QCD Results at LHC

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On behalf of ATLAS & CMS Collaborations

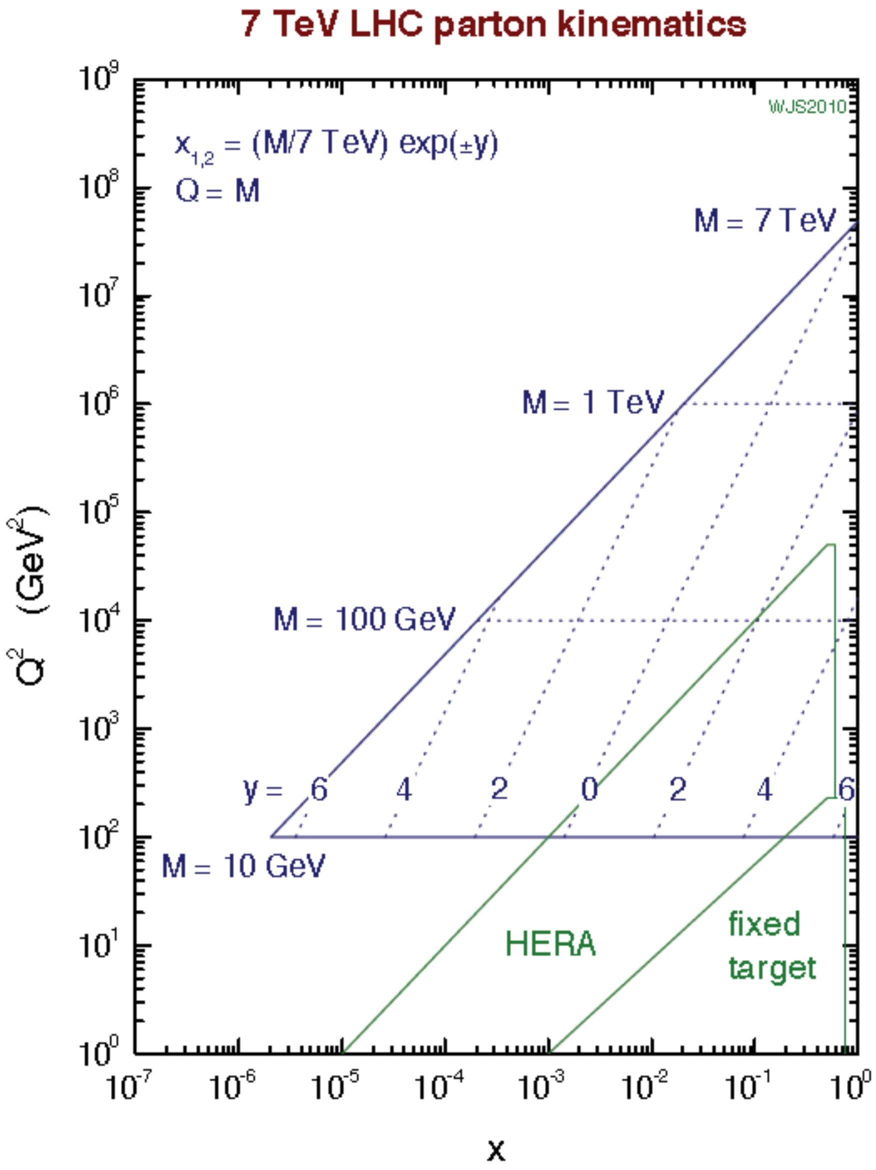
Rencontres de Moriond
March 2nd - 9th, 2013 EW interactions and Unified Theories

- Introduction
- Jet reconstruction
- Jet Energy Scale and Resolution
- QCD with Jets:
  - Inclusive jet cross section
  - Dijet cross section
  - Three to two jet ratio
  - Jet mass and substructure
  - Dijet angular distributions
- Photon reconstruction and Identification
- QCD with Photons:
  - Inclusive photon production
  - Diphoton production
- Summary Conclusions

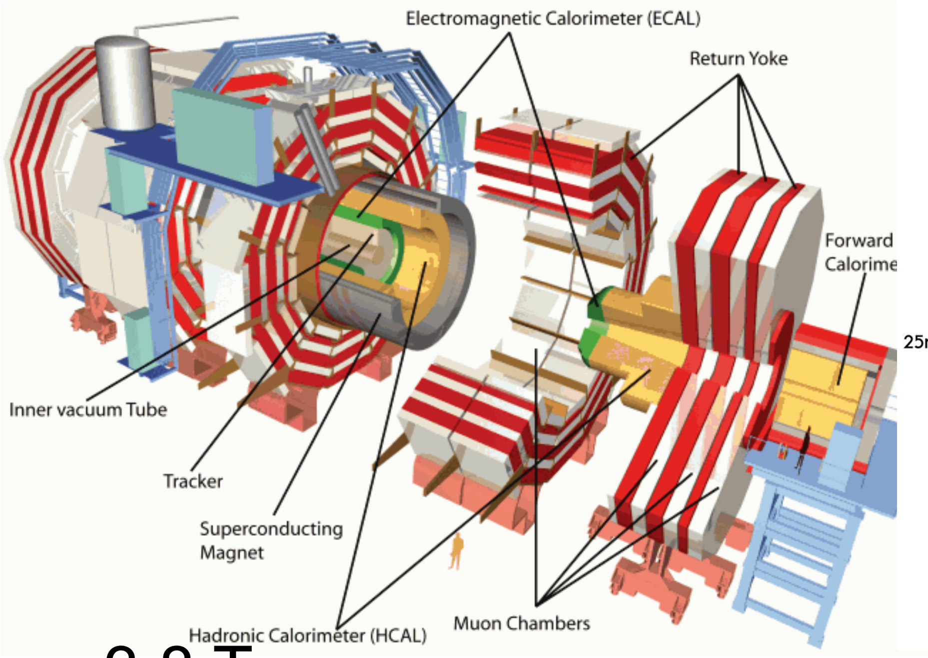
A small selection of results, cannot show everything!!

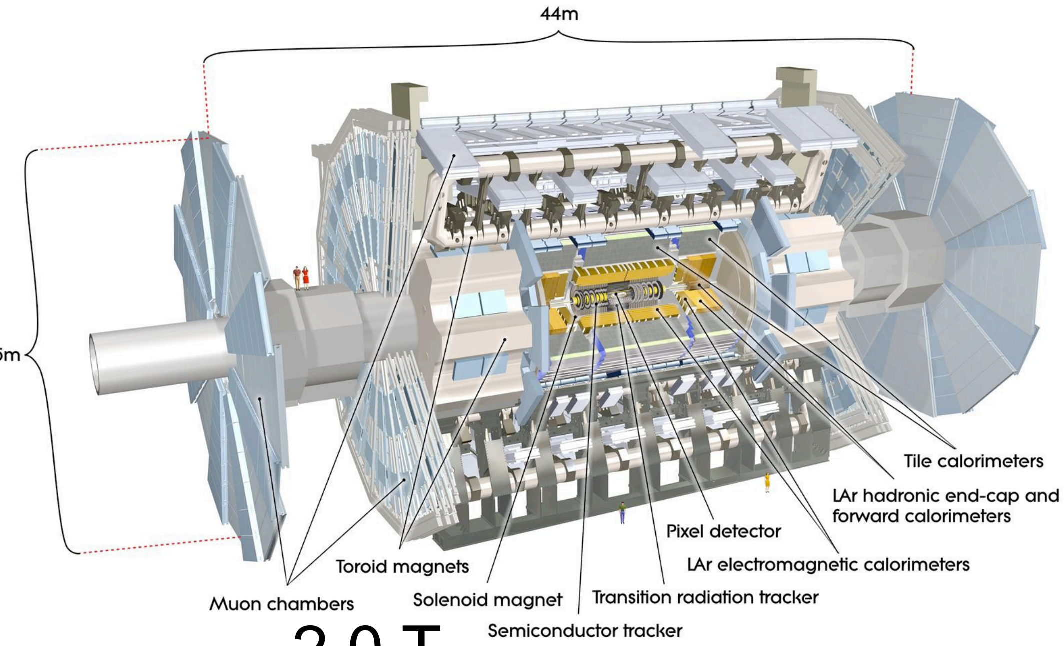
Introduction

- QCD measurements are of great important in order to:
  - **Test pQCD in a new energy regime, in a totally unexplored kinematic region.**
  - **Provide constraints on PDFs, measure strong coupling constant, study initial and final state radiation and parton showering effects.**
  - **Tune Monte Carlo generators in order to better describe the data.**
  - **Measure and understand the main background to most new physics searches, *or get a chance to have a first glimpse of something new and unexpected*.**



ATLAS and CMS Experiments





3.8 T

Pixels

σ/pT~ $1.5 \cdot 10^{-4}$pT(GeV)⊕0.005

Electromagnetic Calorimeter

σE/E ≈ 2.9%/√E(GeV) ⊕ 0.5%⊕0.13GeV/E

Hadronic Calorimeter

σE/E ≈ 120%/√E(GeV) ⊕ 6.9%

Muon Spectrometer

σpT/pT ≈ 1% for low pT muons

σpT/pT ≈ 5% for 1 TeV muons

2.0 T

Pixels,Si strips & Straw tubes

σ/pT~ $3.8 \cdot 10^{-4}$pT(GeV)⊕0.015

Electromagnetic Calorimeter

σE/E ≈ 10%/√E(GeV)⊕0.7%⊕0.2GeV/E

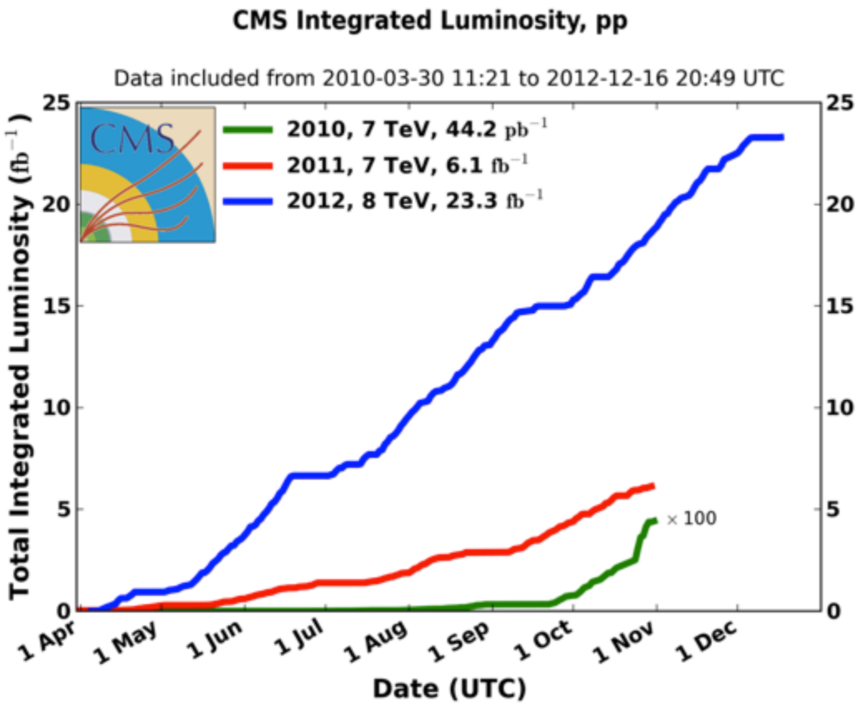
Hadronic Calorimeter

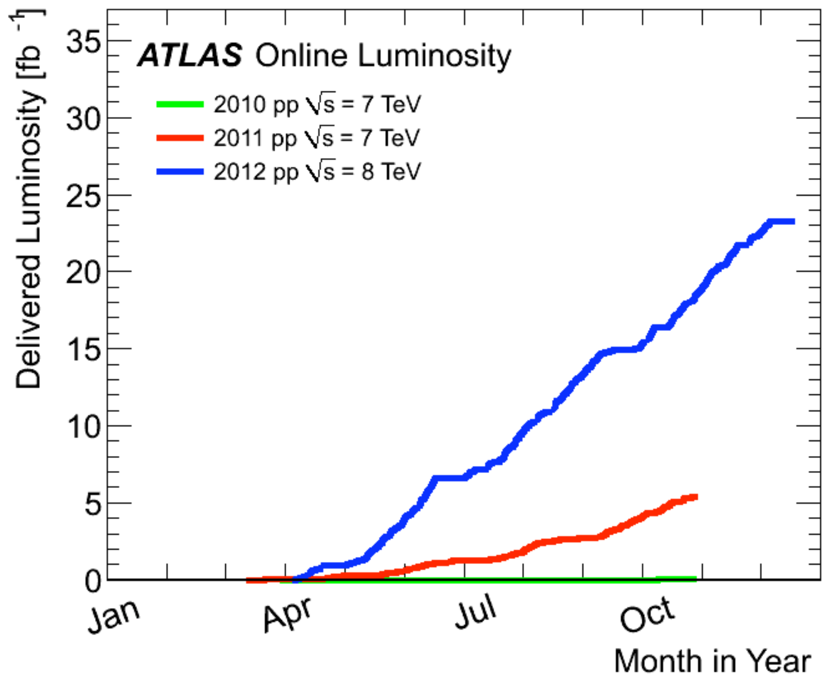
σE/E ≈ 60-100%/√E(GeV) ⊕ 3%

Muon Spectrometer

σpT/pT <10 % up to 1 TeV muons

Data Collection



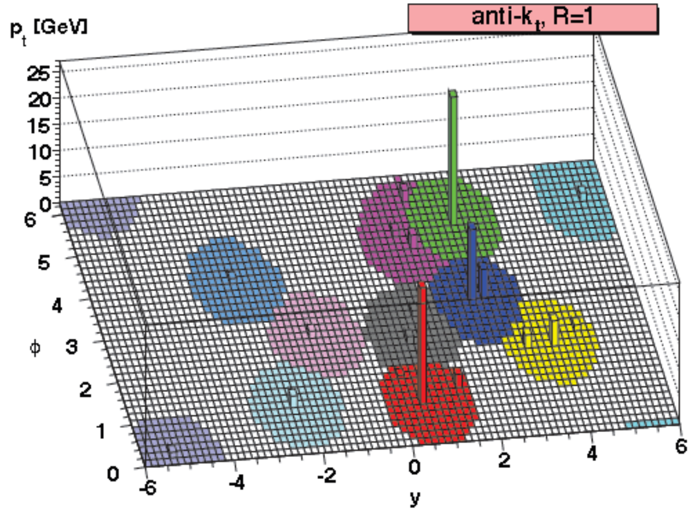


Most of the measurements shown in this talk are from the 7 TeV running period

Some new results from 8 TeV are also going to be shown

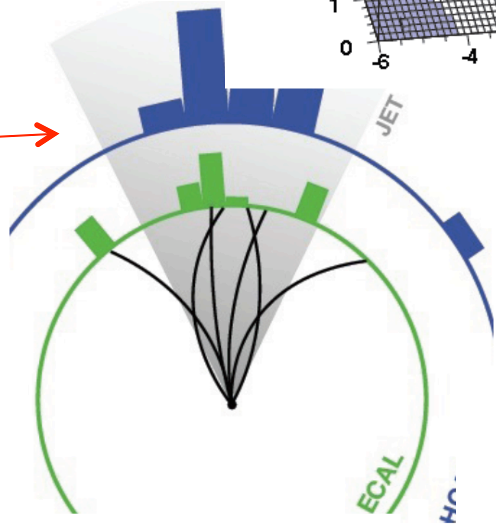
All results shown can be found at:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

Jet Reconstruction

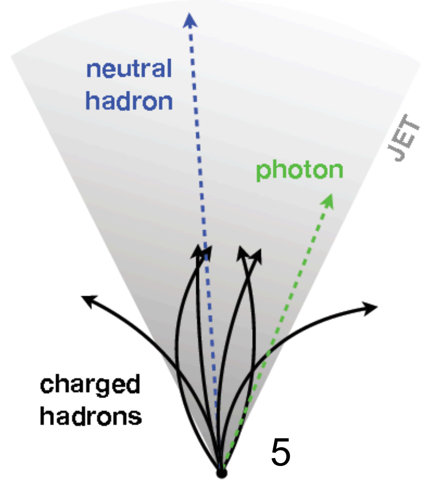


- **Anti-kt clustering algorithm :** with a cone R = 0.5 and 0.7 for CMS and 0.4 and 0.6 for ATLAS, which is infrared and collinear safe, geometrically well defined, and tends to cluster around the hard energy deposits.

- **Calorimeter Jets (ATLAS + CMS) :** Clustering of Calorimeter Towers composed of ECAL and HCAL energy deposits.

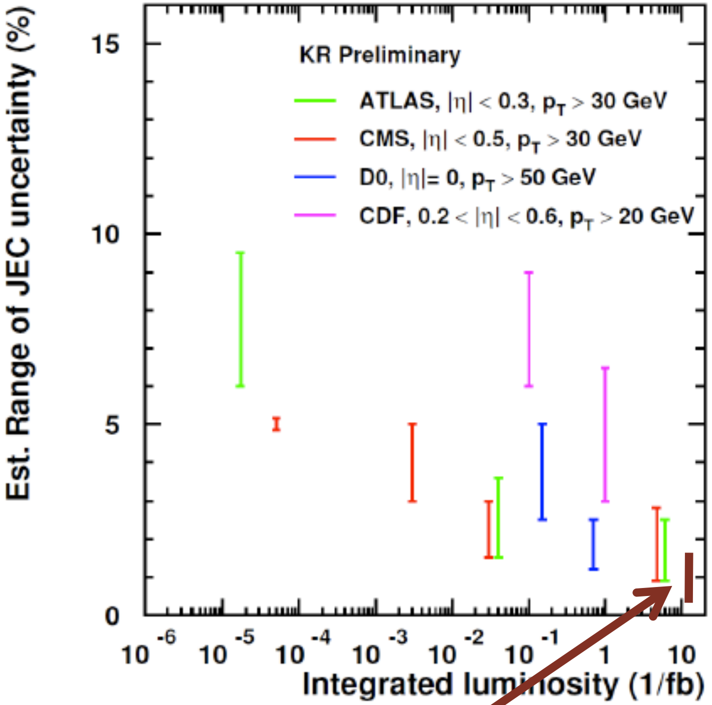


- **Particle Flow Jets (CMS) :** Clustering of Particle Flow candidates constructed combining information from all sub-detector systems.



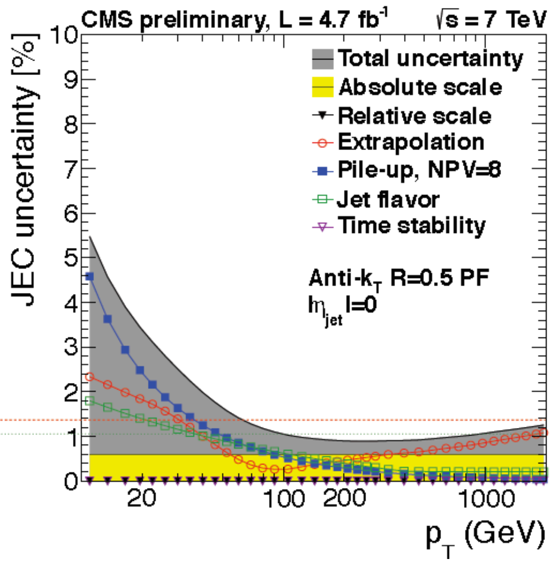
Jet Energy Scale

Plot courtesy: K. Rabbertz

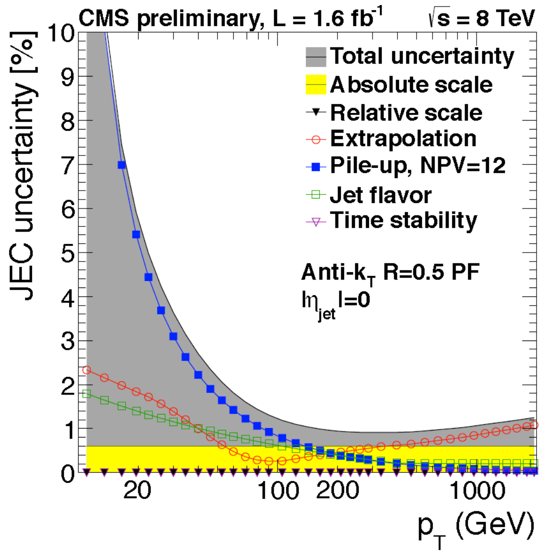


Now at the 1% level!

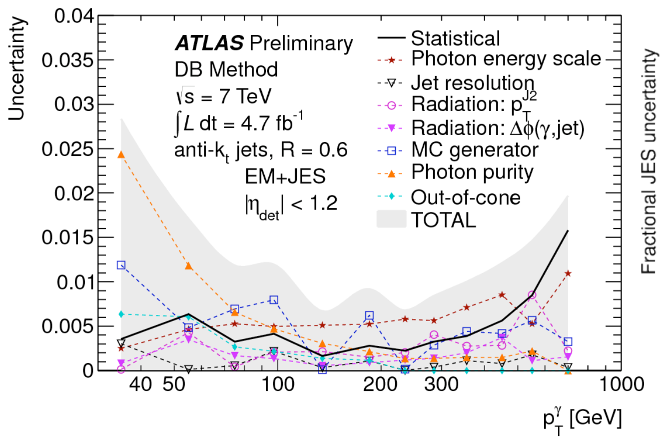
CMS 7 TeV



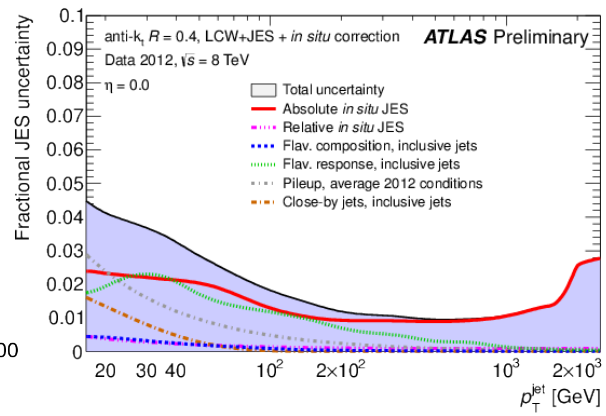
CMS 8 TeV



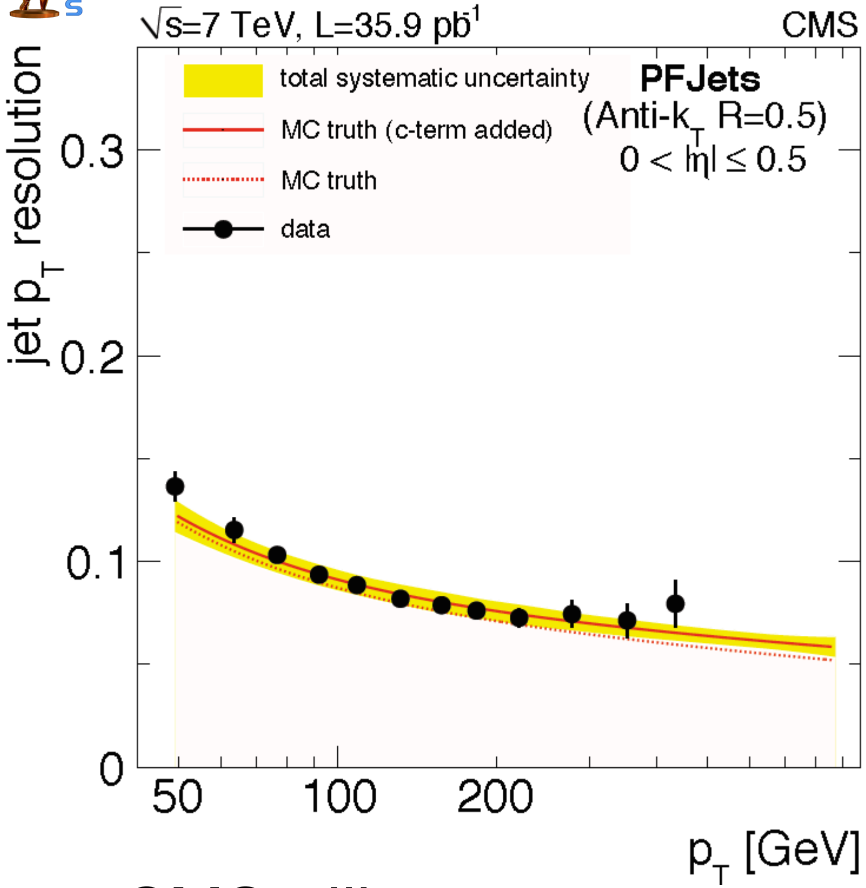
ATLAS 7 TeV

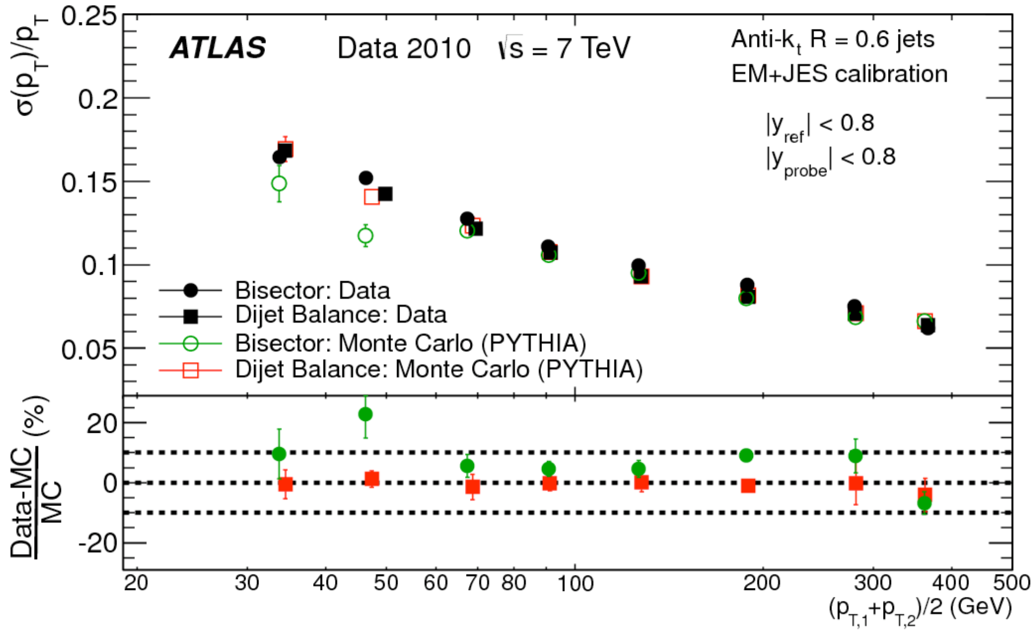


ATLAS 8 TeV



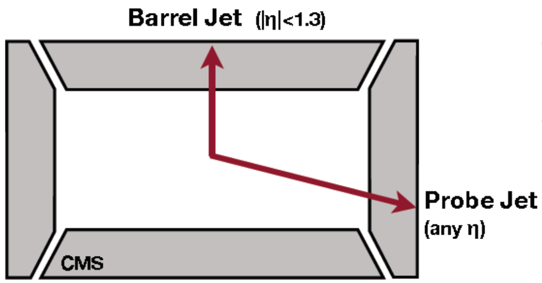
Jet Energy Resolution

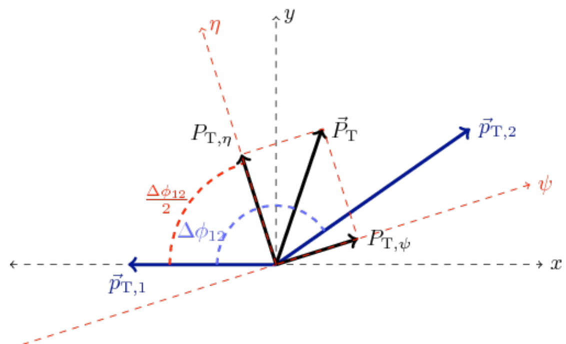




CMS dijet asymmetry

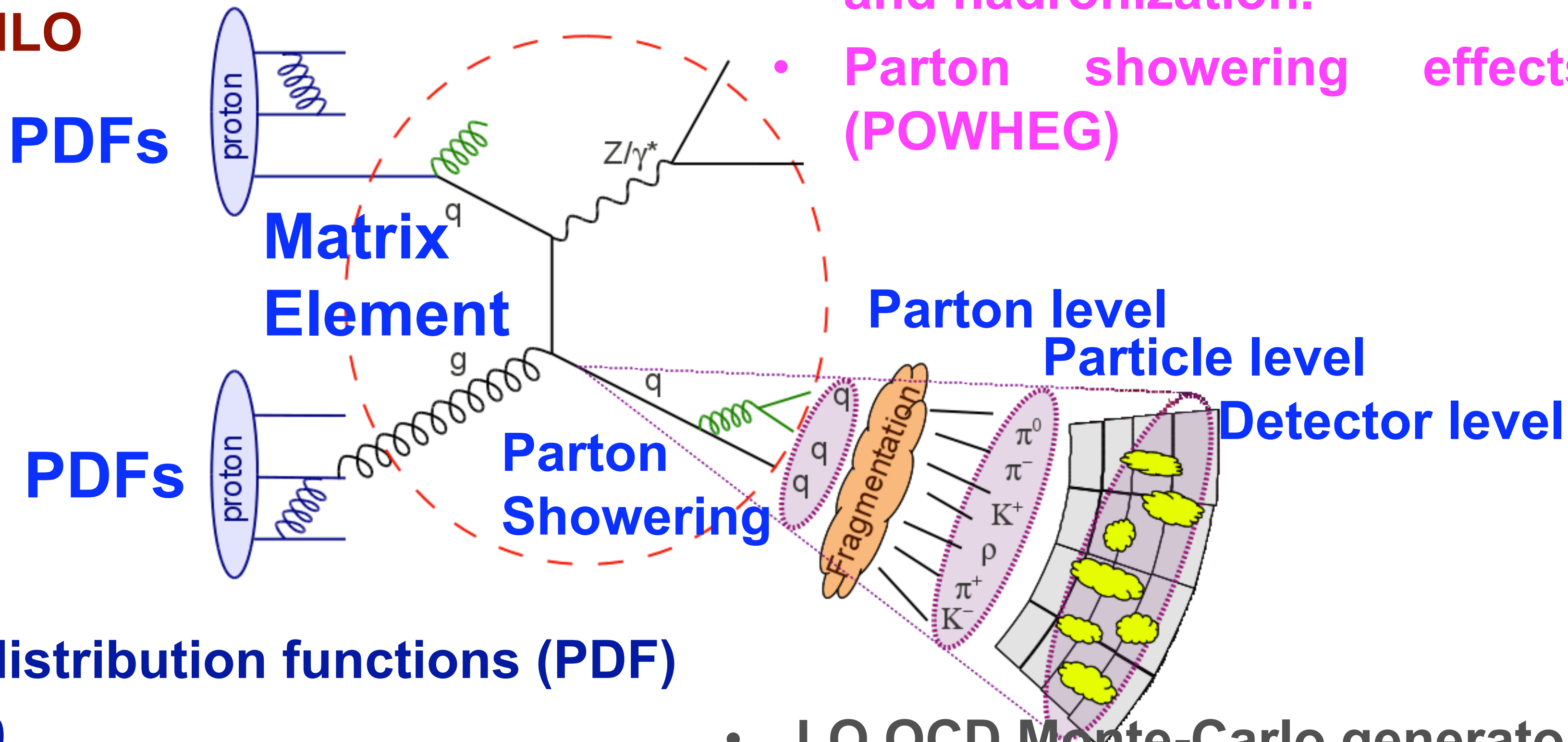
ATLAS bisector method





Theoretical Tools

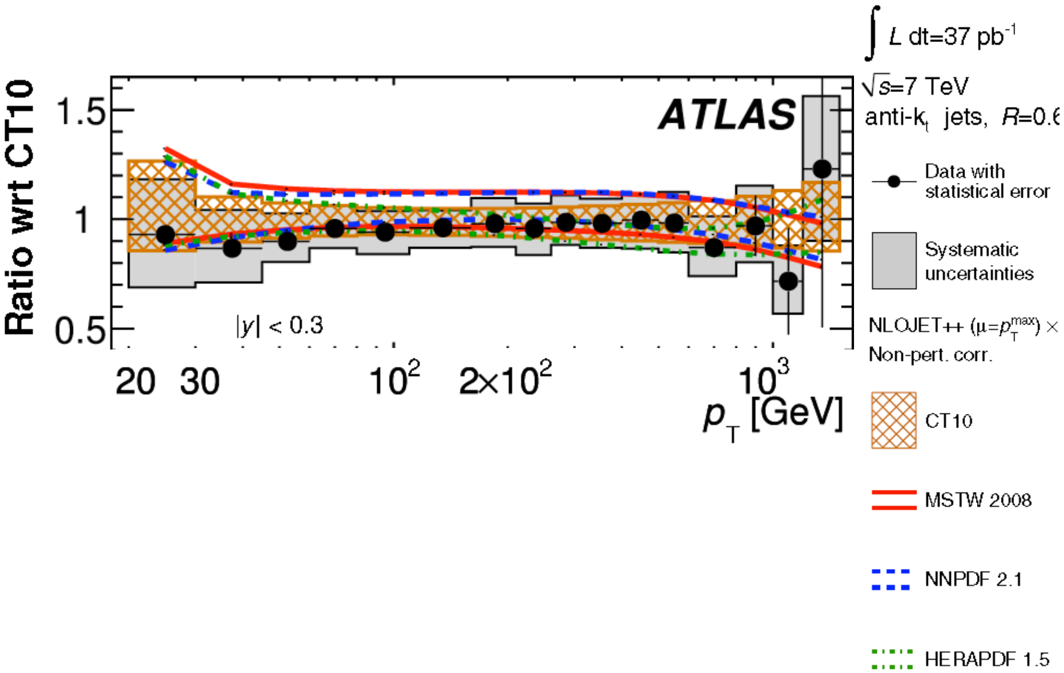
- Perturbative QCD calculations @ NLO
  - NLOJet++/JETPHOX
  - fastNLO
- Non-perturbative corrections for multi-parton interaction and hadronization.
- Parton showering effects (POWHEG)

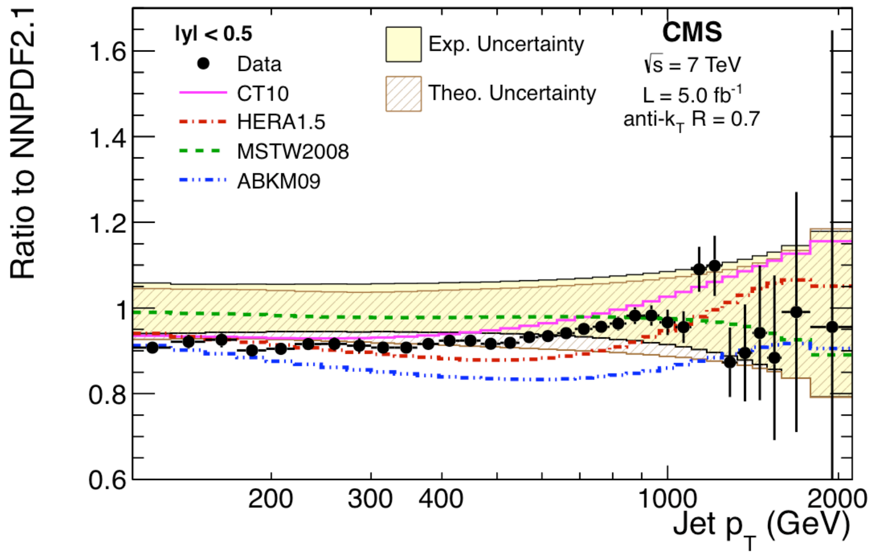


- Parton distribution functions (PDF)
  - CT10
  - MSTW2008
  - NNPDF2.1
  - HERAPDF1.5
  - ABKM09, ABKM11
- LO QCD Monte-Carlo generators
  - PYTHIA6, PYTHIA8
  - HERWIG++
  - ALPGEN
  - MADGRAPH

Inclusive Jet Cross Sections : 7 TeV

$$\frac{d^2\sigma}{dp_T d|y|} = \frac{C_{unfold}}{\varepsilon \cdot L} \cdot \frac{N_{jets}}{\Delta p_T \Delta|y|}$$





- CMS 5 fb^{-1} results submitted to PRD, full error correlation matrices will be available

- Some PDFs describe the data better than others : these measurements useful for PDF tuning and for constraining PDFs

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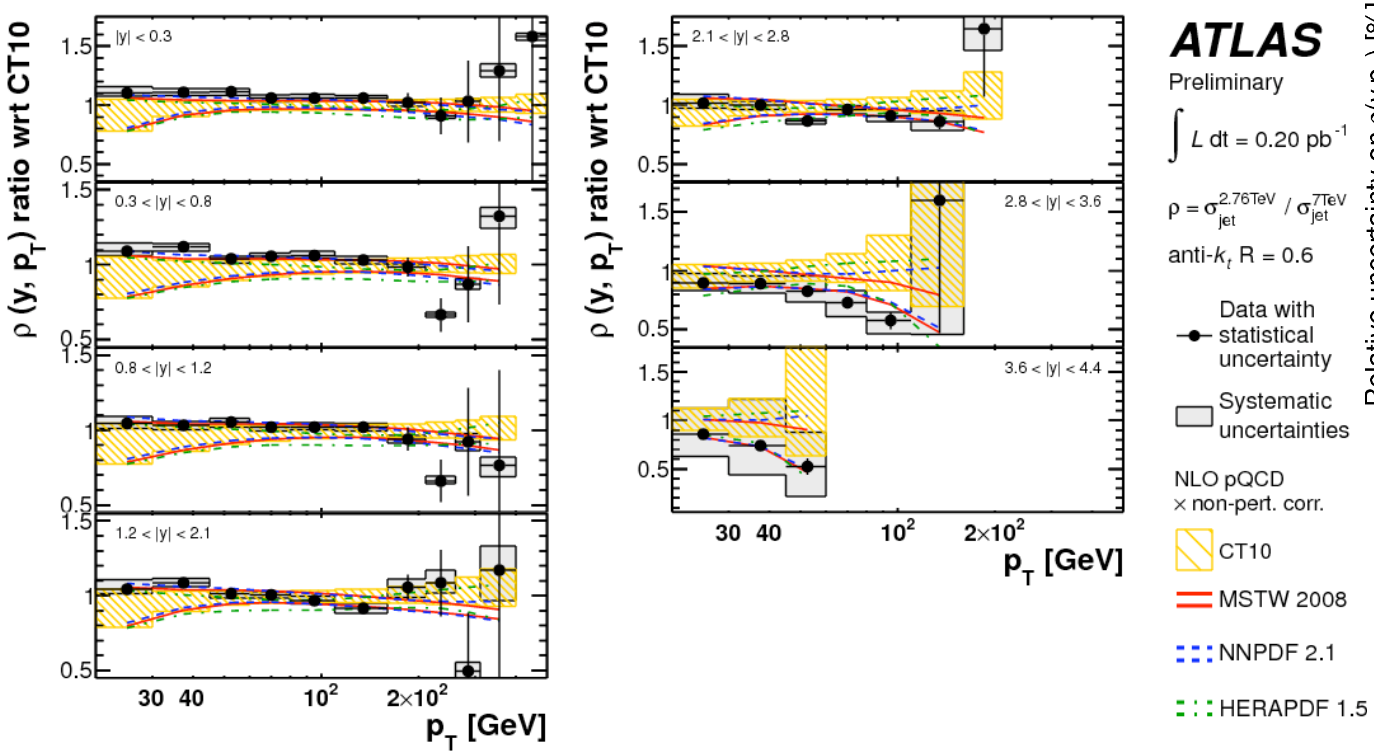
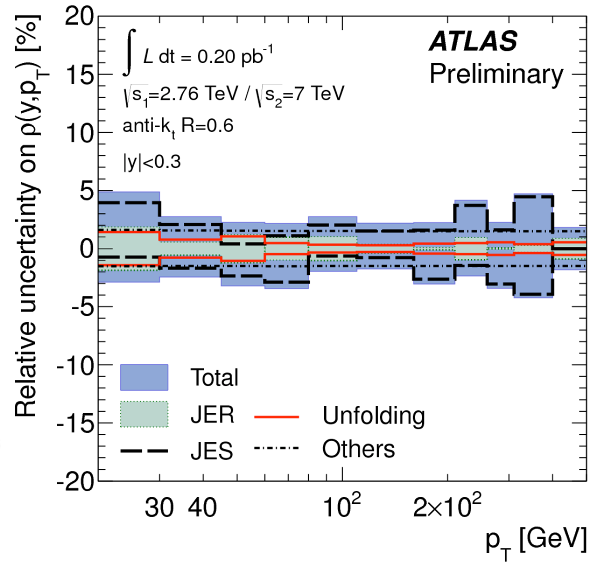
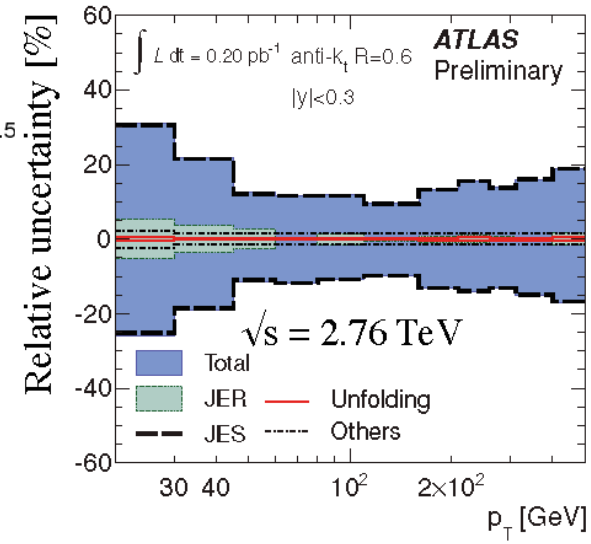
Inclusive Jet Cross Sections ATLAS 2.76 / 7 TeV Ratio

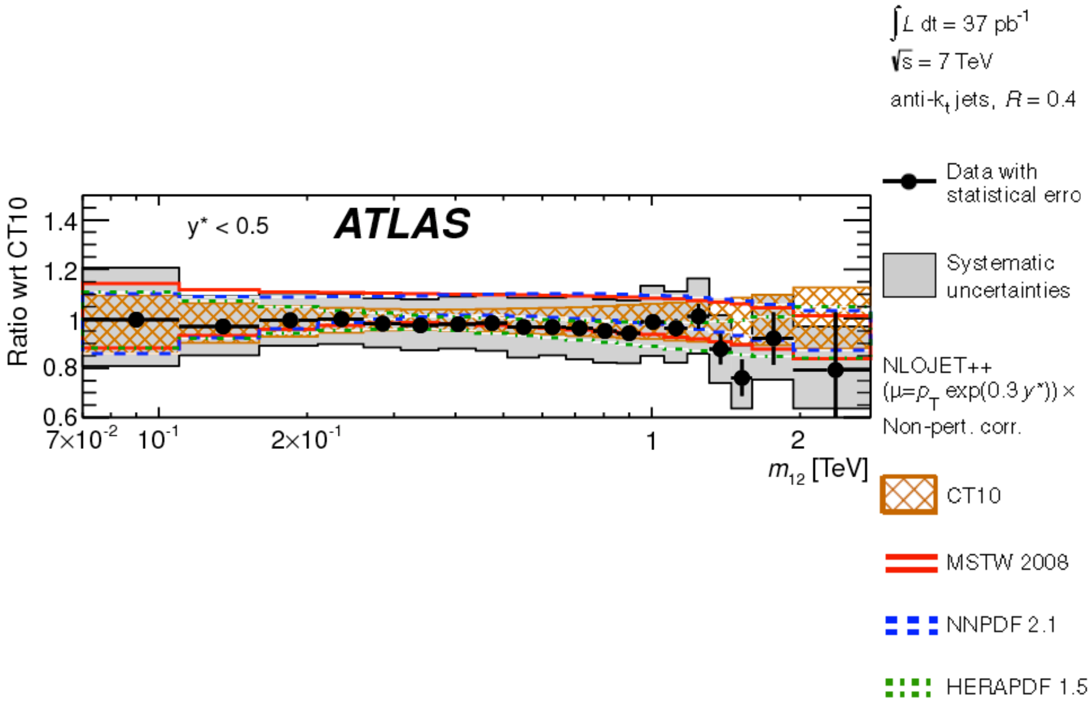


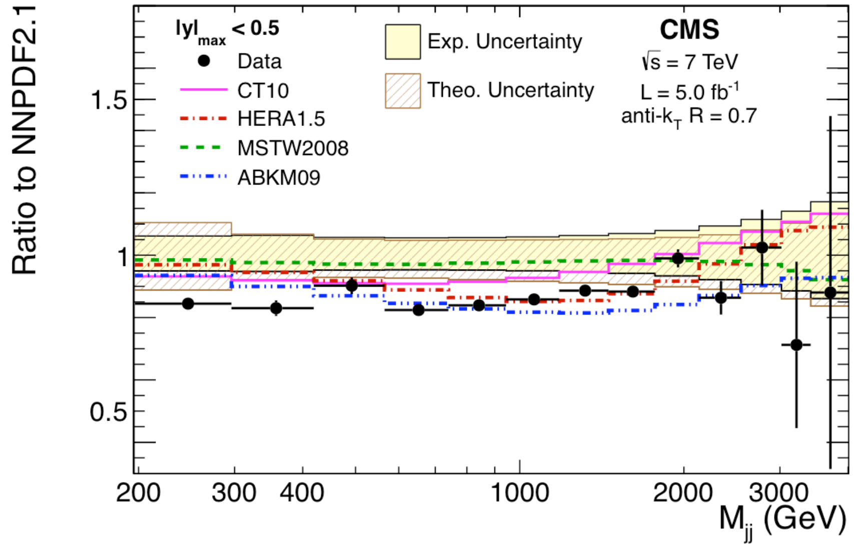




- Most of the experimental uncertainties cancel out in the ratio.
- Ratios of cross sections useful in order to constraint and differentiate between different PDF sets.

Dijet Cross Sections : 7 TeV

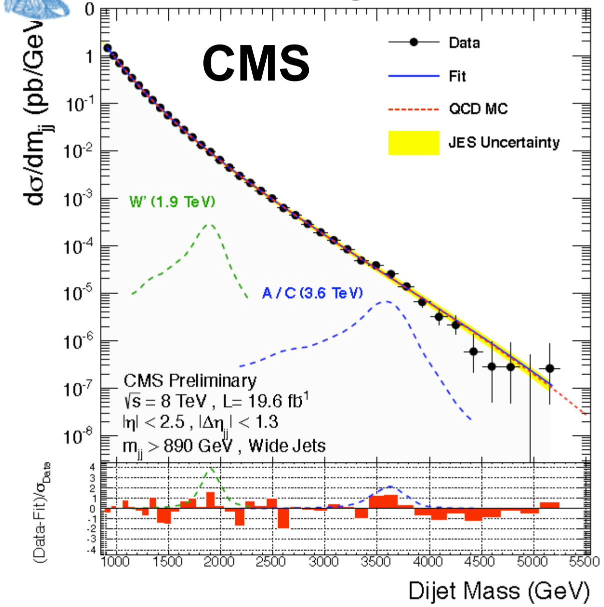


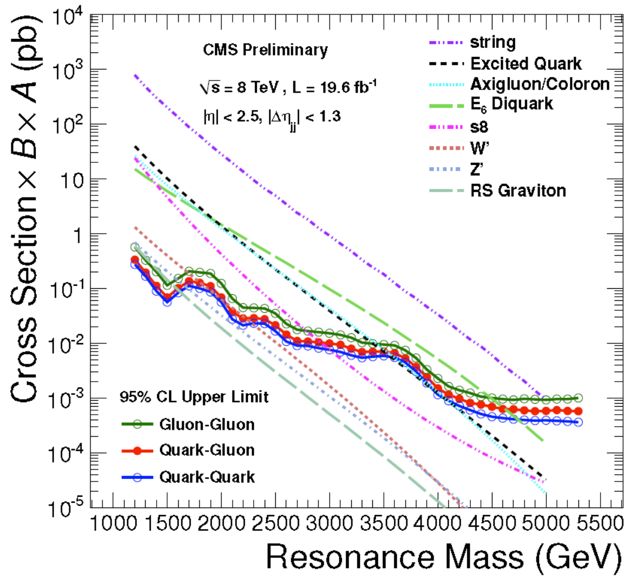


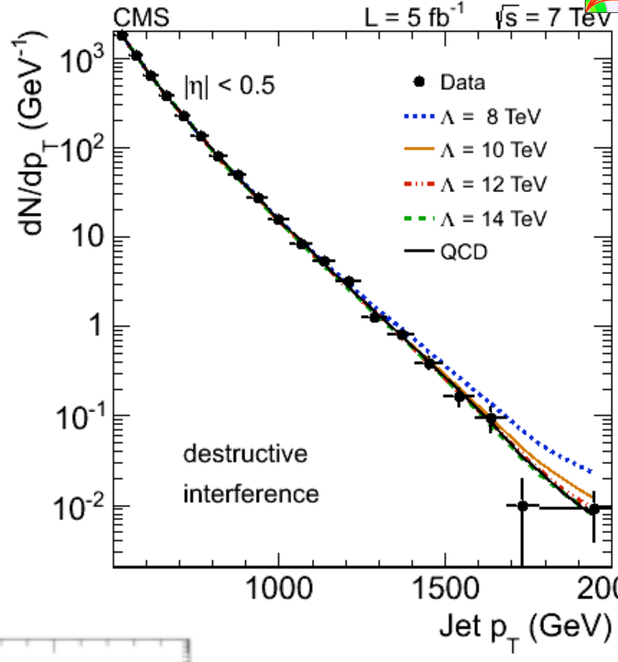
CMS and ATLAS results ~ consistent (given slight differences like cone-sizes, y definitions)

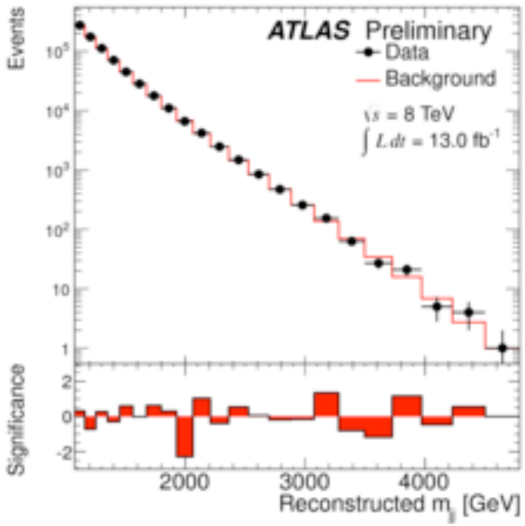
Some PDFs describe the data better than others : these measurements useful for PDF tuning and for constraining PDFs

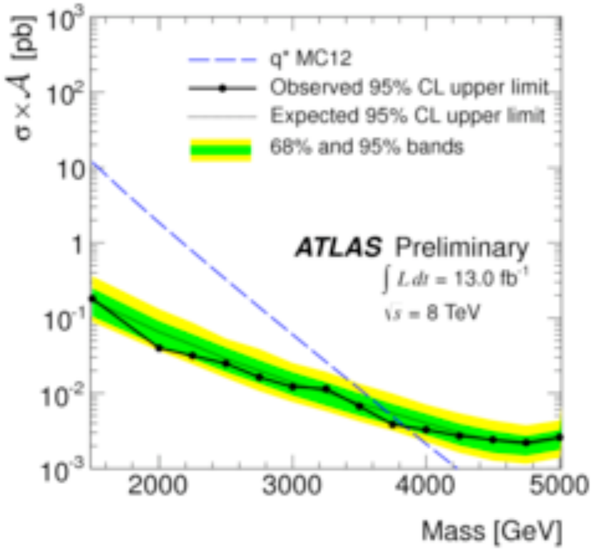
Dijet – Inclusive Jet spectra & NP











- If NP is present it will show up in the “standard” QCD measurements!
- Standard QCD measurements, PDF tuning and uncertainties , VERY important for NP searches!!

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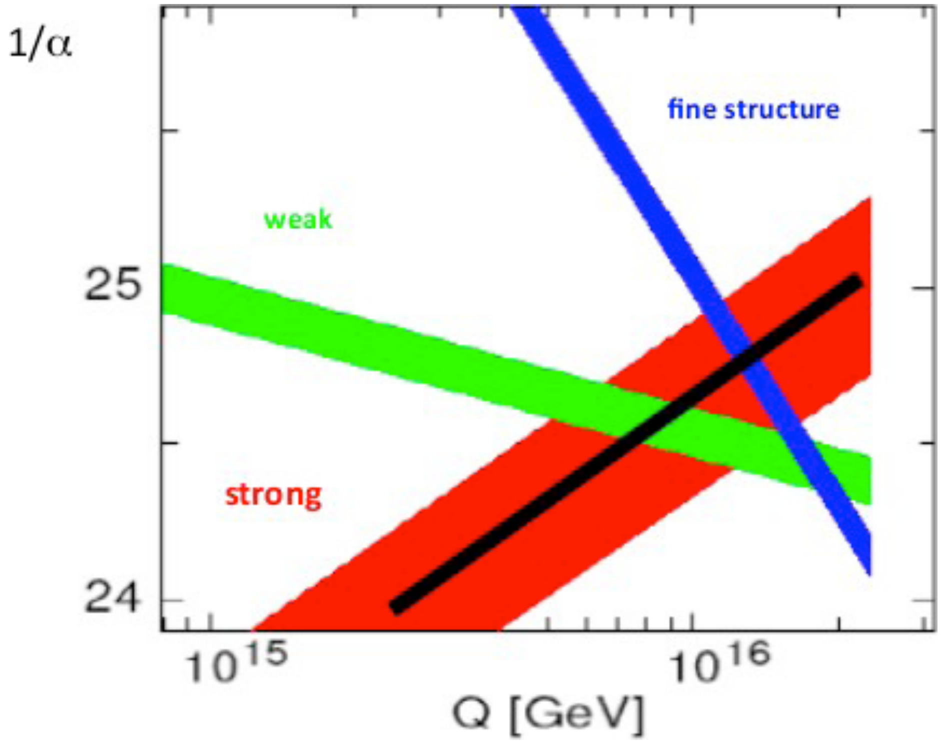
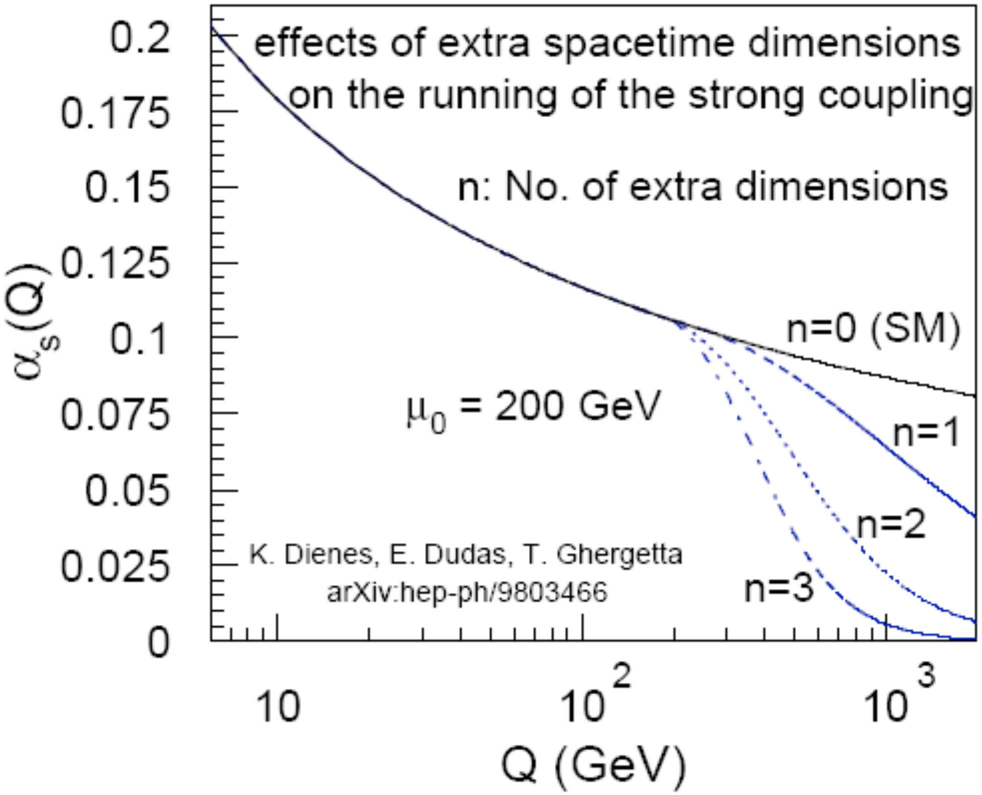
The strong coupling constant : α_S

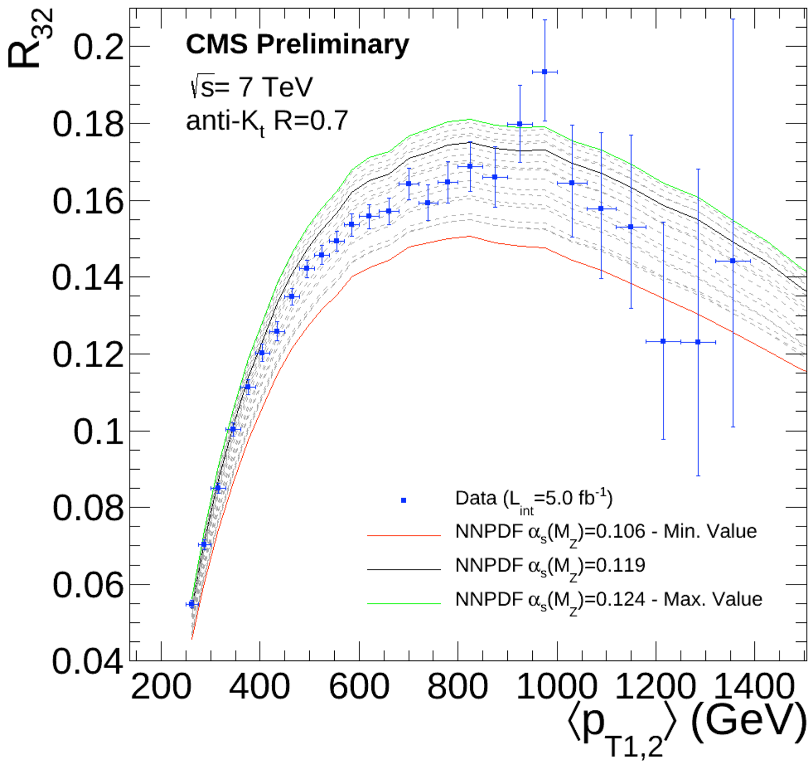


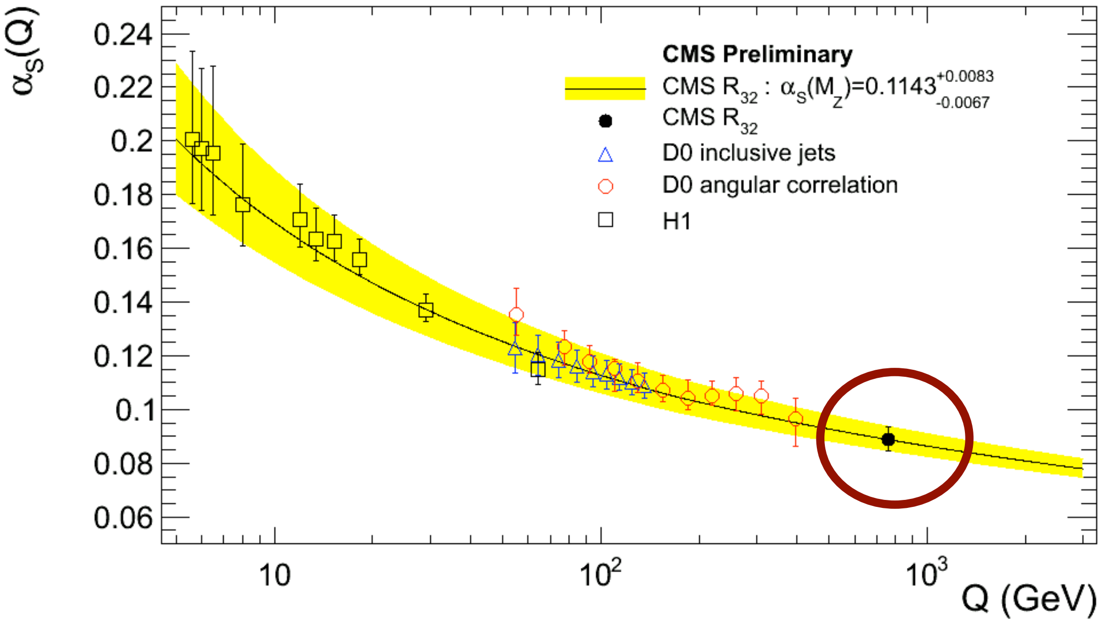


- **Fundamental QCD quantity**
- **Least known of the three coupling constants.**
- **Running of α_S sensitive to new physics!**

Three to two jet ratio and α_s

CMS

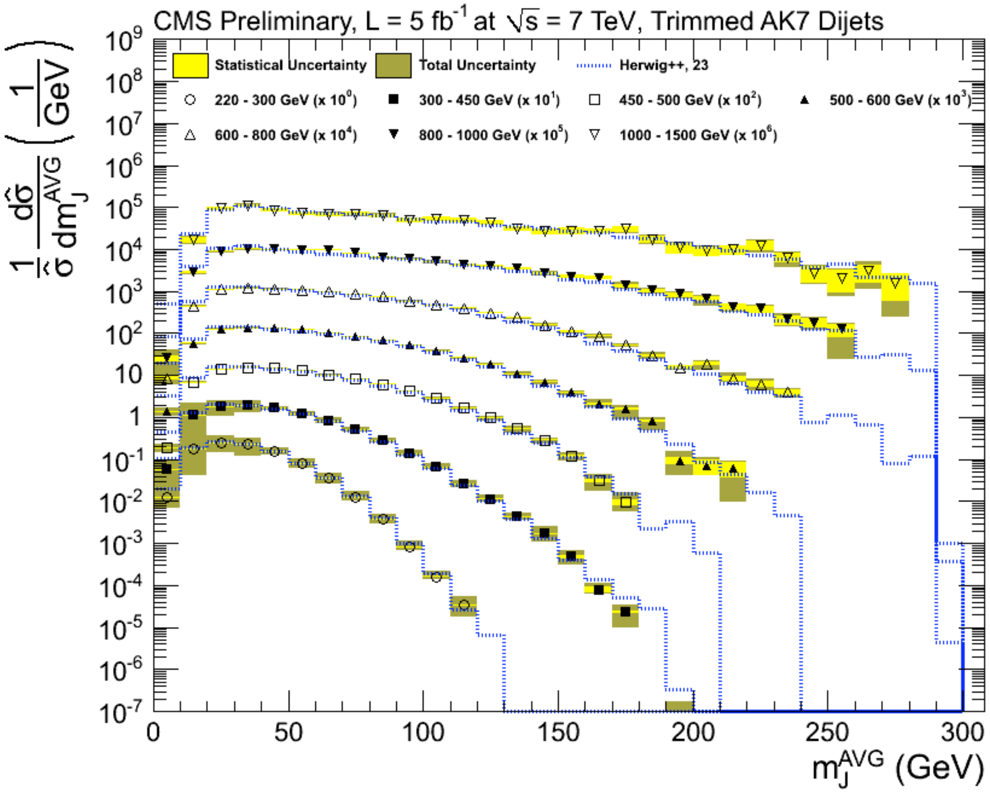


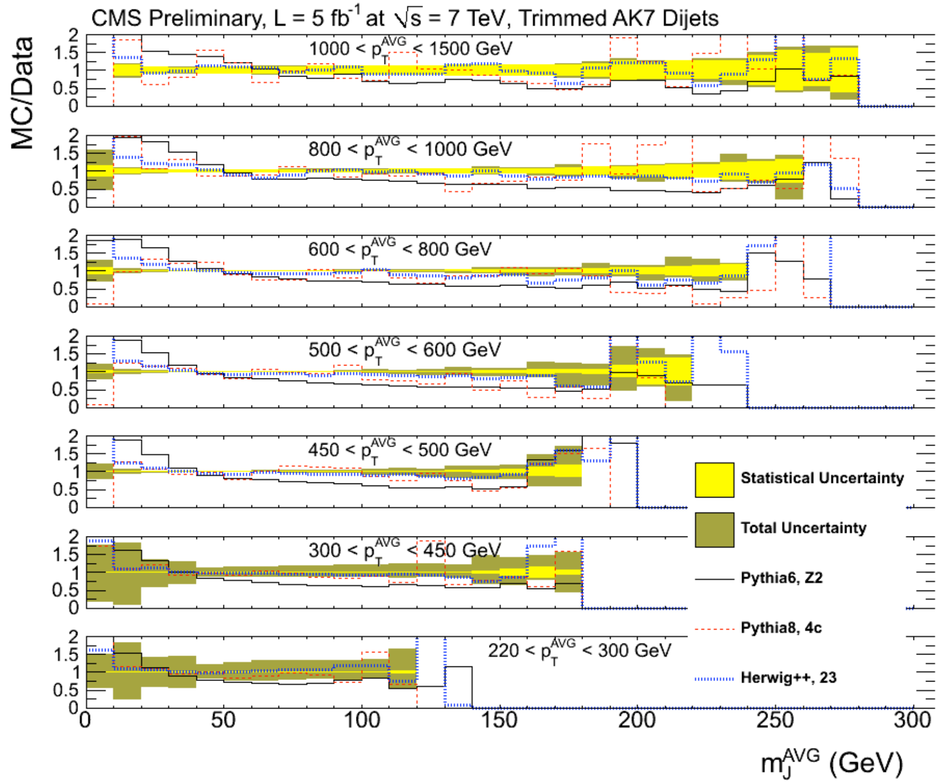


- **Ratio mostly insensitive to many systematic effects**
- **Ratio sensitive to the strong coupling constant.**
- **First and very precise measurement at the TeV scale.**

CMS **New**

Jet Mass





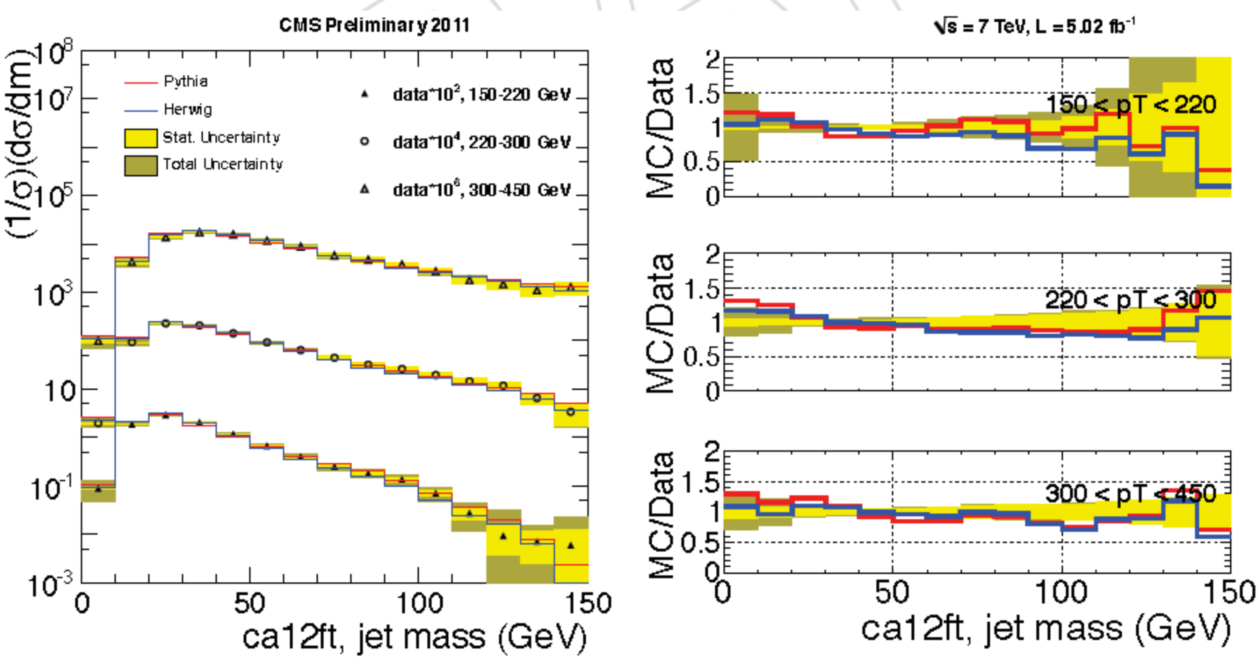
- Jet mass used to discriminate between massive (SM or new physics) particles decaying to jets from QCD.

- Jet "grooming" techniques are designed to separate jets from the decay of heavy boosted particles from quark/gluon initiated jets with large mass.

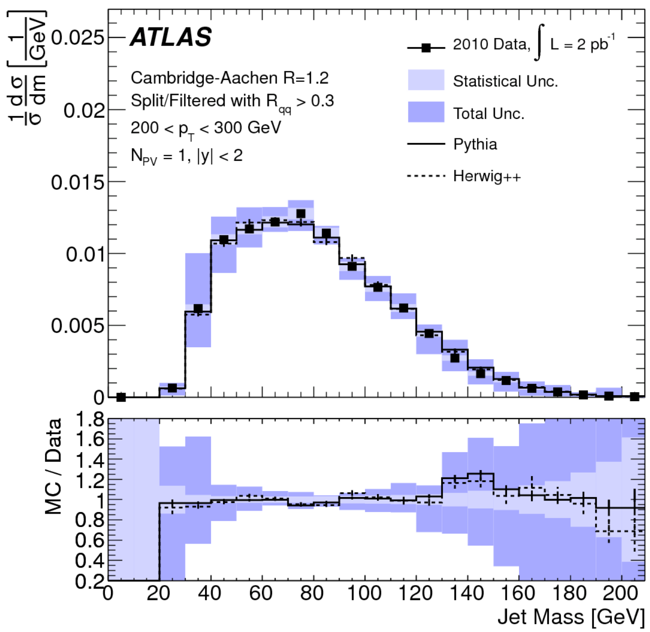
Jet Mass

C.A R=1.2 Algorithm
MCs used : Pythia, Herwig++

CMS **New**



ATLAS



Z+jets

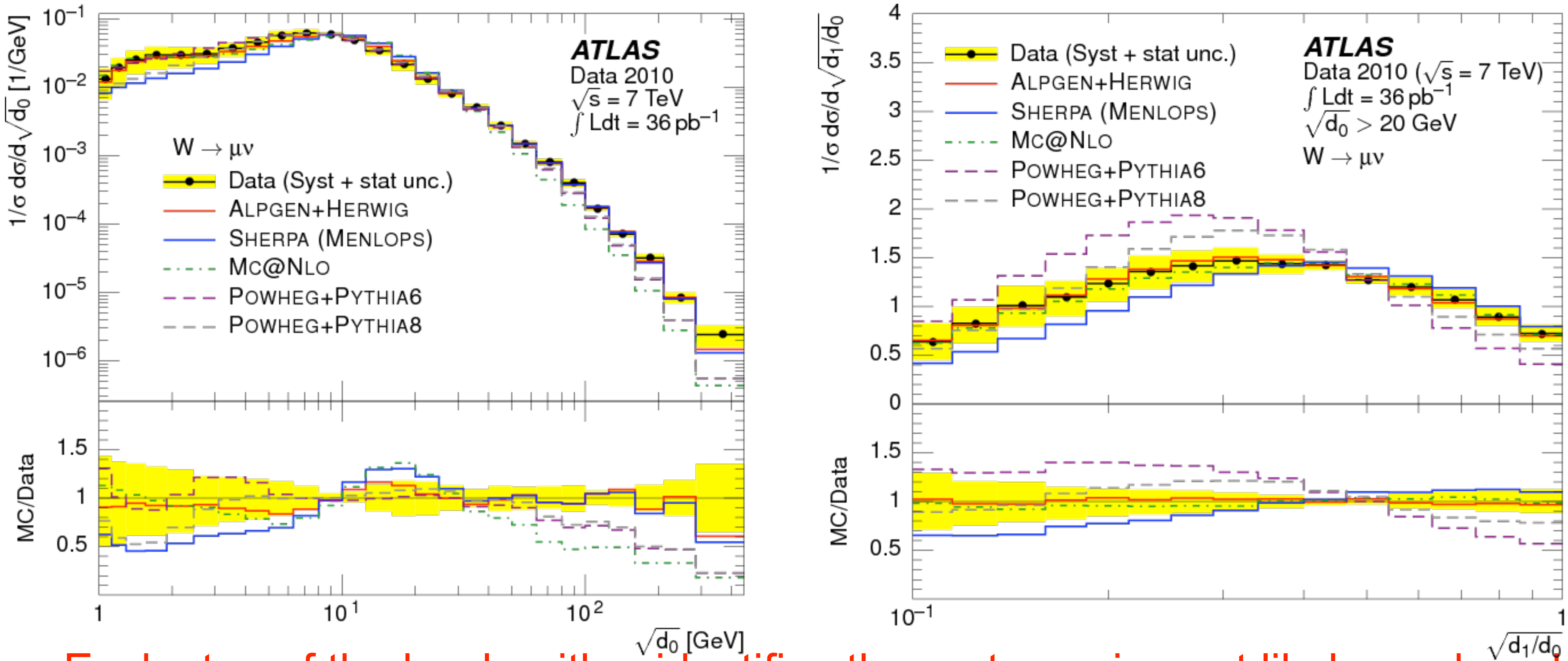
Jets

Better agreement with MC using V+jets events with CMS : better simulation response for quark-originated jet w.r.t. gluon ones.

k_T splitting scales

ATLAS **New**

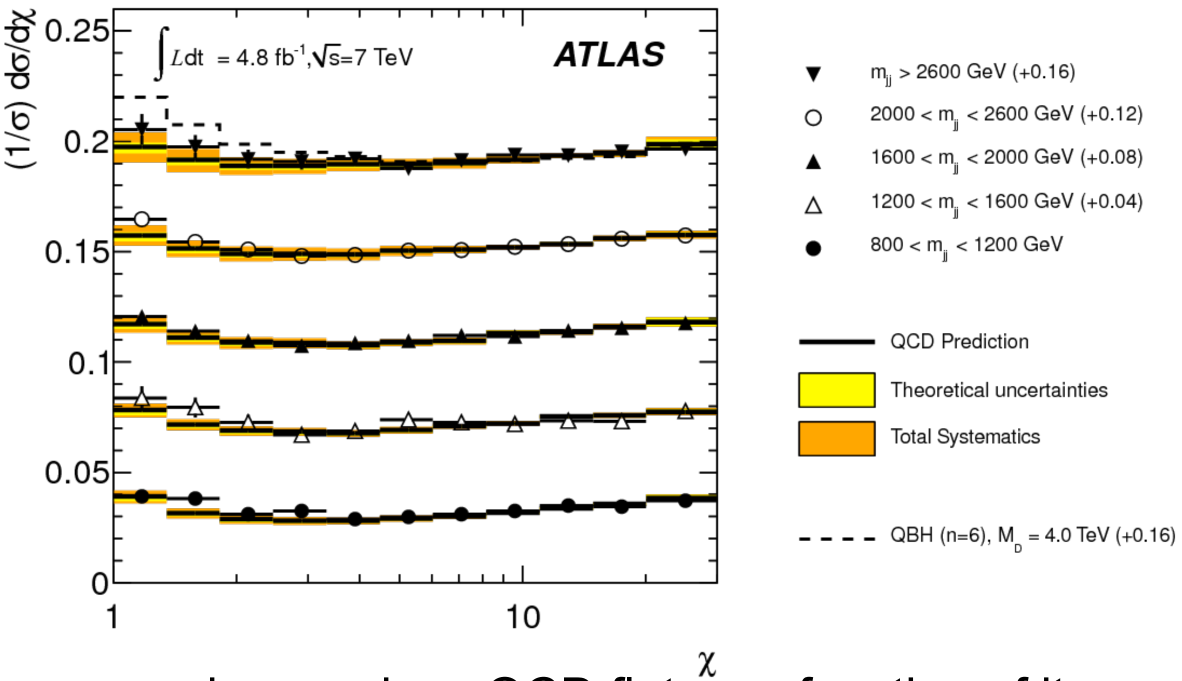
$\sqrt{d_0}$ ~ the transverse momentum of the highest-pT jet

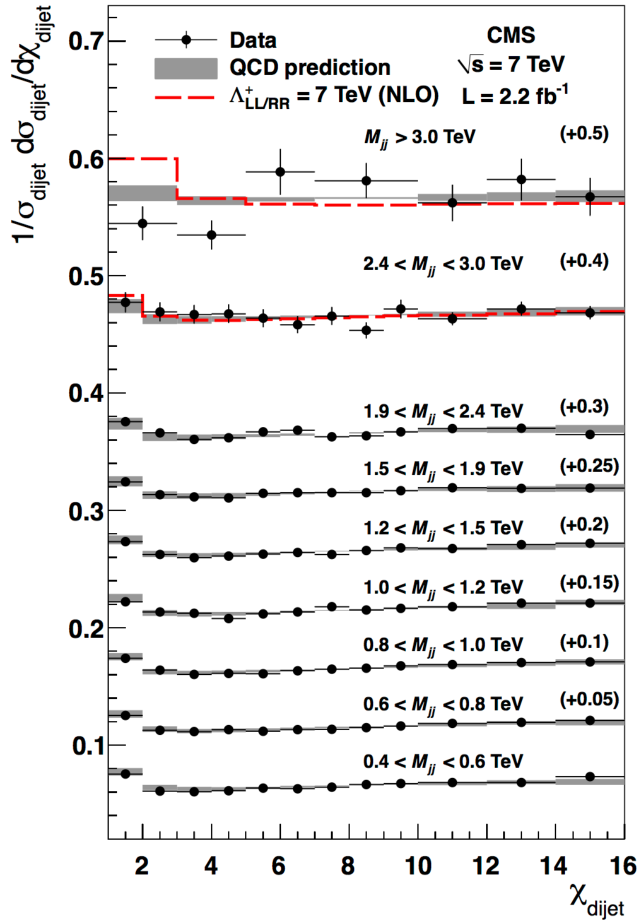


- Each step of the k_T algorithm identifies the parton pair most likely produced by QCD interactions and hence mimics the reversal of QCD evolution. Aim of measurement is to improve theoretical modeling of QCD effects.
- The $\sqrt{d_k}$ contain information about the p_T spectra and substructure of jets
- The "hard" region ($\sqrt{d_k}$ > 20 GeV) dominated by perturbative QCD effects and the "soft" region dominated by MPI and hadronization

Dijet Angular Distributions

$$\chi = e^{|y_1 - y_2|} \approx \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$



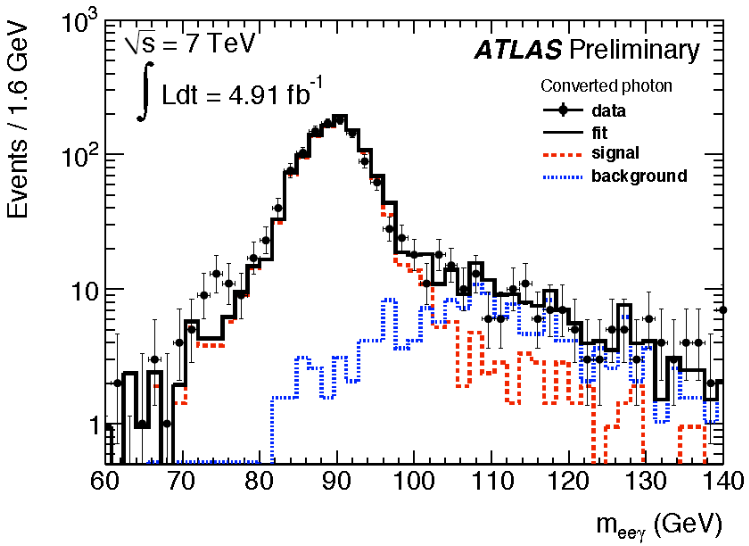


- χ chosen since QCD flat as a function of it .
- Experimental uncertainties dominated by jet resolution and relative (vs η) JES (absolute cancels)
- Theoretical uncertainties dominated by non perturbative corrections and renormalization scale.
- **Good agreement between data and theory. Highest mass bins sensitive to contact interactions.**

Photon reconstruction & identification

- Photons are key objects for both calibration and major discoveries.
- Photons are isolated energy deposits in the ECAL, with no charged track pointing to them, and with a shape compatible with a photon electromagnetic shower.

ATLAS uses calorimetric discriminating variables

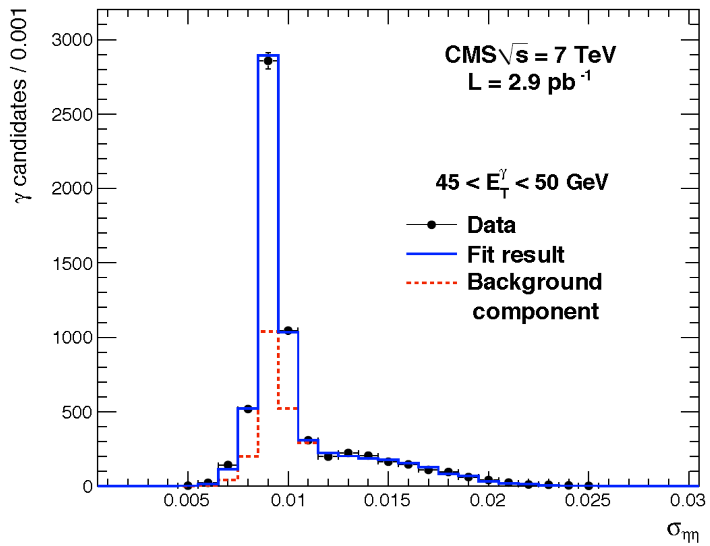


CMS likelihood

Shower Shape Definition

$$\sigma_{i\eta i\eta}^{2} = \frac{\sum(\eta_i - \overline{\eta})^2 w_i}{\overline{w_i}}, \overline{\eta} = \frac{\sum \eta_i w_i}{\sum w_i}$$

$$w_i = \max(0, 4.7 + \log(E_i / E_{5x5}))$$



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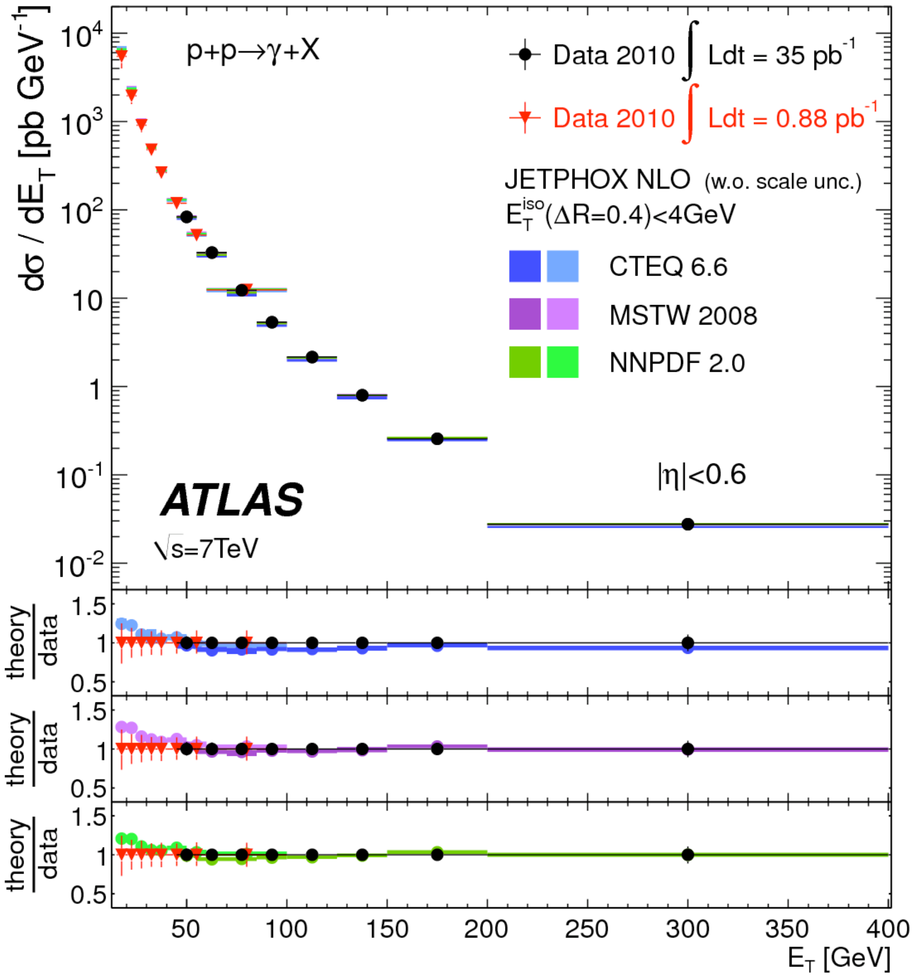
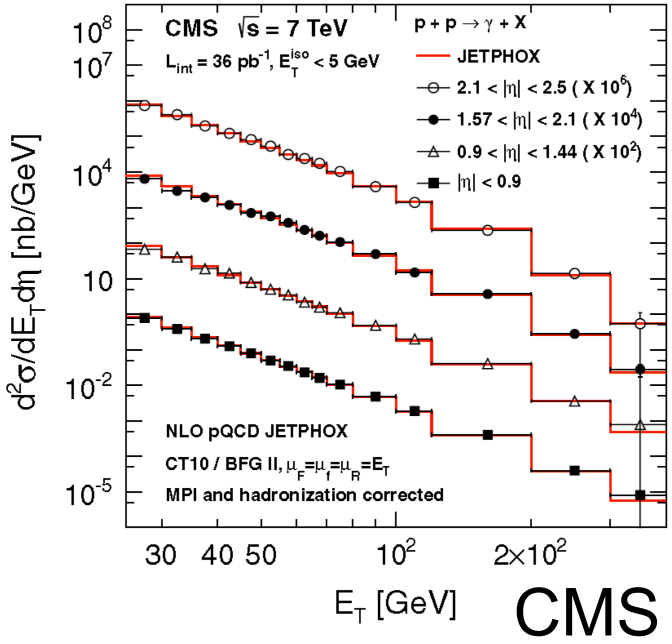
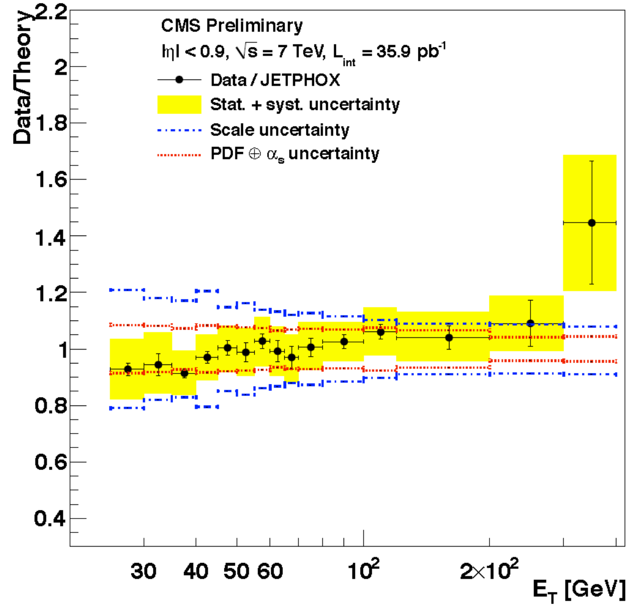
Inclusive Photon Cross Section

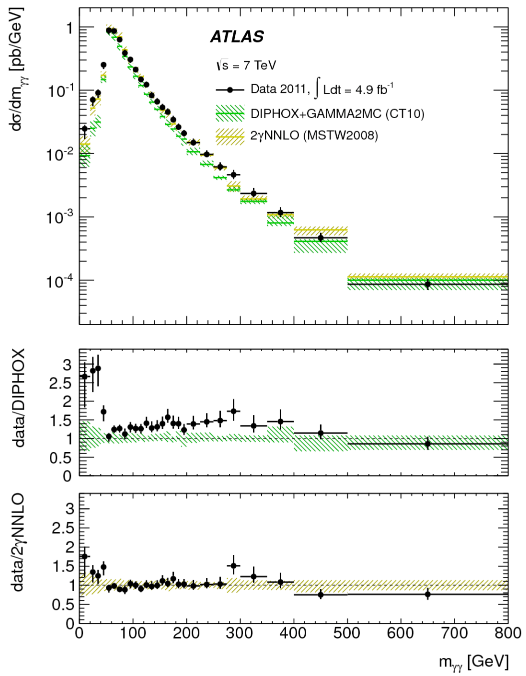






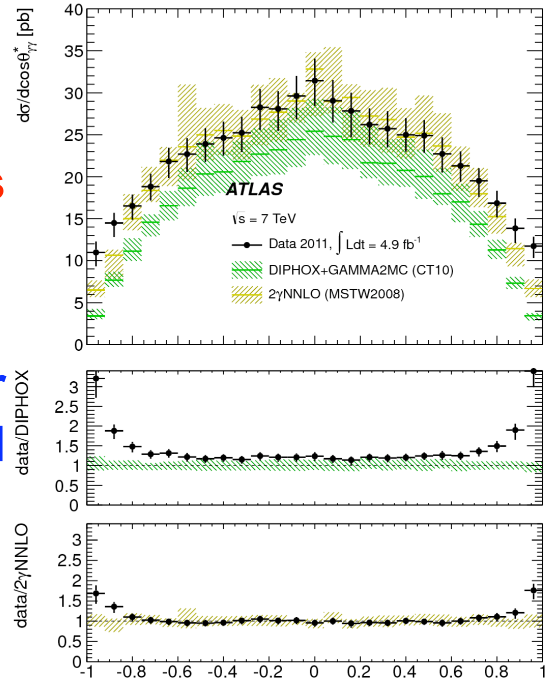
- **Direct photons a direct probe of hard scattering**
- **Potentially sensitivity in PDFs**

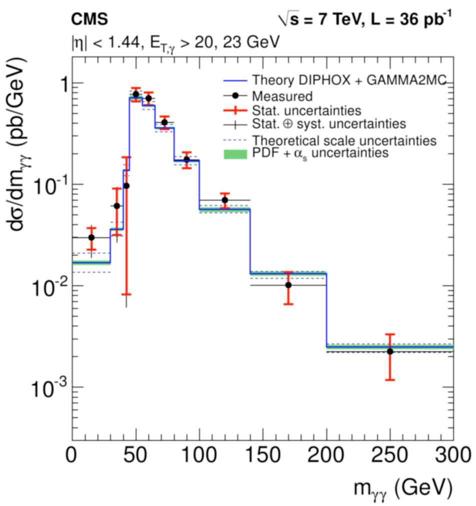
Diphoton Production

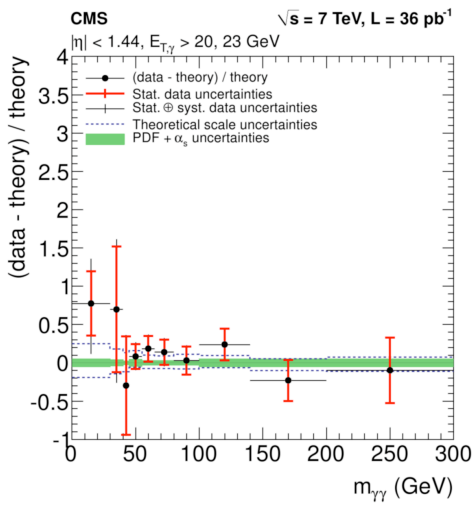


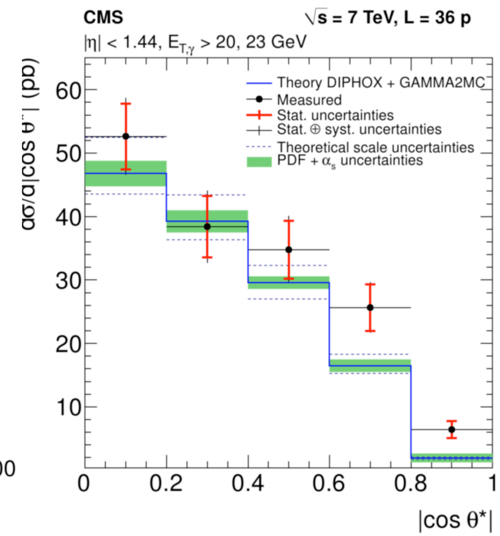
- **Irreducible background to Higgs search and other new phenomena**

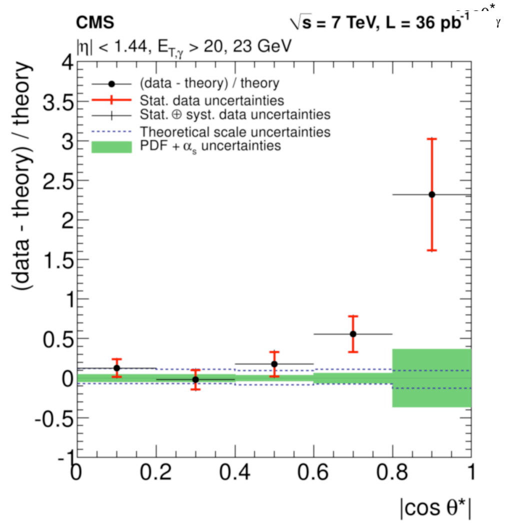
- **ATLAS and CMS see similar trends in low diphoton mass and high cos(θ*)**











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Summary - Conclusions

- Experiments have **excellent understanding** of **jet reconstruction and calibration** as well **as photon reconstruction and identification**, leading to **experimental uncertainties lower** than the **theoretical** ones.

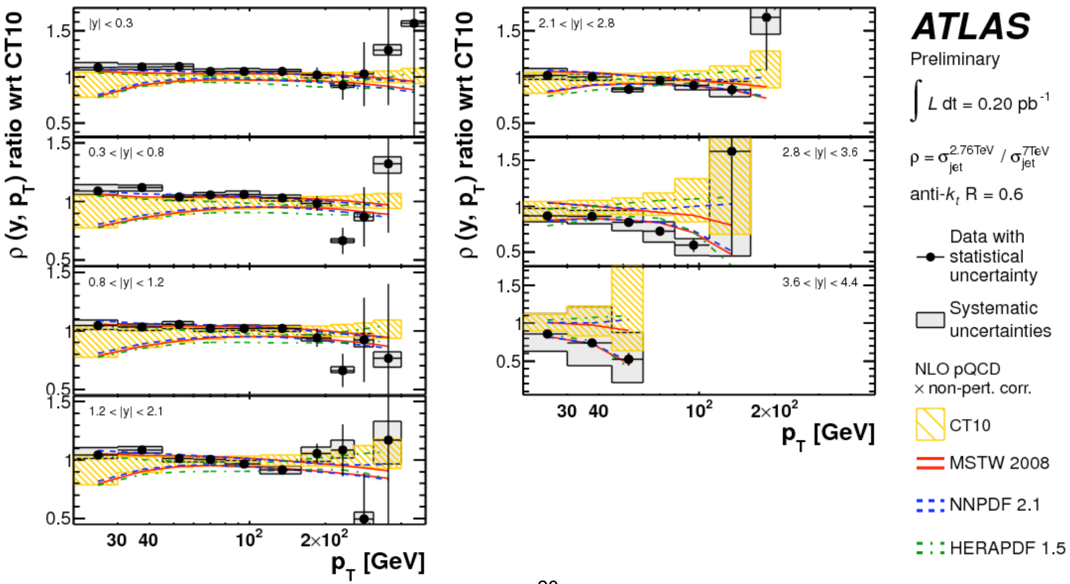
- Using these physics objects **precision QCD measurements** have been performed that are being used for **testing of new physics models**, **constraining and tuning PDFs**, extracting the **strong coupling constant and its running**, study **the effect** of various **jet algorithms**.

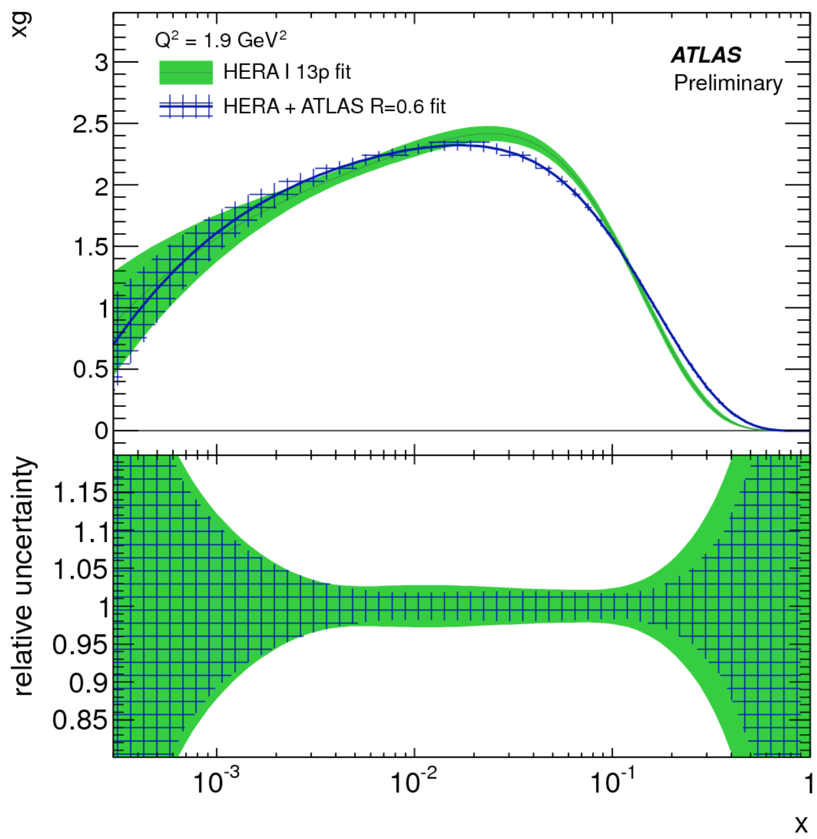
- Results from **ATLAS and CMS** are, in general, in **agreement**. Work is just starting on **"standardizing"** many aspects of the measurements (like **cone-sizes, bin-sizes** etc) where possible in order to **further facilitate comparisons and common usage**.

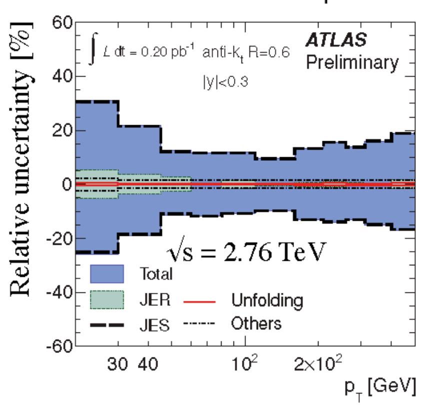
- **There are many more new and interesting ongoing analysis, mostly with the 8 TeV data, and results are imminent, so stay tuned!!**

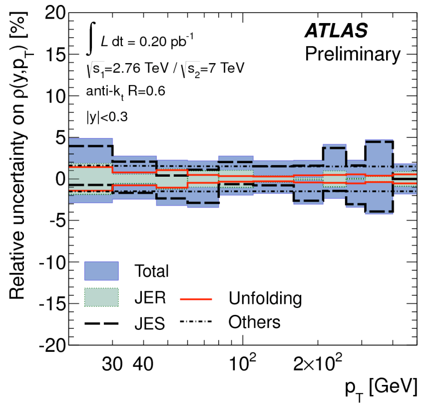
BACKUP

Inclusive Jet Cross Sections ATLAS 2.76 / 7 TeV Ratio





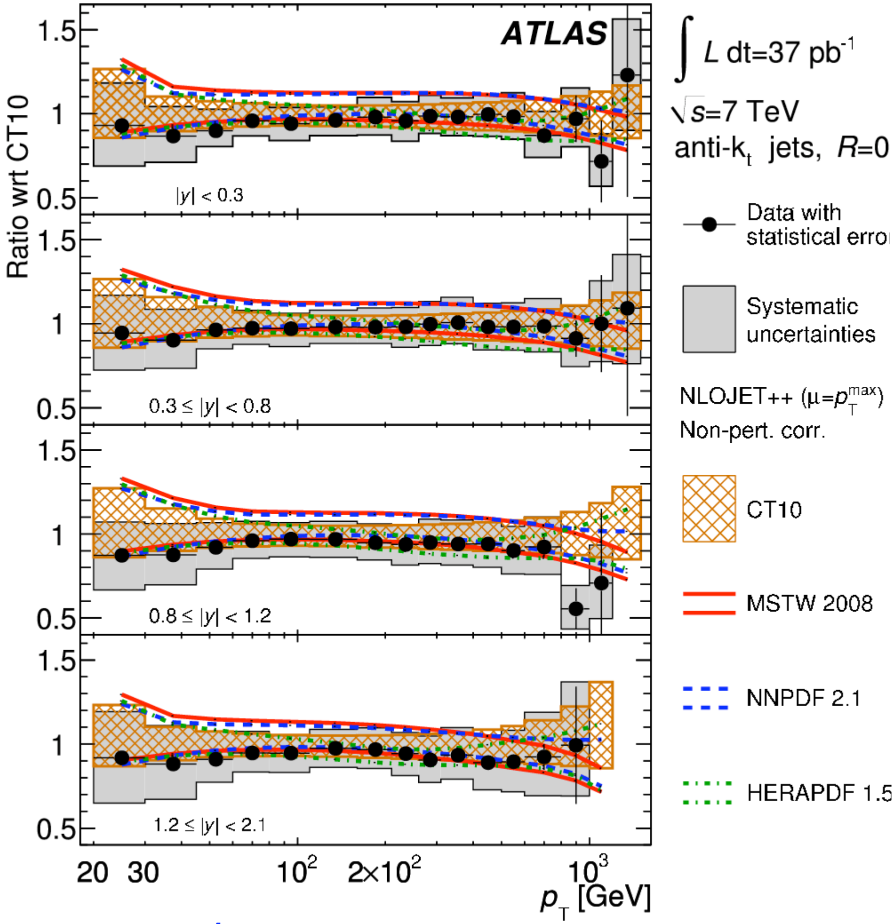


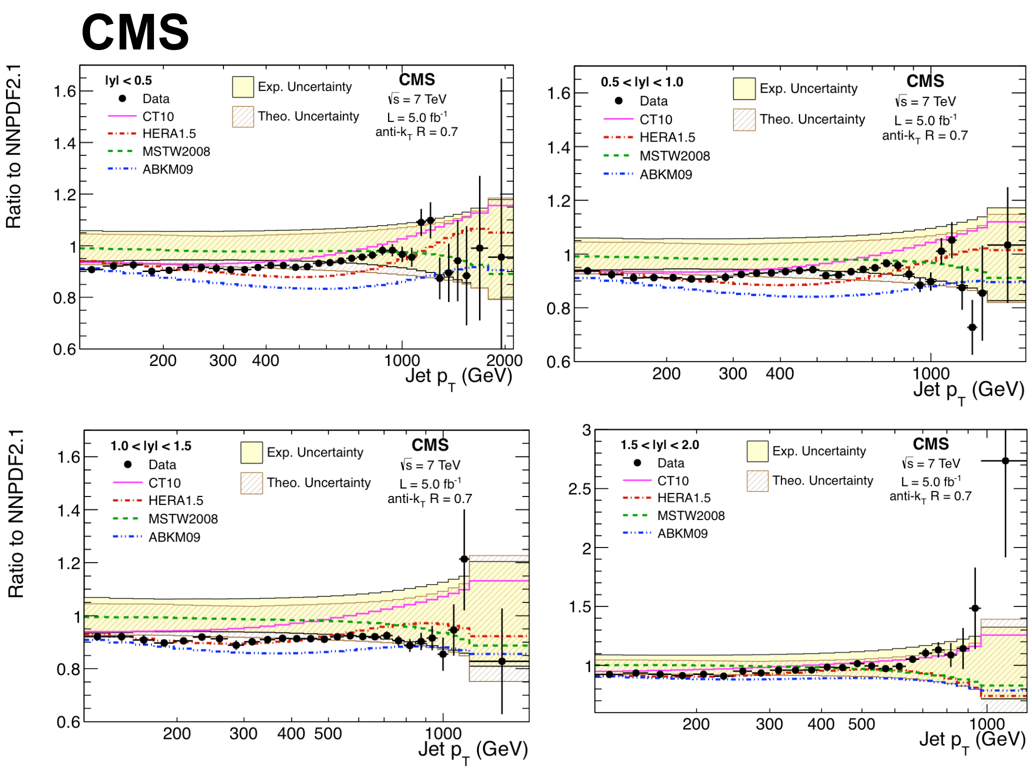


- **Most of the experimental uncertainties cancel out in the ratio.**
- **Ratios of cross sections useful in order to constraint and differentiate between different PDF sets.**

Inclusive Jet Cross Sections : 7 TeV

$$\frac{d^2\sigma}{dp_T d|y|} = \frac{C_{\text{unsm}}}{\epsilon \cdot \mathcal{L}} \cdot \frac{N_{\text{jets}}}{\Delta p_T \Delta|y|}$$

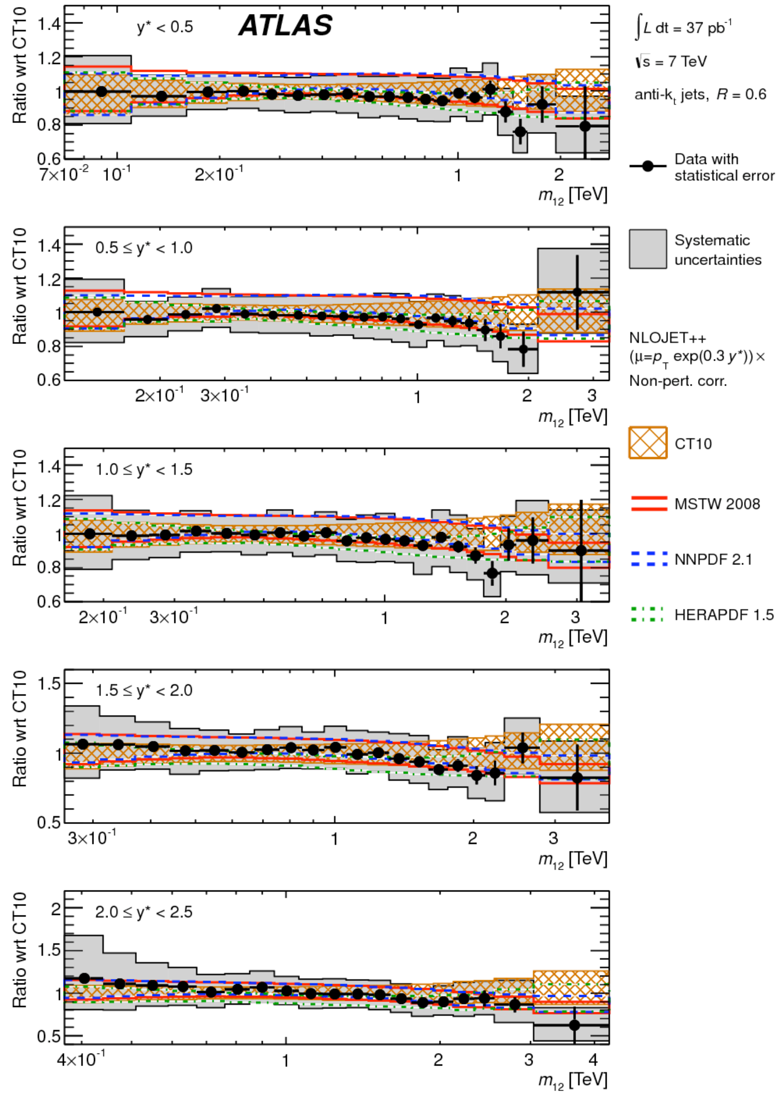


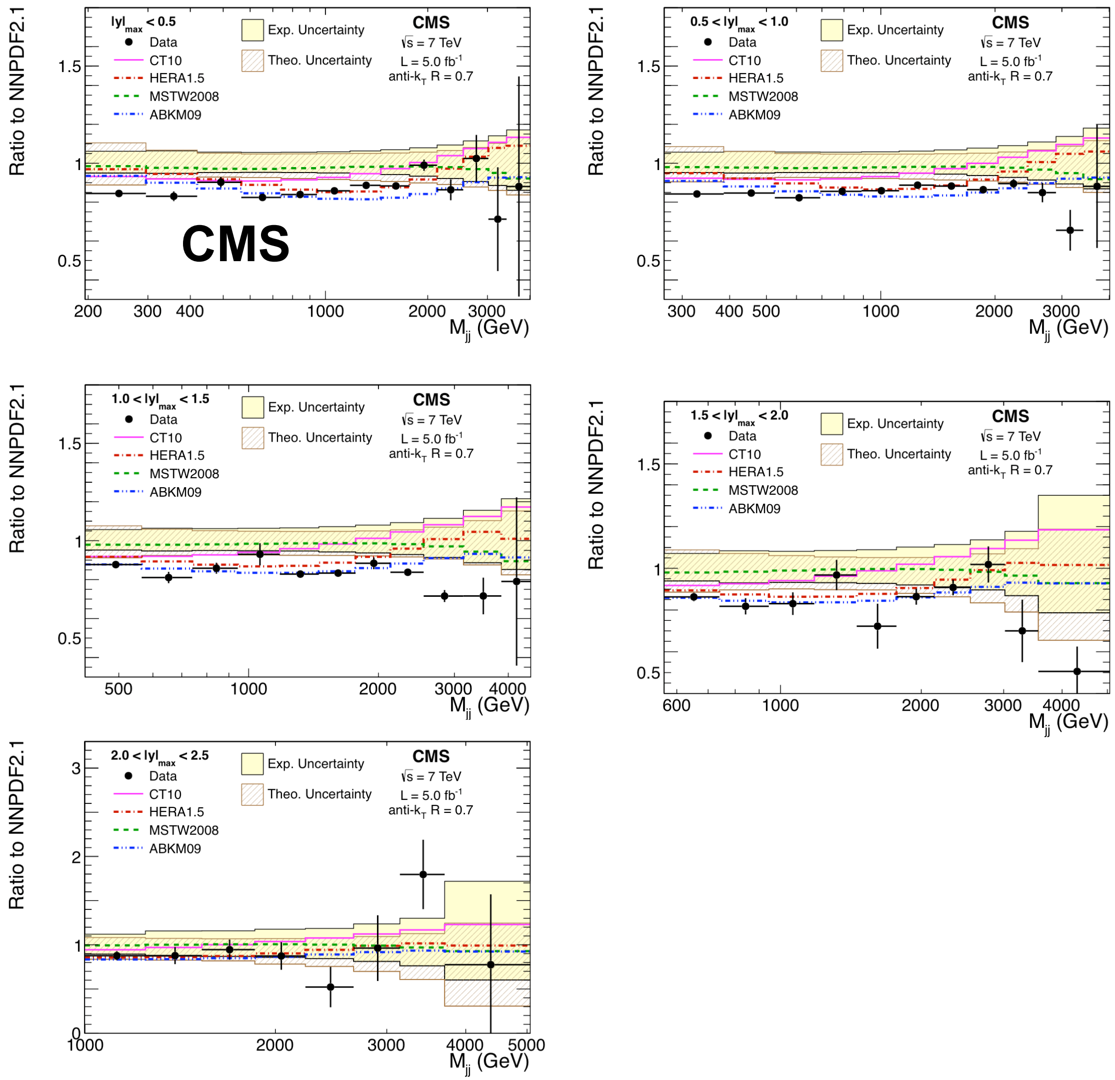


CMS 5 fb^{-1} results submitted to PRD, full error correlation matrices will be available

Some PDFs describe the data better than others : these measurements useful for PDF tuning and for constraining PDFs

Dijet Cross Sections : 7 TeV





CMS and ATLAS results ~ consistent (given slight differences like cone-sizes)

Some PDFs describe the data better than others : these measurements useful for PDF tuning and for constraining PDFs

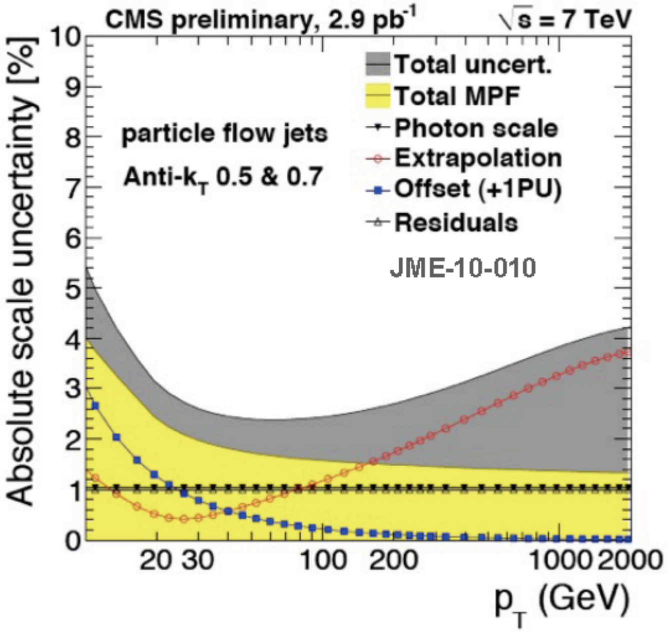
Jet Calibration

- **Dijet asymmetry**

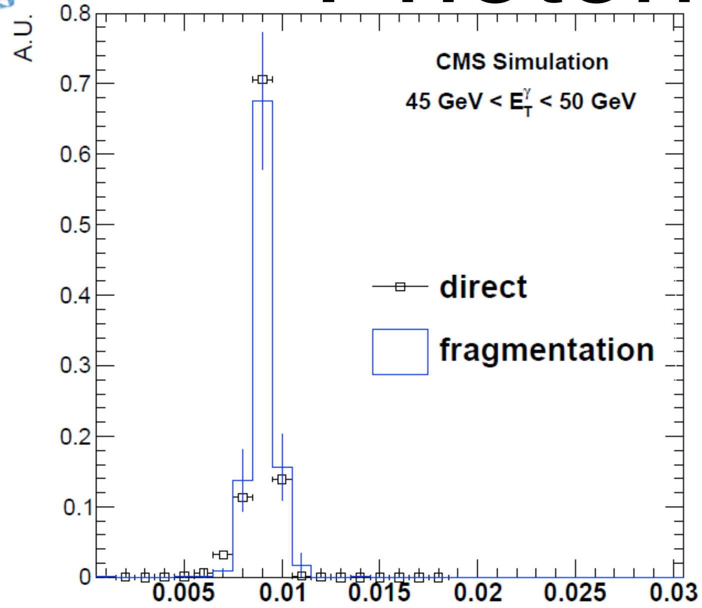
Physics Object

Raw Jet × Offset Correction (pile up) × Relative Response (vs. η) × Absolute Response (vs. p_T) = Calibrated Jet

- **Photon+Jet Balance**

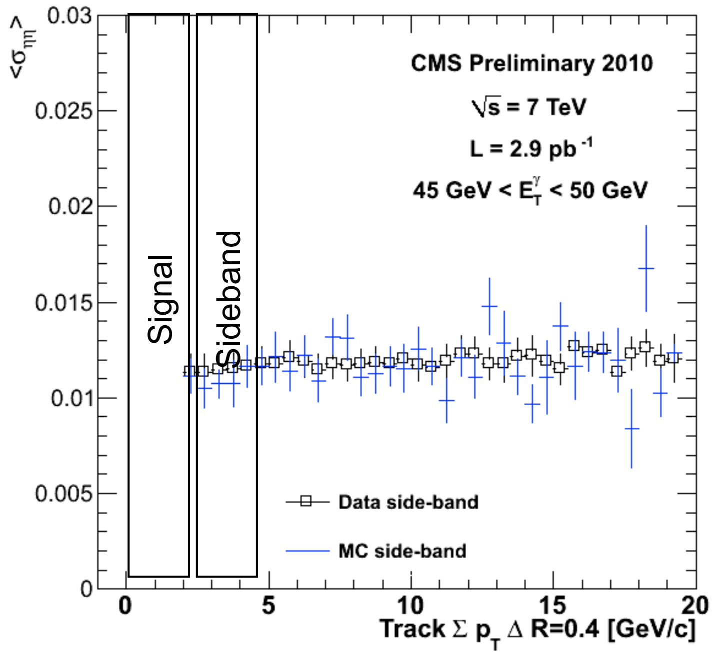


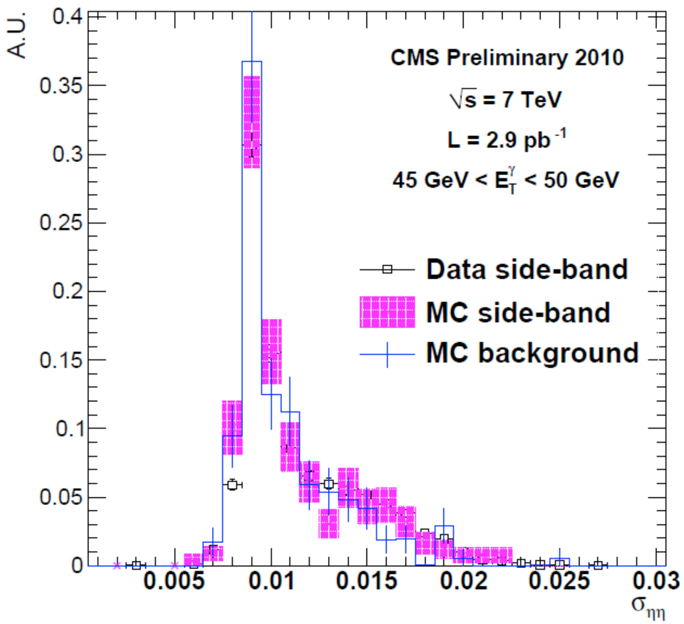
Photon Shower Shape



Signal shape : Pythia MC

Background Shape: Track Isolation Sideband



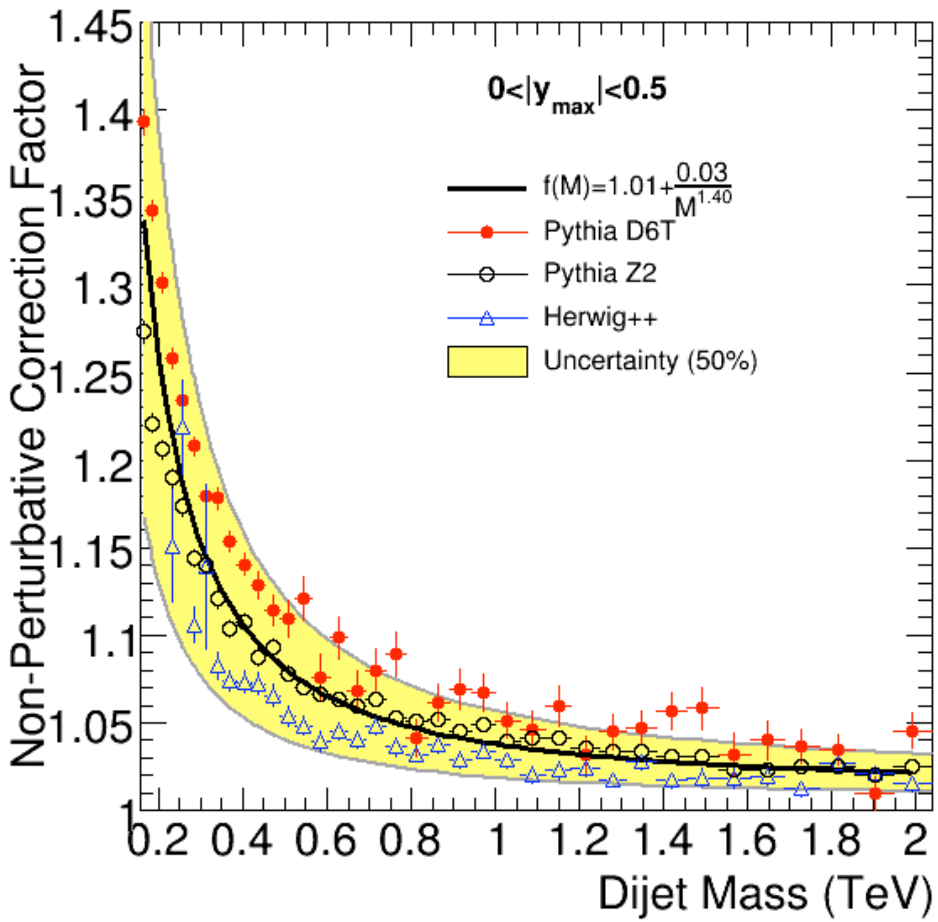


Non perturbative corrections

- Non perturbative corrections needed to go from parton to particle level, and hence be able to compare theory with data.

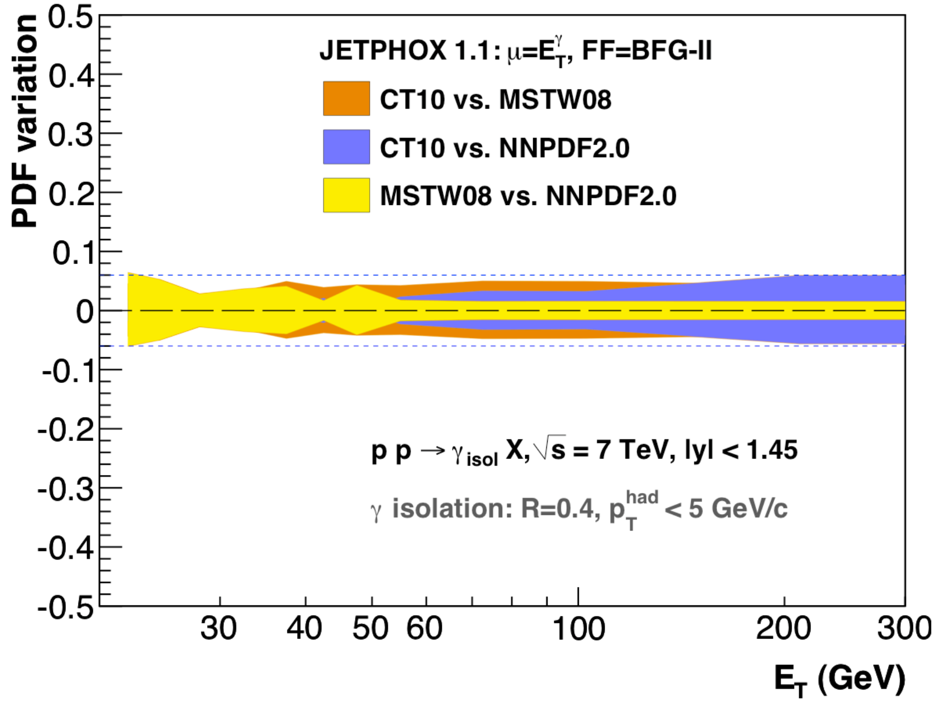
- Non perturbative corrections account for :
  - Multi-parton interactions
  - Hadronization effects

- Use different MC generators to estimate, and take spread as systematic uncertainty.



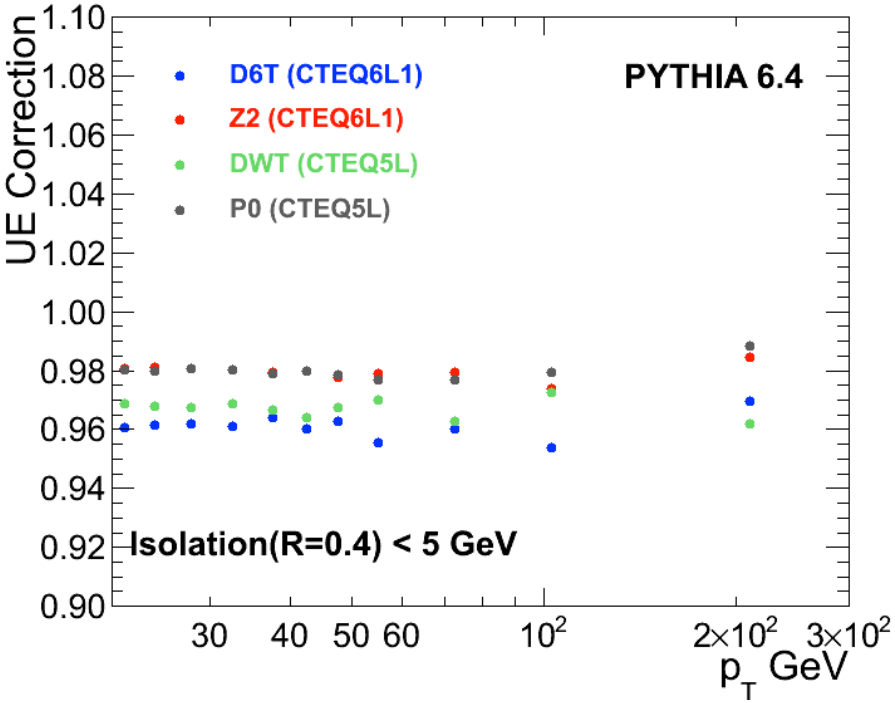
JetPhox Predictions

- NLO pQCD
  - JETPHOX1.1,CT10 PDFs, BFG II FF
  - Renormalization, fragmentation, and factorization scales set to ET
  - Require "isolated" definition: ΣET<5 GeV within R<0.4
- Scale uncertainty
  - 30 to 11% with ET, change all scales to ET/2 and 2ET
- PDF uncertainty
  - 6% over full ET range
- Envelope of CT10, MSTW08 and NNPDF2.0 (PDF4LHC recommendation)
- CTEQ6M instead of CT10: 3%
- BFG I instead of BFG II: <1%



Non Perturbative Corrections

- Non-perturbative effects increase energy in isolation cone
- Correction is obtained by comparing the efficiency of isolation cut of 5GeV in a cone of radius 0.4 with and without:
  - Multi-parton interaction
  - Hadronization
- Final correction is the mean of the four different tunes considered
  - D6T
  - Z2
  - DWT
  - P0
- ~3% overall correction applied to the NLO calculation

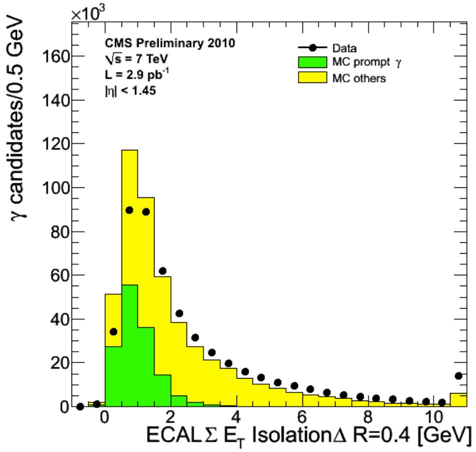


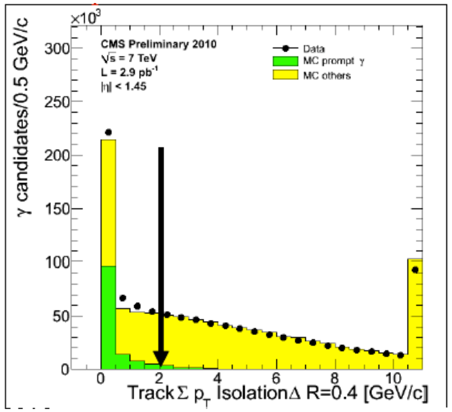
Photon Reconstruction

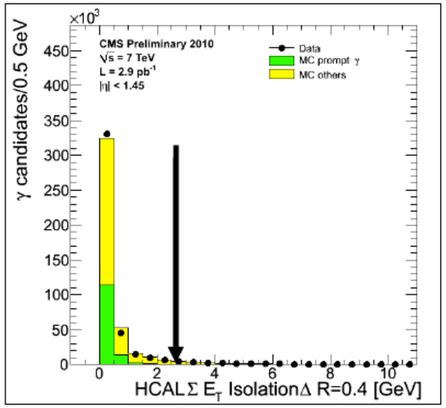
Photons are key objects for both calibration and major discoveries.

(H->γγ and BMS searches)

- Photons are isolated energy deposits in the ECAL, with no charged track pointing to them, and with a shape compatible with a photon electromagnetic Shower.





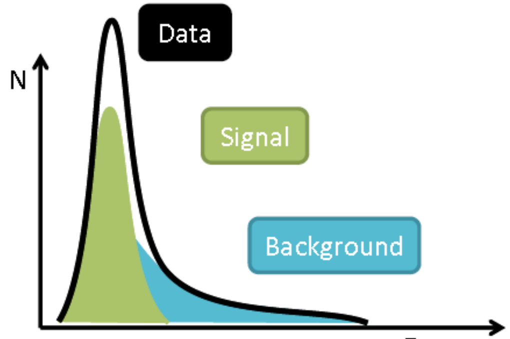


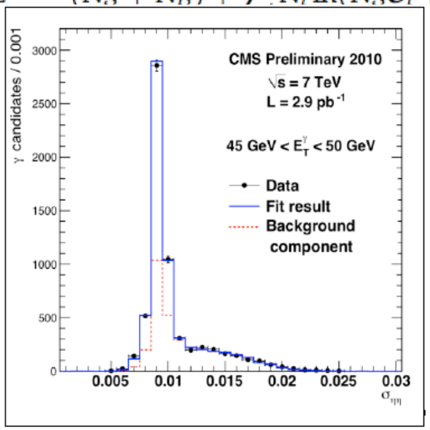
$$\mathcal{L} = -\ln L = -(N_S + N_B) + \sum^{n} N_i \ln(N_S\mathcal{S}_i + N_B\mathcal{B}_i)$$

Shower shape definition

$$\sigma_{i\eta i\eta}{}^2 = \frac{\sum (\eta_i - \bar{\eta})^2 w_i}{\overline{w_i}}, \quad \bar{\eta} = \frac{\sum \eta_i w_i}{\sum w_i}$$

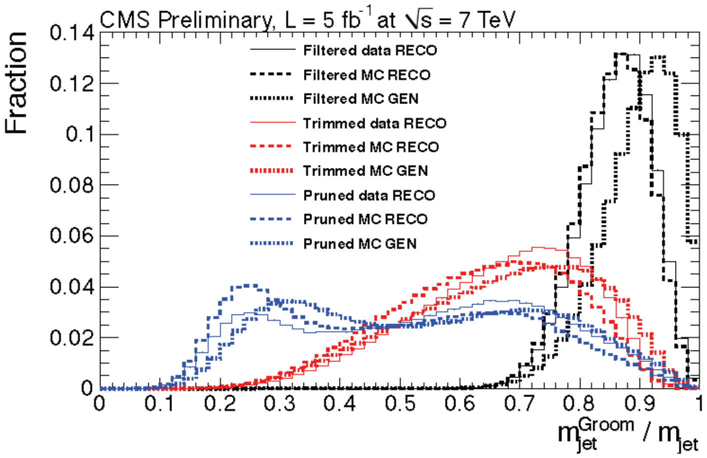
$$w_i = \max(0, 4.7 + \log(E_i / E_{5x5}))$$

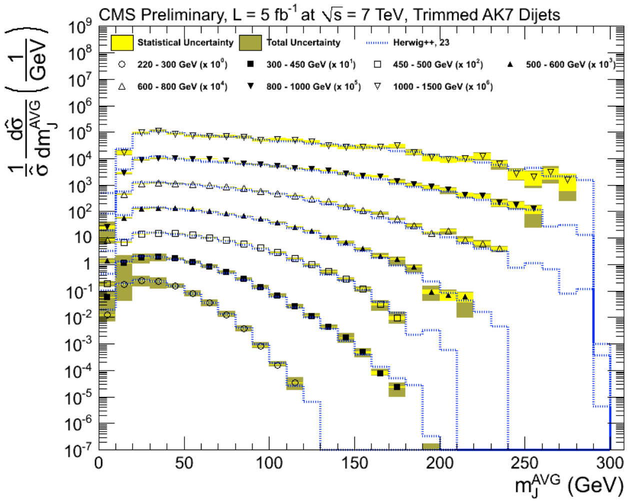


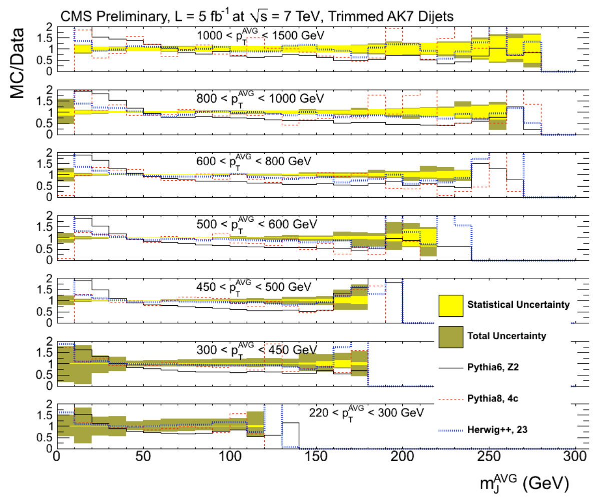


Jet Mass

CMS **New**







- Massive (SM or new physics) particles can be produced with significant Lorentz boosts => decaying into quarks the masses of the evolved jets can be used to discriminate them from lighter objects generated by QCD.

- For large boosts decay products emitted as collimated groupings into small sections of the detector => resulting particles can be clustered into a single jet. Jet "grooming" techniques are designed to separate jets from the decay of heavy boosted particles from quark/gluon initiated jets with large mass.

Photon reconstruction & identification

E_T [GeV]	unconverted γ: $\varepsilon_{ID} \pm (\sum_i (\frac{1}{(\delta x_i)^2}))^{-\frac{1}{2}}$	unconverted γ: $\varepsilon_{ID}{}^{MC} \pm$ stat	unconverted γ: $\varepsilon_{ID}{}^{\text{corrected MC}} \pm$ stat	converted γ: $\varepsilon_{ID} \pm (\sum_i (\frac{1}{(\delta x_i)^2}))^{-\frac{1}{2}}$	converted γ: $\varepsilon_{ID}{}^{MC} \pm$ stat	converted γ: $\varepsilon_{ID}{}^{\text{corrected MC}} \pm$ stat
$0 \le \|\eta\| < 0.6$						
20–25	0.597 ± 0.021	0.621 ± 0.001	0.613 ± 0.001	0.648 ± 0.024	0.667 ± 0.002	0.679 ± 0.002
25–30	0.689 ± 0.025	0.697 ± 0.002	0.686 ± 0.002	0.733 ± 0.035	0.761 ± 0.003	0.759 ± 0.003
30–35	0.769 ± 0.024	0.756 ± 0.002	0.746 ± 0.002	0.777 ± 0.033	0.821 ± 0.004	0.818 ± 0.004
35–40	0.792 ± 0.023	0.793 ± 0.003	0.784 ± 0.003	0.820 ± 0.025	0.851 ± 0.005	0.849 ± 0.005
40–45	0.816 ± 0.026	0.822 ± 0.004	0.806 ± 0.004	0.893 ± 0.049	0.886 ± 0.006	0.882 ± 0.006
45–50	0.847 ± 0.022	0.846 ± 0.001	0.835 ± 0.001	0.911 ± 0.036	0.899 ± 0.002	0.896 ± 0.002
50–60	0.874 ± 0.018	0.864 ± 0.001	0.856 ± 0.001	0.930 ± 0.029	0.923 ± 0.002	0.919 ± 0.002
60–80	0.902 ± 0.013	0.889 ± 0.001	0.883 ± 0.001	0.956 ± 0.027	0.939 ± 0.002	0.936 ± 0.002
80–100	0.918 ± 0.008	0.908 ± 0.001	0.905 ± 0.001	0.962 ± 0.030	0.956 ± 0.001	0.955 ± 0.001
100–125	0.926 ± 0.005	0.914 ± 0.001	0.912 ± 0.001	0.969 ± 0.023	0.962 ± 0.001	0.961 ± 0.001
125–150	0.934 ± 0.006	0.918 ± 0.001	0.917 ± 0.002	0.977 ± 0.023	0.969 ± 0.001	0.968 ± 0.002
150–175	0.930 ± 0.008	0.920 ± 0.001	0.918 ± 0.001	0.985 ± 0.017	0.971 ± 0.001	0.970 ± 0.001
175–250	0.933 ± 0.008	0.918 ± 0.001	0.917 ± 0.001	0.987 ± 0.016	0.971 ± 0.001	0.971 ± 0.001

ATLAS efficiency

ECAL Barrel ($|\eta| < 1.4442$)

ET	MC	DATA	MC Ratio γ/e
20 - 35	84.18 ± 0.20%	86.73 ± 1.69%	1.032 ± 0.003
35 - 45	87.27 ± 0.19%	89.28 ± 1.27%	1.025 ± 0.004
45 - inf	88.50 ± 0.23%	89.04 ± 1.83%	1.005 ± 0.005
TOT	86.30 ± 0.12%	88.41 ± 0.89%	1.012 ± 0.002

ECAL Barrel ($|\eta| < 1.4442$)

ET	MC	DATA	MC Ratio γ/e
20 - 35	69.38 ± 0.18%	69.58 ± 2.80%	1.060 ± 0.004
35 - 45	72.78 ± 0.18%	71.94 ± 2.09%	1.047 ± 0.007
45 - inf	74.93 ± 0.22%	72.48 ± 2.92%	0.995 ± 0.008
TOT	71.90 ± 0.11%	71.31 ± 1.47%	1.028 ± 0.003

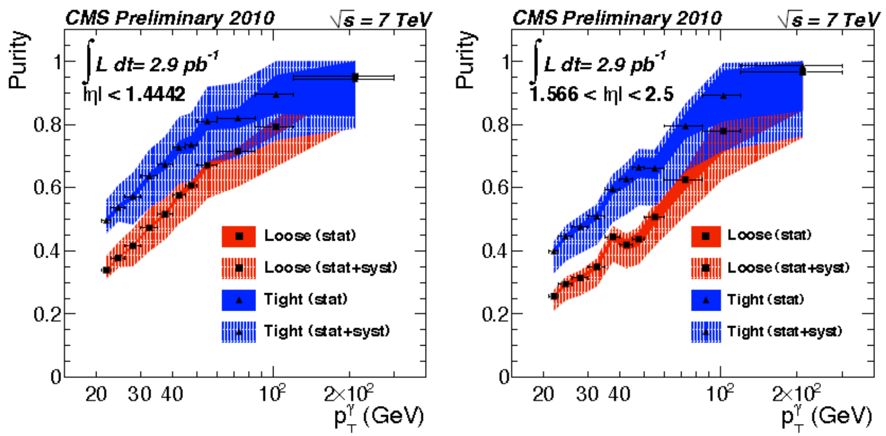
ECAL Endcap ($1.566 < |\eta| < 2.5$)

ET	MC	DATA	MC Ratio γ/e
20 - 35	87.40 ± 0.25%	92.24 ± 2.70%	1.035 ± 0.003
35 - 45	91.33 ± 0.22%	91.43 ± 2.43%	1.008 ± 0.005
45 - inf	92.55 ± 0.26%	91.06 ± 3.23%	1.013 ± 0.005
TOT	90.05 ± 0.14%	91.59 ± 1.60%	1.009 ± 0.002

ECAL Endcap ($1.566 < |\eta| < 2.5$)

ET	MC	DATA	MC Ratio γ/e
20 - 35	71.30 ± 0.28%	71.07 ± 3.94%	1.074 ± 0.006
35 - 45	77.63 ± 0.24%	75.19 ± 3.34%	1.028 ± 0.008
45 - inf	80.87 ± 0.31%	73.48 ± 4.98%	1.006 ± 0.009
TOT	75.85 ± 0.15%	73.31 ± 2.31%	1.019 ± 0.004

CMS Purity



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