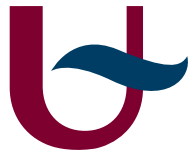
Recent results on vector boson production in association with jets at CMS

Tom Cornelis
for the CMS collaboration



International Symposium on Multiparticle Dynamics, September 2013, Chicago

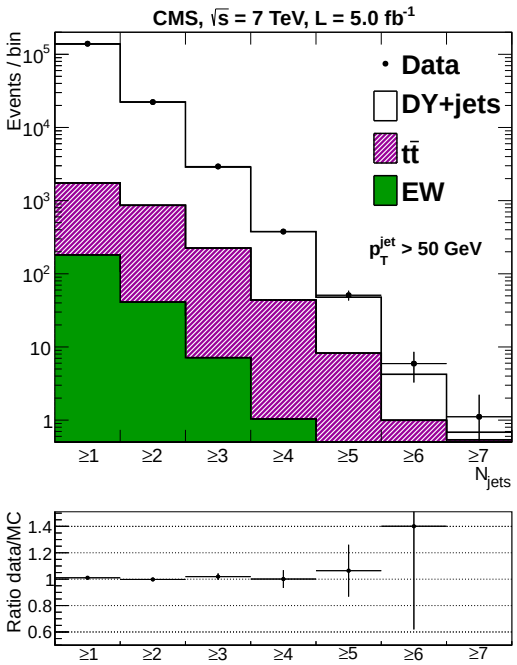
Universiteit Antwerpen

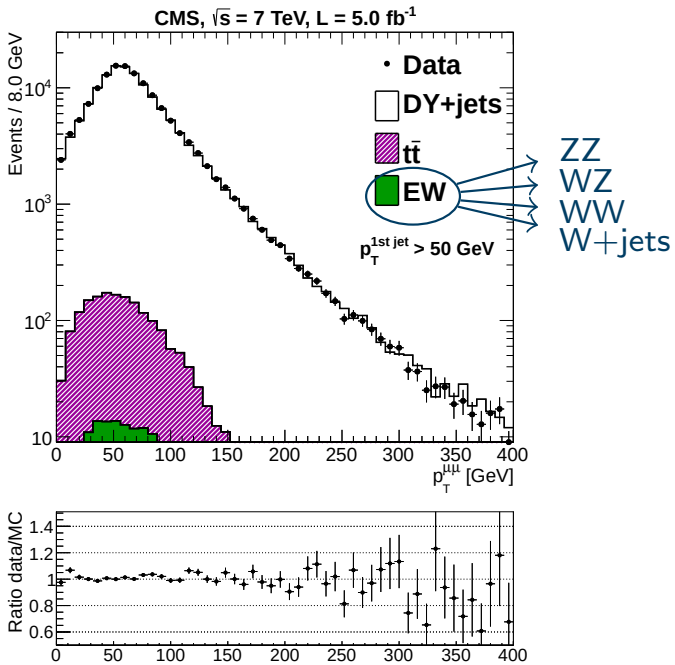
Outline

- Azimuthal correlations & event shapes in Z+jets (7 TeV)
- Z + 1 jet rapidity distributions (7 TeV)
- Double parton scattering in W + jets (7 TeV)
- Electroweak production of Z + 2 jets
  - 7 TeV and **8 TeV**
  - Signal extraction and cross section measurement
  - Studies on hadronic activity, 3rd jet kinematics and radiation patterns

Azimuthal correlations & event shapes in Z+jets

- Using 5 fb^{-1} data at $\sqrt{s} = 7$ **TeV**





Selection criteria:

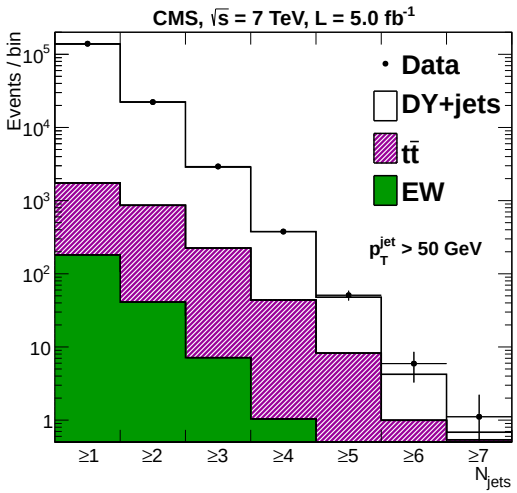
$p_T(\text{jet}) > 50$ GeV $\quad |\ \eta(\text{jet})\ | < 2.5$

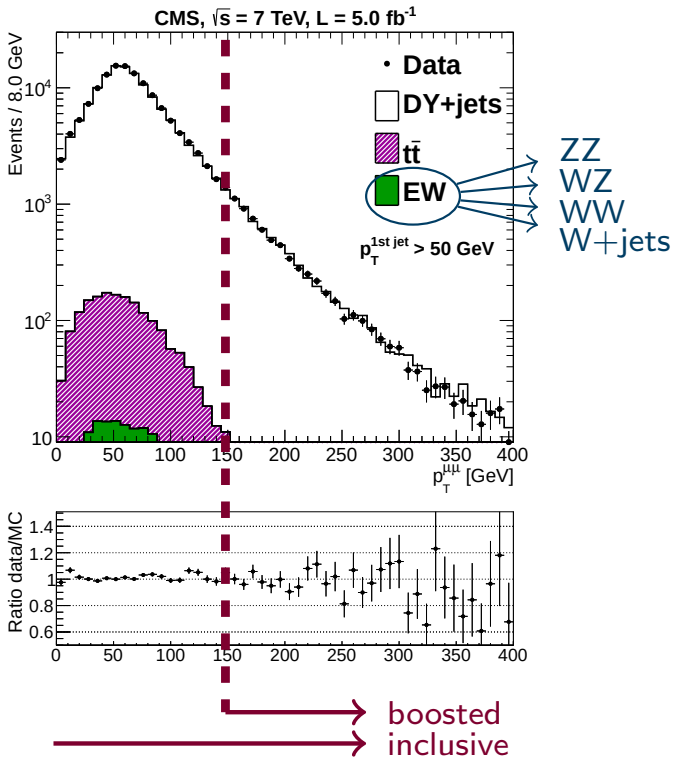
$p_T(l) > 20$ GeV $\quad |\ \eta(l)\ | < 2.4$

$71\ \text{GeV} < m_{ll} < 121\ \text{GeV}$

Azimuthal correlations & event shapes in Z+jets

- Using 5 fb^{-1} data at $\sqrt{s} = 7$ **TeV**





Both inclusively and in a boosted regime: $p_T(Z) > 150$ GeV

$\rightarrow$ Phase space which is very critical for new phenomena

Selection criteria:

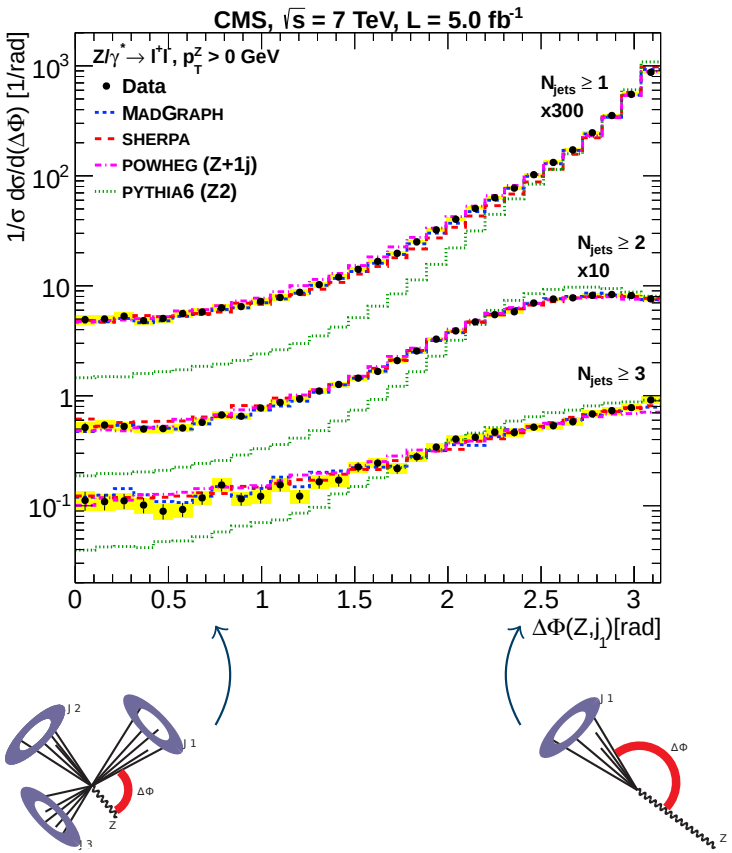
$p_T(\text{jet}) > 50$ GeV $\quad | \eta(\text{jet}) | < 2.5$

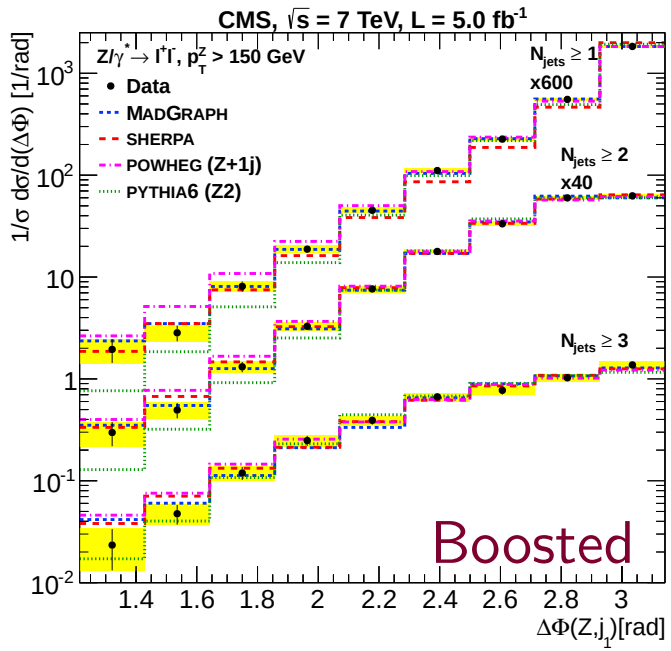
$p_T(l) > 20$ GeV $\quad | \eta(l) | < 2.4$

71 GeV $< m_{ll} < 121$ GeV

Azimuthal correlations & event shapes in Z+jets

Azimuthal angle $\Delta\Phi(Z, J_1)$ between the Z boson and the leading jet:



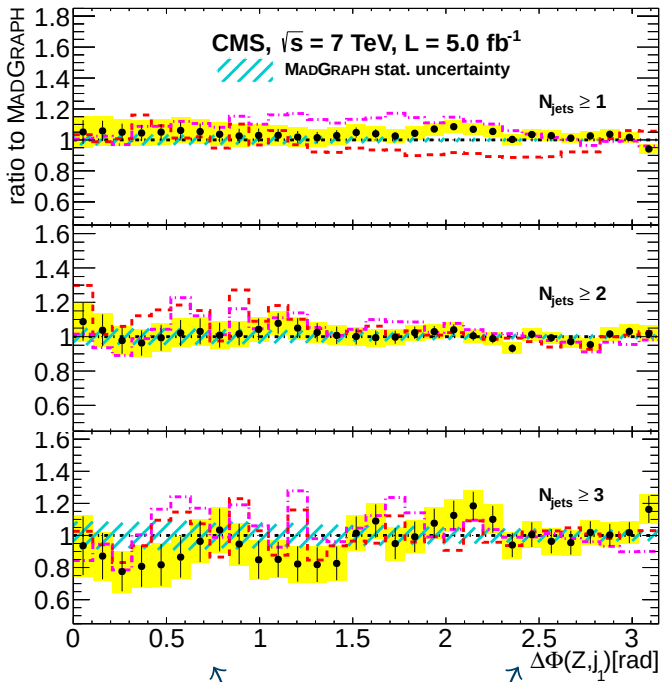


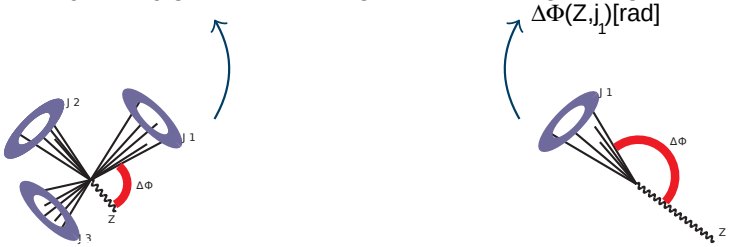
Error bars: statistical uncertainties
Yellow band: sum of statistical and systematic uncertainties

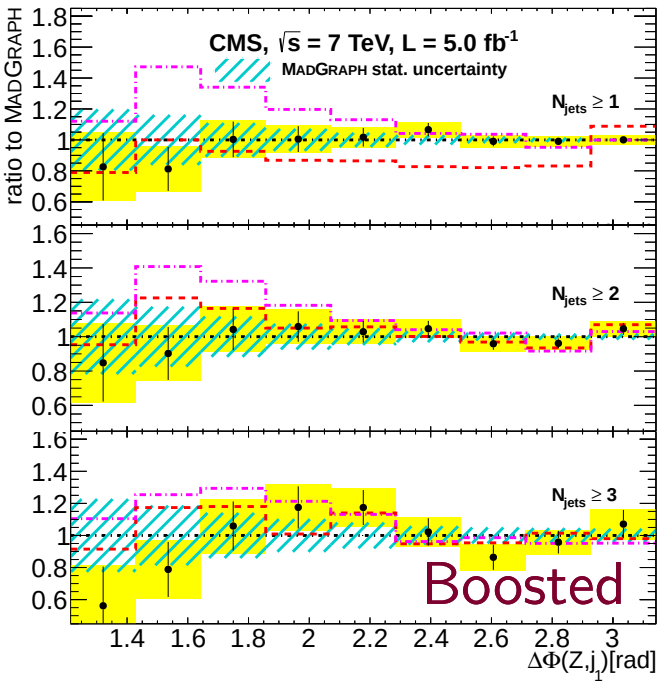
Measurement is in good agreement with MADGRAPH prediction

Azimuthal correlations & event shapes in Z+jets

Azimuthal angle $\Delta\Phi(Z, J_1)$ between the Z boson and the leading jet:







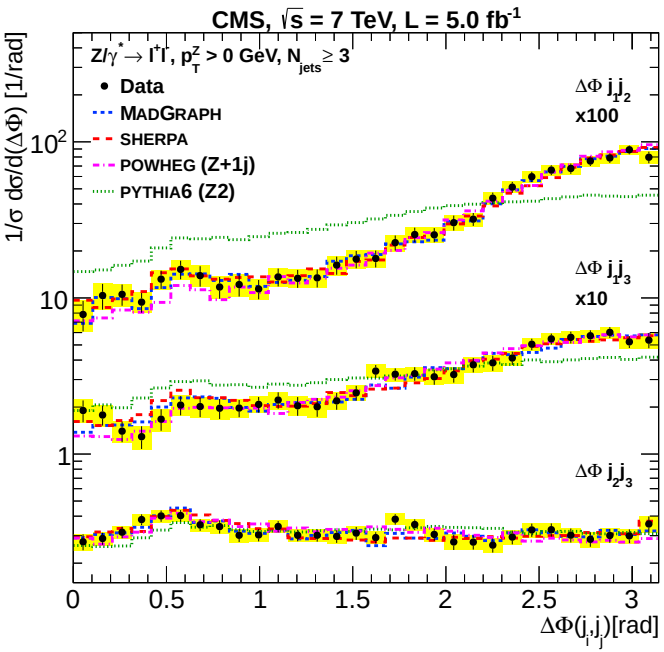
Error bars: statistical uncertainties
Yellow band: sum of statistical and systematic uncertainties

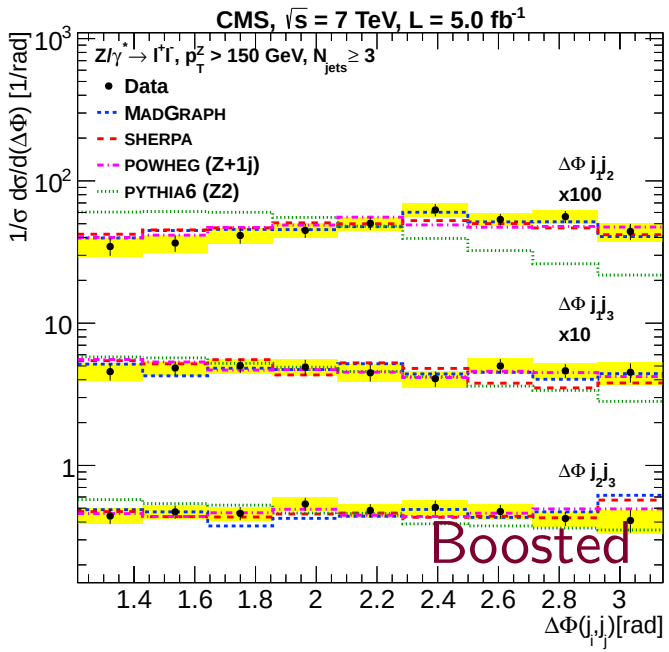
For $N_{\text{jets}} \geq 1$:

- Sherpa undershoots 10%
- Powheg overshoots 10%

Azimuthal correlations & event shapes in Z+jets

Azimuthal angles $\Delta\Phi(J_i, J_k)$ among the three leading jets:

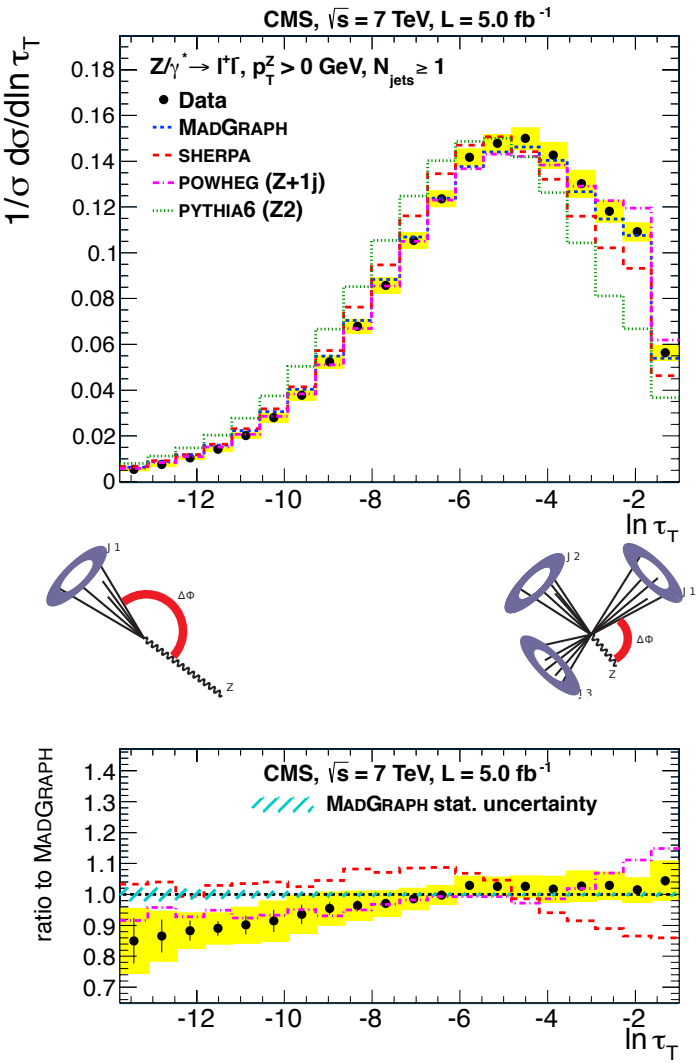




Angles between the jets decorrelate in boosted regime

Error bars: statistical uncertainties
Yellow band: sum of statistical and systematic uncertainties

Azimuthal correlations & event shapes in Z+jets

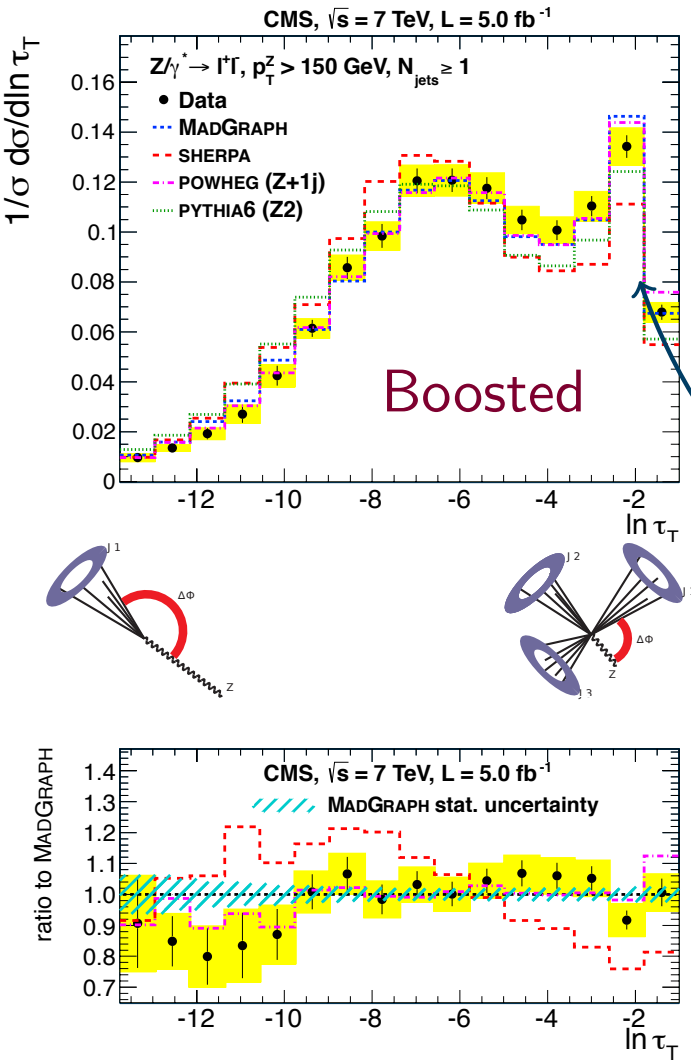


Transverse thrust:

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

- Thrust axis: $\vec{n}_\tau$
- In the limit of a perfectly balanced, pencil-like Z + 1 jet events, τ_T tends to zero
- In the limit of a spherical, homogeneously-distributed events: $\tau_T \to 1 - \frac{2}{\pi}$
- The value of thrust increases with additional jet emission

Azimuthal correlations & event shapes in Z+jets



Transverse thrust:

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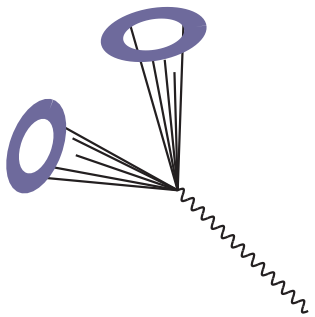
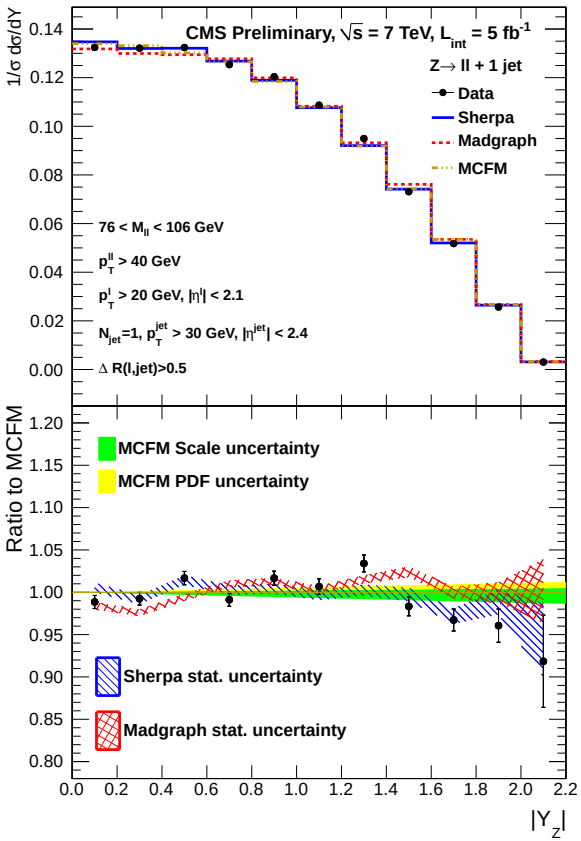
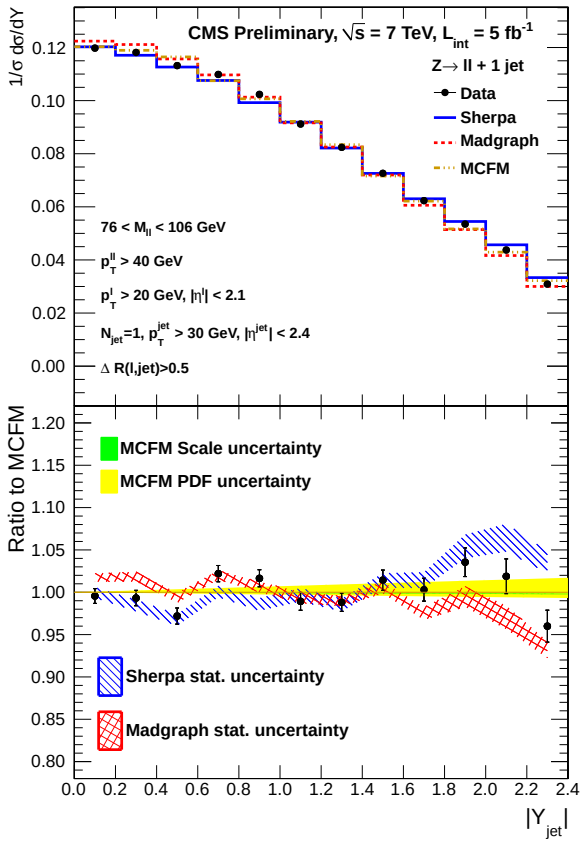


Z + 1 jet rapidity distributions

- Using 5 fb^{-1} data at $\sqrt{s} = 7$ **TeV**





- Data unfolded
- MadGraph + Pythia with MLM matching scheme
- Sherpa + Apacic++ (parton showering) + Pythia 6 fragmentation) with CKKM matching scheme
- MCFM (NLO)
- Good agreement for Y_Z and Y_{jet}

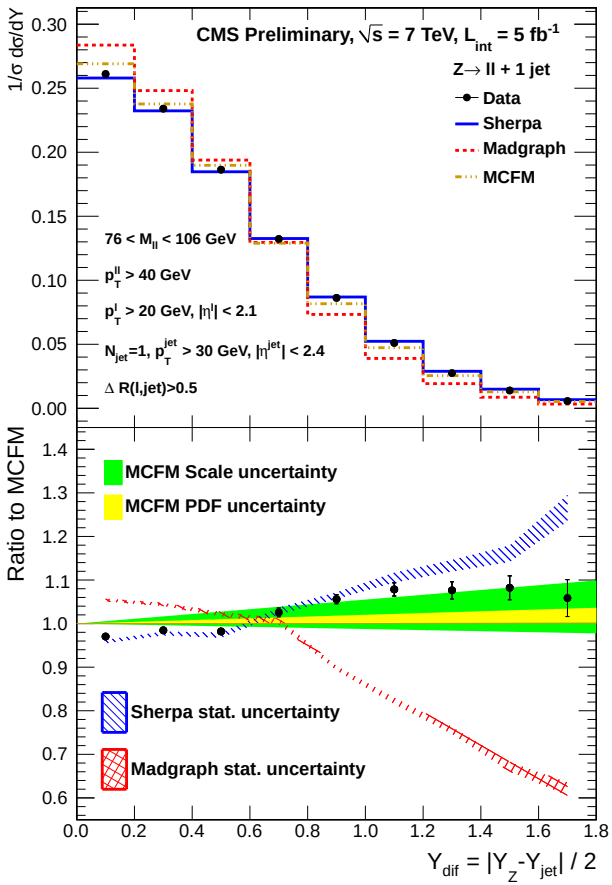
Selection criteria:

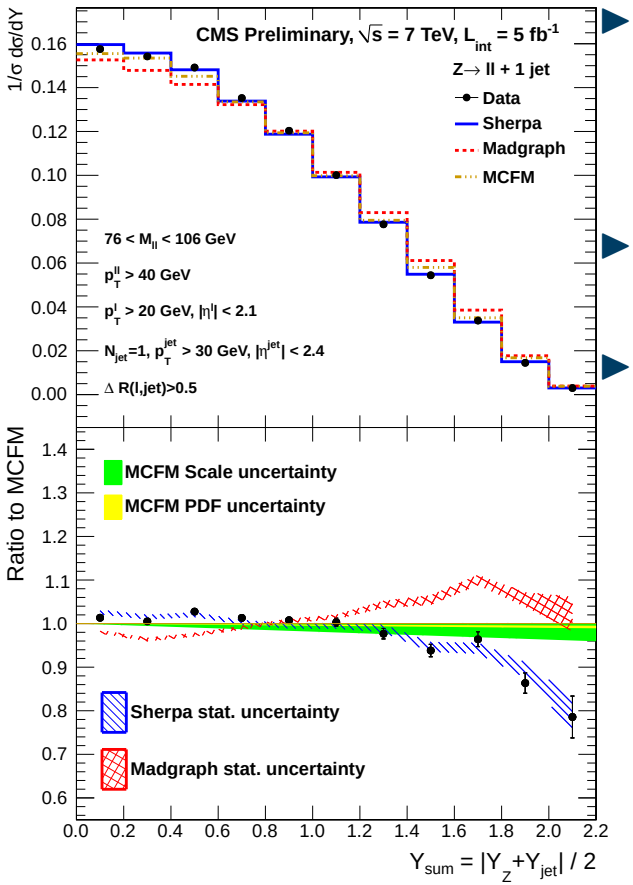
$p_T(\text{jet}) > 30$ GeV $\quad | \eta(\text{jet}) | < 2.4$

$p_T(l) > 20$ GeV $\quad | \eta(l) | < 2.1$

76 GeV $< m_{ll} <$ 106 GeV

Z + 1 jet rapidity distributions





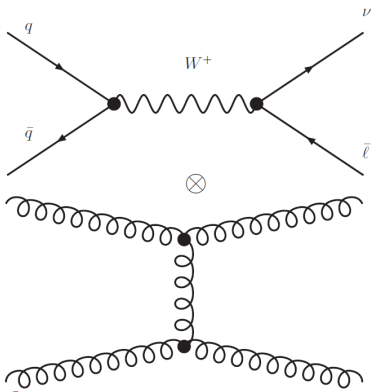
- Rotation in (Y_Z, Y_{jet}) frame to end up with approximately uncorrelated variables
- Y_{sum} is best described by SHERPA
- MCFM better for Y_{dif}

$$Y_{dif} = \frac{|Y_Z - Y_{jet}|}{2}$$

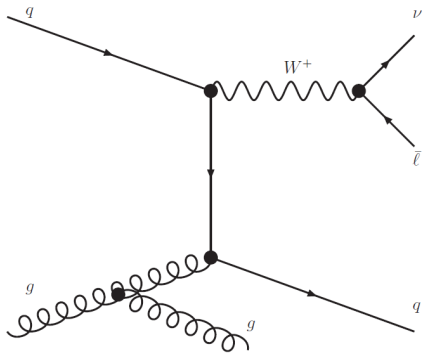
$$Y_{sum} = \frac{|Y_Z + Y_{jet}|}{2}$$

Double parton scattering in W + 2 jets

- Using 5 fb^{-1} data at $\sqrt{s} = 7$ **TeV**
- Double parton scattering investigated in W($\rightarrow \mu\nu$) jets events



signal



background

→ Roberta's talk yesterday

- MadGraph + Pythia 6
- MadGraph + Pythia 6 without MPI
- Pythia 8

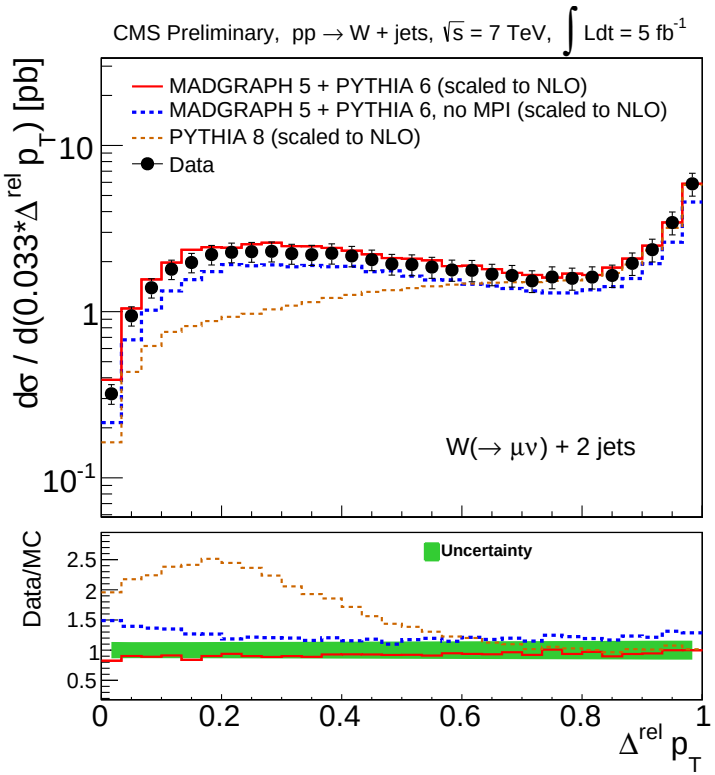
Selection criteria:

$p_T(\text{jet}) > 20$ GeV	$\mid \eta(\text{jet}) \mid < 2$
$p_T(\mu) > 35$ GeV	$\mid \eta(\mu) \mid < 2.1$
$\not{E}_T > 30$ GeV	$m_T(W) > 50$ GeV

Double parton scattering in W + 2 jets

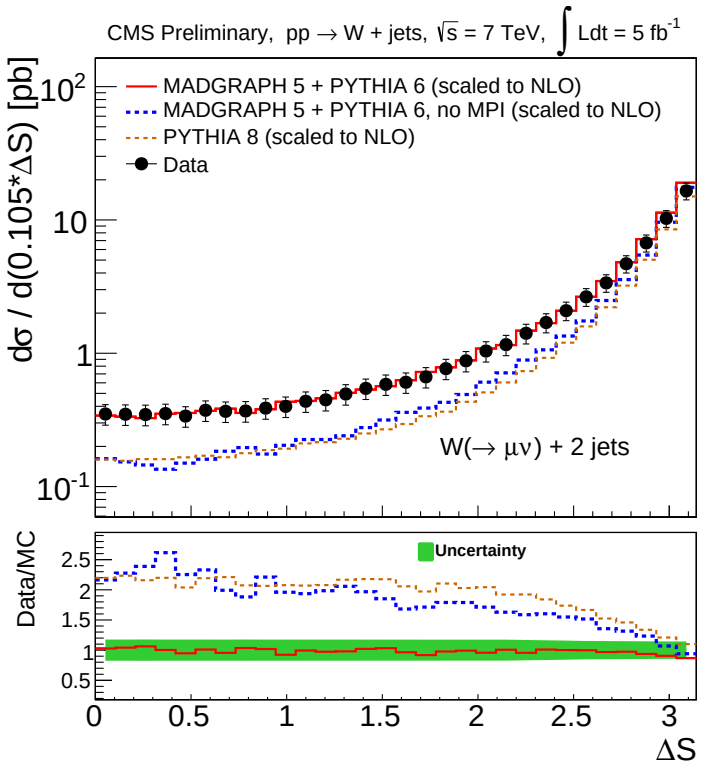
Relative p_T imbalance between two jets:

$$\Delta^{\text{rel}} p_T(j_1, j_2) = \frac{|\vec{p}_T(j_1)+\vec{p}_T(j_2)|}{|\vec{p}_T(j_1)|+|\vec{p}_T(j_2)|}$$



Azimuthal angle between W and dijet system:

$$\Delta S = \arccos\left(\frac{\vec{p}_T(\mu,\not{E}_T)\cdot\vec{p}_T(j_1,j_2)}{|\vec{p}_T(\mu,\not{E}_T)|\cdot|\vec{p}_T(j_1,j_2)|}\right)$$



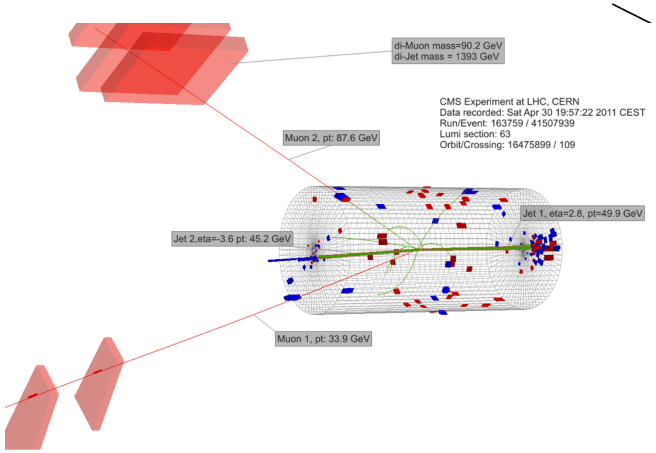
DPS sensitive regions at low $\Delta^{\text{rel}} p_T(j_1, j_2)$ and ΔS are well described if MadGraph + Pythia 6 is used with MPI turned on

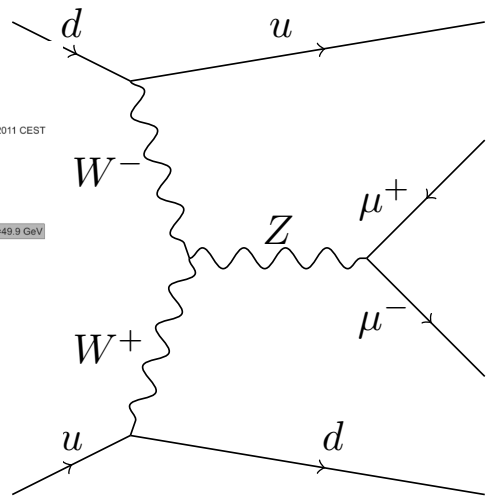
Electroweak production of Z + 2 jets

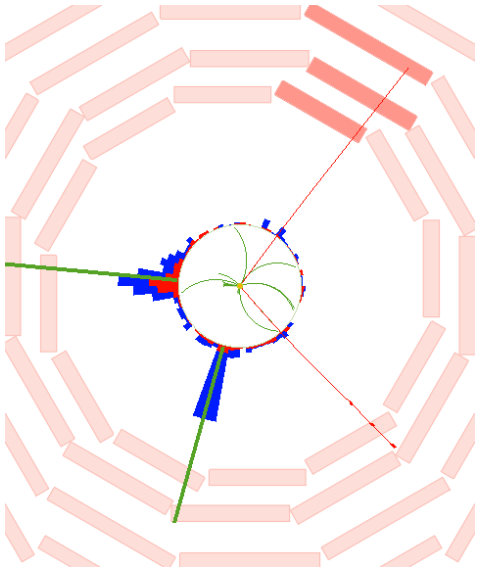
- Results at $\sqrt{s} = 7$ **TeV** with 5 fb^{-1}
- First preliminary results at $\sqrt{s} = 8$ **TeV** with 19.7 fb^{-1}

- Cross section measurement of the pure electroweak production of Z + 2 jets
  - MC based method
  - Data driven method using photon control region
- Measurement of the hadronic activity and kinematics of the 3rd jet
- Measurement of radiation patterns

Electroweak production of Z + 2 jets



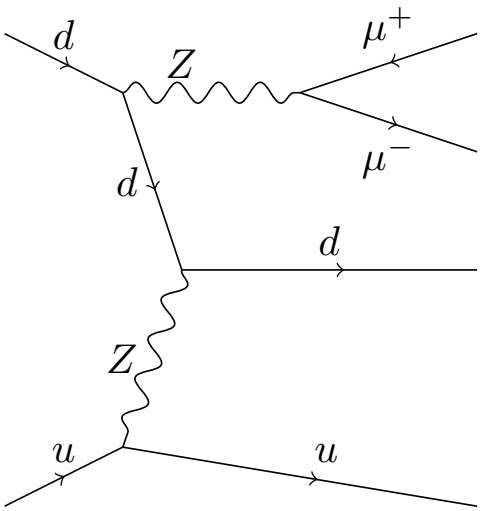




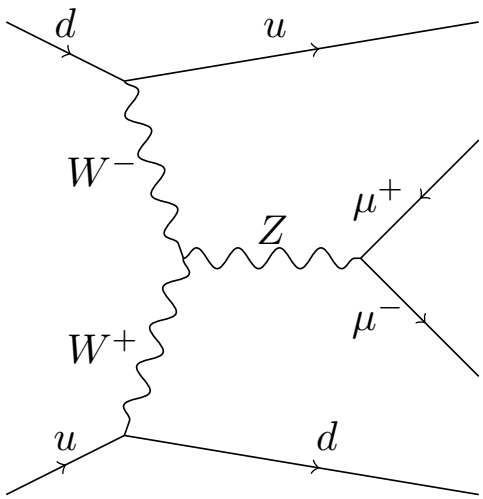
Features of vector boson fusion WW→Z are:

- Central Z decay associated with energetic forward-backward jets
- A large η separation between the jets
- A large invariant dijet mass
- Pure EWK process: no color exchange between the tagging quarks

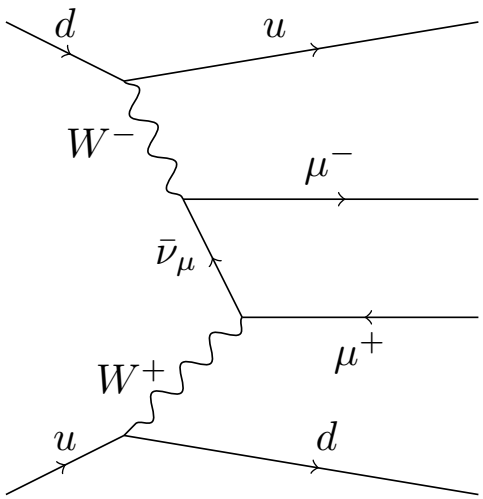
Electroweak production of Z + 2 jets



bremsstrahlung



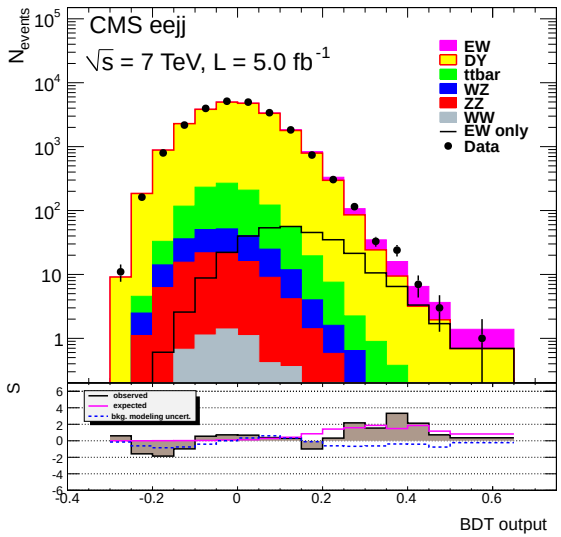
VBF

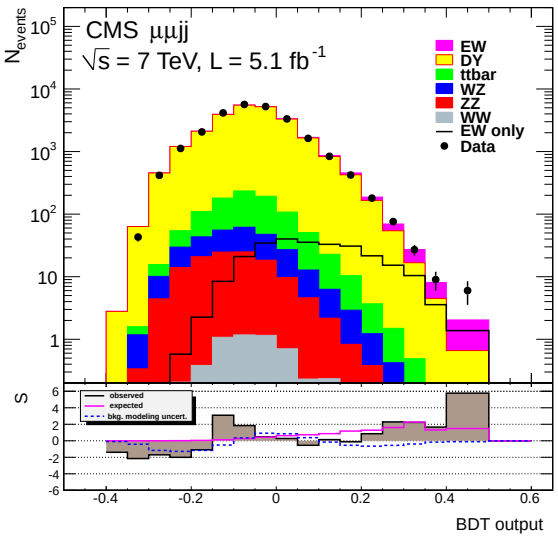


multi-peripheral

- Many other pure electroweak processes lead to the same 2 leptons + 2 jets final state
- Negative interference effects between these diagrams suppress the VBF contribution

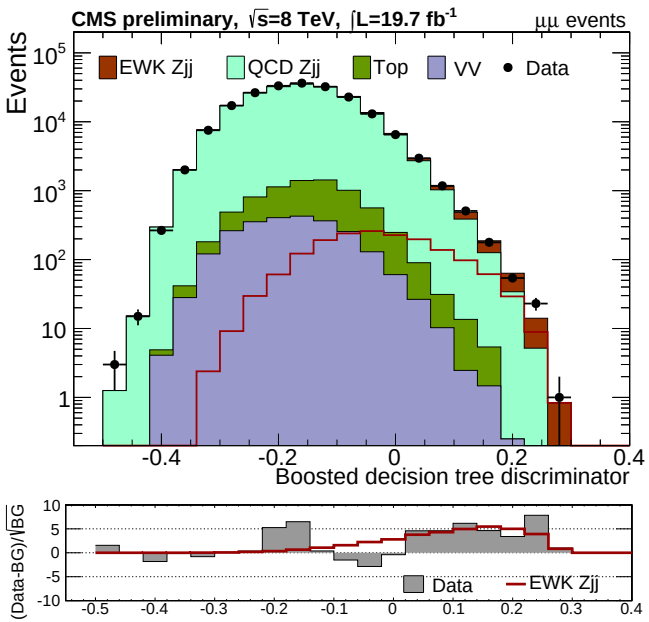
Electroweak Z + 2 jets cross section (I)





Use shape from boosted decision tree to extract signal

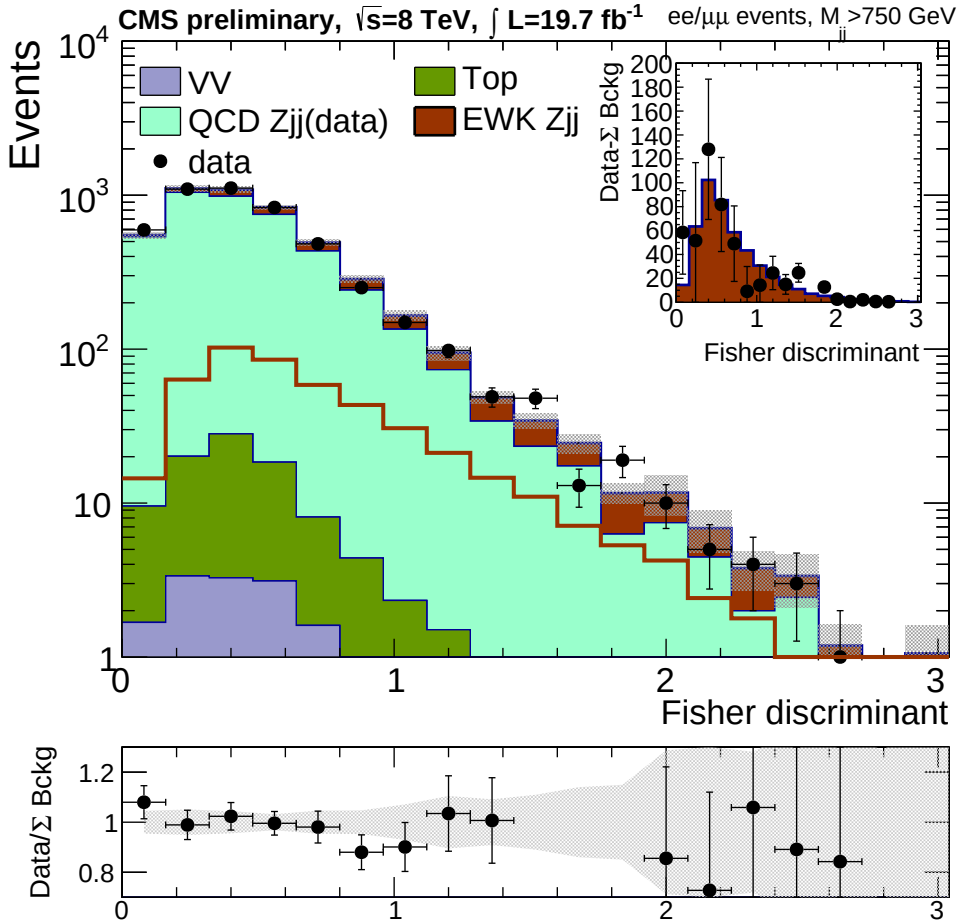
7 TeV: $Z \to \mu\mu$ and $Z \to ee$
8 TeV: $Z \to \mu\mu$

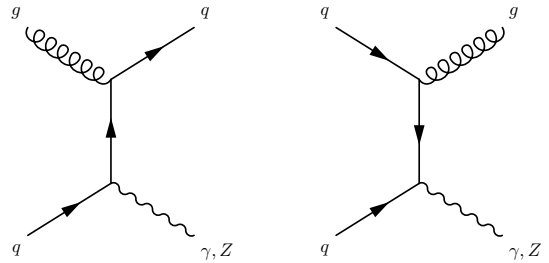


- p_T of the two tagging jets and the Z boson
- dijet kinematics: M_{jj}, $\Delta\phi|jj$, $\Delta\eta_{jj}$, $\eta_{j1} + \eta_{j2}$
- $\Delta\phi(Z, j_1)$ and $\Delta\phi(Z, j_1)$
- y^* (only 7 TeV $\mu\mu$)
- quark-gluon likelihood for the tagging jets (only ee-channel)
- Reweight discribution with NLO/LO factors (using MCFM) as function of M_{jj} and y^*

Electroweak Z + 2 jets cross section (II)

Method II (only at 8 TeV): data driven background estimation using $\gamma + 2$ jets data





Use dijet kinematics in photon events to model dijet kinematics of main background

Fisher discriminant built out of:

- dijet invariant mass M_{jj}
- pseudorapidity separation $\Delta\eta_{jj}$ between the two jets
- $\frac{|\vec{p}_T(j_1,j_2)|}{|\vec{p}_T(j_1)|+|\vec{p}_T(j_2)|}$

Electroweak Z + 2 jets cross section

7 TeV

Combination of

- $\mu\mu$ channel (method I: MC)
- ee channel (method I: MC)

$$\sigma_{meas}^{EW\ lljj} = 154 \pm 24\ (\text{stat})\ \pm 46\ (\text{syst})\ \pm 27\ (\text{theory})\ \pm 3\ (\text{lumi})\ \text{fb}$$

NLO prediction from VBFNLO: $\sigma_{NLO}^{EWlljj} = 166$ fb

8 TeV preliminary

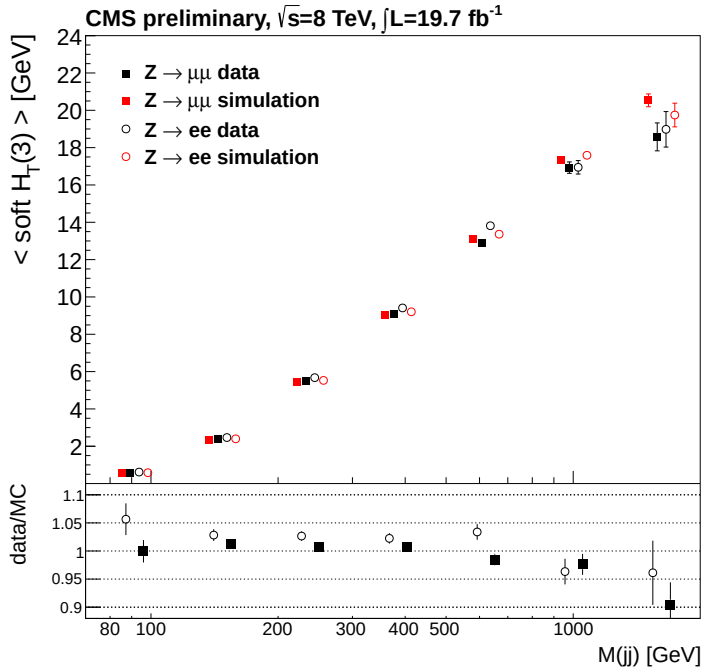
Combination of

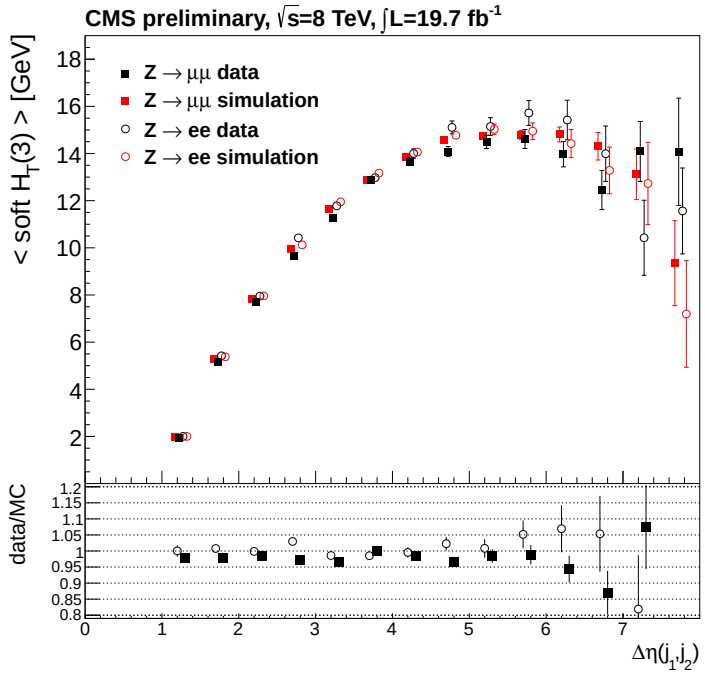
- $\mu\mu$ channel (method I: MC)
- $\mu\mu$ channel (method II: data driven)
- ee channel (method II: data driven)

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

NLO prediction from VBFNLO: $\sigma_{NLO}^{EWlljj} = 239$ fb

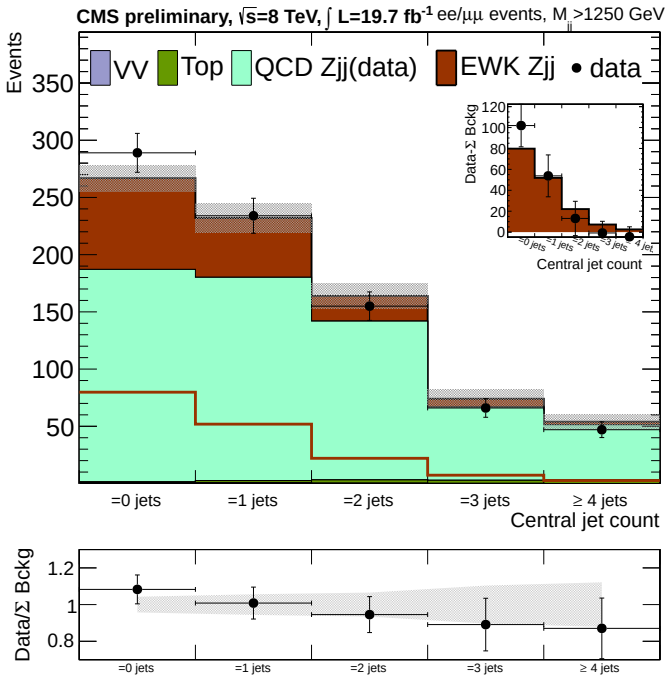
Central hadronic activity

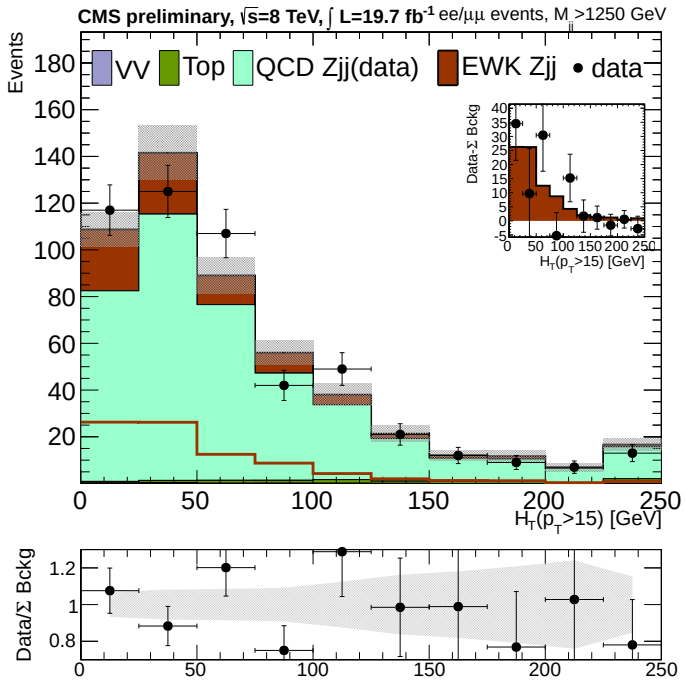




- Use of high-purity tracks associated with the PV, and not associated with the 2 leptons or the 2 jets
- Clustering of these tracks into soft track-jets with anti-k_T algorithm
- Selection of track jets between the 2 tagging jets
  $\Rightarrow \eta_{\text{min}}^{\text{tag.jet}} + 0.5 < \eta < \eta_{\text{max}}^{\text{tag.jet}} - 0.5$
- $H_T(3)$: Scalar sum of 3 leading (p_T-ordered) soft track jets

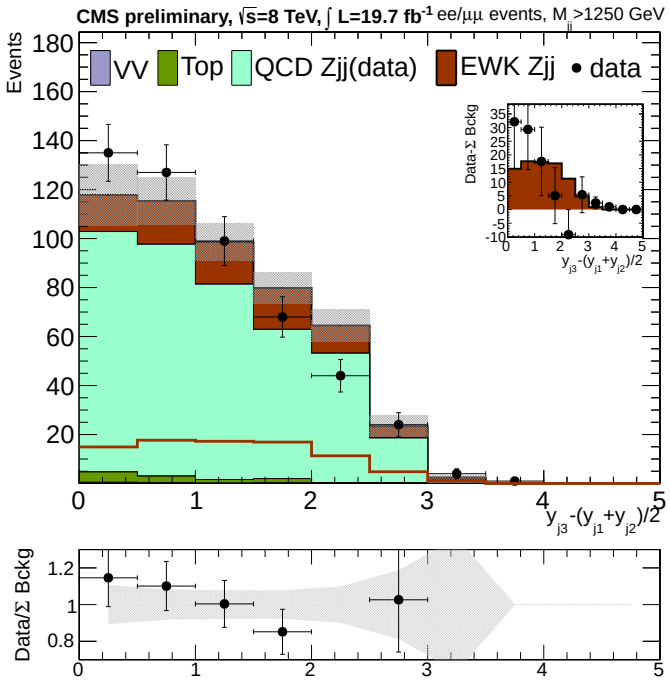
Jets falling in the rapidity distance

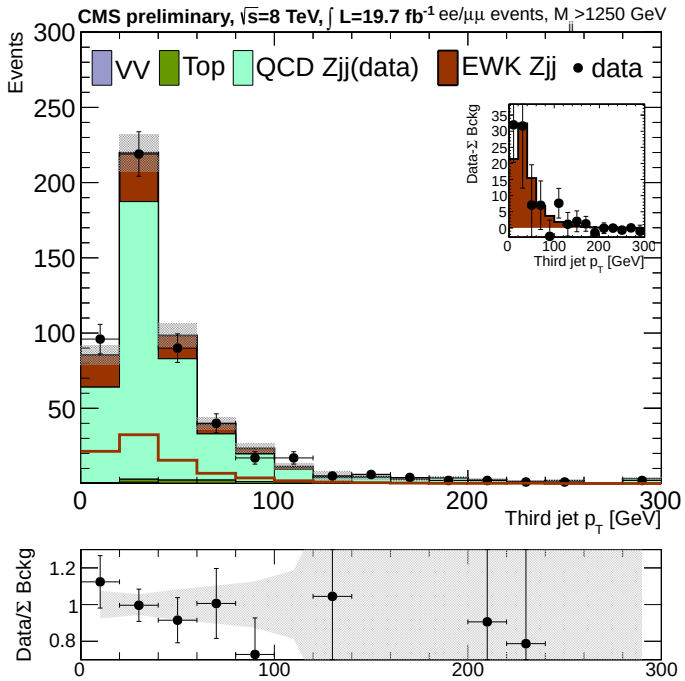




- Use of a relative pure signal region ($M_{jj} > 1250$ GeV)
- Count jets with $p_T > 15$ GeV which fall between the two tagging jets

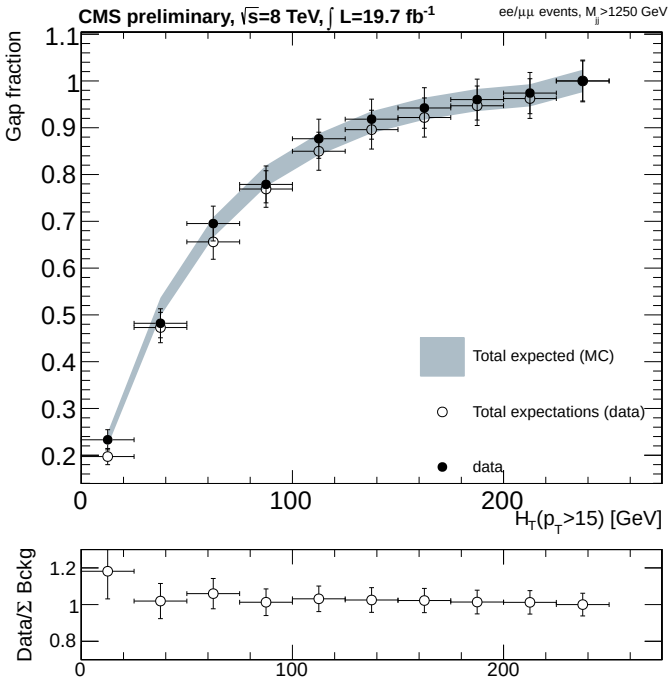
3rd jet kinematics

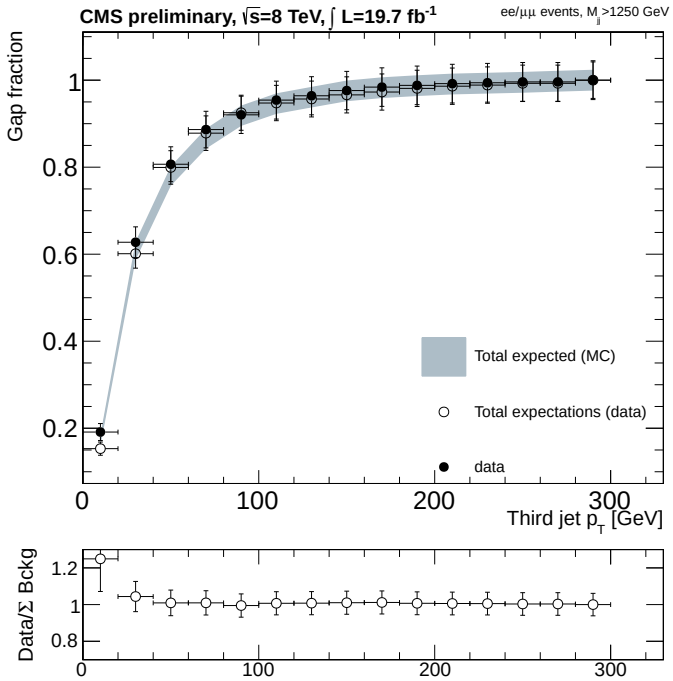




- p_T of 3rd jet is in good agreement with MC prediction
- Small disagreement for Zeppenfeld variable of the 3rd jet: $y^*_{j3} = y_{j3} - \frac{y_{j1}+y_{j2}}{2}$

Gap fraction: hadronic veto efficiencies

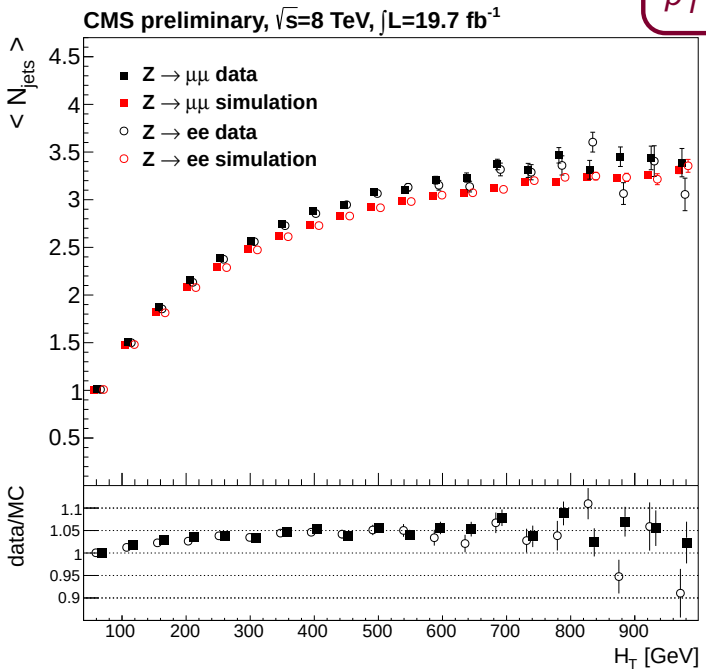


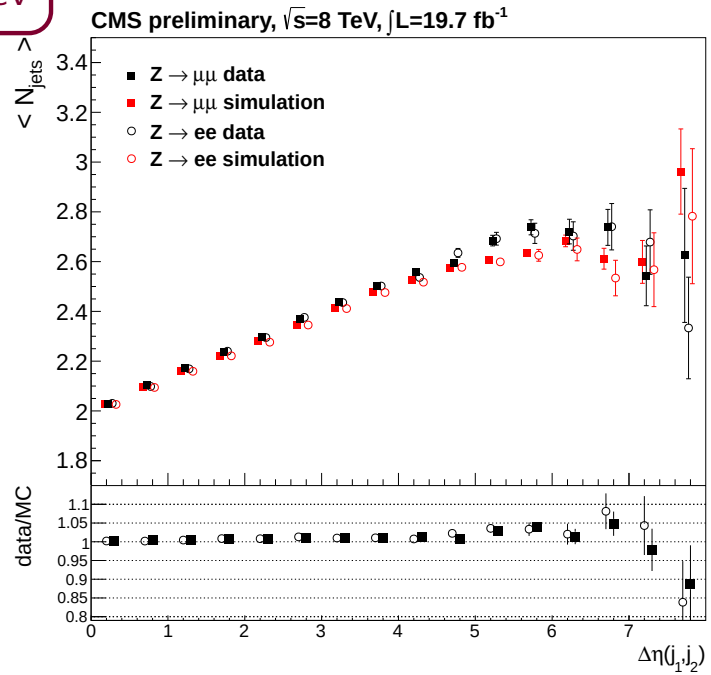


- Compute the central hadronic veto efficiencies using $p_T(j_3)$ or H_T

Radiation patterns in Z+jets events

$p_T(jet) > 40$ GeV





average N_{jets}
vs.
total H_T of jets

average N_{jets}
vs.
$\Delta\eta$ of two leading jets

Data observation is in agreement with `MadGraph + Pythia` (ME+PS) prediction

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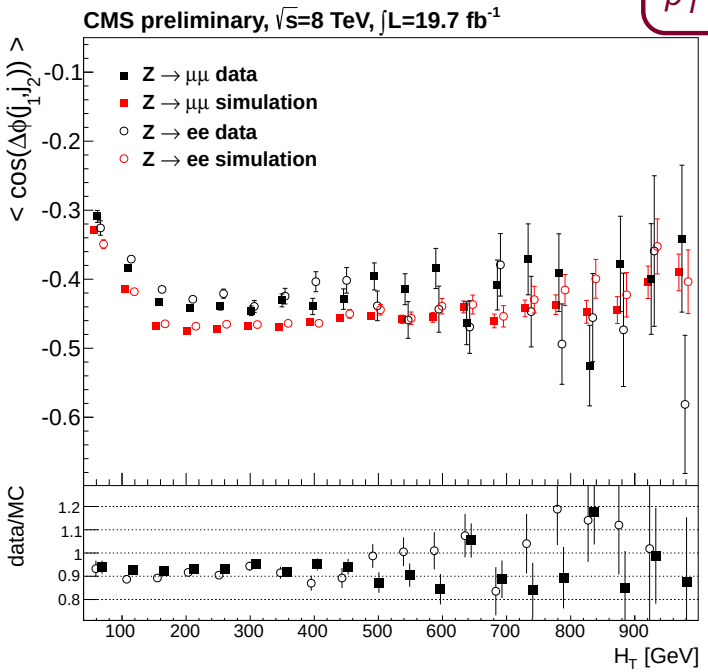
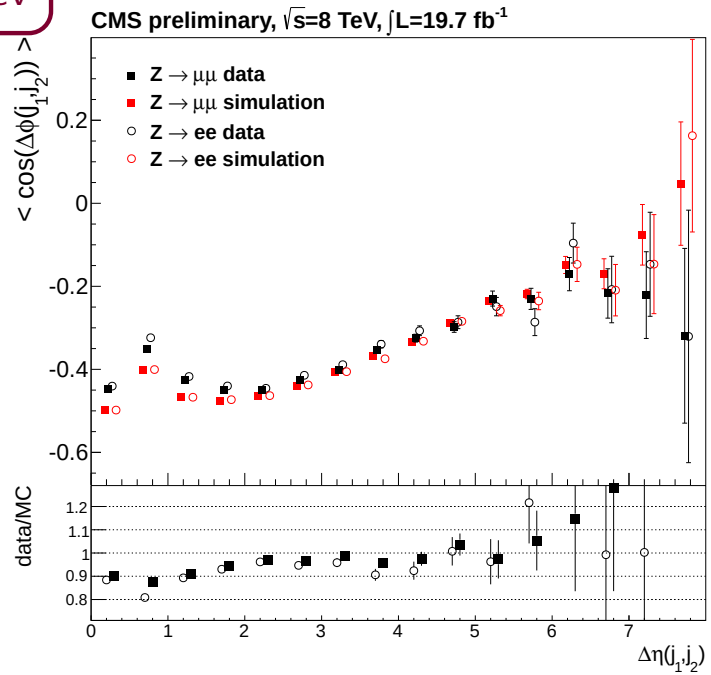




average cos $cos(\Delta\phi_{jj})$ vs. total H_T of jets

average $\cos(\Delta\phi_{jj})$ vs. $\Delta\eta$ of two leading jets

Data observation is in agreement with `MadGraph + Pythia` (ME+PS) prediction

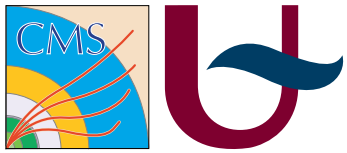
Vector boson + heavy flavour production

Not covered in this talk: V + HF results using 5 fb^{-1} at 7TeV:

- Z/γ^* + b and Z/γ^* + bb cross sections
  (J. High Energy Phys. 06 (2012) 126, CMS PAS SMP-13-004)
- W + bb cross section (CMS PAS SMP-12-026)
- W + c differential cross section (CMS PAS SMP-12-002)
- b hadron correlations in Z + bb (CMS PAS EWK-11-015)

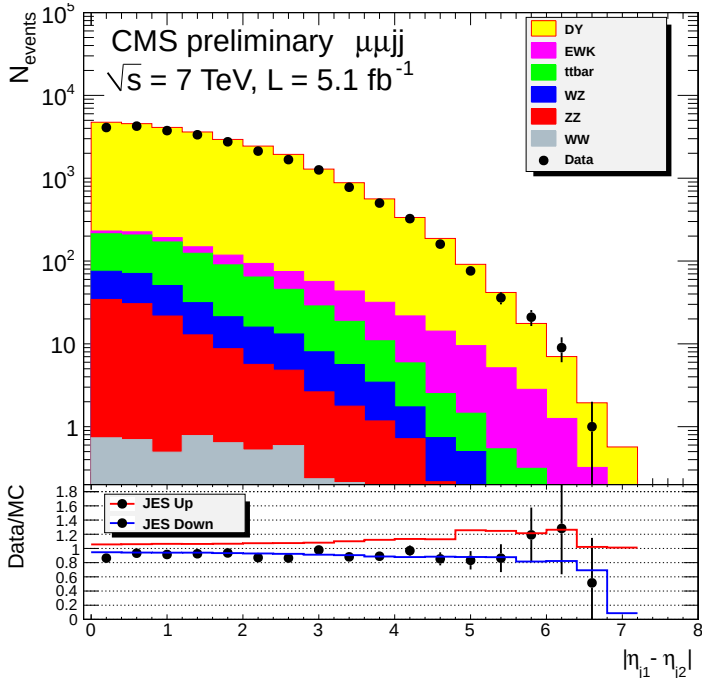
Summary

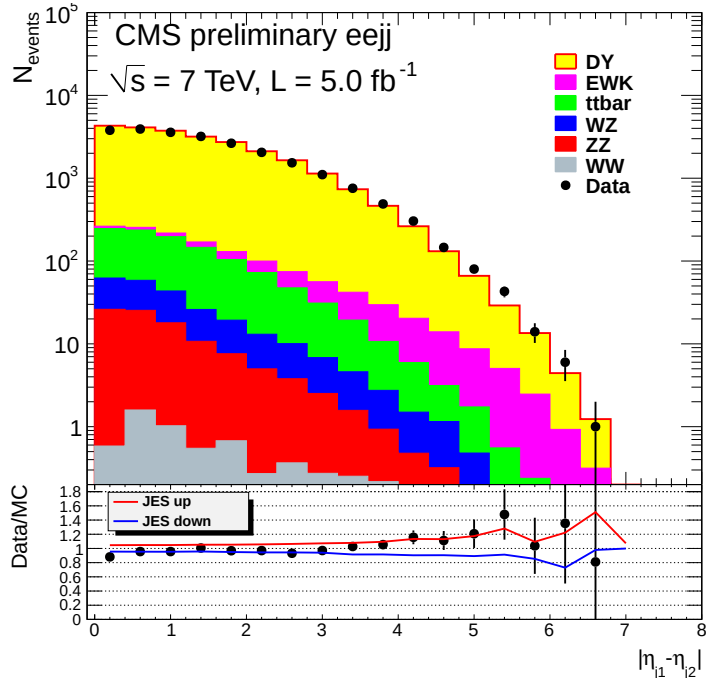
- Azimuthal correlations and event shapes are measured in Z + jet events
- Measurements of the rapidity distributions in Z + 1 jet events
- A first step towards the extraction of double parton scattering in W + 2 jet events is done
- Electroweak production of Z + 2 jets:
  - In addition to the 7 TeV results, very recent results from the **8 TeV** analysis have been shown
  - Cross section measurements in agreement with NLO theory predictions
  - Studies on the hadronic activity, 3rd jet kinematics and radiation patterns
- In general, good agreement between data and simulation
- In the future, more measurements and 8 TeV results will come
- All public results at:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ



Back-up slides

Electroweak production of Z + 2 jets

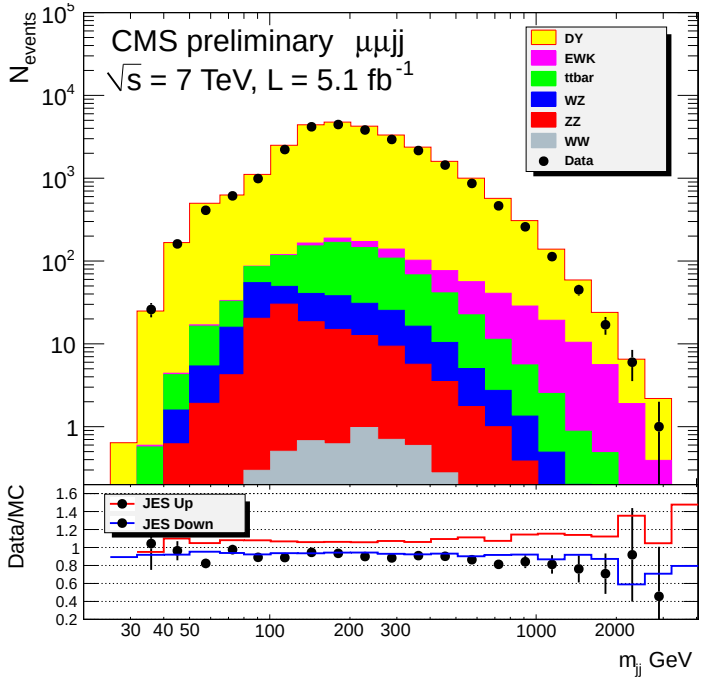


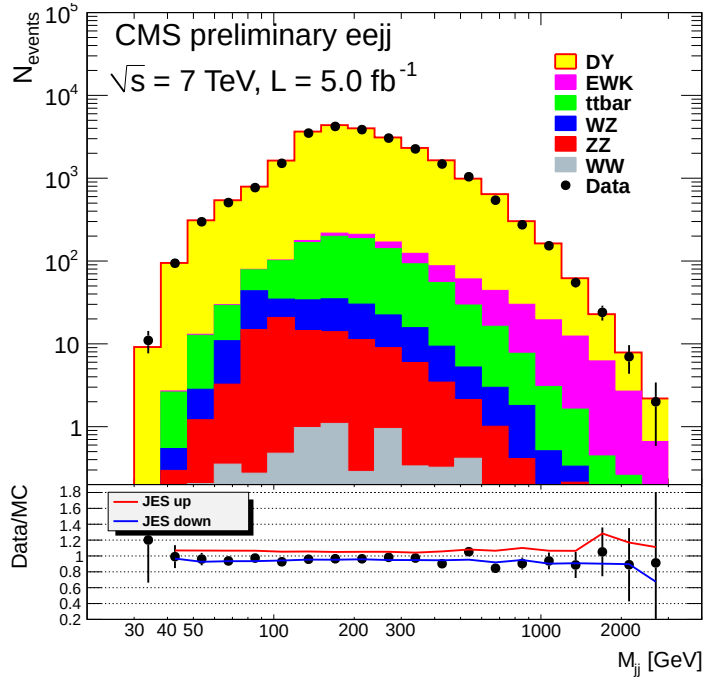


Features of vector boson fusion WW→Z are:

- Central Z decay associated with energetic forward-backward jets
- A large η separation between the jets
- A large invariant dijet mass
- Pure EWK process: no color exchange between the tagging quarks

Electroweak production of Z + 2 jets





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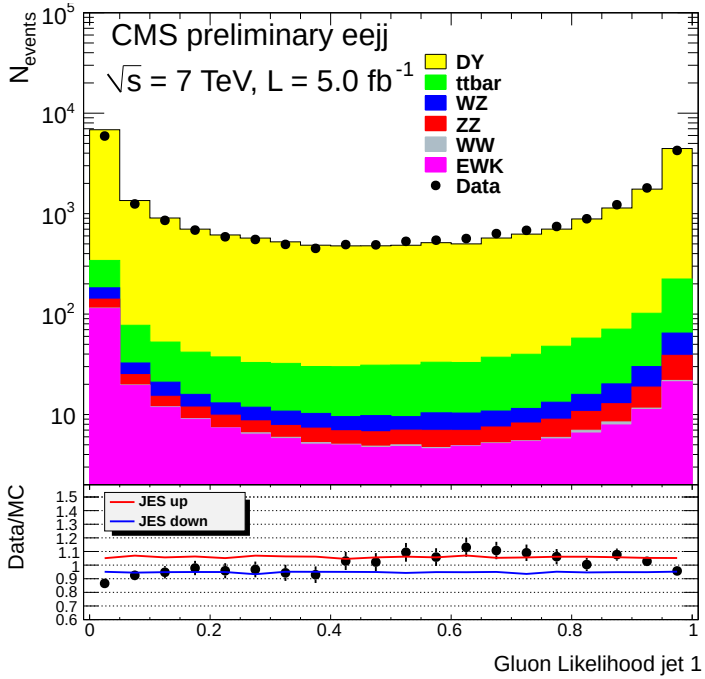
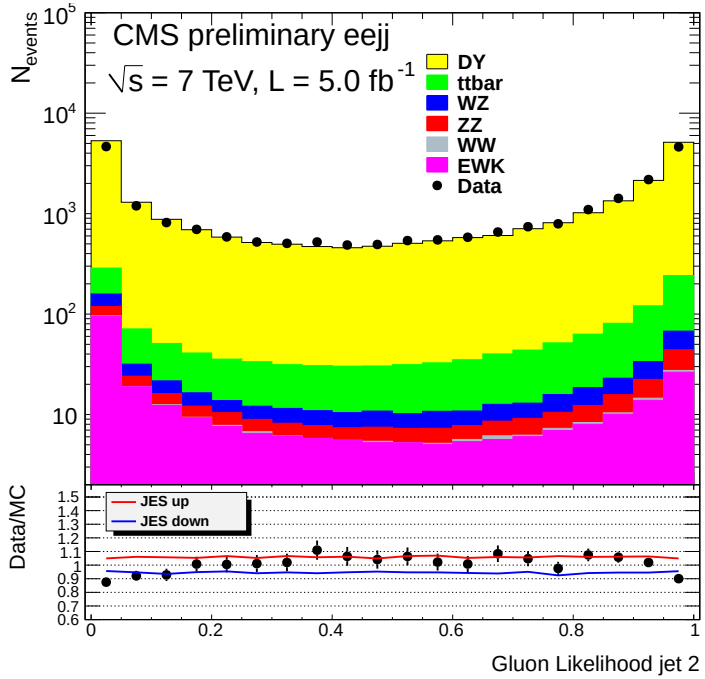
Quark-gluon tagger (*ee*-channel at 7 TeV)



quarks ⟷ gluons



quarks ⟷ gluons

A quark-gluon likelihood, built out of 5 variables (**old version**):

- Major axis of the angular spread (RMS) in the $\eta - \phi$ plane
- Minor axis of the angular spread (RMS) in the $\eta - \phi$ plane
- Asymmetry of the jet constituents with respect to the center of the jet
- Multiplicity of the jet constituents
- Maximum energy fraction carried by a single constituent

Electroweak signal is more quark-like

Method II: use of photon control region

- γ + 2 jet events are selected in a similar way as Z + 2 jet events
- Additional $p_T > 50$ GeV cut in the selection as the low p_T region in the photon sample is affected by multijet production and high trigger prescales
- Reweight photon p_T to match the p_T of the Z boson
- Sample splitted in different M_{jj} categories
- $p_T(\gamma)/p_T(Z)$ is smoothed to dilute statistical fluctuations
- Reweight each photon to describe ee and $\mu\mu$ events seperately
- Electroweak γ + 2 jet contribution is substracted from the shape prediction
- Closure tests show good agreement

Bibliography

- CMS Collaboration, "Azimuthal Correlations and Event Shapes Distributions in Z+jets Production" , CMS PAS EWK-11-021
- CMS Collaboration, "Rapidity distributions in exclusive Z + jet and γ + jet events in pp collisions at $\sqrt{s} = 7$ TeV" , CMS PAS SMP-12-004
- CMS Collaboration, "Study of observables sensitive to double parton scattering in W + 2 jets process in p-p collisions at $\sqrt{s} = 7$ TeV" , CMS PAS FSQ-12-028
- CMS Collaboration, "Measurement of the electroweak production cross section of the Z boson with two forward-backward jets in pp collisions at $\sqrt{s} = 7$ TeV" , CMS PAS FSQ-12-019
- CMS Collaboration, "Measurement of the electroweak production cross section of the Z boson with two forward-backward jets in pp collisions at $\sqrt{s} = 8$ TeV" , CMS PAS FSQ-12-035