Measurements used to tune MC generators

multi-jets (event shapes), color coherence,
cross section ratio with different cone-sizes

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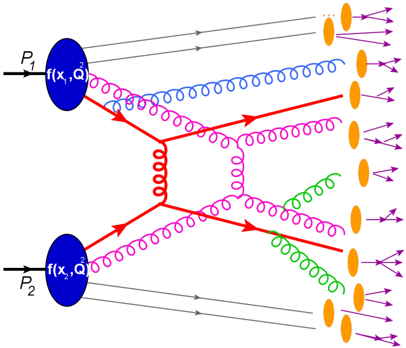
Introduction

The simulation is a multistep process starting with

- Matrix Element calculation

and continuing through the

- Parton Showers
  - Initial State Radiation (ISR)
  - Final State Radiation (FSR)
- Underlying Event (UE)
  - Beam remnants (BR)
  - Multi Parton Interactions (MPI)
- Hadronization
- Hadron decays



$$\sigma_{hadron} = \sigma_{parton} \otimes PDF$$

Input for Monte-Carlo simulation

MC generators combine *perturbative* picture of hard processes involving electroweak and strong interactions, with *non-perturbative* picture of hadronization and underlying event.

Perturbative parameters

- **Factorization/renormalization scales**
  process specific
- **Particle properties**
  masses, widths,..
- **Running couplings**
  consistent with PDF
- **Parton shower**
  evolution kernels

Are chosen/calculated

Non-perturbative parameters

- **MPI and BR**
  p_T^{min} cut-off, energy dependence, ...
- **Hadronization and hadron decays**
  string or cluster constants
- **Primordial k_T**
  intrinsic k_T of incoming partons
- **Parton shower**
  infrared cut-off, $\alpha_s/\Lambda_{\text{QCD}}$

Unknown $\rightarrow$ Need experimental input

rivet.hepforge.org
professor.hepforge.org

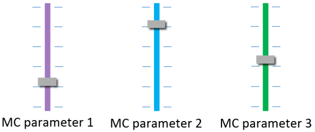
1 RIVET

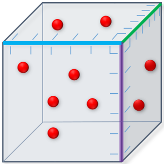
- Framework for generator independent implementation of experimental measurements.
- Uses data available from the HEPDATA database.
- Currently 322 RIVET routines are available,
  including 105 from ATLAS and 36 from CMS!

=> First step to MC tuning is implementation of your measurement in RIVET!

2 PROFESSOR

- Framework for automated Monte-Carlo tuning.
- Random sampling → Filling → Interpolation → Minimization





MC generators and tunes for LHC

The LHC measurements have been used to tune a number of Monte-Carlo generators. The tuning efforts are made to improve modeling **UE**, **MB** and **MPI** processes.

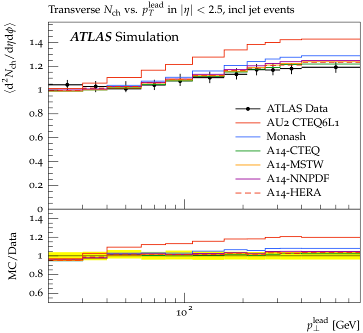
- PYTHIA6: contains a large collection of tunes from authors and LHC experiments
- PYTHIA8: majority of recent tunes from LHC experiments
- POWHEG+PYTHIA: Pythia tunes in presence of NLO+PS matching
- HERWIG/JIMMY: tuned by both authors and LHC experiments
- SHERPA: mainly tuned by authors

Recent MC tunes from ATLAS and CMS

Underlying Event tunes

- Family of **A14** full-scale tunes[1] with various PDFs to most ATLAS jet and underlying-event observables.

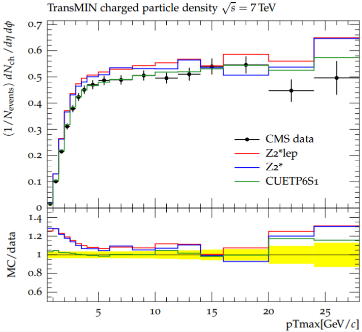
- Optimized MPI and ISR/FSR parameters.



→ Tunes are suitable for high p_T processes.

→ Improved description of UE data, $t\bar{t}$ gap fractions, and 3-to-2 jet ratios.

- CUETP8M1 (MonashStar[1]), CUETP8S and CUETP6S - tunes[2,3] with various PDFs, include CDF and CMS UE data at $\sqrt{s} = 0.9$, 1.96 and 7 TeV.

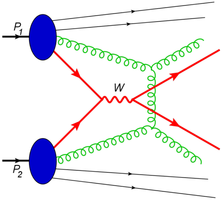


→ Test model of MPI energy dependence.

→ Attempt to describe "soft" and "semi-hard" MPI scatterings.

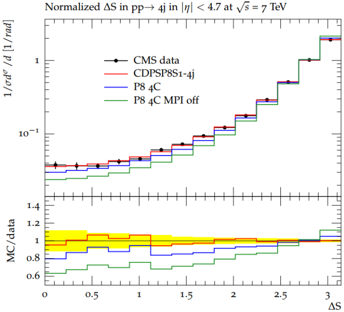
[1] based on Monash2013 tune: MB+AU   [2] based on 4C tune   [3] based on Z2*-lep tune

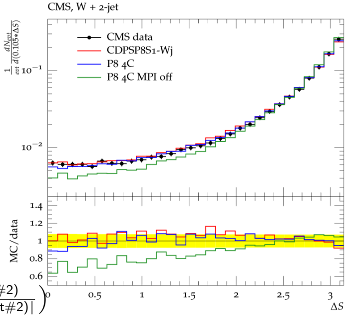
Tuning Double Parton Scattering (DPS) observables



DPS is typically described in terms of effective cross-section parameter

$$\sigma_{\rm eff} = \frac{\sigma_A \sigma_B}{\sigma_{AB}}$$





CDPSTP8S PYTHIA8 tunes - make use of double parton scattering measurements:

- Study of double parton scattering using **W+2-jet** events. CMS: JHEP 1403 (2014) 032
- Measurement of **four-jets** production. CMS-FSQ-12-013

- DPS observables are used to tune **MPI** and **Beam Remnants** parameters.

- The values of $\sigma_{\rm eff}$ extracted with DPS tunes are compatible with experimental measurements.

CMS PAS GEN-14-001

$$\Delta S = arccos\left(\frac{p_T(\text{object}\#1)\cdot p_T(\text{object}\#2)}{|p_T(\text{object}\#1)|\times|p_T(\text{object}\#2)|}\right)$$

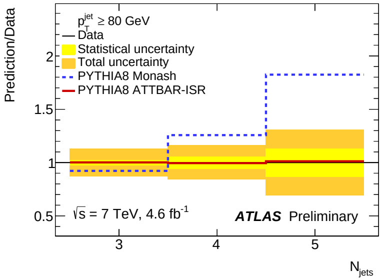
Modeling of $t\bar{t}$ production is sensitive to ISR and FSR and is crucial for precision m_t measurement.

Recent **ATTBAR** tune[1,2] is based on three $t\bar{t}$ measurements:

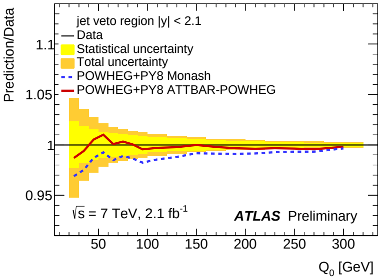
see talk by Liza Mijovic

- Differential $t\bar{t}$ cross-sections as functions of jet multiplicity and jet p_T. ATLAS: JHEP 1501 (2015) 020
- $t\bar{t}$ production with a veto on additional central jet activity (Gap-fraction measurements). ATLAS: Eur. Phys. J. C72(2012) 2043
- Jet shapes in $t\bar{t}$ events. ATLAS: Eur. Phys. J. C73 (2013) 2676

PYTHIA8



POWHEG+PYTHIA8



Gap fraction as a function of threshold Q_0

ATL-PHYS-PUB-2015-007

[1] based on Monash2013 tune: MB+AU

[2] based on 4C tune

Further directions

First LHC measurements already used as input for tuning.
To refine the tunes one can look more in detail at the event topology.

Experimental areas providing input for further MC tuning:

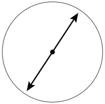
- Event shape variables in multi-jet events
  $\rightarrow$ sensitive to pQCD and non-perturbative aspects of QCD
- Color Coherence
  $\rightarrow$ sensitive to modelling of QCD correlations
- Jets cross-section with different cone sizes
  $\rightarrow$ sensitive to modeling of perturbative radiation, hadronization and UE

Event shapes in multi-jet events

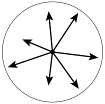
Event shape variables are geometric properties of the energy flow in hadronic final-states.

- Multi-jet events with large momentum transfer.
- Event shape variables are defined to have a maximum for uniformly distributed energy within a multi-jet event:

  Transverse thrust $\tau_T \equiv 1 - \max_{\hat{n}_T} \frac{\sum_i |\boldsymbol{p}_{T_i} \cdot \hat{n}_T|}{\sum_i p_{T_i}}$



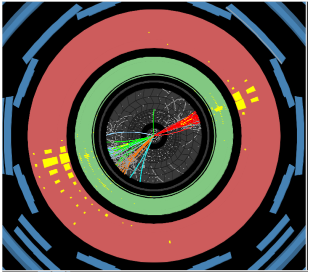
For perfectly balanced two-jets event $\tau_T = 0$

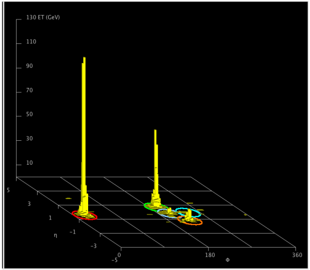


In limit of isotropic multi-jets event $\tau_T = 1 - 2/\pi$

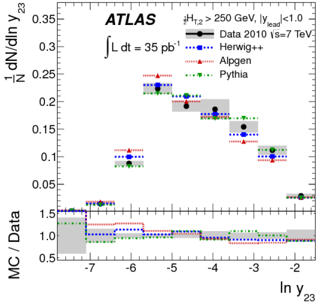
- Jet broadening B_X
- Jet masses ρ_X
- Sphericity S
- Aplanarity A
- Third-jet resolution parameter y_{23}

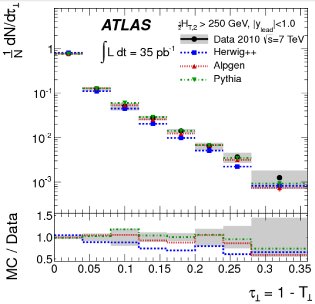
$\rightarrow$ Event shape variables are sensitive to the structure of QCD radiation.





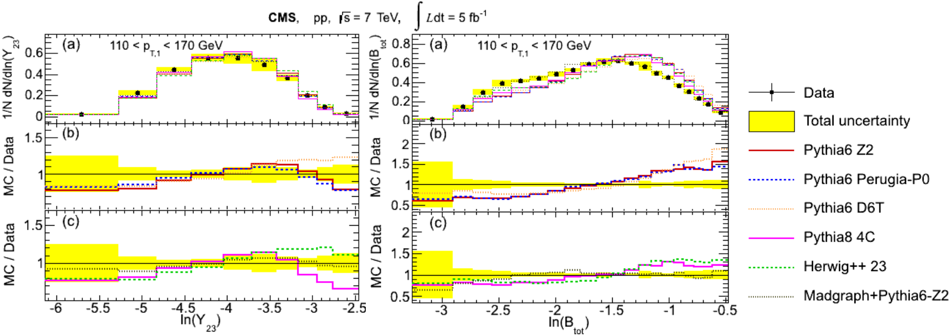
Measurements of event shape variables in multi-jet events





ATLAS *EPJC 72 (2012) 2211*
CMS *JHEP 10 (2014) 087*

- Reasonable agreement with Pythia predictions.
- Best description is given by Madgraph.

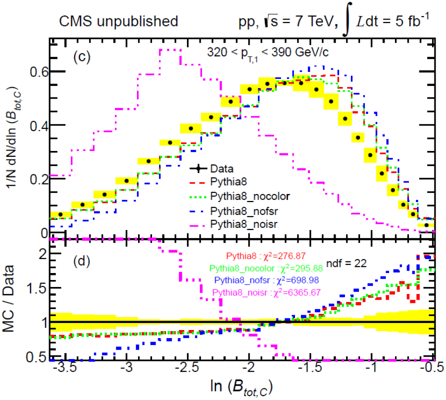


Sensitivity of event shape variables in multijet events

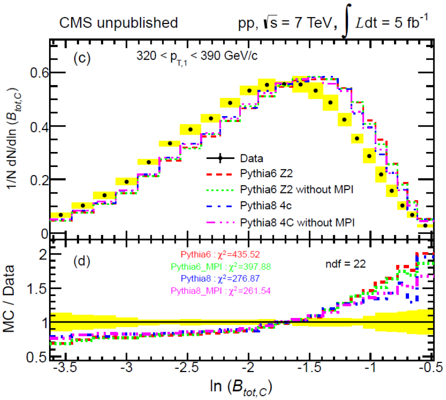
→ Rivet: CMS_2011_S8957746

- Modeling of **color connection** effects between soft scatters and beam remnants, **ISR**, and **FSR** are the *major sources of the discrepancies* between the data and the simulation.
- Jet Broadening is sensitive to ISR, FSR and color coherence effects.
- τ_T is sensitive to ISR/FSR and insensitive to MPI and color coherence effects.

Effect of ISR, FSR and color connection

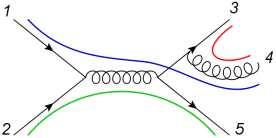


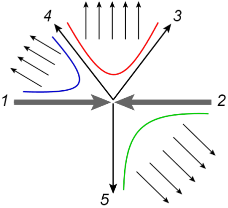
Effect of MPI



Color Coherence

Color coherence effects: interference of soft gluon radiation emitted along color-connected objects.

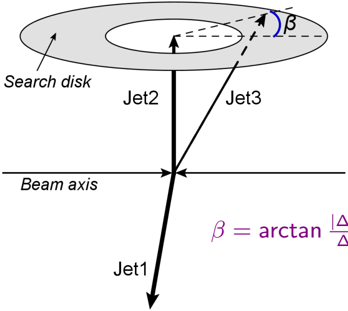




Previously observed in e^+e^- and $p\bar{p}$ collisions.

Experimental signature:

- Events with at least **3 jets**.
- Two leading jets are back-to-back.
- Relative abundance of soft radiation in the region between color-connected final-state partons.



$$\beta = \arctan \frac{|\Delta\phi_{23}|}{\Delta\eta_{23}}$$

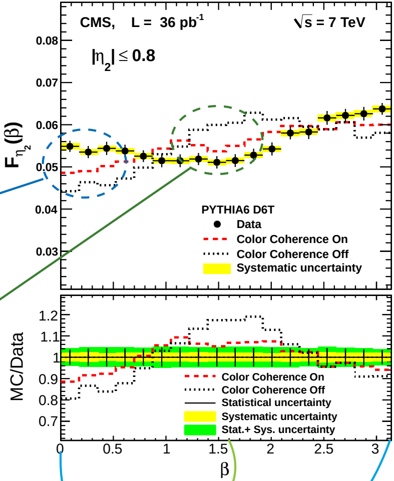
$\rightarrow$ Measure the angular correlation between the 2d and softer 3d jet in the event.

$$\phi_{23} = \phi_3 - \phi_2$$
$$\eta_{23} = \text{sign}(\eta_2)\cdot(\eta_3 - \eta_2)$$

Probe of color coherence effects in multi-jet events

Three leading jets are ordered by their p_T: $p_{T_1} > p_{T_2} > p_{T_3}$ *Eur. Phys. J. C (2014) 74:2901*

$$p_{T_1} > 100 \text{ GeV}, \; p_{T_3} > 30 \text{ GeV}$$
$$0.5 < \Delta R_{23} < 1.5$$
$$M_{12} > 220 \text{ GeV}$$
$$|\eta_1|, |\eta_2| \leq 2.5$$



In presence of color coherence

- along the event plane (in particular near $\beta \approx 0$) third jet population is enhanced.
- out of event plane (where $\beta \approx \pi/2$) third jet population is suppressed.

$\beta = \frac{\pi}{2}$
$\eta_2 = \eta_3$

$\beta = 0, \pi$
$\phi_2 = \phi_3$

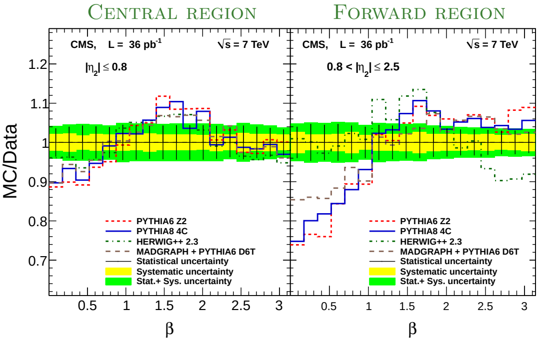
- Variable β is sensitive to color coherence effects.
- Pythia predictions with color coherence effects improve description of the data, although predicted effects are not as strong as observed in data.

Color coherence in Monte-Carlo generators

Herwig++: implements color coherence effects through explicit angular ordering of parton emission using the coherent branching algorithm.

→ central region: describes the data *better* than the other MC generators.

→ forward region: discrepancies at high β.



Pythia: color coherence effects through angular ordering veto algorithm in initial and final-state showers (can restrict angle of the branching).

MadGraph+Pythia: $2 \to \underline{3}$ LO ME + PS, color coherence for hard jets at LO is coming from the exact QCD color amplitudes in the model.

- None of the models describe the data satisfactorily.
- Data clearly support **larger color coherence effects** than in present MC implementations.
- Further study of color coherence models of Monte-Carlo generators is needed.

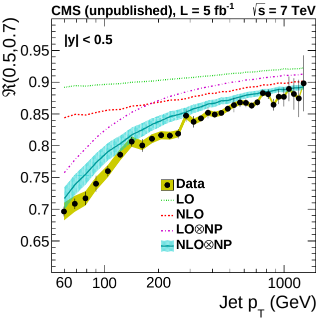
→ Rivet: CMS_2013_I1265659

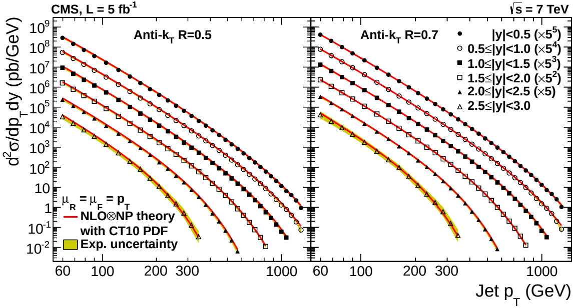
Jets cross-section with different cone sizes

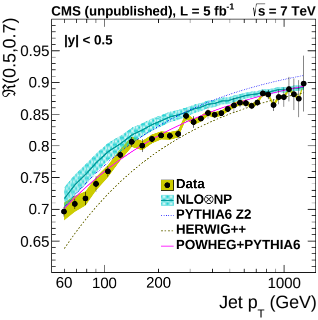
- $\sqrt{s} = 7$ TeV data, $L = 5\text{fb}^{-1}$.
- Measurements of inclusive jet cross-section with $R = 0.5$ and $R = 0.7$.

$$R(0.5, 0.7) = \left(\frac{d\sigma^{(0.5)}}{dp_T} - \frac{d\sigma^{(0.7)}}{dp_T}\right) / \left(\frac{d\sigma^{(0.7)}}{dp_T}\right) + 1$$

- **Ratio** of the measurements as a function of jet rapidity and transverse momentum.
- Ratio below unity due to QCD radiation, effect vanishes at high p_T.







- Choice of the jet radius parameter R determines which aspects of jet formation are emphasized: perturbative radiation / hadronization / UE.
- *Dependence on the jet radius* is generated through **parton showering**, **hadronization** and **UE**.

NLO $\otimes$ NP vs. POWHEG+PYTHIA6

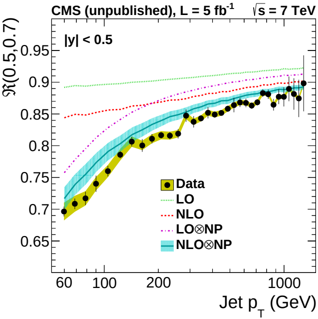
- Modeling of non-perturbative (NP) effects is crucial for describing data.

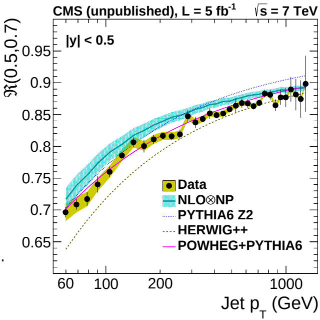
$$C^{NP}_{NLO(LO)} = \frac{\sigma_{NLO(LO)+HAD+MPI}}{\sigma_{NLO(LO)}}$$

- Best description is given by POWHEG+PYTHIA6.

Input for MC tuning

- Detailed look into the *pattern of QCD radiation*.
- Advantage of using *ratio* compare to separate measurements:
  - Cancellation of systematic uncertainties in the ratio $\rightarrow$ more **stringent test** of the theoretical predictions.
  - **Interplay of QCD effects** at different R.





Summary

- ATLAS and CMS jet measurements → many observables studied.
- Most of the measurements are implemented in RIVET.
- Monte-Carlo **tuning results** show significant improvement in description of UE, MPI and hard-scattering processes.
- Valuable input for MC tuning:
  - Events shapes variables provide good sensitivity to the structure of QCD radiation.
  - Color coherence effects are not described by MC at desirable level → larger coherence effects are supported by data.
  - Inclusive jet cross-section with different radius parameter values is sensitive to perturbative effects from parton showers and non-perturbative effects from hadronization and underlying event.

Backup slides

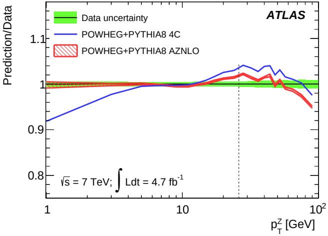
Tunes to Z-boson transverse momentum measurements

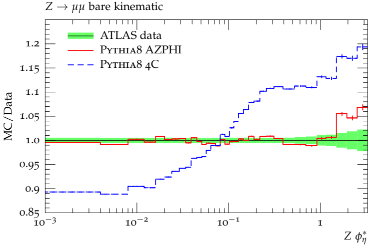
- AZ, AZPHI and AZPHINLO tunes aiming to describe transverse momenta spectrum of Z boson production (p_T, ϕ^*).
  PYTHIA8, POWHEG+PYTHIA8, PYTHIA6, POWHEG+PYTHIA6

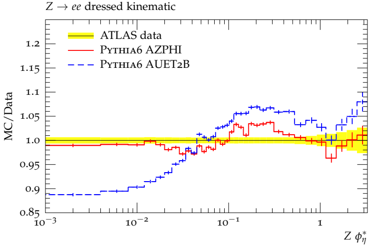
ATL-PHYS-PUB-2013-017
JHEP09(2014)145

Tunes are base on ATLAS measurements:

- Angular correlations in Drell-Yan lepton pairs to probe Z-boson transverse momentum. Phys.Lett.B720(2013)3251
- Measurement of the Z/γ^* boson transverse momentum distribution.

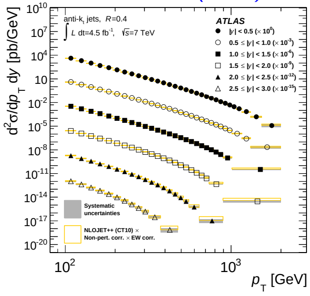


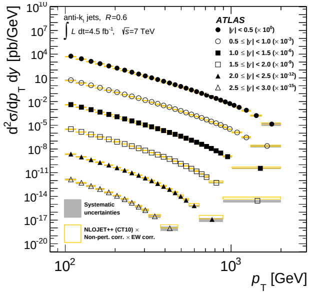


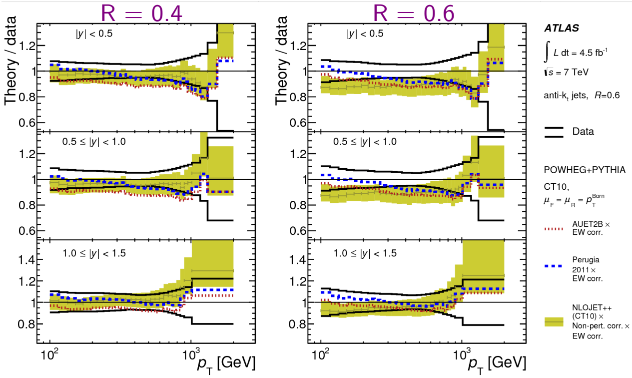


Jet cross-section with different cone sizes

ATLAS *JHEP02(2015)153*



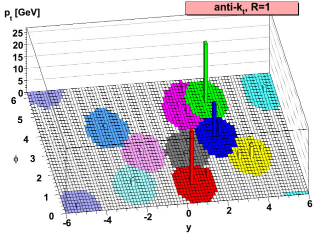




- Jet radius parameters: R=0.4 and R=0.6.
- Corrections for electroweak and non-perturbative effects from **hadronization** and the **underlying event**.
- NLOJET++ predictions are systematically *lower for R=0.6*, compare to R=0.4.
- POWHEG+PYTHIA6 predictions describe both, R=0.4 and R=0.6 in a similar way.

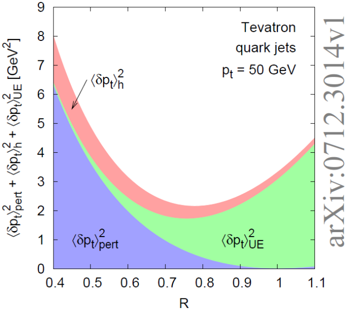
The relative normalization of jet cross sections and theoretical predictions for different jet radii R exhibits a dependence on R.

JHEP 0804 (2008) 063



Three main sources of corrections to the jet p_T:

1. Perturbative radiation,
2. Hadronization,
3. Underlying event.



- Effect of perturbative radiation reduces with grows of R as $\ln R$.
- Hadronization correction reduces as $1/R$.
- UE correction grows like R^2, increasing with jet area.

Hadronic event shapes

ATLAS

events with two leading jets with

- mean transverse momentum $\frac{1}{2}H_{T,2} > 250$ GeV
- $|y| < 1.0$

subleading jets

- $p_T > 30$ GeV
- $|y| < 1.5$

Jets are reconstructed using **anki-kt** algorithm with R=0.6.

Particle-level jets are constructed from all final state particles with lifetimes longer than 10 ps.

CMS

events with at least one jet with

- $p_T > 110$ GeV
- $|\eta| < 2.4$

subleading jets

- $p_T > 30$ GeV
- $|\eta| < 2.4$

Jets are reconstructed using **anki-kt** algorithm with R=0.5.

Particles with a lifetime longer than 30 ps are declared stable.

Color coherence and jets CS ratio (CMS)

Color coherence

events with at least three jets

- $p_T > 30$ GeV
- leading jet $p_{T_1} > 100$ GeV
- two leading jets are central: $|\eta_1|, |\eta_2| < 2.4$
- $0.5 < \Delta R_{23} < 1.5$
- $M_{12} > 220$ GeV

Jets are reconstructed with the **anki-kt** algorithm with R=0.5.

Inclusive jet cross-section ratio with different cone sizes

Jets are reconstructed with the **anki-kt** algorithm with R=0.5 and R=0.7.