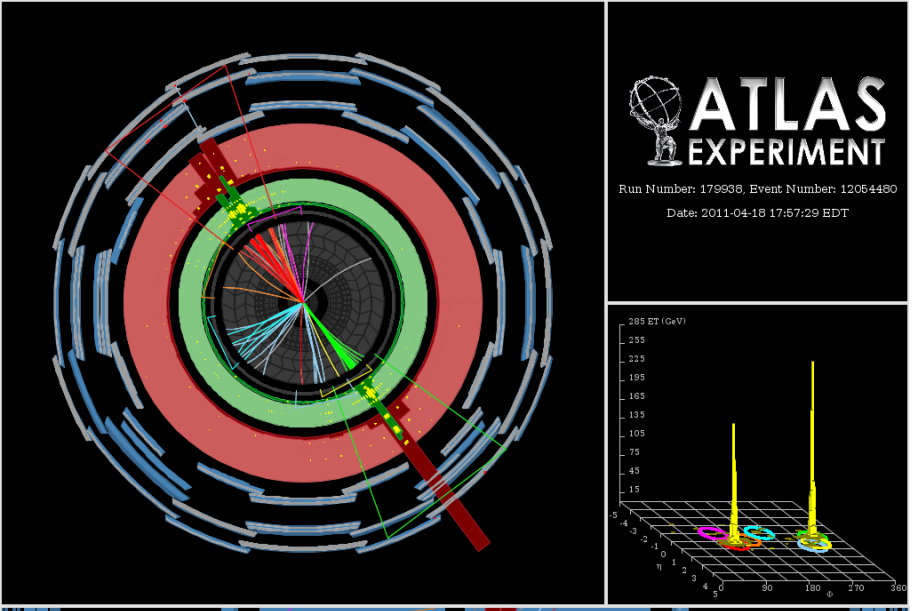
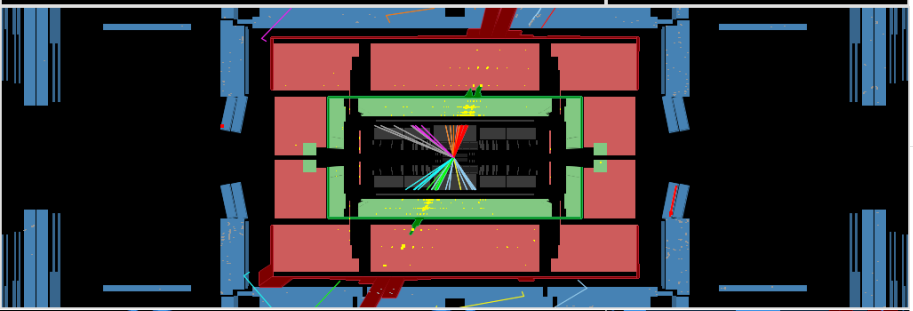
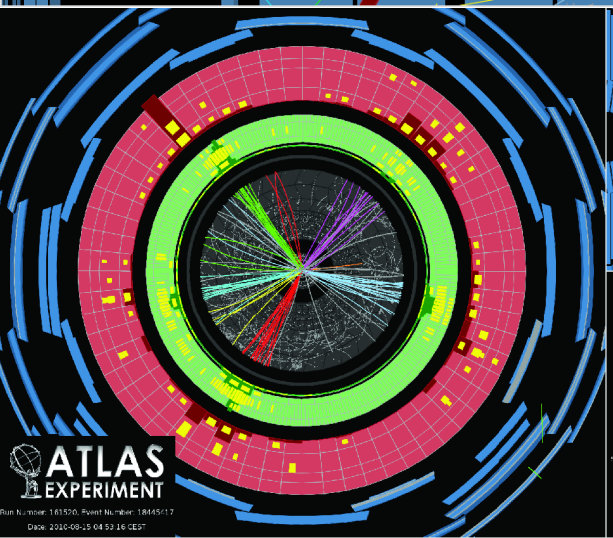
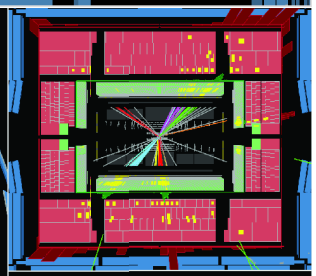
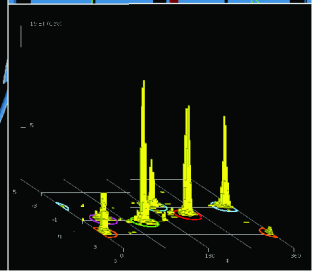
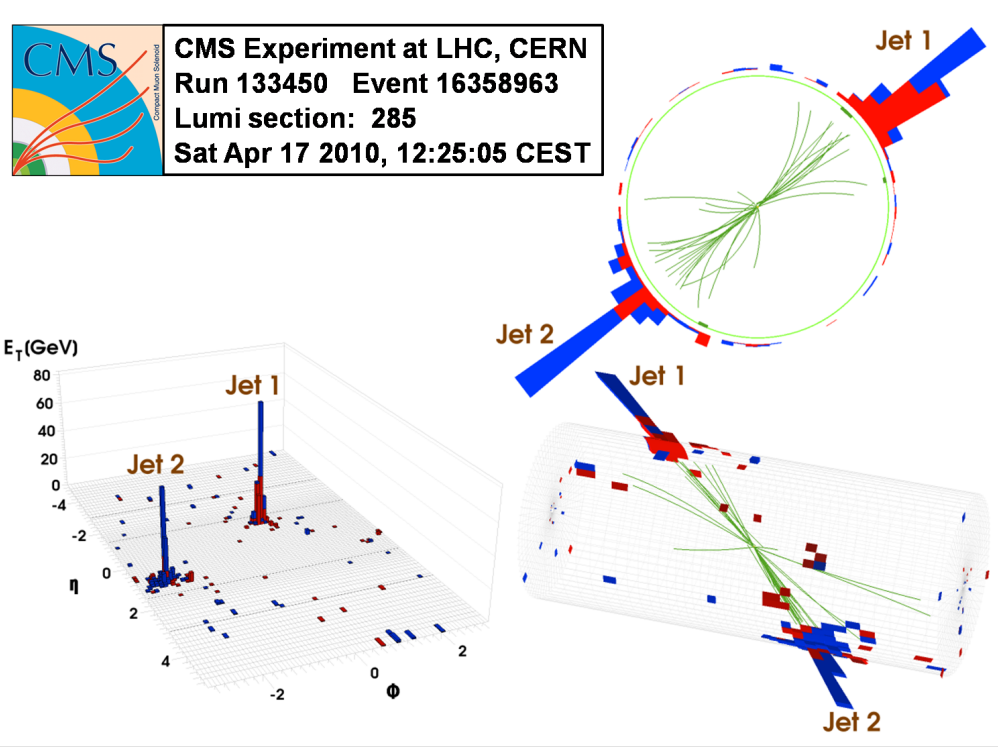












The Experimental Status of QCD

Zach Marshall (CERN)

Lessons from the First Phase of the LHC

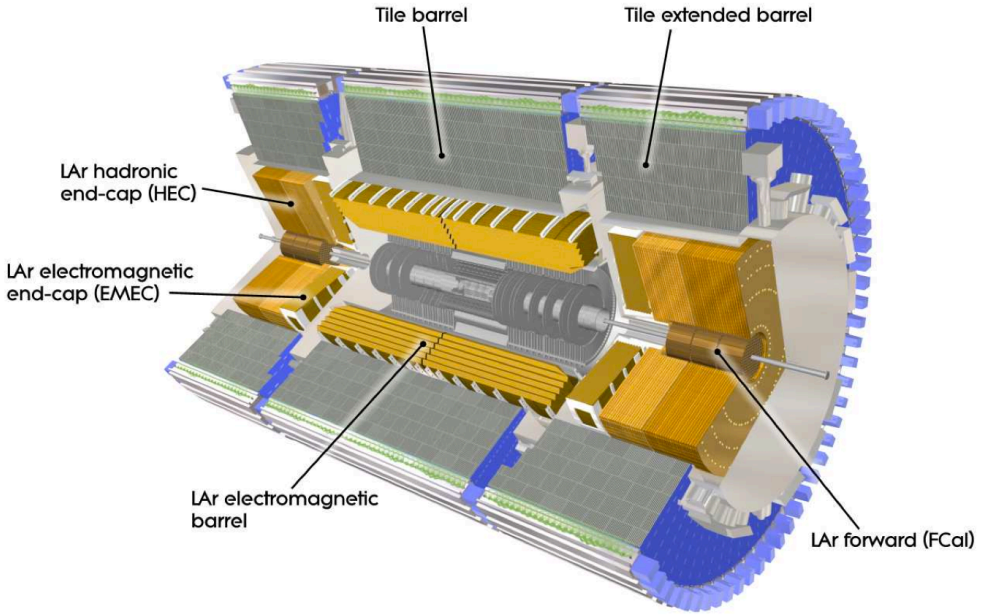
DESY Hamburg, 25 Sept 2012

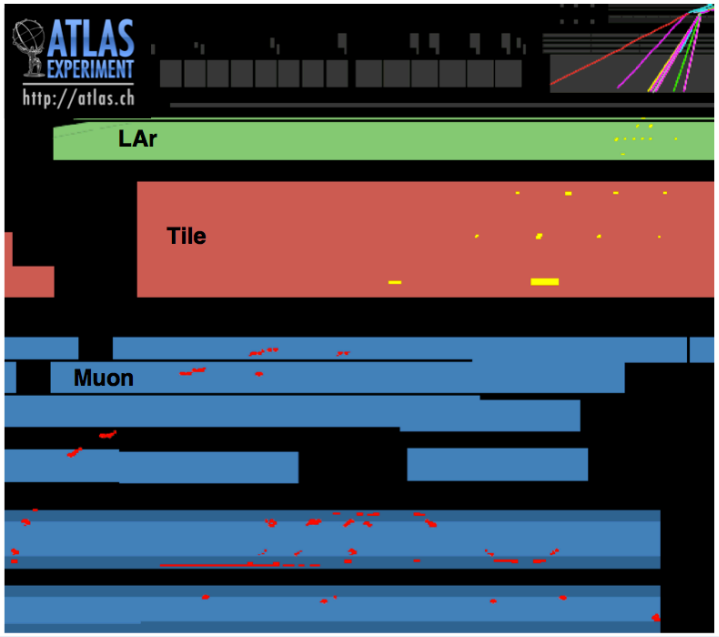
Overview

- Quick reminders of detectors and reconstruction, jet energy scale uncertainties, and associated issues
  - I'll try to focus on the *difference* between ATLAS and CMS
- Standard measurements
  - Many of these distributions are used also for *searches*. Proper Standard Model measurements require the unfolding of detector effects, so you'll see them with somewhat less data.
- Jet properties and substructure
  - Measurements of jet shapes, fragmentation functions, etc are now getting quite extensive. Dependent on numerical models as much as real pQCD theory, but wide-ranging impact.
- Fat jets and their properties
  - The new hot topic for searches – but QCD has to be understood first!
- Jets in heavy ion collisions (briefly)
  - Not standard QCD measurements, but quite interesting!

ATLAS: Calo-centric Jets

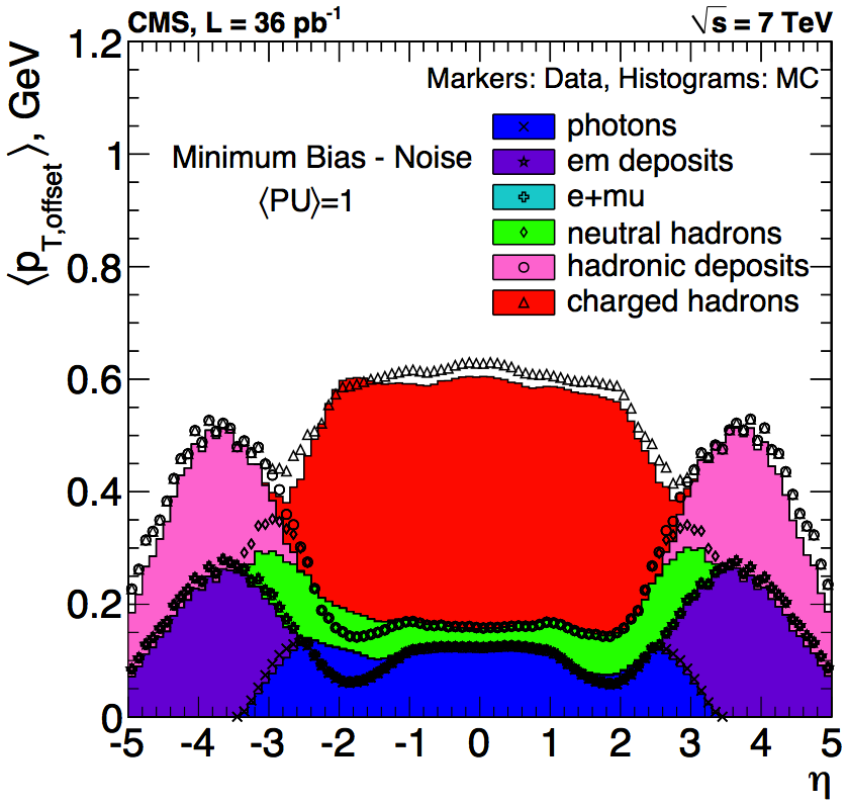
- ATLAS has a thick and high-quality hadronic calorimeter, so simple calorimeter-only reconstruction does well, though punch-through still exists
- Most jets start from *clusters* of energy (for noise suppression)
- Several different calibration techniques to account for non-compensation
- Tracks are used for *corrections* to the calibration, not to replace any calorimeter information
  - Also used to *add* information, in the case of jet-vertex association
- Several calibrated algorithms: anti-k_t R=0.4/0.6/1.2, and C/A R=1.0, 1.2

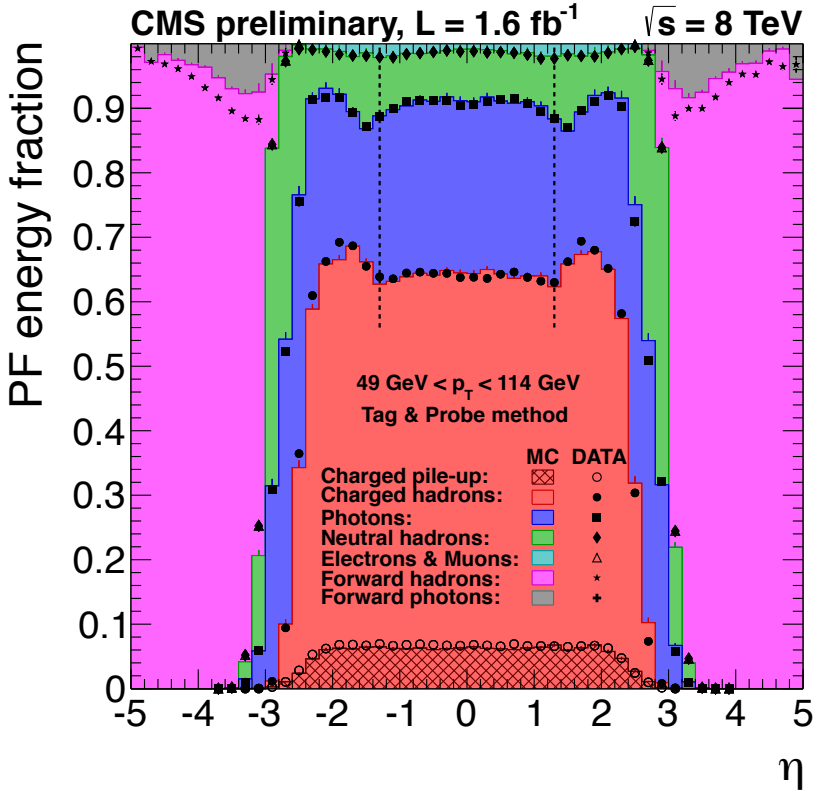




CMS: Global Event Description

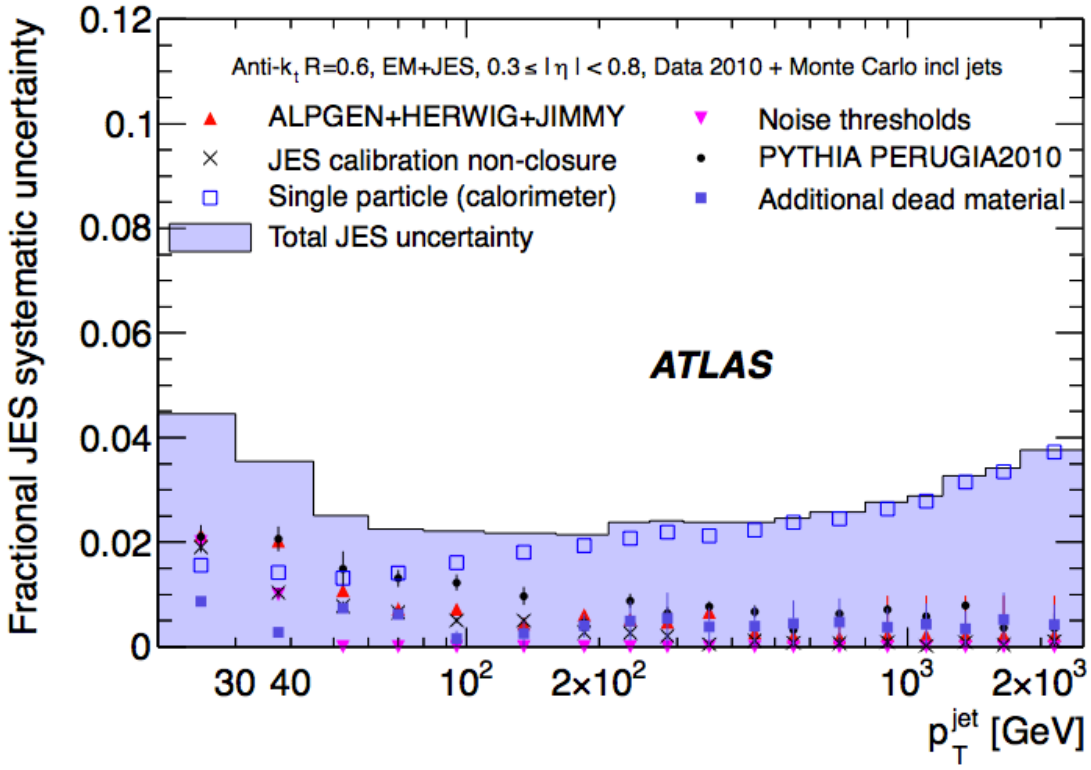
- CMS have an all-silicon tracker used extensively in jet reconstruction
- Particle flow used to *replace* inaccurate calorimeter measurements with more accurate tracker measurements, then sets a component-wise systematic uncertainty
- Requires classifying energy deposits in the calorimeter as EM or hadronic and calibrating them separately
- Focus on anti-k_t jets with R=0.5/0.7; also non-particle flow jets (calo, calo+track)

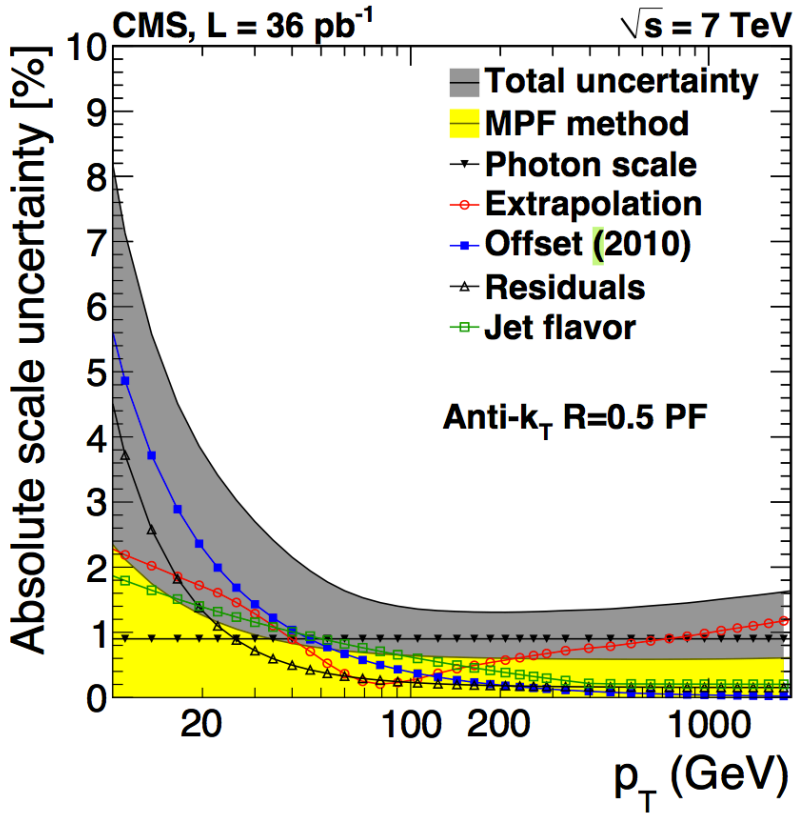




Jet Calibration

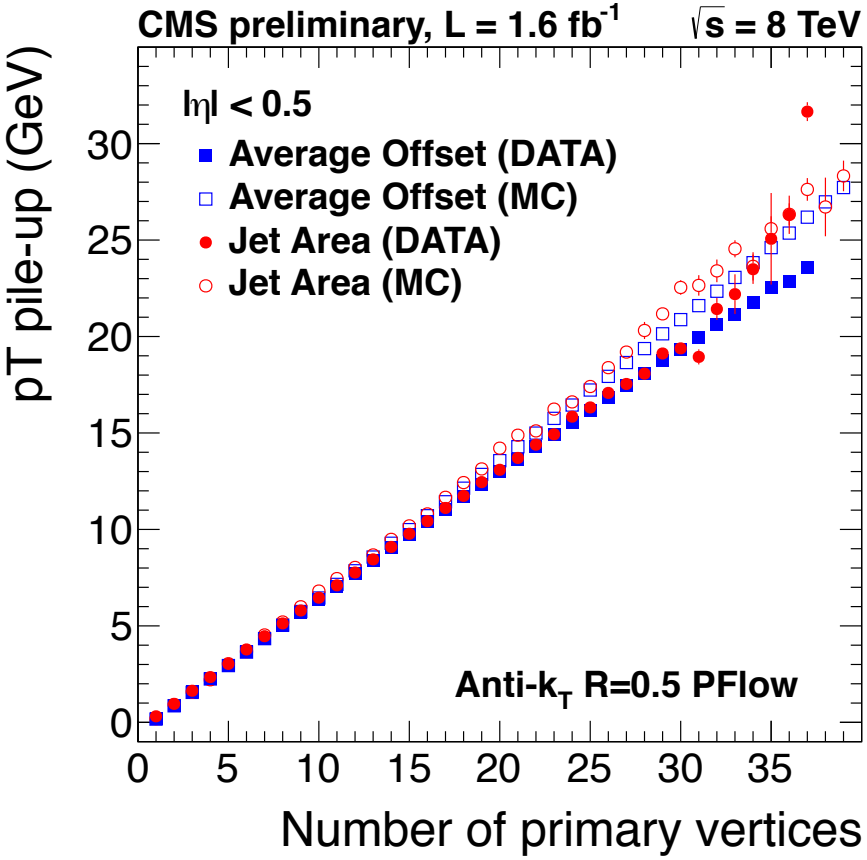
- Both collaborations calibrate to *hadron-level* jets
  - Not the same as parton-level calibrations!
  - Both wrote long papers on our 2010 calibrations, arXiv:1107.4277 and arXiv:1112.6426
- We're both still finishing documentation of the *2011* calibration!
  - More papers, documentation, and discussion coming soon

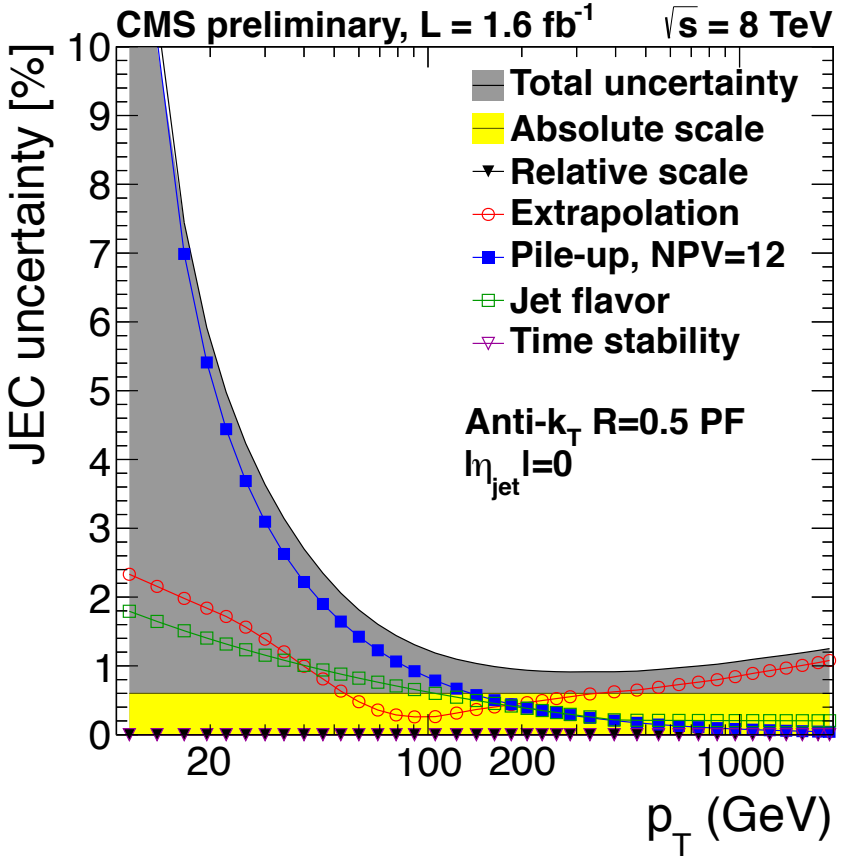




Pile-Up

- In 2011, and even more in 2012, additional pp collisions in each bunch-crossing is a *major* experimental challenge
  - ~10 in 2011, ~15 in 2012, with a tail over 30!
  - Probably the primary reason QCD measurements are slow to come out

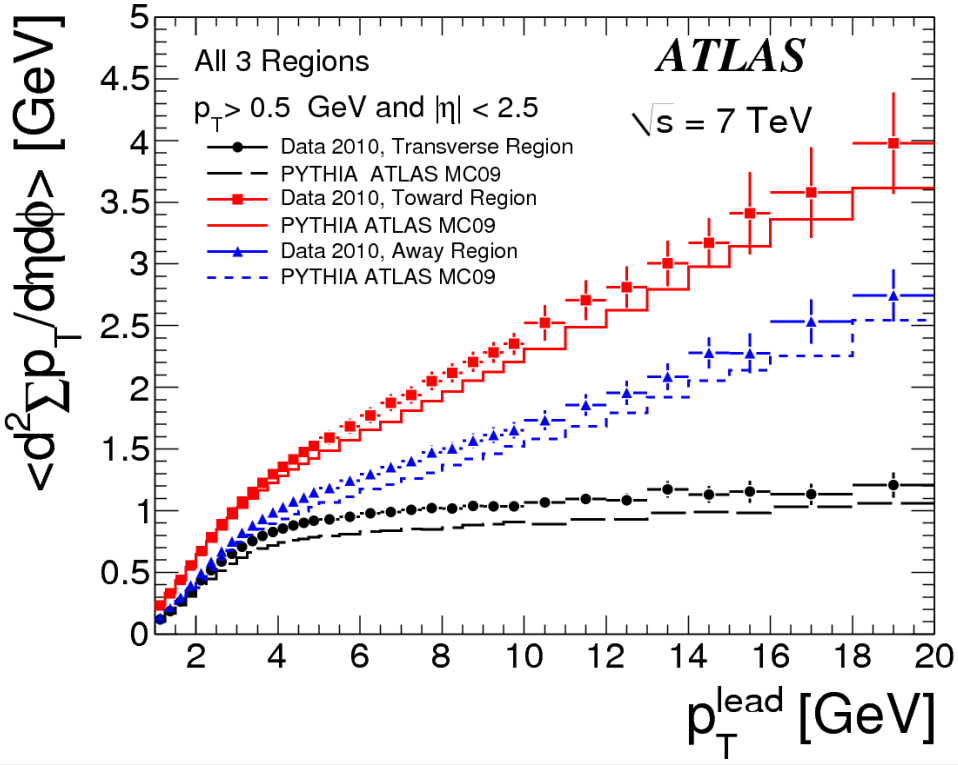


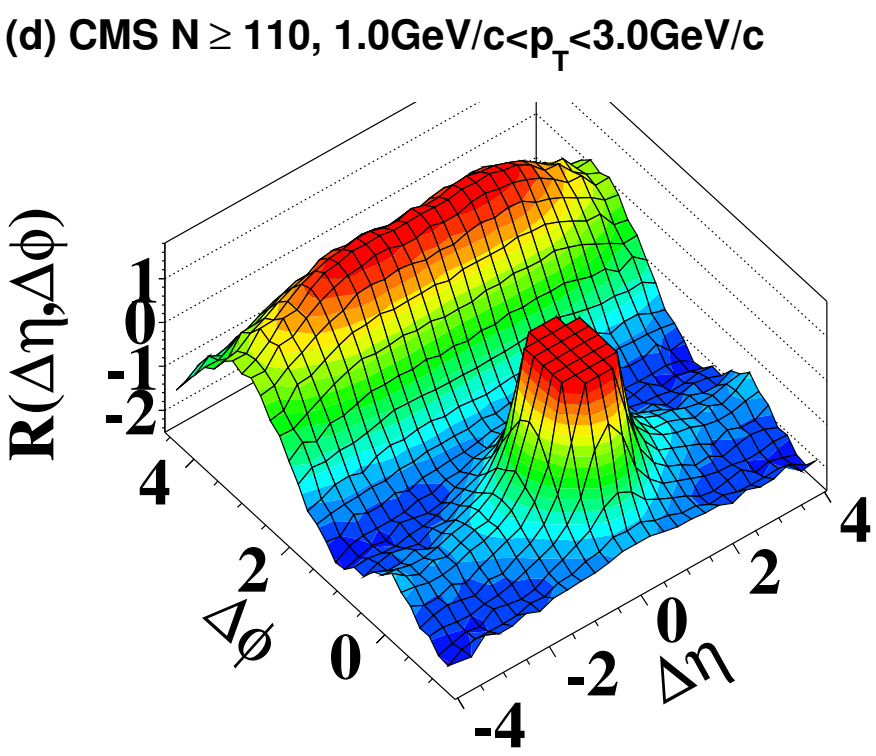


Soft QCD

arXiv:1012.0791 (L)
arXiv:1009.4122 (R)

- I won't say much here about soft QCD except to say that we have measured it in quite some detail (e.g. the usual towards-away-transverse UE)
- So far, the most useful thing to come out of it are the generator tunes that give us faith in our modeling of the soft part of the interactions
- Some significant interest was generated around CMS's angular correlations (right), but it seems to have faded somewhat

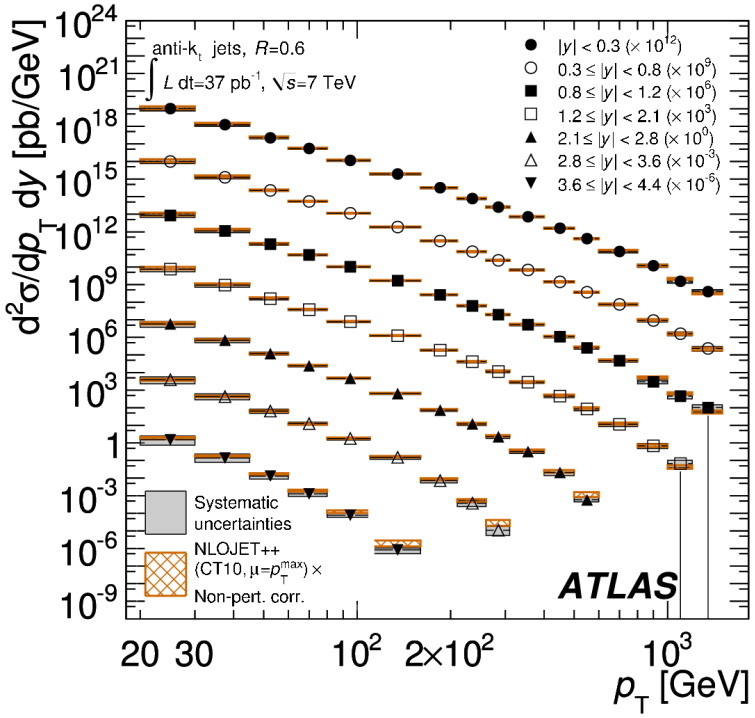


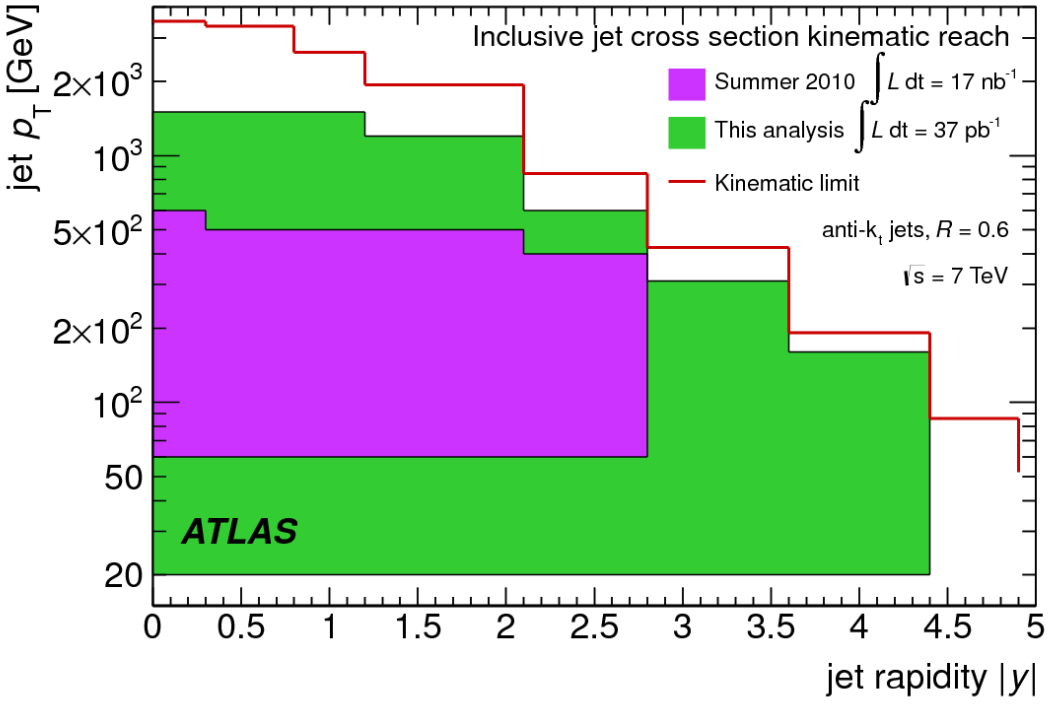


Inclusive Jet Cross-Sections

arXiv:1112.6297
arXiv:1106.0208

- Both experiments have published 2010 cross-section measurements over a huge p_T and η range – almost the entire kinematically accessible region!
- >8 orders of magnitude in cross-section – an impressive achievement, requiring *excellent* understanding of the detector and jet energy scales
- Measured for 4 jet sizes: 0.4 (ATLAS), 0.5 (CMS), 0.6 (ATLAS), 0.7 (CMS)
  - Plans to measure R-dependence explicitly for both ATLAS and CMS

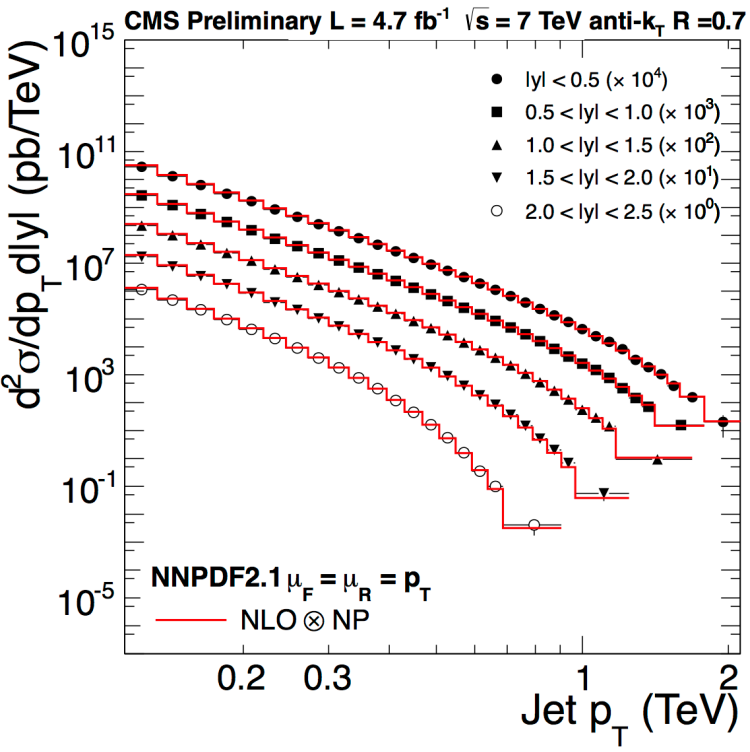


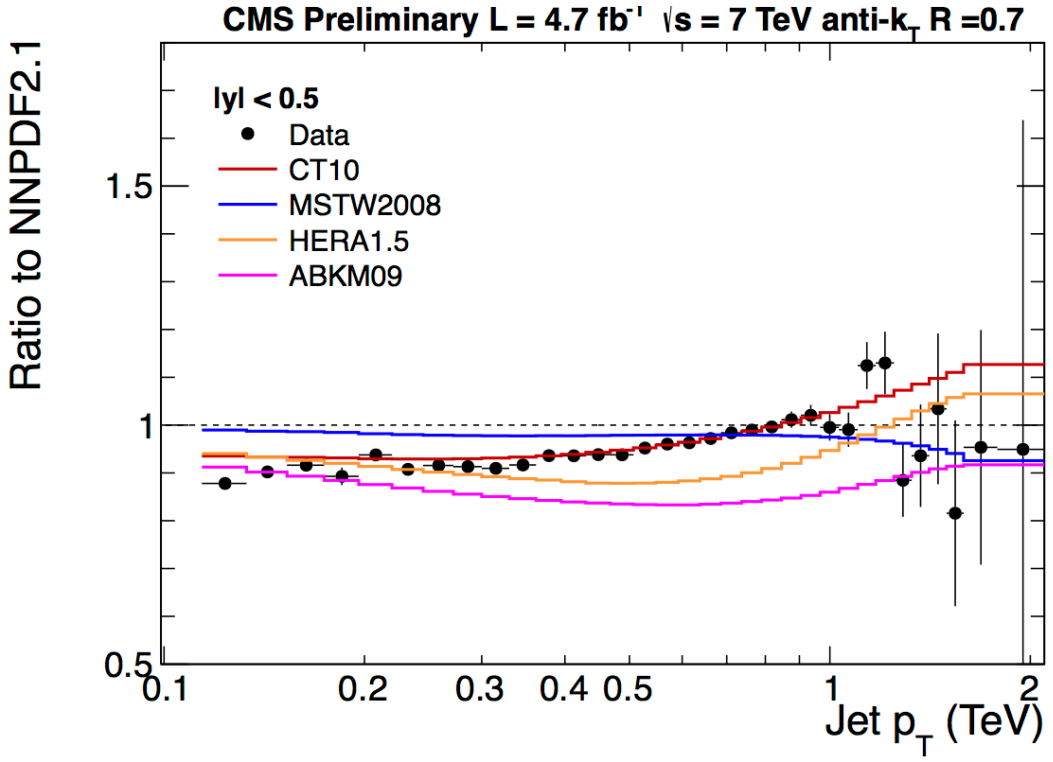


Cross-Sections and PDFs

CMS-PAS-QCD-11-004

- Inclusive cross sections are now feeding into PDF determination, particularly at very low x and high Q^2
  - Note that 2011 data are still preliminary (unpublished!)
- This is always a slower process than a new physics search
  - No indication of any BSM physics here!
- Expect 8 TeV results next year to further constrain PDFs

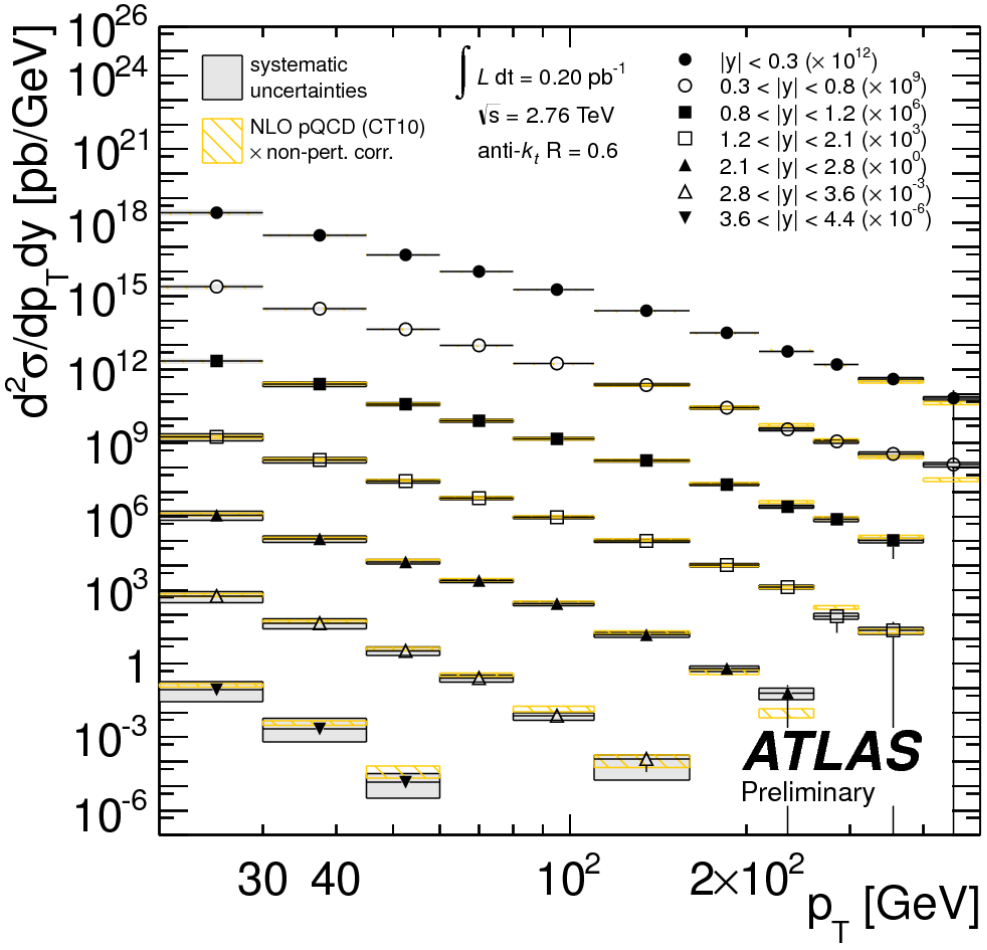


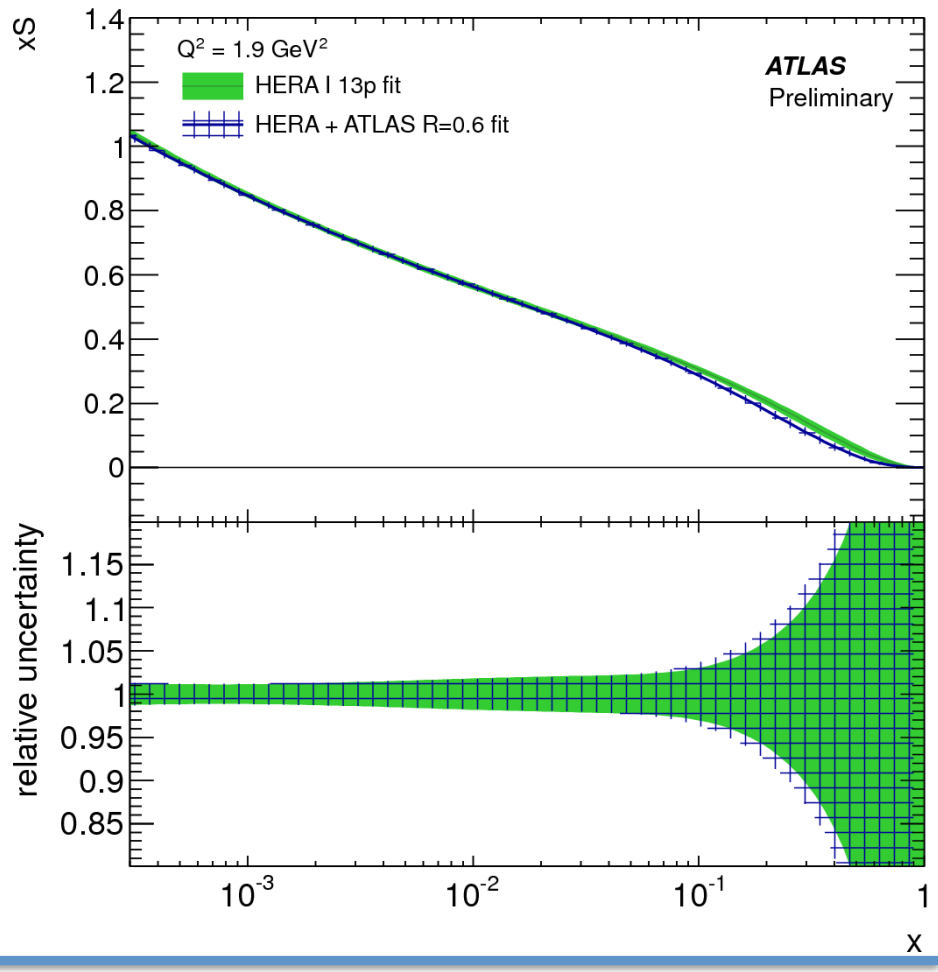


PDFs at Several Energies

Web Only

- Now we've run at four center of mass energies (0.9, 2.76, 7.0, 8.0 TeV)
- All the different energies allow significant PDF constraints with our jet measurements – and more energies will come after the shut down!

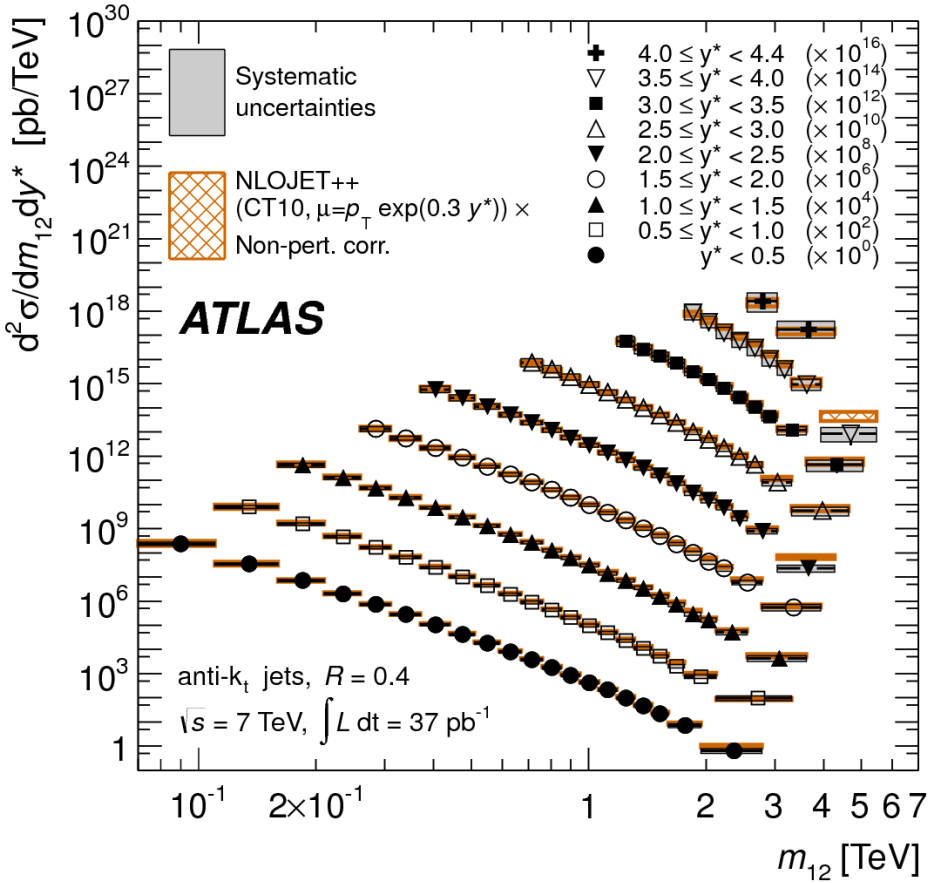


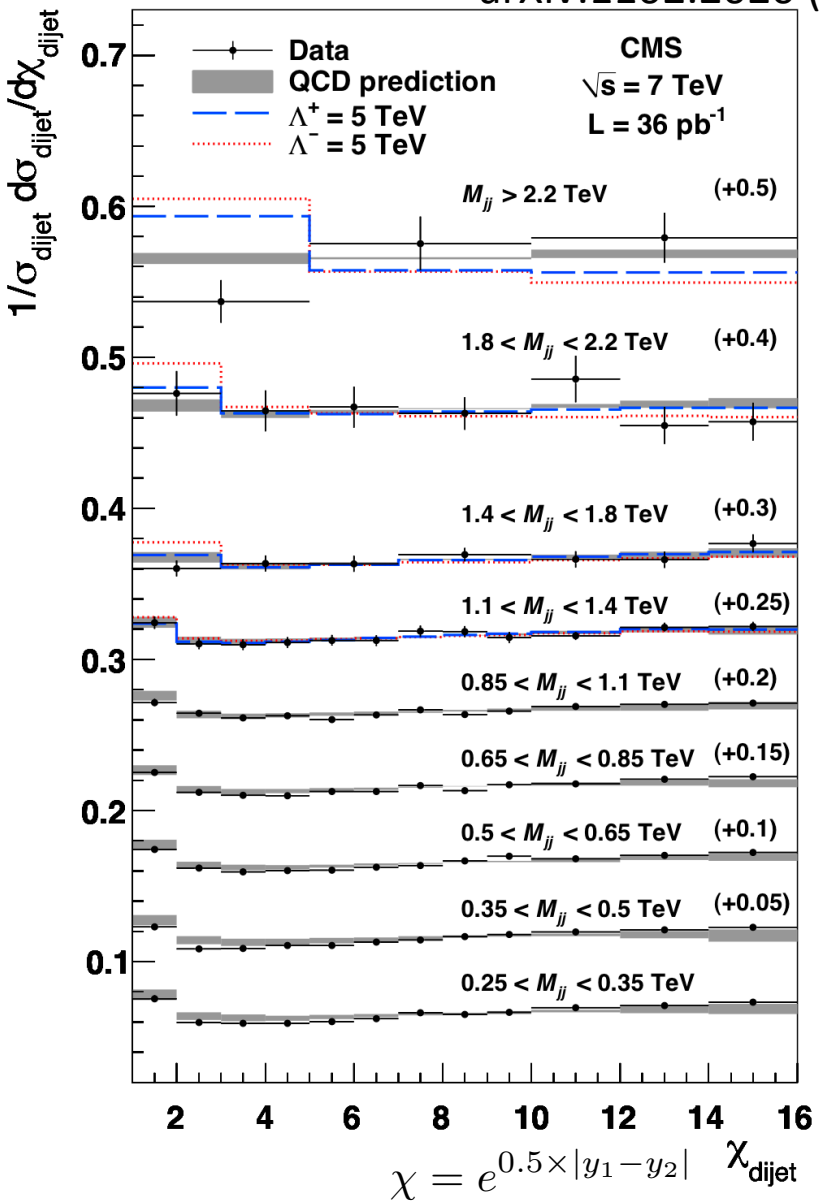


Mass Cross-Sections

arXiv:1112.6297 (L)
arXiv:1104.1693
arXiv:1102.2020 (R)

- Di-jet invariant mass and χ distribution also measured to be in excellent agreement with theory – no quark compositeness hiding here!

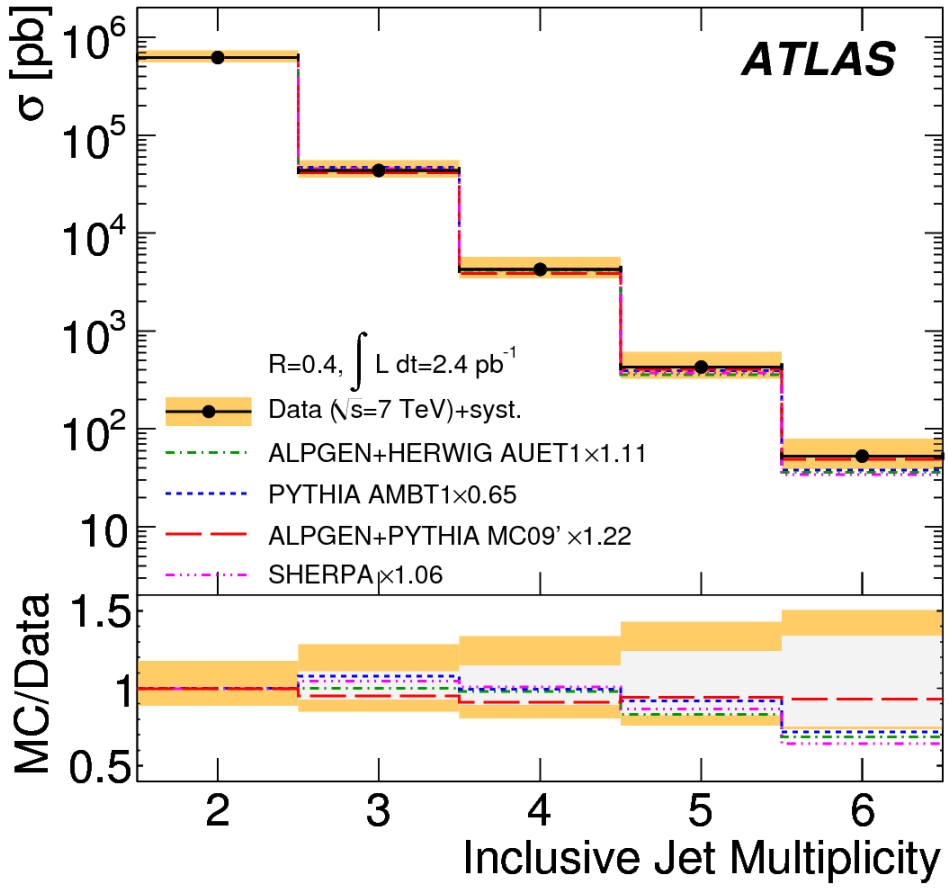


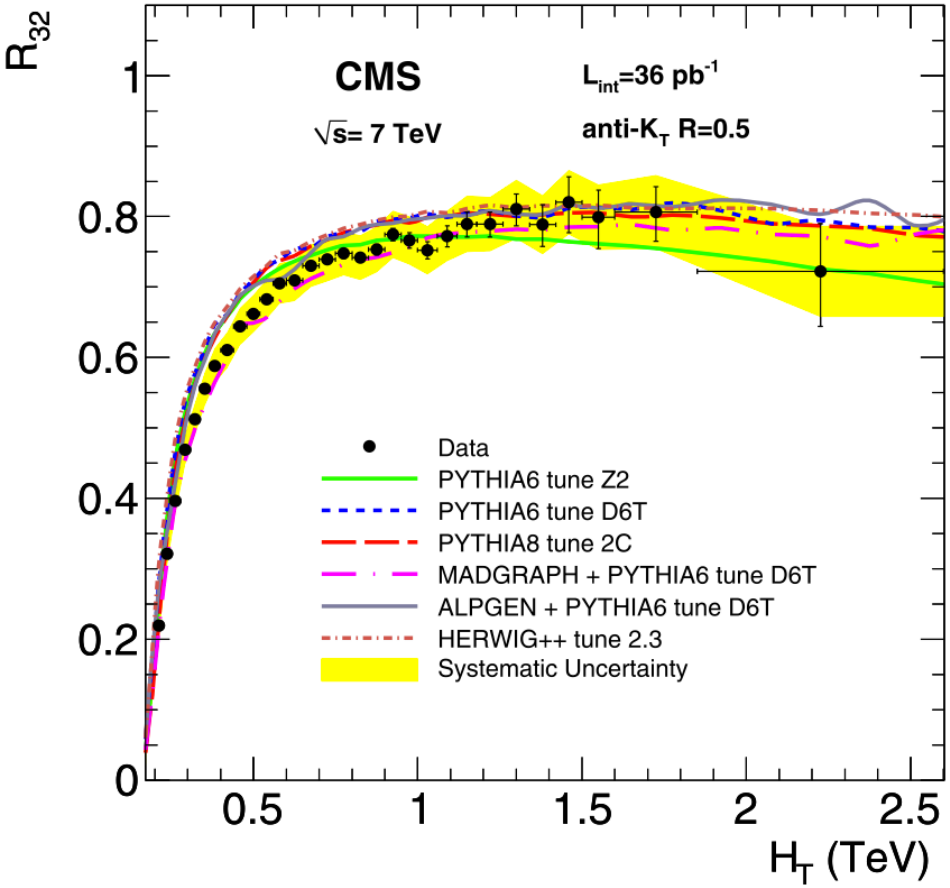


Multiplicity Distributions

arXiv:1107.2092 (L)
arXiv:1106.0647 (R)

- Multi-jet distributions are *very* pile-up sensitive, so unfolding the current data is quite difficult. But measurements with more data and multiplicities up to 10 are coming…

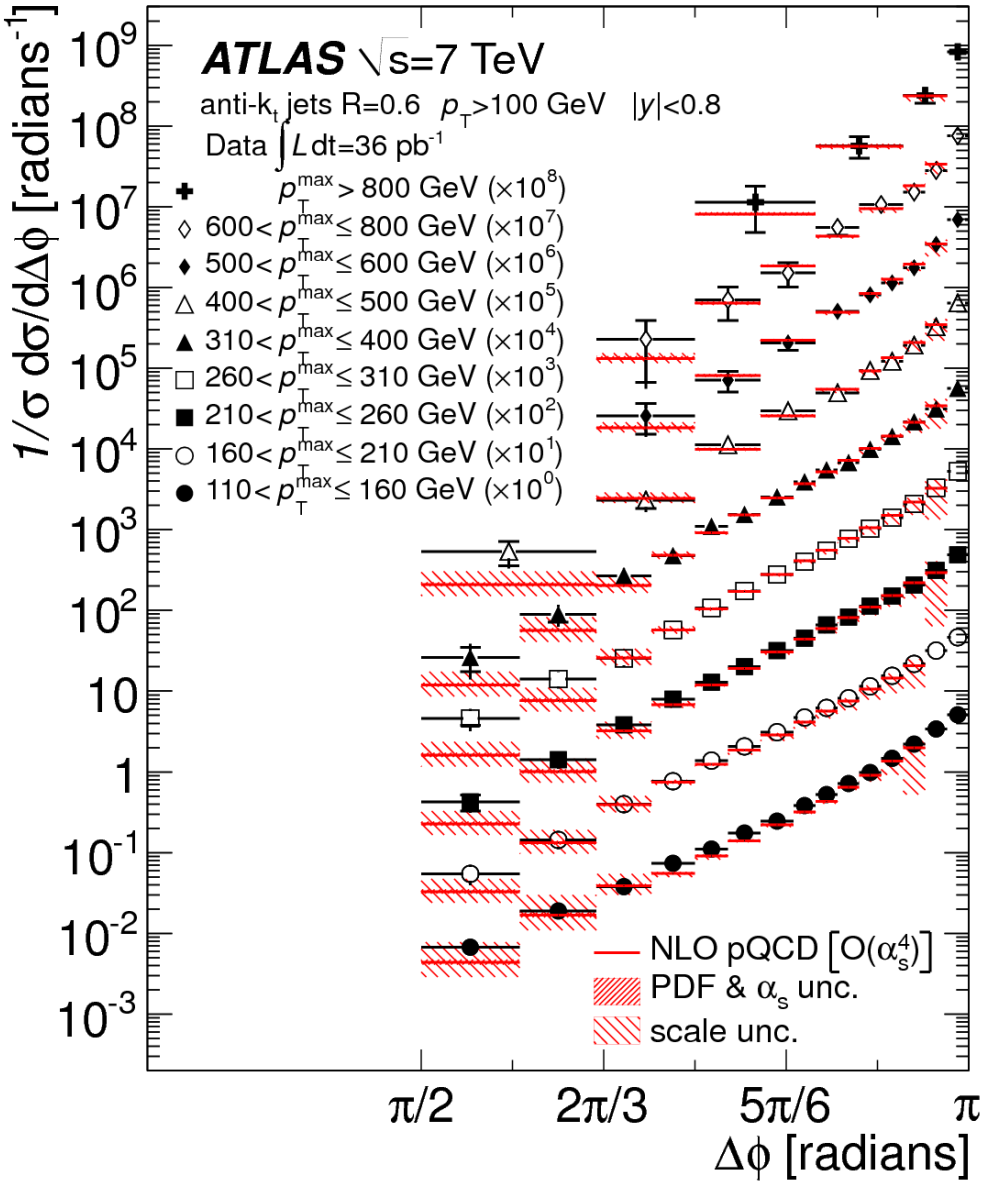




Angular Distributions

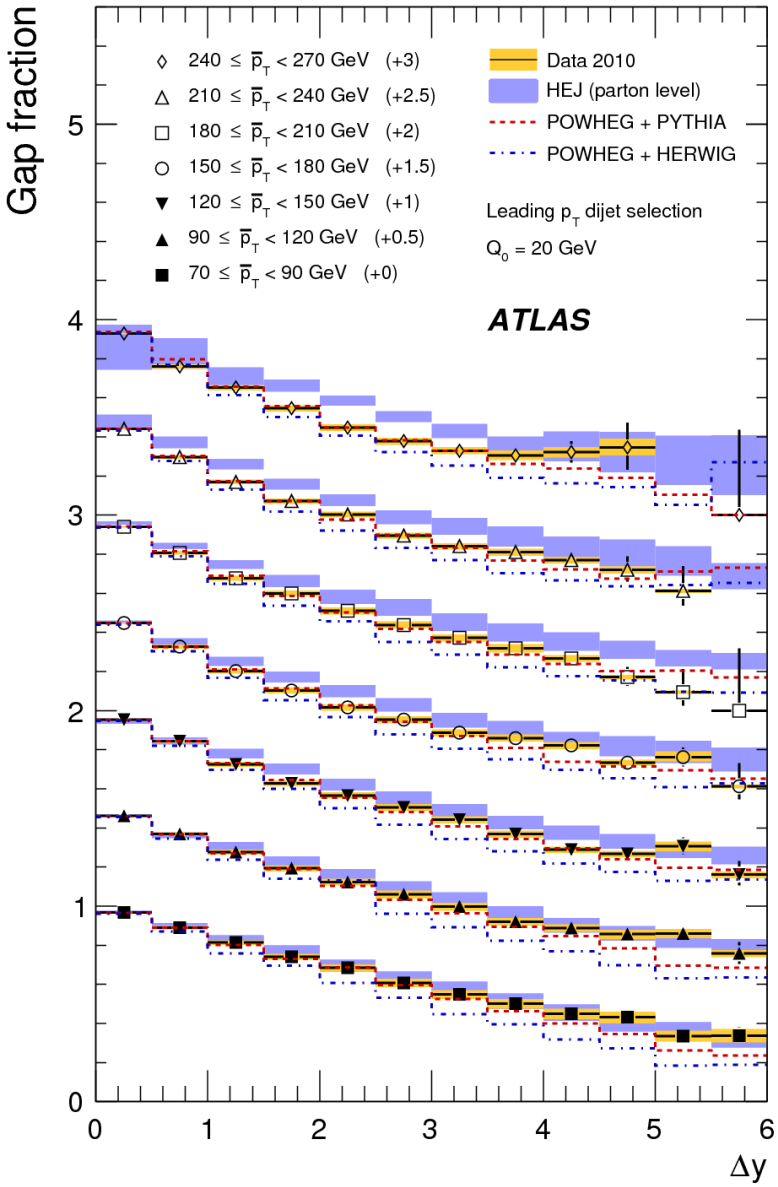
arXiv:1102.2696 (R)
arXiv:1101.5029

- $\Delta\phi$ de-correlations must be well-understood and well-modeled to trust many new physics searches
- Depend greatly on jet multiplicity and splitting effects
- Tails also can depend on the modeling of backgrounds like $Z \rightarrow \nu\nu$+jets
- Again, excellent modeling, excellent agreement with pQCD



Rapidity Gaps

arXiv:1107.1641 (R)
arXiv:1204.0696

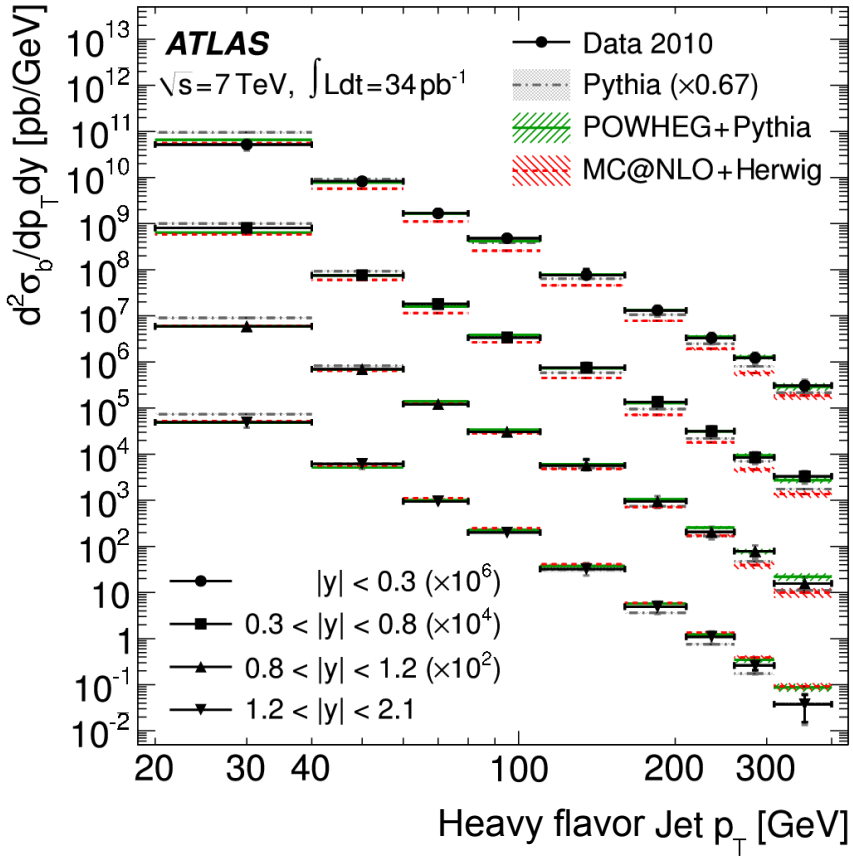


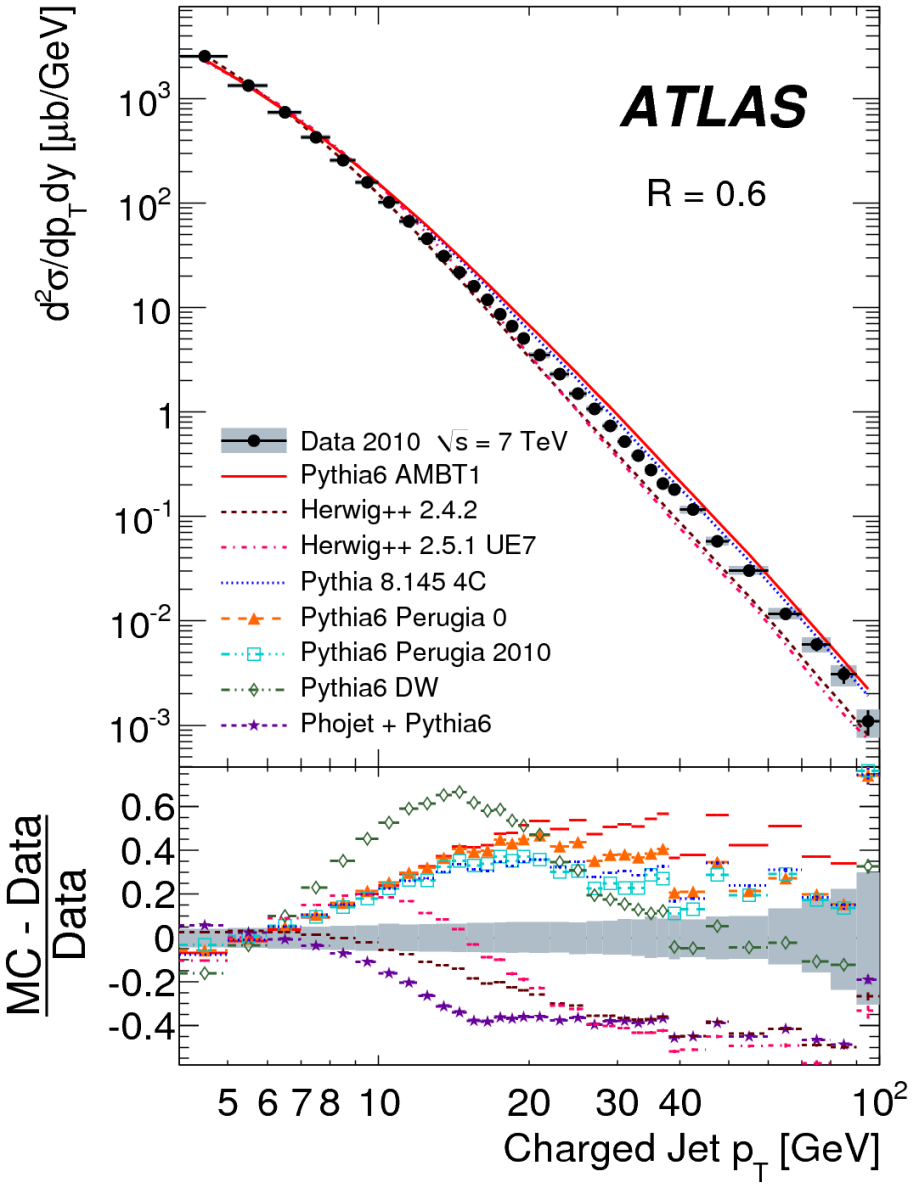
- Fraction of events without a jet (with a gap) between the two highest-p_T jets
- Studies of wide-angle QCD and soft-scale gluon emissions, help with modeling for gluon fusion-like variables
- Some differences are on the scale of the difference between Pythia and Herwig showering, others slightly larger
  - Alpgen doesn't do well here, actually!
- Generally well modeled by Powheg+Pythia
- HEJ, parton-level only, presumably missing some parton shower effects that become important at high p_Ts
- BFKL-motivated generators generally don't do as nice a job of describing the data

Alt. Cross-Section Views

arXiv:1109.6833 (L)
arXiv:1107.3311 (R)

- More complicated cross-section measurements will come with better detector understanding and time
- Several heavy flavor x-section measurements are underway

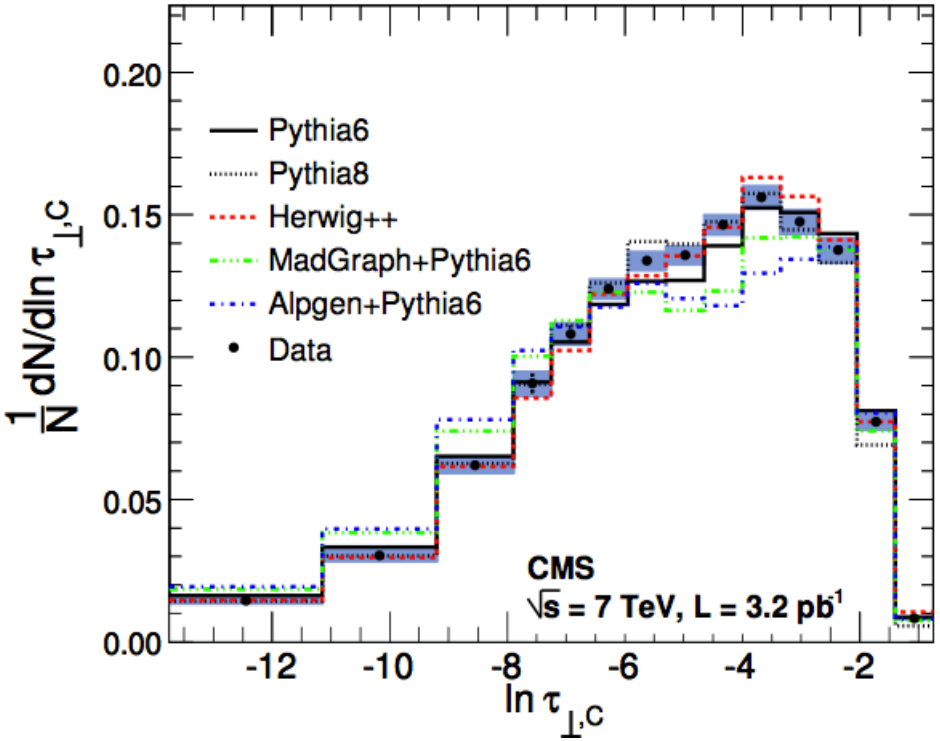


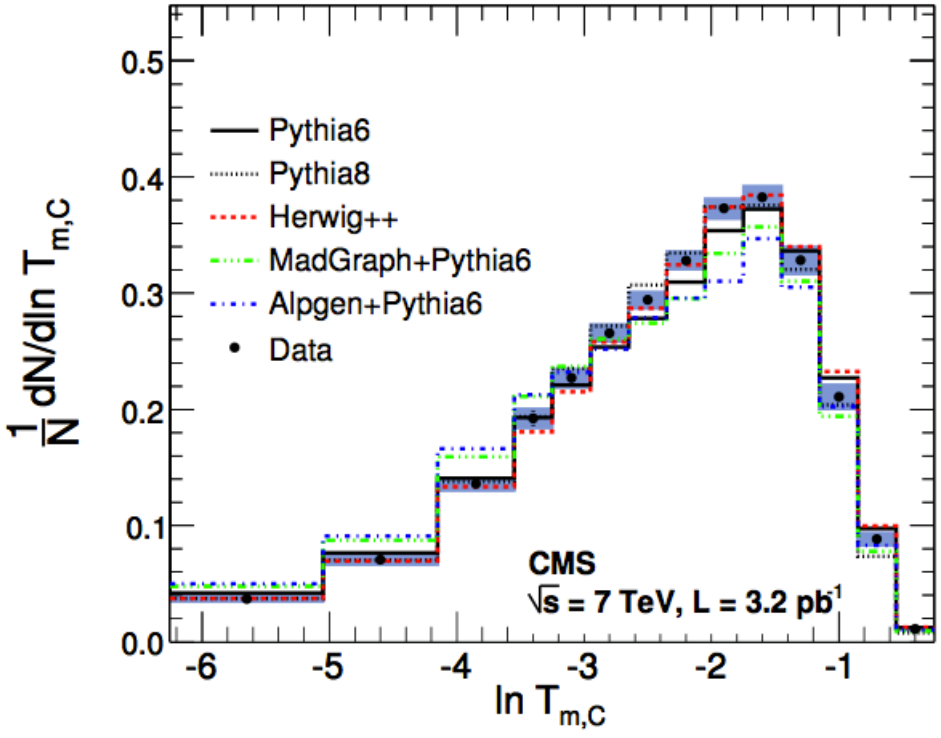


Event Shapes

arXiv:1102.0068 (L&R)
arXiv:1206.2135

- Event shapes (major and minor thrust, sphericity, aplanarity, and third jet resolution parameter) measured in 2010 data
- Described *very* well by the standard MCs
- ATLAS sees far better agreement with Alpgen+Herwig
  - Indication of the sensitivity of these features to *tuning*. One cannot claim that Alpgen will do better *only* because it is 2→N in the matrix element!

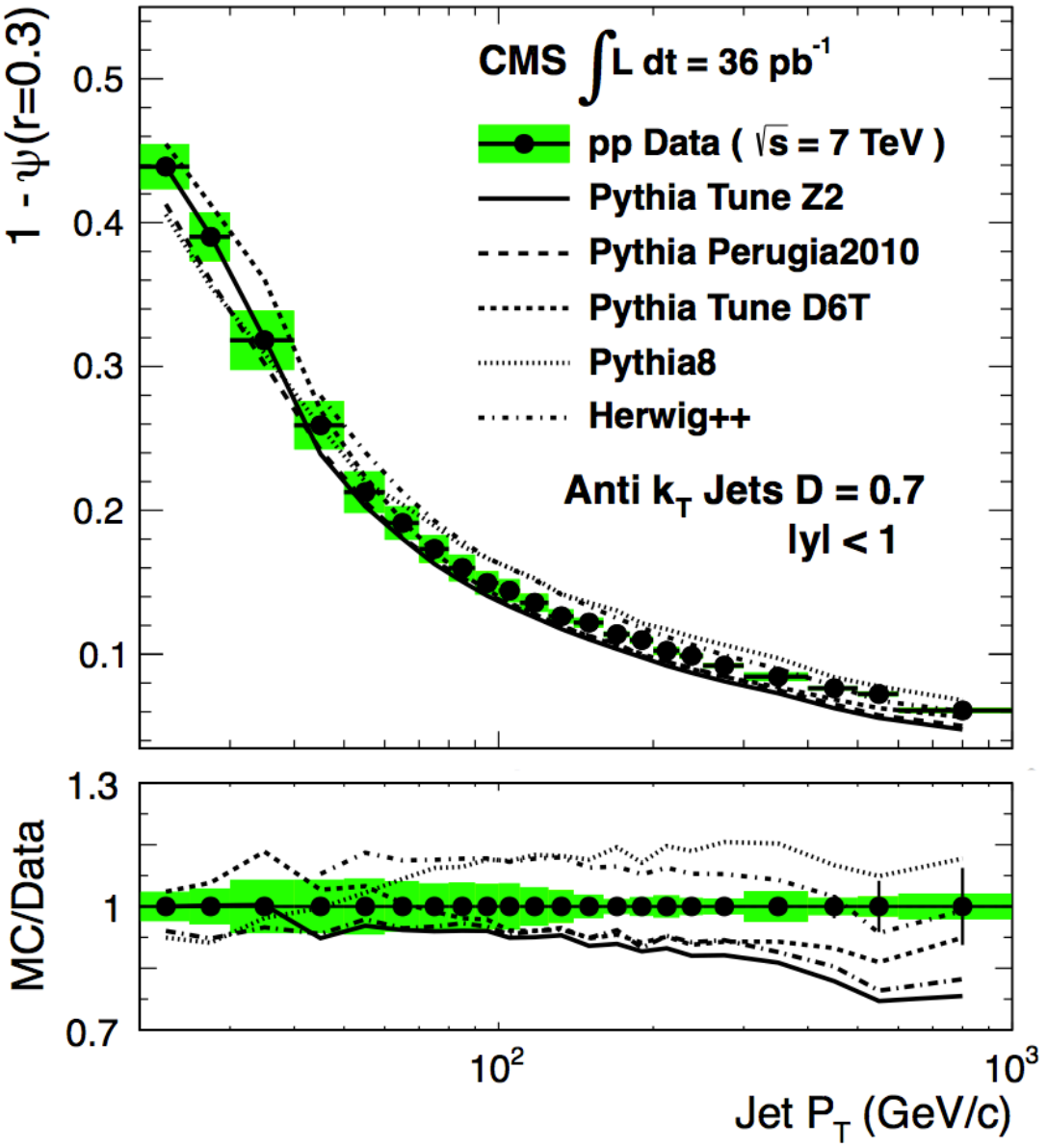




Classical Jet Shapes

arXiv:1204.3170 (R)
arXiv:1101.0070

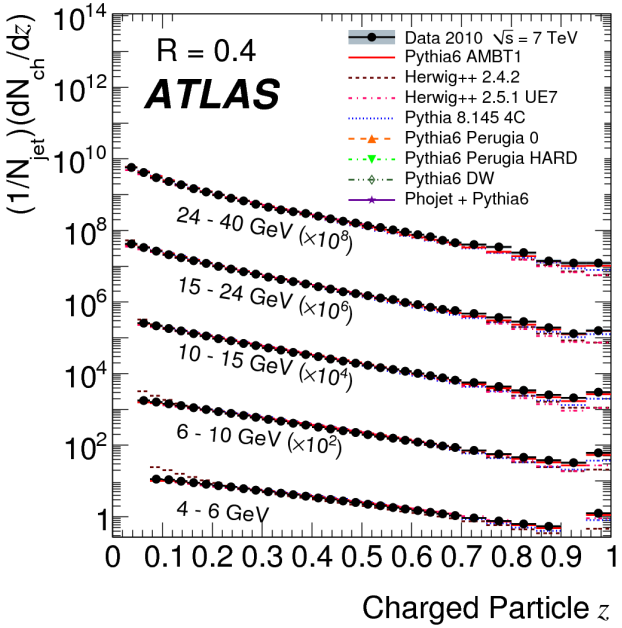
- Extensive dictionary of jet shapes starting from radius-dependent energy densities as measured at the Tevatron
  - These shapes are sensitive to quark / gluon content, but they are more sensitive to the generator tune!
- Similar conclusions in ATLAS and CMS
  - Herwig++ too wide
  - Pythia too narrow
- These have already been fed back into the generator tunes
- With new tunes, the agreement is much improved
  - Little difference with different ME generators

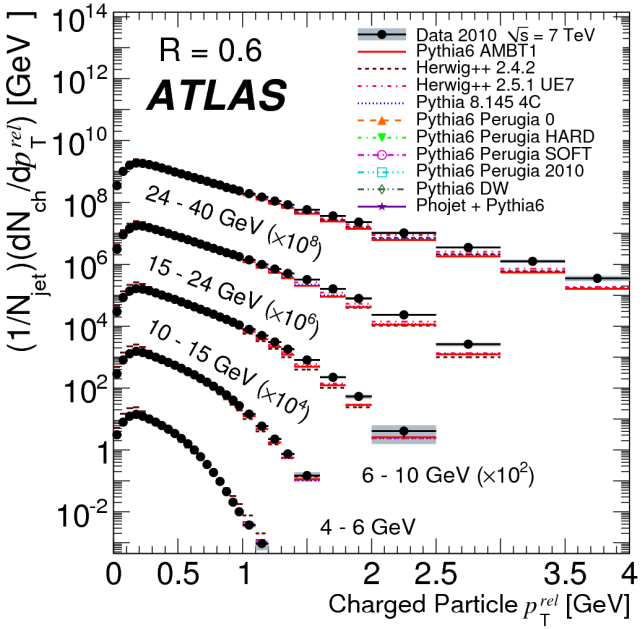


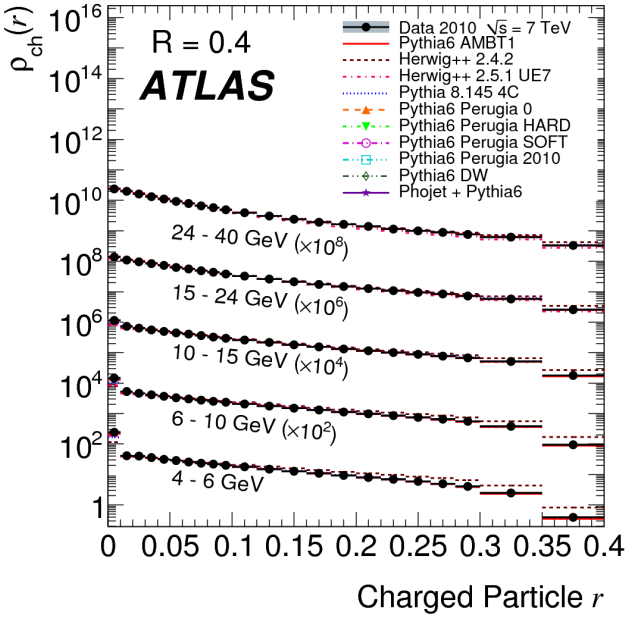
Jet Fragmentation Properties

arXiv:1107.3311
arXiv:1109.5816
arXiv:1204.3170

- Fragmentation properties measured in occasional tour-de-force papers with many variables and distributions
  - Particle multiplicity, momentum fraction, relative p_T, and density in a jet
- These are really feeding into the numerical models (Pythia, Herwig, Sherpa, Powheg) that we use, and are mostly described well
- Still, we hope that theorists pay careful attention to models as they run out of parameters, are unable to describe the data, or model the data incorrectly in a way that might affect your favorite search / measurement



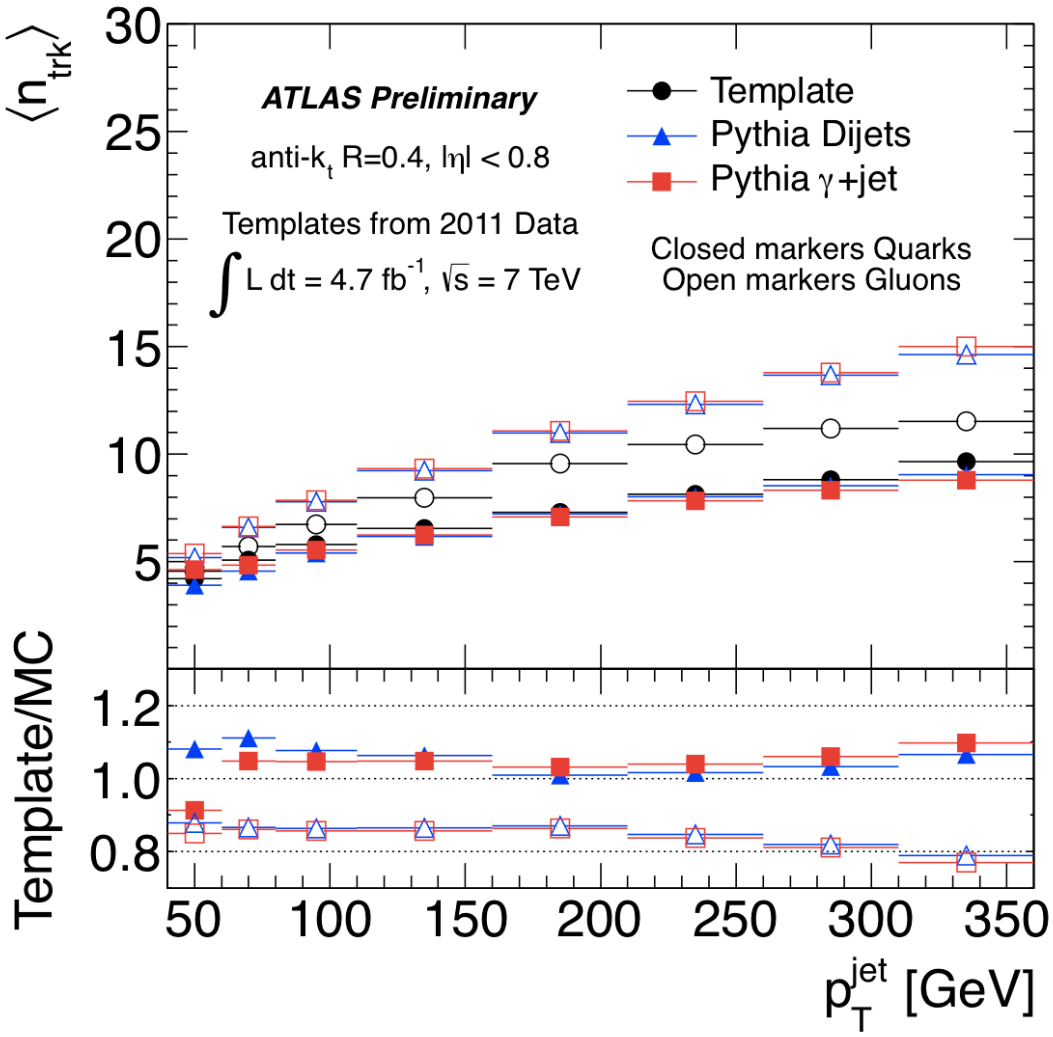




Properties for q/g Tagging

Web Only

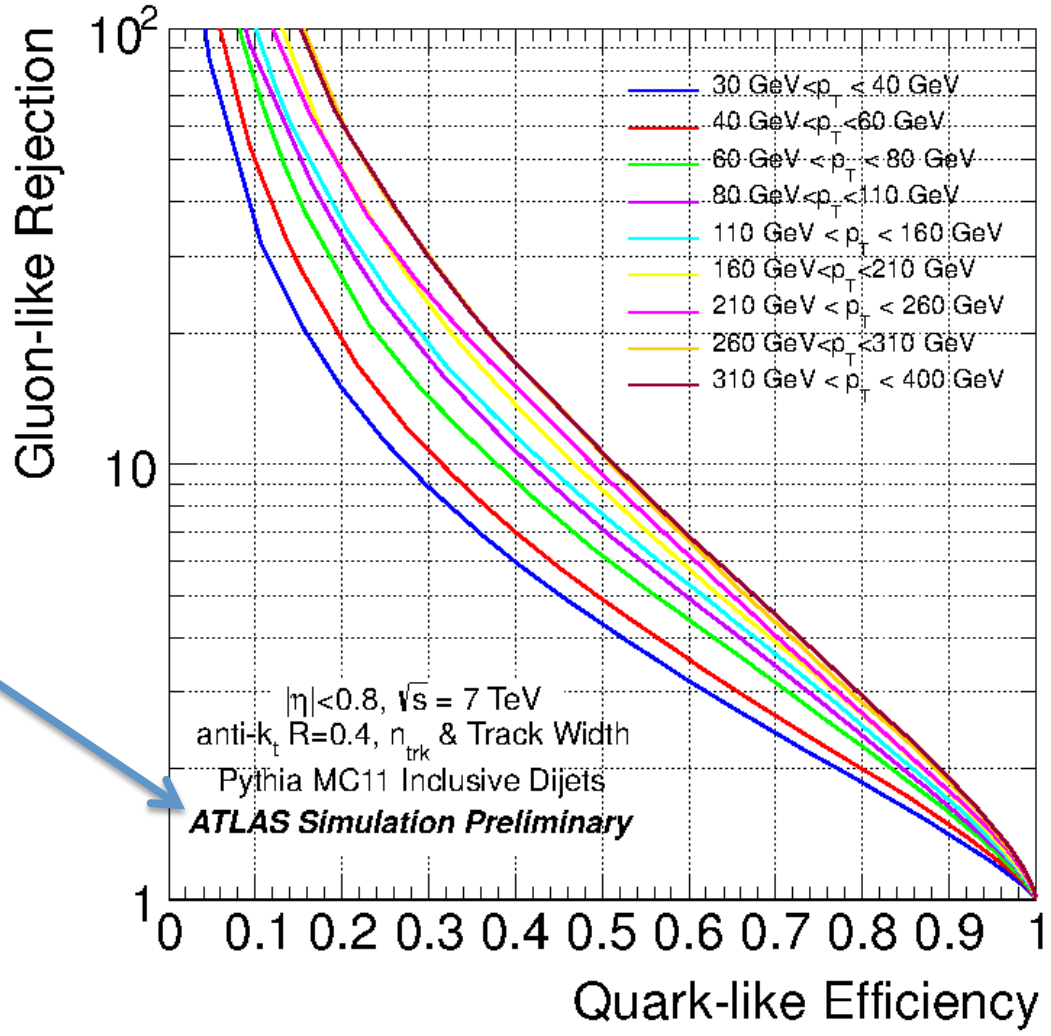
- Recent plots show why these are important, for example in a quark / gluon discriminant
- Very popular in modern Higgs searches /measurements
- Standard MC (Pythia here) *drastically* overestimates the discriminating power between quarks and gluons
- Far reaching implications on:
  - Jet energy scale and uncertainty
  - Tagging / discrimination
  - Potential measurements of quark-enriched / gluon-enriched samples



Web Only

q/g Tagging Potential

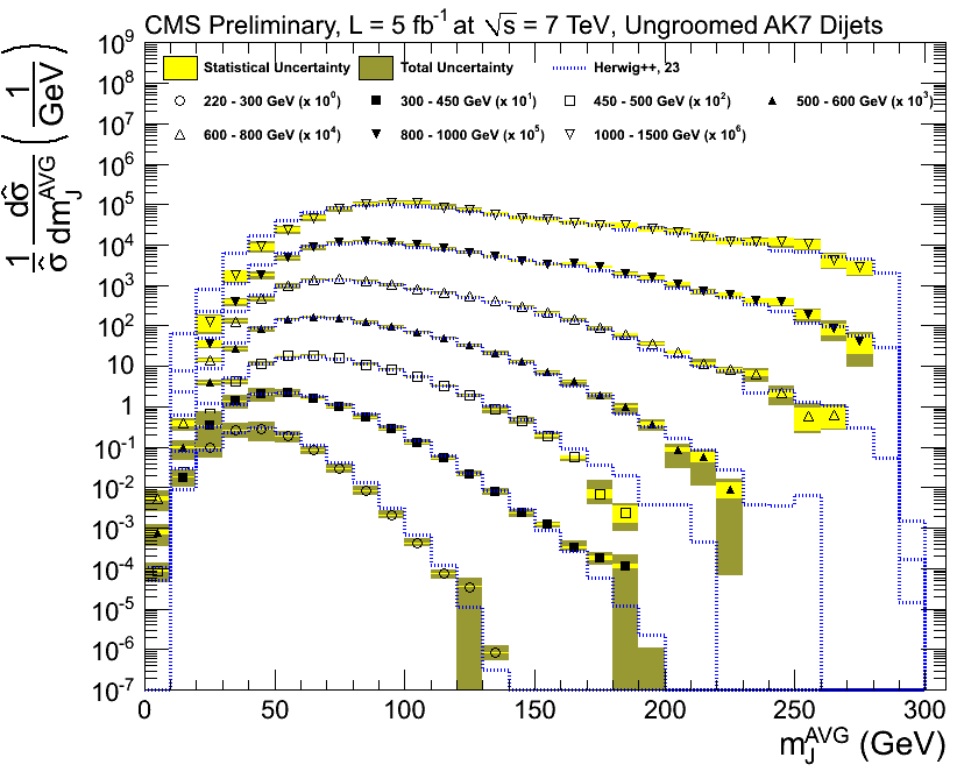
- Recent plots show why these are important, for example in a quark / gluon discriminant
- Very popular in modern Higgs searches /measurements
- Standard MC (Pythia here) *drastically* overestimates the discriminating power between quarks and gluons
  - If the data looked like the MC, we could do quite a bit!
- Far reaching implications on:
  - Jet energy scale and uncertainty
  - Tagging / discrimination
  - Potential measurements of quark-enriched / gluon-enriched samples

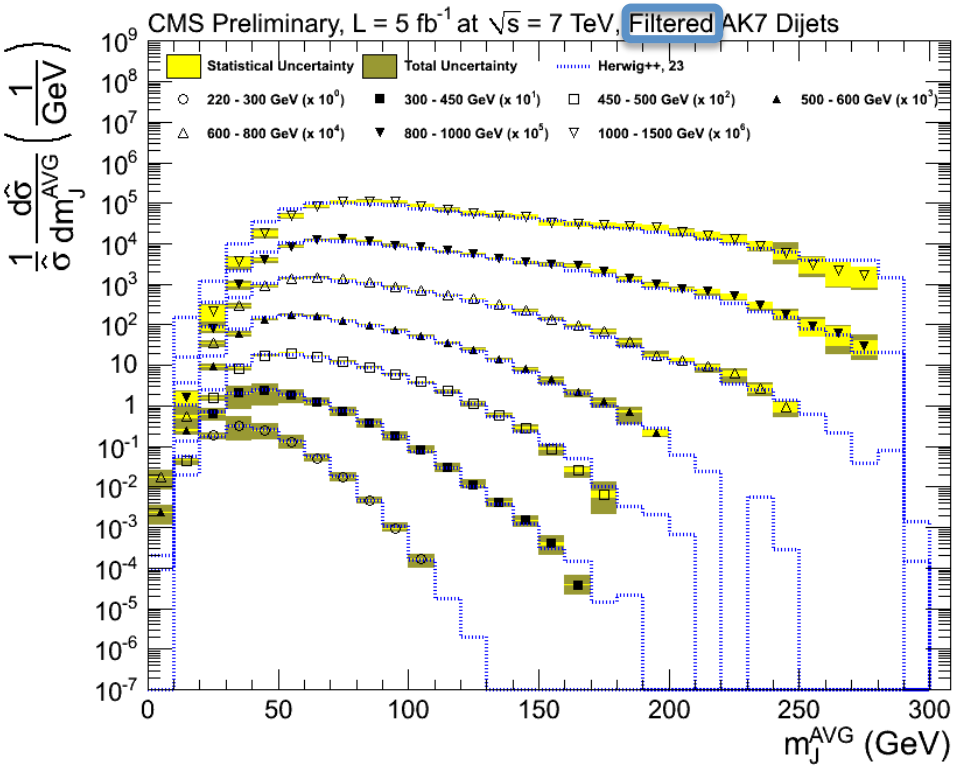


Web Only

Jet Masses

- Jet masses now measured in larger cone jets (R=0.7, 1.0, 1.2)
- Masses are more sensitive to edge effects and pile-up than p_T
- New algorithms to reduce the sensitivity (filtering, pruning, trimming) have been introduced and tested by both experiments – good MC agreement, generally
- Both experiments can say that they do indeed help with pile-up, but without any new physics discovered, it is hard to say if any help in the discovery of new physics!

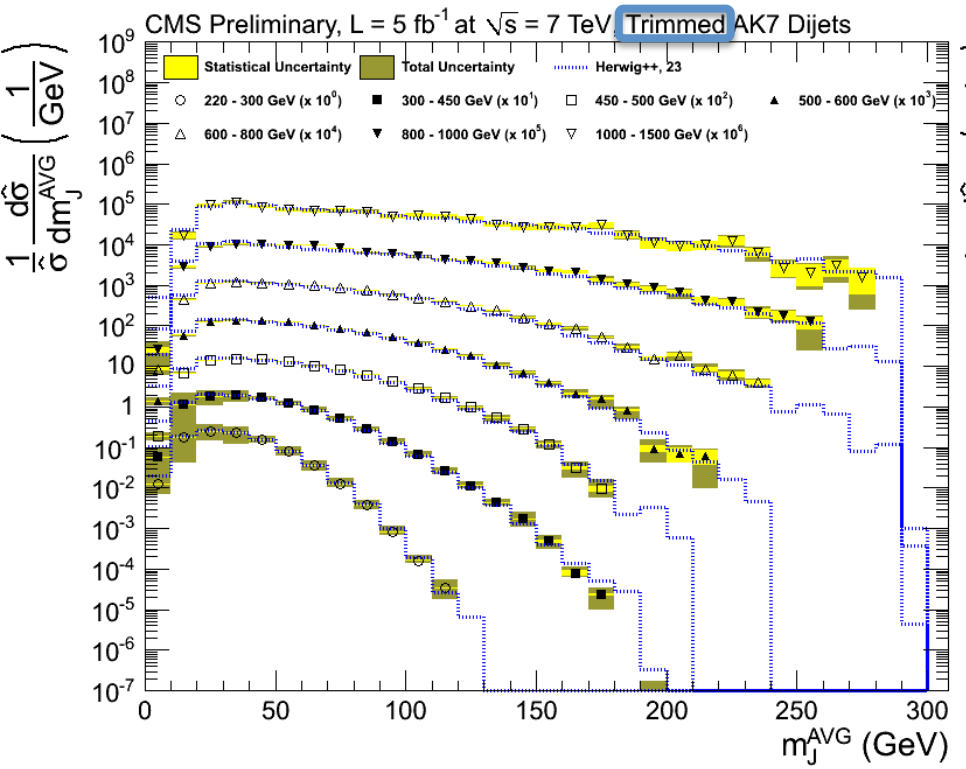


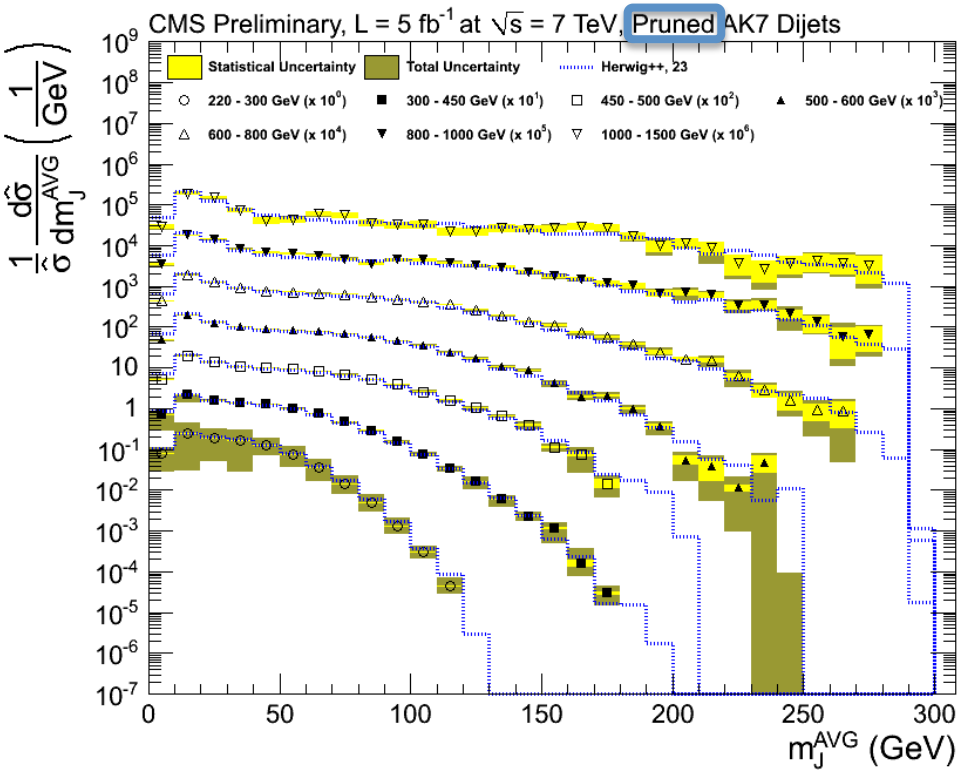


Web Only

Jet Masses

- Jet masses now measured in larger cone jets (R=0.7, 1.0, 1.2)
- Masses are more sensitive to edge effects and pile-up than p_T
- New algorithms to reduce the sensitivity (filtering, pruning, trimming) have been introduced and tested by both experiments – good MC agreement, generally
- Both experiments can say that they do indeed help with pile-up, but without any new physics discovered, it is hard to say if any help in the discovery of new physics!

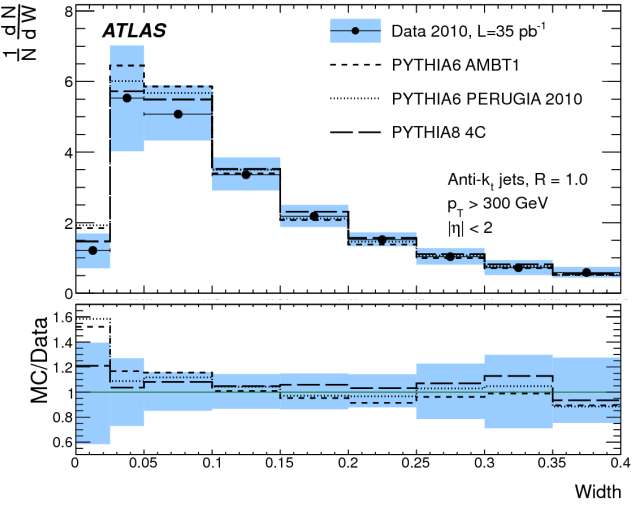


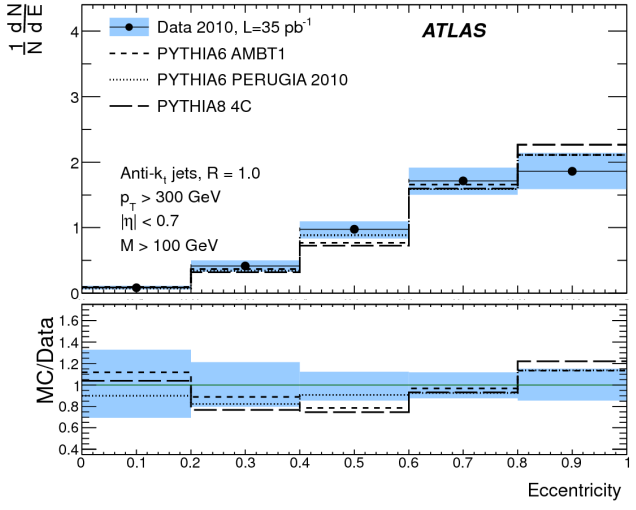


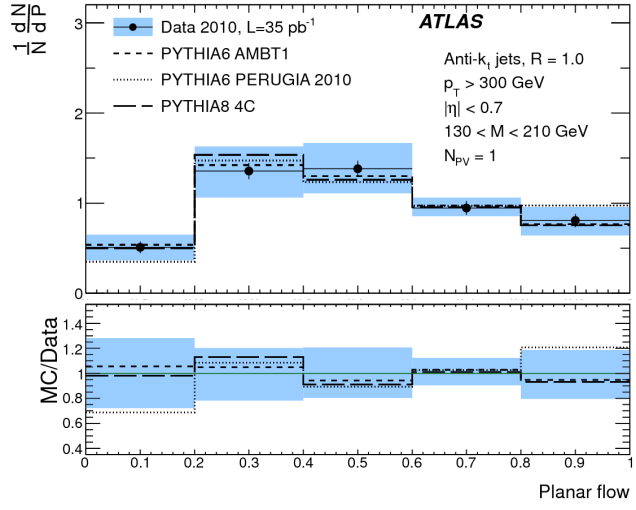
Fat Jets (for Searches)

arXiv:1206.5369
arXiv:1203.4606
CMS-PAS-QCD-10-041

- When heavy objects are boosted, they end up as a single fat jet
  - Fat jets are usually radii >1.0, anti-k_t or Cambridge/Aachen algorithms
  - Can capture an entire W-boson or top quark in one jet
- Have to be sure that QCD is well-modeled to use these for boosted objects
- Validated a large set now as tools for ATLAS and CMS
  - Planar flow, angularity, width, eccentricity, n-subjettiness, subjet multiplicity
  - Pile-up is still a major complication; both experiments have tested various filtering algorithms, as well as some other techniques (e.g. complimentary cone)



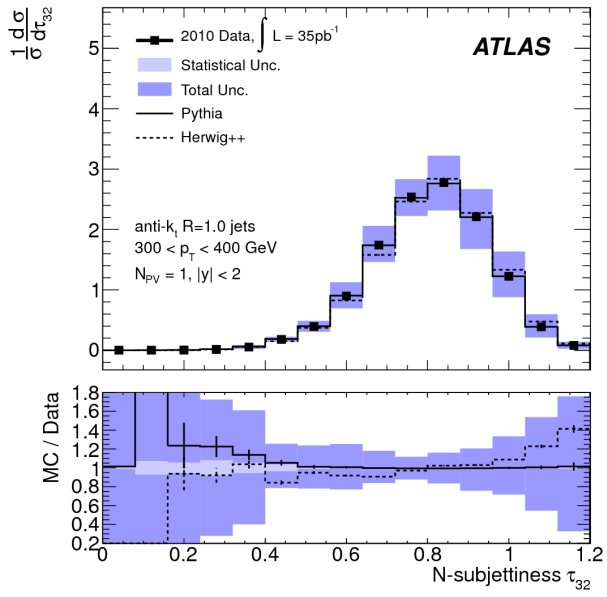


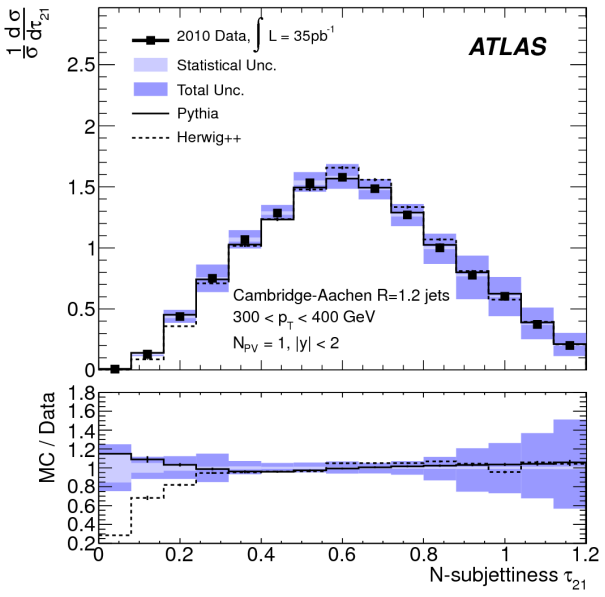


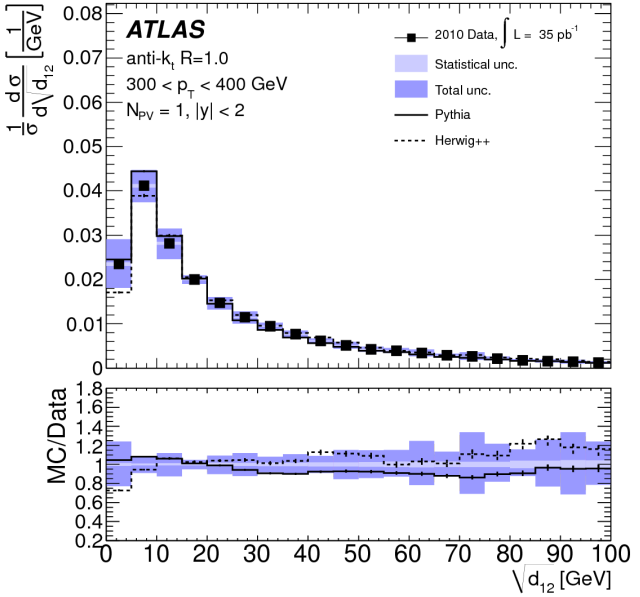
Fat Jets (for Searches)

arXiv:1206.5369
arXiv:1203.4606
CMS-PAS-QCD-10-041

- When heavy objects are boosted, they end up as a single fat jet
  - Fat jets are usually radii >1.0, anti-k_t or Cambridge/Aachen algorithms
  - Can capture an entire W-boson or top quark in one jet
- Have to be sure that QCD is well-modeled to use these for boosted objects
- Validated a large set now as tools for ATLAS and CMS
  - Planar flow, angularity, width, eccentricity, n-subjettiness, subjet multiplicity
  - Pile-up is still a major complication; both experiments have tested various filtering algorithms, as well as some other techniques (e.g. complimentary cone)



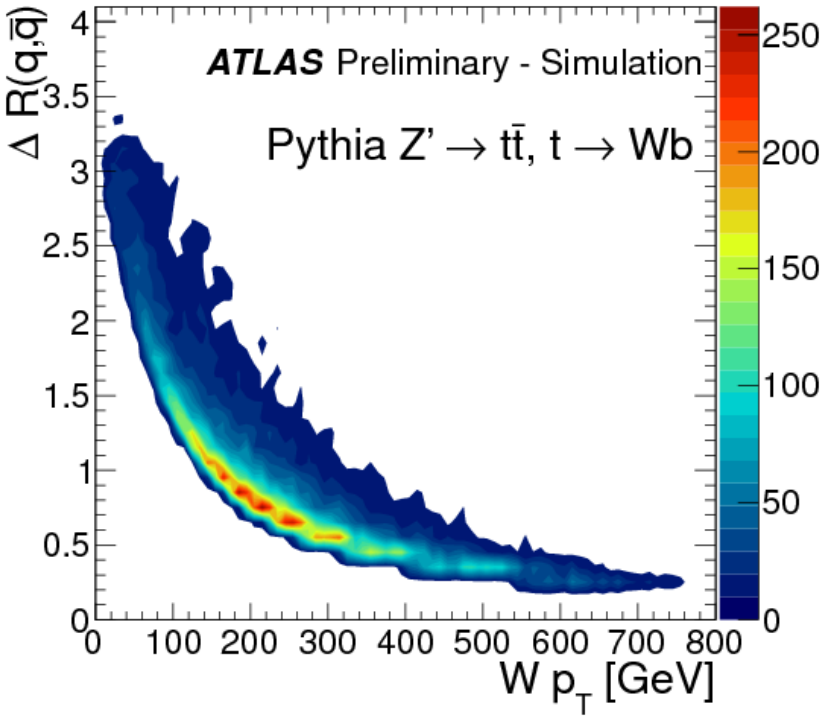


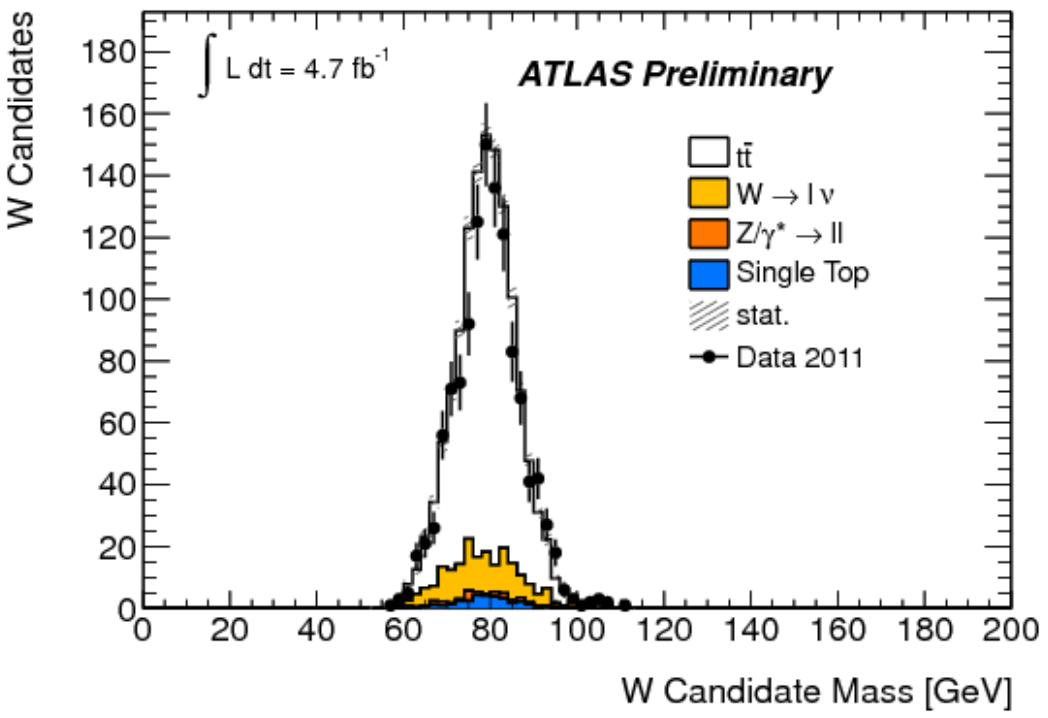


Web Only

Fat Jets (For Measurements?)

- Procedures in place to find fat jets (R=1.5) with familiar-looking structure
- First, apply these to searches for massive particles (some results already out!)
- Next thing is to try to measure the Standard Model using these tools
  - Boosted W/Z, boosted Higgs, boosted top…

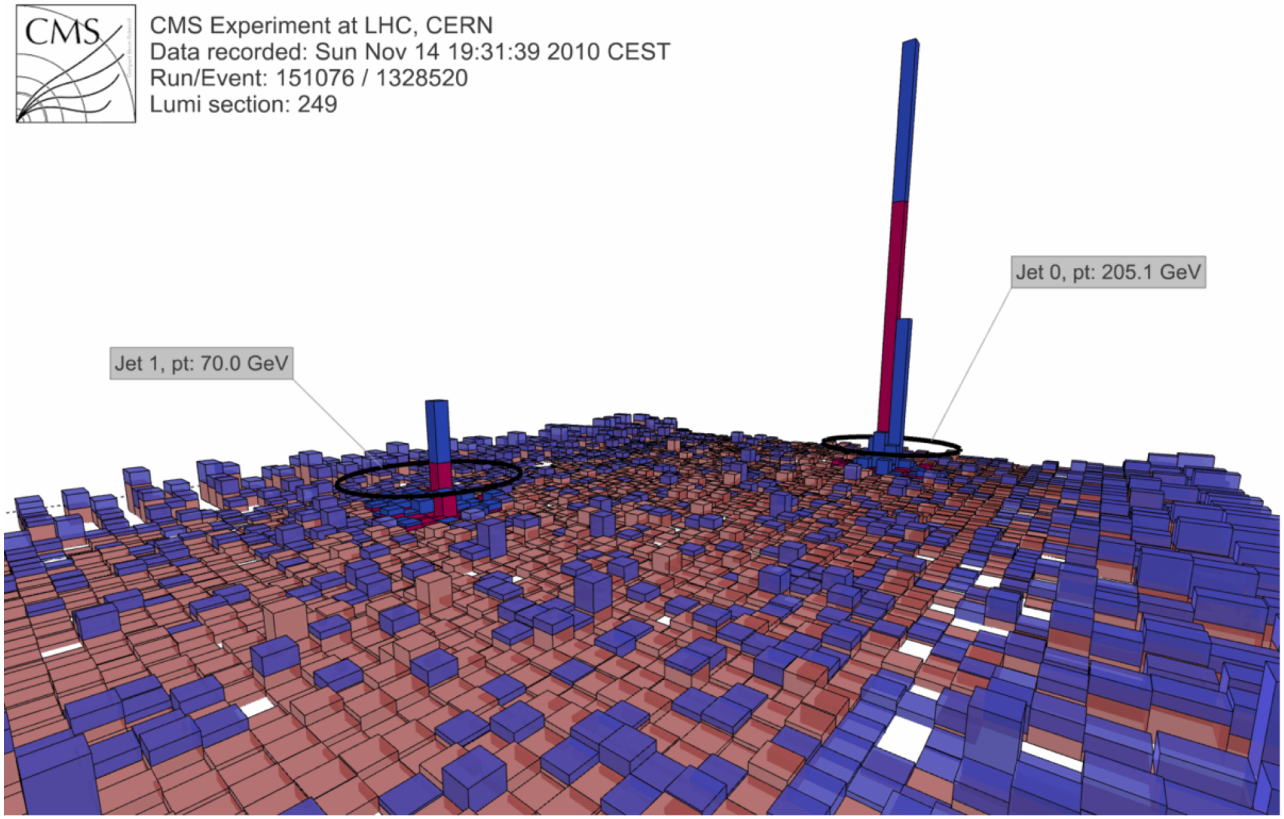




Jets in Heavy Ion Collisions

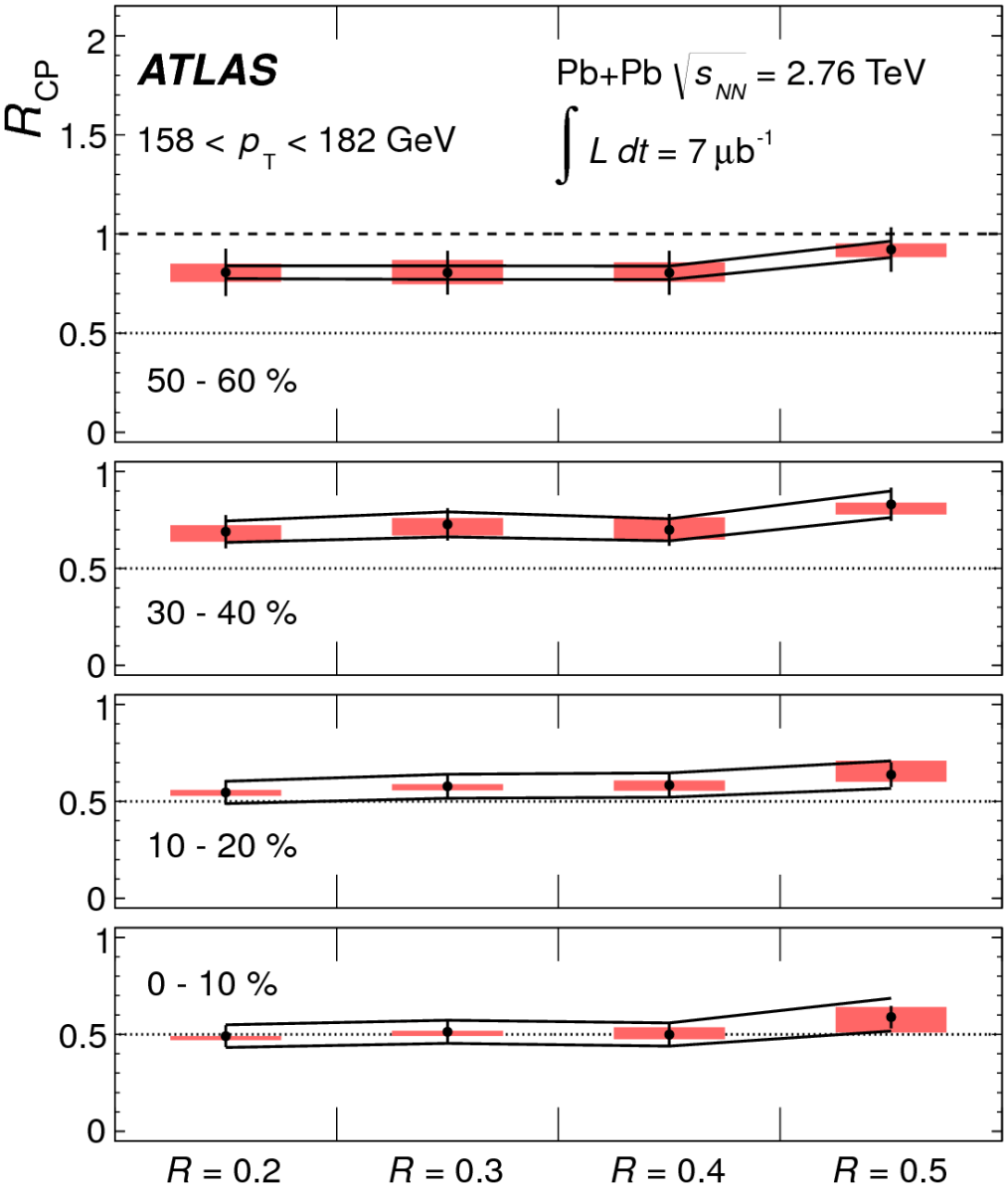
arXiv:1102.1957
arXiv:1202.5022
arXiv:1205.5872

- Heavy ions present a *much* more difficult environment for jet studies, but the payoff can be significant
- Jet suppression in heavy ion collisions was named one of the top 10 results from 2010
- Perhaps a sign of a quark/gluon plasma, but only if we understand the jets!

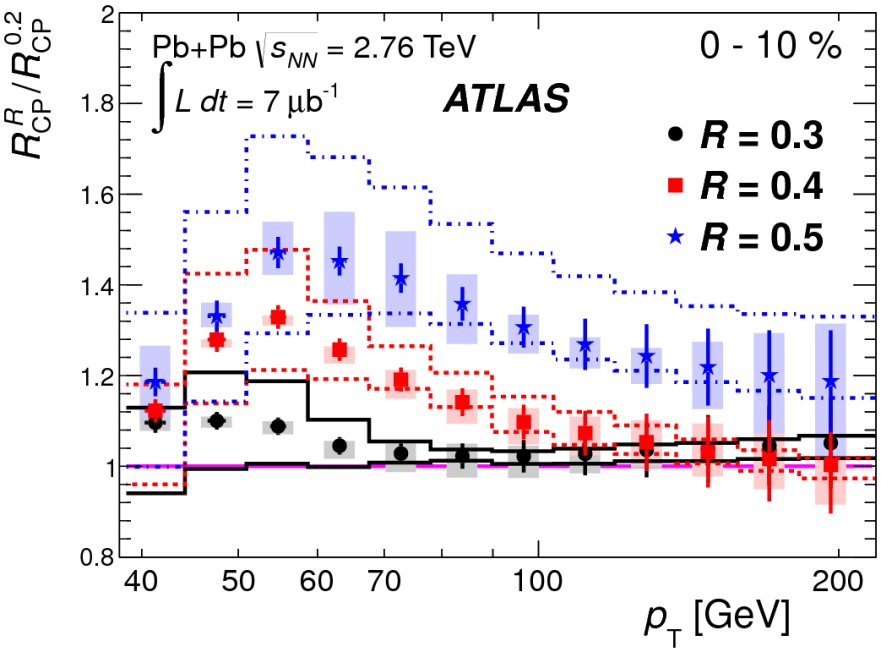


Heavy Ion Jet Suppression

arXiv:1208.1967
arXiv:1011.6182



- Jet suppression shows a modest R-dependence at moderate p_T
- More measurements are underway to try to nail down whether this *really* is the result of parton propagation through a dense medium



Summary

- QCD measurements at the LHC are already rich and precise
  - But they always lag the searches by a bit – it takes time to understand the detectors and data in such fine detail!
- The standard measurements of inclusive spectra are done
  - Some interesting modifications, like particle production inside of jets
- Now we are on to more exciting things!
  - Radius-dependence of jet cross-sections
  - Very high-multiplicity (N>8, N>10?) final state measurements
  - Fat jet performance in preparation for new search methods
- The old Monte Carlo methods are holding up surprisingly well
  - Pythia always does better than anticipated, after tuning especially
- We welcome new developments from our theorist friends
  - Always happy to test new Monte Carlos and tunes
  - Very happy to test new jet properties / structure variables if they might give us some improvement in new physics reach or be interesting alone