

EFT Interpretation of Three Massive Bosons Production

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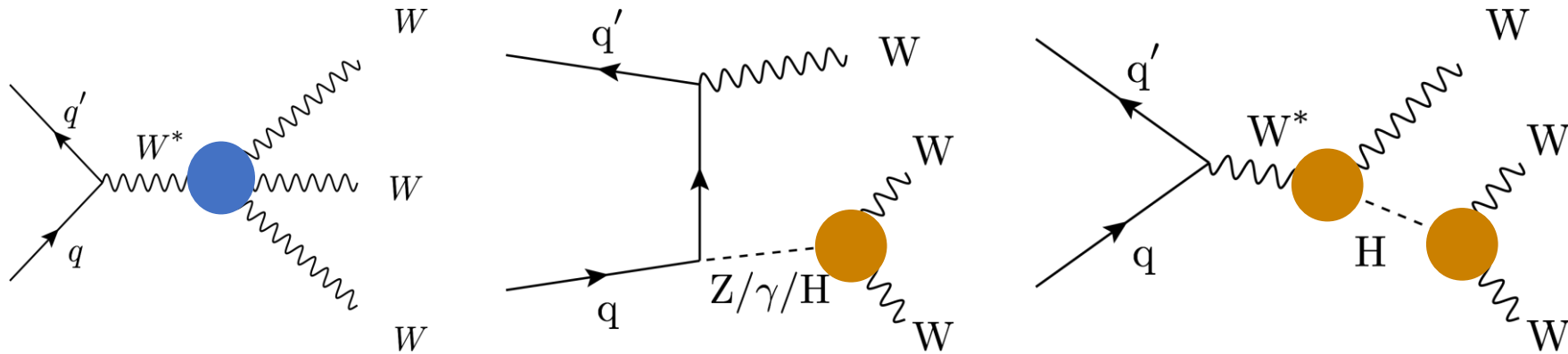


Outline

- Motivation
- Faux NLO sample generation
- Analysis overview
- EFT limit extraction
- Summary

Motivation

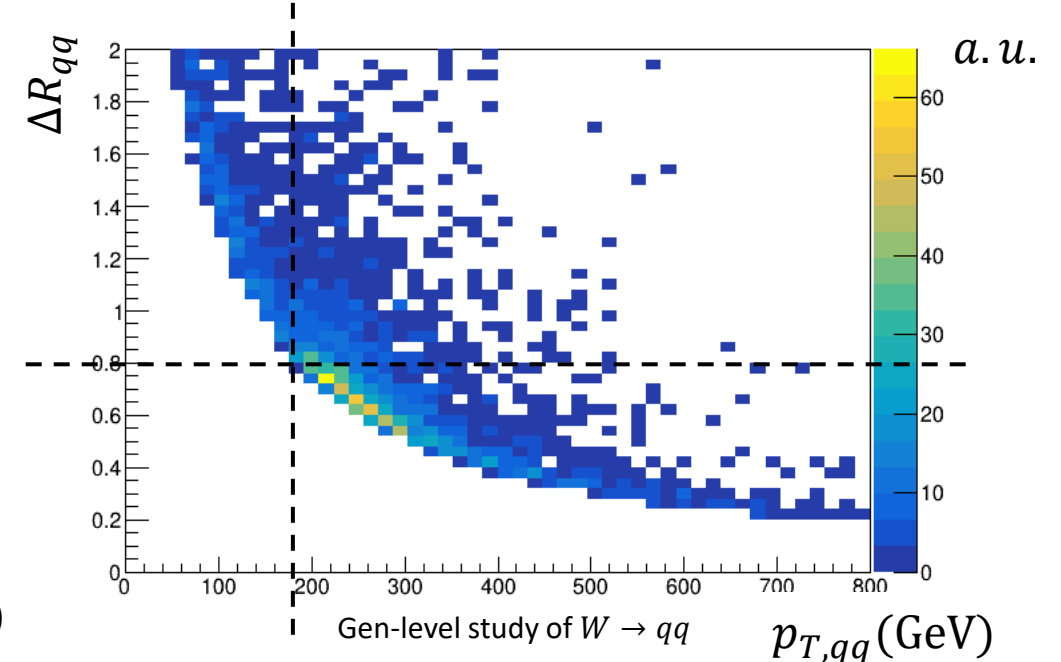
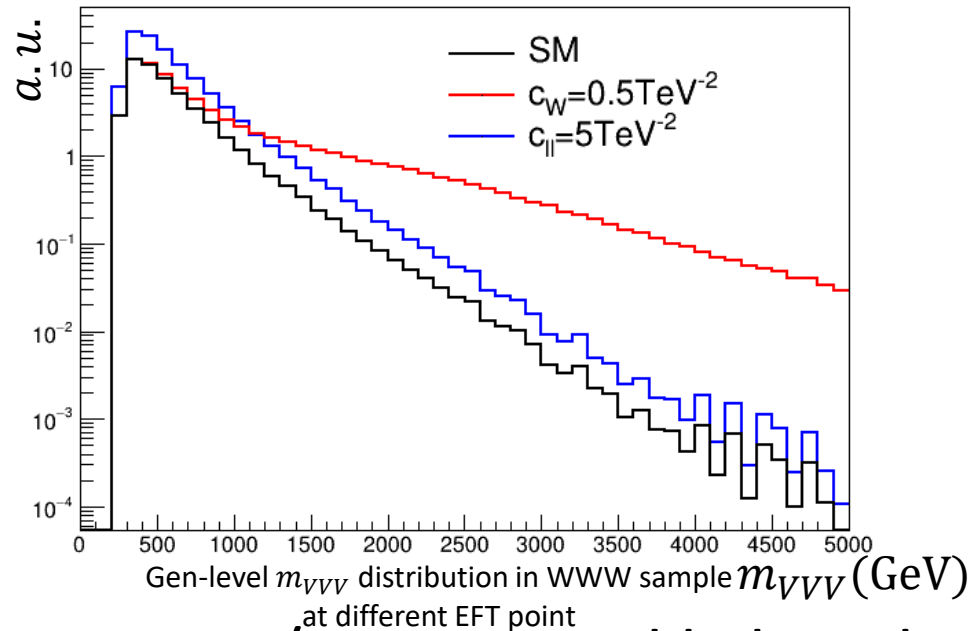
- Production of three massive bosons (VVV) is a rare process, observation reported in [CMS paper](#) and [ATLAS paper](#)
- VVV processes involve TGC, QGC, Higgs-gauge couplings. Deviations in these couplings can potentially lead to large excesses.



- Focus on the EFT interpretation of VVV, with dim-6 and dim-8 operators

Impact of EFT

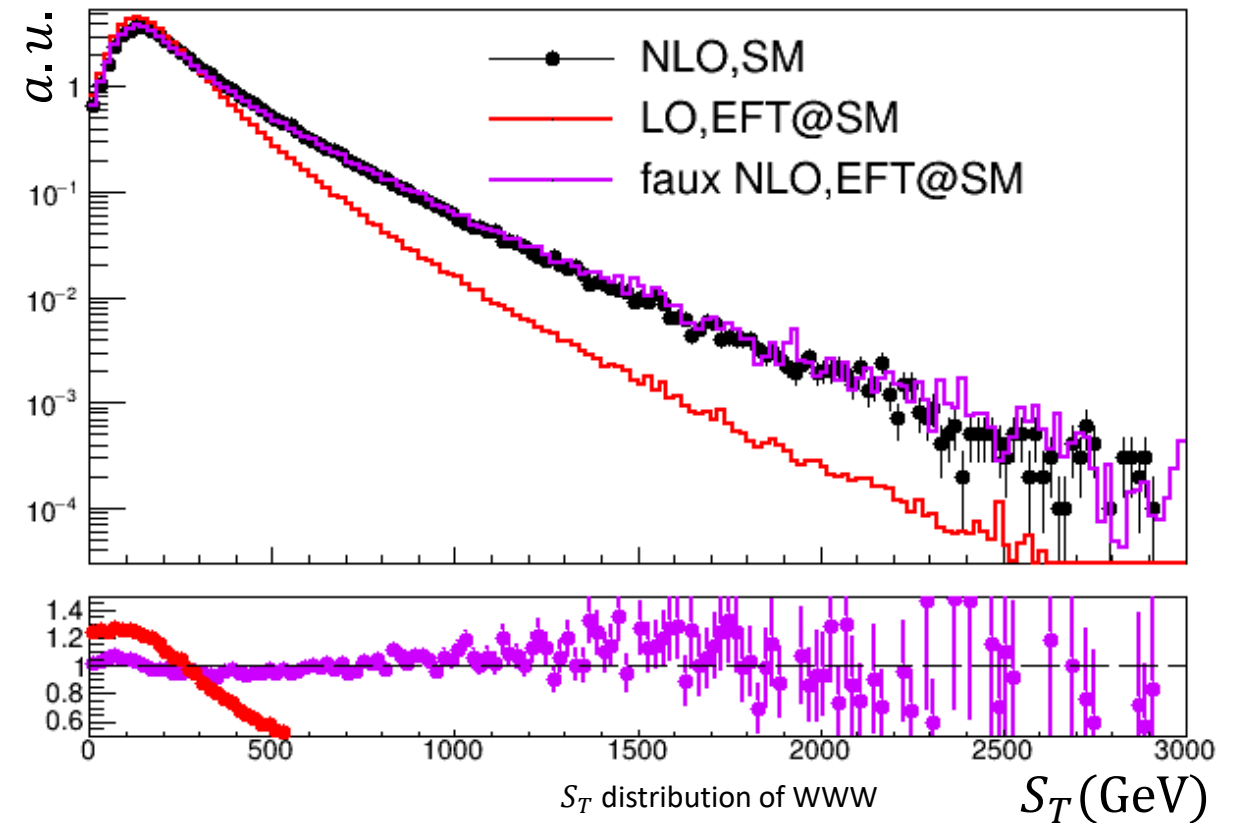
- EFT operators impact the VVV cross section in multiple ways, \mathcal{O}_W , increase the cross section on high \hat{s} . \mathcal{O}_{ll} increase the overall cross section



- In high \hat{s} region, W/Z are more likely to be boosted \rightarrow More energetic leptons and merged jets.

EFT MC Sample Generation

- LO does not provide accurate kinematic distributions at SM point compared to NLO standard sample
- Following [TOP](#) group, we generate faux NLO samples by performing merge and match on VVV and VVV with additional parton
- Faux NLO samples for dim-6 operators have been generated, dim-8 operators to be followed



Analysis Overview

- Semi-leptonic/hadronic decay is studied in high \hat{s} region
- Use ParticleNet W/Z tagger to tag AK8 jets with $p_T > 200\text{GeV}$ (“fatjets”)
- Channels are divided by the number and sign of leptons
 - Each channel chooses appropriate variable representing \hat{s}
 - 3-6 bins in the variable chosen
 - Each channel also defines orthogonal control region(s) to study background

Channel	Targeting	Variable of interest
0 lepton + 2/3 fatjets	WWW,WWZ,WZZ,ZZZ	H_T
1 lepton + 2 fatjets	WWW,WWZ,WZZ	$M_{lvJJ}(M_{VVV})$
2 Opposite-Signed Leptons(OS) + 1 fatjet	WWW,WWZ,WZZ,ZZZ	S_T
2 Same-Signed Leptons(SS) + 1 fatjet	WWW	$S_{T,MET}$

Example: SS+1fatjet Channel

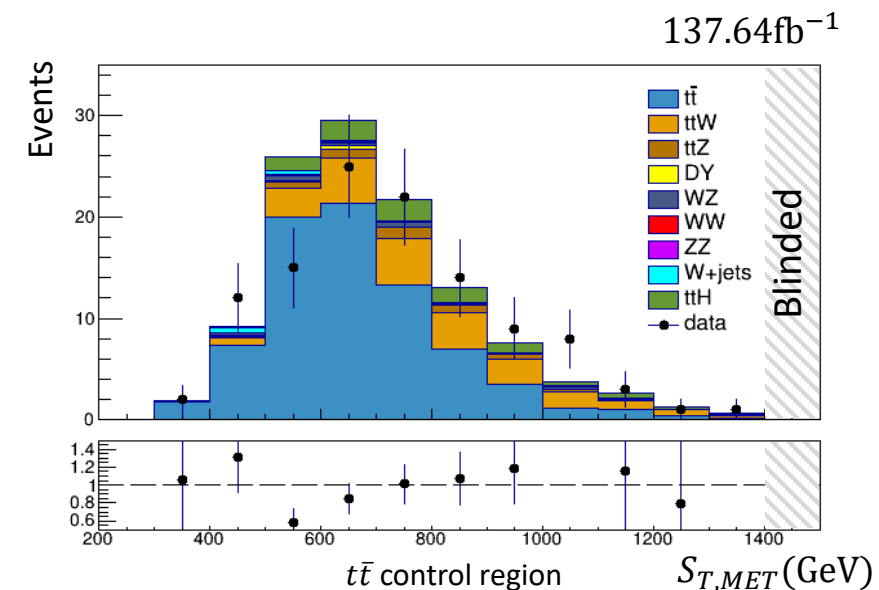
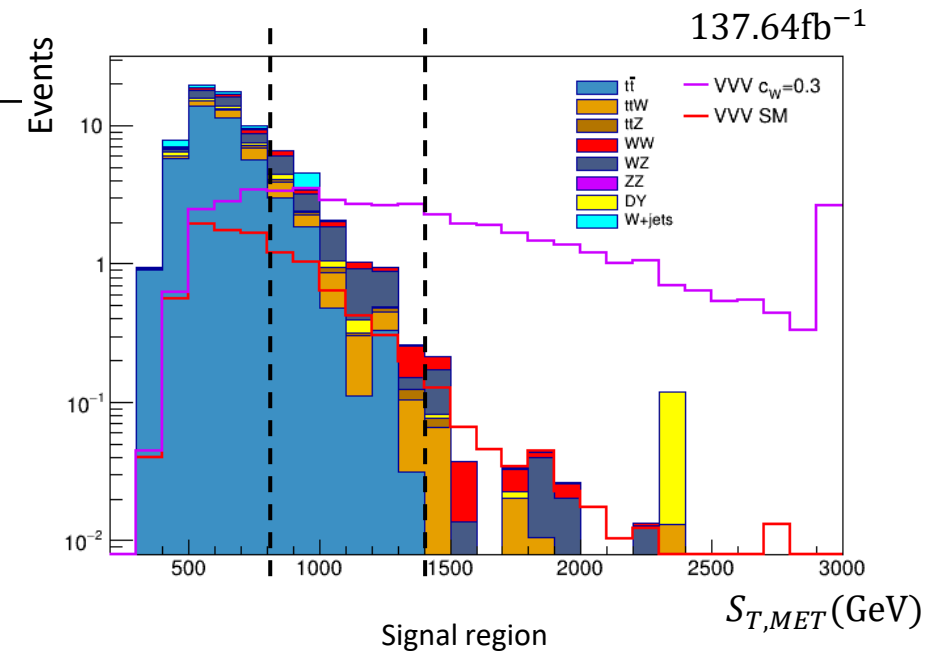
• Signal Region

- Dilepton triggers
- Exactly 2 same sign loose leptons
- ≥ 1 fatjet with medium WP
- No medium b-jet
- Both leptons pass tight ID
- $|m_{ee} - m_Z| > 20 \text{ GeV}$
- $p_{T,l1} > 40 \text{ GeV}, p_{T,l2} > 30 \text{ GeV}$
- $\Delta R_{ll} > 1.2$

• $t\bar{t}$ Control region

- Change b-veto to ≥ 1 medium b-jet
- Data driven $t\bar{t}$ background estimation is under development

	Yield \pm stat.
$t\bar{t}$	28.1 ± 1.2
ttW	4.00 ± 0.14
ttZ	0.83 ± 0.06
WW	1.95 ± 0.14
WZ	6.4 ± 0.6
ZZ	0.162 ± 0.010
$Wjets$	2.9 ± 1.0
DY	1.9 ± 0.4
bkg	46.4 ± 1.7
VVV(SM)	10.1 ± 0.5
VVV($c_W = 0.3$)	17.9 ± 0.7



Yield in last bin

Numbers in the table are indicative

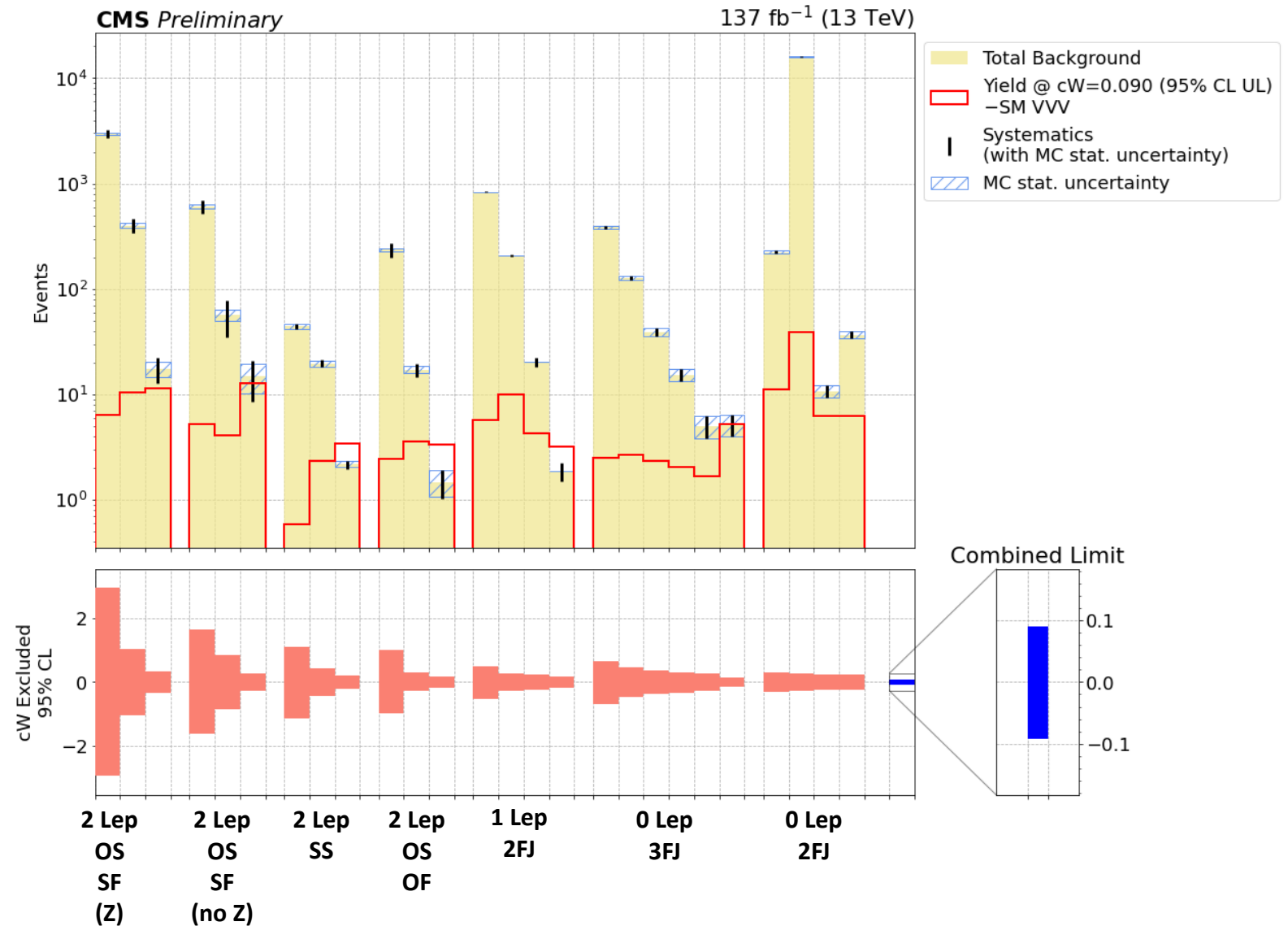
$$N_{EFT} = \text{Quadratic} \times c_{EFT}^2 + \text{Linear} \times c_{EFT} + \text{SM}$$

Channel	Total background	SM VVV	$N_{EFT}@$ $c_W = 0.3$	c_W Quadratic	c_W Linear
0 lepton + 3 fatjets	10.5	0.125	40.9	452.65	0.178
0 lepton + 2 fatjets	4.8	0.175	23.2	254.36	0.578
1 lepton + 2 fatjets	1.65	0.121	13.7	150.75	0.175
2 OS Leptons + 1 fatjet: OF	0.9	0.306	10.9	117.00	0.196
2 OS Leptons + 1 fatjet: SF, no Z	13	0.820	15.8	164.7	0.493
2 OS Leptons + 1 fatjet: SF, Z	16	0.810	11.7	119.7	0.368
2 Same-Signed Leptons + 1 fatjet	0.7	0.924	8.27	79.3	0.672

- Quadratic terms dominate the sensitivity

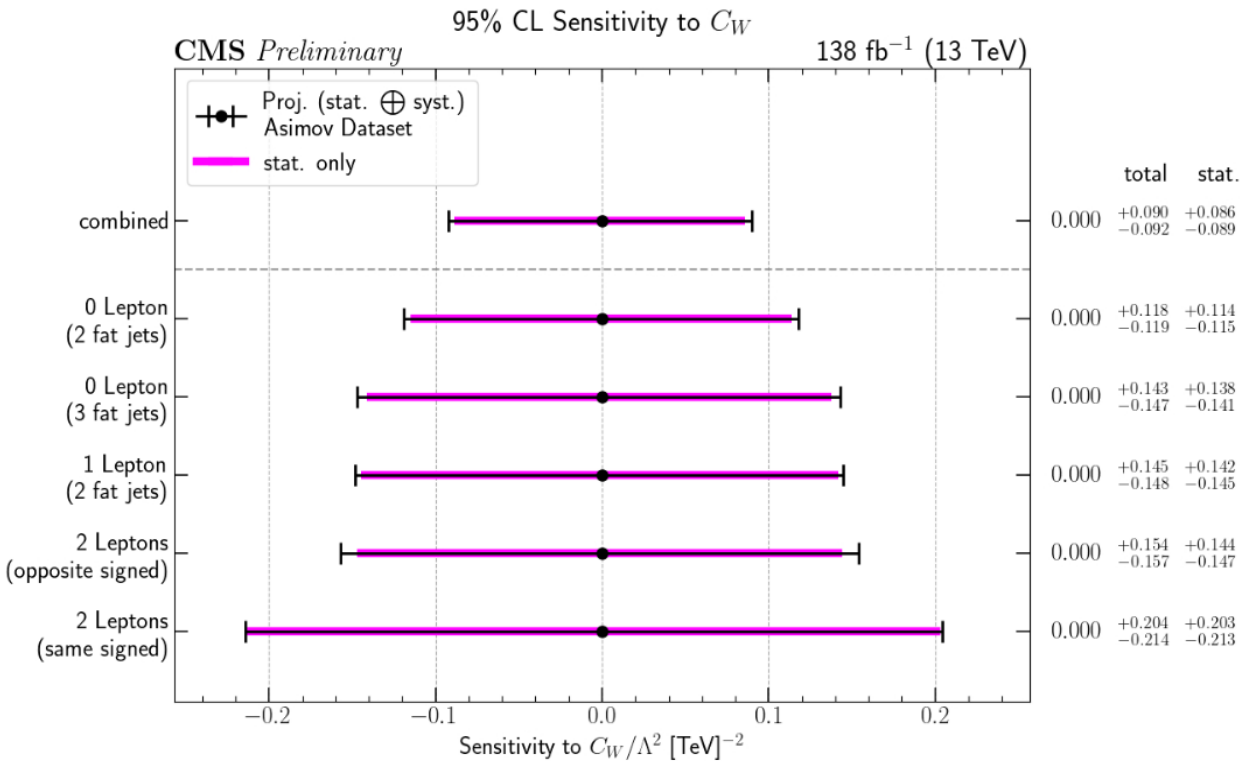
Limits calculation

- Preliminary result with subset of syst. uncertainties
- Top panel: summarized input to Higgs combine
- Bottom panel: limits extracted from Higgs combine
- Channels sorted by channel sensitivity

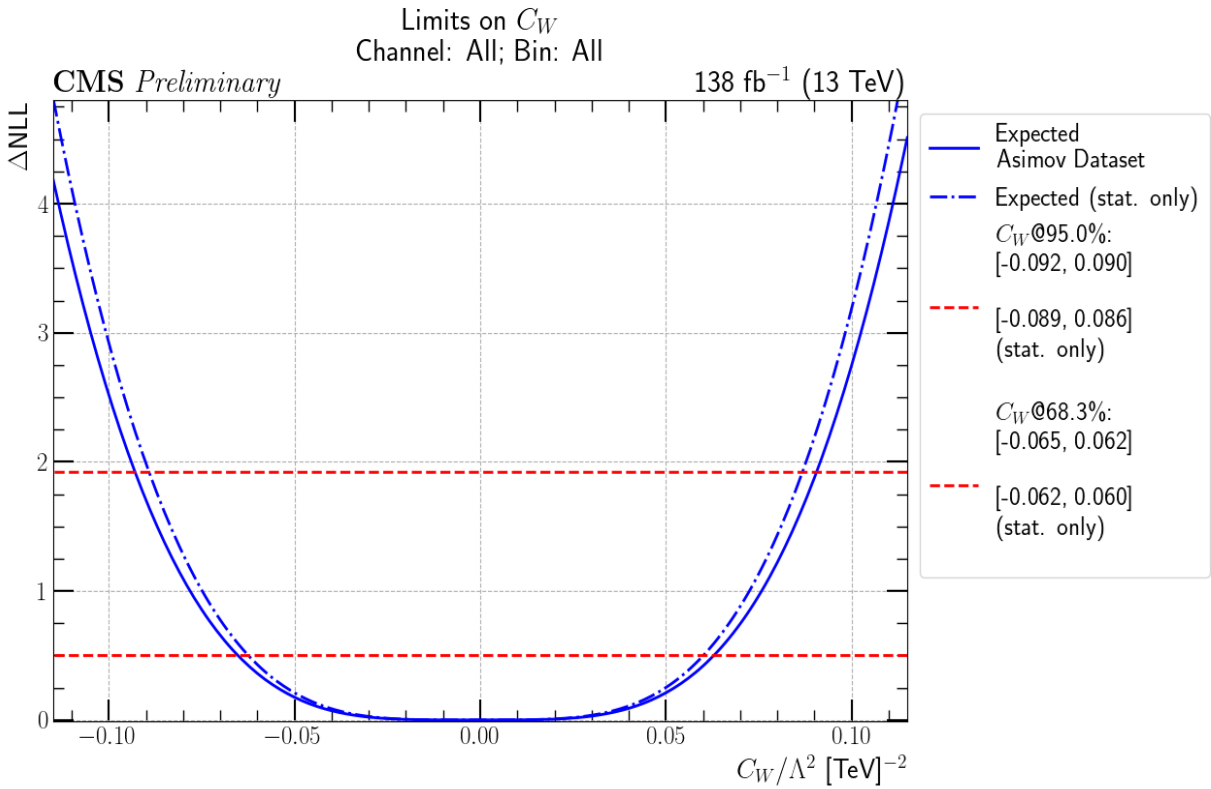


Summary of c_W Limit

95% CL Expected Limits
(full analysis and channel level)



NLL vs. c_W
(output from combine)



Fitting Result

- Preliminary result with subset of syst. uncertainties
- Interesting limits are achieved for dim-6 operators
- f_{T0} and f_{M0} close to the current limit

Wilson Coefficient		Limit @ 95% CL	Current limit in SMP
Dim 6 operators			
	c_W	$[-0.092, 0.090]$	$[-0.125, 0.13]$
	c_{Hq3}	$[-0.18, 0.15]$	$[-0.12, 0.12]$
	c_{Hq1}	$[-0.25, 0.24]$	$[-1.8, 1.6]$
	c_{Hu}	$[-0.44, 0.43]$	$[-2.0, 2.0]$
	c_{Hd}	$[-0.56, 0.56]$	$> [-2.0, 2.0]$
	c_{HW}	$[-1.20, 1.13]$	$[-0.78, 0.6]$
	c_{HB}	$[-1.24, 1.24]$	$[-3.79, 3.80]$
	c_{HWB}	$[-3.8, 3.6]$	$[-0.6, 0.6]$
	c_{Hl3}	$[-2.7, 14]^*$	$[-0.1, 0.1]$
	c_{ll1}	$[-27, 5.3]^*$	$[-0.15, 0.15]$
	$c_{H\Box}$	$[-52, 46]$	$[-3.9, 4.2]$
	c_{HDD}	$[-89, 49]$	$[-1.1, 1.2]$
Dim 8 operators			
Assuming	f_{T0}	$[-0.16, 0.16]$	$[-0.12, 0.11]$
dim-6 is 0	f_{M0}	$[-0.87, 0.89]$	$[-0.69, 0.69]$

*: discontinuous limits

Summary

- The analysis is well developed. The analysis group have defined signal regions, investigated variables of interest, developed binning strategy and defined control region(s)
- Use of faux NLO dim-6 samples provides improved description of signal, dim-8 generation ongoing
- Preliminary fit results indicate strong sensitivity for dim-6 and dim-8 Wilson Coefficients

Thank you

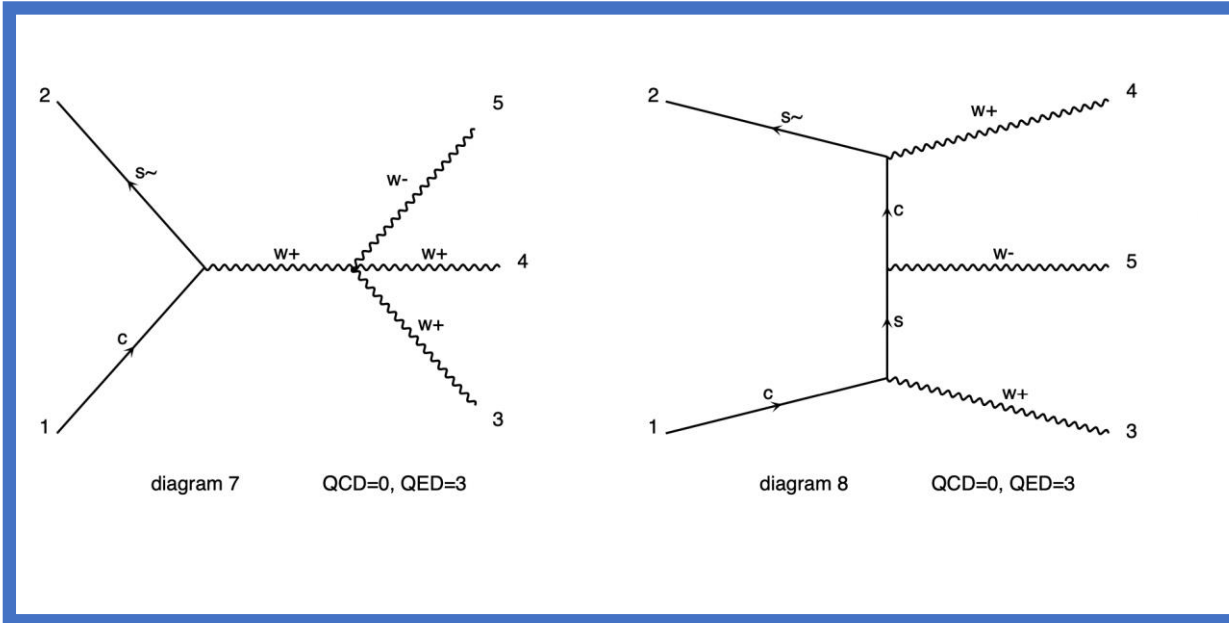
Backup

Table of Wilson Coefficients and Current Limits

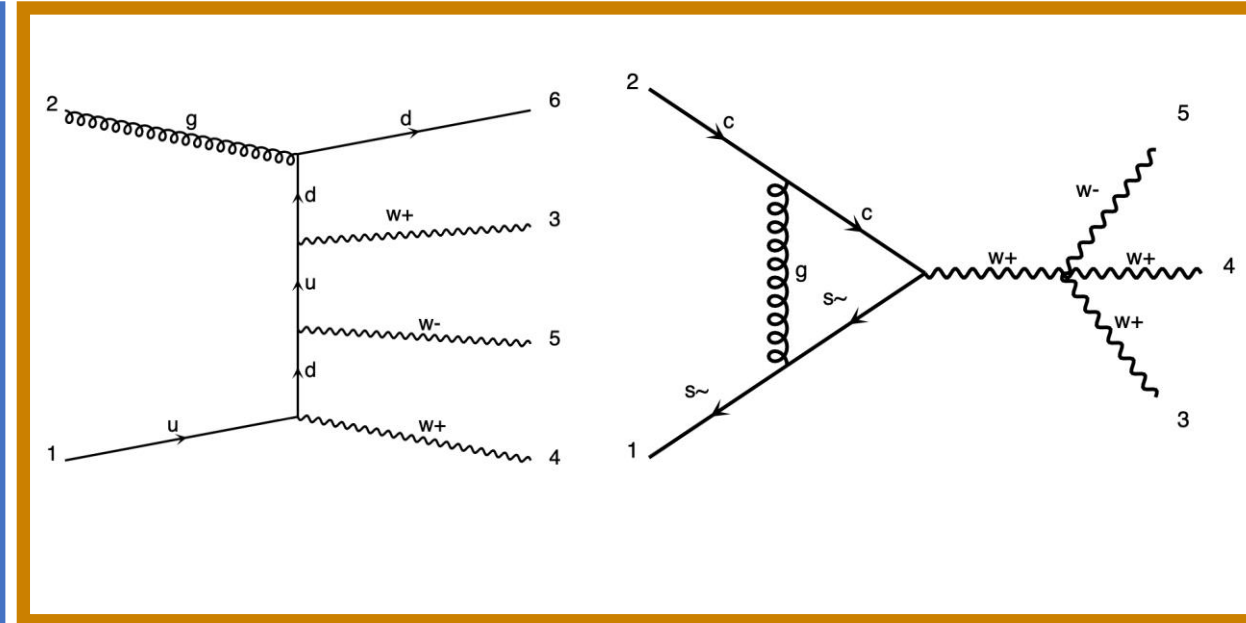
Wilson Coefficient	Current limit in SMP	Source
c_W	$[-0.125, 0.13]$	VBS All Hadronic/ Missing JER/JES and PDF uncertainties
c_{Hq3}	$[-0.12, 0.12]$	VBF W, 100/fb/ Freeze all WC and float one at a time
c_{Hq1}	$[-1.8, 1.6]$	VBF W, 100/fb/ Freeze all WC and float one at a time
c_{Hu}	$[-2.0, 2.0]$	VBF W, 100/fb/ Freeze all WC and float one at a time
c_{Hd}	$> [-2.0, 2.0]$	VBF W, 100/fb/ Freeze all WC and float one at a time
c_{HW}	$[-0.78, 0.6]$	VBS All Hadronic/ Missing JER/JES and PDF uncertainties
c_{HB}	$[-3.79, 3.80]$	Semileptonic VBS WV from analyst*
c_{HWB}	$[-0.6, 0.6]$	VBF W, 100/fb/ Freeze all WC and float one at a time
c_{Hl3}	$[-0.1, 0.1]$	VBF W, 100/fb/ Freeze all WC and float one at a time
c_{ll1}	$[-0.15, 0.15]$	VBF W, 100/fb/ Freeze all WC and float one at a time
$c_{H\Box}$	$[-3.9, 4.2]$	VBF W, 100/fb/ Freeze all WC and float one at a time
c_{HDD}	$[-1.1, 1.2]$	VBS All Hadronic/ Missing JER/JES and PDF uncertainties

***Analysis in progress, obtained through private communication, 59.7/fb**

NLO vs LO



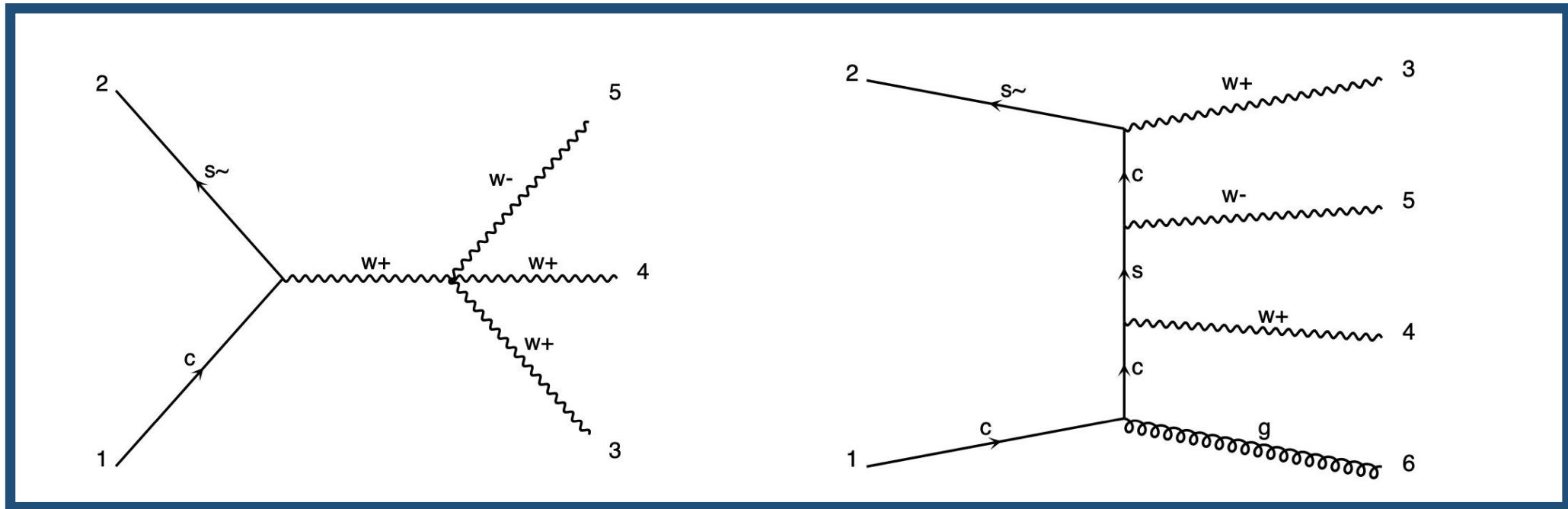
Diagrams associated with the
LO process



Diagrams associated with the
NLO process

Merge and match

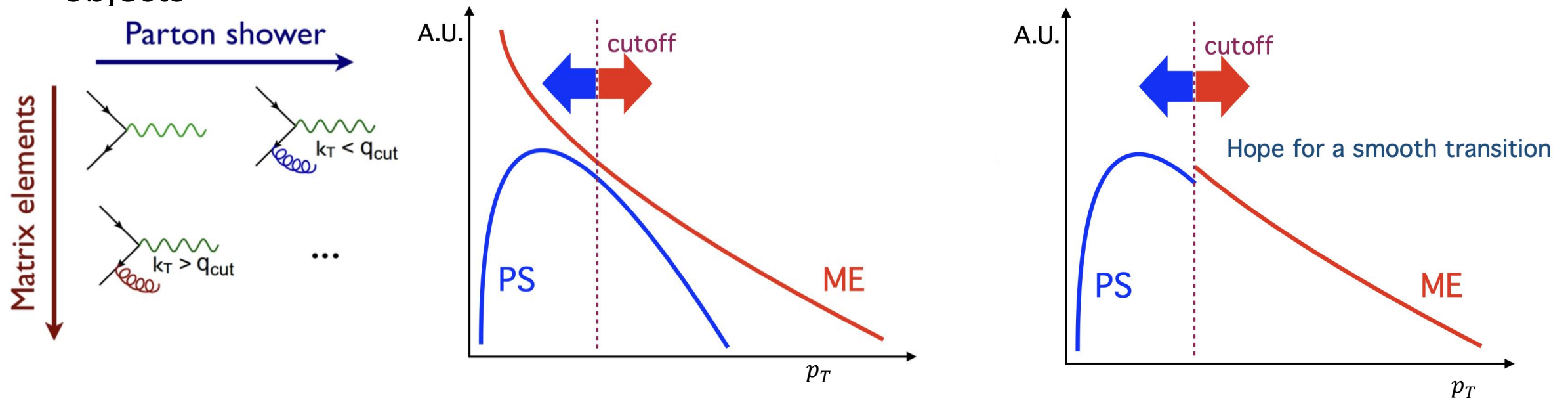
- Generate the leading order process (with its charge conjugate) with an extra jet
 - generate $p p \rightarrow w^+ w^+ w^-$
 - add process $p p \rightarrow w^+ w^+ w^- j$
- This may provide a better description of the event (used by the $t\bar{t}X$ group: <https://arxiv.org/pdf/2012.06872.pdf>)



- Diagrams associated the LO +1 jet process

Merge and match

- To ensure that there is no double counting in the matrix element and parton shower computations, we tune the values of two different parameters
 - $xqcut$: this is a setting in the Madgraph run_card (is a function of the momenta of the partons and their angular separation)
 - If $k_T < xqcut$, the event is not generated
 - $qcut$: this is a pythia setting, where pythia calculates the momenta of every final state objects



[Discussion on Matching/Merging at the GEN Meeting](#)

Object ID

Loose(Tight) Electron

mvaFall17V2Iso_WP90(80)

$$p_T > 10\text{GeV}$$

$$|\eta| < 2.5, \text{ veto } 1.444 < |\eta| < 1.566$$

AK4Jet

$$p_T > 30\text{GeV}$$

$$|\eta| < 3.0$$

$$\Delta R > 0.4 \text{ from lepton}$$

AK8Jet

$$p_T > 200\text{GeV}$$

$$|\eta| < 2.4$$

$$\Delta R > 0.8 \text{ from lepton}$$

Loose(Tight) Muon

Medium POG ID

$$p_T > 10\text{GeV}$$

$$|\eta| < 2.4$$

$$\text{pfRelIso04_all} < 0.25(0.15)$$

Medium b-Jet

$$p_T > 20\text{GeV}$$

$$|\eta| < 2.4$$

$$\Delta R > 0.4 \text{ from lepton}$$

DeepFlavB tagger medium WP

Medium FatJet

AK8 jet

$$65\text{GeV} < m_{sd} < 105\text{GeV}$$

ParticleNetMD W tagger medium WP

Trigger

- All hadronic trigger (0 lepton final state)
 - HLT_AK8PFJet400_TrimMass30
 - HLT_PFHT1050
 - HLT_AK8PFJet500
 - HLT_AK8PFJet400_TrimMass3
- Single lepton trigger (1 lepton final state)
 - 2016
 - HLT_IsoMu24
 - HLT_Ele27_WPTight
 - 2017
 - HLT_IsoMu27
 - HLT_Ele35_WPTight
 - 2018
 - HLT_IsoMu24
 - HLT_Ele32_WPTight
- Dilepton trigger (2 leptons final states)
 - 2016
 - HLT_Ele23_Ele12_CaloldL_TrackIdL_IsoVL_DZ
 - HLT_Mu23/8_TrkIsoVVL_Ele12/23_CaloldL_TrackIdL_IsoVL(_DZ)
 - HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL(_DZ)
 - 2017/2018
 - HLT_Ele23_Ele12_CaloldL_TrackIdL_IsoVL
 - HLT_Mu23/8_TrkIsoVVL_Ele12/23_CaloldL_TrackIdL_IsoVL_DZ
 - HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8

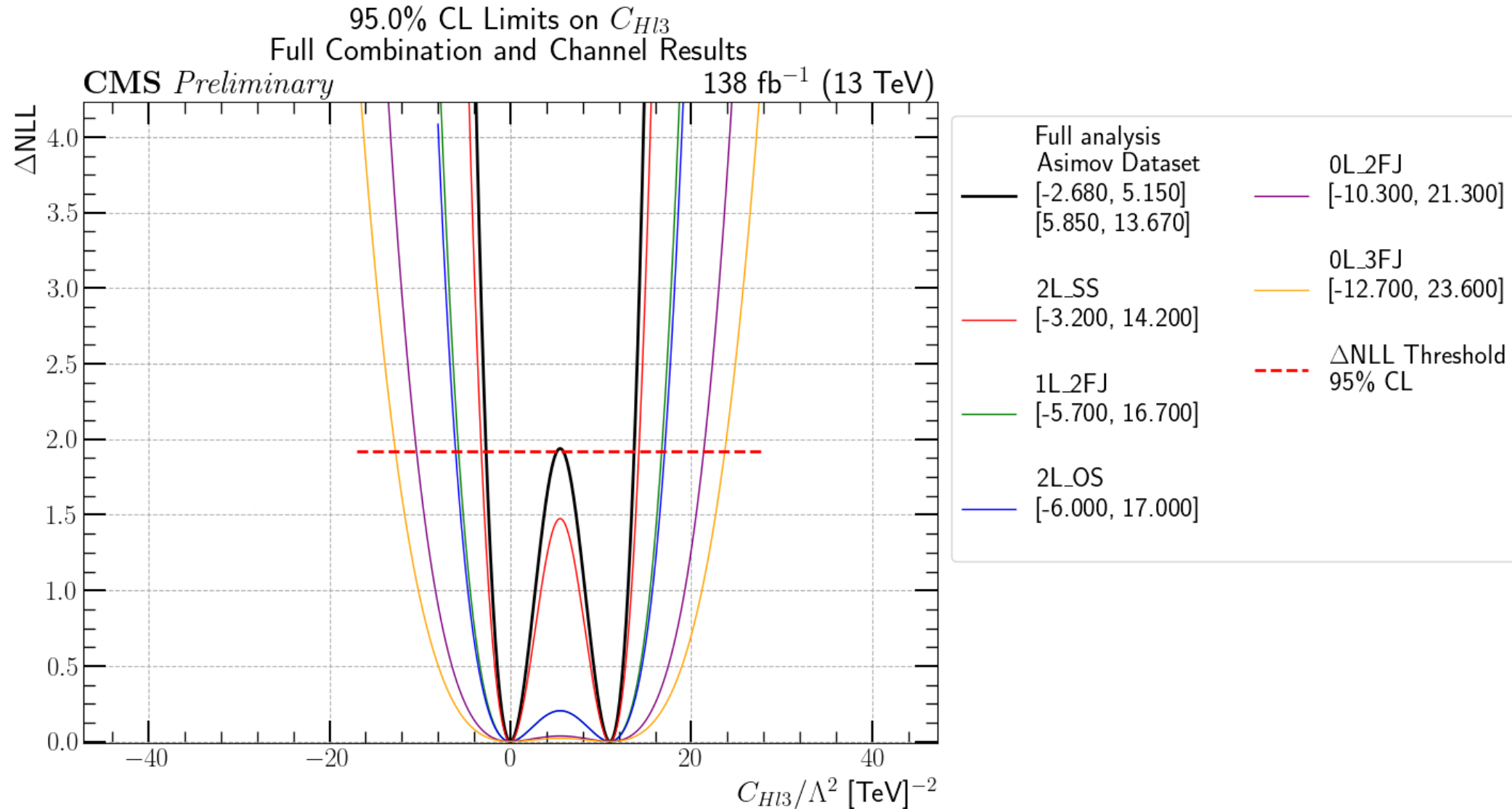
Current Status of Higgs combine Calculation

- ROOT histograms store nominal yield for each background process
- Up/Down template histograms store nominal yields $\pm 1\sigma$ for systematics (shape and norm)
- autoMCStats (threshold=0) used to incorporate MC statistical uncertainty (background processes only) – information stored in bin statistical errors of the nominal yield histograms
- VVV yields are supplied as parabola parameter histograms:
 - SM VVV
 - Quadratic coeff.
 - SM VVV + Linear coeff. + Quadratic coeff. (ensures positive values passed into combine)
- “[AnalyticAnomalousCoupling](#)” add-on to Higgs combine used for EFT parameterization
 - Generates a RooWorkspace
 - Combine calculation run using the “MultiDimFit” method (brute force NLL scan).
- In MultiDimFit, the profiled likelihood function is calculated at each point.
- Current implementation: freeze all Wilson coefficients to zero and float one at a time.

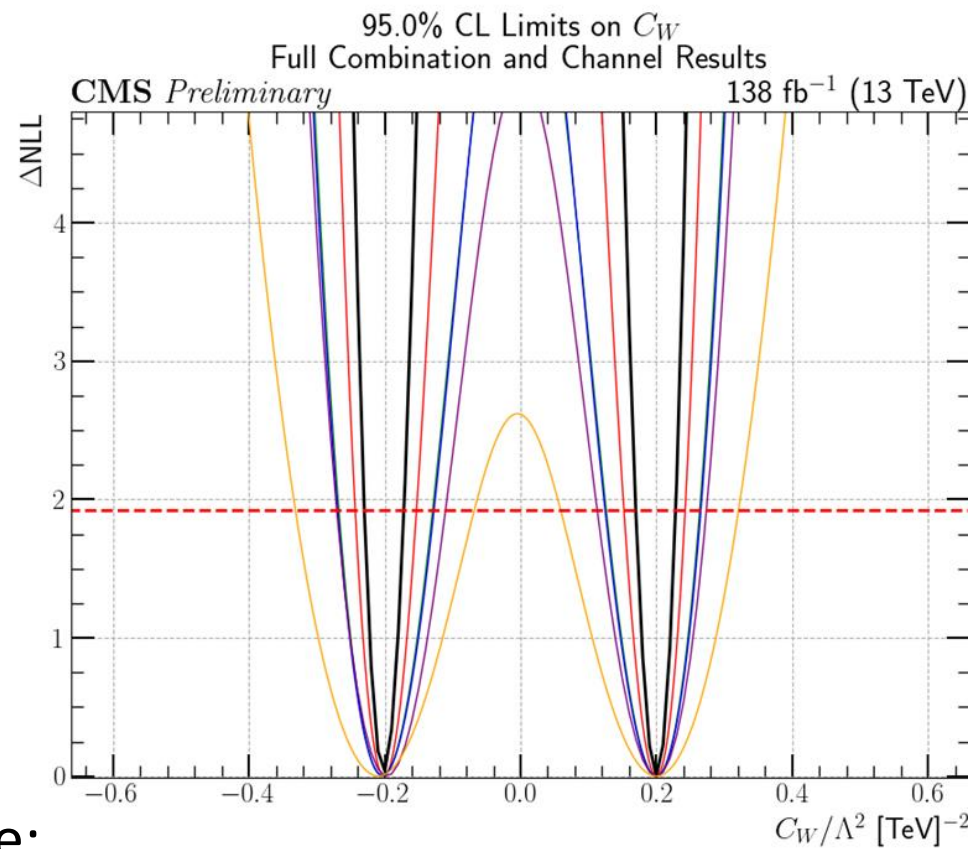
Software Environment: Higgs combine

- Installation most recently built and tested on August 31, 2023 on FNAL LPC.
- VVV codes:
<https://github.com/Saptaparna/EFTAnalysis/tree/master/EFTAnalysisFitting>
- CMSSW: v10.2.13
- Higgs combine: v8.1.0
- AnalyticAnomalousCoupling: head of master
(commit eb032ba356393997ec2db1066638b2d7b22e95e5)
- CombineHarvester: head of master
(commit 610d8ded8d1f71ed4db4d634cd9e2d7b8ae7b560)

Discontinuous limit: C_{Hl3}



Signal Injection ($c_W = 0.2$)



Procedure:

- Set $h_{\text{data_obs}}$ to be:
 $\text{sum}(b_i) + N_{c_W}(0.2)$
- The analysis correctly finds two minima at ± 0.2 (c_W yields are symmetric)
- $c_W = 0$ is excluded!

Pull / Impact Plot

- Used CombineHarvester: “combineTools.py” with “Impact
- Interpretation of impact plot u of the POI
- Impact plot looks more like w (right plot)

