Precision Measurements at the LHC: 
Luminosity and W/Z Cross Section Measurements 
with CMS

And the Observation of EW Production 
of Same-Sign W boson pairs

Jakob Salfeld-Nebgen
19/09/2017

Prague Seminar
Luminosity is a measure for how often we throw dice at the LHC
• Luminosity is reference for all cross section measurements at the LHC and a design parameter for accelerators

\[
\sigma _p = \frac{R_p}{\mathcal{L}}
\]

• Cross section inferred from measured rate \( R_p \) of physical process and measured luminosity \( \mathcal{L} \)

*Luminosity measurement often introduces largest systematic uncertainty*

• *Goal:* probe theoretical prediction:

\[
\sigma_{p_{A'B'} \rightarrow n} = \sum_q \int dx_a dx_b f_{A}(x_a, Q^2) f_{B}(x_b, Q^2) \hat{\sigma}_{ab \rightarrow n}
\]
At LHC protons are distributed over bunches, per bunch instantaneous luminosity given by

$$L = \frac{f_{LHC} N_1 N_2}{2\pi \sigma_x \sigma_y}$$

- $f_{LHC}$: 11245 Hz
- $N$: $10^{11}$
- $\sigma$: 15 $\mu$m
• At LHC protons are distributed over bunches, per bunch instantaneous luminosity given by

$$\mathcal{L} = \frac{f_{LHC} N_1 N_2}{2\pi \sigma_x \sigma_y}$$

• In practice, beam width estimates from machine parameters (emittance, beam optics) imprecise

• Luminosity is measured independently from high rate ($R_A$) “algorithms” in the detector by means of a calibration constant

$$\sigma_p = \frac{R_p}{\mathcal{L}} = \frac{R_p}{R_A} \sigma_{vdM}$$

determined from van-der-Meer scans

f : 11245 Hz
N: $10^{11}$
$\sigma$ : 15 μm
Cross Section Summary

\[ \sigma_p = \frac{R_p}{\mathcal{L}} = \frac{R_p}{R_A} \sigma^{vdM}_A \]

Limited by systematic uncertainties (luminosity uncertainty)

Statistically Limited (integrated luminosity)

All results at: http://cern.ch/go/pN7
LHC exceeds expectations: 17 Hz/nb achieved in 2017
Overview

First part: Luminosity Measurement

\[ \sigma_p = \frac{\int R_p \, dt}{\int \mathcal{L} \, dt} = \frac{N_p}{\epsilon A} \frac{\sigma^v dM}{\int R_A \, dt} \]

Part 2:
Cross Section Measurement

Second part:

a.) W/Z cross section measurement (high cross-section)
b.) EW production of same-sign W boson pairs (VBS, low cross section)
Luminosity Scale Estimation

• Absolute luminosity scale is measured with special LHC machine set-up, pioneered by Simon van der Meer (1968, ISR-PO/68-31)

Beams are scanned across each other in the transverse plane

\[ \sigma_{vdm}^A = \frac{R_A}{L} \]
Luminosity Scale Estimation

- New van der Meer scans are performed every time when we change the center-of-mass energy 5, 7, 8, 13 TeV, and special Heavy Ion Programs

- Beams are scanned across each other in the transverse plane to measure the beam overlap integral

\[ \mathcal{L} = N_1 N_2 \nu_{\text{rev}} O_I \quad O_I = \int_{-\infty}^{\infty} \rho_1(x, y) \rho_2(x, y) \, dx \, dy \]

For simple gaussian beams

\[ \mathcal{L} = \frac{f_{\text{LHC}} N_1 N_2}{2 \pi \sqrt{\sigma_{x,1}^2 + \sigma_{x,2}^2} \sqrt{\sigma_{y,1}^2 + \sigma_{y,2}^2}} = \frac{f_{\text{LHC}} N_1 N_2}{2 \pi \Sigma_x \Sigma_y} \]

- denominator is product of convolved widths of the two bunches
Luminosity Scale Calibration

• Formula can also be derived more generically, under assumption of factorizability

\[ O_I = \int_{-\infty}^{\infty} \rho_1(x) \rho_2(x) \, dx \times \int_{-\infty}^{\infty} \rho_1(y) \rho_2(y) \, dy \]

\[ \mathcal{L}(\Delta x_0, \Delta y_0) = N_1 N_2 f \frac{R(\Delta x_0, \Delta y_0) R(\Delta x_0, \Delta y_0)}{\int_{-\infty}^{\infty} R(\Delta x, \Delta y_0) d(\Delta x) \int_{-\infty}^{\infty} R(\Delta x_0, \Delta y) d(\Delta y)} \]

Convolved bunch widths measured from scan curve cross section (calibration constant) derived

\[ \sigma_{vdM} A = 2\pi \sum_x \sum_y R_A(0) \]
\[ \frac{\sigma_{vdM}}{N_1 N_2 f_{LHC}} \]
Experimental Effects

\[ \sigma_p = \frac{R_p}{\mathcal{L}} = \frac{R_p}{R_A} \cdot \frac{2\pi \sum_x \sum_y R_A(0)}{N_1 N_2 f_{LHC}} \]

- Length (separation) scale of beams
- Assumption on factorizability
- Beam-Beam effects
- Bunch current normalisation

<table>
<thead>
<tr>
<th>Normalization</th>
<th>XY-Correlations</th>
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<tbody>
<tr>
<td>Beam current calibration</td>
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<td>Ghosts and satellites</td>
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<tr>
<td>Length scale</td>
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<tr>
<td>Orbit Drift</td>
<td></td>
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<td>Beam-beam deflection</td>
<td></td>
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<tr>
<td>Dynamic-(\beta)</td>
<td></td>
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</table>
• distance scale of beam movements are calibrated to distance scale to CMS tracking detector

• Specific “length scale scans”
Beam-Beam Effects, Orbit Drift

- Other effects changing the beam separation

- Beam-Beam effects:
  
  - Electromagnetic force of proton charges in colliding bunches introduce a "kick/beam-deflection" and can change the shape (de-focussing, dynamic-\( \beta < 0.5\% \))

- Orbit Drift: Beams may drift from fixed orbit

DOROS

Analytic formula
Beam Shapes (Non-Factorization)

- assumption of factorizability of the beam shapes not perse true

\[ O_I = \int_{-\infty}^{\infty} \rho_1(x)\rho_2(x) \, dx \times \int_{-\infty}^{\infty} \rho_1(y)\rho_2(y) \, dy \]

- tests performed by LHCb collaboration in Run-1 using beam-gas imaging technique
- collision vertex position distribution, to infer 3-dimensional bunch shape
Beam Shapes (Non-Factorization)

- CMS detector not suitable to measure beam-gas interaction vertices (forward tracks)

- However can use one beam to "image" the other

- Beam Imaging: introduced in JINST P03018, 1103.1129

- Keep one beam fixed in the coordinate system of the detector, move other beam across

$$\sum_{n} n^{vtx}(x, y; n\Delta x)\Delta x = \sum_{n} \rho_1(x, y)\rho_2(x + n\Delta x, y)\Delta x \otimes V$$

- Pull per bin in transverse plane

- (simulation)

- Resolution for vertex position
repeat scans with the other beam kept fixed, scan in $X$ and $Y$

4 vertex distribution in the transverse plane, fit simultaneously

$$b_i(x, y) = w_i g_{i,N}(x, y) + (1 - w_i) g_{i,W}(x, y)$$

$$g_{i,j}(x, y) = \frac{1}{2\pi \sigma_{i,j,x} \sigma_{i,j,y} \sqrt{1 - \rho_{i,j}^2}} \exp \left( \frac{-1}{2(1 - \rho_{i,j}^2)} \left[ \frac{x^2}{\sigma_{i,j,x}^2} + \frac{y^2}{\sigma_{i,j,y}^2} - \frac{2\rho_{i,j}xy}{\sigma_{i,j,x} \sigma_{i,j,y}} \right] \right)$$

Simulation
Beam Shapes

- Beam Imaging scans performed in Run-2 vdM scan campaigns
  ➞ non-factorization effects within ~1% observed

Once vertex reconstruction resolution understood, complementary beam overlap measurement can be obtained (decrease systematic uncertainties)

Comparison with fit-model assuming no XY-correlations

Comparison with fit-model with XY-correlations

Triple-Gaussian Model
Beam Currents

\[ \sigma_p = \frac{R_p}{\mathcal{L}} = \frac{R_p}{R_A} \cdot \frac{2\pi \sum_x \sum_y R_A(0)}{N_1 N_2 f_{LHC}} \]

- Full per-beam intensity measured with 0.3% precision (Direct Current Transformer, 10% uncertainty in 2010)
- per-bunch population measured with Fast BCT (25ns integration window), absolute scale not well calibrated, cross calibrated to DCCT
- spurious charges estimated with Longitudinal Density Monitor based on synchrotron radiation

Independent measurement performed by LHCb experiment (Beam-Gas)
Luminosity Rate Algorithms

- CMS operates 5 luminometers to measure luminosity, based on complementary algorithms and detector technology.

- Forward detectors, independent from CMS DAQ:
  - Pixel Luminosity Telescope (online): New installed detector for RunII, rate measurement based on telescope occupancy.
  - Forward Hadron Calorimeter (online): already used in RunI, rate measurement based on occupancy.
  - Beam Condition Monitor (diamond sensors, online): already used during RunI, based on number of MIPs.

- A suitable rate algorithm is pile up independent (low detector occupancy), not filling scheme dependent (no out-of-time response) and is operationally stable (no radiation damage).

- So far for precise CMS offline measurements Pixel Cluster Counting with is used, and monitored using Muon Track rates in Drift Tubes.
Luminosity Rate Algorithms

Forward calorimeter
Muon Drift Tubes

occupancy

track counting

Silicon Pixel Detector

PLT, BCM1f
Pixel Cluster Counting

• Algorithm for Silicon Pixel Detector is based on Pixel Cluster Counts (Rates)

  - 66M channels, <0.1% occupancy at $10^{34} \text{ cm}^{-2}\text{s}^{-1}$, very good stability over time, linear response up to high pile up

• However, limitations from maximum trigger rates during data-taking (lower statistics), per bunch luminosity measurements being commissioned

• Only modules operational during the entire year used
Pixel Cluster Counting

- PCC has two Out-Of-Time response effects leading to bias of the true rate measurement

1. Spill-Over/Time-Walk of electronic pixel signal leaking into next bunch slot (Type 1)

2. Afterglow, exponential decay of activated material surrounding the detector (Type 2)
Stability Reference

- Reference to cross check stability of the Silicon Pixel detector to be determined
  - is there a more stable detector?

- Experimental approach: use complementary rate measurements
  - Drift Tube Muon Rates, Z Boson Rate after efficiency corrections

![Graphs showing stability with efficiency corrections.](image-url)
Systematic Uncertainties

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Correction (%)</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
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<tr>
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<tr>
<td>type 2</td>
<td>0 – 4</td>
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<td>Beam current calibration</td>
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<td>Ghosts and satellites</td>
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<td>Length scale</td>
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<tr>
<td>Dynamic-β</td>
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<tr>
<td>Total</td>
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</table>

\[ \sigma_p = \frac{\int R_p dt}{\int \mathcal{L}} = \frac{N_p}{\epsilon A} \left( \frac{\sigma_{vdM}^A}{\int R_A dt} \pm \Delta \mathcal{L} \right) \]
Fun Facts about Precision

• the convolved beam widths are about 100μm
  => Meaning with 2.7% uncertainty we can probe length sales of about 1μm

• While the LHC probes scales of <10^{-19}m (EW Scale), control over the 10^{-6}m scale enter the cross section measurements

• At High Luminosity LHC target for total integrated luminosity: 3000/fb

2.3% uncertainty would translate into ± 69 fb^{-1} <= similar to the data collected from 2010 to 2016 (7 years of operation)
Z Rate Measurements

• Does LHC deliver same amount of luminosity to ATLAS and CMS Experiments?

- Z rate comparisons at both IPs (Reconstruction and DAQ efficiency corrected) as independent cross check

- Independent to VdM calibration

same Z cross-section
Z Rate Measurements

- Z-$\mu\mu$ rate measurements performed in sub-datasets by ATLAS and CMS

  - same fiducial volume, direct comparison possible
  - corrections for data-taking efficiency applied by each experiment

![Graph showing Z-Rate measurements over time for 2016](chart1.png)

![Graph showing Inclusive Z-Rates for 2016](chart2.png)
General Status

- Luminosity measurements at the LHC is an active field of research

  - Great collective collaborative effort across all four experiments

  - Many effects have been studied/understood during Run-1 though out Run-2, results are still being finalised

<table>
<thead>
<tr>
<th></th>
<th>ALICE</th>
<th>ATLAS</th>
<th>CMS</th>
<th>LHCb</th>
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<td>Running period</td>
<td>2012 pp</td>
<td>2012 pp</td>
<td>2012 pp</td>
<td>2012 pp</td>
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<td>8</td>
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<td>8</td>
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<tr>
<td>$\sigma_L/\mathcal{L}$ [%]</td>
<td>2.4</td>
<td>1.9</td>
<td>2.6</td>
<td>1.2</td>
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</tbody>
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Summary table borrowed from W. Kozancki and M. Gagliardi
W/Z Cross Section Measurement
W/Z Cross section Measurement

- W/Z inclusive and differential cross section measurements probe:
  - QCD and EW higher order corrections
  - Parton Density Distributions of Proton
  - Background for BSM Searches

Valence quarks interact with sea quarks

20-30% increase \( \text{LO} \rightarrow \text{NNLO} \)
Results summarised in Physics Analysis Summaries
SMP-15-004 (W/Z Inclusive) and SMP-15-011(Z differential)
Paper on 13 TeV W/Z cross sections in progress
Results based on 2015 dataset, two different periods

50ns bunch spacing $43/\text{pb} \Rightarrow \sim 30k \ Z \rightarrow \mu \mu \ \text{events (cross section)}$

25ns bunch spacing $2.3/\text{fb} \Rightarrow \sim 1.6M \ Z \rightarrow \mu \mu \ \text{events (differential)}$

Experimental trick used during run one: low pile up!
Not the case in Run-2

2010 7TeV

2012 8TeV
Event Selection/Acceptance

- Topology of Z events is characterised by two leptons of same flavour and opposite charge,

- Topology of W events: one lepton and missing transverse energy from neutrino escaping direct detection

- Acceptance obtained from simulation, fraction of events passing selection cuts on $\eta$ and $p_T$

  - Baseline value obtained from aMC@NLO(+Pythia)

- Theoretical uncertainties enter:

  - (non-)perturbative QCD effects
    - NNLO+NNLL RESBOS, DYRES, HORACE for EWK NLO, FEWZ for >NNLO by scale variations

  - Impact of PDF uncertainties estimated from parameter variations
Lepton Selection Efficiency

- Measured on data directly, using Tag-And-Probe technique

- Use Z-line mass shape, and count number of leptons failing and passing selection requirements

- performed in bins of ($\eta, p_T$)

- tracking, calorimeter cluster reconstruction lepton identification efficiency measured

- Uncertainty estimated from signal and background shape assumptions
  
  - Signal: MC shape*Gaussian (default), Breit-Wigner*Crystal-Ball  
  - Bkg: Exponential (default), linear, ErrF*Exp, MC template from W+jets+QCD  
  - N.B. statistic of the tag&probe sample affects systematic error

$$\varepsilon = \frac{N_{\text{pass}}}{N_{\text{pass}} + N_{\text{fail}}}$$
Z Boson Signal Extraction

- Background subtracted yields (derived from simulation)
- Background: 0.6% ttbar, W+Jets, WZ and $Z \to \tau\tau$ processes estimated from simulation

<table>
<thead>
<tr>
<th>Source</th>
<th>$Z \to e^+e^-$</th>
<th>$W^+ \to e^+\nu$</th>
<th>$W^- \to e^-\bar{\nu}$</th>
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</thead>
<tbody>
<tr>
<td>Yields</td>
<td>$15290 \pm 120$</td>
<td>$12230 \pm 980$</td>
<td>$98200 \pm 950$</td>
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<tr>
<td>Acceptance</td>
<td>$0.33 \pm 0.01$</td>
<td>$0.43 \pm 0.01$</td>
<td>$0.44 \pm 0.01$</td>
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<tr>
<td>Efficiency</td>
<td>$0.56 \pm 0.01$</td>
<td>$0.58 \pm 0.01$</td>
<td>$0.60 \pm 0.01$</td>
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<tr>
<td>Source</td>
<td>$Z \to \mu^+\mu^-$</td>
<td>$W^+ \to \mu^+\nu$</td>
<td>$W^- \to \mu^-\bar{\nu}$</td>
</tr>
<tr>
<td>Yields</td>
<td>$23670 \pm 150$</td>
<td>$167710 \pm 830$</td>
<td>$131250 \pm 910$</td>
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<tr>
<td>Acceptance</td>
<td>$0.36 \pm 0.01$</td>
<td>$0.44 \pm 0.01$</td>
<td>$0.46 \pm 0.01$</td>
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<tr>
<td>Efficiency</td>
<td>$0.80 \pm 0.02$</td>
<td>$0.78 \pm 0.01$</td>
<td>$0.79 \pm 0.01$</td>
</tr>
</tbody>
</table>
W Boson Signal Extraction

- missing transverse energy distribution used to extract signal

  ➤ Important to have precise missing transverse energy reconstruction

- two effects spoiling proper MET model in simulation: pileup contributions, “underlying event” model (proton remnant interactions)

extreme case
• Good MET resolution is indeed crucial

Also here: luminosity is important to control

• QCD component is modelled using Rayleigh Distribution (no genuine MET)
• Obtained improved resolution of missing transverse energy
  => “PUPPI” algorithm used to identify contributions from PU particles (arXiv:1407.6013)

• In addition: correct simulated hadronic recoil to the one observed in data in Z events

apply to simulated W events
Signal Extraction

- With improved resolution $\Rightarrow$ signal extraction possible

- EW contributions, from $Z \rightarrow \tau\tau$, $W \rightarrow \tau\nu$, $t\bar{t}$bar and DY with missing lepton
Systematic Uncertainties

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<tbody>
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<td>1.7</td>
<td>1.8</td>
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<tr>
<td>Bkg. subtraction / modeling [%]</td>
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<td>0.6</td>
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<tr>
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<td>Total experimental [%]</td>
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<td>Lumi [%]</td>
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<tr>
<td>Total [%]</td>
<td>5.6</td>
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<td>5.3</td>
<td>2.3</td>
<td>5.5</td>
<td>2.3</td>
<td>2.2</td>
<td>1.9</td>
</tr>
</tbody>
</table>

- Measurement limited by luminosity uncertainty (note: based on previous preliminary luminosity calibration)
- Otherwise experimental and theoretical uncertainties comparable in size
Total Inclusive Cross Sections

- Cross section extrapolated from fiducial volume
- Good agreement with SM NNLO prediction

- NNLO FEWZ cross section +NNPDF3.0

- Theoretical uncertainties included from PDF and scale variation (dominated by PDF unc.)

- $Z\rightarrow\mu\mu$ update with full dataset: $1870 \pm 2$ (stat) $\pm 35$ (syst) $\pm 51$ (lumi) pb
Parton Distribution Functions

- Comparison performed with different PDF sets

- And ratios, part of the experimental uncertainties cancel
Lepton Universality, Relative PDF Comparisons

- Relative scaling of cross sections for different PDF sets shown
- Universality of Electron and Muon couplings to vector bosons
Differential Result

- Absolute differential cross section measurements performed
- Comparison with FEWZ and event generators (POWHEG, MADGRAPH)
- Soft gluon emission (resummation) handled by PYTHIA, low pT probes NNLL calculations, high pT probes NNLO contributions
Observation of EW Production of same-sign W boson pairs
Vector Boson Scattering

- Vector Boson Scattering is a crucial process to close to fully investigate Higgs mechanism

- Higgs mechanism initially introduced to unitarize $WW \rightarrow WW$ amplitude at the TeV-Scale

- Probes so far unexplored operators in the SM Lagrangian (QGC,TGC)
Evidence for Electroweak Production of $W^\pm W^\pm jj$ in $pp$ Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector

G. Aad et al. (ATLAS Collaboration)

This Letter presents the first study of $W^\pm W^\pm jj$, same-electric-charge diboson production in association with two jets, using 20.3 fb$^{-1}$ of proton-proton collision data at $\sqrt{s} = 8$ TeV recorded by the ATLAS detector at the Large Hadron Collider. Events with two reconstructed same-charge leptons ($\ell^\mp \ell^\mp$, $\ell^\pm \mu^\pm$, and $\mu^\pm \mu^\mp$) and two or more jets are analyzed. Production cross sections are measured in two fiducial regions, with different sensitivities to the electroweak and strong production mechanisms. First evidence for $W^\pm W^\pm jj$ production and electroweak-only $W^\pm W^\pm jj$ production is observed with a significance of 4.5 and 3.6 standard deviations, respectively. The measured production cross sections are in agreement with standard model predictions. Limits at 95\% confidence level are set on anomalous quartic gauge couplings.

Study of Vector Boson Scattering and Search for New Physics in Events with Two Same-Sign Leptons and Two Jets

V. Khachatryan et al. (CMS Collaboration)

A study of vector boson scattering in $pp$ collisions at a center-of-mass energy of 8 TeV is presented. The data sample corresponds to an integrated luminosity of 19.4 fb$^{-1}$ collected with the CMS detector. Candidate events are selected with exactly two leptons of the same charge, two jets with large rapidity separation and high dijet mass, and moderate missing transverse energy. The signal region is expected to be dominated by electroweak same-sign $W$-boson pair production. The observation agrees with the standard model prediction. The observed significance is 2.0 standard deviations, where a significance of 3.1 standard deviations is expected based on the standard model. Cross section measurements for $W^\pm W^\pm$ and $WZ$ processes in the fiducial region are reported. Bounds on the structure of quartic vector-boson interactions are given in the framework of dimension-eight effective field theory operators, as well as limits on the production of doubly charged Higgs bosons.
Event Selection (Run-2 Analysis)

- Exploit the VBS topology and clean same-sign lepton final state
  - Trigger Selecton Single and Double Lepton Triggers, 99% efficiency
  - Two same-sign isolated leptons (electrons or muons) \( p_T > 25, 20 \text{ GeV} \) \( |\eta| < 2.5 \)
  - VBF selection: \( m_{jj} > 500 \text{ GeV} \) 
    \( |\Delta \eta_{jj}| > 2.5 \) cut on \( \max(z^*) < 0.75 \)

- Background rejection
  - 3rd lepton veto (loose ID), >10 GeV
  - \( \text{Im}_{ll} - m(Z) \text{I}>15 \text{ GeV} \)
  - reject events with b-tagged jet
  - MET > 40 GeV

\[ z^*_\ell = |\eta_{\ell} - (\eta_{j1} + \eta_{j2})/2| / |\Delta \eta_{jj}| \]
Event Yields

- Leading background (64%) from non-prompt leptons top-pair production and W+Jets
  - Estimated from loose-to-tight fake rate method
- WZ (18%) and wrong-sign background estimated from the data
- Signal generated at LO using MG5, interference (QCD $\otimes$ EW) estimated using PHANTOM (overall < 5%), considered as systematic unc.
  - small ratio of QCD vs EW production
  - Best sensitivity to study VBS processes

<table>
<thead>
<tr>
<th></th>
<th>$e^+e^+$</th>
<th>$e^+\mu^+$</th>
<th>$\mu^+\mu^+$</th>
<th>$e^-e^-$</th>
<th>$e^-\mu^-$</th>
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<td>67.6 ± 3.8</td>
<td>44.1 ± 3.4</td>
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<td>38.9 ± 3.3</td>
<td>23.9 ± 2.8</td>
<td>205 ± 13</td>
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<td>Signal</td>
<td>6.2 ± 0.2</td>
<td>24.7 ± 0.4</td>
<td>18.3 ± 0.4</td>
<td>2.5 ± 0.1</td>
<td>8.7 ± 0.2</td>
<td>6.5 ± 0.2</td>
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<td>Total bkg.</td>
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<td>25.7 ± 3.4</td>
<td>9.4 ± 1.8</td>
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<td>WZ</td>
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<td>W$\gamma$</td>
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<td>0.5 ± 0.2</td>
<td>5.8 ± 0.8</td>
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<tr>
<td>Wrong sign</td>
<td>1.5 ± 0.6</td>
<td>1.4 ± 0.4</td>
<td>—</td>
<td>1.1 ± 0.5</td>
<td>1.2 ± 0.4</td>
<td>—</td>
<td>5.2 ± 1.1</td>
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</table>
Signal Extraction (First Observation)

- EW production of same-sign W boson pairs extracted using 2-dimensional fit in $m_{ll}$ and $m_{jj}$, charge- and flavor-inclusive

Measured fiducial cross section:
$$3.83 \pm 0.66 \text{ (stat)} \pm 0.35 \text{ (syst)} \text{ fb}$$

Signal Strength $0.90 \pm 0.22$

5.5σ observed
5.7σ expected
• Excess of events could signal doubly charged Higgs production (fermiophobic)

- Extended Higgs sector by SU(2) triplets (real&complex) custodial symmetry preserved at tree-level (Georgi-Machacek Model)

• Model parameters are $m(H^{++})$ and $sH$, the fraction of the $W$ mass generated by the triplet vev
VBF WZ Production

- EW production of pairs of W and Z boson just about to start being significant (QCD vs EW cross section: 70% vs 30%)

- Establish search for charged Higgs bosons first, complementary to current focus of searches for charged Higgs bosons (fermiophobic)

- Similar to WW VBS, exploit VBF topology, fully leptonic final-state, on 2015 and 2016 data

---

HIG-16-027

VBF H+ -> WZ
Statistical Precision at HL-LHC

- High-Luminosity LHC: Expect 3000 fb$^{-1}$ of data being collected until 2038, make naive statistical uncertainty estimate

\[
\frac{1}{\sqrt{\sigma L}} \sim 1.8\% \Rightarrow \text{for 3ab}^{-1} \text{ measurements of processes with cross section above 1 fb will be limited by systematic uncertainties (luminosity)}
\]

54 discussed here
Conclusions

\[ \sigma_P = \frac{N_P}{\epsilon A \int R_A dt} \left( \frac{2\pi \sum_x \sum_y R_A(0)}{N_1 N_2 f_{LHC}} \right) \]

- Elaborated on Luminosity measurements at the LHC
- Discussed W/Z boson production cross section as benchmark for precision measurements at the LHC
  - The measurement is dominated by systematic uncertainties
  - The luminosity estimate introduces one of the leading uncertainties
- First observation of EW same-sign WW production as benchmark for process with large statistical uncertainty with current luminosities
- With more data to come we will have more Standard Model processes with statistical uncertainty of <1%: Precision Higgs Physics
But let's not wait until 2038!
Interesting physics is around the corner
(and discussions on future accelerator projects in full swing)

Thank you for your attention!
Additional Material
Table 2: Systematic uncertainties in percent for the electron channel. “NA” means that the source either does not apply or is negligible.

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## WWss Systematic Uncertainties

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Figure 2: The DCCT with the connexions for the beam image current.
Luminosity Scale Estimation

- Absolute luminosity scale is measured with special LHC machine set-up, pioneered by Simon van der Meer (1968, ISR-PO/68-31)

Beams are scanned across each other in the transverse plane
\[ \mathcal{L}(\Delta x, \Delta y) = N_1 N_2 f \int_{-\infty}^{\infty} \rho_1(x, y)\rho_2(x + \Delta x, y + \Delta y) \, dx \, dy \]