CMS Experiment at LHC, CERN
Data recorded: Tue May 25 06:24:04 2010 CEST
Run/Event: 136100 / 103078800
Lumi section: 348

University of Ioannina

Jet production measurements at CMS

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On behalf of the CMS Collaboration

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European Union
European Social Fund

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EDUCATION AND LIFELONG LEARNING
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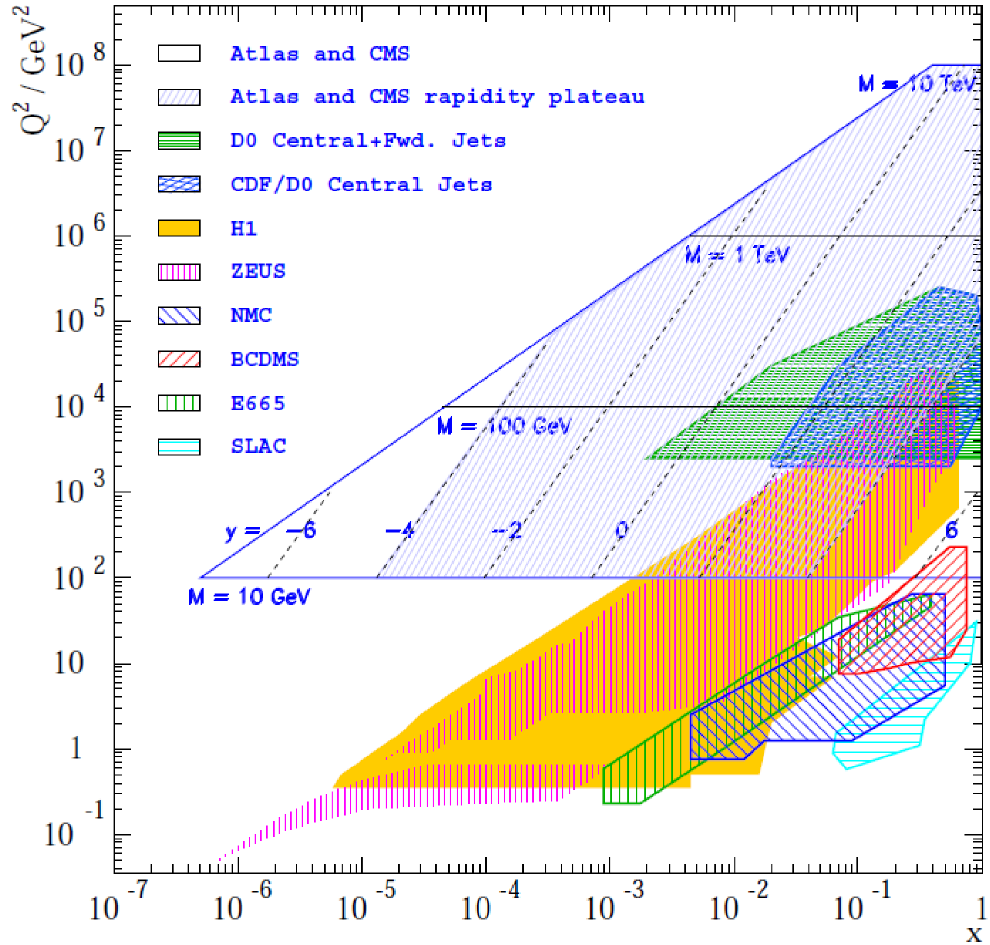
Introduction

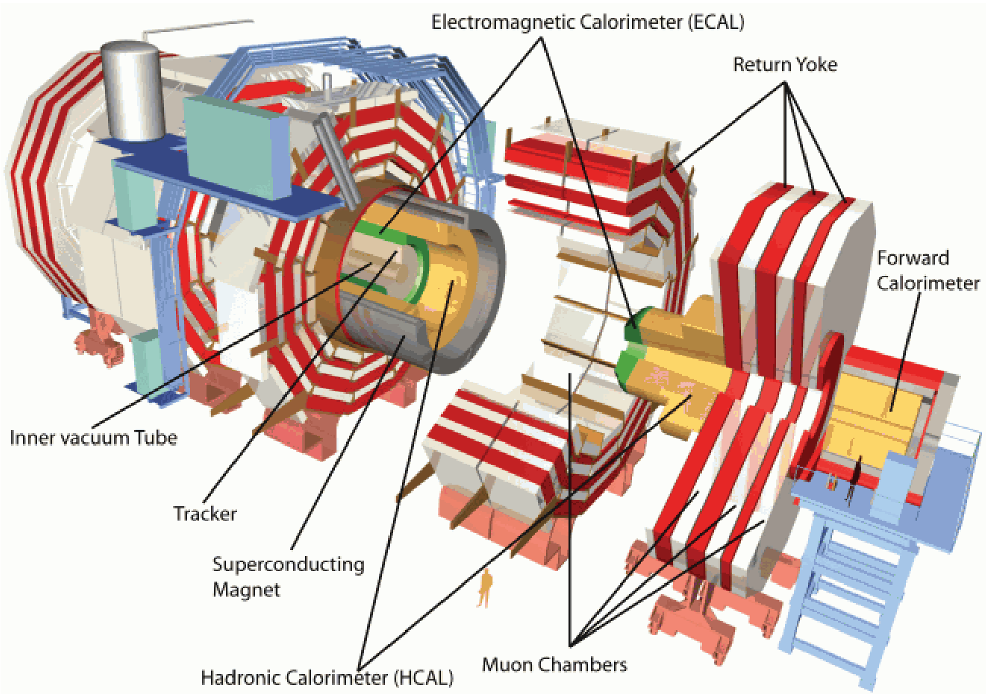
- QCD processes are dominant @ LHC. LHC is a jet factory.
- Jet measurements at LHC are very important:
    - They provide a test of pQCD in a previously unexplored energy region. A huge new phase space is accessible at LHC.
    - Check SM predictions at high energy scales.
    - Measure and understand the main background to many new physics searches.
    - *Determine α_S and provide constraints on PDF's.*

Kinematic plane of process Q^2 vs x



S.Glazov, Braz.J.Ph. 37 (2007) 793

CMS Detector and Integrated Luminosity

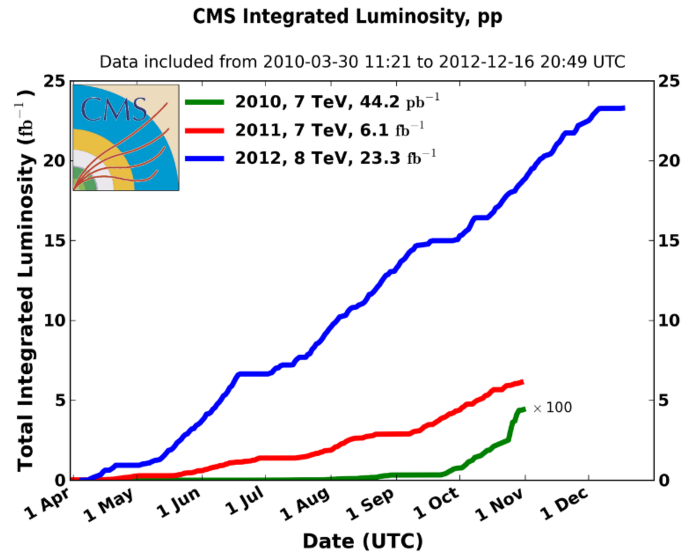


CMS detector pseudorapidity coverage:

- Tracking: |η|<2.5
- Central Calorimetry: |η|<3
- Forward Calorimetry: 3<|η|<5

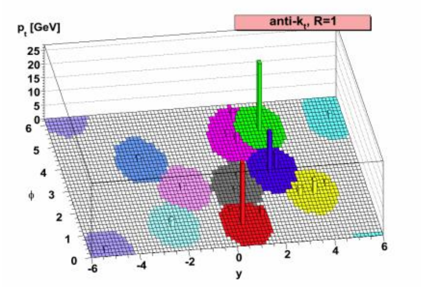
Very successful LHC operation and CMS data recording during Run 1:

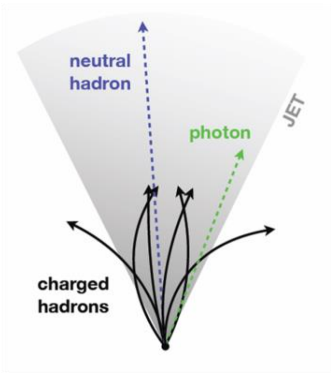
- 7 TeV (2010 & 2011)
- 8 TeV (2012)



Jet Reconstruction and Energy Scale Calibration

- **Anti-k_T clustering algorithm** : Infrared and collinear safe. Used with R=0.5 and 0.7.





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

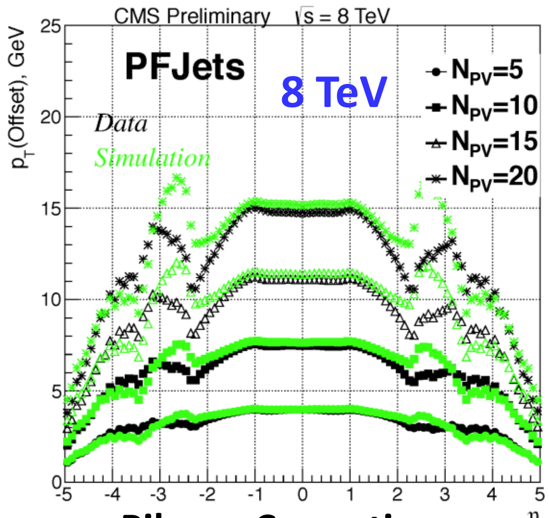
- For the jet energy scale calibration CMS adopted a Factorized approach.

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

- **Offset** → substruction $\rho \times A_{jet}$ (ρ : the global energy density, A_{jet}: the jet area)
- **Relative** → derived from Di-jet Balance
- **Absolute** → derived from $\gamma + jet$ and $Z + jet$ (p_T balance and MPF)

Jet Energy Scale Calibration

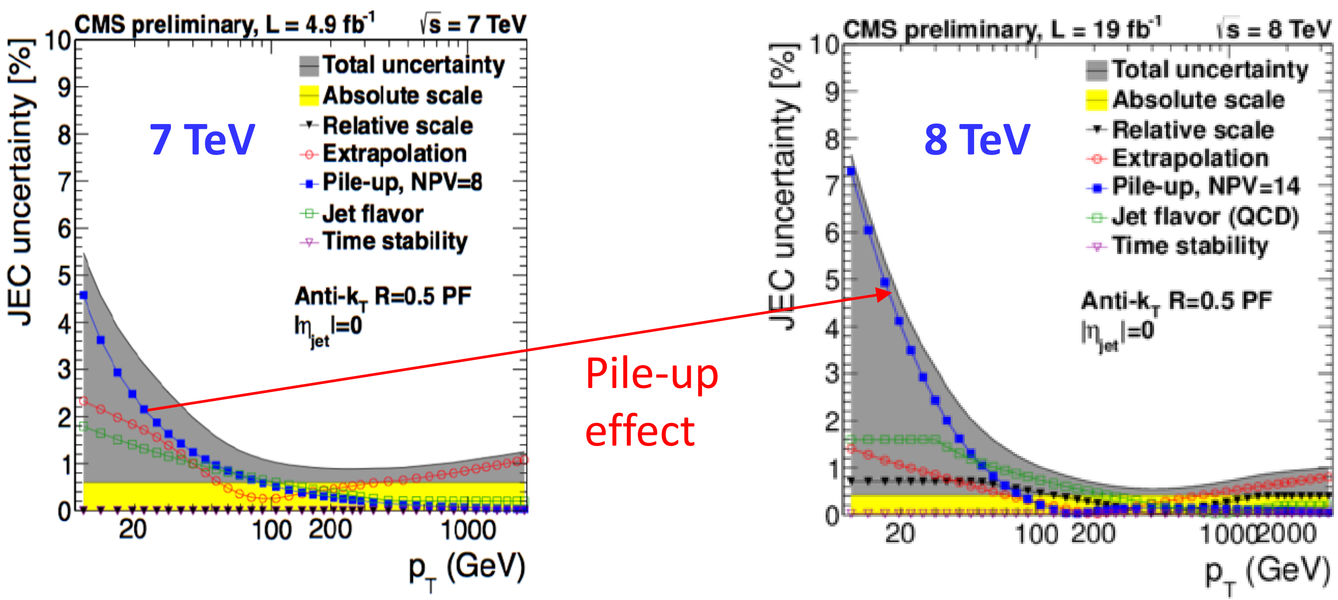
CMS DP-2013-033



Pile-up Corrections

- In the important parts of the phase space JEC uncertainties are of the order of 1-2%.
- Below 100 GeV pile-up correction uncertainties are the dominant.

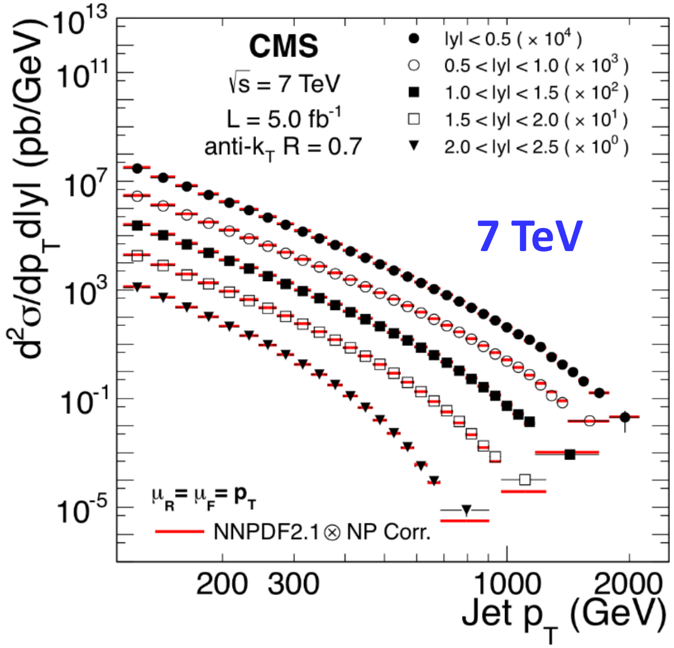
CMS DP-2012-006

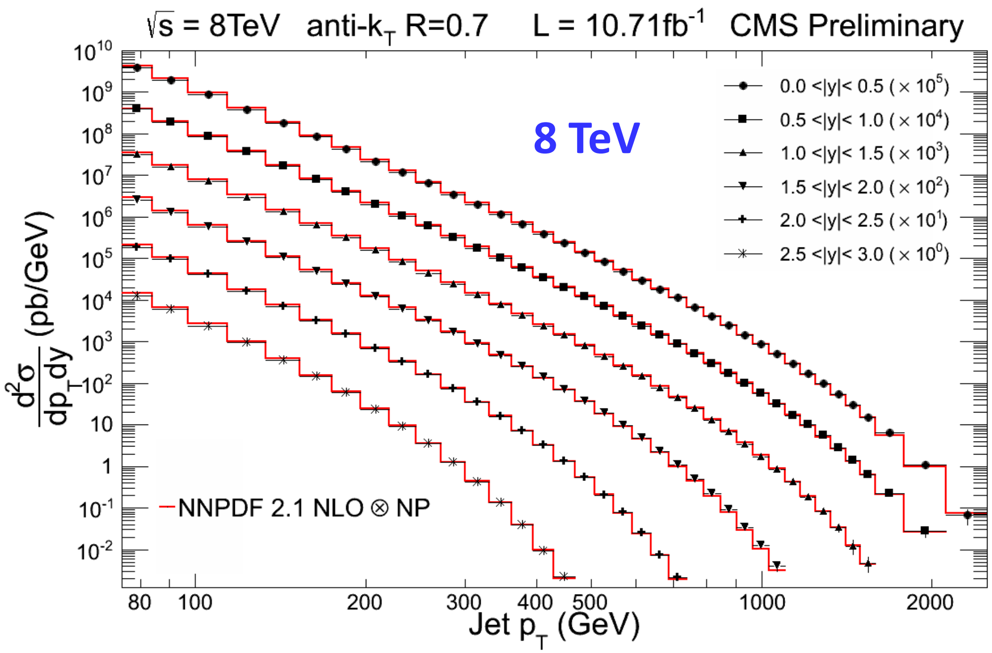


CMS DP-2013-033

Inclusive Jet cross section at 7 and 8 TeV

PRD 87 112002 (2013)





CMS PAS SMP-12-012

- Measurement of the Inclusive jet production cross section in p_T and y at 7 and 8 TeV.

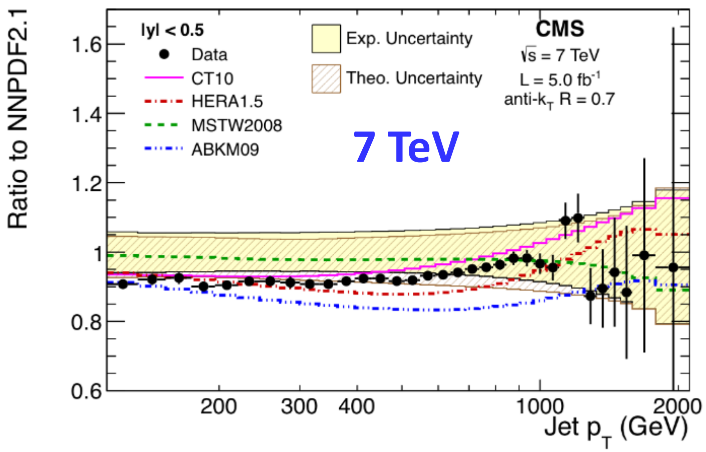
$$\frac{d^2\sigma}{dp_T dy}$$

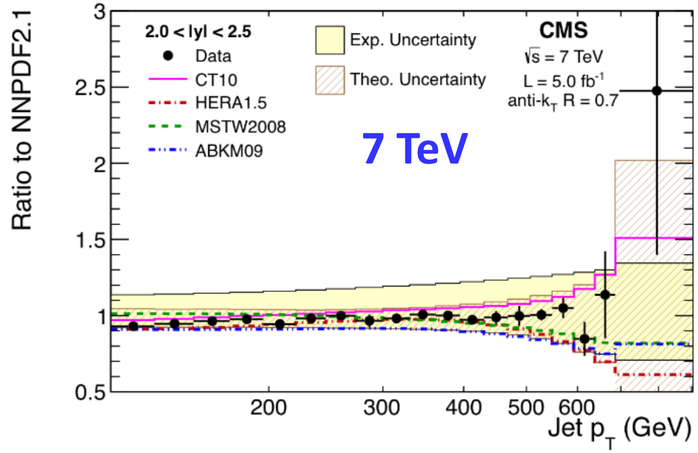
$$7\,\mathrm{TeV}: |y| \leq 2.5 \text{ with } \Delta|y| = 0.5 \text{ and jet } p_T \text{ 114 GeV - 2 TeV}$$

$$8\,\mathrm{TeV}: |y| \leq 3.0 \text{ with } \Delta|y| = 0.5 \text{ and jet } p_T \text{ 74 GeV - 2.5 TeV}$$

- 8 TeV analysis uses the half of the statistics. Analysis with full statistics in progress.

Inclusive Jet cross section at 7 and 8 TeV





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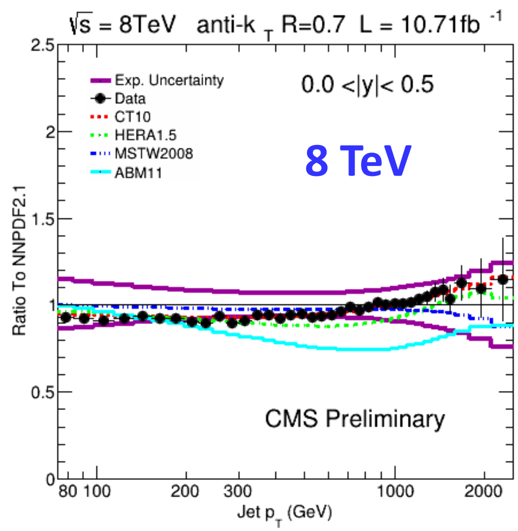
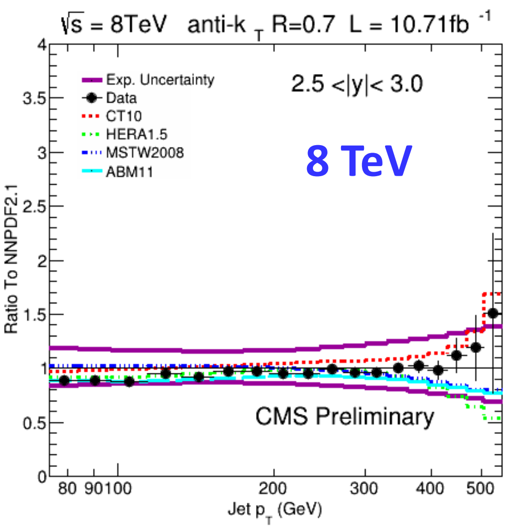




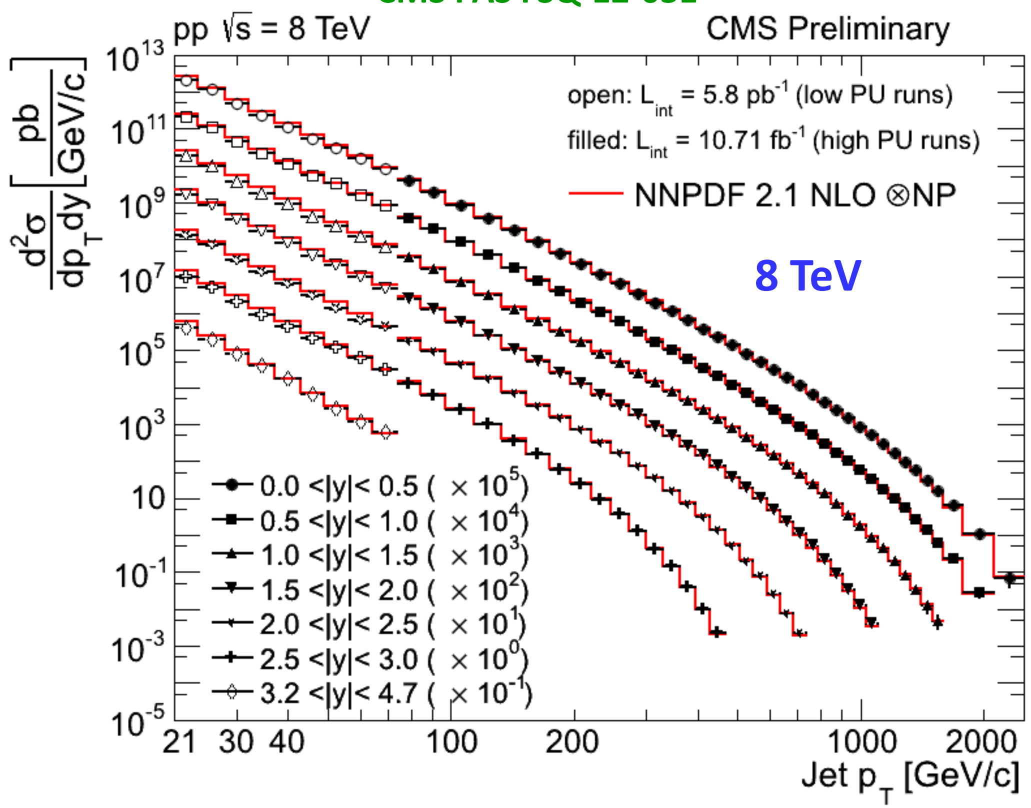
CMS PAS SMP-12-012

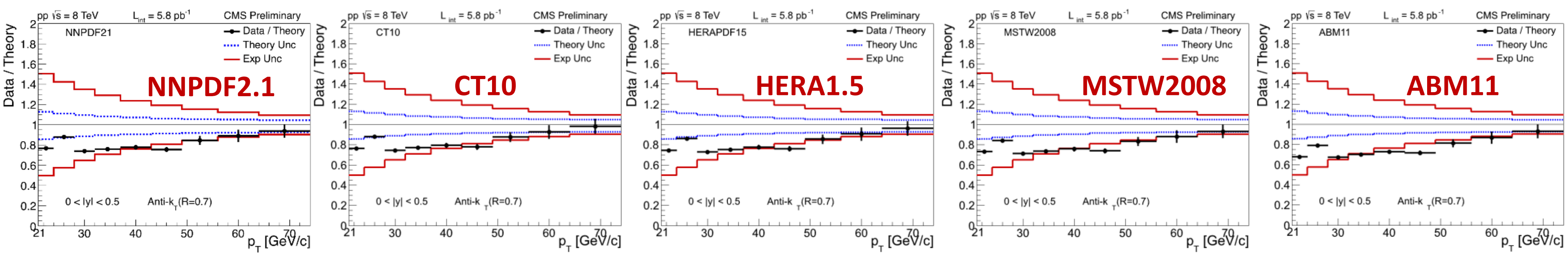
Agreement is observed between data and theory for most PDF sets in all rapidity bins.

Low p_T Inclusive Jet cross section at 8 TeV

- Additional study in the low-p_T region using low pile-up data (5.8 pb^{-1}).
  - Seven rapidity bins up to |y|=4.7
  - Lower jet p_T = 21 GeV.
- pQCD is able to describe the results
  - **Over 2 orders of magnitude in p_T**
  - **Over 14 orders of magnitude in the inclusive cross section.**
- Agreement is observed between data and theory.

CMS PAS FSQ-12-031



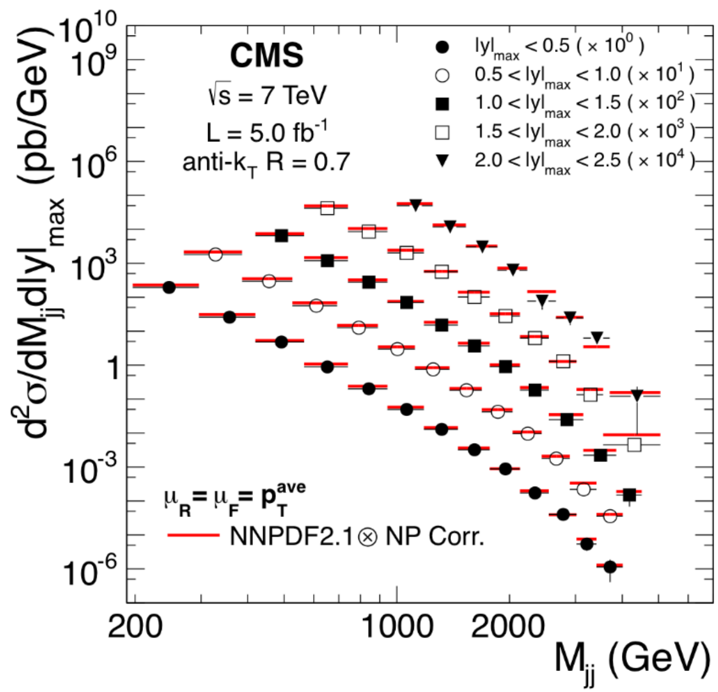


Dijet cross section at 7 TeV

- Measurement of the Dijet production cross section in M_{jj} and y_{max} at 7 TeV.

$$\frac{d^2\sigma}{dM_{jj}dy_{max}} \qquad M_{jj}: \text{Mass of the two leading jets} \qquad |y|_{max} = \max(|y_1|,|y_2|)$$

- Five rapidity bins up to |y|=2.5 and M_{jj} up to 5 TeV.
- Agreement is observed between data and theory.
- Analysis at 8 TeV in progress.



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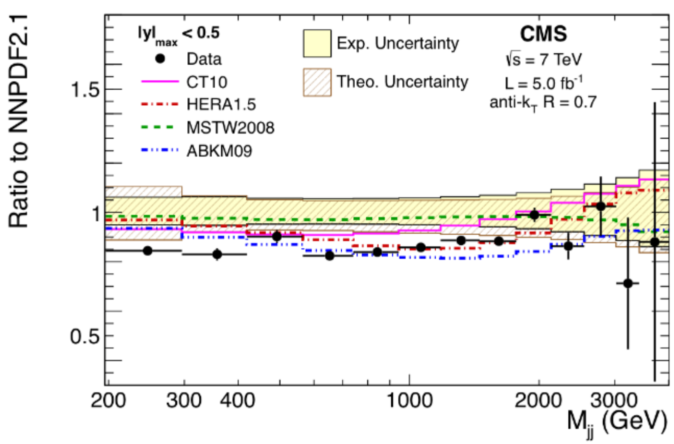
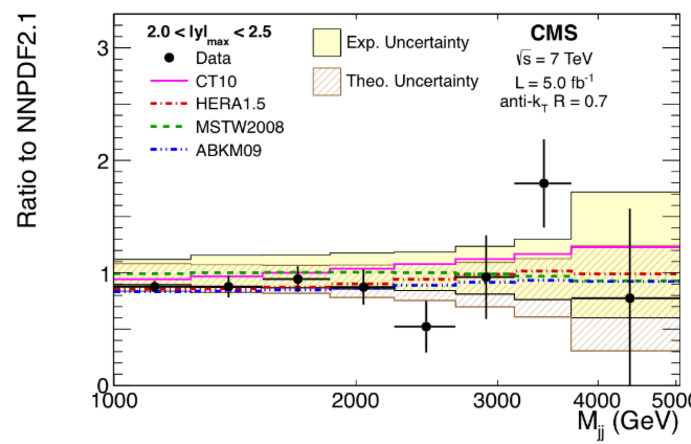




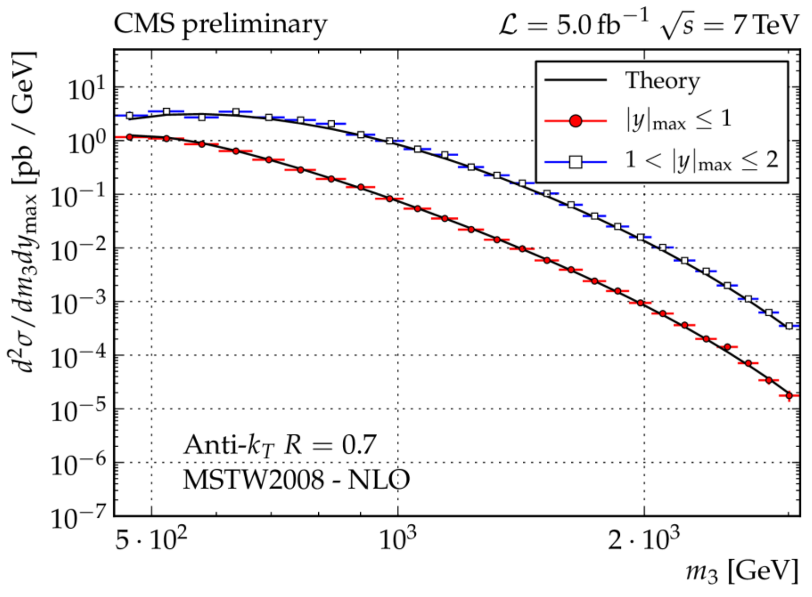
3-jet mass cross section at 7 TeV

- Measurement of the double differential 3-jet cross section in m_3 and y_{max}

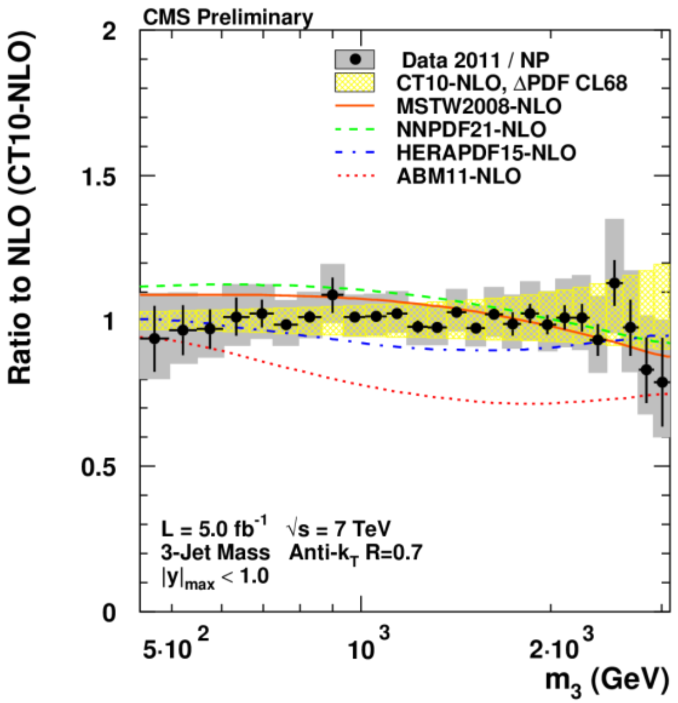
$$\frac{d^2\sigma}{dm_3\, dy_{max}} \qquad m_3^2 = (p_1 + p_2 + p_3)^2 \qquad |y|_{max} = \max(|y_1|, |y_2|, |y_3|)$$

- Measurement in two rapidity bins: $|y|_{max}<1$ and $1<|y|_{max}<2$

CMS PAS SMP-12-027



CMS PAS SMP-12-027

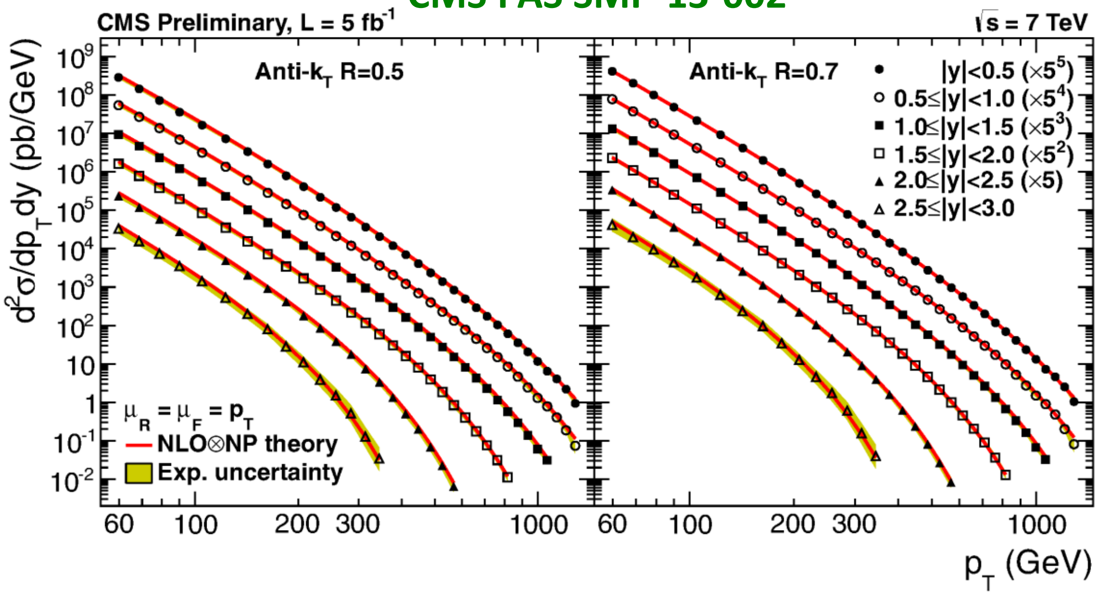


- pQCD is able to describe the 3-jet mass cross section over five orders of magnitude and for 3-jet masses up to 3 TeV.
- Within uncertainties most PDF sets are able to describe the data.

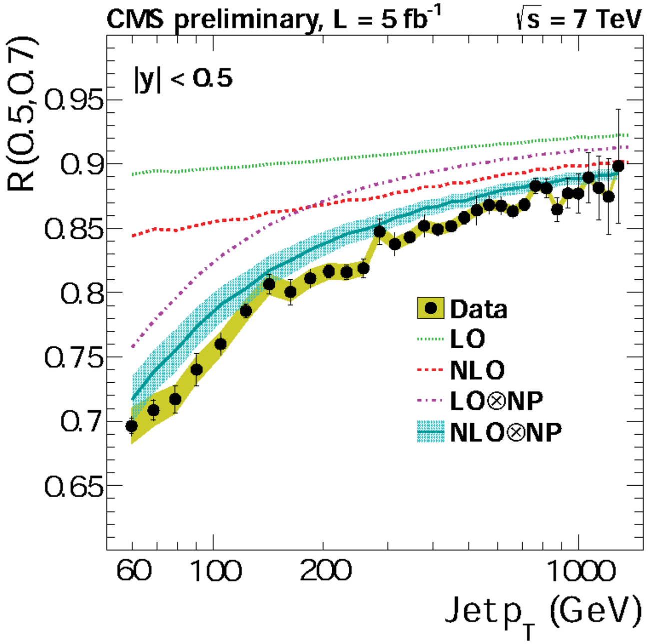
Inclusive jet AK5/AK7 cross section ratio at 7 TeV

- The measurement:
  - Ratio R(0.5,0.7) of incl. jet cross section using the anti-k_T with R=0.5 and R=0.7
  - Sensitive to collinear radiation.

CMS PAS SMP-13-002



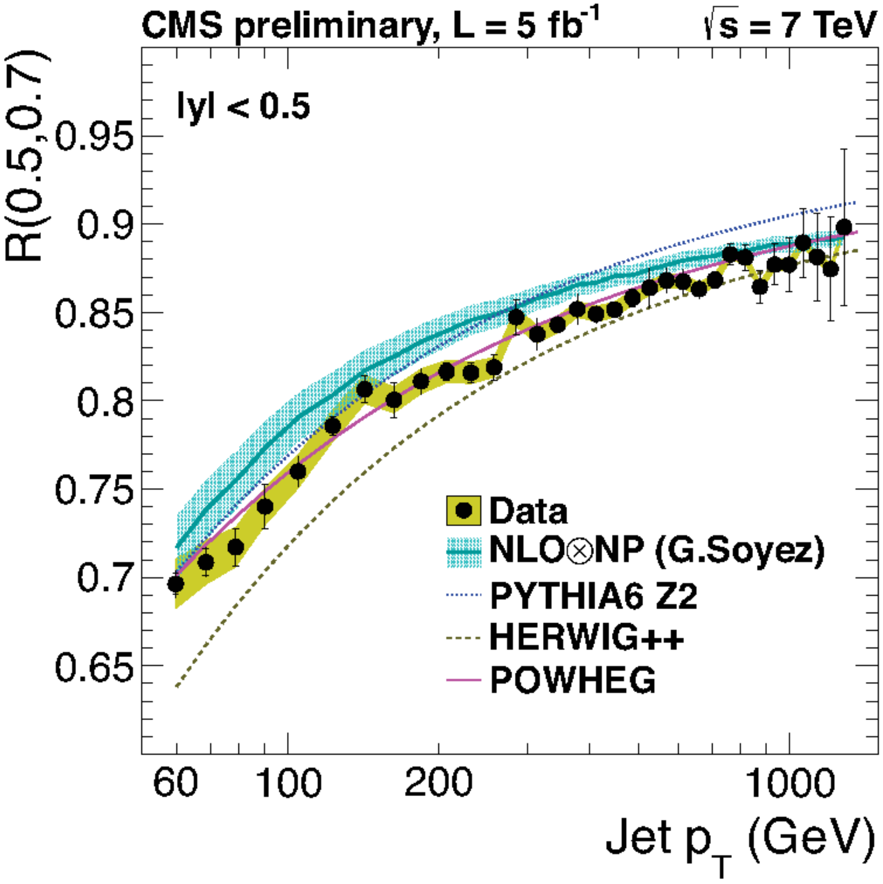
CMS PAS SMP-13-002



- Ratio is compared to pQCD at LO and NLO with and without NP corrections.
- The perturbative QCD predictions are systematically above the data, improving at higher order.

Inclusive jet AK5/AK7 cross section ratio at 7 TeV

CMS PAS SMP-13-002



- Models using LO (PYTHIA6, HERWIG++) or NLO matrix element calculations matched to the parton showers (POWHEG+PYTHIA6), describe better the ratio than the fixed order calculations corrected for non-perturbative effects.
- The best description is obtained by combining the NLO prediction with a parton shower model (POWHEG+ PYTHIA6).

Hadronic Event Shapes at 7 TeV

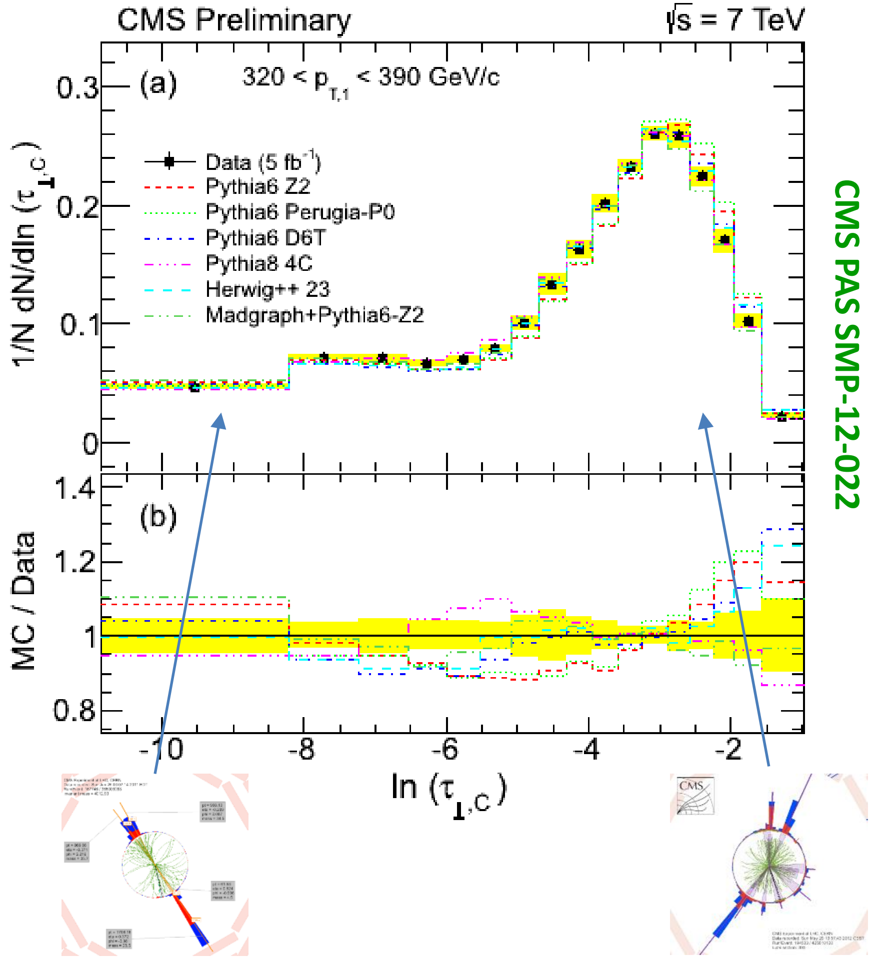
Event shape variables are geometric properties of the energy flow in hadronic final states.

- Sensitive to the details of the features of QCD. (JHEP 1006 (2010) 038)
- Used for the **tuning** and **validation** of various QCD MC event generators.

Transverse Thrust

$$T_{\perp,C} \equiv \max_{\hat{n}_T} \frac{\sum_i \left| \vec{p}_{\perp i} \cdot \hat{n}_T \right|}{\sum_i p_{\perp i}}, \quad \tau_{\perp,C} \equiv 1 - T_{\perp,C}$$

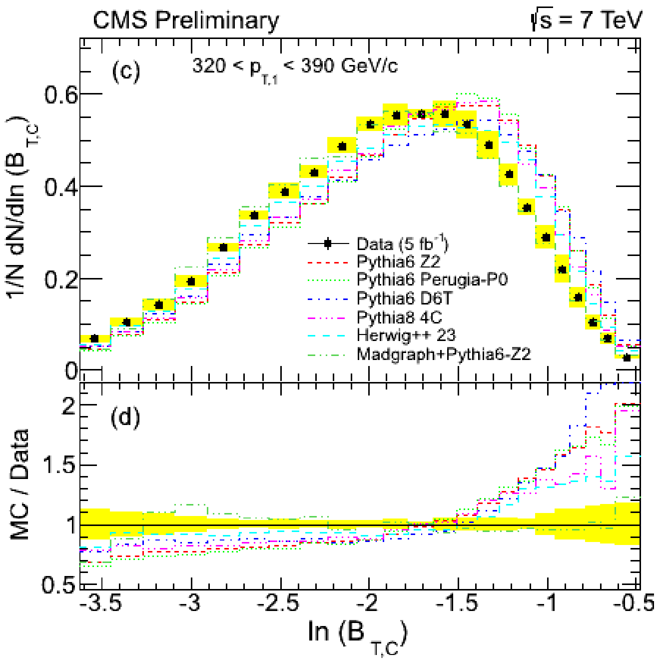
- Sensitive to the modelling of two-jet and multi-jet topologies.
- All generators show an overall agreement with data within 10%. Better agreement from PYTHIA8 and HERWIG++.
- $\hat{n}_T$ splits the transverse region in
  - an upper part C_U with $\vec{p}_T \cdot \hat{n}_T > 0$
  - a lower part C_L with $\vec{p}_T \cdot \hat{n}_T < 0$



CMS PAS SMP-12-022

Hadronic Event Shapes at 7 TeV

CMS PAS SMP-12-022



Jet Broadening

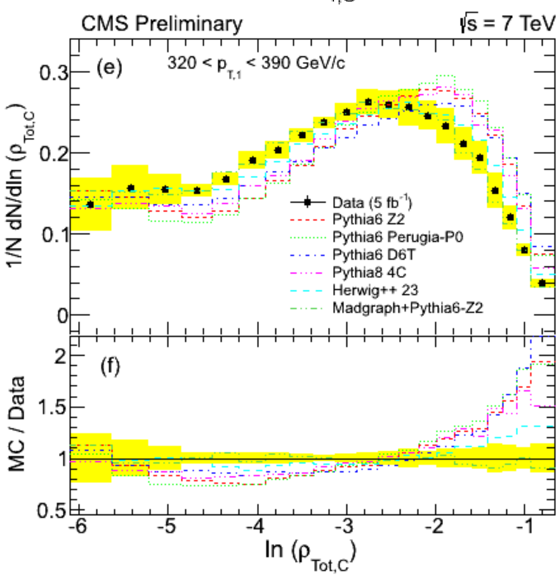
$$B_{tot,C} \equiv B_{U,C} + B_{L,C}$$

$$B_{X,C} \equiv \frac{1}{2P_{\perp}} \sum_{i \in C_X} p_{\perp i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}$$

$$\eta_X = \frac{\sum_{i \in C_X} p_{\perp i} \eta_i}{\sum_{i \in C_X} p_{\perp i}} \ , \ \phi_X = \frac{\sum_{i \in C_X} p_{\perp i} \phi_i}{\sum_{i \in C_X} p_{\perp i}}$$

- Sensitive to ME, PS and color coherence effects.
- The agreement of this event shape variable with predictions is poor.
- Better agreement for MADGRAPH and HERWIG++ generators.

CMS PAS SMP-12-022



Jet Mass

Defined as the sum of the normalized squared invariant masses in the upper and lower regions:

$$\rho_{tot,C} \equiv \rho_U + \rho_L \ , \ \rho_X \equiv \frac{1}{P^2}\left(\sum_{i \in C_X} p_i\right)^2$$

- Same observations with the Jet Broadening observable.

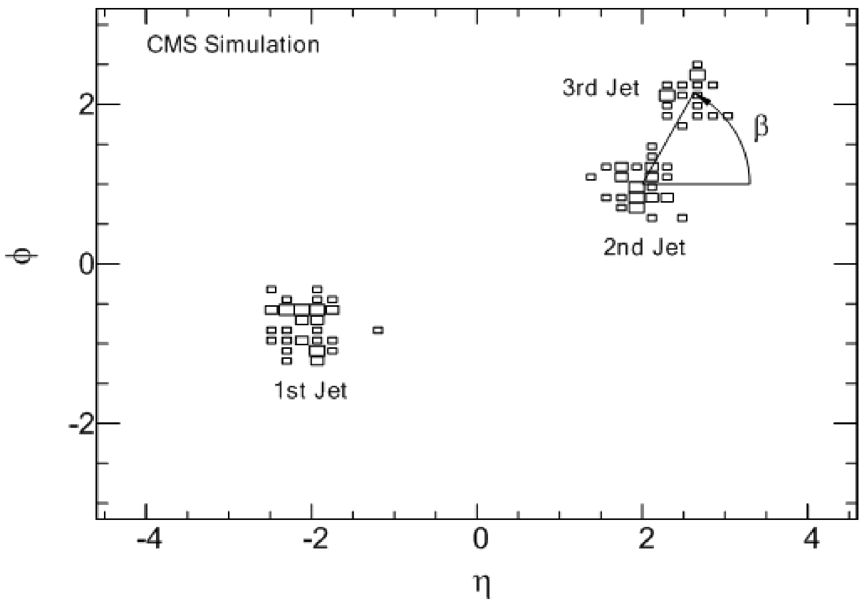
Color coherence

arXiv:1311.5815

- Study 3-Jet events where two leading exhibit a back-to-back topology .
- The observable β is defined as the azimuthal angle of the 3^{rd} jet with respect to the 2^{nd} in (η,ϕ) space:

$$\tan\beta = \frac{|\Delta\phi_{23}|}{\Delta\eta_{23}}$$

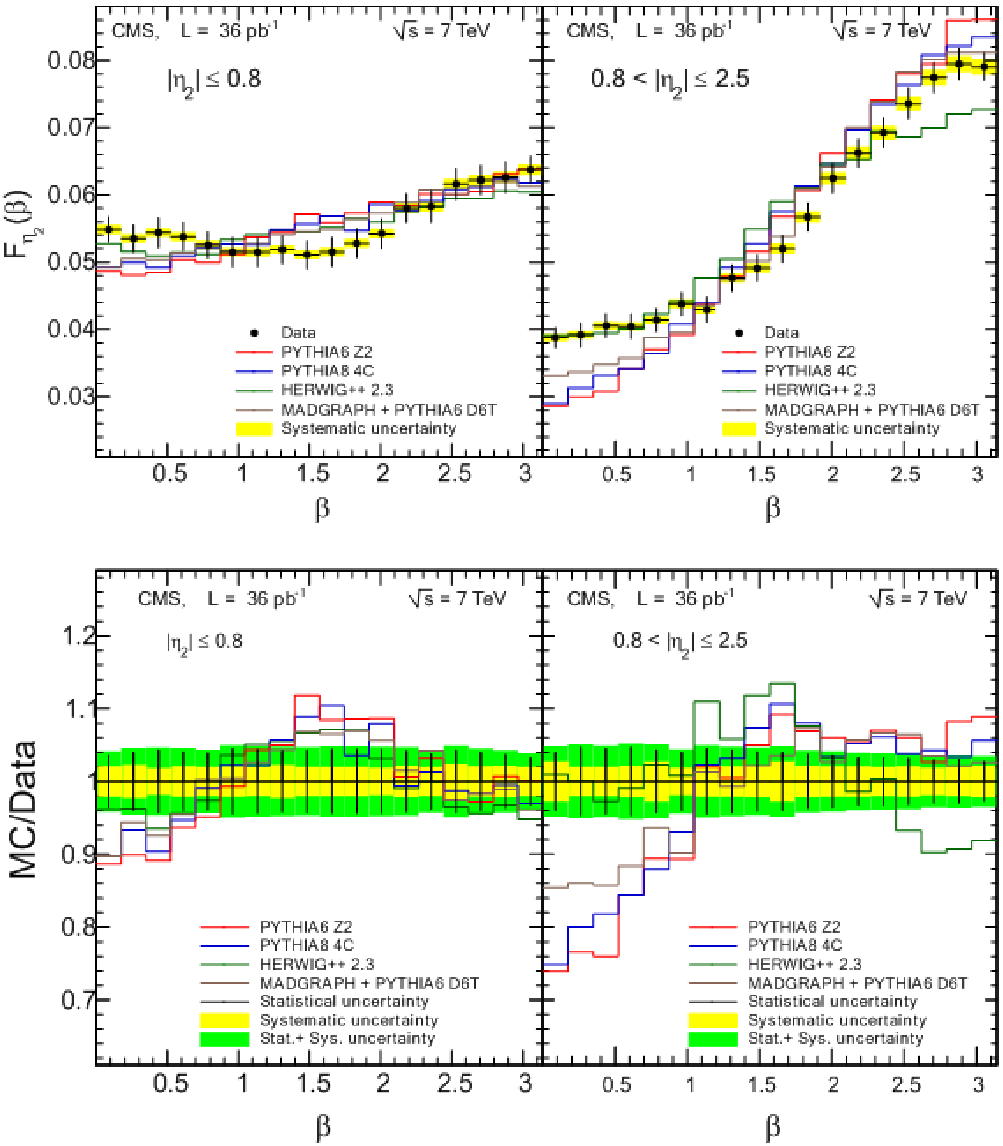
$$\Delta\phi_{23} = \phi_3 - \phi_2$$
$$\Delta\eta_{23} = sign(\eta_2)\cdot(\eta_3 - \eta_2)$$



- Absence of color coherence :
  - no preferred direction of emission of the 3^{rd} parton around the 2^{nd} .
- Presence of color coherence :
  - 3^{rd} parton tends to lie in the event plane defined by the 2^{nd} parton and the beam axis.
  - 3^{rd} jet population will be enhanced for β≈0 and suppressed for β≈π/2.

Color coherence

arXiv:1311.5815



- Data exhibit a clear enhancement of events compared to generators, near the event plane (β=0) and a suppression in the transverse plane (β=π/2).

- None of the models used in the analysis describes data satisfactory.

Summary

- **CMS** has an **excellent understanding** of the **jet reconstruction** and **energy calibration** and together with the **high data quality** make jet measurements **PRECISION PHYSICS**.

- **CMS** has already delivered several **jet measurements** improving the under-standing of **QCD**
  - **7 TeV**: inclusive and di-jet cross sections, multi-jets, event shapes, studies on color coherence effects etc.
  - **8 TeV**: preliminary results on inclusive jet cross sections.

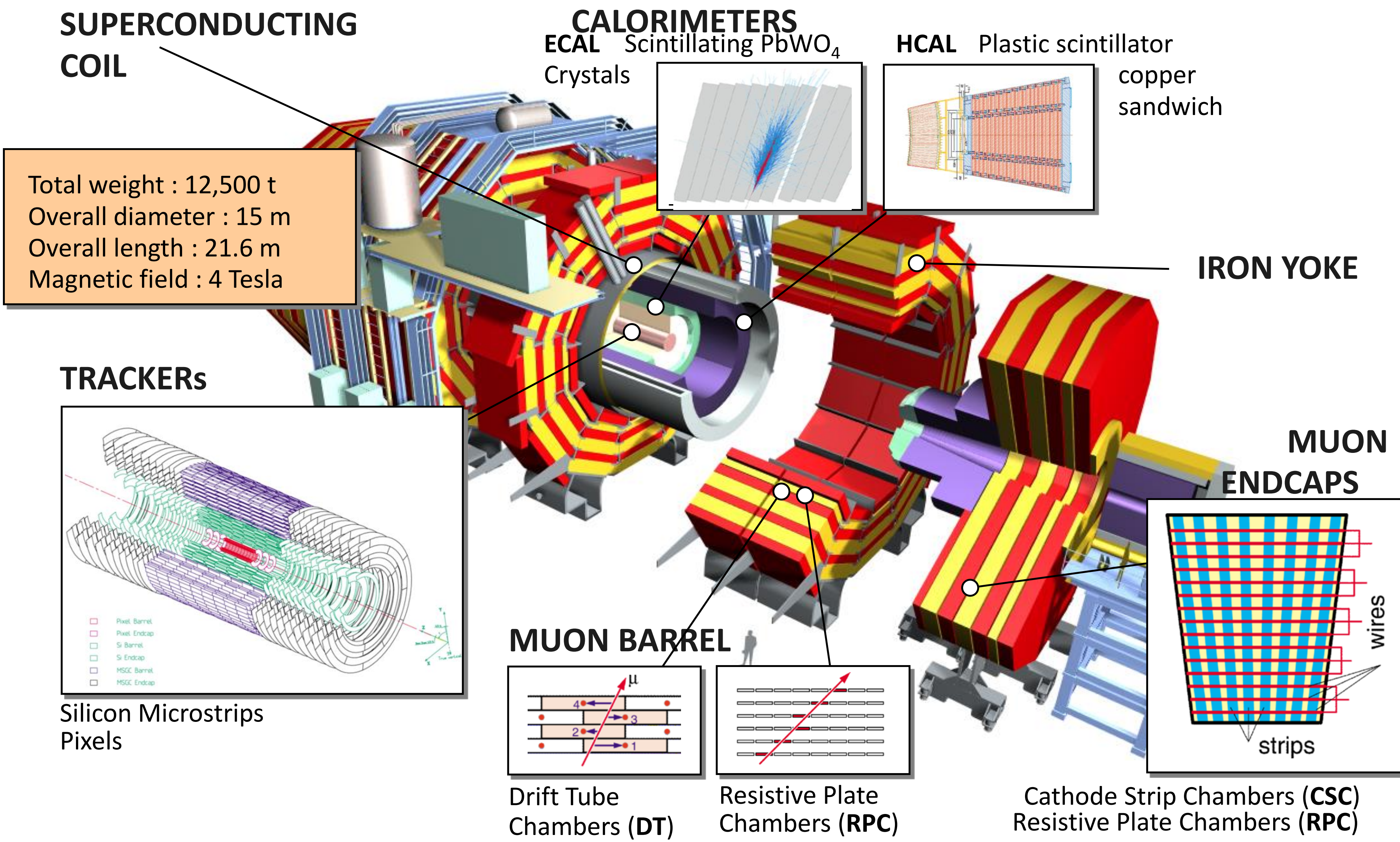
- **CMS** jet measurements are used also to **constrain PDFs** and **extract α_S** (see talk by G.Siebert)

- Several analysis at 8 TeV are currently in progress. And more to come at 13 TeV.

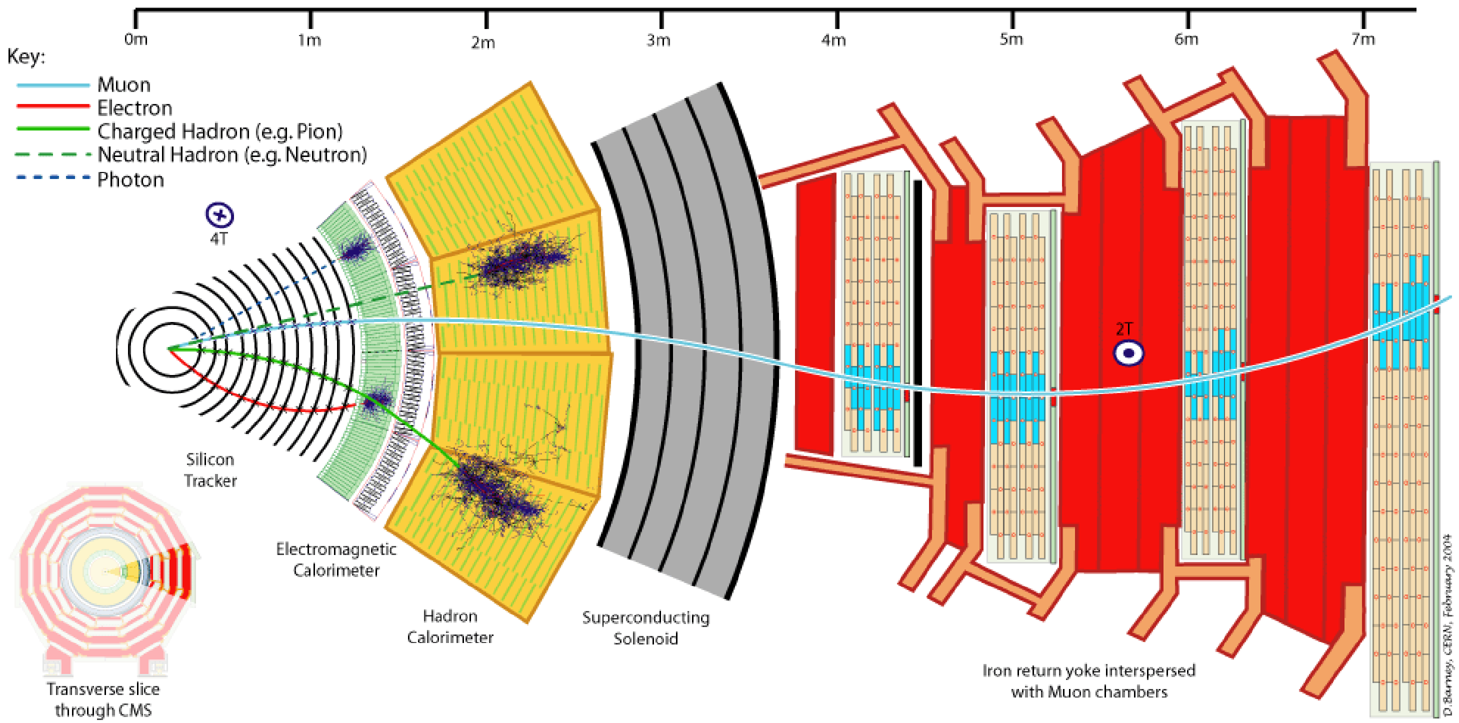
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ

Spare

The CMS Detector



Cross section of the CMS detector

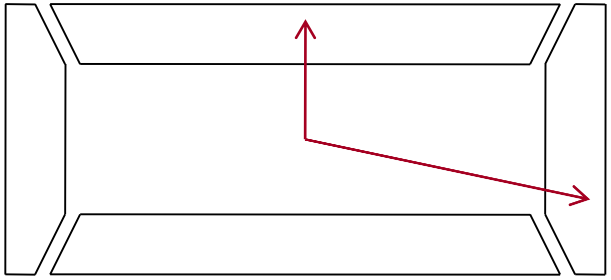


Tracking: |η|<2.5
Central Calorimetry: |η|<3
Forward Calorimetry: 3<|η|<5

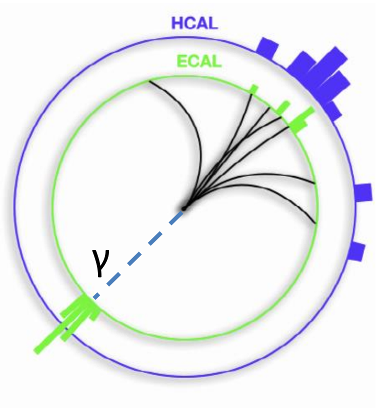
Jet Energy Scale Calibration

- Corrections derived using simulated events and in-situ measurements with dijet and photon+jet events.

- For **relative** corrections:
  - The di-jet p_T balance technique is employed taking the barrel jet ($|\eta|<1.3$) as reference and the other jet (probe jet) at any η.



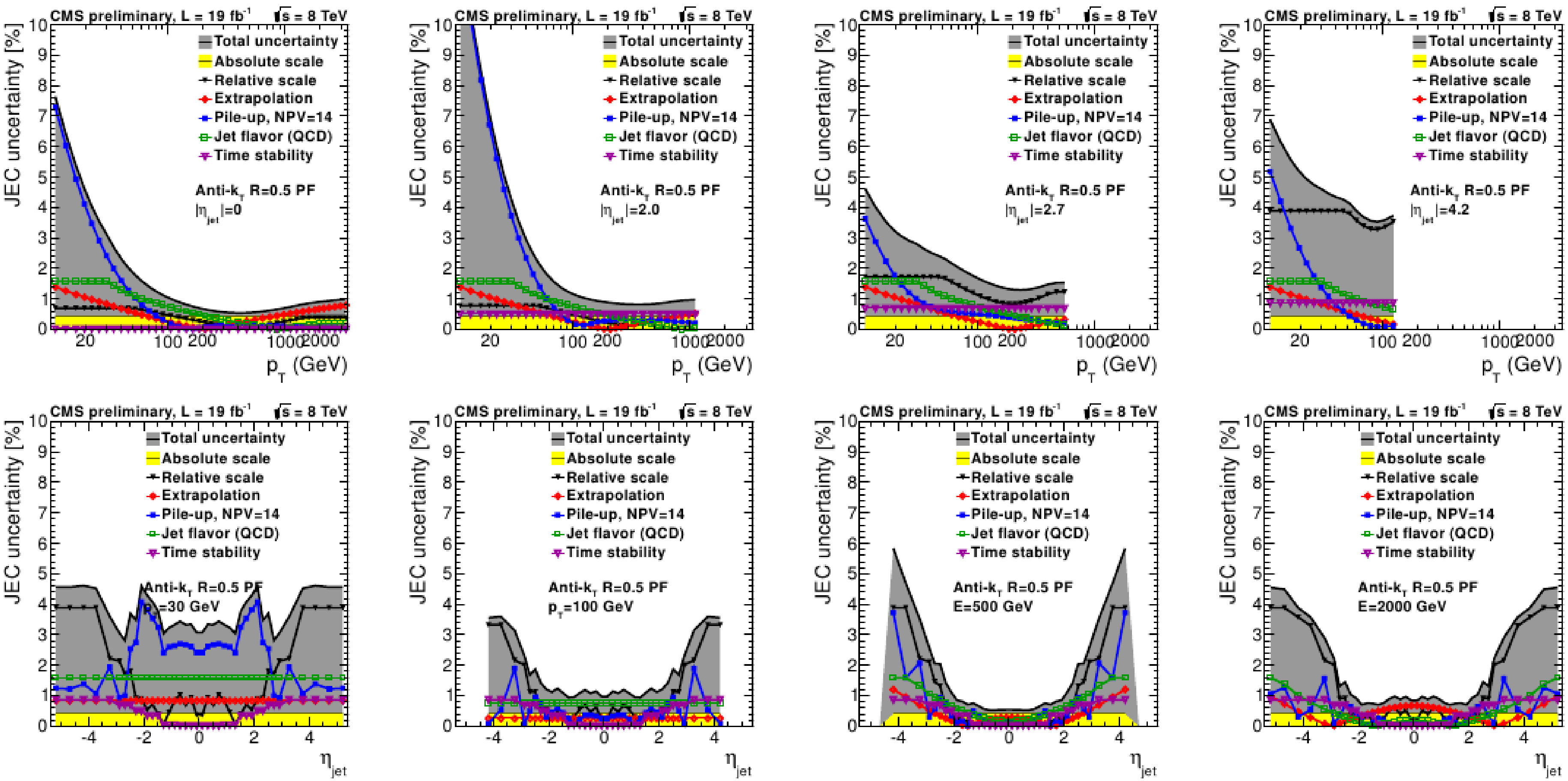
- The **absolute** jet energy response is measured using γ+jet or Z+jets events, with two different methods:
  - The MPF (missing E_T projection fraction)
  - And the p_T balance
- Both methods exploit the balance in the transverse plane between the photon and the recoiling jet.



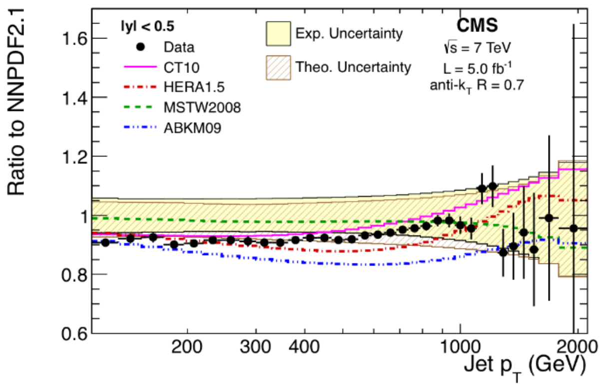
Jet Energy Correction Uncertainties at 8 TeV

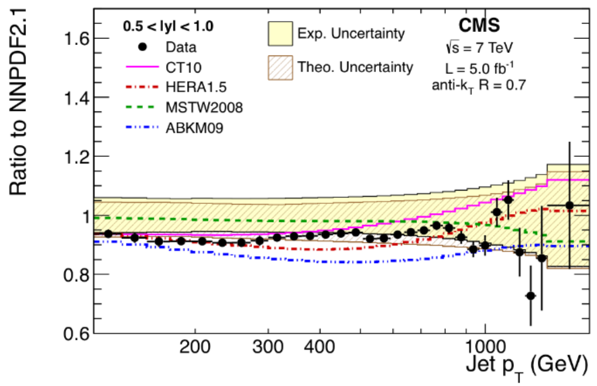
University of Ioannina HEPLAB

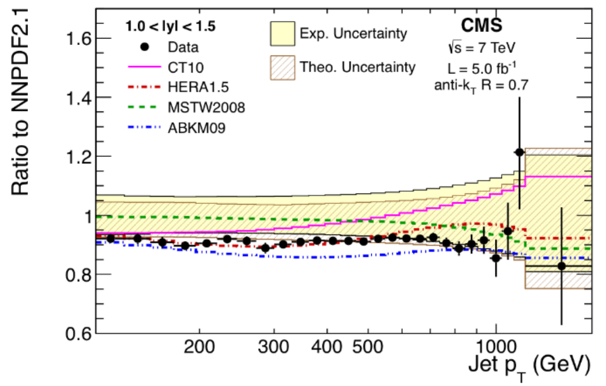
CMS DP-2013-033



Inclusive Jet cross section
Comparison to theory (7 TeV)







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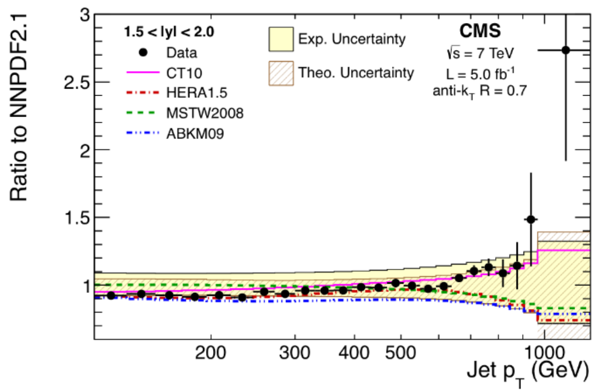
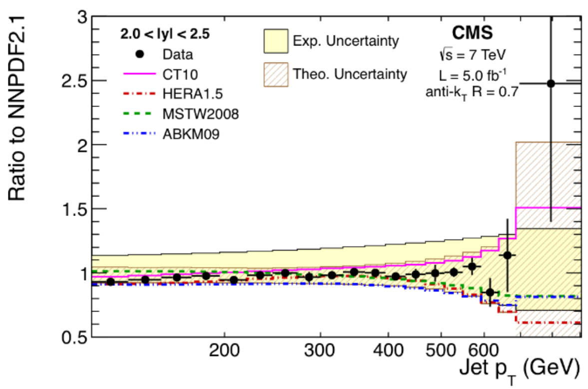
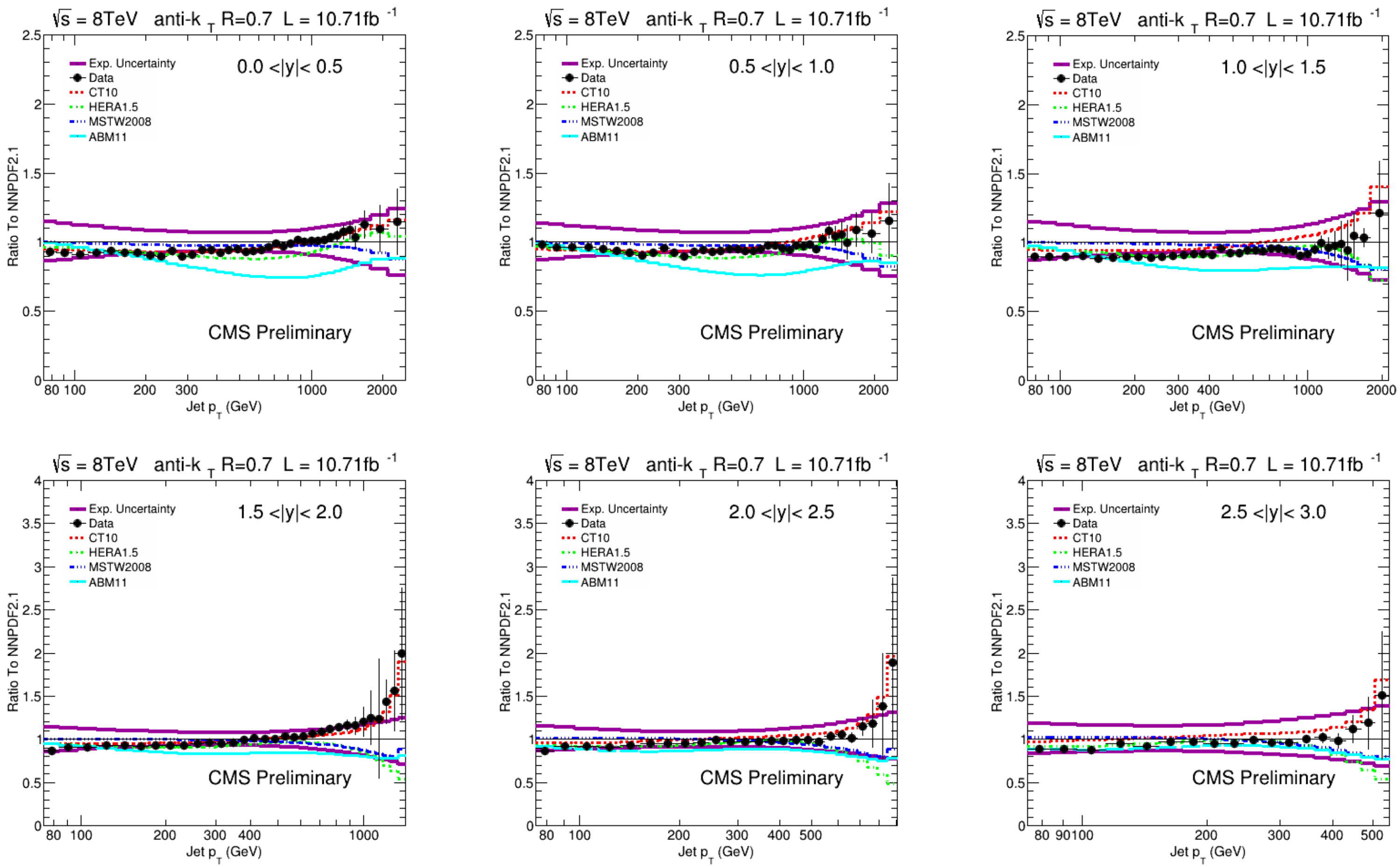




7 TeV : Agreement is observed between data and theory (using NNPDF2.1, CT10, HERA1.5, MSTW2008 and ABKM09 PDF sets) in all rapidity bins.

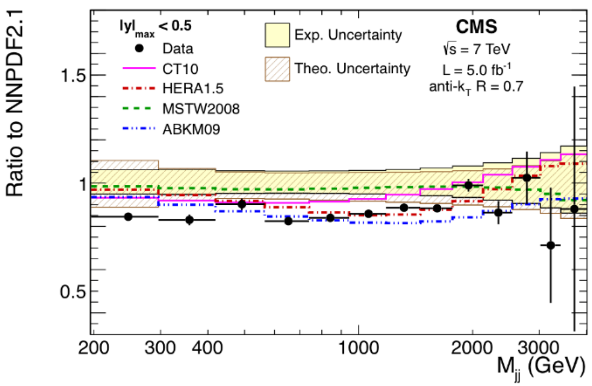
Inclusive Jet cross section
Comparison to theory (8 TeV)

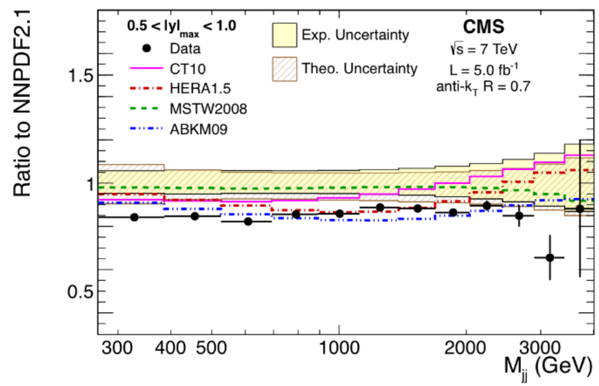


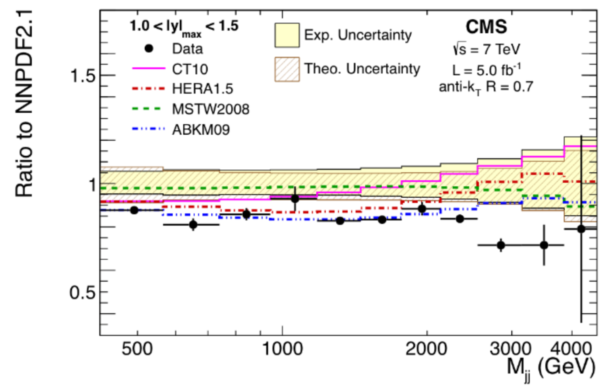
CMS PAS SMP-12-012

8 TeV : Agreement is observed between data and theory (using NNPDF2.1, CT10, HERA1.5 and MSTW2008 PDF sets) in all rapidity bins. Disagreement in central rapidity regions for ABM11.

Di-Jet cross section 7 TeV
Comparison to theory







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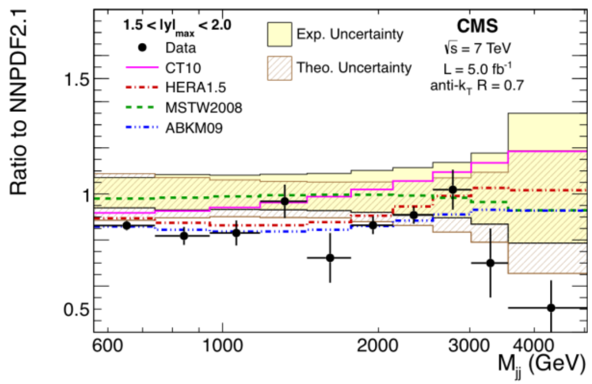
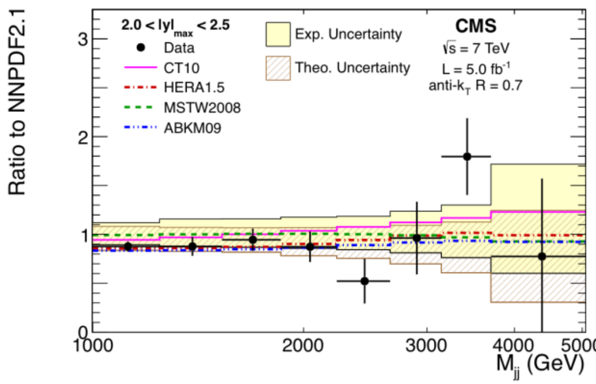


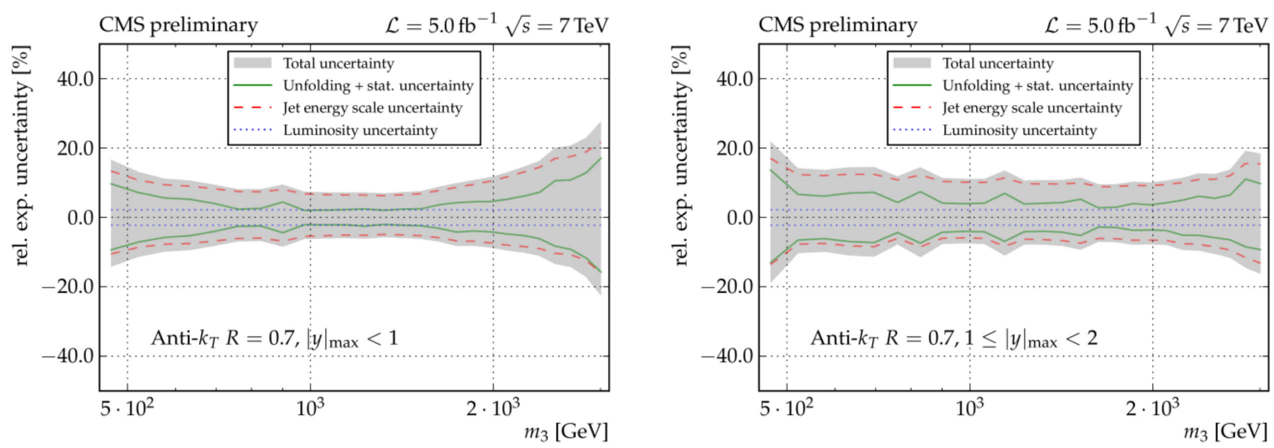


7 TeV : Agreement is observed between data and theory (using NNPDF2.1, CT10, HERA1.5, MSTW2008 and ABKM09 PDF sets) in all rapidity bins

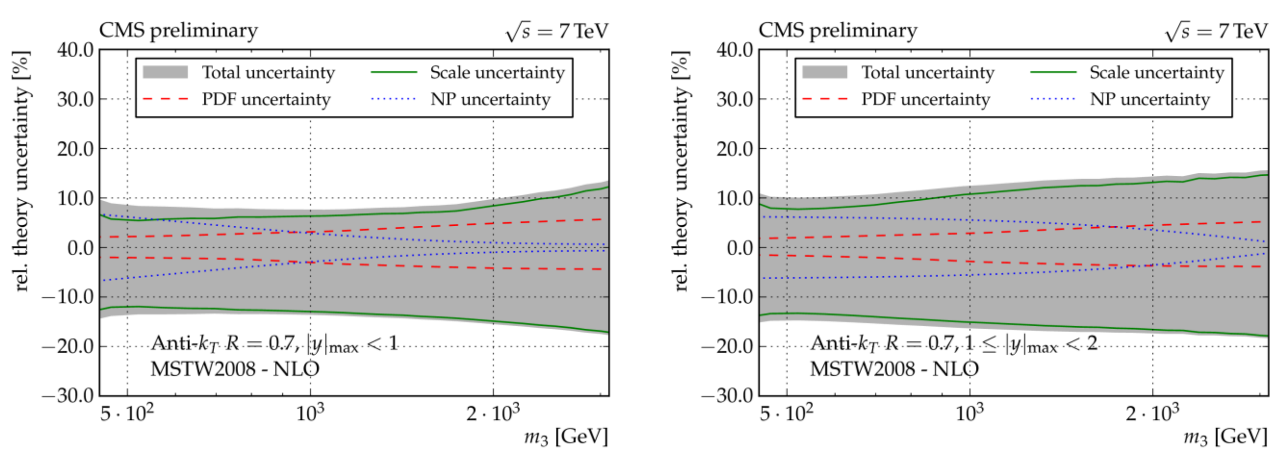
3-jet mass cross section at 7 TeV
Uncertainties

CMS PAS SMP-12-027

Experimental Uncertainties



Theoretical Uncertainties



3-jet mass cross section at 7 TeV
Comparison to theory

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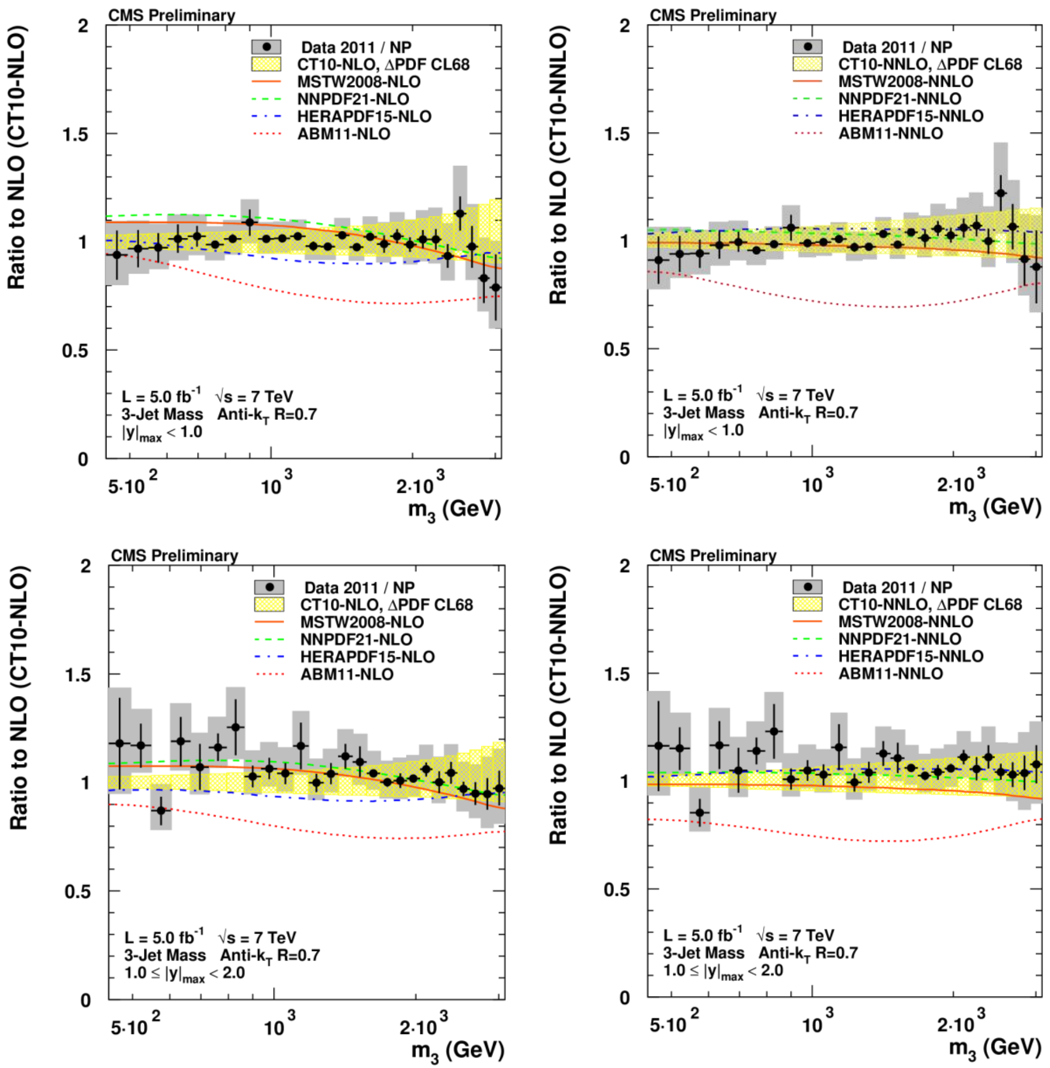

- Within uncertainties most PDF sets are able to describe the data.
- Small deviations are visible with the HERAPDF1.5 NLO set.
- Significant disagreements are exhibited by the ABM11 PDFs.

Hadronic Event Shapes (Transverse Thrust)

The event thrust observable in the transverse plane is defined by:

$$T_{\perp,C} \equiv \max_{\hat{n}_T} \frac{\sum_i \left| \vec{p}_{\perp i} \cdot \hat{n}_T \right|}{\sum_i p_{\perp i}} , \quad \tau_{\perp,C} \equiv 1 - T_{\perp,C}$$

with $\hat{n}_T$ the unit vector that maximizes the projection (transverse thrust axis).

- In the limit of a perfectly balanced two-jet event, $\tau_{\perp,C}$ is zero, while in isotopic multi-jet events it is (1-2/π).
- All generators show an overall agreement with data to within 10%, with PYTHIA8 and HERWIG++ exhibiting a better agreement than the others.

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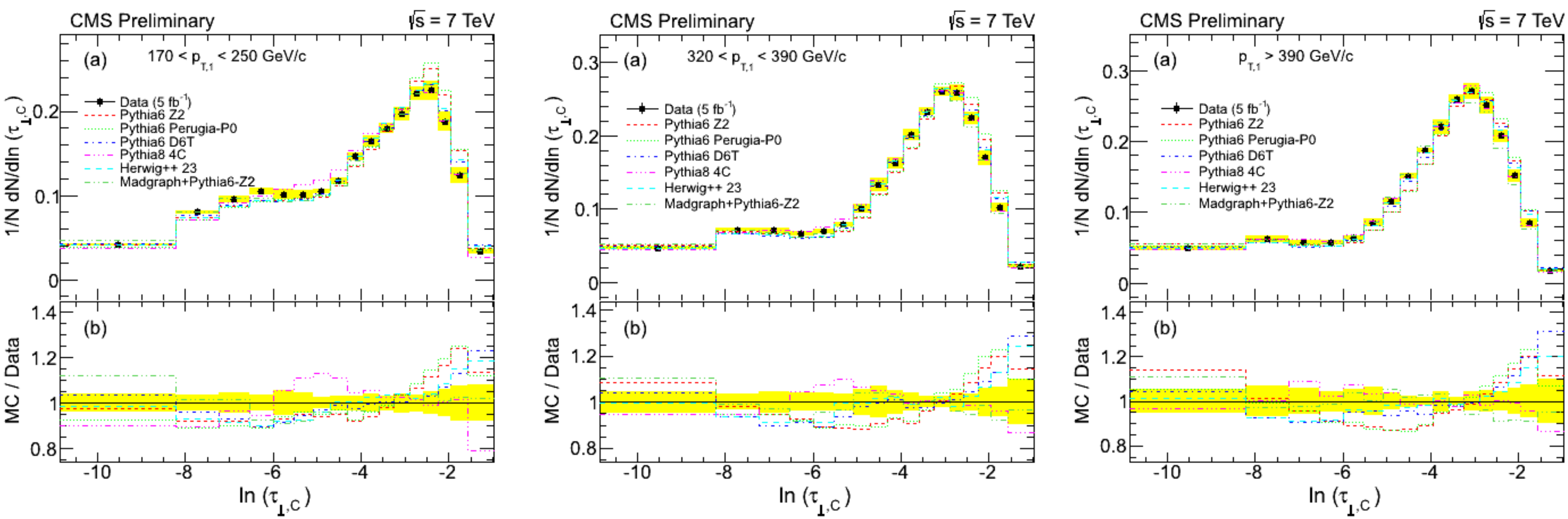

Hadronic Event Shapes (Jet Broadening)

The transverse thrust axis, $\vec{n}_{\perp}$, splits the transverse region in an upper part C_U (with $p_T \cdot n_{\perp}$>0) and a lower part C_L (with $p_T \cdot n_{\perp}$<0). The total jet broadening is defined as:

$$B_{tot,C} \equiv B_{U,C} + B_{L,C}$$

$$B_{X,C} \equiv \frac{1}{2P_{\perp}} \sum_{i \in C_X} p_{\perp i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}$$

$$\eta_X = \frac{\sum_{i \in C_X} p_{\perp i} \eta_i}{\sum_{i \in C_X} p_{\perp i}}, \quad \phi_X = \frac{\sum_{i \in C_X} p_{\perp i} \phi_i}{\sum_{i \in C_X} p_{\perp i}}$$

- Sensitive to ME, PS and color coherence effects. Insensitive to UE and hadronization.
- The agreement of this event shape variable with predictions is poor.
- Better agreement for the MADGRAPH and HERWIG++ generators.

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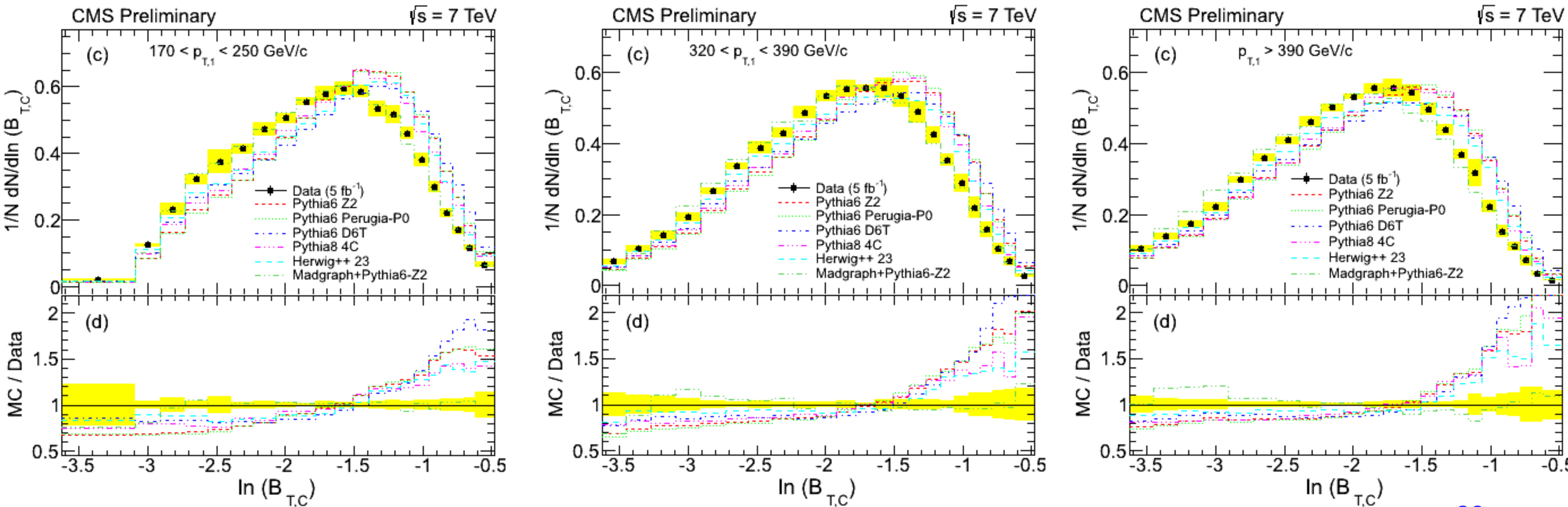

Hadronic Event Shapes (Jet Mass)

For the same definitions of upper and lower regions, the normalized squared invariant mass is defined by:

$$\rho_X \equiv \frac{1}{P^2}\left(\sum_{i\in C_X} p_i\right)^2$$

where P is the scalar sum of the momenta of all the constituents (p_i) in jets. The jet mass is defined as the sum of the masses in the upper and lower regions $\rho_{tot,C} \equiv \rho_U + \rho_L$

- More sensitive to (initial state) forward radiation than the jet broadening.
- Same behaviour as for the jet broadening.
- The transverse jet mass shows better agreement because is less sensitive to longitudinal event flow.

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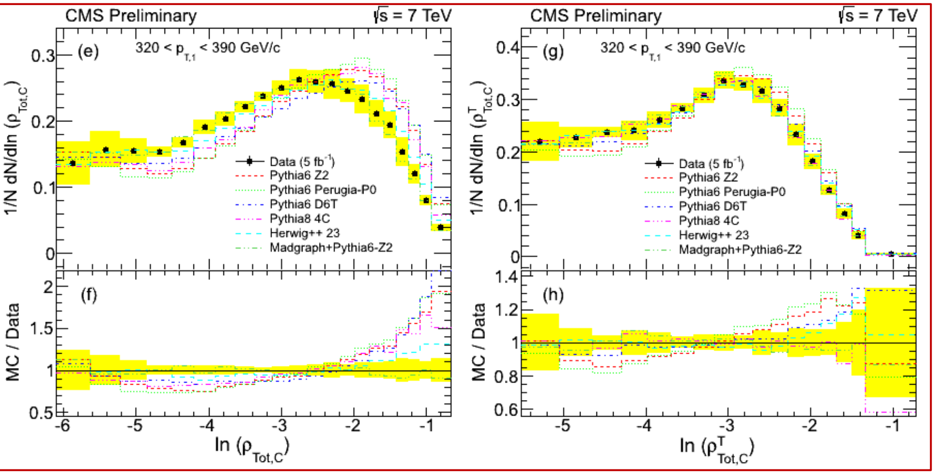

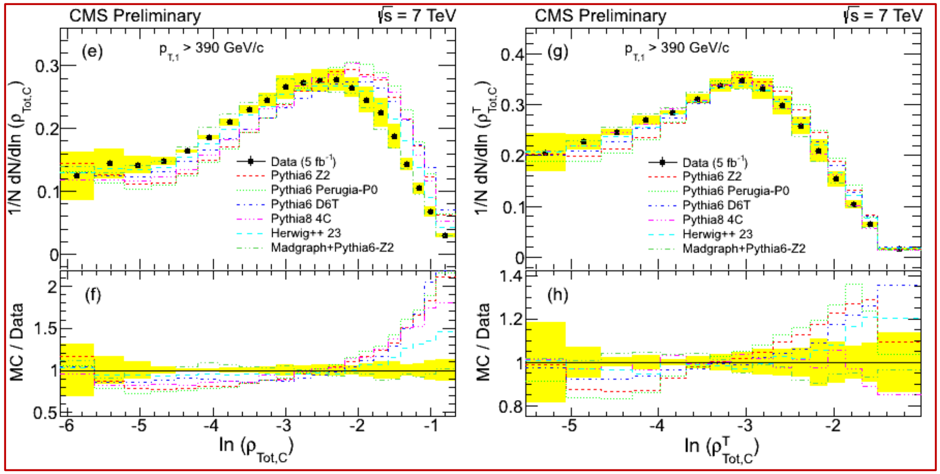

Inclusive jet AK5/AK7 cross section ratio at 7 TeV

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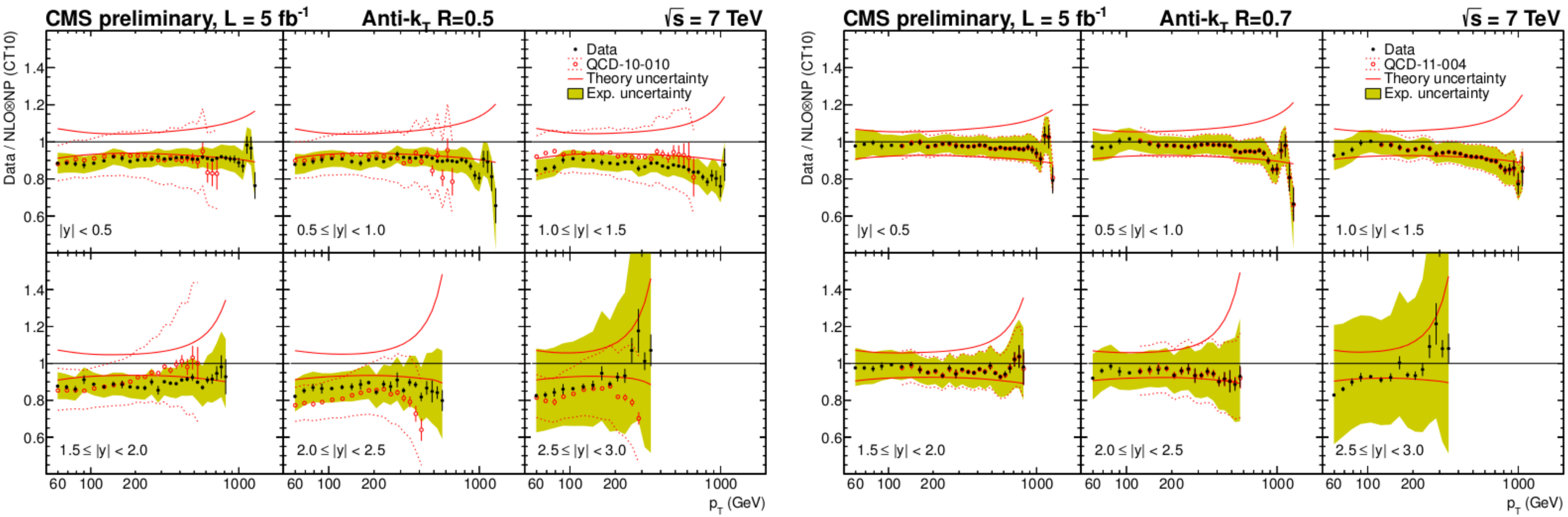
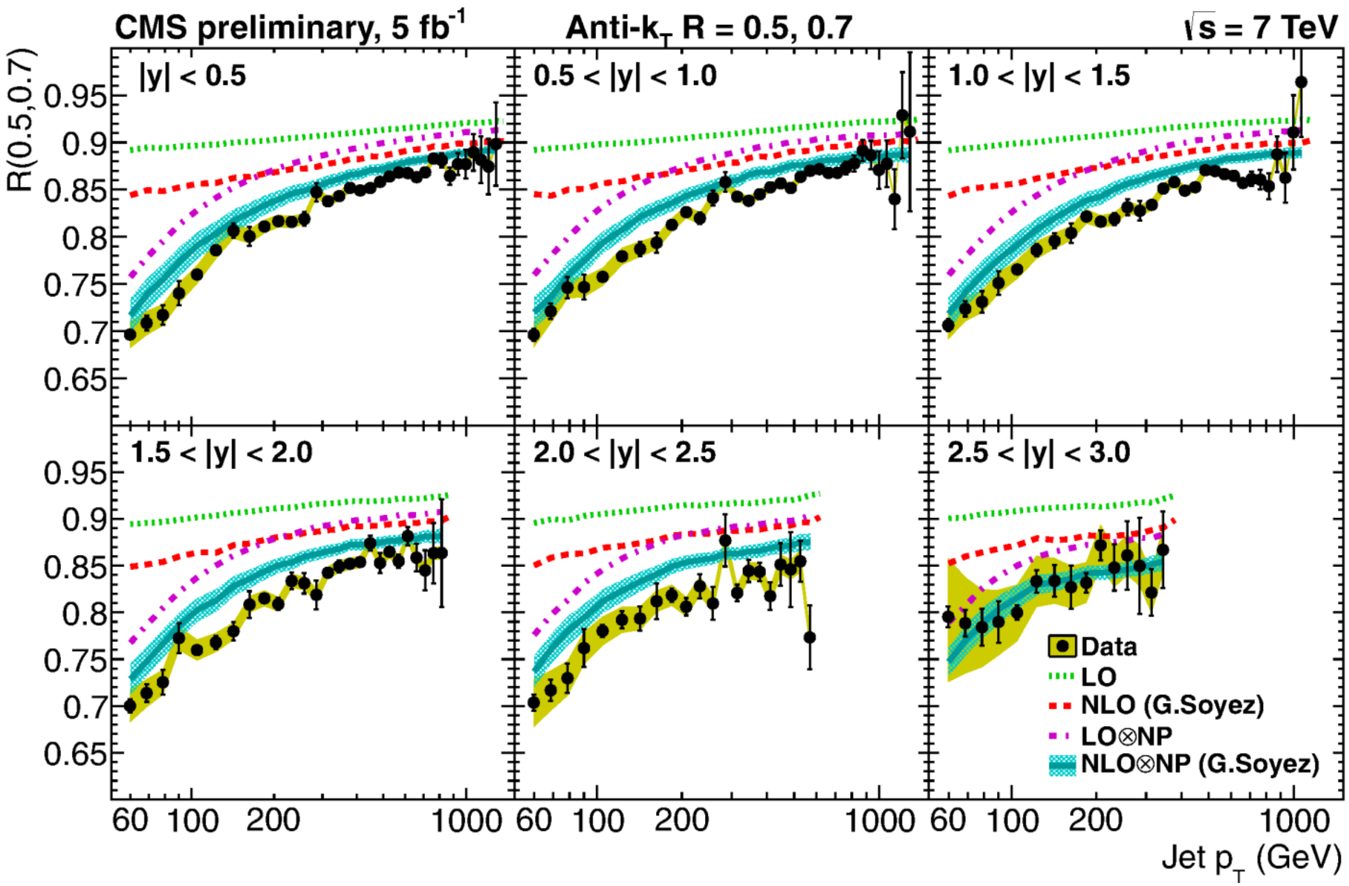


- Comparison to NLOxNP theory prediction: Data agrees with theory within uncertainties for both jet radii.
- **BUT** agreement is slightly better for R = 0.7.

Inclusive jet AK5/AK7 cross section ratio at 7 TeV

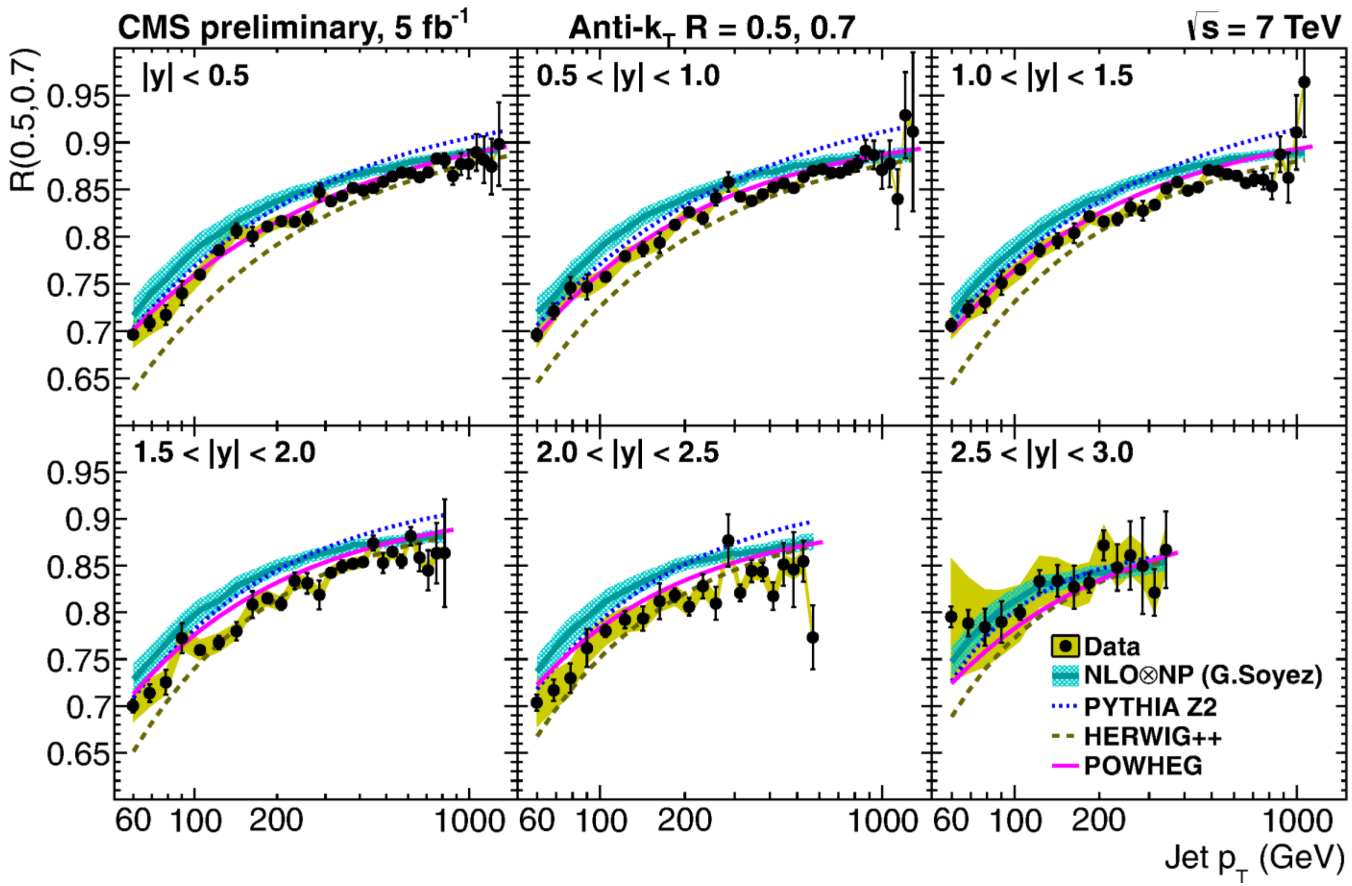
CMS PAS SMP-13-002



- The jet radius ratio R(0.5,0.7) in the six rapidity bins, compared to pQCD predictions.

Inclusive jet AK5/AK7 cross section ratio at 7 TeV

CMS PAS SMP-13-002



- The jet radius ratio R(0.5,0.7) in the six rapidity bins, compared to NLOxNP and MC predictions.

Color coherence

- Measurement done with CMS 2010 data (Integ. Lumi 36 pb^{-1})
- Jet reconstruction antiK_T with R=0.5.
- Min jet p_T=30 GeV.

Table 1: Summary of the event selection.

Selection criteria
$p_{T1} > 100\,\text{GeV}$, $p_{T3} > 30\,\text{GeV}$
$\lvert\eta_1\rvert, \lvert\eta_2\rvert \leq 2.5$
$M_{12} > 220\,\text{GeV}$
$0.5 < \Delta R_{23} < 1.5$

Uncertainty sources	$\lvert\eta_2\rvert \leq 0.8$	$0.8 < \lvert\eta_2\rvert \leq 2.5$
Jet energy scale (JES)	1.0%	1.0%
Jet energy resolution (JER)	0.4%	0.5%
Jet angular resolution (JAR)	0.5%	0.6%
Physics model (PM) used in unfolding	0.6%	0.7%
Statistical uncertainty	4.0%	3.7%