Precise measurement of $Z(\rightarrow ll)\gamma$ final states and search for neutral triple gauge couplings

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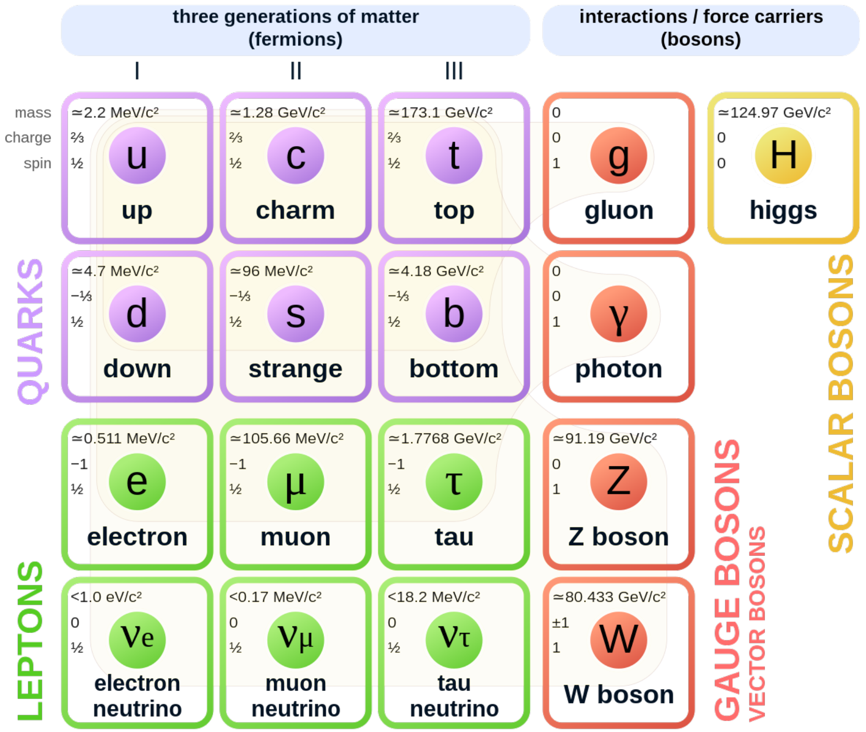
Outline

- Physics motivation
- Signature
- Precise measurement
- EFT interpretation
- Summary
- Additional materials

Introduction to Standard Model

- The Standard Model : the theory describes the fundamental forces (electromagnetic, weak and strong interactions) and how the basic building blocks of matter interact (elementary particles)
- The studies of the fundamental interactions of the SM have been performed with ATLAS experiment, involving W/Z bosons, photons, jets as well as low energy QCD phenomena

Standard Model of Elementary Particles



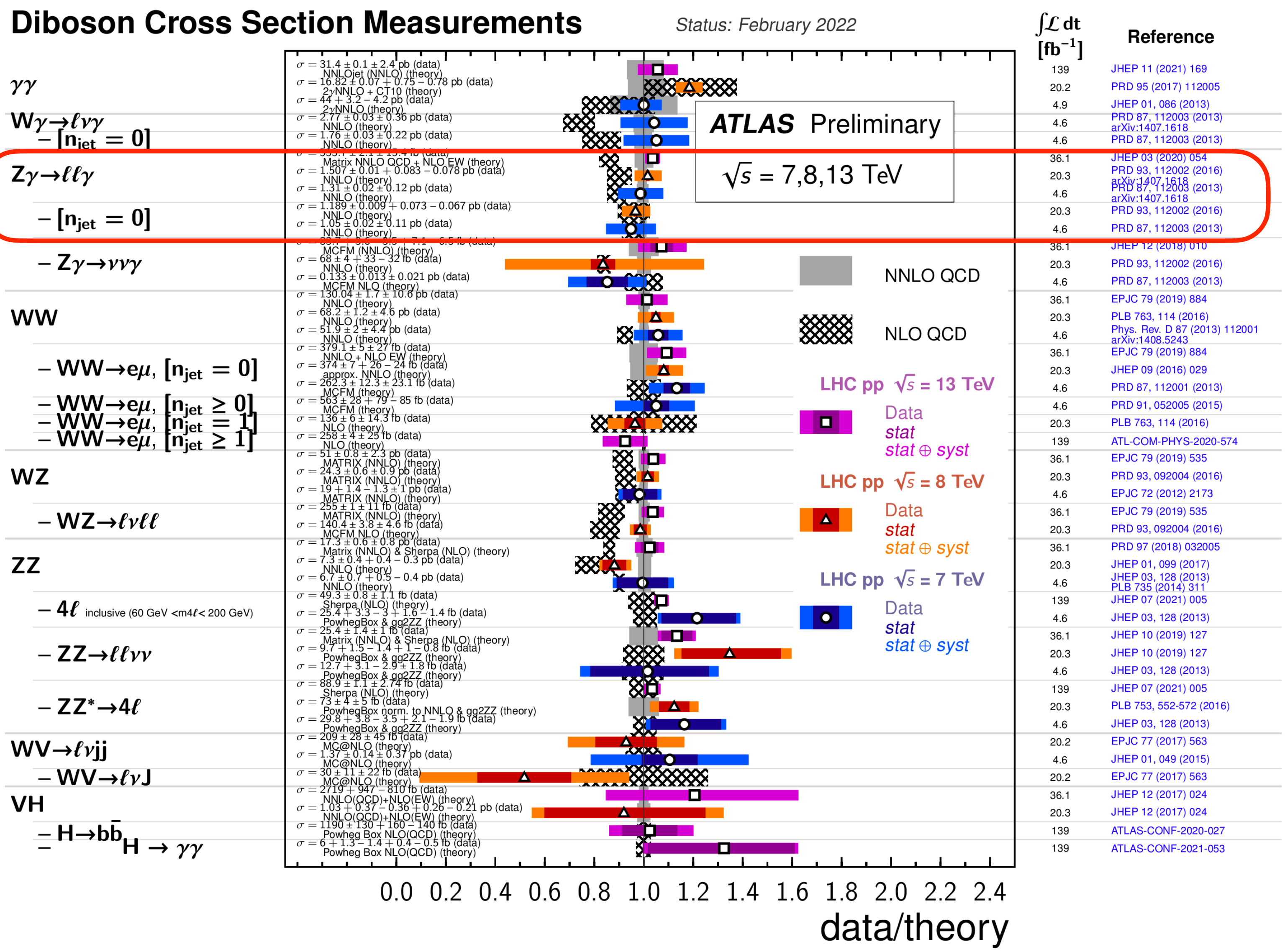
- In this talk :
  - Focus on electroweak gauge boson interactions
  - To introduce the latest **precise measurement results of inclusive $Z+\gamma$ process**
  - To **search for new physics beyond the SM** from EFT extension

[ATLAS Public Results]

Di-boson measurement in ATLAS experiment

A rich program of multi-boson measurements have been performed in the ATLAS experiment

- ☑ Exploring different decay modes
- ☑ Agree with state-of-the-art theoretical calculation in general
- ☑ The precision is getting improved with larger datasets



Why $Z(\to ll)\gamma$ channel ?

Why $Z(\to ll)\gamma$ channel ?

😃 relative large cross-sections

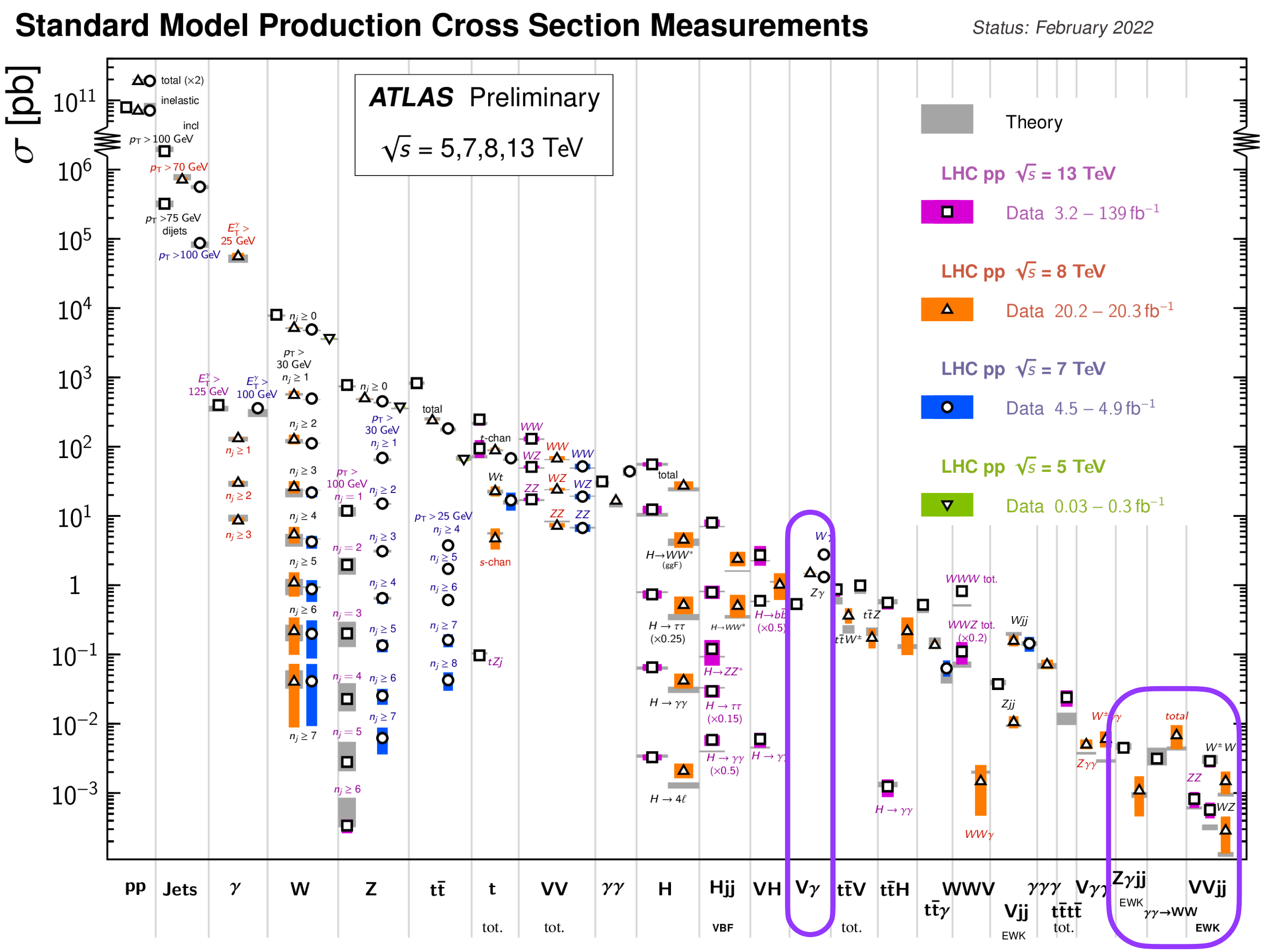
😆 small background contribution

🥳 clear signal signature to apply measurement

What can we do in $Z(\to ll)\gamma$ channel ?

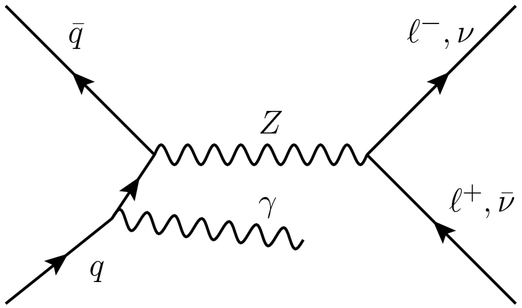
☑ To perform precise measurement (constrain parameters of the SM Lagrangian, test theoretical predictions and etc)

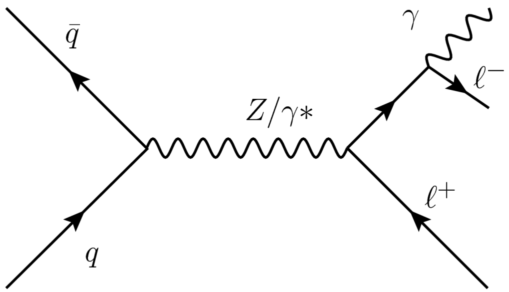
☑ More possibilities for BSM physics (search for axion-like-particles, or EFT interpretation — anomalous couplings)



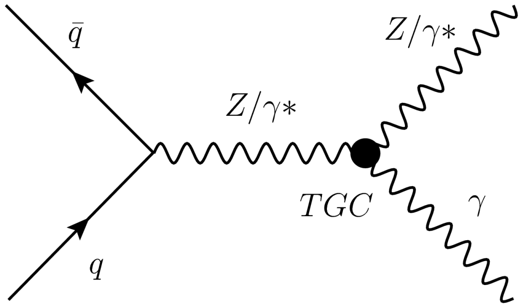
$Z(\rightarrow ll)\gamma$ production modes

SM contribution :





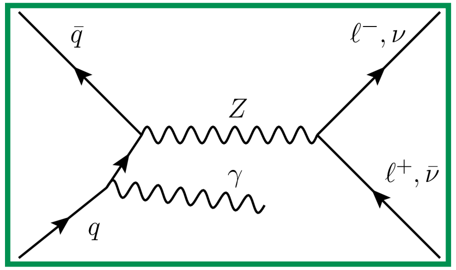
Anomalous coupling :

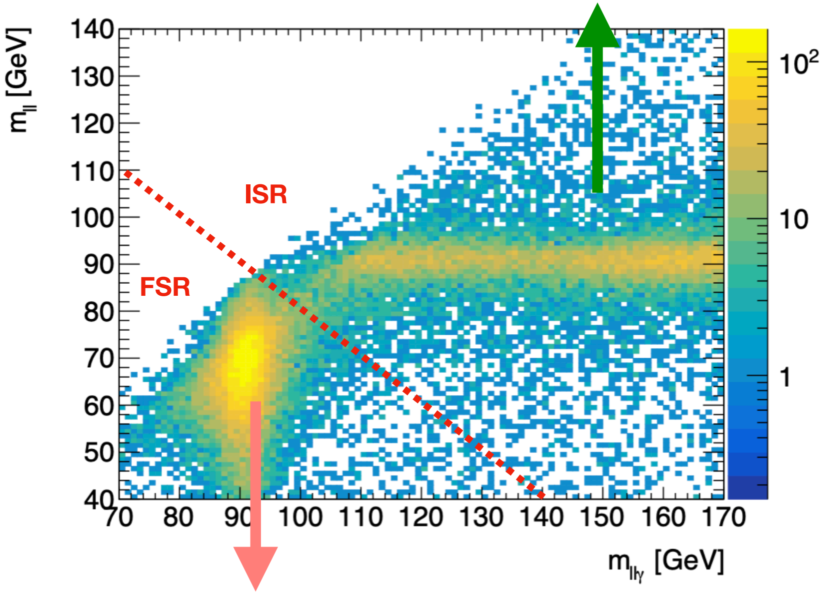


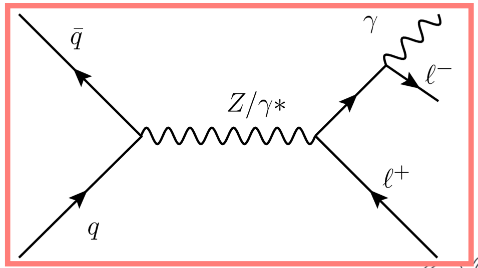
- Dominant production modes :
  - Z plus initial state radiation photon
  - Z plus final state radiation photon

- BSM production mode :
  - Neutral triple gauge couplings $ZZ\gamma/\gamma^*Z\gamma$
  - Forbidden at the SM tree level
  - First appear from dimension-8 Lagrangian

- Process : $Z(\to ll)\gamma$ production in association with hadronic jets
- Event signature :
  - 2 Opposite Sign Same Flavour leptons
  - At least 1 signal photon
  - Inclusive jets
  - Low mass resonances are avoid by requiring $m_{ll} > 40$ GeV, e.g. $\gamma *$
  - FSR events are suppressed by requiring $m_{ll} + m_{ll\gamma} > 182$ GeV







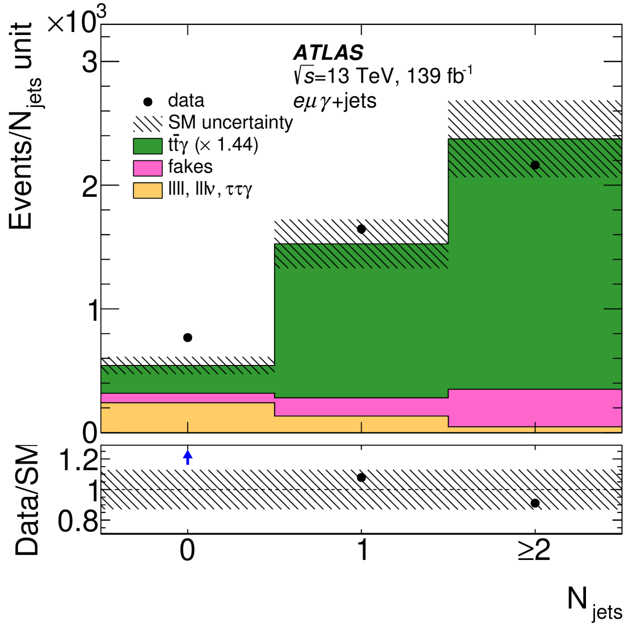
Quantity	Selection criteria
Lepton kinematics	$p_{\mathrm{T}}(\ell_1) > 30$ GeV, $p_{\mathrm{T}}(\ell_2) > 25$ GeV, $\lvert\eta\rvert < 2.47$
Photon kinematics	$p_{\mathrm{T}} > 30$ GeV, $\lvert\eta\rvert < 2.37$, $\Delta R(\gamma, \ell) > 0.4$
Photon isolation	$E_{\mathrm{T}}^{\mathrm{iso}}/E_{\mathrm{T}}^{\gamma} < 0.07$
Jet kinematics	($p_{\mathrm{T}} > 30$ GeV if $\lvert\eta\rvert < 2.5$) or ($p_{\mathrm{T}} > 50$ GeV if $2.5 < \lvert\eta\rvert < 4.5$), $\Delta R(\gamma, \mathrm{jet}) > 0.4$
Invariant mass	$m_{\ell\ell} > 40$ GeV, $m_{\ell\ell} + m_{\ell\ell\gamma} > 182$ GeV

Precise measurement — Strategy

- Background sources
  - Jet fake photon : estimated by 2D sideband method based on photon identification and isolation
  - $t\bar{t}\gamma$: distribution shape taken from MC, and normalisation from data in $e\mu\gamma$ CR
  - Pileup photon : estimated by data-driven method
  - Multi-boson events with $e \rightarrow \gamma$, directly estimated from the MC

- Different variables have been measured
  - Hard variables (represent the hard scale of the process, non-zero at LO)
  - Resolution variables (sensitive to additional QCD variations)

- Systematic sources
  - Experimental systematic (mainly from finite resolution of the objects reconstructed by detector)
  - Theoretical systematic (missing higher order contributions, PDF choices and on strong couplings α_s)

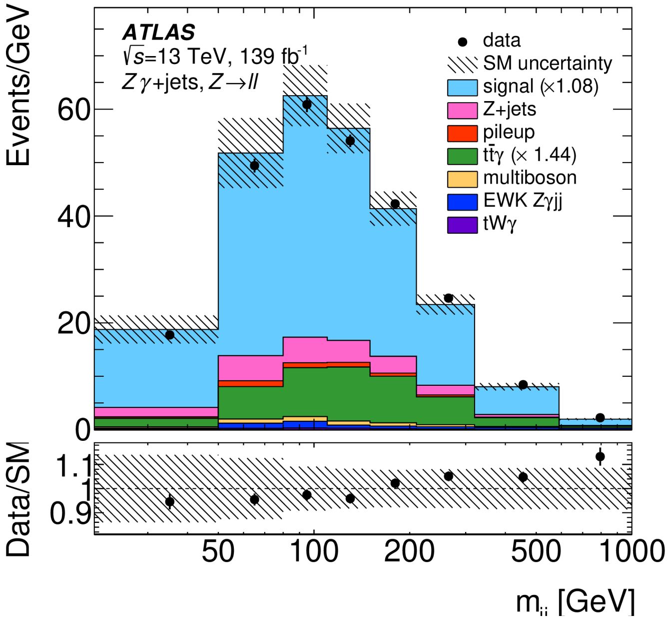


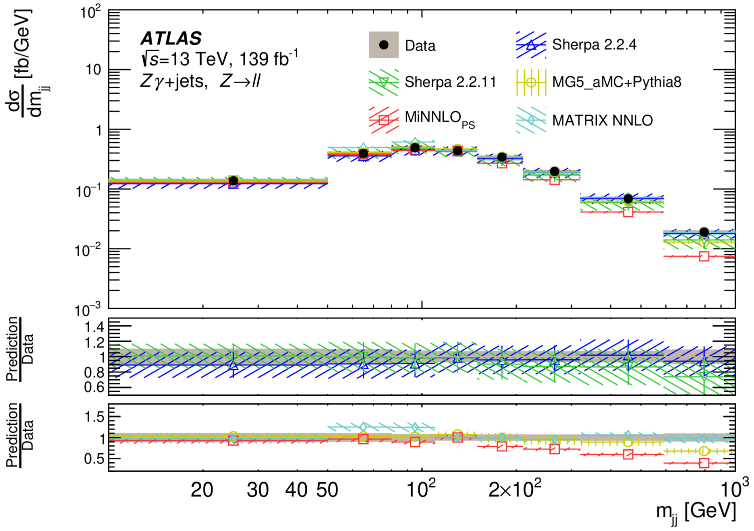
N_{jets}	0	1	2	> 2
Source	Uncertainty [%]			
Electrons	1.0	0.9	0.8	0.8
Muons	0.3	0.3	0.3	0.4
Jets	1.7	1.7	4.5	8.8
Photons	1.4	1.3	1.3	1.2
Pile-up	2.1	0.8	0.2	0.3
Background	1.8	1.8	3.0	4.4
MC statistical	0.1	0.2	0.3	0.4
Data statistical	0.8	1.5	1.8	1.9
Luminosity	1.7	1.7	1.7	1.7
Theory	0.6	0.2	1.4	1.0
Total	4.2	3.8	6.3	10.3

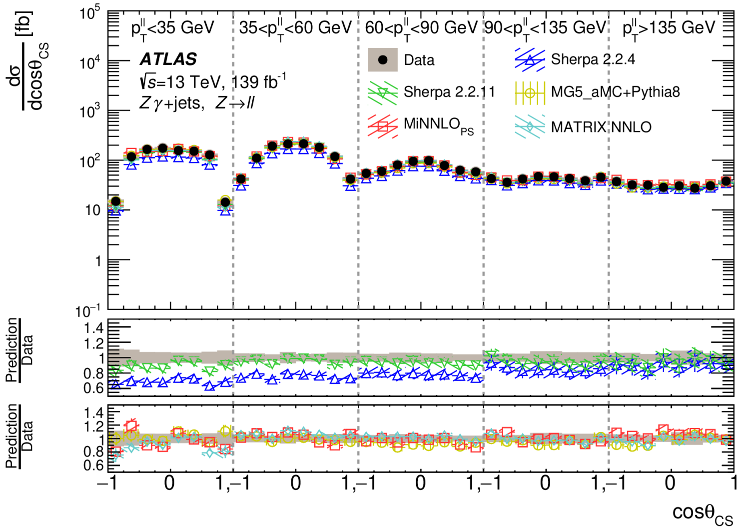
Precise measurement — results

- **Good agreement** between data and MC is generally observed
  - The Sherpa 2.2.11 signal sample is scaled by a normalisation factor of 1.08 to match the data
  - The total uncertainty is ~4% of the total prediction
- **Iterative Bayesian method** is also used to unfold the distribution, and then **compared with different theoretical predictions**
  - Both Sherpa and MadGraph generally describe the data very well
  - MiNNLO$_{PS}$ and NNLO MATRIX predict accurately the observables
  - **Good agreement observed**

Source	$ee+\mu\mu$
$Z\gamma$+jets signal	73 500 ± 50 (stat.) ± 2 600 (syst.)
Z + jets	9 800 ± 460 (stat.) ± 2 100 (syst.)
$t\bar{t}\gamma$	3 600 ± 10 (stat.) ± 540 (syst.)
Pile-up	2 500 ± 70 (stat.) ± 700 (syst.)
Multiboson	950 ± 5 (stat.) ± 280 (syst.)
$tW\gamma$	150 ± 1 (stat.) ± 45 (syst.)
Total prediction	90 500 ± 500 (stat.) ± 3 500 (syst.)
Data	96 410



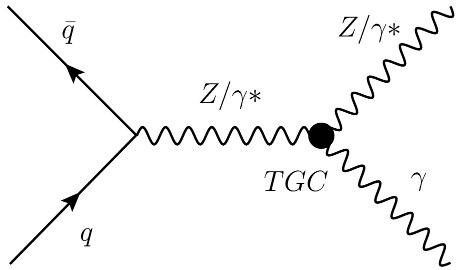




EFT interpretation — nTGCs

- **The nTGCs provide a unique window to the BSM as they can arise from SMEFT operators only at the level of dimension-8 or higher**

JE, GE, HE & Xiao, arXiv : 1902.06631
JE, HE & Xiao, arXiv : 2008.04298
JE, HE & Xiao, arXiv : 2206.11676
Phys. Rev. D 107 035005 (2023) with "Editor's suggestio
John's talk at the LHC EWK-MB meeting



Beyond Dimension-6:

Dimension-8 Operators

- Most analyses focus on dimension-6:

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{i=1}^{2499} \frac{C_i}{\Lambda^2}\mathcal{O}_i$$

- Dimension-8 contributions scaled by quartic power of new physics scale:

$$\Delta\mathcal{L}(\text{dim-8}) = \sum_j \frac{\tilde{c}_j}{\tilde{\Lambda}^4}\mathcal{O}_j = \sum_j \frac{\text{sign}(\tilde{c}_j)}{\Lambda_j^4}\mathcal{O}_j$$

- Study processes without dimension-6 contributions,

JE, Mavromatos & You, arXiv:1703.08450
JE, Mavromatos, Roloff & You, arXiv:2203.17311
JE & Ge, arXiv:1802.02146
JE, Ge & Ma, arXiv:2112.06729

e.g., light-by-light scattering, $gg \to \gamma\gamma, Z\gamma, \ldots$

- Neutral triple-gauge couplings (nTGCs): $\gamma\gamma{*}Z, \gamma ZZ{*}$

JE, Ge, He & Xiao, arXiv:1902.06631
JE, He & Xiao, arXiv:2008.04298
JE, He & Xiao, arXiv:2206.11676

Rui-Qing's talk @ CLHCP 2023

Dimension-8 Operators Contributing to nTGCs

$$\boxed{\begin{aligned} g\mathcal{O}_{G+} &= \widetilde{B}_{\mu\nu}W^{a\mu\rho}(D_\rho D_\lambda W^{a\nu\lambda} + D^\nu D^\lambda W^a_{\lambda\rho}), \\ g\mathcal{O}_{G-} &= \widetilde{B}_{\mu\nu}W^{a\mu\rho}(D_\rho D_\lambda W^{a\nu\lambda} - D^\nu D^\lambda W^a_{\lambda\rho}), \\ \mathcal{O}_{\widetilde{B}W} &= \mathrm{i}\,H^\dagger \widetilde{B}_{\mu\nu}W^{\mu\rho}\{D_\rho, D^\nu\}H + \text{h.c.}, \end{aligned}}$$

$$\begin{aligned} \mathcal{O}_{C+} &= \widetilde{B}_{\mu\nu}W^{a\mu\rho}[D_\rho(\overline{\psi_L}T^a\gamma^\nu\psi_L) + D^\nu(\overline{\psi_L}T^a\gamma_\rho\psi_L)] \\ \mathcal{O}_{C-} &= \widetilde{B}_{\mu\nu}W^{a\mu\rho}[D_\rho(\overline{\psi_L}T^a\gamma^\nu\psi_L) - D^\nu(\overline{\psi_L}T^a\gamma_\rho\psi_L)] \end{aligned}$$

- $\mathcal{O}_{C+,C-}$ related to $\mathcal{O}_{G+,G-,\widetilde{B}W}$ by equations of motion:

$$\begin{aligned} \mathcal{O}_{C+} &= \mathcal{O}_{G-} - \mathcal{O}_{\widetilde{B}W}\,, \\ \mathcal{O}_{C-} &= \mathcal{O}_{G+} - \{\mathrm{i}H^\dagger \widetilde{B}_{\mu\nu}W^{\mu\rho}[D_\rho, D^\nu]H + \mathrm{i}\,2(D_\rho H)^\dagger \widetilde{B}_{\mu\nu}W^{\mu\rho}D^\nu H + \text{h.c.}\} \end{aligned}$$

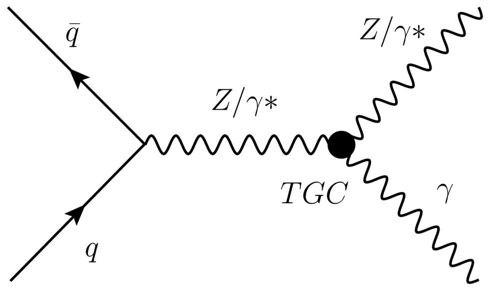
- nTGCs generated:

$$\begin{aligned} \Gamma^{\alpha\beta\mu}_{Z\gamma Z^*(G+)}(q_1,q_2,q_3) &= -\frac{v(q_3^2 - M_Z^2)}{M_Z[\Lambda^4_{G+}]}\left(q_3^2\, q_{2\nu}\epsilon^{\alpha\beta\mu\nu} + 2q_2^\alpha q_{3\nu}q_{2\sigma}\epsilon^{\beta\mu\nu\sigma}\right), \\ \Gamma^{\alpha\beta\mu}_{Z\gamma\gamma^*(G+)}(q_1,q_2,q_3) &= -\frac{s_W v\, q_3^2}{c_W M_Z[\Lambda^4_{G+}]}\left(q_3^2\, q_{2\nu}\epsilon^{\alpha\beta\mu\nu} + 2q_2^\alpha q_{3\nu}q_{2\sigma}\epsilon^{\beta\mu\nu\sigma}\right), \\ \Gamma^{\alpha\beta\mu}_{Z\gamma Z^*(\widetilde{B}W)}(q_1,q_2,q_3) &= \frac{v M_Z(q_3^2 - M_Z^2)}{[\Lambda^4_{\widetilde{B}W}]}\epsilon^{\alpha\beta\mu\nu}q_{2\nu}\,, \\ \Gamma^{\alpha\beta\mu}_{Z\gamma\gamma^*(G-)}(q_1,q_2,q_3) &= -\frac{s_W v M_Z}{c_W[\Lambda^4_{G-}]}\epsilon^{\alpha\beta\mu\nu}q_{2\nu}q_3^2\,. \end{aligned}$$

JE, Ge, He & Xiao, arXiv:1902.06631
JE, He & Xiao, arXiv:2008.04298
JE, He & Xiao, arXiv:2206.11676

EFT interpretation — nTGCs

- **Both ATLAS and CMS analyses ongoing with new nTGC formulation**
- Dimension-8 operators from the SMEFT approach in this analysis :
  - CP-conserving : $O_{G+}, O_{G-}, O_{\tilde{B}W}$
  - CP-violating : O_{BB}, O_{BW}, O_{WW}



- Form factors from the Effective Vertex approach :

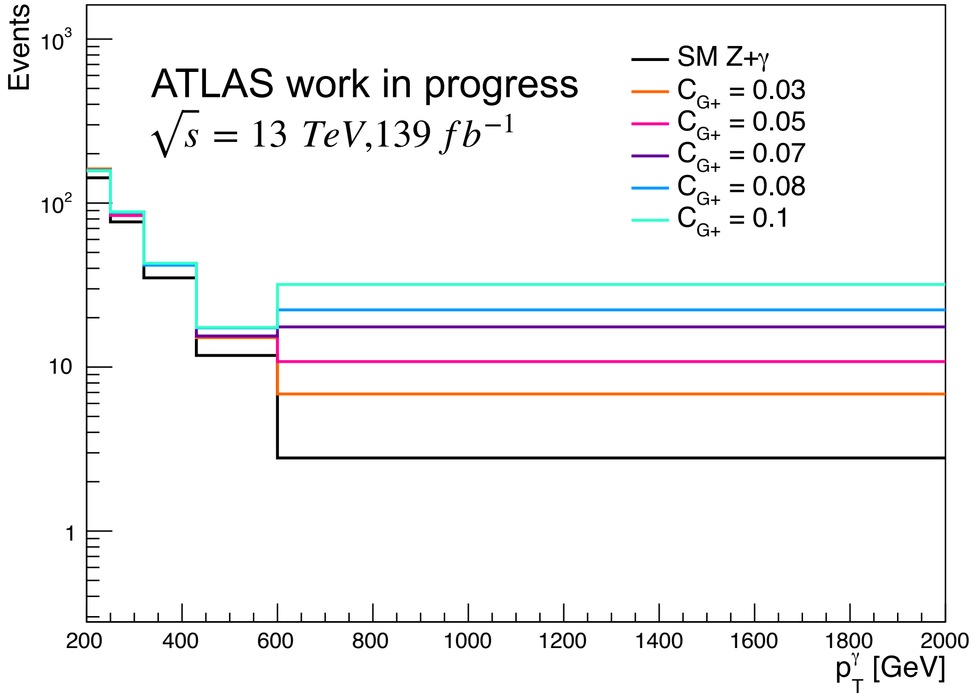
$$h_4^\gamma = -\frac{C_{G+}}{\Lambda^4}\frac{v^2 M_Z^2}{c_w^2},\ h_3^V = 0$$

$$h_4^Z = -\frac{C_{G+}}{\Lambda^4}\frac{v^2 M_Z^2}{s_w c_w},\ h_3^V = 0$$

$$h_3^\gamma = -\frac{C_{G-}}{\Lambda^4}\frac{v^2 M_Z^2}{2c_w^2},\ h_3^Z, h_4 = 0$$

$$h_3^Z = \frac{C_{\tilde{B}W}}{\Lambda^4}\frac{v^2 M_Z^2}{2s_w c_w},\ h_3^\gamma, h_4 = 0$$

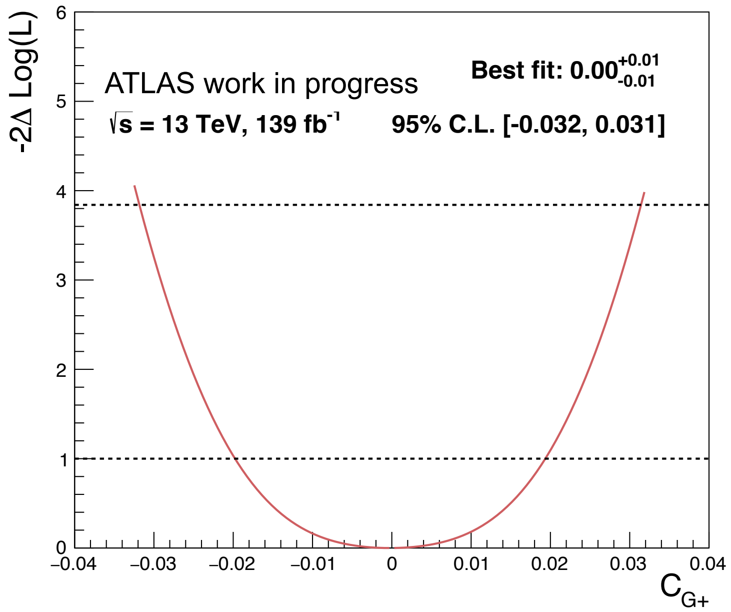
The anomalous value of Wilson coefficients lead to the increase of the $Z\gamma$ cross sections (both integrated and differential)



$$\Gamma^{\alpha\beta\mu(8)}_{Z\gamma V*}(q_1, q_2, q_3) = \frac{e(q_3^2 - M_V^2)}{M_Z^2}\left[(h_3^V + h_5^V \frac{q_3^2}{M_Z^2})q_{2}\epsilon^{\alpha\beta\mu\nu} + \frac{h_4^V}{M_Z^2} q_2^\alpha q_{3\nu} q_{2\sigma}\epsilon^{\beta\mu\nu\sigma}\right]$$

EFT interpretation — nTGCs @ ATLAS

- EFT interpretation performed :
  - With a narrow on-shell invariant mass cut applied
  - With exclusive jet selection considered to remove higher order correction (events with no selected jets)
- Limits extracted on Wilson Coefficients at 95% C.L. are given below :
  - Extracted with Asimov Data
  - With Unfolded p_T^γ distribution, sensitive to nTGC in high p_T region with high resolution



Work in progress

CP - Conserving	Expected Limits [TeV-4]	CP - violating	Expected Limits [TeV-4]
C_{G+}	[-0.03, 0.03]	C_{BB}	[-0.42, 0.42]
C_{G-}	[-1.08, 0.98]	C_{BW}	[-1.00, 1.08]
$C_{\tilde{B}W}$	[-0.58, 0.57]	C_{WW}	[-1.98, 1.83]

EFT interpretation — nTGCs @ ATLAS

- The latest constraints extracted with new nTGC formulation :
  - Expected limits for form factors extracted with Asimov Data
  - Transformed from limits of dimension-8 operators
  - **Overestimated limits have been corrected** compared with conventional formulation and previous analysis
  - Two orders of magnitude looser than the limits given from neutrino channel (with fully gauge invariant treatment applied)

$$h_4^{\gamma} = -\frac{C_{G+}}{\Lambda^4}\frac{v^2 M_Z^2}{c_w^2},\ h_3^V = 0$$

$$h_4^{Z} = -\frac{C_{G+}}{\Lambda^4}\frac{v^2 M_Z^2}{s_w c_w},\ h_3^V = 0$$

$$h_3^{\gamma} = -\frac{C_{G-}}{\Lambda^4}\frac{v^2 M_Z^2}{2c_w^2},\ h_3^Z, h_4 = 0$$

$$h_3^{Z} = \frac{C_{\tilde{B}W}}{\Lambda^4}\frac{v^2 M_Z^2}{2s_w c_w},\ h_3^{\gamma}, h_4 = 0$$

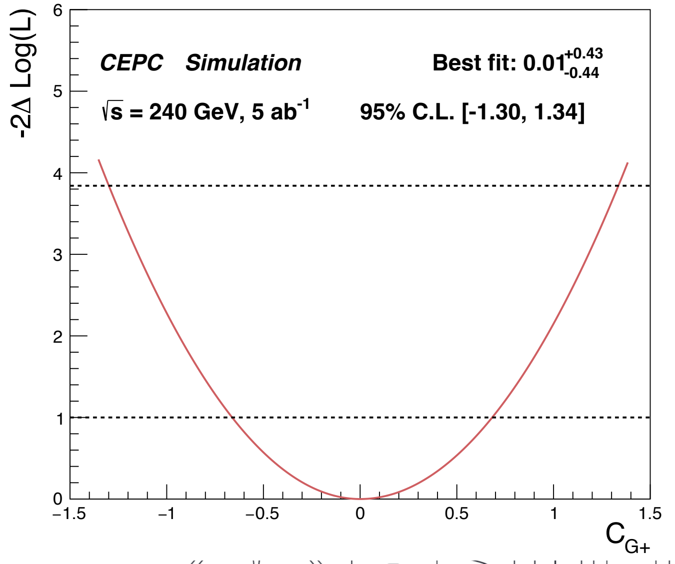
Work in progress

Lepton Channel		Neutrino Channel	
h_4^{γ}	$[-2.2\times^{-5}, 2.2\times 10^{-5}]$	h_4^{γ}	$[-5.1\times^{-7}, 5.0\times 10^{-7}]$
h_4^{Z}	$[-4.0\times^{-5}, 4.1\times 10^{-5}]$	h_4^{Z}	$[-5.3\times^{-7}, 5.1\times 10^{-7}]$
h_3^{γ}	$[-3.2\times^{-4}, 3.5\times 10^{-4}]$	h_3^{γ}	$[-4.2\times^{-4}, 4.3\times 10^{-4}]$
h_3^{Z}	$[-3.4\times^{-4}, 3.4\times 10^{-4}]$	h_3^{Z}	$[-3.8\times^{-4}, 3.8\times 10^{-4}]$

EFT interpretation — nTGCs @ CEPC

- nTGC is also studied with Future Lepton Collider (CEPC)
  - The well defined energy and momentum is benefit for angular variable which is highly related to the interfere between SM and pure BSM
  - High statistics but with rather clean environment compare to Hadron Colliders
- The expected limits listed below (both from SMEFT and Vertex approaches)
  - The range defined as the Wilson coefficient value of nTGCs that demarcate the central 95% of the integral of the likelihood distribution
  - The outer range is excluded

SMEFT	Expected Limits [TeV-4]	Form Factor	Expected Limits [TeV-4]
O_{G+}	[-0.46, 0.47]	h_4^γ	$[-3.1\times10^{-4}, 3.0\times10^{-4}]$
		h_4^Z	$[-5.6\times10^{-3}, 5.5\times10^{-3}]$
O_{G-}	[-6.46, 6.93]	h_3^γ	$[-2.3\times10^{-3}, 2.1\times10^{-3}]$
$O_{\tilde{B}W}$	[-6.48, 6.47]	h_3^Z	$[-3.9\times10^{-3}, 3.9\times10^{-3}]$



Summary and prospect

- The latest results from ATLAS experiment of $Z(\rightarrow ll)\gamma$ in association with jet activities is presented here
  - Good agreement can be observed between the data and MC simulation, or theoretical predictions
  - Important for studies of the electroweak theories at the TeV scale
- The status of EFT interpretation is also presented here
  - An effective way to explore new physics beyond the SM
  - The study of nTGCs is performed both on hadron collider and future lepton collider
  - Promising to get the latest experimental constraints based on the new nTGC formulation
- More works are ongoing !!!

Thank You !

Additional Materials

Different variables have been measured

1D observables :

- Interesting for QCD studies : $N_{jets}, p_T^{jet1}, p_T^{jet2}, p_T^{jet1}/p_T^{jet2}, m_{ll\gamma j}, m_{jj}$
- Used in other analysis : $H_T, p_T^{\gamma}/H_T, \Delta\Phi(j,\gamma), \Delta R(l,l), p_T^{ll}$

QCD-sensitive 2D variables

- $p_T^{ll\gamma}/m_{ll\gamma}$ in 3 slices of $m_{ll\gamma}$
- $p_T^{ll} - p_T^{\gamma}$ in 3 slices of $p_T^{ll} + p_T^{\gamma}$
- $p_T^{ll\gamma j}$ in 3 slices of $p_T^{ll\gamma}$
- $p_T^{ll} - p_T^{\gamma}$, $p_T^{ll} + p_T^{\gamma}$, $p_T^{ll\gamma j}$ are also measured inclusively

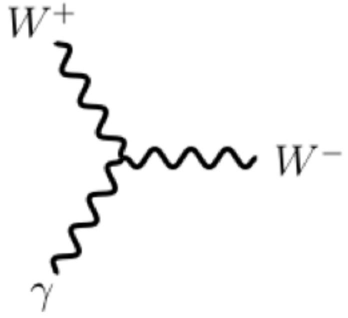
Hard variables : represent the hard scale of the process (non-zero at LO)
Resolution variables : sensitive to additional QCD variations

Polarisation-sensitive 2D variables

- $cos\theta_{CS}$ in 5 bins of p_T^{ll}
- ϕ_{CS} in 5 bins of p_T^{ll}
- First time to measure the lepton angular coefficient in DY events with γ

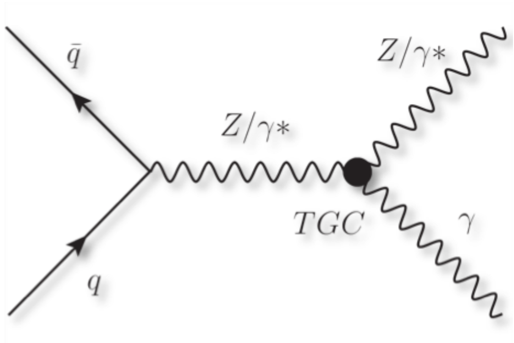
Anomalous couplings

- Non - Abelian nature of SU(2)×U(1) allows for self-couplings of the gauge bosons in fermions interactions : triple gauge couplings
- Allowed are vertices with charged gauge couplings : $WWZ, WW\gamma$



Allowed in SM

- Neutral boson gauge couplings are forbidden at tree level in the SM, but can arise in theories beyond the SM via anomalous couplings. Limits on anomalous couplings will provide constraints on BSM models



Forbidden anomalous triple gauge coupling — nTGC

Neutral Triple Gauge Couplings

- Why to search for nTGCs ?
  - First appear through the gauge invariant dimension-8 operators in the SMEFT, any indication of a non-vanishing nTGC would be direct evidence for new physics beyond the SM
  - New non-trivial relationship among the form factor parameters are derived that ensures a truly consistent form factor formulation of the neutral Triple Gauge Vertices and remove unphysical large energy-dependent terms
  - Mostly, new formulation will correct the overestimated limits based on the conventional form factor h_4 which does not have fully gauge invariant treatment applied
- Why in $Z + \gamma$ channel
  - Large cross-section but small background contributions (rather clean than other channels)
  - Highly sensitive to nTGCs especially in high pT region
  - Easy to reconstruct four-momentum of on-shell Z bosons with charged lepton decays, which is specifically benefit to nTGC formulation

Neutral Triple Gauge Vertices with on-shell $Z\gamma$

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

Dimension-8 SMEFT:

$$\Gamma^{\alpha\beta\mu}_{Z\gamma Z^*(G+)}(q_1,q_2,q_3) = -\frac{v(q_3^2-M_Z^2)}{M_Z\,[\Lambda^4_{G+}]}\left(q_3^2\,q_{2\nu}\epsilon^{\alpha\beta\mu\nu}+2q_2^\alpha q_{3\nu}q_{2\sigma}\epsilon^{\beta\mu\nu\sigma}\right),$$

$$\Gamma^{\alpha\beta\mu}_{Z\gamma\gamma^*(G+)}(q_1,q_2,q_3) = -\frac{s_W v\,q_3^2}{c_W M_Z\,[\Lambda^4_{G+}]}\left(q_3^2\,q_{2\nu}\epsilon^{\alpha\beta\mu\nu}+2q_2^\alpha q_{3\nu}q_{2\sigma}\epsilon^{\beta\mu\nu\sigma}\right),$$

$$\Gamma^{\alpha\beta\mu}_{Z\gamma Z^*(\widetilde{B}W)}(q_1,q_2,q_3) = \frac{v\,M_Z\,(q_3^2-M_Z^2)}{[\Lambda^4_{\widetilde{B}W}]}\epsilon^{\alpha\beta\mu\nu}q_{2\nu}\,,$$

$$\Gamma^{\alpha\beta\mu}_{Z\gamma\gamma^*(G-)}(q_1,q_2,q_3) = -\frac{s_W\,v\,M_Z}{c_W[\Lambda^4_{G-}]}\epsilon^{\alpha\beta\mu\nu}q_{2\nu}q_3^2\,.$$

Conventional form factor parameterization: $\Gamma^{\alpha\beta\mu}_{Z\gamma V*}(q_1,q_2,q_3) = \frac{e\,(q_3^2-M_V^2)}{M_Z^2}\left(h_3^V\,q_{2\nu}\epsilon^{\alpha\beta\mu\nu}+\frac{h_4^V}{M_Z^2}\,q_2^\alpha\,q_{3\nu}\,q_{2\sigma}\epsilon^{\beta\mu\nu\sigma}\right),$

Full SU(2)×U(1) gauge constraints: $\Gamma^{\alpha\beta\mu(8)}_{Z\gamma V^*}(q_1,q_2,q_3) = \frac{e\,(q_3^2-M_V^2)}{M_Z^2}\left[\left(h_3^V+h_5^V\frac{q_3^2}{M_Z^2}\right)q_{2\nu}\epsilon^{\alpha\beta\mu\nu}+\frac{h_4^V}{M_Z^2}\,q_2^\alpha\,q_{3\nu}\,q_{2\sigma}\,\epsilon^{\beta\mu\nu\sigma}\right],$

$\mathcal{O}(E^5)$ terms must cancel each other in amplitude with longitudinal Z:

$$\mathcal{T}[f\bar{f}\to Z_L\gamma] = h_3^V O(E^3)+h_4^V O(E^5)+h_5^V O(E^5) = \Lambda_j^{-4}O(E^3)\,.$$

$\mathcal{T}[f\bar{f}\to Z_L\gamma]$ as contributed by the gauge-invariant dimension-8 nTGC operators must obey the equivalence theorem (ET):

$$\mathcal{T}_{(8)}[Z_L,\gamma_T] = \mathcal{T}_{(8)}[-\mathrm{i}\pi^0,\gamma_T]+B = \mathcal{O}(E^3)\,,$$

See more details in Rui-Qing Xiao's talk

SJTU

EFT interpretation — nTGCs

- Neutral Triple Gauge Couplings (nTGCs)

JE, GE, HE & Xiao, arXiv : 1902.06631
JE, HE & Xiao, arXiv : 2008.04298
JE, HE & Xiao, arXiv : 2206.11676
Phys. Rev. D 107 035005 (2023) with "Editor's suggestion"
John's talk at the LHC EWK-MB meeting

$$L = L_{SM} + \Delta L(dim-8) = L_{SM} + \sum_j \frac{\tilde{c}_j}{\tilde{\Lambda}^4}\mathcal{O}_j = L_{SM} + \sum_j \frac{sign(\tilde{c}_j)}{\Lambda_j^4}\mathcal{O}_j$$

  - Forbidden at the SM tree level, nor exist in dimension-6 Lagrangian
  - First appear in the dimension-8 Lagrangian, as an extension of the SM Lagrangian

- New nTGC formulation
  - Proposed by Prof. John Ellis, Prof. Hong-Jian He and Dr. Rui-Qing Xiao
  - Proposed with brand new fully gauge invariant treatment SU(2) × U(1) symmetry
  - Two extra dimension-8 operators O_{G+}, O_{G-} are proposed and studied to make the correct transformation

$$g\mathcal{O}_{G+} = \tilde{B}_{\mu\nu}W^{\alpha\mu\rho}(D_\rho D_\lambda W^{\alpha\nu\lambda} + D^\nu D^\lambda W^\alpha_{\lambda\rho})$$

$$g\mathcal{O}_{G-} = \tilde{B}_{\mu\nu}W^{\alpha\mu\rho}(D_\rho D_\lambda W^{\alpha\nu\lambda} - D^\nu D^\lambda W^\alpha_{\lambda\rho})$$

$$\mathcal{O}_{\tilde{B}W} = iH^\dagger\tilde{B}_{\mu\nu}W^{\mu\rho}\{D_\rho, D^\nu\}H + h.c.$$