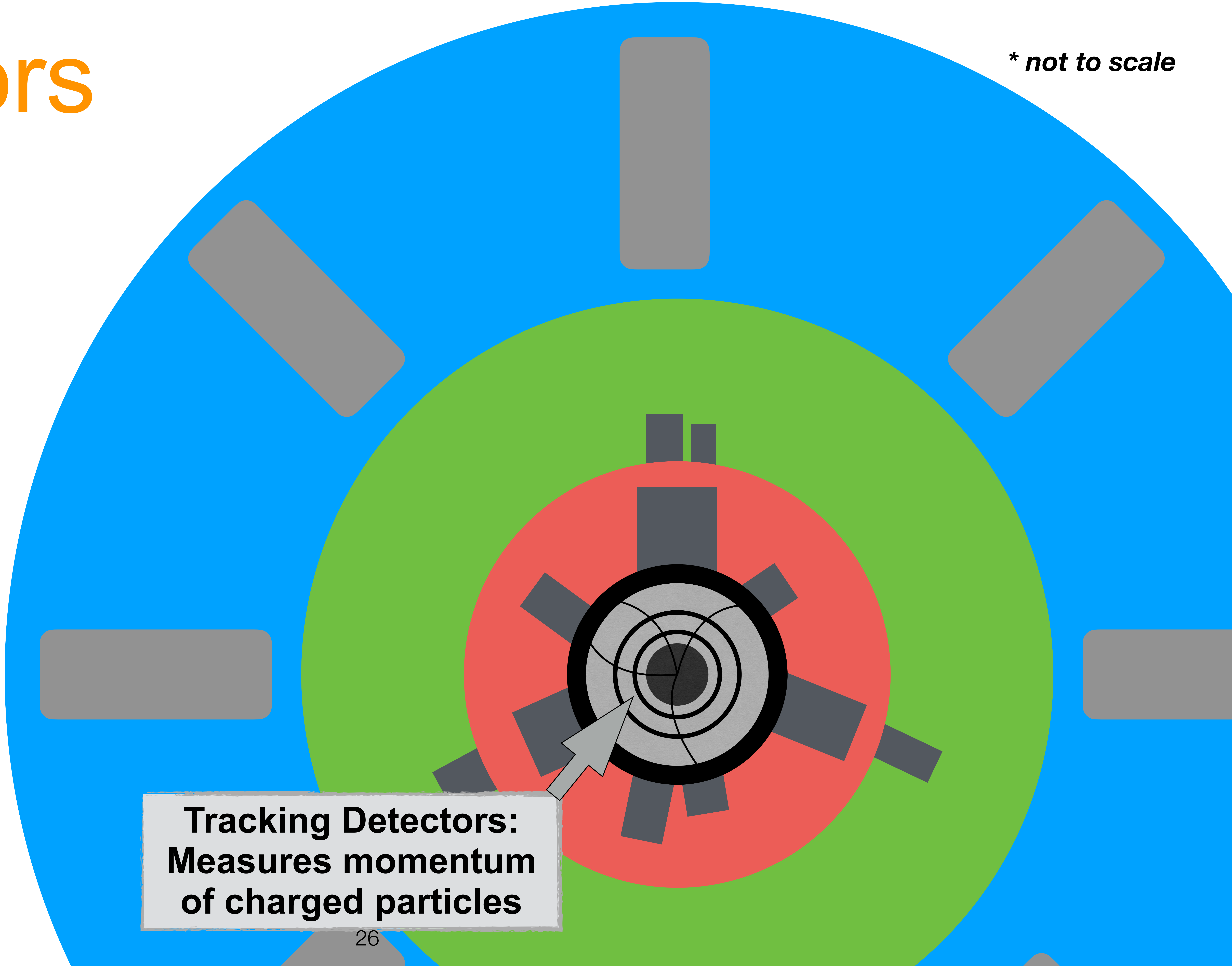
- ATLAS and CMS are general-purpose detectors at the LHC with a broad range of physics goals



the detectors

Tracking detectors

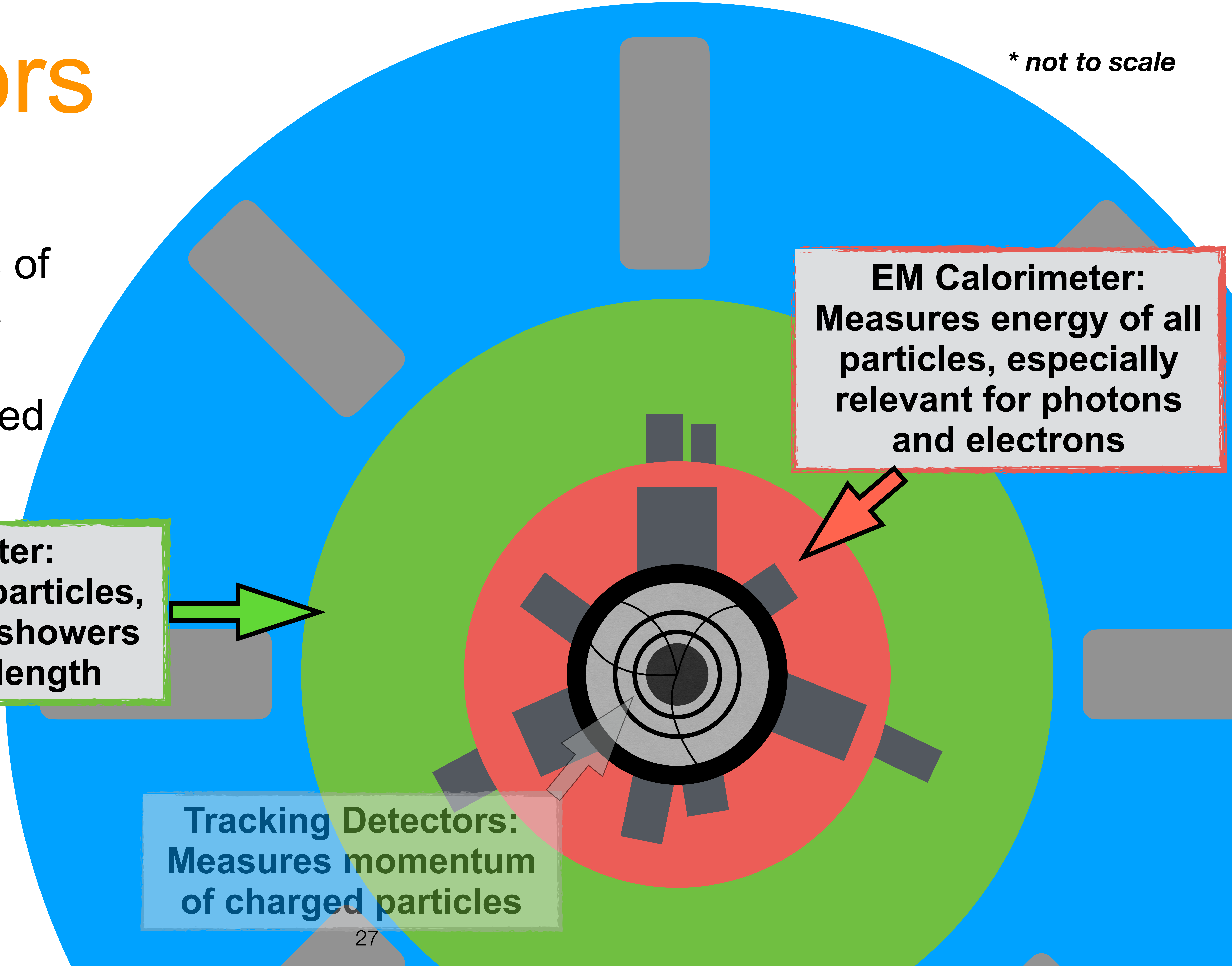
- Precise angular resolution, especially for low p_T particles
- Measure *charged* particles
- Trajectory of particles bent by magnetic field, giving ability to measure the momentum



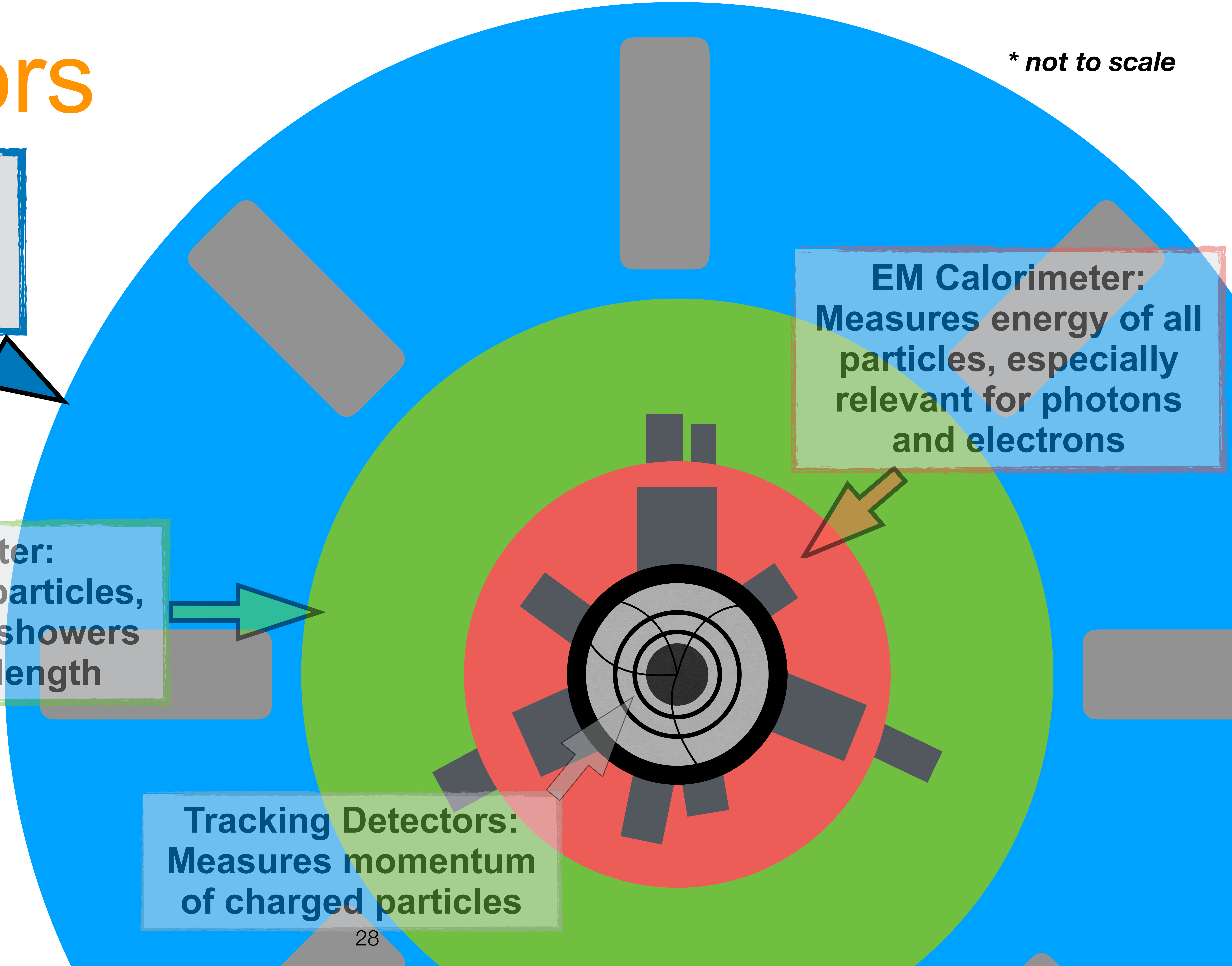
the detectors

Calorimeters

- Precise measurements of energies of all particles
- Angular resolution limited by cell area

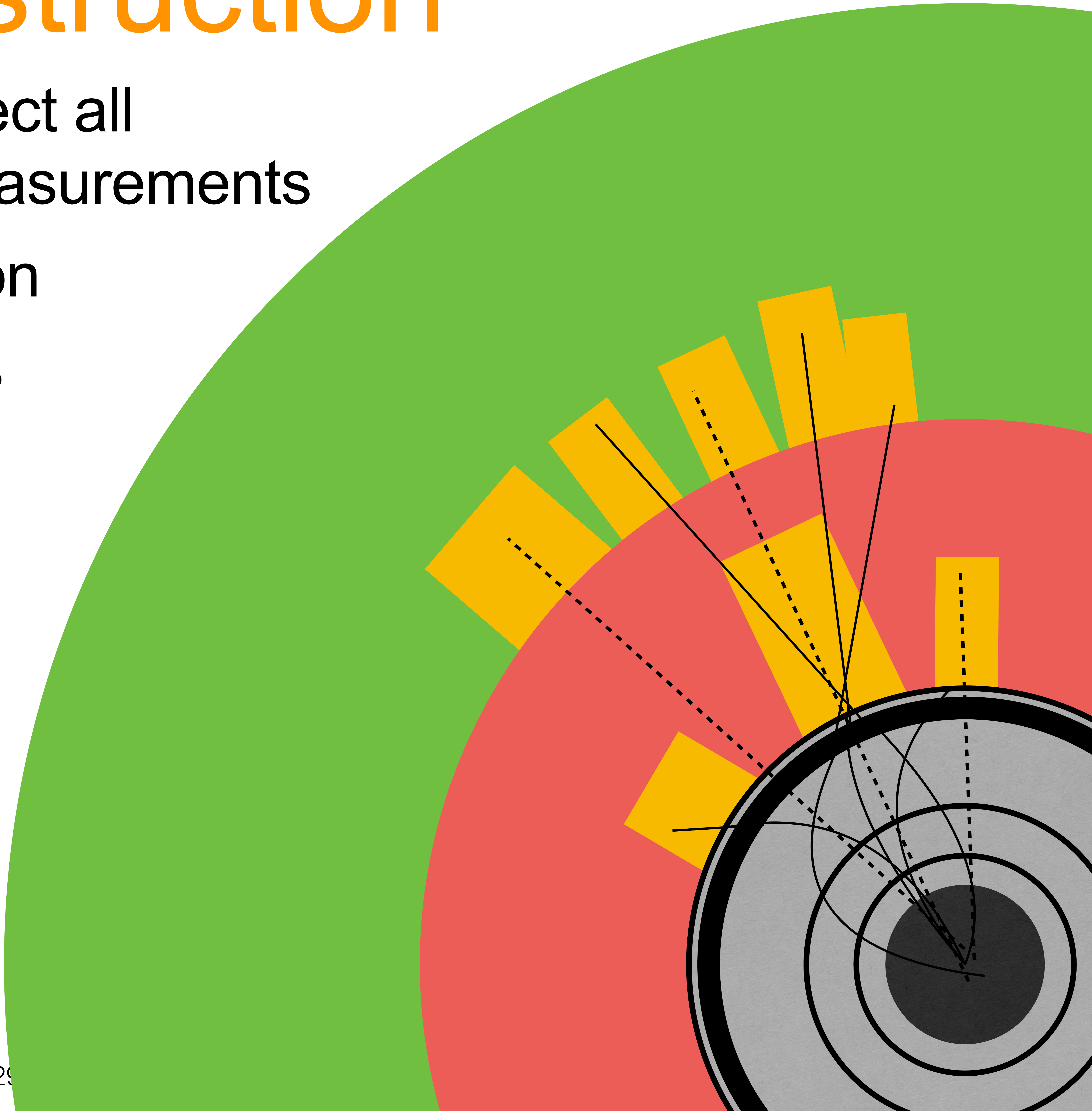


the detectors



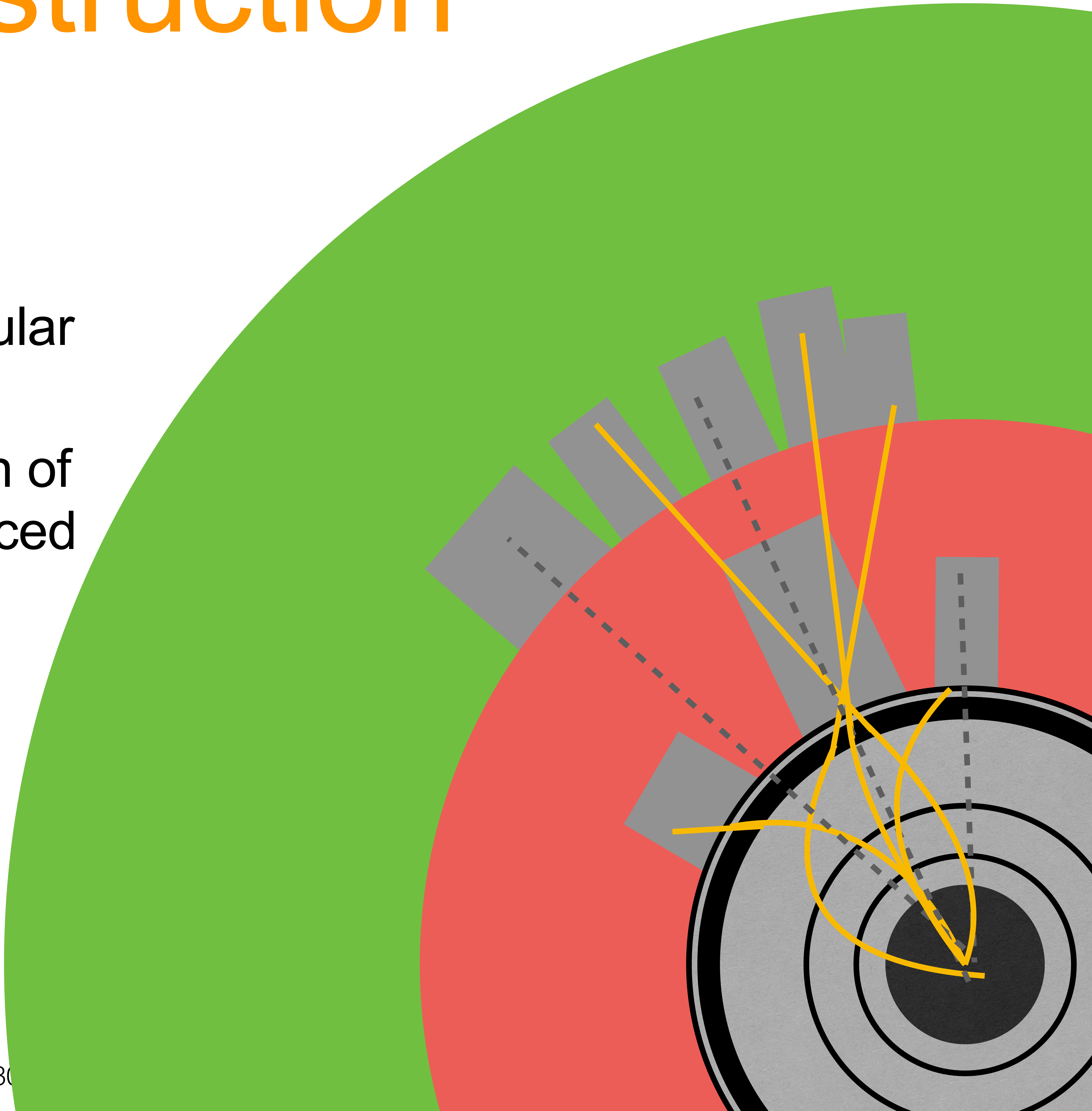
inputs to jet reconstruction

- Need calorimeter information to detect all particles, and for precise energy measurements
  - Sometimes just use this information
  - ATLAS used these for many years (*topoclusters*)



inputs to jet reconstruction

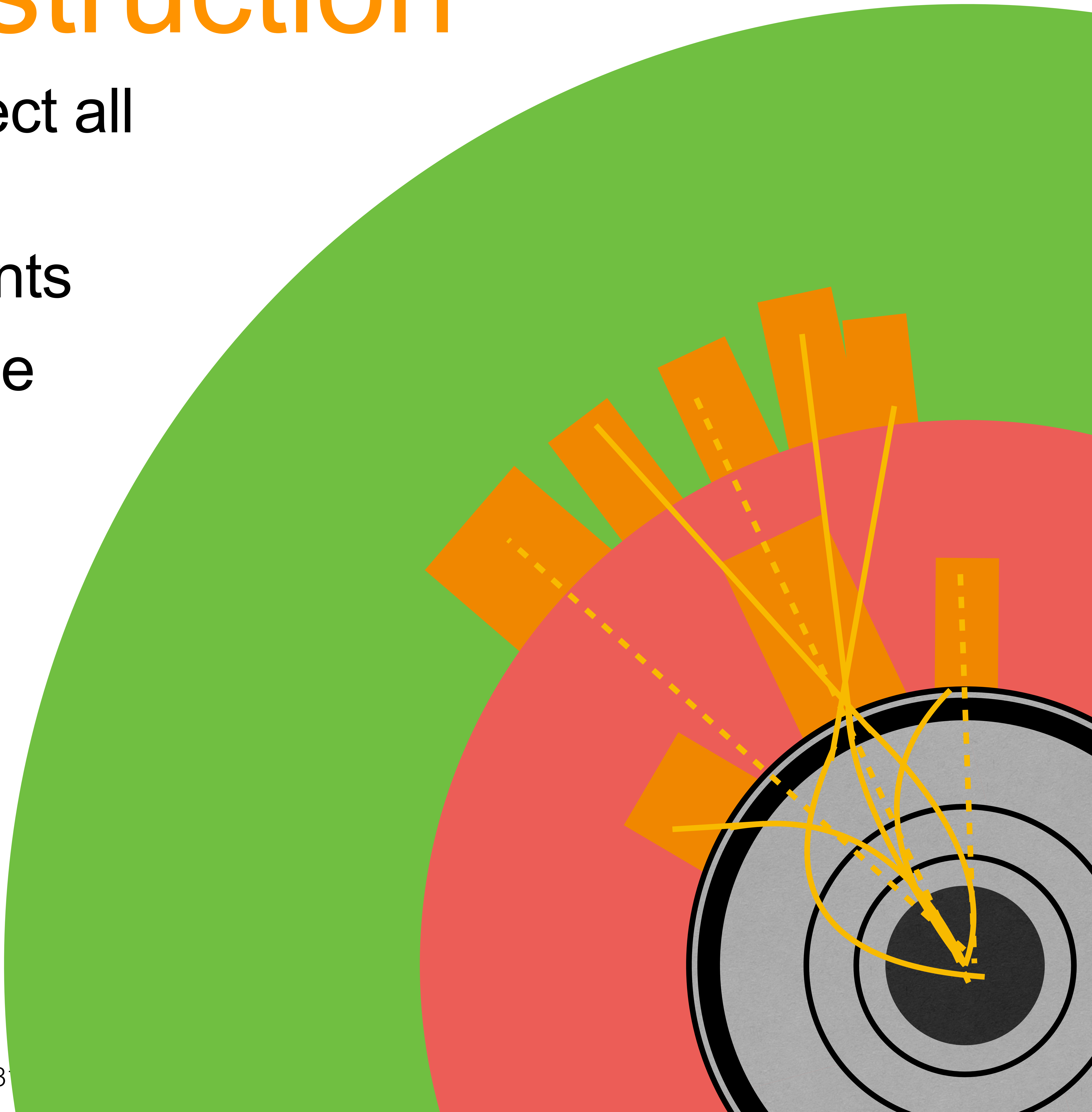
- Need calorimeter information to detect all particles
  - Gives precise energy measurements
- Tracking information provides precise angular information
  - Also provides information on the position of the vertex where the particles are produced
  - No information on neutral particles…



inputs to jet reconstruction

- Need calorimeter information to detect all particles
  - Gives precise energy measurements
- Tracking information provides precise angular information
  - But misses neutral particles…

- Can combine tracking and calorimeter information to create more powerful objects (particle-flow algorithms)
  - Typically what is used by ATLAS and CMS



a complication: pileup

- Naively, can think of collisions as two protons colliding
  - Protons are composite objects → individual partons (quarks/gluons) collide
  - Primarily interested high-p_T (hard) collisions

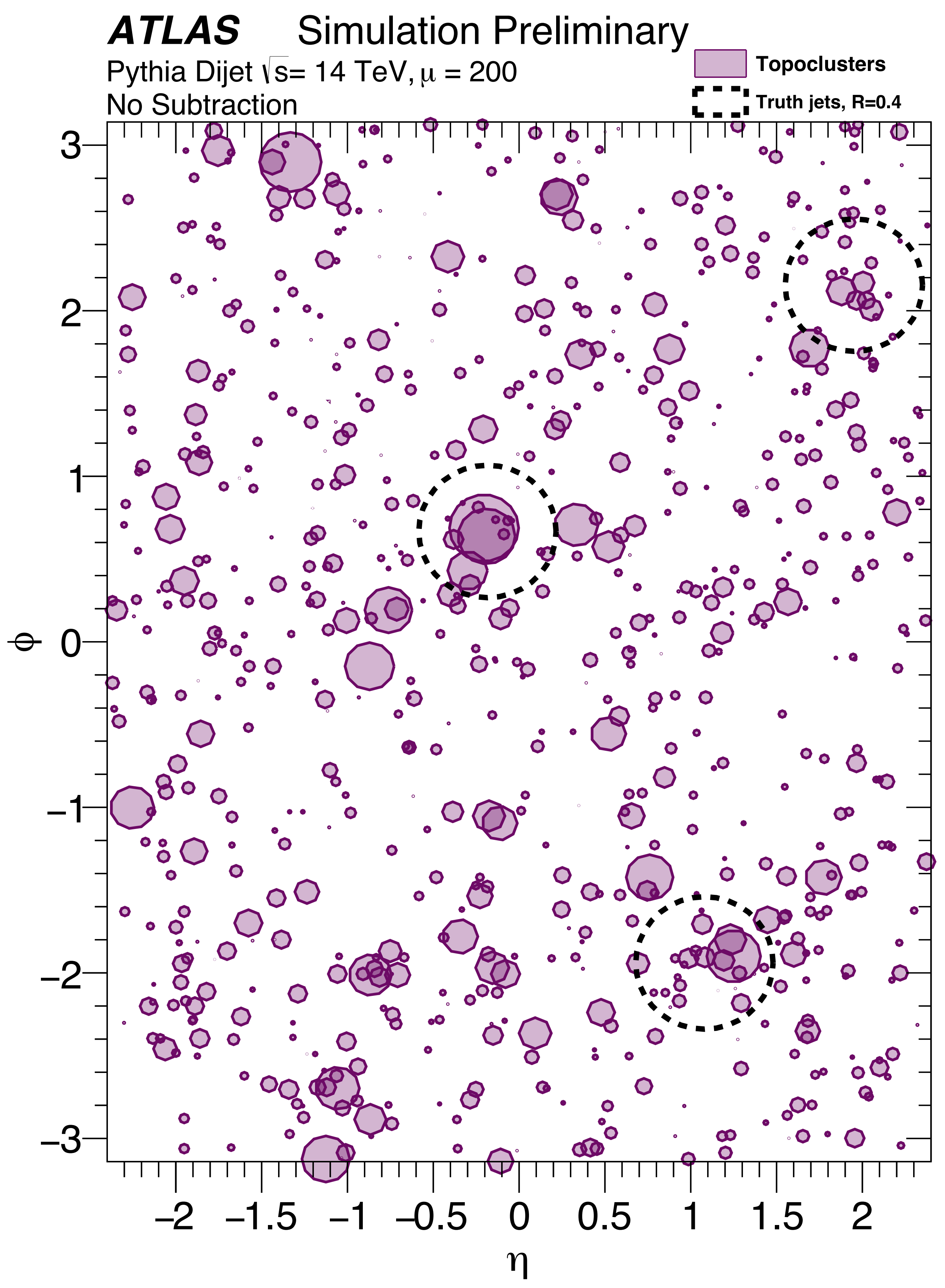
a complication: pileup

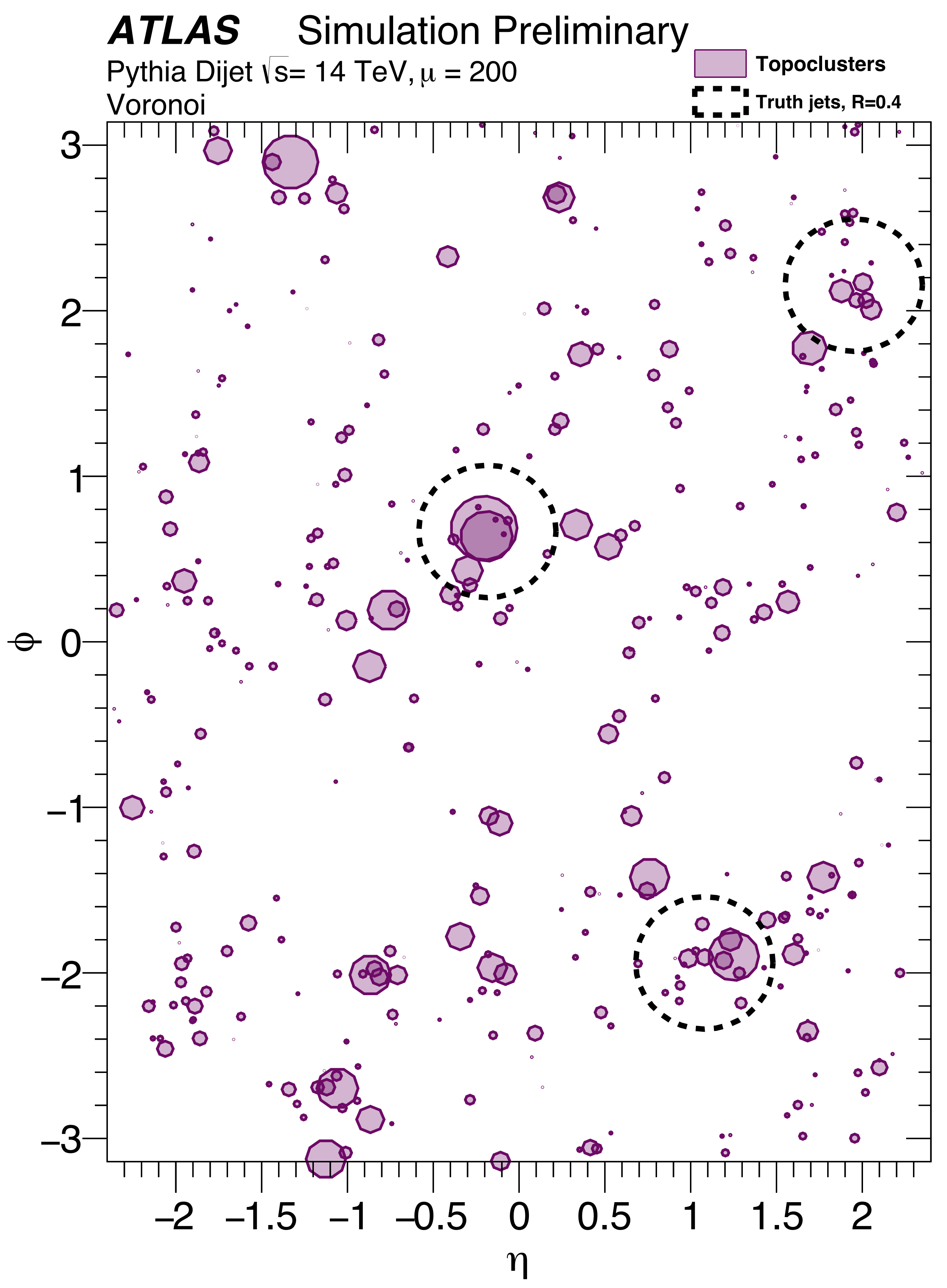
- Reality is much more complicated
  - Many simultaneous collisions (*pileup*), usually only (up to) one hard collision
    - Produces a lot of low-p_T hadrons, with relatively uniform distribution
    - Collisions happen in slightly different positions, and at slightly different times
    - Expect to eventually have up to **200** collisions per bunch crossing!


ATLAS
EXPERIMENT
HL-LHC $t\bar{t}$ event in ATLAS ITK
at <μ>=200

pileup mitigation

- Pileup adds noise to an event → important to mitigate it
- For charged particles, can identify the associated vertex, and remove particles not associated with the vertex of interest (‘*primary vertex*’)
- Several algorithms dedicated to pileup mitigation for neutral particles (PUPPI, Constituent Subtraction, SoftKiller, …)
  - *Not going through these algorithms today*
- Typically apply pileup mitigation after reconstructing particles, but before clustering jets

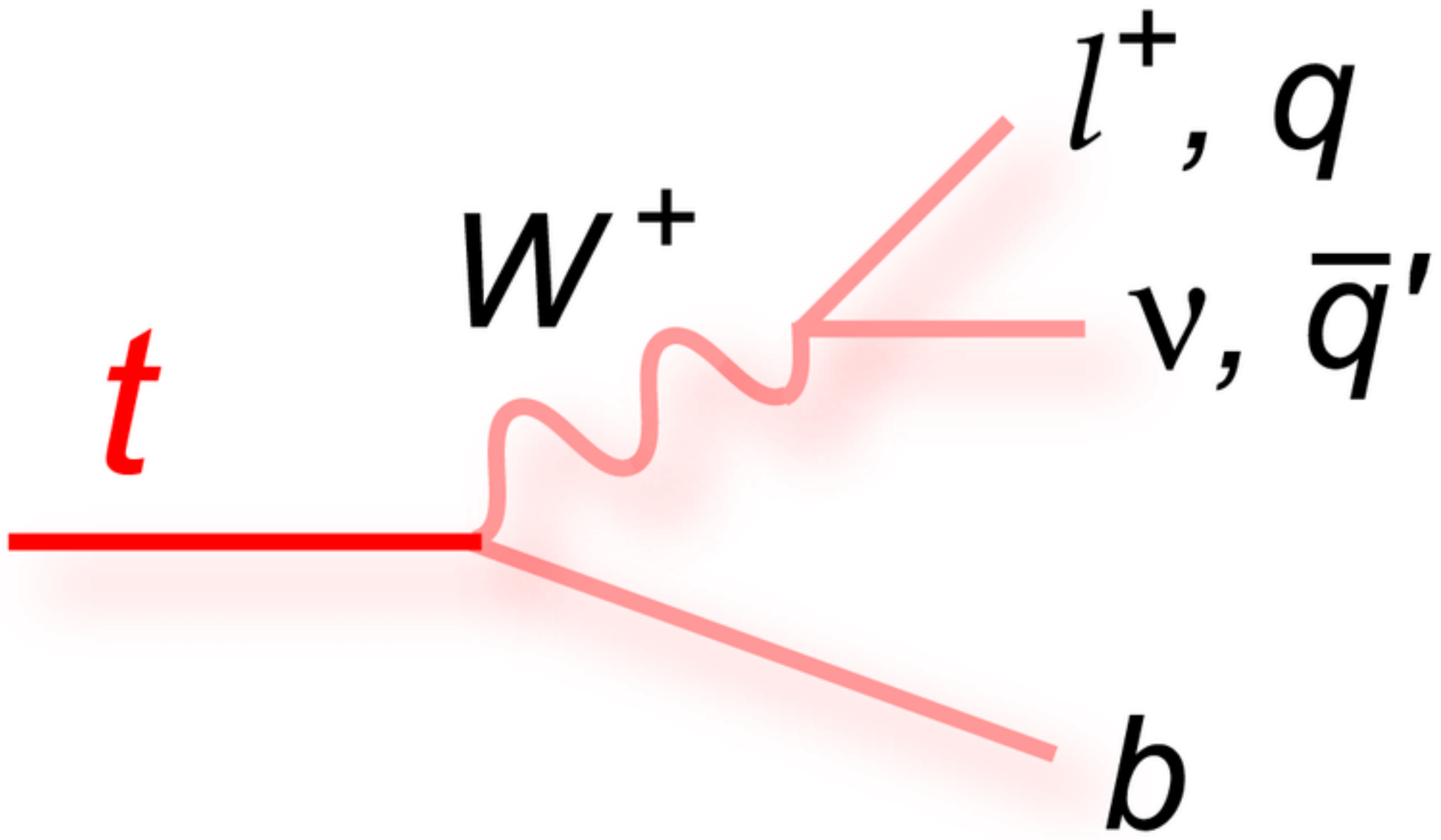




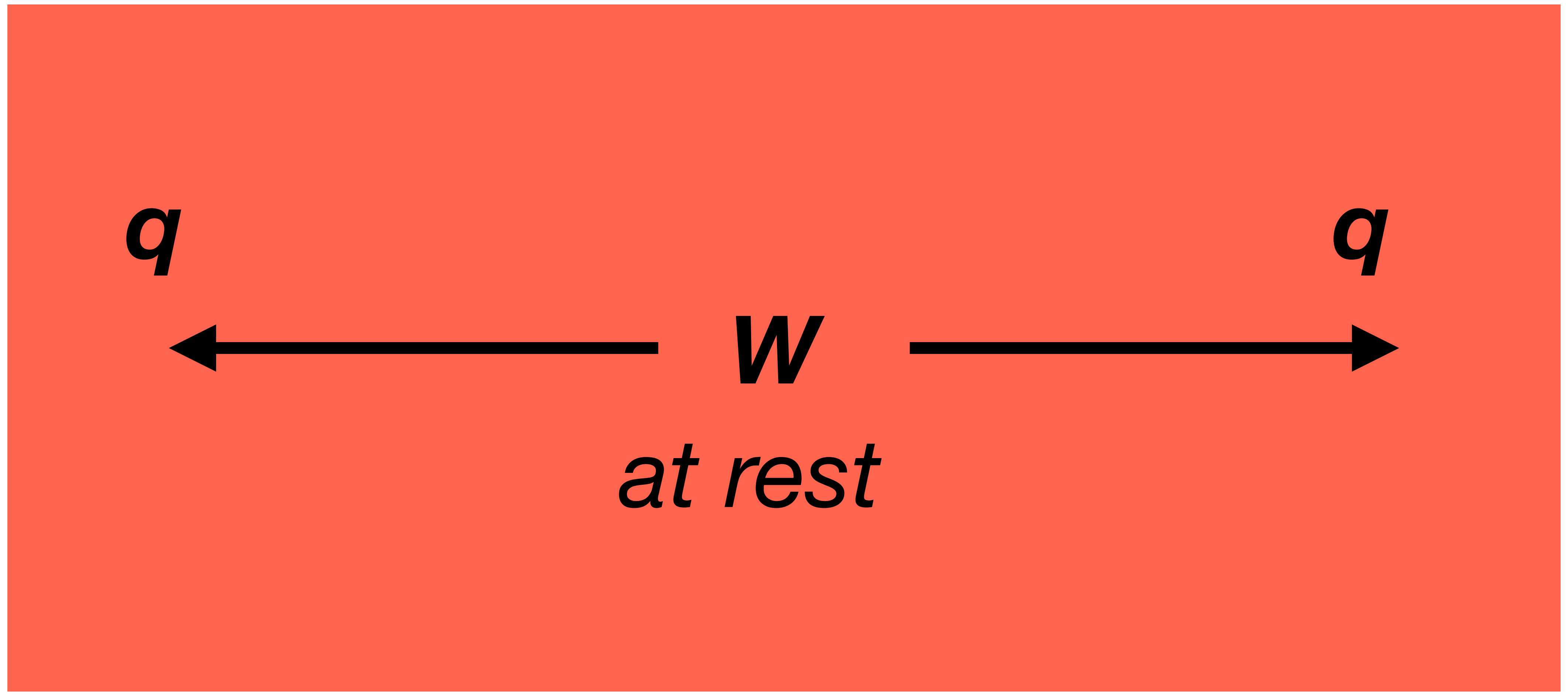
jet substructure and tagging

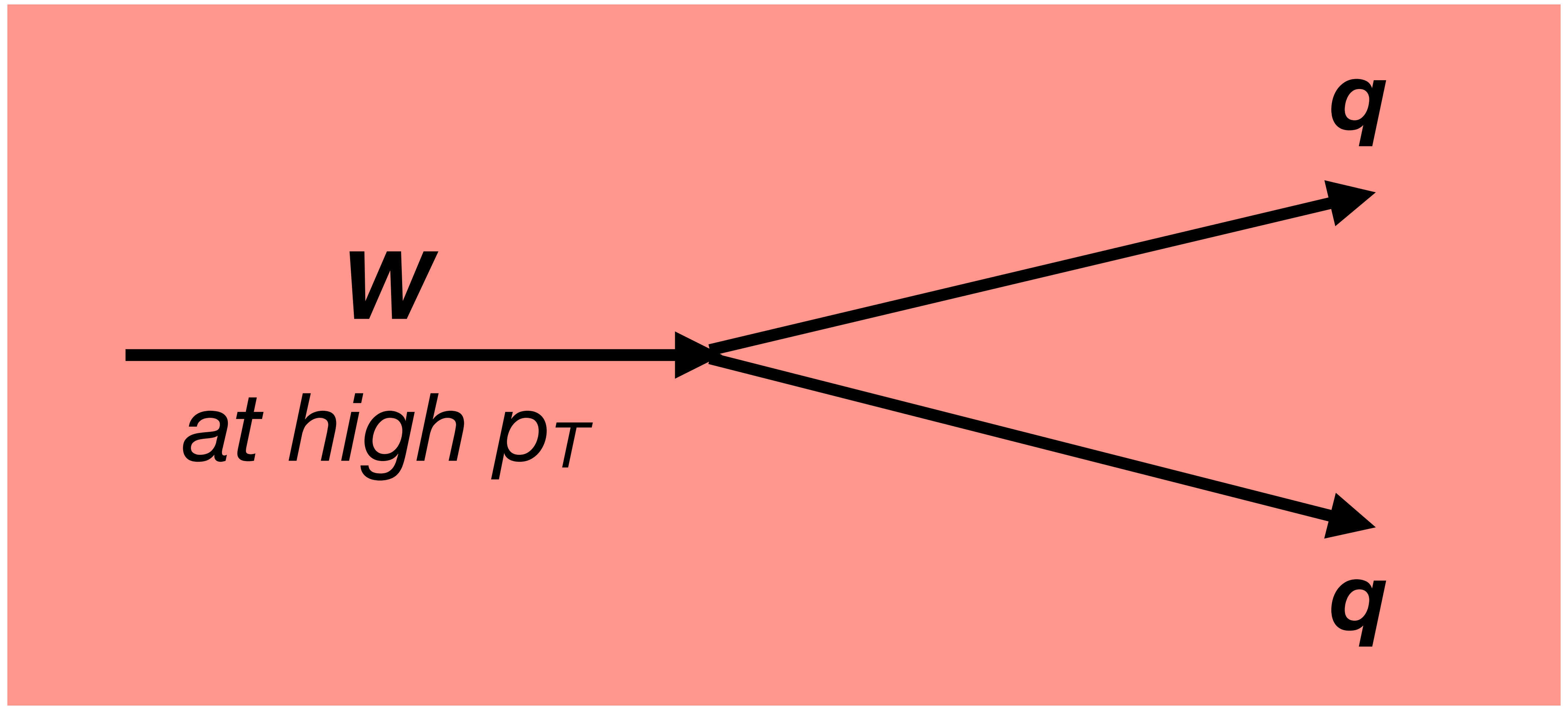
heavy particle decays

- Many particles decay before we detect them
  - Top quarks decay to a W-boson + a b-quark ($t \to Wb$)
  - W-bosons decay in two main ways:
    - Two quarks ($W \to qq$): 68%
    - Lepton + neutrino ($W \to \ell\boldsymbol{\nu}$): 32%
- This means that top quarks will decay to either $t \to qqb$ or $t \to \ell\boldsymbol{\nu}b$
  - When decaying to quarks (*decaying hadronically*), the quarks will have parton showers and hadronization, just like for quark/gluon jets



boosted objects

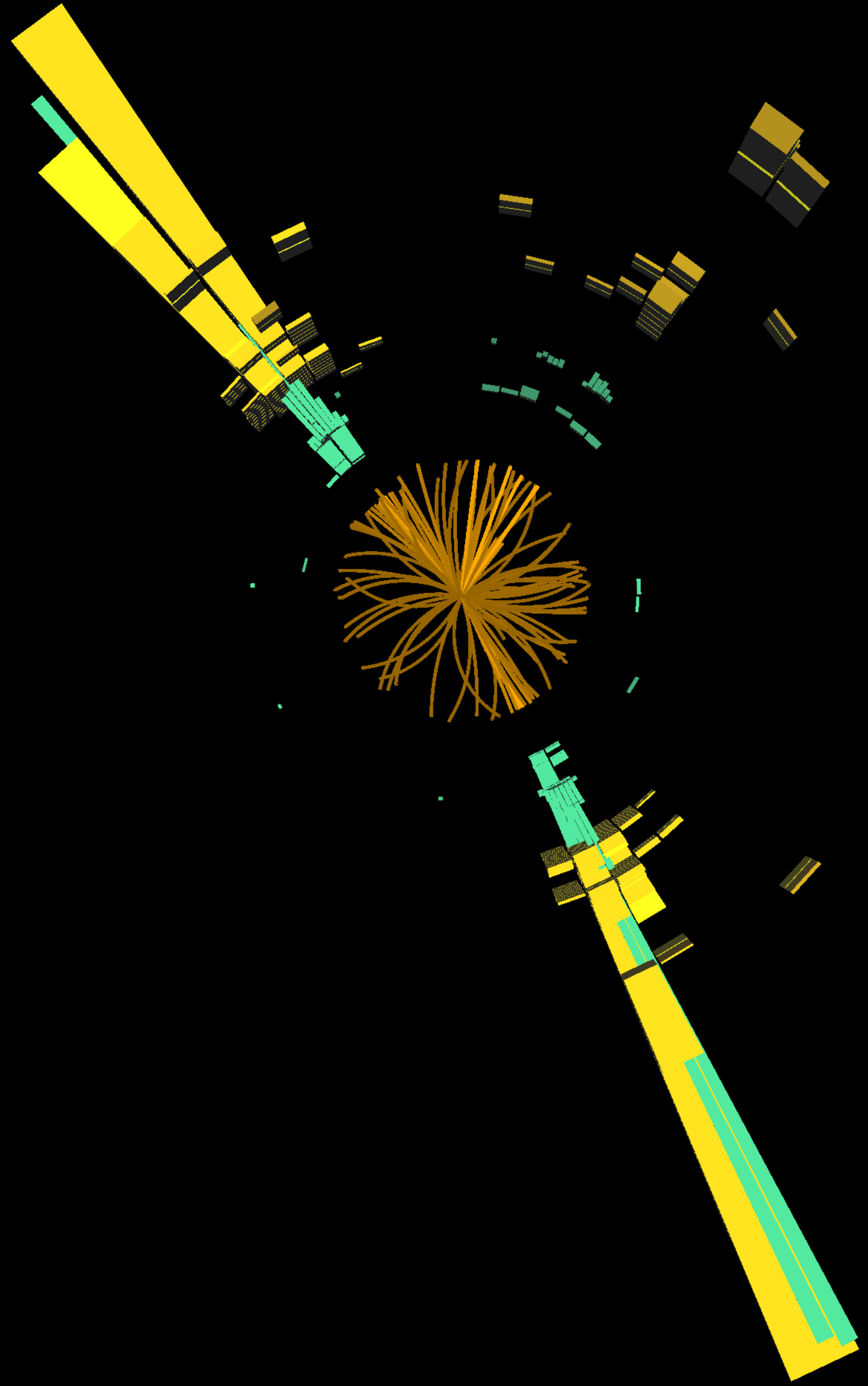


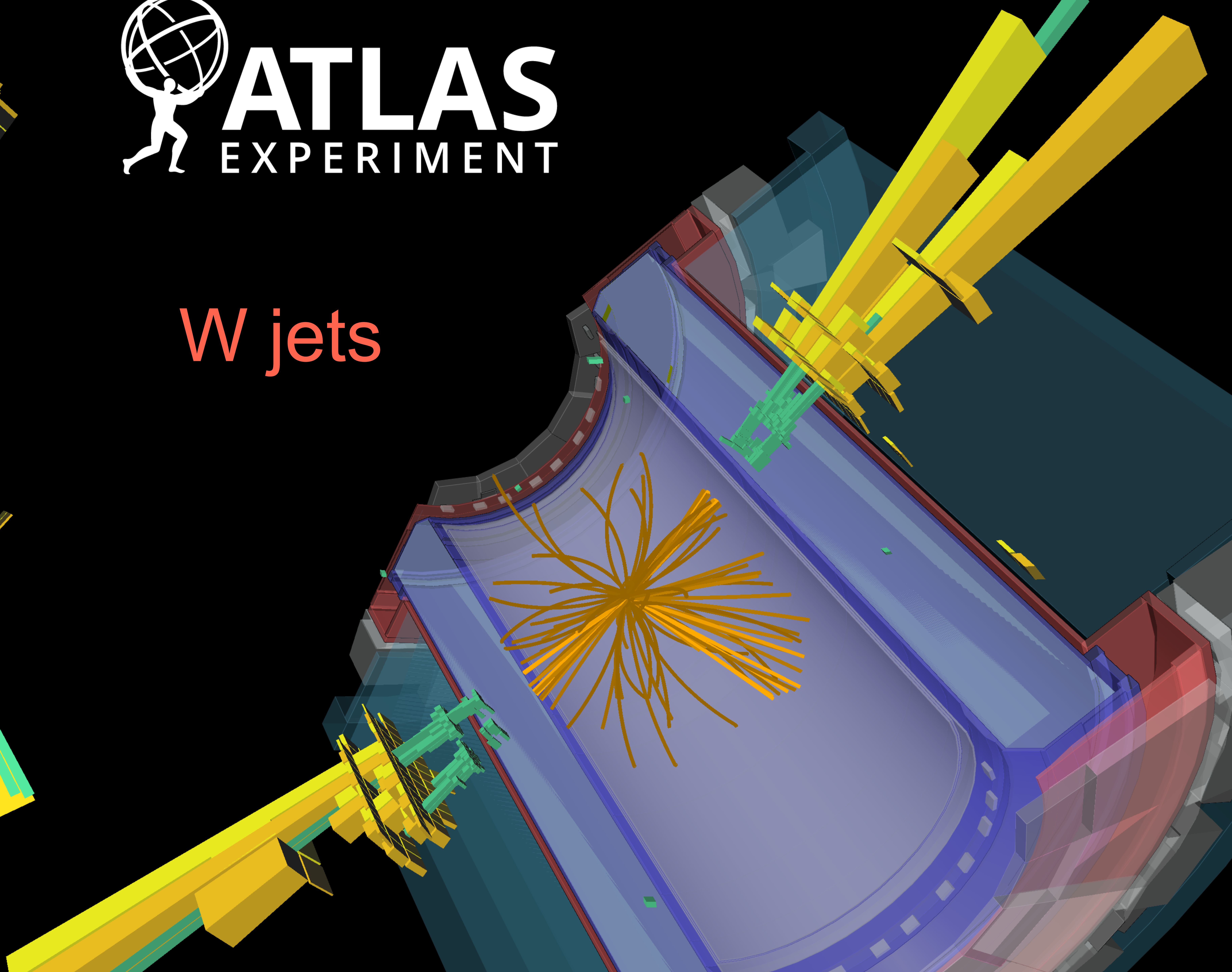


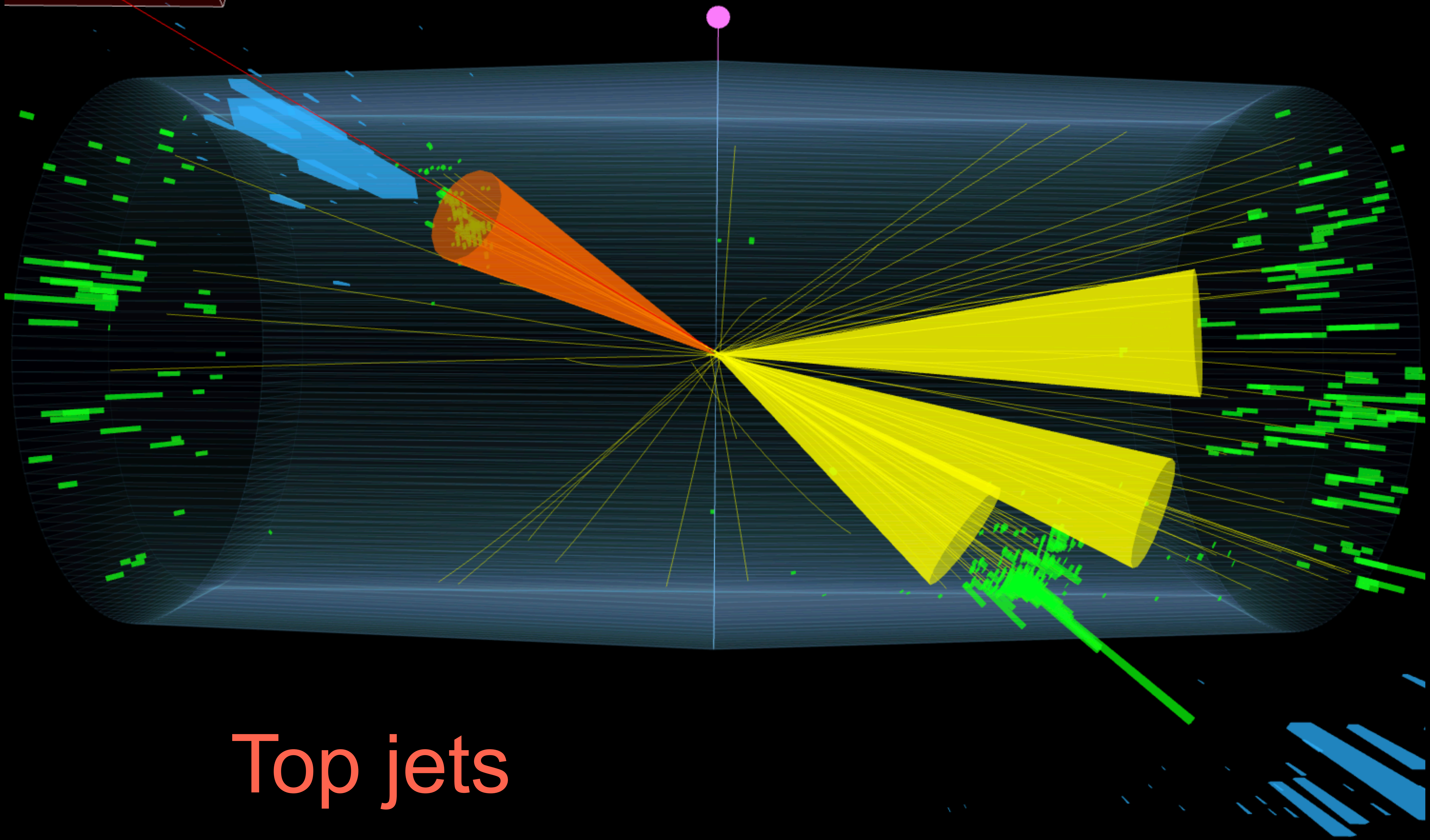
- At rest (or in the reference frame of the W), the decay products will be back-to-back
- When the W has a large p_T, decay products become collimated (*boosted objects*)
  - Entire decay can be reconstructed into a single jet!
- *Similar story for top quark decays, but with 3 decay products instead of 2*

ATLAS EXPERIMENT

W jets



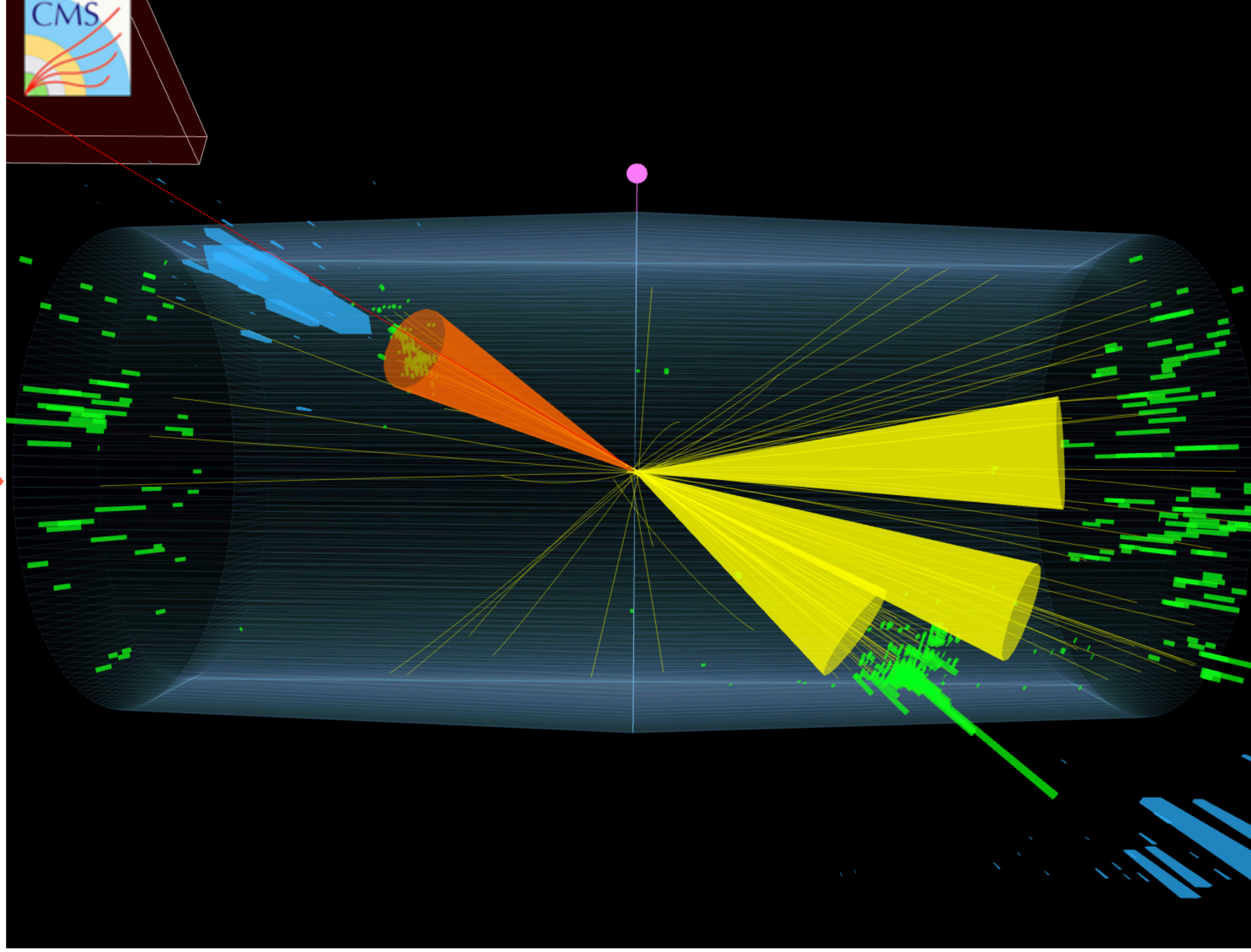


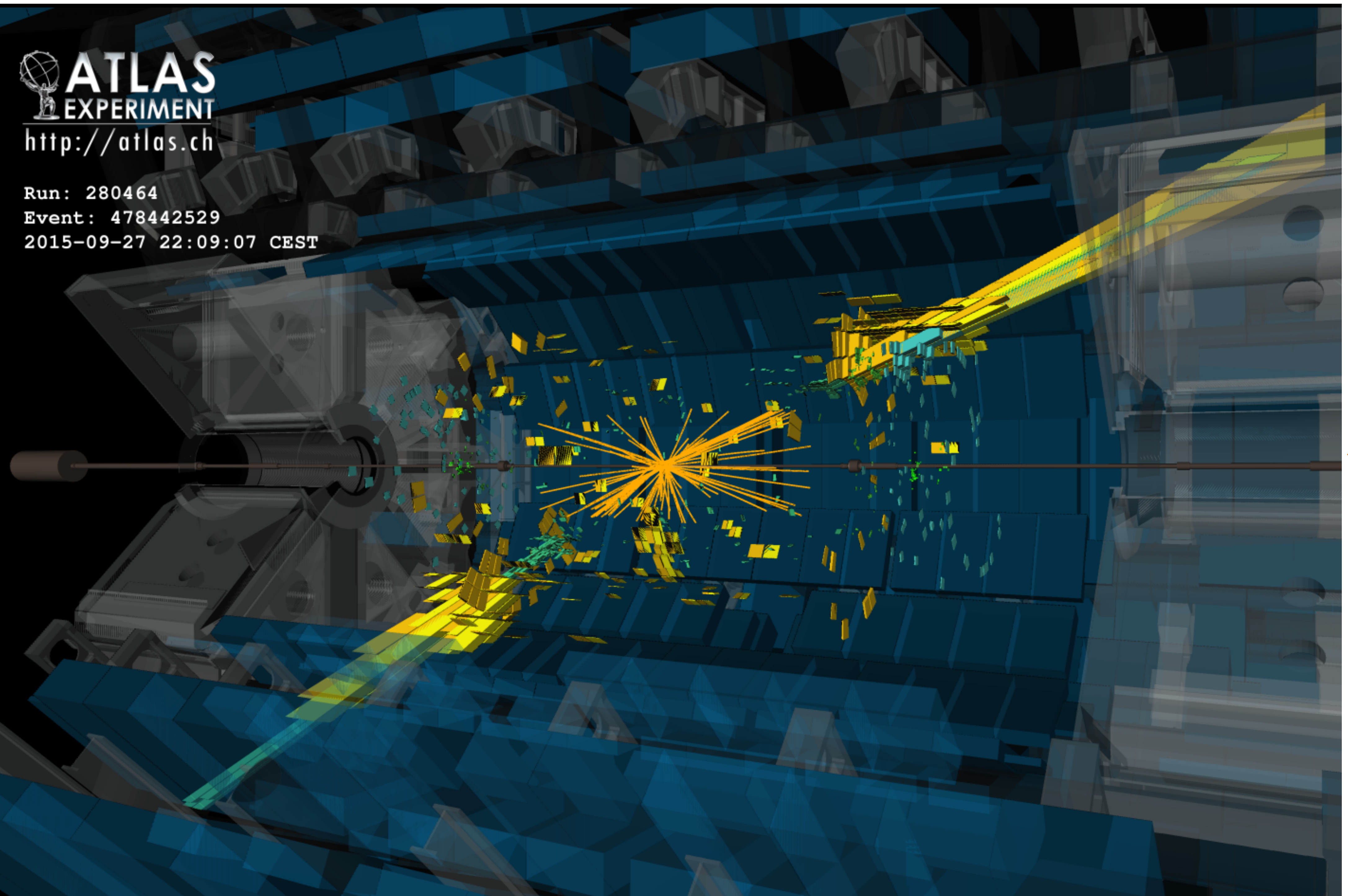


Top jets

jet substructure

- Top jets tend to have three prongs, one for each decay product
  - Each quark will have an associated parton shower and hadronization process → top jets have more complexity than 3 distinct prongs

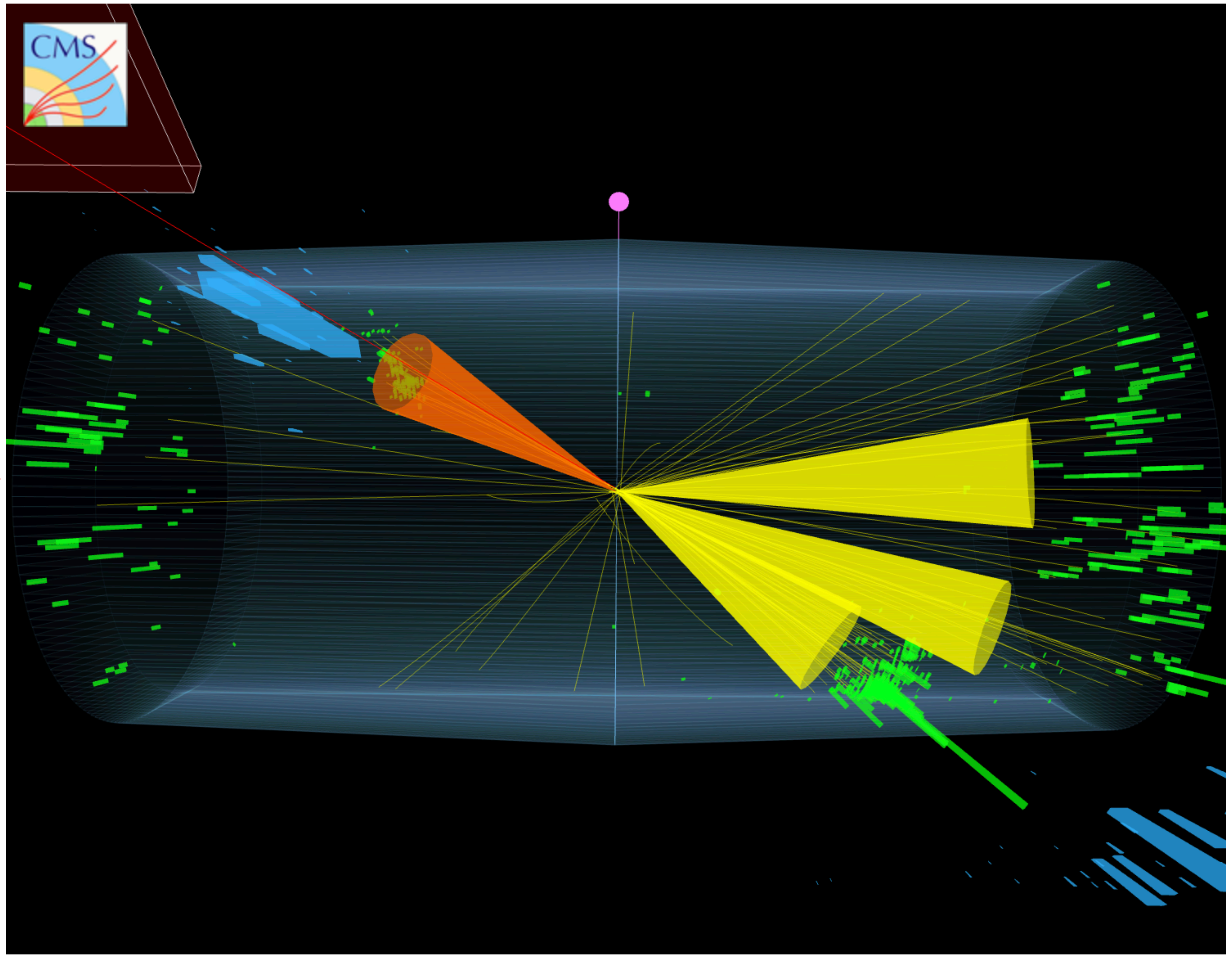




- Quark and gluon jets tend to be more collimated into a single prong
  - Still has some structure from the parton shower, but typically less pronounced

jet substructure

- Each prong of a jet from a W or top decay produces a narrow shower
  - Most of the interesting physics in the high-p_T (*hard*) particles, and at relatively small angles to one of the jet prongs
- Pileup tends to be roughly uniform, and low-p_T (*soft*)
  - Impacts jets everywhere, but most noticeable at large angles, since it adds particles where we would not expect them
  - Often, remove (some of) these particles through '*jet grooming*'
- Similar effects from the '*underlying event*'



jet grooming

- *Grooming essentially removes noisy information*
  - Prongs of a jet much more apparent, removes constituents from other parts of the collision, pileup, etc.
  - Brings the mass of a *W* or top jet closer to the *W* or top mass
  - Can make it easier to distinguish different types of jets
- Many different grooming algorithms (*trimming, pruning, softdrop, …*), *but not discussing the details today*

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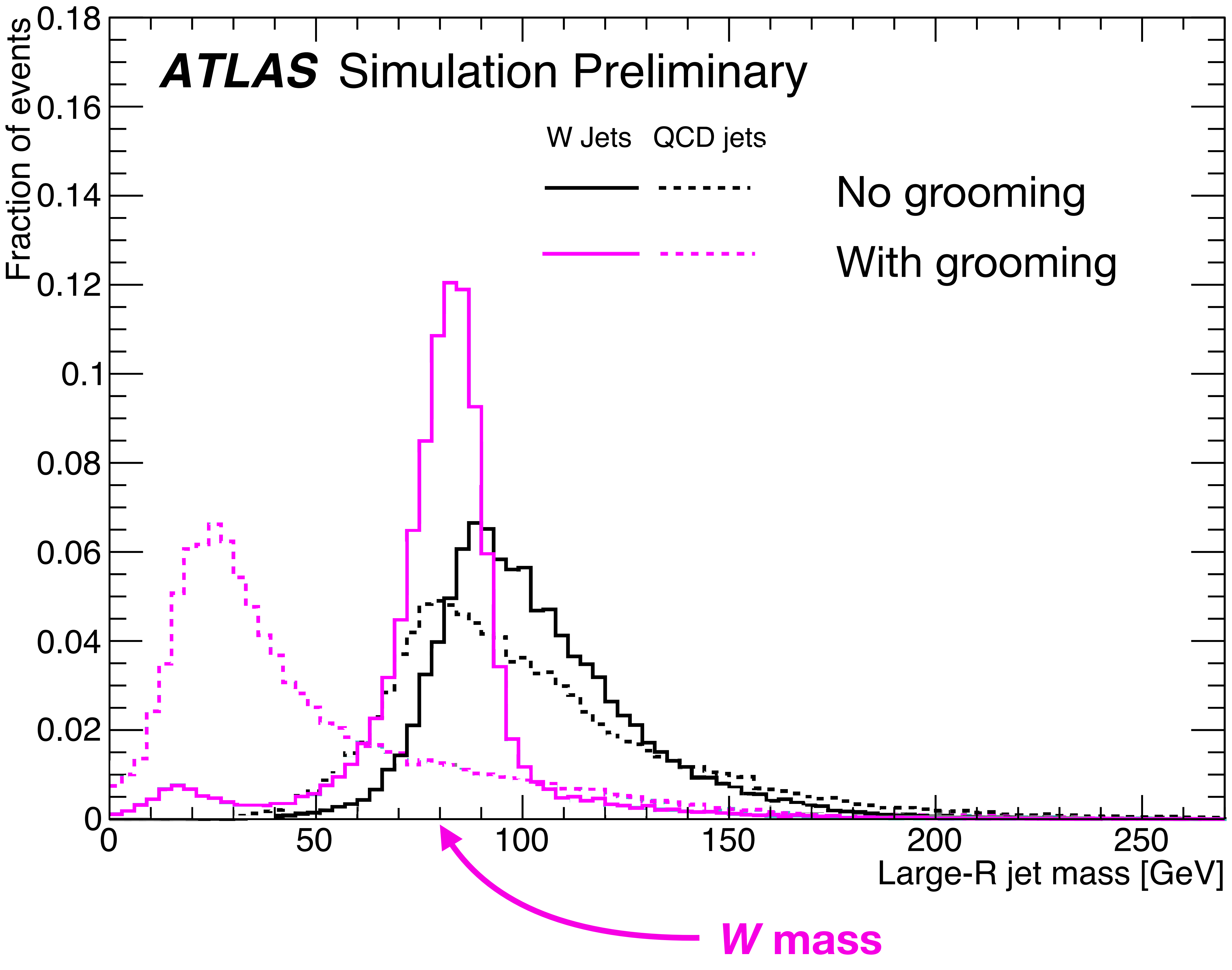
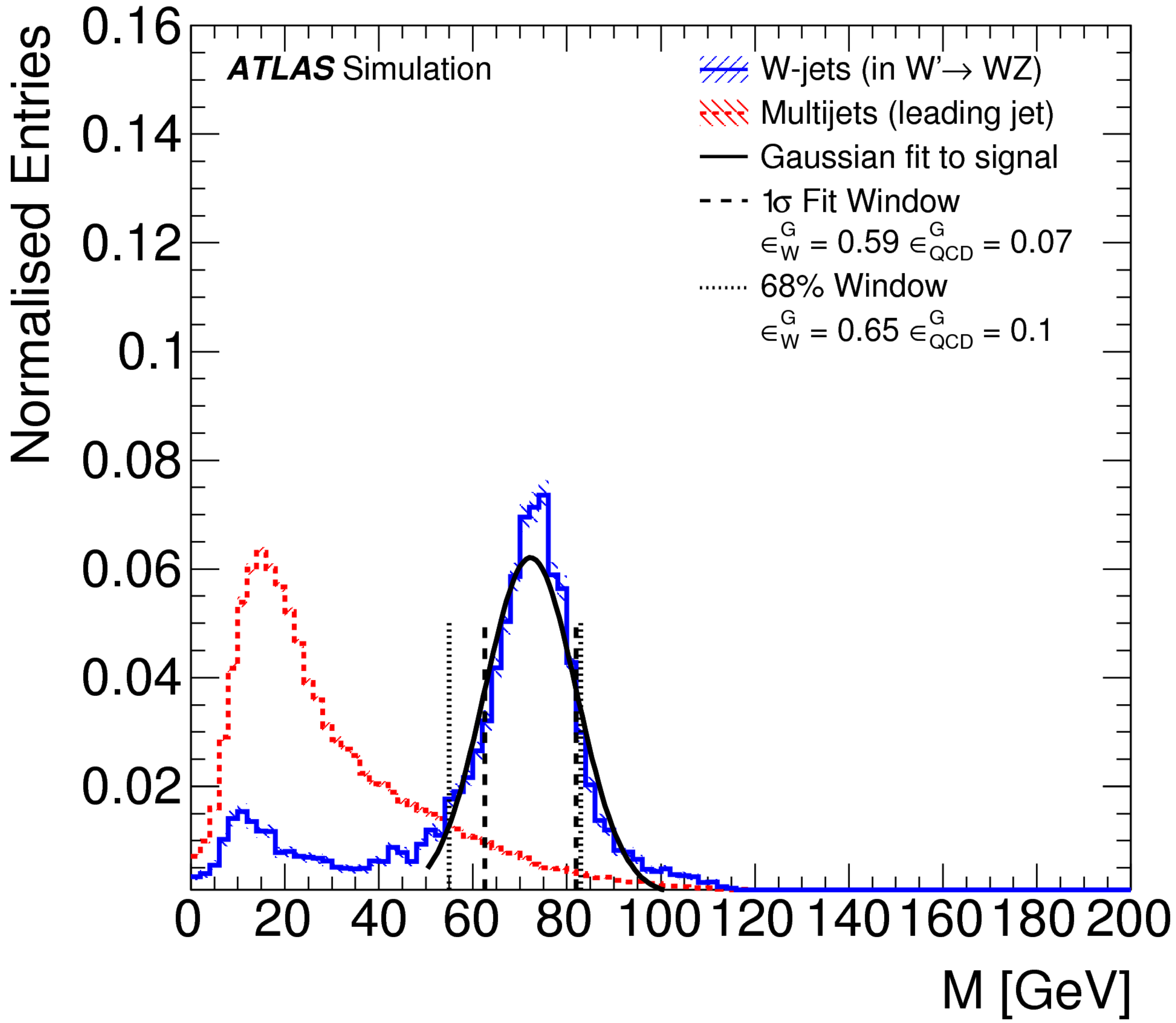


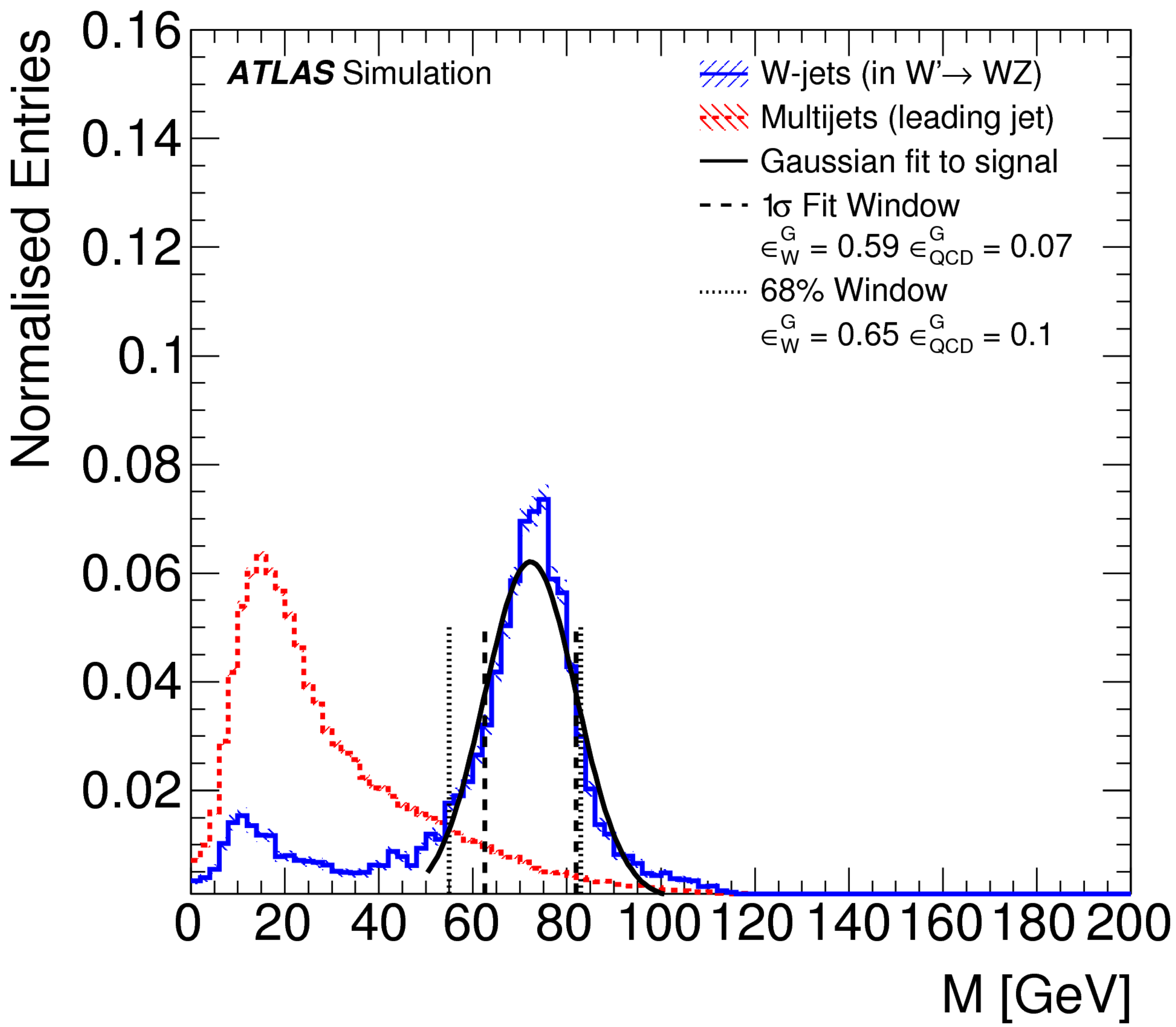
the jet mass

- The invariant mass is defined as
  $$M = \sqrt{(E_1 + E_2)^2 - ||p_1^2 + p_2^2||}$$
- For E >> m, approximately
- $$M = \sqrt{2p_{T,1}p_{T,2}(cosh(\eta_1 - \eta_2) - cos(\phi_1 - \phi_2))}$$
- If we have any two particles with some angle between them, they will have a non-zero invariant mass!
  - A decay does not change the invariant mass of a system
- Parton showers result in jets that have mass, even though quarks and gluons are roughly massless!
  - *Large-angle emissions or high-p_T emissions → large masses*



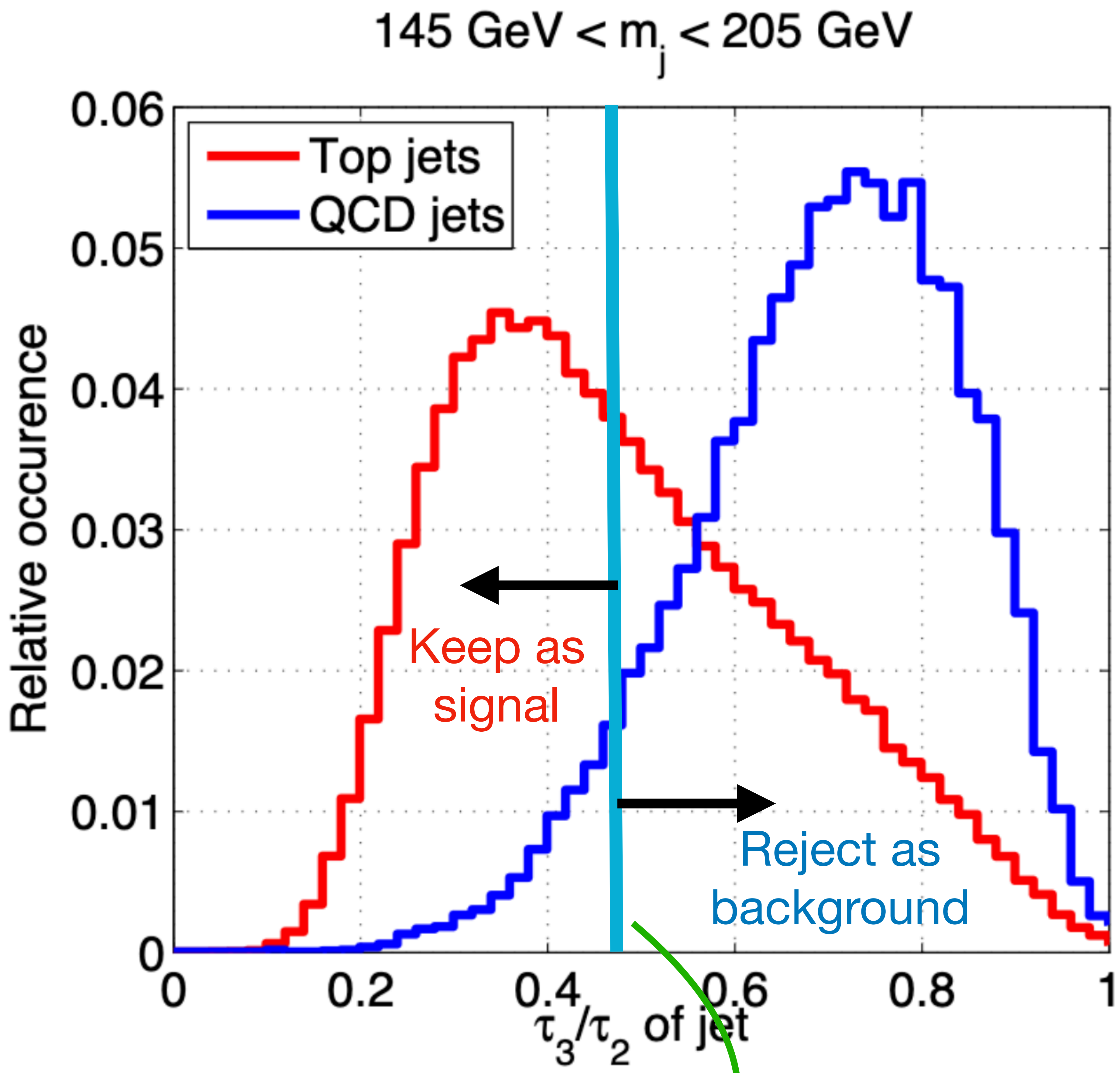
the jet mass

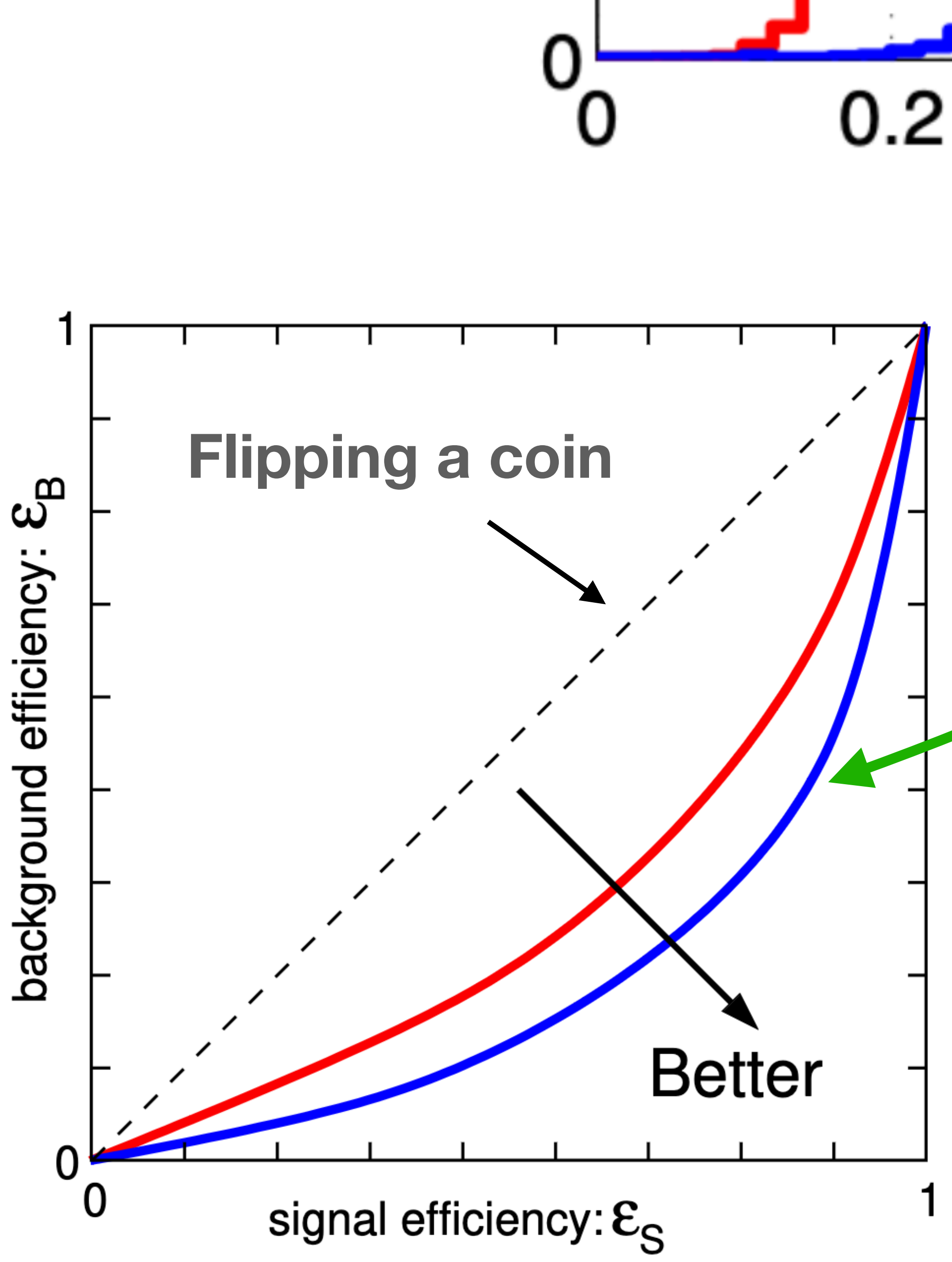
- The jet mass is an obvious observable to distinguish between different types of jets
  - Use invariant mass of all jet constituents
  - For top jets, the mass should be around 173 GeV
  - For *W* jets, around 80 GeV
- Clear physical meaning, but performance depends on the transverse momentum (p_T) of the jets
  - At higher p_T, q/g jets have larger masses



designing a tagger

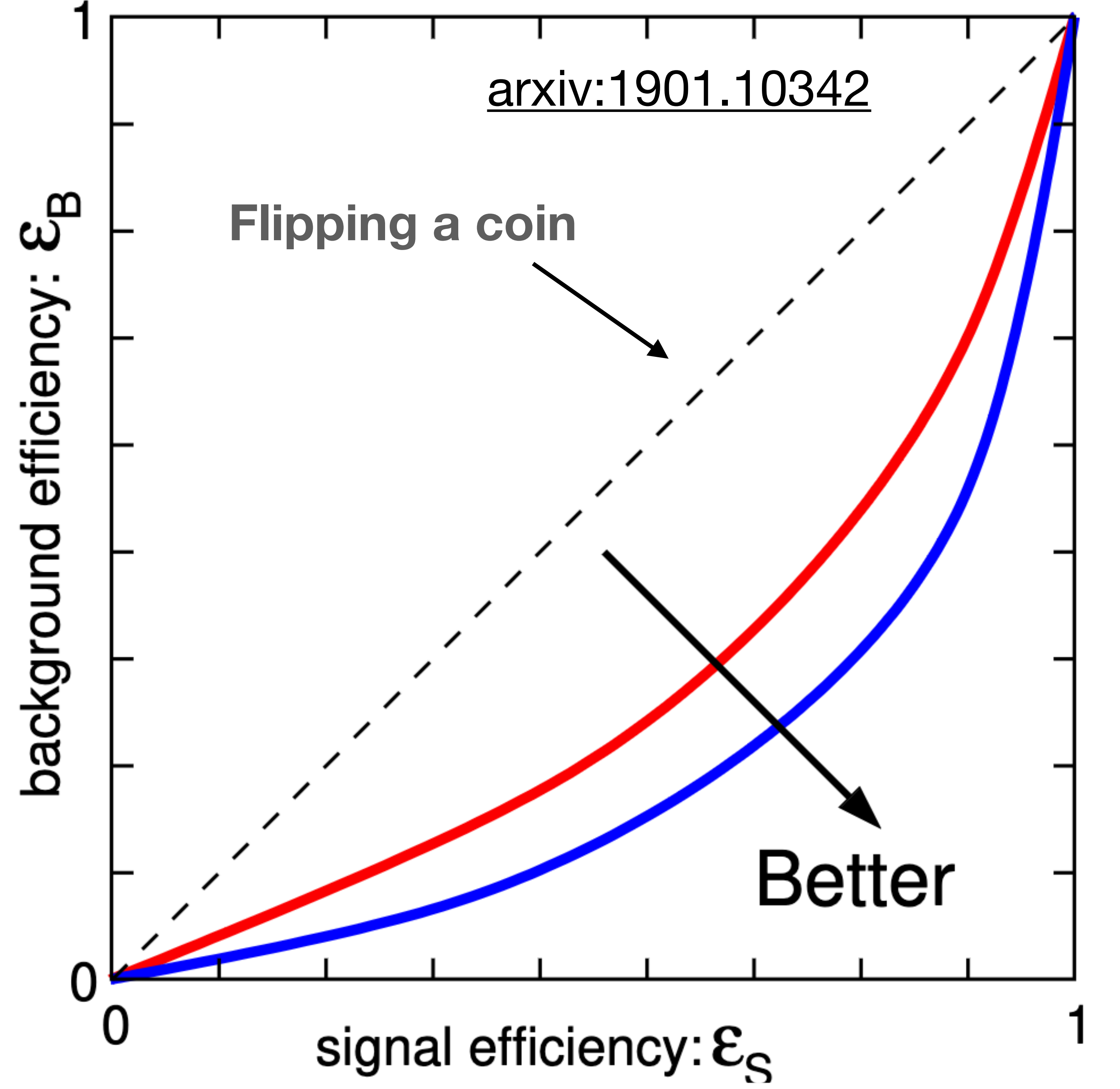
- To tag a jet, place a cut on some observable
  - This cut will result in some signal efficiency (ϵ_S) and background efficiency (ϵ_B)
    - *The optimal choice depends on the context*
  - Can also scan a range of potential cuts on an observable to obtain ϵ_B as a function of ϵ_S

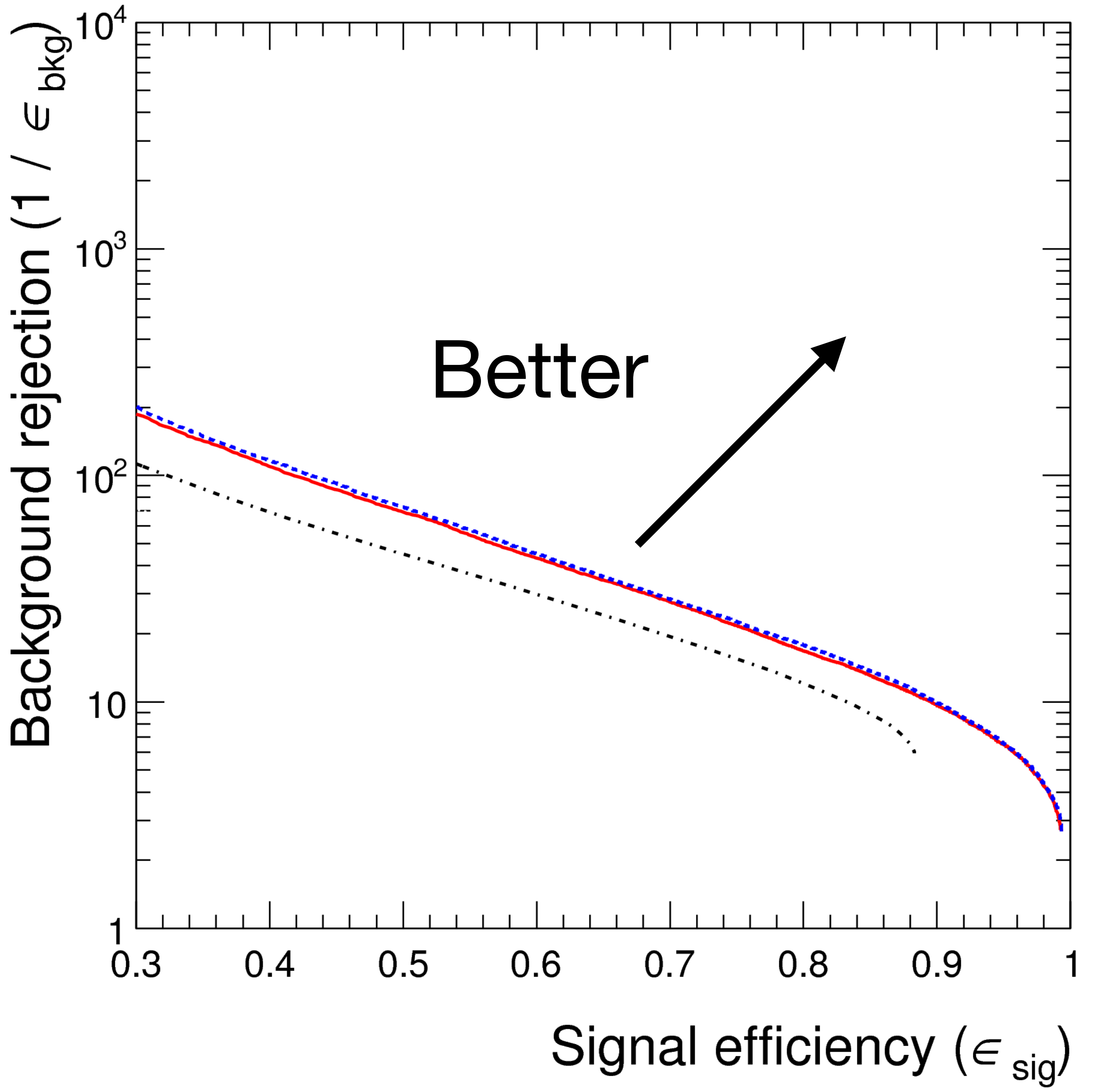




designing a tagger

- Typically use receiver-operator characteristic curves (ROC curves) to compare different tagging strategies
  - Compares the background rejection as a function of the signal efficiency (ϵ_S)
- Be careful reading these plots — multiple options for the y-axis!
  - Background efficiency (ϵ_B)
  - Background rejection ($1/\epsilon_B$)
  - *Some others not mentioned here — always check!*
- In many cases, the ROC curves for different taggers can cross
  - Optimal choice depends on if you want a high or low signal efficiency
    - *e.g.* with high statistics, you can throw away a lot of events, so a lower signal efficiency might be fine





designing a tagger

- Combining observables can result in more powerful tagger

- For instance, D2 and the jet mass are fairly uncorrelated → can determine cuts on them separately

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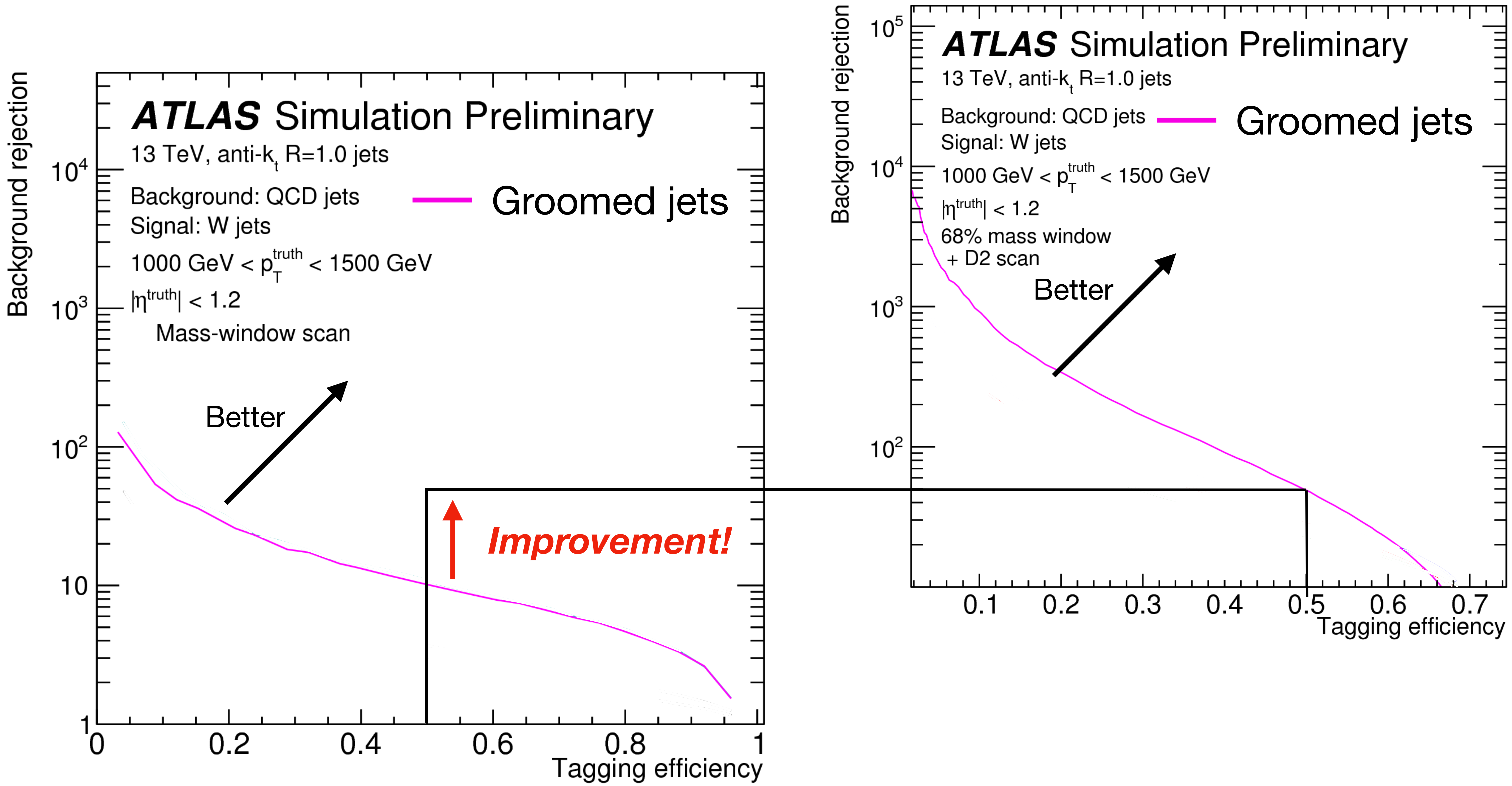


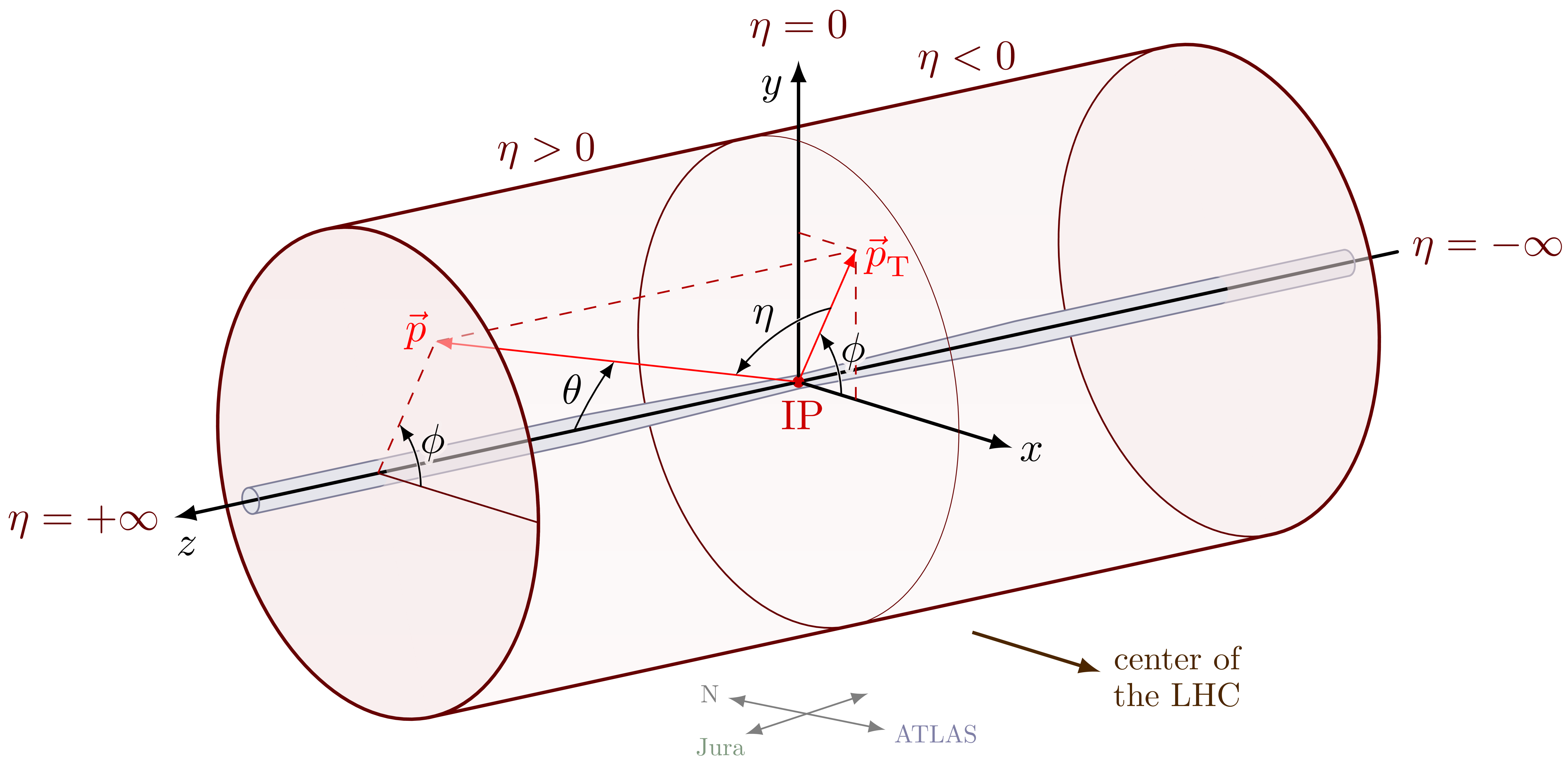
summary

- Jets are complicated objects → reconstructing the jets relies on understanding QCD and on innovative experimental techniques
  - *Lots of interplay between theoretical and experiment*
- Developments in jet reconstruction feed directly into improving the scope and quality of the research that we do at the LHC
  - *Precision of many results is limited by precision on jets and QCD → increasingly relevant as our statistical uncertainties shrink with more data*
- There is a lot that I couldn’t cover in today’s talk!
  - *How to calibrate jets, details of the algorithms, theory developments in jet modeling, machine learning strategies, …*
- Feel free to reach out if you have any questions or thoughts!

backup and bonus

the coordinate system

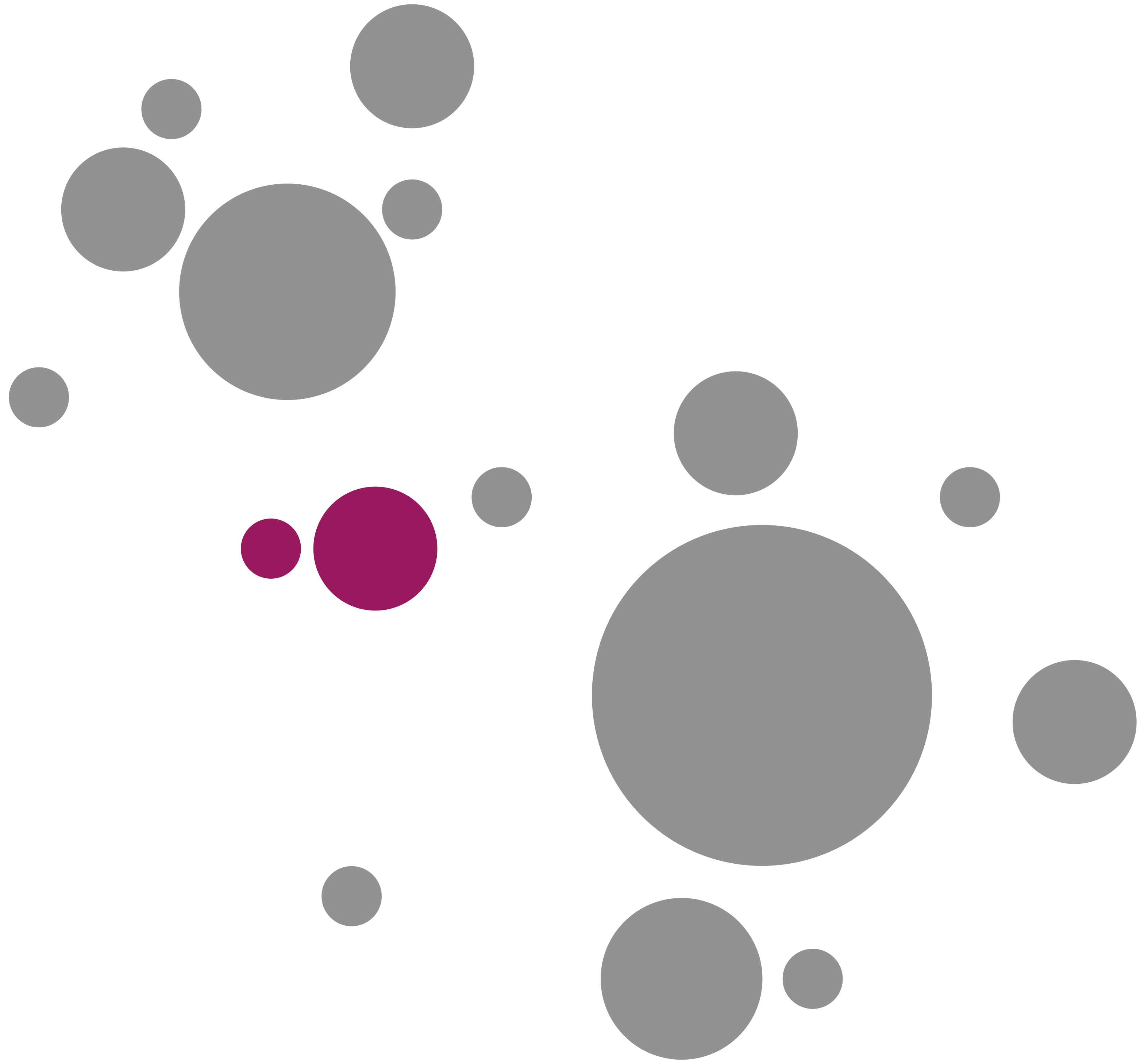
- Use a cylindrical coordinate system to describe particle momenta
- Jet algorithms cluster particles together with similar angles
  - Typically use the pseudorapidity η and azimuthal angle Φ
- For hadron colliders, typically use the transverse momentum (p_T) of a particle instead of the energy



jet algorithms

Cambridge-Aachen: $d_{ij} = \frac{\Delta_{ij}^2}{R^2}$

- Only depends on the distance between particles
- Produces irregularly-shaped jets
- Clustering history related to parton shower models

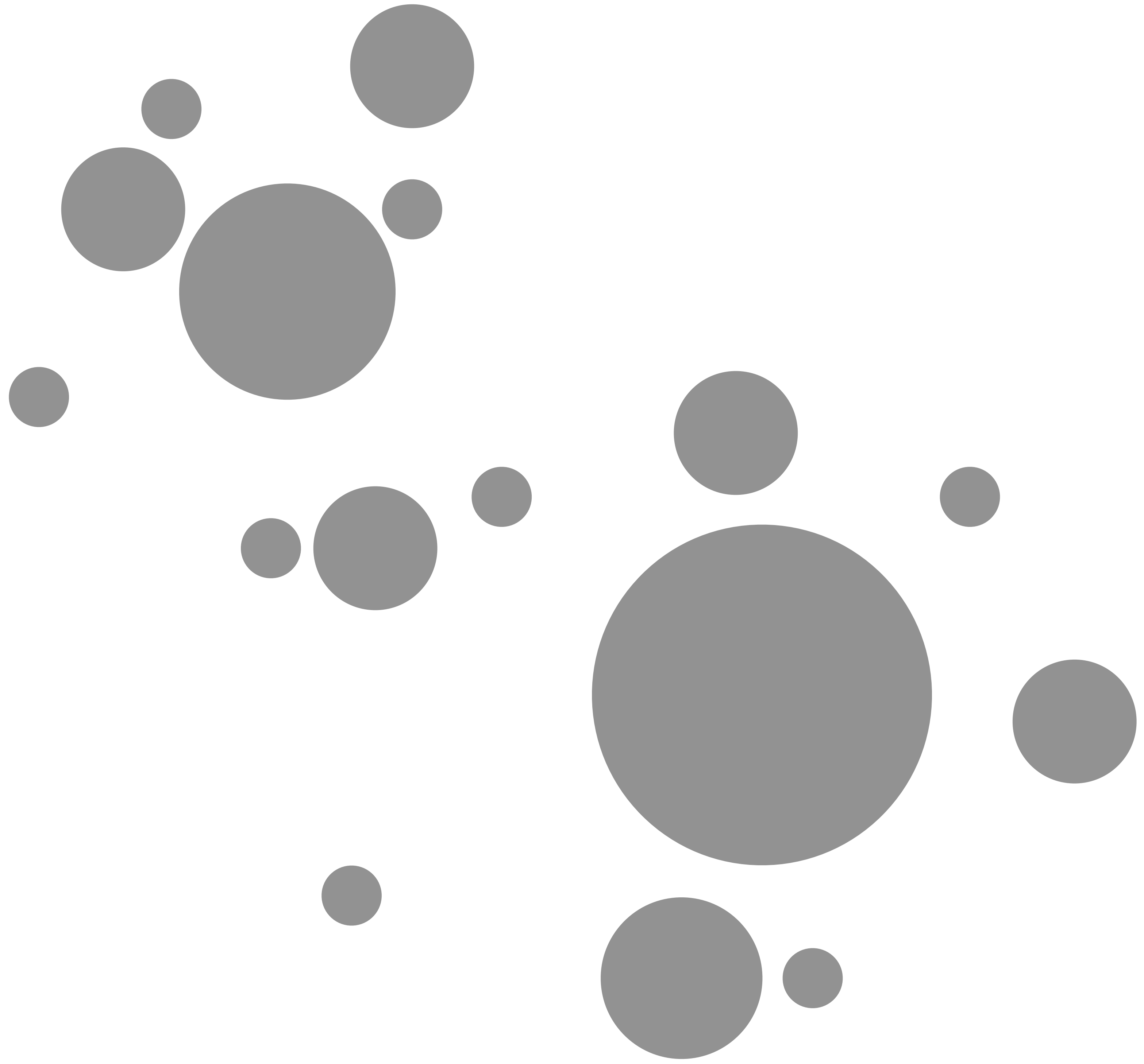


Anti-k$_t$: $d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2}) \frac{\Delta_{ij}^2}{R^2}$

- Particles get clustered in with nearest high-p$_T$ particle
- Produces circular jets (good for calibration)
- Clustering history not physically meaningful

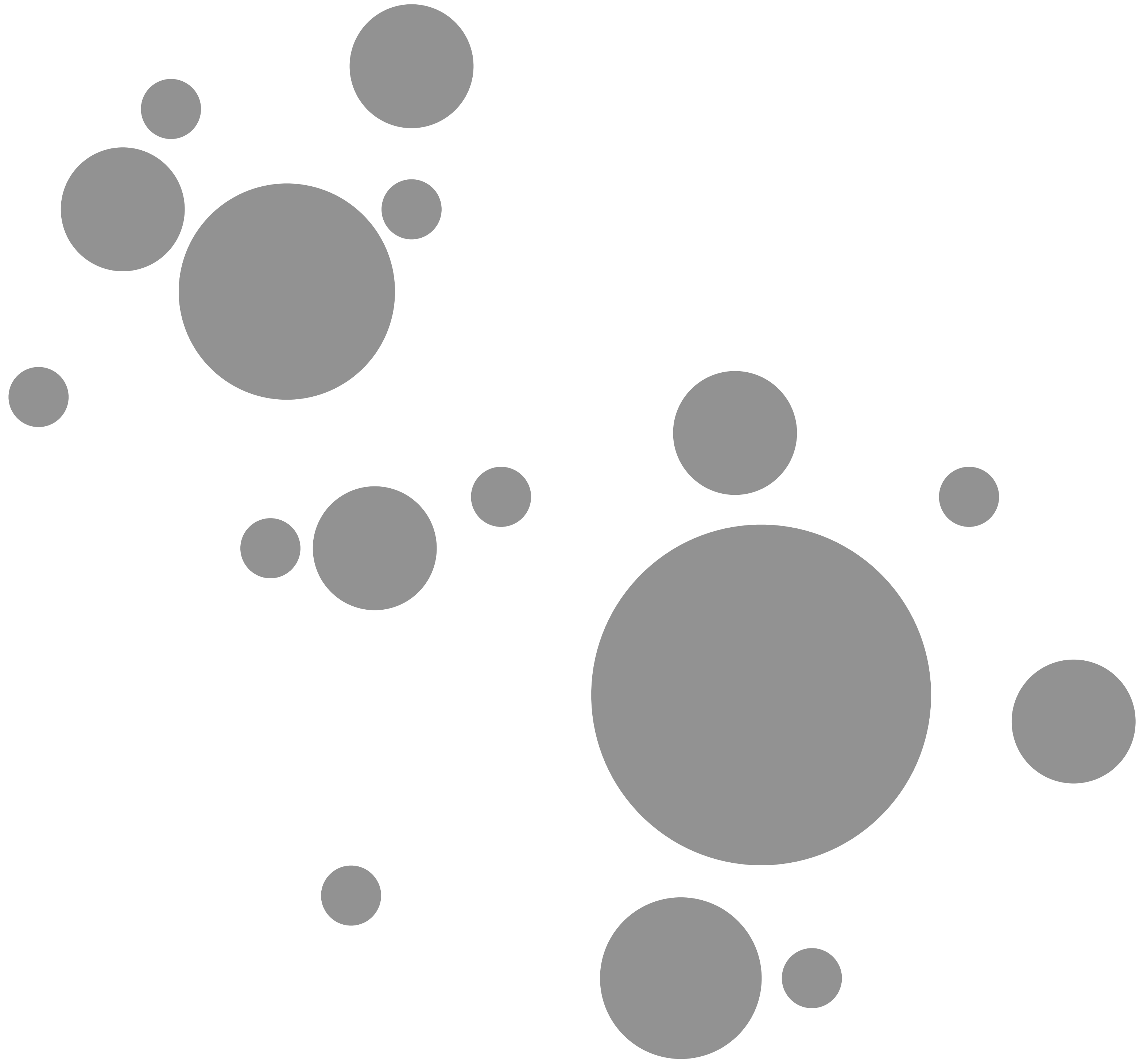
Cambridge-Aachen: $d_{ij} = \frac{\Delta_{ij}^2}{R^2}$

- Only depends on the distance between particles
- Produces irregularly-shaped jets
- Clustering history related to parton shower models



Anti-k$_t$: $d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2}) \frac{\Delta_{ij}^2}{R^2}$

- Particles get clustered in with nearest high-p_T particle
- Produces circular jets (good for calibration)
- Clustering history not physically meaningful



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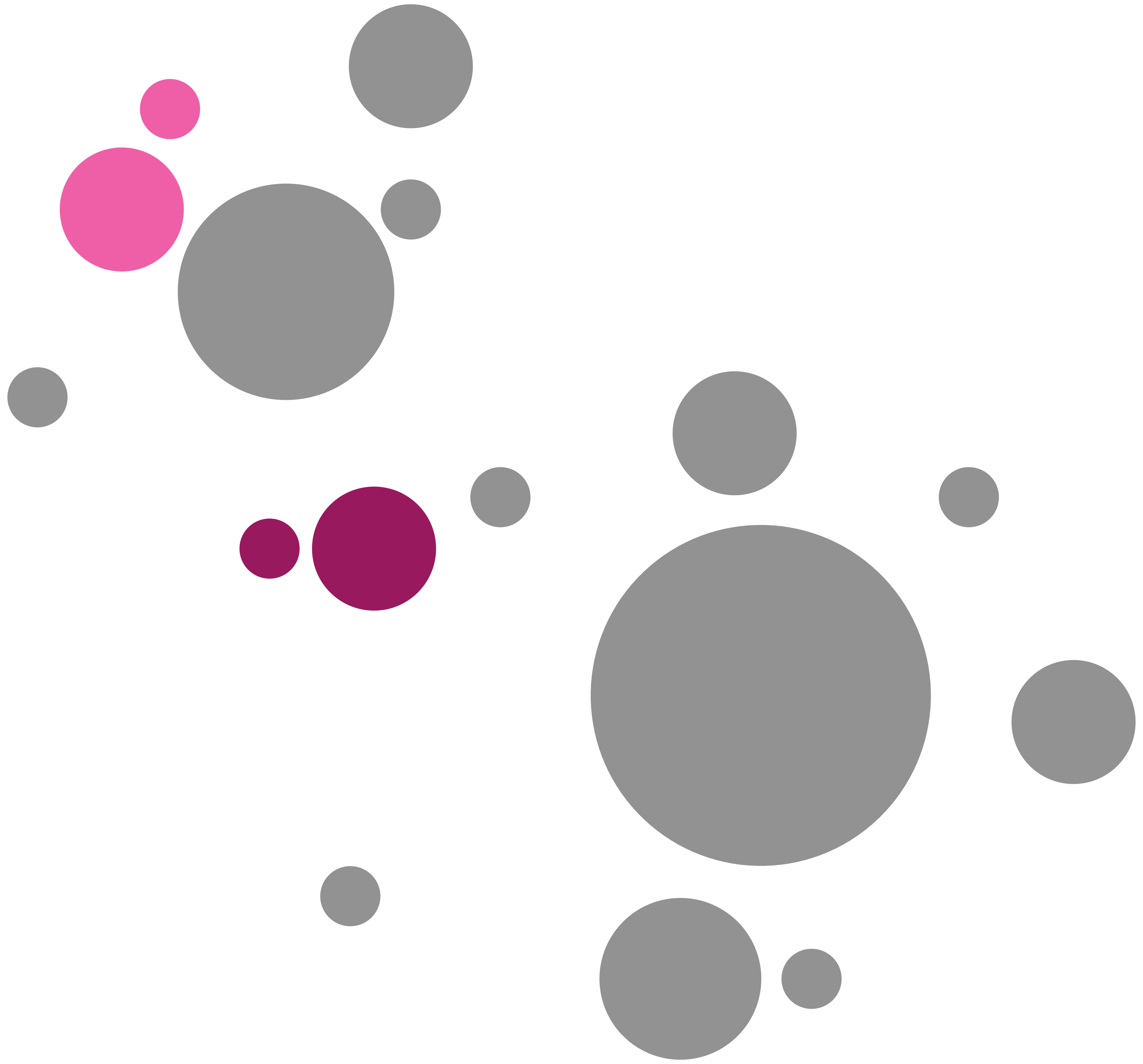

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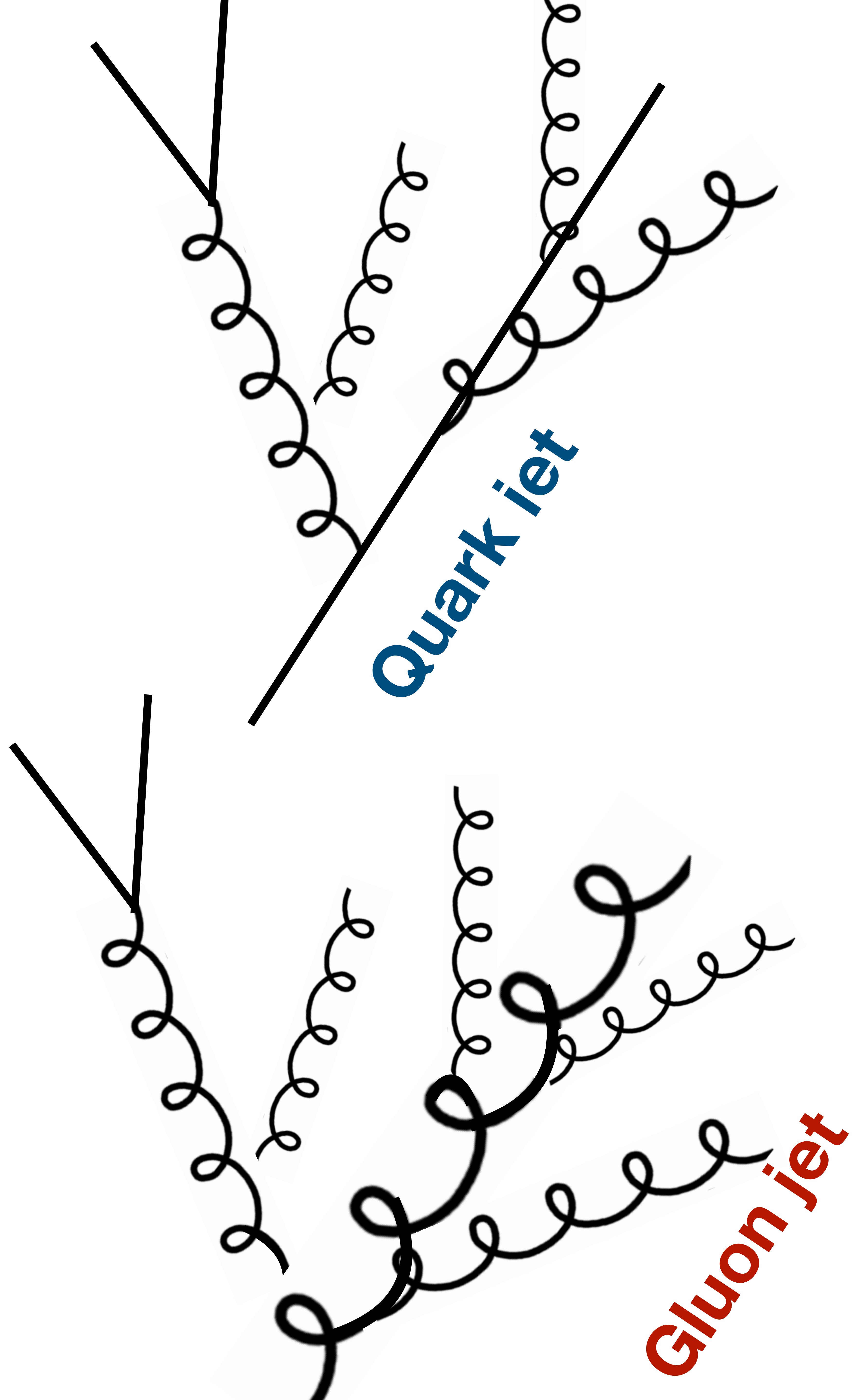
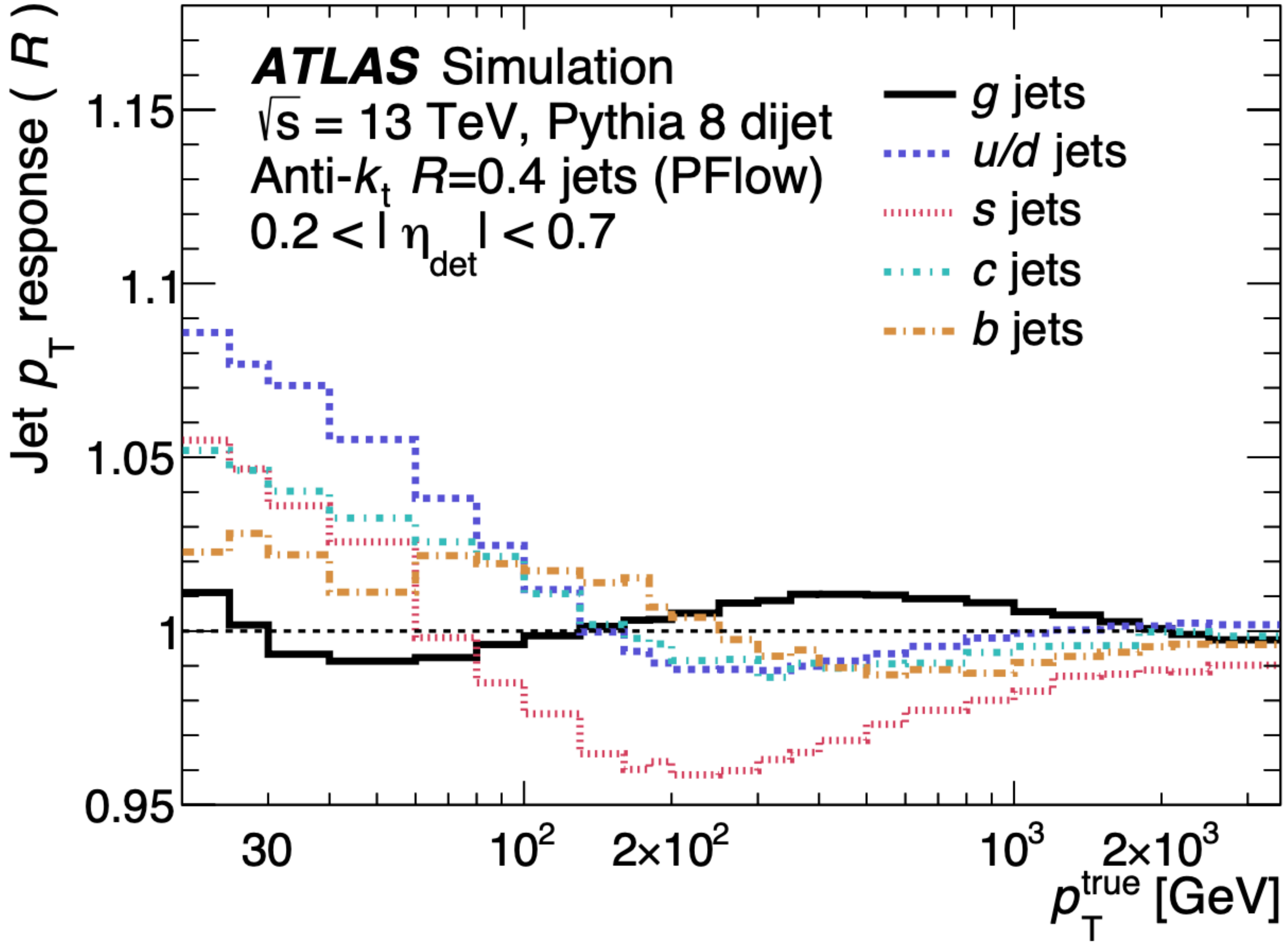
jet calibration

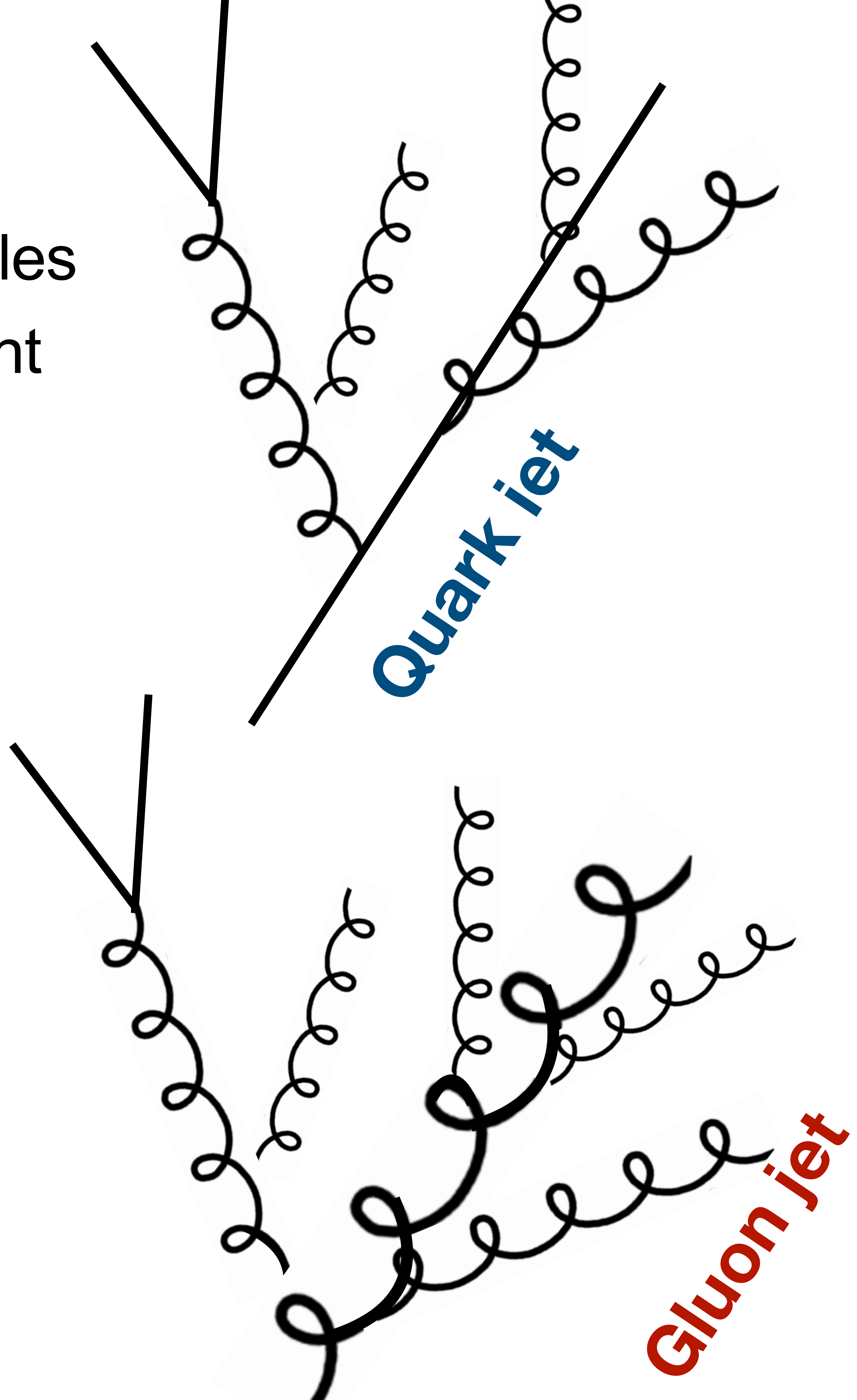
- Reconstructed jet energy differs from the energy of the truth jet
  - Pileup adds energy to the jet
  - Multiple detector components with different behaviors
  - **Detector response changes with *energy* of particle and *type of hadron***
    - *And different types of jets produce different particles*
    - *Gluons tend to have a broader shower with more particles*



jet calibrations

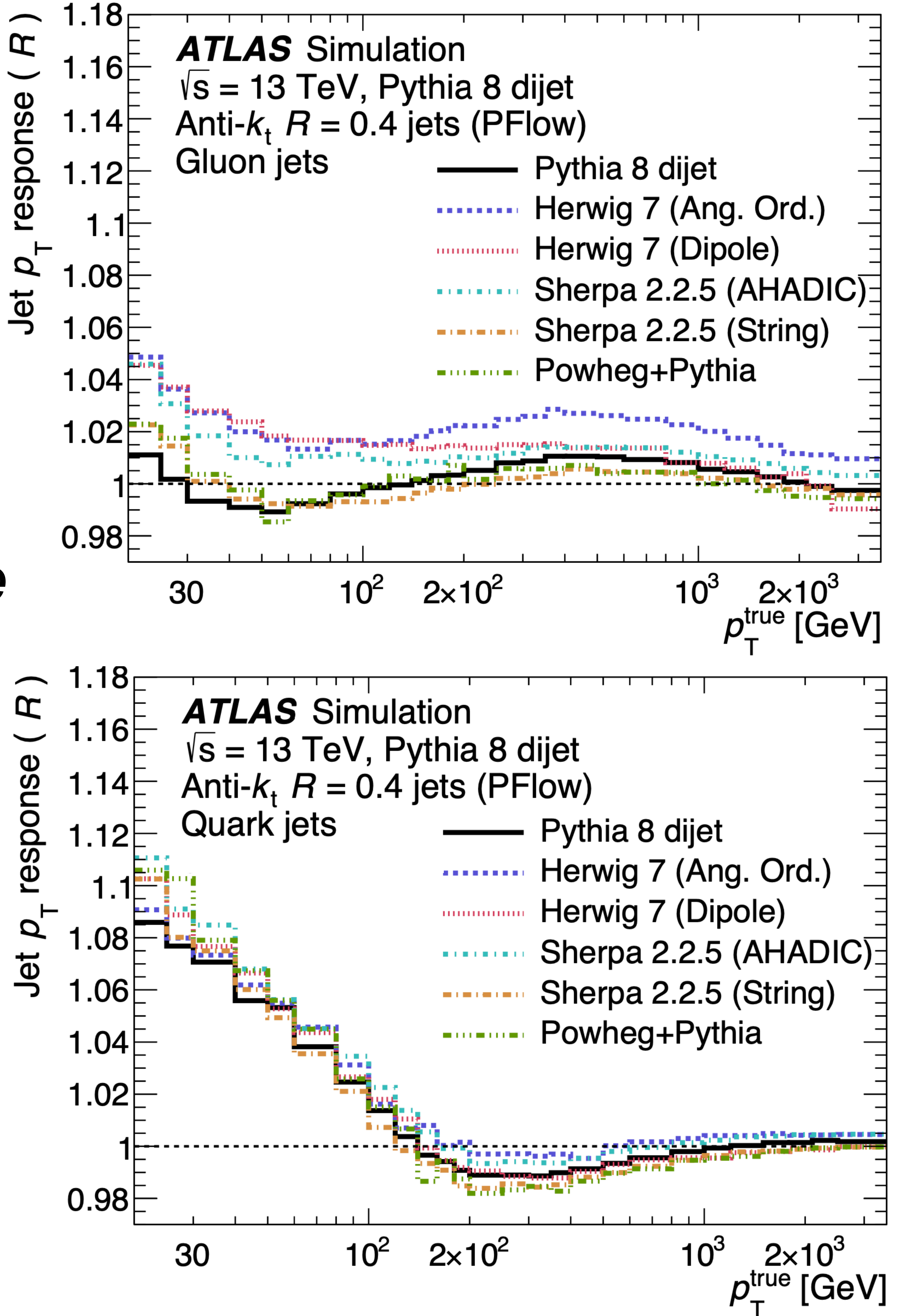
- Quarks and gluons have different distributions of particles
  - Gluon jets have more, and lower-p_T particles, different types of hadrons that tend to be produced
  - Different response for different jet *flavors*





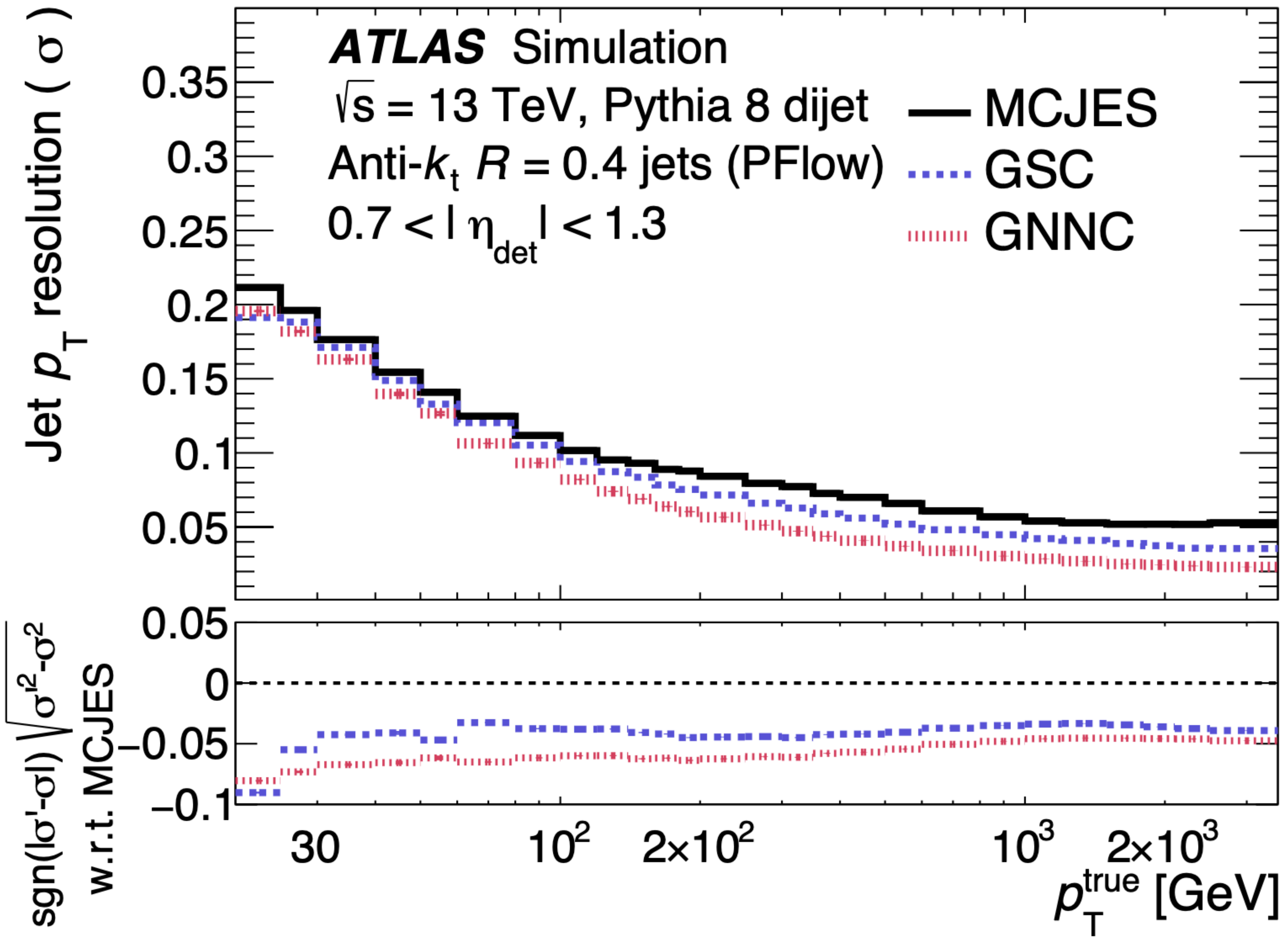
jet modeling

- Jet energy scale differs among Monte Carlo predictions
  - *Different hadrons, different distributions of particles, etc. → different detector response*
- More variation for gluon jets than quark jets
  - *Especially among Monte Carlo predictions*
- Challenging to produce a jet calibration that works universally



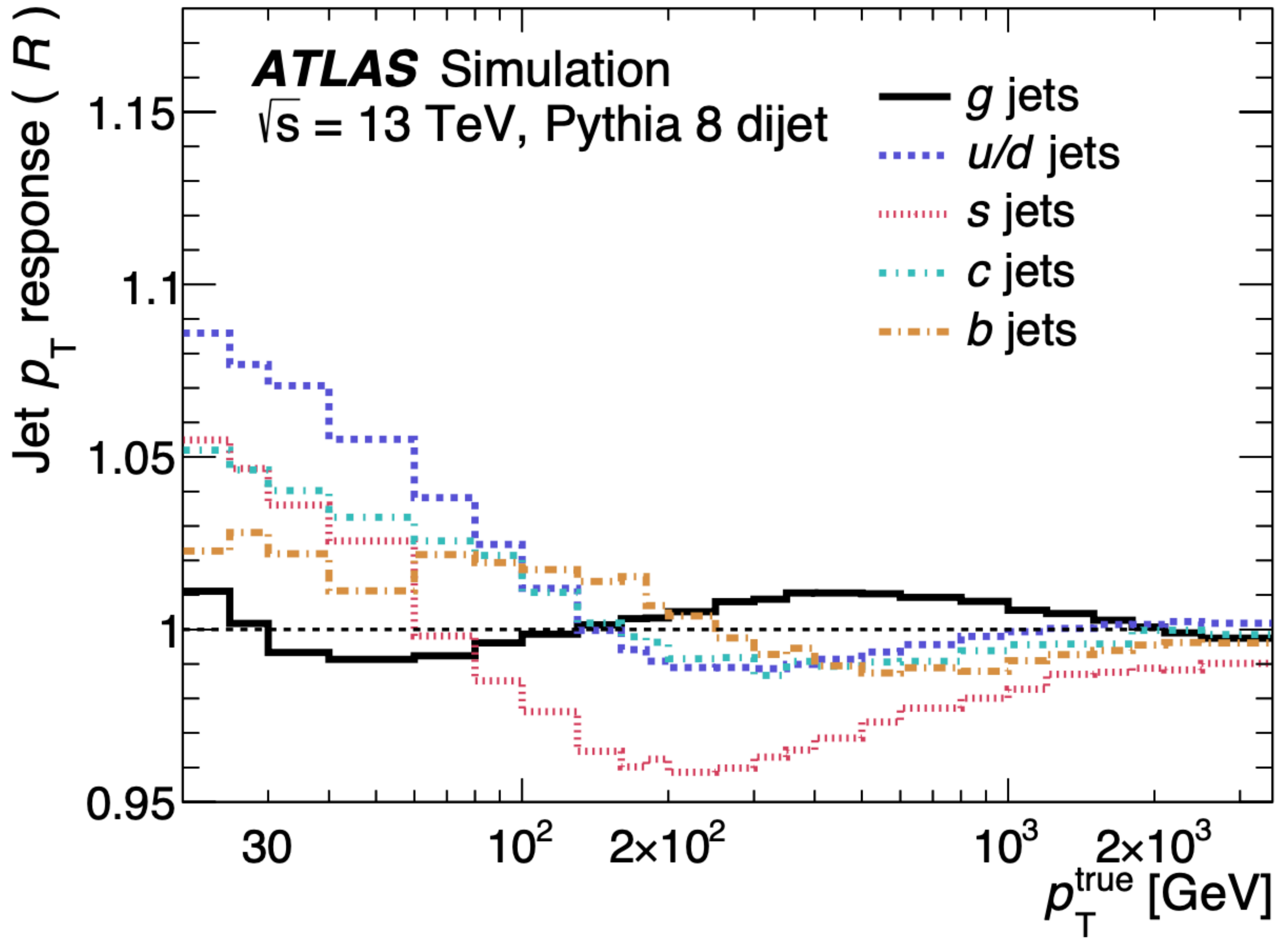
jet calibrations

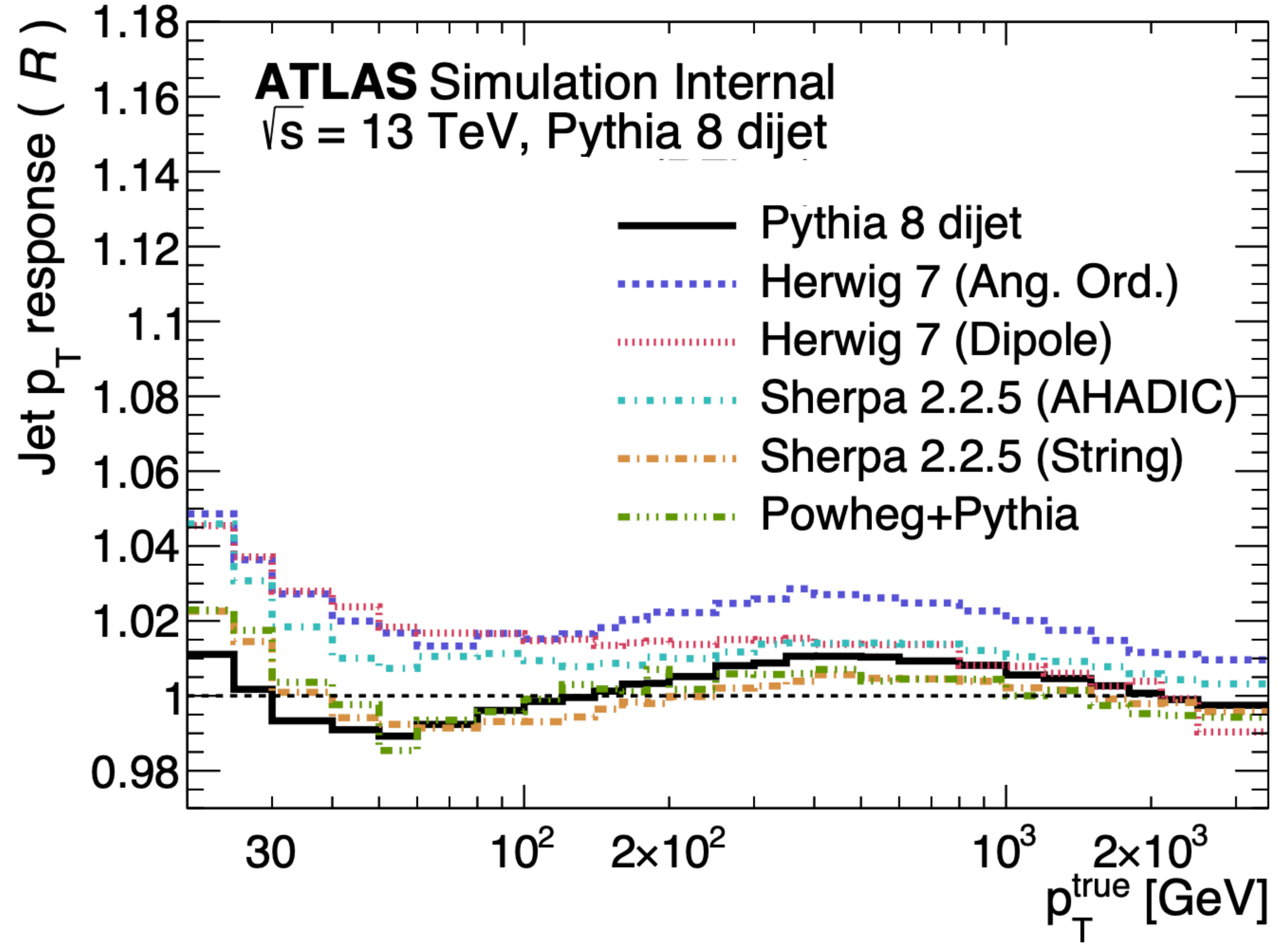
- Can use machine learning to derive a correction based on various jet properties
  - Can include any number of inputs
  - *Potential to replace full Monte Carlo calibration with a single step!*
- Up to 10% improvement in jet energy resolution!



jet calibrations

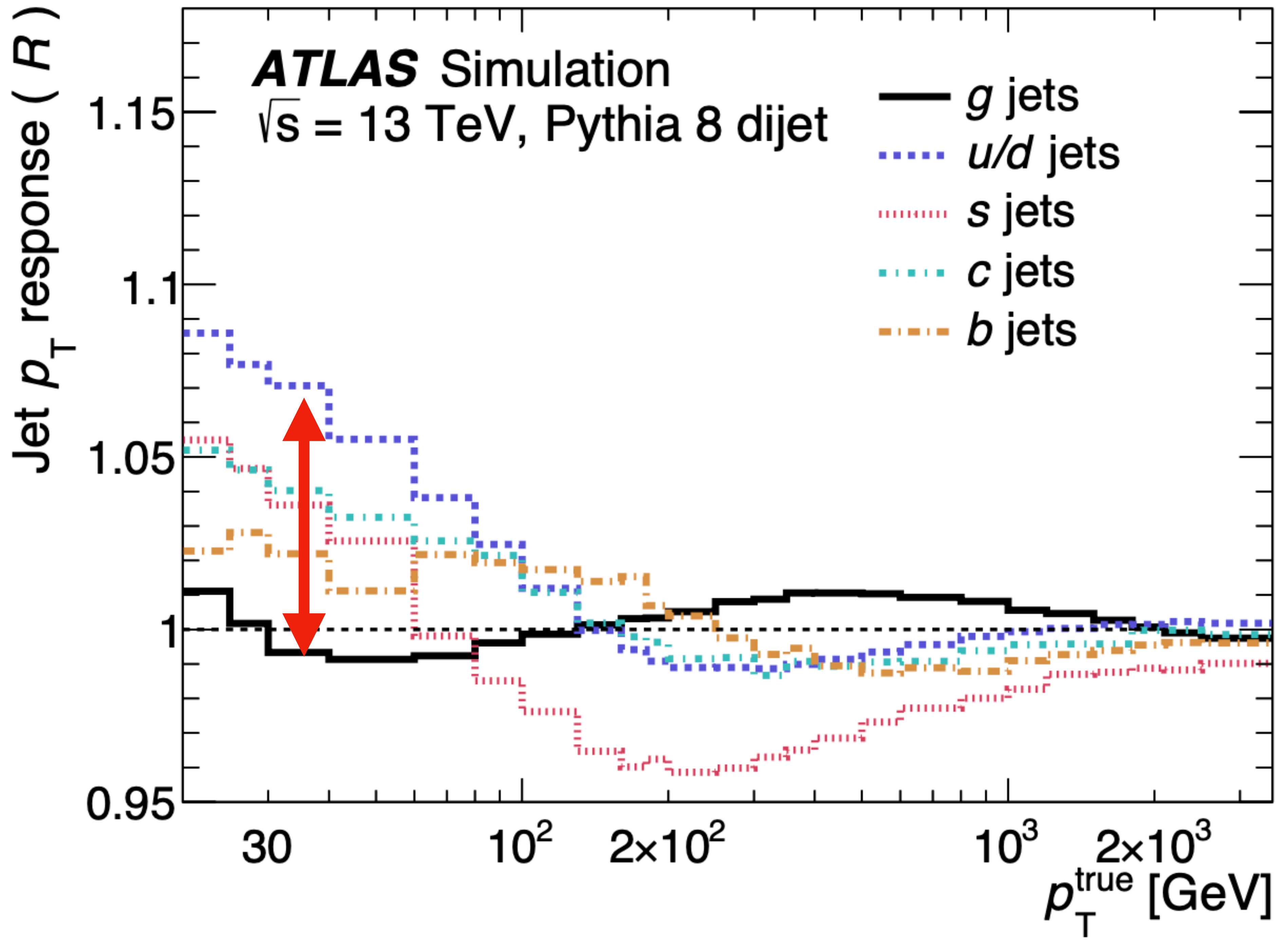
- Two different uncertainties on jet modeling:
  - *Does the jet calibration apply if you have jets of different flavors?*
    -
  - *How uncertain are we of the predictions used to derive the calibrations?*
    -

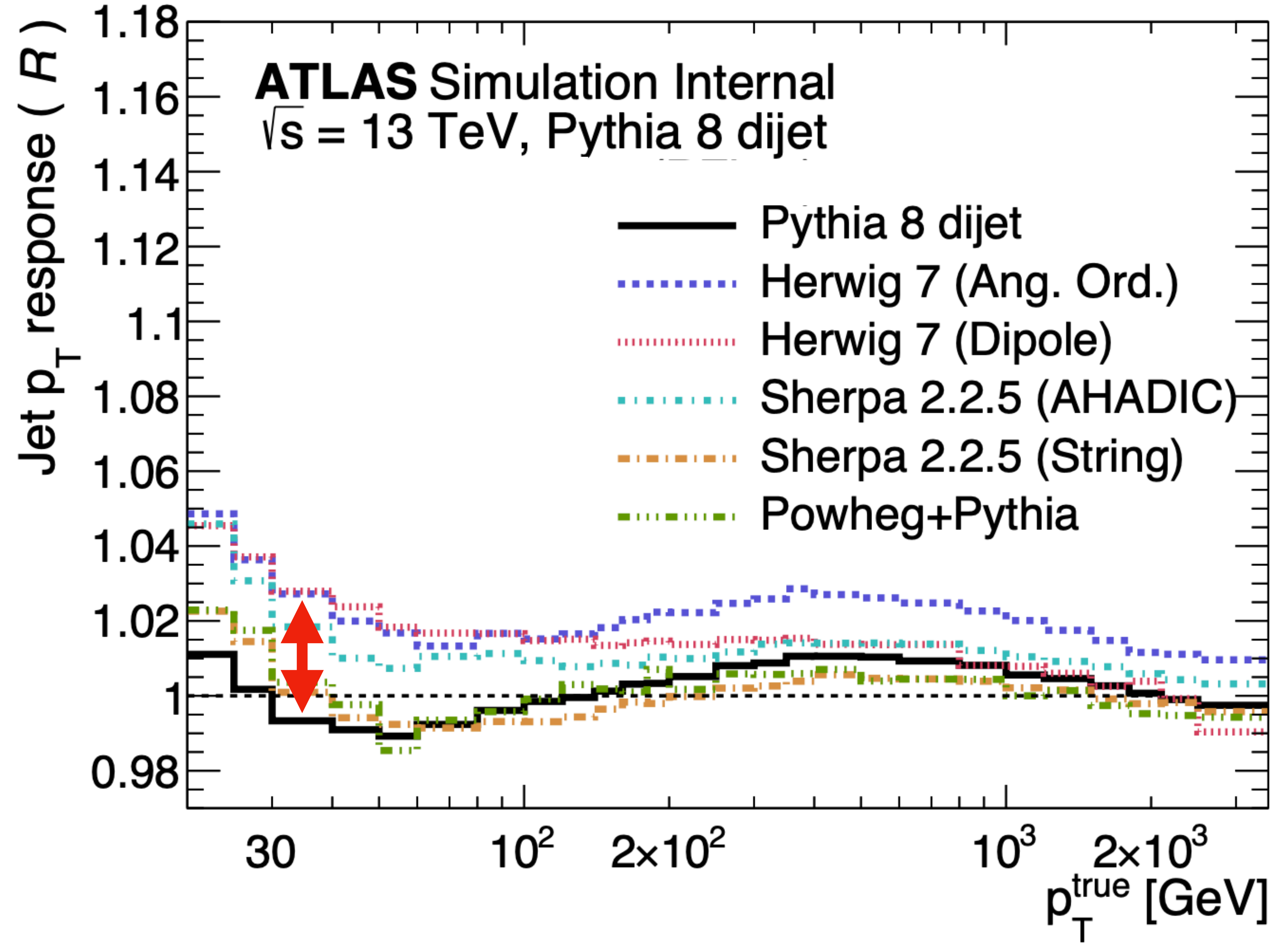




jet calibrations

- Two different uncertainties on jet modeling:
  - *Does the jet calibration apply if you have jets of different flavors?*
    - Two-point difference between quark and gluon jet response
  - *How uncertain are we of the predictions used to derive the calibrations?*
    - Two-point difference between different MC predictions





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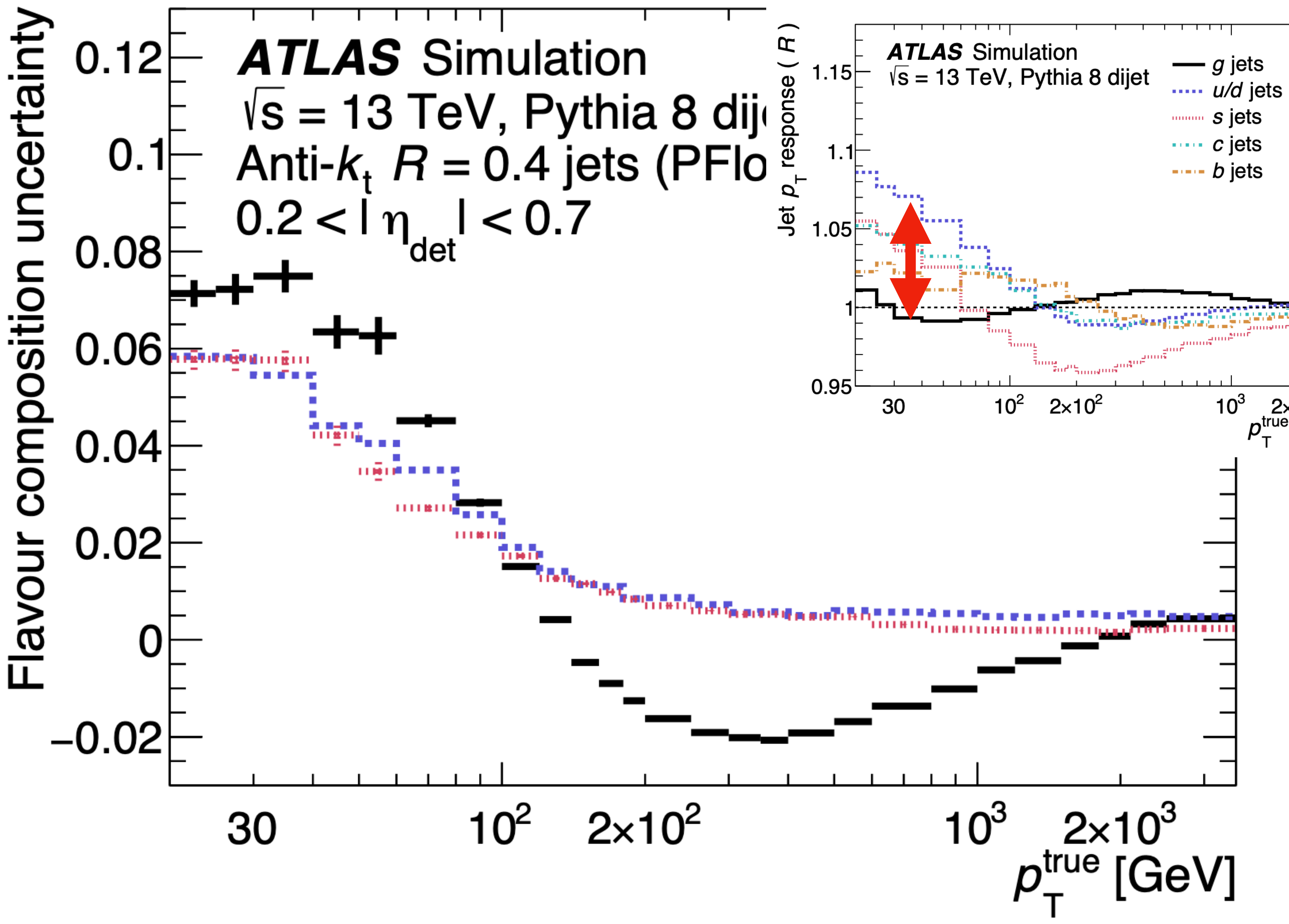
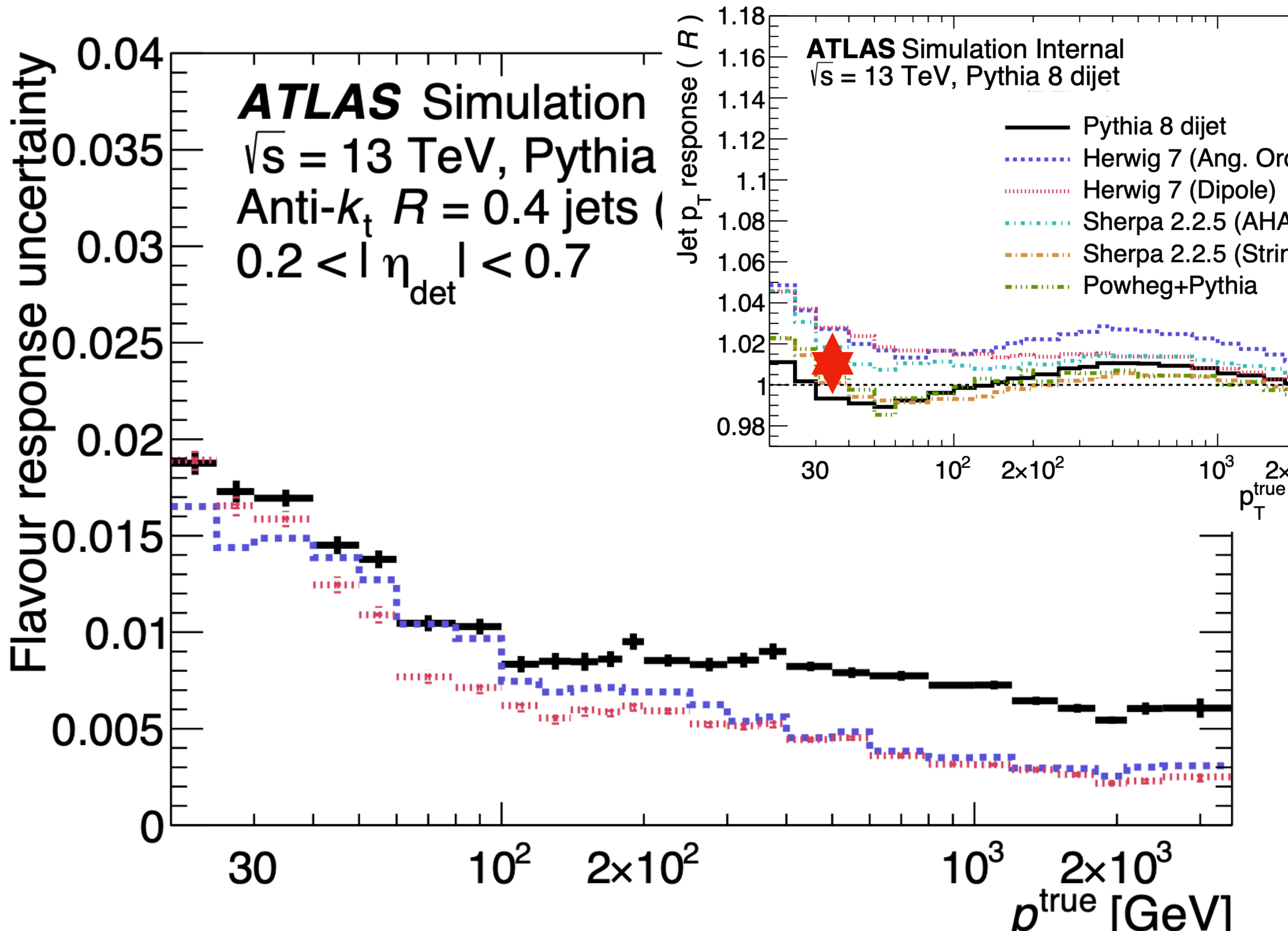
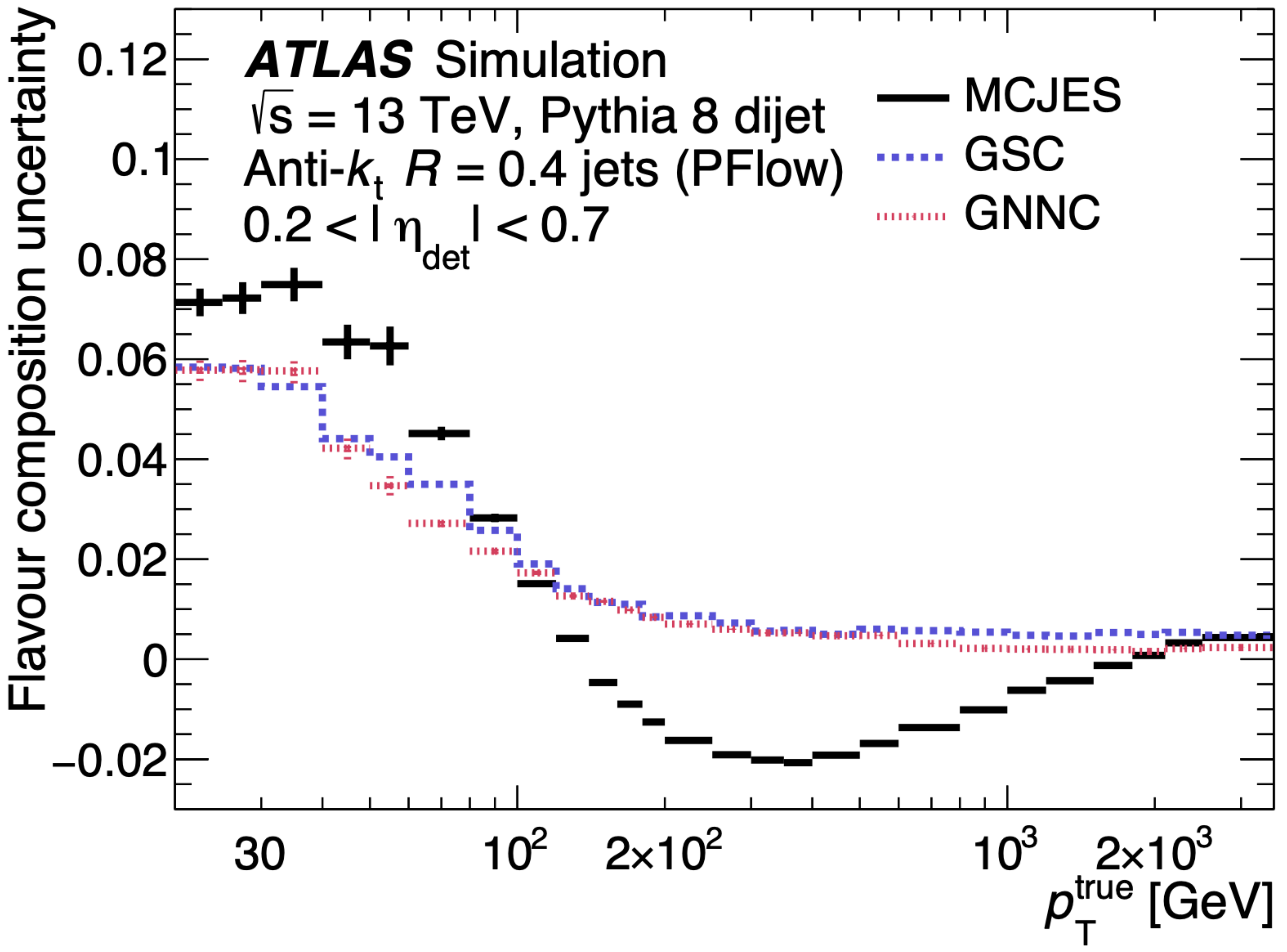
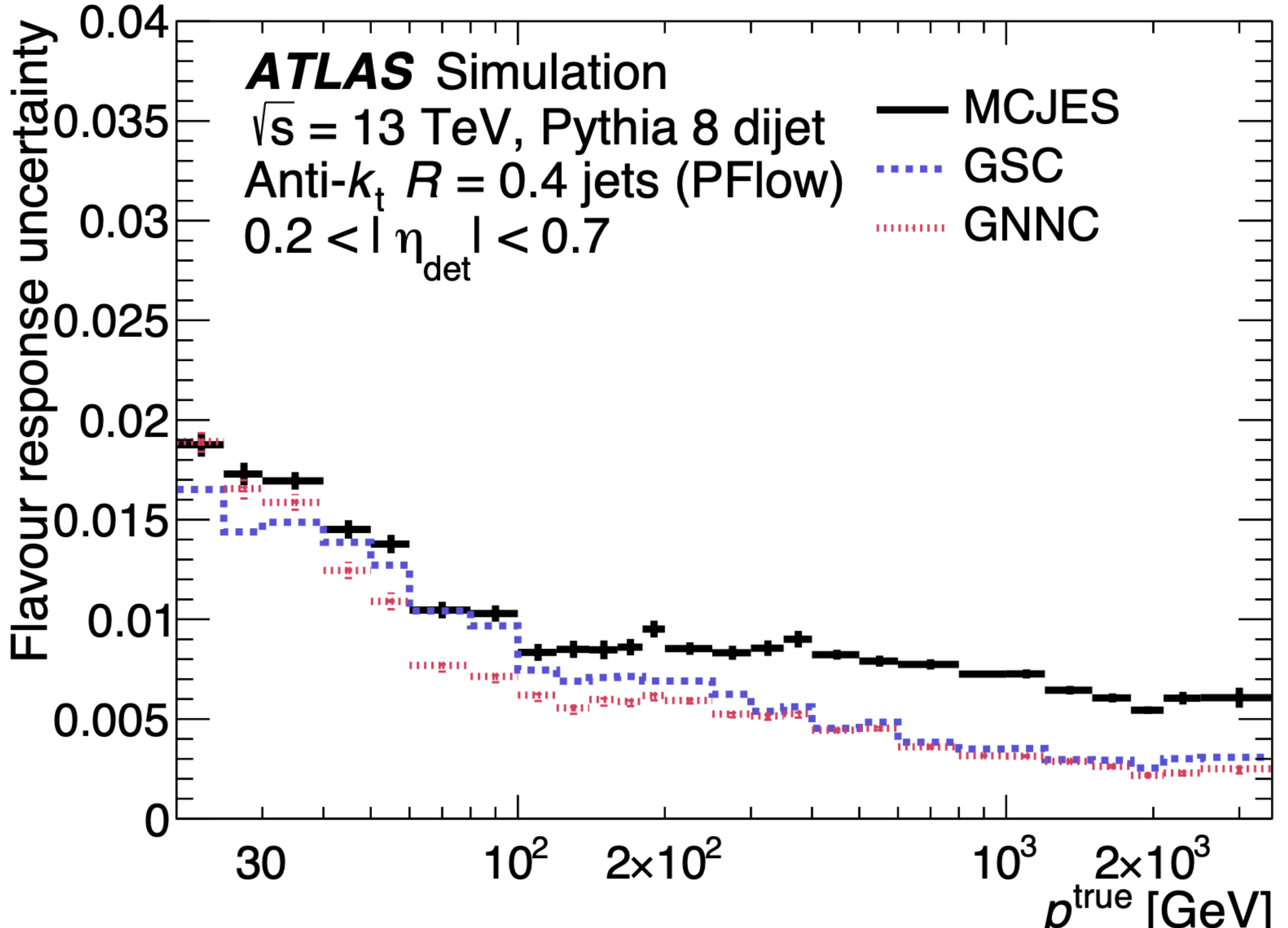




jet calibrations

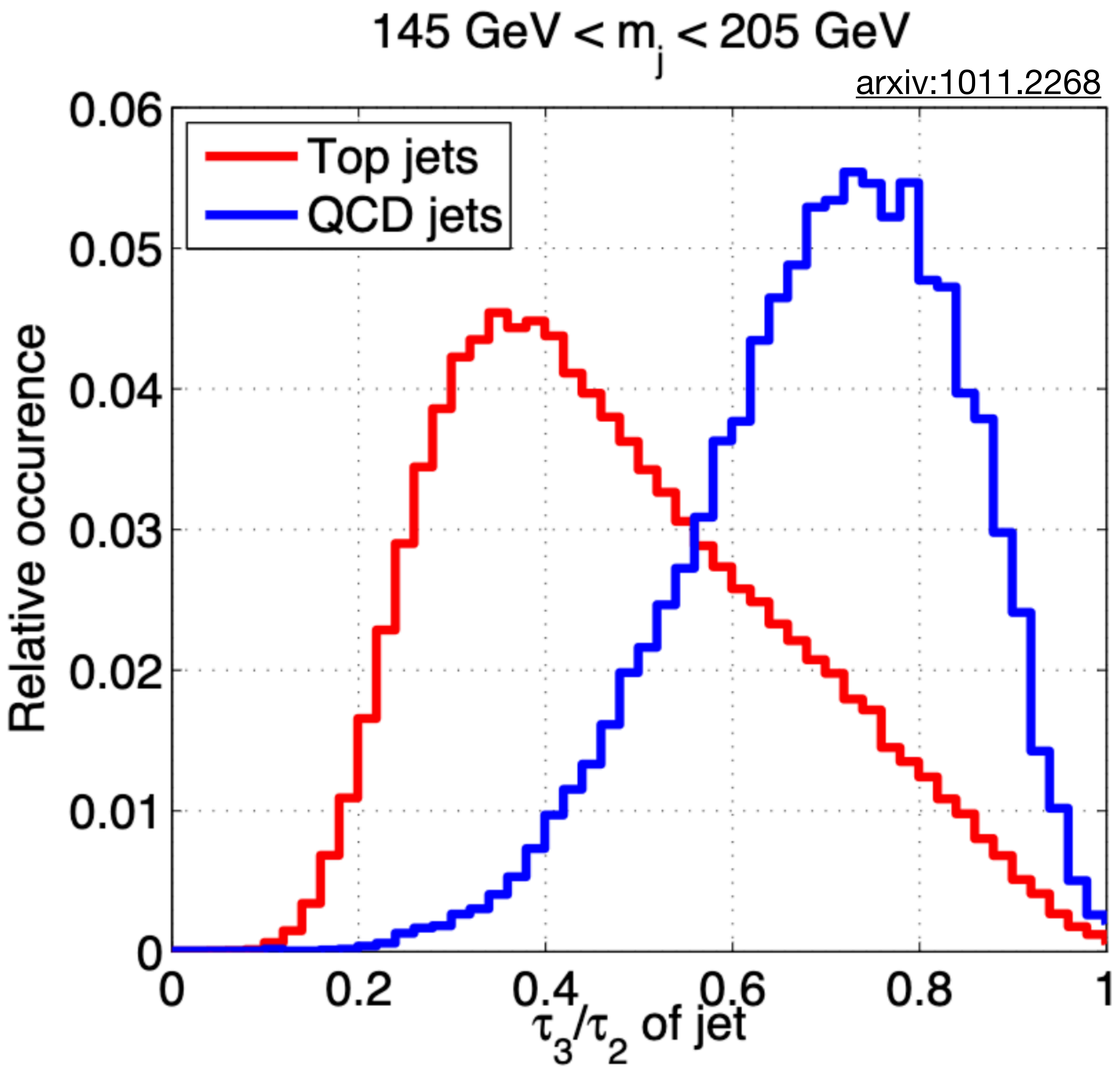
- Two different uncertainties on jet modeling:
  - *Does the jet calibration apply if you have jets of different flavors?*
  - *How uncertain are we of the predictions used to derive the calibrations?*
- Corrections based on jet shape significantly reduce these uncertainties
  - Machine-learning calibration brings further reductions to quark-gluon differences
  - Many future improvements, but also relying on our Monte Carlo predictions





n-subjettiness

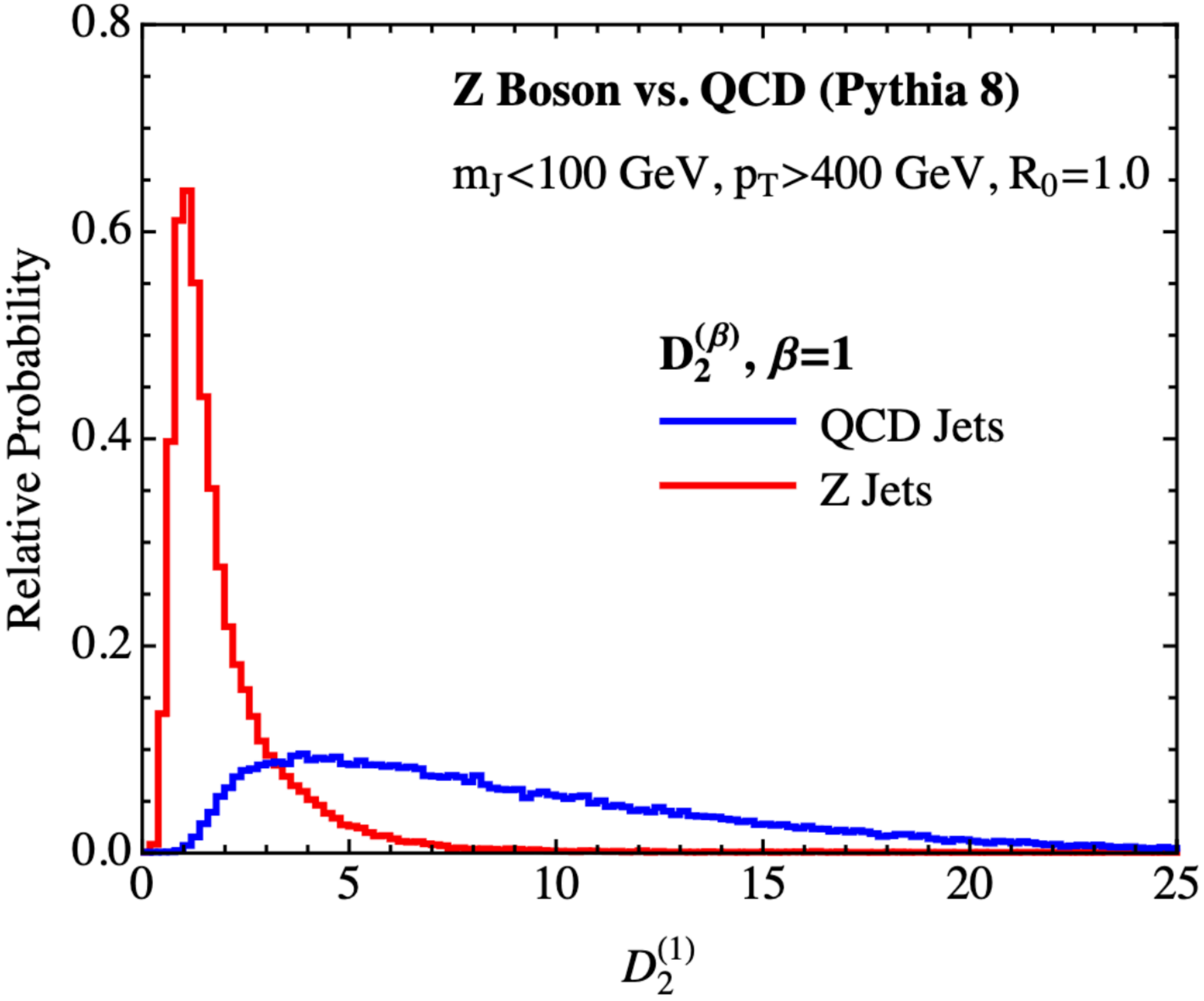
- *i.e.* Does this jet have *N* prongs?
- $$\tau_N = \frac{1}{d0}\sum_k p_{T,k} min(\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k})$$
- Minimized when the jet has exactly *N* collimated prongs
- Top jets tend to have 3-prongs, while q/g jets tend to have 1
- Ratios of N-subjettiness produces better separation, since quark/gluon jets can have large values of τ_3
  - Many taggers use τ_{32} as an input to tagging tops
- Many ways to define the prongs of a jet
  - Several possible algorithms, details not relevant here
  - *See arxiv:1011.2268 for more details*
- *See the notebook (part 1) for plotting this $\tau_{32} = \tau_3 / \tau_2$ with our dataset*



energy correlation functions (ecfs)

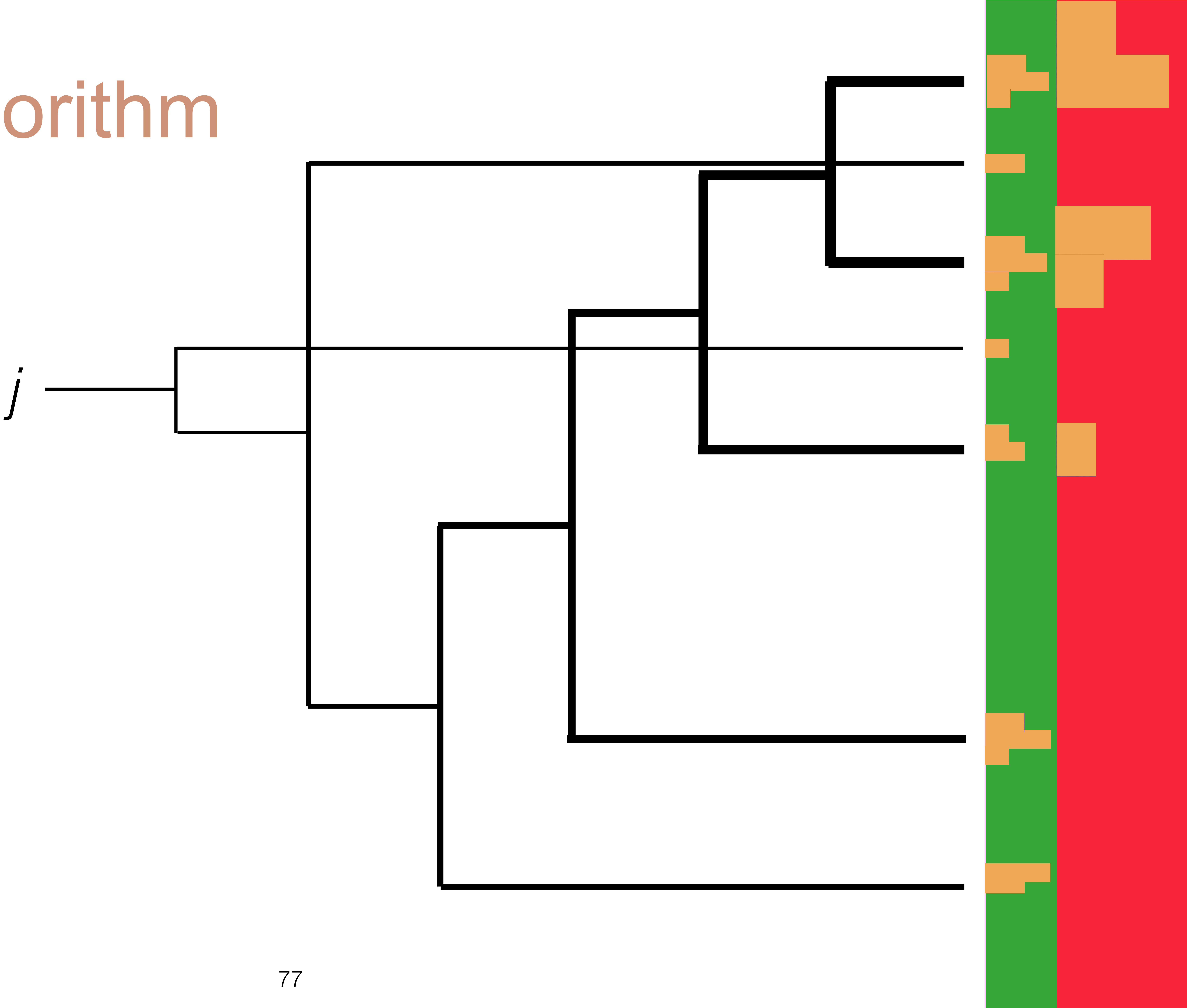
arxiv:1409.6298

- ECFs are products of energies and angles of jet constituents, often used for taggers
- $$ECF(N,\beta) = \sum_{i_1<i_2<\ldots<i_N\in J} \left(\prod_{a=1}^{N} p_{T,i_a} \right) \left(\prod_{b=1}^{N-1} \prod_{c=b+1}^{N} (R_{i_b,i_c})^\beta \right)$$
- Complicated formula, so consider the case of β=2
  - $$ECF(2,\beta) = \sum_{i<j\in J} p_{T,i}p_{T,j}(R_{ij})^\beta$$
  - Value increases for larger constituent p_T or large angle between constituents
    - 1-prong jets have small values, 2-prong jets have large values
- Ratios of correlations can improve performance
- *See the notebook (part 1) for plotting ECFs in our dataset*



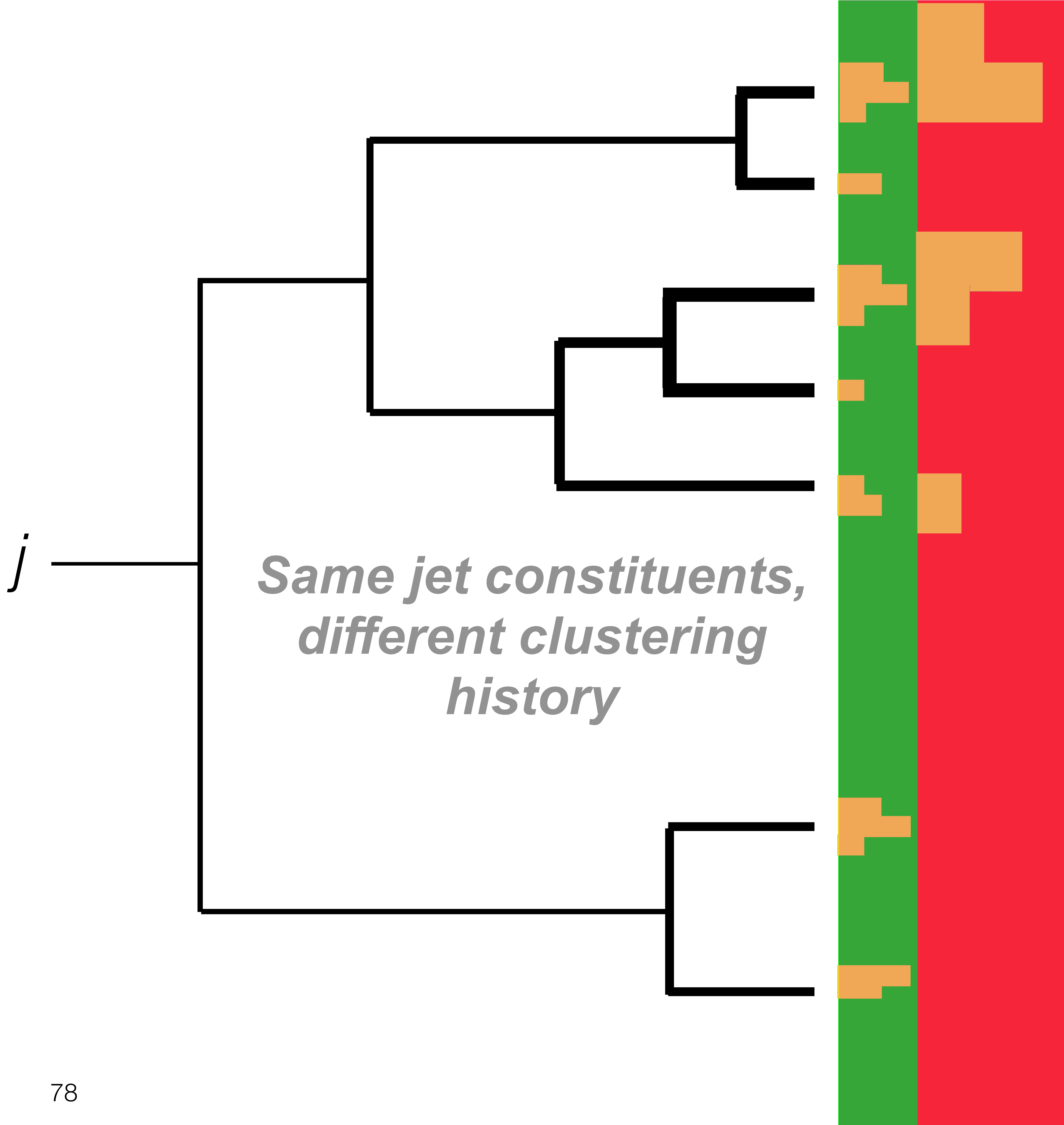
the soft drop algorithm

- Run jet finding using the **anti-k_t algorithm**



the soft drop algorithm

- Recluster its constituents with the Cambridge/Aachen algorithm to get an **angular-ordered shower history**



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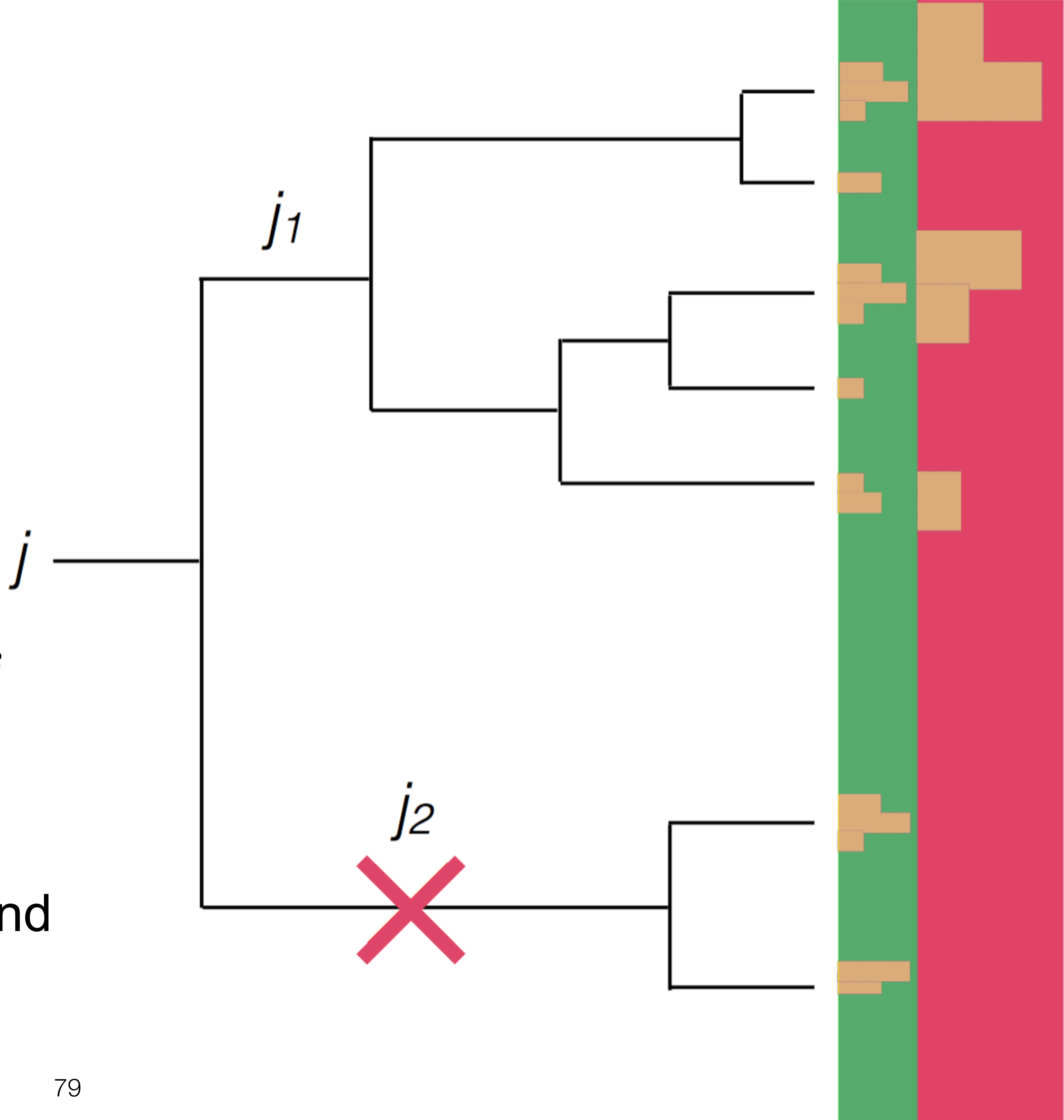
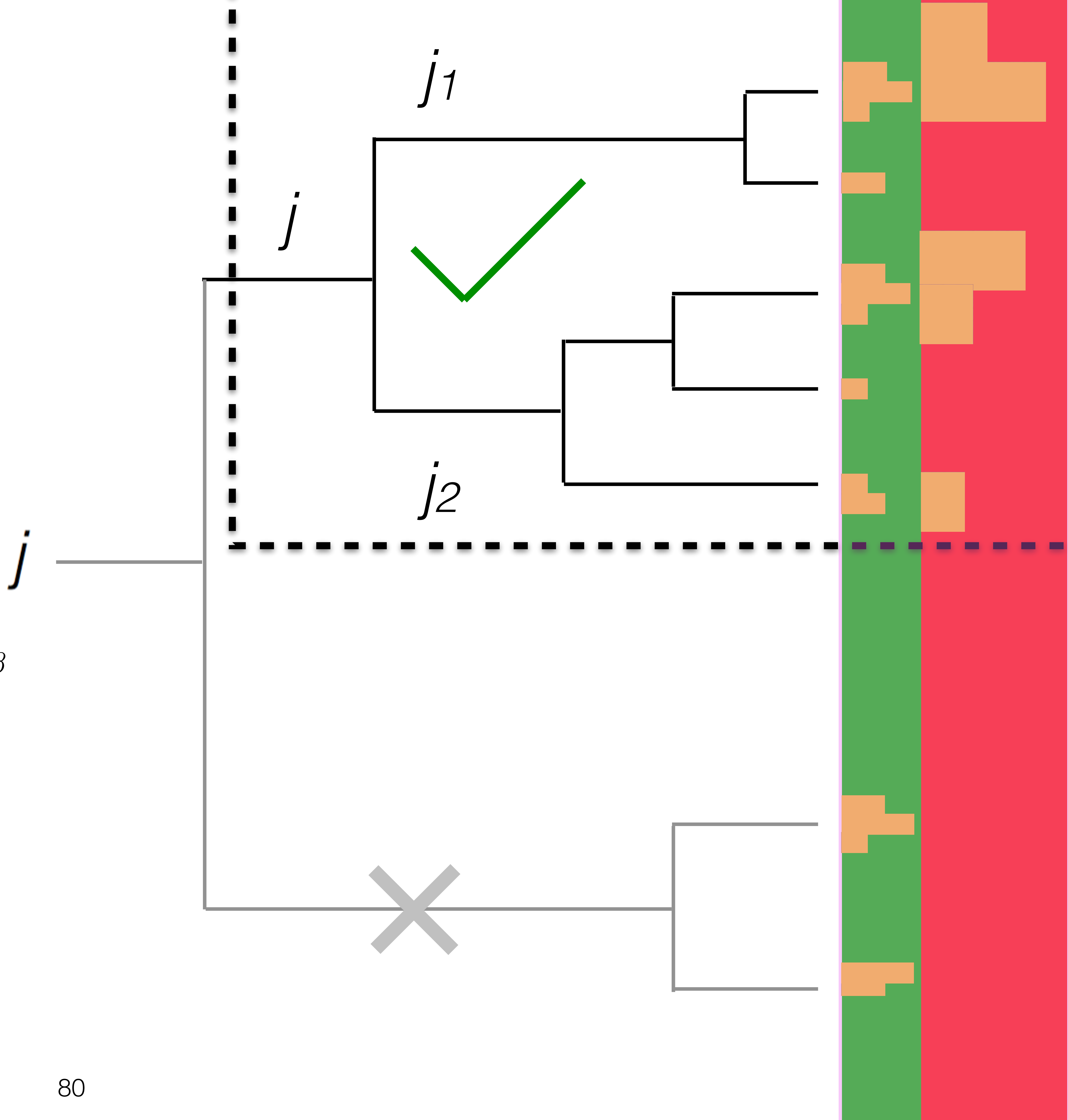


- Check if $\frac{min(p_{T,j1}, p_{T,j2})}{(p_{T,j1} + p_{T,j2})} > z_{cut}(\frac{\Delta R_{j1,j2}}{R})^{\beta}$
  - If not, drop the softer branch (*j2*), and repeat with the harder branch (*j1*)

the soft drop algorithm



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  - If so, stop grooming, and the jet is defined

the soft drop algorithm

- This gives us (approximate) access to the original parton and its splitting!