Boosting Beyond:

BOOST-related developments for the HL-LHC, FCC, and SPPC

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on behalf of the ATLAS and CMS collaborations

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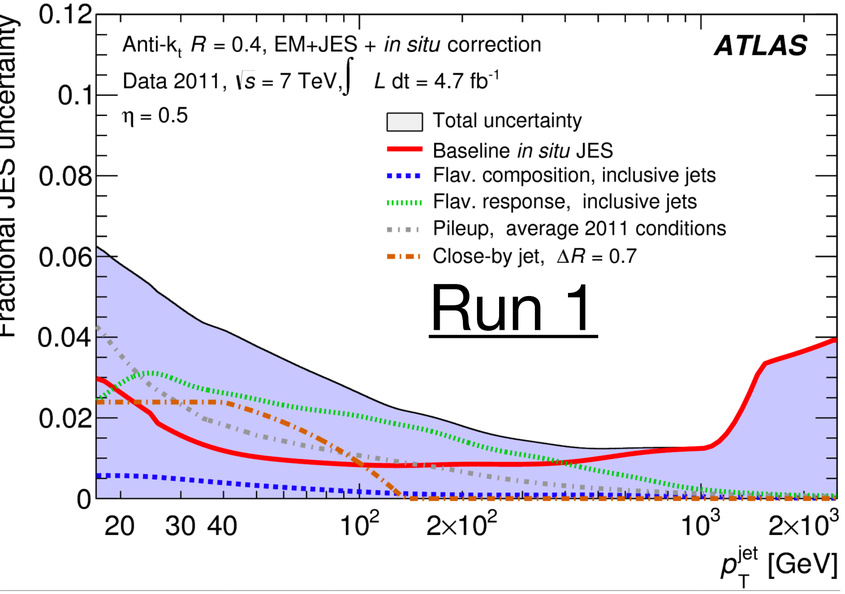
BOOST

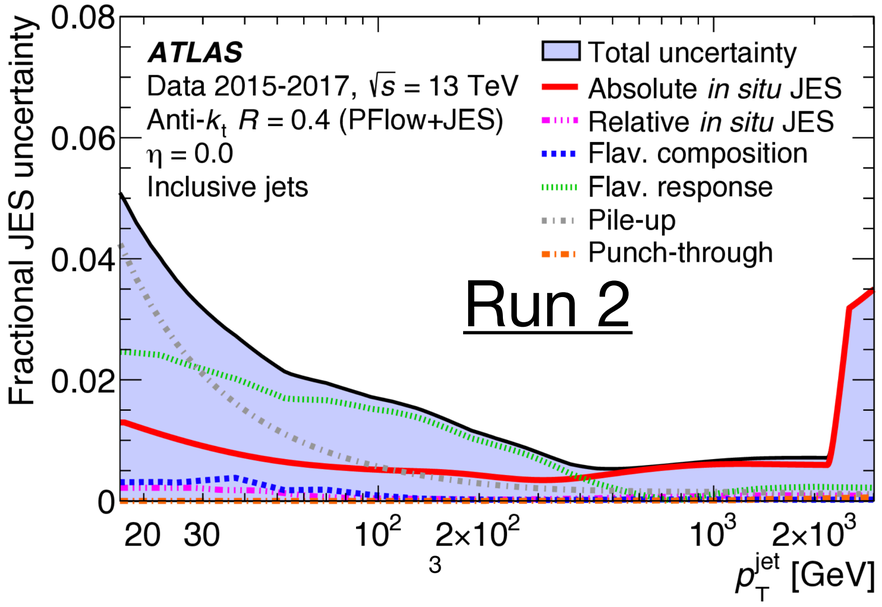
The HL-LHC: Quick Summary

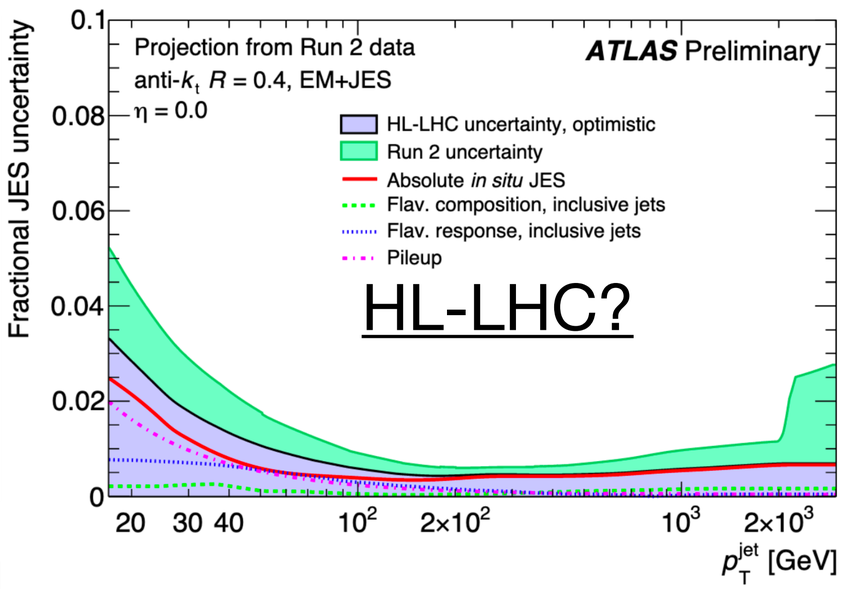
- Large dataset of HL-LHC will open up possibilities, particularly for precision measurements
  - Expect to get around 3000 fb^{-1} of data over the span of ~a decade, with similar center-of-mass energy as Run-3
  - Comes with a number of challenges, with increased pileup, and detectors which need to survive massive amounts of radiation
- Physics prospects for the HL-LHC published in the 2019 Yellow Report
  - Wide range of goals, ranging from precision measurements, to novel searches

Jet Reconstruction Algorithms

- Jets are fundamental to most searches and measurements done at hadron colliders
- Jet reconstruction is inherently tied to our understanding of QCD
  - Some improvements since Run-1, even with higher pileup conditions
  - But we also hope for significant reductions to our uncertainties for the HL-LHC

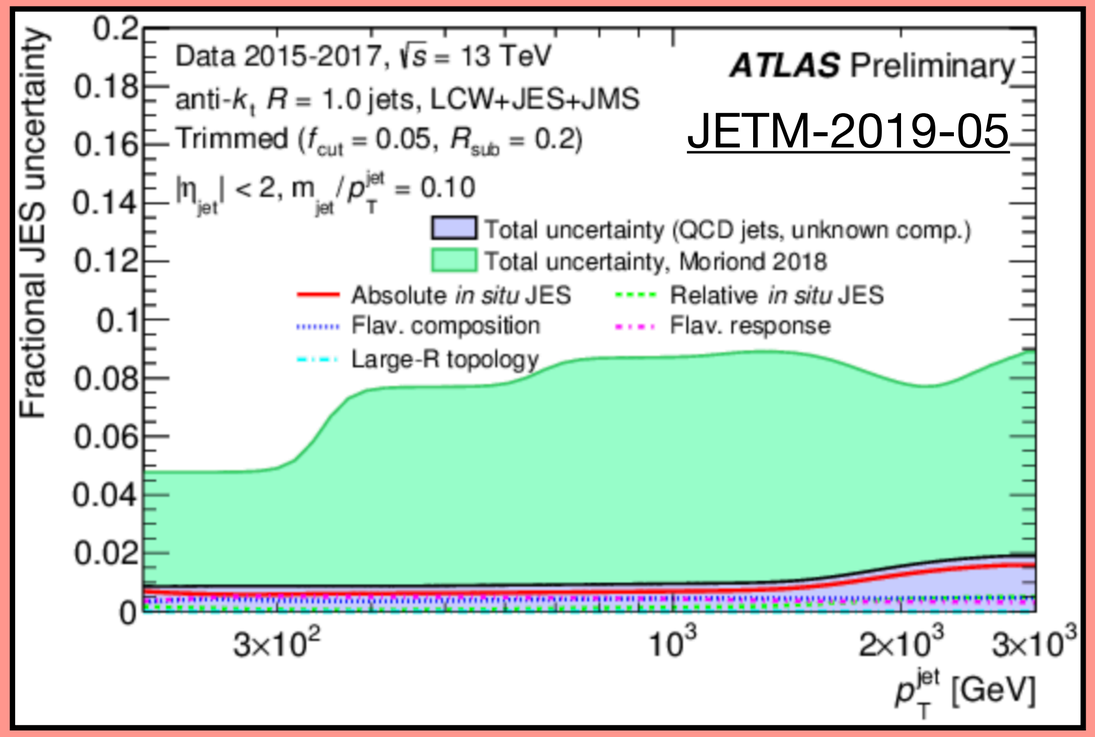


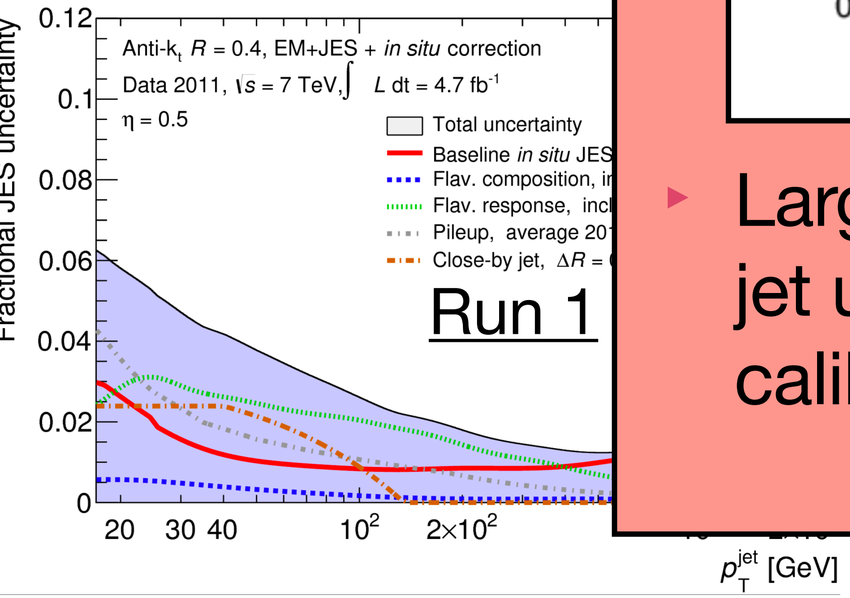


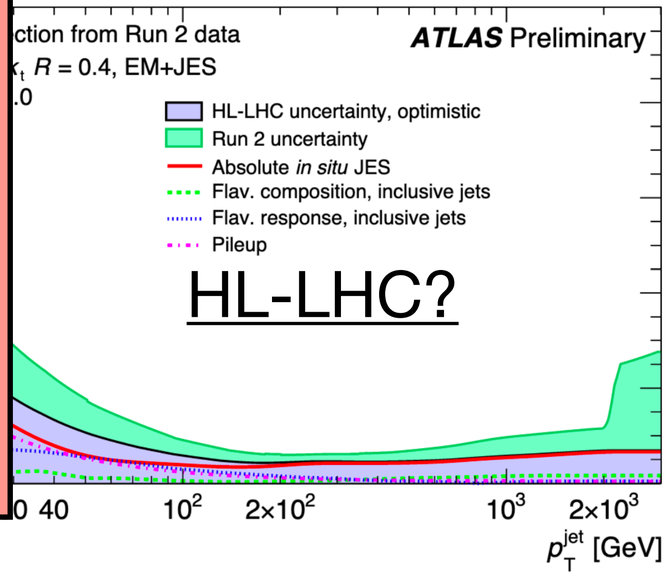


Jet Reconstruction Algorithms

- Jets are funda ents done at hadron collide
- Jet reconstruc ng of QCD
  - Some impro ileup conditions
  - But we also certainties for the HL-LHC



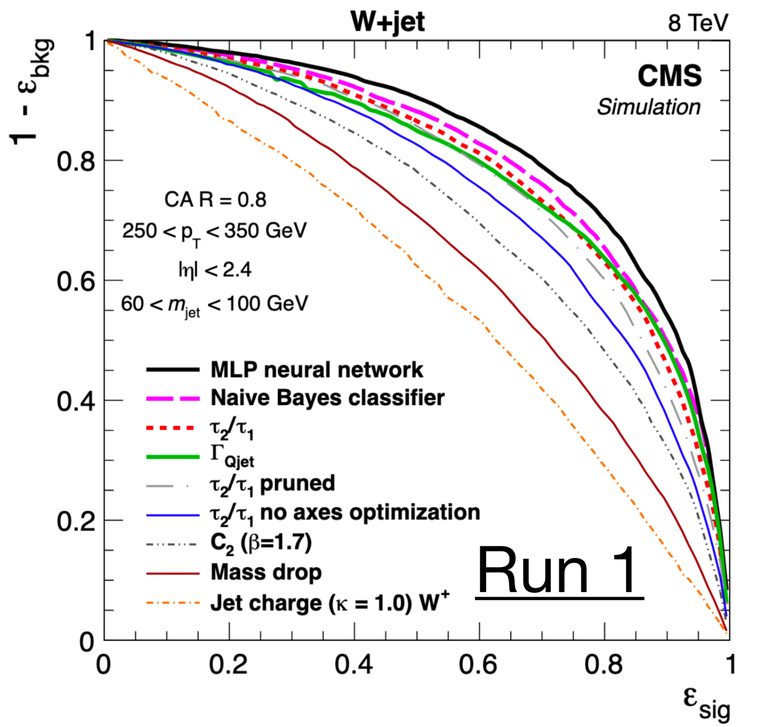


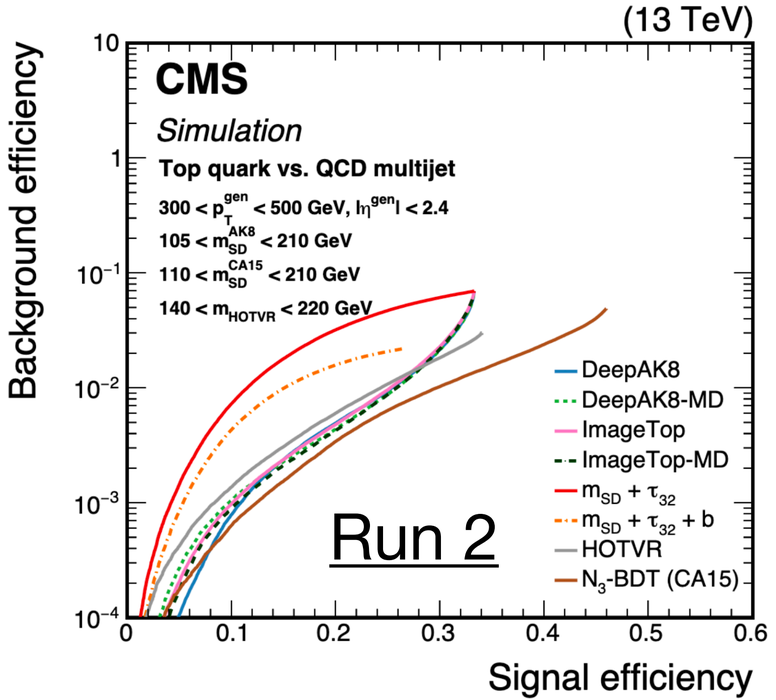


- Large improvements in our large-R jet uncertainties through *in-situ* calibrations

Jet Reconstruction Algorithms

- Jet tagging has provided access to a broad range of physics topics
  - W-tagging *(Diboson searches, Electroweak measurements, …)*
  - Top tagging *(All-hadronic ttbar searches, …)*
  - Higgs tagging *(H→bb, BSM Higgs searches…)*
  - Quark/gluon tagging *(VBS/VBF measurements, …)*
- Taggers in Run-1 typically relied on just a couple variables
  - Since then, developments in grooming algorithms, substructure variables, and tagging techniques
  - Machine learning tagging algorithms exist using both jet substructure observables, as well as low-level inputs





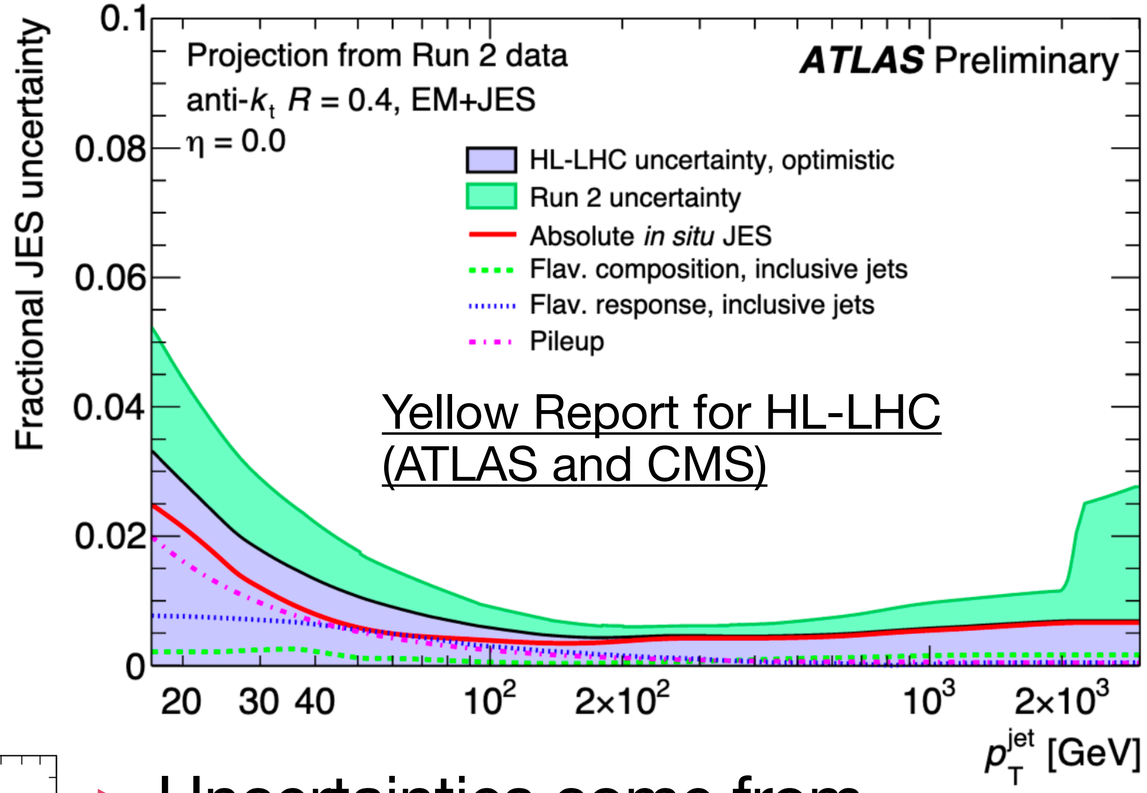
How do we continue to improve our jet reconstruction and jet tagging for the HL-LHC?

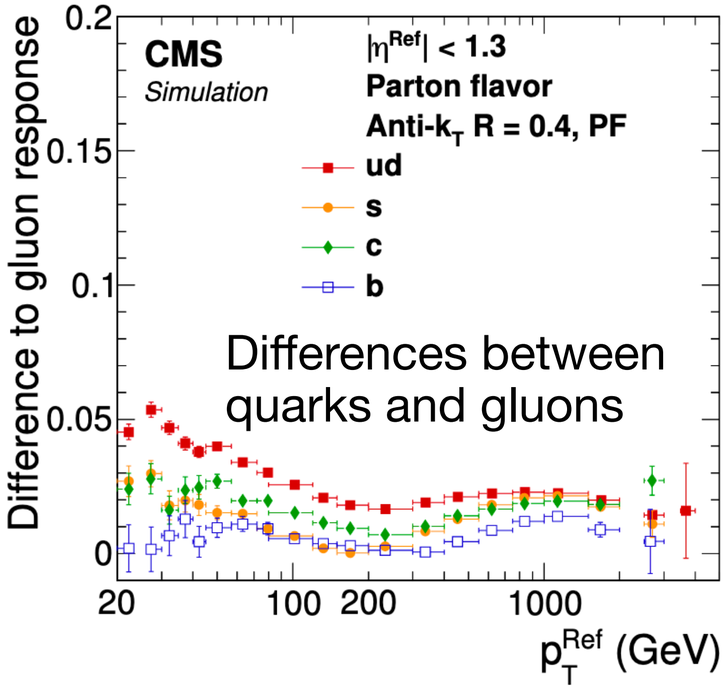
What physics will be enabled by these improvements?

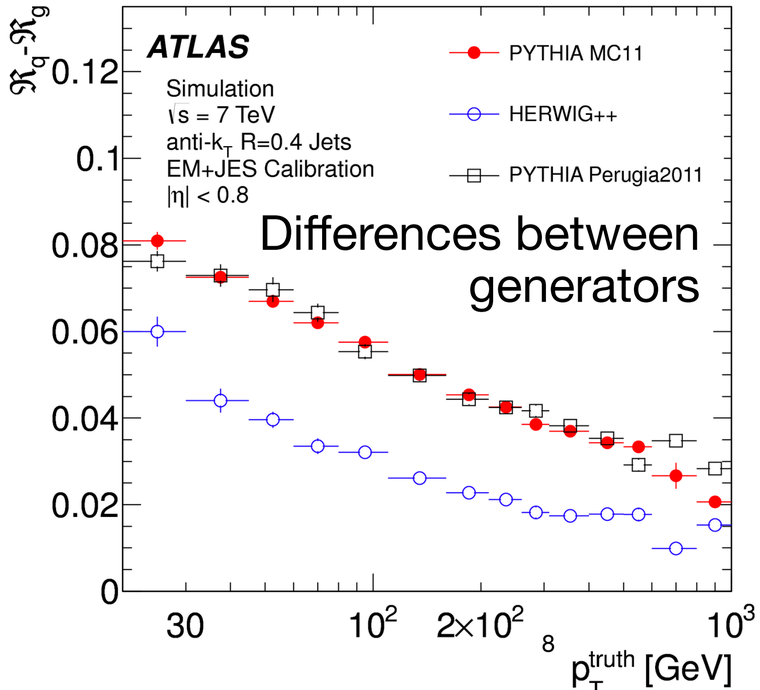
1. Jet modeling

Jet Modeling

- Jet energy scale/resolution uncertainties are a dominant uncertainty for a wide range of analyses
- ATLAS and CMS aim to improve jet modeling uncertainties by a *factor of 2*
  - Modeling uncertainties roughly unchanged since Run-1…







- Uncertainties come from differences between MC predictions, and calibration differences between quarks and gluons
  - Need improved understanding of gluon jets to reduce uncertainties

Jet Modeling

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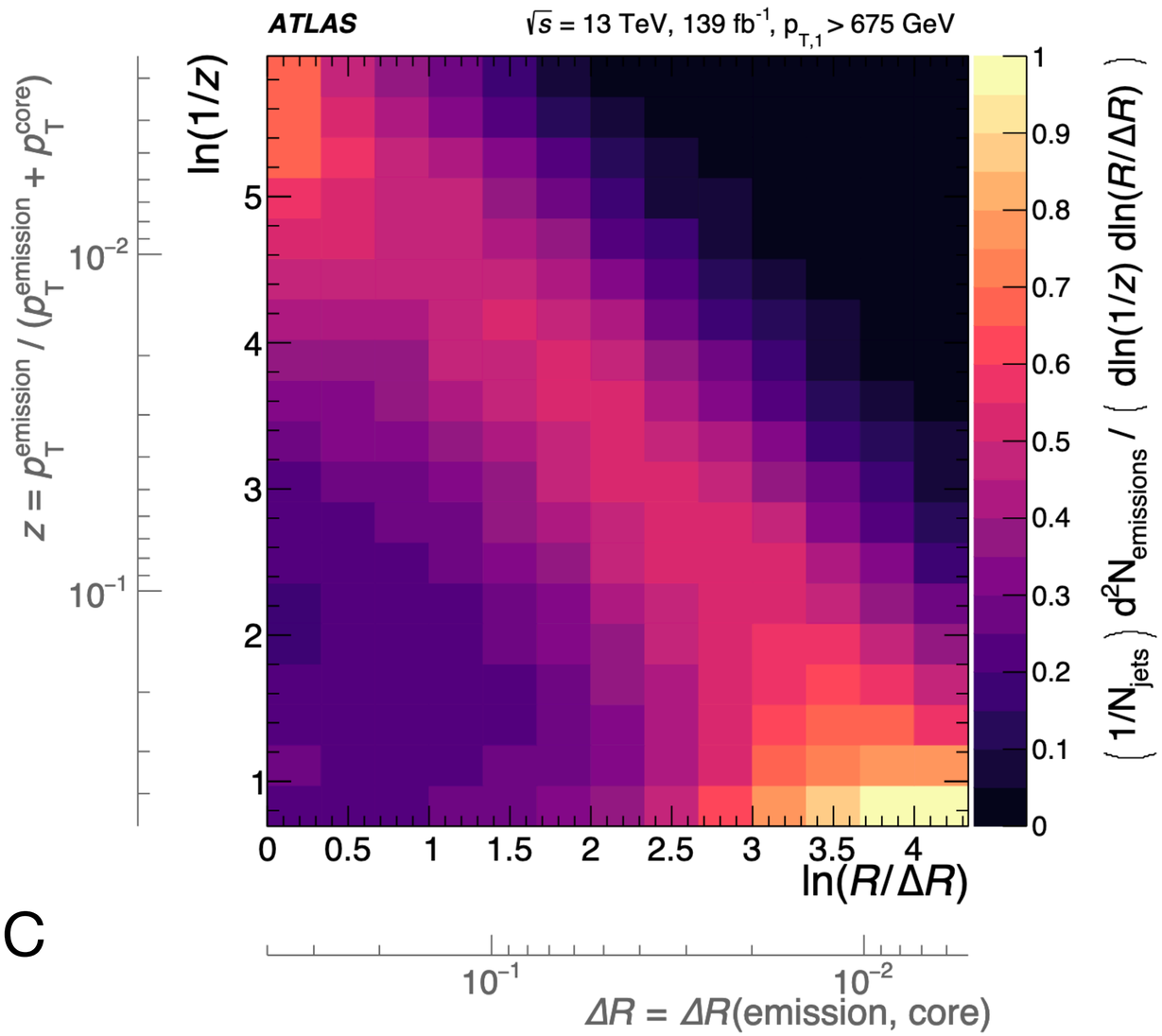
- Precision substructure measurements provide a window into QCD across many scales
  - Access to hard splittings and hadronization in a single measurement!
- Now have precision calculations beyond leading logarithmic accuracy
- Even without theoretical predictions, sensitive to tuning parton showers and hadronization models
- Need to start doing more measurements now to enable improvements for the HL-LHC

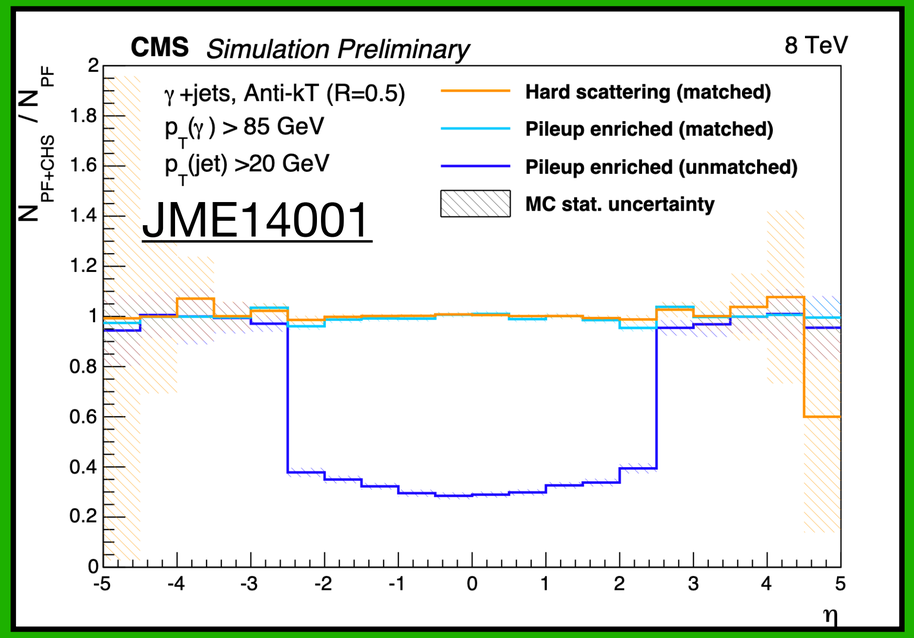


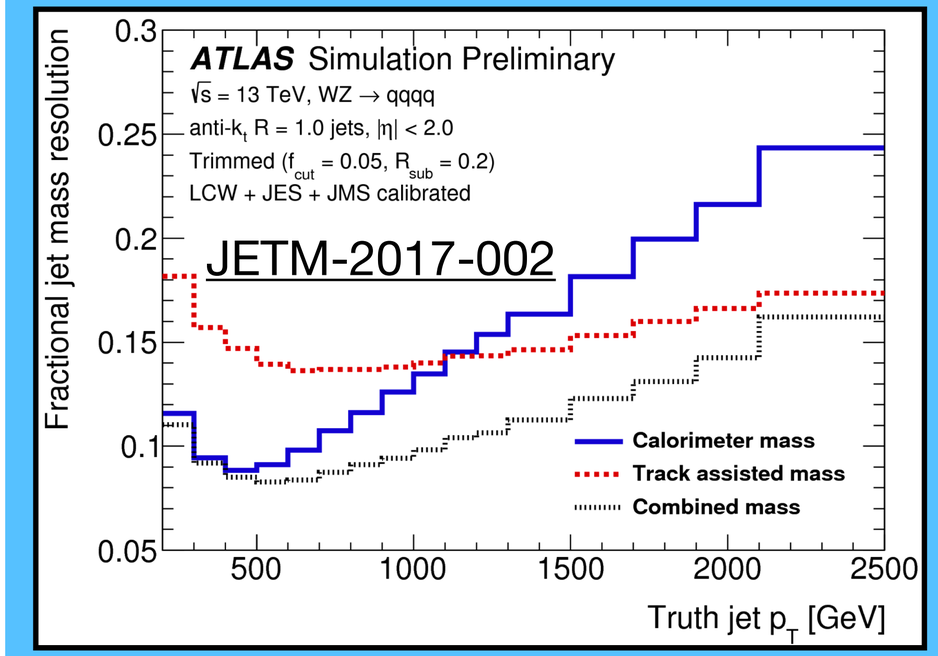
1. Jet modeling

2. Tracking information

Tracking

- Removing charged pileup objects reduces pileup jet rate by up to 80%
  - Further pileup jet reduction by tagging pileup jets

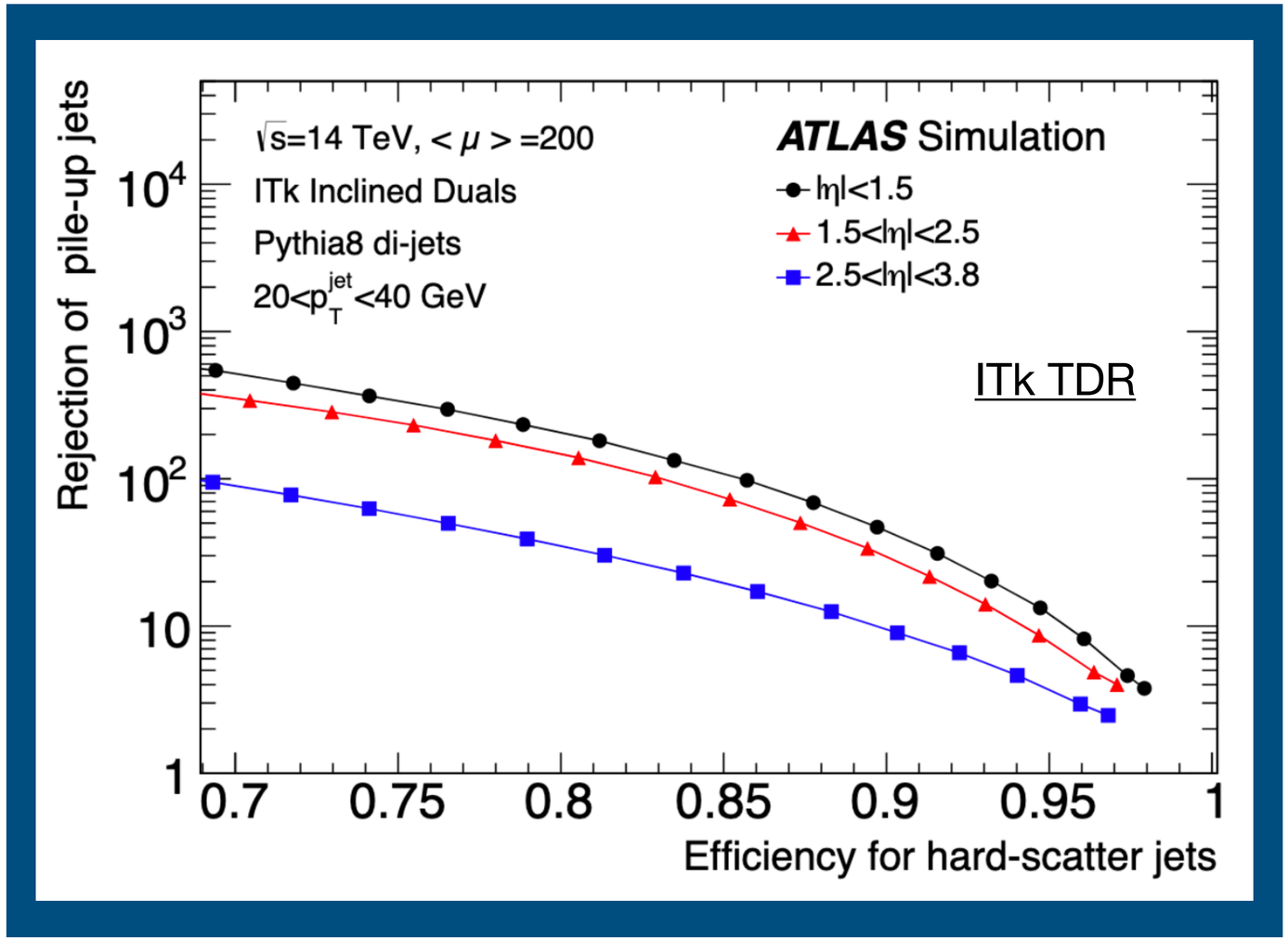




- Combining tracking information with calorimeter information provides better substructure resolution, particularly for high-p_T jets

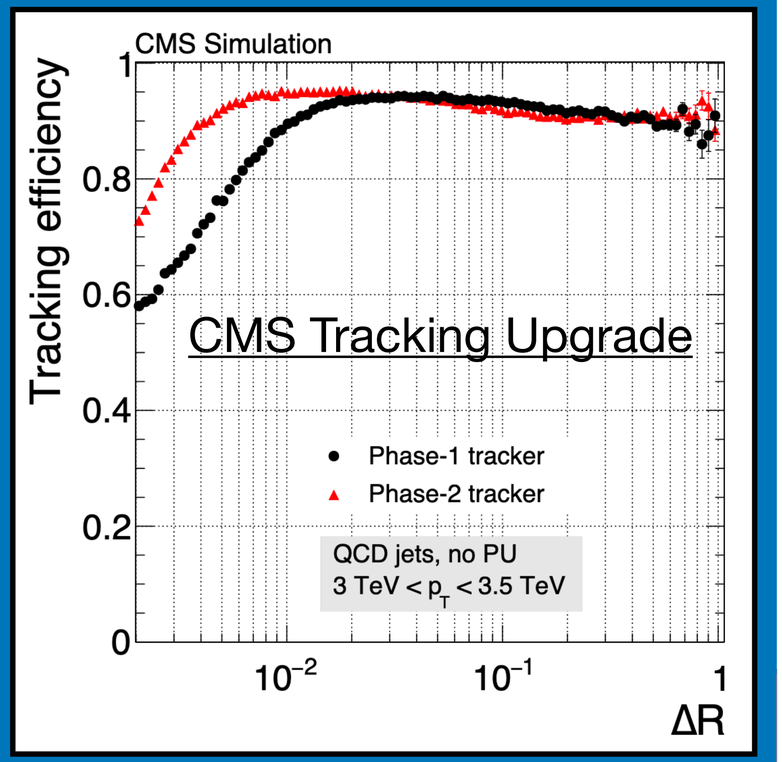
Tracking upgrades

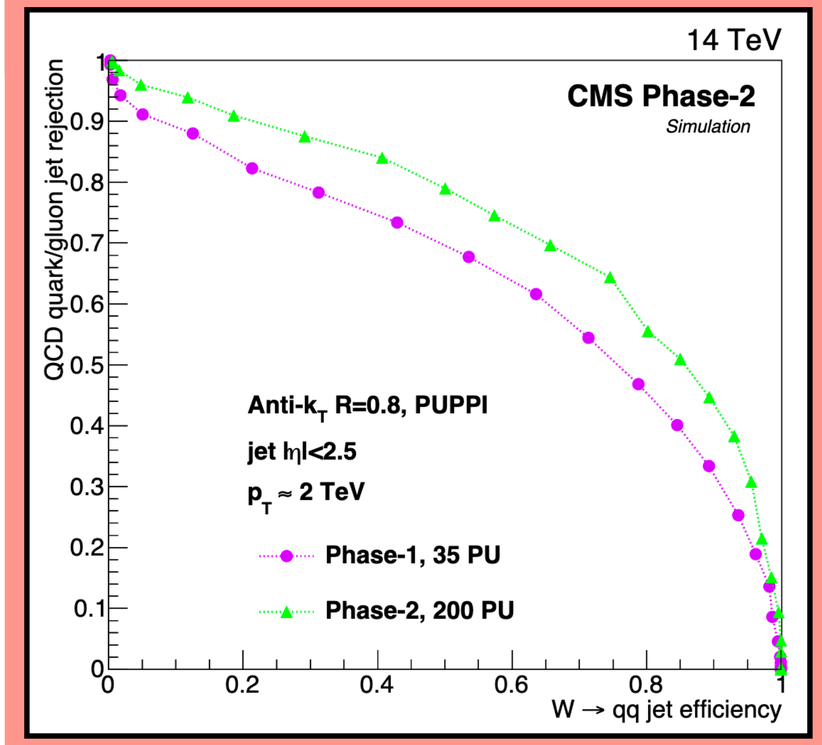
- The ATLAS and CMS upgrades extend tracking coverage from η < 2.5 to η < 4.0
  - Extends the range of PFlow reconstruction, charged pileup removal
- Better pileup rejection and quark/gluon tagging
  - Both of these rely heavily on tracking information
- Rejection expected to be worse than the central region, but still a significant improvement



Tracking upgrades

- Track reconstruction difficult in core of jets
  - Difficult to correctly assign hits, merging of hits
- Trackers at the HL-LHC will have better granularity
  - Better tracking efficiency in jet core, even without optimization!





- Tracking in dense environments important for substructure reconstruction
- Higher granularity results in better W-tagging performance than current data, despite higher pileup conditions!

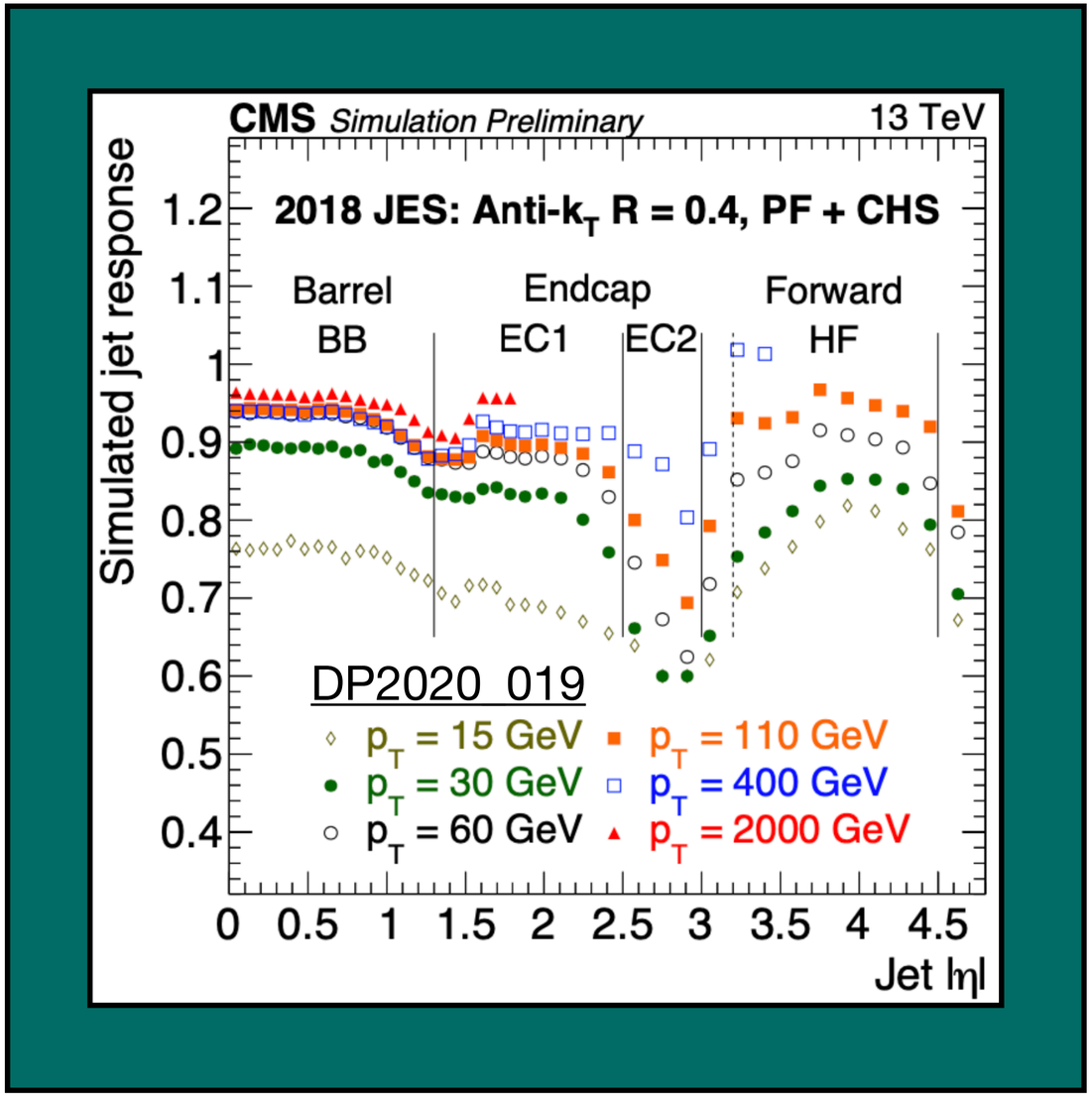
1. Jet modeling

2. Tracking information

3. Calorimeter information

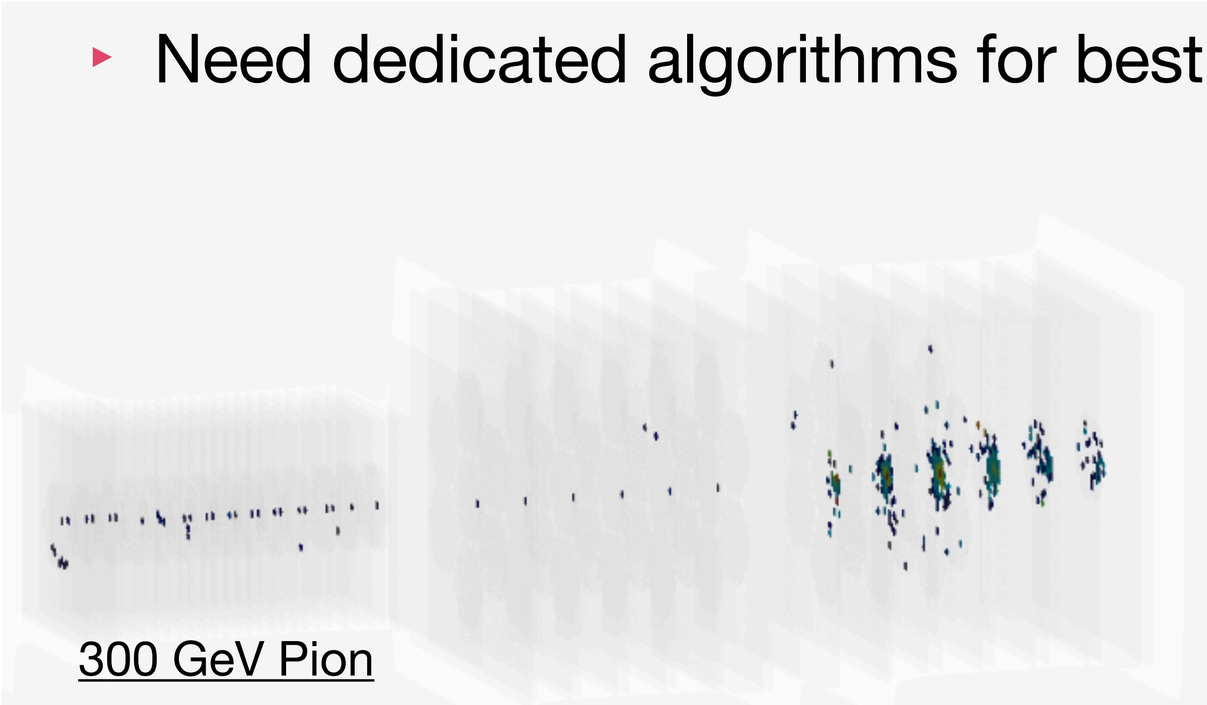
The Calorimeter

- Reconstruction of forward jets is very challenging
  - Tracking will help, but won't solve all of the problems
- Calorimeter granularity becomes larger → difficult to provide accurate reconstruction
- Detector becomes less uniform → jet energy corrections vary more with η

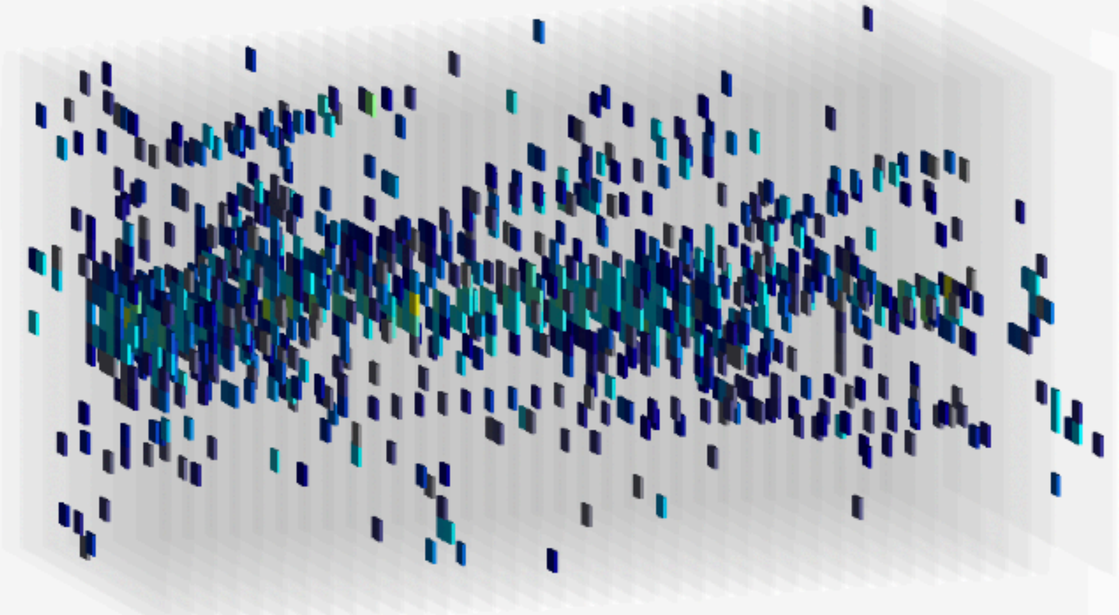


The High-Granularity Calorimeter

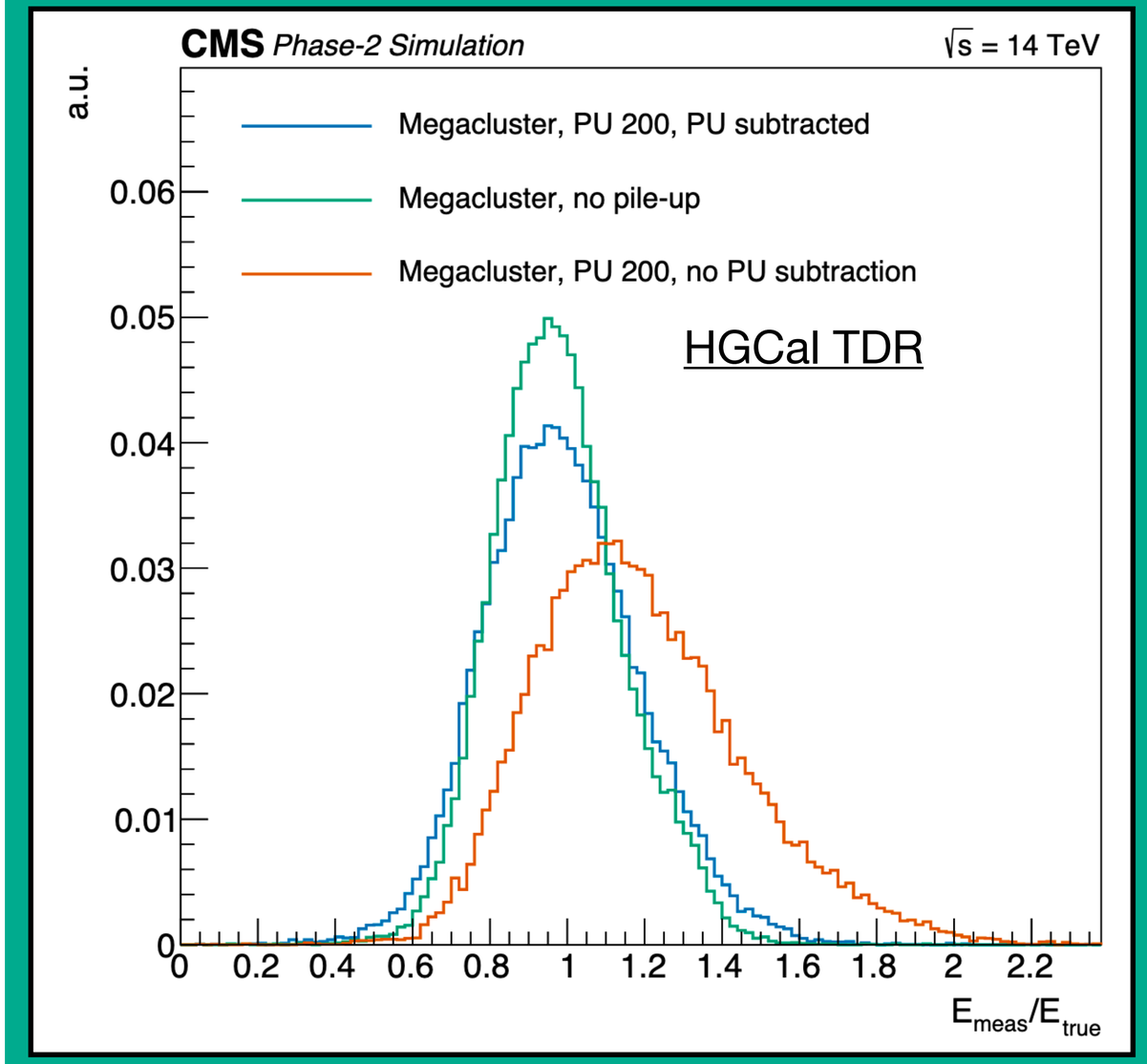
- CMS is planning a high-granularity calorimeter in the forward region with cell size of 0.5-1.2 cm^2, with 28 longitudinal layers
- Current studies use a multi-staged clustering scheme to reconstruct hadronic showers
  - Methods used for photons and electrons do not work for hadronic showers
  - Hadronic showers are much broader and more irregular
  - Need dedicated algorithms for best performance



300 GeV Pion



The High-Granularity Calorimeter



- Current clustering strategy identifies *seed* clusters, and the adds in energies from nearby cells
  - Contamination from noise and pileup results in degraded response and resolution
- Input-level pileup mitigation will be critical
  - Timing resolution has potential to add further gains in pileup reduction
- Need further studies in order to optimize the clustering strategy

1. Jet modeling

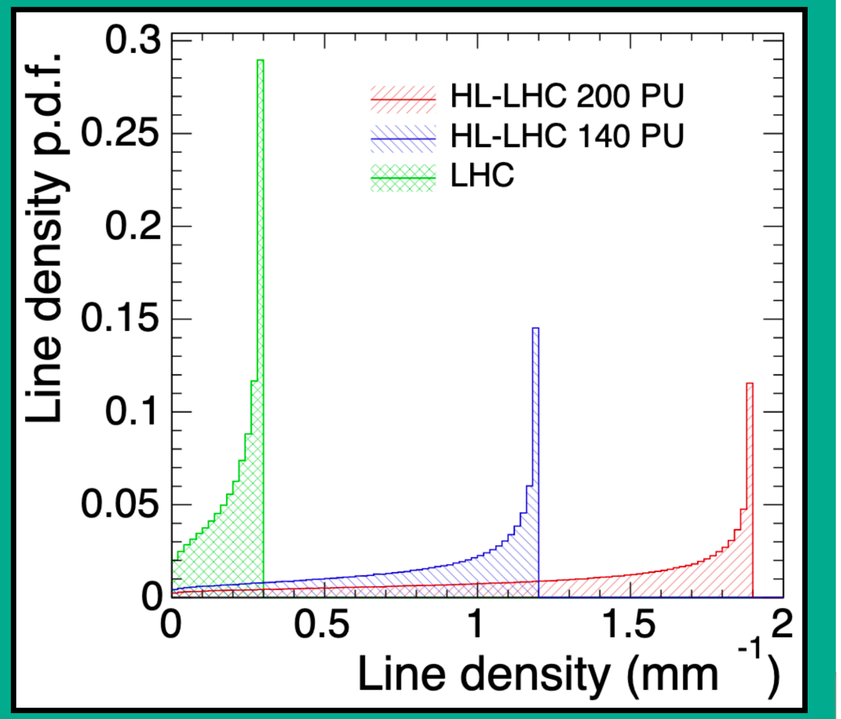
2. Tracking information

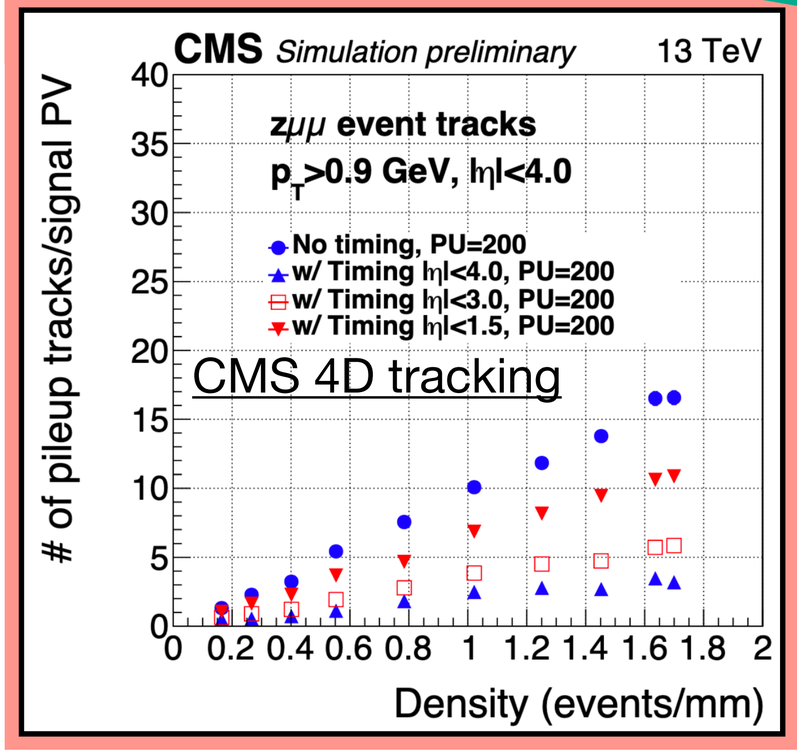
3. Calorimeter information

4. Timing information

Timing information

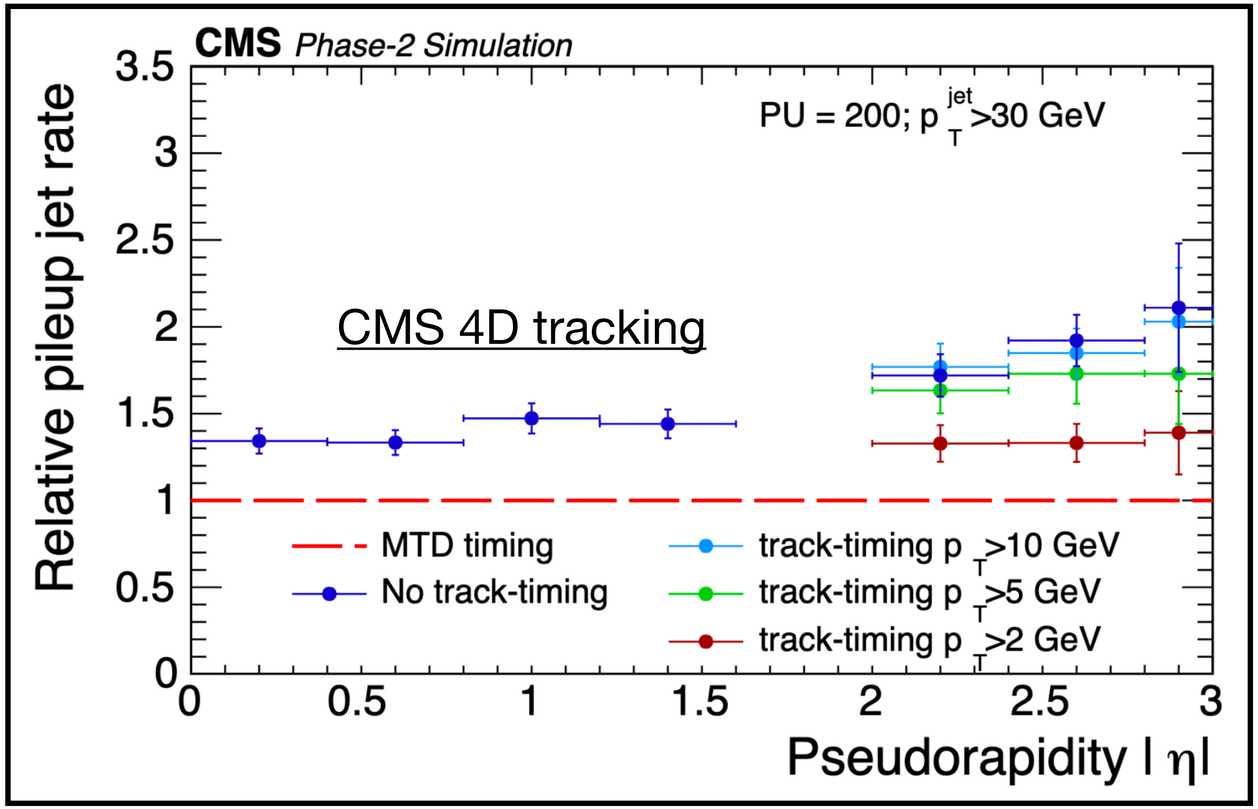
- Vertex density at HL-LHC expected to be much higher than for Run-2
- The number of tracks associated to the primary vertex depends on the pileup density
  - Up to 30% of tracks associated to the hard-scatter vertex could be pileup!





- Extra pileup tracks will result in degradation of jet resolution, pileup jet rate, substructure performance, and more
- 4D tracking (3D + timing) helps reduce this rate
  - Improvement depends on η coverage of the tracker

Timing information

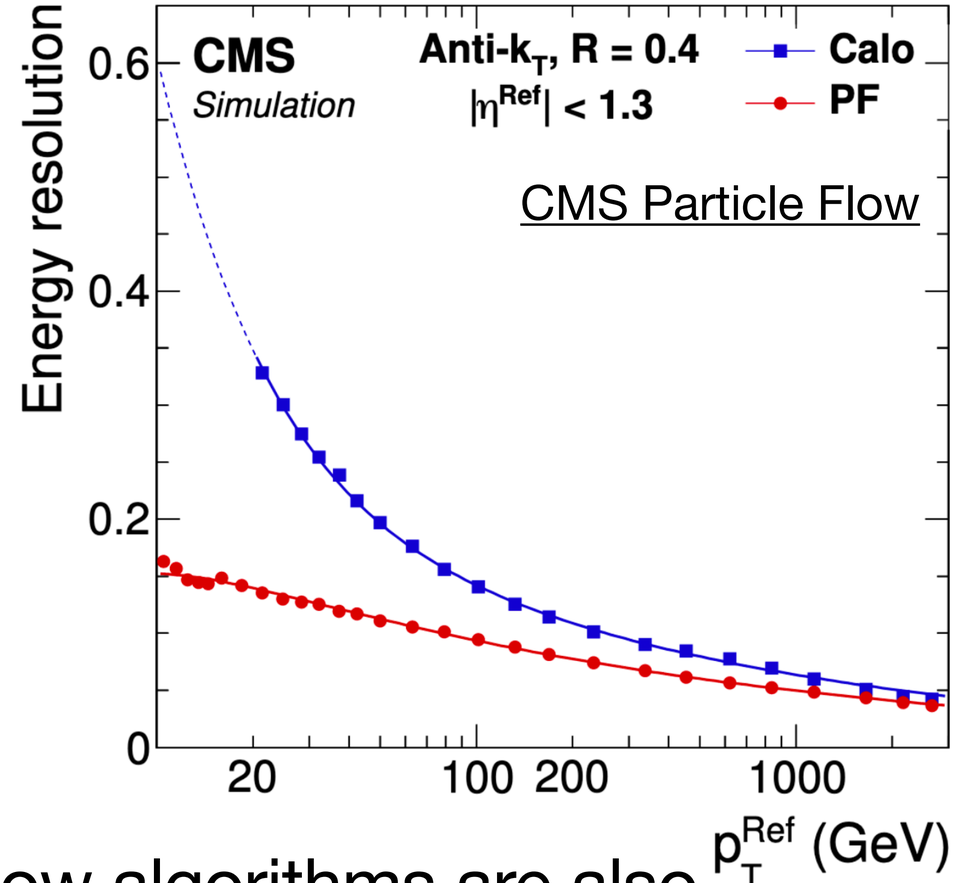


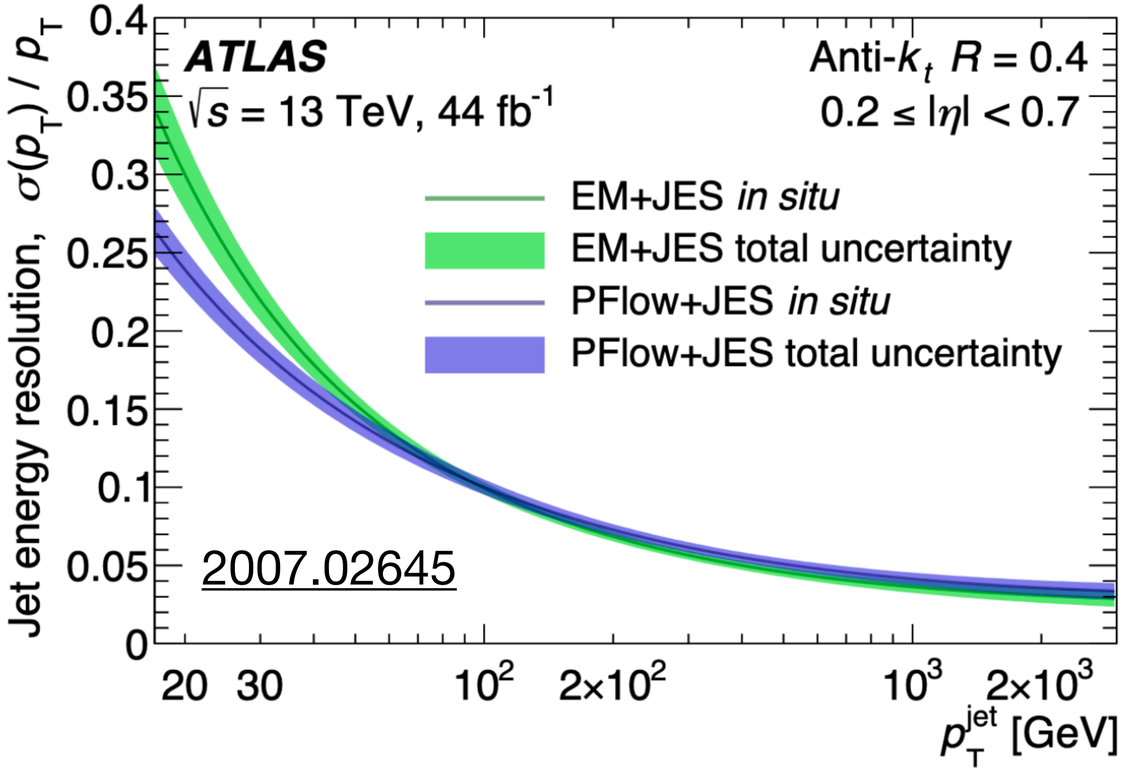
- The CMS timing layer will have ~30ps resolution for |η|< 3.0
- ATLAS high-granularity timing detector (HGTD) will have similar timing resolution for 2.4 < |η|< 4.0
- Timing can provide another dimension to associate tracks to vertices
  - Provides up to 100% better pileup jet rejection in the forward region

1. Jet modeling
2. Tracking information
3. Calorimeter information
4. Timing information
5. Jet input reconstruction

Particle Flow Algorithms

- Particle flow algorithms are important for jet reconstruction at the LHC
  - Improve jet resolution, particularly at low-p_T
  - Reduce pileup sensitivity by removing charged pileup contributions

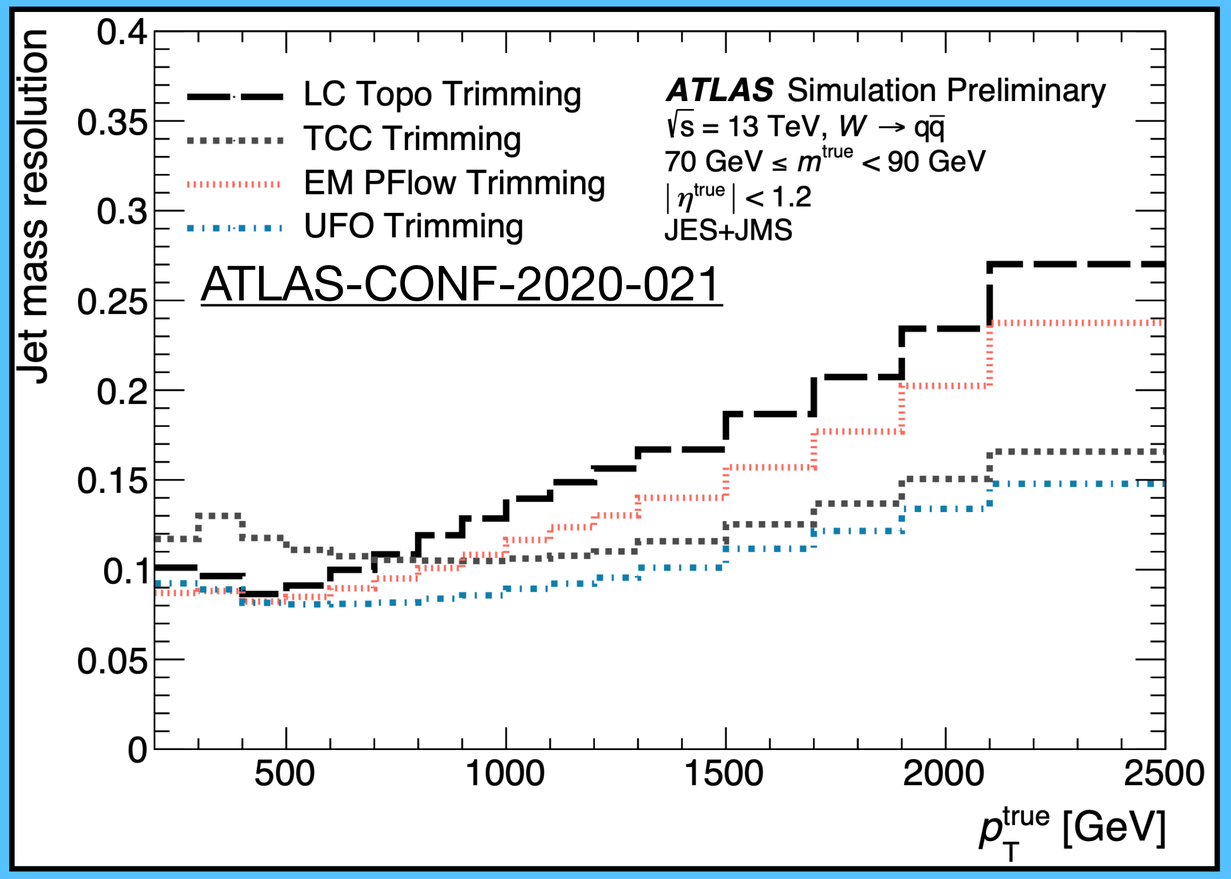




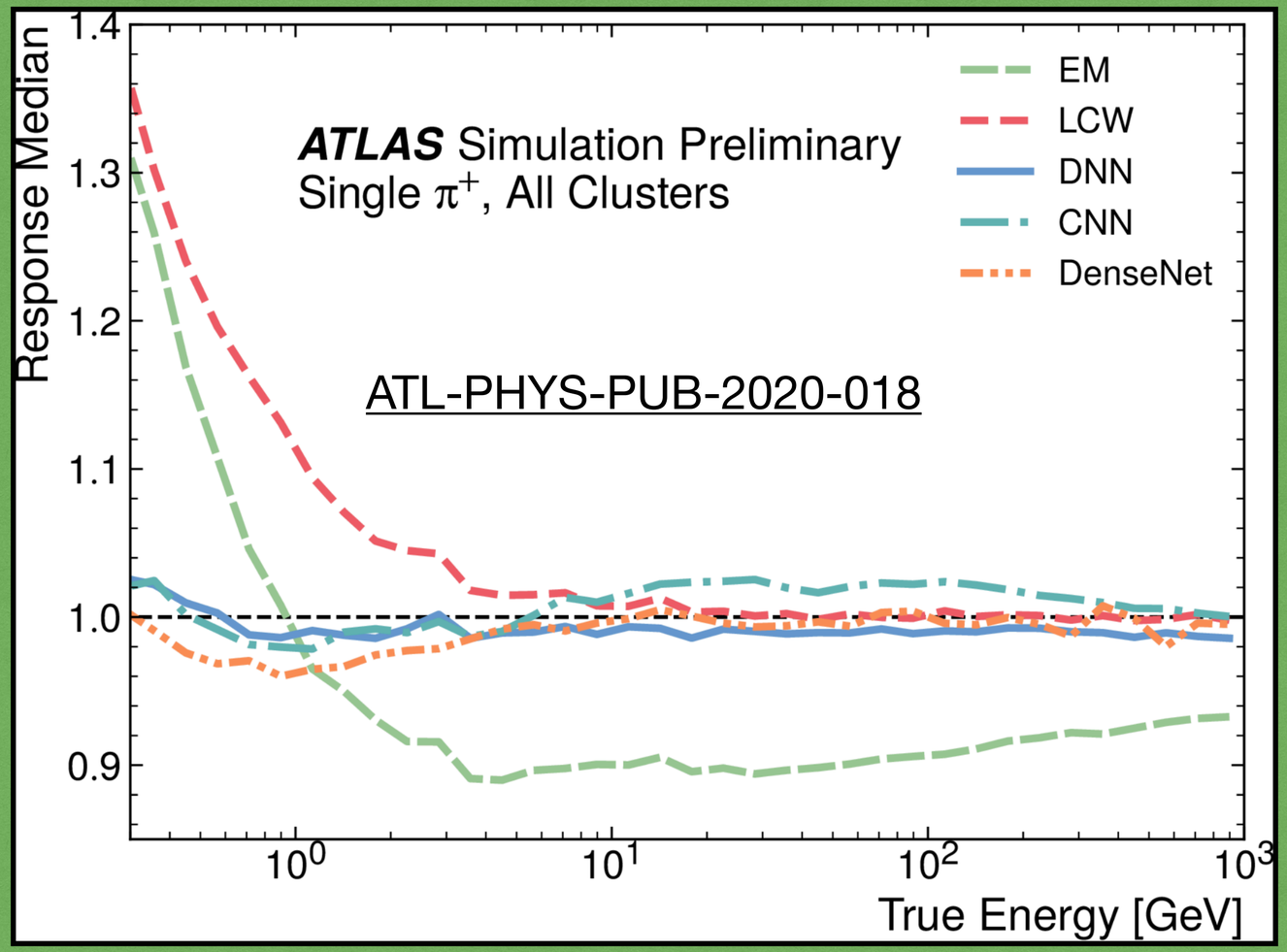
- Particle flow algorithms are also important for substructure reconstruction
  - Provide closer correlation between particles and detector objects, especially for highly boosted objects

Particle Flow Algorithms

- Need to optimize particle flow algorithms for jet substructure
  - Algorithms that only combine tracker & calorimeter where reconstruction is clean aren't good for dense substructure (*PFlow*)
  - Algorithms that just use tracks to split calorimeter objects (*TCCs*) do not fully utilize the detector
  - Algorithms which combine these aspects (*UFOs*) can bring significant gains for substructure reconstruction
- Need to continue to develop methods which are focused on substructure



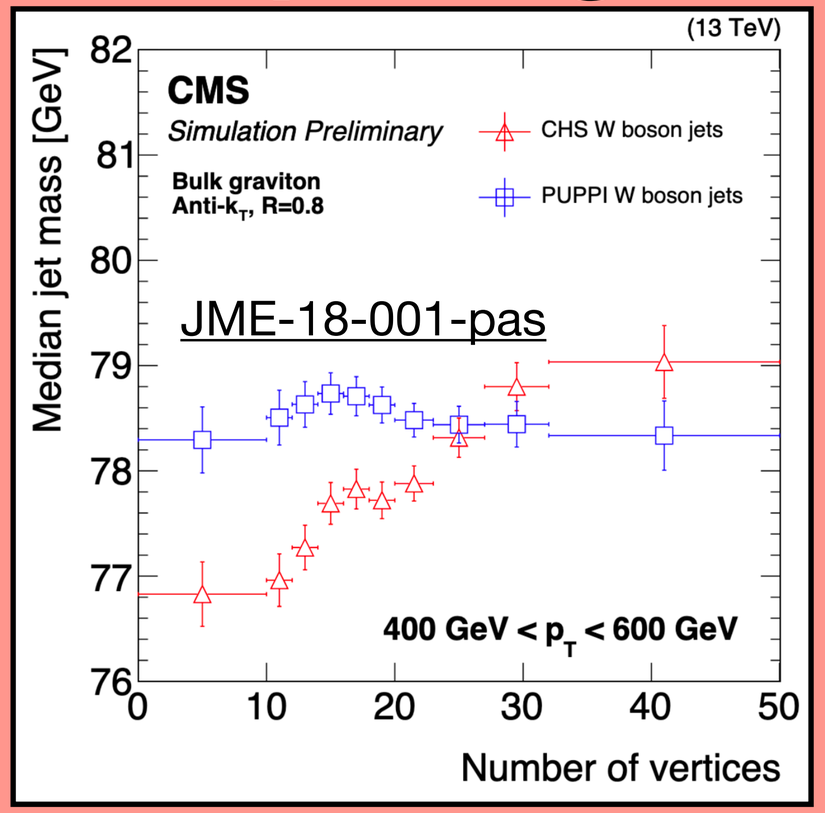
Particle Flow Algorithms



- Machine learning techniques can be useful for both *classifying* particles and *calibrating* their energies
- Need to continue developments of jet input calibration to improve resolution of jets and their substructure

1. Jet modeling
2. Tracking information
3. Calorimeter information
4. Timing information
5. Jet input reconstruction
6. Pileup mitigation

Pileup Mitigation



- Constituent-level pileup mitigation algorithms help improve stability of substructure observables
- CMS uses PUPPI for both small-R and large-R jet reconstruction

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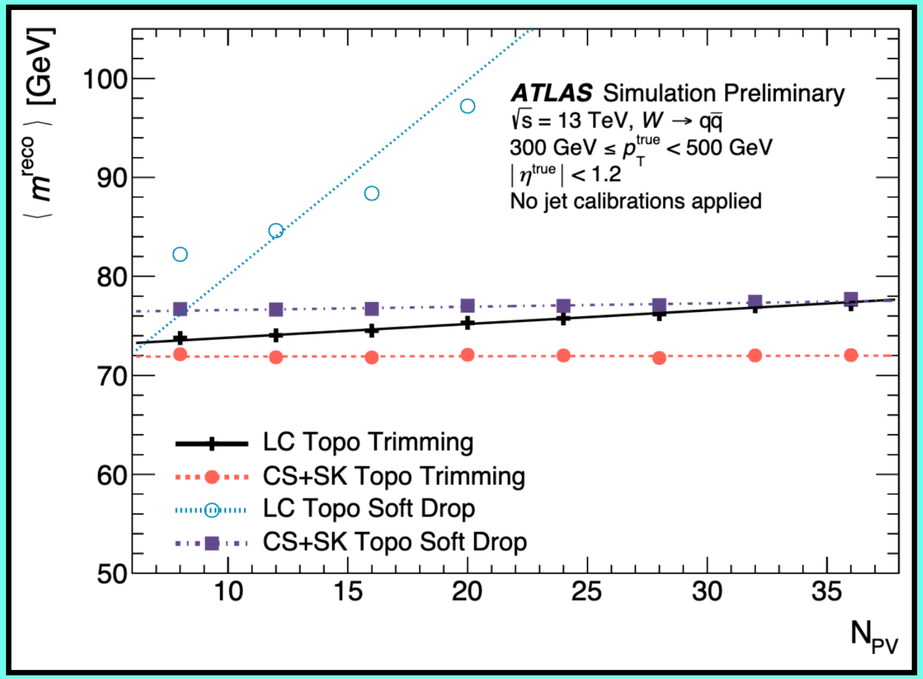
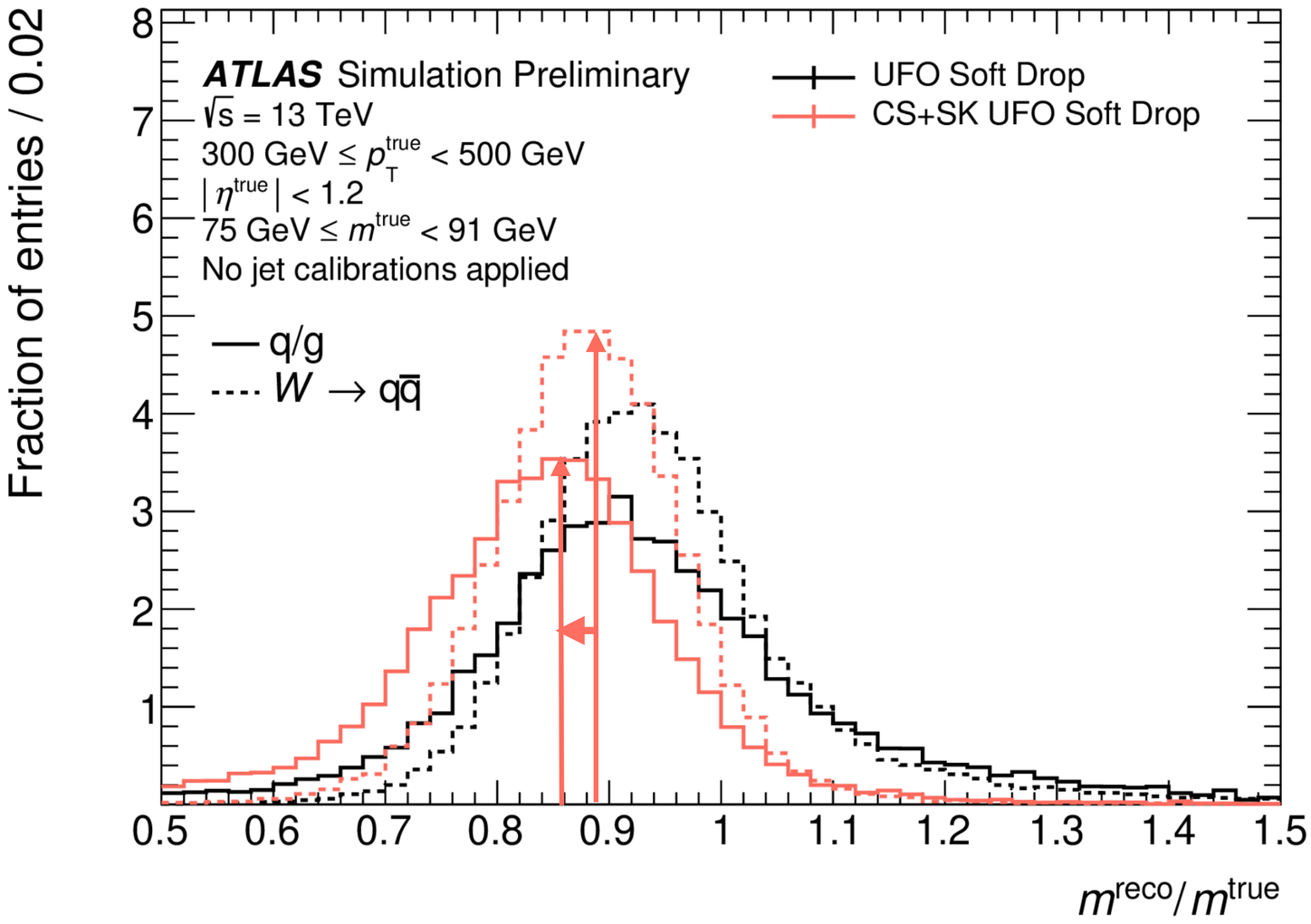


- ATLAS plans to use Constituent Subtraction + SoftKiller for large-R jet reconstruction

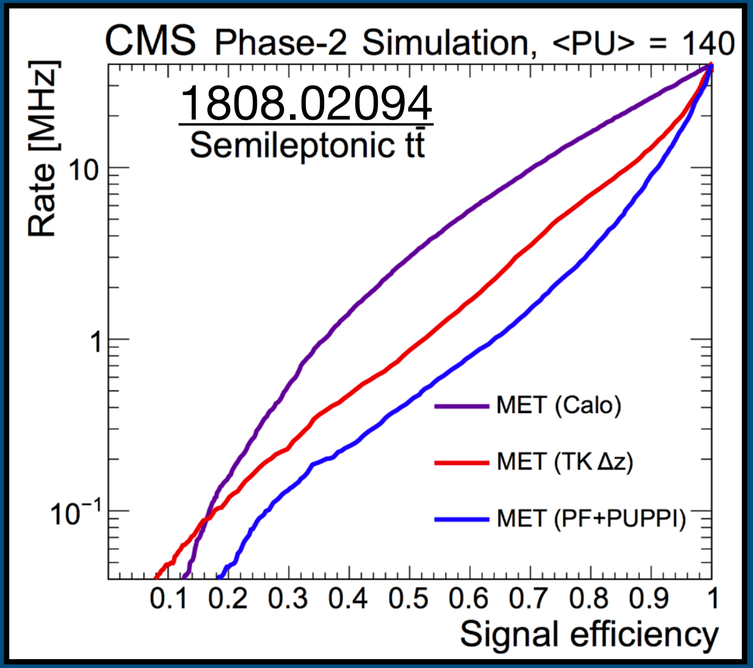
Pileup Mitigation

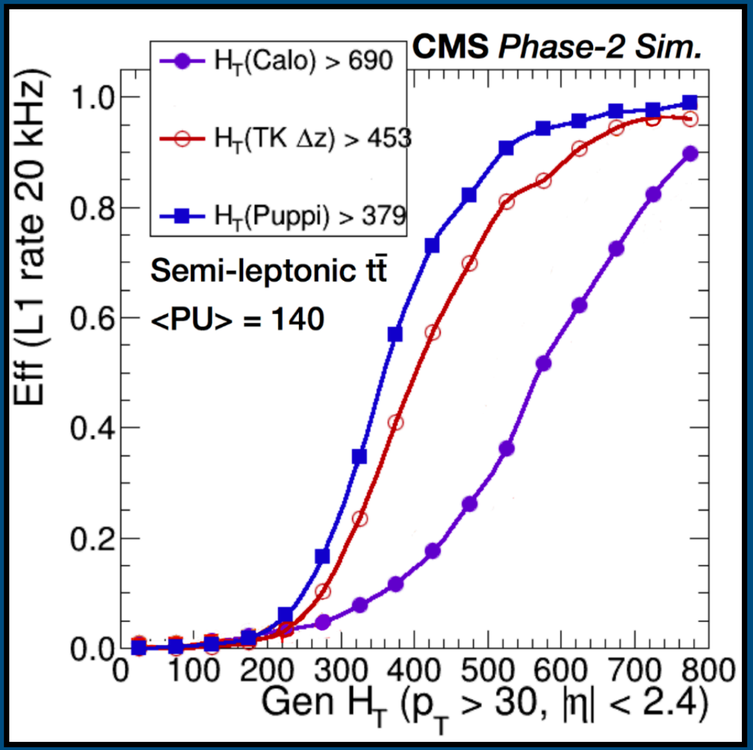
- Many pileup mitigation algorithms already available
- Different effects on different types of jets
  - Changes mass scale for q/g jets more than W jets
- Distribution and momenta of particles within jets changes for different types of jets
  - Not surprising that this might happen, but worth further study



Pileup Mitigation

- CMS is expecting to using PUPPI for the Level-1 trigger
  - Modified particle flow algorithm to simplify performance
  - Using look-up table to be able to put PUPPI algorithm in an FPGA
- Increasing similarity between trigger-level objects and offline objects helps lower trigger thresholds and improve performance
  - Also opens up possibilities for trigger-level analyses, even with the Level-1 trigger!

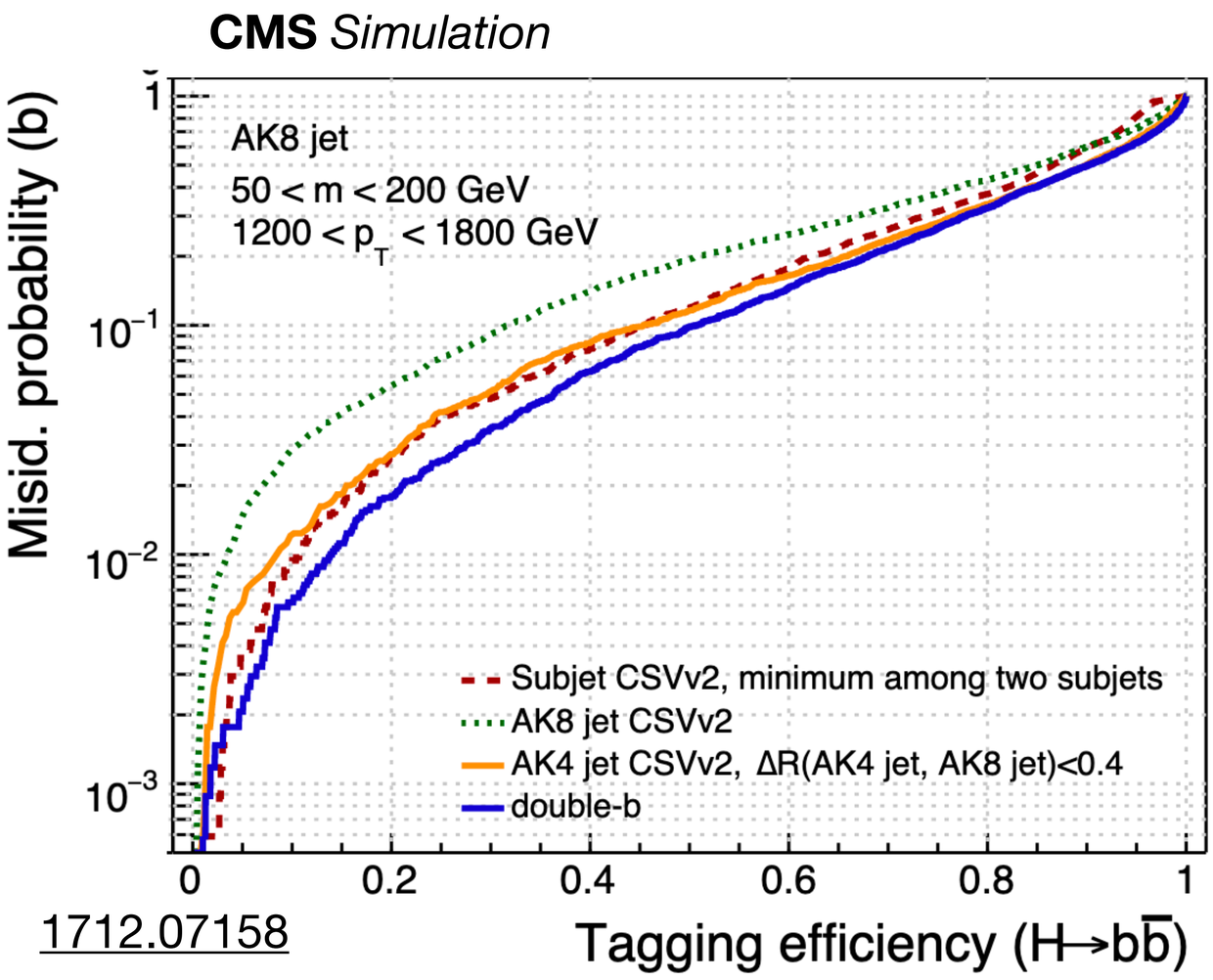




1. Jet modeling
2. Tracking information
3. Calorimeter information
4. Timing information
5. Jet input reconstruction
6. Pileup mitigation
7. Jet tagging

Tagging Performance

- Double b-tagging is important for high-p_T $H \rightarrow bb$
  - Ordinary b-taggers won't work, because the two b's are merged into a single jet
  - Can require a double b-tag on large-R jets, but even this breaks down at very high p_T
- Dedicated taggers from both CMS and ATLAS improve background rejection
  - Requires understanding of substructure, vertexing, tracking, and more for optimal taggers



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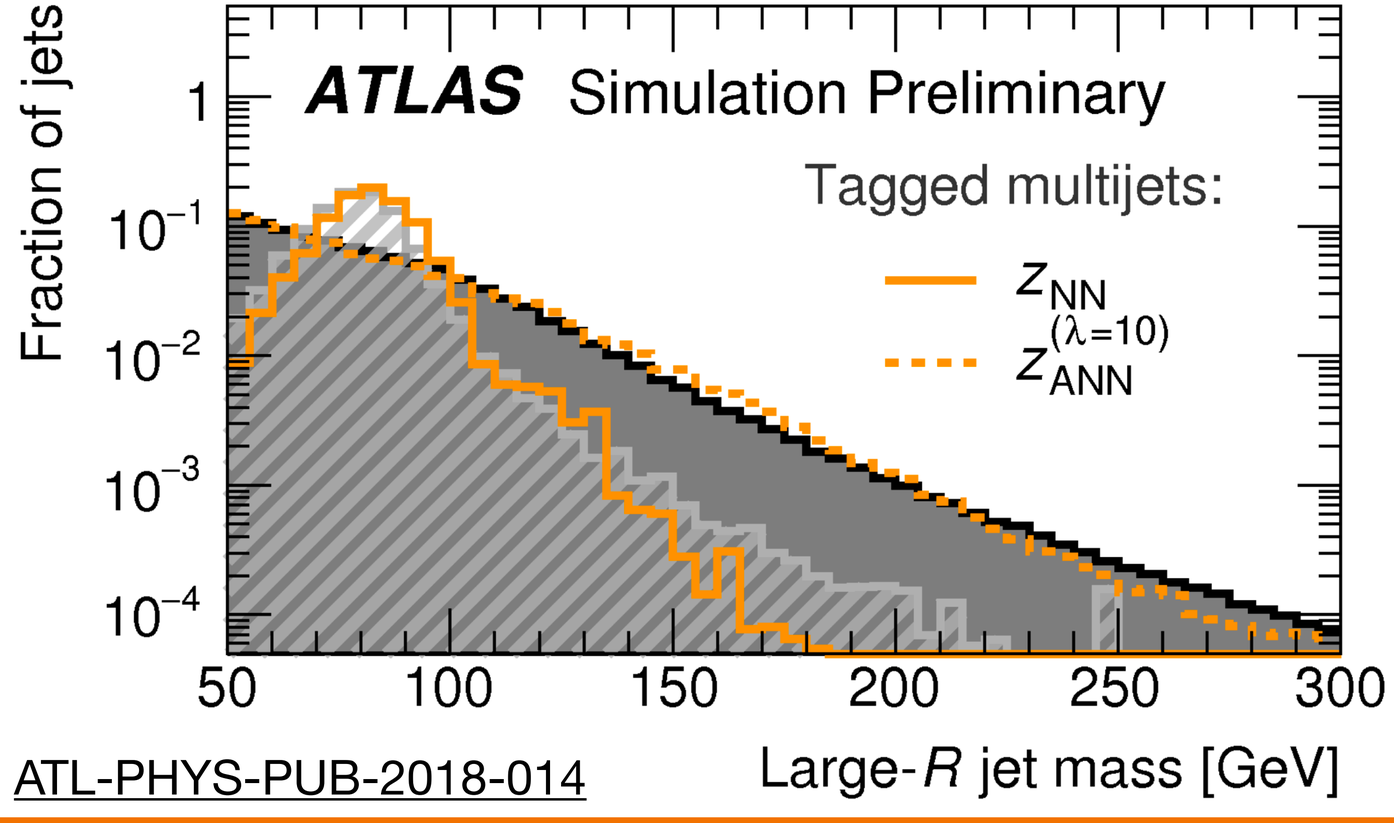
Tagging Performance



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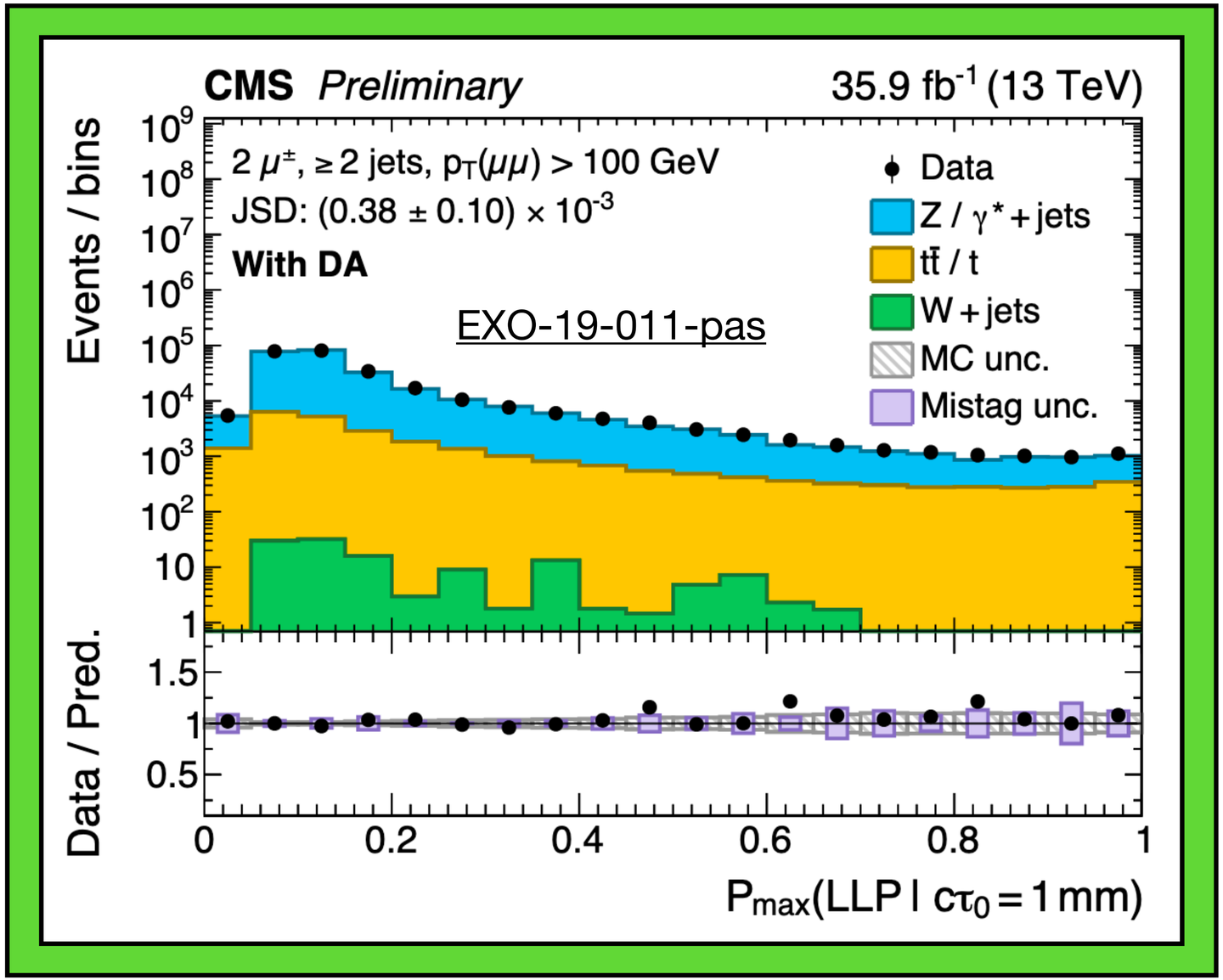
- Decorrelated taggers are becoming important for a variety of searches
- Several techniques proposed to deal with decorrelation, all of which pose different challenges

Tagging Performance

- Calibration of taggers is challenging, especially for rare processes
- May need more thought for how to calibrate taggers, especially as we move towards more exotic jets



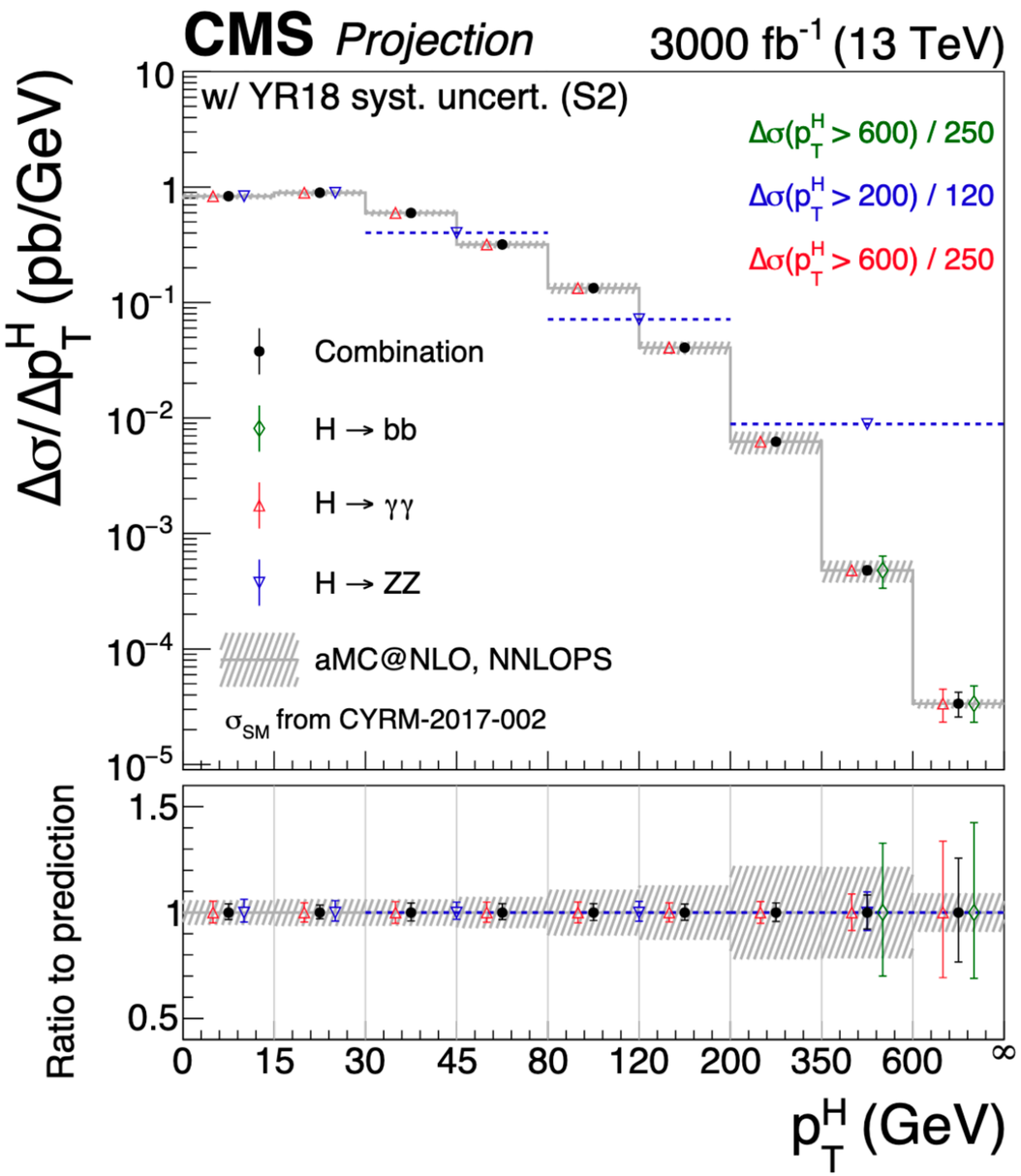
And the real question…

What physics will all of these improvements give us access to?

Higgs p_T measurement

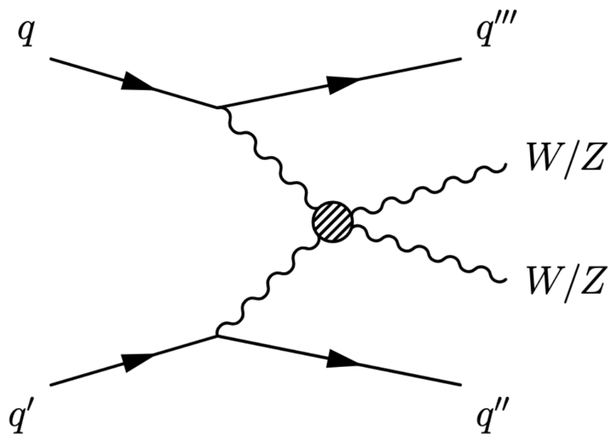
FTR-18-011 HIG-17-028-pas

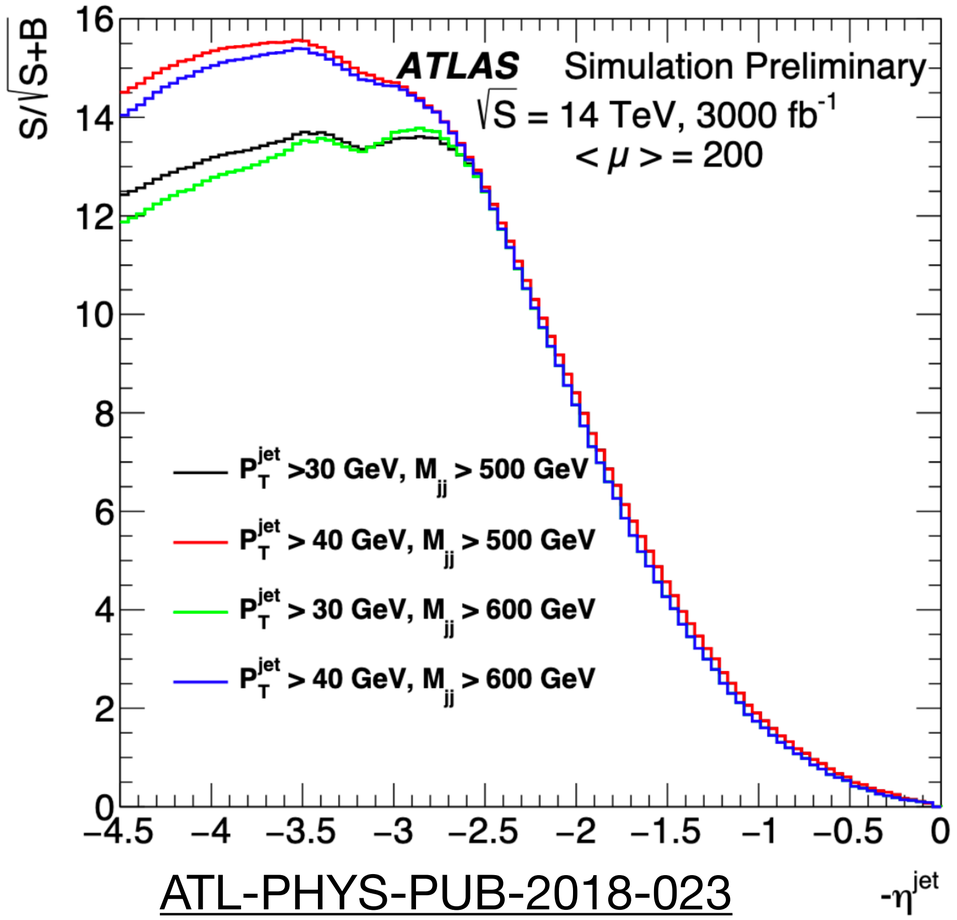
- Differential measurement of the Higgs p_T is important for constraining new physics
  - Significant changes to the p_T spectrum from different couplings of Higgs to quarks or to other bosons
- Limited statistics at high-p_T, and high branching ratio to bb
  - Need to combine different decay channels to be sensitive
- At high p_T (>350 GeV), can use large-R jets to measure the H→bb channel
  - Large reduction in backgrounds over non-boosted case
  - Requires dedicated double-b taggers to improve sensitivity



Electroweak Measurements

- Electroweak processes have tiny cross-sections → significant improvement with HL-LHC dataset
- Typically rely on vector-boson scattering to access these interactions
- VBS/VBF measurements tend to have two forward jets initiated by quarks
- Several handles to distinguish from background (very important for low cross-section processes)
  - Event topology tends to be distinct (two forward jets with large dijet mass)
  - Quark/gluon discrimination can help reduce backgrounds from similar topologies





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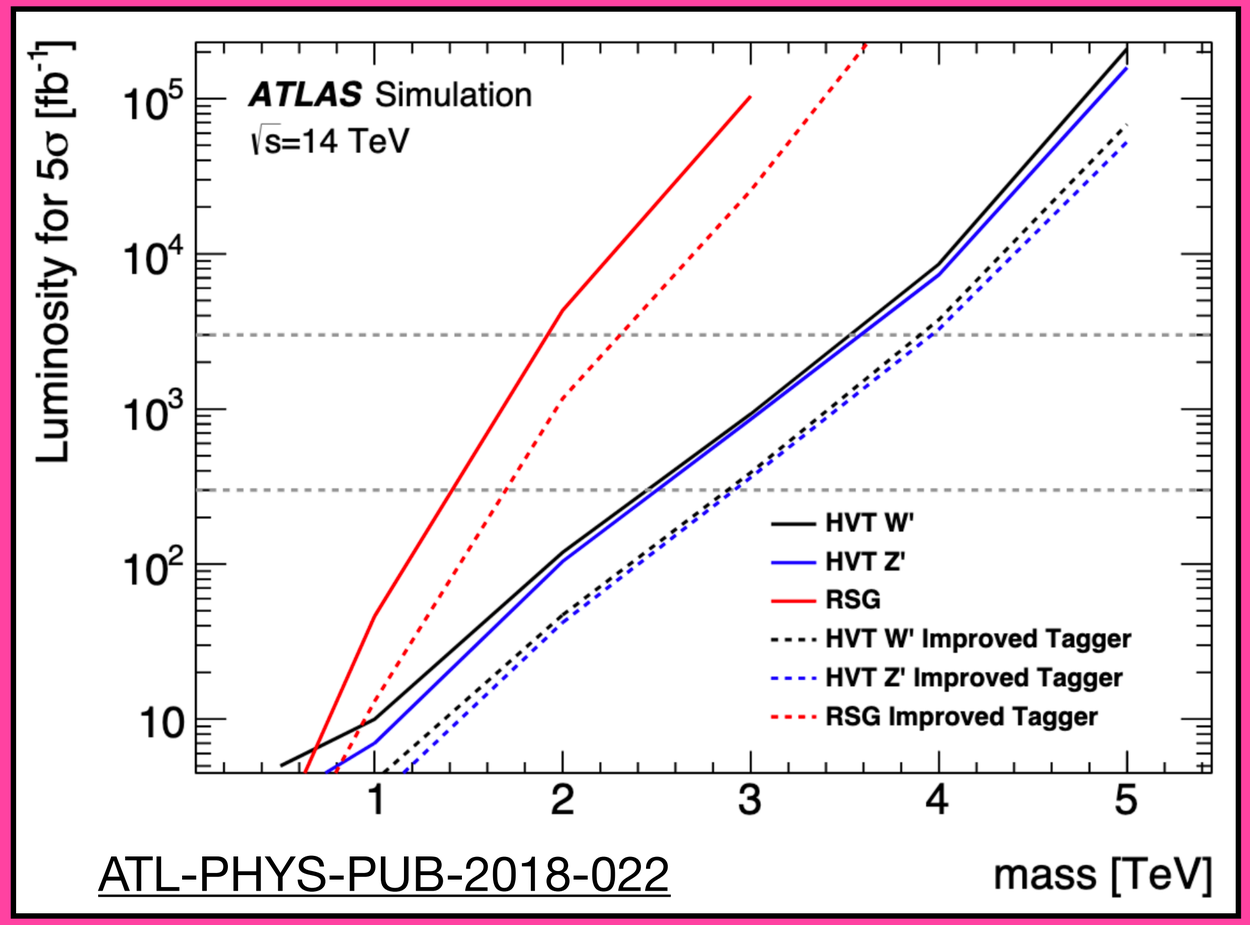
Diboson Searches

- Diboson searches are sensitive to a wide variety of models of BSM physics
- Hadronic or semi-hadronic decays provide larger cross-sections, less missing transverse momentum
- Rely on W/Z to reduce background
  - A 50% increase in tagging performance would result in better reach with less luminosity!
- Other searches will also see gains by improving the tagging performance



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Jet Substructure Measurements

- Calorimeter-only substructure measurements are less precise than track or PFlow measurements
- Larger tracking range in upgrades will allow better exploration of jet substructure in forward region
  - Useful for both track-based methods and PFlow reconstruction
  - May provide better handles on quark/gluon extraction
- More difficult to produce calculations for track-based measurements
  - Track-based measurements still useful for tuning
  - Some ideas, but either challenging (track functions), or not universally applicable (EECs)

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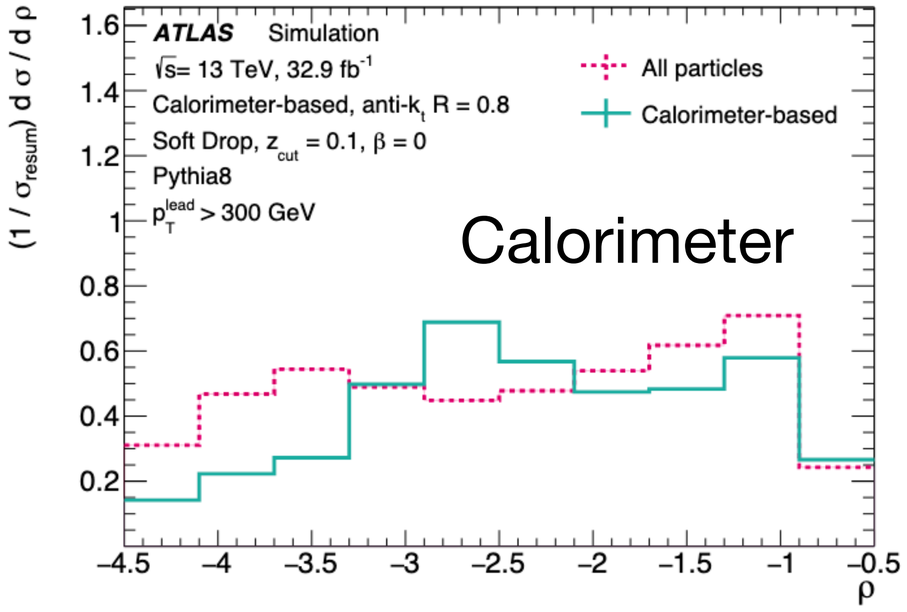

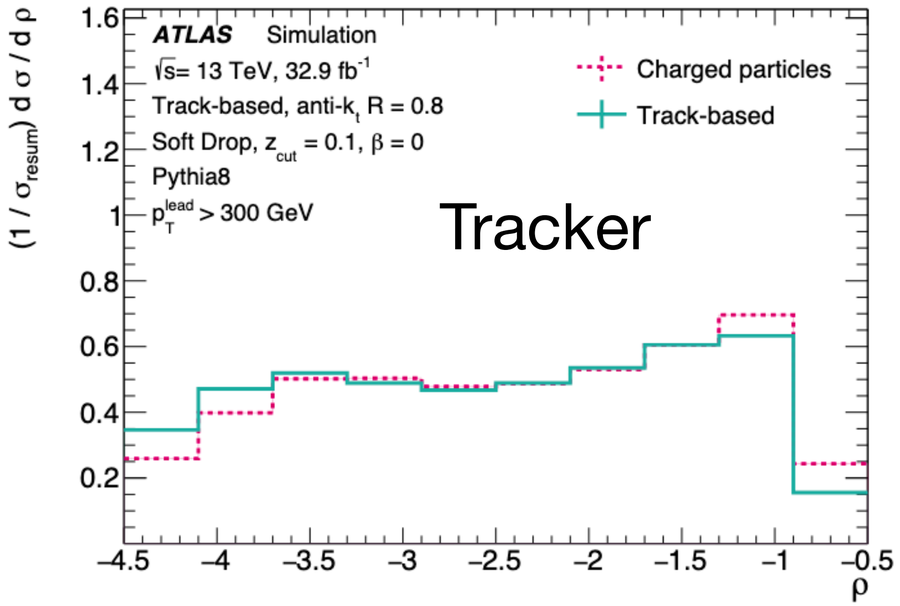

Quark/Gluon Extractions

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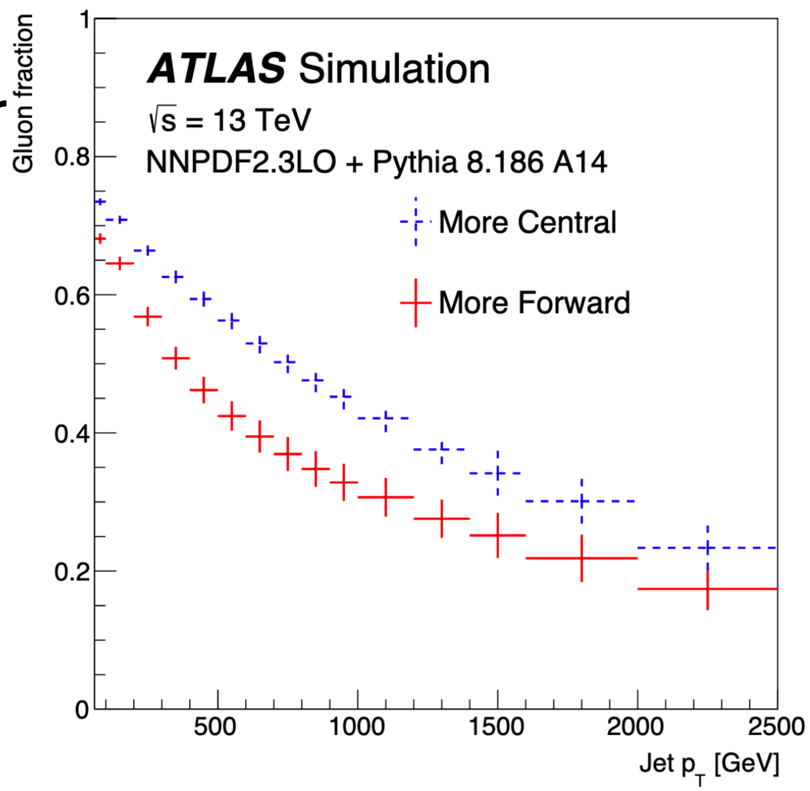
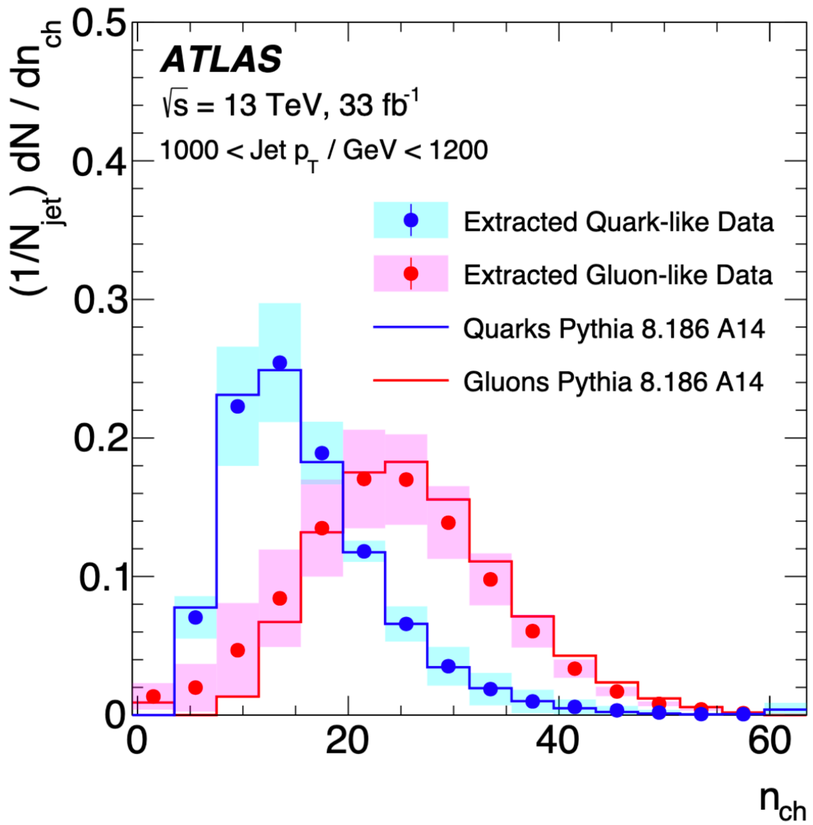
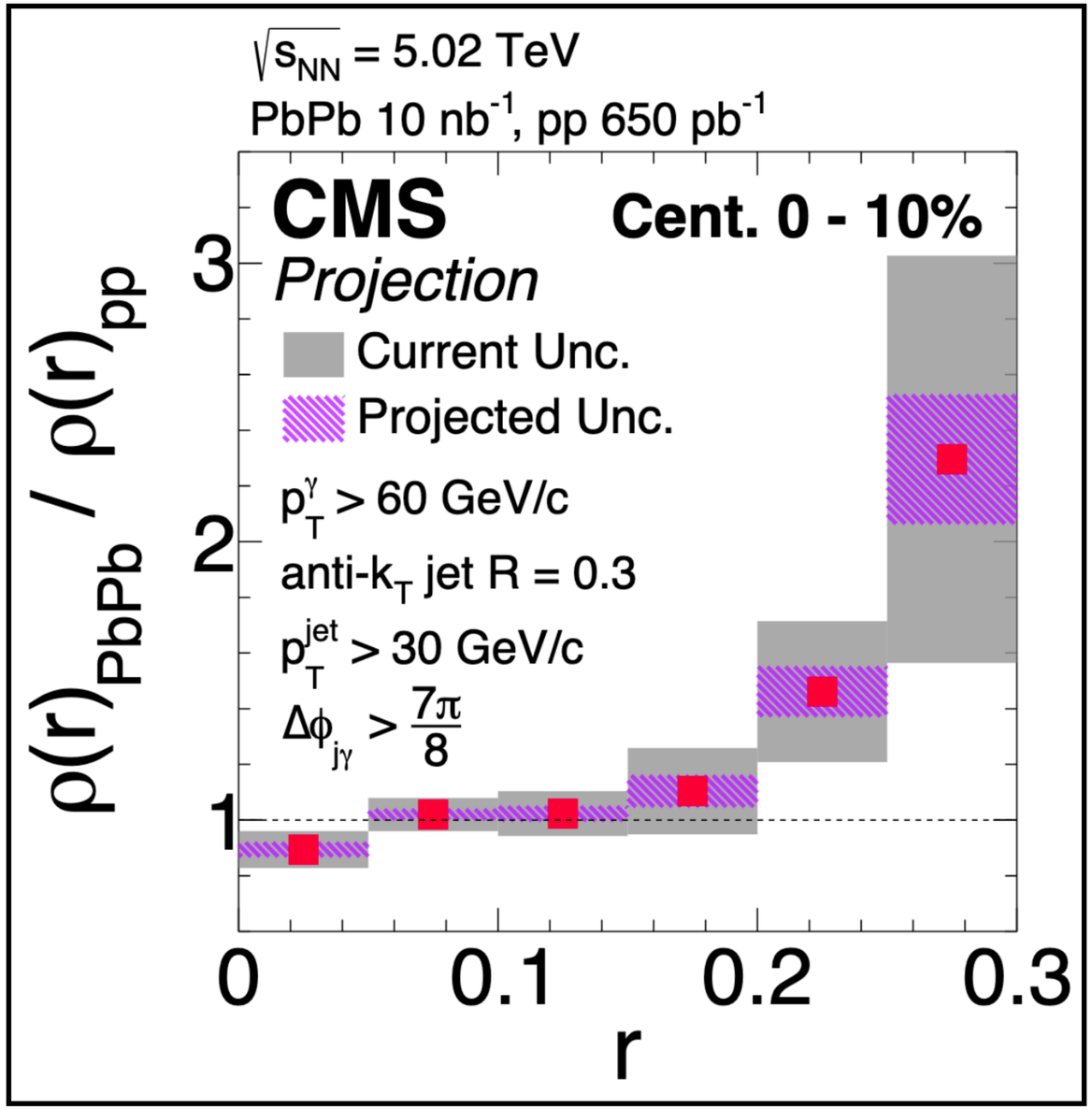
- Central jets tend to be more gluon dominated than forward jets
- Can use measurements of substructure in regions with different gluon fractions to extract the quark and gluon distributions (no q/g tagging required!)

- By going more forward, can get bigger differences between samples!
- This can provide better gluon measurements, which will help reduce modeling uncertainties





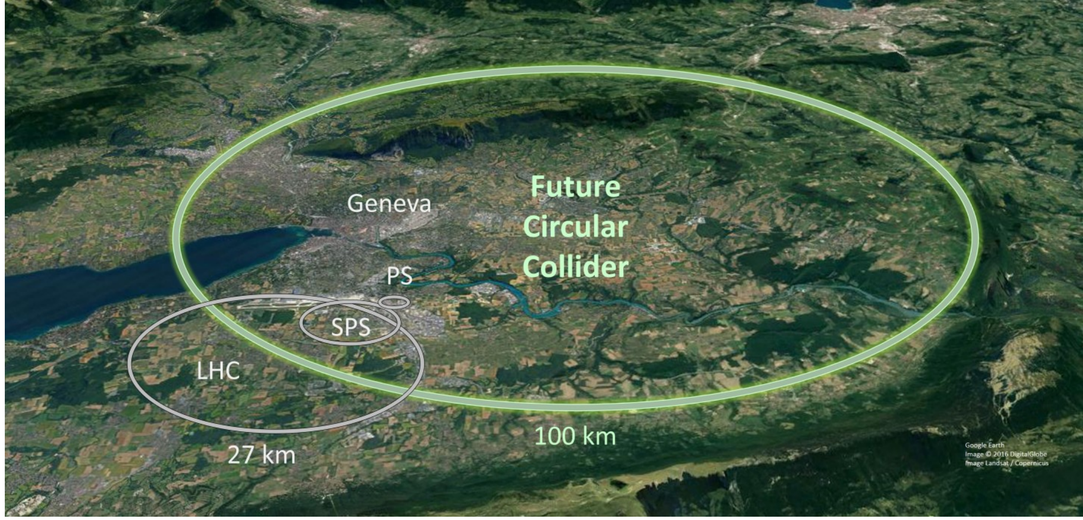
Heavy Ion Measurements



- Improved tracking will allow higher precision (and smaller uncertainties) for heavy ion measurements
- Measurements of jet fragmentation and substructure will provide deeper understanding of jet quenching

Boosting Up

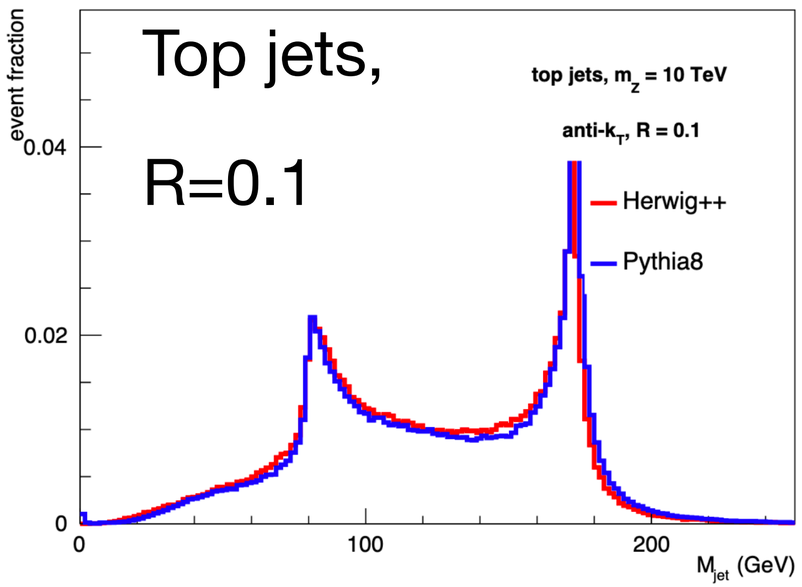
Future Colliders

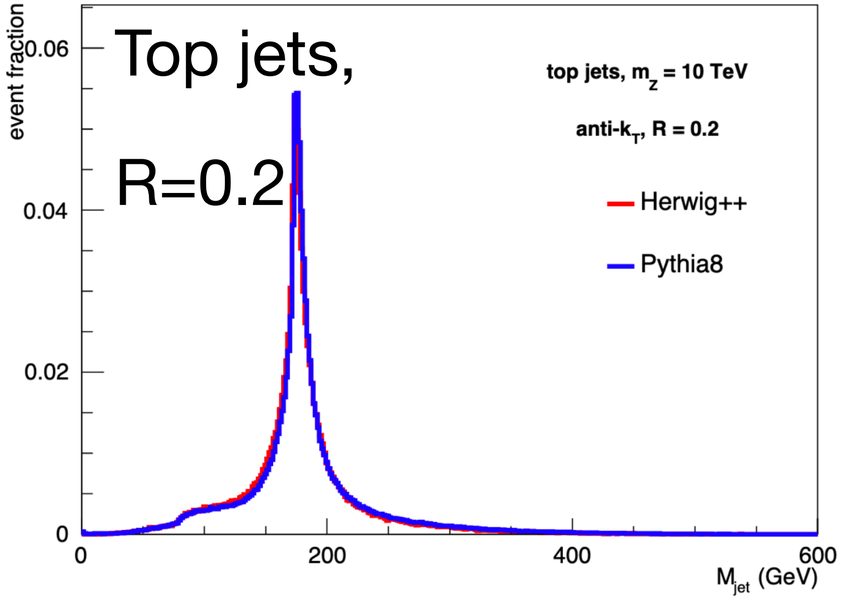


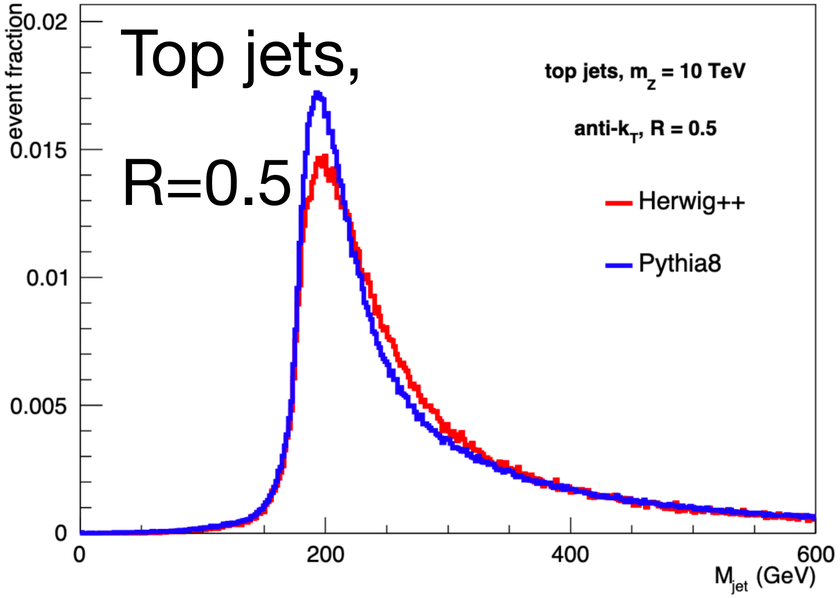
- Two proposals for future hadron colliders
  - FCC @ 100 TeV
  - SPPC @ 70 TeV
- Higher energies mean we will be sensitive to a wide range of new physics models
- Also able to do precision measurements of rare processes
- Need precise jet reconstruction across range of scales
- Interested in reconstructing both quark/gluon jets (e.g. dijet searches, ttbar searches), as well as W/Zs (diboson searches)
  - These types of resonance searches probe some of the highest masses accessible from these colliders
  - Tagging boosted objects will be important for (hopefully) discovering new physics

Future Colliders

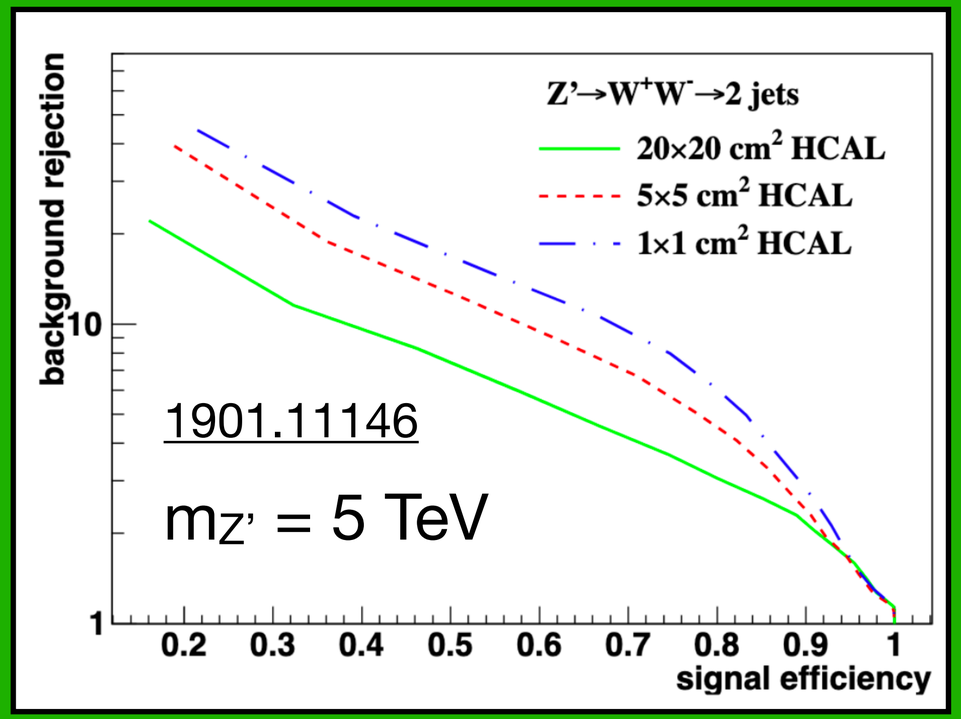
- Need excellent boosted object reconstruction to be able to tag W/Z/top jets for some of these searches
- Boosted jets at FCC/SPPC energies will look significantly different than at the LHC
  - Containment will happen for much smaller jet radii than at the LHC
  - The decay products of W/Z decays could conceivably be collimated within a single calorimeter cell!





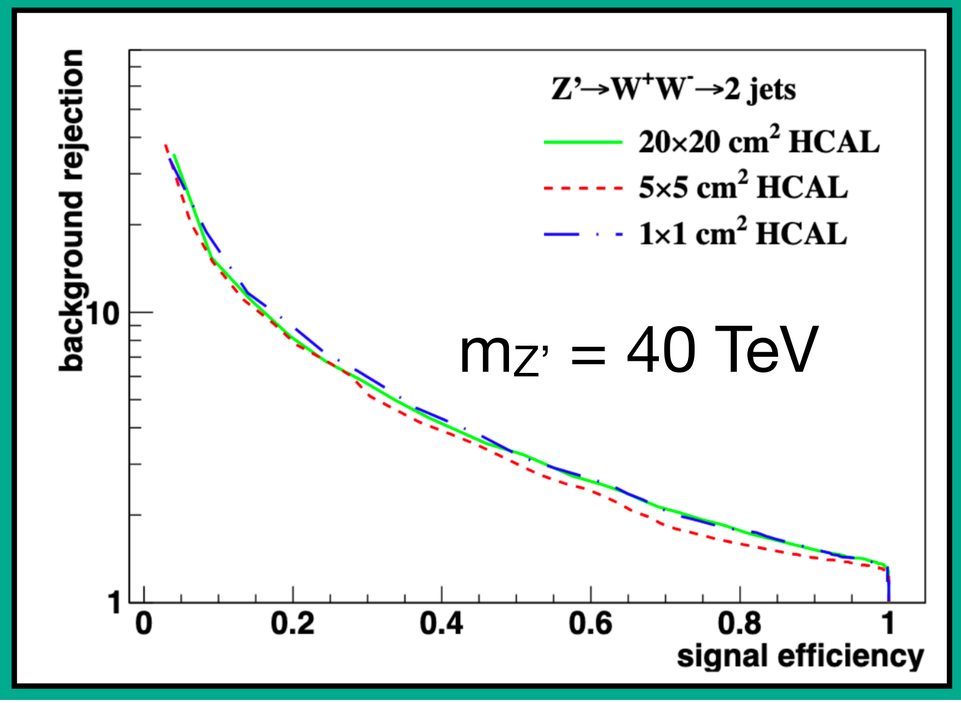


Future Colliders



- Highly collimated decays → need to rethink *detector design* and *jet reconstruction* algorithms
  - Small calorimeter cells will help improve substructure resolution

- For 40 TeV Z', not much difference between the different granularity choices
  - Particle flow algorithms will be critical in reconstructing jet substructure

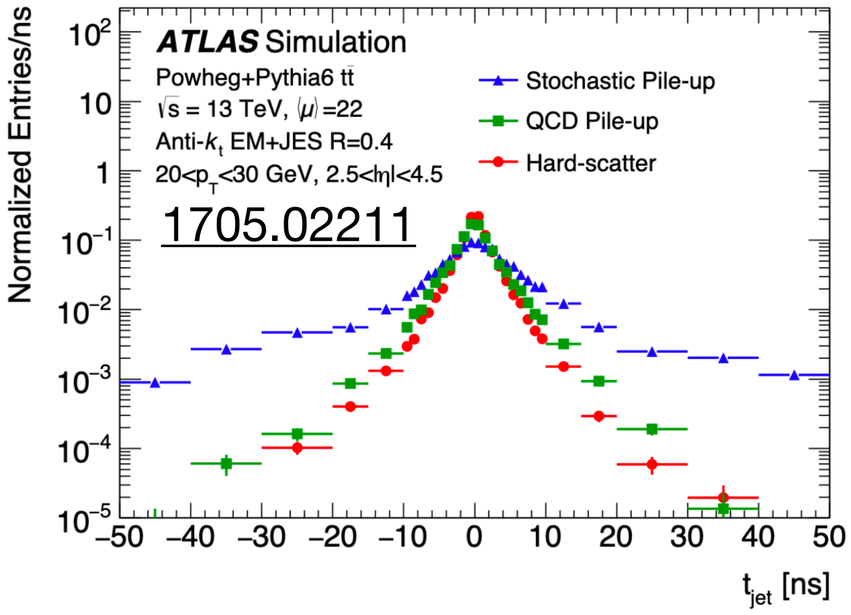


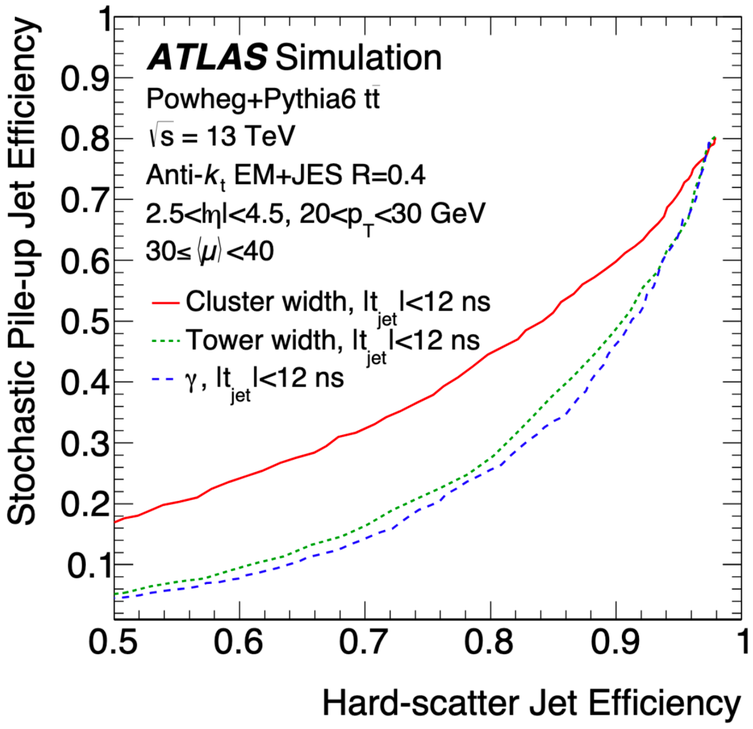
- *Substructure is relevant to everything from precision measurements to BSM searches*
  - Tagging is used for a broad set of analyses at the LHC
  - QCD modeling has a direct impact on improving precision of all analyses that use jets
- *Everything is interconnected*
  - For best performance, need good understanding of detectors, object reconstruction, and QCD
- *Substructure-focused designs are critical*
  - Reconstruction for other objects may not be sufficient for jet substructure
  - Important to make a clear case for substructure when making upgrade / future detector decisions
- *Discussions between experimentalists and theorists are crucial for developments*

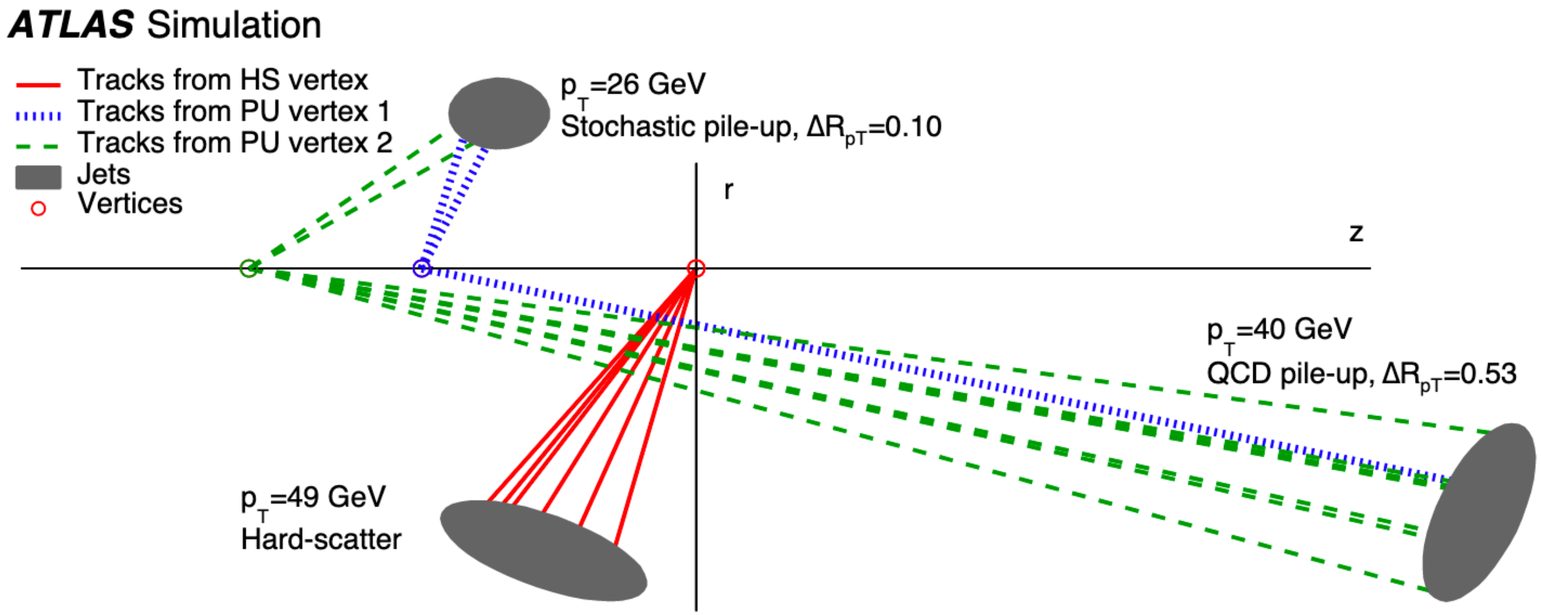
Boost on!

Forward Pileup Jet Removal

- Event topology can be used to identify forward pileup jets
- Can use information about jet width and time to further discriminate

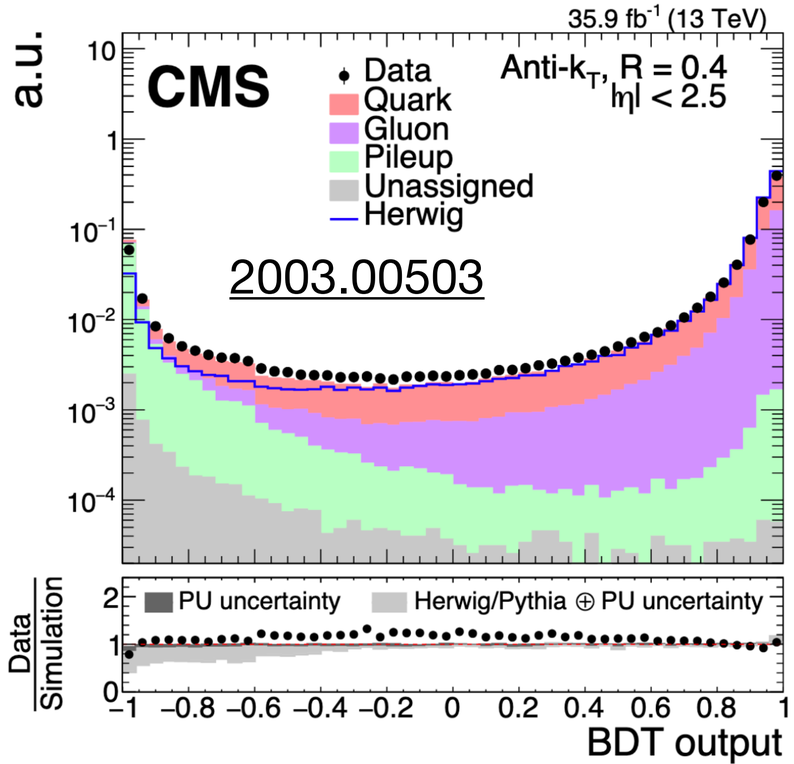


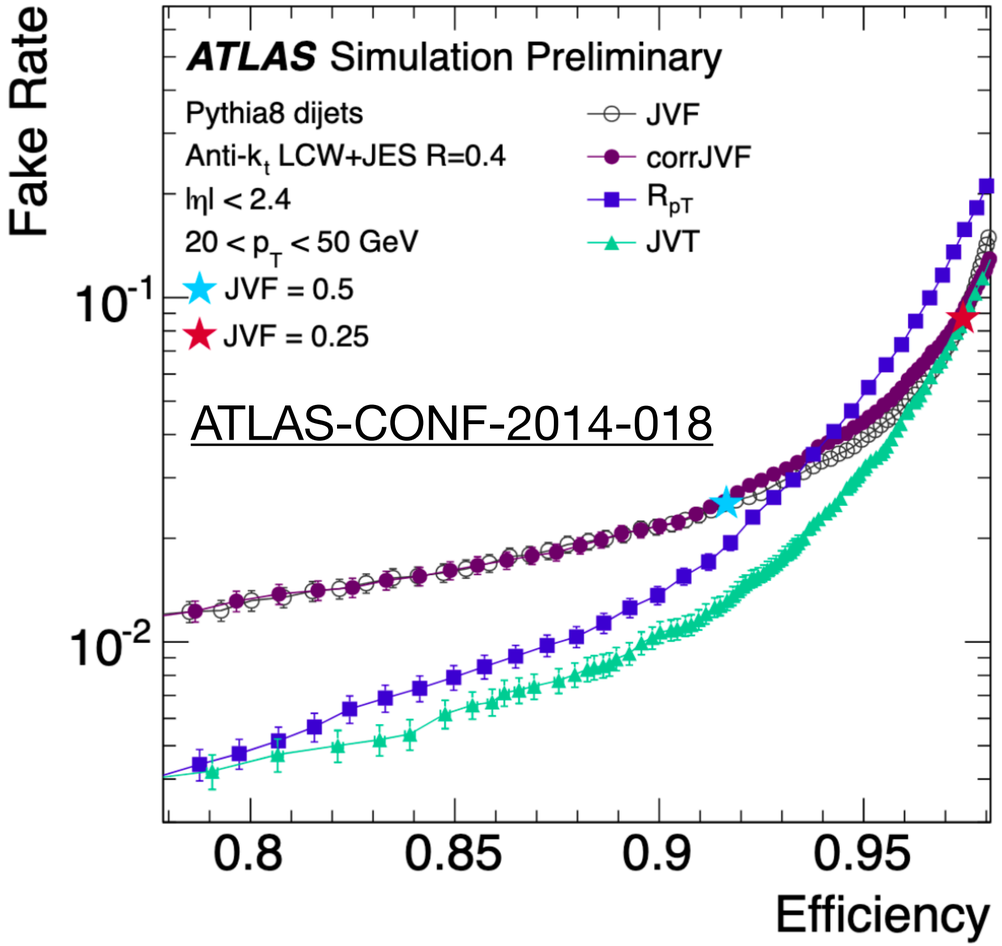




Pileup Jet Tagging

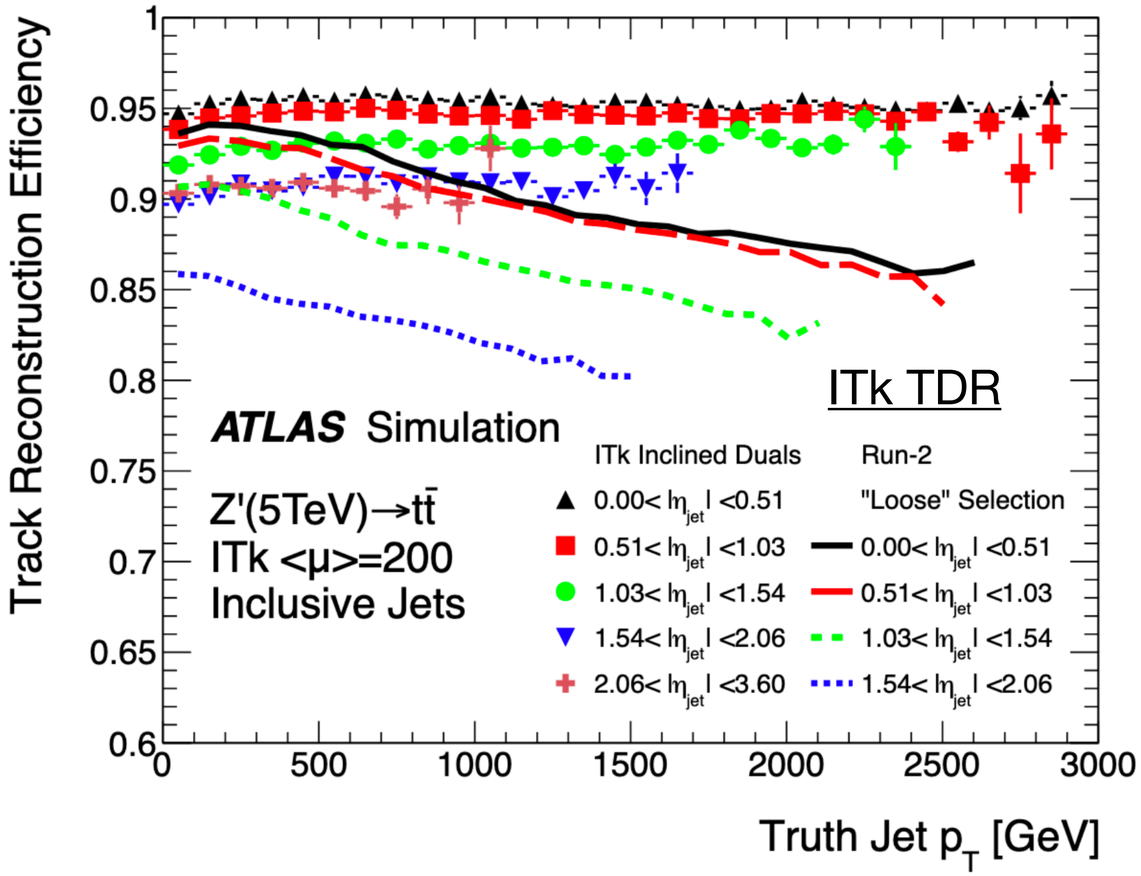
- ATLAS and CMS both have taggers to remove pileup jets
  - Particularly important for low-p_T jets
  - Use jet shapes, charged particle information, and more to identify these jets

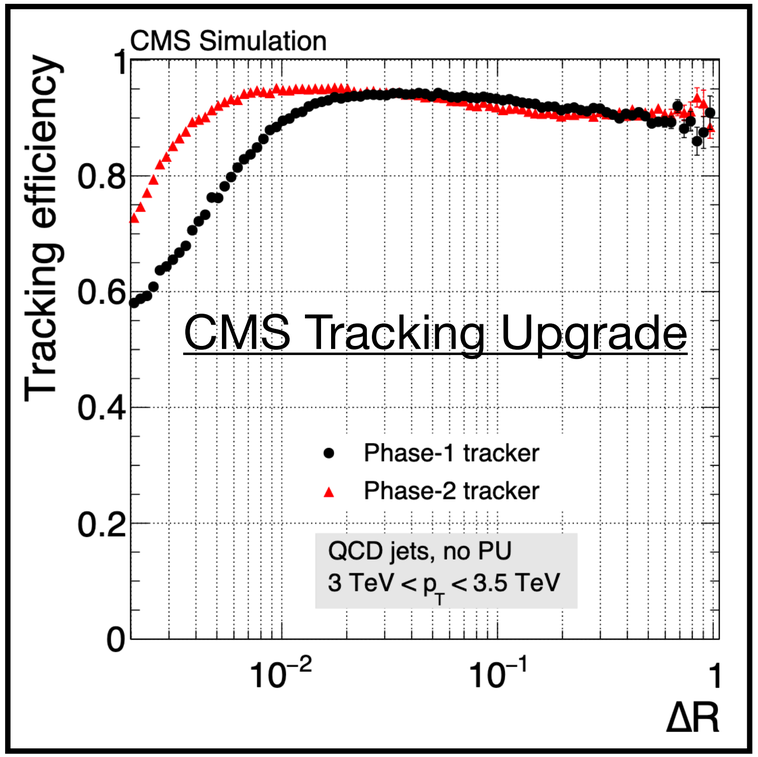




Tracking upgrades

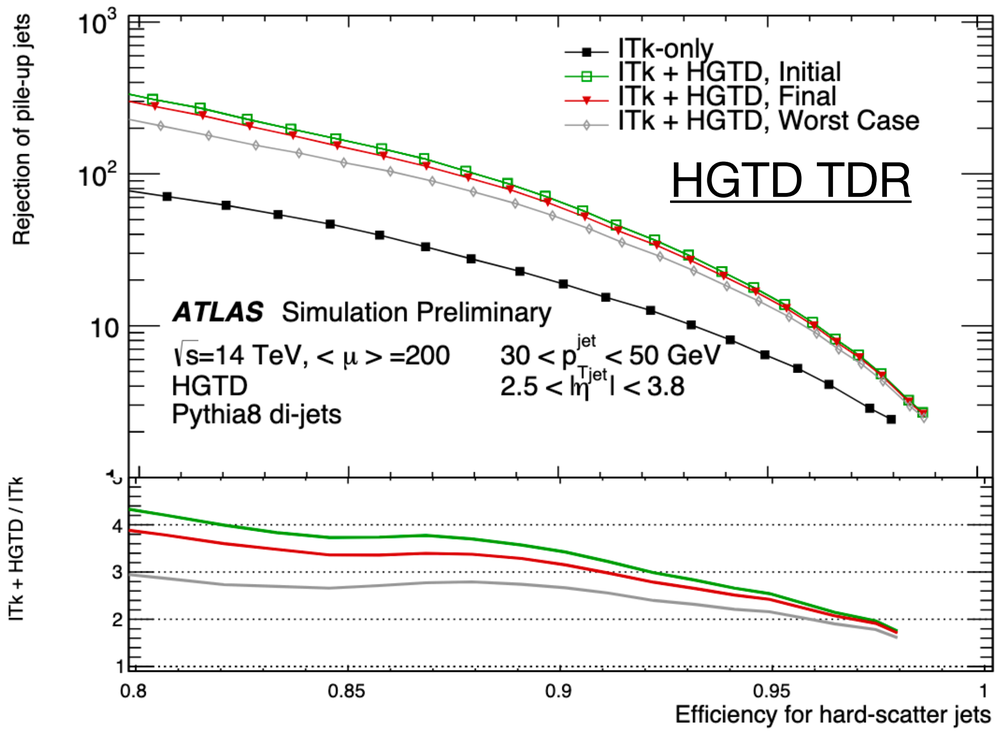
- Track reconstruction difficult in core of jets
  - Difficult to correctly assign hits, merging of hits
- Trackers at the HL-LHC will have better granularity



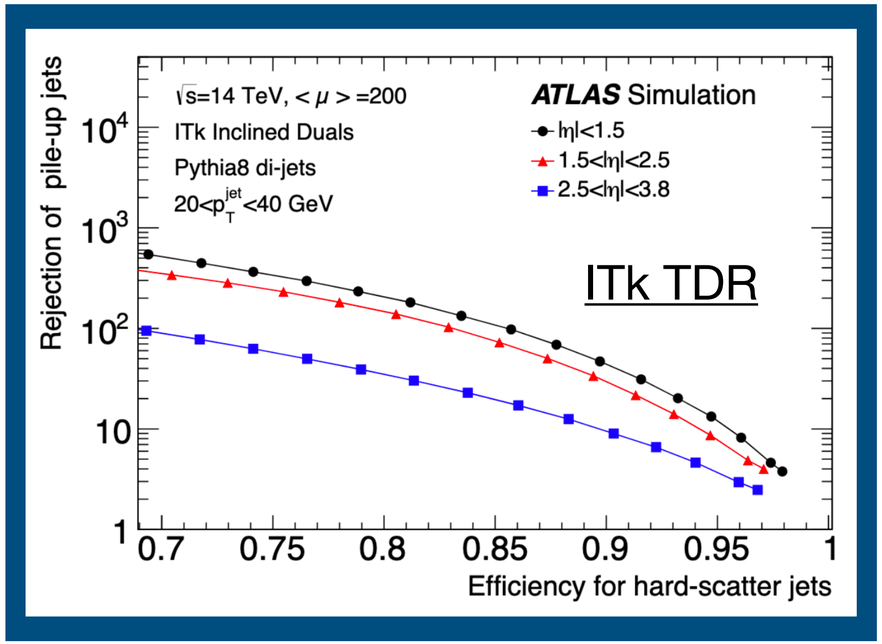


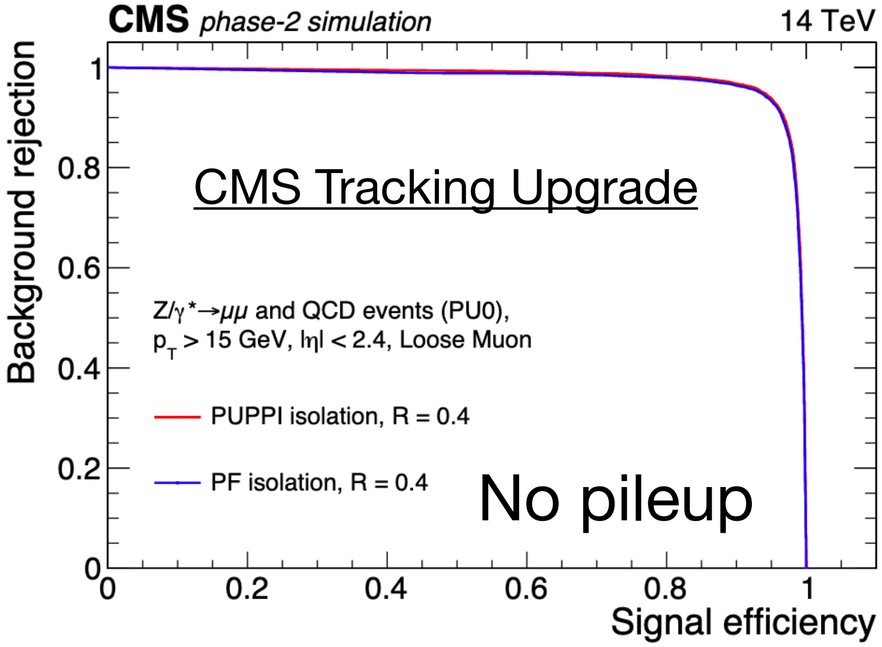
Timing Algorithms

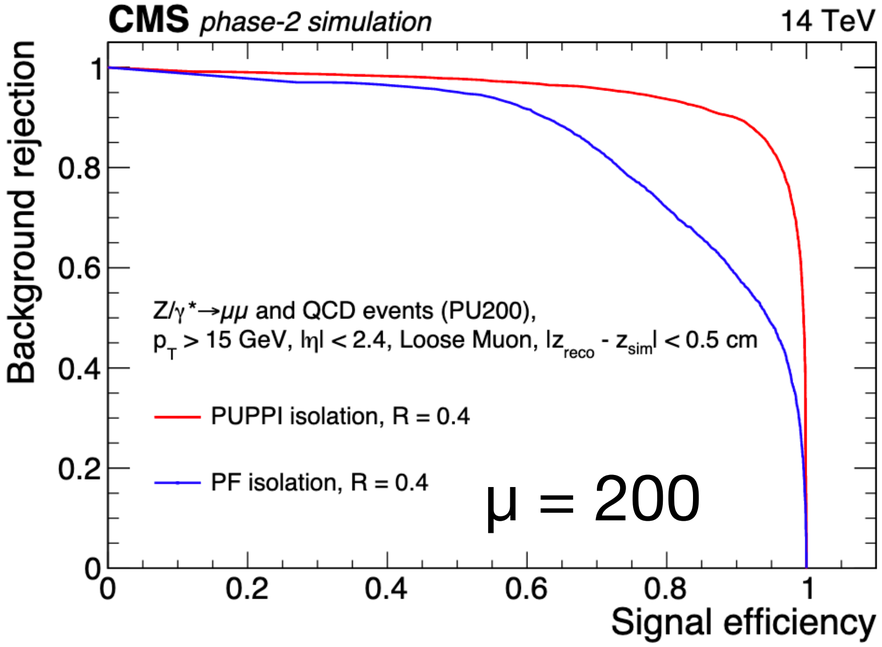
- The ATLAS HGTD will cover a different η region than the CMS timing detector
- Expected to significantly reduce pileup in these regions
  - Impact analyses with forward jets, such as VBS analyses
  - Also relevant for MET calculations



Tracking upgrades







Jet Modeling

- Precision substructure measurements provide a window into QCD across many scales
  - Access to hard splittings and hadronization in a single measurement!

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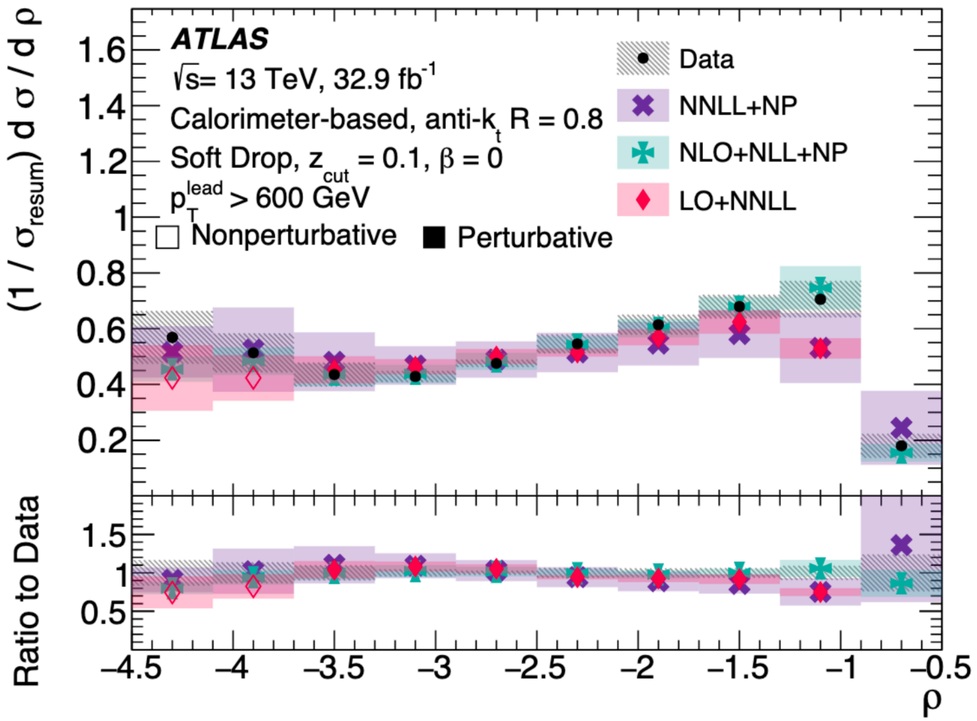

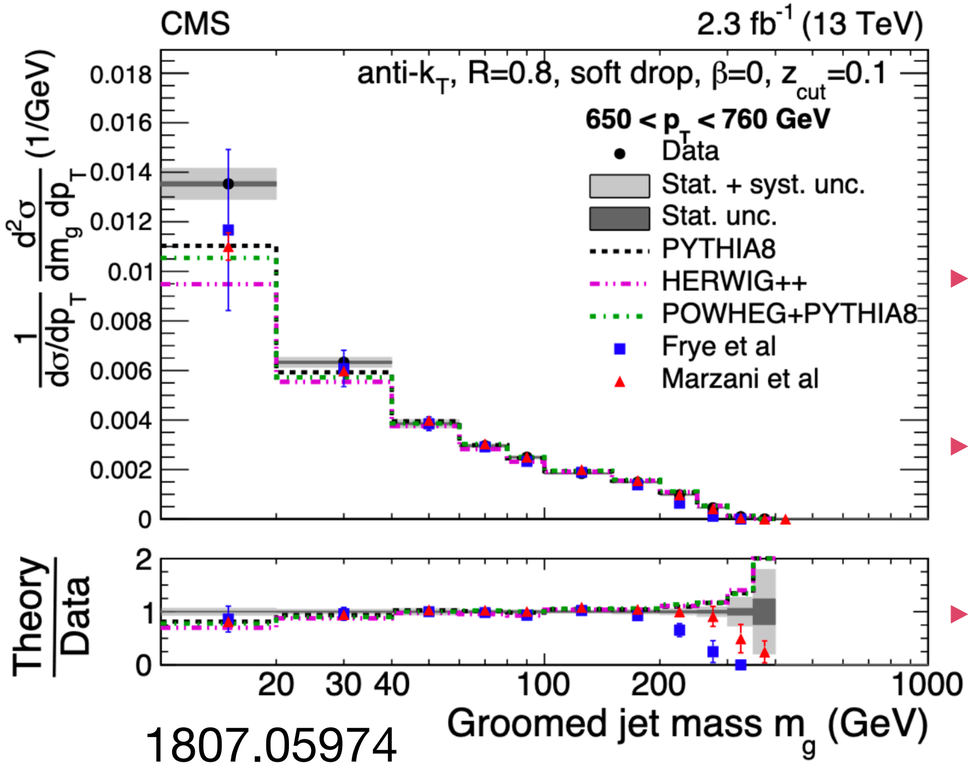

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- Now have precision calculations beyond leading logarithmic accuracy
- Even without theoretical predictions, sensitive to tuning parton showers and hadronization models
- Need to start doing more measurements now to enable improvements for the HLLHC

Particle Flow Algorithms

- Particle flow algorithms typically rely on combining information from the calorimeter and tracker to produce better measurement
  - Usually work best when the tracks and clusters are fairly isolated
- Typically, track resolution is good at low p_T, while calorimeter resolution good at high p_T
- Several challenges related to particle flow reconstruction
  - Track resolution degrades at high energies → still reliant on calorimeter resolution
  - Many tracks may point towards the same calorimeter object → need to think about better algorithms!
- Requires good tracking and calorimeter to work effectively

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