Hight p_T jets in Run II of the ATLAS Experiment

Jan Lochman

Czech Technical University

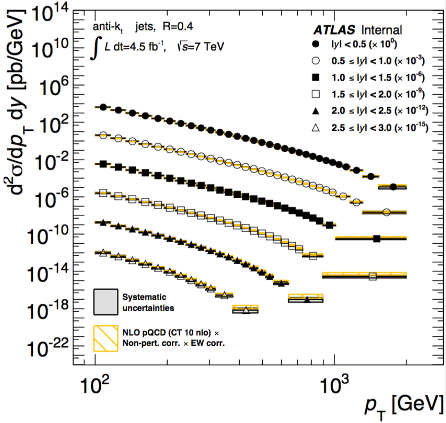
jan.lochman@cern.ch

ATLAS Meeting

May 14, 2015

My Analysis

Inclusive jet double differential cross section in p_T and rapidity y (inclusive means $pp \rightarrow$ jet + "anything") in Run II of the ATLAS Experiment ($\sqrt{s} = 13\,\text{TeV}$)



Why Inclusive Jets?

- They Cover a *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 PDFs
- They *appreciate the increase in the center-of-mass energy* as no other physics process observed on hadron colliders

My Analysis

Data

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)

Jet Corrections

Cross section corrected from the detector to the particle level in two steps

- Calibration
- Unfolding

LO vs. NLO QCD

Particle level cross section from PYTHIA8 (LO QCD) compared with the parton level NLO QCD cross section prediction.

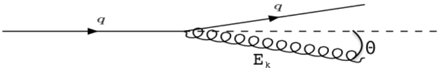
Why Do We Need Jets?

Gluon radiation cross section:

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

Divergences:

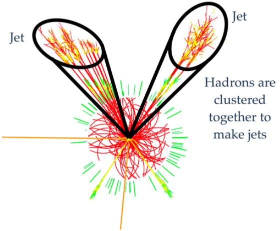
- *Infrared* ($E_k = 0$)
- *Collinear* ($\theta = 0$)



Jet: 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, of if the particle is split into more collinear particles.



Summary: q or g CANNOT be observed. Jets CAN.

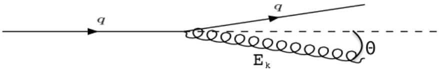
Why Do We Need Jets?

Gluon radiation cross section:

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

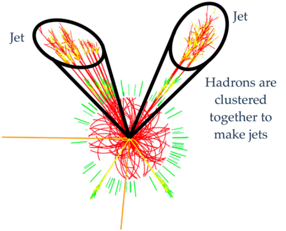
Divergences:

- *Infrared* ($E_k = 0$)
- *Collinear* ($\theta = 0$)



Jet: A group of collimated particles
Jet algorithm: A prescription, how particles (or other objects) are clustered into separate jets. It should fulfill

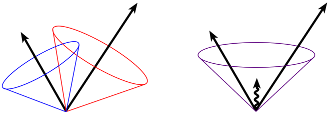
- *Infrared safety:* The presence of an additional soft particle should not affect the recombination of particles into a jet.
- *Collinear safety:* Jet reconstruction should not depend on the fact, if the energy is carried by one particle, of if the particle is split into more collinear particles.



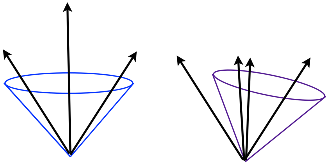
Summary: q or g CANNOT be observed. Jets CAN.

Cone Jet Algorithms

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



infrared unsafety



collinear unsafety

Algorithm:

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

k_t Jet Algorithms

Algorithm:

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

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

   - $p = 1$ k_t algorithm,
   - $p = 0$ Cambridge/Aachen algorithm,
   - $p = -1$ anti-k_t algorithm.

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.

k_t Jet Algorithms

Algorithm:

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

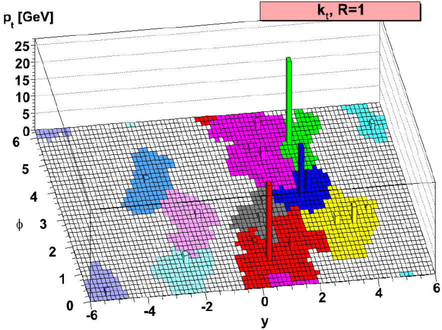
$$d_i = p_{T,i}^{2p} \quad , \quad d_{ij} = \min\left(p_{T,i}^{2p}, p_{T,j}^{2p}\right)\frac{\Delta y^2 + \Delta\phi^2}{R^2} \qquad (R = 0.4)$$

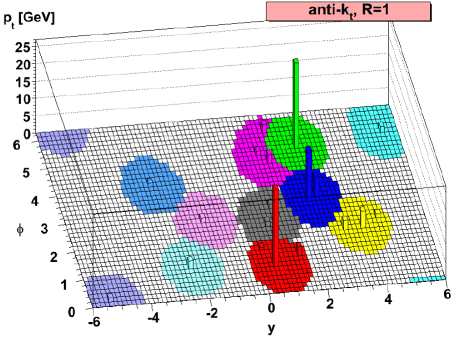
   - $p = 1$ k_t algorithm,
   - $p = 0$ Cambridge/Aachen algorithm,
   - $p = -1$ anti-k_t algorithm.

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.

k_t Jet Algorithms



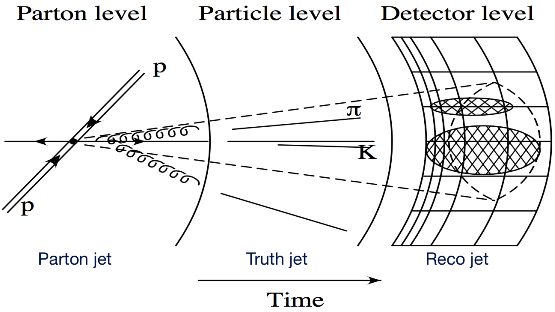


- k_t jet algorithms are both infrared and collinear safe
- ATLAS uses anti-k_t jet algorithm

Jet Reconstruction

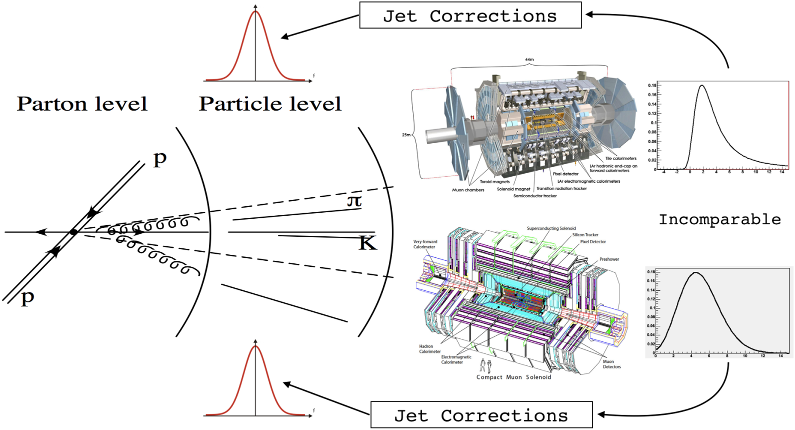
Jet can be defined on a *three different levels of collision*:

- **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** - recorded signal. Detector imperfections cause a *distortion of observables*.



Jet Corrections

- Correct observables derived from detector to particle level by removing the detector effects
- Two main procedures - *Calibration* and *Unfolding*



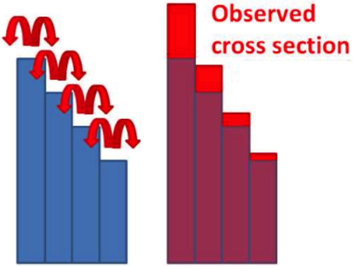
Calibration

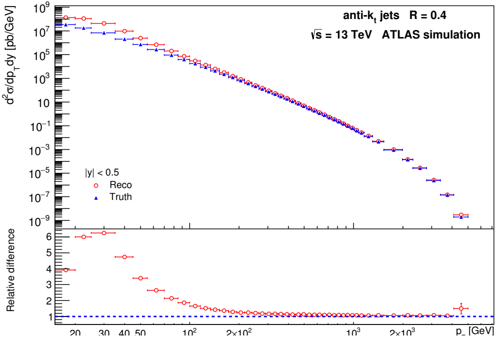
- Modifies the kinematic properties of *individual jets* - the most important correction: Energy
- Tries to minimize the calorimeter non-compensation, noise, losses in dead material and cracks, longitudinal leakage and particle deflection in magnetic field.
- *Universal* for each jet analysis. Uses the 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 have:** $g(x)$ (distribution of unphysical variable x)

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

- Detector smearing described by $A(x, p_T)$
- Complicated *integral equation* for $f(p_T)$
- 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*, with A being called *Transfer Matrix*

$$g = Af$$

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 have:** $g(x)$ (distribution of unphysical variable x)

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

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

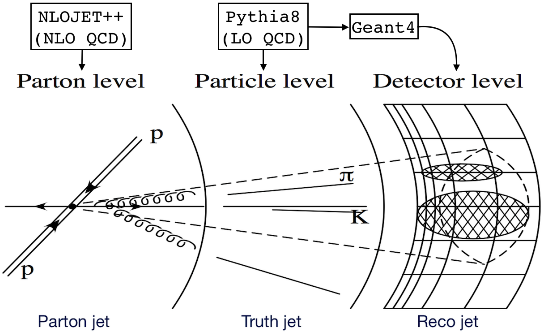
$$g_i = \int_{N(i)} g(x) dx \quad , \quad f_i = \int_{N(i)} f(p_T) dp_T$$

- So the response of the detector is described by a "simple" *matrix equation*, with A being called *Transfer Matrix*

$$g = Af$$

Data Characteristics

- *pp* collisions at $\sqrt{s} = 13\,\text{TeV}$, 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

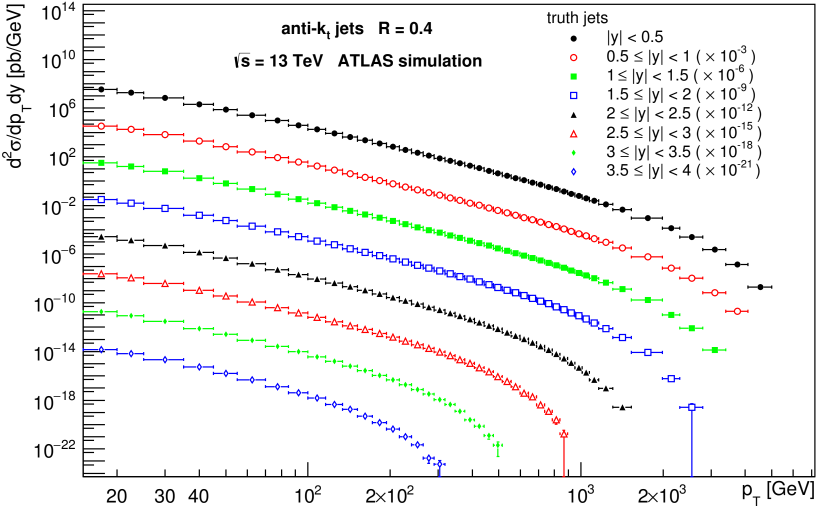
- Events were generated in a slices according to the leading truth jet p_T.
- Slices differ in event weight which is for all event calculated as

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

- 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

p_T spectra of Truth Jets



Event Selection

Remove the jets with p_T and rapidity y out of used binning

- **$\mathbf{p_T}$ Cut**
  Reco and truth jets with $p_T > 15\,\mathrm{GeV}$ were kept.
- **y Cut**
  Reco and truth jets with $|y| < 4$ were kept.

Remove the events badly reconstructed by the detector

- **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

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

Event Selection

Remove the jets with p_T and rapidity y out of used binning

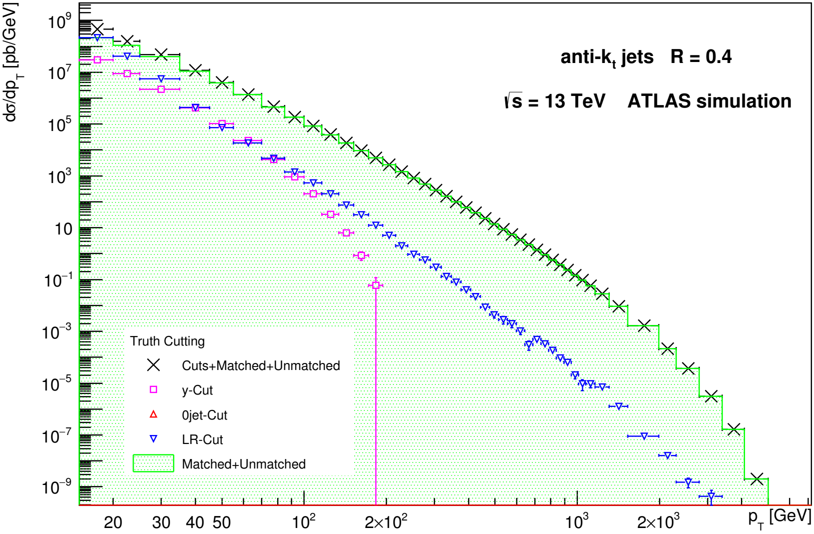
- **$\mathbf{p_T}$ Cut**
  Reco and truth jets with $p_T > 15\,\mathrm{GeV}$ were kept.
- **y Cut**
  Reco and truth jets with $|y| < 4$ were kept.

Remove the events badly reconstructed by the detector

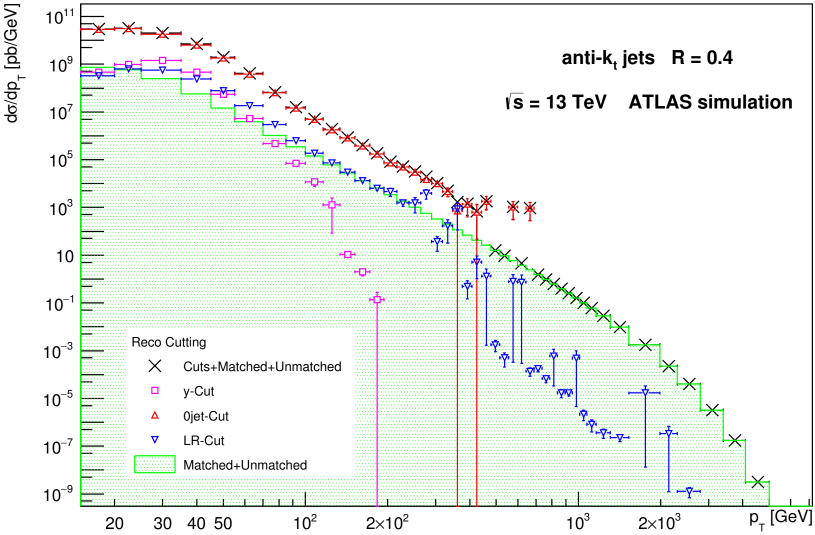
- **Zero Jet (0-jet) Cut**
  Events with at least one reco and one truth jet, after the p_T and y cuts, are considered.
- **Leading Ratio (LR) Cut**
  If $0.6 < LR < 1.4$ the event is considered

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

Event Selection - Truth Jets



Event Selection - Reco Jets



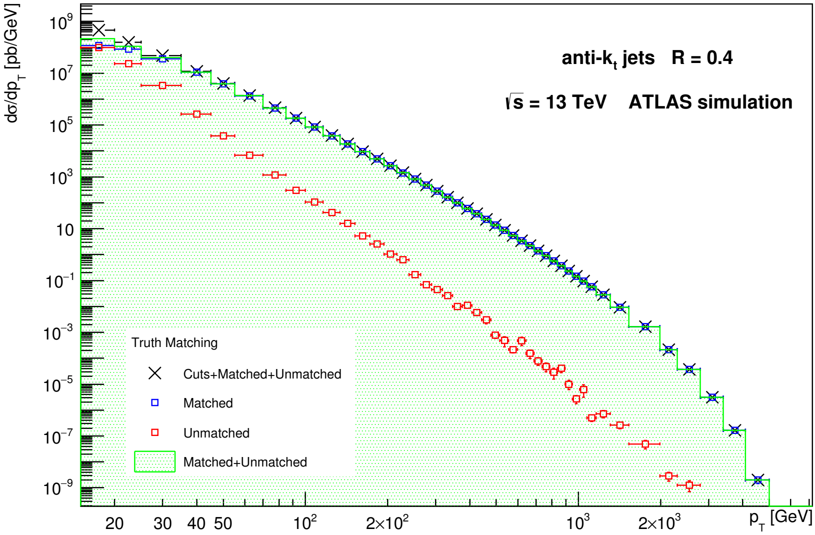
Jet Matching

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

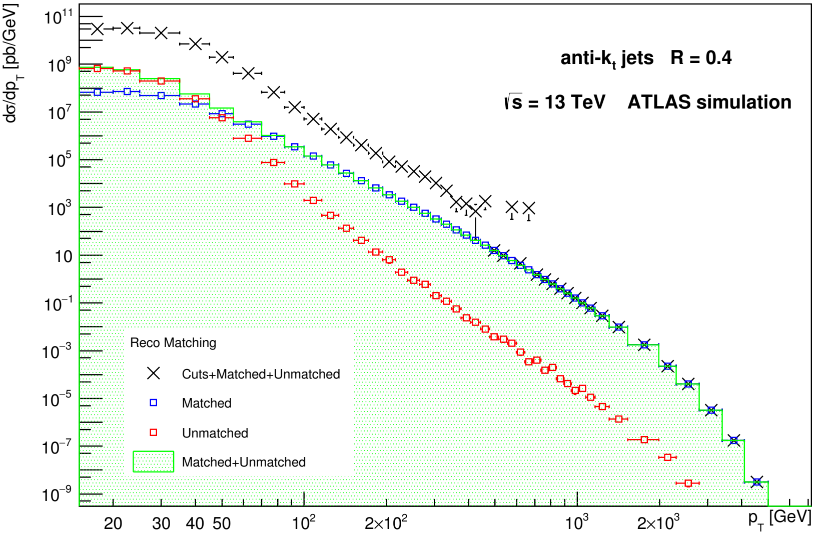
$$dR_{ij} = \sqrt{d\phi_{ij}^2 + dy_{ij}^2}$$

  2. If $\min(dR_{ij}) = dR_{pq} < dR^{cutoff} = 0.2$ the jets (p,q) were matched and further not assumed
  3. 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

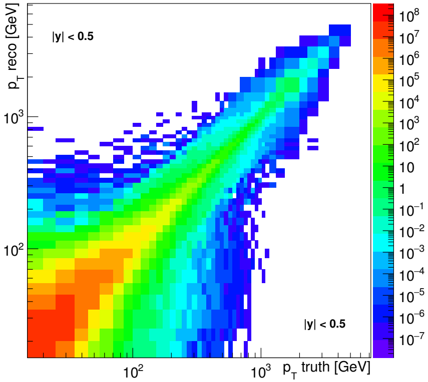
Unfolding(calibrated reco spectrum) $\approx$ truth spectrum

- Inputs for unfolding procedure
  - **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
- I test two approaches to the unfolding, allowing a dealing with the double binning (in p_T and y)

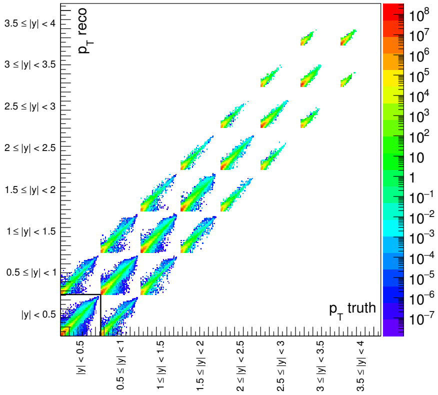
1. **Simple unfolding**
   Matching jets within different rapidity bins is not allowed. There are 8 independent 46x46 transfer matrices, one for each rapidity bin ($46 =$ number of p_T bins)
2. **2D unfolding**
   Matching within different rapidity bins allowed. Only one 368x368 transfer matrix ($368 = 8 \times 48$)

Transfer Matrices

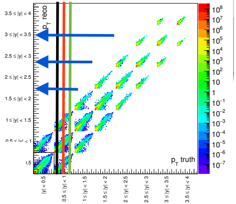
Simple unfolding

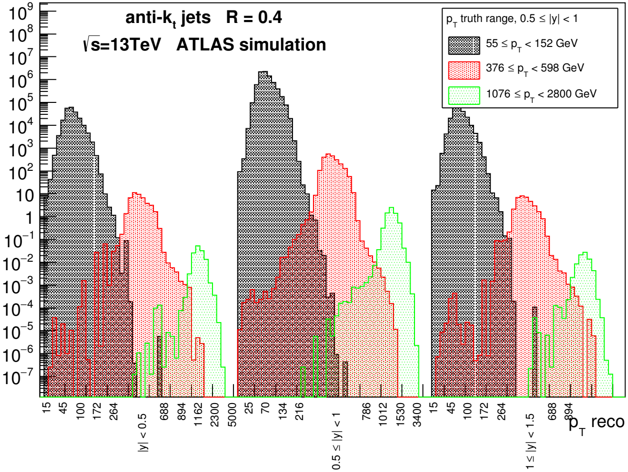


2D unfolding



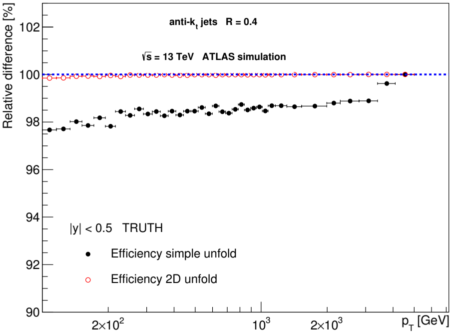
Slices in Transfer Matrix of 2D Unfolding



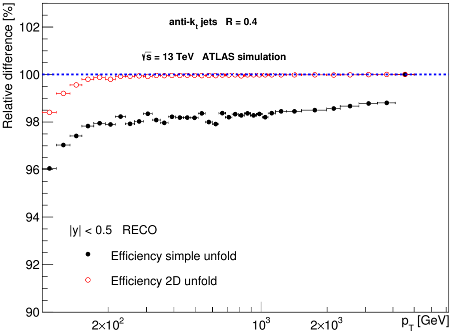


Matching Efficiencies

Truth jets



Reco jets



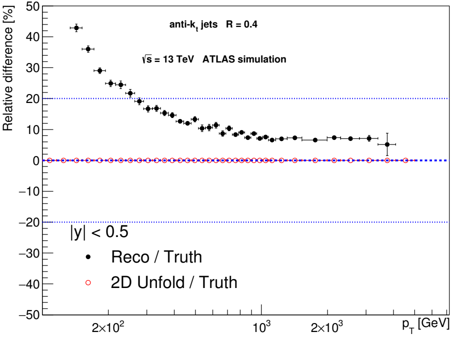
Steps of Unfolding

Three main steps of the unfolding procedure

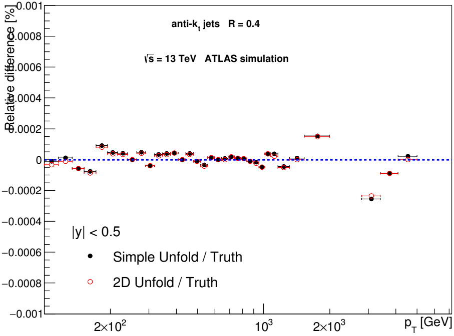
1. Input data are multiplied by the matching efficiencies of reco jets
2. Transfer matrix is used to correct data spectrum for detector effects. I use the *Iterative Dynamical Stabilized* unfolding method with one iteration
3. The spectrum obtained by the step 2 is divided by the matching efficiencies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

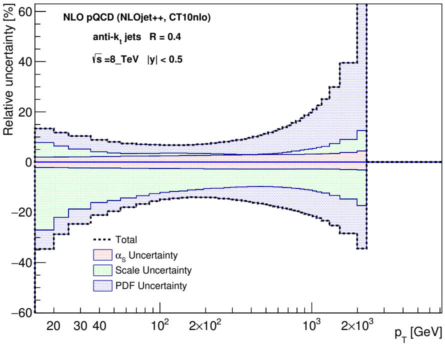
- NLO QCD predictions on parton level for $\sqrt{s} = 8\,\text{TeV}$ and $\sqrt{s} = 13\,\text{TeV}$
- *Theoretical uncertainties* which are taken into account
  - **Scale uncertainty**
    Choice of renormalization and factorization scales, including neglecting the higher order terms beyond the NLO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

NLO QCD Prediction

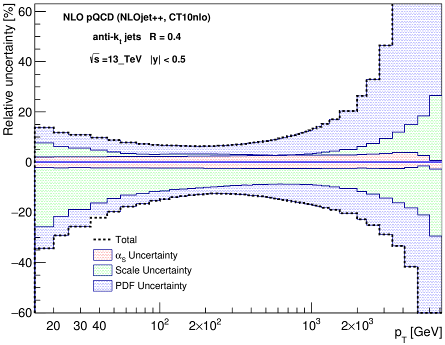
- NLO QCD predictions on parton level for $\sqrt{s} = 8\,\text{TeV}$ and $\sqrt{s} = 13\,\text{TeV}$
- *Theoretical uncertainties* which are taken into account
  - **Scale uncertainty**
    Choice of renormalization and factorization scales, including neglecting the higher order terms beyond the NLO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

NLO Systematic Errors

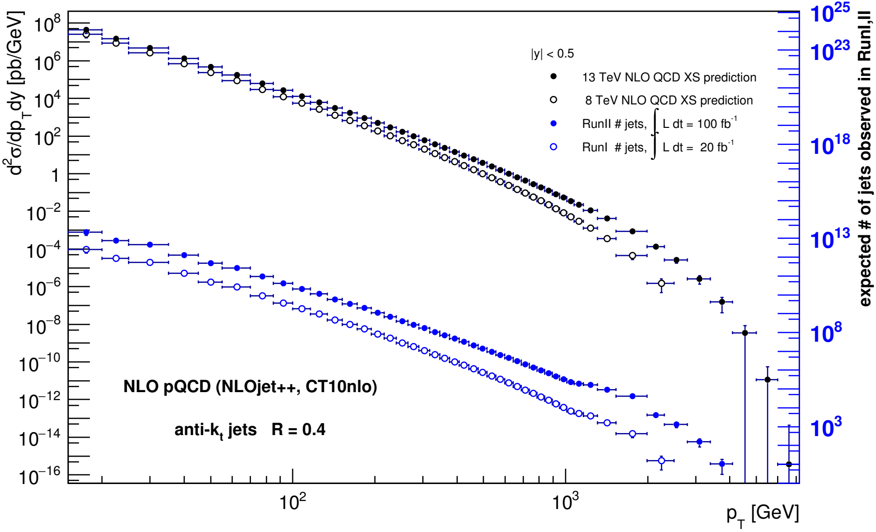
$\sqrt{s} = 8\,\mathrm{TeV}$



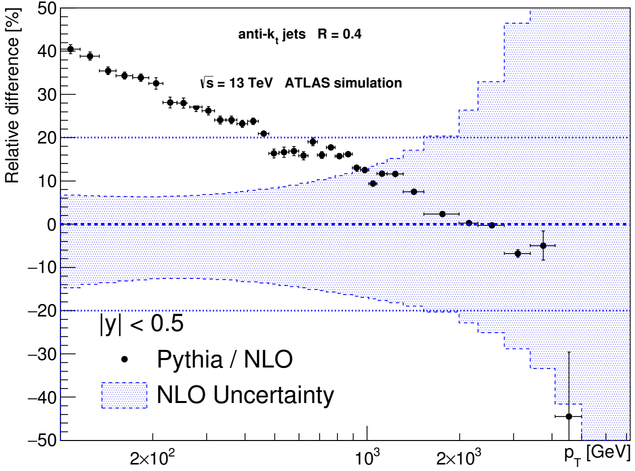
$\sqrt{s} = 13\,\mathrm{TeV}$



Comparison of NLO QCD Predictions



Comparison of LO and NLO QCD



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.