LHC potential to study quartic electroweak gauge boson couplings

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Outline

- I. Basic facts
- II. Quartic couplings not containing photons
- III. Quartic couplings with photons
- IV. LHC capability to study quartic couplings
- V. Conclusions

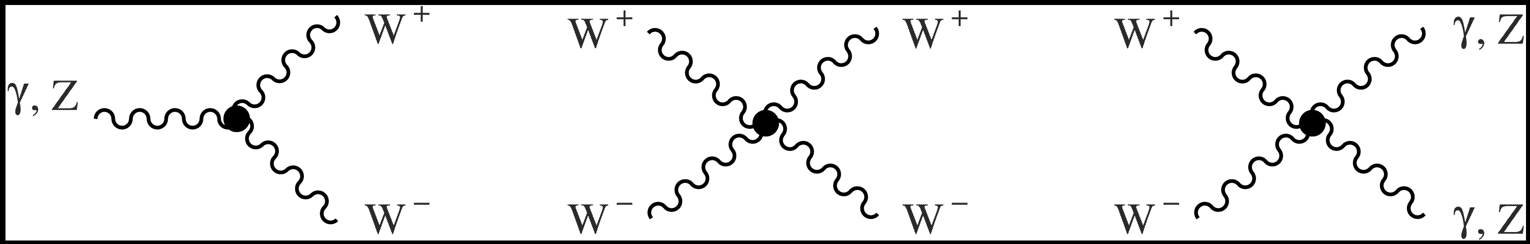
I. Basic facts

- What we know:

$$\mathcal{L} = \mathcal{L}^{\rm f}_{\rm kinetic} + \mathcal{L}^{\rm GB}_{\rm kinetic} + \mathcal{L}_{\rm ffv} + \mathcal{L}_{\rm vvv} + \mathcal{L}_{\rm vvvv} + \mathcal{L}_{\rm EWSB}$$

- $\mathbf{SU(3)_c \times SU(2)_L \times U(1)_Y}$ gauge interaction between fermions and gauge bosons tested at 0.1% level.

- The couplings between the gauge bosons are fixed by the gauge symmetry, e.g.



✪ $\mathbf{W_L^+ W_L^- \to W_L^+ W_L^-}$ scattering (Cornwall; Lee-Quigg-Thacker; etc)

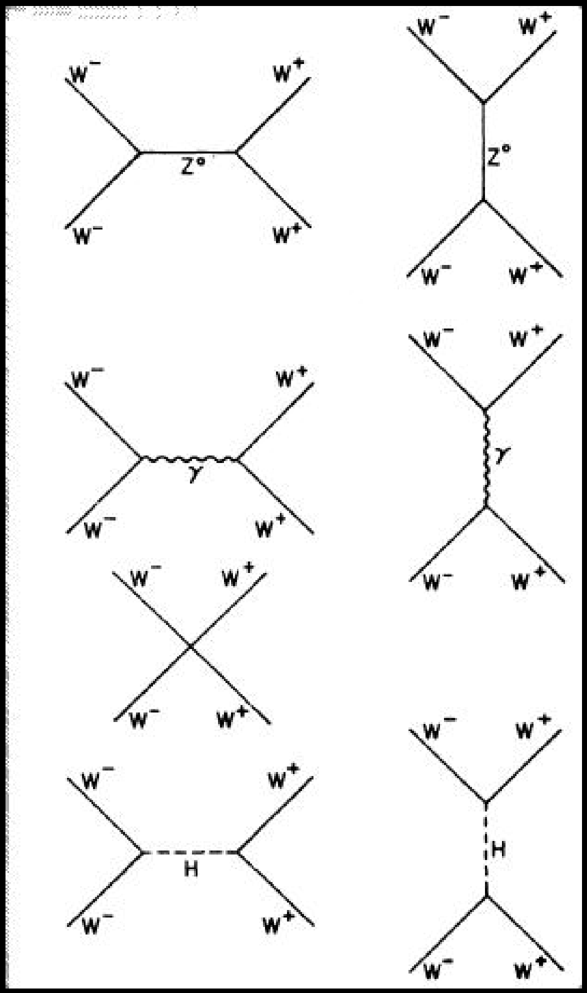
☆ $\mathbf{J = 0}$ partial wave

$$\mathbf{A} = \mathbf{A}_4 \frac{\mathbf{E}^4}{\mathbf{M_W^4}} + \mathbf{A}_2 \frac{\mathbf{E}^2}{\mathbf{M_W^2}} + \cdots$$

☆ Unitarity implies that $\mathbf{A_4}$ and $\mathbf{A_2}$ must vanish

☆ $\mathbf{A_4} \propto \mathbf{g_{WWWW}} - \mathbf{g^2_{WWZ}} - \mathbf{g^2_{WW\gamma}}$ vanishes automatically in the SM.

☆ Additional particles/interactions are needed to cancel the $\mathbf{A_2}$ term as well.



✪ Quartic couplings can be modified in extensions of the SM

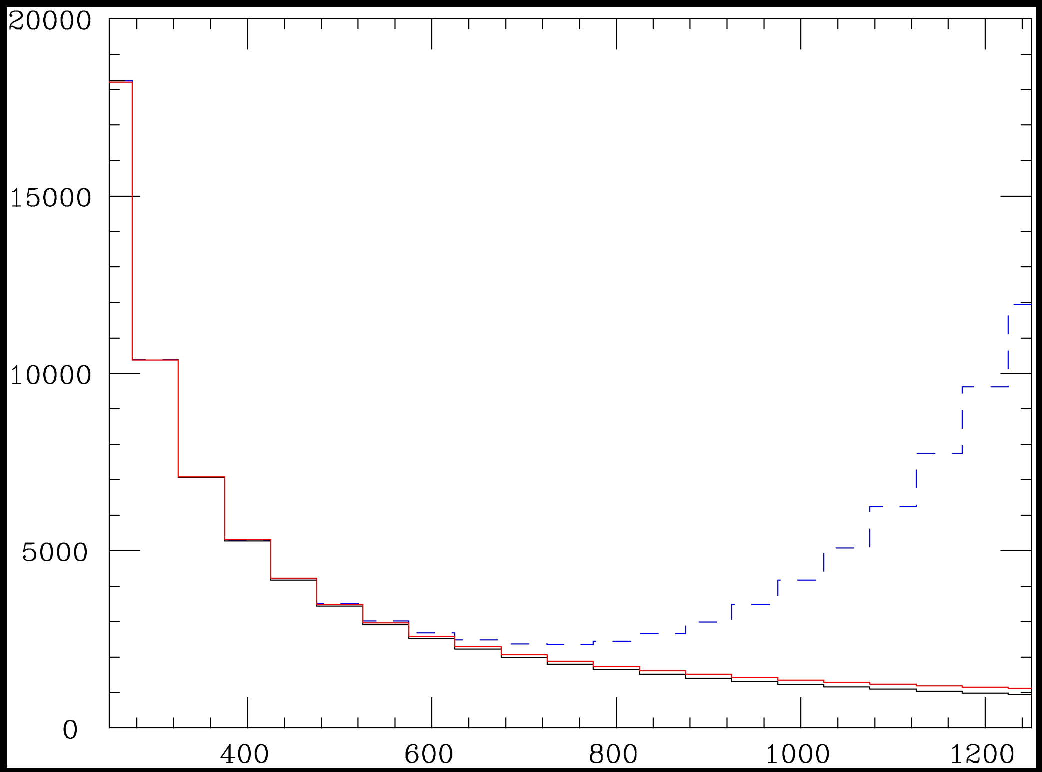
☆ In Higgsless models the Higgs is replaced by a tower of KK excitations of the gauge bosons

☆ The cancelation of the E^4 growth of the scattering amplitudes requires that (Csaki–Grojean–Murayama–Pilo–Terning)

$$\mathbf{g_{WWWW} = g^2_{WWZ} + g^2_{WW\gamma} + \sum_i \left(g^{(i)}_{WWV_i}\right)^2}$$

☆ Quartic couplings in these models can easily differ by a few percent from the SM values.

✪ Simple way to look for anomalous (quartic) couplings is through the cross section growth



$\frac{d\sigma}{dM_{WW}}(\mathbf{WW} \to \mathbf{WW})$ for $\mathbf{g_{WWWW} = 1.01 g^{SM}_{WWWW}}$

II. Quartic couplings not containing photons

☆ Possible Lorentz invariant structures without $\mathbf{W}$ and $\mathbf{Z}$ derivatives

$$\mathcal{O}_0^{\mathbf{WW}} = \mathbf{g}^{\alpha\beta}\mathbf{g}^{\gamma\delta}\left[\mathbf{W}^+_\alpha \mathbf{W}^-_\beta \mathbf{W}^+_\gamma \mathbf{W}^-_\delta\right] \; , \qquad \mathcal{O}_1^{\mathbf{WW}} = \mathbf{g}^{\alpha\beta}\mathbf{g}^{\gamma\delta}\left[\mathbf{W}^+_\alpha \mathbf{W}^+_\beta \mathbf{W}^-_\gamma \mathbf{W}^-_\delta\right]$$

$$\mathcal{O}_0^{\mathbf{WZ}} = \mathbf{g}^{\alpha\beta}\mathbf{g}^{\gamma\delta}\left[\mathbf{W}^+_\alpha \mathbf{Z}_\beta \mathbf{W}^-_\gamma \mathbf{Z}_\delta\right] \; , \qquad \mathcal{O}_1^{\mathbf{WZ}} = \mathbf{g}^{\alpha\beta}\mathbf{g}^{\gamma\delta}\left[\mathbf{W}^+_\alpha \mathbf{W}^-_\beta \mathbf{Z}_\gamma \mathbf{Z}_\delta\right] \; ,$$

$$\mathcal{O}_0^{\mathbf{ZZ}} = \mathcal{O}_1^{\mathbf{ZZ}} \equiv \mathcal{O}^{\mathbf{ZZ}} = \mathbf{g}^{\alpha\beta}\mathbf{g}^{\gamma\delta}\left[\mathbf{Z}_\alpha \mathbf{Z}_\beta \mathbf{Z}_\gamma \mathbf{Z}_\delta\right] \; ,$$

and we write $\mathcal{L}^{\mathbf{VVV'V'}} \equiv \mathbf{c}_0^{\mathbf{VV'}}\, \mathcal{O}_0^{\mathbf{VV'}} + \mathbf{c}_1^{\mathbf{VV'}}\, \mathcal{O}_1^{\mathbf{VV'}}$.

✪ In the SM

$$\mathbf{c}^{\mathbf{WW}}_{\mathbf{0},\mathrm{SM}} = -\mathbf{c}^{\mathbf{WW}}_{\mathbf{1},\mathrm{SM}} = \frac{\mathbf{2}}{\mathbf{c}^2_{\mathbf{W}}}\mathbf{c}^{\mathbf{WZ}}_{\mathbf{0},\mathrm{SM}} = -\frac{\mathbf{2}}{\mathbf{c}^2_{\mathbf{W}}}\mathbf{c}^{\mathbf{WZ}}_{\mathbf{1},\mathrm{SM}} = \mathbf{g}^2 \qquad \mathbf{c}^{\mathbf{ZZ}}_{\mathrm{SM}} = \mathbf{0}$$

☆ Form of the low energy lagrangian depends on the existence, or not, of a Higgs boson

Linear realization of the gauge symmetry

⋆ We are interested in effective operators leading to quartic couplings but not triple couplings

⋆ The lowest dimension operators are dimension 8, e.g.

$$\mathcal{L}_{S,0} = \frac{f_0}{\Lambda^4} \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right] ,$$

$$\mathcal{L}_{S,1} = \frac{f_1}{\Lambda^4} \left[(D_\mu \Phi)^\dagger D^\mu \Phi \right] \times \left[(D_\nu \Phi)^\dagger D^\nu \Phi \right] .$$

which lead to

$$\mathbf{\Delta c_i^{WW} = \frac{g^2 v^4 f_i}{8\Lambda^4} \equiv \qquad \Delta c_i^{WZ} = \frac{g^2 v^4 f_i}{16 c_W^2 \Lambda^4} \qquad \Delta c^{ZZ} = \frac{g^2 v^2 (f_0 + f_1)}{32 c_W^4 \Lambda^4}}$$

Non-Linear realization of the gauge symmetry

✪ Without the Higgs $\Longrightarrow$ non-linear realization of the symmetry $\Longrightarrow$ "chiral lagrangians". At lowest order, O$(\mathbf{p}^4)$,

	2 pt. vtx.	3 pt. vtx. (TGC)	4 pt. vtx. (QGC)
$v^2\bar{\mathcal{L}}_0$	$\surd$		
$\bar{\mathcal{L}}_1$	$\surd$	$\surd$	
$\bar{\mathcal{L}}_2$		$\surd$	$\surd$
$\bar{\mathcal{L}}_3$		$\surd$	$\surd$
$\bar{\mathcal{L}}_4$			$\surd$
$\bar{\mathcal{L}}_5$			$\surd$
$\bar{\mathcal{L}}_6$			$\surd$
$\bar{\mathcal{L}}_7$			$\surd$
$\bar{\mathcal{L}}_8$	$\surd$	$\surd$	$\surd$
$\bar{\mathcal{L}}_9$		$\surd$	$\surd$
$\bar{\mathcal{L}}_{10}$			$\surd$

⋆ The operators that respect the $\mathbf{SU(2)}$ custodial are

$$\mathcal{L}_4^{(4)} = \alpha_4 \left[\mathrm{Tr}\left(\mathbf{V}_\mu \mathbf{V}_\nu\right)\right]^2 \qquad \mathcal{L}_5^{(4)} = \alpha_5 \left[\mathrm{Tr}\left(\mathbf{V}_\mu \mathbf{V}^\mu\right)\right]^2$$

with $\mathbf{D}_\mu \mathbf{\Sigma} \equiv \partial_\mu \mathbf{\Sigma} + \mathbf{ig}\frac{\tau^\mathbf{a}}{\mathbf{2}}\mathbf{W}^\mathbf{a}_\mu \mathbf{\Sigma} - \mathbf{ig}'\mathbf{\Sigma}\frac{\tau^\mathbf{3}}{\mathbf{2}}\mathbf{B}_\mu$ and $\mathbf{V}_\mu \equiv \left(\mathbf{D}_\mu \mathbf{\Sigma}\right)\mathbf{\Sigma}^\dagger$

leading to

$$\mathbf{\Delta c^{WW}_{0(1)}} = \mathbf{g^2}\alpha_{\mathbf{4(5)}} \qquad \mathbf{\Delta c^{WZ}_{0(1)}} = \frac{\mathbf{g^2}}{\mathbf{2c^2_W}}\alpha_{\mathbf{4(5)}} \qquad \mathbf{\Delta c^{ZZ}} = \frac{\mathbf{g^2}}{\mathbf{4c^4_W}}\left(\alpha_\mathbf{4} + \alpha_\mathbf{5}\right)$$

- **Example:** integrating out a heavy Higgs leads to

$$\alpha_4 = \mathbf{0} \qquad \alpha_5 = \frac{\mathbf{1}}{\mathbf{8}} \frac{\mathbf{v^2}}{\mathbf{M_H^2}}$$

- Integrating out a heavy spin-1 particle leads to

$$\alpha_4 = -\alpha_5 = \mathbf{12}\pi \frac{\mathbf{v^4}}{\mathbf{M_\rho^4}} \frac{\mathbf{\Gamma_\rho}}{\mathbf{M_\rho}}$$

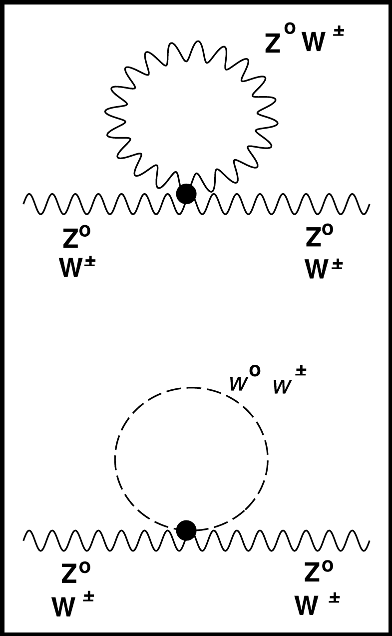
Constraints on the anomalous QVC

✪ Precision electroweak measurements can constrain the anomalous QVC

⋆ there is a contribution only to ϵ_1 leading to

$$-0.32 < \quad \alpha_4 \quad < 0.085 \; ,$$
$$-0.81 < \quad \alpha_5 \quad < 0.21 \; .$$

at 99% CL



✪ The strongest bounds come from unitarity.

⋆ Only considering $\mathbf{J = 0}$ for $\mathbf{V_L V_L \to V_L V_L}$ we have

$$
\begin{aligned}
|4\alpha_4 + 2\alpha_5| &< 3\pi \frac{v^4}{\Lambda^4}, \\
|3\alpha_4 + 4\alpha_5| &< 3\pi \frac{v^4}{\Lambda^4}, \\
|\alpha_4 + \alpha_6 + 3(\alpha_5 + \alpha_7)| &< 3\pi \frac{v^4}{\Lambda^4}, \\
|2(\alpha_4 + \alpha_6) + \alpha_5 + \alpha_7| &< 3\pi \frac{v^4}{\Lambda^4}, \\
|\alpha_4 + \alpha_5 + 2(\alpha_6 + \alpha_7 + \alpha_{10})| &< \frac{6\pi}{5} \frac{v^4}{\Lambda^4}.
\end{aligned}
$$

⋆ For $\mathbf{\Lambda = 1}$ TeV the bounds are $\simeq \mathbf{0.01}$

III. Quartic couplings with photons

☆ Using the non-linear representation there are 14 $\mathcal{O}(\mathbf{p}^4)$ effective operators that respect custodial $\mathbf{SU(2)}$ symmetry

☆ these are associated to eleven independent tensor structures

☆ For instance, the operators containing two photons are

$$\begin{aligned}\mathcal{L}_{eff} &= -\pi\alpha\beta_0\left(\frac{1}{2}F^{\mu\nu}F_{\mu\nu}W^{+\alpha}W^-_\alpha + \frac{1}{4\cos^2\theta_W}F^{\mu\nu}F_{\mu\nu}Z^\alpha Z_\alpha\right) \\ &\quad -\pi\alpha\beta_c\left(\frac{1}{4}F^{\mu\alpha}F_{\mu\beta}(W^+_\alpha W^{-\beta} + W^+_\beta W^{-\alpha}) + \frac{1}{4\cos^2\theta_W}F^{\mu\alpha}F_{\mu\beta}Z_\alpha Z^\beta\right)\end{aligned}$$

Present constraints:

☆ Direct searches at LEP in $\mathbf{e^+e^- \to W^+W^-}\gamma$ and $\mathbf{Z}\gamma\gamma$ lead to 95% CL bounds

$$-4.9 \times 10^{-3} \text{ GeV}^{-2} < \beta_0 < 5.6 \times 10^{-3} \text{ GeV}^{-2} ,$$
$$-5.4 \times 10^{-3} \text{ GeV}^{-2} < \beta_c < 9.8 \times 10^{-3} \text{ GeV}^{-2} .$$

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⋆ Electroweak precision measurements: these QGV contribute to $\epsilon_{\mathbf{2,3}}$

Λ (TeV)	Parameter	β_0 (GeV^{-2})	β_c (GeV^{-2})
0.5	S	($-$0.09 , 1.5)$\times 10^{-4}$	($-$0.29 , 4.9)$\times 10^{-4}$
	U	($-$5.4 , 1.9)$\times 10^{-4}$	($-$18. , 6.2)$\times 10^{-4}$
2.5	S	($-$0.04 , 0.69)$\times 10^{-4}$	($-$0.15 , 2.5)$\times 10^{-4}$
	U	($-$2.5 , 0.88)$\times 10^{-4}$	($-$9.1 , 3.2)$\times 10^{-4}$

⋆ Unitarity violation in $\gamma\gamma \to \mathbf{VV}$ leads to the constraint

$$\left(\frac{\alpha\beta s}{16}\right)^2 \left(1-\frac{4M_W^2}{s}\right)^{1/2} \left(3-\frac{s}{M_W^2}+\frac{s^2}{4M_W^4}\right) \leq N \text{ for } V=W \ ,$$

$$\left(\frac{\alpha\beta s}{16c_W^2}\right)^2 \left(1-\frac{4M_Z^2}{s}\right)^{1/2} \left(3-\frac{s}{M_Z^2}+\frac{s^2}{4M_Z^4}\right) \leq N \text{ for } V=Z \ ,$$

where $\beta = \beta_0$ or β_c and $N = 1/4\ (4)$ for β_0 (β_c). For instance, unitarity is violated for $\gamma\gamma$ invariant masses above 240 GeV for $\beta_0 = 5.6 \times 10^{-3}$ GeV^{-2} (one of the present LEP bounds).

IV. LHC capability to study quartic couplings

QGC with two photons

(Lietti, Gonzalez–Garcia, OE, S. Novaes)

- $\gamma\gamma \mathbf{W}(\mathbf{Z})$ production

$$\mathbf{p} + \mathbf{p} \rightarrow \gamma + \gamma + (\mathbf{W}^* \rightarrow)\ \ell + \nu \qquad \text{and} \qquad \mathbf{p} + \mathbf{p} \rightarrow \gamma + \gamma + (\mathbf{Z}^* \rightarrow)\ \ell + \ell$$

- To have a meaningful limit we introduce the form factor

$$\beta_{\mathbf{0,c}} \longrightarrow \left(\mathbf{1} + \frac{\mathbf{M}^{\mathbf{2}}_{\gamma\gamma}}{\mathbf{\Lambda}^{\mathbf{2}}} \right)^{-\mathbf{n}} \times \beta_{\mathbf{0,c}}$$

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- Parton level analysis using MadGraph adding the anomalous quartic interactions.

- P. Bell has a MC ready for full simulations.

- Basic acceptance cuts

$$
\begin{aligned}
p_T^{(\ell,\nu)} &\geq 25 \text{ GeV for } \ell = e \ \ (\mu) \\
E_T^{\gamma} &\geq 20 \text{ GeV} \\
|\eta_{\gamma,e}| &\leq 2.5 \\
|\eta_{\mu}| &\leq 1.0 \\
\Delta R_{ij} &\geq 0.4 \ ,
\end{aligned}
$$

- To select W's

$$\mathbf{65} \text{ GeV } \leq \mathbf{M_T^{\ell\nu}} \leq \mathbf{100} \text{ GeV}$$

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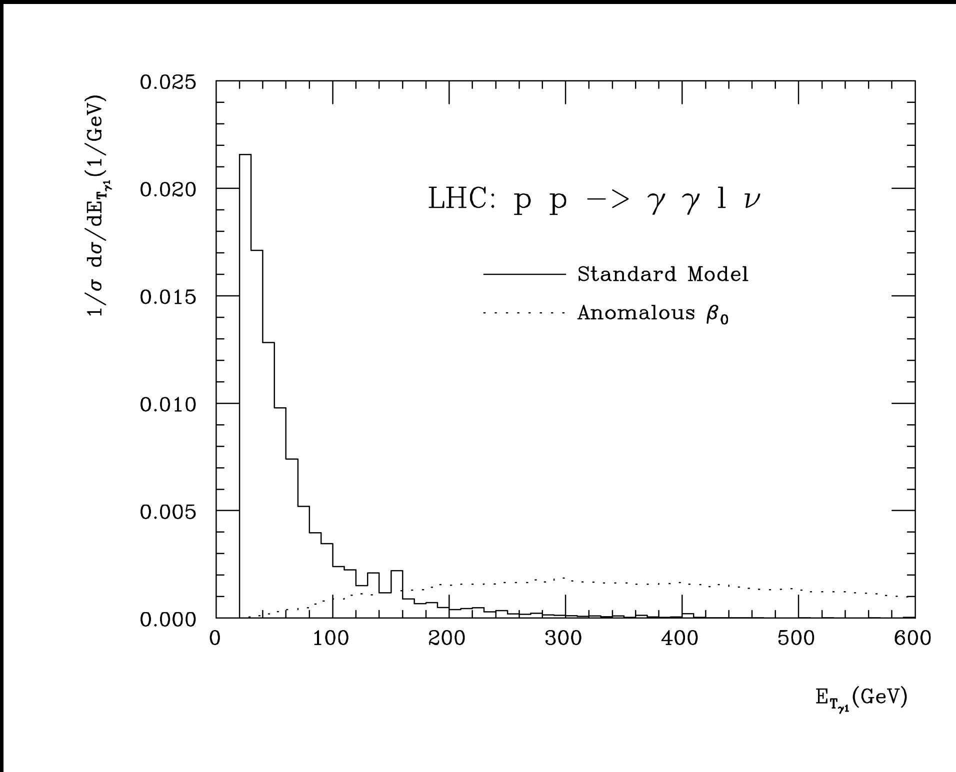

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$$\mathbf{65} \text{ GeV } \leq \mathbf{M_T^{\ell\nu}} \leq \mathbf{100} \text{ GeV}$$

- To enhance the signal

$$\mathbf{E_T^{\gamma_{1(2)}}} \geq \mathbf{200} \;\; \mathbf{(100)} \text{ GeV}$$

- We write that $\sigma \equiv \sigma_{\mathbf{sm}} + \beta\, \sigma_{\mathbf{inter}} + \beta^{\mathbf{2}}\, \sigma_{\mathbf{ano}}$

- Assuming that $\mathbf{\Lambda = 2.5}$ TeV we get that

Process	β_0 (TeV^{-2})	β_c (TeV^{-2})
$pp \to l^{\pm}\nu_{l^{\pm}}\gamma\gamma$	($-$76. , 76.)	($-$110. , 100.)

⋆ A bit better than the bounds imposed by precision measurements

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- WBF $\gamma\gamma$ production

$$\mathbf{p + p \to q + q + (W^* + W^* \text{ or } Z^* + Z^*) \to q + q + \gamma + \gamma}$$

- Basic acceptance cuts for the jets

$$p_T^{j_{1(2)}} > 40\ (20)\ \text{GeV} \quad , \quad |\eta_{j_{(1,2)}}| < 5.0\ ,$$
$$|\eta_{j_1} - \eta_{j_2}| > 4.4 \quad , \quad \eta_{j_1} \cdot \eta_{j_2} < 0 \quad \text{and}$$
$$\Delta R_{jj} > 0.7\ .$$

- Basic acceptance cuts for the photons

$$E_T^{\gamma(1,2)} > 25\ \text{GeV} \quad , \quad |\eta_{\gamma_{(1,2)}}| < 2.5\ ,$$
$$\text{min}\{\eta_{j_1}, \eta_{j_2}\} + 0.7 < \eta_{\gamma_{(1,2)}} < \text{max}\{\eta_{j_1}, \eta_{j_2}\} - 0.7\ ,$$
$$\Delta R_{j\gamma} > 0.7 \quad \text{and} \quad \Delta R_{\gamma\gamma} > 0.4$$

- Basic acceptance cuts for the jets

$$p_T^{j_{1(2)}} > 40\ (20)\ \text{GeV} \quad , \quad |\eta_{j_{(1,2)}}| < 5.0\ ,$$
$$|\eta_{j_1} - \eta_{j_2}| > 4.4 \quad , \quad \eta_{j_1} \cdot \eta_{j_2} < 0 \quad \text{and}$$
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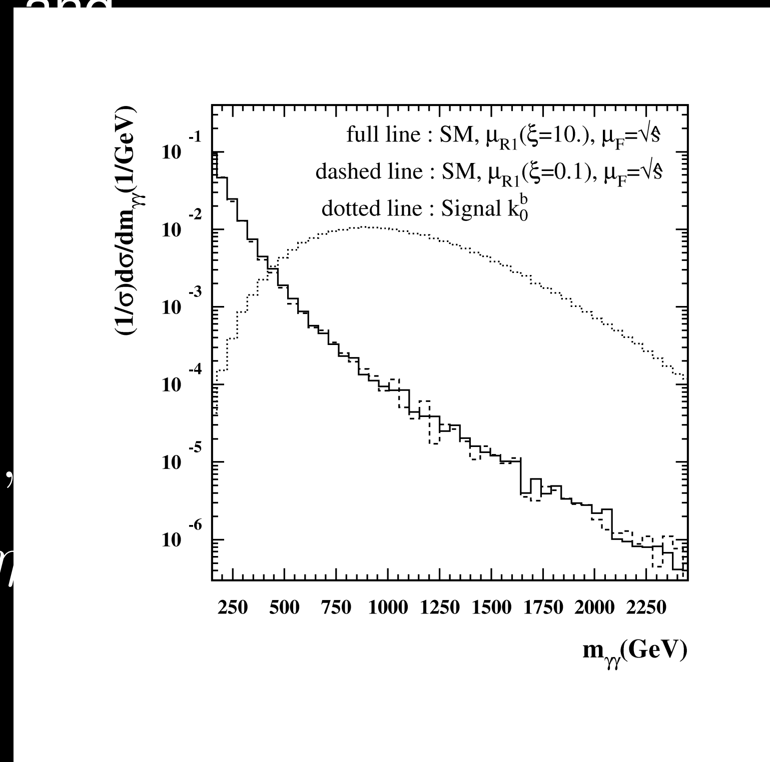
$$\Delta R_{j\gamma} > 0.7 \quad \text{and} \quad \Delta R_{\gamma\gamma} > 0.4$$



- To enhance the signal

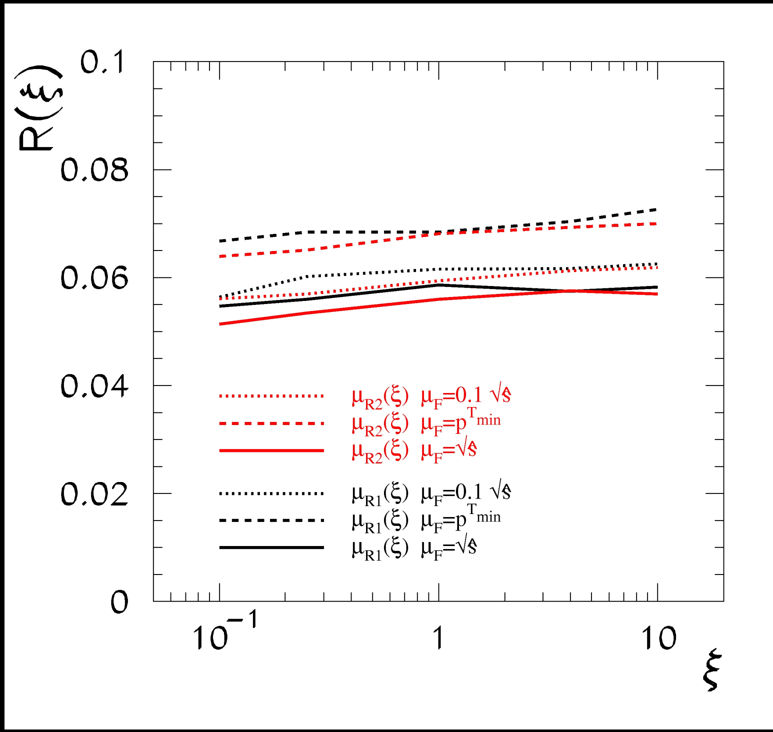
$$400\ \text{GeV} \ \leq \mathbf{m}_{\gamma\gamma} \leq 2500\ \text{GeV}.$$

☆ The predictions for the SM backgrounds vary by a factor of 10 when we change the QCD scales

✪ We must extract the SM background from data.

✪ The best variable to define the control region is the $\gamma\gamma$ invariant mass

$$\mathbf{R}(\xi) = \frac{\sigma(400 \text{ GeV } < \mathbf{m}_{\gamma\gamma} < 2500 \text{ GeV })}{\sigma(100 \text{ GeV } < \mathbf{m}_{\gamma\gamma} < 400 \text{ GeV })} \; .$$



✪ The QCD uncertainty is 15% in LO

✪ $N_{bck} = 143$ for 100 fb^{-1}

☆ Bounds: $|\beta_0| < \mathbf{0.057}$ TeV^{-2} and $|\beta_c| < \mathbf{0.21}$ TeV^{-2}

☆ 2 to 3 orders improvement over $\gamma\gamma W$

QGC without photons

(Mizukoshi, Gonzalez–Garcia, OE)

- We studied two processes

$$\mathbf{p+p\to jjW^{+}W^{-}\to jje^{\pm}\mu^{\mp}\nu\nu} \quad \text{and} \quad \mathbf{p+p\to jjW^{\pm}W^{\pm}\to jje^{\pm}\mu^{\pm}\nu\nu}$$

- Let's concentrate on the anomalous QGC α_4 and α_5
- Main SM backgrounds: W^+W^-jj, $t\bar{t}$, $t\bar{t}j$, $t\bar{t}jj$
- Basic acceptance cuts

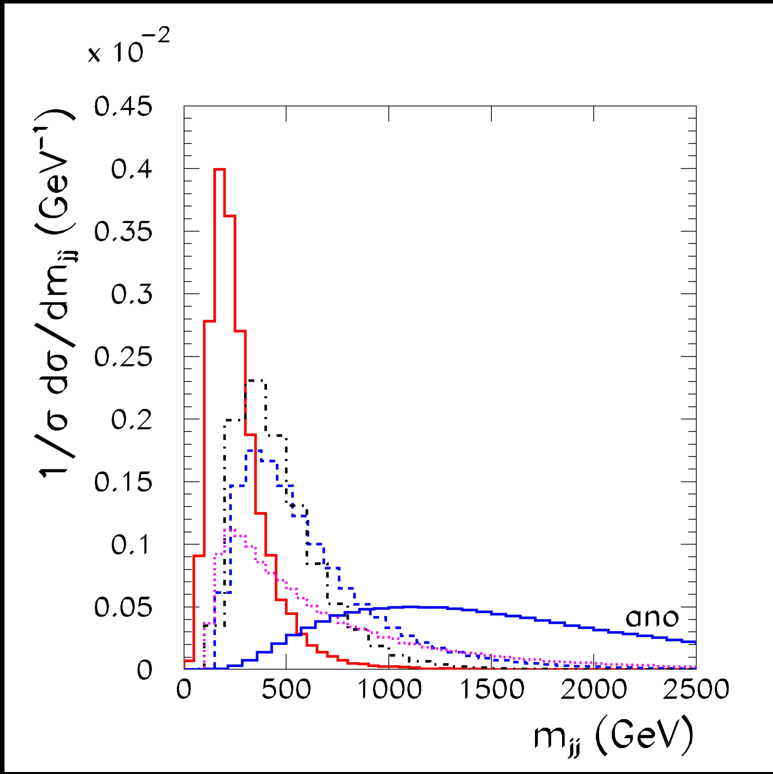
$$\begin{aligned}
p_T^j > 20 \text{ GeV} \quad &, \quad |\eta_j| < 4.9 \;, \\
|\eta_{j1}-\eta_{j2}| > 3.8 \quad &, \quad \eta_{j1}\cdot\eta_{j2} < 0 \;. \\
|\eta_\ell| \le 2.5 \quad &, \quad \eta^j_{\min} < \eta_\ell < \eta^j_{\max} \\
\Delta R_{\ell j} \ge 0.4 \quad &, \quad \Delta R_{\ell\ell} \ge 0.4 \\
p_T^\ell \ge 100 \text{ GeV} \quad &, \quad p^T_{missing} \ge 30 \text{ GeV} \;.
\end{aligned}$$

✳ To further suppress the background in the $e^{\pm}\mu^{\mp}jj$ final state

$$\mathbf{M_{jj} \geq 1000} \text{ GeV} ,$$

✳ We also veto extra jet activity

$$\mathbf{p_T^j < 20} \text{ GeV} \quad \text{if} \quad \eta^j_{\rm min} < \eta_j < \eta^j_{\rm max} .$$

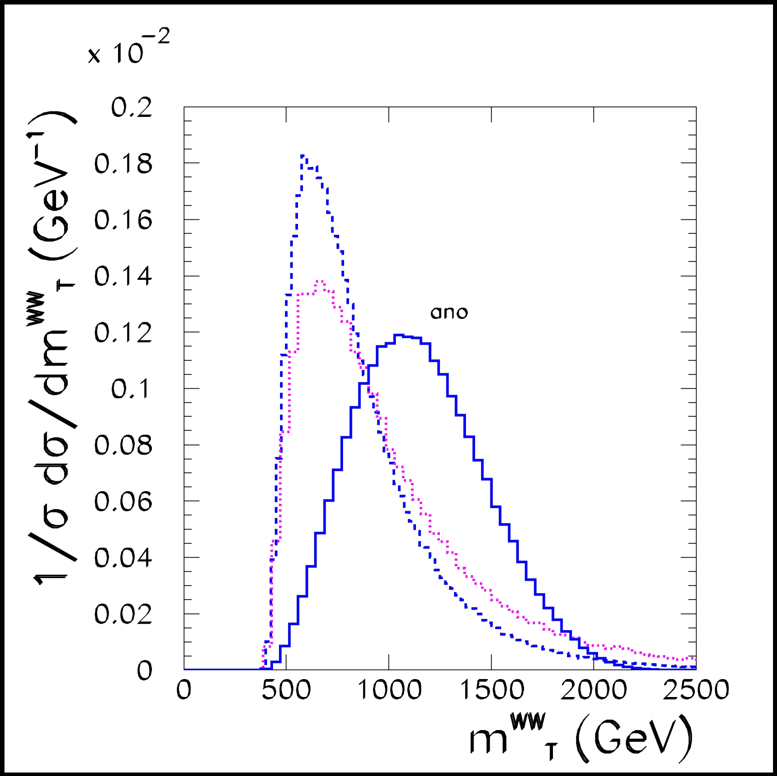


- Anomalous QGC leads larger cross sections for large WW invariant masses
- We define the transverse mass

$$M_T^{WW} = \left(\sqrt{(p_T^{e\mu})^2 + m_{e\mu}^2} + \sqrt{\not{p}_T^2 + m_{e\mu}^2} \right)^2 - (\vec{p}_T^{e\mu} + \vec{\not{p}}_T)^2$$

- Further cut

$$M_T^{WW} \geq 800 \text{ GeV}$$



✳ The effect of the cuts in $e^{\pm}\mu^{\mp}jj$ is

background/cut	basic [20 GeV]	basic	$+M_{jj}$ cut	jet veto	jet veto $\times P_{\rm surv}$	angle $\times P_{\rm surv}$
IRED$+-$ (QCD)	20.0	1.12	0.26	0.26	0.058	0.035
IRED$+-$ (EW)	4.4	0.30	0.24	0.24	0.14	0.089
$t\bar{t}$	217.	6.96	0.0306	0.0306	0.0069	0.0068
$t\bar{t}j$	1860.	73.8	8.88	0.776	0.175	0.158
$t\bar{t}jj$	682.	77.2	2.21	0.0140	0.0032	0.0031
Anomalous σ_{00}	2710	1710	1310	1310	786	758

scenario	channel	$\sigma_{\rm bck}$	σ_0	σ_1	σ_{00}	σ_{11}	σ_{01}
	$pp \to e^{\pm}\mu^{\mp}\nu\nu jj$	0.067	—	—	300	655	822
$m_h = 120$ GeV	$pp \to e^{+}\mu^{+}\nu\nu jj$	0.029	-0.46	-0.20	400	94	380
	$pp \to e^{-}\mu^{-}\nu\nu jj$	0.045	-0.11	-0.04	91	21	87
	$pp \to e^{\pm}\mu^{\mp}\nu\nu jj$	0.07	1.3	2.1	300	655	822
No light Higgs boson	$pp \to e^{+}\mu^{+}\nu\nu jj$	0.017	-4.9	-2.3	400	94	380
	$pp \to e^{-}\mu^{-}\nu\nu jj$	0.017	-1.2	-0.54	91	21	87

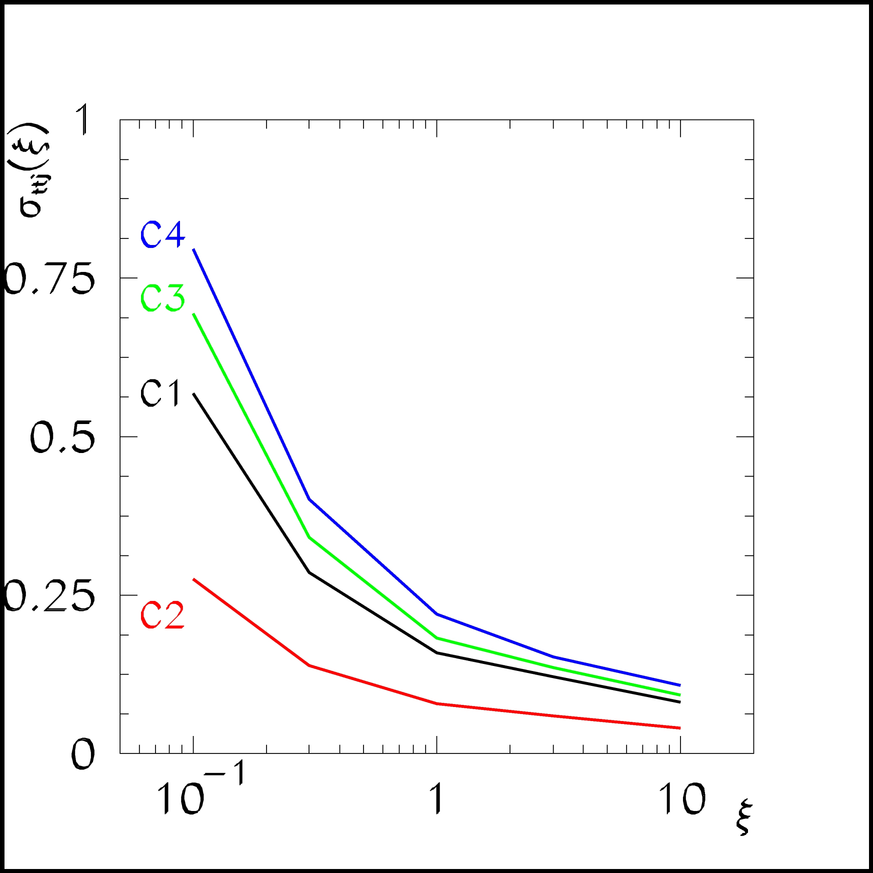
- We need to extract the background from data due to QCD uncertainties
- For opposite charge leptons we use $M_T(WW)$ in the extrapolation

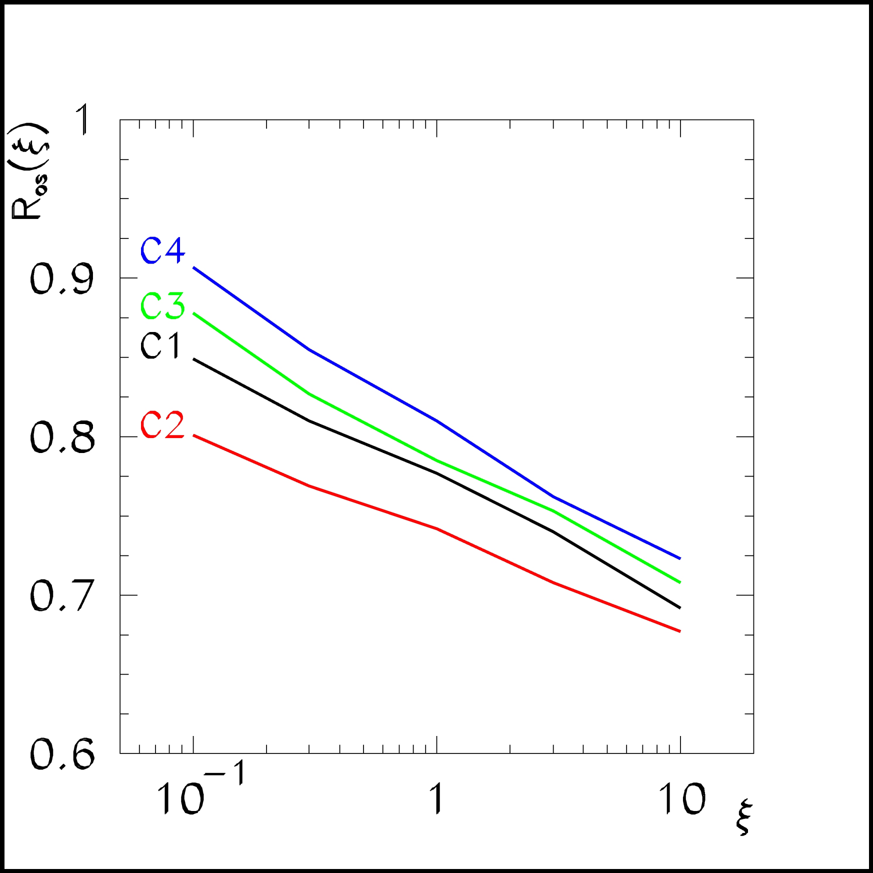
$$\mathbf{R}_{\rm os} = \frac{\sigma_{\rm bck}(\mathbf{M_T^{WW}} > \mathbf{800}\ \text{GeV})}{\sigma_{\rm bck}(\mathbf{M_T^{WW}} < \mathbf{800}\ \text{GeV})} ,$$

- For same charge leptons we use p_T^ℓ in the extrapolation

$$\mathbf{R}_{\rm ss} = \frac{\sigma_{\rm bck}(\mathbf{p_T^\ell} > \mathbf{100}\ \mathrm{GeV})}{\sigma_{\rm bck}(\mathbf{30} < \mathbf{p_T^\ell} < \mathbf{100}\ \mathrm{GeV})}$$

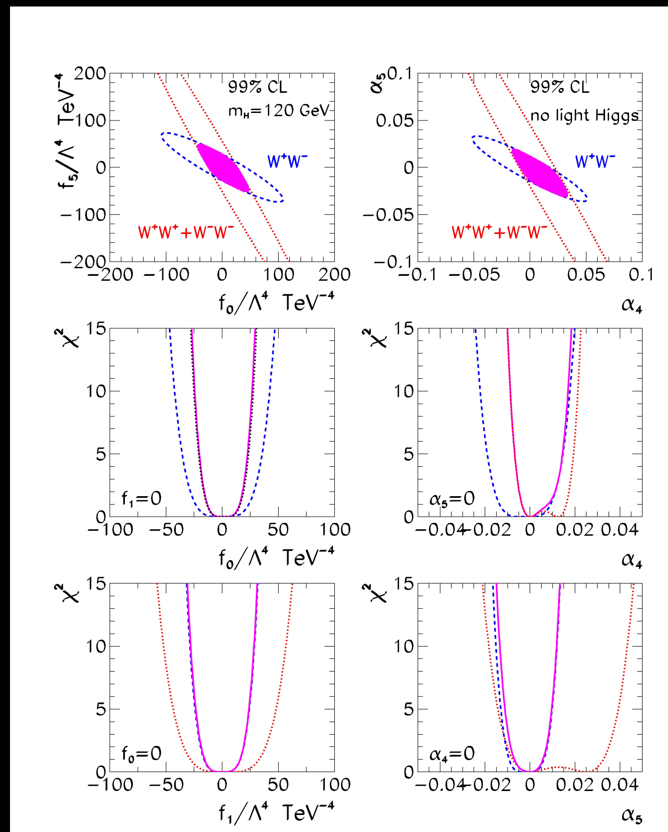
✳ We need to extract the background from data due to QCD uncertainties (e.g. for ttj)





✳ the extrapolation uncertainties are in between 15% for OS (7.5% for SS)

✳ Finally we can estimate that achievable bounds are



✳ Finally we can estimate that achievable 99% CL bounds are

$$-22 < \frac{f_0}{\Lambda^4}(\mathrm{TeV}^{-4}) < 24 \;, \quad (1)$$

$$-25 < \frac{f_1}{\Lambda^4}(\mathrm{TeV}^{-4}) < 25 \;, \quad (2)$$

in the linear case and

$$-7.7 \times 10^{-3} < \alpha_4 < 15 \times 10^{-3} \;, \quad (3)$$

$$-12 \times 10^{-3} < \alpha_5 < 10 \times 10^{-3} \;. \quad (4)$$

in models without a light Higgs.

V. Conclusions

❄ The LHC has a good potential to extend our knowledge on the QGC

❄ WBF will be an important tool for the analysis of anomalous quartic couplings $\Longrightarrow$ we should invest more time understanding its details.