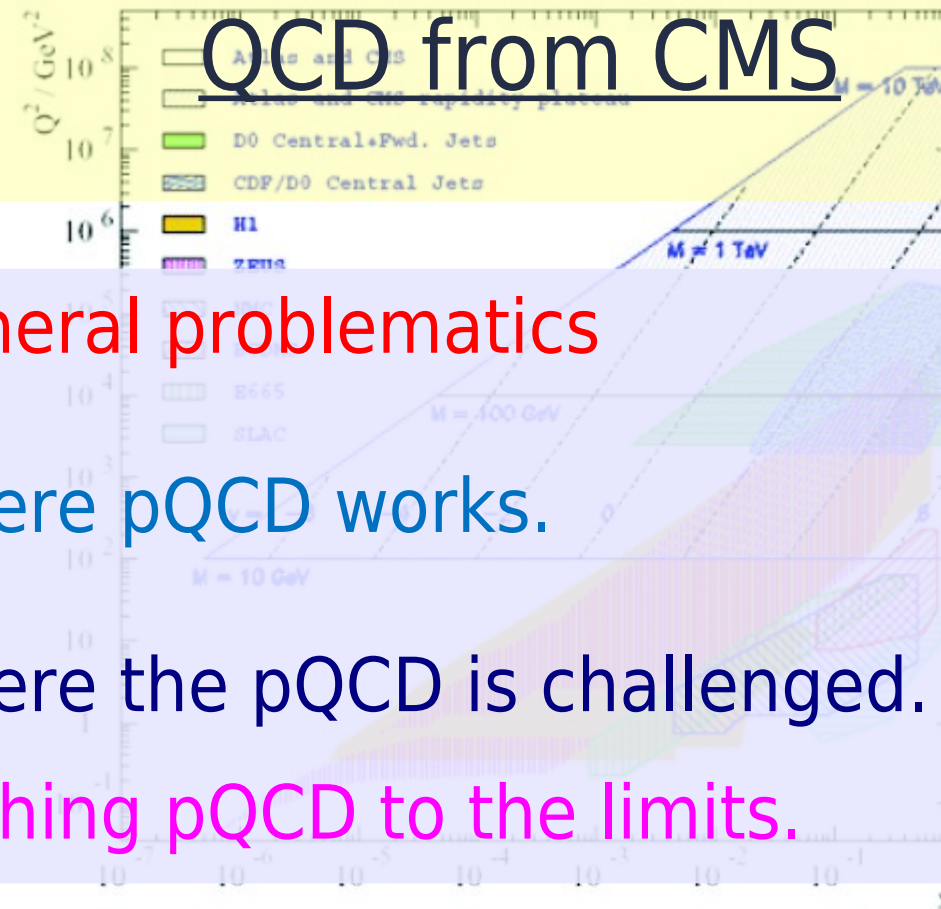







## QCD from CMS

- 1) General problematics
- 2) Where pQCD works.
- 3) Where the pQCD is challenged.
- 4) Pushing pQCD to the limits.

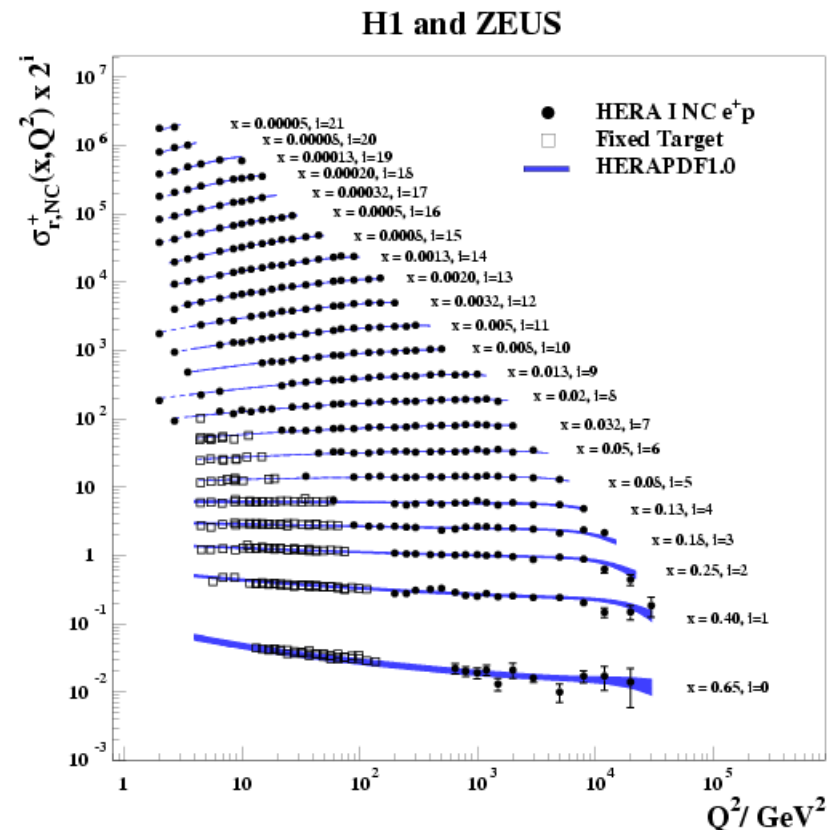


# 1.1) Common wisdom about QCD

- QCD is ONE theory: SU3 + free coupling parameter.
  - Well established in ee and ep colliders:  $\alpha_s$  value and running, interaction mediator (gluon), SU3 gauge group, pQCD at NNLO, factorization theorem for hadrons PDFs...
- But MANY regimes with associated approximations:
  - NP regime (lattice QCD, phenomenology): spectroscopy
    - Common wisdom: complicated chemistry. 
  - Intermediate (phenomenology): fragmentation functions, UE, Min bias collisions.
    - Common wisdom: “tuning and witchcraft”. 
  - Hard interaction (pQCD): jets physics, inelastic hadrons PDFs.
    - Common wisdom: “well understood, just need to cross check it works”. 
- At CMS: till now O(50) dedicated papers.
  - <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP>

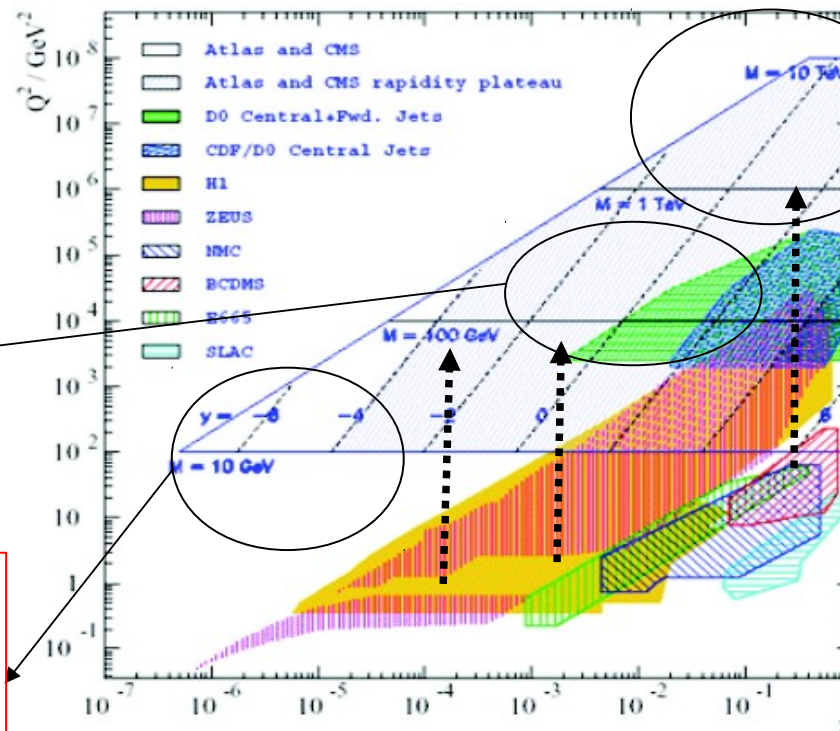
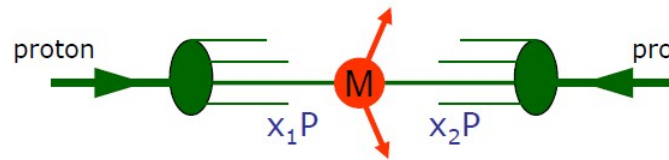
## 1.2) pQCD before the hadron colliders

- I would try to dispel the common wisdom that pQCD is so well understood and show where/why hadron colliders may and shall contribute.
- At LEP/HERA we got used that NLO (or NNLO when possible) contains most of the perturbative effects. UE and parton showering are minor corrections.
- It seems that this is not always true for the hadron colliders. Let's have a look on it.



# 1.3) Kingdom of the pQCD

- Factorization theorem: hard matrix element calculated at NLO factorized from proton PDFs, parametrized (mainly) in ep collision and evolved by DGLAP evolution at NLO (or NNLO).



“Higgs and SM region”

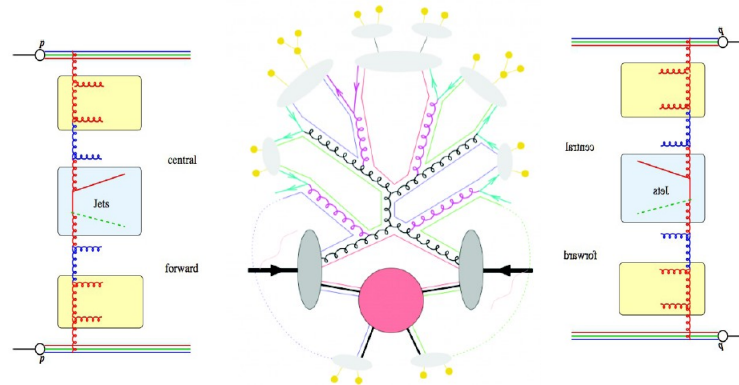
Terra incognita: forward physics

“Exotica searches region”

CMS Experiment at the LHC, CERN

# Where pQCD works

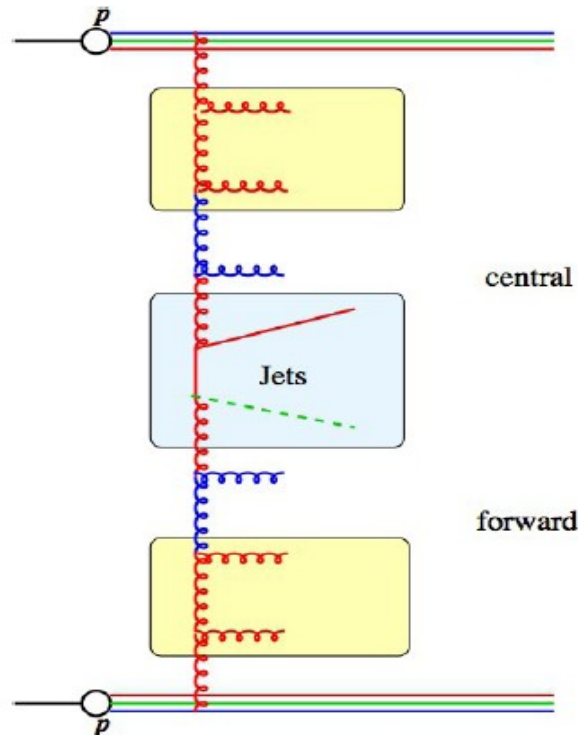
## Central jets production and “Exotica region”



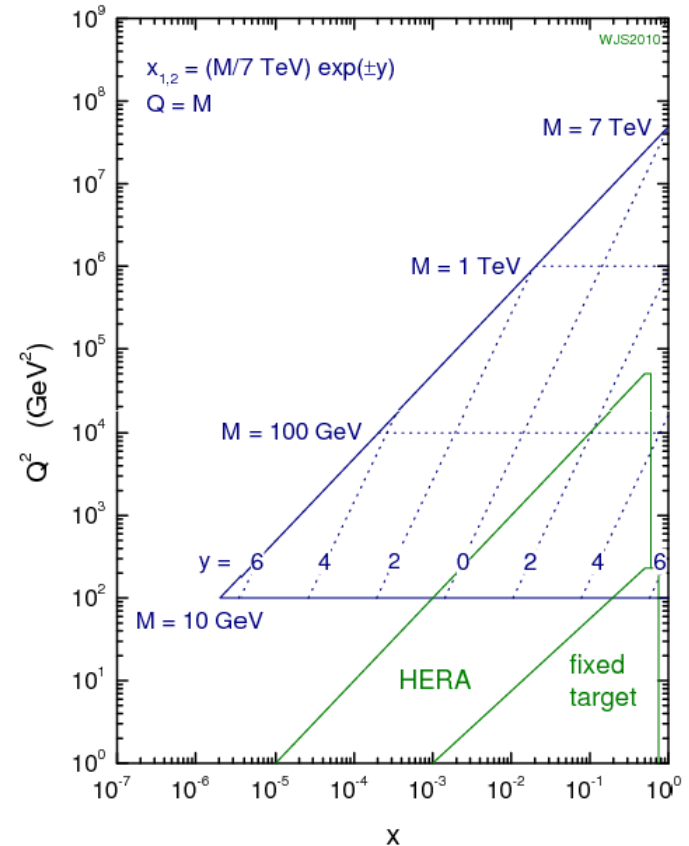
## 2.1.1) Inclusive hard jets production

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

- pp collisions: 2 ladders.
  - Central jets: symmetric collisions  $x_1 \sim x_2$ .  
DGLAP (strong  $k_T$  ordering) expected to perform well.
  - Forward jets: asymmetric collisions  $x_1 \ll x_2$ . May need  $\log(1/x)$  resummation and alternative evolution (BFKL, CCFM)



7 TeV LHC parton kinematics



## 2.1.2) Experimental setup

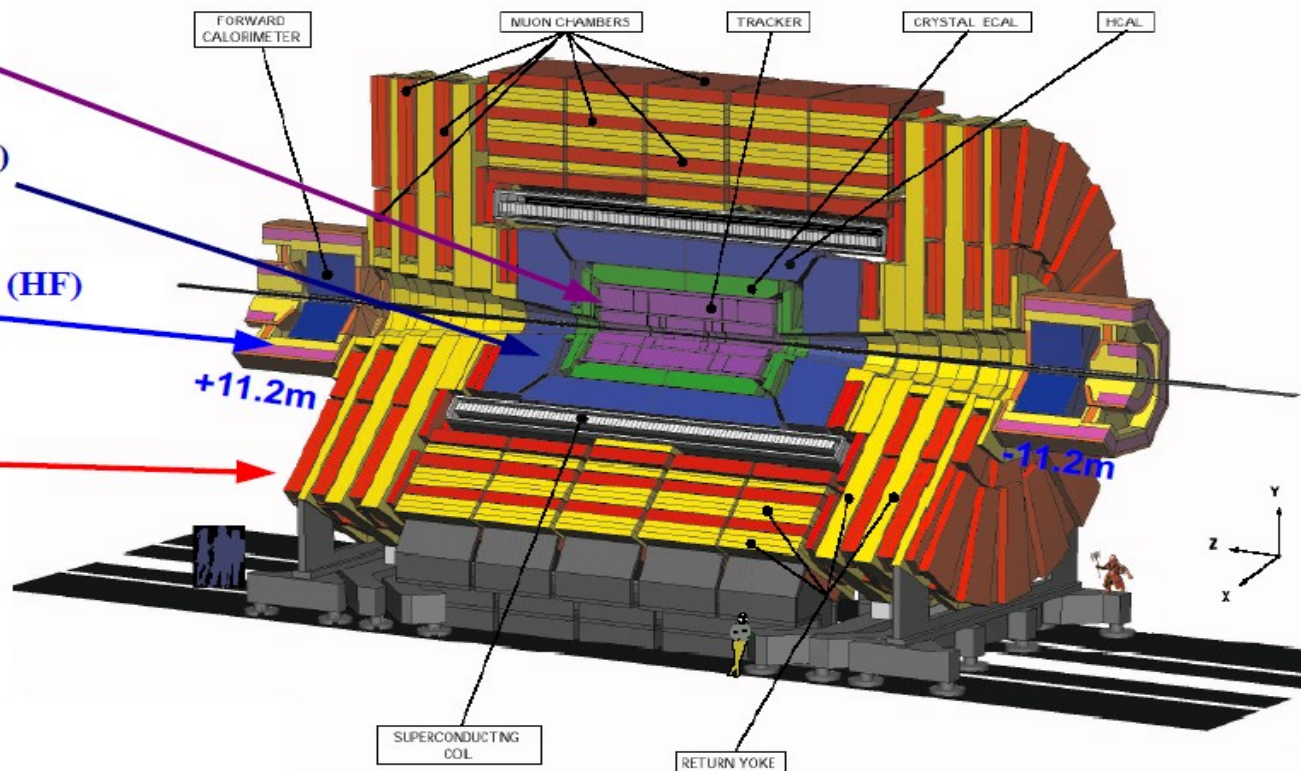
**Trackers**  
 $|\eta| < 2.5$

**Calorimeters  
(EM and Hadronic)**  
 $|\eta| < 3.0$

**Hadronic Forward (HF)  
Calorimeters**  
 $2.9 < |\eta| < 5.2$

**Muon Chambers**  
 $|\eta| < 2.5$

### A Compact Solenoidal Detector for LHC



CMS-PARA-001-11/07/97 JLB.PP

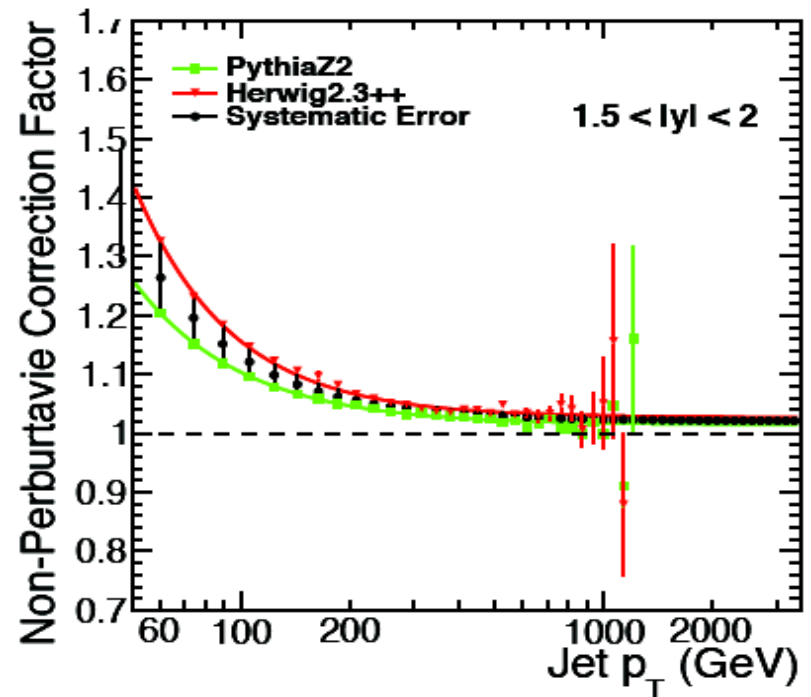
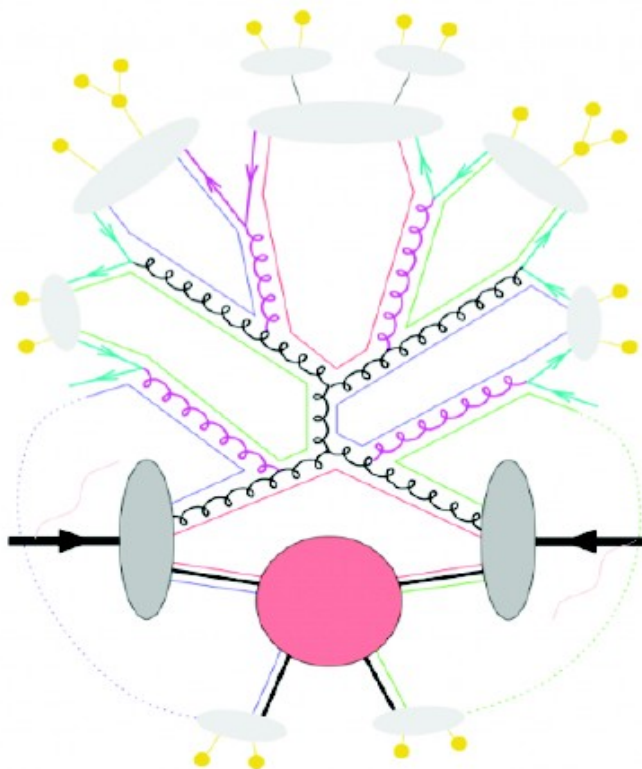
- Central region  $|\eta, y| < 2.5$  : tracker + calorimeters. Particle Flow reconstruction allow very precise measurement by combining all detectors and allow pile-up (PU) removal.
- Forward region:  $|\eta, y| > 3.0$  : calorimeters only, but jets collimated and have large energy. Low handle on PU and large UE.

## 2.2.1) Measurement of inclusive jets

$$\frac{d\sigma_{Data}^2}{dp_T dy} = \frac{d\sigma_{Det}^2}{dp_T dy} C_{Det}$$

$$\frac{d\sigma_{Thr}^2}{dp_T dy} = \frac{d\sigma_{NLO}^2}{dp_T dy} C_{NP}$$

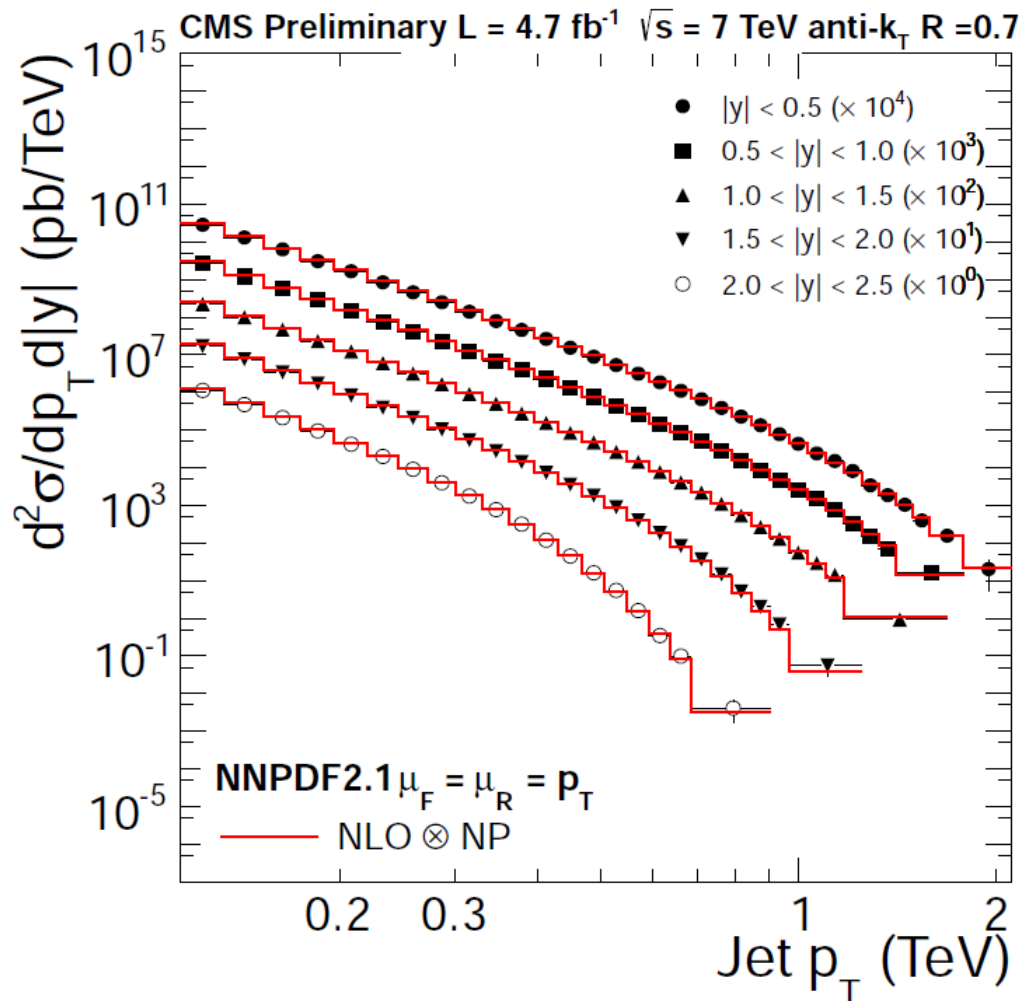
- Measurement: corrected for detector effect to “hadrons level” -  $C_{DET}$ .
- NLO calculation: corrected for hadronization and MPI effects estimated from LO+PS MC -  $C_{NP}$ .





## 2.2.2) Inclusive jets : 7 TeV with R=0.7

CMS-PAS-11-004

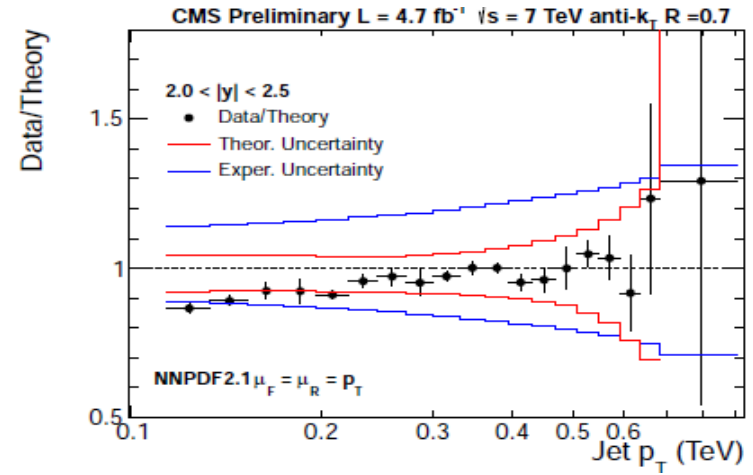
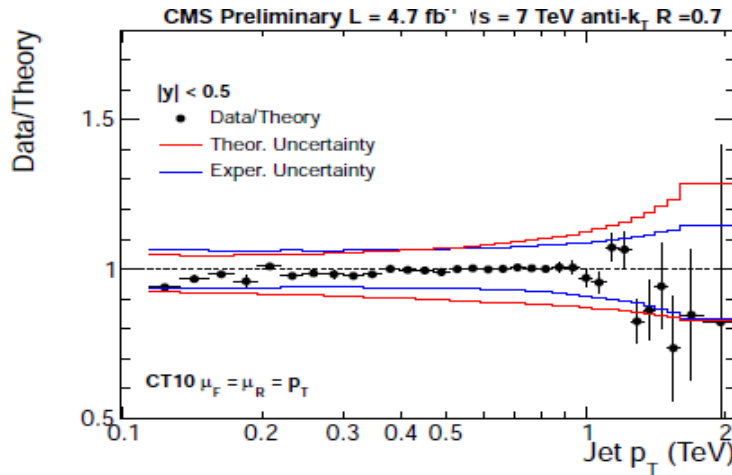


Jets reconstructed with sequential anti-k<sub>T</sub> algorithm with R=0.7

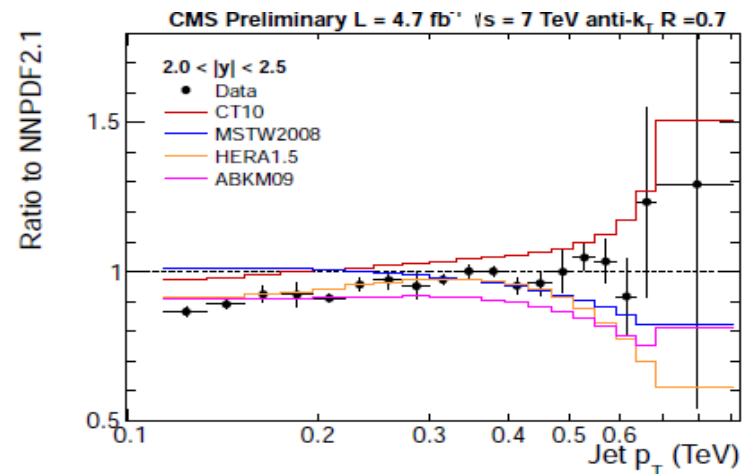
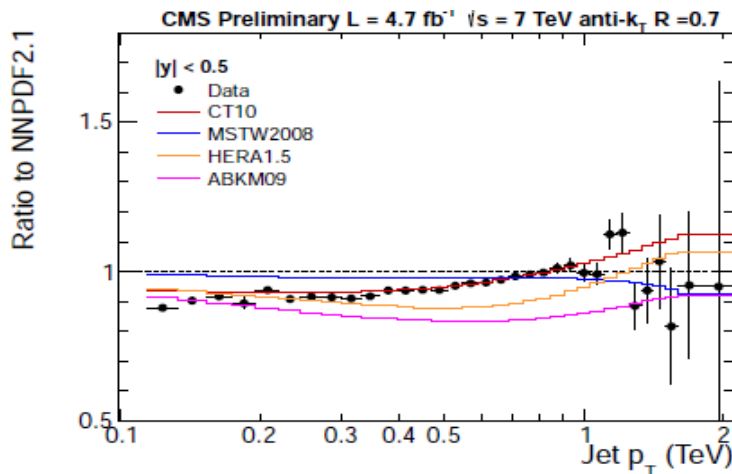
- Generally excellent agreement over 12 orders of magnitude with NLO+NP calculations.
- Let's look in more details.

## 2.2.3) Inclusive jets : 7 TeV with R=0.7

CMS-PAS-11-004

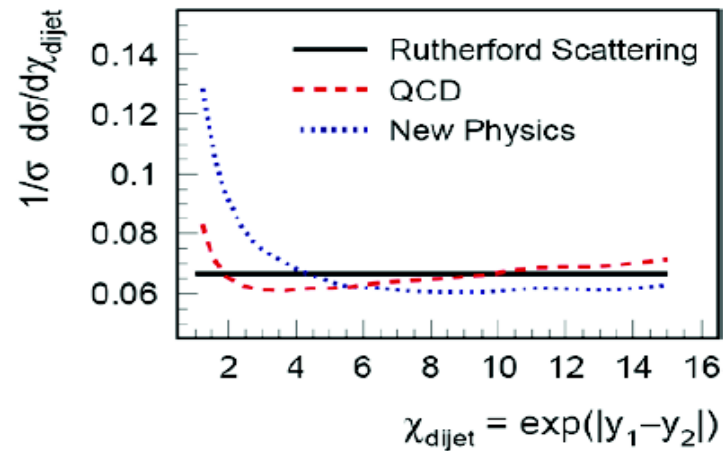
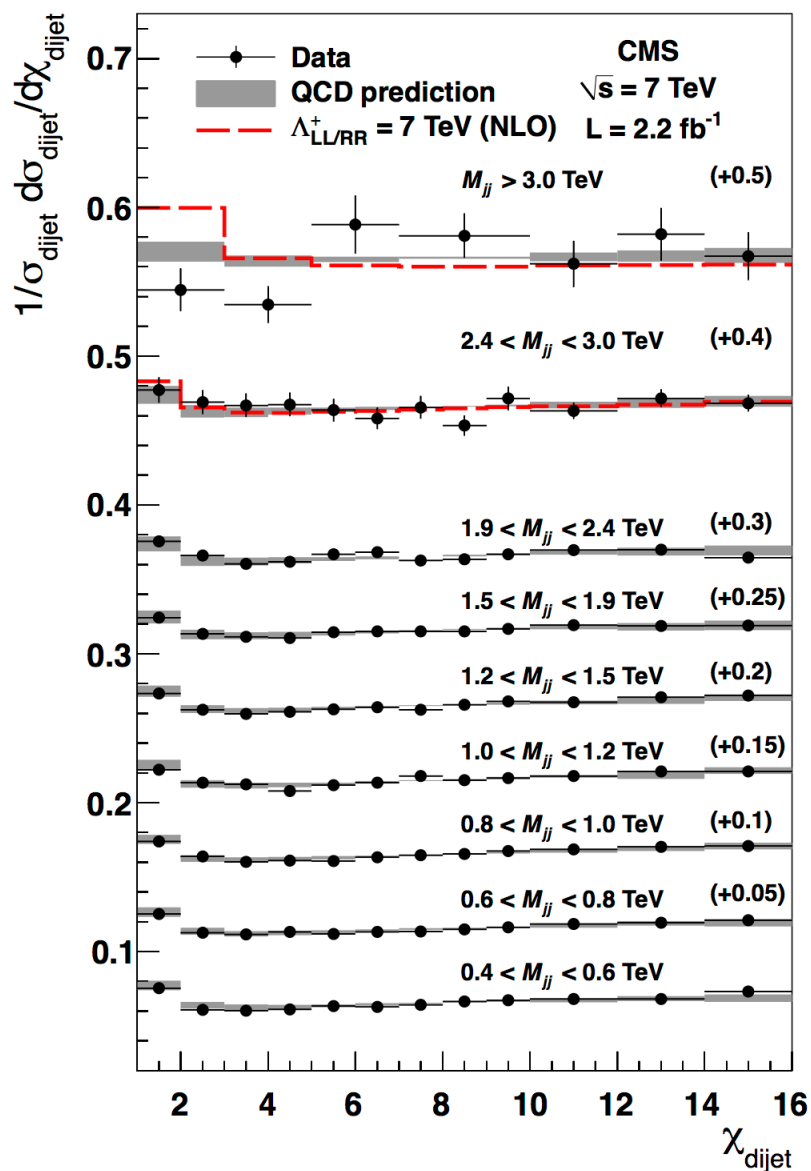


- Exp. Uncertainties – dominated by Jet Energy Scale.
- Theory uncertainty : low  $p_T$  - NP, middle/high  $p_T$  – scales, PDF.
- Promising data to constraint proton PDF within DGLAP evolution.



## 2.3) Dijet angular correlation

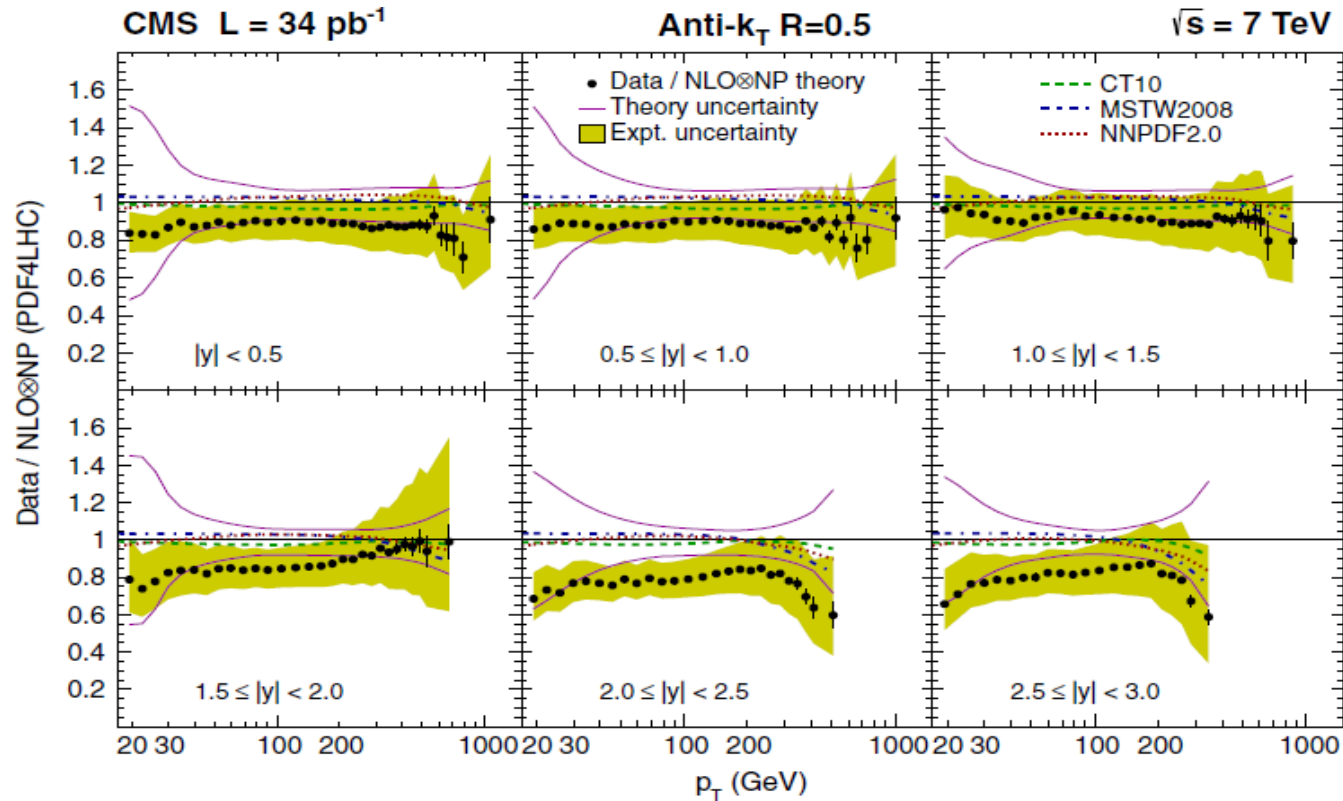
arXiv:1202.5535



- LO matrix element at LHC : dijet production.
- Anti- $k_T$  with  $R=0.5$  used.
- Each  $M_{jj}$  region normalised to 1.
- « Unfortunately » well described by pQCD in shape and no CI or resonances observed.

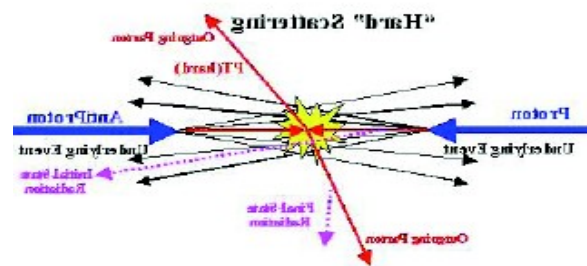
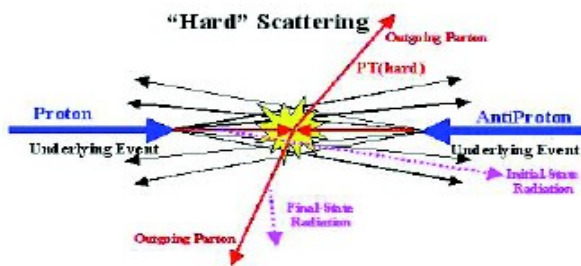
## 2.4) Inclusive jets : 7 TeV with R=0.5

Phys. Rev. Lett. 107  
(2011) 132001

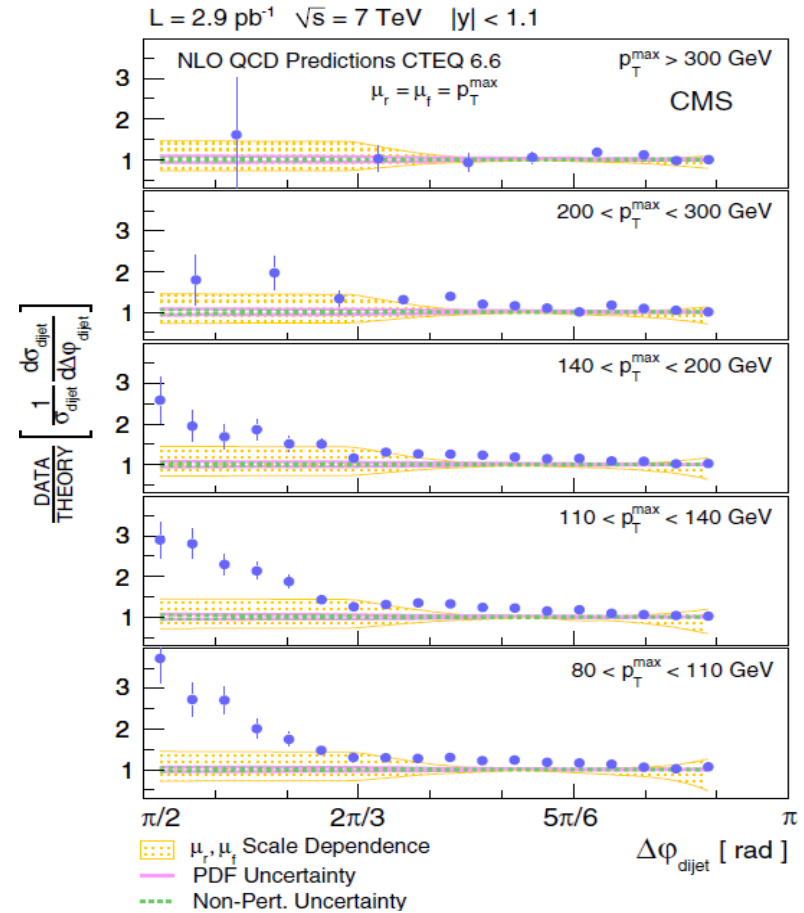
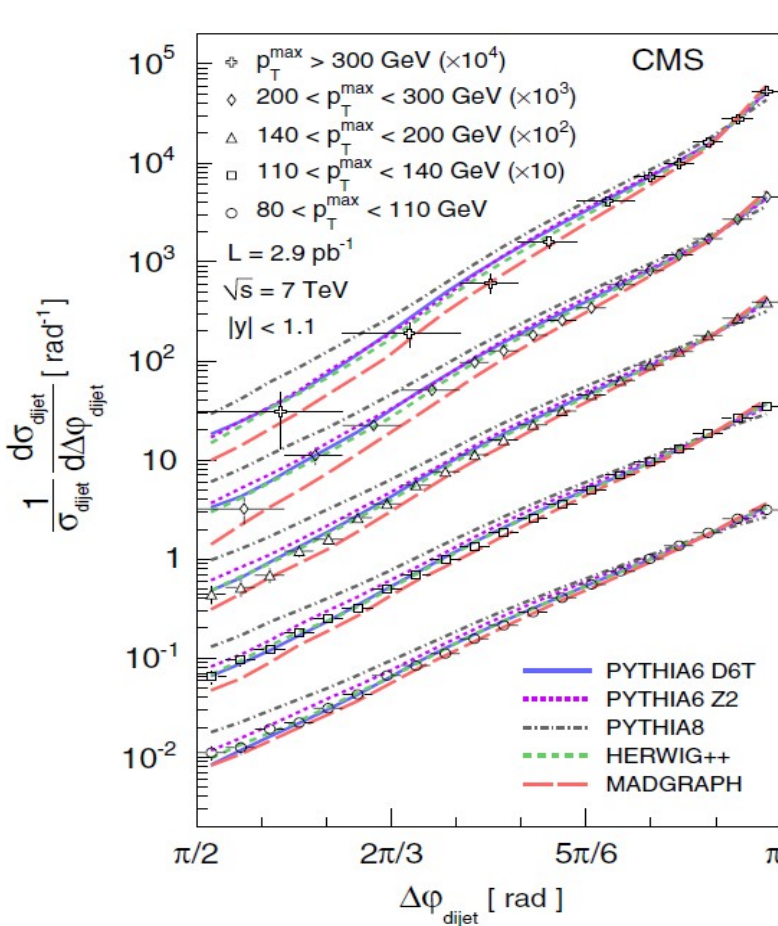


- The results for anti- $k_T$  with  $R=0.5$  are not so glorious:( Even if the difference is covered by uncertainties.
- Why ?

# Where pQCD is challenged Small radius and/or forward jets

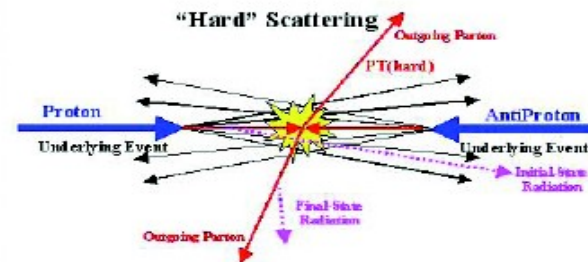
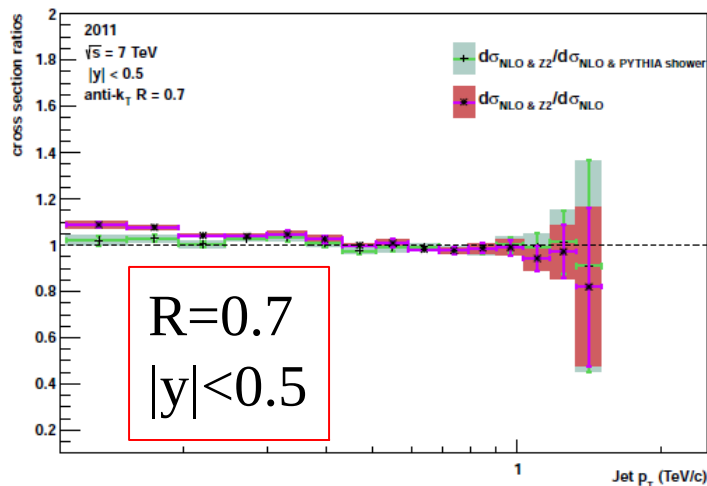
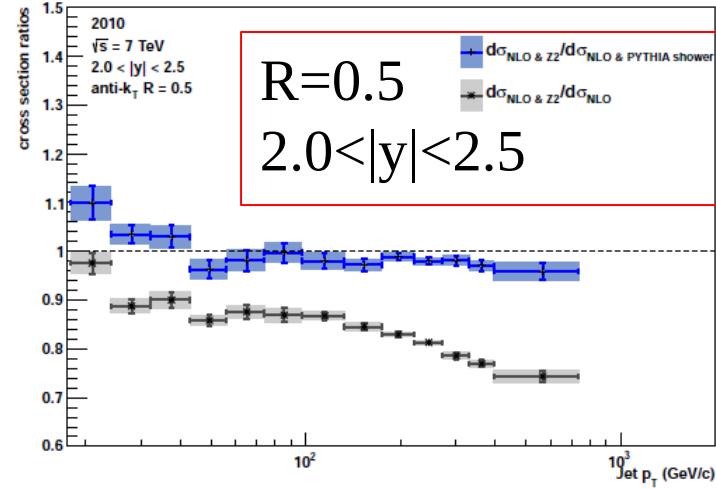
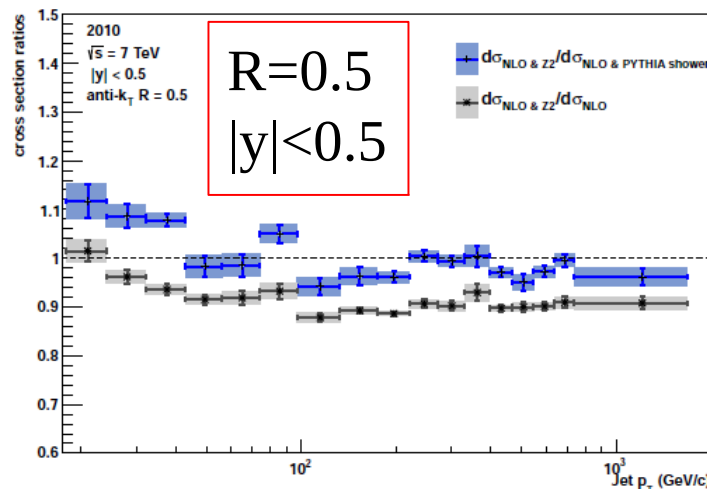


# 3.1) Dijet azimuthal decorrelation



- At LO 2 jets are back to back :  $\Delta\phi \sim \pi$ . True at large  $p_T$ .
- At low  $p_T$  ISR and FSR play a significant rôle. NLO+NP starts to fail to describe decorrelation. But LO+PS MC describe well.
- Simple evidence of importance of PS : large corrections beyond NLO!

# 3.2) POWHEG : NLO + PS + NP

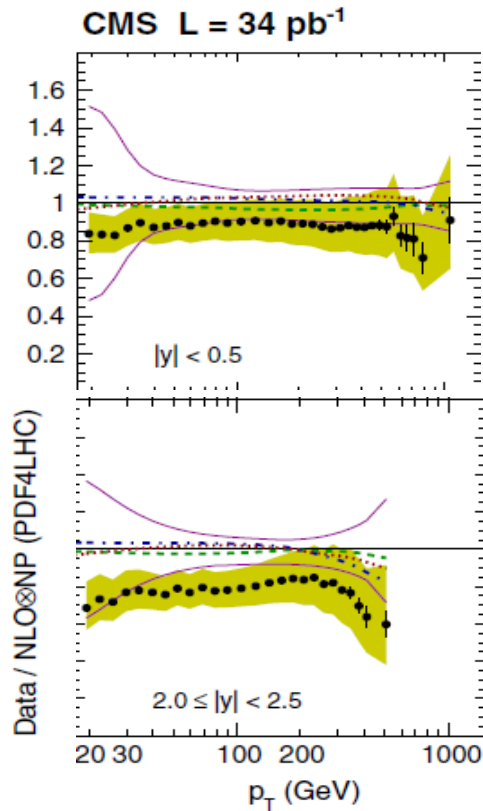


- PS corrections are more important in forward direction and for smaller R (leaking out effect).
- Applying NP corrections from LO+PS MC to NLO is inconsistent when PS effects are large.

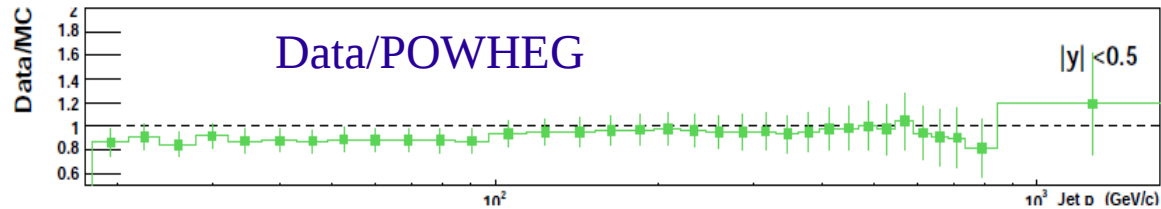
### 3.3) POWHEG vs NLO+NP

Phys. Rev. Lett. 107  
(2011) 132001

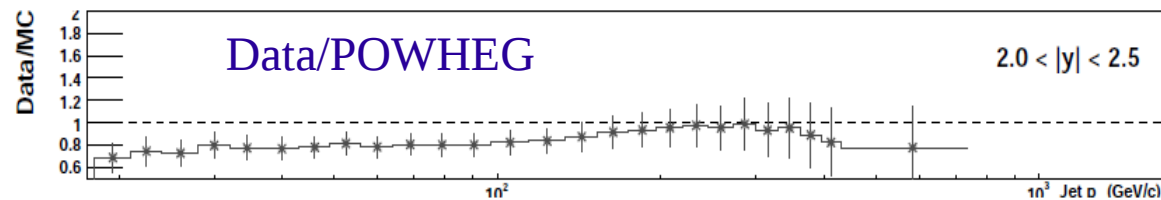
S. Dooling, H. Jung



$R=0.5$   $|y| < 0.5$



$R=0.5$   $2.0 < |y| < 2.5$



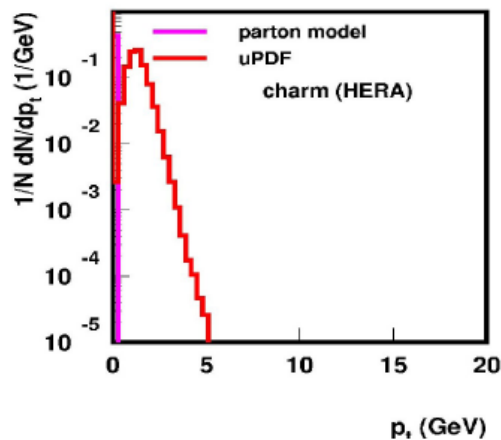
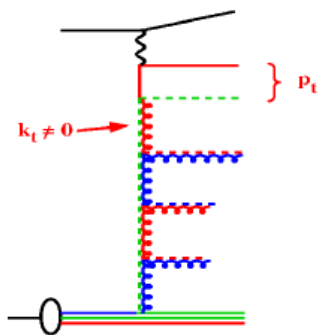
- POWHEG by itself describes better  $R=0.5$  data than NLO+NP. PS represent part of the missing orders.
- Agreement not perfect at large  $y$ , but covered by systematics.



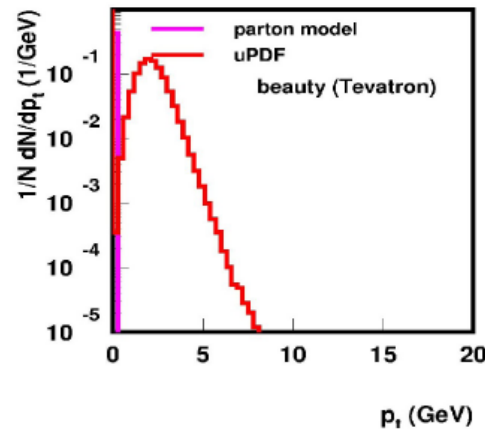
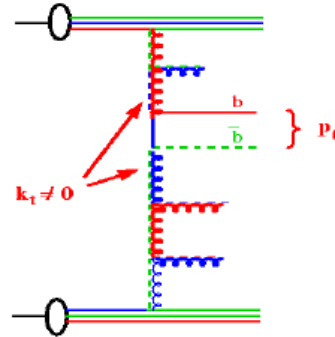
# 3.4) uPDFs : way to include PS into PDFs

J. Collins, H. Jung hep-ph/0508280

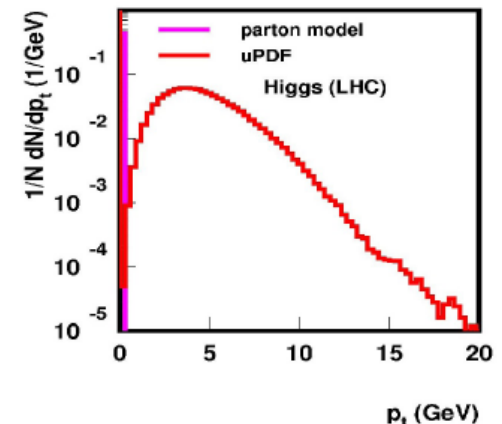
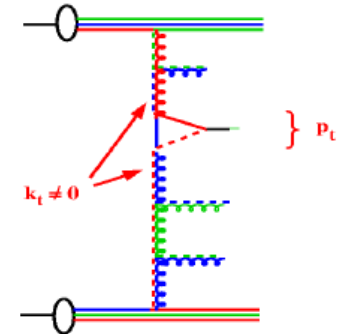
## heavy quarks at HERA



## heavy quarks in pp



## Z/W/Higgs in pp

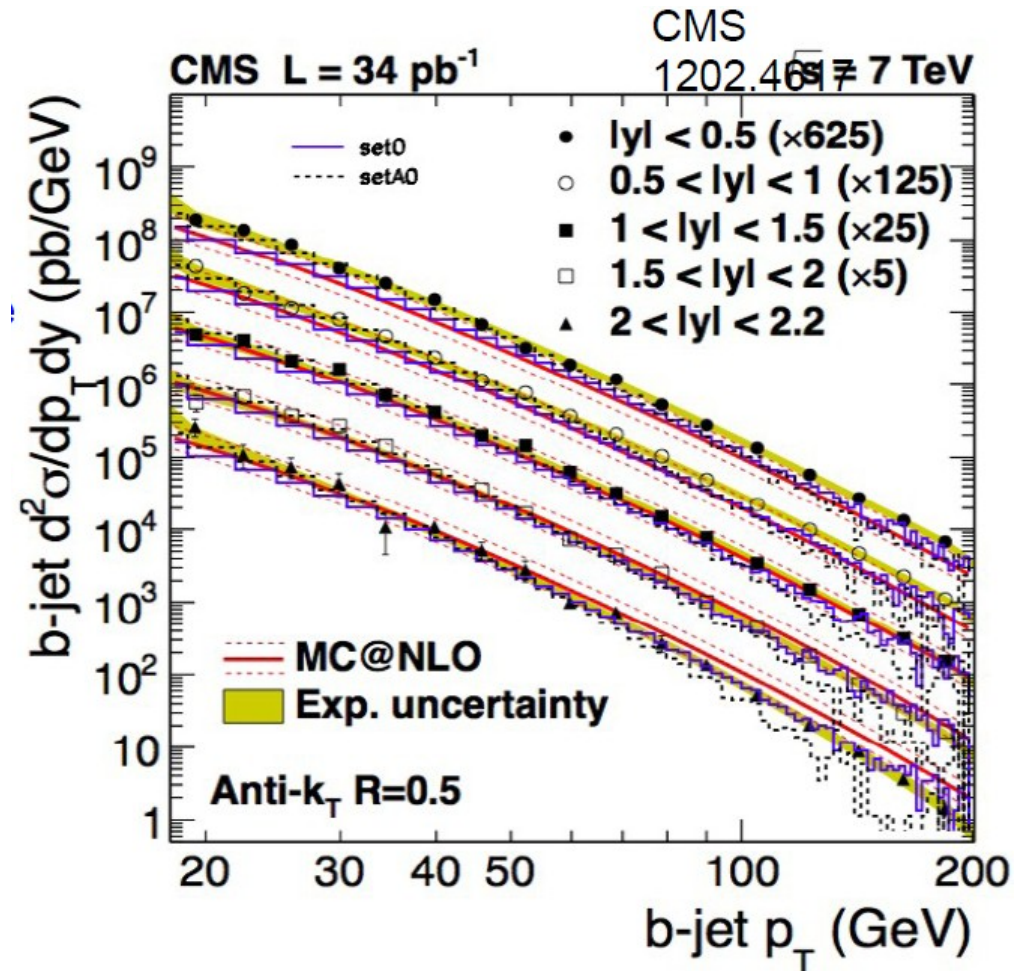


- Doing correctly kinematics at LO may reduce the NLO and PS resummation corrections. May be important when including large  $\log(1/x)$ .
- Finite transverse momenta play a role in cross sections calculations.

## 3.5) uPDFs : b-quarks example

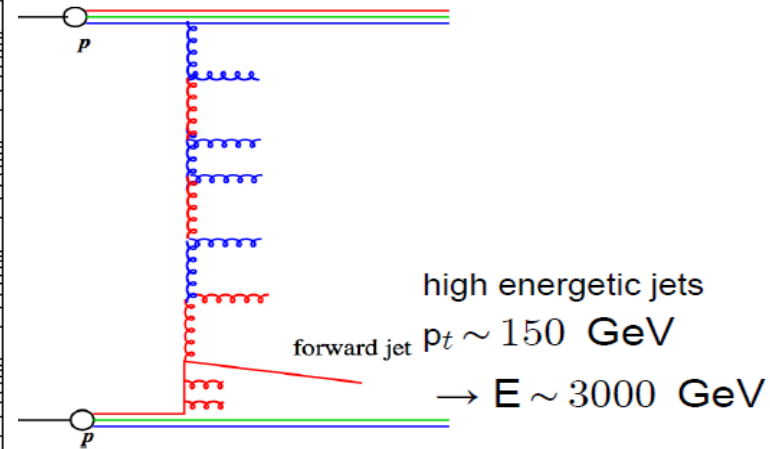
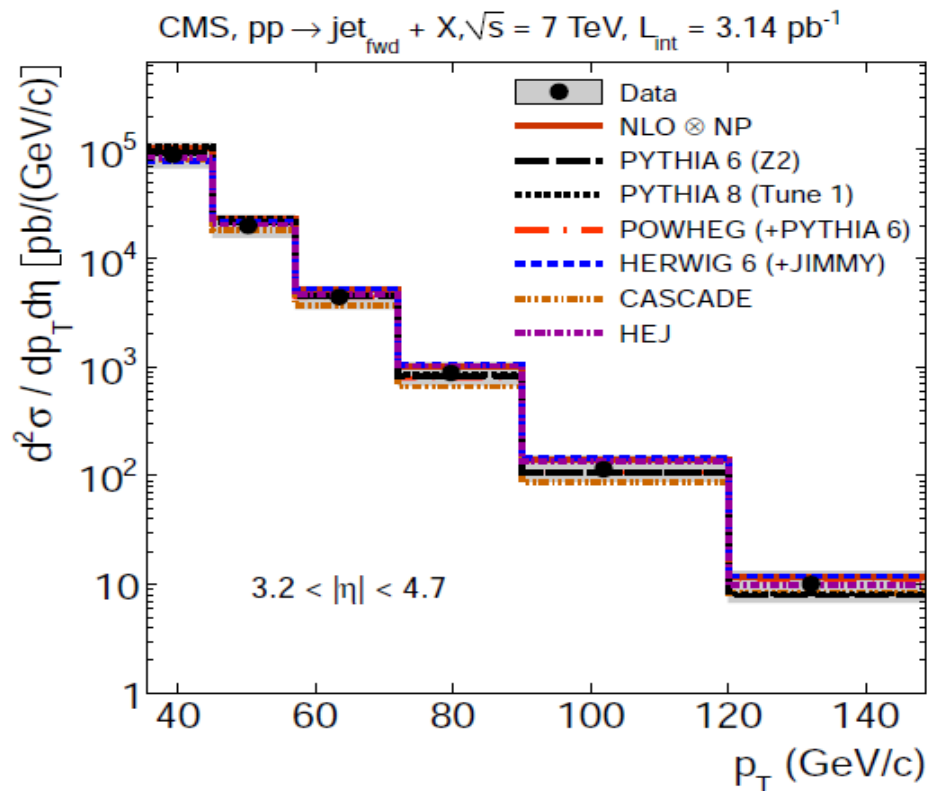
H. Jung

- Inclusive b production is gluon initiated at LO :  $gg \rightarrow bb$
- Challenging measurement wrt to inclusive jets. Uncertainty from b-tagging.
- Test uPDF (2 tunes) of the gluon at LO with CASCADE vs  $MC@NLO$ .
- Comparable at low  $p_T$  of set0 and  $MC@NLO$ , but better at large  $p_T$ .



## 3.6) Inclusive jets : Forward region

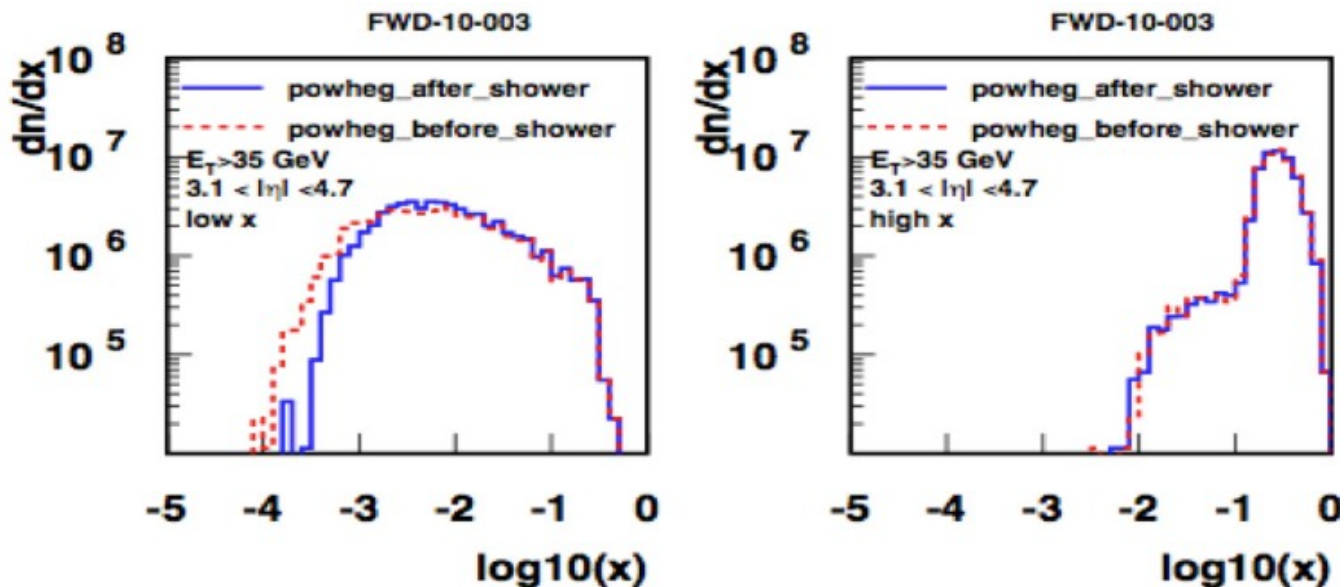
arXiv 1202.0704



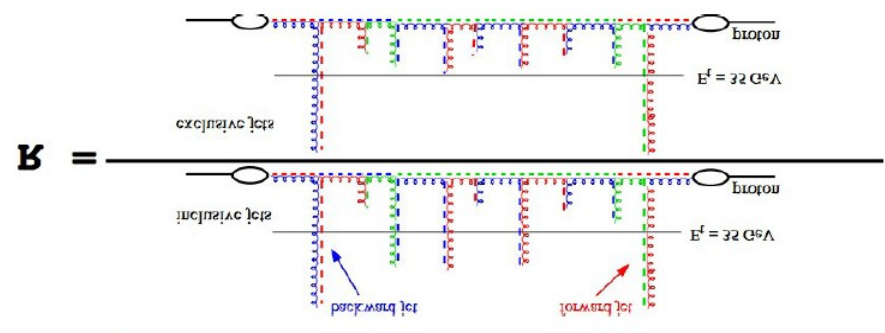
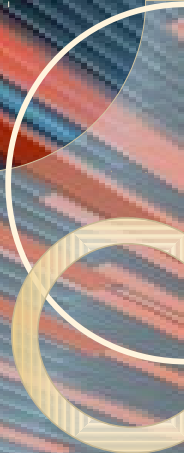
- $3.2 < |\eta| < 4.7$
- JES dominating systematic.
- All models agree within systematics.

### 3.7) Inclusive jets : 7 TeV with R=0.7

FWD-PAS-10-003

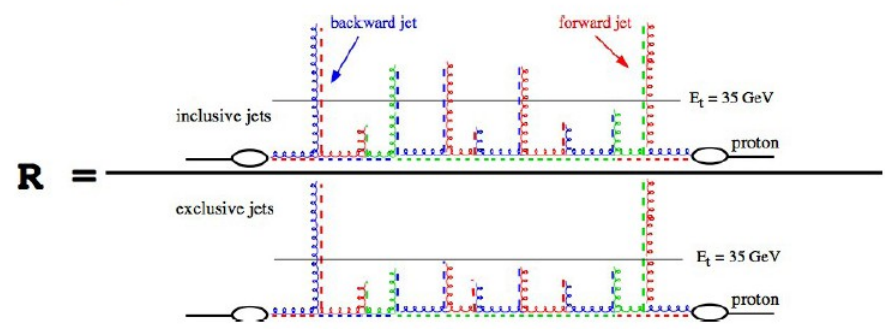


- Access to very low x region. But sensitive to ISR there. To be understood.
- May be used to measure proton PDF ?

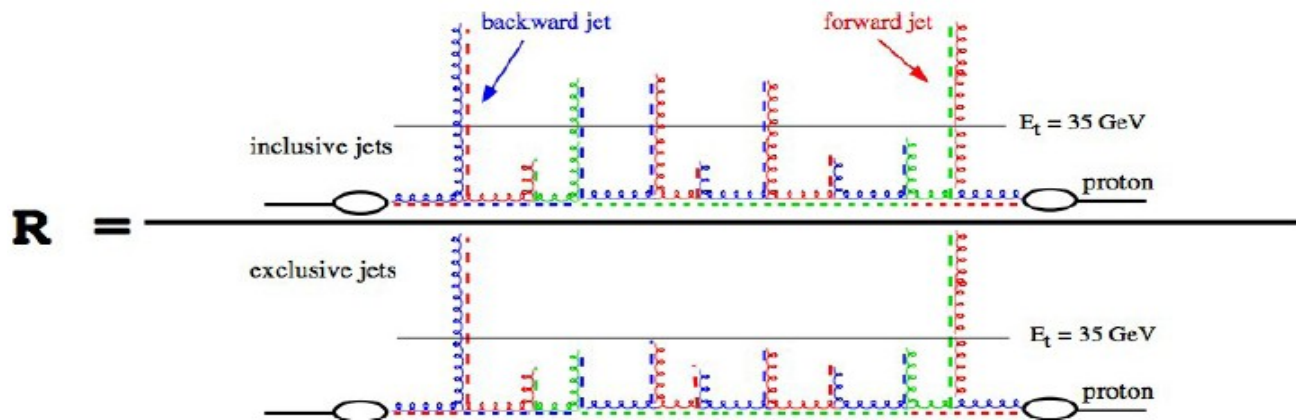


# Pushing pQCD to the limits

## large $|\Delta\eta|$



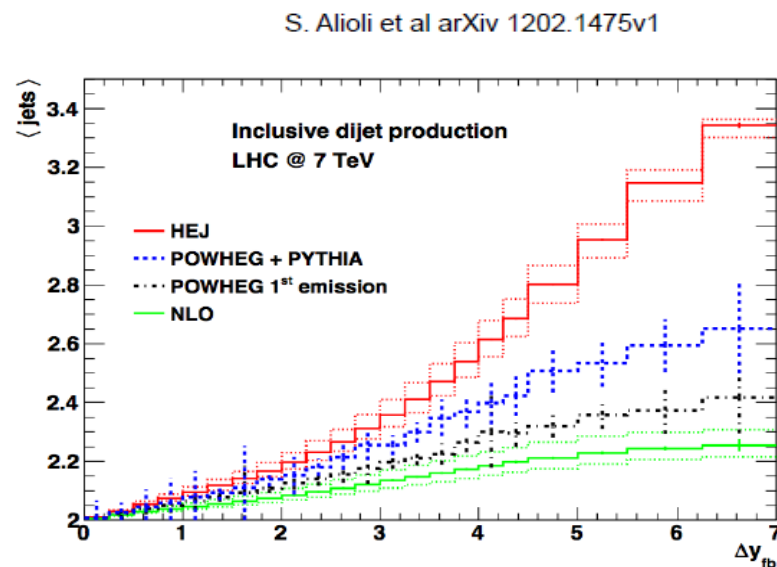
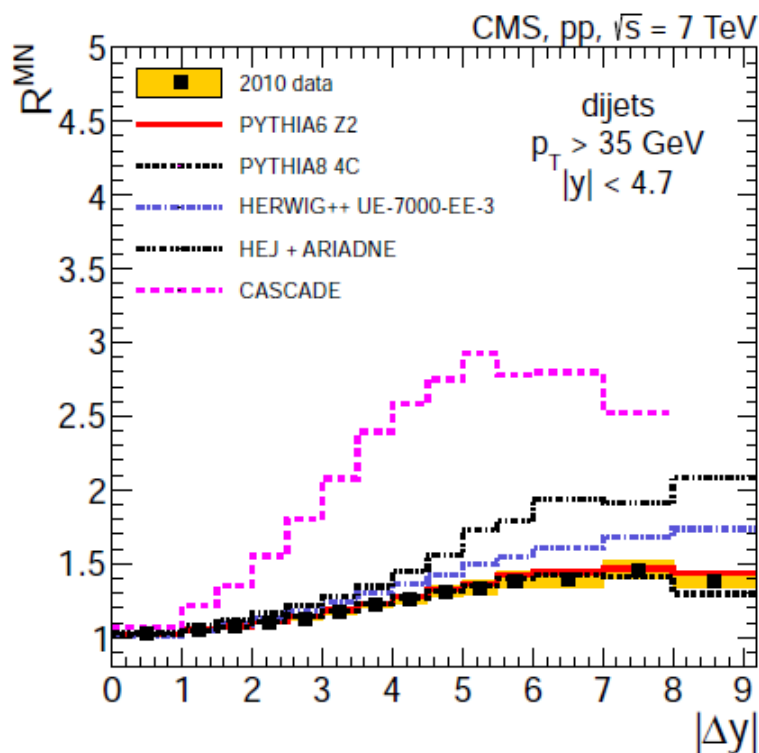
- Jets with  $p_T > 35$  GeV and  $|y| < 4.7$ ,  $R = 0.5$ .
- Measure ration of inclusive dijets events to exclusive dijet events : cancleration of systematics
- $|\Delta y| \sim |\Delta \eta| < 9$  !!! between the two most external jets (Mueller-Navlett).
- Hope to see non DGLAP dynamics in the ladders between two jets.
- Strategic region for VBF physics : large  $|\Delta y|$  and central jets veto !!!



## 4.2) Inclusive to exclusive dijet ratio

arXiv 1204.0696

- Ratio only described by PYTHIA (surprising ?). Influence of the tune and MPI small.
- Deviation of most of the other models at large  $|\Delta y|$ .
- Cascade, HEJ : include elements of CCFM or BFKL like dynamics.



# SUMMARY

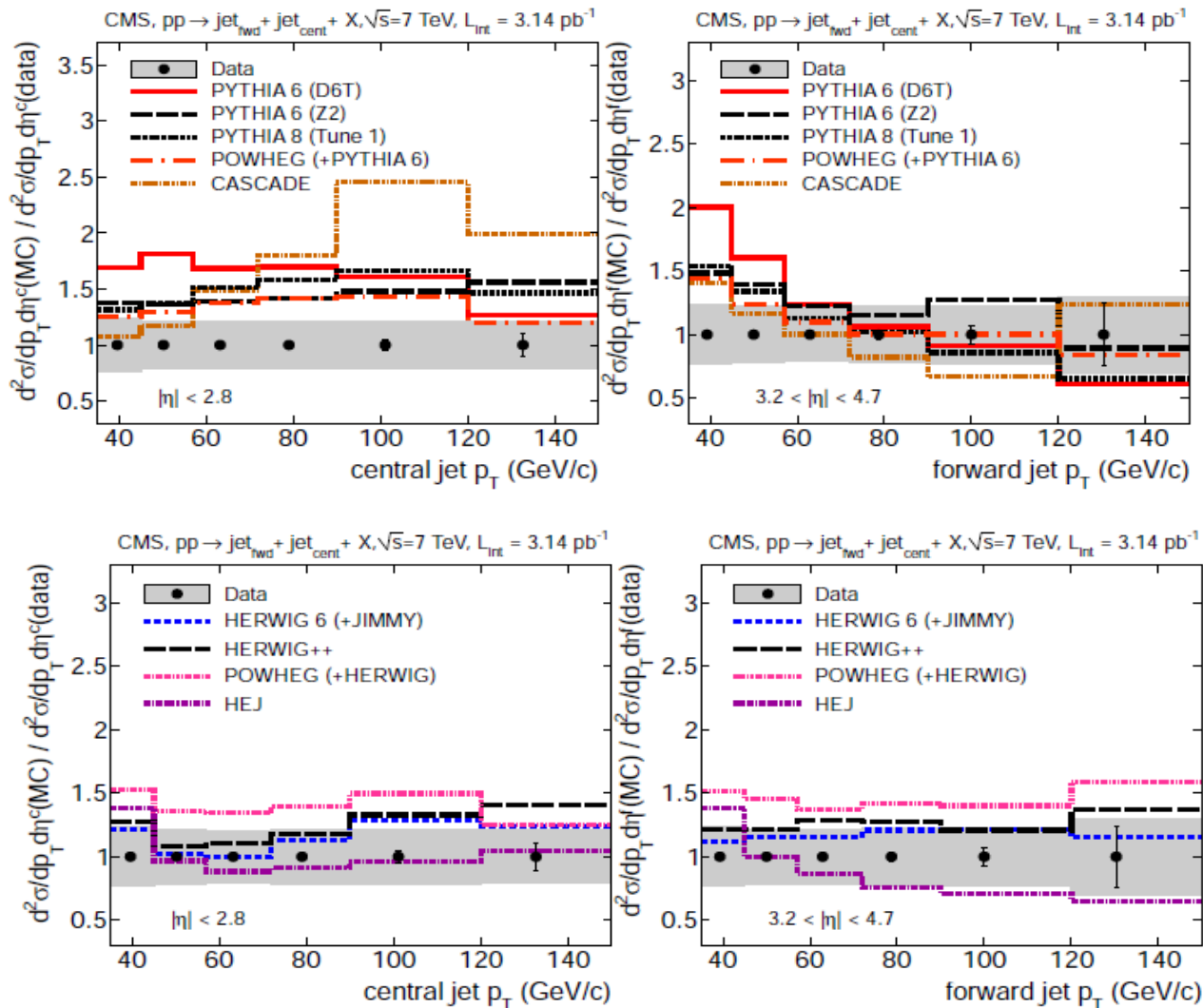
- 1) The understanding of QCD at LHC is a still challenging question even when considering simple observables as inclusive jets with low jet radius.
- 2) There are some QCD observables which are sufficiently well understood to use LHC data to constraint proton PDFs.
- 3) But for many others the NLO calculations are not sufficient in pp in contrary to ee, ep collisions. Parton Showers and other kind of leading log resummations seems to play an appreciable role.
- 4) This subject have to be understood since QCD is a background to non leptonic QCD searches and to the VBF production.



# BACKUP



# 4) Dijets : 1 central jet + 1 forward jet



- All models fails. The closest is HEJ