

Studies of jets and their properties using the ATLAS detector at the LHC

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On Behalf of the ATLAS Collaboration

EP/PP/LPCC, 7/6/2011

- Why study jets?
- How we measure them
- What we learn...
- Summary and Prospects

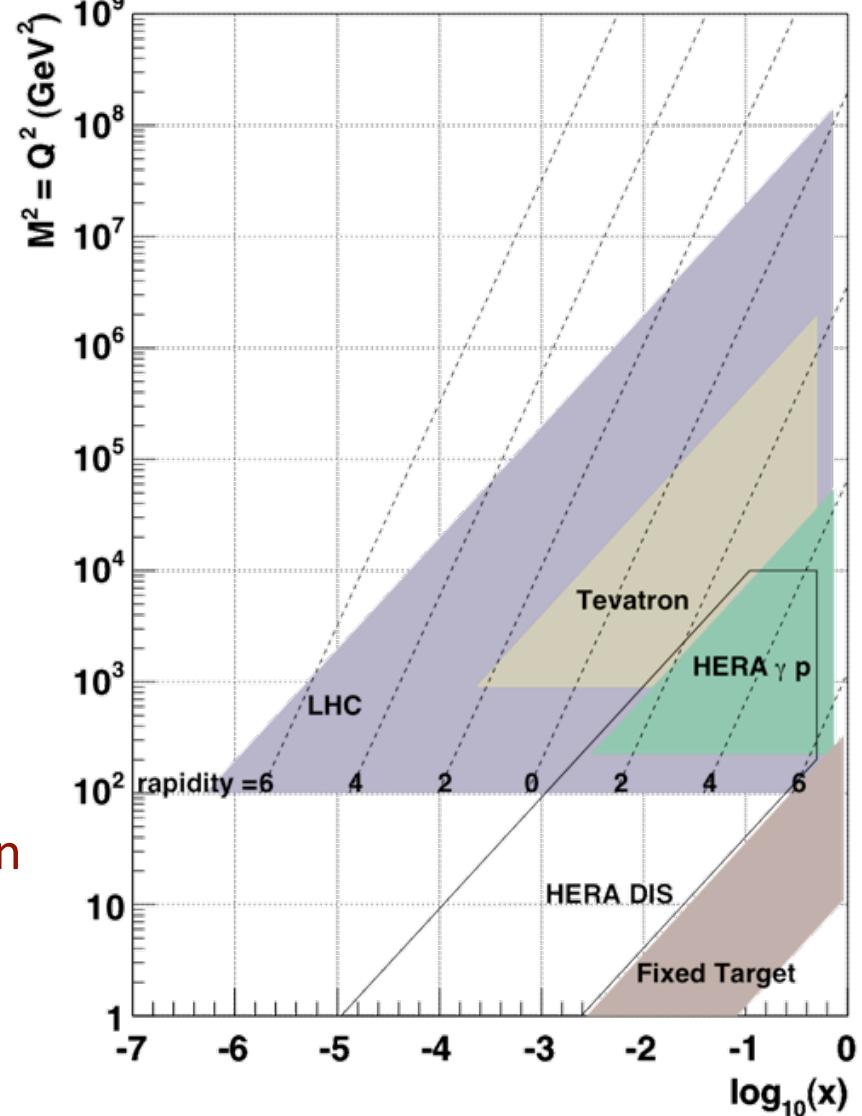
Why study jets?

QCD Sector of the Standard Model

- QCD is a fundamental force responsible most of the baryonic mass of the universe
- Determines total cross sections at high energy
- Asymptotically free
 - can use perturbative techniques
- Still, a relatively large coupling
 - high cross sections, high multiplicities, big phase space coverage
- Surprising “emergent behaviour” even in the perturbative regime
 - It is the only gauge field theory we can study under such circumstances
- Up to what scale does it work?

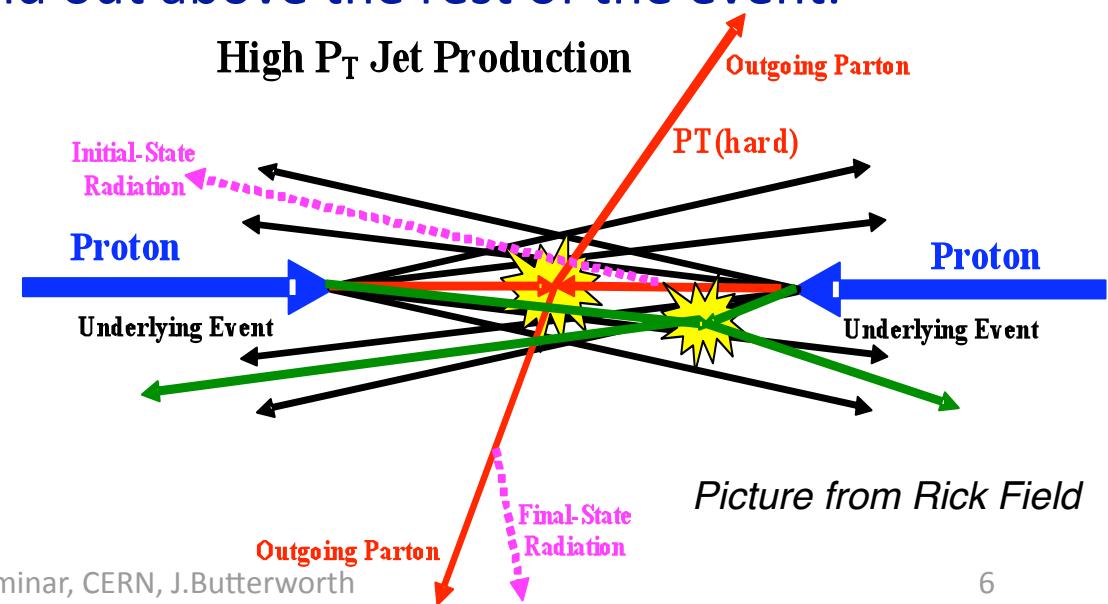
Jets at the LHC

- x and Q^2 reach
- Large logarithms (multiple scales, rapidity, x ...)
- Plenty of energy for high multiplicities
- Huge phase space for perturbative evolution after a QCD scatter
 - Electroweak scale is somewhere in the middle of this



What is a Jet?

- Protons are made up of quarks and gluons.
- Quarks and gluons are coloured and confined – we only ever see hadrons.
- A jet of hadrons is the signature of a quark or gluon in the final state.
- The gross properties (energy, momentum) reflect the properties of the quark or gluon, and stand out above the rest of the event.

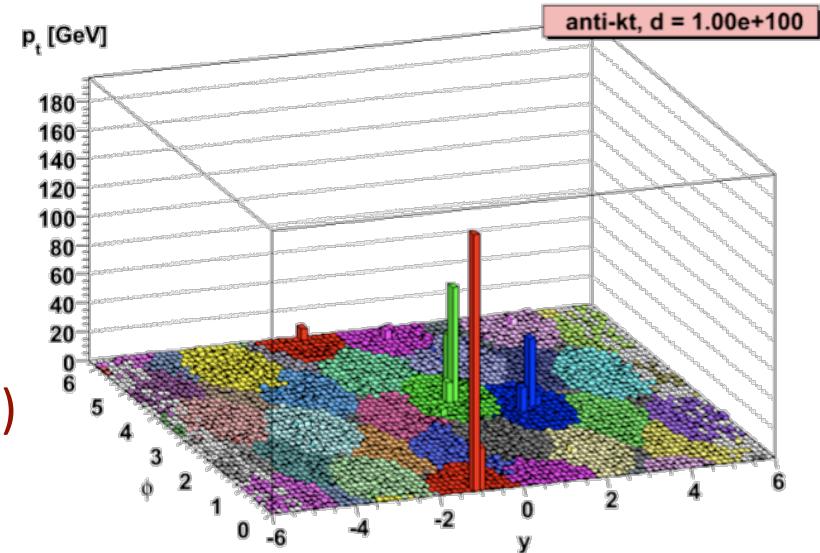


Jet finder(s)

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2},$$

$$d_{iB} = k_{ti}^{2p},$$

- Form a list
 - (of particles, tracks, clusters or partons)
- Merge the smallest pair
- Iterate
- Anti- k_t : $p = -1$ (default. Use $R=0.4, 0.6$)
 - Stable, “circular” jets built around highest p_T regions
- Also used later:
 - Cambridge/Aachen: $p = 0$. Based only on angular information
 - k_t : $p = 1$. Merging scales are physically meaningful



Cacciari, Salam, Soyez
JHEP 0804:063, 2008

Dokshitzer, Leder, Morretti,
Webber (JHEP 08 (1997)
01; Wobisch and Wengler
[hep-ph/9907280](#)

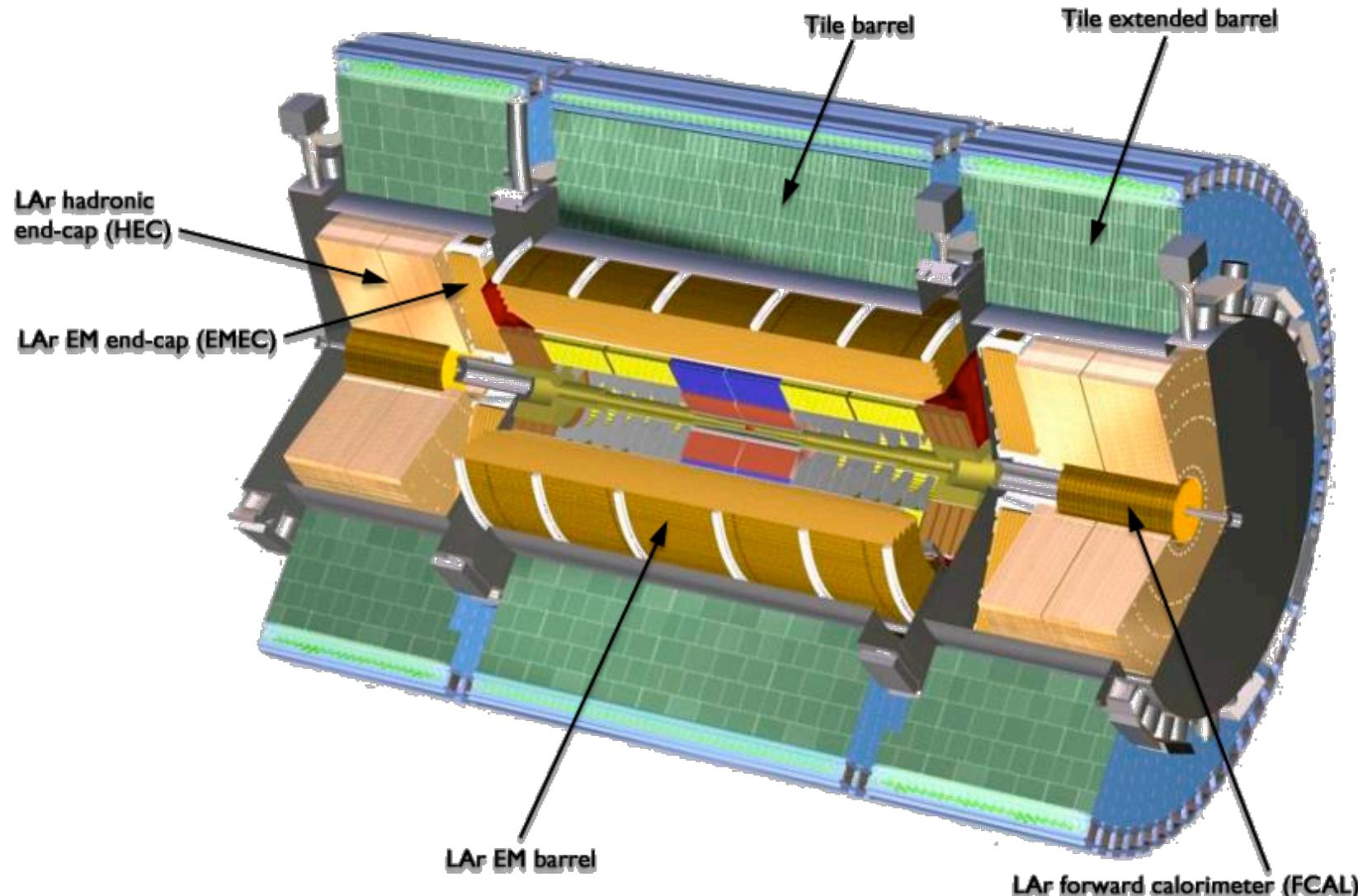
Catani et al Phys Lett B269
(1991); Nucl. Phys. B406
(1993); Ellis and Soper
Phys Rev D48 (1993).

Theory Comparisons

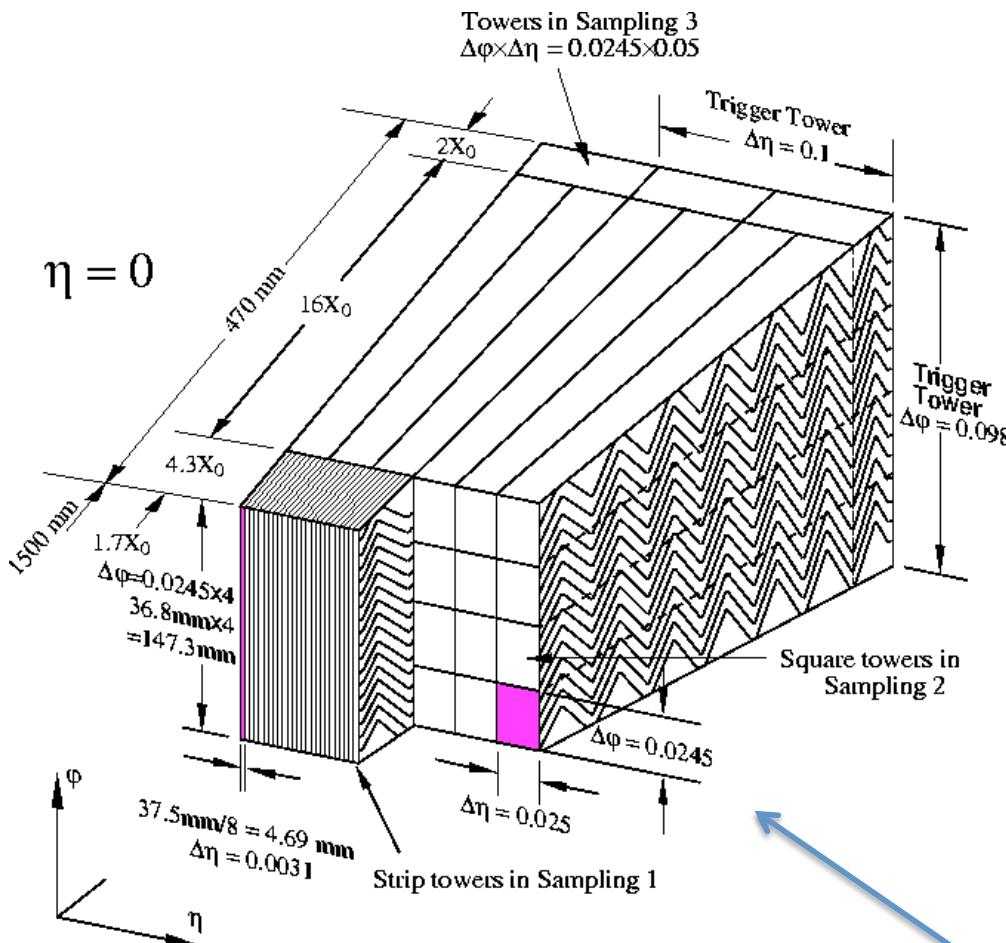
- Fixed (next-to-leading) order calculations
 - NLOjet, POWHEG
 - Parton showers
 - $\ln Q^2$, p_T^2 or angle (Herwig, Pythia, Sherpa)
 - Matched to tree-level ME
 - High multiplicities (Alpgen, Sherpa)
 - Higher order (POWHEG)
 - Also other large logarithms can be implemented
 - HEJ includes rapidity evolution
 - Make comparisons at the particle level
 - Physically well-defined
 - Requires application of soft corrections (Underlying event, hadronisation) to the theory
- $Z. Nagy, \textit{Phys. Rev. D} 68 (2003) 094002$
 $S. Alioli \textit{et al} arXiv:1012.3380 [hep-ph], arXiv:1002.2581 [hep-ph]$
- $M. Bahr \textit{et al. Eur. Phys. J. C} 58 (2008) 639–707.$
 $G. Corcella \textit{et al.}, JHEP 01 (2001) 010$
- $T. Sjostrand, S. Mrenna, P. Skands, JHEP 05 (2006) 026.$
- $T. Gleisberg \textit{et al.}, J. High Energy Phys. 02, 007 (2009).$
- $M. L. Mangano \textit{et al.}, JHEP 07 (2003) 001.$
- $J. R. Andersen and J. M. Smillie, arXiv:1007.4449 [hep-ph], arXiv:1101.5394 [hep-ph].$

How we measure jets

Calorimeters



Calorimeters



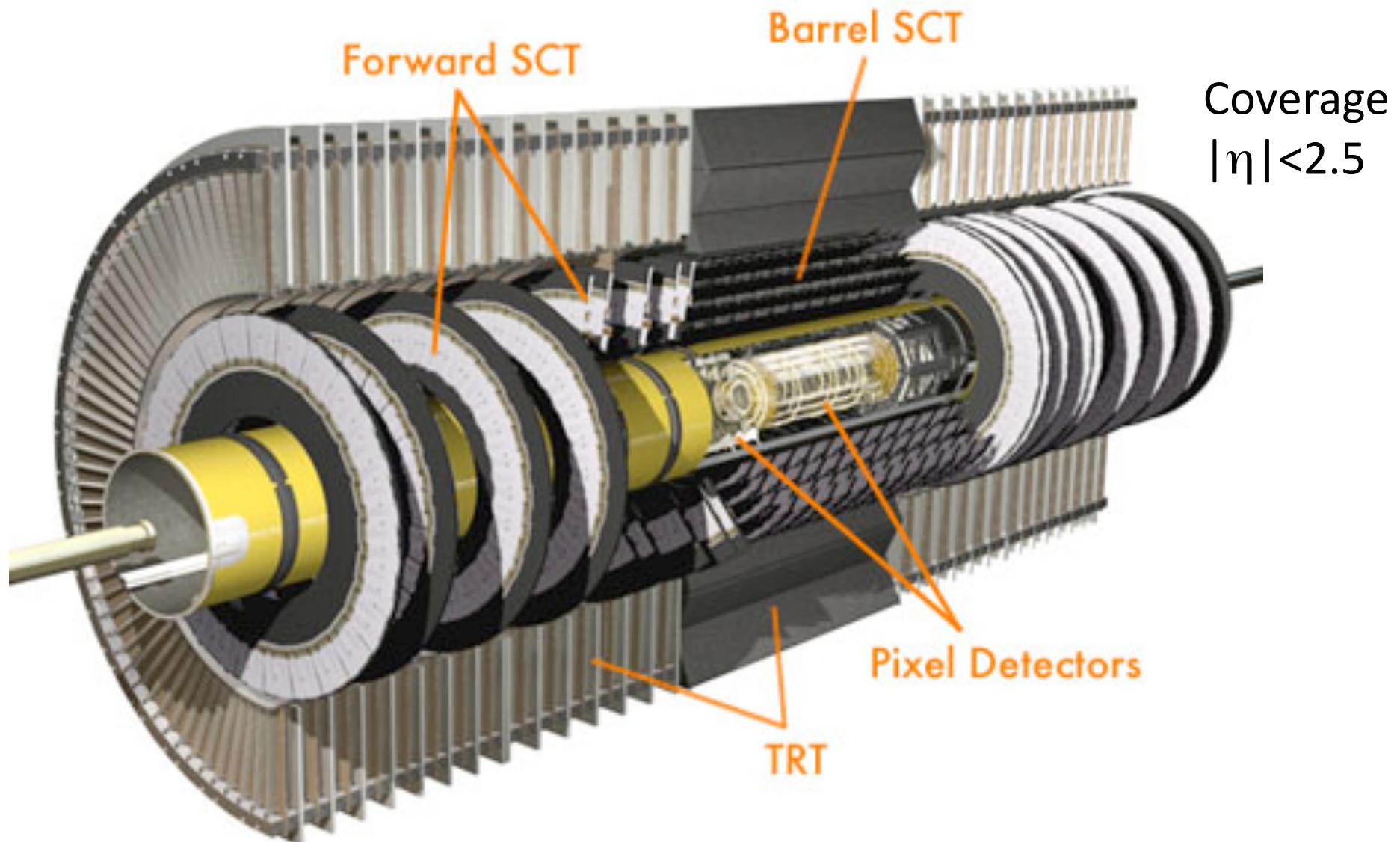
Pseudorapidity coverage
 $|\eta| < 4.9$; No azimuthal cracks or discontinuities.

Nominal Hadronic energy resolution $50\%/\sqrt{E} \oplus 3\%$ ($|\eta| < 3.2$) to $100\%/\sqrt{E} \oplus 5\%$ ($3.2 < |\eta| < 4.9$) (EM resolution $\sim 5x$ better in barrel)

Position resolution $\sim 0.05 \text{ mrad}$

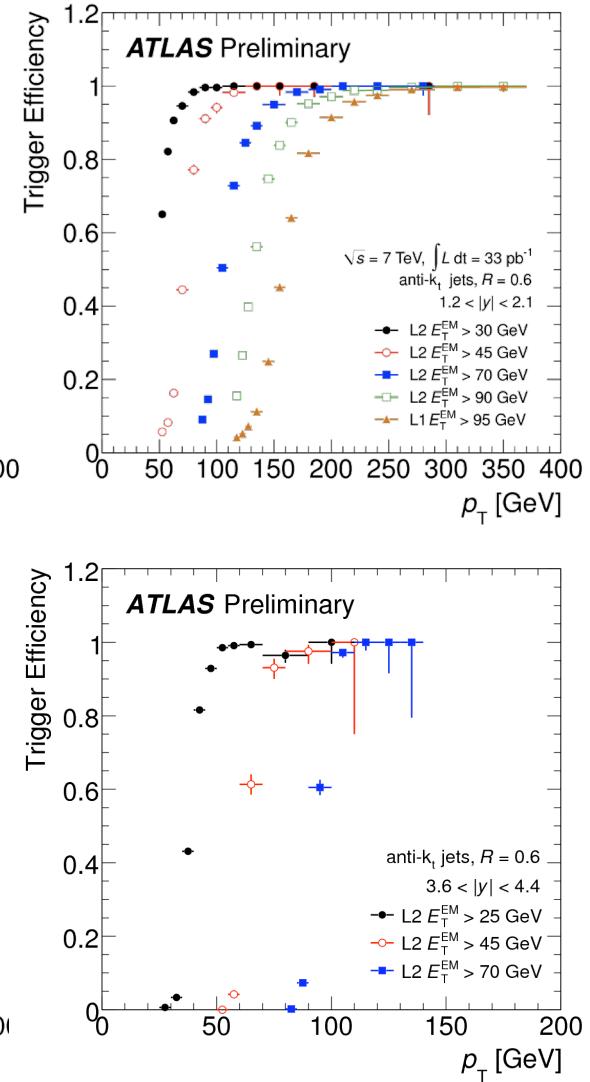
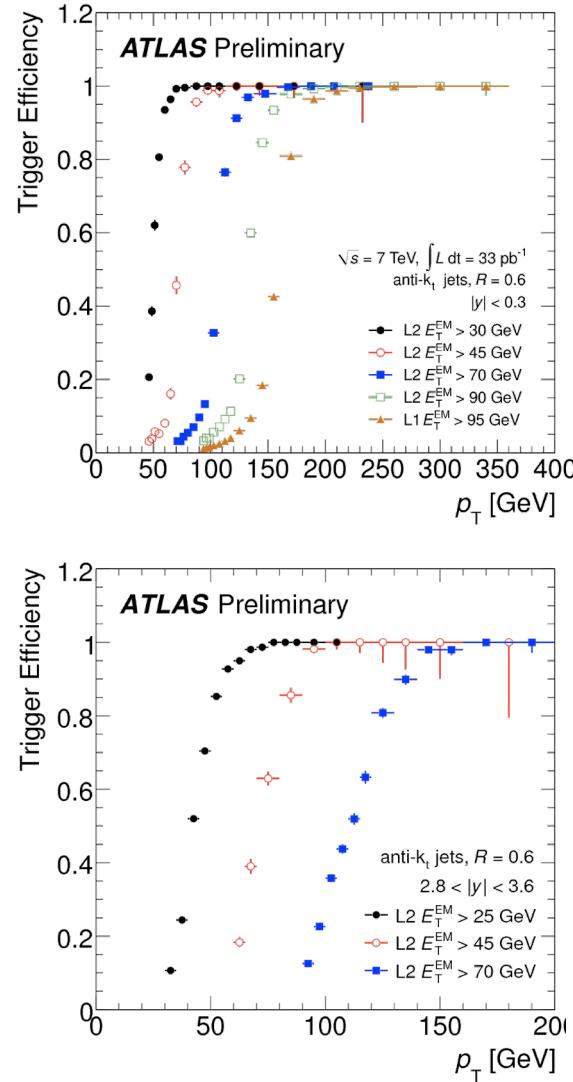
Finest granularity in EM calorimeter $\sim 0.025 \times 0.025$

Trackers



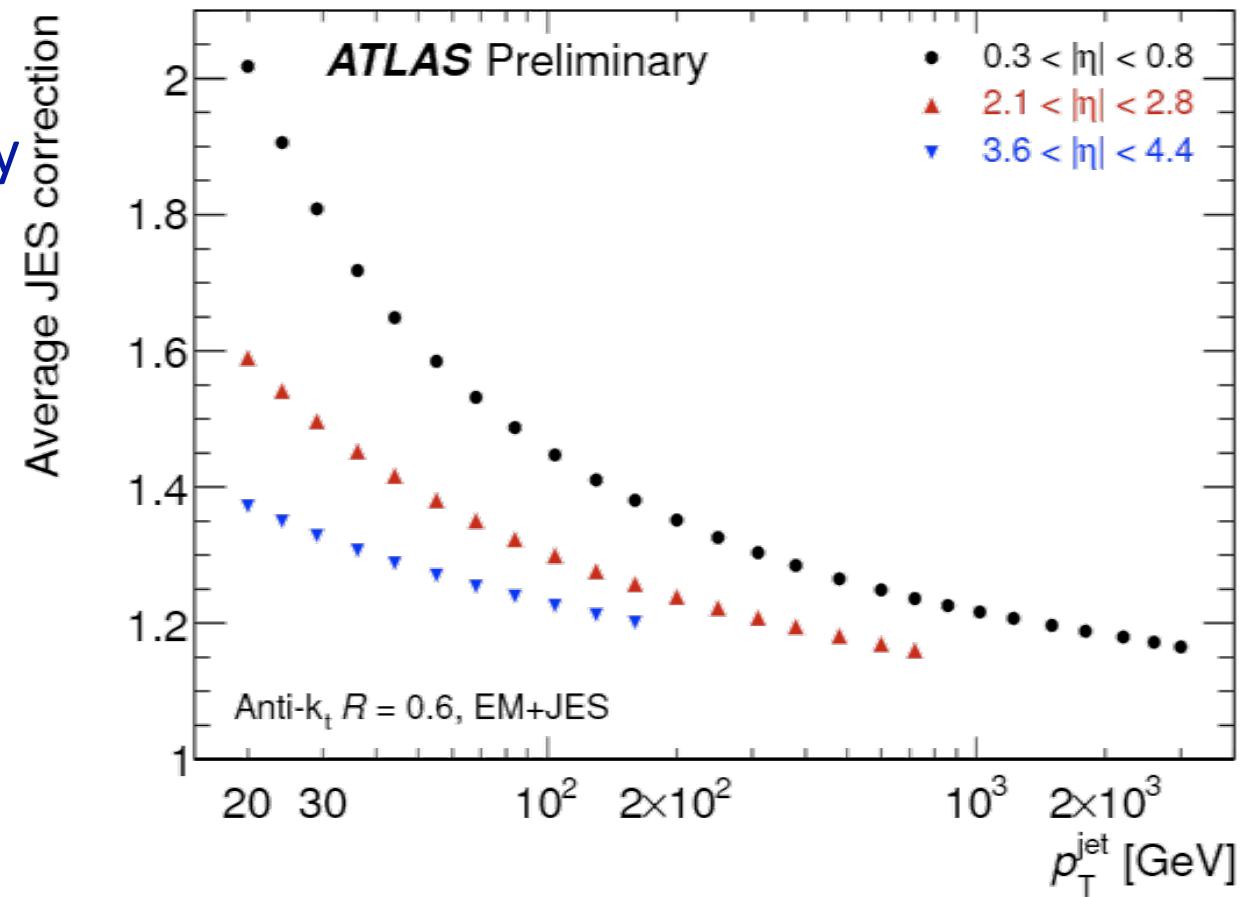
Trigger

- During 2010, triggers included
 - Minimum bias trigger scintillator (lowest p_T jets)
 - Single jet (central and forward), dijets, multijets
 - Sum E_T
 - Topological triggers ($\Delta\eta$ or $\Delta\Phi$)
- Allowed very wide coverage
 - Variety of prescales
 - Changes responding to beam conditions
- Continues in 2011



Calibrating Jets

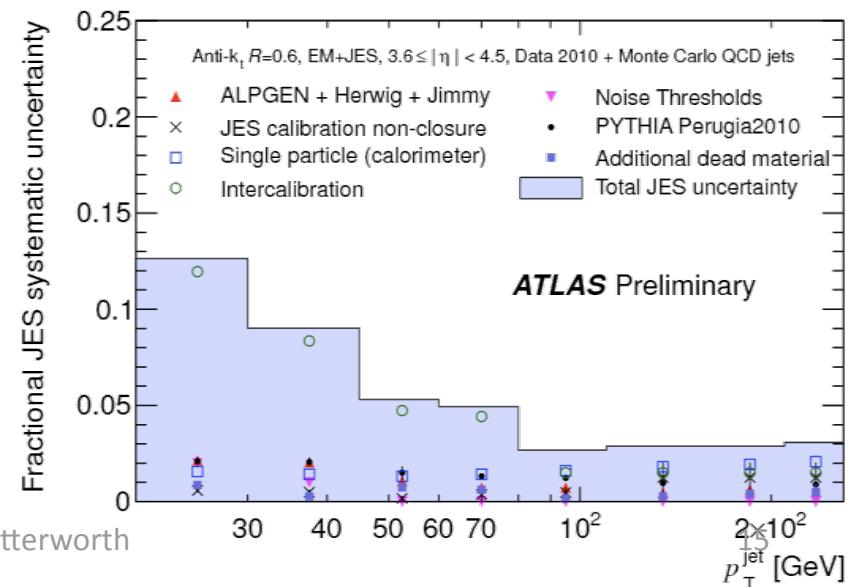
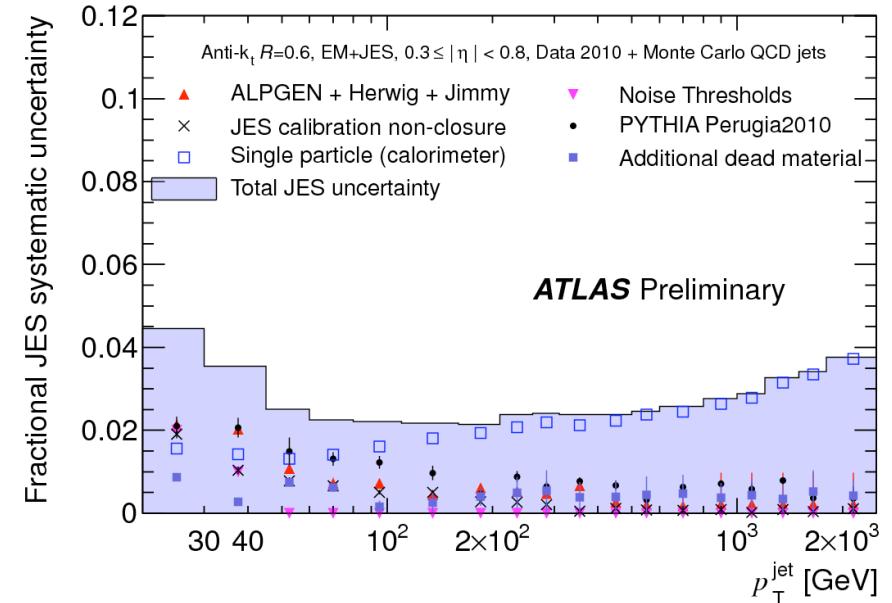
- Apply corrections from calorimeter energy → true particle level energy of the jet
- Corrects for
 - Differences in hadronic/ electromagnetic response
 - Material in front of calorimeter
 - Noise thresholds
 - Pile up
 - ...



ATLAS-CONF-2011-032

Calibrating Jets

- Jet Energy Scale systematic uncertainties.
- Evaluated using excellent (test-beam based) simulation of detector, validated in situ using
 - E/p
 - Dijet balance
 - Photon/jet balance

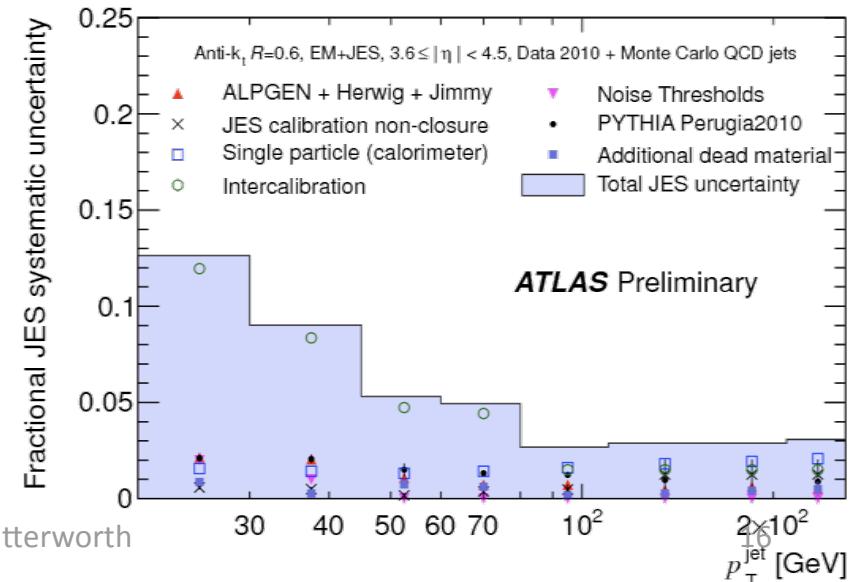
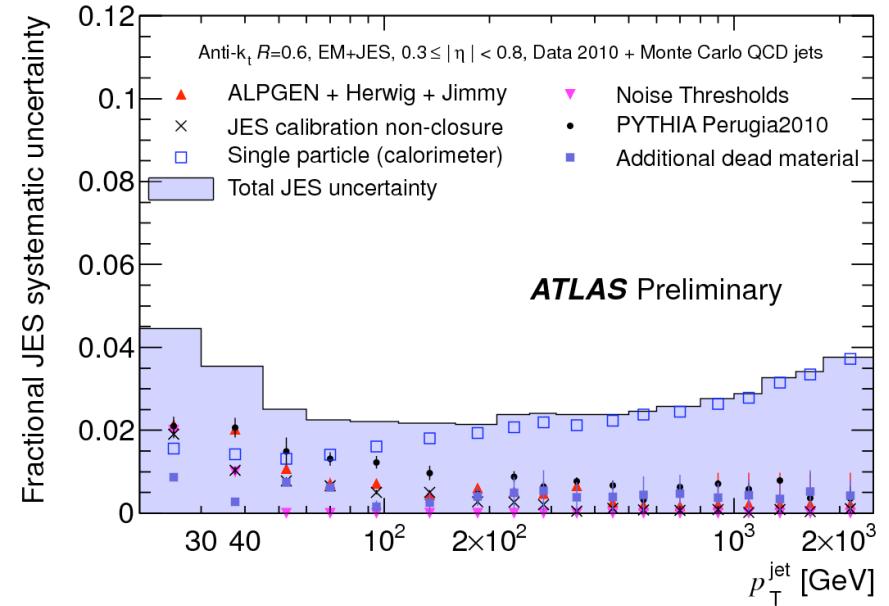


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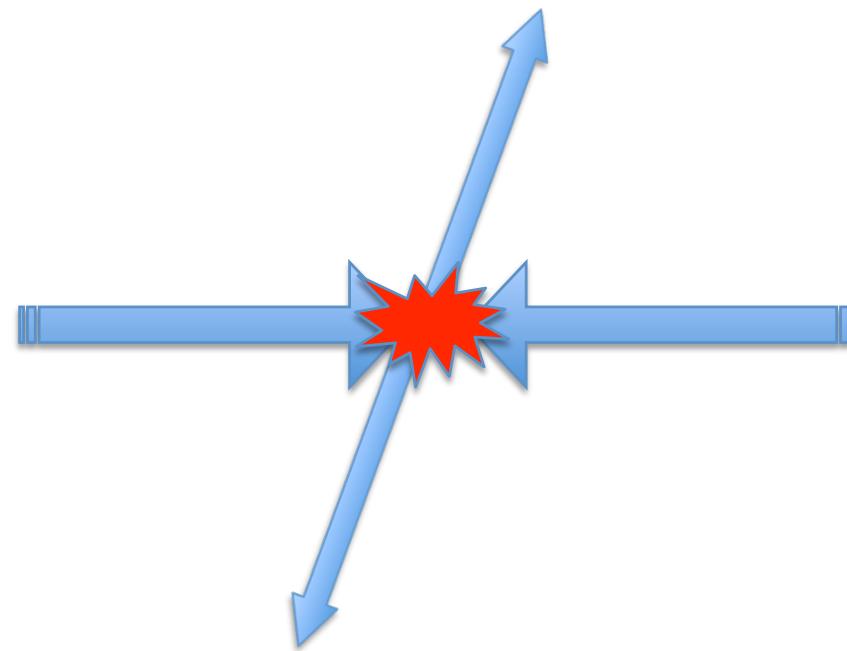
Calibrating Jets

- Jet Energy Scale systematic uncertainties.
- Range from $\sim 12.5\%$ (low p_T , forward) to $\sim 2.5\%$ (medium p_T , fairly central)
- Additional pile up uncertainty $\sim 1\text{-}2\%$, negligible above 200 GeV p_T , depends upon number of vertices.
- Shown for “average” isolated jets: Additional uncertainties for close-by jets, and flavour dependence

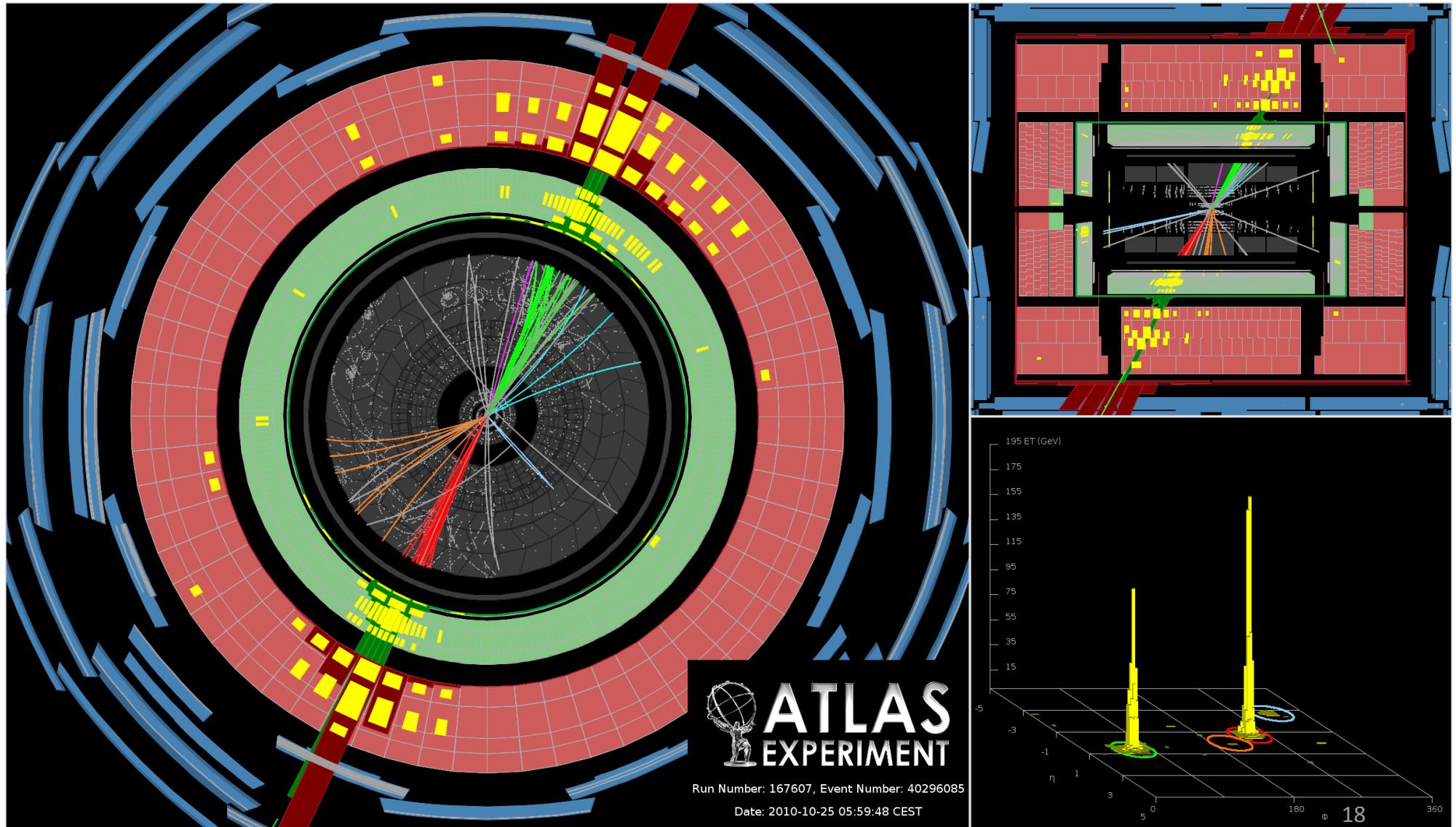
ATLAS-CONF-2011-032



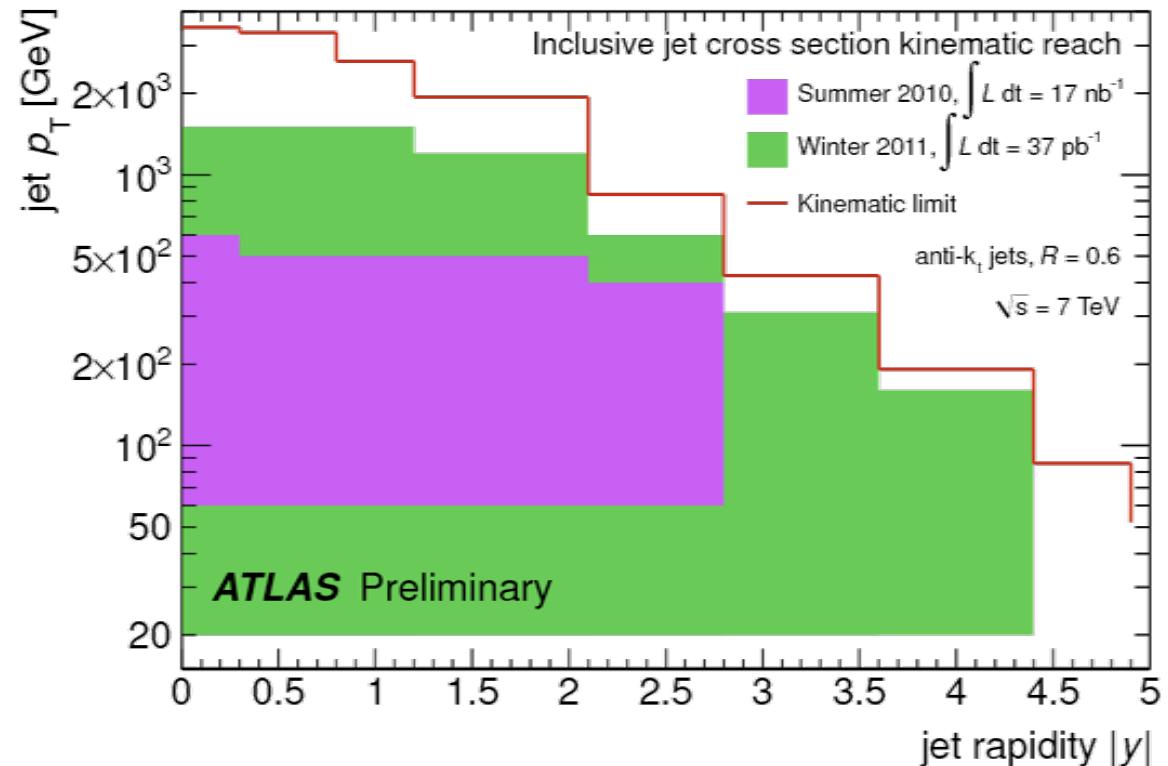
Inclusive and dijets



Inclusive and dijets

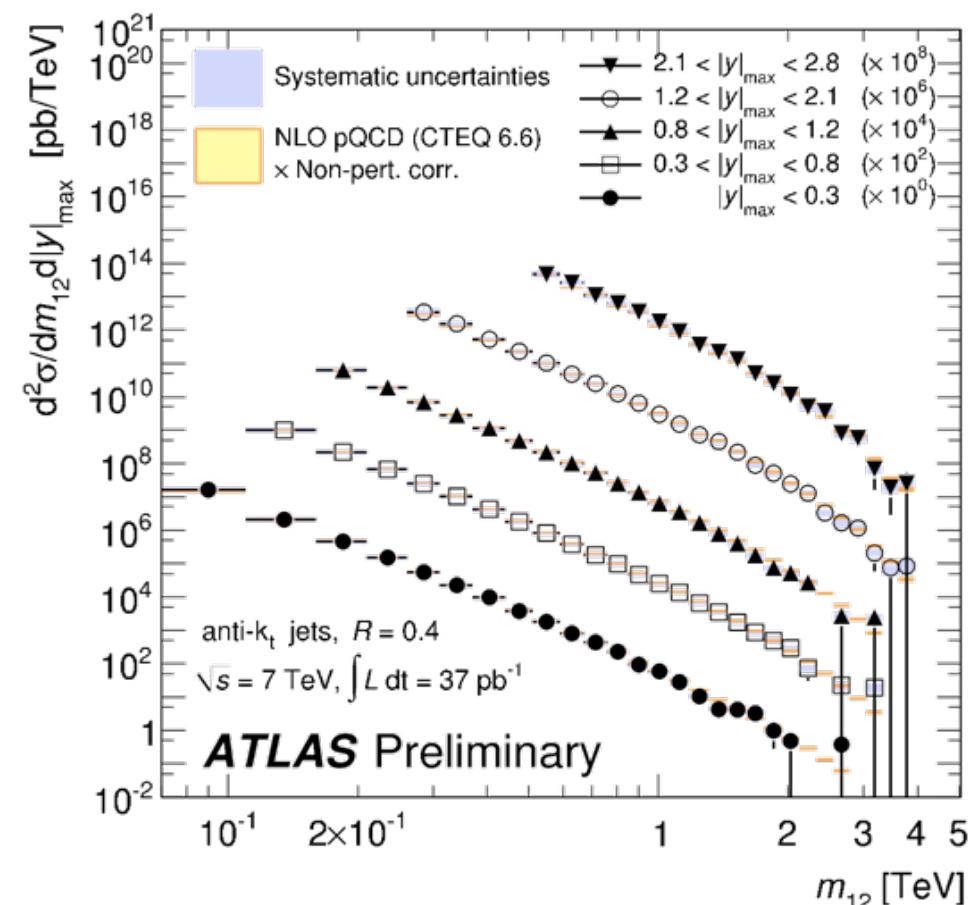
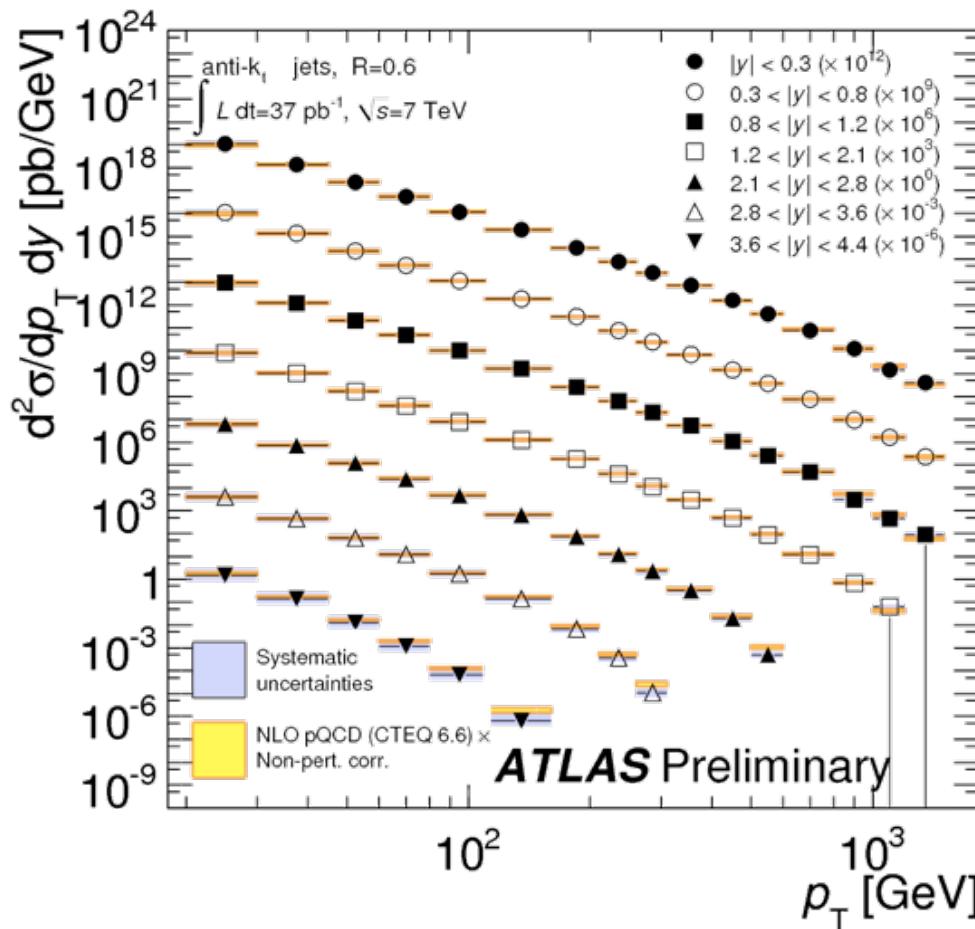


Inclusive jets and dijets

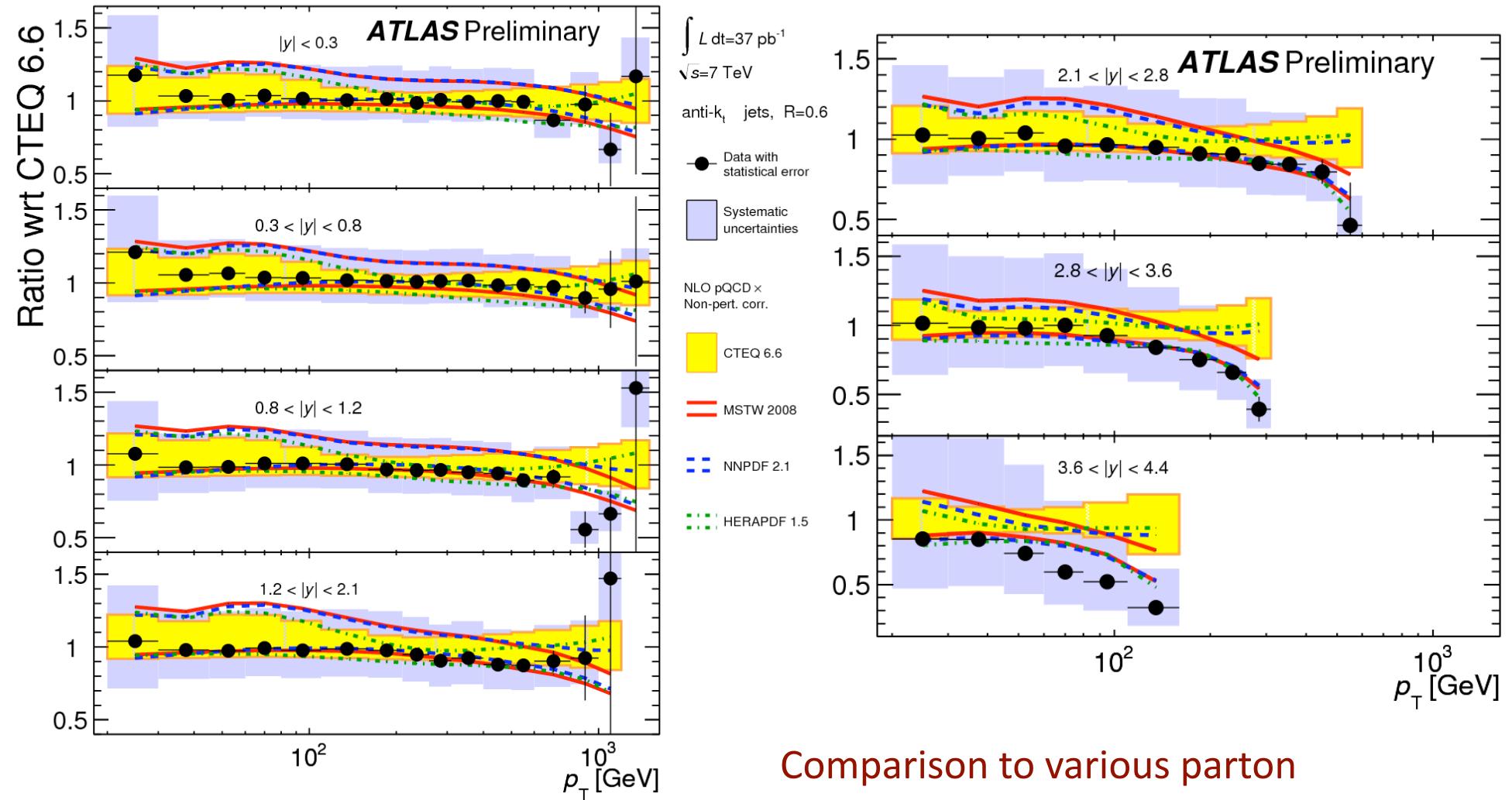


- Published our first measurement on 17 nb^{-1}
 - Eur.Phys.J.C71:1512,2011
- Updated with full 2010 data set
 - ATLAS-CONF-2011-047

Inclusive and dijets

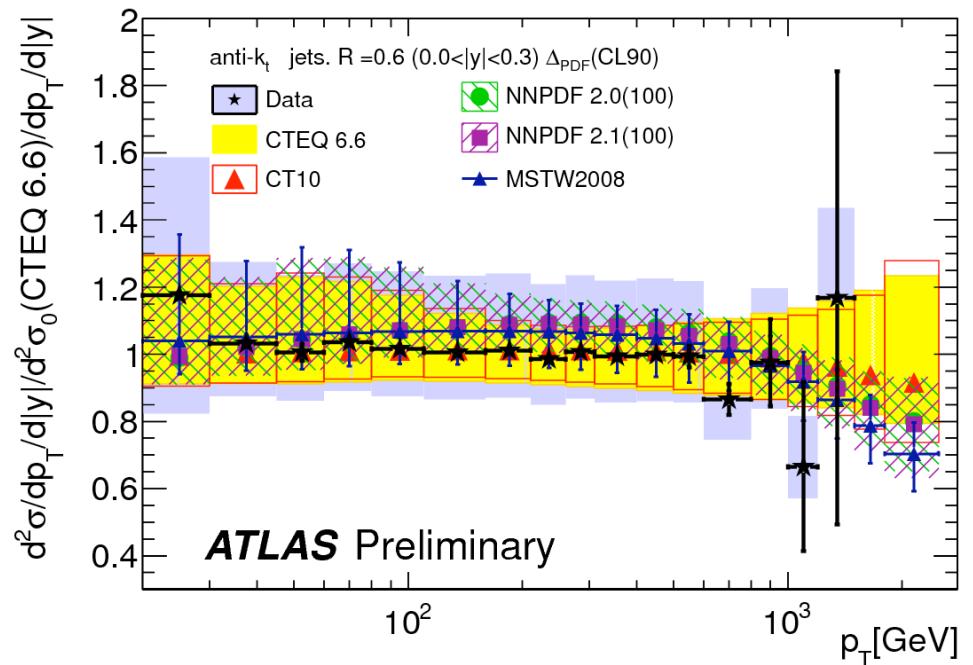
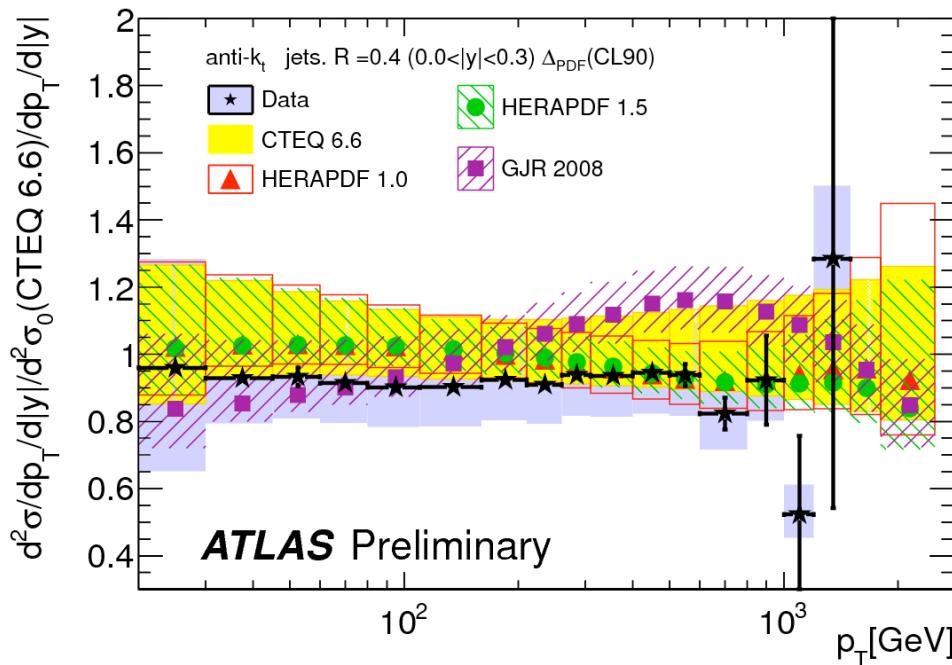


Inclusive jets



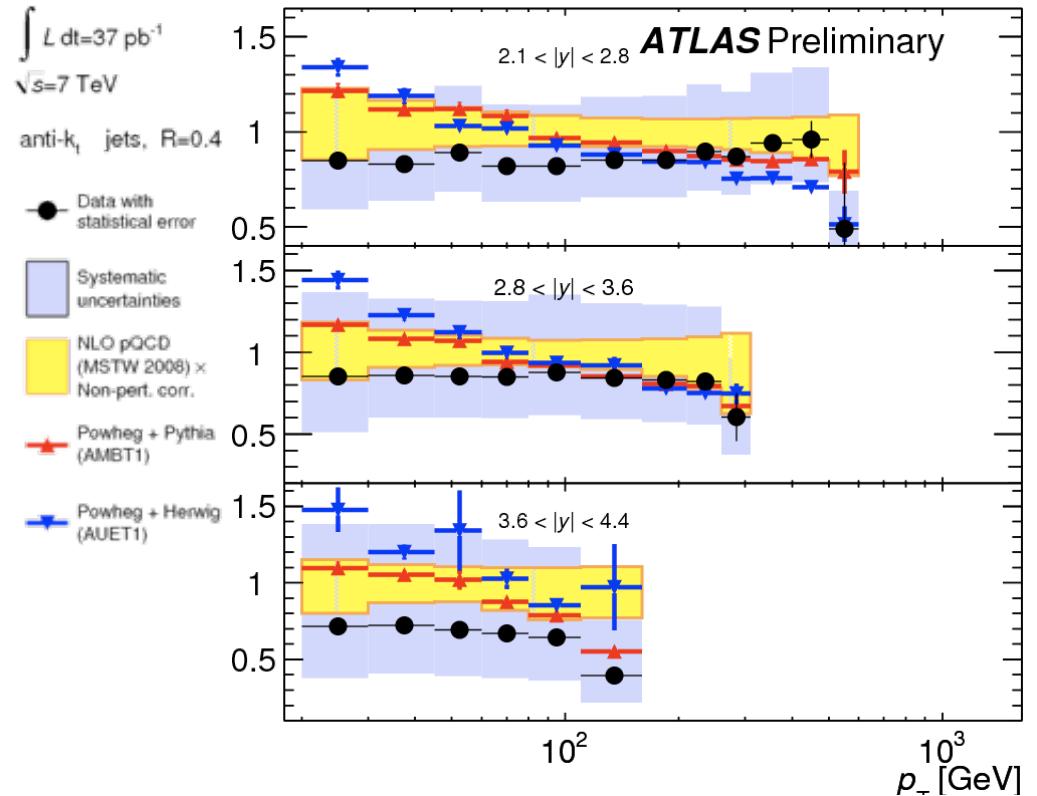
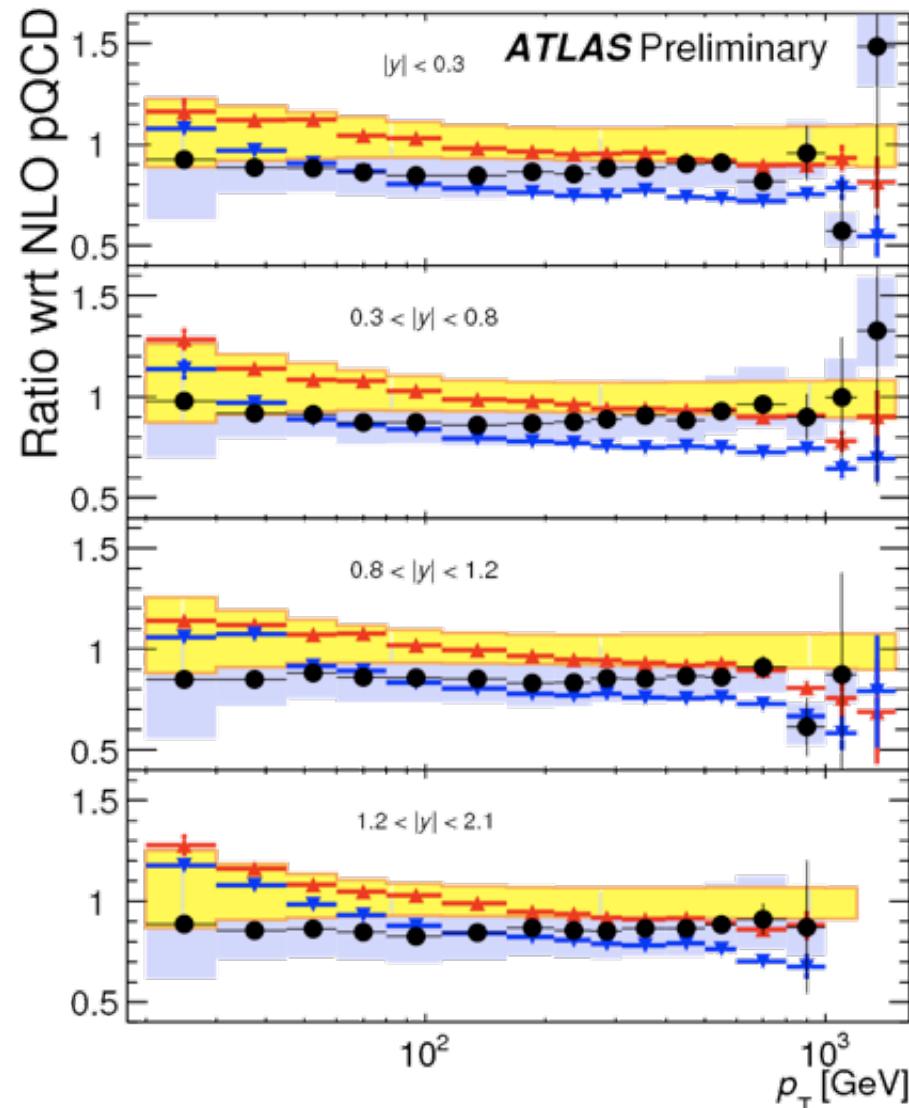
Comparison to various parton density sets

Inclusive jets



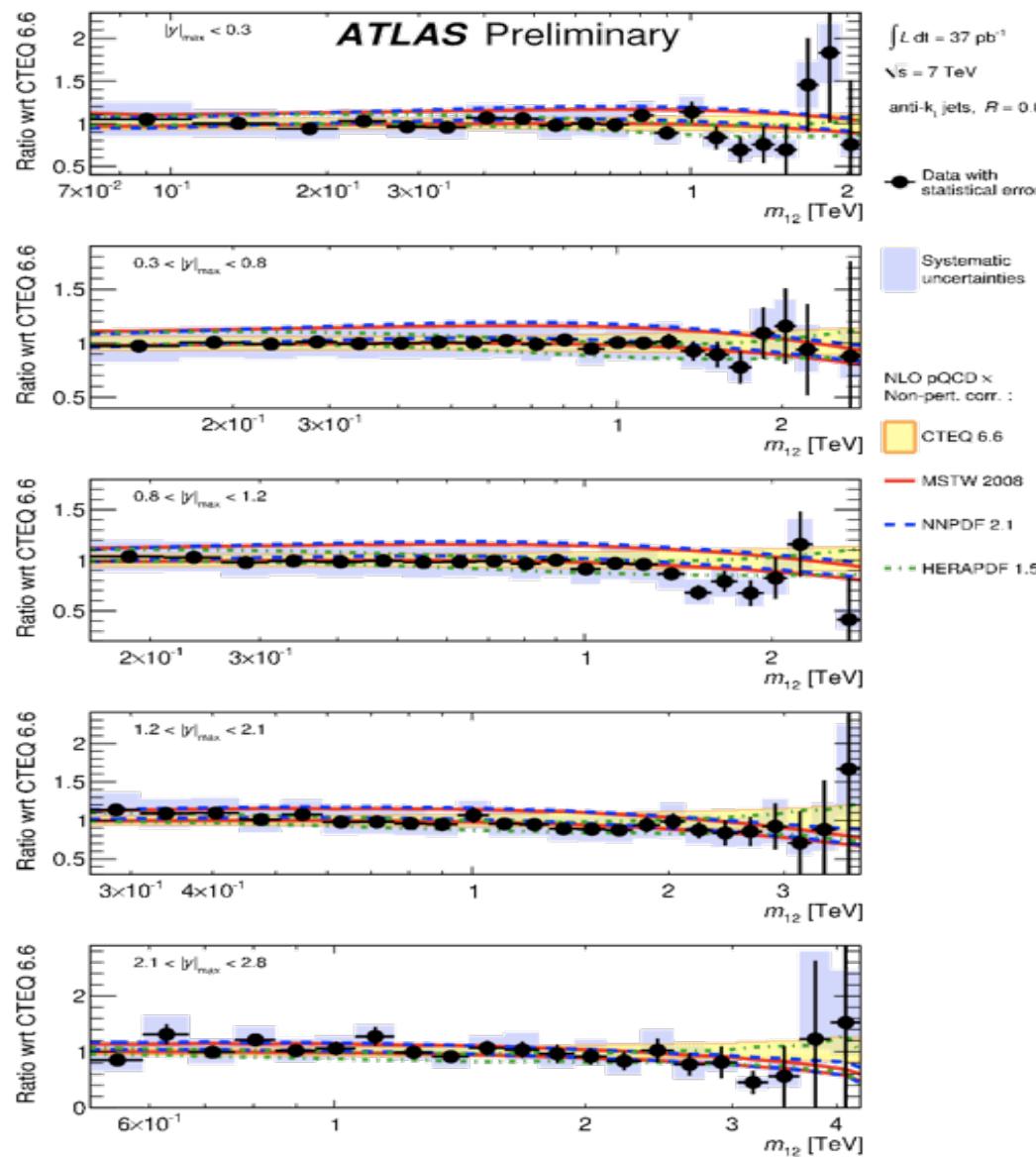
Comparison to various parton density sets

Inclusive jets



Comparison to POWHEG matched to
HERWIG/PYTHIA parton shower and UE

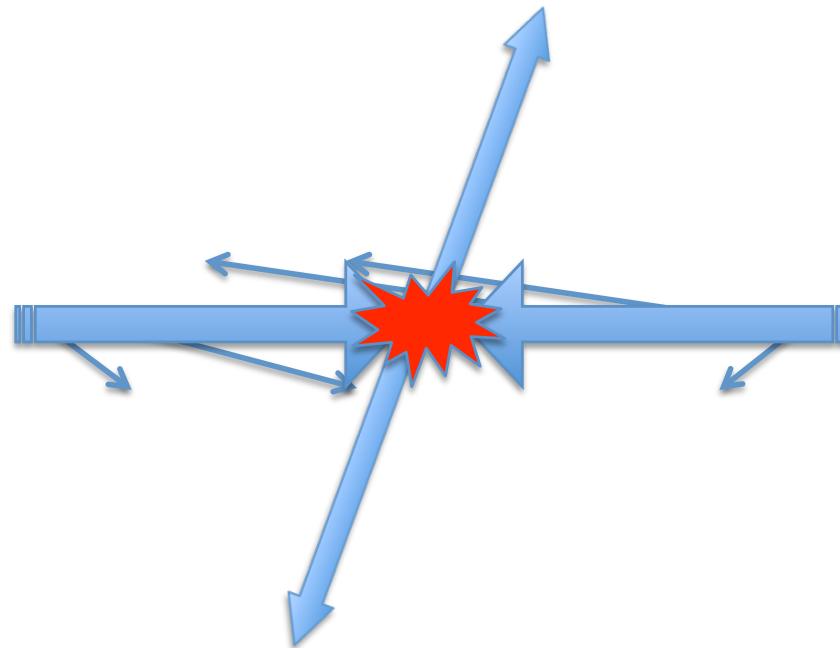
Dijets



Dijet cross section as a function of dijet mass, binned in rapidity of the more forward jet

Dijet ϕ Decorrelation

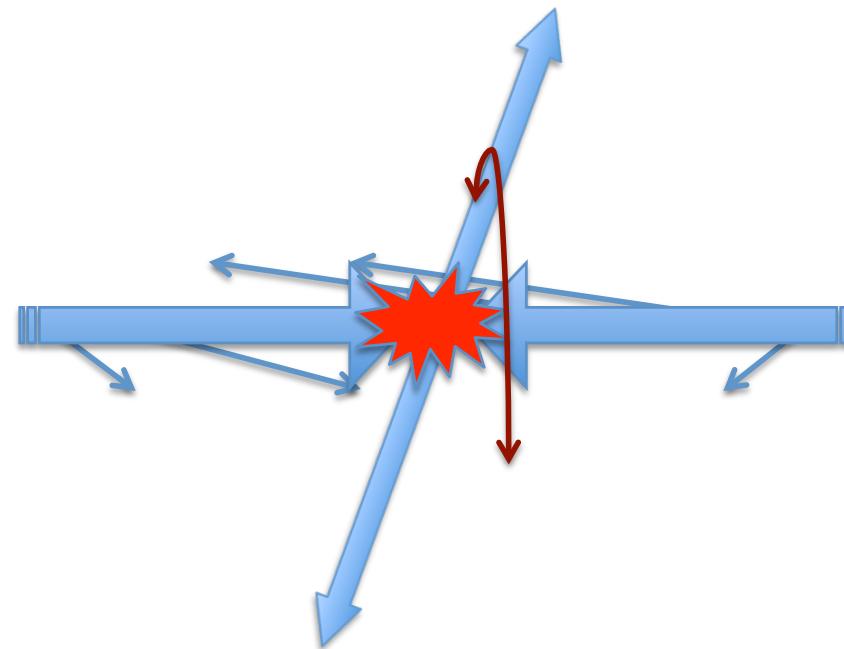
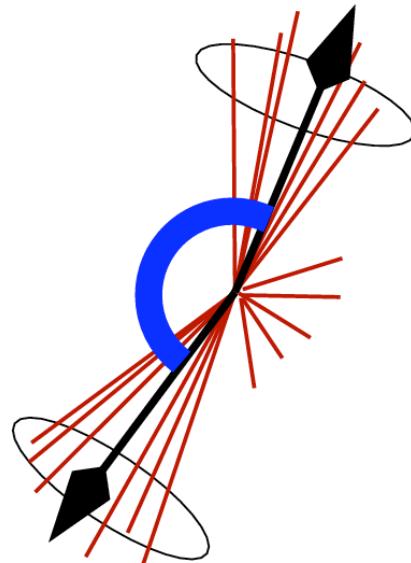
- Study how additional QCD radiation introduces an imbalance between the two highest p_T jets



Phys. Rev. Lett. 106, 172002 (2011)

Dijet ϕ Decorrelation

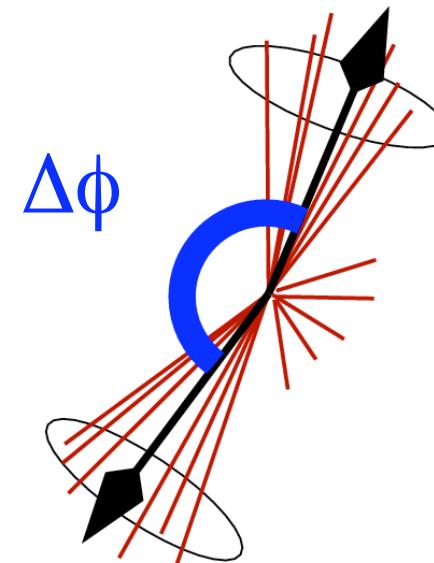
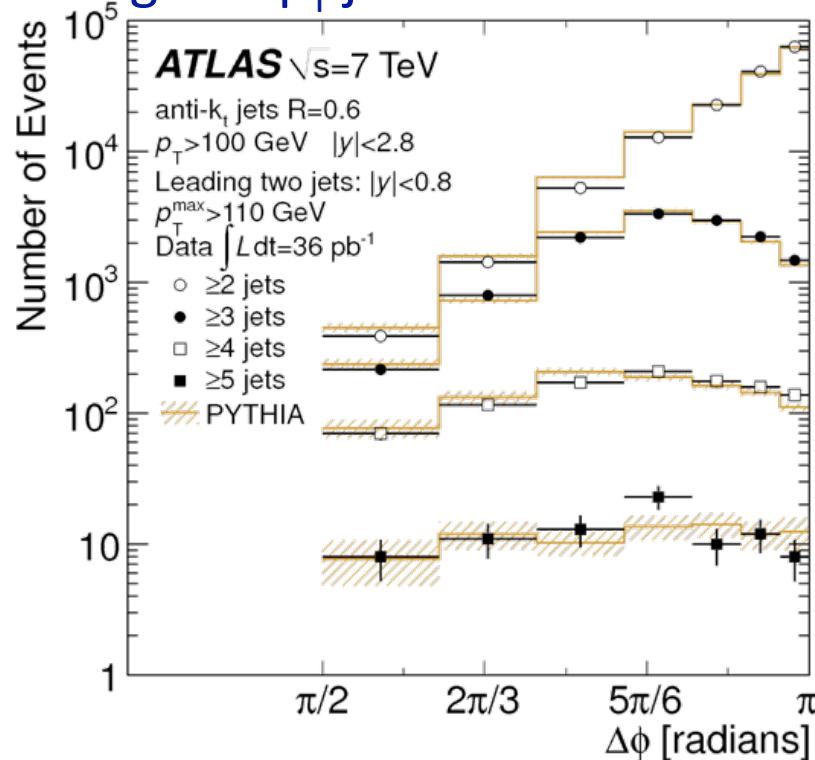
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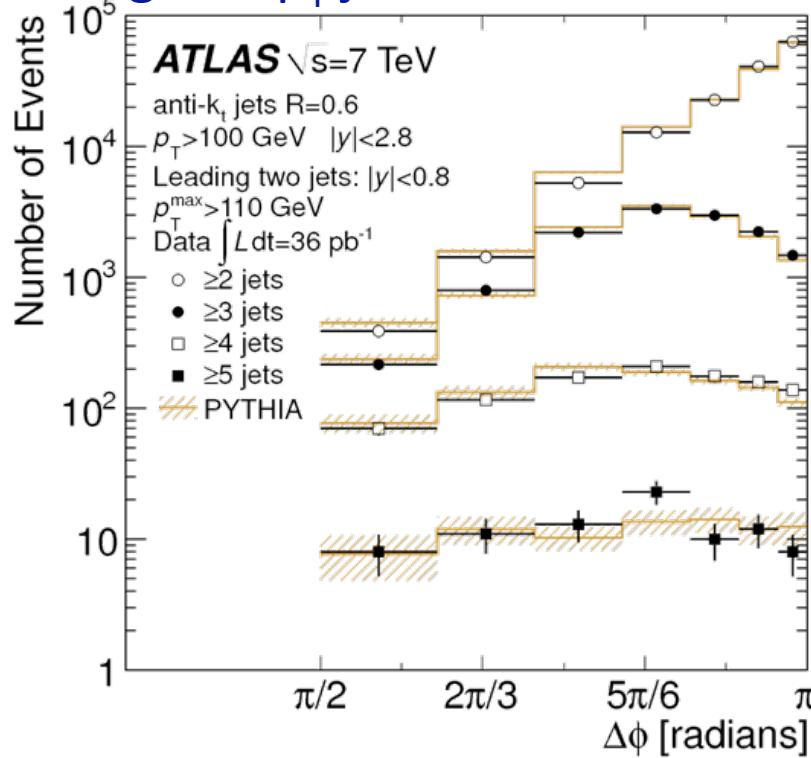
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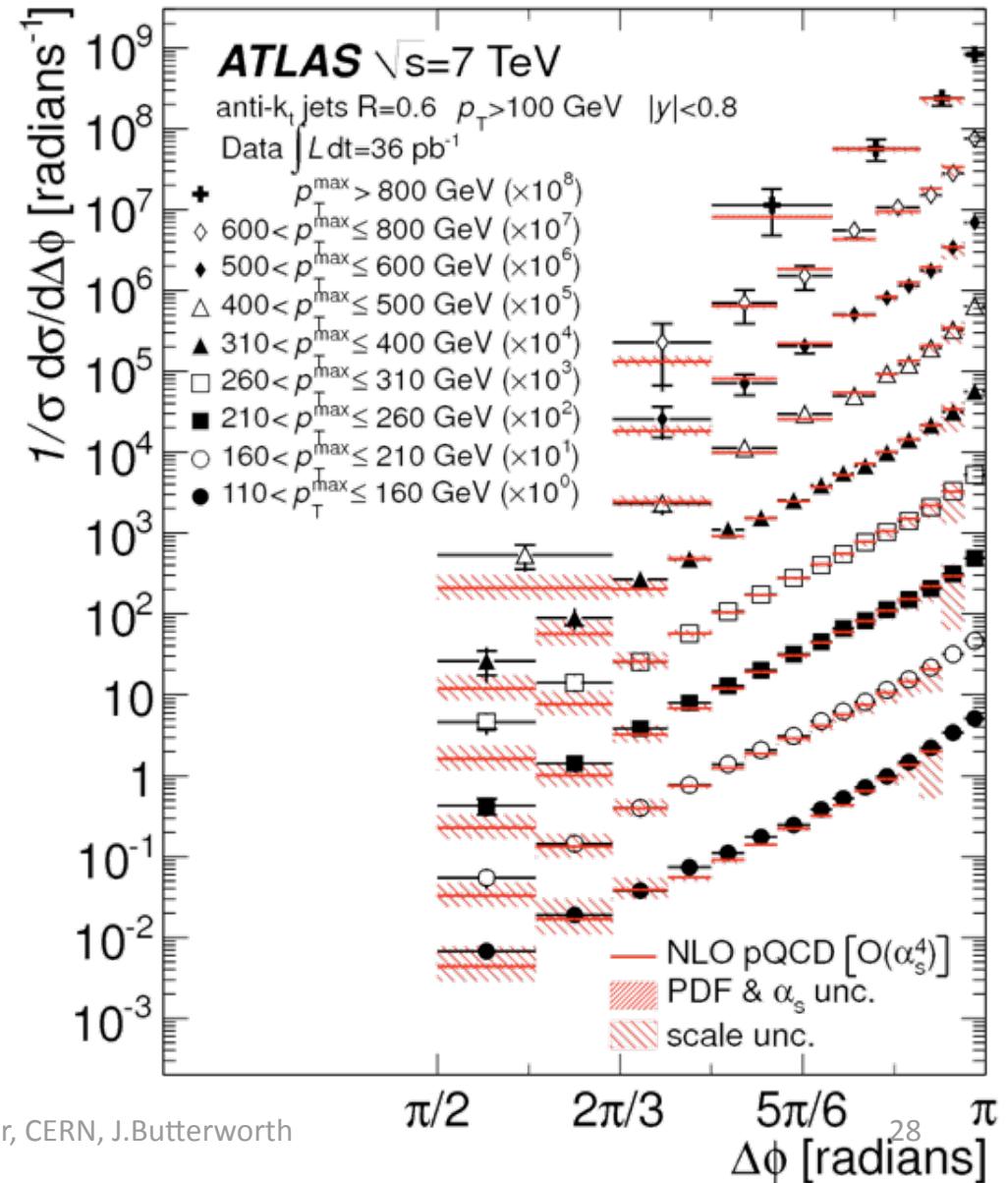
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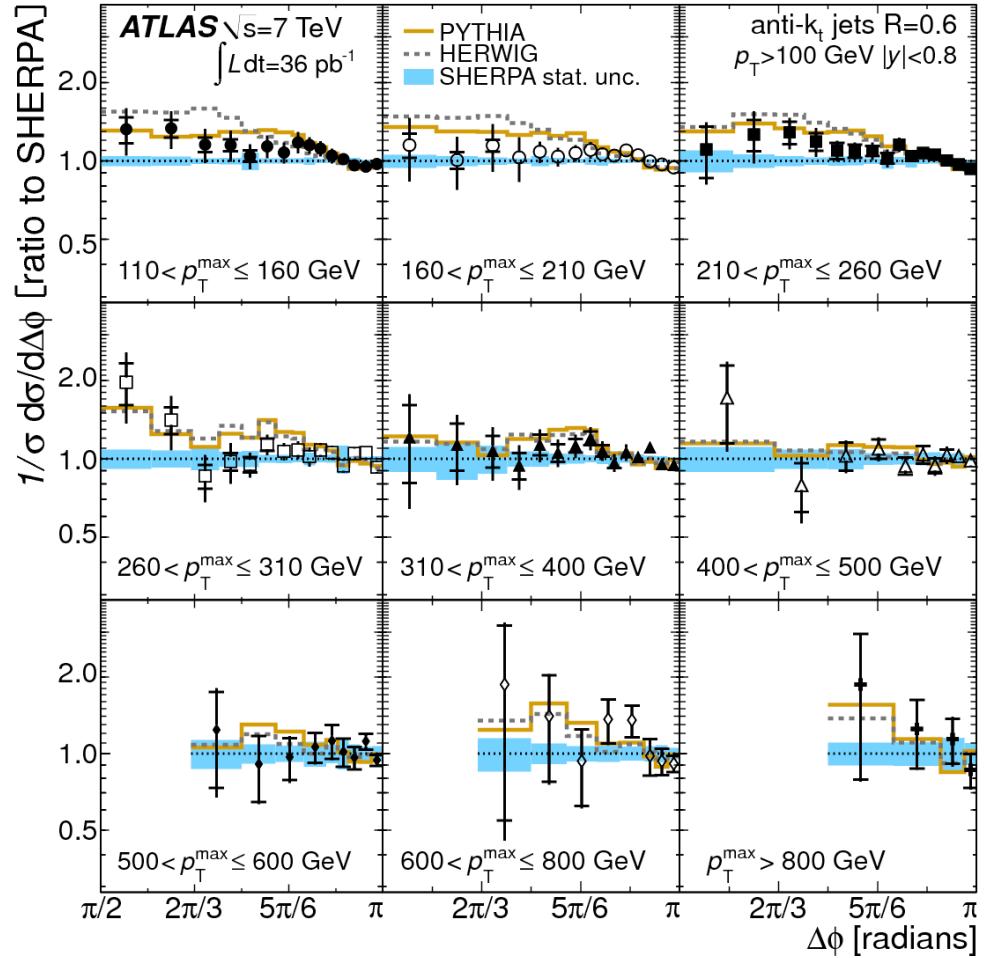
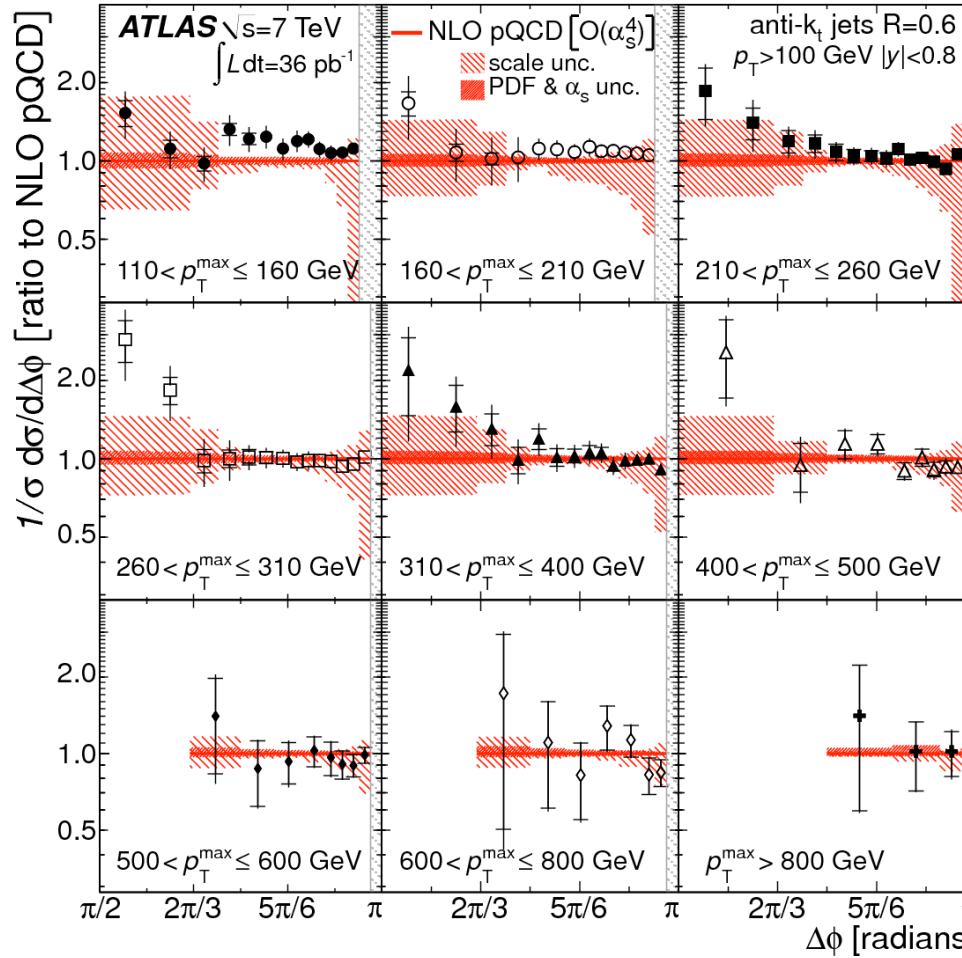
7 June 2011



LPCC Seminar, CERN, J.Butterworth

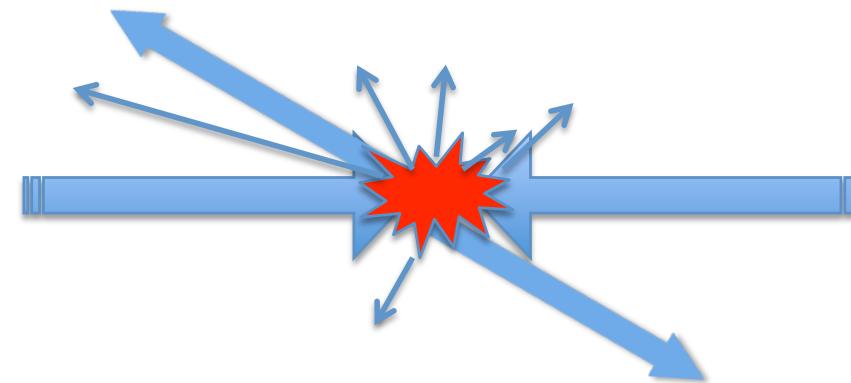
28

Dijet ϕ Decorrelation



Dijets with veto

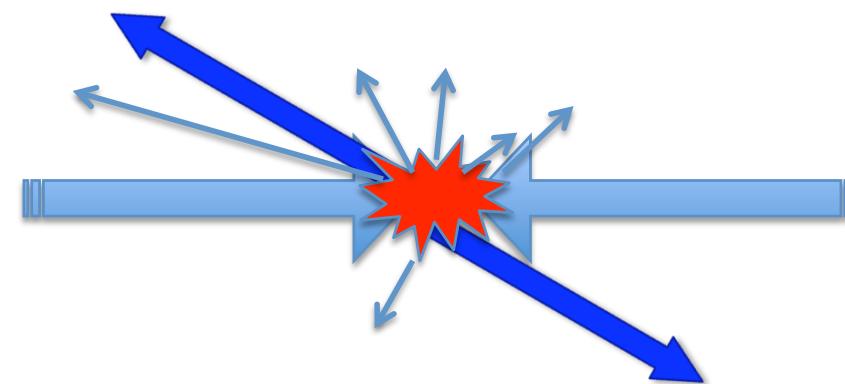
Select two jet separated
by a large rapidity interval



Dijets with veto

Select two jet separated
by a large rapidity interval

Selection A: highest pT
jets in event

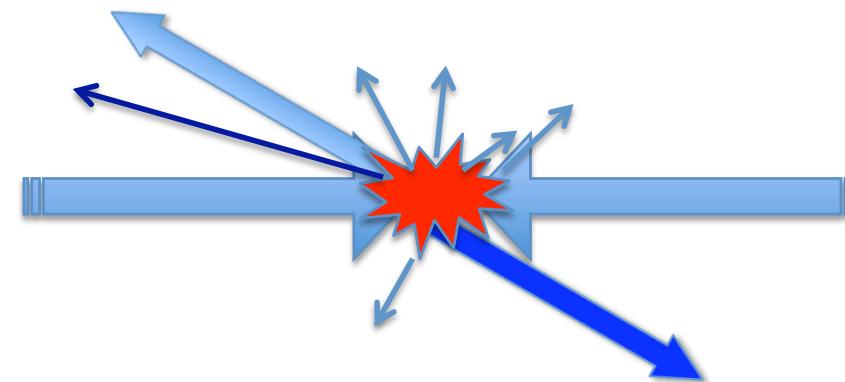


Dijets with veto

Select two jet separated
by a large rapidity interval

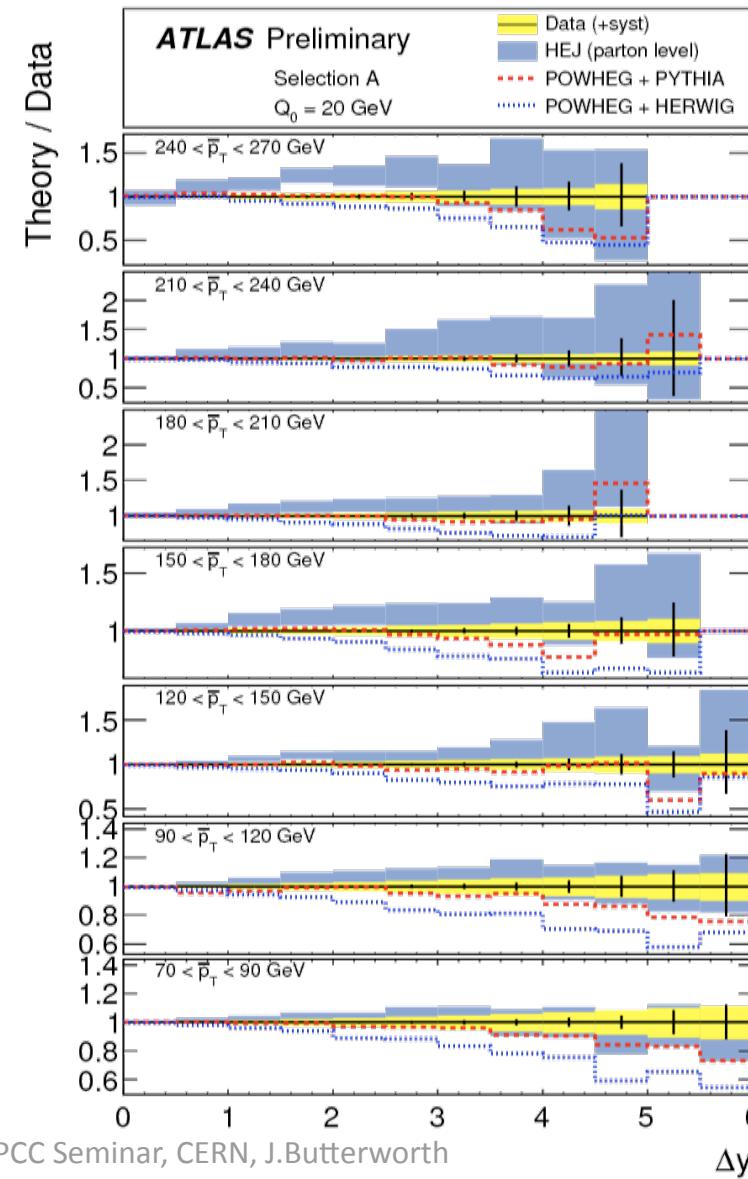
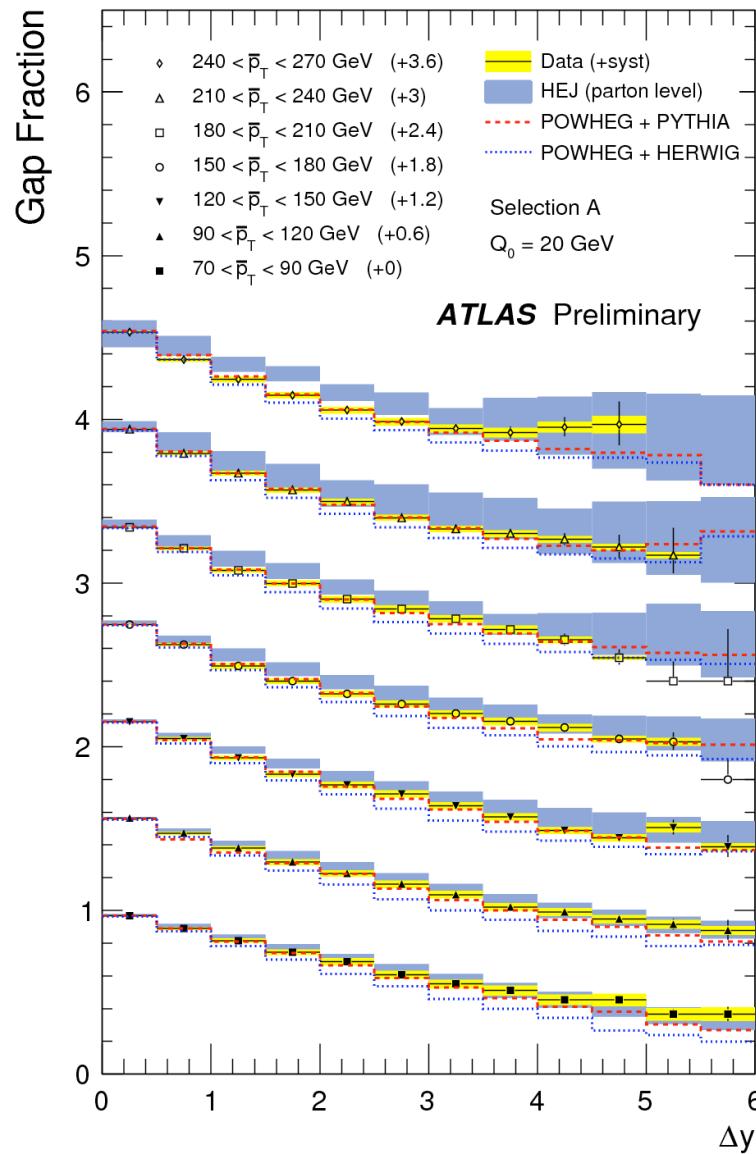
Selection A: highest p_T
jets in event

Selection B: most forward
and backward jets above
some cut.



Gap fraction = $\frac{\text{(Number of event with no jets in the gap)}}{\text{(All events)}}$

Dijets with veto

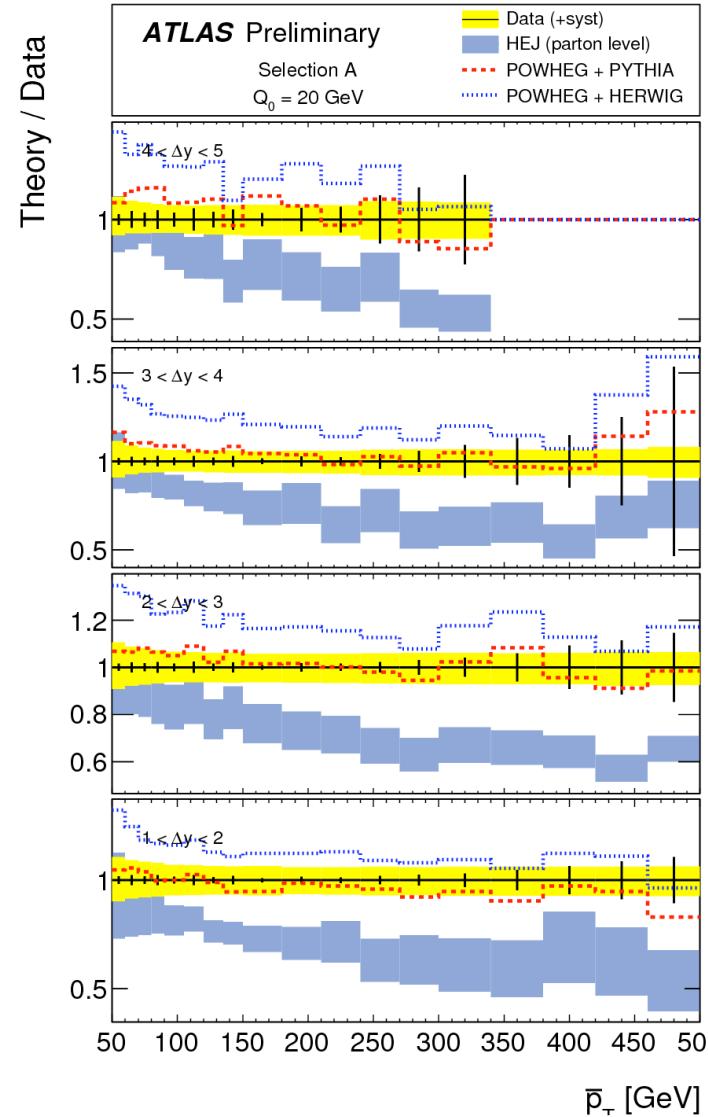
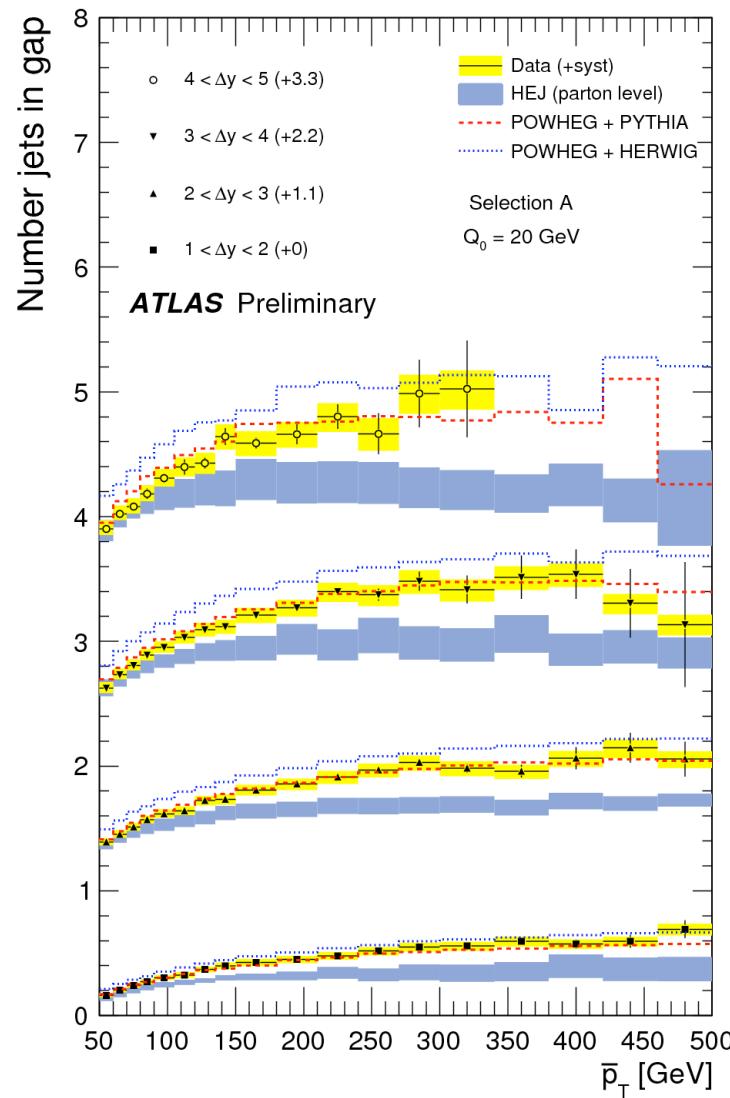


Gap fraction falls with Δy

Fairly well described by theory
(HERWIG parton shower or JIMMY gives too few gaps?)

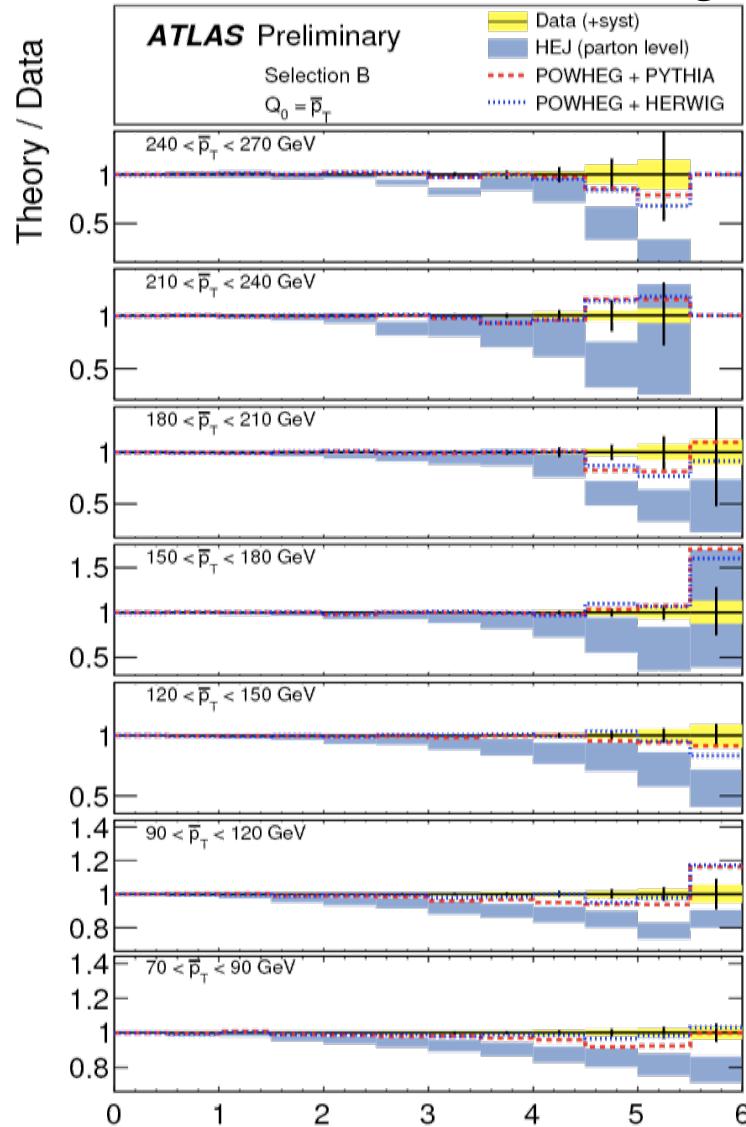
HEJ doing somewhat better

Dijets with veto



However,
number of
events in gaps
not well
modelled by
HEJ – much
better with
NLO + PYTHIA
parton
shower

Dijets with veto



Possibly because HEJ does not contain Q^2 logarithms?

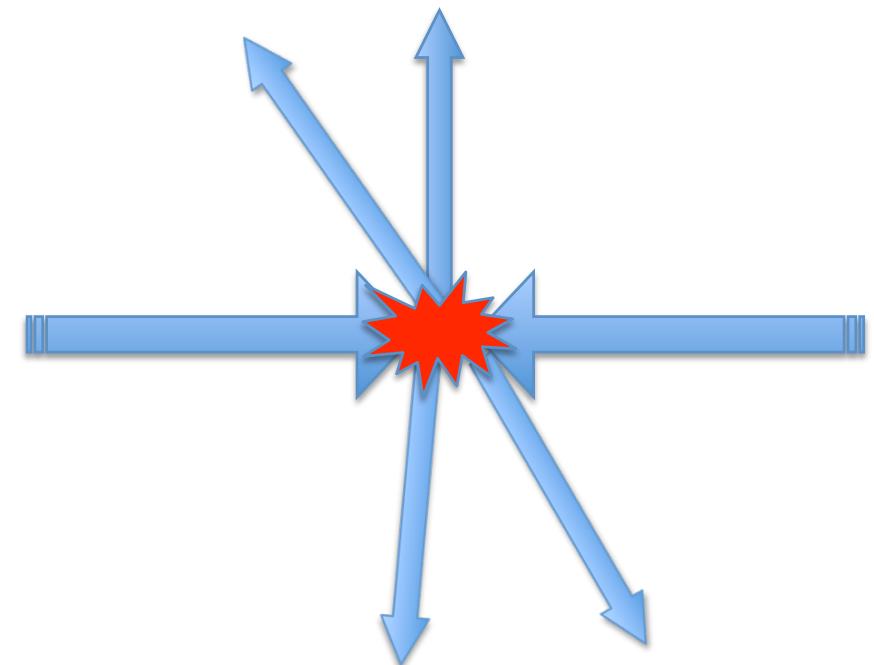
$$\ln(Q_0/p_T)$$

So, try fixing $Q_0 = p_T$

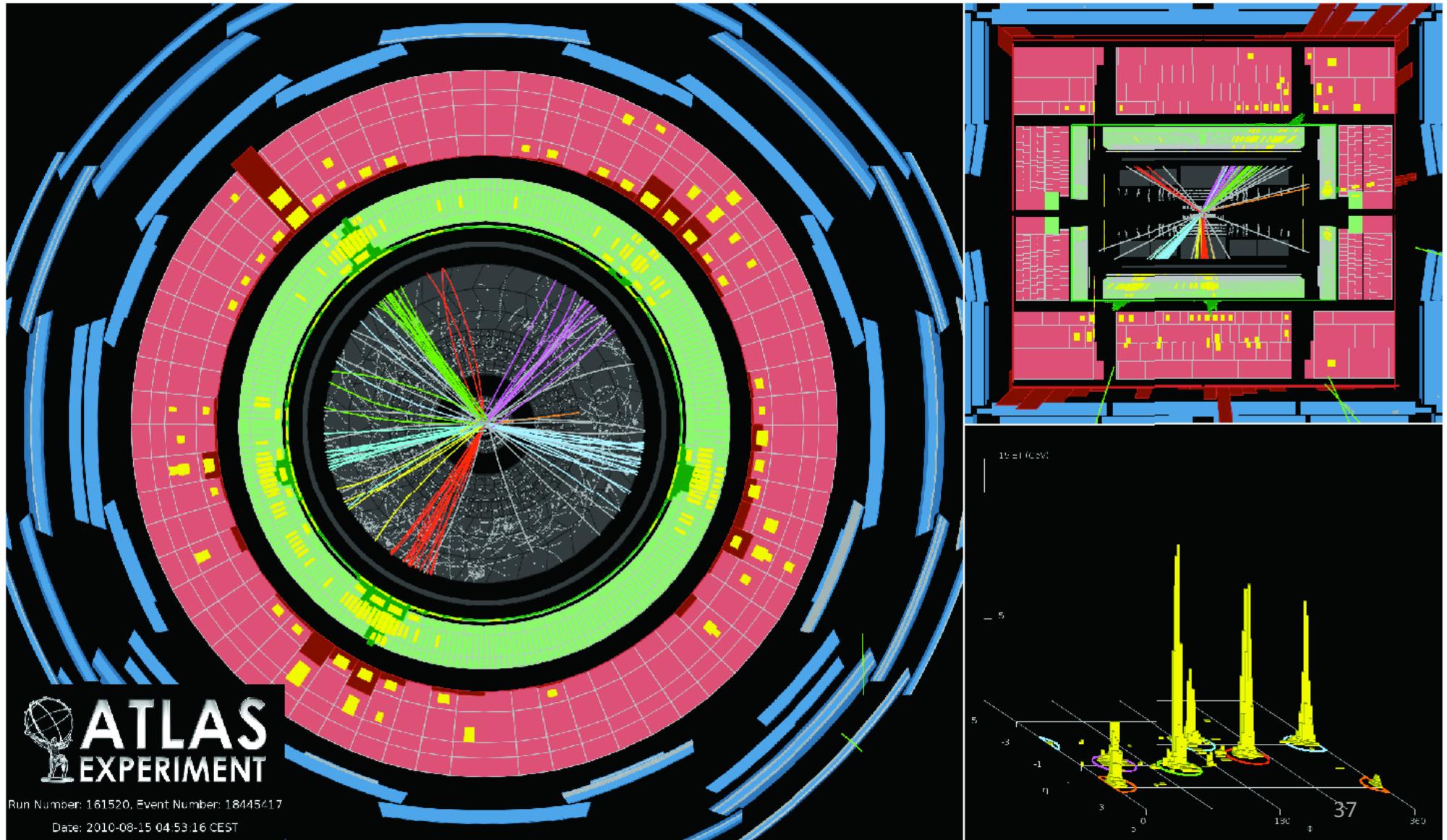
Not much improvement.

Multijets

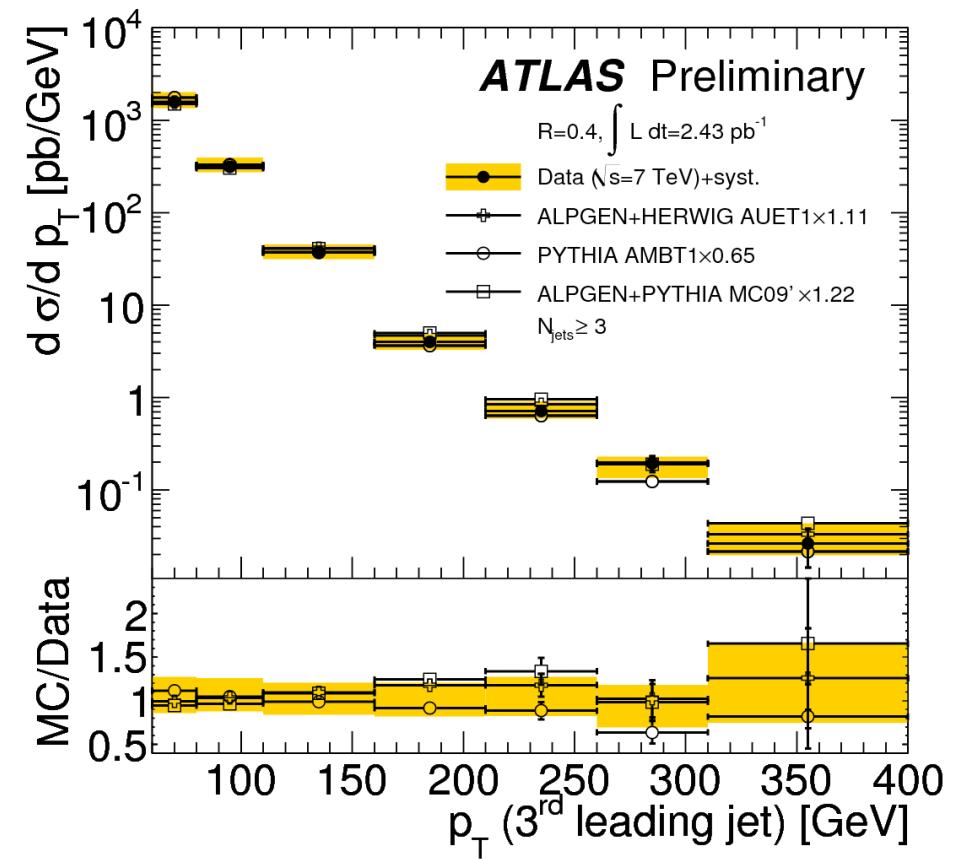
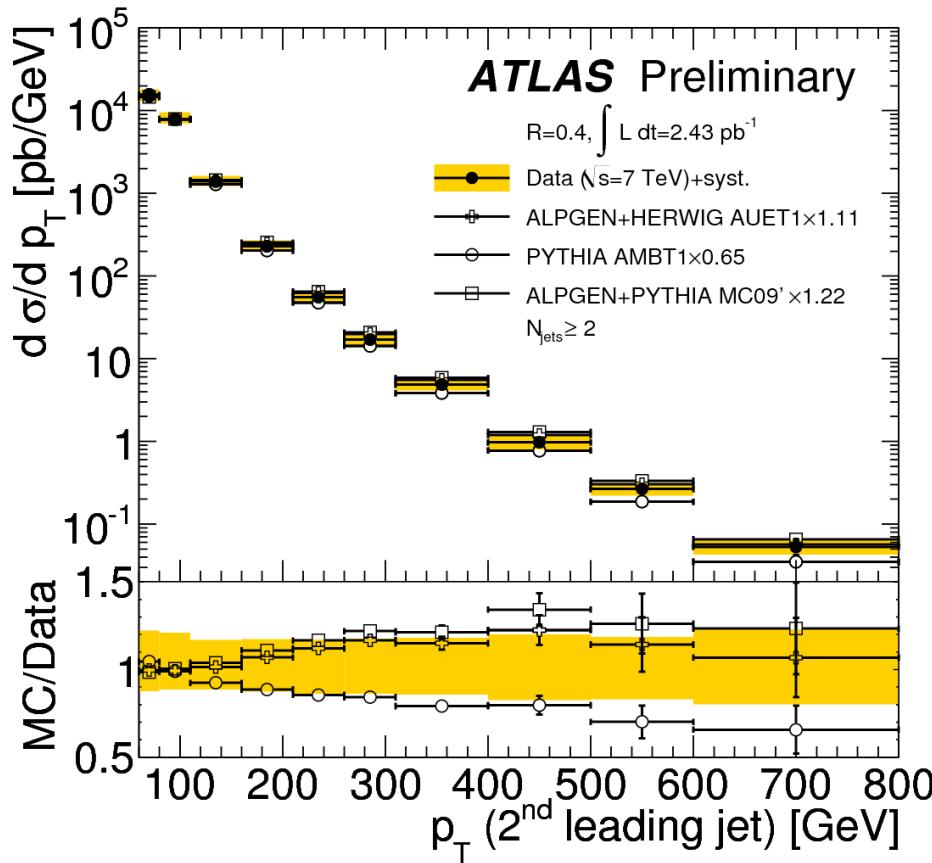
- Treat jets on an equal footing (no special privileges for the highest momentum pair).
- Zone where fixed order α_s QCD should work well
- Also matrix element+parton shower
- Do we need the extra trees in the matrix element?
- Measured here for jets with $p_T > 60 \text{ GeV}$ (and one $> 80 \text{ GeV}$)



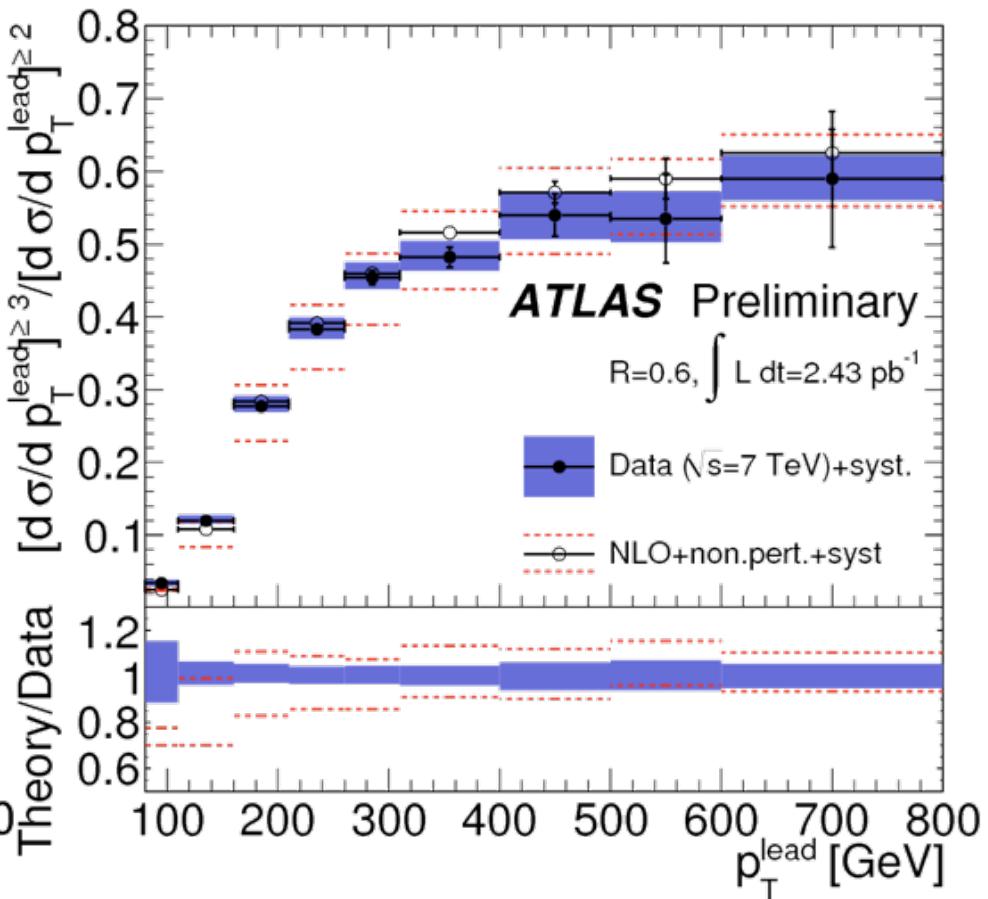
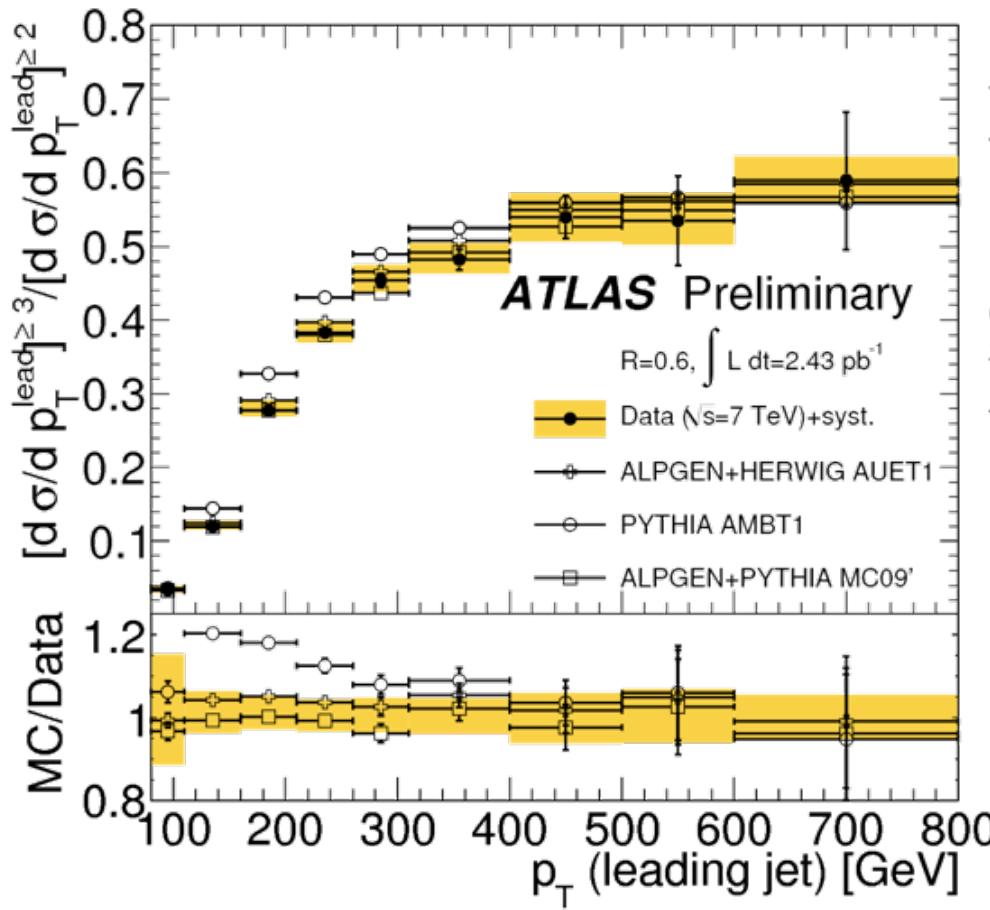
Multijets



Multijets

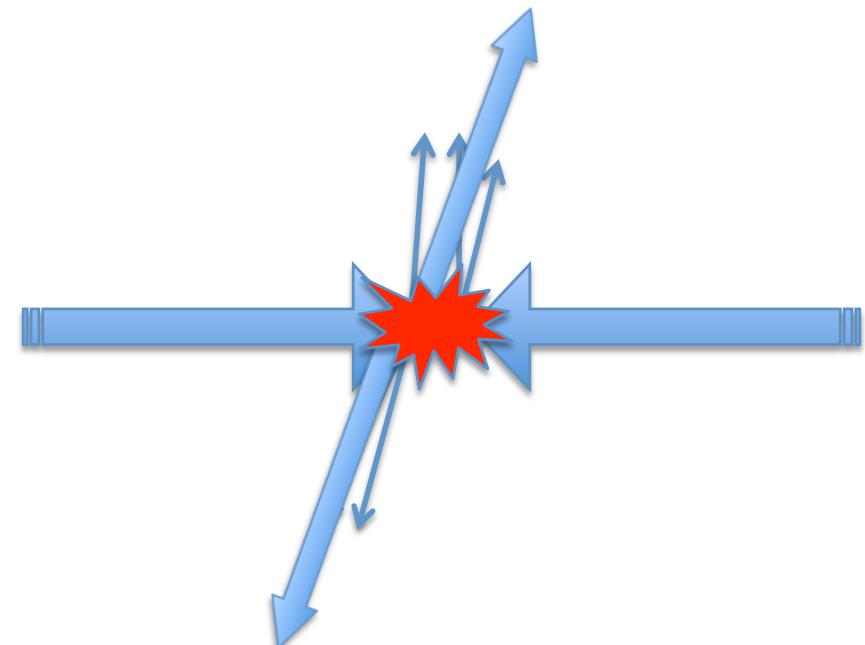


Multijets



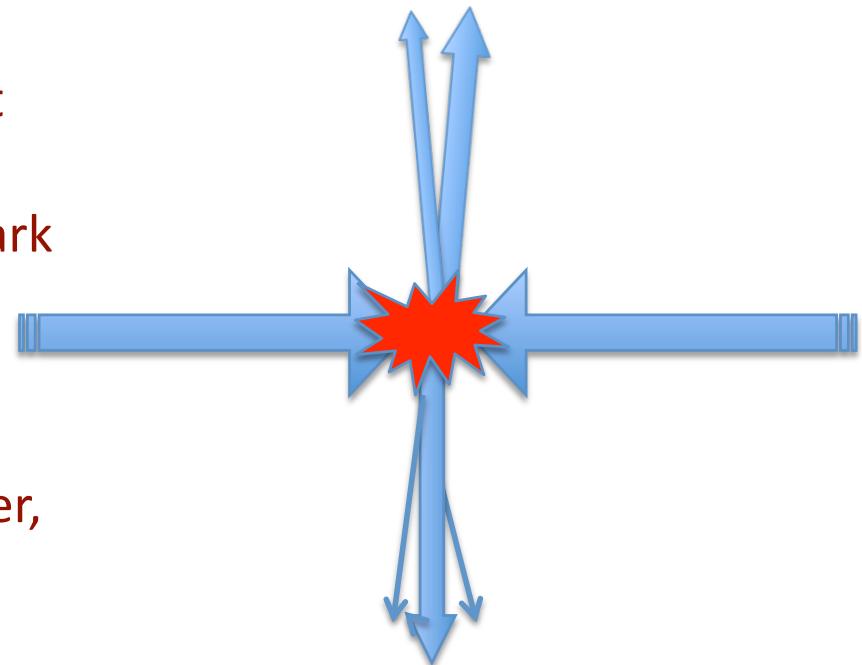
Inside the jets

- Internal structure of jets is sensitive to hadronisation, underlying event
 - Non-perturbative effects
 - Measurements useful for tuning models, which can then lead to improved measurements



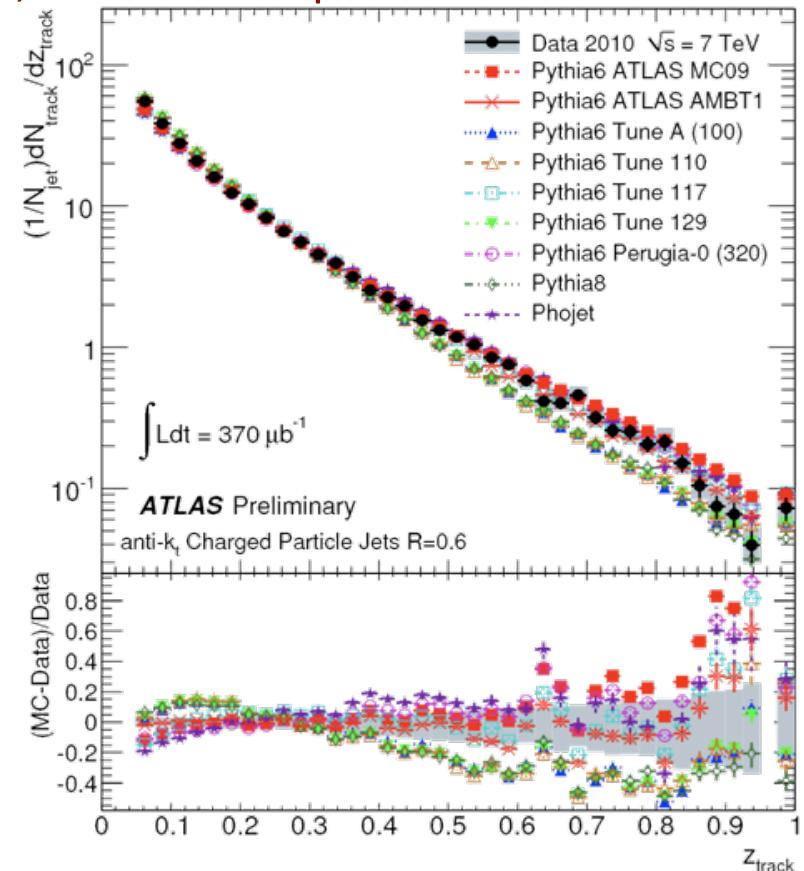
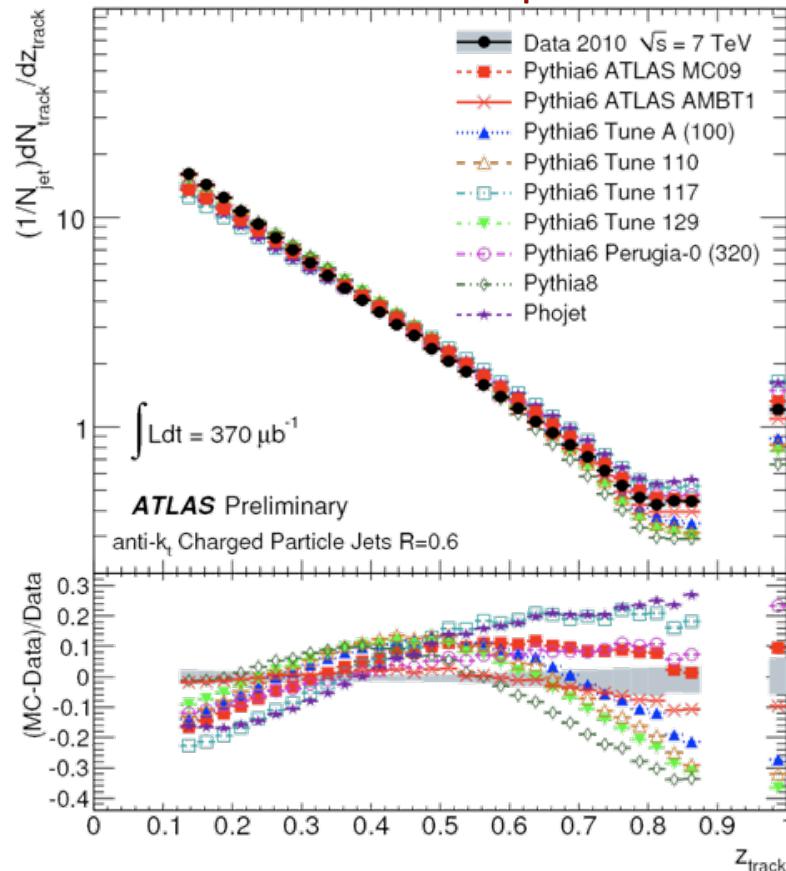
Inside the jets

- However, at the LHC there is a lot of room for perturbative evolution between jets scales of a few 100 GeV and the soft regime around 1 GeV
 - Perturbative predictions for QCD jet substructure
 - B hadrons either from leading b quark or from gluon splitting
 - This energy range encompasses the electroweak scale.
 - There could be electroweak, or other, physics inside the jets!



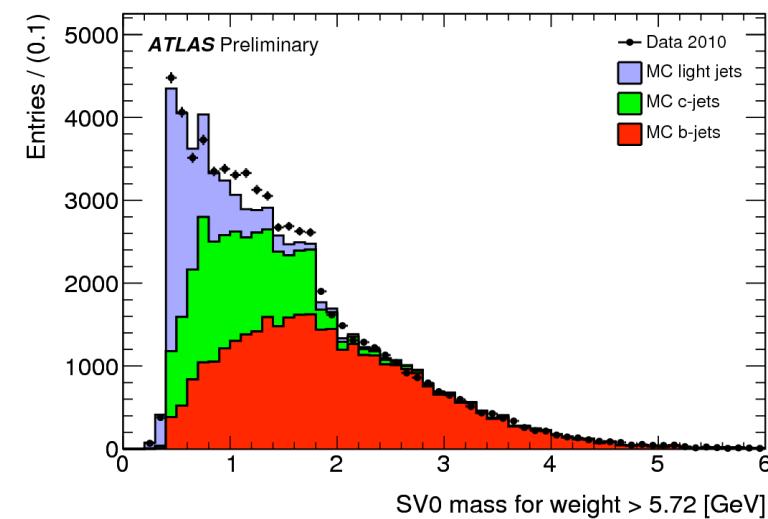
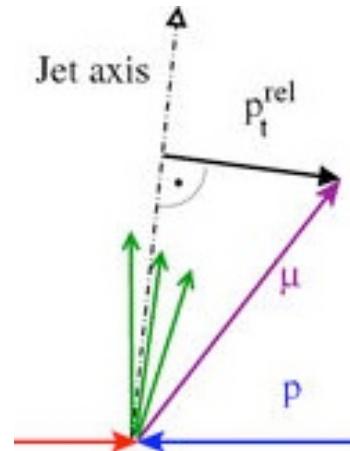
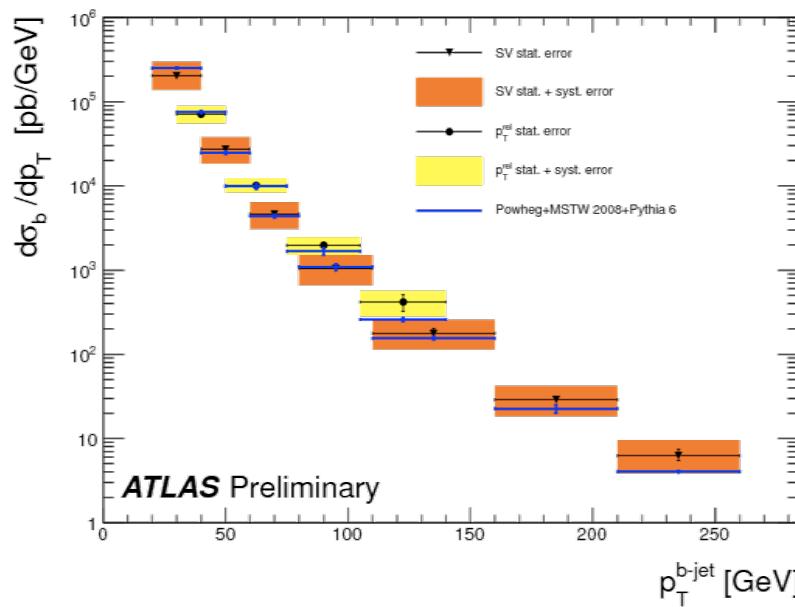
Charged particle jets

- Find jets using tracks measured in the inner detector, measure fragmentation function
 - Very low in pT (4-6 GeV left, 15-24 GeV right)
 - Sensitive to non-perturbative fragmentation, as well as to parton shower



B jets

- Tag bottom hadrons with p_T^{rel} or secondary vertex

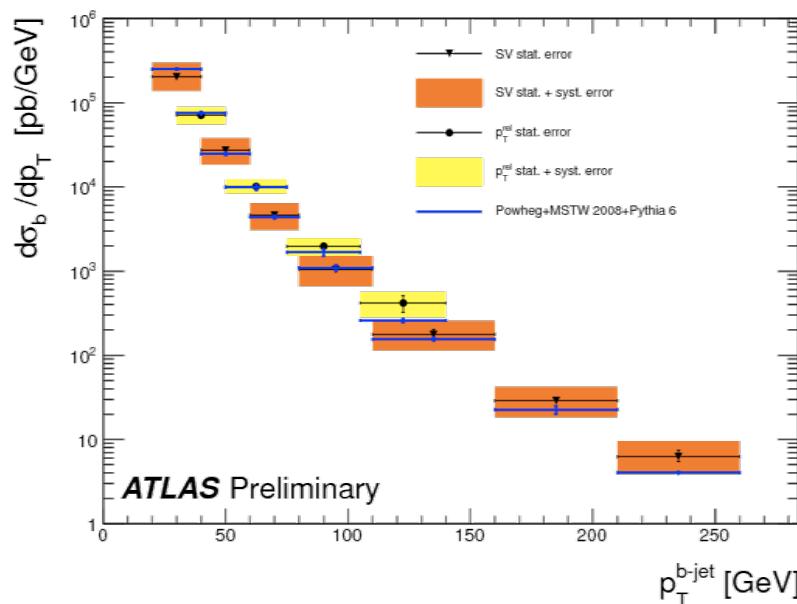


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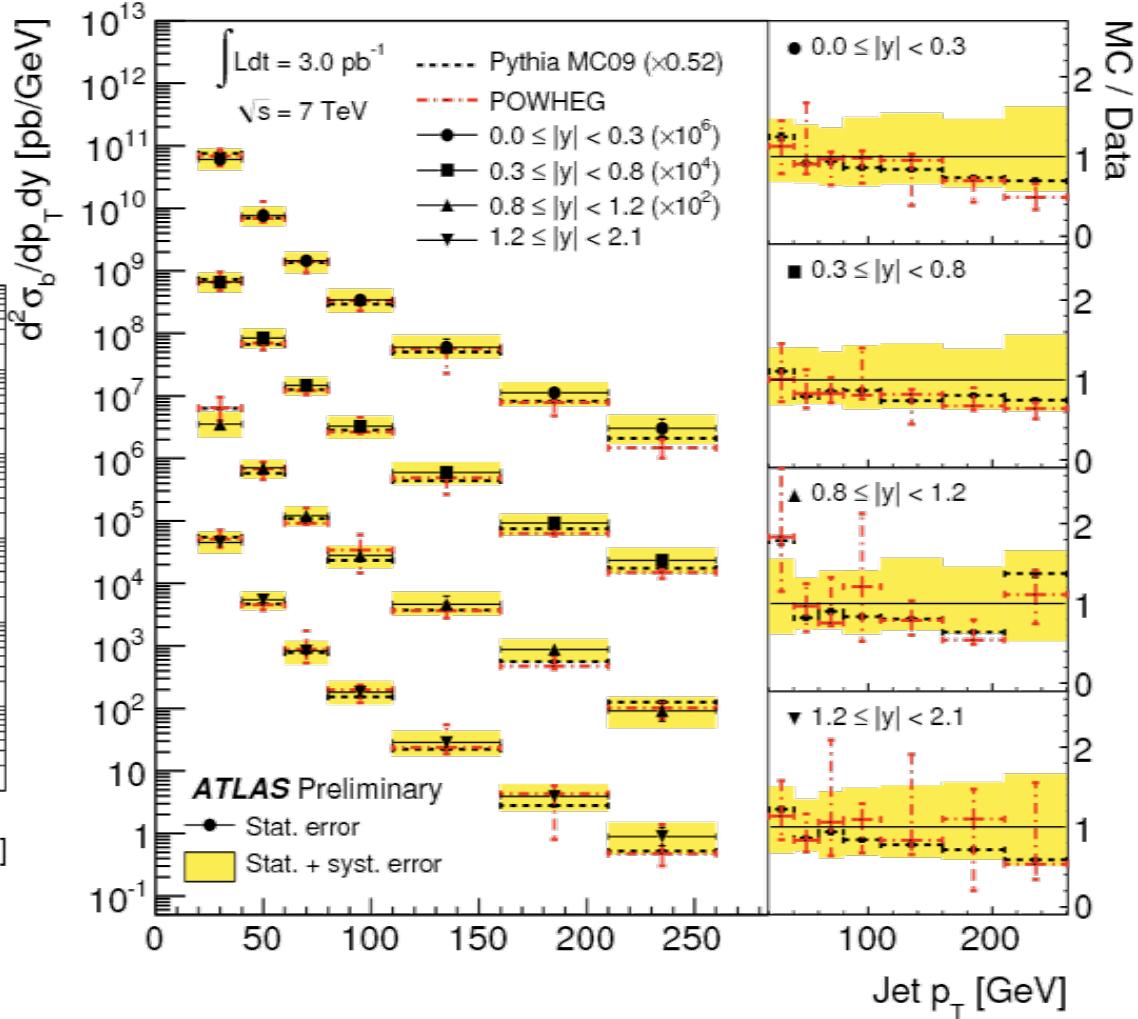
B jets

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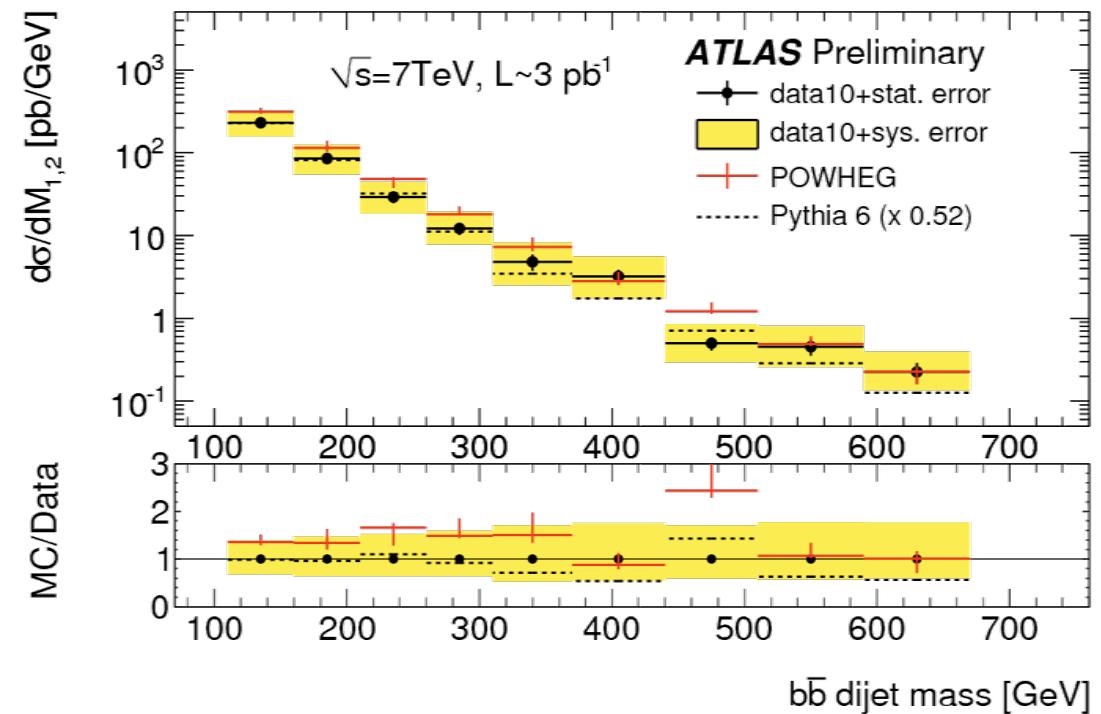
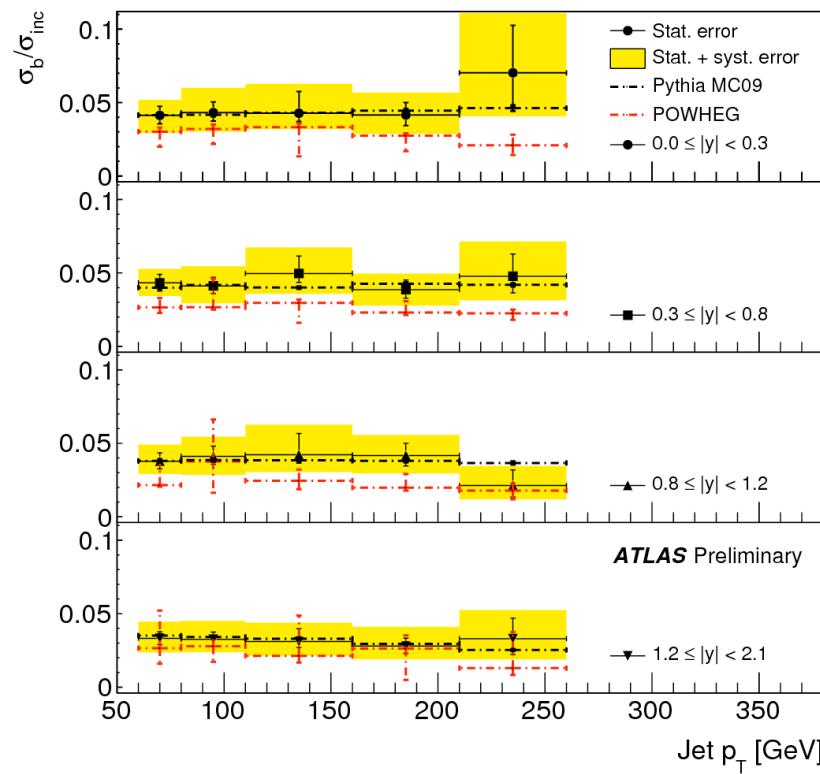


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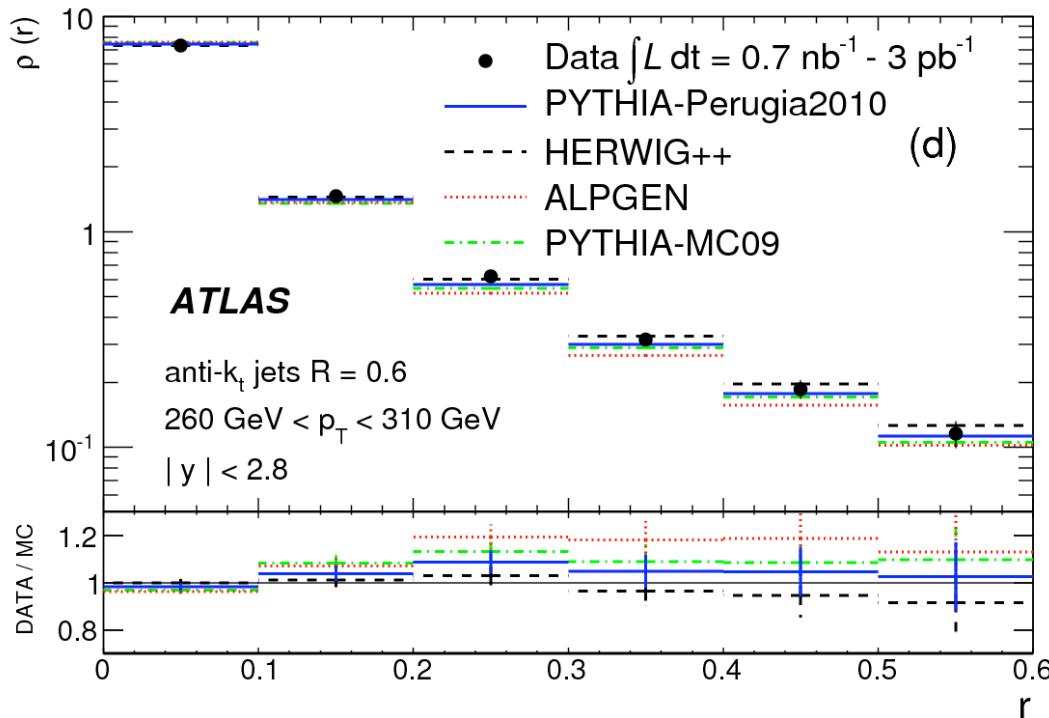
B jets



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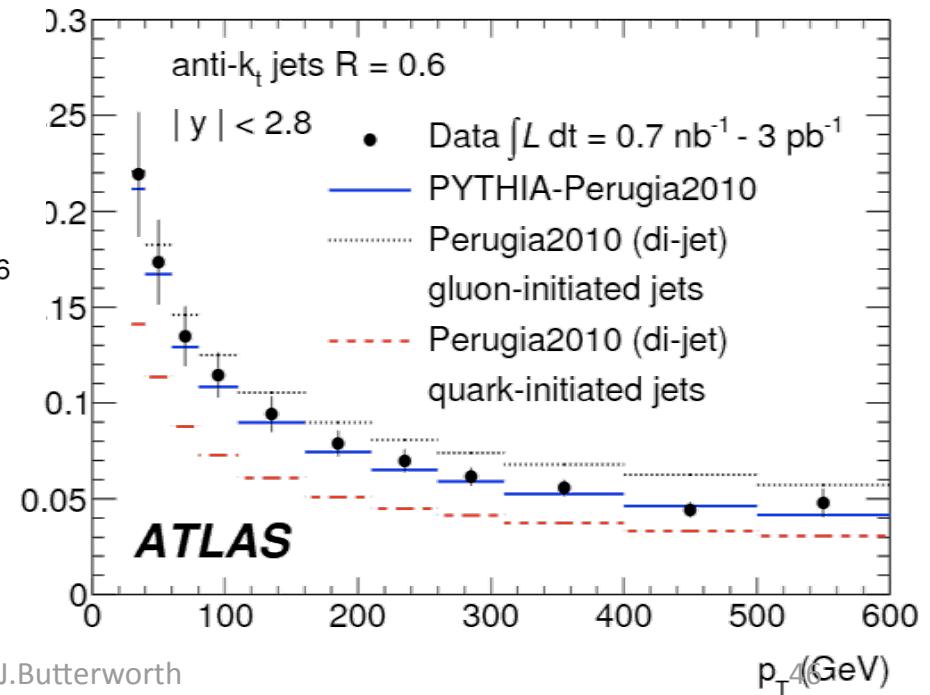
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Jet Shapes



$\rho = \text{fraction of } p_T \text{ in annulus } r - \delta r/2 \rightarrow r + \delta r/2 \text{ (divided by } \delta r)$

Phys. Rev. D 83, 052003 (2011)



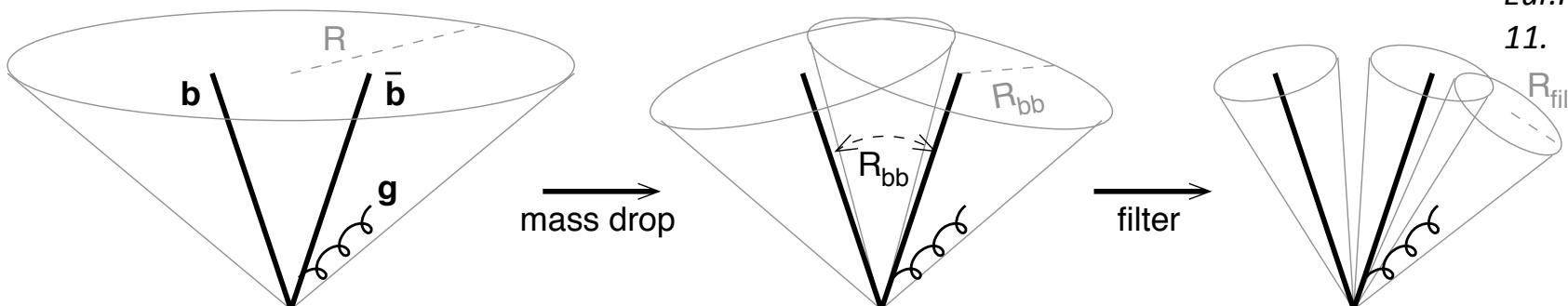
Fat Jets

- Boosted heavy objects decaying to hadrons can appear as very close-by jets, or even a single jet. How to find them?
- Make the jet bigger (to catch more of them) then look inside it.
- Three new variables:
 - Single jet mass (mass of decaying object?)
 - Final merging scale of the k_T cluster (relative p_T of the decay products)
 - Look for a mass drop and then filter the jet to remove soft radiation (filtered mass)

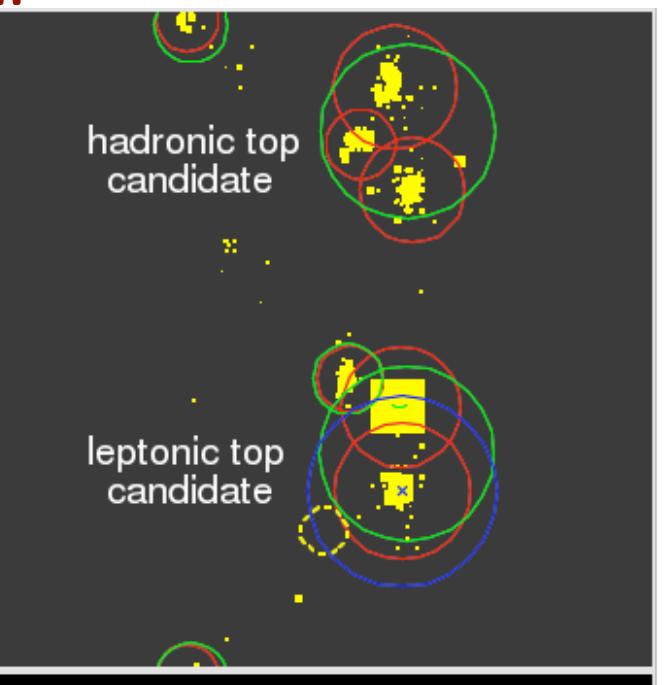
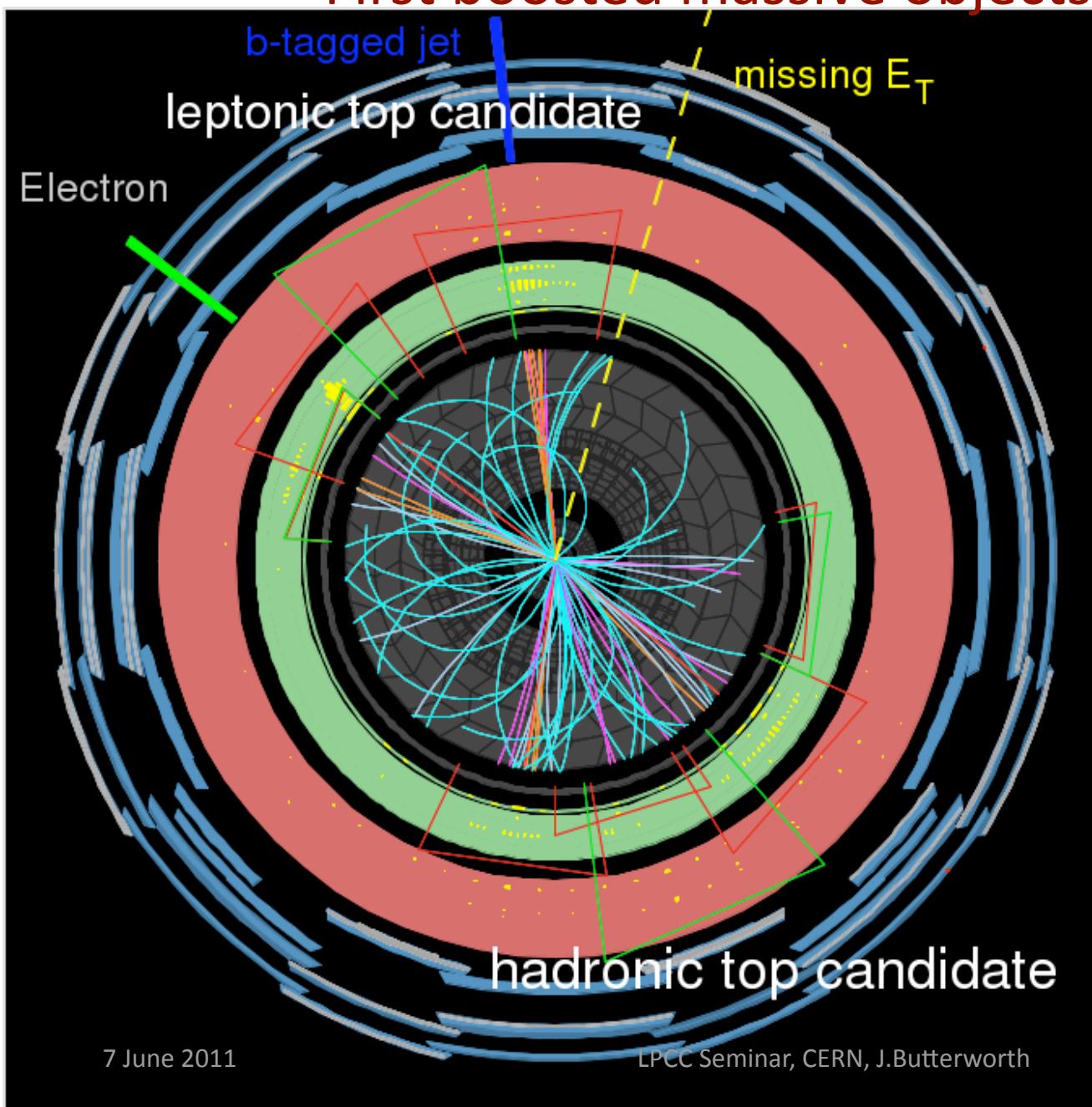
*M.H.Seymour,
Z.Phys.C62:127-138,
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JMB, Cox, Forshaw,
PRD 65; 096014
(2002)*

*BDRS, PRL 100,
242001 (2008).
Kaplan, et al PRL 101,
142001 (2008)*

*A. Abdesselam et al.
Eur.Phys.J.C71:1661,20
11.*



First boosted massive objects...



 **ATLAS**
EXPERIMENT

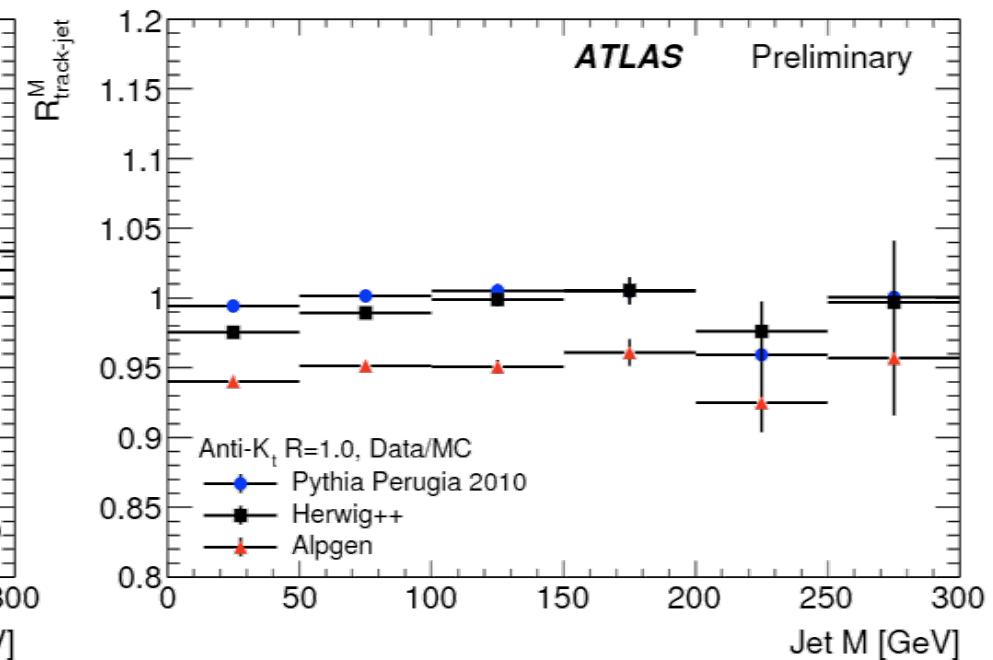
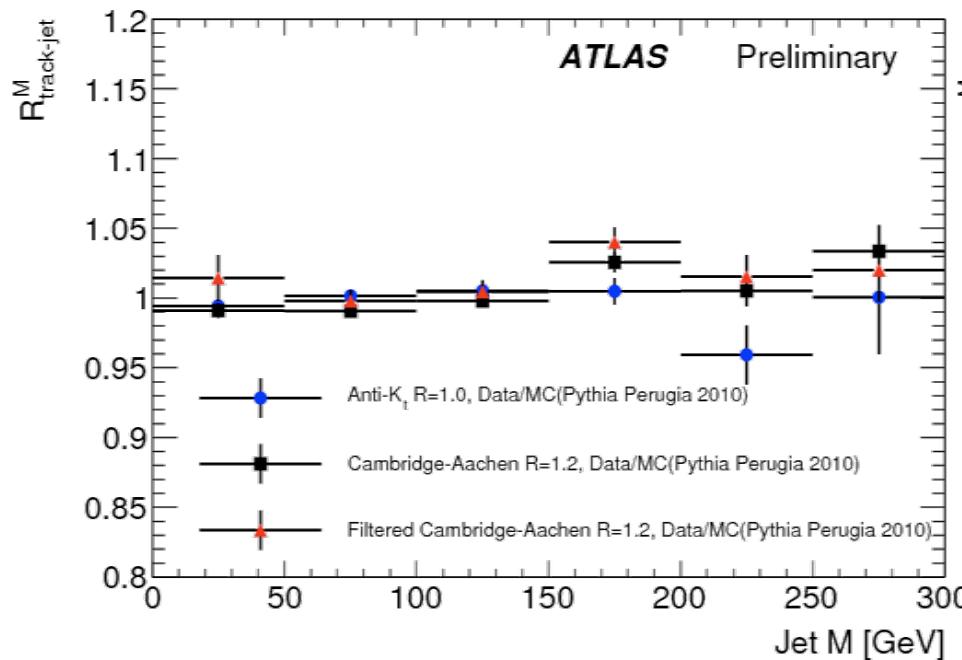
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Date: 2010-10-11 23:57:42 CEST

Calibrating Jet Substructure

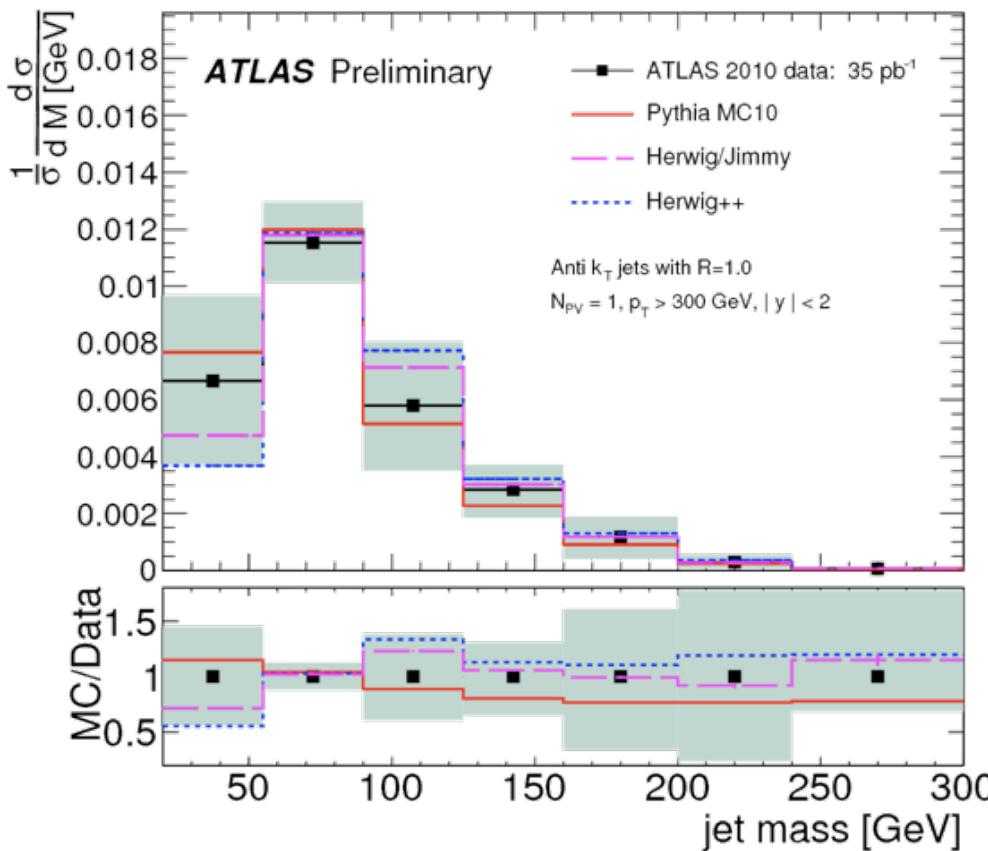
- How well can we measure these new variables?
- Mass calibration from comparing tracking and calorimeter (double ratio) within tracking volume

$$R_{\text{track-jet}}^M = (M_{\text{calorimeter}}/M_{\text{tracks}})_{\text{Data}} / (M_{\text{calorimeter}}/M_{\text{tracks}})_{\text{MC}}$$

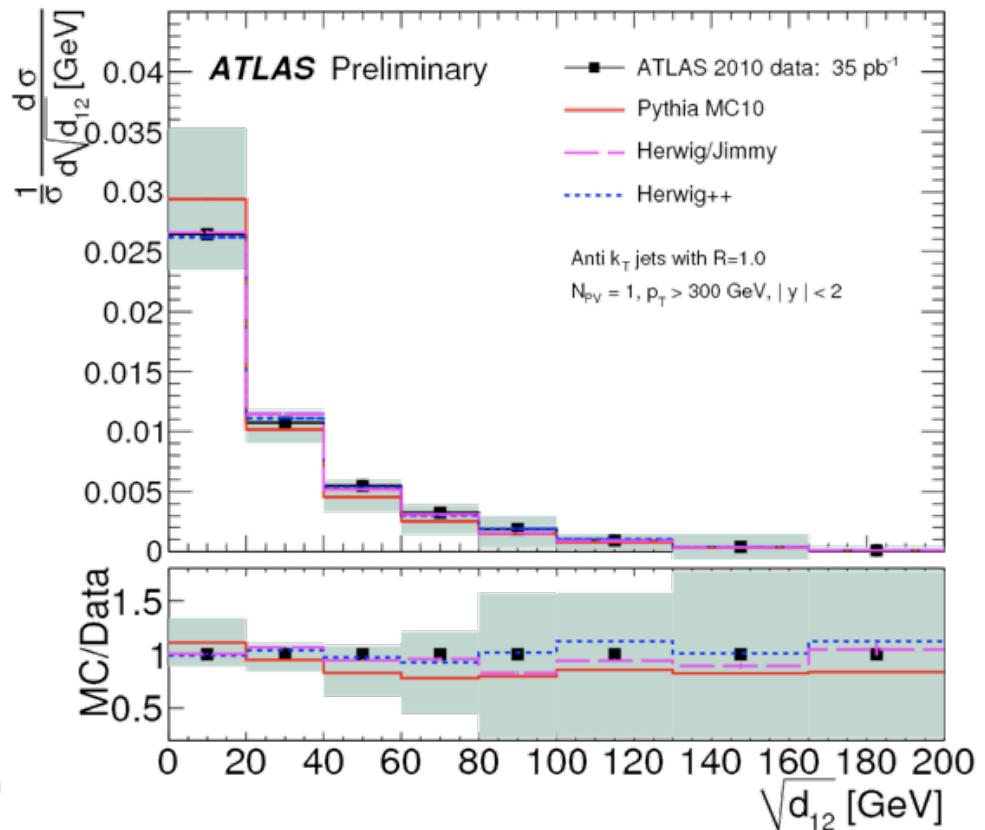


Jet mass and substructure

- Anti- k_T jet mass

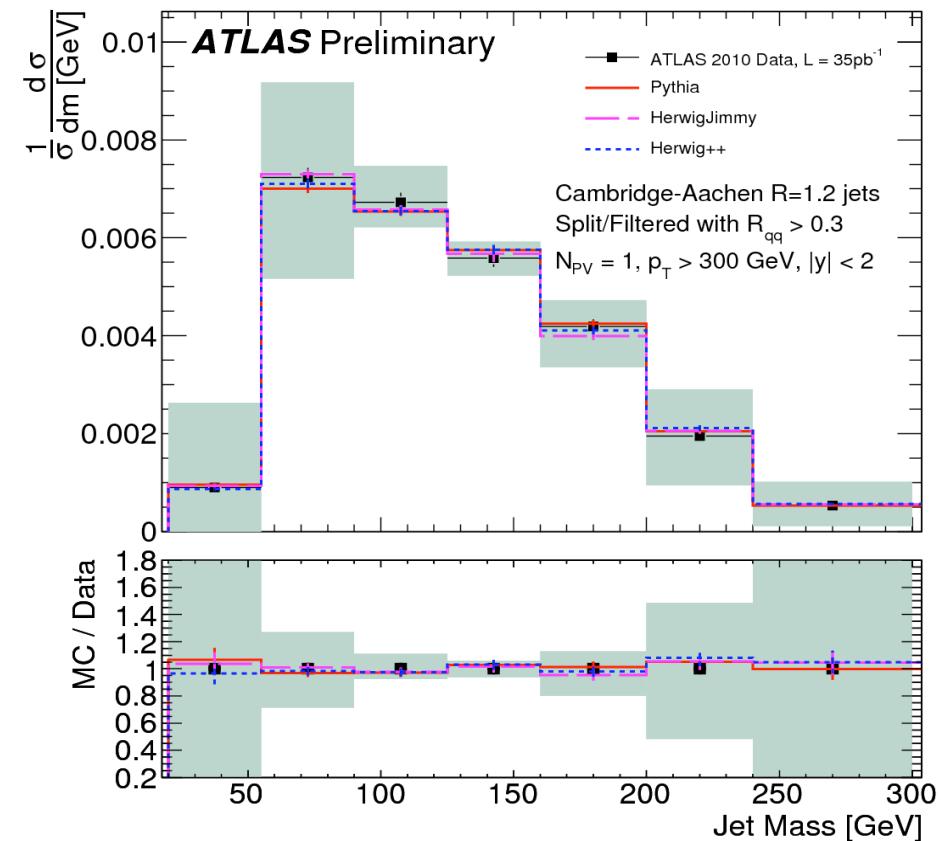
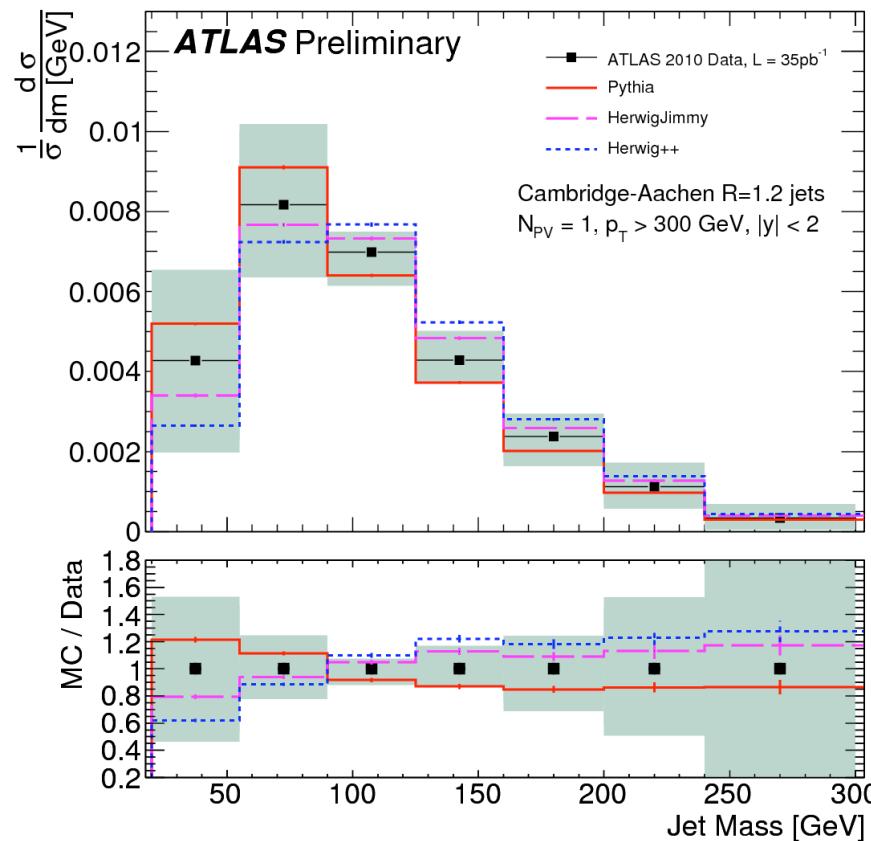


k_T y scale



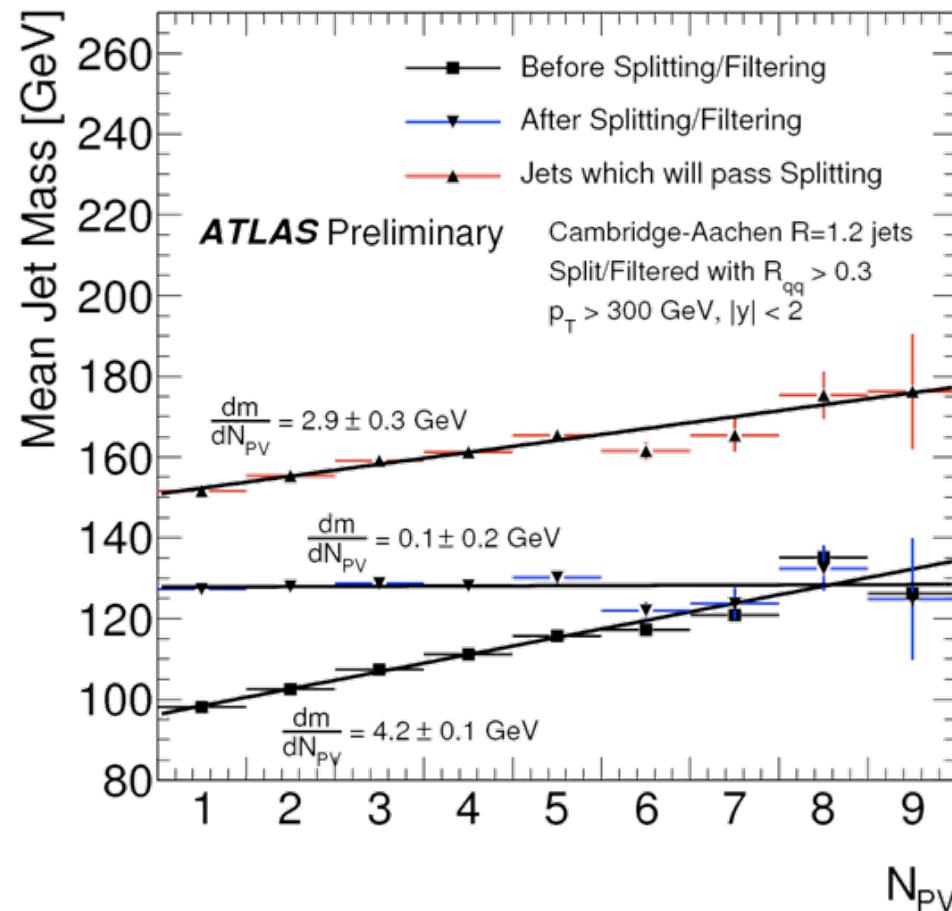
Jet mass and substructure

- Unfiltered and filtered Cambridge/Aachen jet mass



Exploiting jet substructure

- Pile up resilience.



Summary

- ATLAS is performing very well, triggering on and measuring jets over a huge range
- The results shown here challenge perturbative QCD over an unprecedented kinematic range
 - “Standard” Leading-Logarithmic parton showers alone are not enough (though they do very well where they are expected to)
 - NLO and high multiplicity matrix elements matching to parton showers generally doing well (and required)
 - Summation of new kinematic enhancements has some successes, some problems
- Not covered here:
 - Soft physics and underlying event models play a role and are being tuned/ improved
 - Many ATLAS results studying jets in association with W, Z etc
 - Many searches using jets – understanding described here is essential

Prospects

- Heavy flavour jet measurements are just beginning
 - Essential to understand e.g. gluon $\rightarrow b$ anti- b splitting
 - Good description by POWHEG at current precision
- Experimental uncertainties comparable to PDF uncertainties
 - Understand theory uncertainties
 - Incorporate data in fits
- Leading logarithmic parton showers describe jet substructure well
 - New variables are relatively insensitive to soft physics and pile up
 - Detector is equal to the task of measuring them
 - Electroweak scale physics *inside* jets is a qualitatively new feature of physics at 7 TeV
- We will do a lot more physics with jets over the coming months and years

