Measurements of production cross sections of polarized same-sign W boson pairs in association with two jets in proton-proton collisions at $\sqrt{13}$ TeV

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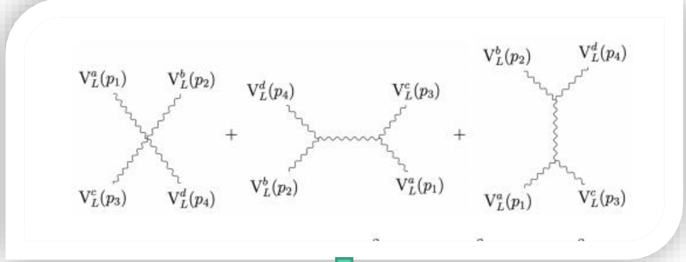
Motivation

- A major source of interest in VBS arises from the theoretical observation that at tree level unitarity of cross section amplitude for longitudinal gauge bosons restored in the standard model by the Higgs boson with a mass lower than about 1 TeV. (W and Z gauge bosons acquire mass via the Brout–Englert–Higgs mechanism)
  - Sensitive to the electroweak symmetry breaking mechanism at high energy scales.
  - Effect of BSM on VBS is studied and any deviations of VBS measurements from SM prediction can be sign of new physics.

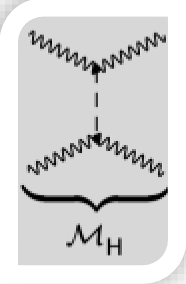
Introduction

- Longitudinal polarization of w-boson is proportional to it's 4-momentum so at high energies longitudinally polarized gauge bosons yield the dominant contribution to the $W^+W^- \rightarrow W^+W^-$ cross section.
- The amplitude for the scattering of two longitudinally polarized gauge bosons, without Higgs contributions

$$\mathcal{M}^{gauge} = -\frac{g_w^2}{4m_W^2}u + \mathcal{O}\left(\left[\frac{E}{m_W}\right]^0\right).$$



- After adding the amplitude of the Higgs-exchange contributions:



$$\mathcal{M}^{\text{Higgs}} = -\frac{g_w^2}{4m_W^2}\left[\frac{(s-m_W^2)^2}{s-m_H^2} + \frac{(t-m_W^2)^2}{t-m_H^2}\right].$$

In the high-energy limit →

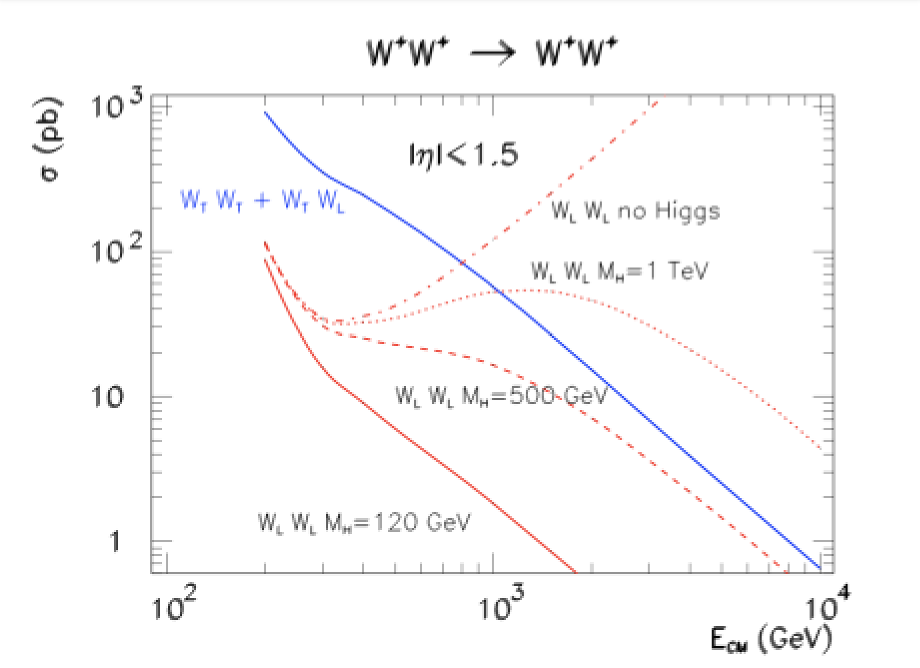
$$\mathcal{M}^{\text{Higgs}} = \frac{g_w^2}{4m_W^2}u.$$

- so, the terms rising with energy cancel and leave a constant term which is not violating unitarity. This only holds if the Higgs boson behaves as described in the SM. Without the SM-Higgs boson, unitarity of the S-matrix would be violated in all VBS channels through the high-energy behavior of the scattering of longitudinally polarized vector bosons.

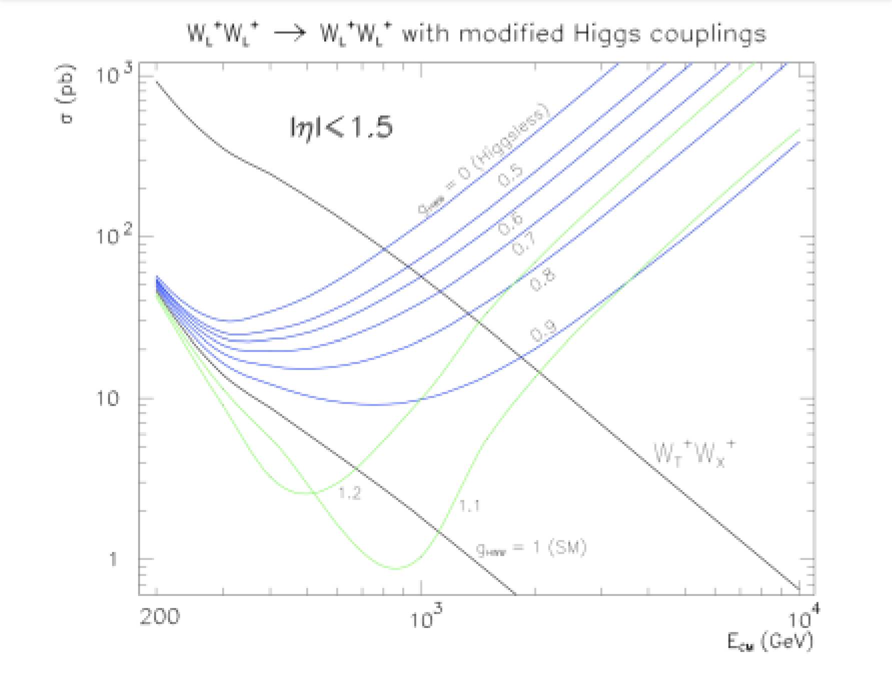
Introduction

- VBS cross section as a function of the center of mass energy:

Different Higgs mass



Different Higgs coupling



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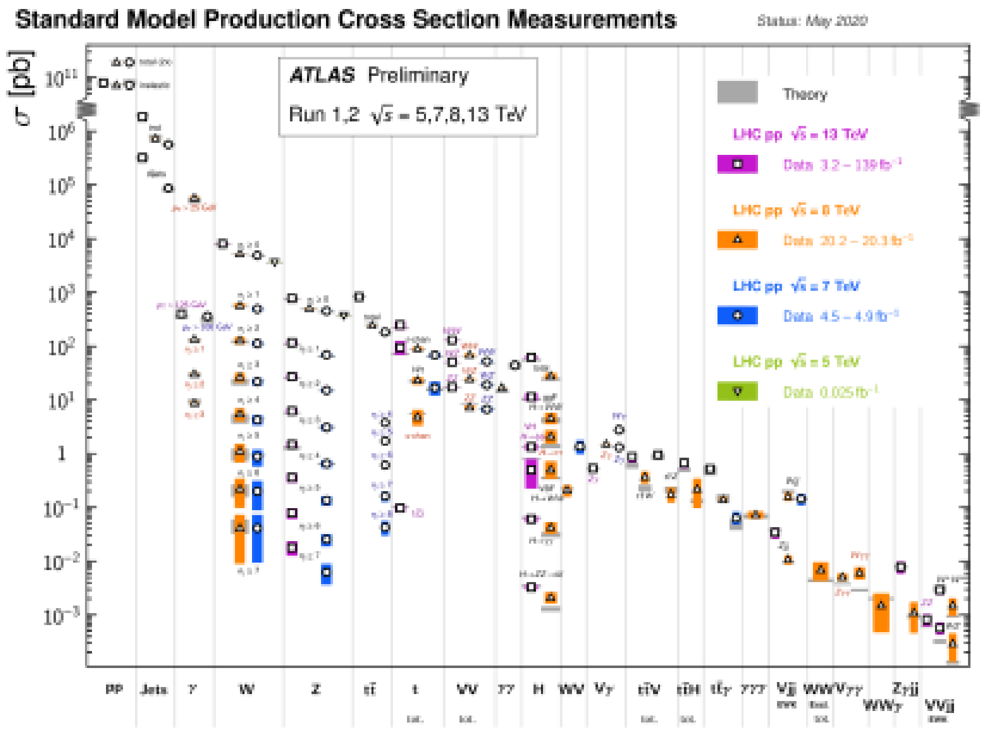
Introduction



- VBS scattering appears on the very right of the table.

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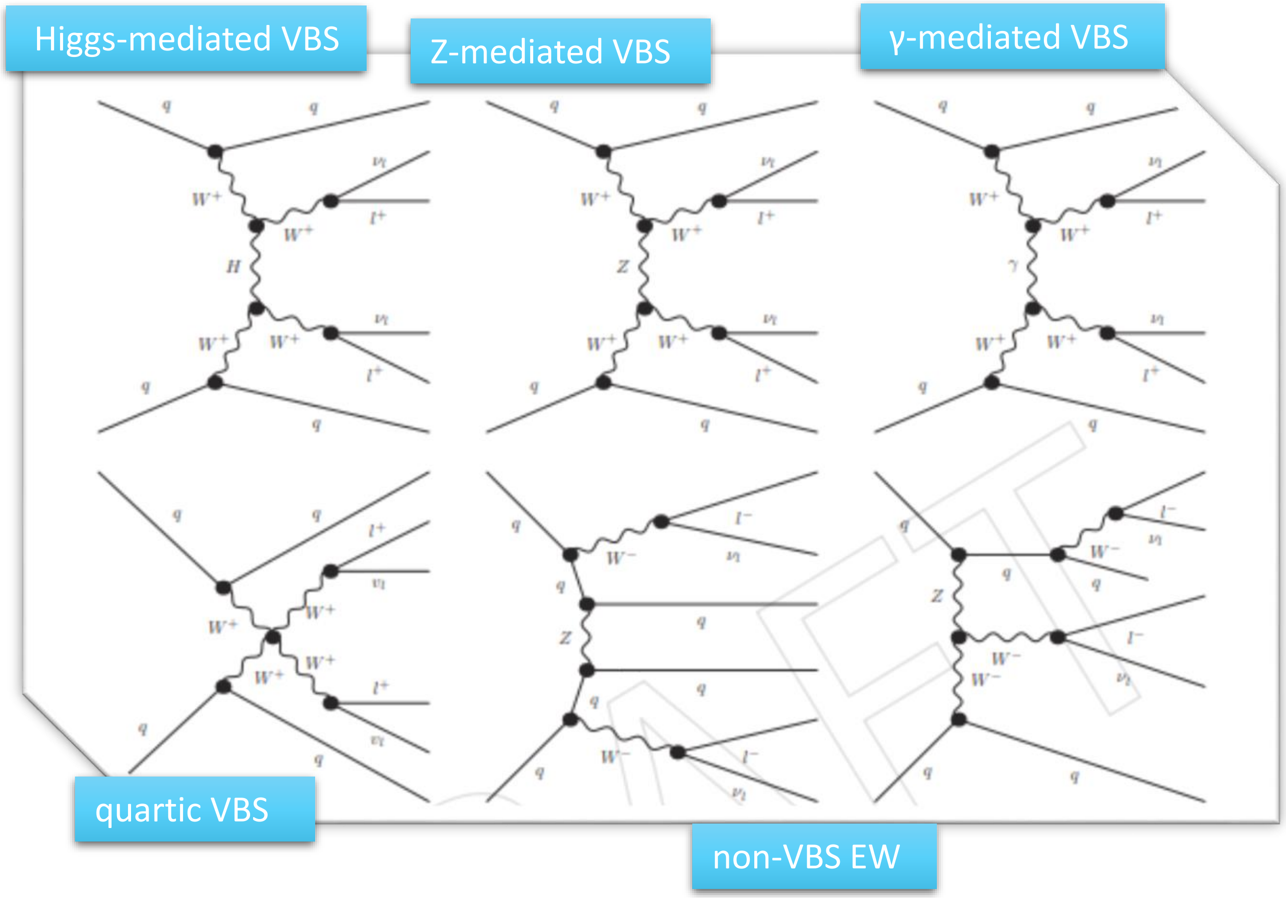
The big advantage:

- experimentally clean signature. WW-> WW has best signal to bkg ratio between all VBS channels
- perturbatively well under control

Disadvantage:

- VBS is rare process

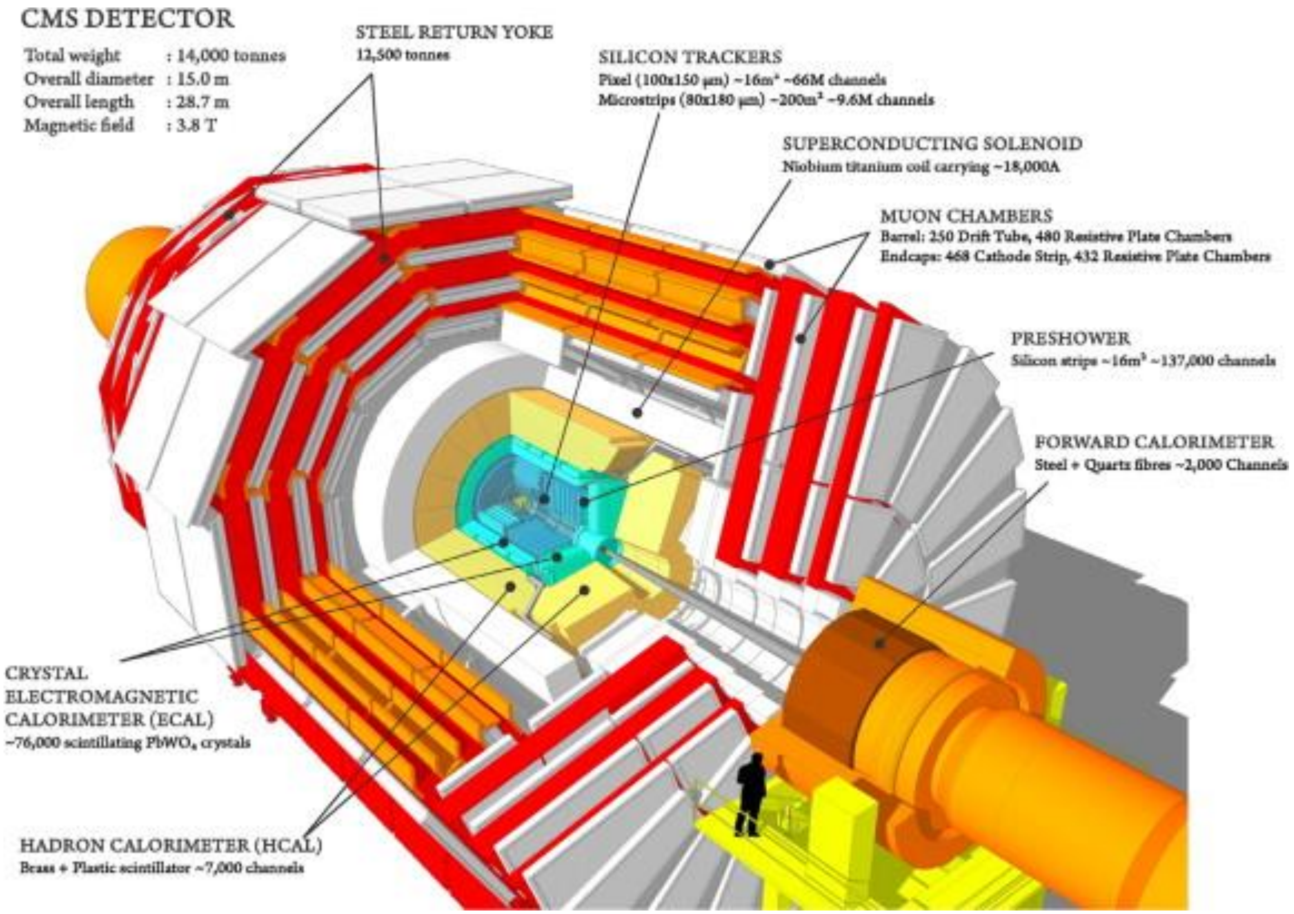
VBS model

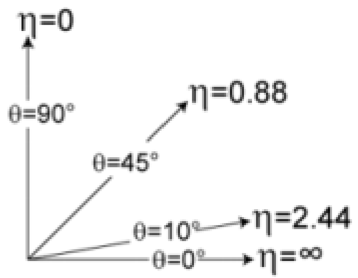


- 2 same-sign leptons(e/muon), 2 neutrinos, 2 energetic jets in final state.
- The W boson polarization reconstructed from decay products

- In the $w^{\pm} w^{\pm}$ channel, each of the W bosons can be polarized either longitudinally (w_L) or transversely (w_T), leading to three distinct contributions $w_L^{\pm} w_L^{\pm}$, $w_L^{\pm} w_T^{\pm}$, and $w_T^{\pm} w_T^{\pm}$.

CMS Detector





- CMS Trigger system
  - L1 Trigger reduces the event rate to 1000 kHz using Ecal.
  - reduces the event rate to 1 kHz using Tracker.

https://doi.org/10.1016/j.crhy.2015.03.018.

Data and MC samples

- The data sample of proton-proton (pp) collisions at 13 TeV corresponds to an integrated luminosity of 137/fb collected with the CMS detector during the years 2016, 2017, and 2018.
- MC samples are simulated to the NLO precision.(α^7) , (α^6, α_s)
- Main Backgrounds:
  - WZ, ZZ, non-prompt leptons, tVx(tZq).
- triggers
  - single-electron (single-muon)
    - require the presence of an isolated lepton with p_T > 27 (24) GeV
  - dilepton triggers
    - with lower p_T thresholds, with p_T > 23(8) GeV or lower for the leading and sub-leading lepton.

Background estimation

- A combination of methods based on control samples in data and simulation is used to estimate background contributions.
- charge misidentification
  - Oppositely charged dilepton final states from tt, tW, w^+w^-, and Drell–Yan processes.
- non-prompt lepton
  - originating from leptonic decays of heavy quarks, hadrons misidentified as leptons, and electrons from photon conversion are suppressed by the identification and isolation requirements imposed on electrons and muons. The remaining contribution from the non-prompt lepton. background is estimated directly from data
- **Background-enriched control regions (CRs)** are used to select event samples enriched with WZ, non-prompt lepton, tZq, and ZZ background events.

The WZ CR is defined by requiring three leptons where the opposite-sign same-flavor leptons from the Z boson candidate have p_T > 25 and 10 GeV with the dilepton mass within 15 GeV of the nominal Z boson mass. In events with three same-flavor leptons, the opposite-sign lepton pair with the dilepton mass closest to m_Z is associated with the Z boson. The remaining lepton with p_T > 20 GeV is associated with the W boson. In addition, the trilepton mass m_{lll} is required to be greater than 100 GeV and max(z_l^*) must be less than 1.0.

The non-prompt lepton CR is defined by requiring the same selection as for the w^+w^- SR, but with the b jet veto requirement inverted. The selected sample is enriched with events from the non-prompt lepton background and dominated by semi-leptonic tt events. Similarly, the tZq CR is defined by requiring the same selection as the WZ CR, but with the b quark veto requirement inverted. The selected sample is dominated by the tZq background process. Finally, the ZZ CR requirements select events with four leptons with the same VBS requirements as the w^+w^- SR. The four CRs are used to estimate the normalization of the main background processes from data.

Event reconstruction

- Events are reconstructed using the CMS particle-flow (PF) algorithm with an optimized combination of all subdetector information. The missing transverse momentum vector p_T^{miss} is defined as the projection onto the plane perpendicular to the beam axis of the negative vector sum of the momenta of all reconstructed PF objects in an event.
- Jets are reconstructed by clustering PF candidates using the anti-kT algorithm with a distance parameter of 0.4. Jets are calibrated in the simulation, and separately in data, accounting for energy deposits of neutral particles from pileup and any nonlinear detector response. Corrections to jet energies to account for the detector response are propagated to p_T^{miss}.
- The effect of pileup is mitigated through a charged-hadron subtraction technique, which removes the energy of charged hadrons not originating from the primary vertex (PV) of the event.
- The PV is defined as the vertex with the largest value of summed physics-object p_T^2.
- Electrons and muons are reconstructed by associating a track reconstructed in the tracking detectors with either a cluster of energy in the ECAL and a track in the muon system

SR Object selection

- At first Electrons and muons have loose identification criteria with $p_T > 10\ GeV$ and $|\eta| < 2.5$ (2.4) for electrons (muons).
- At the final stage of the lepton selection the tight working points criteria are chosen.
- impact parameter of the candidates with respect to the PV and their isolation with respect to other particles in the event are mostly produced in the central rapidity region with respect to the two selected jets. The candidate $W^{\pm}W^{\pm}$ events are required to maximize the Zeppenfeld variable.

$$z_l^* = \left|\eta^l - (\eta^{j1} + \eta^{j2})/2\right| / \Delta\eta_{jj}$$

- Candidate events with one or more jets with $p_T > 20$ GeV and $|\eta| < 2.4$ that are consistent with the fragmentation of a bottom quark are rejected to reduce the number of top quark background events.

Summary of the requirements defining the $w^{\pm}w^{\pm}$ SR.

Variable	Requirement
Leptons	Exactly 2 same-sign leptons, $p_T > 25/20$ GeV
p_T^j	>50 GeV
$\lvert m_{\ell\ell} - m_Z\rvert$	>15 GeV (ee)
$m_{\ell\ell}$	>20 GeV
p_T^{miss}	>30 GeV
b quark veto	Required
Max(z_ℓ^*)	<0.75
m_{jj}	>500 GeV
$\lvert\Delta\eta_{jj}\rvert$	>2.5

Extracting polarization information

- W bosons can each be longitudinally or transversely polarized.
- The W_L bosons tend to be radiated at a smaller angle with respect to the incoming quark direction.
  - leading to different kinematic distributions, reflected in the kinematical properties of the two leptons, the two jets, and p_T^{miss}.
  - So by reconstructing the decay products of w-bosons based on their scattering amplitude in the W^+W^- center-of-mass energy frame or base on scattering angles, polarizations information can be extracted.
- Multivariate techniques are used to enhance the separation between the different processes. We implement boosted decision trees (BDTs) with gradient boosting using the TMVA package.

Event yields and uncertainties

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

Table 4: Systematic uncertainties of the $W^{\pm}_{L}W^{\pm}_{L}$ and $W^{\pm}_{X}W^{\pm}_{T}$, and $W^{\pm}_{L}W^{\pm}_{X}$ and $W^{\pm}_{T}W^{\pm}_{T}$ cross section measurements in units of percent.

Source of uncertainty	$W^{\pm}_{L}W^{\pm}_{L}$ (%)	$W^{\pm}_{X}W^{\pm}_{T}$ (%)	$W^{\pm}_{L}W^{\pm}_{X}$ (%)	$W^{\pm}_{T}W^{\pm}_{T}$ (%)
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

- Data and MC have good agreement.

Results

Helicity eigen states defined in the $W^{\pm}W^{\pm}$ center-of-mass frame.

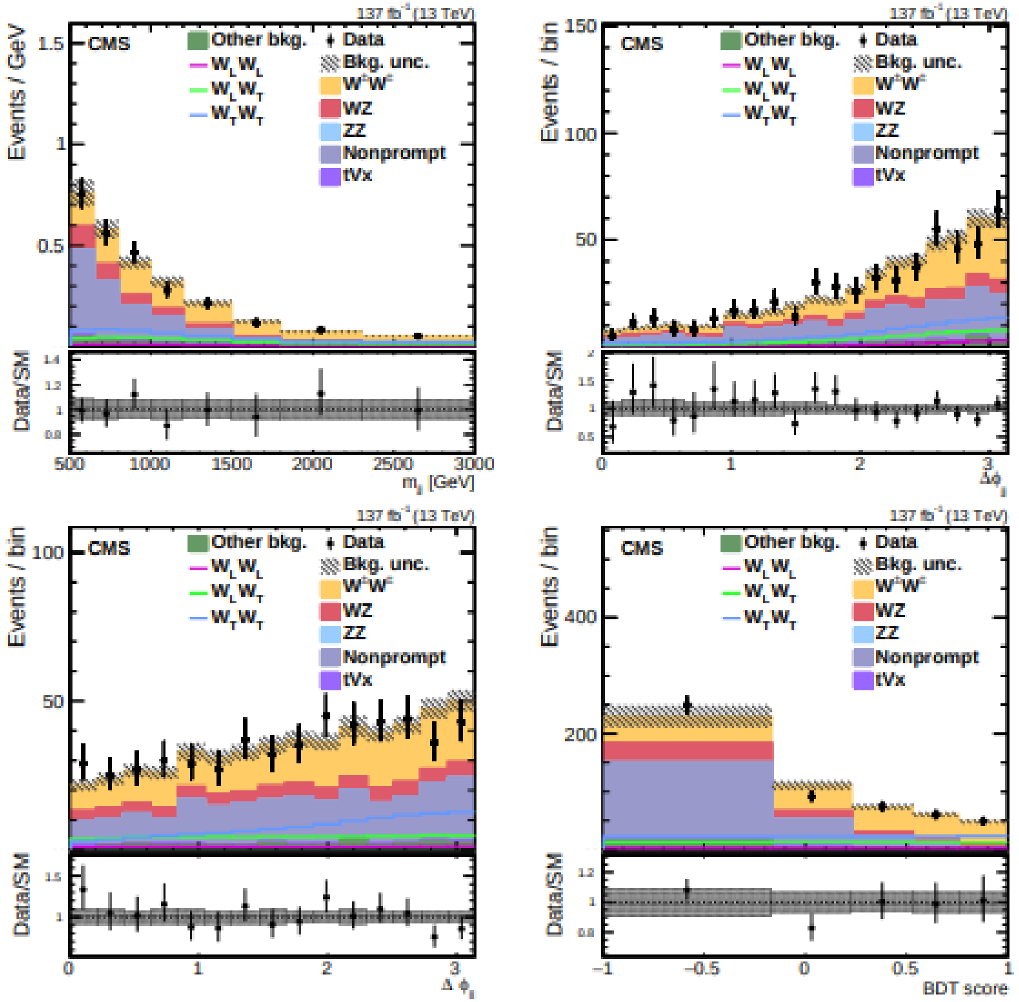
Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^{\pm}W_L^{\pm}$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W_X^{\pm}W_T^{\pm}$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W_L^{\pm}W_X^{\pm}$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W_T^{\pm}W_T^{\pm}$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

Helicity eigen states defined in the parton-parton center-of-mass frame.

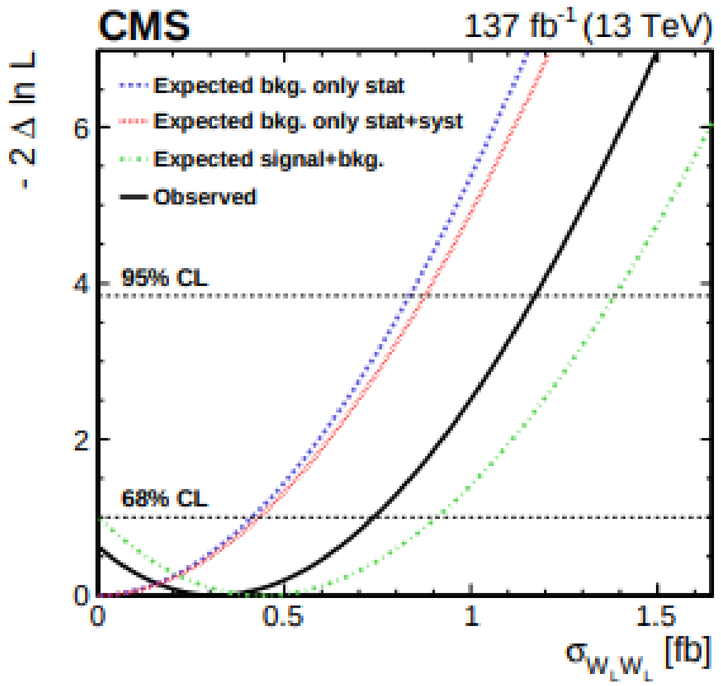
Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^{\pm}W_L^{\pm}$	$0.24^{+0.40}_{-0.37}$	0.28 ± 0.03
$W_X^{\pm}W_T^{\pm}$	$3.25^{+0.50}_{-0.48}$	3.32 ± 0.37
$W_L^{\pm}W_X^{\pm}$	$1.40^{+0.60}_{-0.57}$	1.71 ± 0.19
$W_T^{\pm}W_T^{\pm}$	$2.03^{+0.51}_{-0.50}$	1.89 ± 0.21

- The theoretical predictions including the (α^7) , (α^6, α_s) correction.
- The cross-section for $W^+W^- \rightarrow W^+W^-$ or EW-induced pp W^+W^- jj is Lorentz invariant. However, because the polarization of a particle is not Lorentz invariant, the polarized cross sections $W_L^{\pm}W_L^{\pm} \rightarrow W_L^{\pm}W_L^{\pm}$ and pp $\rightarrow W_L^{\pm}W_L^{\pm}$jj depend on the choice of reference frame. The natural reference frame to use is the WW center-of-mass frame.

Results



CMS
137 fb^{-1} (13 TeV)
Other bkg.
Data
W_LW_L
Bkg. unc.
W_LW_T
$W^\pm W^\pm$
W_TW_T
WZ
ZZ
Nonprompt
tVx
Events / GeV
Events / bin
Data/SM
m_{jj} [GeV]
$\Delta\phi_{jj}$
BDT score



CMS
137 fb^{-1} (13 TeV)
Expected bkg. only stat
Expected bkg. only stat+syst
Expected signal+bkg.
Observed
95% CL
68% CL
$-2\,\Delta\ln L$
$\sigma_{W_LW_L}$ [fb]

Thanks for your attention!