Vector Boson Fusion Results from CMS Experiment

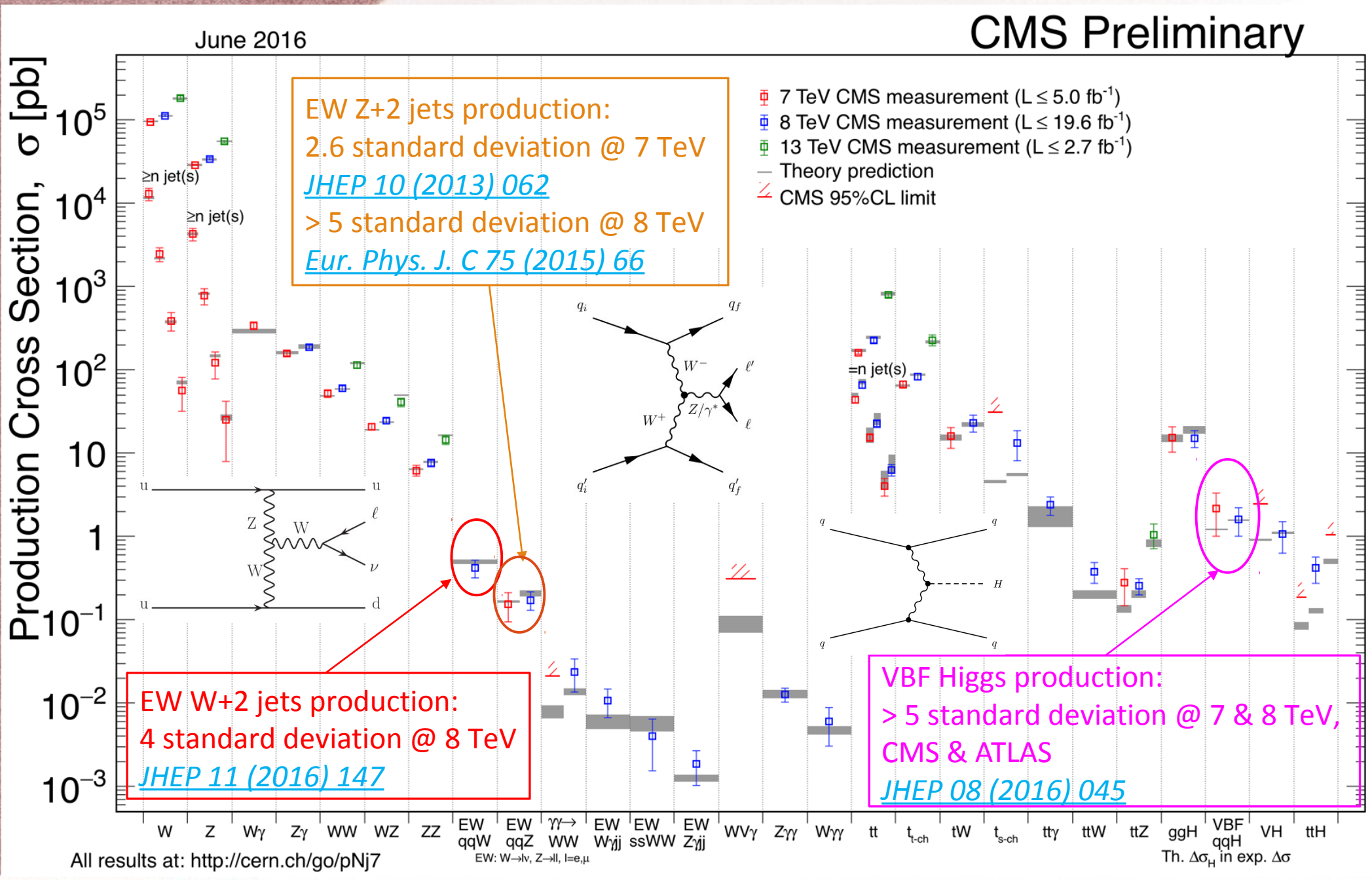
Jing Li
Peking University, Beijing, China

On behalf of the CMS Collaboration

18th December 2016

Second China LHC Physics Workshop (CLHCP 2016)
16-19 December 2016 Peking University Bejing China

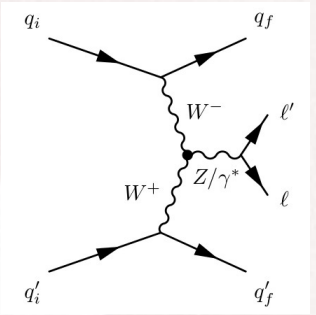
Overview

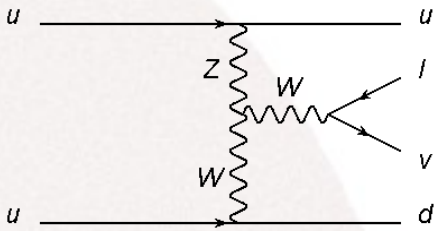

CMS Preliminary
June 2016
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
13 TeV CMS measurement (L ≤ 2.7 fb-1)
Theory prediction
CMS 95%CL limit
≥n jet(s)
≥n jet(s)
=n jet(s)
EW Z+2 jets production:
2.6 standard deviation @ 7 TeV
JHEP 10 (2013) 062
> 5 standard deviation @ 8 TeV
Eur. Phys. J. C 75 (2015) 66
EW W+2 jets production:
4 standard deviation @ 8 TeV
JHEP 11 (2016) 147
VBF Higgs production:
> 5 standard deviation @ 7 & 8 TeV, CMS & ATLAS
JHEP 08 (2016) 045
W
Z
Wγ
Zγ
WW
WZ
ZZ
EW qqW
EW qqZ
γγ→ WW
EW Wγjj
EW ssWW
EW Zγjj
WVγ
Zγγ
Wγγ
tt
t t-ch
tW
t s-ch
ttγ
ttW
ttZ
ggH
VBF qqH
VH
ttH
EW: W→lν, Z→ll, l=e,μ
Th. Δσ_H in exp. Δσ
All results at: http://cern.ch/go/pNj7

Introduction

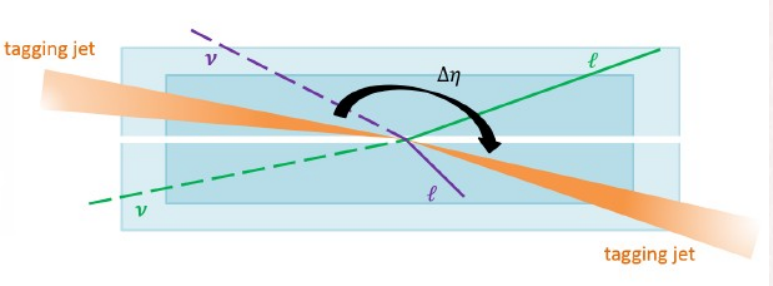
Vector Boson Fusion (VBF) Standard Model (SM) processes

- Rare and novel processes: first measurement of VBF Z+2 jets and W+2 jets process





- Clean environment with less QCD activity (jets property measurement)



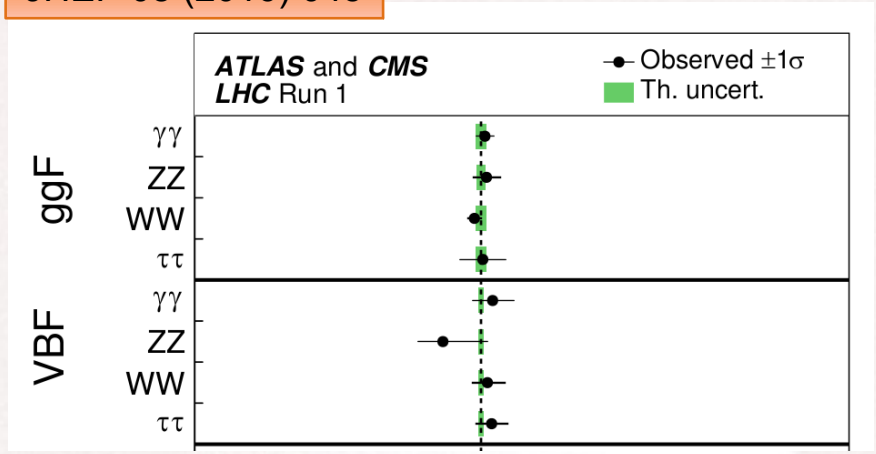
- Crucial tests of SM unitarity at high energy

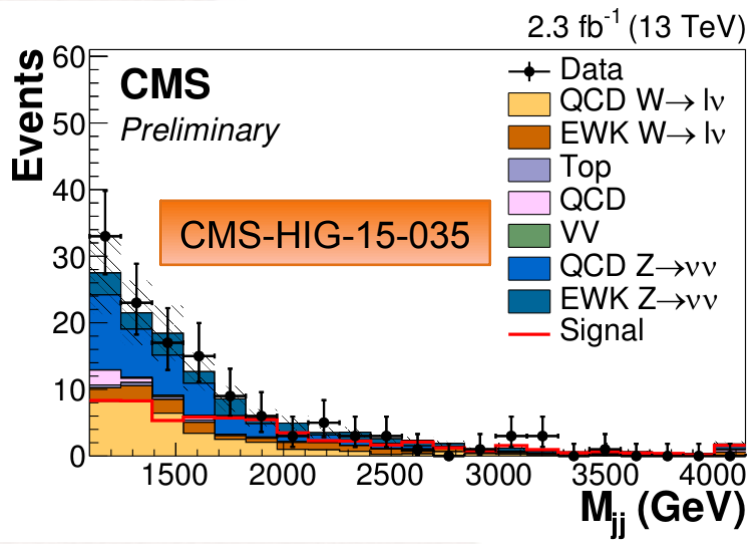
Introduction

Higgs boson produced through VBF established at > 5 σ

- Important production process of Higgs boson
- Constraints on Higgs boson couplings

JHEP 08 (2016) 045

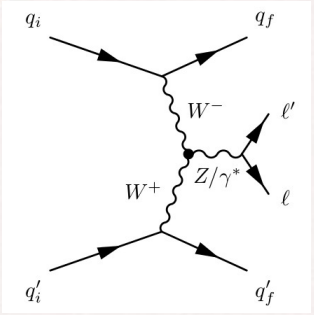




- VBF Z+2 jets and W+2 jets are important backgrounds of SM Higgs in VBF channel and in searching invisible Higgs

VBF characteristics

- Two VBF tagged jets



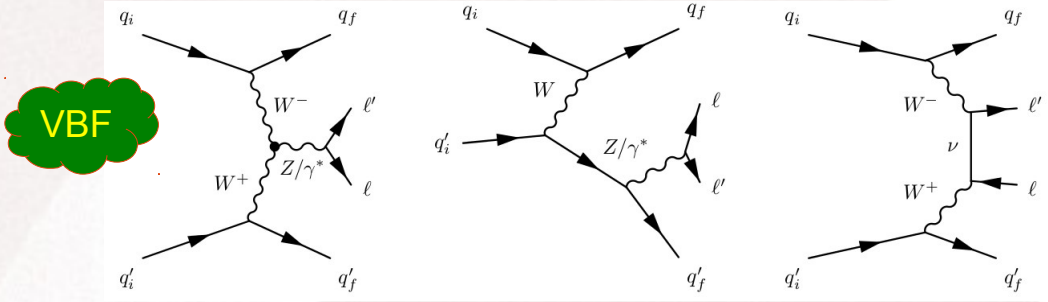
  - More quark-like
  - High energy and large dijet invariant mass m_{jj}
  - Separated by a large rapidity interval $|\Delta\eta_{jj}|$
- Lower central hadronic activities
  - Extra gluon emission is suppressed
  - Occupied by the boson, which is balanced with respect to the dijet system

$$y^* = y_Z - \frac{1}{2}(y_{j_1} + y_{j_2}).$$

$$Rp_T^{hard} = \frac{|\vec{p}_{Tj_1} + \vec{p}_{Tj_2} + \vec{p}_{TZ}|}{|\vec{p}_{Tj_1}| + |\vec{p}_{Tj_2}| + |\vec{p}_{TZ}|} = \frac{|\vec{p}_T^{hard}|}{|\vec{p}_{Tj_1}| + |\vec{p}_{Tj_2}| + |\vec{p}_{TZ}|},$$

Theoretical inputs

- Diagrams other than VBF-like (EW Z+2 jets / EW W+2 jets)
  - Large negative interference between the pure VBF process and the other categories
  - Suppressed in VBF selection region



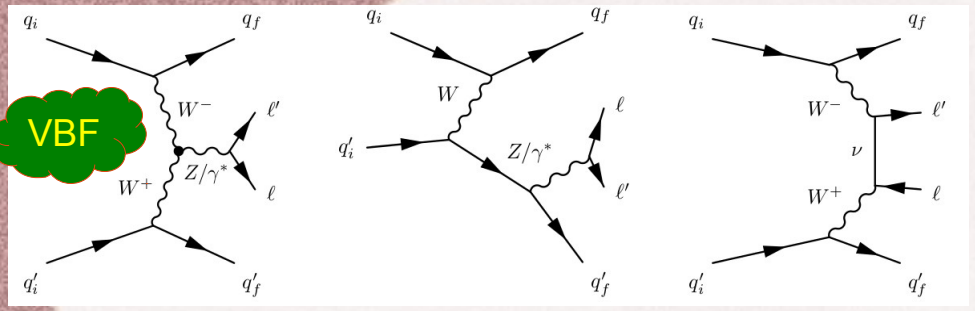
- NLO/LO k-factors
  - VBFNLO, usually flat and near unity in VBF region
- Interference
  - Between EW and QCD, modeled by MadGraph, included inside nominal result or for systematics

8 TeV

CMS-FSQ-12-035

Eur. Phys. J. C 75 (2015) 66

EW Zjj



Signal sample:
– Simulated by MadGraph at leading order (consistent with results with VBFNLO)
– Use VBFNLO to derive NLO/LO k-factor
– Interference effect included inside nominal result and for systematics

Main background:
– QCD Z+jets production: simulated from MadGraph MLM matching, NLO/LO k-factor with MCFM, cross section normalized to NNLO prediction calculated with FEWZ, validated in control region

Event selection:

- Two same flavor opposite sign isolated leptons with $p_T > 20$ GeV
- More than two jets with leading jet $p_T > 50$ GeV, second leading jet $p_T > 30$ GeV

- q-g discriminator
- $m_{jj} > 200$ GeV
- $|y_Z - (y_{j1} + y_{j2})/2| < 1.2$
- $|m_Z - m_{ll}| < 15$ GeV

- Signal region: $R_{pT}^{hard} < 0.14$
- Control region: $R_{pT}^{hard} >= 0.14$, with only one jet

8 TeV

CMS-FSQ-12-035

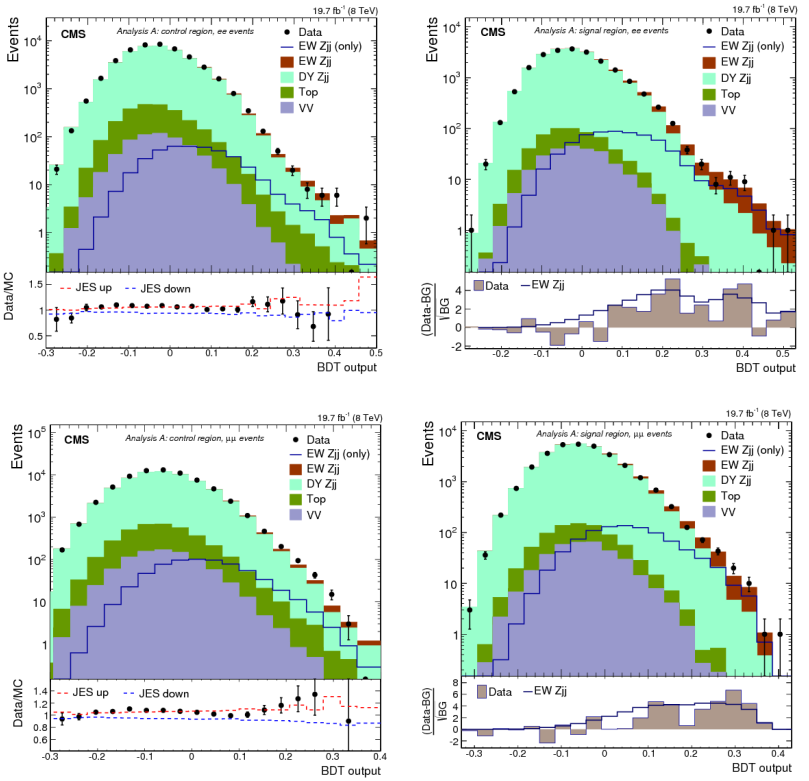
Eur. Phys. J. C 75 (2015) 66

EW Zjj

Signal extraction
– Using MVA methods to enhance the separation
– Signal extracted with CIs method, in both signal and control regions

$$\hat{N}^{\ell\ell jj}(\mu, v) = \mu N_{\text{EW Zjj}} + \sqrt{\mu v} N_{\text{I}} + v N_{\text{DY Zjj}},$$

Dominant systematic
– QCD Z+2 jets prediction
– Interference effect
– Jet energy scale and resolution



Fiducial region:

- $M_{ll} > 50$ GeV, $m_{jj} > 120$ GeV, $p_{Tj} > 25$ GeV, $|\eta_j| < 5$

$$\sigma_{\text{EW}}(\ell\ell jj) = 174 \pm 15\,(\text{stat}) \pm 40\,(\text{syst})\ \text{fb},$$

Good agreement with theoretical LO prediction

$$\sigma_{\text{LO}}(\text{EW}\ \ell\ell jj) = 208^{+8}_{-9}\,(\text{scale}) \pm 7\,(\text{PDF})\ \text{fb},$$

> 5 standard deviation

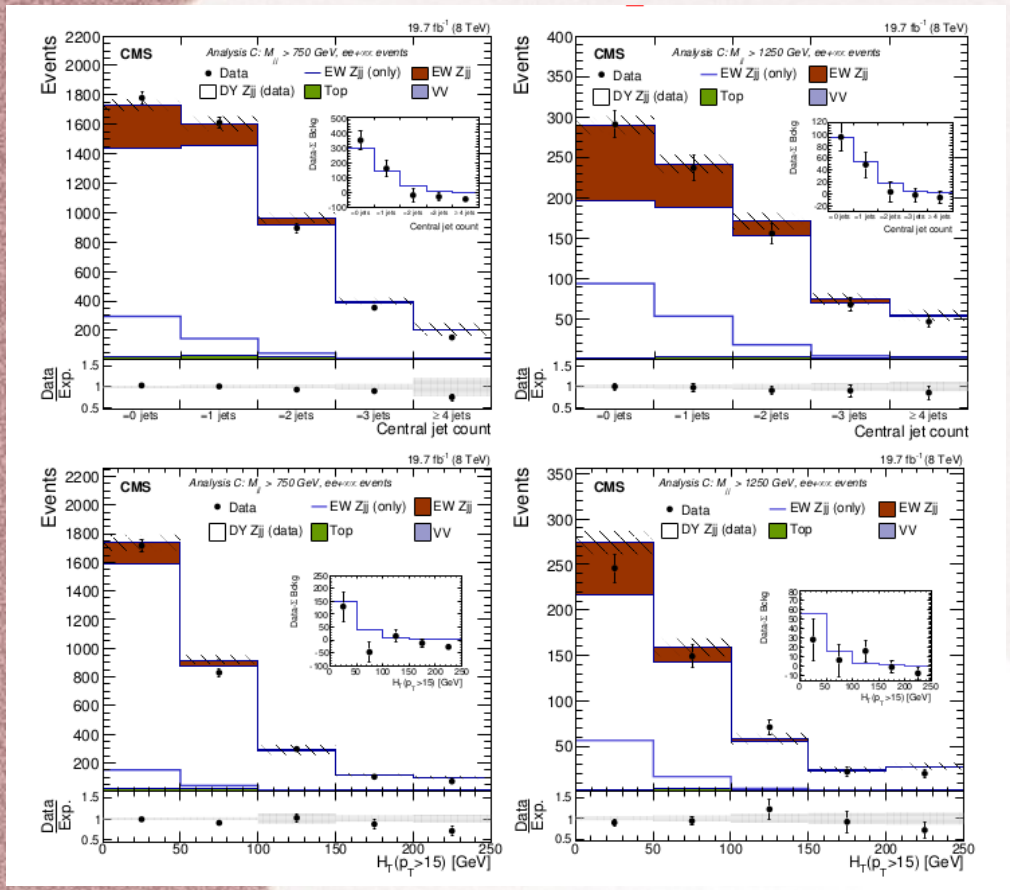
8 TeV

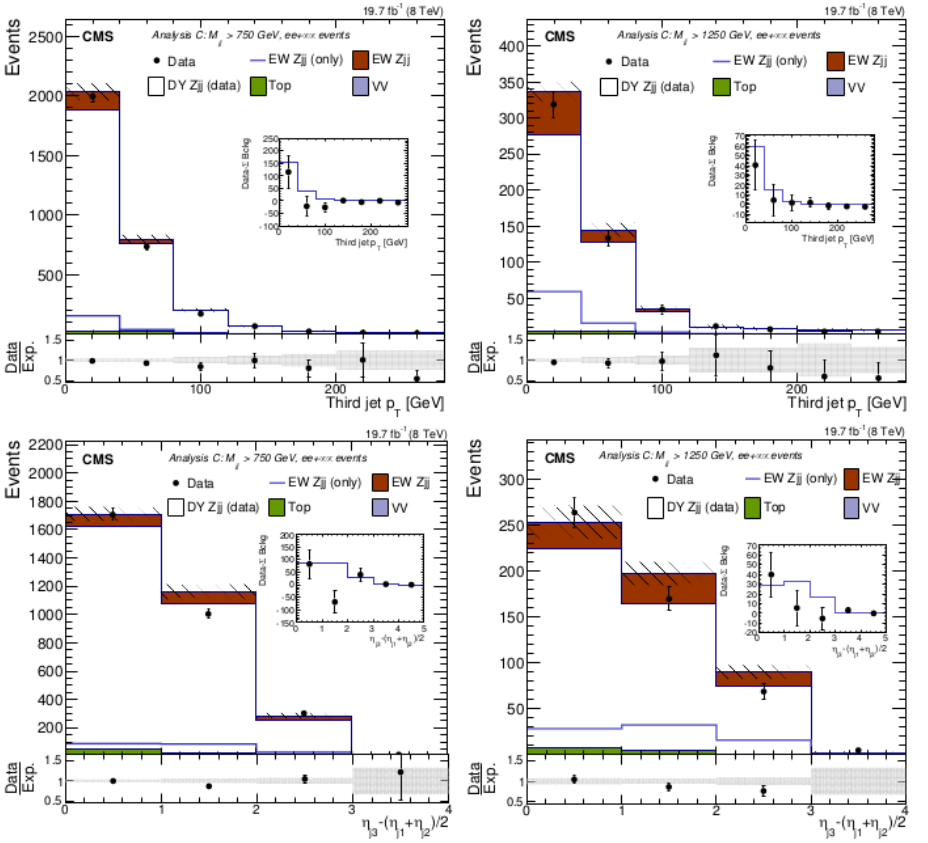
CMS-FSQ-12-035

Eur. Phys. J. C 75 (2015) 66

EW Zjj

- Study of hadronic activities



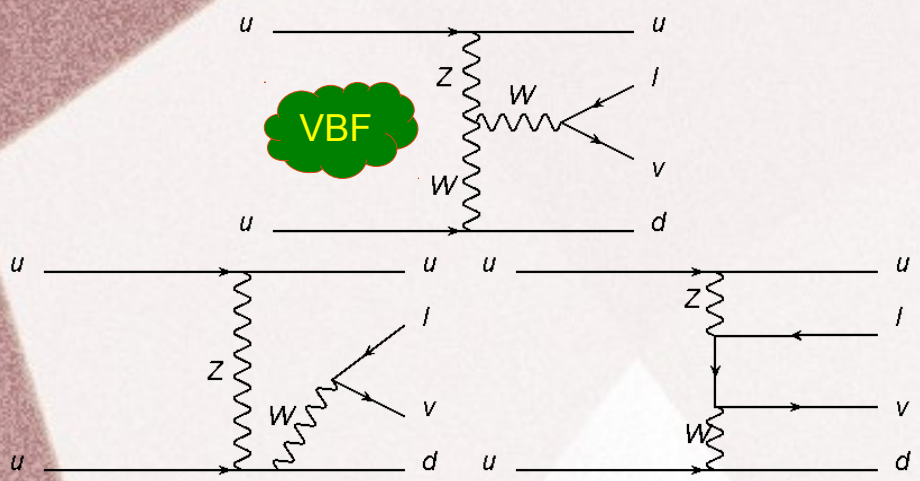


8 TeV

CMS-SMP-13-012

JHEP 11 (2016) 147

EW Wjj



Event selection:

- One isolated elecrtrom (muon) with p_T > 30 (25) GeV
- More than two jets with leading jet p_T > 60 GeV, second leading jet p_T > 50 GeV
- Significant MET > 30 (25) GeV

- m_{jj} > 1000 GeV
- $|y_w - (y_{j1} + y_{j2})/2| < 1.2$
- Second lepton veto

Signal sample:
– Simulated by MadGraph at leading order
– Use VBFNLO to derive NLO/LO k-factor: variation in signal strength < 1%
– Interference effect treated as systematic

Main background:
– QCD W+jets production: simulated from MadGraph MLM matching, cross section normalized to NNLO prediction calculated with FEWZ, data-driven normalization & shape correction

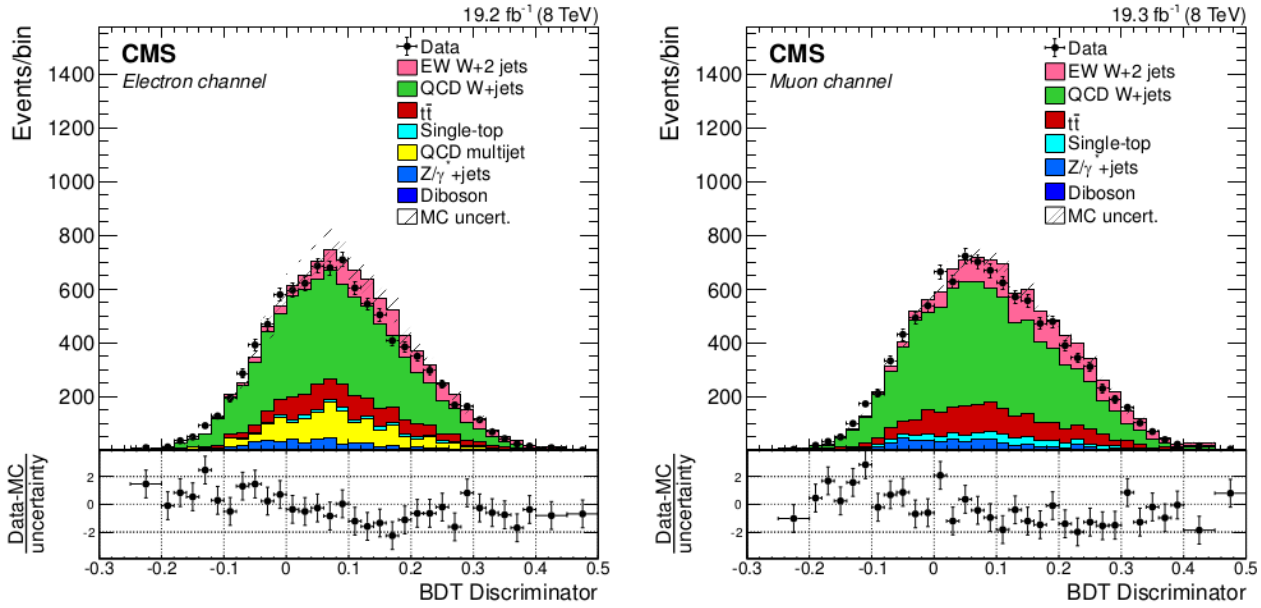
8 TeV

CMS-SMP-13-012

JHEP 11 (2016) 147

EW Wjj

Data-driven QCD W+jets normalization:
– Using MVA methods to define a QCD control region
– Trained to distinguish between EW W+2 jets and QCD W+jets events



Signal free region: BDT<0.1
Overestimation of the QCD W+jets event yield

- Normalization scale factors: 0.71 ± 0.02 (stat) ± 0.03 (syst) for electron channel, 0.70 ± 0.02 (stat) ± 0.05 (syst) for muon channel

8 TeV

CMS-SMP-13-012

JHEP 11 (2016) 147

EW Wjj

Signal extraction
– Unbinned maximum likelihood fit to m_{jj}
– Floating QCD W+jets shape

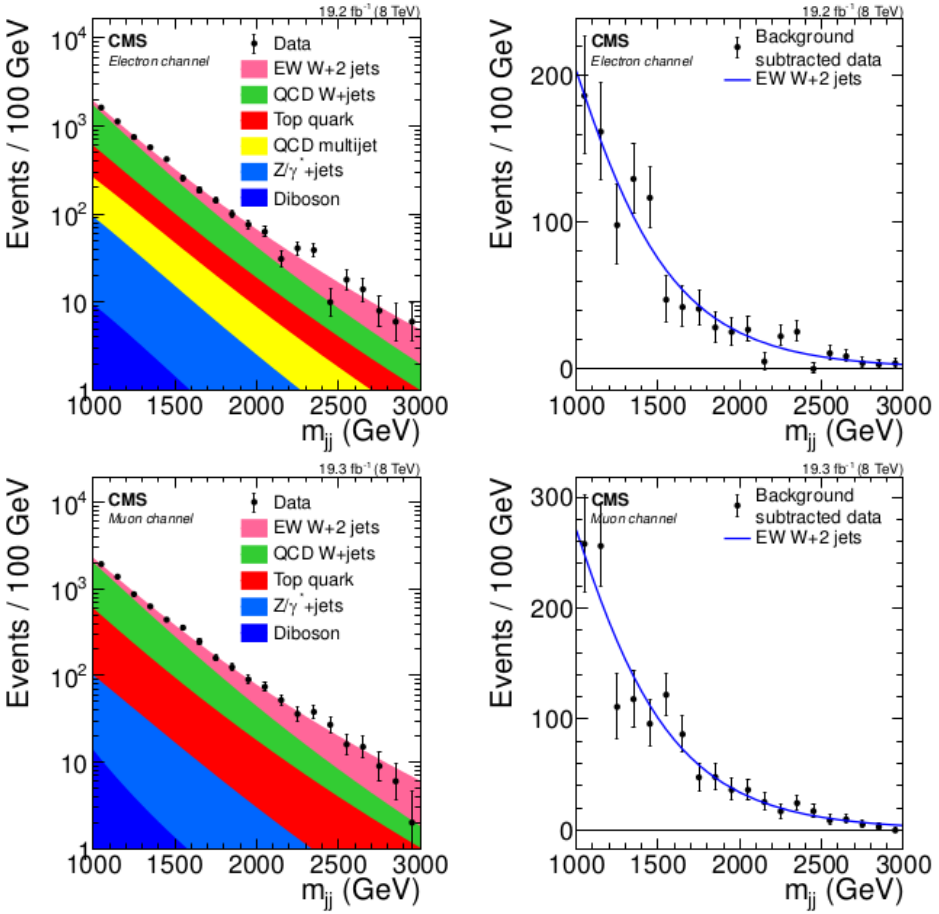
$$\mathcal{F} = \frac{1}{m_{jj}^{a_0 + a_1 \ln(m_{jj}/8000)}},$$

Dominant systematic
– QCD W+2 jets prediction
– Interference effect
– Jet energy scale and resolution

Fiducial region:

- $p_T^{j1} > 60$ GeV, $|\eta^{j1}| < 4.7$, $p_T^{j2} > 50$ GeV, $|\eta^{j2}| < 4.7$, $m_{jj} > 1000$ GeV
- W decays to μν or eν

Channel	Measured cross section
Electron	$0.41 \pm 0.04\,(\text{stat}) \pm 0.09\,(\text{syst}) \pm 0.01\,(\text{lumi})$ pb
Muon	$0.43 \pm 0.04\,(\text{stat}) \pm 0.10\,(\text{syst}) \pm 0.01\,(\text{lumi})$ pb
Combined	$0.42 \pm 0.04\,(\text{stat}) \pm 0.09\,(\text{syst}) \pm 0.01\,(\text{lumi})$ pb



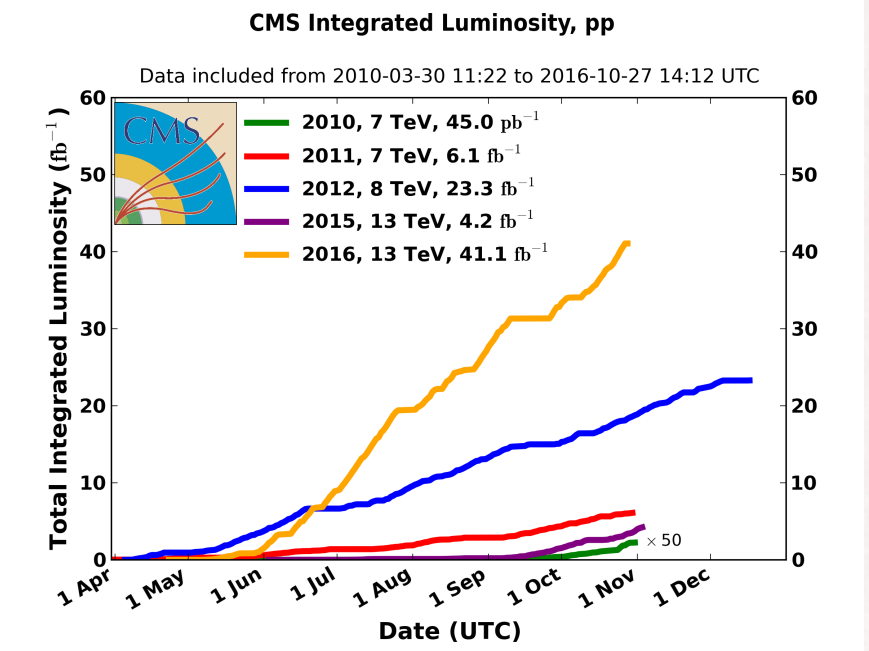
Good agreement with theoretical LO prediction

$$0.50 \pm 0.02(\text{scale}) \pm 0.02(\text{PDF})\ \text{pb}$$

First measurement

Summary

- Vector Boson Fusion (VBF) Higgs established at > 5 σ
- First measurement of VBF Z+2 jets and W+2 jets process
- With limited statistics, VBF topology has been studied
- With O(100 fb^{-1}) data of Run2, a lot more to do!



Thank you!

Backup

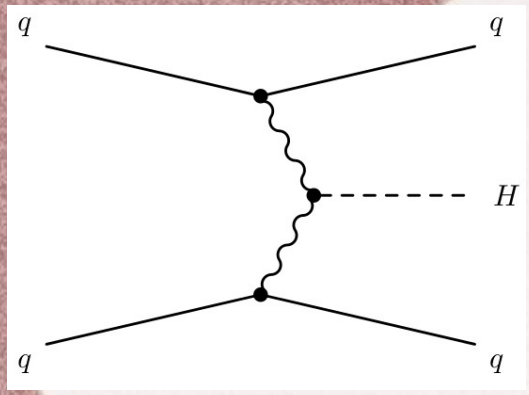
Backup

7&8 TeV

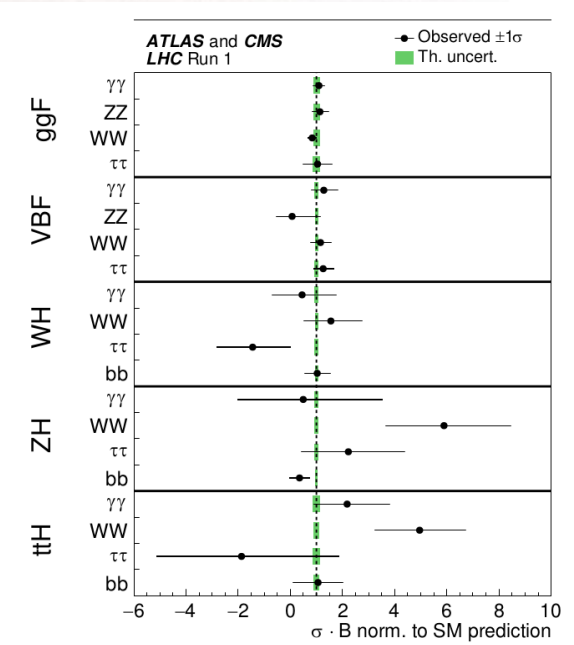
CMS-HIG-15-002

JHEP 08 (2016) 045

VBF Higgs



VBF Higgs production:
Measured with H → YY, ZZ, WW, ττ
Signal sample: simulated with POWHEG



Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6

Production process		Decay mode								
		$H \to \gamma\gamma$ [fb]			$H \to ZZ$ [fb]			$H \to WW$ [pb]			$H \to \tau\tau$ [fb]		
		Best fit value	Uncertainty Stat	Syst	Best fit value	Uncertainty Stat	Syst	Best fit value	Uncertainty Stat	Syst	Best fit value	Uncertainty Stat	Syst
VBF	Measured	$4.6^{+1.9}_{-1.8}$	$^{+1.8}_{-1.7}$	$^{+0.6}_{-0.5}$	3^{+46}_{-26}	$^{+46}_{-25}$	$^{+7}_{-7}$	$0.39^{+0.14}_{-0.13}$	$^{+0.13}_{-0.12}$	$^{+0.07}_{-0.05}$	125^{+39}_{-37}	$^{+34}_{-32}$	$^{+19}_{-18}$
		$(^{+1.8}_{-1.6})$	$(^{+1.7}_{-1.6})$	$(^{+0.5}_{-0.4})$	$(^{+60}_{-39})$	$(^{+60}_{-39})$	$(^{+8}_{-5})$	$(^{+0.15}_{-0.13})$	$(^{+0.13}_{-0.12})$	$(^{+0.07}_{-0.06})$	$(^{+39}_{-37})$	$(^{+34}_{-32})$	$(^{+19}_{-18})$
	Predicted	3.60 ± 0.20			42.2 ± 2.0			0.341 ± 0.017			100 ± 6		
	Ratio	$1.3^{+0.5}_{-0.5}$	$^{+0.5}_{-0.5}$	$^{+0.2}_{-0.1}$	$0.1^{+1.1}_{-0.6}$	$^{+1.1}_{-0.6}$	$^{+0.2}_{-0.2}$	$1.2^{+0.4}_{-0.4}$	$^{+0.4}_{-0.3}$	$^{+0.2}_{-0.2}$	$1.3^{+0.4}_{-0.4}$	$^{+0.3}_{-0.3}$	$^{+0.2}_{-0.2}$