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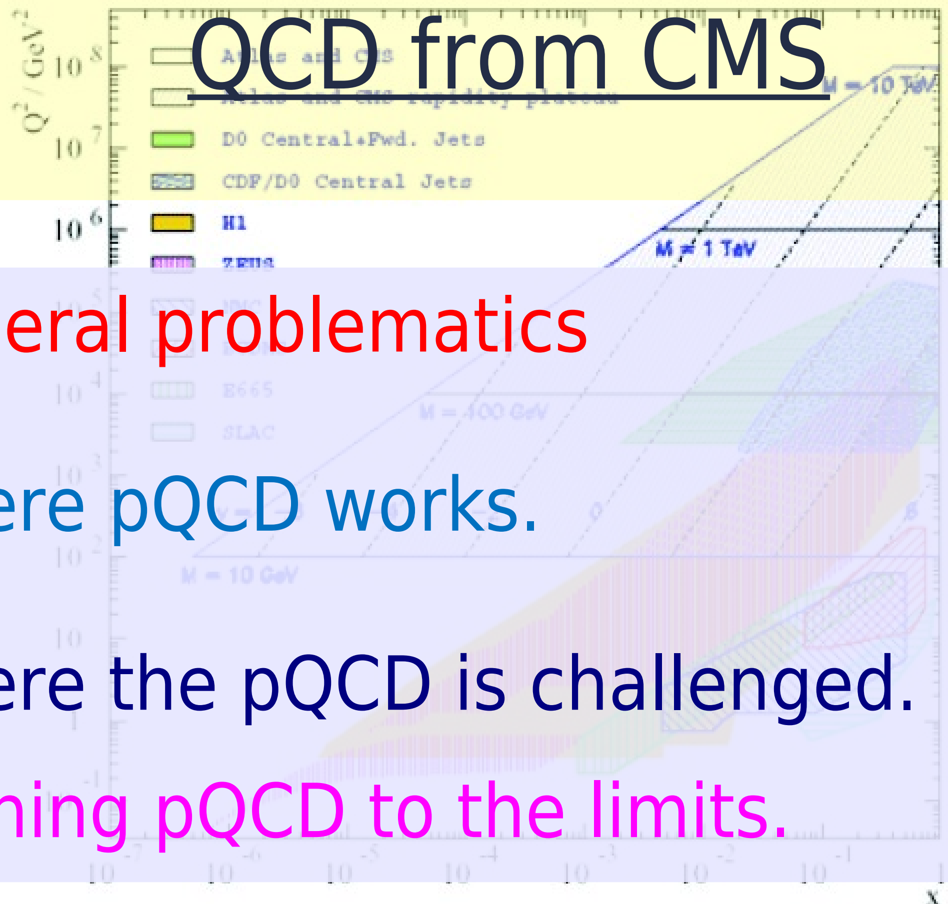
QCD from CMS



1) General problematics

2) Where pQCD works.

3) Where the pQCD is challenged.

4) Pushing pQCD to the limits.

Thanks to H. Jung, S. Dooling for help in preparation

1.1) Common wisdom about QCD

- QCD is <u>ONE</u> theory: SU3 + free coupling parameter.
  - Well established in ee and ep colliders: α_s value and running, interaction mediator (gluon), SU3 gauge group, pQCD at NNLO, factorization theorem for hadrons PDFs...

- But <u>MANY</u> regimes with associated approximations:
  - NP regime (lattice QCD, phenomenology): spectroscopy
    - Common wisdom: complicated chemistry.

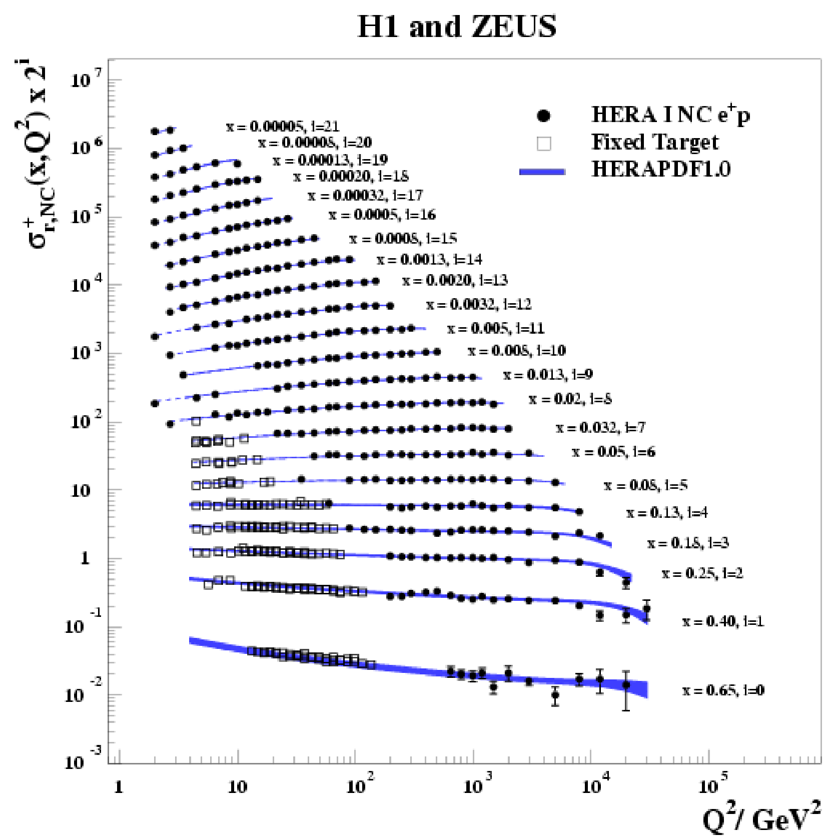
  - Intermediate (phenomenology): fragmentation functions, UE, Min bias collisions.
    - Common wisdom: "tuning and witchcraft".

  - 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.

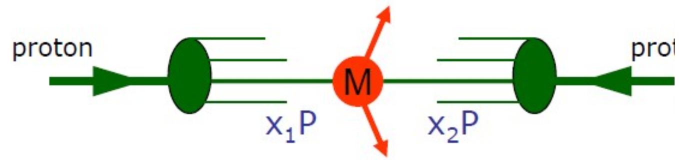


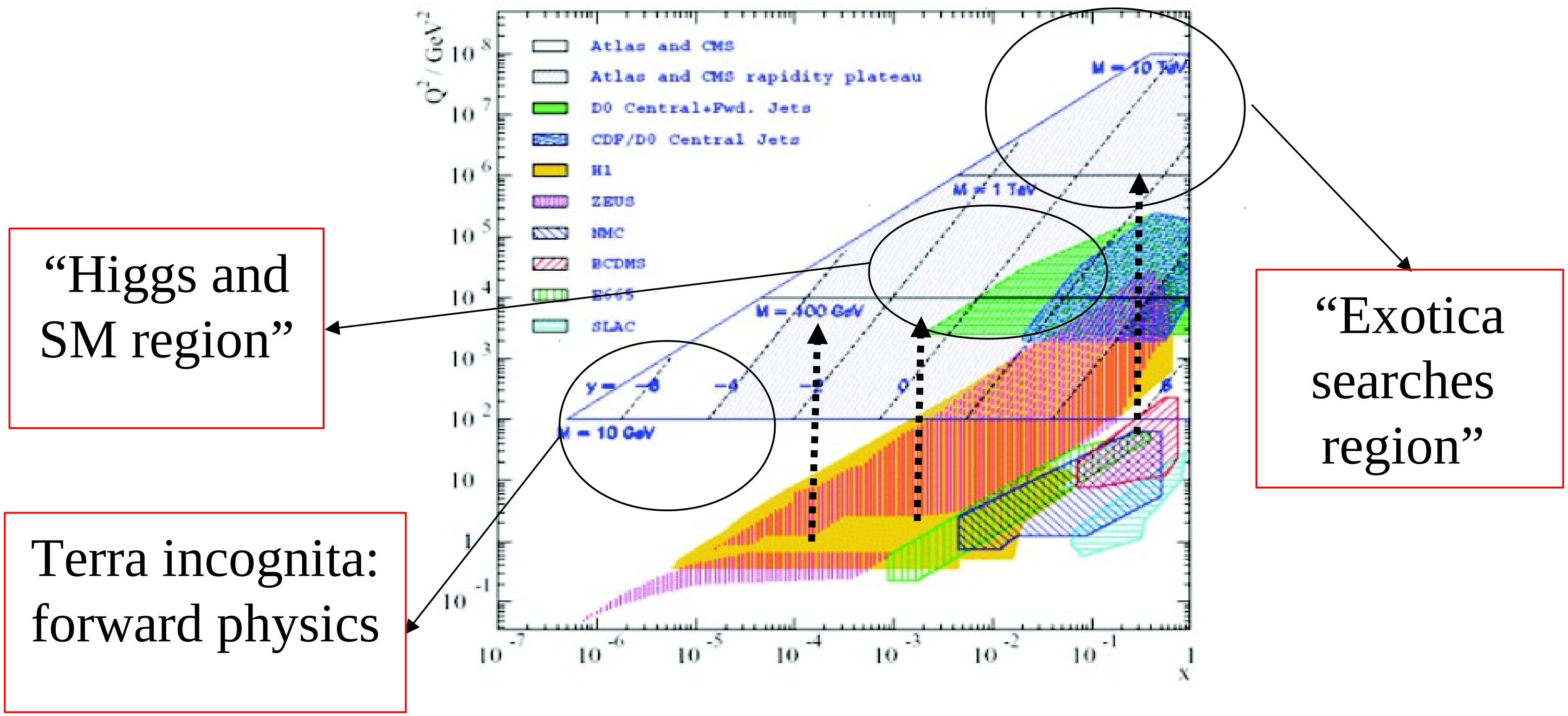
- It seems that this is not always true for the hadron colliders. Let's have a look on it.

CMS Experiment at the LHC, CERN

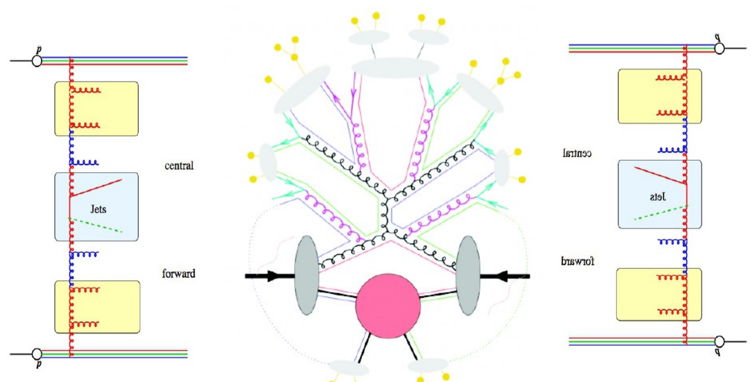
1.3) Kingdom of the pQCD

- 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).





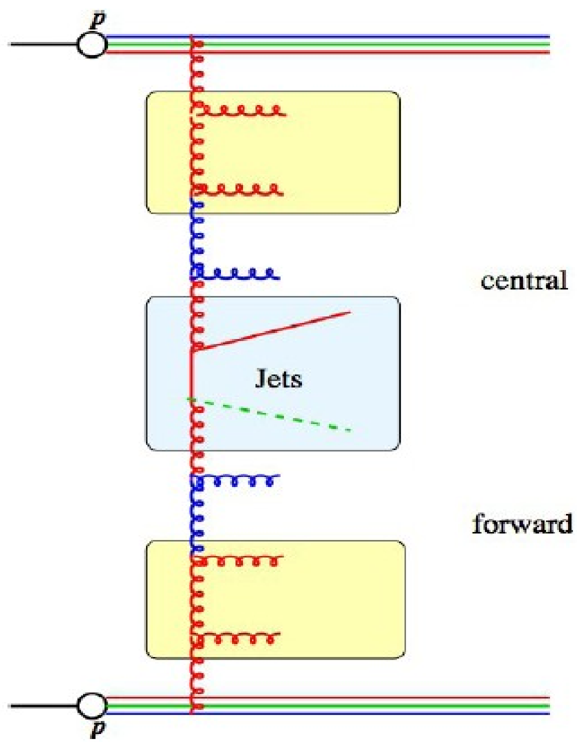
Where pQCD works
Central jets production and "Exotica region"

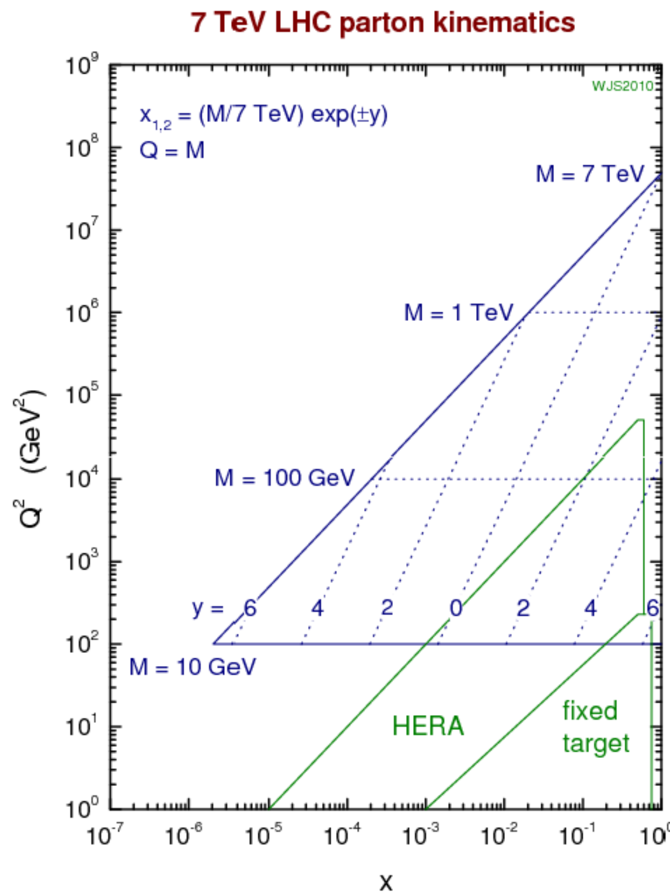


2.1.1) Inclusive hard jets production

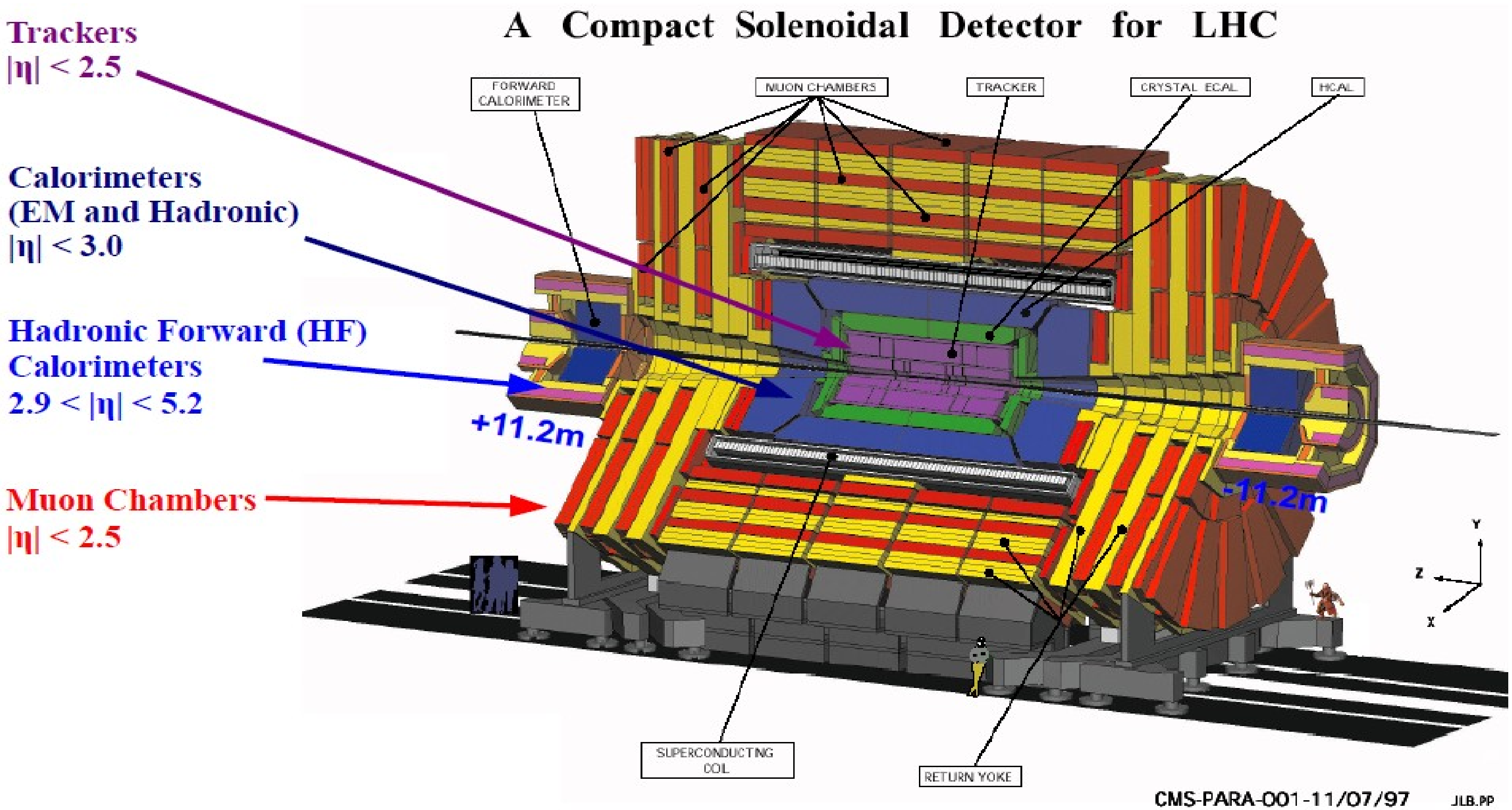
$$x = \frac{2p_t}{\sqrt{s}} \exp(\pm y)$$

- pp collisions: 2 ladders.
  - Central jets: symmetric collisions x1 ~ x2.
    DGLAP (strong kT ordering) expected to perform well.
  - Forward jets: asymmetric collisions x1 << x2. May need log(1/x) resummation and alternative evolution (BFKL, CCFM





2.1.2) Experimental setup



• Central region |η,y|<2.5 : tracker + calorimeters. Particle Flow reconstruction allow very precise measurement by combining all detectors and allow pile-up (PU) removal.

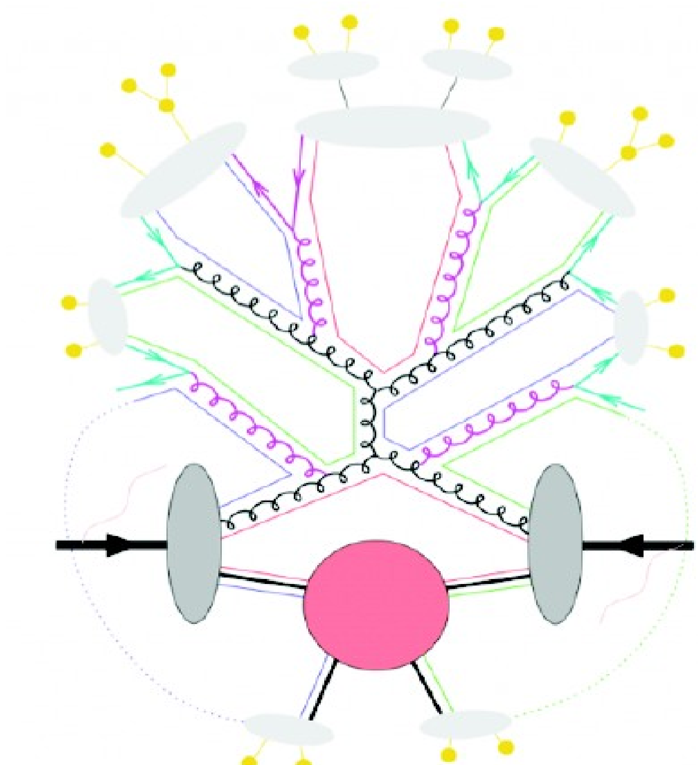
• Forward region: |η,y|>3.0 : calorimeters only, but jets collimated and have large energy. Low handle on PU and large UE.

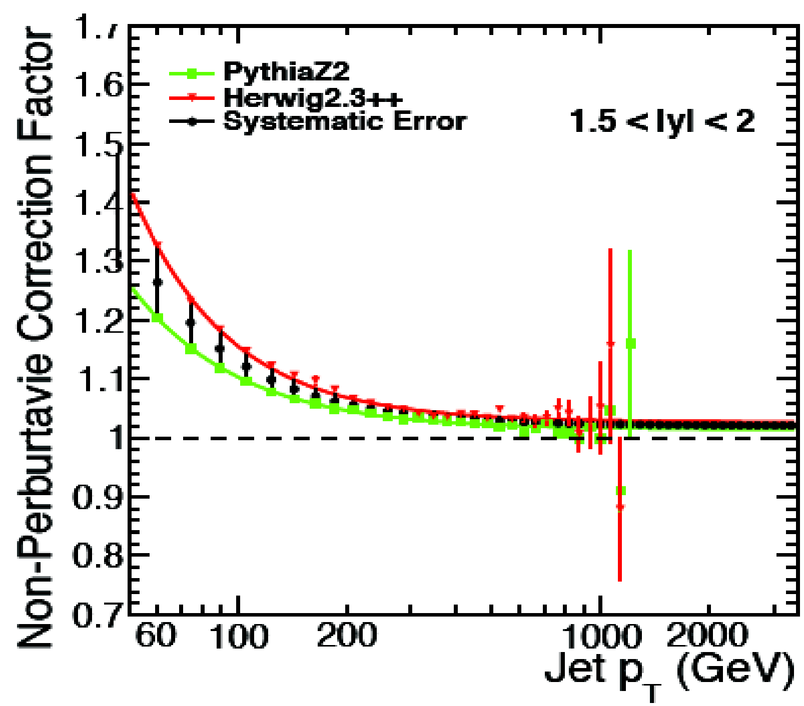
2.2.1) Measurement of inclusive jets

$$\frac{d\sigma^2_{Data}}{dp_T\,dy} = \frac{d\sigma^2_{Det}}{dp_T\,dy} C_{Det}$$

$$\frac{d\sigma^2_{Thr}}{dp_T\,dy} = \frac{d\sigma^2_{NLO}}{dp_T\,dy} C_{NP}$$

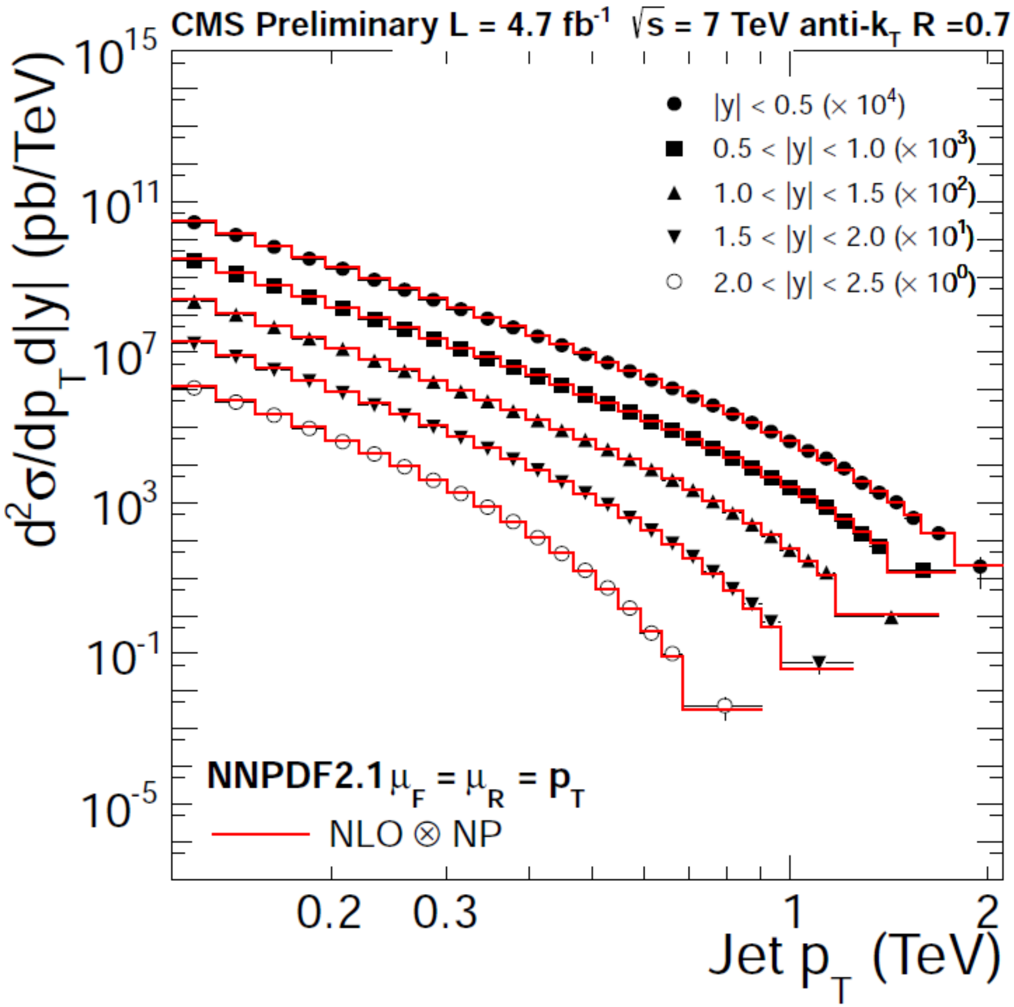
- Measurement: corrected for detector effect to "hadrons level" - C_{DET}.
- NLO calculation: corrected for hadronization and MPI effects estimated from LO+PS MC - C_{NP}.





2.2.2) Inclusive jets : 7 TeV with R=0.7

CMS-PAS-11-004

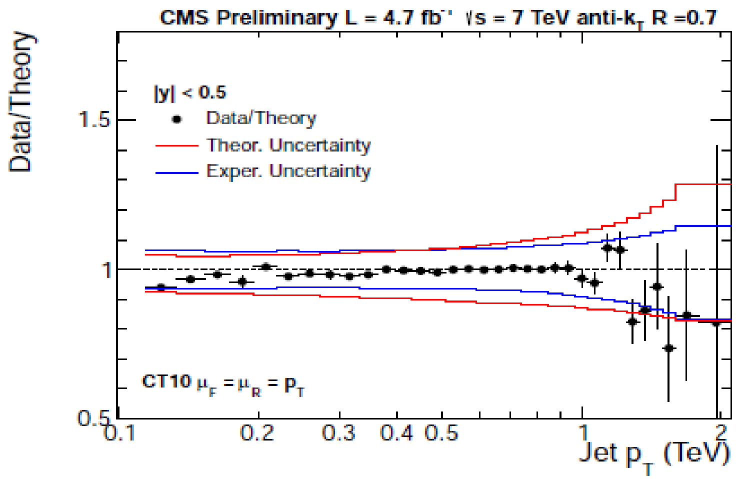


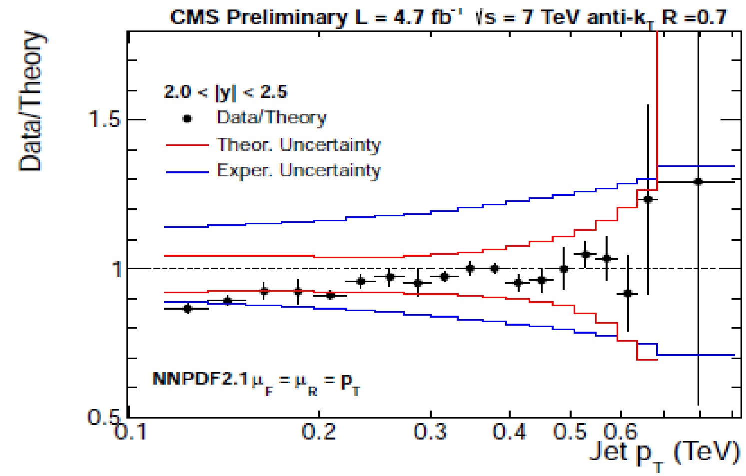
Jets reconstructed with sequential anti-k_T algorithm with R=0.7

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

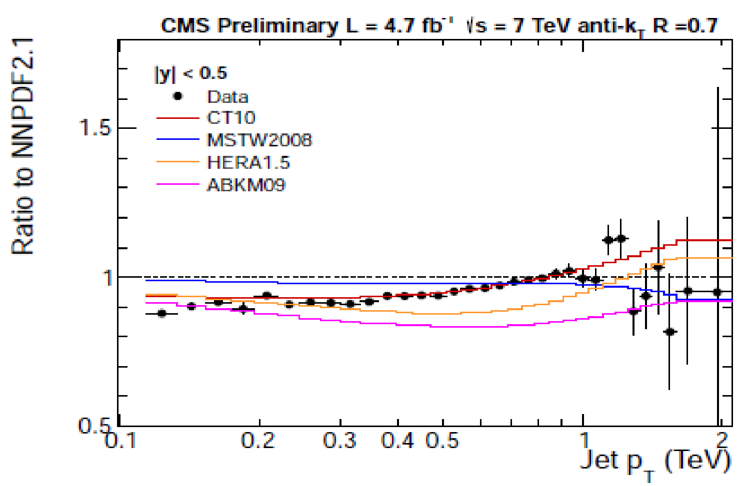
2.2.3) Inclusive jets : 7 TeV with R=0.7

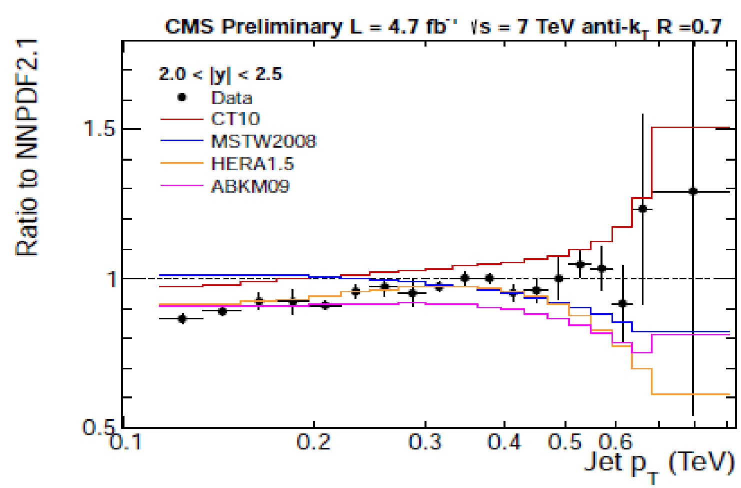
CMS-PAS-11-004





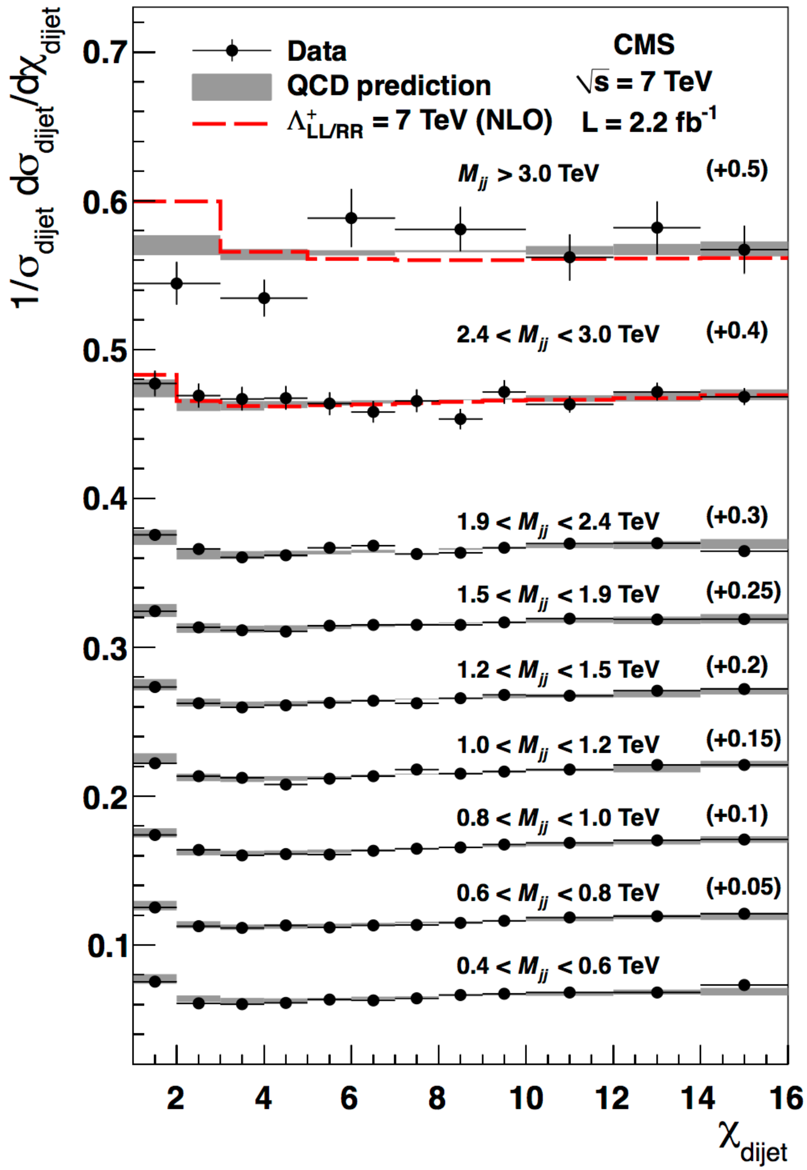
- Exp. Uncertainties – dominated by Jet Energy Scale.
- Theory uncertanty : low pT - NP, middle/high pT – scales, PDF.
- Promising data to constraint proton PDF within DGLAP evolution.

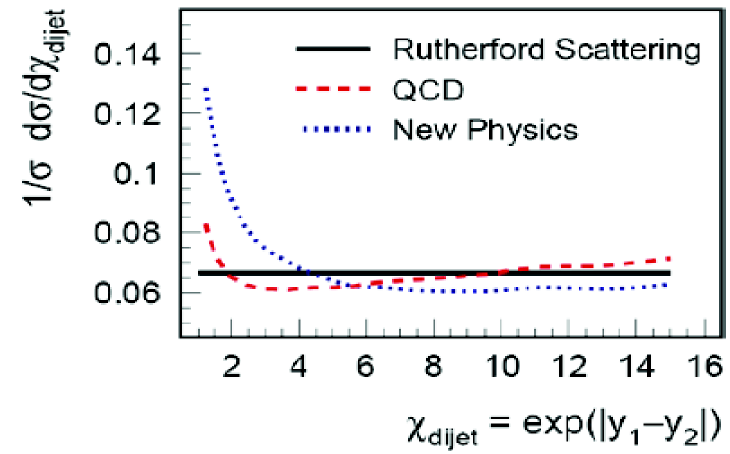




2.3) Dijet angular correlation

arXiv:1202.5535

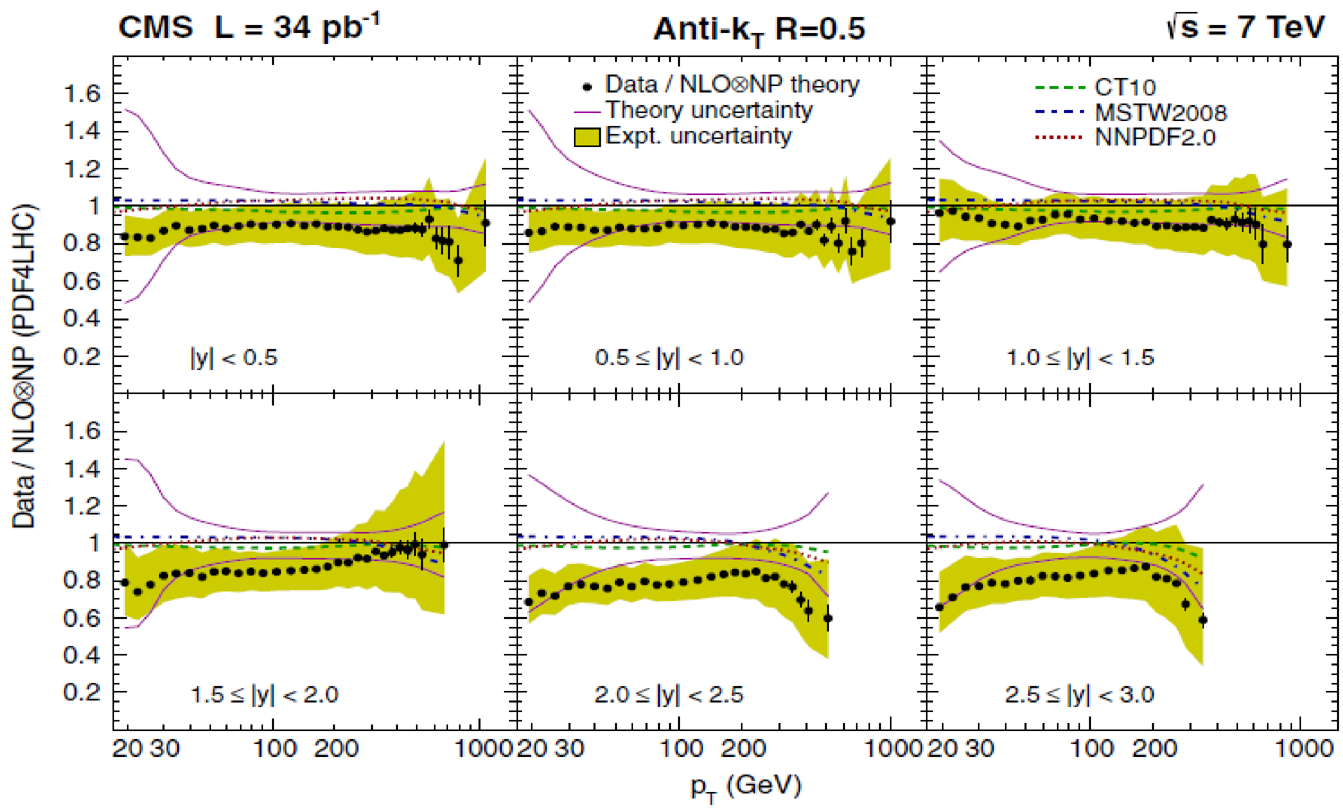




- LO matrix element at LHC : dijet production.
- Anti-kT with R=0.5 used.
- Each Mjj region normalised to 1.
- « Unfortunately » well described by pQCD in shape and no CI or resonances observed.

2.4) Inclusive jets : 7 TeV with R=0.5

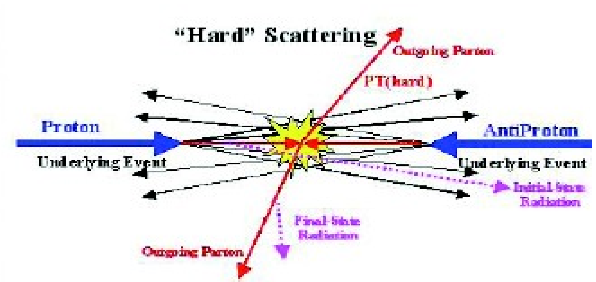
Phys. Rev. Lett. 107 (2011) 132001

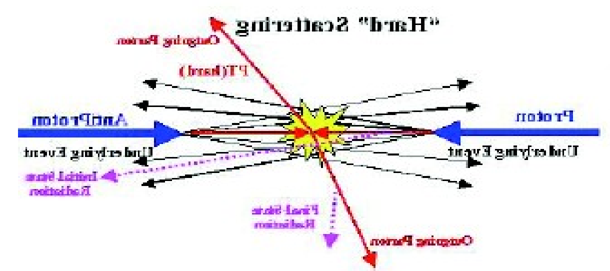


- The results for anti-kT with R=0.5 not so glorious even if the difference is covered by uncertainties.
- Why ?

Where pQCD is challanged

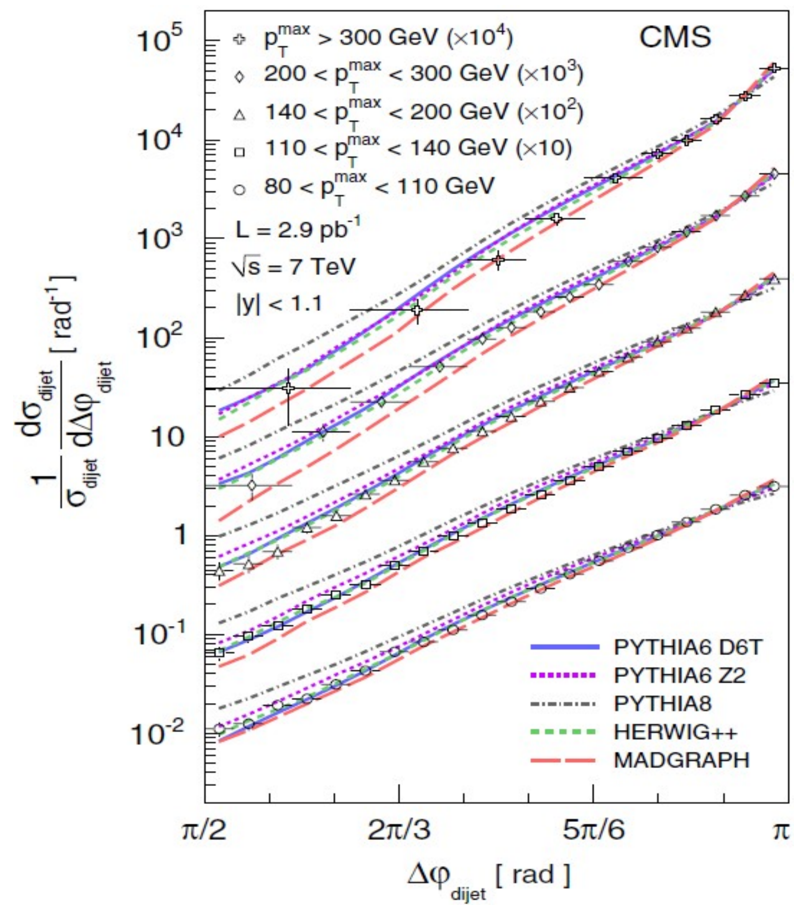
Small radius and/or forward jets

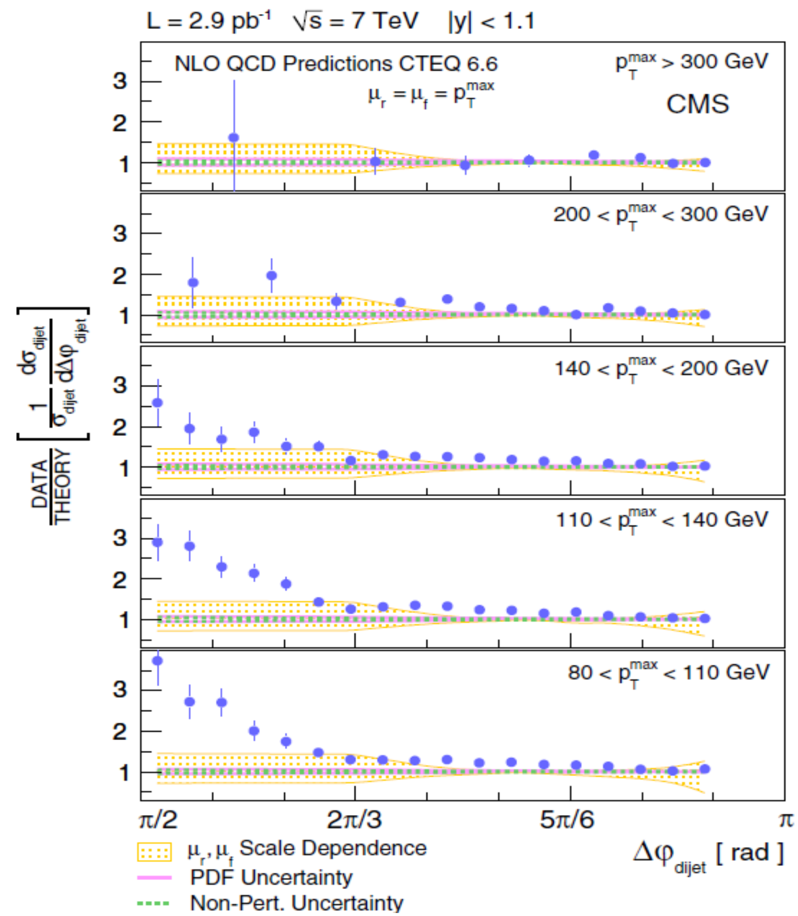




3.1) Dijet asimuthal decorrelation

PhysRevLett.106.122003

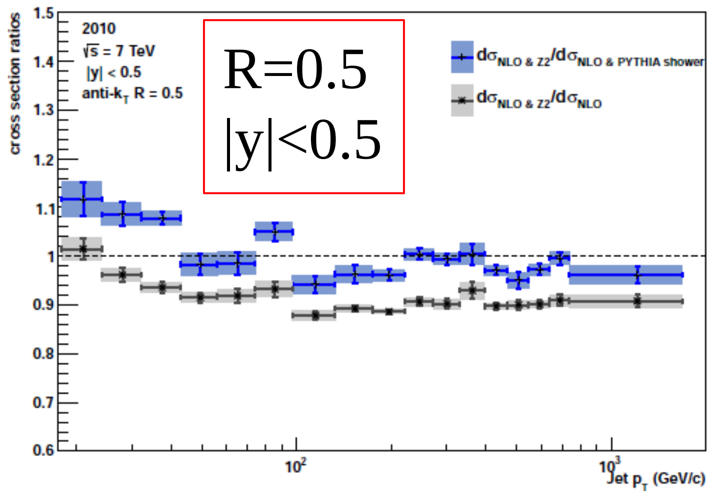


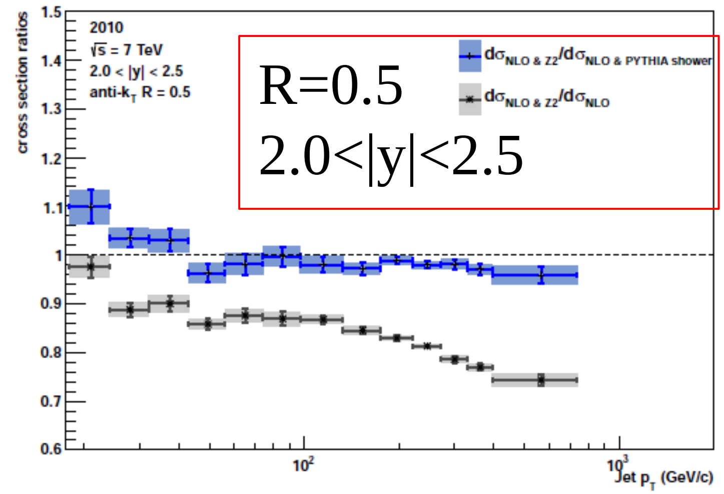


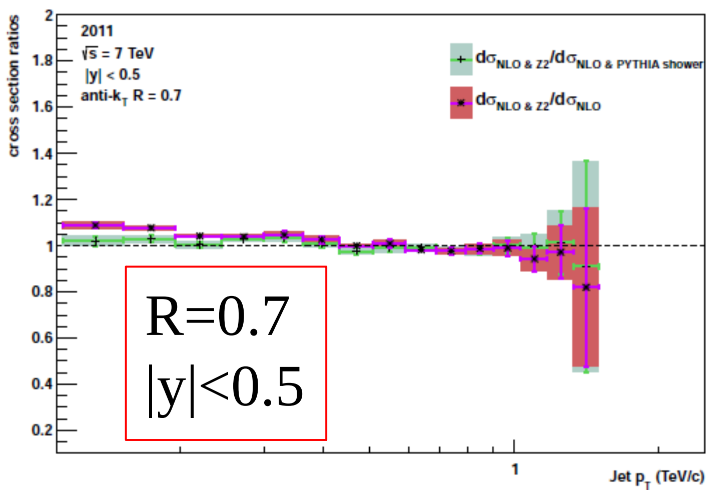
- At LO 2 jets are back to back : Δφ ~ π. True at large pT.
- At low p_T ISR and FSR plays a significant rôle. NLO+NP start to fail to describe decorrelation. But LO+PS MC describe well.
- Simple evidence of importance of PS : large corrections beyond NLO!

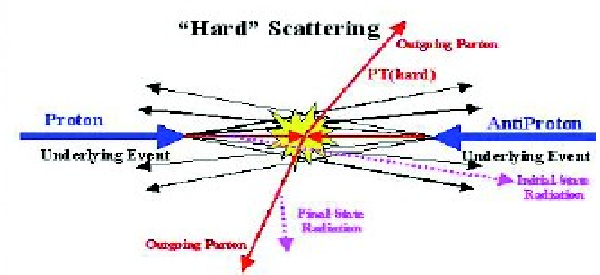
3.2) POWHEG : NLO + PS + NP

S. Dooling, H. Jung







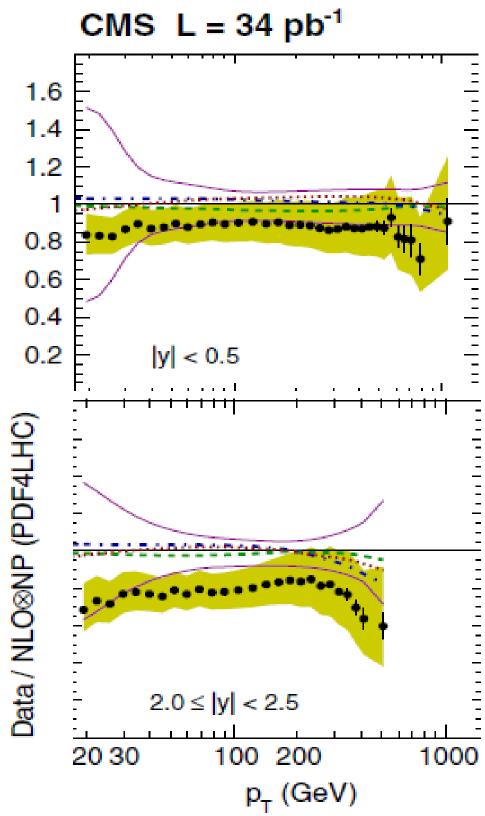


- PS corrections are more important in forward direction and for smaller R (leaking out effect).
- Applying NP corrections from LO+PS MC to NLO is inconsistent when PS effects are large.

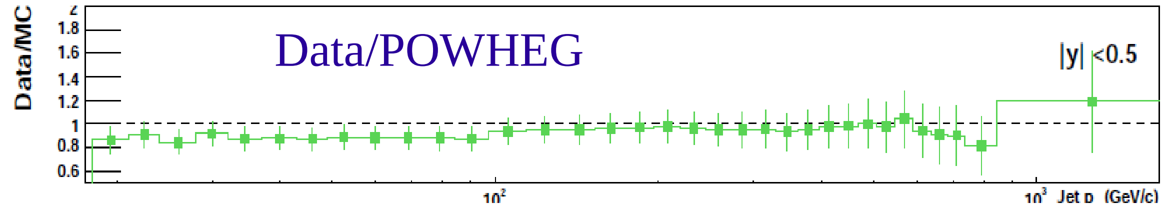
3.3) POWHEG vs NLO+NP

Phys. Rev. Lett. 107 (2011) 132001

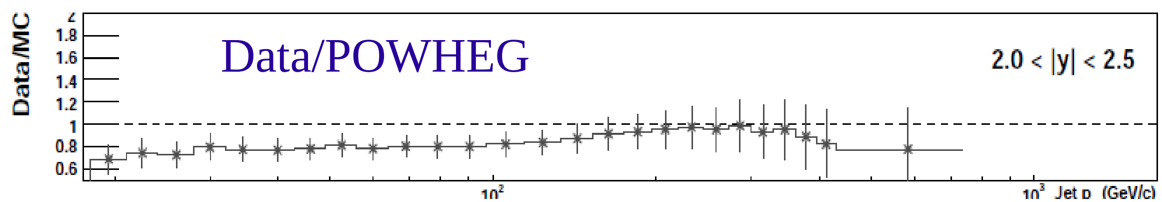
S. Dooling, H. Jung



R=0.5 |y|<0.5



R=0.5 2.0<|y|<2.5



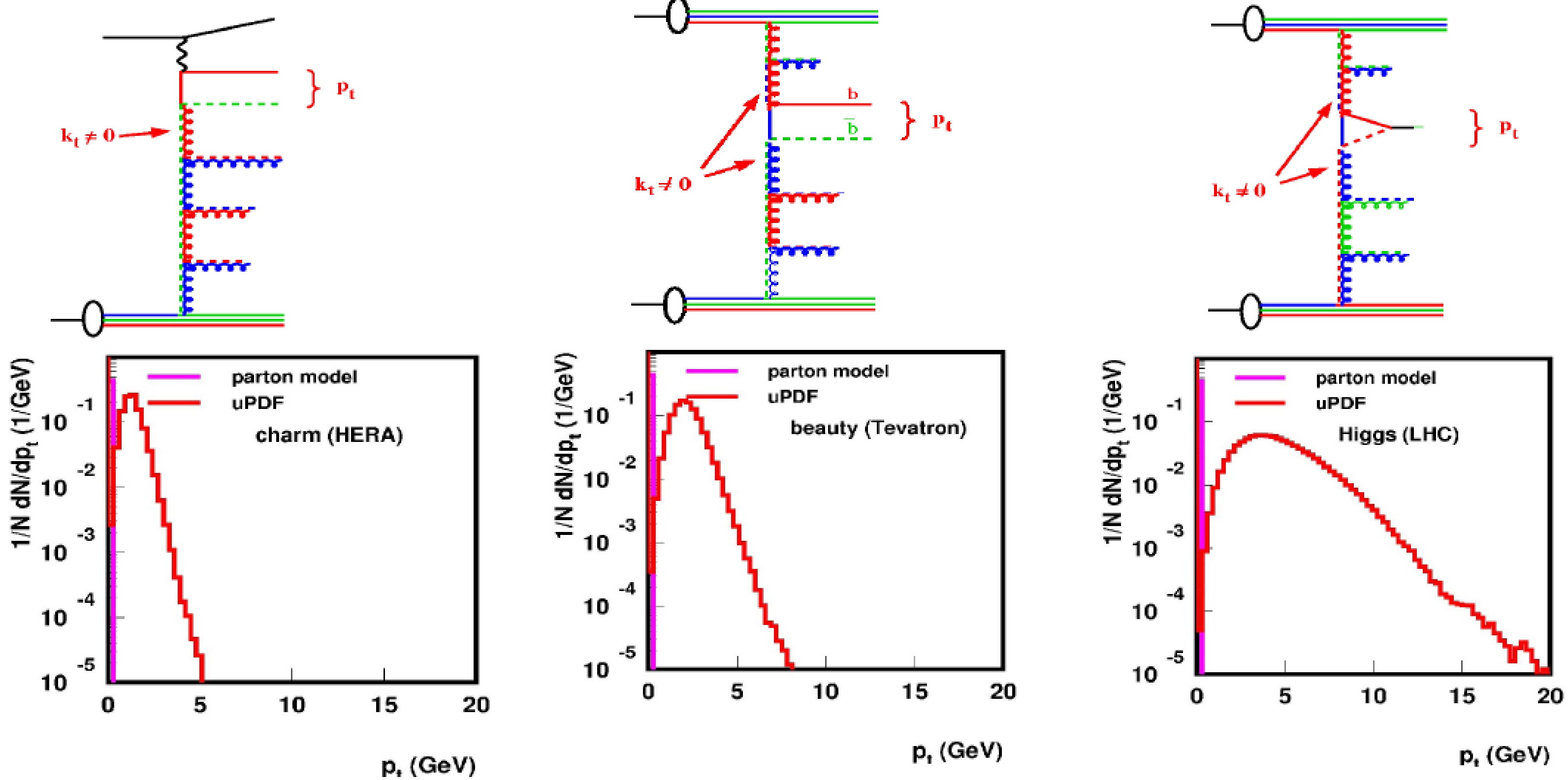
- POWHEG by itself decribes better R=0.5 data than NLO+NP. PS represent part of the missing orders.
- Agreement not perfect at large y, but covered by systematics.

CMS Experiment at the LHC, CERN

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



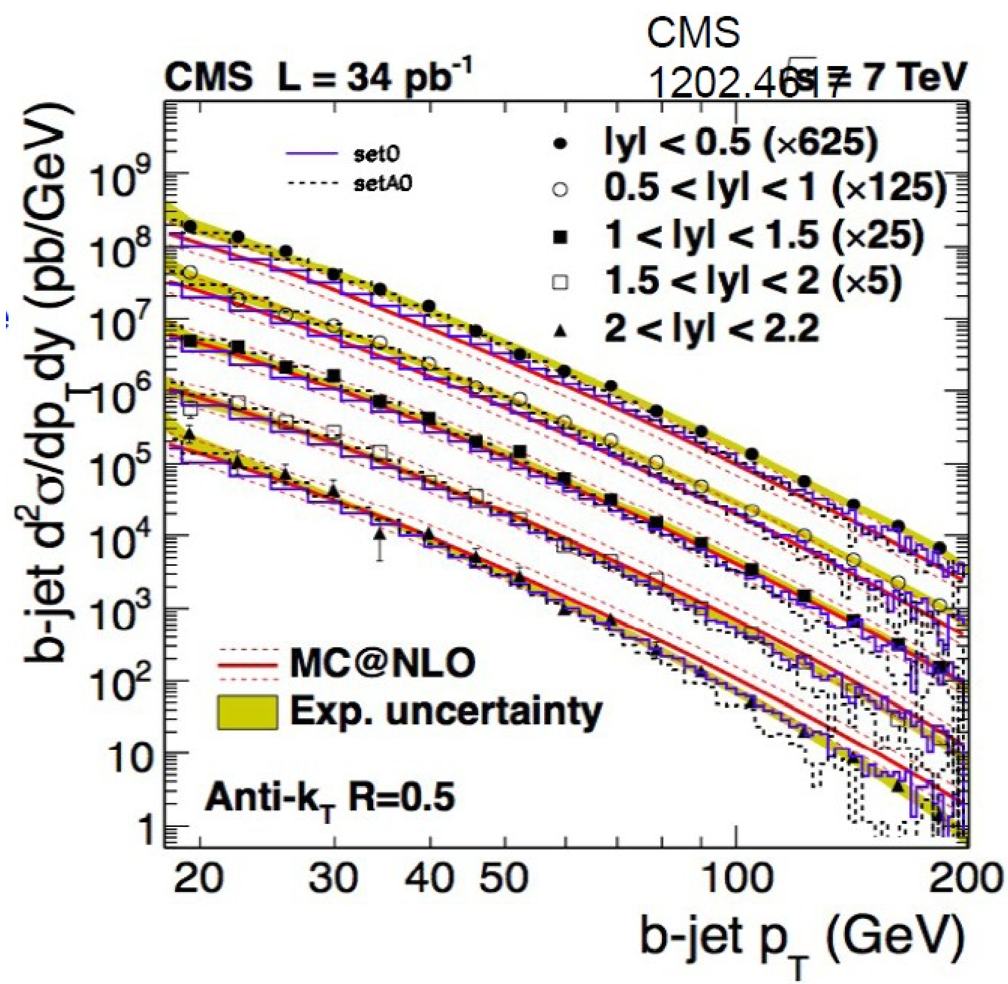
- Doing correctly kinematics at LO may reduce the NLO and PS resummation corrections. May be important when including large log(1/x).
- Finite transverse momenta plays a rôle in cross sections calculations.

3.5) uPDFs : b-quarks example

J. High Energy Phys. 04 (2012) 084

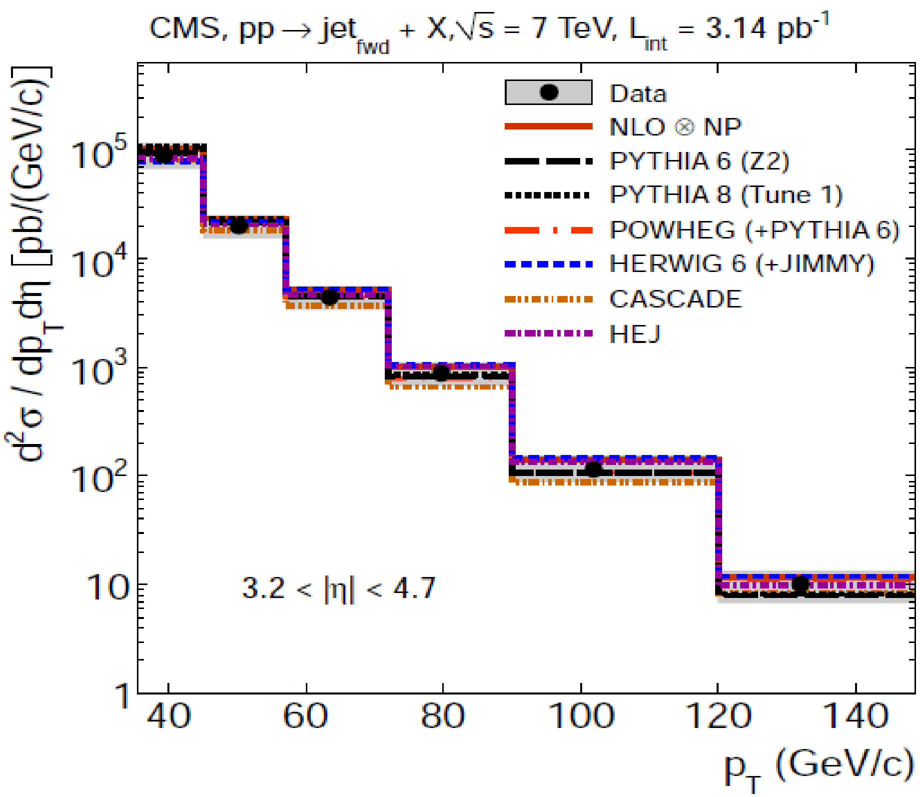
H. Jung

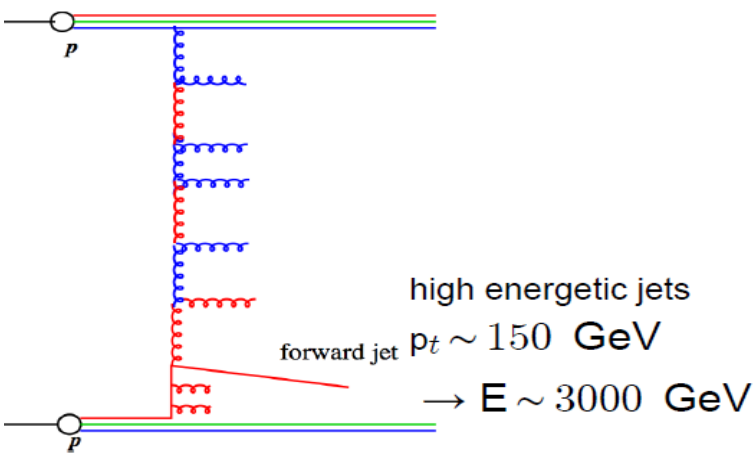
- Inclusive b production is gluon initiated at LO : gg→bb
- Cahlleging measurement wrt to inclusive jets. Uncertainty from b-tagging.
- Test uPDF (2 tunes) of the gluon at LO with CASCADE vs MC@NLO.
- Comparable at low p_T of set0 and MC@NLO, but better at large p_T.



3.6) Inclusive jets : Forward region

arXiv 1202.0704

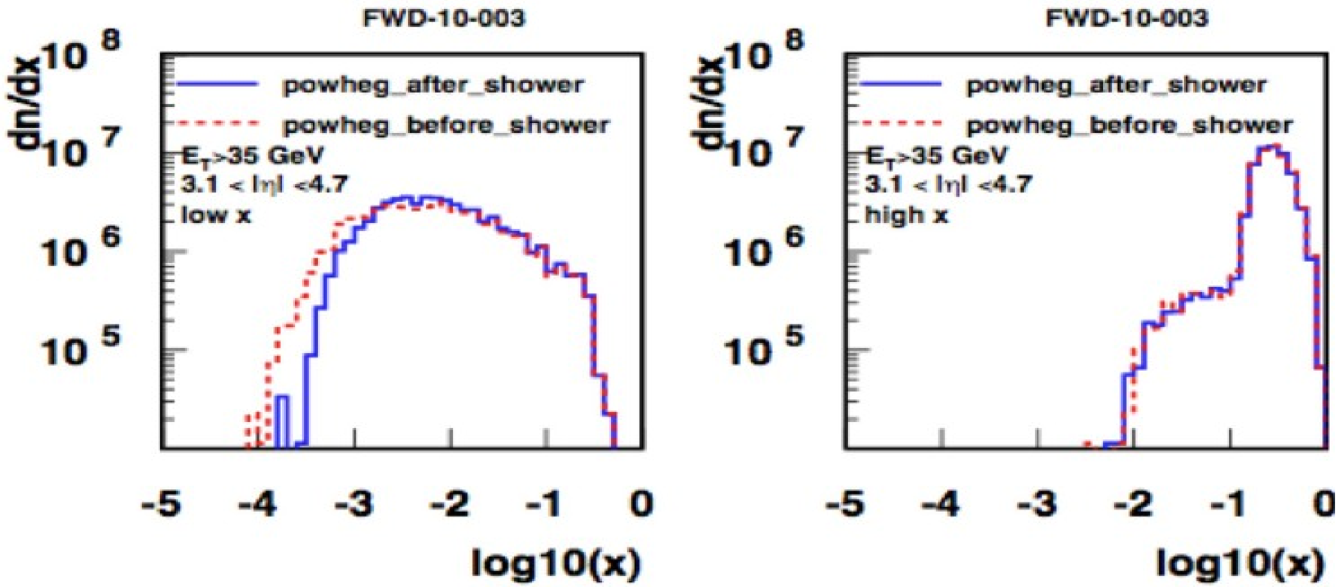




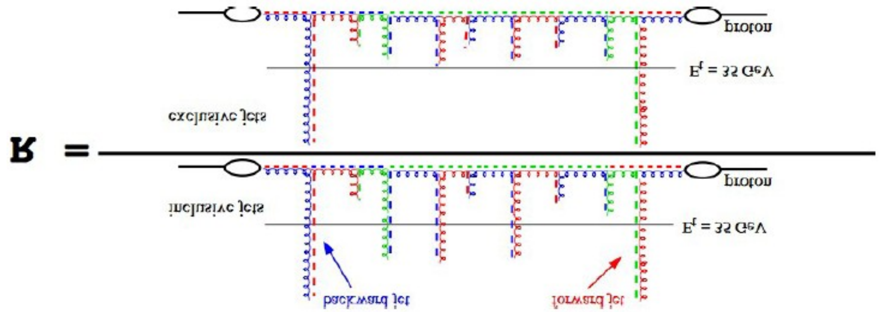
- 3.2<|η|<4.7
- JES dominating systematic.
- All models agrees within systematics.

3.7) Inclusive jets : 7 TeV with R=0.7

FWD-PAS-10-003

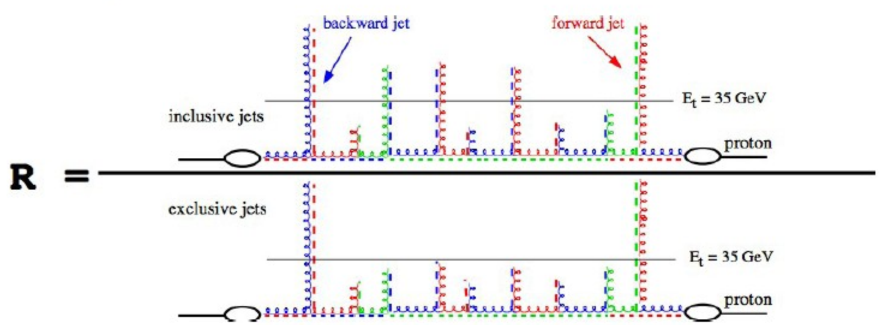


- Access to very low x region. But sensitive to ISR there. To be understood.
- May be used to measure proton PDF ?



Pushing pQCD to the limits

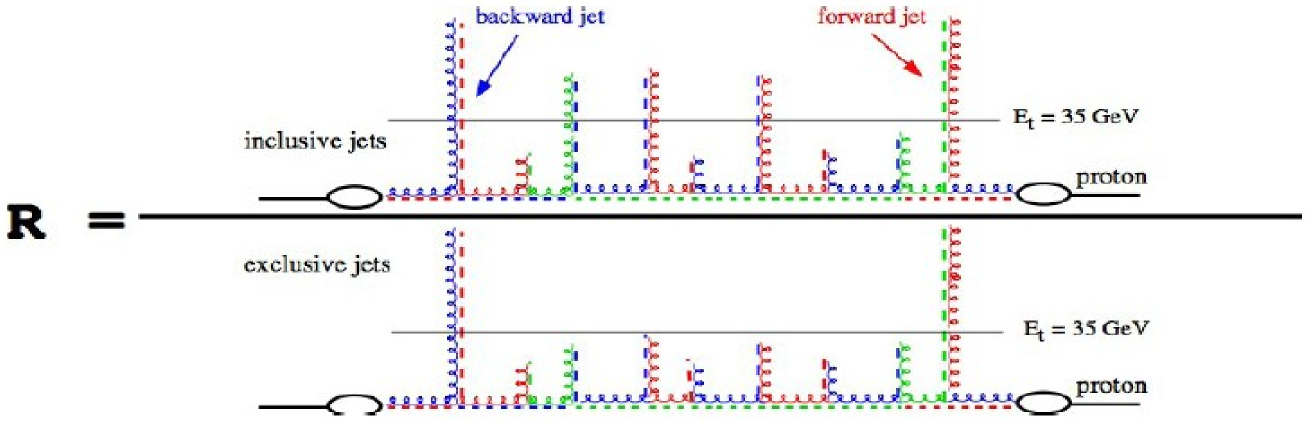
large |Δη|



4.1) Inclusive to exclusive dijet ratio

arXiv 1204.0696

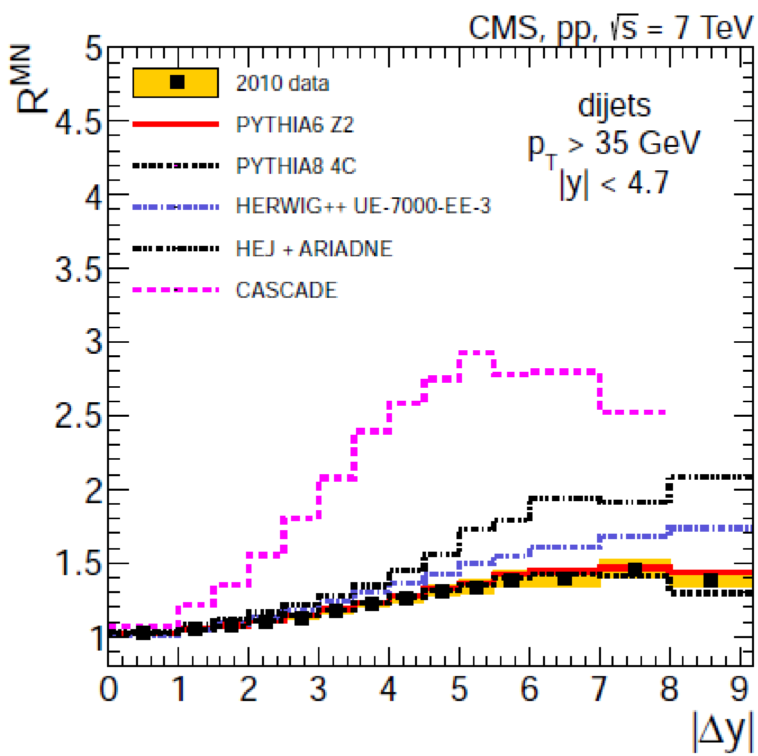
- Jets with pT > 35 GeV and |y| < 4.7, R = 0.5.
- Measure ration of inclusive dijets events to exclusive dijet events : calcelation of systematics
- $|\Delta y| \sim |\Delta\eta| < 9$!!! between the two most external jets (Mueller-Navlett).
- Hope to see non DGLAP dynamics in the ladders between two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



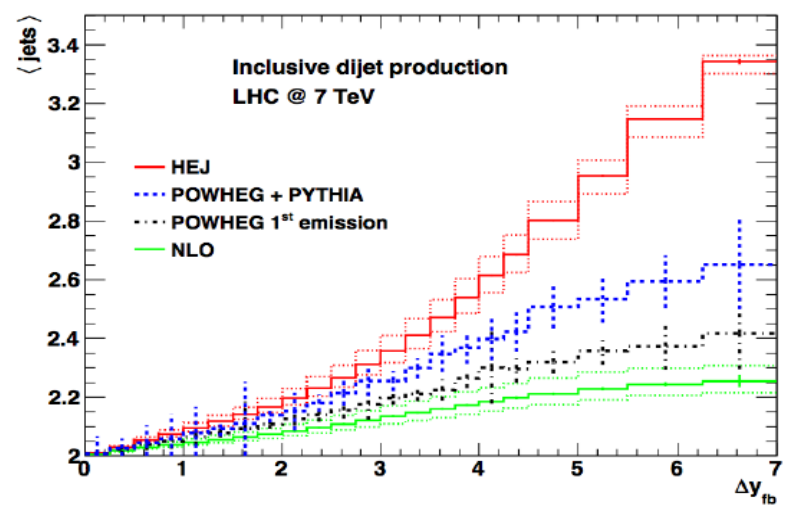
4.2) Inclusive to exclusive dijet ratio

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 |Δy|.
- Cascade, HEJ : include elements of CCFM or BFKL like dynamics.



S. Alioli et al arXiv 1202.1475v1



SUMMARY

1) The understanding of QCD at LHC is a still challenging question even when considering simples observables as inclusive jets with low jet radius.

2) There are some QCD observables which are sufficiently well understood to use LHC data to contraint proton PDFs.

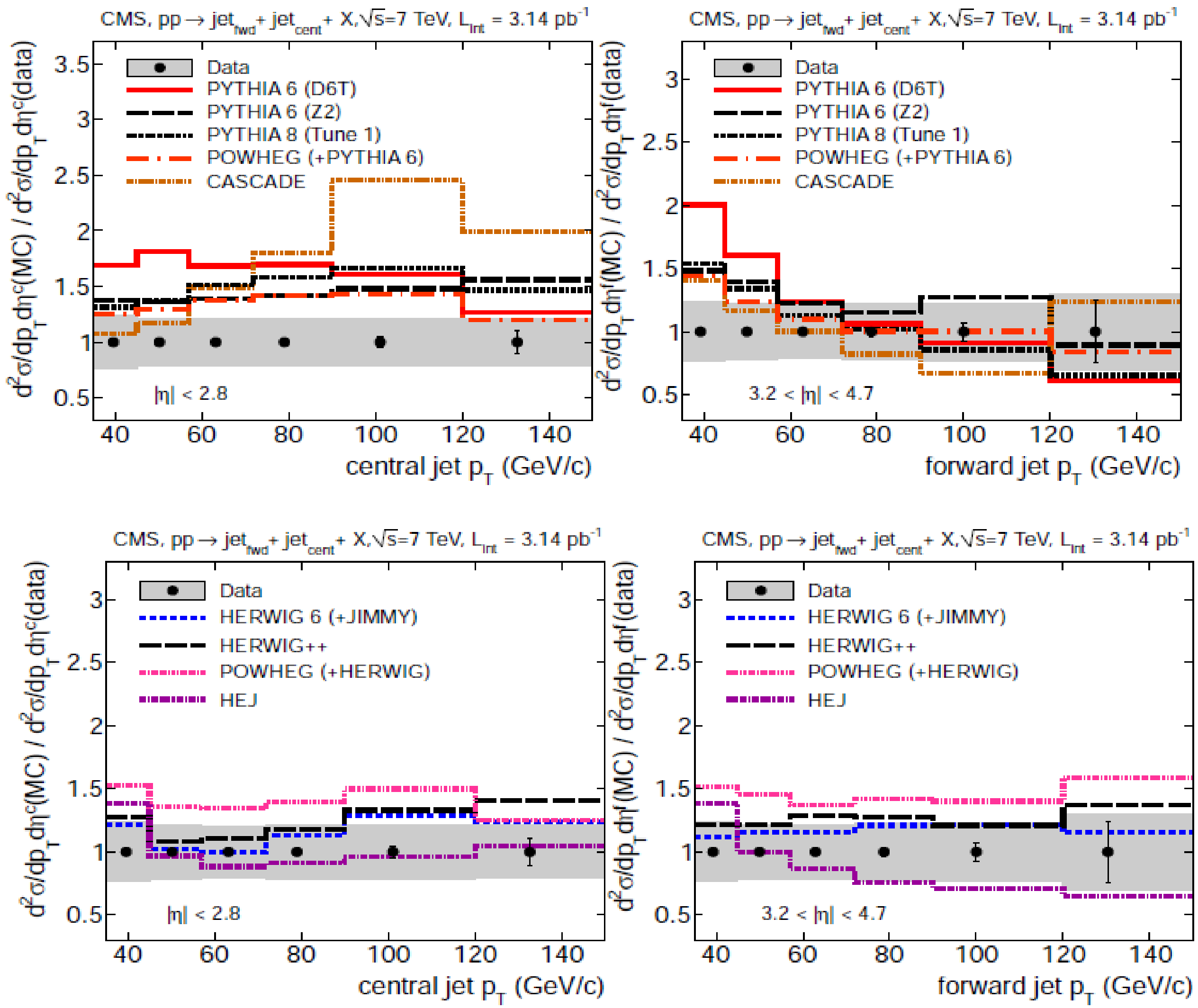
3) But for many others the NLO calculations are not sufficient in pp in contrary to ee, ep collisions. Parton Showers and other kind of leading log resummations seems to play an appreciable role.

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

QCD-PAS-11-004



- All models fails. The closest is HEJ

CMS Experiment at the LHC, CERN