Multi-Boson interactions 2019

Summary Talk

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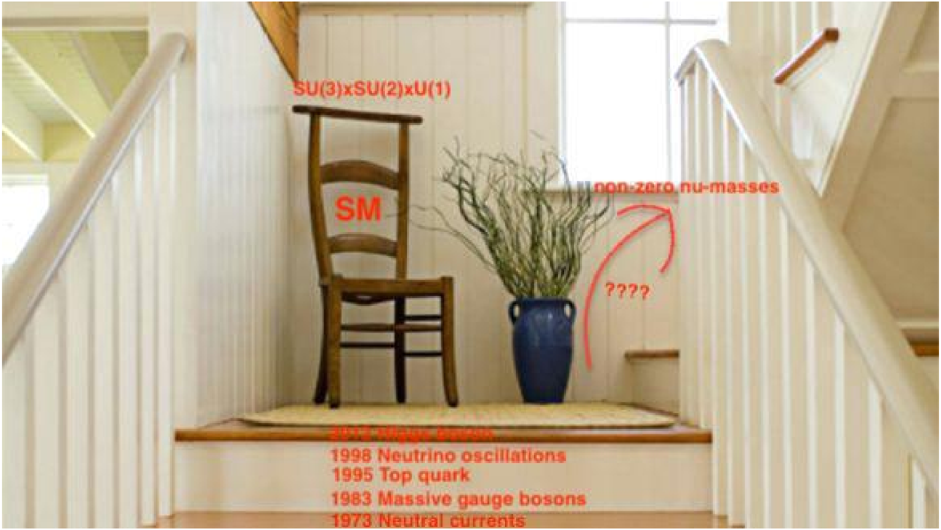
MBI 2019, Thessaloniki, Greece

Outline

Outline

Personal view of the current SM state...



EW gauge boson interactions

Multi-boson interactions probe the non-abelian local symmetry of the gauge sector.

In the SM there two triple,

$$W^+W^-\gamma\,,\;W^+W^-Z$$

and four quartic,

$$W^+W^-\gamma\gamma\,,\;W^+W^-Z\gamma\,,\;W^+W^-ZZ\,,\;W^+W^-W^+W^-$$

gauge boson vertices. No pure "neutral particle" vertices exist at tree level.

$D \leq 4$ and Gauge Invariance $\rightarrow$ 2 SM Parameters: $\{g', g\}$ OR $\{e, \sin\theta_W\}$

Anomalous Triple Gauge Couplings (aTGCs)

Historically[1], aTGCs parametrized by a general Lorentz invariant Lagrangian

$$
\begin{aligned}
\frac{\mathcal{L}_{WWV}}{g_{WWV}} &= i g_1^V \left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu} \right) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} \\
&+ \frac{i\lambda_V}{m_W^2} W^\dagger_{\rho\mu} W^\mu{}_\nu V^{\nu\rho} - g_4^V W^\dagger_\mu W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \\
&+ g_5^V \epsilon^{\mu\nu\rho\sigma} (W^\dagger_\mu \overleftrightarrow{\partial}_\rho W_\nu) V_\sigma + i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} \\
&+ \frac{i\tilde{\lambda}_V}{m_W^2} W^\dagger_{\rho\mu} W^\mu{}_\nu \tilde{V}^{\nu\rho}
\end{aligned}
$$

[1] K. Hagiwara, R. D. Peccei, D. Zeppenfeld and K. Hikasa, Nucl. Phys. B **282** (1987) 253.

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&+ g_5^V \epsilon^{\mu\nu\rho\sigma} (W^{\dagger}_{\mu} \overleftrightarrow{\partial}_{\rho} W_{\nu}) V_{\sigma} + i\tilde{\kappa}_V W^{\dagger}_{\mu} W_{\nu} \tilde{V}^{\mu\nu} \\
&+ \frac{i\tilde{\lambda}_V}{m_W^2} W^{\dagger}_{\rho\mu} W^{\mu}{}_{\nu} \tilde{V}^{\nu\rho}
\end{aligned}$$

where

$V = V^{\dagger} = Z, \gamma$, $V_{\mu\nu} = \partial_{\mu} V_{\nu} - \partial_{\nu} V_{\mu}$, $\tilde{V}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} V^{\rho\sigma}$. $W^{\mu} \equiv W^{\mu -}$ and $W_{\mu\nu} = \partial_{\mu} W_{\nu} - \partial_{\nu} W_{\mu}$

$\lambda_V, \tilde{\lambda}_V$ are dimension-6 operator couplings

$2 \times 7 = 14$ parameters

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Some terms in this parametrization explicitly break gauge invariance that we know it is valid from LEP.

Anomalous Triple Gauge Couplings (aTGCs)

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&+ \frac{i\tilde{\lambda}_V}{m_W^2} W^\dagger_{\rho\mu} W^\mu{}_\nu \tilde{V}^{\nu\rho}
\end{aligned}
$$

Better formulated as deviations from SM TGCs

SM tree level: $g_1^V = \kappa_V = 1\ ,\ \lambda_V = \tilde{\lambda}_V = g_4^V = g_5^V = \tilde{\kappa}_V = 0$

$$g_{WW\gamma} = e\ ,\ g_{WWZ} = e \cot\theta_W$$

GBET and Unitarity

Goldstone Boson Equivalence Theorem (GBET)[1]

At High Energies (HE) relative to the W-mass, massive gauge bosons $W^{\pm}, Z$ can be replaced by the corresponding Goldstone Bosons $G^{\pm}, G^{0}$ in scattering processes.

$$S[W_L^{\pm},\ \text{physical}] = i^n \times S[G^{\pm},\ \text{physical}]$$

Dynamics of V_Ls is directly linked to GBET and $SU(2)_L \times U(1)_Y$ invariance restoration at HE.

[1] M. S. Chanowitz and M. K. Gaillard, Nucl. Phys. B **261** (1985) 379;
G. J. Gounaris, R. Kogerler and H. Neufeld, Phys. Rev. D **34** (1986) 3257.

GBET and Unitarity

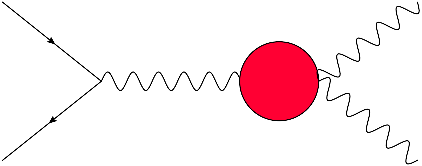
Tree Level Unitarity[1]

" the N-particle S-matrix elements in the tree approximation must grow no more rapidly than E^{4-N} in the limit of HE, at fixed non-zero angles "

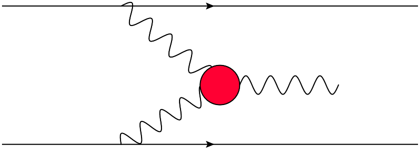
In the SM all multi Goldstone Boson interactions do not contain momenta and therefore leading s-behaviour cancels against s, t and u exchanges of vector and Higgs-boson mediated amplitudes.

[1] J. M. Cornwall, D. N. Levin and G. Tiktopoulos, Phys. Rev. D **10**, 1145 (1974); B. W. Lee, C. Quigg and H. B. Thacker, Phys. Rev. D **16**, 1519 (1977); C. E. Vayonakis, Lett. Nuovo Cim. **17**, 383 (1976).

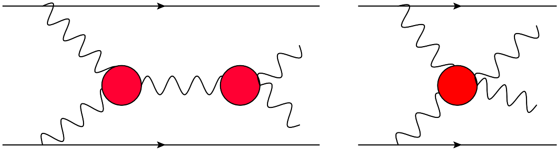
Processes



Diboson Production



Vector Boson Fusion (VBF)



Vector Boson Scattering (VBS)

Diboson Production

- Experimental uncertainties have been surpassed the 10% uncertainty so we have to go to few present theoretically.
- All NNLO QCD corrections have been completed! They are included in a code (MATRIX+OneLoops)[2]
- Excellent agreement between NNLO and data
- NNLO QCD + NLO EW corrections[3] giant K-factors in observables for ZZ, WW, WZ
- At HE, NLO EW/LO = -40% - 50%.
- One must set jet-veto at high-s since the process is driven away from aTGC searches

[2] Review talk by Marius Wiesemann
[3] Review talk by Jonas Lindert

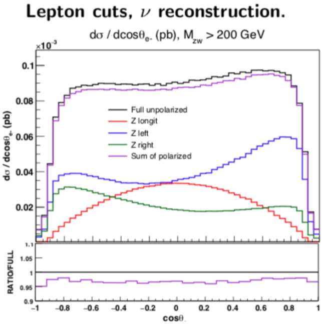
VBF and VBS

- $pp \to e^+ \nu_e \mu^+ \mu^- jj$ at NLO EW/QCD corrections for $W^+ Z$ scattering at the LHC: corrections of order $O(\alpha_s \alpha^6)$ and $O(\alpha^7)$ the latter being large $\sim -17.5\%$ especially at high p_{Tj} (Sudakov enhancement)[4]
- Progress in QCD effects in borderline between perturbative and non-perturbative regime dictated by the factorization theorem discussed[5]

[4] Talk by Christopher Schwan
[5] Talk by Simon Plaetzer

Polarization

- Important to provide accurate theory predictions for polarized VBS for LHC analyses
- A nice formula but assumes no lepton cuts so interference effects vanish[6]



[6] Talk by Giovanni Pellicciolli

EFTs

Systematic deviations from the SM can be studied effectively within EFT as long as the scale of New Physics, Λ, is $\Lambda^2 >> M_W^2$ **and** $s = (p_1 + p_2)^2$.

A particularly interesting EFT scenario is SMEFT.

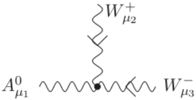
SMEFT: Assuming there is nothing but the SM below, say $\Lambda \sim 1$ TeV, and the Higgs field belongs to the SU(2)-doublet, SM is augmented with high dimensional gauge invariant operators

"Warsaw basis"[7] is a non-redundant basis. The complete set of Feynman Rules have been completed for $d \leq 6$ operators in Unitary and R_ξ-gauges.[8]

`SmeftFR` code[9] generates FRs and interfaces them to `UFO` and `FeynArts` for various event generator and symbolic calculations.

[7] B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, arXiv:1008.4884
[8] AD, W. Materkowska, M. Paraskevas, J. Rosiek and K. Suxho, arXiv:1704.03888
[9] AD, M. Paraskevas, J. Rosiek, K. Suxho and L. Trifyllis, arXiv:1904.03204.

$\gamma W^+ W^-$ in SMEFT with $d \leq 6$ operators



$$
\begin{aligned}
&+\frac{i\bar{g}\bar{g}'}{\sqrt{\bar{g}^2+\bar{g}'^2}}\left(\eta_{\mu_1\mu_2}(p_1-p_2)^{\mu_3}+\eta_{\mu_2\mu_3}(p_2-p_3)^{\mu_1}+\eta_{\mu_3\mu_1}(p_3-p_1)^{\mu_2}\right)\\
&-\frac{6i\bar{g}'}{\sqrt{\bar{g}^2+\bar{g}'^2}}C^{W}\left(p_3^{\mu_1}p_1^{\mu_2}p_2^{\mu_3}-p_2^{\mu_1}p_3^{\mu_2}p_1^{\mu_3}+\eta_{\mu_1\mu_2}\left(p_1^{\mu_3}p_2\cdot p_3-p_2^{\mu_3}p_1\cdot p_3\right)\right.\\
&\left.+\eta_{\mu_2\mu_3}\left(p_2^{\mu_1}p_1\cdot p_3-p_3^{\mu_1}p_1\cdot p_2\right)+\eta_{\mu_3\mu_1}\left(p_3^{\mu_2}p_1\cdot p_2-p_1^{\mu_2}p_2\cdot p_3\right)\right)\\
&+\frac{i\bar{g}^2v^2}{\left(\bar{g}^2+\bar{g}'^2\right)^{3/2}}C^{\varphi WB}\left(\eta_{\mu_1\mu_2}(\bar{g}^2p_1^{\mu_3}+\bar{g}'^2p_2^{\mu_3})+\eta_{\mu_2\mu_3}(\bar{g}'^2p_3^{\mu_1}-\bar{g}'^2p_2^{\mu_1})\right.\\
&\left.+\eta_{\mu_3\mu_1}(-\bar{g}'^2p_3^{\mu_2}-\bar{g}^2p_1^{\mu_2})\right)\\
&-\frac{2i\bar{g}'}{\sqrt{\bar{g}^2+\bar{g}'^2}}C^{\widetilde{W}}\left(\epsilon_{\mu_1\mu_2\mu_3\alpha_1}\left(p_1^{\alpha_1}p_2\cdot p_3+p_2^{\alpha_1}p_1\cdot p_3+p_3^{\alpha_1}p_1\cdot p_2\right)\right.\\
&+\epsilon_{\mu_1\mu_2\alpha_1\beta_1}(p_1-p_2)^{\mu_3}p_1^{\alpha_1}p_2^{\beta_1}+\epsilon_{\mu_2\mu_3\alpha_1\beta_1}(p_2-p_3)^{\mu_1}p_2^{\alpha_1}p_3^{\beta_1}\\
&\left.+\epsilon_{\mu_3\mu_1\alpha_1\beta_1}(p_3-p_1)^{\mu_2}p_3^{\alpha_1}p_1^{\beta_1}\right)\\
&+\frac{i\bar{g}^2v^2}{\sqrt{\bar{g}^2+\bar{g}'^2}}C^{\varphi\widetilde{W}B}\epsilon_{\mu_1\mu_2\mu_3\alpha_1}p_1^{\alpha_1}
\end{aligned}
$$

"Triboson" parameters in EFT with $d \leq 6$ operators:
CP-invariant parameters : 5 new - 2 constraints = 3
CP-violating parameters = 2

One should be very careful with EFTs !

- $s, M_W^2 << \Lambda^2$ – otherwise using EFT is nonsense!
- Bounds on Wilson coefficients are given in particular operator basis (e.g. Warsaw, SILH, etc)
- Bounds on Wilson coefficients should be given in a particular input scheme e.g. one has to trade $\bar{g}, \bar{g}', v$ with measurable quantities like for example[10]
  - $\{\alpha_{em}, m_Z, G_F, m_h, m_t, ...\}$-scheme
  - $\{m_W, m_Z, G_F, m_h, m_t, ...\}$-scheme
  - ....

[10] I. Brivio and M. Trott, arXiv:1701.06424

SMEFT@NLO

- The S-matrix must be renormalization scale independent (up to a fixed order in loop and EFT expansion.
- in SMEFT one has to include running from all operators so that the result is gauge invariant
- Overview of NLO calculations in SMEFT[11]. Several observable studies fully at 1-loop in SMEFT.
- A first step towards SMEFT@NLO QCD has been done. NLO EW fully automated?

[11] Review talk by Cen Zhang

Non-linear EFT

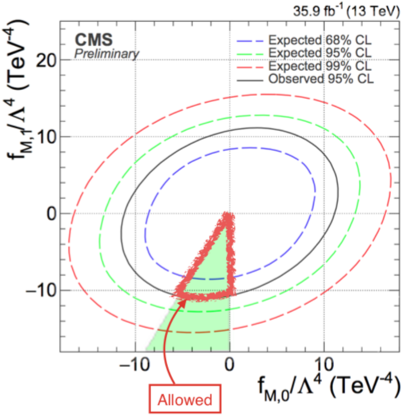
- Non Linear EFT[12] : the Higgs field does not reside in the $SU(2)_L$ doublet
- EFT is now more involved. $d = 8$ operators are promoted to $d = 6$ operators that reach easily unitarity bound, $|a_J(s)| = 1.$, because for example VBS amplitudes grow with $A \sim s^2$
- There must be a cut-off at scales much before the typical Λ^2: there are unitarization suggestions

My opinion: a prototype model (if it exists) could be used as a benchmark to be used in experimental studies

[12] Talk by Rafael Lopez Delgado

Positivity constraints: In every QFT based on analyticity, unitarity, Lorentz invariance there are certain bounds on certain linear combinations of $d=8$ operators in SMEFT[13]

$$\sum_i C_i^{(8)} x_i \geq 0$$



[13] Talk by Cen Zhang

BSM Models and EFTs[14]

- SMEFT at HE: there are 4 parameters that grow with $\sigma \sim s$ in diboson processes. Observables are WW, WZ, HW, HZ. Possible to probe "weak coupling regime" where g_*^2/M^2 with $g^* \sim g \lesssim 0.1\%$.
- Currently we are probing the strong coupling regime $g_* \sim (4\pi)$ in diboson searches.
- A composite model related to TGCs presented.
- One way to compete with LEP precision is by going to HE and study ZH production. Due to GBET we have a contact term that dominates the amplitude far from resonances.[15]

[14] Review talk by Marc Montull
[15] Talk by Sandeepan Gupta

Outline

1 Theory

2 Experimental Searches
- Diboson Production
- VBF and VBS
- Polarization

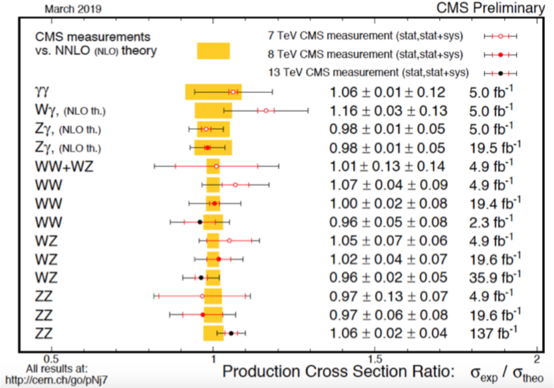
3 Constraints on aTGCs

4 Constraints on aQGCs

5 Future sensitivity

6 Epilogue

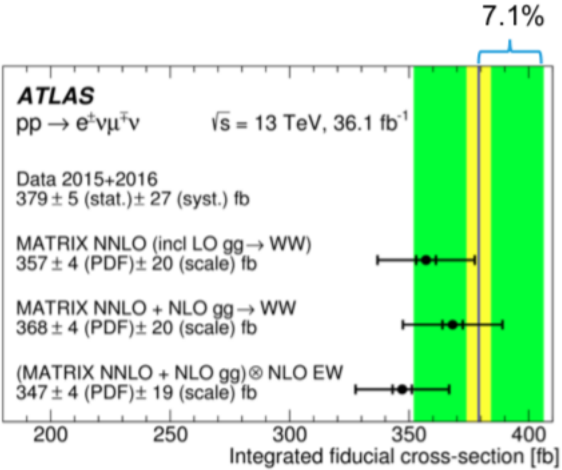
CMS $\mathcal{L} = 137 fb^{-1}$ (partly Run-II data included) total and differential Xsections. Report [16]on WW, WZ, ZZ leptonic final states as well as on



Precision of 5% reached.

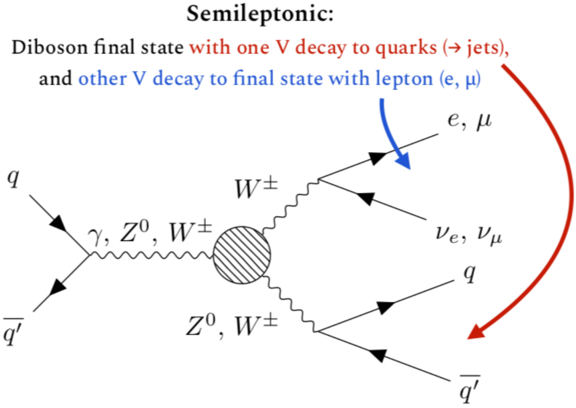
[16]Talk by Alicia Calderon

ATLAS fiducial and diff Xsections Reports on WW and ZZ[16]



[16] Talk by Valerie Lang

Measurement of Diboson production in semileptonic decay modes and anomalous Couplings[17]



[17] Review talk of ATLAS and CMS results by Robin Cameron Aggleton

Measurement of Diboson production in semileptonic decay modes and anomalous Couplings[17]

Direct Searches for NP in diboson searches: limits on KK gravitons, V' and W' masses ≥ 1.5 TeV.[18]

[17] Review talk of ATLAS and CMS results by Robin Cameron Aggleton
[18] Talk by Antonis Agapitos

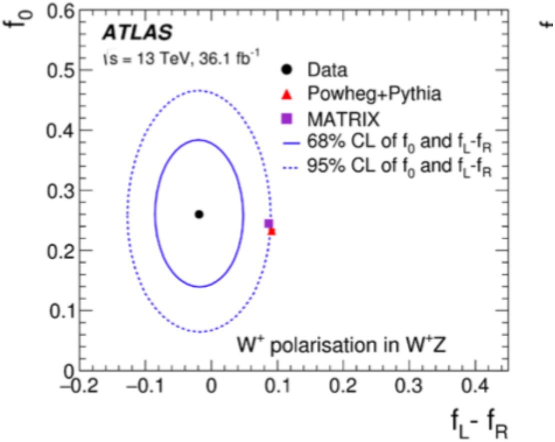
- $ssWWjj$, $WZjj$ and $ZZjj$ at $\sqrt{s} = 13$ TeV seem to have been observed at ATLAS
- Also photons in the final state[19]: $Z\gamma jj$ (strong evidence for both ATLAS and CMS) or $\gamma\gamma jj$ (observation in heavy ions by ATLAS)
- Higgs VBF and Z/W VBF presented[20]. The former agrees with the SM while the latter are dominated by systematics.
- Jet-veto technics based on event-by-event selection may help in VBF/VBS signal/background in SM and BSM searches[21]

[19] Talk by Narei Lorenzo Martinez
[20] Talk by Dag Gillberg
[21] Talk by Richard Ruiz

Polarization

Probing GBET directly. ATLAS search for WZ channel[22]

- F0 is measured different from 0 at more than 3 sigma and in agreement with predictions
- FL-FR at 2 σ from predictions in W⁺



[22] Talk by Corinne Goy

Outline

Dibosons

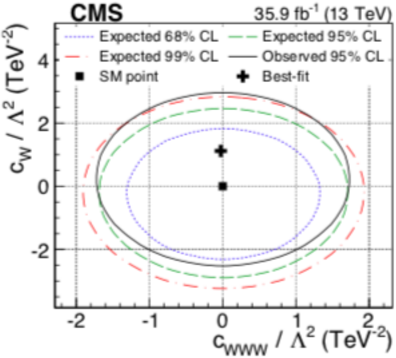
CMS at 13 TeV (1D and 2D limits). Semileptonic final state.[23]. Big improvements w.r.t 8 TeV results

Parametrization	aTGC	Expected limit	Observed limit	Observed best-fit	CMS 8 TeV observed limit
EFT	c_{WWW}/Λ^2 (TeV^{-2})	[-1.44, 1.47]	[-1.58, 1.59]	-0.26	[-2.7, 2.7]
	c_W/Λ^2 (TeV^{-2})	[-2.45, 2.08]	[-2.00, 2.65]	1.21	[-2.0, 5.7]
	c_B/Λ^2 (TeV^{-2})	[-8.38, 8.06]	[-8.78, 8.54]	1.07	[-14, 17]
LEP	λ_Z	[-0.0060, 0.0061]	[-0.0065, 0.0066]	-0.0010	[-0.011, 0.011]
	Δg_1^Z	[-0.0070, 0.0061]	[-0.0061, 0.0074]	0.0027	[-0.009, 0.024]
	$\Delta\kappa_Z$	[-0.0074, 0.0078]	[-0.0079, 0.0082]	-0.0010	[-0.018, 0.013]

[23]Talk by Robin Cameron Aggleton

Dibosons

CMS at 13 TeV (1D and 2D limits). Semileptonic final state.[23]. Big improvements w.r.t 8 TeV results

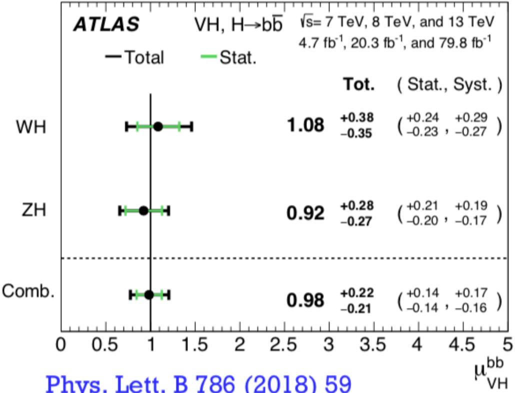


[23]Talk by Robin Cameron Aggleton

VH and HH

$V(\ell\ell)H(\bar{b}b)$ has been observed[24]. HH is currently being searched for.

At High p_T is an interesting probe for NP (see theory talks on EFTs)



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[24] Talk by Stephane Cooperstein

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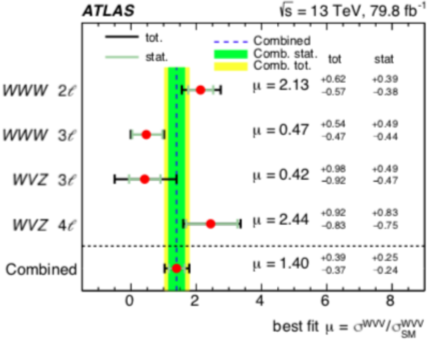
[24] Talk by Stephane Cooperstein

Triboson Production

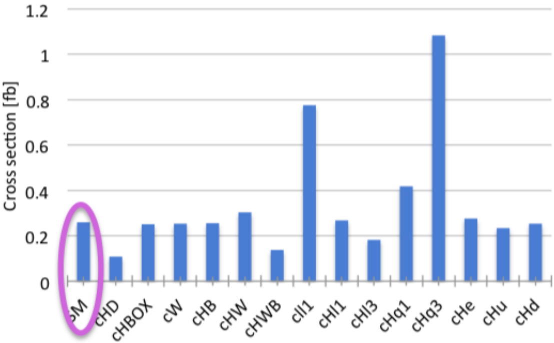
There is evidence for triboson production at ATLAS[25].



Triboson searches are under investigation also at CMS.[26]

[25] Talk by Andrea Sciandra
[26] Talk by Miaoyuan Liu

Effects on VBS Xsection from SMEFT parameters (Warsaw basis) in WZ production[27]



[27] Talk by Despoina Sampsonidou

Outline

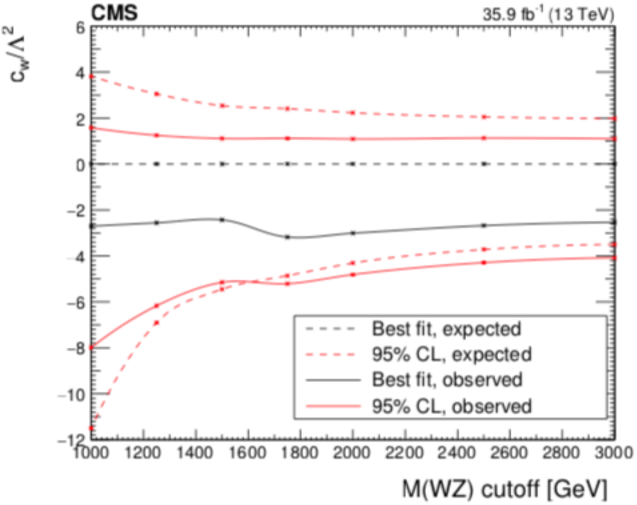
Limits on $d = 8$ Wilson coefficients in VBS (CMS, EWK VV production, semileptonic mode)[28]

	Obs Low	Obs High	Exp Low	Exp High
$F_{S,0}$	−2.7	2.7	-4.2	4.2
$F_{S,1}$	-3.4	3.4	-5.2	5.2
$F_{M,0}$	−0.69	0.70	-1.0	1.0
$F_{M,1}$	-2.0	-2.1	-3.0	3.0
$F_{M,6}$	-1.3	1.3	-1.4	1.4
$F_{M,7}$	-3.4	3.4	-5.1	5.1
$F_{T,0}$	-0.12	0.11	-0.17	0.16
$F_{T,1}$	-0.12	0.13	-0.18	0.18
$F_{T,2}$	-0.28	0.28	-0.41	0.41

Bounds on F/Λ^4 are in TeV^{-4} units. These are the best limits so far.

[28] Talk by Andrew Levin

The plot created most discussions![29]



[29] Talk by Hannes Mildner

Outline

- Polarization in VBS at HL-LHC : projective evidence for LL at few σs per experiment but for the $VV \to V_L V_L$
- But, using machine learning techniques ATLAS+CMS at $3000 fb^{-1}$ each may reach 5σ for ssWW and VBS ZZ scattering[30]
- HH prospects ....[31]

[30] Talk by Meng Lu
[31] Talk by Stephane Cooperstein

Outline

Epilogue

- We had a constructive and focused meeting, a "real" gathering of both experimenters and theorists
- We learnt about cutting edge techniques and results in multi-boson interactions

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Many thanks to the organizers, Chara, Spyros, Dimos and Kostas !!