

# A sensitivity study of VBS and diboson WW to dimension-6 EFT operators at the LHC

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## Presentation on a LHE study, probing the **sensitivity of VBS measurements to constrain dimension-6 EFT operators** and their interplay with diboson $W^+W^-$ :

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<https://arxiv.org/pdf/2108.03199v2.pdf>

### Index:

- ▶ Introduction
- ▶ The processes
- ▶ Analysis strategy
- ▶ Results

A sensitivity study of VBS and diboson WW to dimension-6 EFT operators at the LHC

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# Theory Introduction

SM tested with unprecedented accuracy with LHC Run II statistics. **Recent evidence for tensions...**

There are known SM shortcomings → the SM is thought to be a low level manifestation of a UV-complete theory at large scale.

## EFT interpretation can shed light on NP

### SMEFT

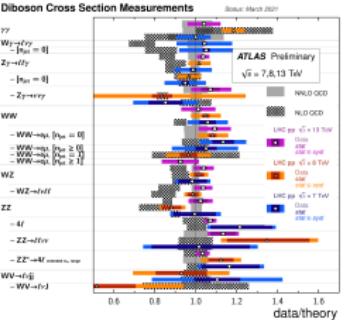
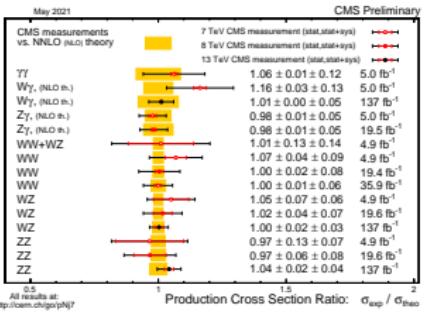
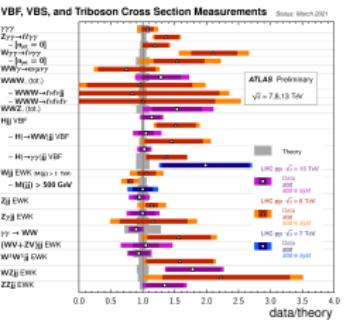
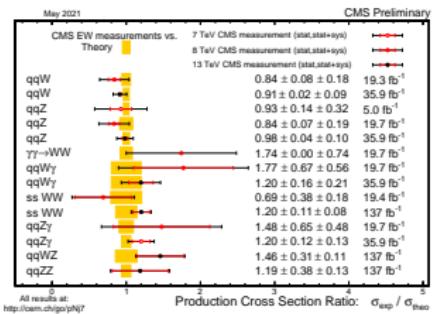
- ▶ Built upon SM fields
- ▶  $SU(3)_C \times SU(2)_L \times U(1)_Y$  invariant
- ▶ Higgs-like in  $SU(2)$  doublet. Linear realization of EWSB
- ▶ Describe ∼ all UV-complete theories

Neglecting B/L violating dim-5 and dim-7 operators

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)} + \frac{c_i}{\Lambda^4} O_i^{(8)} + \dots$$

Λ unknown NP energy scale

# Experimental Overview



## VBS

- $L \sim 137 \text{ fb}^{-1}$  allows new measurements.
  - Statistically dominated.
  - BSM in aQGC or EFT dim-8.
  - dim-6 can be important (and should be considered)
- [ arXiv:1809.04189 ]

## Diboson

- Well known processes.
- High cross-section, syst. dominated.
- BSM in aTGC or EFT dim-6.
- Limited operators studied.

The case for a LHE study:

- ▶ LHC **VBS** results usually interpreted in terms of dim-8 operators. But **dim-6** should be considered
- ▶ Global EFT fit will be needed, **combination is key**: **top** + **Higgs** + **EW** + **non-LHC (LEP, Tevatron,...)**, ... . What's the sensitivity reach / interplay of VBS and WW?
- ▶ **Ranking of common observables** based on the operator-by-operator sensitivity
- ▶ A study of the **impact of  $\Lambda^{-4}$**  dim-6 terms
- ▶ Analysis of the **EFT contributions from the major background**
- ▶ First exercise with a **new statistical model for EFT fits** and combinations within CMS.

# SMEFT Monte Carlo Generations

15 dim-6 SMEFT operators with various field content from [Warsaw basis](#)  
[\[arXiv:1008.4884v3\]](#).

$U(3)^5$  flavour symmetry,  $\{m_W, m_Z, G_F\}$  input scheme, CP-even,  $\Lambda = 1 \text{ TeV}$ .

ψΦ2D	$Q_{Hl}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_p)$	$Q_{Hl}^{(3)} = (H^\dagger i\overleftrightarrow{D}_\mu^3 H)(\bar{l}_p \sigma^i \gamma^\mu l_p)$
	$Q_{Hq}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_p)$	$Q_{Hq}^{(3)} = (H^\dagger i\overleftrightarrow{D}_\mu^3 H)(\bar{q}_p \sigma^i \gamma^\mu q_p)$
(LL)(LL)	$Q_{ll} = (\bar{l}_p \gamma_\mu l_p)(\bar{l}_r \gamma^\mu l_r)$	$Q_{ll}^{(1)} = (\bar{l}_p \gamma_\mu l_r)(\bar{l}_r \gamma^\mu l_p)$
	$Q_{qq}^{(1)} = (\bar{q}_p \gamma_\mu q_p)(\bar{q}_r \gamma^\mu q_r)$	$Q_{qq}^{(1,1)} = (\bar{q}_p \gamma_\mu q_r)(\bar{q}_r \gamma^\mu q_p)$
	$Q_{qq}^{(3)} = (\bar{q}_p \gamma_\mu \sigma^i q_p)(\bar{q}_r \gamma^\mu \sigma^i q_r)$	$Q_{qq}^{(3,1)} = (\bar{q}_p \gamma_\mu \sigma^i q_r)(\bar{q}_r \gamma^\mu \sigma^i q_p)$
Φ6, Φ4D2	$Q_{HD} = (H^\dagger D_\mu H)(H^\dagger D^\mu H)$	$Q_{H\square} = (H^\dagger H) \square (H^\dagger H)$
XΦ2	$Q_{HWB} = (H^\dagger \sigma^i H) W_{\mu\nu}^i B^{\mu\nu}$	$Q_{HW} = (H^\dagger H) W_{\mu\nu}^i W^{\mu\nu}$
X3	$Q_W = \epsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$	

Generated at LO with SMEFTsim  
[\[arXiv: 2012.11343\]](#) interfaced with  
 MadGraph5\_aMC@NLO (2.6.5).  
 Insertion of one operator per diagram  
 in production or decay.

$$N \propto \overbrace{|\mathcal{A}_{SM}|^2}^{\text{SM}} + \sum_{\alpha} \frac{c_{\alpha}}{\Lambda^2} \cdot \underbrace{2 \operatorname{Re}(\mathcal{A}_{SM} \mathcal{A}_{Q_{\alpha}}^{\dagger})}_{\text{Lin}} + \frac{c_{\alpha}^2}{\Lambda^4} \cdot \overbrace{|\mathcal{A}_{Q_{\alpha}}|^2}^{\text{Quad}} + \sum_{\alpha, \beta} \frac{c_{\alpha} c_{\beta}}{\Lambda^4} \cdot \underbrace{\operatorname{Re}(\mathcal{A}_{Q_{\alpha}} \mathcal{A}_{Q_{\beta}}^{\dagger})}_{\text{Mix}}$$

Two complementary approaches employed:

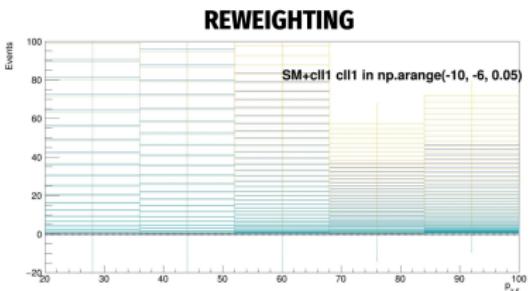
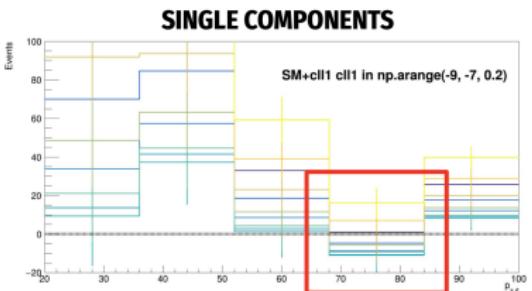
- Generate single components,  $c_{\alpha} = 1$ :  $n(n+3)/2 = 135 \forall$  processes
- Generate events once, LO MG re-weight to different Wilson coeff. Algebra to extract components.

# Amplitude decomposition

While the advantage of **amplitude decomposition** while generating EFT contributions at fixed orders in  $E/\Lambda$  is a better PS sampling, it has the disadvantage that the nominal value for  $N \propto |\mathcal{A}_{SM} + \mathcal{A}_6|^2$  **can be negative** due to the fact that each contribution is evaluated on a different PS.

→ **The reweighting method** (LO  $w^N = w^0 |\mathcal{M}_h^N|^2 / |\mathcal{M}_h^0|^2$ ) computes weights for new hypothesis fixing the PS and **guarantees positive definiteness**. Handy when working with pdfs.

Closure tests performed between standalone components and reweighted one, agreement within statistical error.

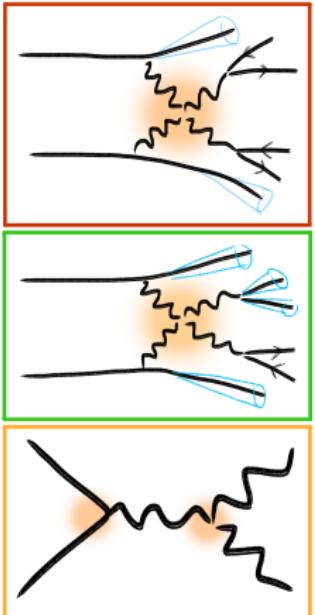


## Technical Details

# Processes of interest

Processes already investigated (or under development) by LHC collaborations. Where appropriate, **background contributions** ( $\alpha_s^2 \alpha_{EW}^4$ ) **generated for both SM and EFT**. Fully-leptonic and semi-leptonic final states investigated. **LHC-like selections performed (slides 23,24,25)**

- **Same-sign WW:**  $p p > e^+ \nu_e \mu^+ \nu_\mu jj$
- **Opposite-sign WW (QCD):**  $p p > e^+ \nu_e \mu^- \bar{\nu}_\mu jj$
- **WZ+2j(QCD):**  $p p > e^+ e^- \mu^+ \nu_\mu jj$
- **ZZ+2j(QCD):**  $p p > e^+ e^- \mu^+ \mu^-$
- **ZV+2j(QCD):**  $p p > z w^+ (w^-, z) > l^+ l^- jjjj$
- **WW:**  $p p > e^+ \nu_e \mu^- \bar{\nu}_\mu$



An integrated luminosity of **100 fb<sup>-1</sup>** is assumed. Projection of constraints on slide 30

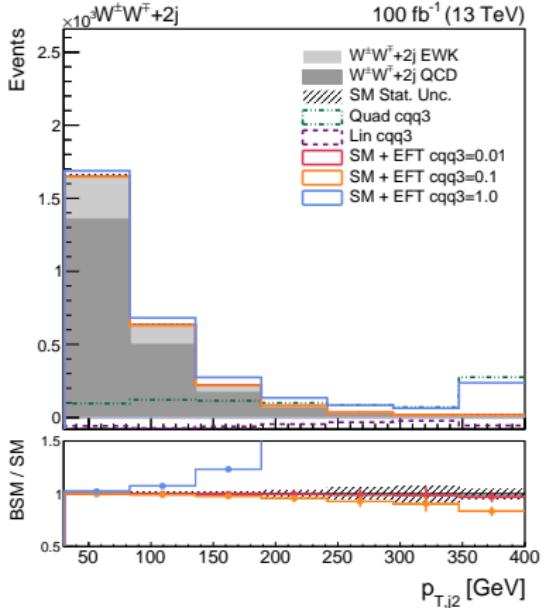
# Processes of interest - EFT sensitivity

Summary of the sensitivity of each process to the operator subset. Empty cells = impossible to insert EFT vertices in diagrams.

proc / op	$Q_{HD}$	$Q_{H\square}$	$Q_{HWB}$	$Q_{Hq}^{(1)}$	$Q_{Hq}^{(3)}$	$Q_{HW}$	$Q_W$	$Q_{HI}^{(1)}$	$Q_{HI}^{(3)}$	$Q_{ll}^{(1)}$	$Q_{qq}^{(3)}$	$Q_{qq}^{(3,1)}$	$Q_{qq}^{(1,1)}$	$Q_{qq}^{(1)}$	$Q_{ll}$
SSWW-EW	✓	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	✓	✓	(✓)
OSWW-EW	✓	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	✓	✓	(✓)
WZ-EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(✓)
ZZ-EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(✓)
ZV-EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
WW	✓		✓	✓	✓		✓	(✓)	✓	✓					
ZV-QCD	✓		✓	✓	✓		✓	✓	✓	✓					
OSWW-QCD	✓		✓	✓	✓		✓	✓	✓	✓					
WZ-QCD	✓		✓	✓	✓		✓	✓	✓	✓					(✓)
ZZ-QCD	✓		✓	✓	✓			✓	✓	✓					(✓)

# Introduction to shape analysis

$$N \propto SM^{EWK} + SM^{QCD} + \frac{c_\alpha}{\Lambda^2} \left( Lin^{EWK} + Lin^{QCD} \right) + \frac{c_\alpha^2}{\Lambda^4} \left( Quad^{EWK} + Quad^{QCD} \right)$$



- ▶ When EFT only in EWK:  
 $Lin^{QCD} = Quad^{QCD} = 0$ ,  $SM^{QCD}$  acts as a fixed background contribution
- ▶ Overflow counts in last bin
- ▶ Conservative binning for each observable
- ▶ At least one SM count in each bin

Solid colored lines represent SM+EFT for a given value of  $c_\alpha$  ( $\Lambda = 1$  TeV). Ratio plot of BSM/SM to inspect for sensitivity in bulk or tail. Trend inversion happen when  $c_\alpha^2 Quad > c_\alpha Lin$  negative interference

# Fit procedure

Shape analysis on distributions of continuous observables

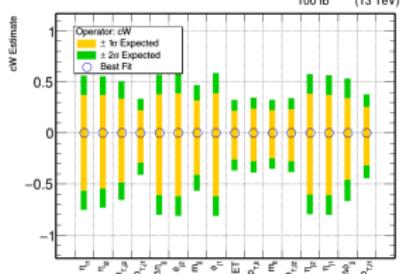
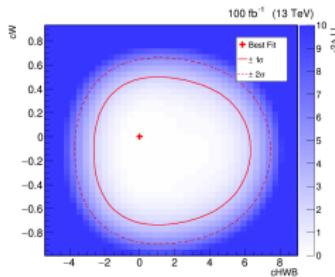
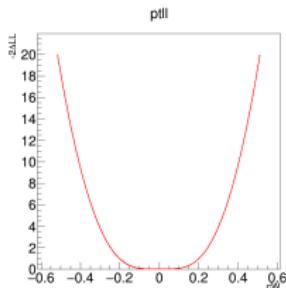
$$\mathcal{L}(\mathbf{c}) = \underbrace{\prod_{bin=k} \frac{(N_k(\mathbf{c}))^{n_k}}{n_k!} e^{-N_k(\mathbf{c})}}_{Poisson} \times \overbrace{\prod_{syst=j} \pi(\tilde{\theta}|\theta)}^{Nuisances}$$

- $N(\mathbf{c}) = SM + \sum c_\alpha \cdot Lin_\alpha + c_\alpha^2 \cdot Quad_\alpha + \sum_{\alpha\beta} c_\alpha c_\beta Mix_{\alpha\beta}$
- $n = N(\mathbf{o}) \rightarrow$  SM expectation
- Only one nuisance: correlated 2% between all yields, samples, and bins (proxy LHC lumi). Flat prior
- under SM, sensitivity estimated as  $-2\Delta \log \mathcal{L} < 1$  (2.30) and  $-2\Delta \log \mathcal{L} < 3.84$  (5.99) for 1(2) W.C.

# Analysis strategy

- Fit each variable for each process operator/s
- $\forall$  operator/s, rank variables based on 68% range (area in 2D).
- $\forall$  operator/s, combine best variables for each process

**Process repeated for:** Individual, bi-dimensional fits.  
Best individual variables used for profiled fits.

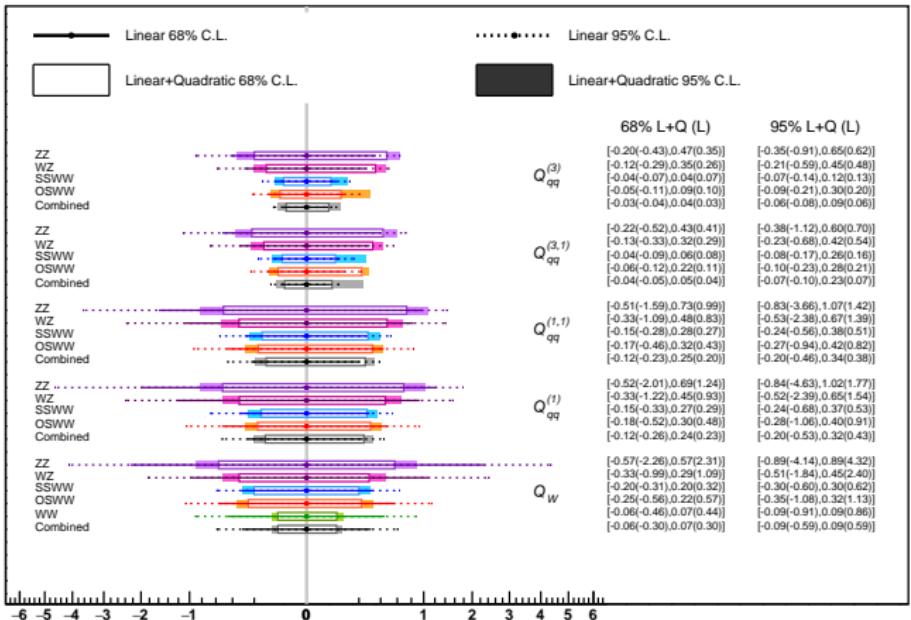


Given process, operator and variable a likelihood scan is performed.

Results are collected and best variable selected

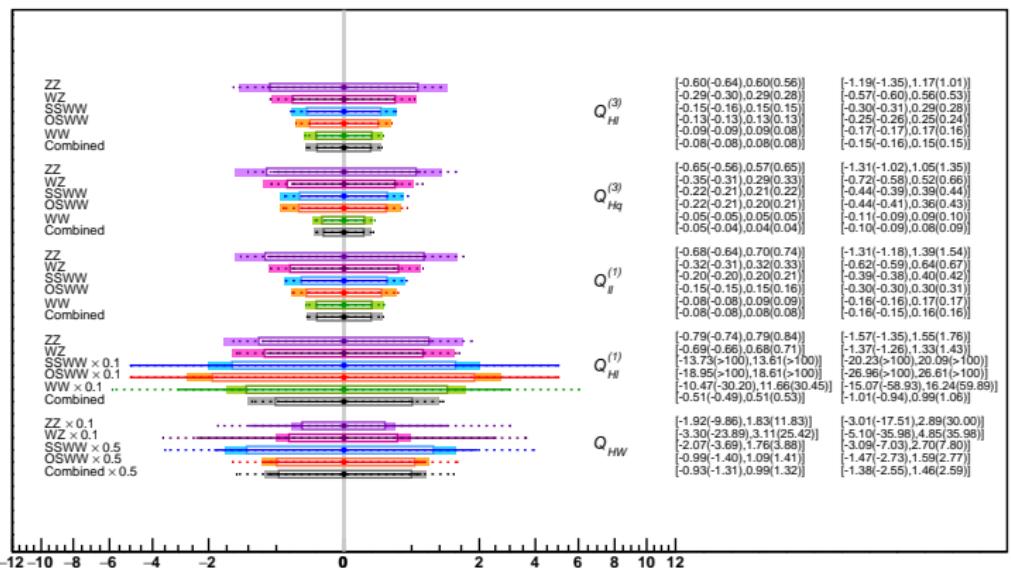
# Individual constraints - VBS+WW Combination

$\Lambda=1 \text{ TeV} \quad 100 \text{ fb}^{-1} \quad (13 \text{ TeV})$



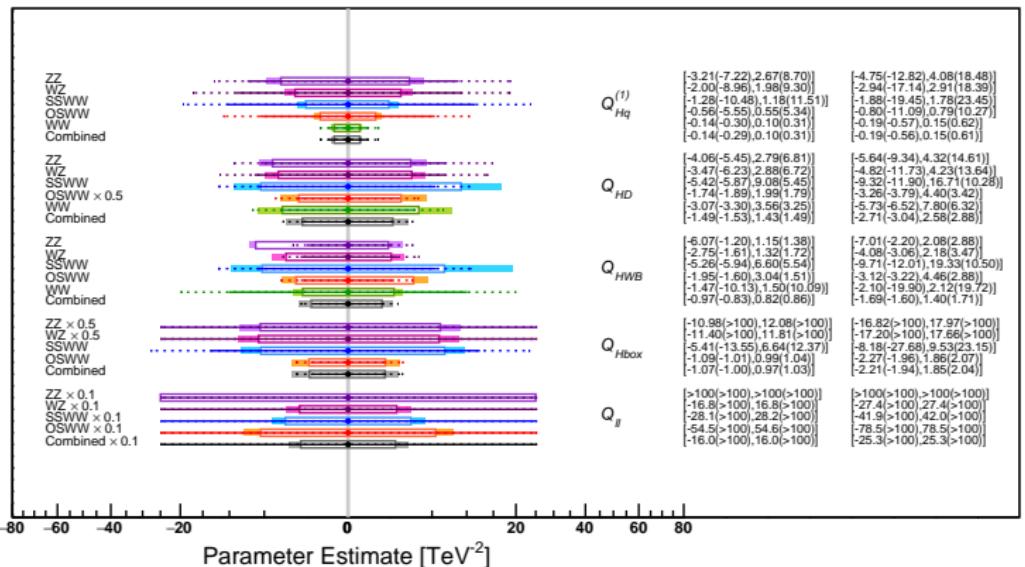
- Most stringent constraints from VBS to **4-fermion ops**, agrees with previous studies [[arXiv:1809.04189](https://arxiv.org/abs/1809.04189)]

# Individual constraints - VBS+WW Combination



- ▶  $Q_{HL}^{(1)}, Q_{HW}$  ( $Q_{H\square}$  next slide) only constrained by VBS.
- ▶  $Q_{HI}^{(1)}$  mostly constrained by VBS WZ/ZZ

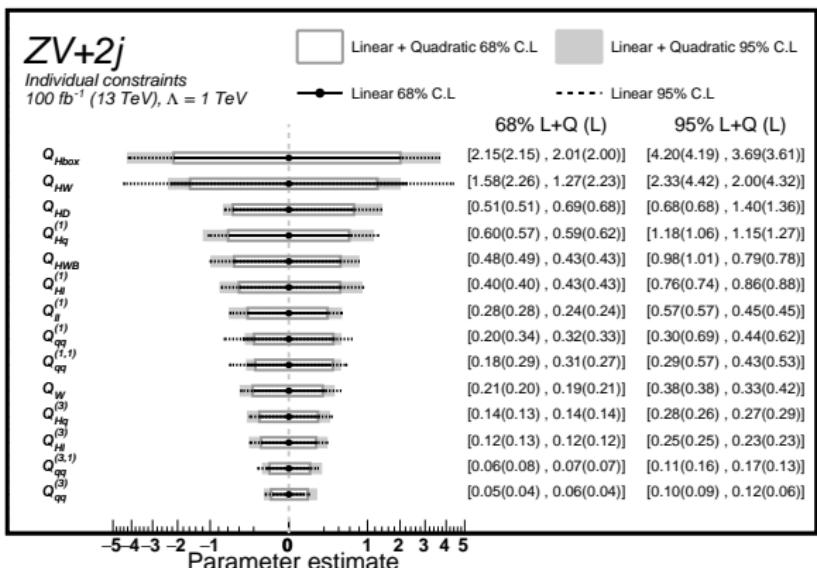
# Individual constraints - VBS+WW Combination



- ▶ **Strong impact of fits including  $O(\Lambda^{-4})$  terms** for  $\frac{1}{2}$  operators. For the remaining, no difference observed.
- ▶ Among VBS, **SSWW, OSWW > WZ, ZZ** due to higher x-sec

# Individual constraints - VBS semi-leptonic

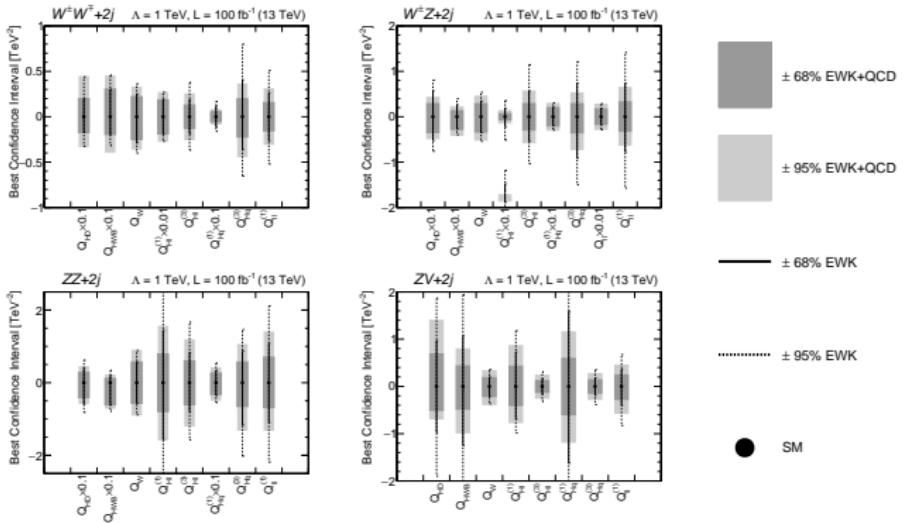
Lack of Z+jets background  $\alpha_s^4 \alpha_{EW}^2$  (dominant in ZV semi-leptonic)  $\rightarrow$  not included in the combination. However, **constraints competitive with diboson  $W^+ W^-$**  and slightly better than any other VBS channel considered, especially for  $Q_{H\ell}^{(1)}$ . Impact of  $O(\Lambda^{-4})$  less prominent w.r.t. other channels.



# Impact of QCD EFT dependence

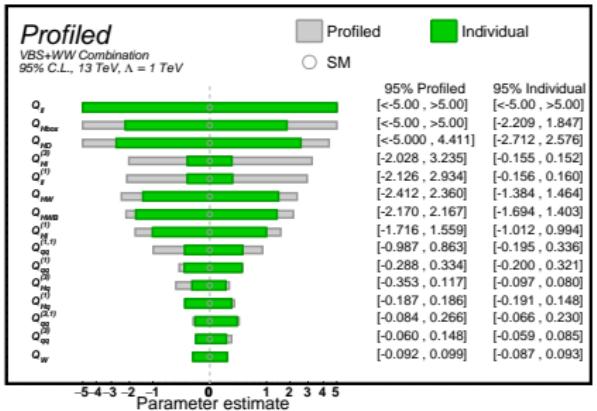
$$N(\text{EWK+QCD}) \propto SM^{\text{EWK}} + SM^{\text{QCD}} + \frac{c_\alpha}{\Lambda^2} (Lin^{\text{EWK}} + Lin^{\text{QCD}}) + \frac{c_\alpha^2}{\Lambda^4} (Quad^{\text{EWK}} + Quad^{\text{QCD}})$$

$$N(\text{EWK}) \propto SM^{\text{EWK}} + SM^{\text{QCD}} + \frac{c_\alpha}{\Lambda^2} Lin^{\text{EWK}} + \frac{c_\alpha^2}{\Lambda^4} Quad^{\text{EWK}}$$



**including the background QCD dependence improves the sensitivity reach of all analyses.**

# Profiled constraints - VBS+WW Combination



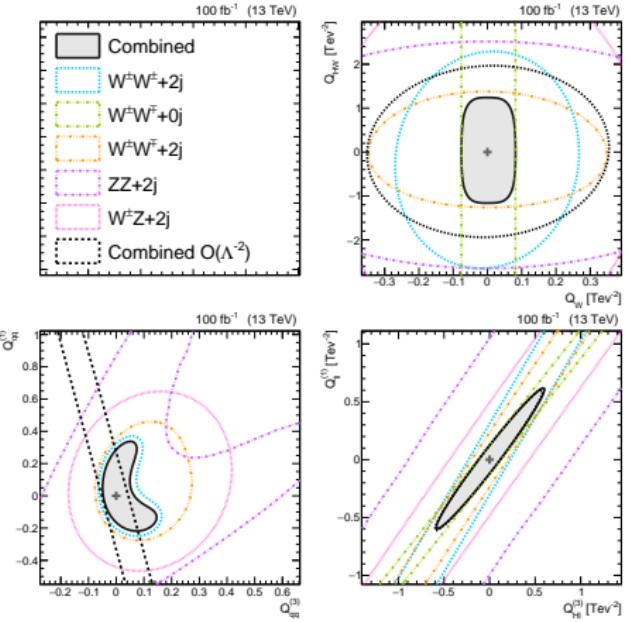
**Global fit guarantees**  
**SMEFT model and basis**  
**independence. VBS + WW**  
**marginalised constraints**  
including all  $\Lambda^{-4}$  terms.

- All parameters free to float in likelihood maximisation
- Individual limits on operators obtained by **profiling** uninteresting parameters (**unconstrained nuisances** in the range [-5,5])
- **Profiled  $\sim 1 - 20 \times$  Individual**
- Low sensitivity → need for a global fit involving more measurements
- Flat direction in  $Q_{Hl}^{(3)} - Q_{ll}^{(1)}$

# 2D constraints - VBS+WW Combination

## Complementarity of VBS and diboson measurements:

- ▶  $Q_{qq}$  operators only constrained by VBS
- ▶  $Q_{H\square}, Q_{HW}$  operators only constrained by VBS
- ▶ Degeneracy on  $Q_{HI}^{(1)}$  resolved by VBS ZZ/WZ
- ▶ Flat directions resolved thanks to combination.



## Impact of $O(\Lambda^{-4})$ terms non negligible:

- Distorts the linear elliptic c.l. in a non-trivial way
- Linear-only sometimes better (differently from 1D): Mixed interference between dim-6 amplitudes can mitigate deviations

# Summary

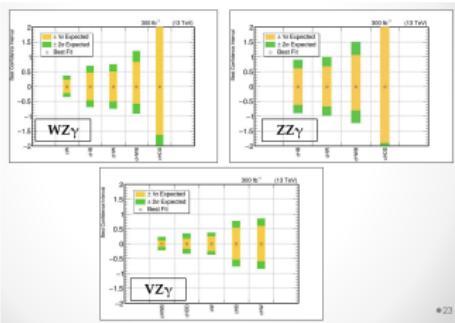
In this work we presented **a comprehensive study at parton level of EFT dimension-6 effects on VBS and diboson  $W^+W^-$**

- ▶ VBS  $2 \rightarrow 6$  simulated for most channels
- ▶ Individual sensitivity increases with  $\Lambda^{-4}$  terms
- ▶ Effect of  $\Lambda^{-4}$  terms not trivial in more dimensions
- ▶ EFT dependence of the QCD induced sample ( $\alpha_s^2 \alpha_{EW}^4$ ) increases sensitivity
- ▶ Addressed sensitivity reach of ZV+2j (semileptonic)
- ▶ Orthogonality of VBS and diboson measurements in more dimensions

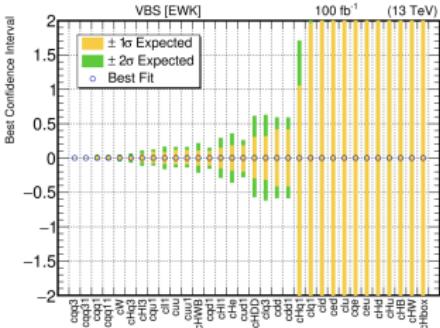
# Future perspectives

This was just the first step. **Possible future developments based on this work**

- ▶ Include the complete set of dim-6 operators
- ▶ Propagate to detector level (hadronisation, pile-up, reducible and not. backgrounds,...)
- ▶ Correct treatment of ZV+2j background (Z+jets)
- ▶ Combine with Higgs measurements
- ▶ Possible interplay of polarisation measurements
- ▶ VBS as tool to discriminate between different operators



WW Cristiano Tarricone

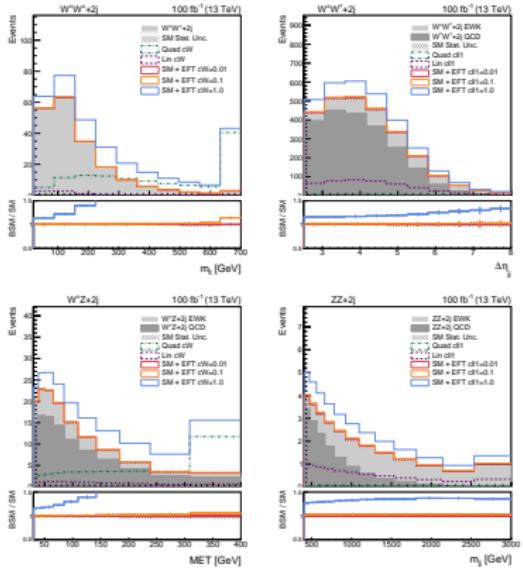


VBF-Z Giorgio Pizzati

# BACKUP

# VBS fully-leptonic

Standard VBS LHC cuts searching for two forward jets with high invariant mass and large  $\eta$  gap, Central leptons and MET. ZZ+2j implements VBS enriched and inclusive selections.

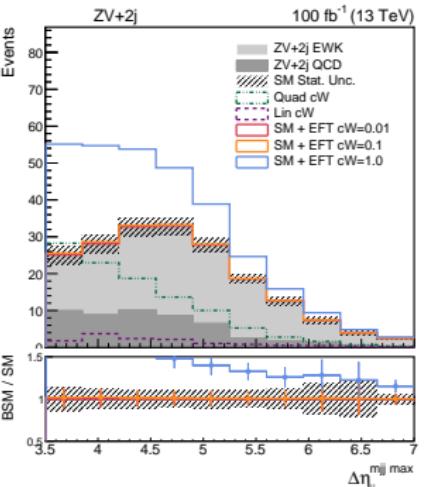


Process	Variables of interest	Selections
$W^\pm W^\pm + 2j$ ( $pp \rightarrow 2l 2\nu jj$ )	$MET, m_{jj}, m_{ll}, \phi_{\vec{p}}, p_{T,j}$ $p_{T,l}, p_{T,\bar{l}}, \Delta\eta_{jj}, \Delta\phi_{jj}, \eta_{\vec{p}}, \eta_l$	$MET > 30$ GeV $m_{jj} > 500$ GeV $m_{ll} > 20$ GeV $p_{T,p} > 25$ GeV $p_{T,p} > 20$ GeV $p_{T,j} > 30$ GeV
$W^+ W^- + 2j$ ( $pp \rightarrow 3l 2\nu jj$ )	$MET, m_{jj}, m_{ll}, \phi_{\vec{p}}, p_{T,j}, p_{T,l}$ $p_{T,l}, \Delta\eta_{jj}, \Delta\phi_{jj}, \eta_l, \eta_{\bar{l}}, m_{3l}$ $p_{T,j}, m_{W2}, \delta\eta_{W2}, \delta\phi_{W2}, \Phi_{planes}$	$\Delta\eta_{jj} > 2.5$ $ \eta_{\vec{p}}  < 5$ $ \eta_l  < 2.5$
$W^\pm Z + 2j$ ( $pp \rightarrow 4l 2j$ )	$m_{jj}, m_{ll}, m_{ll}, m_{4l}, \phi_{\vec{p}}, p_{T,j}, p_{T,\bar{l}}$ $p_{T,l}, p_{T,\bar{l}}, \Delta\phi_{jj}, \Delta\eta_{jj}, \eta_{\vec{p}}, \eta_l$	$m_{jj} > 400$ GeV $60 < m_{ll} < 120$ GeV $m_{4l} > 180$ GeV $p_{T,p} > 20$ GeV $p_{T,p} > 10$ GeV $p_{T,j} > 5$ GeV $p_{T,j,z} > 30$ GeV $\Delta\eta_{jj} > 2.4$ $ \eta_l  < 4.7$ $ \eta_{\vec{p}}  < 2.5$ $\Delta R(l^+, l^{\bar{}})^2 > 0.4$
$ZZ + 2j$ ( $pp \rightarrow 4l 2j$ )	$m_{jj}, m_{ll}, m_{ll}, m_{4l}, \phi_{\vec{p}}, p_{T,j}, p_{T,\bar{l}}$ $p_{T,l}, p_{T,\bar{l}}, \Delta\phi_{jj}, \Delta\eta_{jj}, \eta_{\vec{p}}, \eta_l$	

Same Sign WW distributions:   
Opposite Sign WW distributions:   
VBS ZZ distributions:   
VBS WZ distributions:

# VBS semi-leptonic

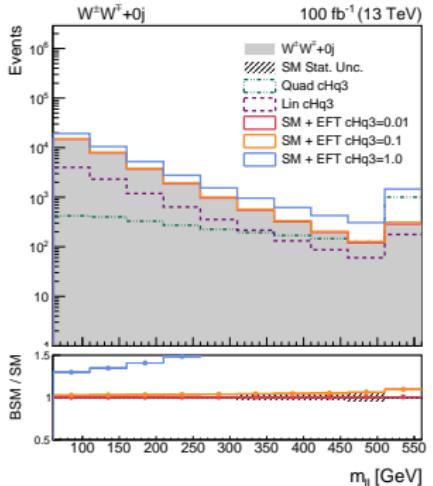
- ▶ First evidence for semi-leptonic VBS this year  
[CMS-PAS-SMP-20-013](#)
- ▶  $W \rightarrow q\bar{q}$ : **more statistics, more backgrounds.**
- ▶ Major background: **Z+jets, not simulated** → separate treatment.
- ▶ Highest  $m_{jj}$  partons tagged as VBS jets ( $\epsilon \sim 75\%$ ).



VBS ZV distributions:

Process	Variables of interest	Selections
$ZV + 2j$ ( $pp \rightarrow 2ljjjj$ )	$m_{jj}, m_{ll}, \phi_j, p_{T,j}, p_{T,l}$ $p_{T,ll}, \Delta\eta_{jj}, \Delta\phi_{jj}, \eta_j$ $\eta_l$	$m_{jj} > 1500 \text{ GeV}$ $60 < m_{jj}^V < 110 \text{ GeV}$ $85 < m_{ll} < 95 \text{ GeV}$ $p_{T,l^+} > 25 \text{ GeV}$ $p_{T,l^-} > 20 \text{ GeV}$ $p_{T,j} > 100 \text{ GeV}$ $\Delta\eta_{jj} > 3.5$ $ \eta_j  < 5$ $ \eta_l  < 2.5$

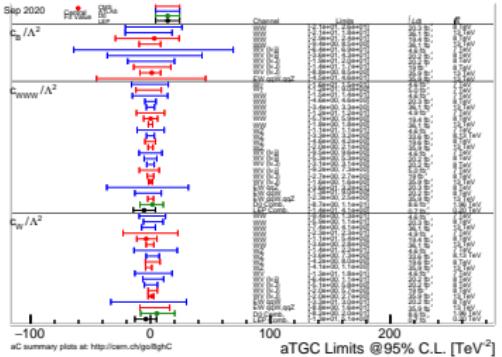
# Diboson $W^+W^-$



Diboson WW distributions:

Process	Variables	Selections
$W^+W^- + \text{0j}$ $(pp \rightarrow 2l\nu)$	$MET, m_{ll}, p_{T,l^1}, p_{T,l^2}, \eta_{l^1}, \eta_{l^2}$	$MET > 30 \text{ GeV}$ $m_{ll} > 60 \text{ GeV}$ $p_{T,l^1} > 25 \text{ GeV}$ $p_{T,l^2} > 20 \text{ GeV}$ $ \eta_{l^1}  < 2.5$

- ▶ Highest cross section
- ▶ Historically main playground for aTGC and dim-6 EFT
- ▶ usually **few operators studied:**  $Q_W, Q_{WW}, Q_B$  and CP violating (HISZ basis)
- ▶ DF 0-jet category **high purity** (main backgrounds  $t\bar{t}$ , non-prompt, DY)



# Analysis setup

## Ntuples and LHE generation framework

[\[https://github.com/UniMiBAnalyses/D6EFTStudies\]](https://github.com/UniMiBAnalyses/D6EFTStudies)

UniMiBAnalyses / D6EFTStudies

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Giacomo Boldrini Updated SMEFTsim 9863a25 3 days ago 218 commits

DatacardCreator	changing names for lin and quad components in datacard	9 months ago
PostPlots	minor changes	13 months ago
analysis	adding option to change folder when reading LHE files, histograms pl...	16 months ago
fit	adding pieces	2 years ago
generation	Updated SMEFTsim	3 days ago
heracles_generation	Update README.md	13 months ago
madgraph_model	Restriction cards for the v3_0 SMEFTsim model <a href="https://github.com/S...">https://github.com/S...</a>	8 months ago
utils	Added pte and mre variables, specific for the WZ(emu) final state ...	6 months ago
.gitignore	Added grouping options and fixed bugs, now mkPlot works fine	9 months ago
README.md	Something more	6 months ago

About EFT studies with Dim6 Warsaw basis

Readme

Releases No releases published Create a new release

Packages No packages published Publish your first package

Contributors 11

# Analysis setup

Post-processing, QCD merging, and shape maker based on  
<https://github.com/GiacomoBoldrini/D6tomkDatacard>

The screenshot shows the GitHub repository page for `GiacomoBoldrini/D6tomkDatacard`. The repository has 83 commits, the most recent being 3 days ago. It includes files like `cfg`, `ignore`, `README.md`, and several Python scripts for QCD merging and shape making. The repository has 1 star, 1 fork, and 1 watch.

File	Description	Last Commit
<code>cfg</code>	mlb>60	3 days ago
<code>ignore</code>	Added grouping options and fixed bugs, now mlPlot works fine	9 months ago
<code>README.md</code>	Update README.md	9 months ago
<code>combineQCD.py</code>	Option to always add QCD as bkg	4 months ago
<code>combineQCD_profile.py</code>	Added --v to debug	3 months ago
<code>createCondor.py</code>	New combine options	2 months ago
<code>createCondorDP.py</code>	Upgrade version	4 months ago
<code>createProfile.py</code>	Add explanation, should be run after mlDatacard	4 months ago
<code>makeDummies.py</code>	Added Script to merge two folders into one [to combine EWK and QC...	5 months ago

Tailored to `latinos` framework datacard maker  
<https://github.com/latinos/LatinoAnalysis>

# Analysis setup

EFT analysis inside CMS problematic. The fitting tool [Combine](#) does not allow negative shapes (such as linear and mixed interference).

Workaround: **redefine each component as positive-definite.**

Combine model for EFT studies with up to  $O(\Lambda^{-4})$  and possibility to add dim-8 operators: [AnalyticAnomalousCoupling](#)

More details in [CMS internal note](#).

$$\begin{aligned}
 N = & S \cdot \left( 1 - \sum_i k_i + \sum_{i,i < j} \sum_j k_i \cdot k_j \right) \\
 & + \left[ \sum_i k_i - \sum_{i \neq j} k_i \cdot k_j \right] \cdot (S + L_i + Q_i) \\
 & + \sum_i (k_i^2 - k_i) \cdot Q_i \\
 & + \sum_{i,i < j} \sum_j k_i \cdot k_j \cdot [S + L_i + L_j + Q_i + Q_j + 2 \cdot M_{ij}]
 \end{aligned}$$

# Generations

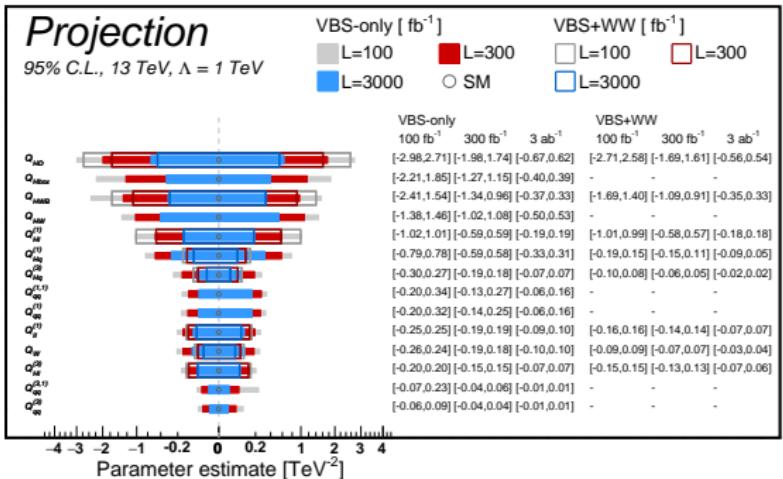
SMEFTsim newest version:

[\[https://github.com/SMEFTsim/SMEFTsim\]](https://github.com/SMEFTsim/SMEFTsim)

<b>SSWW-EW</b>	generate p p > e+ ve mu+ vm j j QCD=0 SMHLOOP=0
<b>OSWW-EW</b>	generate p p > e+ ve mu- vm j j QCD=0 SMHLOOP=0
<b>WZ-EW</b>	generate p p > e+ e- mu+ vm j j QCD=0 SMHLOOP=0
<b>ZZ-EW</b>	generate p p > e+ e- mu+ mu- j j QCD=0 SMHLOOP=0
<b>ZV-EW</b>	generate p p > z w+(w-,z) j j QCD=0 SMHLOOP=0, z > l+ l-, w+(w-,z) > j j
<b>WW</b>	generate p p > e+ ve mu- vm SMHLOOP=0
<b>ZV-QCD</b>	generate p p > z w+(w-,z) j j QCD==2 SMHLOOP=0, z > l+ l-, w+(w-,z) > j j
<b>OSWW-QCD</b>	generate p p > e+ ve mu- vm j j QCD==2 SMHLOOP=0
<b>WZ-QCD</b>	generate p p > e+ e- mu+ vm j j QCD==2 SMHLOOP=0
<b>ZZ-QCD</b>	generate p p > e+ e- mu+ mu- j j QCD==2 SMHLOOP=0

$\sqrt{s} = 13$  TeV, NNLO pdfs from NNPDF  $\alpha_s = 0.118$  (lhaid=325500) and 4-flavour scheme.  $U(3)^5$  symmetry group and  $\{m_W, m_Z, G_F\}$  input scheme.  $\Lambda = 1$  TeV

# Expected constraints at future colliders



**Projection of individual constraints to future LHC phases**

Integrated luminosities: LHC Run II  $\sim 100\text{fb}^{-1}$ , LHC Run III  $> 300\text{fb}^{-1}$ , HL-LHC  $\sim 3\text{ ab}^{-1}$ . No scaling of the nuisance constraint involved.

At the HL-LHC, the VBS-only combination is expected to constrain all operators to less than [-1,1], including diboson lowers the range to [-0.5,0.5].  
Roughly a factor  $\sim 5$  improvement expected from LHC Run II to HL-LHC.