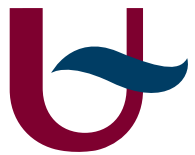
Jet physics and vector boson plus jet physics at CMS

Tom Cornelis



Universiteit Antwerpen

International workshop on discovery physics at the LHC, Kruger 2012

Outline

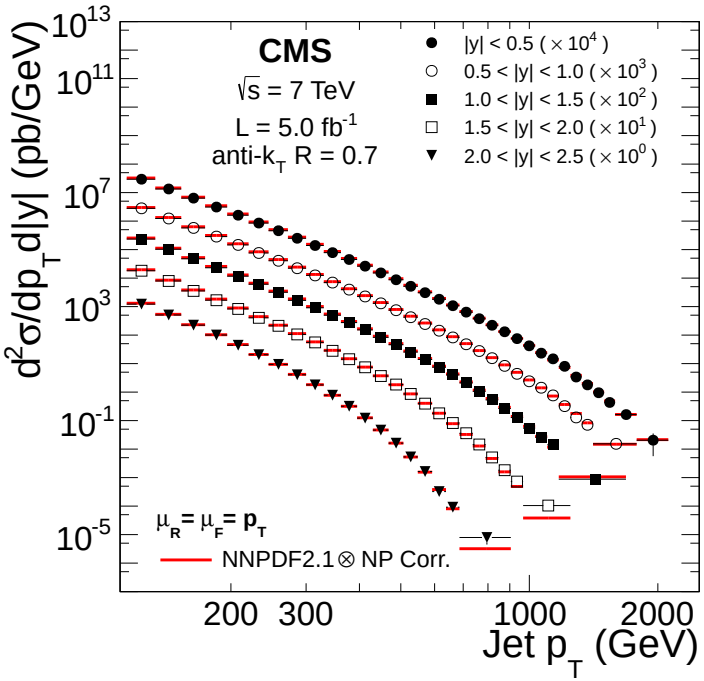
- Measurement of differential jet cross section
- Jet mass in dijet and W/Z+jet events
- Jet production in association with vector bosons
- Azimuthal correlations & event shapes in Z+jets
- EWK production of Z+jets

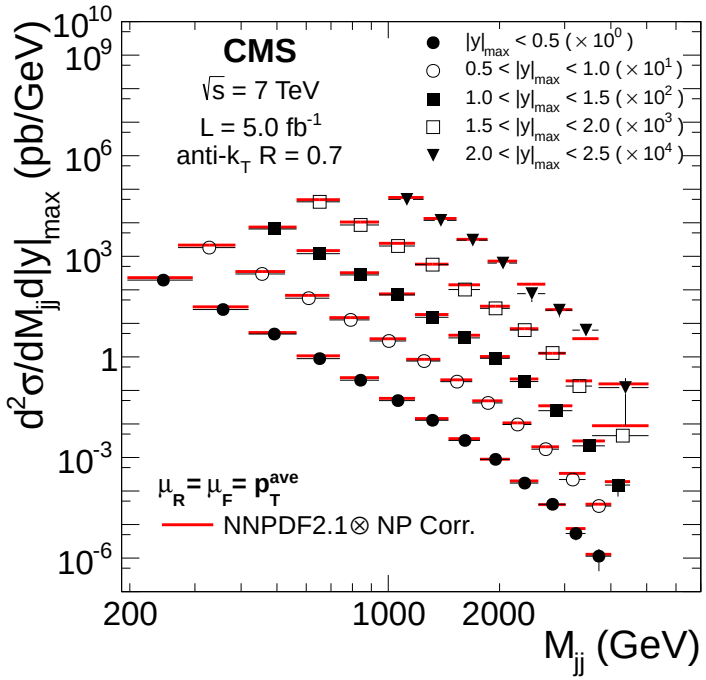
Measurement of differential jet cross section

- Analysis done with 2011 CMS data at $\sqrt{s} = 7$ TeV
- 4.67 fb^{-1}
- anti-k_T clustering algorithm with size parameter $R = 0.7$
- extending to rapidity $| y | < 2.5$

- Measurement of the double-differential inclusive jet cross section with 0.1 TeV $< p_T(\text{jet}) <$ 2 TeV
- Measurement of the double-differential dijet cross section with 0.3 TeV $< M_{jj} <$ 5 TeV

Measurement of differential jet cross section



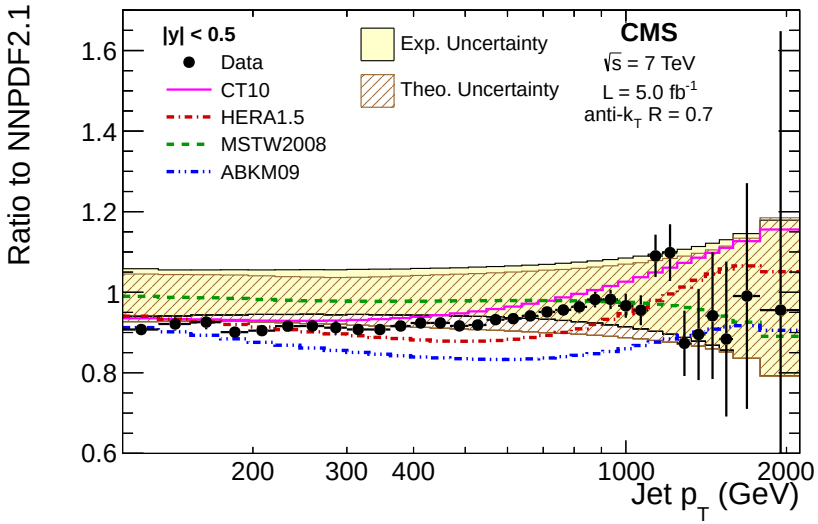


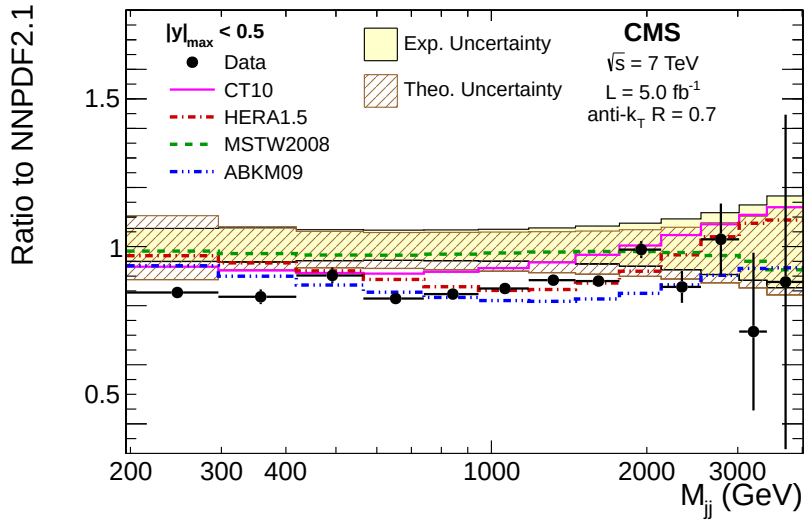
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_T\,\mathrm{d}|y|} = \frac{1}{\epsilon\mathcal{L}_{\mathrm{eff}}}\frac{N_{\mathrm{jets}}}{\Delta p_T \Delta|y|}$$

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}M_{\mathrm{jj}}\,\mathrm{d}|y|_{\mathrm{max}}} = \frac{1}{\epsilon\mathcal{L}_{\mathrm{eff}}}\frac{N}{\Delta M_{\mathrm{jj}} \Delta|y|_{\mathrm{max}}}$$

$\Rightarrow$ Good agreement between pQCD@NLO and data

Ratio of the cross sections to the NNPDF2.1 set:

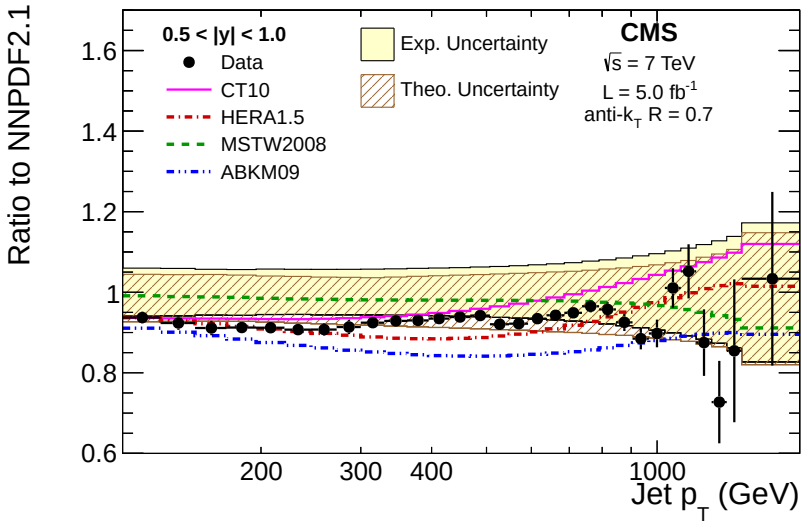


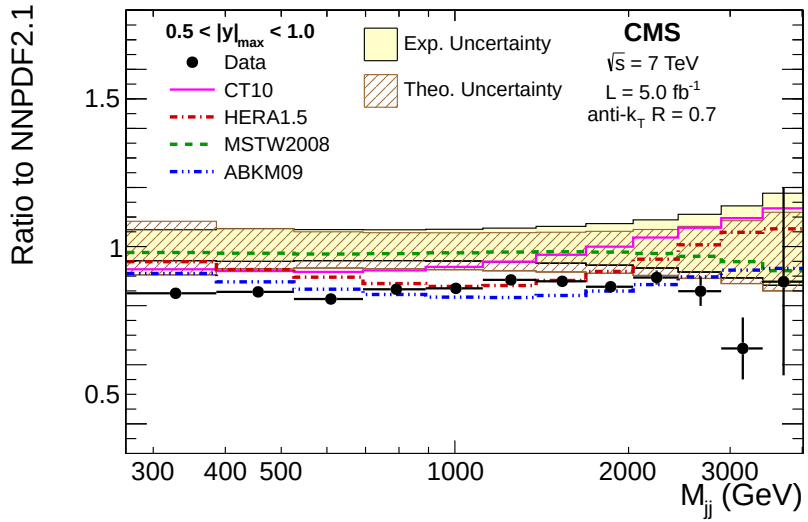


$0 <| y |< 0.5$

- Within errors all PDF agree with our measurements
- Theoretical and experimental uncertainties are comparable

Ratio of the cross sections to the NNPDF2.1 set:

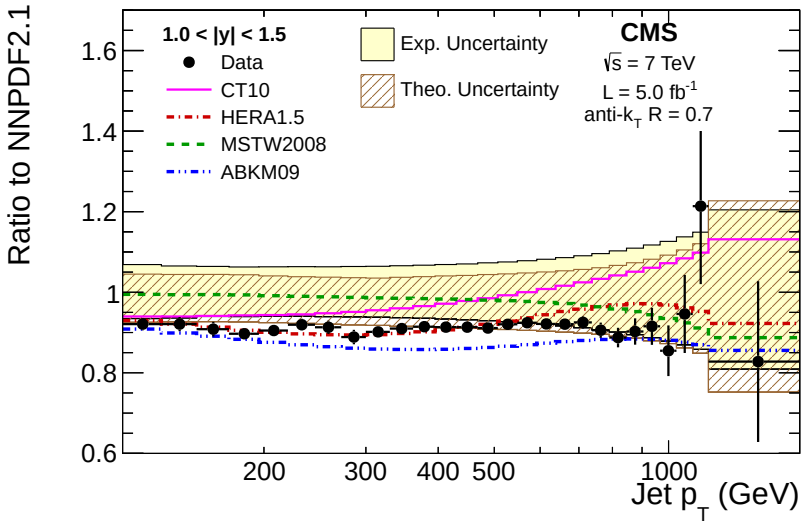


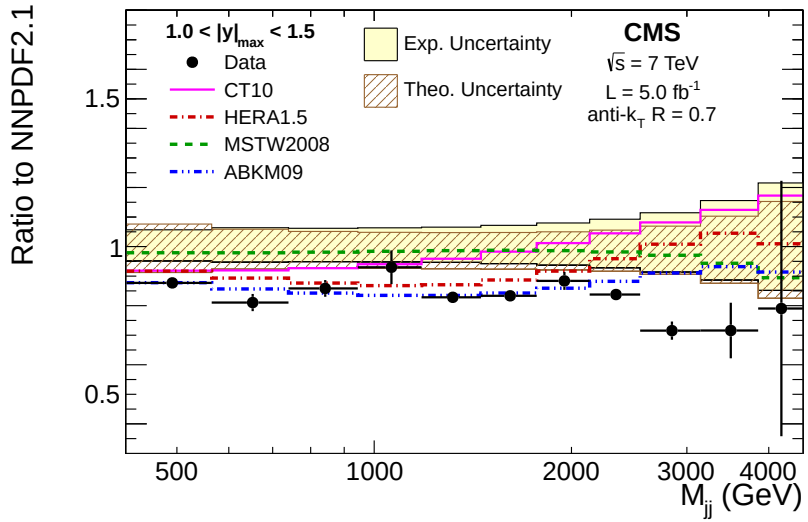


$0.5 <| y |< 1$

- Within errors all PDF agree with our measurements
- Theoretical and experimental uncertainties are comparable

Ratio of the cross sections to the NNPDF2.1 set:

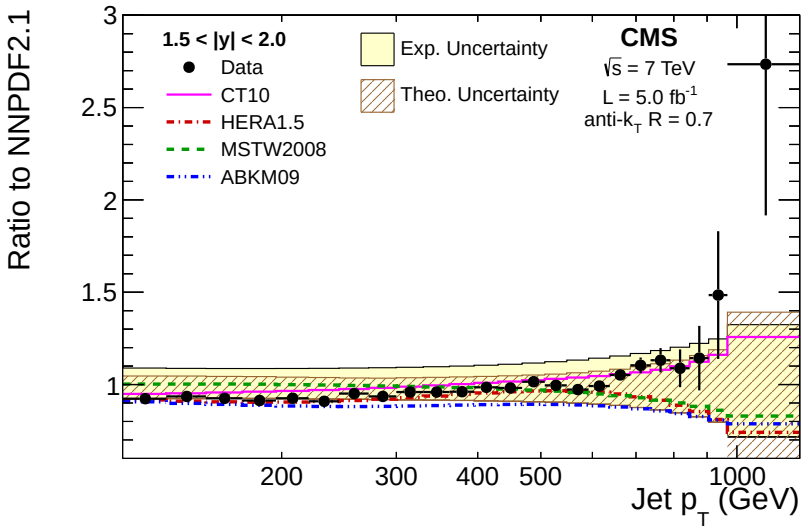


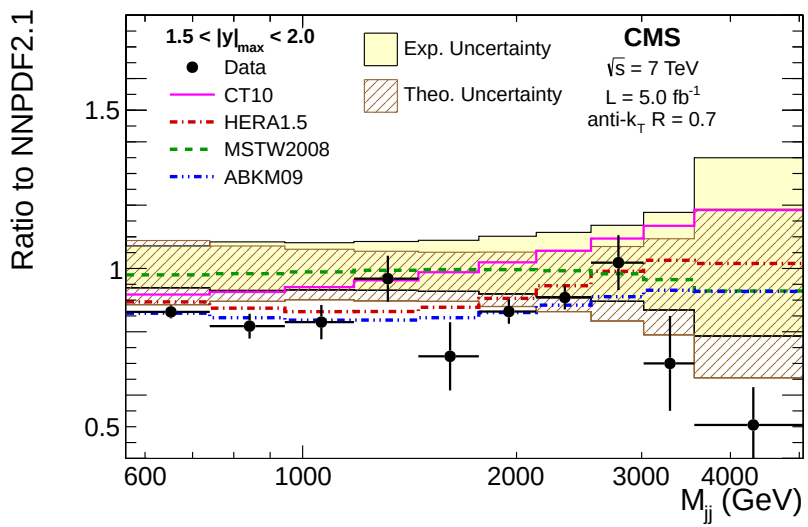


$1 <| y |< 1.5$

- Within errors all PDF agree with our measurements
- Theoretical and experimental uncertainties are comparable

Ratio of the cross sections to the NNPDF2.1 set:

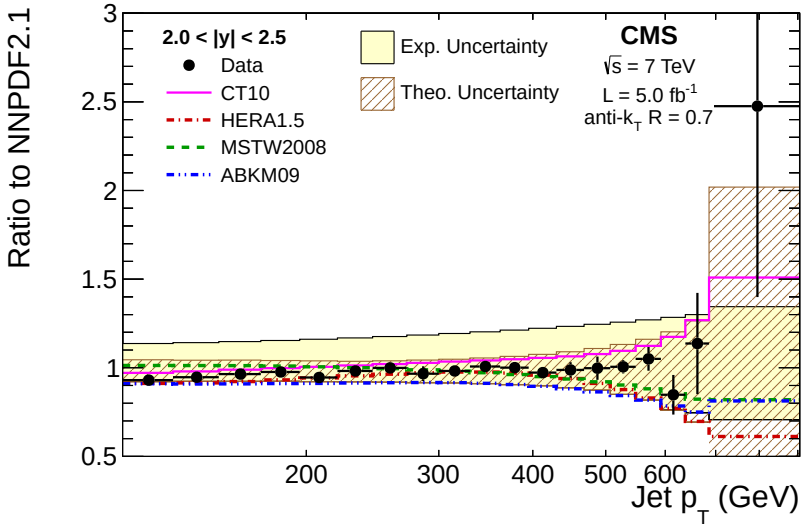


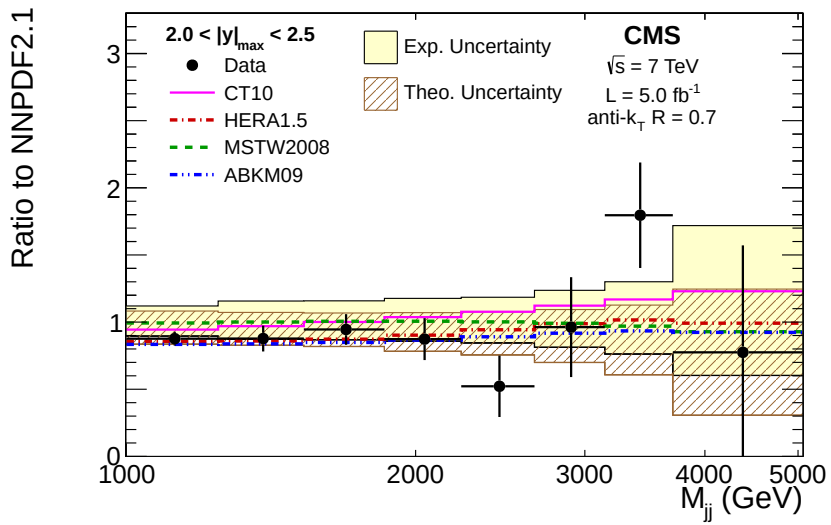


$1.5 <| y |< 2$

- Within errors all PDF agree with our measurements
- Theoretical and experimental uncertainties are comparable

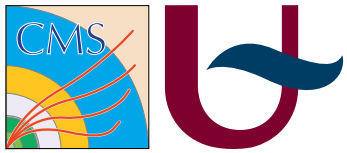
Ratio of the cross sections to the NNPDF2.1 set:





$2 <| y |< 2.5$

- Within errors all PDF agree with our measurements
- Theoretical and experimental uncertainties are comparable

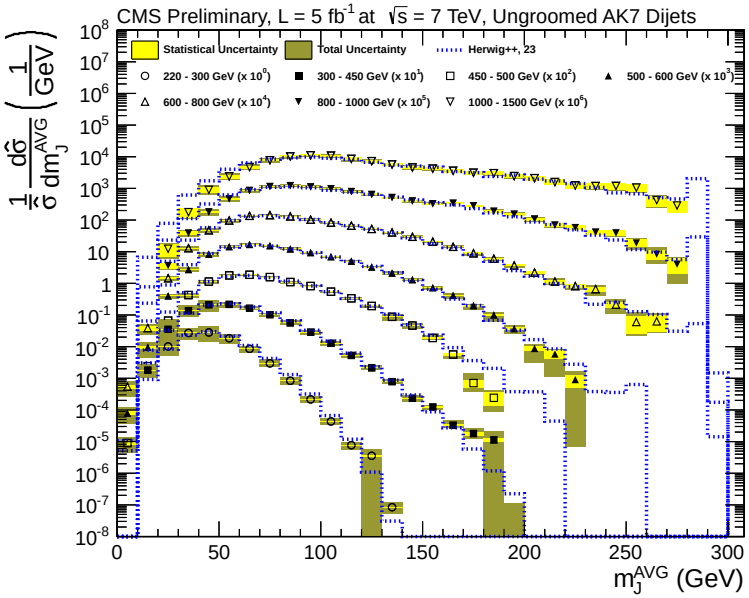


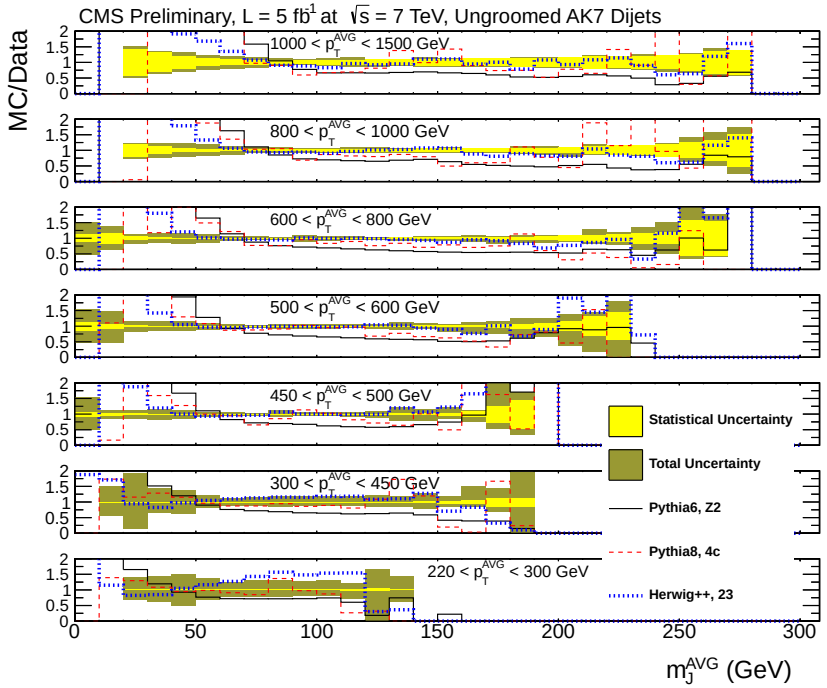
Jet mass in dijet and W/Z+jet events

- Analysis done with 2011 CMS data at $\sqrt{s} = 7$ TeV
- 5 fb^{-1}
- anti-k_T clustering algorithm with size parameter $R = 0.7$
- extending to rapidity $| y | < 2.5$

- Measurement of the jet mass in dijet events
- Measurement of the jet mass in W+jet events
- Measurement of the jet mass in Z+jet events

Jet mass in dijet events

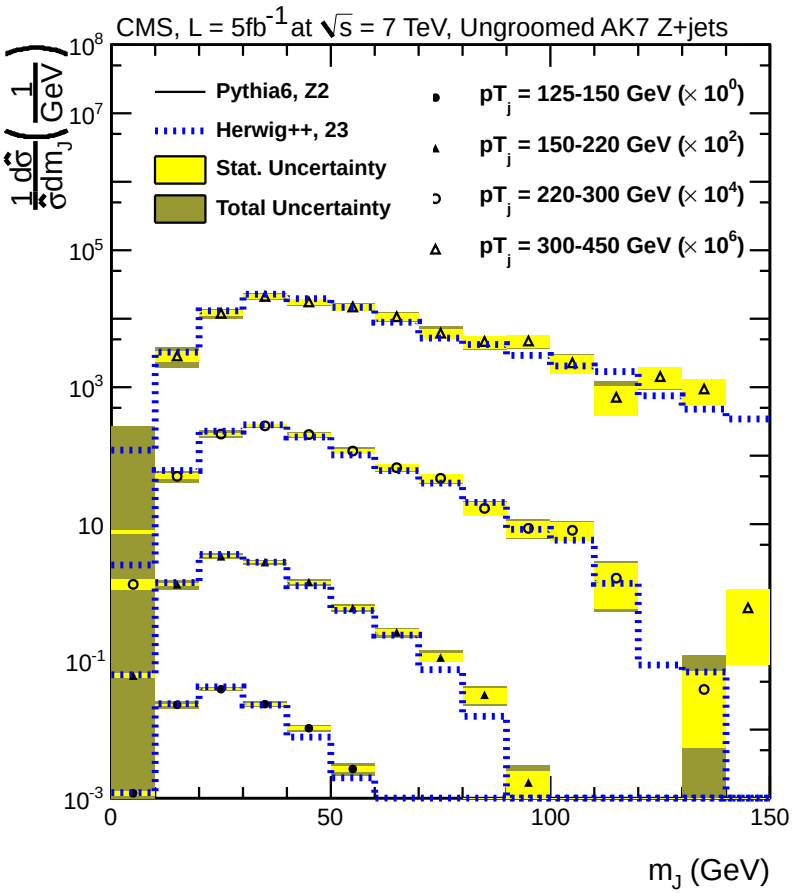


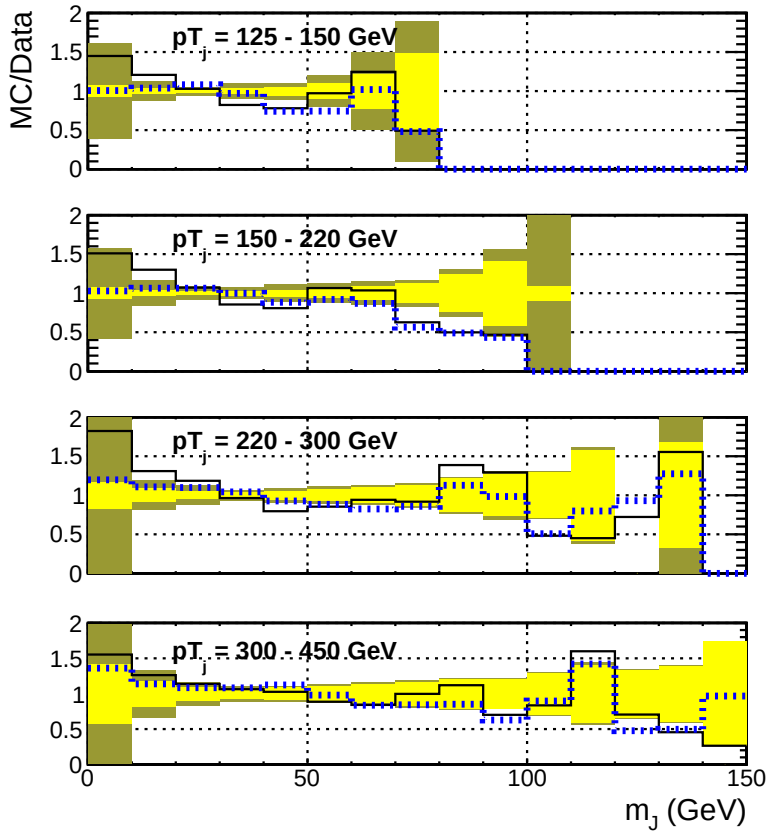


$$p_T^{AVG} = \frac{(p_{T_1} + p_{T_2})}{2} \quad m_J^{AVG} = \frac{(m_{J_1} + m_{J_2})}{2}$$

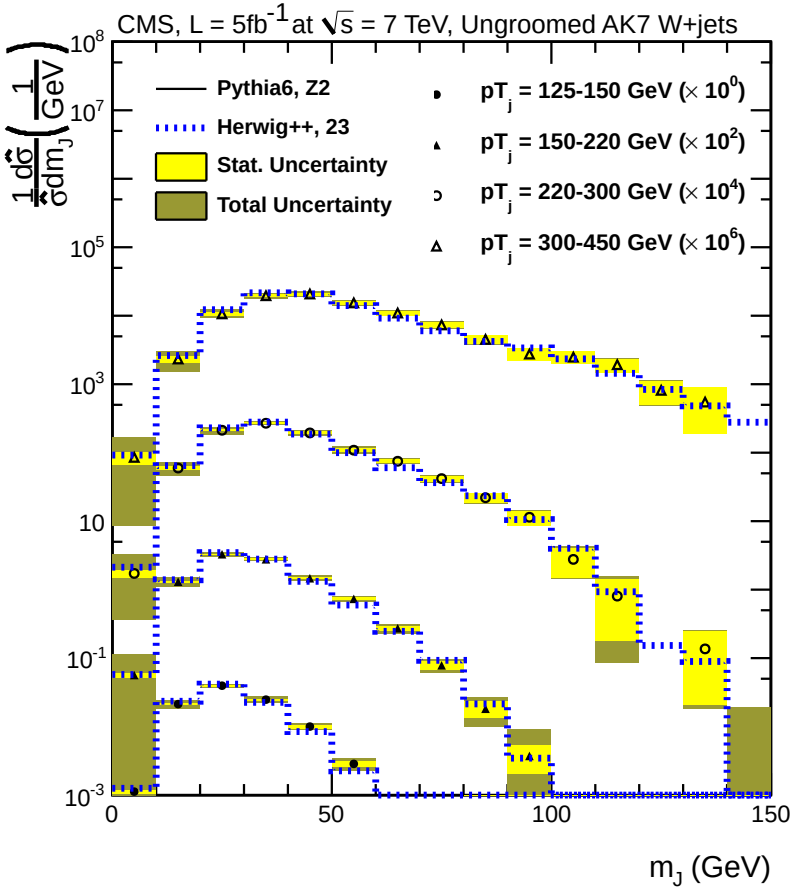
- Best agreement with Herwig++ parton shower model
- Disagreement largest at very low jet masses → most sensitive region to UE/PU, MC underestimates showering

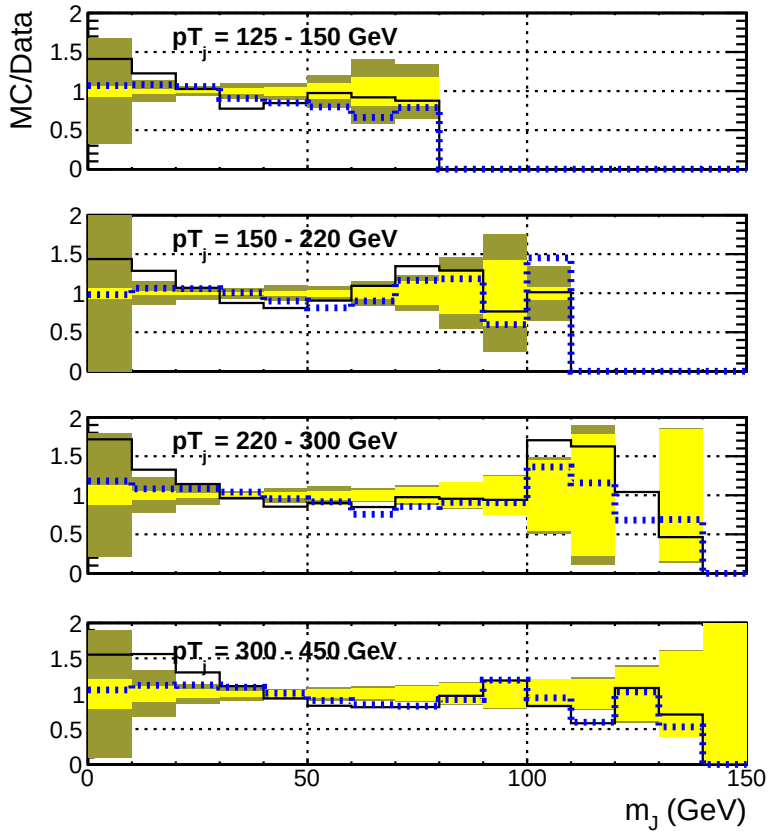
Jet mass in Z+jet events





Jet mass in W+jet events



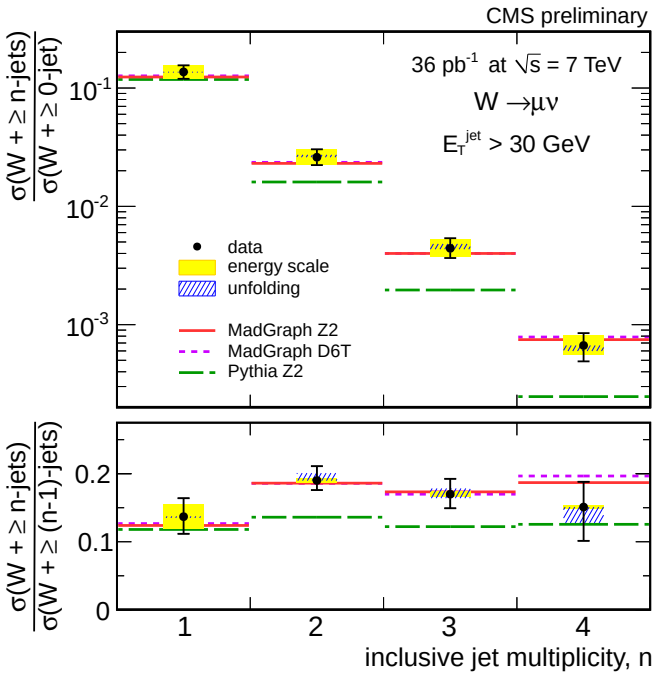


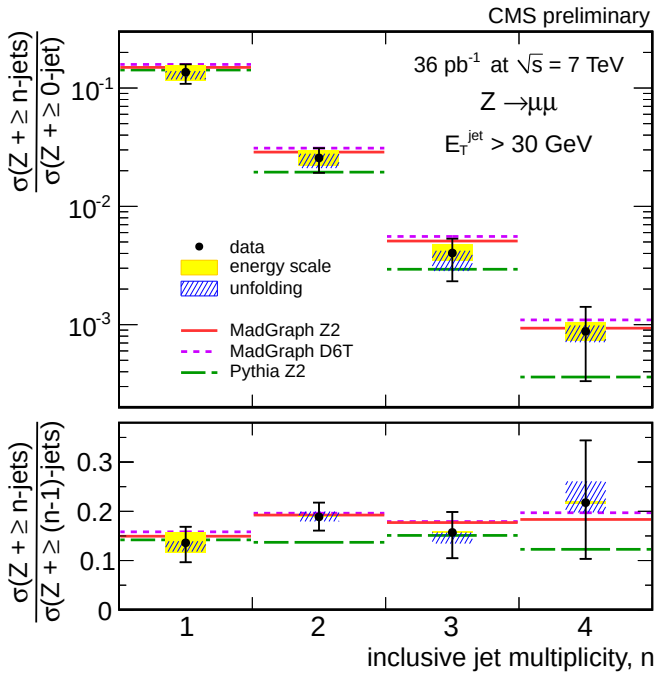
Jet production in association with vector bosons

- Analysis done with 2010 CMS data at $\sqrt{s} = 7$ TeV
- 36 pb^{-1}
- $p_T(\text{jet}) > 30$ GeV

- Measurements of $\sigma(V+ \geq n \text{ jets})/\sigma(V)$
- Measurements of $\sigma(V+ \geq n \text{ jets})/\sigma(V+ \geq (n-1) \text{ jets})$
- Test of the Berends-Giele scaling
- Measurements of $\sigma(W+ \geq n \text{ jets})/\sigma(Z+ \geq n \text{ jets})$
- Measurement of the W charge asymmetry A_W

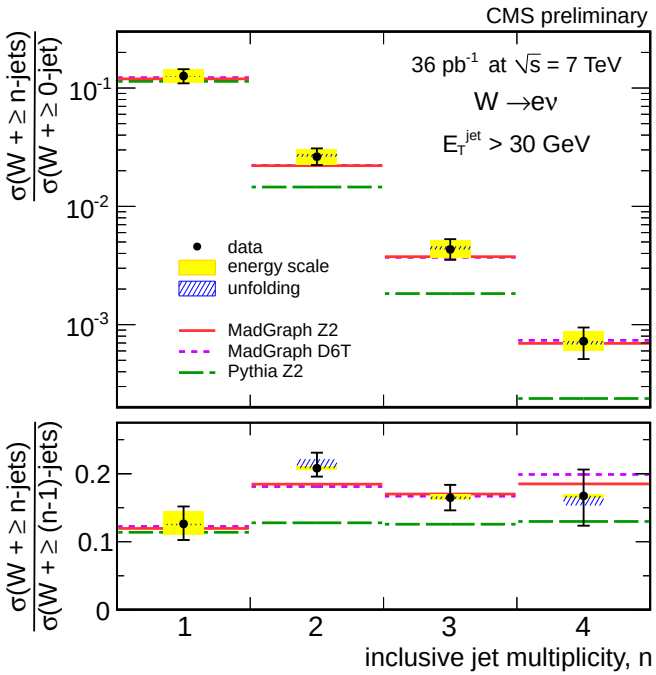
$\sigma(V+ \geq n \text{ jets})/\sigma(V+ \geq 0\text{jets})$

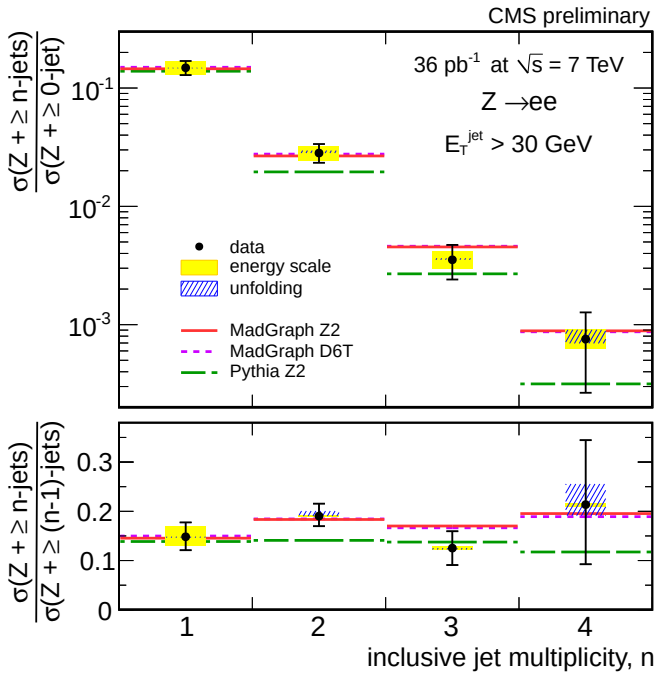




- MadGraph simulation agrees well with the data

$\sigma(V+ \geq n \text{ jets})/\sigma(V+ \geq 0\text{jets})$

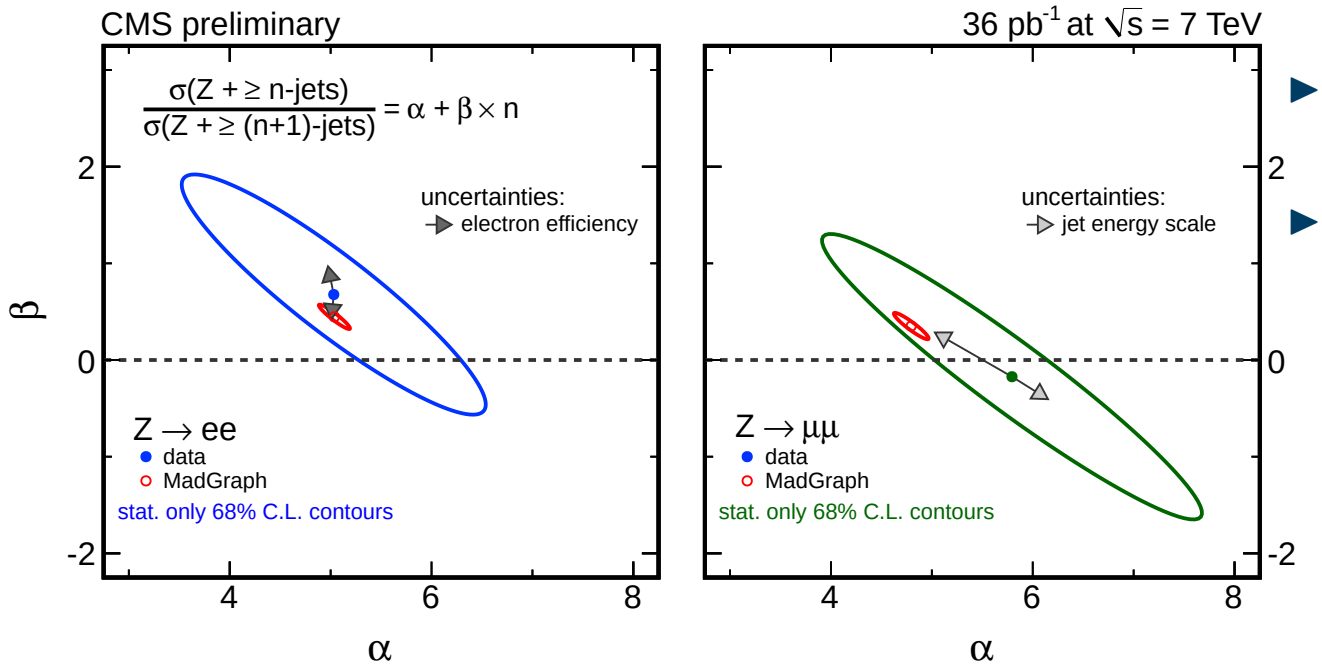




- MadGraph simulation agrees well with the data

Berends-Giele scaling

- Test the constant scaling law $\frac{\sigma(V+\geq n \text{ jets})}{\sigma(V+\geq (n+1) \text{ jets})} = \alpha$
- Additional parameter β for possible deviation



- Good agreement between MadGraph and data
- β compatible with 0

Berends-Giele scaling

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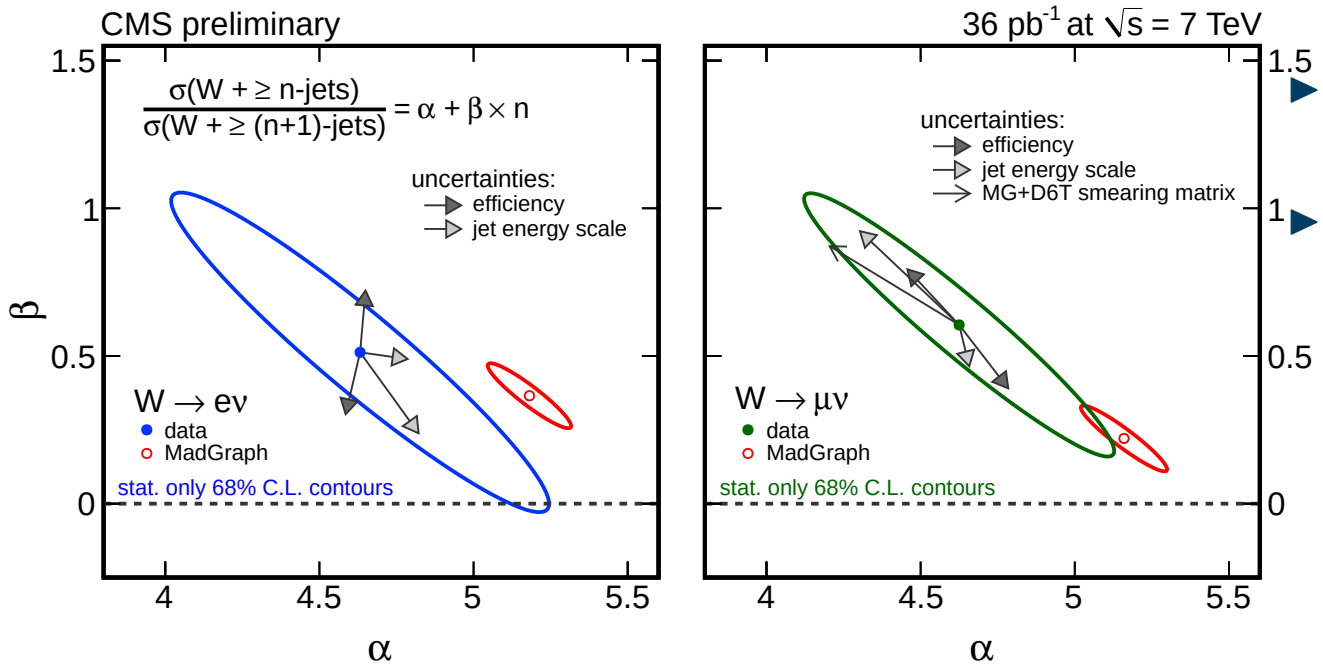
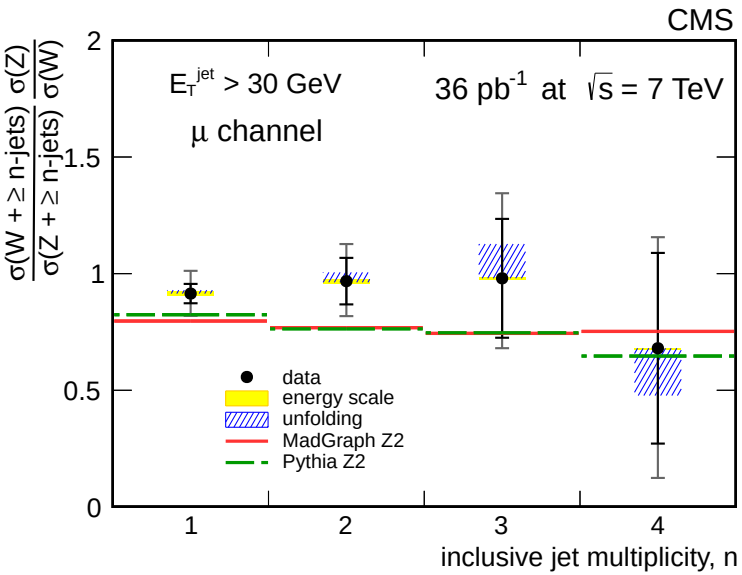
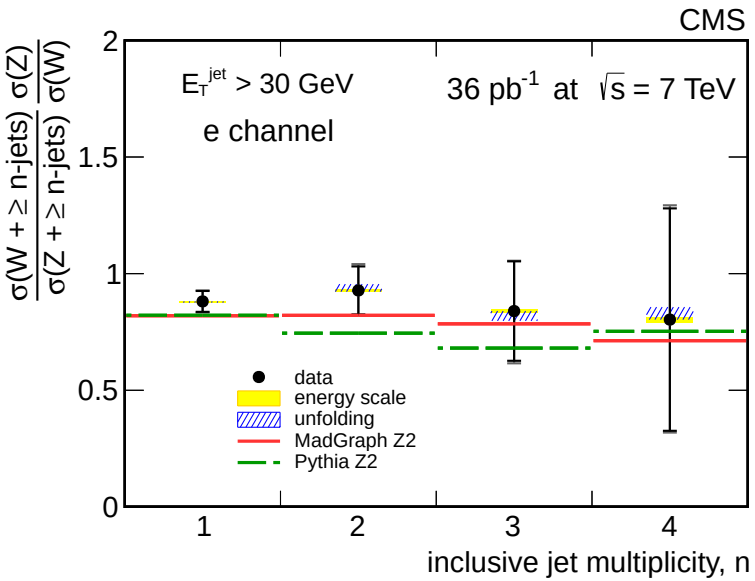


- Good agreement between MadGraph and data
- β compatible with 0

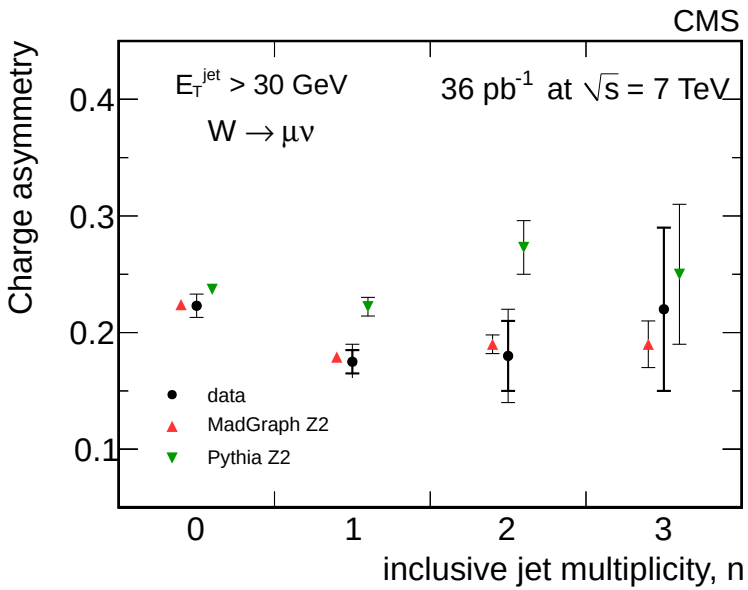
$\sigma(W+ \geq n \text{ jets})/\sigma(Z+ \geq n \text{ jets})$

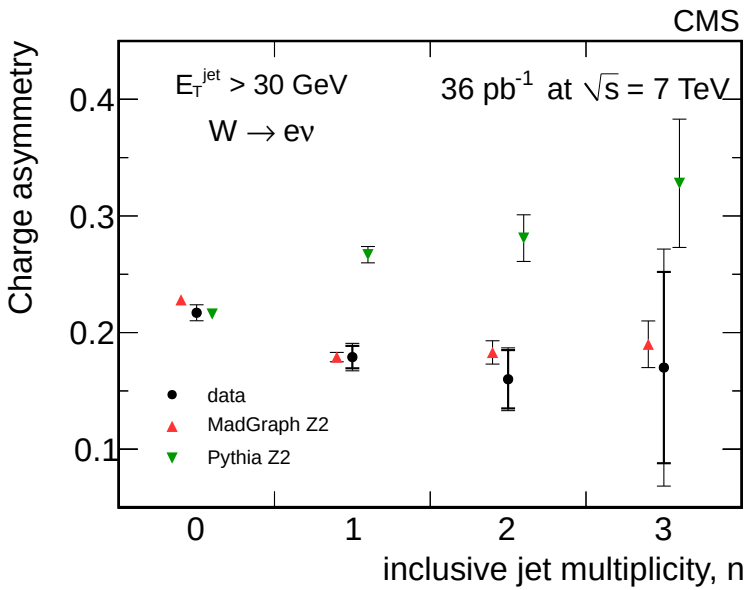




- Many important systematics cancel in the ratio
- The maximal difference between expected and measured values is at the level of one standard deviation

W charge asymmetry





$$A_W = \frac{\sigma(W^+) - \sigma(W^-)}{\sigma(W^+) + \sigma(W^-)}$$

- A_W depends on the number of associated jets because the fraction of u/d quarks contributing to the process is different in each case

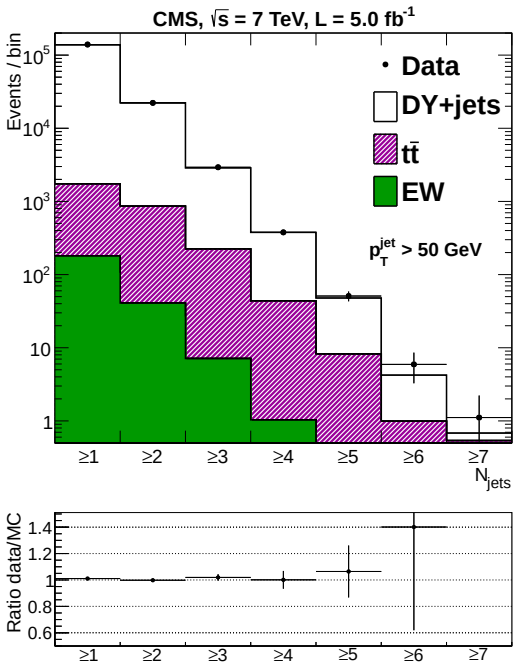
Azimuthal correlations & event shapes in Z+jets

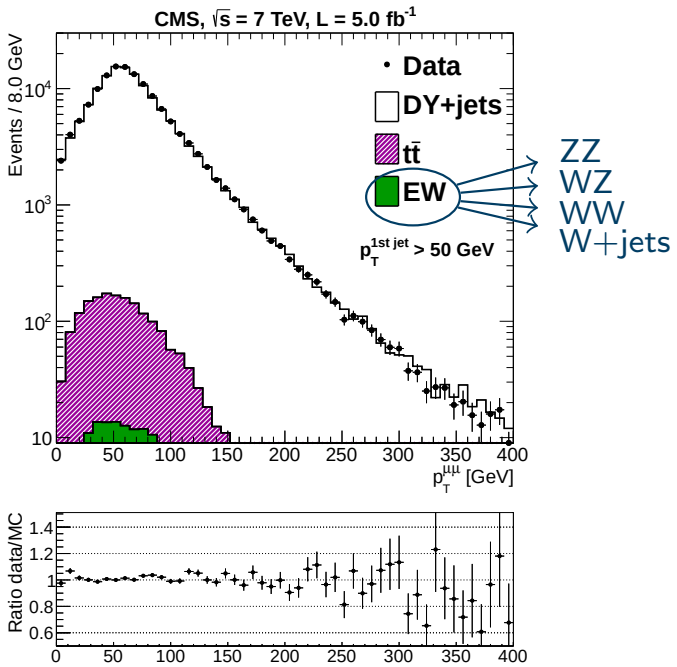
- Analysis done with 2011 CMS data at $\sqrt{s} = 7$ TeV
- 5 fb^{-1}
- $p_T(\text{jet}) > 50$ GeV

Measurements of

- $\Delta\Phi(Z, J_1)$
- $\Delta\Phi(J_i, J_k)$
- Transverse thrust

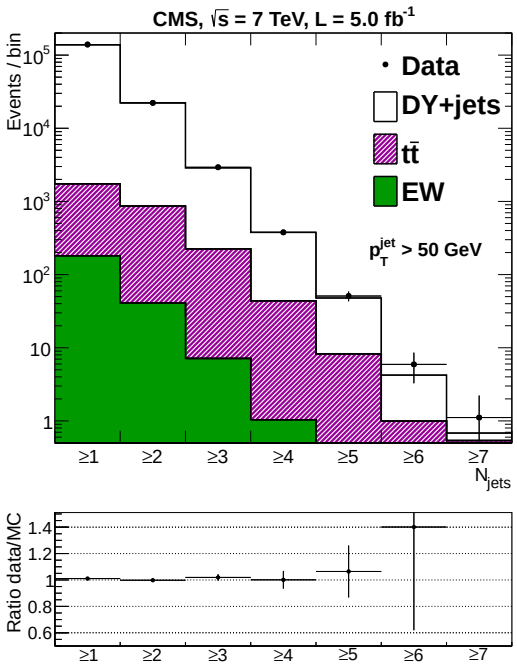
Azimuthal correlations & event shapes in Z+jets

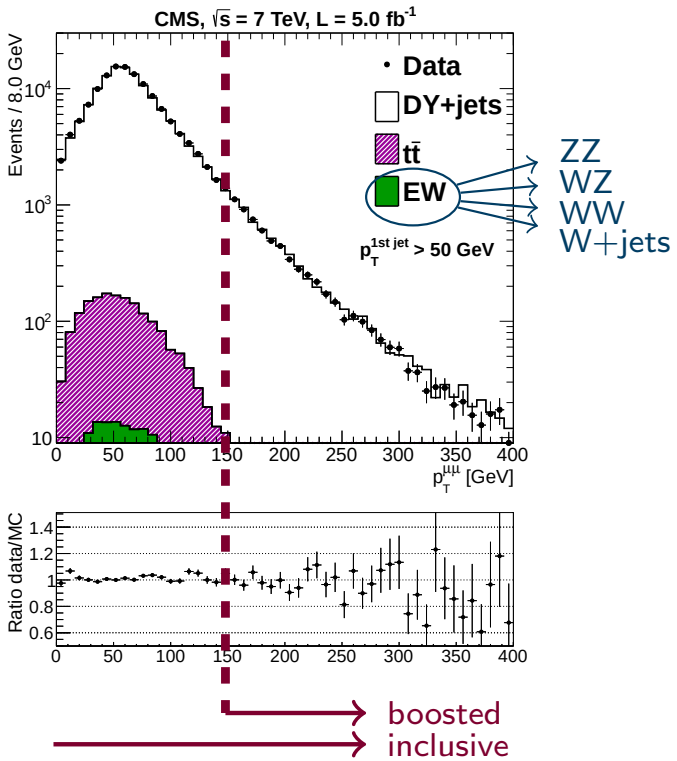




- $p_T(j) > 50$ GeV
- $|\eta(j)| < 2.5$

Azimuthal correlations & event shapes in Z+jets

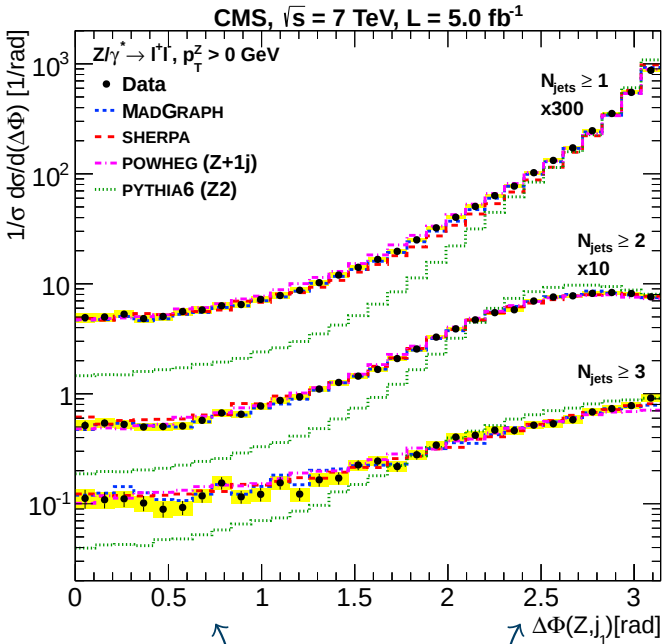


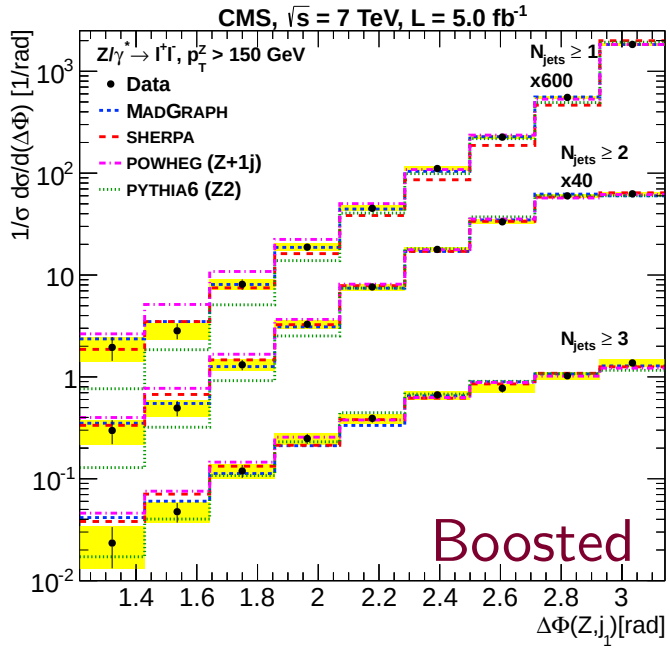


- $p_T(j) > 50$ GeV
- $|\eta(j)| < 2.5$
- Both inclusively and in a boosted regime: $p_T(Z) > 150$ GeV
  $\rightarrow$ Phase space which is very critical for new phenomena

$\Delta\Phi(Z, J_1)$

Azimuthal angles between the Z boson and the leading jet:



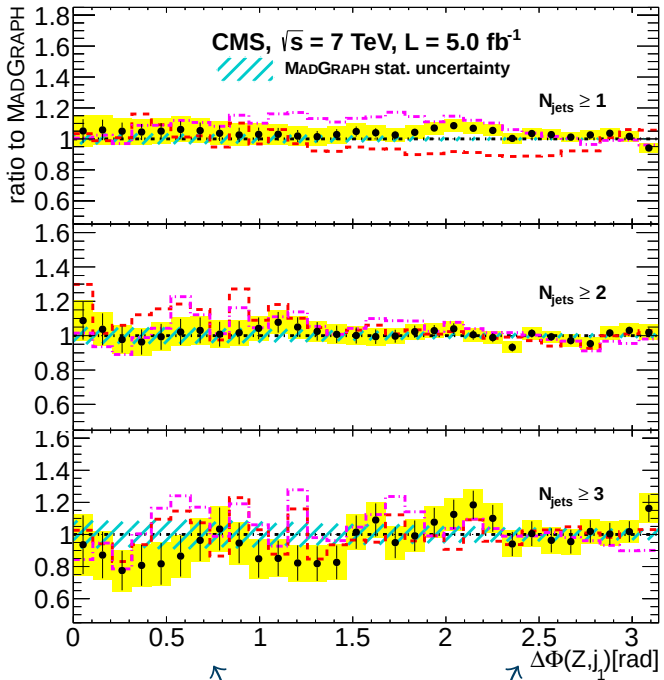


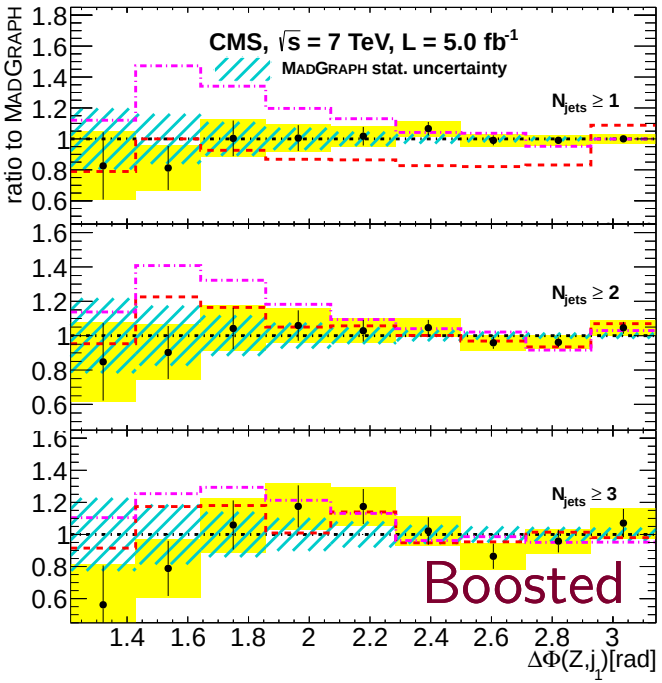
Measurement is in good agreement with MadGraph prediction

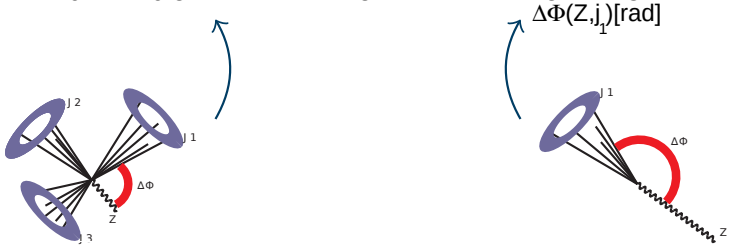
Error bars: statistical uncertainties
Yellow band: sum of statistical and systematic uncertainties

$\Delta\Phi(Z, J_1)$

Azimuthal angles between the Z boson and the leading jet:







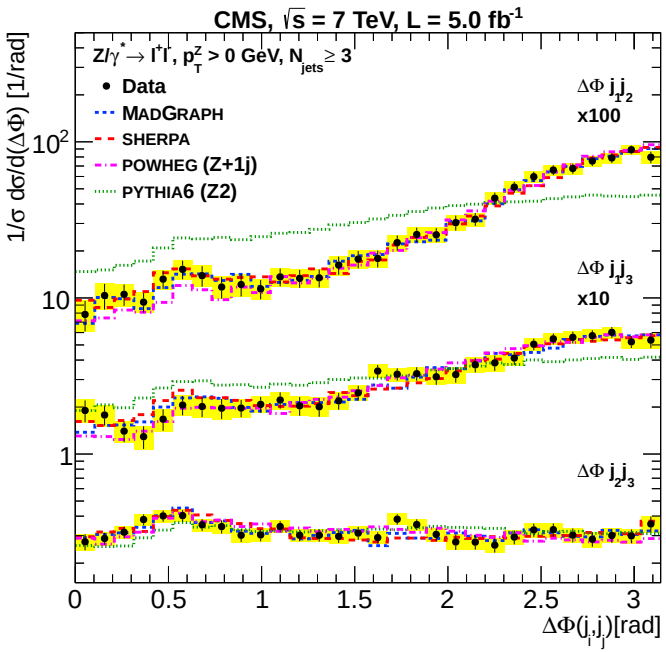
Error bars: statistical uncertainties
Yellow band: sum of statistical and systematic uncertainties

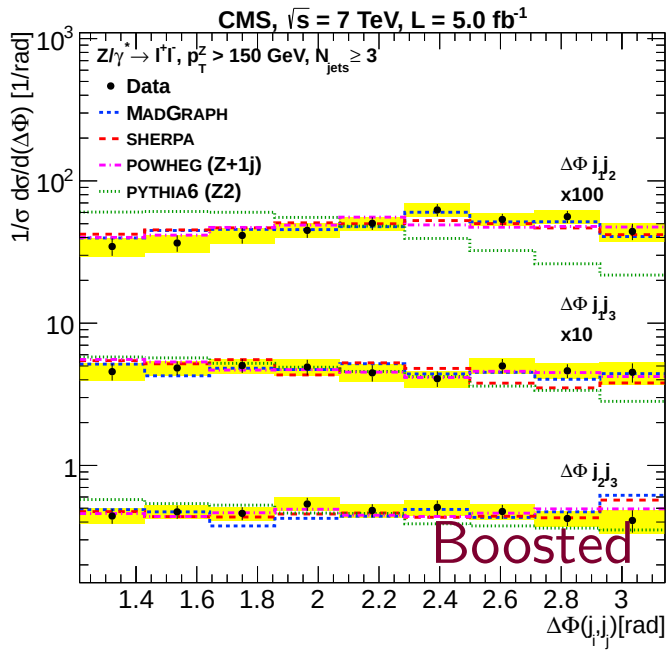
For $N_{\text{jets}} \geq 1$:

- SHERPA undershoots 10%
- POWHEG overshoots 10%

$\Delta\Phi(J_i, J_k)$

Azimuthal angles among the three leading jets:

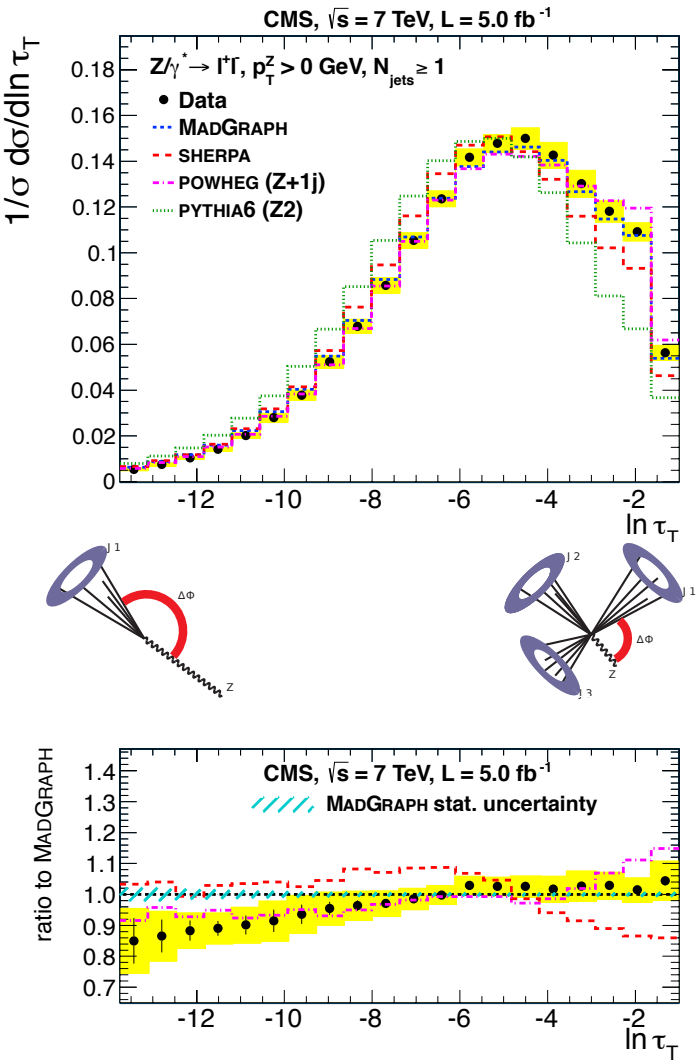




Angles between the jets decorrelate in boosted regime

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

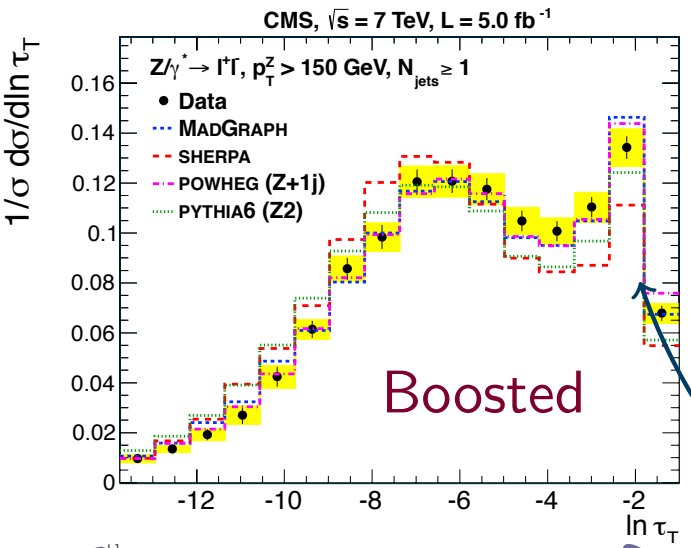
Transverse thrust

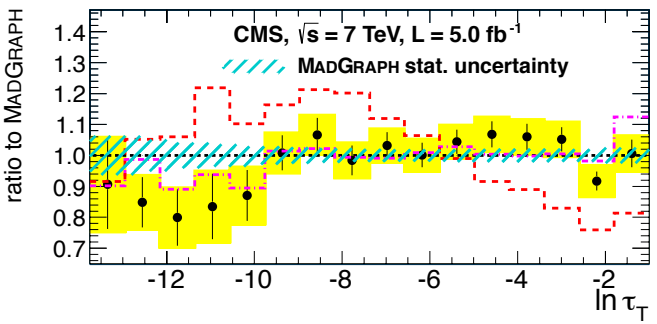


$$\tau_{\mathrm{T}} \equiv 1 - \max_{\vec{n}_\tau} \frac{\sum_i |\vec{p}_{\mathrm{T},i} \cdot \vec{n}_\tau|}{\sum_i p_{\mathrm{T},i}}$$

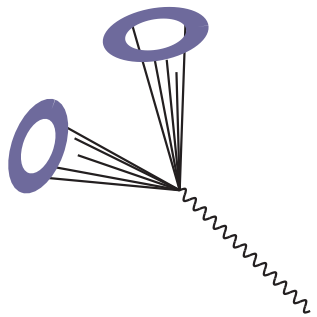
- Thrust axis: $\vec{n}_\tau$
- In the limit of a perfectly balanced, pencil-like Z + 1 jet events, τ_{T} tends to zero
- In the limit of a spherical, homogeneously-distributed events: $\tau_{\mathrm{T}} \to 1 - \frac{2}{\pi}$
- The value of thrust increases with additional jet emission

Transverse thrust





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

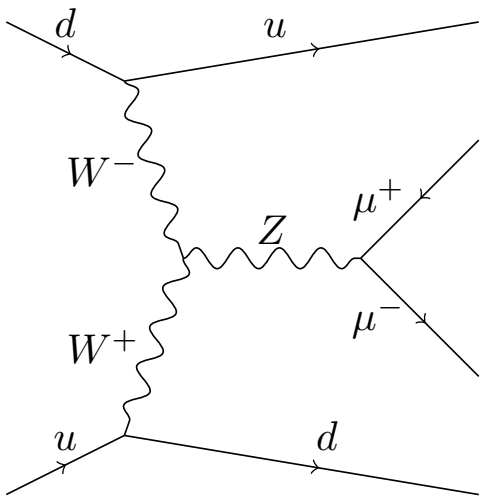


EWK production of Z+jets

- Analysis done with 2011 CMS data at $\sqrt{s} = 7$ TeV
- 5 fb^{-1}

- Cross section measurement of the pure EWK production of Z+2jets
- Measurement of the hadronic activity
- Measurement of radiation patterns

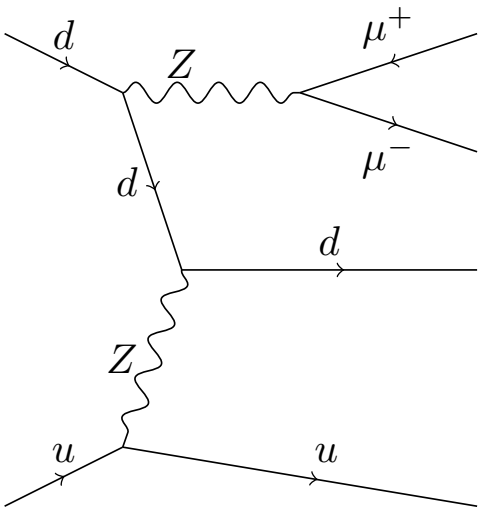
Vector boson fusion in Z+2jets



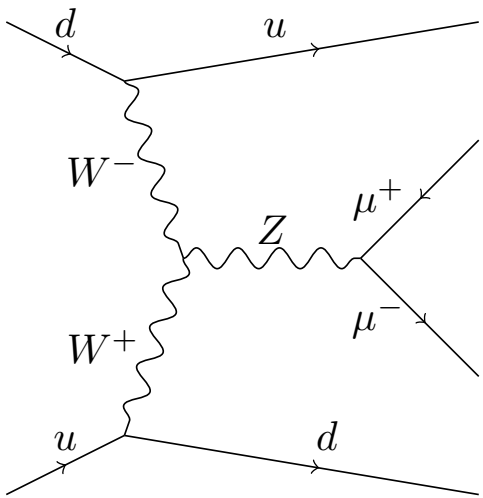
Features of VBF WW→Z are:

- 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

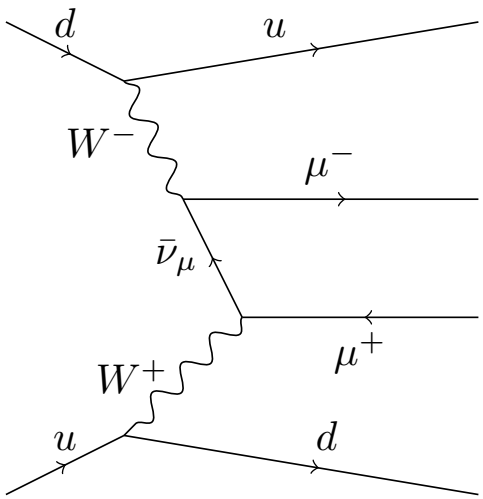
Vector boson fusion in Z+2jets



bremsstrahlung



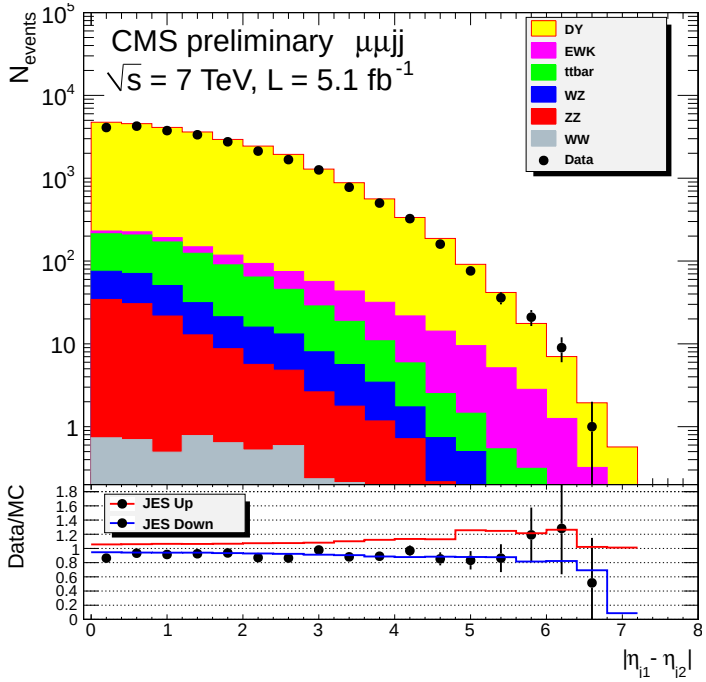
VBF

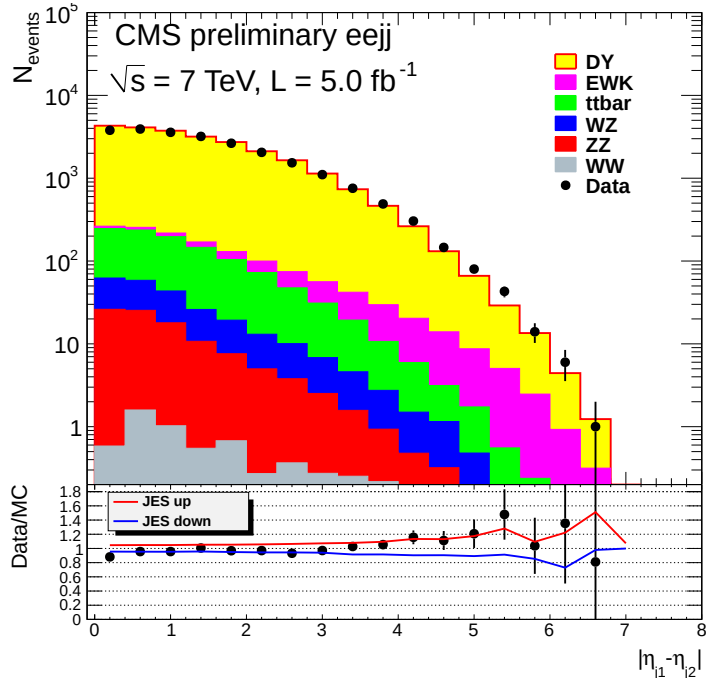


multi-peripheral

- Many other pure EWK processes lead to the same 2 leptons + 2 jets final state
- There are strong negative interference effects between these diagrams (EWK gauge cancellations)

Vector boson fusion in Z+2jets

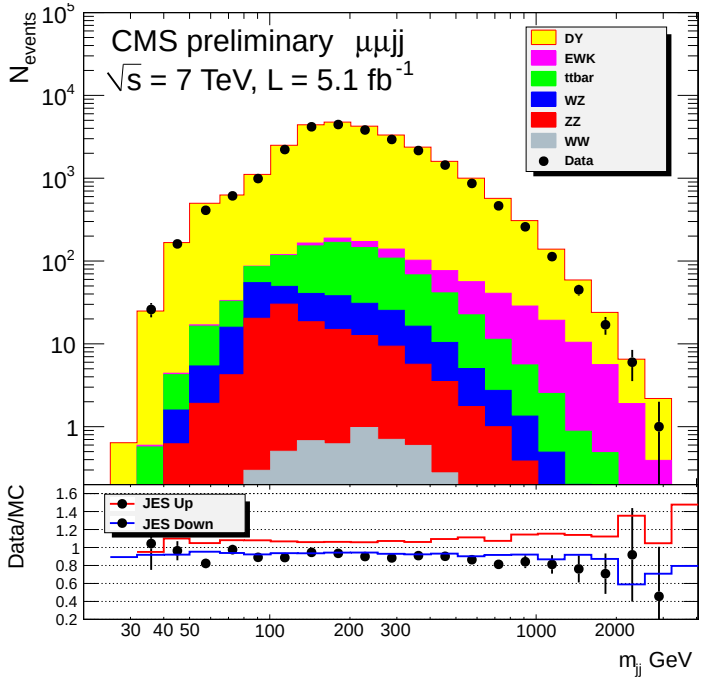


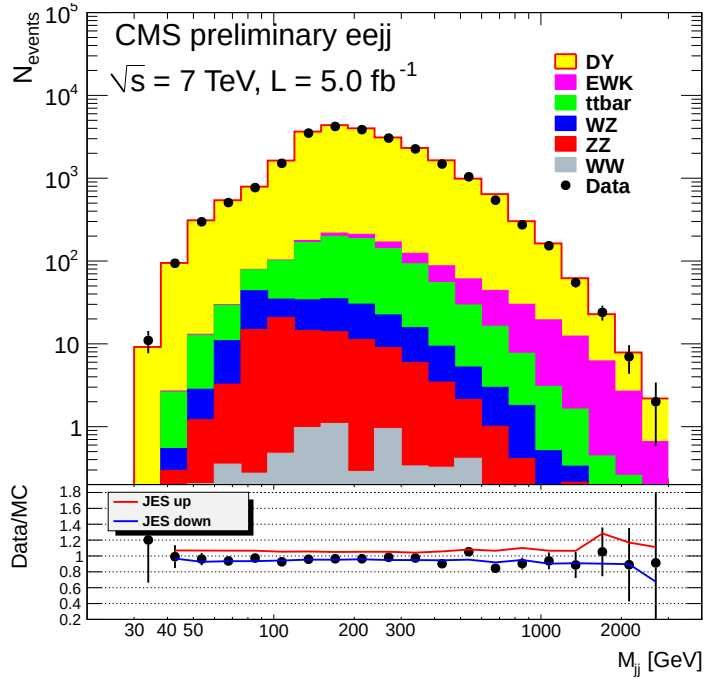


Features of VBF WW→Z are:

- 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

Vector boson fusion in Z+2jets





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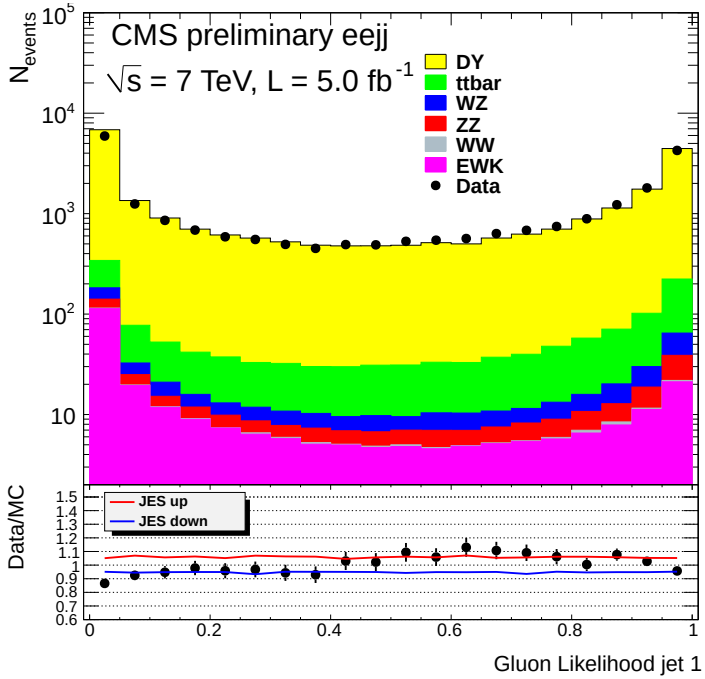
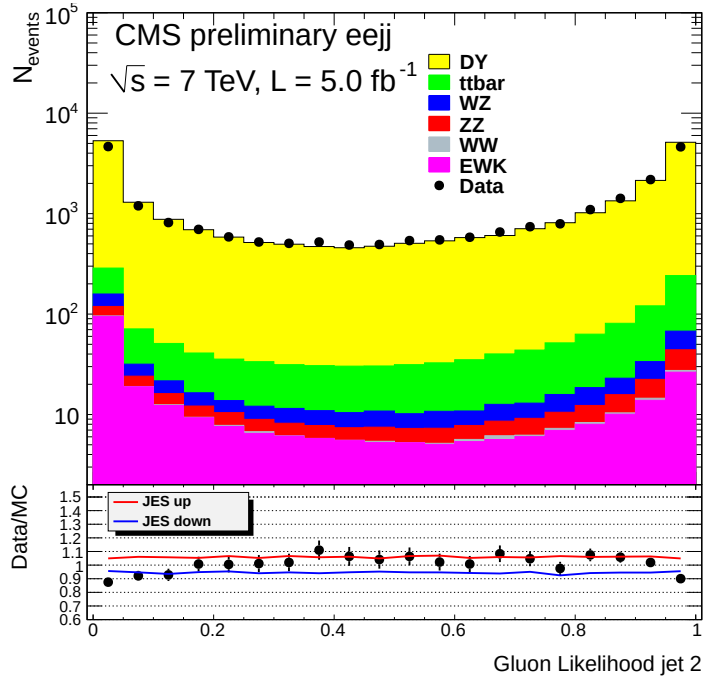
Quark-gluon tagger



quarks ⟷ gluons



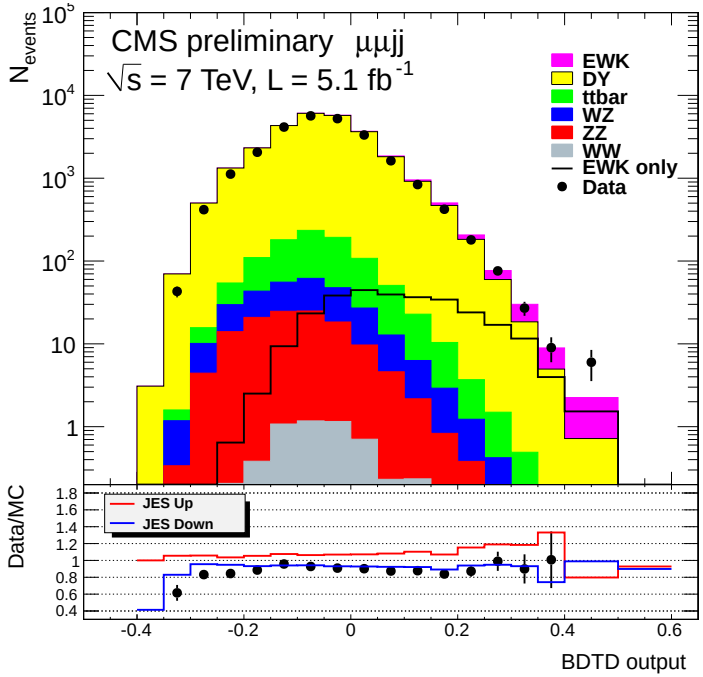
quarks ⟷ gluons

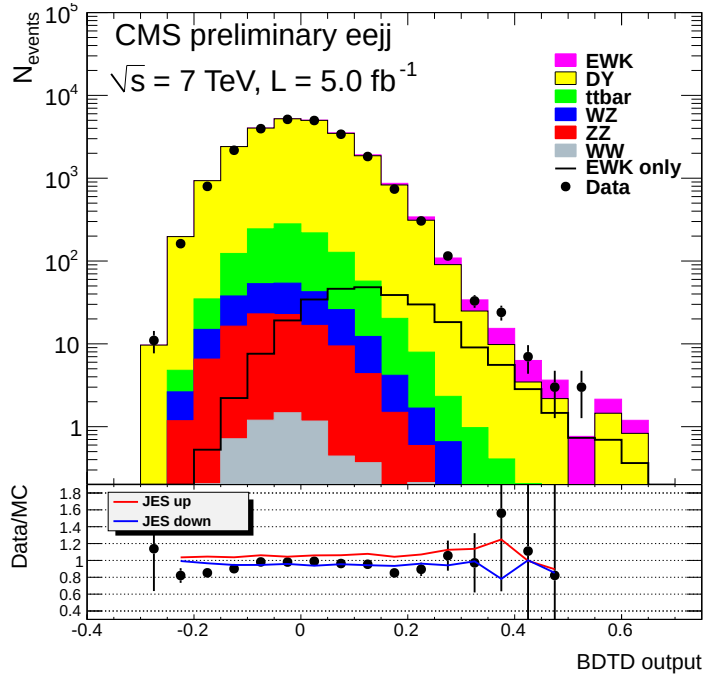
A quark-gluon likelihood, built out of 5 variables:

- 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

EWK signal is more quark-like

Cross section measurement





Fit the contributions of EWK signal and backgrounds to BDTD output:

$$\sigma^{EWK}_{meas,\mu\mu+ee} = 154 \pm 24\ (\text{stat}) \pm 46\ (\text{syst}) \pm 27\ (\text{theory}) \pm 3\ (\text{lumi})\ \text{fb}$$

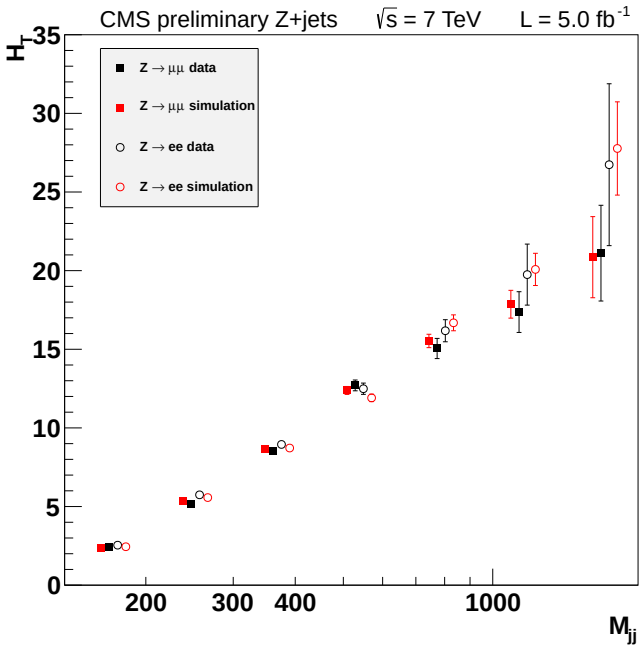
NLO prediction from VBFNLO: $\sigma^{EWK}_{NLO} = 166$ fb [CT10 PDFs, scale = 90 GeV]

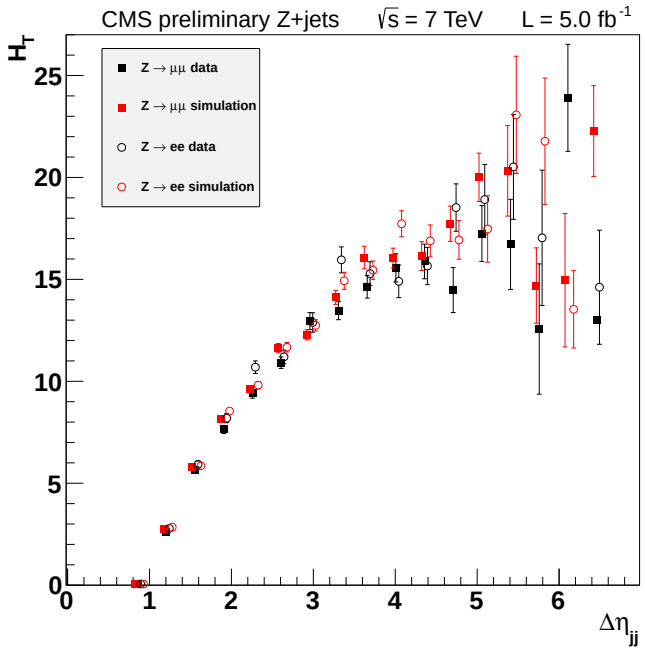
Kinematic region of the reported cross section:

$M_{ll} > 50$ GeV $\quad M_{jj} > 120$ GeV

$p_T(\text{jet}) > 25$ GeV $\quad |\ \eta(\text{jet})\ | < 4.0$

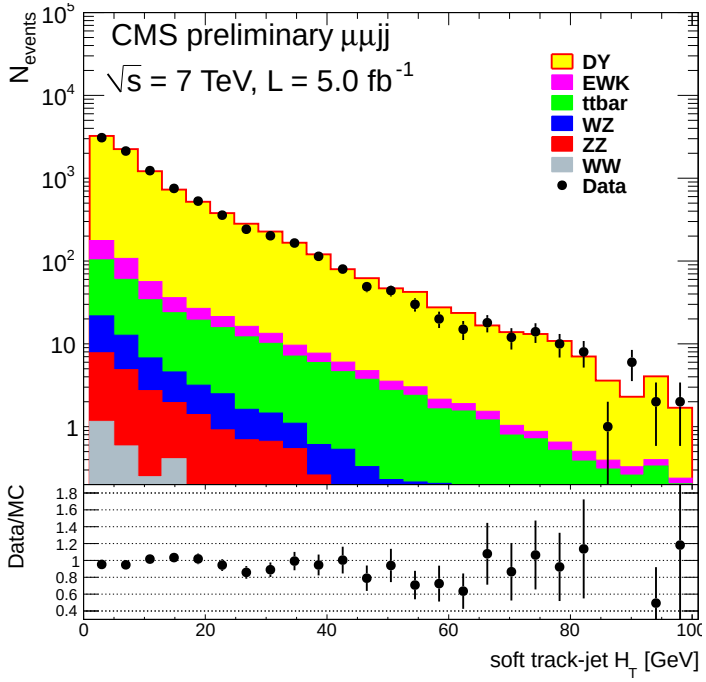
Central hadronic activity

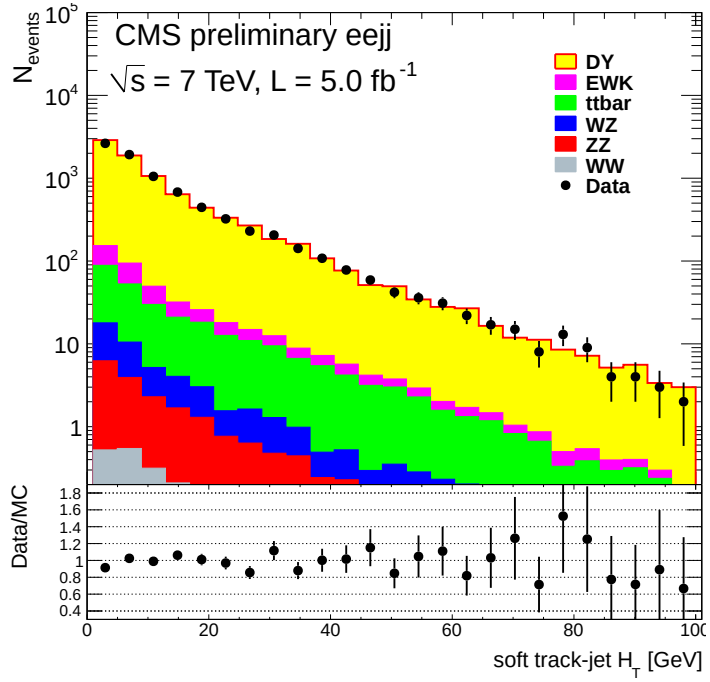




- Use of high-purity tracks associated with the PV, and not associated with the 2 leptons or the 2 jets
- Clustering of these tracks into soft track-jets with anti-k_T algorithm
- Selection of track jets between the 2 tagging jets
  $\Rightarrow \eta_{\text{min}}^{\text{tag.jet}} + 0.5 < \eta < \eta_{\text{max}}^{\text{tag.jet}}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

Central hadronic activity





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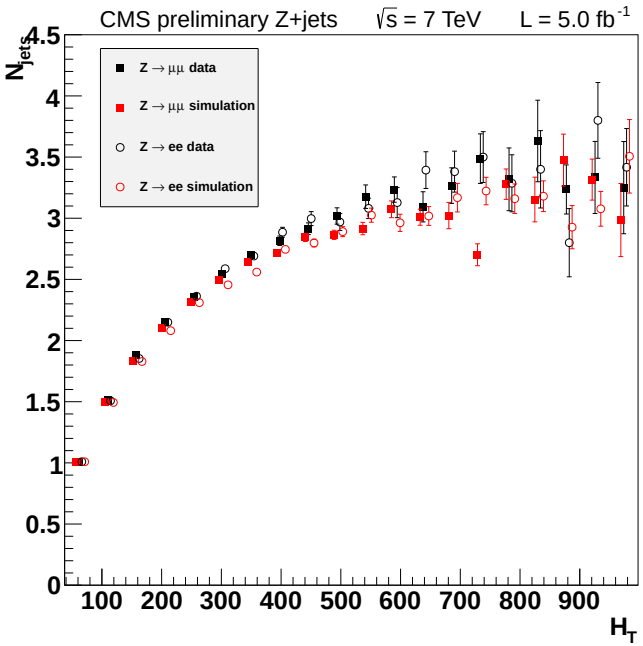
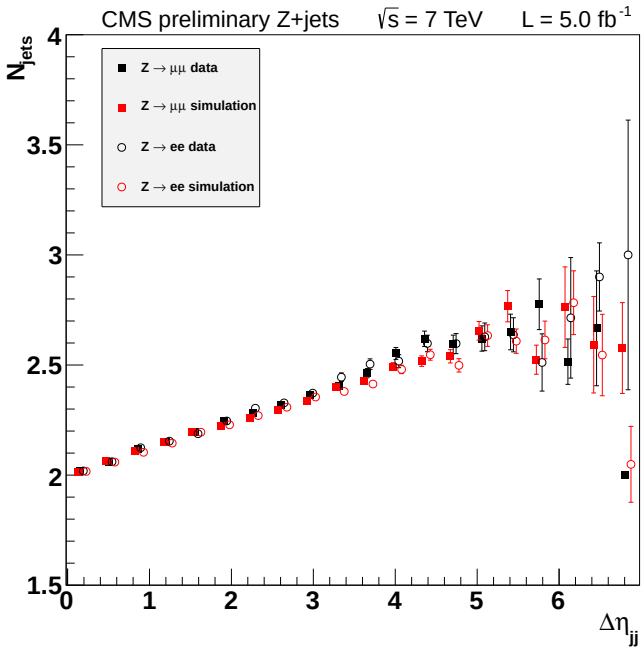
Radiation patterns in Z+jets events

$p_T(jet) > 40$ 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

Radiation patterns in Z+jets events

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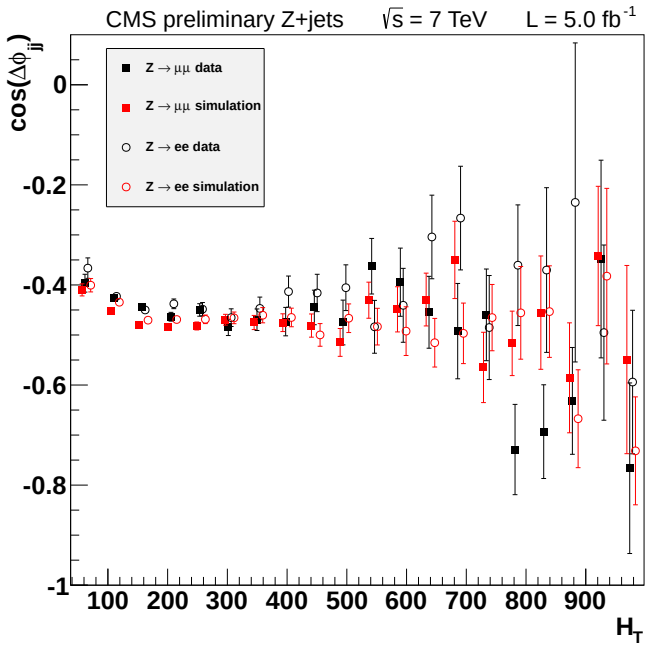
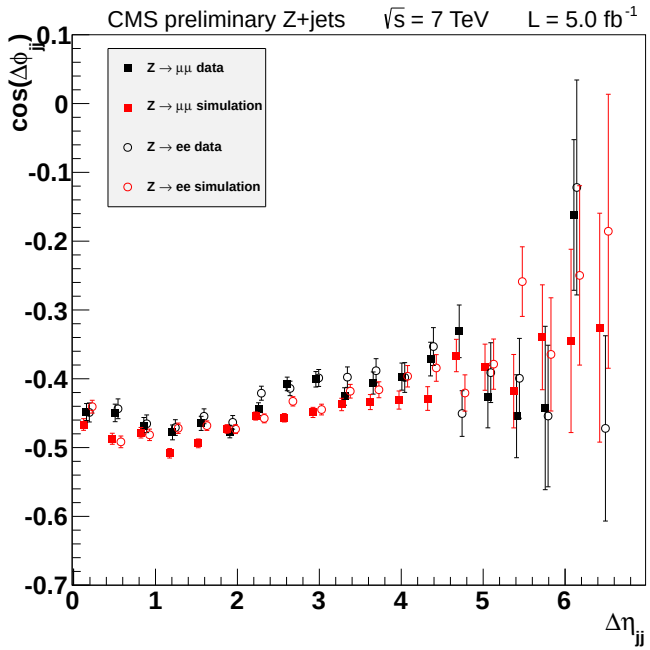




average cos $cos(\Delta\phi_{jj})$ vs. total H_T of jets

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

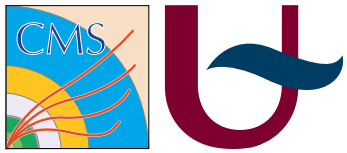
Data observation is in agreement with `MadGraph + Pythia` (ME+PS) prediction

Conclusions of EWK Z+jets analysis

- We have measured the EWK production of Z+jets in the di-muon and di-electron channels at $\sqrt{s} = 7$ TeV giving a combined result of $\sigma^{EWK}_{meas,\mu\mu+ee} = 154$ fb which is in good agreement with the VBFNLO prediction
- We presented results on the hadronic activity between the two tagging jet using soft track-jet activity
- We have performed radiation pattern measurements

Conclusions

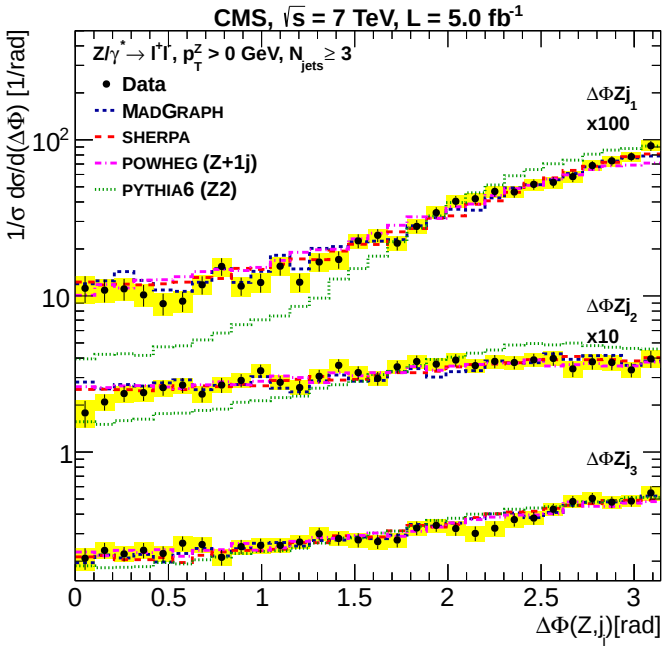
- A selection of results of jet physics and vector boson plus jet physics from pp data at $\sqrt{s} = 7$ TeV have been presented:
  - Cross section measurements
  - Angular correlations
  - Hadronic activity
  - ...
- In general good agreement between data and MC predictions
- Analyses will be updated in the future with 2012 LHC 8TeV data

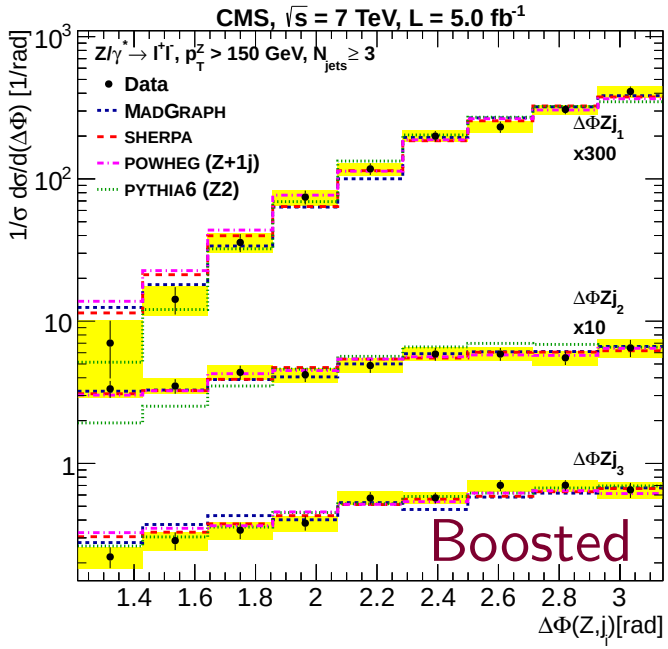


Back-up slides

$\Delta\Phi(Z, J_i)$

Azimuthal angles between the Z boson and the i^{th} leading jet:





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

$\Delta\Phi(Z, J_i)$

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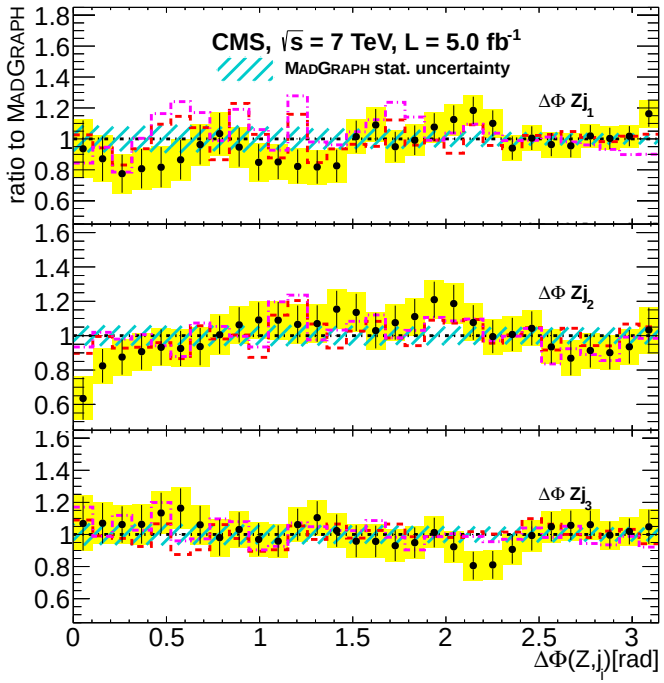
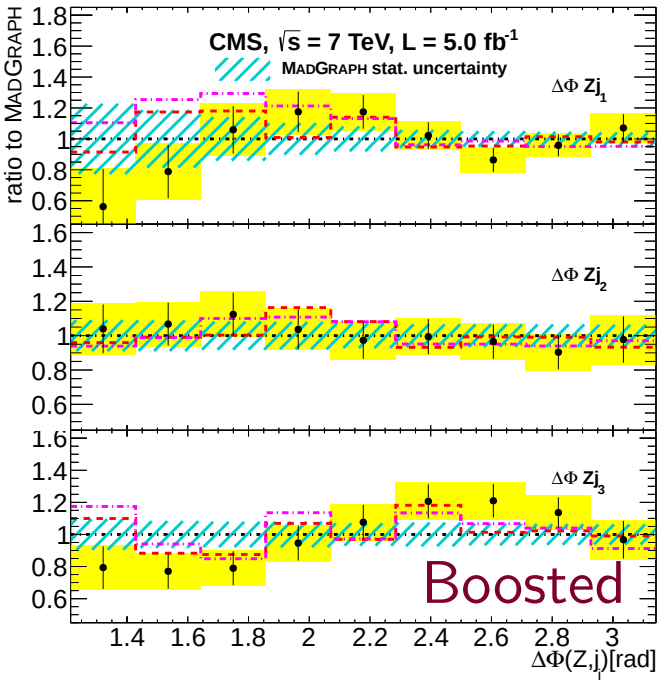
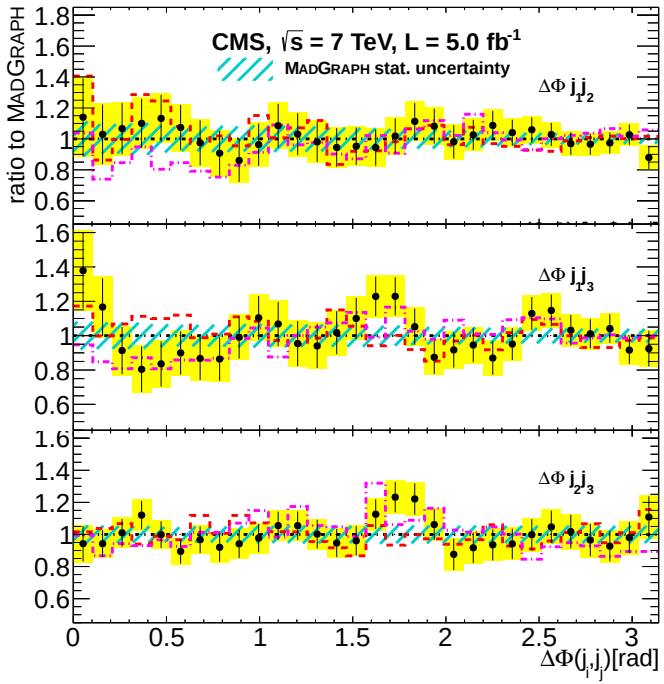


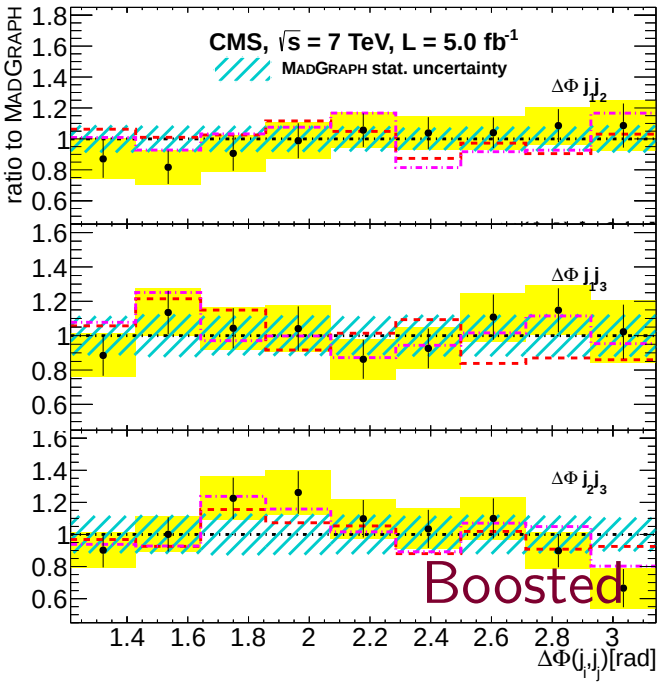


Error bars: statistical uncertainties
Yellow band: sum of statistical and systematic uncertainties

$\Delta\Phi(J_i, J_k)$

Azimuthal angles among the three leading jets:





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

BDTD variables in EWK Z+2jets

- p_T^{j1}, p_T^{j2}
- M_{jj}
- Zeppenfeld variable: $\mathrm{y}^* = y_Z - \frac{y_{j1}+y_{j2}}{2}$
- $p_T^{\mu\mu}$ and $\mathrm{y}_{\mu\mu}$
- $\Delta\eta_{jj} = |\eta_{\mathrm{j1}} - \eta_{\mathrm{j2}}|$
- $\eta_{\mathrm{j1}} + \eta_{\mathrm{j2}}$
- $\phi_{\mathrm{j1}} - \phi_{\mathrm{j2}}$
- $\phi_{\mu\mu} - \phi_{\mathrm{j1}}$ and $\phi_{\mu\mu} - \phi_{\mathrm{j2}}$
- Quark-gluon likelihood for the 2 tagging jets (only in e^+e^- mode)

Uncertainties EWK Z+2jets

source of uncertainty	uncertainty	
	$\mu^+\mu^-$ mode	$\mathrm{e}^+\mathrm{e}^-$ mode
background modeling	0.15	0.16
signal modeling	0.05	0.05
JES+JER	0.22	0.29
pileup modeling	0.03	0.03
MC stat.	0.13	0.19
gluon-quark discriminator	not used	0.02
$\mathrm{t\bar{t}}$ cross-section	0.03	0.03
diboson cross-sections	0.02	0.02
dilepton selection	0.02	0.02
luminosity	0.02	0.03

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- CMS Collaboration, "Jet Production Rates in Association with W and Z Bosons in pp Collisions at $\sqrt{s} = 7$ TeV", CMS PAS EWK-10-012
- CMS Collaboration, "Azimuthal Correlations and Event Shapes Distributions in Z+jets Production" , CMS PAS EWK-11-021
- CMS Collaboration, "EWK production of Z bosons with Forward/Backward Jets" , CMS PAS FSQ-12-019