Jet production in association with vector bosons at LHC with the CMS detector

Jet rates in W/Z+jets

Azimuthal correlations and event shapes in Z+jets

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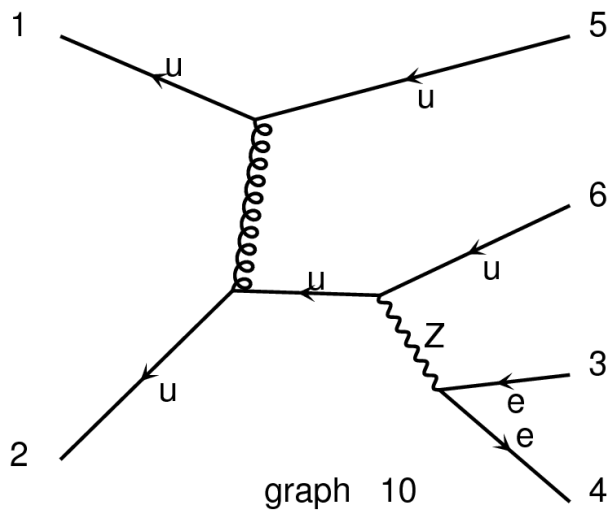
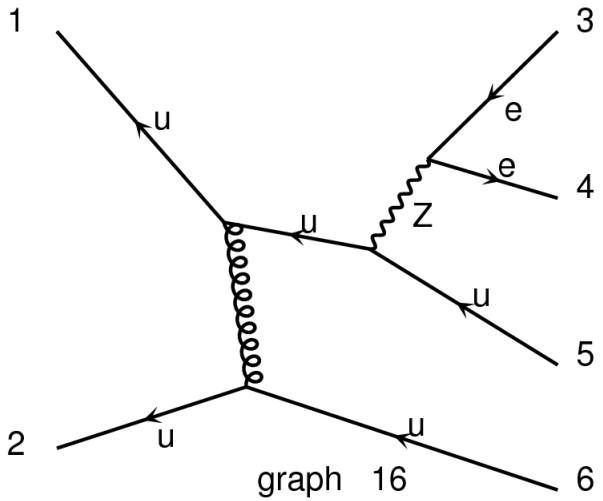
On behalf of the CMS collaboration

ICHEP 2012

V+jets at LHC

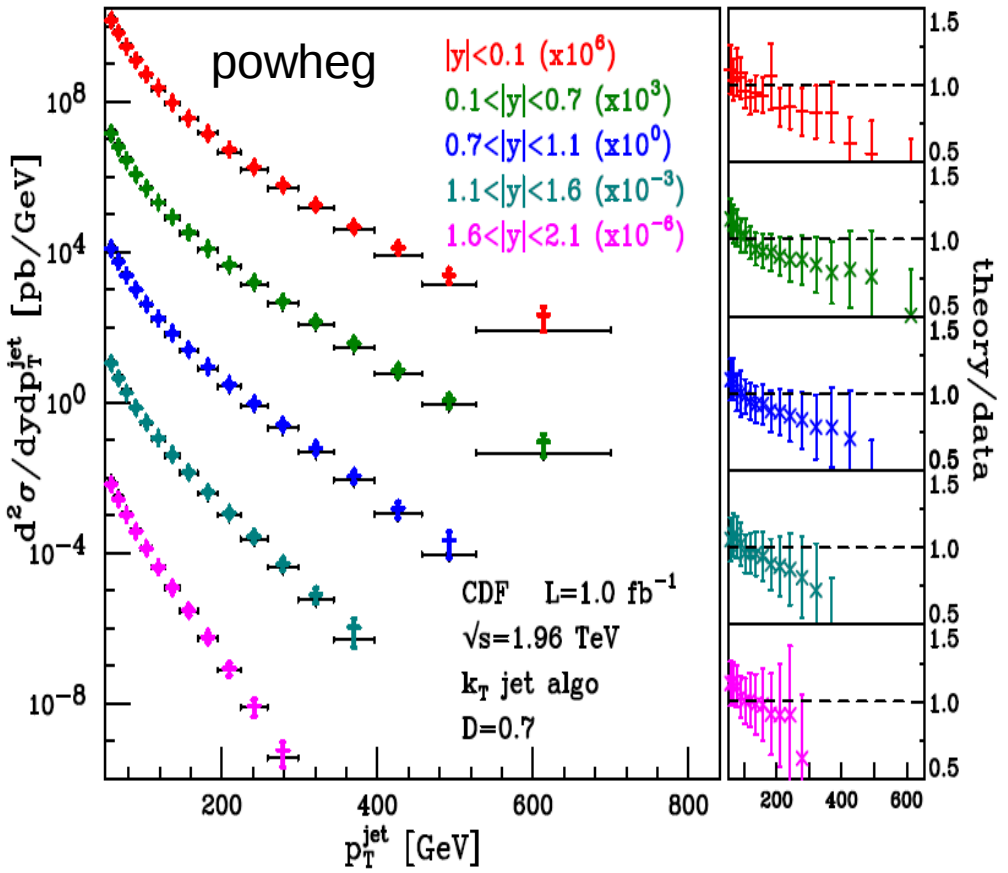
- Important for two broad classes of reasons
  - It is an ubiquitous source of background for virtually any signal (both SM and searches) at a hadron collider
  - It is a tool to test the predictions of perturbative QCD
    - The current understanding of our detector allows us to do **precision** QCD measurements
- 2010 and 2011 LHC data recorded by the CMS detector at 7 TeV provided high statistics for precision tests of perturbative QCD predictions and Monte Carlo techniques





Available predictions

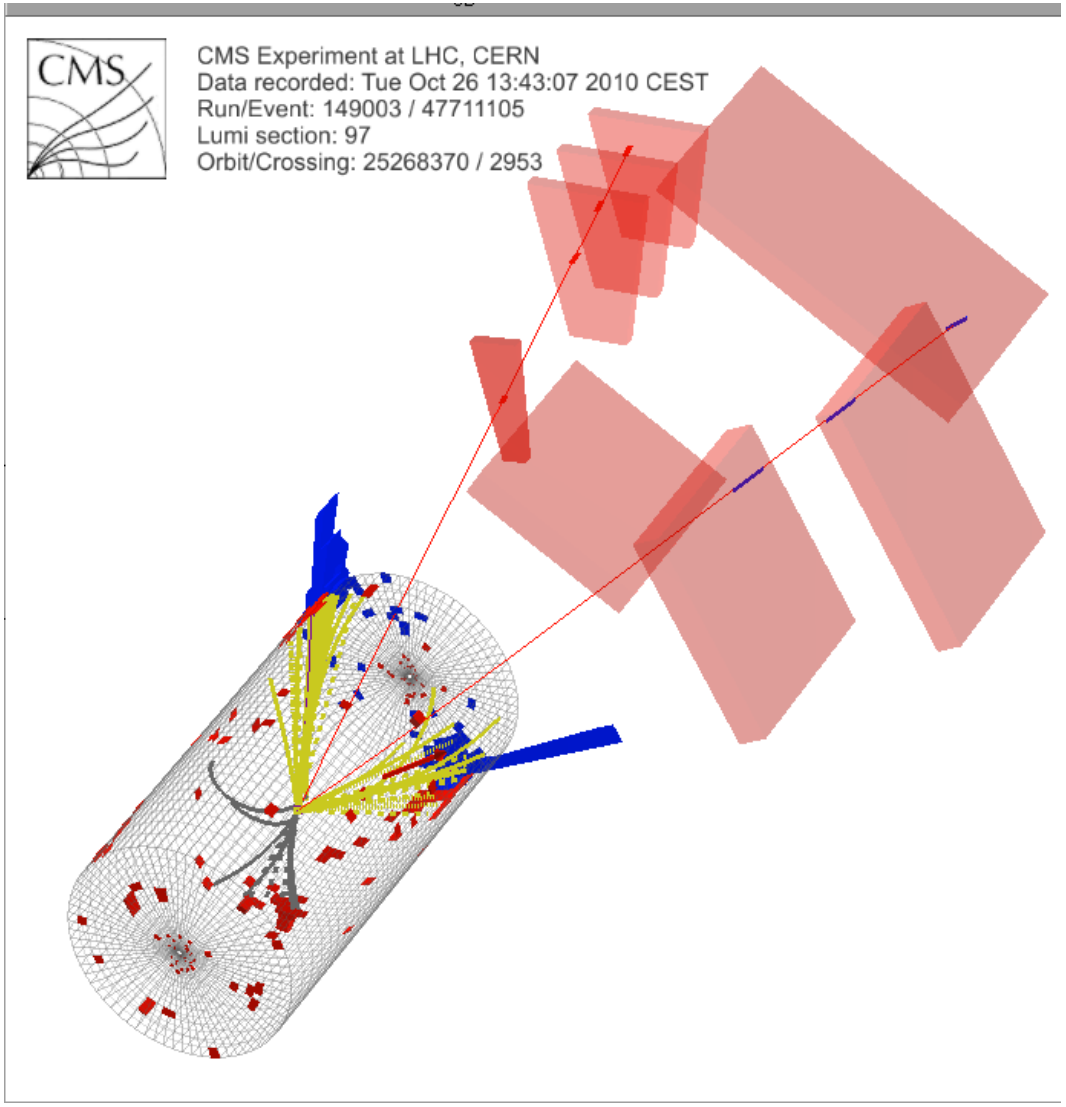
- Accurate predictions for W/Z+jets production at the LHC are available
  - Monte Carlo event generators
    - NLO + parton shower (MC@NLO, POWHEG...)
    - LO (many legs) + parton shower (Alpgen, MadGraph, Sherpa)
  - Parton level codes for distributions at NLO
    - BlackHat, Rocket...
- Modern parton distribution functions
  - LHC data start to contribute to PDF fits



Jet rates in V+jets

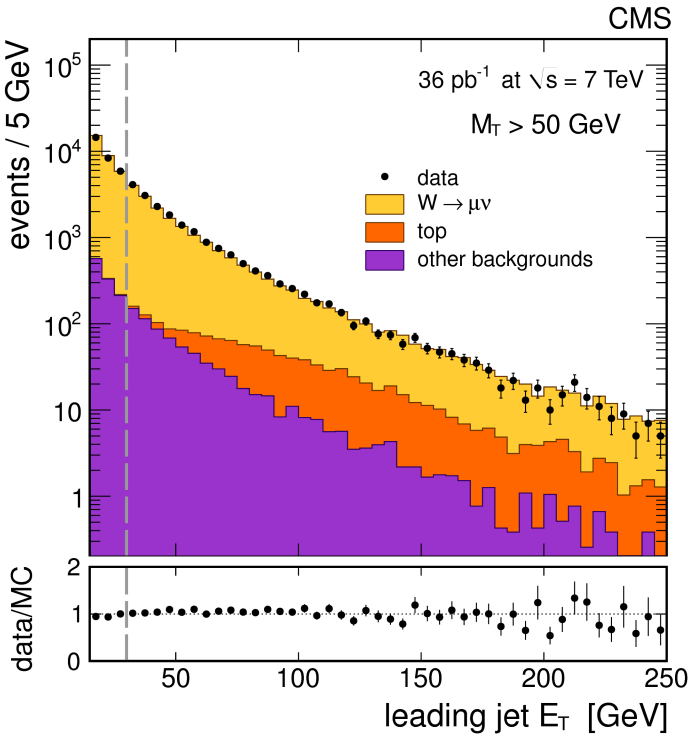
J. High Energy Phys. 01 (2012) 010

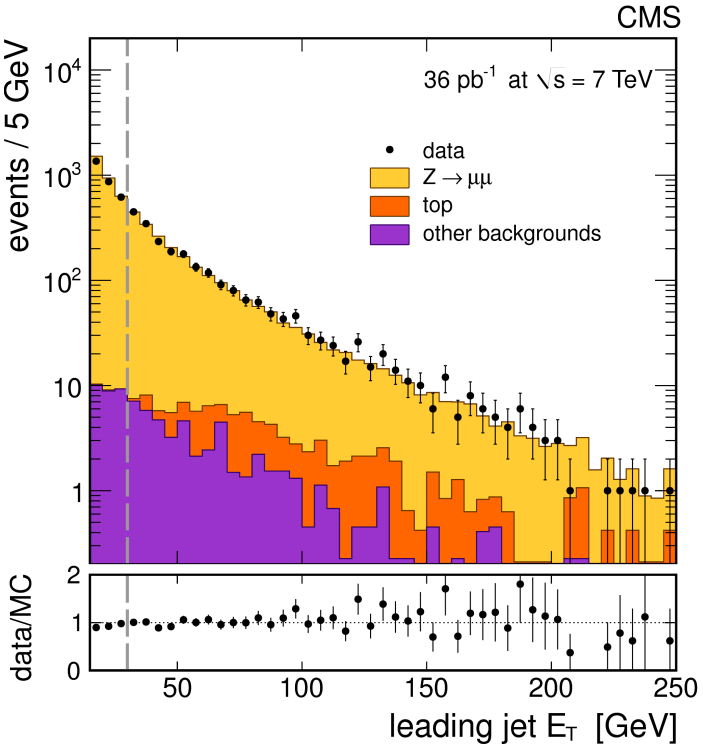
- CMS published jet rates and related observables for W/Z+jets using 2010 36pb^{-1} data sample and selecting the electron and muon decay channels
  - Jet rates normalized to the inclusive cross section
  - Ratios of events with n/n-1 jets
  - Ratios of W/Z versus the number of jets
  - W charge asymmetry versus the number of jets
- The use of ratios allows the cancellation of several systematic uncertainties either completely...
  - Luminosity in particular
- ...or largely
  - Jet energy scale in particular
- All results are quoted in the leptonic kinematic acceptance and detector effects have been unfolded



Event selection

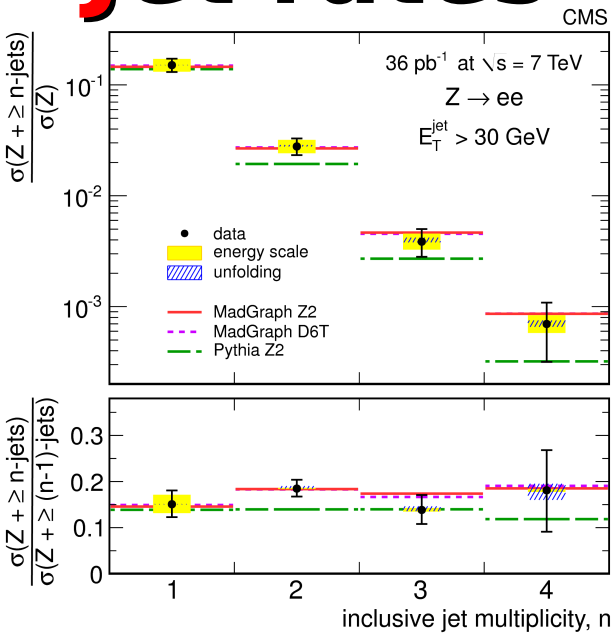
- pT(l) > 20 GeV, |η|<2.4,
  - Z: 60GeV<M(ll)<120GeV
  - W: M_T>20 GeV
- Jets definition
  - anti-kt algorithm with radius parameter 0.5 and pT threshold of 30 GeV and |η|<2.4
  - The average energy added by pile-up interactions has been removed with the FastJet median subtraction techniques on an event by event basis

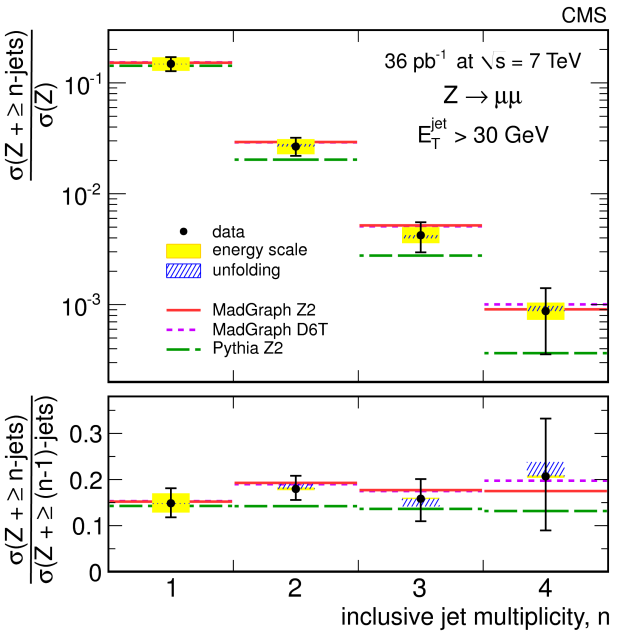


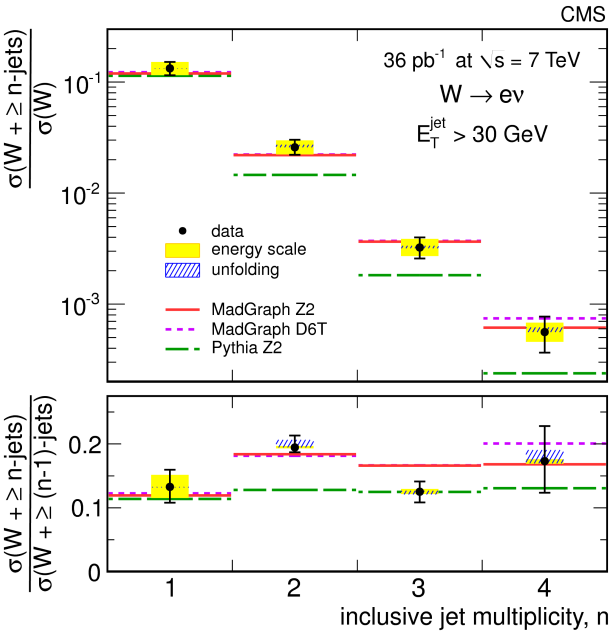


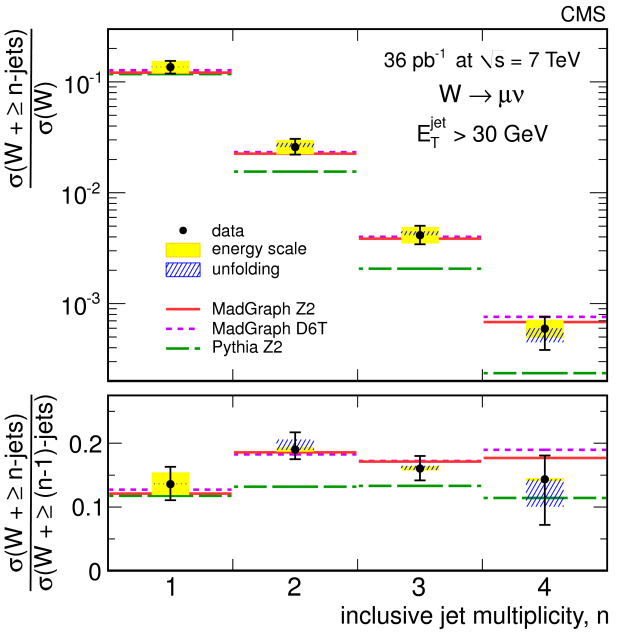
Jet rates

- Jet rates
  - Normalized to the inclusive cross section
  - n/(n-1) jets
- The comparison to the predictions of multi-leg matrix element + parton shower (Madgraph) shows good agreement
  - Pure parton shower (Pythia) fails to predict multi-jet final states
- Given the pT threshold on jets the sensitivity to underlying event is negligible



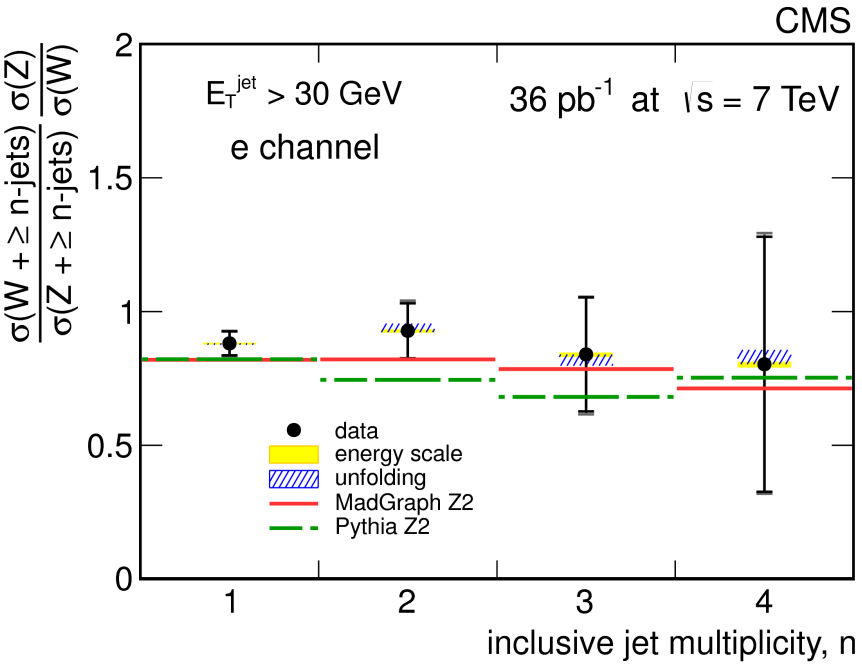


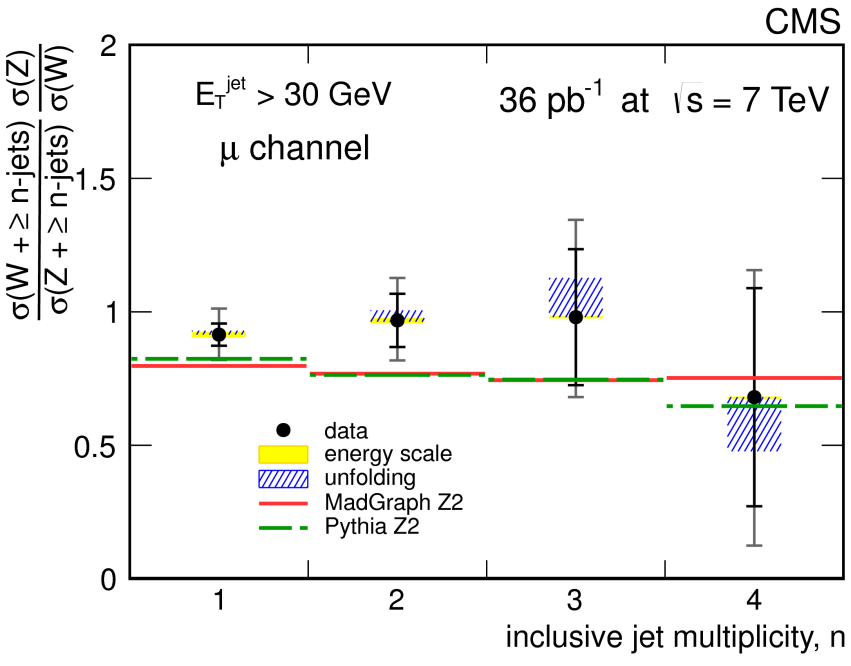




Double ratio

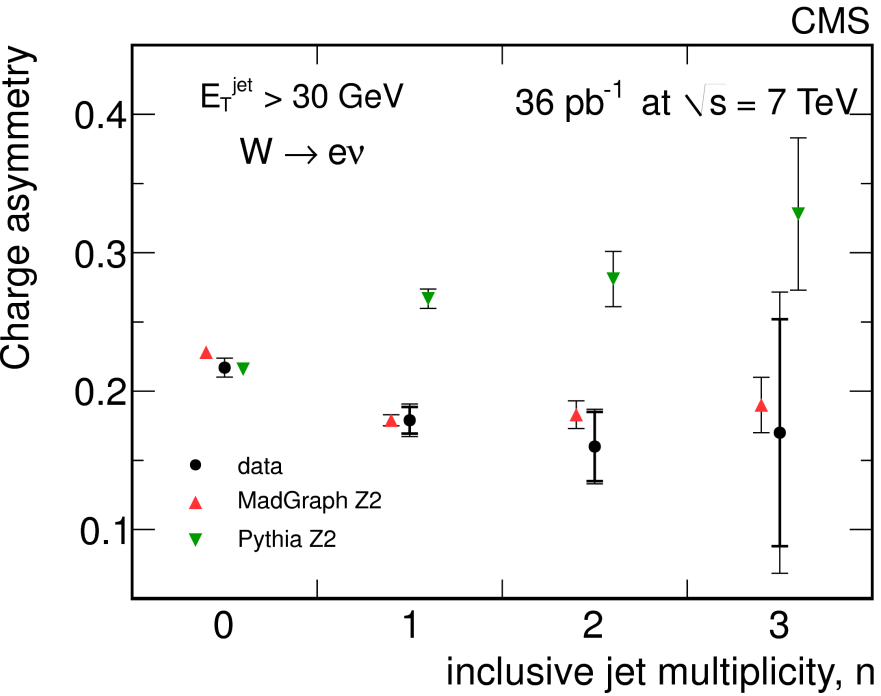
- Defined as [σ(W+jet)/σ(W)] / [σ(Z+jet)/σ(Z)]
  - It is an observable with very small systematic uncertainty
  - Jet energy scale systematic cancels almost completely

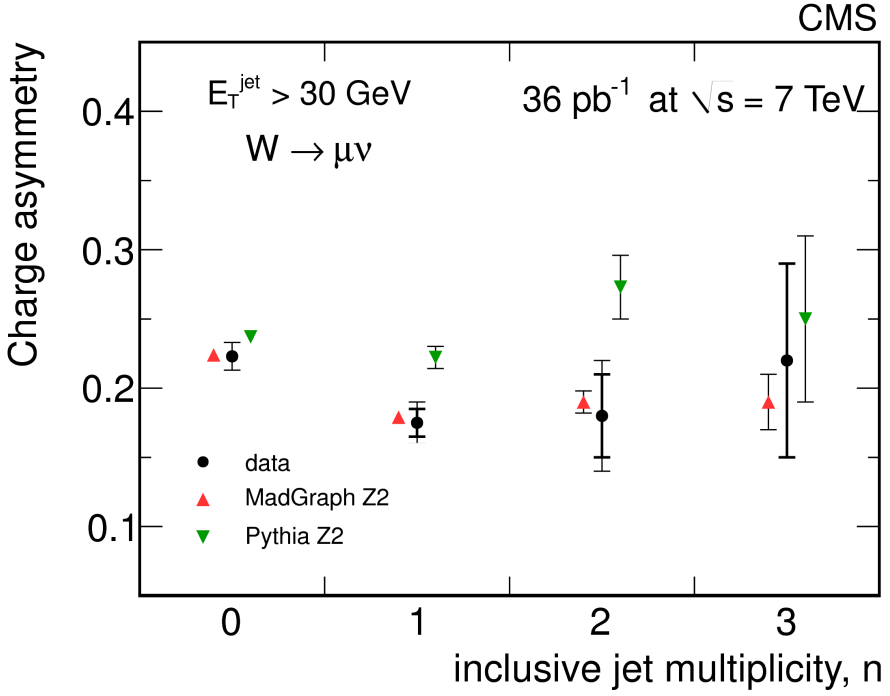




Charge asymmetry

- Charge asymmetry $[\sigma(W^+)-\sigma(W^-)]/ [\sigma(W^+)+\sigma(W^-)]$ as a function of jet multiplicity
  - Depends on the number of associated jets due to the fraction of u (d) quarks contributing to the different multiplicities
- It was measured fitting for the two charges independently
- Good agreement with Madgraph+Pythia predictions
  - Parton shower only (Pythia) departs from data already for jet multiplicity=1



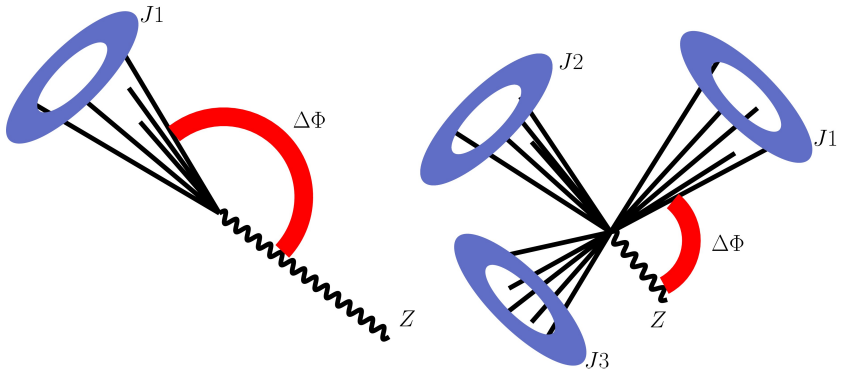


Azimuthal correlation in Z+jets

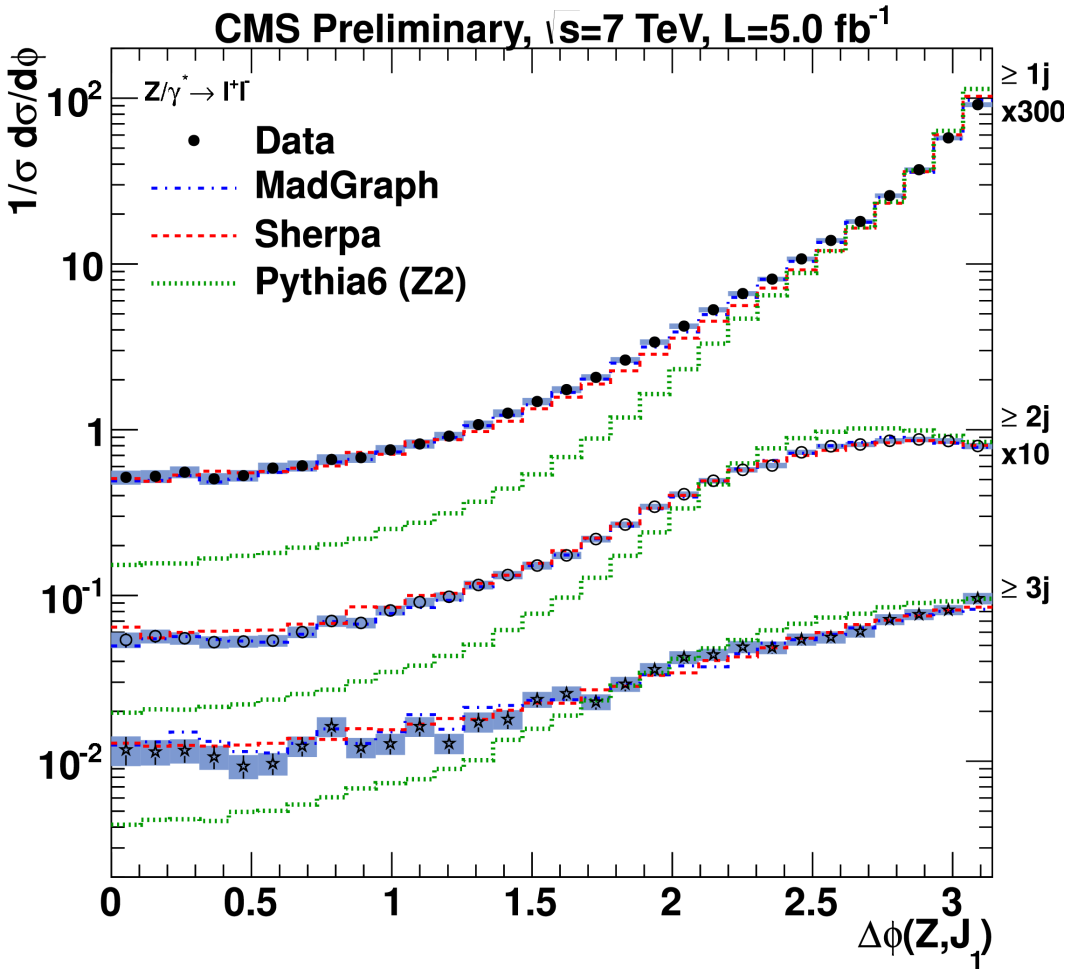
- In depth characterization of the topology of Z+jets using 2011 CMS data (5 fb^{-1})
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11021
  - Full kinematic information is available for Z
- Useful as a test of QCD predictions and for searches
  - Searches with invisible Z irreducible background, searches for resonances decaying in Z+X
- We measured the azimuthal correlation between the Z and the leading jet, and between the jets
  - Both inclusively and in a boosted Z regime, pT(Z)>150 GeV
- Jet reconstruction:
  - anti-kt with radius of 0.5 and pT>50 GeV
- Event selection:
  - pT(l)>20GeV, |η|<2.4, 71GeV<M(ll)<111GeV, at least one jet with pT>50GeV, |η|<2.5
- Results unfolded at particle level
- Muon and electron lepton flavors are combined at “dressed” level

Δφ(Z, J1)

- Shows a peak for Z back to back to the jet, and a long tail for events with many jets



- Both Sherpa (version 1.3.1. with default tune) and Madgraph give a good description of data
  - Sherpa slightly undershoots at intermediate values
    - Fewer events at intermediate jet multiplicity
  - Pythia is unable to describe multi-jet configurations



Error bars on data points: statistical uncertainty after unfolding
Shaded blue band: total data systematic

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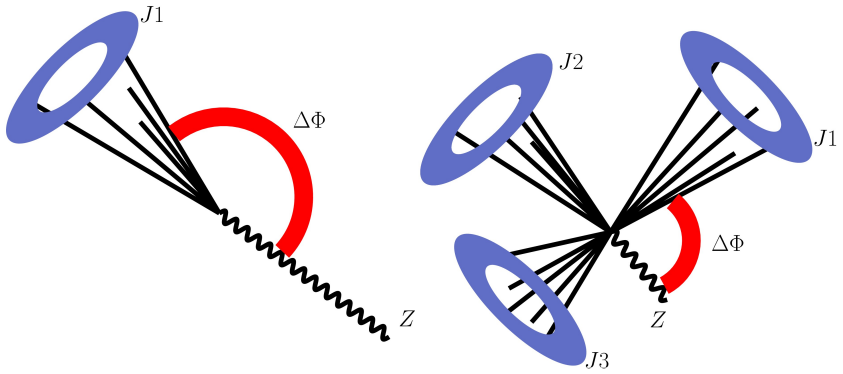

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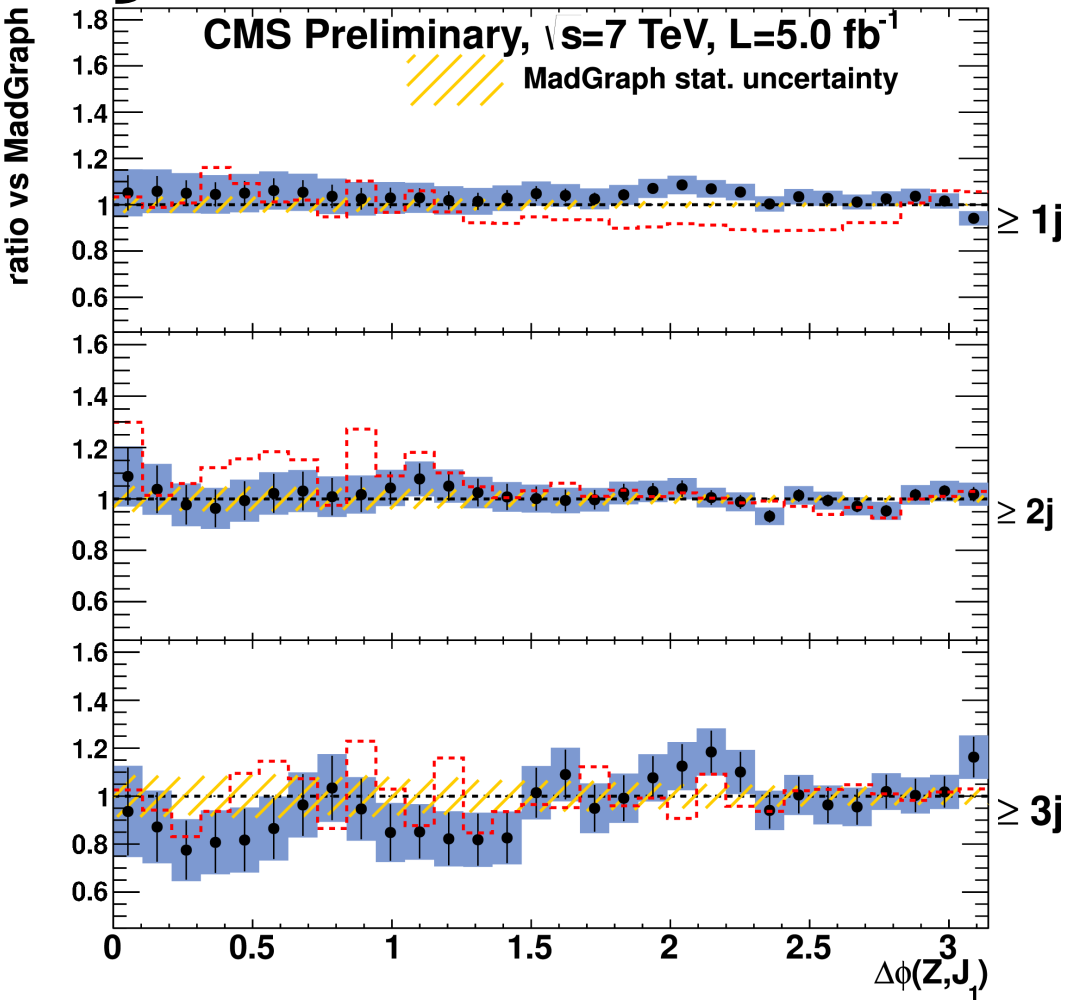
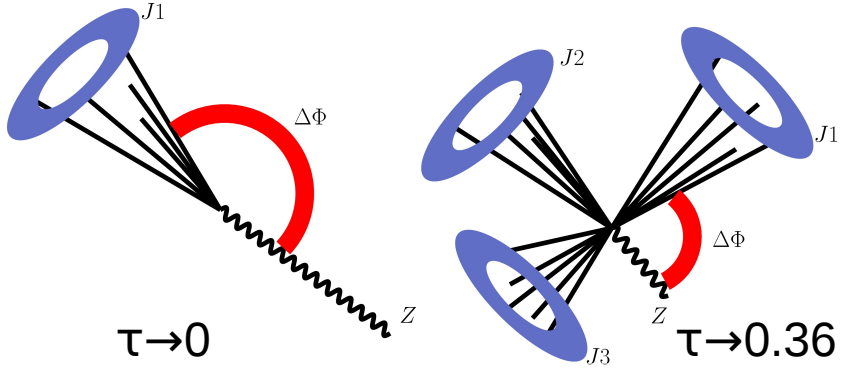


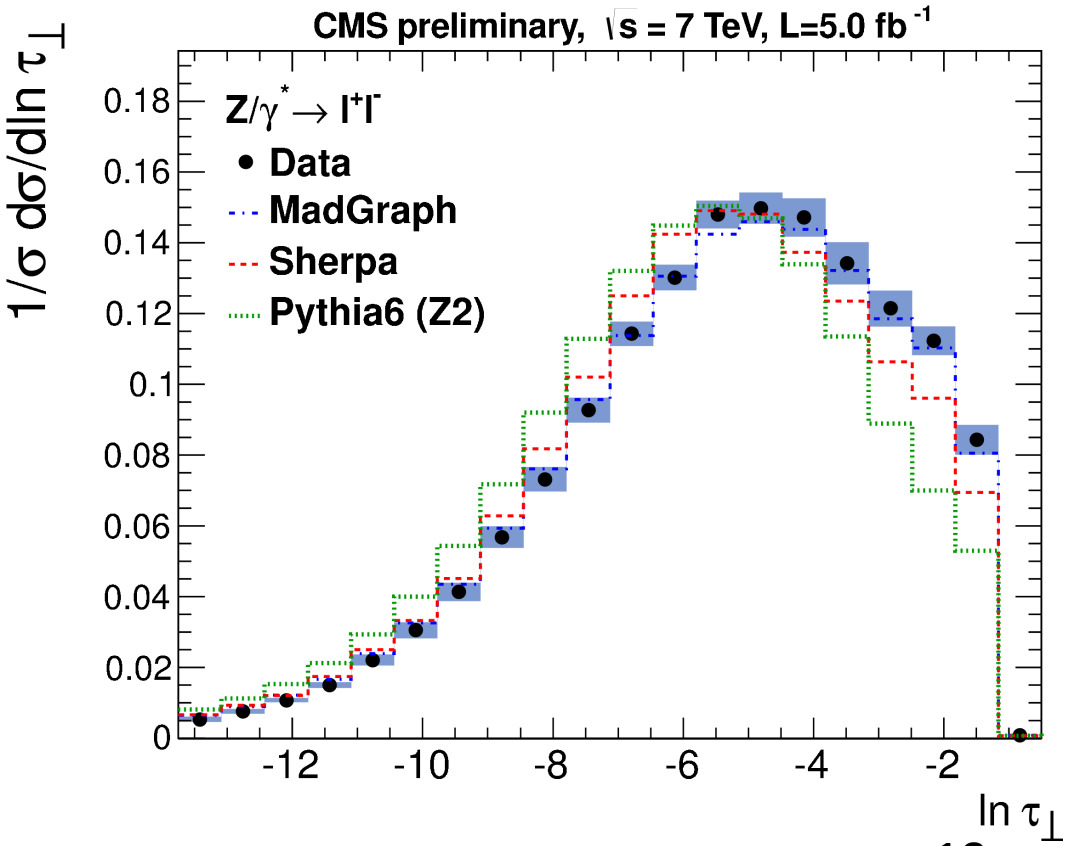
Error bars on data points: statistical uncertainty after unfolding
Shaded blue band: total data systematic
Hatched band: statistical uncertainty on Madgraph

Event shapes

$$\tau_\perp \equiv 1 - \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_i p_{\perp,i}}$$

- Another way of looking at angular correlations in Z+jets is through event shapes
  - It embeds more information than angular separation
  - It holds information from momenta
- The transverse momentum of the Z and of the jets are used as input to the computation of the transverse thrust
  - The peak at $\Delta\Phi=\pi$ gets diluted in a long tail
- Madgraph shows nice agreement with data
- Sherpa is shifted to the left
  - Consistent with the pattern observed in the $\Delta\Phi$ distribution
    - Fewer events with many jets





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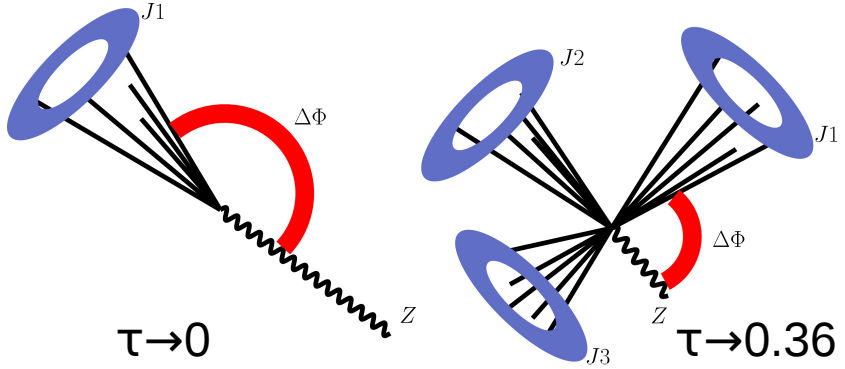
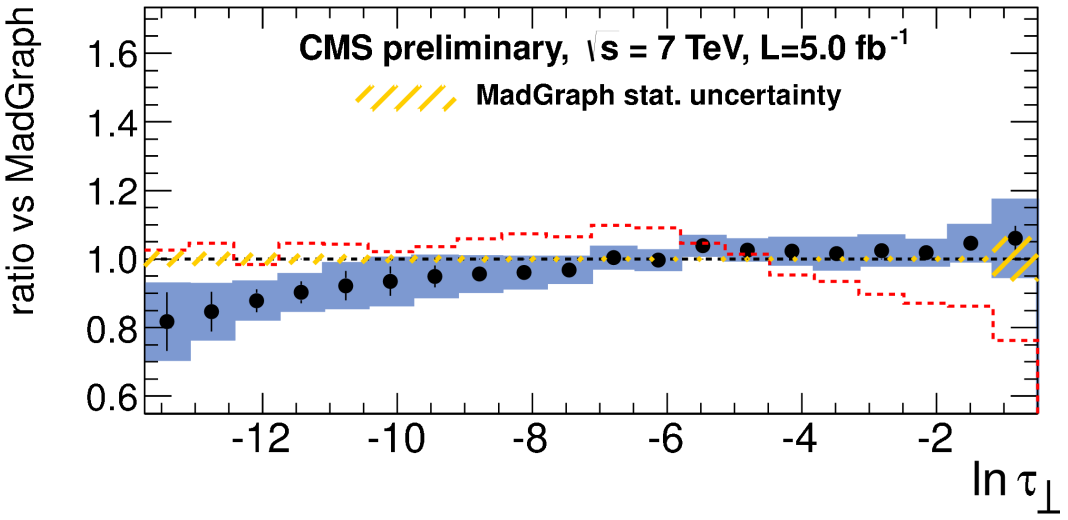
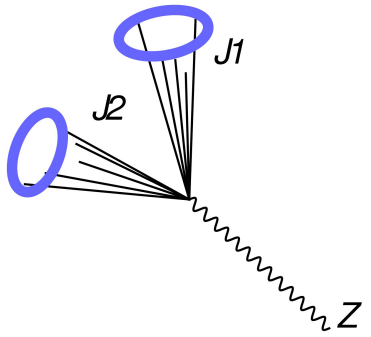
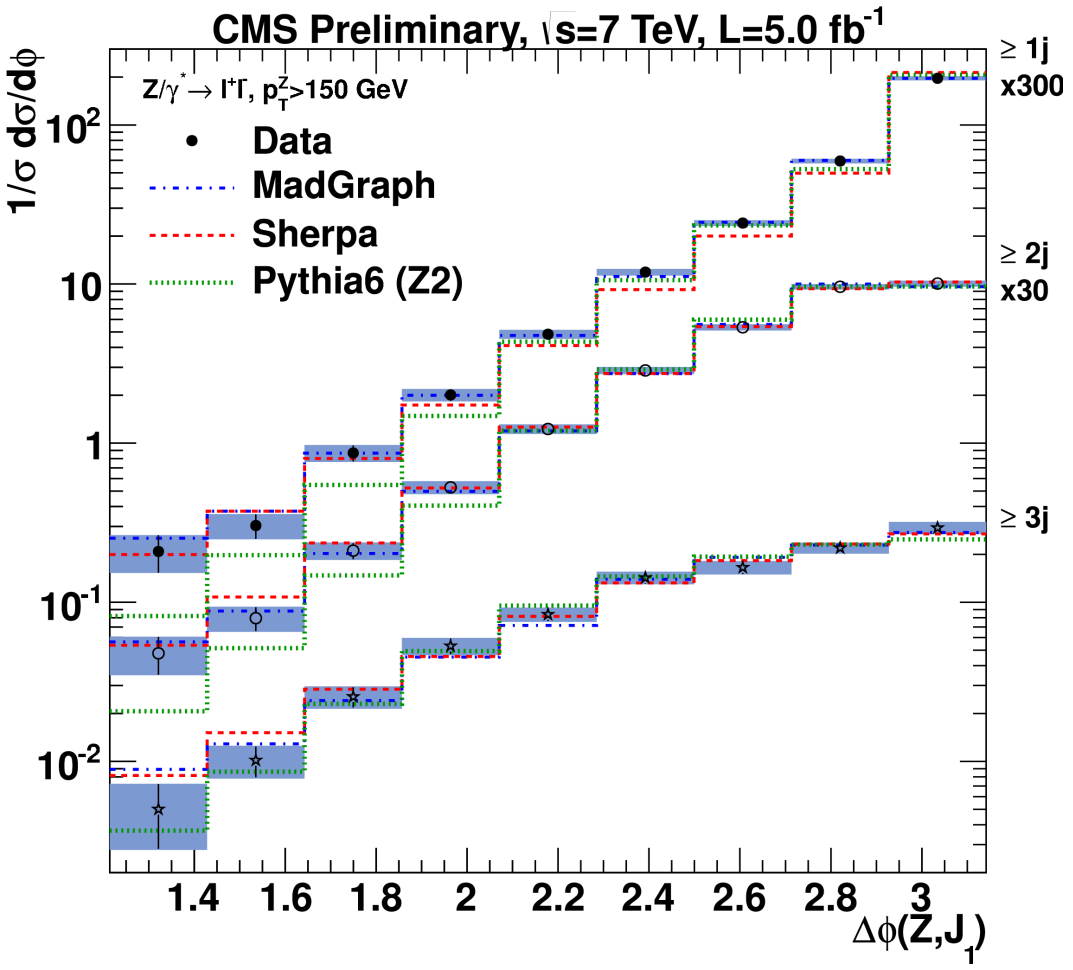




Δφ(Z, J1) with ptZ>150 GeV



- The request of high pT for the Z boson enhances configurations with most of the hadronic activity recoiling in the other direction
- Distributions become flatter
  - When the Z recoils against a hard jet an additional jet is less correlated with the Z direction than it was in the inclusive case
- In this Z+1 jet dominated phase space, the discrepancy with Pythia is less evident



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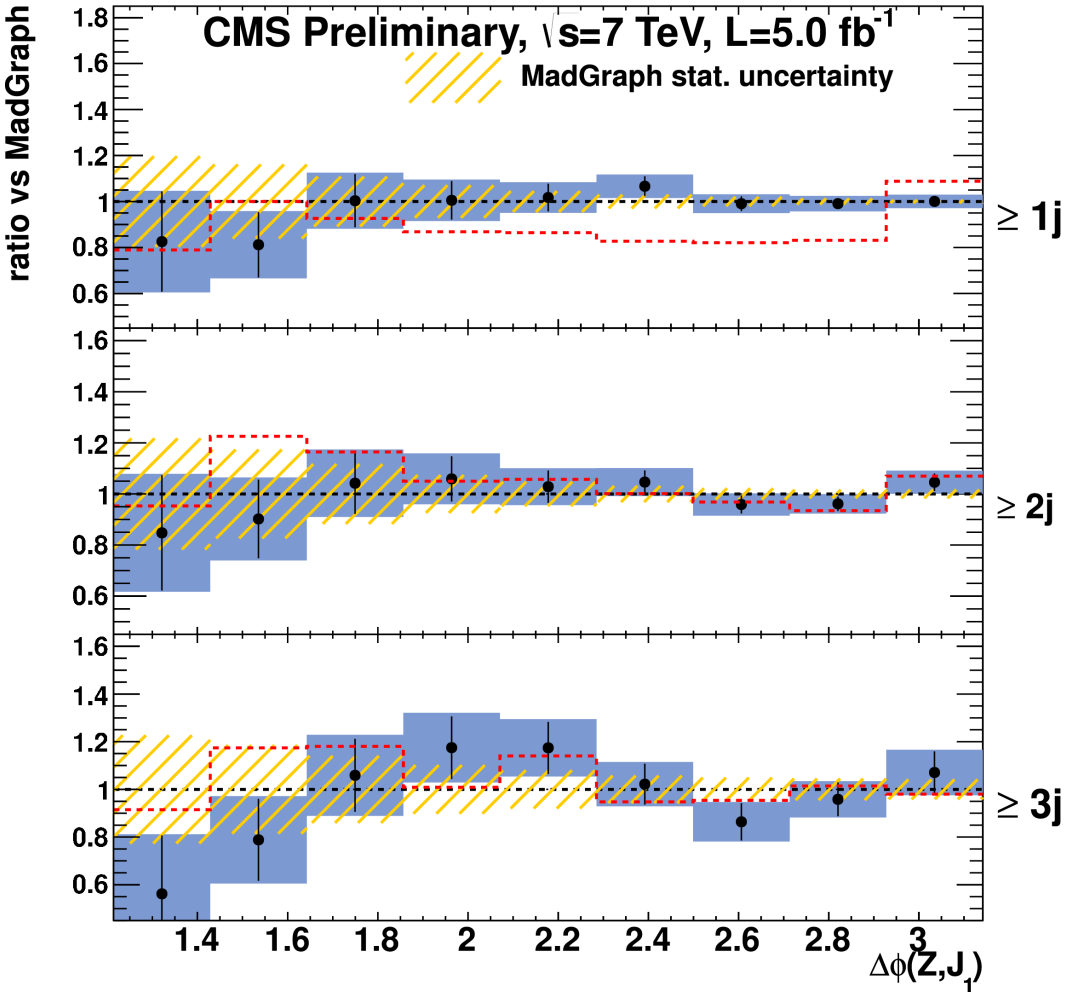
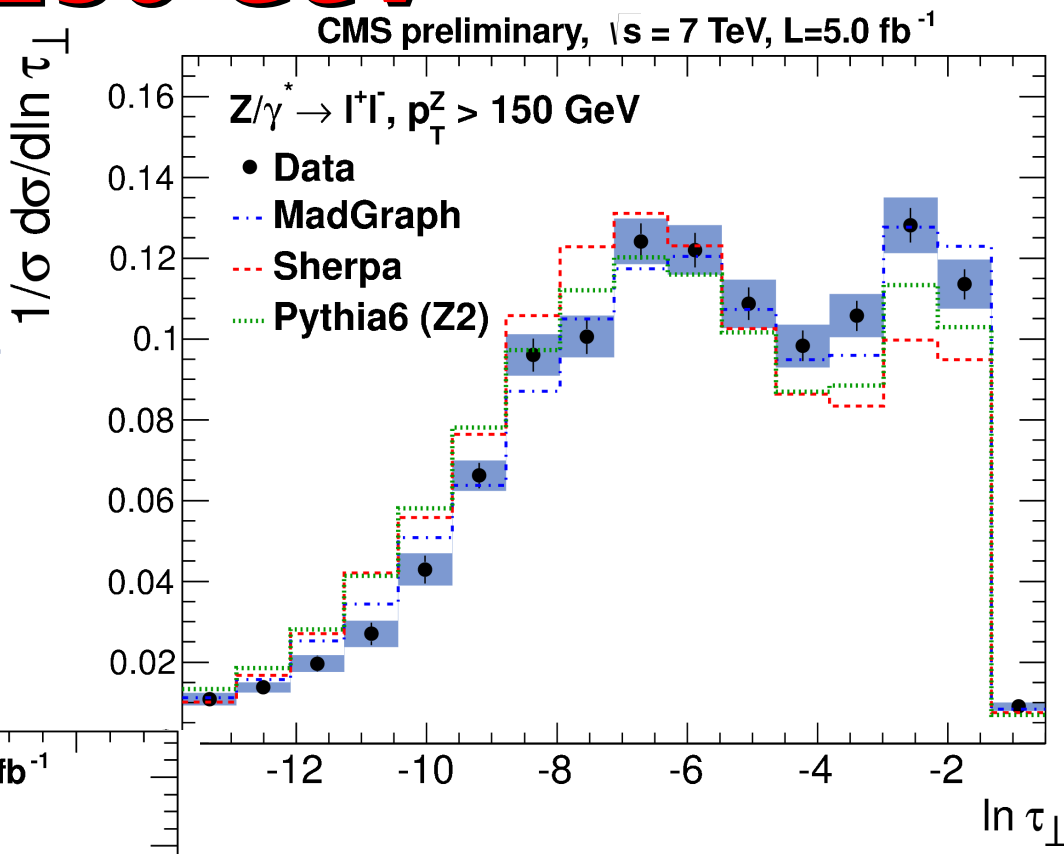
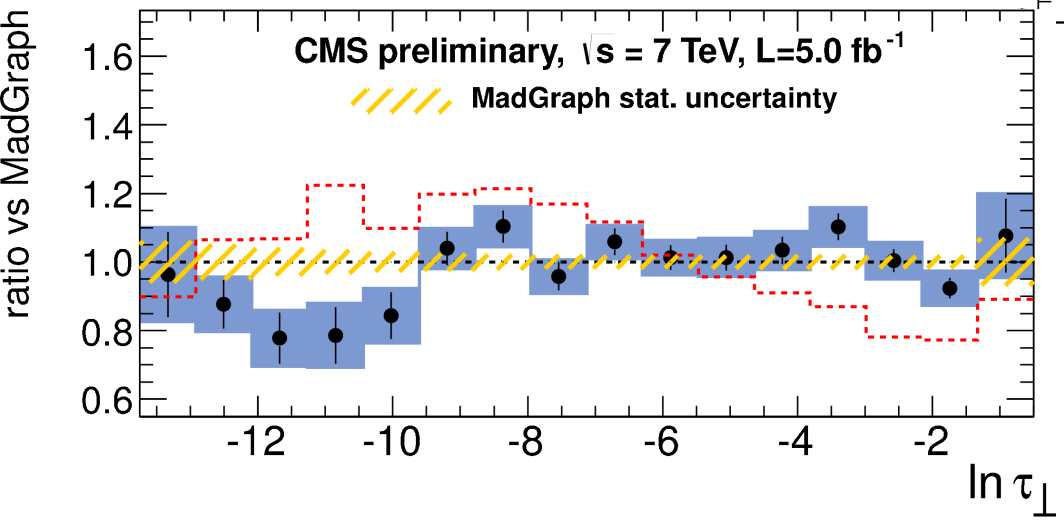


Event shapes for pT(Z)>150 GeV

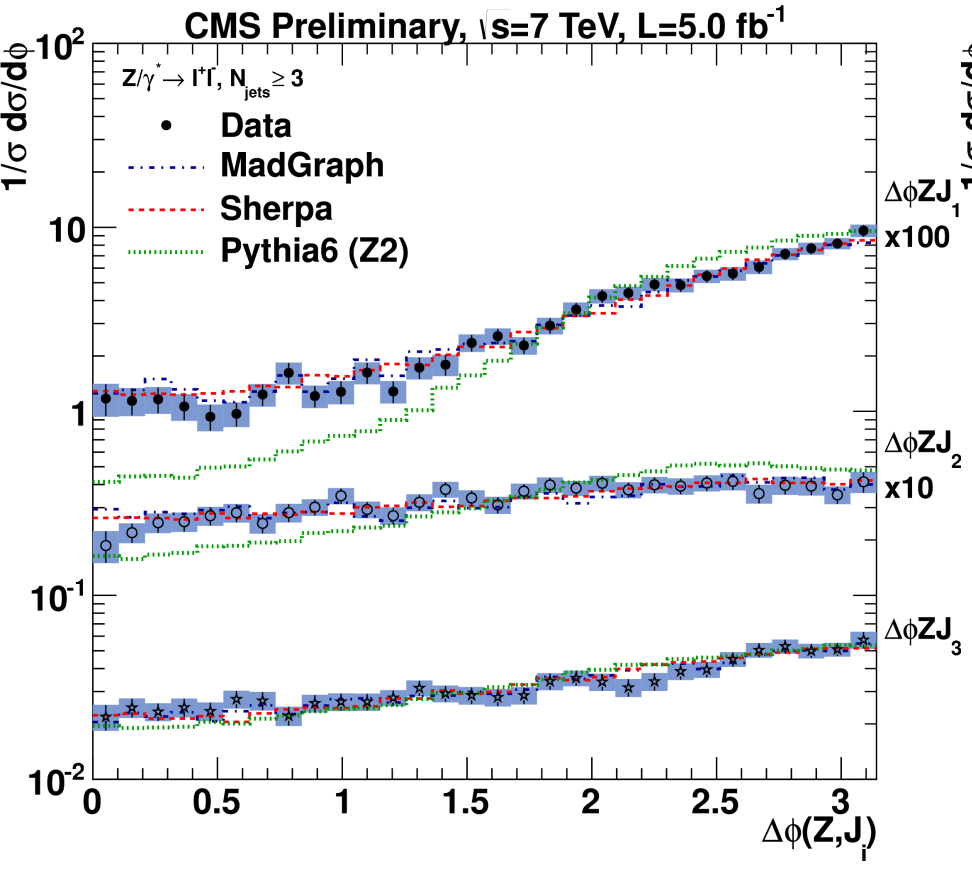
- The requirement on pT(Z) shifts the distribution towards lower values
- The selection enhances Z+1 jet topologies

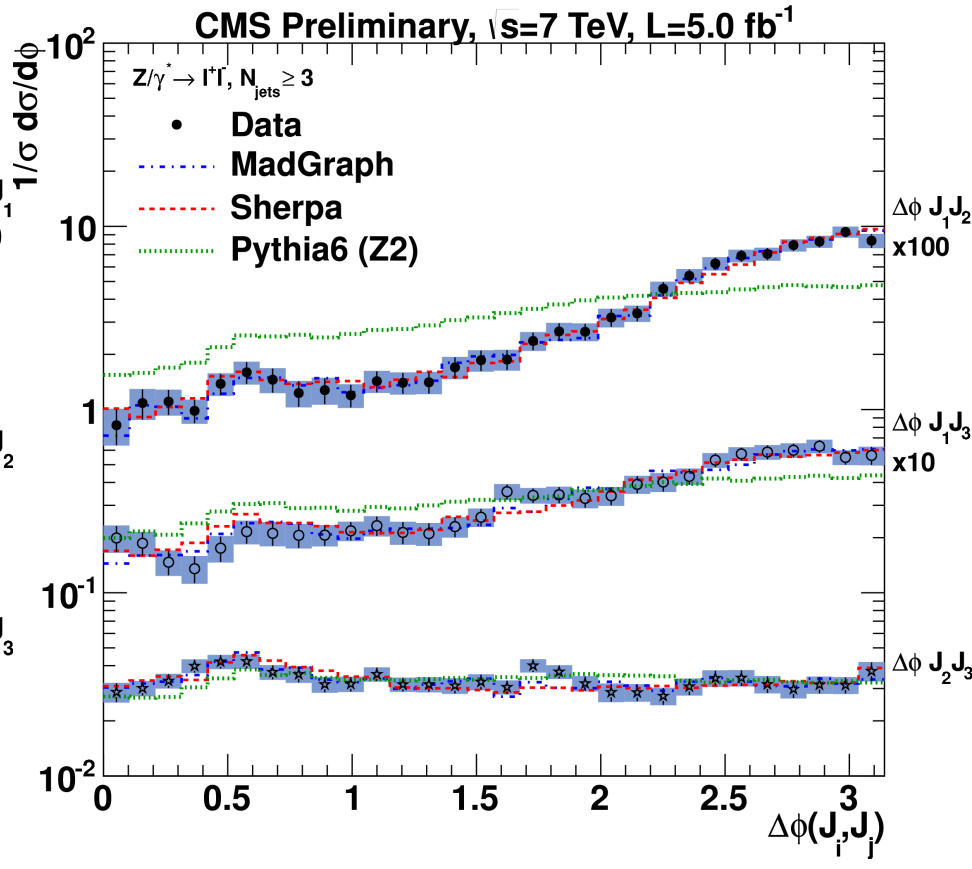




High hadronic activity

- We checked the azimuthal separation between the Z and the jets and between jets in events with high hadronic activity (at least 3 jets)
  - The dominant configuration is Z and a sub-leading jet balancing together the leading jet
  - The ME+PS descriptions are in good agreement with data





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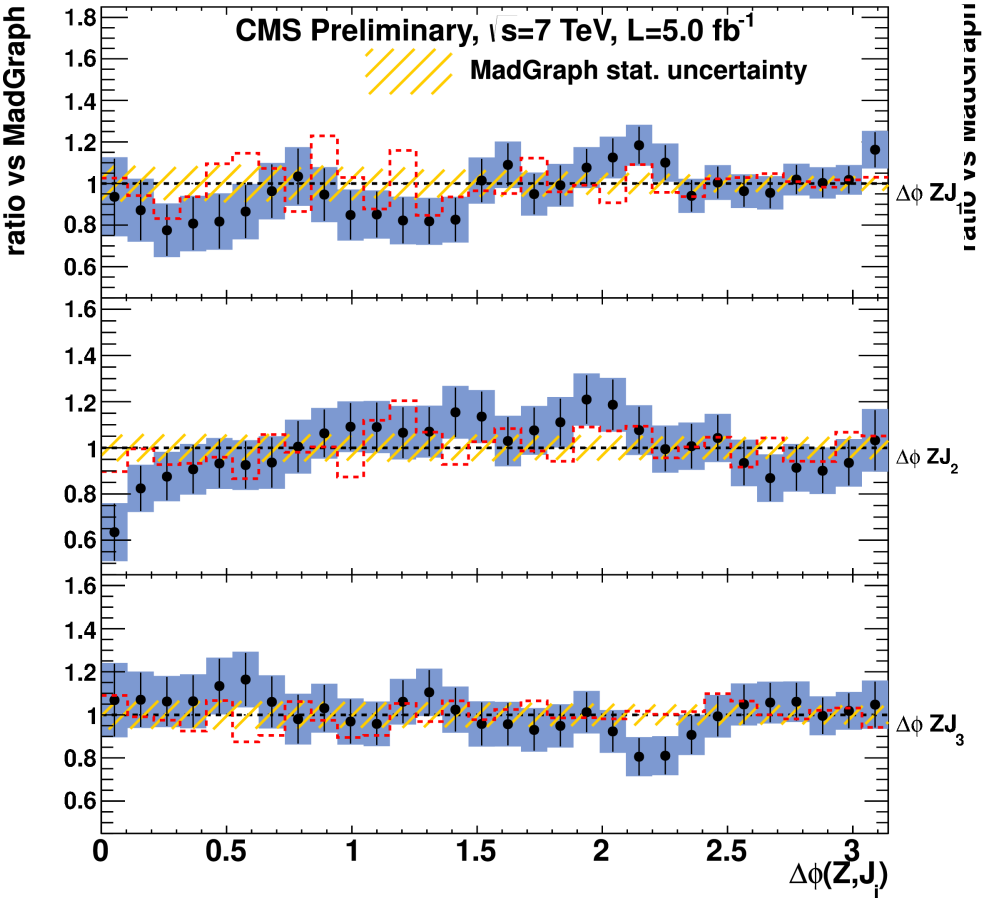
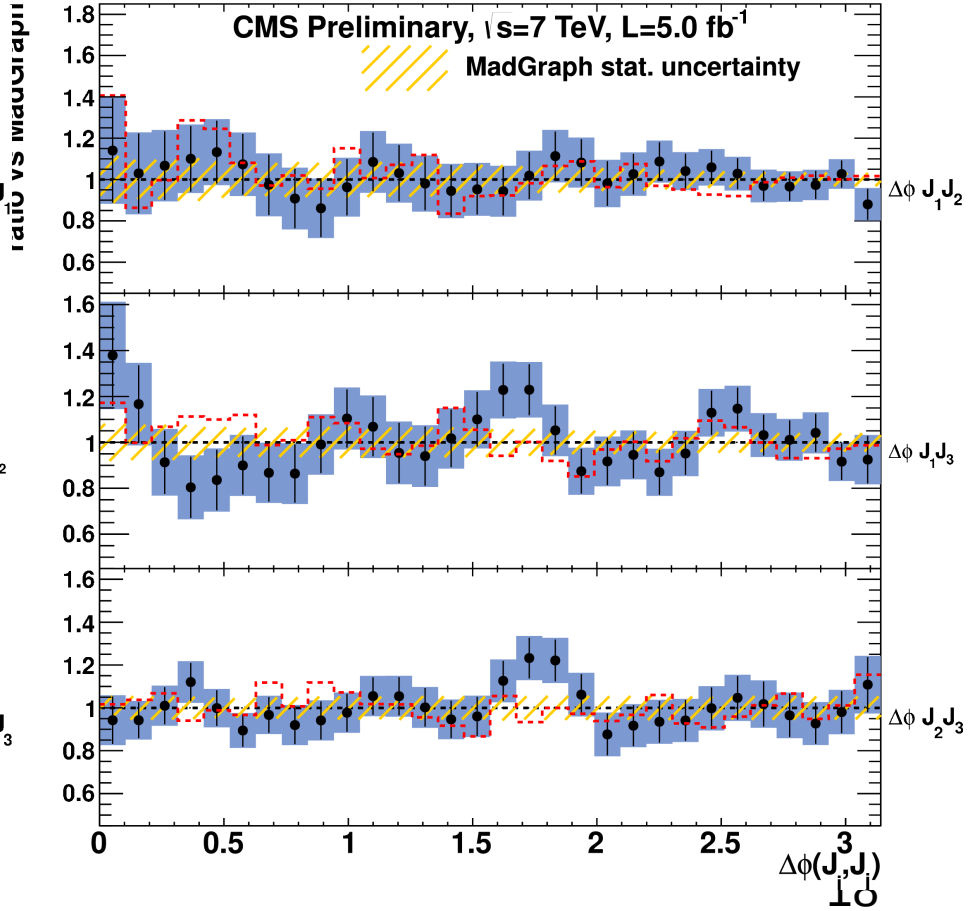
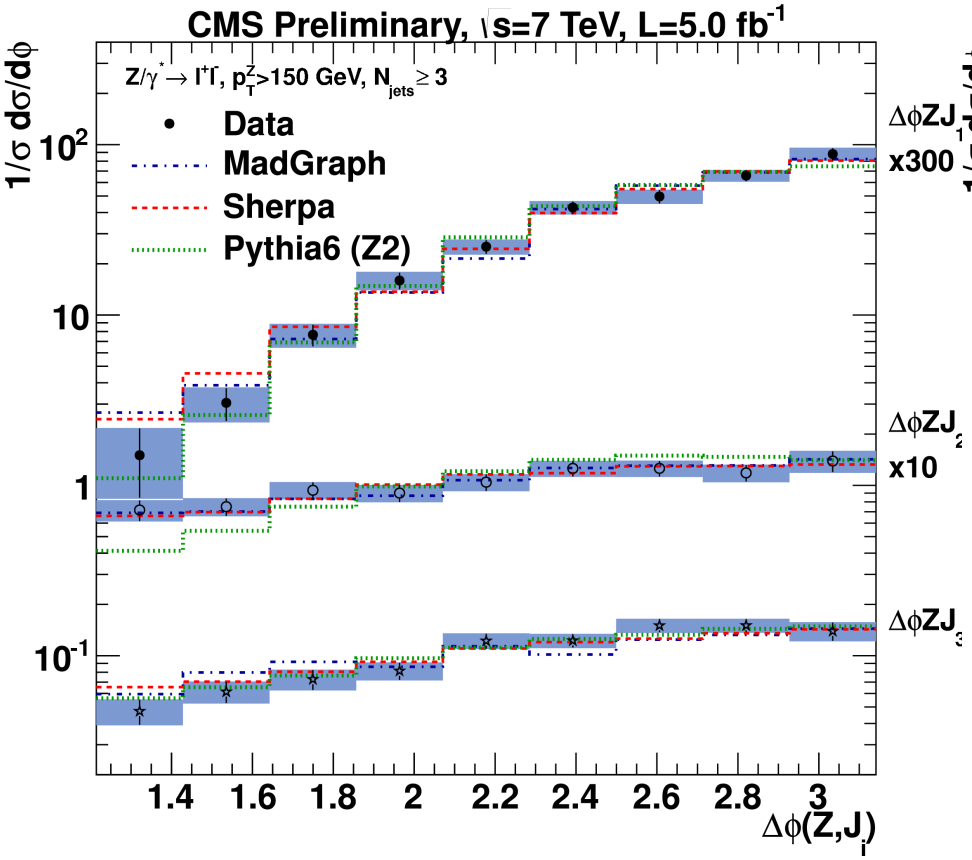
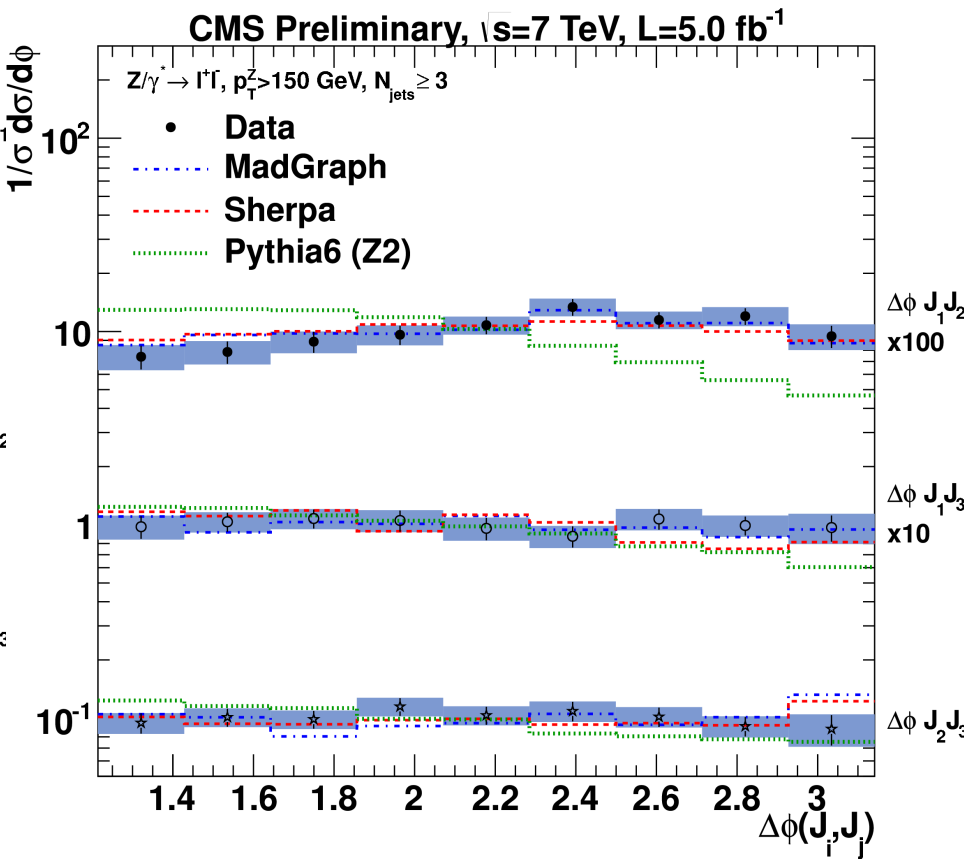




High hadronic activity and Z boost

- The most extreme kinematic region we have explored is the one with at least three jets and a highly boosted Z
  - It is particularly interesting to notice that in this regime the correlation between the jets becomes flat





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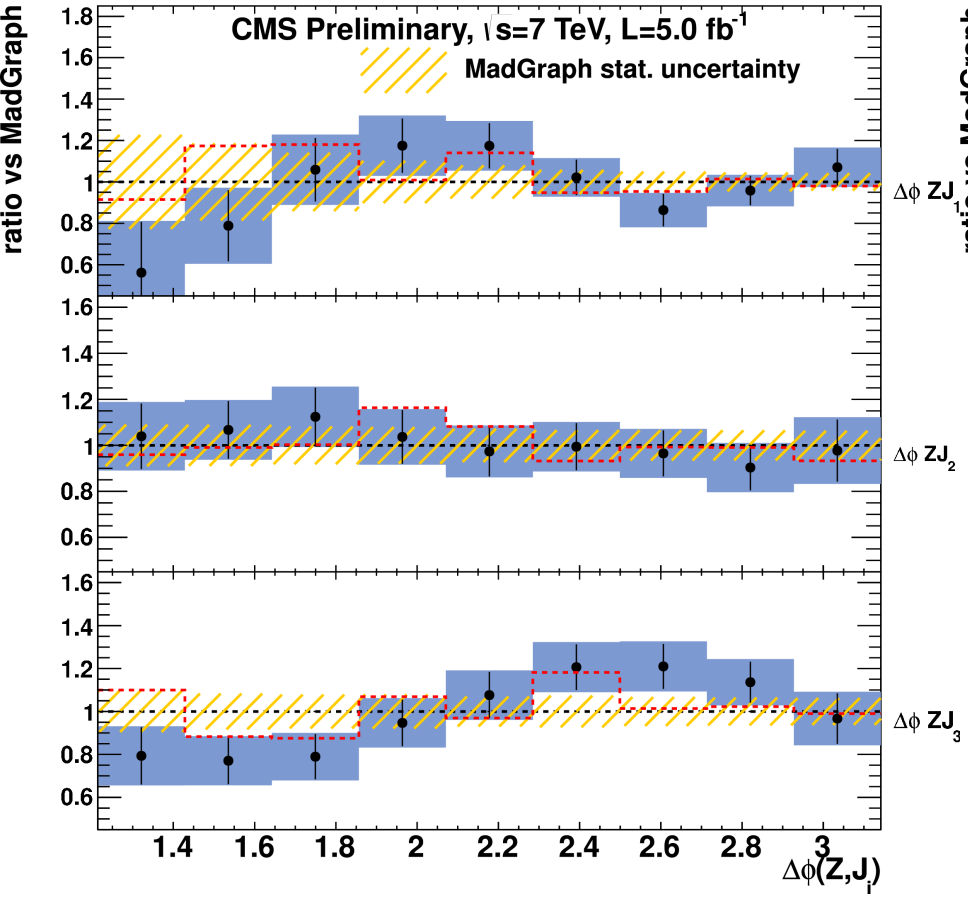
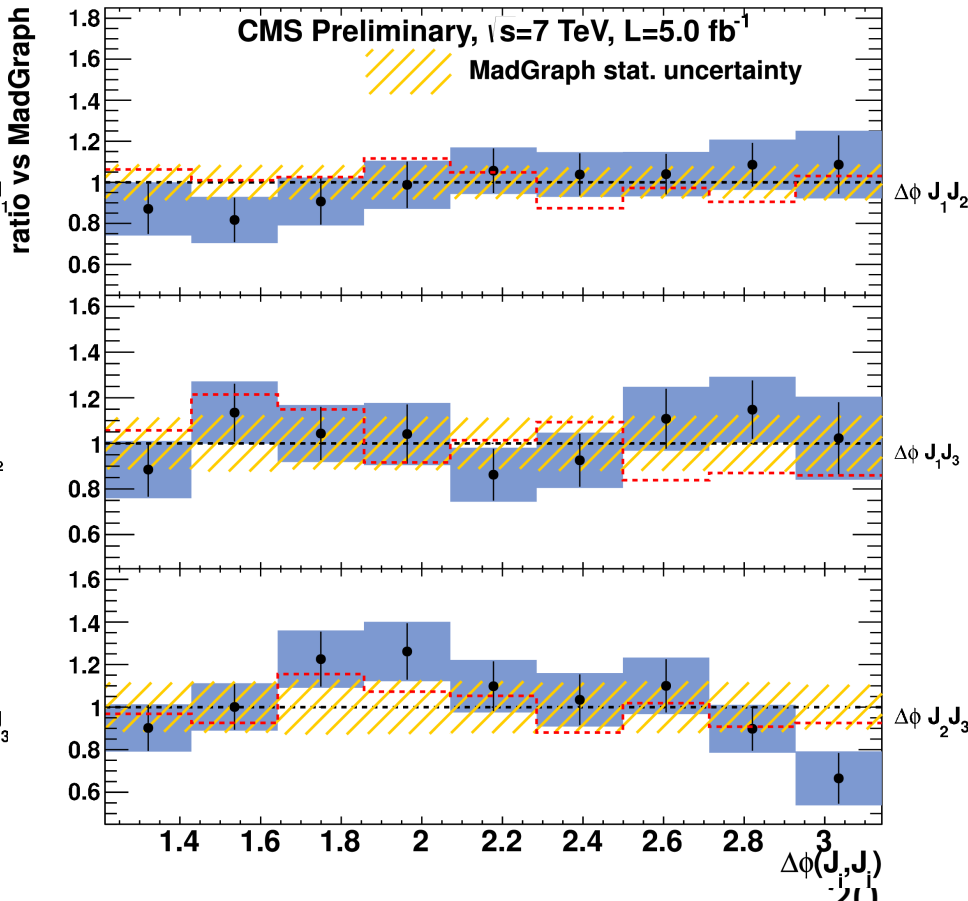
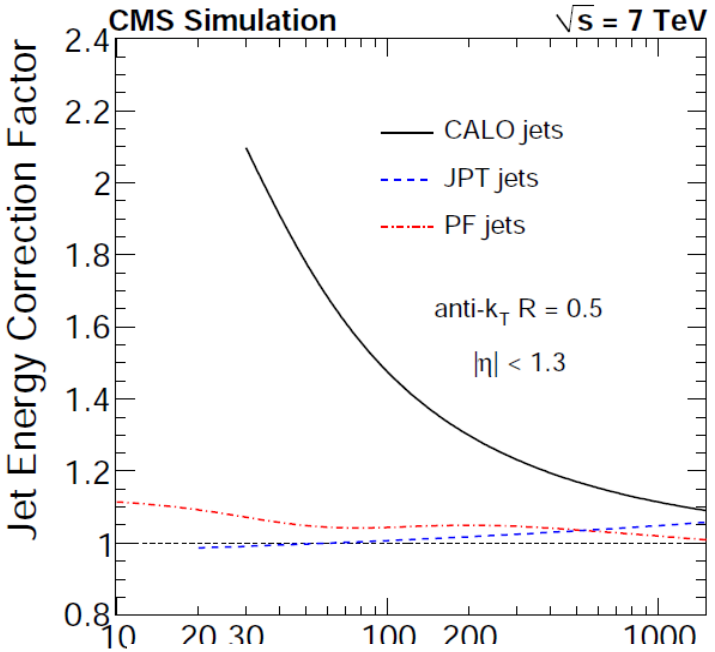


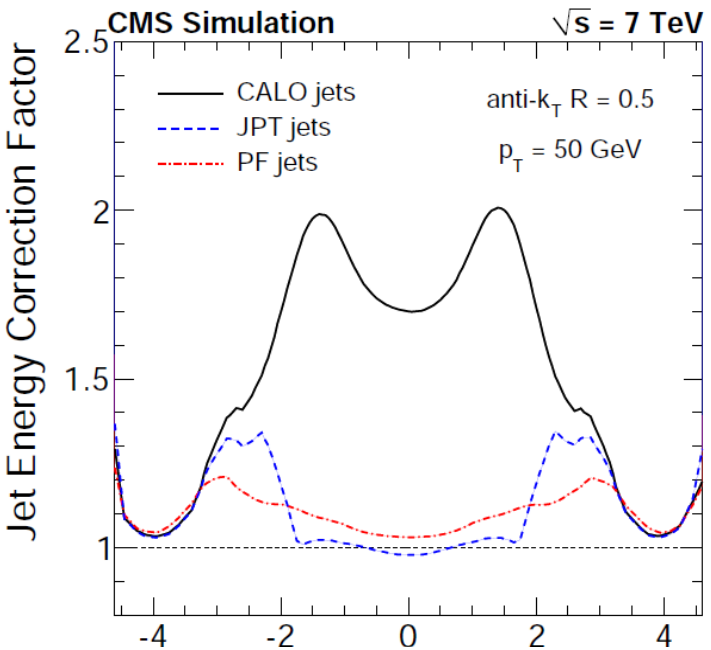


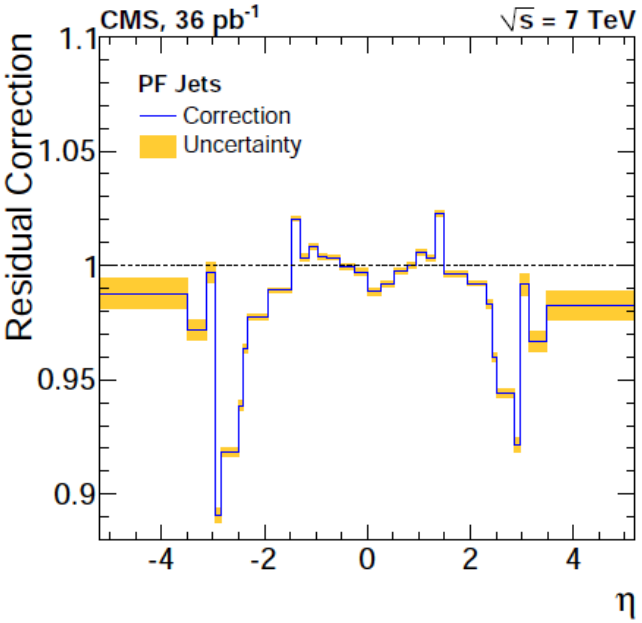
Conclusion

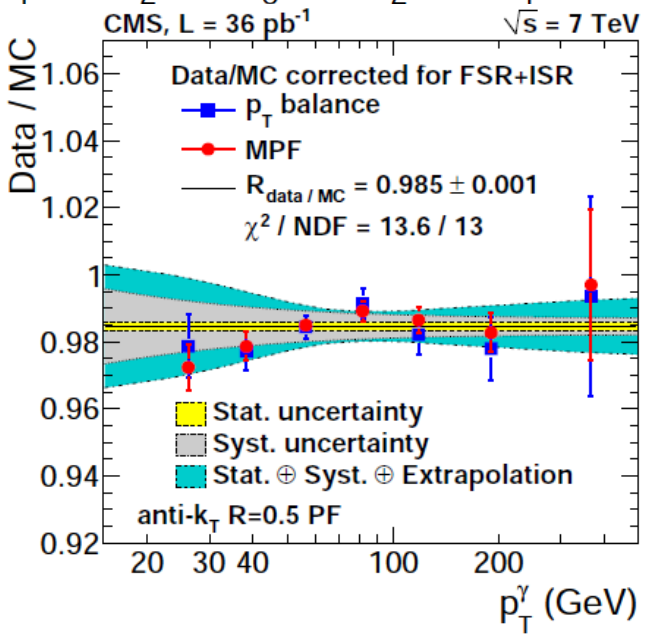
- Results from CMS in W/Z+jets have been presented
  - Jet rates and related observables in 2010 data sample at 7 TeV (36 pb^{-1})
  - Azimuthal correlation and event shapes in Z+jets at 7 TeV (5 fb^{-1})
- These observables probe perturbative QCD in an unprecedented energy regime
  - Excellent agreement with predictions from matched Matrix Element + Parton Shower

Backup


CMS Simulation
√s = 7 TeV
Jet Energy Correction Factor
CALO jets
JPT jets
PF jets
anti-k_T R = 0.5
|η| < 1.3


CMS Simulation
√s = 7 TeV
Jet Energy Correction Factor
CALO jets
JPT jets
PF jets
anti-k_T R = 0.5
p_T = 50 GeV


CMS, 36 pb^-1
√s = 7 TeV
Residual Correction
PF Jets
Correction
Uncertainty
η


CMS, L = 36 pb^-1
√s = 7 TeV
Data / MC
Data/MC corrected for FSR+ISR
p_T balance
MPF
R_data / MC = 0.985 ± 0.001
χ² / NDF = 13.6 / 13
Stat. uncertainty
Syst. uncertainty
Stat. ⊕ Syst. ⊕ Extrapolation
anti-k_T R=0.5 PF
p_T^γ (GeV)

Systematic uncertainties

- The main systematic uncertainty on the jet counting is the jet energy scale

Selection strategy

- Online selection:
  - Single electron and single muon triggers
- Reconstructed lepton selection
  - Events with at least one electron/muon with pT above 20 GeV are selected
  - If a second, looser (pT > 15 GeV), same species lepton is found, it is assigned to the Z sample, otherwise to the W sample
- Lepton identification
  - Isolation requirements for both muons and electron
- Z selection: two opposite charge lepton with invariant mass between 60 and 120 GeV
- W selection: transverse mass cut at 20 GeV

High hadronic activity and Z boost

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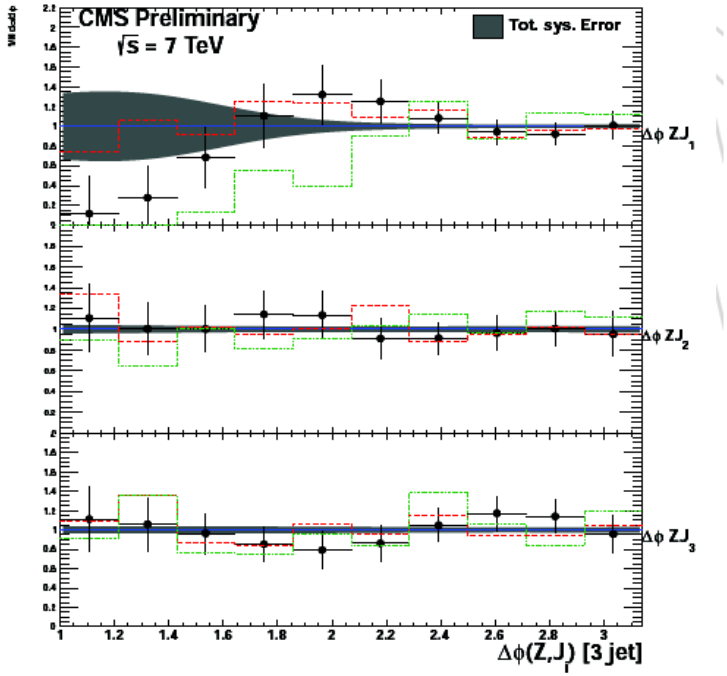
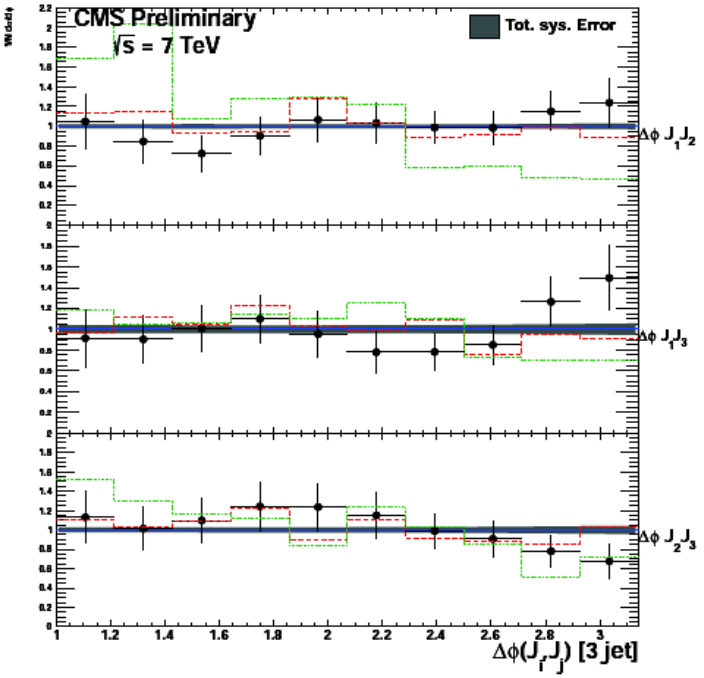
  - It is particularly interesting to notice that in this regime the correlation between the jets becomes flat



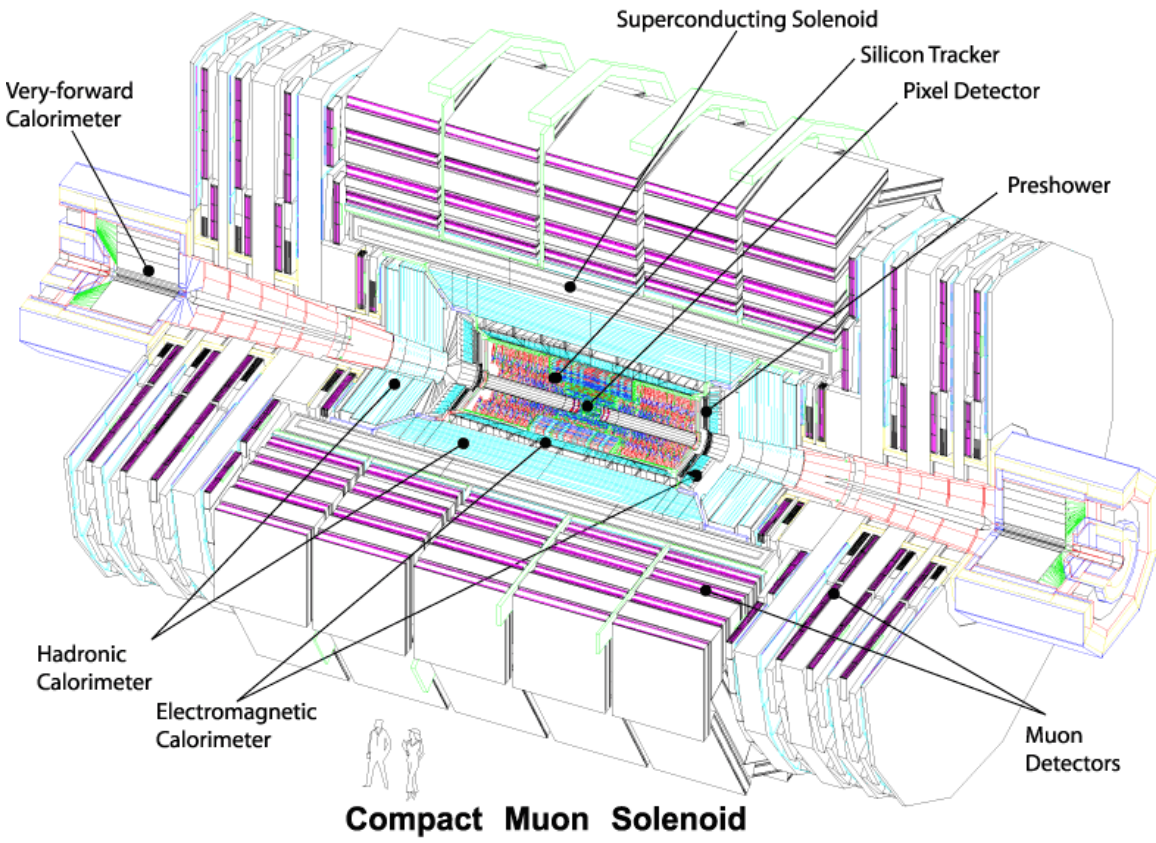


Hard QCD at LHC

- Hard QCD processes are important for two broad classes of reasons
  - They represent a ubiquitous source of background for virtually any signal (both SM and searches) at a hadron collider
  - They provide a tool to test the predictions of perturbative QCD
    - The current understanding of our detectors allows both ATLAS and CMS collaborations to do precision QCD measurements

CMS detector

- 4 T solenoid
- Pixel + SiStrip tracker
- Scintillating crystals ($PbWO_4$) electromagnetic calorimeter
- Brass/plastic hadron calorimeter (non-compensating)
- Muon spectrometer in the magnet iron return yoke



Jet reconstruction

- Jets are reconstructed with the anti-kt algorithm, with radius of 0.5 or 0.7
- 3 available algorithms for jet reconstruction
  - Calo-Jets: use only the calorimeter towers
  - Jet-Plus-Track Jets: improve the calorimeter jets using the tracks in the jet cone
  - Particle-Flow jets: uses particle flow candidates as input to the clustering algorithm
    - Particle flow reconstruction:
      - global event reconstruction
      - Identifies muons, electrons, taus, photons, charged hadron, neutral hadrons
      - Combines the information from all detectors

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Jet energy scale

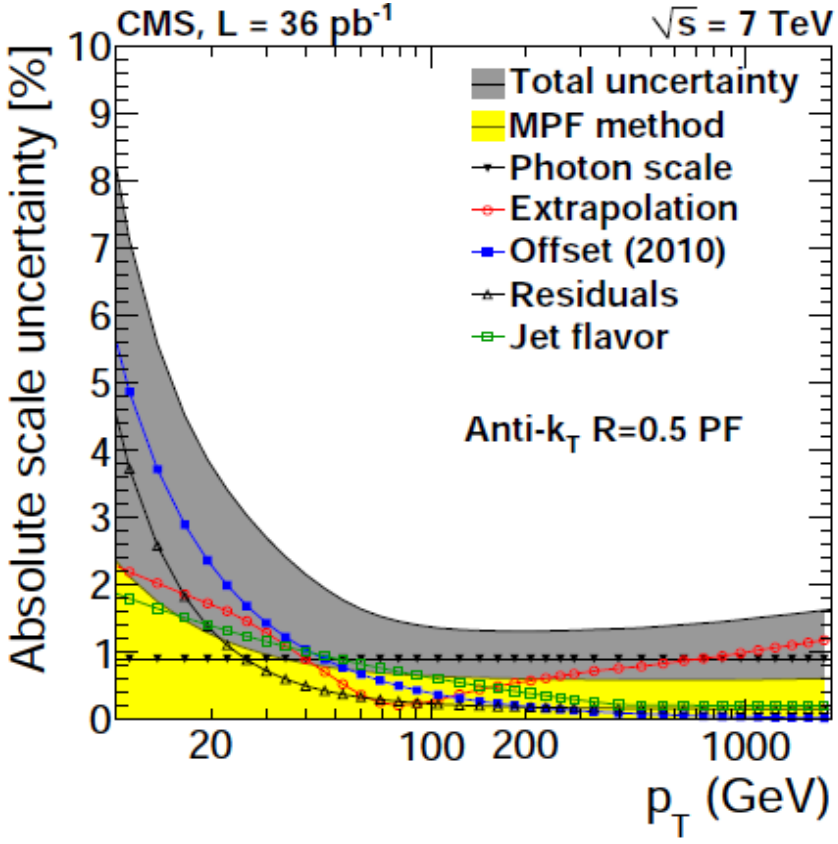
- We use a multi-step procedure to correct the energy of our jets

$$p_\mu^{cor} = \mathcal{C} \cdot p_\mu^{raw}. \qquad \mathcal{C} = C_{\text{offset}}(p_T^{raw}) \cdot C_{\text{MC}}(p_T', \eta) \cdot C_{\text{rel}}(\eta) \cdot C_{\text{abs}}(p_T'')$$

  - C_{offset} accounts for detector noise and pile-up
  - The method uses correction factors extracted from the full simulation of CMS, C_{MC}
  - Residual differences with respect to data are accounted for as further scaling factors
    - C_{rel} accounts for non-uniformity in eta. It is obtained applying on data and MC the di-jet balance method
    - C_{abs} accounts for residual absolute scale differences between data and MC. It is obtained applying on data and MC the γ+jet and Z +jet pT balancing
  - In this MC + residual method effects like the presence of additional radiation spoiling dijet or γ+jet and Z +jet balancing enter only at second order

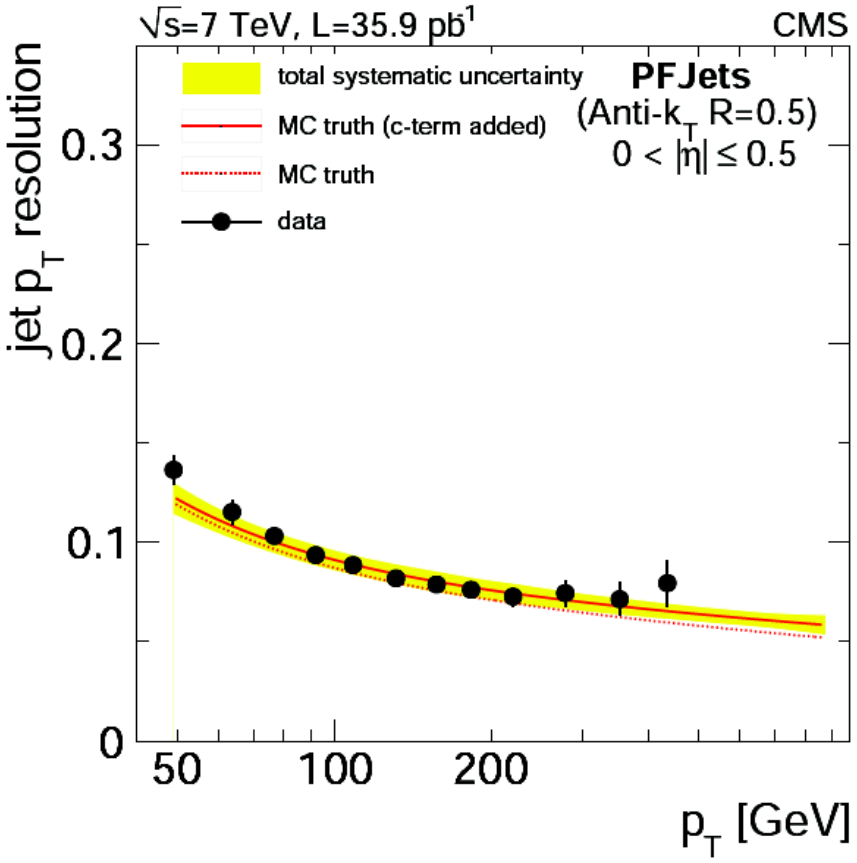
Jet energy scale

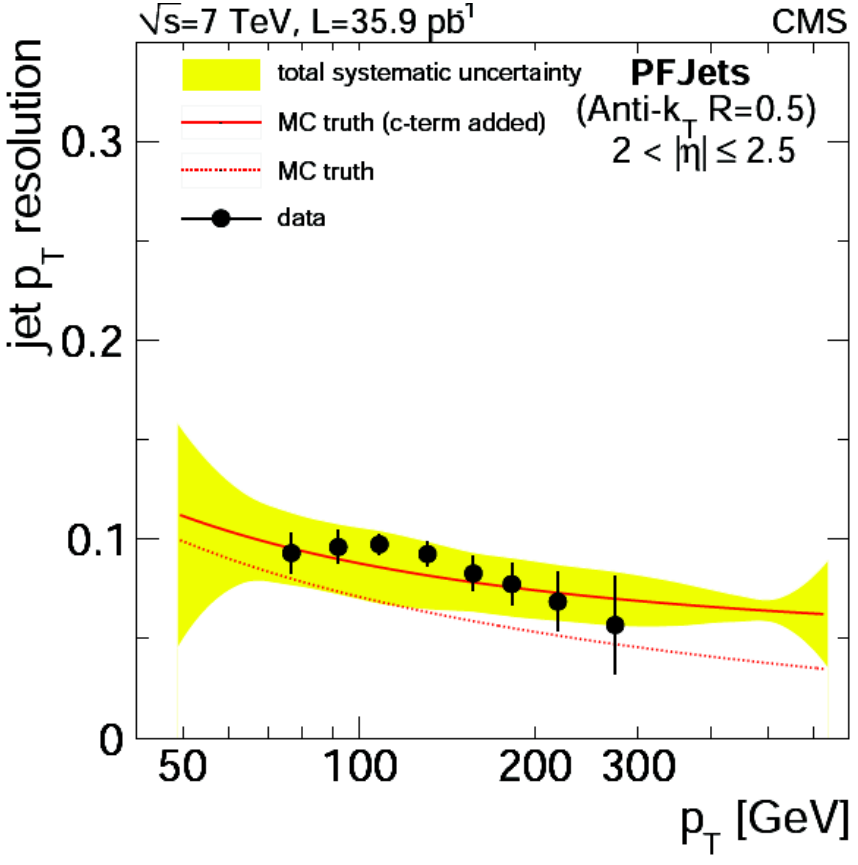
- Total systematic uncertainty on the energy scale for particle-flow jets
- The main sources of uncertainty are:
  - The photon energy scale, known at 1%
  - The relative response across detector regions
  - Pile-up effects
  - Extrapolations down to 0 for the additional activity in the balance methods
  - Dependency on jet flavor in the MC used



Jet energy resolution

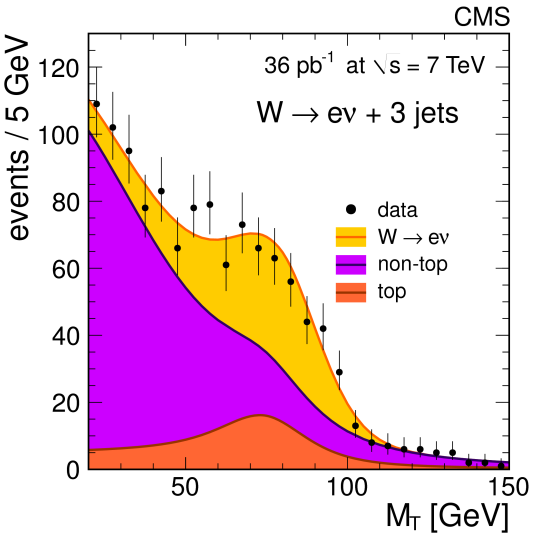
- Determined with di-jet and γ+jet pT balance
  - Plots show two example regions in η
  - Resolution is of the order of 10% around 50 GeV

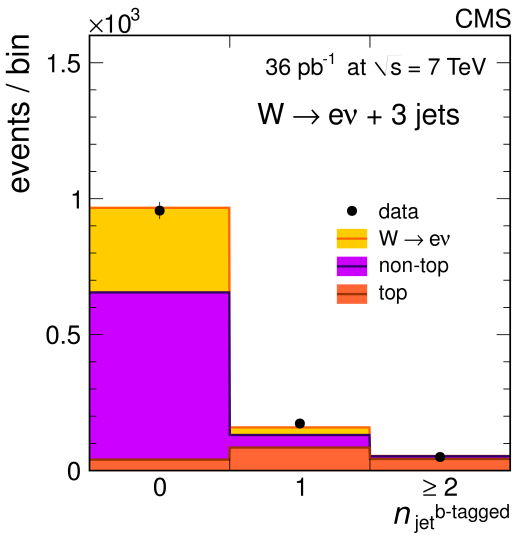


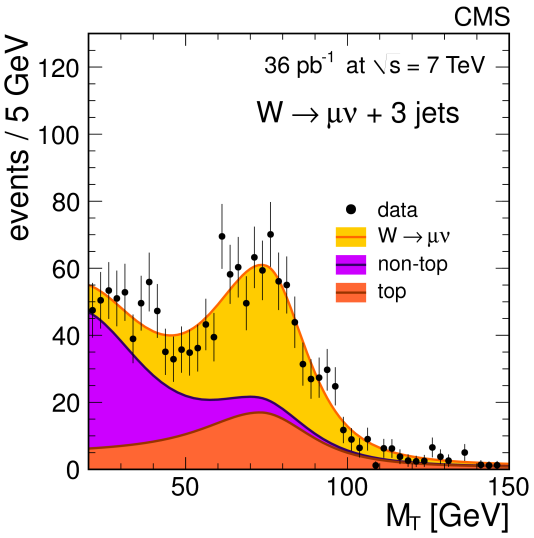


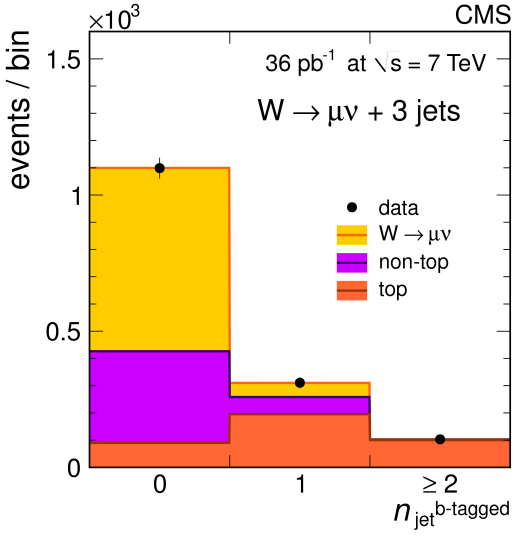
Signal extraction

- Main backgrounds
  - QCD dijets with fake leptons
  - Ttbar, especially for the W
  - Z+jets for the W
- For Z (W) the signal is extracted with a fit to the dilepton invariant mass (transverse mass)
  - In the W channel, due to the presence of real W from ttbar a b-tagging estimator has been added to the fit
- Background shapes
  - From inverted identification criteria for QCD
  - From data ttbar sample for ttbar
- Efficiency correction
  - Estimated with tag and probe methods





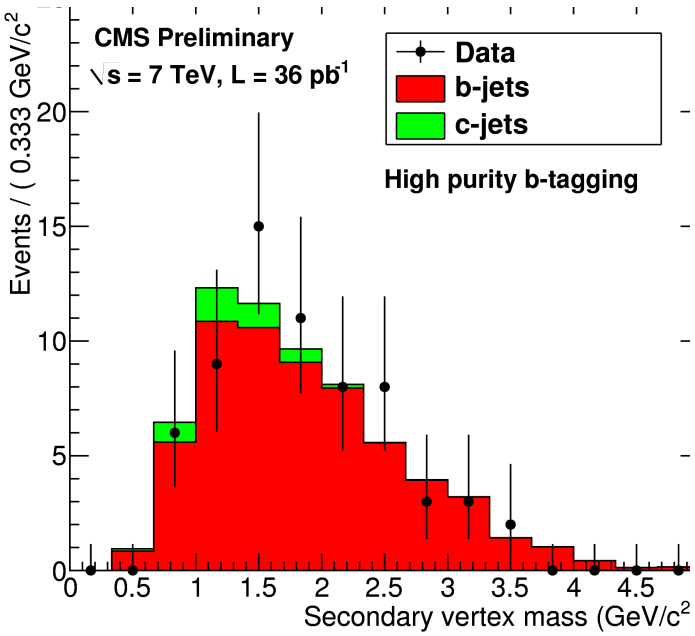




W/Z+jets

- CMS measured the associated production of Z + b-jets
  - Z selection plus high purity b-tagging
  - Main systematics: JES, b-tagging efficiency and mis-tag rate
  - The ratio between the Z+ b jets and Z + any jet has been measured for both electron and muon decay channels

CMS-PAS-EWK-10-015



Sample	$\mathcal{R}(Z \to ee)$ (%), $p_T^e > 25$ GeV, $\lvert\eta^e\rvert < 2.5$	$\mathcal{R}(Z \to \mu\mu)$ (%), $p_T^\mu > 20$ GeV, $\lvert\eta^\mu\rvert < 2.1$
Data HE	$4.3 \pm 0.6(stat) \pm 1.1(syst)$	$5.1 \pm 0.6(stat) \pm 1.3(syst)$
Data HP	$5.4 \pm 1.0(stat) \pm 1.2(syst)$	$4.6 \pm 0.8(stat) \pm 1.1(syst)$
MADGRAPH	$5.1 \pm 0.2(stat) \pm 0.2(syst) \pm 0.6(theory)$	$5.3 \pm 0.1(stat) \pm 0.2(syst) \pm 0.6(theory)$
MCFM	$4.3 \pm 0.5(theory)$	$4.7 \pm 0.5(theory)$