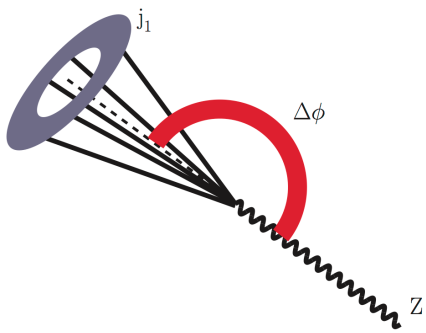
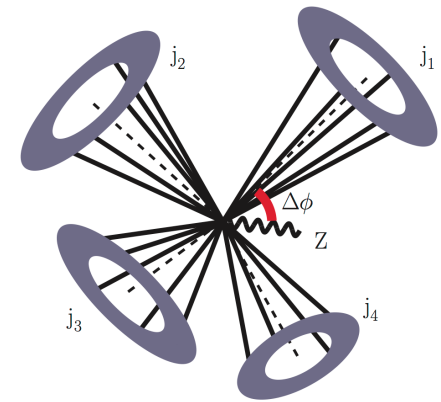
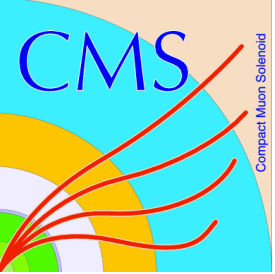


# V+jets production at the CMS



Mehmet T. ZEYREK  
*METU Ankara, Turkey*  
*on behalf of CMS Collaboration*  
IPMLHC 2013- Tehran, Iran  
October 10, 2013

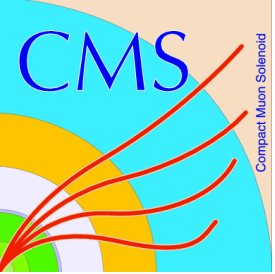




# MOTIVATION



- Processes involving W & Z boson production are of the best understood processes at hadron colliders
- Test of perturbative QCD
- Precision measurements are sensitive to BSM effects.
- Leptons from Z and W events are used to understand the efficiencies.
- Provide constraints to PDFs
- Improve MC generators
- Backgrounds to New Physics & Higgs Searches



# OUTLINE



## @ 7TeV

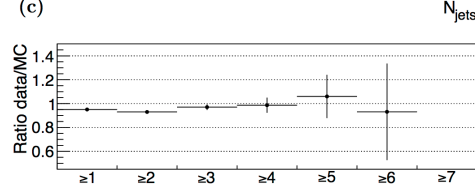
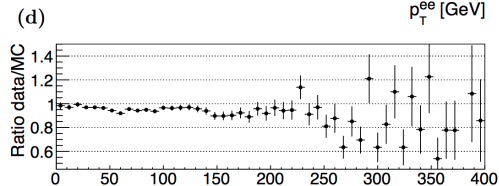
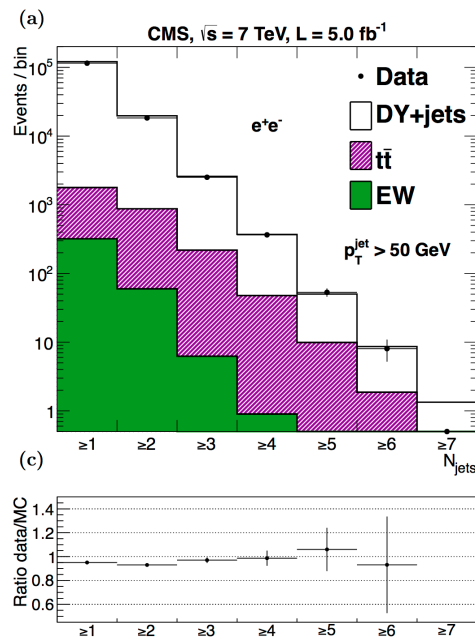
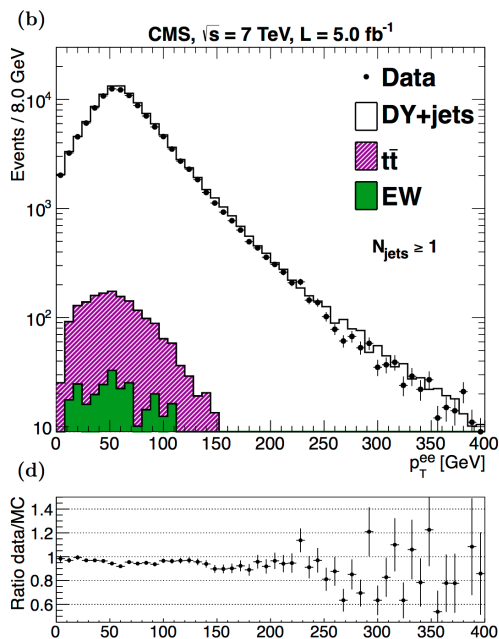
- Z+jets, azimuthal correlations and event shape (*Phys. Lett. B* 722 (2013) 238–261)
- Photon+jets differential cross section (*CMS-PAS-QCD-11-005*)
- Z+1 jet and photon+1 jet rapidity distributions (*CMS-PAS-SMP-12-004*)
- W+2 jets, dijet mass spectrum (*Phys.Rev.Lett.* 109 (2012) 251801)
- Double parton scattering in W+jets (*PAS-FSQ-12-028*)
- Electroweak Z + forward-backward jets production (*arXiv:1305.7389*)

# Z + Jets: Event-Shape Distributions



$\sqrt{s}=7\text{ TeV}, 5\text{ fb}^{-1}$

- Measurement of this process can be confronted with predictions of pQCD
- BG to many LHC processes → Improved understanding of Z+jets provide a tool extracting small signals



Z → ee + jets

→ Two leptons with  $P_T > 20\text{ GeV}$  and  $|\eta| < 2.4$  and  $71 < M_Z < 111\text{ GeV}$

→ At least one jet with  $P_T > 50\text{ GeV}$  and  $|\eta| < 2.5$

→ Detector level, before background subtraction, after detector efficiency corrections.

→ The MC (MadGraph) normalized to the data luminosity

# Z + Jets: Angular Correlations

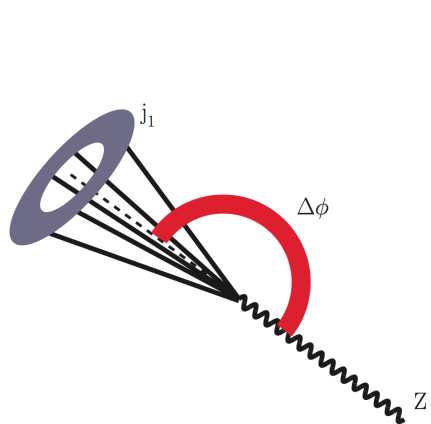


$\sqrt{s}=7 \text{ TeV}, 5 \text{ fb}^{-1}$

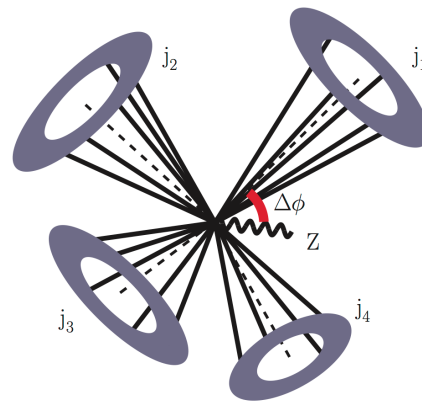
Measurements in two different regimes

$P_T(Z) > 0 \text{ GeV}$  (Inclusive) &  $P_T(Z) > 150 \text{ GeV}$  (Boosted regime)

- Boosted regime is of particular interest: critical in BSM searches
- Uncertainty of BG contribution is limited by the accuracy of MC models
  - Accuracy of current MC models can be improved by studying correlations of Z & Jets



$\Delta\phi(Z, j_1) = \pi$   
 $\ln \tau_T \rightarrow -\infty$



$\Delta\phi(Z, j_1) \ll \pi$   
 $\ln \tau_T \rightarrow 1$

Transverse Trust: kinematic topology

$$\tau_T \equiv 1 - \max_{\vec{n}_\tau} \frac{\sum_i |\vec{p}_{T,i} \cdot \vec{n}_\tau|}{\sum_i p_{T,i}}$$

# Z + Jets: Angular Correlations

$\sqrt{s}=7\text{ TeV}, 5\text{ fb}^{-1}$

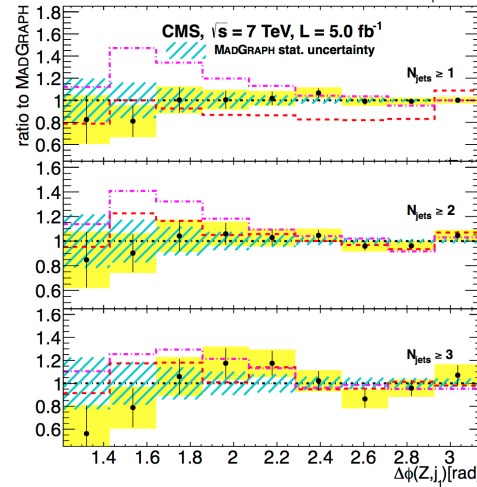
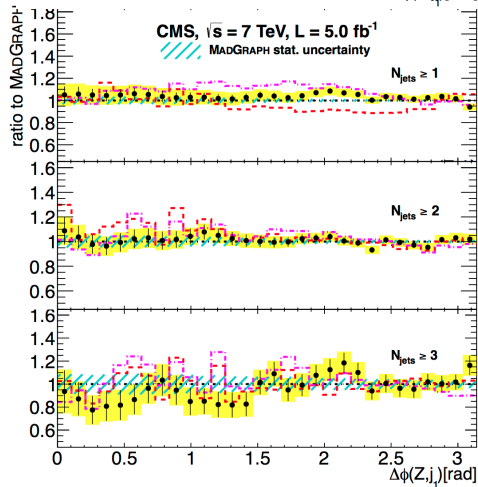
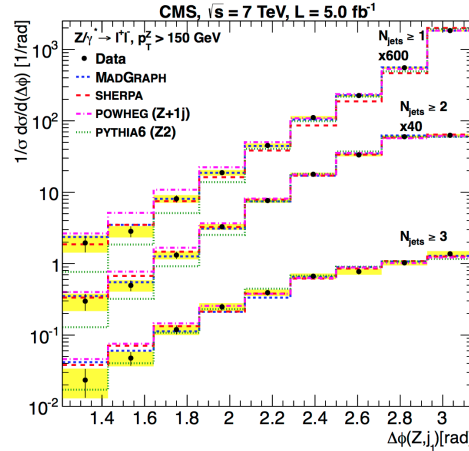
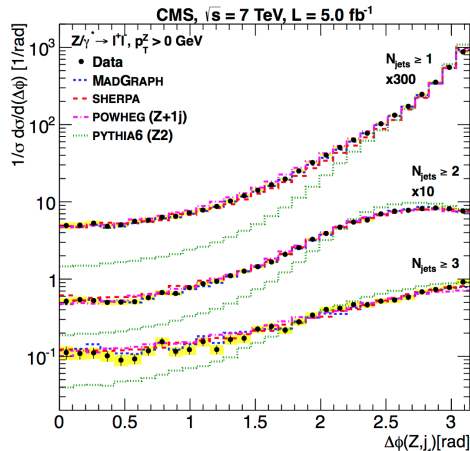


Inclusive

Boosted Regime

- Unfolding to correct for detector effects
- Direct comparison with theory
- MC simulations from Sherpa, Pythia6, Powheg and MadGraph.

- The error bars on data represent statistical uncertainty after unfolding
- The shaded (yellow) bands represent the sum of statistical and systematic errors.

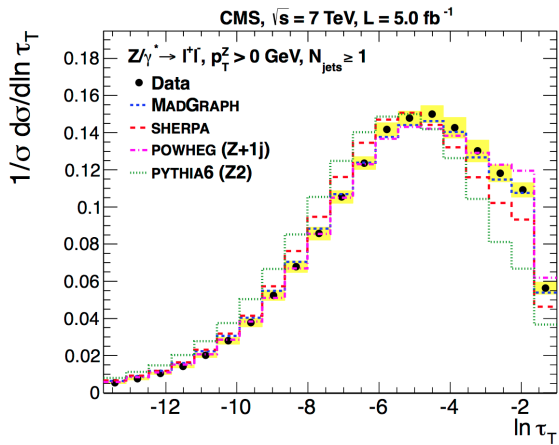


# Z + Jets: Angular Correlations

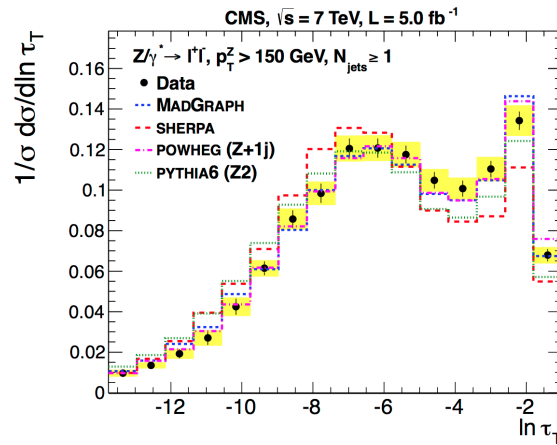


$\sqrt{s}=7\text{ TeV}, 5\text{ fb}^{-1}$

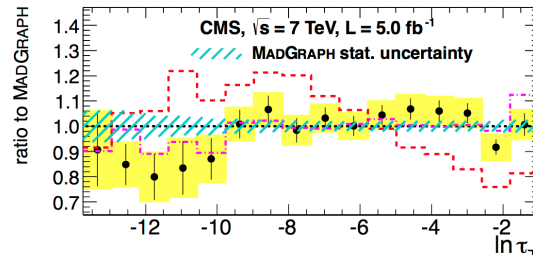
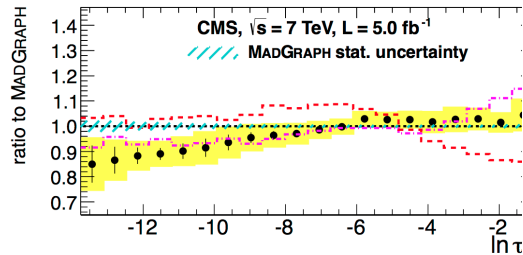
## Inclusive



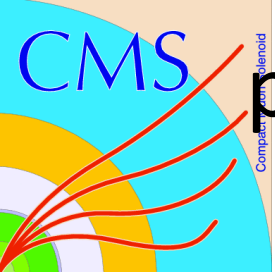
## Boosted Regime



→ MadGraph and Powheg reproduces data well  
 → Pythia6 (PS only) and Sherpa underestimate data



$\ln \tau_T$

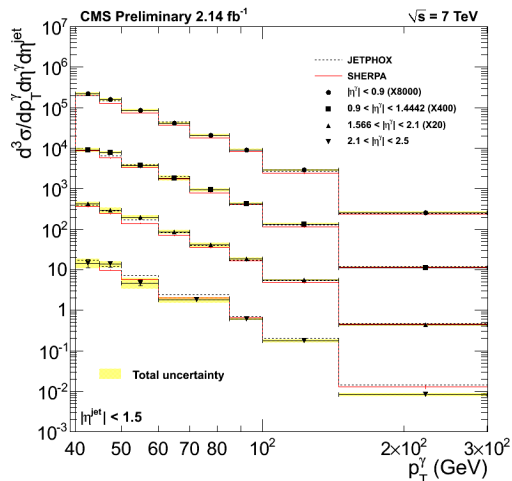


# photon+jets differential cross section

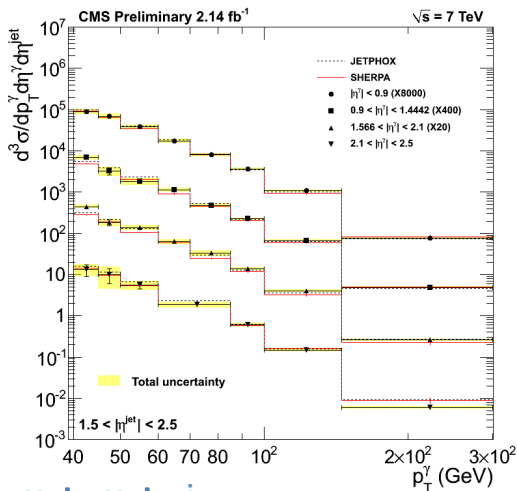


$\sqrt{s}=7\text{ TeV}, 2.14\text{ fb}^{-1}$

- Production of  $\gamma$  +jets directly sensitive to gluon PDF in proton
- BG for many processes,  $H \rightarrow \gamma\gamma$ , BSM searches
- Can be used for calibrating jet energies
- Photons and jets are reconstructed within  $|\eta| < 2.5$
- $P_{T}^j > 30\text{ GeV}$   $40 < P_{T}^{\gamma} < 300\text{ GeV}$



$d^3\sigma / dP_{T}^{\gamma} d\eta^{\gamma} d\eta^j$



→ Error bars are statistical uncertainties

→ Yellow bands are the total uncertainties obtained by adding in quadrature statistical and systematic uncertainties.

→ Comparison with :

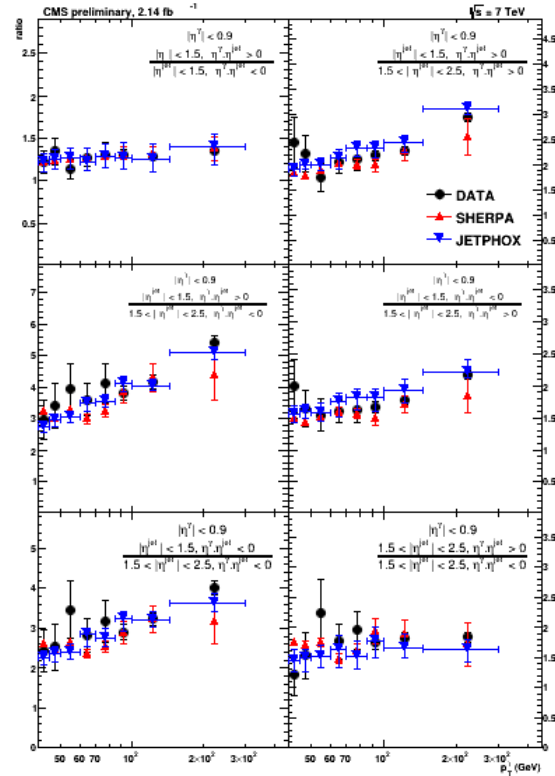
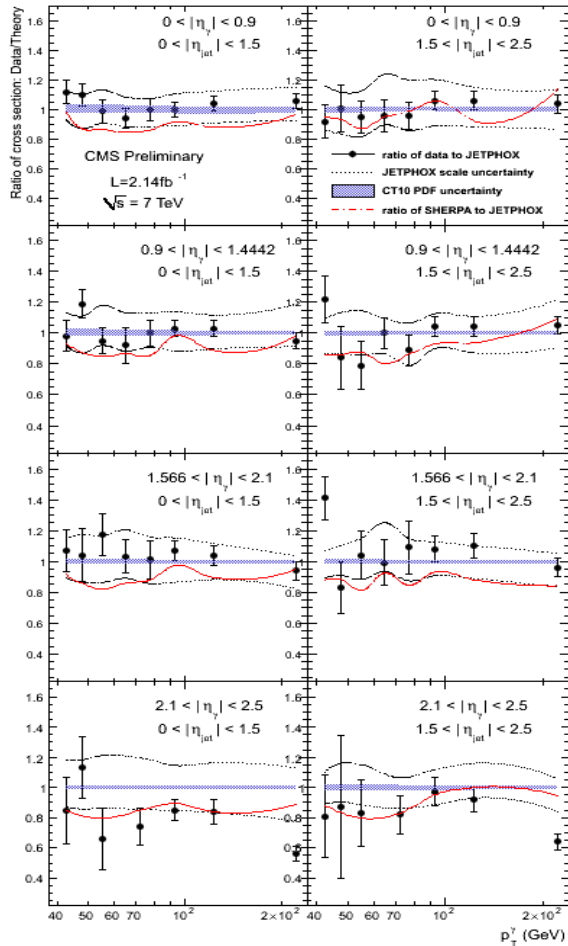
- SHERPA tree-level Monte Carlo generator
- NLO perturbative QCD calculation from JETPHOX



# photon+jets differential cross section

Data/Theory

$\sqrt{s}=7$  TeV,  $2.14 \text{ fb}^{-1}$



Ratios of cross section for various jet orientations wrt photon

→ JETPHOX generally agrees with the data well

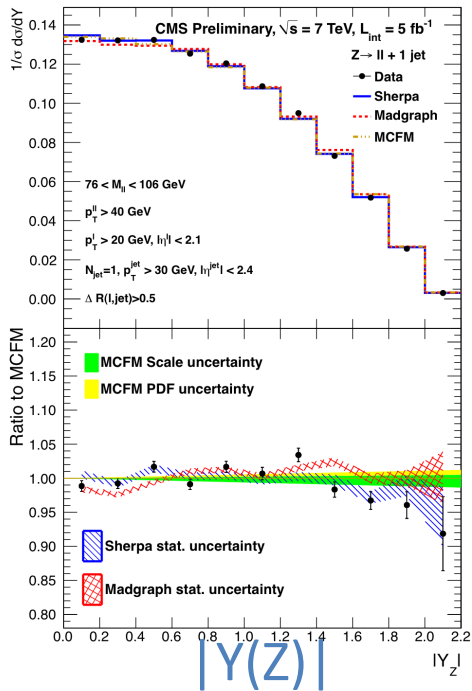
→ SHERPA systematically underestimate the data

# Z+1 jet rapidity distributions

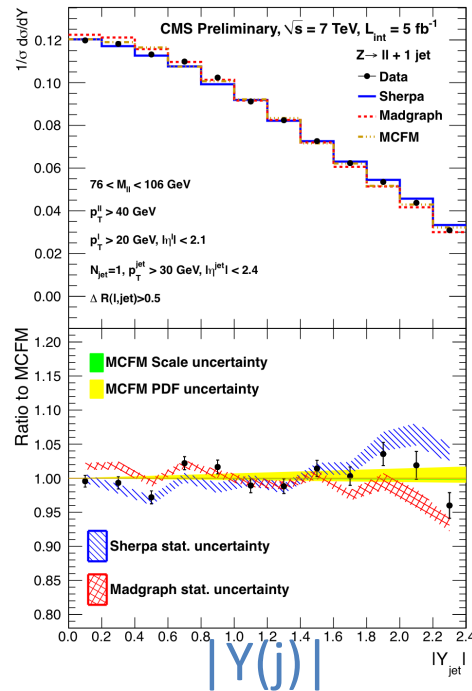
$\sqrt{s}=7\text{ TeV}, 5\text{ fb}^{-1}$



- Angular distributions is crucial in understanding structure & interactions of matter since Rutherford
- Measurement of  $Y$  in Z+jet events provides modeling of H properties in theory calc.
- Presence of EWK vertex makes the perturbative calc. more stable
- NLO pQCD calc. exist for Z+ up to 4 jets &  $\gamma$ +jet



M. T. Zeyrek



IPMLHC 2013

→ The rapidity distributions for events with a Z boson + one jet

- $Z \rightarrow l^+l^- + 1 j, l = e, \mu$
- $P_T(l) > 20. \text{ GeV}$
- $|\eta(l)| < 2.1$
- $76 \text{ GeV} < M_Z < 106 \text{ GeV}$
- $P_T(l) > 40 \text{ GeV}$
- $P_T(j) > 30. \text{ GeV}$
- $|\eta(j)| < 2.4$

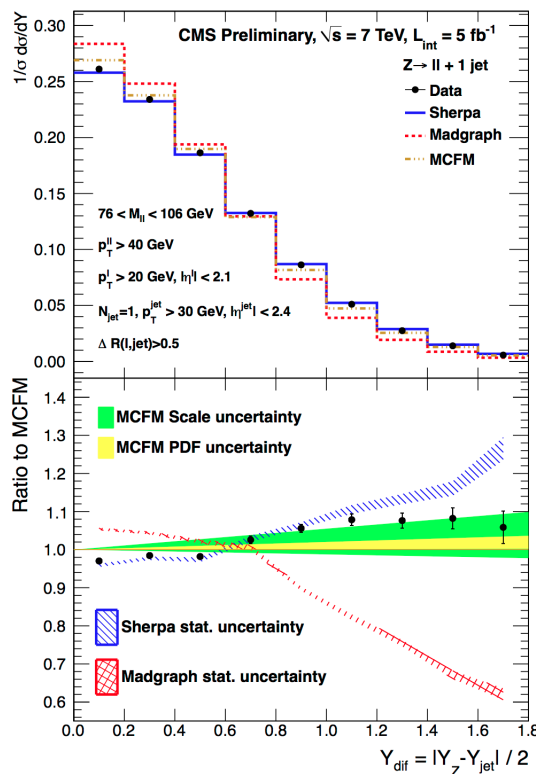
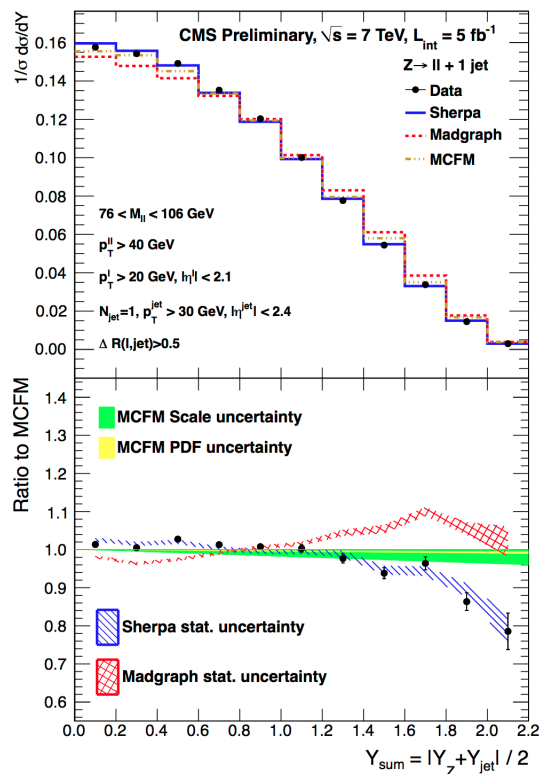
# Z+1 jet rapidity distributions

$\sqrt{s}=7\text{ TeV}, 5\text{ fb}^{-1}$



→ The rapidity distributions for events with a Z boson + one jet

→ Comparison with Sherpa, Madgraph MCFM.  
→ Sherpa agrees better.



$$Y_{\text{sum}} = (|Y(Z) + Y(j)|) / 2$$

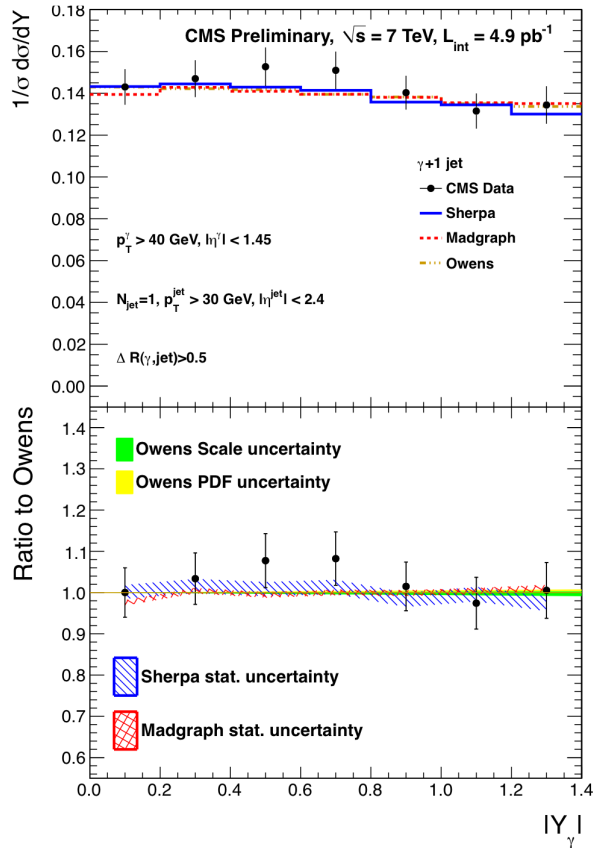
$$Y_{\text{diff}} = (|Y(Z) - Y(j)|) / 2$$

# photon+1 jet rapidity distributions

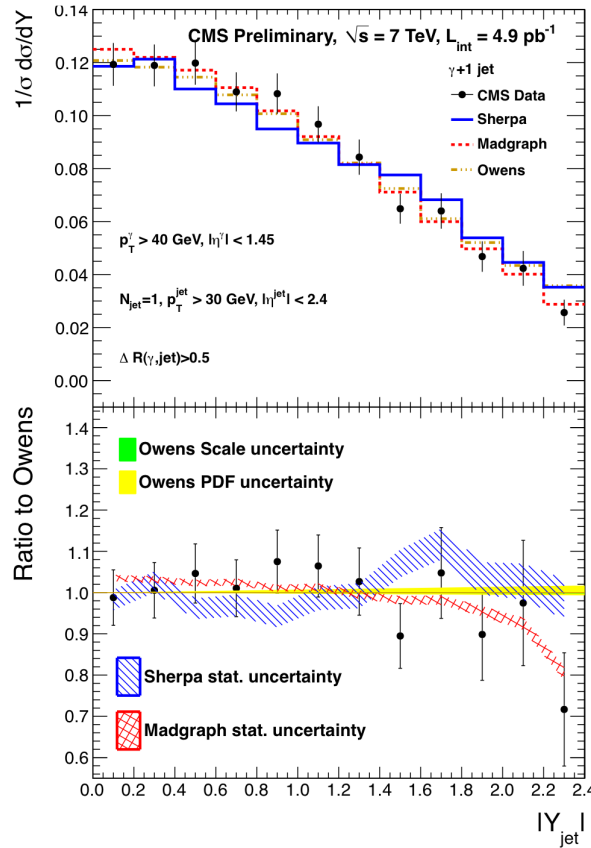


$\sqrt{s}=7\text{ TeV}, 5\text{ fb}^{-1}$

→ The rapidity distributions for events with a real photon + one jet



$|Y(\gamma)|$



$|Y(j)|$

- $p_T(\gamma) > 30\text{ GeV}$
- $|\eta(\gamma)| < 1.4$
- $P_T(j) > 30\text{ GeV}$
- $|\eta(j)| < 2.4$

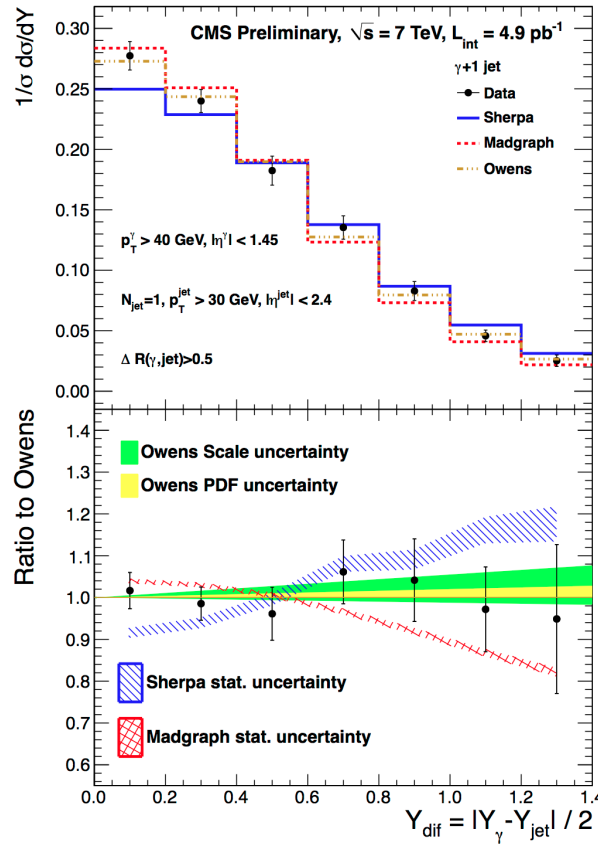
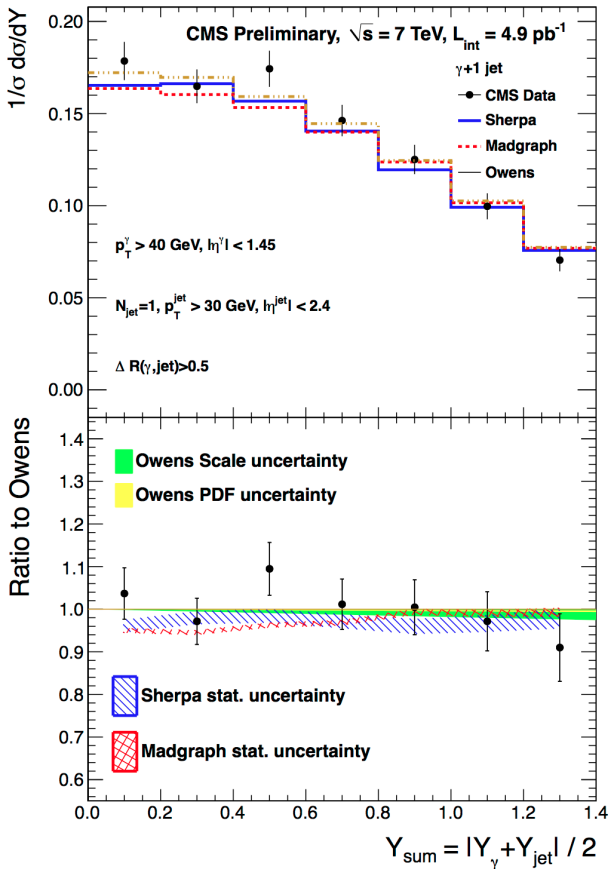
# photon+1 jet rapidity distributions



$\sqrt{s}=7 \text{ TeV}, 5 \text{ fb}^{-1}$

→ The rapidity distributions for events with a real photon + one jet

→ Comparison with Owens, Sherpa & Madgraph



$$Y_{\text{sum}} = (|Y(\gamma) + Y(j)|) / 2$$

$$Y_{\text{diff}} = (|Y(\gamma) - Y(j)|) / 2$$

# W+2 jets, dijet mass spectrum

$\sqrt{s}=7 \text{ TeV}, 5 \text{ fb}^{-1}$



→ Search for a former CDF bump in invariant mass spectrum of the two jets with highest transverse momentum in  $pp \rightarrow W+2\text{-jet}$  and  $W+3\text{-jet}$  events

$W \rightarrow \ell\nu$  selection

Single-lepton trigger

Lepton identification and isolation

$p_T^{\mu(e)} > 25 \text{ (35) GeV}$

$E_T^{\mu(e)} > 25 \text{ (30) GeV}$

$M_T > 50 \text{ GeV}$

Exclude events with  $> 1$  lepton

Jet selection

$p_T^{j1} > 40 \text{ GeV}$

$p_T^{j2}, p_T^{j3} > 30 \text{ GeV}$

$\|\vec{p}_T^{j1} + \vec{p}_T^{j2}\| > 45 \text{ GeV}$

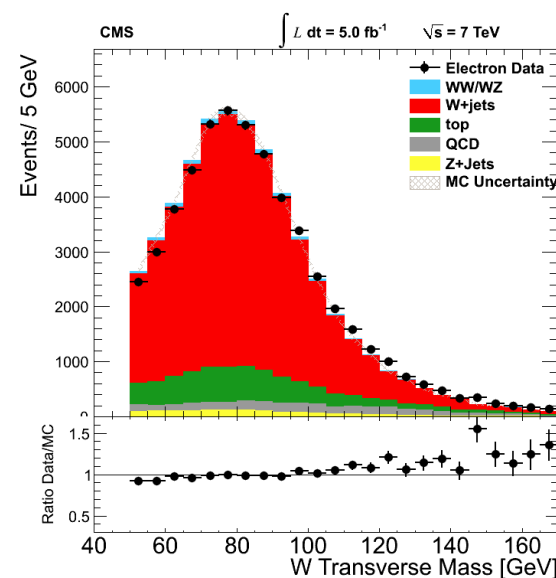
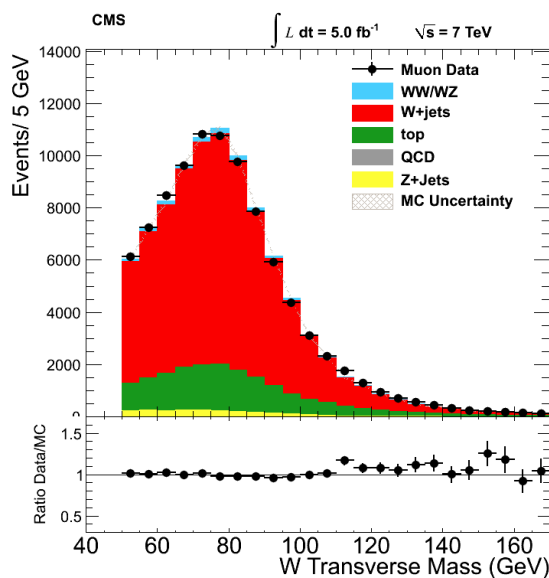
$|\Delta\eta(j1, j2)| < 1.2$

$\Delta\phi(E_T, j1) > 0.4$

$0.3 < p_T^{j2} / m_{jj} < 0.7$

→  $pp \rightarrow W(\rightarrow \ell\nu) + jj$  final states

Control plot: W transverse mass ( $M_T$ ) →



# W+2 jets, dijet mass spectrum

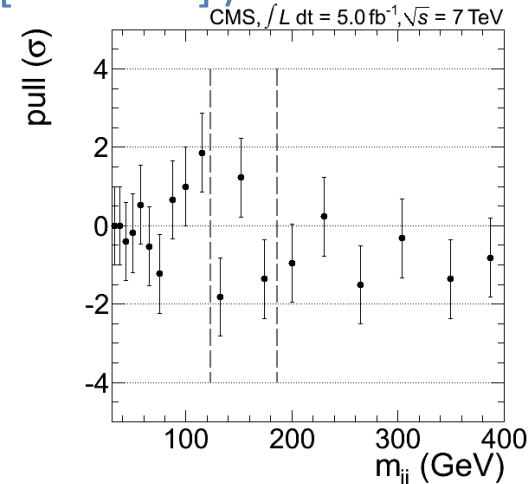
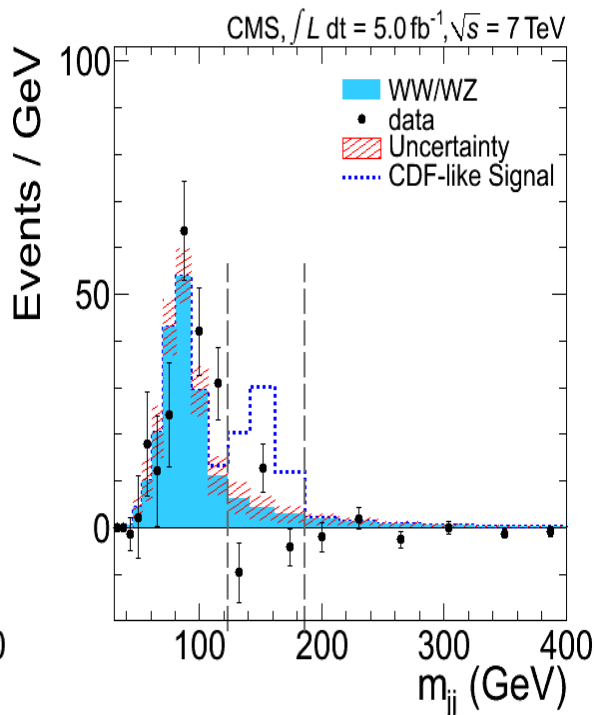
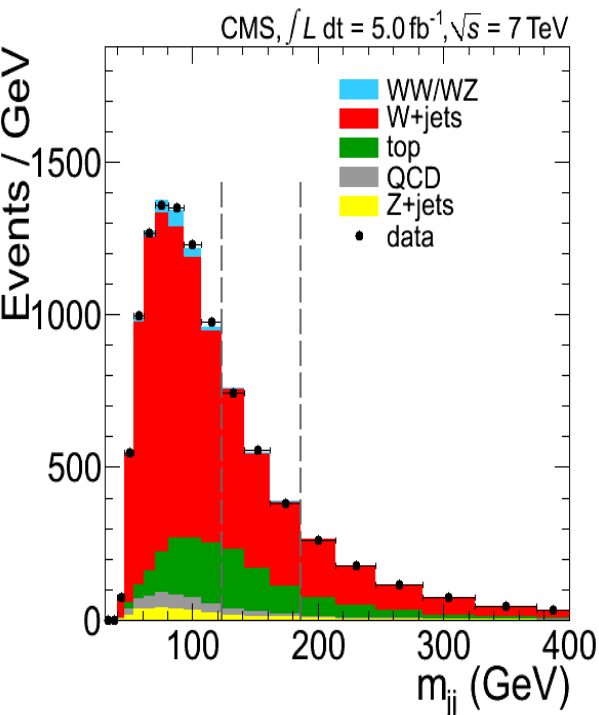


$\sqrt{s}=7$  TeV,  $5 \text{ fb}^{-1}$

M(j1j2) data ( $\mu+2$  j,  $\mu+3$  j,  $e+2$  j, and  $e+3$  j combined) before BG subtraction (left) and after BG subtraction except WW/WZ (right)

Pull distribution

[data - fit] / fit uncertainty



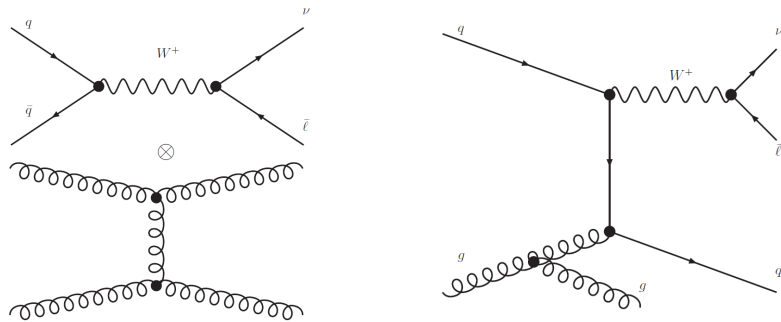
→ No excess is observed  
 → An upper limit of 5.0 pb @ 95 % confidence level on the production cross section for a generic Gaussian signal with mass near 150 GeV.

# Double parton scattering in W+jets



$\sqrt{s}=7 \text{ TeV}, 5 \text{ fb}^{-1}$

- p-p collisions @LHC energies probe small x values carried by partons
  - The large parton densities at small x increase probability of 2 parton-parton scattering producing 2 identifiable hard scattering in p-p interaction
- DPS studies provide info on spatial structure of hadrons
- Constitute as BG to new physics searches @LHC



Feynman Diagrams for W+ 2j production from DPS (left) and single parton scattering (right).

W → μν selection	Jet selection
Single muon trigger	anti-kT PF jet with R = 0.5
Muon ID and isolation	$p_T > 20 \text{ GeV}/c,  \eta  < 2.0$
Exactly one muon $p_T > 35 \text{ GeV}/c,  \eta  < 2.1$	$\beta > 0.4$
$E_T > 30 \text{ GeV}/c$	$\Delta R(\text{jet} - \mu) > 0.5$
W transverse mass $> 50 \text{ GeV}/c^2$	

- Double parton scattering (DPS) is investigated in W-  
→ μν + 2j final states
- Exclusive W+2 jets events
- Inclusive W+2 jets events



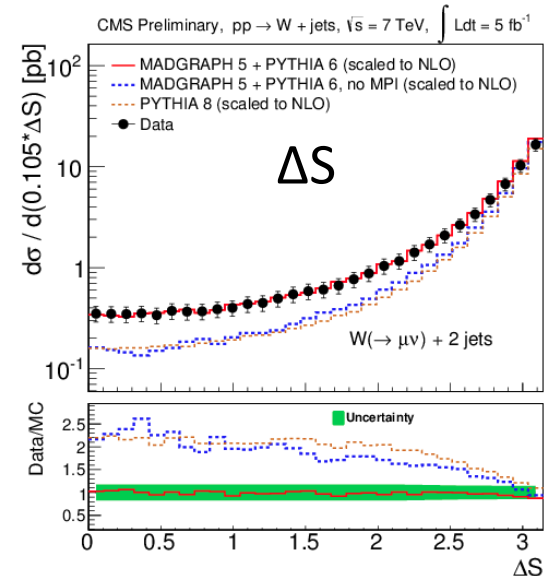
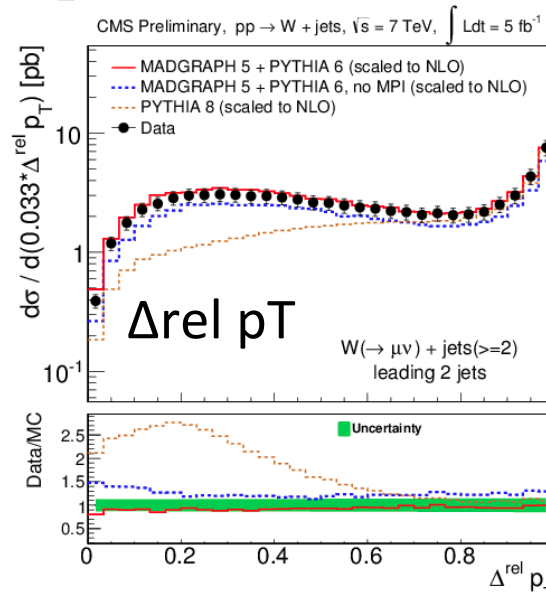
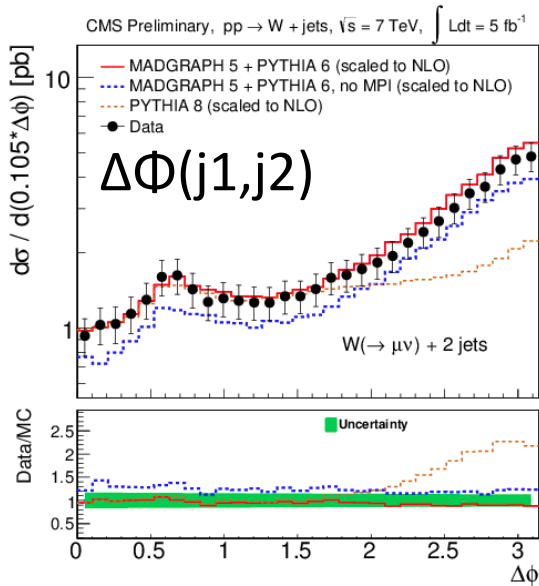
# Double parton scattering in W+jets

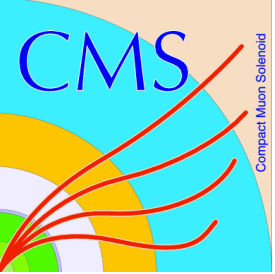


$\sqrt{s}=7\text{ TeV}, 5\text{ fb}^{-1}$

- Unfolded  $\Delta\Phi(j1,j2)$ ,  $\Delta_{\text{rel}} p_T$ , and  $\Delta S$  distributions for W+2j exclusive sample
- MC predictions of MADGRAPH nicely describe the measurements
- The MC prediction without MPI & Pythia fails to describe the differential x-sec as well as the shape
- First step towards the upcoming extraction of the underlying DPS fraction@ LHC energies.

$$\Delta S = \arccos\left(\frac{\vec{P}_T(\mu, \cancel{E}_T) \cdot \vec{P}_T(j1, j2)}{|\vec{P}_T(\mu, \cancel{E}_T)| \cdot |\vec{P}_T(j1, j2)|}\right) \quad \Delta_{\text{rel}} p_T = \frac{|\vec{p}_T(j1) + \vec{p}_T(j2)|}{|\vec{p}_T(j1)| + |\vec{p}_T(j2)|}$$



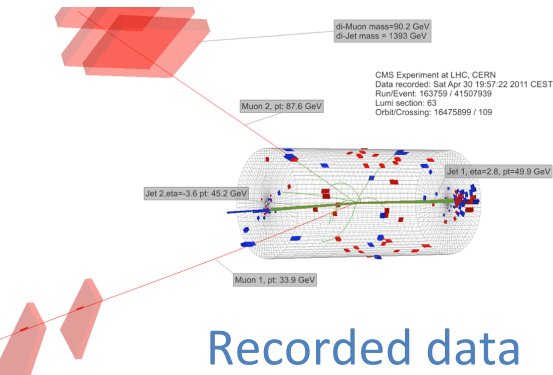


# Electroweak Z + forward-backward jets production

$\sqrt{s}=7\text{ TeV}, 5\text{ fb}^{-1}$

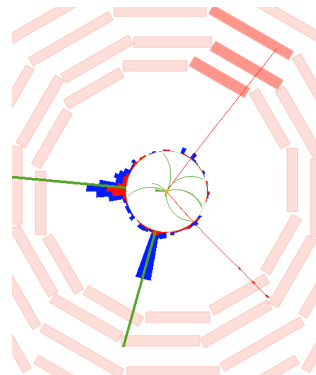


- EW production of W,Z + 2 well separated jets is quite sizeable @LHC
- Study of these processes are important for
  - VBF studies
  - Higgs boson searches
  - Measurements of EWK gauge couplings & Vector Boson scattering
- EWK cross sections of the Z boson with two forward-backward jets

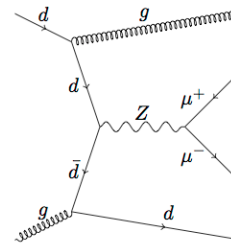


Recorded data

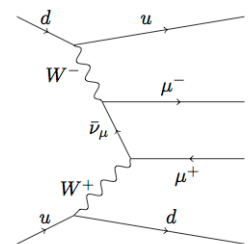
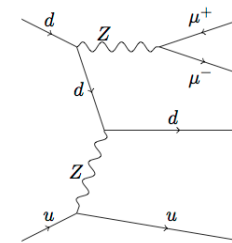
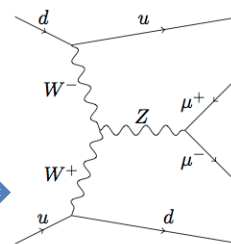
$M(\mu\mu)=90.2\text{ GeV}$   $M(jj)=1.4\text{ TeV}$ .



→ Main background: DY + 2j



← DY + 2j



EW  $ljj$  production (for  $l=\mu$ ): VBF (left), bremsstrahlung (middle), and multiperipheral → (right).

# Electroweak Z + forward-backward jets production



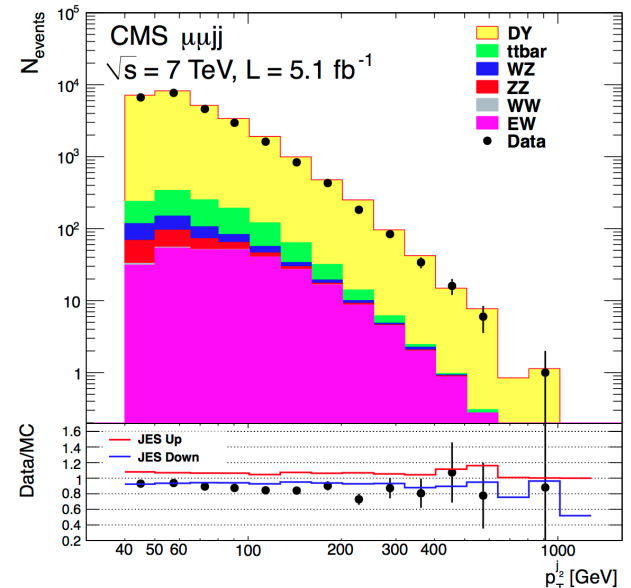
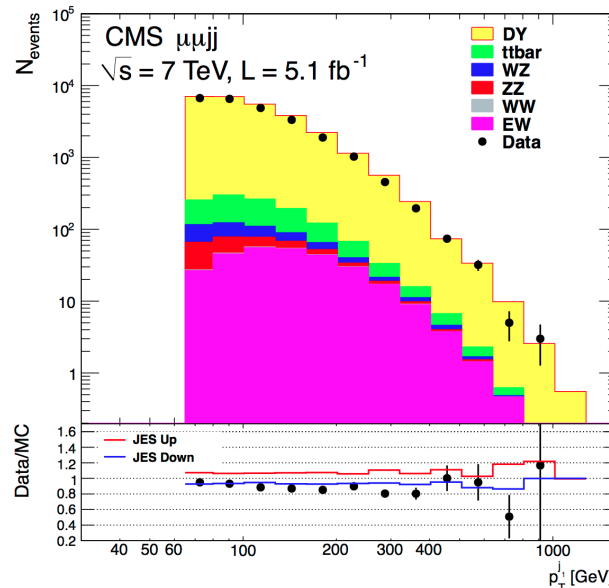
$\sqrt{s}=7\text{ TeV}, 5\text{ fb}^{-1}$

→ Unfolded to parton level selections:  $m_{\ell\ell} > 50\text{ GeV}$ ,  $p_{Tj} > 25\text{ GeV}$ ,  $|\eta_j| < 4.0$ ,  $m_{jj} > 120\text{ GeV}$

$$\sigma_{\text{meas}} = 154 \pm 24(\text{stat}) \pm 46(\text{exp.syst}) \pm 27(\text{th.syst}) \pm 3(\text{lumi})\text{ fb}$$

$$\sigma_{\text{th}} = 166\text{ fb @NLO}$$

$p_{Tj1}$  (left) and  $p_{Tj2}$  (right) distributions after applying the  $Z_{\mu\mu}$  selection and the tagging jet requirement TJ1





# Electroweak Z + forward-backward jets production



$\sqrt{s}=8 \text{ TeV}, 19.7 \text{ fb}^{-1}$

@8TeV

→ two methods of signal extraction to confirm & cross-check the presence of the signal.

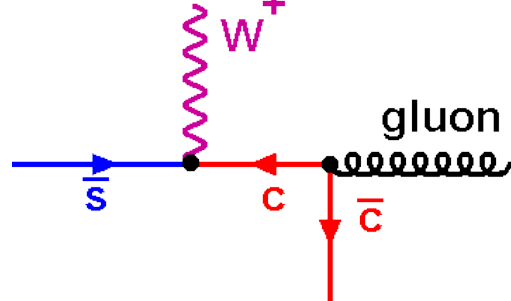
→ MVA analysis as in 7 TeV

→ New method using data to model the main background

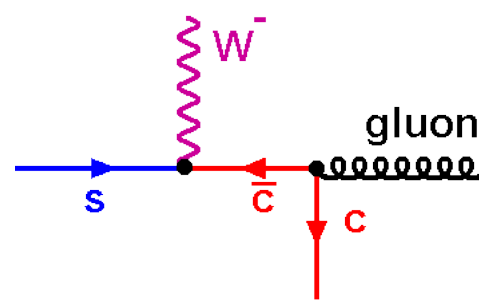
→ Unfolded to parton level selections:  $m_{\ell\ell} > 50 \text{ GeV}$ ,  $p_{tj} > 25 \text{ GeV}$ ,  $|\eta_j| < 5.0$ ,  $m_{jj} > 120 \text{ GeV}$

$$\sigma_{\text{meas}} = 226 \pm 26(\text{stat}) \pm 35(\text{syst}) \text{ fb}$$

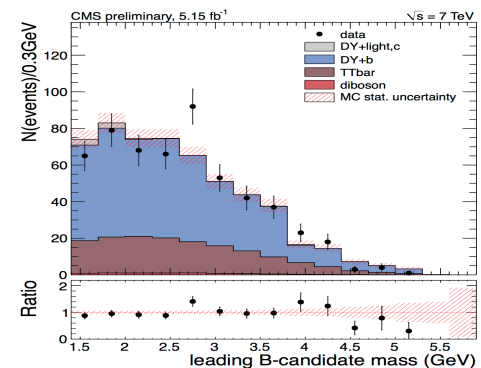
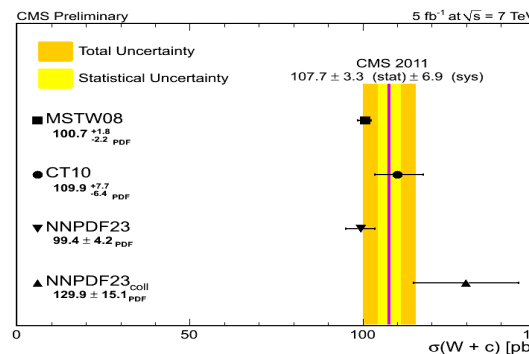
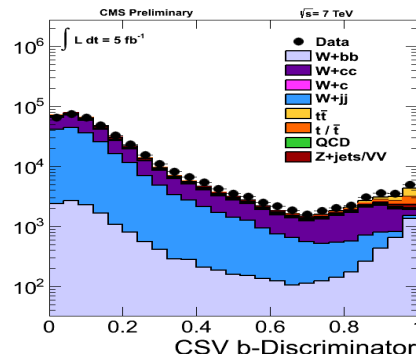
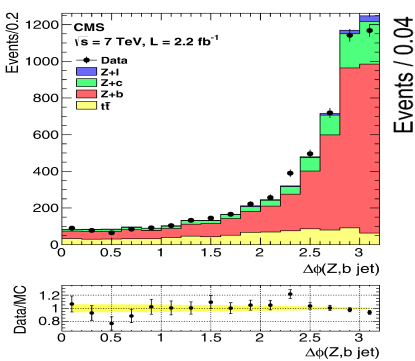
$$\sigma_{\text{th}} = 239 \text{ fb @NLO}$$



V+HF



- Z+b, bb jet cross sections at 7 TeV (*JHEP 06 (2012) 126, CMS-PAS SMP-13-004*)
- W+bb cross section at 7 TeV (*CMS-PAS-SMP-12-026*)
- W+c differential cross section at 7 TeV (*CMS-PAS-SMP-12-002*) arXiv:1310:1138
- Z+bb jets, b hadron angular correlations at 7 TeV (*CMS EWK-11-015*) arXiv:1310.1349



- Enough sensitivity to constrain the strange-quark PDF with the W+c measurements
- Generally good agreement with data, in shapes for MC ME+PS, and in overall normalisation for NLO calculations, in W/Z+bb measurements

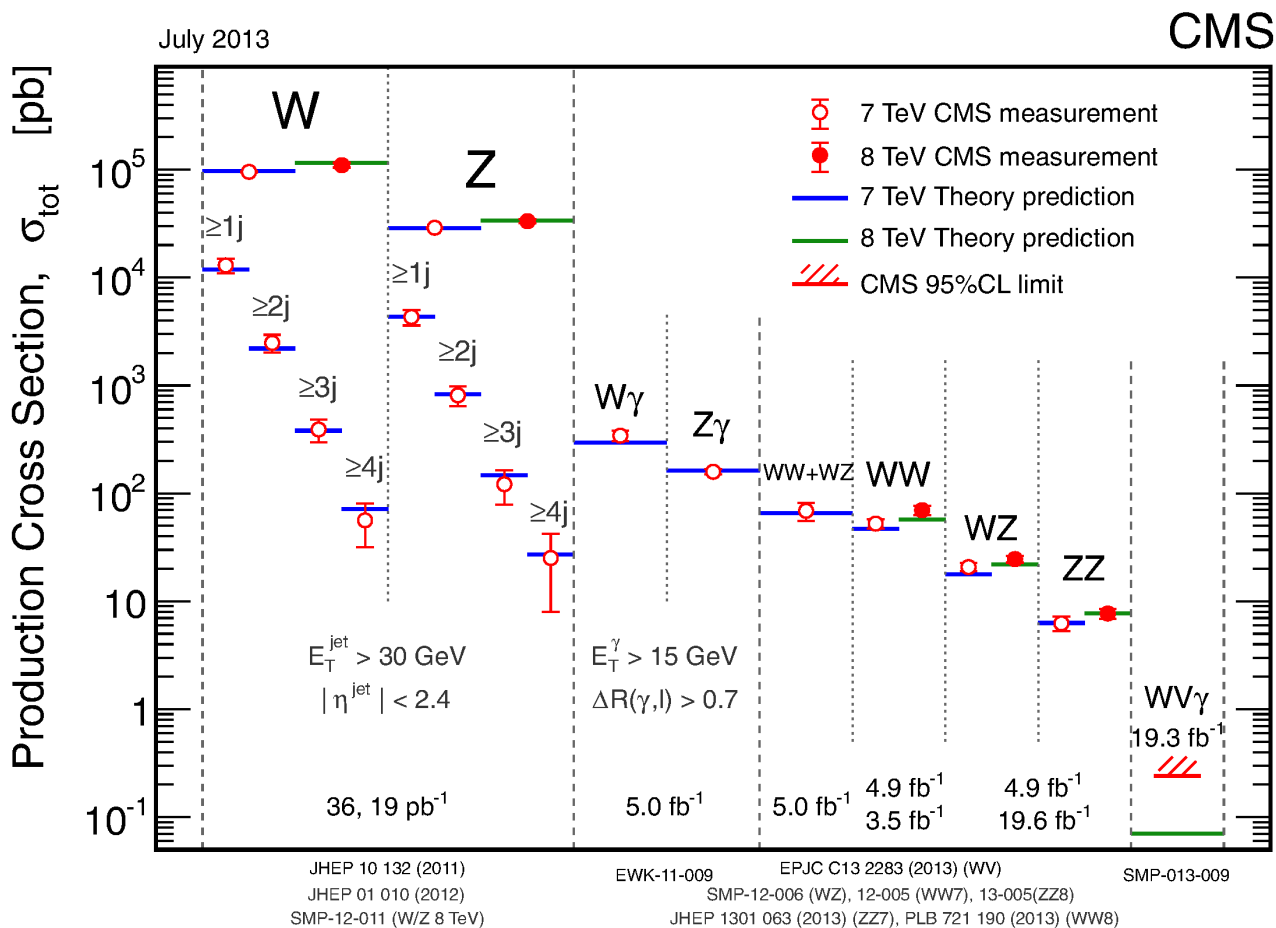


# SUMMARY



- The measurements provide a detailed description of V+jets production topological structure
  - Testing the validity of QCD
  - Providing confidence in existing MC models for;
    - Describing SM
    - Determining BG in BSM searches
- Overall scale good agreement between Data and SM Monte Carlo predictions
- Only 7 TeV V+jet results; more precise results to come with full 20 fb<sup>-1</sup> data @8 TeV
- All CMS SMP public results can be found under the following link:  
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP>

# SUMMARY





THANK YOU!

