Jet physics in ATLAS

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QCD, Heavy Flavours and Higgs physics

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27 June 2012

Jets in the LHC era

At the Large Hadron Collider (LHC), jet production is the dominant high transverse-momentum (p_T) process.

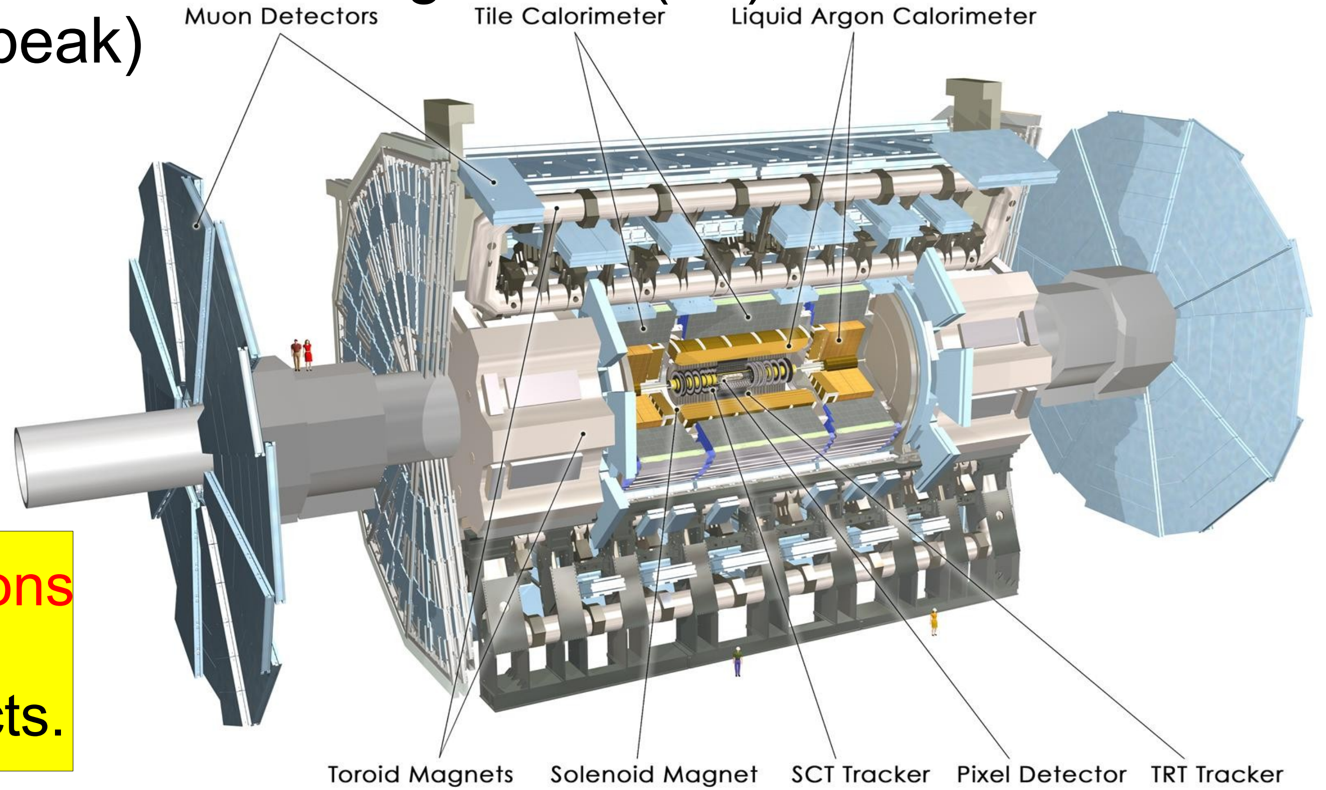
It gives the first glimpse of physics at the TeV scale.

Jet cross sections and properties are key observables in high-energy particle physics.
Measured in $\mathbf{e^+e^-}$, **ep** , $\mathbf{p\bar{p}}$, and **pp** colliders,
and in $\boldsymbol{\gamma}$**p** and $\boldsymbol{\gamma\gamma}$ collisions.

- Measurements of the strong coupling constant.
- Information about the structure of the proton and photon.
- Tools for understanding the strong interaction
- Tools for searching for physics beyond the Standard Model.

ATLAS Detector overview

Magnetic field: one solenoid surrounding the ID (2T), one toroid (muon spectrometer - 4T peak)

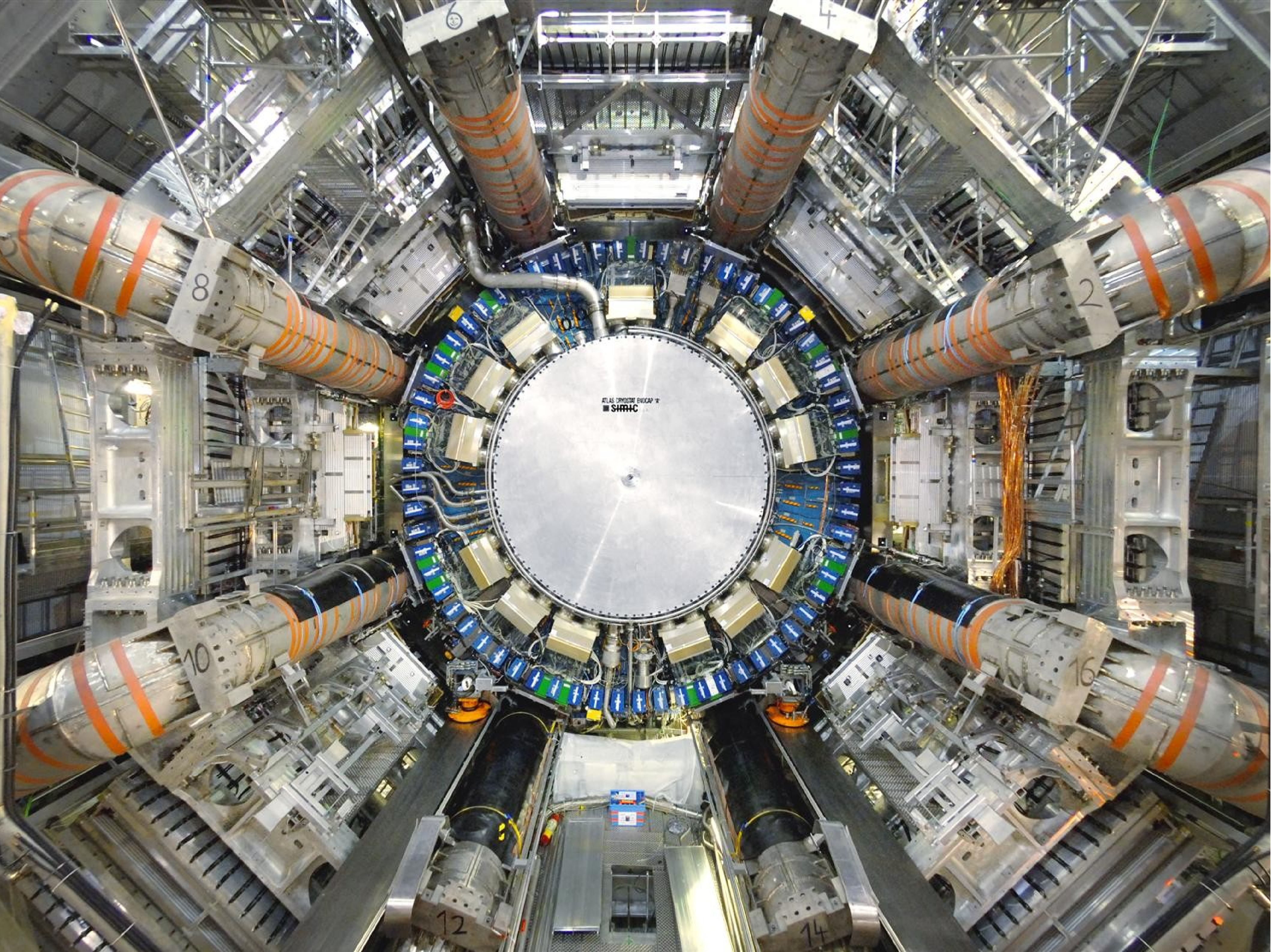


ID made up of three different detectors (Pixel, SCT, TRT): High resolution tracking in $|\eta| < 2.5$

EM calorimeter - two sections covering up to $|\eta| \approx 3.2$. High resolution on e/γ objects.

HAD calorimeter - 3 sections covering up to $|\eta| \approx 5$
Good containment, good resolution for jet measurement

Muon system (4 different technologies) covering up to $|\eta| = 2.7$
High precision muon momentum measurement (also standalone)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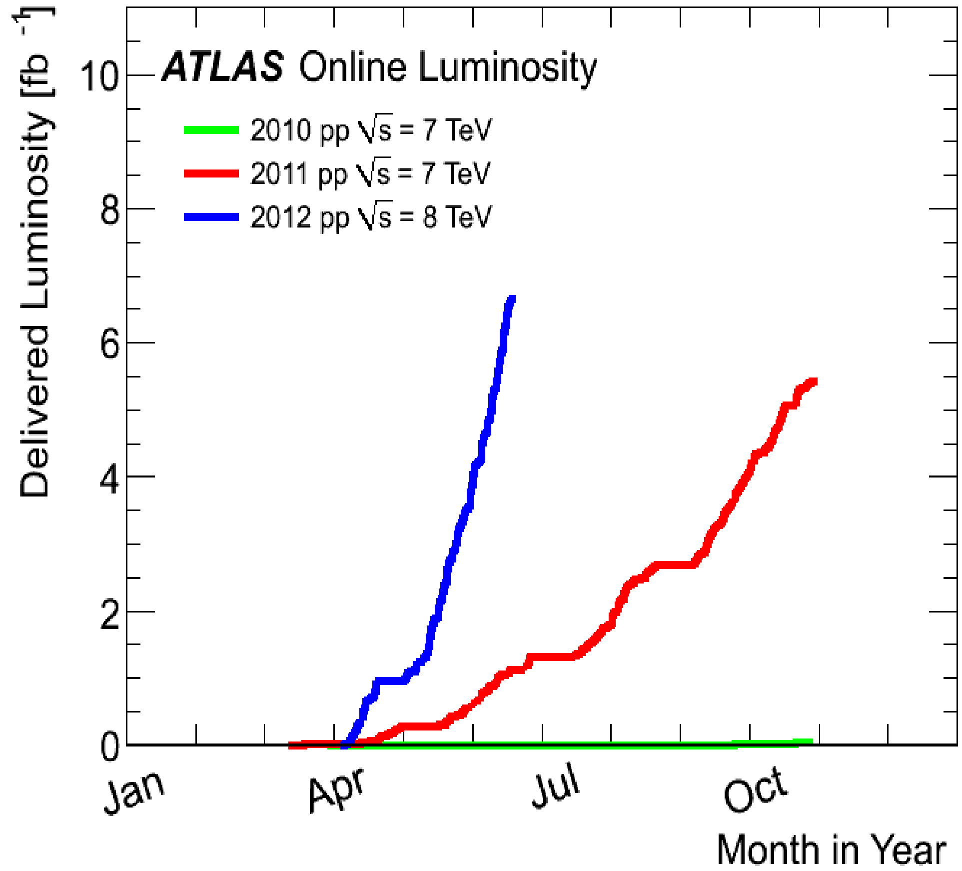
Data Taking

Successful operation for the LHC machine
and for the ATLAS experiment.

~40 pb^{-1} in 2010 (sqrt(s)=7TeV)
~5 fb^{-1} in 2011 (sqrt(s)=7TeV)
~ 6 fb^{-1} june 2012 (sqrt(s)=8TeV)



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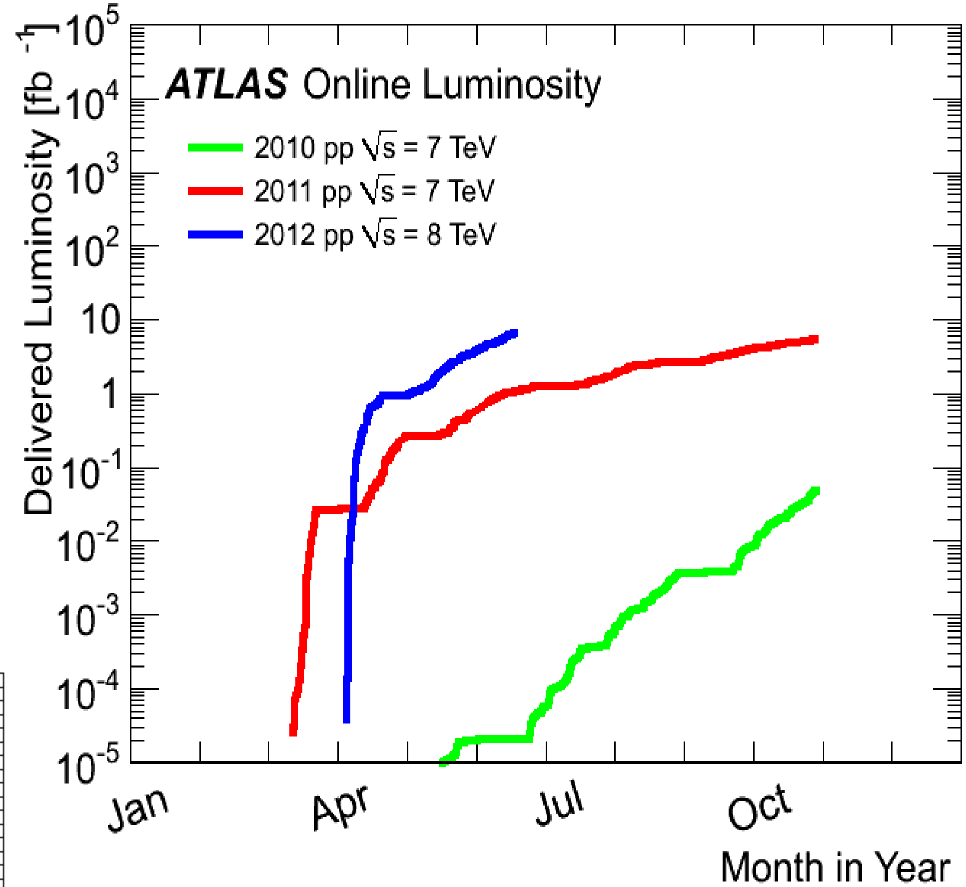
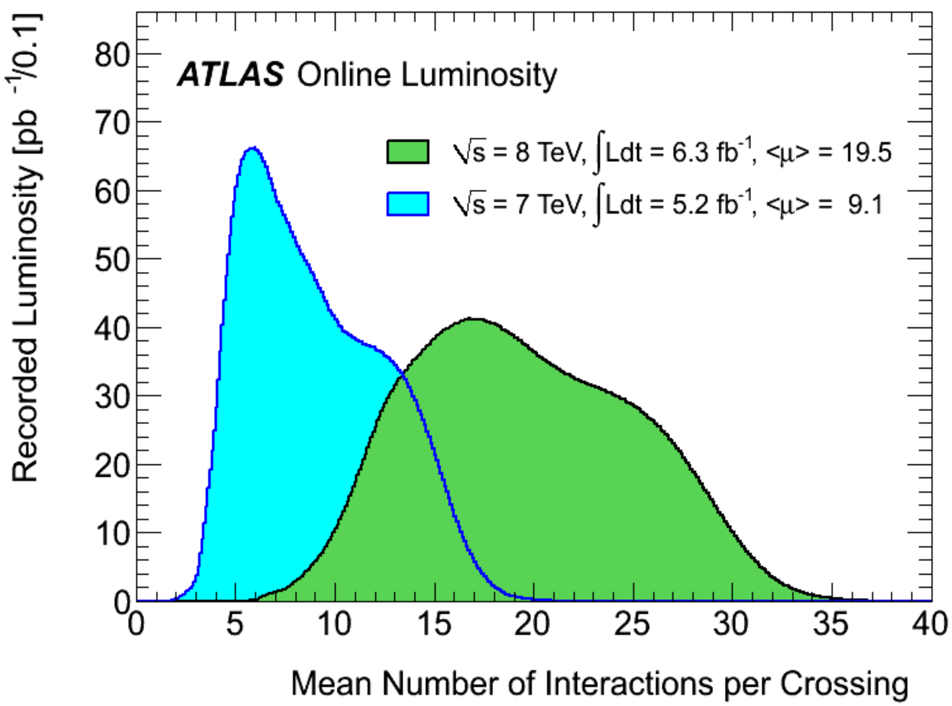




Change in pile-up conditions:

In 2012 ~ 9 interactions per bunch crossing.

Outlook

In this talk:

→ Jet reconstruction and performance

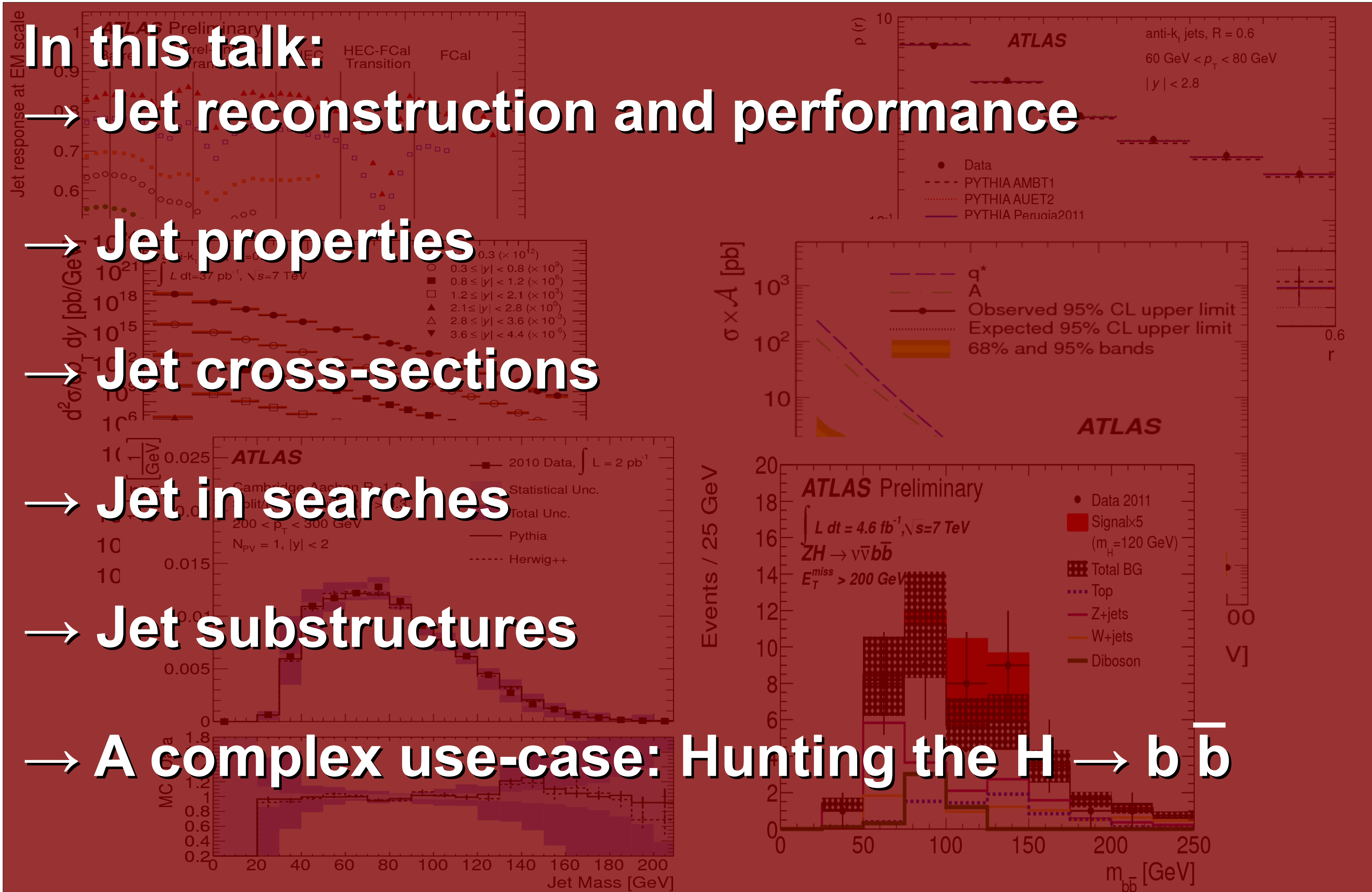
→ Jet properties

→ Jet cross-sections

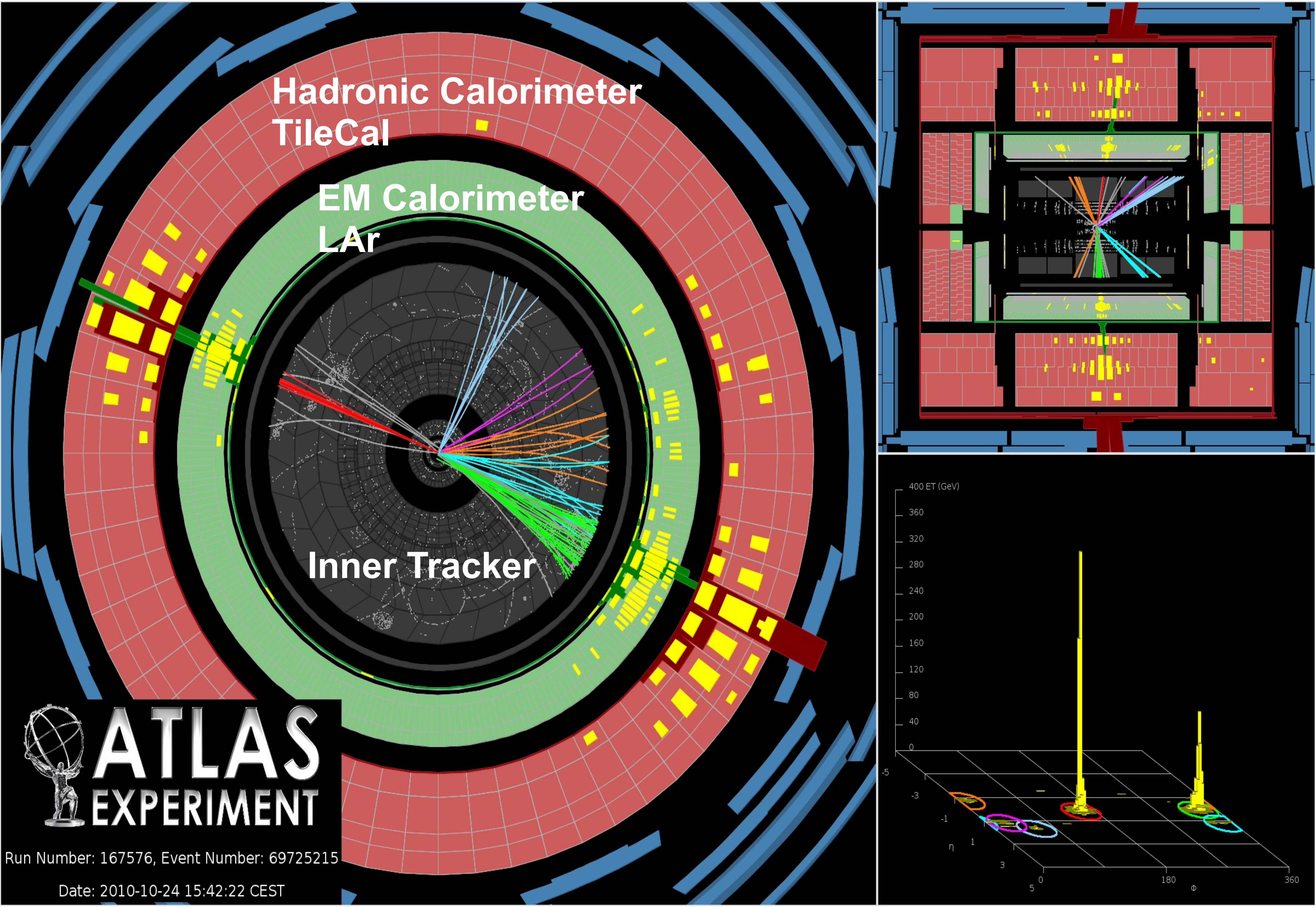
→ Jet in searches

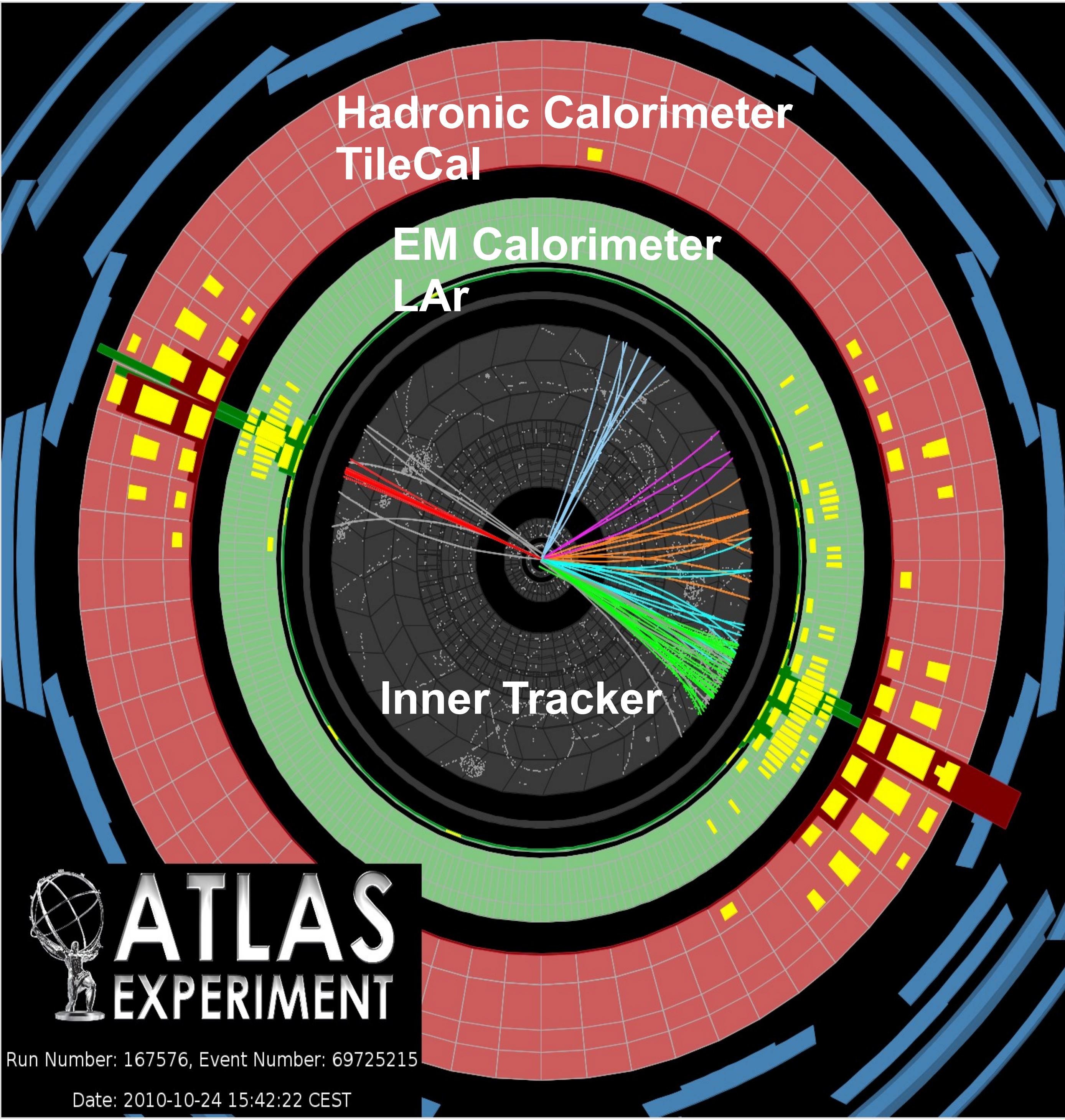
→ Jet substructures

→ A complex use-case: Hunting the $H \rightarrow b\bar{b}$

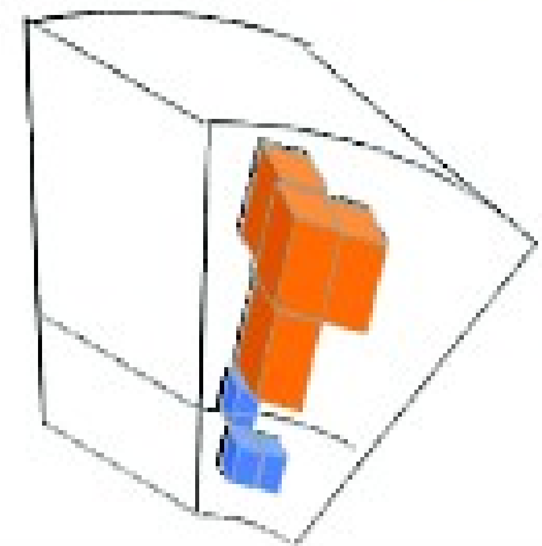


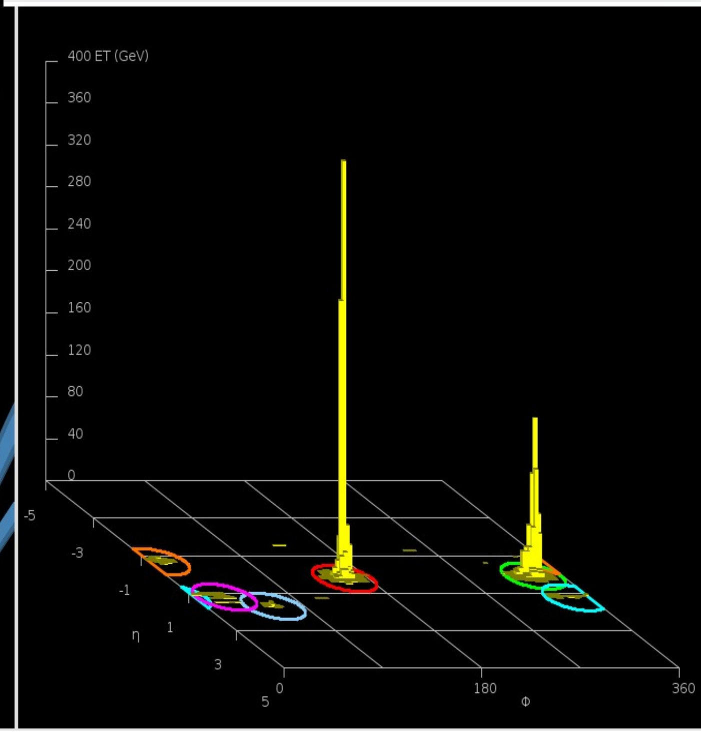
Jet reconstruction and performance


Hadronic Calorimeter
TileCal
EM Calorimeter
LAr
Inner Tracker
ATLAS
EXPERIMENT
Run Number: 167576, Event Number: 69725215
Date: 2010-10-24 15:42:22 CEST
400 ET (GeV)
360
320
280
240
200
160
120
80
40
0
-5
-3
-1
1
3
5
η
0
180
360
Φ

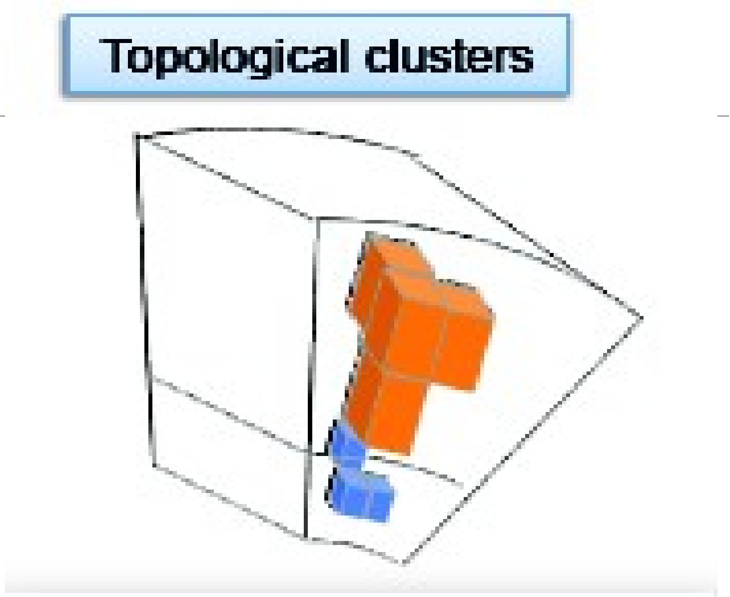


Topological clusters





Jet Reconstruction



Inputs:

3D Calorimetric clusters:

find local cell energy maxima and cluster neighboring cells

Pro: noise suppression

Jet Algorithm: JHEP 0804 (2008) 063 [0802.1189]

The Anti-K_T (infrared safe) algorithm has been taken as the default jet algorithm.

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \Delta R_{ij}^2 / R^2$$

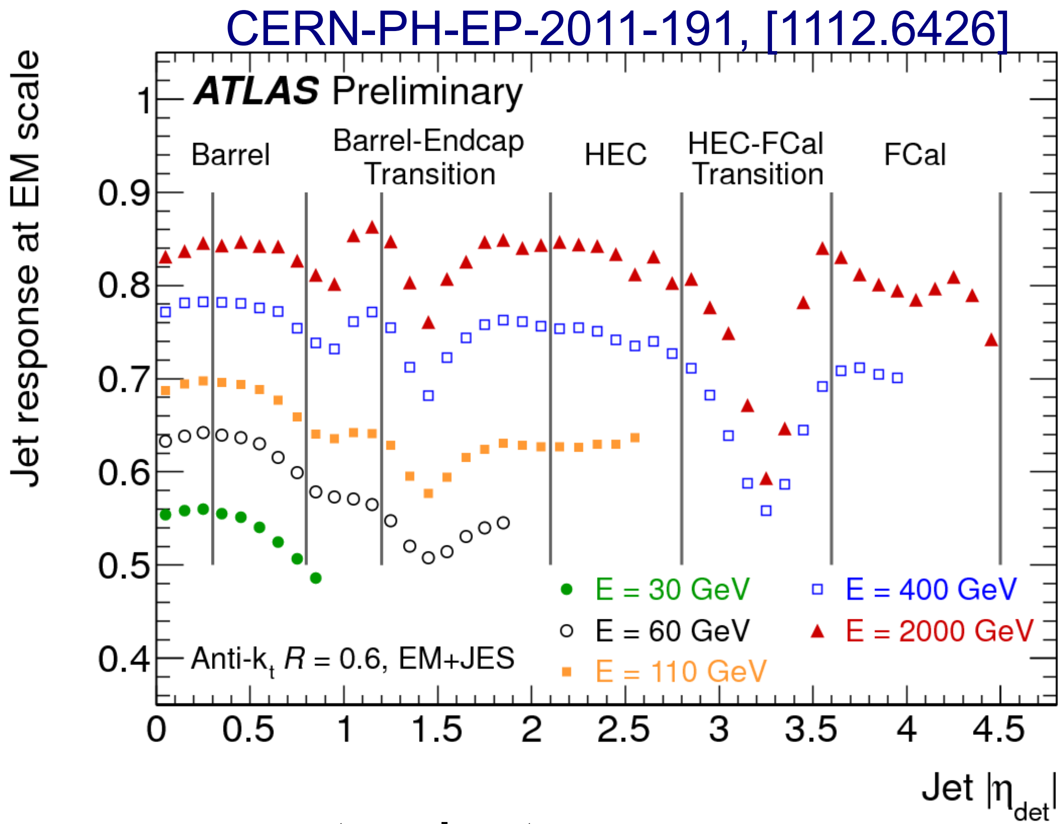
The Anti-K_T is a sequential recombination jet algorithms with p= -1, (K_T, p=1) which behaves like an idealized cone algorithm.

Cambridge/Aachen (p=0) and K_T (p=1) algorithms used for jet-substructure studies.

C/A algorithm has a distance which depends only on angular distance.

Calorimetric calibration

Electromagnetic (EM) scale:
Baseline cluster calibration, established using test beam with e and μ in the calorimeters.
Good estimate of the energy deposited by γ and e.
60-70% estimate of the energy deposited for hadrons and jets



Hadronic Calibration. Why?:
In the ATLAS Calorimeters,

•Response to hadrons lower than response to electrons.

•Energy losses in inactive regions of the detector.

•Out of cone effects.

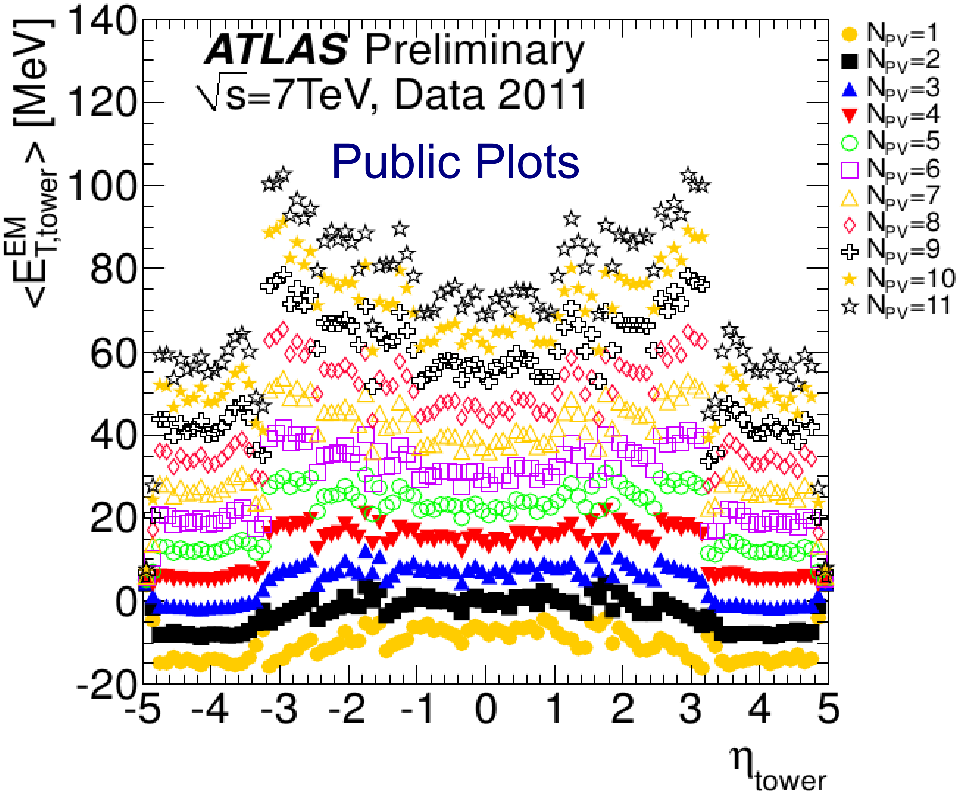
Hadronic Jet Calibration driven by MC description (EM+JES).

1) Pile-up subtraction accounting for in-time and out-of-time pile-up

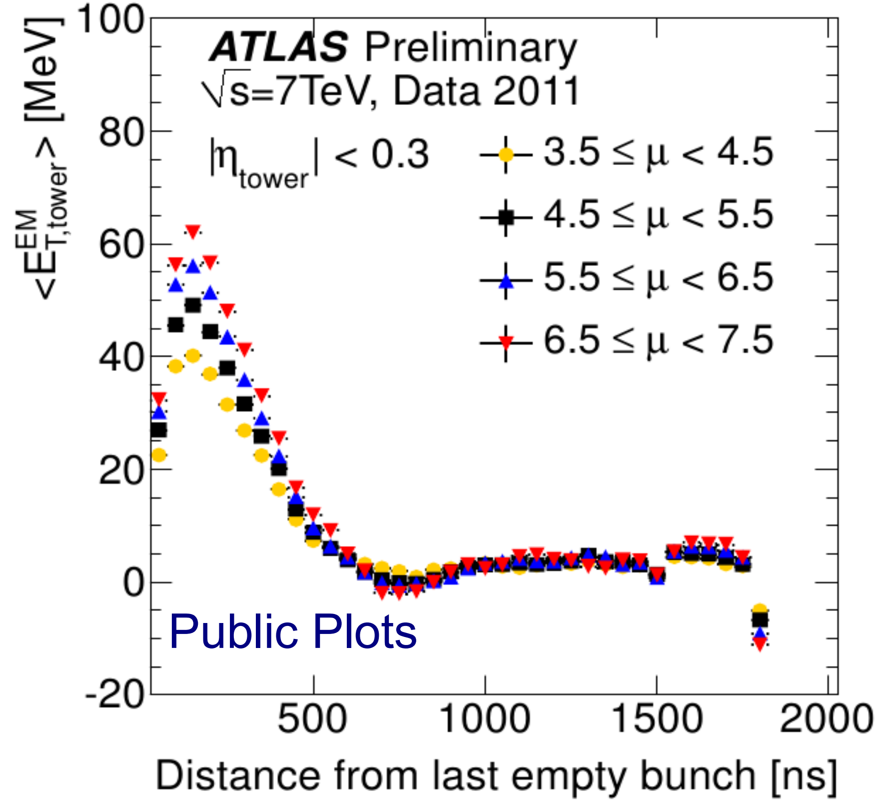
2) Correction factor: $p_T^{Calibrated} = C(E^{EM},\eta)\ p_T^{EM}$

Pile-up correction

In-time pile-up (2010-2011-2012):
multiple interactions in same bunch crossing
additional soft diffuse radiation



Out-of-time pile-up (2011-2012):
overlapping signal from collisions in other bunch crossings
affects calorimeter energy reconstruction

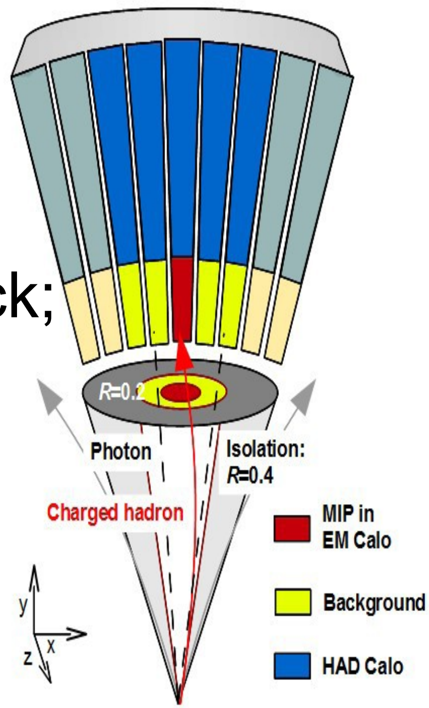


Checks on the EM scale simulation

The simulation has been validated using test-beam and collision data.

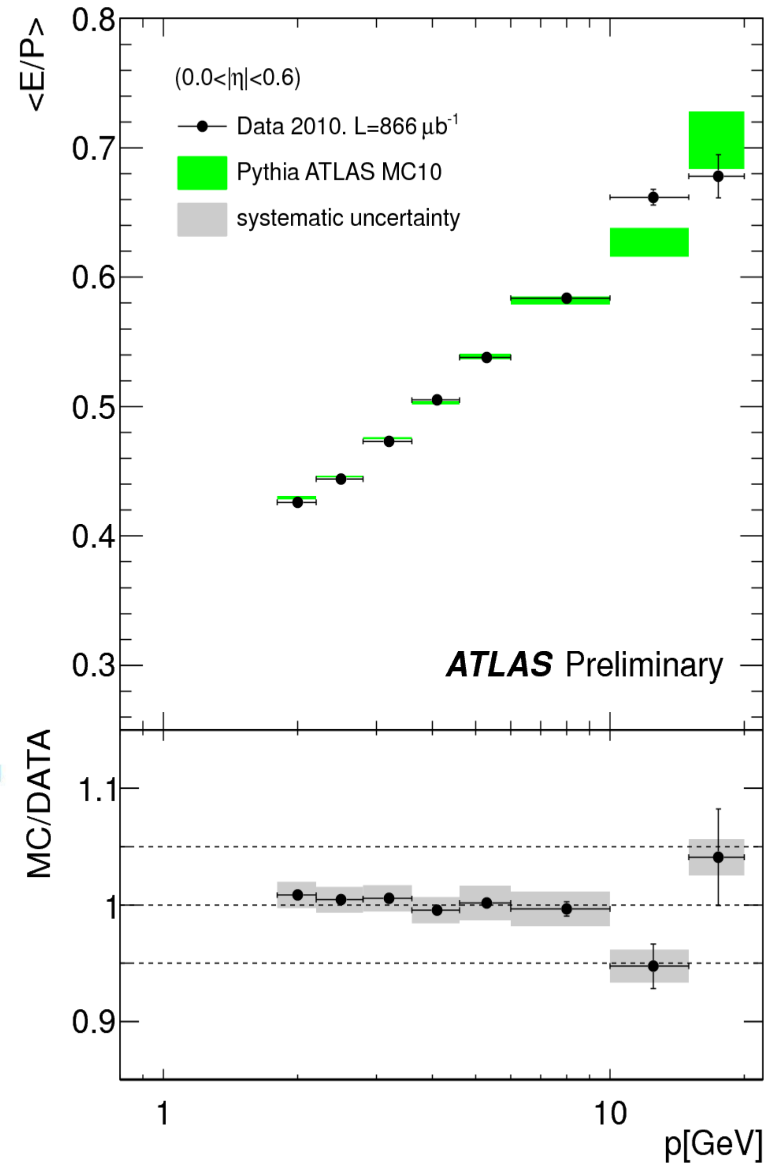
Checks on Collisions data:

- Select isolated tracks;
- Collect the energy in the calorimeter around the track;
- Compare to MC.



<E/P> measured in

- $|\eta| < 2.3$
- 2 GeV < p < 20 GeV



The calorimeter response to isolated hadrons shows agreement between Data and MC at the 5% level for most of the calorimeter.

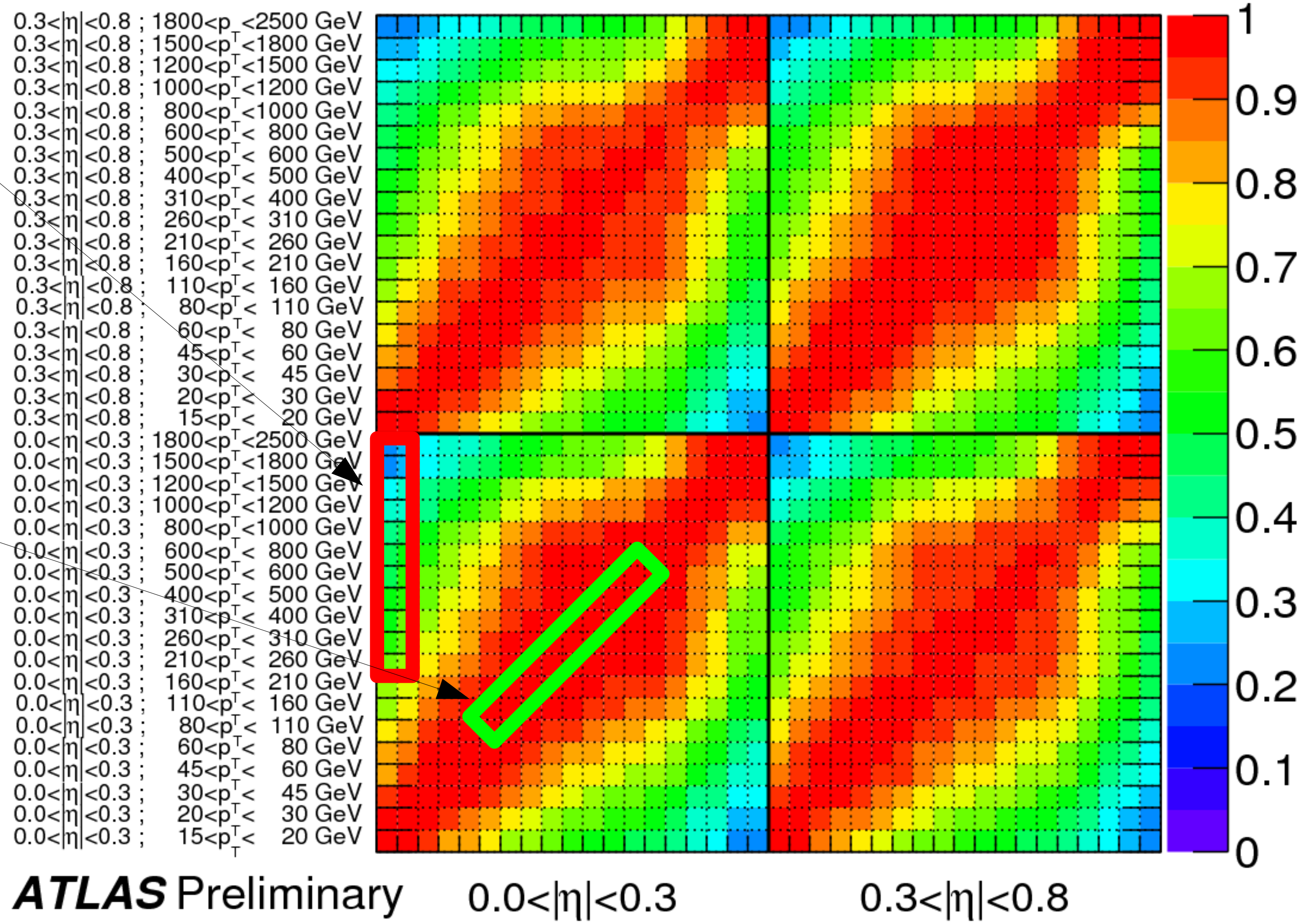
CERN-PH-EP-2012-005 [1203.1302]

Correlations on the calorimeter response

Propagate single isolated hadron uncertainties to jets to obtain estimate of calorimeter JES

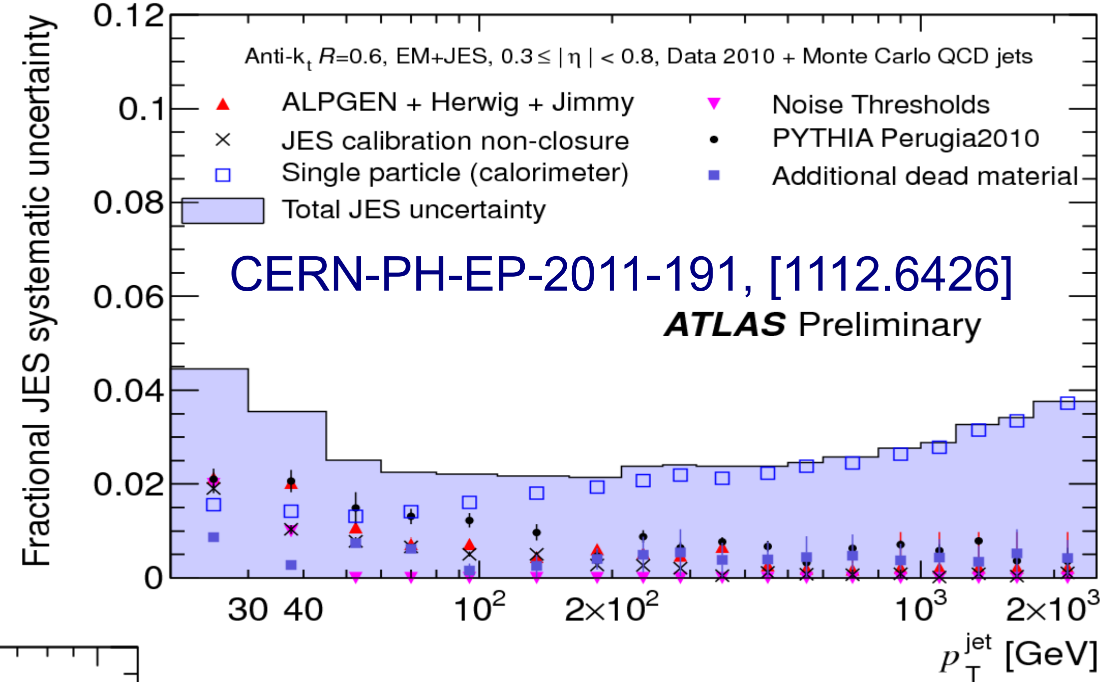
Long Range correlations

Strong diagonal correlations

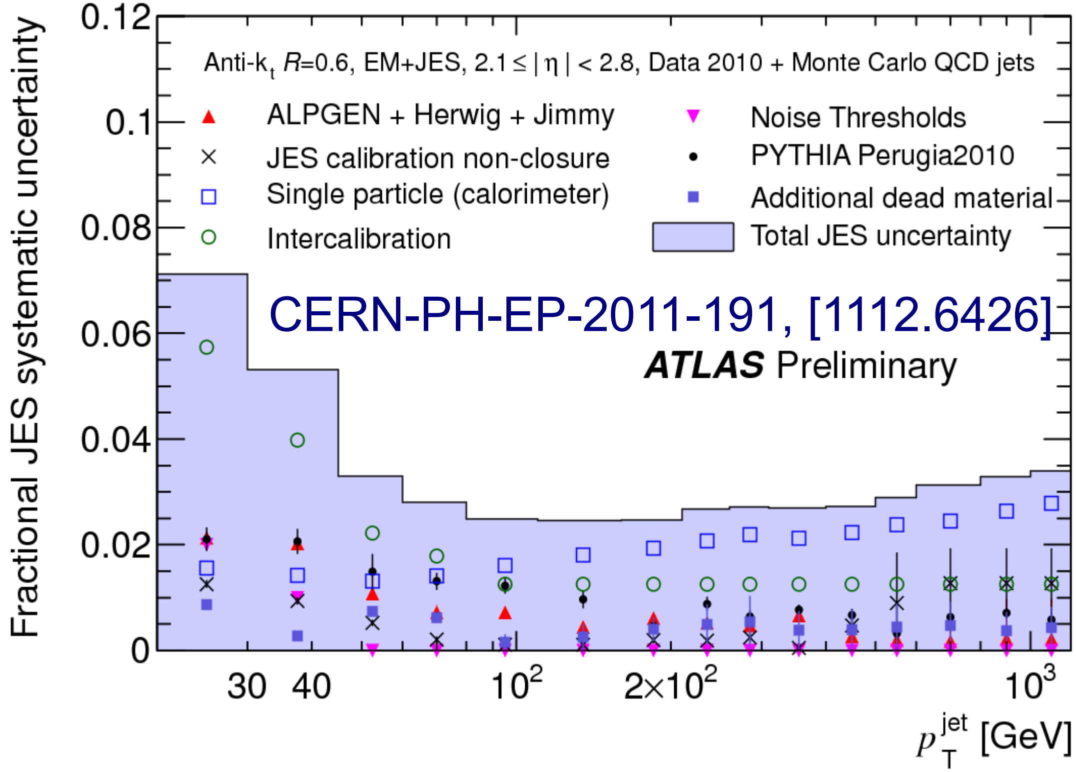


CERN-PH-EP-2012-005 [1203.1302]

Jet Energy Scale Uncertainty



Uncertainties:
~2% for central jets with p_T ~100 GeV

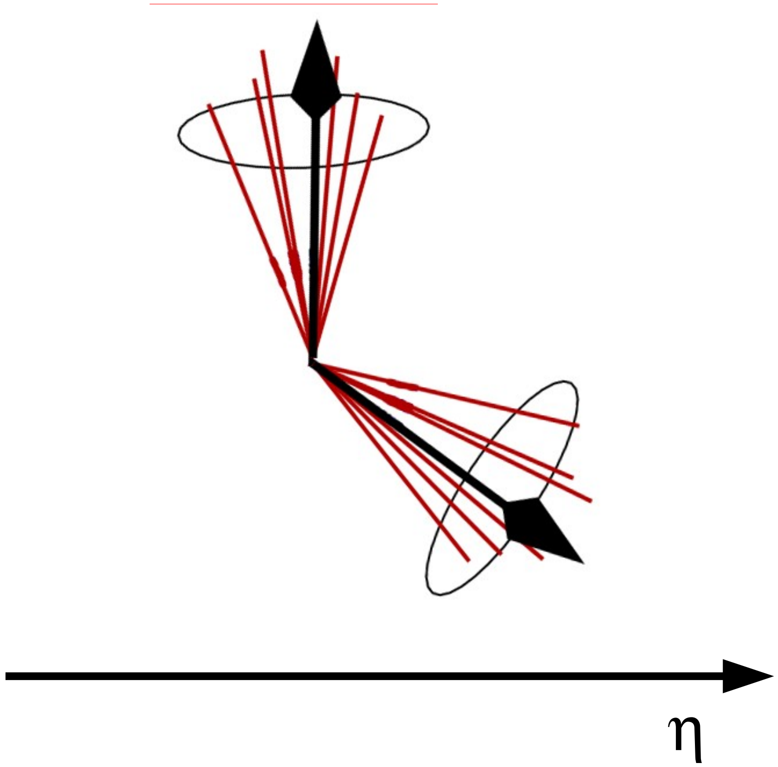


Dominant:
- Single particle response
- Noise description
- Dead Material
- η intercalibration

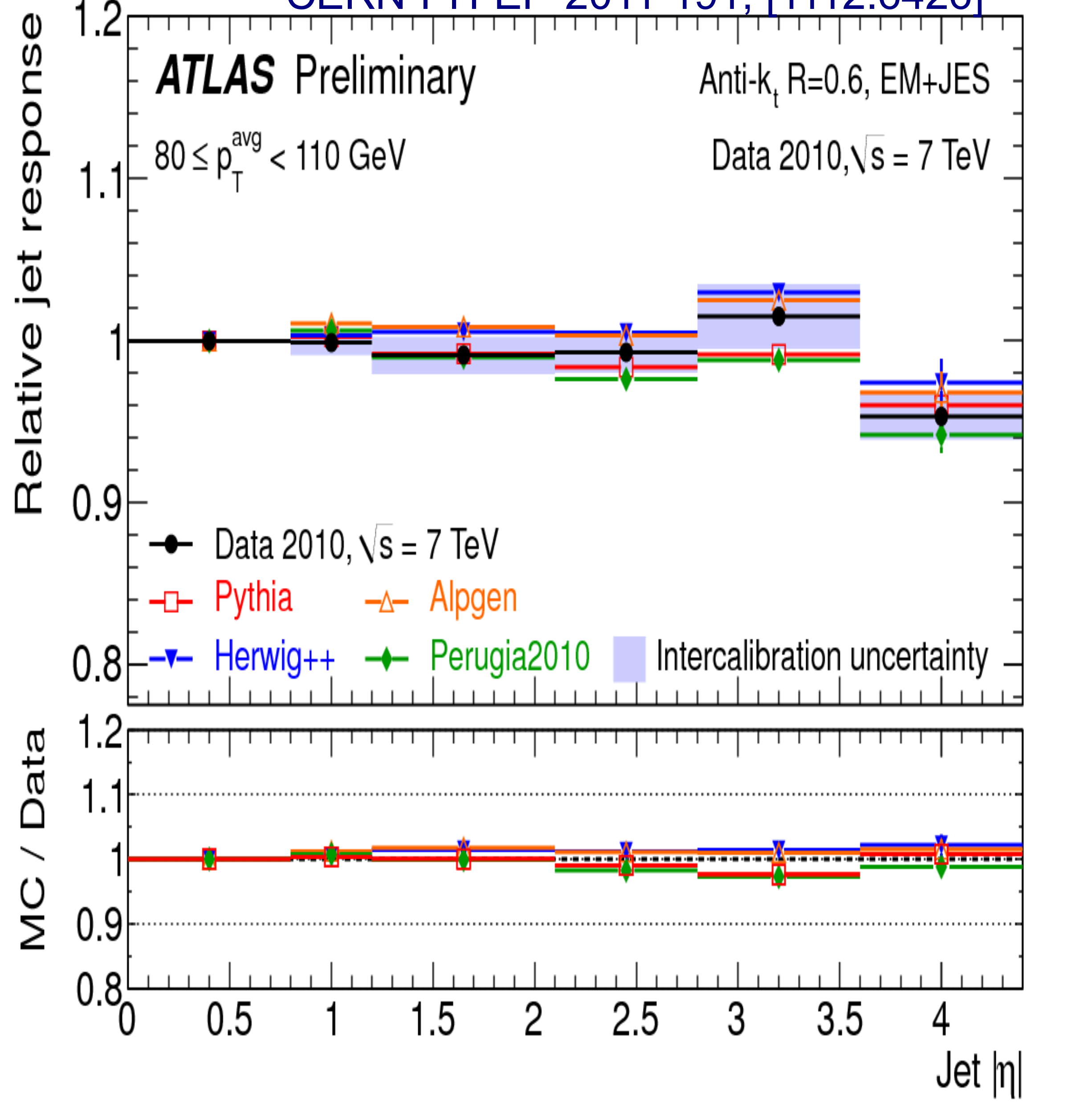
Smaller:
- Hadronization
- Underlying Event
- Parton Shower
- Pileup

Jet Calibration VS. η

Reference region

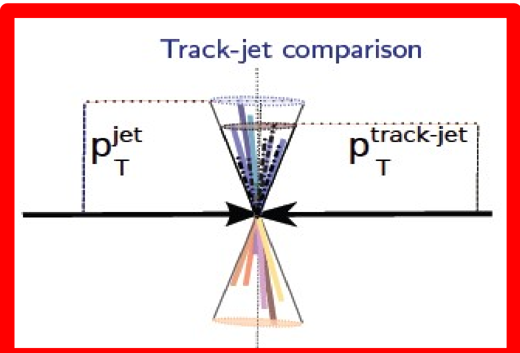


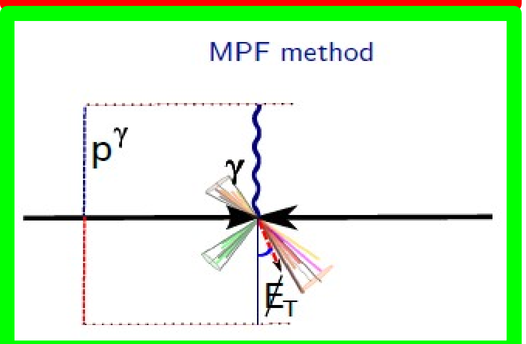
CERN-PH-EP-2011-191, [1112.6426]

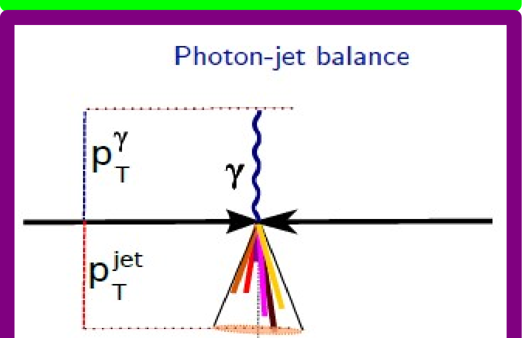


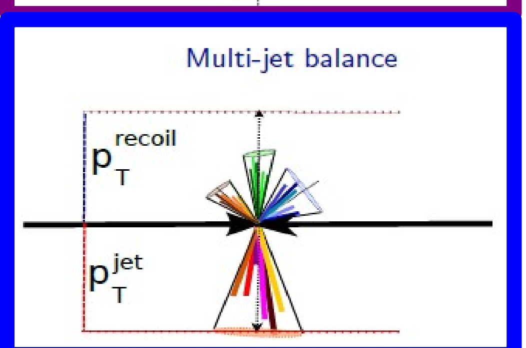
Small (~2%) deviation at high pseudo-rapidity

Checks on the jet energy scale uncertainty

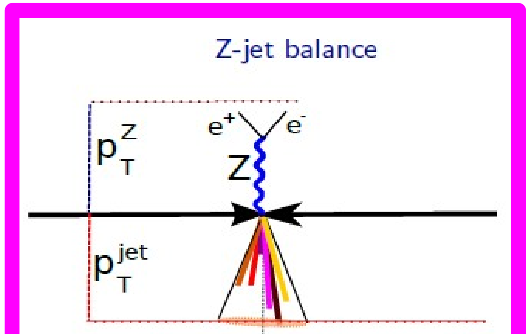


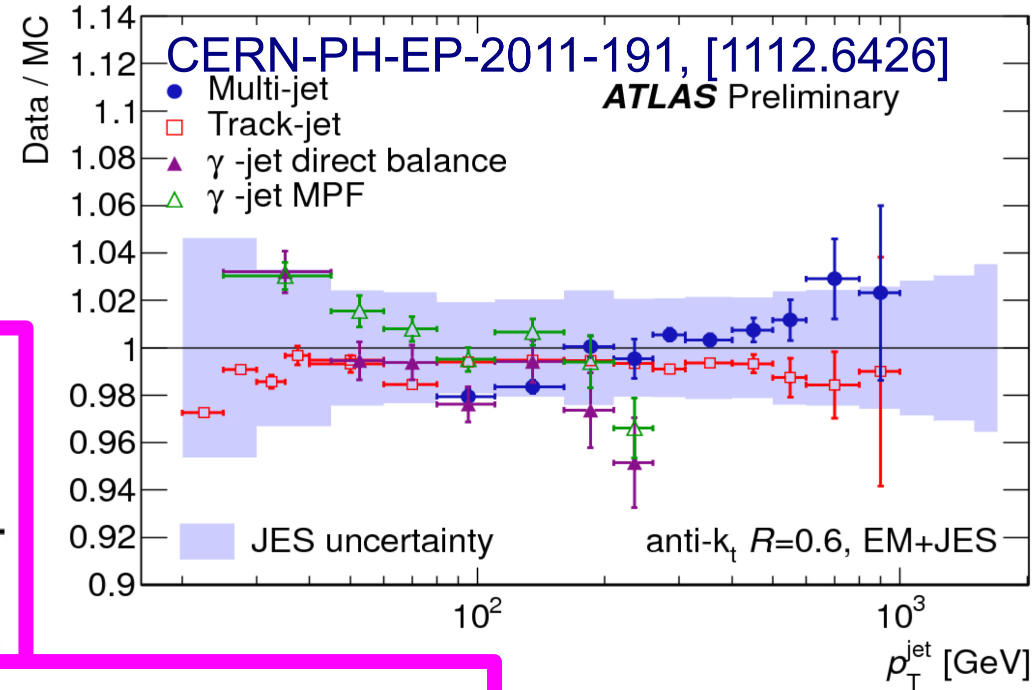


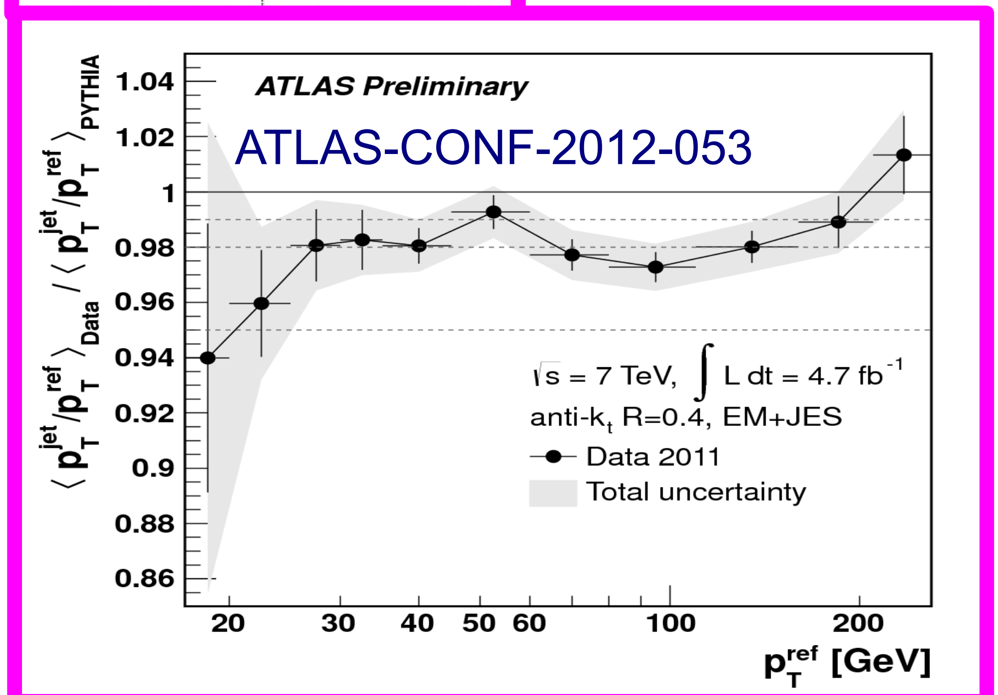




C. Doglioni







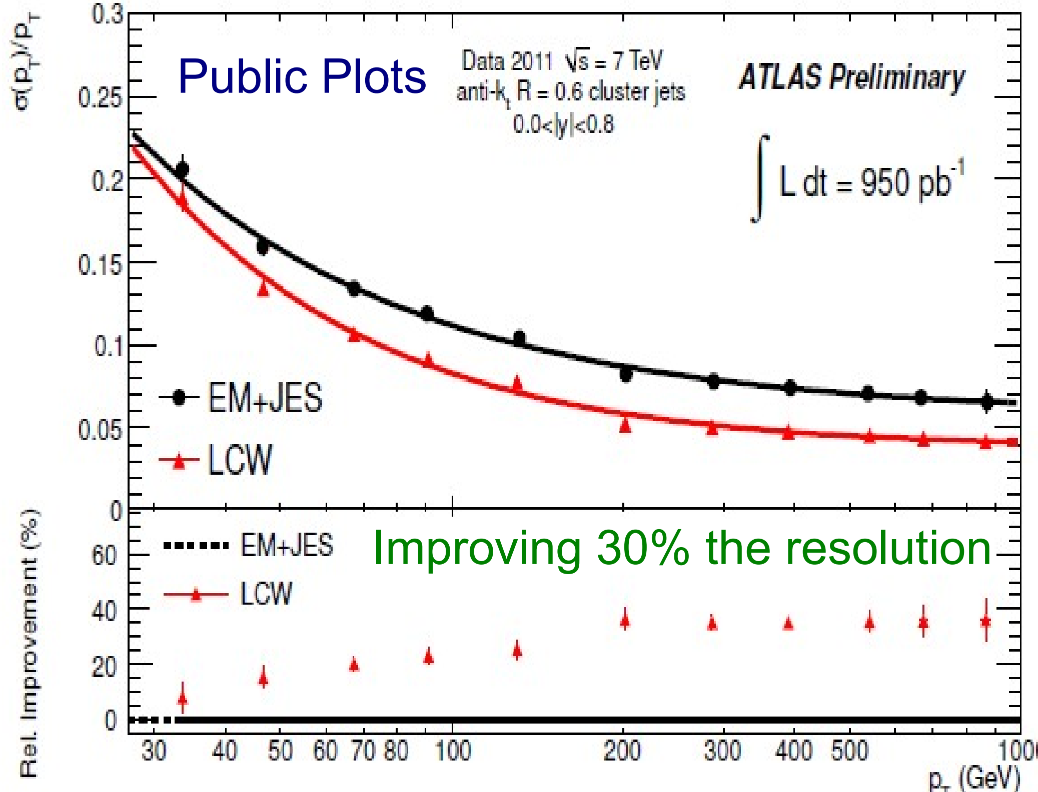
Constrain of the JES by using these measurements:

ONGOING (public soon).

Alternative hadronic calibrations

Local Cluster Weighting (LCW) :
Factorized corrections derived from cluster properties in single pion MC,independent from jet context.

Pro:
→ Improving the jet energy resolution
→ Calibration does not depend on jet context. More flexibility for substructure studies.
→ Coherent hadronic calibration for the clusters which do not belong to any jet
(used in the Missing Et)



So why did we use EM+JES for the first analyses?
→ *EM+JES allow direct and fast estimate of uncertainties.*

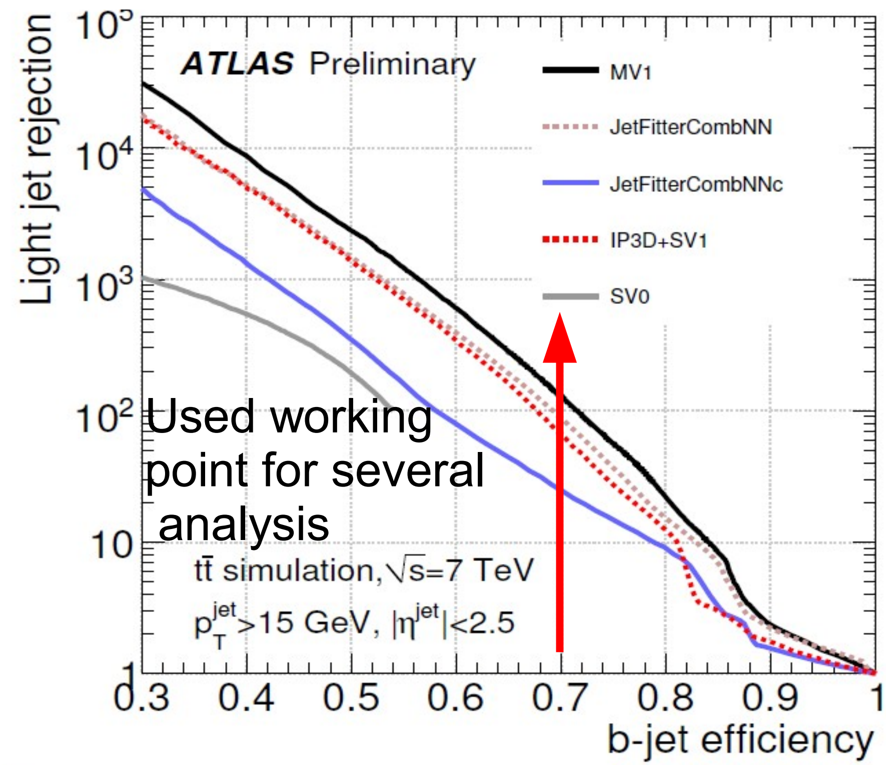
LCW already used for some measurements in 2011-2012

Heavy flavor jets

ATLAS-CONF-2012-043

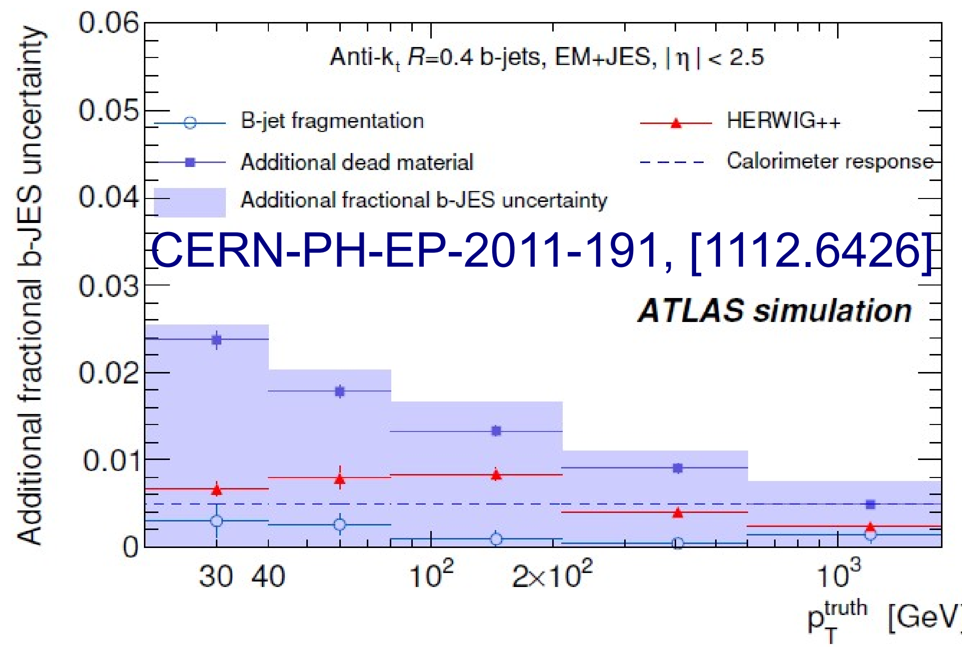
Heavy b-jets identified exploiting the long lifetime of b-hadrons.

Several tagging algorithms combined to improve the performance (MV1).



Calibration done with the standard EM+JES (or LCW).

Ad-hoc estimate of the systematic uncertainty on the JES.

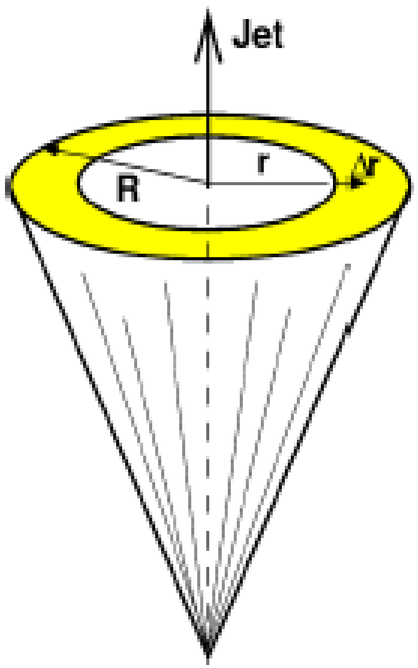


CERN-PH-EP-2011-191, [1112.6426]

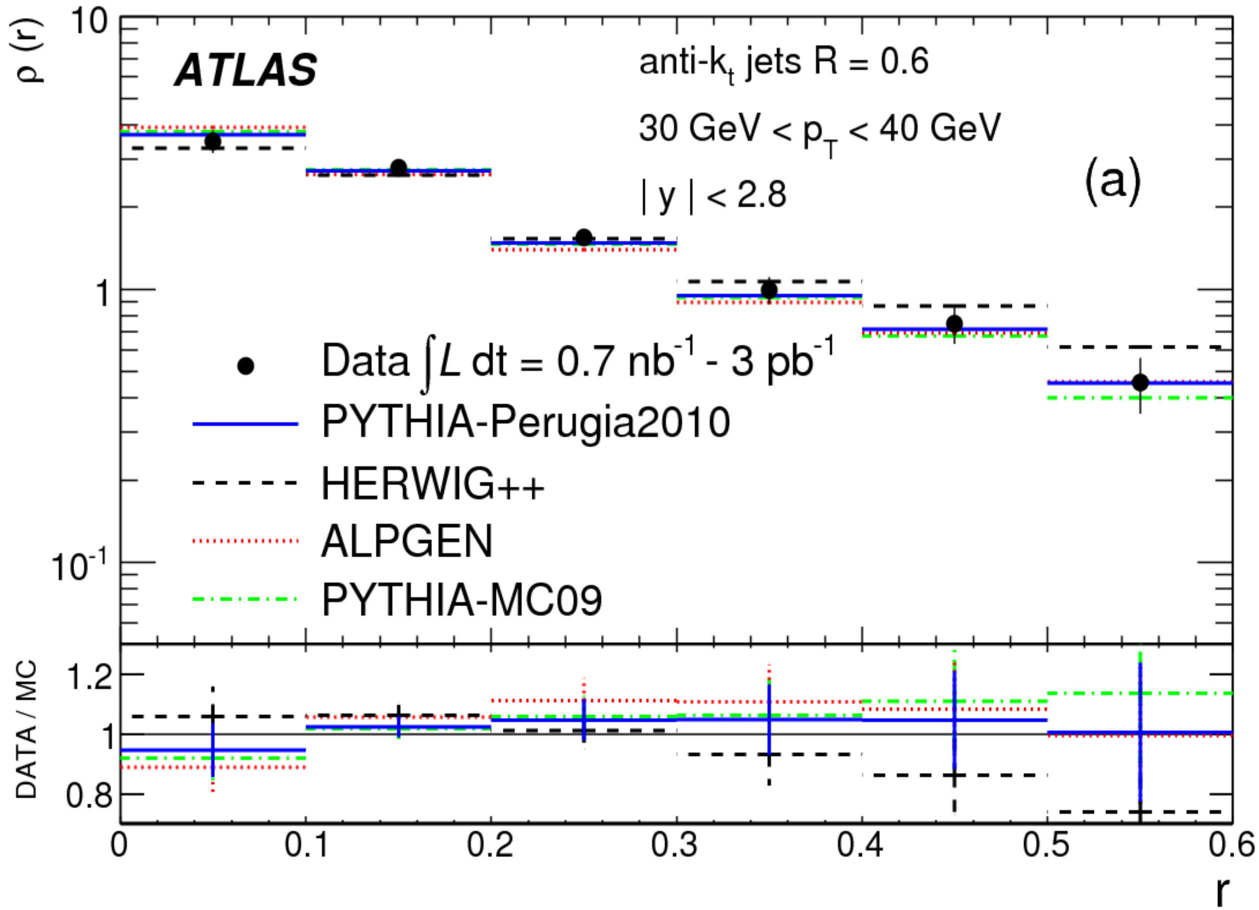
Jet properties:
From the constituents to the topologies

Jet Shapes

Energy flow around the jet core



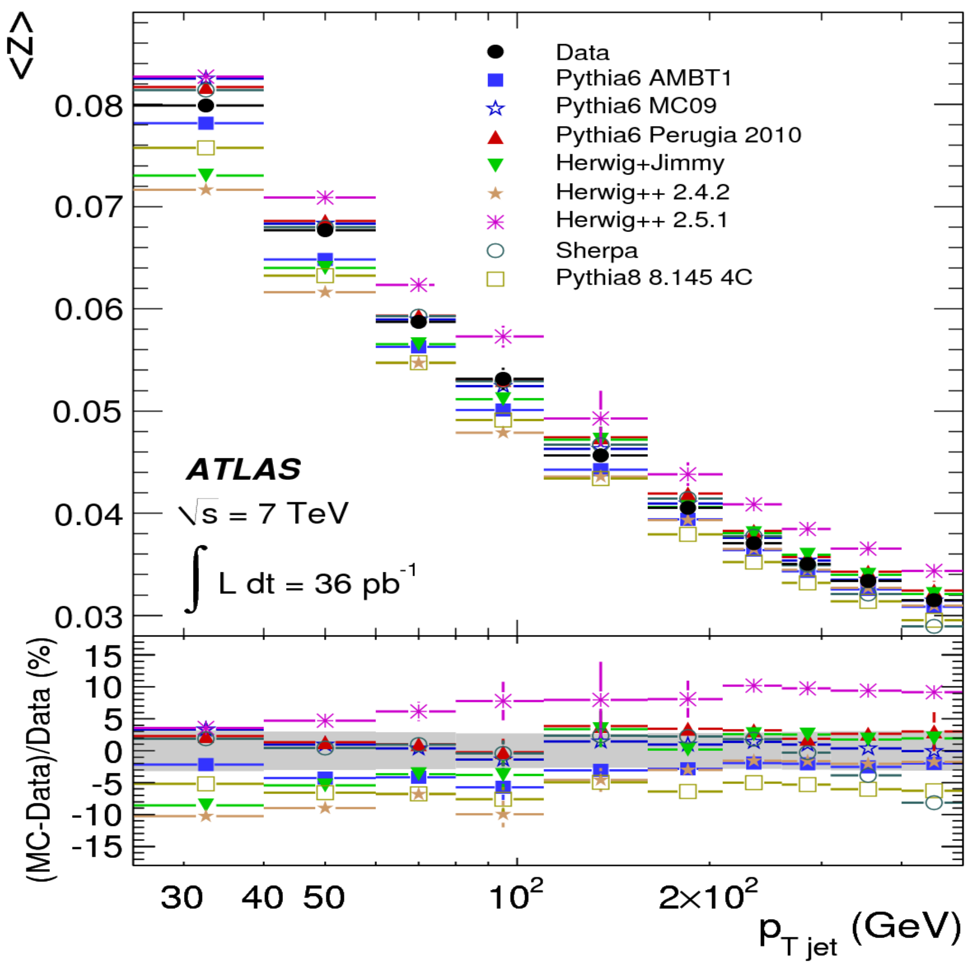
Phys.Rev. D83 (2011) 052003 [1101.0070]

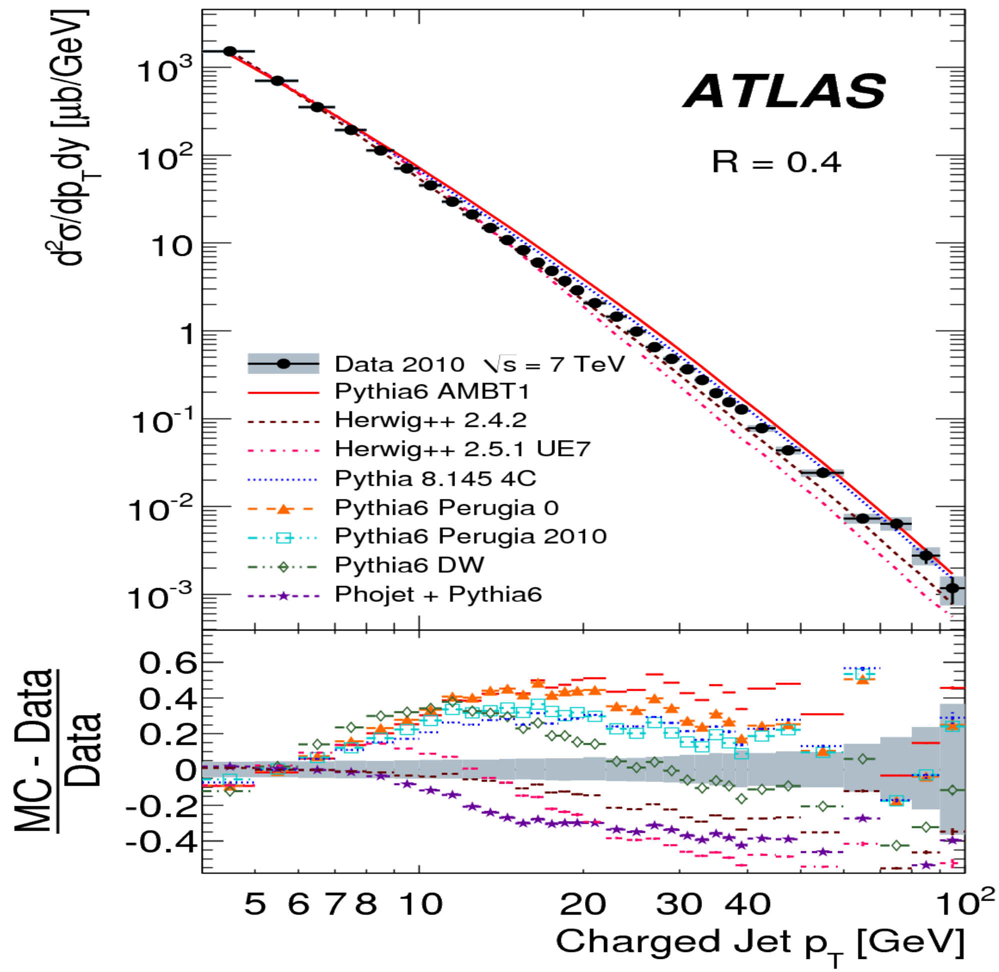


Sensitive to parton-shower, underlying event and fragmentation detiails.

Tracks in jets: Fragmentation

The tracks are a useful input to the jet clustering to study the jet fragmentation in charged particles and to improve the fragmentation models used in the MC simulations



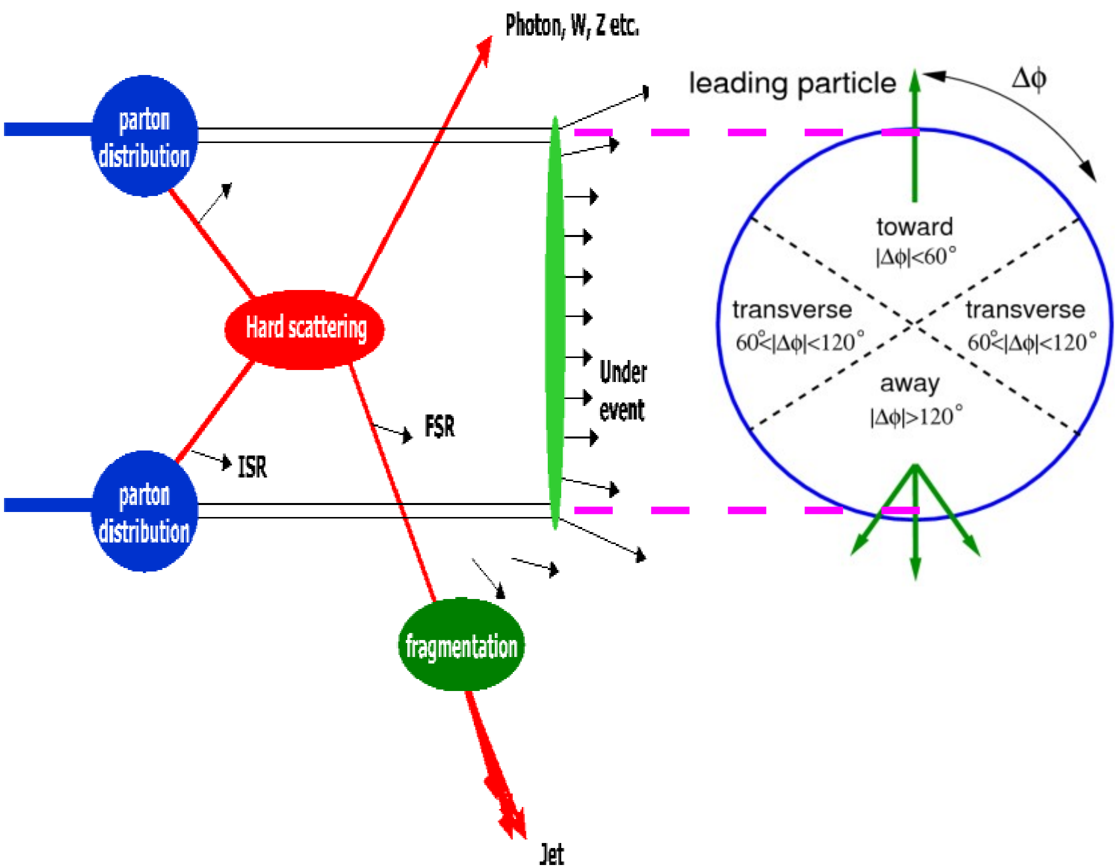


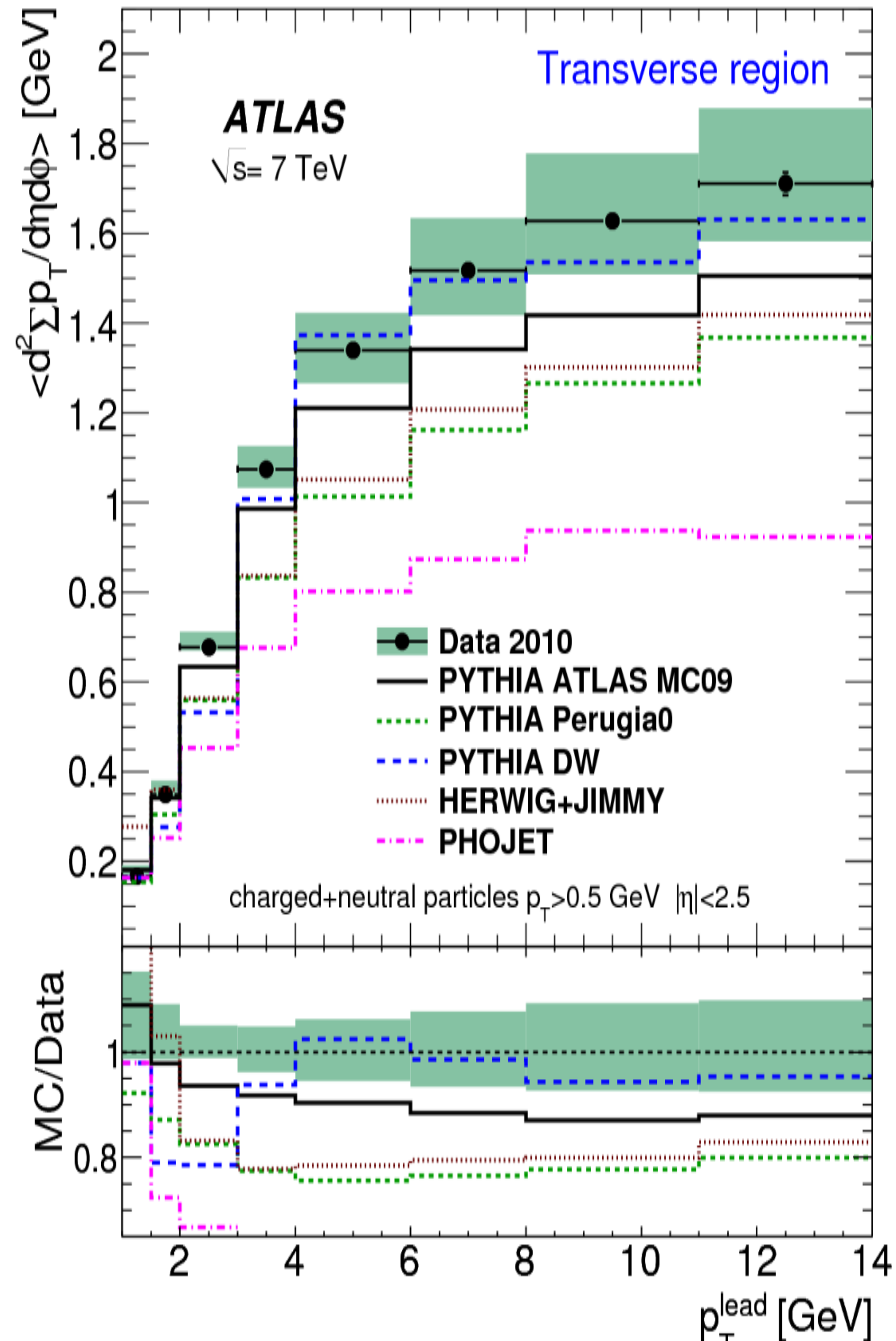
$Z_{track} = p_T^{track} / p_T^{Jet}$

is the relative p_T contribution to the jet.

Eur.Phys.J.C 71 (2011) 1795 [1109.5816]

Underlying event

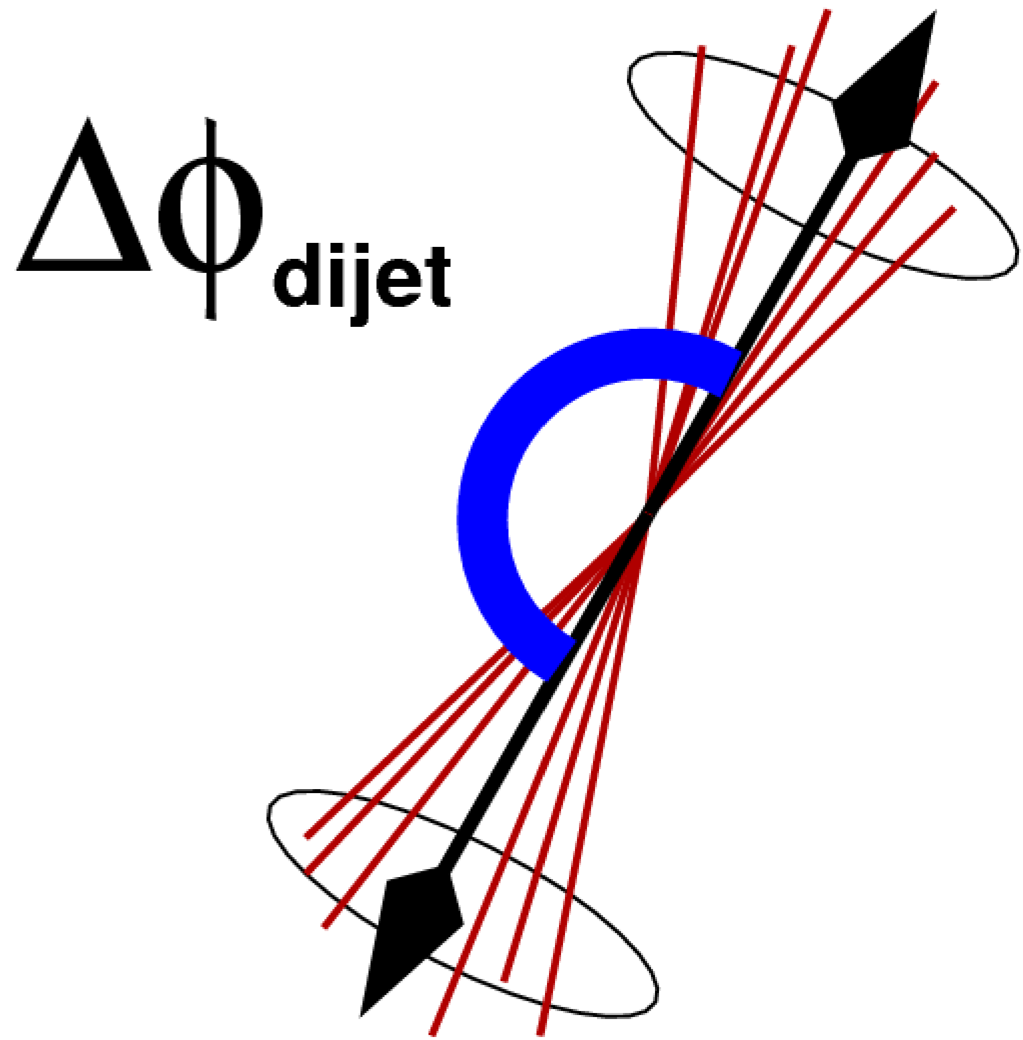




Measuring the properties of the underlying event is crucial to properly describe in the MC jet vetos, low p_T jets, isolations,...

Phys. Rev. D83 (2011) 112001 [1012.0791]

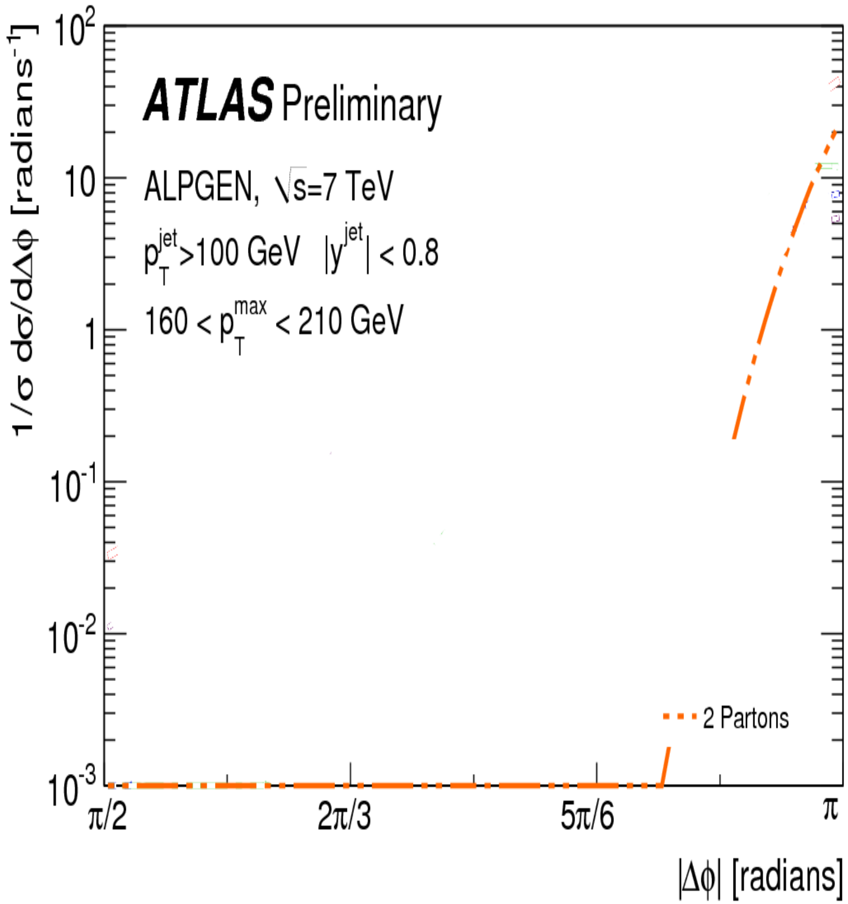
Azimuthal decorrelation

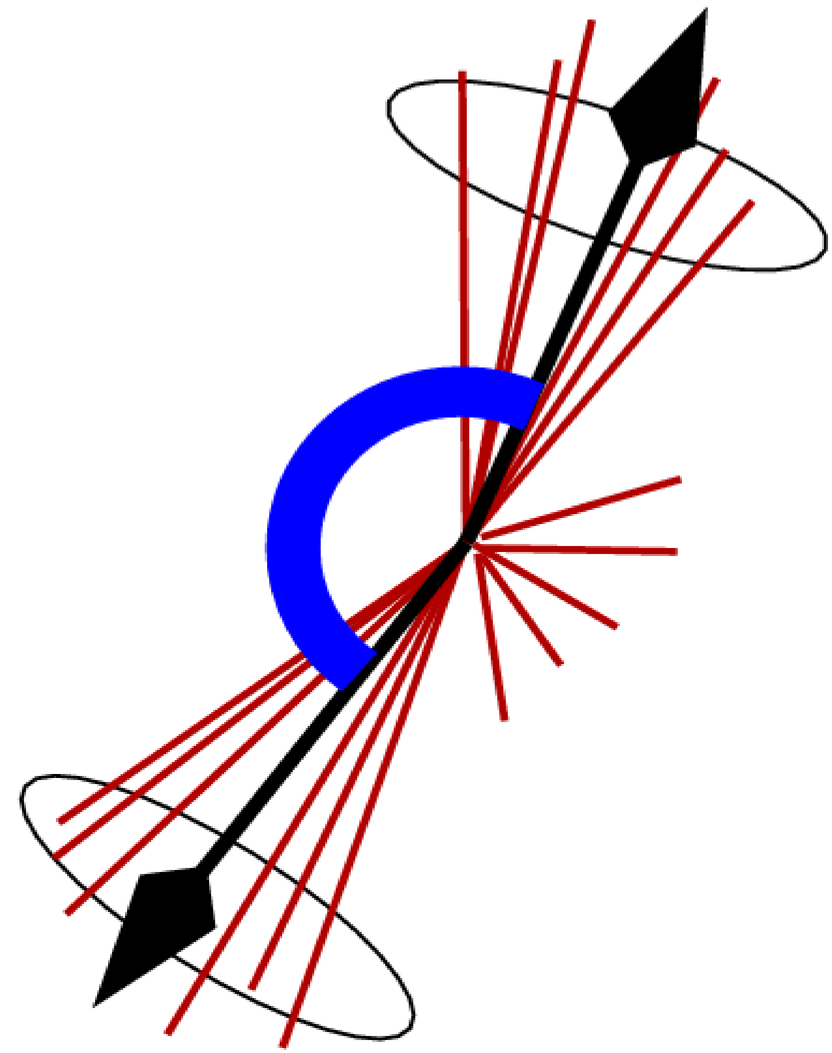


Dijet production at leading order (LO) results in two jets with equal p_T and correlated azimuthal angles $\Delta\varphi=\pi$.

Phys.Rev.Lett. 106 (2011) 172002 [1102.2696]

Azimuthal decorrelation

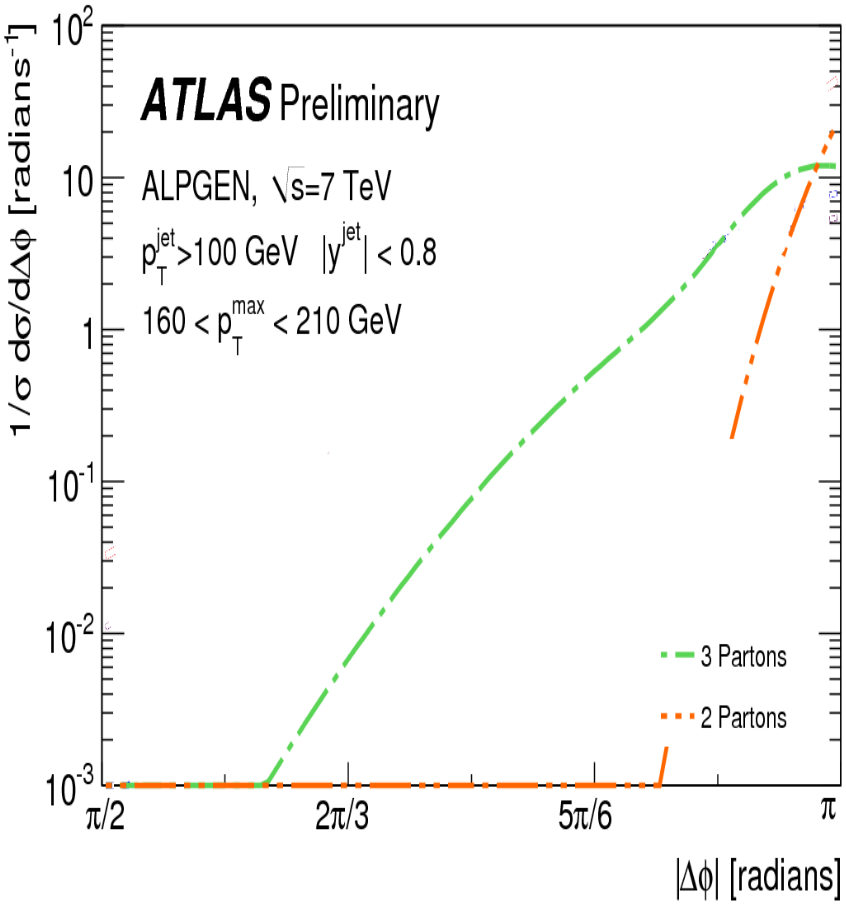


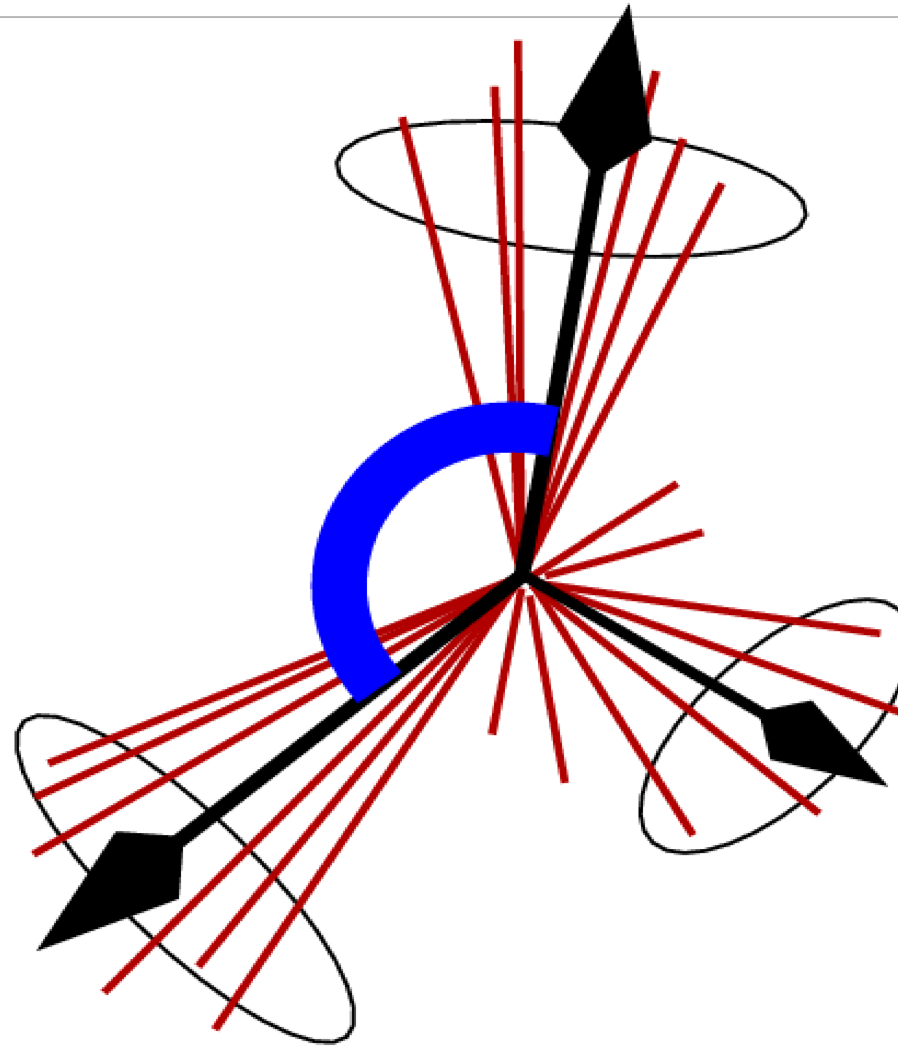


Soft radiation in dijet events starts to produce a decorrelation in Δφ.

Phys.Rev.Lett. 106 (2011) 172002 [1102.2696]

Azimuthal decorrelation





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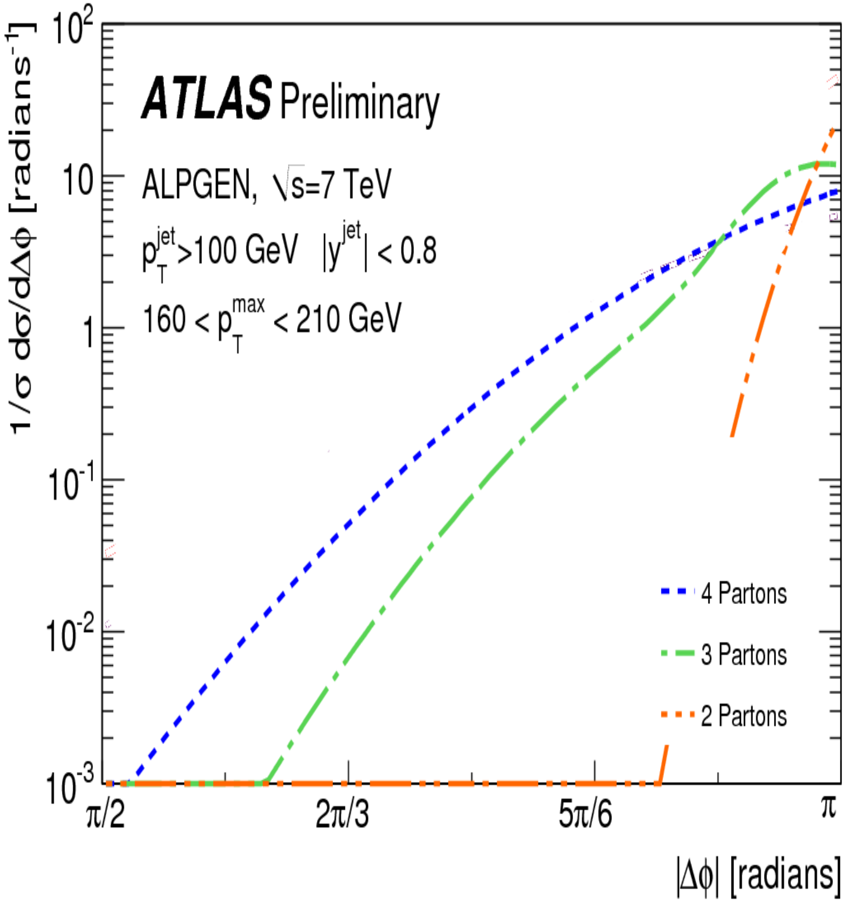

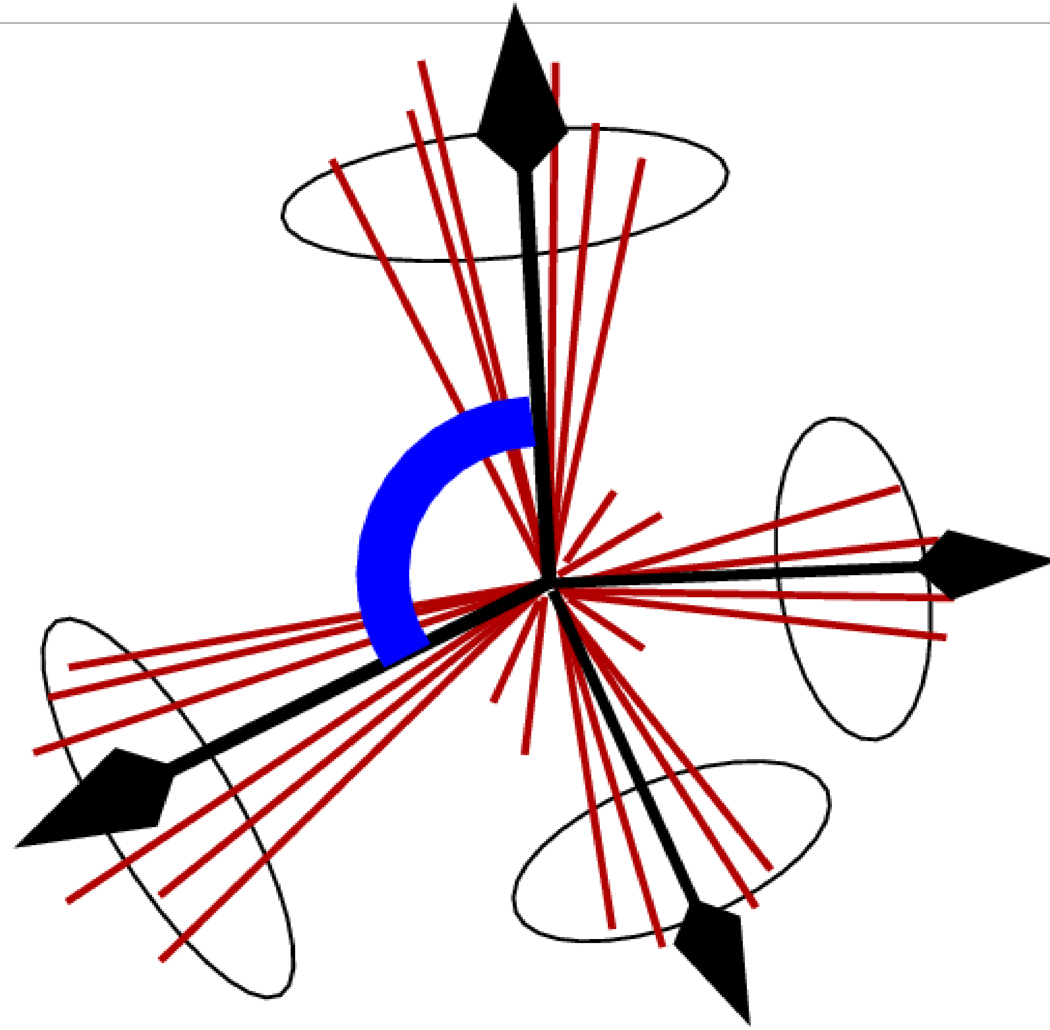

Phys.Rev.Lett. 106 (2011) 172002 [1102.2696]

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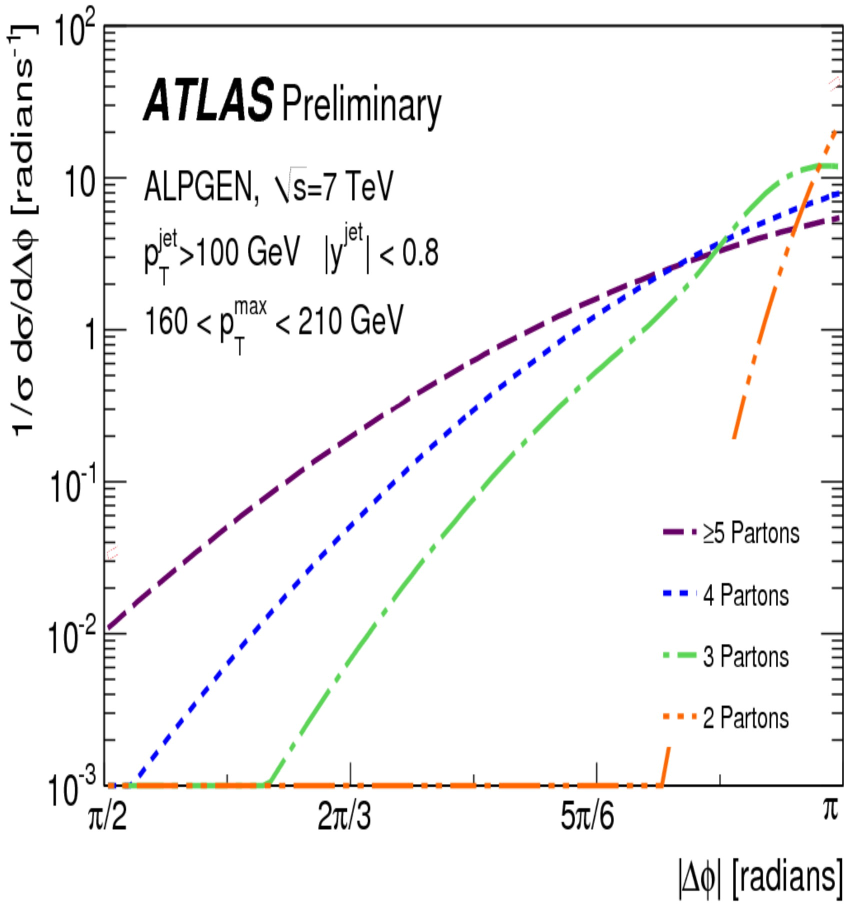

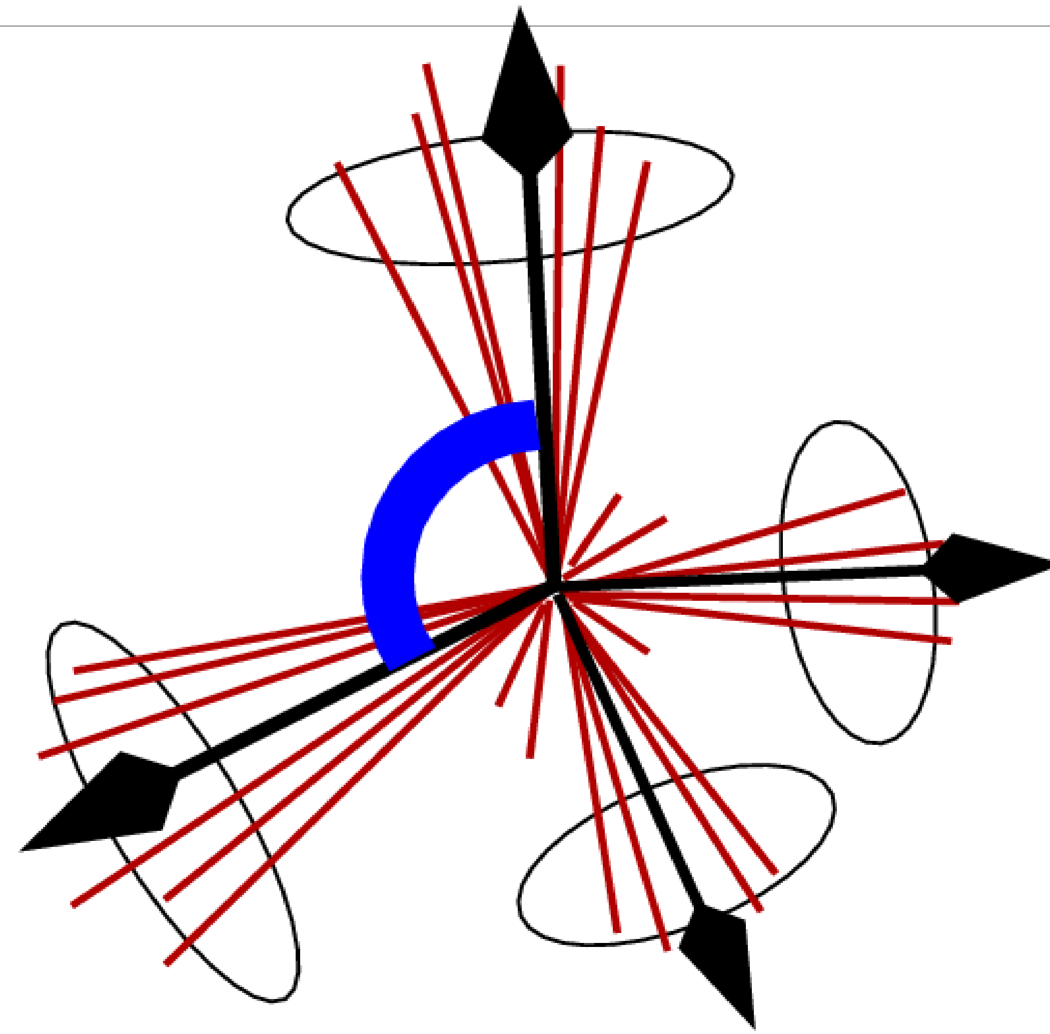

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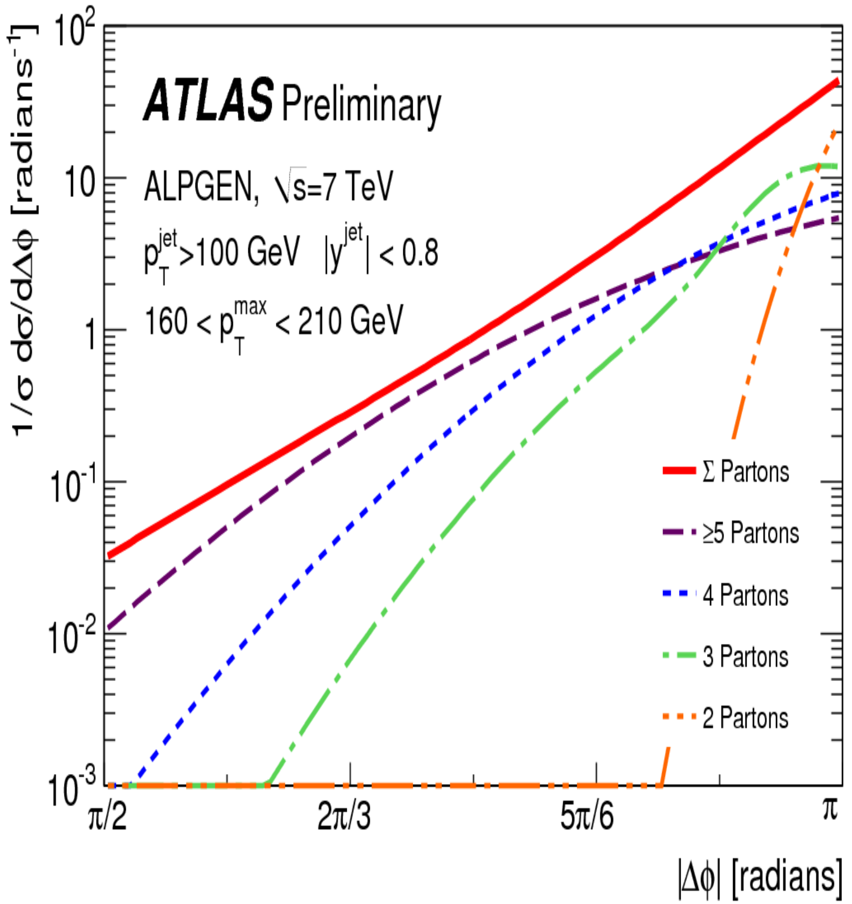
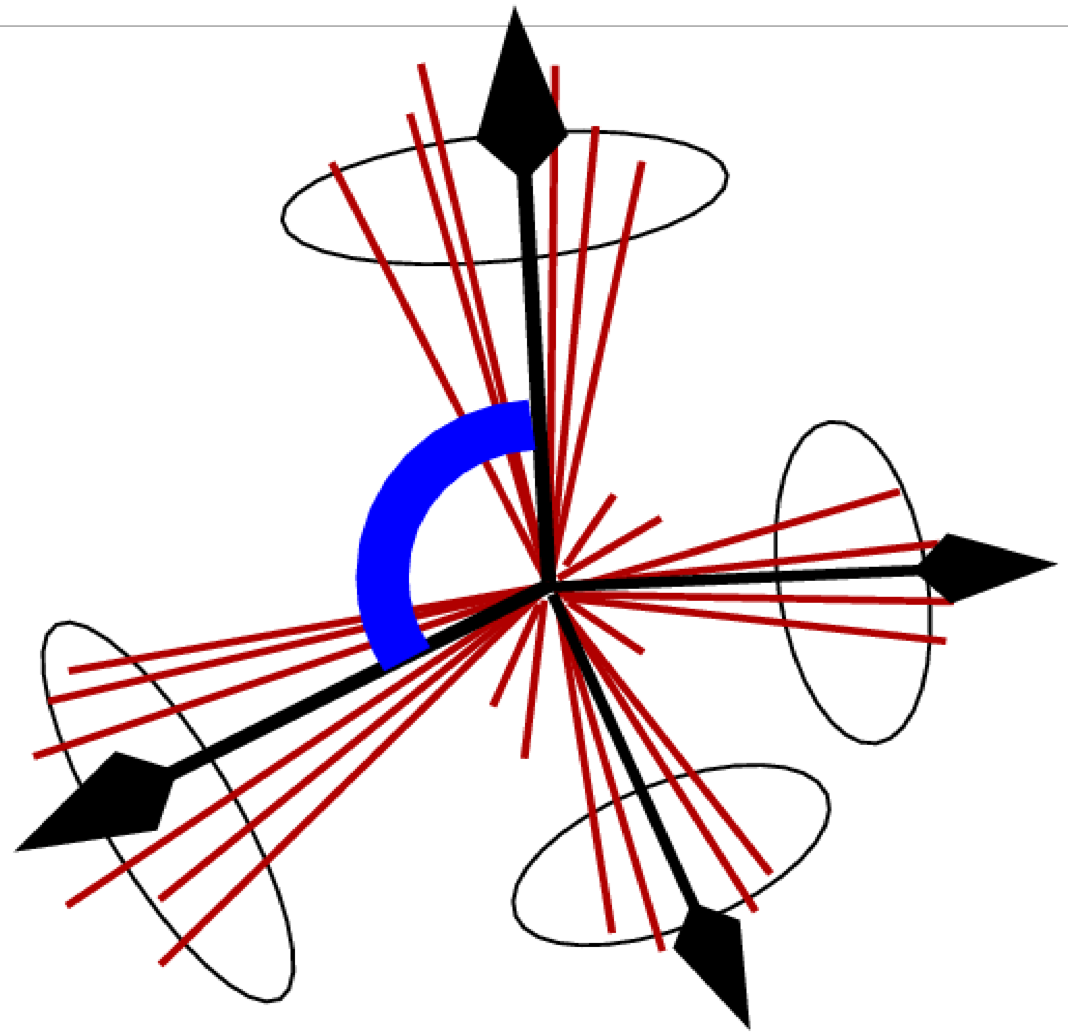




The azimuthal decorrelation Δφ is a test higher-order perturbative QCD (pQCD) calculations without requiring the reconstruction of additional jets and a way to examine the transition between soft and hard QCD processes with a single observable.

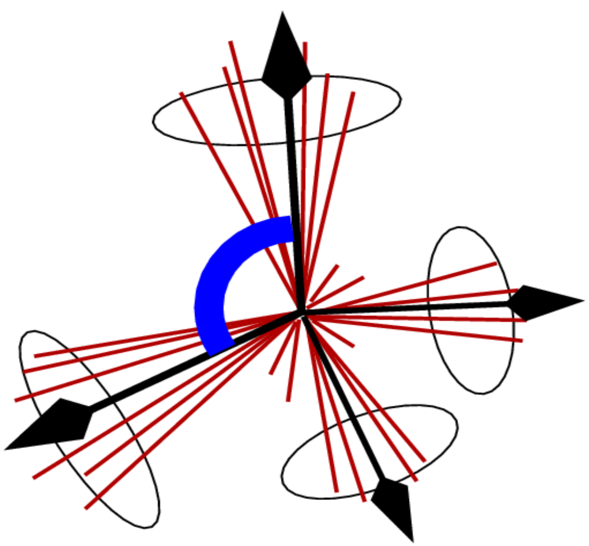
Phys.Rev.Lett. 106 (2011) 172002 [1102.2696]

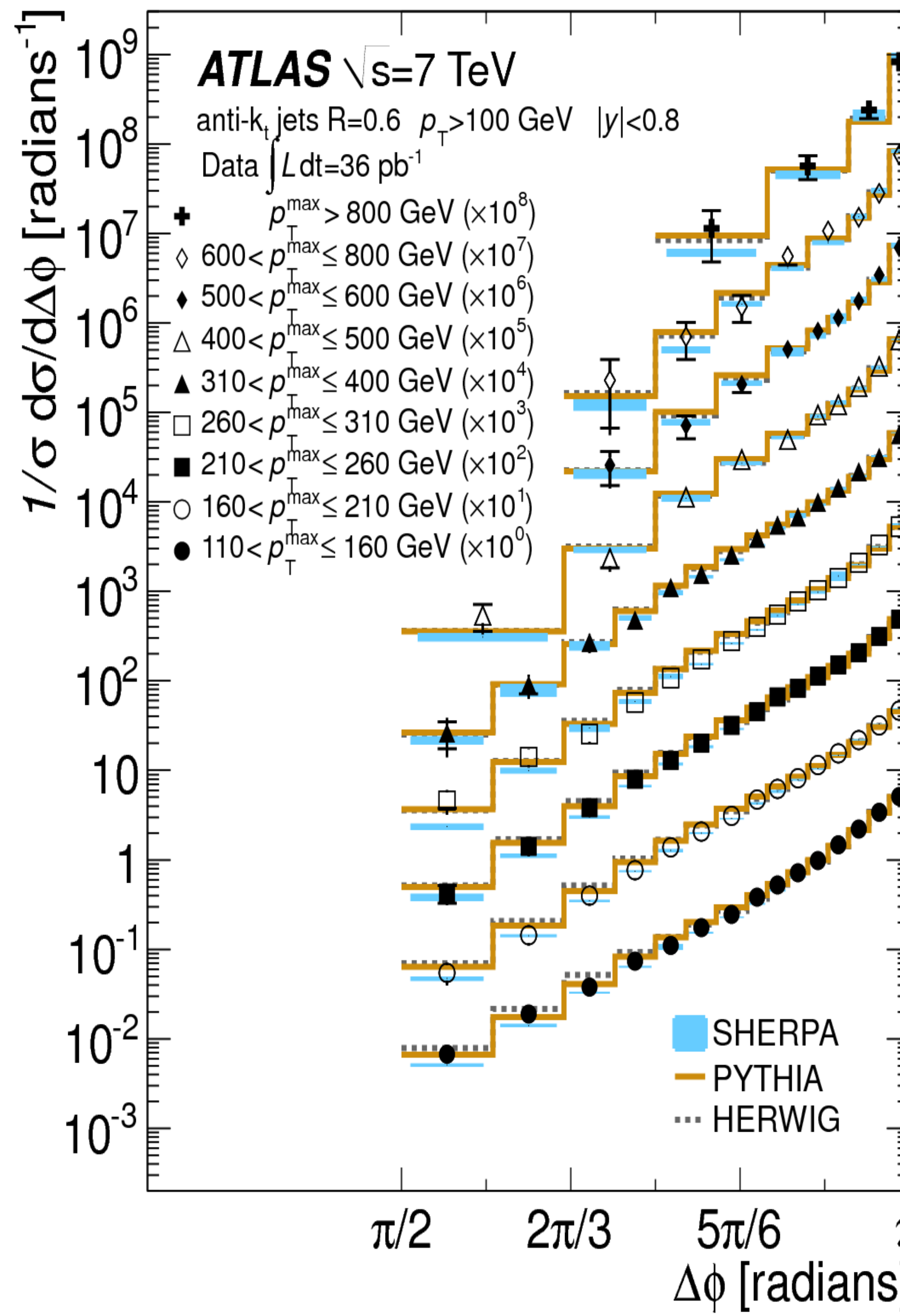
Azimuthal decorrelation

Monte Carlos show good agreement with data.

Similar agreement for the NLO calculation (NLOJET++)

Phys.Rev.Lett. 106 (2011) 172002 [1102.2696]





Cross Sections

Cross Section: Inclusive Single Jet

Measurements of inclusive cross-sections are important verifications of perturbative QCD and probes of new physics (e.g. quark compositeness, etc.).

Cross Sections:
Inclusive single-jet double-differ. cross-sections as a function of p_T and y

$d^2\sigma/dP_{T,jet}\, d|y|$

Transverse momentum: **$p_T > 20$ GeV** **Rapidity: $|y| < 4.4$**

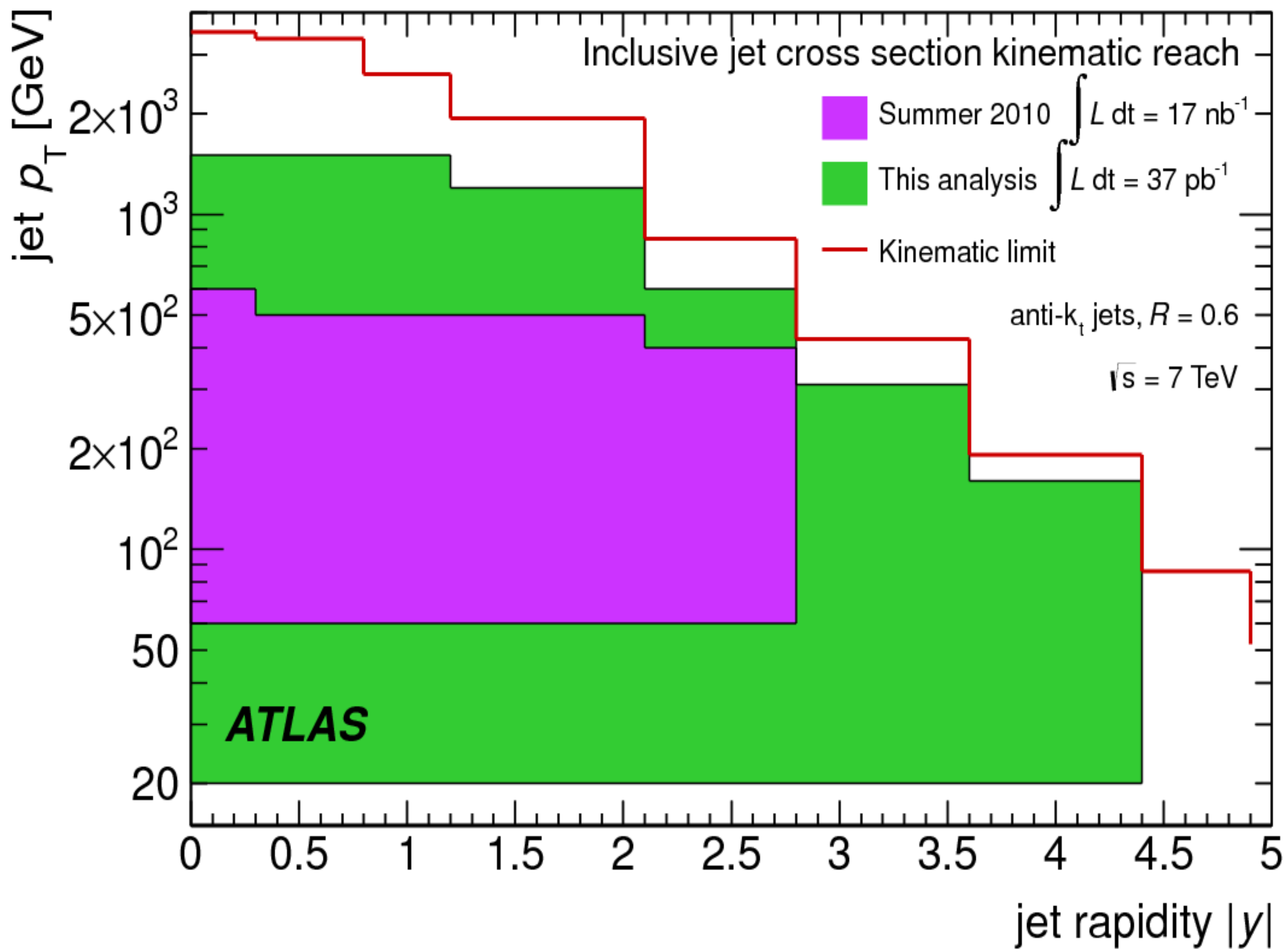
Jet Algorithm: Anti-K_T jets with R=0.4 and R=0.6

Integrated Luminosity: ~ 40 pb^{-1}
The cross section is corrected by the detector effects

Cross Section: Inclusive Single Jet

CERN-PH-EP-2011-192 [1112.6297]

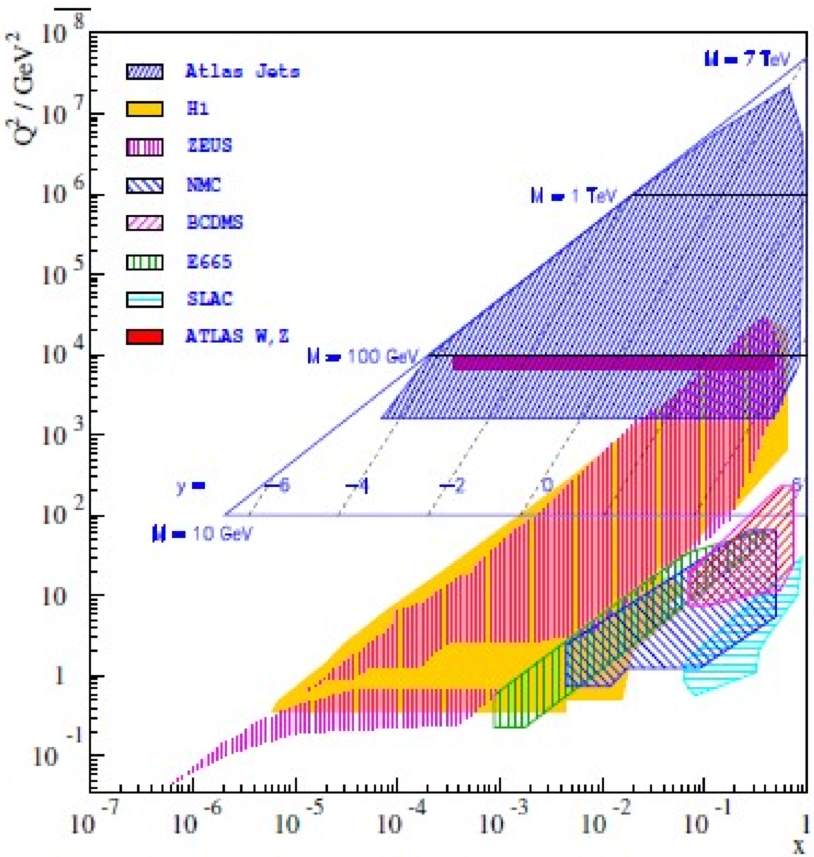
Measurement done in a new regime of phase space



Cross Section: Inclusive Single Jet

CERN-PH-EP-2011-192 [1112.6297]

Measurement done in a new regime of phase space



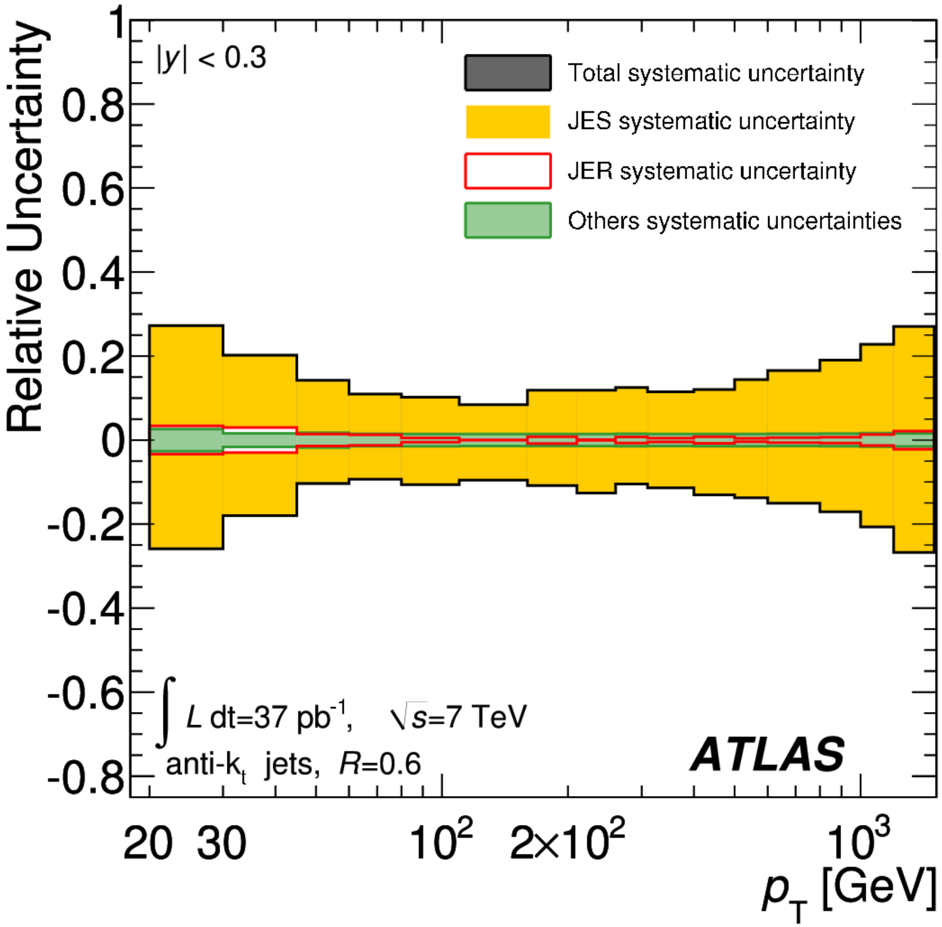
$$7 \cdot 10^{-5} < x < 0.9$$
$$Q^2 > 2 \cdot 10^7 \ \text{GeV}^2$$

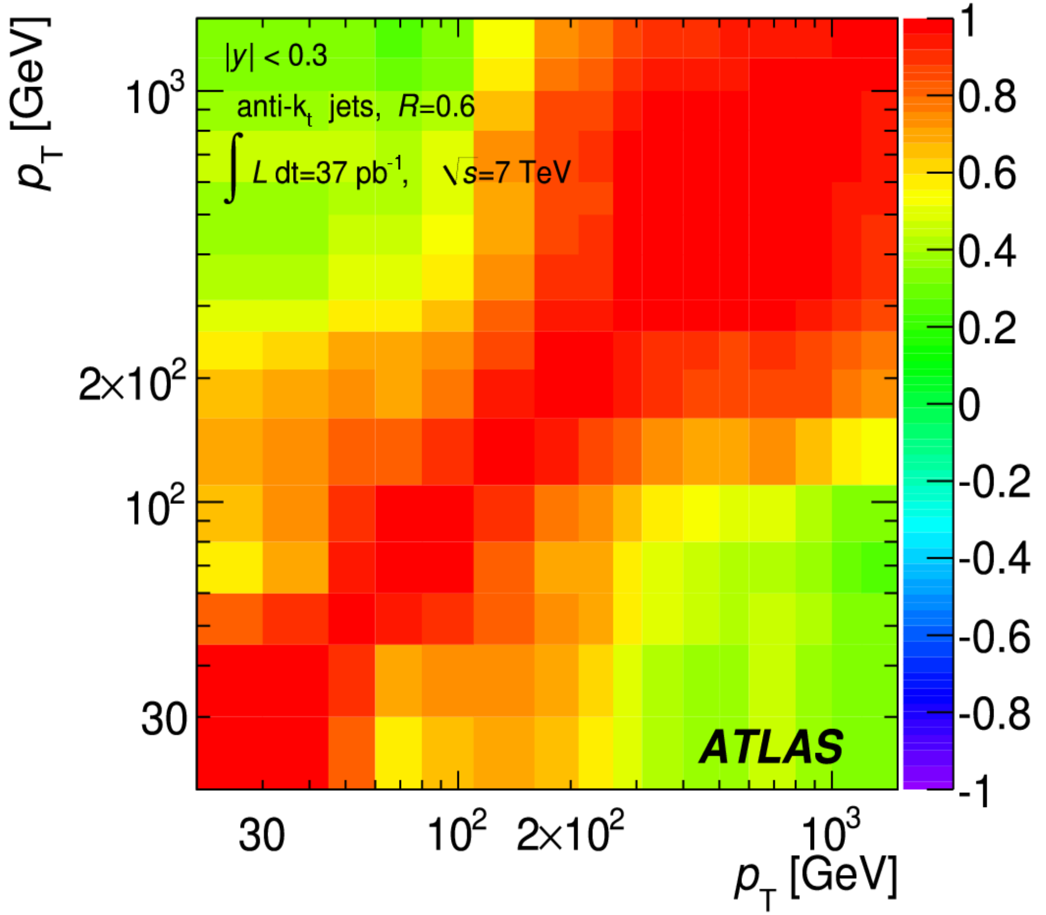
Already used for:
1) determination of alpha_s
2) constrain the gluon PDF

Cross Section: Inclusive Single Jet

CERN-PH-EP-2011-192 [1112.6297]

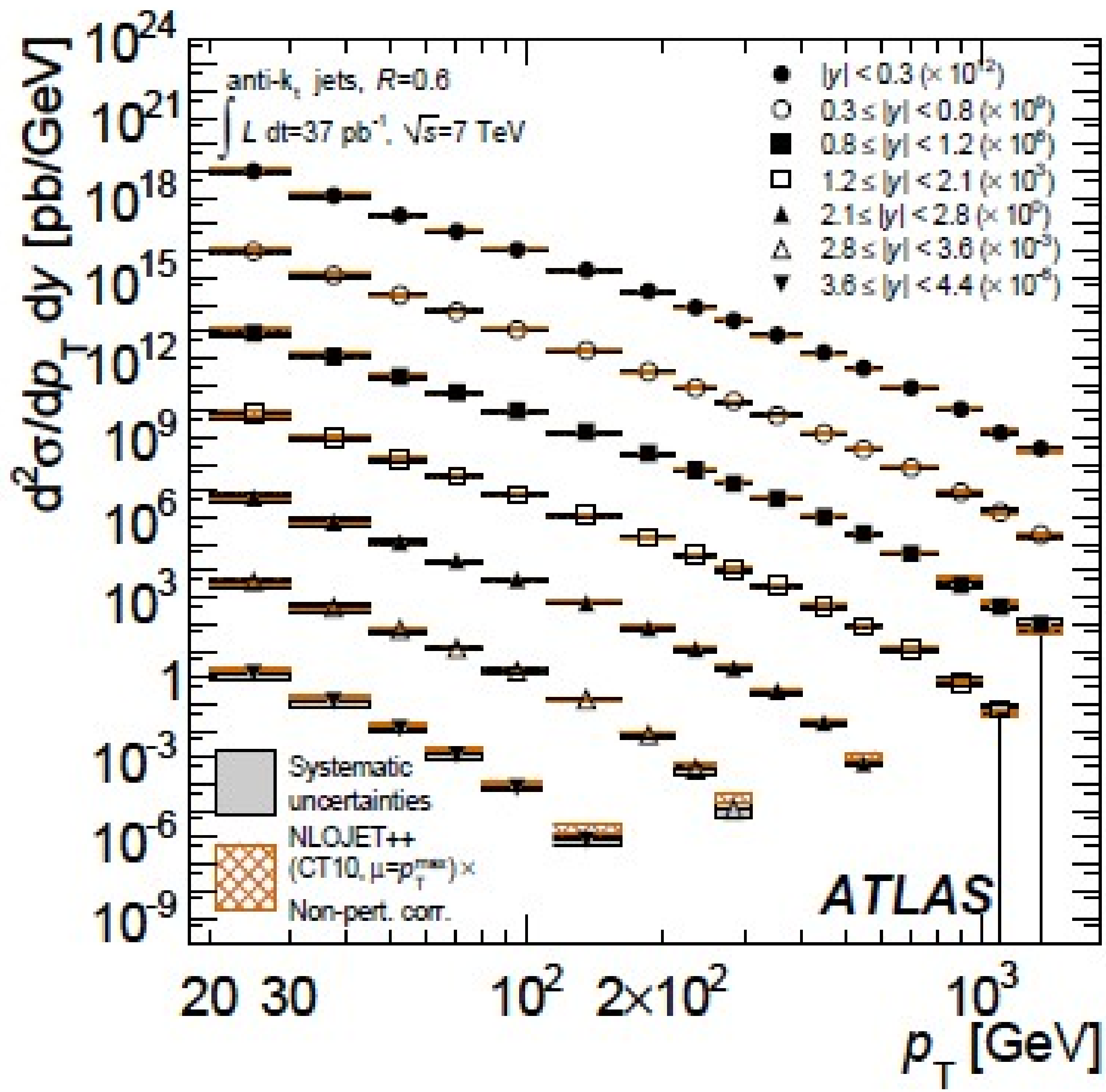
QCD fits gained from the complete study of the systematic correlations: ~90 independent components





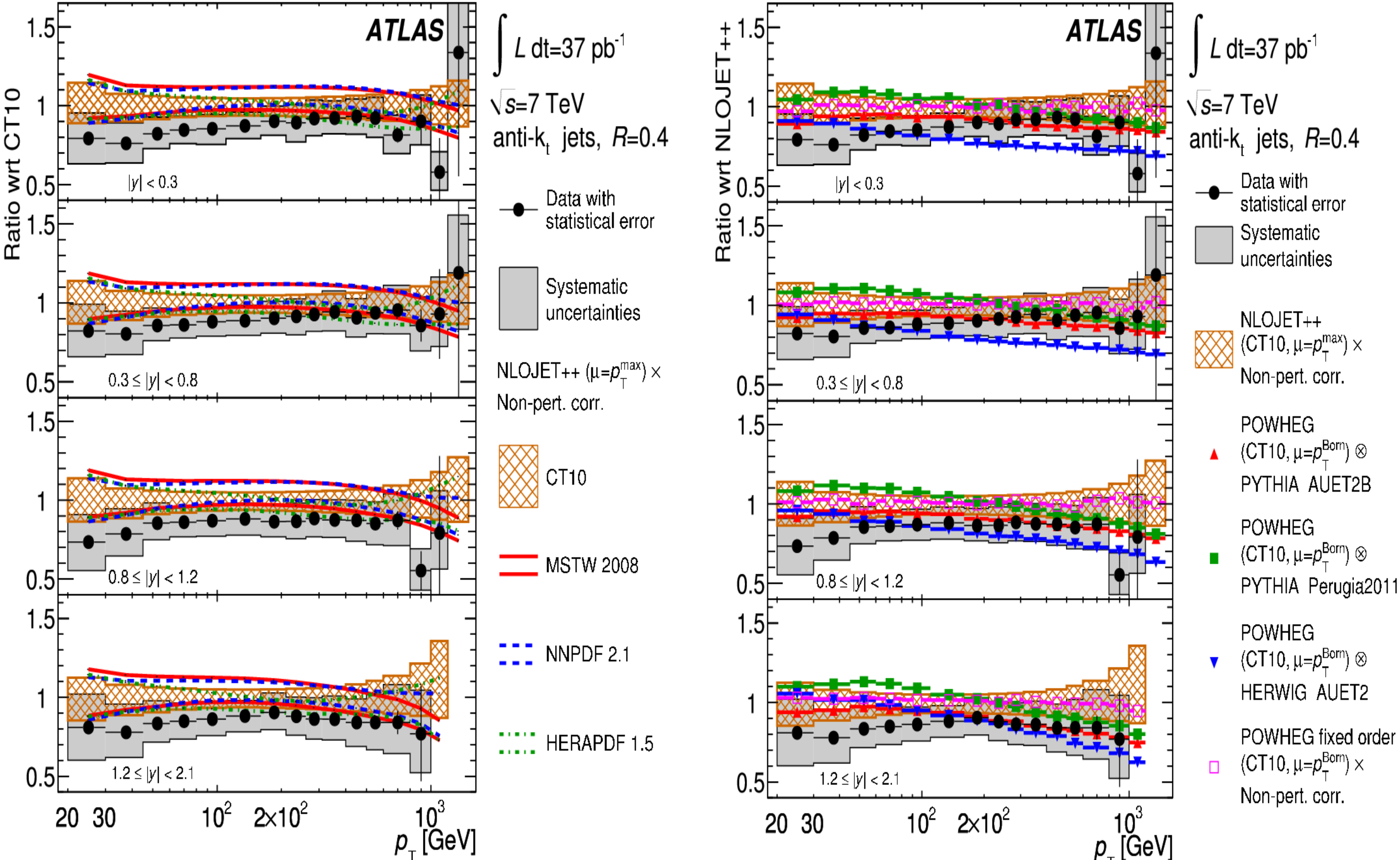
Cross Section: Inclusive Single Jet

CERN-PH-EP-2011-192 [1112.6297]

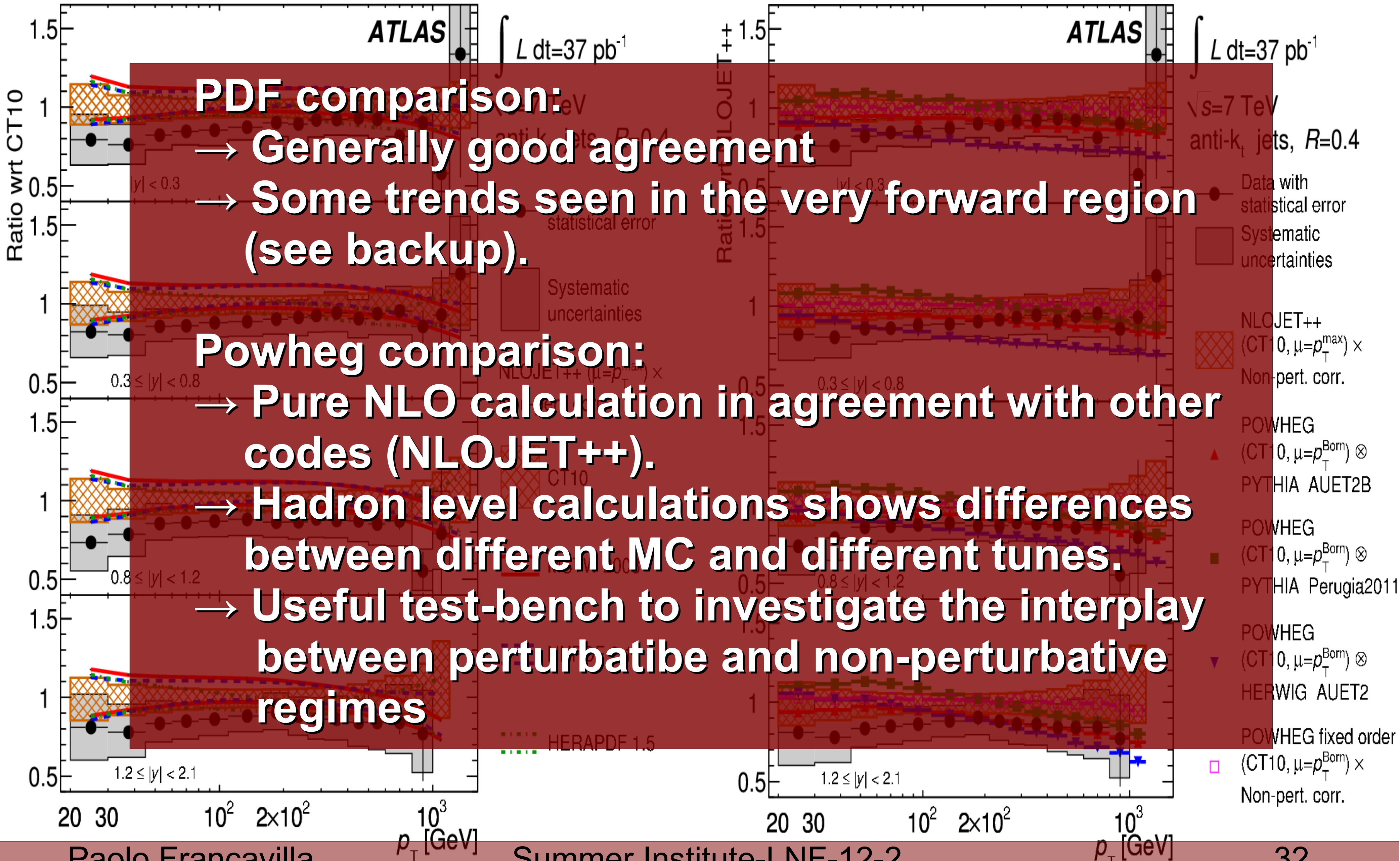


Cross Section: Inclusive Single Jet R=0.4

CERN-PH-EP-2011-192 [1112.6297]



Cross Section:
Inclusive Single Jet R=0.4



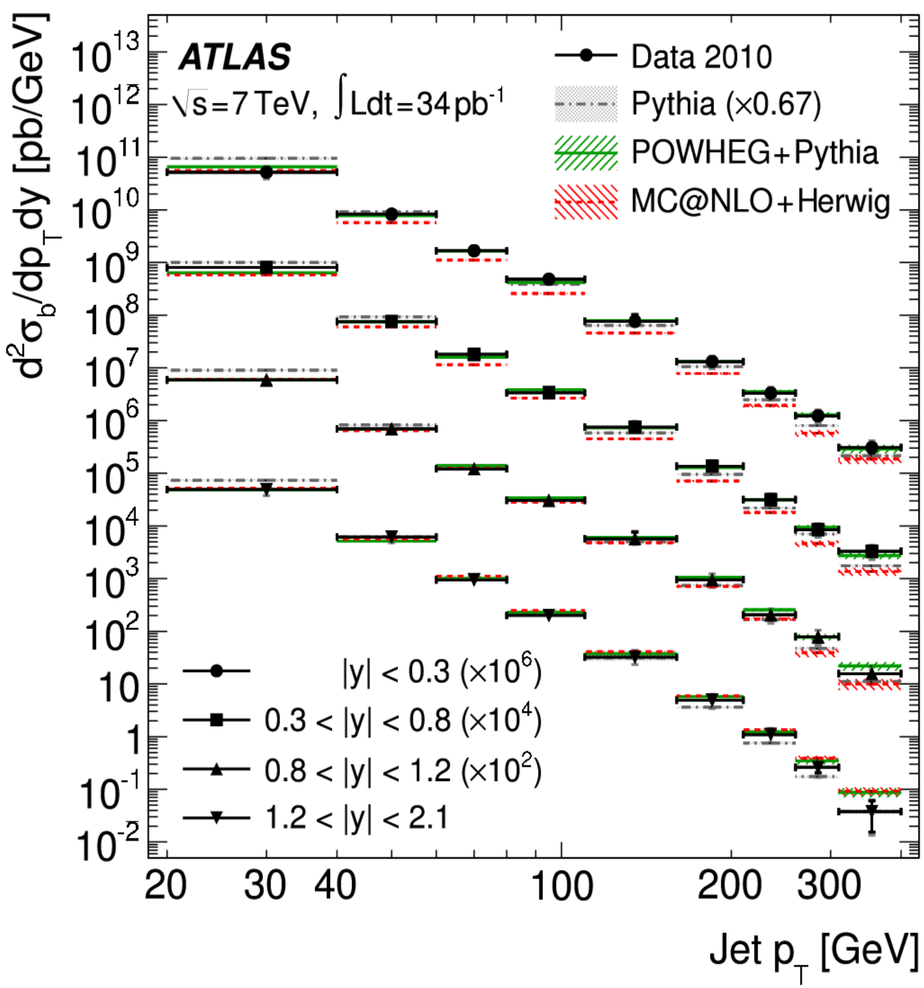
PDF comparison:
→ Generally good agreement
→ Some trends seen in the very forward region (see backup).

Powheg comparison:
→ Pure NLO calculation in agreement with other codes (NLOJET++).
→ Hadron level calculations shows differences between different MC and different tunes.
→ Useful test-bench to investigate the interplay between perturbatibe and non-perturbative regimes

Cross Section with heavy flavour jets

Bottom

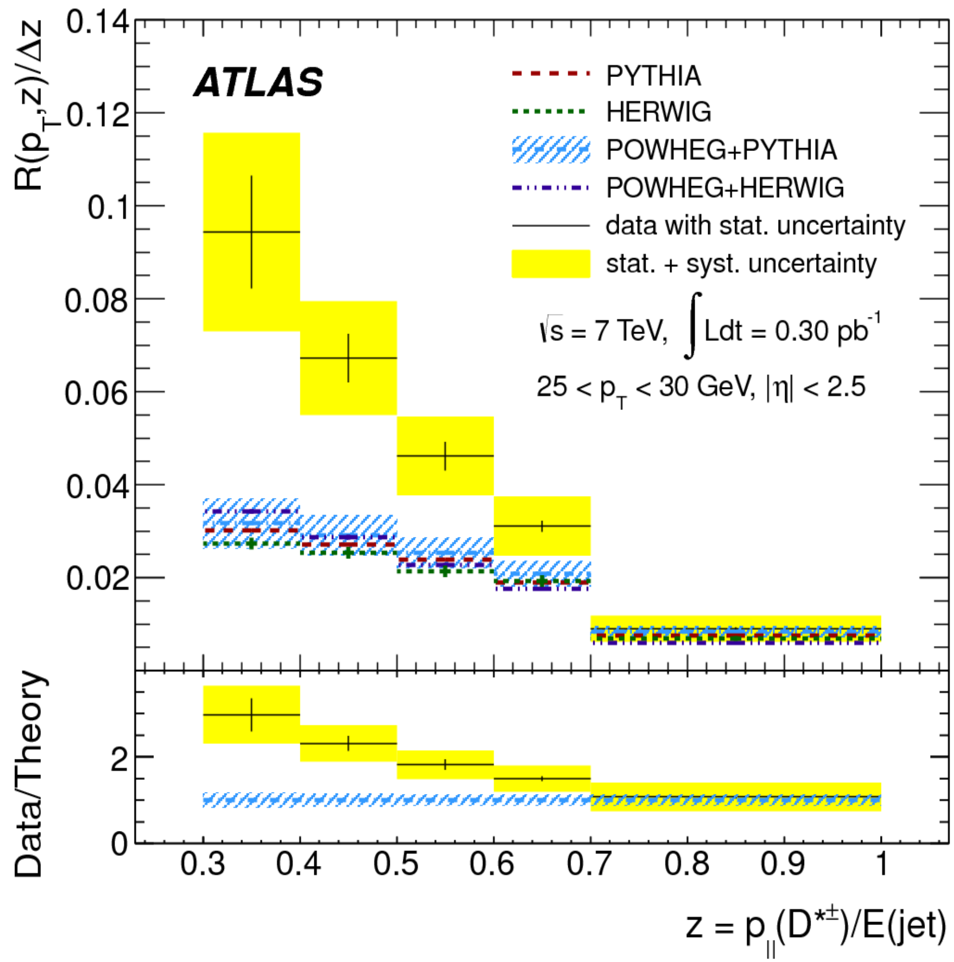
B-jets cross section.
General good agreement.



Eur.Phys.J.C 71 (2011) 1846 [1109.6833]

Charm

Production of jets with associated D*.
MC fail to describe the D* relative energy.



Phys. Rev. D85 (2012) 052005 [1112.4432]

Cross Section: Di-Jets

Cross Sections:
Di-jet cross-sections as a function of di-jet mass and angle.

$$d^2\sigma/dM_{1,2}\, dy^*$$

$M_{1,2}$ is invariant mass of first two leading jets with $P_{T,1}$> 30 GeV and $P_{T,2}$>20 GeV

$$y^* = \frac{1}{2} \ln \left(\frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|} \right)$$

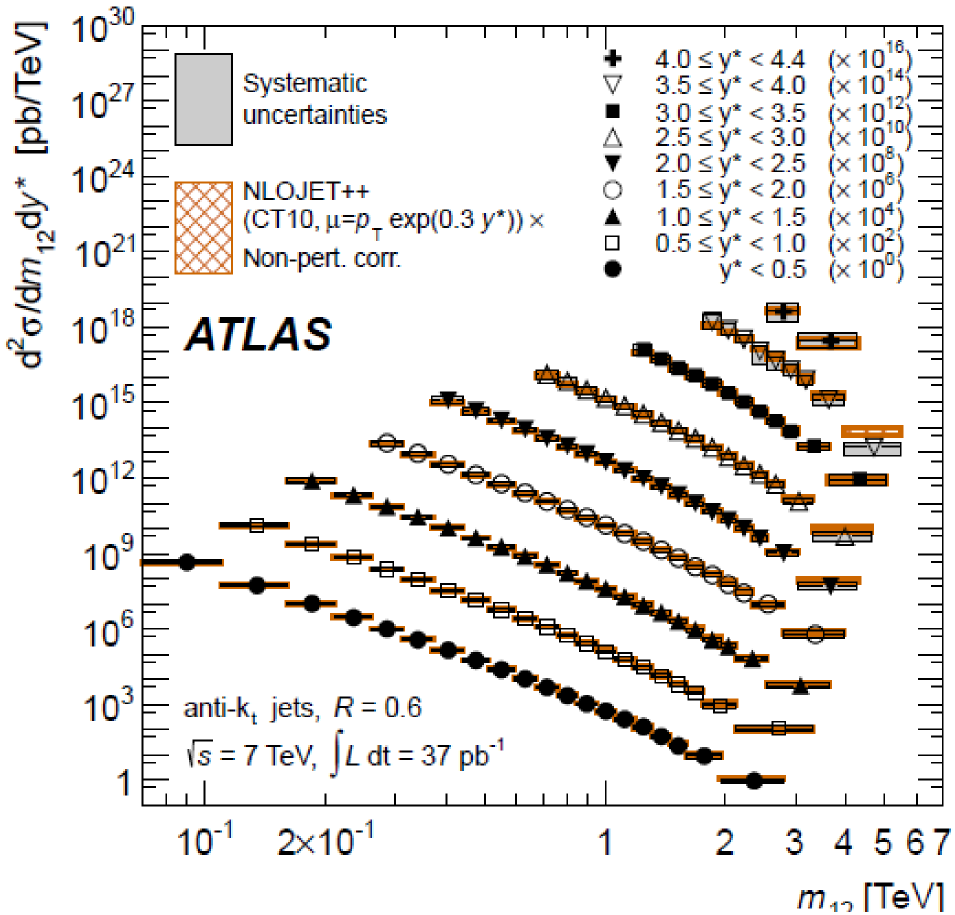
Y* is the rapidity in the two-jet center of mass system.

Jet Algorithm: Anti-K_T jets with R=0.4 and R=0.6

Integrated Luminosity: ~40 pb^{-1} (2010) and ~ 5fb^{-1} (2011)
The cross section is corrected by the detector effects

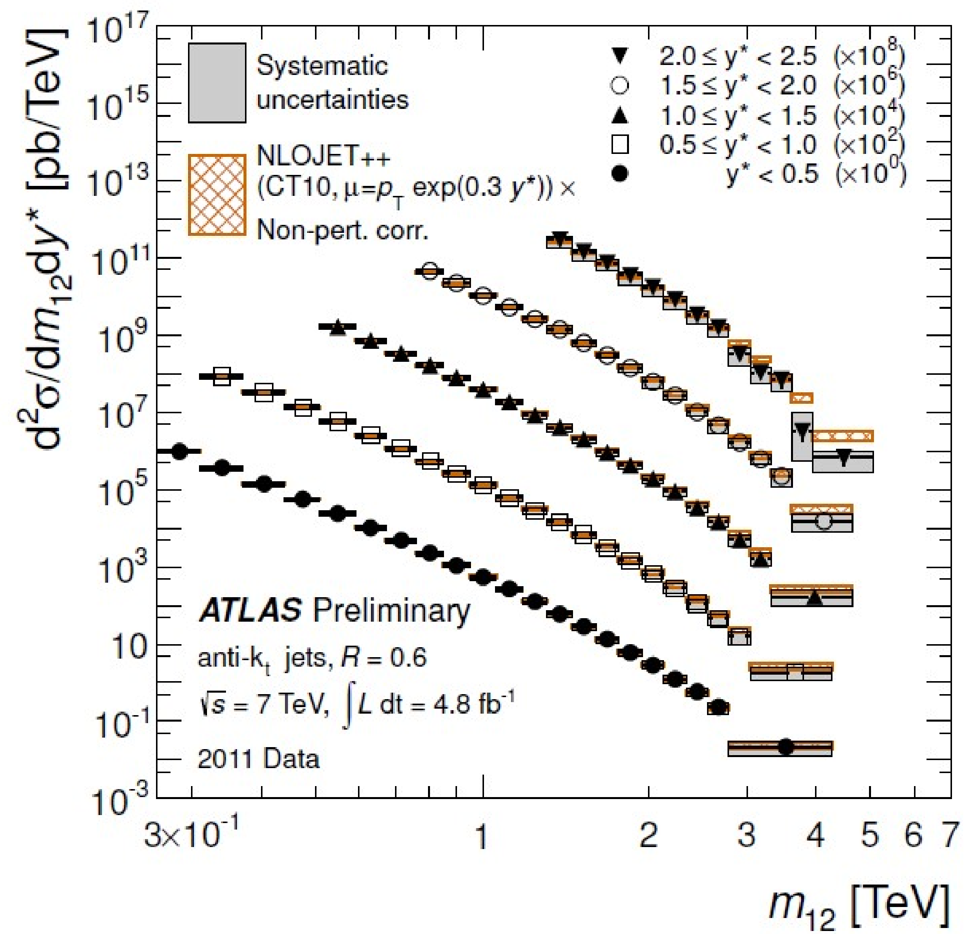
Cross Section: Di-Jets

2010



CERN-PH-EP-2011-192 [1112.6297]

2011



ATLAS-CONF-2012-021

Cross Section: Multi-Jets

A first step toward the measurement of complex QCD final states

- Important as a measurement in itself
  (i.e. to extract the strong coupling constant)
- Fundamental to start the controls for the QCD background for
  searches.

Cross Sections:

Multi-Jet cross section:

Multi Jet rates

p_T spectrum for the 1st, 2nd, 3rd, 4th jet (ordered in p_T)

H_T distribution for different multiplicity

Cuts: leading jets: p_T > 80 GeV, subleading jets p_T > 60 GeV

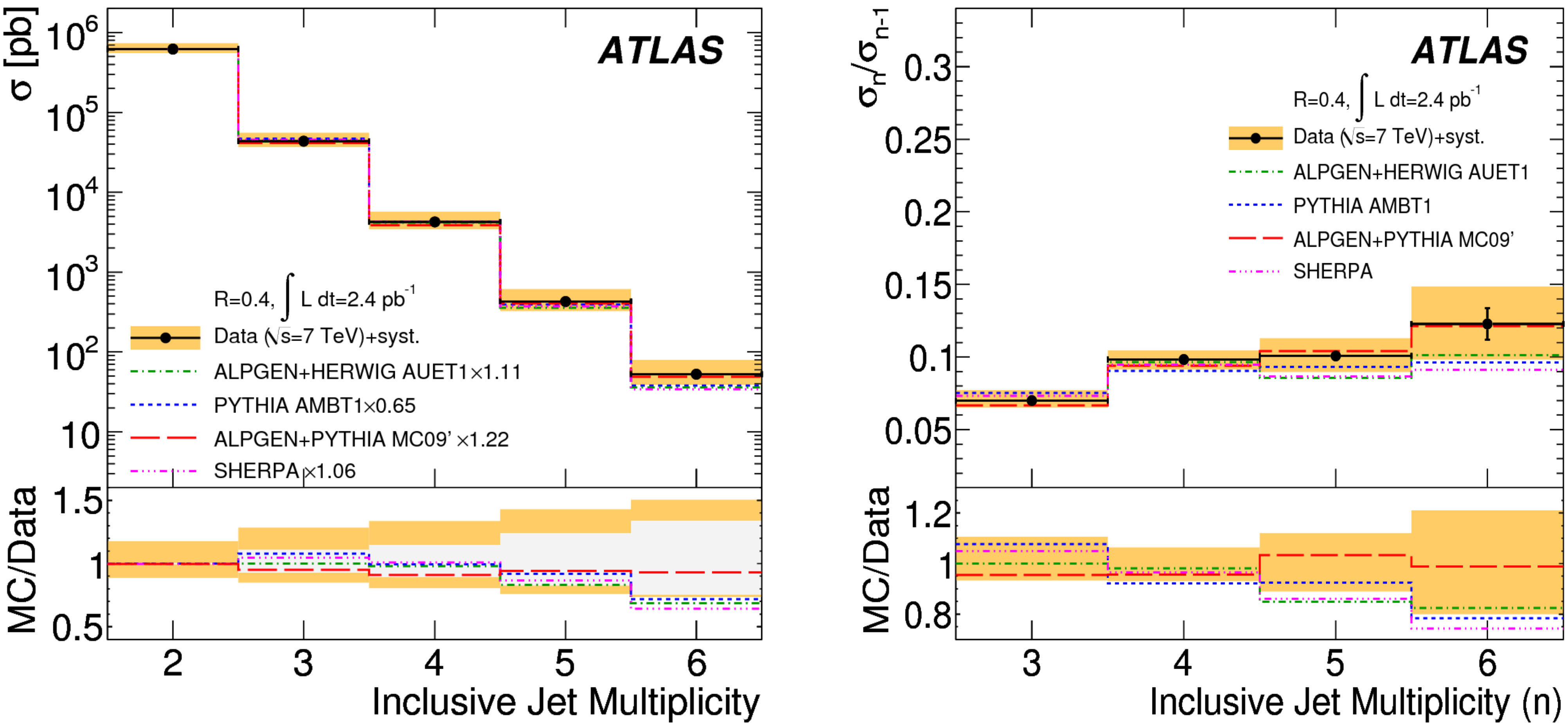
Jet Algorithm: Anti-K_T jets with R=0.4

Integrated Luminosity: 2.4 pb^{-1}

The cross section is corrected by the detector effects

Cross Section: Multi-Jets

Eur.Phys.J. C71 (2011) 1763 [1107.2092]



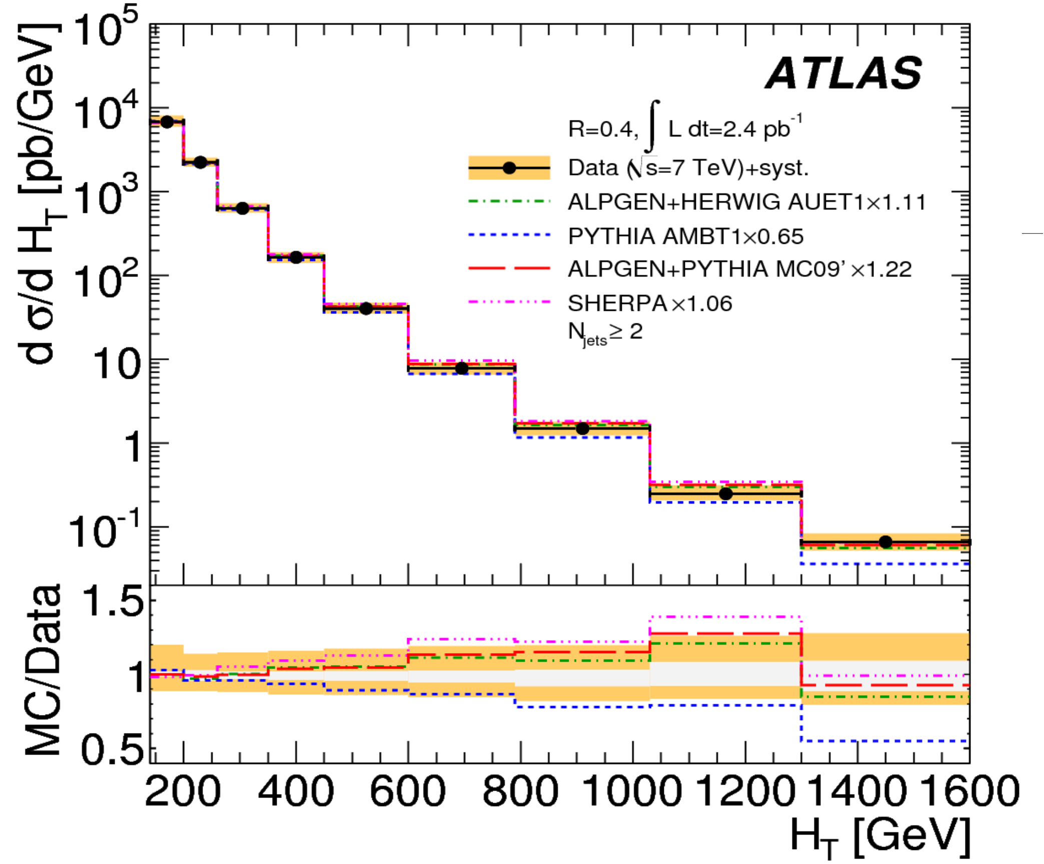
Alpgen+Pythia describes better the data.
Pythia has a factor 0.65

Cross Section: Multi-Jets

Eur.Phys.J. C71 (2011) 1763 [1107.2092]

***$H_T = \Sigma p_T$* of selected jets**

Inclusive variable to describe the events.

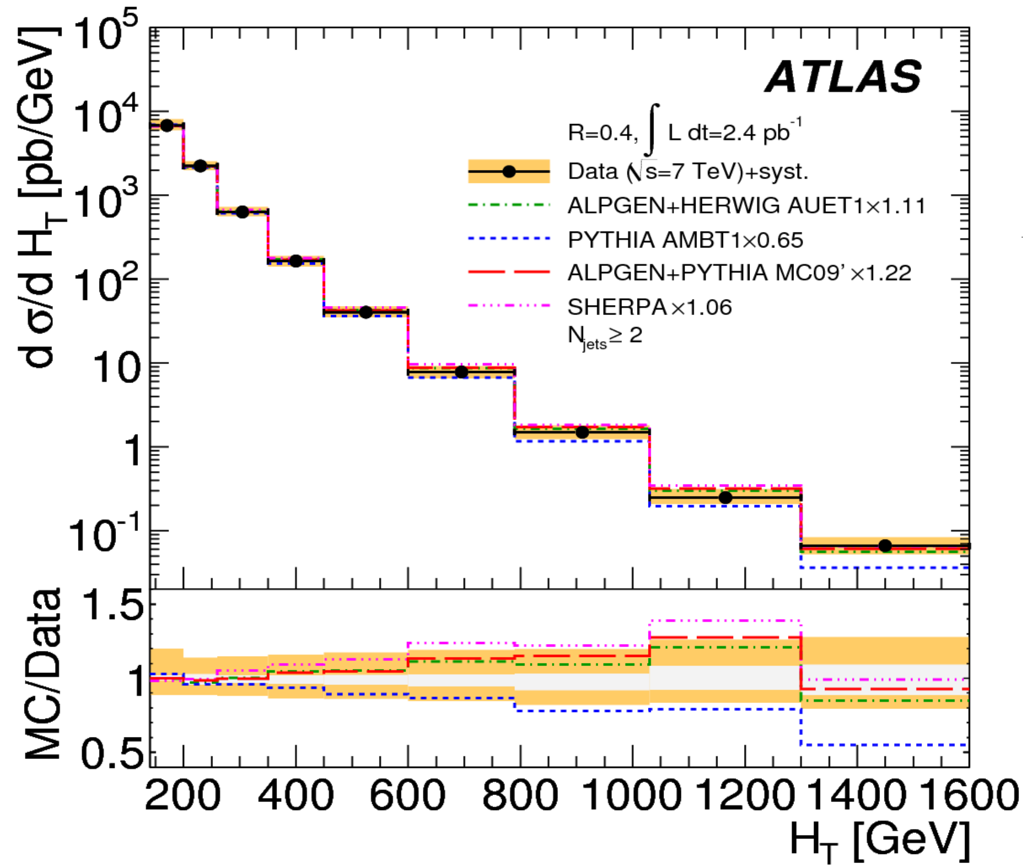


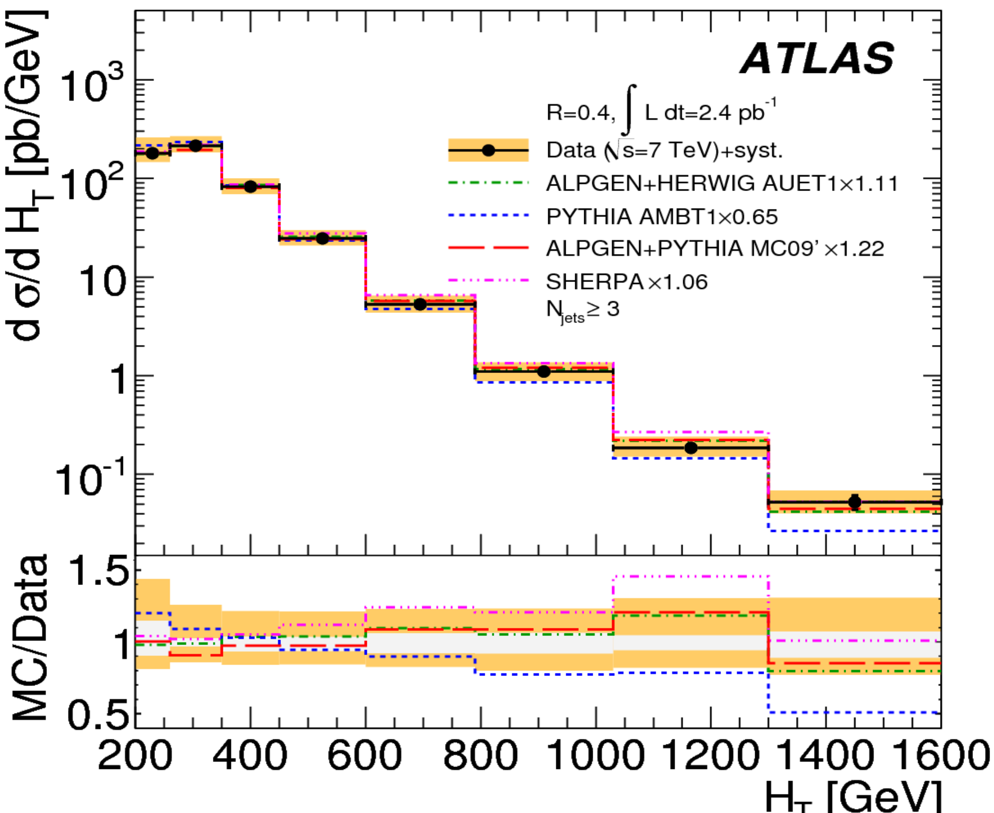
Cross Section: Multi-Jets

Eur.Phys.J. C71 (2011) 1763 [1107.2092]

***$H_T = \Sigma p_T$* of selected jets**

Inclusive variable to describe the events.



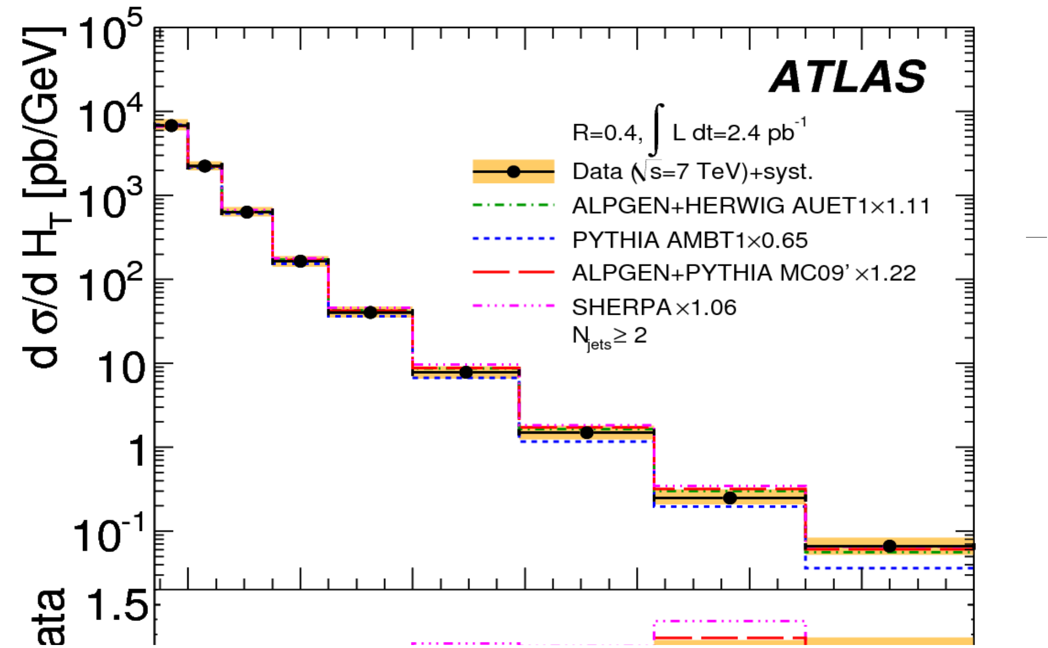


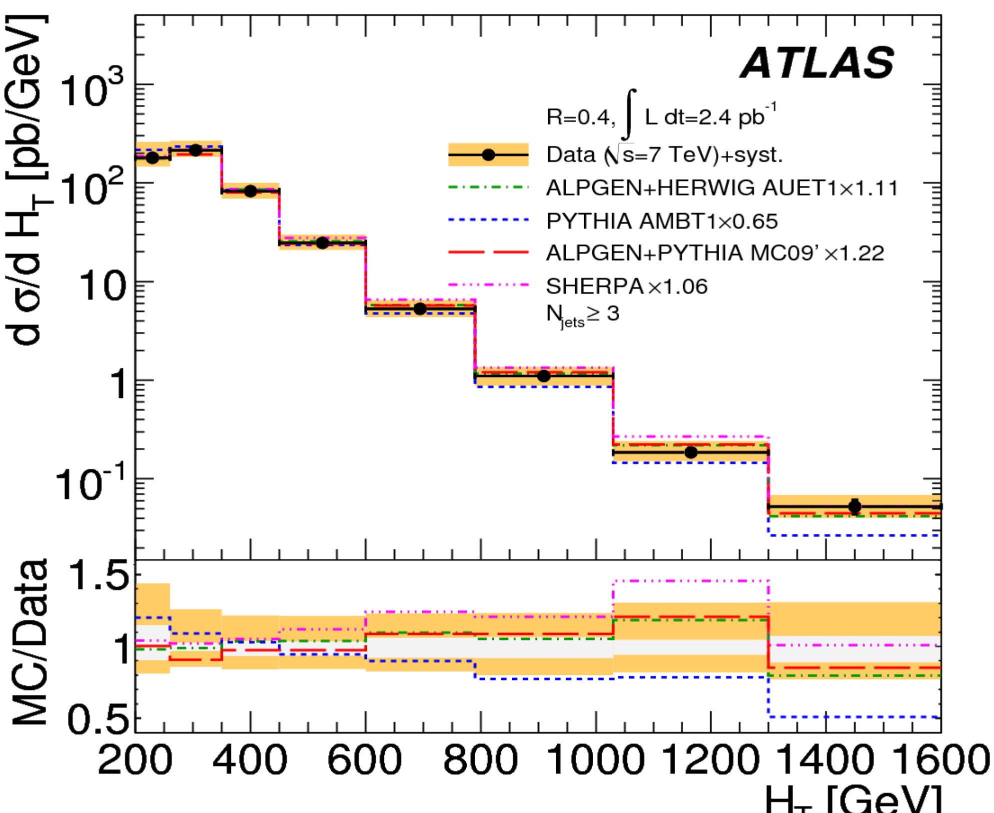
Cross Section: Multi-Jets

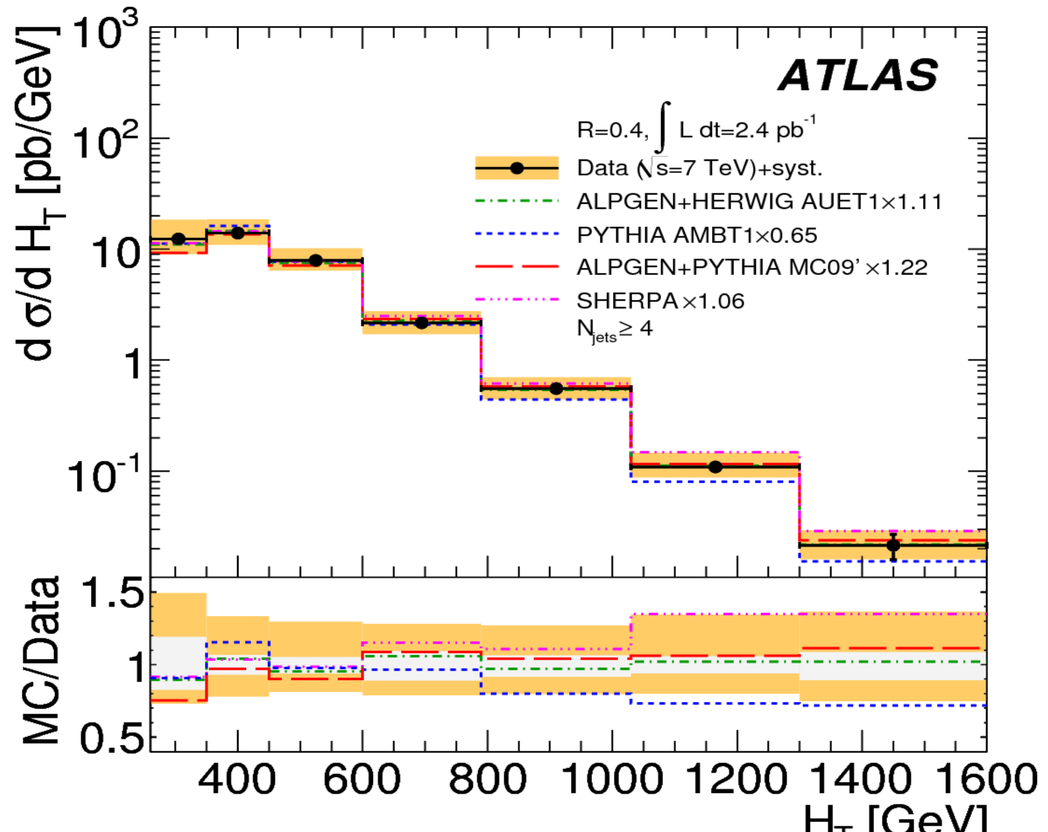
Eur.Phys.J. C71 (2011) 1763 [1107.2092]

$H_T = \Sigma p_T$ of selected jets

Inclusive variable to describe the events.







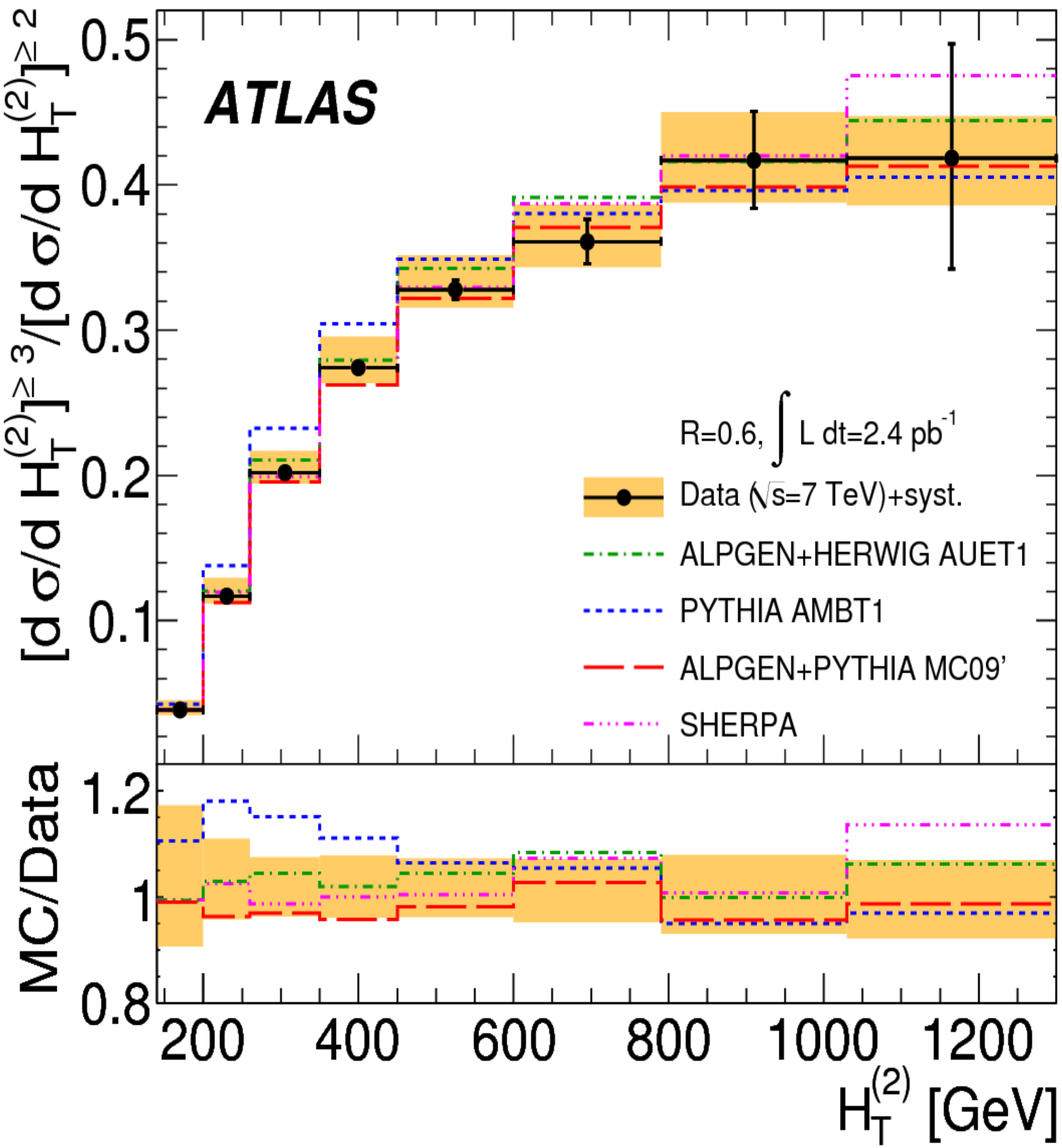
Cross Section: Multi-Jets

By making the ratio, part of the systematics cancel out.

Useful as an input for the strong coupling constant evaluation

(rough indication of the scaling violation).

Eur.Phys.J. C71 (2011) 1763 [1107.2092]



Jets in searches

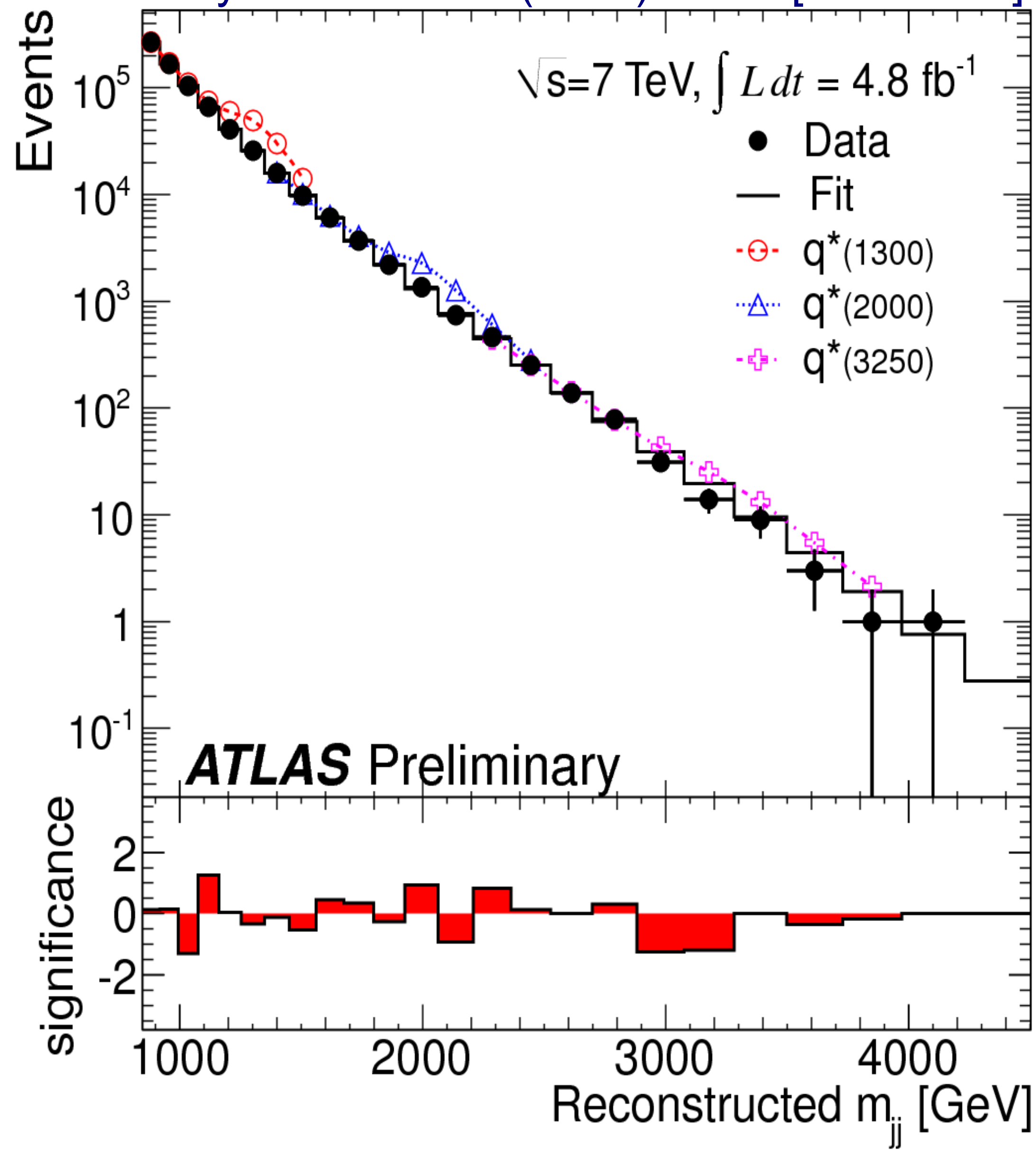
Exclusions: Di-jet Mass

By using the di-jet measurements, limits on new physics can be studied.

Search for bumps in the di-jet spectrum.

The fluctuation are not statistically significant.

Phys. Lett. B 708 (2012) 37-54 [1108.6311]

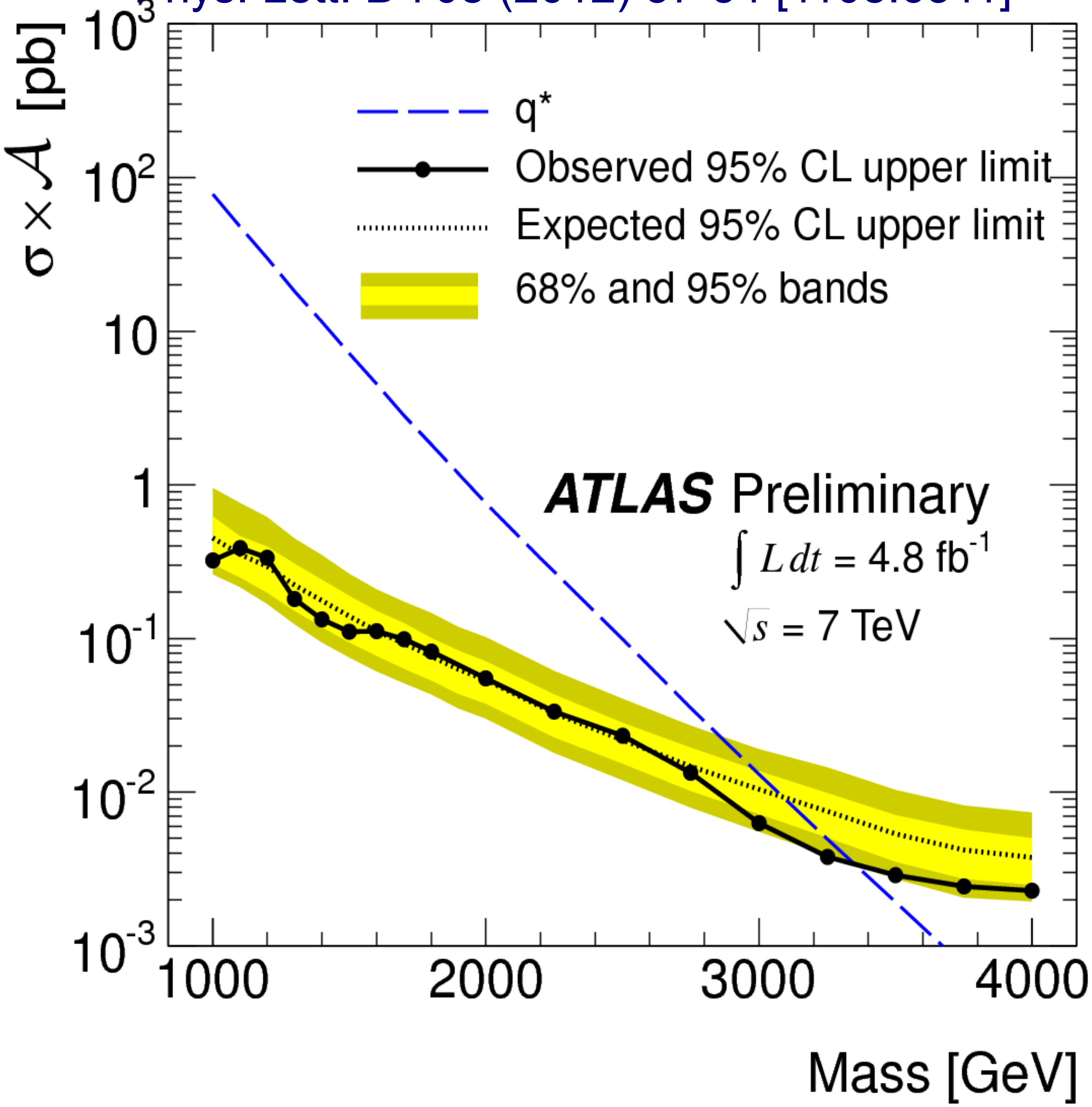


Exclusions: Di-jet Mass

Assuming a narrow di-jet resonance, the di-jet mass measurement can be used to exclude a certain cross section for the production of a resonance at a certain mass

This result can be used to exclude regions in the plane masses/couplings for effective theories.

Phys. Lett. B 708 (2012) 37-54 [1108.6311]



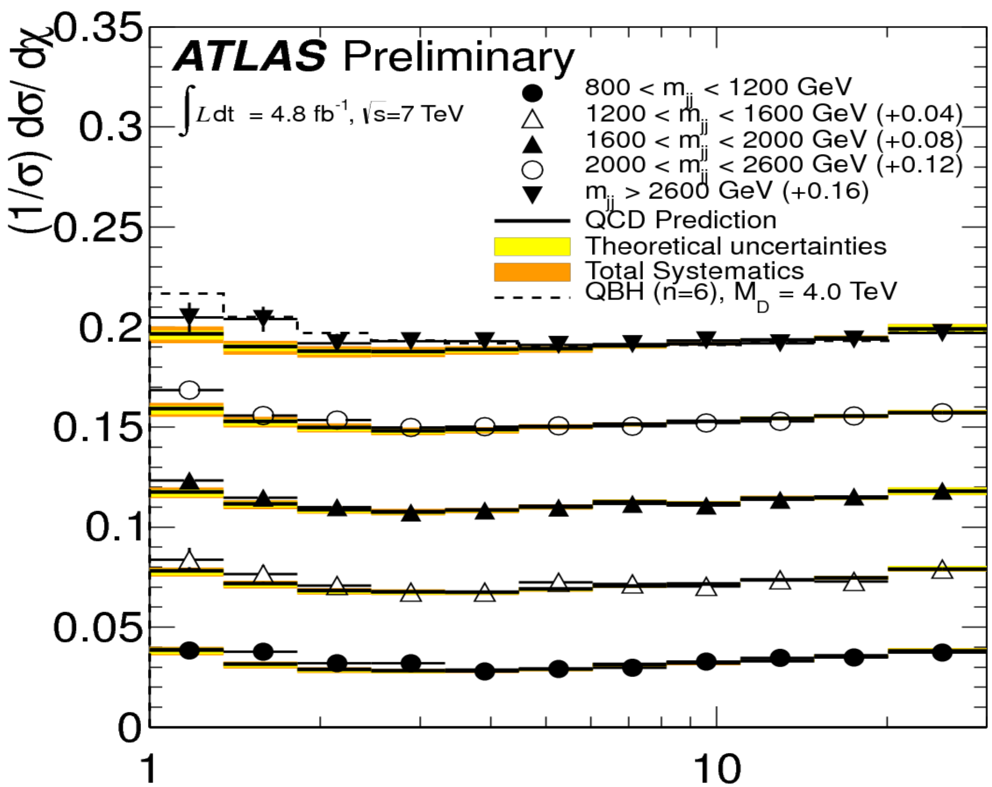
Exclusions: Di-jet Angles

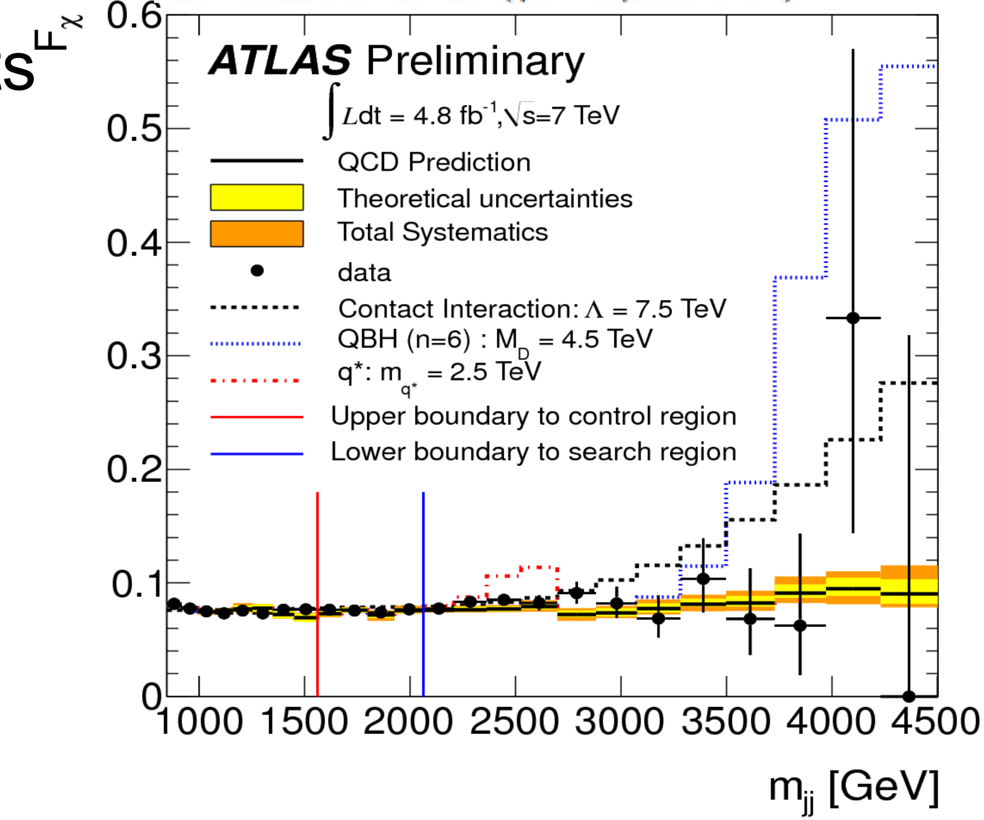
$$F_\chi(m_{jj}) = \frac{N(|y*| < 0.6)}{N(|y*| < 1.7)}$$

Even the angular distribution for jets have an important role to constrain models of new physics:

i.e. contact interaction

$$\chi = \exp(|y_1 - y_2|)$$



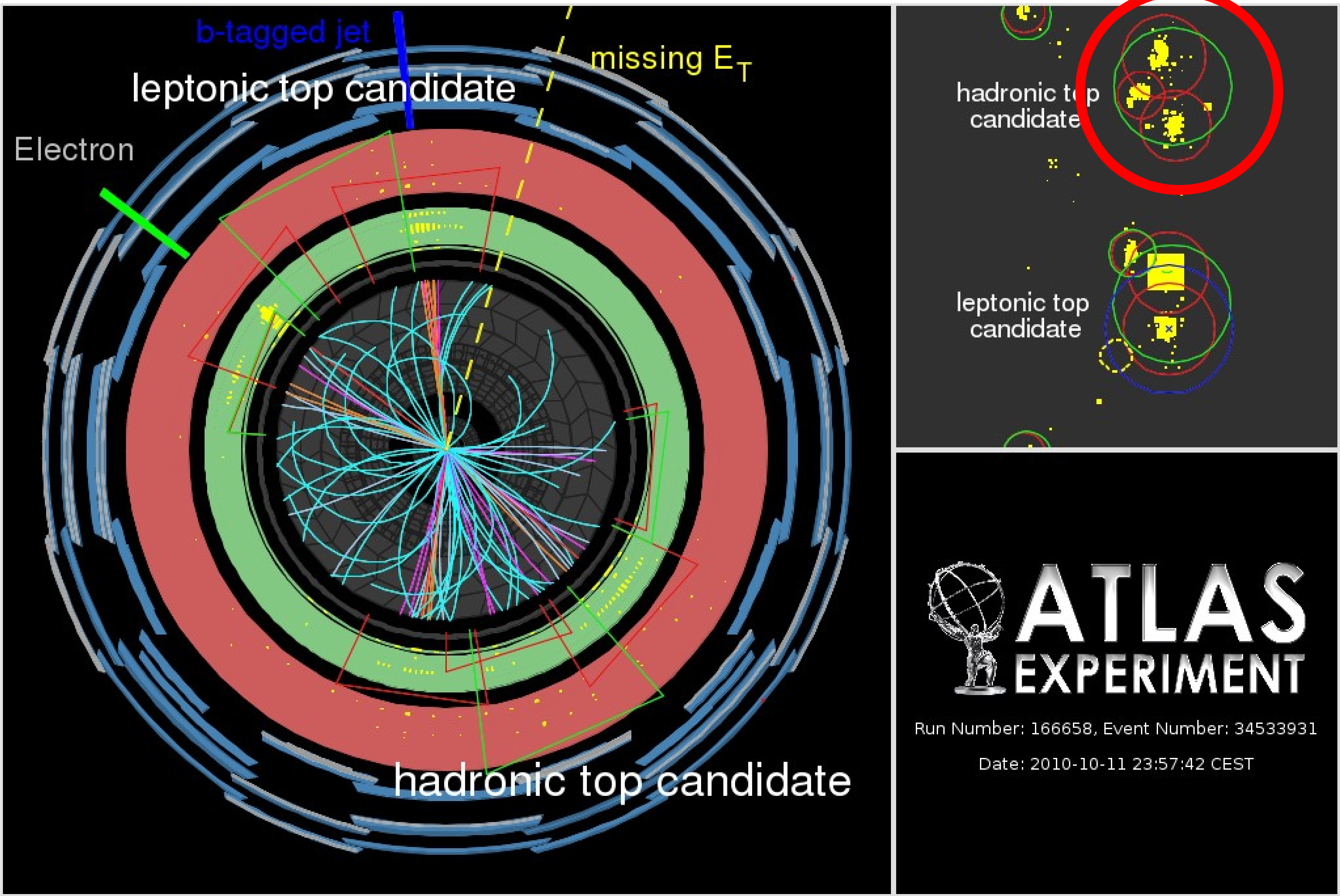


Model, and Analysis Strategy	95% C.L. Limits (TeV) Expected	Observed
Excited quark, mass of q^*		
Resonance in m_{jj}	3.09	3.35
Resonance in $F_\chi(m_{jj})$	2.97	2.58
Colour octet scalar, mass of s8		
Resonance in m_{jj}	1.94	1.94
Quantum Black Hole for $n = 6$, M_D		
$F_\chi(m_{jj})$	4.14	4.11
11-bin χ, $m_{jj} > 2.6$ TeV	4.23	3.96
Contact interaction, Λ, destructive interference		
$F_\chi(m_{jj})$	8.2	7.6
11-bin χ, $m_{jj} > 2.6$ TeV	8.7	7.8

Phys. Lett. B 708 (2012) 37-54 [1108.6311]

Jets substructure

Not just a crowded event



Observation of heavy particles in 1 fat-jet

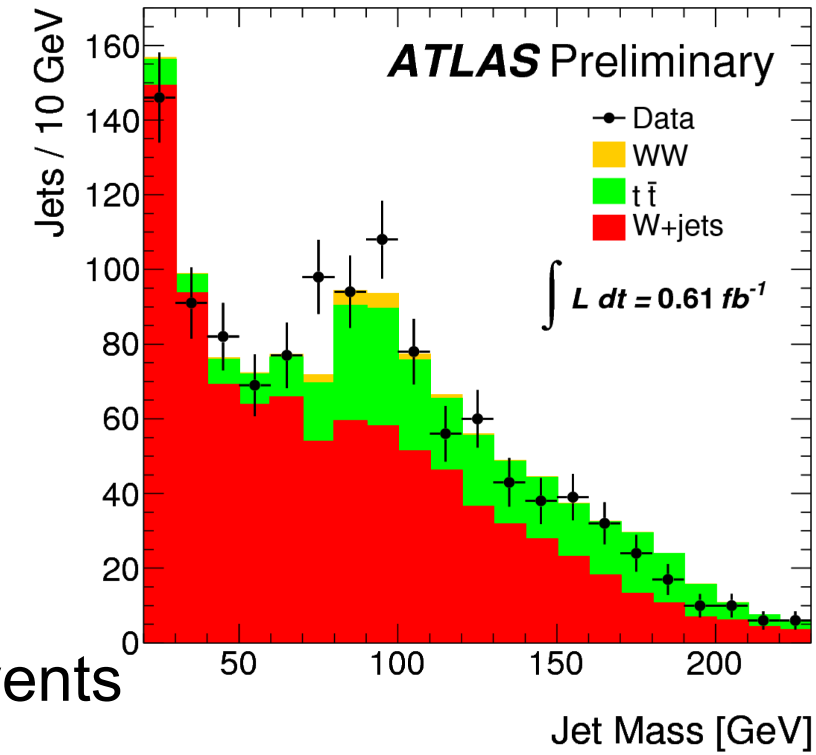
t-tbar events are good candidates to look for heavy particles reconstructed in one fat-jet.

top → Wb → qqb: Three local sub-jets.

Two useful candles:

1) FatJet(qqb): The fat-jet integrates in its catchment area the three quarks.
We expect to have a mass for this jet ~ 170-180 GeV

2) FatJet(qq): The fat jet integrates in its catchment area the two q from W decay.
We expect to have a mass for this jet ~ 70-90 GeV
Seen in MET+lepton+jets(pT>180 GeV) events



ATLAS-CONF-2011-103

The jet mass as observable

Different aspects needs to be under control to use of the jet mass to look for particles reconstructed as a single jet.

The jet mass is a complex QCD observables:

→ In Monte Carlo, non trivial dependence on Parton shower+ non perturbative effects (fragmentation+UE)

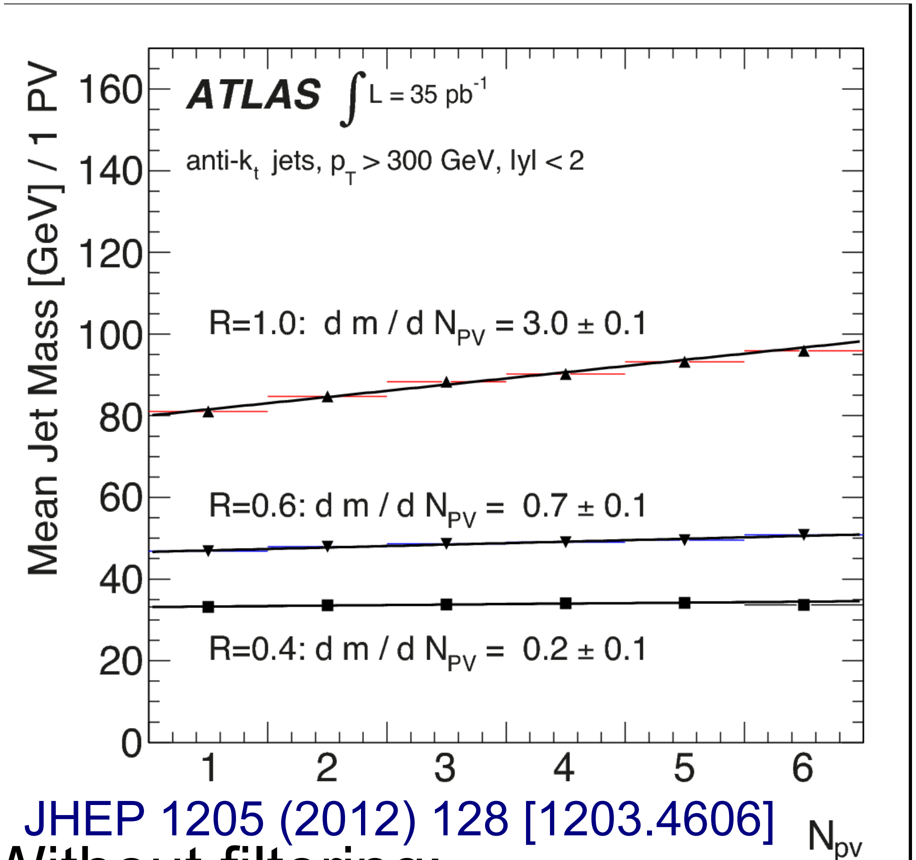
→ At the detector level, the capability to distinguish local deposition depends on the calorimeter granularity and on the size of the hadronic shower in the detector.

→ The particles produced in extra partonic interaction (pile-up) can drastically change the mass.

In the last years different techniques have been developed to overcome these limitations, and some of them have been tested on data

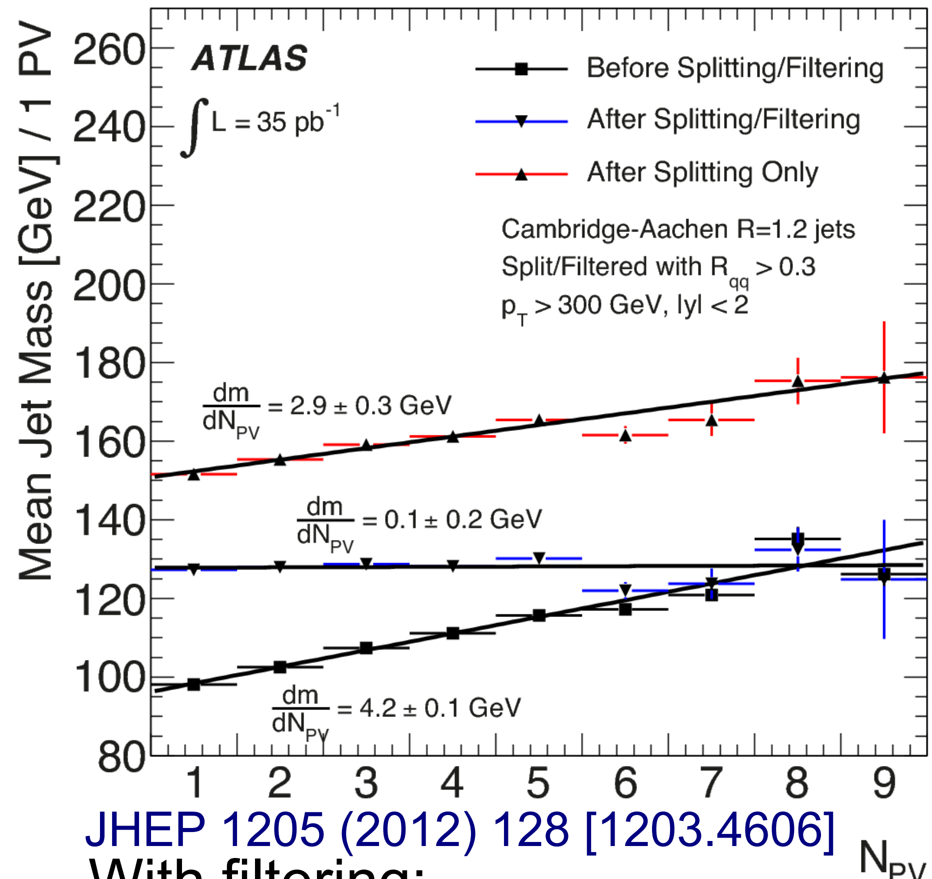
The jet mass in presence of pile-up

Jet filtering: filter away UE and pile-up contamination while retaining hard perturbative radiation from the haevy particle decay (i.e. Higgs).
Phys.Rev.Lett.100:242001,2008 [0802.2470]



JHEP 1205 (2012) 128 [1203.4606]

Without filtering:
Impact of pile-up increase with R



JHEP 1205 (2012) 128 [1203.4606]

With filtering:
Stable mass even for big R

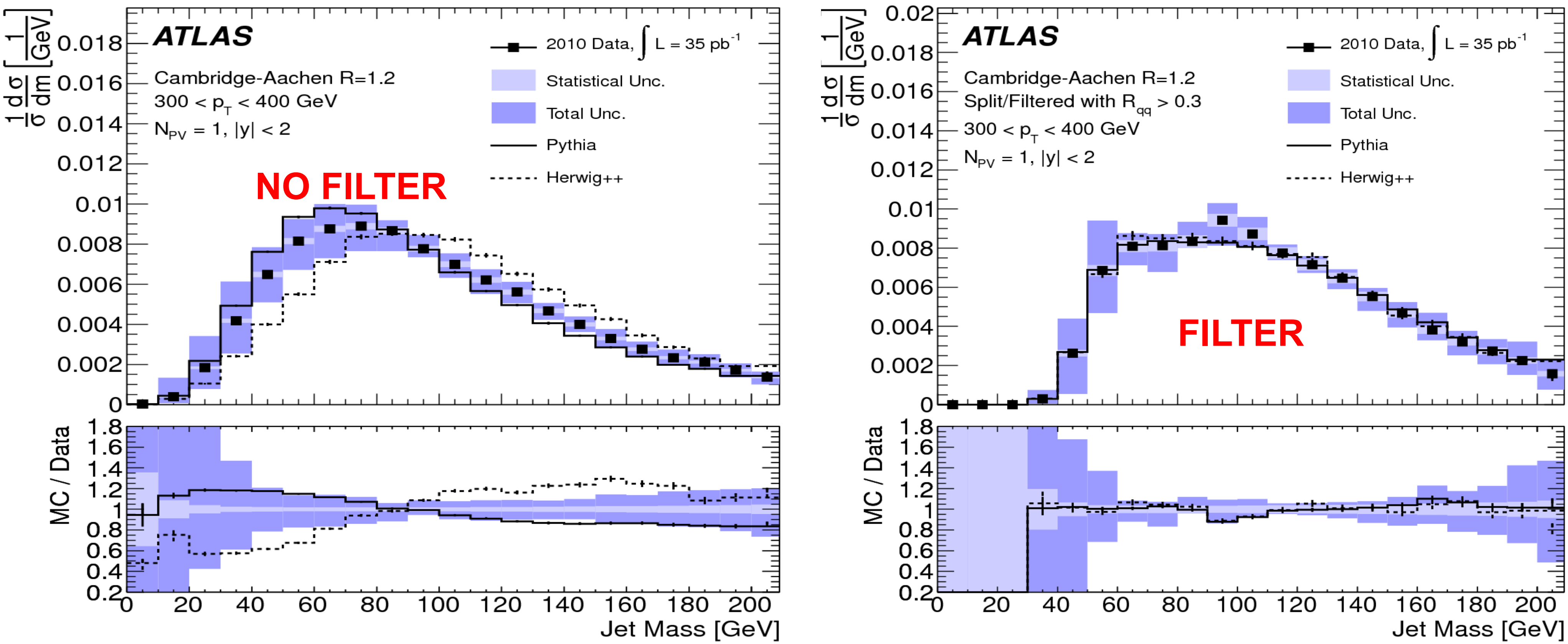
Measuring the QCD jet mass

Mass of single jet: JHEP 1205 (2012) 128 [1203.4606]

→ Validation of the Monte Carlo description;

→ Validation of the filtering techniques on data;

→ Information on parton-shower properties:



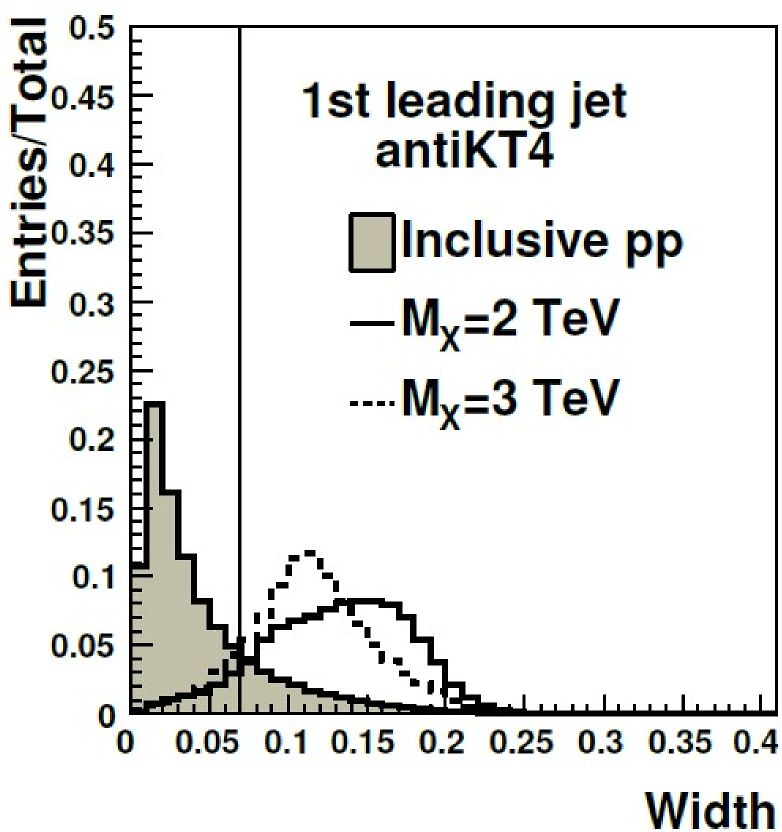
Filtered mass reduces dependence on soft physics

Better agreement data-MC(s)

Jet width

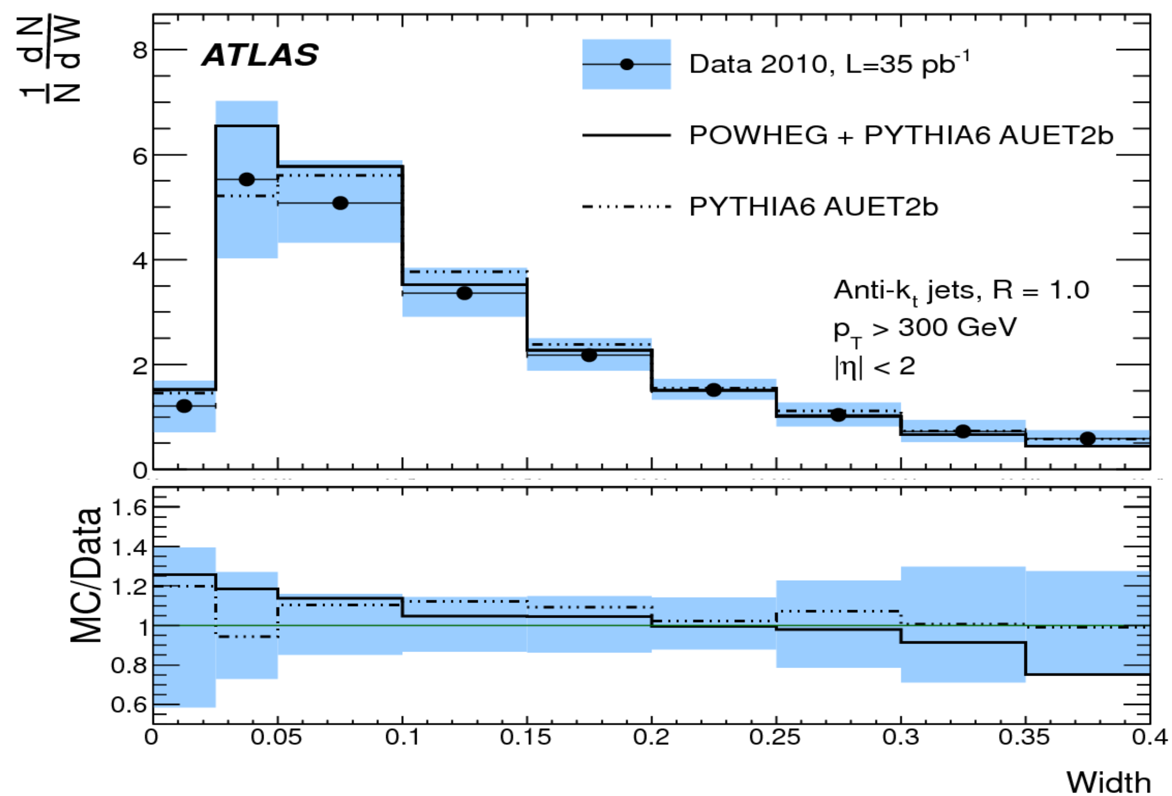
The shape of the jet is giving extra information on its properties, and it can be used to discriminate resonances from QCD jets. Several variable measured in .

Expectation



ANL-HEP-PR-10-2 [1002.3982]

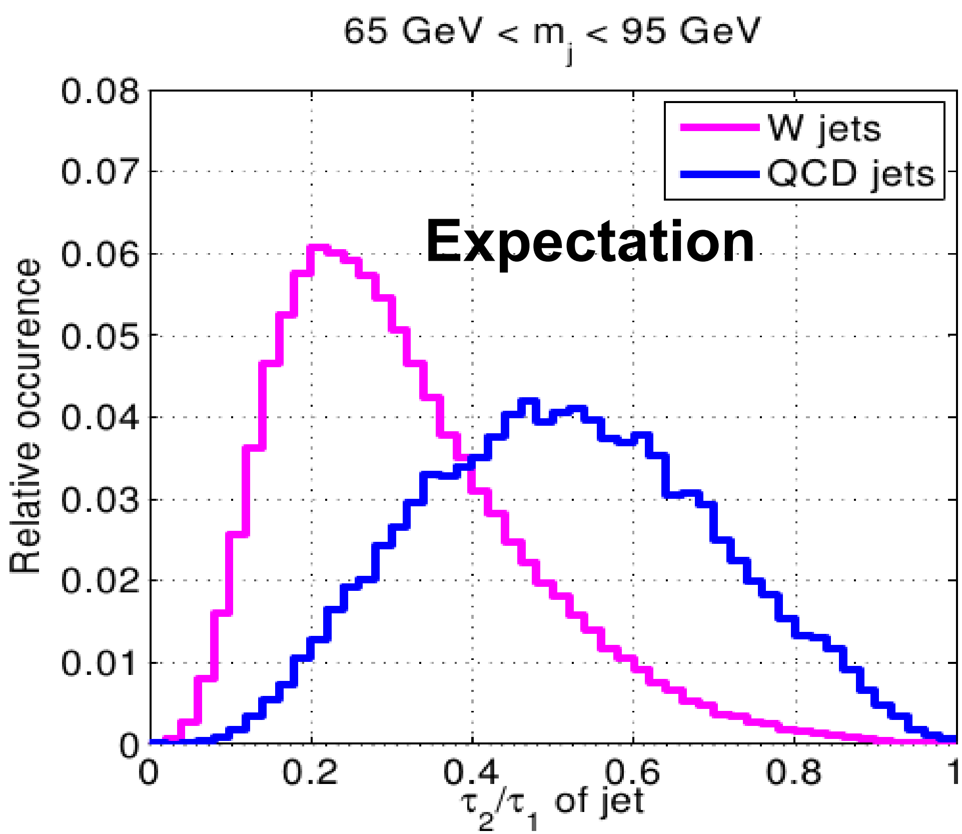
Measurement in QCD jets



ATLAS-CONF-2012-044

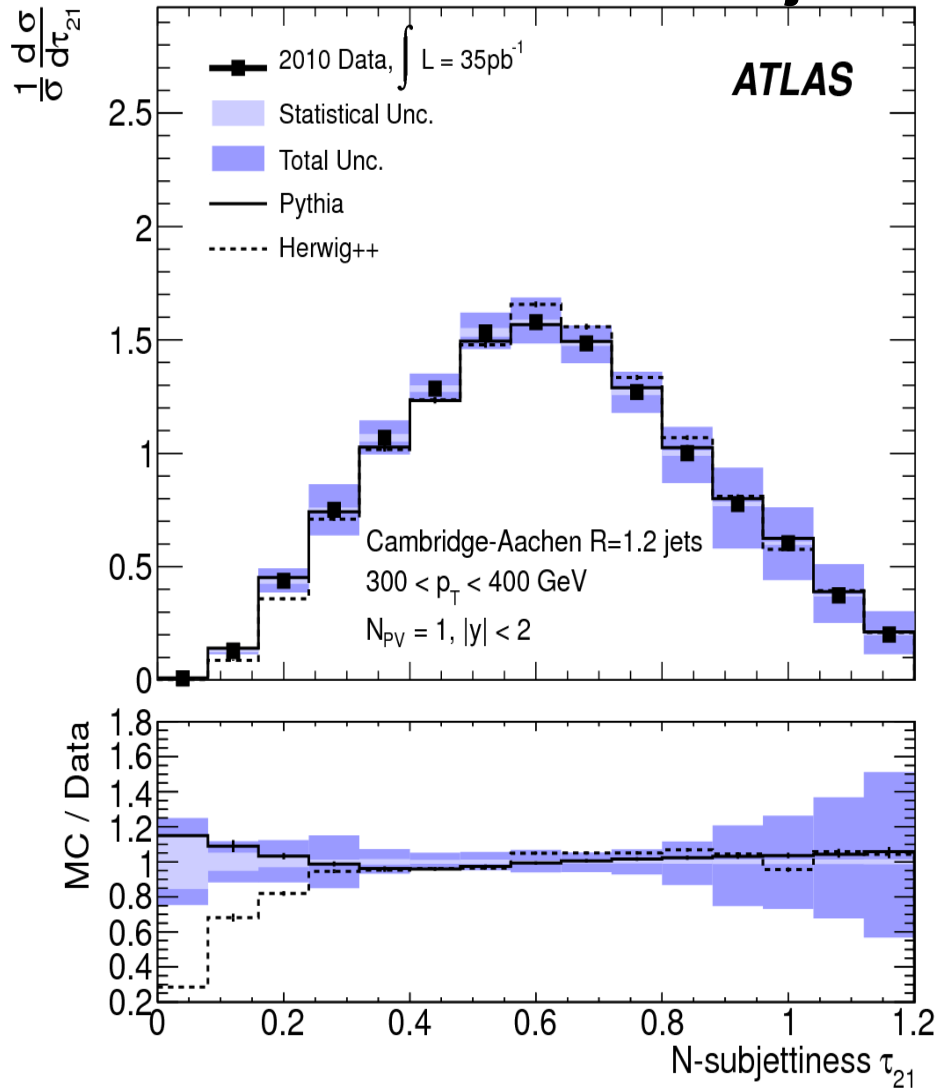
Sub-jetness

τ_n sub-jetness: Testing the hypothesis that a jet is composed by n-subjets, by using its constituents.



JHEP 1103:015,2011 [1011.2268]

Measurement in QCD jets



JHEP 1205 (2012) 128 [1203.4606]

Current MC describes quite well this variable.

A complex use-case: $H \rightarrow b\,\bar{b}$

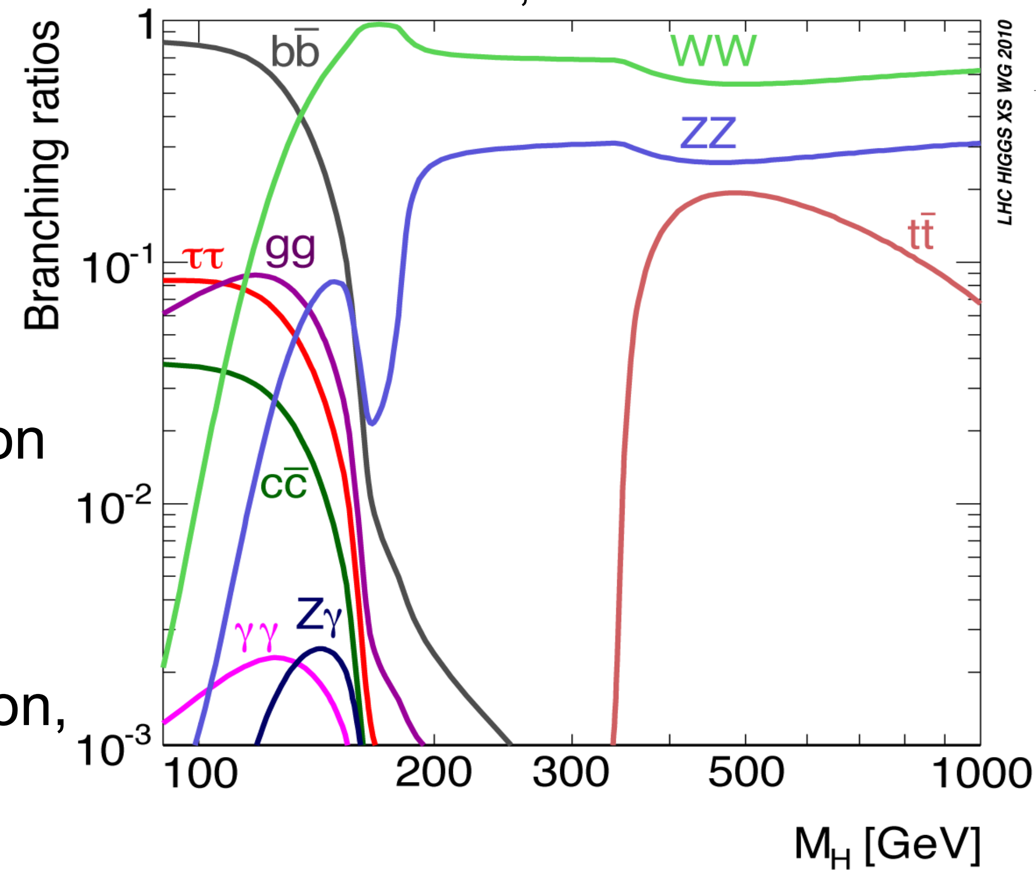
Introduction

H → b b is the dominant decay mode for low masses.

To reduce the QCD background, one can study the associated production with vector bosons **VH**:
WH and ZH.

By requiring a boost for the vector boson, the signal/background increase.

CERN-2011-002; arXiv:1101.0593

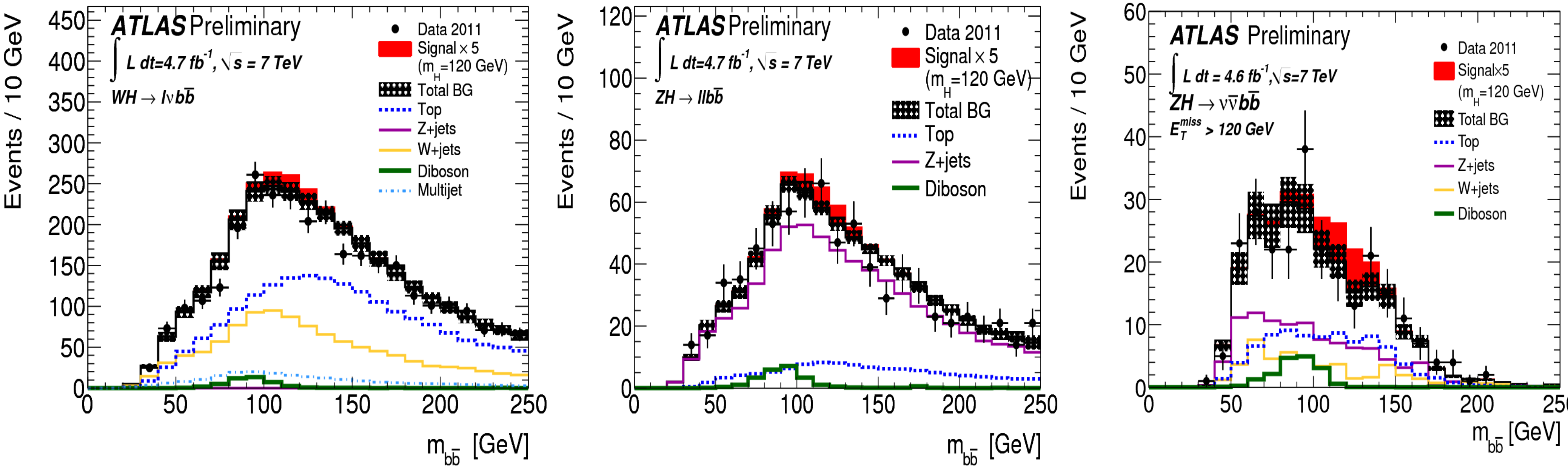


In this way, the b-bbar system start to be in a collimated topology.
One of the channels where analysis with jet substructure tecniques can be really useful.

Several experimental and theoretical aspects enters in the analysis.
They need to be dominated to get the best sensitivity on this channel.

2011 preliminary results

ATLAS-CONF-2012-015



Systematic component	B-tagging	Jets and MET	Background normalization	Theory
	1-10%	2-15%	3-5%	1-20%

Different backgrounds need to be understood.
Experimental systematic uncertainties, and background normalization can be constrained by measuring control region + side bands properties.

Theory uncertainty is mostly dominated by the V p_T uncertainty and the m_{bb} shape variation from different MC predictions.

Questions for “classic” and “sub-jet” analysis

1) how well do we know the truth properties of b-jets:
   → B jet shapes measurement (i.e. in tt events?)

2) The b-bbar system can emit an extra gluon. Is this properly described for the signal and for the background in the Monte Carlo?

3) How well do we simulate the boosted b-bar system:
   We need to model several background, mostly with Monte Carlo.
   Different generators are available, and they could be in disagreement.
   We need to define region where these properties for the boosted b-bar system can be measured and constrained.

4) How well the B hadrons properties in jets are reproduced by MC?
   (we have seen that the D* are not properly simulated).
   How much is this affecting the final result?

Different challenges on these channel. Stay tuned!!

Conclusions

Jet reconstruction and performances:

→ Good understanding of the jet energy scale and resolution
in 2010 and 2011 ATLAS data.

Jet properties:

→ Several measurements used to tune the MC simulations, and to understand the non perturbative effects, such as UE and fragmentation.

Cross section measurements:

→ Good agreement of data and pQCD.
First steps towards precision measurements (i.e. inclusive jet cross section).

Searches with jets:

→ No evidence of new phenomena in inclusive jet finals state → limit setting.

Jet substructure:

→ inclusive QCD substructure measurements:
first milestone for identification of boosted objects.

Improvements in the description of more exclusive final state will “boost” our searches with jet.

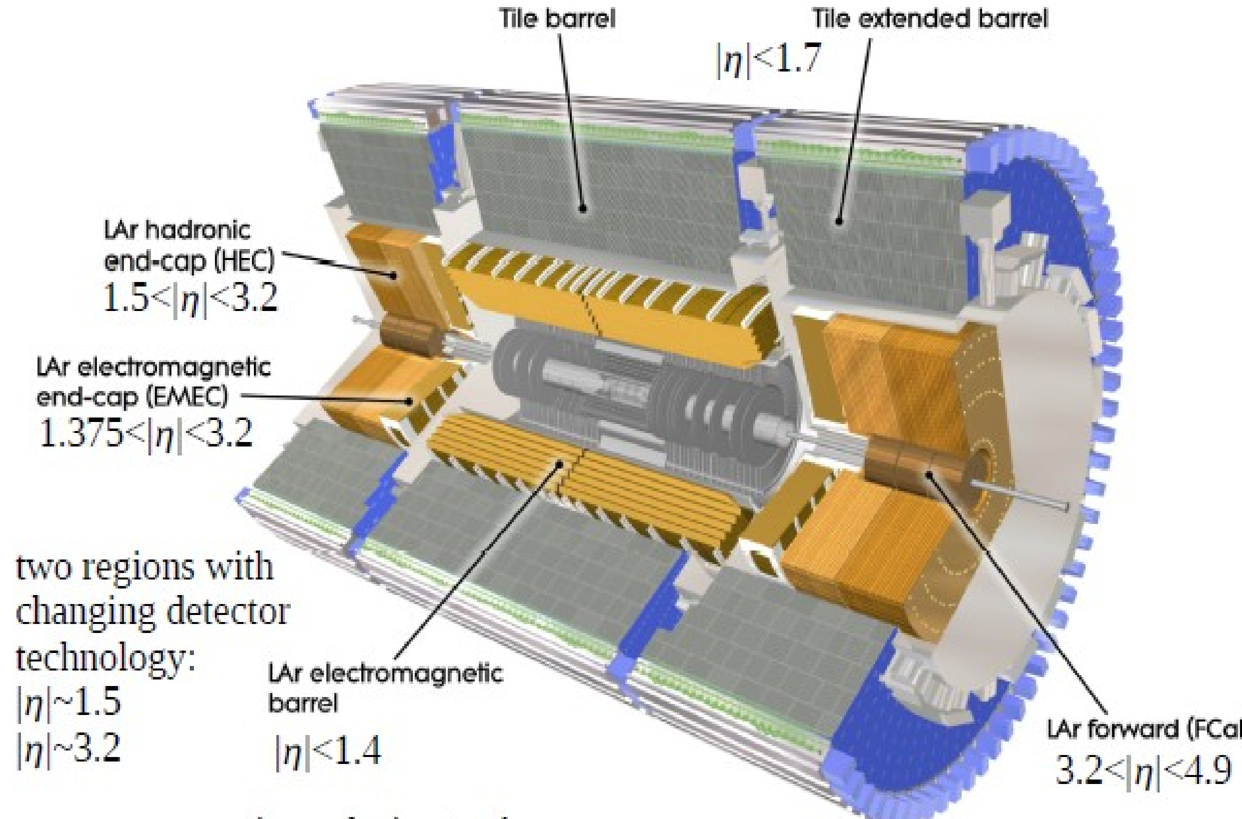
BACKUP

ATLAS Calorimeter System

EM LAr: |η| < 3 - Pb/LAr calorimeter, high resolution for e/γ objects. e/h ~1.7

Central hadronic calorimeter (TileCal): |η| < 1.7: Fe(82%), scintillator (18%) - e/h = 1.36

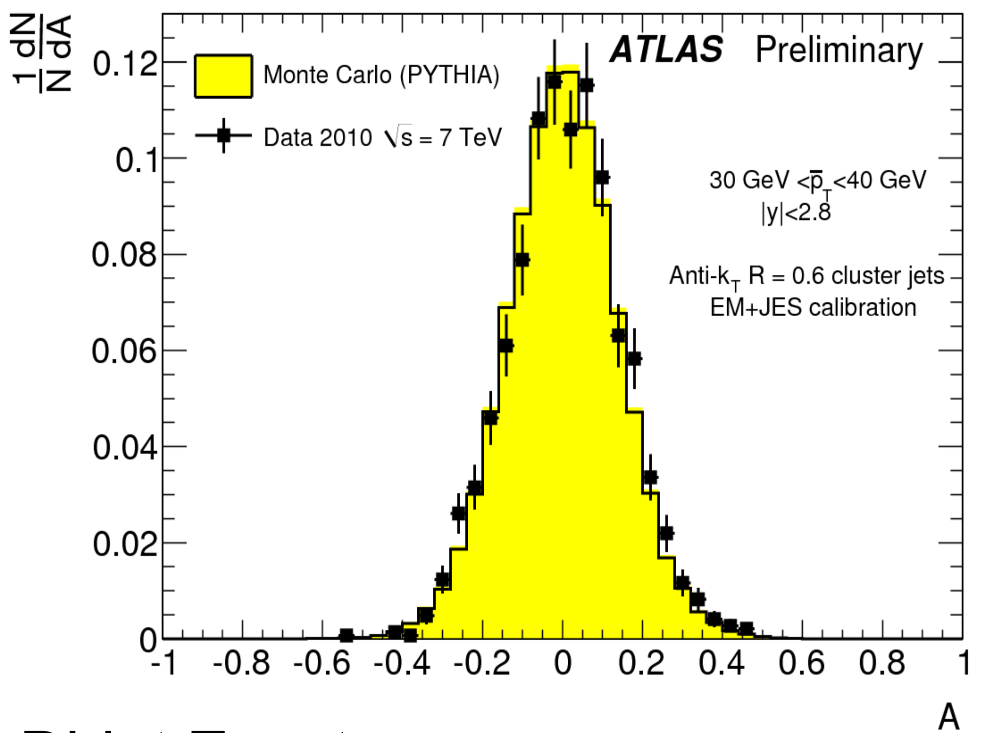
End Cap Hadronic Calorimeter (HEC): 1.7 < |η| < 3.2 - Cu/LAr



Forward calorimeter: 3 < |η| < 4.9. First layer EM (Cu/LAr), the two remaining layers HAD.

Highly hermetical (|η| < 5), non compensating calorimeters.

Jet Resolution



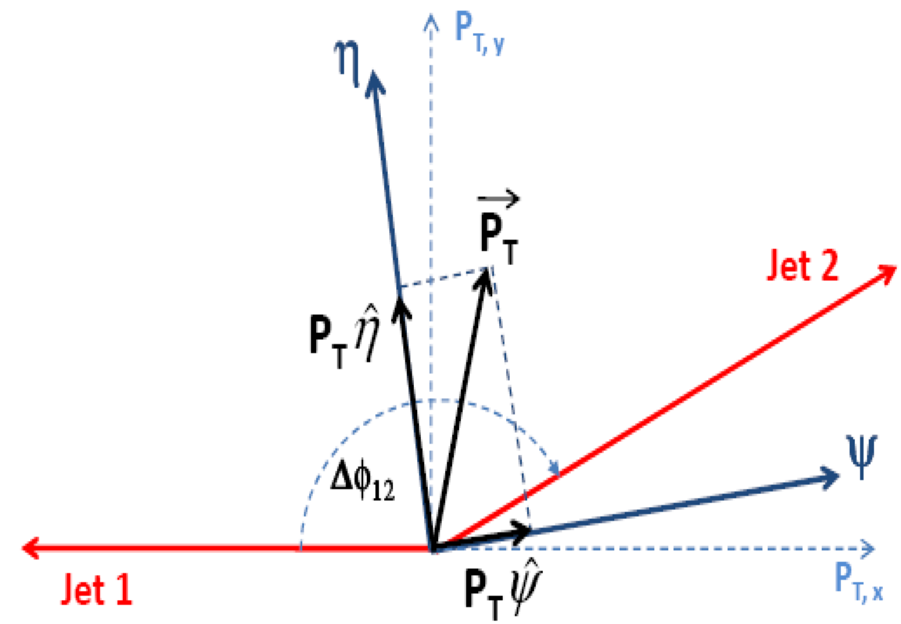
Di-jet Events

$\Delta\varphi>2.8$ and p_T[3rd jet]<10 GeV

$A=(p_T[1]-p_T[2]) / \langle p_T \rangle$

$\sigma(p_T)/p_T=\sqrt{2}\,\sigma_A$

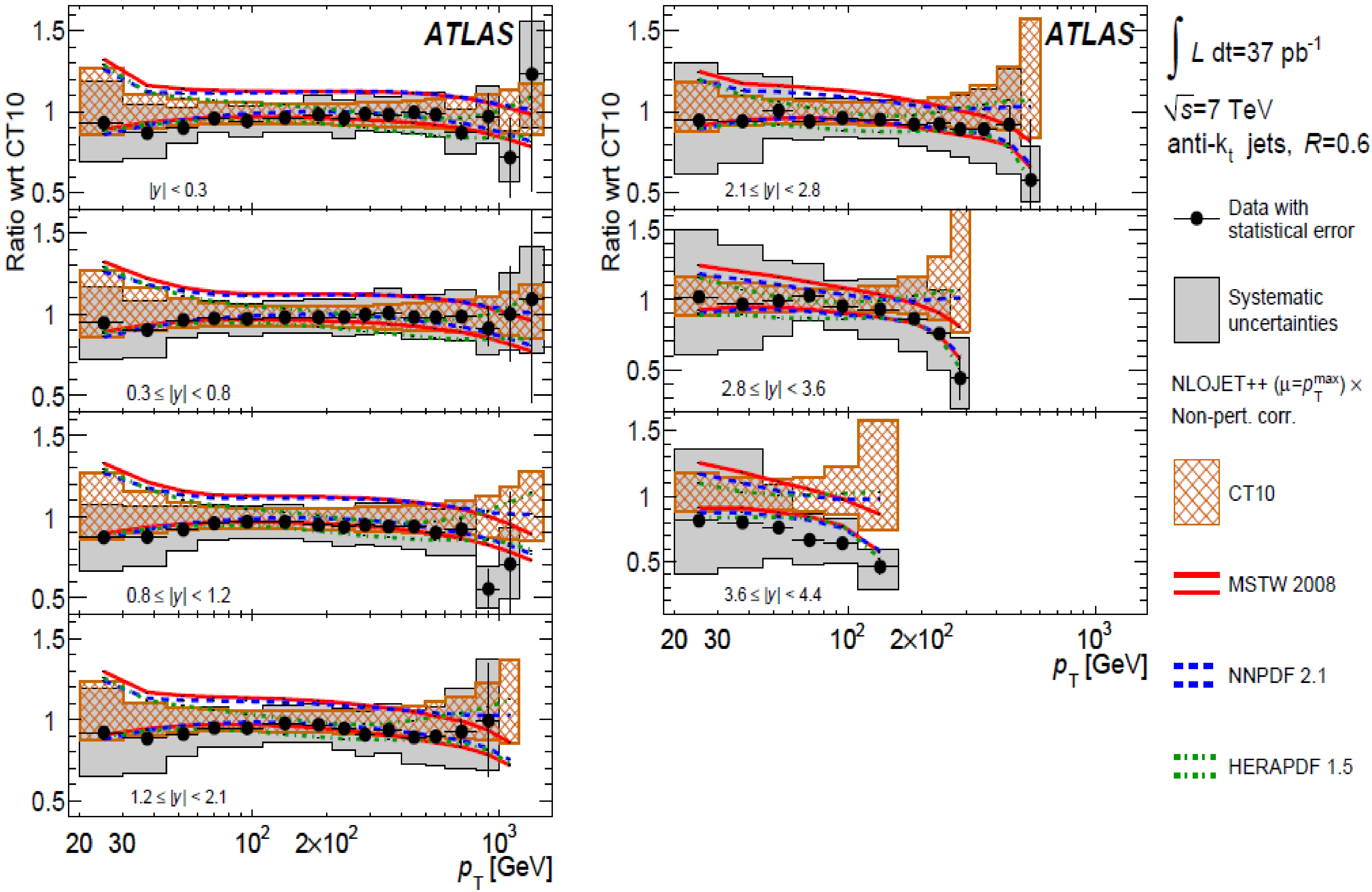
Estimate of the unbalance due to soft radiation.



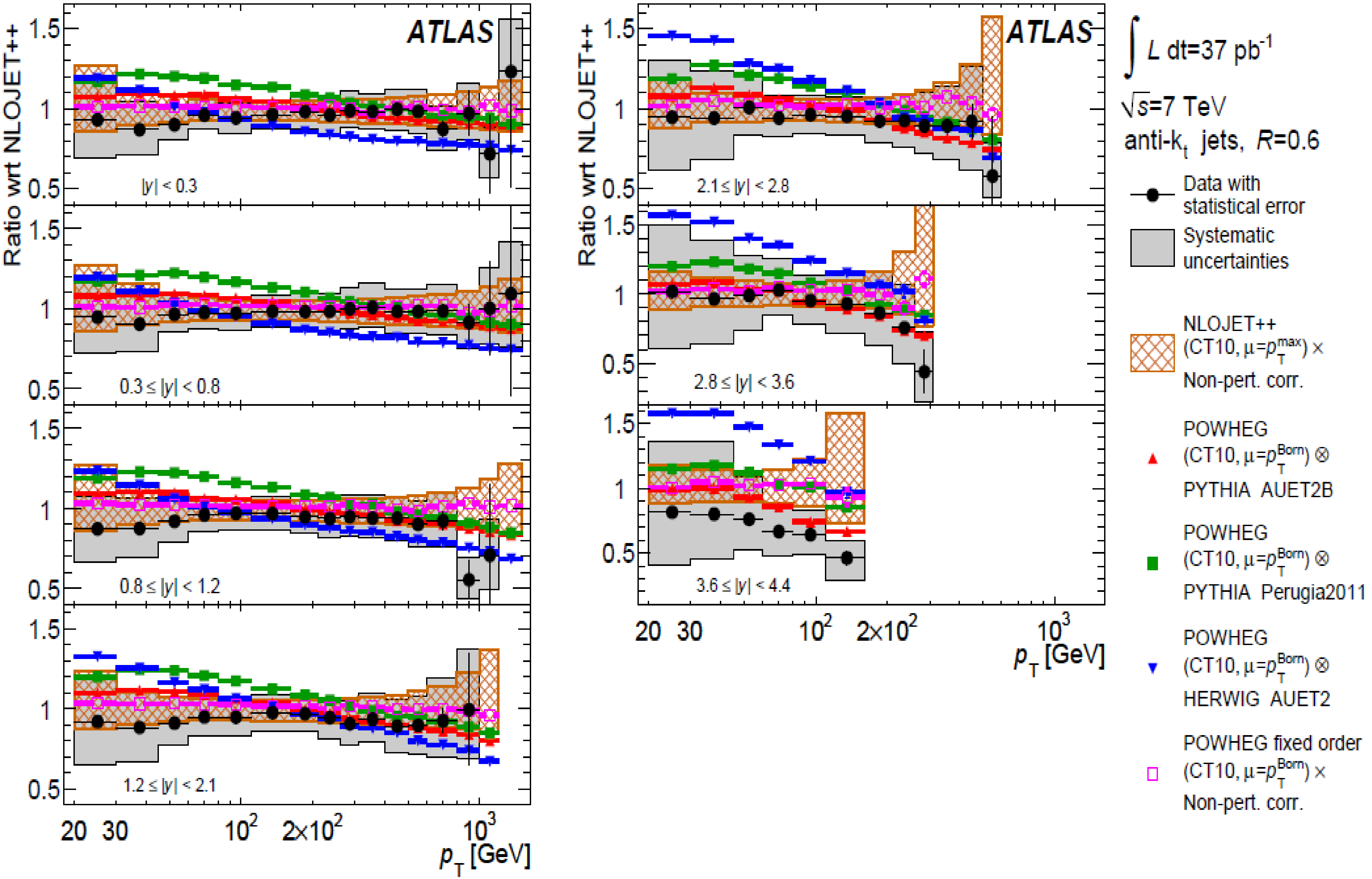
Particle Level: $\sigma_\psi \sim \sigma_\eta \neq 0$ Radiation

Detector Level:

$$\sigma(p_T)/p_T= \frac{\sqrt{(\sigma_\psi^2-\sigma_\eta^2)}}{\sqrt{2}\langle p_T \rangle\,|\cos(\Delta\varphi_{12})|}$$

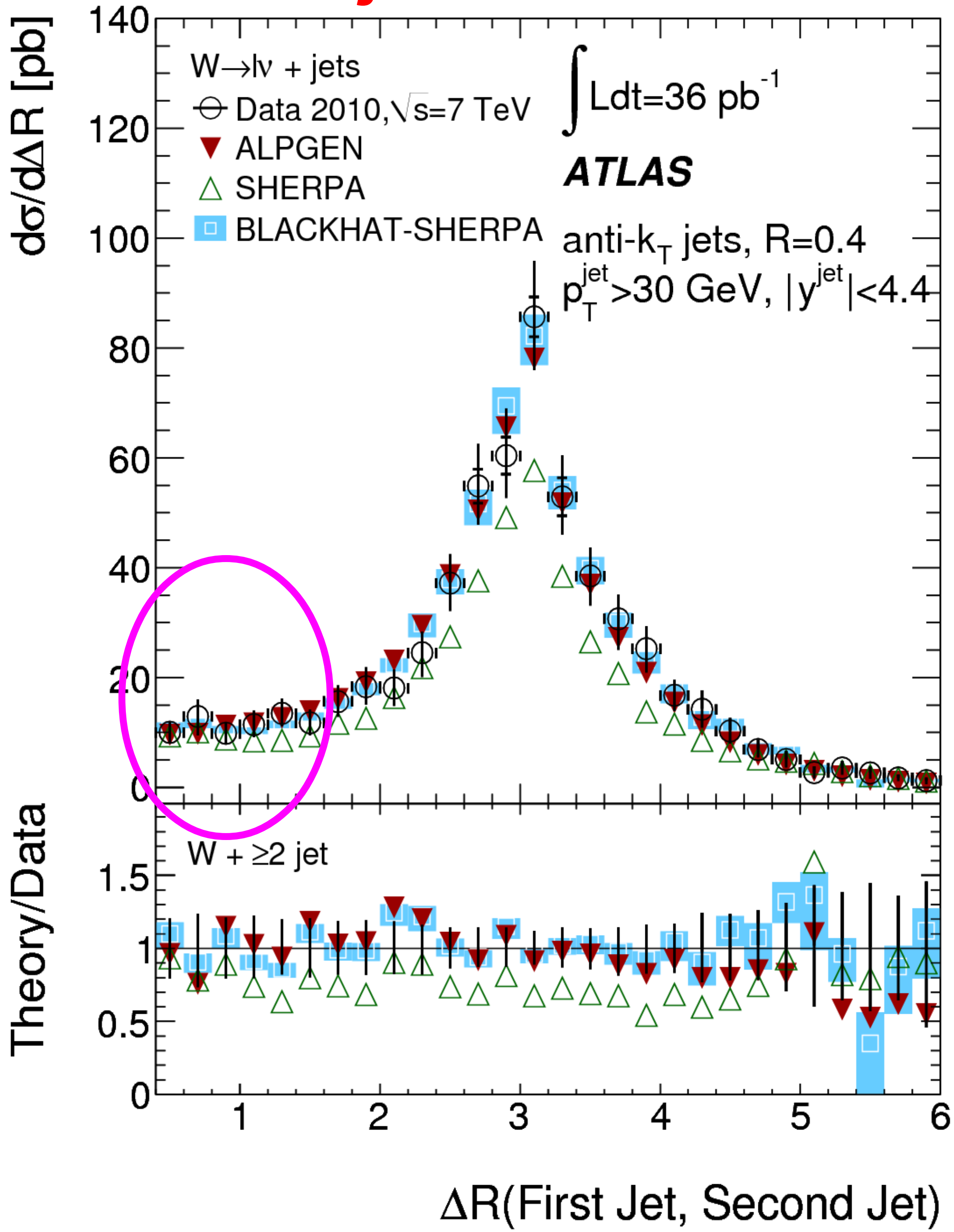


ATLAS
ATLAS
Ratio wrt CT10
|y| < 0.3
0.3 ≤ |y| < 0.8
0.8 ≤ |y| < 1.2
1.2 ≤ |y| < 2.1
2.1 ≤ |y| < 2.8
2.8 ≤ |y| < 3.6
3.6 ≤ |y| < 4.4
p_T [GeV]
$\int L\, dt$=37 pb^{-1}
$\sqrt{s}$=7 TeV
anti-k_t jets, R=0.6
Data with statistical error
Systematic uncertainties
NLOJET++ ($\mu=p_T^{max}$) × Non-pert. corr.
CT10
MSTW 2008
NNPDF 2.1
HERAPDF 1.5

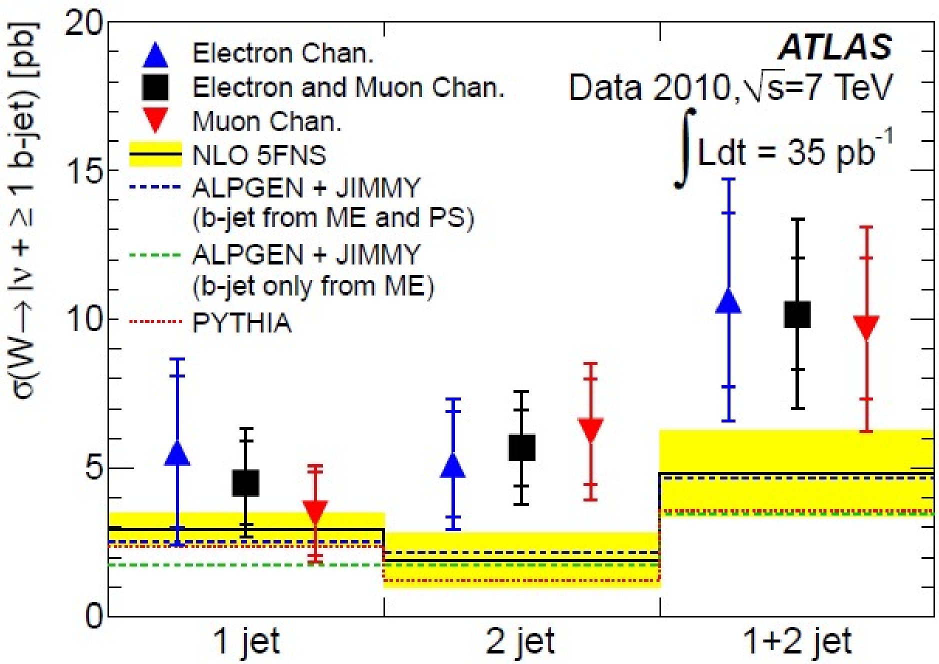


ATLAS
Ratio wrt NLOJET++
|y| < 0.3
0.3 ≤ |y| < 0.8
0.8 ≤ |y| < 1.2
1.2 ≤ |y| < 2.1
2.1 ≤ |y| < 2.8
2.8 ≤ |y| < 3.6
3.6 ≤ |y| < 4.4
p_T [GeV]
∫ L dt=37 pb^-1
√s=7 TeV
anti-k_t jets, R=0.6
Data with statistical error
Systematic uncertainties
NLOJET++ (CT10, μ=p_T^max) × Non-pert. corr.
POWHEG (CT10, μ=p_T^Born) ⊗ PYTHIA AUET2B
POWHEG (CT10, μ=p_T^Born) ⊗ PYTHIA Perugia2011
POWHEG (CT10, μ=p_T^Born) ⊗ HERWIG AUET2
POWHEG fixed order (CT10, μ=p_T^Born) × Non-pert. corr.

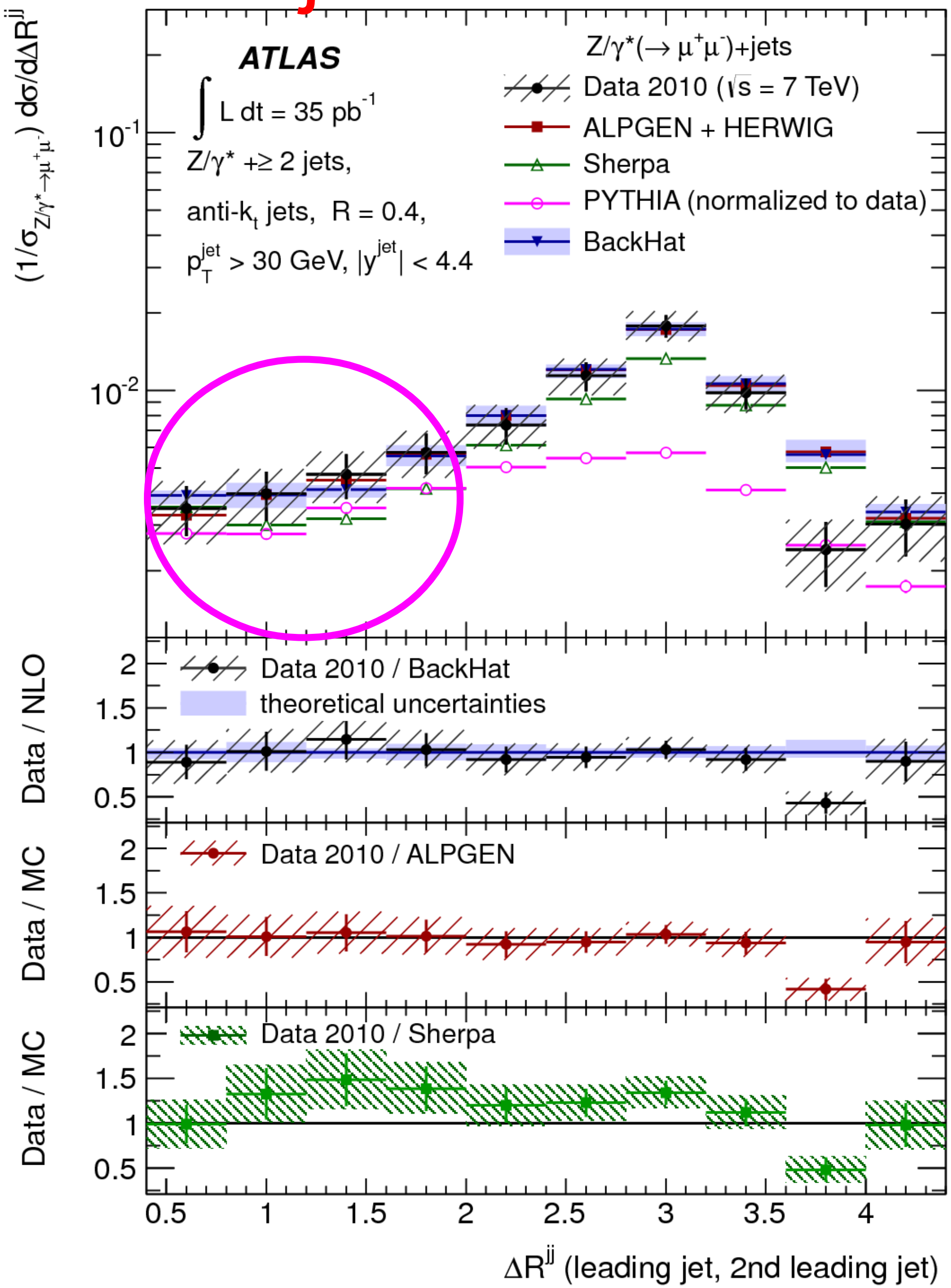
W+j cross section



Wb cross section



Z+j cross section



Zb cross section