Experiences on QCD MC simulations: a user point of view on the inclusive jet cross-section

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Jet Reconstruction and Spectroscopy
at hadron collider
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Inclusive 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.
1.5 TeV reached with the first 40 pb^{-1}

$P_T > 1$ TeV ~ $d < 10^{-3}$ fm

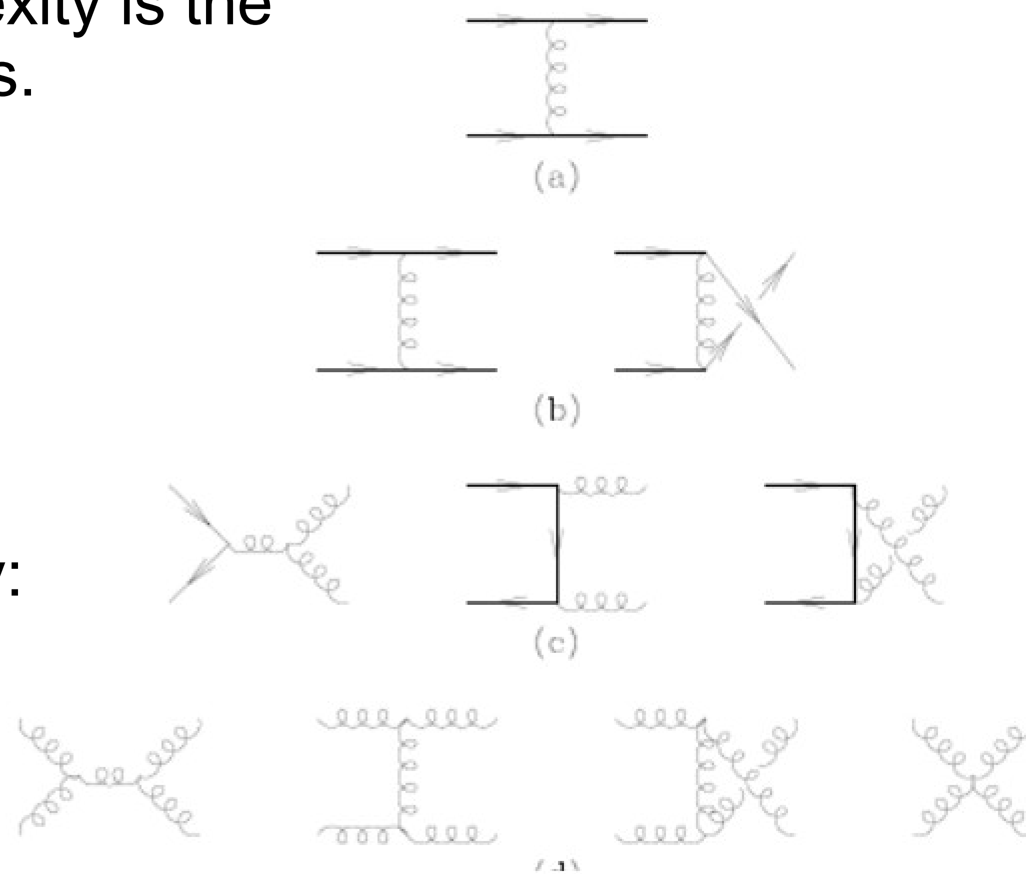
- Measurement of the strong coupling constant.
- Information about the structure of the proton.
- Tools to understand the strong interaction.
- Tools to search for physics beyond the Standard Model.

This talk is not a review, is mostly a collection of experiences

From the leading order
To the next to leading order

Theoretical predictions: Leading Order

The first step toward the complexity is the leading order 2->2 QCD process.



Two partons from the protons structure collide and form a 2 parton final state.

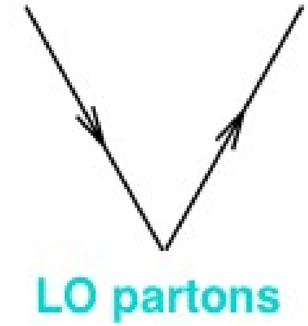
The kinematic in this first approximation is really easy: Only two back to back partons.

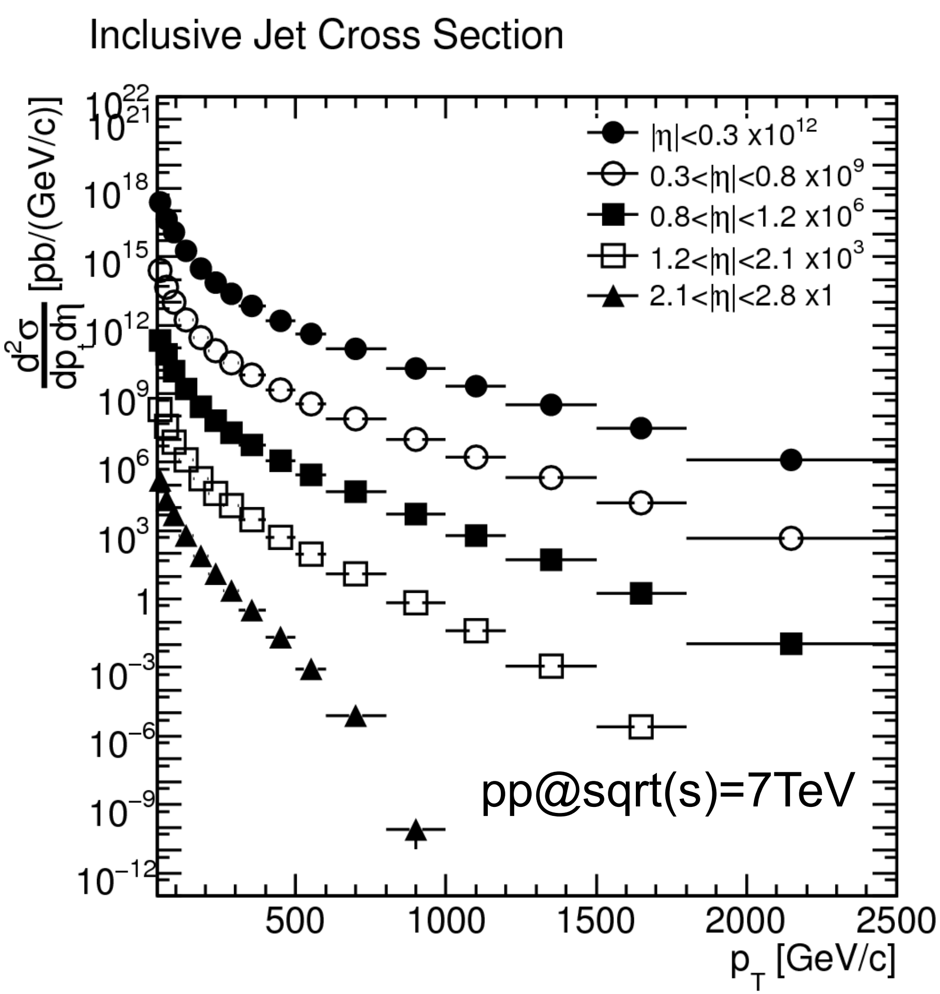
(Usually) no differences between the jets and the final partons:

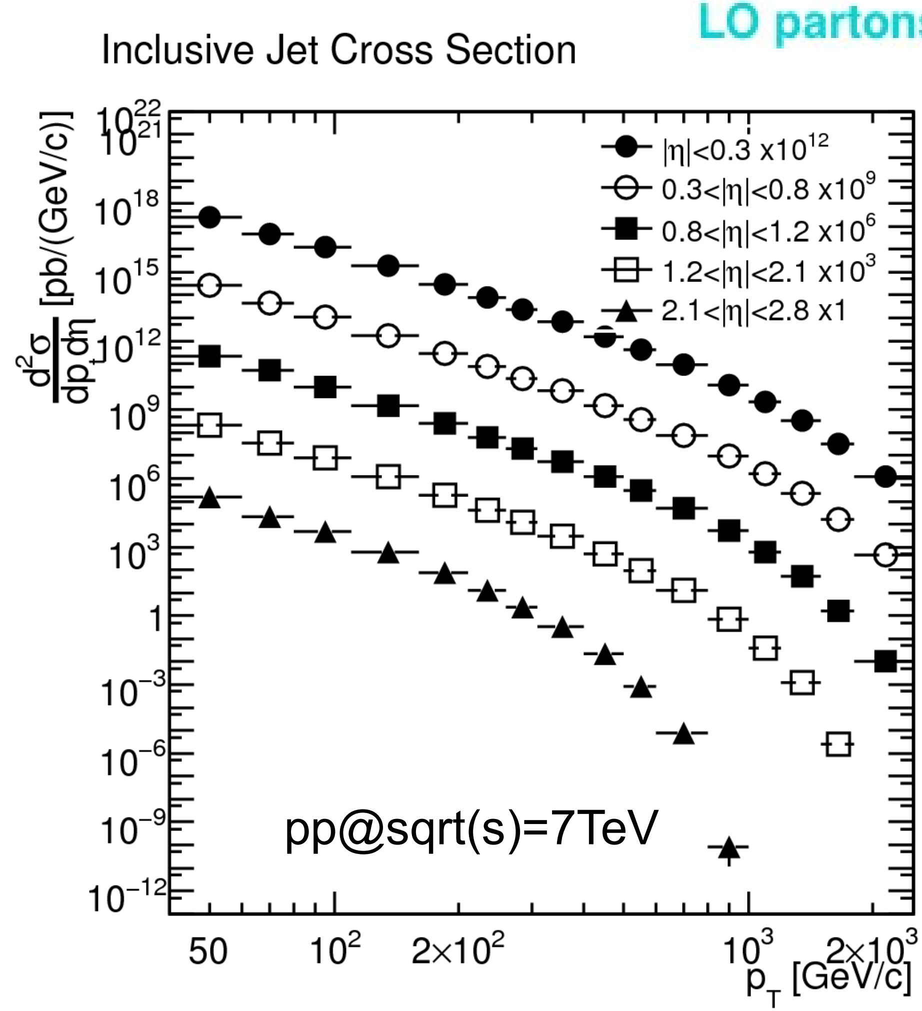
1 parton <-> 1 jet

(for 2->2 LO)

Leading Order: Predictions





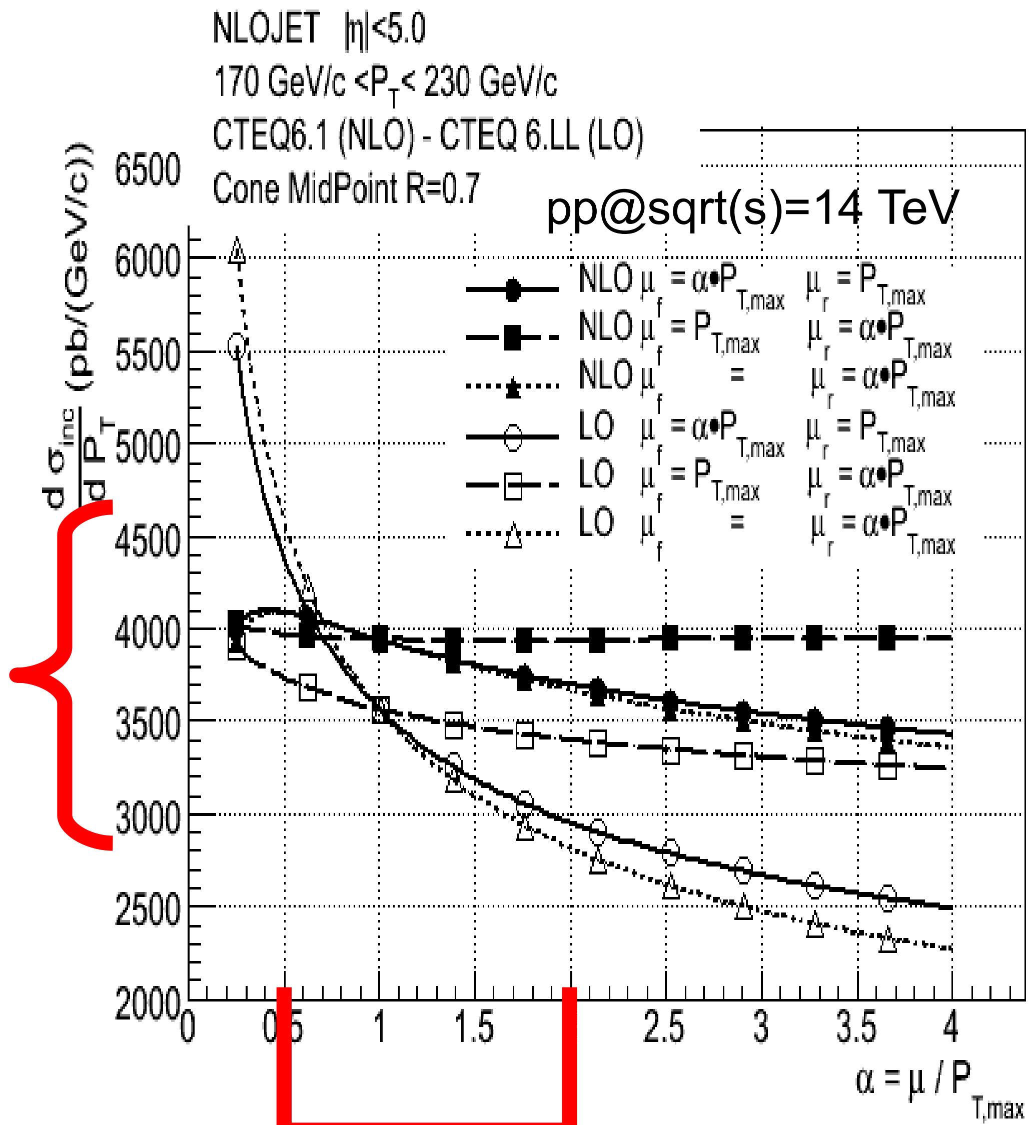


From Leading Order to Next to Leading Order

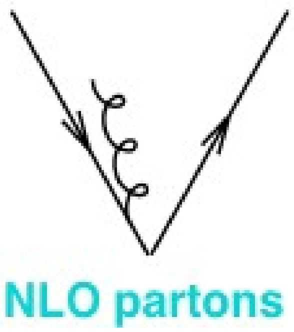
Is this prediction good enough?

The estimate of the error is not straight-forward, but we can variate the scales to test the stability.
Dramatic variation of the cross section as a function of the renormalization and factorization scale.

Leading Order Parton Level
Cons: important higher orders
    Result not stable
Cons: final state with only two partons – no description of the jet



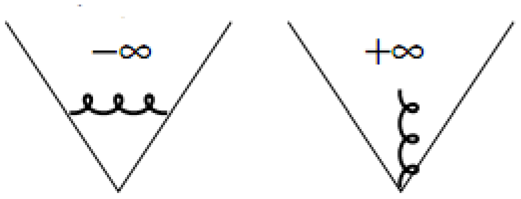
A new order – the next



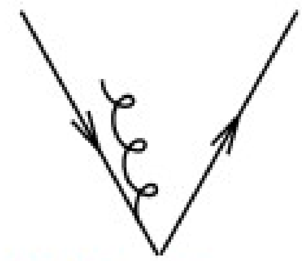
To get a more precise prediction,
a new order in the perturbative correction has been calculated:

$$\text{Cross section} = C_2\, \alpha_S^2 + C_3\, \alpha_S^3$$

For this purpose, we need two different components:
The 1 loop contribution and the real emission.
Both contributions are divergent, but if the observable is “safe”, the divergences cancel out

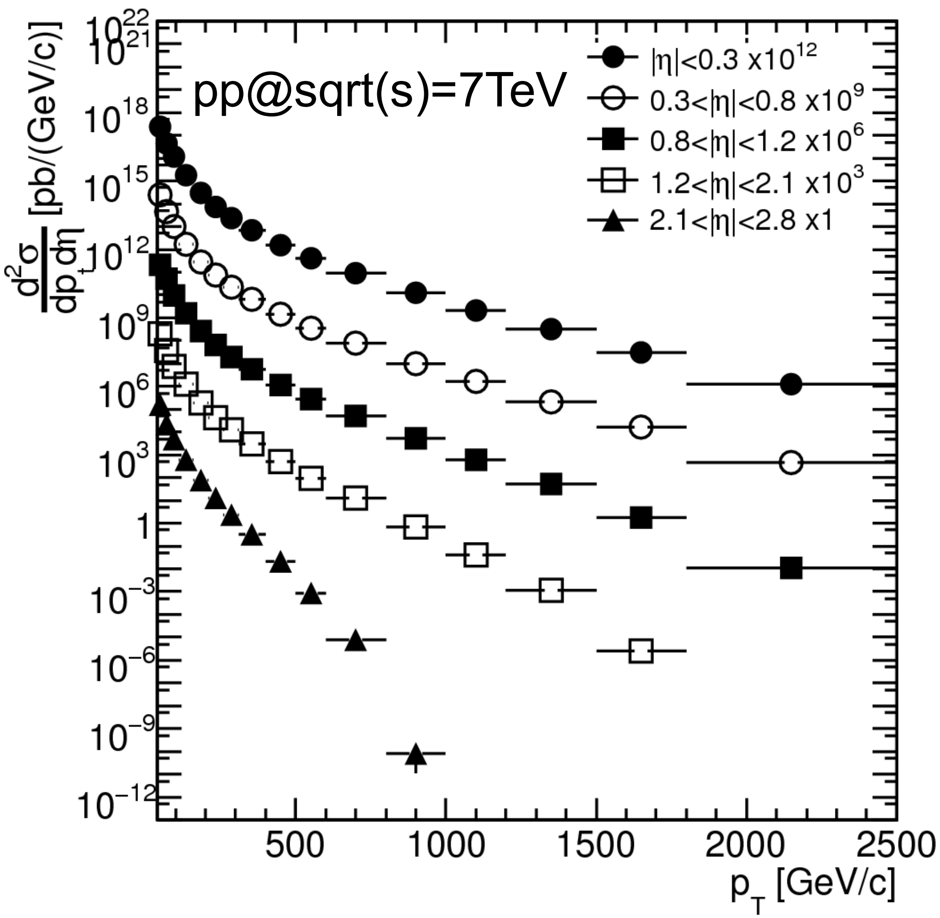


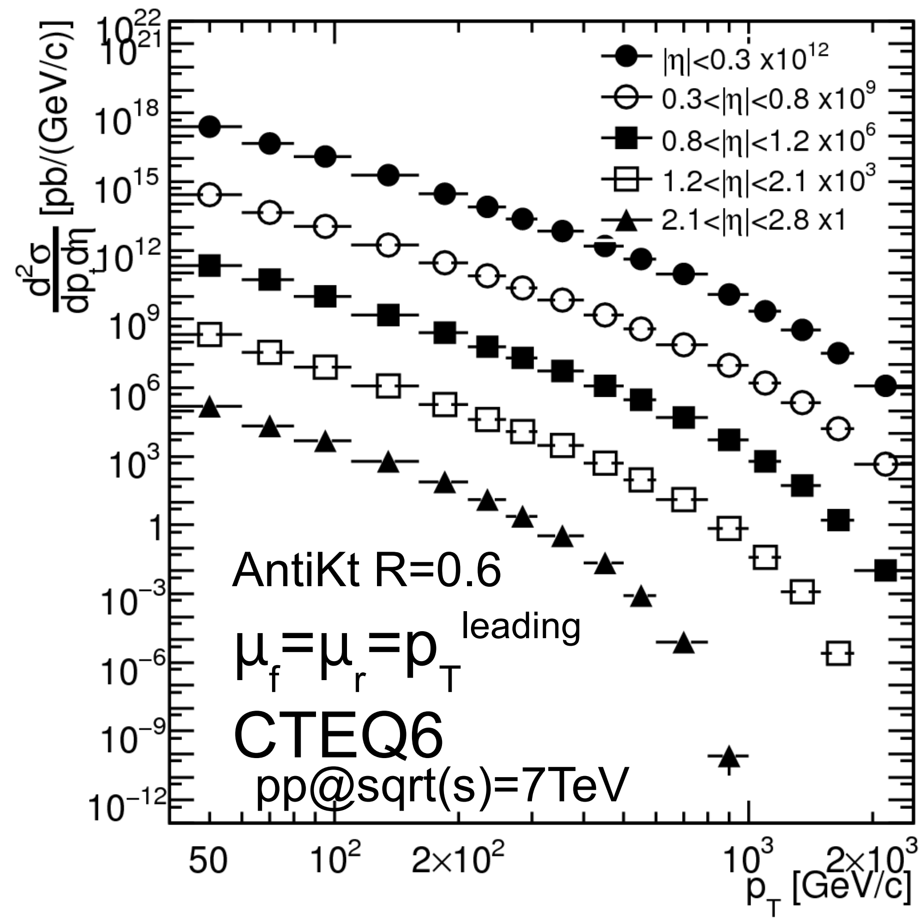
Next to Leading Order: Predictions



NLO partons

Inclusive Jet Cross Section



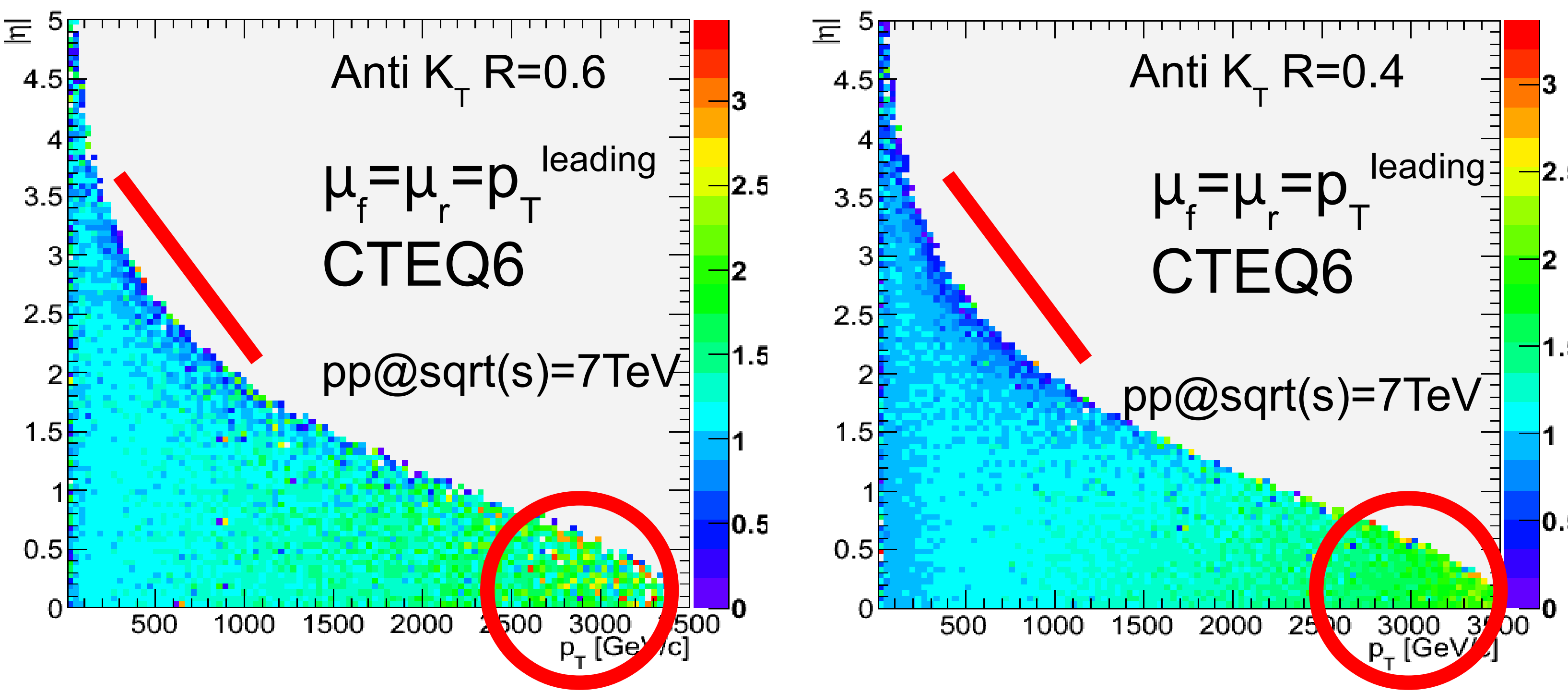


Comparing LO and NLO

How much the cross section change from LO to NLO? NLO/LO

Main effects at the end of the phase space.
Smaller radius shows more structures at low p_T and forward regions

Colors:
NLO/LO



Scale dependence and uncertainty

Scale variation at NLO:

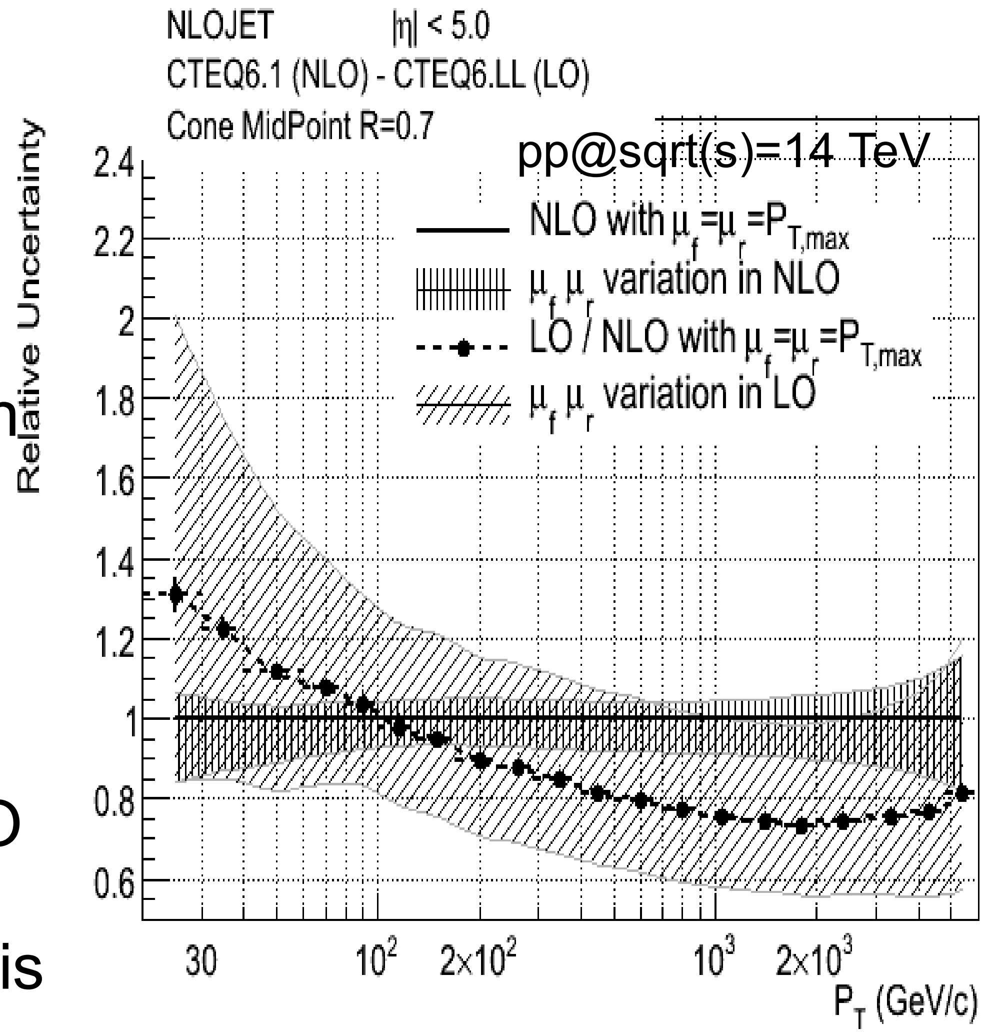
Variation with respect to $\mu_f = \mu_r = p_T^{leading}$

Estimate: independent variation of muf and mur:

$0.5\ p_T < \mu < 2.0\ p_T$

Stability:
30% @ LO → 5 – 10 % @ NLO

Higher orders could improve this uncertainty



From LO to NLO: better stability of the cross section.

Is anything missing ?

Final State

2 → 2(3) partons in the final state → 2 or 3 jets
This means that each jet has 1 or 2 partons.

Are **different jet algorithms** reconstructing **different jets** if there are **only 3 partons** in the final state which must balance in the transverse plane?

Example: Recombination algorithms with the same R (Kt, C/A, AntiKt):
If there are only three final partons which must balance in the transverse plane, only two of them can eventually be clustered.

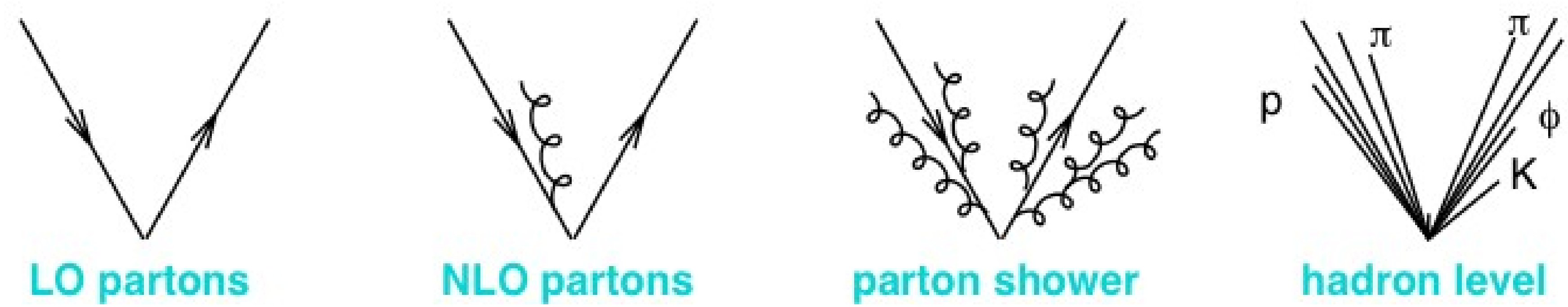
They are merged together if $\Delta R < R$ for all the recomb. algorithms:

NO numerical difference in the NLO prediction for the inclusive jet Cross section when using the different recombination jet algorithms.

The use of different recombination jet algorithms is sensitive to order/non pert effects.

Final State II

A final state with 3 objects is not very realistic.
We have a spray of particles in the final state.

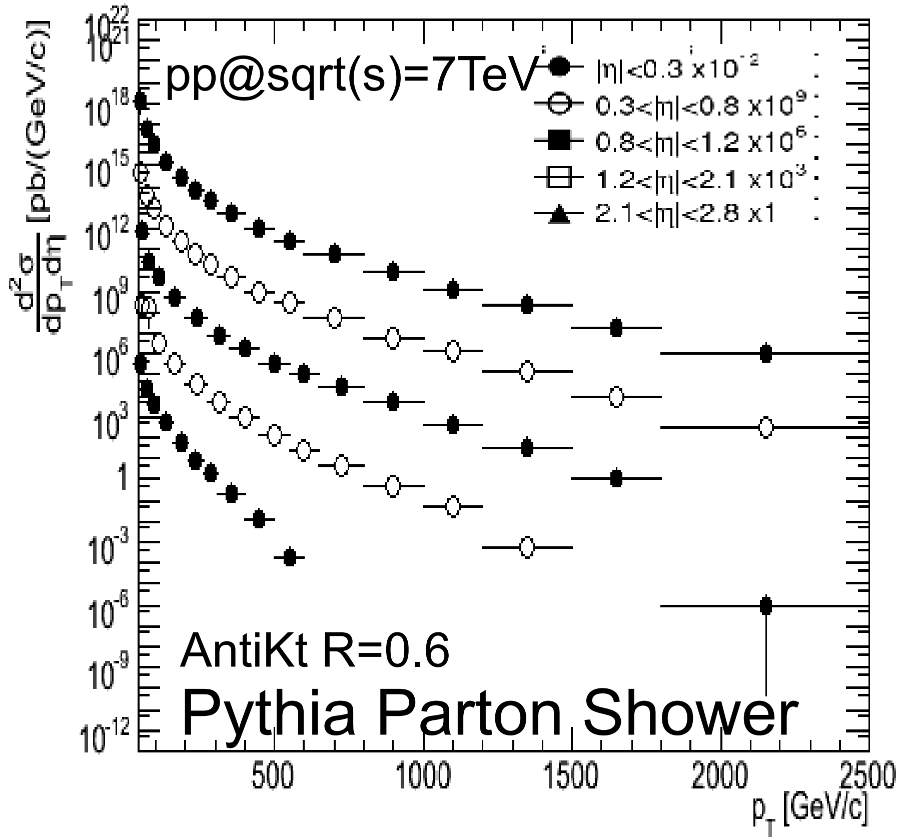


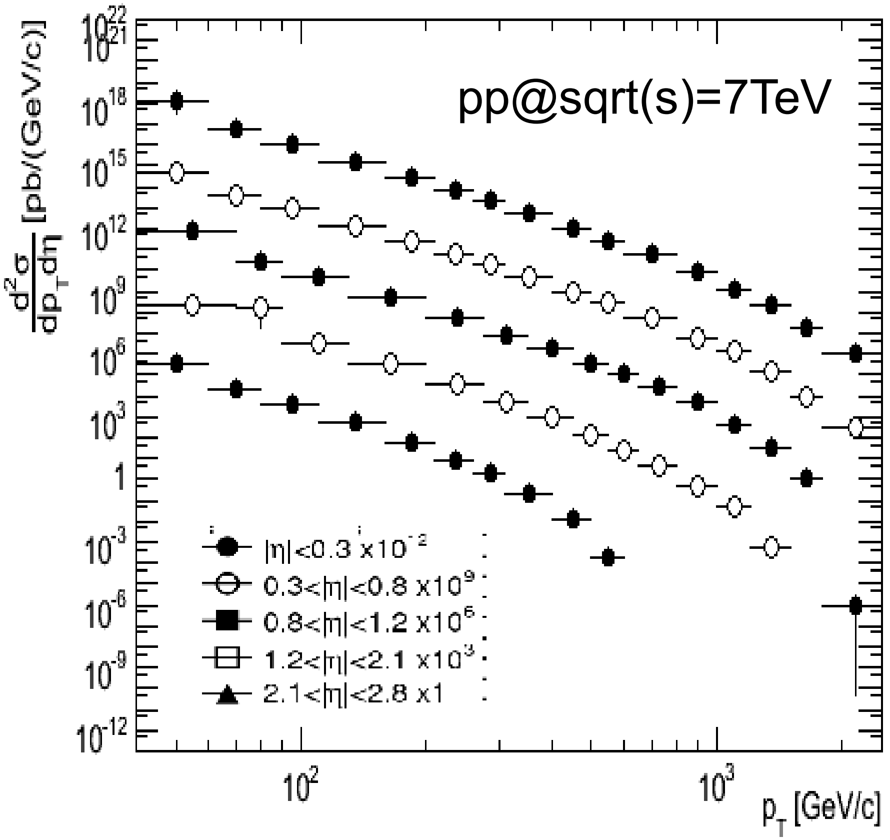
The collinear emission of partons can be approximated with a Parton Shower algorithm.

Many MCs have their own prescription for the parton shower.
Most of the MC are LO+ Parton Shower (Pythia, Herwig, Sherpa,....).
Recently NLO+PS.

By using the Parton Shower,
the outgoing jets start to have a complex structure.

Leading order + Parton Shower - Pythia





Comparing LO and Parton Showers

Division of the LO+PS by the LO prediction.

We start to see differences between the AntiKt R=0.4 and the AntiKt R=0.6

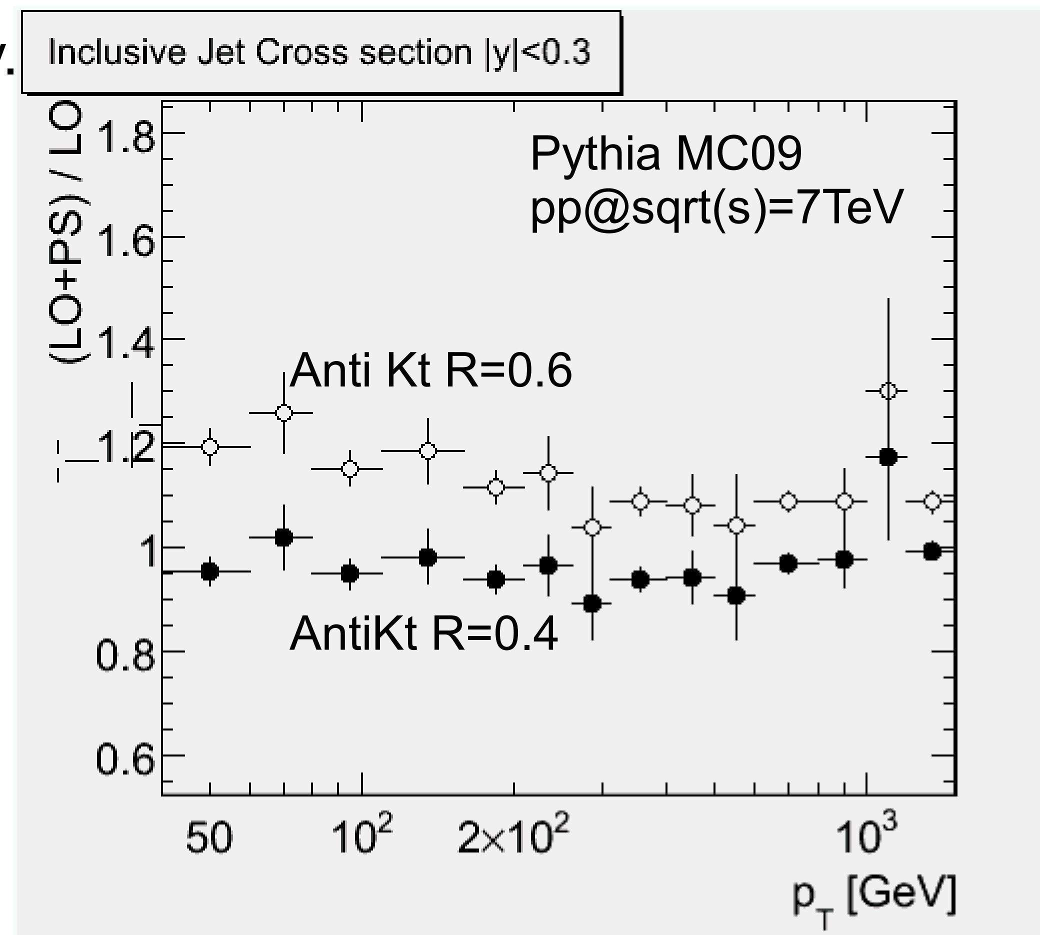
Bigger radius integrates more energy.

The effect is almost flat in p_T,

The main contribution is an overall scale in the cross section.

This result depends on the PDF used to make the prediction.

In this case: MSTW LO*



Other effects?

At the end of the parton shower, we end up with a bundle of collimated partons for each jet.

The final state is more realistic than just 2 or 3 partons.

PRO:

Models to describe the passage from the parton level to the particle level:

- Hadronization
- Underlying event (i.e. extra parton-parton interactions in the same proton-proton collision)
- The models can be tuned to reproduce as much as possible the data

CONS:

The normalization of the cross section is accurate at the LO

The LO+ PS is a good tool to check the properties of the jets, but we should try to use the knowledge of the NLO cross section for our theoretical prediction.

HOW?

How to get a prediction

NLO with non perturbative correction: The traditional way

Ingredients:

1) NLO cross section at parton level σ^{Parton}_{NLO}

2) Cross sections generated with MC (Pythia, Herwig,...)

For the MC we can decide to stop the simulation before the hadronization and the UE

$\sigma^{Parton}_{ue\ off,\ had\ off}$ (shown in pg.14)

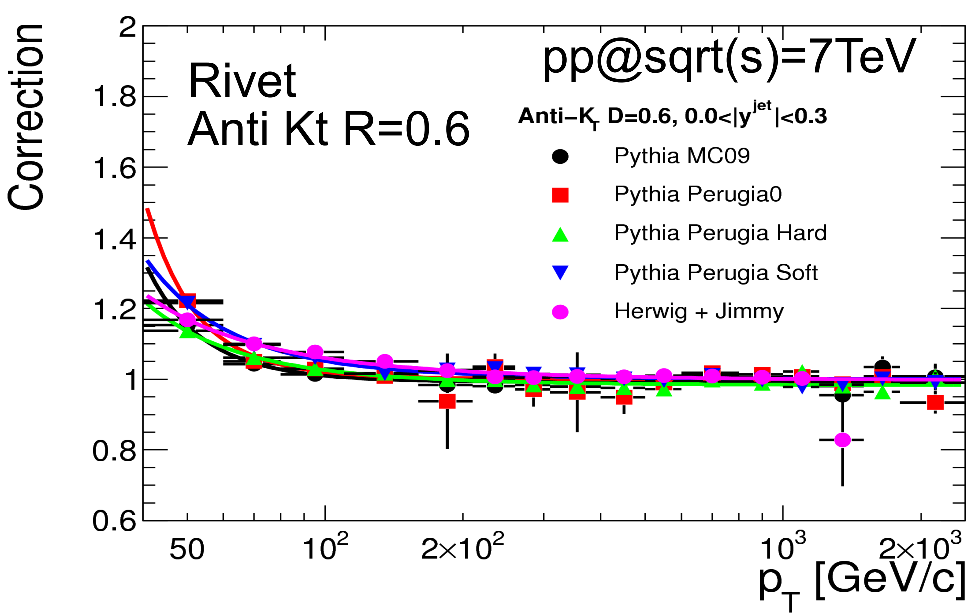
We can check the effect of the hadronization and of the underling event by comparing $\sigma^{Parton}_{ue\ off,\ had\ off}$ with the cross section at hadron level

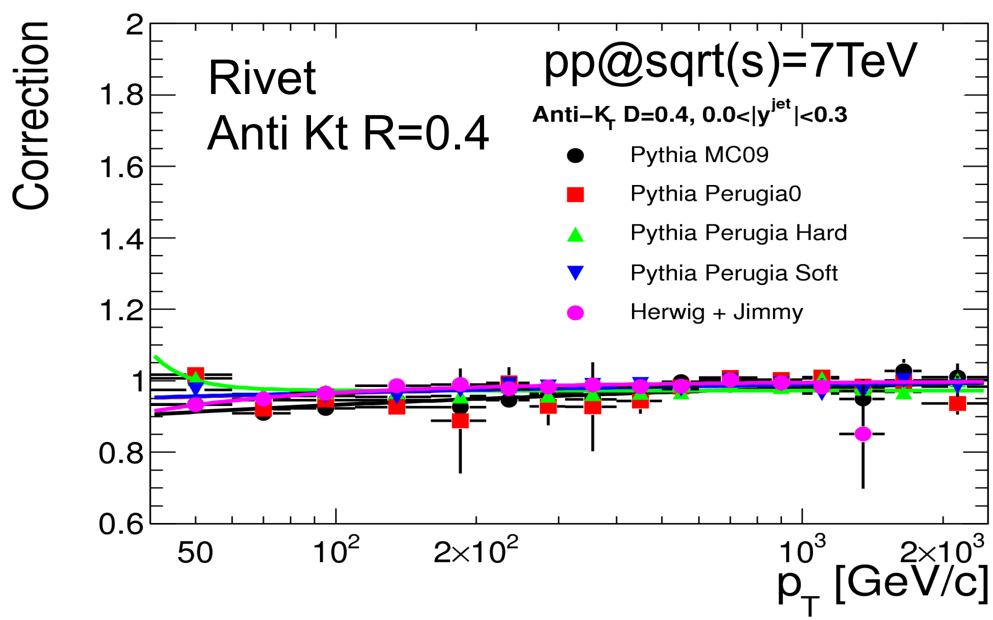
$$C=\sigma^{Hadron}_{ue\ on,\ had\ on}/\sigma^{Parton}_{ue\ off,\ had\ off}$$

Theortical Prediction: C σ^{Parton}_{NLO}

Non perturbative corrections

The non perturbative corrections are usually derived from different MC generators.
Different models for the Hadronization and the Underlying event.
The correction depends on the area of the jet.
Bigger Area = UE contribution becomes dominant
= More energy in the cone= correction > 1
Smaller Area = less UE contribution in the cone = correction <~1



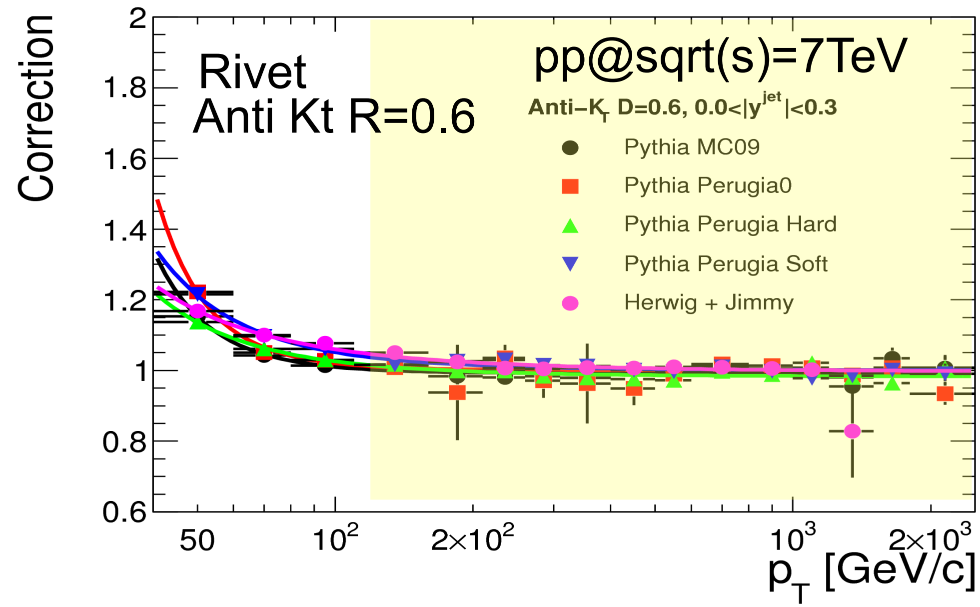


The plots seem to show that the correction above 100-200 GeV are ~1.

Non perturbative corrections

In the yellow region, the non perturbative effects give a small contribution

The cross section at NLO should be ~ OK.



BUT, can we have a more coherent way to incorporate:
- •NLO?
- •Parton Shower?
- •Hadronization?
- •Underling event/ MPI ?

NLO+Parton showers

Different methods to construct NLO event generators are available for a considerable number of hadron collider processes.

Two main formalism, the MC@NLO and the Powheg:

MC@NLO
S. Frixione and B. R. Webber, JHEP 06 (2002) 029
Higgs boson, vector bosons, heavy quark pair, single top,....

Powheg
S. Frixione, P. Nason, and C. Oleari, JHEP 11 (2007) 070
Higgs boson, vector bosons, heavy quark pair, single top, dijets ....

And different implementations:
Herwig++, Sherpa,....

POWHEG

Positive Weight Hardest Emission Generator

A method to interface NLO calculations with Parton Shower (NLO+PS)

- Formulation of the method: P.N. 2004
- First implementation: $hh \to ZZ + X$, Ridolfi, P.N. 2006
- General formulation of the method: Frixione, Oleari, P.N. 2007
- POWHEG BOX: Alioli, Oleari, Re, P.N. 2010

P.Nason - QCD at the LHC, Trento,
29 Sept. 2010

The POWHEG simulated events can be showered by Pythia, Herwig, Pythia8, Herwig++,....

It is useful to check the differences introduced by the different Monte Carlo generators

POWHEG-BOX

From the POHWEG Box web page

Processes:

Single vector-boson production with decay,
S. Alioli, P. Nason, C. Oleari and E. Re, JHEP 0807 (2008) 060

Vector boson plus one jet production with decay,
S. Alioli, P. Nason, C. Oleari and E. Re, JHEP 1101 (2011) 095

Single-top production in the s- and t-channel
S. Alioli, P. Nason, C. Oleari and E. Re, JHEP 0909 (2009) 111

Single-top production associated with a W boson
E. Re, Eur. Phys. J. C71 (2011) 1547

Higgs boson production in gluon fusion
S. Alioli, P. Nason, C. Oleari and E. Re, JHEP 0904 (2009) 002

Higgs boson production in vector boson fusion
P. Nason and C. Oleari, JHEP 1002 (2010) 037

Jet pair production
S. Alioli, K. Hamilton, P. Nason, C. Oleari and E. Re

Heavy-quark pair production
S. Frixione, P. Nason and G. Ridolfi, JHEP 0709 (2007) 126

W+ W+ plus dijet production
T. Melia, P. Nason, R. Rontsch, G. Zanderighi, arXiv:1102.4846

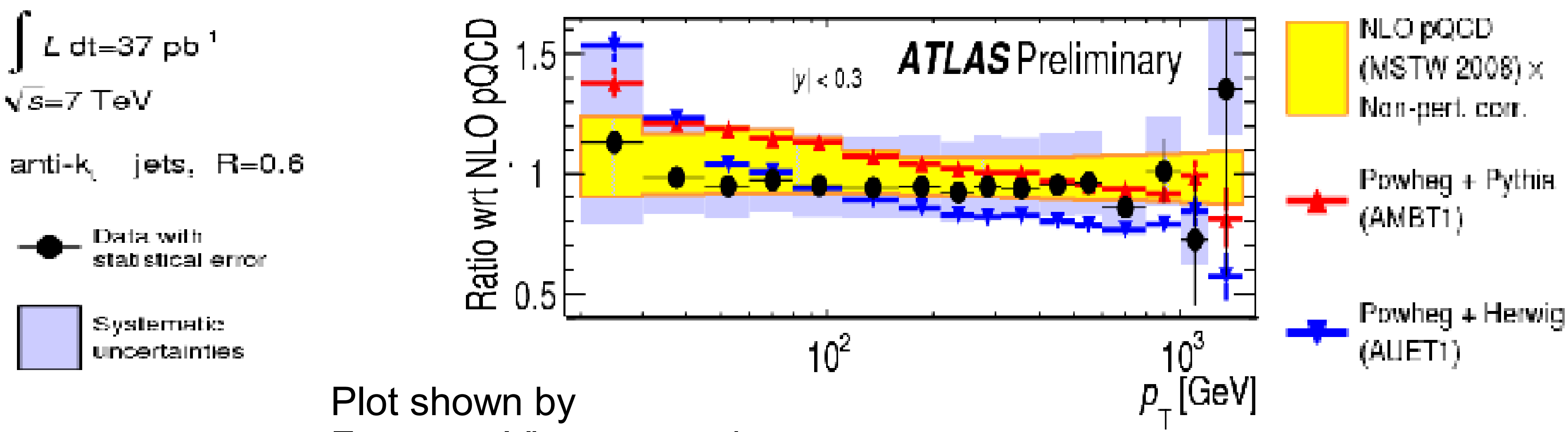
Why jet pair production is interesting?

Extraordinary efforts in producing NLO+PS for different processes,   but only few of the processes have in the leading order 2 final partons.

Jet pair production was the first process.

A natural benchmark to test the method and to check the predictions, important in the optic of moving to other processes with two or more jets + other objects.

Comparing the theories



Plot shown by
Francesc Vives yesterday

Comments:

0) **NO tunes for Powheg for the moment.**
Tunes inherited from standalone Pythia and (Herwig+Jimmy).

1) **Powheg + Pythia != Powheg + (Herwig+Jimmy)**
→ The variation is similar to yellow width (theoretical uncertainty).
→ But we have seen that the non pert. corrections above 200 GeV ~ 1

2) **The slopes of the NLO and of Powheg are different.**
→ Is there something missing in the traditional way to estimate the cross section?

3) **Which PDF should we use in this estimate?**

Conclusions

A rich set of progresses in the last years from the theoretical side in describing the jet production at LHC.

Some revolutions:

- New jet algorithms
- A really long list of processes known at the NLO (at least)
- New NLO+MC codes for an increasing number of processes
- New ideas to get information from the higher order and
- the non perturbative effects

The fast feedbacks from the experimental measurements of jets are crucial to constrain as much as possible the QCD predictions.

Important measurement to have a robust understanding of the QCD backgrounds for jet spectroscopy at LHC.