

via Vector Boson Scattering at the ATLAS Detector Studies of Electroweak Interactions

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Electroweak Multiboson Interactions Electroweak Multiboson Interactions

Triggere Efficiency **& Object Overlap Rem^{y/Z}al Studies in W(**à**munu)gamma2j Channel** \square The Standard Model (SM) of elementary particles predicts triple and quartic gauge couplings between the electroweak bosons due to the non-Abelian **Studies in W(**à**munu)gamma2j Channel** \Box The Standard Model (SM) of elementary particles $w \rightarrow w$ partic standard moder (sivi) or elementary particles predicts tripic driv quartic gauge couplings bety v Experiental studies in W/ Δ munu)commo?i Ch $\boldsymbol{\mu}$ tuult \boldsymbol{s} important tests of the SM electroweak theory W- W- W- W- W- m unu)gammazj Channel wystranienia (m. 1917) W- W- W- W- W- \overline{Z}

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> VBS Wgamma2j Analysis Group Meeting LINI IT.VT.LULU VBS Wgamma2j Analysis Group Meeting CERN 14.04.2020

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□ Heavy vector bosons couple with the SM Higgs boson q According to the SM, the massive electroweak bosons obtain their masses and hence, $\mathcal{A}(\mathcal{A})$ The Higgs boson $\mathcal{A}(\mathcal{A})$ the Higgs boson $\mathcal{A}(\mathcal{A})$ 484 The Higgs boson b

Gia Khoriauli University of Würzburg Gia Khoriauli University of Würzburg W⁺ W⁺ W⁺ W⁺ W- W- W- W- !**Fig. ¹⁷.²** Higgs boson exchange diagrams for W+W[−] [→] ^W+W−. W⁺ W⁺ W⁺ W⁺ W- W- W- W- !**Fig. ¹⁷.²** Higgs boson exchange diagrams for W+W[−] [→] ^W+W−. can have longitudinal polarisations via the Higgs mechanism of the spontaneously v Measurements of polarisation observables in the multiboson interactions are the direct probes of this mechanism H W-W⁺ gW*m*^W H Z Z gZ*m*^Z gZ*m*^Z H W-W⁺ gW*m*^W H Z

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tial cross sections, GEBN 14.04.2020 15/02/2024 Gia Khoriauli Testing the Electroweak Theory in Mutliboson Measurements in ATLAS LLWI24 2 **❖** Fiducial and differertial cross sections, effective field theory interpretations, etc.

Electroweak Vector Boson Scattering $\text{C}\text{C}\text{C}\text{C}\text{C}$ and $\text{C}\text{C}\text{C}\text{C}\text{C}$ has an effect on the cross section of the c

- \Box Electroweak VBS processes $V_1 V_2 \rightarrow V_3 V_4$ have not been studied experimentally before the LHC experiments
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Studies in Augustian Cross sections (~ fh) even at ❖ Low production cross sections (~ fb) even at the LHC energies
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$VVjj$ Production with $V = W, Z, \gamma$ at Leading Order

 \Box Pure EW & s-/t-channel production with the Higgs boson propagator

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4

*q*2

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g **quoting** $\overline{q_2}$

VBS and Electroweak Symmetry Breaking Mechanism

of the spontaneously broken
clastrau ask a managimum \Box The SM massive electroweak bosons obtain their masses and longitudinal polarisations via the Higgs mechanism electroweak symmetry

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State in Measurements of polarisation ◆ Measurements of polarisation observables in the multiboson interactions are the direct probes of this mechanism

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با
با \mathbb{R}^n with \mathbb{R}^n with \mathbb{R}^n H $\Phi(f) + \Phi(f)$ \sim \sim \sim W- W- W- W- !**Fig. ¹⁷.²** Higgs boson exchange diagrams for W+W[−] [→] ^W+W−. $\sum_{\tau_{\tau_{\tau_{\tau}}} \neq \tau_{\tau_{\tau}}} \frac{1}{\sqrt{\tau_{\tau_{\tau}}}^2}$ W⁺ W⁺ W⁺ W⁺ this mech $(a) \n\widetilde{} f$ $\mathcal{L} \rightarrow \mathcal{L}$ in $\mathcal{L} \rightarrow \mathcal{L}$ in $\mathcal{L} \rightarrow \mathcal{L}$ The Higgs mechanism generates the masses of the electroweak gauge bosons in a $\mathcal{L} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$ + $\frac{1}{2}$ + $\frac{1}{2}$ + $\frac{1}{2}$ manner that \mathcal{P} is the \mathcal{P} $\frac{1}{\sqrt{2}}$ \Box \Box \Box \Box H \mathbb{R} W \mathbb{R} W \mathbb{R} $\mathbf T$ \sim 1, \sim 2, \sim \mathcal{A} W \mathcal{A} W \mathcal{A} W \mathcal{A} W⁺ $\frac{1}{2}$ bos $\frac{1}{2}$ id is ge 10⁸ **17.2 Lagrangians in Quantum Field Theory** !**Fig. ¹⁷.²** Higgs boson exchange diagrams for W+W[−] [→] ^W+W−. \sqcap א ר' של א \sqcup W⁺ Gia \mathcal{L} γ /Z **Q** Diagrams with Higgs boson are crucial $+$ γ /Z γ /Z The Higgs mechanism is described in terms of the Lagrangian of the Standard \blacktriangleright in processes $T_{\text{max}} = \frac{1}{\mathbb{E}[\mathbf{r}_1, \mathbf{r}_2]}$, the mass in and \mathbf{r}_1 \mathbb{C} are described by \mathbb{C} , single particles are described by \mathbb{C} W- W- W- W- W- $\overline{}$ W- W- W- W- W- $\overline{}$ μ invariance that preserves the local gauge invariance of the Standard Model. that satisfy the appropriate \mathbb{R} **1 The lowest-order Feynman diagrams for M 17** The lowest-order Fewnman diagrams for W+W−. The formal diagrams for M−. The formal diagram, corresponds to the f \mathbb{R} M- \mathbb{R} \ge and \mathbb{R} $\mathbf{r}_{1}^{\text{1}}$ $\mathbf{r}_{2}^{\text{2}}$ $\mathbf{r}_{3}^{\text{3}}$ $\mathbf{r}_{4}^{\text{4}}$ $\begin{array}{ccc} \mathcal{L} & \mathcal$ $\mathcal{L} \times \mathcal{L} = \mathcal{L} \times \mathcal{L}$!**Fig. ¹⁷.¹** The lowest-order Feynman diagrams for W+W[−] [→] ^W+W−. The ^fnal diagram, corresponds to the quartic $\frac{1}{\sqrt{1}}$ $\frac{1}{\sqrt{1}}$ $\frac{1}{\sqrt{1}}$ $\frac{1}{\sqrt{1}}$ **University** coupling of four W bosons. $+\frac{1}{4}$ $\frac{1}{2}$ in $\frac{1}{2}$ denotes in $\frac{1}{2}$ acoupling to the four W \blacksquare for a state of a contributions. The dynamics of \blacksquare to avoid the unity violation due t δ^2 $\left[\begin{array}{ccc} 1 & 0 \end{array}\right]$ coupling of \equiv **17.2 Lagrangians in Quantum Field Theory** be expressed in terms of the Lagrangian density. While the United \sim MII α $\mathop{{\sf bo}}\nolimits$ som is Λ Ω Λ Λ Λ Λ Λ Λ Λ $M_A \sim 1$ with $M_A \sim 1$ \overline{a} W⁺ \blacksquare \blacksquare $\zeta \rightarrow 1$ W $\zeta \rightarrow 1$ When $\zeta \rightarrow 0$ W⁺ \sim \sim 40000 μ the discussion of the \sim + + the rising scattering ig cross section of $_{10^0}$ is to a pedagogical introduction to the \mathcal{L} $f = 100$ GEO² 1 f ² –
from Nucl. Phys. B525 (1 $T \sim T$ is described in terms of the Lagrangian of the Lagrangian of the Standard in the Standard Standard in the Standard Standard in the Standard India which ultimately contains all of the fundamental particle physics. In the fundamental particle physics in \mathbb{R} J $\mathbb{F}_{\mathbb{F}_{\mathbb{Z}}^{n}}$ end $\mathbb{F}_{\mathbb{Z}}$ end \sim In an are described by wavefunctions, single particles are described by wavefunctions \sim λ γ /Z H $\begin{array}{ccc} \uparrow & \downarrow & \downarrow & \downarrow \ \uparrow & \downarrow & \downarrow & \downarrow \end{array}$ \mathcal{S}_1 in \mathcal{S}_2 in \mathcal{S}_3 in \mathcal{S}_4 in \mathcal{S}_5 in \mathcal{S}_7 in \mathcal{S}_8 in \mathcal{S}_9 in \mathcal{S}_8 in \mathcal{S}_9 in \mathcal{S}_8 in \mathcal{S}_9 in \mathcal{S}_9 in \mathcal{S}_9 in \mathcal{S}_9 in \mathcal{S}_9 in \mathcal{S}_9 in **17.2.1 Classical felds** !**Fig. ¹⁷.²** Higgs boson exchange diagrams for W+W[−] [→] ^W+W−. $+$ \downarrow^{th} \downarrow^{th} \downarrow^{th} \mathcal{L} we will define \mathcal{L} W- W- W- W- \mathcal{L} $\begin{array}{cccccccccccccc} \mathcal{L} & \mathcal{L} & \mathcal{L} & \mathcal{N} &$ W- W- W- W- $\overline{}$ $longitudinal$ rized W bosons: \mathcal{L} are described by excitations of a satisfies that satisfies that satisfies that satisfies the appropriate that satisfies the appropriate that satisfies the appropriate that satisfies the appropriate the appropriat \sim Such pro **™पहले । स्थित के स्थान के स्थान के प्रसार** !**Fig. ¹⁷.²** Higgs boson exchange diagrams for W+W[−] [→] ^W+W−. ा . 1700 प्रधान के प्रस्तु क प्रस्तु सम्पाद प $\frac{L_{10^{2}}}{200}$ **`** 12² M− 2² J₂² diagrams for W+ γ of a straight method in the dynamics of a \sim In \mathbb{R} and the motion of \mathbb{R} . The description of \mathbb{R} coupling of the coupling of th $\sum_{i=1}^{n}$ \mathbb{F}_q mechanism generation \mathbb{F}_q and \mathbb{F}_q $\frac{1}{2}$ or $\frac{1}{2}$ $\frac{1}{2}$ ູ່ ໄປປັ້ 500 109m \mathcal{L} and \mathcal{L} of \mathcal{L} and \mathcal{L} T_{c} , GeV \rightarrow electronic $W_I W_I \rightarrow W$ necessary for the discussion of the Higgs mechanism. The purpose of this section *L* \sim *T* \sim *T* \sim *Y*, *T* \sim *T* manner that preserves the local gauge invariance of the Standard Model. first time is to provide a pedagogical introduction to the Standard Model, all of the Standard Model, and the fundamental
Which ultimately contains all of the fundamental particle physics. In the fundamental particle physics. In the **17.2 Lagrangians in Quantum Field Theory** H **17.2 Lagrangians in Quantum Field Theory** H from Sull. Pays. B5214 Programs Group Meating $\overline{}$ **17.2 Lagrangians in Quantum Field Theory** W- W- W- W- !**Fig. ¹⁷.²** Higgs boson exchange diagrams for W+W[−] [→] ^W+W−. THE IND WANISM IS DESCRIPTED IN TERMS OF THE LAGRANGIAN OF THE LAGRANGIAN OF THE LAGRANGIAN OF THE STANDARD IS **17.2.1 Classical felds** $\frac{1}{\sqrt{2}}$ are described by wavefunctions are described by wavefunctions are described by $\frac{1}{\sqrt{2}}$ $\frac{\partial u}{\partial x}$ W- W- W- W- 99§029-50 10000 \sqrt{s}/GeV y $/ \mathrm{GeV}$ $CERN$ PB-4 PC-92-025 (1998) 029-5010000 \sqrt{s}/GeV $10000 \quad \sqrt{s}/\text{GeV}$ s \sqrt{s}/GeV

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equations of motion can be obtained from the Lagrangian *L* defined as

The Higgs mechanism generates the masses of the masses of the electroweak gauge bosons in \mathbf{v}

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I In processes involving quartic couplings, the Higgs

 $\sum_{n=1}^{\infty}$

I Such processes became experimentally accessible for the

Searches for New Physics Effects

 \Box No non-SM particles & resonances are discovered at the LHC so far

T If there are any their masses are likely beyond the reach of \Box If there are any, their masses the LHC energy

physics observables as virtual \Box They can still cause measurable effects on some particles

Symmetries / SMEFT

Ad-hoc introduction of new particles and interactions

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Searches for New Physics Effects **Effective Field Theories and Tools**

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- are likely beyond the reach of **Fig. 1.2. The spontanel certain** \bigwedge \Box If there are any, their masses **Effective Effective Effective Effective Figure 1** \mathscr{A}_{S} $\mathfrak{F}_{\mathsf{C}}$
	- physics observables as virtual \square They can still cause measurable effects on some particles \blacksquare \blacks $\begin{bmatrix} 0 & s \ s & s \end{bmatrix}$ es *incaderance*: priyon observe \mathbf{r} subset allows to enforce symmetries symmetries

 \Box Searches for those effects are normally performed in model-independent ways using effective field theory (EFT) frameworks *lingua franca* of extensions of the Standard Model

theory is renormalizable up to the chosen order in

• since all counter terms are already included, the

Searches for New Physics Effects with E 1. Linear realization of the gauge symmetry ASSUMING THAT CLIENCES WILLE **Effective Field Theories and Tools**

 \Box Low energy effective field theory to parameterize new effects with the help of high dimension (n>4) operators \mathcal{A} assuming that the new state observed in \mathcal{A} the help of high dimension (n>4) operators the SM Higgs boson and that it belongs boson and that it belongs to an electroweak \mathcal{L} , effective field theory to parameterize new $ln(1)$ open \mathbf{u} (i.e. \mathbf{v} operators

 \triangleleft Linear realization of the SM $SU(2)_L \otimes U(1)_Y$ gauge symmet scalar doublet, we can construct a low-energy effective n of the SM $\,SU(2)_L\otimes U(1)_Y\,$ gauge symme $\frac{1}{2}$ $U(x)$ σ σ σ σ σ σ σ $\mathcal{L}(t)$ **b** and $\mathcal{L}(t)$

$$
\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{n=5}^{\infty} \sum_{i} \frac{f_i^{(n)}}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}
$$

3.1 The Effective Lagrangian

dimensionless couplings 5 (6)

processes become relevant.

Searches for New Physics Effects with E 1. Linear realization of the gauge symmetry ASSUMING THAT CLIENCES WILLE **Effective Field Theories and Tools**

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Eboli et al., 2020

 \Box Some dimension-6 and 8 operators are interesting in m bosons, Higgs doublets, fermionic fields, and covariant ridious tripic driu quartic gauge cou be anomalous trinle and quartic gauge cour $\frac{d}{d}$ they generate anomalous triple and quartic gauge coup $R_{\rm B}$ \mathbf{S} systematic expansion of \mathbf{S}

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\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{i} \frac{f_i^{(6)}}{\Lambda^2} O_i + \sum_{j} \frac{f_j^{(8)}}{\Lambda^4} O_j + \dots
$$

where \$8*,* ⁹ are the 8*,* 9 dimension-6*,* 8 operators respectively and involve SM fields with respective

It is important to note that the energy scale ⇢ of the considered process must be ⇢ *<* ⇤. However, the important parameters in the expansion are the expansion are the scale α and 5 α and 5 α specific UV complete model, so even for ⇢ *<<* ⇤, simple counting of powers may be misleading. That is, the contribution of dimension-6 (D-6) operators to a given process may be suppressed compared to

may be subleading compared to \mathcal{D}_2 terms. In the case of the two processes studied here, the D-6 \mathcal{D}_3

 \mathbb{R}^n . The natural approach to the SM, making the SM, making the EFT absolute new, short-distance new, short-distance new, short-distance new, short-distance new, short-distance new, short-distance new, short-distan

3.1 The Effective Lagrangian

Searches for New Physics Effects with E 1. Linear realization of the gauge symmetry ASSUMING THAT THE NEW STATE OF THE NEW STATE OF THE NEW STATE IS IN THE NEW STATE OF THE NEW STATE IS IN THE N **Encts with I**

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generate aQGC but not aTGC $\begin{array}{|c|c|c|c|}\hline \mathcal{O}_{M,2} & \mathcal{O}_{M,3} & \mathcal{O}_{M,4} & \mathcal{O}_{M,5} & \multicolumn{2}{|c|}{X} & \multicolumn{2$ are dimension-8 operators $\sqrt{\frac{O_{T,5} \sqrt{O_{T,6} O_{T,7}}}{O_{T,6} O_{T,7}}}$ Q Lowest order operators that $\frac{O_{S,0}, O_{S,1}}{O_{M,0}, O_{M,1}, O_{M,6}, O_{M,7}}$ x 3 **dimensionless couplings 5 (6)** $\sigma_{M,0}, \sigma_{M,1}, \sigma_{M,6}, \sigma_{M,1}, \sigma_{M,6}, \sigma_{M,1}, \sigma_{M,6}, \sigma_{M,1}, \sigma_{M,6}, \sigma_{M,1}, \sigma_{M,1}, \sigma_{M,2}, \sigma_{M,3}, \sigma_{M,4}, \sigma_{M,5}, \sigma_{M,6}, \sigma_{M,7}, \sigma_{M,8}, \sigma_{M,1}, \sigma_{M,1}, \sigma_{M,1}, \sigma_{M,1}, \sigma_{M,2}, \sigma_{M,3}, \sigma_{M,4}, \sigma_{M,5}, \sigma_{M,6$ processes become relevant.

TABLE II: Quartic vertices modified with **X**. the number of gauge-boson strength fields contained in the specific UV complete model, so even for ⇢ *<<* ⇤, simple counting of powers may be misleading. That $\frac{1}{100}$ is, the contribution-6 (D-6) operators to a given process may be suppressed compared to a given process may be suppressed compared to a given process may be suppressed compared to a given process may be suppre

Production of EFT Samples for VBS Measurements **Samples for VBS Measurements** used, extracted from the sample that has been produced with Sherpa 2.2.2. Effective field theories that respect the field α

 \Box EFT "model" for new physics: only dimension-8 operators have non-zero coefficients **↑ (for some reason) the new physics has an effect only on the quartic gauge couplings** rysics. Siny annens \Box EFT "model" for new physics: only dimension-8 operators have non-:

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Studies in W(à**munu)gamma2j Channel A** Amplitude of a VBS final state with EFT contributions: $|A_{SM} + \sum c_i A_i|$, where $c_i = \frac{f_i^{(8)}}{\Lambda^4}$ **a** Amplitude of a vbs final state with EFT contributions: $\frac{|A_{\text{SM}} + \sum_{i} C_i A_i|}{n}$

$$
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\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{i} \frac{f_i^{(6)*} \mathbf{0}}{\Lambda^2} O_i + \sum_{j} \frac{f_j^{(8)}}{\Lambda^4} O_j + \dots
$$

Studies in W(à**munu)gamma2j Channel a** Amplitude of a VBS final state with EFT contributions: $|A_{SM} + \sum c_i A_i|$, where $c_i = \frac{f_i^{(8)}}{\Lambda^4}$ $|A_{\rm SM} +$ $\overline{\nabla}$ i $c_i A_i$, where $c_i = \frac{J_i}{\Lambda^4}$ \overline{i} $\frac{1}{i}$ \Box Amplitude of a VDC final state with FFT contributions: \Box \Box \Box **a** Amplitude of a vbs final state with EFT contributions: $\frac{|A_{\text{SM}} + \sum_{i} C_i A_i|}{n}$

ce quadratic and cross terms of the total squared amplitude te, quadratic and cross terms of the total squared amplitude
———————————————————— $\overline{}$ 282 ⁹2'4(8⇤ ard Model, interference, quadratic and cross terms of t □ Standard Model, interference, quadratic and cross terms of the total squared amplitude

$$
|A_{\rm SM} + \sum_i c_i A_i|^2 = |A_{\rm SM}|^2 + \sum_i c_i 2Re(A_{\rm SM}^* A_i) + \sum_i c_i^2 |A_i|^2 + \sum_{ij, i \neq j} c_i c_j 2Re(A_i A_j^*)
$$

Production of EFT Samples for VBS Measurements **Samples for VBS Measurements** used, extracted from the sample that has been produced with Sherpa 2.2.2. Effective field theories that respect the field α

 \Box EFT "model" for new physics: only dimension-8 operators have non-zero coefficients ◆ (for some reason) the new physics has an effect only on the quartic gauge couplings rysics. Siny annens In the EFT approach, the EFT approach operators are added to the SM Lagrangian and the matrix element of a subp can be determined in the model of the interest of the contribution in the contribu \Box EFT "model" for new physics: only dimension-8 operators have non-: \triangle (for some reason)

$$
\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{i} \frac{f_i^{(6)*} \mathbf{0}}{\Lambda^2} O_i + \sum_{j} \frac{f_j^{(8)}}{\Lambda^4} O_j + \dots
$$

Studies in W(à**munu)gamma2j Channel a** Amplitude of a VBS final state with EFT contributions: $|A_{SM} + \sum c_i A_i|$, where $c_i = \frac{f_i^{(8)}}{\Lambda^4}$ $|A_{\rm SM} +$ $\overline{\nabla}$ i $c_i A_i$, where $c_i = \frac{J_i}{\Lambda^4}$ \overline{i} $\frac{1}{i}$ \Box Amplitude of a VDC final state with FFT contributions: \Box \Box \Box **a** Amplitude of a vbs final state with EFT contributions: $\frac{|A_{\text{SM}} + \sum_{i} C_i A_i|}{n}$

ce quadratic and cross terms of the total squared amplitude the individual D-8 operation of the local squared amplication.

The contribution of the coefficient 28 \pm 2007 \overline{a} $\sqrt{2}$ $\overline{\text{m}}$ cross to erms or the total squared 282 ⁹2'4(8⇤ ard Model, interference, quadratic and cross terms of t □ Standard Model, interference, quadratic and cross terms of the total squared amplitude

$$
|A_{\rm SM} + \sum_i c_i A_i|^2 = |A_{\rm SM}|^2 + \sum_i c_i 2Re(A_{\rm SM}^* A_i) + \sum_i c_i^2 |A_i|^2 + \sum_{ij, i \neq j} c_i c_j 2Re(A_i A_j^*)
$$

University of Würzburg ted u ' g or ly individu re generated using only individual terms at a time re generated asing only individual terms at a th \sim e-Carlo samples are generated using only individual terms at a time between the SM and the EFT operator (interference term), Õ \square Monte-Carlo samples are generated using only individual terms at a time DIMente Carle comples are generated using only individual to research \blacksquare Monte-Carlo samples are generated using only individual terms at a

nonzero values at a time κ_i and c_j (for generation of cross term samples) are set to \mathcal{L} and the SM and the EFT operator (interference term), \mathcal{L} $\mathcal{L}(\mathbf{w},\mathbf{w})$ and $\mathcal{L}(\mathbf{w},\mathbf{w})$ and $\mathcal{L}(\mathbf{w},\mathbf{w})$ and $\mathcal{L}(\mathbf{w},\mathbf{w})$ I_n and I_n (for generation or cross term samples) are set to α or angles as α and α (for congration of cross term samples) are \Box Only one c_i or one pair of c_i and c_j (for generation of cross term samples) are set to σ values using σ and σ \sum only one of or one pair or of and of its openeration or or ooo $\frac{1}{6}$

an be scaled by app i be scaled by appropriate c_i , c_i^2 , or $c_i c_j$ of the analysis included by comparing the full production with the sum of the sum of the sum of the sum of the decomposed by composed by composed by composed by composed by \mathcal{L} Respective sample can be scaled by appropriate c_i , c_i^2 , or $c_i c_j$ \blacktriangledown Respective sample can be scaled by appropriate c_i , c_i , or c_ic_j

 $L = 2L_0$
 $\mathbf{S} = 200$ \div **2015-2018:** $\sqrt{s} = 13$ TeV $0 \ L \geq L_0$, $L_{max} = 2.1L_0$ $L = 2L_0$

\square ATLAS reference frame

✦ Rapidity: $y = 1/2\ln[(E + p_z)/(E - p_z)]$ $\vec{p}_{\text{S}} = \frac{1}{p_{\text{T}}}$

and the missing transverse energy *E*miss

\mathcal{L} and \mathcal{L} angle of the experiment

Discriminator Variables in VBS Measurements *u*¯

\Box VBS event topology

- \dots Two jets with leading transverse momenta in the forward regions
- **Trigger Company and Trigger Company of Large rapidity gap** Δy_{jj} **(Lorentz invariant!)**
	- \circ Large invariant mass m_{ij}
	- **Studies in W(**à**munu)gamma2j Channel** ❖ Vector bosons in a central region
	- \clubsuit No additional jet activity in the gap region

o Ngapjets

Z

W

 γ *u* \longrightarrow \longleftarrow *u* γ

 W^+

 $u \rightarrow \longrightarrow$ d

 W_{\sim}^+

 γ

g g

d

u

 \bar{u}

d

Q Invariant mass of leading jets:
$$
m_{jj} = \sqrt{(p_{j1} + p_{j2})^2}
$$

Q Lepton-photon centrality:
$$
\xi_{l+\gamma} = |y_{l+\gamma} - \frac{y_{j1}+y_{j2}}{2}|/|\Delta y_{jj}|
$$

 \blacklozenge Can be also defined for other objects or combinations of objects $\overline{}$ electron, is and MET reconstructions as well as well as $\overline{}$

 \Box $W^{\pm}W^{\pm}jj$ has the largest ratio of the electroweak to Q among all vector boson scattering (VBS) sensitive $VVjj$

❖ As the QCD leading order diagrams with initial gluons are

 \Box $W^{\pm}W^{\pm}jj$ has the largest ratio of the electroweak to Q among all vector boson scattering (VBS) sensitive $VVjj$ t

❖ As the QCD leading order diagrams with initial gluons are

 \Box Data, signal and background pre-fit event yields in the Signal Region

> **← 2 sub-regions for electron-** $W^{\pm}Zjj$ QCD muon pairs distinguished by the leading- p_T lepton flavour

EW signal purity of 52% vs. Total expected 55 \pm 4 $\overline{\mathbf{a}}$ $\overline{\mathbf{b}}$ 5.4% of QCD background

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 \Box Fiducial cross section = MC fiducial cross section \times fitted singal normalisation

simultaneous profile-likelihood fit to the m_{jj} distributions in the signal region, the low- \mathcal{S}_j control region and the integrated (single bin) QCD $WZjj$ \Box The signal and the main QCD $WZjj$ background normalisations obtained from the m_{jj} control region and the integrated (single bin) QCD $WZjj$ control region

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 \Box Good agreement found for the fiducial cross sections with the SM predictions within the measurement uncertainties

van die van die verwysins van die verw
Verwysings die verwysins van die verwy www.certification.com ✦ Total uncertainty: 9.8% (data statistical: 7.4%, instrumental and theoretical: 6.4%)

 \Box Differential cross sections obtained using the profile-likelihood unfolding method

the individual D-8 operators that contribute to the Lagrangian with a coefficient ²⁸ ⁼ ⁵ (8) Same Sign $\pmb{W}^\pm \pmb{W}^\pm \pmb{j} \pmb{j}$ Measurement

obtain limits on a corresponding c_i (or and c_J in case of two-unnensional
hits) that is a free narameter of the fit \square Simulated and reconstructed EFT samples are fitted to the detector-level m_{ll} distributions in the SR and CRs to $dim\ 1$ c_i and c_j in case of two-dimensional limits) that is a free parameter of the fit

- In Madgraph, one can generate individual samples using only one term at a time (SM, interference, \triangle Only one c_i (or c_i and c_j pair) is taken as non-zero at a time
- $\frac{1}{\sqrt{1-\frac{1$ ← Nominal predictions for the SM signal
← $\frac{1}{\pi}$ assumed. The 1 TeV is assumed. Results for alternative values of the new-physics for and backgrounds are assumed , can be obtained by multiplying the constraints on the D-8 coefficients on the D-8 coefficients by $(«₁)+1/«₁)(…₁)+1/«₁)(…₁)(…₁)(…₁)(…₁)(…₁)(…₁)(…₁)(…₁)(…₁$

$$
|A_{\rm SM}|^2 + \sum_{i} c_i 2Re(A_{\rm SM}^* A_i) + \sum_{i} c_i^2 |A_i|^2 + \sum_{ij, i \neq j} c_i c_j 2Re(A_i A_j^*)
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the individual D-8 operators that contribute to the Lagrangian with a coefficient ²⁸ ⁼ ⁵ (8) Same Sign $\pmb{W}^\pm \pmb{W}^\pm \pmb{j} \pmb{j}$ Measurement

Obtain limits on a corresponding c_i **(or** $\sum_{N=10^4}^{\infty} \frac{1}{10^4} \sqrt{10^4} = \frac{\sqrt{5}}{p_p} = \frac{13 \text{ TeV}}{10^{14}} = \frac{13 \text{ TeV}}{10^{1$ and c_j in ease of two-differential lines. The solution of $\frac{c}{\text{S}}$ of $\frac{1}{\text{S}}$ sm prefit $\frac{1}{\text{S}}$ of $\frac{1}{\text{S}}$ and $\frac{1}{\text{S}}$ and $\frac{1}{\text{S}}$ and $\frac{1}{\text{S}}$ are narameter of the fit $\frac{1}{\text{S}}$ and \square Simulated and reconstructed EFT samples are fitted to the detector-level m_{ll} distributions in the SR and CRs to $\epsilon_{\rm d}^{\rm s}$ $\epsilon_{\rm d}^{\rm s}$ and $\epsilon_{\rm d}^{\rm s}$ c_i and c_j in case of two-dimensional $c_j \stackrel{\text{d}}{\text{if}} \varepsilon_{\text{m} \text{ and } j}$ limits) that is a free parameter of the fit

- $m_{\tilde q}$ the appropriate value $\frac{1}{2}$ as non-zero at a time
- $\frac{1}{\sqrt{1-\frac{1$ and backgrounds are assumed

University of the University the truth particle level and the truth particle level **3.3 The United School and** the unit of the contract of the co with different cut-off scales applied to

Trigger Effects on the *WWWW* coupling

TABLE II: Quartic vertices modified b q **Competitive limits** (@ 95% C.L.) are set on the coefficients of the relevant EFT dimension-8 operators that have large

TABLE II: Quartic vertices modified by each dimension-8 operator are marked with *X*.

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$ZZ(\rightarrow 4l)jj$ Differential Cross Section $\overline{}$, the candidate is defined as the $\overline{}$

\Box Differential cross sections are measured in VBSenhanced ($\zeta < 0.4$) and VBS-suppressed ($\zeta > 0.4$) regions has the largest value of |H✓✓ |. The invariant mass of the four leptons is required to satisfy <4✓ *>* 130 GeV \mathbf{H} is \mathbf{V} to satisfy the signal lepton discussed earlier. event that have [⁹¹ ⇥ [⁹² *<* 0. The dijet system is required to satisfy |H9 9 | *>* 2*.*0 and <9 9 *>* 300 GeV.

***** Three types of observables are measured

- o **VBS observables**
- \circ VBS ODSETVADIES
 \circ Polarisation, charge conjugation and narity observables \circ Polarisation, charge conjugation and parity observables regions using the centrality of the four-lepton system,
	- \circ QCD-sensitive observables

V Both EW and QCD production mechanisms are probed

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	- o QCD-sensitive observables
- **V** Both EW and QCD production mechanisms are probed

 $\frac{1}{\sqrt{1-\frac{1$ opposite-charge lepton pairs strate that \Box Two Z bosons are selected from the same-flavour

- \triangleleft Have smallest $|m_{11} m_{2}|$
- ❖ Are formed from different leptons

Process Event yield \overline{P} jet in the dijet system. The VBS-enhanced (VBS-suppressed) region is defined as Z *<* 0*.*4 (Z *>* 0*.*4).

Vanalysis Group Meeting Meetin strong $4\ell jj$ (Sherpa) *EW 4ℓjj (MG5+Px8)* **Prompt background** *Non-prompt background 3* Total prediction
Data Data 169 53

$ZZ(\rightarrow 4l)jj$ Differential Cross Sections

 \Box Event distributions of the invariant masses of four leptons (left) and two leading jets (right) in the VBS-enhanced signal region

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Eurg

$ZZ(\rightarrow 4l)jj$ Differential Cross Sections

 \Box Iterative Bayesian unfolding is used to measure differential cross sections

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$ZZ (\to 4l) jj$ Differential Cross Sections → All UIL Ditterential Crocc Sections τ at η η bindiction of σ or σ at σ

and limits (@ 95% C.L.) on anomalous $\frac{O_{T,8}, O_{T,9}}{TABLE II: Quartic vertices modified by eq}$ **Studies in America**
Studies in Working Channel Control Channel and Channel C \square EFT samples combined with the SM signal are fitted simultaneously to the unfolded m_{4l} and m_{jj} distributions couplings of dimension-8 operators **couplings** of the SM LAGRANGER COUPLING A TABLE II: Quartic Vertices are obtained **9 Effective field theory interpretation** med (CC DO70 C.L.) ON MIDITIUTOUD $f_{\mathrm{T},i}$

TABLE II: Quartic vertices modified by each dimension-8 operator are marked with *X*.

$ZZ (\to 4l) jj$ Differential Cross Sections → AI)11 Ditterential Crocc Sections τ at η η bindiction of σ at the state value of σ

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efe
e*f***e**
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efe
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e*f***e**
e*f***e**
e*f***e** med (CC DO70 C.L.) ON MIDITIUTOUD $\overline{\nabla}$ $f_{\mathrm{T},i}$

Wilson $|M_{ds}|^2$

TABLE II: Quartic vertices modified by each dimension-8 operator are marked with *X*.

Much stronger limits are set on these three couplings by the same sign WM measurement (see earlier slides)

 \Box Measurement in the high photon transverse momentum phase-space: $E_{T,\gamma} > 150$ GeV

v Enhanced sensitivity to a possible aQGC

***** Tighter threshold values in EFT fits

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❖ Enhanced sensitivity to a possible aQGC

❖ Tighter threshold values in EFT fits

Studies in W(à**munu)gamma2j Channel** \Box Profile-likelihood fit to the Boosted Decision Tree classifier in the SR and m_{jj} distributions in all three CRs

❖ Free signal and two main background normalisations

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$\left| \begin{array}{ll} \hbox{z} & Z (\to \nu \nu) \gamma jj \end{array} \right.$ Measurement and jets at the particle level. These stable final-state particles (with proper decay length 2g *>* 10 mm) are $\frac{1}{R}$ and $\frac{1}{R}$ interactions with the detector. The detector with the veto are reconstructed at the particle level, with a correction for fully recovered final-state radiation for \mathbf{r} \blacksquare \blacksquare \blacktriangle (\rightarrow \blacktriangledown γ) γ) γ) we assurement $\frac{1}{2}$ particle level; however, the detector-level $\frac{1}{2}$

reconstructed in simulation, prior to their interactions with the detector. The leptons used in the veto are

 \Box Observed (expected) significance: **3.2** σ **(3.7** σ **)** reconstructed at the particle level, with a correction for fully recovered final-state radiation applied. No $\begin{bmatrix} \mathbf{a}_{\mathbf{S}_{i}^*} \end{bmatrix}$ \blacksquare Observed (expected) significance: **3.20 (3.70)** The particle-level $\mathcal{L}_{\mathcal{A}}$ is applied to the particle-level $\mathcal{L}_{\mathcal{A}}$ \vec{s} \vec{v} \vec{v} \vec{v} \vec{v} of the dineutrino superficience: **3.2** σ **(3.7** σ **)**

◆ After combination with the ATLAS previous measurement in a low energy phase-space of $15 < E_{T,\gamma} < 115$ GeV: **6.3** σ **(6.6** σ **)** \mathcal{L} \mathbf{a} \bullet ALC (combination with the ALAS previous measurement $L_{T,\gamma}$ corrections and scale uncertainties corrections and scale uncertainties computed with VBFNLO. Its value is value is value in $L_{T,\gamma}$

EXPLEM CHANNEL Predicted and measured fiducial cross sections: fpred / WEWK = 0*.*98 ± 0*.*02 (stat.) ± 0*.*09 (scale) ± 0*.*02 (PDF) fb*.*

 $s_{\rm eff}$

 $\sigma_{Z\gamma\text{EWK}}^{\text{pred}} = 0.98 \pm 0.02 \text{ (stat.)} \pm 0.09 \text{ (scale)} \pm 0.02 \text{ (PDF) fb}$ σ_{Zy} EWK = 0.77^{+0.34} fb = 0.77^{+0.25} (stat.)^{+0.22} (syst.) fb

 \mathcal{S} shows the observed and expected event yields of the signal and backgrounds in the SR and CRS and CRS

 α and BDT classifier response of α and BDT classifier response of α

The breakdown of the impact of groups of groups of systematic uncertainties on the cross-section measurement is

shown in Table 4, with the theoretical uncertainties of the electroweak signal and the /(aa¯)W99 QCD

Table 3 shows the observed and expected event yields of the signal and backgrounds in the SR and CRs

after the fit is performed. The post-fit is performed. The positive α

The breakdown of the impact of groups of groups of systematic uncertainties on the cross-section measurement is

shown in Table 4, with the theoretical uncertainties of the electroweak signal and the /(aa¯)W99 QCD

background having the largest impact.

background having the largest impact.

and the summary plot for all of the regions is shown in Figure 5.

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 δ crmed in the side \square EFT interpretation performed in the signal region $T = 3$ shows the observed and expected and σ the signal and σ and fit is performed. The post-fit is performed. The post-fit is performed. The post-fit is given in Figure 4, $\frac{1}{10}$ \blacksquare Let interpretation performed

Adjusting (tightening) the event selection $E_{T,\gamma}$ and 10^{-1} threshold by optimisation of the expected limits $\frac{1}{2}$ **For the considered dim-8 operators** $\frac{1}{8}$ $\frac{1}{1.5}$ background having the largest input in $\mathsf{f}\mathsf{or}$ the co

background having the largest impact.

Without and with applying an energy

TABLE II: Quartic vertices modified by example and the strengence of the contract of the strength of the \mathbf{C} UII scale to the invariant mass $m\chi\gamma$ **□ Competitive limits (@ 95% C.L.) are** obtained on the coefficients of seven relevant EFT dimension-8 operators cut-off scale to the invariant mass $\bm{m}_{\bm{Z}\bm{\gamma}}$

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Summary

- \Box Measurements of electroweak processes sensitive to vector boson scattering allow to test the gauge interactions of the SM electroweak theory and its symmetry breaking mechanism
- Trigger Activities and the other plant and all **NDC** measurements using λ Are begind results of the electroweak vbs measurements using the run K
dataset of proton-proton collisions collected at $\sqrt{s} = 13$ TeV were reviewed \Box ATLAS public results of the electroweak VBS measurements using the full Run-2
- \Box All presented results are consistent with the Standard Model predictions within the measurement uncertainties
- □ More VBS measurements using the full Run-2 dataset should be available for public this year

Tuesday 05.03., T.38: Standard model 1 (electroweak/bosons)

Thank you!

Content

 \Box Electroweak vector boson self-interactions in the Standard Model ❖ Vector boson scattering (VBS)

The VBS as a probe of the SM electroweak symmetry breaking mechanism

Studies in W(à**munu)gamma2j Channel** \square Searches for anomalous quartic gauge couplings in VBS processes ❖ Effective field theory (EFT) framework

 \Box EWK VBS-sensitive measurements in the ATLAS detector using the full Run-2 dataset

- isai Chicht McGio
Vlantonic ◆ Highlights of the measurement methods and results
	- \circ Same sign *WW j j*, fully leptonic

 \circ -Opposite sign $WWjj,$ fully leptonic

 \circ $ZZ(\rightarrow 4l)jj$ \circ $Z(\rightarrow \nu \nu)$ *yjj* \odot $Z(\rightarrow ll)\gamma H$

 140 fb⁻¹ roton-proton collision data collected at $\sqrt{s} = 13$ TeV

\Box Summary

05/03/2024

 c_5 if c_6

In this work we complement the existing literature on the $\frac{1}{2}$ \mathcal{R} $\sum_{i=1}^n \left[\frac{1}{\sqrt{2}}\right]$ t^{∞} sim K (d Ω of electrons and Ω α \mathbb{Z} $\frac{v_{\text{in}}}{v_{\text{in}}}}$ relevant to derive the most stringent limits in some $\frac{1}{2}$ several operators are considered of $\frac{1}{2}$

 $\frac{1}{2}$ Ω \mathcal{P}_max $\mathcal{O}(\frac{1}{2})$

the relevant operators in both linear and nonlinear realiza-

 $\mathbf{u} \in \mathbb{R}^{n}$ σ , σ \mathbb{Z} s basic expressions of \mathbb{Z}

taking into account all coupled channels and all possible h_{max} and $\overline{h}_{\text{max}}$ M_{\odot} is the M_{\odot} \mathbf{r} $\mathcal{L}(\mathbf{z})$ and $\mathcal{L}(\mathbf{z})$

 $T_{\rm{max}}$ $\mathscr{D} \in \mathbb{C}^{n \times d}$ Λ ^{s let}r \mathcal{Q}_I studies.

 $\frac{1}{2}$ and $\frac{1}{2}$ as well as $\frac{1}{2}$

 1.1

bosons, Higgs doublets, fermionic fields, and covariant

 $A = \frac{1}{2}$ the SM Higgs boson and that it belongs to an electroweak scalar doublet, we can construct a low-energy effective theory where the SUð2Þ^L ⊗ Uð1Þ^Y gauge symmetry is

 \mathcal{S} introduce \mathcal{S} Λ

Here, we introduce the effective interactions considered in this work, as well as the unitarity relations that we use to

Assuming that the new state observed in 2012 is in fact the SM Higgs boson and that it belongs to an electroweak scalar doublet, we can construct a low-energy effective theory where the SUð2Þ^L ⊗ Uð1Þ^Y gauge symmetry is

New Physics Searches - Anomalous Gauge Couplings W FIIYSICS JEDI $\left\| \boldsymbol{\epsilon} \boldsymbol{\epsilon} \right\|$ New Physics Searches α i rivates acuicites \blacksquare **Belling by Prival in Section** $\sum_{n=1}^{\infty}$ bos Anomalous \overline{C} des \overline{C} Anduladuus ϵ Maw Physics Searches — Anomalous Gauge Counlings the QCGG operators that we consider in our analyses, as well a **our studies. Section III contains our results, which are such as a section of the section are such as a sectio**
International contains our results, which are seen in the section of the section of the section of the sectio omalous Gauge $\overline{\mathcal{L}}$

• 종鼻 □ Dimension-8 operators refinement of operators and ^σ^j (^j ^¼ ¹, 2, 3) represent the Pauli matrices. In the second class of genuine QGC, the operators exhibit two covariant derivatives of the Higgs field, as $\frac{1}{2}$ $\frac{1}{2}$ $\$ $\mathbf{F}_{\mathbf{s}}$ and $\mathbf{F}_{\mathbf{s}}$ summetrision of open $\overline{}$ $\mathsf{SDD}\mathsf{P}\mathsf{S}$ operators in the unitarity bounds in the unitarity bounds in

 $\mathcal{O}_{\mathrm{S},2}=[(D_\mu\Phi)^\dagger D_\nu\Phi]\times[(D^\nu\Phi)^\dagger D^\mu\Phi]$ $\mathcal{O}_{S,0} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right]^\dagger$ $\mathcal{O}_{S,1} = \left[(D_{\mu} \Phi)^{\dagger} D^{\mu} \Phi \right] \times \left[(D_{\nu} \Phi)^{\dagger} D^{\nu} \Phi \right]$ $\mathcal{O}_{\varepsilon \rho} = [(D \ \Phi)^{\dagger} D \ \Phi] \times [(D^{\mu} \Phi)^{\dagger} D^{\nu} \Phi]$ $\overline{1}$ $\mathcal{O}_{S,0} = [(\mathcal{D}_{\mu} \Psi) \mathcal{D}_{\nu} \Psi] \wedge [(\mathcal{D} \Psi) \mathcal{D} \Psi]$ $\mathcal{O}_{S,1} = [(D_{\mu} \Phi)^{\dagger} D^{\mu} \Phi] \times [(D_{\nu} \Phi)^{\dagger} D^{\nu} \Phi]$ $\mathcal{O}_{S,2}=[(D_\mu\Phi)^\dagger D_\nu\Phi]\times[(D^\nu\Phi)^\dagger D^\mu\Phi]$ $\mathcal{O}_{S,1} = [(\mathcal{D}_\mu \Phi)^\dagger \mathcal{D}_\mu \Phi] \wedge [(\mathcal{D}_\nu \Phi)$ $U_{S,2} = [(D_{\mu} \Psi)^{\dagger} D_{\nu} \Psi] \times [(D^{\dagger} \Psi)]$ Φ stands for the Φ standards for the covariant of the covarian the multidimensional parameter space of the coefficients of t $(D_{\mu} \Phi)^{\dagger} D_{\nu} \Phi] \times [(D^{\mu} \Phi)^{\dagger} D^{\nu} \Phi]$ $\mathcal{O}_{S,1} = [(D_\mu \Phi)^\dagger D^\mu \Phi] \times [(D_\nu \Phi)^\dagger D^\nu \Phi] \qquad \qquad \qquad D_\mu \Phi = (\partial_\mu + \partial_\mu \Phi)^\dagger D^\mu \Phi \qquad \qquad \qquad$ $\mathcal{O}_{S,2} = [(D_u \Phi)^{\dagger} D_v \Phi] \times [(D^{\nu} \Phi)^{\dagger} D^{\mu} \Phi]$ \mathcal{P} $\left[\left(D, \Phi\right)^{\dagger} D, \Phi\right] \times \left[\left(D / \Phi\right)^{\dagger} D / \Phi\right]$

 $\mathcal{O}_{M,0} = \text{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times [(D_{\beta}\Phi)^{\dagger} D^{\beta}\Phi],$ $\hat{W}_{\mu\nu} \equiv W^j_{\mu\nu} \frac{\sigma^j}{2}$ σ^j (j = 1, 2, 3) $\mathcal{O}_{M,0} = \text{Tr}[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}] \times [(D_{\beta} \Phi)^{\dagger} D^{\beta} \Phi],$ $\hat{W}_{\mu\nu} \equiv W^j_{\mu\nu} \frac{\sigma^j}{2}$ $\mathcal{O}_{M,1} = \text{Tr}[\hat{W}_{\mu\nu} \hat{W}^{\nu\beta}] \times [(D_\beta \Phi)^\dagger D^\mu \Phi],$ $Q_{\text{tot}} = \left[R - R^{\mu\nu}\right] \times \left[(D_{\mu}\Phi)^{\dagger}D^{\beta}\Phi\right]$ $\mathcal{O}_{M,2}=[B_{\mu\nu}B^{\mu\nu}]\times[(D_{\beta}\Phi)^{\dagger}D^{\beta}\Phi],$ $\mathcal{O}_{M,3}=[B_{\mu\nu}B^{\nu\beta}]\times[(D_\beta\Phi)^\dagger D^\mu\Phi],$ $\mathcal{O}_{M,4}$ $\qquad \qquad [\langle \mu \rangle \cap \rho \nu \rangle]$ $\mathcal{O}_{M,5} = [(\mathcal{D} \ \Phi)^{\dagger} \hat{W}_a \ \hat{W}^{\beta \mu} \mathcal{D}^{\nu} \Phi]$ $\sum_{i=1}^{n} \frac{1}{i} \sum_{j=1}^{n} \frac{1}{j} \sum_{j=1}^{n} \frac{1}{j$ $\mathcal{O}_{M,4} = [(D_{\mu} \Phi)^{\dagger} \hat{W}_{\beta\nu} D^{\mu} \Phi] \times B^{\beta\nu},$ $\mathcal{O}_{M,5}=[(D_\mu\Phi)^\dagger\hat{W}_{\beta\nu}D^\nu\Phi]\times B^{\beta\mu}+\text{H.c.},$ $\mathcal{O}_{M,7} = \left[(D_{\mu} \Phi)^{\dagger} \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^{\nu} \Phi \right].$ $\qquad \qquad \mathcal{O}_{S,0}, \mathcal{O}_{S,1}$ $\mathcal{O}_{M,4} = [(\mathcal{O}_\mu \mathcal{I})^{\dagger} \hat{W}_\alpha \mathcal{D}^{\nu} \mathbf{0}] \times \mathcal{R}^{\beta \mu} + \mathbf{H}_\beta$ $U_{M,5} = \left[(D_{\mu} \mathbf{\Psi})^{\dagger} W_{\beta \nu} D^{\dagger} \mathbf{\Psi} \right]$ $\mathcal{L}(\mathcal{C}, \mathcal{F}')$ field strengths: relevant to derive the most stringent limits in some stringent limits in some stringent limits in some stringen $\mathcal{O}_{M,4} = [(\mathcal{D}_{\mu} \Phi)^{\dagger} \hat{W}_{\beta\nu} D^{\nu} \Phi] \times B^{\beta\mu} + \text{H.c.},$ $W_{\mu\nu}$, we $Tr[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}] \times [(D_{\rho}\Phi)^{\dagger}D^{\mu}\Phi].$ $\left[\prod_{\mu\nu}W^{\mu\nu}\right] \times \left[\left(D_{\beta}\Psi\right)^{\nu}D^{\nu}\Psi\right],$ $\mathcal{O}_{M,7} = [(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\nu \Phi].$ $A = Tr[\hat{W} \hat{W}^{\nu\beta}] \times [(D, \Phi)]^{\dagger}$ $\frac{1}{20}$

 $\times B_{\varrho} B^{\nu\alpha}$ $\mathcal{O}_{T,8}=B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta},\qquad \mathcal{O}_{T,9}=B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}.$ $\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \times \text{Tr}[\hat{W}_{\beta\nu} \hat{W}^{\nu\alpha}],$
TABLE II: Quartic vertices modified by each dimension-8 operator are marked with X. $\mathcal{O}_{\bm{\tau},0} = \text{Tr}[\hat{W}...\hat{W}^{\mu\nu}] \times \text{Tr}[\hat{W}_{\mu\rho}\hat{W}^{\alpha\beta}].$ ${\cal O}_{T,1}={\rm Tr}[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times {\rm Tr}[\hat{W}_{\mu\rho}\hat{W}^{\alpha\nu}]$ $\mathcal{O}_{T,3} = \text{Tr}[\hat{W}, \hat{W}^{\mu\beta}] \times \text{Tr}[\hat{W}, \hat{W}^{\nu\alpha}]$ $\mathcal{O}_{T,5} = \text{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times B_{\alpha\beta}B^{\alpha\beta}$ TABLE II: ${\cal O}_{T,6}={\rm Tr}[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times B_{\mu\beta}B^{\alpha\nu},$ \mathcal{O}_{T} 7 = Tr $[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}]$ ${\cal O}_{T,7}={\rm Tr}[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}]\times B_{\beta\nu}B^{\nu\alpha}$ $\mathcal{O}_{T,0}=\text{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}]\times\text{Tr}[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}],$ $\mathcal{O}_{T,1} = \text{Tr}[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}] \times \text{Tr}[\hat{W}_{\mu\rho}\hat{W}^{\nu\alpha}]$ II. ANALYSES FRAMEWORK FRAMEWORK $\mathbf{D}^{u\beta}$ $\mathbf{D}^{u\alpha}$ $\big[\nabla_{\mu\nu}\hat{W}^{\mu\beta}\big] \times \text{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\alpha\nu}]$ \hat{M} ¹ $\partial \alpha$ $\mathcal{O}_{\text{max}} = B B \mu \nu R R R^{\alpha \beta} \qquad \mathcal{O}_{\text{max}} = B B \mu \beta R R R^{\alpha \beta}$ $\mu\nu$ derivatives of these fields. Each operator has a correspondence of these fields. Each operator has a correspondence of $\mu\nu$

 $D_{\mu}\Phi = (\partial_{\mu} + igW_{\mu}^{j}\frac{\sigma^{j}}{2} + ig'B_{\mu}\frac{1}{2})\Phi_{\mu}$ Φ idR^{-1}) Φ $D_\mu \Phi=(\partial_\mu+igW^j_\mu\frac{\sigma^j}{2}+ig^{\prime}B_\mu\frac{1}{2})\Phi^j$

b],
$$
\hat{W}_{\mu\nu} \equiv W_{\mu\nu}^{j} \frac{\sigma^{j}}{2} \qquad \sigma^{j} \ (j = 1, 2, 3)
$$

Assuming that the new state observed in 2012 is in fact the SM Higgs boson and that it belongs to an electroweak OTEN OTEN TRIA NEWSLET WAS ARRESTED FOR A WORK AND THE UPPER STRUCK AND THE UPPER STRUCK AND THE UPPER STRUCK ⁱ ; ð1Þ $05/03/2024$ Assuming that the new state observed in the new state of the new state of the new state of the new state of th
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the SM Higgs boson and that it belongs boson and that it belongs to an electroweak and the leaders to an elect

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 Display *D* PUZUZ4 stands for the Uð1Þ^Y one. 05/03/2024 Gia Khoriauli Studies of Electroweak Interactions via Vector Boson Scattering at the ATLAS Detector DPG2024

 \Box Monte-Carlo signal and background samples

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 \square Event selection signal and control regions

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 \Box Differential cross section messurement with profile-likelihood unfolding

- \triangle Post-fit distributions obtained in the fit of differential cross section as a function of m_{11}
	- \circ Signal from different particle-level m_{II} slices (numbered in brackets) is shown in different shades of blue

A finally sume Sign $W^{\pm}W^{\pm}jj$ **Measurement 7.2 Differential cross section extraction** s_{max}

also a free parameter. No regularisation is applied in the unfolding. Signal events that fail the fiducial

 $\frac{125}{22}$ □ Differential cross sections obtained using the profile-likelihood unfolding method ್ಣಾ_≸ ∟ Differentia

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Same Sign $W^{\pm}W^{\pm}jj$ Measurement me sign $\bm{v} \bm{v} = \bm{v} \bm{v} - \bm{f} \bm{f}$ ivieasurement measured as a function of the number of the number of jets between the two signal jets in rapidity, and the two

 \square Differential cross sections obtained using the profile-likelihood unfolding method

 \Box Search for the doubly charged Higgs boson of the GM (Georgi and Machacek) model

 \Box Excess observed at $m_T = 450$ GeV with the local (global) significance of 3.3 σ (2.5 σ)

 \Box To dimensional scan for limits in the fit with contributions of two different EFT operators to the SM signal

Observation of Opposite Sign W^+W^-j

 \Box ATLAS observed the electroweak VBS W^+W^-jj production in fully leptonic final states

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* Leptons are required to have the second to have the second to have the second to the second the second to the second the second terms of the **Studies in Mayouts** different flavours

 \Box Top quark (mainly the $t\bar{t}$) along with QCD W^+W^-jj production make huge background to the signal

respectively, in contrast with 3% signal contribution \div 66% and 24% contributions to the total (post-fit) event prediction in the inclusive signal region,

 \Box Signal region is split into the exclusive 2- and 3-jet event categories to enhance the sensitivity

 \Box Control region for the top quark background combines defined by requiring one of the two leading jets to be b

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Observation of Opposite Sign W^+W^-jj

- \Box Neural Network (TMVA) is trained separately in the 2- and 3-jet signal regions
	- ◆ Signal, top quark and QCD background events are used in the NN training
- **Trigger Area Controller Controller Intervention Control and 2 signal regions** \Box Profile-likelihood fit method is used to fit simultaneously the signal, top and QCD

SETVED
Studies in the studies of the stu \Box Observed Events Events Data **DEWK W⁺W** jj Data **EWK W⁺W** jj Data **in EWK W⁺W** ij $EWK W^+$ **ATLAS** Preliminary
 \sqrt{s} = 13 TeV, 140 fb⁻¹ **ATLAS** Preliminary
 \sqrt{s} = 13 TeV, 140 fb 10^{5} E_{w} EWK W⁺W jj Top EWK W⁺W jj Top EWK W⁺W jj Top $\sqrt{s} = 13$ TeV, 140 fb⁻ 4 10 (expected) signal Strong W⁺W jj Z+jets Strong W⁺W jj Z+jets Strong W⁺W jj **Z**+jets $10⁴$ Multibosons W+jets Multibosons W+jets Multibosons W+jets Top CR 2 jets SR 3 jets SR ///Uncertaint $\%$ Uncertaint $10⁴$ Uncertainty significance is **7.1** Post-Fit Post-Fit Post-Fit 10^{3} 10^{3} $10³$ **(6.2) TIPIPIPIPIP**IPIPIP 10^{2} 10^{2} **❖ Statistical** 10^{2} gia Khoriaulia (h. 1972).
1905 - Antonio III, politik espainiar espainiar espainiar espainiar espainiar espainiar espainiar espainiar e
1910 - Antonio II, politik espainiar espainiar espainiar espainiar espainiar espainiar uncertainty of the 10 10 10 measured signal University of Würzburg <mark>university of Würzburg und Schweizburg und Schweizburg und Schweizburg und Schweizburg und
University of Würzburg und Schweizburg und Schweizburg und Schweizburg und Schweizburg und Schweizburg und </mark> 1 1 1 Data / Pred. Data / Pred. Data / Pred. normalisation is Pred 1.25 1.25 1.25 Data / **12.3%** with **18.5%** 1 1 1 0.75 0.75 0.75 0.5 0.5 0.5 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 total uncertainty NN output NN output NN output

 \square Signal fiducial cross section is measured to 2. $65^{+0.52}_{-0.48} \, fb$ vs. predicted 2. $20^{+0.14}_{-0.13} \, fb$

 \cdot Fiducial volume defined closely to detector level selection but requiring $m_{jj} > 500$ GeV

Observation of Opposite Sign W^+W^-jj

 \Box Object and event selection for the signal region at the detector level (left) and the definition of the measurement fiducial region at the particle level (right)

EFT Limits on Coefficients of Dimension-8 Operators

 \Box ss $WWjj$ (left) and $ZZjj$ in 4 leptons final state (right)

95% confidence interval $[TeV^{-4}]$

 $[-0.98, 0.93]$ $[-1.00, 0.97]$
 $[-23, 17]$ $[-19, 19]$

 $[-1.2, 1.2]$ $[-1.3, 1.3]$
 $[-160, 120]$ $[-140, 140]$

[-2.5, 2.4] [-2.6, 2.5]
[-74, 56] [-63, 62]

[-2.5, 2.4] [-2.6, 2.5]
[-79, 60] [-68, 67]

[-3.9, 3.9] [-4.1, 4.1]
[-64, 48] [-55, 54]

[-8.5, 8.1] [-8.8, 8.4]
[-260, 200] [-220, 220]

 $[-4.5, 4.5]$ $[-4.7, 4.7]$
 $[7.5, 5.5] \times 10^4$ $[-6.4, 6.3] \times 10^4$

 $[-2.1, 2.1]$ $[-2.2, 2.2]$
 $[-4.6, 3.1] \times 10^4$ $[-3.9, 3.8] \times 1$

 $[-140, 140]$

 $[-3.9, 3.8] \times 10^4$
 $[-4.7, 4.7]$

 $[-23, 17]$

 $[-74, 56]$

 $[-79, 60]$

 $[-64, 48]$

 $[-260, 200]$

 $[-7.5, 5.5] \times 10^4$

EFT Limits on Coefficients of Dimension-8 Operators

\Box ss $WWjj$ (top) and $Z(\nu\nu)\gamma jj$ (bottom)

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in Section 6.

$Z(\rightarrow ll)\gamma jj$ Measurement process measurements. This selection significantly reduces the number of events with the number of \mathbb{R}^n final state in ϵ in the number of ϵ $\mathbf{Z} \subset \mathbf{Z}$ are performed to verify the procedure robustness of the procedure: and injection test with \mathbf{Z} $\frac{d}{dx}$ \mathcal{L} values to check if the use of alternative mass of alternative MC \mathcal{L} predictions for the *QCD-Z*W99 process and data-driven reweighting of the MC templates using the same $\mathcal{S}_{\mathcal{S}}$, which gives: $\mathcal{S}_{\mathcal{S}}$ in Section 6.

통원 □ EW (sensitive to VBS) and extended EW (EW+QCD) production fiducial and differential cross sections are measured in leptonic final states, ee and $\mu\mu$ U VDJ and CALCHUCU EW (EW 'QCD) cial and differential cross sections are $\,$ α udition galacity, of and $\mu\mu$ \overrightarrow{a} and \overrightarrow{a} and differential cross sections are nic final states pp and uu $\sum_{i=1}^{\infty}$ and $\sum_{i=1}^{\infty}$ component includes uncertainties 7BS) and extended EW (EW+QCD) and $\overline{}$ from electrons, photons, muons, jets, flavour tagging and pileup. The "EW mod." component includes interference, component includes merging scale, resummation scale, PDF and QCD scale uncertainties in the *QCD-Z*W99 process.

[◆] The EW measurements employ a control region to \bullet **Solution** Constrain the QCD background
 $\zeta(Z\gamma) = \left| \frac{y_{Z}\gamma - (y_{11} + y_{12})^2}{y_{j_1} - y_{j_2}} \right|$ **THE CONSTRAINE SIGNAL STRENGT SIGNAL STRE** \circ SR: $\zeta(\mathbf{Z}\gamma)$ < 0.4, CR: $\zeta(\mathbf{Z}\gamma)$ > 0.4 $\overline{1}$ $\overline{}$ $\overline{}$ $\overline{}$ $y_{Z\gamma} - (y_{j_1} + y_{j_2})/2$ $y_{j_1} - y_{j_2}$ $S(ZY) \le 0.4$, Cn. $S(ZY) \ge 0.4$ from employ a control region to parton shower, ^PDF and ^PDF and ^{PDF} and ² process. The ^{EW-Z}W99 process. The ¹ $\zeta(Z\gamma) = \frac{|\zeta(Z\gamma)|}{|\zeta(Z\gamma)|}$ $\frac{|\mathbf{v}_{zv} - (\mathbf{v}_{i} + \mathbf{v}_{i})/2|}{|\mathbf{v}_{zv} - (\mathbf{v}_{i} + \mathbf{v}_{i})/2|}$ $f(\mathbf{z} \cdot \mathbf{y}) > 0$ 4 $\begin{bmatrix} s(\mathbf{z} \cdot \mathbf{y}) - 1 & y_{j_1} - y_{j_2} \end{bmatrix}$

 \Box Profile-likelihood fit to m_{jj} distributions in the SR and CR (in case of the EW measurement) is used to extract signal normalisation \rightarrow evaluate fiducial cross sections split into a signal region (SR, Z (/W) *<* 0*.*4) and a QCD control region (CR, Z (/W) *>* 0*.*4) as explained in \mathbb{R} CR (in case of the FW measurement) is used to extract well above 5 standard deviations. The normalisation parameter of the *QCD-Z*W99 background, constrained signal normalisation \rightarrow evaluate fiducial cross sections T T T cross-section of the fiducial phase space, which is the final phase space, which is the final phase space, which includes the final phase space, which is the final phase space, which includes the final phase s **LVV**-THCQ901 CHICHC_p is asculto cation.

* Both EW and extended EW fiducial cross sections are University of Würzburg

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University of Würzburg of Würzburg in a good agreement with the SM predictions the region Z (/W) *<* 0*.*4 is used, referred to as 'Extended SR'. This variable has been chosen to build the \mathbb{R} \bullet \bullet Both EW and extended EW fiducial cross-sections are **Example 2008** in a good agreement with the SM predictions **zended EW-fiducial cross sections are the fiducial strength value o** Therit with the sivi predictions of Madernie with the sum of M $\mathcal{L} = \mathcal{L} = \mathcal{L} = \mathcal{L} \mathcal{L}$ ^f/ W ⁼ ¹⁶*.*8+2*.*⁰ 1*.*⁸ fb*,*

 $\sigma_{EW} = 3.6 \pm 0.5 \text{ fb}$ Fxtended FW $\sigma_{Z\gamma} = 16.8^{+2}_{-1}$ (see Section 3), which gives \mathbb{R} $(m_{jj} > 500 \text{ GeV}) \frac{e^{pred}}{EW} = 3.5 \pm 0.2 \text{ fb}$ EW

 $t_0 = 3.5 \pm 0.2$ fb $(m_{jj} > 150$ GeV $)$ $\sigma_{7}^{pred} = 15.7^{+5.0}_{-2.6}$ fb Extended EW

 $\sigma_{\text{EW}} = 3.6 \pm 0.5 \text{ fb}$ Extended EW $\sigma_{Z\gamma} = 16.8^{+2.0}_{-1.8} \text{ fb}$ $(m_{jj} > 150 \text{ GeV})$ $\sigma_{Z\gamma}^{pred} = 15.7^{+5.0}_{-2.6} \text{ fb}$

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The maintain source of the cross-section of the cross-section of the contract of the CNA Table 3: The breakdown of the Bown of the systematic uncertainties in the lowest bin of the systematic uncertainties in the systematic uncertainties in the lowest bin of the Background Table 3: The SW9 cross-sections. The **5 Background estimation estimation estimation estimation estimation estimation estimation estimation estimatio** ◆ Unfolded observables are in a good agreement with SM The Differential cross sections are measured using profile-likelihood uncertainties in the profile-likelihood using the profile-likelihood using the profile-likelihood using the Differential cross sections are measured usi (EW contribution) and Sherpa 2.2.11 (QCD contribution): $\frac{1}{\sqrt{2}}$ sections are measured using profile-il The prediction is observed in the lowest hin of the procedure described in the ϵ **Section 6. Uncertated are treated as uncorrelated as uncorrelated between the** *CDD-ZU***
Intributional cross-structures 3, 2009 and** *QCD-ZW99 contributions***.** Section 6. Uncertainties are treated as uncorrelated between the *EW-Z*W99 and *QCD-Z*W99 contributions.

from electrons, photons, muons, jets, flavour tagging and pileup. The "EW mod." component includes interference,

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Component includes uncertainties uncertainties of Electroweak Interactions via Vector Boson Scattering and and
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