

Hight p_T jets in Run II of the ATLAS Experiment

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My Analysis

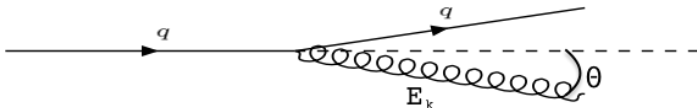
- ▶ Inclusive jet double differential cross section in p_T and rapidity y (inclusive means $pp \rightarrow \text{jet} + \text{anything}$) in Run II of the ATLAS Experiment (meaning $\sqrt{s} = 13 \text{ TeV}$)
- ▶ Data
 1. Monte Carlo generated events of pp collisions at $\sqrt{s} = 13 \text{ TeV}$.
 - ▶ Collisions generated with PYTHIA8 (particle level)
 - ▶ ATLAS Detector response obtained with GEANT4 full simulation (detector level)
 2. NLO QCD predictions (parton level)
- ▶ Cross section corrected from the detector to the particle level in two steps
 - ▶ Calibration
 - ▶ Unfolding
- ▶ Particle level cross section from PYTHIA8 (LO QCD) compared with the parton level NLO QCD cross section prediction.

Jet Necessity

- ▶ Gluon radiation cross section

$$\sigma_{q \rightarrow qg} \sim \frac{d\theta}{|\sin \theta|} \frac{dE_k}{E_k}$$

- ▶ Divergences
 - ▶ Infrared ($E_k = 0$)
 - ▶ Collinear ($\theta = 0$)
- ▶ Good observables are IR and collinear safe, i.e. they are not affected by soft and collinear splittings of final state partons.



Jet Requirements

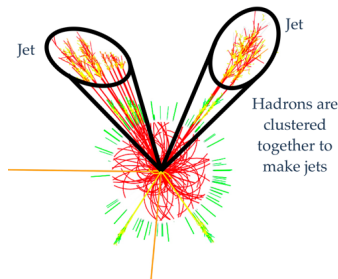
- ▶ Jet can be naively seen as a group of collimated particles
- ▶ Jet algorithm: A prescription, how particles (or other objects) are clustered into separate jets. It should fulfill

- ▶ Infrared safety

The presence of an additional soft particle should not affect the recombination of particles into a jet.

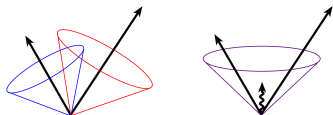
- ▶ Collinear safety

Jet reconstruction should not depend on the fact, if the energy is carried by one particle, or if the particle is split into more collinear particles.

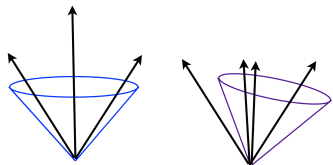


Fixed Cone Jet Algorithms

- ▶ The most illustrative jet algorithms. Different modifications.
- ▶ Used in Tevatron. Not used in ATLAS.



infrared unsafety



collinear unsafety

1. Take particle with highest $p_T > p_T^{cutoff}$
2. Recombine all particle within the fixed cone
3. Update cone direction
4. If direction have changed go to 2, else you have a jet
5. Go to 1 until there is no particle left with $p_T > p_T^{cutoff}$

Anti- k_t Jet Algorithm

1. For each input object i and all pairs of input objects (i, j) calculate

$$d_i = p_{T,i}^{-2} \quad , \quad d_{ij} = \min \left(p_{T,i}^{-2}, p_{T,j}^{-2} \right) \frac{\Delta y^2 + \Delta \phi^2}{R^2} \quad (R = 0.4)$$

2. Find minimum d_{min} between all d_{ij} and d_i

- ▶ d_{min} is between d_{ij} 's.

Recombine i, j into a new object k . Remove i, j from the list, add k to the list.

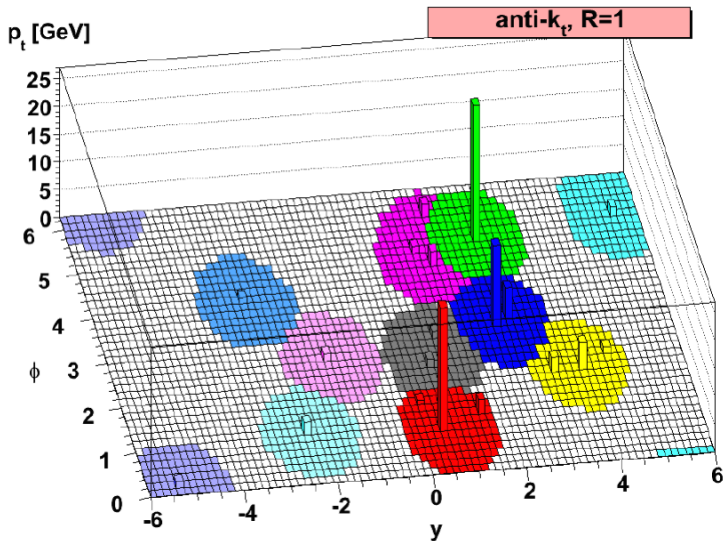
- ▶ d_{min} is between d_i 's.

Object i is a jet. Remove i from the list.

3. Go to 1 until all input objects are part of a jet.

This jet algorithm is both infrared and collinear safe

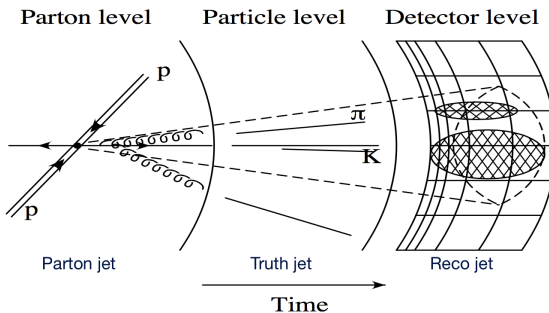
Anti- k_t Jet Algorithm



Jet Reconstruction

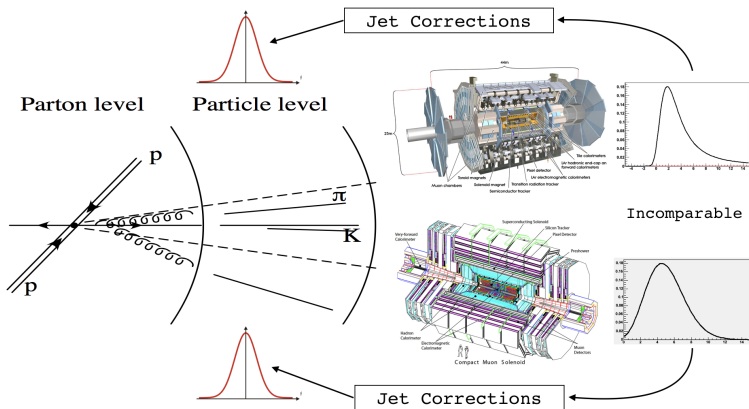
Jet can be defined on three different levels of collisions

- ▶ Parton level - quarks, gluons and other particles created just after the collision. Directly connected to the QCD processes
- ▶ Particle level - particles created by the hadronization.
- ▶ Detector level - from recorded signal. Detector imperfections cause a distortion of observables.



Jet Corrections

- ▶ Correct observables derived from detector level to particle level by removing the detector effects
- ▶ Two main procedures - Calibration and Unfolding
- ▶ Both procedures are trained on Monte Carlo data



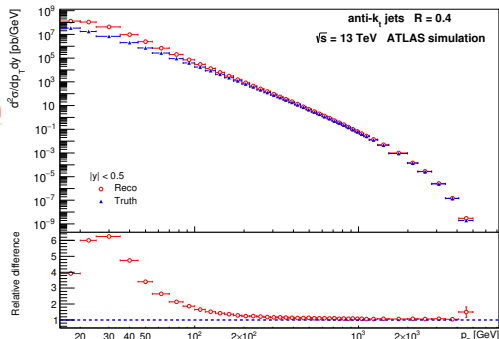
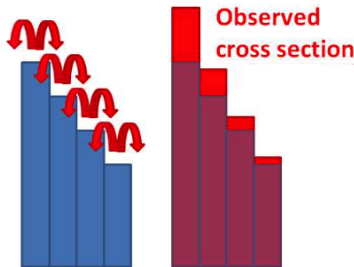
Calibration

- ▶ Modifies the kinematic properties of individual jets - the most important correction: Energy
- ▶ Tries to minimize the calorimeter non-compensation, noise, losses in dead material and cracks, longitudinal leakage and particle deflection in magnetic field.
- ▶ Universal for each jet analysis. Uses the standard `APPLYJETCALIBRATION` library.

Jet index	0	1	2	3	4
pT (Before calibration) [GeV]	112.647	74.6027	69.601	39.5936	24.4818
pT (After calibration) [GeV]	150.576	115.018	103.515	54.6169	32.5758
E (Before calibration) [GeV]	120.755	163.125	147.191	327.249	105.504
E (After calibration) [GeV]	161.763	254.623	223.325	460.422	142.304
Eta (Before calibration)	0.348982	-1.41703	1.37864	-2.80151	2.1387
Eta (After calibration)	0.355368	-1.4309	1.40124	-2.82141	2.15266

Unfolding

- ▶ Corrects the observables from detector level, to observables on particle level.
- ▶ Tries to minimize the effects of detector finite resolution.
- ▶ Analysis dependent.



Unfolding - Mathematical Formulation

- ▶ I want: $f(p_T)$ (distribution of inclusive jet p_T for $p_T \in \langle a, b \rangle$)
- ▶ From detector level I get: $g(x)$ (distribution of unphysical variable x)

$$g(x) = \int_a^b A(x, p_T) f(p_T) dp_T$$

- ▶ Detector smearing described by $A(x, p_T)$
- ▶ Luckily $g(x)$ and $f(p_T)$ are for practical purpose discretized and in analysis, I assume $x \in \langle a, b \rangle$, $N(i) \subset \langle a, b \rangle$

$$g_i = \int_{N(i)} g(x) dx \quad , \quad f_i = \int_{N(i)} f(p_T) dp_T$$

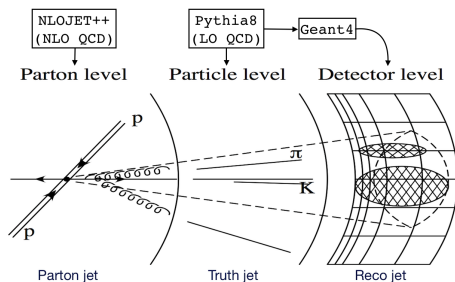
- ▶ So the response of the detector is described by a simple matrix equation

$$g = Af$$

- ▶ Here A is called the Transfer Matrix

Data Characteristics

- ▶ pp collisions at $\sqrt{s} = 13$ TeV, anti- k_t jet algorithm with $R = 0.4$, CT10 PDFs, AU2
- ▶ Measuring of inclusive jet double differential cross section in p_T and rapidity y
- ▶ Parton level - cross section prediction calculated with NLOJET++ program (NLO QCD)
- ▶ Particle level - events generated by PYTHIA8 (LO QCD)
- ▶ Detector level - detector response on PYTHIA8 events obtained by GEANT4 full detector simulation.



PYTHIA8 Data Characteristics

- ▶ Events were generated in a slices according to the leading truth jet p_T .
- ▶ Slices differ in event weight which is for all event calculated as

$$\text{weight} = \frac{(\text{Cross-section}) \cdot (\text{Filter Efficiency}) \cdot w_0}{(\# \text{ events})}$$

- ▶ w_0 is additional weight factor stored in `EventInfoAux` container

JZ	p_T range (GeV)			Cross-section (fb)	Filter Efficiency	# events
JZ0W	0	-	20	7.8420e+13	9.7193e-01	3498000
JZ1W	20	-	80	7.8420e+13	2.7903e-04	2998000
JZ2W	80	-	200	5.7312e+10	5.2261e-03	500000
JZ3W	200	-	500	1.4478e+09	1.8068e-03	499500
JZ4W	500	-	1000	2.3093e+07	1.3276e-03	477000
JZ5W	1000	-	1500	2.3793e+05	5.0449e-03	499000
JZ6W	1500	-	2000	5.4279e+03	1.3886e-02	493500
JZ7W	2000	+		9.4172e+02	6.7141e-02	497000

Event Selection

- ▶ **p_T Cut**

Reco and truth jets with $p_T > 15 \text{ GeV}$ were kept.

- ▶ **y Cut**

Reco and truth jets with $|y| < 4$ were kept.

- ▶ **Zero Jet (0-jet) Cut**

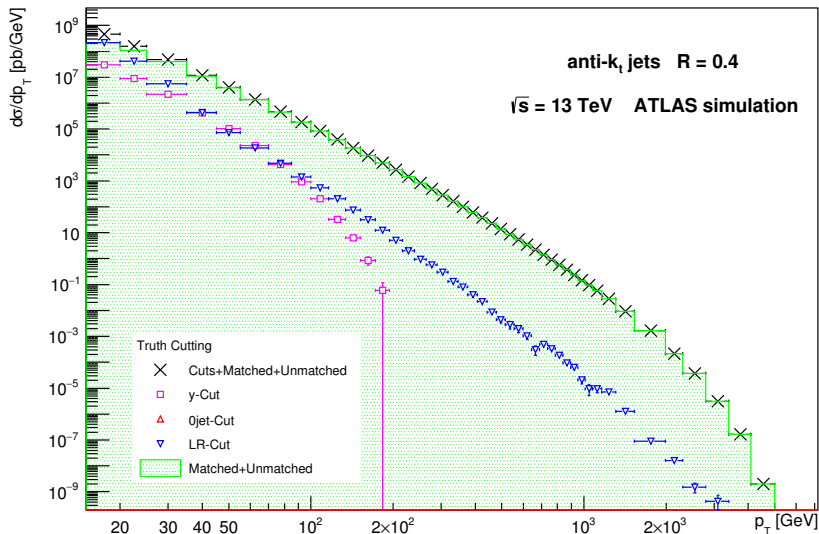
Events with at least one reco and one truth jet, after the p_T and y cuts, are considered.

- ▶ **Leading Ratio (LR) Cut**

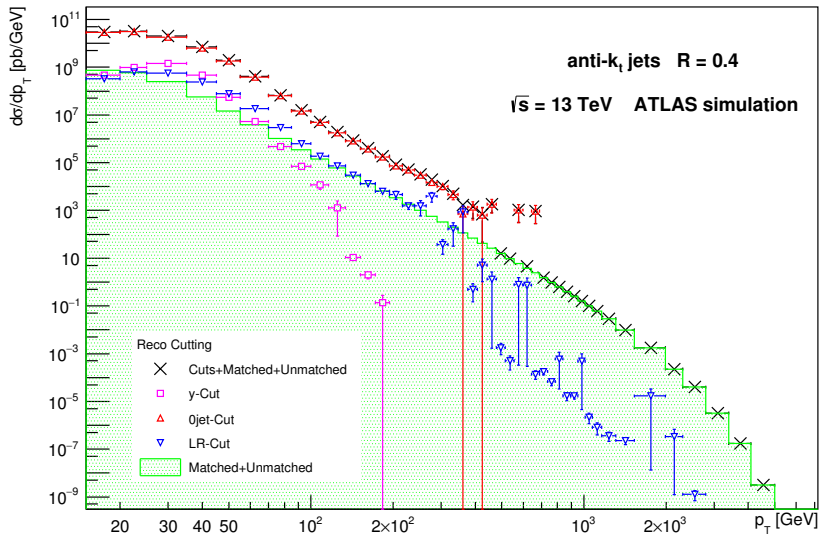
If $0.6 < LR < 1.4$ the event is considered

$$LR = p_{T,\text{leading}}^{\text{reco}} / p_{T,\text{leading}}^{\text{truth}}$$

Event Selection - Truth Jets



Event Selection - Reco Jets



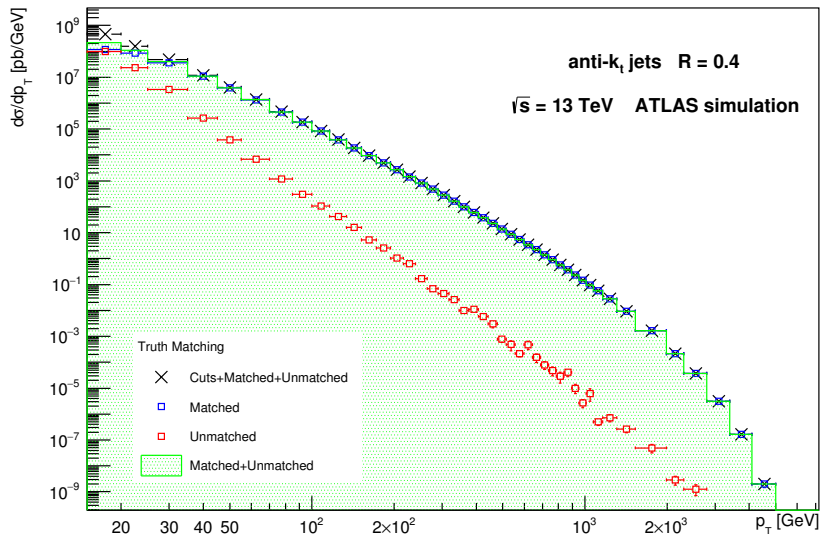
Jet Matching

- ▶ In each event, for each truth jet, the corresponding reco jet has to be found.
- ▶ I have used angular matching
 - ▶ For each pair (i, j) of reco and truth jets

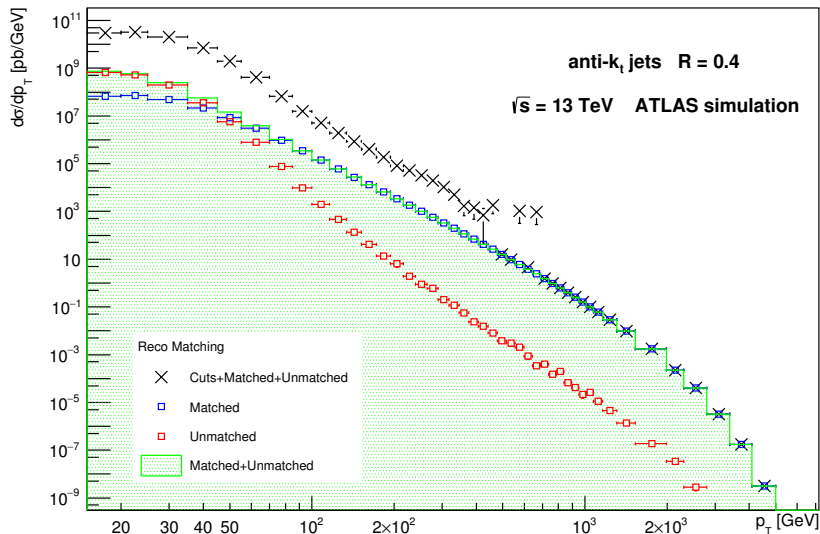
$$dR_{ij} = \sqrt{d\phi_{ij}^2 + dy_{ij}^2}$$

- ▶ If $\min(dR_{ij}) = dR_{pq} < dR^{cutoff} = 0.2$ the jets (p, q) were matched and further not assumed
- ▶ Matching was done, when $\min(dR_{ij}) < dR^{cutoff}$ was not satisfied or all of the reco or truth jets were matched.

Jet Matching - Truth Jets



Jet Matching - Reco Jets



Inputs for Unfolding

Unfolding (calibrated reco spectrum) \approx truth spectrum

- ▶ Inputs for unfolding procedure are
 - ▶ Matching efficiencies - describing the ratio of matched jets to all jets
 - ▶ Transfer matrix A_{ij} - containing the number of reco jets in bin i with a matched truth jets generated in bin j
- ▶ To deal with the double binning (in p_T and y), I use two approaches to the unfolding

1. Simple unfolding

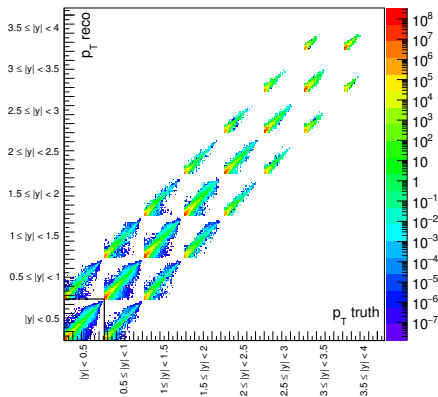
Matching jets within different rapidity bins is not allowed. There are 8 independent 46×46 transfer matrices, one for each rapidity bin (46 = number of p_T bins)

2. 2D unfolding

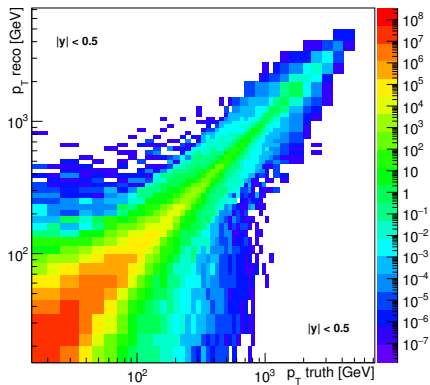
Matching within different rapidity bins allowed. Only one 368×368 transfer matrix ($368 = 8 \times 48$)

Transfer Matrices

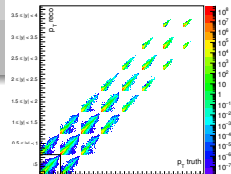
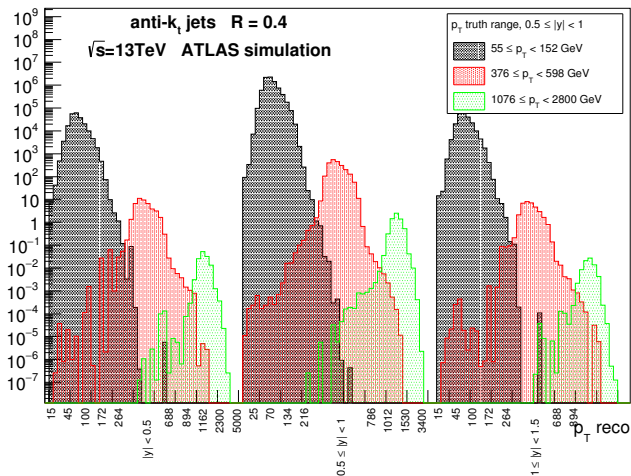
2D unfolding



Simple unfolding

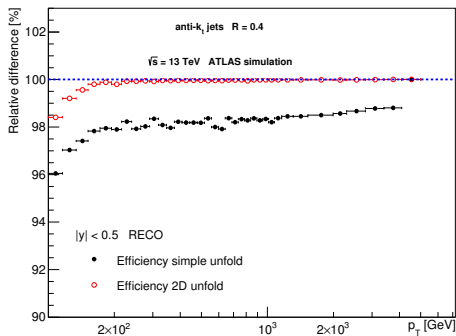


Slices in Transfer Matrix of 2D Unfolding

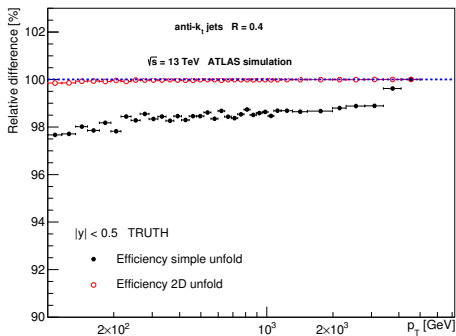


Matching Efficiencies

Truth jets



Reco jets



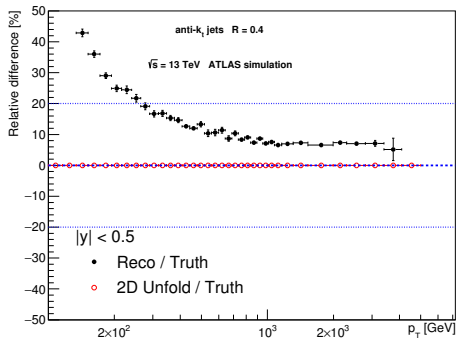
Steps of Unfolding

Unfolding procedure can be divided into three main steps

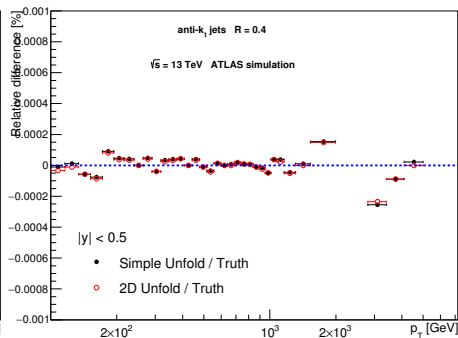
1. Input data are multiplied by the matching efficiencies of reco jets
2. Transfer matrix is used to correct data spectrum for detector effects. I use the Iterative Dynamical Stabilized unfolding method with one iteration
3. The spectrum obtained by the step 2 is divided by the matching efficiencies of truth jets, in order to correct resulting spectrum for the unmatched truth jets

Unfolding Results

Reco and Unfolded vs. Truth Spectrum



Simple and 2D unfolded vs. Truth Spectrum

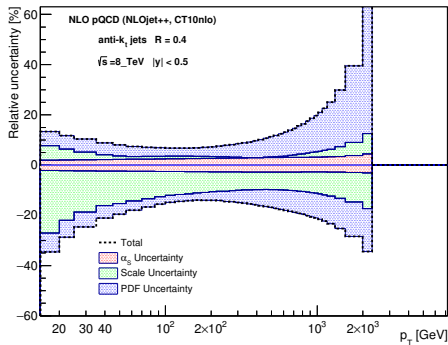


NLO QCD Prediction

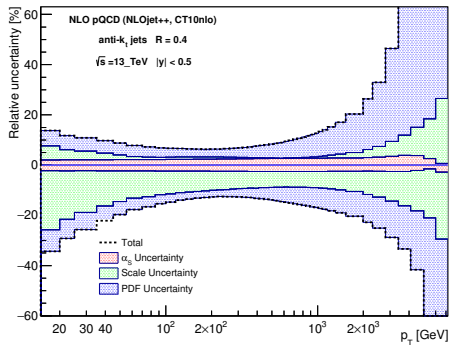
- ▶ NLO QCD predictions on parton level for $\sqrt{s} = 8 \text{ TeV}$ and $\sqrt{s} = 13 \text{ TeV}$
- ▶ Theoretical uncertainties which are taken into account
 - ▶ **Scale uncertainty**
Choice of renormalization and factorization scales, including neglecting the higher order terms beyond the NLO
 - ▶ α_S **uncertainty**
Because of experimental measurements of α_S .
 - ▶ **PDF uncertainty**
Prediction depends on the concrete choice of a PDF
- ▶ Other uncertainties (not so significant)
 - ▶ **Nonperturbative corrections uncertainty**
Hadronization and Underlying Event corrections.
 - ▶ **Electroweak corrections uncertainty**
Next to the QCD processes, the electroweak processes should be assumed.

NLO Systematic Errors

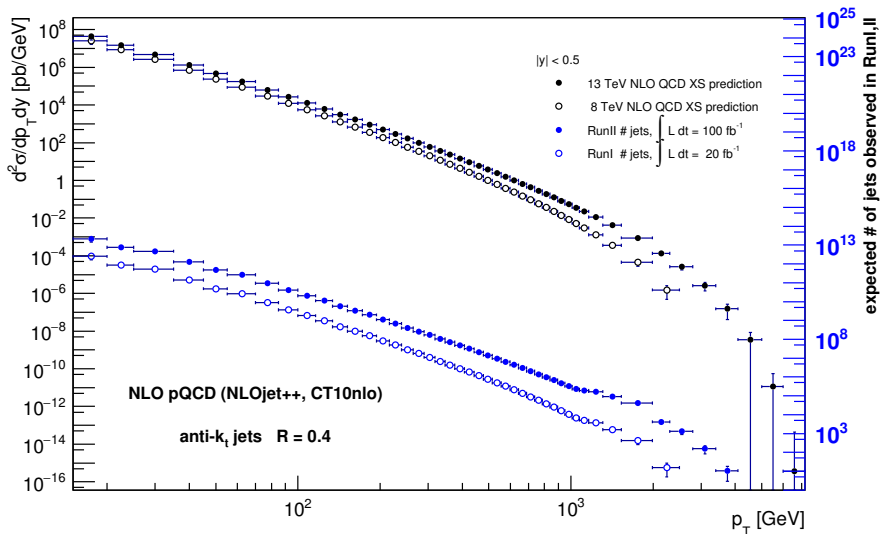
$$\sqrt{s} = 8 \text{ TeV}$$



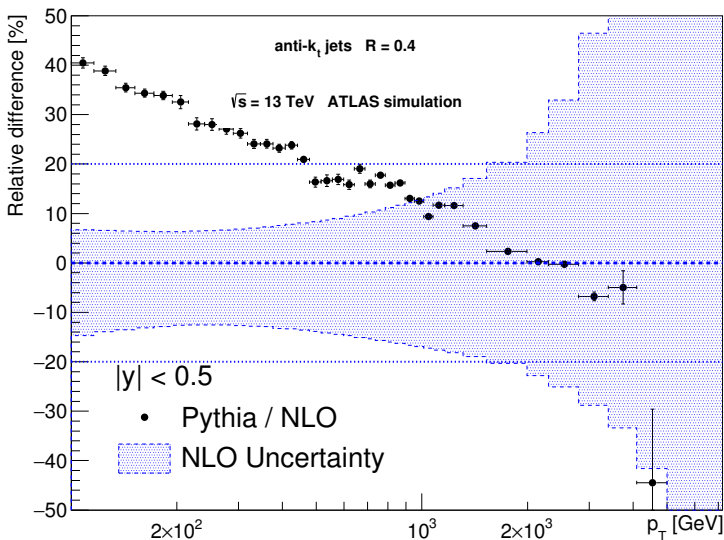
$$\sqrt{s} = 13 \text{ TeV}$$



Comparison of NLO QCD Predictions



Comparison of LO and NLO QCD



Inclusive Jet Conclusions

Why Inclusive Jets?

They Cover wide range of momentum transfers ($\sim 1 \text{ GeV} - 1 \text{ TeV}$ on the LHC) \rightarrow predictions sensitive to the properties of the running coupling constant α_S

They probe the structure of proton at small distance scales

$$\lambda \sim 1/p_T \sim \text{TeV}^{-1} \sim 10^{-19} \text{ m}$$

They contribute to our understanding of PDF

They appreciate the increase in the transverse momentum as no other physics process observed on hadron colliders

Thesis Conclusions

Unfolding

Two approaches were probed.

No significant differences between these two approaches imply, for the real analysis, the Simple Unfolding approach should be used for its simpler implementation.

Agreement of the unfolded p_T spectra with the truth p_T spectra up to systematic error $< 10^{-3} \%$.

LO and NLO QCD

Significant differences showing the influence of the NLO QCD processes on physical observables.