electroweak (VBF) production of the Z boson and jets at CMS

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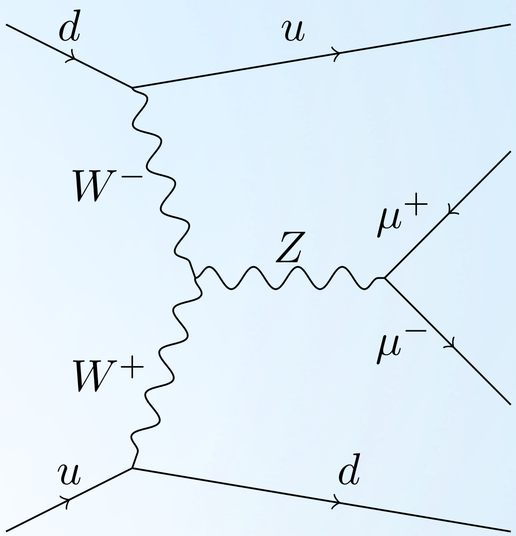
Jet Vetoes and Jet Multiplicity Observables at the LHC

IPPP Durham, July 18th 2013

outline

* VBF & EWK Z + 2 jets final states
* Analysis ingredients & strategy
* Central rapidity gap hadronic activity
* Z+2 jets radiation patterns
* Signal yield measurements

VBF Z process



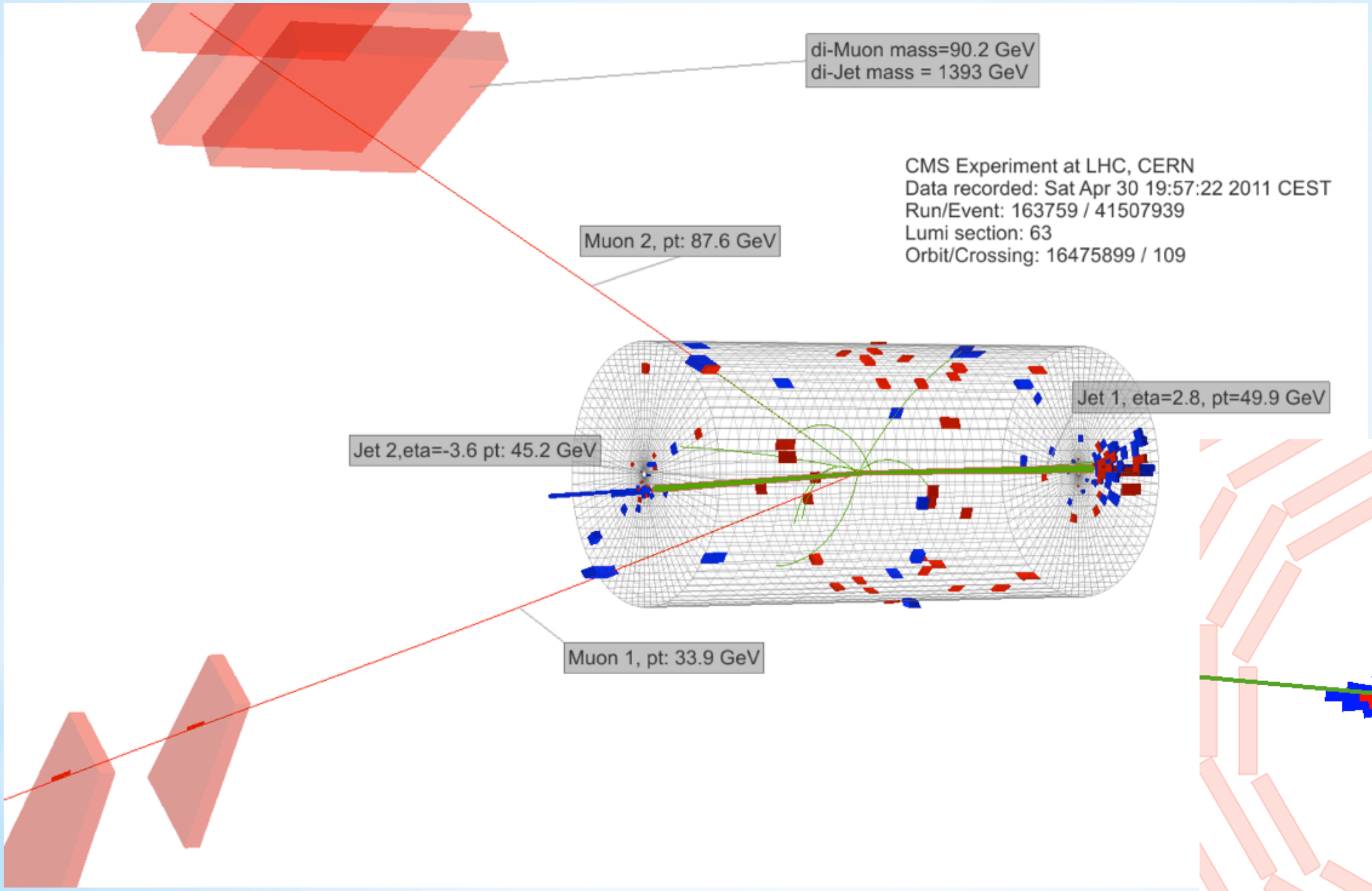
features of a VBF Z are:

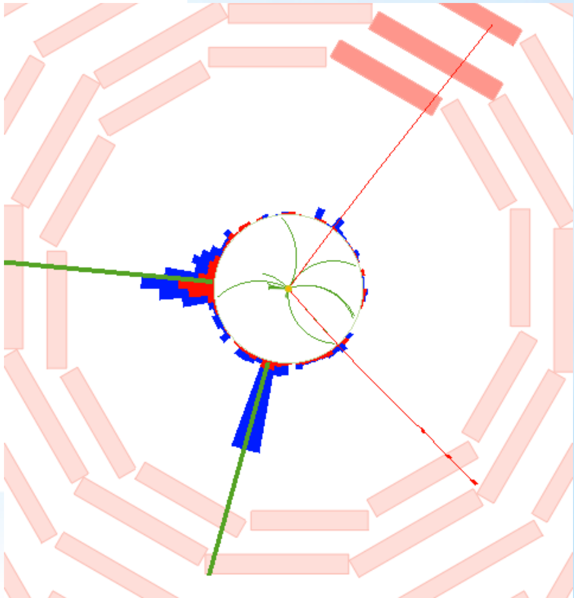
- Central Z decay associated with energetic forward-backward jets
- A large η separation between the jets
- A large invariant dijet mass

- Pure EWK process: suppressed color exchange between the tagging quarks

→ low hadronic activity in the central part of the detector

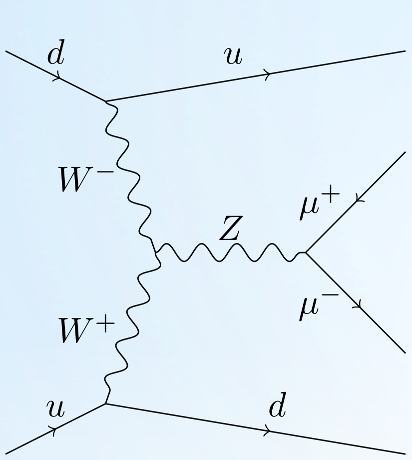
VBF Z candidate

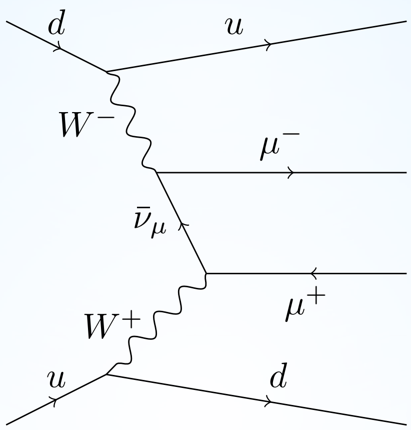


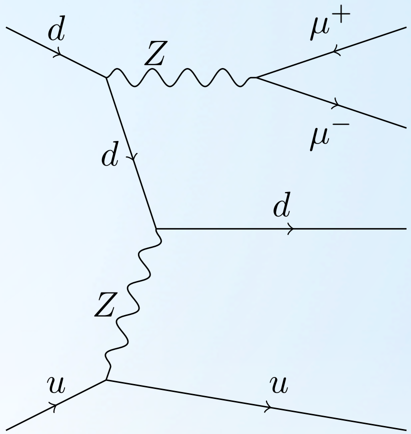


VBF & EWK Z/γ*(→ll) + 2 jets

many other pure EWK processes lead to the lljj final state





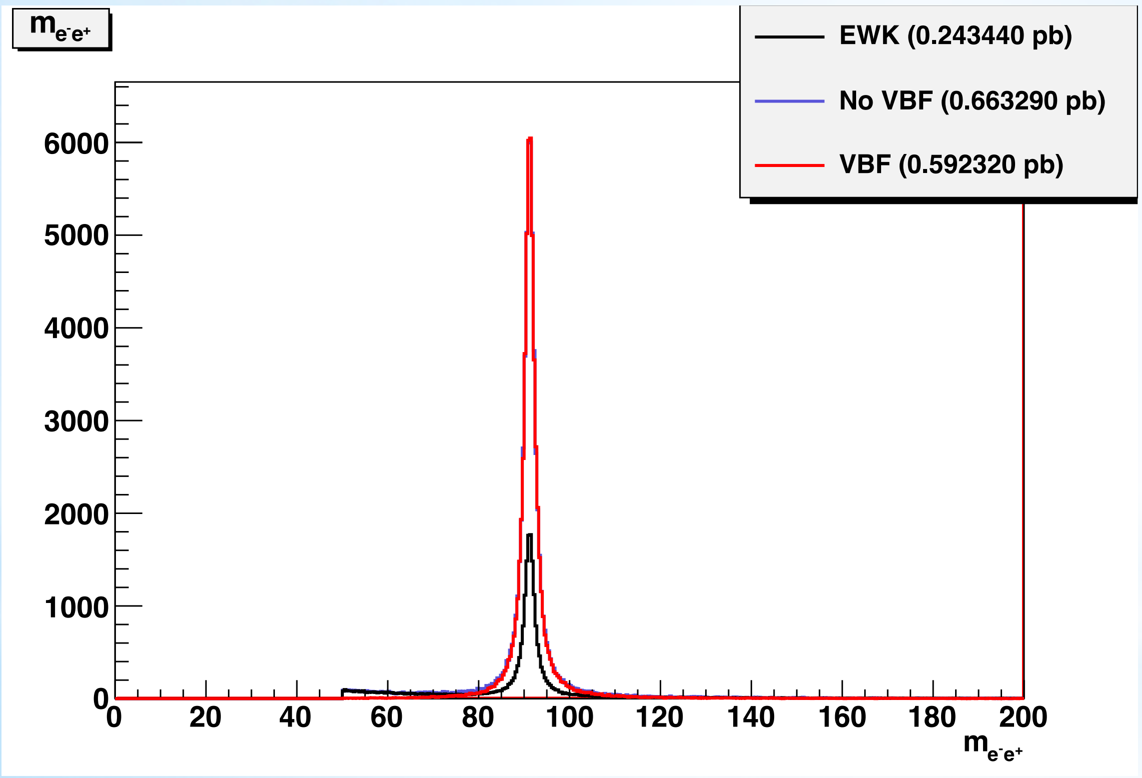


strong negative interference effects (EWK gauge cancellations)

EWK pp> lljj cross section @7TeV with: pT(j)>10 GeV |η(j)|<7 m(jj)>120 m(ll)>50
σ(7TeV) = **0.243 pb / lepton flavor** (mjj>120, excludes WZ,ZZ)

VBF & EWK Z/γ*>ll + 2jets

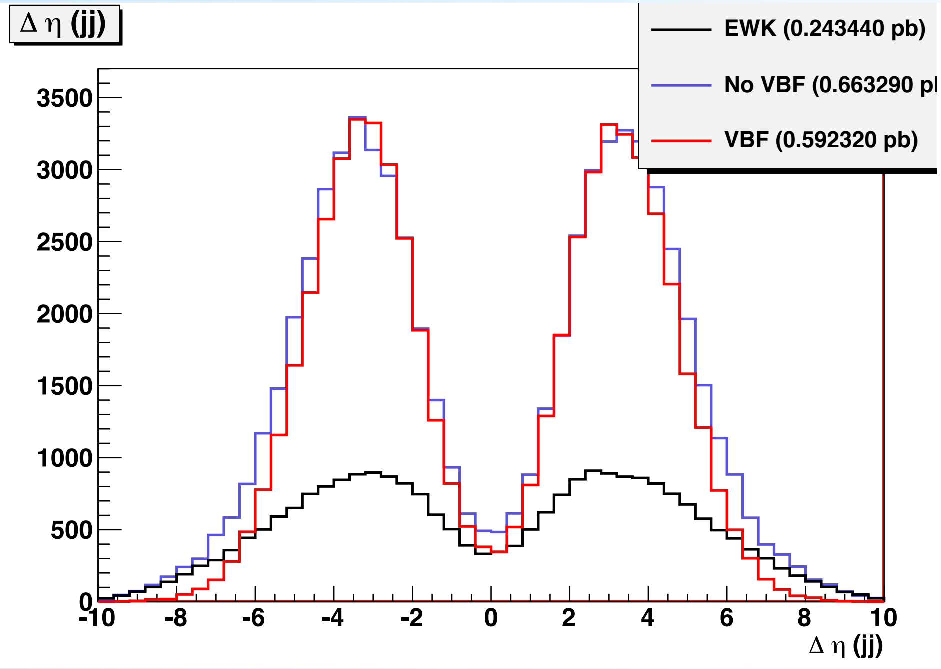
pp> lljj cross sections @7TeV with: pT(j)>10 GeV |η(j)|<7 m(jj)>120 m(ll)>50

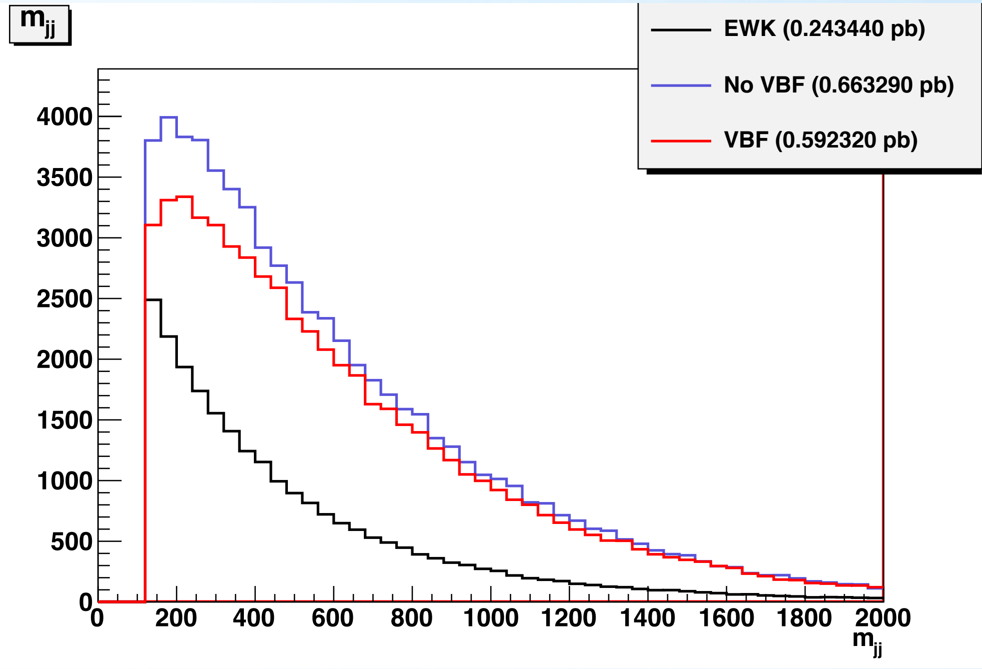


VBF	592 fb	+
no VBF	663 fb	=

EWK	243 fb	

VBF & EWK Z/γ*>ll + 2jets

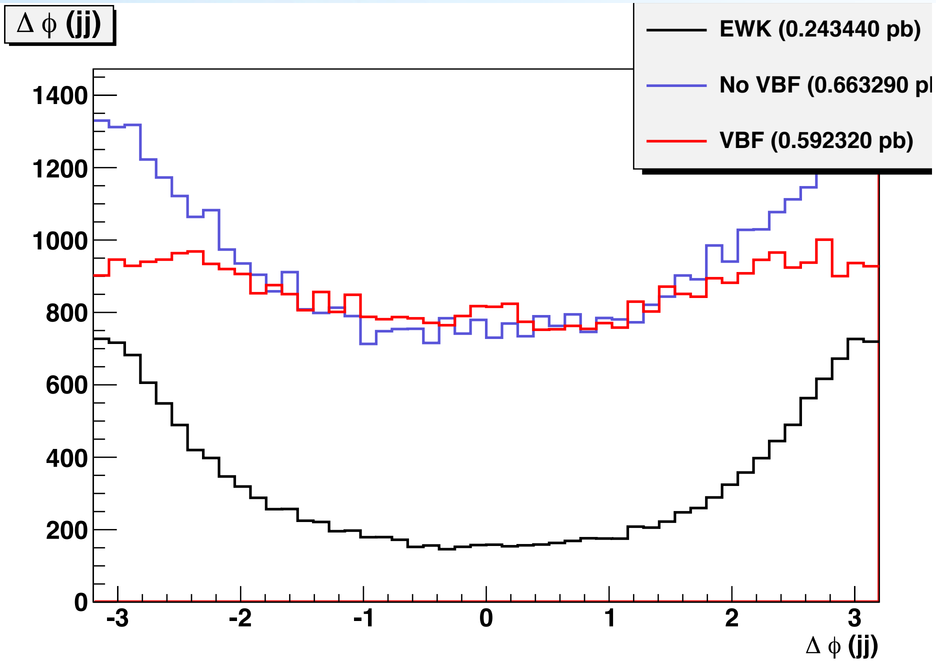




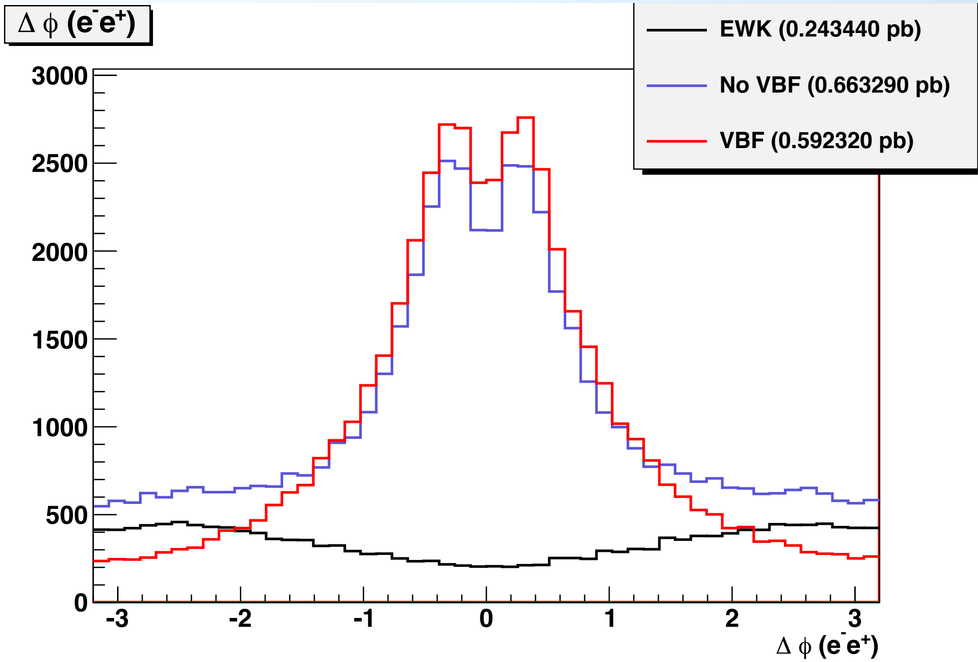
di-parton eta opening

di-parton invariant mass

VBF & EWK Z/γ*>ll + 2jets



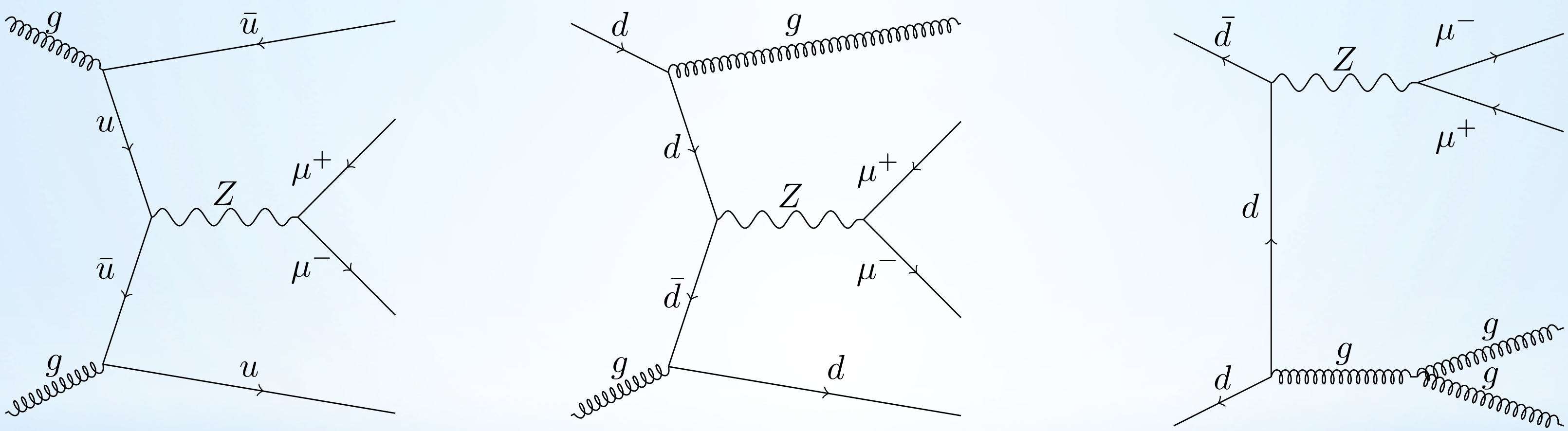
di-parton azimuthal opening



di-lepton azimuthal opening

Drell-Yan Z/γ* plus two jets

mixed QCD+EWK processes



σ(7TeV) = 3.048 nb for all ll(+jets) with m(ll)>50

Motivations

- find evidence for the presence of a purely electroweak production of Z+jets
- benchmark for other VBF analyses (Higgs) and VV scattering
- use selected Z+2jets events to study the central hadronic activity as a probe for rapidity gaps and jet vetoes

- Chehime, Zeppenfeld: **Phys.Rev.D 47, 3898** (1993)
- Baur, Zeppenfeld: **arXiv:hep-ph/9309227** (1993)
- Rainwater, Szalapski, Zeppenfeld: **Phys.rev.D 54, 6680** (1996)
- Green: **arXiv:hep-ex/0502009** (2005)
- Govoni, Mariotti: **arXiv:1001.4357** (2010)

Analysis Strategy

- **Signal is generally covered by the DY background (tough to find selections of Z+2jets phase space with S/B>0.1)**
  - **Use different techniques to extract signal**
  - **Confirm signal in ee and μμ modes**
  - **Use different methods of jet reconstruction**

Analyzed ~5/fb of pp collision data at 7 TeV (2011)

Event Selection

- Isolated leptons
  - $p_T > 20$ GeV, $|\eta| < 2.4$
  - $|m_{ll} - m_Z| < 15$ GeV(μμ) - 20 GeV (ee)

PF and JPT Jets : with $|\eta(j)| < 3.6$

Cuts optimized to maximize cut & count significance S/sqrt(B)

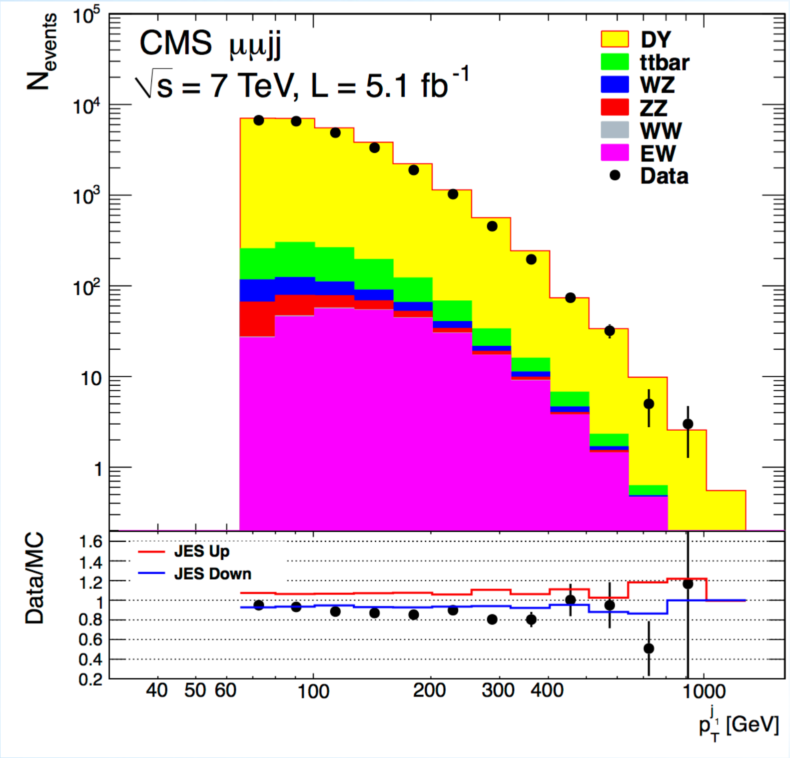
pT(j1)>65 GeV pT(j2)>40 GeV (TJ1)

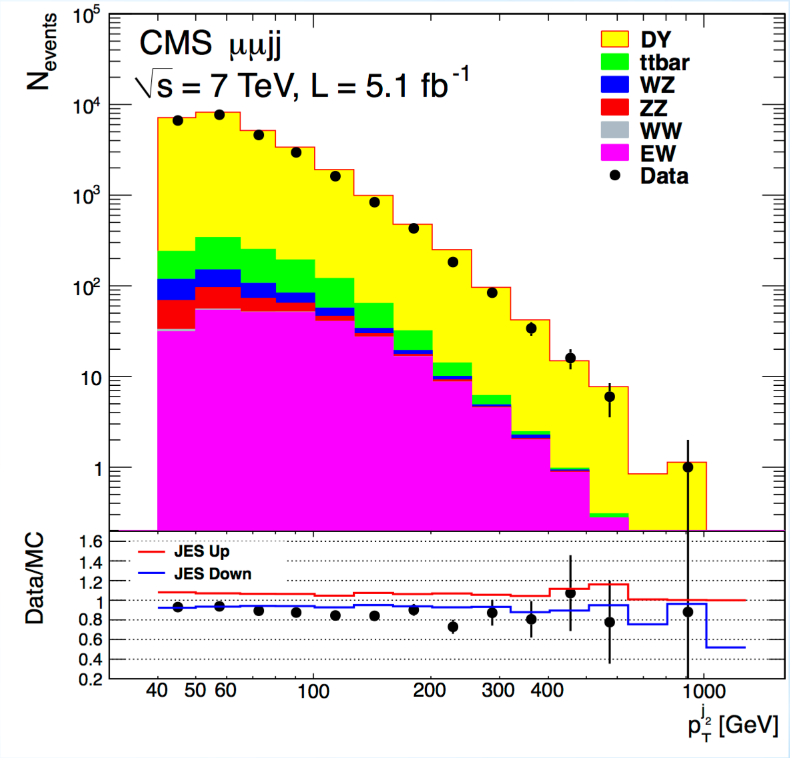
$|y^*| = |y_Z - 0.5(y_{j1} + y_{j2})| < 1.2$ (YZ)

m(jj)>600 GeV (TJ2)

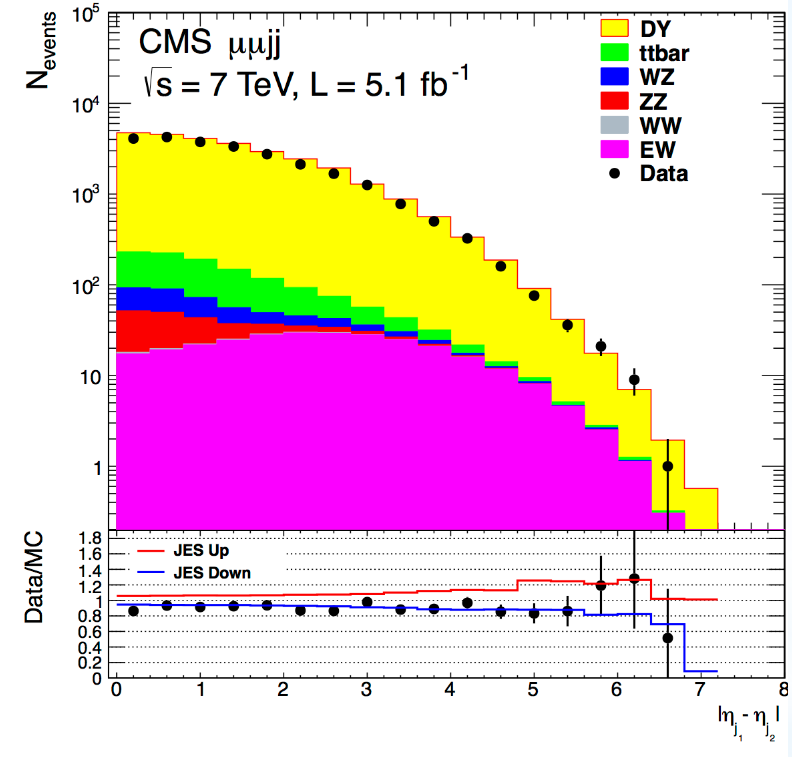
data/MC measured corrections applied

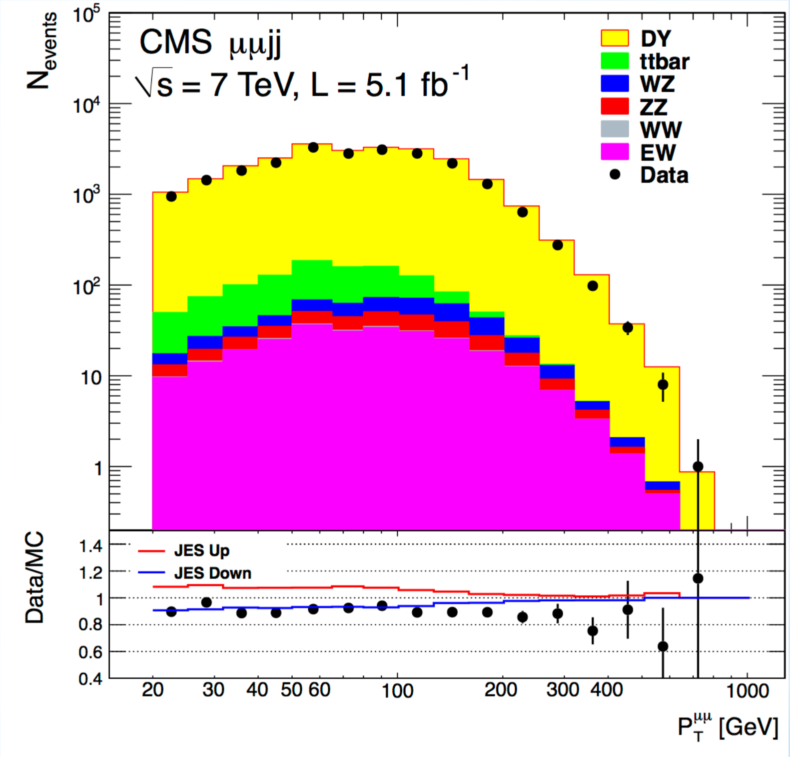
Jets p_T spectra





dijet η opening and Z p_T





Event Yields

Selection	Jet type	Data	EW $\ell\ell$jj	DY $\ell\ell$jj	$t\bar{t}$	WW	WZ	ZZ
$Z_{\mu\mu}$		1.7×10^6	460	1.7×10^6	1400	300	1300	850
requirement TJ1	JPT	25000	290	26000	690	5.2	180	120
	PF	26000	280	26000	680	5.3	170	110
requirement YZ	JPT	15000	210	16000	590	3.4	98	83
	PF	16000	200	16000	580	3.4	93	76
requirement TJ2	JPT	600	74	600	14	0	2.2	1.3
	PF	640	72	610	14	0	2.4	1.2

selection	data	EW $\ell\ell$jj	DY $\ell\ell$jj	$t\bar{t}$	WW	WZ	ZZ
Z_{ee}	1.5×10^6	410	1.5×10^6	1600	340	1100	720
requirement TJ1	24000	270	23000	880	6.0	150	97
requirement YZ	15000	200	15000	760	3.7	90	68
requirement TJ2	560	67	550	17	0.3	2.5	1.0

quark / gluon jet tagging

approximately half of the jets in DY + Jets events are gluon originated : we make use of the following jet composition / shape variables to separate them from the signal quark-induced jets

For **Central** (|eta|<2) jets

1. Axis1 (major ηφ RMS)
2. Axis2 (minor ηφ RMS)
3. Pull (asymmetry)
4. N_Chg
5. R_ch = max(pTi_ch)/sum(pTi)

All variables with charged-PU subtraction

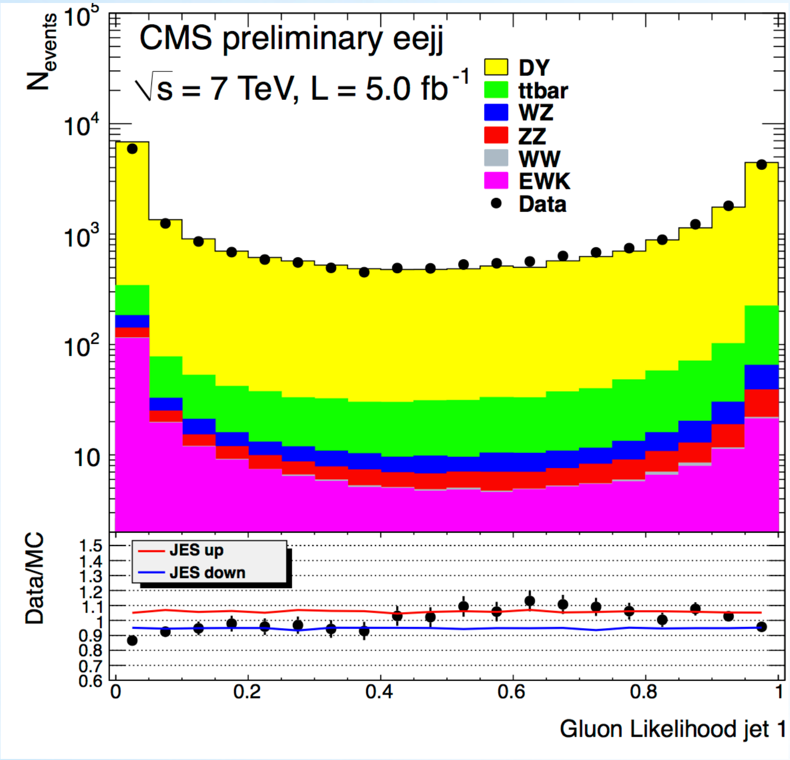
For **Transition**(2<|eta|<3) jet and **Forward** (3<|eta|<4.7) jets

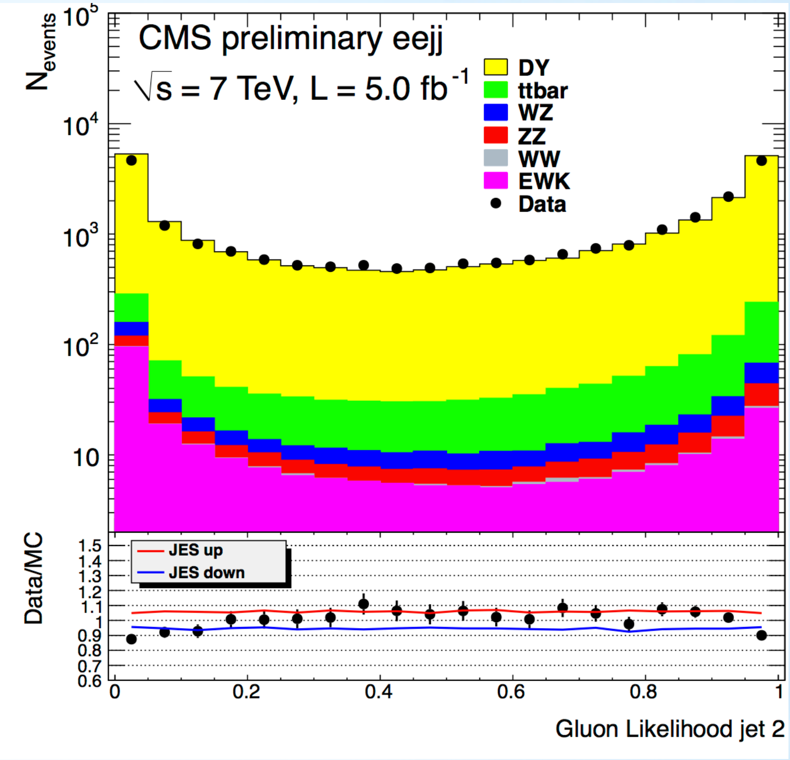
1. Axis1
2. Axis2
3. Pull
4. N_Chg + N_Neu
5. R = max(pTi)/sum(pTi)

All variables without charged-PU subtraction

combined with a simple likelihood
(no correlations exploited)

quark / gluon jet tagging





Central Jet Vetoes

- **Tagging jet selections:**
  - **two leading p_T jets, $p_{Tj1,j2} > p_T^{cut}$**
  - **$\eta_{j1}\ \eta_{j2} < 0$**
  - **$m_{j1j2} > m^{cut}$**
  - **$|\eta_{j1}-\eta_{j2}| > \Delta\eta^{cut}$**
- **Central Jet Veto (CJV):**
  - **no jets p_T > 20 GeV, $|\eta|<2.0$, $\beta > 0.2$**

  within rapidity gap $\eta_{min}^{tag.j} < \eta < \eta_{max}^{tag.j}$

Central Jet Vetoes results

Table 4: Efficiency of the central jet veto with $p_T^{j_3} > 20\,\text{GeV}$ for three different selections on the tagging jets for a pseudorapidity separation of $\Delta\eta_{j_1 j_2} > 3.5$ measured in data and predicted by the MADGRAPH simulation. The quoted uncertainty is statistical only.

$p_T^{j_1(j_2)}$	>25 GeV	>35 GeV	>45 GeV
data	0.78 ± 0.01	0.68 ± 0.01	0.63 ± 0.02
simulation	0.80	0.71	0.66

with a larger p_T for the two tagging jets, there is a larger probability to have additional jet(s) between them

data confirms simulation predictions

Central Jet Vetoes results

Table 5: Efficiency of the central jet veto with $p_T^{j_3} > 20$ GeV and $p_T^{j_1(j_2)} > 30$ GeV for three different selections for $\Delta\eta_{j_1j_2}$ with and without the selection on $m_{j_1j_2}$, measured in data and predicted by the MADGRAPH simulation. The quoted uncertainty on the data efficiency is only statistical.

$\Delta\eta_{j_1j_2}$	>2.5	>3.5	>4.5
data	0.71 ± 0.01	0.68 ± 0.01	0.66 ± 0.02
simulation	0.73	0.71	0.67
with $m_{j_1j_2} > 700$ GeV selection			
data	0.56 ± 0.03	0.58 ± 0.03	0.62 ± 0.04
simulation	0.56	0.57	0.58

with a larger rapidity separation between the two tagging jets, there is a larger probability to have additional jet(s) between them…

not after a m(jj)>700 GeV cut, that makes p_T of tagging jets harder at smaller $\Delta\eta_{j1j2}$

data confirms simulation predictions

track-jets gap activity

build the collection of “Extra Tracks” with

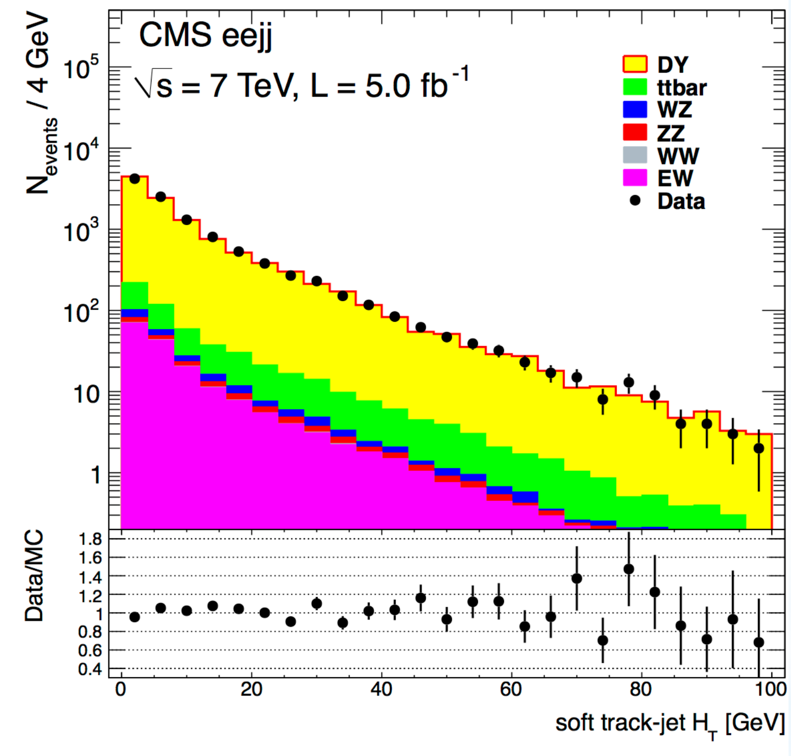
- *highPurity* tracks, p_T>300 MeV
- not associated to the leptons nor to the two leading jets
- make minimum $|d_z(PV)|$ when associated to the hardest PV
- $|d_z(PV)|$<2mm $|d_z(PV)|<3\sigma_z(PV)$ to the hardest PV

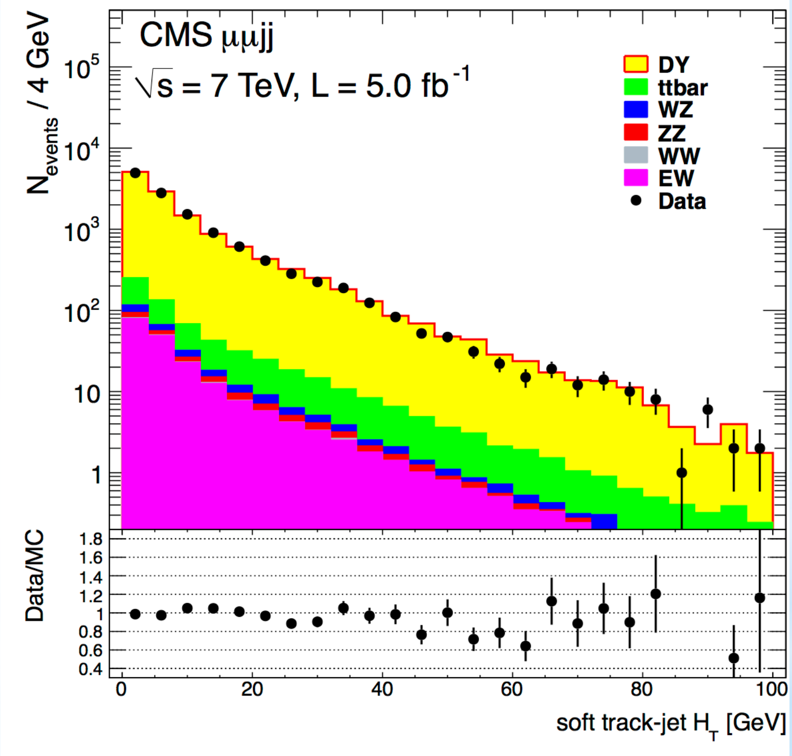
cluster “soft” TrackJets with the “Extra Tracks” collection with

- anti-kt 0.5
- p_T>1 GeV

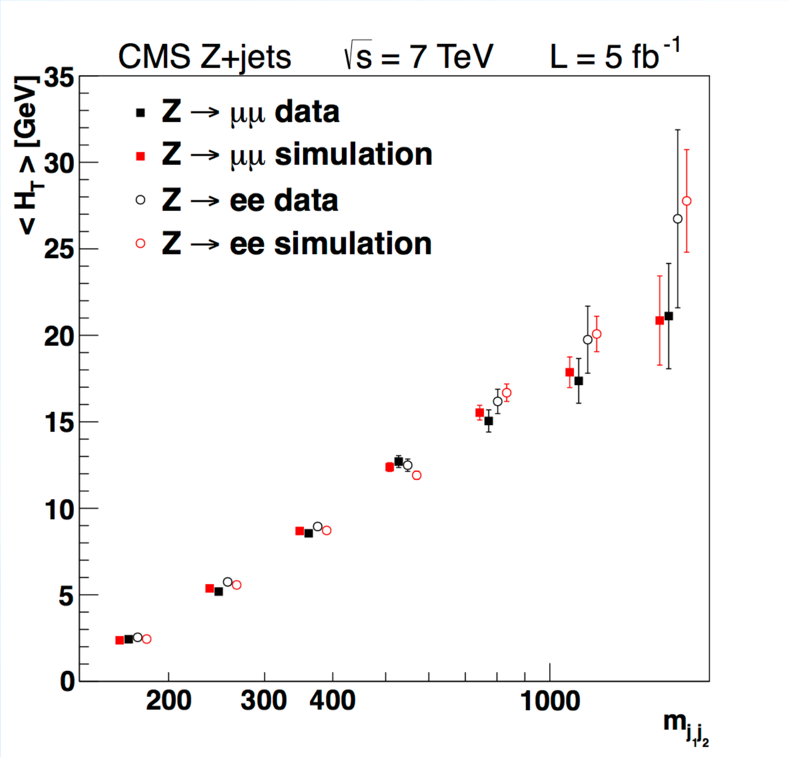
Central Region defined as η(jet-bkw)+0.5 < η < η(jet_fwd)-0.5

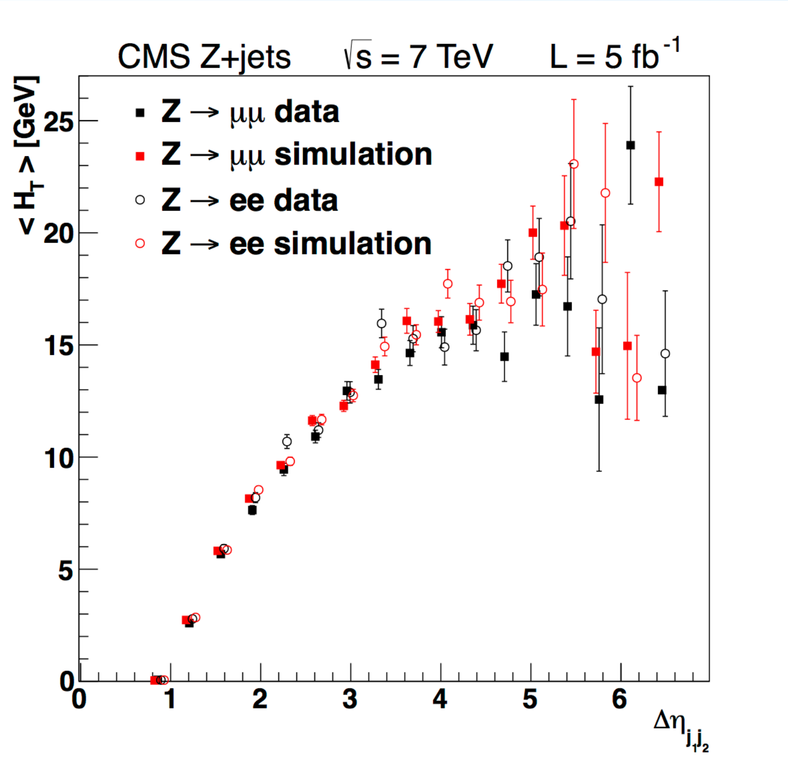
charged hadronic gap activity





charged gap activity evolution

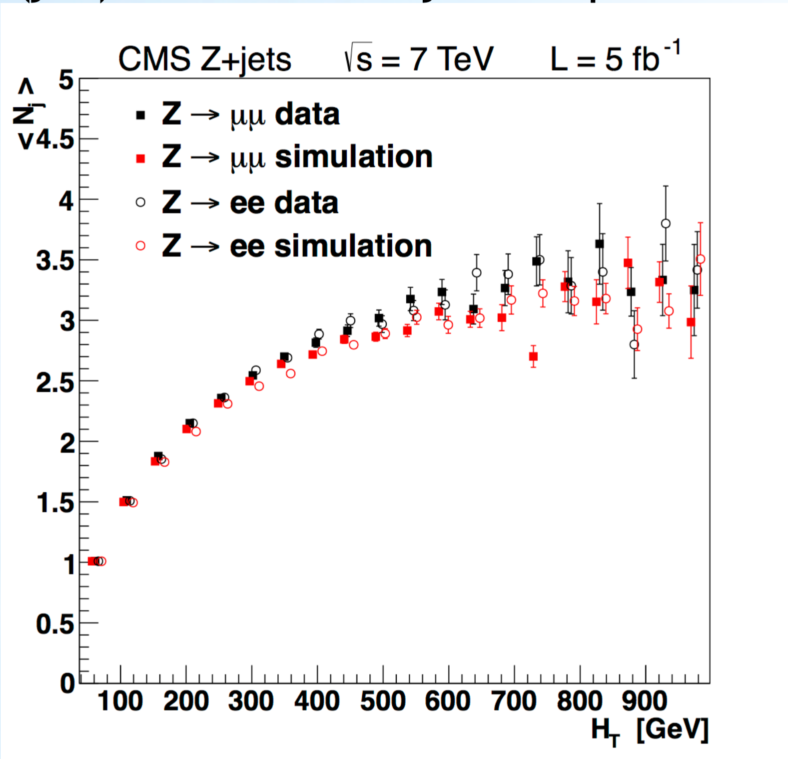


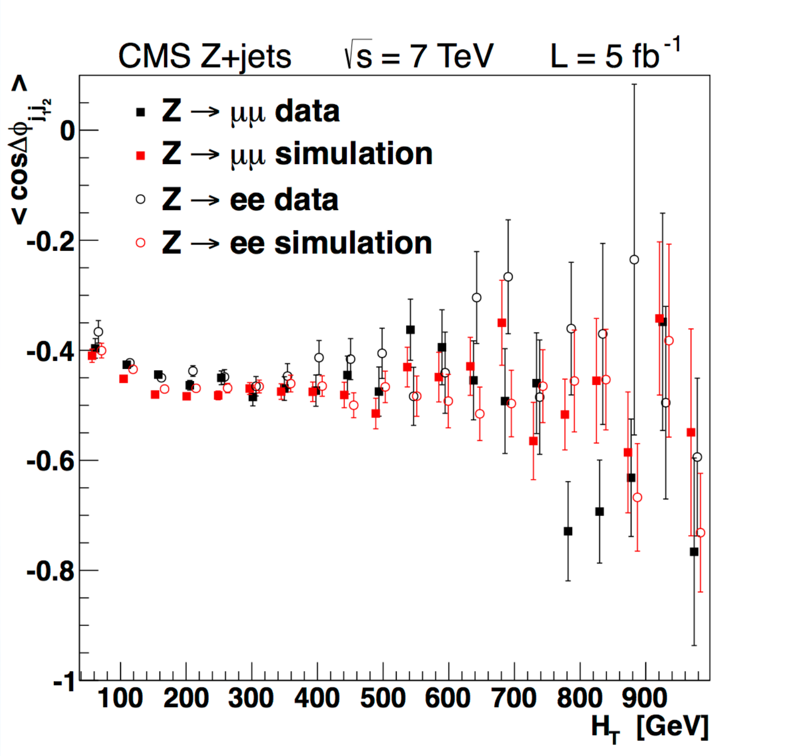


Z + 2 jets patterns

from studies proposed in the Les Houches report
http://arxiv.org/pdf/arXiv:1003.1241 (pages 72 & 130)

N(jets) is the number of jets with pT>40 GeV





HT is the scalar sum of the pT of jets with pT>40 GeV

good agreement with MG+PY6

Z + 2 jets patterns

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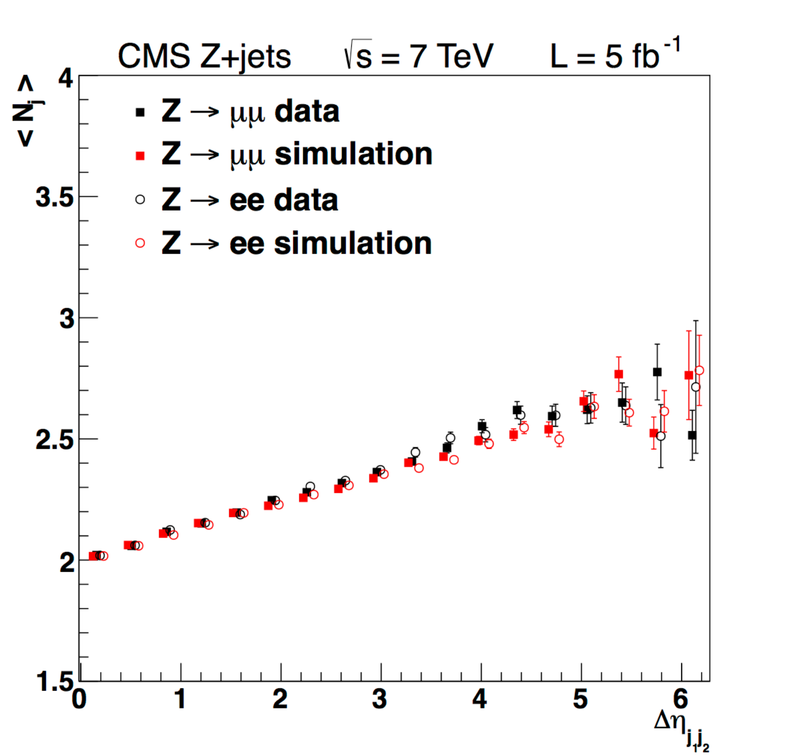
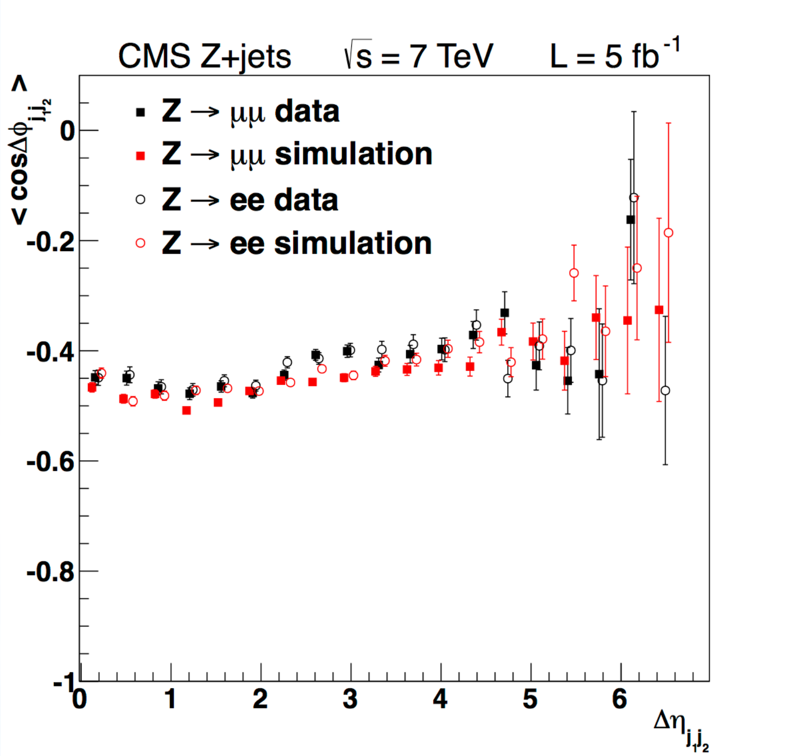




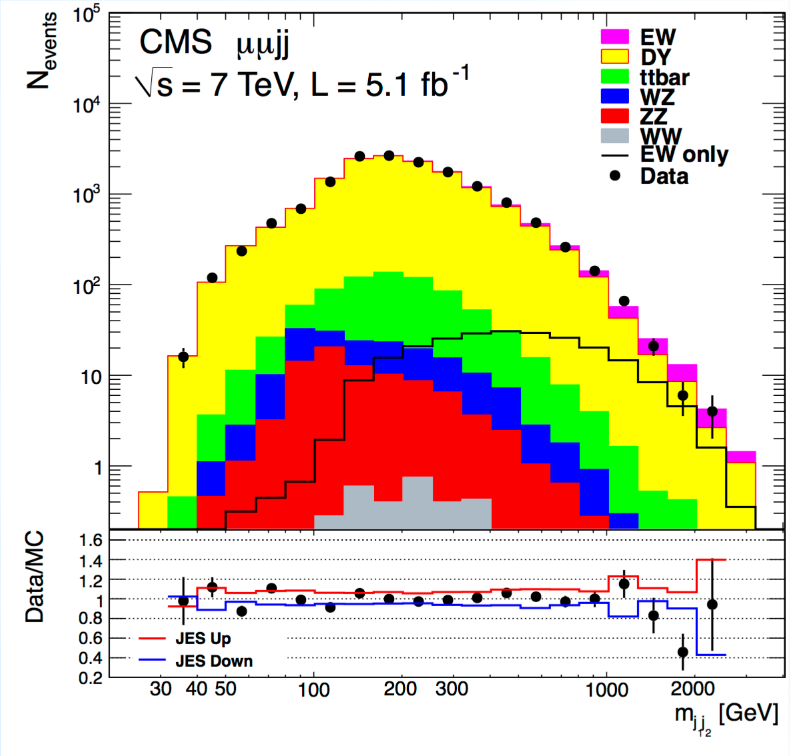
Δη is the maximum Δη among jets with pT>40 GeV

good agreement with MG+PY6

Signal measurement

Fit to m(jj) distribution (dimuons)

Fit m_{jj} distribution in the range 32 – 2500 GeV to K_{DY} (b) and K_{EWK} (s) parameters



K_{DY} and K_{EWK} are scaling factors for DY and Signal MC
Contributions form top and vector boson pairs are fixed

Maximum likelihood fit with Barlow-Beeston procedure

JPT jets
K_{DY} = 0.869 +/- 0.008 (stat)
K_{EWK} = 1.14 +/- 0.28 (stat)

PF jets
K_{DY} = 0.987 +/- 0.008 (stat)
K_{EWK} = 1.14 +/- 0.30 (stat)

Fit to m(jj) distribution (dimuons)

Systematic Uncertainties

Source of uncertainty	Uncertainty
Theoretical uncertainties	
Background modeling	0.20
Signal modeling	0.05
$t\bar{t}$ cross section	0.02
Diboson cross sections	0.01
Total	0.21
Experimental uncertainties	
JES+JER	0.44
Pileup modeling	0.05
MC statistics	0.14
Dimuon selection	0.02
Total	0.47
Luminosity	0.02

BDT discrimination

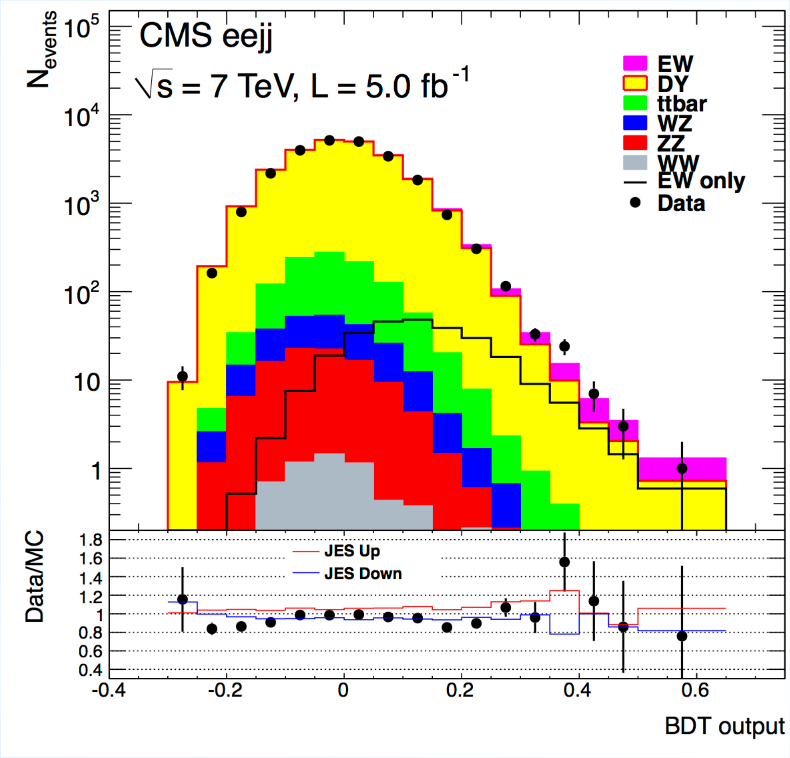
To enhance the signal / background separation makes use of the following variables

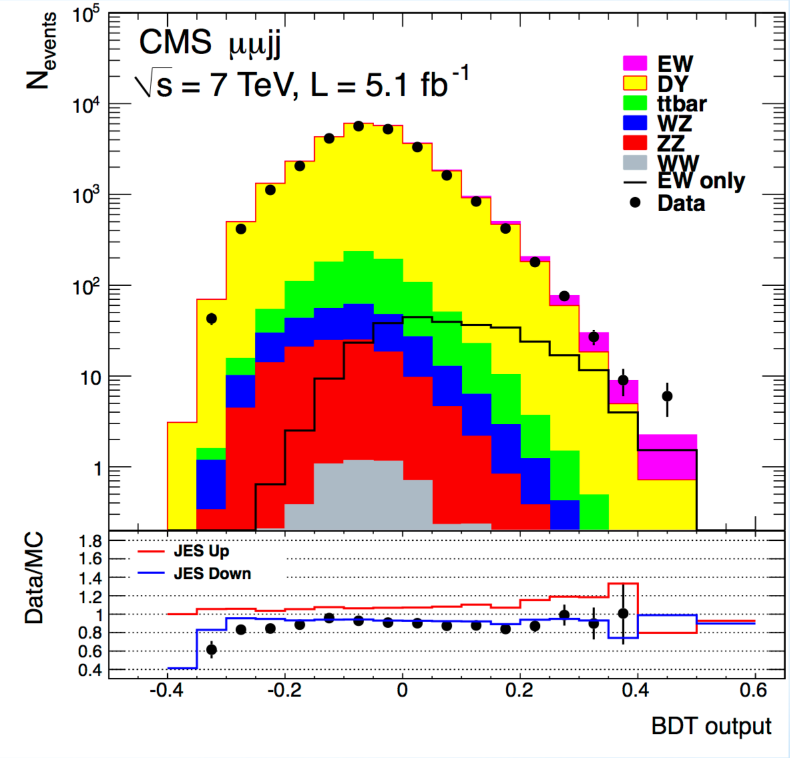
- $p_T(Z)$
- $\eta(Z)$
- $p_T(jet1)$
- $p_T(jet2)$
- $\Delta\varphi(Z,jet1)$
- $\Delta\varphi(Z,jet2)$
- $\Delta\varphi(jet1,jet2)$
- $\Delta\eta(jet1,jet2)$
- $\eta(jet1)+\eta(jet2)$
- $M(jet1+jet2)$
- gLike(jet1)
- gLike(jet2)

Preselection cuts:

$|m(ll)-m_Z|<15\text{-}20$ GeV $p_T(jet1)>65$ GeV $p_T(jet2)>40$GeV

BDT discrimination





PF jets
K_{DY} = 0.957 +/- 0.010 (stat)
K_{EWK} = 1.17 +/- 0.27 (stat)

JPT jets
K_{DY} = 0.905+/- 0.006 (stat)
K_{EWK} = 0.90 +/- 0.19 (stat)

PF jets
K_{DY} = 0.937 +/- 0.007 (stat)
K_{EWK} = 0.85 +/- 0.18 (stat)

BDT fit systematic uncertainties

Source of uncertainty	Uncertainty	
	$\mu^+\mu^-$ channel	e^+e^- channel
Theoretical uncertainties		
Background modeling	0.15	0.16
Signal modeling	0.05	0.05
$t\bar{t}$ cross section	0.03	0.03
Diboson cross sections	0.02	0.02
Total	0.16	0.17
Experimental uncertainties		
JES+JER	0.22	0.29
Pileup modeling	0.03	0.03
MC statistics	0.13	0.19
Gluon-quark discriminator	not used	0.02
Dilepton selection	0.02	0.02
Total	0.26	0.35
Luminosity	0.02	0.03

Conclusions

* measured the EWK (VBF) production of Z + 2 jets in the di-muon and di-electron channels at 7 TeV **defined with M(jj)>120 M(ll)>50 pT(j)>25 |η(j)|<4 :**

σ^{EW}(pp->eejj)(7 TeV) = 190±44(stat)±57(exp.syst)±27(th.syst)±4(lumi) fb

σ^{EW}(pp->μμjj)(7 TeV) = 146±31(stat)±42(exp.syst)±26(th.syst)±3(lumi) fb

combined

σ^{EW}(pp->lljj)(7 TeV) = 154±24(stat)±46(exp.syst)±27(th.syst)±3(lumi) fb

in agreement with VBFNLO σ^{EW}(pp->lljj)(7 TeV) = 166 fb (157 fb@LO)

Conclusions

* Produced results on the **hadronic activity in the gap** between the two tagging jets with measurements of

1) jet vetoes efficiencies and

2) soft track-jet activity.

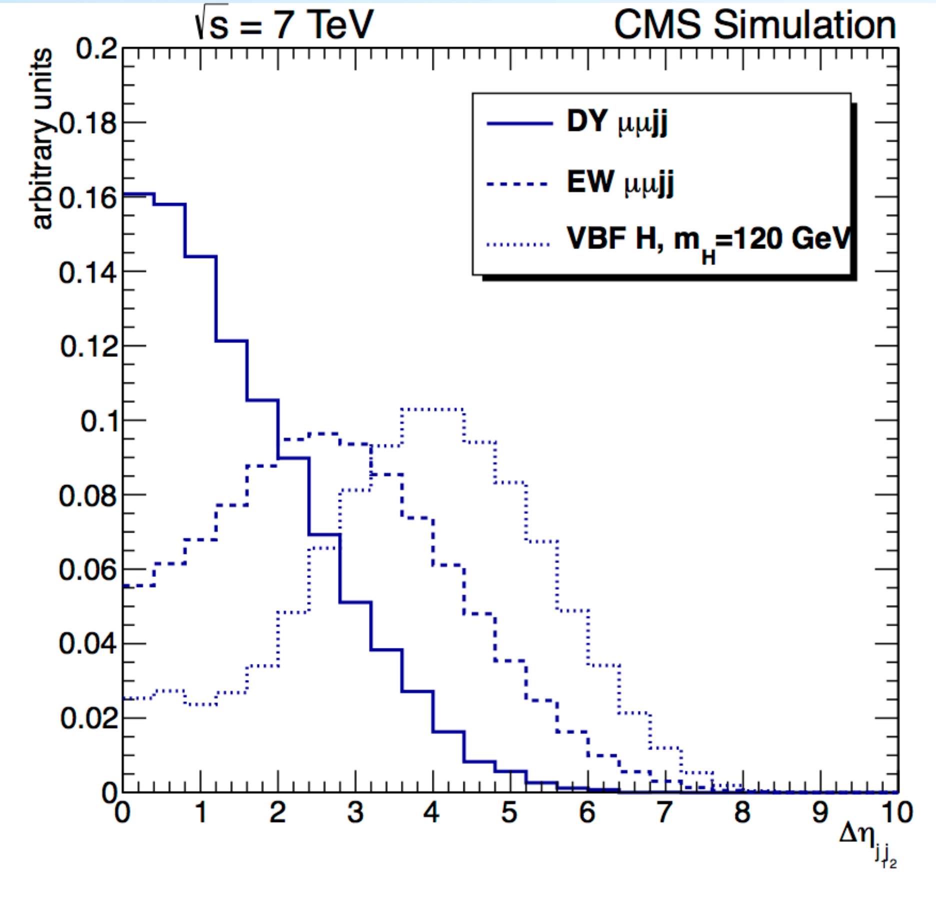
Observed good agreement with the predictions from the DY+jets simulation.

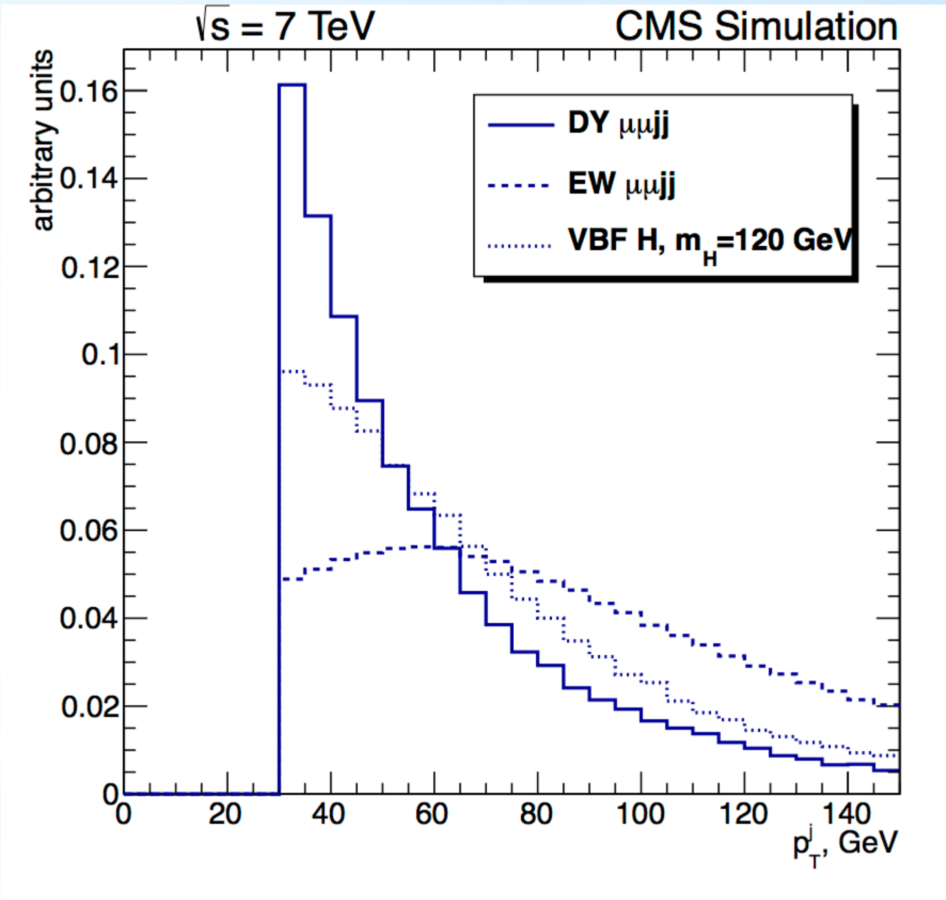
* Performed **radiation pattern measurements** following Les Houches report prescriptions: found good agreement with ME+PS (MadGraph+Pythia) predictions

* Thanks for your attention !

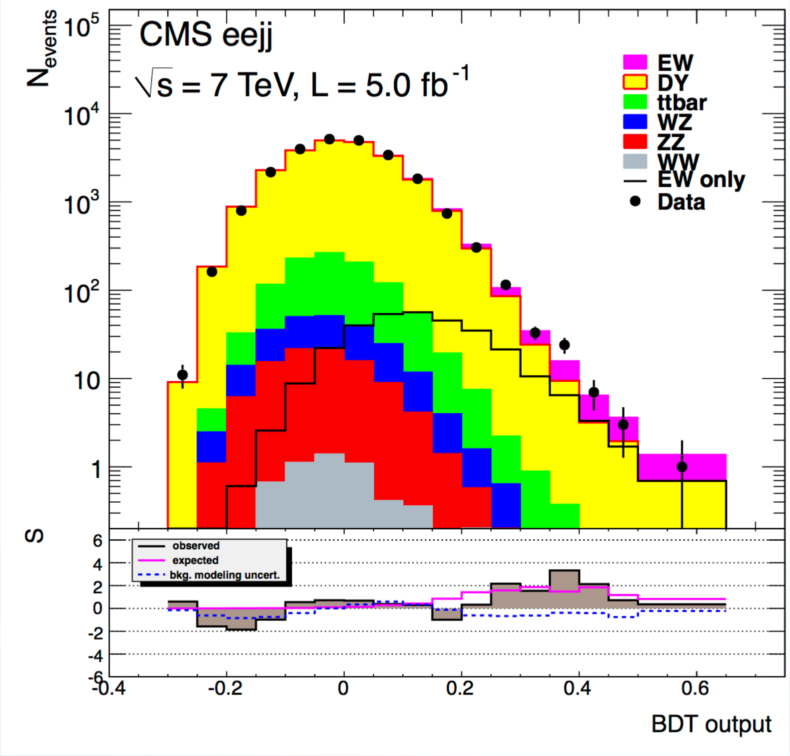
Backup

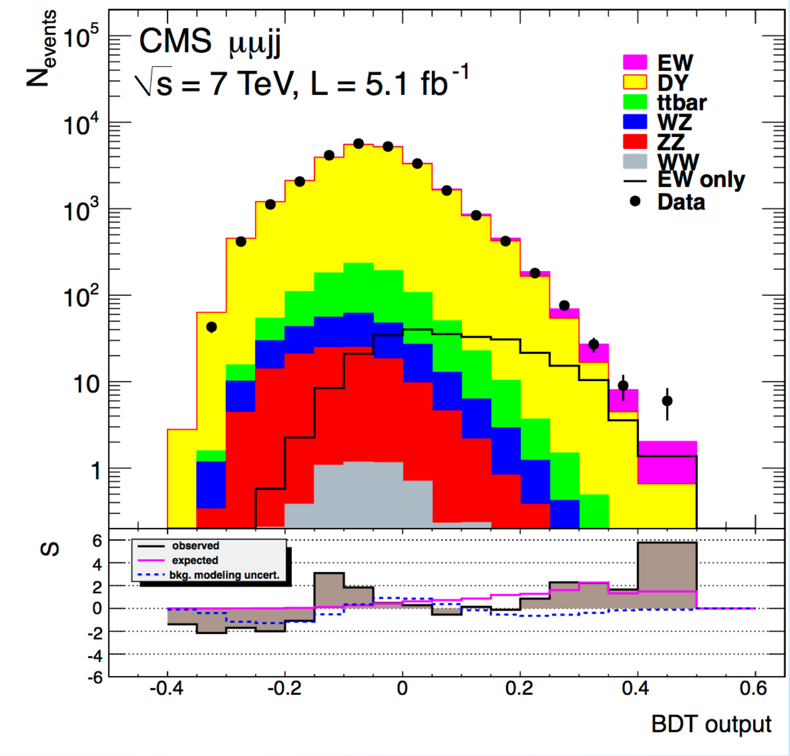
VBF Higgs(120) - EW Zjj - DY Zjj



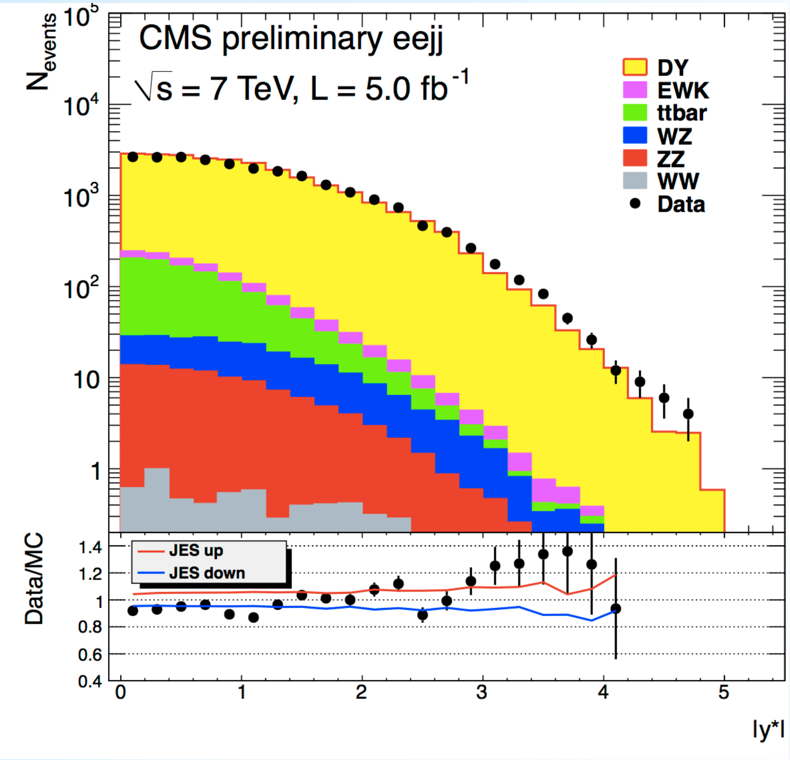


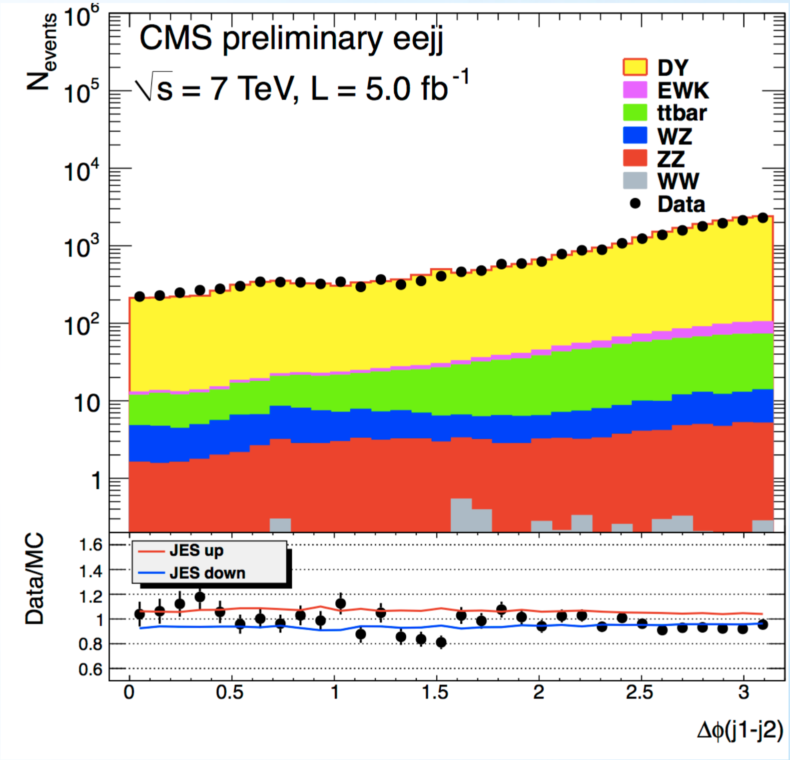
Signal significance





y* & Δφ distributions





Reference

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CMS-FSQ-12-019

CERN-PH-EP/2013-060
2013/06/03

Measurement of the hadronic activity in events with a Z and two jets and extraction of the cross section for the electroweak production of a Z with two jets in pp collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

Abstract

The first measurement of the electroweak production cross section of a Z boson with two jets (Zjj) in pp collisions at $\sqrt{s} = 7$ TeV is presented, based on a data sample recorded by the CMS experiment at the LHC with an integrated luminosity of 5 fb^{-1}. The cross section is measured for the $\ell\ell$jj ($\ell = $ e, μ) final state in the kinematic region $m_{\ell\ell} > 50$ GeV, $m_{jj} > 120$ GeV, transverse momenta $p_T^j > 25$ GeV and pseudorapidity $|\eta^j| < 4.0$. The measurement, combining the muon and electron channels, yields $\sigma = 154 \pm 24\,(\text{stat.}) \pm 46\,(\text{exp. syst.}) \pm 27\,(\text{th. syst.}) \pm 3\,(\text{lum.})$ fb, in agreement with the theoretical cross section. The hadronic activity, in the rapidity interval between the jets, is also measured. These results establish an important foundation for the more general study of vector boson fusion processes, of relevance for Higgs boson searches and for measurements of electroweak gauge couplings and vector boson scattering.

Submitted to the Journal of High Energy Physics