Anomalous triple-gauge-boson interaction in vector-boson pair production with RECOLA2

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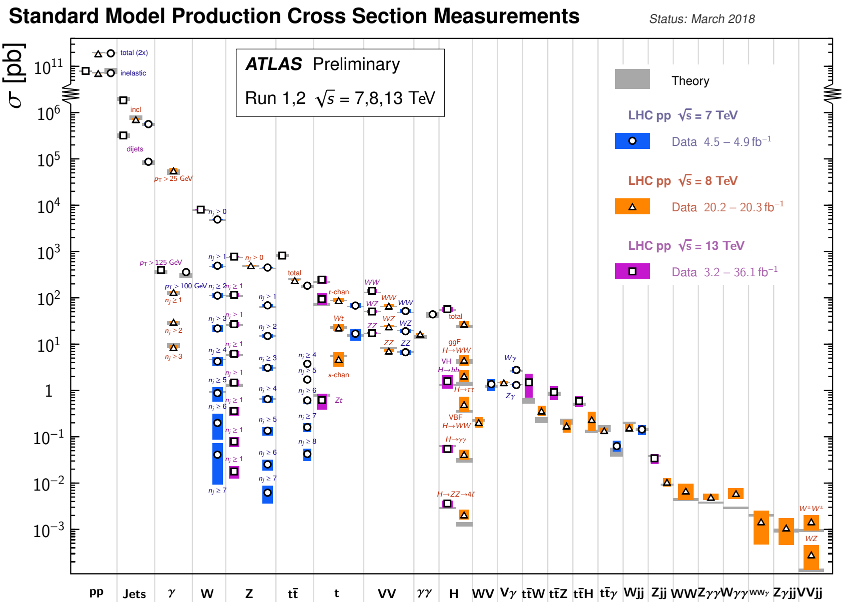
based on arXiv:1804.01477

in collaboration with A. Denner and J.-N. Lang

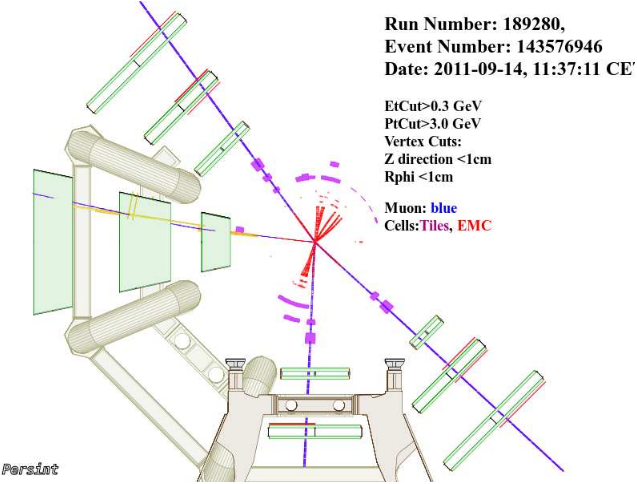
Outline

1. Diboson production at LHC
2. aTGCs in $pp \to VV'$
3. Anomalous triple-gauge-boson interaction with RECOLA2
4. Sample numerical results

Motivations (1): large cross section

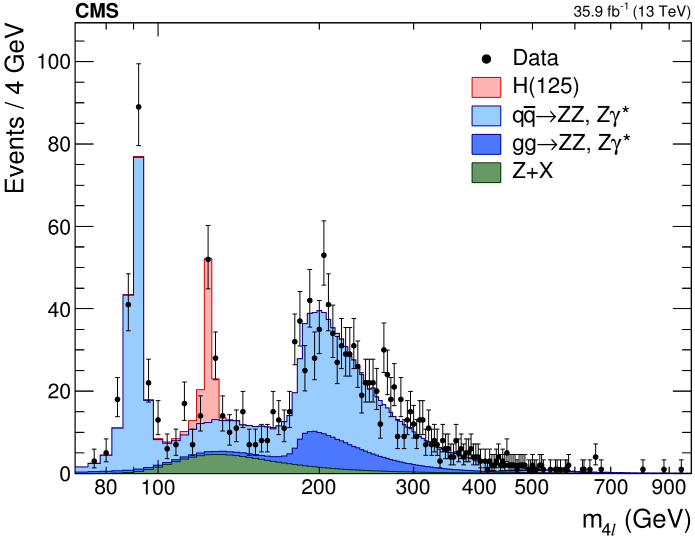


Motivations (2): clean experimental signatures[1]



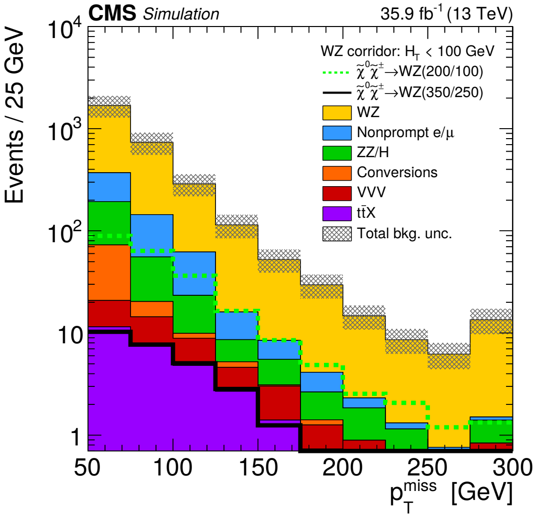
[1] 4μ candidate event, ATLAS-CONF-2011-162.

Motivations (3): background to other SM measurements[2]



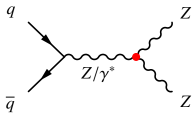
[2]from JHEP **11** (2017) 047

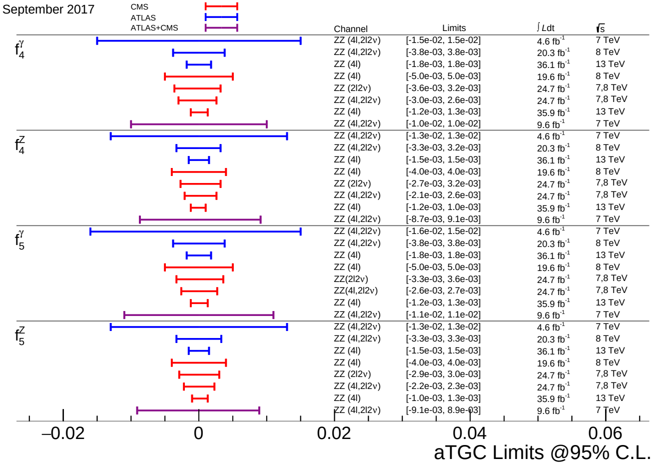
Motivations (4): SM background to NP searches[3]



[3] from arXiv:1801.03957

Motivations (5): sensitivity to non SM gauge boson interactions[4]





[4] from https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Theoretical predictions for $pp \to VV'$: current status

QCD

- NNLO : $qq \to VV' \to 4f$
- NNLO+NNLL : massive $V^{(')}$, inclusive observables
- NLO+PS : $V^{(')}$ decays, exclusive observables

EW

- NLO : $qq \to VV' \to 4f$

Theoretical predictions for $pp \to VV'$: current status

QCD

- NNLO : $qq \to VV' \to 4f$

  Grazzini et al. 1507.06257,1604.08576,1605.02716,1711.06631, Heinrich et al. 1710.06294

- NNLO+NNLL : massive $V^{(')}$, inclusive observables

  Grazzini et al. 1507.02565, Dawson et al. 1606.01034

- NLO+PS : $V^{(')}$ decays, exclusive observables

  Frixione et al. hep-ph/0204244, Nason et al. hep-ph/0606275,1311.1365, Hamilton 1009.5391, Höche et al. 1008.5399, Melia et al. 1107.5051

EW

- NLO : $qq \to VV' \to 4f$

  Biedermann et al. 1605.03419, 1601.07787, 1611.05338, 1708.06938, Kallweit et al. 1705.00598

Anomalous VVV interaction: aTGCs

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}'_{WWV}$$

most general interaction terms compatible with a given set of symmetries

$$\begin{aligned}\mathcal{L}'_{WWV} =& {\rm i} g_{WWV} \Big(\delta g_1^V (W^+_{\mu\nu} W^{-\mu} - W^{+\mu} W^-_{\mu\nu}) V^\nu + \delta\kappa_V W^+_\mu W^-_\nu V^{\mu\nu} \\ & + \frac{\lambda_V}{M_{\rm W}^2} W^{+\mu\nu} W_\nu^{-\rho} V_{\rho\mu} - \tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} - \frac{\tilde{\lambda}_V}{M_{\rm W}^2} W^{+\mu\nu} W_\nu^{-\rho} \tilde{V}_{\rho\mu} \Big)\end{aligned}$$

no clear generalization beyond LO

Anomalous VVV interaction: EFT

$$\mathcal{L}^{\text{eff.}} = \mathcal{L}^{\text{SM}} + \sum_i \frac{c_6^i}{\Lambda^2}\mathcal{O}_6^i + \sum_i \frac{c_8^i}{\Lambda^4}\mathcal{O}_8^i + \cdots$$

$$\begin{aligned}
\mathcal{O}_{WWW} &= -\frac{g_\text{w}^3}{4}\epsilon_{ijk} W^i_{\mu\nu} W^{\nu\rho\, j} W_\rho{}^{\mu\, k} \\
\mathcal{O}_{W} &= -\text{i} g_\text{w} (D_\mu\Phi)^\dagger \frac{\tau_k}{2} W^{\mu\nu\, k} (D_\nu\Phi) \\
\mathcal{O}_{B} &= +\text{i} \frac{g_1}{2} (D_\mu\Phi)^\dagger B^{\mu\nu} (D_\nu\Phi) \\
\mathcal{O}_{\widetilde{W}WW} &= +\frac{g_\text{w}^3}{4}\epsilon_{ijk} \widetilde{W}^i_{\mu\nu} W^{\nu\rho\, j} W_\rho{}^{\mu\, k} \\
\mathcal{O}_{\widetilde{W}} &= +\text{i} g_\text{w} (D_\mu\Phi)^\dagger \frac{\tau_k}{2} \widetilde{W}^{\mu\nu\, k} (D_\nu\Phi)
\end{aligned}$$

Dim6 operators

defined beyond LO

Anomalous VVV interaction: EFT vs aTGCs

at LO, for constant aTGCs (no form factors):

$$g_1^Z = 1 + c_W \frac{M_Z^2}{2\Lambda^2}$$

$$\kappa_\gamma = 1 + (c_W + c_B) \frac{M_{M_W}^2}{2\Lambda^2},$$

$$\kappa_Z = 1 + \left(c_W - c_B \frac{s_w^2}{c_w^2} \right) \frac{M_{M_W}^2}{2\Lambda^2}$$

$$\lambda_\gamma = \lambda_Z = c_{WWW} g_w^2 \frac{3M_{M_W}^2}{2\Lambda^2}$$

$$\tilde{\kappa}_\gamma = c_{\tilde{W}} \frac{M_{M_W}^2}{2\Lambda^2}$$

$$\tilde{\kappa}_Z = -c_{\tilde{W}} \frac{s_w^2}{c_w^2} \frac{M_{M_W}^2}{2\Lambda^2}$$

$$\tilde{\lambda}_\gamma = \tilde{\lambda}_Z = c_{\tilde{W}WW} g_w^2 \frac{3M_{M_W}^2}{2\Lambda^2}$$

Anomalous VVV interaction: aTGCs (2)

$$
\begin{aligned}
\mathcal{L}_{VVV} \quad = \quad & \frac{e}{M_Z^2}\Bigg[-[f_4^\gamma(\partial_\mu A^{\mu\beta}) - f_4^Z(\partial_\mu Z^{\mu\beta})]Z_\alpha(\partial^\alpha Z_\beta) \\
& + [f_5^\gamma(\partial^\sigma A_{\sigma\mu}) - f_5^Z(\partial^\sigma Z_{\sigma\mu})]\widetilde{Z}^{\mu\beta} Z_\beta \\
& + [h_1^\gamma(\partial^\sigma A_{\sigma\mu}) - h_1^Z(\partial^\sigma Z_{\sigma\mu})]Z_\beta A^{\mu\beta} \\
& + [h_3^\gamma(\partial_\sigma A^{\sigma\rho}) - h_3^Z(\partial_\sigma Z^{\sigma\rho})]Z^\alpha \widetilde{A}_{\rho\alpha} \\
& + \left\{ \frac{h_2^\gamma}{M_Z^2}[\partial_\alpha\partial_\beta\partial^\rho A_{\rho\mu}] - \frac{h_2^Z}{M_Z^2}[\partial_\alpha\partial_\beta(\Box + M_Z^2)Z_\mu] \right\} Z^\alpha A^{\mu\beta} \\
& - \left\{ \frac{h_4^\gamma}{2M_Z^2}[\Box\partial^\sigma A^{\rho\alpha}] - \frac{h_4^Z}{2M_Z^2}[(\Box + M_Z^2)\partial^\sigma Z^{\rho\alpha}] \right\} Z_\sigma \widetilde{A}_{\rho\alpha} \Bigg]
\end{aligned}
$$

Anomalous VVV interaction: EFT (2)

Dim8 operators:

$$\mathcal{O}_{BW} = -\mathrm{i}\,\Phi^\dagger B_{\mu\nu}\frac{\tau_i}{2}W^{\mu\rho\,i}\{D_\rho, D^\nu\}\Phi + \mathrm{h.c.}$$
$$\mathcal{O}_{WW} = \mathrm{i}\,\Phi^\dagger \frac{\tau_i}{2}\frac{\tau_j}{2}W^i_{\mu\nu}W^{\mu\rho\,j}\{D_\rho, D^\nu\}\Phi + \mathrm{h.c.}$$
$$\mathcal{O}_{BB} = \mathrm{i}\,\Phi^\dagger B_{\mu\nu}B^{\mu\rho}\{D_\rho, D^\nu\}\Phi + \mathrm{h.c.}$$
$$\mathcal{O}_{\widetilde{B}W} = -\mathrm{i}\,\Phi^\dagger \widetilde{B}_{\mu\nu}\frac{\tau_i}{2}W^{\mu\rho\,i}\{D_\rho, D^\nu\}\Phi + \mathrm{h.c.}$$

no Dim6 operator contributes to neutral TGCs

Anomalous VVV interaction: EFT vs aTGCs (2)

at LO, for constant aTGCs (no form factors):

$$f_4^\gamma = \frac{\mathrm{vev}^2 M_Z^2}{4c_\mathrm{w} s_\mathrm{w} \Lambda^4} \left(c_\mathrm{w} s_\mathrm{w} c_{WW} - \left(c_\mathrm{w}^2 - s_\mathrm{w}^2\right) c_{BW} - 4 c_\mathrm{w} s_\mathrm{w} c_{BB} \right)$$

$$f_4^Z = \frac{M_Z^2 \mathrm{vev}^2}{4c_\mathrm{w} s_\mathrm{w} \Lambda^4} \left(c_\mathrm{w}^2 c_{WW} + 2 c_\mathrm{w} s_\mathrm{w} c_{BW} + 4 s_\mathrm{w}^2 c_{BB} \right)$$

$$f_5^\gamma = \frac{\mathrm{vev}^2 M_Z^2}{4c_\mathrm{w} s_\mathrm{w}} \frac{c_{\widetilde{B}W}}{\Lambda^4}$$

$$h_1^\gamma = -\frac{\mathrm{vev}^2 M_Z^2}{4c_\mathrm{w} s_\mathrm{w} \Lambda^4} \left(s_\mathrm{w}^2 c_{WW} - 2 c_\mathrm{w} s_\mathrm{w} c_{BW} + 4 c_\mathrm{w}^2 c_{BB} \right)$$

$$h_1^Z = \frac{\mathrm{vev}^2 M_Z^2}{4c_\mathrm{w} s_\mathrm{w} \Lambda^4} \left(-c_\mathrm{w} s_\mathrm{w} c_{WW} + \left(c_\mathrm{w}^2 - s_\mathrm{w}^2\right) c_{BW} + 4 c_\mathrm{w} s_\mathrm{w} c_{BB} \right)$$

$$f_5^Z = h_2^\gamma = h_2^Z = h_3^\gamma = h_4^Z = h_4^\gamma = 0$$

$$h_3^Z = \frac{\mathrm{vev}^2 M_Z^2}{4c_\mathrm{w} s_\mathrm{w}} \frac{c_{\widetilde{B}W}}{\Lambda^4}$$

Theoretical predictions for $pp \to VV'$ with anomalous VVV interactions

aTGC framework

- WW at NLO QCD in NWA (Baur et al. hep-ph/9507336) , including leptonic decays (Campbell et al. hep-ph/9905386,1105.0020)
- WZ at NLO QCD in NWA (Baur et al. hep-ph/9410266) , including leptonic decays (Campbell et al. hep-ph/9905386,1105.0020)
- ZZ at LO in NWA (Baur et al. hep-ph/0008063)

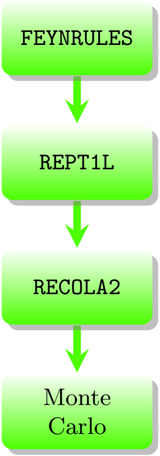
aTGCs for $WW\gamma$ and WWZ available at NLO QCD in MCFM, MADLOOP, POWHEG, VBF@NLO.

aTGCs for neutral and charged aTGCs available in SHERPA

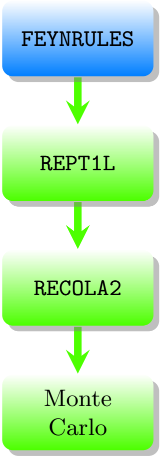
EFT framework:

- WW at NLO QCD with OS Ws (Baglio et al. 1708.03332)
- WZ at NLO QCD+PS (Franceschini et al. 1712.01310)
- ZZ at LO (Degrande 1308.6323)

Anomalous triple-gauge-boson interaction with RECOLA2



Anomalous triple-gauge-boson interaction with RECOLA2

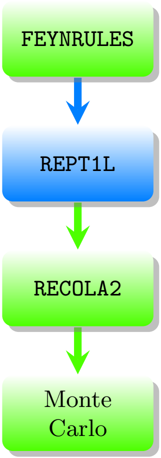


- $\mathcal{L}_{SM}$ and relevant Dim6/8 operators implemented in a FEYNRULES model file

- FEYNRULES writes the corresponding Feynman rules in a UFO model file

Feynrules: Christensen et al. 0806.4192, Alloul et al. 1310.1921
UFO: Degrande et al. 1108.2040

Anomalous triple-gauge-boson interaction with RECOLA2

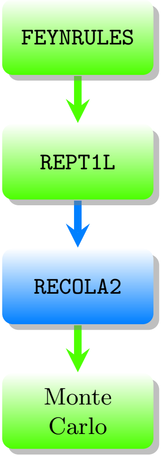


REPT1L:

- converts the UFO model file in a RECOLA model file
- computes R2 terms
- performs renormalization
- writes the corresponding Feynman rules in the RECOLA model file

RECOLA: Actis et al. 1605.01090

Anomalous triple-gauge-boson interaction with RECOLA2

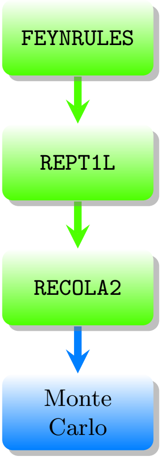


RECOLA2:

- enhanced version of RECOLA
- generates and computes LO and one-loop matrix elements
- can be linked to any user-provided RECOLA model file

RECOLA2: Denner et al. 1705.06053,1711.07388

Anomalous triple-gauge-boson interaction with RECOLA2



- RECOLA2 has been interfaced to multichannel Monte Carlo integrator
- for cross-checks RECOLA2 has been interfaced also to POWHEG-BOX-V2

POWHEG-BOX-V2: Nason hep-ph/0409146, Frixione et al. 0709.2092, Alioli et al. 1002.2581

$pp \to WZ \to e^+\nu_e\mu^+\mu^-$ at $\sqrt{s} = 13$ TeV (1)

ATLAS setup (1603.02151):

$$p_{\mathrm{T},l_i} > 15\,\mathrm{GeV}, \quad |\eta_{l_i}| < 2.5, \quad p_{\mathrm{T},l_\mathrm{W}} > 20\,\mathrm{GeV}, \quad |\eta_{l_\mathrm{W}}| < 2.5,$$
$$|M^{\mathrm{inv}}_{l_1 l_2} - M_\mathrm{Z}| < 10\,\mathrm{GeV}, \quad M_{\mathrm{T,W}} > 30\,\mathrm{GeV},$$
$$\Delta R_{l_i,l_\mathrm{W}} > 0.3, \quad \Delta R_{l_1,l_2} > 0.2, \quad p^{\mathrm{max}}_{\mathrm{T},l} > 25\,\mathrm{GeV}$$

CMS setup (1609.05721):

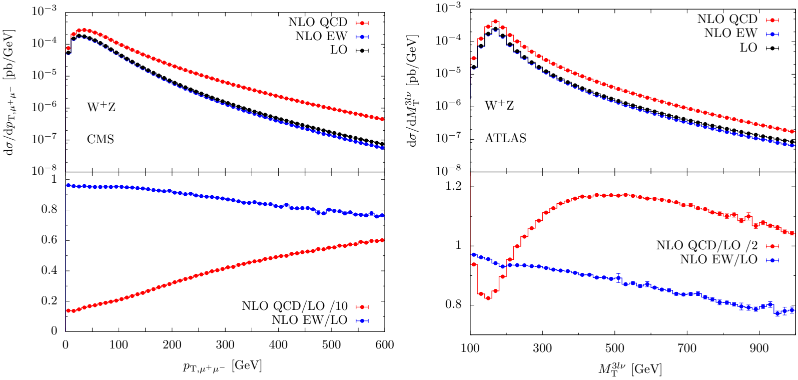
$$p_{\mathrm{T},l} > 20\,\mathrm{GeV}, \quad |\eta_l| < 2.5, \quad E^{\mathrm{miss}}_\mathrm{T} > 30\,\mathrm{GeV}, \quad M^{\mathrm{inv}}_{3l} > 100\,\mathrm{GeV},$$
$$M^{\mathrm{inv}}_{l_1 l_2} \in [71, 111]\,\mathrm{GeV}, \quad \Delta R_{l_i,l_\mathrm{W}} > 0.1$$

$pp \to WZ \to e^+\nu_e\mu^+\mu^-$ at $\sqrt{s} = 13$ TeV (2)

Setup	LO [fb]	NLO QCD [fb]	NLO EW [fb]
W^-Z ATLAS	$12.6455(9)^{+5.5\%}_{-6.8\%}$	$23.780(4)^{+5.5\%}_{-4.6\%}$	$11.891(4)^{+5.6\%}_{-6.9\%}$
W^-Z CMS	$9.3251(8)^{+5.3\%}_{-6.7\%}$	$17.215(4)^{+5.4\%}_{-4.3\%}$	$8.870(2)^{+5.5\%}_{-6.7\%}$
W^+Z ATLAS	$18.875(1)^{+5.2\%}_{-6.4\%}$	$34.253(6)^{+5.3\%}_{-4.3\%}$	$17.748(8)^{+5.3\%}_{-6.5\%}$
W^+Z CMS	$14.307(1)^{+5.0\%}_{-6.2\%}$	$26.357(6)^{+5.4\%}_{-4.3\%}$	$13.600(4)^{+5.1\%}_{-6.3\%}$

- $\delta_{\rm EW} \simeq -5/6\%$
- $\delta_{\rm QCD} \simeq +80/90\%$ (gq channels open at NLO QCD)

$pp \to WZ \to e^+\nu_e\mu^+\mu^-$ at $\sqrt{s} = 13$ TeV (3)



$$M_T^{3l\nu} = \sqrt{\left(\sum_{\ell_i=1}^{3} p_{T,\ell_i} + |\vec{p}_T^{\,\text{miss}}|\right)^2 - \left[\left(\sum_{\ell_i=1}^{3} p_{\ell_i,x} + p_x^{\text{miss}}\right)^2 + \left(\sum_{\ell_i=1}^{3} p_{\ell_i,y} + p_y^{\text{miss}}\right)^2\right]}$$

Remark: $1/\Lambda^2$ expansion

$$\sigma = \sigma_{\mathrm{SM}^2} + \sigma_{\mathrm{SM}\times\mathrm{EFT6}} + \sigma_{\mathrm{EFT6}^2} + \sigma_{\mathrm{SM}\times\mathrm{EFT8}} + \sigma_{\mathrm{EFT8}^2} + \dots$$

with

$$\sigma_{\mathrm{SM}\times\mathrm{EFT6}} \propto \frac{c_6}{\Lambda^2}, \quad \sigma_{\mathrm{EFT6}^2} \propto \frac{c_6^2}{\Lambda^4} \quad \sigma_{\mathrm{SM}\times\mathrm{EFT8}} \propto \frac{c_8}{\Lambda^4}, \quad \sigma_{\mathrm{EFT8}^2} \propto \frac{c_8^2}{\Lambda^8}$$

if Dim8 operators are not included:

- in general including the σ_{EFT6^2} is not consistent
- the σ_{EFT6^2} term may be included in specific models where $c_8 \ll c_6^2$

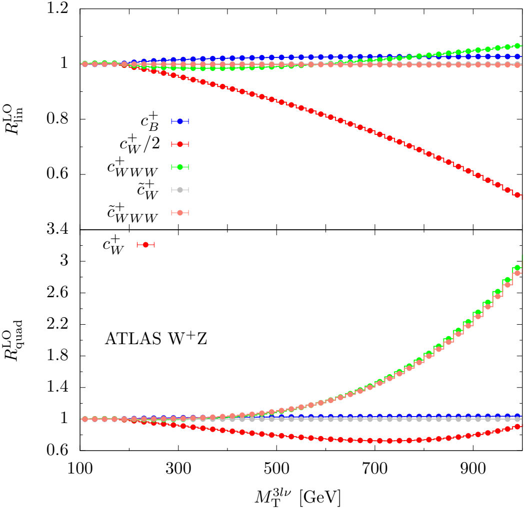
Input parameters: Dim6 Wilson coefficients

$$\frac{c_W^+}{\Lambda^2} = 3\times10^{-6}\,\mathrm{GeV}^{-2}, \qquad \frac{c_W^-}{\Lambda^2} = -3\times10^{-6}\,\mathrm{GeV}^{-2},$$
$$\frac{c_B^+}{\Lambda^2} = 1.5\times10^{-5}\,\mathrm{GeV}^{-2}, \qquad \frac{c_B^-}{\Lambda^2} = -1.5\times10^{-5}\,\mathrm{GeV}^{-2},$$
$$\frac{c_{WWW}^+}{\Lambda^2} = 3\times10^{-6}\,\mathrm{GeV}^{-2}, \qquad \frac{c_{WWW}^-}{\Lambda^2} = -3\times10^{-6}\,\mathrm{GeV}^{-2},$$
$$\frac{\tilde{c}_W^+}{\Lambda^2} = 1\times10^{-6}\,\mathrm{GeV}^{-2}, \qquad \frac{\tilde{c}_W^-}{\Lambda^2} = -1\times10^{-6}\,\mathrm{GeV}^{-2},$$
$$\frac{\tilde{c}_{WWW}^+}{\Lambda^2} = 3\times10^{-6}\,\mathrm{GeV}^{-2}, \qquad \frac{\tilde{c}_{WWW}^-}{\Lambda^2} = -3\times10^{-6}\,\mathrm{GeV}^{-2}$$

Experimental limits (from 1703.06095)

	c_{WWW}/Λ^2 (TeV^{-2})	c_B/Λ^2 (TeV^{-2})	c_W/Λ^2 (TeV^{-2})
*	$[-2.7, 2.7]$	$[-14, 17]$	$[-2.0, 5.7]$
[6]	$[-5.7, 5.9]$	$[-29.2, 23.9]$	$[-11.4, 5.4]$
[7]	$[-4.61, 4.60]$	$[-20.9, 26.3]$	$[-5.87, 10.54]$
[43]	$[-4.6, 4.2]$	$[-260, 210]$	$[-4.2, 8.0]$
[44]	$[-3.9, 4.0]$	$[-320, 210]$	$[-4.3, 6.8]$

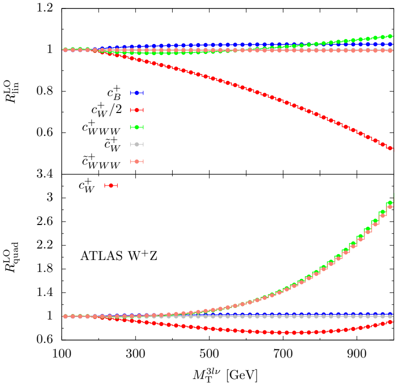
$pp \to WZ \to e^+\nu_e\mu^+\mu^-$ at $\sqrt{s} = 13$ TeV (4)



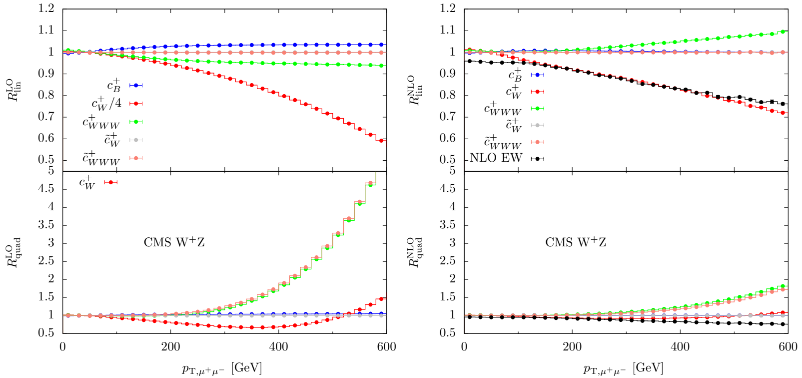
$$R_{\rm lin} = 1 + \frac{d\sigma_{\rm SM\times EFT6}/dX}{d\sigma_{\rm SM}/dX}$$

$$R_{\rm quad} = R_{\rm lin} + \frac{d\sigma_{\rm EFT6^2}/dX}{d\sigma_{\rm SM}/dX}$$

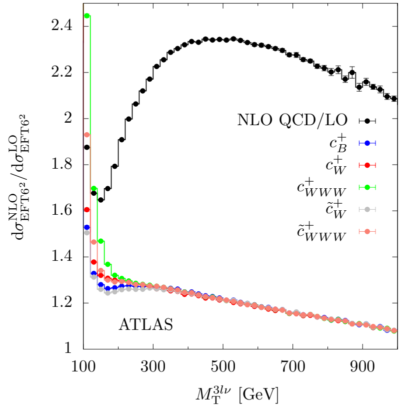
$pp \to WZ \to e^+\nu_e\mu^+\mu^-$ at $\sqrt{s} = 13$ TeV (5)

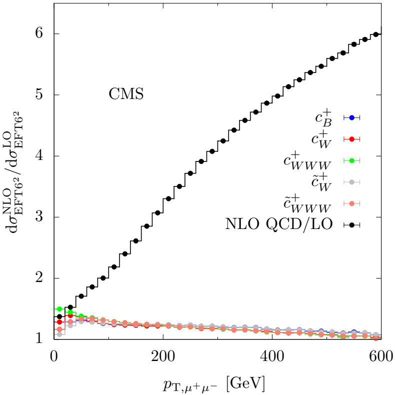


$pp \to WZ \to e^+\nu_e\mu^+\mu^-$ at $\sqrt{s} = 13$ TeV (5)



$pp \to WZ \to e^+\nu_e\mu^+\mu^-$ at $\sqrt{s} = 13$ TeV (6)





$$\frac{\mathrm{d}\sigma^{\mathrm{NLO}}_{\mathrm{EFT6}^2}}{\mathrm{d}\sigma^{\mathrm{NLO}}_{\mathrm{SM}^2}} = \frac{\mathrm{d}\sigma^{\mathrm{LO}}_{\mathrm{EFT6}^2}}{\mathrm{d}\sigma^{\mathrm{LO}}_{\mathrm{SM}^2}} \frac{\delta^{\mathrm{QCD}}_{\mathrm{EFT6}^2}}{\delta^{\mathrm{QCD}}_{\mathrm{SM}}}, \quad \text{with} \quad \delta^{\mathrm{QCD}}_{\mathrm{EFT6}^2} = \frac{\mathrm{d}\sigma^{\mathrm{NLO}}_{\mathrm{EFT6}^2}}{\mathrm{d}\sigma^{\mathrm{LO}}_{\mathrm{EFT6}^2}}, \quad \delta^{\mathrm{QCD}}_{\mathrm{SM}} = \frac{\mathrm{d}\sigma^{\mathrm{NLO}}_{\mathrm{SM}}}{\mathrm{d}\sigma^{\mathrm{LO}}_{\mathrm{SM}}}$$

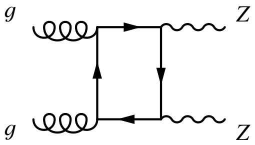
$pp \to ZZ \to e^+e^-\mu^+\mu^-$ at $\sqrt{s} = 13$ TeV (1)

ATLAS setup (1610.07585):

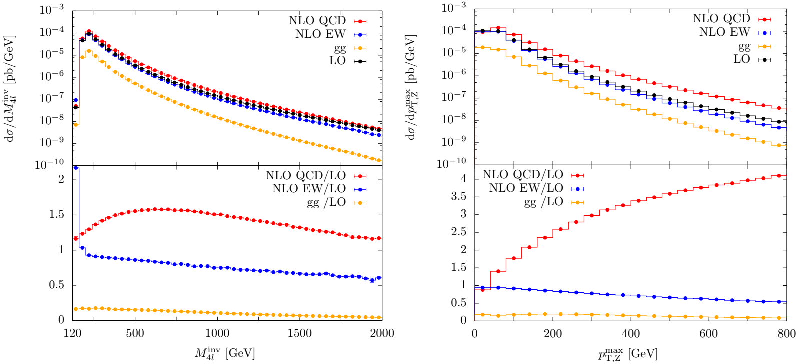
$$p_{\mathrm{T},l} > 7\,\mathrm{GeV}, \quad |\eta_l| < 2.5, \quad p_{\mathrm{T},l}^{\max} > 25\,\mathrm{GeV}, \quad \Delta R_{l_i,l_j} > 0.2,$$
$$M^{\mathrm{inv}}_{\mathrm{Z}_1} \in [66, 116]\ \mathrm{GeV}, \quad M^{\mathrm{inv}}_{\mathrm{Z}_2} \in [66, 116]\ \mathrm{GeV}$$

LO [fb]	NLO QCD [fb]	NLO EW [fb]	gg [fb]
$11.0768(5)^{+6.3\%}_{-7.5\%}$	$14.993(2)^{+3.1\%}_{-2.4\%}$	$10.283(2)^{+6.4\%}_{-7.6\%}$	$1.8584(4)^{+25\%}_{-18\%}$

- $\delta_{\mathrm{EW}} \simeq -8\%$
- $\delta_{\mathrm{QCD}} \simeq +35\%$
- $\delta_{gg} \simeq +17\%$



$pp \to ZZ \to e^+e^-\mu^+\mu^-$ at $\sqrt{s} = 13$ TeV (2)



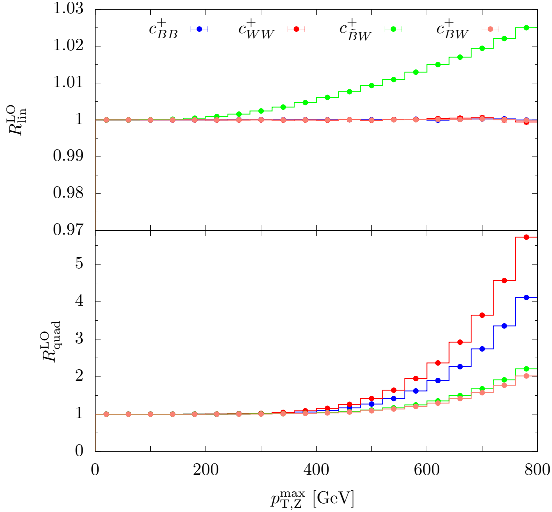
Input parameters: Dim8 Wilson coefficients

$$\frac{c^+_{BB}}{\Lambda^4} = 2\times10^{-12}\,\text{GeV}^{-4}, \quad \frac{c^-_{BB}}{\Lambda^4} = -2\times10^{-12}\,\text{GeV}^{-4},$$
$$\frac{c^+_{WW}}{\Lambda^4} = 3.5\times10^{-12}\,\text{GeV}^{-4}, \quad \frac{c^-_{WW}}{\Lambda^4} = -3.5\times10^{-12}\,\text{GeV}^{-4},$$
$$\frac{c^+_{BW}}{\Lambda^4} = 2\times10^{-12}\,\text{GeV}^{-4}, \quad \frac{c^-_{BW}}{\Lambda^4} = -2\times10^{-12}\,\text{GeV}^{-4},$$
$$\frac{c^+_{\tilde{B}W}}{\Lambda^4} = 2\times10^{-12}\,\text{GeV}^{-4}, \quad \frac{c^-_{\tilde{B}W}}{\Lambda^4} = -2\times10^{-12}\,\text{GeV}^{-4}$$

Experimental limits (from ATLAS-CONF-2017-031)

EFT parameter	Expected 95% CL [TeV^{-4}]	Observed 95% CL [TeV^{-4}]
$C_{\tilde{B}W}/\Lambda^4$	−8.1, 8.1	−5.9 , 5.9
C_{WW}/Λ^4	−4.0, 4.0	−3.0 , 3.0
C_{BW}/Λ^4	−4.4, 4.4	−3.3 , 3.3
C_{BB}/Λ^4	−3.7, 3.7	−2.7 , 2.8

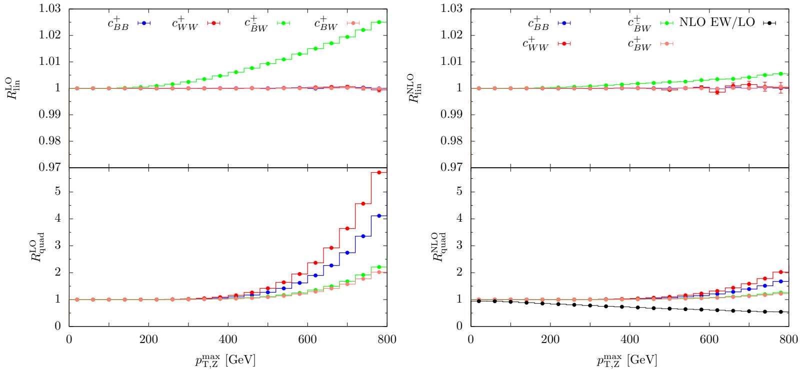
$pp \to ZZ \to e^+e^-\mu^+\mu^-$ at $\sqrt{s} = 13$ TeV (2)



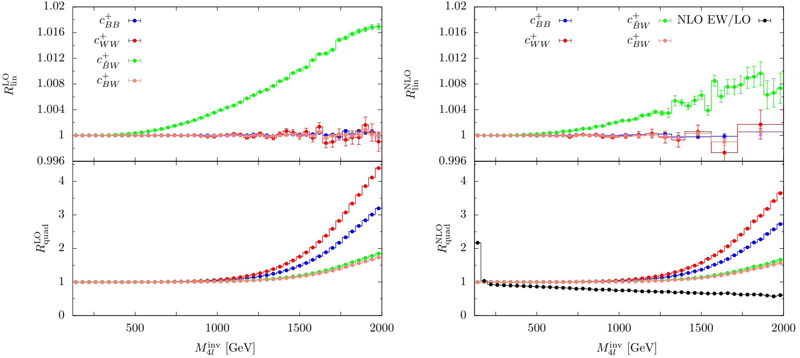
$$R_{\rm lin} = 1 + \frac{d\sigma_{\rm SM \times EFT8}/dX}{d\sigma_{\rm SM}/dX}$$

$$R_{\rm quad} = R_{\rm lin} + \frac{d\sigma_{\rm EFT8^2}/dX}{d\sigma_{\rm SM}/dX}$$

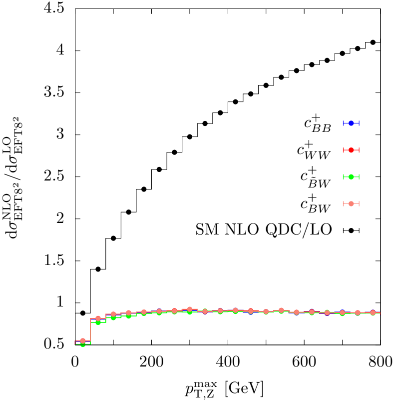
$pp \to ZZ \to e^+e^-\mu^+\mu^-$ at $\sqrt{s} = 13$ TeV (3)

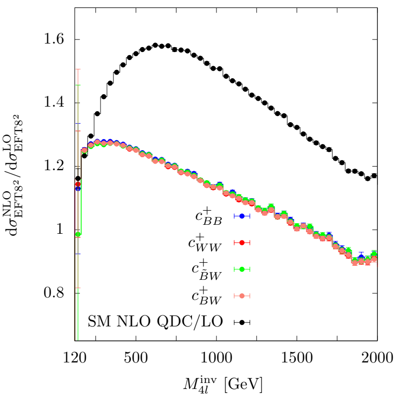


$pp \to ZZ \to e^+e^-\mu^+\mu^-$ at $\sqrt{s} = 13$ TeV (4)



$pp \to ZZ \to e^+e^-\mu^+\mu^-$ at $\sqrt{s} = 13$ TeV (5)





$$\frac{\mathrm{d}\sigma^{\mathrm{NLO}}_{\mathrm{EFT8}^2}}{\mathrm{d}\sigma^{\mathrm{NLO}}_{\mathrm{SM}^2}} = \frac{\mathrm{d}\sigma^{\mathrm{LO}}_{\mathrm{EFT8}^2}}{\mathrm{d}\sigma^{\mathrm{LO}}_{\mathrm{SM}^2}} \frac{\delta^{\mathrm{QCD}}_{\mathrm{EFT8}^2}}{\delta^{\mathrm{QCD}}_{\mathrm{SM}}}, \quad \text{with} \quad \delta^{\mathrm{QCD}}_{\mathrm{EFT8}^2} = \frac{\mathrm{d}\sigma^{\mathrm{NLO}}_{\mathrm{EFT8}^2}}{\mathrm{d}\sigma^{\mathrm{LO}}_{\mathrm{EFT8}^2}}, \quad \delta^{\mathrm{QCD}}_{\mathrm{SM}} = \frac{\mathrm{d}\sigma^{\mathrm{NLO}}_{\mathrm{SM}}}{\mathrm{d}\sigma^{\mathrm{LO}}_{\mathrm{SM}}}$$

Conclusions

- $WW/WZ/ZZ(\to 4f)$ in the EFT framework at NLO QCD
- impact of Dim6/8 operators compared to NLO QCD and NLO EW corrections in the SM
- automated computation of all matrix elements with the same tool (RECOLA2)
- first application of RECOLA2 in the EFT framework

Backup Slides

Input parameters: SM

$$
\begin{aligned}
G_\mu &= 1.1663787 \times 10^{-5}\,\mathrm{GeV}^{-2}, & & \\
M_\mathrm{W}^\mathrm{OS} &= 80.385\,\mathrm{GeV}, & \Gamma_\mathrm{W}^\mathrm{OS} &= 2.085\,\mathrm{GeV}, \\
M_\mathrm{Z}^\mathrm{OS} &= 91.1876\,\mathrm{GeV}, & \Gamma_\mathrm{Z}^\mathrm{OS} &= 2.4952\,\mathrm{GeV}, \\
M_\mathrm{H} &= 125\,\mathrm{GeV}, & \Gamma_\mathrm{H} &= 4.097\,\mathrm{MeV}, \\
m_\mathrm{t} &= 173.2\,\mathrm{GeV}, & \Gamma_\mathrm{t} &= 1.369\,\mathrm{GeV}
\end{aligned}
$$

All other masses set to 0

$V_\mathrm{CKM} = \mathrm{Id}$

`NNPDF23_nlo_as_0118_qed`