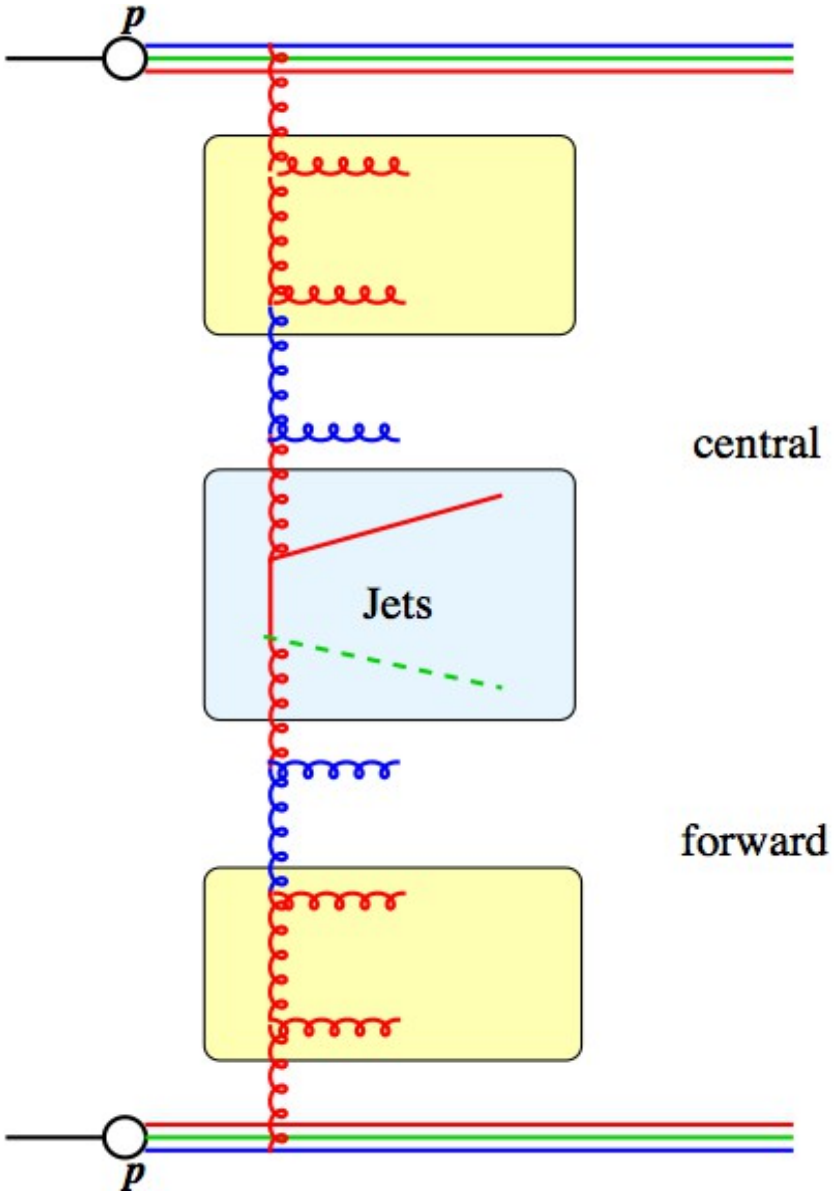
Challenges in hard QCD at LHC

H. Jung (DESY, Univ Antwerp)

Outline:

- Where pQCD calculations describe measurements:
  - inclusive jets, heavy flavors at central rapidities
- Where measurements challenge theory:
  - at forward rapidities
- Looking a bit deeper into pQCD calculations
  - do we need uPDFs/TMDs ?
- Where descriptions are completely off:
  - jets at large rapidity separations

Jet production



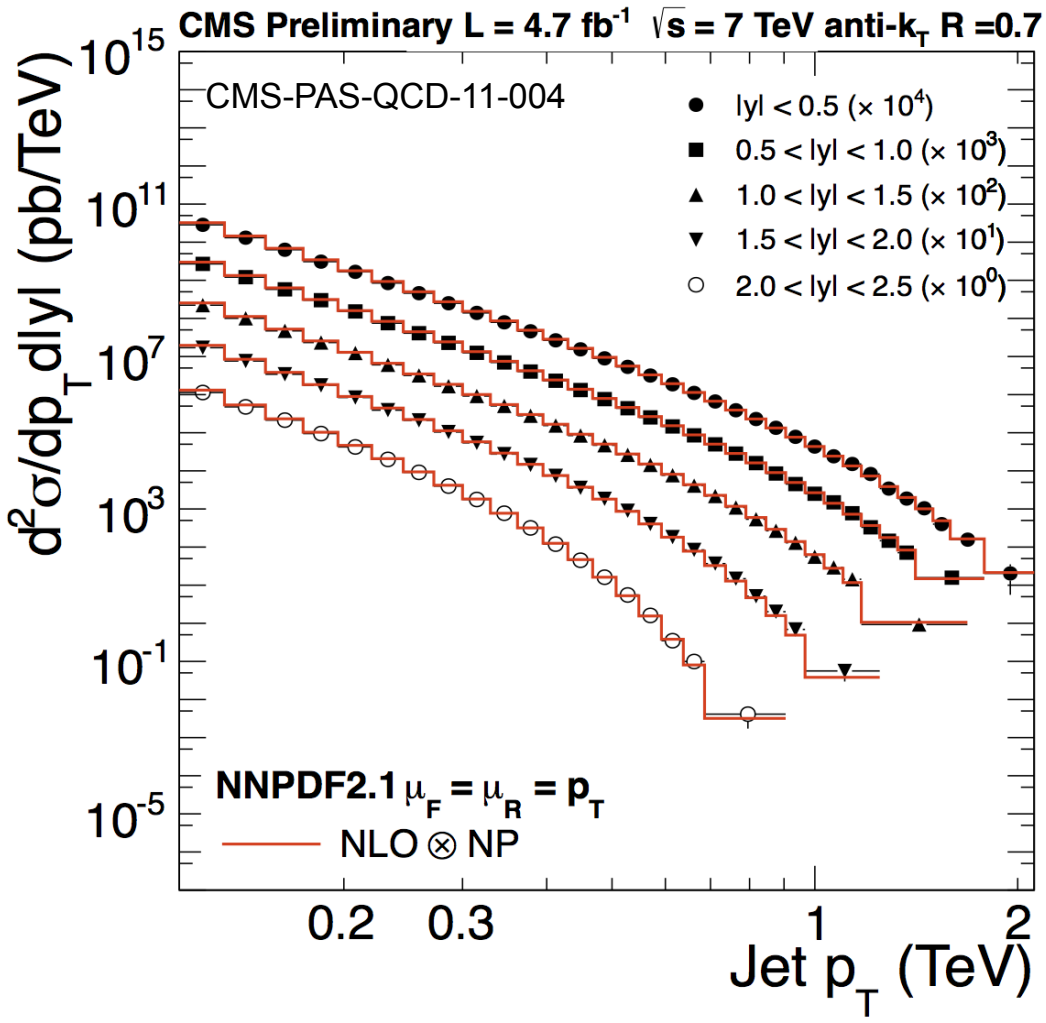
accessible values at $\sqrt{s}$ = 7 TeV

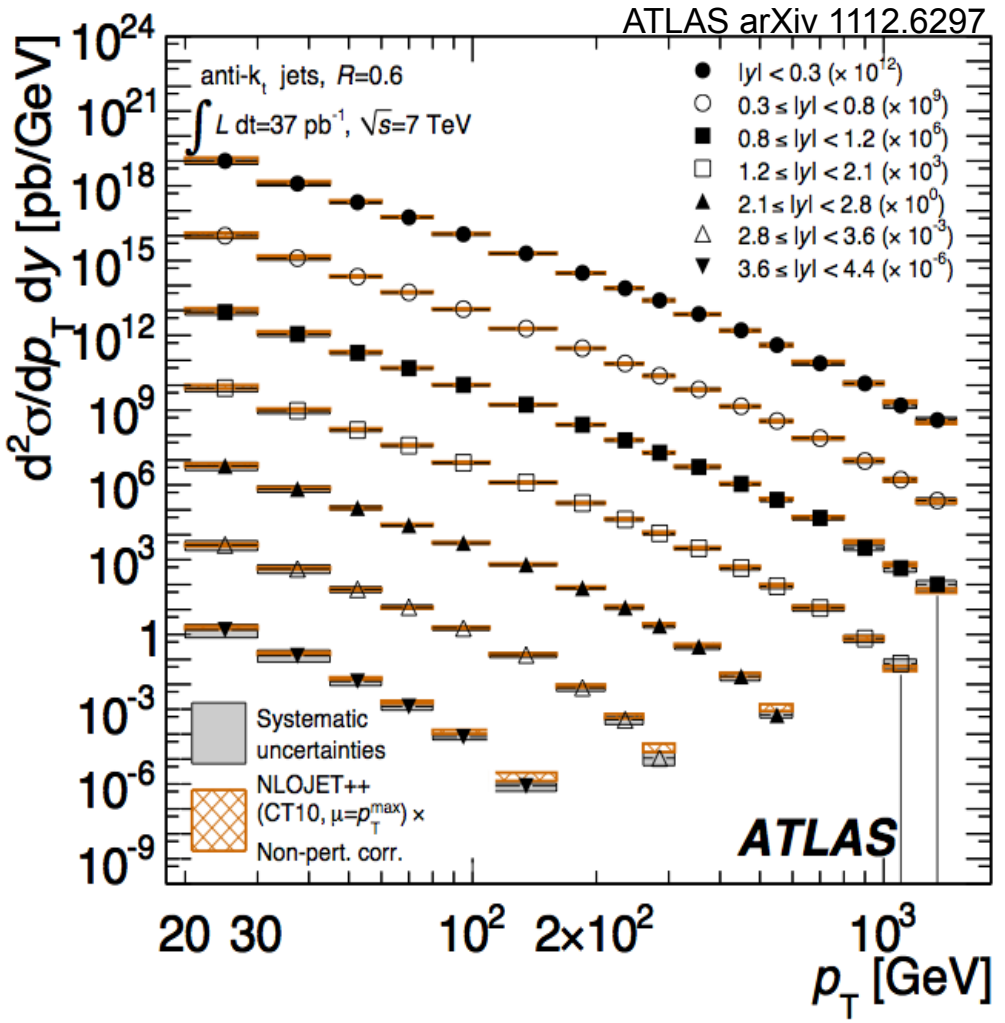
$$x = \frac{2p_t}{\sqrt{s}} \exp(\pm y)$$

p_t	central (η=0)	forward (η=3)
35	$1\ 10^{-2}$	$0.2, 5\ 10^{-4}$
100	0.03	$0.6, 1.5\ 10^{-3}$
150	0.04	$0.8, 2\ 10^{-3}$
500	0.14	–
1000	0.28	–
2000	0.57	–
3500	1.0	–

- study of small and large x !!!

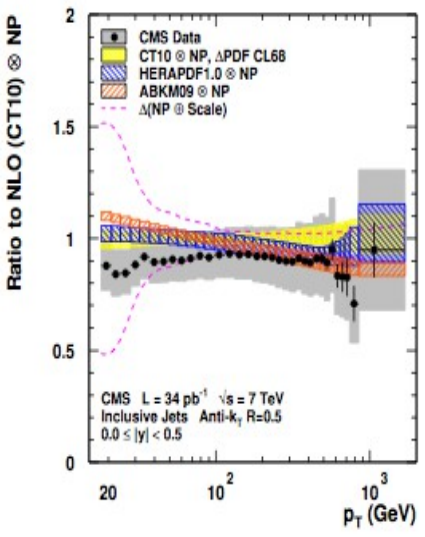
Where NLO calc work: inclusive jets

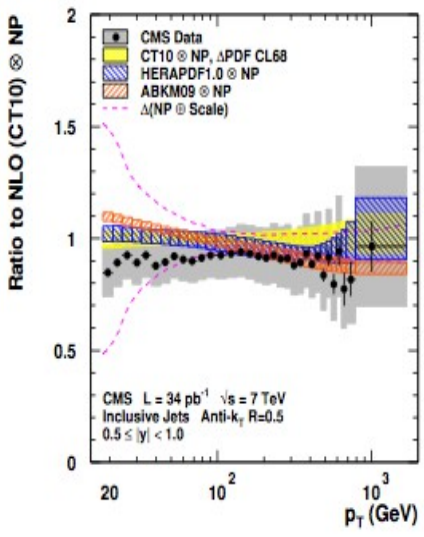


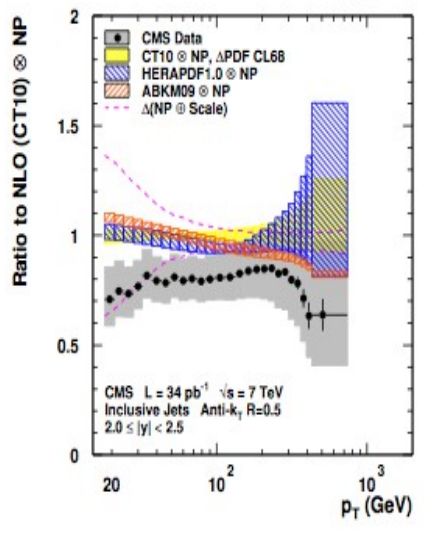


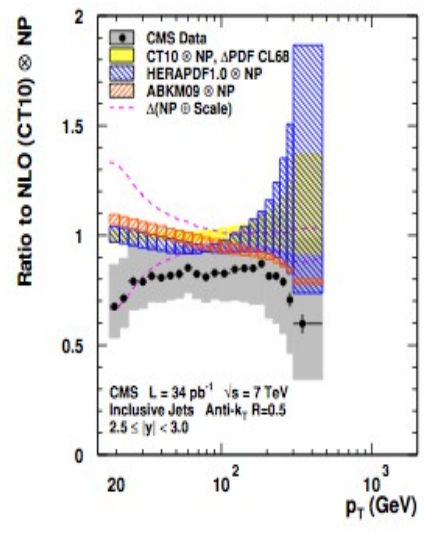
- Very good agreement between NLO calculation and measurements over a hugh range in pt, now reaching up to 2 TeV ($x \sim 0.6$) !

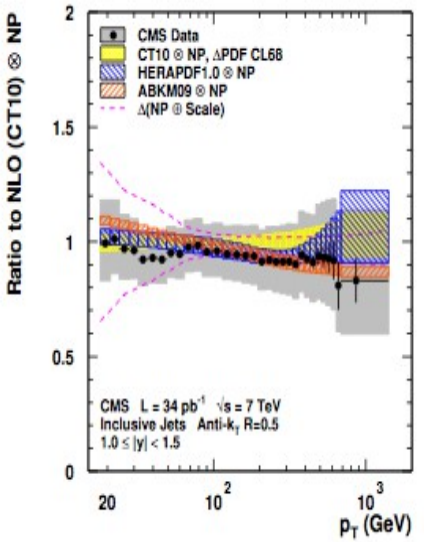
Where NLO calc work …

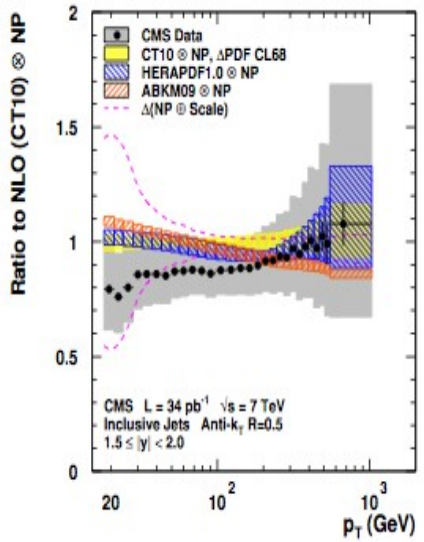


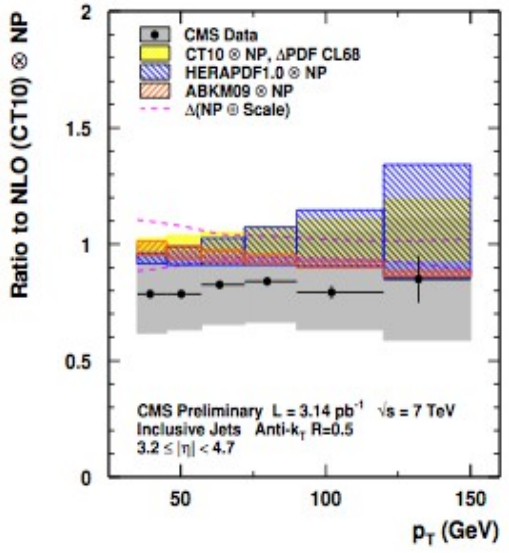












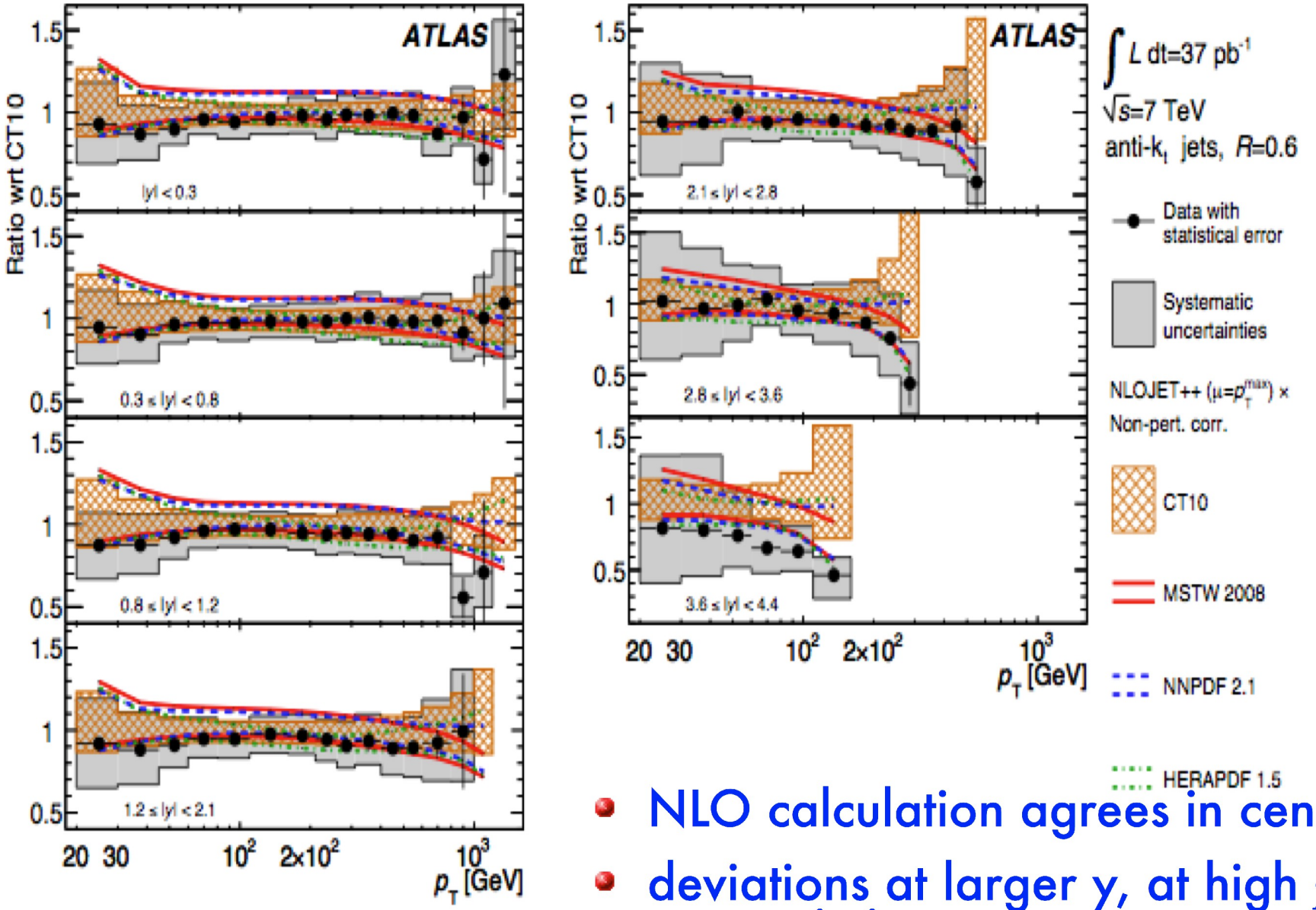
from: K. Rabbertz
CMS note 2011/004

NOTE:
2010
data

- Agreement within experimental uncertainties in central y range
- NLO starts deviating in forward region

Where NLO calc work …

ATLAS arXiv 1112.6297



- NLO calculation agrees in central y
- deviations at larger y, at high p_t outside uncertainties

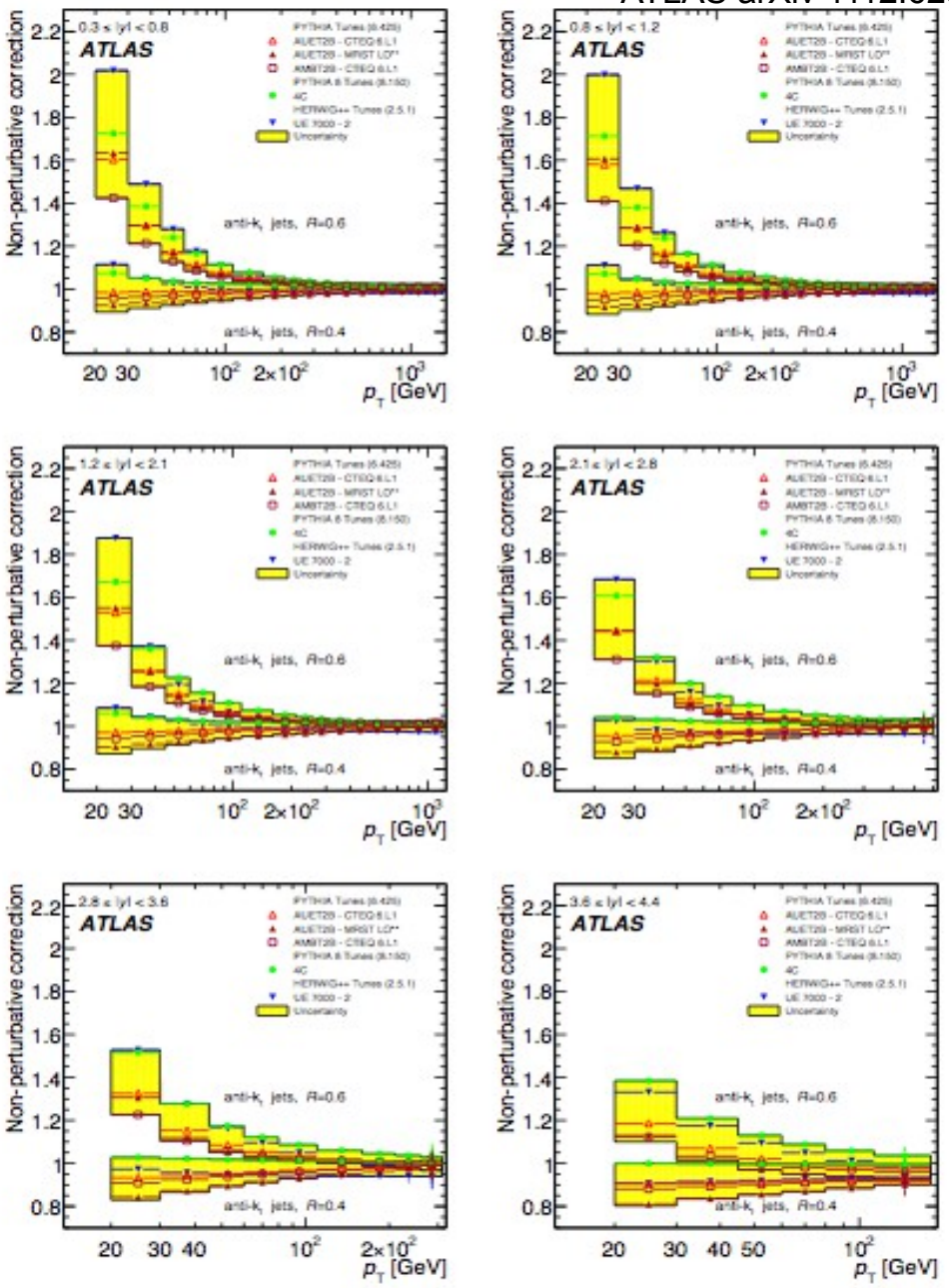
"non-perturbative" corrections

- Measurements corrected to stable hadron level
- corrections from hadron to NLO parton level needed
  - ➔ "non-perturbative" corrections (NP) (really non-perturbative ???)
  - ➔ calculated from MC generators PYTHIA/HERWIG

$$C_{np} = \frac{N_{MC}^{PS+MPI+had}}{N_{MC}^{PS}}$$

- Jet cone radius: competition between PS and MPI !

ATLAS arXiv 1112.6297

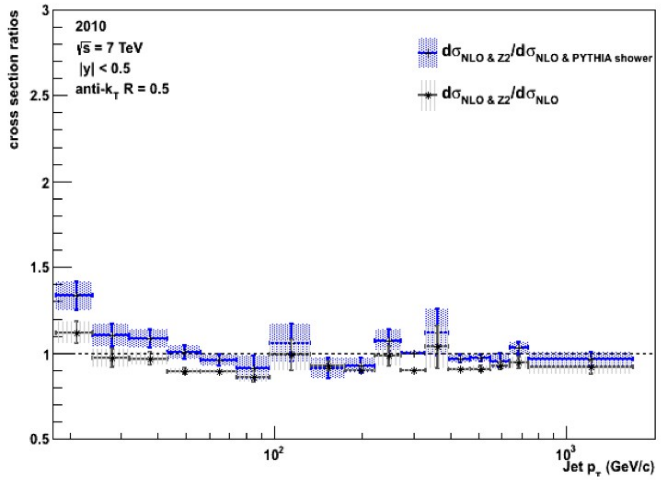


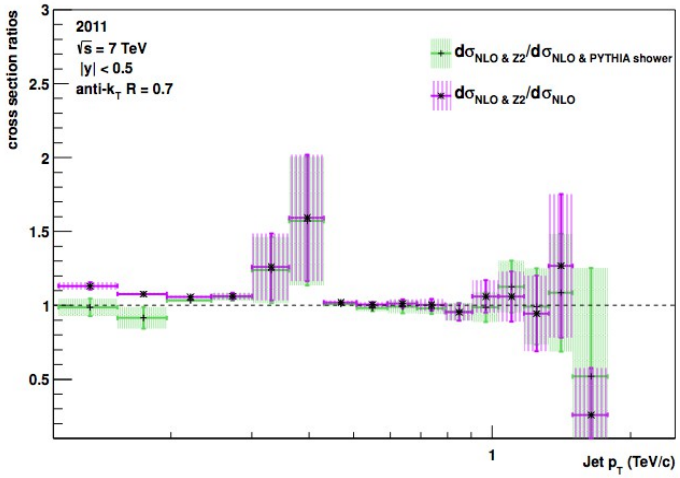
"non-perturbative" corrections

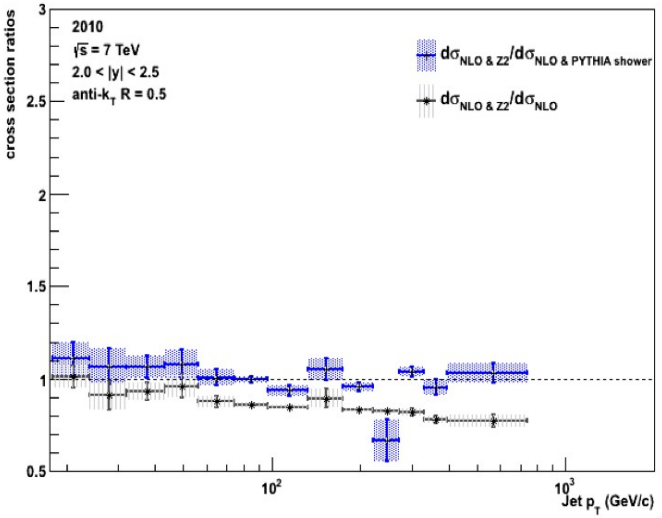
- NP Corrections from POWHEG

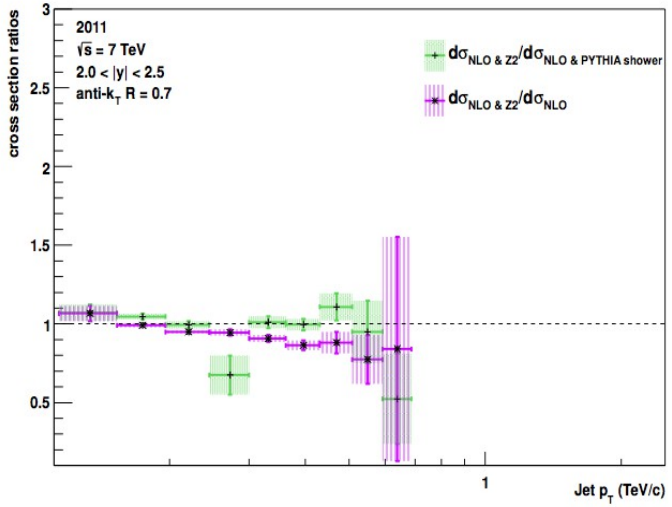
$$C^{a}_{np} = \frac{N^{PS+MPI+had}_{POWHEG}}{N^{PS}_{POWHEG}}$$

$$C^{b}_{np} = \frac{N^{PS+MPI+had}_{POWHEG}}{N_{POWHEG}}$$









- for fixed order NLO, using NP corrections from LO MCs is inconsistent !!!

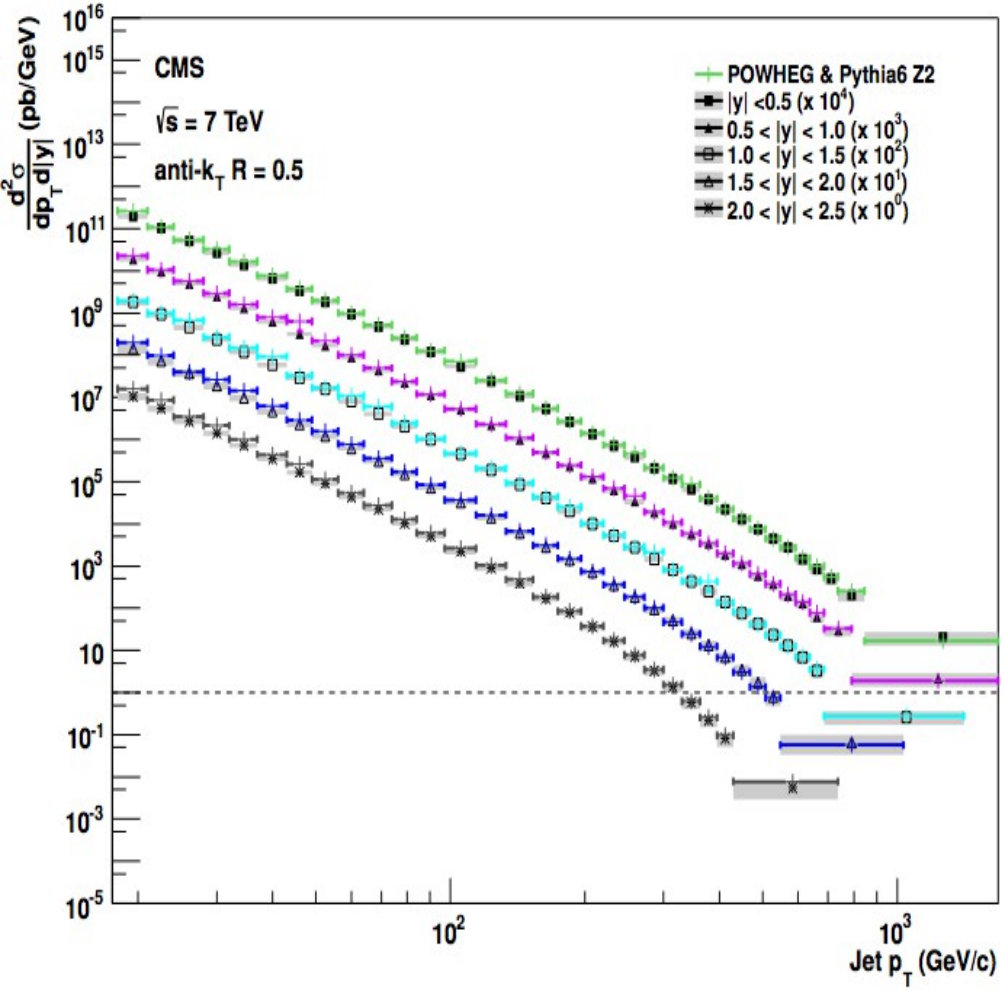
- NP corrections depend whether PS is included:
  - ➔ for fixed order NLO no PS should be applied

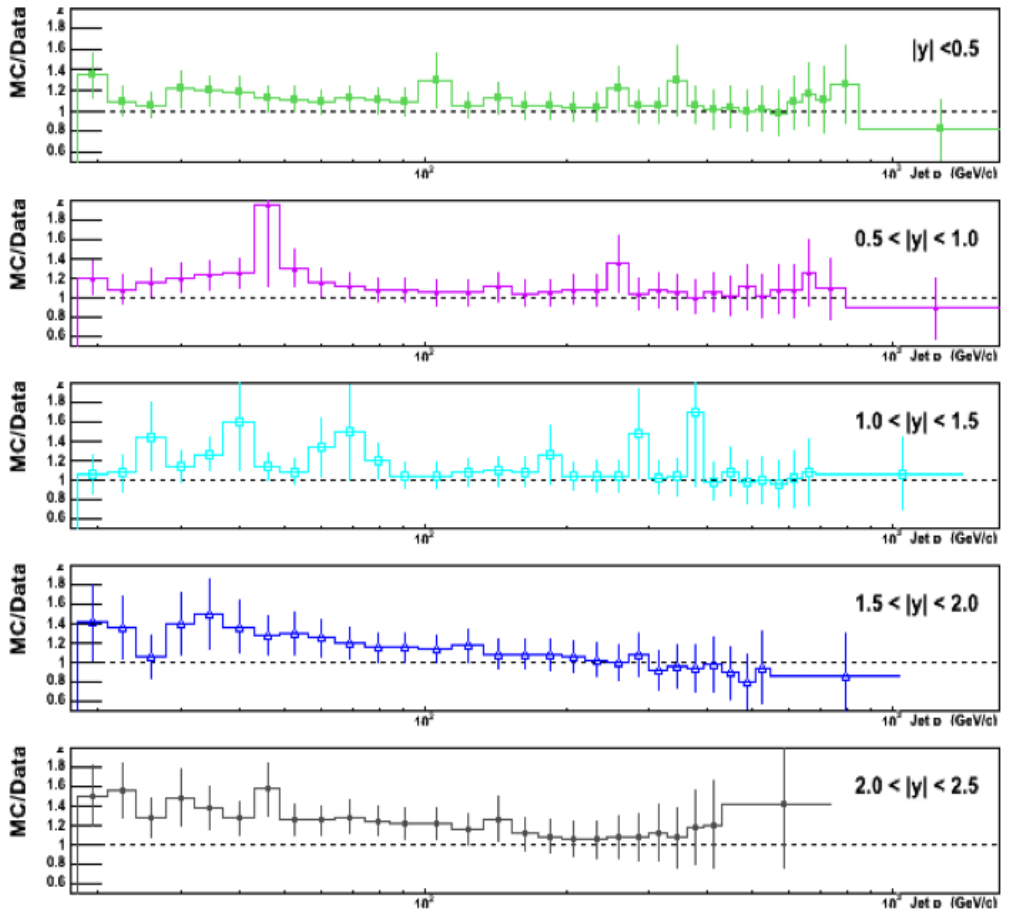
NOTE:
different to what is obtained from from PYTHIA/HERWIG

H. Jung, *Challenges in hard QCD at LHC*, Event Generator & Resummation workshop, May 2012,

Where NLO+resummation works ?

S. Dooling DESY-CMS

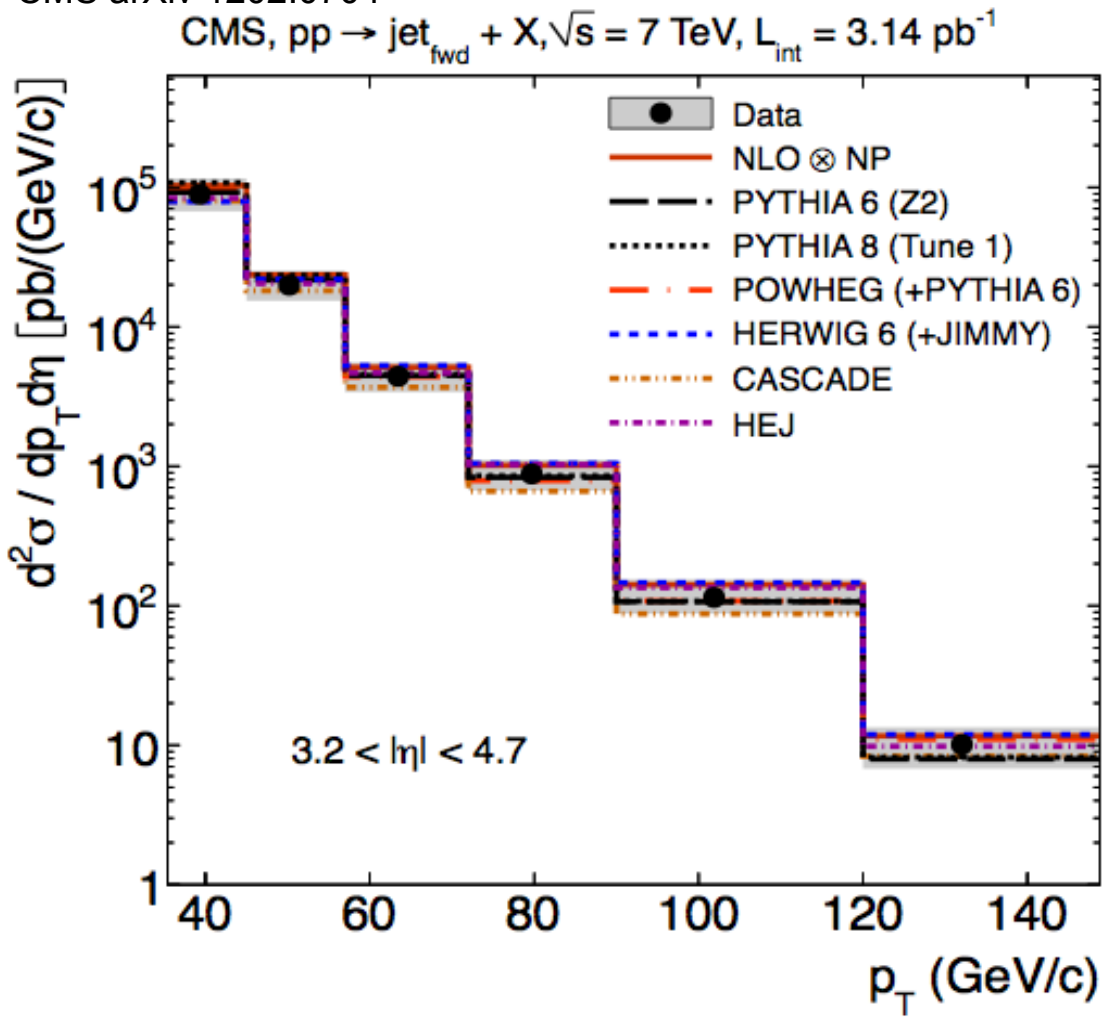


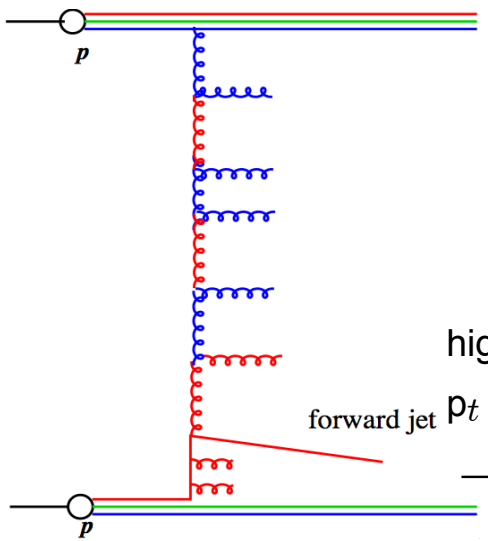


- POWHEG PYTHIA describes inclusive jets at stable hadron level
- no additional corrections applied !
- increasing differences towards forward region |y| > 2

Inclusive forward jet measurement

CMS arXiv 1202.0704





high energetic jets

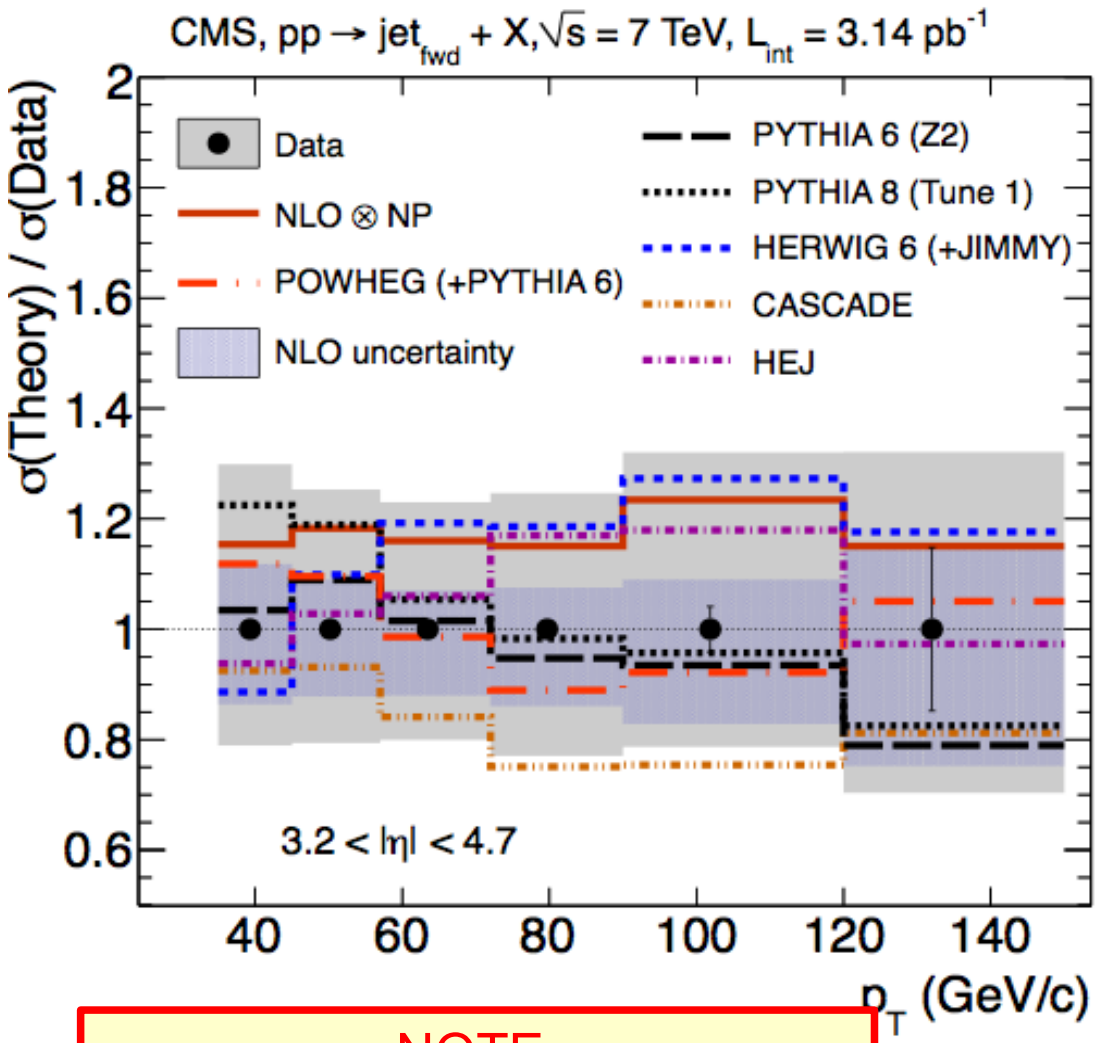
$p_t \sim 150$ GeV

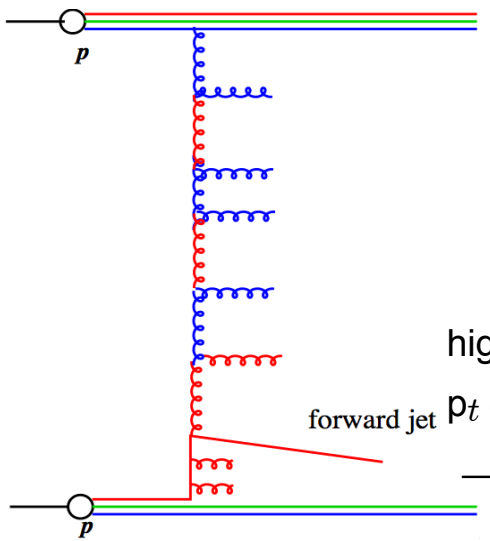
$\rightarrow E \sim 3000$ GeV

- jets measured in $3.4 < |\eta| < 4.7$
- largest systematic uncertainty: Jet energy scale
- all theory predictions agree with data within experimental uncertainties

Inclusive forward jet measurement

CMS arXiv 1202.0704





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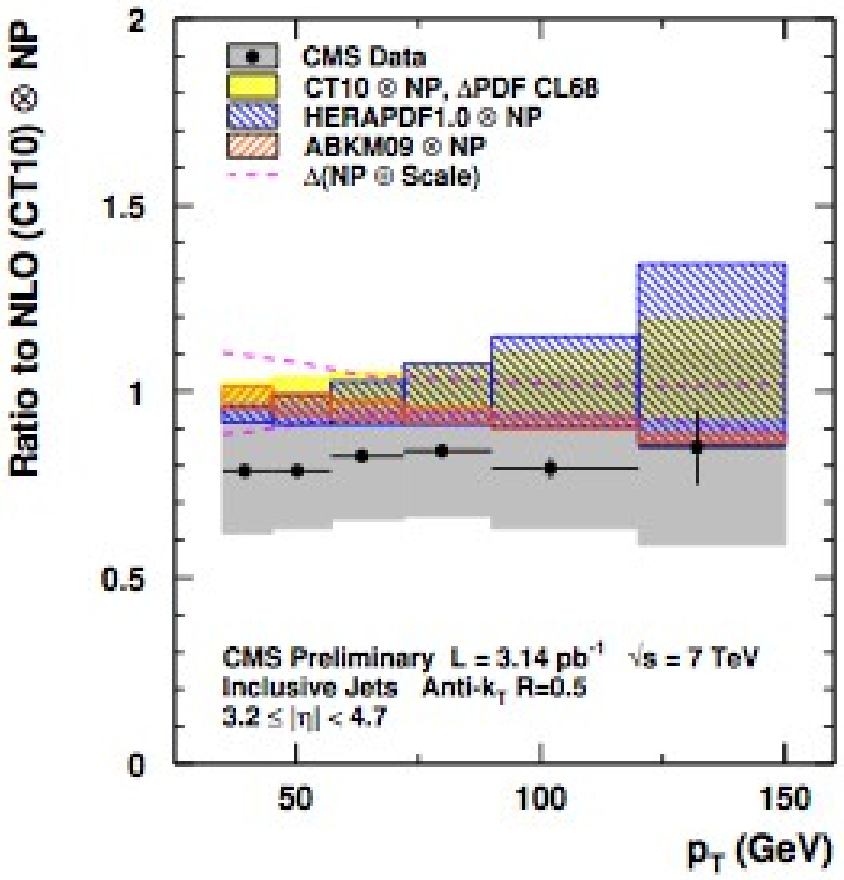
NOTE:
NLO ⊗ NP ≠
POWHEG + PYTHIA

Inclusive forward jet measurement

CERN-CMS-note 2011-004

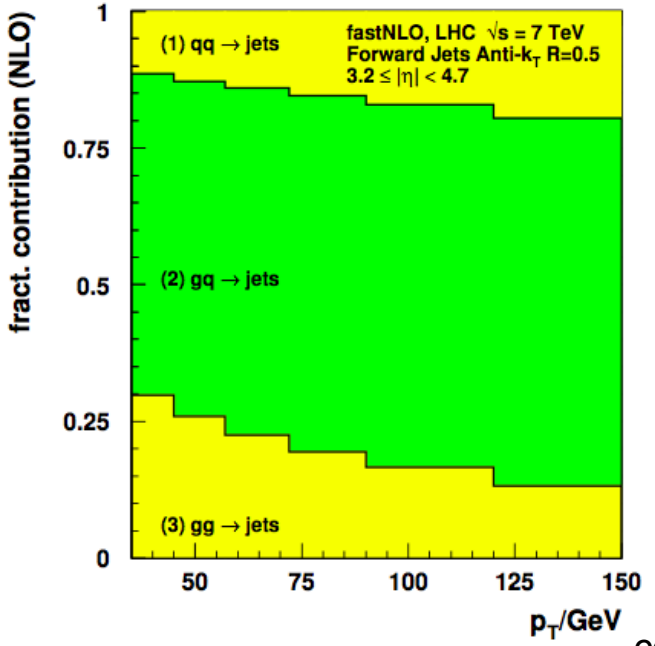


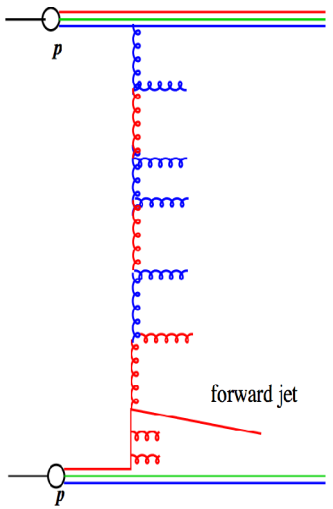
- scale: μ_f & μ_r varied by 2 independently

➔ ~ 10 %

- PDF uncertainties largest at large p_t coming from large x partons

~ 10 … 30 %

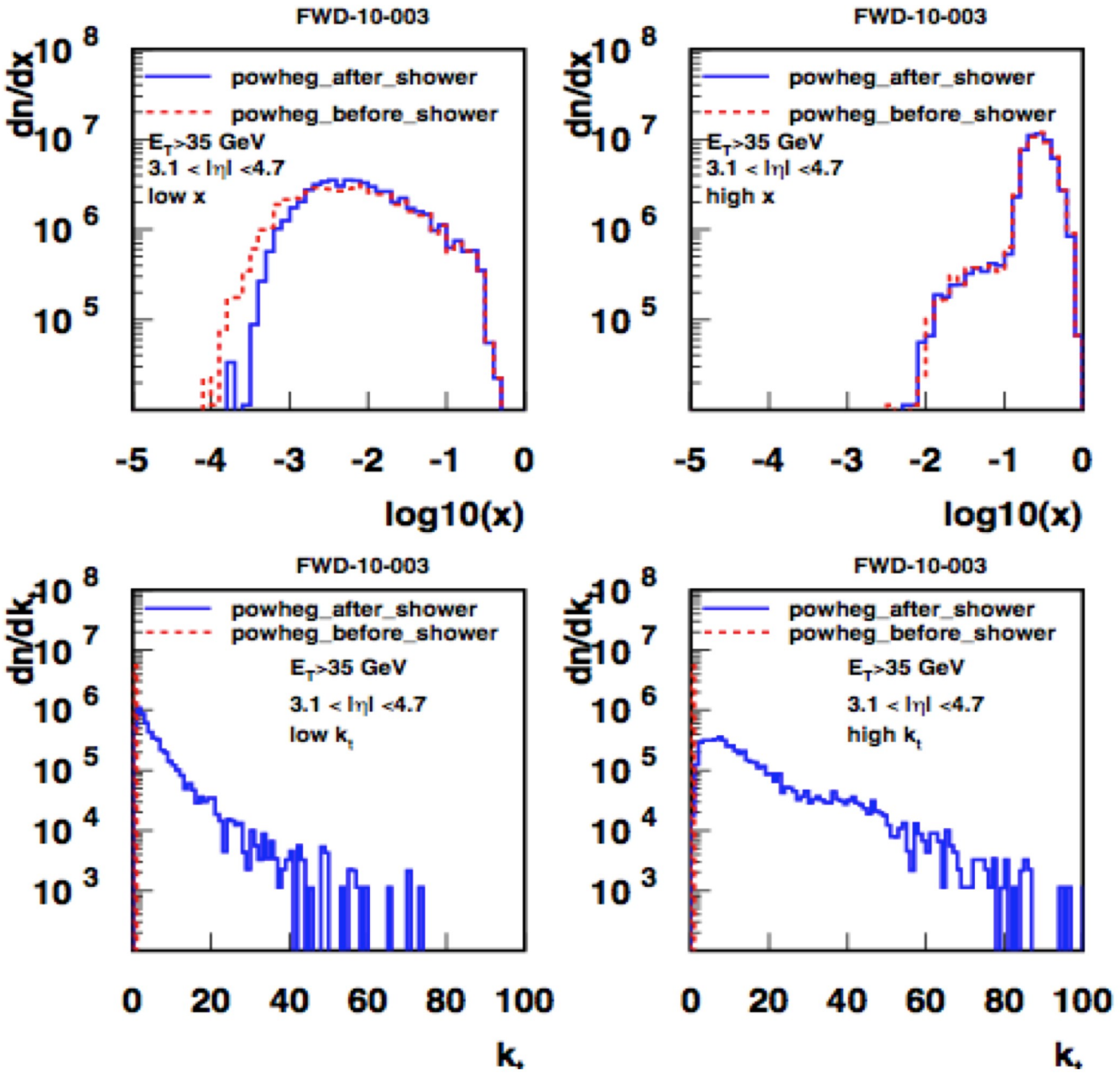




courtesy K. Rabbertz

- forward jet measurement can constrain high x and low x parton distributions

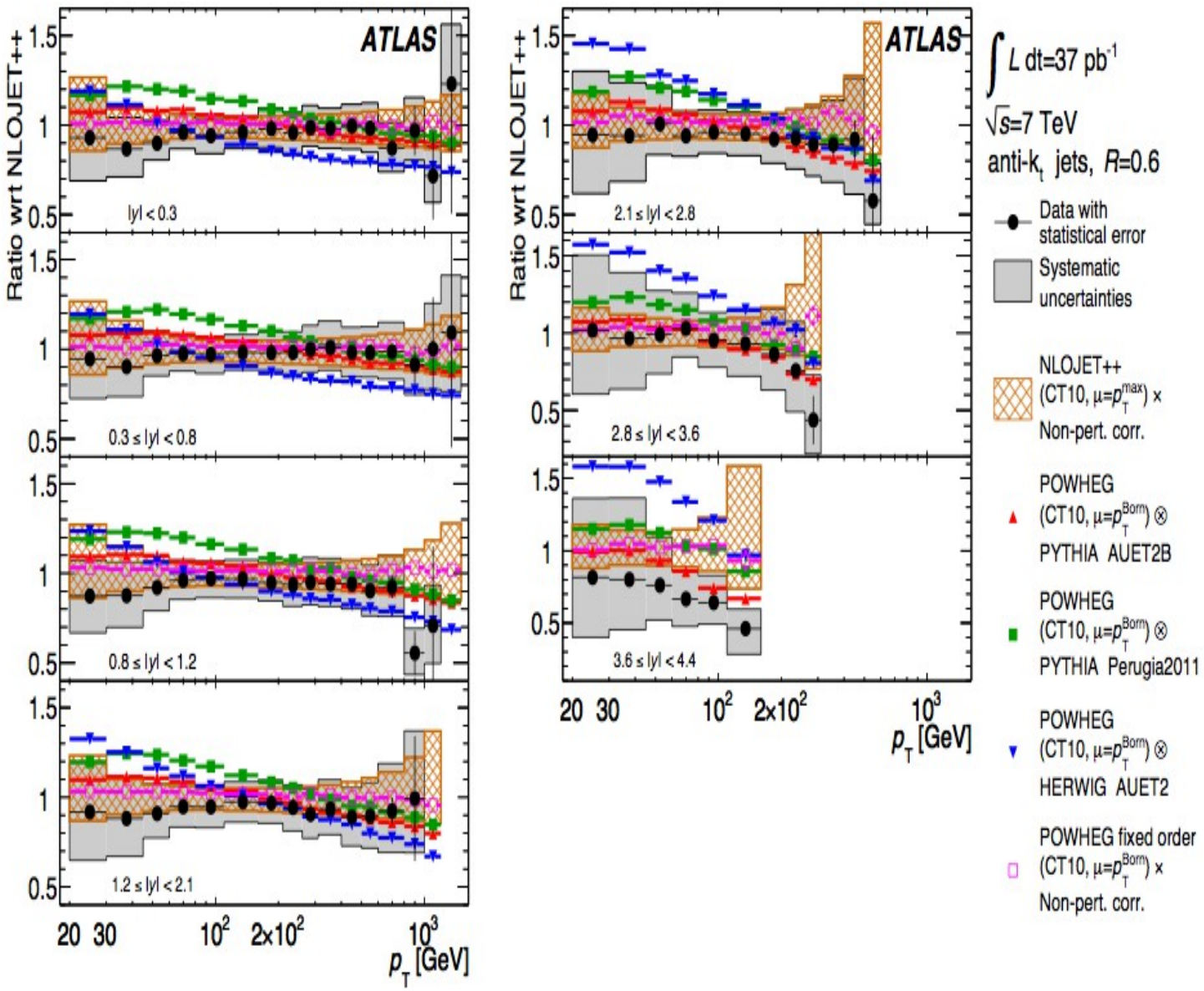
Using inclusive Jets for PDFs ?



- x distribution for inclusive jets in POWHEG different after shower
- can this be consistently used in PDF fits ?

Where measurements challenge theory

ATLAS arXiv 1112.6297



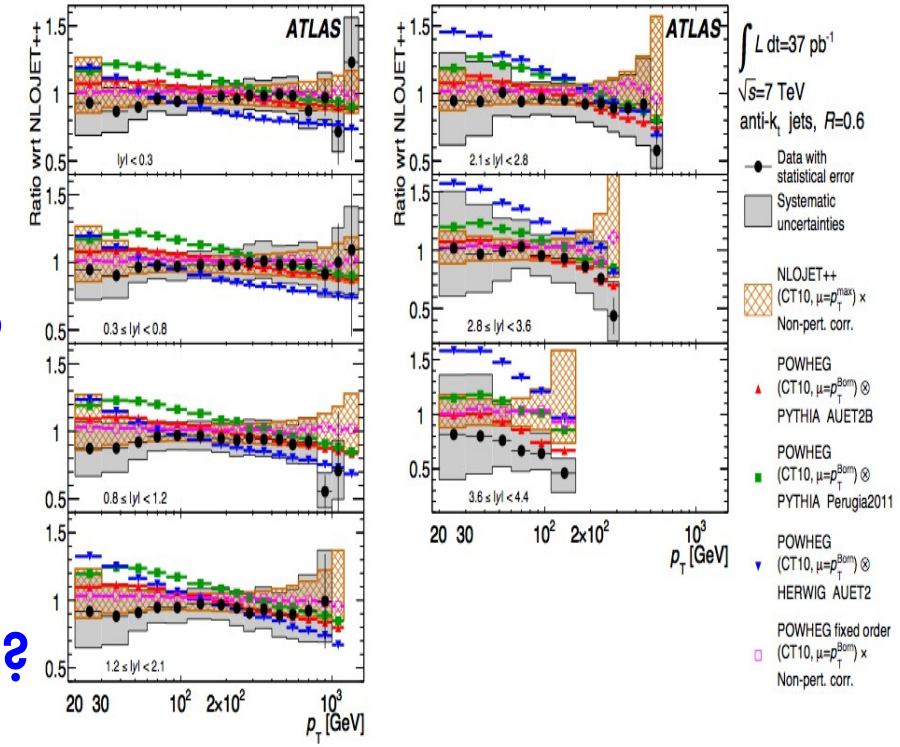
- Comparison with POWHEG
- large differences with PYTHIA and HERWIG PS seen in forward regions
- differences seen even in different tunes !

Where measurements challenge theory

ATLAS arXiv 1112.6297

Differences of PYTHIA/HERWIG PS show sensitivity to higher order radiation in inclusive jets > $O(\alpha^3_s)$

- BUT: higher order contributions also treated by scale variations … which are very different….
- Are differences from different PS or due to different kinematic matching ?



HELP:

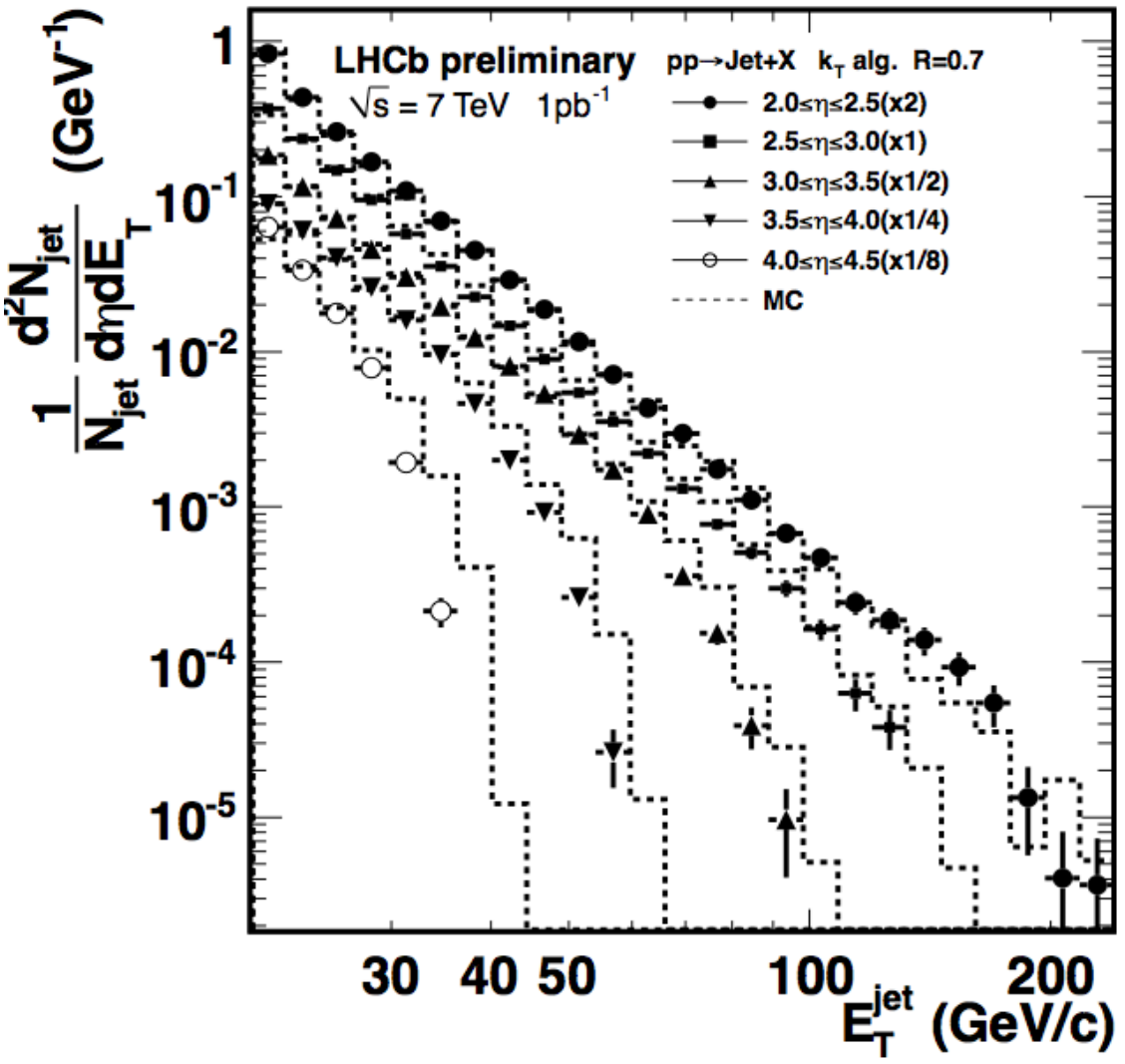
Most inclusive jet measurement suffers from higher orders !

Deviations at forward η

LHCb CONF-2011-015

- kt-algo jets p_t > 20 GeV
- PYTHIA at detector level
  - small η, MC describes data
  - large η, large p_t, MC significantly above data

➔is this just a problem of MC or is there physics behind ?

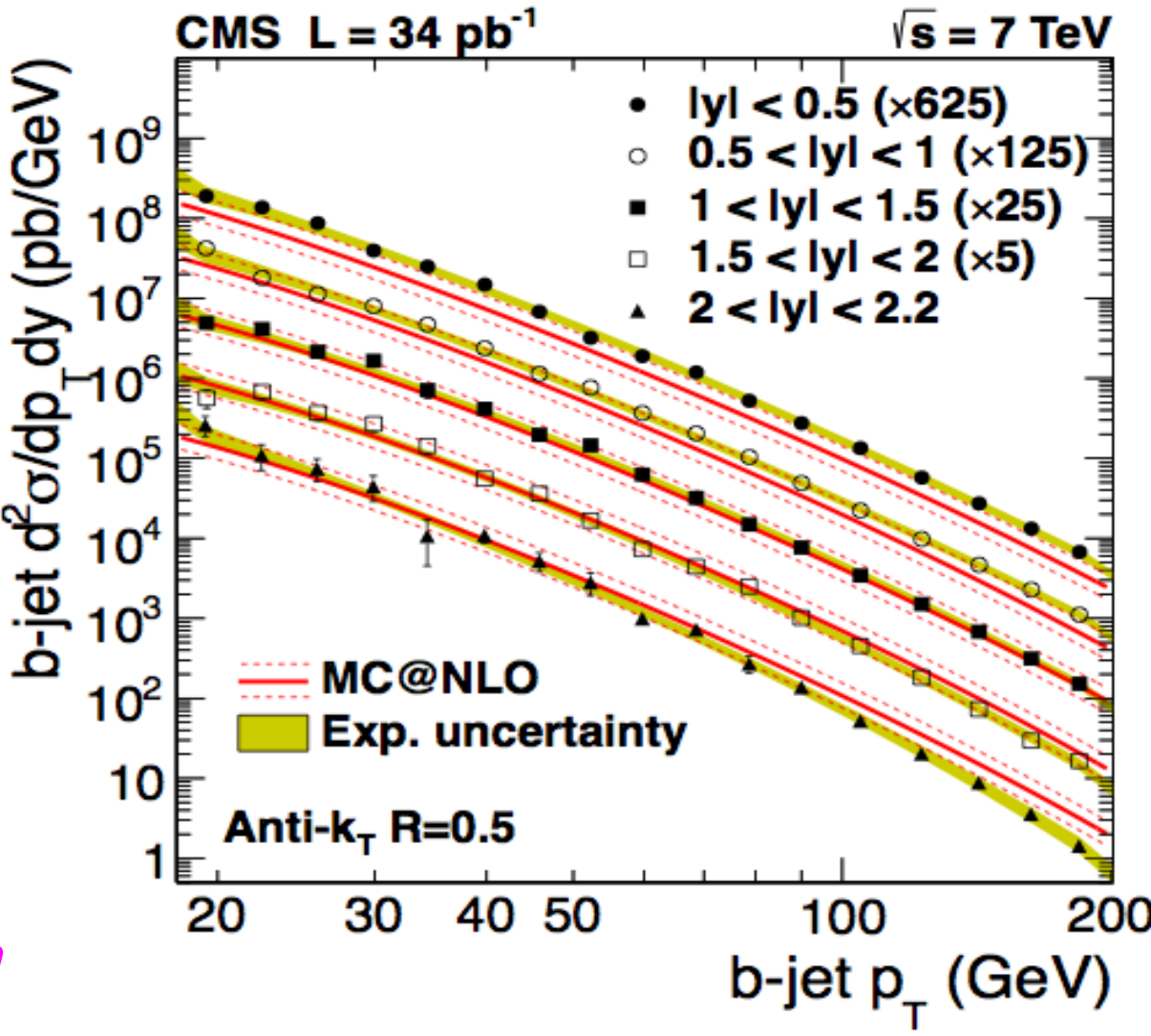


Challenge: inclusive b-jets

- b-jet production $gg \to b\bar{b}$ dominates
- inclusive b-jets: probe of gluon density
- Reasonable description by MC@NLO at central rapidities
- data significantly below prediction at large rapidity and large p_t

➔ similar to incl.jets at large η

CMS 1202.4617



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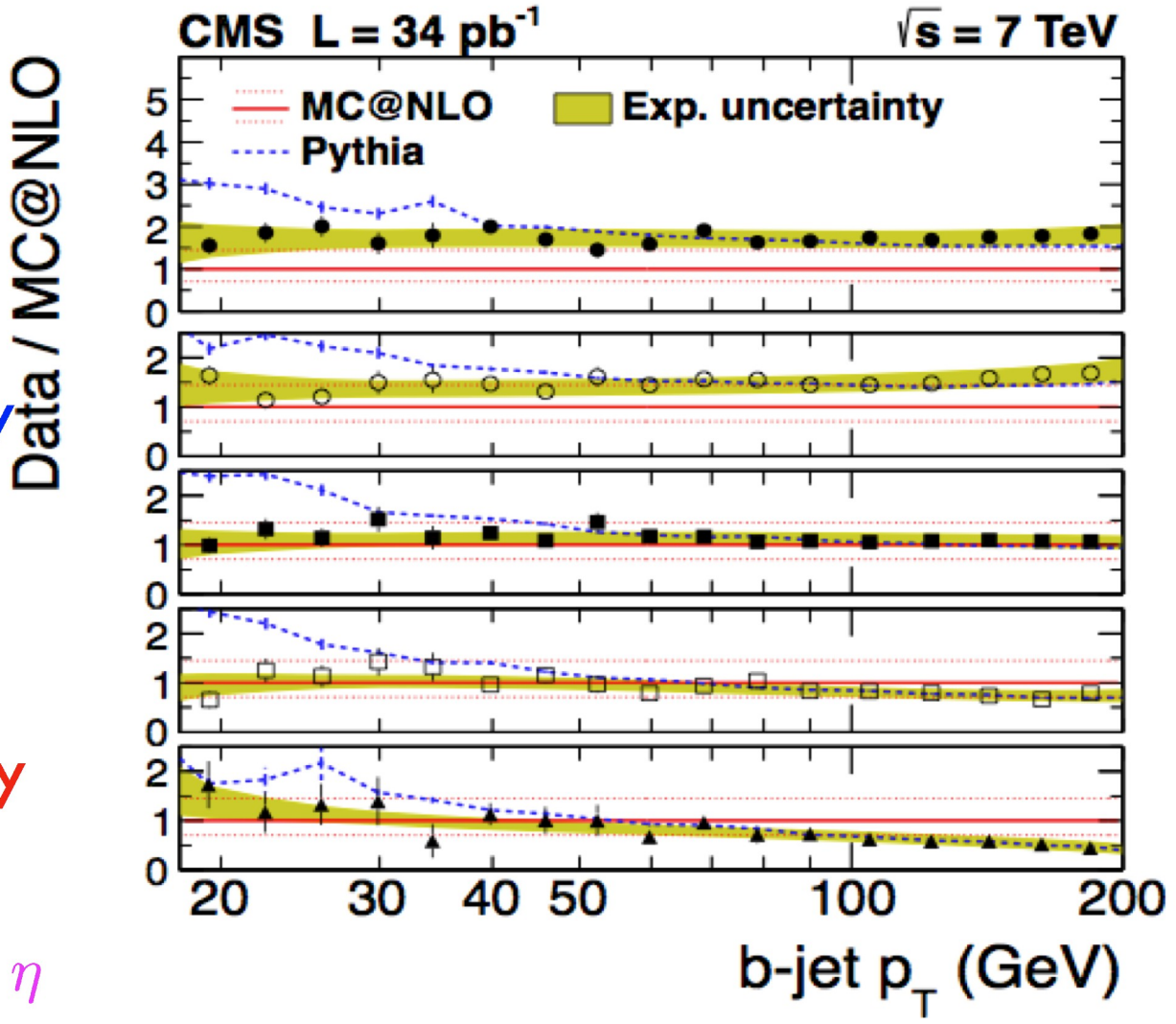
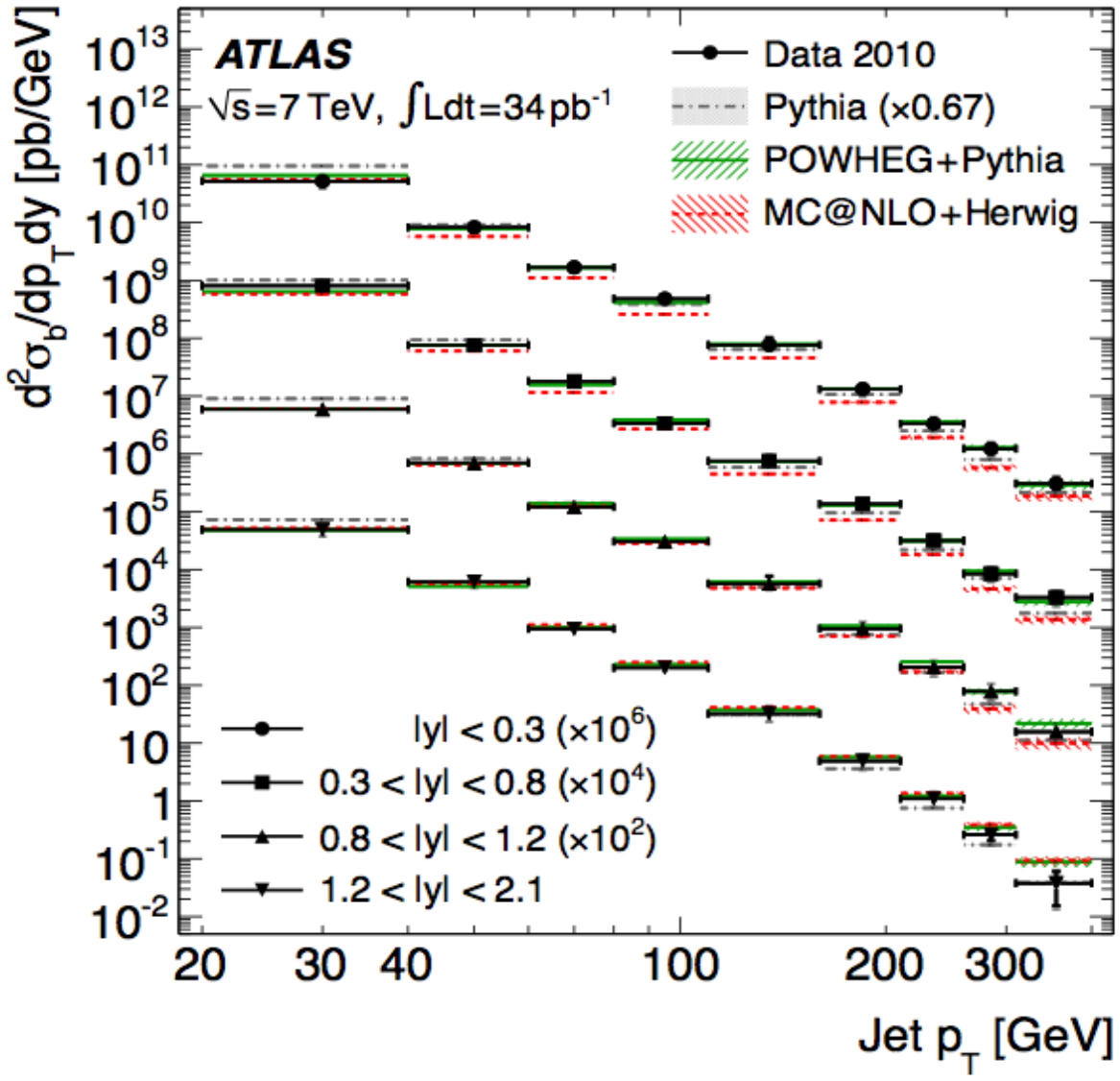


Challenge: inclusive b-jets

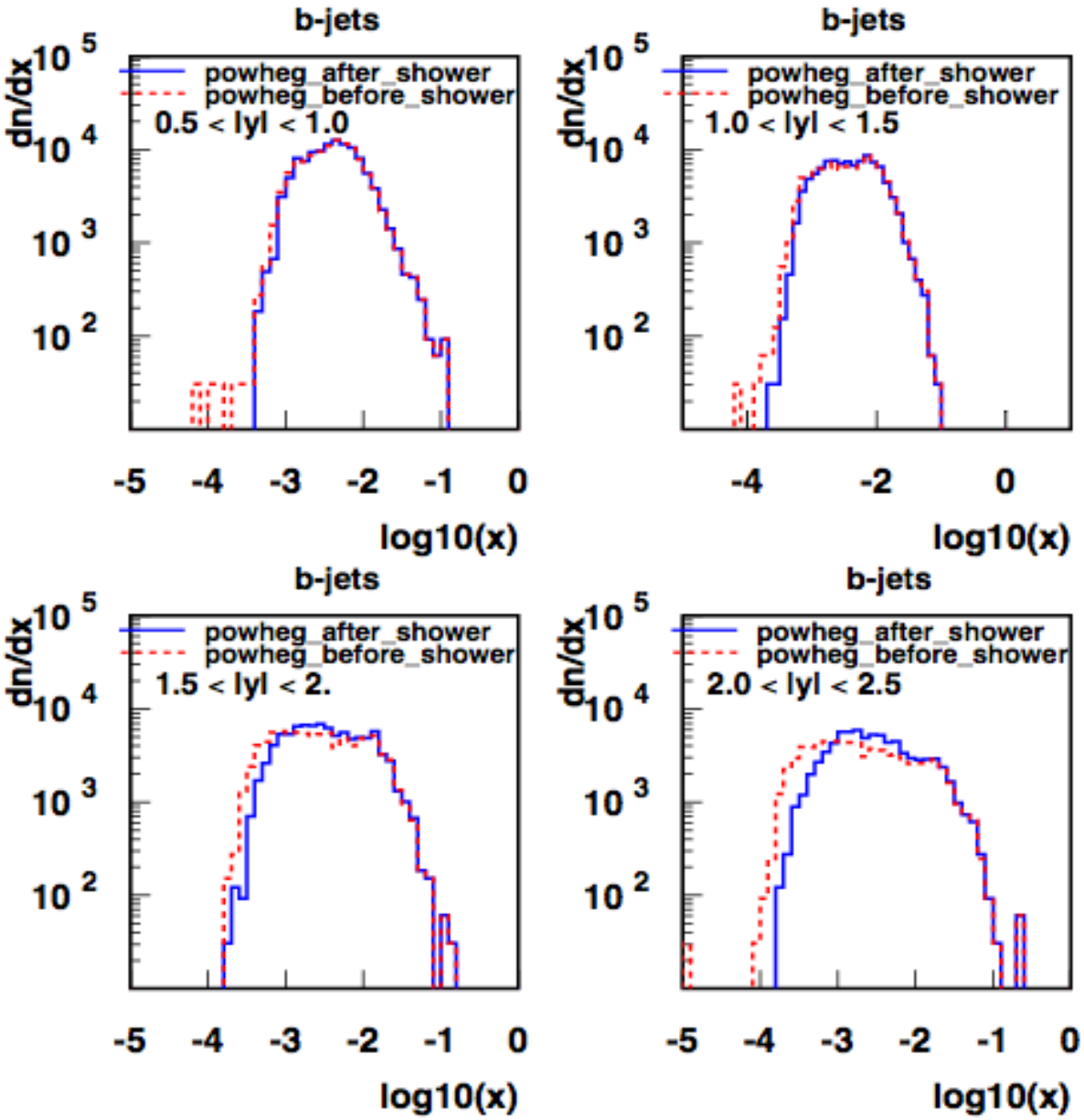
- b-jet production $gg \to b\bar{b}$ dominates
- inclusive b-jets: probe of gluon density
- Reasonable description by POWHEG and MC@NLO at central rapidities
- data significantly below POWHEG and MC@NLO at large rapidity and large p_t

ATLAS arXiv 1109.6833



➔ Both MCs give similar behavior !

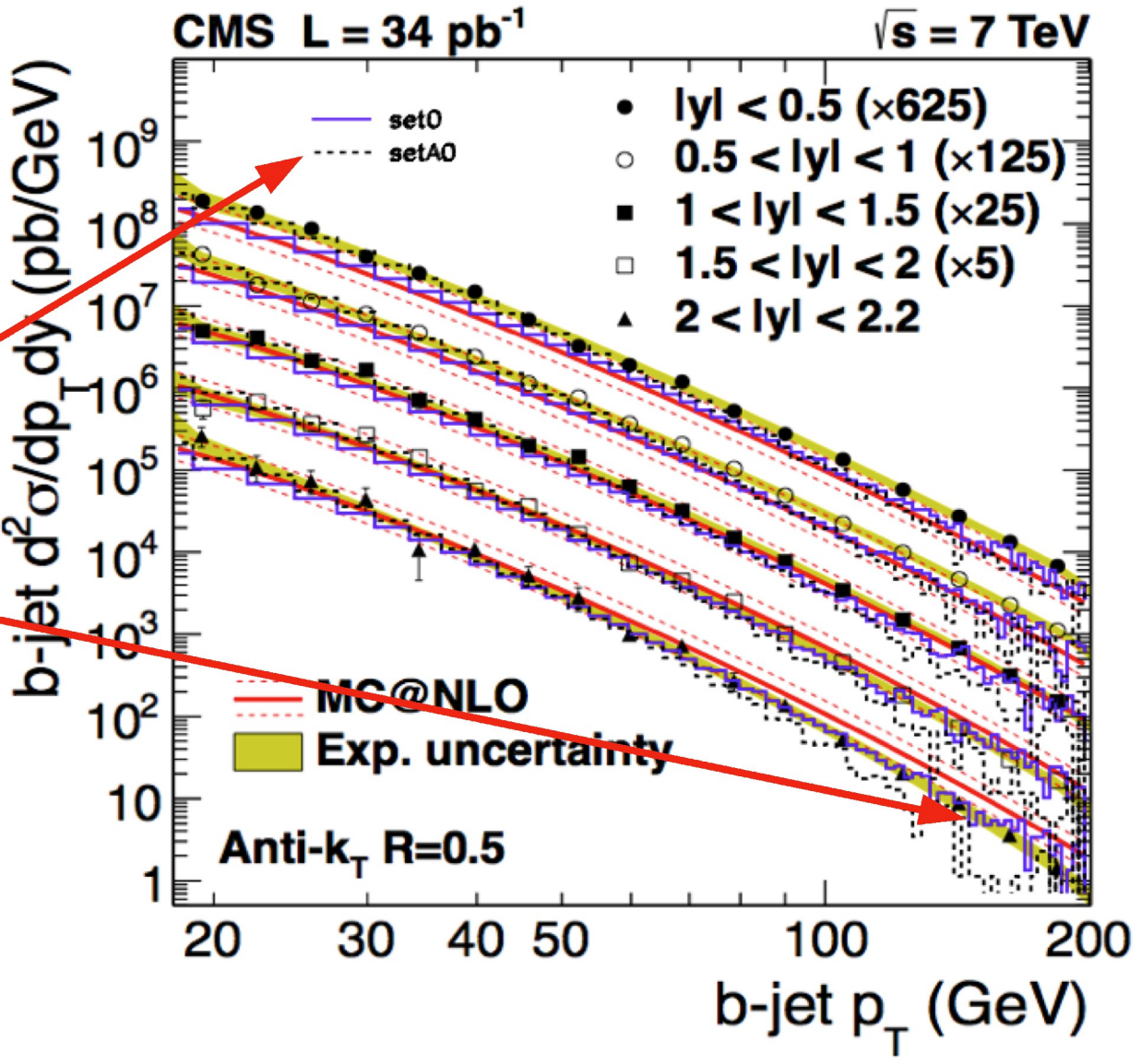
Kinematics with shower in b-jets



- momentum fraction of gluon changes due to kinematics after shower
- low x region influences high p_t tail
- different x after shower → different gluon density ...

Inclusive b-jets

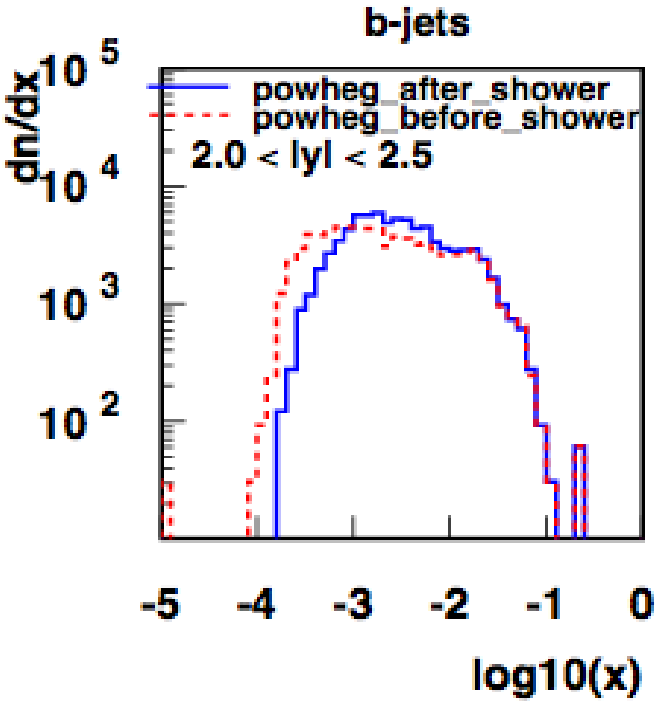
- b-jet production $gg \to b\bar{b}$ dominates
- inclusive b-jets: probe of gluon density
- test of unintegrated gluon (TMD) obtained from F_2 fit (CASCADE)
- description similar to MC@NLO at central rapidities
- BUT shape at large p_t much better described

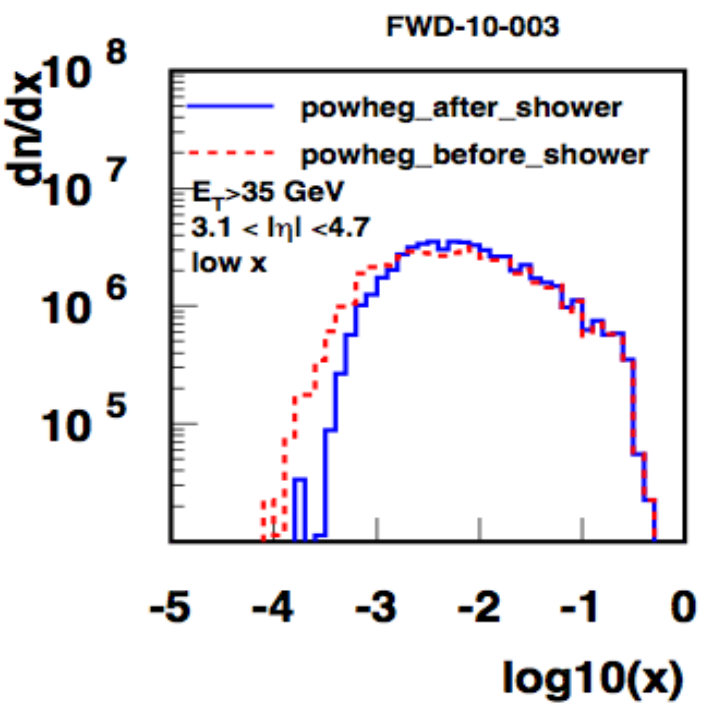


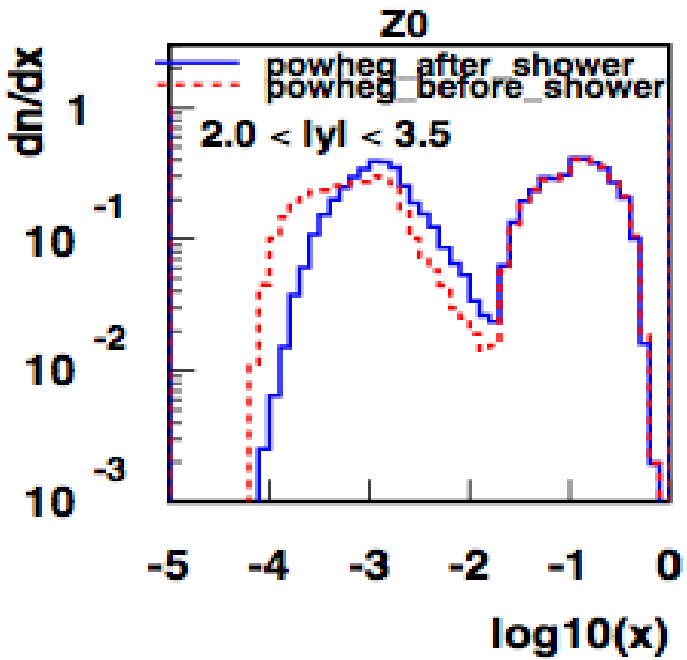
➔ Is this effect of small x resummation or just kinematics ?

Why TMDs ?

- x distribution for b-jets in POWHEG different after shower
- x distribution for incl jets in POWHEG different after shower
- x distribution for Z0 in POWHEG different after shower





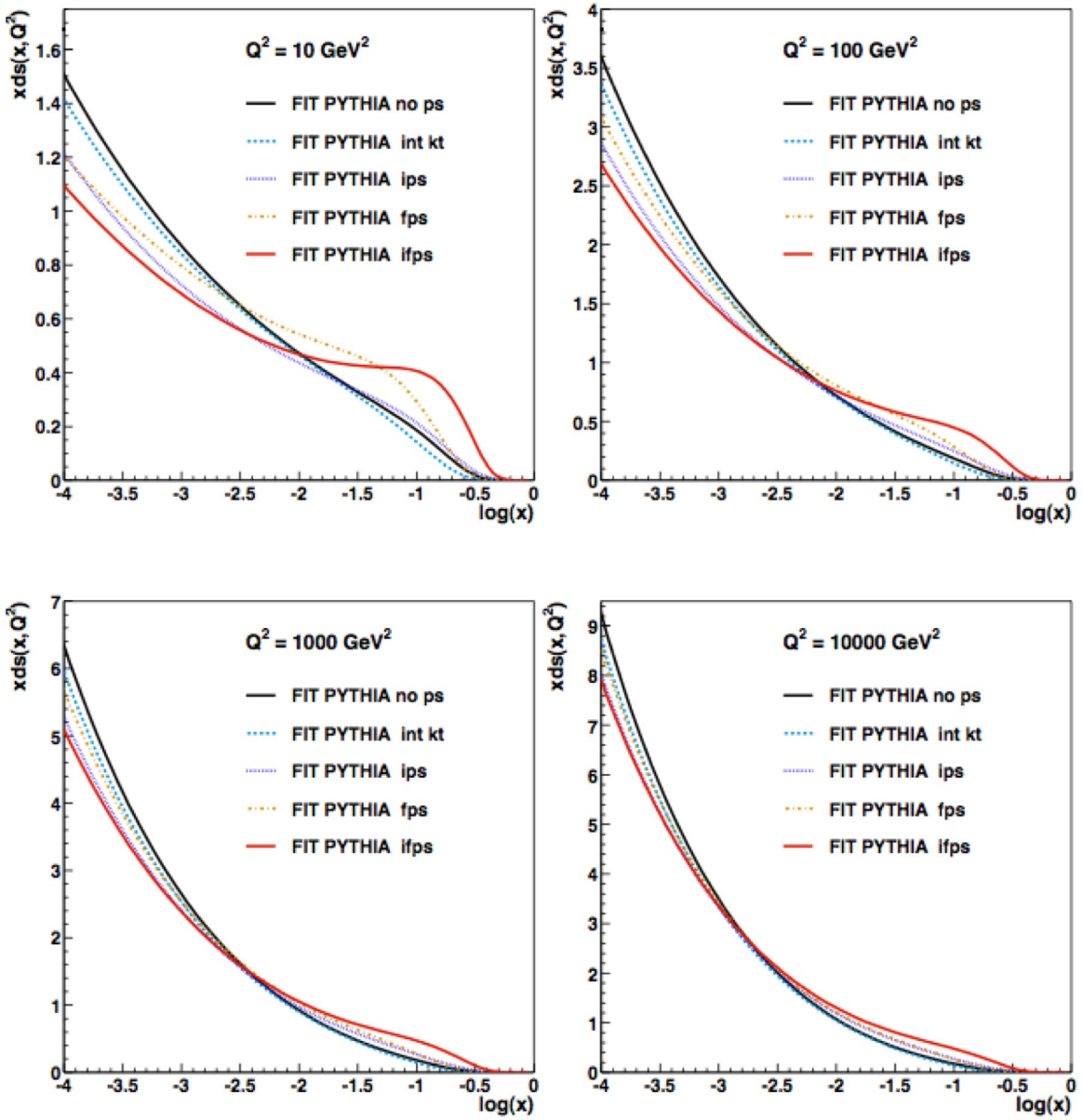


➔ pure NLO parton level could give wrong results !

The PDF4MC project

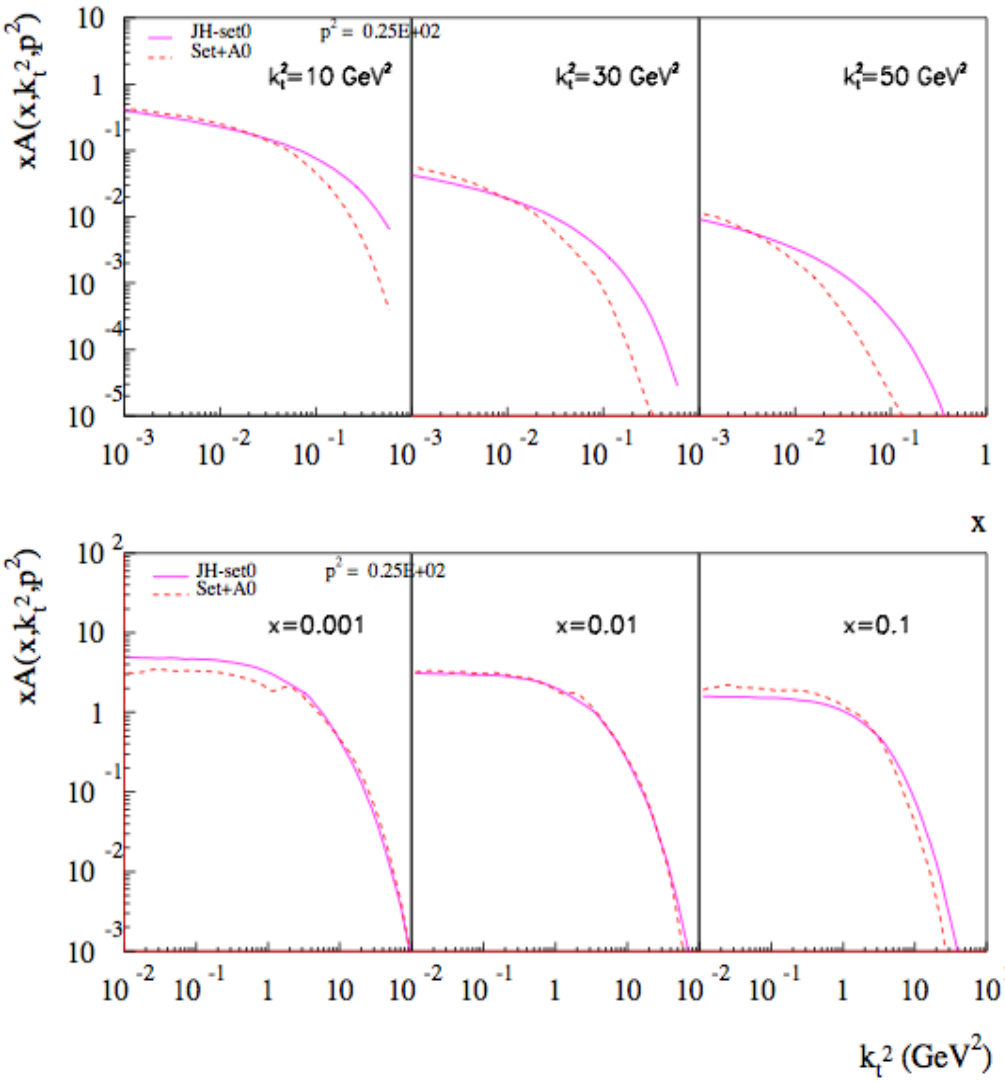
- perform fits to F_2 using a Monte Carlo event generator which includes parton showers and intrinsic k_t
- the resulting PDFs agree with standard LO ones if no PS and intrinsic k_t is applied.
- the final PDFs are different because of kinematic effects coming from transverse momenta of PS and intrinsic k_t

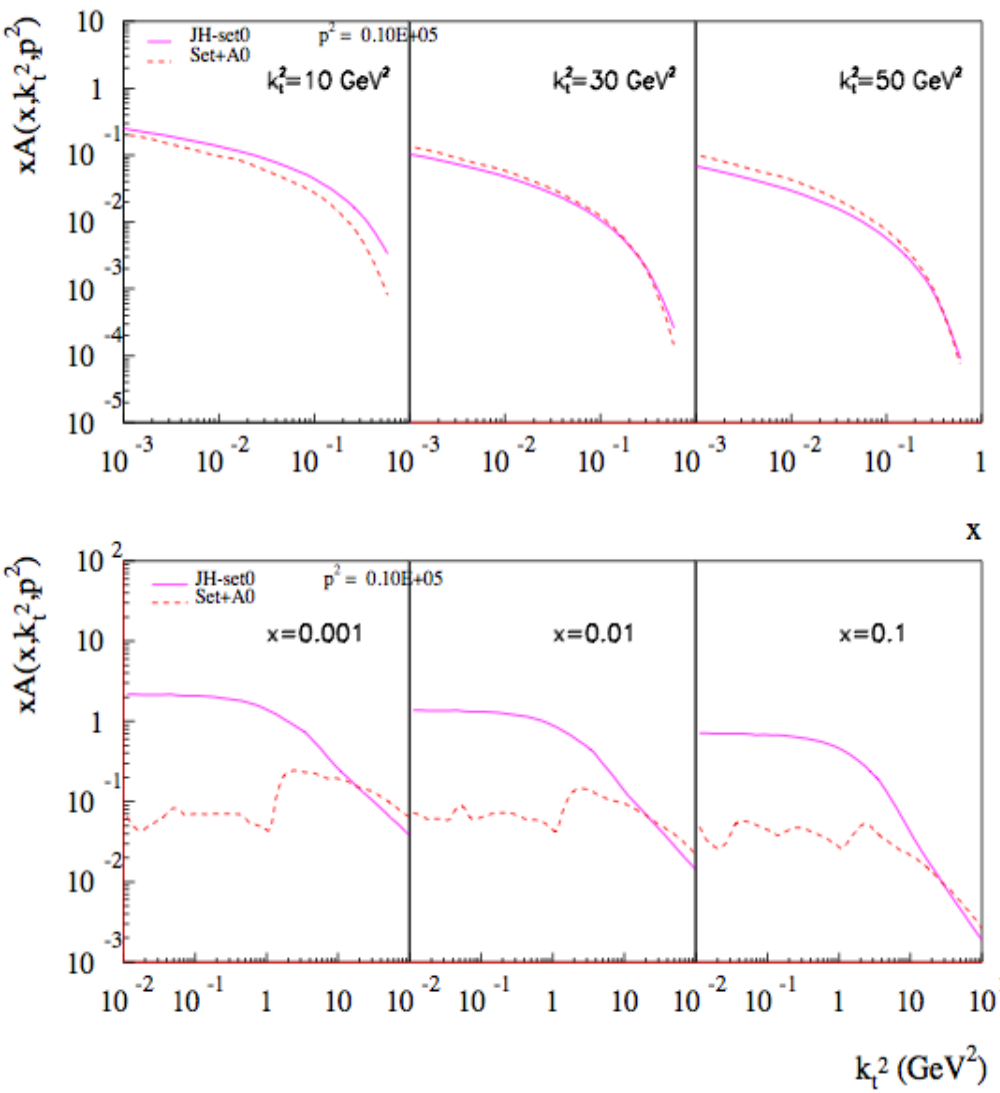
Determination of parton density functions using Monte Carlo event generators (Diploma 2009) Federico C. A. von Samson-Himmelstjerna



CCFM TMDs: from a fit to F_2

- evolved to $p^2 = 25$ GeV^2
- evolved to $p^2 = 10000$ GeV^2

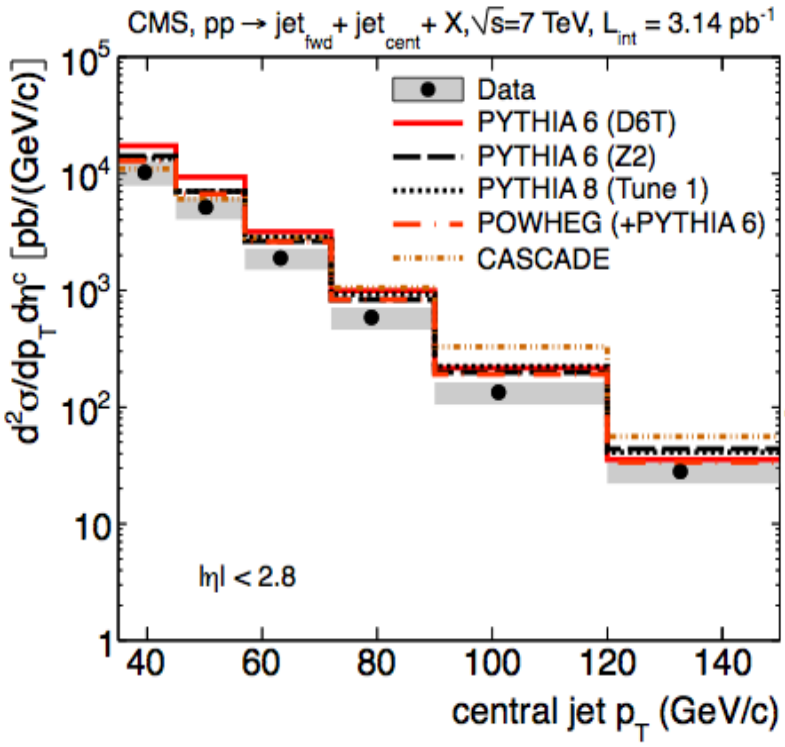


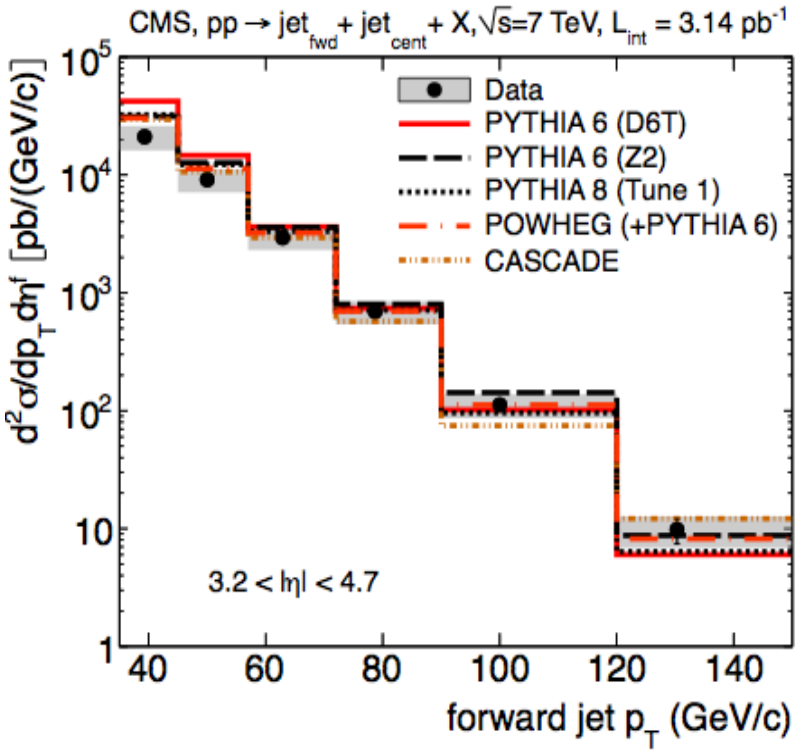


Where measurements challenge theory

CMS arXiv 1202.0704

- associated forward & central jets
  - E_t > 35 GeV (anti-kt, R=0.5)
  - leading jets in $|\eta_c|$< 2.8 and 3.2 < $|\eta_f|$ < 4.7

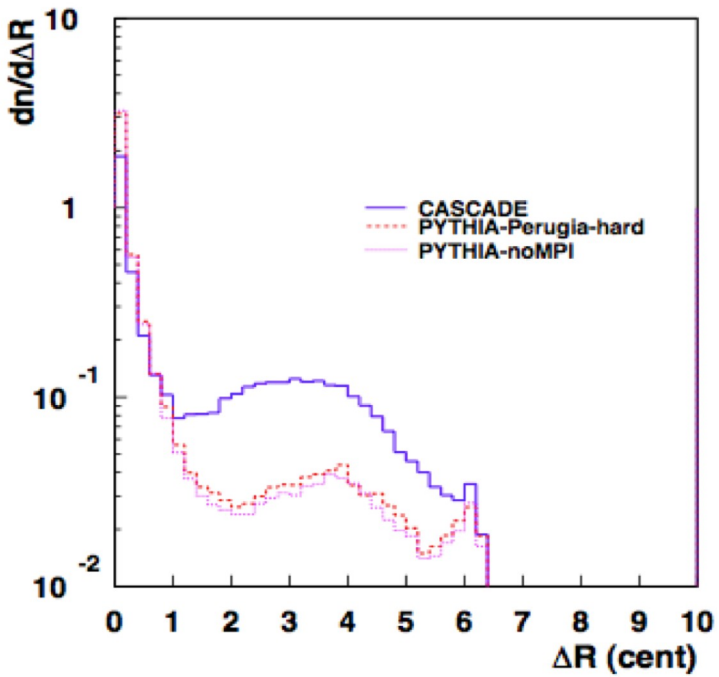


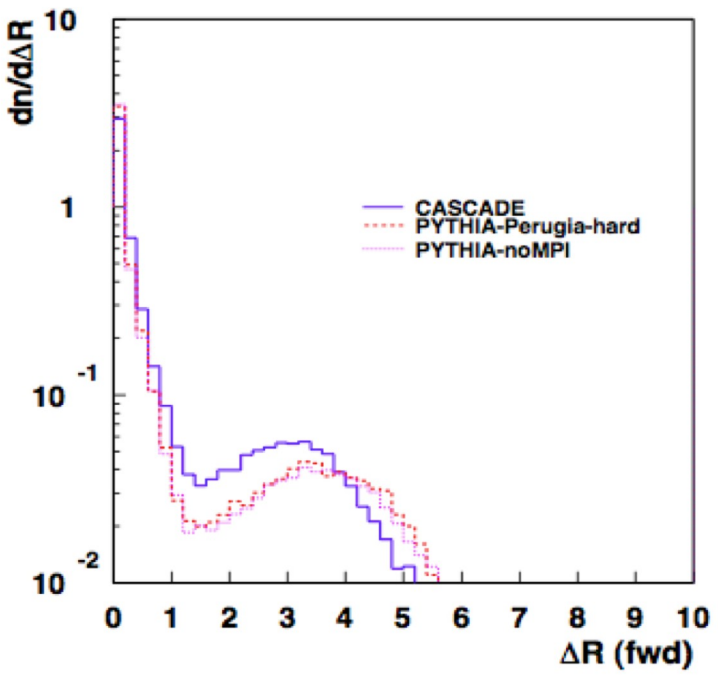


Where measurements challenge theory

Deak et al arXiv 1012.6037

- associated forward & central jets
  - are 2 → 2 ME partons producing central & forward jets ?
  - ➔ jets can come from shower partons !

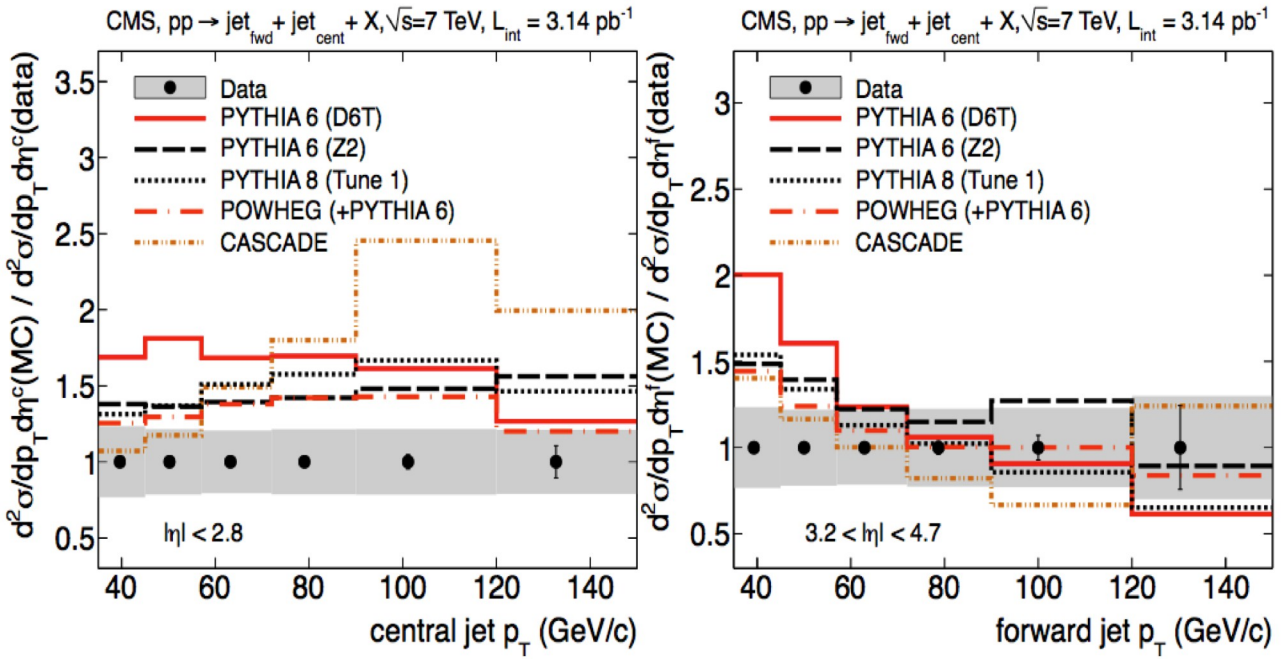


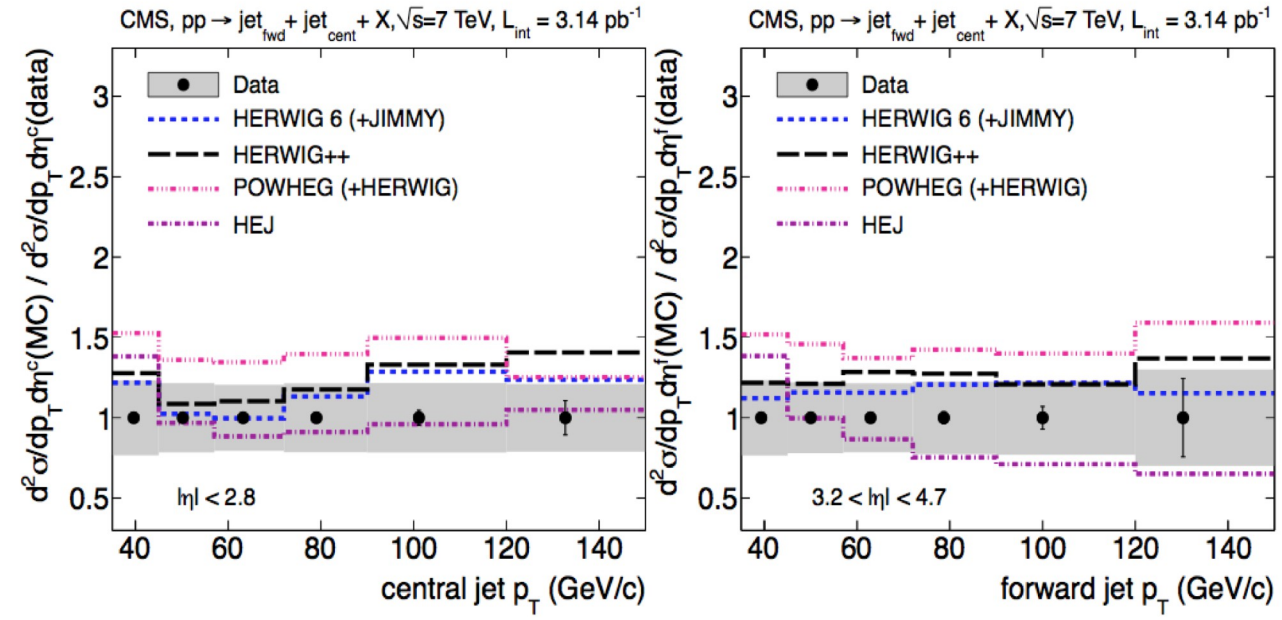


- depends on shower: collinear or kt factorized shower

Where measurements challenge theory

CMS arXiv 1202.0704





Correlations of jets:

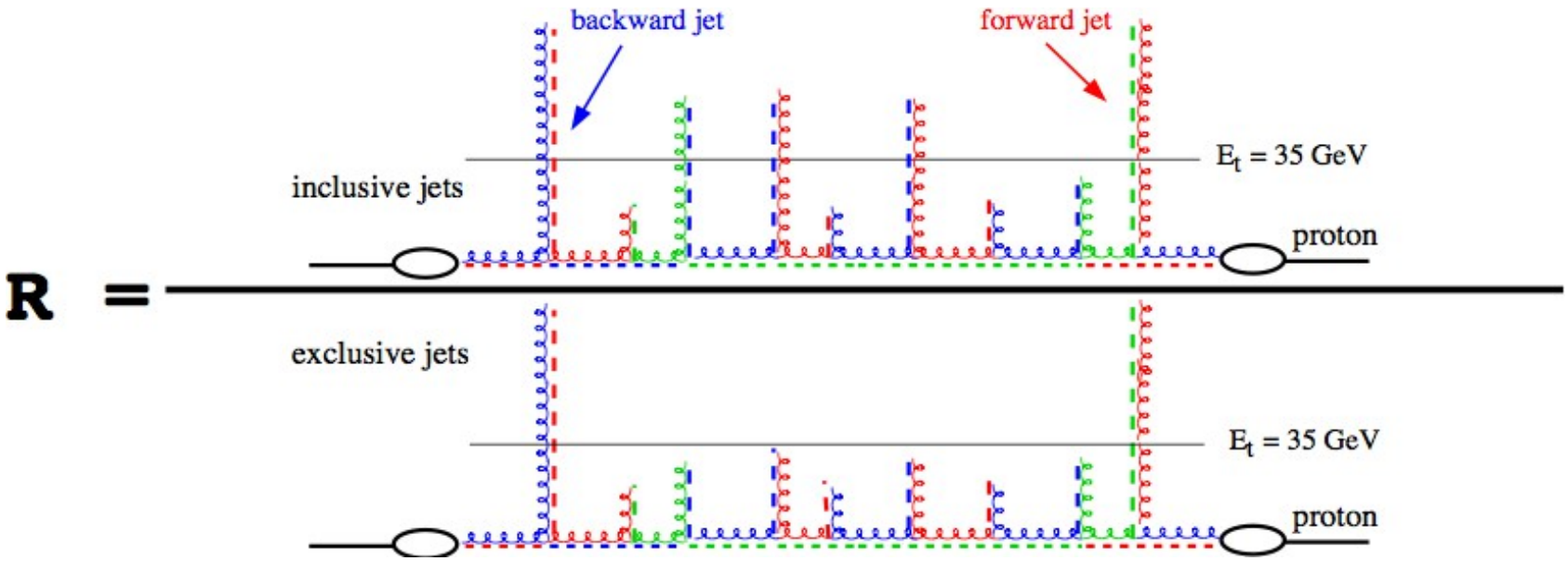
- Shape and norm not described
- POWHEG/PYTHIA also off
- CASCADE off
- POWHEG/HERWIG closer to data
- HEJ within uncertainties

➔ **BUT different to inclusive jets !!!!**

Dijets at large Δy

CMS arXiv 1204.0696

- select (anti-kt) dijets with $p_{t\,min} = 35\ \mathrm{GeV},\ |y| < 4.7$ as function of rapidity separation Δy between jets
- for large Δy expect rising xsection due to increased phase space (BFKL effects)
- measure ratio of exclusive/inclusive xsection (many systematic cancel)

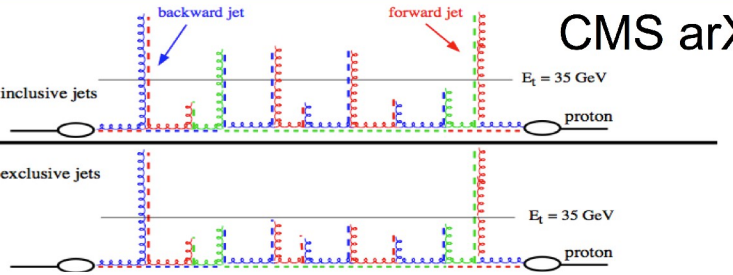


➔measure up to Δy < 9 !!!

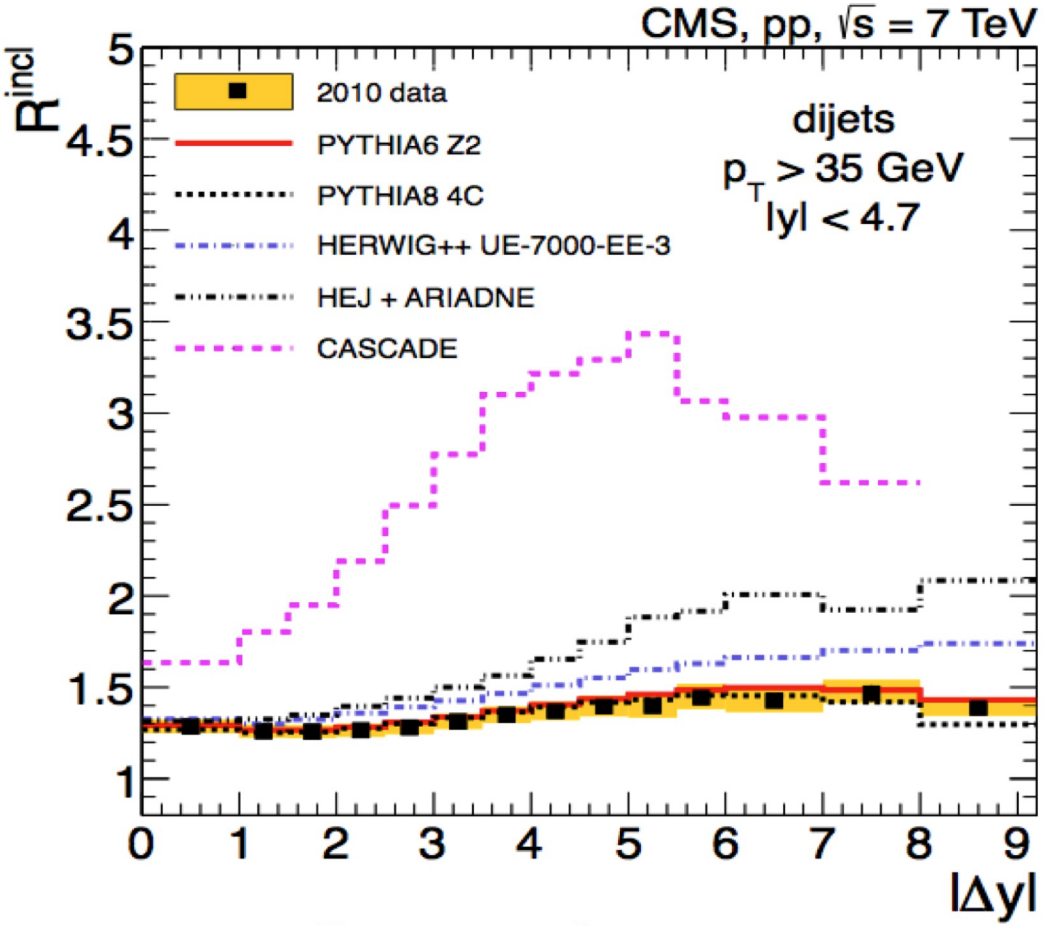
Dijets at large Δy

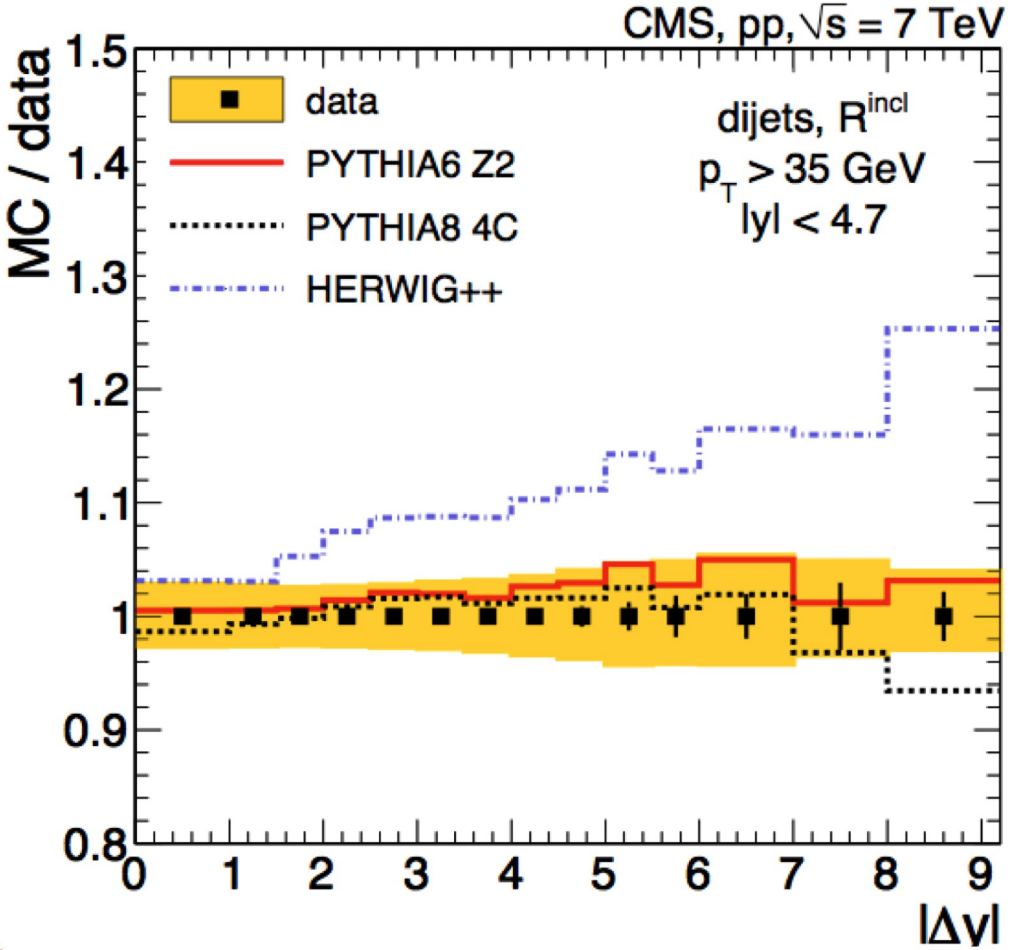
- select all (anti-kt) dijets with

$p_{t\,min} = 35$ GeV, $|y| < 4.7$



CMS arXiv 1204.0696



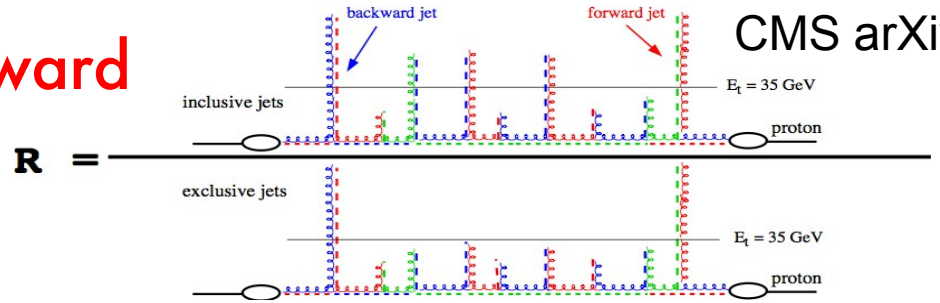


- Significant deviations at large Δy (except PYTHIA)

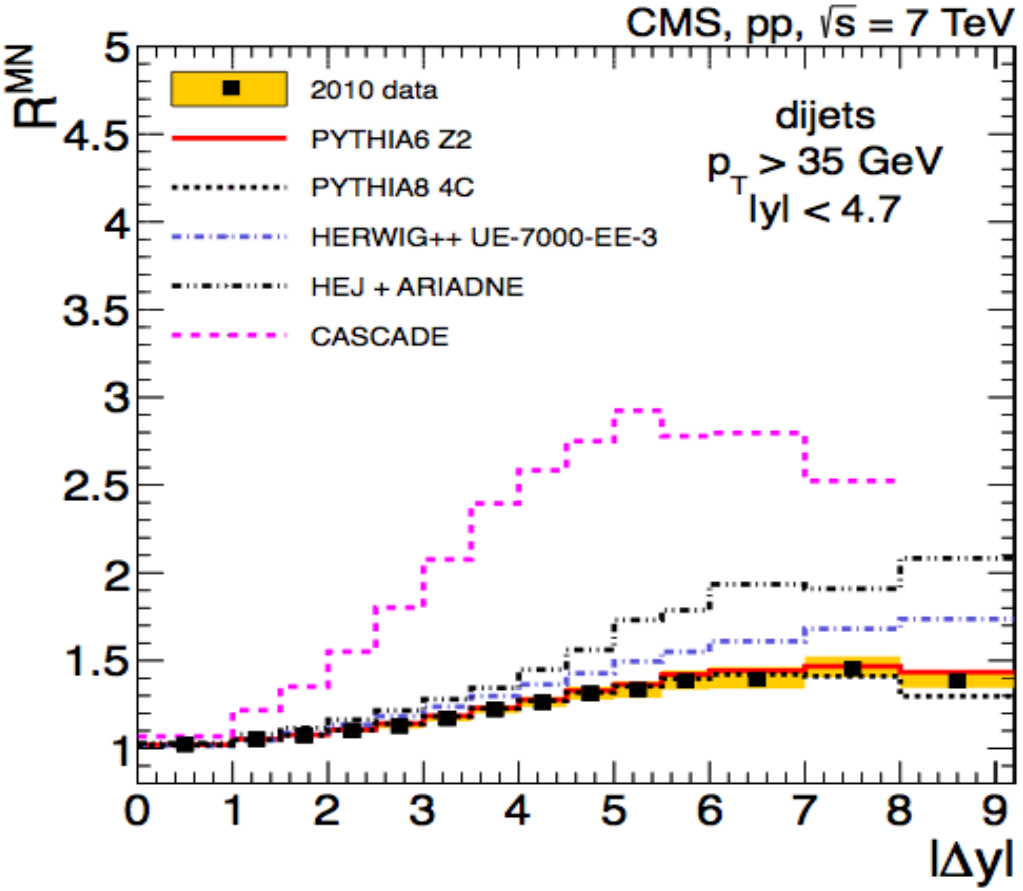
Dijets at large Δy

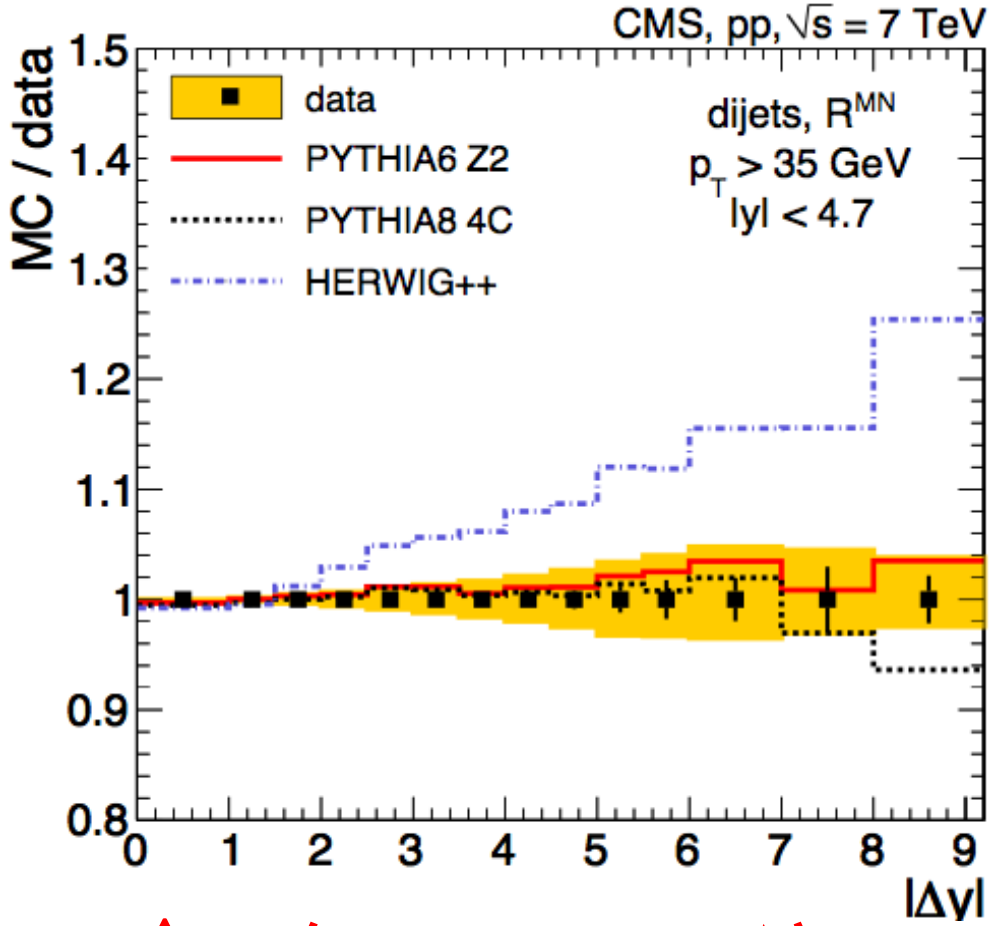
- select most forward/backward (anti-kt) dijets with

$p_{t\,min} = 35$ GeV, $|y| < 4.7$



CMS arXiv 1204.0696



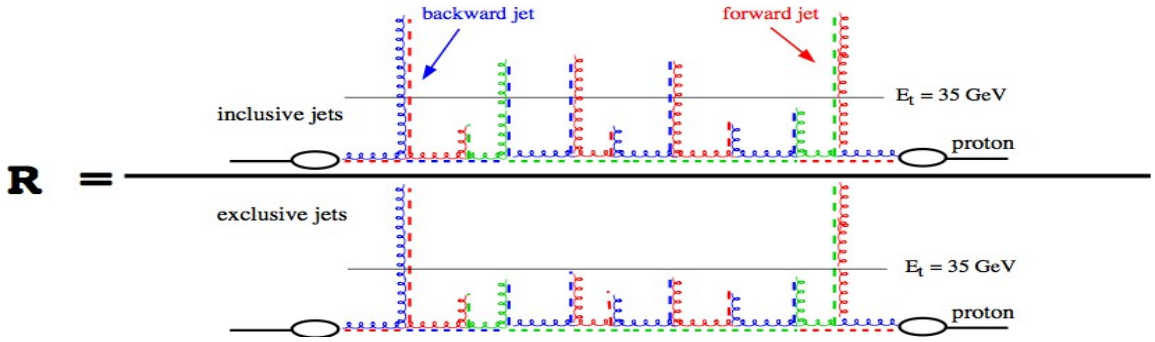


- Significant deviations at large Δy (except PYTHIA)

Dijets at large Δy

CMS arXiv 1204.0696

- (anti-kt) dijets with
  $p_{t\,min} = 35$ GeV, $|y| < 4.7$

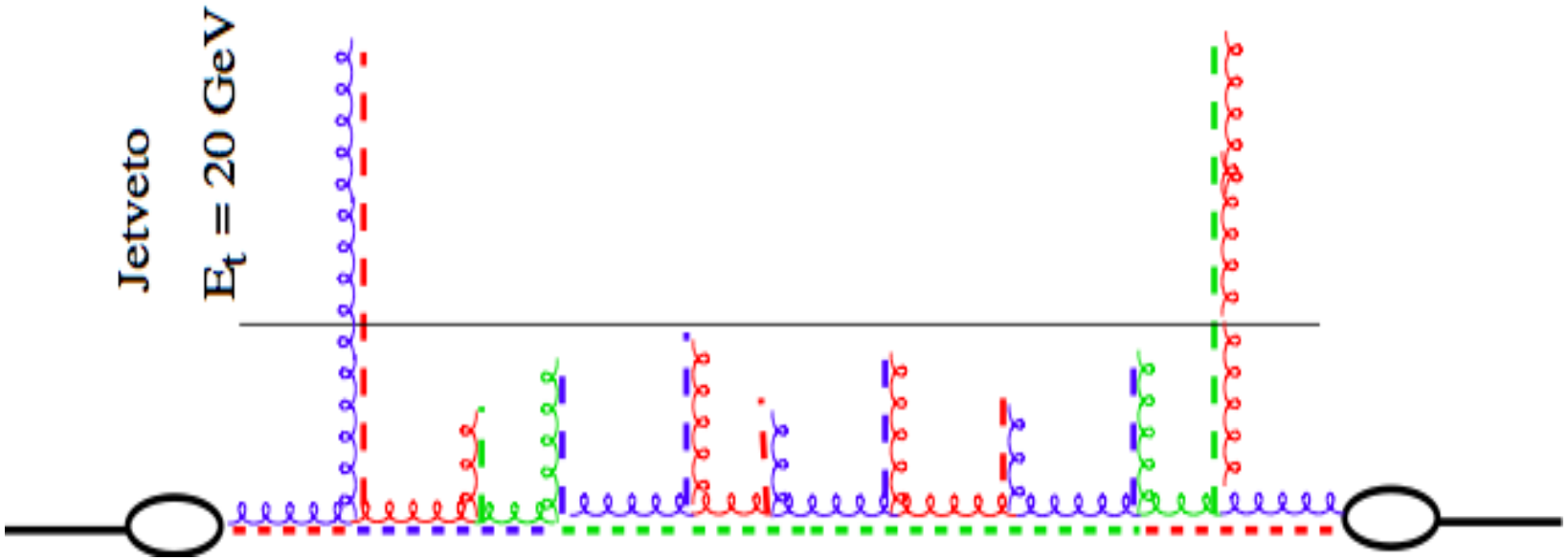


- Ratio is only described by PYTHIA (and POWHEG)
  - influence on Tune and MPI very small
- Large deviations at large Δy
  - HERWIG (and POWHEG)
  - HEJ
  - CASCADE

➔ **Where is signal for BFKL at large Δy ?**

Dijets with jet veto

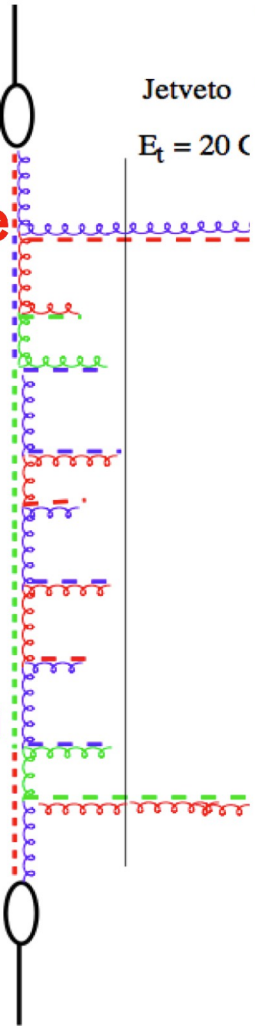
- **Jets with** $p_t > 20\,GeV \quad \bar{p}_t > 50\,GeV$**, Jet veto** $Q_0 = 20\,GeV$

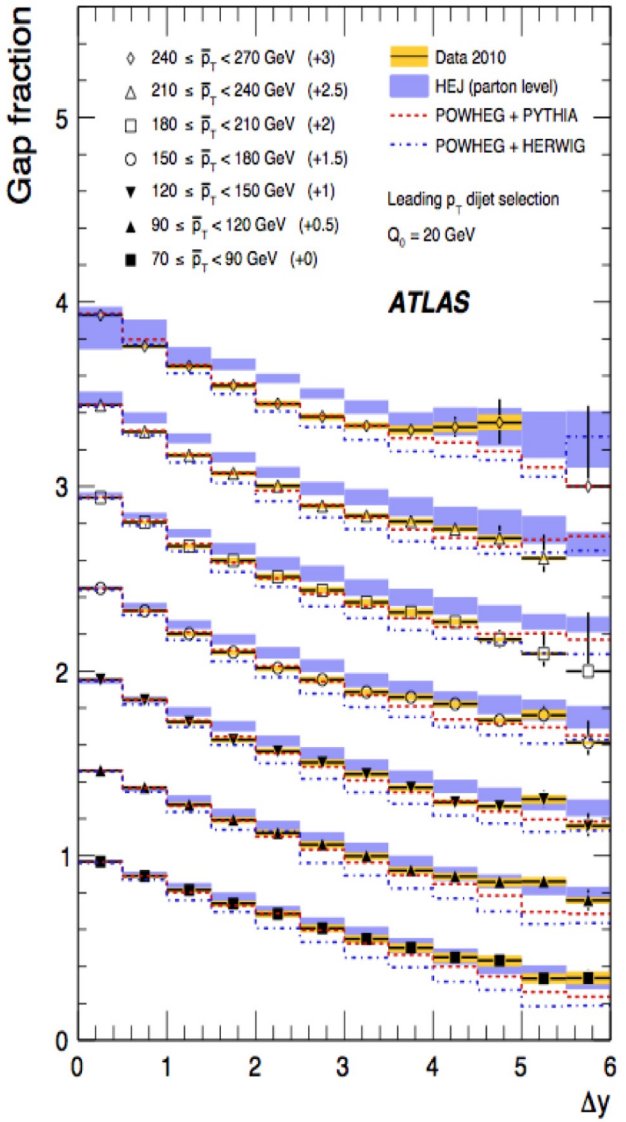


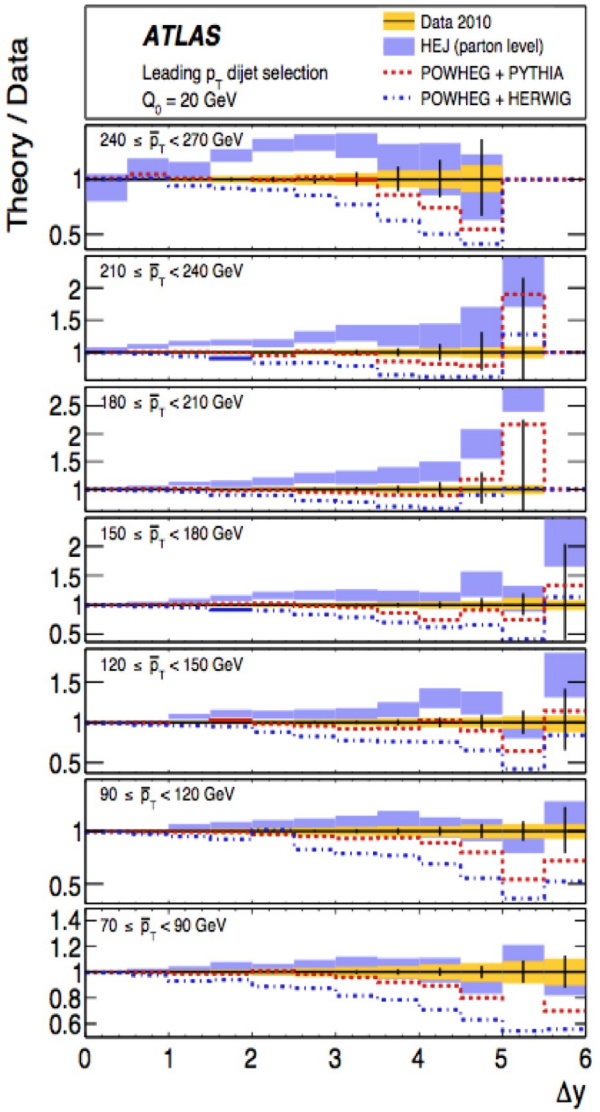
- Measure "gap"-fraction (no jet with p_t > Q_0) as function of $\Delta\ y$

Dijets with jet veto

- Jets with $p_t > 20\,GeV$ $\bar{p}_t > 50\,GeV$, Jet veto $Q_0 = 20\,GeV$
- Leading pt jets
- POWHEG too low at large Δy
- HEJ describes large Δy
  - small x resummation needed

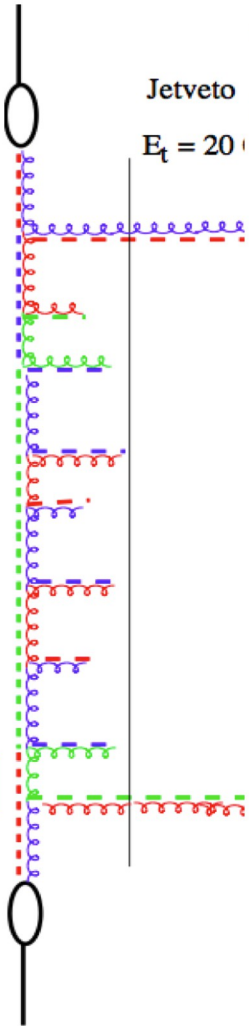


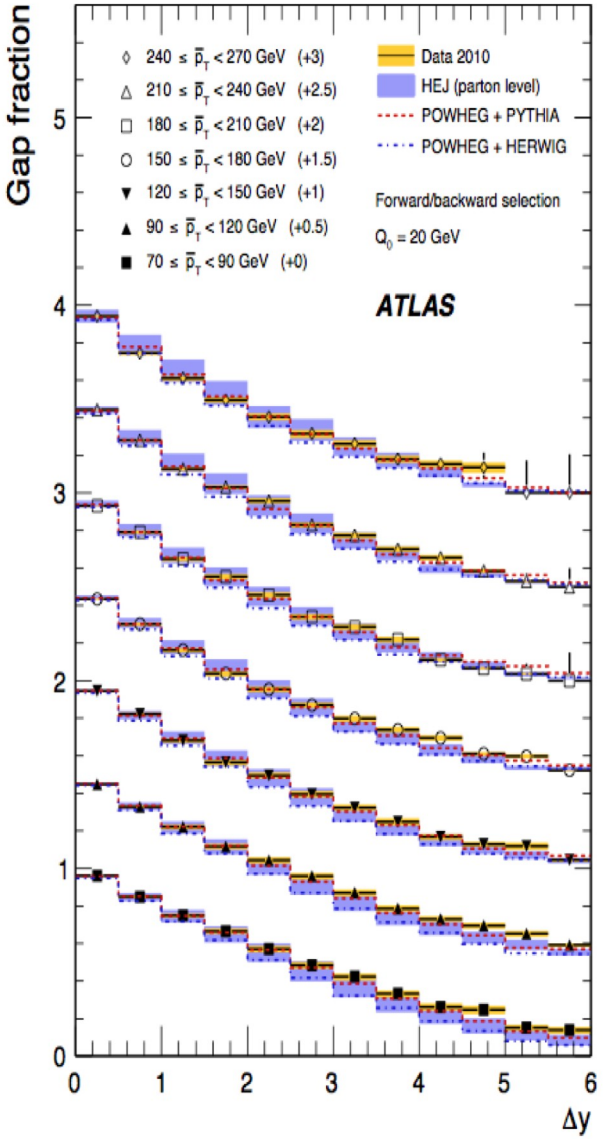


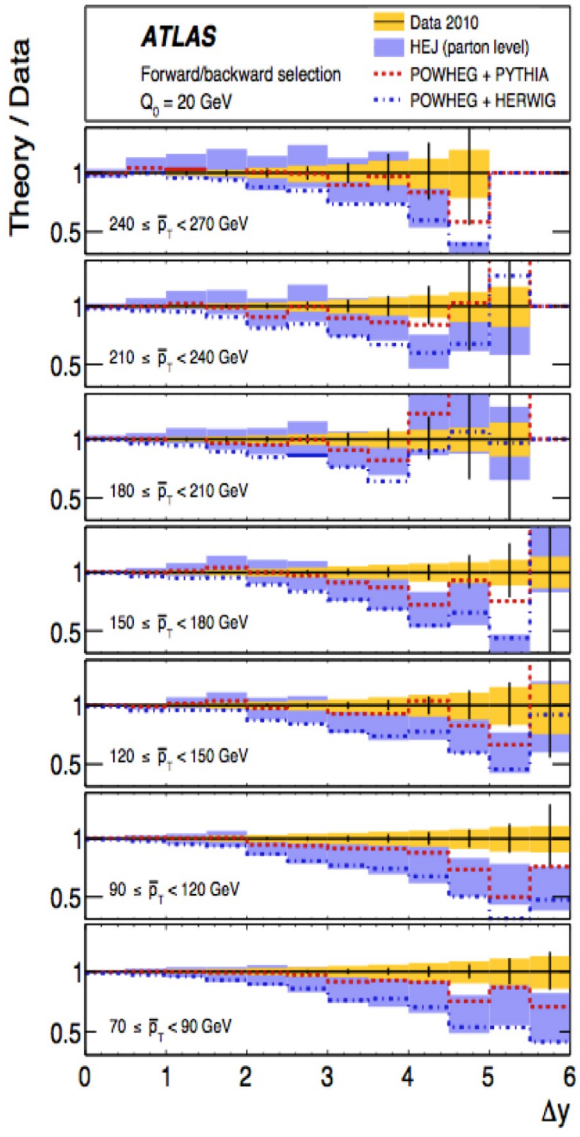


Dijets with jet veto

- Jets with $p_t > 20\,GeV$ $\bar{p}_t > 50\,GeV$, Jet veto $Q_0 = 20\,GeV$
- Most fwd/bwd jets
- POWHEG/HEJ too low at large $\Delta\, y$
- Δ p_t increases with $\Delta\, y$
- many relatively soft jets between tagged jets possible



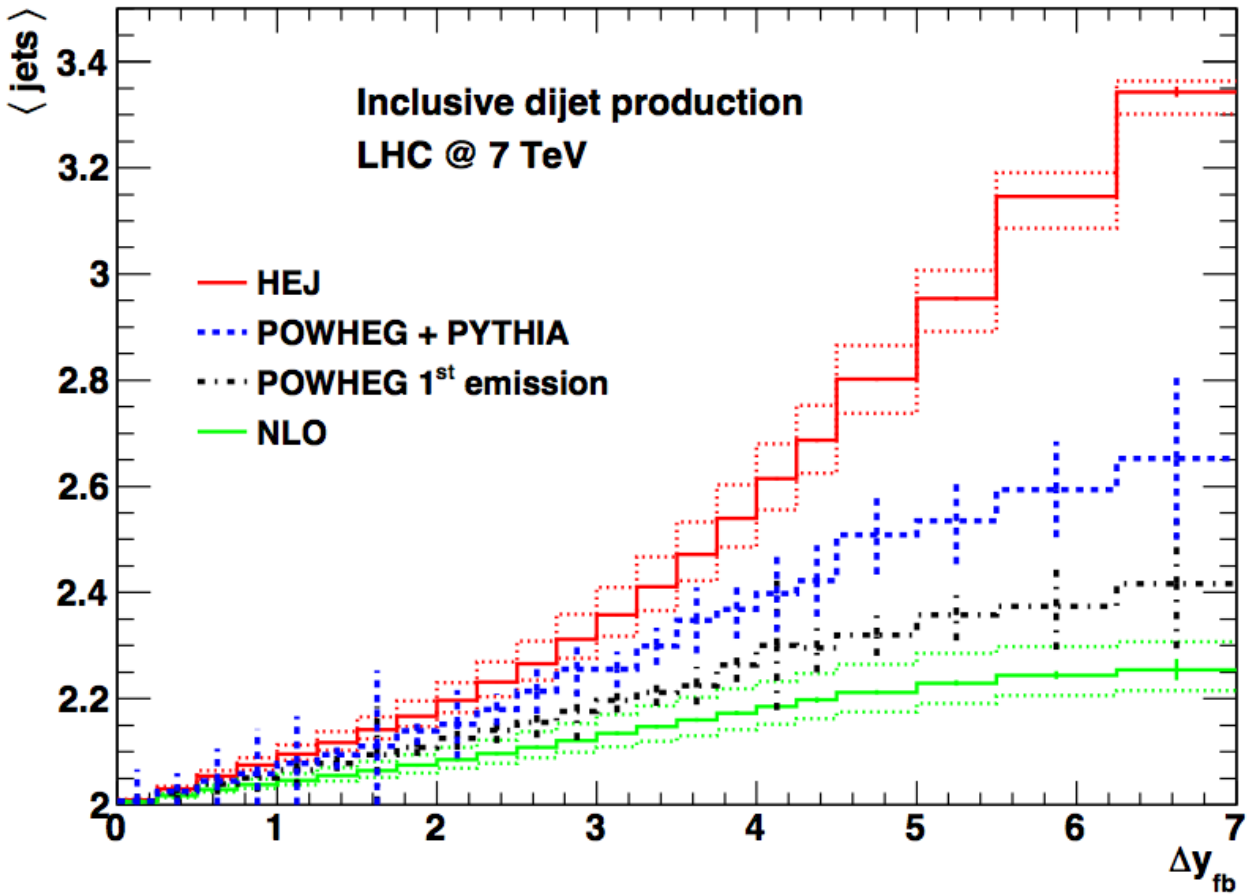




Understanding dijets at large Δy

- With increased phase space at large Δy more jets can be produced
- NLO (dijet) < 3 jets
- HEJ with small x enhanced parton emissions produces more jets at large Δy

S. Alioli et al arXiv 1202.1475v1

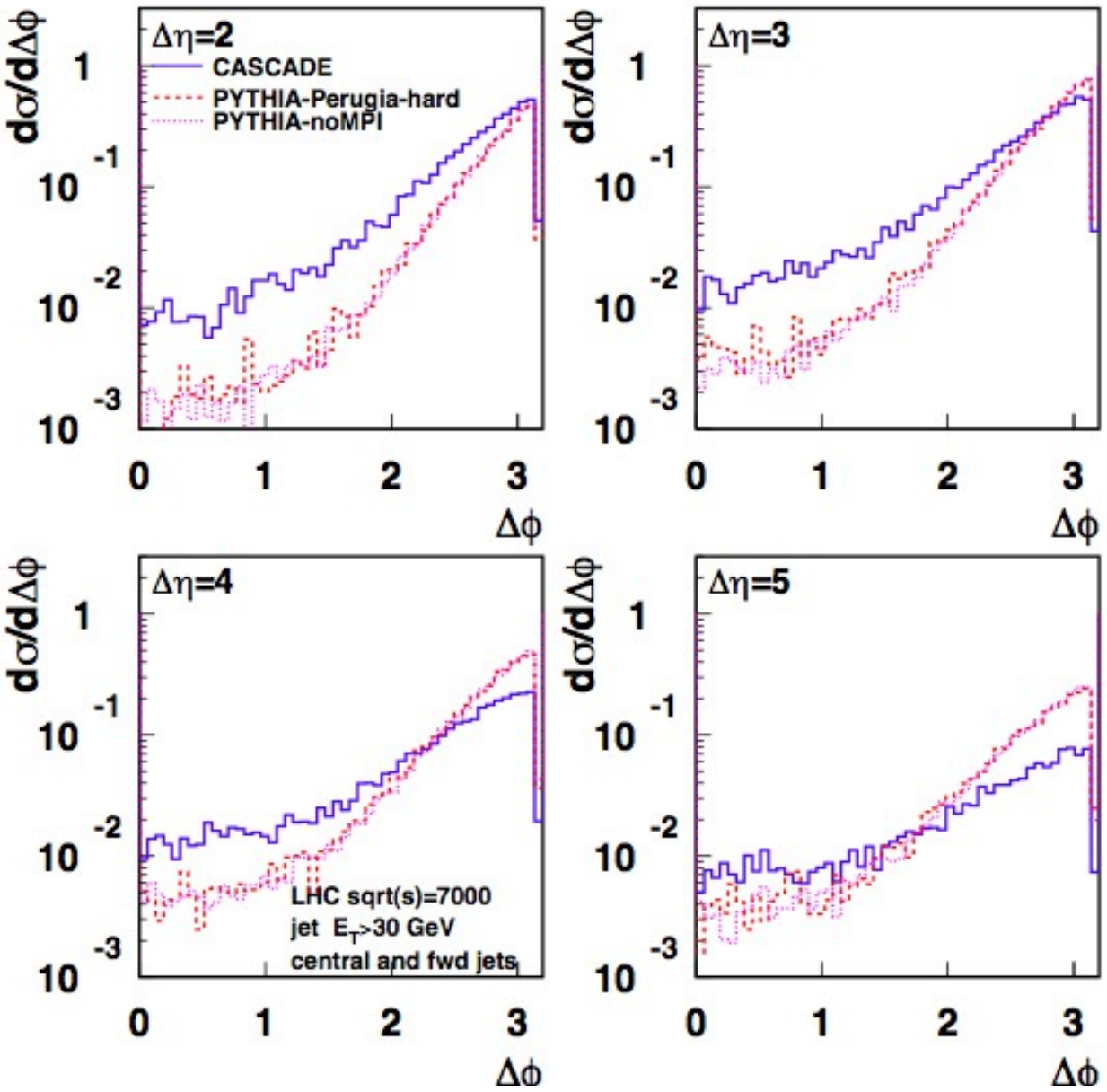


- Differences in parton shower mechanism visible
- test with experiment !!!

Understanding dijets at large $\Delta\ y$

Deak et al arXiv 1012.6037

- Decorrelation increase with increasing $\Delta\ y$
- Decorrelation at large $\Delta\ y$ reflects details of parton showering
- larger decorrelations expected from k_t -factorized shower



Summary

- Jet measurements from LHC challenge theory
  - inclusive jets at central η are well described by NLO dijets
    - how to determined NP corrections needed for parton level ?
  - deviations from NLO predictions are seen at forward $|y|$>2:
    - inclusive jets are subject to higher order corrections
    - differences in parton shower + NLO !
  - deviations in dijet correlations:
    - forward-central jets
    - jet veto: gap fraction
    - dijets at large $|y|$ separation
- TMDs might be necessary for proper treatment of kinematics

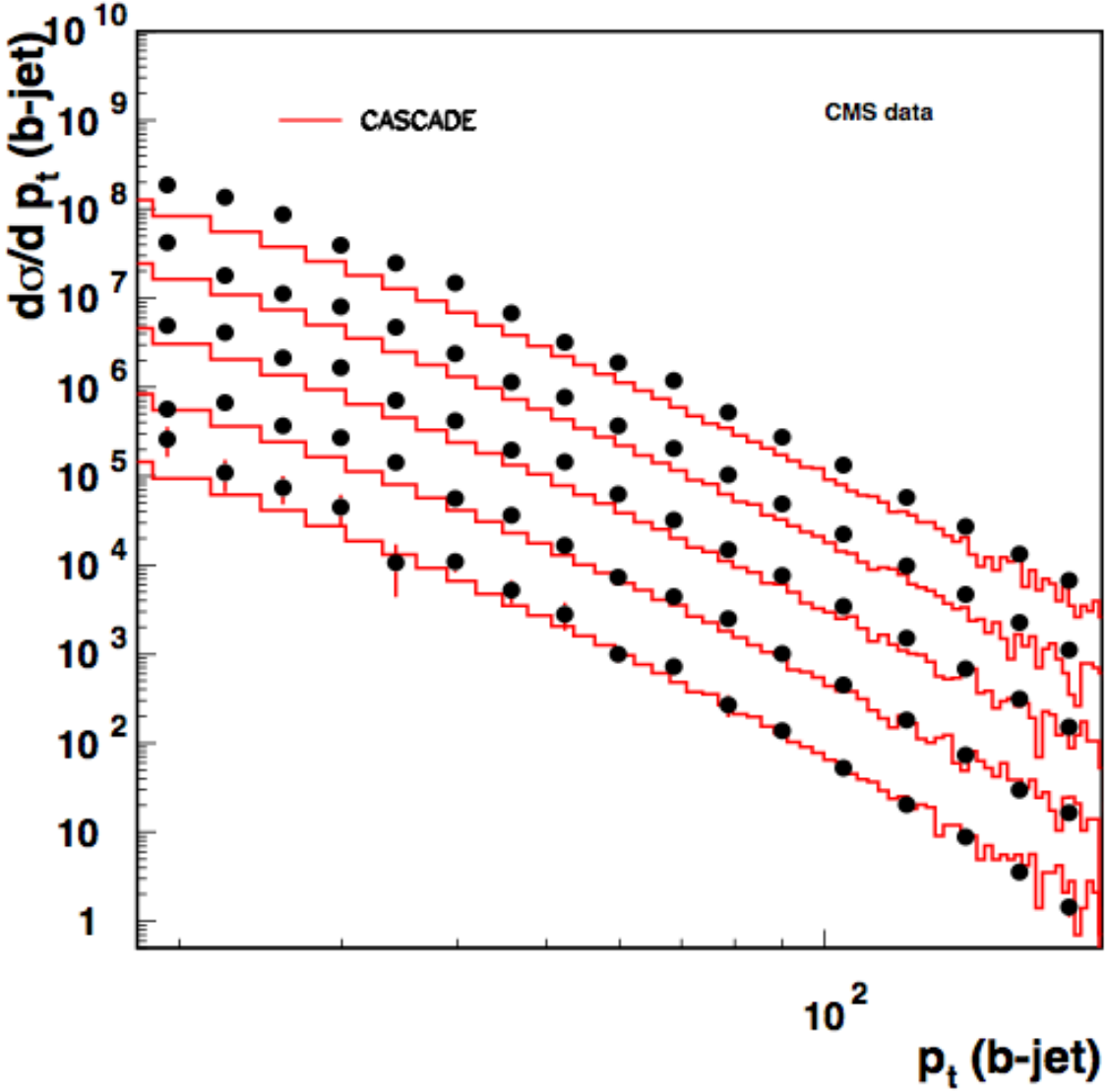
and ...

- It's quite interesting and challenging doing QCD at LHC:
  - even during the Higgs race ....
- Upcoming issues:
  - small x – high energy behavior of QCD
    - where is BFKL, saturation and all this ?
  - high x – exclusive limit, threshold behavior
    - is there interesting QCD at highest luminosities ?

Backup

Inclusive b-jets

- b-jet production $gg \to b\bar{b}$ dominates
- inclusive b-jets: probe of gluon density
- test of unintegrated gluon (TMD) obtained from F_2 fit
- description similar to MC@NLO at central rapidities
- BUT shape at large p_t much better described



➔Is this effect of small x resummation or just kinematics ?