Cross Section Measurements of Polarized $W^{\pm}W^{\pm}$ Scattering in Fully Leptonic Decay with the CMS Detector

Based on CMS-SMP-20-006 (arXiv:2009.09429)

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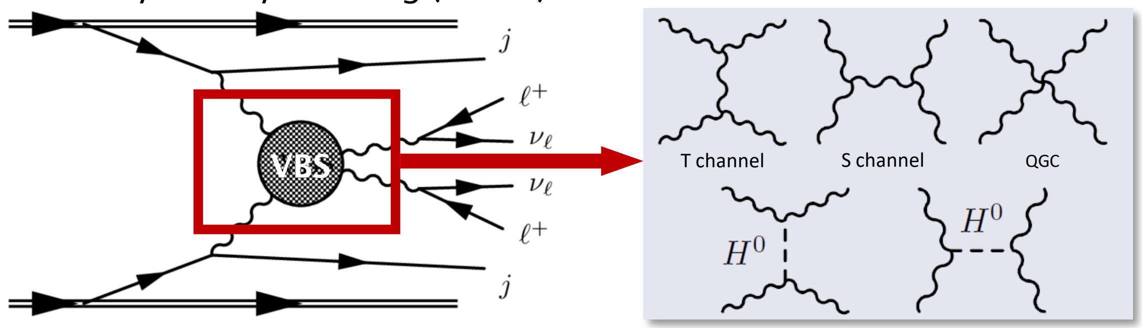
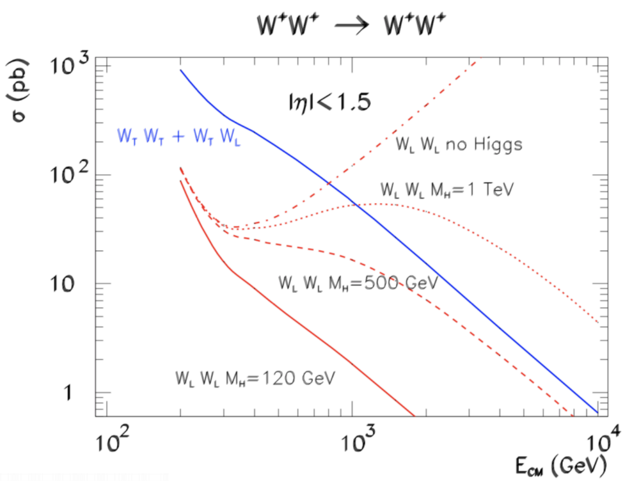
VV polarized scattering

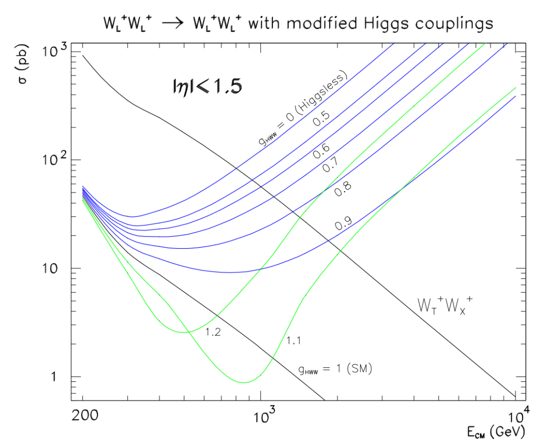
- The Vector Boson Scattering (VBS) processes are the key to experimentally probe the Stand Model (SM) nature of Electro-Weak Symmetry Breaking (EWSB).



- The polarized VBS amplitudes at high energies are sensitive to the Higgs mass and also Higgs-to-Vector-Boson couplings, and the triple and quartic vector boson couplings (TGC and QGCs).
- Uniqueness of VBS $W^\pm W^\pm$:
  - EW production dominant over QCD-induced
  - The only process for which the cross-talk amplitudes are completely negligible

  (**L**: longitudinal polarization status, **T**: transverse polarization status, **X = L or T**)



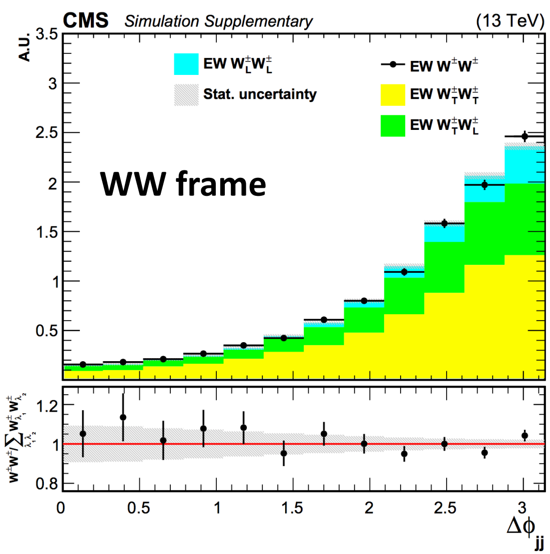


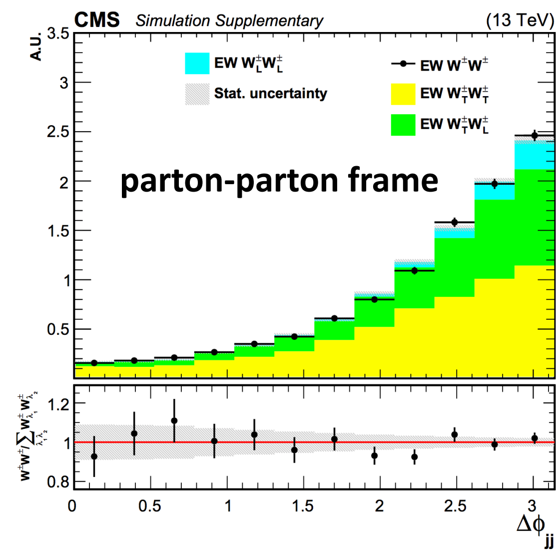
Signal samples

- Generated samples with m_{jj} > 200 GeV and p_T^{jet} > 10 GeV
  - Polarization vector is not Lorentz invariant for massive particles, longitudinal and transverse polarizations require a choice of reference frame.

Cross sections with $m_{jj} > 200\,\mathrm{GeV}$ and $p_T^j > 10\,\mathrm{GeV}$			
Mode	σ parton-parton frame (fb/%)	σ WW frame (fb/%)	σ lepton-lepton frame (fb/%)
$W_L W_L$	2.119 / 7.3	3.193 / 10.9	2.492 / 8.1
$W_L W_T$	10.87 / 37.4	9.288 / 31.9	9.756 / 31.9
$W_T W_T$	16.10 / 55.3	16.67 / 57.2	18.4 / 60.0
Total	29.1 / 100	29.1 / 100	30.6 / 100

  - Polarization fraction of LL in the WW c.m. frame is the largest
- Closure of signal samples at generator level





  - Good agreement between incoherent sum of the polarized cross sections and for the unpolarized cross sections

Overview of the analysis

- Data
  - Full Run-II dataset with 137 fb^{-1} of integrated luminosity
    - 16 & 17: MuonEG, DoubleMuon, DoubleElectron, SingleMuon and SingleElectron
    - 18: MounEG, DoubleMuon, SingleMuon and Egamma
- Triggers
  - Single and Double Lepton triggers
  - ~ 100% efficiency
- Backgrounds (Follow the EW same-sign WW and EW WZ measurements Phys.Lett.B 809 (2020) 135710)
  - All simulated samples are normalized to best theoretical cross section prediction, events are reweighted to correct for the pileup, lepton and trigger efficiencies to agree with the data distribution

Category	Estimation
WW QCD	From simulation
WW DPS	From simulation
WZ/γ^* QCD	From simulation
WZ EW	From simulation
Tribosons & ttV	From simulation
ZZ	From simulation
Wrong-sign leptons	From charge mis-ID S.F.s and simulated OS events
Nonprompt leptons	From fake rates and “Tight+Loose” “Loose+Loose” data events

- Simultaneous fits of W_LW_L/W_XW_T and W_LW_X/W_TW_T components in signal and control regions
  - Machine learning is used in signals extraction

Event selection

- Signal region and several background enriched control region selections are defined:
  - Signal region: SSWW
  - Control region: Nonprompt, WZ, WZb, ZZ

Variable	SSWW	WZ	ZZ
leptons	2 same-sign leptons p_T > 25/20 GeV	1 opposite-sign pair + 1 p_T > 25/10/20 GeV	4 leptons p_T > 25/20/10/10GeV
$\mathbf{\|m_{ll}\text{-}m_Z\|}$	> 15 GeV (ee)	<15 GeV	< 15 GeV (both pairs)
$\mathbf{m_{ll}}$	> 20 GeV	-	-
$\mathbf{m_{lll}}$	-	> 100 GeV	-
$\mathbf{max(Z^*_l)}$	< 0.75	< 1.0	< 0.75
$\mathbf{p_T^{jet}}$	> 50 GeV	> 50 GeV	> 50 GeV
$\mathbf{p_T^{miss}}$	> 30 GeV	> 30 GeV	-
$\mathbf{m_{jj}}$	> 500 GeV	> 500 GeV	> 500 GeV
$\mathbf{\|\Delta\eta_{jj}\|}$	> 2.5	> 2.5	> 2.5
Anti b-tagging	Applied	Applied	-
tau veto	Applied	Applied	-

$Z^*_l = |\,\eta_l - (\eta_{j1} + \eta_{j2}) / 2| / |\Delta\eta_{jj}|$

- Nonprompt region is same as SSWW region, except "Anti b-tagging" is inverted
- WZb region is same as WZ region, except "Anti b-tagging" is inverted

Application of Machine Learning

- Machine learning is used to improve the sensitivity
  - The LL component represents a small fraction of the total cross section and has observables that are largely similar to the unpolarized process.
  - Therefore, machine learning techniques are important in order to harness correlations between variables and to extract as much information as possible from the finite dataset.

- Define two BDTs (DNN used for the cross-check analysis)

- **Signal BDTs**: $W_L W_L$ vs. $W_X W_T$ and $W_L W_X$ vs. $W_T W_T$
  - 15 variables are used to look for differences in the emission process of the W_T/W_L bosons from the incoming quarks
    - jet kinematics
    - vector boson kinematics
    - variables related to both lepton and jet kinematics
  - Different trainings for the WW and parton-parton c.m. frames

- **Inclusive BDT**: EW $W^{\pm}W^{\pm}$ vs. nonVBS events
  - Use 10 discriminating variables which are more powerful to separate EW $W^{\pm}W^{\pm}$ and nonVBS background, e.g. m_{jj}
  - NonVBS events are dominated by non-prompt ttbar events

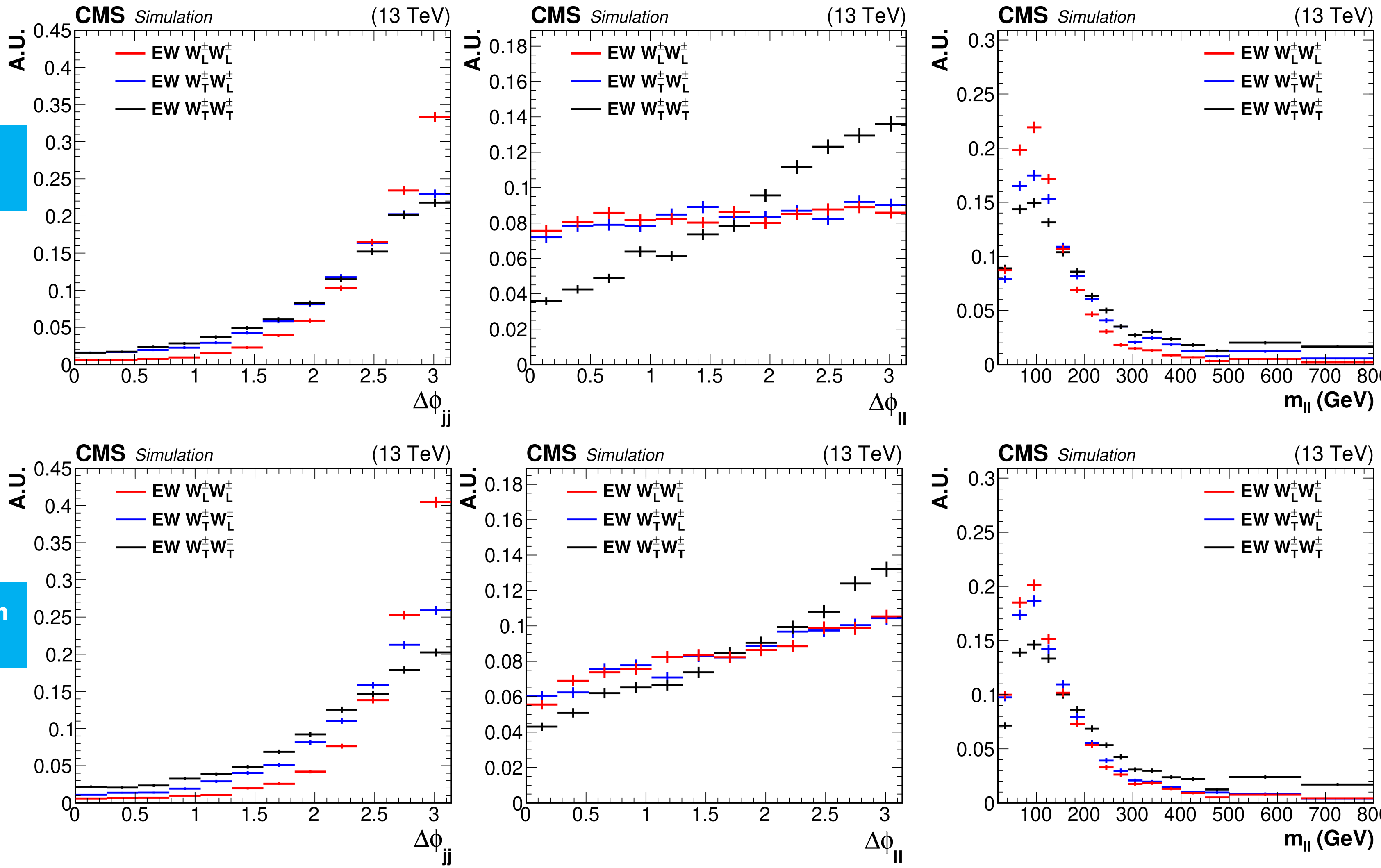
Signal BDTs

- Distributions of three variables with great separation power are shown

$\Delta\phi_{jj}$ | $\Delta\phi_{ll}$ | m_{ll}

WW c.m. frame

Parton-parton c.m. frame



Signal extraction

- Simultaneously fit the signal and several control regions
  - Normalizations of ZZ, tZq, EW WZ, and QCD WZ backgrounds are included in the fit along with LL/TX (or LX/TT) normalizations.
- Signal region: 2D distribution
  - Signal BDT and inclusive BDT
- Nonprompt control region
  - m_{jj}: [500,800,1200,1800, inf]
- WZ control region
  - m_{jj} : [500,1000,1500, 2000, inf]
- WZb control region
  - m_{jj} : [500,800,1200,1800, inf]
- ZZ control region
  - m_{jj} : [500,800,1200,1800, inf]

Systematic uncertainties

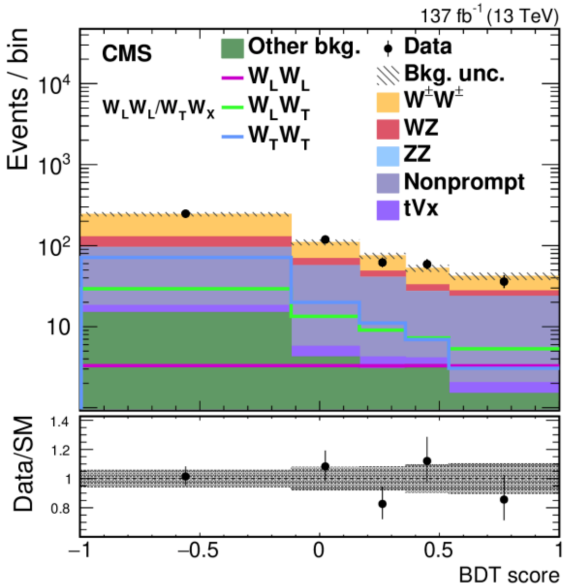
- Systematic uncertainties of the W_LW_L and W_XW_T, and W_LW_X and W_TW_T cross section measurements in units of percent

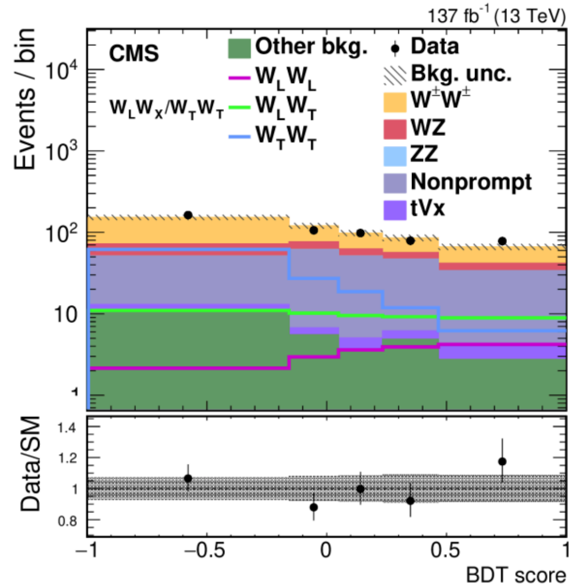
Source of uncertainty	$W_L^\pm W_L^\pm$ (%)	$W_X^\pm W_T^\pm$ (%)	$W_L^\pm W_X^\pm$ (%)	$W_T^\pm W_T^\pm$ (%)
Integrated luminosity	3.2	1.8	1.9	1.8
Lepton measurement	3.6	1.9	2.5	1.8
Jet energy scale and resolution	11	2.9	2.5	1.1
Pileup	0.9	0.1	1.0	0.3
b tagging	1.1	1.2	1.4	1.1
Nonprompt lepton rate	17	2.7	9.3	1.6
Trigger	1.9	1.1	1.6	0.9
Limited sample size	38	3.9	14	5.7
Theory	6.8	2.3	4.0	2.3
Total systematic uncertainty	44	6.6	18	7.0
Statistical uncertainty	123	15	42	22
Total uncertainty	130	16	46	23

- Measurements are statistically dominated

Signal region

- Signal BDT score distributions in signal region
  - Data and Standard Model (SM) prediction have good agreement
  - The histograms for the $W^\pm W^\pm$ process include the contributions from the $W_L W_L$, $W_L W_T$ and $W_T W_T$ processes (shown as solid lines), QCD $W^\pm W^\pm$ and interference



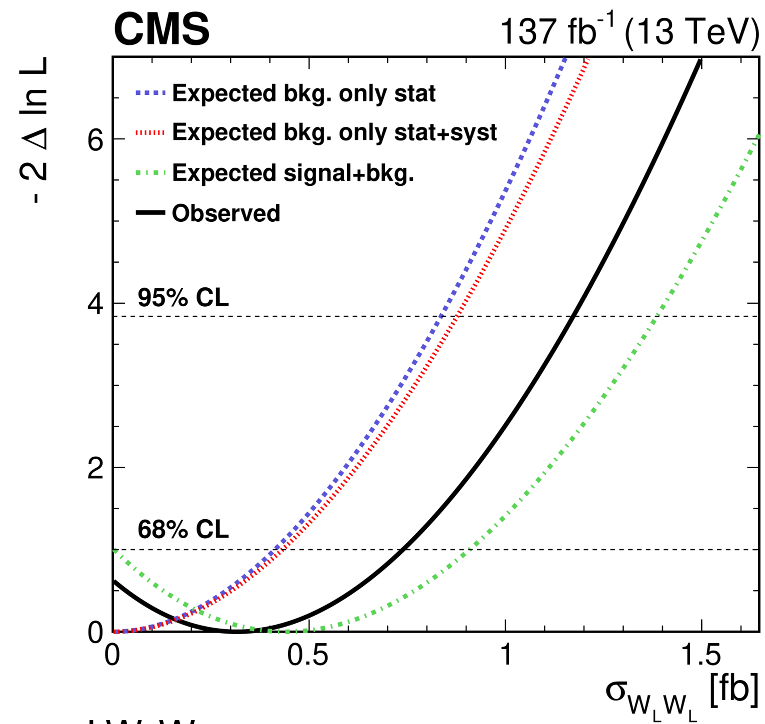


- Expected yields from various SM processes and observed data events
  - Data and SM prediction have good agreement
  - The uncertainties of LL component is large

Process	Yields in $W^\pm W^\pm$ SR
$W^\pm_L W^\pm_L$	16.0 ± 18.3
$W^\pm_L W^\pm_T$	63.1 ± 10.7
$W^\pm_T W^\pm_T$	110.1 ± 18.1
QCD $W^\pm W^\pm$	13.8 ± 1.6
Interference $W^\pm W^\pm$	8.4 ± 0.6
WZ	63.3 ± 7.8
ZZ	0.7 ± 0.2
Nonprompt	213.7 ± 52.3
tVx	7.1 ± 2.2
Other background	26.9 ± 9.9
Total SM	522.9 ± 60.7
Data	524

Results

- Profile likelihood ratio as a function of $W_L W_L$ cross section
  - 95% CL upper limits obtained from the profile likelihood ratio scan
- WW c.m. frame
  - Observed (expected) significance of 2.3 (3.1) sigma for $W_L W_X$ production
  - Observed (expected) limit of 1.17 (0.88) fb for $W_L W_L$ production
- Parton-parton c.m. frame
  - Observed (expected) significance of 2.6 (2.9) sigma for $W_L W_X$ production
  - Observed (expected) limit of 1.06 (0.85) fb for $W_L W_L$ production



- Cross section measurements for $W_L W_L$, $W_X W_T$, $W_L W_X$, and $W_T W_T$

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^\pm_L W^\pm_L$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W^\pm_X W^\pm_T$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^\pm_L W^\pm_X$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W^\pm_T W^\pm_T$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

WW c.m. frame

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^\pm_L W^\pm_L$	$0.24^{+0.40}_{-0.37}$	0.28 ± 0.03
$W^\pm_X W^\pm_T$	$3.25^{+0.50}_{-0.48}$	3.32 ± 0.37
$W^\pm_L W^\pm_X$	$1.40^{+0.60}_{-0.57}$	1.71 ± 0.19
$W^\pm_T W^\pm_T$	$2.03^{+0.51}_{-0.50}$	1.89 ± 0.21

Parton-parton c.m. frame

- The combination of the statistical and systematic uncertainties is shown

Summary

- First measurement of production cross sections of polarized EW $W^{\pm}W^{\pm}$
  - Measurements agree with SM predictions
- Using full Run-II dataset, in WW c.m. frame
  - Observed (expected) significance of 2.3 (3.1) sigma for $W_L W_X$ production
  - Observed (expected) limit of 1.17 (0.88) fb for $W_L W_L$ production cross section
- Results are also reported with the polarizations defined in the parton-parton c.m. frame

Additional materials

Higher order corrections

- Full NLO computation have been done for unpolarized EW W±W± process

$$\begin{tikzcd}[column sep=small]
\textbf{LO} & & \mathcal{O}(\alpha^6) \arrow[dl, "\mathrm{EW}"'] \arrow[dr, "\mathrm{QCD}"] & & \mathcal{O}(\alpha_s\alpha^5) \arrow[dl, "\mathrm{EW}"'] \arrow[dr, "\mathrm{QCD}"] & & \mathcal{O}(\alpha_s^2\alpha^4) \arrow[dl, "\mathrm{EW}"'] \arrow[dr, "\mathrm{QCD}"] & \\
\textbf{NLO} & \mathcal{O}(\alpha^7) & & \mathcal{O}(\alpha_s\alpha^6) & & \mathcal{O}(\alpha_s^2\alpha^5) & & \mathcal{O}(\alpha_s^3\alpha^4)
\end{tikzcd}$$

All contributing orders at both LO and NLO

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{\mathrm{NLO}}$ [fb]	$-0.2169(3)$	$-0.0568(5)$	$-0.00032(13)$	$-0.0063(4)$	$-0.2804(7)$
$\delta\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$ [%]	-13.2	-3.5	0.0	-0.4	-17.1

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- NLO EW and QCD [$\mathcal{O}(\alpha^7)$,$\mathcal{O}(\alpha_s\alpha^6)$] corrections are considered

- EW corrections are large and negative (~-15%) in the fiducial region and increasing with dijet and dilepton masses

- NLO corrections for the polarized samples are not known (α_s corrections expected to be the same for the 3 modes. α corrections expected to be small for the longitudinal modes).
  - Apply α_s corrections on LL, LT, and TT
  - Apply α corrections for TT
  - Take the size of α corrections as uncertainty for LL and LT

Motivation on Experimental

- For the first measurement of the polarized VBS:
  - What can we say already with Run-II data? The longitudinal scattering contributes to about ~10% of the overall EW production
  - Consider same-sign lepton pair + jet events (small QCD induced backgrounds but 2 neutrinos in the final state)
  - The most precise measurement of VBS $W^{\pm}W^{\pm}$ cross section to date (~10% precision) ☞

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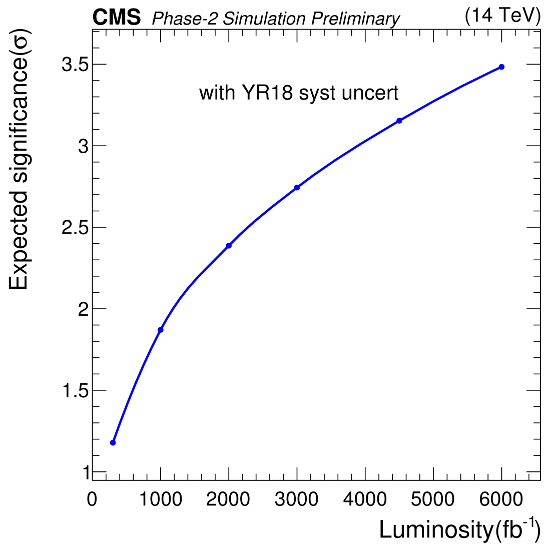
- One of the high profile analyses for HL-LHC



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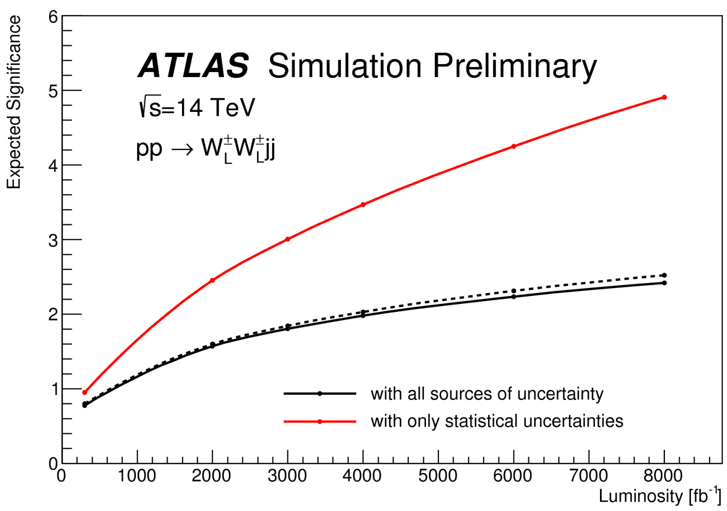

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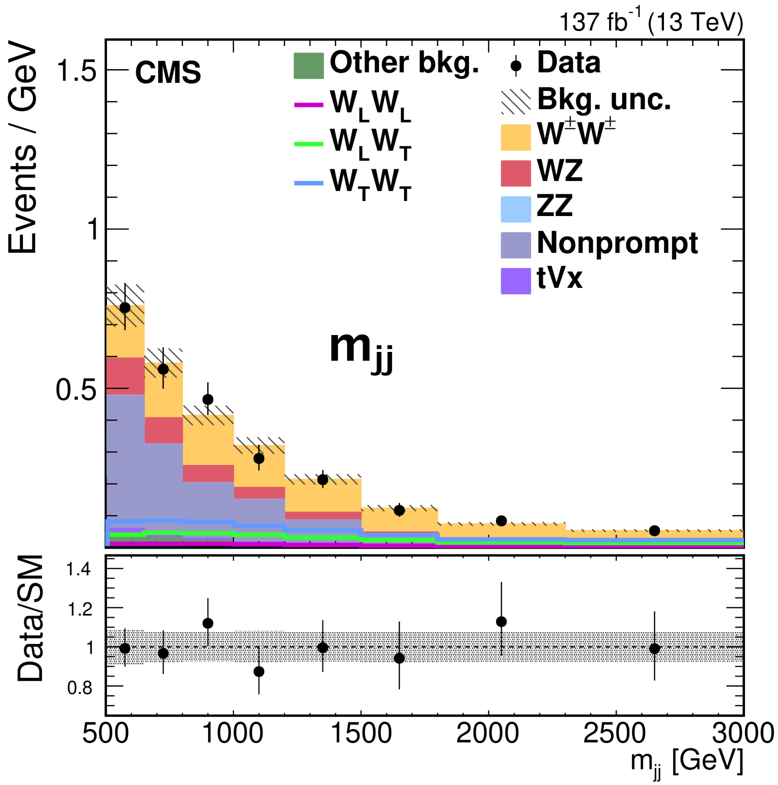
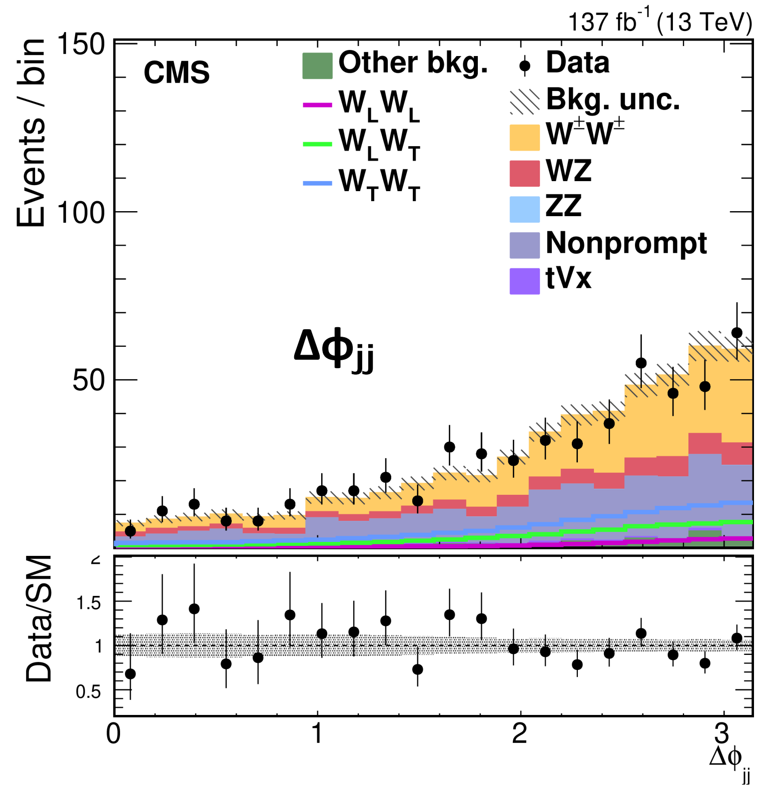
Signal region

- m_{jj} and $\Delta\phi_{jj}$ distributions in signal region





- The histograms for the $W^{\pm}W^{\pm}$ process include the contributions from the W_LW_L, W_LW_T and W_TW_T processes (shown as solid lines), QCD $W^{\pm}W^{\pm}$ and interference

Object definitions

- **Muons**
  - two selected leptons: $|\eta| < 2.4$, $p_T > 20$ GeV
    - 2016: cut-based tight ID & PF relative isolation < 0.15
    - 2017: muon MVA tight WP & mini isolation tight WP
    - 2018: cut-based tight ID & mini isolation tight WP
  - Fakeable object: tight ID, PF relative isolation < 0.40 & tracker relation isolation < 0.40, $|\eta| < 2.4$, $p_T > 10$ GeV
  - Veto object: cut-based loose ID, $|\eta| < 2.4$, $p_T > 10$ GeV
- **Electrons**
  - two selected leptons: $|\eta| < 2.5$, $p_T > 20$ GeV
    - 2016-17-18: electron MVA tight WP & triple charge requirement
  - Fakeable object: HLT-safe WP, $|\eta| < 2.5$, $p_T > 10$ GeV
  - Veto object: cut-based loose ID, $|\eta| < 2.5$, $p_T > 10$ GeV

- **Tau**: Veto hadronically decay tau

- **E_T^{miss}**
  - Particle-Flow E_T^{miss} using PF candidates
  - type-I correction applied

- **Jets**
  - anti-kT with R = 0.4 , PF jets, $|\eta_j| < 4.5$

- **Anti B-tagging**
  - 2016-17-18 : DeepCSV, medium WP

Nonprompt leptons

- Fake rate ϵ_{fake}
  - Defined as the efficiency for fakeable objects to pass full lepton selection
  - Measured in a QCD-enriched sample
  - η and p_T dependence (2D e/μ fake rate for each year in backup slide 35)

- Extrapolate the background yields
  - from “tight+loose” and “loose+loose” data events in “SR”
  - by weighted

“tight+loose”:

$$w_i = \frac{\epsilon_{\text{fake}}(p_{\text{Ti}}, \eta_i)}{1 - \epsilon_{\text{fake}}(p_{\text{Ti}}, \eta_i)}$$

“loose+loose”:

$$(w_{ij} = \frac{\epsilon_{\text{fake}}(p_{\text{Ti}}, \eta_i)}{1 - \epsilon_{\text{fake}}(p_{\text{Ti}}, \eta_i)} \times \frac{\epsilon_{\text{fake}}(p_{\text{Tj}}, \eta_j)}{1 - \epsilon_{\text{fake}}(p_{\text{Tj}}, \eta_j)})$$

  - and with real lepton from simulation subtraction

$$N^{non-prompt} = \left(\sum_i w_i^{data} - \sum_i w_i^{MC} - \sum_{i,j} w_{ij}^{data} + \sum_{i,j} w_{ij}^{MC}\right) N_{tt/tl}$$

Charge mis-ID

- Charge mis-ID rate ε_{sim} and ε_{data}
  - Studies by the muon POG show that the charge mis-ID rate for **muons** is **negligible**
  - For **electrons**
    - Measured from *Z* plus jets sample with two electrons
    - As ratio between same sign and opposite sign dielectron events
    - similarly in data
- Estimate the background yields by applying charge mis-ID scale factor: $\varepsilon_{data}/\varepsilon_{sim}$ to two opposite-sign simulated events in "SR"

Fiducial region

- The definition of fiducial region for the cross section measurements
  - Two same-sign leptons: $p_T > 20$ GeV, $|\eta|<2.5$, $m_{ll} > 20$ GeV
  - Two jets: $p_T > 50$ GeV, $|\eta| < 4.7$
  - $m_{jj}>500$ GeV, $|\Delta\eta_{jj}|>2.5$

Signal BDTs

- Signal BDTs to improve the sensitivity to polarized scattering
  - Train LL against (LT+TT) and train (LL+LT) against TT
  - Use 15 discriminating variables
    - jet kinematics
    - vector boson kinematics
    - variables related to both lepton and jet kinematics

Variables	Definitions
$\Delta\phi_{\mathrm{jj}}$	Difference in azimuthal angle between the leading and subleading jets
$p_{\mathrm{T}}^{\mathrm{j1}}$	p_{T} of the leading jet
$p_{\mathrm{T}}^{\mathrm{j2}}$	p_{T} of the subleading jet
$p_{\mathrm{T}}^{\ell_1}$	Leading lepton p_{T}
$p_{\mathrm{T}}^{\ell_2}$	Subleading lepton p_{T}
$\Delta\phi_{\ell\ell}$	Difference in azimuthal angle between the two leptons
$m_{\ell\ell}$	Dilepton mass
$p_{\mathrm{T}}^{\ell\ell}$	Dilepton p_{T}
$m_{\mathrm{T}}^{\mathrm{WW}}$	Transverse WW diboson mass
$z^*_{\ell_1}$	Zeppenfeld variable of the leading lepton
$z^*_{\ell_2}$	Zeppenfeld variable of the subleading lepton
$\Delta R_{\mathrm{j1},\ell\ell}$	ΔR between the leading jet and the dilepton system
$\Delta R_{\mathrm{j2},\ell\ell}$	ΔR between the subleading jet and the dilepton system
$(p_{\mathrm{T}}^{\ell_1} p_{\mathrm{T}}^{\ell_2})/(p_{\mathrm{T}}^{\mathrm{j1}} p_{\mathrm{T}}^{\mathrm{j2}})$	Ratio of p_{T} products between leptons and jets
$p_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse momentum

Inclusive BDT

- Isolate EW $W^{\pm}W^{\pm}$ against nonVBS background
  - Dominated by non-prompt ttbar events
  - Use 10 discriminating variables

Variables	Definitions
m_{jj}	Dijet mass
$\lvert\Delta\eta_{\mathrm{jj}}\rvert$	Difference in pseudorapidity between the leading and subleading jets
$\Delta\phi_{\mathrm{jj}}$	Difference in azimuth angles between the leading and subleading jets
$p_{\mathrm{T}}^{\mathrm{j1}}$	p_{T} of the leading jet
$p_{\mathrm{T}}^{\mathrm{j2}}$	p_{T} of the subleading jet
$p_{\mathrm{T}}^{\ell_1}$	Leading lepton p_{T}
$p_{\mathrm{T}}^{\ell\ell}$	Dilepton p_{T}
$z^*_{\ell_1}$	Zeppenfeld variable of the leading lepton
$z^*_{\ell_2}$	Zeppenfeld variable of the subleading lepton
$p_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse momentum