Electroweak diboson scattering results from CMS

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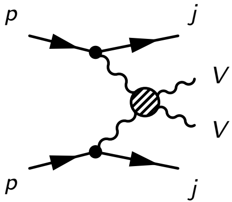
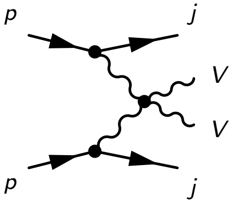
Electroweak scattering processes have a rich phenomenology
that has not been fully explored yet

- **Electroweak vector boson scattering** is an example of a **largely untested** phenomenon tightly tied to the **gauge structure** of the electroweak theory.
- Very small cross sections ($\mathcal{O}(\text{fb})$). The LHC is the first hadron collider where it's possible to study this kind of phenomena.



Introduction (2/2)



Some features of the events:

- No color connection between the tagging jets. Clean rapidity gap.
- Higgs mediated contribution yields the scattering of longitudinal vector bosons unitary.

This is a process sensitive to differences in the quartic gauge coupling. Differences from the SM prediction can be studied via:

- Effective Field Theories (EFT), if the scale of New Physics is not experimentally accesible.
- Complete BSM models, otherwise.

VBS-VV measurements at CMS

Measurements of VBS-VV processes is a rich physics program at CMS

Electroweak scattering

- $\boxed{pp \to W^{\pm}W^{\pm}jj}$ **TODAY** (`arXiv:1410.6315, submitted to PRL`)
- $pp \to W^{\pm}W^{\mp}jj$
- $pp \to W^{\pm}Zjj$
- $pp \to W^{\pm}\gamma jj$
- $pp \to Z\gamma jj$

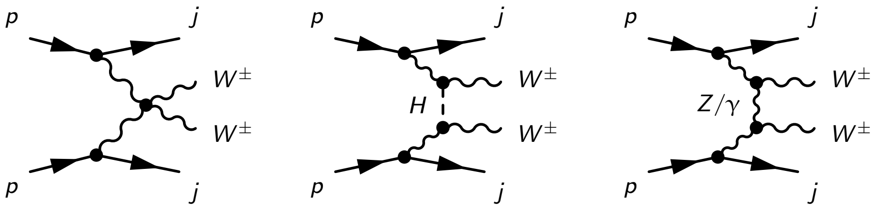
Exclusive photo-production

- $\gamma\gamma \to W^{+}W^{-}$

VBF Higgs processes

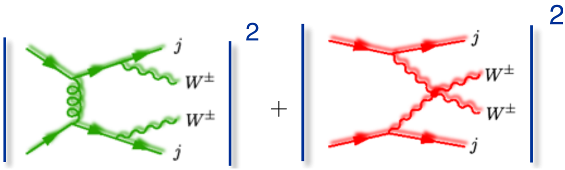
- $pp \to Hjj \to W^{+}W^{-}jj$
- $pp \to Hjj \to ZZjj$

Same-sign WW scattering



- Measurement done in the $\mu^+\mu^+\nu_\mu\nu_\mu jj$, $e^+e^+\nu_e\nu_e jj$, $\mu^+e^+\nu_\mu\nu_e jj$ (and CP-conjugates) final states.
- Same-sign requirement supresses the strong (QCD) production of W-boson pairs.
- High-mass, large rapidity-gap, jet pair to identify the electroweak vector-boson scattering.

Signal definition



+ Interference Terms

Two common options for "signal" definition

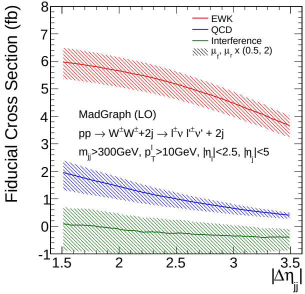
- (QCD + EWK + Interference) as signal.
- (EWK + Interference) as signal, QCD as background.

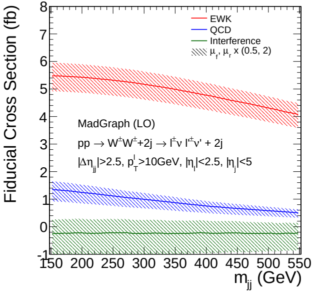
The signal in the second option does not have a proper physical meaning and the separation is only possible at leading order.
Despite the interpretation ambiguity, we report the observed significance for both options.

Fiducial cross section definition

We define a fiducial region for the measurement where the "electroweak component" is dominant.

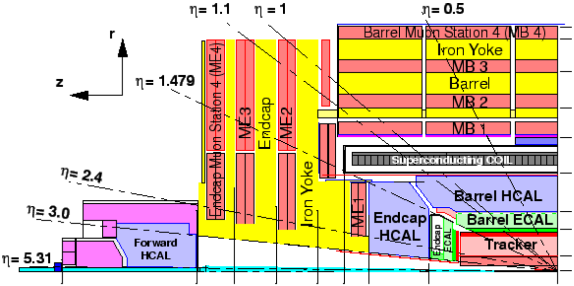
- $p_T^\ell > 10$ GeV
- $|\eta_\ell| < 2.5$
- $p_T^{\text{jet}} > 20$ GeV
- $|\eta_{\text{jet}}| < 5.0$
- $m_{jj} > 300$ GeV
- $|\Delta\eta_{jj}| > 2.5$





- We use VBFNLO to calculate a NLO/LO flat *k-factor* in the fiducial region (0.87)
- The *k-factor* is used to correct the MADGRAPH prediction, yielding $\sigma_{\text{fid}}(W^\pm W^\pm jj) = 5.8 \pm 1.2\,\text{fb}$ (QCD+EWK+Interference)

The CMS detector and the data



CMS is a general purpose detector

Object acceptances used in this measurement

- Jets $|\eta^{\text{jet}}| < 4.7$
- Muons $|\eta^{\mu}| < 2.4$
- Electrons $|\eta^{e}| < 2.5$

This measurement uses the full $\sqrt{s} = 8\,\text{TeV}$ data set corresponding to an integrated luminosity of $19.4 \pm 0.5\,\text{fb}^{-1}$.

Basic event selection

Two same-sign leptons and two jets

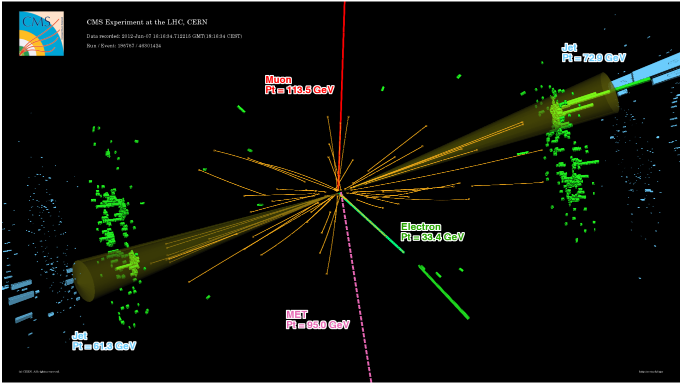
- Two same-sign leptons (electrons or muons) with $p_T^{\ell} > 20\,\text{GeV}$,
- At least two jets with $p_T^{\text{jet}} > 30\,\text{GeV}$.

VBS selection

- $m_{jj} > 500\,\text{GeV}$,
- $|\Delta\eta_{jj}| > 2.5$.

Neutrinos

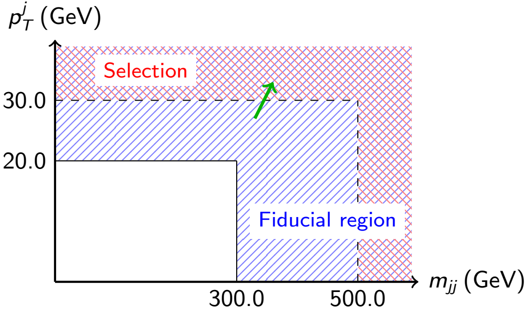
- $E_T^{\text{miss}} > 40\,\text{GeV}$



Signal efficiency

- The fiducial volume in which we measure the cross section is larger than the one defined by the event selection.
- The larger fiducial region is closed with respect to energy fluctuations.
- The extrapolation to a larger fiducial region introduces scale uncertainties in the signal efficiency.

- Fiducial region (acceptance × efficiency): 7.9%
- Ratio of acceptance between the fiducial region defined by the event selection and the one used in the measurement: 36%



Backgrounds and additional selection

With only the basic selection, the signal/background ≈ 0.1.

Main sources of backgrounds

- WZ events
- $t\bar{t}$ events
- $V+$jets events

Background rejection

- $m_{\ell\ell} > 50\,\text{GeV}$ to supress non-prompt leptons.
- Events are not consistent with a top quark decay.
  - Reject events with extra non-isolated soft muons ($p_T > 3\,\text{GeV}$),
  - Reject events with b-jets identified by their secondary vertex.
- Events are not consistent with a Z-boson decay.
  - Veto events with a loosely isolated third lepton with $p_T^{\ell} > 10\,\text{GeV}$,
  - Veto events in which one of the identified leptons and a third lepton (without isolation requirement) have invariant mass consistent with a Z boson.
  - Veto events in which one of the identified leptons and an isolated track have invariant mass consistent with a Z boson.

WZ background

- Simulated with MADGRAPH
- Normalization measured in data by selecting a third lepton with $p_T^\ell > 10\,\mathrm{GeV}$ consistent with a Z boson decay.
  - Require a third lepton in the event with $p_T^\ell > 10\,\mathrm{GeV}$,
  - Remove the requirement that the two highest p_T leptons have same sign,
  - Require the opposite-sign same-flavor pair to be consistent with a Z boson decay $|m_{\ell\ell} - m_Z| < 15\,\mathrm{GeV}$.
- This is equivalent to a cross section measurement. Using the same fiducial region as defined for the $W^\pm W^\pm jj$ measurement, we obtain:

$$\sigma_{\mathrm{fid}}(WZjj) = 10.8 \pm 4.0\,(\mathrm{stat.}) \pm 1.3\,(\mathrm{syst.})\,\mathrm{fb}$$

- SM expectation (using MADGRAPH with *k-factor* from VBFNLO): $14.4 \pm 4.0\,\mathrm{fb}$.
- The *WZ* fiducial cross section is dominated by the strong component.

Other backgrounds and event composition

Non-prompt leptons

- Measured in data using a sample of loosely isolated leptons.
- "Fake-rate" probability measured with a dijet data control sample.

Wrong sign leptons

- Negligible in final states with muons.
- Suppressed in final states with electrons by applying a very strict requirement on the charge measurement.
  - Charge measured with the pixel detector.
  - Charge measured by the tracker with Kalman Filter reconstruction.
  - Charge measured by the tracker with Gaussian Sum Filter reconstruction.

Other sources of background are very small and estimated with MC simulation.

	Nonprompt	WZ	VVV	Wrong sign	WW DPS	Total bkg.	$W^\pm W^\pm jj$	Data
$\mu^\pm\mu^\pm$	2.1 ± 0.6	0.2 ± 0.1	0.1 ± 0.1	—	—	2.4 ± 0.6	3.0 ± 0.1	2
$e^\pm e^\pm$	0.6 ± 0.2	0.3 ± 0.1	0.1 ± 0.1	—	—	1.0 ± 0.2	1.4 ± 0.1	3
$e^\pm\mu^\pm$	1.5 ± 0.4	0.5 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	2.3 ± 0.5	4.5 ± 0.1	7
W^+W^+	2.1 ± 0.6	0.6 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	3.1 ± 0.6	7.1 ± 0.1	10
W^-W^-	2.1 ± 0.5	0.4 ± 0.1	0.1 ± 0.1	—	—	2.6 ± 0.5	1.8 ± 0.1	2
$W^\pm W^\pm$	4.2 ± 0.8	1.0 ± 0.1	0.3 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	5.7 ± 0.8	8.9 ± 0.1	12

After background rejection, signal/background ≈ 1.5

Uncertainties

Systematic uncertainties (%) in the signal and background components:

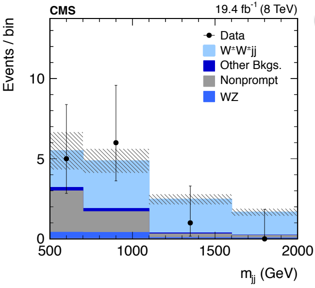
Source	Signal	*WW* DPS	*WZ*	Wrong sign	VVV	Non-prompt
Luminosity	2.6	2.6	-	2.6	2.6	-
Lepton efficiency	3.6	3.6	3.6	3.6	3.6	-
Momentum resolution	0.2	0.2	0.2	0.2	0.2	-
b-tagging	2.0	2.0	-	2.0	2.0	-
E_T^{miss}	1.0	1.0	1.0	1.0	1.0	-
JES	3.0	3.0	3.0	3.0	3.0	-
PDF	7.7	7.0	7.1	-	-	-
QCD scales EWK	5.0	-	-	-	-	-
QCD scales VVV	-	-	-	-	50.0	-
WZ normalization	-	-	37.0	-	-	-
Wrong sign normalization	-	-	-	10.0	-	-
Non-prompt normalization	-	-	-	-	-	36.0
MC statistics	2.0	57.0	15.0	55.0	18.0	19.0

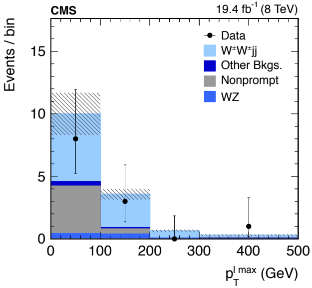
Statistical uncertainty: $+60\%$, -50%.

The measurement is heavily statistically limited!

Results - cross section

The data is analyzed in four bins of m_{jj}, separately for each charge final state.





Fiducial cross section

$$\sigma_{\text{fid}}(W^{\pm}W^{\pm}jj) = 4.0^{+2.4}_{-2.0}\,(\text{stat.})^{+1.1}_{-1.0}\,(\text{syst.})\text{ fb} \qquad (\sigma^{\text{SM}}_{\text{fid}} = 5.8 \pm 1.2\text{ fb})$$

Significance

- (QCD + EWK + Interference) signal: 3.1σ (exp), 2.0σ (obs)
- (EWK + Interference) signal: 2.9σ (exp), 1.9σ (obs)

EFT analysis and anomalous quartic gauge couplings

Any BSM physics can be described by a series of operators with mass dimension larger than 4.

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}}[A_j] + \sum_{d>4} \sum_{k} \frac{F_k}{\Lambda_k^{d-4}} \mathcal{O}_k^{(d)}[A_j]$$

- If the scale Λ of the new physics is large, only the first few terms will be relevant.
- Each individual term is not renormalizable and will violate tree-level unitarity at some energy.
- This is not a problem. It just means that, at these energies, the EFT approach is no longer valid.

- BSM theories can generate specific combinations of higher-dimensional operators based on the symmetries they respect.
- The measurement of a non-zero higher-dimensional coupling constant can guide the search for New Physics in the future by **constraining the form** and **giving an energy scale**.

- The first higher-dimension purely electroweak operators have mass dimension 6.
- These operators modify vector boson propagators (S, T, U parameters) and generate anomalous triple gauge couplings.
- Some of these operators, eg. $\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}]$, generate anomalous quartic gauge couplings.
- They are much better constrained with other measurements.

Quartic gauge couplings and dimension-eight operators

- The first operators that generate aQGCs while not modifying the S, T, U parameters nor generating aTGCs are dimension-eight.
- There are three classes of dimension-eight operators that generate aQGC.

Tensor operators

$$\mathcal{O}_{T0} = Tr[W_{\mu\nu}W^{\mu\nu}] \times Tr[W_{\alpha\beta}W^{\alpha\beta}]$$
$$\mathcal{O}_{T1} = Tr[W_{\mu\nu}W^{\alpha\beta}] \times Tr[W_{\alpha\beta}W^{\mu\nu}]$$
$$\mathcal{O}_{T2} = Tr[W_{\mu\alpha}W^{\alpha\nu}] \times Tr[W_{\nu\beta}W^{\beta\nu}]$$

Scalar operators

$$\mathcal{O}_{S0} = [(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\mu\Phi)^\dagger D^\nu\Phi]$$
$$\mathcal{O}_{S1} = [(D_\mu\Phi)^\dagger D^\mu\Phi] \times [(D_\nu\Phi)^\dagger D^\nu\Phi]$$

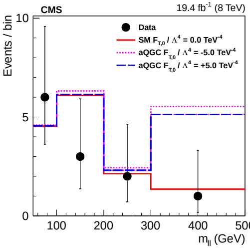
Mixed operators

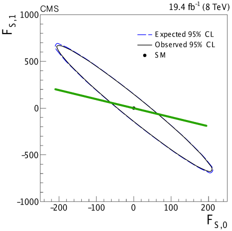
$$\mathcal{O}_{M0} = Tr[W_{\mu\nu}W^{\mu\nu}] \times [(D_\mu\Phi)^\dagger D^\mu\Phi]$$
$$\mathcal{O}_{M1} = Tr[W_{\mu\nu}W^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\mu\Phi]$$
$$\mathcal{O}_{M6} = [(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\nu}(D^\mu\Phi)]$$
$$\mathcal{O}_{M7} = [(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\mu}(D^\nu\Phi)]$$

- The combination $(f/\Lambda^4)(\mathcal{O}_{S0} - \mathcal{O}_{S1})$ only modifies the SM quartic couplings by $(1 + fv^4/8\Lambda^4)$.
- In the absence of unitarization procedures, these operators can be related to the LEP parametrization (Éboli, Gonzalez-Garcia, Mizukoshi PRD **74**:073005,2006)

Limits on dimension-eight operators

We place limits on the Wilson coefficients using templates in $m_{\ell\ell}$, generated for different coupling constants values using MADGRAPH.



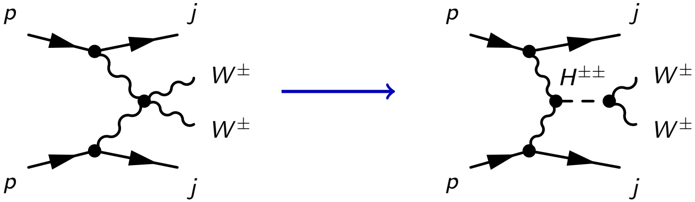


Operator coefficient	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity limit
F_{S0}/Λ^4	−42	43	−38	40	0.016
F_{S1}/Λ^4	−129	131	−118	120	0.050
F_{M0}/Λ^4	−35	35	−33	32	80
F_{M1}/Λ^4	−49	51	−44	47	205
F_{M6}/Λ^4	−70	69	−65	63	160
F_{M7}/Λ^4	−76	73	−70	66	105
F_{T0}/Λ^4	−4.6	4.9	−4.2	4.6	0.027
F_{T1}/Λ^4	−2.1	2.4	−1.9	2.2	0.022
F_{T2}/Λ^4	−5.9	7.0	−5.2	6.4	0.08

Doubly-charged Higgs

- The higher-dimensional operators can be interpreted as the result of integrating out heavy fields in the BSM theory.
- When the mass scale of these heavy fields is experimentally accessible, the EFT approach does not work.
- In this case, only complete BSM models can be tested.

Here, we will present a seach for doubly-charged Higgs, that can generate the same-sign *WW* topology



Georgi-Machacek model

- Doubly-charged Higgs are predicted in models with new Higgs triplets.
- We consider the Georgi-Machacek model that introduces two new triplets in addition to the usual Higgs doublet.
- The two triplets have common VEV v_Ξ. The non-minimal field content does not introduce additional custodial symmetry breaking.

H boson masses

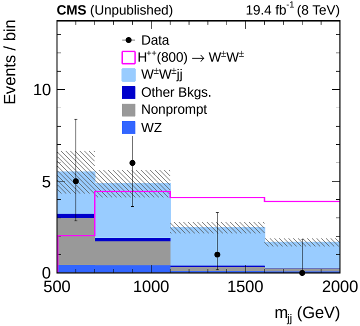
$$m_{H_0}^2 = 2(2\lambda_1 v_\Phi^2 + 2(\lambda_3 + 3\lambda_4)v_\Xi^2 + m_{\Phi\Xi}^2)$$
$$m_{H_0'}^2 = 2(2\lambda_1 v_\Phi^2 + 2(\lambda_3 + 3\lambda_4)v_\Xi^2 - m_{\Phi\Xi}^2$$
$$m_{H_3}^2 = \frac{1}{2}\lambda_5(v_\Phi^2 + 8v_\Xi^2)$$
$$m_{H_5}^2 = \frac{3}{2}\lambda_5 v_\Phi^2 + 8\lambda_3 v_\Xi^2$$

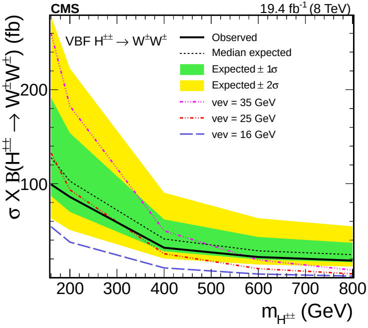
- We choose $\lambda_1 = 1$, $\lambda_2 = 1$, $\lambda_3 = 1$.
- λ_4 and λ_5 are chosen so that $m_{H_0}^2 = 125\,\text{GeV}$ and m_{H_5} is the doubly-charged Higgs mass hypothesis

	$m_{H_5} = 200\,\text{GeV}$	$m_{H_5} = 800\,\text{GeV}$
λ_4	2.37	4.00
λ_5	0.432	7.26

Limits on the production of doubly-charged Higgs

- The cross section for VBS production of $H^{\pm\pm}$ and decay to $W^{\pm}W^{\pm}$ is directly proportional to the triplet VEV v_{Ξ}.
- We use the m_{jj} distribution to set limits on $\sigma_{H^{\pm\pm}} \times \mathcal{B}(H^{\pm\pm} \rightarrow W^{\pm}W^{\pm})$





Summary

- We present a study of the electroweak scattering of same-sign W bosons in the fully leptonic final state.
- The vector boson scattering process is tagged by a high-mass, large rapidity gap jet pair.

- We measure the cross section of the process $pp \to W^{\pm}W^{\pm}jj \to 2\ell 2\nu jj$ in a fiducial region dominated by electroweak scattering.
- The $WZjj$ cross section is measured in the same fiducial region, but is dominated by strong scattering.

- We place the first limits on dimension-eight electroweak operators that generate aQGC.
- We place limits on the production of doubly charged Higgs bosons.

- The measurements are statistically limited and will be improved during the next run of the LHC.
- The measurement of the dimension-eight operators will also benefit from the increase in center-of-mass energy.
- In the future, we will be able to study the scattering of longitudinally polarized W boson pairs, which is a direct probe into Higgs physics.