From discovery to precision: The journey of vector boson scattering at the LHC experiments

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Outline

- **Why do we study vector boson scattering (VBS):** theory introduction (from very far in the past)

- **Experimental results from LHC Run-I:** the first VBS analyses, evidences and observations

- **Legacy VBS results from LHC Run II:** 138 fb^{-1} provide access to a wide range of VBS final states $\rightarrow$ plethora of result

- **VBS in the future:** what do we need and what to expect from LHC Run-III and Run-IIII

From weak interactions to gauge boson scattering

The experimental evidence of a new "weak" force in the beginning of 20th century puzzled particle physicists for half a century

- **Fermi (1934):** interpretation of the neutron β-decay as a four-point interaction [1]

- **Wu (1957):** left and right eigenstates of the chirality behave differently under the weak force, thus maximally violating Pairty [2]

- **Lederman**, **Christenson (1957, 1964):** weak interactions violate CP [3,4]

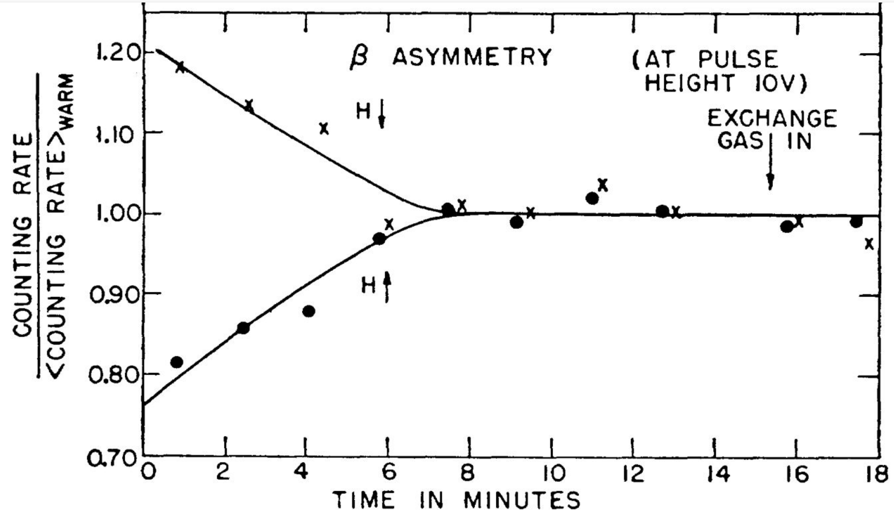
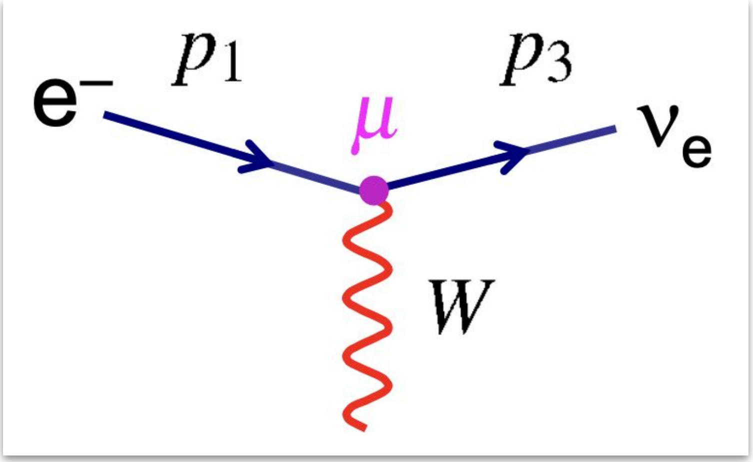


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

The form for weak interaction is determined from experiment to be ***V-A***: right-handed fermions do not interact

$$J_{\mu,l} = \bar{\psi}_{\nu_l}\gamma_\mu(1-\gamma_5)\psi_l = J^V_\mu - J^A_\mu$$



PROBLEMS

1) Weak force acts feebly at a short distance: mediated by **massive spin-1 vector bosons from SU(2) symmetry group**

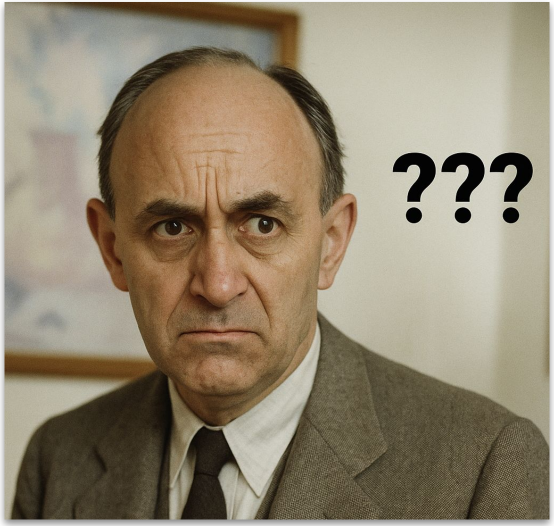
2) **Mass terms break gauge invariance**

$$-m_l(\bar{l}_L l_R + \bar{l}_R l_L)$$

Weak Interactions and Electroweak unification

The form for weak interaction is determined from experiment to be ***V-A***: right-handed fermions do not interact

$$J_{\mu,l} = \bar{\psi}_{\nu_l}\gamma_\mu(1-\gamma_5)\psi_l = J_\mu^V - J_\mu^A$$



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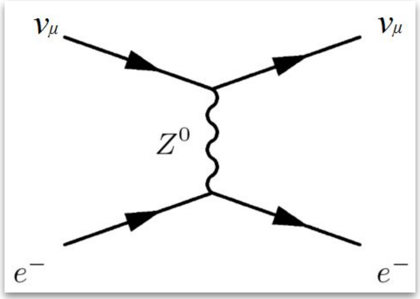
$$\cancel{-m_l(\bar{l}_L l_R + \bar{l}_R l_L)}$$

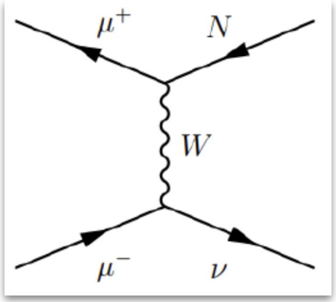
The first theory to describe weak forces within a unified framework with electromagnetism emerged in the 1960s, with Glashow [5], Weinberg [6], and Salam [7]: Electroweak theory.

Describe weak and electromagnetic interactions with $SU(2)_L \times U(1)$ gauge symmetry

$$\mathcal{L}_{g+f} = \underbrace{-\frac{1}{4} W_a^{\mu\nu} W^a_{\mu\nu}}_{\text{SU(2) field tensor}} \underbrace{- \frac{1}{4} B^{\mu\nu} B_{\mu\nu}}_{\text{U(1) field tensor}} + \underbrace{\bar{\psi}_L i\gamma^\mu D_\mu \psi_L}_{\text{Yukawa SU(2) doublets}} + \underbrace{\bar{\psi}_R i\gamma^\mu D_\mu \psi_R}_{\text{Yukawa SU(2) singlets}}$$

Neutral and Charged Currents + QED

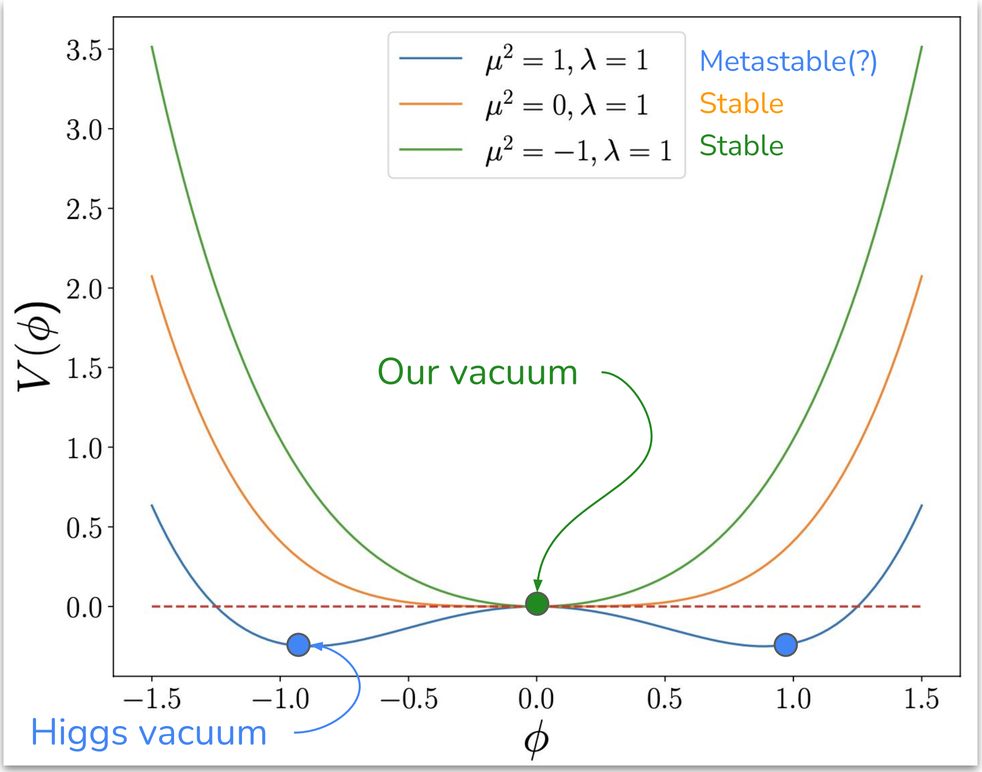




The success of the EW theory relies on the mechanism with which vector bosons acquire mass:

BEH mechanism [8,9,10]

Infinite minima at $e^{i\rho}\sqrt{\mu^2/2\lambda}$



BEH mechanism: generate mass while retaining gauge symmetry

Introduce **complex scalar fields ϕ** transforming as a doublet under *SU(2)*, with **non-vanishing v.e.v**

$$\phi \equiv (\phi_u, \phi_d) \qquad \langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$$

ϕ is subject to a scalar potential $V(\phi^\dagger\phi)$

$$\mathcal{L}_h = (D_\mu\phi)^\dagger(D^\mu\phi) + \underbrace{\mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2}_{-V(\phi^\dagger\phi)}$$

Scalar Lagrangian

The **Lagrangian** is invariant but **the vacuum is not** → **Spontaneous Symmetry Breaking**

Expanding around the minima we find only one physical field: **the Higgs field (*h*)**

Local expansion — Goldstone bosons — Rotation + gauge choice

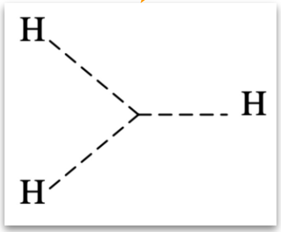
$$\phi(x) = \frac{e^{i\theta_k \frac{\sigma_k}{2}}}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \approx \frac{1}{\sqrt{2}} \begin{pmatrix} \eta_1(x) + i\eta_2(x) \\ v + h(x) + i\eta_3(x) \end{pmatrix} \xrightarrow{SU(2)} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

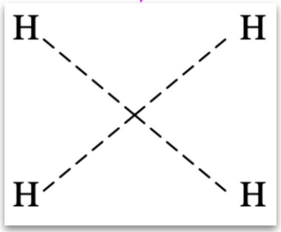
The scalar potential in unitary gauge shows that **the Higgs field is a massive scalar boson**

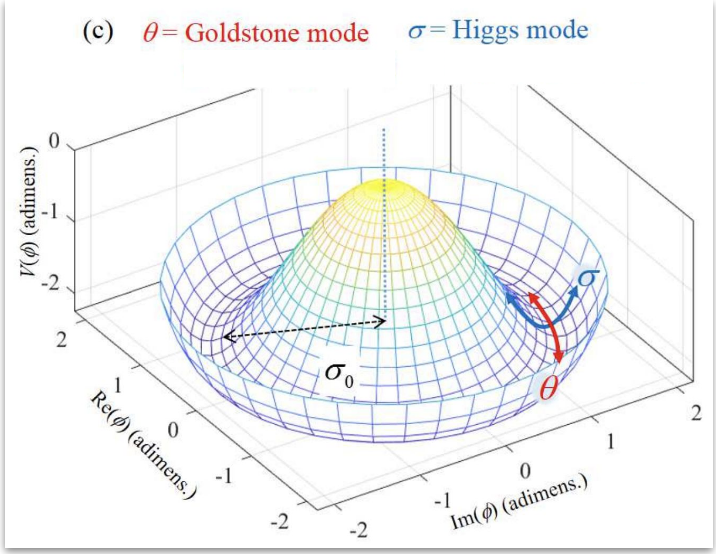
$$V(\phi^\dagger \phi) = -\mu^2 h^2 - \lambda v h^3 - \lambda h^4 / 4$$

Mass term

$$\boxed{m_h = \sqrt{2\lambda} v}$$







The origin of the electroweak gauge boson masses comes from the kinetic term of the scalar Lagrangian evaluated on the non-vanishing v.e.v: $SU(2)_L \times U(1)_Y \rightarrow U(1)_Y$

$$\boxed{\langle 0|\phi|0\rangle = \langle\phi\rangle_0}$$

Covariant derivative
$SU(2)_L \otimes U(1)_{Y_L}$

$$\left\langle (D_\mu\phi)(D^\mu\phi)\right\rangle_0 = \frac{1}{2}\begin{pmatrix}0 & v\end{pmatrix}\left(gW^a_\mu T^a + g'Y_L B_\mu\right)^2\begin{pmatrix}0\\ v\end{pmatrix}$$

Three massive bosons and a massless one

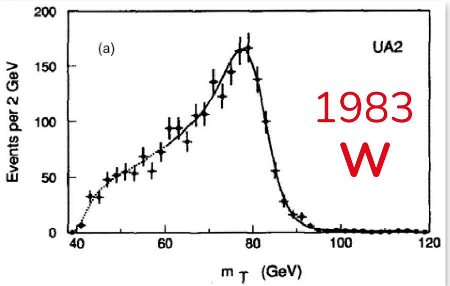
$$= \frac{1}{2}\frac{v^2}{4}\left[g^2(W^1_\mu)^2 + g^2(W^2_\mu)^2 + (-gW^3_\mu + g'B_\mu)^2\right]$$

Mass eigenstates

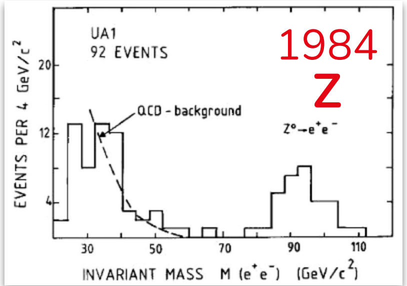
$$W^\pm_\mu = \frac{1}{\sqrt{2}}(W^1_\mu \mp iW^2_\mu); \quad m_W = g\frac{v}{2}$$

$$Z_\mu = \frac{1}{\sqrt{g^2+g'^2}}(gW^3_\mu - g'B_\mu); \quad m_Z = \sqrt{g^2+g'^2}\,\frac{v}{2}$$

$$A_\mu = \frac{1}{\sqrt{g^2+g'^2}}(g'W^3_\mu + gB_\mu); \quad m_A = 0$$



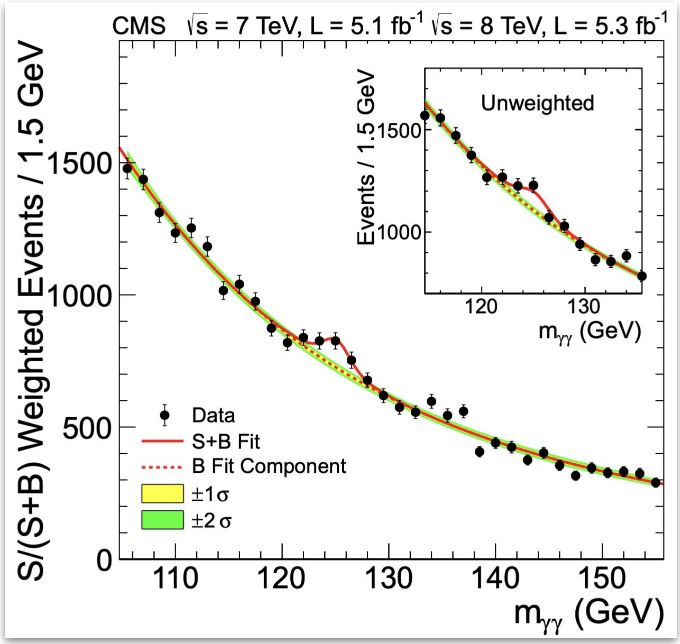
Phys.Lett.B 122 (1983) 476-485

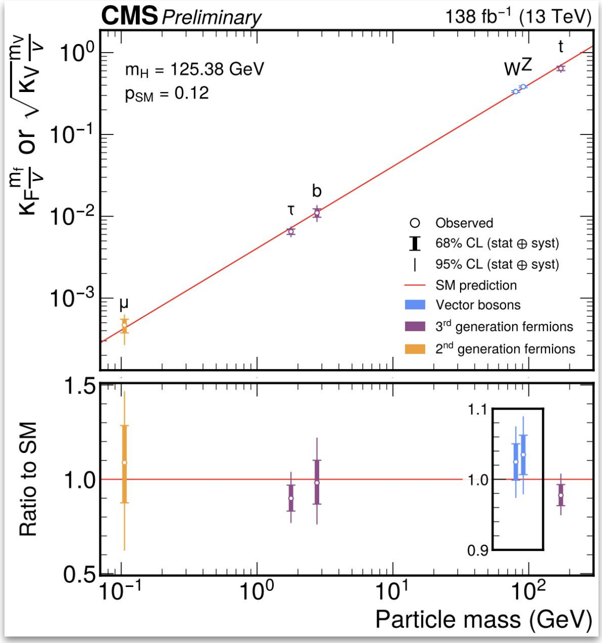


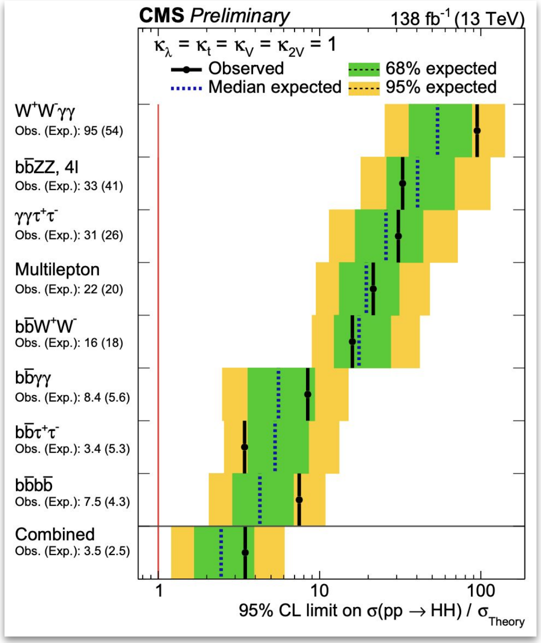
Phys.Lett.B 126 (1983) 398-410

A major focus of the physics at ATLAS and CMS is to understand how electroweak symmetry breaking occurs in nature: the Higgs boson is the main character

Discovery [11]	Couplings [12]	Self-Coupling [13]

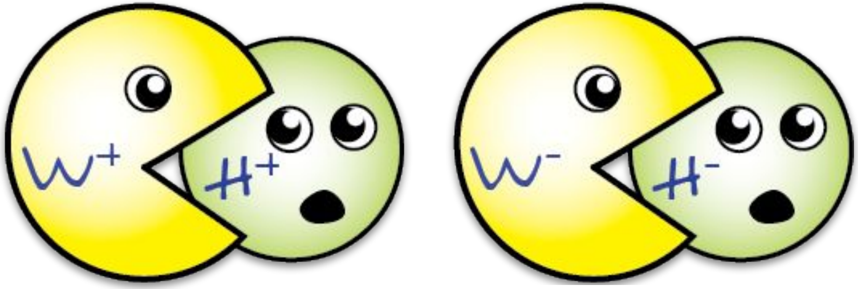






Experimental aspects of EWSB

Precisely studying the physical particle of the BEH mechanism only yields a partial picture of EWSB: A Tale of Goldstone Bosons



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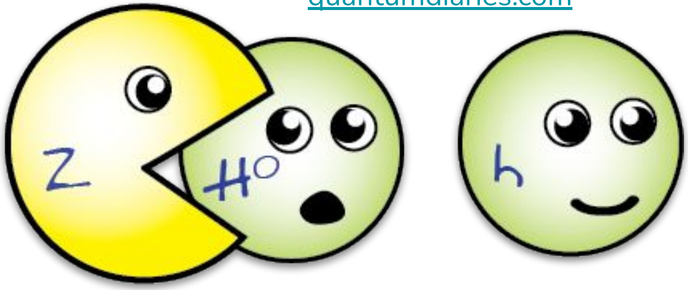
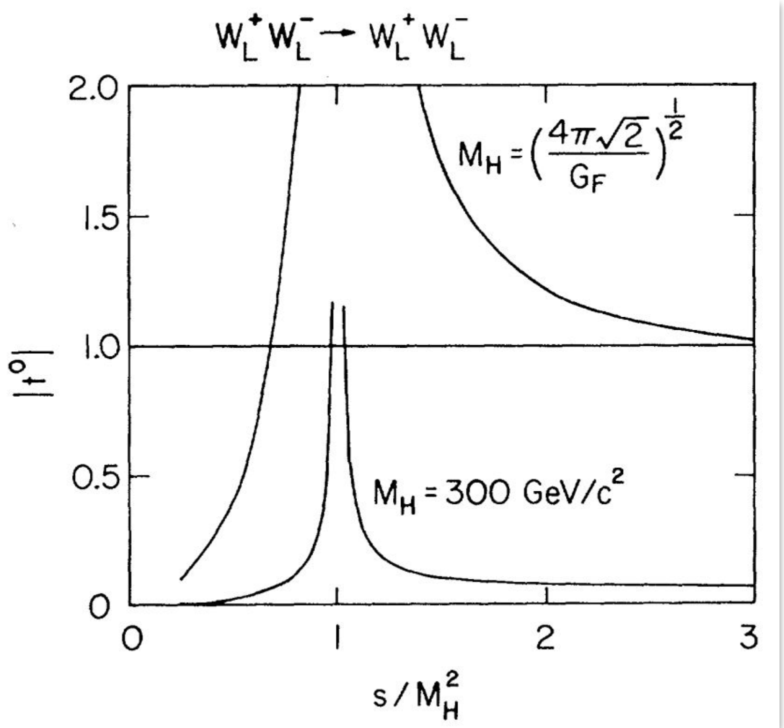


The **longitudinal** W and Z bosons are the **“eaten” Goldstone modes (π) from the Higgs field.** These modes are not physical particles, but become the third polarization state of the massive W and Z after EWSB.

At high energies, scattering of longitudinal W/Z bosons probes the dynamics of EWSB **and the underlying Goldstone structure: Equivalence Theorem [14,15,16]**

$$\mathcal{A}(V_L V_L \to V_L V_L) \cong \mathcal{A}(\pi\pi \to \pi\pi)$$

Before discovering the Higgs boson, we already knew that mass values above ~1 TeV would violate unitarity for longitudinally polarized gauge boson scattering



Benjamin W. Lee et al. (1977) [17]

$$M_H^2 \leqslant \frac{8\pi\sqrt{2}}{3G_F} \equiv M_c^2 \approx 1\ (\mathrm{TeV}/c^2)^2.$$

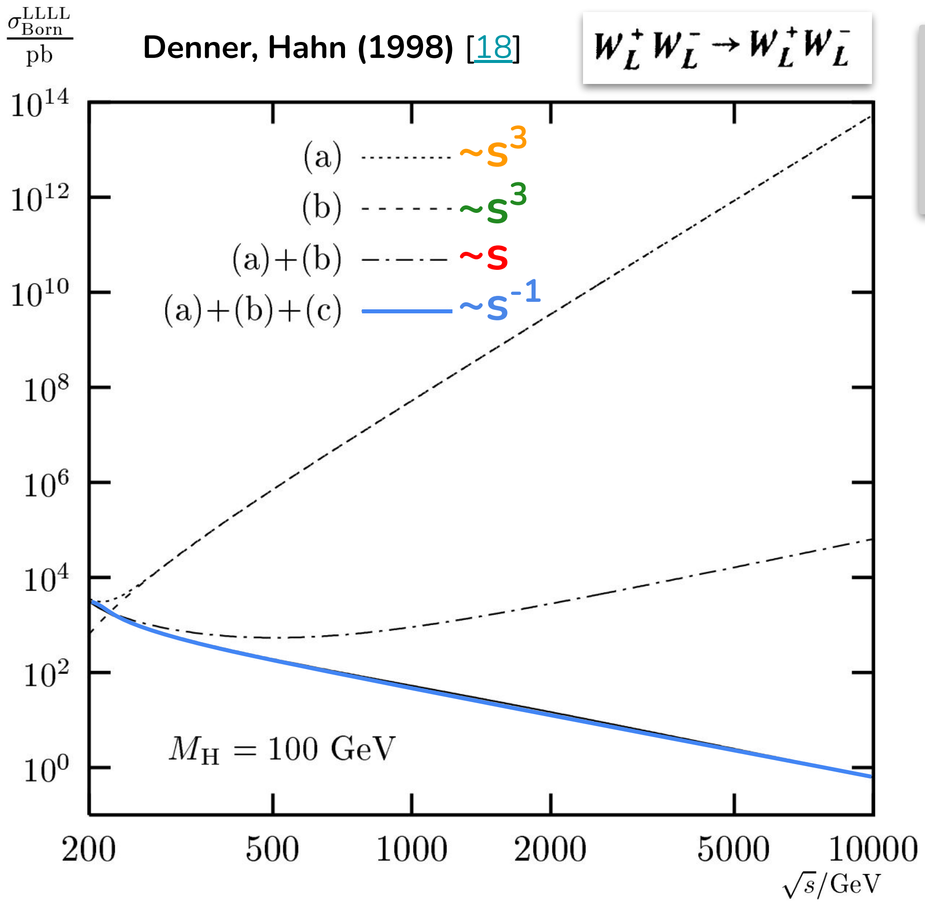
For Higgs boson mass values above M_C ~ 1 TeV:

- Gauge bosons could create a scalar bound state which serves as a low-mass Higgs boson.

- Weak interactions do become strong and begin to display the attributes exhibited in the GeV energy regime by strong interactions

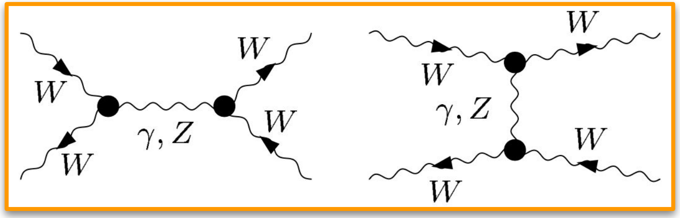
Scattering of gauge bosons - unitarization

Denner, Hahn (1998) [18]

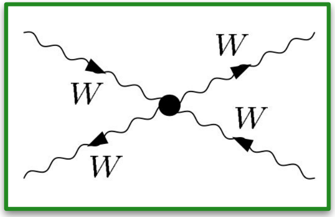


The SM Higgs boson (4.5 GeV < m_h < ~$2m_W$) cancels the energy growth of purely-bosonic $V_LV_L \to V_LV_L$ scattering, preserving unitarity.

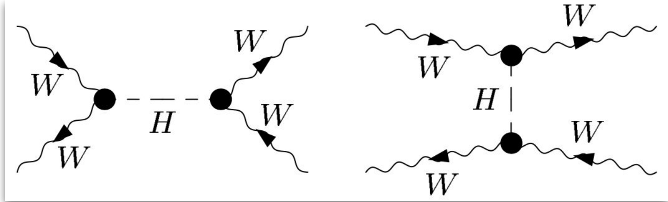
(a)



(b)



(c)

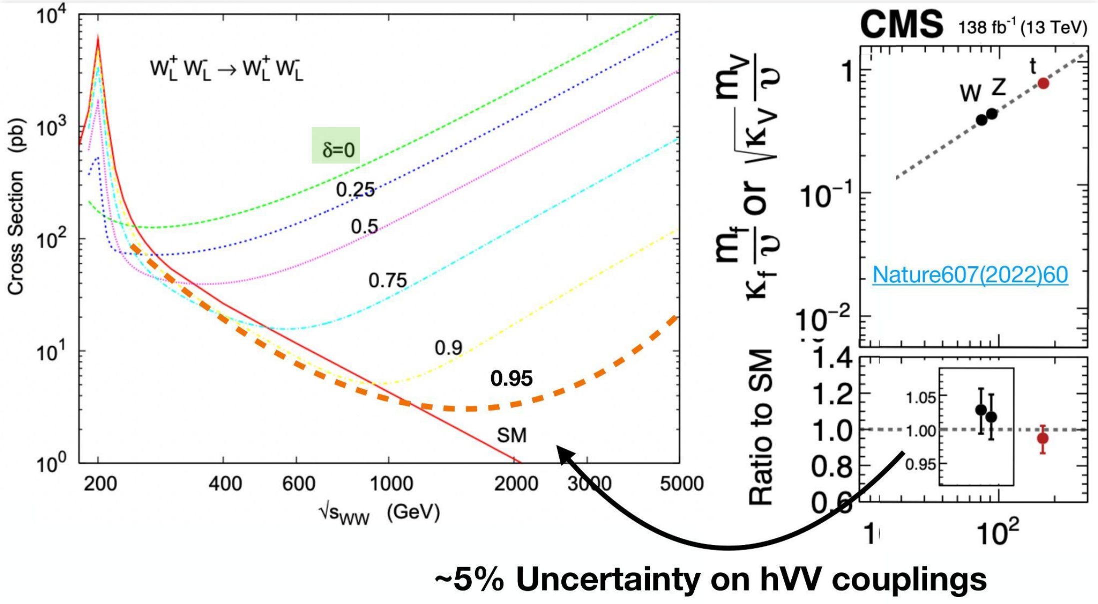


Scattering of gauge bosons - unitarization

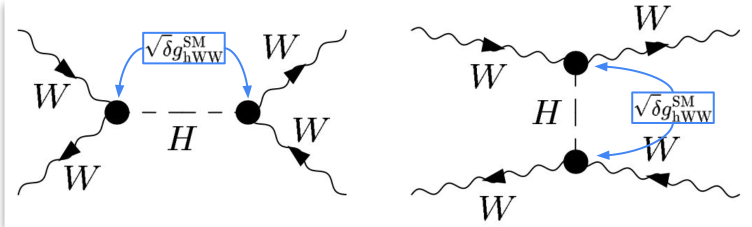
The discovery of a light Higgs at 125 GeV doesn't fully settle the story of longitudinal vector boson scattering

In UV complete models **EWSB is not realized solely by a light Higgs boson** (2HDM, Little Higgs, ...) → **strong $V_L V_L$ scattering between m_h and UV scale**

K Cheung et al. [19]



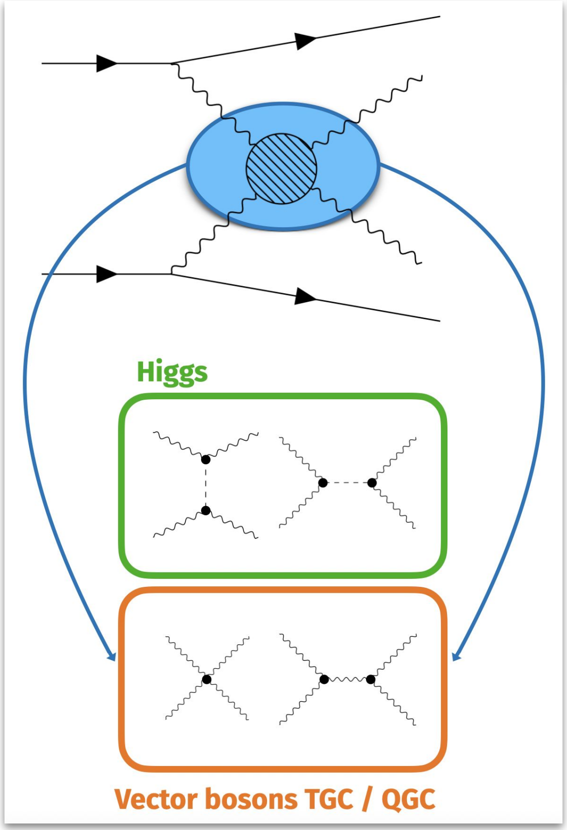
Assume hWW coupling is only a fraction **($\sqrt{\delta}$)** of its SM value



The delicate cancellation between gauge (g) **and higgs** (h) **diagrams does not happen if $\delta \neq 1$**

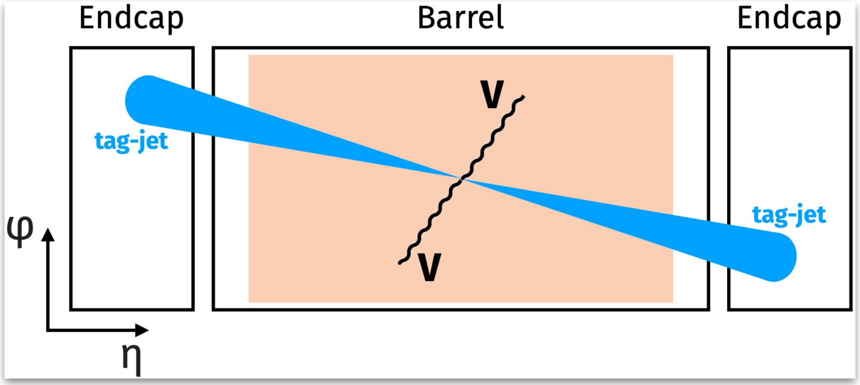
$$i\mathcal{M}^g + i\mathcal{M}^h \sim -i\frac{g^2}{4m_W^2} + \delta\frac{g^2}{4m_W^2}$$

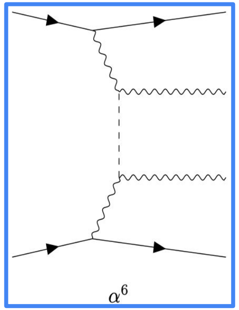
VBS at the LHC - Run I and the first observations

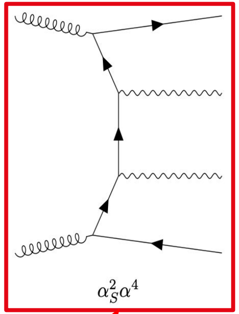


Vector boson scattering (VBS) happens at the LHC when the two incoming partons radiate electroweak vector bosons that interact with each other

- **Final state with 6 fermions (VV) or 4 fermions + γ (Vγ):** 2 from the initial state partons, the others from the scattered bosons decay
- **Peculiar kinematical properties:** high $\Delta\eta_{jj}$ and m_{jj}, low additional hadronic activity in the rapidity gap

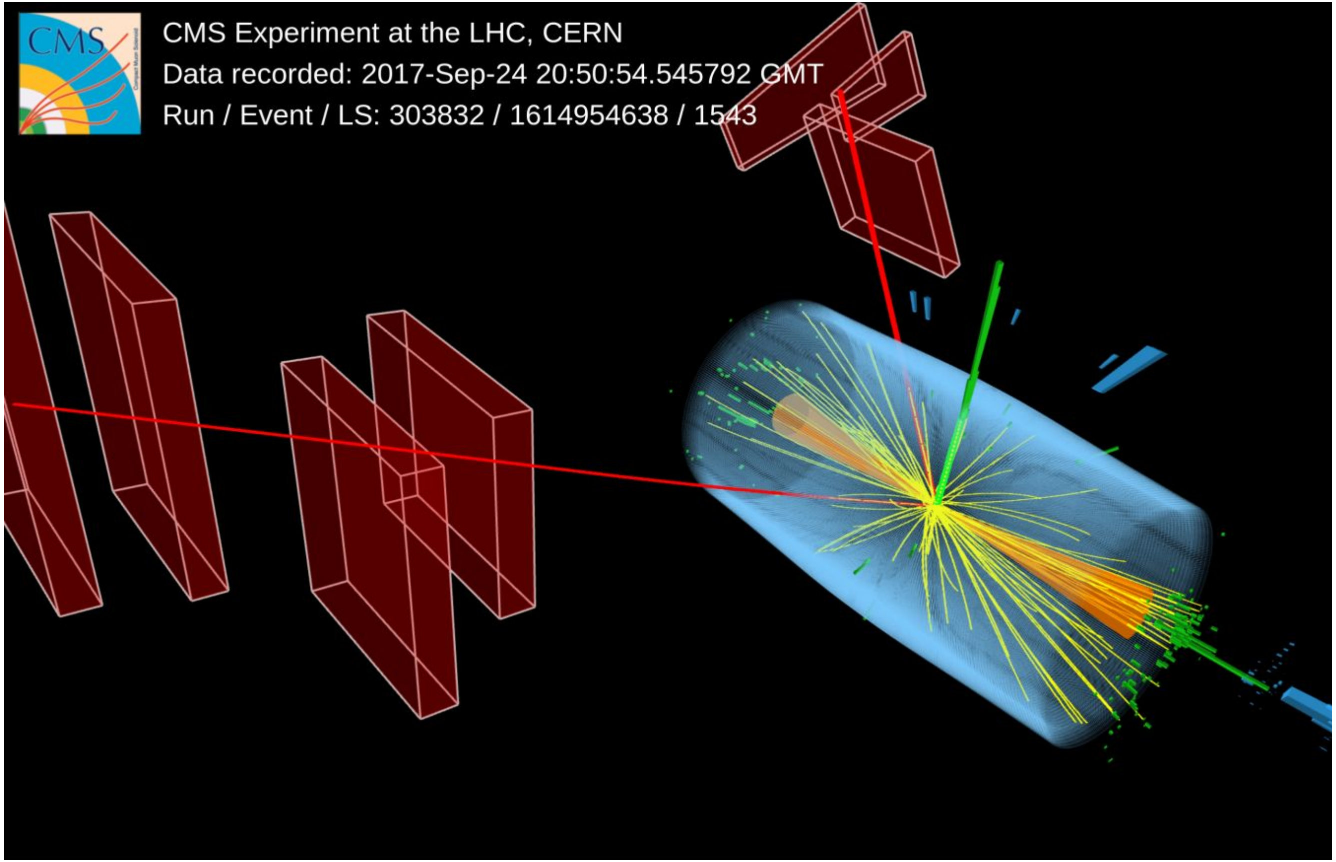






- At LO VBS contributions come from purely-EW processes α^6, QCD-induced $\alpha_s{}^2\alpha^4$ and the interference

VBS signature at hadron colliders

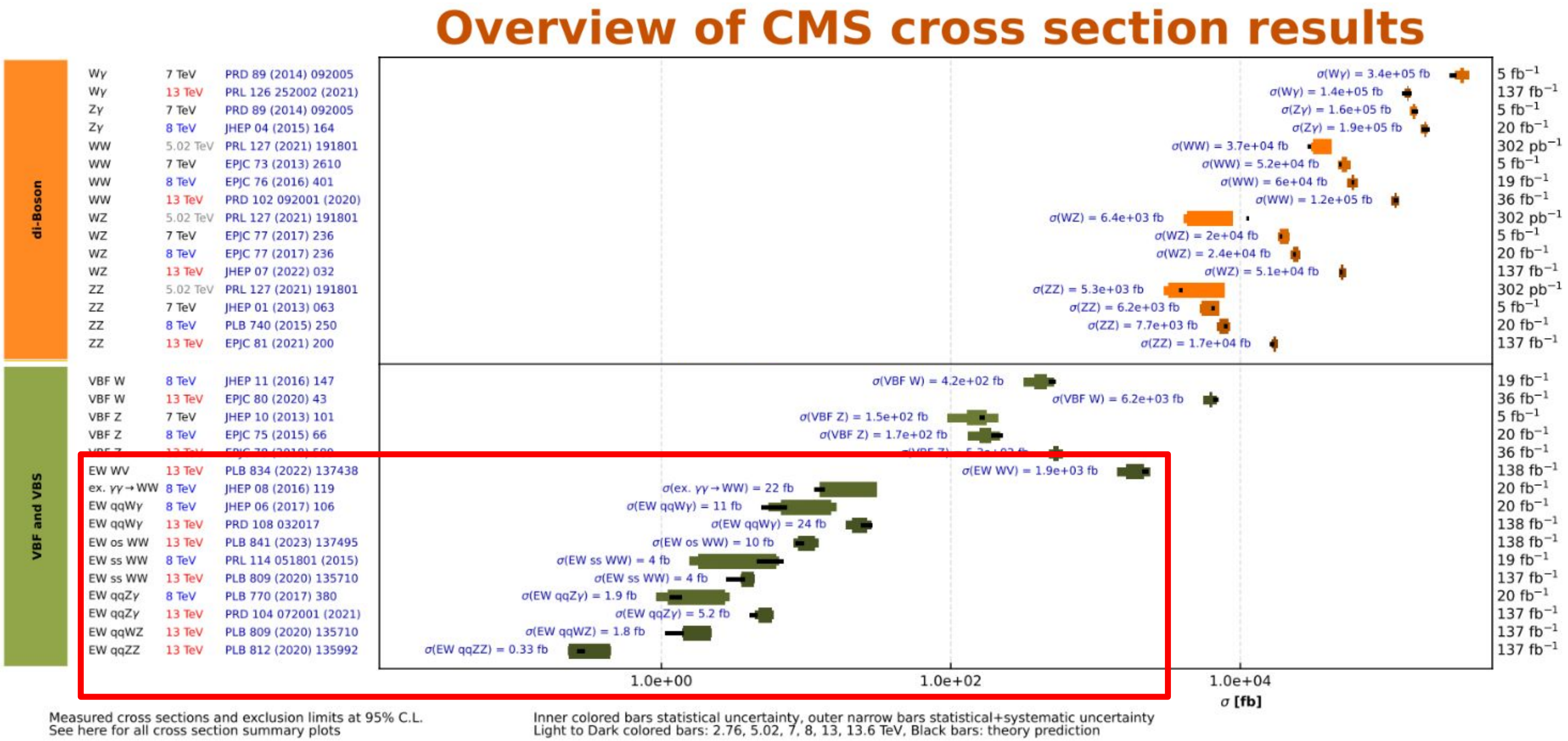


$$W^{\pm}Zjj \to e^{\pm}\nu_e\mu^+\mu^-jj$$

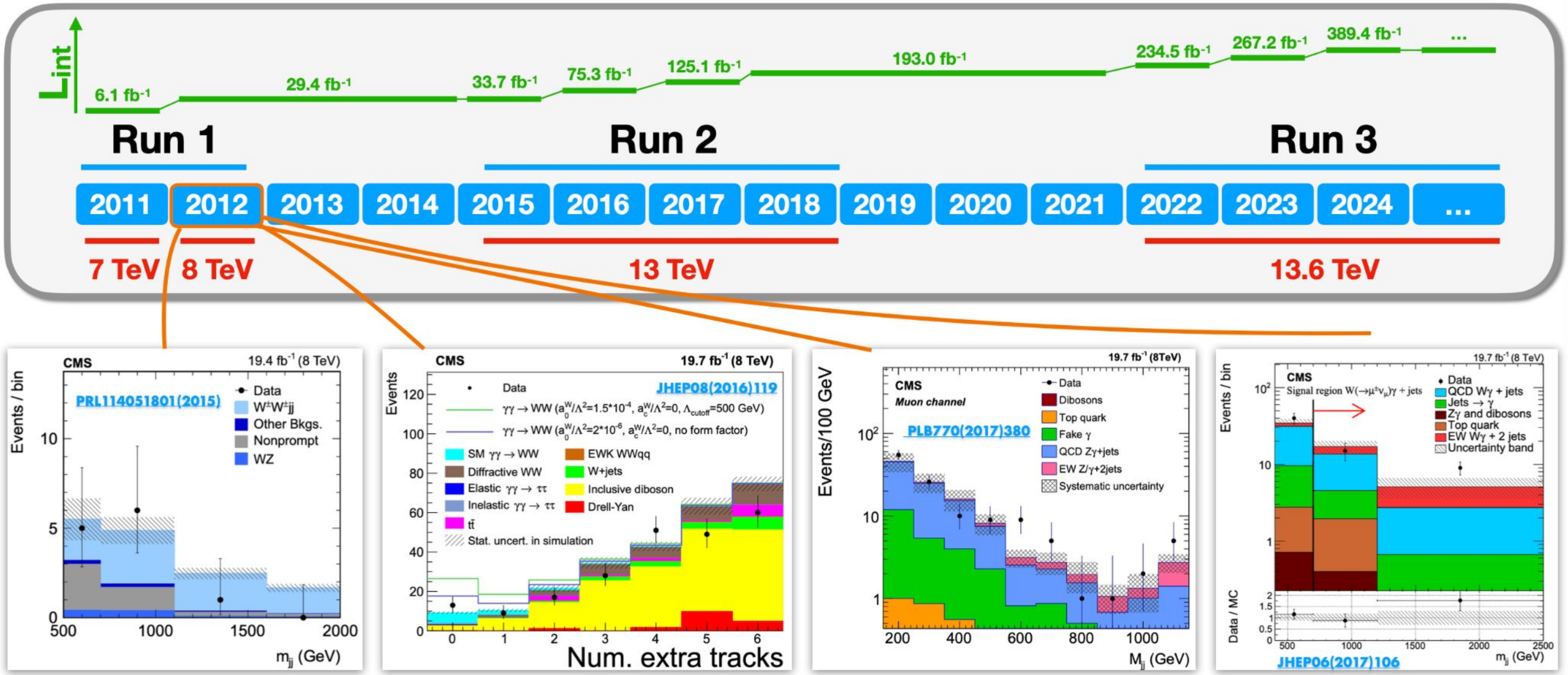
- VBS "tag" forward jets
- Electron energy deposited in ECAL
- Muons detected in muon chambers

Neutrinos escape detection and are inferred from missing momentum in the final state.

VBS processes are among the rarest at the LHC — and separating them by polarization makes the measurement even more challenging.

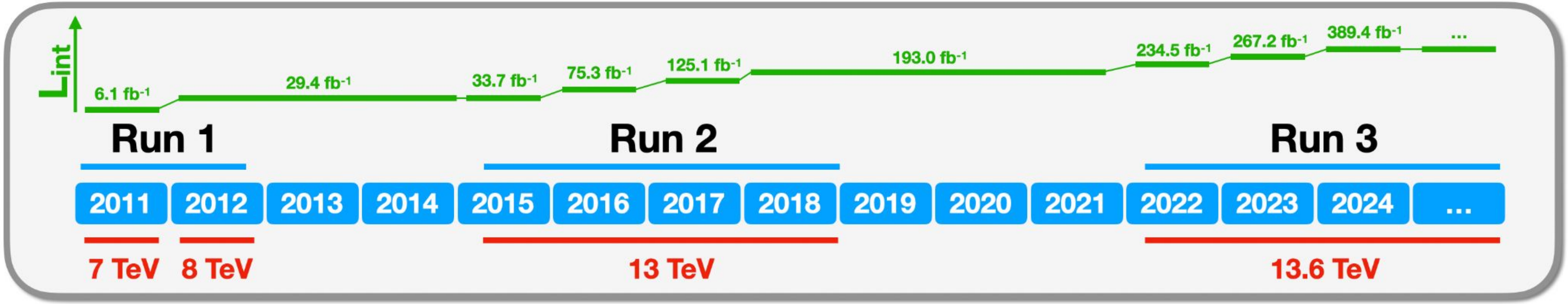


Experimental aspects of EWSB



Run I VBS searches focused on **clean signatures** exploiting photons to increase statistics (Zγ, Wγ) or **central exclusive production**. Limited energy reach for observables due to √s = 8 TeV. First VBS evidences at the LHC

Experimental aspects of EWSB

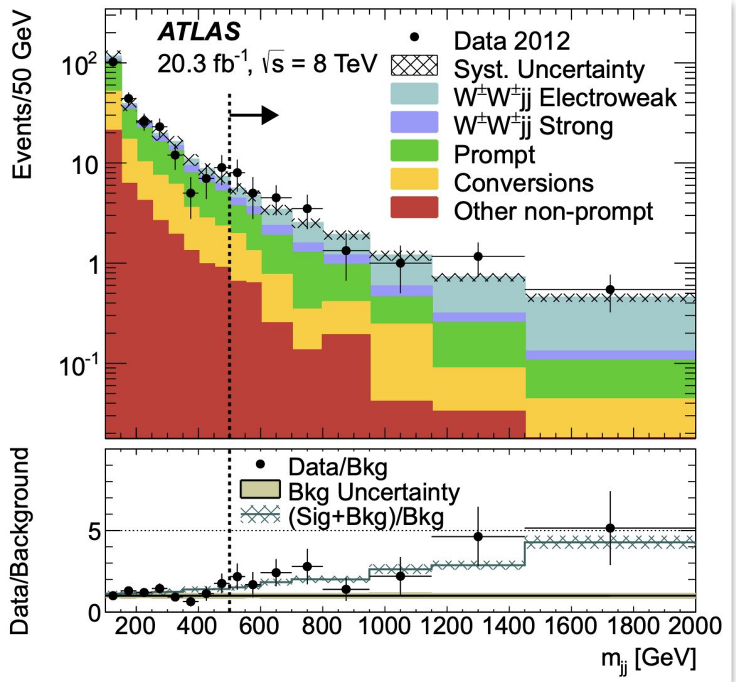


$\sqrt{s}$	$\mathcal{L}_{INT}$	Process	Article	Comments
8 TeV	$19.4\ fb^{-1}$	EW $W^{\pm}W^{\pm}jj(2l2\nu jj)$	PhysRevLett.114.051801	CMS finds 2σ
	$19.7\ fb^{-1}$	EW $Z\gamma jj(\nu\nu/ll\gamma jj)$	PhysLettB770(2017)380-402	CMS finds 3σ
	$19.7\ fb^{-1}$	EW $W^{\pm}\gamma jj(l\nu\gamma jj)$	JHEP06(2017)106	CMS finds 2.7σ
	$19.4\ fb^{-1}$	EW $W^{\pm}Zjj(3l\nu jj)$	PhysRevLett.114.051801	CMS finds 2σ

Run I VBS searches focused on **clean signatures** exploiting photons to increase statistics (Zγ, Wγ) or **central exclusive production**. Limited energy reach for observables due to √s = 8 TeV. **First VBS evidences at the LHC**

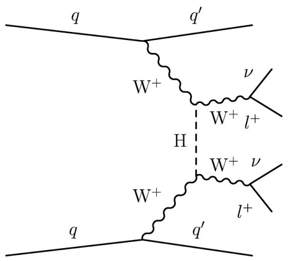
Run I VBS Same-sign WW - ATLAS

- $W^{\pm}Zjj \rightarrow 3\ell\nu jj$ ~90% - undetected lepton
- $W^{\pm}\gamma jj$ where $\gamma \rightarrow e^+e^-$ or charge misidentified
- $W + \text{jets}, t\bar{t}$ jet faking lepton



[Phys. Rev. Lett. 113, 141803 (2014)](#)

VBS Same-sign WW Golden channel: the presence of two same-signed leptons reduces drastically the QCD-induced background



ATLAS measured **SSWW (EW+QCD)** in an inclusive region and **SSWW (EW)** in a more restrictive region m_{jj} > 500 GeV, $|\Delta y_{jj}|$ > 2.4. EW-QCD interference always part of signal.

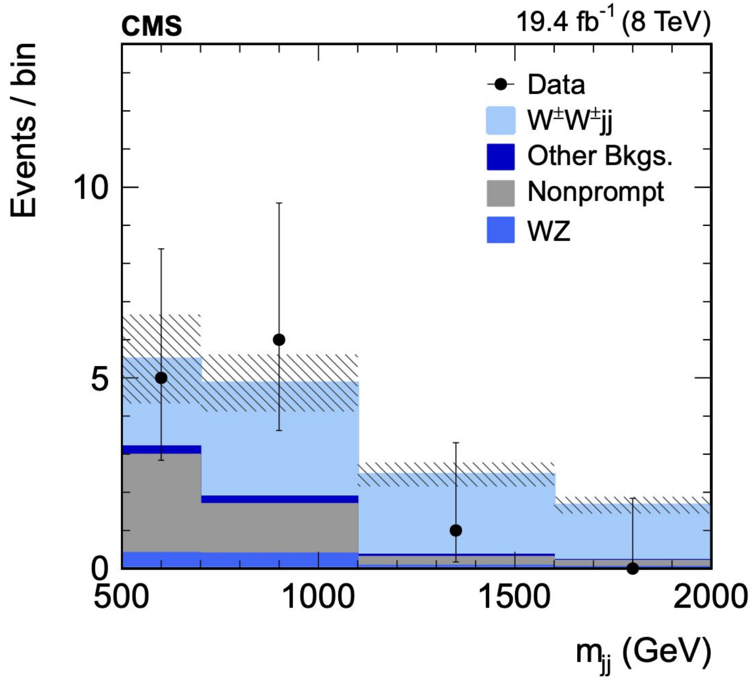
First evidence of Vector Boson Scattering

EW+QCD 4.5 s.d - EW 3.6 s.d.

Fiducial region	σ measured	σ SM@LO
Inclusive (EW+QCD)	2.1 ± 0.6 fb	1.52 ± 0.11 fb
VBS (EW)	1.3 ± 0.4 fb	0.95 ± 0.06

Run I VBS Same-sign WW - CMS

- $W + \text{jets}, t\bar{t}$ jet faking lepton
- $\gamma \to e^+e^-$ jet faking lepton or charge misidentified
- $W^\pm Zjj \to 3\ell\nu jj$ ~90% - undetected lepton



Phys. Rev. Lett. 114, 051801 (2015)

CMS performed the same analysis shortly after ATLAS result: similar selections, slightly different background composition

Process	CMS	ATLAS	CMS/ATLAS
Prompt ($\sim W^\pm Z$)	1.0 ± 0.1	8.3 ± 1.2	12%
Nonprompt	4.3 ± 0.8	6.3 ± 1.1	68%
Total Bkg	5.7 ± 0.8	15.9 ± 1.9	36%
EW+QCD $W^\pm W^\pm jj$	8.9 ± 0.1	15.2 ± 0.8	59%
S/B	1.6	0.9	177%

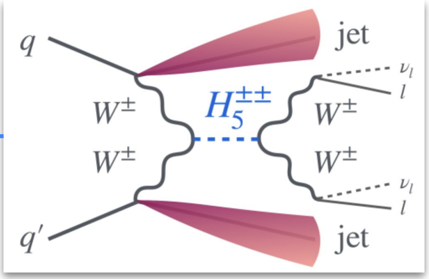
First VBS analysis in CMS - no evidence

EW+QCD 2.0 s.d - EW 1.9 s.d.

Looser (m_{jj} > 300 GeV) fiducial regions w.r.t ATLAS (m_{jj} > 500 GeV)

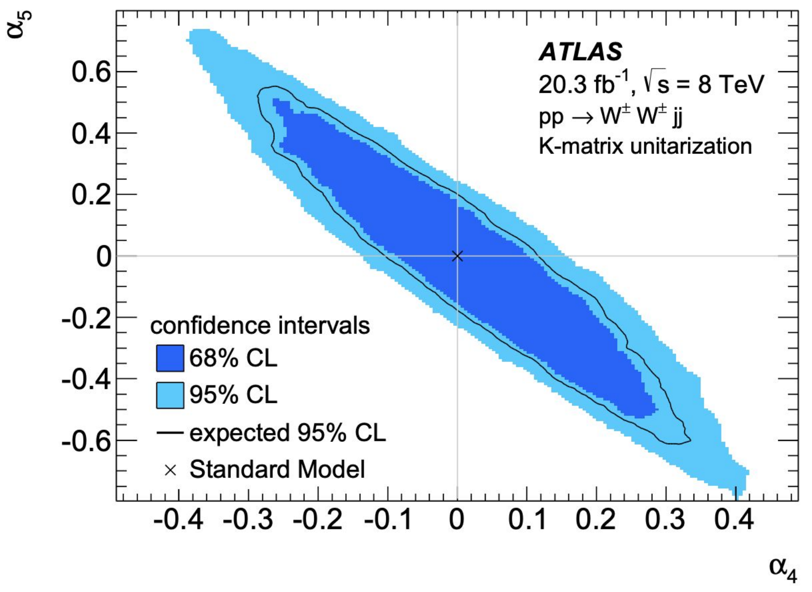
Fiducial region	σ measured	σ SM
$W^\pm W^\pm$ (EW+QCD)	$4.0^{+2.6}_{-2.2}$ fb	5.8 ± 1.2 fb (NLO)
$W^\pm Z$ (EW+QCD)	10.8 ± 4.2 fb	14.4 ± 4.0 (LO)

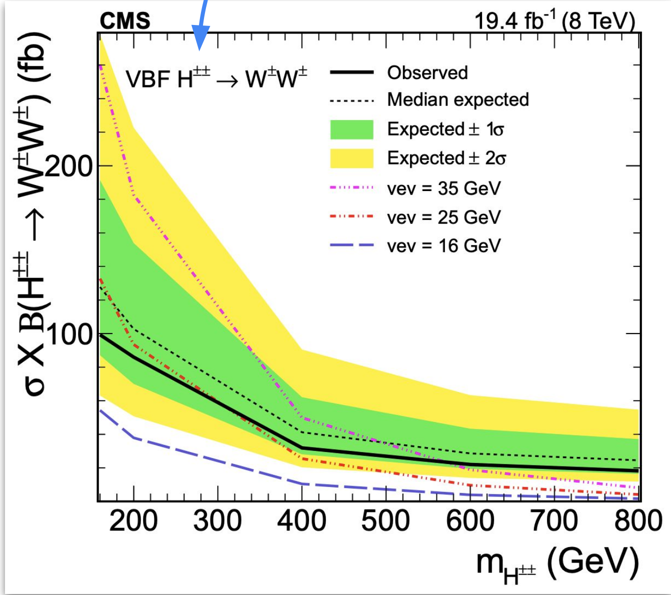
SSWW VBS at LHC → First time probing VVVV quartic interactions!



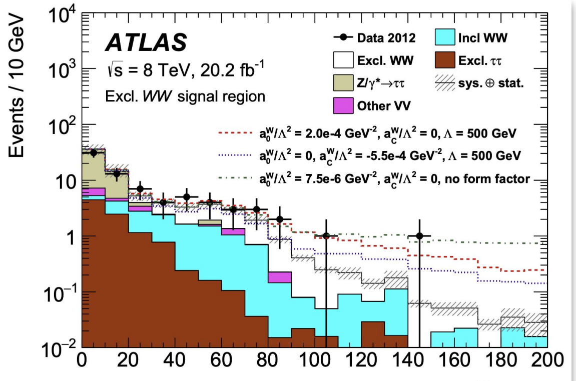
Searches for new physics in terms of

- **Indirect (ATLAS m_{jj} & CMS m_{ll})**: Anomalous quartic gauge couplings (aQGC)
- **Direct (CMS)**: Georgi–Machacek Higgs triplet $H^{\pm\pm}$ [20]

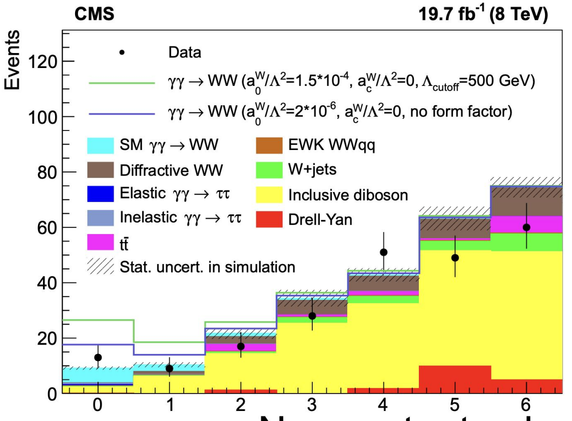




Run I Central exclusive production $\gamma\gamma \to WW$

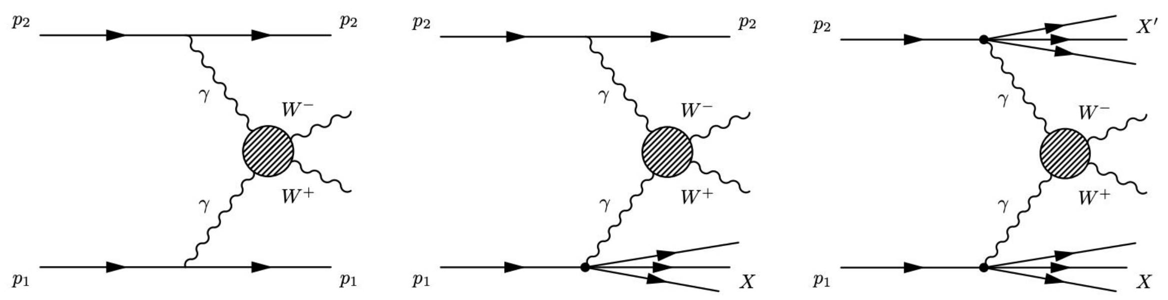


CERN-EP-2016-123



JHEP 08 (2016) 119

LHC as a photon collider: each proton radiate a photon probing $\gamma\gamma$WW quartic coupling → protons are not detected

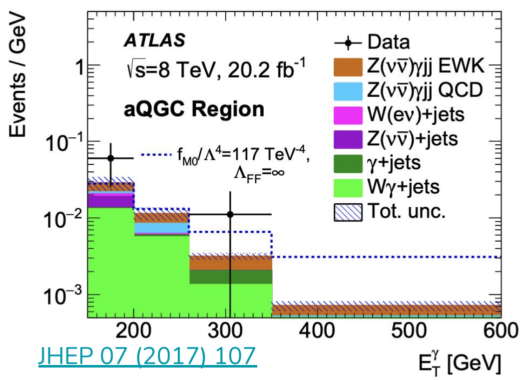


- **Exclusive:** The detector is almost empty, no additional tracks associated with l^+l^- vertex
- **Inclusive**: additional radiation from UE associated with l^+l^- vertex

First evidence of diboson exclusive production

Analysis	σ obs	σ SM	S.D.
ATLAS	6.9 ± 2.6	4.4 ± 0.3 fb,	3.0
CMS	10.8 ± 4.5 fb	6.2 ± 0.5 fb	3.4

Run I VBS Wγ and Zγ



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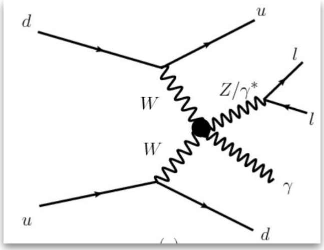

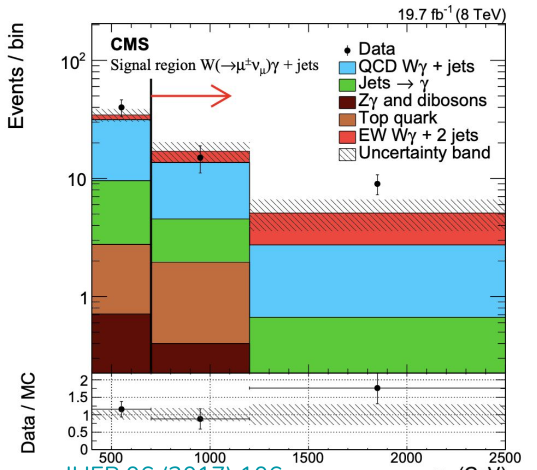

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VBS of a massive vector boson (W,Z) + γ

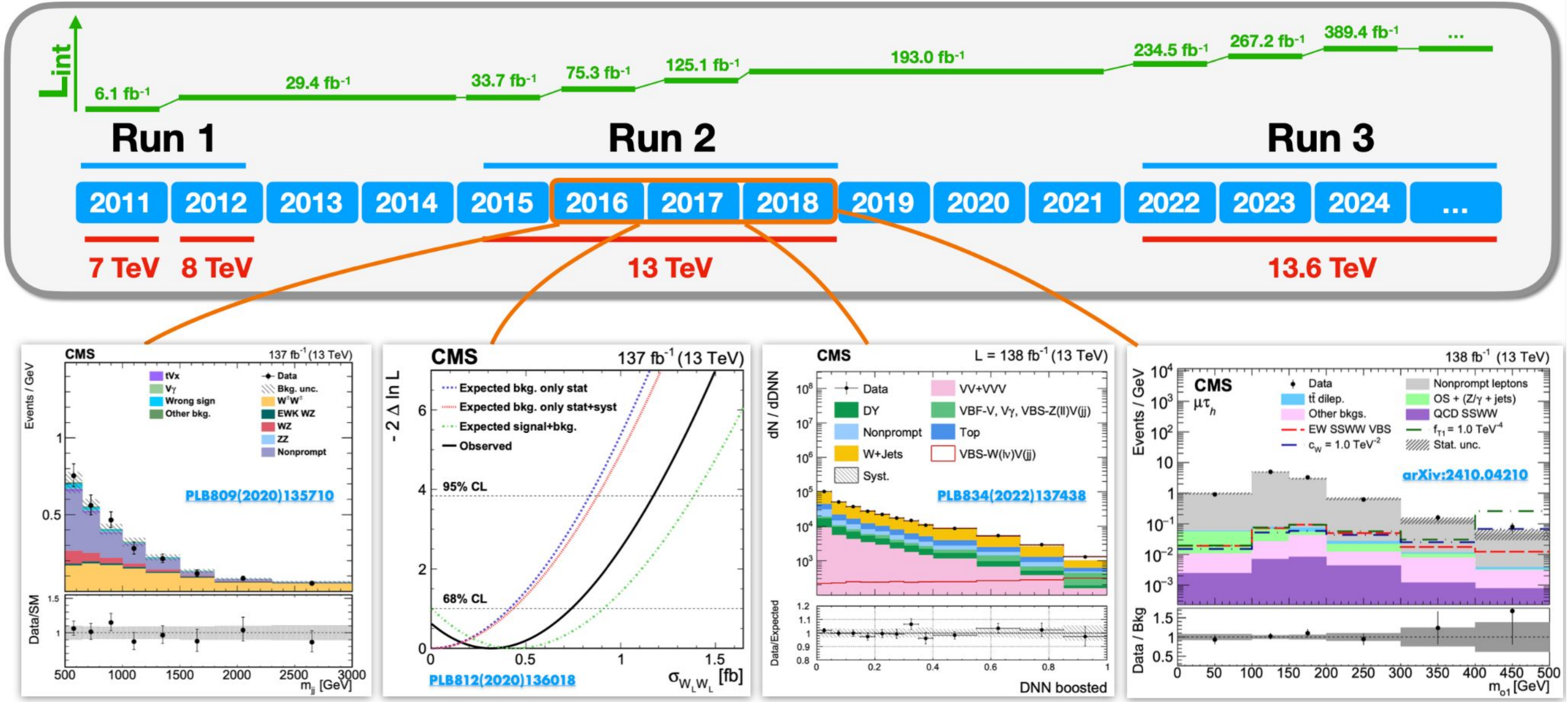
- Unique probe of WW$\gamma\gamma$ and WWZγ vertex
- Highest VBS cross-section (α^5)
- Clean signature: leptons + photon + VBS jets
- Probes SM-forbidden neutral QGC: ZZZγ, ZZ$\gamma\gamma$ and Z$\gamma\gamma\gamma$

Fiducial cross-sections and limits on aQGC show good agreement with SM. Statistically limited for EW

Analysis	Signal	σ obs	σ SM	S.D.
CMS $W\gamma$	EW	10.8 ± 5.3 fb fb	6.1 ± 1.2 fb	2.7
	EW +QCD	23.2 ± 4.7 fb	23.5 ± 5.4 fb	7.7
ATLAS $Z\gamma$	EW	1.1 ± 0.6 fb	0.94 ± 0.1 fb	2.0
	EW+QCD	3.4 ± 0.5fb	4.0 ± 0.4 fb	-
CMS $Z\gamma$	EW	1.7 ± 0.9 fb	1.2 ± 0.1 fb	3.0
	EW+QCD	5.9 ± 1.5 fb	5.1 ± 1.2 fb	-

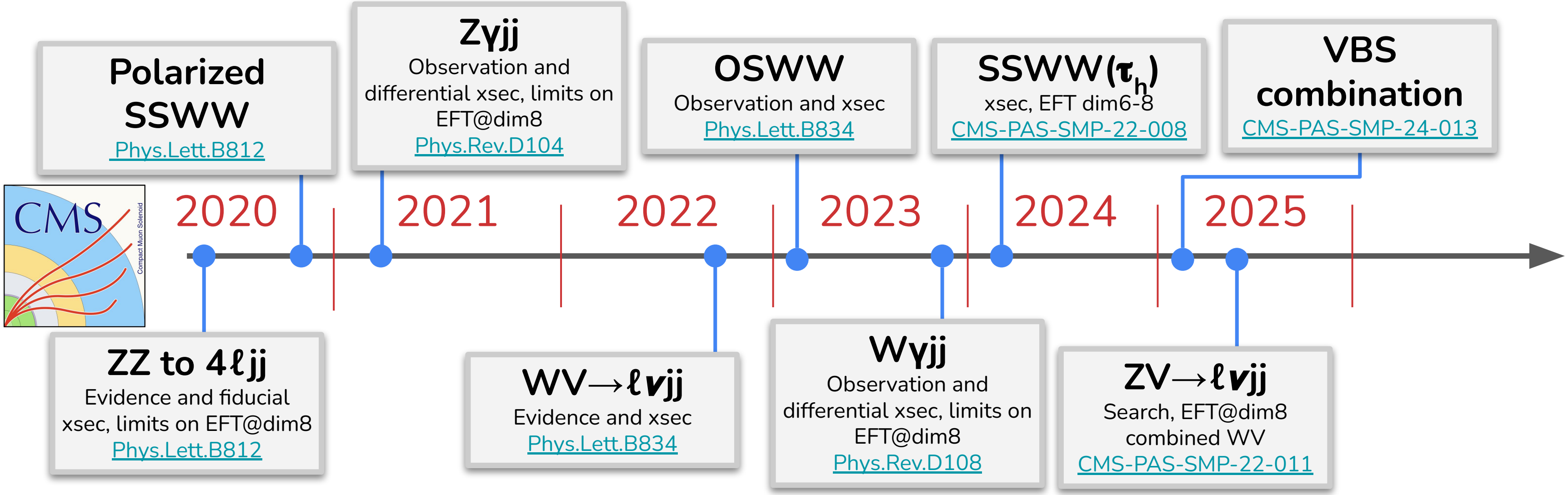
VBS at the LHC - Run II and precision measurements

Experimental aspects of EWSB

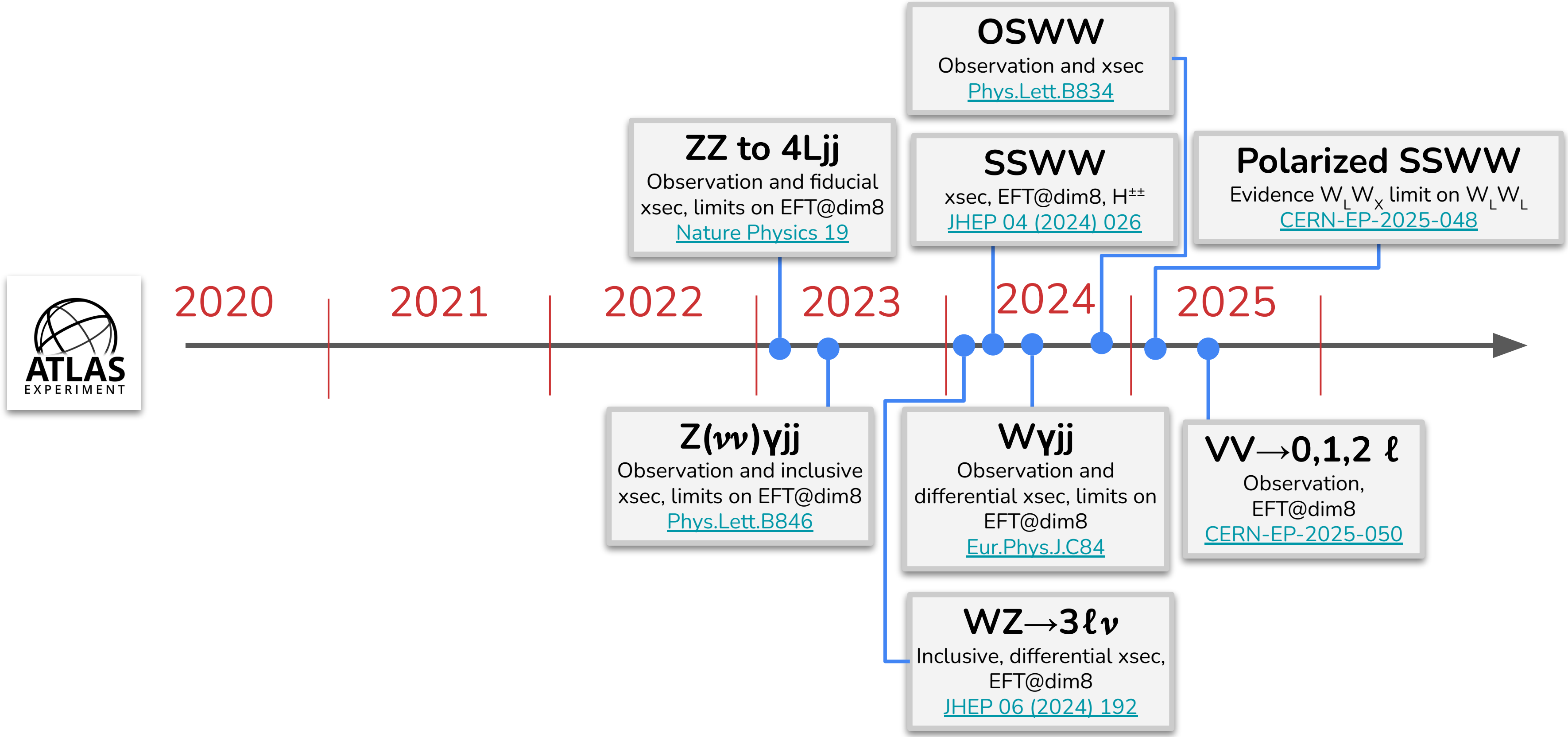


Run II VBS searches refined analyses with clean channels, **multiple observations and evidences**. **First time targeting polarized $V_LV_L \rightarrow V_LV_L$**. $\sqrt{s}$ = 13 TeV allows for stronger constraints on **aQGC / EFT parameters**.

Vector Boson Scattering results with LHC Run-II statistics

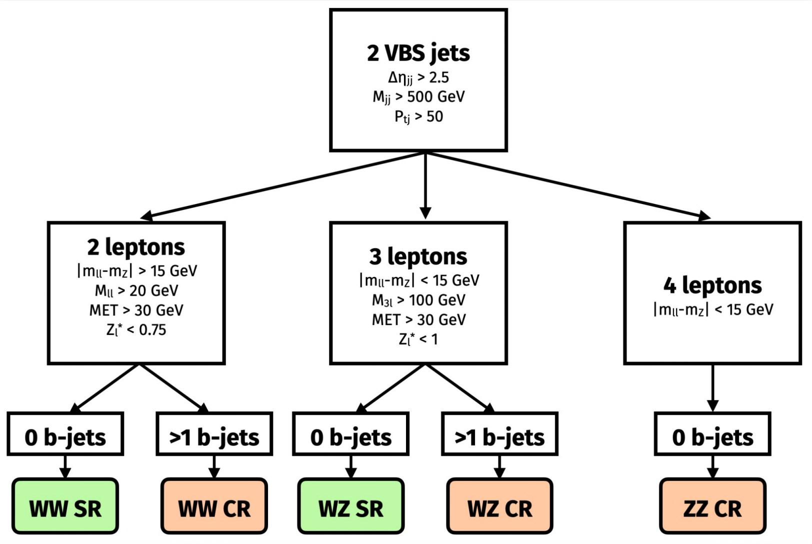


Vector Boson Scattering results with LHC Run-II statistics



Refined Run-I analysis with higher com energy $\sqrt{s}$=13 TeV and ~10x more statistics

- EW VBS WZ→ 3lν contaminates SSWW: analyze them together
- Energy reach extended from 2 to 3 TeV
- Signal extraction: m_{jj}:m_{ll} for SSWW, BDT for WZ

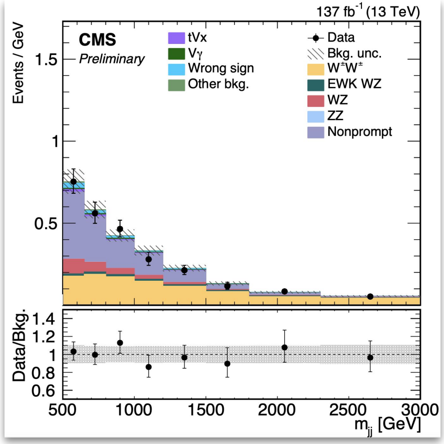


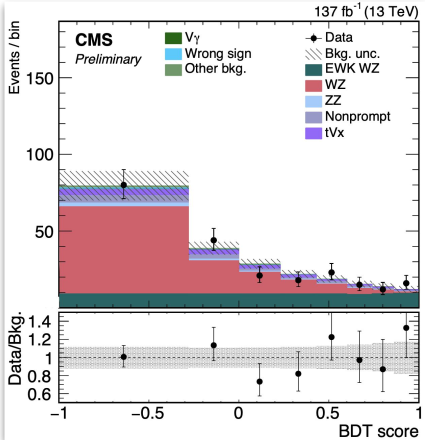
Dominant Backgrounds

- **SSWW:** nonprompt (~62%) estimated from data
- **WZ:** QCD-induced VBS WZ production (~73%)

Process	EW-WZ	EW-WW	QCD-WZ	Nonprompt	tVx
SSWW	17.8 ± 3.9	210 ± 26	42.7 ± 7.4	193 ± 40	7.4 ± 2.2
WZ	69 ± 15	-	117 ± 17	14.4 ± 6.7	14.3 ± 2.8

Phys. Lett. B 809 (2020) 135710



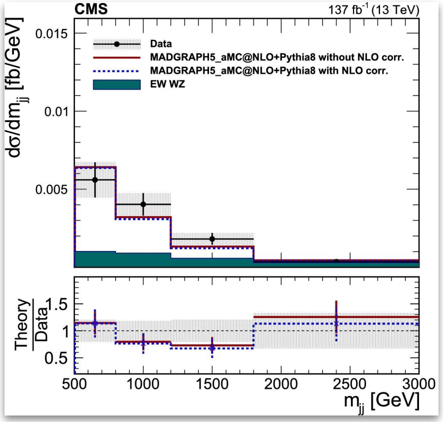


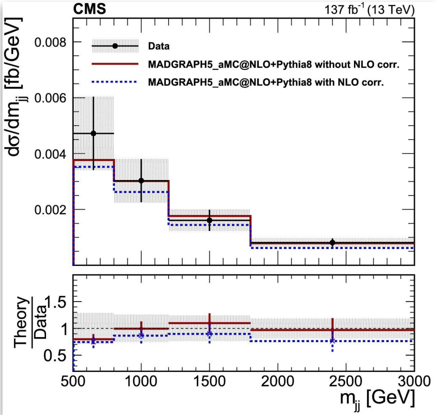
Observed EW SSWW with significance >> 5 s.d. and EW WZ with 6.8 s.d.

Run II VBS Same-sign WW / WZ - CMS

Differential cross-sections measurements in VBS-enhanced fiducial regions: first time for VBS

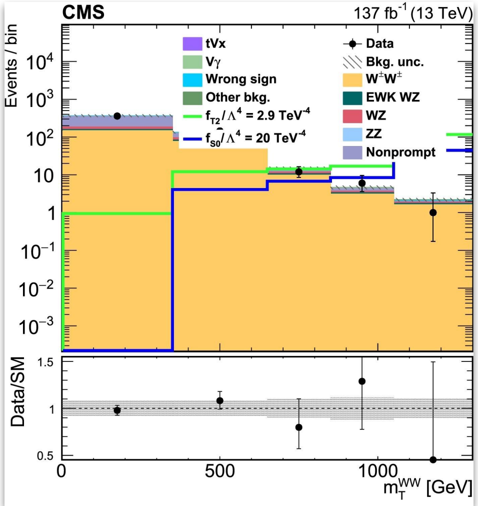
Process	$\sigma\mathcal{B}$ (fb)	Theory prediction (fb)	Theory prediction with NLO corrections (fb)
EW $W^{\pm}W^{\pm}$	3.98 ± 0.45 (0.37 (stat)) ± 0.25 (syst))	3.93 ± 0.57	3.31 ± 0.47
EW+QCD $W^{\pm}W^{\pm}$	4.42 ± 0.47 (0.39 (stat)) ± 0.25 (syst))	4.34 ± 0.69	3.72 ± 0.59
EW WZ	1.81 ± 0.41 (0.39 (stat)) ± 0.14 (syst))	1.41 ± 0.21	1.24 ± 0.18
EW+QCD WZ	4.97 ± 0.46 (0.40 (stat)) ± 0.23 (syst))	4.54 ± 0.90	4.36 ± 0.88
QCD WZ	3.15 ± 0.4 (0.45 (stat)) ± 0.18 (syst))	3.12 ± 0.70	3.12 ± 0.70

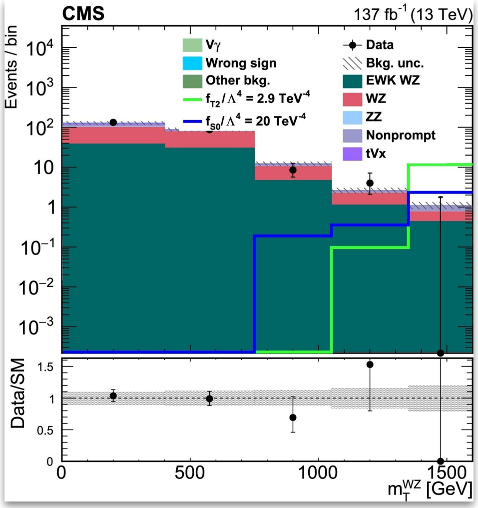




aQGC search carried under EFT framework constraining dimension-8 operators with **m_T(VV) and m_{jj}**

$$m_T(VV) = \sqrt{(\sum_i E_i)^2 - \sum_i p_{z,i})^2}$$



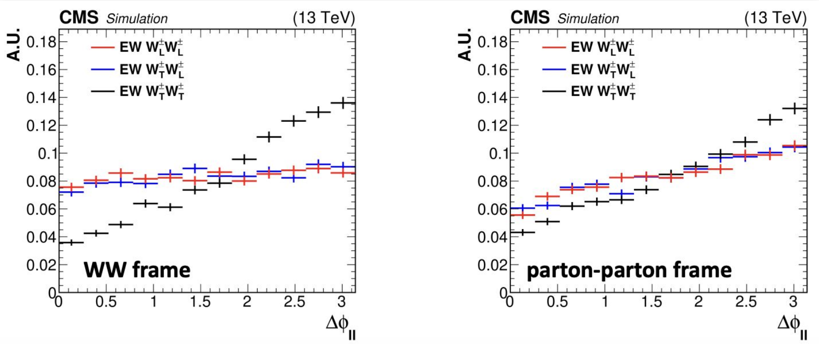


No excess of events with respect to the SM is observed
→ aQGC limits 2x stronger than Run-I

The first ever measurement of production cross sections of polarized Vector Boson Scattering:
Simultaneous fits of W_LW_L/W_XW_T and W_LW_X/W_TW_T

Polarizations depend on the reference frame

- LL fraction in the WW c.m. frame is the largest
- Lab frame directly tied to observables



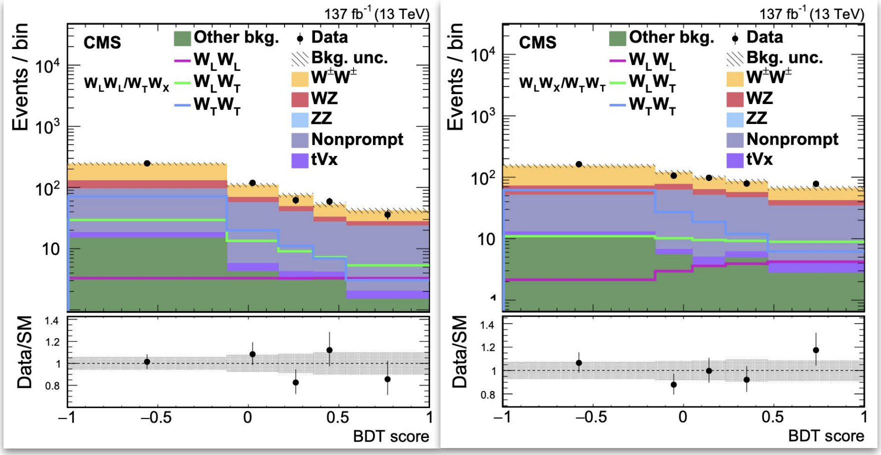
Corrections makes a difference

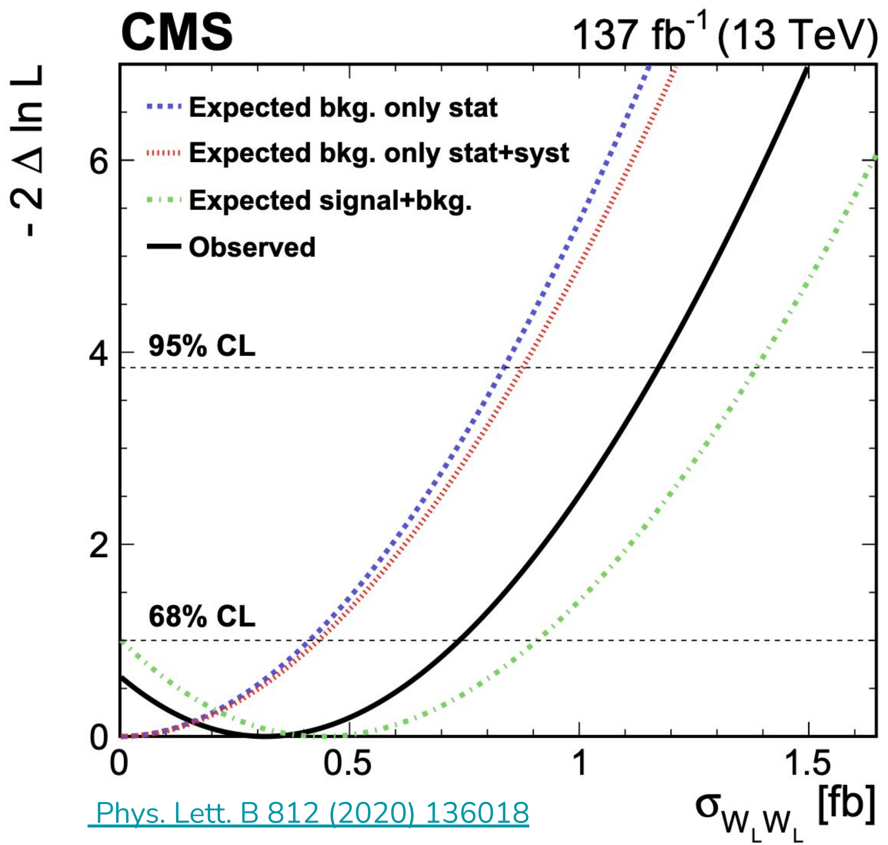
- The interference between the polarized samples is small
- NLO α_S correction applied and equal for all modes
- NLO α small for LL: applied to TT, uncertainty on LL/T

Two BDTs to extract signals

- **Signal BDT:** separate LL from TX or LX from TT. Different training for each reference frame
- **Inclusive BDT:** unpolarized WW versus backgrounds

→ 2D Fit Signal:Inclusive BDT in SSWW+WZ regions





[Phys. Lett. B 812 (2020) 136018]

$W_L W_X$ significance of 2.3 s.d. , 95% upper limit on $W_L W_L$ production cross section of 1.17 fb

All measurements statistically dominated

Lab

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb) NLO QCD+EW
$W_L^\pm W_L^\pm$	$0.24^{+0.40}_{-0.37}$	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

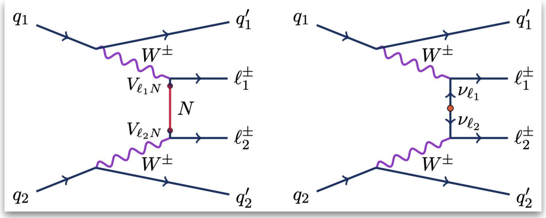
WW c.m

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb) NLO QCD+EW
$W_L^\pm W_L^\pm$	$0.32^{+0.42}_{-0.40}$	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

Same-sign WW can be used to test "seesaw" models involving heavy Majorana neutrinos

Complementarity with neutrinoless double β decays

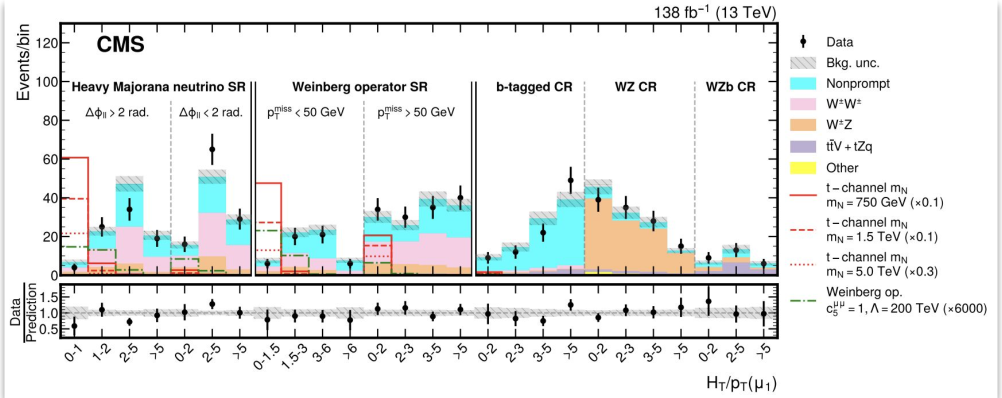
Heavy neutrino Weinberg operator



- Low-energy experiments study m_{ee} upper limit at 90% of 61–165 meV [27] and 79–180 meV [28]
- Muons heavier and $m_{\mu\mu}$ can be studied at LHC
- 90% upper limit on $m_{\mu\mu}$ of 55 GeV from NA62 [29]

50 GeV < m_N < 25 TeV from $|V_{\mu N}|^2$
Effective μμ Majorana neutrino mass < 10.8 GeV

Same objects and regions of SM SSWW analysis



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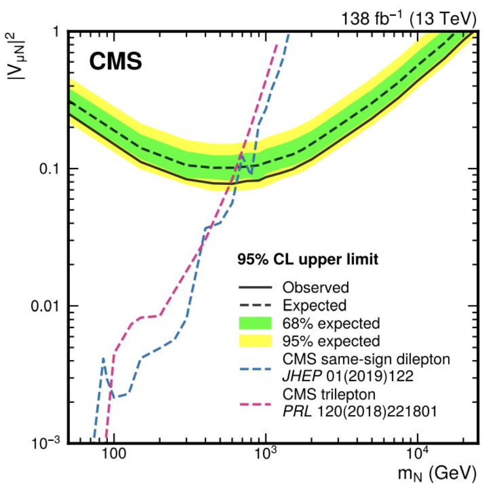
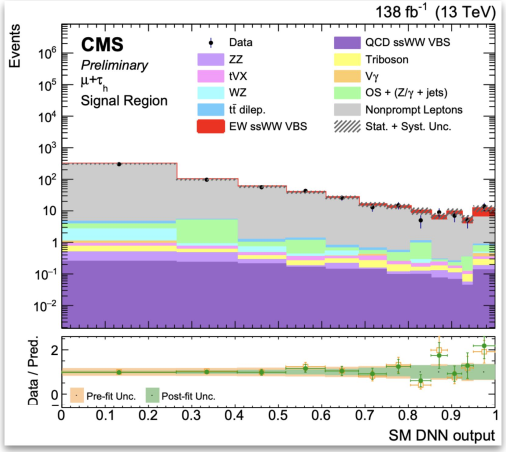


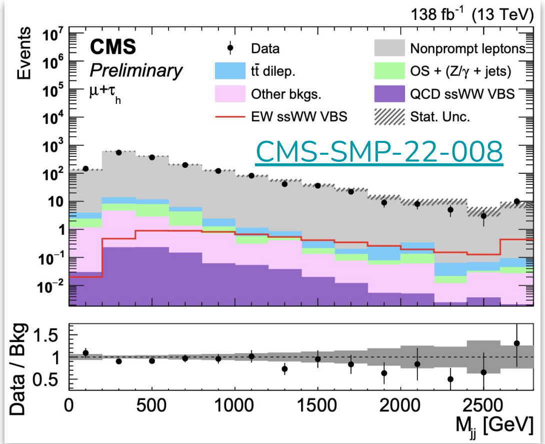
Run II VBS Same-sign WW(τ_h) - CMS

Same-sign WW. One τ_h→first time in VBS

τ Decay	e	μ	π^-	$\pi^-\pi^0$	3π	Other
BR (%)	18	18	11	25	18	10

Region	EW-VBS	Fake	$t\bar{t}$	OS+Z/γ	QCD-VBS
SR $e\tau_h$	3.0%	92.2%	0.9%	2.0%	0.3%
SR $\mu\tau_h$	3.1%	93.3%	0.5%	1.7%	0.3%
$t\bar{t}$ CR	-	37.1%	61.6%	8.2%	-
OS CR	-	56.4%	7.9%	35.1%	-





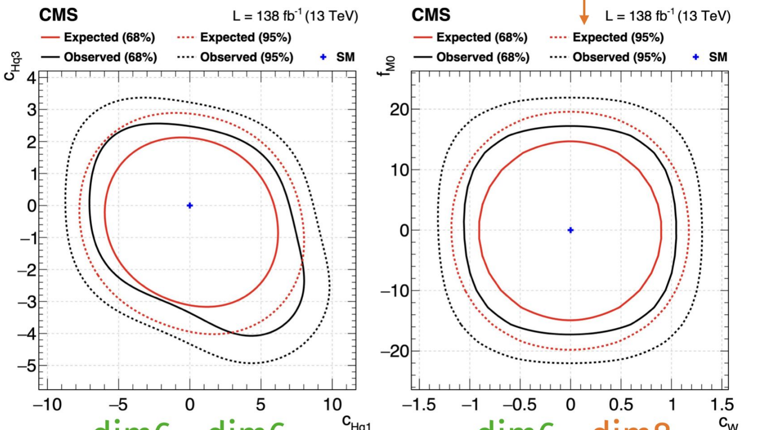
EW W±W±jj → ℓτh2νjj significance of 2.7 σ (2.9σ EW+QCD)

BSM search in the context of SMEFT up to dimension-8: no deviations from SM

$$|\mathcal{A}|^2 = |\mathcal{A}_{SM}|^2 + \sum_{\alpha} \frac{c_\alpha}{\Lambda^2} \cdot 2\,\mathrm{Re}(\mathcal{A}_{SM}\mathcal{A}^\dagger_{Q_\alpha}) + \sum_{\alpha,\beta} \frac{c_\alpha c_\beta}{\Lambda^4} \cdot (\mathcal{A}_{Q_\alpha}\mathcal{A}^\dagger_{Q_\beta})$$

$$+ \sum_i \left[\frac{f_i}{\Lambda^4} \cdot 2\,\mathrm{Re}(\mathcal{A}_{SM}\mathcal{A}^\dagger_{\mathcal{O}_i}) + \frac{f_i^2}{\Lambda^8} \cdot |\mathcal{A}_{\mathcal{O}_i}|^2 \right]$$

First time in VBS!



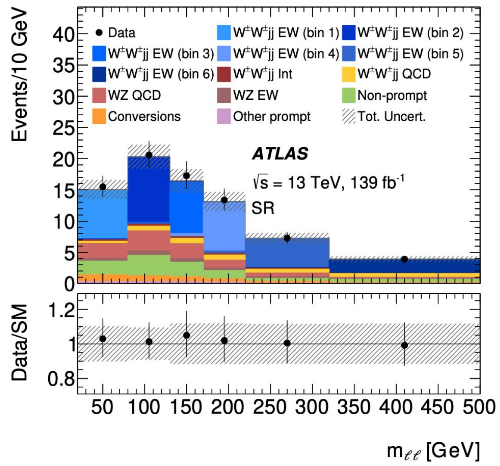
dim6 - dim6

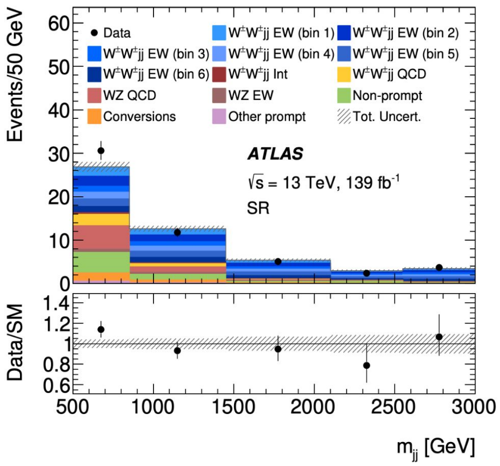
dim6 - dim8

Recent ATLAS updated Run-II measurement of VBS-SSWW

- Similar CMS approach: SSWW SR, low-m_{jj} and WZ CRs
- Different background composition: QCD-WZ dominant, high nonprompt rejection

Process	EW-WZ	EW-WW	QCD-WZ	QCD-WW	Nonprompt
SSWW-SR	14.9 ± 1.2	235 ± 5	83 ± 9	24 ± 7	56 ± 16
%	3.3	52.5	18.5	5.3	12.5



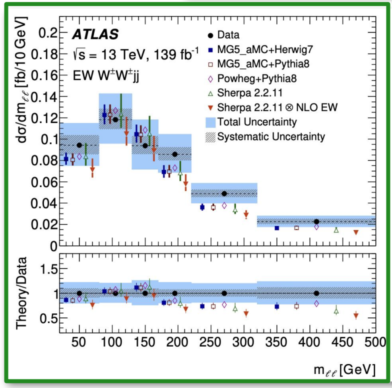


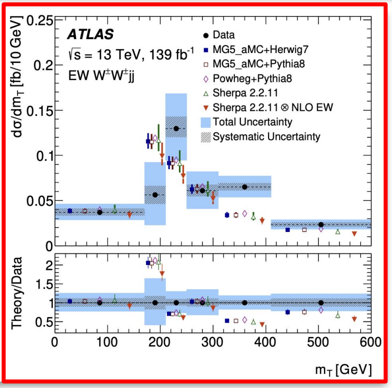
Measured inclusive fiducial cross section show excess over predictions

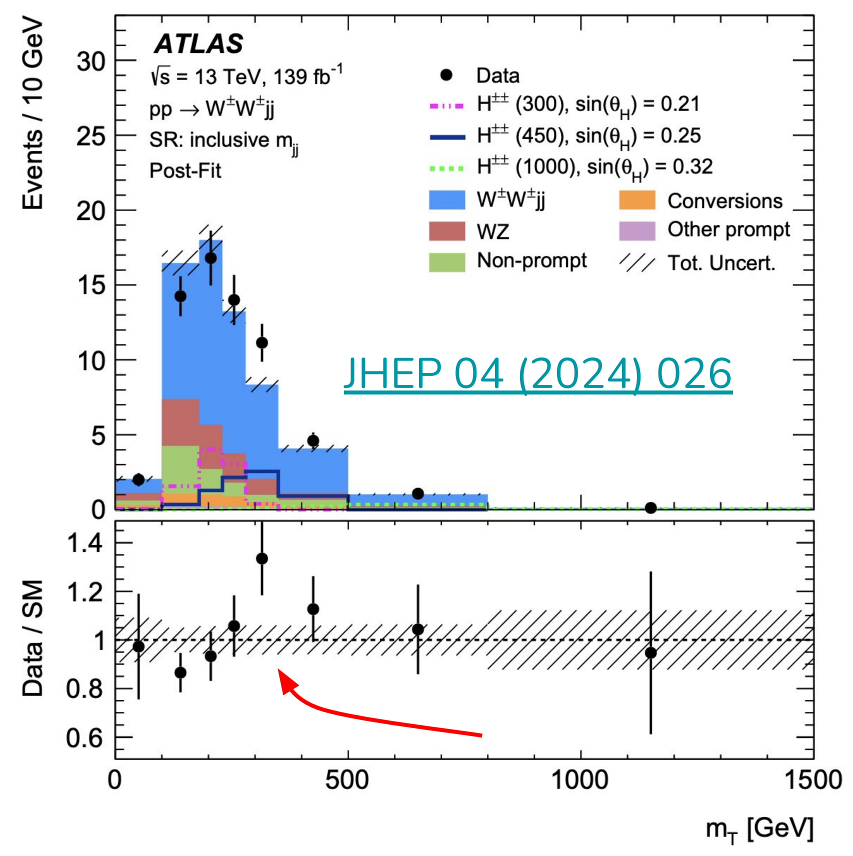
Description	$\sigma_{\text{fid}}^{\text{EW}}$ [fb]	$\sigma_{\text{fid}}^{\text{EW+Int+QCD}}$ [fb]
Measured cross section	2.92 ± 0.22 (stat.) ± 0.19 (syst.)	3.38 ± 0.22 (stat.) ± 0.19 (syst.)
MG5_aMC+Herwig7	2.53 ± 0.04 (PDF) $^{+0.22}_{-0.19}$ (scale)	2.92 ± 0.05 (PDF) $^{+0.34}_{-0.27}$ (scale)
MG5_aMC+Pythia8	2.53 ± 0.04 (PDF) $^{+0.22}_{-0.19}$ (scale)	2.90 ± 0.05 (PDF) $^{+0.33}_{-0.26}$ (scale)
Sherpa	2.48 ± 0.04 (PDF) $^{+0.40}_{-0.27}$ (scale)	2.92 ± 0.03 (PDF) $^{+0.60}_{-0.40}$ (scale)
Sherpa ⊗ NLO EW	2.10 ± 0.03 (PDF) $^{+0.34}_{-0.23}$ (scale)	2.54 ± 0.03 (PDF) $^{+0.50}_{-0.33}$ (scale)
Powheg Box+Pythia	2.64	–

Differential fiducial cross sections (EW and EW+QCD) show **large mismodelling for m_T**. Agreement in other observables

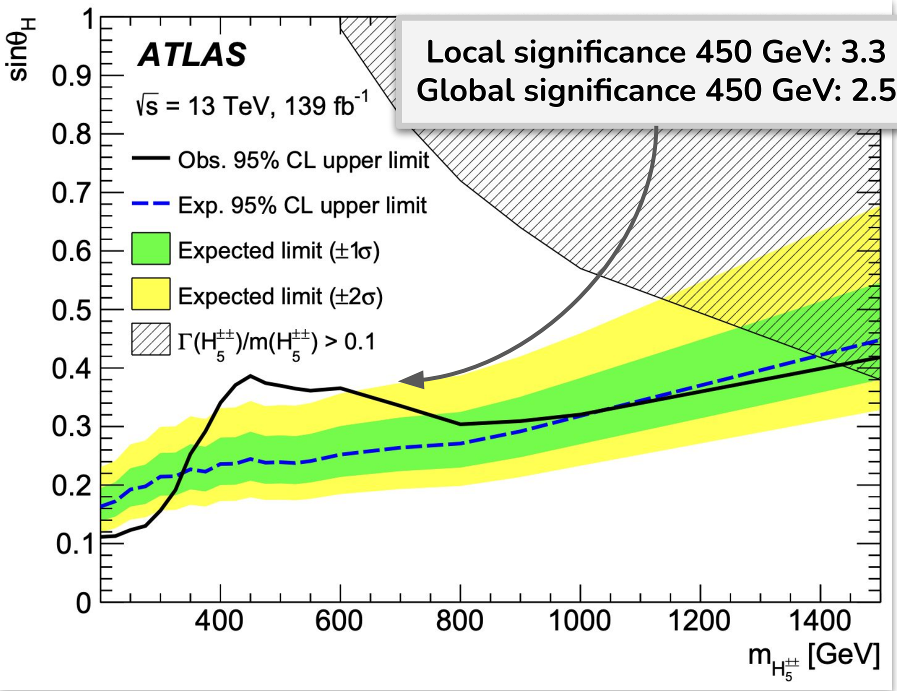
Variable	EW $W^\pm W^\pm jj$ χ^2/N_{dof}	EW $W^\pm W^\pm jj$ p-value	Inclusive $W^\pm W^\pm jj$ χ^2/N_{dof}	Inclusive $W^\pm W^\pm jj$ p-value	Max. value in data
$m_{\ell\ell}$	4.5/6	0.605	7.34/6	0.291	1081 GeV
m_T	13.0/6	0.043	16.33/6	0.012	1270 GeV





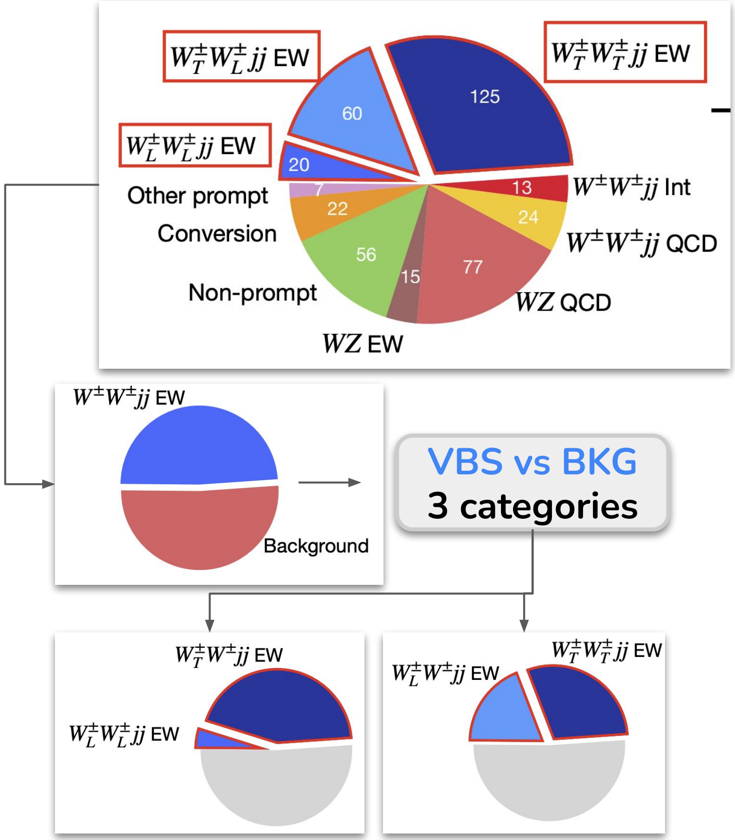


Upper limits at 95% CL on the product of the cross section and branching fraction for **doubly charged Higgs $H^{\pm\pm}$** (Georgi–Machacek [20]) show **excess at 450 GeV following m_T discrepancy**



Local significance 450 GeV: 3.3
Global significance 450 GeV: 2.5

Run II VBS Same-sign polarized - ATLAS



2 DNN Polarization discriminators

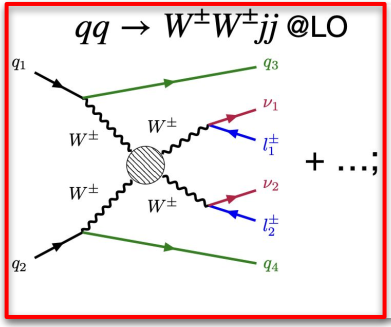
ATLAS recently interpreted its Run II VBS SSWW measurement in terms of polarization states

CERN-EP-2025-048

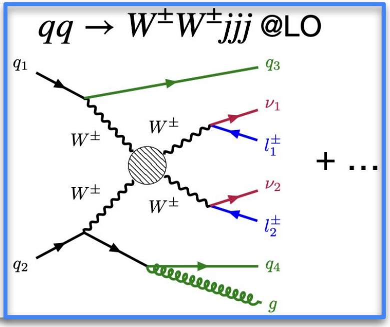
- **CMS approach:** inclusive DNN (VBS vs Bkg) and polarization DNN (LL vs TX & LX vs TT)

- **Precise predictions**: real QCD correction @LO (3j) (SHERPA [21])+ full NLO EW corrections for polarizations [22]

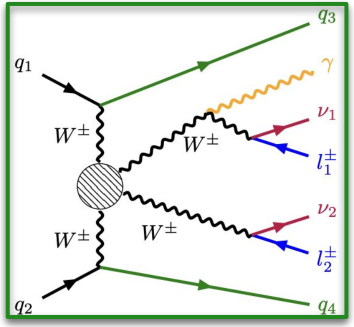
LO 2→6



LO 2→7 QCD



NLO EW



Run II VBS Same-sign polarized - ATLAS

ATLAS reports first evidence for longitudinal polarization in vector boson scattering $W_L W_X$ 3.3σ (CMS 2.3σ).

95% CL upper limit of 1.5 x SM, 0.45 fb on $W_L W_L$ (CMS 1.17)

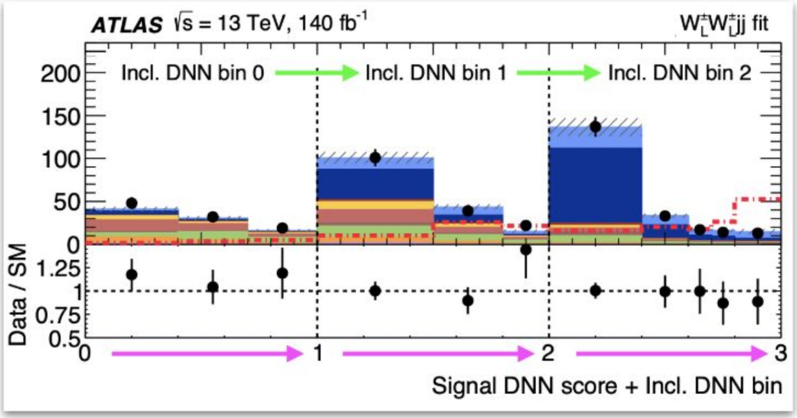
Inclusive fiducial cross sections ($W_L W_X$ 0.88 ± 0.30 fb) **in agreement with SM predictions → Statistically limited**

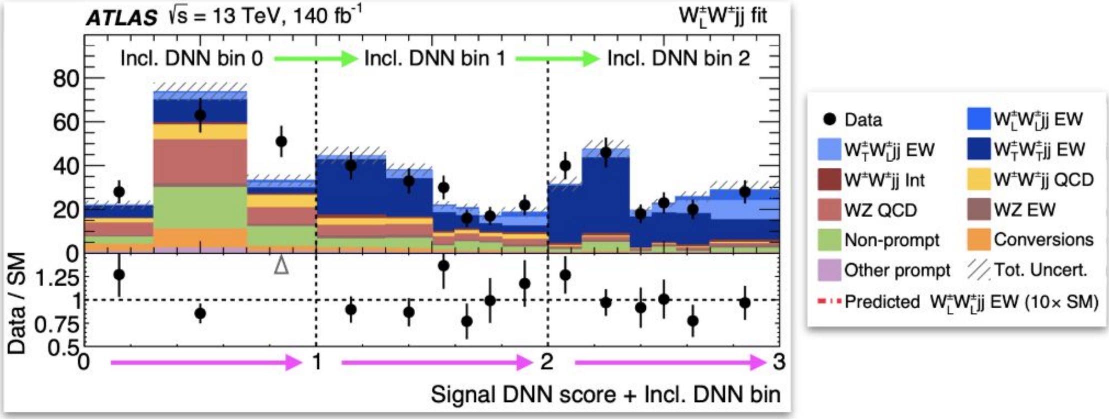
Process	Predicted $\sigma\mathcal{B}$ (fb)	Measured $\sigma\mathcal{B}$ (fb)	U
$W^\pm_L W^\pm_L jj$	0.29 ± 0.07	0.01 ± 0.21 (tot.)	±0.20 (stat.)
$W^\pm_T W^\pm jj$	2.56 ± 0.64	3.39 ± 0.35 (tot.)	±0.30 (stat.)
$W^\pm_L W^\pm jj$	1.18 ± 0.29	0.88 ± 0.30 (tot.)	±0.28 (stat.)
$W^\pm_T W^\pm_T jj$	1.67 ± 0.40	2.49 ± 0.32 (tot.)	±0.30 (stat.)

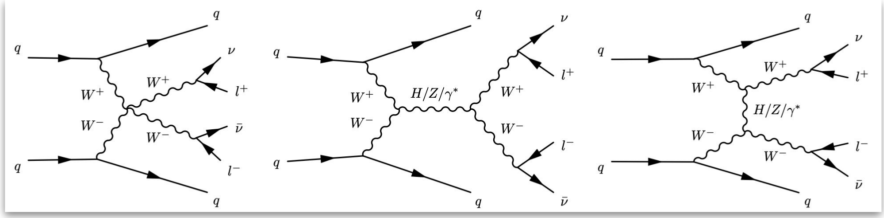
All results reported in WW c.m. rest frame but also done, with limited sensitivity with Lab rest frame.

Slight tension with unpolarized results + WZ EW not floating

μ Unpolarized	$WZ(QCD)$ 0.67 ± 0.07	$WW(EW)$ 1.15 ± 0.12	WW 1.16 ± 0.11
μ Polarized	$WZ(QCD)$ 0.74 ± 0.08	$W_L W_L$ 0.75 ± 0.08	$W_L W_X$ 0.75 ± 0.08







VBS of two W bosons with opposite charge W^+W^-

- **Unitarization via s/t/u Higgs exchange**
- **Overwhelmed by backgrounds (tt, DY, QCD-VBS)**

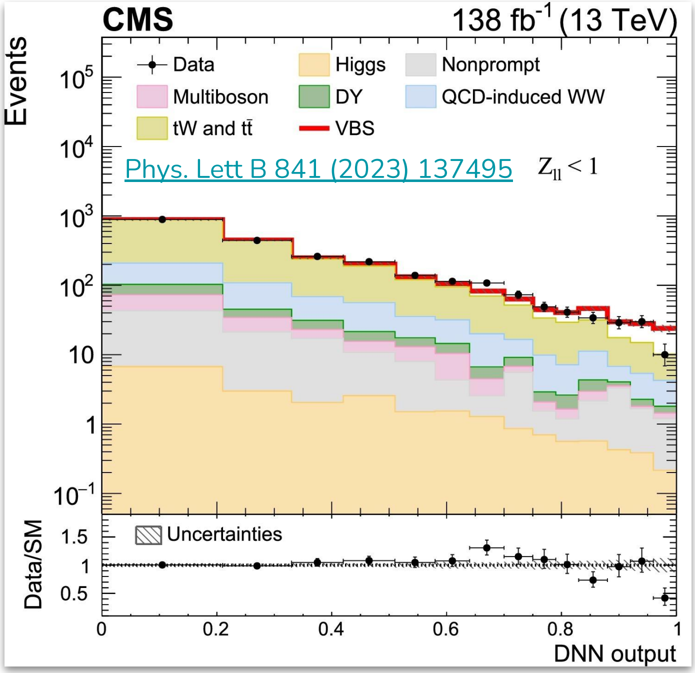
CMS studied leptonic OSWW WW→ (ee, eμ, μμ)$\nu\nu$

Flavour-dependent background composition & signal extraction. Fine stratification to control DY background (hard and PU) in $\Delta\eta_{jj}$ bins

- **ee, μμ** → Dominant DY. 8 bins of m_{jj} and $\Delta\eta_{jj}$ for residual sensitivity
- **eμ** → Dominant $t\bar{t}$, reduced DY. DNN trained in Z≲1 dominates sensitivity

The VBS EW production of W^+W^- is observed for the first time with a significance 5.6σ

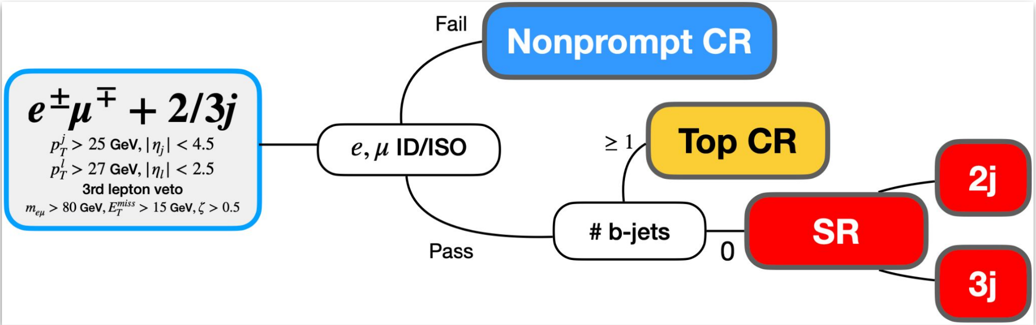
Fiducial region	σ meas	σ SM@LO
Inclusive ($m_{qq} > 100$ GeV)	99 ± 20 fb	89 ± 5 fb
Exclusive ($m_{qq} > 300$ GeV)	10.2 ± 2.0 fb	9.1 ± 0.6



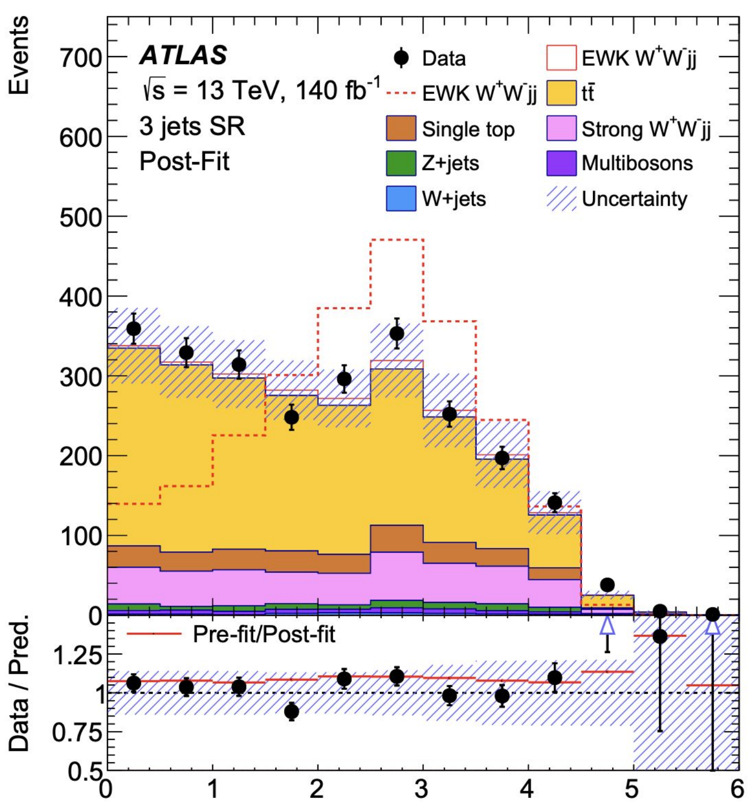
Run II Opposite Sign WW - ATLAS

ATLAS analyzed leptonic OSWW but only in eμ final state.

- m(eμ) < 80 GeV suppresses VBF-h
- Missing E_T > 15 GeV further suppresses Drell-Yan
- **No m_{jj} cut but SR split by jet multiplicity (2/3) → 1σ increase**
- Simpler analysis w.r.t CMS → backgrounds more stable

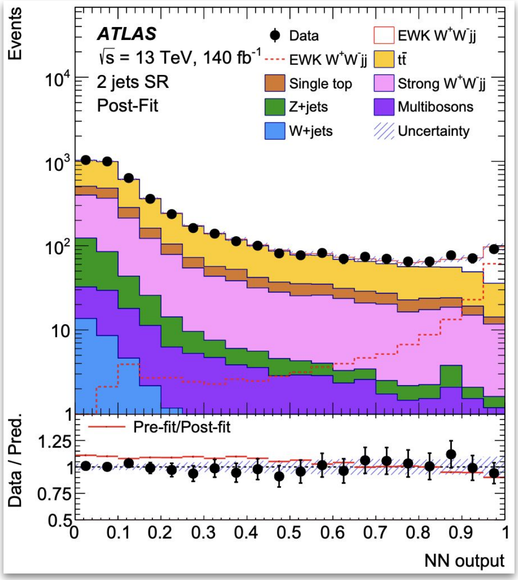


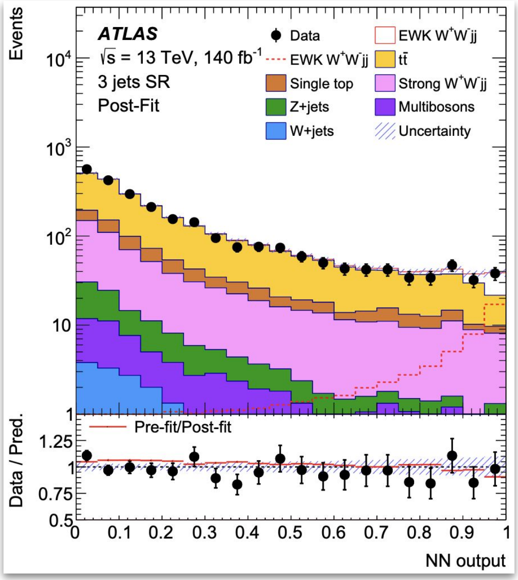
Region	EW-VBS	QCD-VBS	Top
SR2j	3.4%	26.3%	62.6%
SR3j	2.1%	20.2%	72.7%



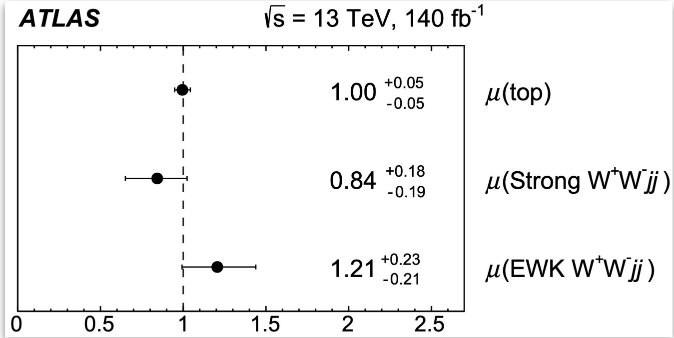
JHEP 07 (2024) 254

Run II Opposite Sign WW - ATLAS





Two DNNs trained in 2j and 3j SR to distinguish EW VBS from tt + single-t + QCD-VBS: [Observation of EW $W^{\pm}W^{\mp}jj \rightarrow e\mu 2\nu jj$ with a significance of 7.1σ]



Same amount of signal in CMS, ATLAS eμ SRs less bkg in CMS→ ATLAS improvement from DNN

- Trained with additional inputs: $m_{\ell\ell}$, $m_{\ell j}$, $\Delta\phi_{jj}$, miss E_T , ζ, Z_{j3}
- **CMS** last bin: s ~ 14, b ~ 10 → **s/√b ~ 4.4**
- **ATLAS** last bin: s ~ 60, b ~ 35 → **s/√b ~ 10.1**

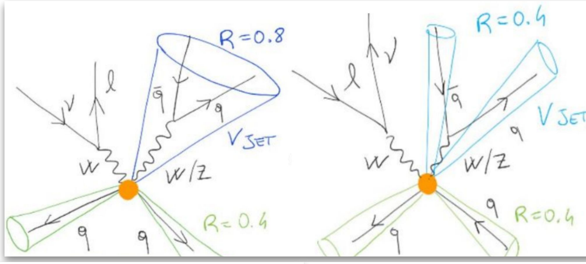
Source	Impact %
Total	**18.5**
Data stat.	12.3
Tot. syst.	13.8
MC stat.	7.7
Top theory	6.3
Sig. theory	5.8
JES	4.9
Top norm.	4.9
...	...

Fiducial x-sec in region close to the SR with additional m_{jj} > 500 GeV (~ DNN > 0.6): suppress triboson

$$\sigma^{fid}_{obs} = 2.65^{+0.49}_{-0.46}\,\text{fb}; \quad \sigma^{fid}_{exp} = 2.20^{+0.14}_{-0.13}\,\text{fb}$$

Run II semileptonic WV/ZV - CMS

L=139 fb^{-1} allowed CMS to first study semileptonic VBS signatures: WV→ ℓνjj and ZV→ ℓℓjj

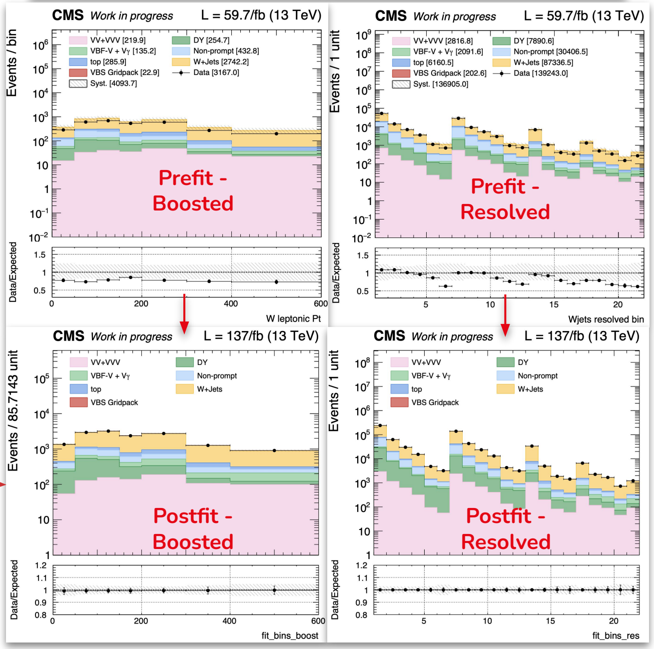


- Hadronic decay: **merged or resolved topologies**
- Select large-R tagged jet or 2 small-R jets
- Quark-gluon likelihood to distinguish V from q/g from jets

Harsh multijet background. Main source from V+jets production → Difficult background modelling

- **V+Jets MC:** NLO W+Jets brings no improvement + larger stat. uncertainty → Madgraph+Pythia8 samples, HT binned up to 4 partons LO@QCD.

- **Data-driven correction to the V+Jets LO sample** measure V+jets normalization in bins of p_T^V and subleading VBS jet p_T



Trading off systematic uncertainties for a better background description → Need for precise background predictions for future measurements

Run II semileptonic WV/ZV - CMS

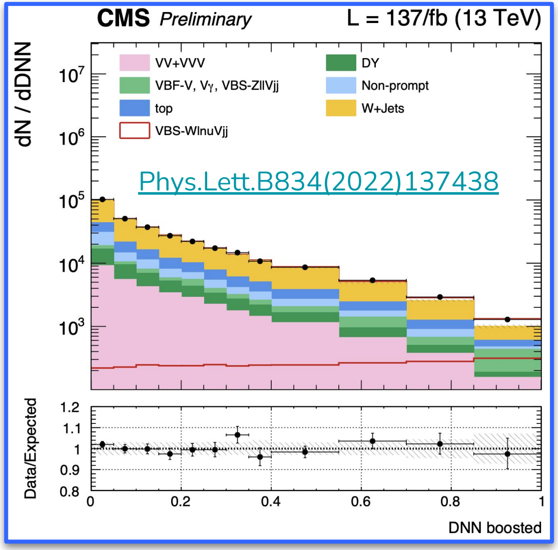
- **DNNs used for signal extraction** (boost/res): ~3x better than mjj
- **ZV further split for N. b-tag** to better model Z+jets

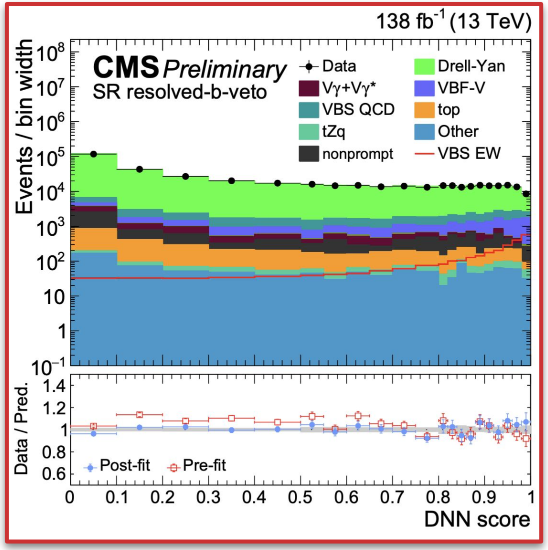
CMS reports first evidence for EW WV 4.4σ. EW ZV 1.3σ. Results are statistically dominated

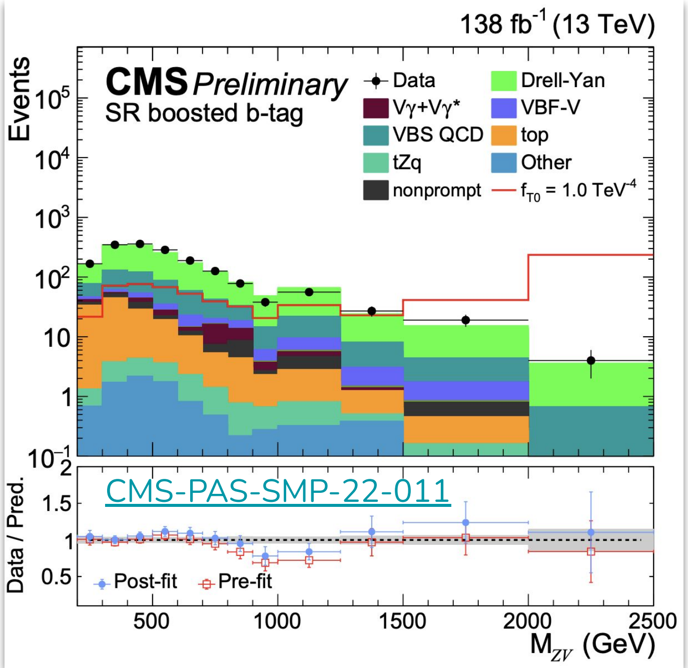
Very stringent limits on **dimension-8 EFT** coefficients (~aQGC) from the combination of the **two semileptonic boosted channels (WV+ZV)** using VV mass→ **No excess over SM background is observed**

$$\mu_{EW} = 0.85 \pm 0.12(\text{stat})^{+0.19}_{-0.17}(\text{syst}) = 0.85^{+0.23}_{-0.21}$$
$$\mu_{EW+QCD} = 0.97 \pm 0.06(\text{stat})^{+0.19}_{-0.21}(\text{syst}) = 0.97^{+0.20}_{-0.22}$$

$$\mu_{EW} = 0.63^{+0.53}_{-0.51}\left(1.00^{+0.61}_{-0.58}\right)$$



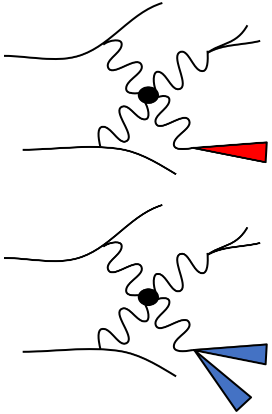


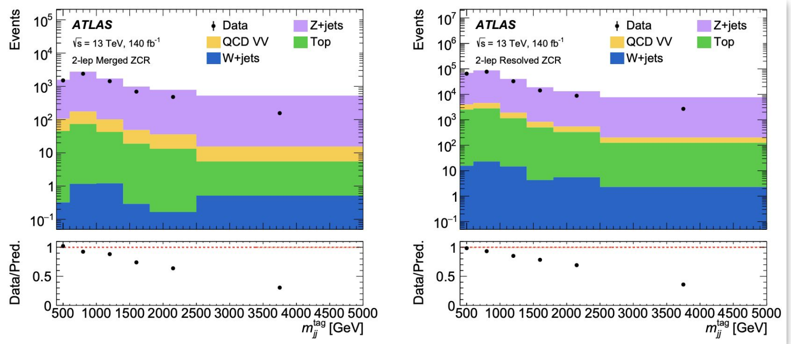


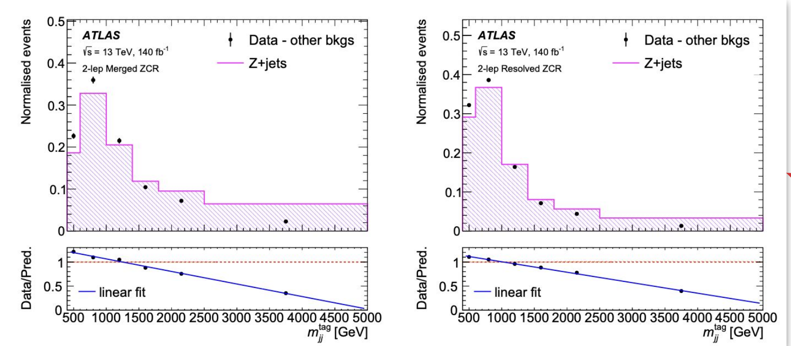
ATLAS recently analyzed semileptonic VBS channels including Z→*νν* decays (0-lep). Similar CMS approach:

- Hadronic decay: **merged or resolved topologies**
- Select **large-R** tagged jet or **2 small-R** jets

0-lepton	SR VjjCR	ZZ → νν2j
1-lepton	SR WCR TopCR	W±V → lνjj
2-lepton	SR ZCR	ZV → 2l2j



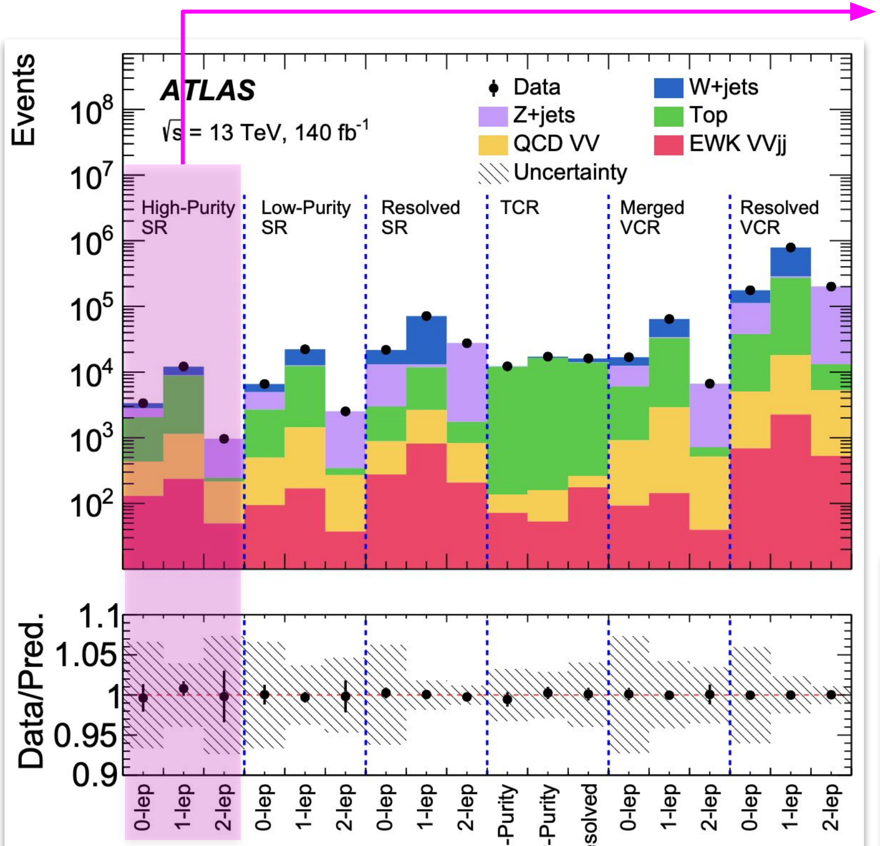




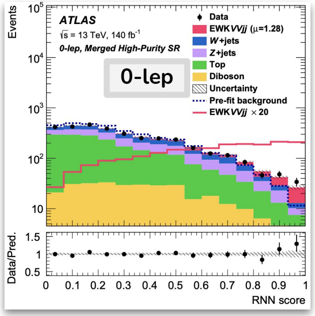
As for CMS, W+jets and Z+jets are not well-modelled i 0,1,2 lep regions as function of m_{jj} → **Data driven correction to V+jets**

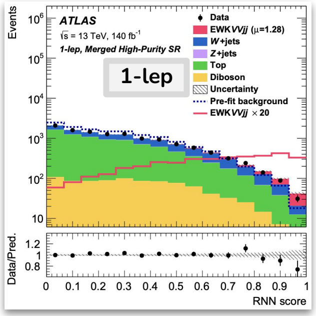
- **Linear fit to** data - bkg m_{jj} normalized to unity for W(Z)+jets in 1(2)-lep
- Extract W+jets and Z+jets together in 0-lep

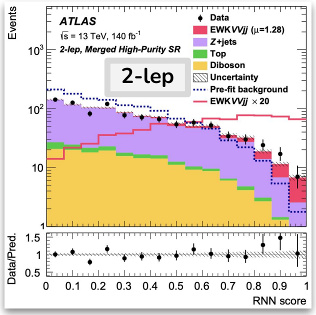
Run II semileptonic WV/ZV - ATLAS



CERN-EP-2025-050





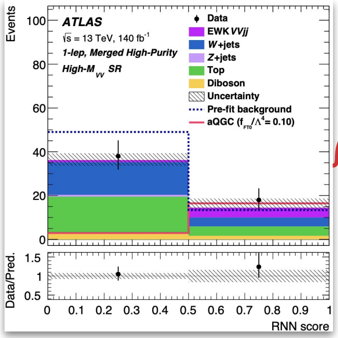


Fit to **Recurrent Neural Network** trained on VBS VV against Bkg

ATLAS reports first observation for semileptonic VBS 7.4σ

$$\mu_{\rm EW}^{\rm obs} = 1.28^{+0.23}_{-0.21} = 1.28 \pm 0.09\,(\text{stat.})\,^{+0.20}_{-0.19}\,(\text{syst.})$$

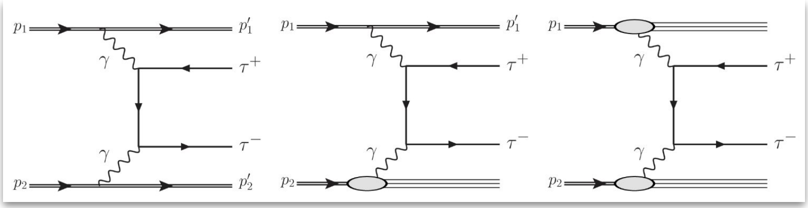
Dominated by signal modelling and jet reconstruction uncertainties

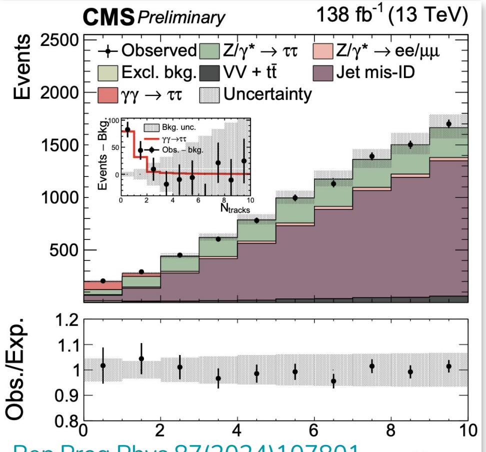


Limits on EFT dimension-8 operators ~ 2/3 times worse than CMS despite additional 0-lep channel and higher sensitivity to SM

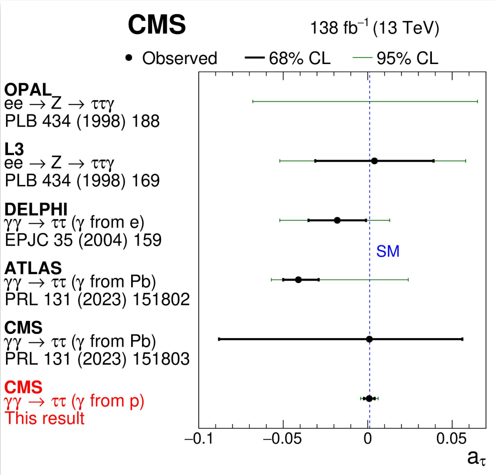
Other interesting Run II results

Observation of central exclusive production of τ pair
Probing QED quantum corrections → a_τ

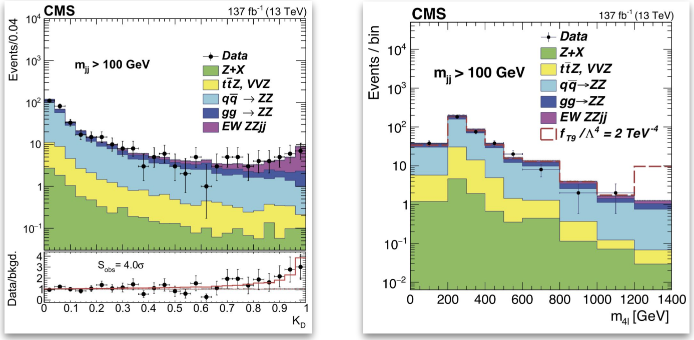




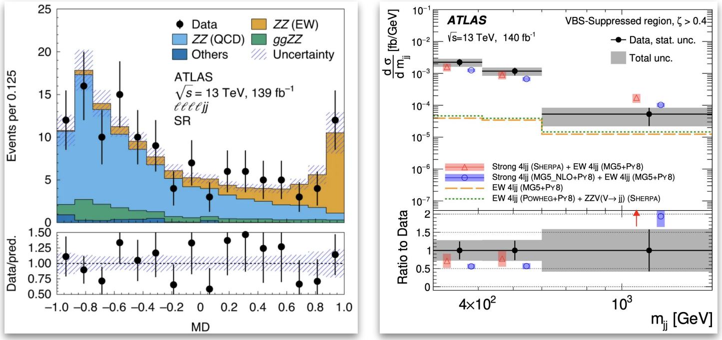
[Rep.Prog.Phys.87(2024)107801]



CMS reports evidence for VBS ZZ(4ℓ) 4.0σ
[PLB 812 (2021) 135992]



ATLAS observes VBS ZZ(4ℓ) + differential xsec
[Nature19(2023)] and [JHEP01(2024)004]



Piecing together the puzzle: a comprehensive look at vector boson scattering in CMS

CMS-PAS-SMP-24-013

Multiple CMS results in VBS, sensitive to a mixture of vector bosons types → Combination

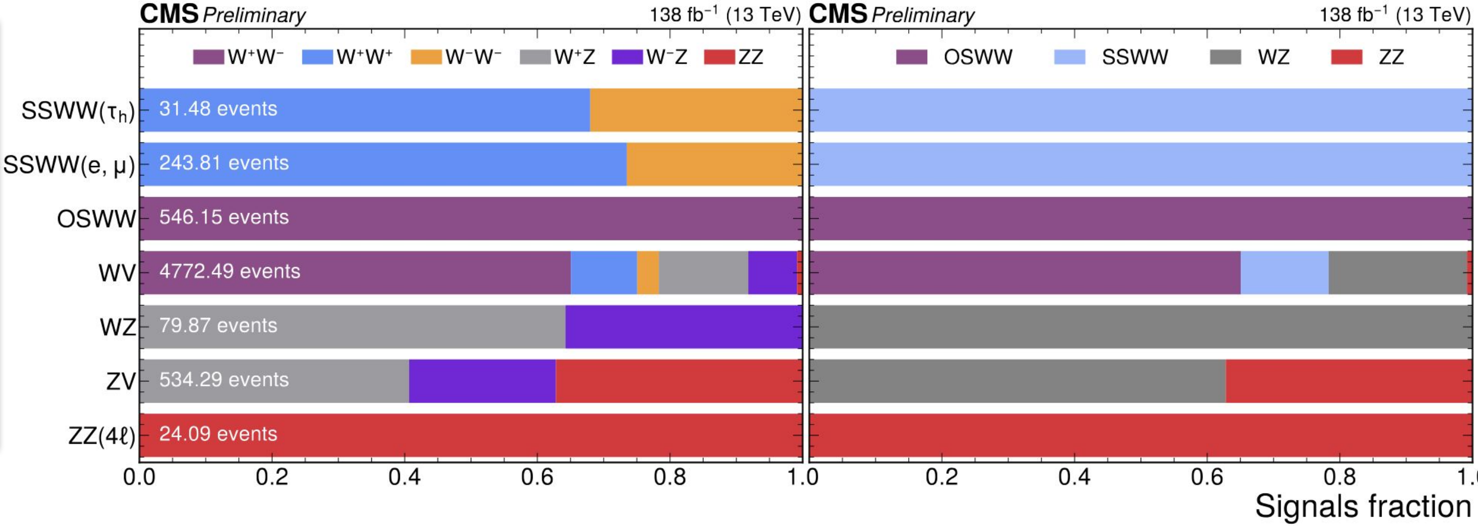
6 parameters

$W^{\pm}W^{\mp}, W^{+}W^{+}, W^{-}W^{-}, W^{+}Z, W^{-}Z, ZZ$

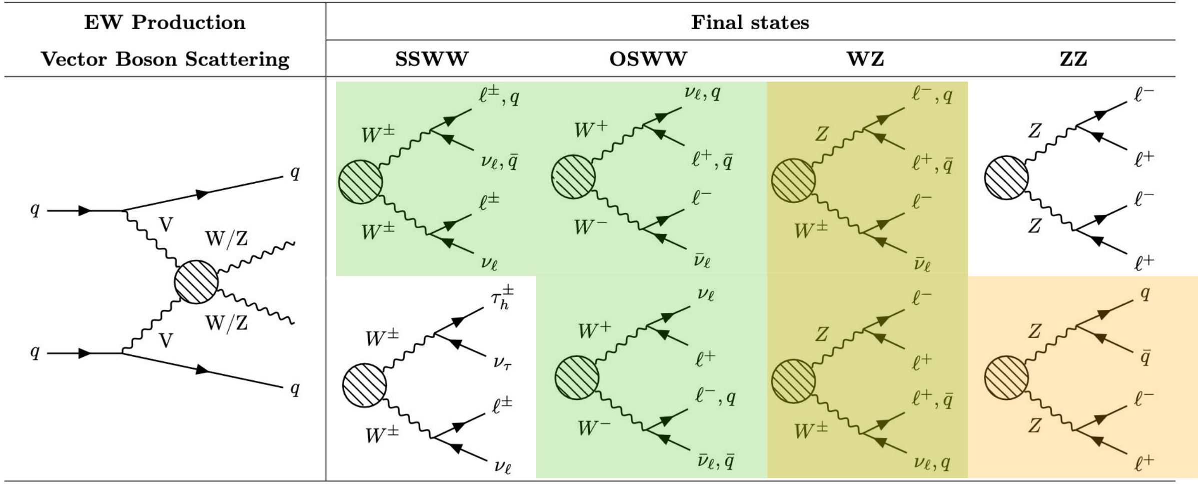
4 parameters

$W^{\pm}W^{\pm}, W^{\pm}W^{\mp}, W^{\pm}Z, ZZ$

Testing production charge asymmetry at LHC by splitting for W boson electric charge → 6 parameters

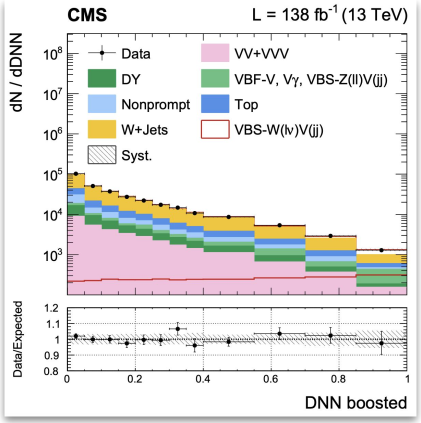


Run II VBS Combination - CMS



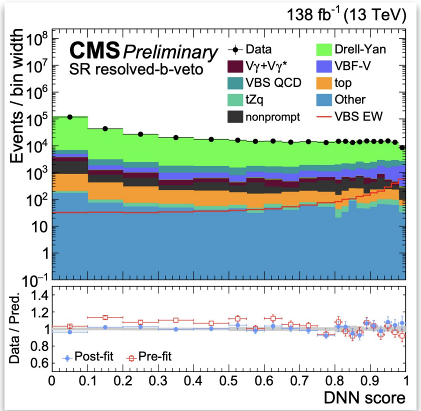
Shorthand name	Production modes	Final state	N. ℓ	Reference
WV	$pp \to W^+W^-jj, W^\pm W^\pm jj, W^\pm Zjj$	$\ell\nu jjjj$	1	[28]
SSWW (e, μ)	$pp \to W^\pm W^\pm jj$	$\ell^\pm\ell^\pm 2\nu jj$	2	[24]
OSWW	$pp \to W^+W^-jj$	$\ell^+\ell^- 2\nu jj$	2	[26]
ZV	$pp \to W^\pm Zjj, ZZjj$	$2\ell jjjj$	2	[29]
SSWW (τ_h)	$pp \to W^\pm W^\pm jj$	$\ell^\pm\tau_h^\pm 2\nu jj$	2	[25]
WZ	$pp \to W^\pm Zjj$	$3\ell\nu jj$	3	[24]
ZZ(4ℓ)	$pp \to ZZjj$	$4\ell jj$	4	[27]

Phys. Lett. B 834 (2022) 137438



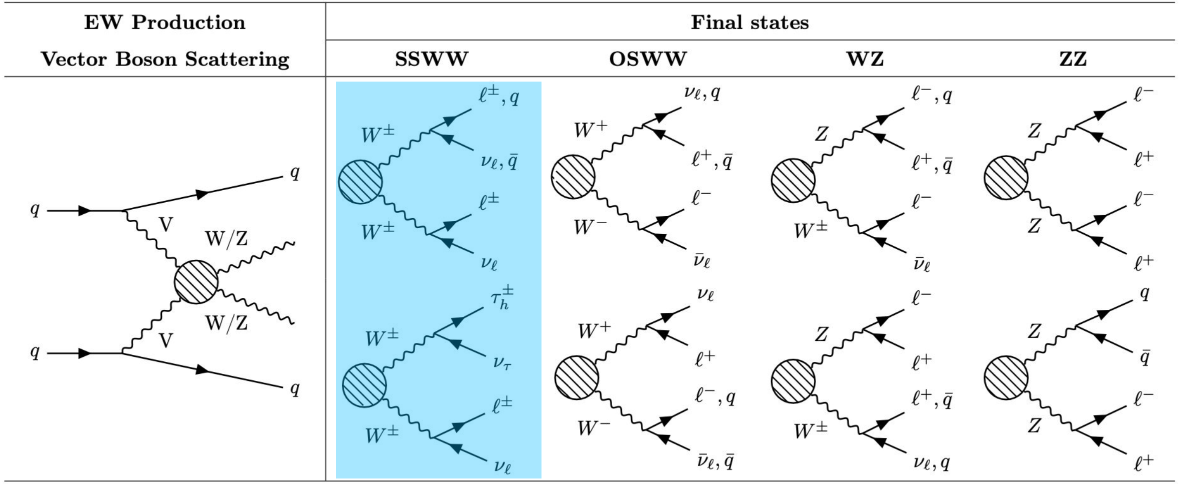
WV

CMS-PAS-SMP-22-011



ZV

Run II VBS Combination - CMS



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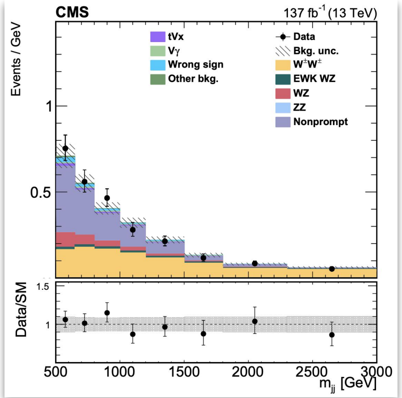
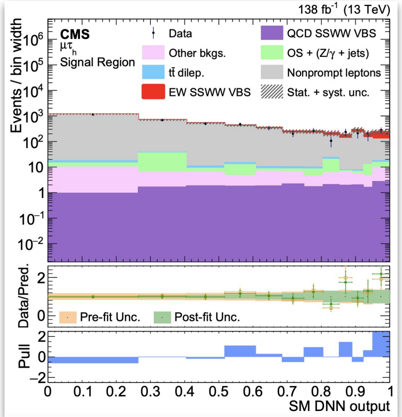
ZZ(4ℓ)	$pp \to ZZjj$	$4\ell jj$	4	[27]

Phys. Lett. B 809 (2020) 135710



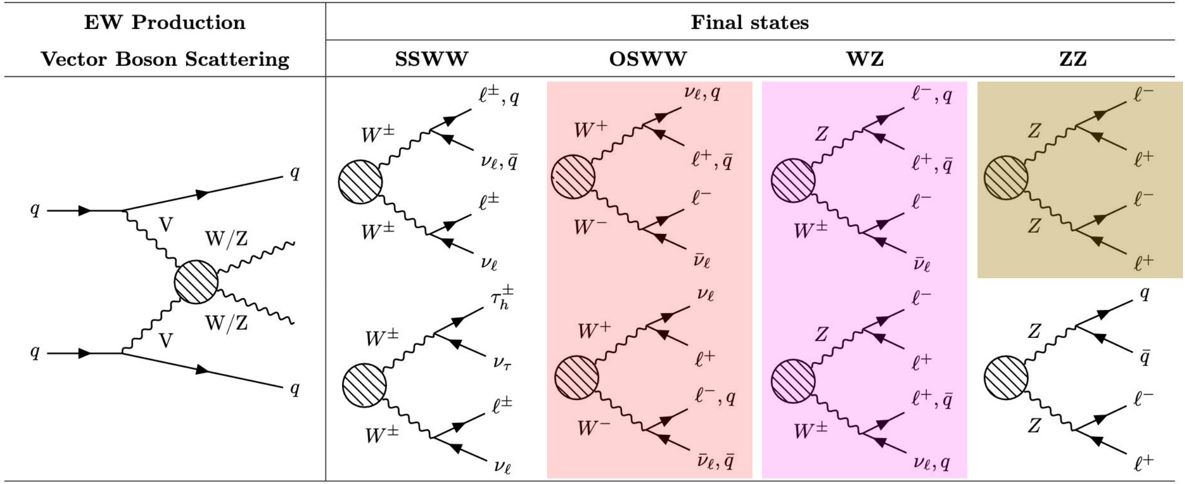
(e, μ)

CMS-SMP-22-008



(τ_h)

Run II VBS Combination - CMS



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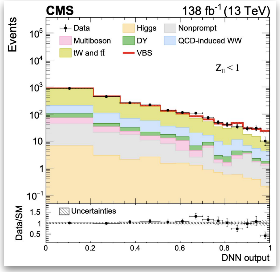
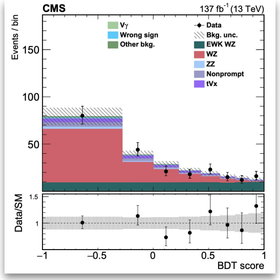


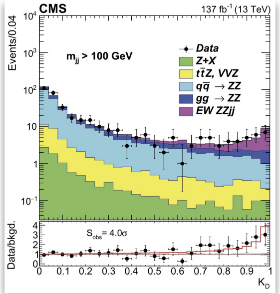
OSWW

Phys. Lett B 841 (2023) 137495



WZ

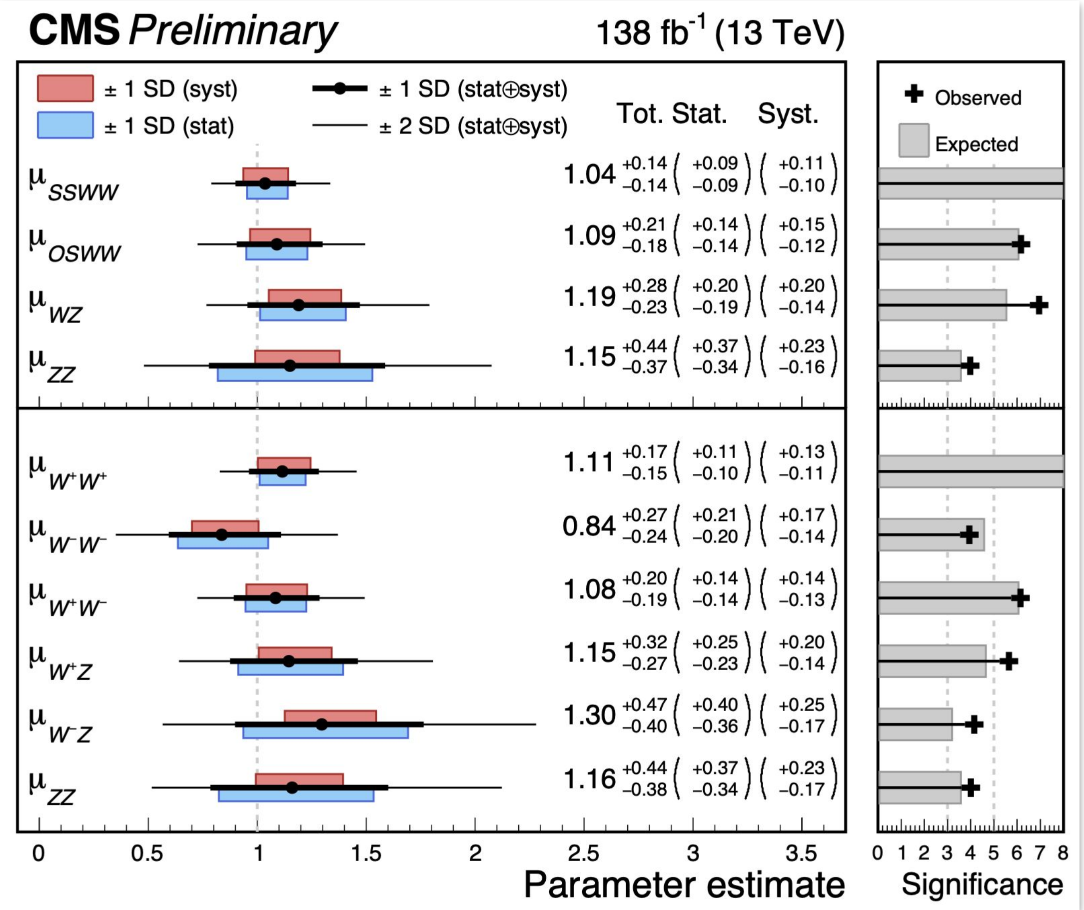
Phys. Lett. B 809 (2020) 135710

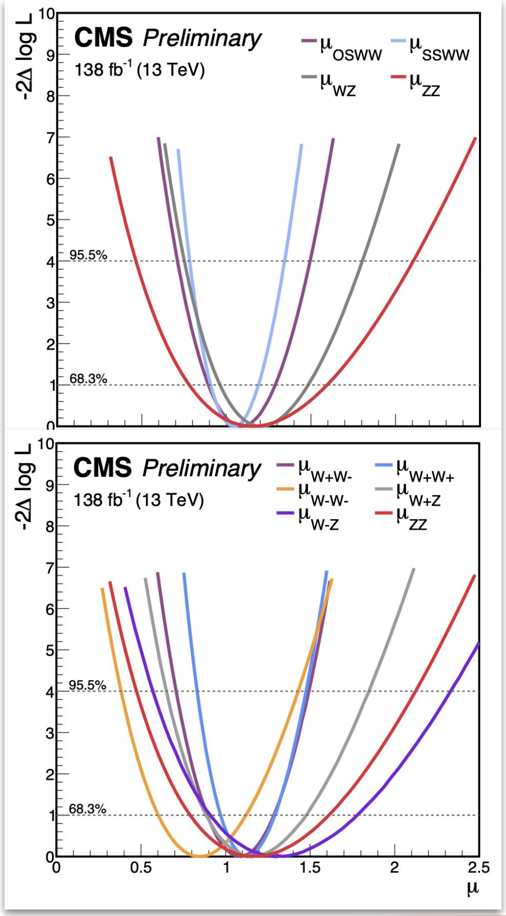


ZZ(4ℓ)

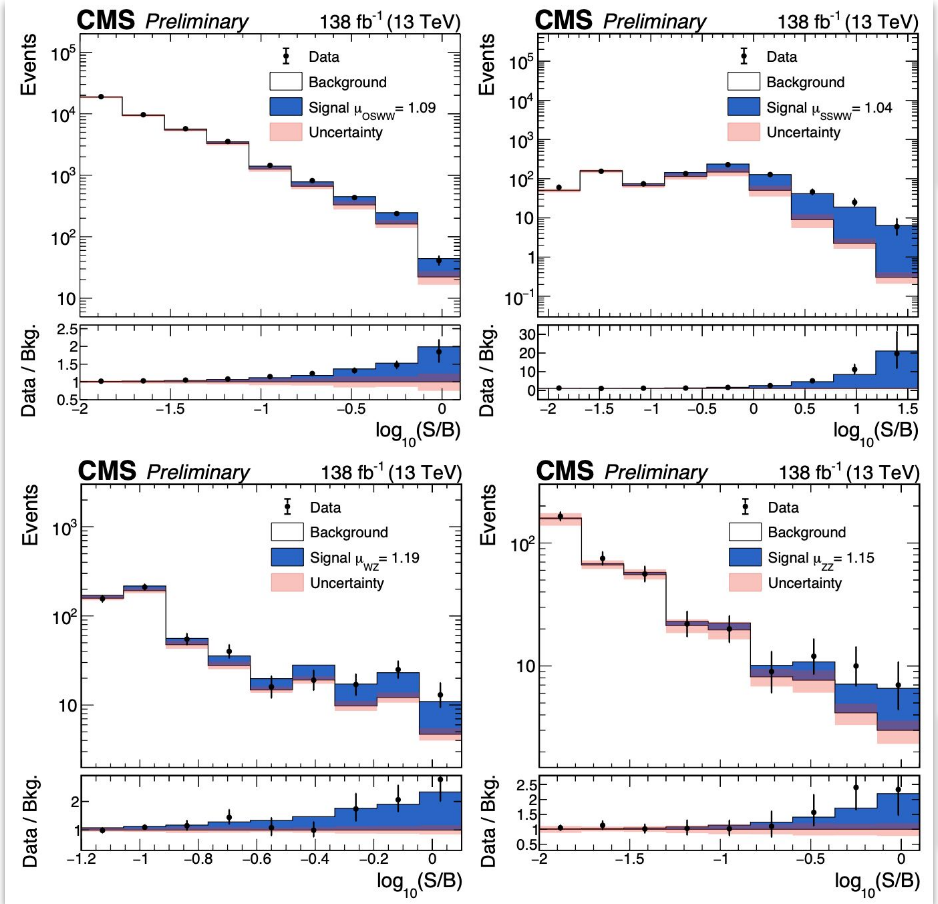
Phys. Lett. B 812 (2020) 135992

Run II VBS Combination - CMS





Run II VBS Combination - CMS



Investigate global deviations differentially with S/B distributions

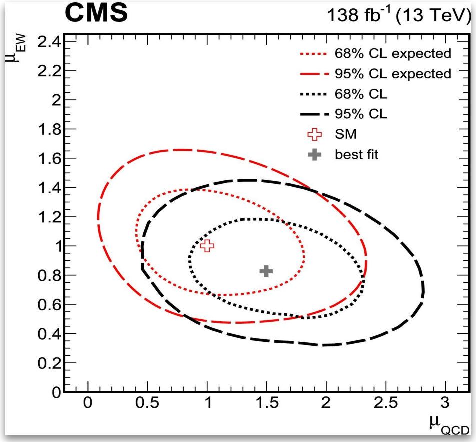
- For all bins of the input templates, prefit $\log[S(\mu = 1)/B]$ is computed
- Postfit yields of signal, backgrounds and data is assigned to the leading signal distribution, in terms of yield → data is not shown twice.
- Uncertainty on background prediction computed with 500 toys

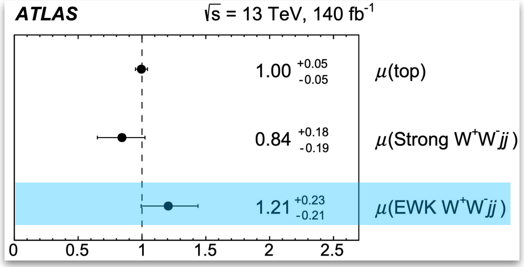
High S/B values are correlated with high energies (m_{jj}) → no excess over SM observed

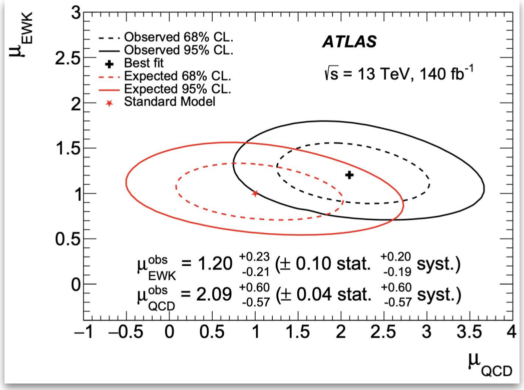
The future of VBS at LHC and HL-LHC

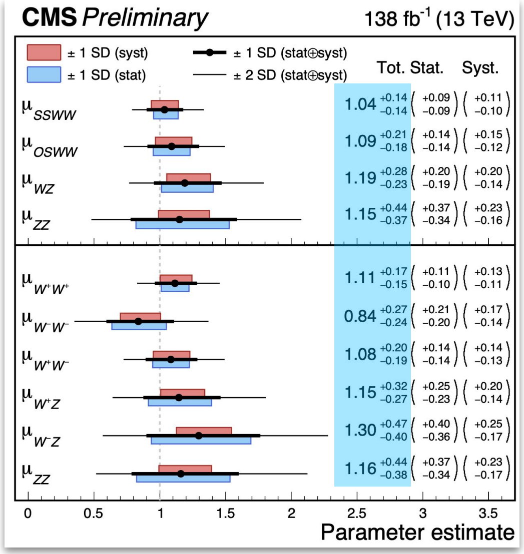
*Omitting the obvious: **analyze Run-3 data** in particular for statistically limited processes $ZZ(4\ell)$, WV, ZV, ...

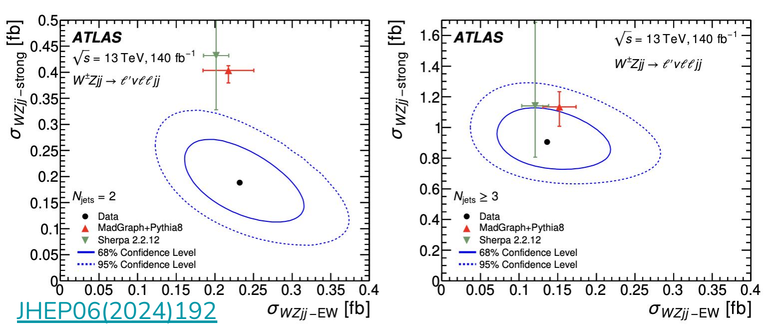
Excesses...











JHEP06(2024)192

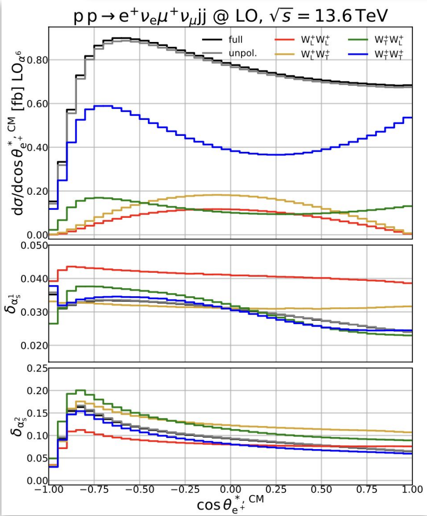
Description	σ^{EW}_{fid} [fb]	$\sigma^{EW+Int+QCD}_{fid}$ [fb]
Measured cross section	2.92 ± 0.22 (stat.) ± 0.19 (syst.)	3.38 ± 0.22 (stat.) ± 0.19 (syst.)
MG5_aMC+Herwig7	2.53 ± 0.04 (PDF) $^{+0.22}_{-0.19}$ (scale)	2.92 ± 0.05 (PDF) $^{+0.34}_{-0.27}$ (scale)
MG5_aMC+Pythia8	2.53 ± 0.04 (PDF) $^{+0.22}_{-0.19}$ (scale)	2.90 ± 0.05 (PDF) $^{+0.33}_{-0.26}$ (scale)
Sherpa	2.48 ± 0.04 (PDF) $^{+0.40}_{-0.27}$ (scale)	2.92 ± 0.03 (PDF) $^{+0.60}_{-0.40}$ (scale)
Sherpa ⊗ NLO EW	2.10 ± 0.03 (PDF) $^{+0.34}_{-0.23}$ (scale)	2.54 ± 0.03 (PDF) $^{+0.50}_{-0.33}$ (scale)
Powheg Box+Pythia	2.64	–

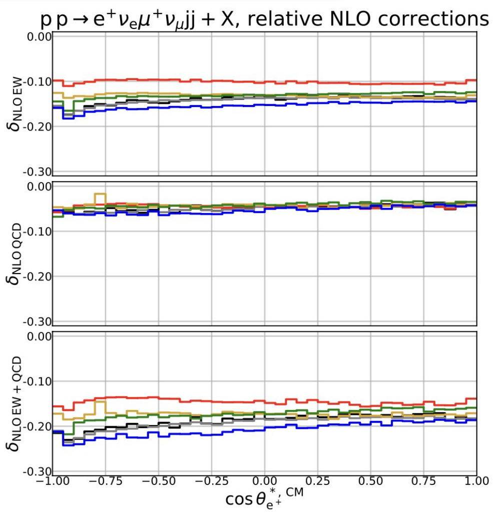
Theory advancements in VBS

VBS predictions highly sensitive to NLO EW corrections → Lowers predictions by >20%: Excesses could get even larger

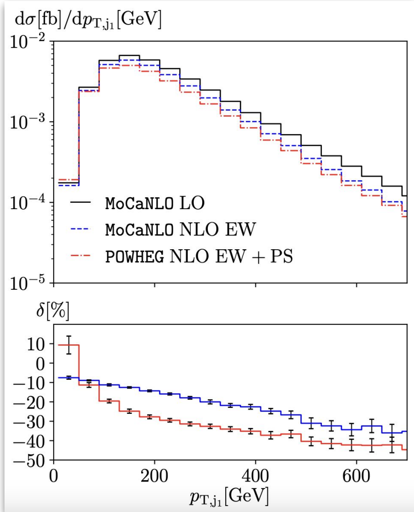
- NLO QCD available matched to PS in public tools like POWHEG-BOX, Sherpa, MG5_aMC@NLO
- NLO EW + PS only available for SSWW [23], ZZ [24], (unpolarized). Fixed order for OSWW [25]
- No available NLO computation for semileptonic VBS → only LO in DPA [26] paves the way for NLO

Fixed-order full NLO polarised W±W± (leptonic) [23]

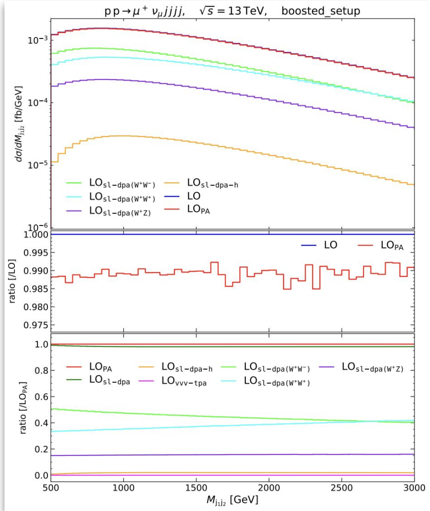




NLO+PS SSWW [24]



LO WV DPA [26]



VBS and effective field theory

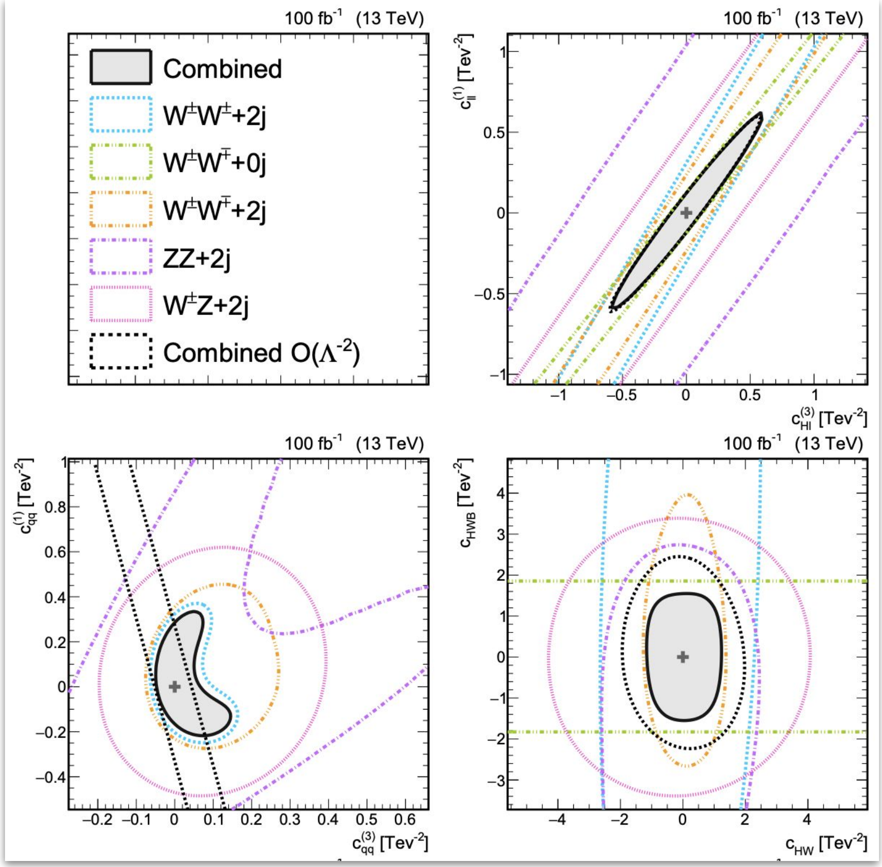
If no new physics is observed at the LHC → EFT could point us to the correct direction (model independent)

Violates B,L

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \ldots$$

Leading deviation from SM

- **VBS dominate** EFT sensitivity to **dimension-8** due to tree-level quartic gauge couplings
- Recent phenomenological studies showed that **VBS can be important at in global EFT fits at dimension-6 [27, 28, 29, 30, 31]**

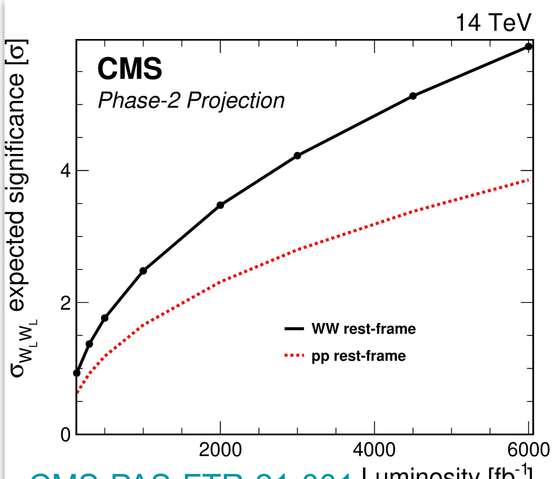


JHEP05(2022)039

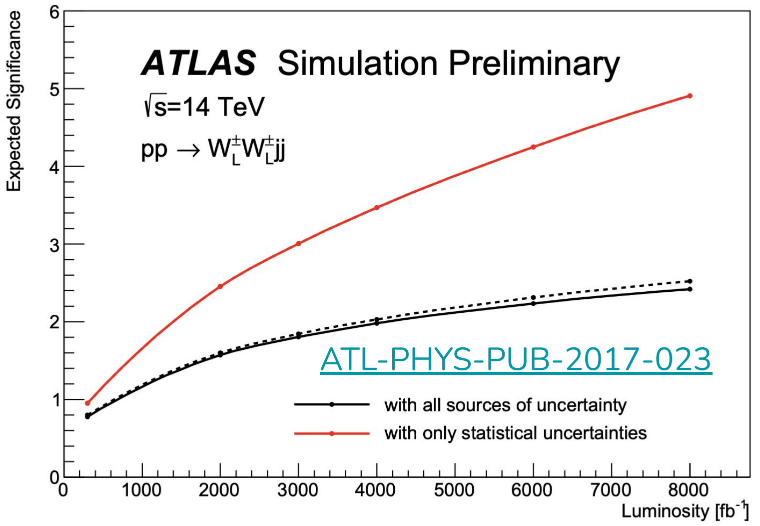
Both ATLAS and CMS experiments are expected to have evidence for fully longitudinally polarized WW scattering at the HL-LHC (3 ab^{-1})

- Projections based on very old results → Run-3 analyses should tune the curve
- Only statistical enhancement. Optimistic scenario reducing by 50% uncertainties on data driven backgrounds

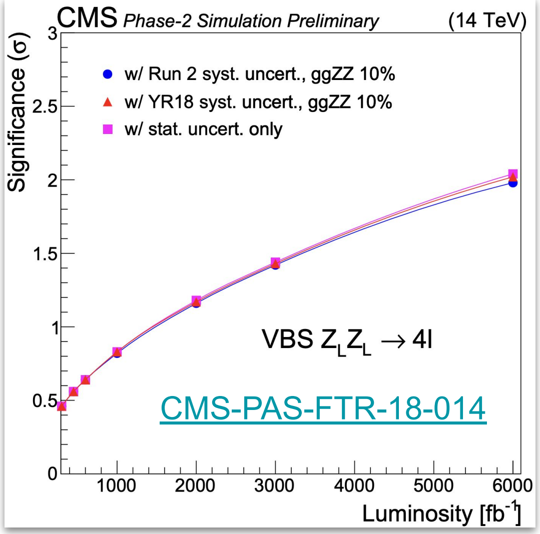
Evidence for $W_L W_L$ at LHC combining ATLAS + CMS Run2+Run3 ?



CMS-PAS-FTR-21-001



ATL-PHYS-PUB-2017-023



CMS-PAS-FTR-18-014

Conclusions

Conclusions

I hope I convinced you that measurements of vector boson scattering are interesting!

- **Probe ingredients of the EWSB** and realization of the Higgs mechanism independently from direct Higgs boson measurements

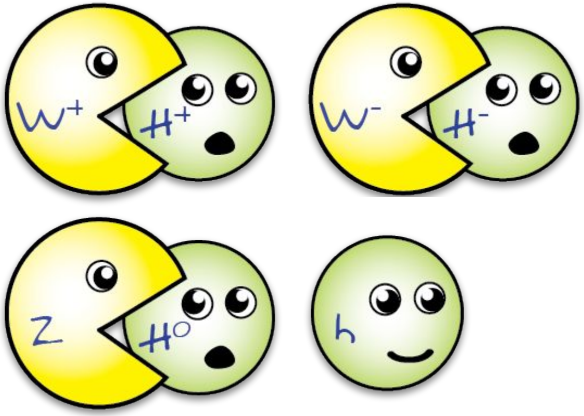
- **Interesting corner to study new physics:** tree-level sensitivity to hVV, QGCs, TGCs → doubly charged Higgs, Heavy neutrinos, anomalous couplings in Effective Field Theory

During LHC Run-I and Run-II, our understanding of Vector Boson Scattering advanced dramatically, evolving from a once-elusive theoretical concept to a domain of precise experimental measurement.

However…

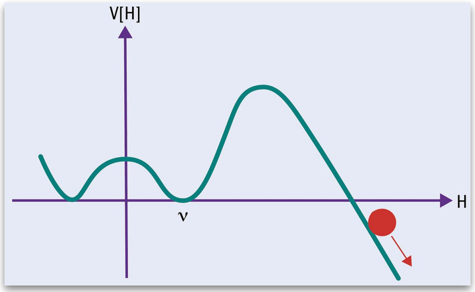
- **Predictions limited at LO** for polarized VBS (except SSWW) and for unpolarized semileptonic → theory community is actively working on the topic!

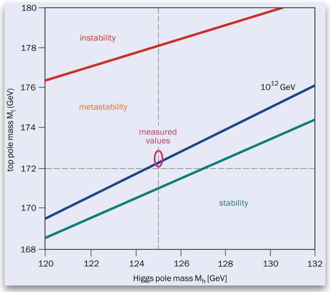
- Statistics is still an issue → **VBS will largely benefit of Run-3 data**



$$V(\phi^\dagger\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

Why $\mu^2<0$? We don't know…





[The Higgs and the fate of the universe]