Karlsruher Institut für Technologie

Summary

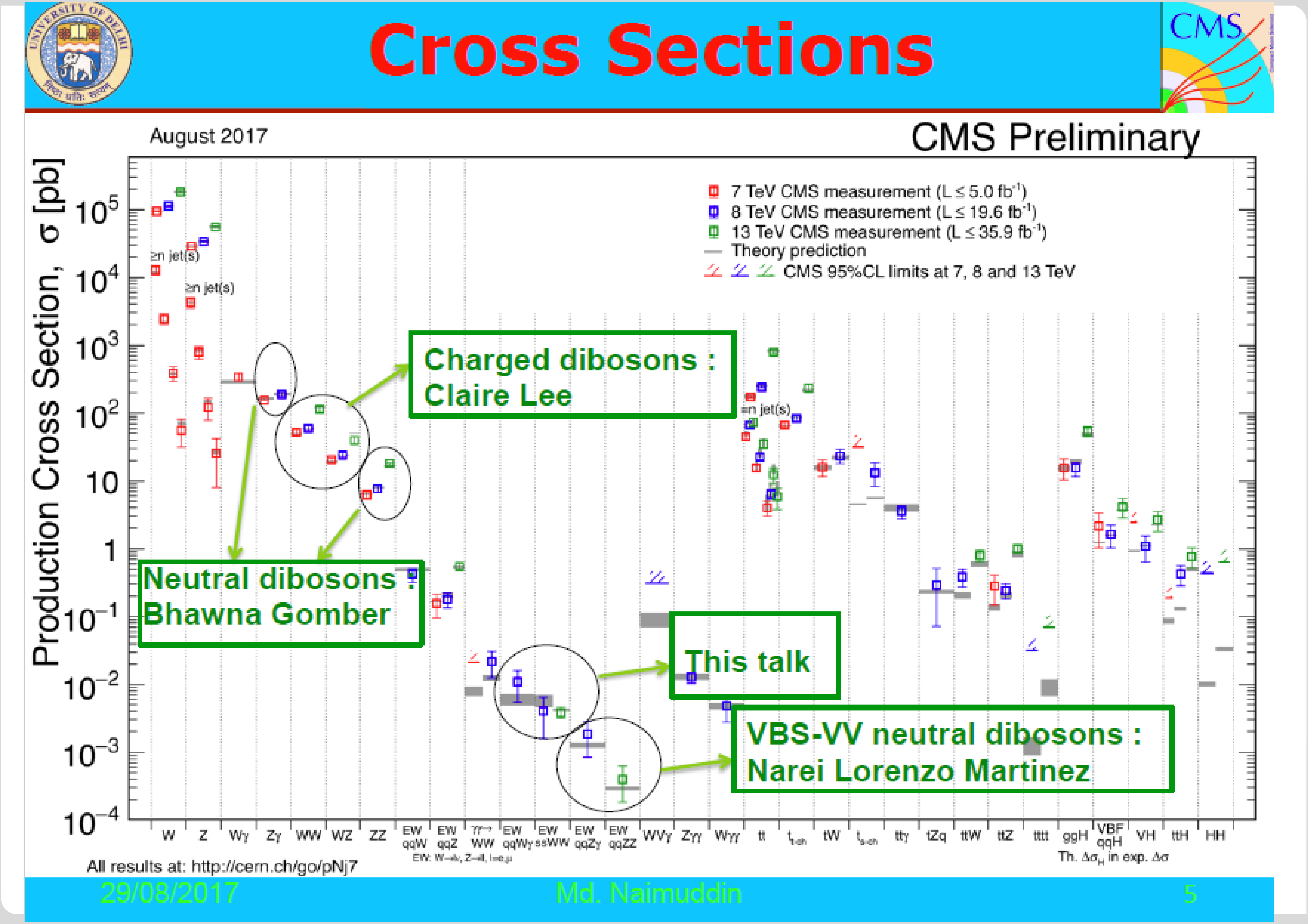
Dieter Zeppenfeld, KIT
Multi Boson Interactions 2017, Karlsruhe

KIT Center Elementary Particle and Astroparticle Physics - KCETA

Many great talks, covering experiment and theory

- New experimental results on many fronts
  - VV production: Lee, Gomber
  - VBS: Lorenzo Martinez, Naimuddin
  - VVV and Higgs: Brun, Helary, Vanlaer
  - Searches and techniques: Mozer, Xi
- Monte Carlo generators and their theoretical basis: Kilian, Mimasu, Rauch, Schumann
- Models of BSM: Butter, Delgado, Pomarol, Riva, Wulzer,
- Progress on precision calculations:
  - NNLO QCD corrections: Grazzini
  - NLO EW corrections: Pellen
- Future accelerators: Roloff

Good interaction/discussions between theory and experiment



Cross Sections

Charged dibosons : Claire Lee

Neutral dibosons : Bhawna Gomber

This talk

VBS-VV neutral dibosons : Narei Lorenzo Martinez

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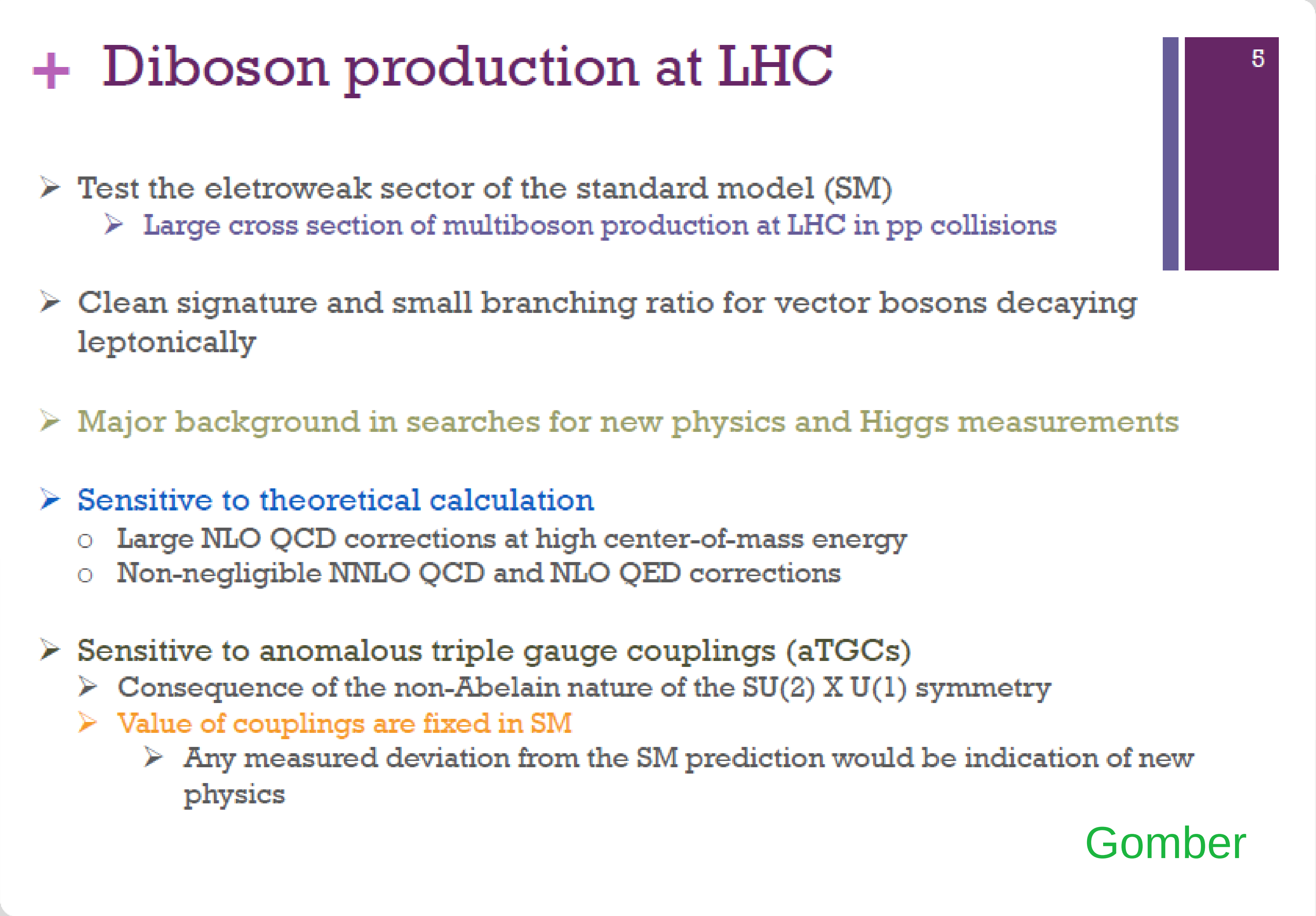
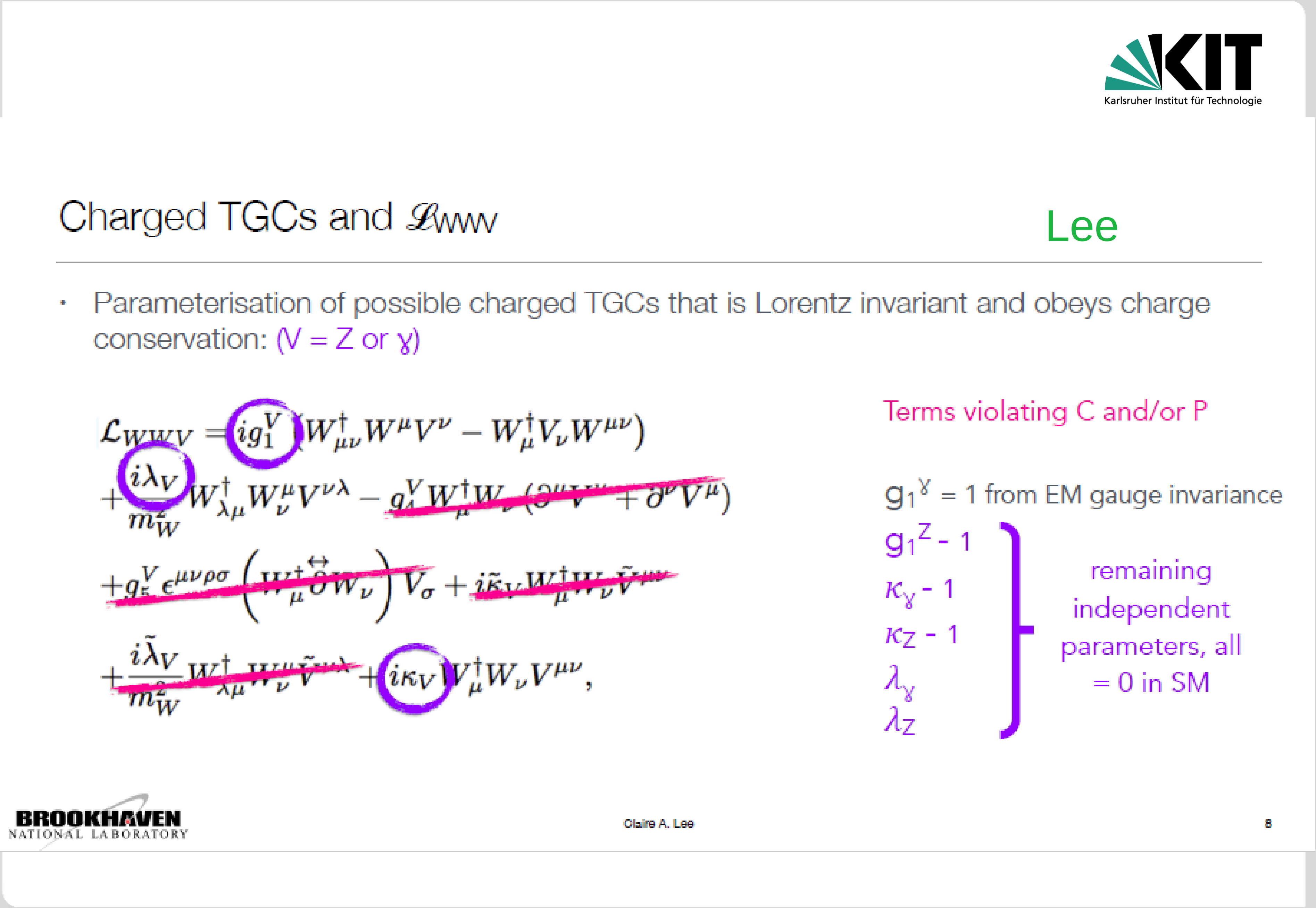


+ Diboson production at LHC

- Test the eletroweak sector of the standard model (SM)
    - Large cross section of multiboson production at LHC in pp collisions
- Clean signature and small branching ratio for vector bosons decaying leptonically
- Major background in searches for new physics and Higgs measurements
- Sensitive to theoretical calculation
    - Large NLO QCD corrections at high center-of-mass energy
    - Non-negligible NNLO QCD and NLO QED corrections
- Sensitive to anomalous triple gauge couplings (aTGCs)
    - Consequence of the non-Abelain nature of the SU(2) X U(1) symmetry
    - Value of couplings are fixed in SM
        - Any measured deviation from the SM prediction would be indication of new physics

Gomber



Charged TGCs and $\mathscr{L}_{WWV}$

Lee

- Parameterisation of possible charged TGCs that is Lorentz invariant and obeys charge conservation: (V = Z or γ)

$$\begin{aligned}\mathcal{L}_{WWV} = {}& \boxed{ig_1^V}\left(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}\right)\\ &+ \frac{\boxed{i\lambda_V}}{m_W^2} W^\dagger_{\lambda\mu}W^\mu_\nu V^{\nu\lambda} - \cancel{g_4^V W^\dagger_\mu W_\nu\left(\partial^\mu V^\nu + \partial^\nu V^\mu\right)}\\ &+ \cancel{g_5^V \epsilon^{\mu\nu\rho\sigma}\left(W^\dagger_\mu \overleftrightarrow{\partial}_\rho W_\nu\right)} V_\sigma + \cancel{i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu}}\\ &+ \cancel{\frac{i\tilde{\lambda}_V}{m_W^2} W^\dagger_{\lambda\mu}W^\mu_\nu \tilde{V}^{\nu\lambda}} + \boxed{i\kappa_V} W^\dagger_\mu W_\nu V^{\mu\nu},\end{aligned}$$

Terms violating C and/or P

g_1^γ = 1 from EM gauge invariance

$$\left.\begin{array}{l} g_1^Z - 1\\ \kappa_\gamma - 1\\ \kappa_Z - 1\\ \lambda_\gamma\\ \lambda_Z \end{array}\right\}\ \text{remaining independent parameters, all} = 0 \text{ in SM}$$

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Claire A. Lee

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Lee

EFT Approach

- An alternative framework for describing modifications of diboson production is an EFT that is assumed to be valid below an energy scale Λ, formed by adding higher-dimension operators to the SM Lagrangian:

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathscr{O}_i + \sum_j \frac{f_j}{\Lambda^4}\mathscr{O}_j + \dots$$

- There are three CP-conserving dimension-6 operators, with coefficients that are zero in the SM, and are related to the LEP-constrained aTGC parameters.
-

$$\begin{aligned} \mathcal{O}_W &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)\,, \\ \mathcal{O}_B &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)\,, \\ \mathcal{O}_{WWW} &= Tr[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}]\,. \end{aligned}$$

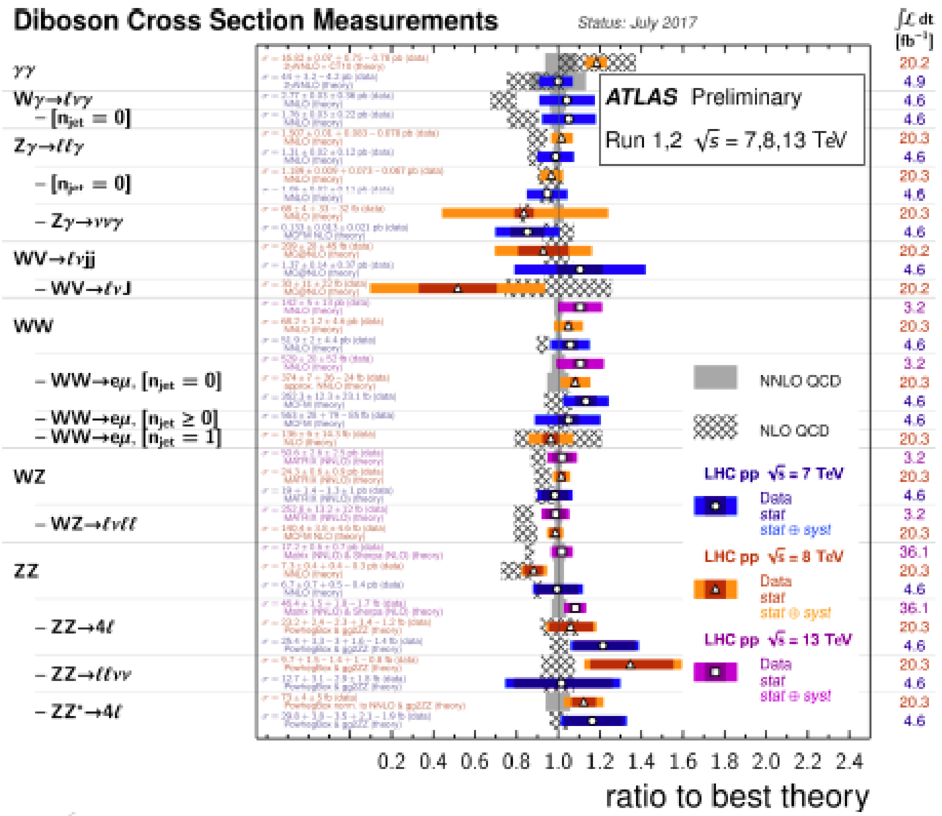
$$\begin{aligned} \frac{c_W}{\Lambda^2} &= \frac{2}{m_Z^2}\Delta g_1^Z\,, \\ \frac{c_B}{\Lambda^2} &= \frac{2}{m_W^2}\Delta\kappa_\gamma - \frac{2}{m_Z^2}\Delta g_1^Z\,, \\ \frac{c_{WWW}}{\Lambda^2} &= \frac{2}{3g^2 m_W^2}\lambda\,. \end{aligned}$$

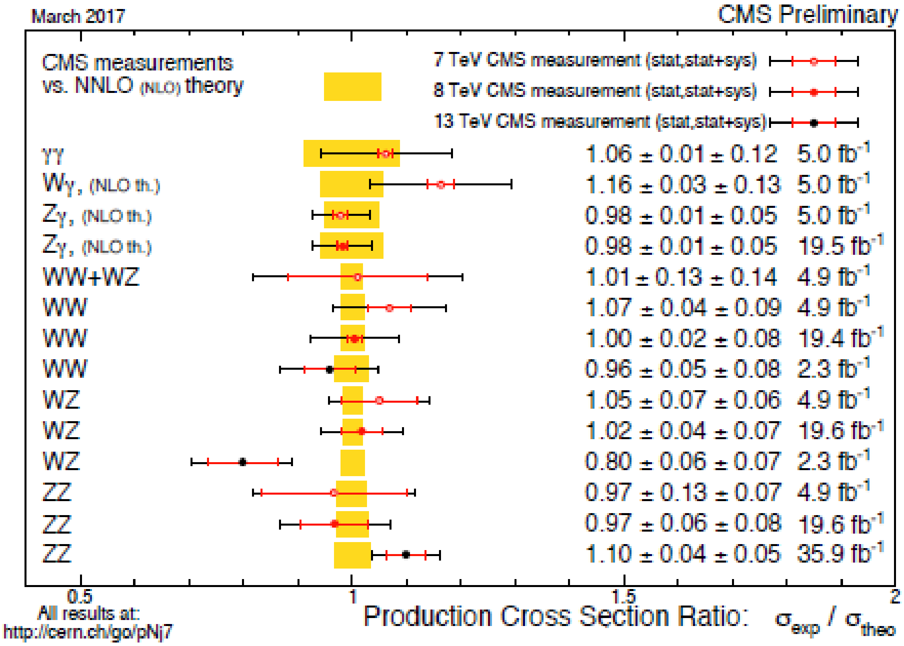
- Since the LHC results have now surpassed LEP/Tevatron limits, the LHC aGC Taskforce recommends to now move towards using the dimension-6 EFT operators in our results.

Cross sections agree with SM expectations

Current Status of Diboson Measurements

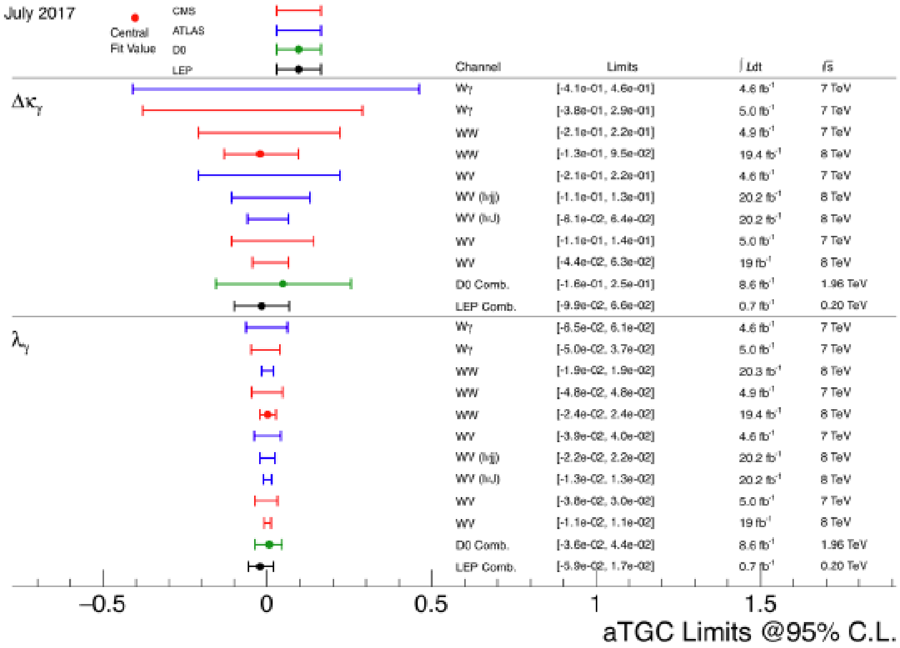
Lee



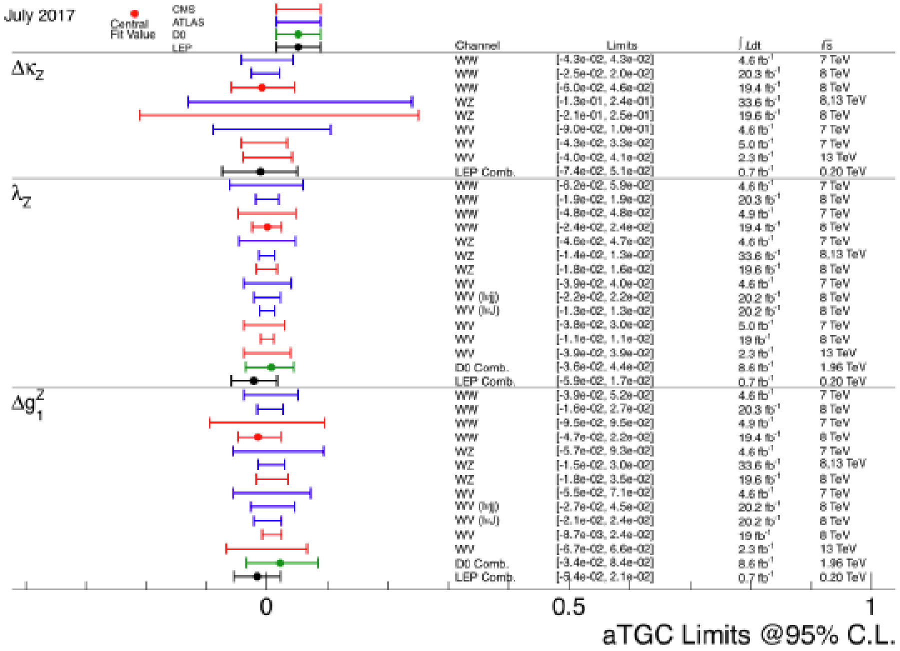


Current Status of Charged aTGC Limits

Coupling	Parameter	Channel
WWɣ	$\lambda_\gamma, \Delta\kappa_\gamma$	WW,Wɣ
WWZ	$\lambda_Z, \Delta\kappa_Z, \Delta g_1^Z$	WW,WZ



	Channel	Limits	$\int L dt$	$\sqrt{s}$
$\Delta\kappa_\gamma$	Wγ	[-4.1e-01, 4.6e-01]	4.6 fb^{-1}	7 TeV
	Wγ	[-3.8e-01, 2.9e-01]	5.0 fb^{-1}	7 TeV
	WW	[-2.1e-01, 2.2e-01]	4.9 fb^{-1}	7 TeV
	WW	[-1.3e-01, 9.5e-02]	19.4 fb^{-1}	8 TeV
	WV	[-2.1e-01, 2.2e-01]	4.6 fb^{-1}	7 TeV
	WV (lνjj)	[-1.1e-01, 1.3e-01]	20.2 fb^{-1}	8 TeV
	WV (lνJ)	[-8.1e-02, 6.4e-02]	20.2 fb^{-1}	8 TeV
	WV	[-1.1e-01, 1.4e-01]	5.0 fb^{-1}	7 TeV
	WV	[-4.4e-02, 6.3e-02]	19 fb^{-1}	8 TeV
	D0 Comb.	[-1.6e-01, 2.5e-01]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-9.9e-02, 6.6e-02]	0.7 fb^{-1}	0.20 TeV
λ_γ	Wγ	[-6.5e-02, 6.1e-02]	4.6 fb^{-1}	7 TeV
	Wγ	[-5.0e-02, 3.7e-02]	5.0 fb^{-1}	7 TeV
	WW	[-1.9e-02, 1.9e-02]	20.3 fb^{-1}	8 TeV
	WW	[-4.8e-02, 4.8e-02]	4.9 fb^{-1}	7 TeV
	WW	[-2.4e-02, 2.4e-02]	19.4 fb^{-1}	8 TeV
	WV	[-3.9e-02, 4.0e-02]	4.6 fb^{-1}	7 TeV
	WV (lνjj)	[-2.2e-02, 2.2e-02]	20.2 fb^{-1}	8 TeV
	WV (lνJ)	[-1.3e-02, 1.3e-02]	20.2 fb^{-1}	8 TeV
	WV	[-3.8e-02, 3.0e-02]	5.0 fb^{-1}	7 TeV
	WV	[-1.1e-02, 1.1e-02]	19 fb^{-1}	8 TeV
	D0 Comb.	[-3.6e-02, 4.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.9e-02, 1.7e-02]	0.7 fb^{-1}	0.20 TeV



	Channel	Limits	$\int L dt$	$\sqrt{s}$
$\Delta\kappa_Z$	WW	[-4.3e-02, 4.3e-02]	4.6 fb^{-1}	7 TeV
	WW	[-2.5e-02, 2.0e-02]	20.3 fb^{-1}	8 TeV
	WW	[-6.0e-02, 4.6e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-1.3e-01, 2.4e-01]	33.6 fb^{-1}	8,13 TeV
	WZ	[-2.1e-01, 2.5e-01]	19.6 fb^{-1}	8 TeV
	WV	[-9.0e-02, 1.0e-01]	4.6 fb^{-1}	7 TeV
	WV	[-4.3e-02, 3.3e-02]	5.0 fb^{-1}	7 TeV
	WV	[-4.0e-02, 4.1e-02]	2.3 fb^{-1}	13 TeV
	LEP Comb.	[-7.4e-02, 5.1e-02]	0.7 fb^{-1}	0.20 TeV
λ_Z	WW	[-6.2e-02, 5.9e-02]	4.6 fb^{-1}	7 TeV
	WW	[-1.9e-02, 1.9e-02]	20.3 fb^{-1}	8 TeV
	WW	[-4.8e-02, 4.8e-02]	4.9 fb^{-1}	7 TeV
	WW	[-2.4e-02, 2.4e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-4.6e-02, 4.7e-02]	4.6 fb^{-1}	7 TeV
	WZ	[-1.4e-02, 1.3e-02]	33.6 fb^{-1}	8,13 TeV
	WZ	[-1.8e-02, 1.6e-02]	19.6 fb^{-1}	8 TeV
	WV	[-3.9e-02, 4.0e-02]	4.6 fb^{-1}	7 TeV
	WV (lνjj)	[-2.2e-02, 2.2e-02]	20.2 fb^{-1}	8 TeV
	WV (lνJ)	[-1.3e-02, 1.3e-02]	20.2 fb^{-1}	8 TeV
	WV	[-3.8e-02, 3.0e-02]	5.0 fb^{-1}	7 TeV
	WV	[-1.1e-02, 1.1e-02]	19 fb^{-1}	8 TeV
	WV	[-3.9e-02, 3.9e-02]	2.3 fb^{-1}	13 TeV
	D0 Comb.	[-3.6e-02, 4.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.9e-02, 1.7e-02]	0.7 fb^{-1}	0.20 TeV
Δg_1^Z	WW	[-3.9e-02, 5.2e-02]	4.6 fb^{-1}	7 TeV
	WW	[-1.6e-02, 2.7e-02]	20.3 fb^{-1}	8 TeV
	WW	[-9.5e-02, 9.5e-02]	4.9 fb^{-1}	7 TeV
	WW	[-4.7e-02, 2.2e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-5.7e-02, 9.3e-02]	4.6 fb^{-1}	7 TeV
	WZ	[-1.5e-02, 3.0e-02]	33.6 fb^{-1}	8,13 TeV
	WZ	[-1.8e-02, 3.5e-02]	19.6 fb^{-1}	8 TeV
	WV	[-5.5e-02, 7.1e-02]	4.6 fb^{-1}	7 TeV
	WV (lνjj)	[-2.7e-02, 4.5e-02]	20.2 fb^{-1}	8 TeV
	WV (lνJ)	[-2.1e-02, 2.4e-02]	20.2 fb^{-1}	8 TeV
	WV	[-8.7e-03, 2.4e-02]	19 fb^{-1}	8 TeV
	WV	[-6.7e-02, 6.6e-02]	2.3 fb^{-1}	13 TeV
	D0 Comb.	[-3.4e-02, 8.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.4e-02, 2.1e-02]	0.7 fb^{-1}	0.20 TeV

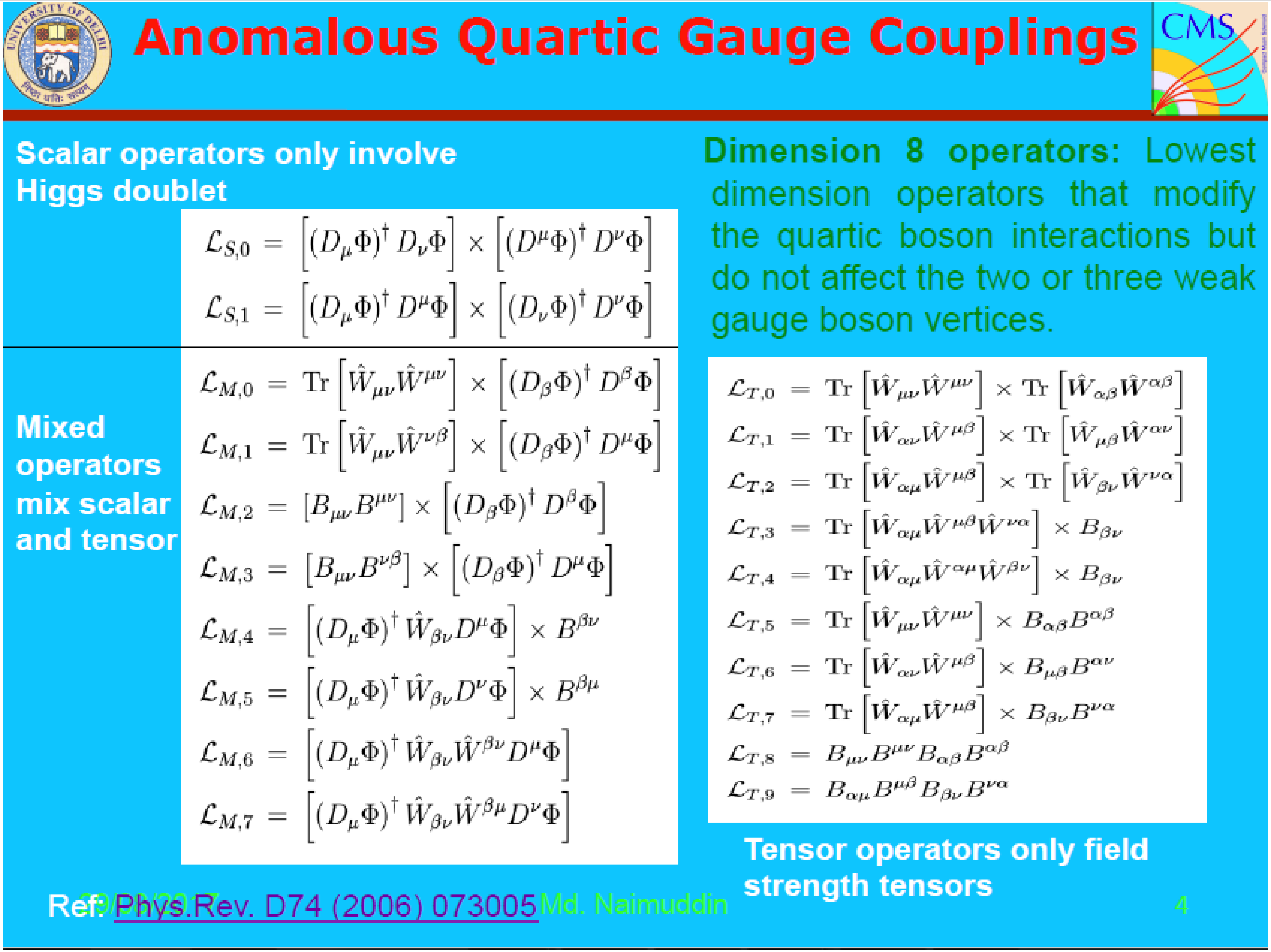
Lee

Vector boson scattering

The $m_h = 125$ GeV Higgs will unitarize $VV \to VV$ scattering provided it has SM hVV couplings

$\Longrightarrow$ Check this by either

- precise measurements of the hVV couplings at the light Higgs resonance
- measurement of $VV \to VV$ differential cross sections at high p_T and invariant mass



Anomalous Quartic Gauge Couplings

Scalar operators only involve Higgs doublet

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

Mixed operators mix scalar and tensor

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu}$$

$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu}$$

$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$$

$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

Dimension 8 operators: Lowest dimension operators that modify the quartic boson interactions but do not affect the two or three weak gauge boson vertices.

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$

$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$

$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$

$$\mathcal{L}_{T,3} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\hat{W}^{\nu\alpha}\right] \times B_{\beta\nu}$$

$$\mathcal{L}_{T,4} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\alpha\mu}\hat{W}^{\beta\nu}\right] \times B_{\beta\nu}$$

$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$

$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$

$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

Tensor operators only field strength tensors

Ref: Phys.Rev. D74 (2006) 073005

Md. Naimuddin

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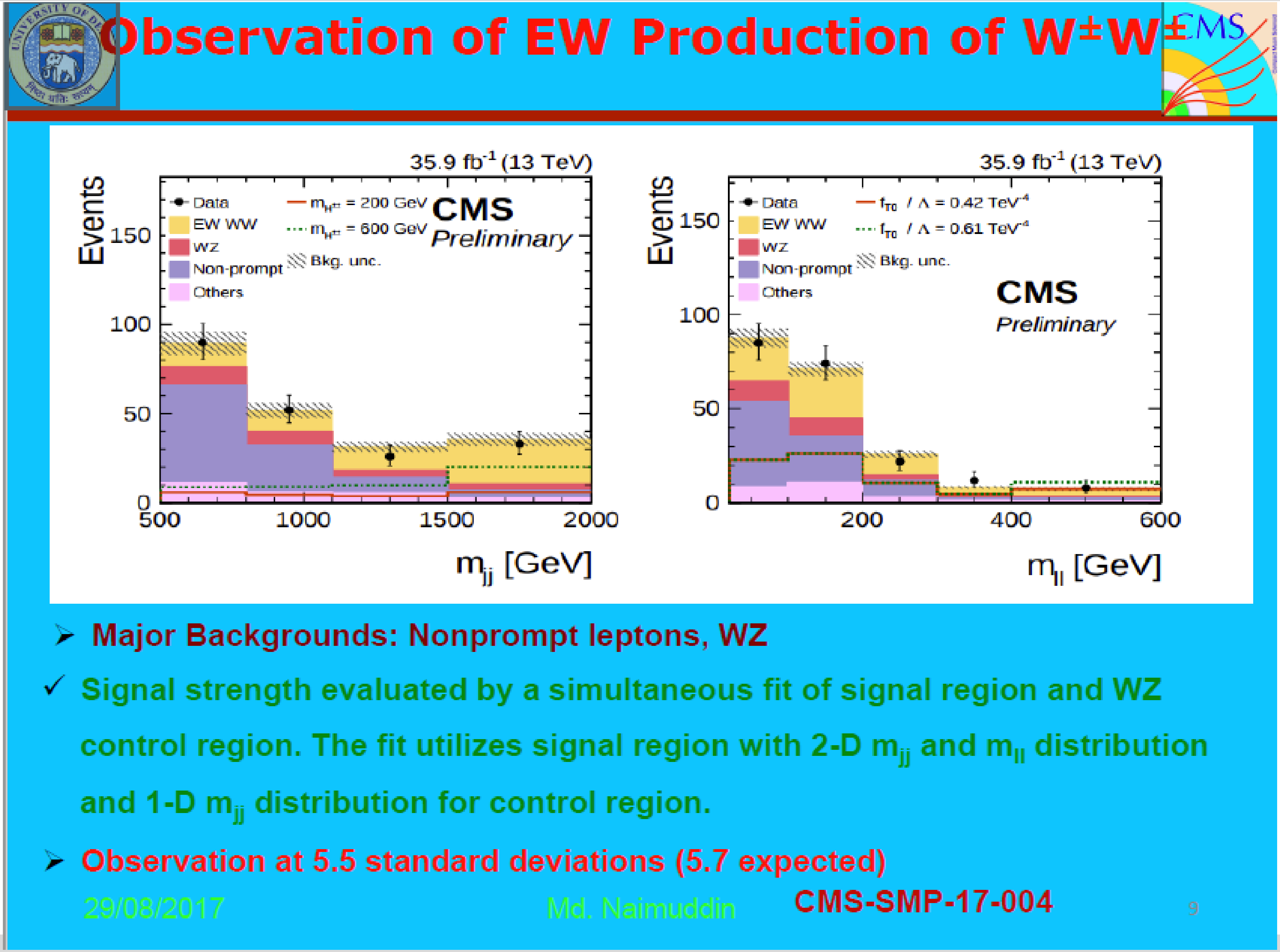


Observation of EW Production of W±W±

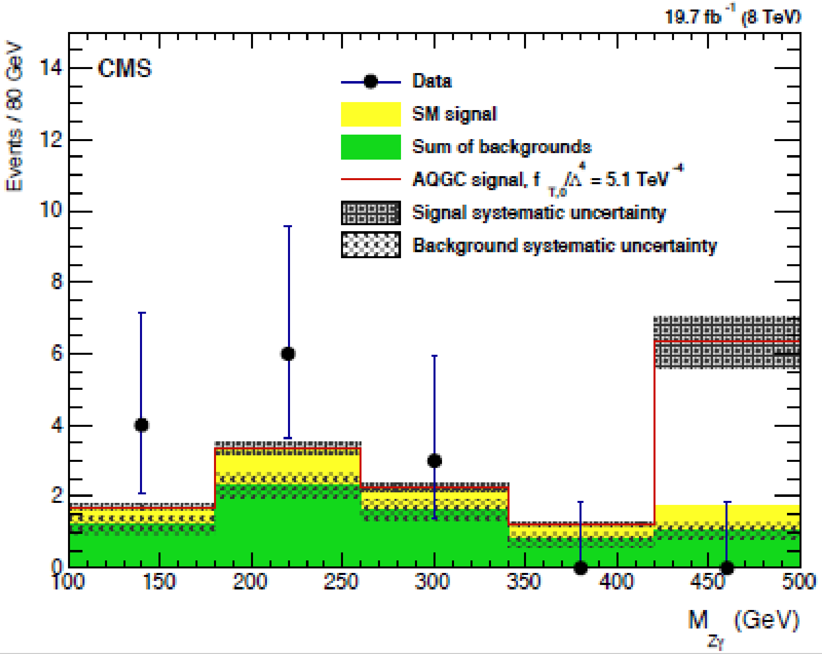
- ➢ **Major Backgrounds: Nonprompt leptons, WZ**
- ✓ **Signal strength evaluated by a simultaneous fit of signal region and WZ control region. The fit utilizes signal region with 2-D m_{jj} and m_{ll} distribution and 1-D m_{jj} distribution for control region.**
- ➢ **Observation at 5.5 standard deviations (5.7 expected)**

29/08/2017 Md. Naimuddin **CMS-SMP-17-004** 9

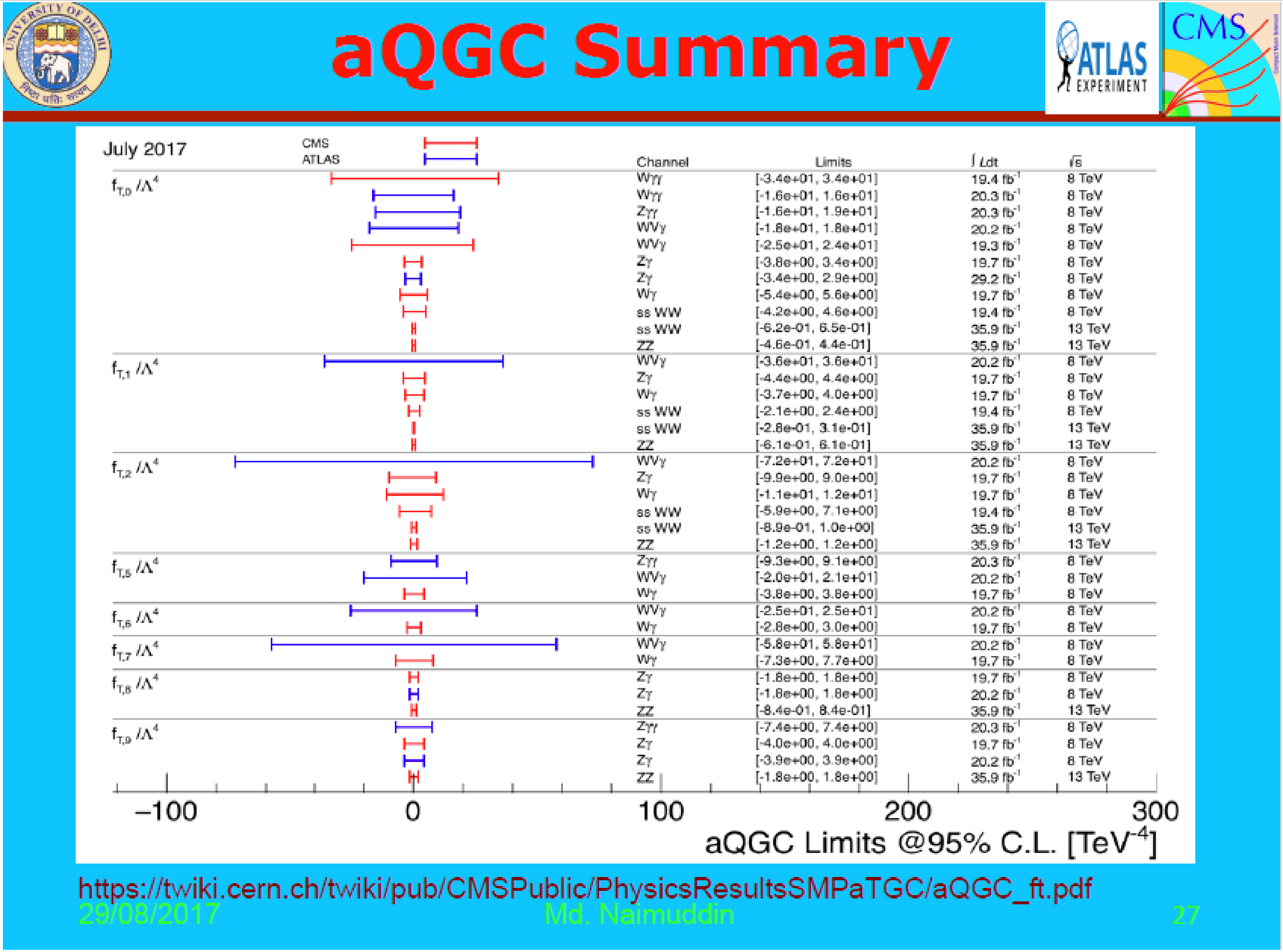
aQGC strategy and results - CMS: Zγ

Lorenzo Martinez

- On top of baseline region:
  - $E_{T\gamma}$>60 GeV, ΔY>2.5, m_{jj}>400 GeV
- Likelihood ratio test on $M_{Z\gamma}$ distribution
- EFT dim8, Lagrangian of aQGC implemented in MadGraph
- Each coupling varied over a set of discrete values, other parameters set to 0
- Unitarity bound checked with **VBFNLO**
  - no form factors introduced, limits on all aQGC parameters (except FT9) are set in the **unitary unsafe region**



Observed limits (TeV^{-4})	Expected limits (TeV^{-4})
$-71 < f_{M0}/\Lambda^4 < 75$	$-109 < f_{M0}/\Lambda^4 < 111$
$-190 < f_{M1}/\Lambda^4 < 182$	$-281 < f_{M1}/\Lambda^4 < 280$
$-32 < f_{M2}/\Lambda^4 < 31$	$-47 < f_{M2}/\Lambda^4 < 47$
$-58 < f_{M3}/\Lambda^4 < 59$	$-87 < f_{M3}/\Lambda^4 < 87$
$-3.8 < f_{T0}/\Lambda^4 < 3.4$	$-5.1 < f_{T0}/\Lambda^4 < 5.1$
$-4.4 < f_{T1}/\Lambda^4 < 4.4$	$-6.5 < f_{T1}/\Lambda^4 < 6.5$
$-9.9 < f_{T2}/\Lambda^4 < 9.0$	$-14.0 < f_{T2}/\Lambda^4 < 14.5$
$-1.8 < f_{T8}/\Lambda^4 < 1.8$	$-2.7 < f_{T8}/\Lambda^4 < 2.7$
$-4.0 < f_{T9}/\Lambda^4 < 4.0$	$-6.0 < f_{T9}/\Lambda^4 < 6.0$



aQGC Summary

	Channel	Limits	$\int \mathcal{L}dt$	$\sqrt{s}$
$f_{T,0}/\Lambda^4$	$W\gamma\gamma$	[-3.4e+01, 3.4e+01]	19.4 fb^{-1}	8 TeV
	$W\gamma\gamma$	[-1.6e+01, 1.6e+01]	20.3 fb^{-1}	8 TeV
	$Z\gamma\gamma$	[-1.6e+01, 1.9e+01]	20.3 fb^{-1}	8 TeV
	$WV\gamma$	[-1.8e+01, 1.8e+01]	20.2 fb^{-1}	8 TeV
	$WV\gamma$	[-2.5e+01, 2.4e+01]	19.3 fb^{-1}	8 TeV
	$Z\gamma$	[-3.8e+00, 3.4e+00]	19.7 fb^{-1}	8 TeV
	$Z\gamma$	[-3.4e+00, 2.9e+00]	29.2 fb^{-1}	8 TeV
	$W\gamma$	[-5.4e+00, 5.6e+00]	19.7 fb^{-1}	8 TeV
	ss WW	[-4.2e+00, 4.6e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-6.2e-01, 6.5e-01]	35.9 fb^{-1}	13 TeV
	ZZ	[-4.6e-01, 4.4e-01]	35.9 fb^{-1}	13 TeV
$f_{T,1}/\Lambda^4$	$WV\gamma$	[-3.6e+01, 3.6e+01]	20.2 fb^{-1}	8 TeV
	$Z\gamma$	[-4.4e+00, 4.4e+00]	19.7 fb^{-1}	8 TeV
	$W\gamma$	[-3.7e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV
	ss WW	[-2.1e+00, 2.4e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-2.8e-01, 3.1e-01]	35.9 fb^{-1}	13 TeV
	ZZ	[-6.1e-01, 6.1e-01]	35.9 fb^{-1}	13 TeV
$f_{T,2}/\Lambda^4$	$WV\gamma$	[-7.2e+01, 7.2e+01]	20.2 fb^{-1}	8 TeV
	$Z\gamma$	[-9.9e+00, 9.0e+00]	19.7 fb^{-1}	8 TeV
	$W\gamma$	[-1.1e+01, 1.2e+01]	19.7 fb^{-1}	8 TeV
	ss WW	[-5.9e+00, 7.1e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-8.9e-01, 1.0e+00]	35.9 fb^{-1}	13 TeV
	ZZ	[-1.2e+00, 1.2e+00]	35.9 fb^{-1}	13 TeV
$f_{T,5}/\Lambda^4$	$Z\gamma\gamma$	[-9.3e+00, 9.1e+00]	20.3 fb^{-1}	8 TeV
	$WV\gamma$	[-2.0e+01, 2.1e+01]	20.2 fb^{-1}	8 TeV
	$W\gamma$	[-3.8e+00, 3.8e+00]	19.7 fb^{-1}	8 TeV
$f_{T,6}/\Lambda^4$	$WV\gamma$	[-2.5e+01, 2.5e+01]	20.2 fb^{-1}	8 TeV
	$W\gamma$	[-2.8e+00, 3.0e+00]	19.7 fb^{-1}	8 TeV
$f_{T,7}/\Lambda^4$	$WV\gamma$	[-5.8e+01, 5.8e+01]	20.2 fb^{-1}	8 TeV
	$W\gamma$	[-7.3e+00, 7.7e+00]	19.7 fb^{-1}	8 TeV
$f_{T,8}/\Lambda^4$	$Z\gamma$	[-1.8e+00, 1.8e+00]	19.7 fb^{-1}	8 TeV
	$Z\gamma$	[-1.8e+00, 1.8e+00]	20.2 fb^{-1}	8 TeV
	ZZ	[-8.4e-01, 8.4e-01]	35.9 fb^{-1}	13 TeV
$f_{T,9}/\Lambda^4$	$Z\gamma\gamma$	[-7.4e+00, 7.4e+00]	20.3 fb^{-1}	8 TeV
	$Z\gamma$	[-4.0e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV
	$Z\gamma$	[-3.9e+00, 3.9e+00]	20.2 fb^{-1}	8 TeV
	ZZ	[-1.8e+00, 1.8e+00]	35.9 fb^{-1}	13 TeV

https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsSMPaTGC/aQGC_ft.pdf

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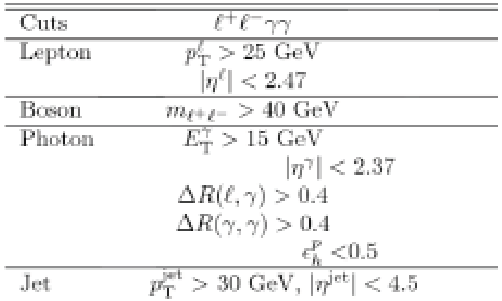
Z→(ll) γγ

ATLAS: *Phys. Rev. D 93, 112002 (2016)*
CMS: arXiv:1704.00366 submitted to JHEP

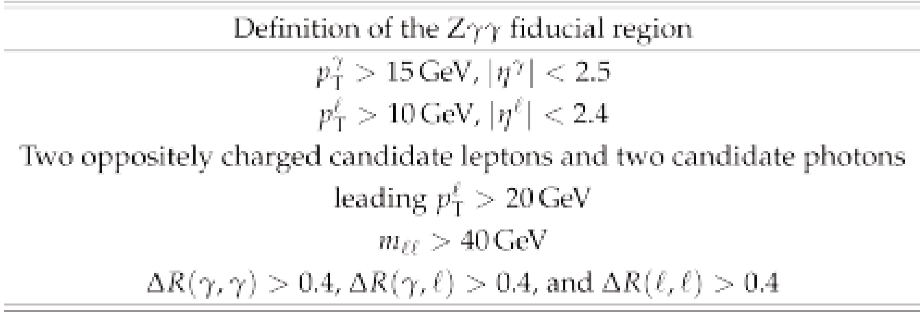
- First experimental observation (>5σ) for triboson production at hadron collider reported by ATLAS in 2016!
- Fiducial definition:

ATLAS:



Cuts	$\ell^+\ell^-\gamma\gamma$
Lepton	$p_T^\ell > 25$ GeV $\lvert\eta^\ell\rvert < 2.47$
Boson	$m_{\ell^+\ell^-} > 40$ GeV
Photon	$E_T^\gamma > 15$ GeV $\lvert\eta^\gamma\rvert < 2.37$ $\Delta R(\ell,\gamma) > 0.4$ $\Delta R(\gamma,\gamma) > 0.4$ $\epsilon_h^p < 0.5$
Jet	$p_T^{\text{jet}} > 30$ GeV, $\lvert\eta^{\text{jet}}\rvert < 4.5$ $\Delta R(\text{jet},\ell/\gamma) > 0.3$ $\Delta R(\text{jet},\gamma) > 0.3$ Inclusive : $N_{\text{jet}} \geq 0$, Exclusive : $N_{\text{jet}} = 0$

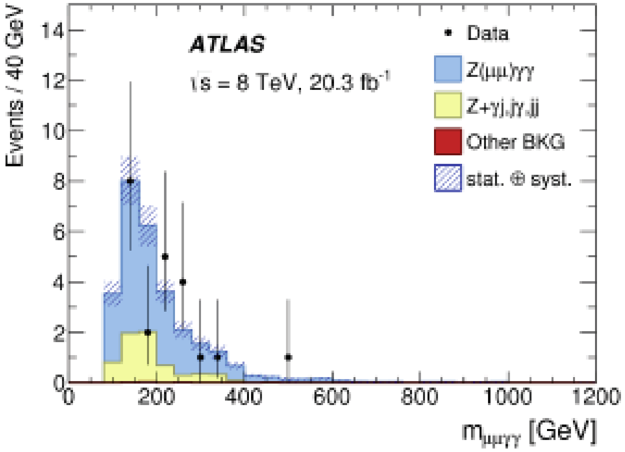
CMS:

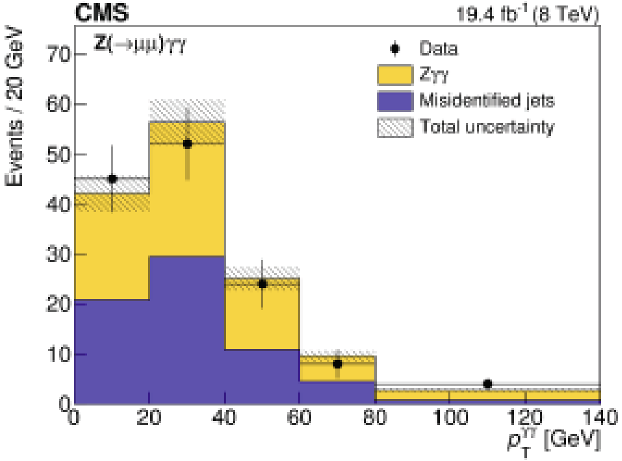


Definition of the $Z\gamma\gamma$ fiducial region
$p_T^\gamma > 15$ GeV, $\lvert\eta^\gamma\rvert < 2.5$
$p_T^\ell > 10$ GeV, $\lvert\eta^\ell\rvert < 2.4$
Two oppositely charged candidate leptons and two candidate photons
leading $p_T^\ell > 20$ GeV
$m_{\ell\ell} > 40$ GeV
$\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\gamma,\ell) > 0.4$, and $\Delta R(\ell,\ell) > 0.4$

- Backgrounds:
  - *Z+jets and Zγ+jet (2D fit of isolation and Photon ID), other bkg negligible.*

Helary

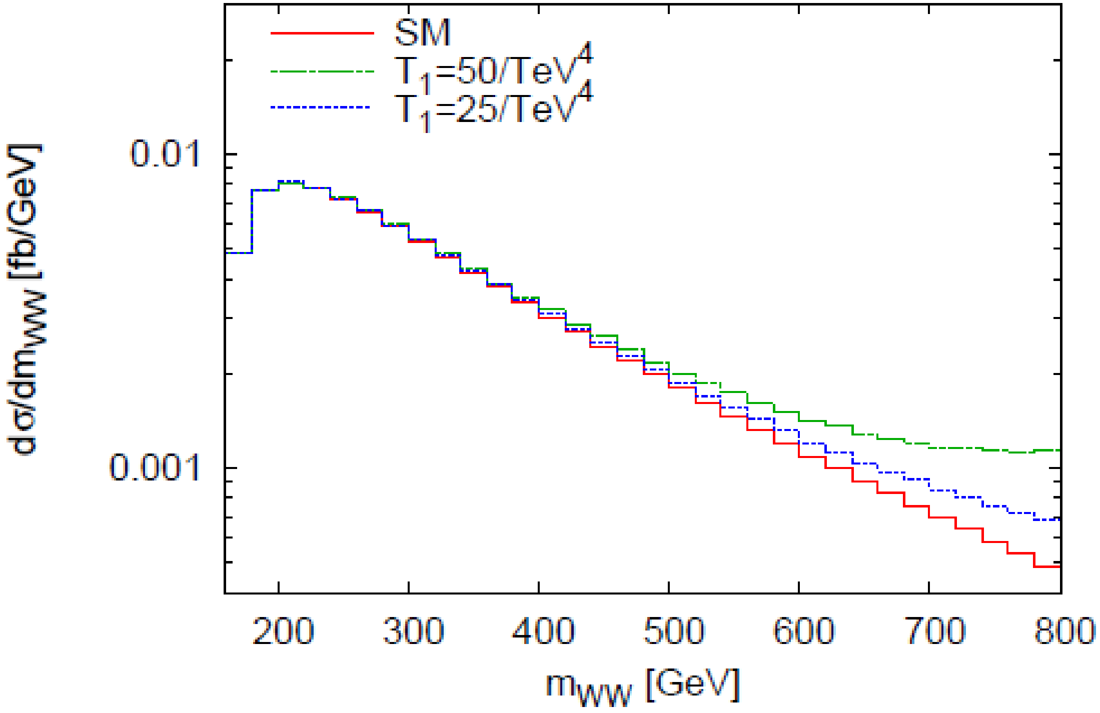




$VV \to W^+W^-$ with dimension 8 operators

Effect of $\mathcal{L}_{eff} = \frac{f_{M,1}}{\Lambda^4} \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$

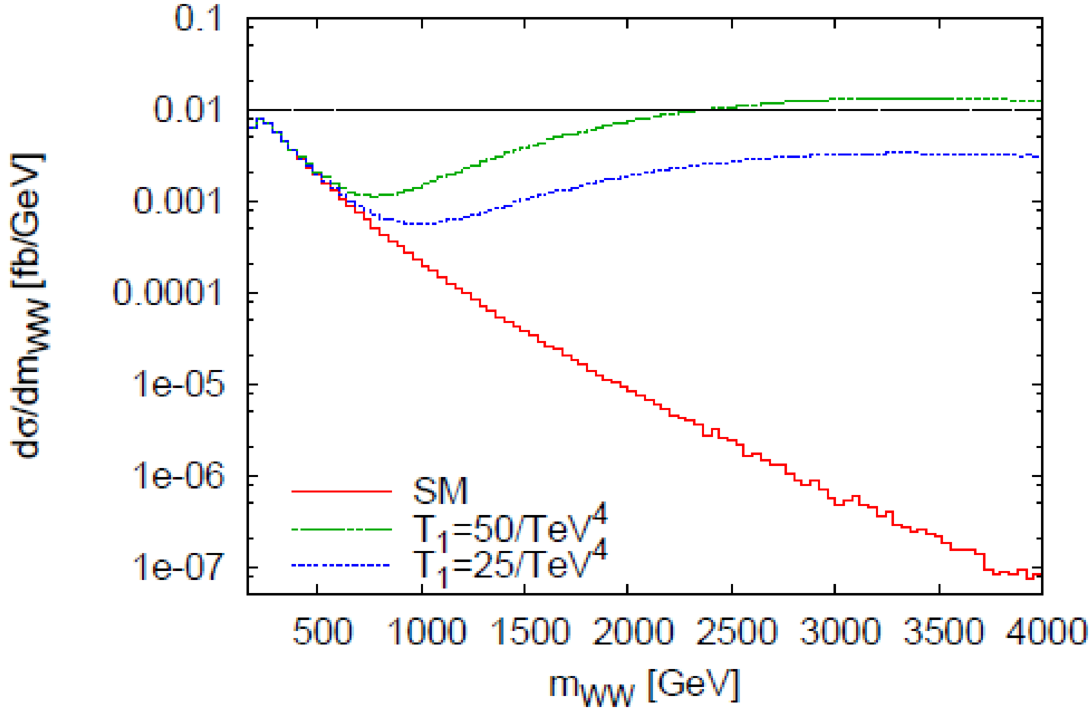
with $T_1 = \frac{f_{M,1}}{\Lambda^4}$ constant on $pp \to W^+W^-jj \to e^+\nu_e\mu^-\bar{\nu}_\mu jj$



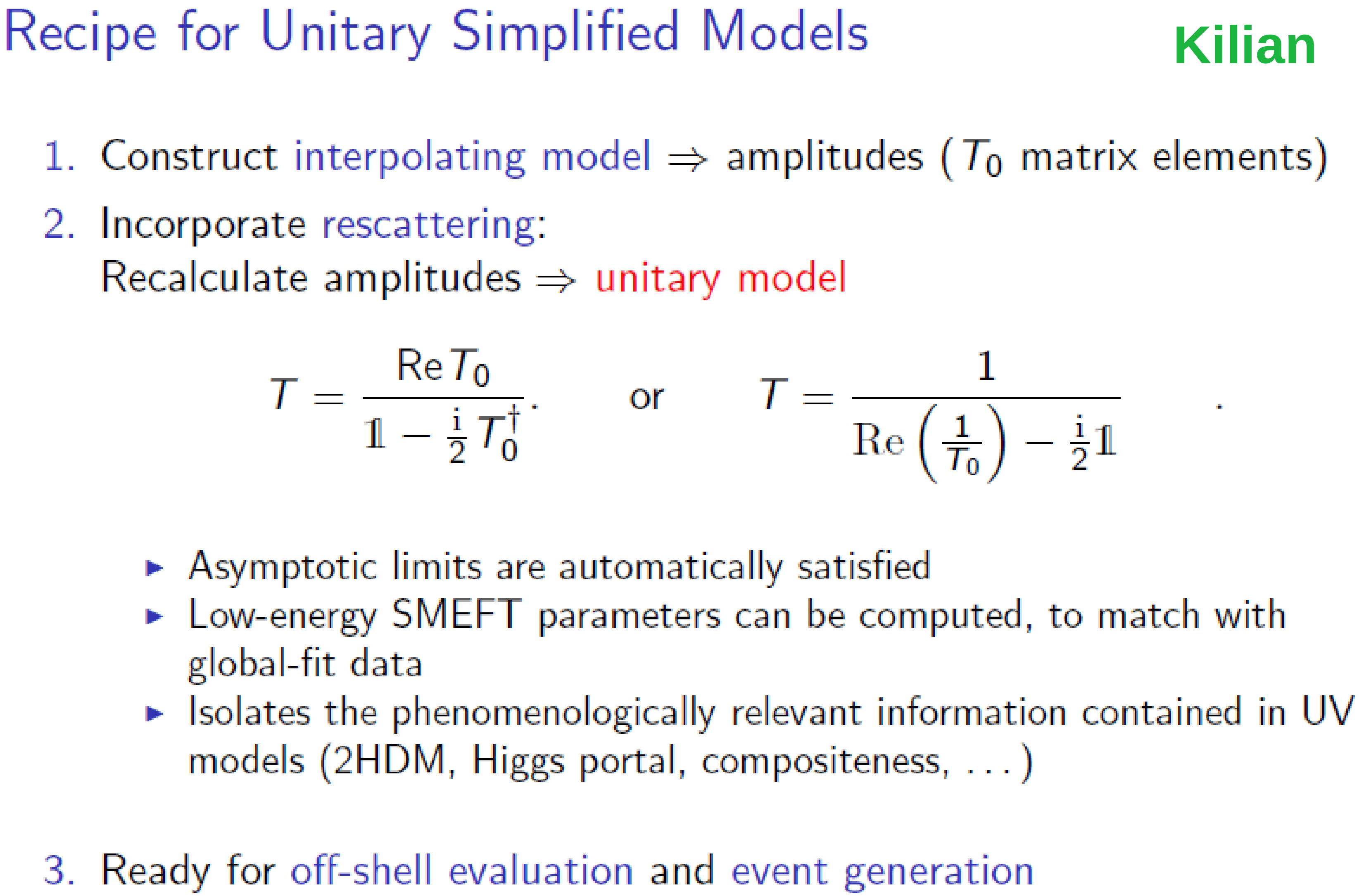
- Small increase in cross section at high WW invariant mass??

$VV \to W^+W^-$ with dimension 8 operators

Effect of constant $T_1 = \frac{f_{M,1}}{\Lambda^4}$ on $pp \to W^+W^-jj \to e^+\nu_e\mu^-\bar{\nu}_\mu jj$



- Huge increase in cross section at high m_{WW} is completely unphysical
- Need form factor for analysis or some other unitarization procedure



Recipe for Unitary Simplified Models

Kilian

1. Construct interpolating model ⇒ amplitudes (T_0 matrix elements)
2. Incorporate rescattering:
   Recalculate amplitudes ⇒ unitary model

$$T = \frac{\operatorname{Re} T_0}{\mathbb{1} - \frac{\mathrm{i}}{2} T_0^\dagger}. \qquad \text{or} \qquad T = \frac{1}{\operatorname{Re}\left(\frac{1}{T_0}\right) - \frac{\mathrm{i}}{2}\mathbb{1}} \qquad .$$

   - Asymptotic limits are automatically satisfied
   - Low-energy SMEFT parameters can be computed, to match with global-fit data
   - Isolates the phenomenologically relevant information contained in UV models (2HDM, Higgs portal, compositeness, ...)

3. Ready for off-shell evaluation and event generation

Implemented in Whizard. Similar approach also in VBFNLO

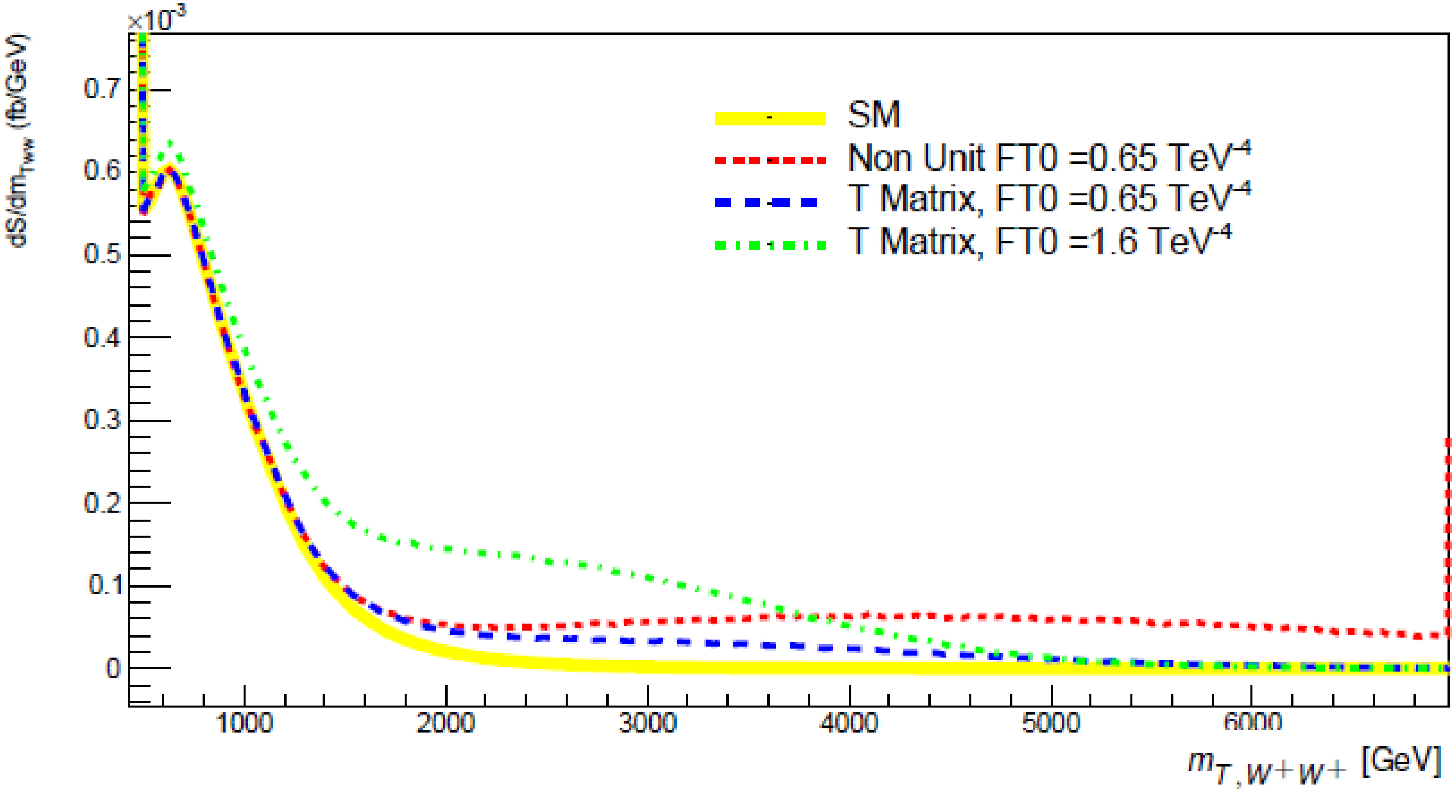
Results

Rauch

(preliminary, work in progress)

[Perez, Sekulla, Zeppenfeld]

$pp \to W^+W^+jj \to \ell^+\nu\ell^+\nu jj$



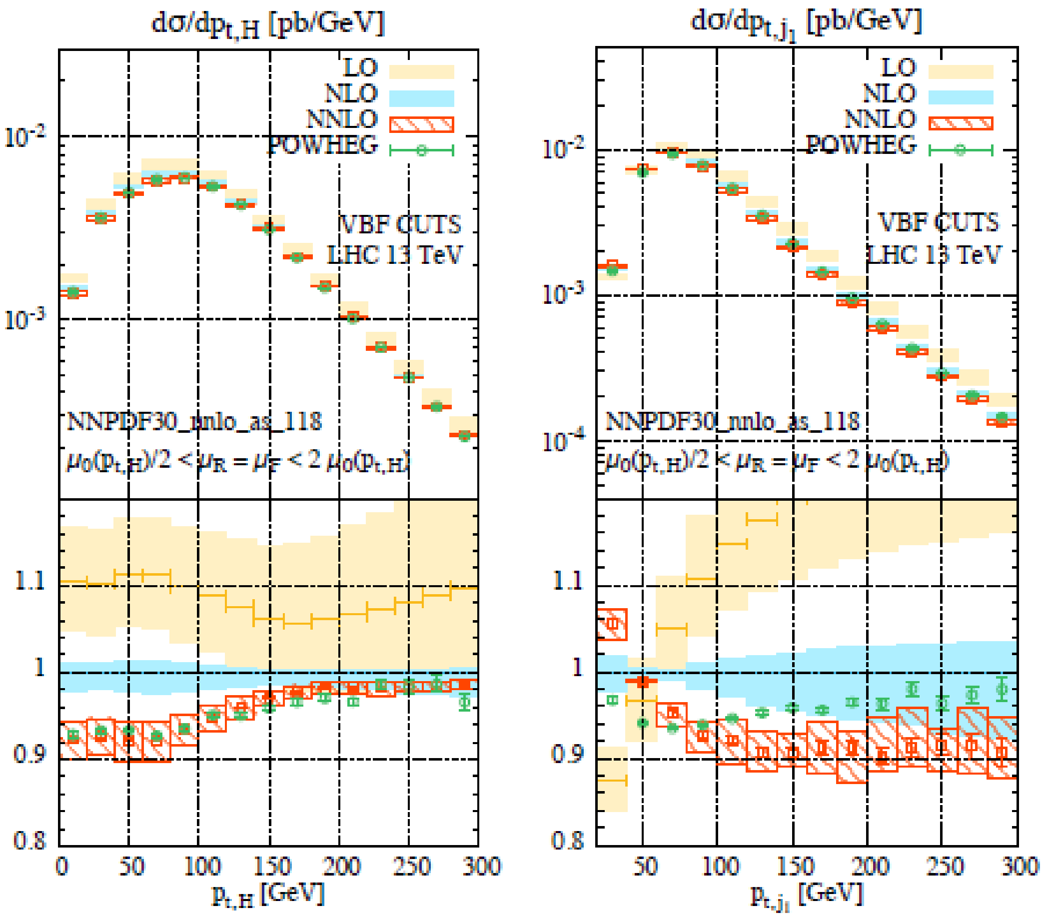
- Experiment: no excess events at high W+W+ mass
- Translation to EFT parameters depends on unitarization model
- Search also for deviations which stay well below unitarity limit for all mT

NNLO QCD corrections to VBF-Higgs

Rauch

VBF-Higgs production in NNLO QCD

[Cacciari, Dreyer, Karlberg, Salam, Zanderighi]



	$\sigma^{\text{(no cuts)}}$ [pb]	$\sigma/\sigma^{\text{NLO}}$
LO	$4.032\,^{+0.057}_{-0.069}$	1.026
NLO	$3.929\,^{+0.024}_{-0.023}$	1
NNLO	$3.888\,^{+0.016}_{-0.012}$	0.990

	$\sigma^{\text{(VBF cuts)}}$ [pb]	$\sigma/\sigma^{\text{NLO}}$
LO	$0.957\,^{+0.066}_{-0.059}$	1.092
NLO	$0.876\,^{+0.008}_{-0.018}$	1
NNLO	$0.826\,^{+0.013}_{-0.014}$	0.943

central scale:

$$\mu_0^2(p_{T,H}) = \frac{M_H}{2}\sqrt{\left(\frac{M_H}{2}\right)^2 + p_{T,H}^2}$$

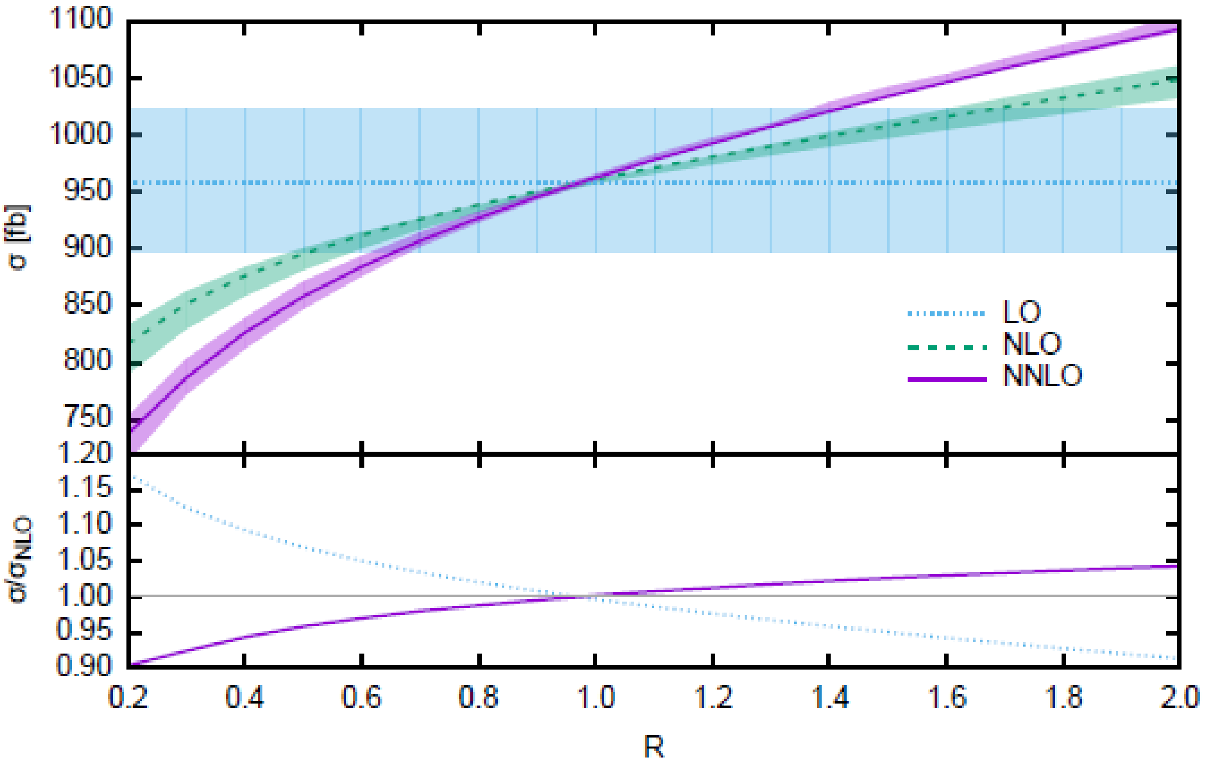
jets: anti-k_T, $R = 0.4$,
$p_{T,j} > 25$ GeV, $|y_j| < 4.5$
VBF cuts: $m_{jj} > 600$ GeV,
$\Delta y_{jj} > 4.5$, $y_{j1} \cdot y_{j2} < 0$

- tiny corrections to inclusive cross section
- significant ($\mathcal{O}(-10\%)$) corrections in VBF region

Integrated Cross Section

VBF-Hjj, $\sqrt{S} = 13$ TeV, $m_{jj} > 600$ GeV, $\Delta y_{jj} > 4.5$

[MR, Z



- Broader quark jets at NNLO generic for VBF/VBS: reduced m(jj) for small R
- R-dependence 5-10% stronger at NNLO than NLO: corresponding NNLO correction not covered by NLO scale bands

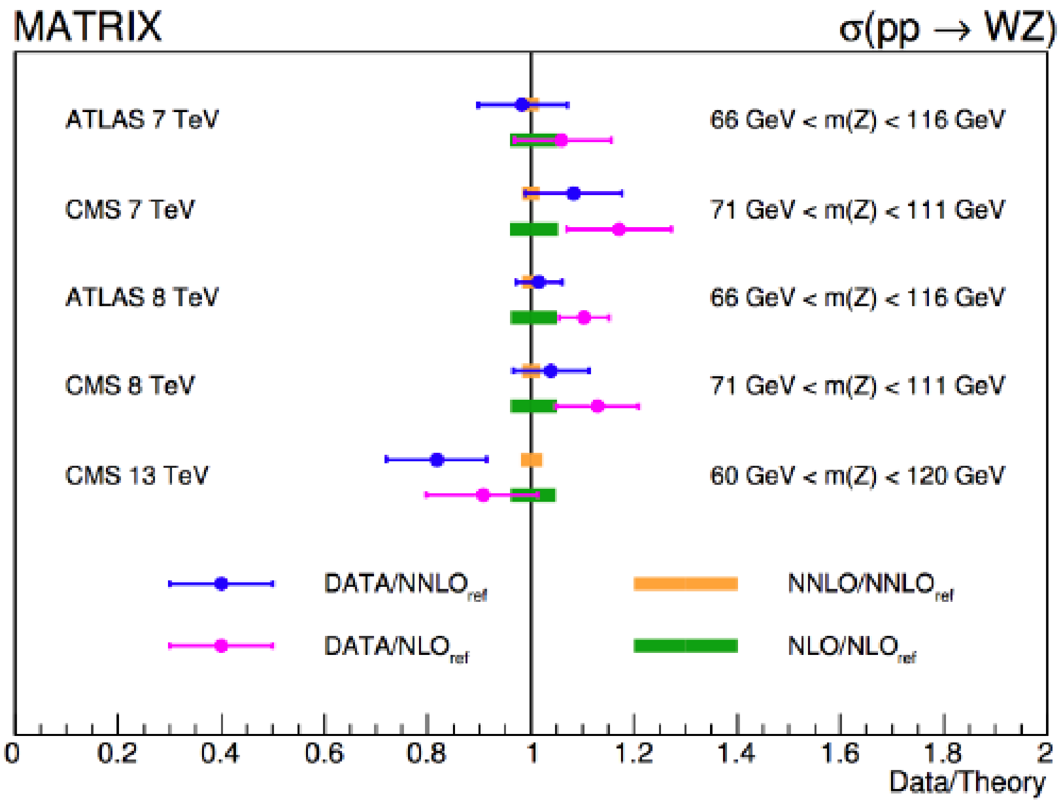
Status of NNLO QCD calculations

Grazzini

$pp\to Z/\gamma^*\ (\to l^+l^-)$	☑	validated with DYNNLO 1.5 and analytically
$pp\to W(\to l\nu)$	(☑)	validated against DYNNLO 1.5 and FEWZ
$pp\to H$	☑	validated analytically
$pp\to \gamma\gamma$	☑	validated with 2γNNLO (version nov. 2015)
$pp\to W\gamma\to l\nu\gamma$	☑	
$pp\to Z\gamma\to l^+l^-\gamma$	☑	
$pp\to ZZ(\to 4l)$	☑	
$pp\to WW\to (l\nu l'\nu')$	☑	
$pp\to ZZ/WW\to ll\nu\nu$	☑	NEW
$pp\to WZ\to l\nu ll$	☑	
$pp\to HH$	(☑)	not in first public release

WZ: inclusive cross section

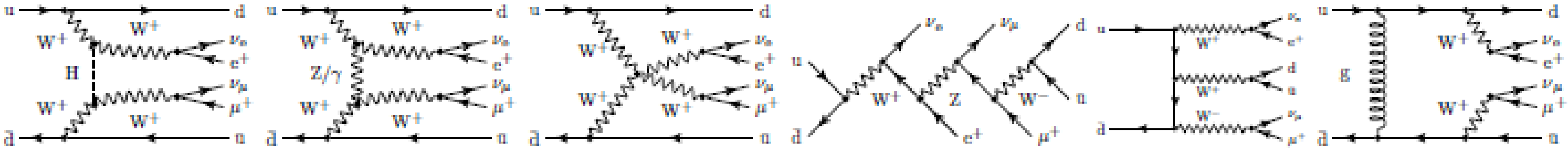
S. Kallweit, D. Rathlev, M. Wiesemann, MG (2016)



Grazzini

NNLO corrections nicely improve the agreement with the data (with the exception of CMS at 13 TeV where, however, the uncertainties are still large)

→ New: **[Biedermann, Denner, MP; 1708.00268, 1611.02951]**



LO contributions at $\mathcal{O}\left(\alpha^6\right)$, $\mathcal{O}\left(\alpha_s\alpha^5\right)$, and $\mathcal{O}\left(\alpha_s{}^2\alpha^4\right)$

$$\begin{tikzcd}
\textbf{LO} & & \mathcal{O}(\alpha^6) \arrow[dl, "\text{EW}"'] \arrow[dr, "\text{QCD}"] & & \mathcal{O}(\alpha_s\alpha^5) \arrow[dl, "\text{EW}"'] \arrow[dr, "\text{QCD}"] & & \mathcal{O}(\alpha_s{}^2\alpha^4) \arrow[dl, "\text{EW}"'] \arrow[dr, "\text{QCD}"] & \\
\textbf{NLO} & \mathcal{O}(\alpha^7) & & \mathcal{O}(\alpha_s\alpha^6) & & \mathcal{O}(\alpha_s{}^2\alpha^5) & & \mathcal{O}(\alpha_s{}^3\alpha^4)
\end{tikzcd}$$

NLO contributions at $\mathcal{O}\left(\alpha^7\right)$, $\mathcal{O}\left(\alpha_s\alpha^6\right)$, $\mathcal{O}\left(\alpha_s{}^2\alpha^5\right)$, and $\mathcal{O}\left(\alpha_s{}^3\alpha^4\right)$

→ Order $\mathcal{O}\left(\alpha_s\alpha^6\right)$ and $\mathcal{O}\left(\alpha_s{}^2\alpha^5\right)$: QCD and EW corrections mix

→ Combined measurement for pp → $\mu^+\nu_\mu e^+\nu_e jj$

→ LO fiducial cross sections:

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	Sum
$\sigma_{\rm LO}$ [fb]	1.4178(2)	0.04815(2)	0.17229(5)	1.6383(2)

→ NLO fiducial cross sections: (normalised to $\sum \sigma_{\rm LO}$)

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{\rm NLO}$ [fb]	−0.2169(3)	−0.0568(5)	−0.00032(13)	−0.0063(4)	−0.2804(7)
$\delta\sigma_{\rm NLO}/\sigma_{\rm LO}$ [%]	−13.2	−3.5	0.0	−0.4	−17.1

[Biedermann, Denner, MP; 1708.00268]

→ Large EW corrections at $\mathcal{O}(\alpha^7)$

→ Negative corrections at $\mathcal{O}(\alpha_s\alpha^6)$:

$\sim$ 0.6% difference with respect to VBS approximation
(negelecting s-channel and t-/u-channel interferences)

→ Tuned comparison against [Denner, et al.; 1209.2389] and [Jäger, et al.; 0907.0580]

→ VBS approximation in RECOLA

→ Photon PDF contribution at NLO (not included in NLO definitions):

+1.50% with LUXqed [Manohar et al.; 1607.04266]

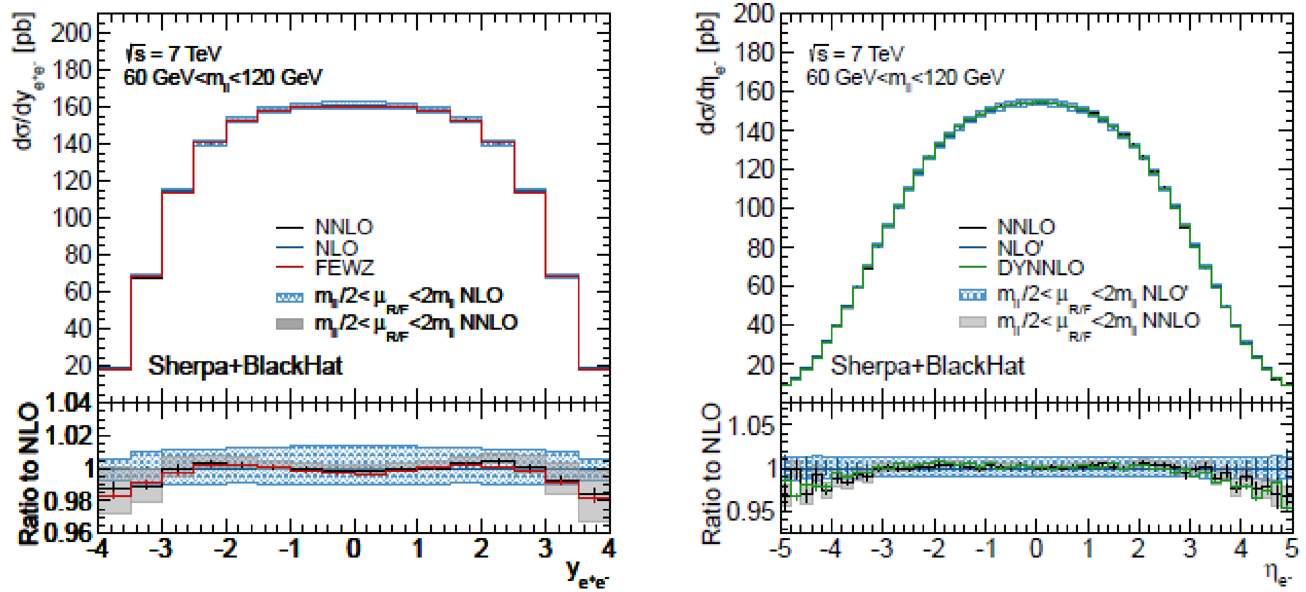
Progress on Monte Carlo generators: Sherpa

NNLO QCD accuracy

Schumann

Comparison of SHERPA DY at NNLO QCD with FEWZ/DYNNLO

[Höche et al. Phys. Rev. D **91** (2015) 074015]



↪ fully differential NNLO calculation using BLACKHAT for one-loop amplitudes

↪ perfect agreement with dedicated codes FEWZ/DYNNLO

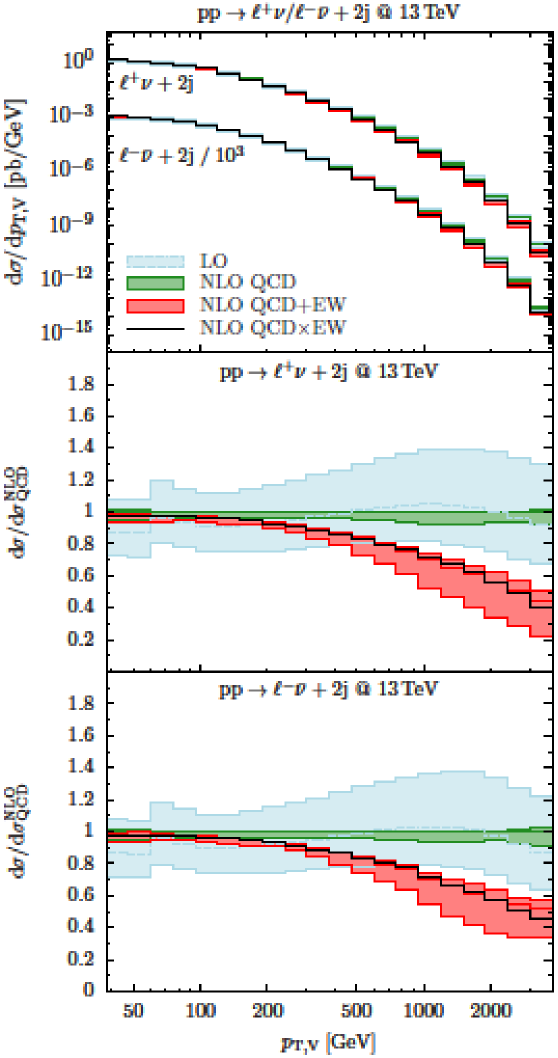
[Gavin et al. CPC **182** (2011) 2388] & [Catani et al. Phys. Rev. Lett. **103** (2009) 082001]

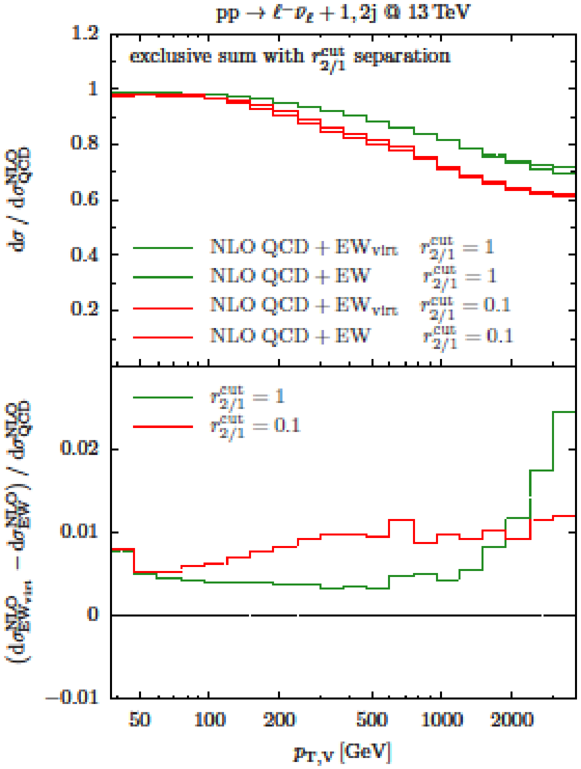
↪ largely reduced uncertainties compared to NLO

NLO QCD & EW accuracy Schumann

NLO QCD & EW corr. to $pp \to V +$ jets SHERPA +OPENLOOPS/COLLIER

[Kallweit et al. JHEP **1504** (2015) 012 & JHEP **1604** (2016) 021]





↪ virtual approximation of NLO EW

$$d\sigma_{n,\mathrm{NLO\,EW_{virt}}} = \left[\mathrm{B}_n(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n)\right] d\Phi_n$$

↪ applicable as mere K-factor (MEPS@NLO)

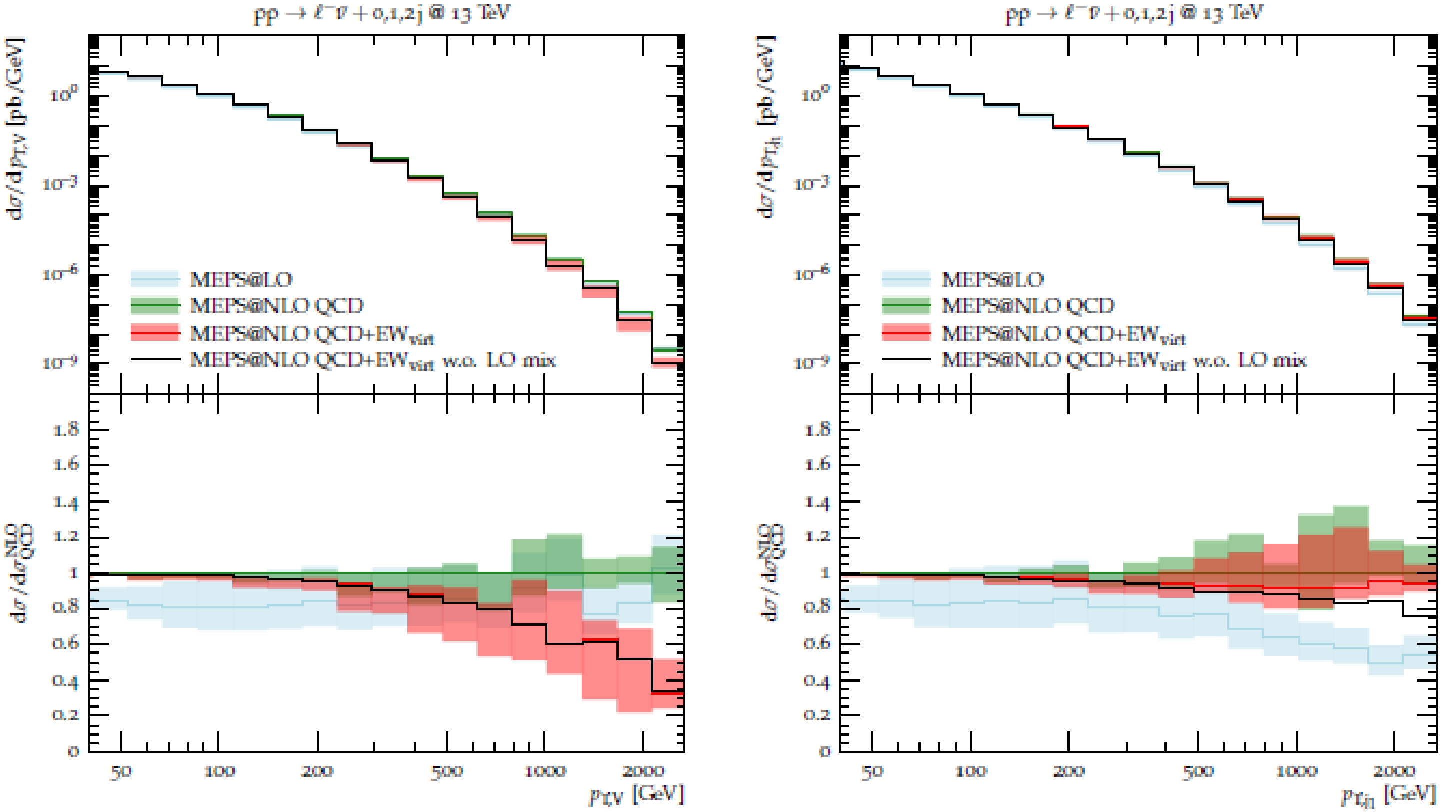
QCD Parton Showers, Matching & Merging: EW corr.

MEPS@NLO QCD+EW$_{\text{virt}}$ for W+jets with OPENLOOPS +SHERPA

[Kallweit et al. JHEP **1604** (2016) 021]

- ↪ NLO EW often suffers from large higher-order QCD corrections
- ↪ MEPS@NLO of $W(\to l\nu) + 0, 1, 2$j incl. virtual EW & Born interference
- ↪ captures full QCD corrections & dominant EW effects of Sudakov-type

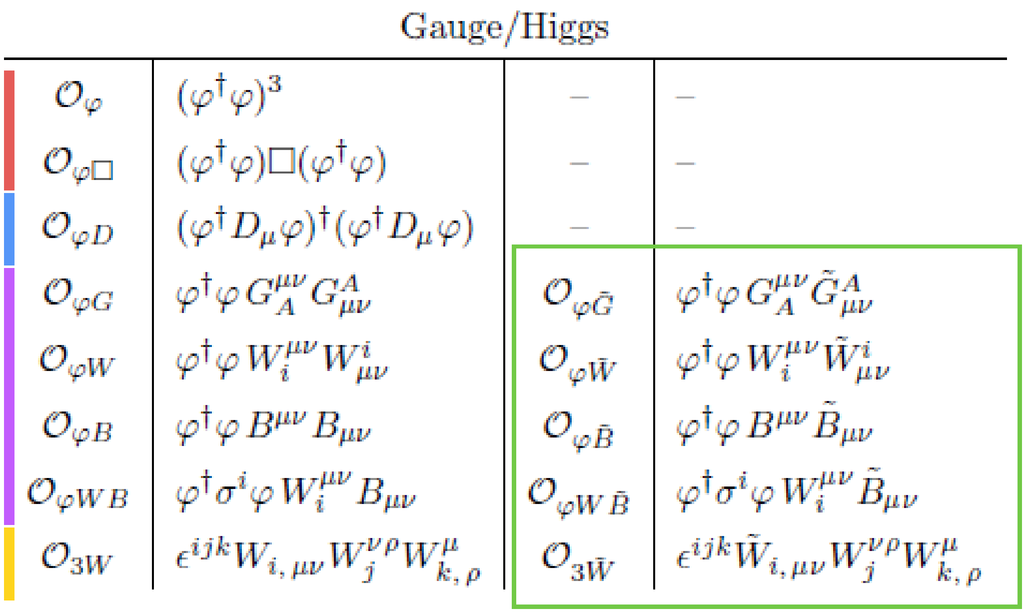
Schumann



Inclusion of EFT couplings in MadGraph (Mimasu)

SMEFT@NLO in QCD

- Merger of HELatNLO and Top/Higgs-EFT
  - Use Warsaw basis but basis independent input choice will be provided by Rosetta (also preparing an MG5_aMC plugin)



	Gauge/Higgs			
Higgs vev & kinetic term	$\mathcal{O}_{\varphi}$	$(\varphi^\dagger\varphi)^3$	–	–
	$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	–	–
mz (cust. sym.)	$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D_\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$	–	–
Gauge/Higgs & gauge kinetic terms/mixing	$\mathcal{O}_{\varphi G}$	$\varphi^\dagger\varphi\, G^{\mu\nu}_A G^A_{\mu\nu}$	$\mathcal{O}_{\varphi\tilde{G}}$	$\varphi^\dagger\varphi\, G^{\mu\nu}_A \tilde{G}^A_{\mu\nu}$
	$\mathcal{O}_{\varphi W}$	$\varphi^\dagger\varphi\, W^{\mu\nu}_i W^i_{\mu\nu}$	$\mathcal{O}_{\varphi\tilde{W}}$	$\varphi^\dagger\varphi\, W^{\mu\nu}_i \tilde{W}^i_{\mu\nu}$
	$\mathcal{O}_{\varphi B}$	$\varphi^\dagger\varphi\, B^{\mu\nu} B_{\mu\nu}$	$\mathcal{O}_{\varphi\tilde{B}}$	$\varphi^\dagger\varphi\, B^{\mu\nu} \tilde{B}_{\mu\nu}$
	$\mathcal{O}_{\varphi WB}$	$\varphi^\dagger\sigma^i\varphi\, W^{\mu\nu}_i B_{\mu\nu}$	$\mathcal{O}_{\varphi W\tilde{B}}$	$\varphi^\dagger\sigma^i\varphi\, W^{\mu\nu}_i \tilde{B}_{\mu\nu}$
Triple gauge,…	$\mathcal{O}_{3W}$	$\epsilon^{ijk} W_{i,\mu\nu} W^{\nu\rho}_j W^{\mu}_{k,\rho}$	$\mathcal{O}_{3\tilde{W}}$	$\epsilon^{ijk} \tilde{W}_{i,\mu\nu} W^{\nu\rho}_j W^{\mu}_{k,\rho}$

CP violation

HZZ anomalous coupling measurements (Brun)

- Effective Lagrangian approach for the description of BSM interactions – Higgs Characterisation Model. (JHEP 1311 (2013) 043)

$$\begin{aligned}\mathcal{L}_0^V = & \Big\{\kappa_{\mathrm{SM}}\left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu}\right] \\ & -\tfrac{1}{4}\left[\kappa_{Hgg} g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + \tan\alpha\, \kappa_{Agg} g_{Agg} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}\right] \\ & -\tfrac{1}{4}\tfrac{1}{\Lambda}\left[\kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \tan\alpha\, \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}\right] \\ & -\tfrac{1}{2}\tfrac{1}{\Lambda}\left[\kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + \tan\alpha\, \kappa_{AWW} W^+_{\mu\nu} \tilde{W}^{-\mu\nu}\right]\Big\} X_0 .\end{aligned}$$

assuming no new BSM particles below Λ (1TeV)

- **BSM couplings:**
  - κ_{HVV} = CP-even scalar iteration with vector bosons
  - κ_{AVV} = CP-odd pseudo-scalar iteration with vector bosons
  - κ_{Agg} = CP-odd BSM iteration with gluons
  - assumed to be the same for W and Z, α taken as 45 degrees

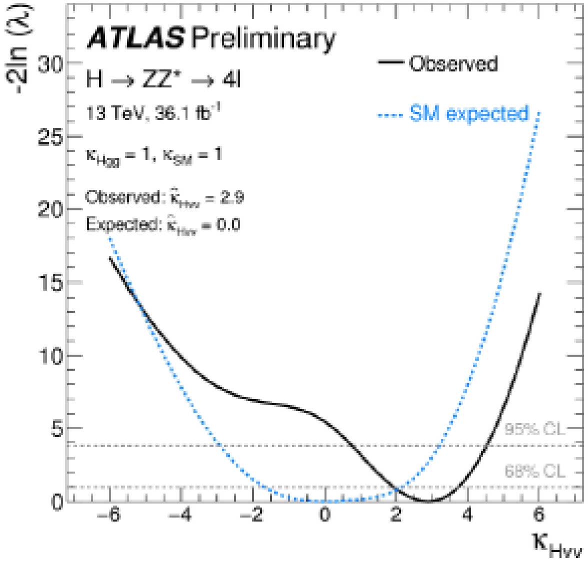
- **SM Higgs:**
  - $\kappa_{SM} = 1$, $\kappa_{Hgg}=1$ + other BSM couplings set to 0

Anomalous couplings: (ATLAS)

- Results :

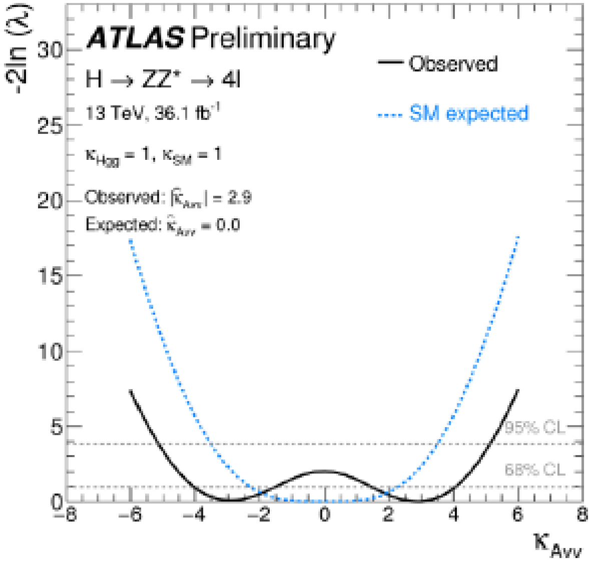
Brun

CP-even coupling to vector bosons



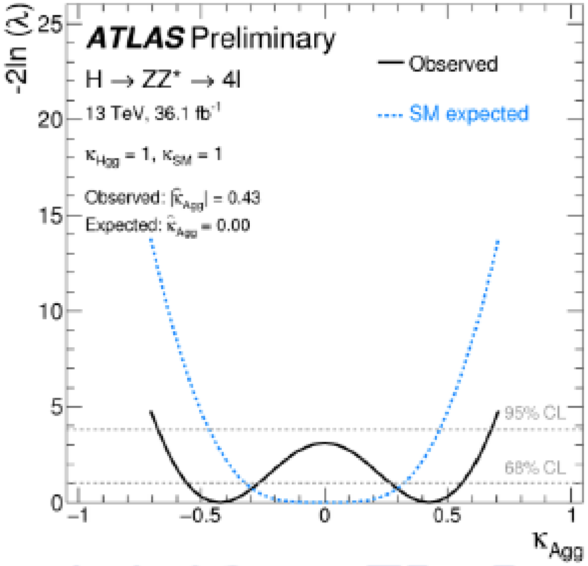
Agreement with SM 2.3σ for κ_{Hvv}

CP-odd coupling to vector bosons



Agreement with SM 1.4σ for κ_{Avv}

CP-odd coupling to gluons



Agreement with SM 1.8σ for κ_{Agg}

No deviation from SM observed

Theory

Butter: SFITTER

- $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$-symmetry, SM particles
- Dim6: 59 baryon/lepton number conserving operators
- P and C - even operators
- Data driven approach

Dimension 6 operators

$$\mathcal{O}_{GG} = \phi^\dagger \phi \, G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{BB} = \phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi$$

$$\mathcal{O}_{W} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_{B} = (D_\mu \phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right)$$

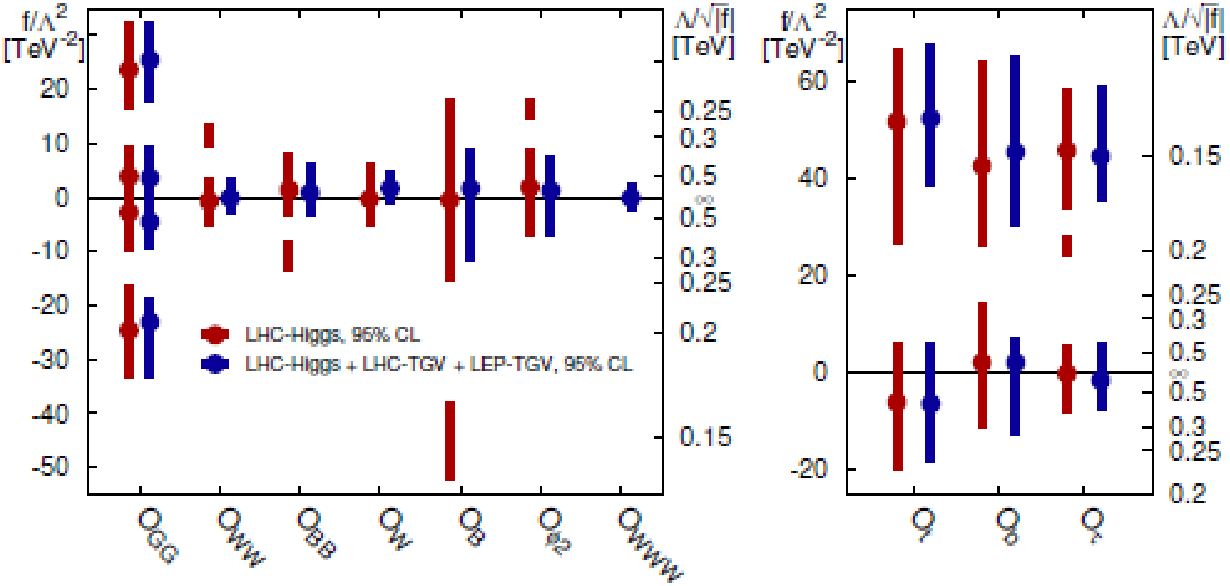
$$\mathcal{O}_{e\phi,33} = (\phi^\dagger \phi)(\bar{L}_3 \phi e_{R,3}) \qquad \mathcal{O}_{u\phi,33} = (\phi^\dagger \phi)(\bar{Q}_3 \tilde{\phi} u_{R,3}) \qquad \mathcal{O}_{d\phi,33} = (\phi^\dagger \phi)(\bar{Q}_3 \phi d_{R,3})$$

$$\mathcal{O}_{WWW} = \mathrm{Tr} \left(\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}^{\mu}_{\rho} \right) .$$

$\longrightarrow$ 10 parameters for global fit, 3 parameters for TGV-only fit

Combined results

Butter: SFITTER



- First combination of all the di-boson production channels at LHC Run I in combination with Higgs channels [1604.03105]
- secondary solutions are excluded for $\mathcal{O}_{WW}, \mathcal{O}_{BB}, \mathcal{O}_{B}$ and $\mathcal{O}_{\phi 2}$
- strongly increased precision for $\mathcal{O}_{B}$ and $\mathcal{O}_{W}$
- $\mathcal{O}_{WWW}$ among best measured dimension–six operators
- improvements on all operators due to correlations

Conclusions

- LHC ist starting to probe aTGC‘s in a significant way in VV production.
- Interference region at modest m_VV allows to study relatively small deviations from SM due to theory errors below 10% from availability of NNLO QCD and NLO EW corrections → must study both small deviations and large differential cross section changes
- VBS and VVV production have much lower statistics and curently can only probe strong coupling effects in aQGC.
- Remarkable progress on the theory side also, in higher order calculations and improved event simulation.
- Fruitful interplay of experiment and theory and the fact that we are just starting to probe VBS and VVV production makes MBI physics a fun topic to work on.