QCD measurements at the LHC

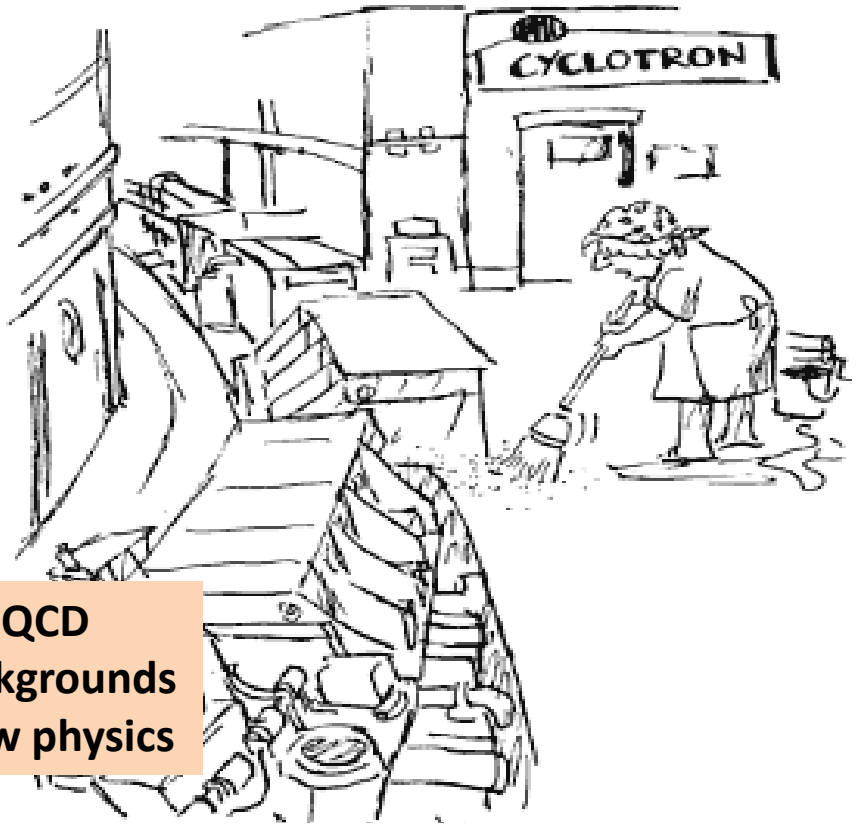
M. Martinez

24th Rencontres de Blois, May 2012

Outline

- LHC Performance
- Soft QCD[1]
- Jet Production
- B-jet Production
- Jet Internal Structure
- Prompt Photons
- Photon+jets
- W/Z+jets Production
- W/Z+HFs
- Final Notes

Stringent tests of pQCD and important backgrounds in searches for new physics



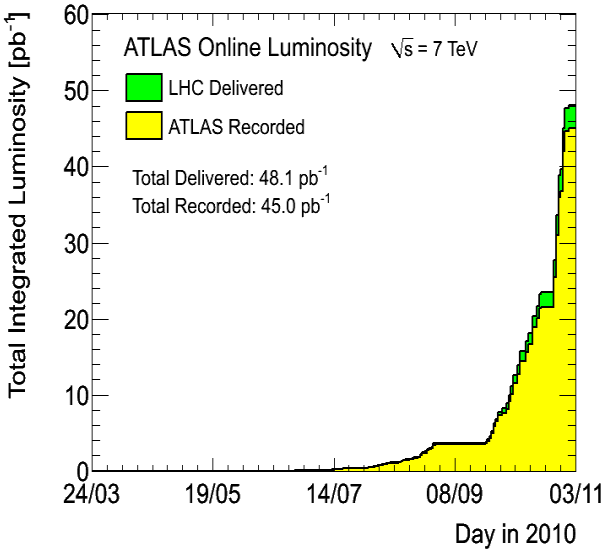
Some of the topics not covered in this talk

- Many results from Soft QCD, particle correlations,…
- Fragmentation Functions
- Diffraction, Rapidity Gaps, Forward Physics
- Hadron Spectroscopy
- Heavy Ions
- ……

See contributions to parallel sessions

(1) Only few examples out of many available results ….

LHC Performance (2010-2011)

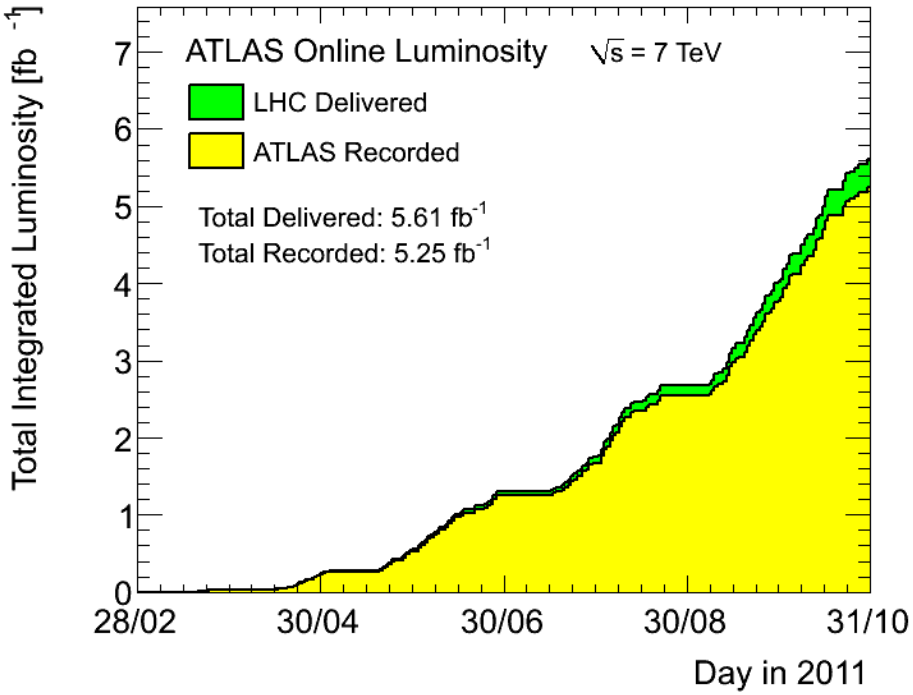


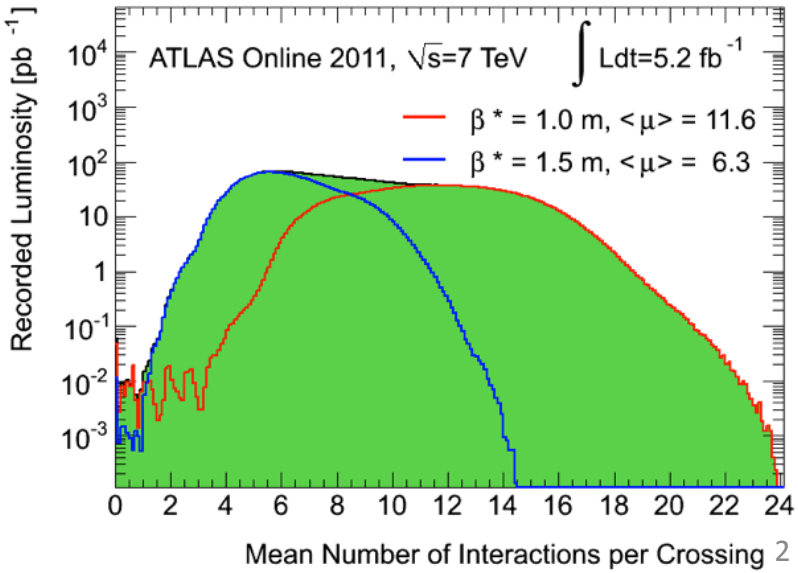
Spectacular LHC performance

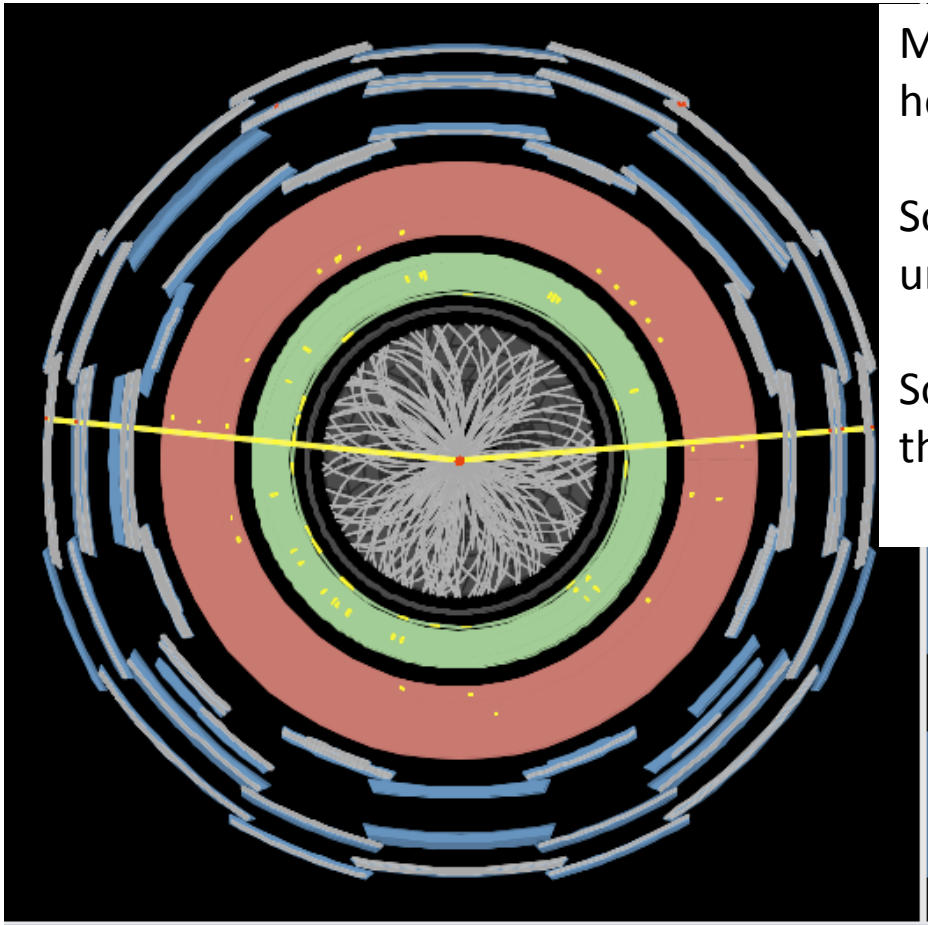
More than 5 fb-1 on tape per experiment (ATLAS/CMS)

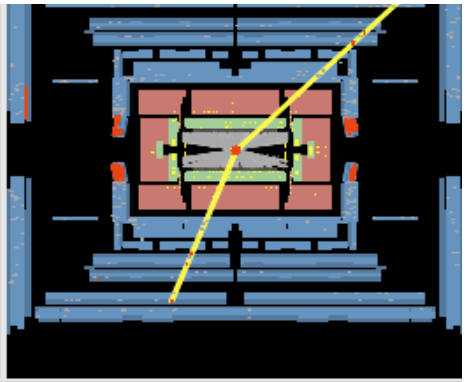
→ (around 40 pb-1 in 2010)

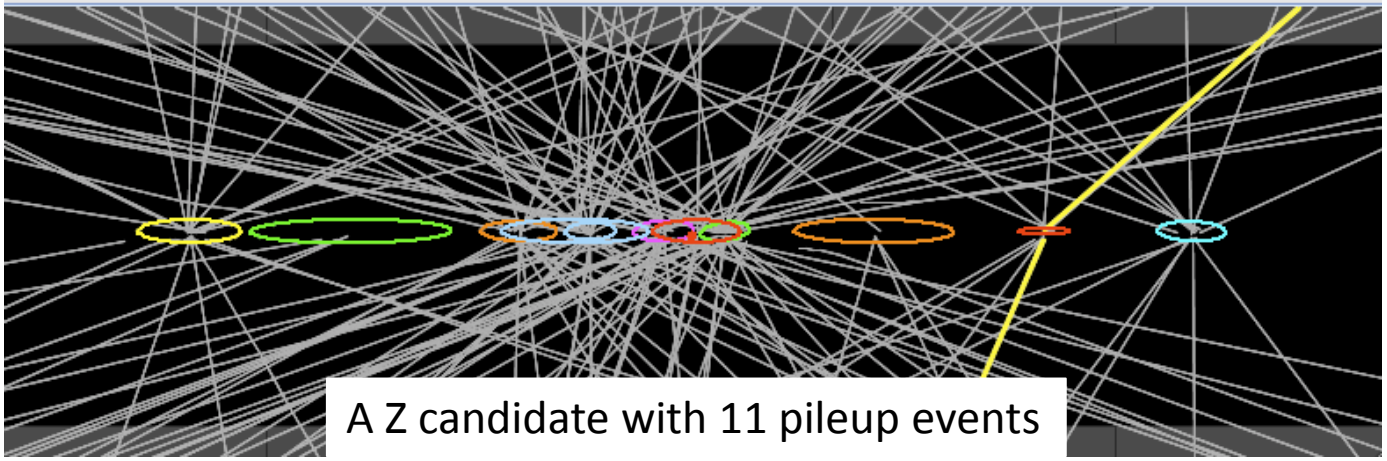
2010 : on average 2 interactions/crossing
2011 : significant increase of pile-up











A Z candidate with 11 pileup events

Many of the results presented here used the 2010 data at 7 TeV

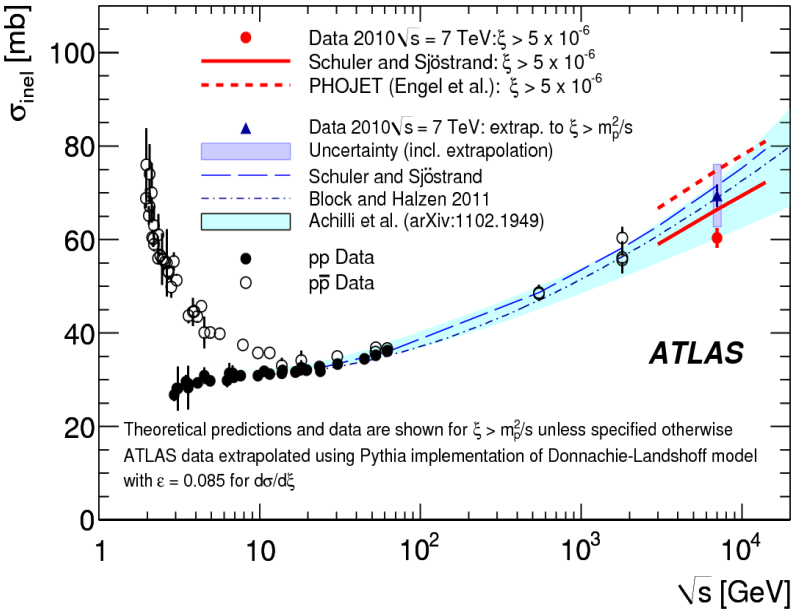
Some of the measurements are unique since they require low pile-up

Some analyses already included the full 2011 dataset (7 TeV)

$\sigma^{\text{inelastic}}$ (pp)

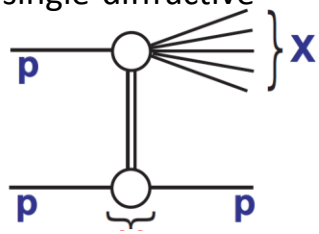
Nat. Commun. 2 (2011) 463

(see also Eur. Phys. J. C72 (2012) 1926)



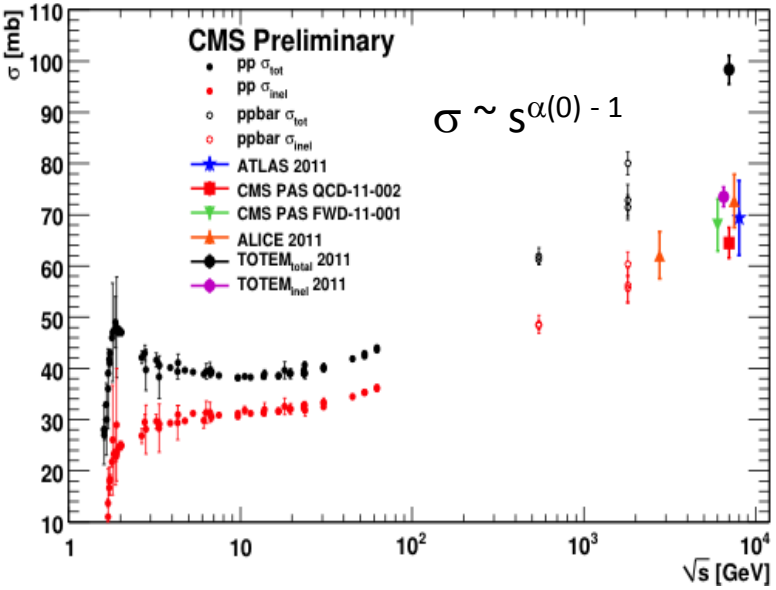
Fundamental measurement
Input to cosmic ray physics, …..

single-diffractive

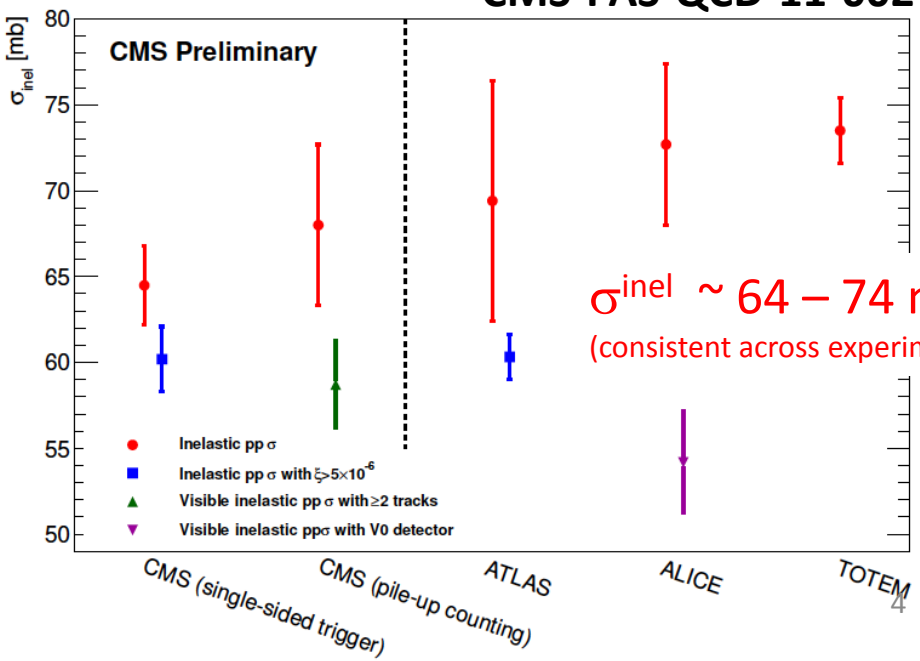


contributions from non-diffractive and diffractive processes

Experiments (ATLAS/CMS) sensitive to
$\xi = M_X^2 / s > 5\ 10^{-6}$ ($M_X > 16$ GeV)
(about 10% extrapolation to full acceptance)



CMS-PAS-QCD-11-002

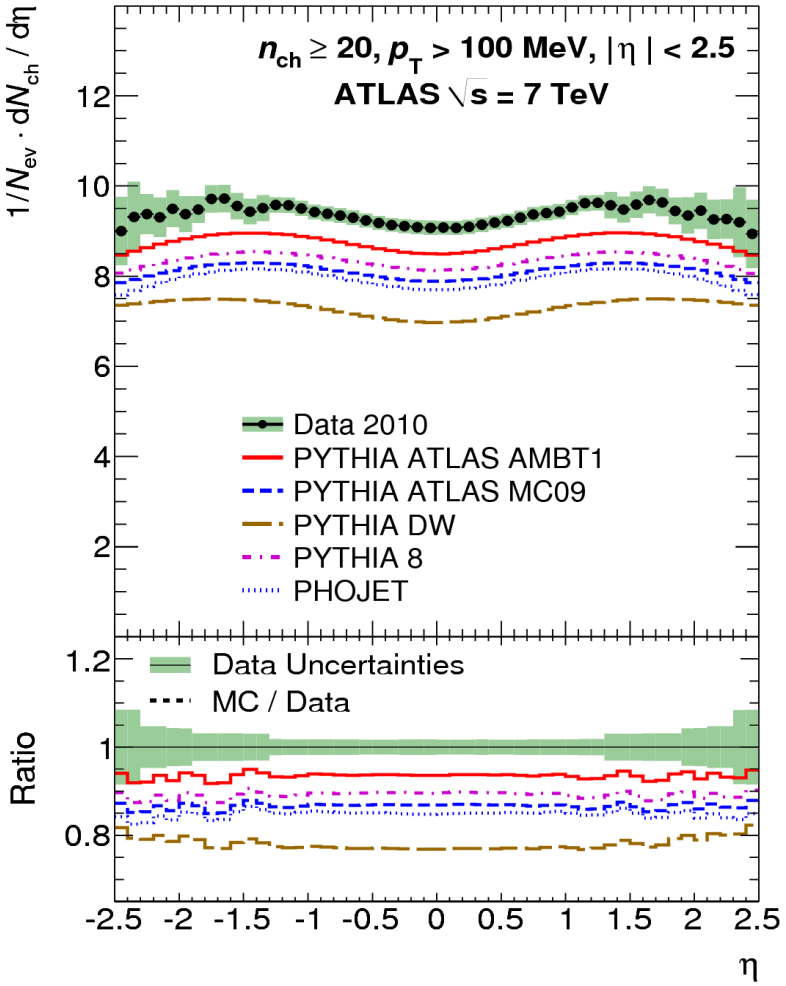


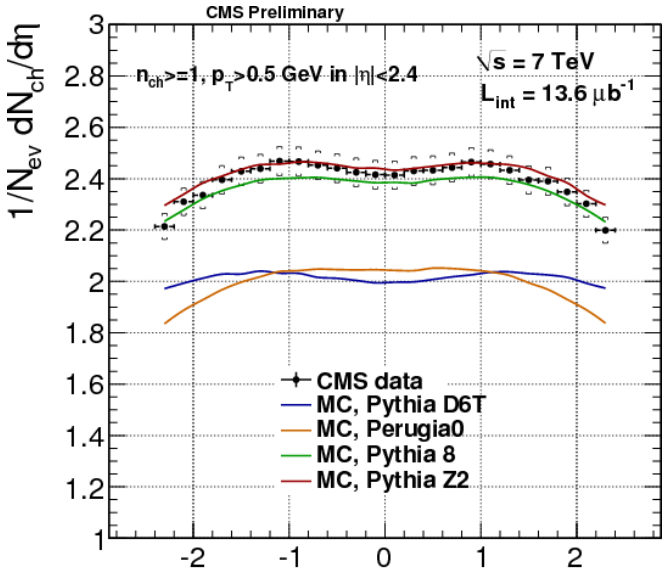
σ^{inel} ~ 64 – 74 mb
(consistent across experiments)

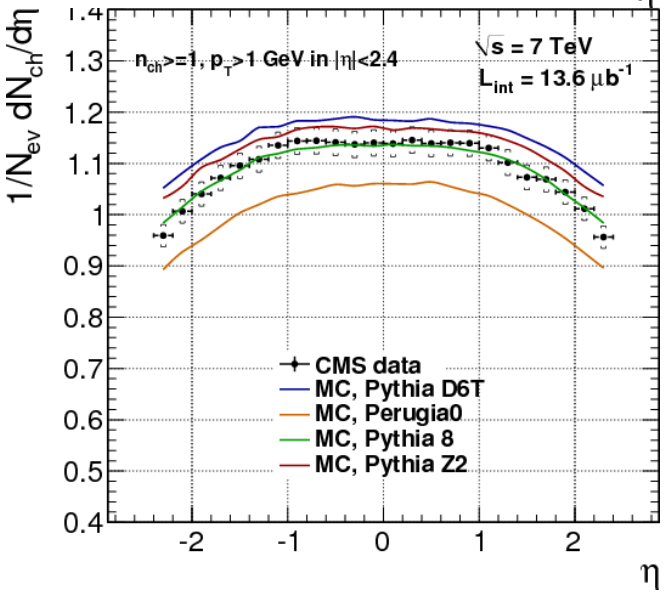
Soft QCD

(charged particle multiplicity)

Measurements on MB particle multiplicities (fundamental for understanding of pile-up)



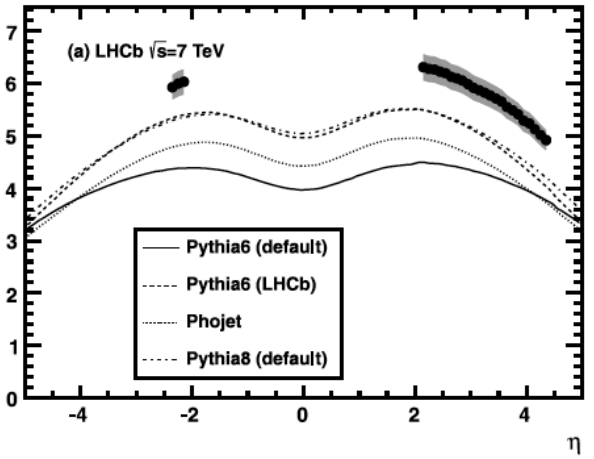


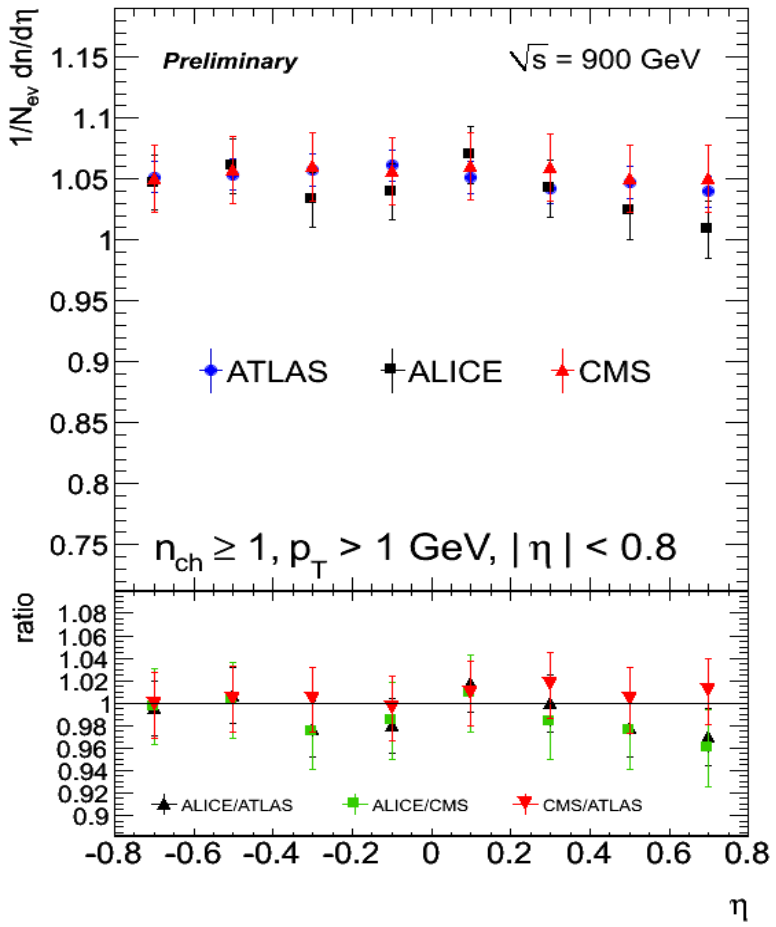


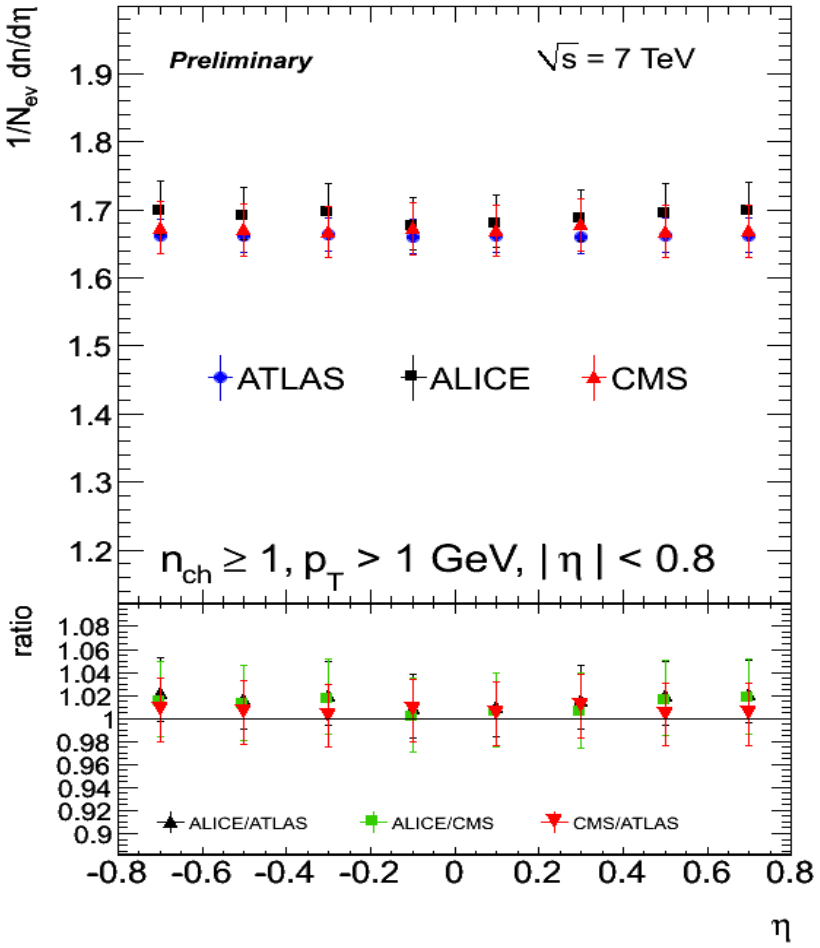
Basic for the tune of the MC models

Soft QCD

Consistent measured charged particle multiplicity across LHC experiments

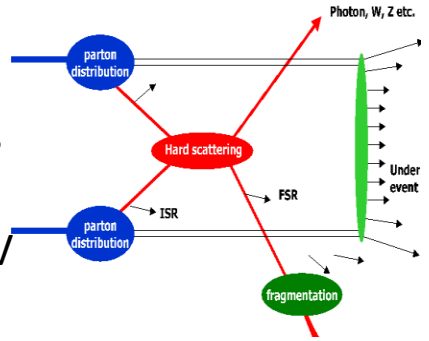


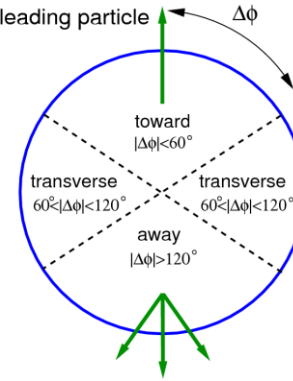




UE studies

charged and neutral particles

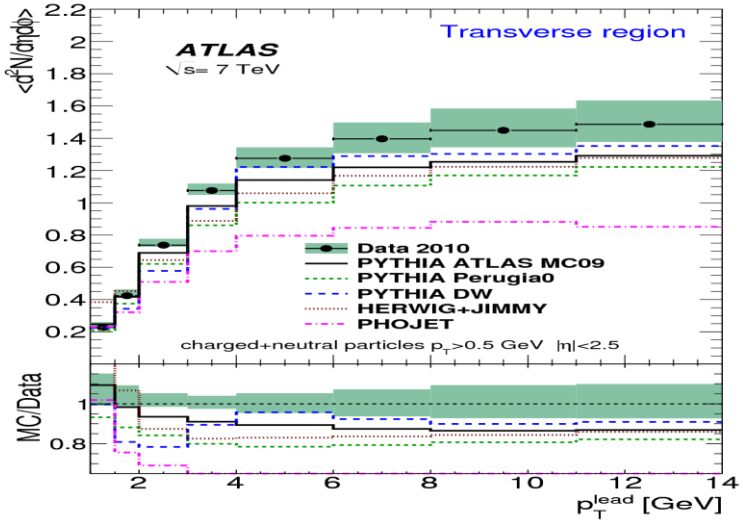


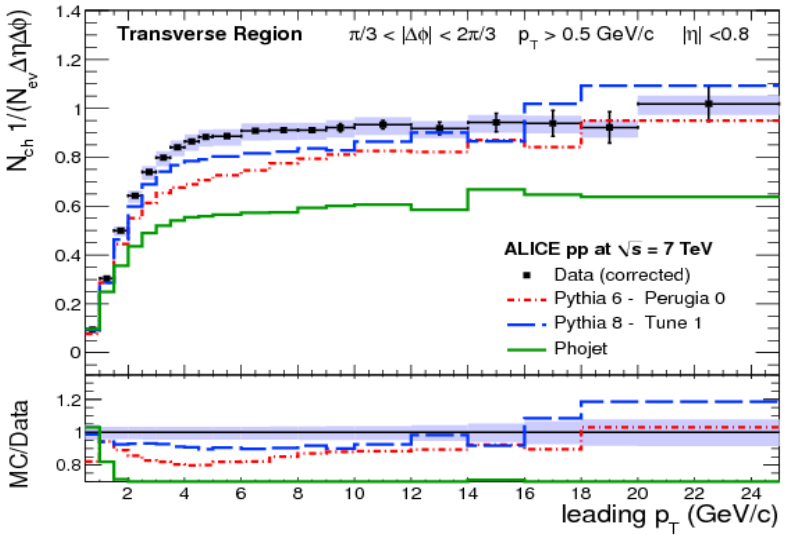


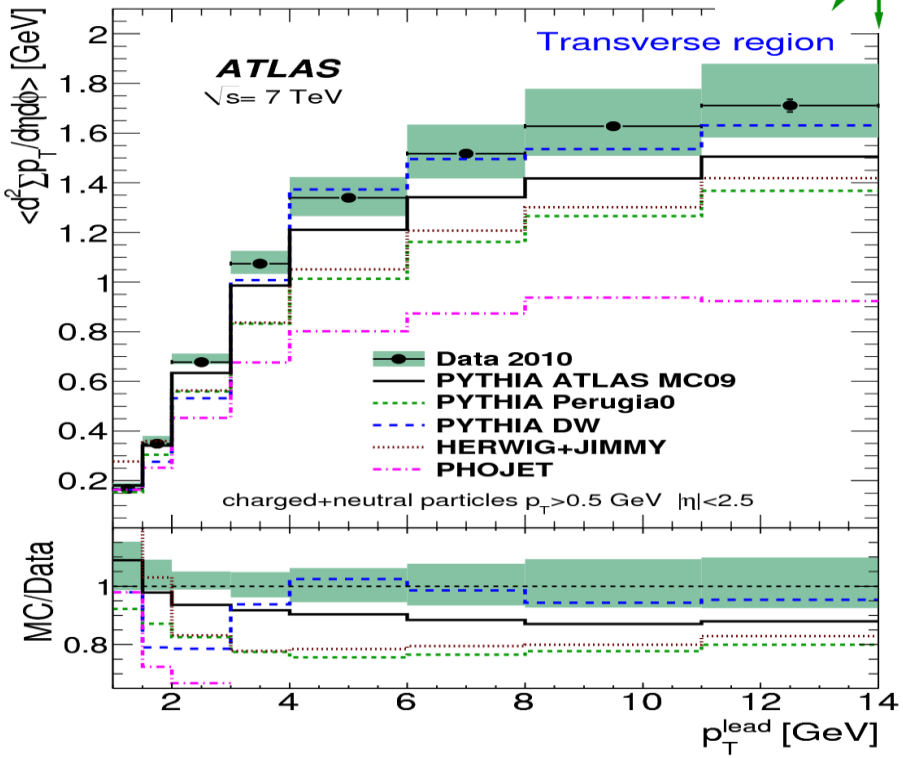
Essential for a proper modeling of low p_T jets, jet vetoes, isolation, etc..

$p_T > 0.5$ GeV

$|\eta| < 2.5$





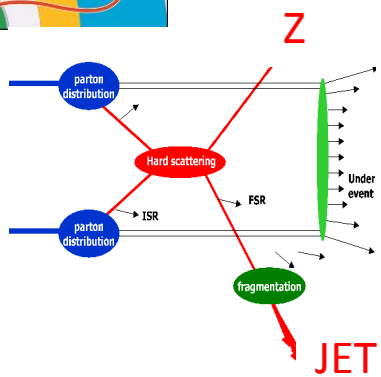


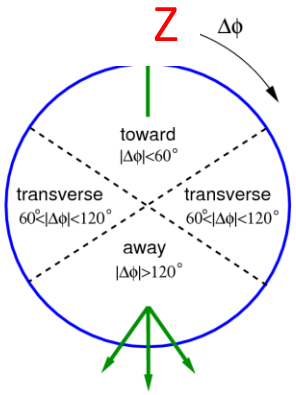
The activity in the transverse region reaches a plateau indicating that MPI/UE somehow decouples from the rest of the event

Data intensively used to tune the MC models

UE studies in DY

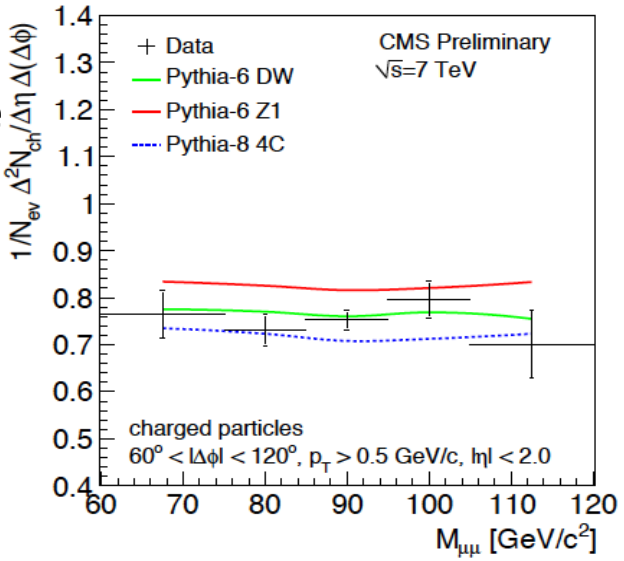
CMS_QCD_11_012

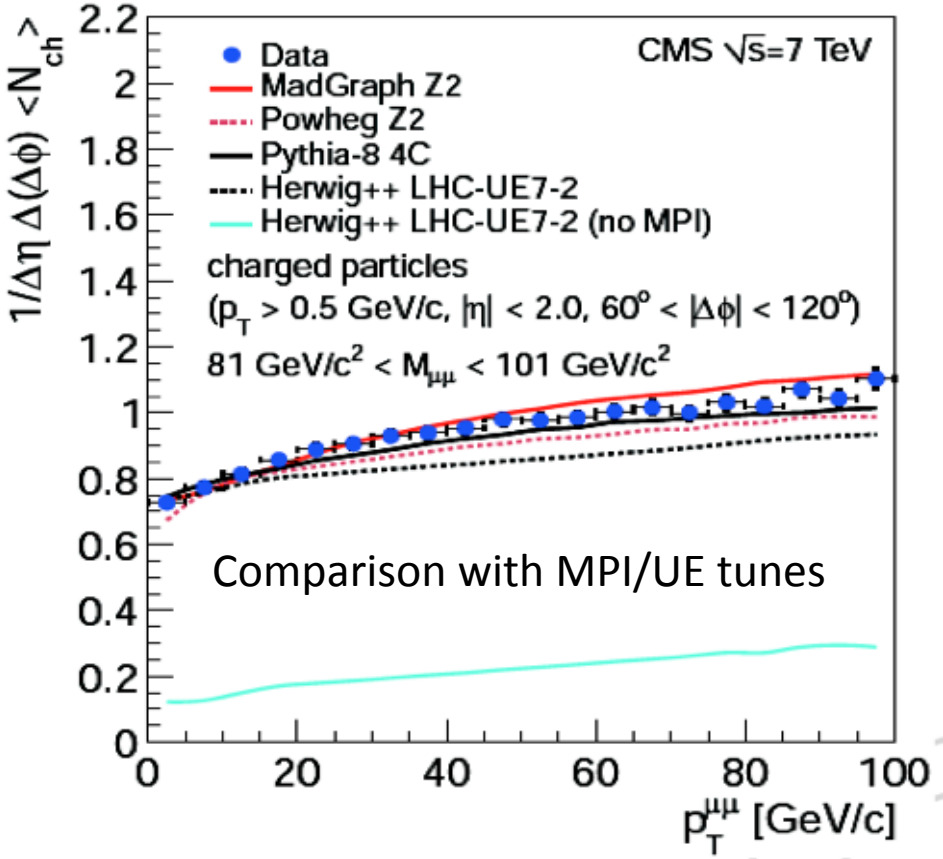




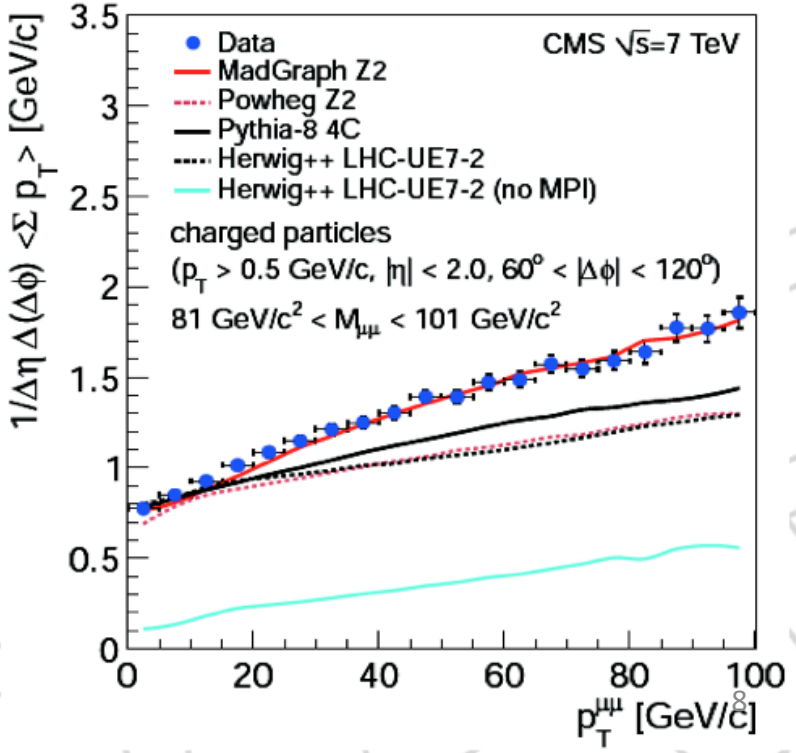
Activity in the transverse region saturated at the Z-mass scale

Moderate increase with Z p_T mostly due to ISR





Comparison with MPI/UE tunes

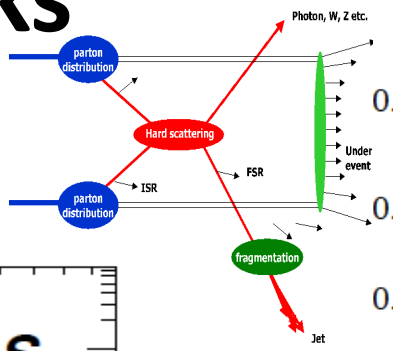


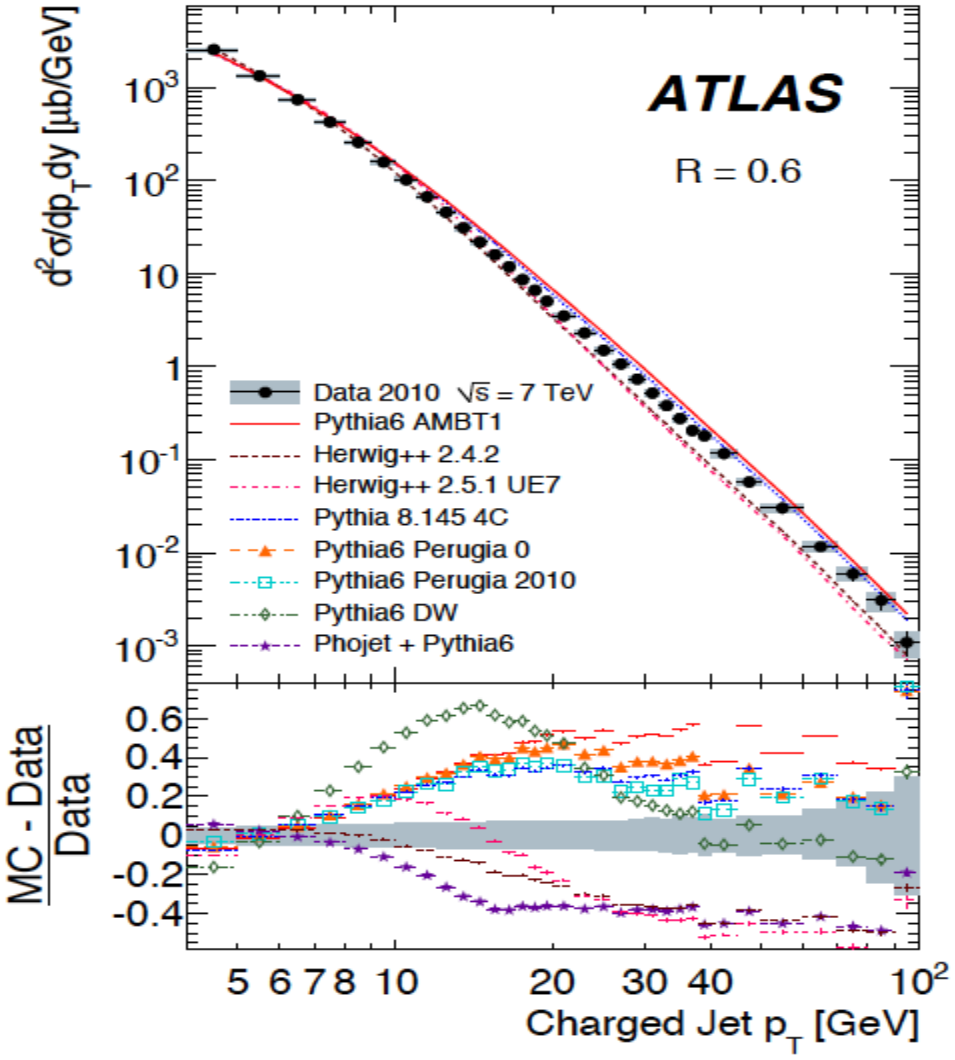
Jets with tracks

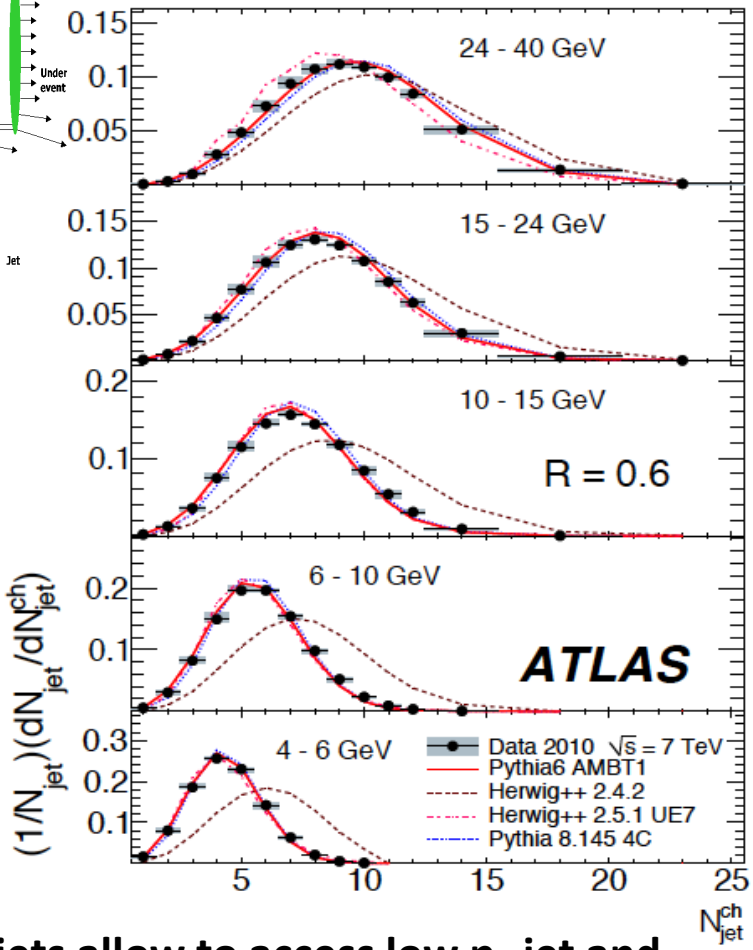
Phys. Rev.D 84 (2011) 054001

anti-K_T jets with R=0.4, 0.6

Jet $p_T > 4$ GeV, $|Y| < 1.9$







Track jets allow to access low p_T jet and study the transition between soft collisions and the pQCD regime

Important input to future MC tunes
Complementary to MB and UE studies

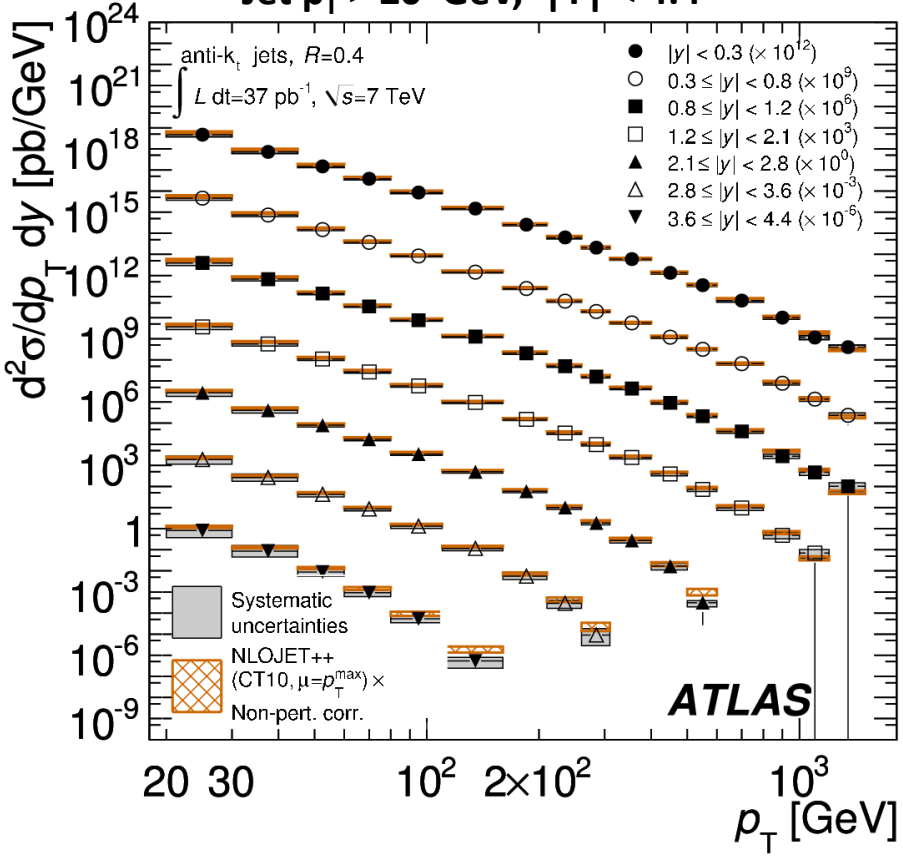
Inclusive Jet Production

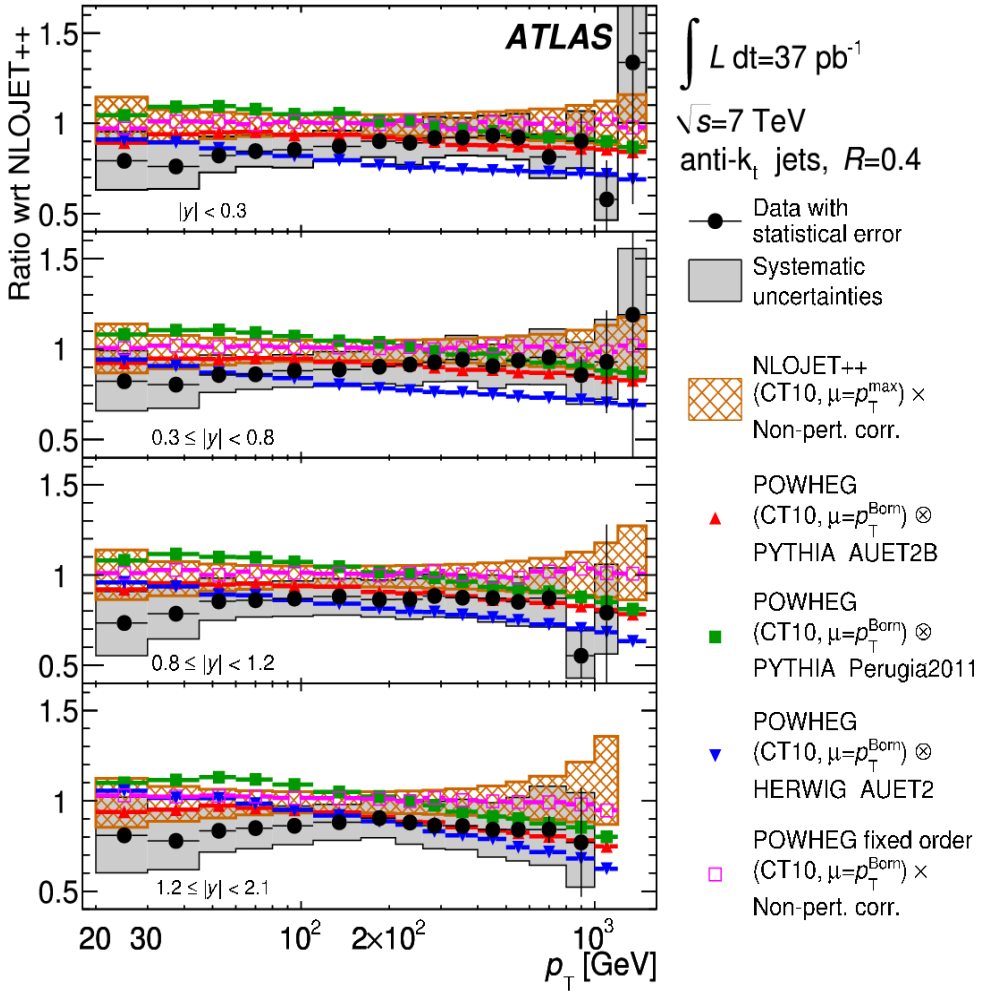
CERN-PH-EP-2011-192

Stringent test of pQCD predictions (sensitive to quark compositeness)

anti-K_T jets with R=0.4, 0.6

Jet p_T > 20 GeV, |Y| < 4.4





Data compared to NLO pQCD predictions (including non-pQCD corrections) and to NLO ME + PS (POWHEG) with different PS + UE/MPI implementations

Measured cross section in agreement with NLO pQCD predictions

Clear sensitivity to the details of the NLO ME+PS implementation

NEW !!

Inclusive Jets

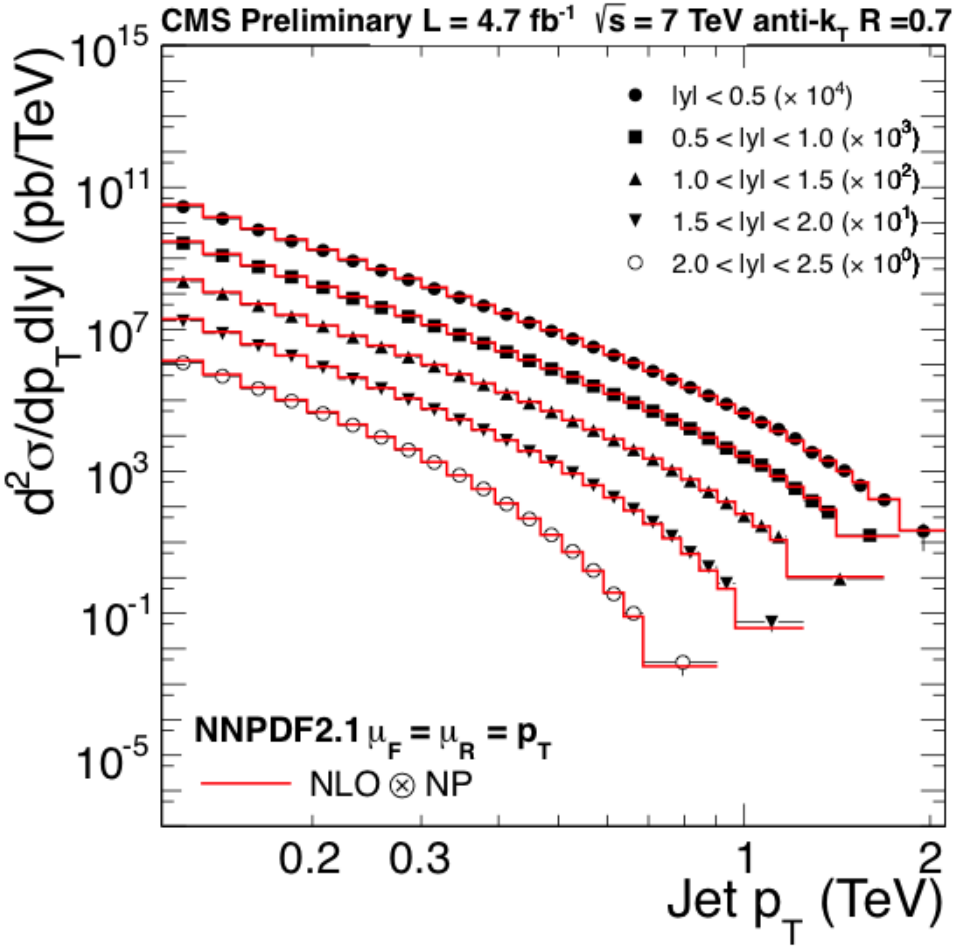
CMS-PAS-QCD-11-004

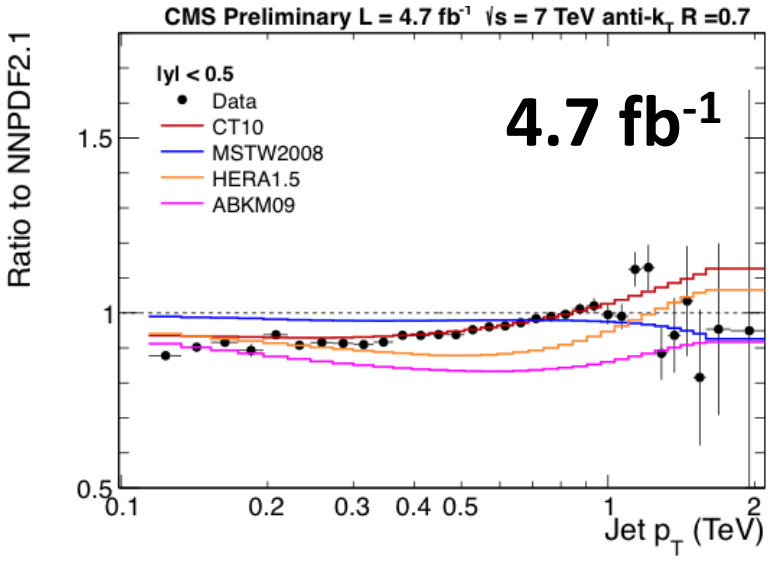
Phys. Rev. Lett. 107, 132001 (2011)

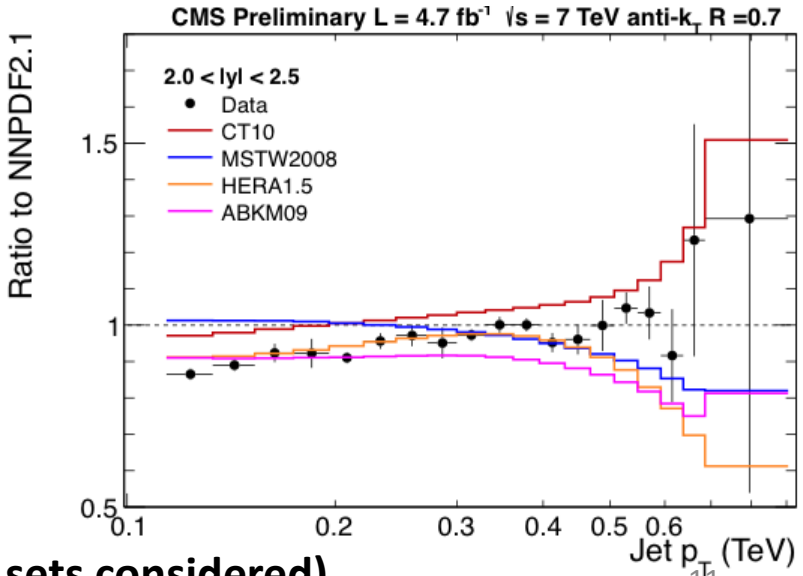
(R=0.5, p_T > 18 GeV, |y| < 3)

anti-k_T jets with R=0.7

Jet p_T > 114 GeV, |Y| < 2.5



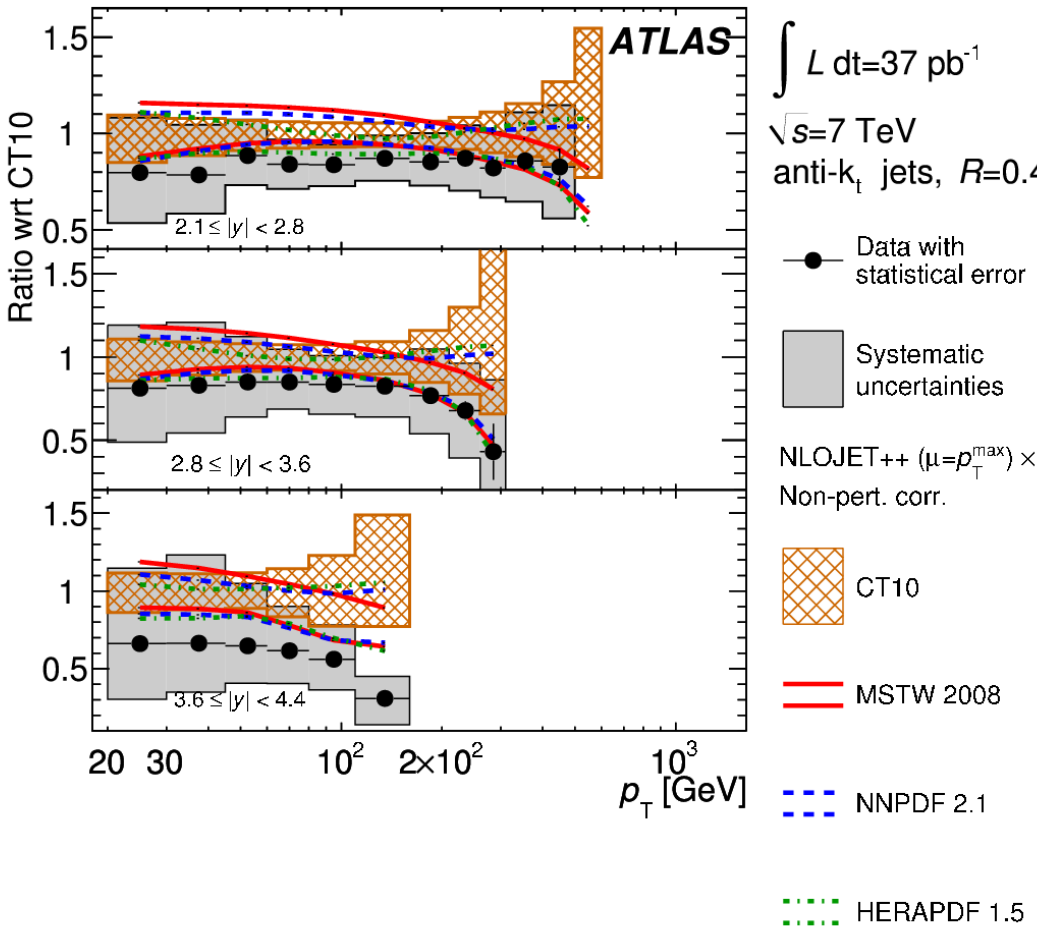


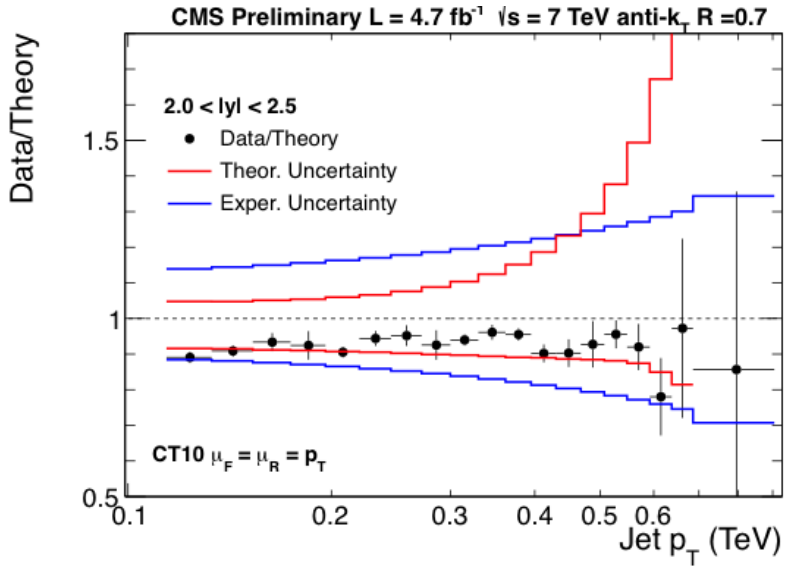


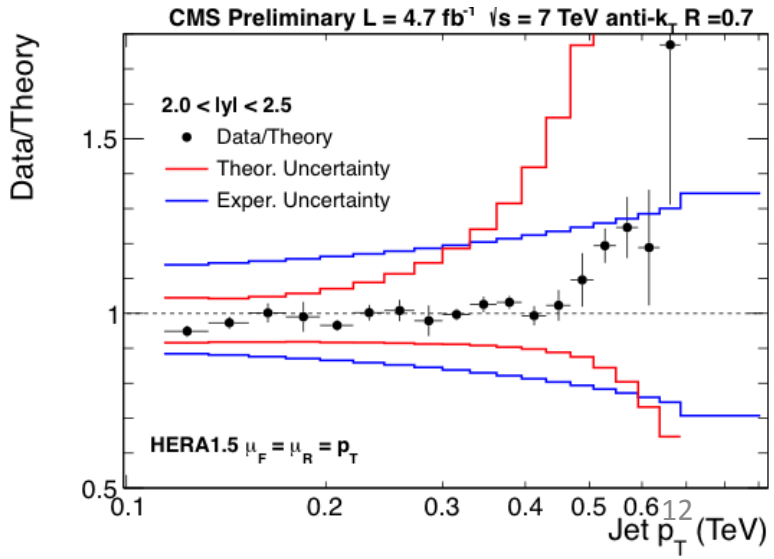
Measurement up to almost 2 TeV for central jets

Good agreement with NLO pQCD predictions (5 PDF sets considered)

Inclusive Jets & PDFs







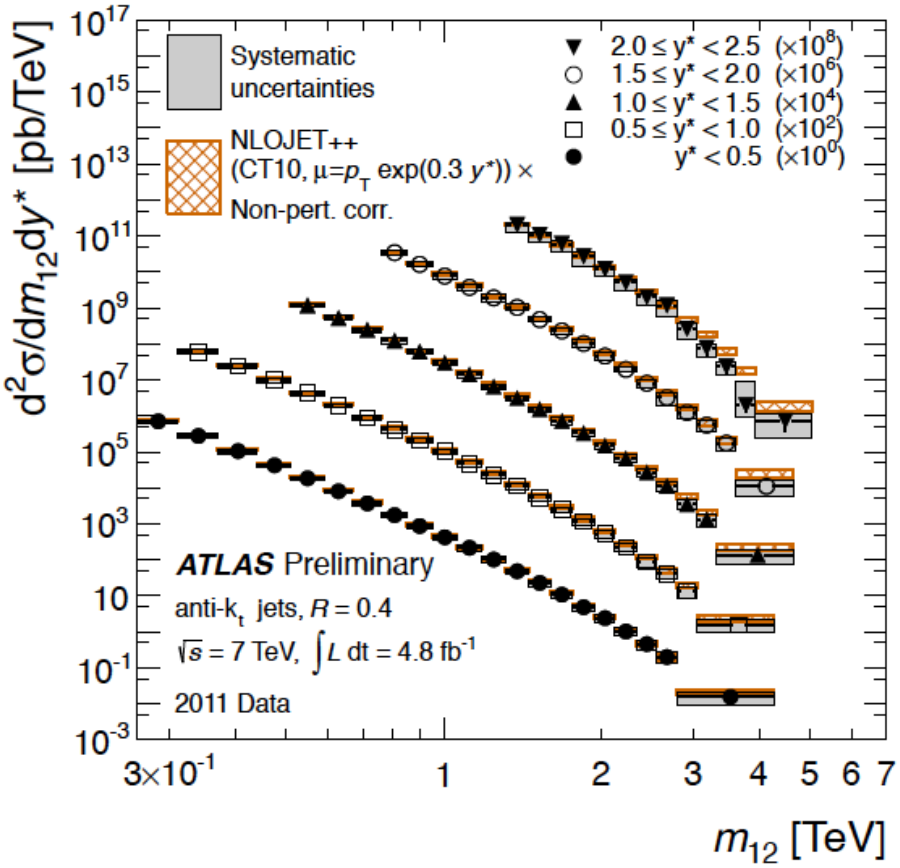
Data at the edge of the phase space in the forward promise to further constrain the gluon PDFs (in a region with limited p_T where no new physics is expected)

Di-jets

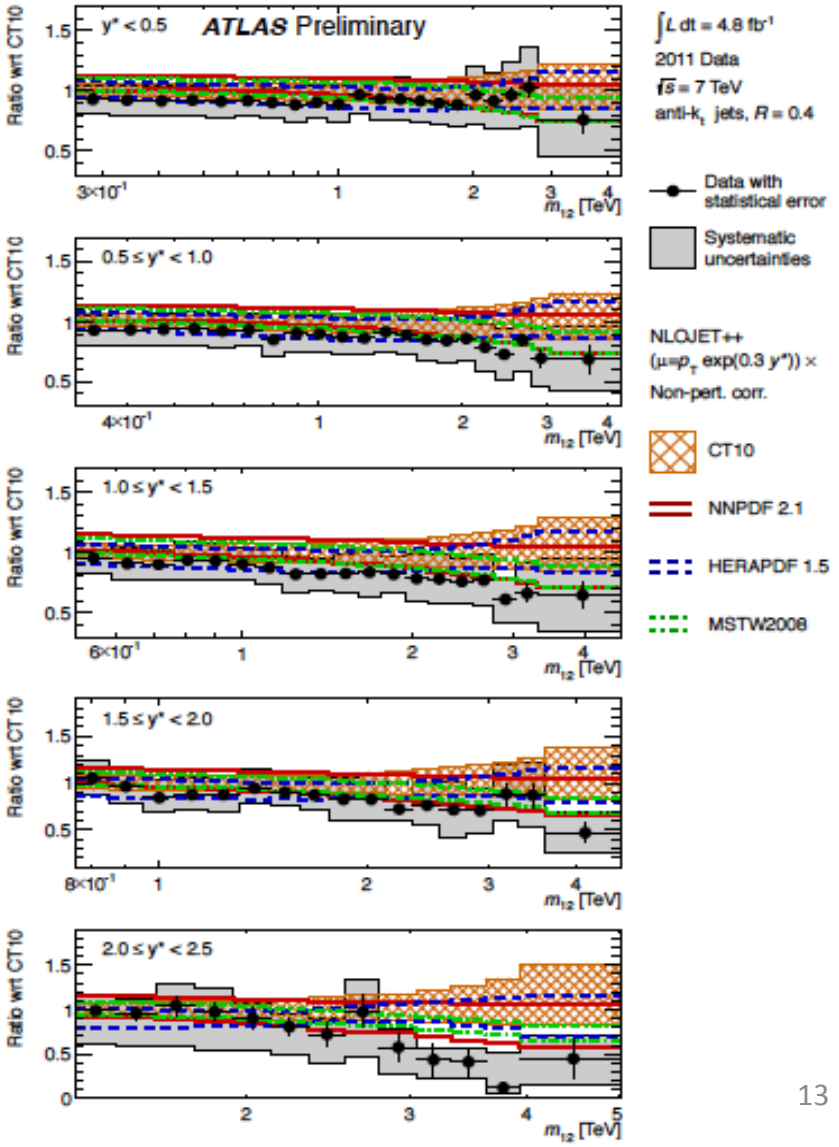
4.8 fb^{-1} **NEW !!** **ATLAS-CONF-2012-021**

$$M_{jj} > 260 GeV$$

$$y^* = |y^1 - y^2|/2 < 2.5$$



Stringent pQCD test
(sensitive to new dijet resonance production)



Invariant masses up to 5 TeV
Reasonably well described by NLO pQCD
(some tension at very large dijet masses)

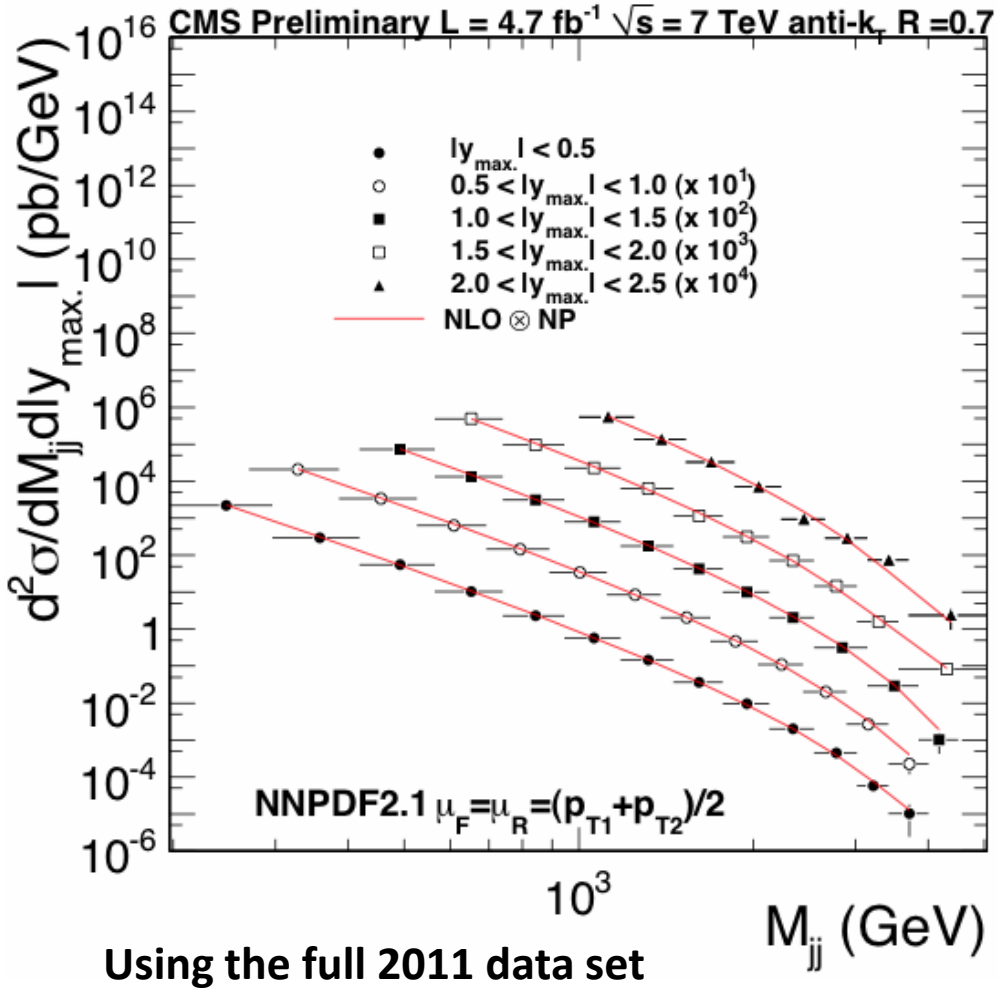
Dijet Production

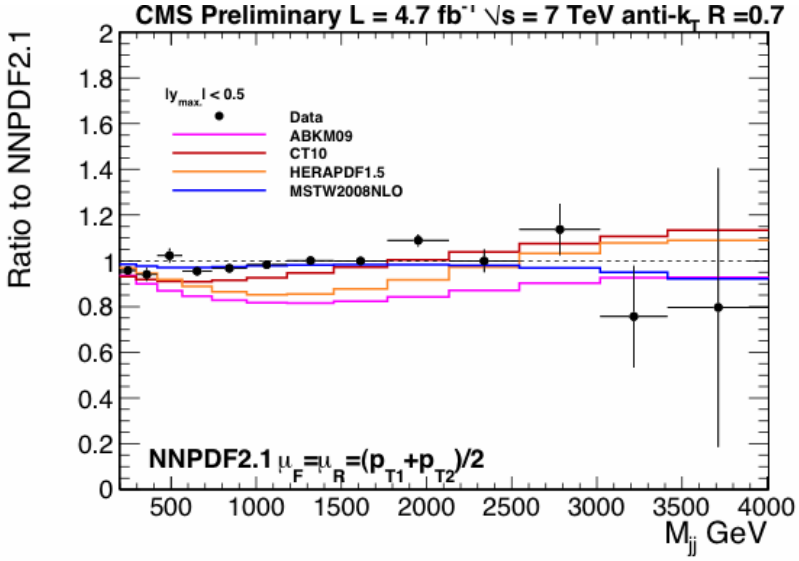
NEW !!

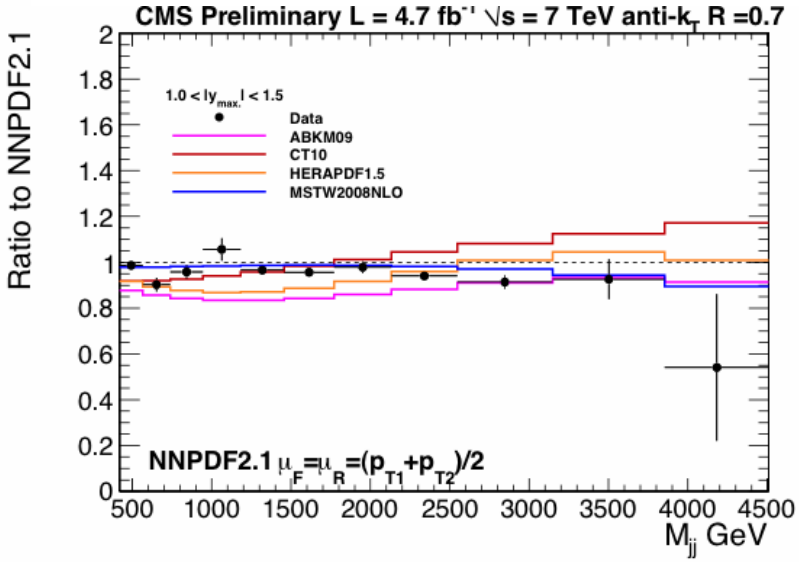
CMS-PAS-QCD-11-004

$M_{jj} > 300 GeV$

$|y^{max}| < 2.5$







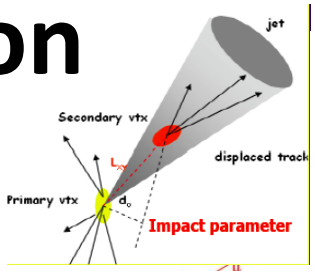
Using the full 2011 data set

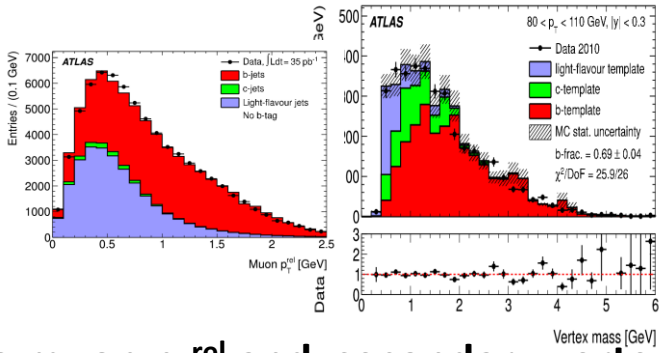
Good agreement with NLO pQCD predictions

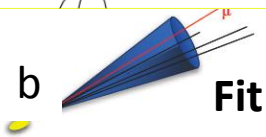
B-jets Production

anti-K_T jets with R=0.4

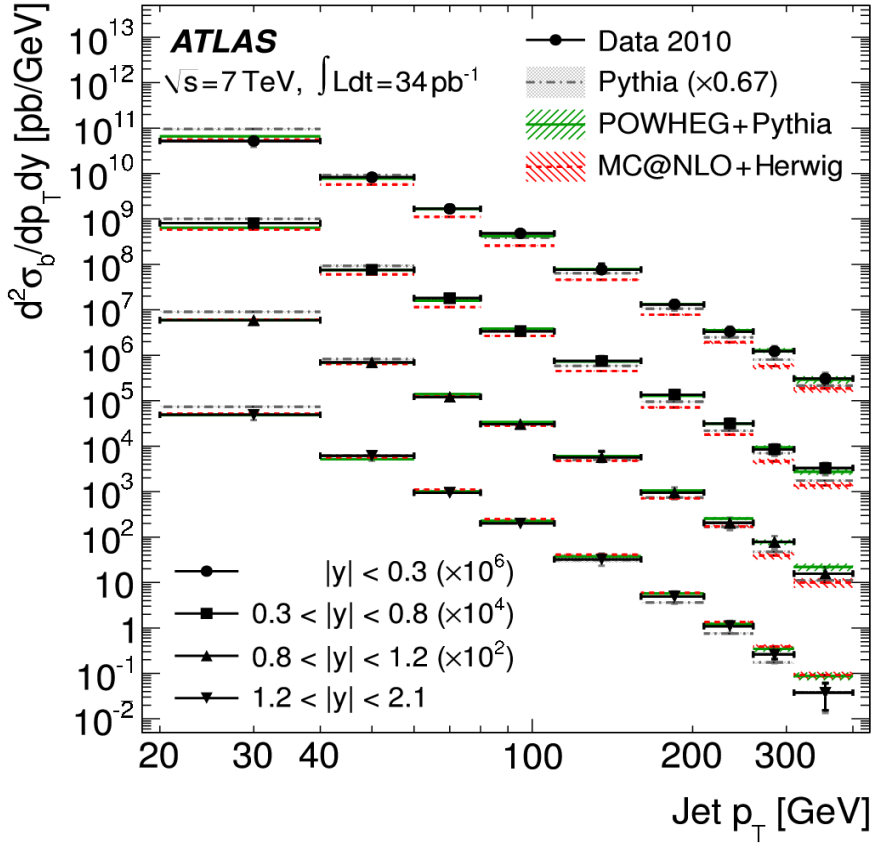
Jet p_T > 20 GeV, |Y| < 2.1



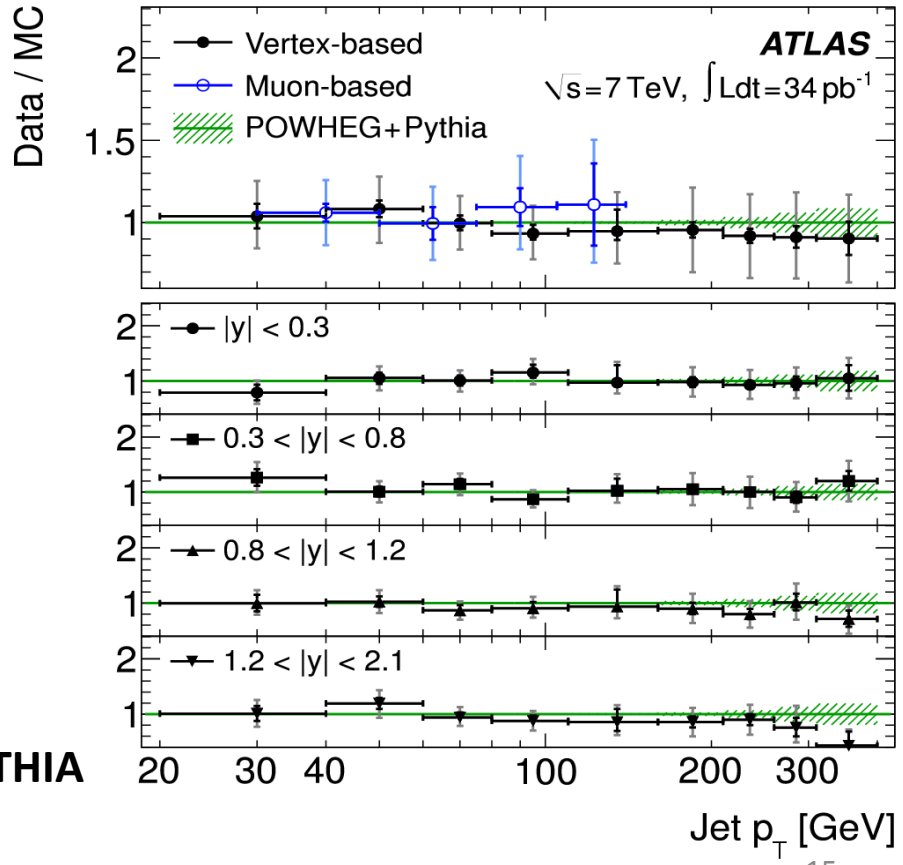




Eur.Phys.J.C 71 (2011) 1846



Fit to muon p_T^{rel} and secondary vertex mass to extract the b-jet contribution



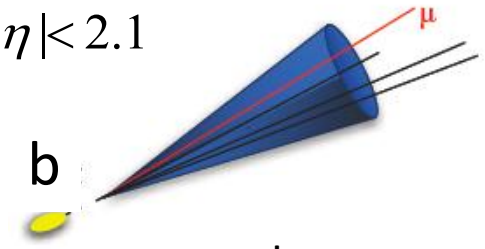
Cross sections well described by POWHEG+PYTHIA
MC@NLO+HERWIG below the data specially
for central jets at large transverse momentum

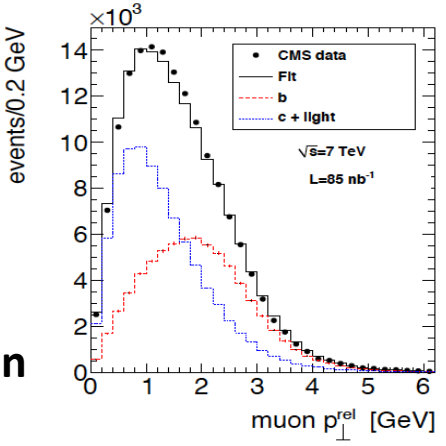
Inclusive b-hadron production

JHEP 3 (2011) 90

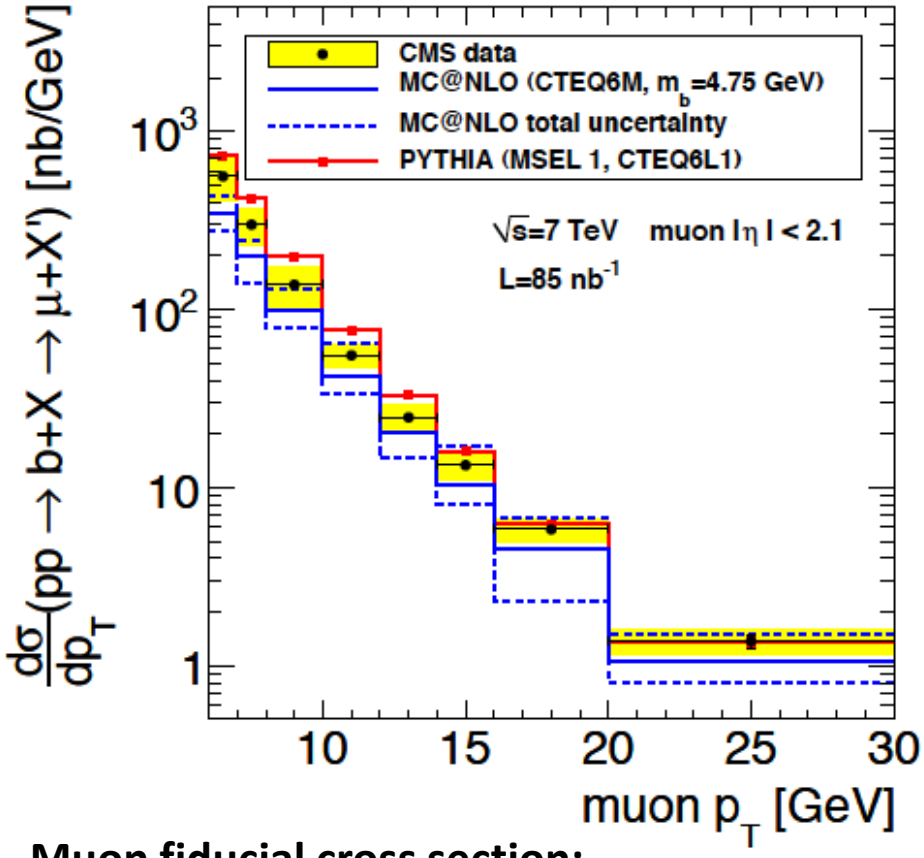
$p_T^{\mu} > 6GeV$

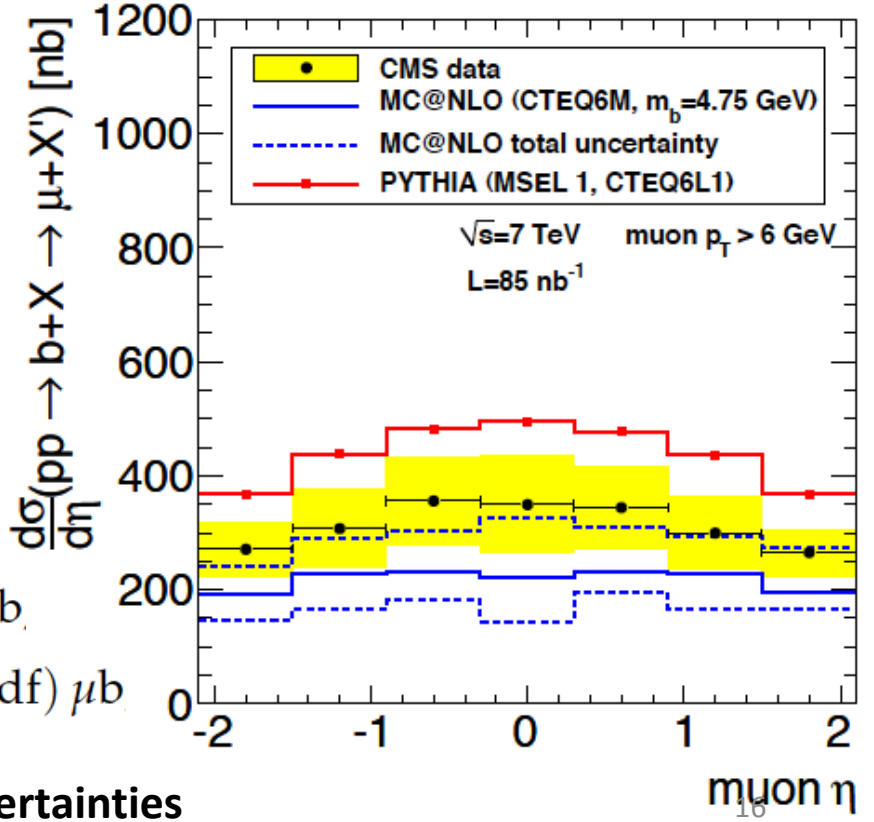
$|\eta| < 2.1$





Fit to p_T^{rel} distribution





Muon fiducial cross section:

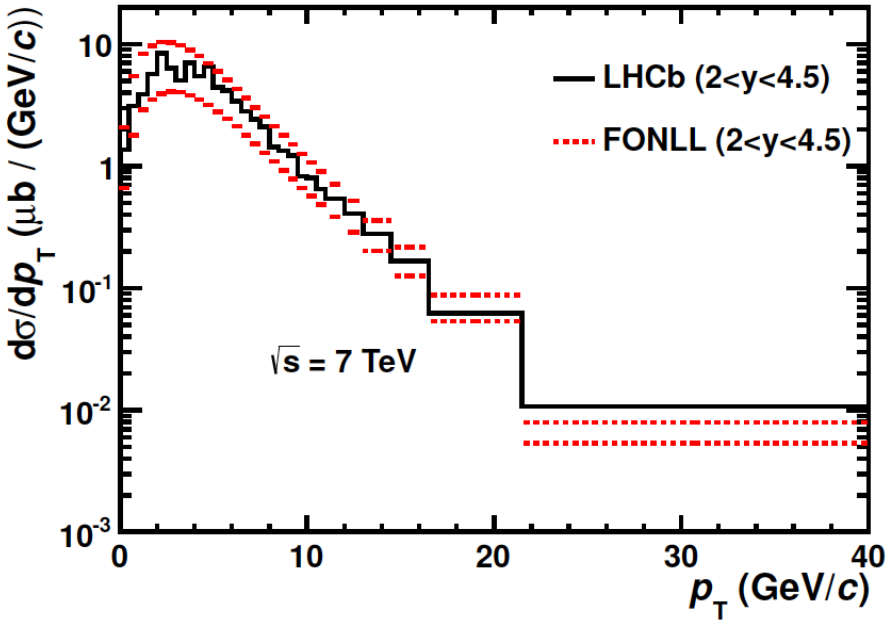
$$\sigma = 1.32 \pm 0.01(\text{stat}) \pm 0.30(\text{syst}) \pm 0.15(\text{lumi})\ \mu\text{b}$$

$$\sigma_{\text{MC@NLO}} = 0.84^{+0.36}_{-0.19}(\text{scale}) \pm 0.08(m_b) \pm 0.04(\text{pdf})\ \mu\text{b}$$

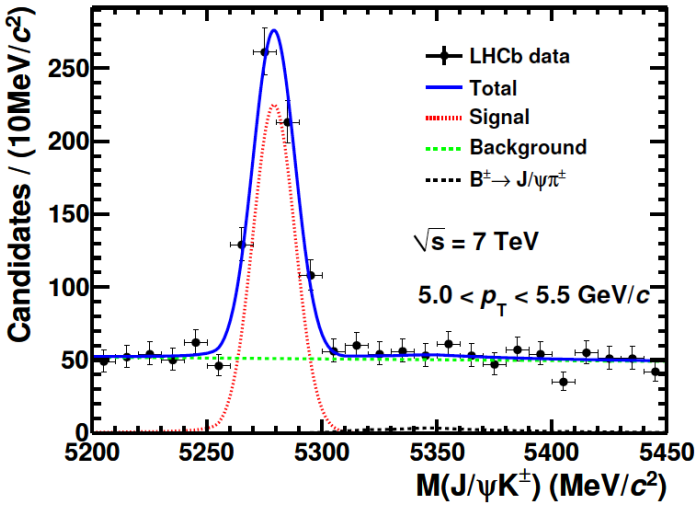
Still in agreement within the large theoretical uncertainties

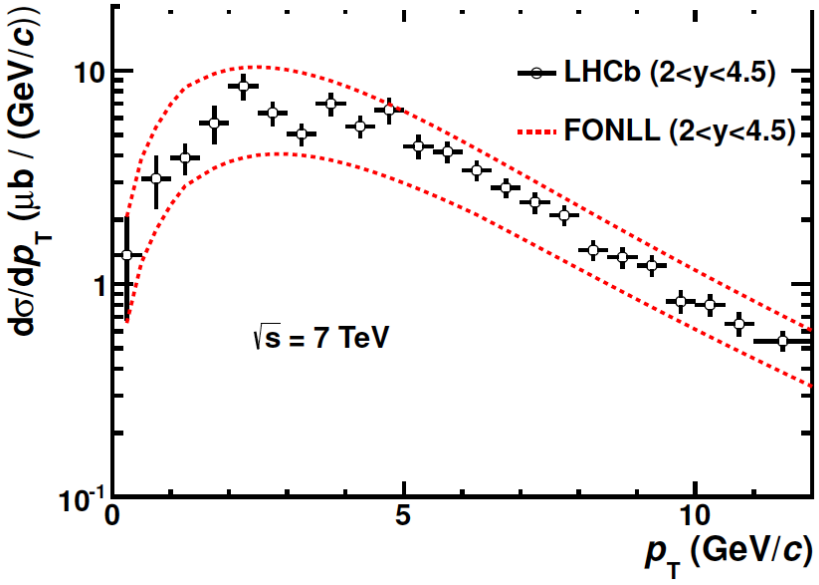
J. High Energy Phys. 04 (2012) 093

B-jet Forward Production



$B^{\pm} \to J/\psi K^{\pm}$ $J/\psi \to \mu^+\mu^-$

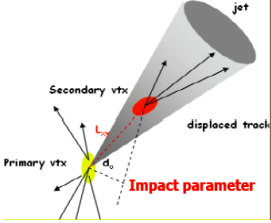




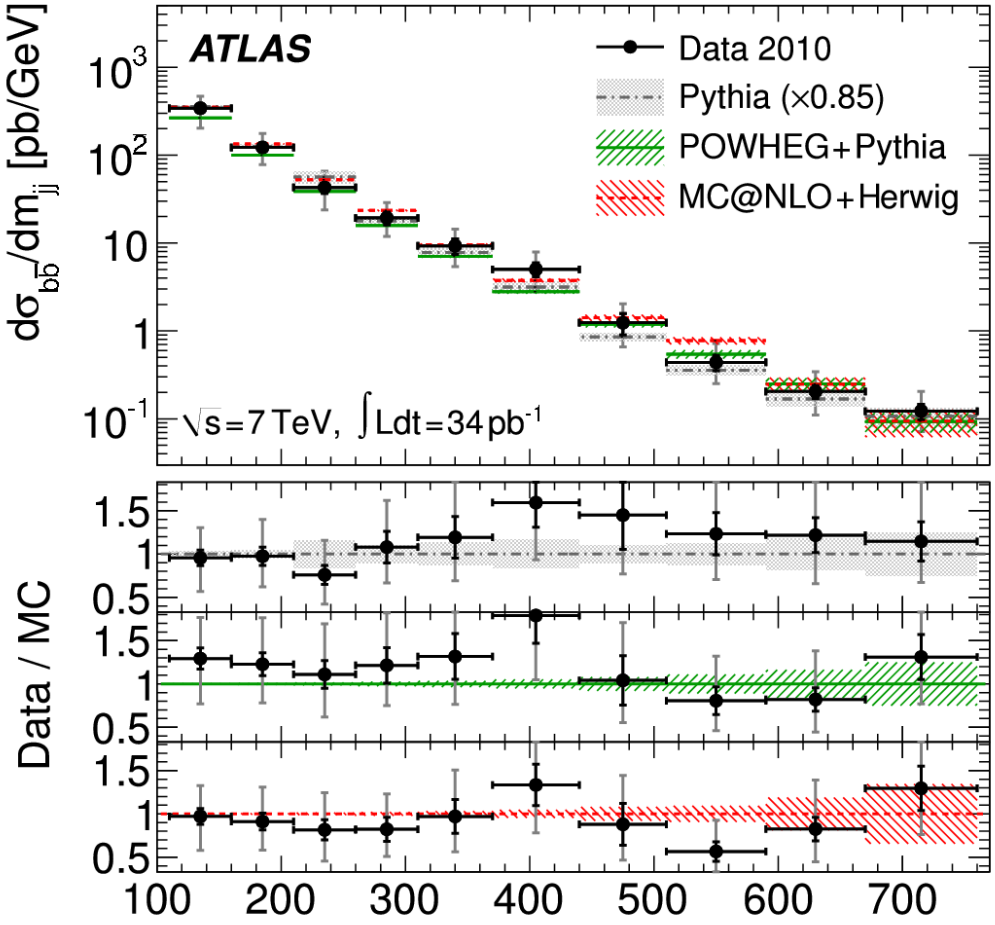
$p^B_T < 40$ GeV , $2 < y^B < 4.5$

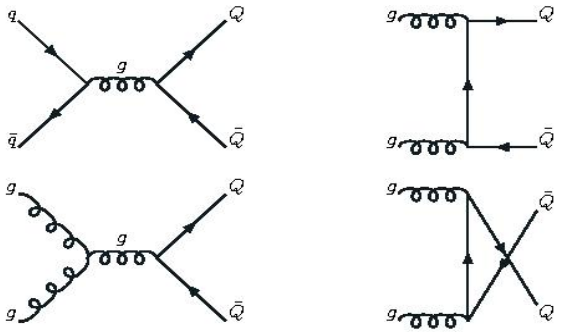
Measured B+/- cross section in the forward region well described by fixed-order plus next-to-leading-log pQCD predictions (within large scale uncertainties)

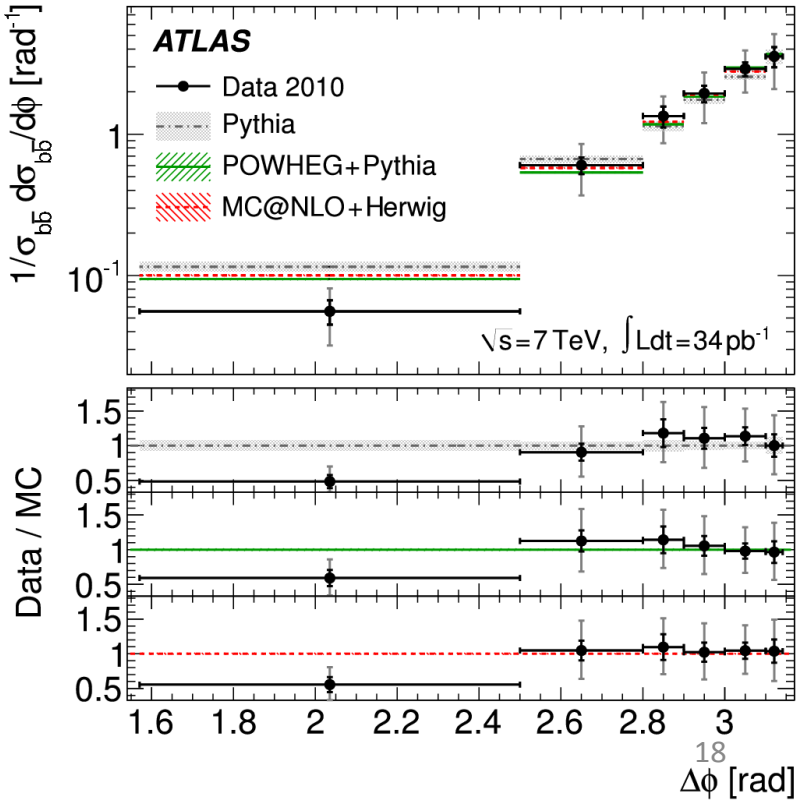
Dijet (bb) production



Eur.Phys.J.C 71 (2011) 1846



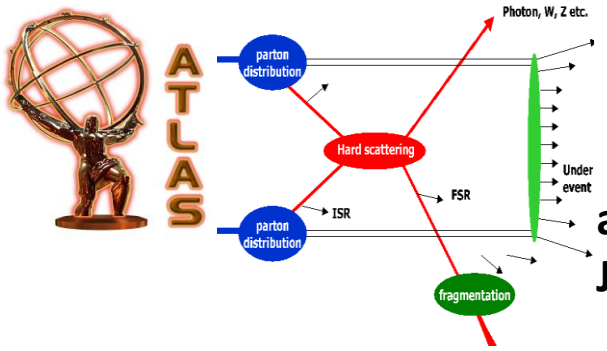




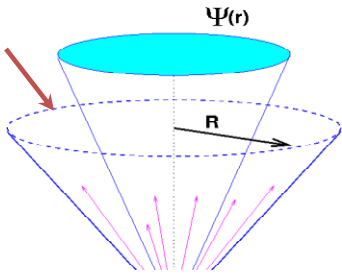
Good agreement observed between data and NLO ME+PS MC predictions

PYTHIA (x 0.85) describes the data

Jet Shapes

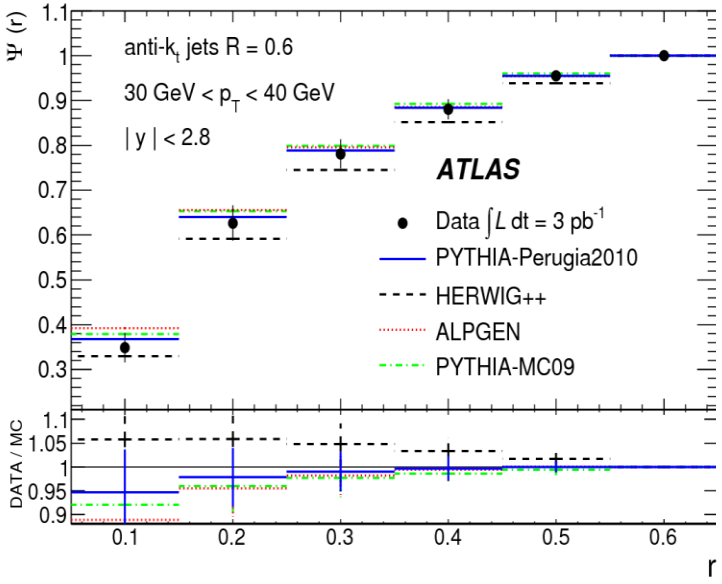


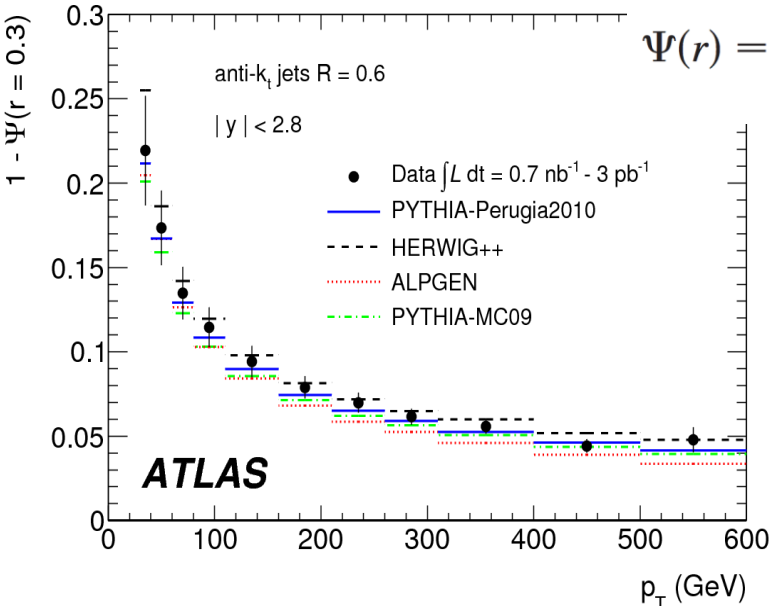
$1-\Psi(r)$



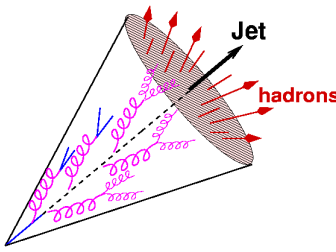
Phys. Rev. D 83, 052003 (2011)
ATL-PHYS-PUB-2011-010

anti-K_T jets R=0.6
Jet p_T > 30 GeV, |Y| < 2.8





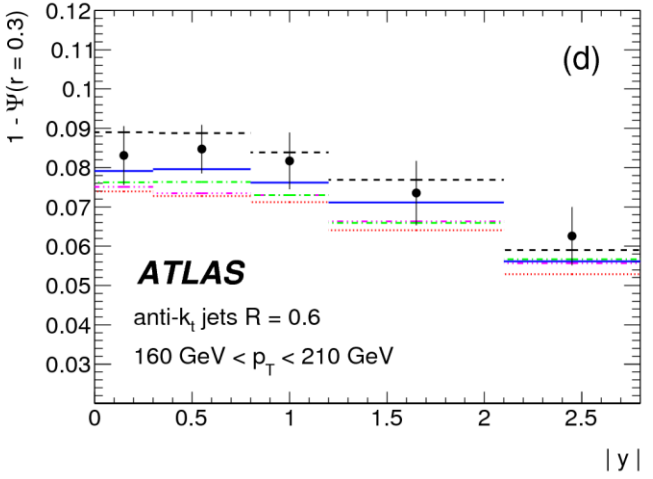
$$\Psi(r) = \frac{1}{N^{\text{jet}}} \sum_{\text{jets}} \frac{p_T(0,r)}{p_T(0,R)}$$



- Jet shape dictated by multi-gluon emission form primary parton
- Test of parton shower models and their implementations
- Sensitive to underlying event structure in the final state

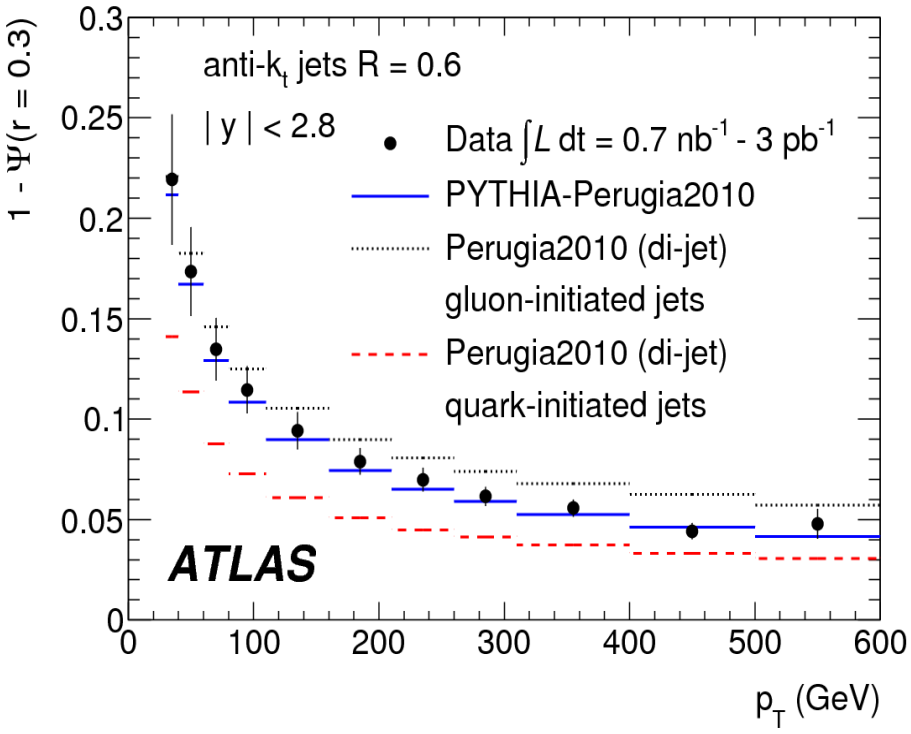
→ Basic step towards the study of boosted final states

Jets get narrower at large p_T and in the forward region



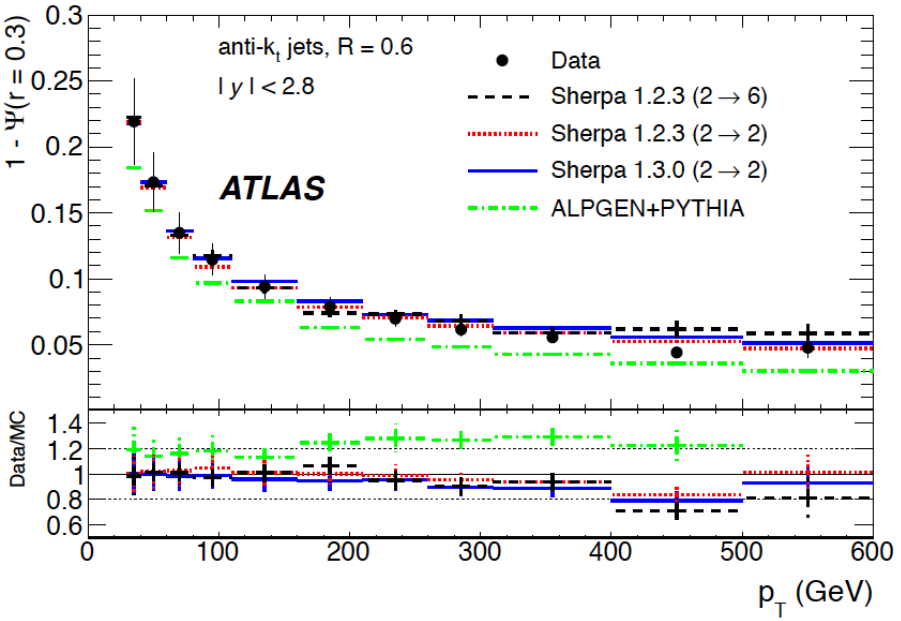
Jet Shapes & MC Modeling

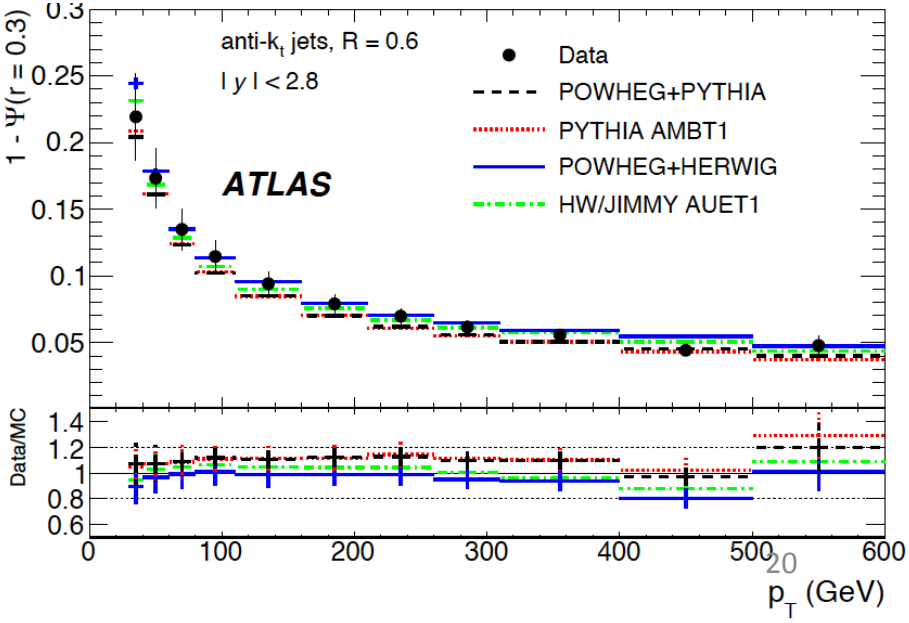
As expected, sensitive to the mixture of quark- and gluon-initiated jets in the final state



Comparison with LO ME + PS & NLO ME + PS

The Jet Shape mainly dictated by the details of the PS and the UE modeling at low P_T





Sub-jets

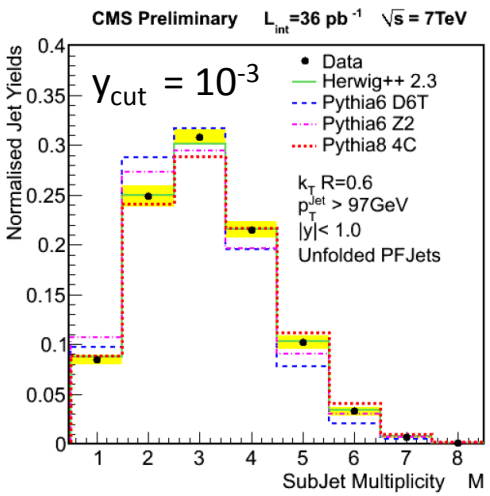
CMS-PAS-QCD-10-041

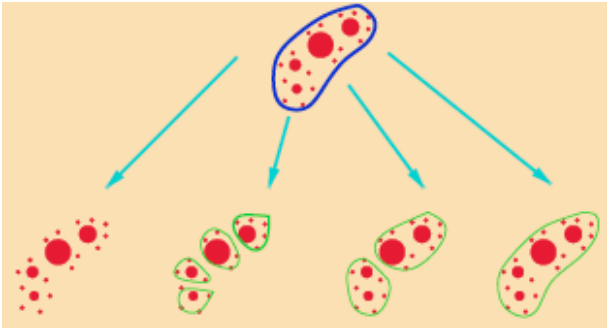
NEW !!

Jets reconstructed with the k_T algorithm (R=0.6)

$$d_{ij} = \min(P^2_{T,i}, P^2_{T,j}) \frac{\Delta R_{ij}^{\ 2}}{R^2}$$

$$d_{cut} = y_{cut} \times P_T^2(jet)$$

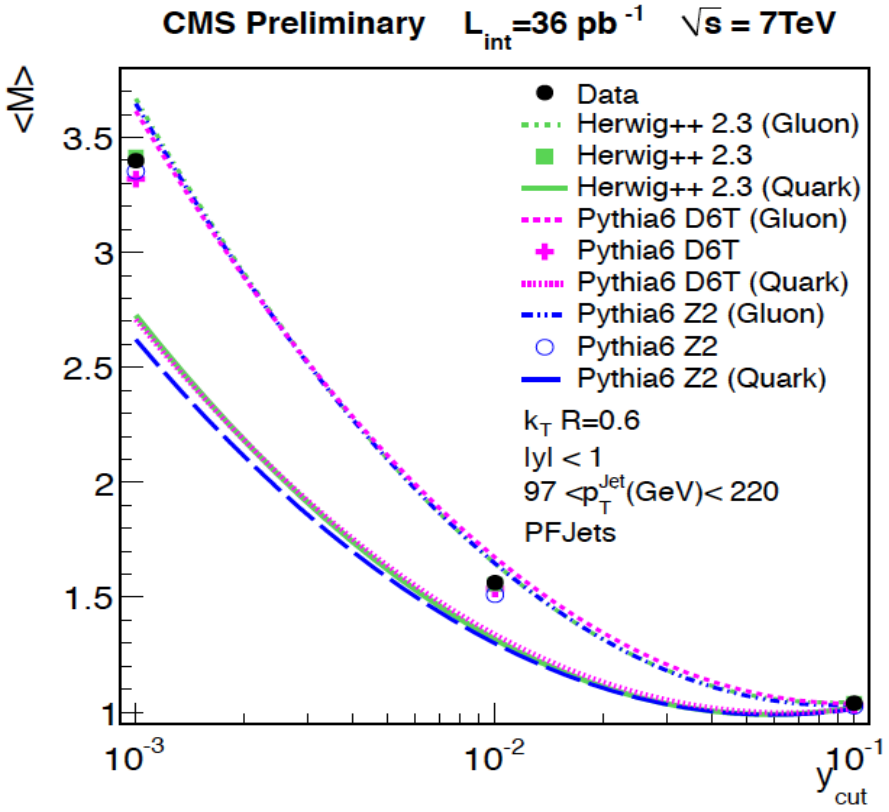


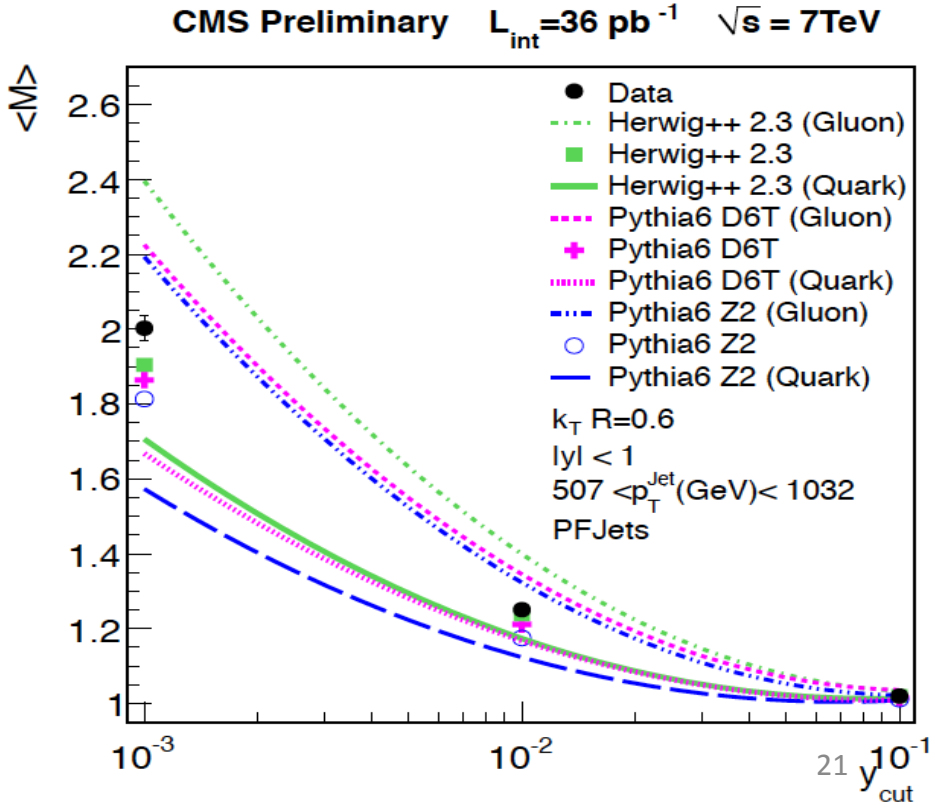


re-running k_T inside the jet

Increasing y_{cut}

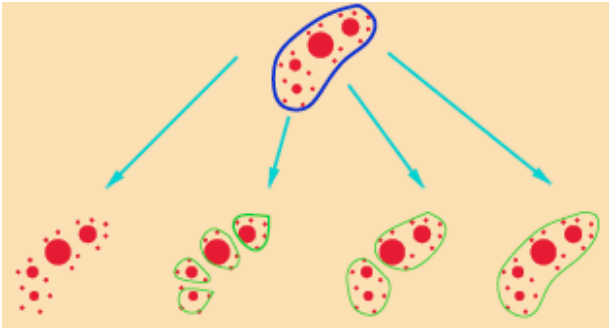
resolution parameter



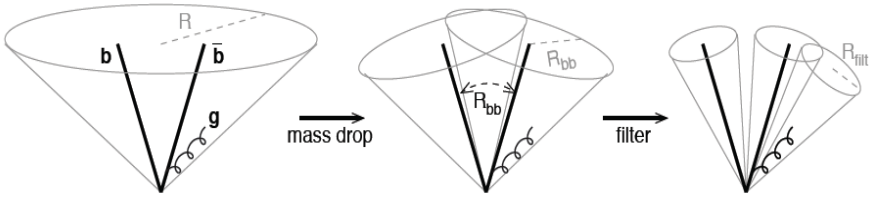


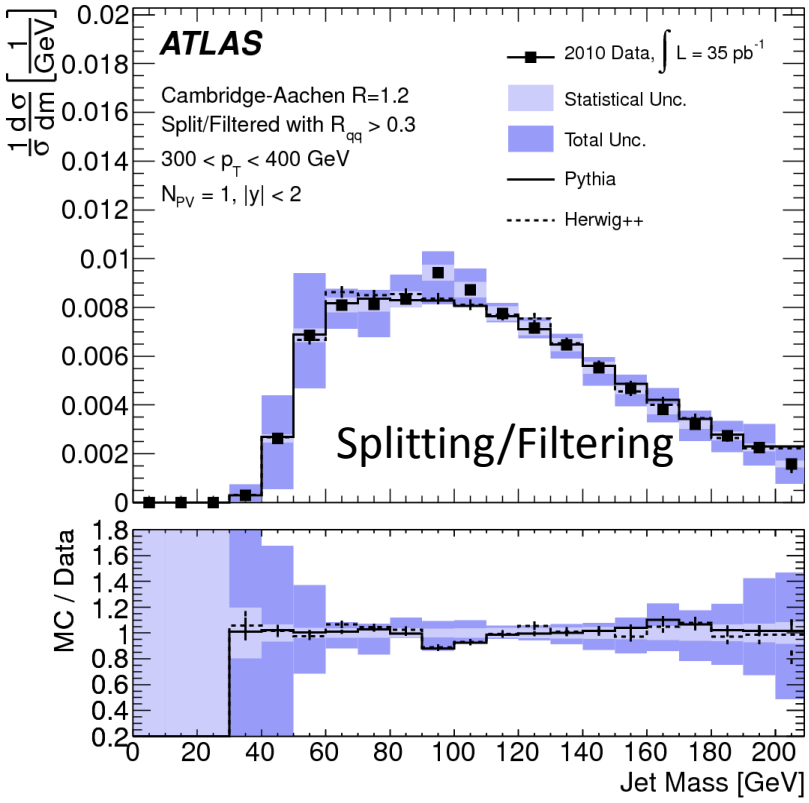
CERN-PH-EP-2012-031
ATLAS-CONF-2012-044

sub-jet structure

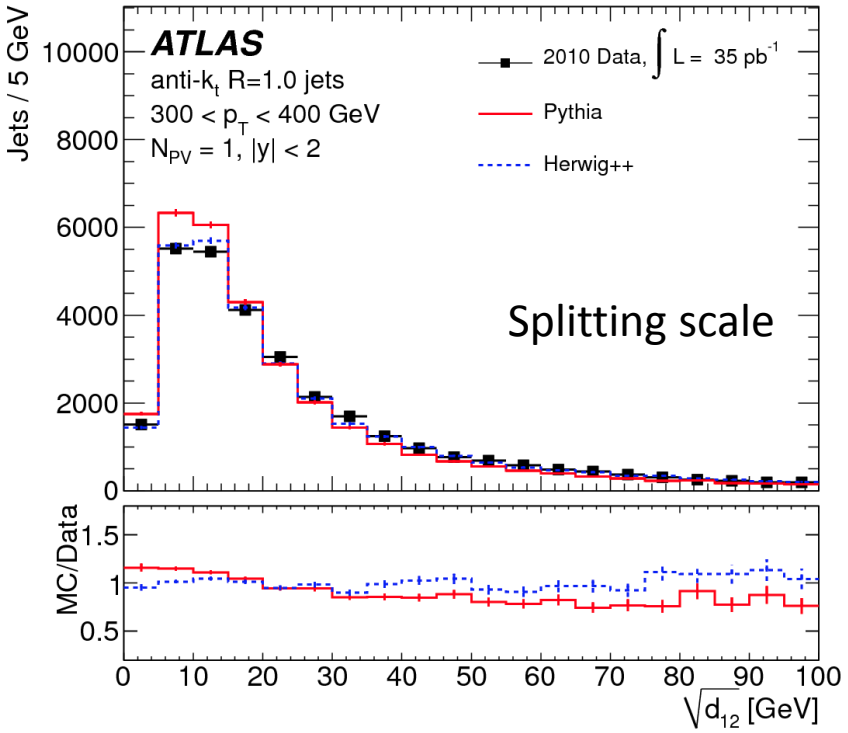


One example of a very active field motivated by the search for the SM Higgs (H→ bb) and heavily boosted new particles decaying into dijets





$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2})\delta R_{12}$$

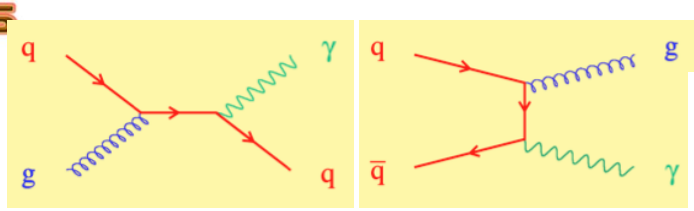


Current studies aim to determine whether the observables/procedures are experimentally robust and whether the underlying background is described by the QCD MC models

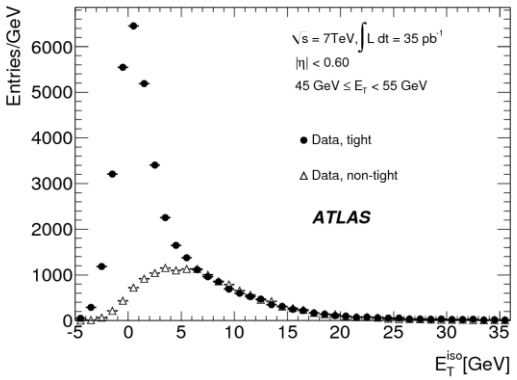
Inclusive photons

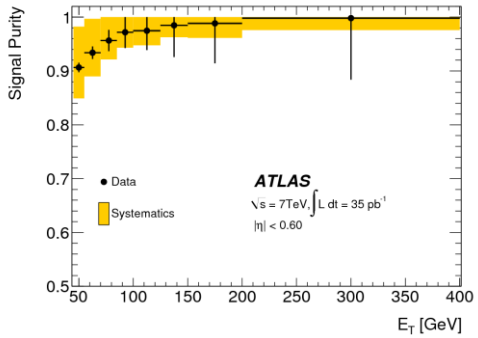
(cross section for isolated photons)

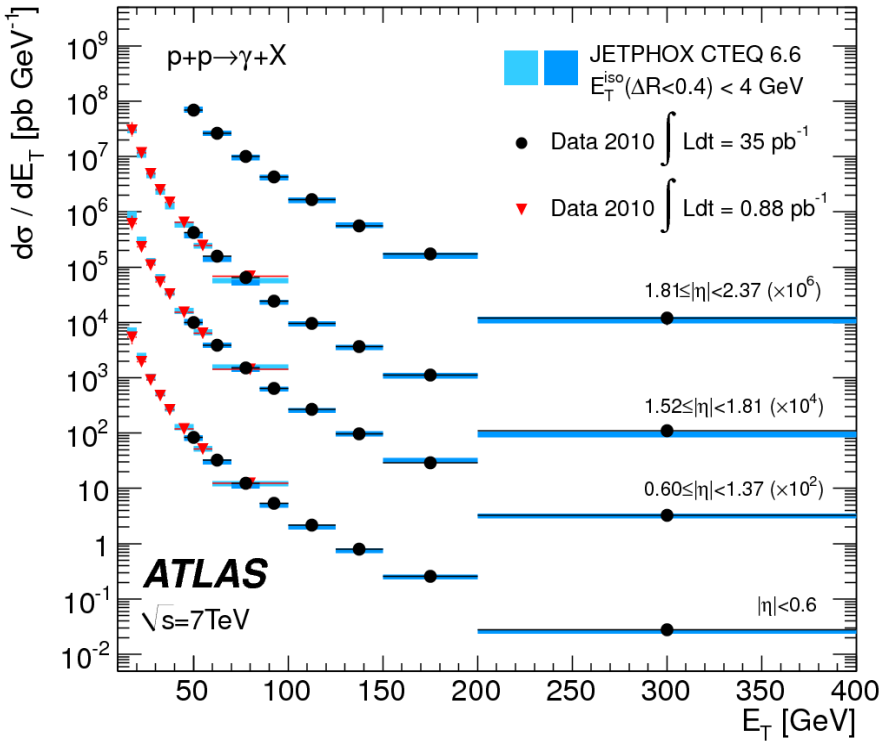
Phys. Lett. B706 (2011) 150-167
Phys. Rev. D83 (2011) 052005

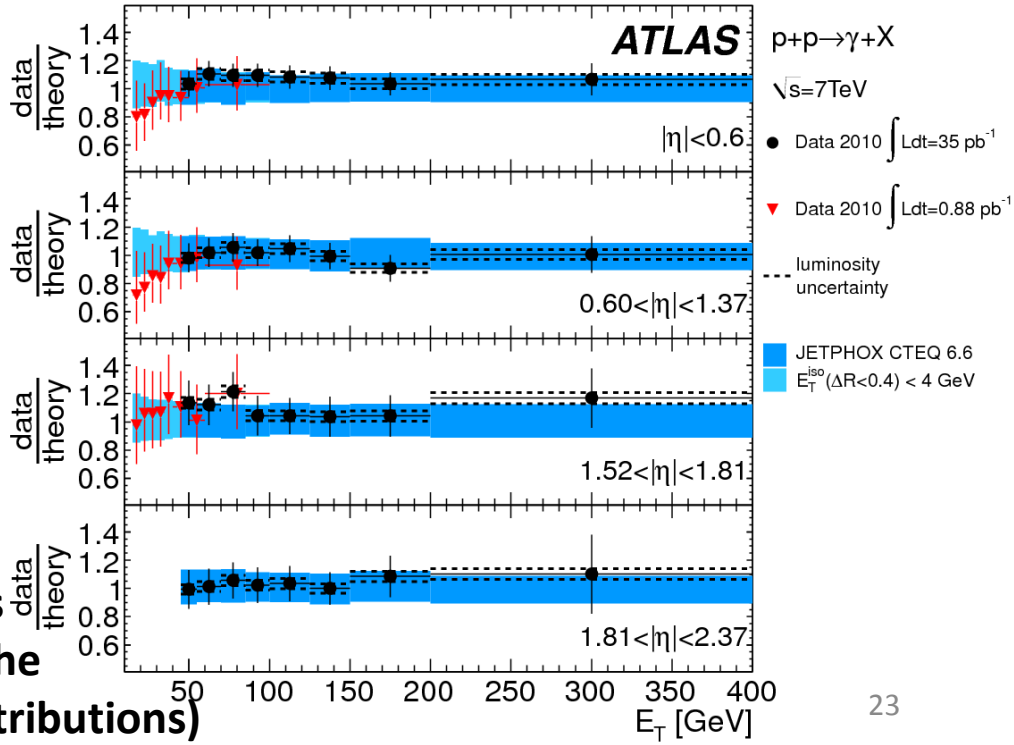


Isolation distribution used to extract the background contributions







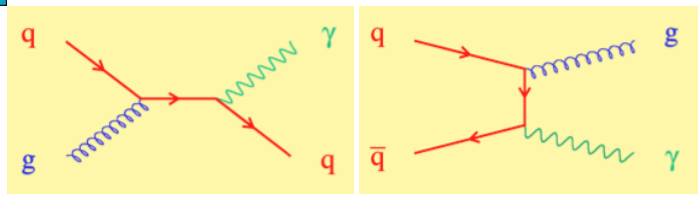


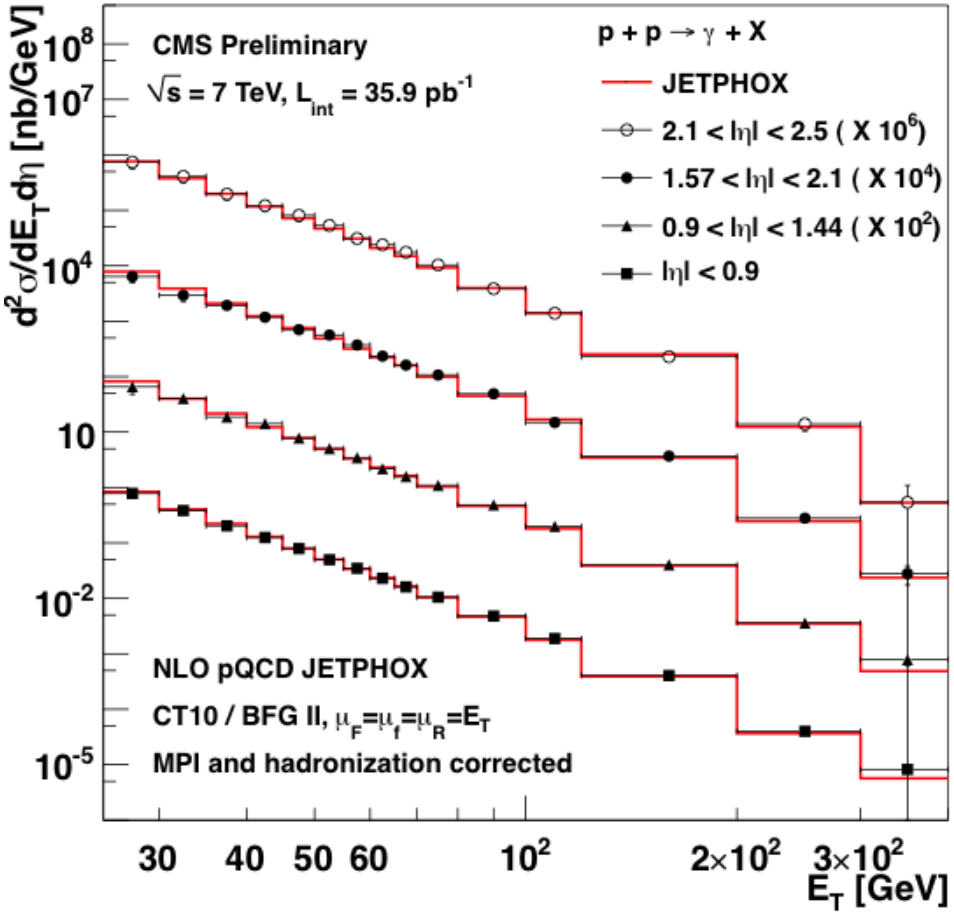
Good agreement with NLO pQCD predictions (at very low E_T^γ predictions are affected by the limited knowledge of the fragmentation contributions)

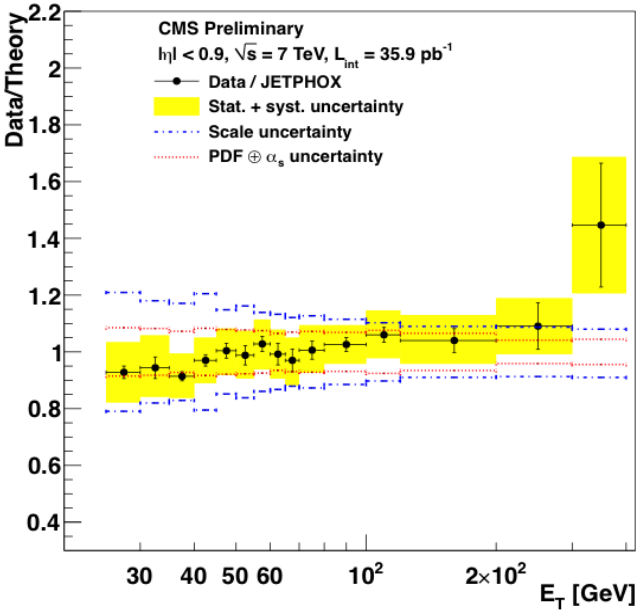
Inclusive photons

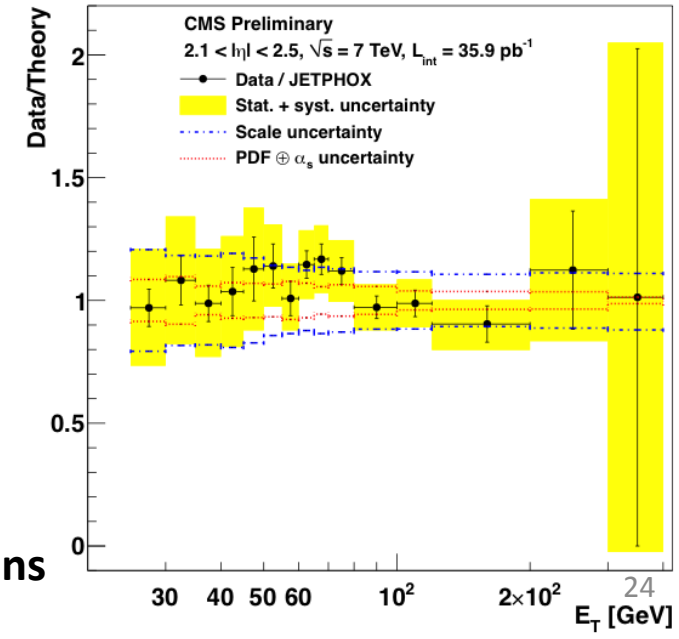
(cross section for isolated photons)

Phys. Rev. Lett. 106 (2011) 082001





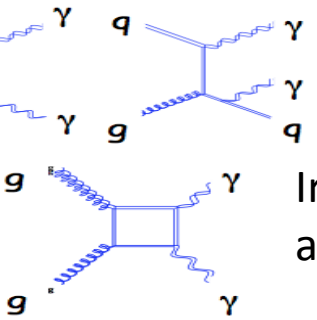




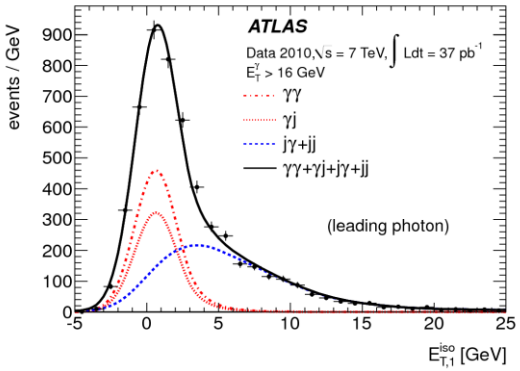
Good agreement between data and NLO pQCD predictions

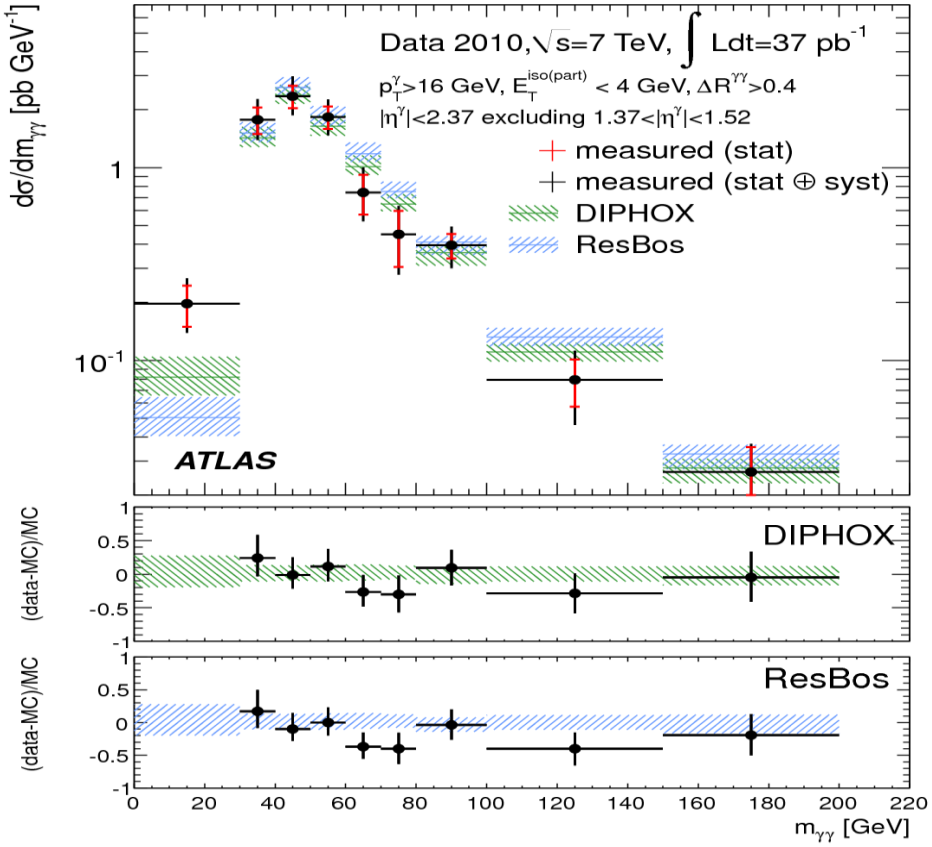
Di-photons

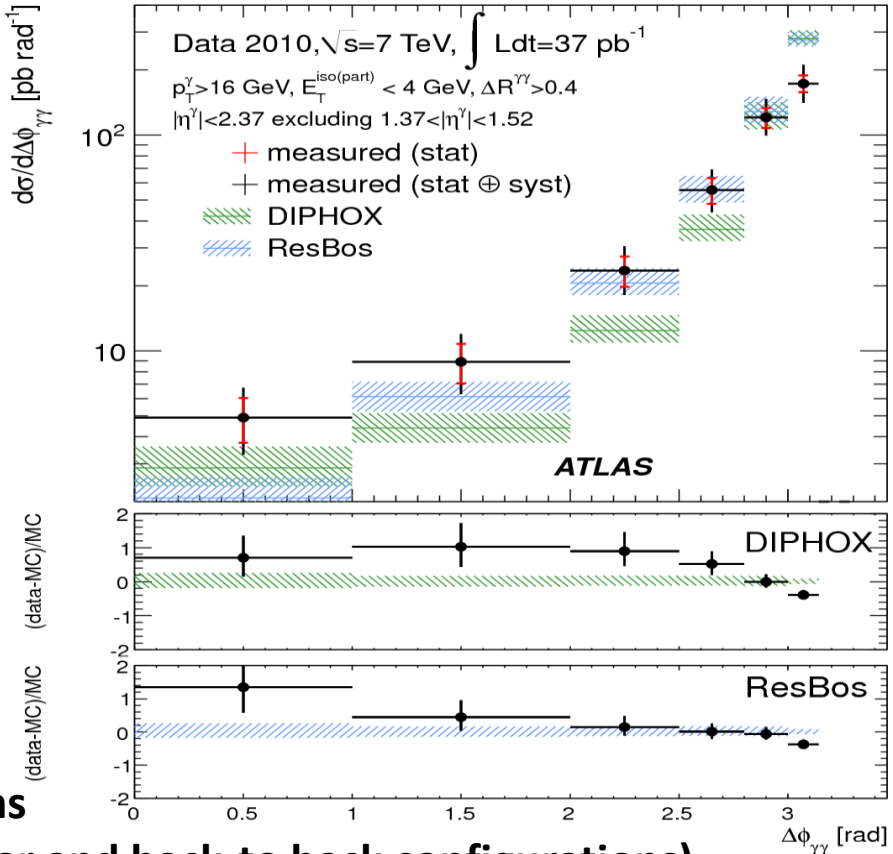
Phys. Rev. D85 (2012) 012003



Irreducible background for SM Higgs and many exotic searches (UED, RS)





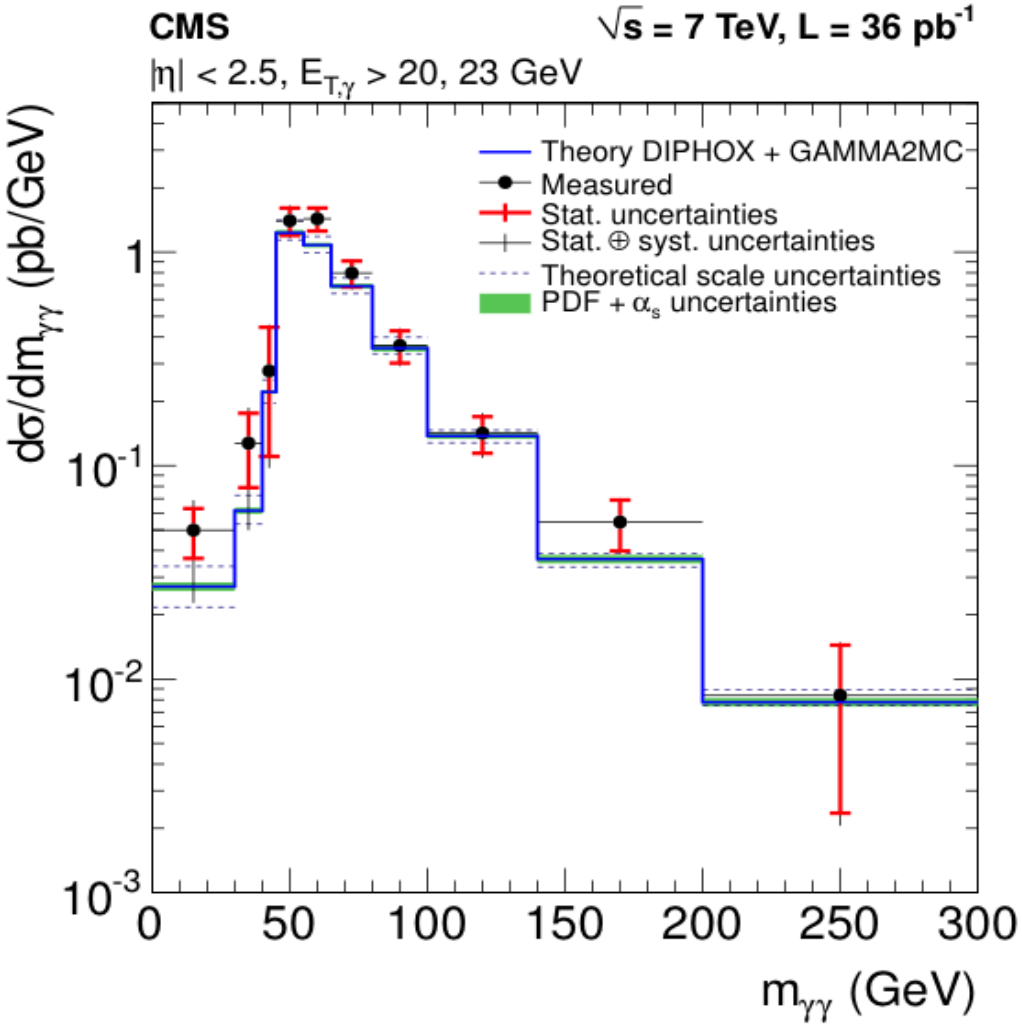


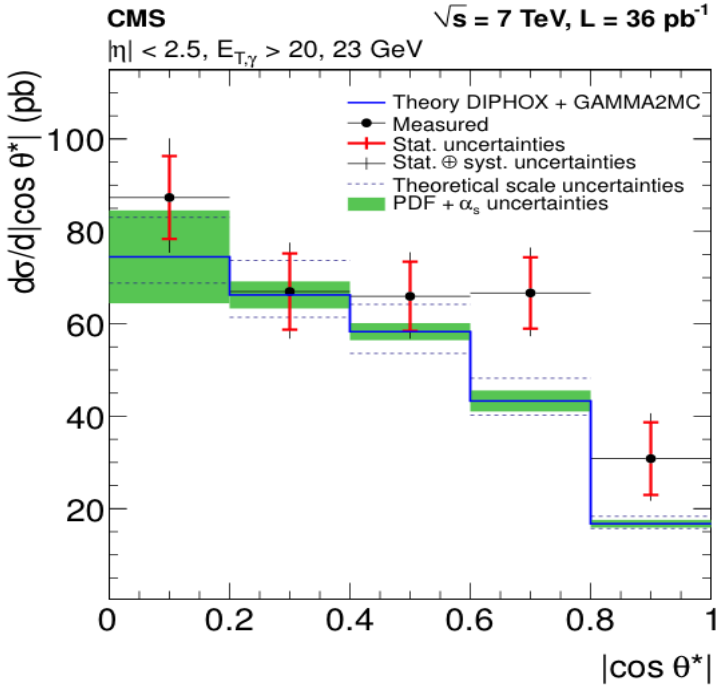
The measured $m_{\gamma\gamma}$ is well described by predictions

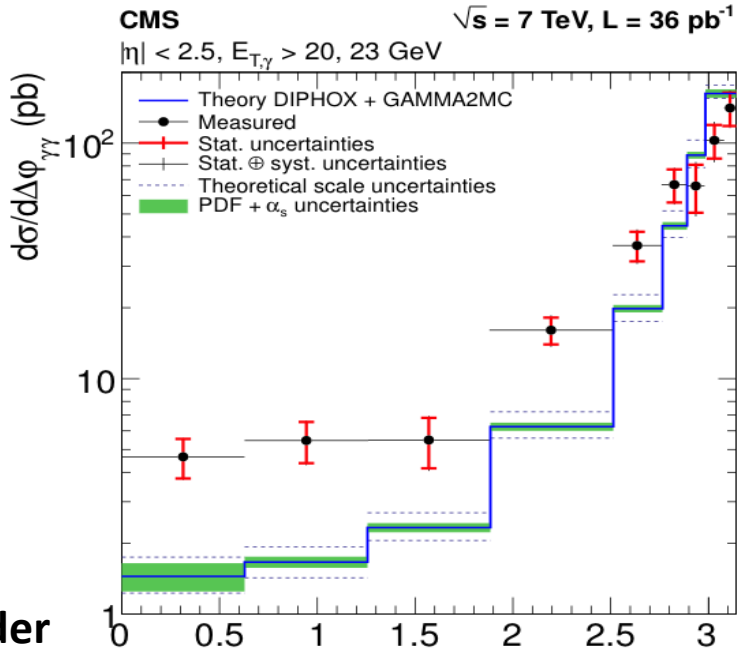
The discrepancies in the $\Delta\phi^{\gamma\gamma}$ distribution (collinear and back-to back configurations) indicates the importance/need for higher order pQCD terms

JHEP 01 (2012) 133

Di-photons





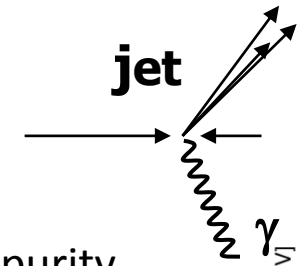


Good description of the invariant mass distribution

The angular distributions evidence the lack of higher order contributions & proper understanding of the fragmentation processes.

γ+jet

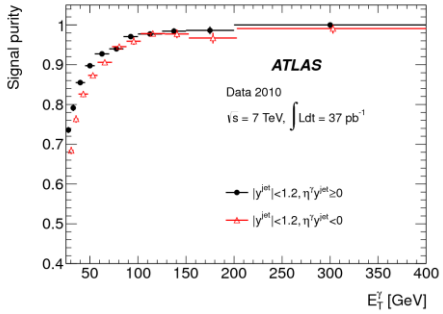
NEW !! CERN-PH-EP-2012-009

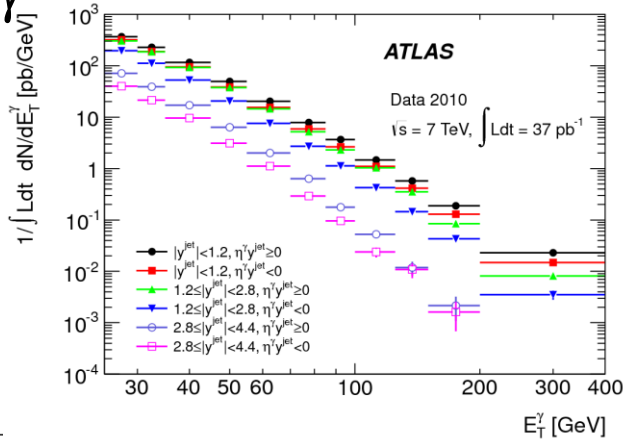


Jet $p_T > 20$ GeV
photon $E_T > 25$ GeV

Measured cross sections with
$\eta^\gamma y^{jet} > 0$ & $\eta^\gamma y^{jet} < 0$

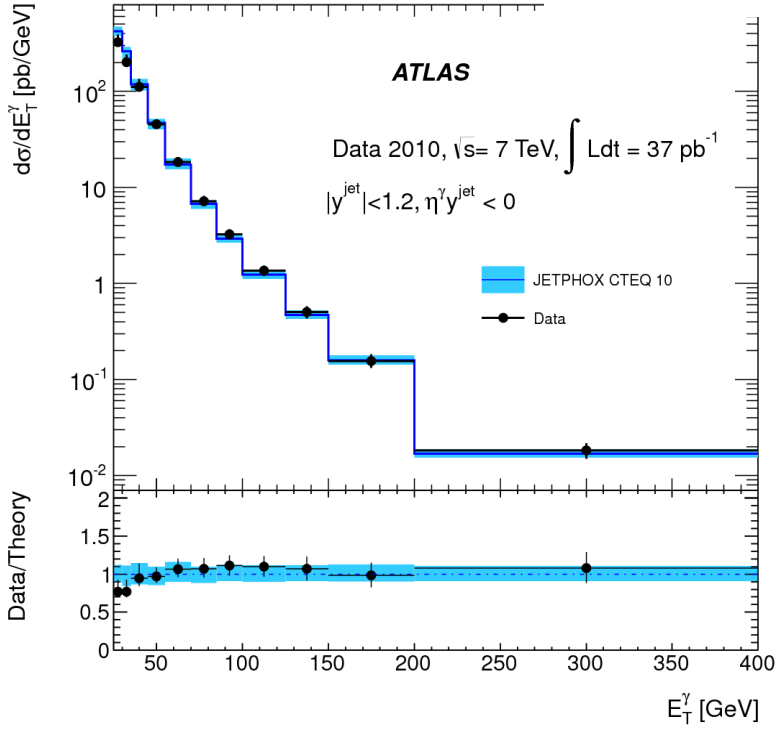
photon purity



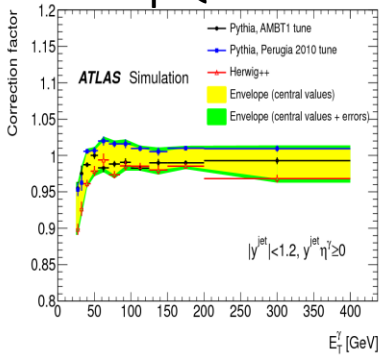


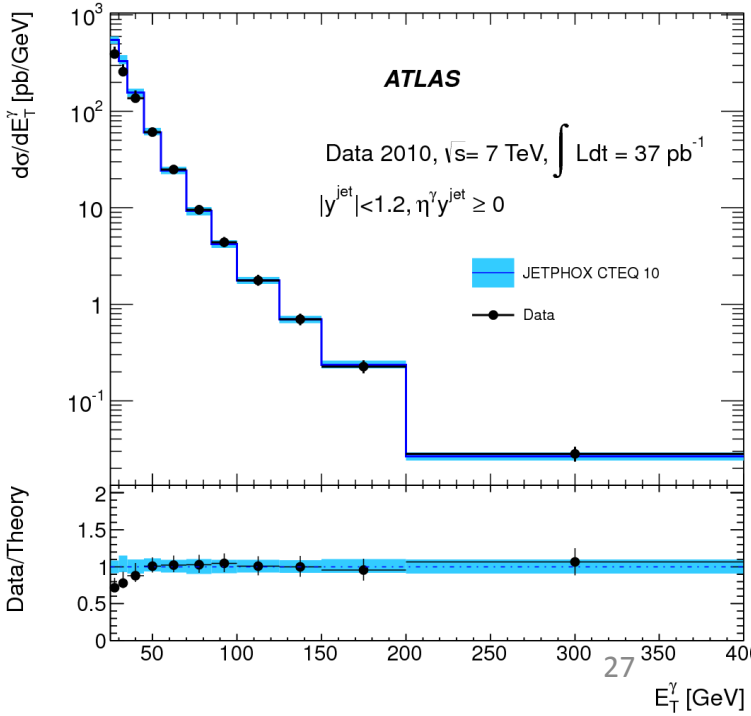
Fair agreement with NLO pQCD except at very low E_T^γ (< 45 GeV)

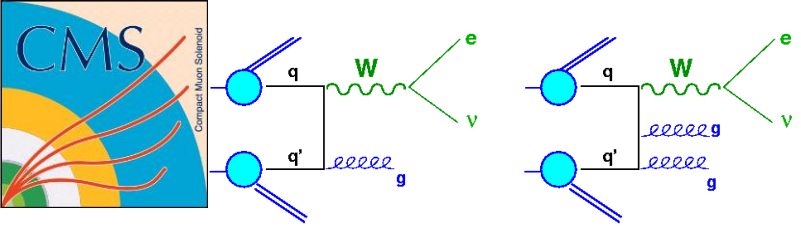
difficult region where photon purity decreases and non-pQCD corrections are sizable



non-pQCD







W/Z+jets

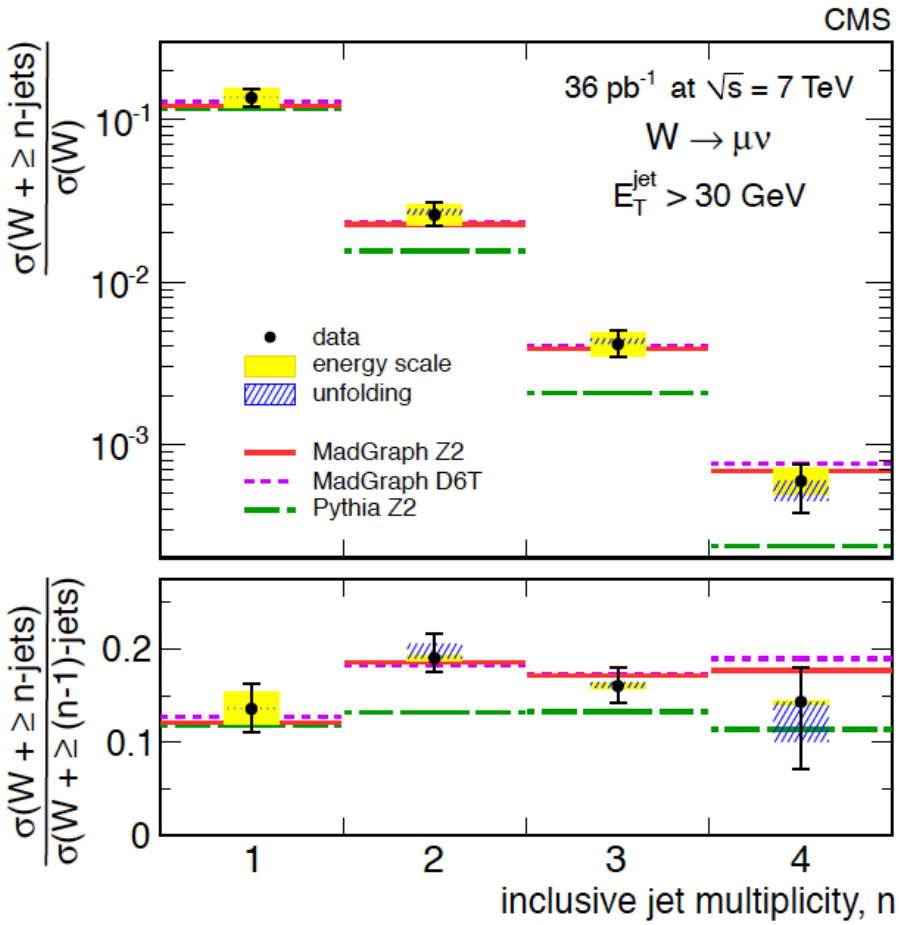
J. High Energy Phys. 01 (2012) 010

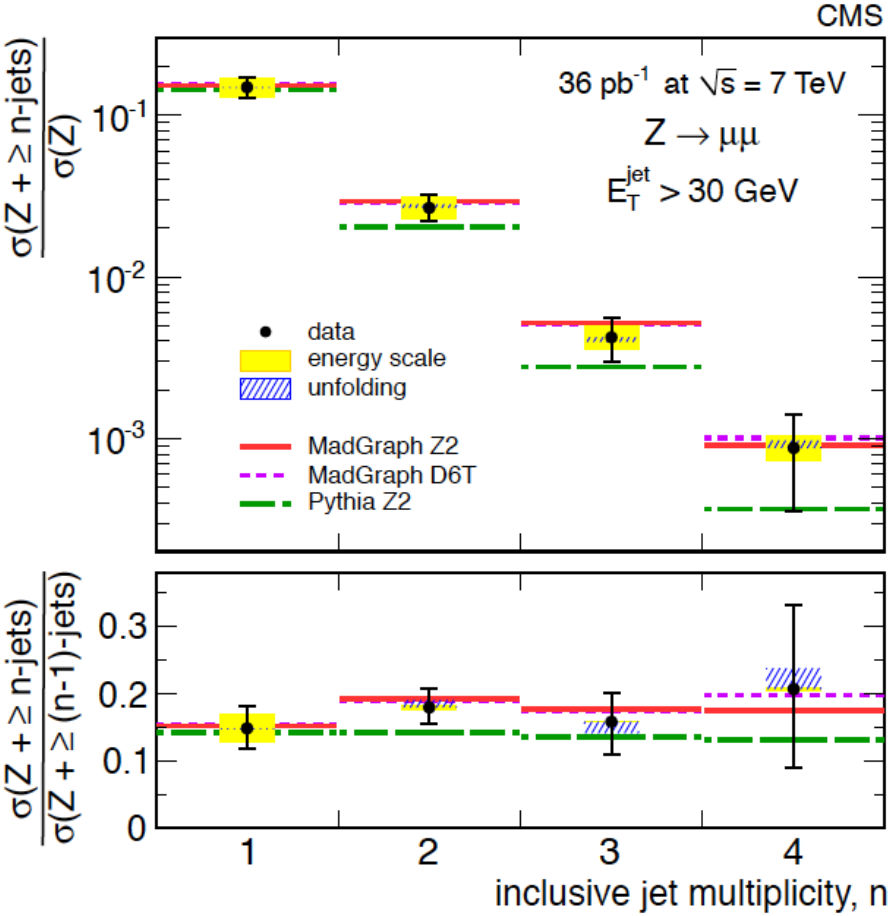
(electron and muon channels)

W/Z+jets backgrounds in searches for new physics

→Precise measurements are mandatory

→ Fundamental tests of LO ME + PS predictions





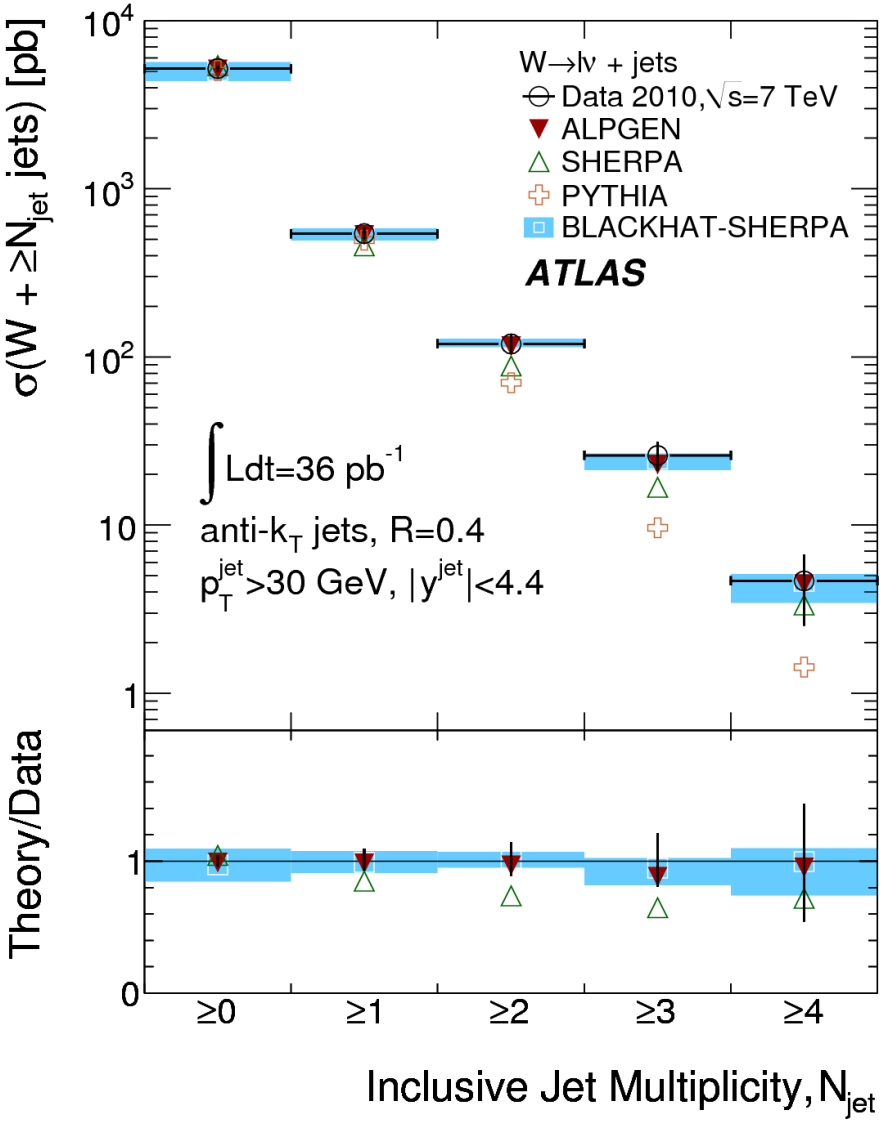
MADGRAPH describes the data well

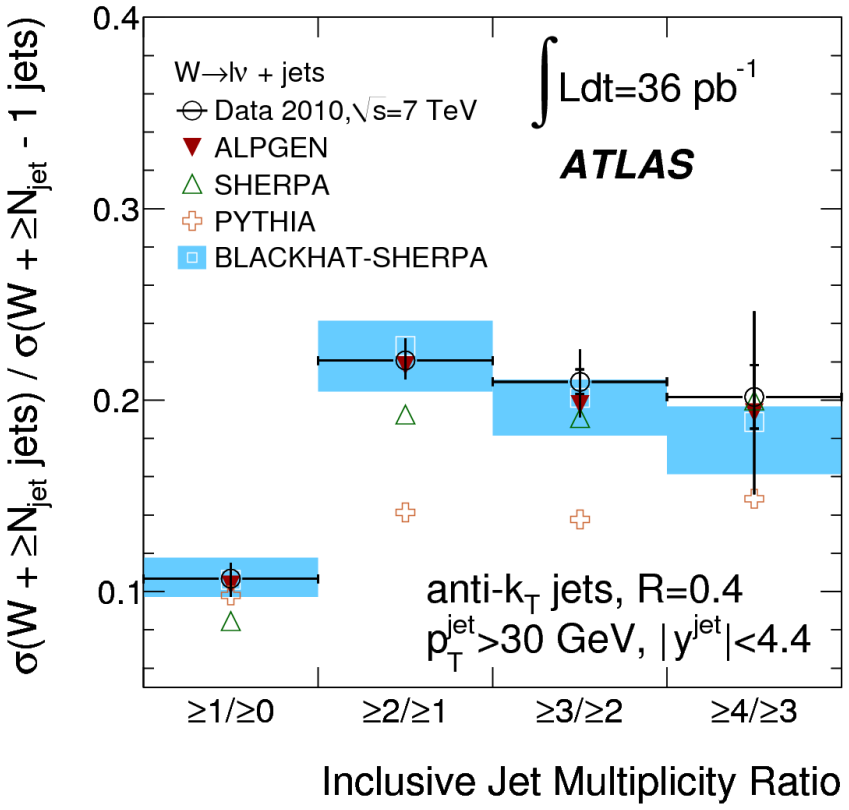
PYTHIA (as expected) underestimates the cross sections at large jet multiplicities

W+jets

Phys. Rev. D85 (2012) 092002

electron/muon combined





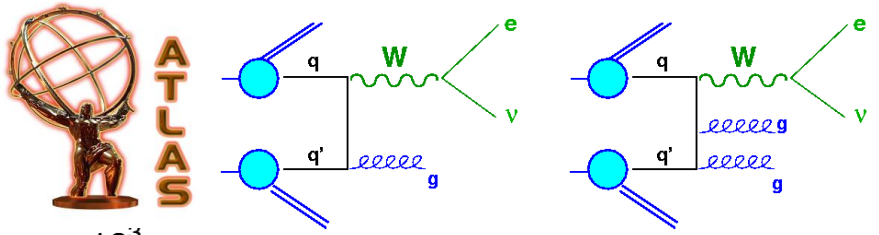
Data well described by NLO pQCD predictions

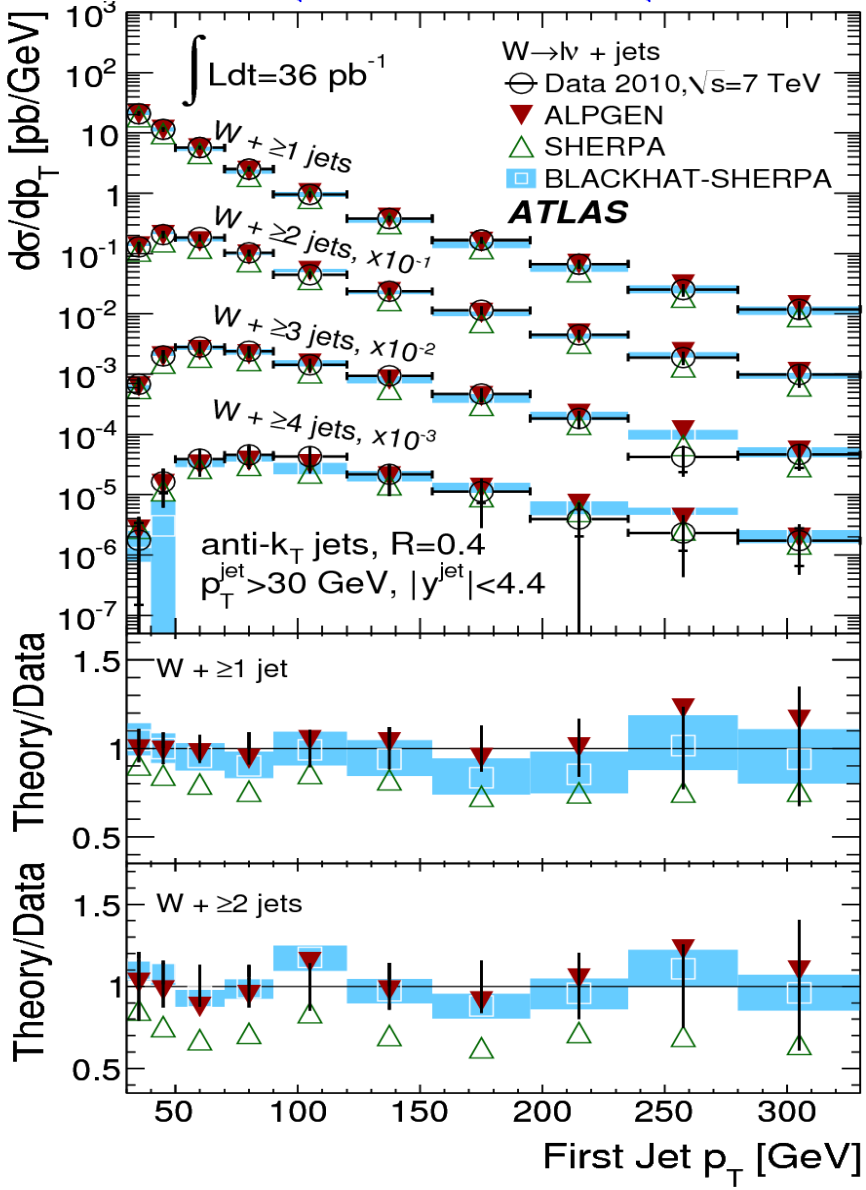
LO ME + PS (ALPGEN) describes de data well (followed closely by SHERPA predictions)

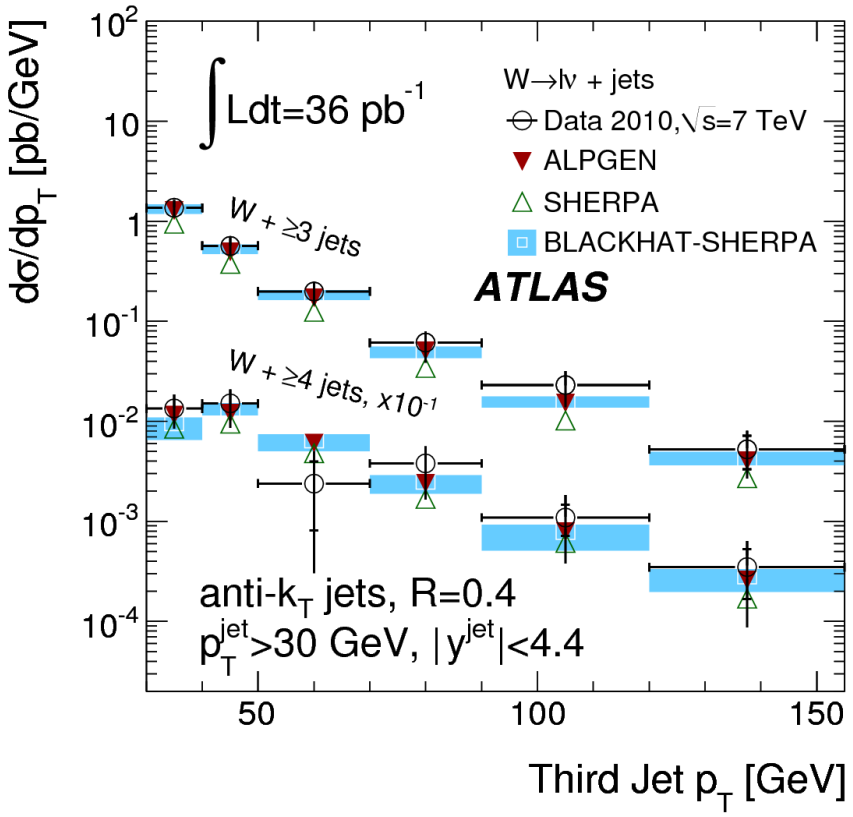
Again, PYTHIA fails at large jet multiplicities

W+jets

Phys. Rev. D85 (2012) 092002







Very good description of the different Jet p_T distributions by NLO pQCD and LO ME + PS (ALPGEN)

Non trivial test of the ME - PS implementation & matching procedures built inside the MCs

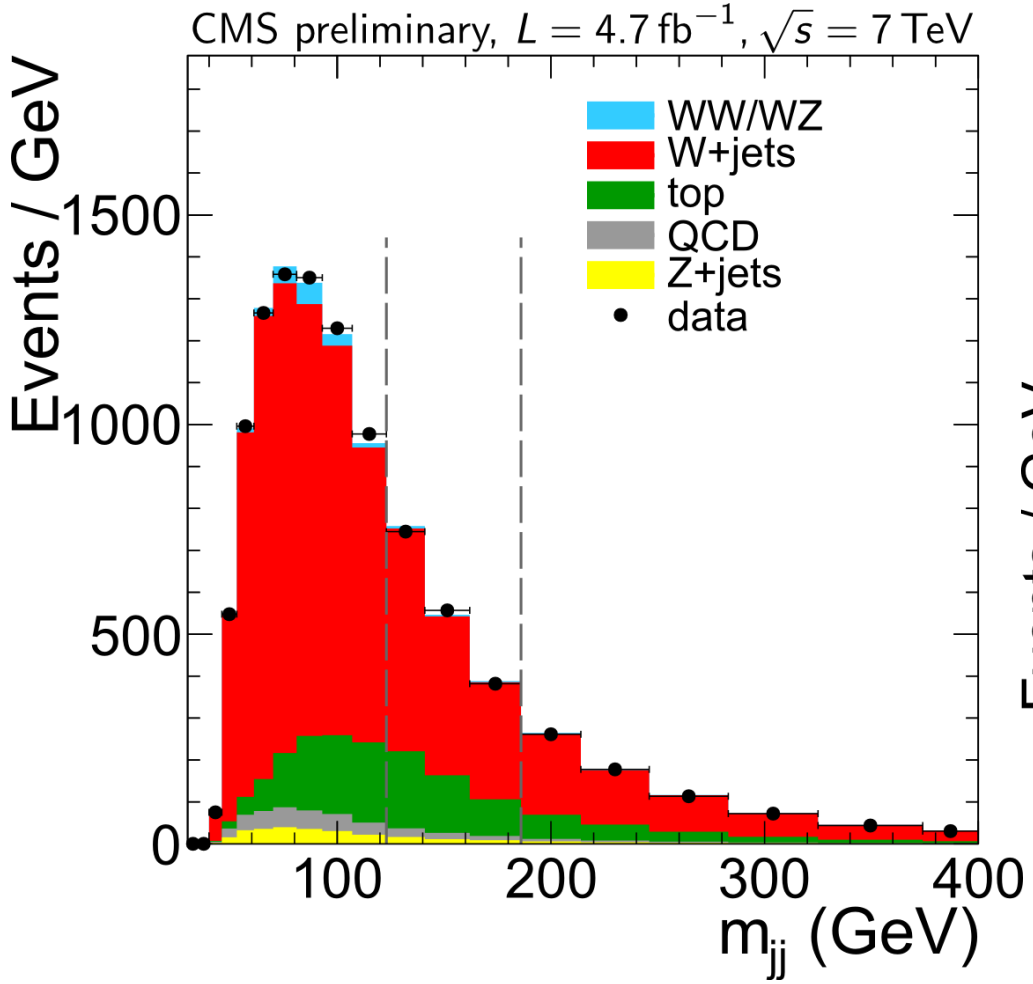
→ Input to future MC tunes

NEW !!

M_{jj} in W+2jets

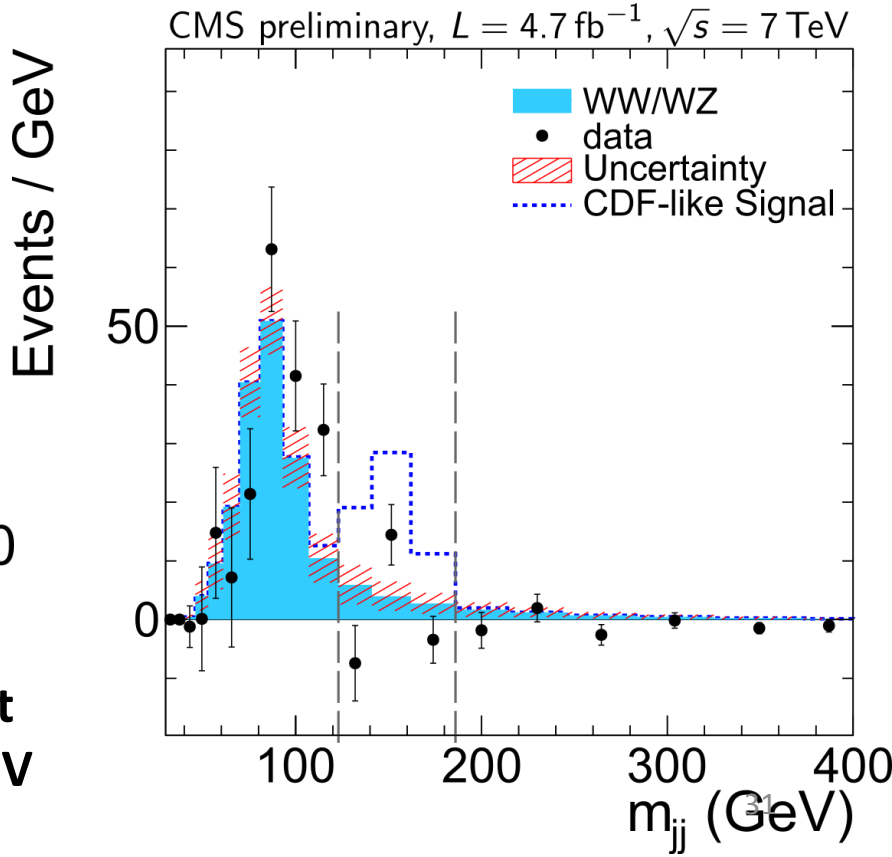
CMS-PAS-EWK-11-017

4.7 fb^{-1}



Dedicated search motivated by previous CDF results (not confirmed by D0)

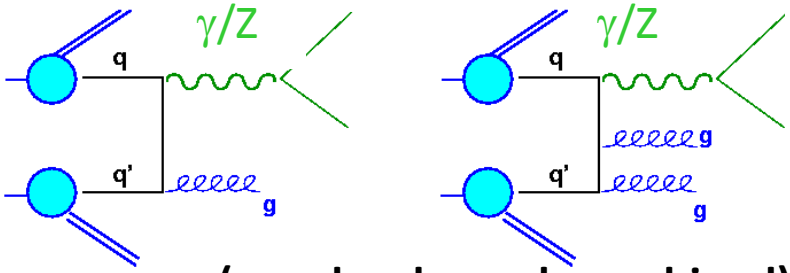
Phys. Rev. Lett. **106** 171801 (2011)
Phys. Rev. Lett. **107** 011804 (2011)



No evidence for a resonant enhancement in the dijet mass distribution near 150 GeV

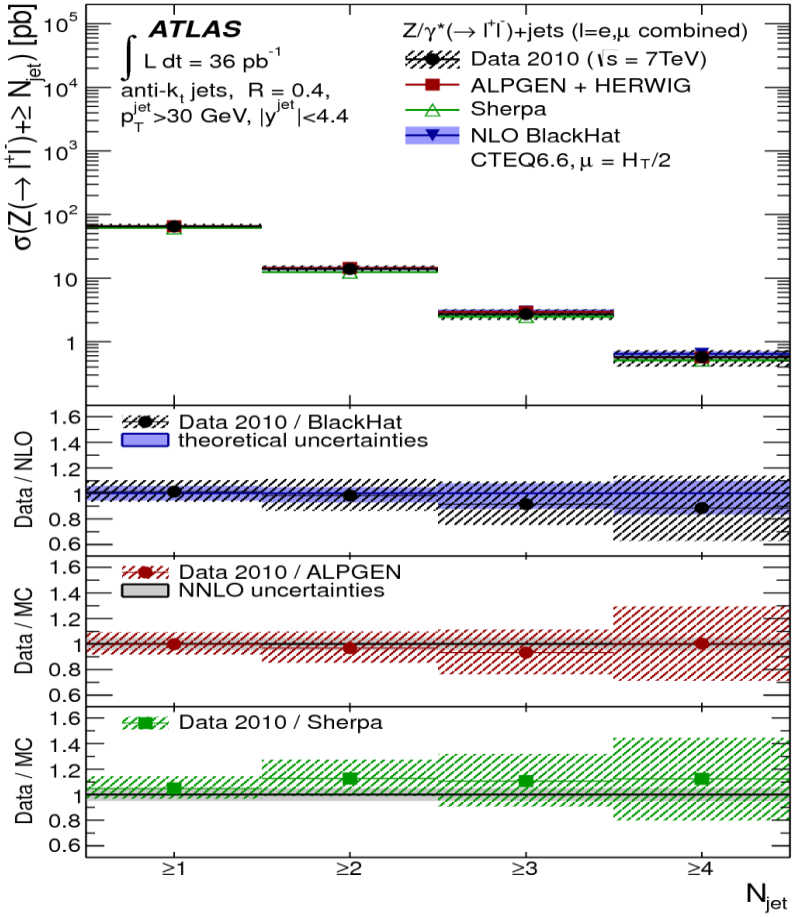
Z+jets

Phys. Rev. D 85, 032009 (2012)



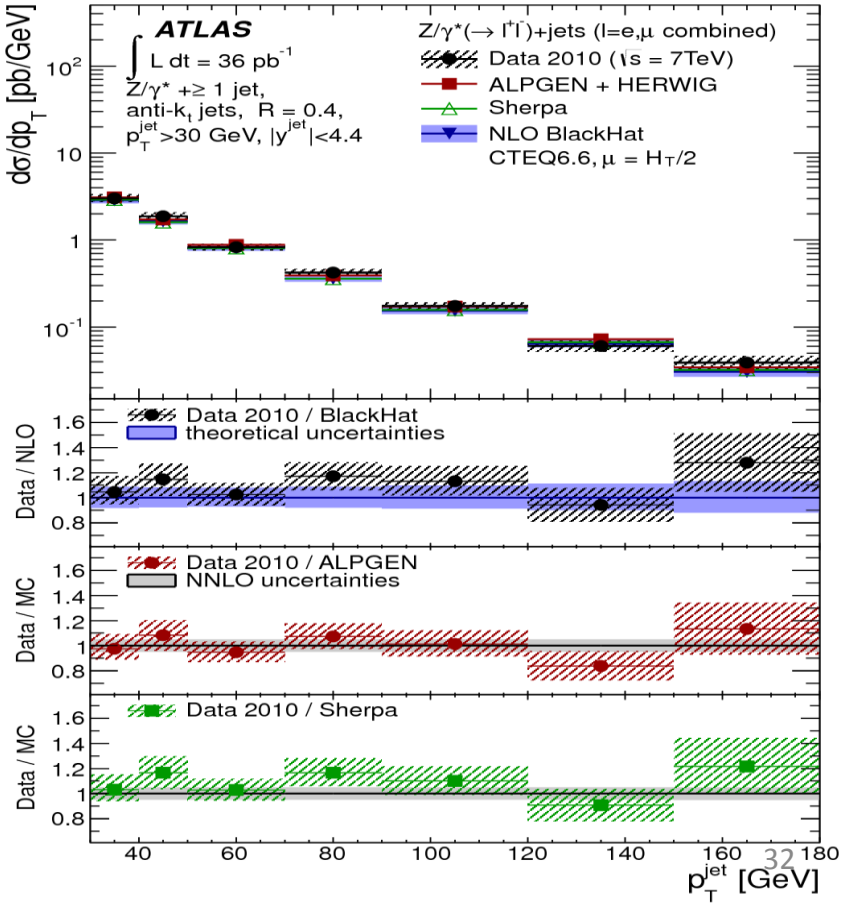
Z (→ νν)+jets irreducible background
In searches for SUSY, LED, etc….

(e and μ channels combined)



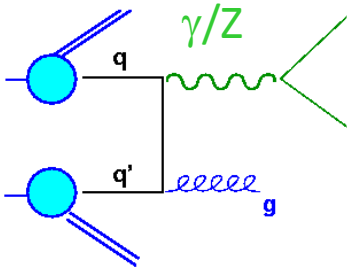
Data well described by NLO pQCD and ME + PS (ALPGEN/SHERPA) predictions

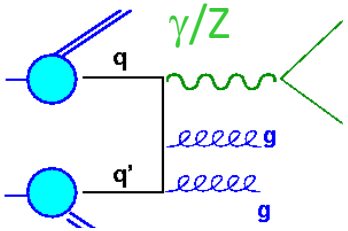
Z (→ ll)+jets fundamental SM measurement…
→ Very clean samples with no missing E_T



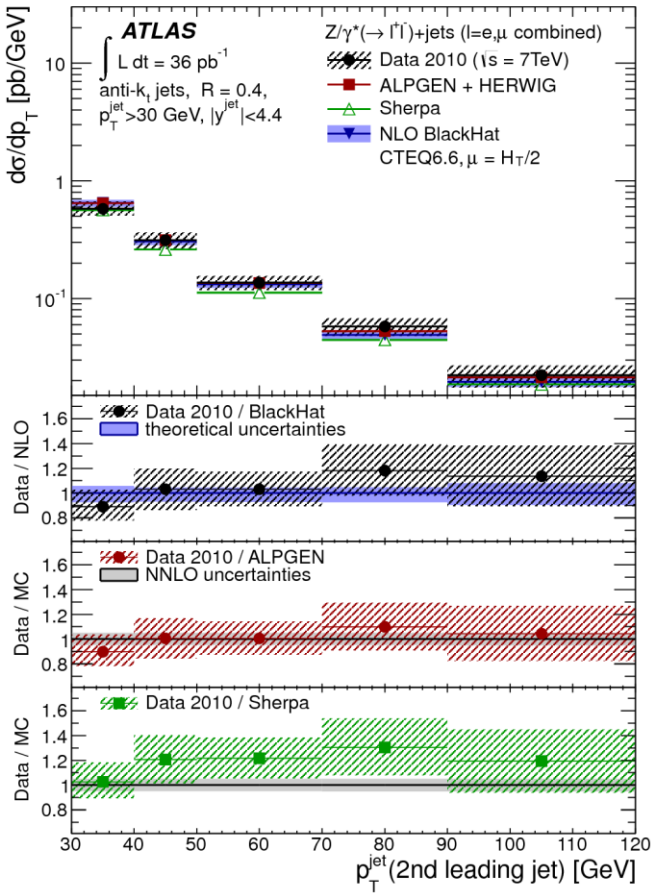
Z+jets

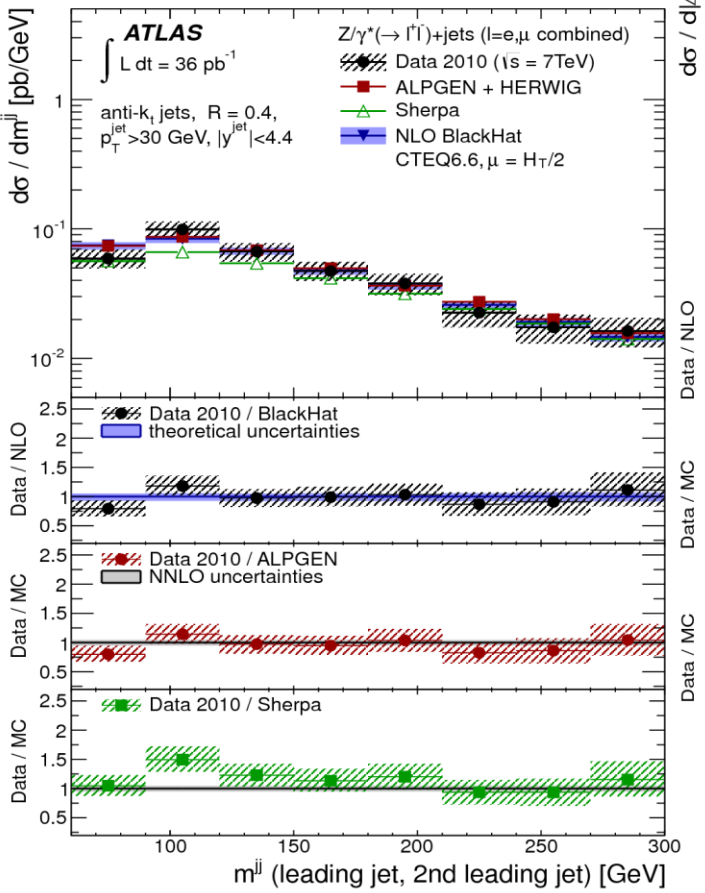
Phys. Rev. D 85, 032009 (2012)

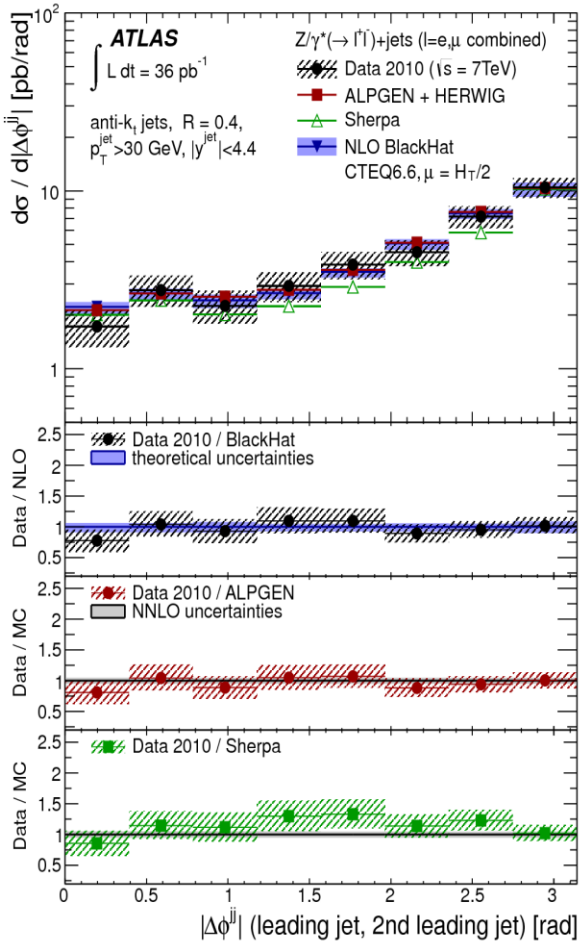




Z + 2jets topologies well described by QCD theory







Data sensitive to details of the LO ME+PS implementation (room for improvement in SHERPA)

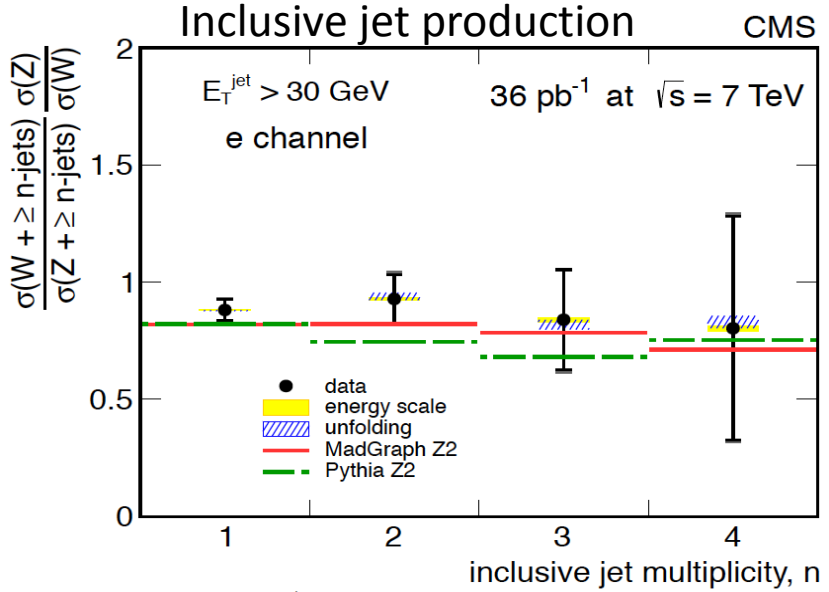
Several groups very active using the data to tune the MCs

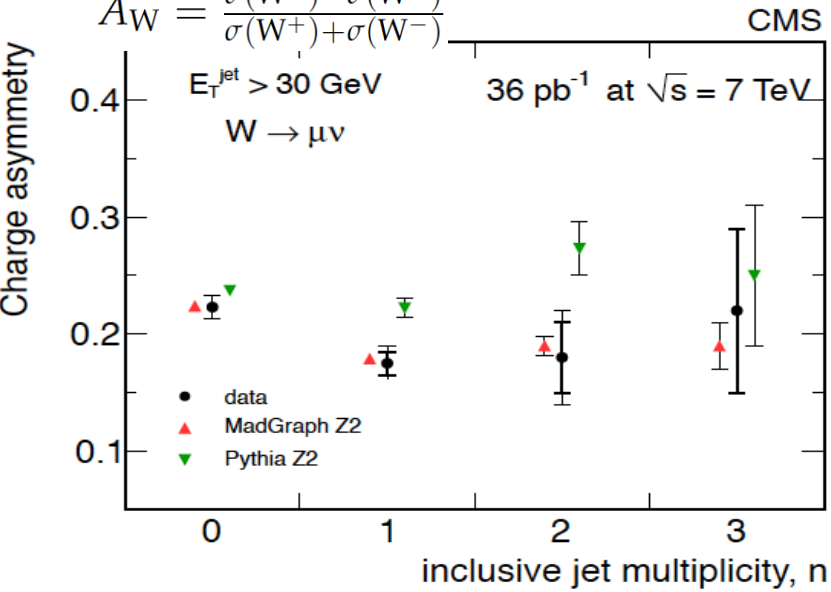
J. High Energy Phys. 01 (2012) 010

Phys. Lett.B 708 (2012) 221-240

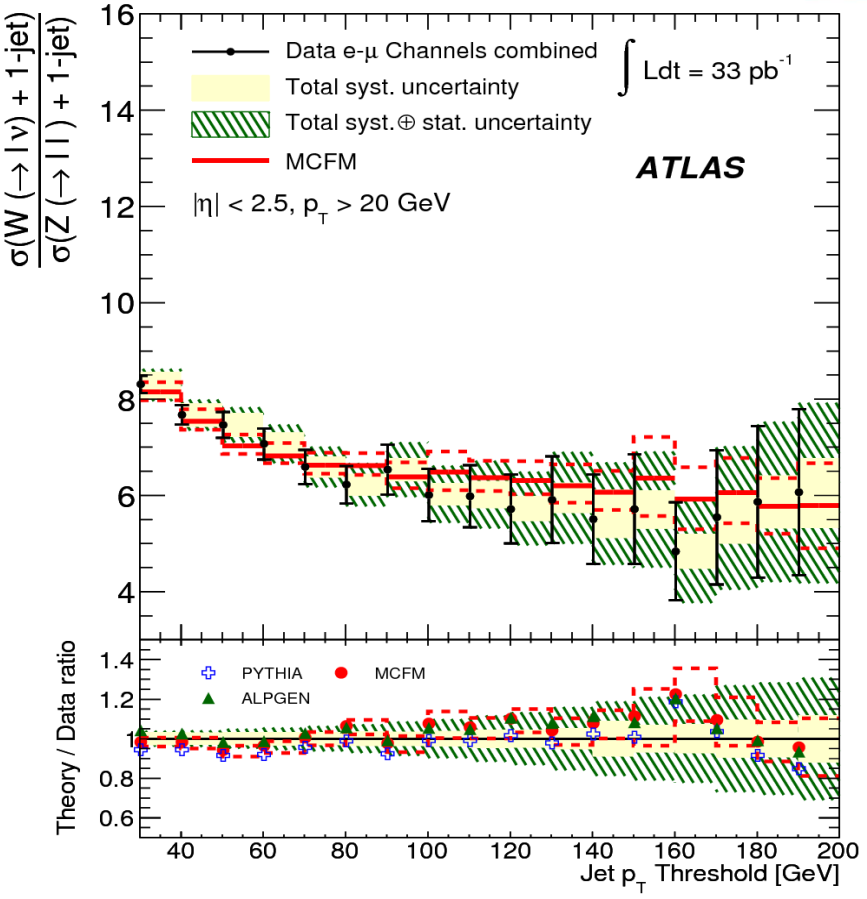
W+jets/Z+jets ratios

Inclusive jet production



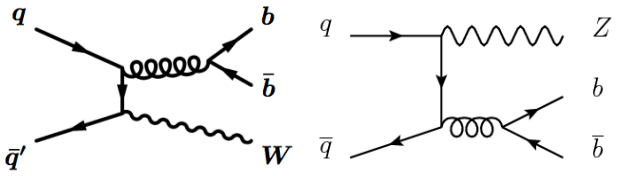


Exclusive one jet production

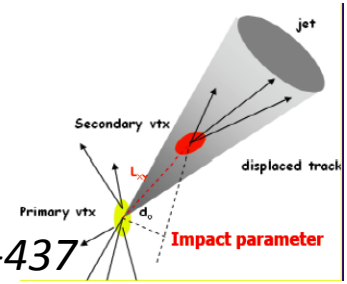


Ratios cancel out theoretical and experimental systematic uncertainties

Sensitive to the potential presence of new physics entering in one of the channels



W/Z + b-jets

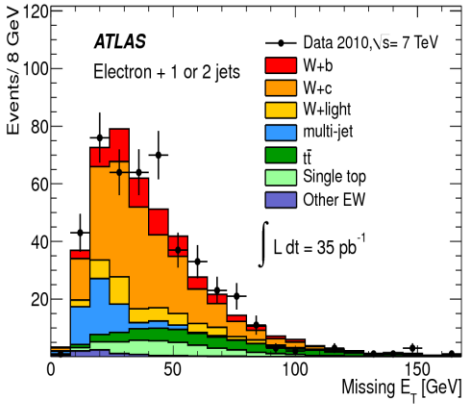


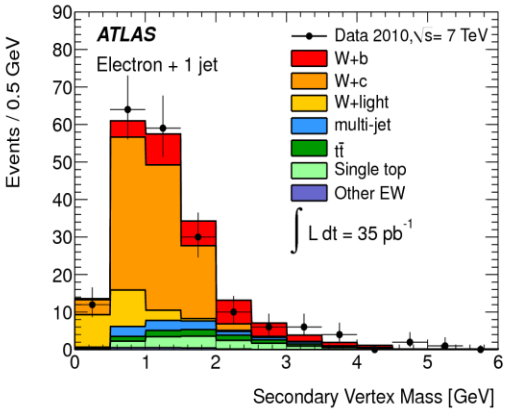
Important backgrounds to Higgs and SUSY

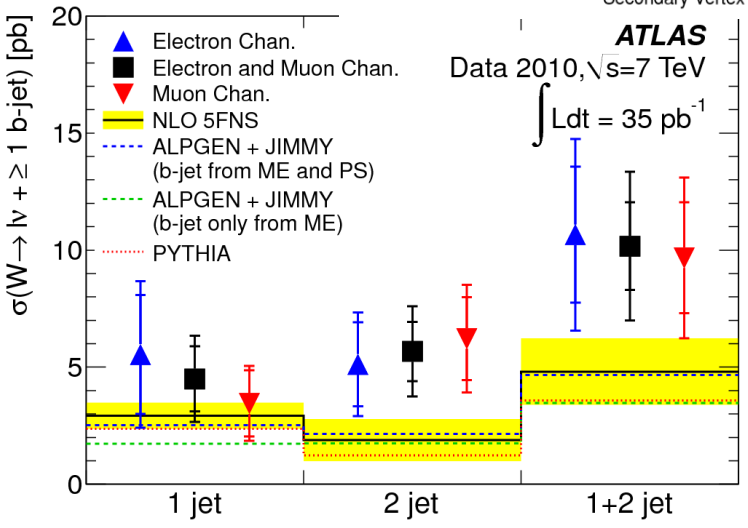
Phys.Lett. B707 (2012) 418-437

Phys.Lett. B706 (2012) 295-313

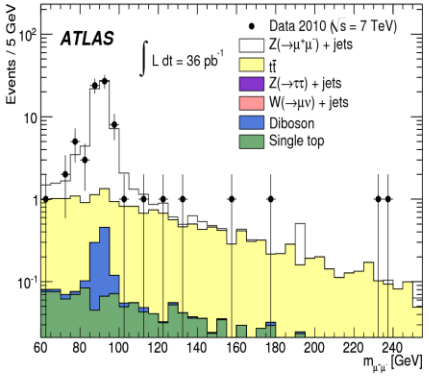
W+ b-jet

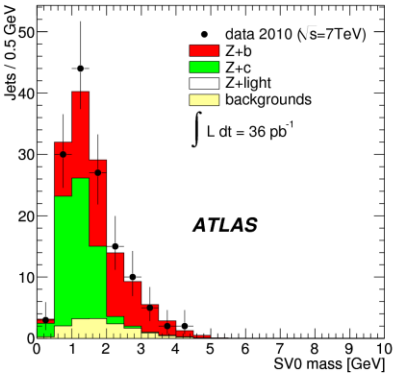






Z+ b-jet





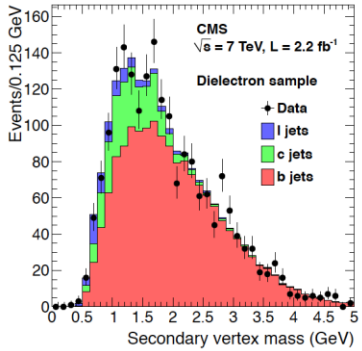
Experiment	$3.55^{+0.82}_{-0.74}(\text{stat})^{+0.73}_{-0.55}(\text{syst}) \pm 0.12(\text{lumi})$ pb
MCFM	3.88 ± 0.58 pb
ALPGEN	2.23 ± 0.01 (stat only) pb
SHERPA	3.29 ± 0.04 (stat only) pb

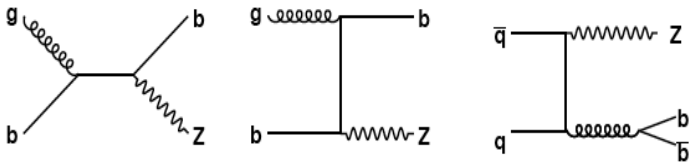
Measured inclusive V+b-jet cross sections well described by NLO pQCD predictions

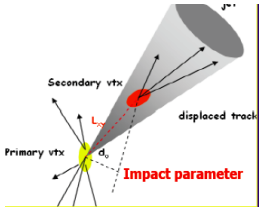
LO ME + PS still compatible with the data (more data and work needed in this area…)

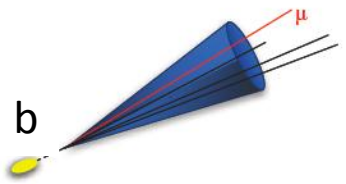
Z+b & Z+bb

NEW !!



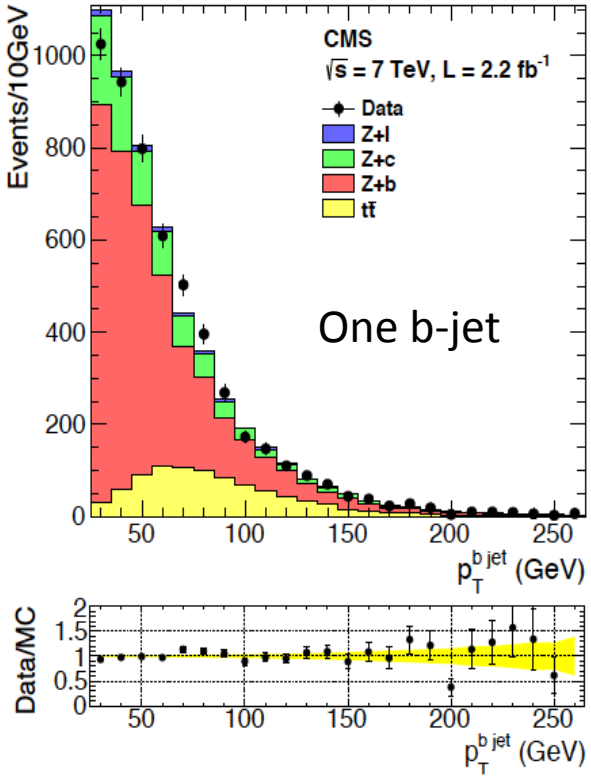




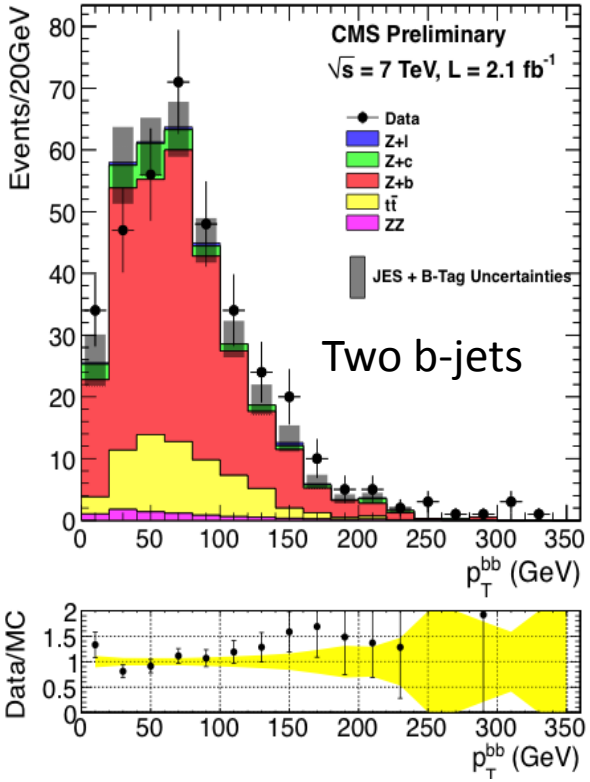


anti-K_T jets with R=0.5
Jet p_T > 25 GeV, |Y| <2.1

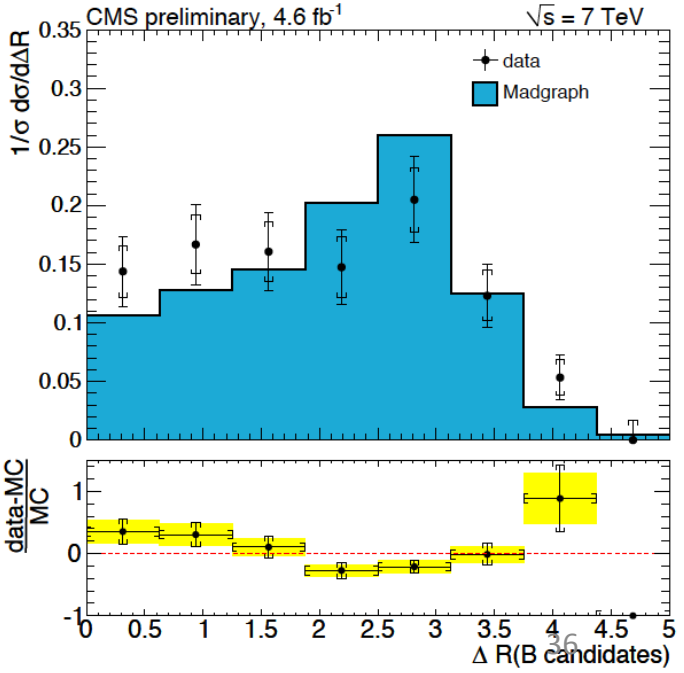
CERN-PH-EP-2012-049



CMS-PAS-SMP-12-003



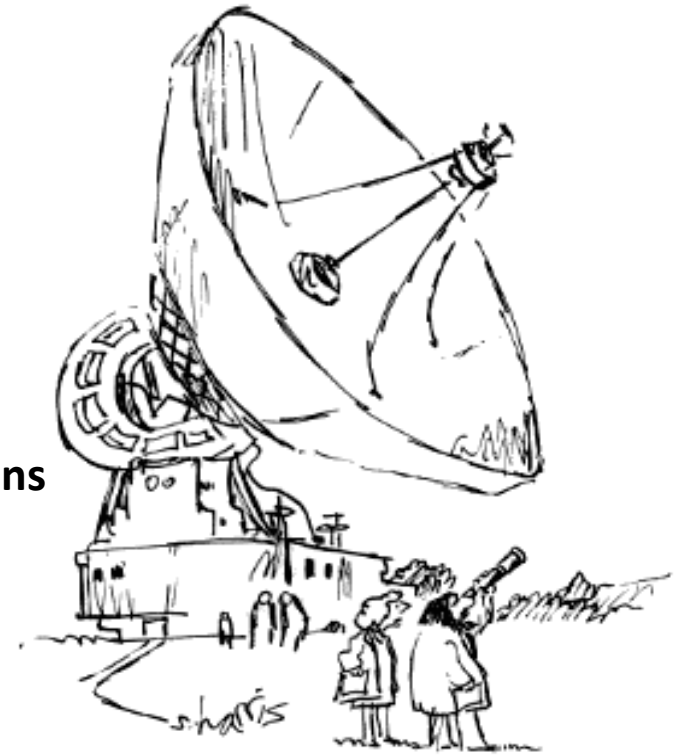
CMS-PAS-EWK-11-015
No jet selection applied
(study of collinear configurations)

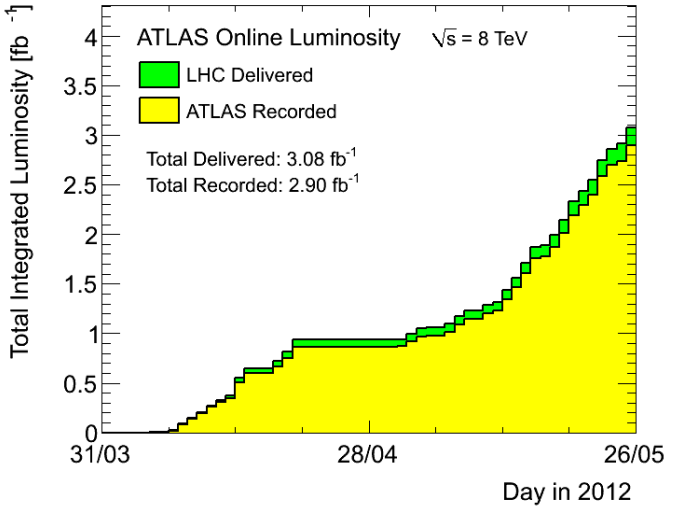


MADGRAPH provides a reasonable description of the data

Summary

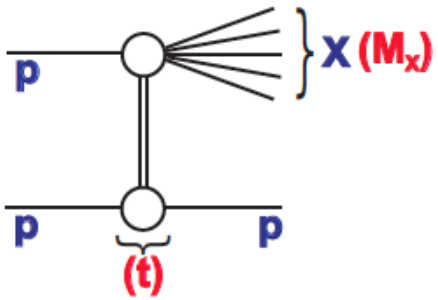
- Spectacular performance of the LHC machine and the experiments in 2010-2011
- The experiments carried out a wide and comprehensible program of precise QCD measurements compared to SM predictions
- Overall, good agreement is observed with QCD predictions This requires the use of the newest theory tools (NLO + PS, high-multiplicity ME+PS…..)
- A solid ground towards eventual future discoveries of new physics… but more data and work needed in some areas (like, for example, W/Z+HFs)
- More will come with 2011 analyses (performed in a challenging pile-up configuration)
- In 2012 LHC plans to deliver about 20 fb^{-1} of data at 8 TeV opening a new phase of precise QCD analyses
- A combination of 7 TeV and 8 TeV should translate into constrains of model uncertainties like, for example, PDFs.

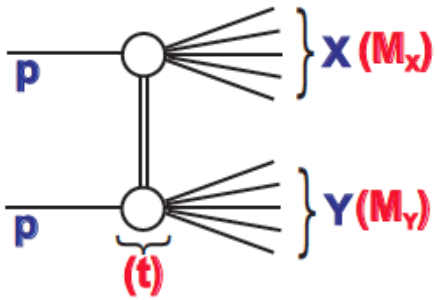


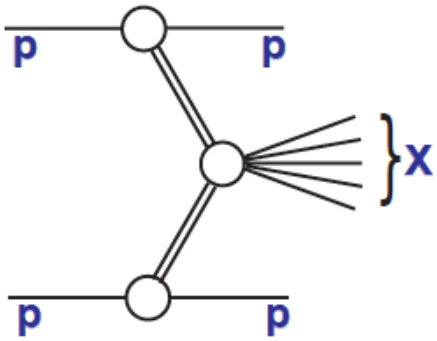


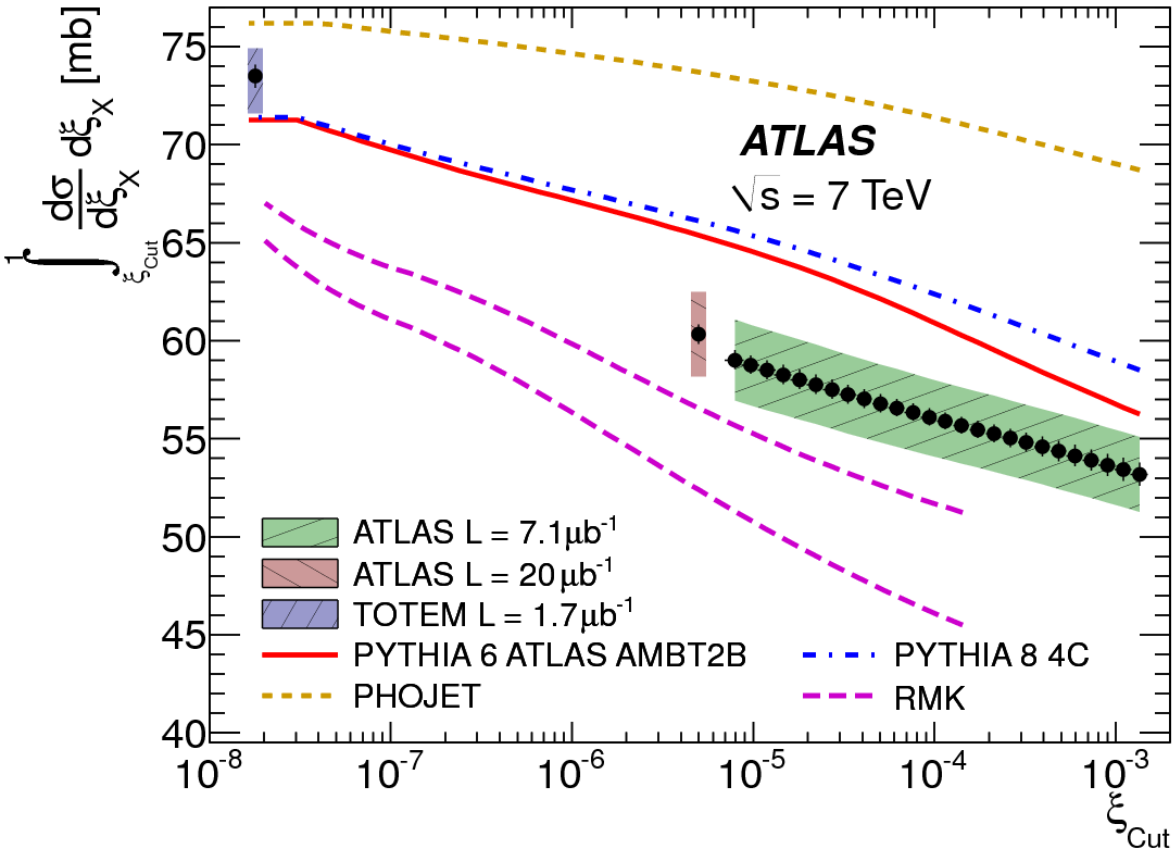
Back-up slides

$\sigma^{\text{rapidity-gap}}$





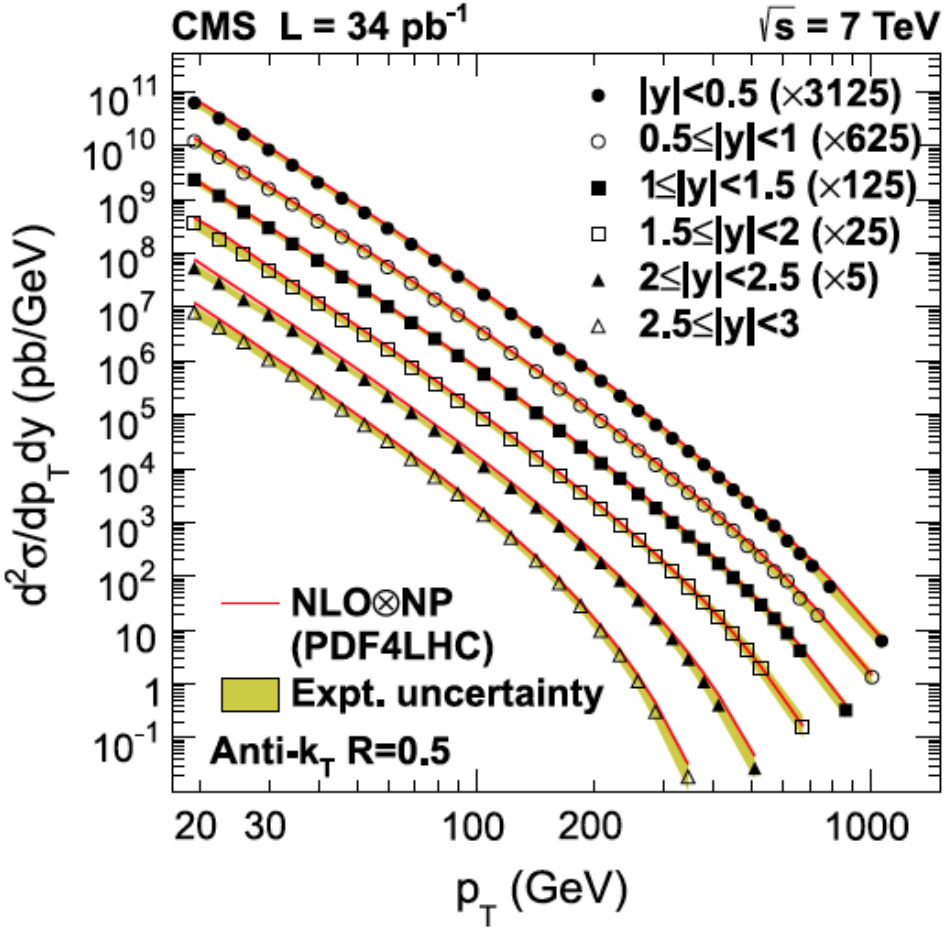


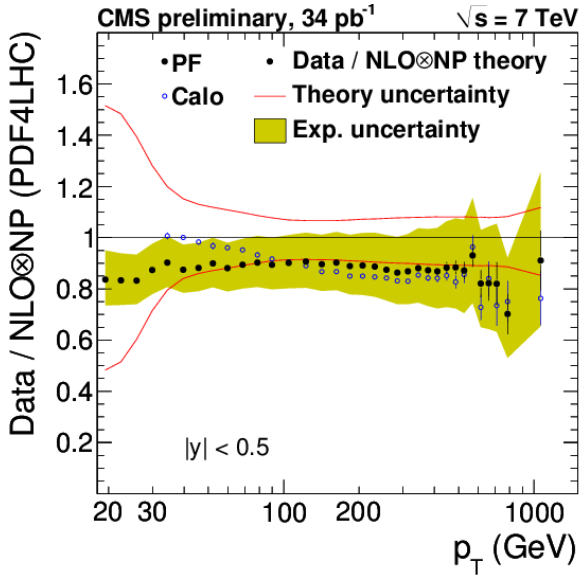


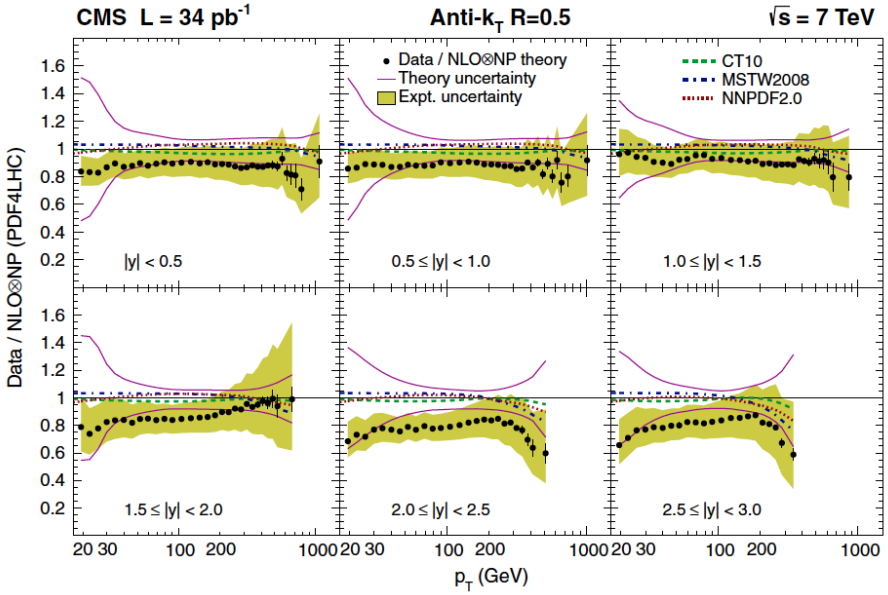
Phys. Rev. Lett. 107, 132001 (2011)

Inclusive Jet Production

anti-K_T jets with R=0.5
Jet p_T > 18 GeV, |Y| < 3





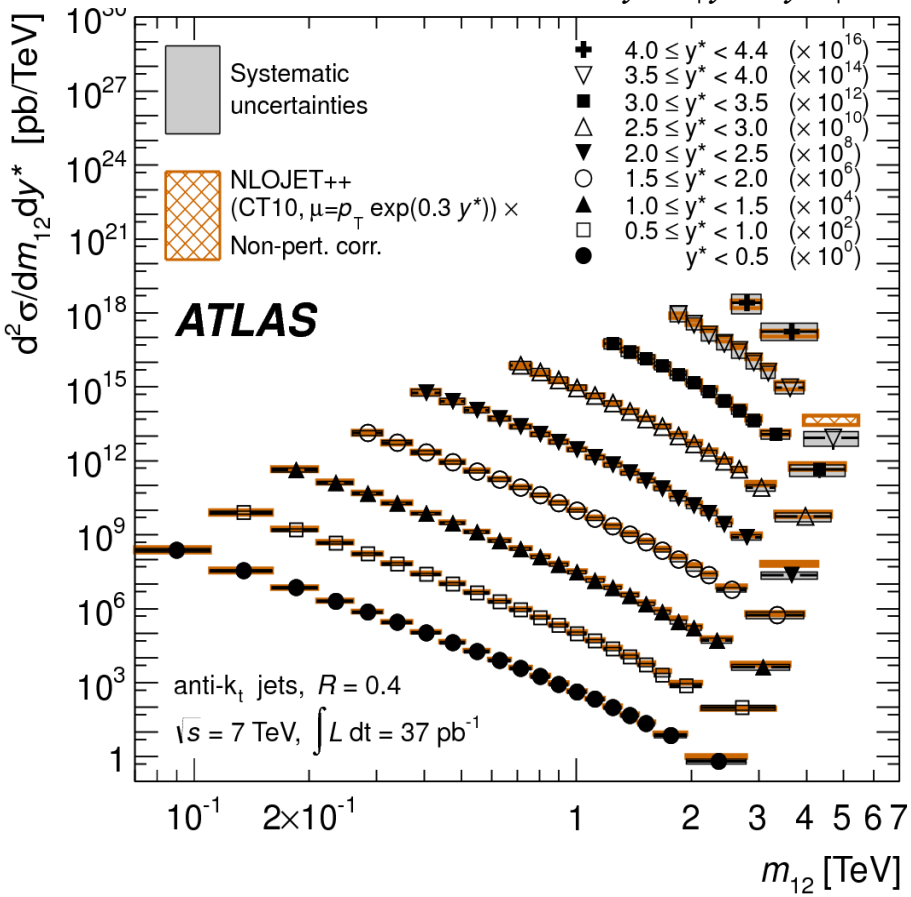


Di-jets Production

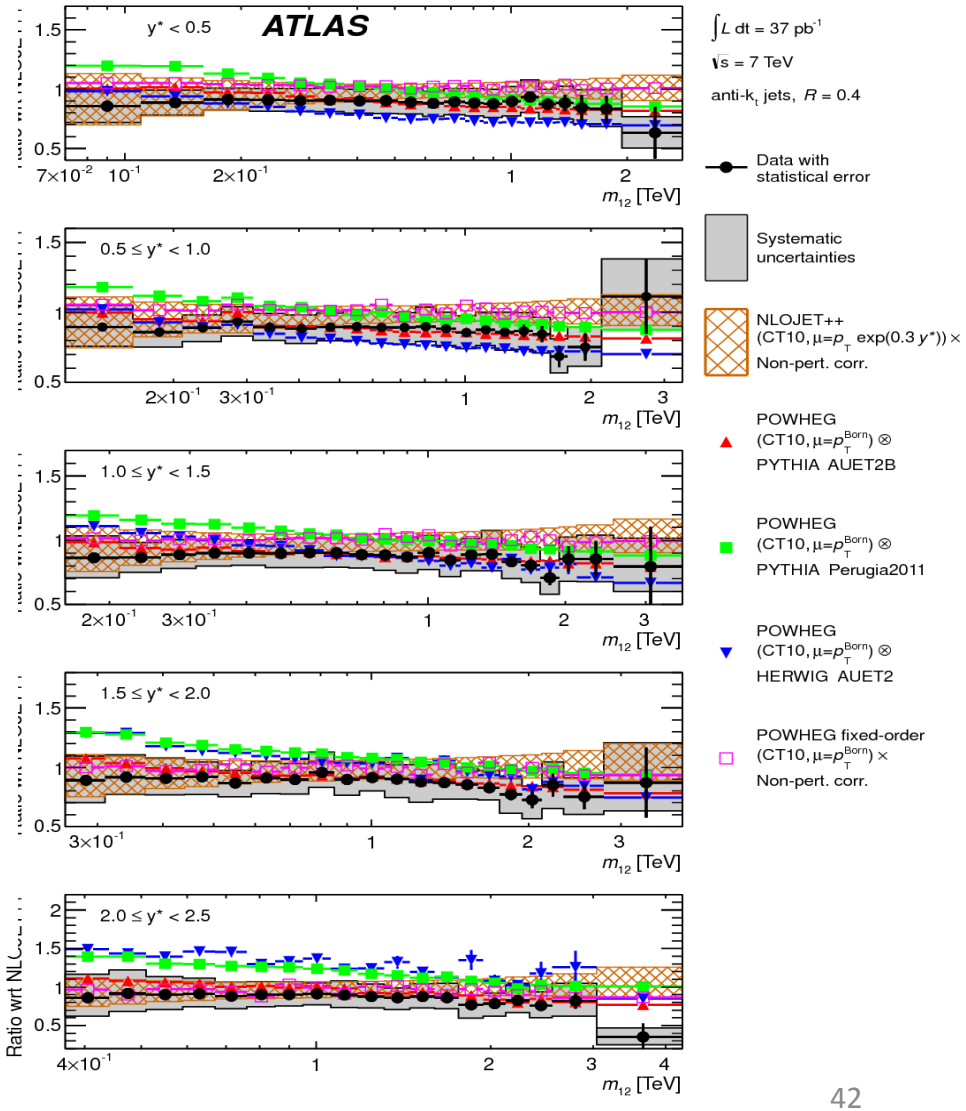
CERN-PH-EP-2011-192

$M_{jj} > 70GeV$

$y^* = |y^1 - y^2|/2$



Stringent pQCD test
(sensitive to new dijet resonance production)

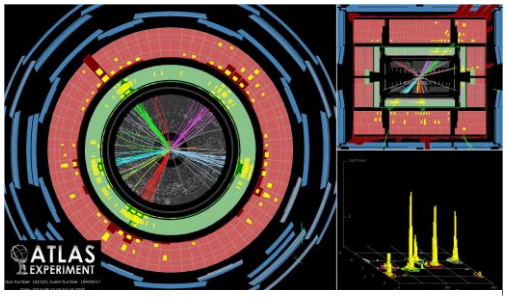


Invariant masses up to 5 TeV
Well described by NLO pQCD predictions

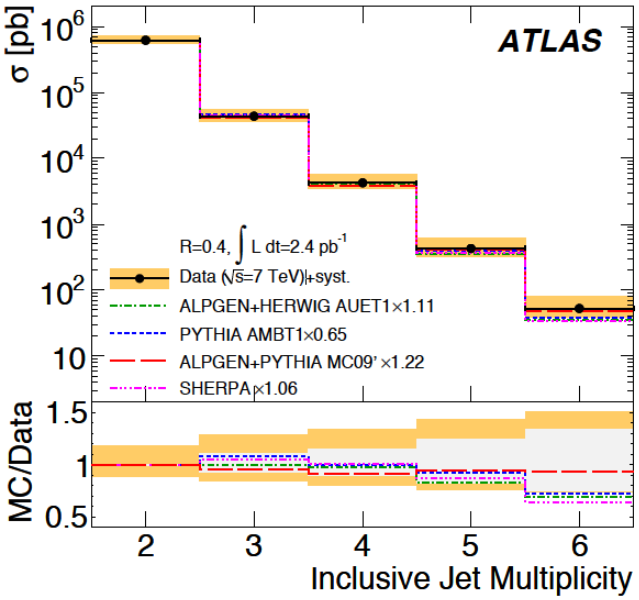
Compared to NLO ME + PS models

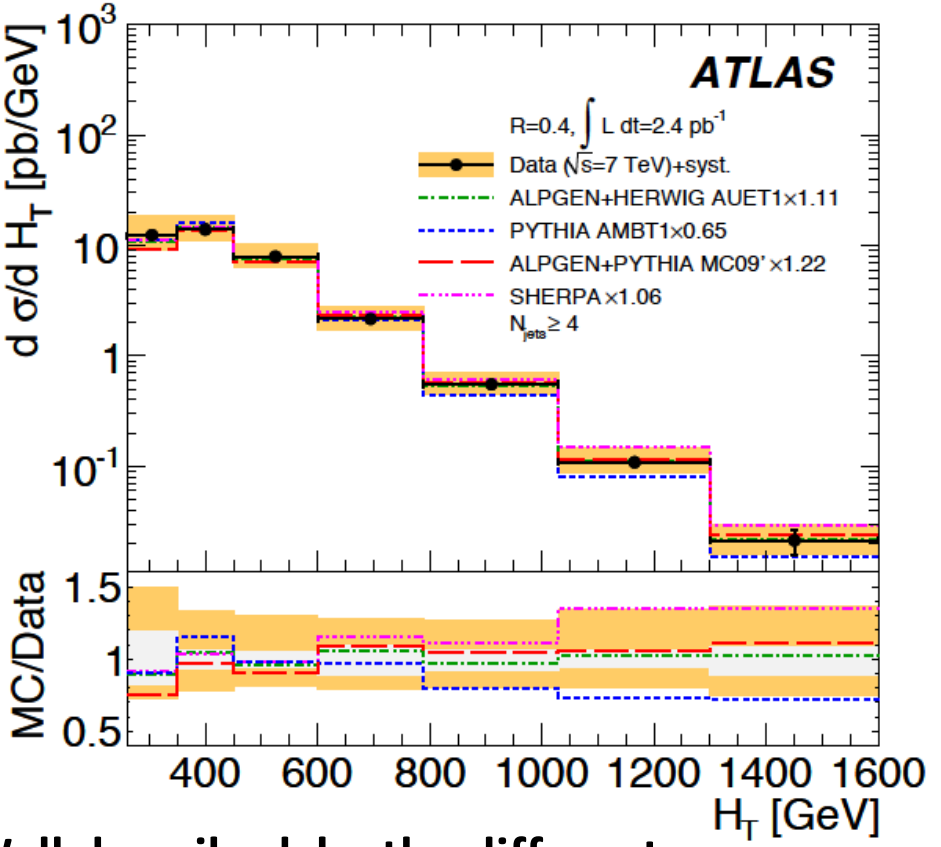
Multi-jets

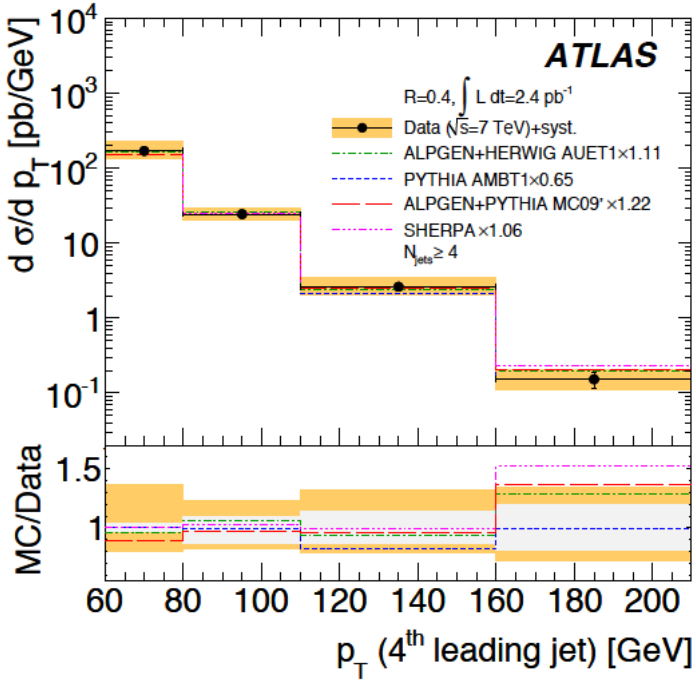
Eur.Phys.J.C 71 (2011) 1763



anti-K_T jets with R=0.4
Jet p_T > 60 GeV, |Y| < 2.8





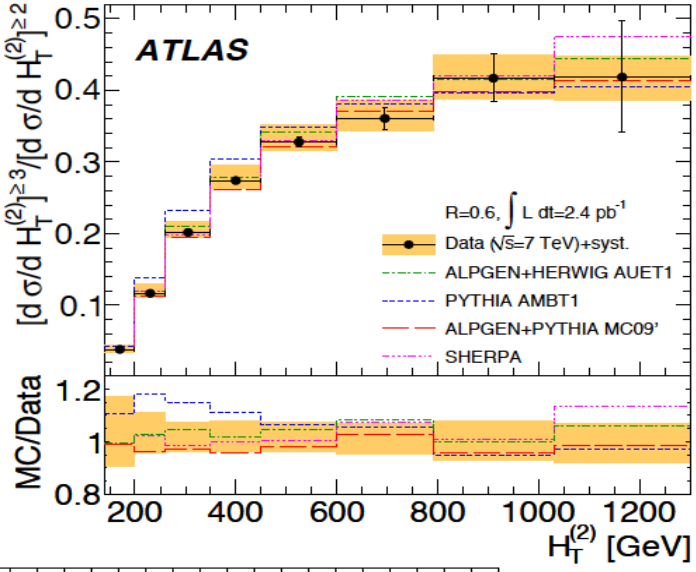


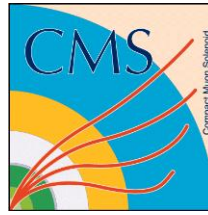
Well described by the different LO ME + PS MC predictions (globally scaled to fit the data)

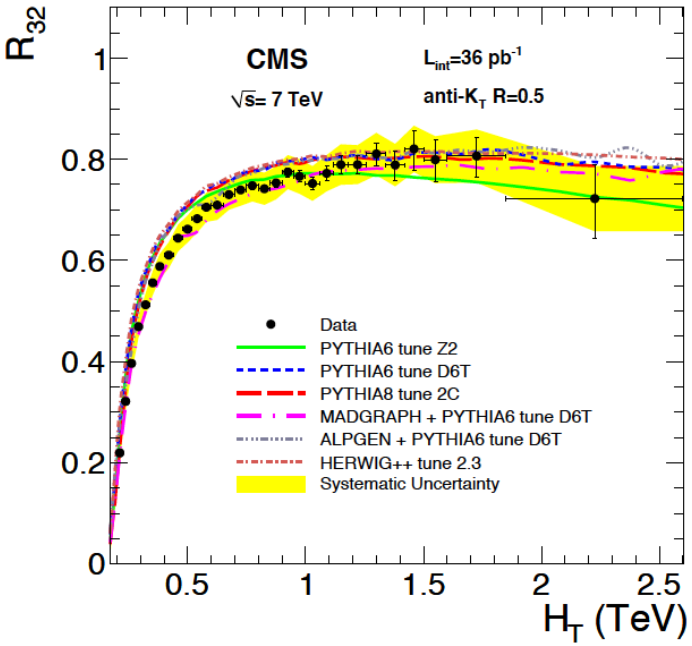
Eur.Phys.J.C 71 (2011) 1763

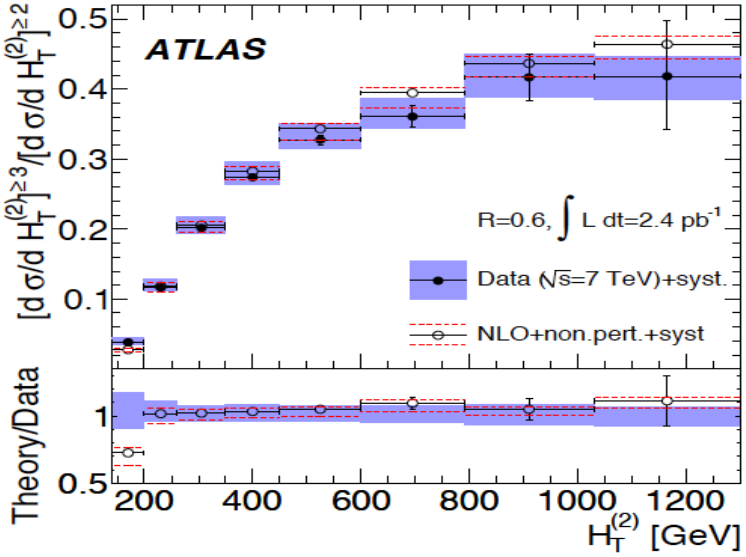
ratio 3jets/2jets

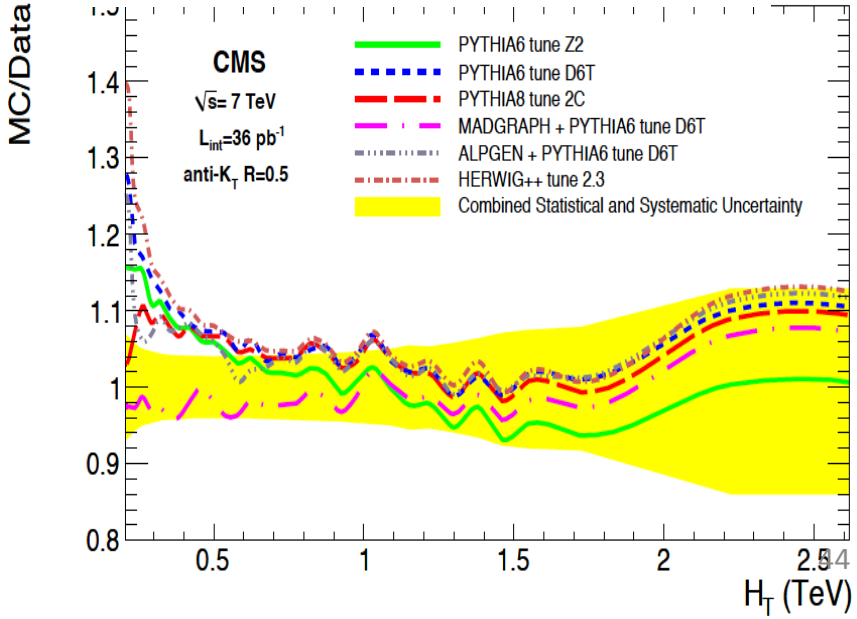
Phys. Lett. B 702 (2011) 336











Well described by NLO pQCD and LO ME+ PS predictions except at low H_T

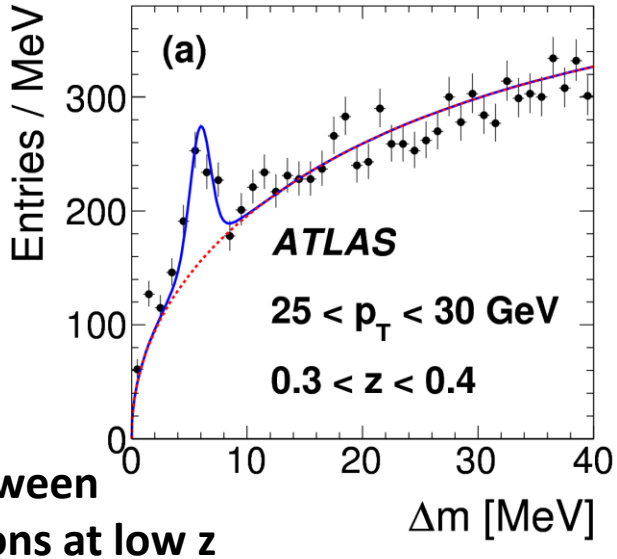
D* inside jets

Phys. Rev. D85 (2012) 052005

$$D^{*+} \rightarrow D^0 \pi^+$$

$$D^0 \rightarrow K^- \pi^+$$

anti-K_T jets R=0.6
Jet $25 < p_T > 70$ GeV, $|Y| < 2.5$

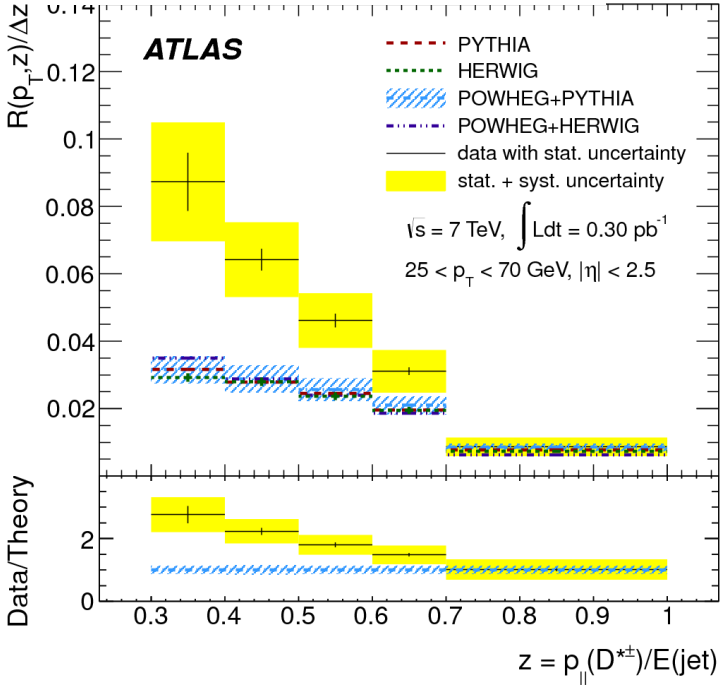


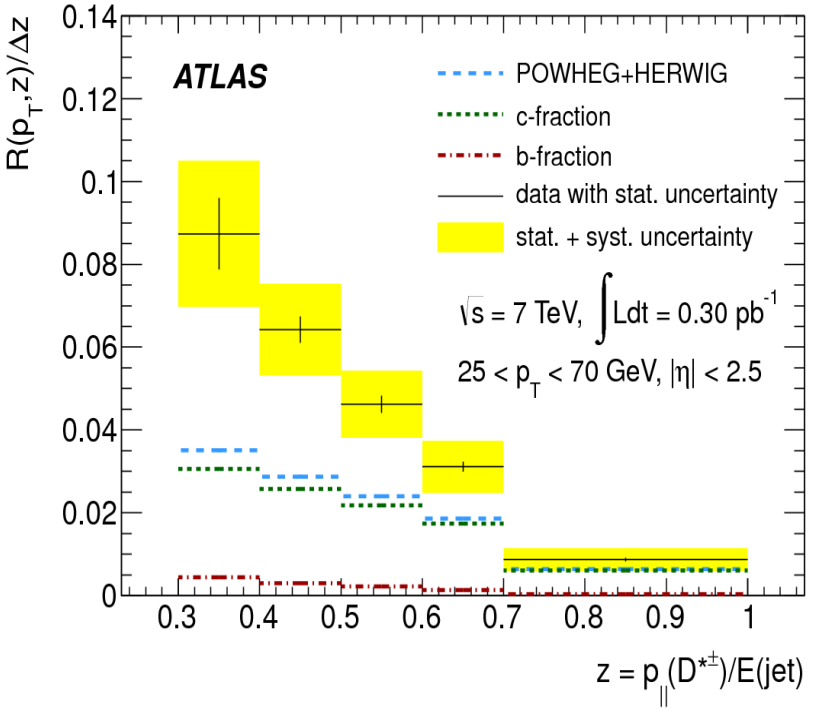
D* candidates matched to jets

$$z = p_{||}(D^{*\pm})/E(\text{jet})$$

$$\mathcal{R}(p_T, z) = \frac{N_{D^{*\pm}}(p_T, z)}{N_{\text{jet}}(p_T)}$$

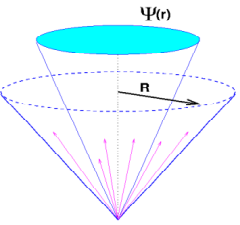
Clear discrepancy between data and MC predictions at low z

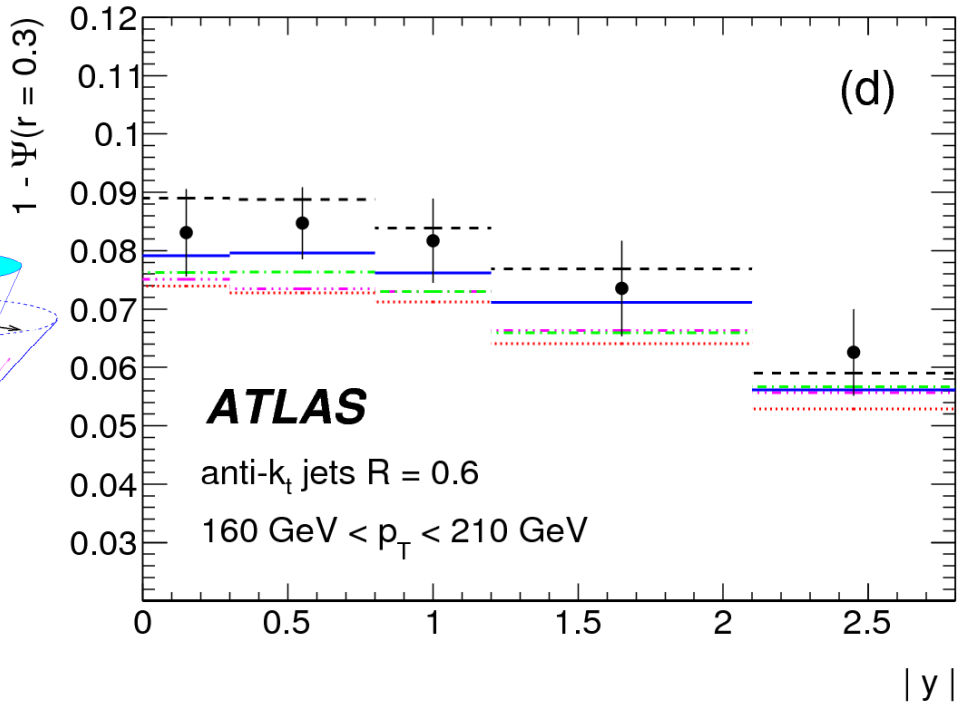


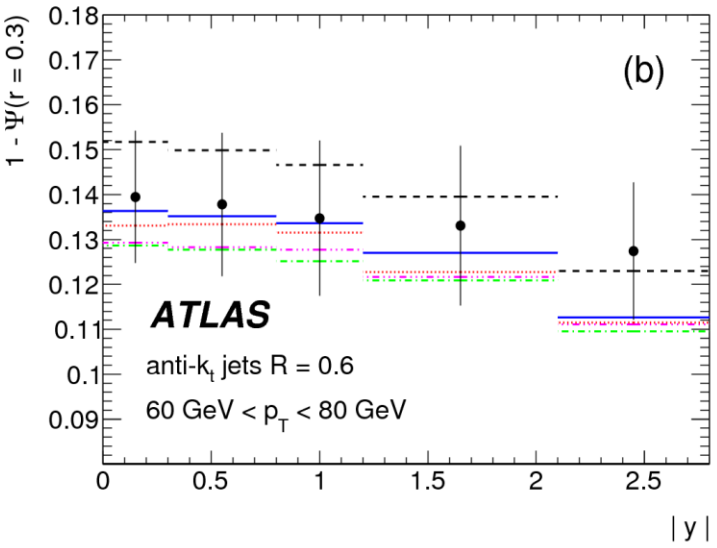


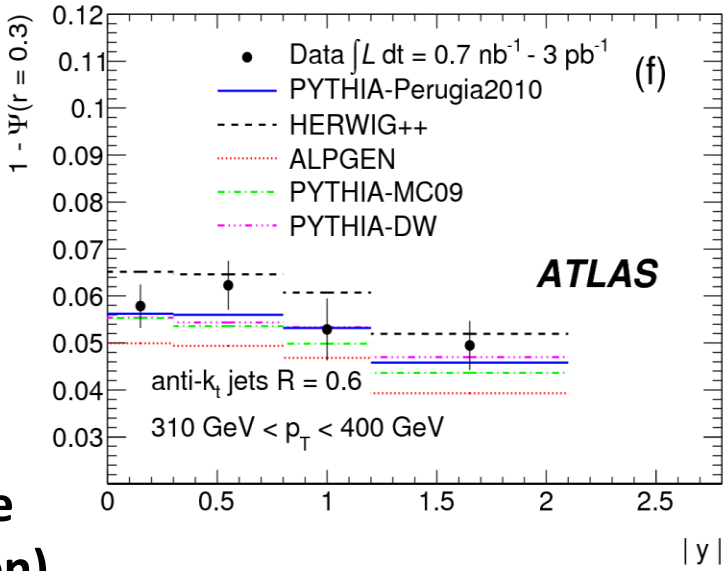
Jet Shapes

Measurements carried out in 5 different jet rapidity regions and as a function of p_T



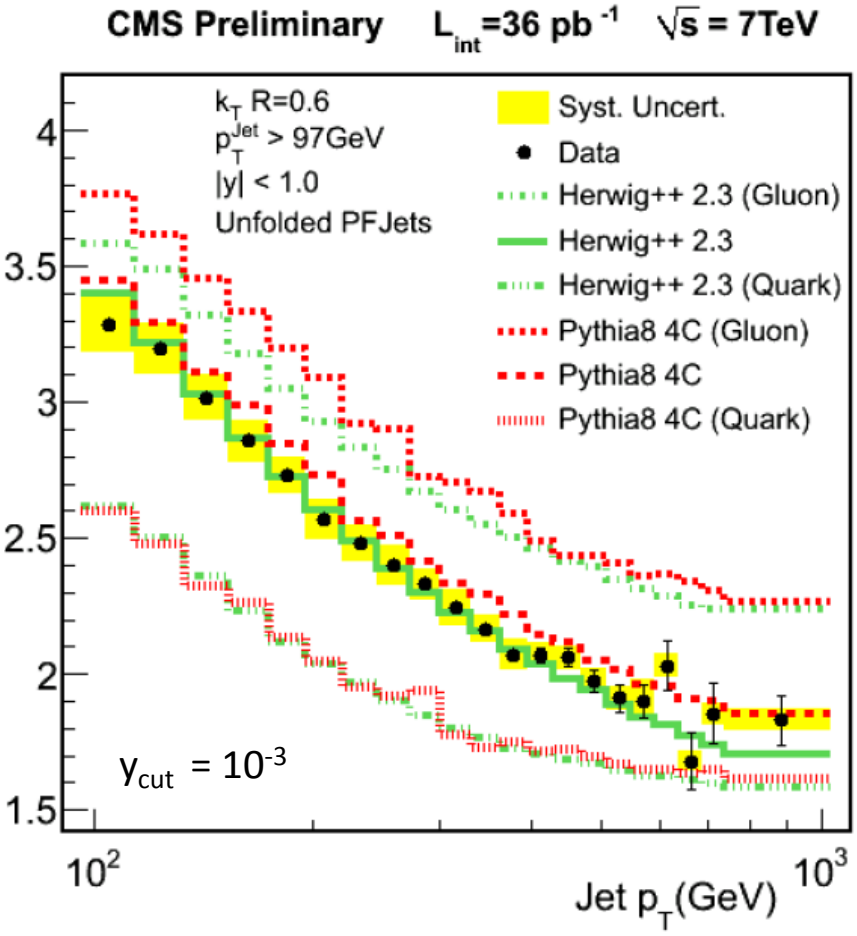


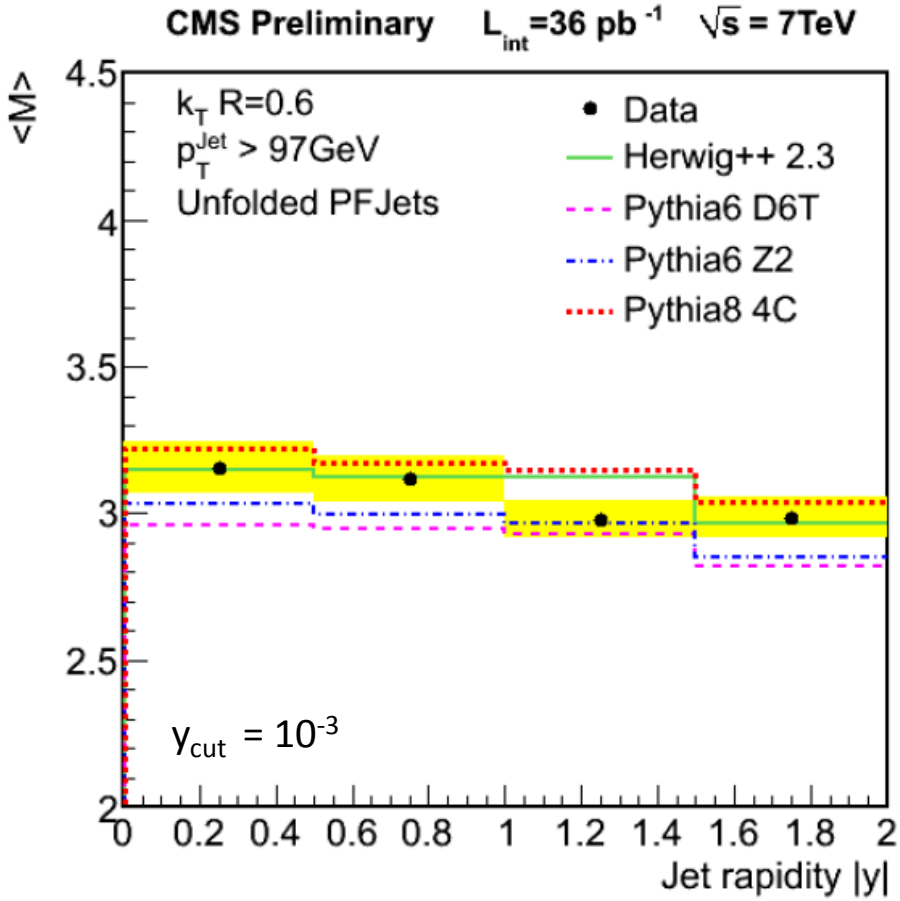




The jet shapes present a mild rapidity dependence (jet become slightly narrower in the forward region)
→ Followed by the MC predictions

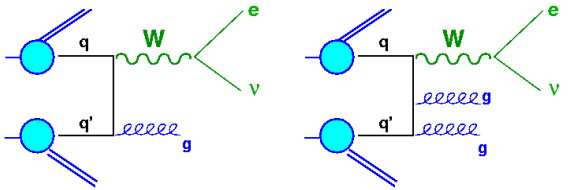
Sub-jet multiplicity

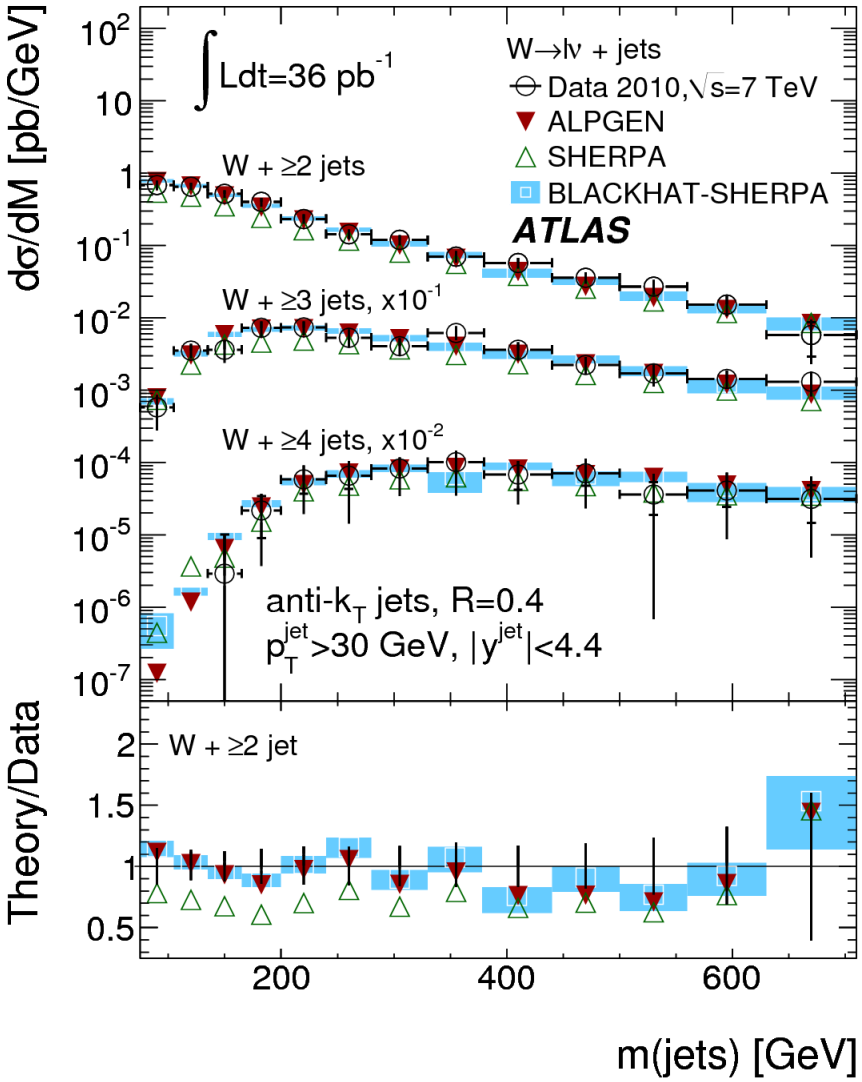


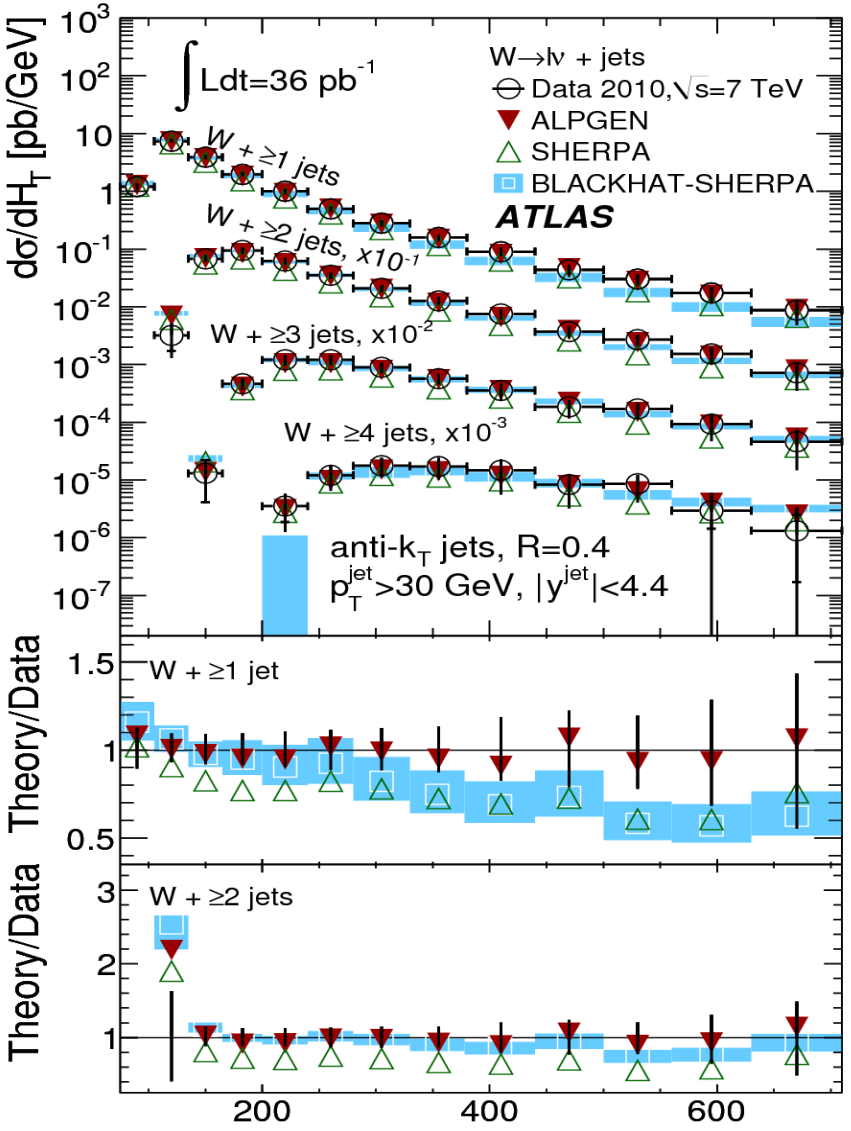


→N-subjets decreases with jet p_T : jets getting narrower
→Mild rapidity dependence (narrower in the forward region)
→ Sensitivity to quark/gluon mixture
→Sensitivity to proper PS modeling and UE tune

W+jets





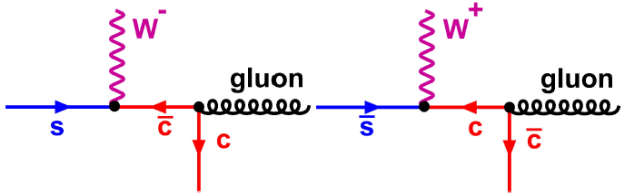


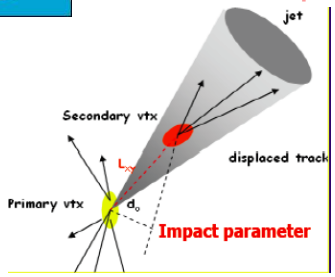
Good description of the measured invariant masses and H_T measured distributions

→ No evidence for any resonant enhancement

W+c

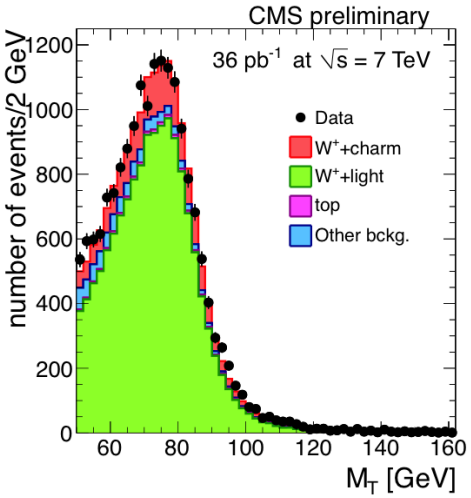
CMS-PAS-EWK-11-013

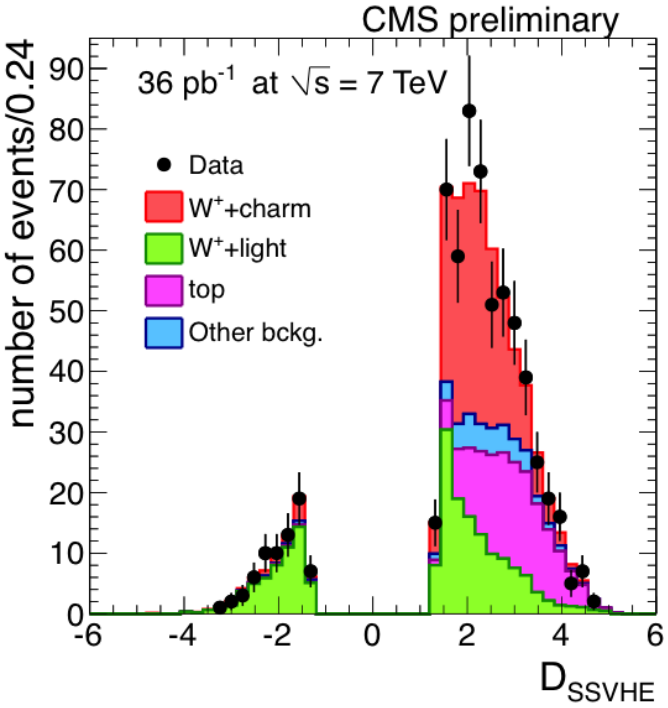


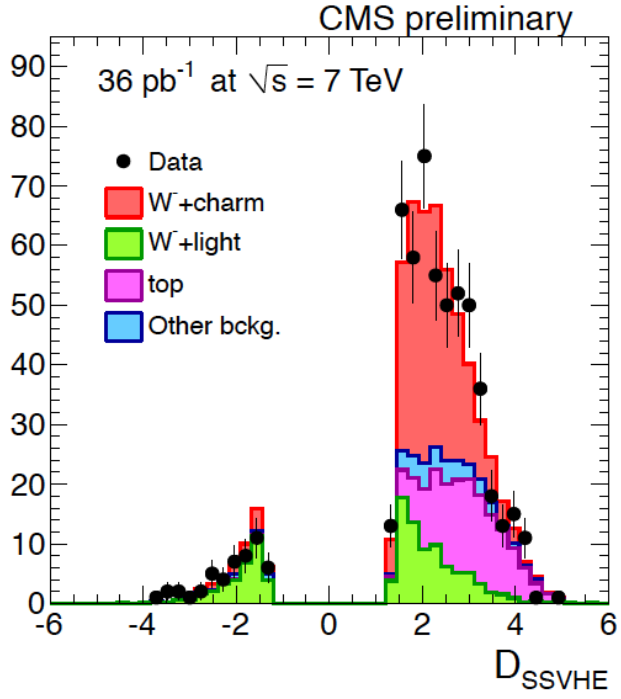


W+jet sample in the muon channel
Identification of secondary displaced vertex

Measurements useful to constrain PDFs







Template fit to extract the W+c component based on a discriminatior (DSSVHE) defined in terms of the 3D decay length significance (S)

$$D_{SSVHE} = sign(S)\ log(1 + abs(S))$$

Jet $p_T > 20$ GeV, $|\eta| < 2.1$
muon $p_T > 25$ GeV, $|\eta| < 2.1$

$$\sigma(W^+\bar{c})/\sigma(W^-c)$$

$$0.92 \pm 0.19\ (stat.) \pm 0.04\ (syst.)$$

$$TH(MCFM) : 0.91 \pm 0.04$$

$$\sigma(W + c)/\sigma(W + jets)$$

$$0.143 \pm 0.015\ (stat.) \pm 0.024\ (syst.)$$

$$TH(MCFM) : 0.13 \pm 0.02$$

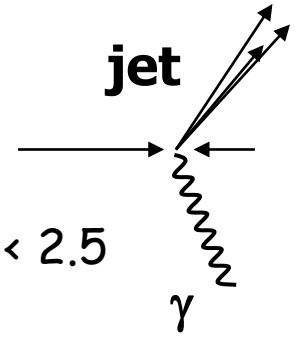
In agreement with NLO pQCD predictions (MCFM, CTQ10)

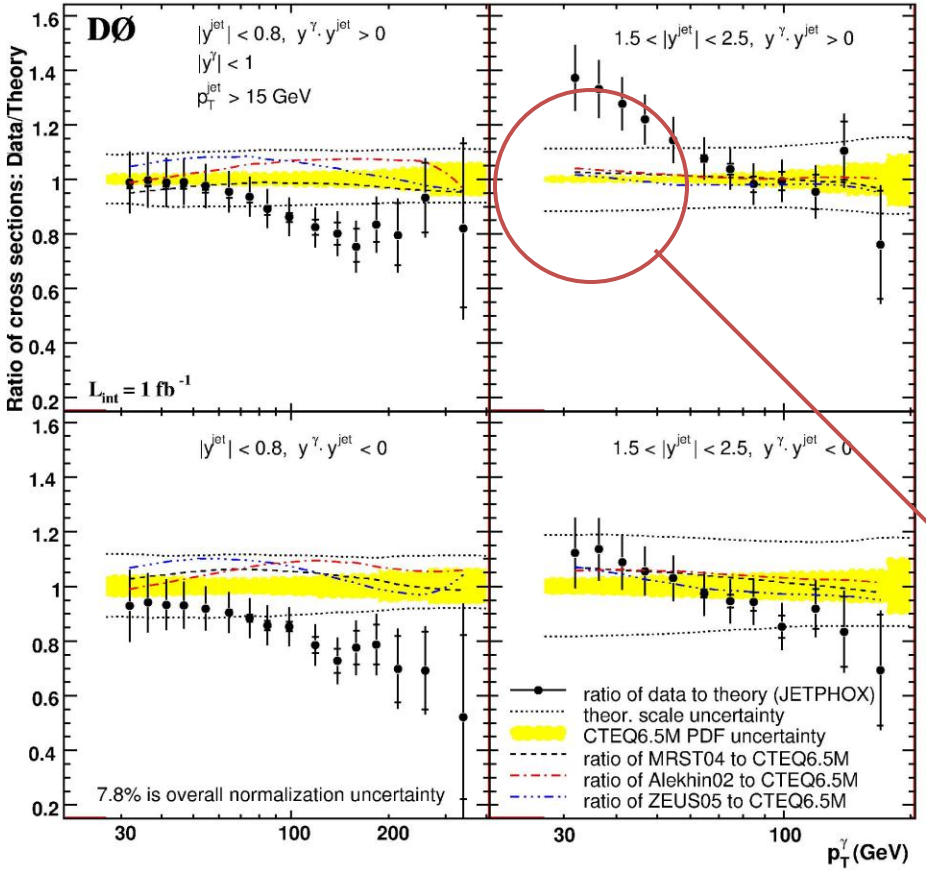
γ+jets results

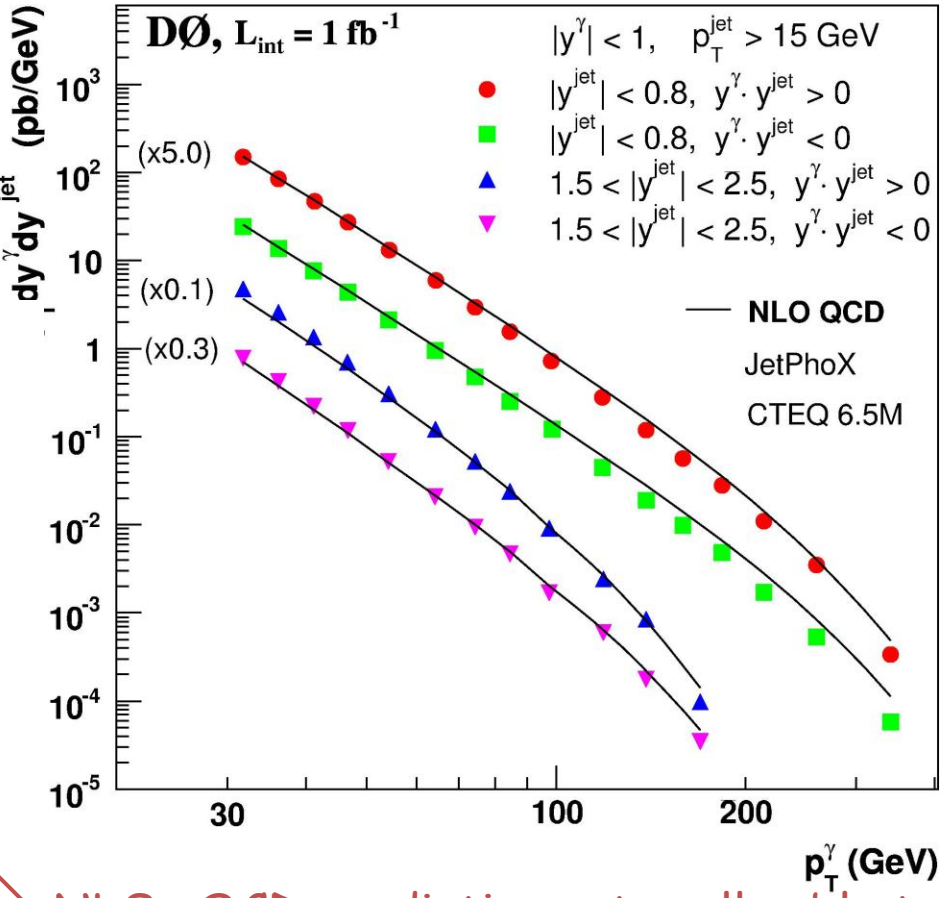
PLB 666, 2435 (2008)

Isolated photons
P_t> 30 GeV/c, $|\eta| < 1.0$

Jets with $P_t > 15$ GeV/c
$|\eta^{jet}| < 0.8$ or $1.5 < |\eta^{jet}| < 2.5$





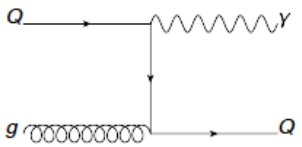


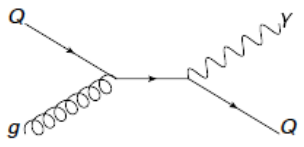
NLO pQCD prediction not really able to follow the data in some regions of the photon-jet phase space…

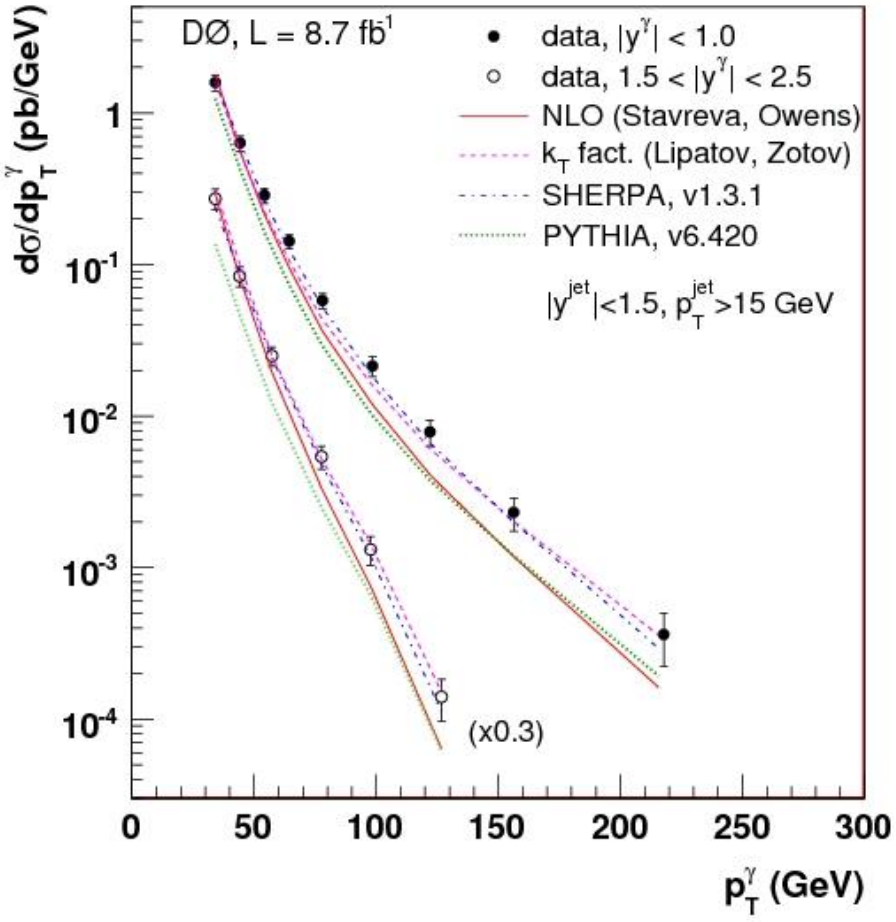
Very interesting for theorist if CDF could provide similar results…

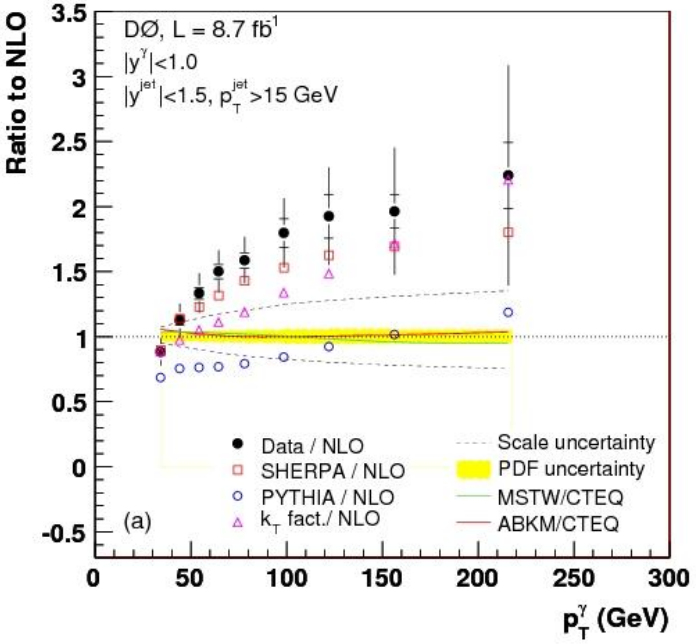
8.7 fb^{-1} γ + b

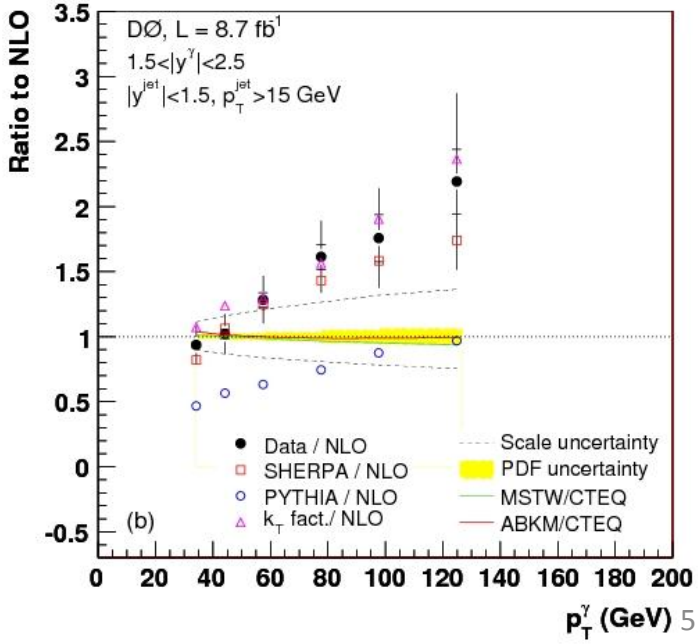
Fermilab-PUB-12-082-E



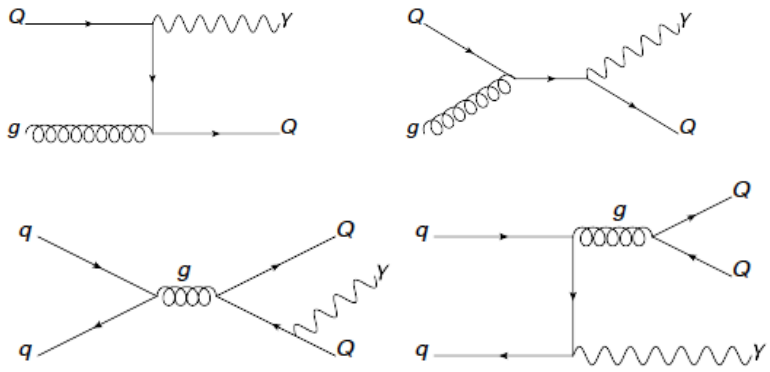




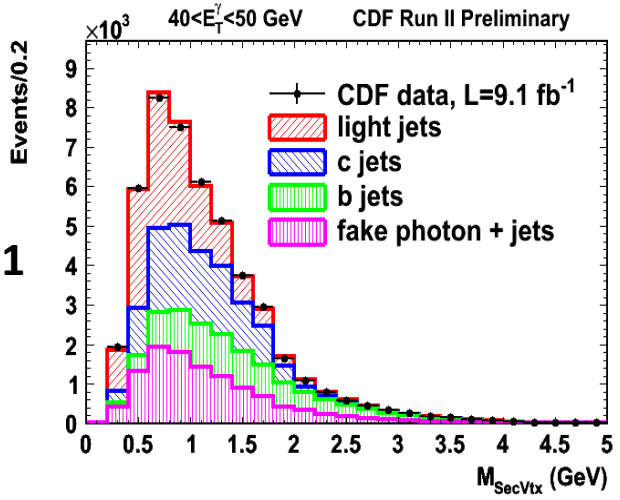


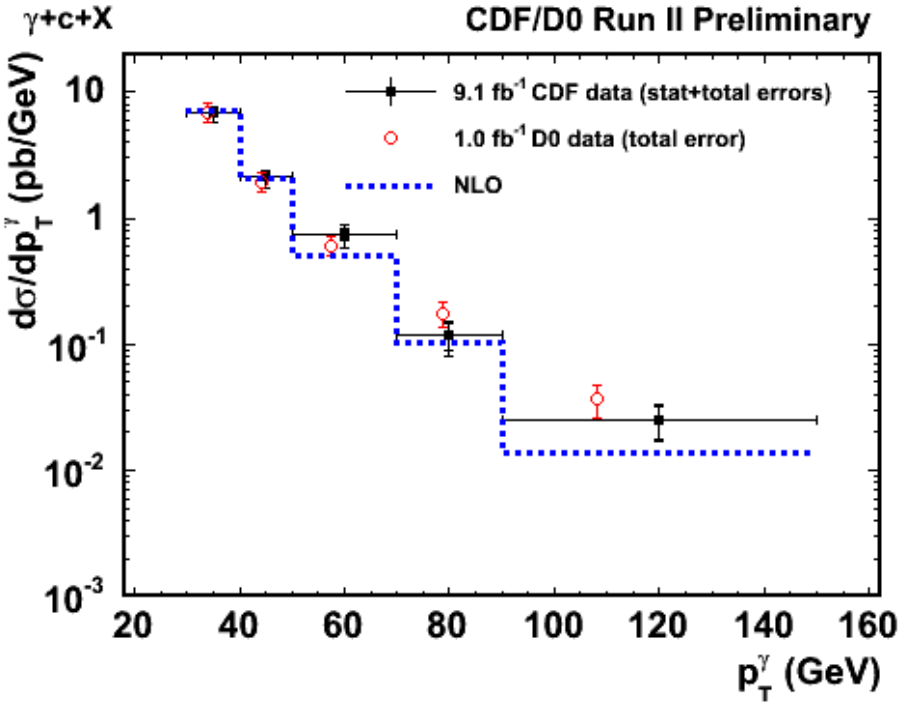


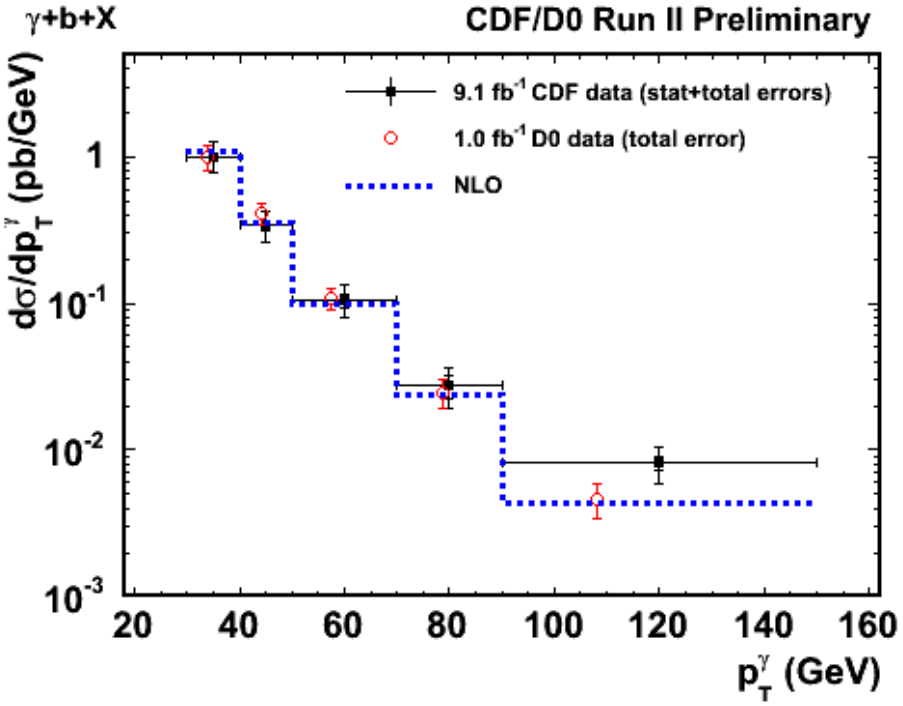
9.1 fb^{-1} γ + b/c



Jet $p_T > 20$ GeV, $|y| < 1.5$
photon $E_T > 30$ GeV, $|\eta| < 1$





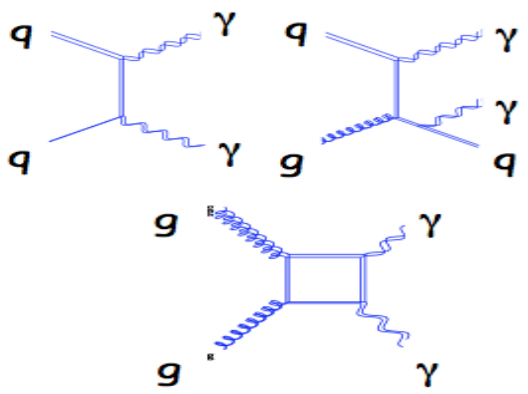


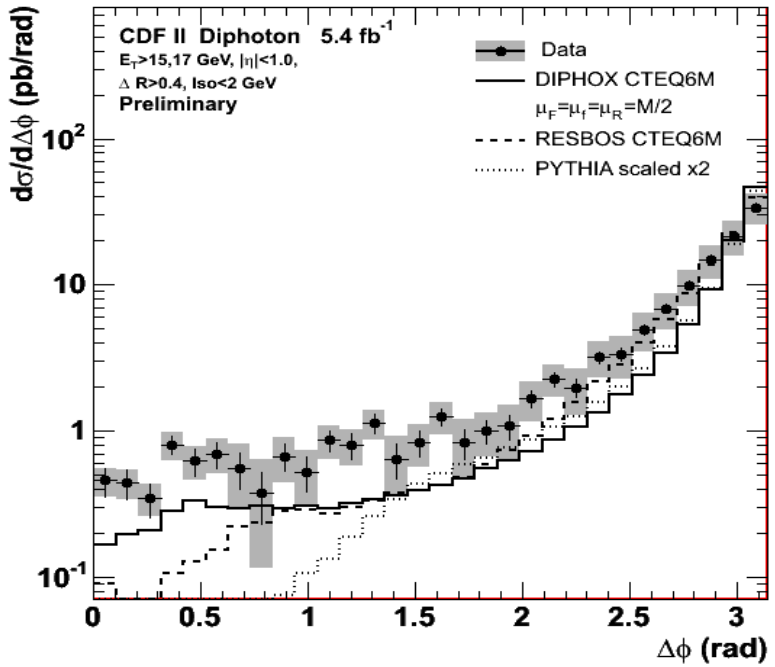
Similar tendency observed in CDF data

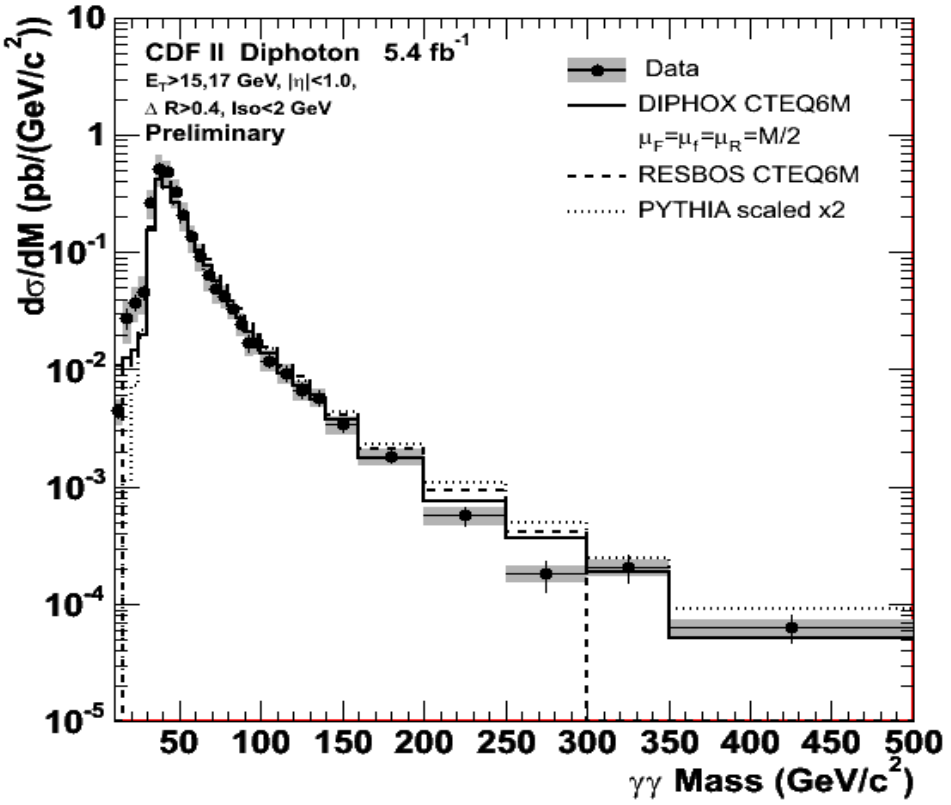
5.4 fb^{-1}

Di-photon Production

Very relevant for Higgs, SUSY, ED searches







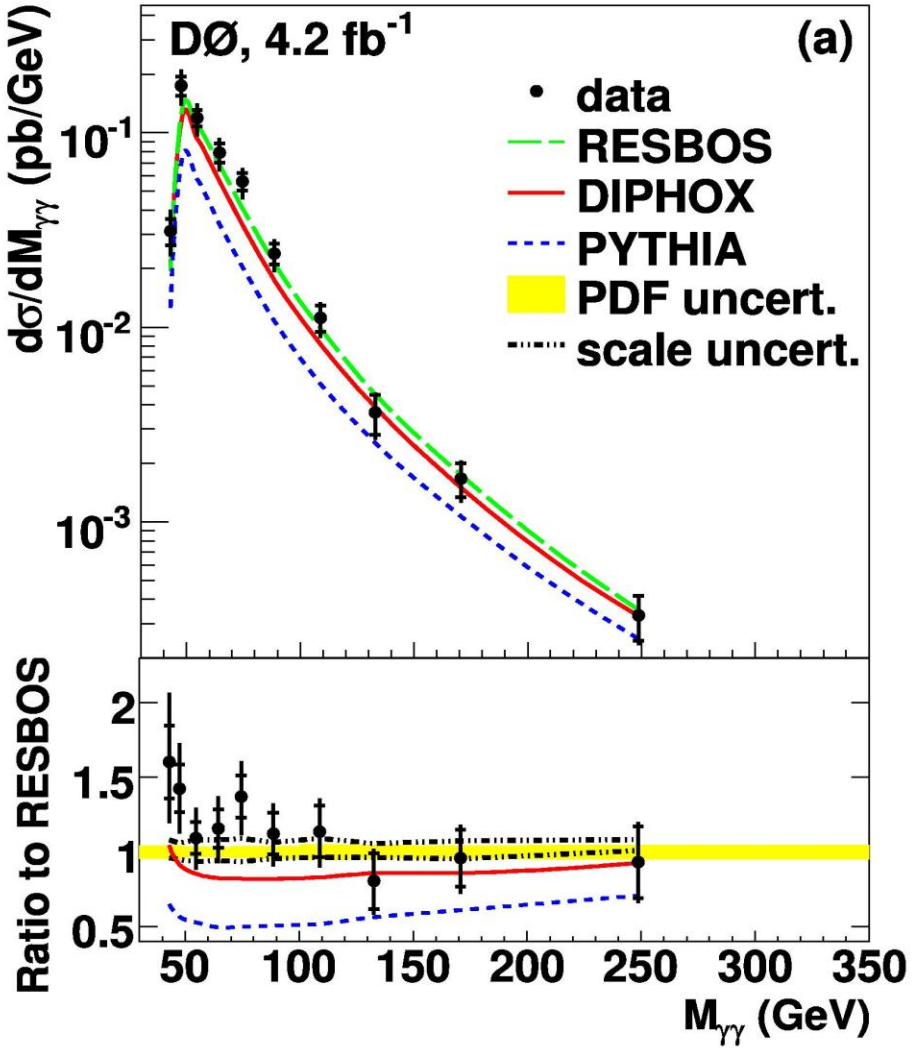
Measured cross sections for central isolated photons compared to

- **PYTHIA (L0 ME + PS) (x2 scaled)**
- **RESBOS (NLO + re-summed soft ISR)**
- **DIPHOX (NLO … only LO for gg→ γγ)**

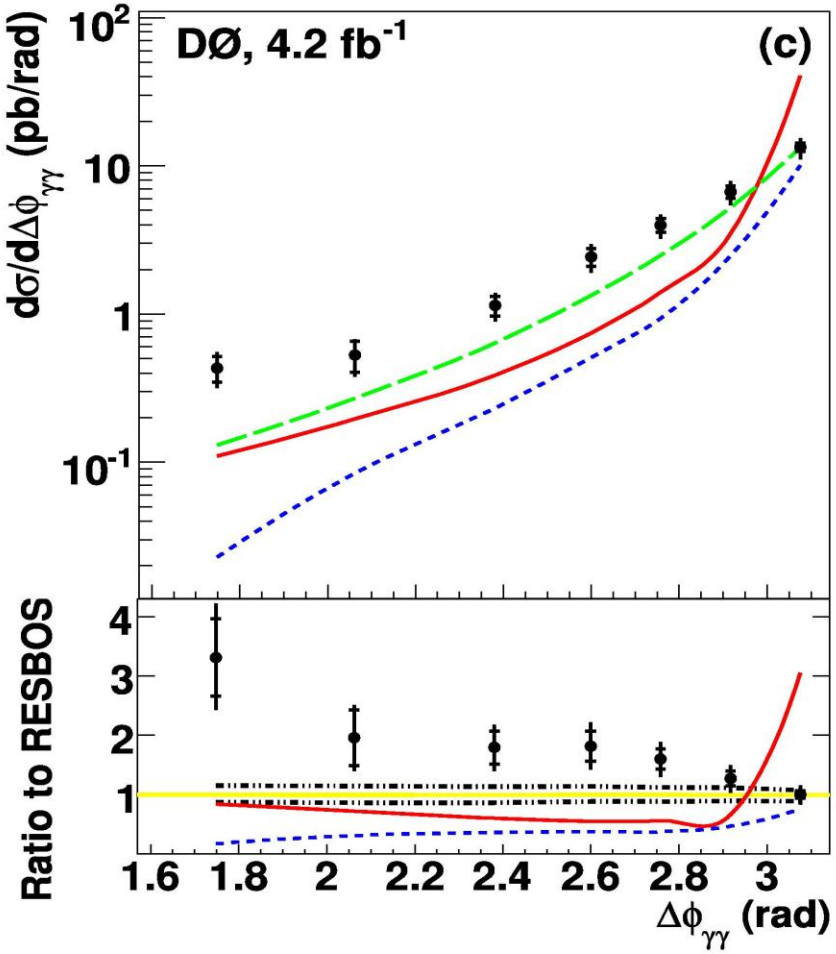
None of them describe the data well….

4.2 fb^{-1}

Di-photon Production



RESBOS closer to the data but with large discrepancies at low $M_{\gamma\gamma}$ (low $P^{\gamma\gamma}_T$) and low $\Delta\phi^{\gamma\gamma}$

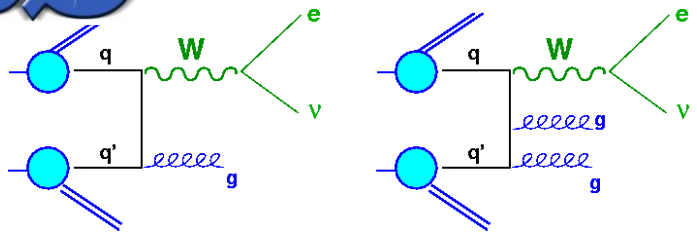


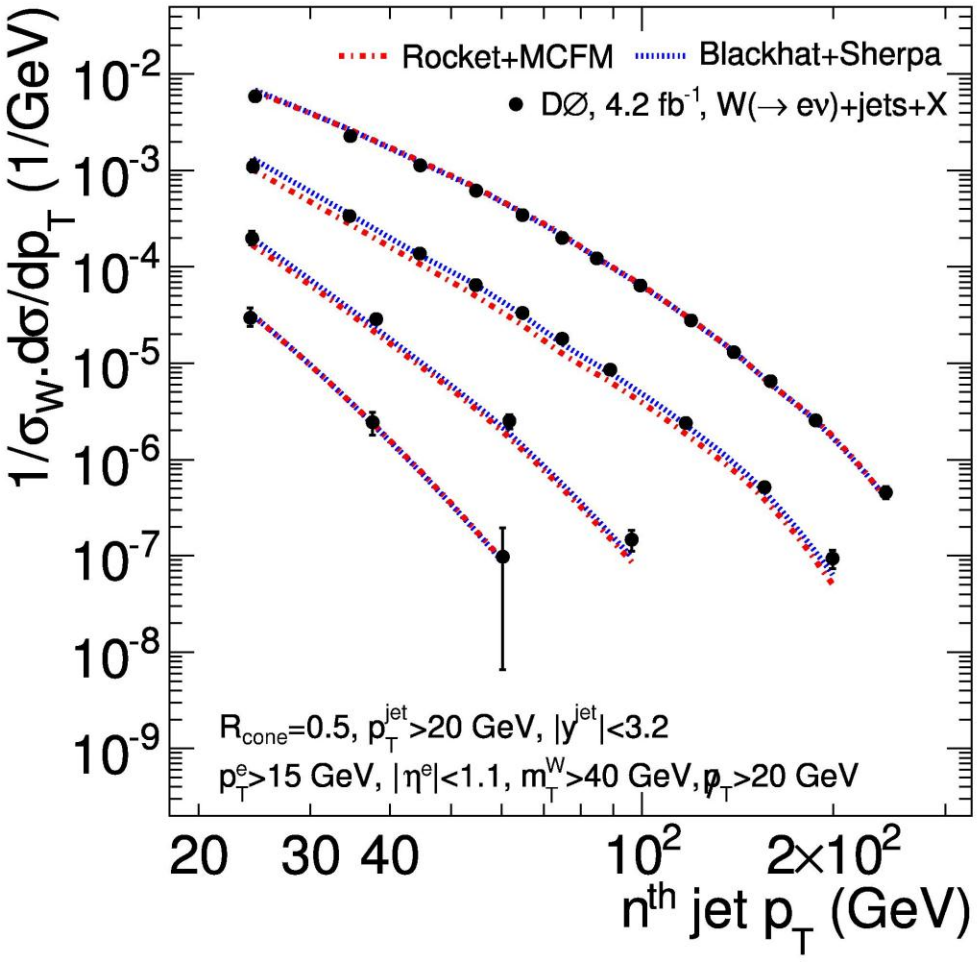
CDF and D0 results:
Would indicate the need for NNLO terms and the importance of the proper treatment of fragmentation contributions

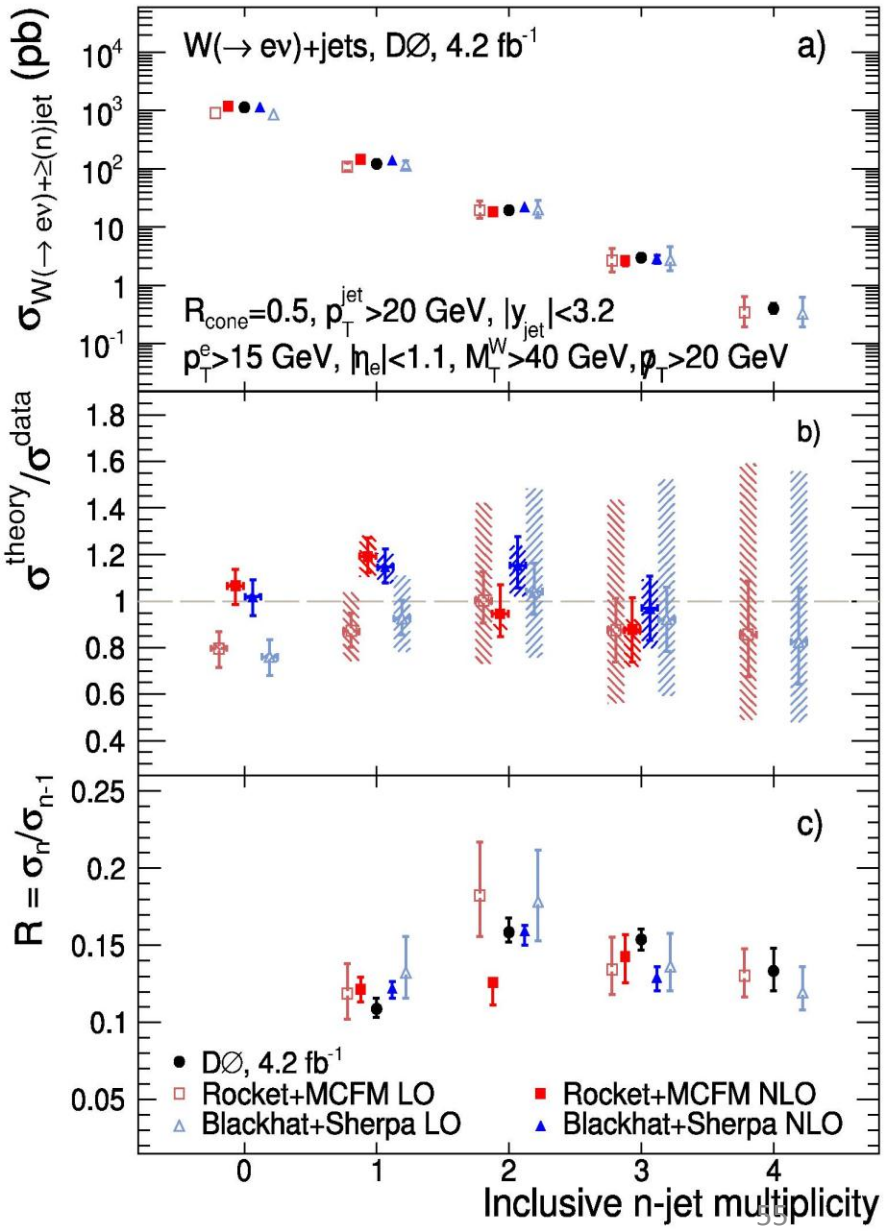
W+jet(s)

4.2 fb^{-1}

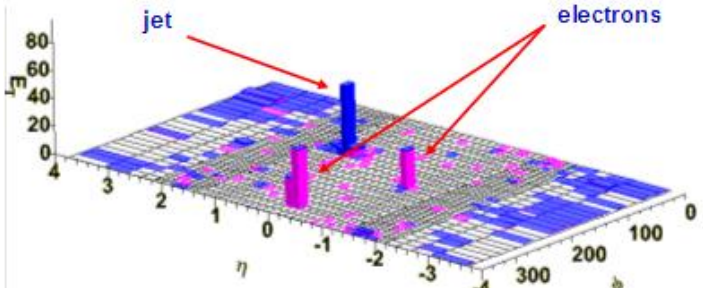
Fermilab-PUB-11/246-E

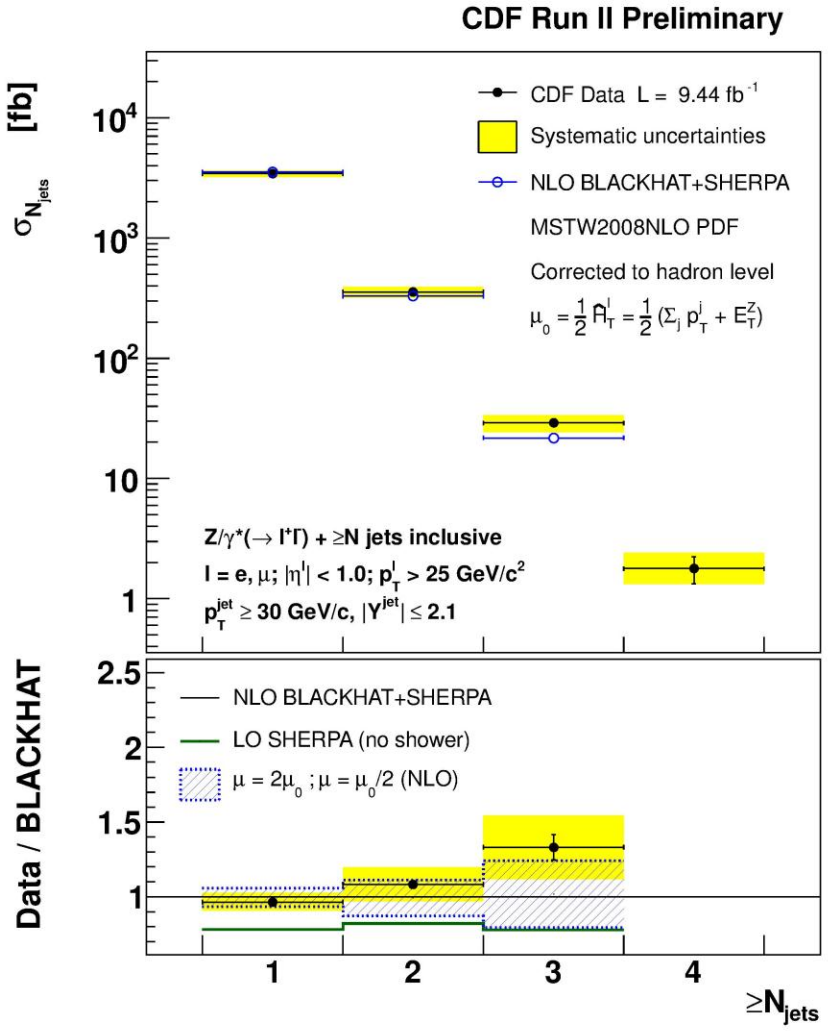


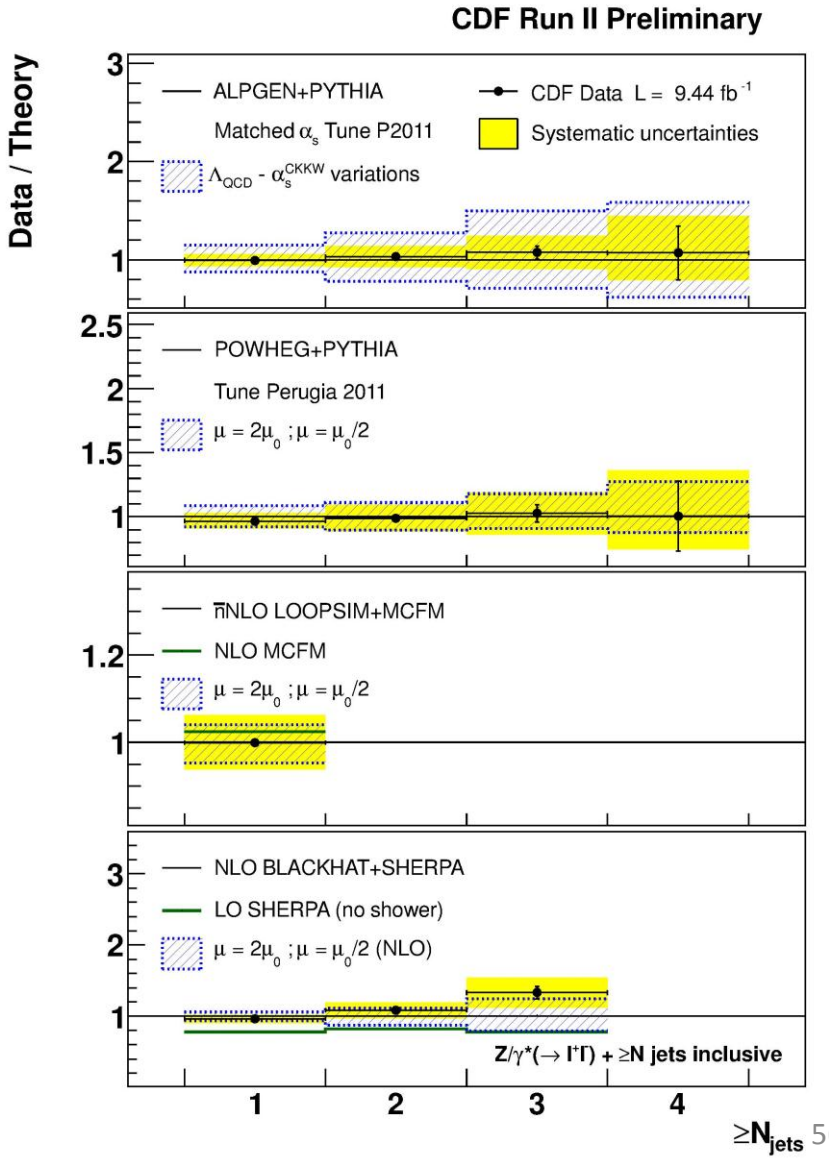




9.4 fb^{-1} $Z/\gamma^*(\to ll)$ +jet(s)







9.1 fb^{-1} $Z/\gamma^*(\to ll)$ + b-jet