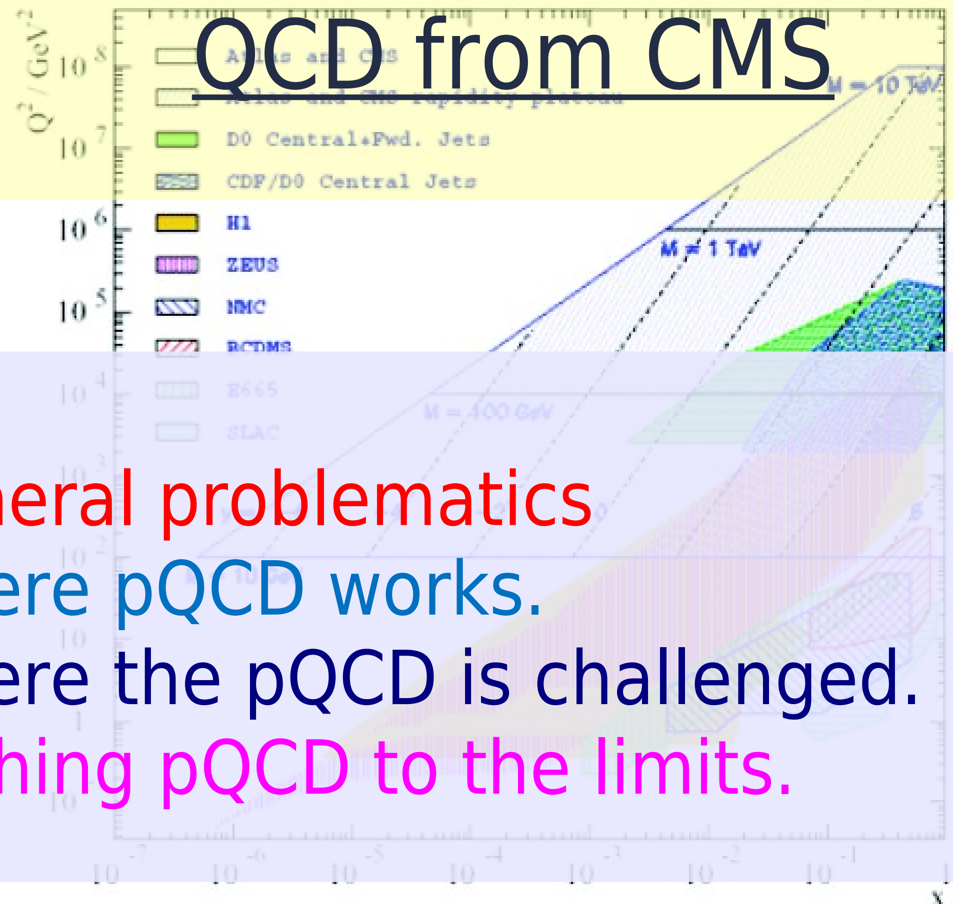
Maxime Gouzevitch
On behalf of CMS collaboration

QCD from CMS



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

CMS Experiment at the LHC, CERN

1.1) Common wisdom about QCD

- QCD is ONE 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 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”.

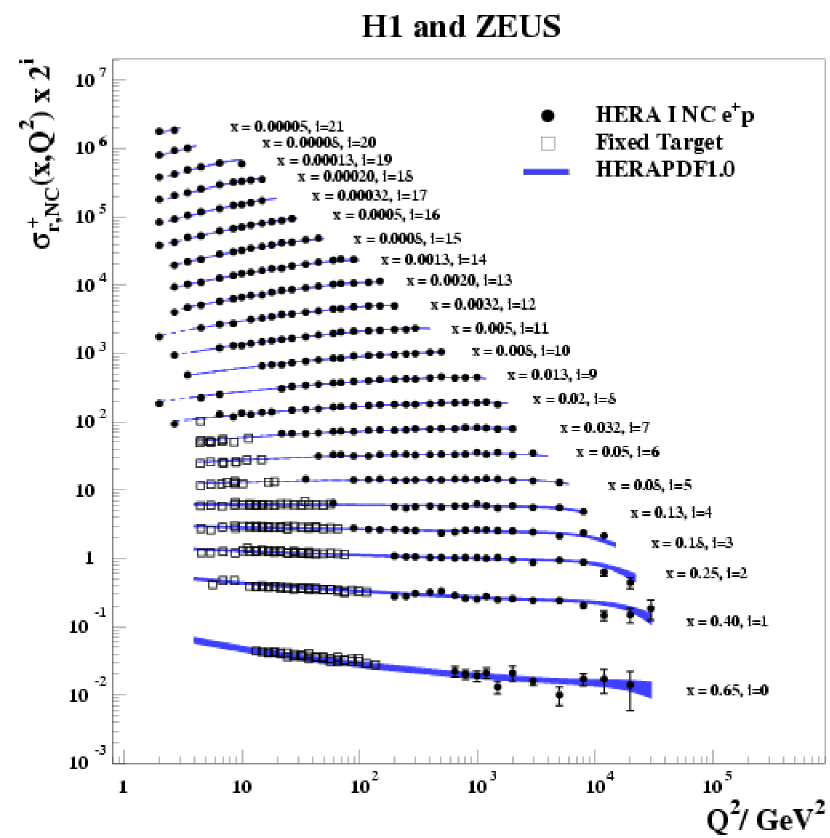
  - Hard interaction (pQCD): jets physics, inelastic hadrons PDFs.
    - Common wisdom: “well understood, just need to cross check it works”.

- At CMS: till now O(50) dedicated papers.
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ

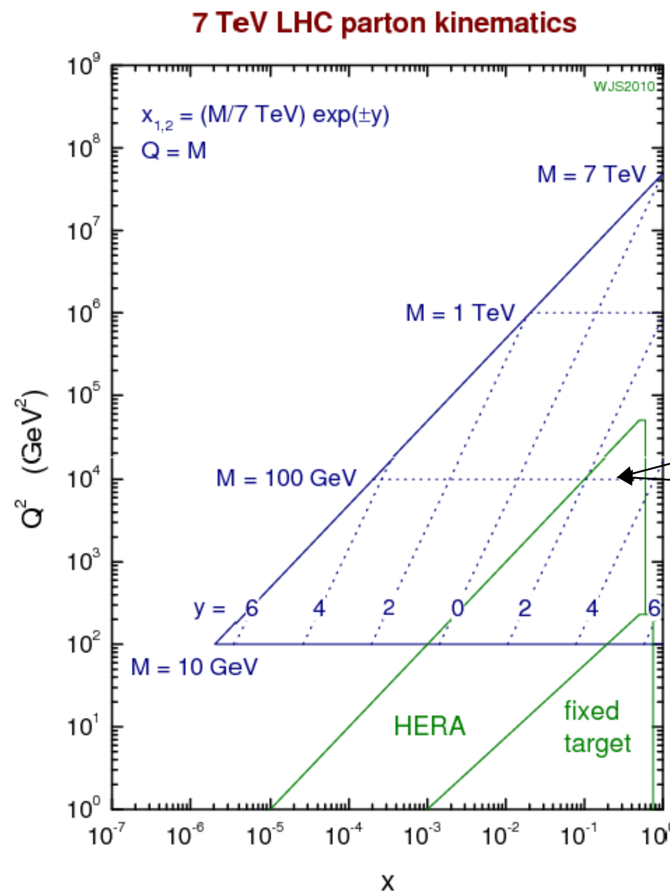
1.2) pQCD before the hadron colliders

- 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.

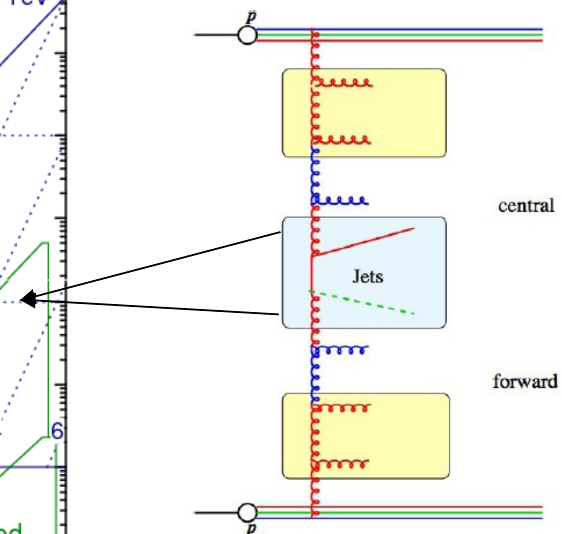
- It seems that this is not always true for the hadron colliders. Let's have a look on it.



1.3) Inclusive hard jets production



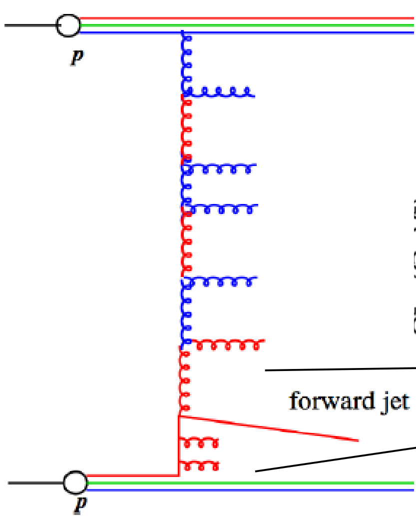
Central jets: x1 ~ x2
DGLAP expected to perform well.

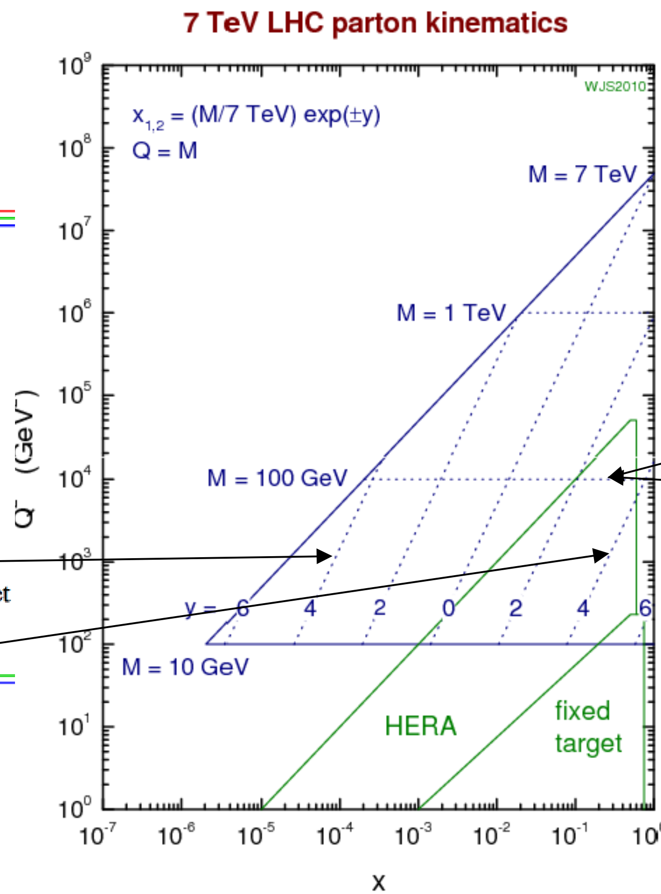


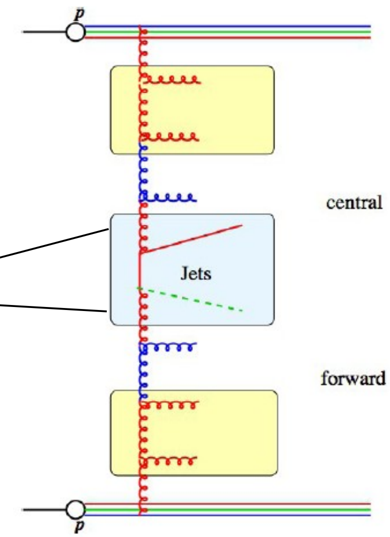
1.3) Inclusive hard jets production

Forward jets: x1<< x2
May need log(1/x) resummation (BFKL, CCFM)

Central jets: x1 ~ x2
DGLAP expected to perform well.



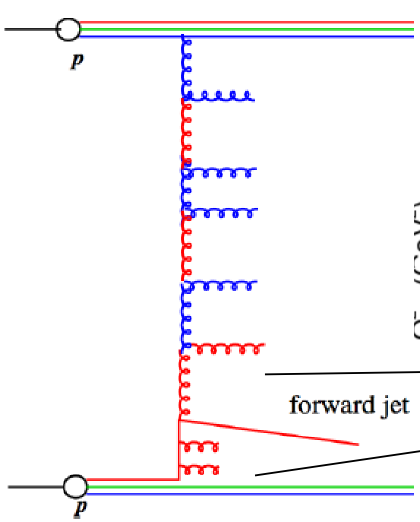


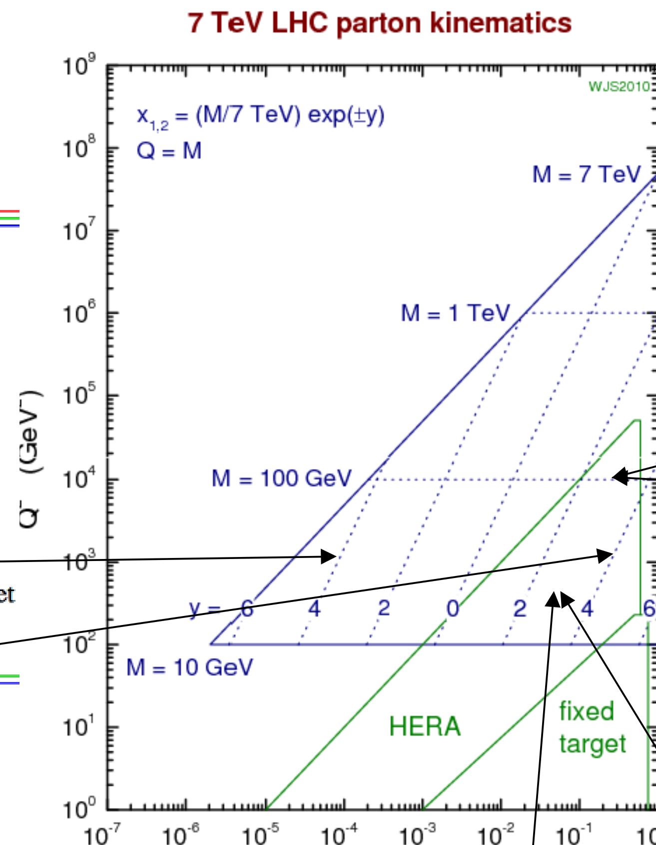


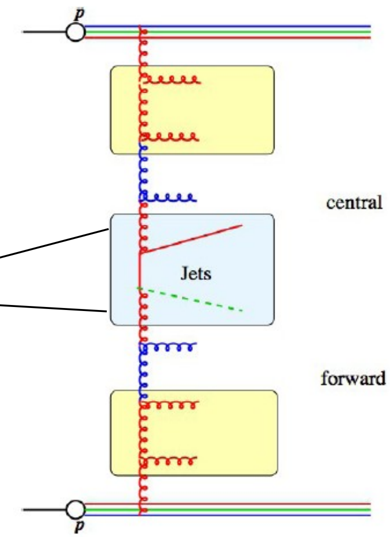
1.3) Inclusive hard jets production

Forward jets: x1<< x2
May need log(1/x)
resummation
(BFKL, CCFM)

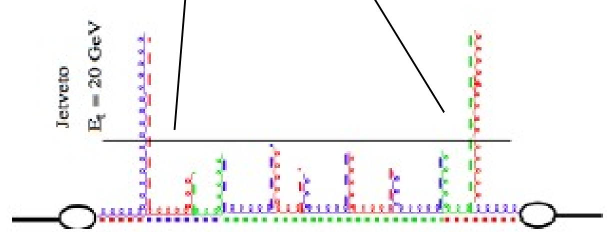
Central jets: x1 ~ x2
DGLAP expected to
perform well.



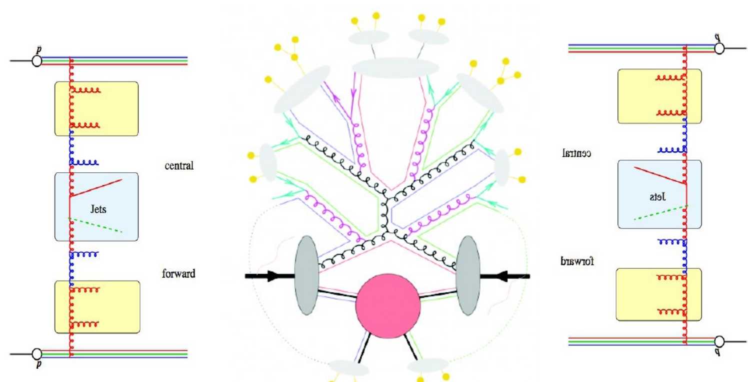




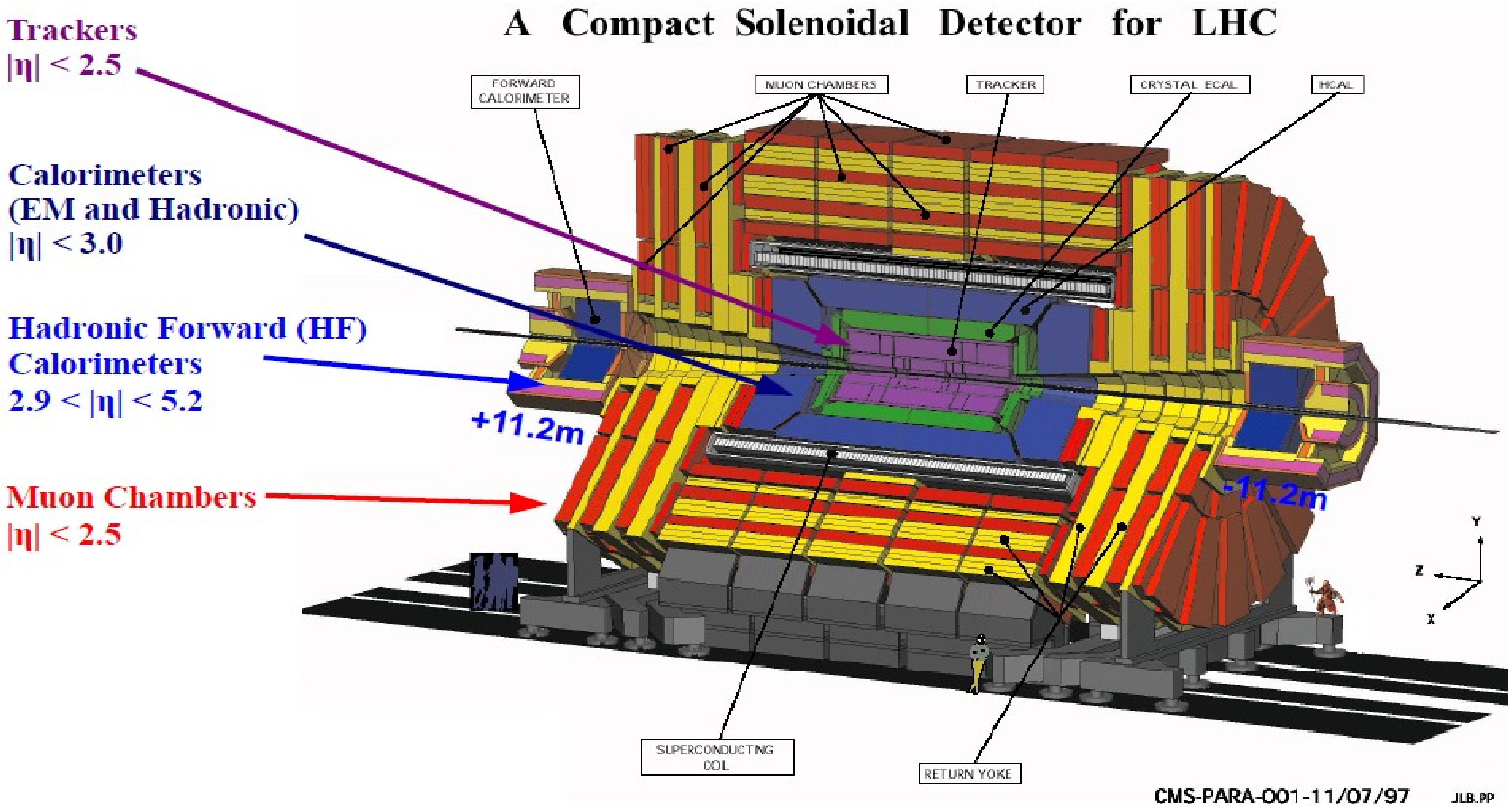
Mueller-Navlett:
x1~x2=O(0.1)
large ϕ-space left for radiation
between jets.



Where pQCD works
Central jets production and “Exotica region”



2.1.1) Experimental setup



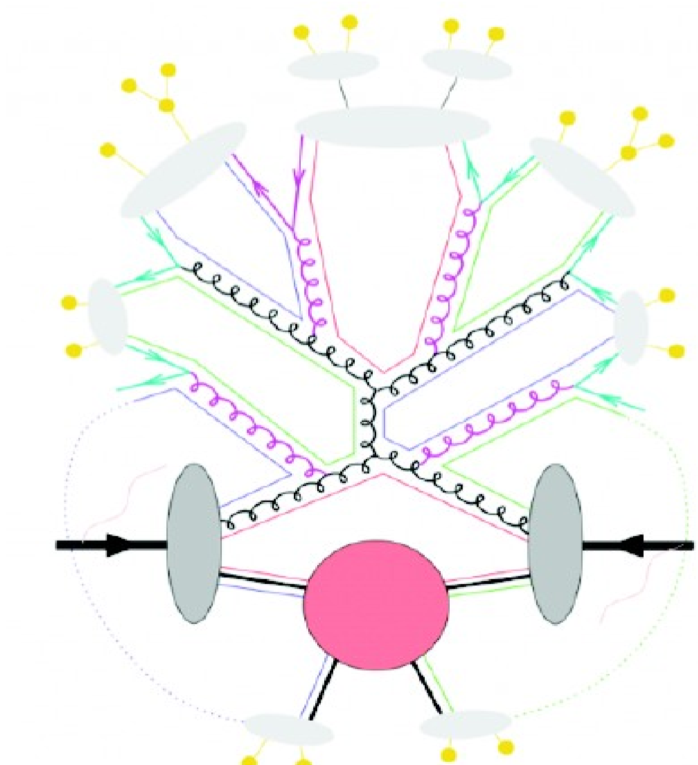
- Central region |η,y|<2.5 : tracker + calorimeters. Particle Flow reconstruction allow very precise measurement by combining all detectors and allow pile-up (PU) removal.
- Forward region: |η,y|>3.0 : calorimeters only, but jets collimated and have large energy. Low handle on PU and large UE.

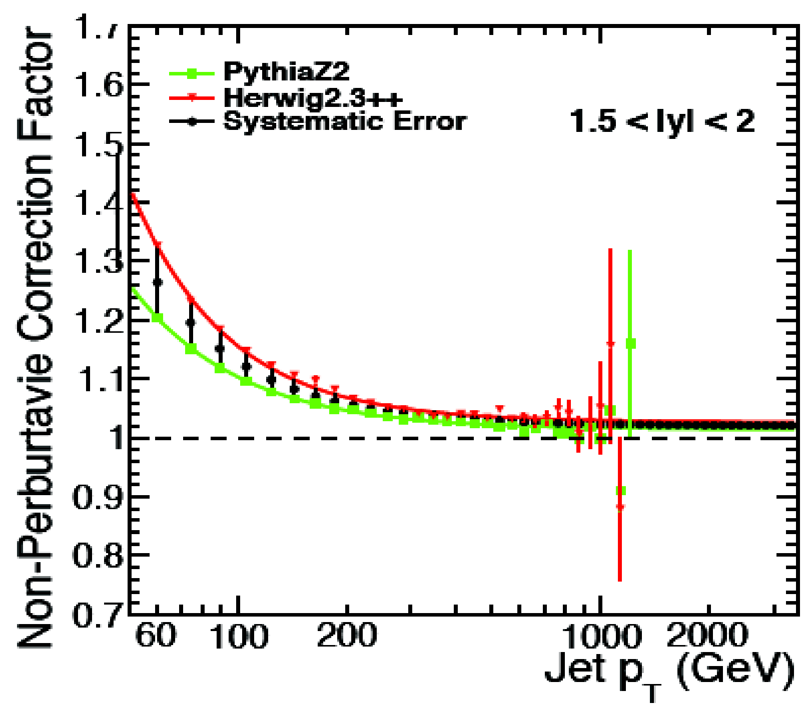
2.1.2) Measurement of inclusive jets

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

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

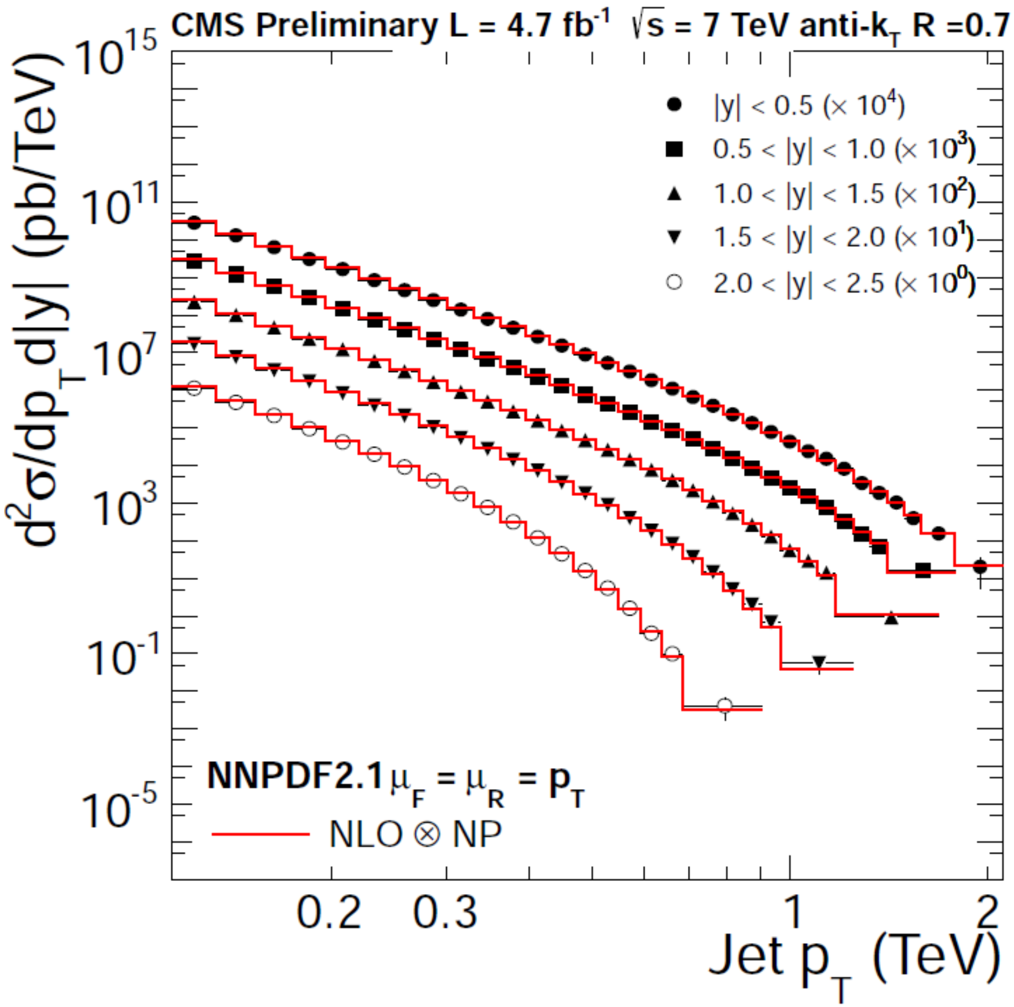
- Measurement: corrected for detector effect to “hadrons level” (unfolding) - C_{DET}.
- NLO calculation: corrected for hadronization and MPI effects estimated from LO+PS MC - C_{NP}.





2.2.1) Inclusive jets : 7 TeV with R=0.7

arXiv:1212.6660
Submitted to PRD

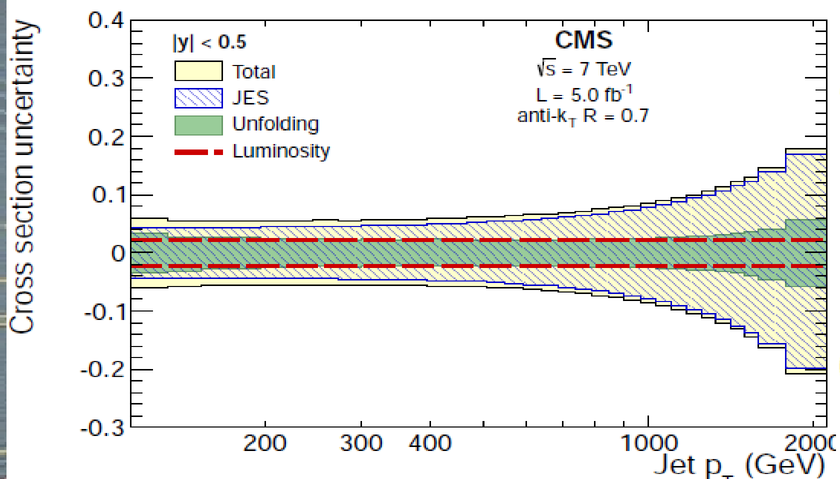


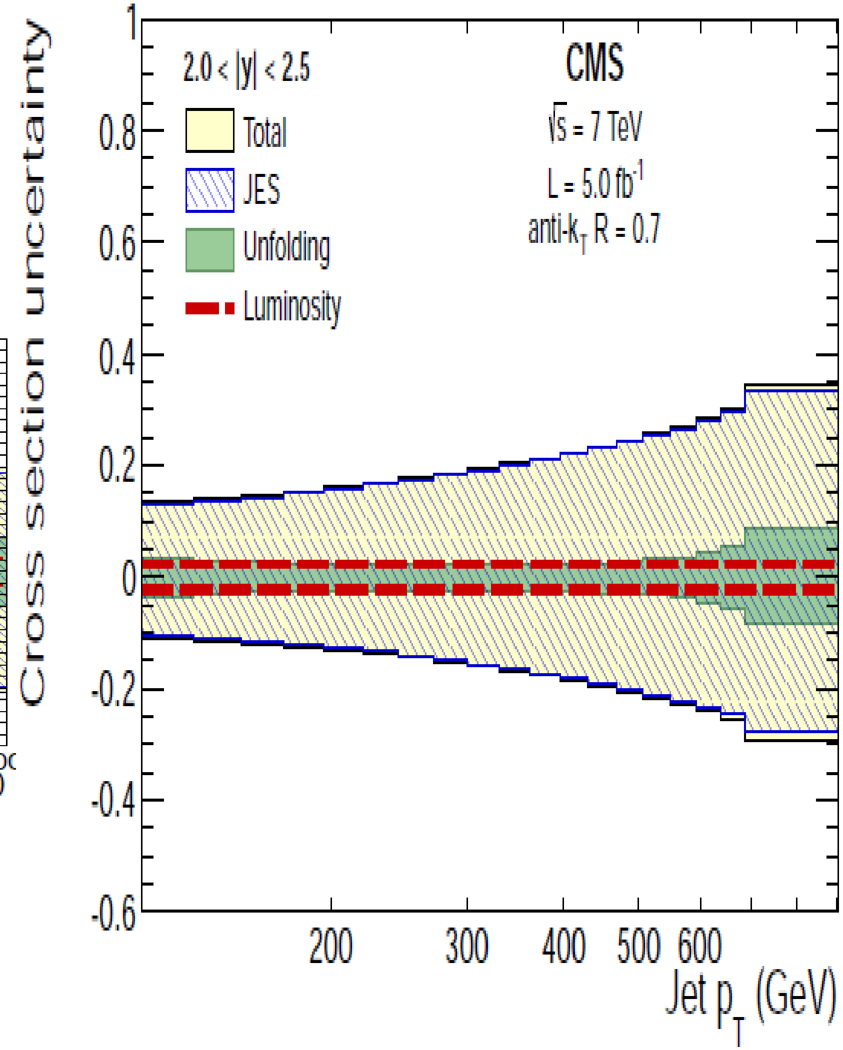
Jets reconstructed with sequential anti-k_T algorithm with R=0.7

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

2.2.2) Inclusive jets : 7 TeV with R=0.7

arXiv:1212.6660
Submitted to PRD

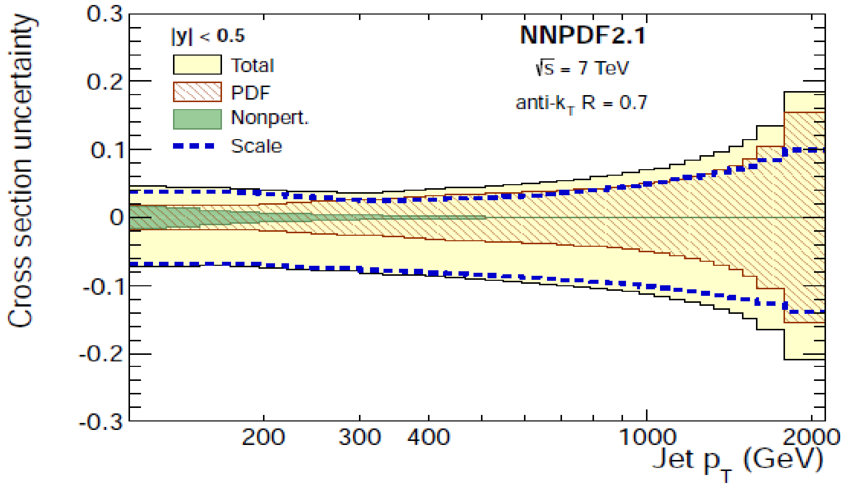


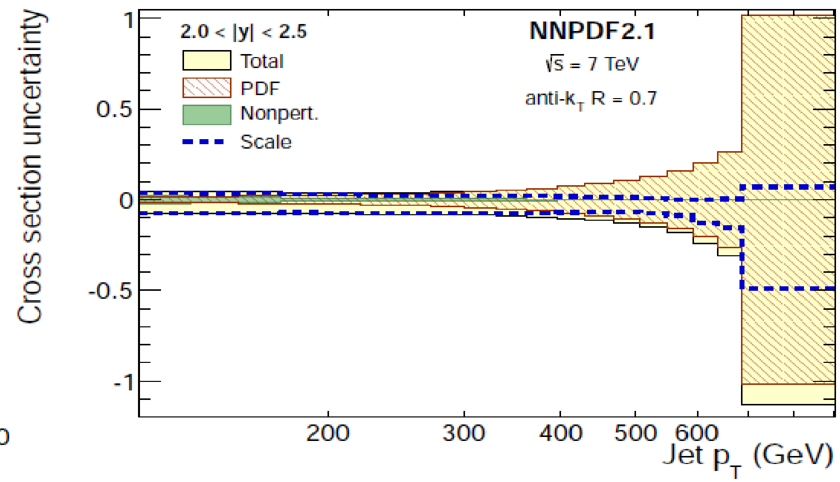


- Exp. Uncertainties – dominated by Jet Energy Scale especially in the forward region.

2.2.3) Inclusive jets : 7 TeV with R=0.7

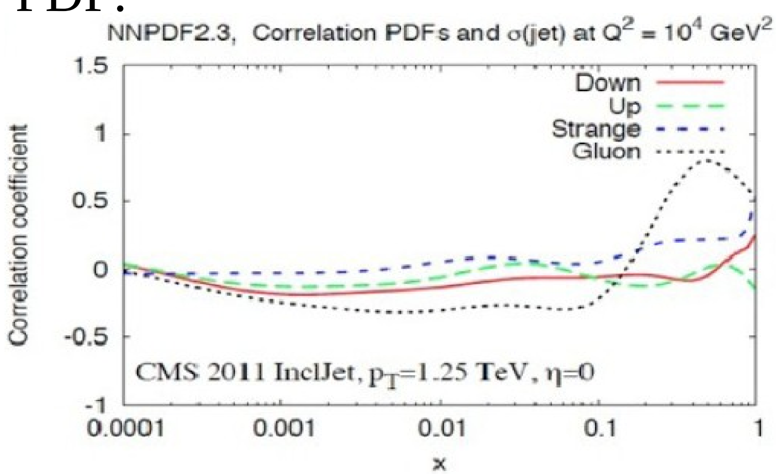
arXiv:1212.6660
Submitted to PRD

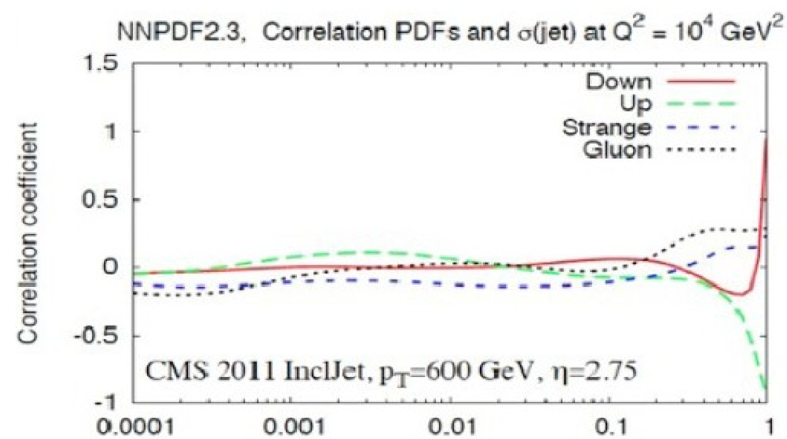




- Theory uncertanty : low p_T - NP, middle/high p_T – scales, PDF.

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

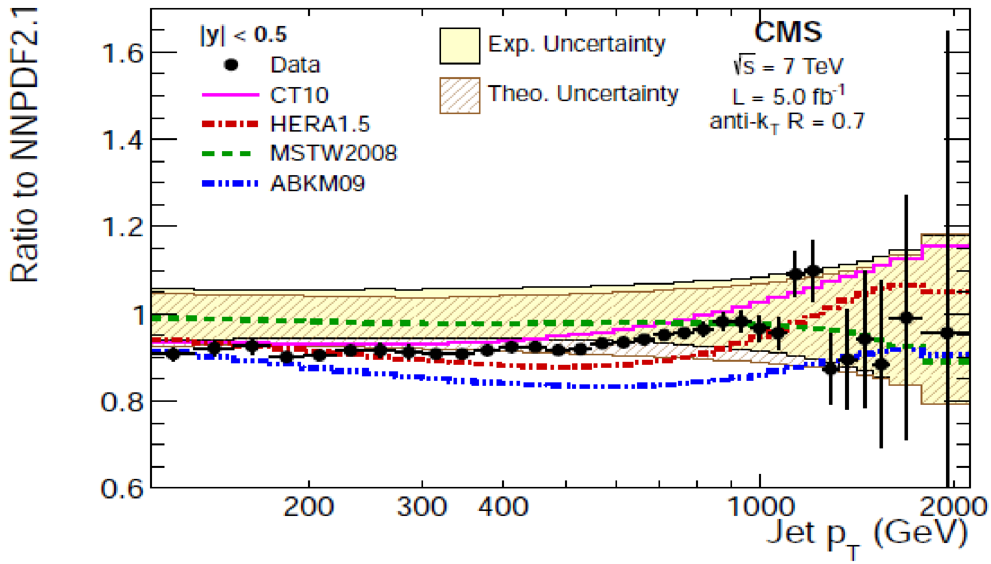


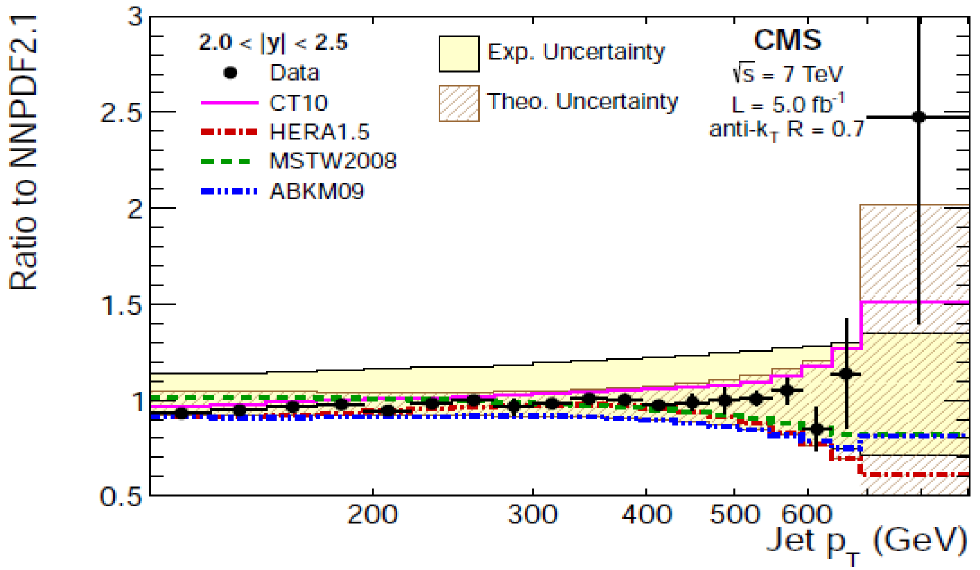


- Expected constraints on the high Xgluon.

2.2.4) Inclusive jets : 7 TeV with R=0.7

arXiv:1212.6660
Submitted to PRD



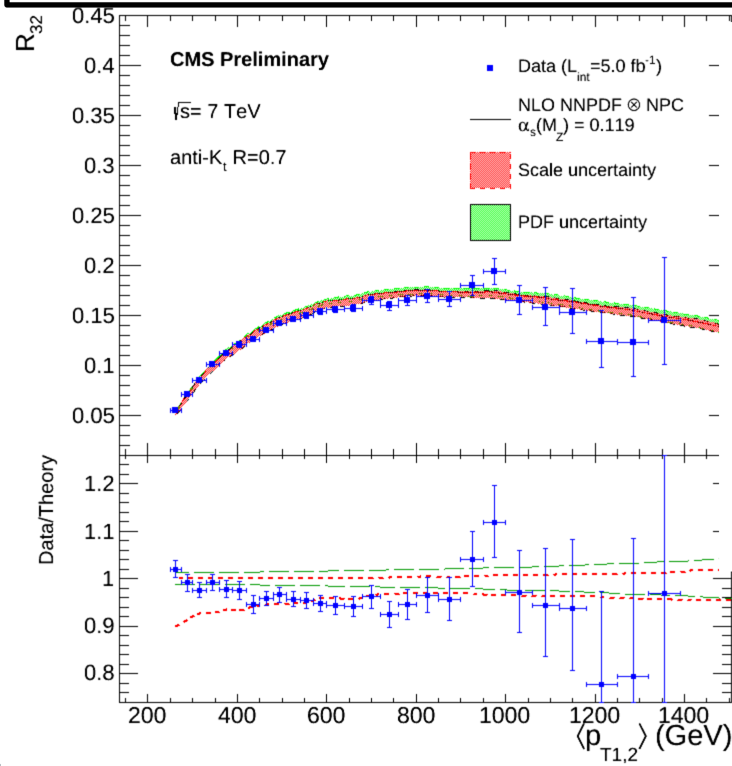


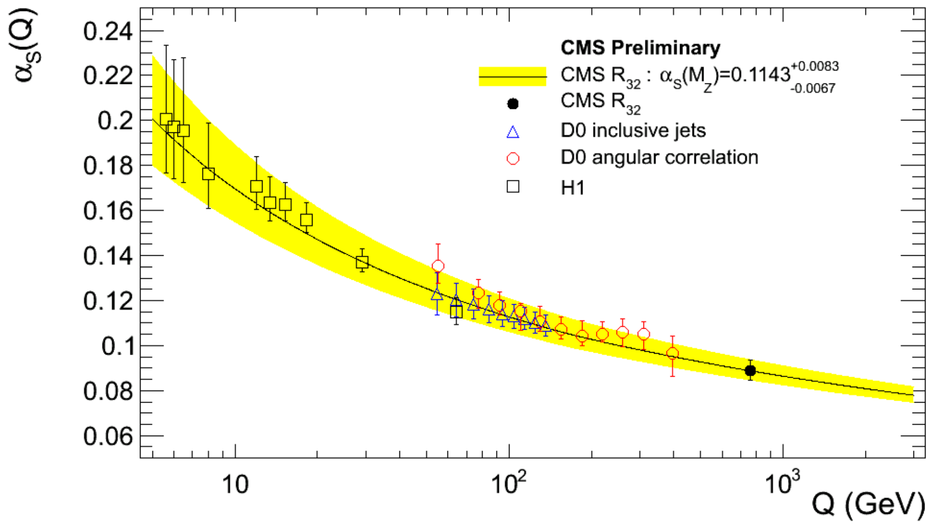
- Experimental uncertainties are still quite large, but very correlated among pT bins.
- First fit tests of PDF constraints teach us that they come from :
  - Large y, large pT.
  - Correlation between different y bins (large x range correlations).

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

2.3) αS from 3/2 jets ratio

QCD-11-003





Robust measurement at Q ~ 800 GeV confirming the running in this region with low dependance on the running assumptions in PDFs.

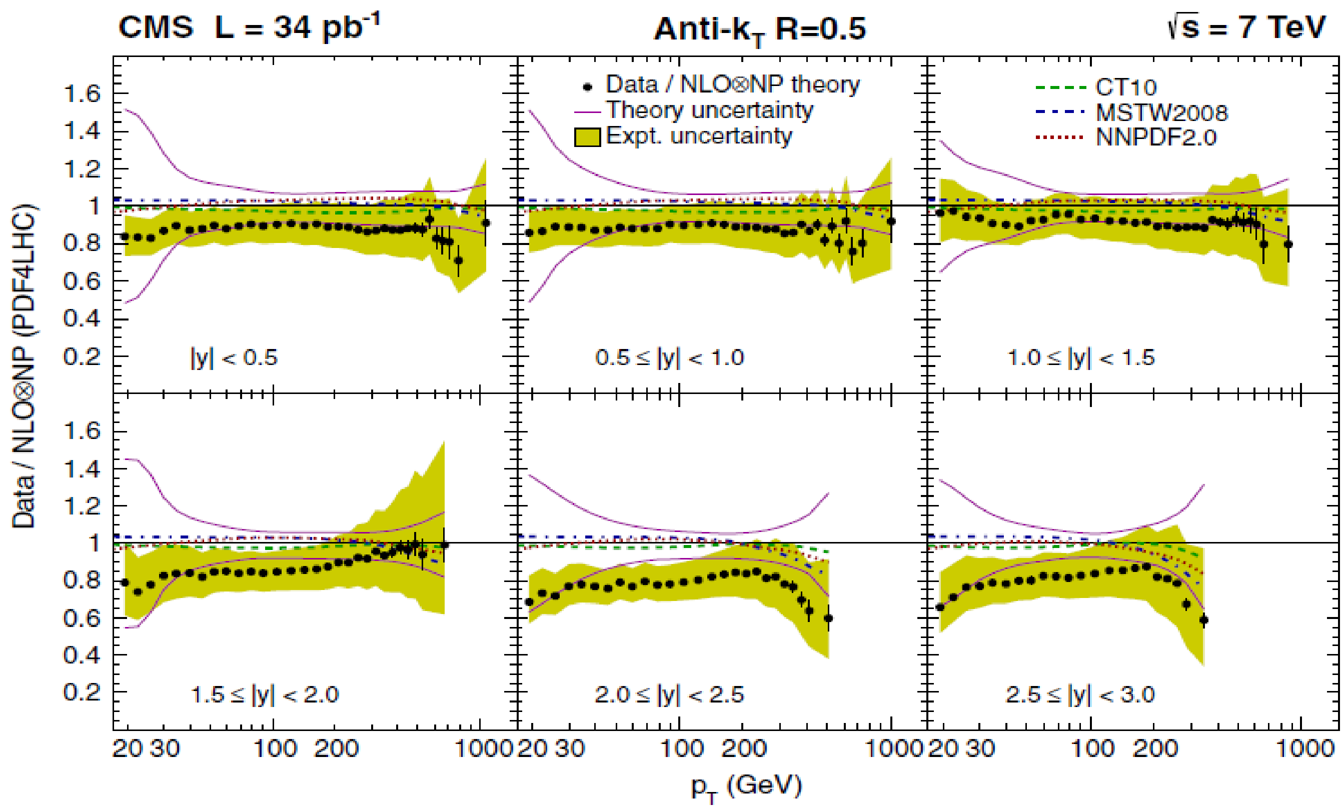
- Low scale dependace under assumtion that 3-jets and 2-jets scale dependance is « correlated ».

- Low PDF sensitivity : 3-rd jet emission is partially decorrelated from x1 and x2.

- Linear sensitivity to α_s at LO.

2.4) Inclusive jets : 7 TeV with R=0.5

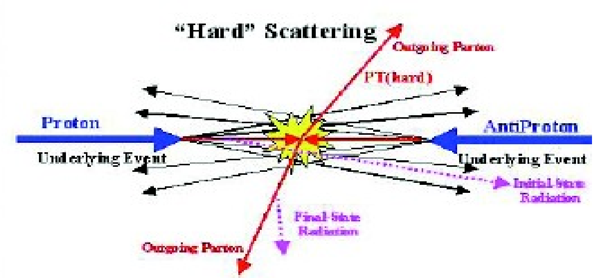
Phys. Rev. Lett. 107 (2011) 132001

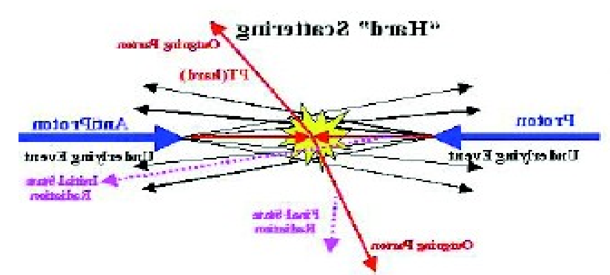


- The results for anti-k_T with R=0.5 are not so glorious:(Even if the difference is covered by uncertainties.
- Why ?

Where pQCD is challenged

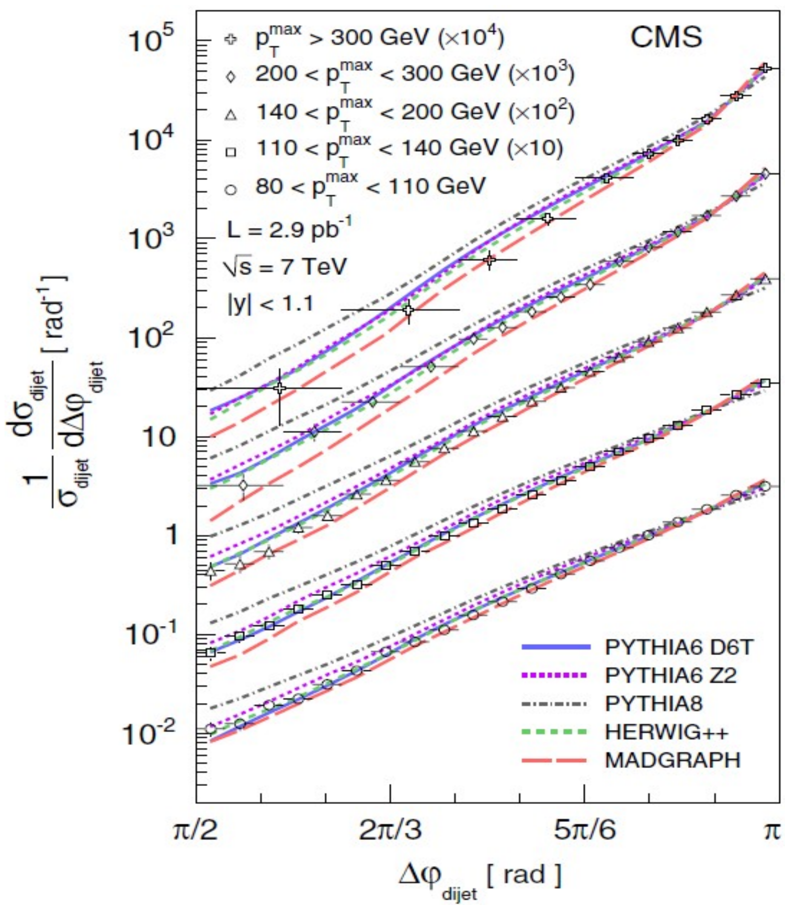
Small radius and/or forward jets

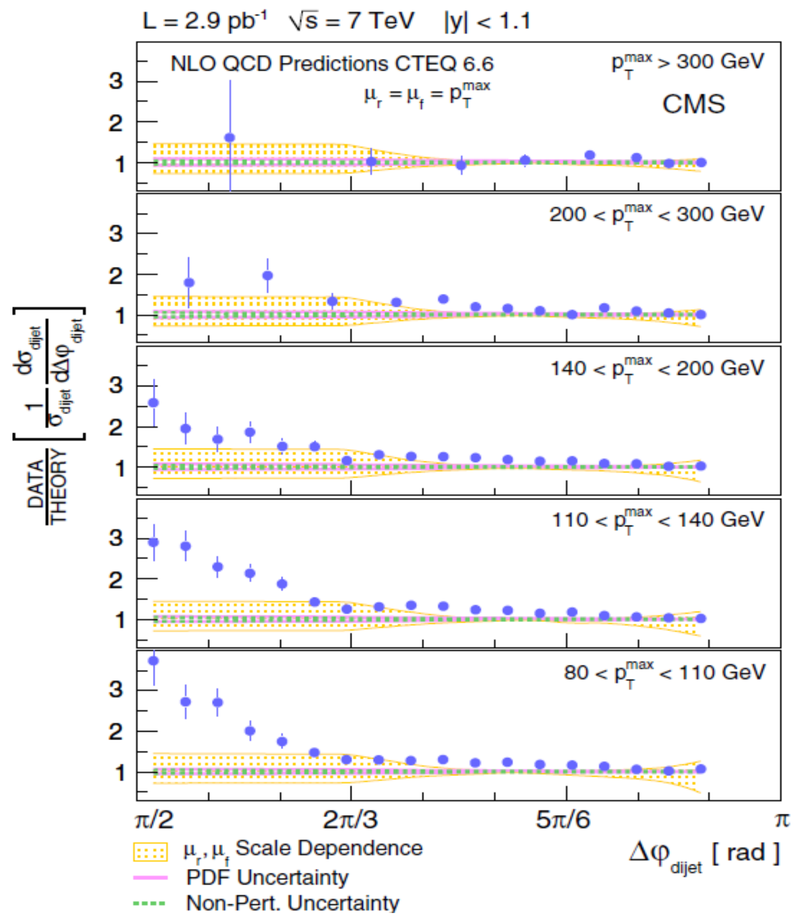




3.1) Dijet azimuthal decorrelation

PhysRevLett.106.122003

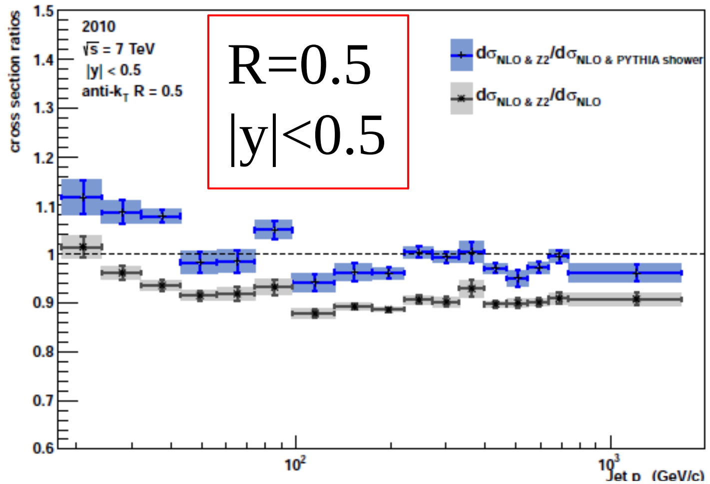


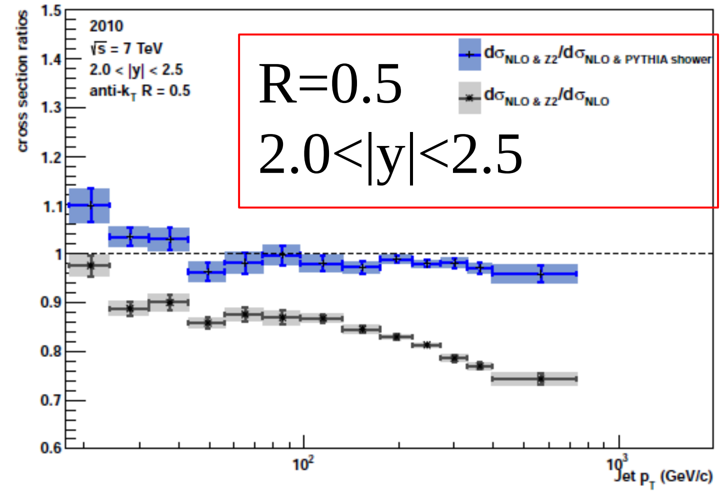


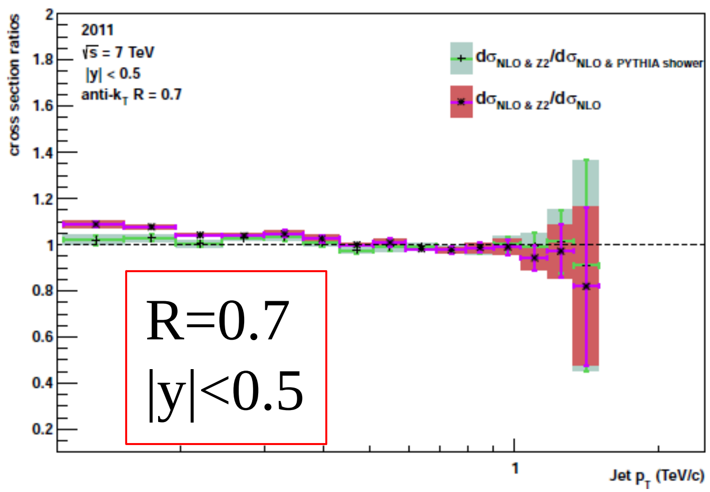
- At LO 2 jets are back to back : Δφ ~ π. True at large p_T.
- At low p_T ISR and FSR play a significant role. NLO+NP starts to fail to describe decorrelation. But LO+PS MC describe well.
- Simple evidence of importance of PS : large corrections beyond NLO!

3.2.1) POWHEG : NLO + PS + NP

arXiv:1212.6164







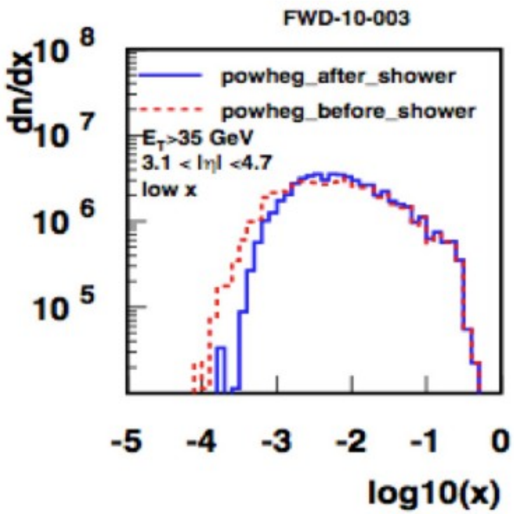
- NLO+Z2 = POWHEG Matched to PYTHIA Z2.
- NLO+PYTHIA Shower = MPI and NP switched off.
- NLO: fixed order calculations from POWHEG.

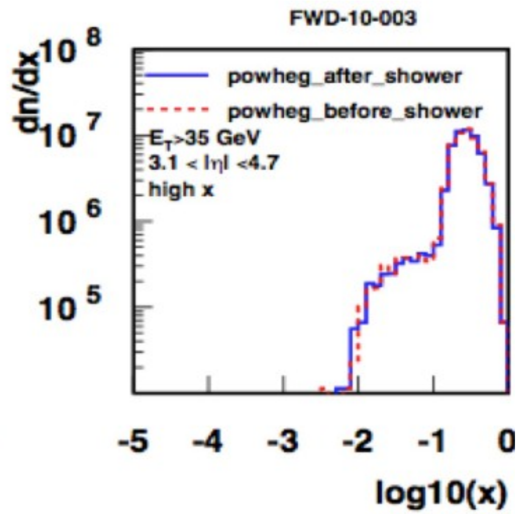
- PS corrections are more important in forward direction and for smaller R (leaking out effect).
- Applying NP corrections from LO+PS MC to NLO is inconsistent when PS effects are large.

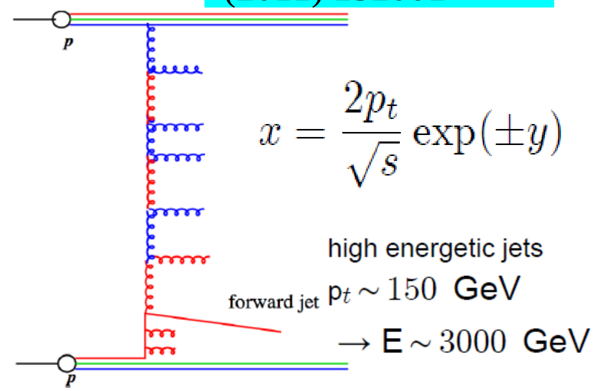
3.2.2) POWHEG : NLO + PS + NP

arXiv:1212.6164

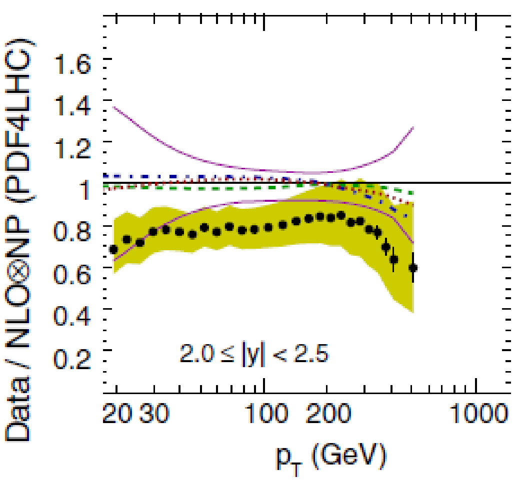
Phys. Rev. Lett. 107 (2011) 132001



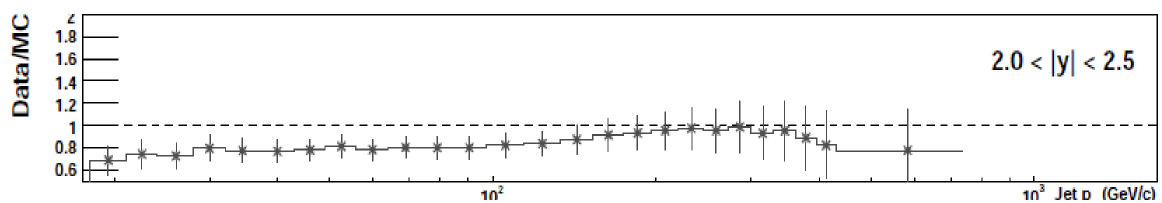


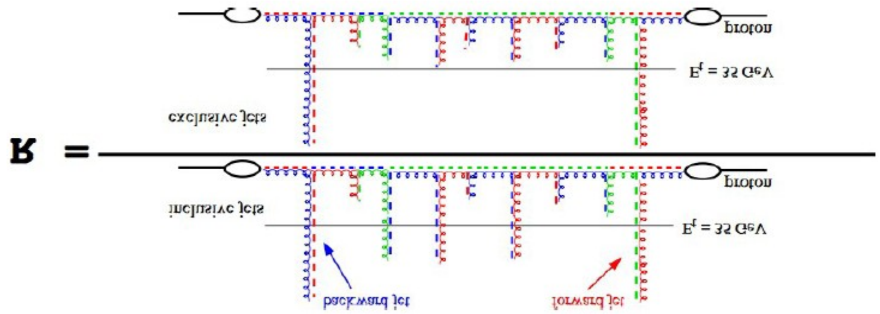


- In forward region asymmetric collisions.
- PS modify x of the low x part.
- PS (= collinear resummation) represent part of the missing orders



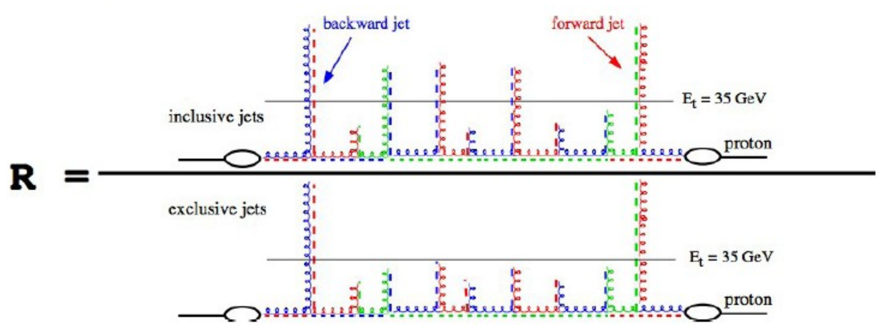
R=0.5 2.0<|y|<2.5





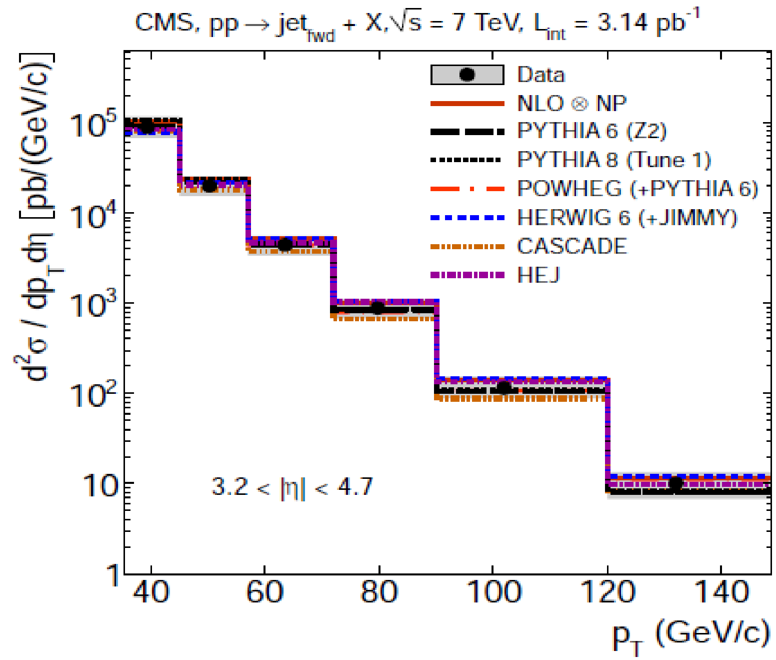
Pushing pQCD to the limits

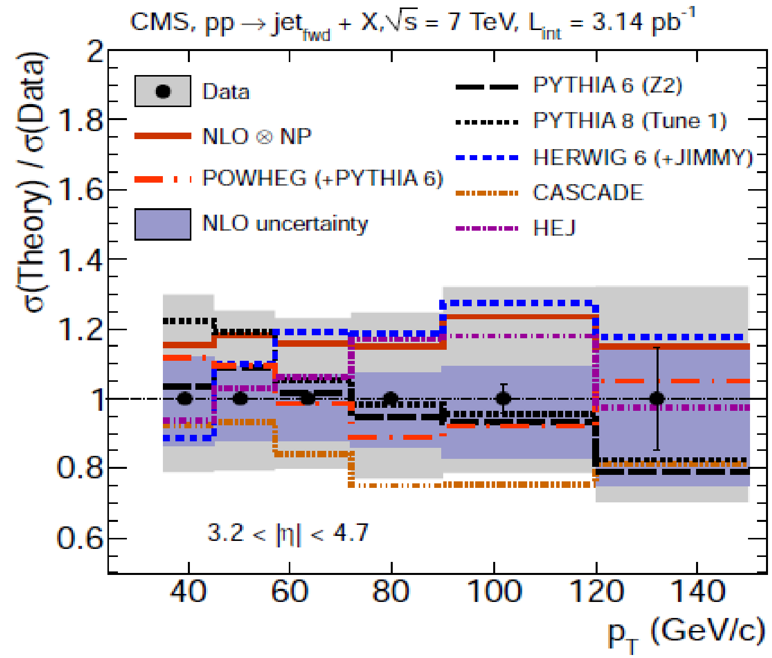
large |Δη|



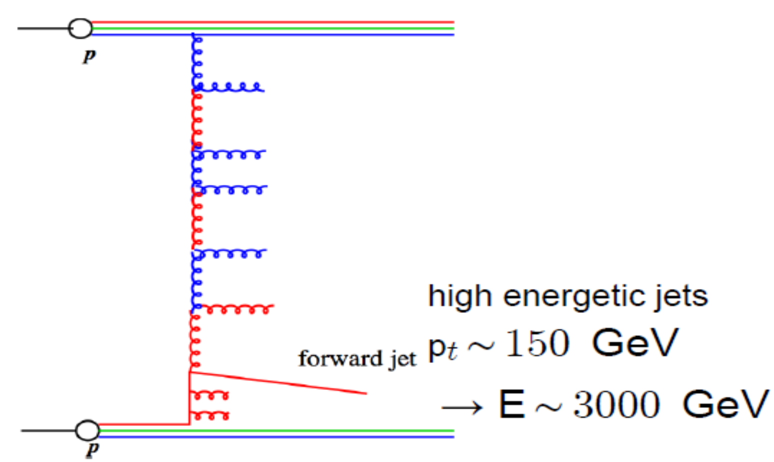
4.1) Inclusive jets : Forward region

arXiv 1202.0704
JHEP 1206 36 (2012)





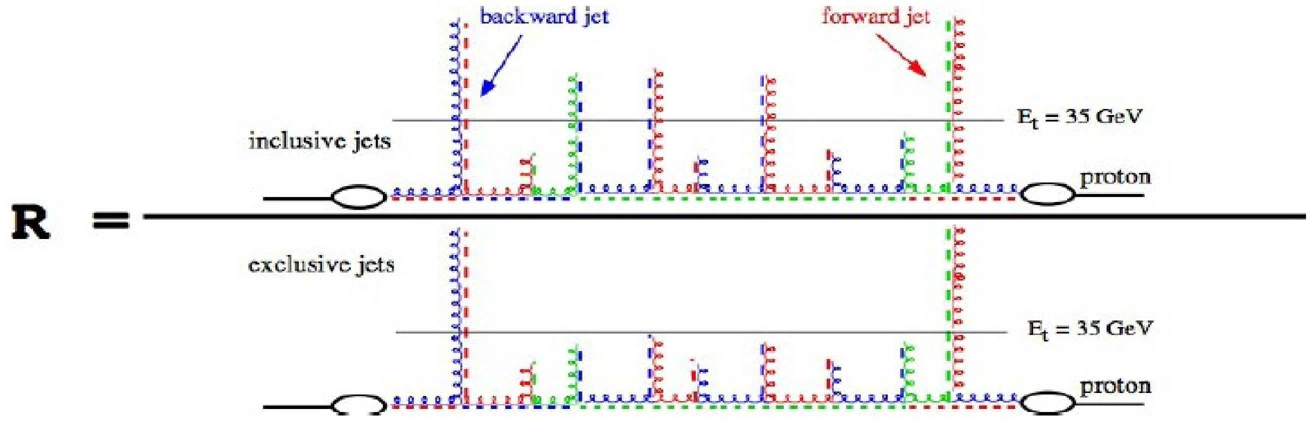
- 3.2<|η|<4.7
- JES dominating systematic.
- All models agree within systematics.



4.2) Inclusive to exclusive dijet ratio

arXiv 1204.0696
EPJC72(2012) 2216

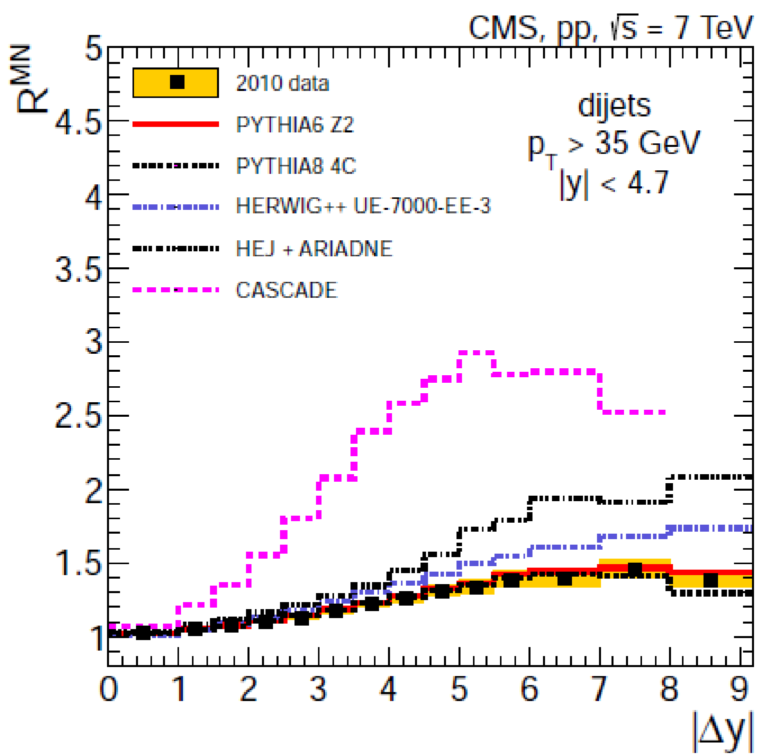
- Jets with pT > 35 GeV and |y| < 4.7, R = 0.5.
- Measure ratio of inclusive dijets events to exclusive dijet events : canlcelation of systematics
- |Δy| ~|Δη| < 9 !!! between the two most external jets (Mueller-Navlett).
- Hope to see non DGLAP dynamics in the ladders between two jets.
- Strategic region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

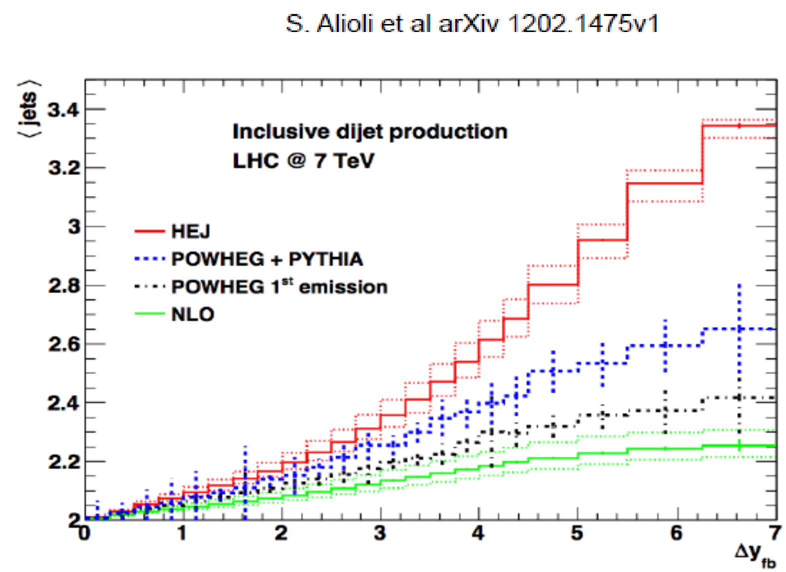


4.3) Inclusive to exclusive dijet ratio

ArXiv 1204.0696
EPJC72(2012) 2216

- 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.





CMS Experiment at the LHC, CERN

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 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) Never underestimate the importamce of the Radius parameter in the jet definition: competition between PS, PU and MPI.

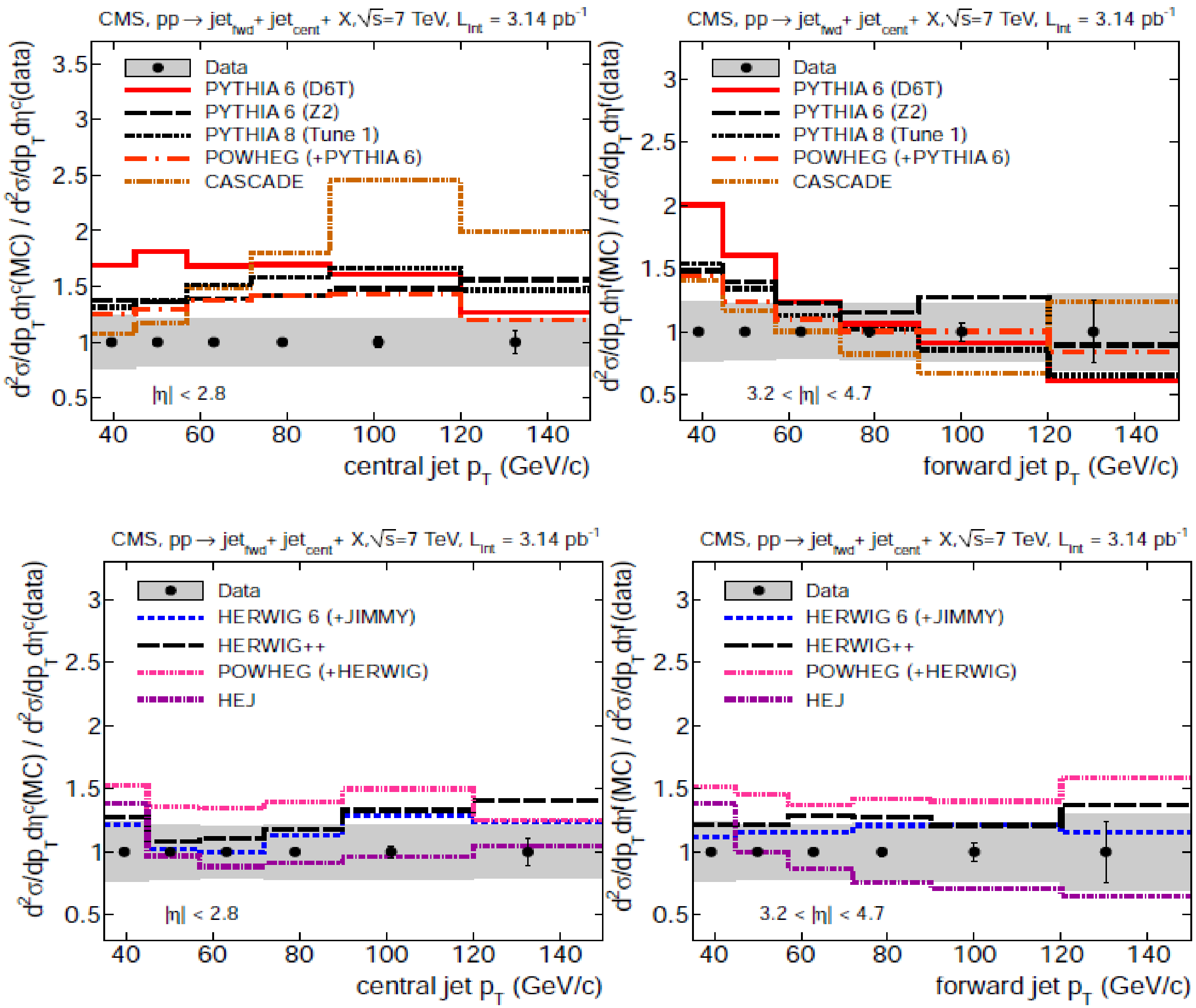
5) This subject have to be understood since QCD is a background to any search for new physics and any SM bosons measurement.

BACKUP

CMS Experiment at the LHC, CERN

4) Dijets : 1 central jet + 1 forward jet

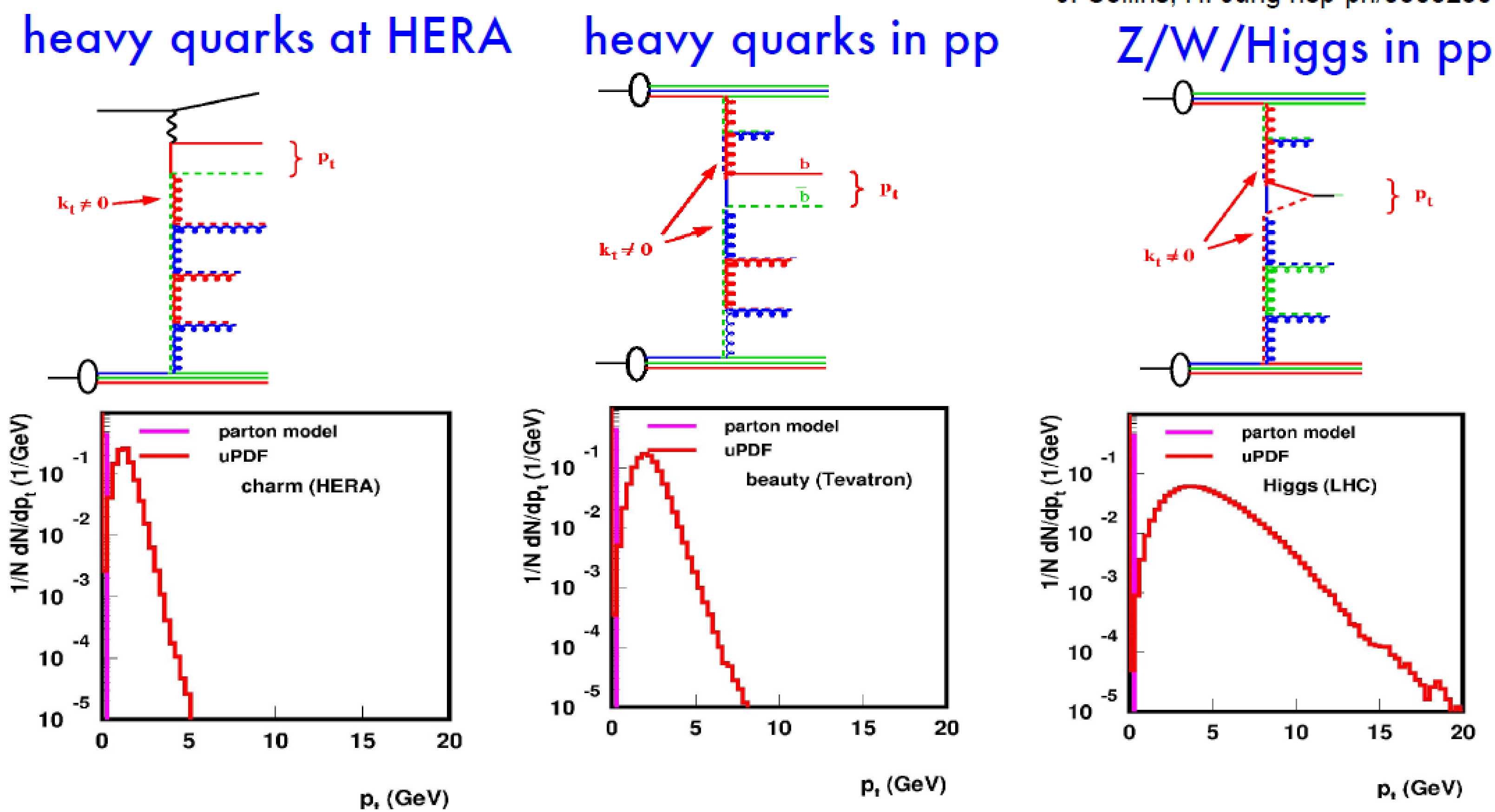
QCD-PAS-11-004



- All models fails. The closest is HEJ

3.4) uPDFs : way to include PS into PDFs

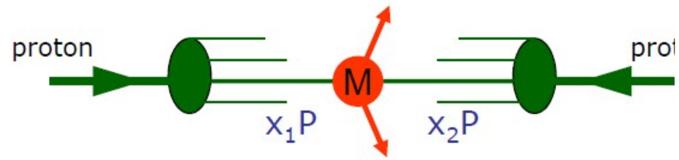
J. Collins, H. Jung hep-ph/0508280

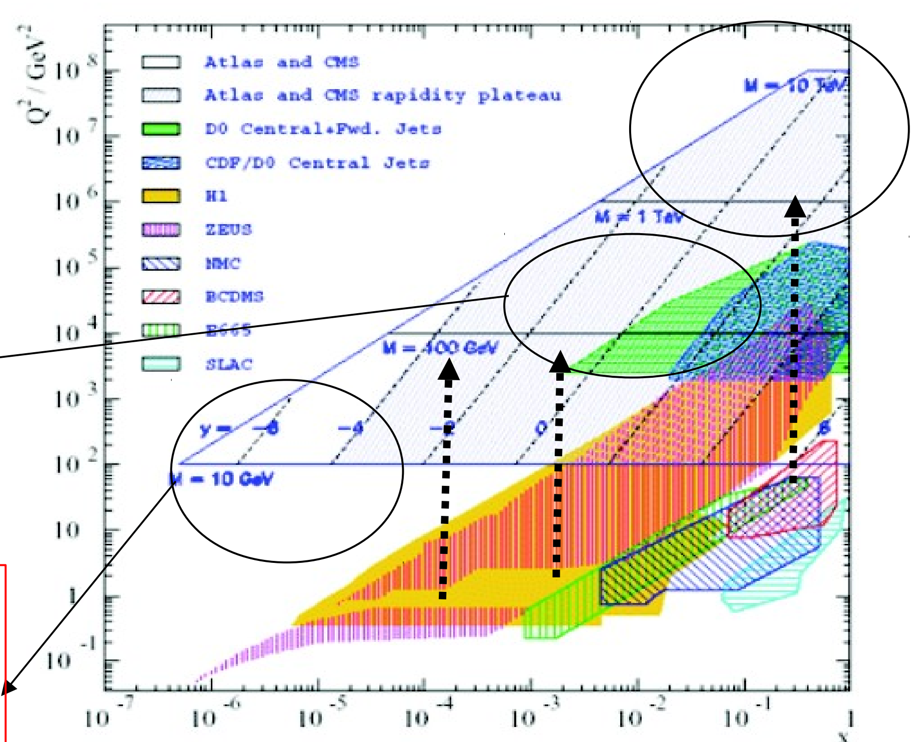


- Doing correctly kinematics at LO may reduce the NLO and PS resummation corrections. May be important when including large log(1/x).
- Finite transverse momenta play a role in cross sections calculations.

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).





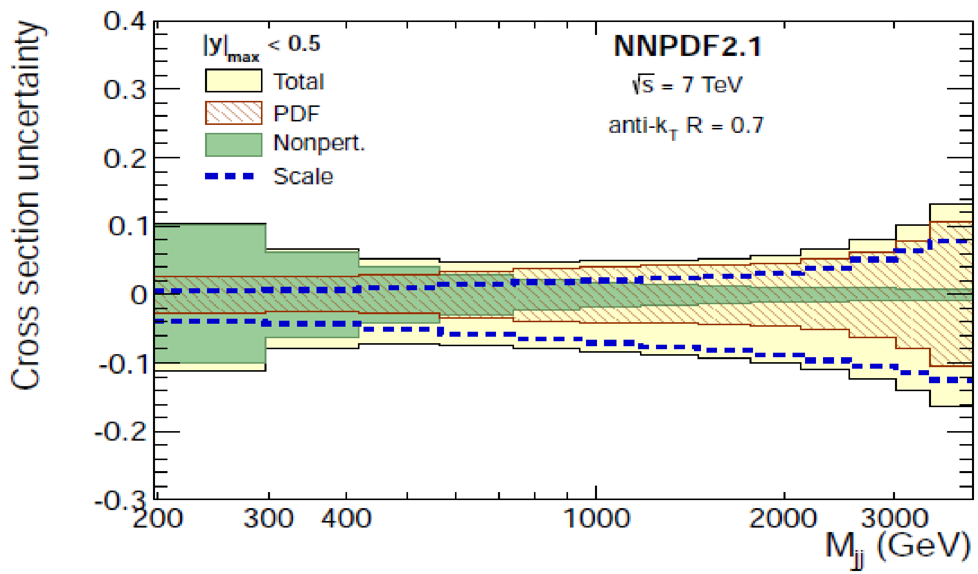
"Higgs and SM region"

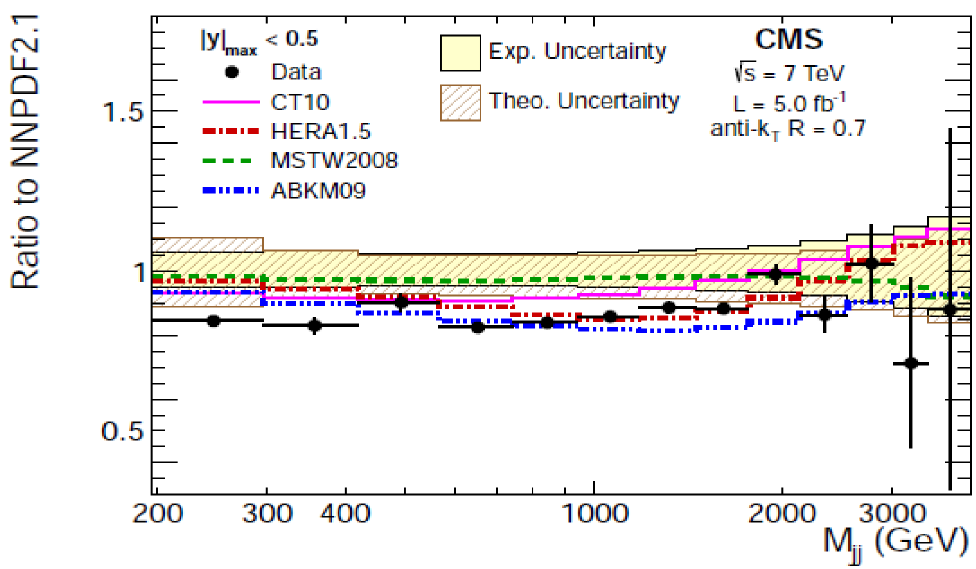
"Exotica searches region"

Terra incognita: forward physics

2.3.1) Dijets : 7 TeV with R=0.7

arXiv:1212.6660
sub. to PRD





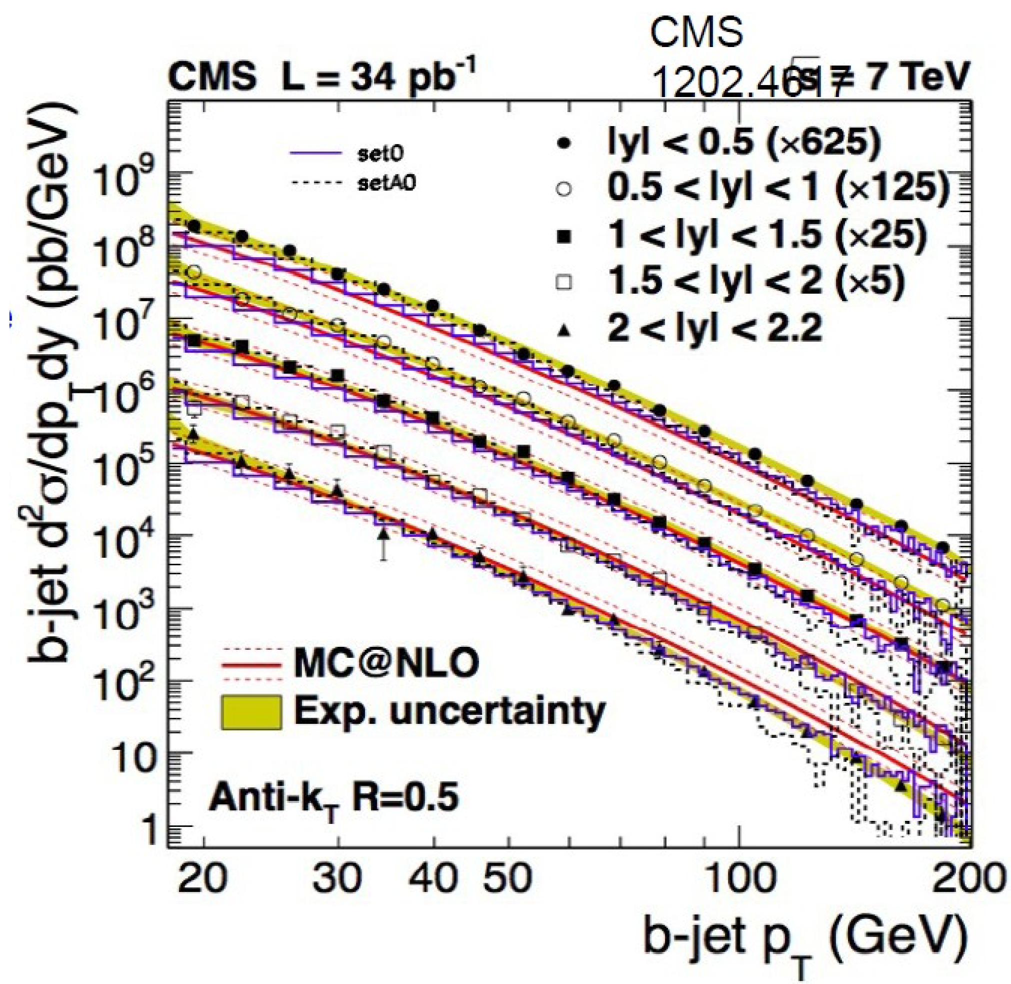
- Dijet mass situation experimentally more simple : single jet « noise effects ».
- Theoretically it seems that this variable is more sensitive than inclusive jets to soft QCD radiation :
  - Influence jet-jet angles.
  - Influence of jet mass sensitive to PU, MPI, fragmentation.
- Still described by QCD@NLO within error bands.

3.5) uPDFs : b-quarks example

J. High Energy Phys. 04 (2012) 084

H. Jung

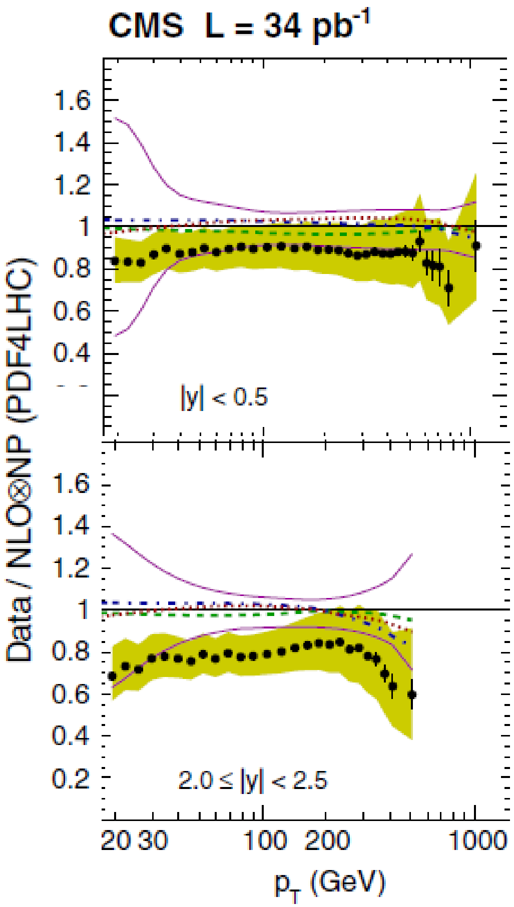
- Inclusive b production is gluon initiated at LO : gg→bb
- Challenging measurement wrt to inclusive jets. Uncertainty from b-tagging.
- Test uPDF (2 tunes) of the gluon at LO with CASCADE vs MC@NLO.
- Comparable at low p_T of set0 and MC@NLO, but better at large p_T.



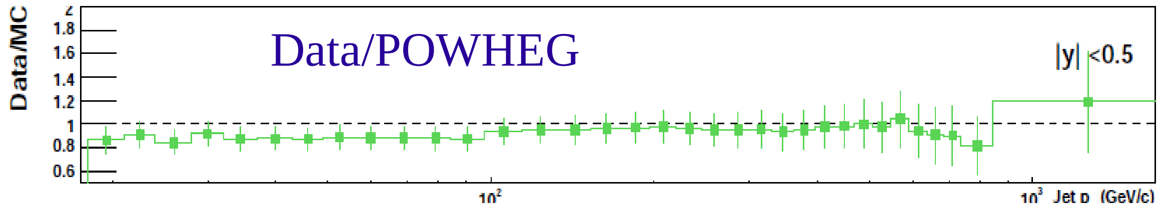
3.3) POWHEG vs NLO+NP

Phys. Rev. Lett. 107 (2011) 132001

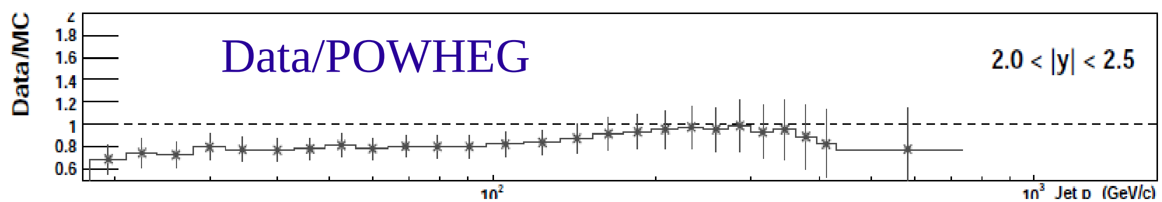
S. Dooling, H. Jung



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.