Searches for NP and EFT limits in multi-boson final states

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Multi-boson Interactions | 23 August 2022

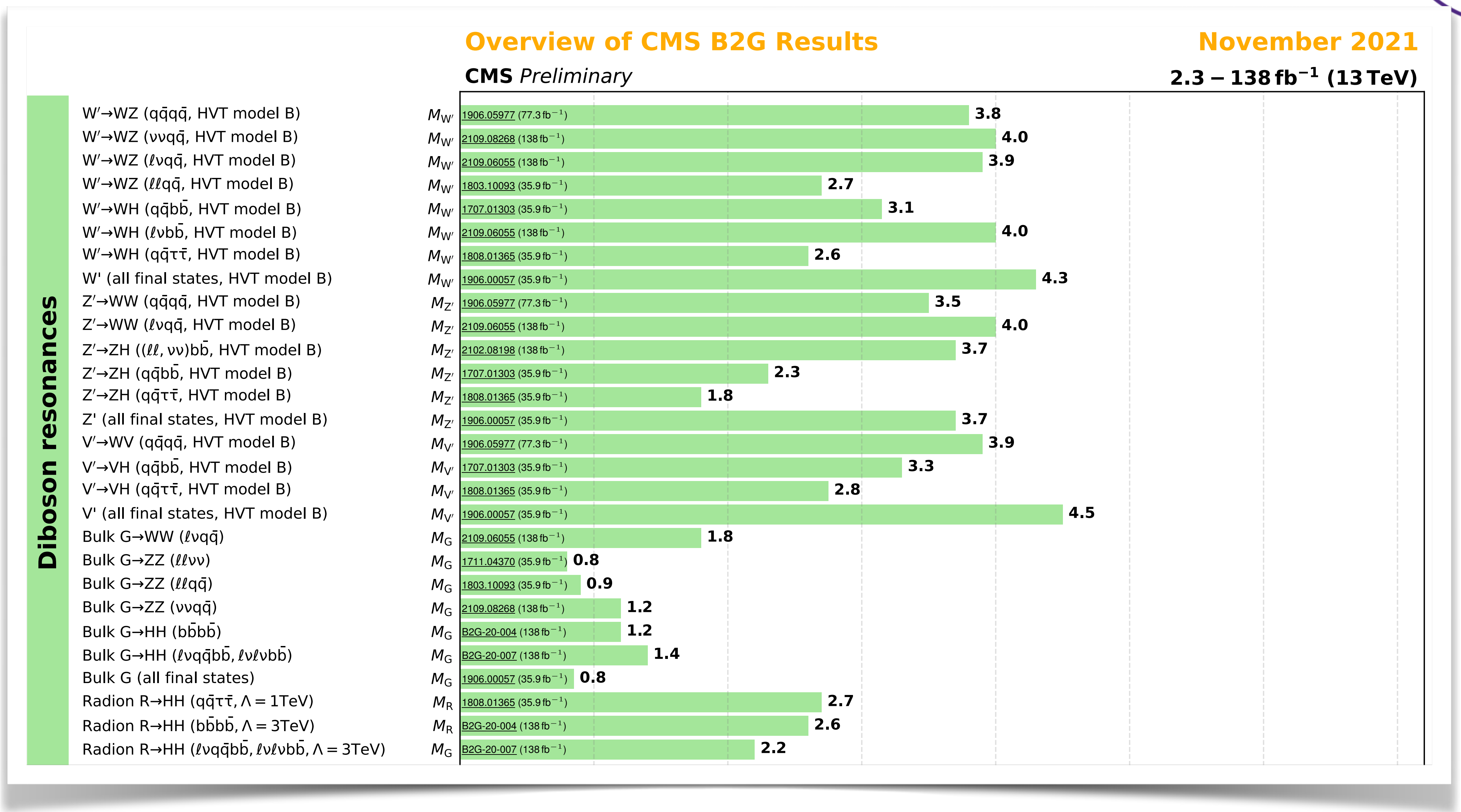
Introduction

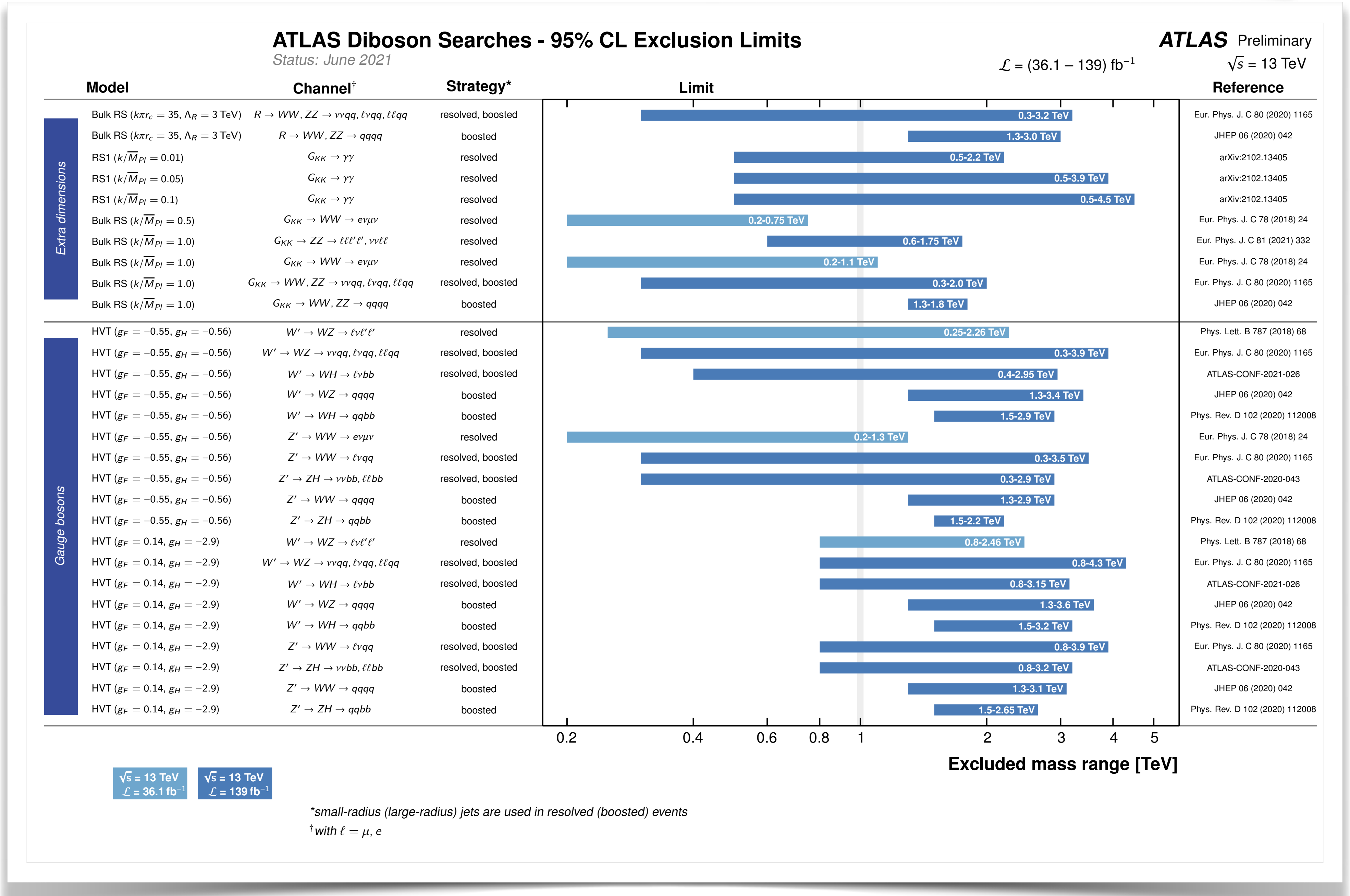
- Multi-boson processes are powerful probes of new physics, as they are sensitive to a wide array of possible BSM effects

- Not covered today: direct searches
  - ATLAS and CMS have extensive search programs covering many multi-boson final states
  - So far, no compelling indication of new physics

- ⇒ How can we probe for indirect evidence of NP in our SM measurements?

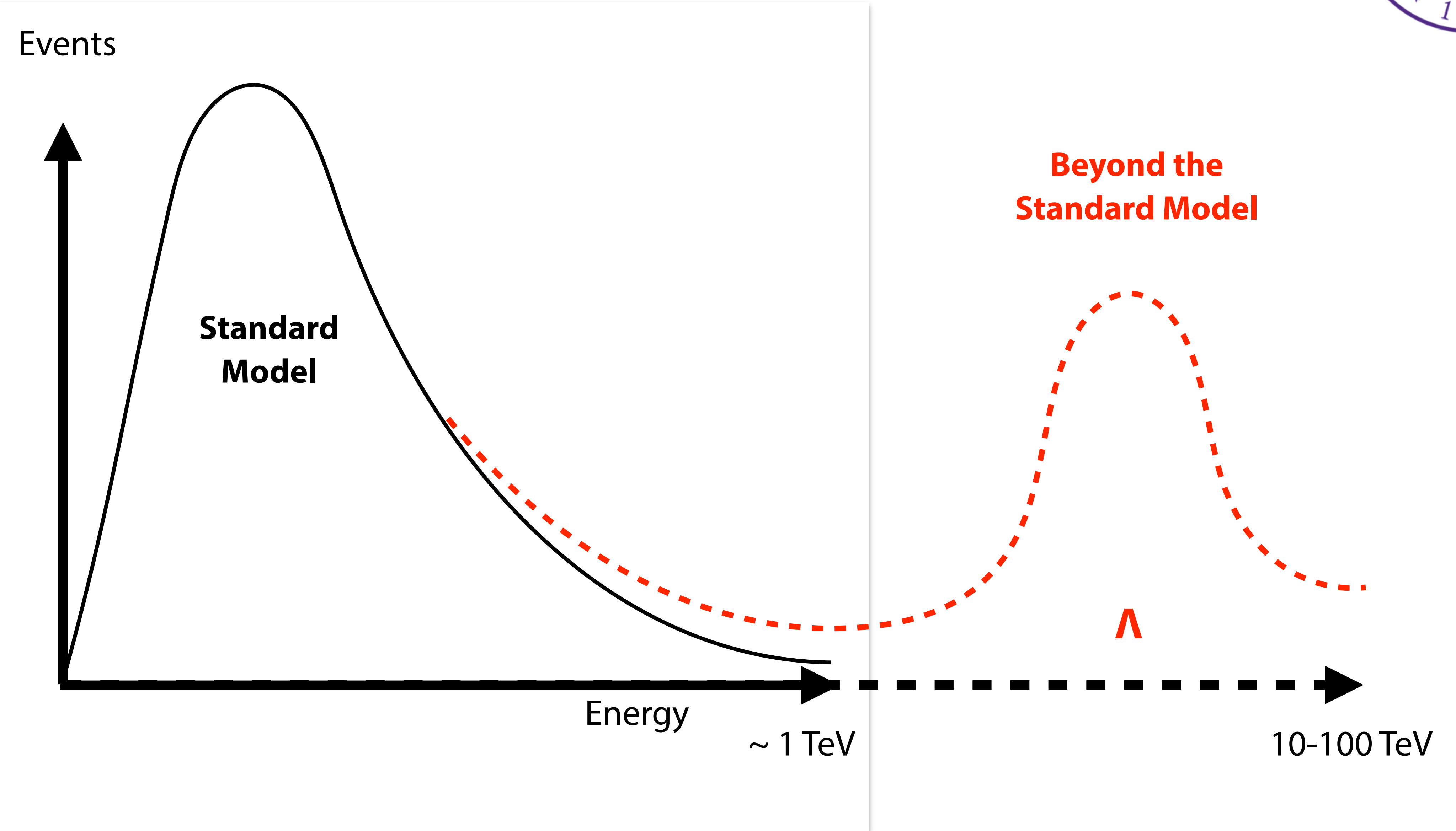
- Outline of this talk:
  - Introduction & motivation for EFT analysis
  - Anomalous triple gauge couplings (aTGCs)
  - Neutral triple gauge couplings (nTGCs)
  - Quartic gauge couplings (QGCs)
  - Combined EFT interpretation





Effective field theory approach

- Strong motivation for new physics at the TeV scale
  - Energy scale of new physics (Λ) may be beyond our direct reach
- Construct an effective field theory starting from the known SM fields and symmetries
  - No specific high-energy (UV complete) theory required
  - Provides a renormalisable quantum field theory
  - Universal - can connect to other experiments
- Expand in powers of (1/Λ):



$$L_{\mathrm{EFT}} = L_{\mathrm{SM}} + \underbrace{\sum_i \cancel{\frac{C_i^{(5)}}{\Lambda}}\mathcal{O}_i^{(5)}}_{\text{Lepton-number violating}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \underbrace{\sum_i \cancel{\frac{C_i^{(7)}}{\Lambda^3}}\mathcal{O}_i^{(7)}}_{\text{Violates B-L}} + \sum_i \frac{C_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \ldots$$

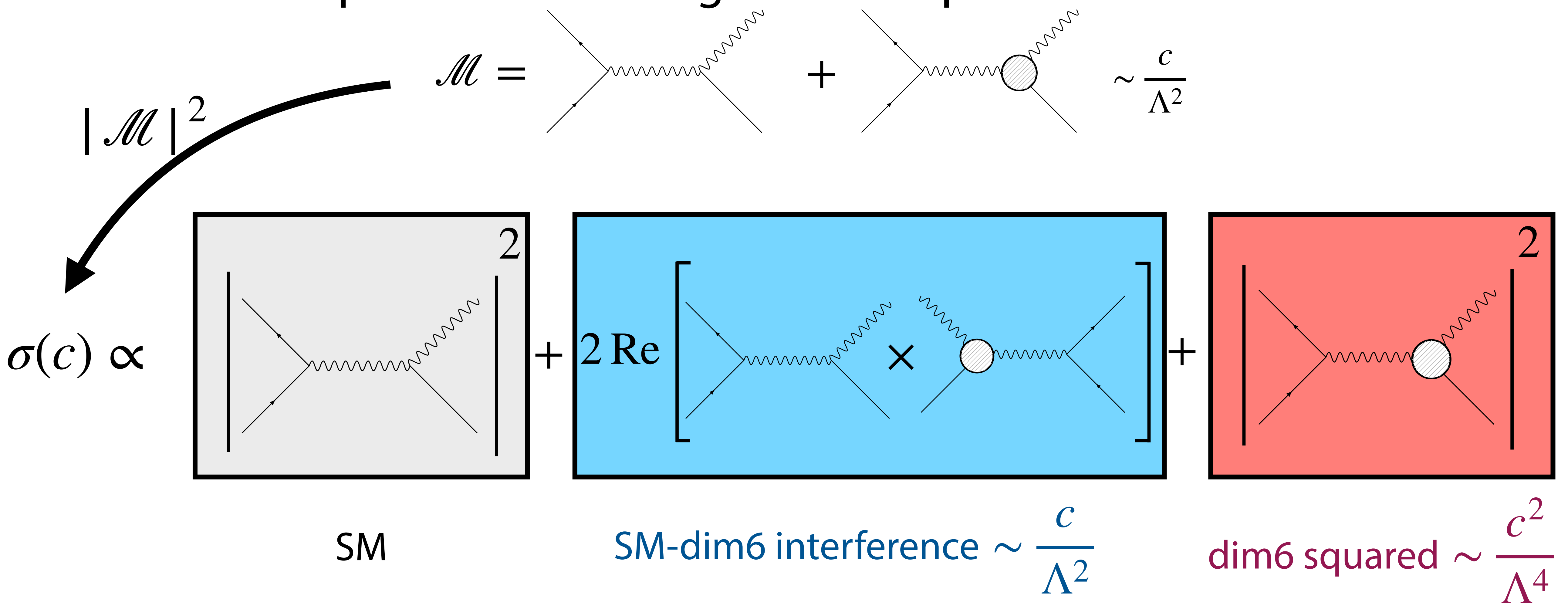
$\mathcal{O}_i$: operators = interaction terms at a given expansion order

C_i : operators = Wilson coefficients, free parameters

- First relevant order at dimension 6
  - Multi-boson: connection to anomalous triple gauge couplings
- Dimension 8 also important
  - Tree-level neutral triple gauge coupling
  - Quartic gauge couplings

Effective field theory approach

- Dim-6: up to 2499 distinct operators [1312.2014], reduced to 85 with flavour assumptions
- Cross section in the presence of a single dim-6 operator:



- Gives all Λ^{-2} terms ⇒ linear in dim-6 coefficients (c_i)
- With multiple operators also have $c_i c_j/\Lambda^4$ interference terms
- But Λ^{-4} incomplete ⇒ neglects SM-dim8 interference at the same order
  - In practice parameterisations may neglect quadratic c^2 terms
  - Ideally: dim-6 squared small, but for many measurements not the case

Operators involving bosonic fields

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

4-fermion operators (most flavour general case)

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu \tau^I q_r)(\bar q_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu \tau^I l_r)(\bar q_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

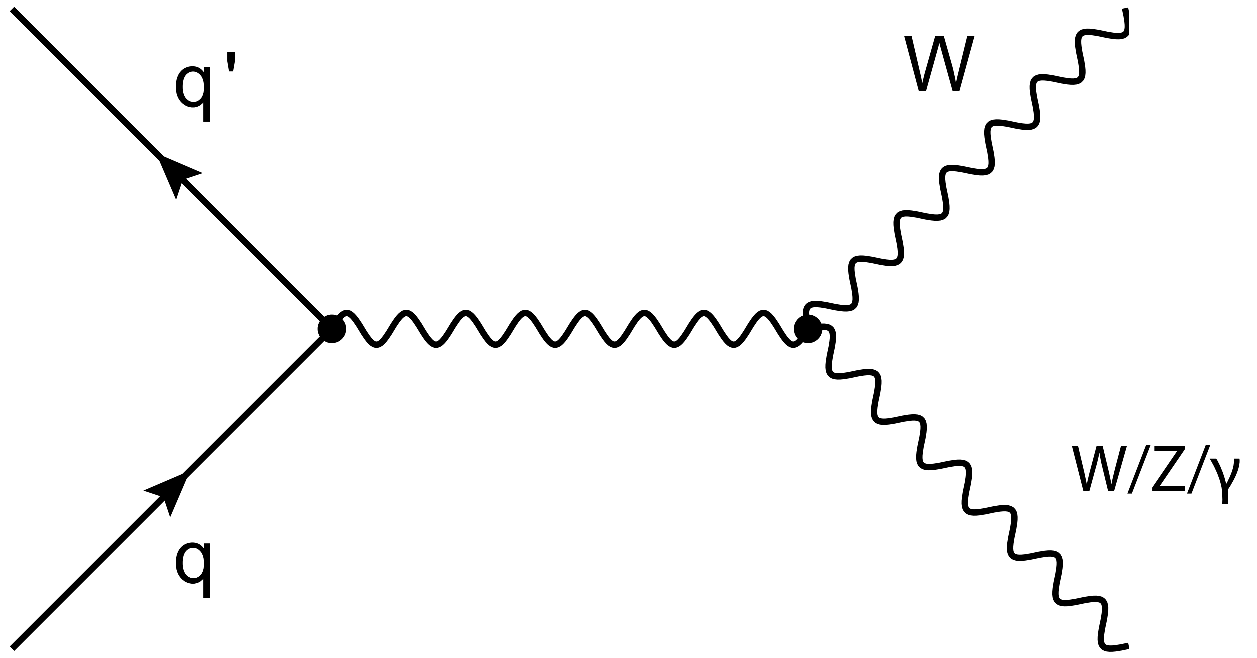
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$		

"Warsaw" basis [1008.4884]

Anomalous triple gauge couplings

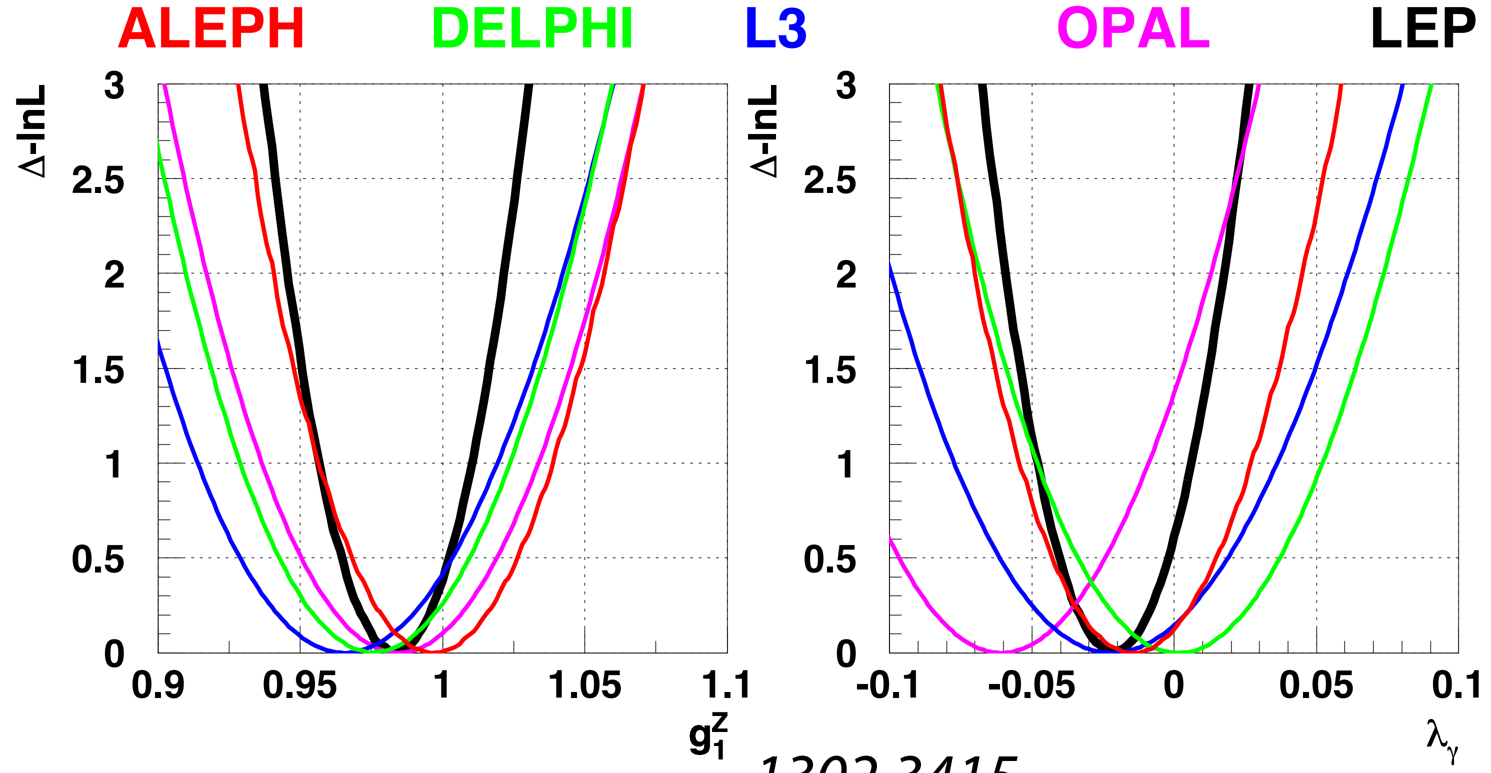
Anomalous triple gauge couplings

- Long history of constraining BSM effects in the WWV triple gauge coupling:



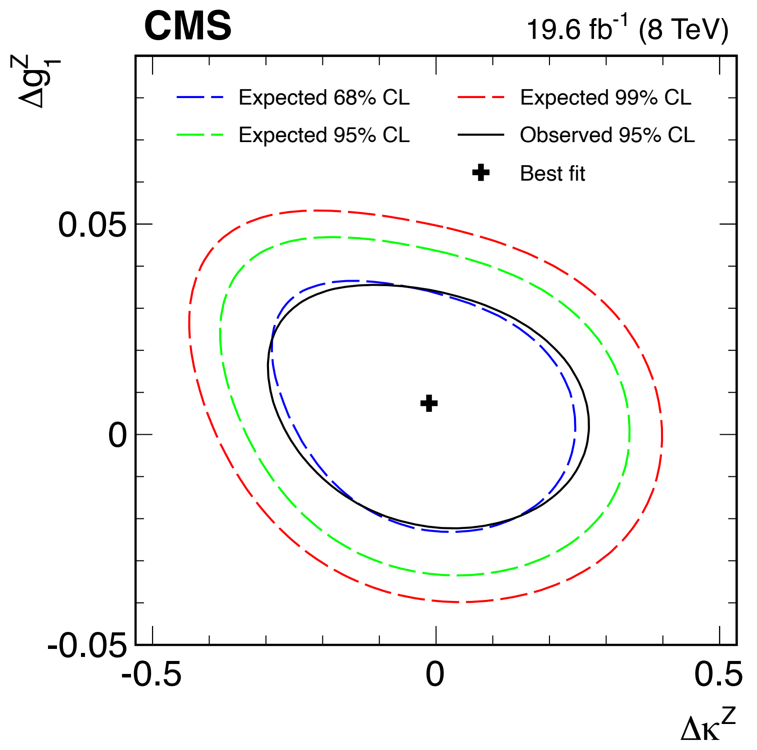
$$\mathcal{L}_{\rm tgc} = ie\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)A_\nu + ie\frac{c_\theta}{s_\theta}\left(1+\delta g_{1,z}\right)\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)Z_\nu$$
$$+ ie(1+\delta\kappa_\gamma)A_{\mu\nu}\,W^+_\mu W^-_\nu + ie\frac{c_\theta}{s_\theta}(1+\delta\kappa_z)\,Z_{\mu\nu}\,W^+_\mu W^-_\nu$$
$$+ i\frac{\lambda_z e}{m_W^2}\left[W^+_{\mu\nu}W^-_{\nu\rho}A_{\rho\mu} + \frac{c_\theta}{s_\theta}W^+_{\mu\nu}W^-_{\nu\rho}Z_{\rho\mu}\right] ,$$

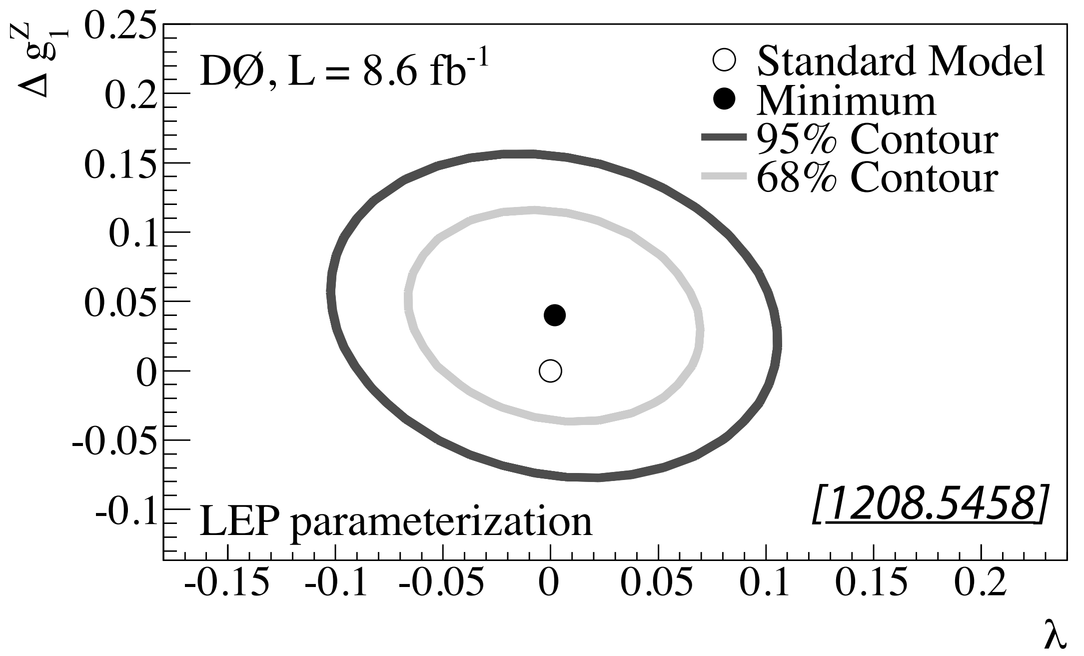
[1609.06312]



1302.3415

- EFT interpretation now more common
  - For historical reasons, many LHC interpretations have used HISZ basis *[PRD 48 (1993) 2182]*
  - Gradual move to towards Warsaw basis *[1008.4884]* (as in Higgs & top)





- aTGC parameters can be related to coefficients in HISZ and Warsaw bases:

$$\delta g_{1z} = \frac{g^2+g'^2}{8}f_W\frac{v^2}{\Lambda^2} \qquad \delta\kappa_\gamma = \frac{g^2}{8}(f_W+f_B)\frac{v^2}{\Lambda^2}, \qquad \lambda_z = \frac{3g^4}{8}f_{WWW}\frac{v^2}{\Lambda^2},$$

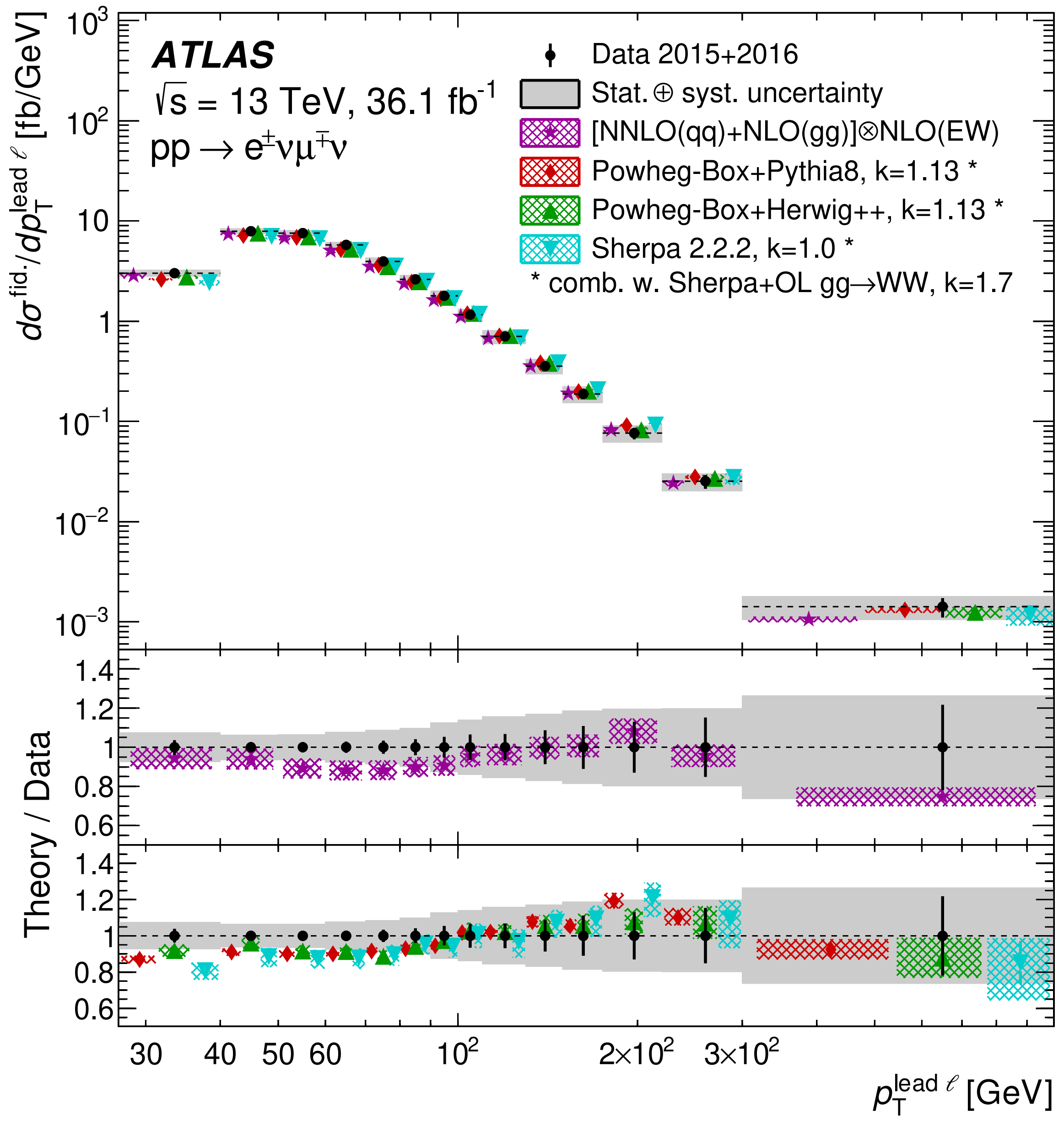
$$\delta g_{1,z} = -\frac{v^2}{\Lambda^2}\frac{g_L^2+g_Y^2}{4(g_L^2-g_Y^2)}\left(4\frac{g_Y}{g_L}w_{\phi WB} + w_{\phi D} - [w_{\ell\ell}]_{1221} + 2[w^{(3)}_{\phi\ell}]_{11} + 2[w^{(3)}_{\phi\ell}]_{22}\right) ,$$

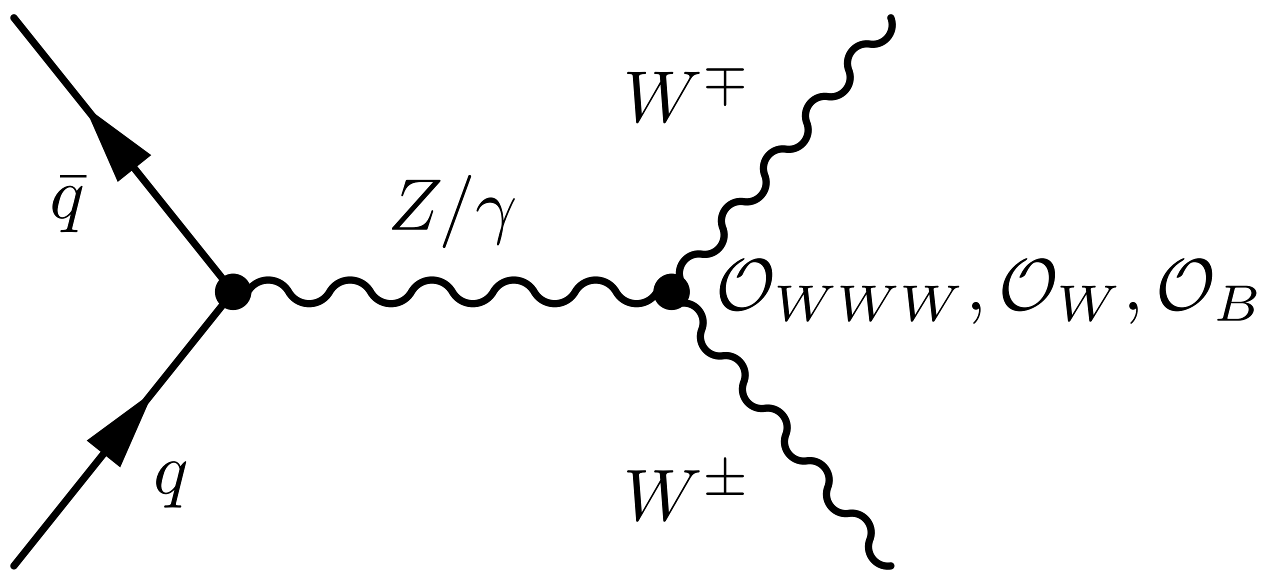
$$\delta\kappa_\gamma = \frac{v^2}{\Lambda^2}\frac{g_L}{g_Y}w_{\phi WB} , \qquad \lambda_z = -\frac{v^2}{\Lambda^2}\frac{3}{2}g_L w_W ,$$

[LHCHXSWG-INT-2015-001]

W+W-

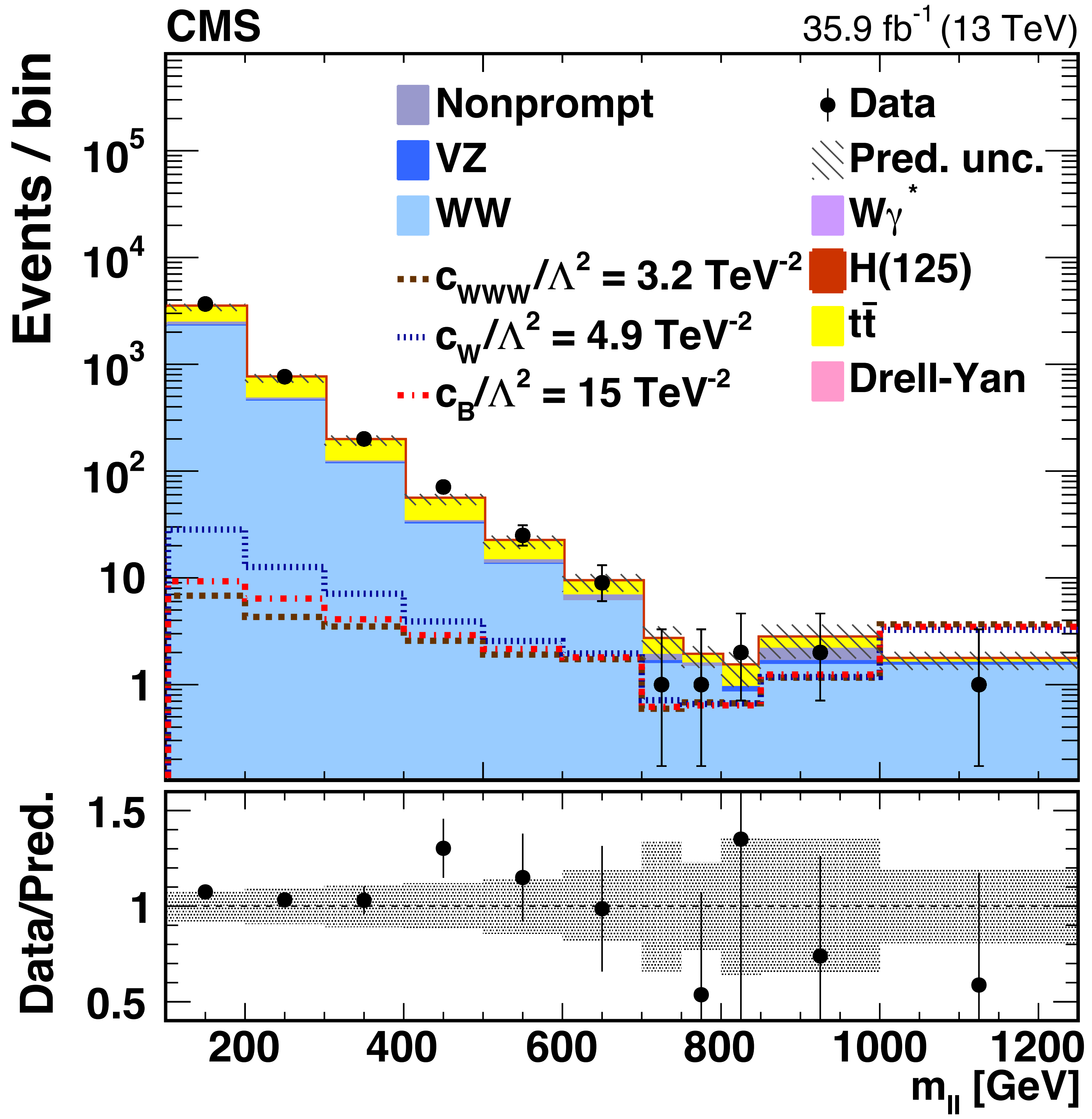
- Both experiments set EFT constraints in the **HISZ** basis
- **ATLAS**: constraints set via unfolded leading lepton p_T, on both CP-even and CP-odd operators
- **CMS**: direct fit to m_{ll} distribution





Limits with and without quadric EFT terms

Operator	95% CL (linear and quadratic terms)	95% CL (linear terms only)
c_{WWW}/Λ^2	$[-3.4\ \text{TeV}^{-2}, 3.3\ \text{TeV}^{-2}]$	$[-179\ \text{TeV}^{-2}, -17\ \text{TeV}^{-2}]$
c_W/Λ^2	$[-7.4\ \text{TeV}^{-2}, 4.1\ \text{TeV}^{-2}]$	$[-13.1\ \text{TeV}^{-2}, 7.1\ \text{TeV}^{-2}]$
c_B/Λ^2	$[-21\ \text{TeV}^{-2}, 18\ \text{TeV}^{-2}]$	$[-104\ \text{TeV}^{-2}, 101\ \text{TeV}^{-2}]$



Parameter	Observed 95% CL [TeV^{-2}]	Expected 95% CL [TeV^{-2}]
c_{WWW}/Λ^2	[−3.4 , 3.3]	[−3.0 , 3.0]
c_W/Λ^2	[−7.4 , 4.1]	[−6.4 , 5.1]
c_B/Λ^2	[−21 , 18]	[−18 , 17]
$c_{\tilde{W}WW}/\Lambda^2$	[−1.6 , 1.6]	[−1.5 , 1.5]
$c_{\tilde{W}}/\Lambda^2$	[−76 , 76]	[−91 , 91]

[Eur. Phys. J. C 79 (2019) 884]

Coefficients (TeV^{-2})	68% confidence interval		95% confidence interval	
	expected	observed	expected	observed
c_{WWW}/Λ^2	$[-1.8, 1.8]$	$[-0.93, 0.99]$	$[-2.7, 2.7]$	$[-1.8, 1.8]$
c_W/Λ^2	$[-3.7, 2.7]$	$[-2.0, 1.3]$	$[-5.3, 4.2]$	$[-3.6, 2.8]$
c_B/Λ^2	$[-9.4, 8.4]$	$[-5.1, 4.3]$	$[-14, 13]$	$[-9.4, 8.5]$

[Phys. Rev. D 102 (2020) 092001]

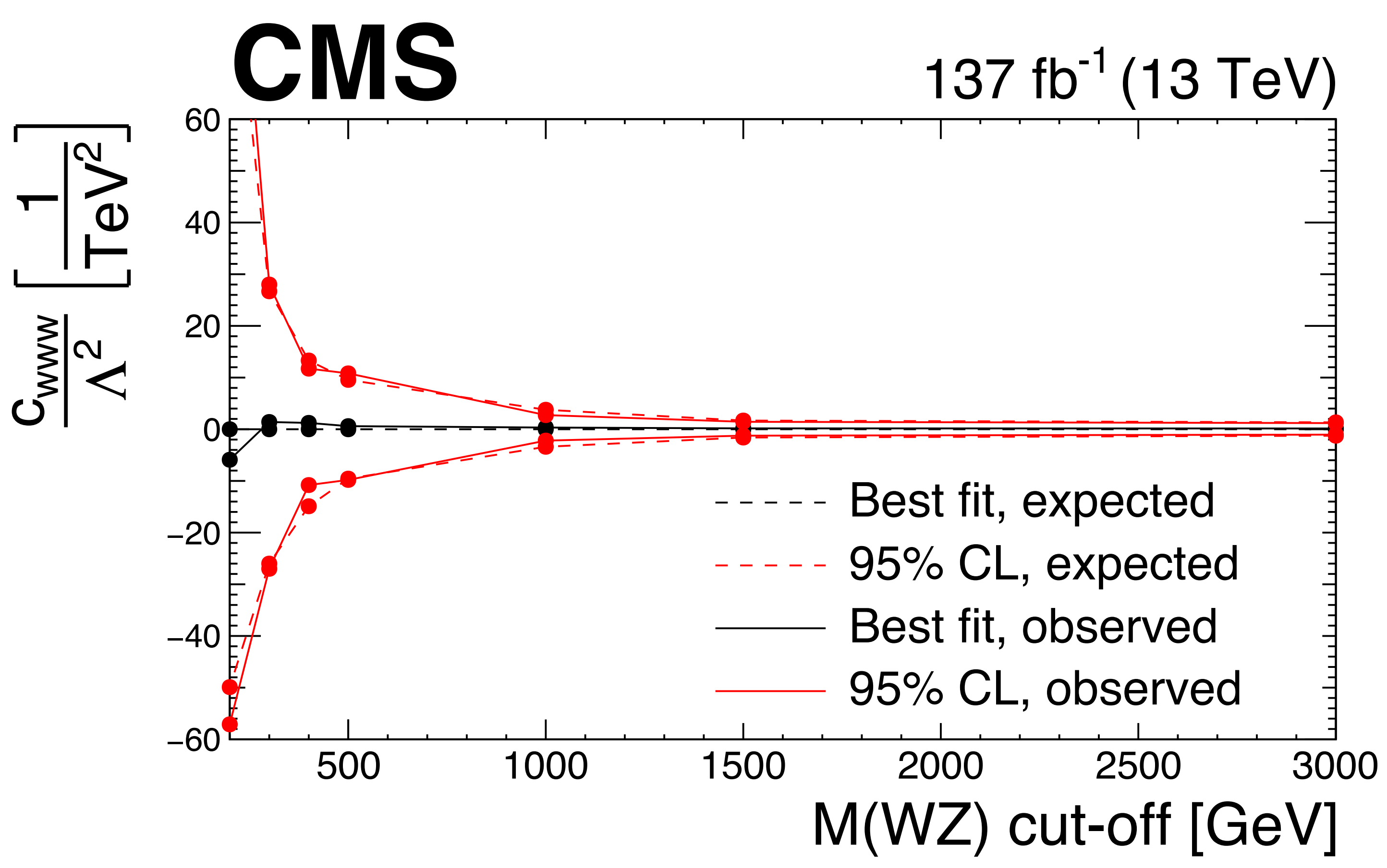
WZ (3l)

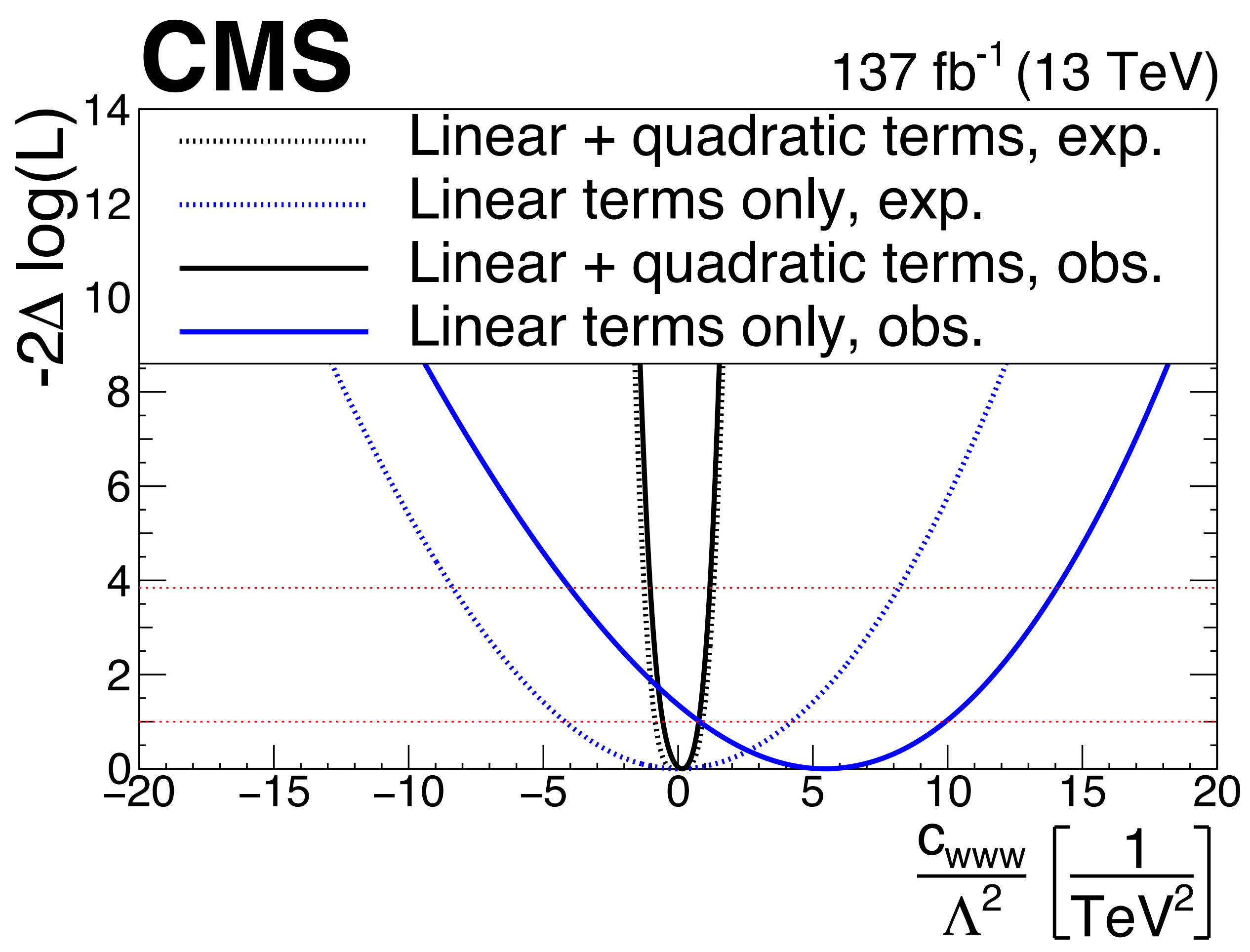
[JHEP 07 (2022) 032]

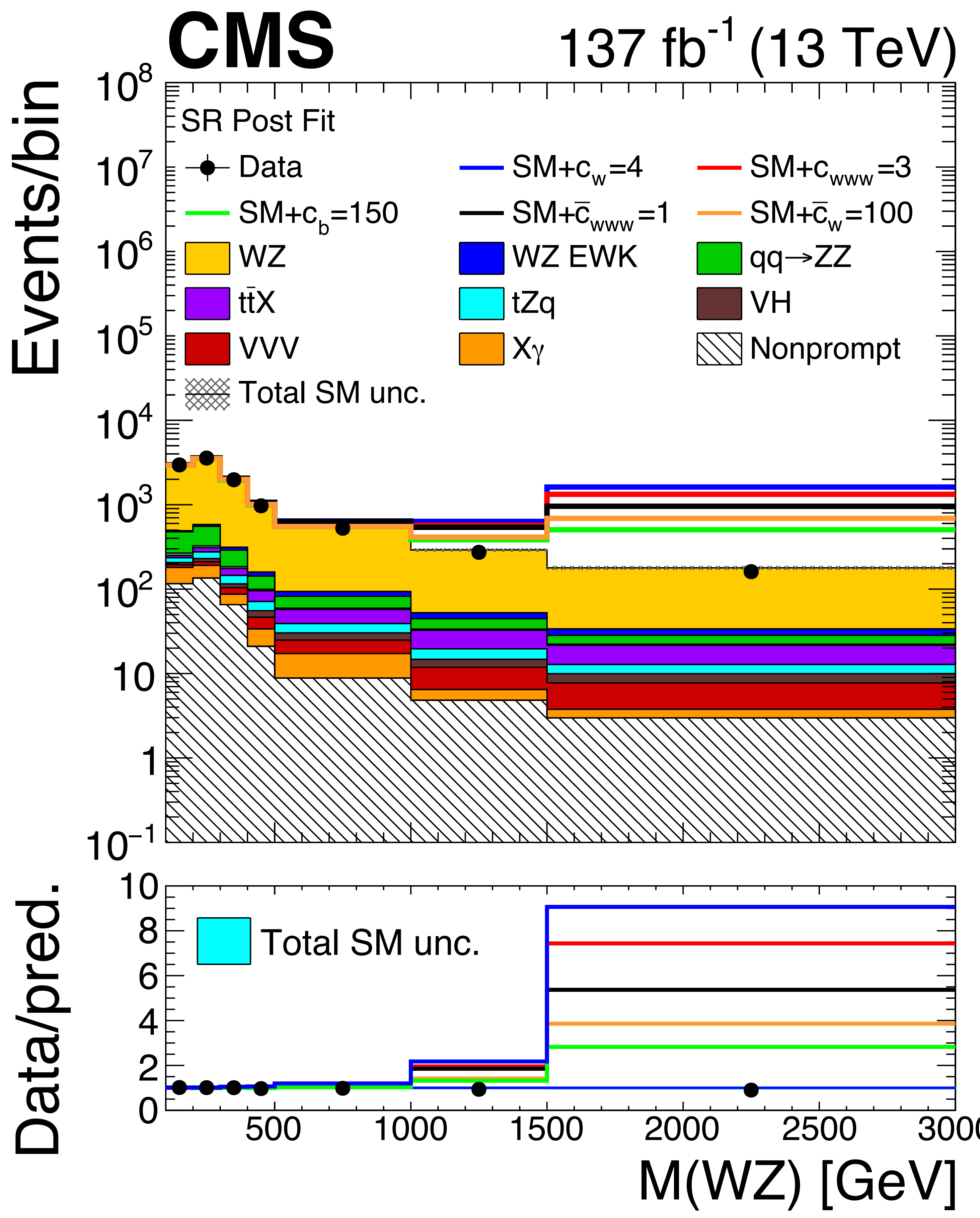
- Also sets limits in the **HISZ** basis coefficients
  - Best sensitivity for $\mathbf{c_W}$

Parameter	95% CI, exp. (TeV^{-2})	95% CI, obs. (TeV^{-2})	Best fit, obs. (TeV^{-2})
c_{W}/Λ^2	$[-2.0, 1.3]$	$[-2.5, 0.3]$	-1.3
$c_{\mathrm{WWW}}/\Lambda^2$	$[-1.3, 1.3]$	$[-1.0, 1.2]$	0.1
c_{b}/Λ^2	$[-86, 125]$	$[-43, 113]$	44
$\tilde{c}_{\mathrm{WWW}}/\Lambda^2$	$[-0.76, 0.65]$	$[-0.62, 0.53]$	-0.03
$\tilde{c}_{\mathrm{W}}/\Lambda^2$	$[-46, 46]$	$[-32, 32]$	0

- Limits given as a function of maximum M(WZ) included in the fit
- And with and without the inclusion of the quadratic EFT term

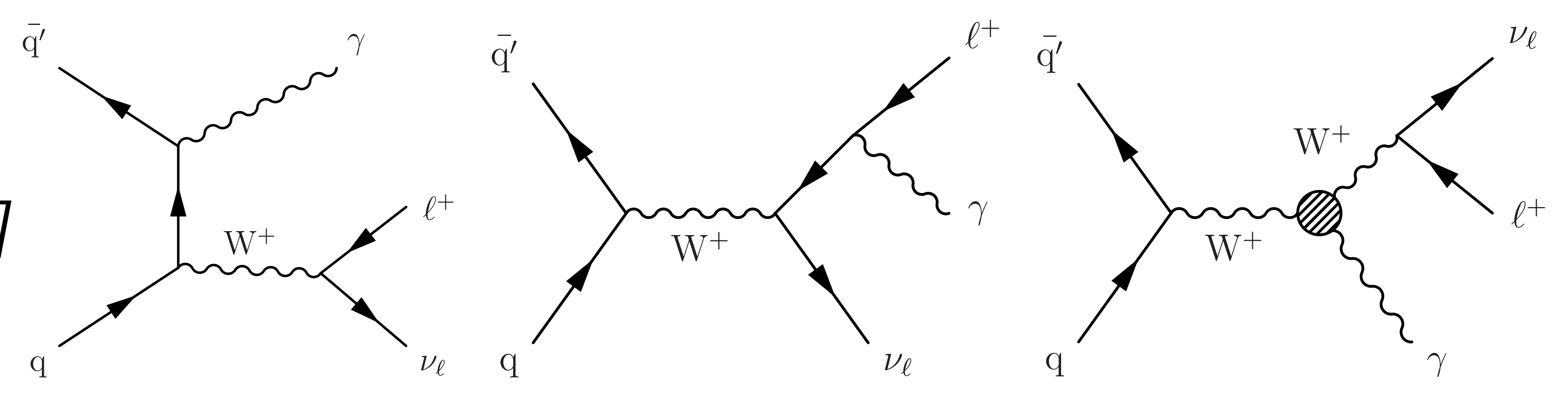






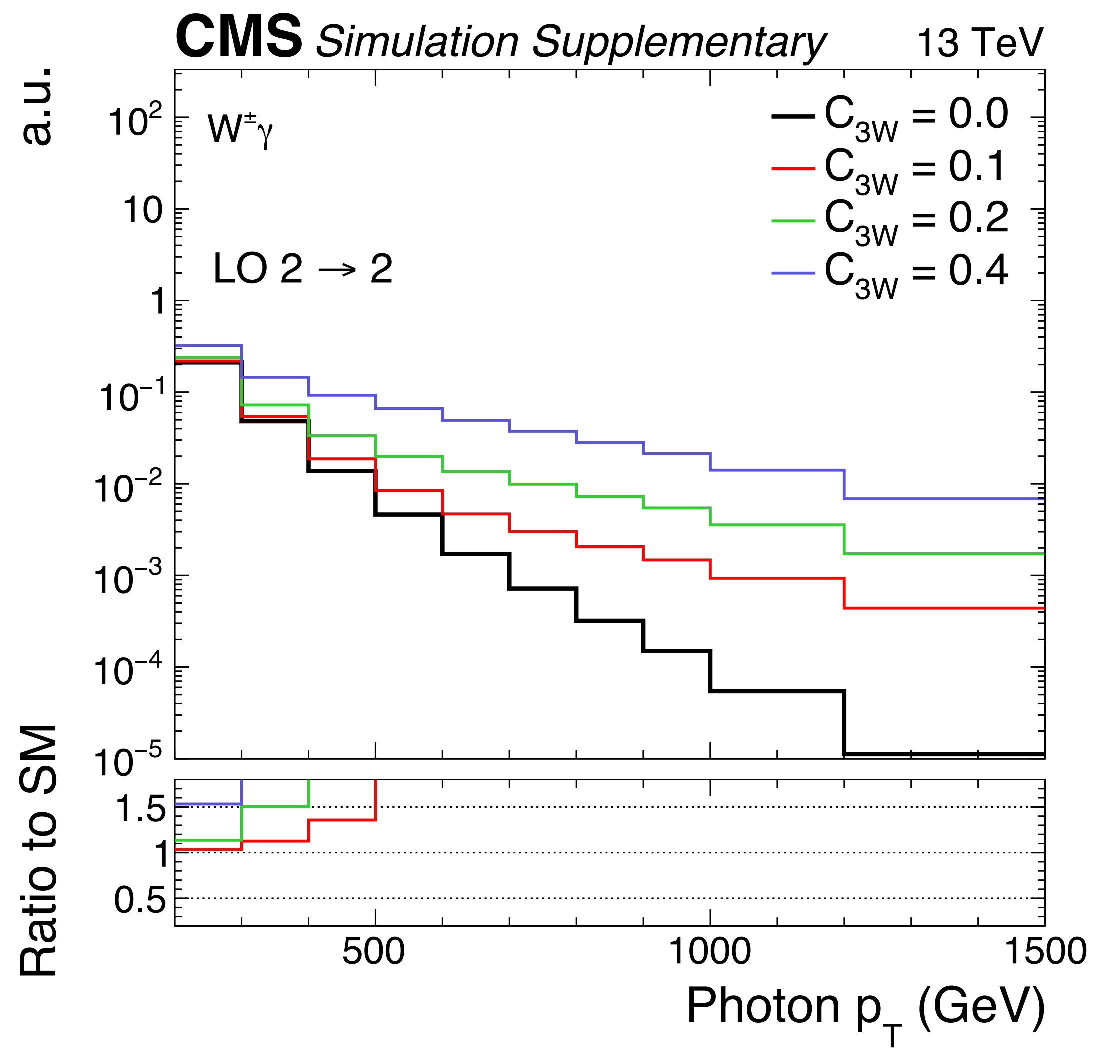
Wγ: interference resurrection

[Phys. Rev. D 105 (2022) 052003]



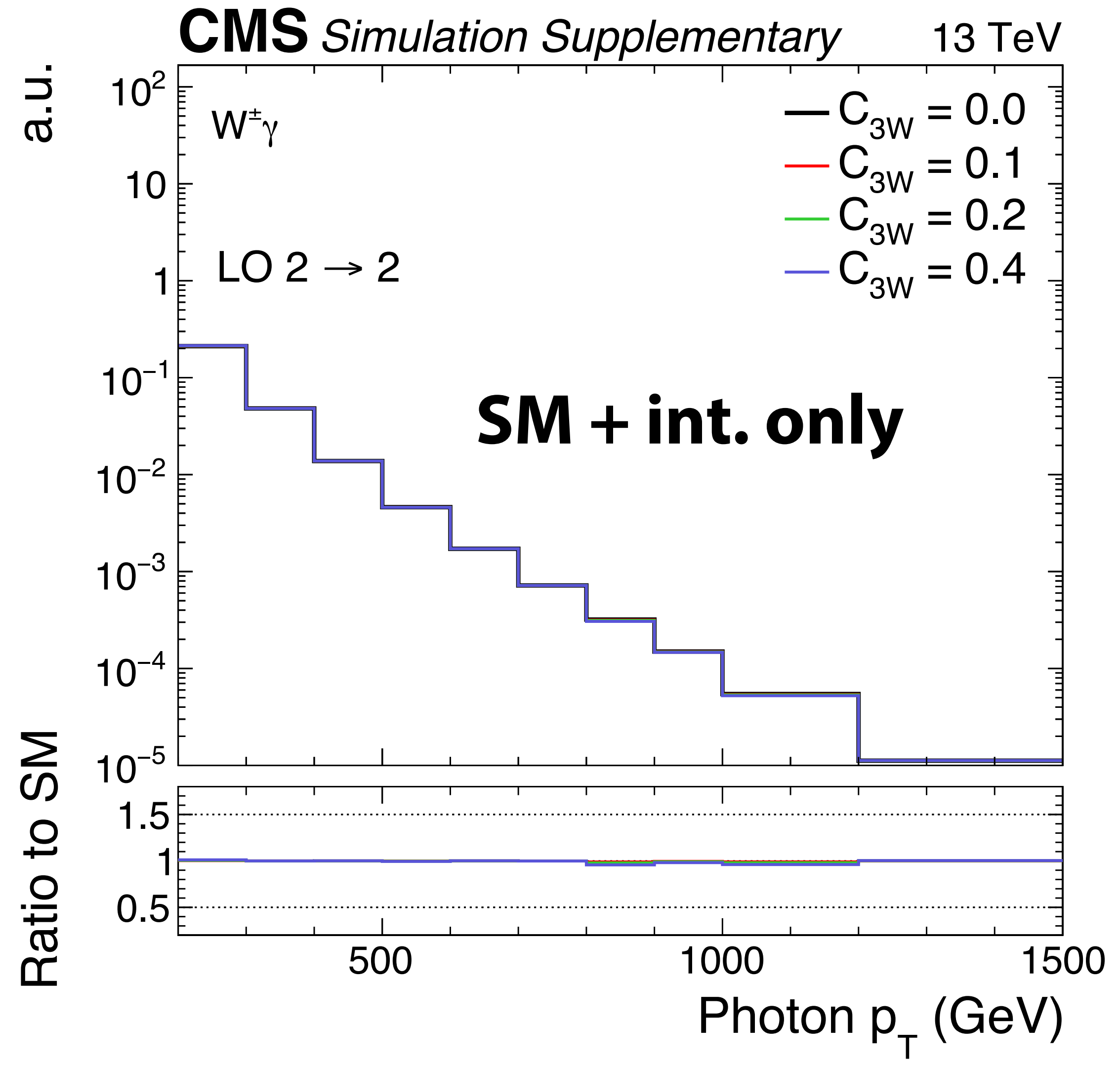
- CMS analysis of the W±(lν)γ channel
- Focus on the $\mathcal{O}_{3W}$ operator: $\mathcal{O}_{3W} = \epsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$
  - with Wilson coefficient **C_{3W}** in the **Warsaw basis** (also denoted **C_W**)
- Start with standard approach:
  - Exploit energy growth of BSM ⇒ measure high p_T^γ

$$\sigma = \sigma_{\rm SM} + C_{3W}\sigma_{\rm int} + C_{3W}^2\sigma_{\rm BSM}$$



- Issue: pure BSM term drives current sensitivity
  - We neglect SM-dim8 interference which also enters at $1/\Lambda^4$ - validity becomes model dependent
- At LO, SM-dim6 interference not observable in inclusive quantities like p_T^γ
- Effect due to helicity suppression

$$\sigma = \sigma_{\rm SM} + C_{3W}\sigma_{\rm int} + \cancel{C_{3W}^2\sigma_{\rm BSM}}$$



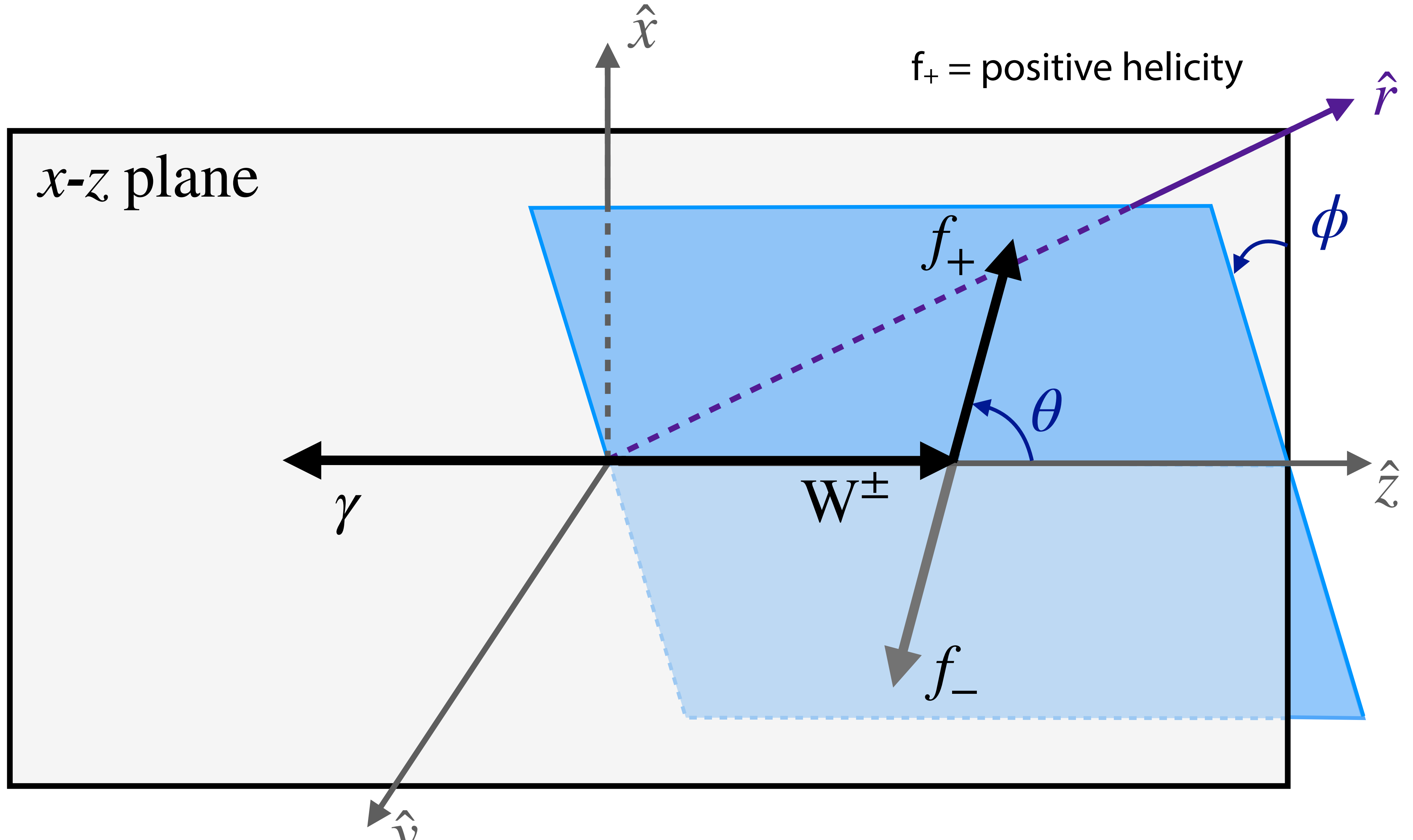
	SM	BSM
$q_{L,R}\bar{q}_{L,R} \to V_L V_L(h)$	~ 1	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_L(h)$	$\sim m_W/E$	$\sim m_W E/M^2$
$q_{L,R}\bar{q}_{L,R} \to \boxed{V_\pm V_\pm}$	$\boxed{\sim m_W^2/E^2}$	$\boxed{\sim E^2/M^2}$
$q_{L,R}\bar{q}_{L,R} \to \boxed{V_\pm V_\mp}$	$\boxed{\sim 1}$	$\boxed{\sim 1}$

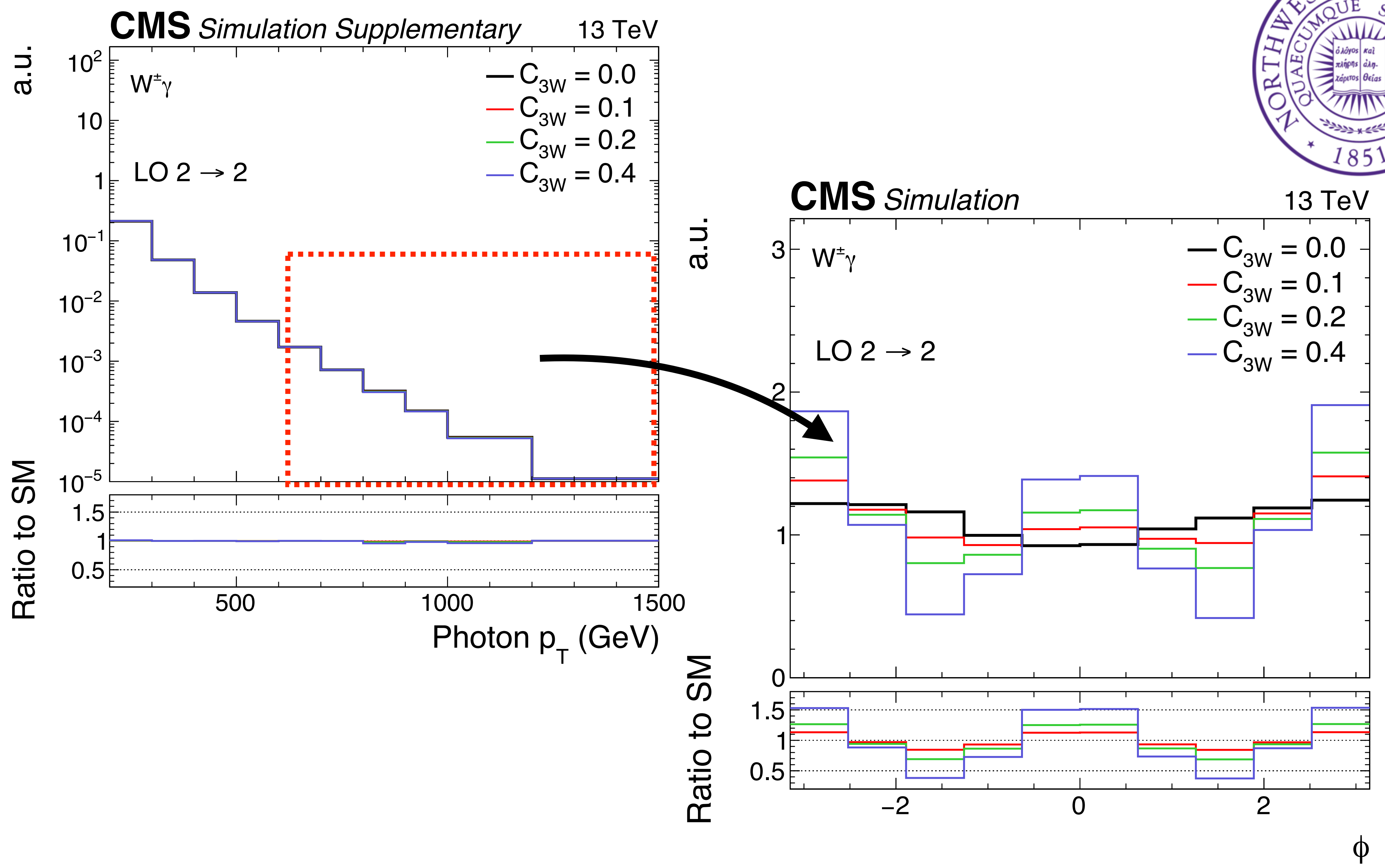
[Azatov, Contino, Machado, Riva, 2016]

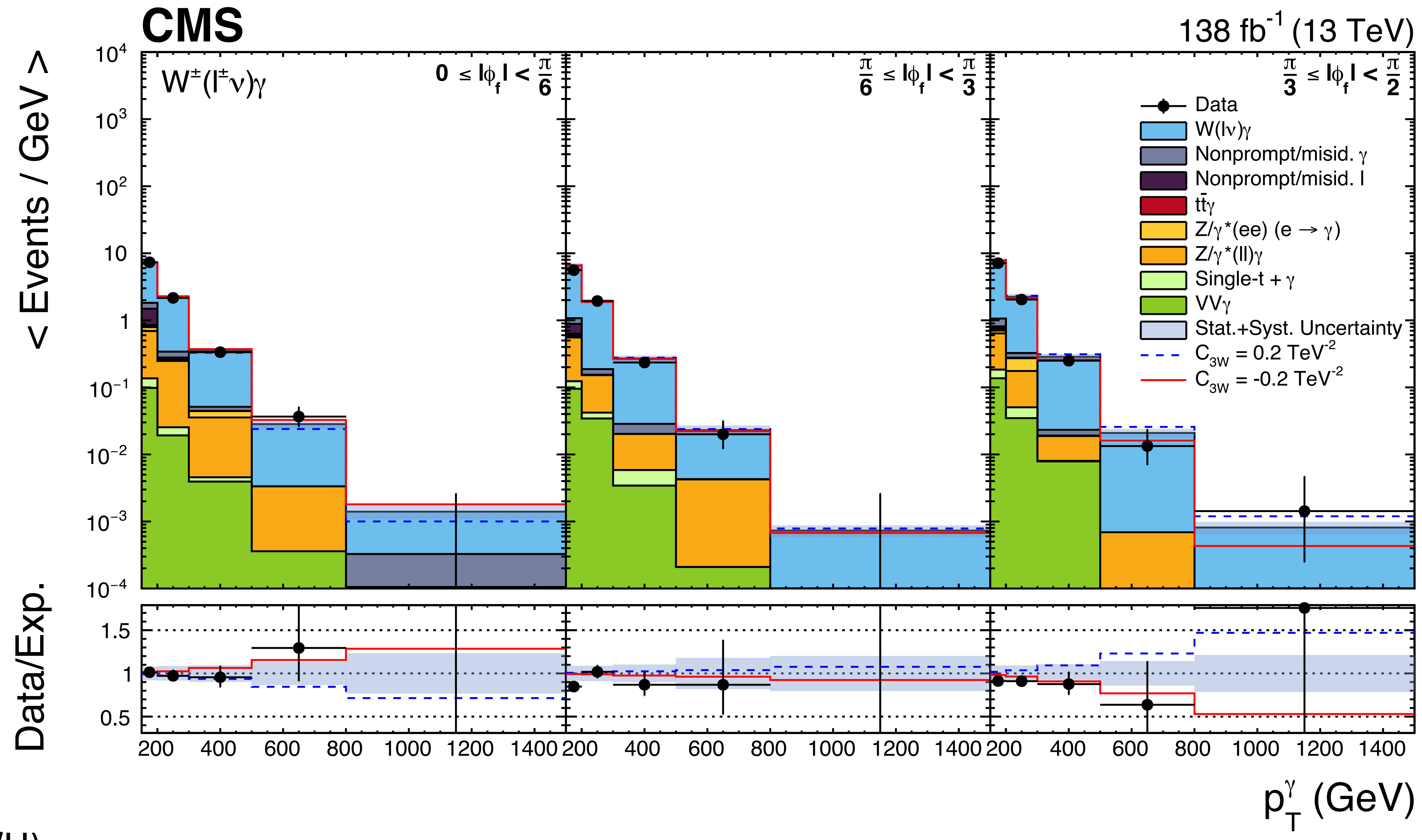
BSM enhanced where SM suppressed.
No energy growth at the interference level

Wγ: interference suppression

- "Interference resurrection" technique proposed *[PLB 776 (2018) 473, JHEP 04 (2019) 075]*
  - Measure decay angle φ of the final state fermions in a special reference frame
  - Interference causes characteristic modulation
- To constrain interference make a simultaneous measurement of p_T^{γ} and $|\varphi_f|$

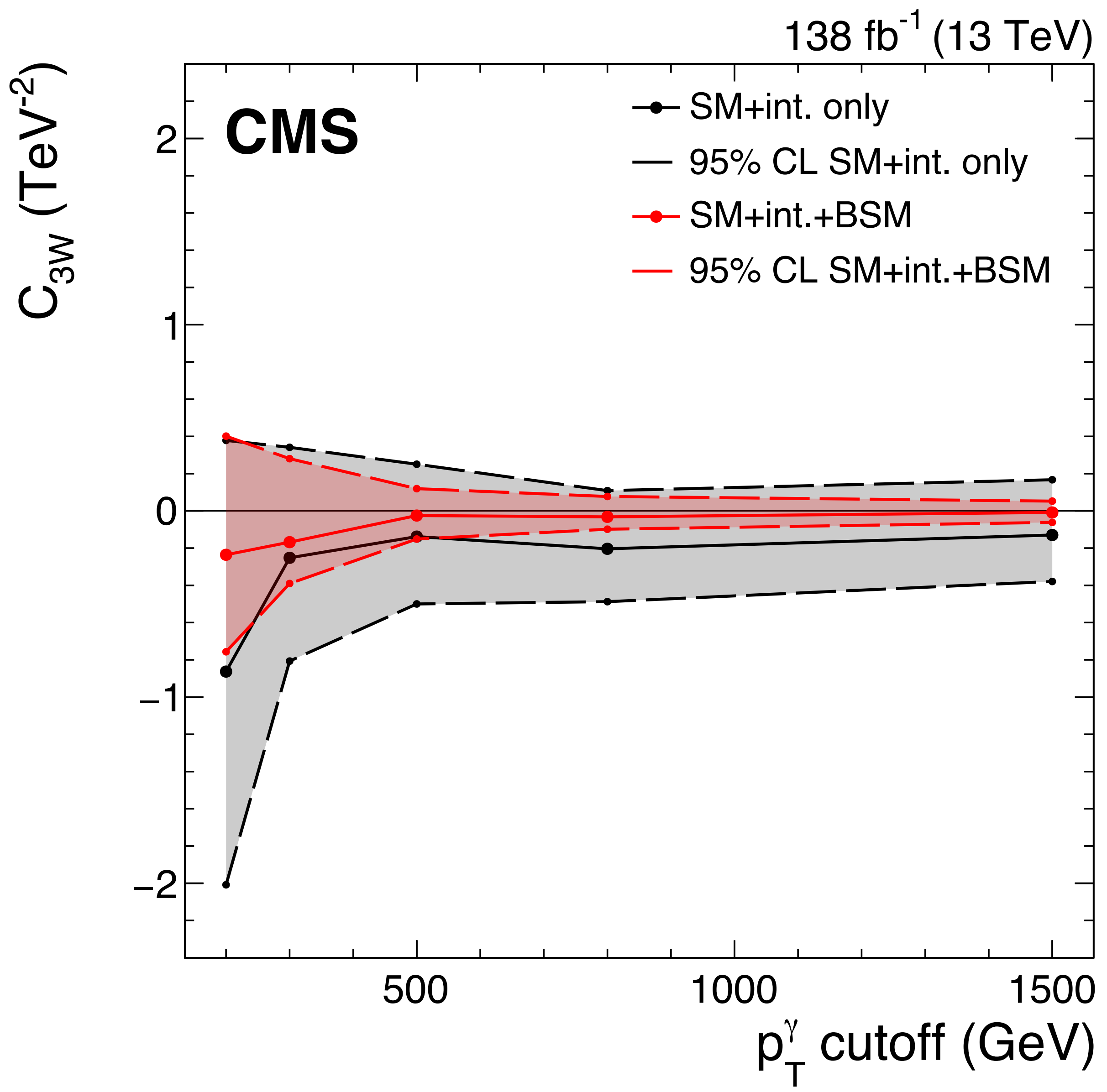


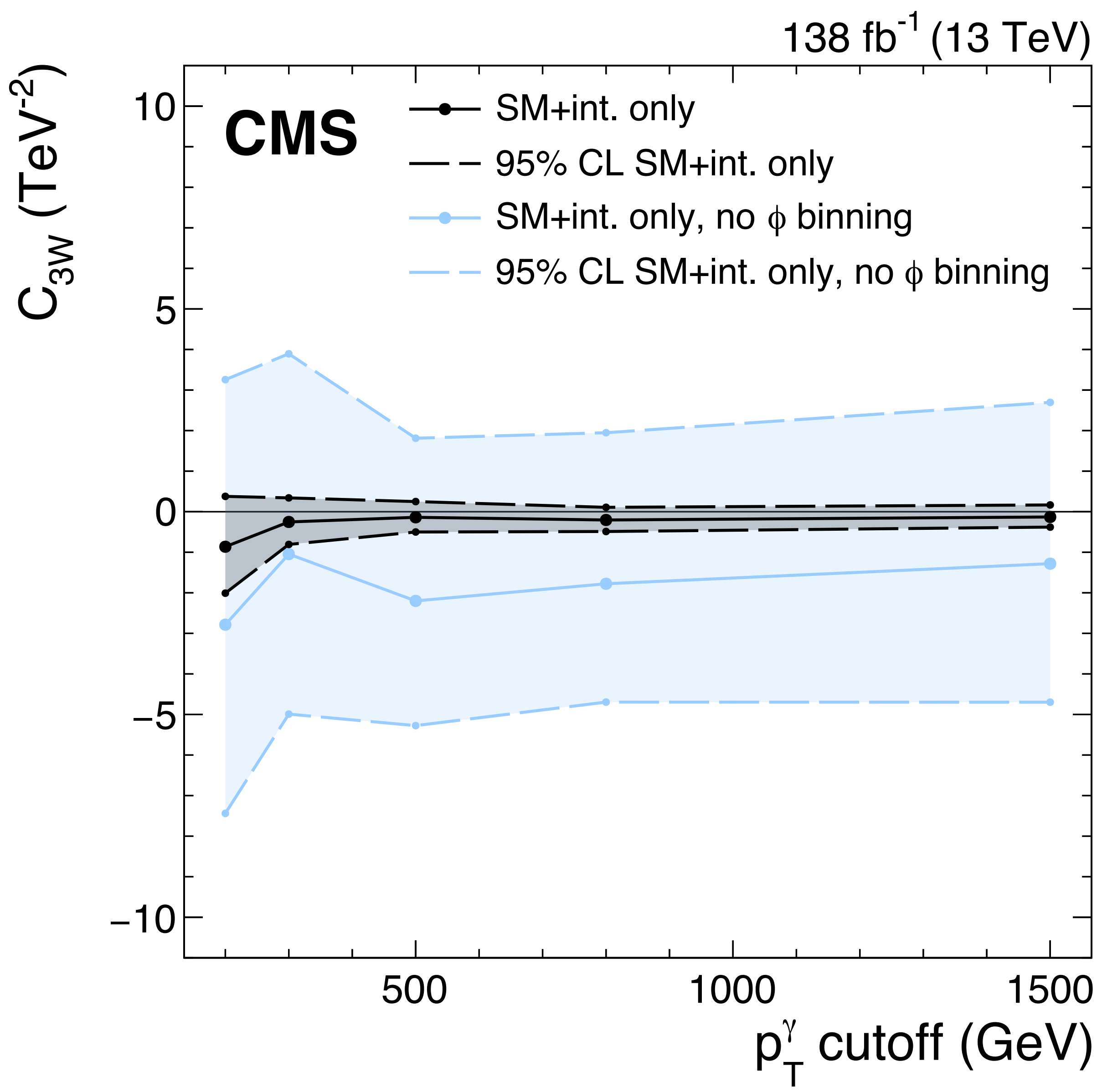


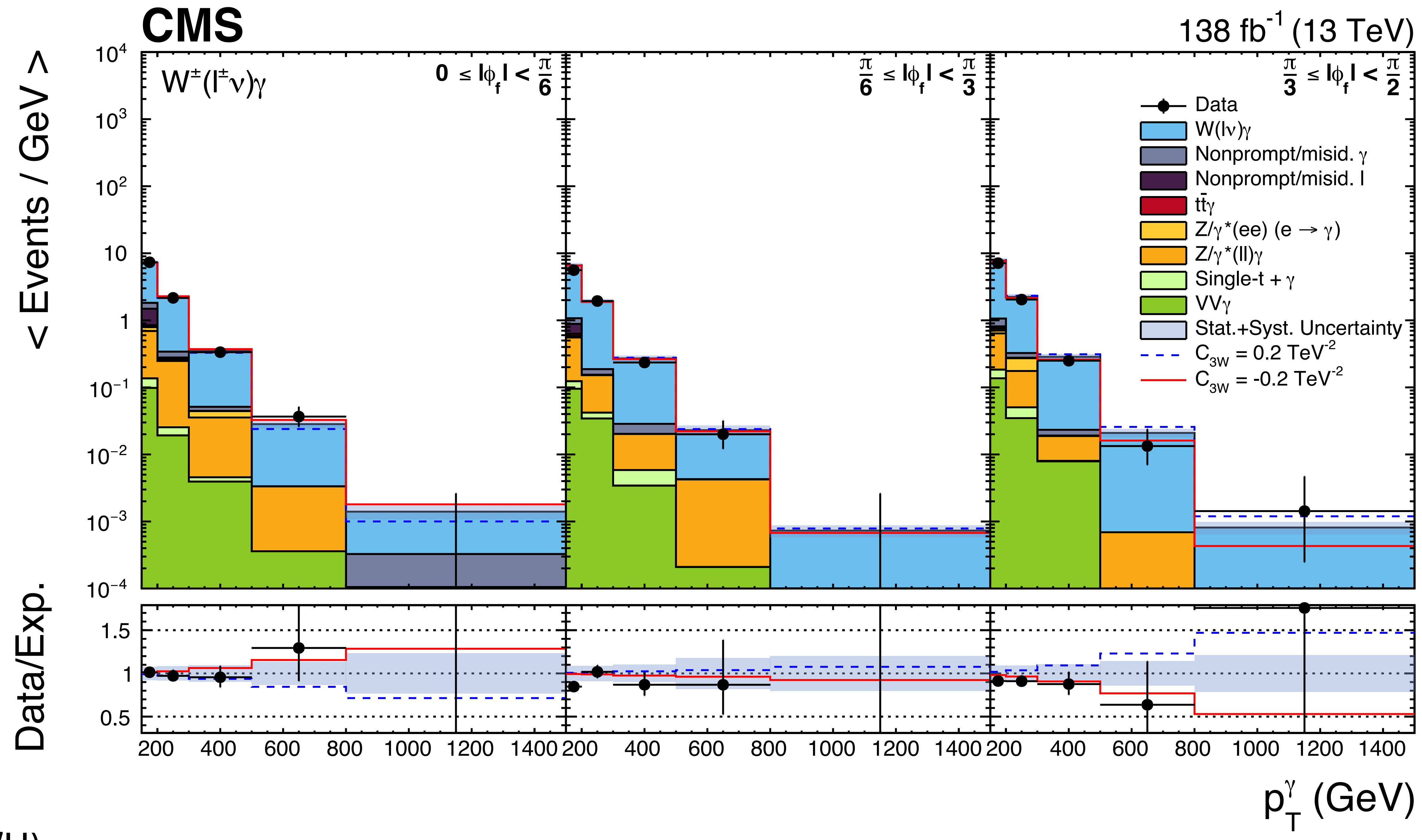


Wγ: interference suppression

- Extract 95% CL intervals on C_{3W} vs. maximum $p_T(\gamma)$ bin included in fit
- Overall sensitivity still dominated by pure BSM contribution…
  - … but with increasing integrated luminosity, probe smaller values of C_{3W} where interference term will come to dominate
- Binning in φ significantly improves sensitivity to SM-BSM interference, up to a factor of 10
  - Improves the validity of the constraints
  - Significant gain in fits where only the leading interference effects are included

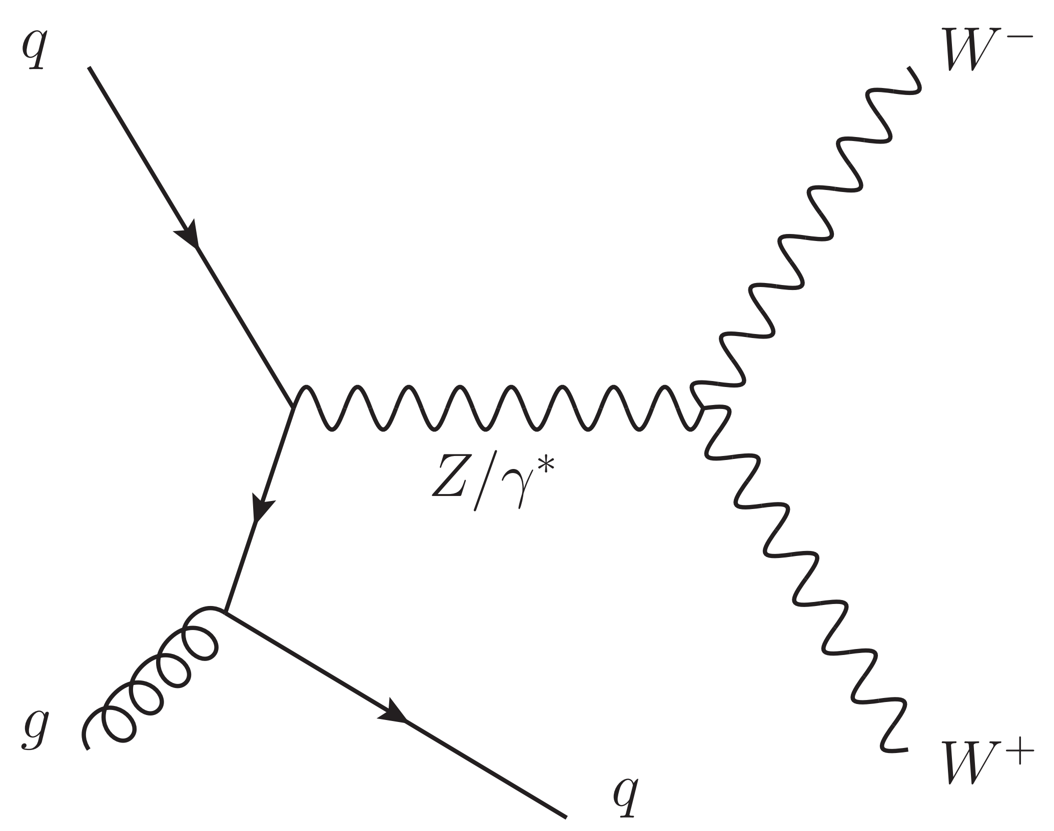




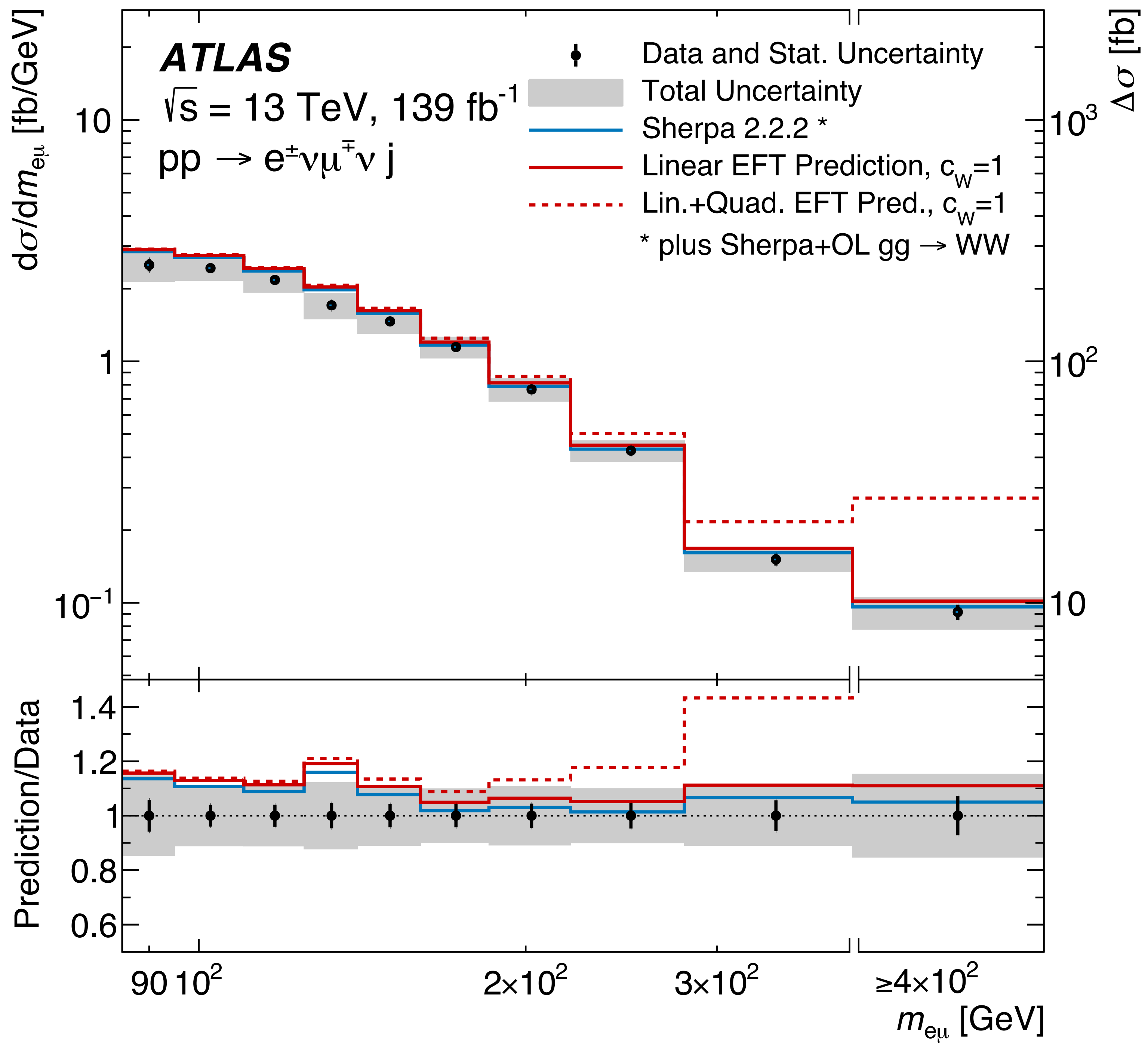


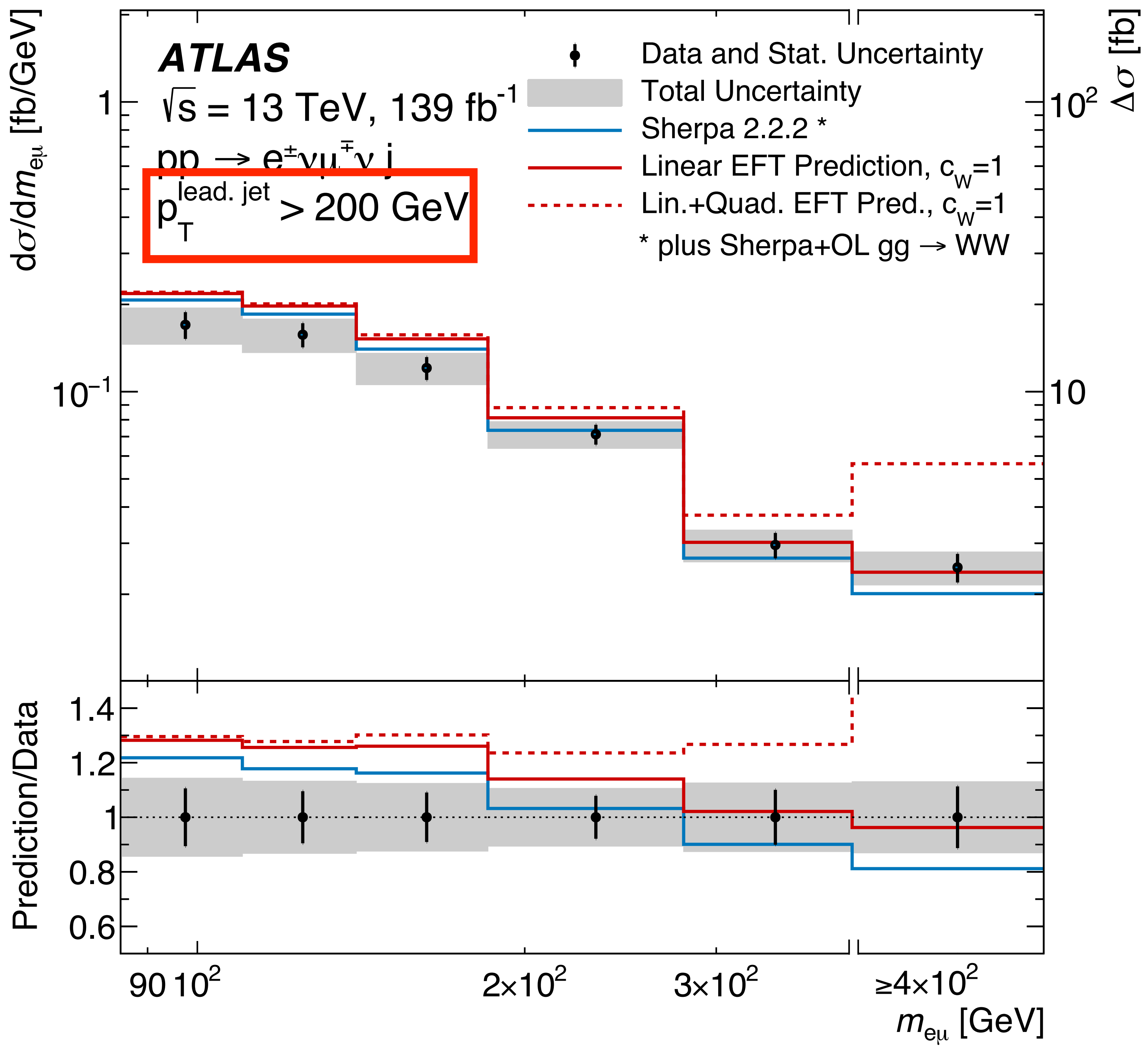
WW + 1 jet: interference suppression

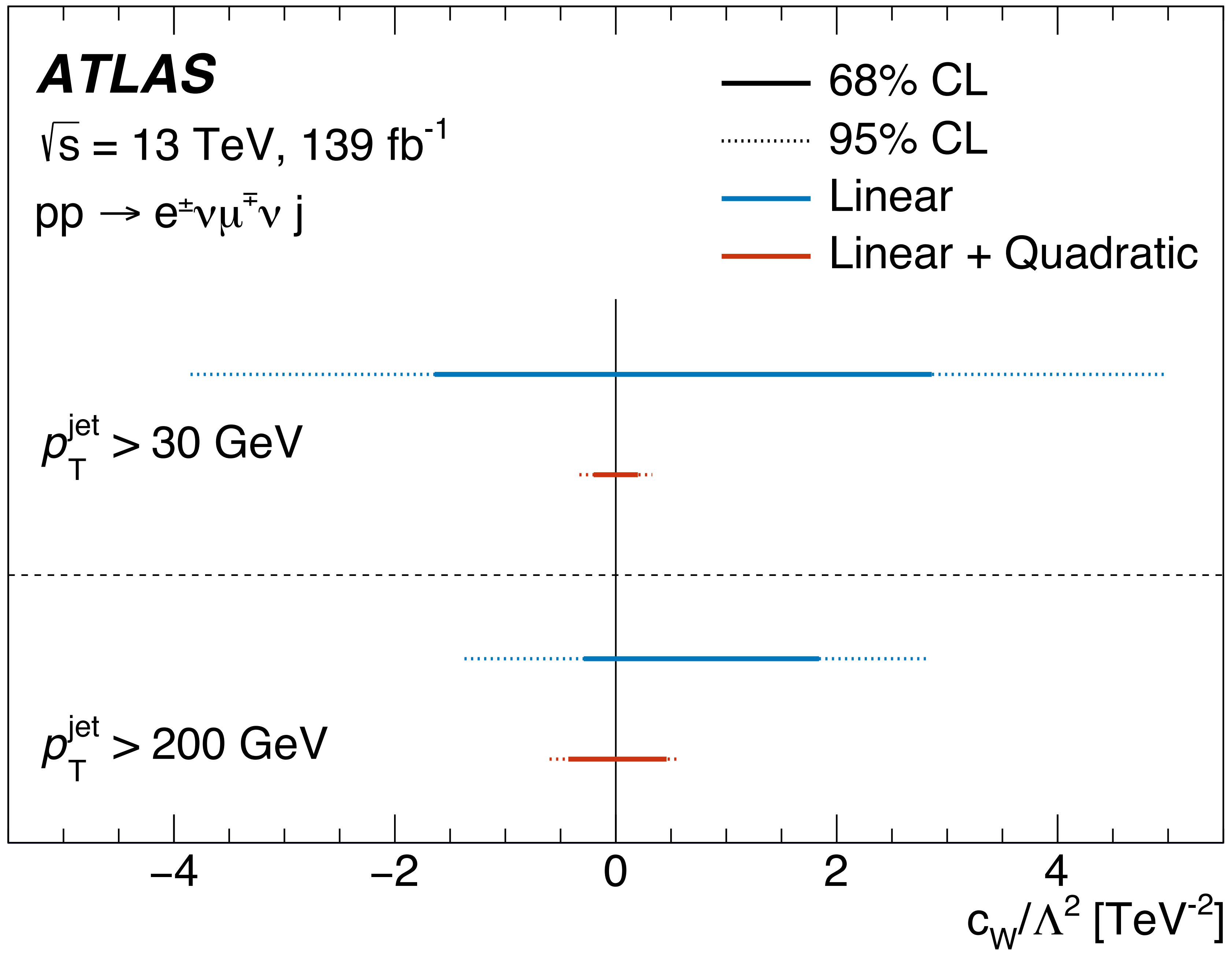
[JHEP 06 (2021) 003]



- Another way to break the helicity suppression
  - Additional jet requirement introduces different helicity configurations ⇒ reduced suppression
- Parameterisation of most sensitive observable ($m_{e\mu}$)
  - Raising jet p_T cut to 200 GeV improves sensitivity to the interference part
  - Overall sensitivity remains dominated by pure BSM part



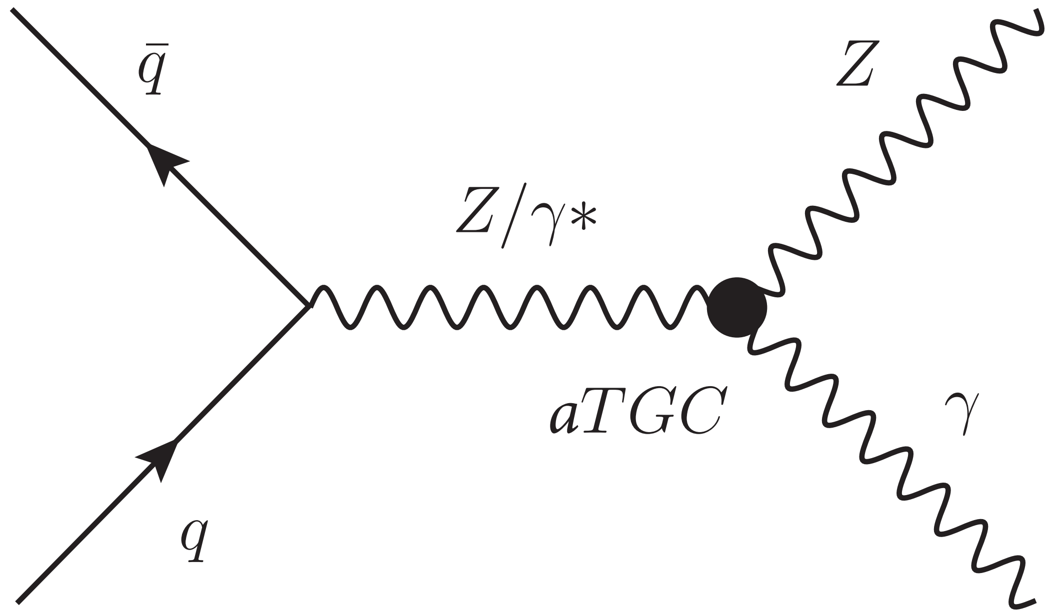




Neutral triple gauge couplings

Neutral triple gauge couplings

- Neutral triple gauge couplings forbidden at tree level (ZZγ, Zγγ)
- Traditional anomalous vertex parameterisation:
  - All f_i^V, h_i^V = 0 in the SM



ZZ production ←

$$ie\Gamma^{\alpha\beta\mu}_{ZZV}(q_1,q_2,q_3) = \frac{-e(q_3^2-m_V^2)}{M_Z^2}\left[f_4^V(q_3^\alpha g^{\mu\beta}+q_3^\beta g^{\mu\alpha}) - f_5^V\epsilon^{\mu\alpha\beta\rho}(q_1-q_2)_\rho\right], \quad (1.1)$$

Zγ production ←

$$ie\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1,q_2,q_3) = \frac{-e(q_3^2-m_V^2)}{M_Z^2}\left\{h_1^V(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}) + \frac{h_2^V}{M_Z^2} q_3^\alpha[(q_3 q_2)g^{\mu\beta} - q_2^\mu q_3^\beta] - h_3^V \epsilon^{\mu\alpha\beta\rho}q_{2\rho} - \frac{h_4^V}{M_Z^2} q_3^\alpha \epsilon^{\mu\beta\rho\sigma} q_{3\rho} q_{2\sigma}\right\} \quad (1.2)$$

where V = Z,γ (off-shell)

CP violating

CP conserving

- Related to dim-8 EFT operators:

$$\mathcal{O}_{BW} = i\, H^\dagger B_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H,$$
$$\mathcal{O}_{WW} = i\, H^\dagger W_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H,$$
$$\mathcal{O}_{BB} = i\, H^\dagger B_{\mu\nu} B^{\mu\rho} \{D_\rho, D^\nu\} H.$$
$$\mathcal{O}_{\widetilde{B}W} = i\, H^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H,$$

[JHEP 02 (2014) 101]

$$h_1^Z = \frac{M_Z^2 v^2 \left(-c_w s_w \frac{C_{WW}}{\Lambda^4} + \frac{C_{BW}}{\Lambda^4}({c_w}^2 - {s_w}^2) + 4 c_w s_w \frac{C_{BB}}{\Lambda^4}\right)}{4 c_w s_w}$$
$$h_2^Z = 0$$
$$h_1^\gamma = -\frac{M_Z^2 v^2 \left({s_w}^2 \frac{C_{WW}}{\Lambda^4} - 2 c_w s_w \frac{C_{BW}}{\Lambda^4} + 4 {c_w}^2 \frac{C_{BB}}{\Lambda^4}\right)}{4 c_w s_w}$$
$$h_2^\gamma = 0.$$

NB: new modified form factors proposed: [*Ellis, He, Xiao '22*]

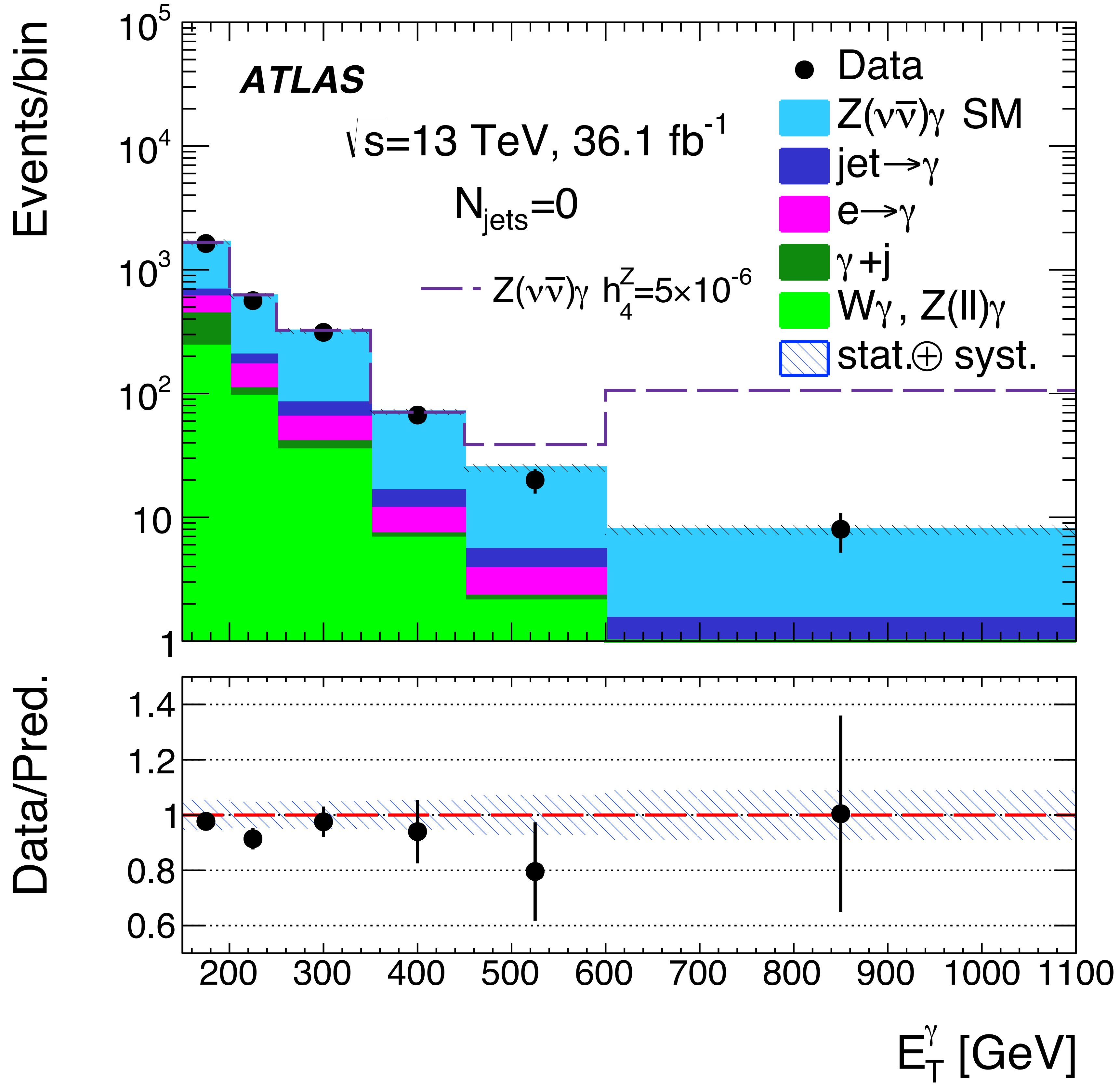
Z(νν)γ

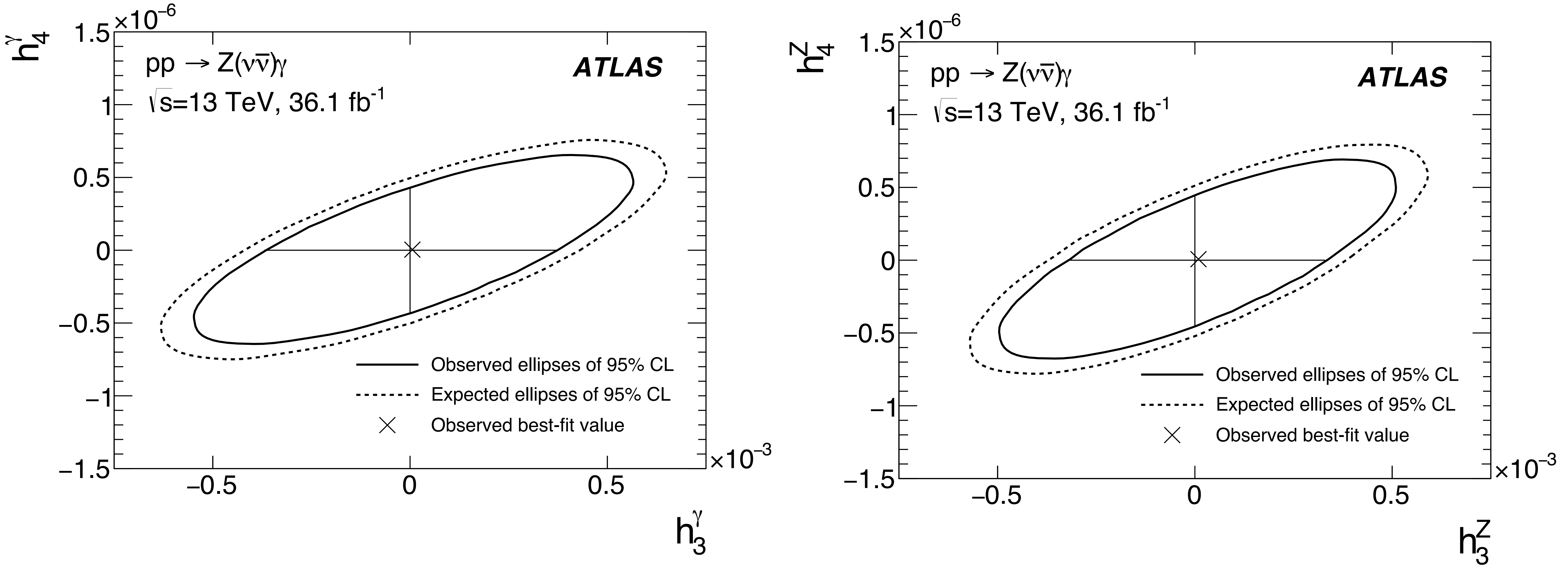
[JHEP 12 (2018) 010]

- nTGC sensitivity will be in statistically limited high p_T^{γ} region
  - ⇒ benefit from Z→ νν branching ratio vs. Z→ll
- Strongest constraints to date

Limits on CP-conserving couplings:
(CP-violating not distinguishable)

Parameter	Limit 95% CL Measured	Limit 95% CL Expected
h_3^{γ}	$(-3.7\times10^{-4}, 3.7\times10^{-4})$	$(-4.2\times10^{-4}, 4.3\times10^{-4})$
h_3^{Z}	$(-3.2\times10^{-4}, 3.3\times10^{-4})$	$(-3.8\times10^{-4}, 3.8\times10^{-4})$
h_4^{γ}	$(-4.4\times10^{-7}, 4.3\times10^{-7})$	$(-5.1\times10^{-7}, 5.0\times10^{-7})$
h_4^{Z}	$(-4.5\times10^{-7}, 4.4\times10^{-7})$	$(-5.3\times10^{-7}, 5.1\times10^{-7})$





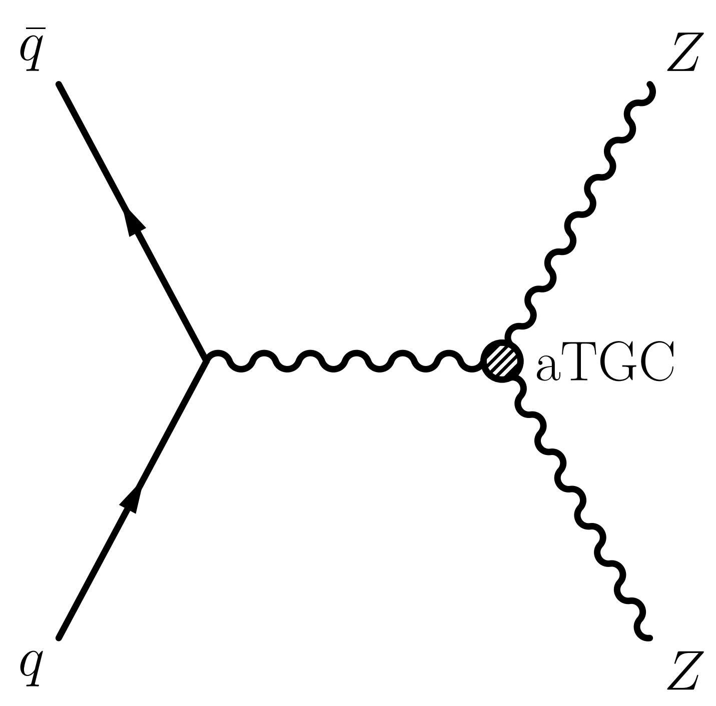
Translated to dim-8 EFT:

Parameter	Limit 95% CL Measured [TeV^{-4}]	Limit 95% CL Expected [TeV^{-4}]
$C_{\widetilde{B}W}/\Lambda^4$	$(-1.1, 1.1)$	$(-1.3, 1.3)$
C_{BW}/Λ^4	$(-0.65, 0.64)$	$(-0.74, 0.74)$
C_{WW}/Λ^4	$(-2.3, 2.3)$	$(-2.7, 2.7)$
C_{BB}/Λ^4	$(-0.24, 0.24)$	$(-0.28, 0.27)$

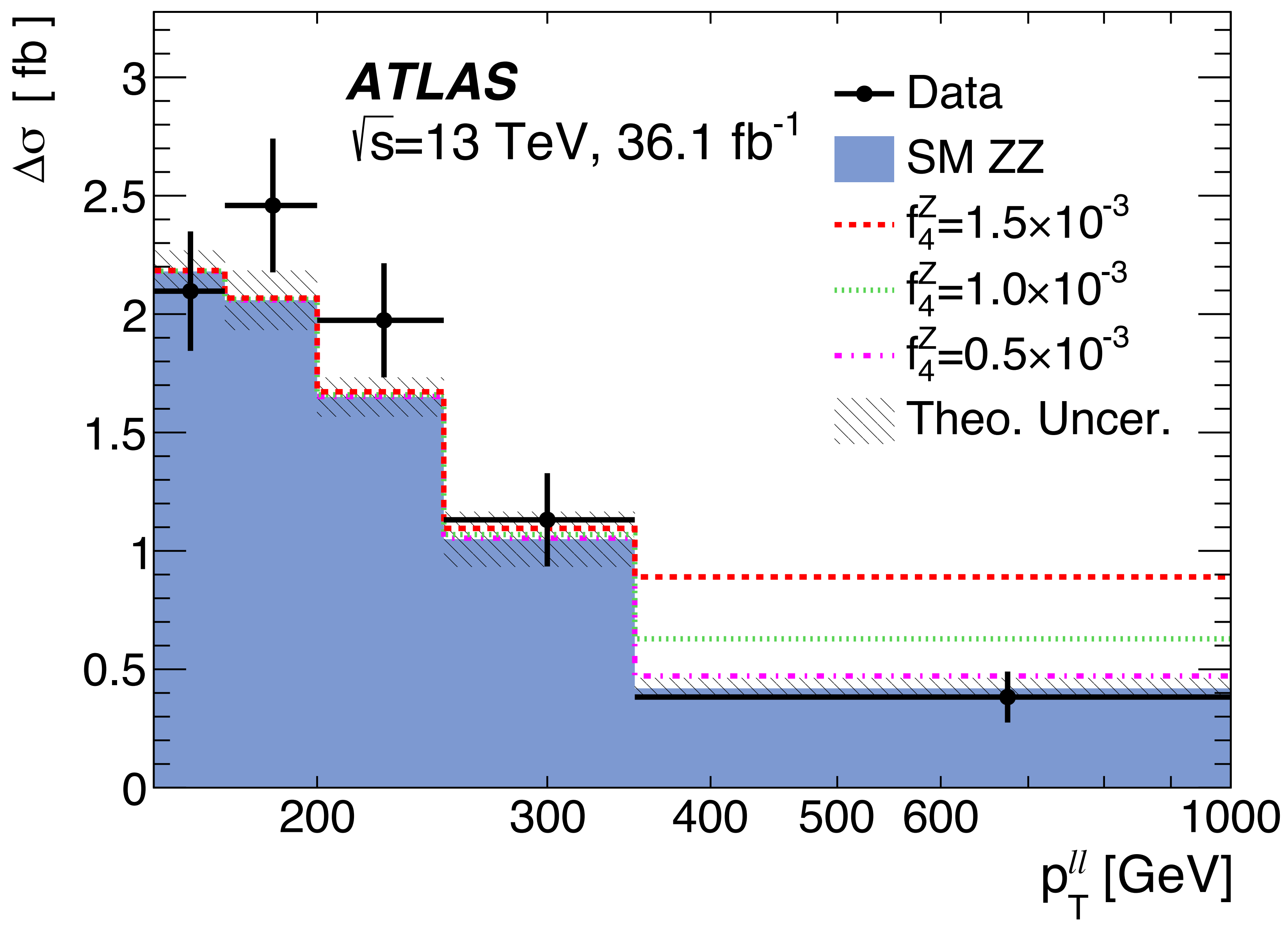
Z(ll)Z(νν), ZZ(4l)

[EPJC 81 (2021) 200]

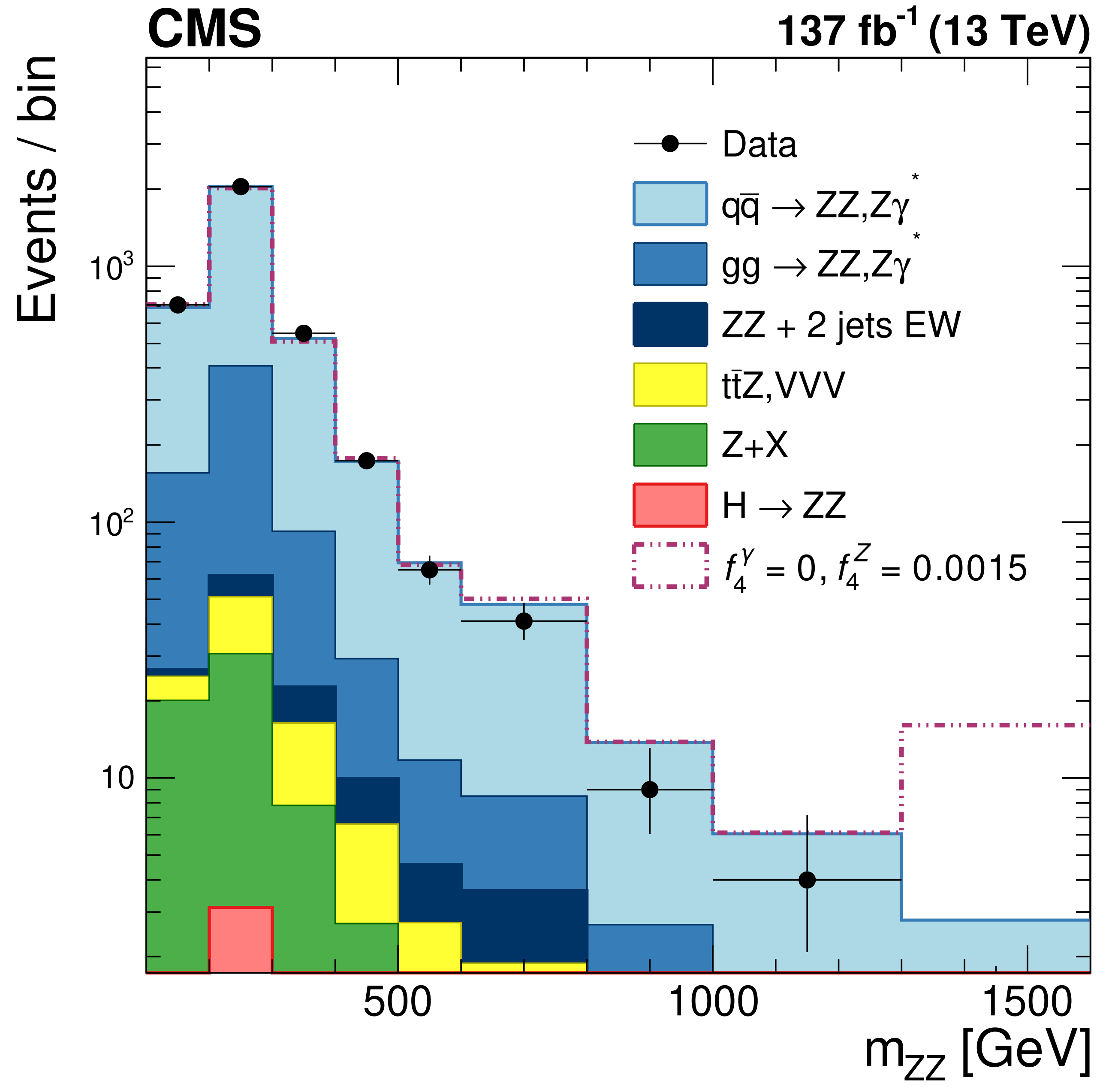
- **ATLAS analysis** of 2015+16 data in **llνν** channel
- Interpretation via unfolded p_T^{ll} distribution



- **CMS analysis** of full Run 2 in **4l** channels
- Fit to m_{ZZ} distribution



Both analyses require good control of SM process:
qq-induced:
NNLO QCD + NLO EW
gg-induced:
NLO QCD



	f_4^γ	f_4^Z	f_5^γ	f_5^Z
Expected $[\times 10^{-3}]$	$[-1.3,\ 1.3]$	$[-1.1,\ 1.1]$	$[-1.3,\ 1.3]$	$[-1.1,\ 1.1]$
Observed $[\times 10^{-3}]$	$[-1.2,\ 1.2]$	$[-1.0,\ 1.0]$	$[-1.2,\ 1.2]$	$[-1.0,\ 1.0]$

[JHEP 10 (2019) 127]

Comparable sensitivity, with trade-offs in:
- Integrated lumi
- Observable sensitivity
- νν vs ll branching ratio

	Expected 95% CL	Observed 95% CL
aTGC parameter	$\times 10^{-4}$	$\times 10^{-4}$
f_4^Z	-8.8 ; 8.3	-6.6 ; 6.0
f_5^Z	-8.0 ; 9.9	-5.5 ; 7.5
f_4^γ	-9.9 ; 9.5	-7.8 ; 7.1
f_5^γ	-9.2 ; 9.8	-6.8 ; 7.5
EFT parameter	TeV^{-4}	TeV^{-4}
$C_{\tilde{B}W}/\Lambda^4$	-3.1 ; 3.3	-2.3 ; 2.5
C_{WW}/Λ^4	-1.7 ; 1.6	-1.4 ; 1.2
C_{BW}/Λ^4	-1.8 ; 1.9	-1.4 ; 1.3
C_{BB}/Λ^4	-1.6 ; 1.6	-1.2 ; 1.2

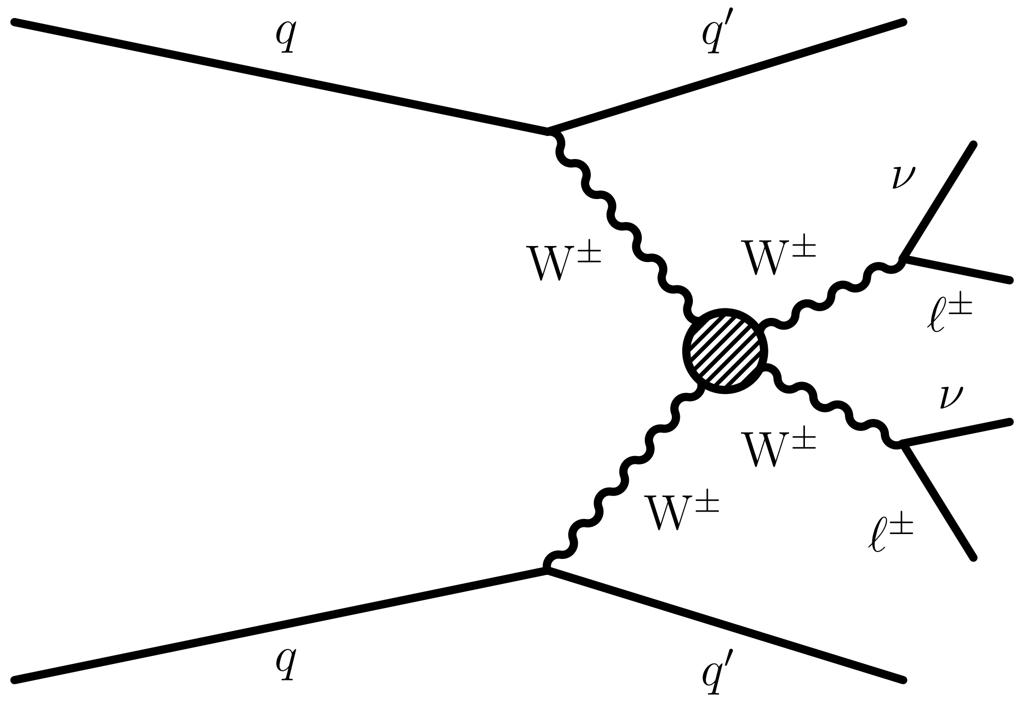
Anomalous quartic gauge couplings

EFT parameterisation

- Represented by dim-8 operators:

$$L_{\mathrm{EFT}} = L_{\mathrm{SM}} + \sum_i \frac{C_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)}$$

- Set of 20 CP-conserving operators built from covariant derivate of the Higgs doublet and the SU(2) gauge fields strength tensors
- Primarily studied in **vector boson scattering** processes:



- Typical signature:
  - Exploit both leptonic and hadronic V decays
  - Large pseudo-rapidity separation and invariant mass of the jets
  - Strong cross section growth with energy for non-zero Wilson coeff.

Longitudinal

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

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

Mixed

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

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

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

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

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

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

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

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

Transverse

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

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

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

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

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

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

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

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

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

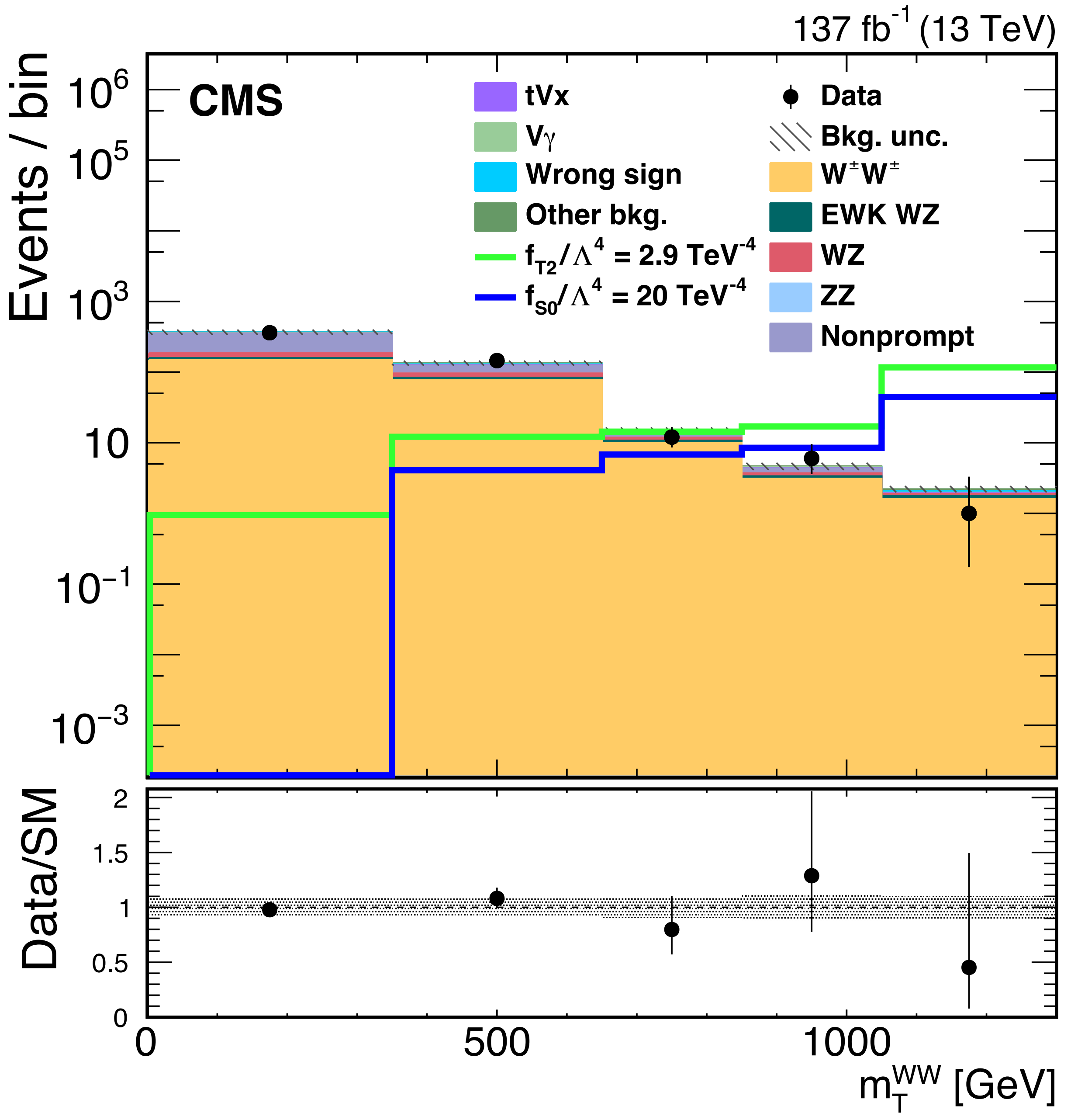
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}.$$

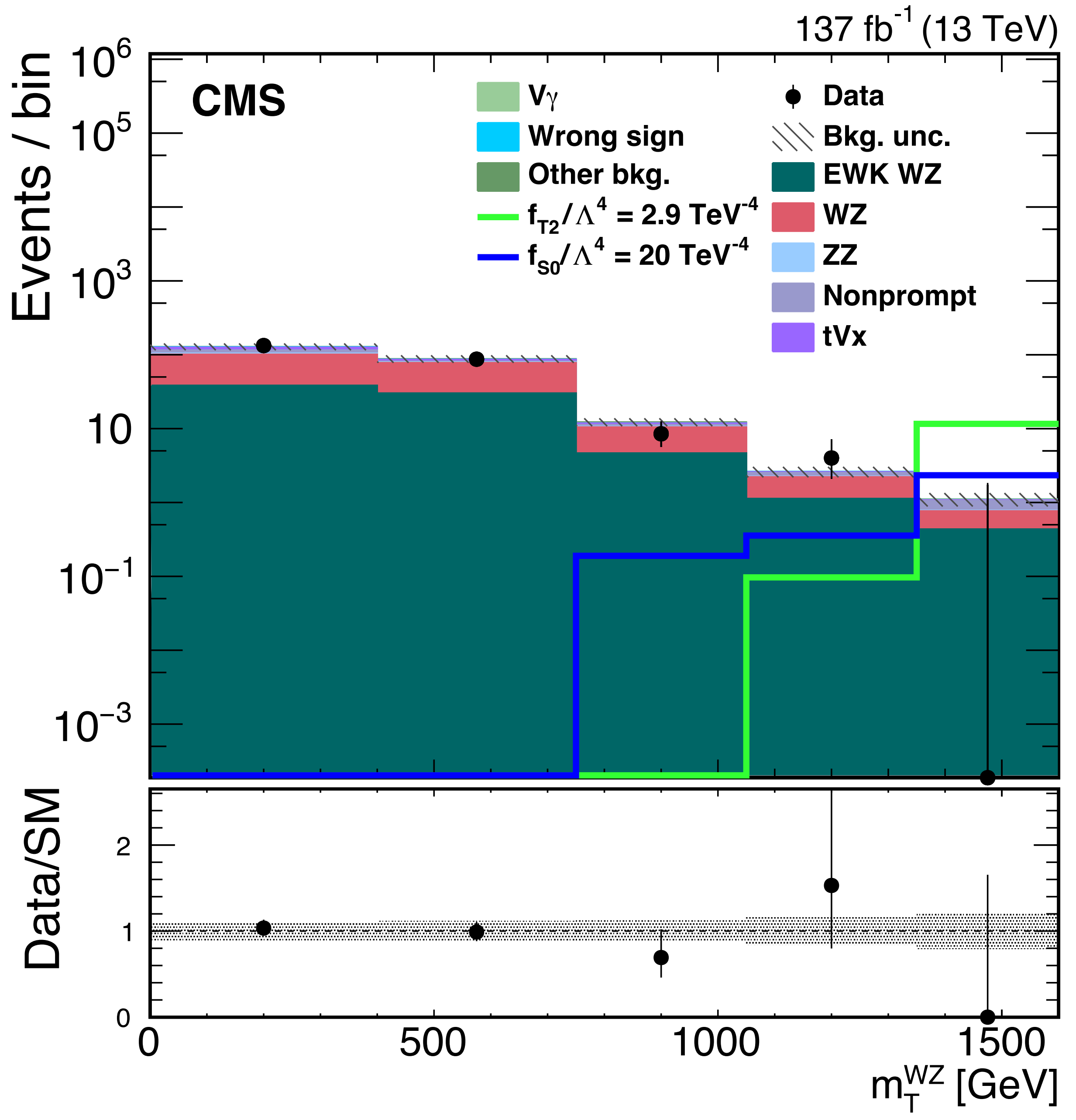
$W^\pm W^\pm$ / WZ

[PLB 809 (2020) 135710]

- $W^\pm W^\pm$ final state with much reduced background compared with $W^\pm W^\mp$
- Transverse di-boson mass as sensitive observable:

$$m_{\mathrm{T}}(\mathrm{VV}) = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i p_{z,i}\right)^2},$$





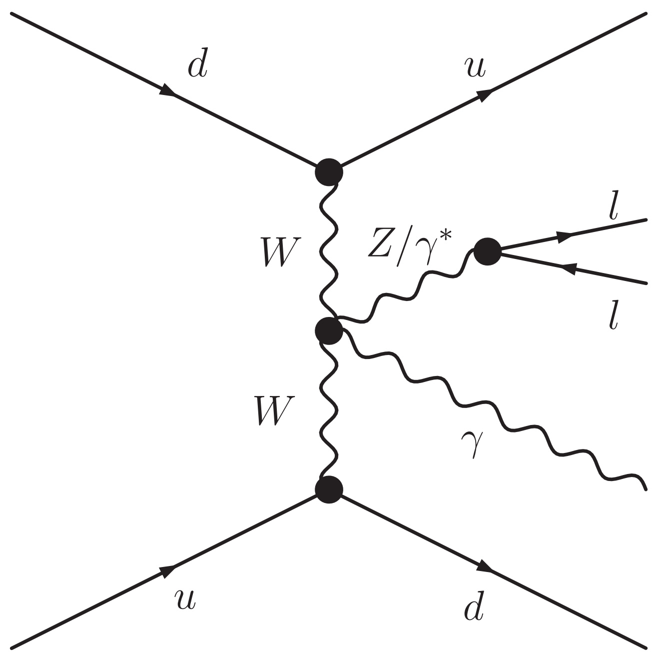
- Limits recomputed after applying unitarity constraint
  - No enhancement when M(VV) above unitarity limit (~ 1.5 TeV) - calculated with VBFNLO 1.4.0
  - Sensitivity worsens by factor ~ 5

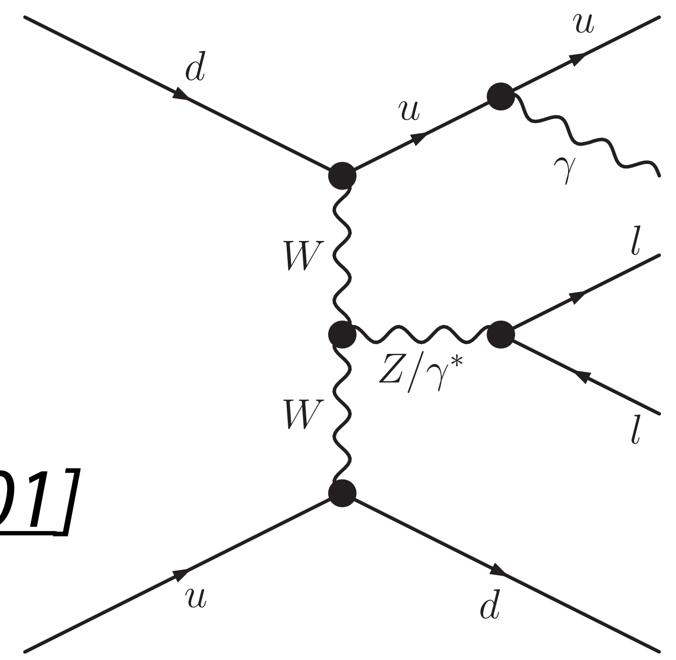
	Observed ($W^\pm W^\pm$) (TeV^{-4})	Expected ($W^\pm W^\pm$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-0.28, 0.31]	[-0.36, 0.39]	[-0.62, 0.65]	[-0.82, 0.85]	[-0.25, 0.28]	[-0.35, 0.37]
f_{T1}/Λ^4	[-0.12, 0.15]	[-0.16, 0.19]	[-0.37, 0.41]	[-0.49, 0.55]	[-0.12, 0.14]	[-0.16, 0.19]
f_{T2}/Λ^4	[-0.38, 0.50]	[-0.50, 0.63]	[-1.0 , 1.3]	[-1.4, 1.7]	[-0.35, 0.48]	[-0.49, 0.63]
f_{M0}/Λ^4	[-3.0, 3.2]	[-3.7, 3.8]	[-5.8, 5.8]	[-7.6, 7.6]	[-2.7, 2.9]	[-3.6, 3.7]
f_{M1}/Λ^4	[-4.7, 4.7]	[-5.4, 5.8]	[-8.2, 8.3]	[-11, 11]	[-4.1, 4.2]	[-5.2, 5.5]
f_{M6}/Λ^4	[-6.0, 6.5]	[-7.5, 7.6]	[-12, 12]	[-15, 15]	[-5.4, 5.8]	[-7.2, 7.3]
f_{M7}/Λ^4	[-6.7, 7.0]	[-8.3, 8.1]	[-10, 10]	[-14, 14]	[-5.7, 6.0]	[-7.8, 7.6]
f_{S0}/Λ^4	[-6.0, 6.4]	[-6.0, 6.2]	[-19, 19]	[-24, 24]	[-5.7, 6.1]	[-5.9, 6.2]
f_{S1}/Λ^4	[-18, 19]	[-18, 19]	[-30, 30]	[-38, 39]	[-16, 17]	[-18, 18]

Apply unitarity constraint

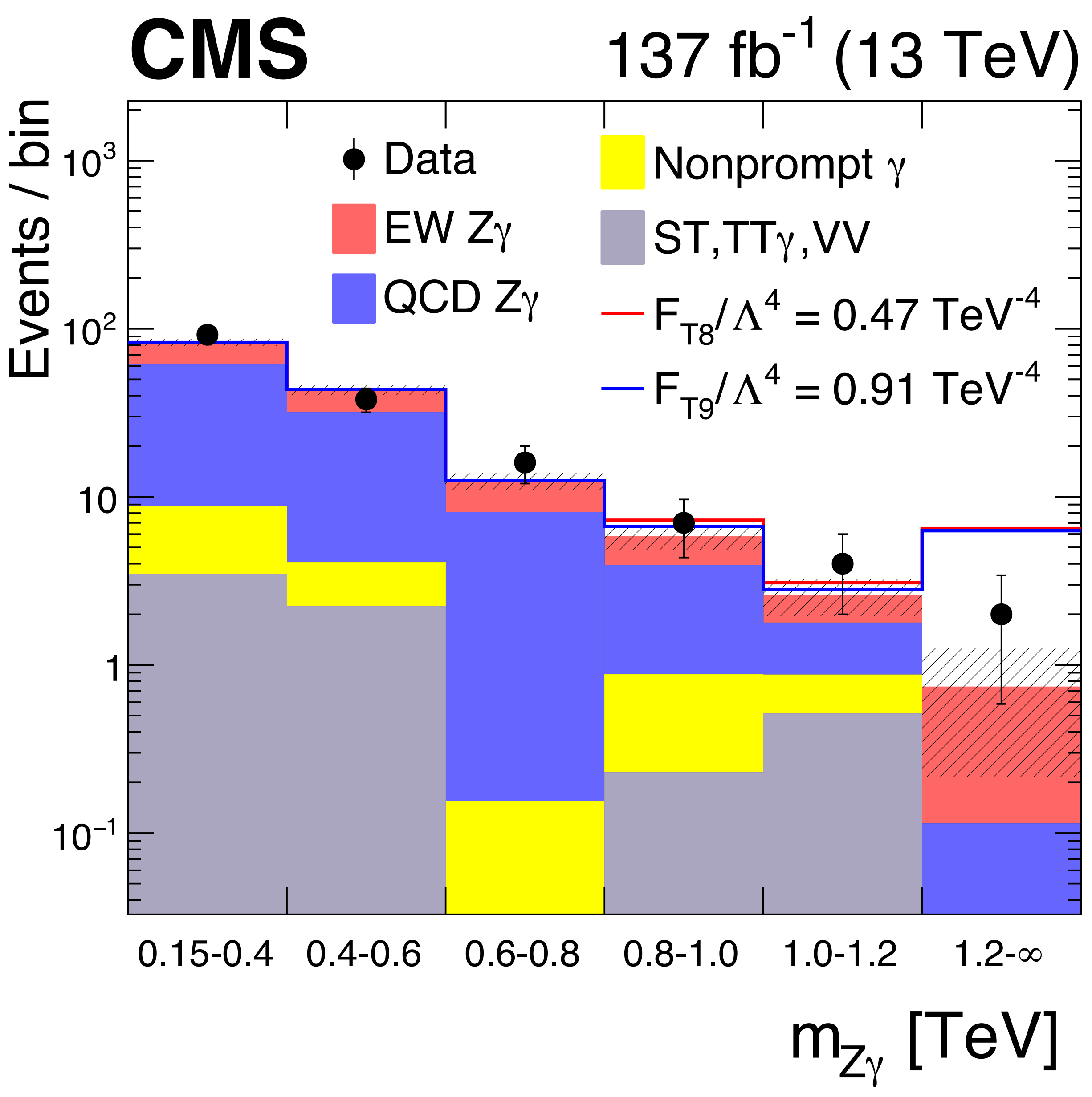
	Observed ($W^\pm W^\pm$) (TeV^{-4})	Expected ($W^\pm W^\pm$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-1.5, 2.3]	[-2.1, 2.7]	[-1.6, 1.9]	[-2.0, 2.2]	[-1.1, 1.6]	[-1.6, 2.0]
f_{T1}/Λ^4	[-0.81, 1.2]	[-0.98, 1.4]	[-1.3, 1.5]	[-1.6, 1.8]	[-0.69, 0.97]	[-0.94, 1.3]
f_{T2}/Λ^4	[-2.1, 4.4]	[-2.7, 5.3]	[-2.7, 3.4]	[-4.4, 5.5]	[-1.6, 3.1]	[-2.3, 3.8]
f_{M0}/Λ^4	[-13, 16]	[-19, 18]	[-16, 16]	[-19, 19]	[-11, 12]	[-15, 15]
f_{M1}/Λ^4	[-20, 19]	[-22, 25]	[-19, 20]	[-23, 24]	[-15, 14]	[-18, 20]
f_{M6}/Λ^4	[-27, 32]	[-37, 37]	[-34, 33]	[-39, 39]	[-22, 25]	[-31, 30]
f_{M7}/Λ^4	[-22, 24]	[-27, 25]	[-22, 22]	[-28, 28]	[-16, 18]	[-22, 21]
f_{S0}/Λ^4	[-35, 36]	[-31, 31]	[-83, 85]	[-88, 91]	[-34, 35]	[-31, 31]
f_{S1}/Λ^4	[-100, 120]	[-100, 110]	[-110, 110]	[-120, 130]	[-86, 99]	[-91, 97]

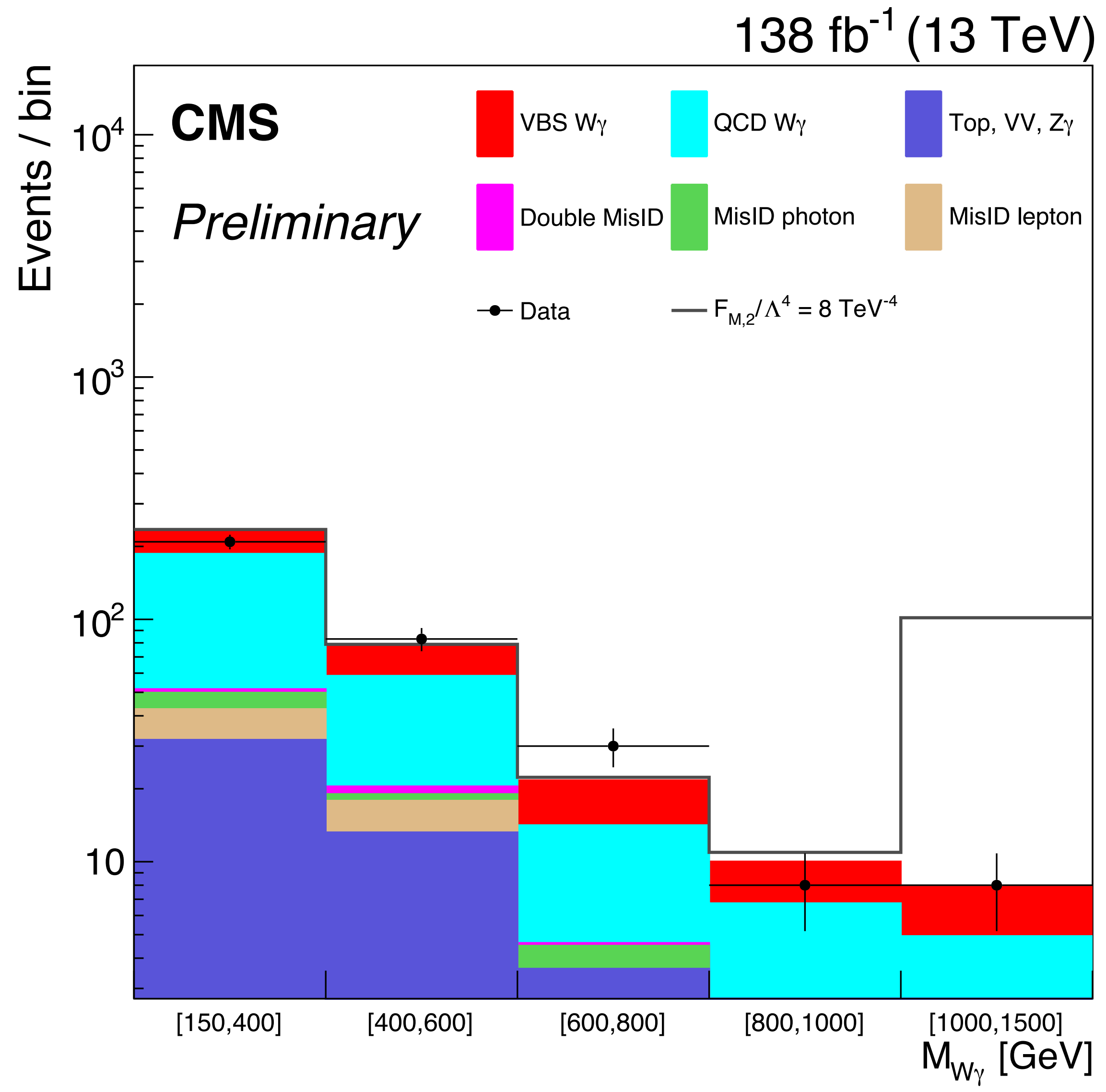
W(lν)γ / Z(ll)γ





[PRD 104 (2021) 072001]





[CMS-PAS-SMP-21-011]

Unitarity:
- No explicit clipping
- U_{bound} reported: scattering energy, given coupling of observed limit at which unitarity violated

Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
F_{M0}/Λ^4	−12.5	12.8	−15.8	16.0	1.3
F_{M1}/Λ^4	−28.1	27.0	−35.0	34.7	1.5
F_{M2}/Λ^4	−5.21	5.12	−6.55	6.49	1.5
F_{M3}/Λ^4	−10.2	10.3	−13.0	13.0	1.8
F_{M4}/Λ^4	−10.2	10.2	−13.0	12.7	1.7
F_{M5}/Λ^4	−17.6	16.8	−22.2	21.3	1.7
F_{M7}/Λ^4	−44.7	45.0	−56.6	55.9	1.6
F_{T0}/Λ^4	−0.52	0.44	−0.64	0.57	1.9
F_{T1}/Λ^4	−0.65	0.63	−0.81	0.90	2.0
F_{T2}/Λ^4	−1.36	1.21	−1.68	1.54	1.9
F_{T5}/Λ^4	−0.45	0.52	−0.58	0.64	2.2
F_{T6}/Λ^4	−1.02	1.07	−1.30	1.33	2.0
F_{T7}/Λ^4	−1.67	1.97	−2.15	2.43	2.2
F_{T8}/Λ^4	−0.36	0.36	−0.47	0.47	1.8
F_{T9}/Λ^4	−0.72	0.72	−0.91	0.91	1.9

Most stringent limits on **T8/T9**

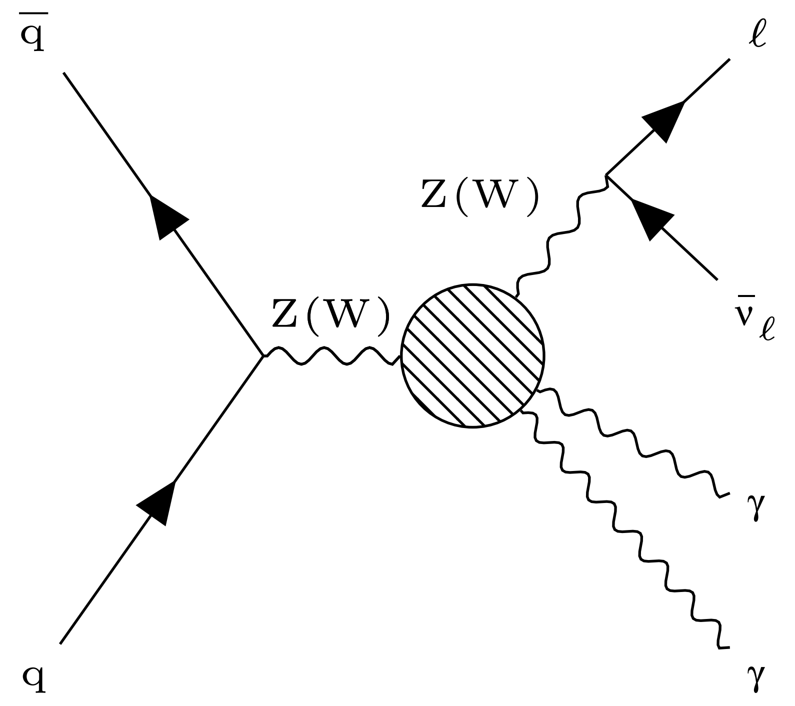
Most stringent limits on **M2-5, T6-7**

Expected. limit	Observed. limit	U_{bound}
$-5.1 < f_{M0}/\Lambda^4 < 5.1$	$-5.6 < f_{M0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M1}/\Lambda^4 < 7.4$	$-7.8 < f_{M1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M2}/\Lambda^4 < 1.8$	$-1.9 < f_{M2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M3}/\Lambda^4 < 2.5$	$-2.7 < f_{M3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M4}/\Lambda^4 < 3.3$	$-3.7 < f_{M4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M5}/\Lambda^4 < 3.6$	$-3.9 < f_{M5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T0}/\Lambda^4 < 0.51$	$-0.47 < f_{T0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T1}/\Lambda^4 < 0.31$	$-0.31 < f_{T1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T2}/\Lambda^4 < 0.92$	$-0.85 < f_{T2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T5}/\Lambda^4 < 0.31$	$-0.31 < f_{T5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T6}/\Lambda^4 < 0.25$	$-0.25 < f_{T6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T7}/\Lambda^4 < 0.68$	$-0.67 < f_{T7}/\Lambda^4 < 0.73$	3.1

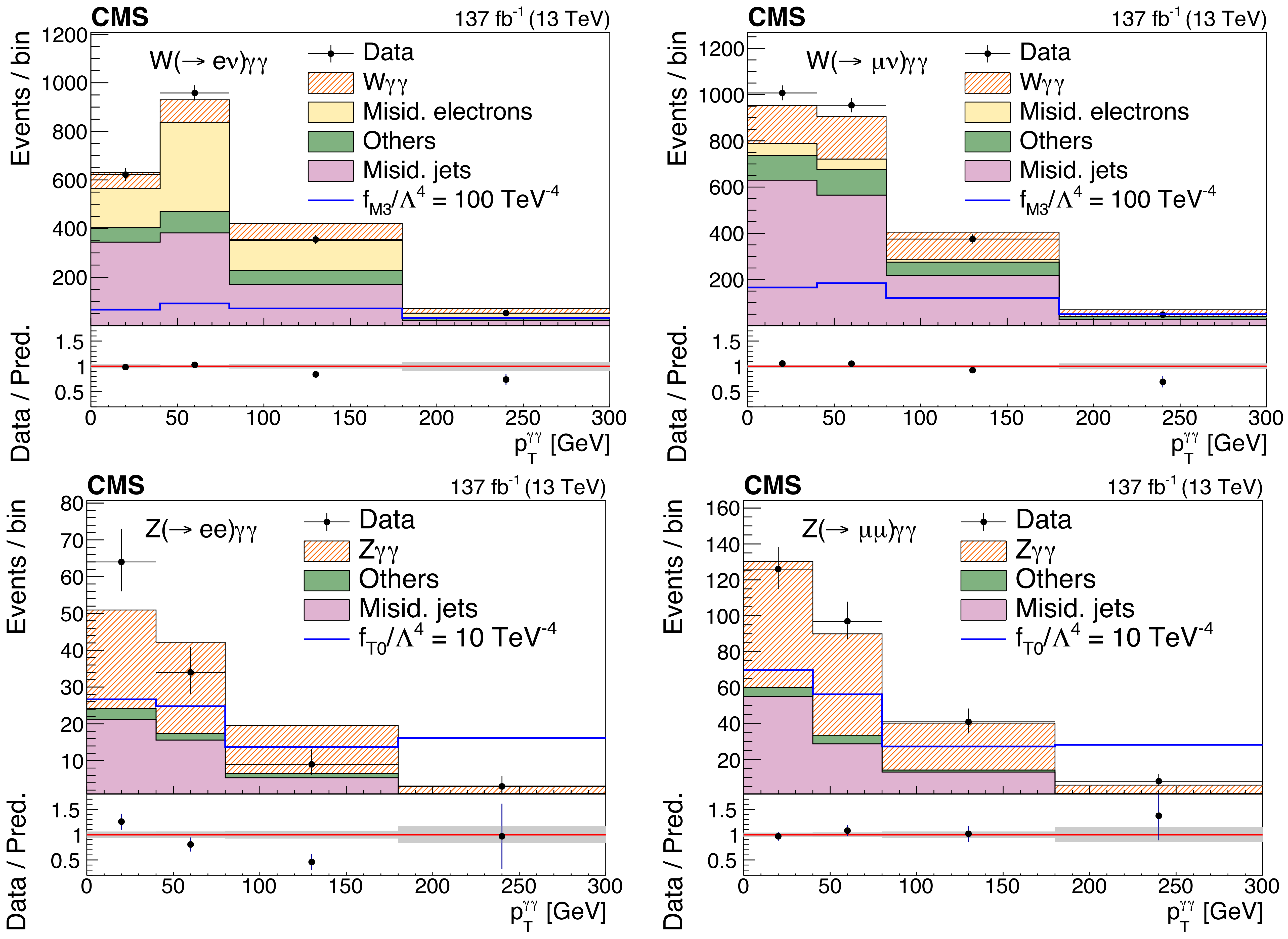
Tri-boson production

[JHEP 10 (2021) 174]

- Analysis target W(lν)γγ and Z(ll)γγ channels
- Complementary to VBS processes
  - Several parameter constraints competitive



Parameter	Wγγ (TeV^{-4}) Expected	Wγγ (TeV^{-4}) Observed	Zγγ (TeV^{-4}) Expected	Zγγ (TeV^{-4}) Observed
f_{M2}/Λ^4	[−57.3, 57.1]	[−39.9, 39.5]	—	—
f_{M3}/Λ^4	[−91.8, 92.6]	[−63.8, 65.0]	—	—
f_{T0}/Λ^4	[−1.86, 1.86]	[−1.30, 1.30]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T1}/Λ^4	[−2.38, 2.38]	[−1.70, 1.66]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T2}/Λ^4	[−5.16, 5.16]	[−3.64, 3.64]	[−9.72, 9.32]	[−11.4, 10.9]
f_{T5}/Λ^4	[−0.76, 0.84]	[−0.52, 0.60]	[−2.44, 2.52]	[−2.92, 2.92]
f_{T6}/Λ^4	[−0.92, 1.00]	[−0.60, 0.68]	[−3.24, 3.24]	[−3.80, 3.88]
f_{T7}/Λ^4	[−1.64, 1.72]	[−1.16, 1.16]	[−6.68, 6.60]	[−7.88, 7.72]
f_{T8}/Λ^4	—	—	[−0.90, 0.94]	[−1.06, 1.10]
f_{T9}/Λ^4	—	—	[−1.54, 1.54]	[−1.82, 1.82]

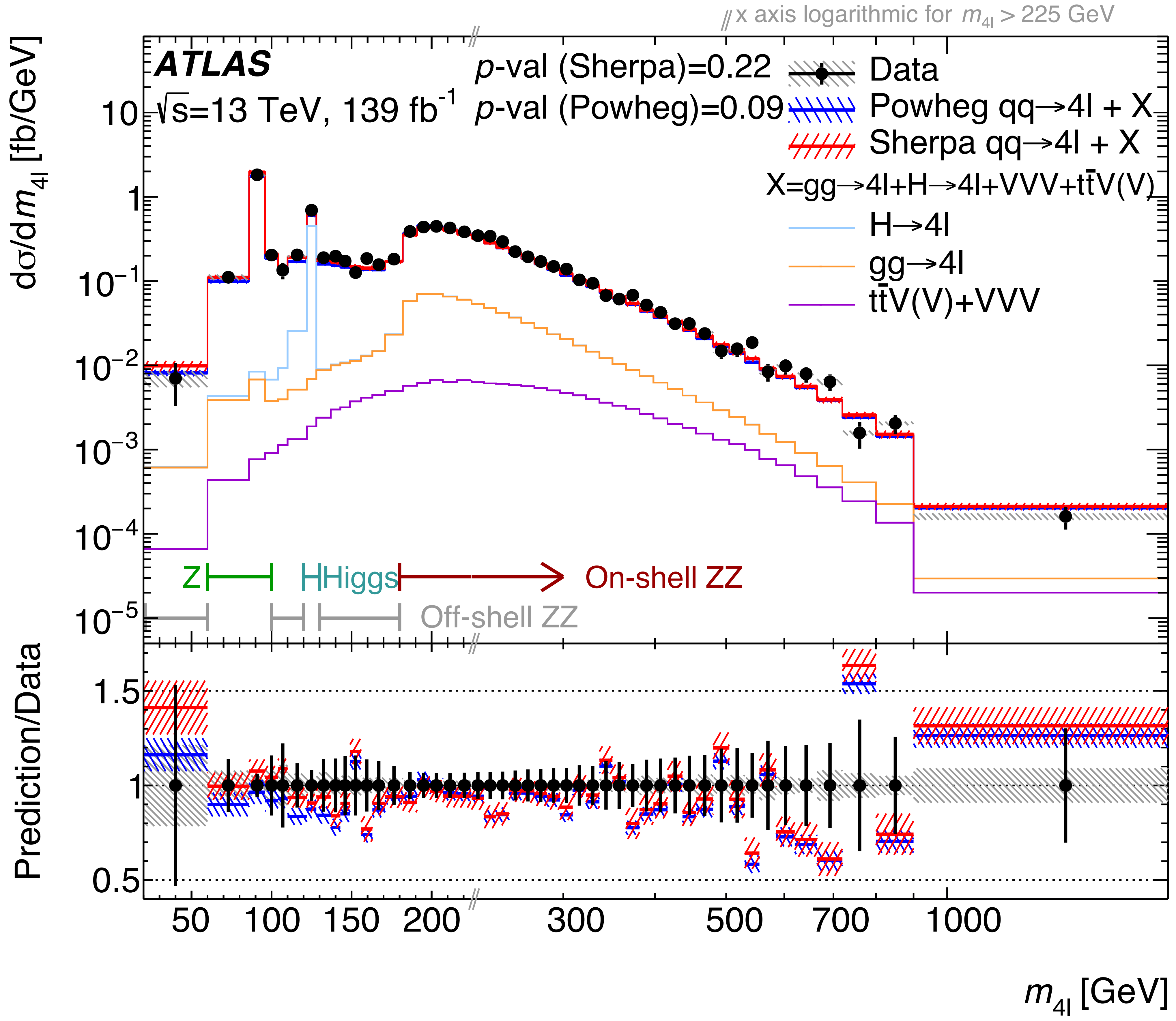


Global fits

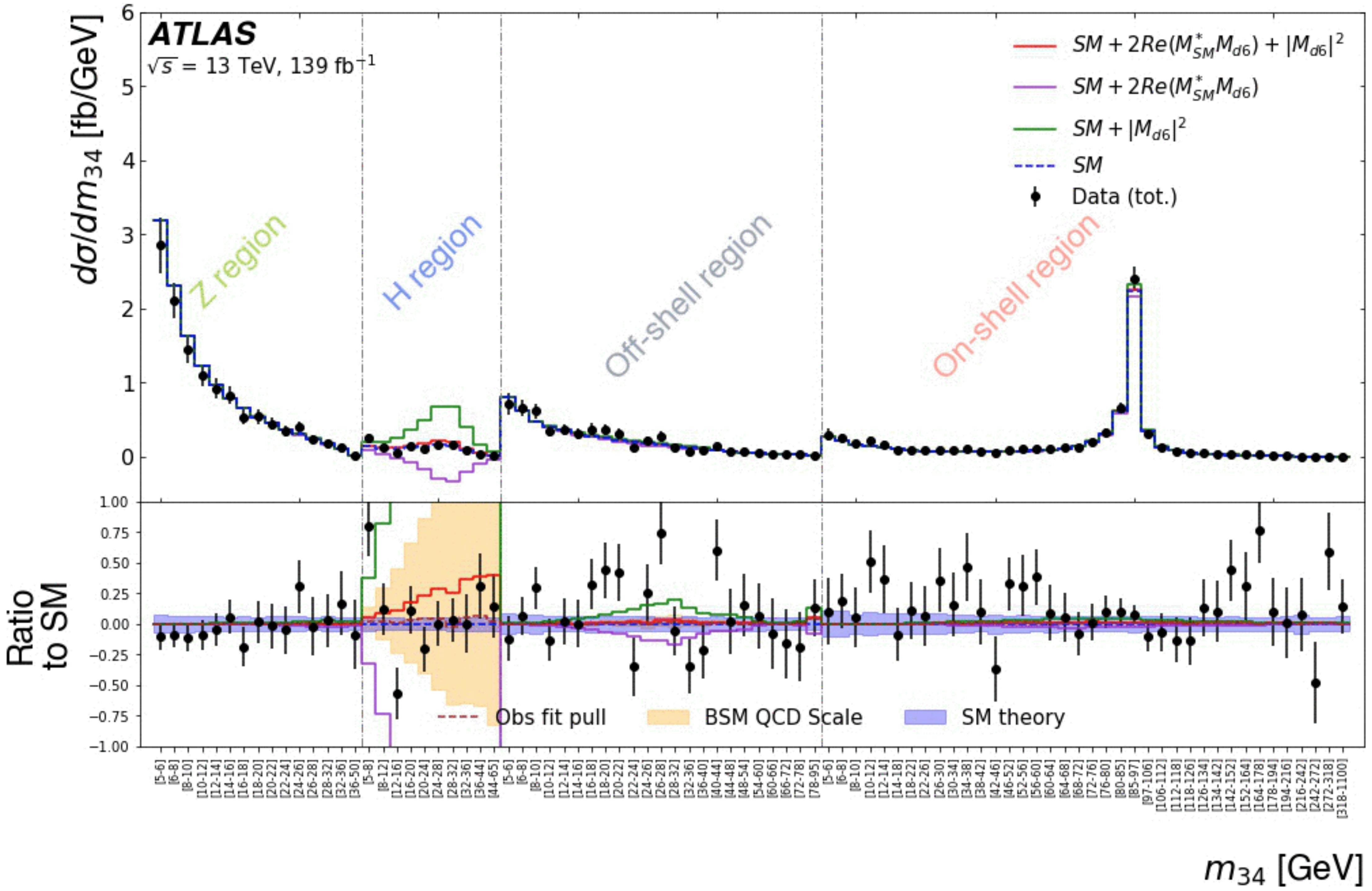
pp→4l

[JHEP 07 (2021) 005]

- Analysis considers all possible EFT contributions to 4l final state at dim-6
  - Not only triple gauge couplings
- Fit to the optimal unfolded observable for each operator, e.g. m_{34}:



$c_{HG} = -0.13$



- Many operators would create a similar pattern in the data
  - Not possible to determine all coefficients simultaneously
- Others are more strongly constrained elsewhere
  - E.g. Z→ll constraints from LEP precision measurements
- Strong motivation for combined EFT fits of multiple processes

pp→4l

[JHEP 07 (2021) 005]

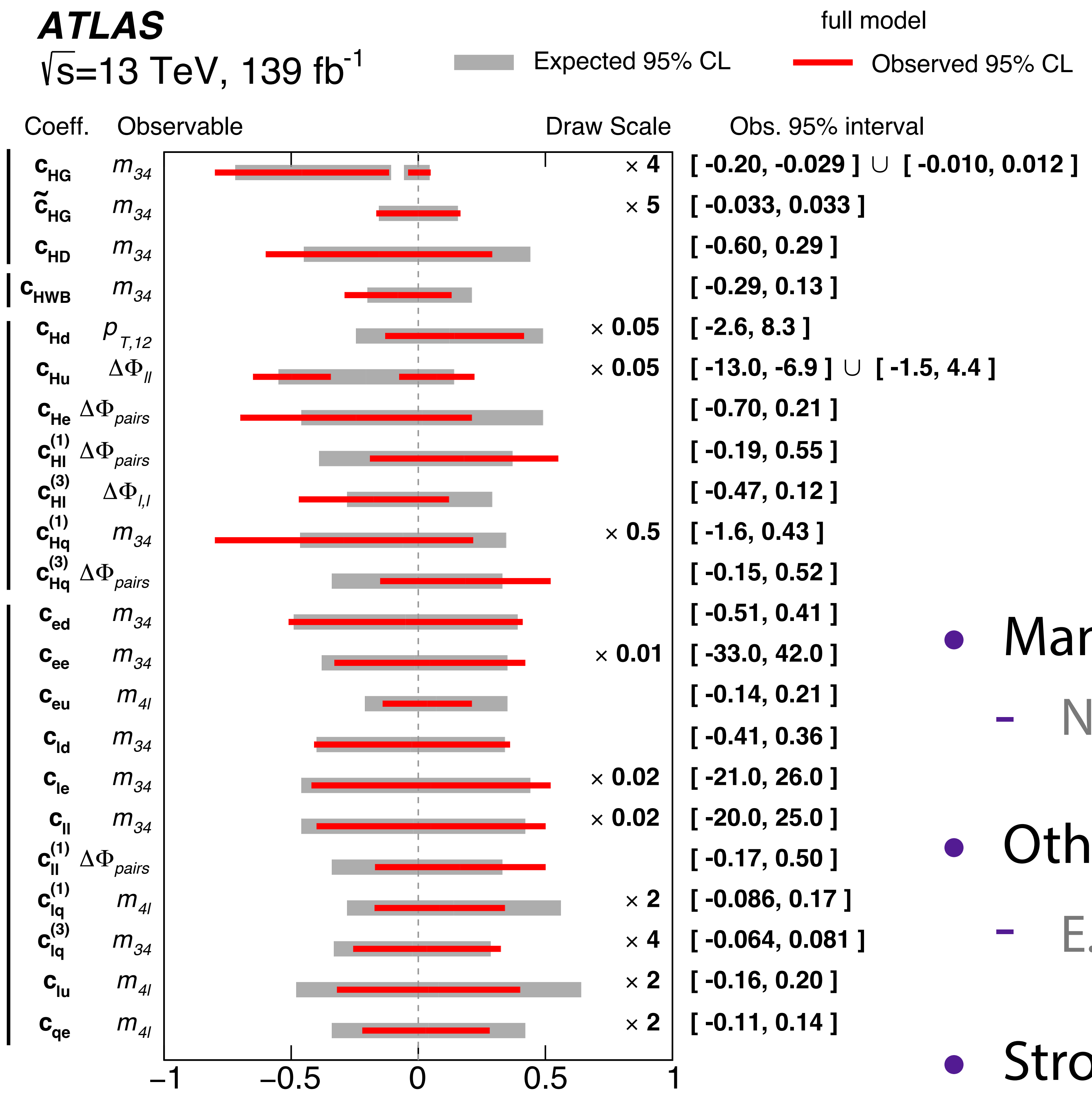
- Analysis considers all possible EFT contributions to 4l final state at dim-6
  - Not only triple gauge couplings
- Fit to the optimal unfolded observable for each operator, e.g. m_{34}:

Higgs couplings

Gauge boson couplings

Z→ll vertex

4-fermion interactions



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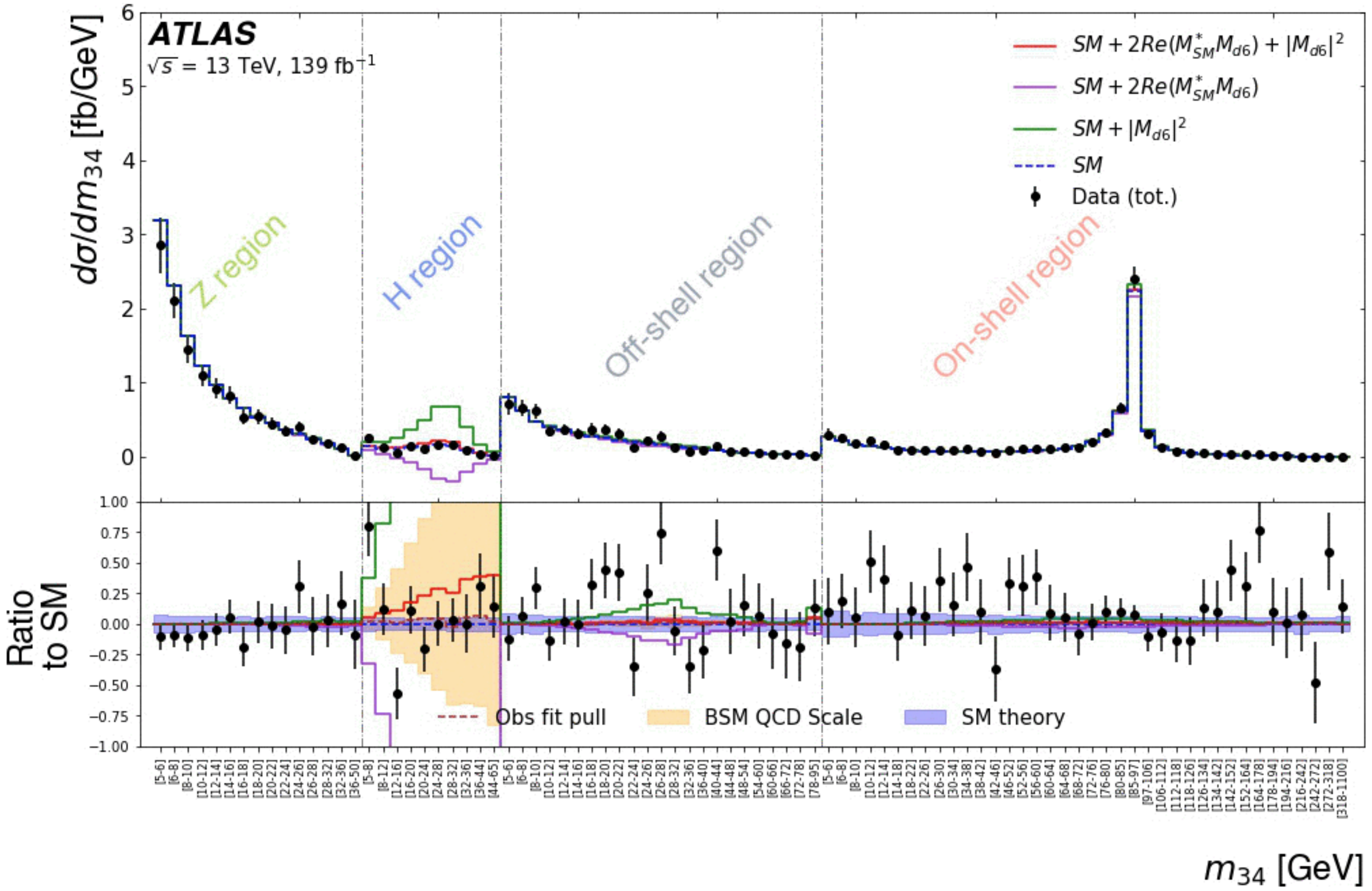

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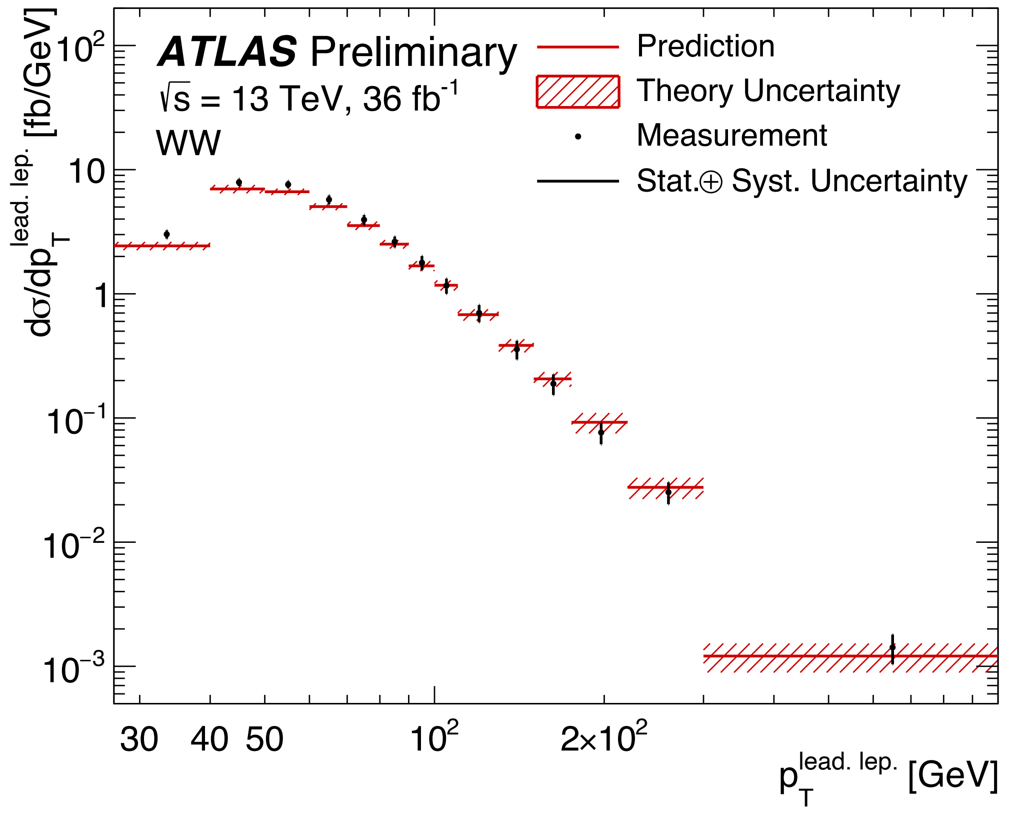
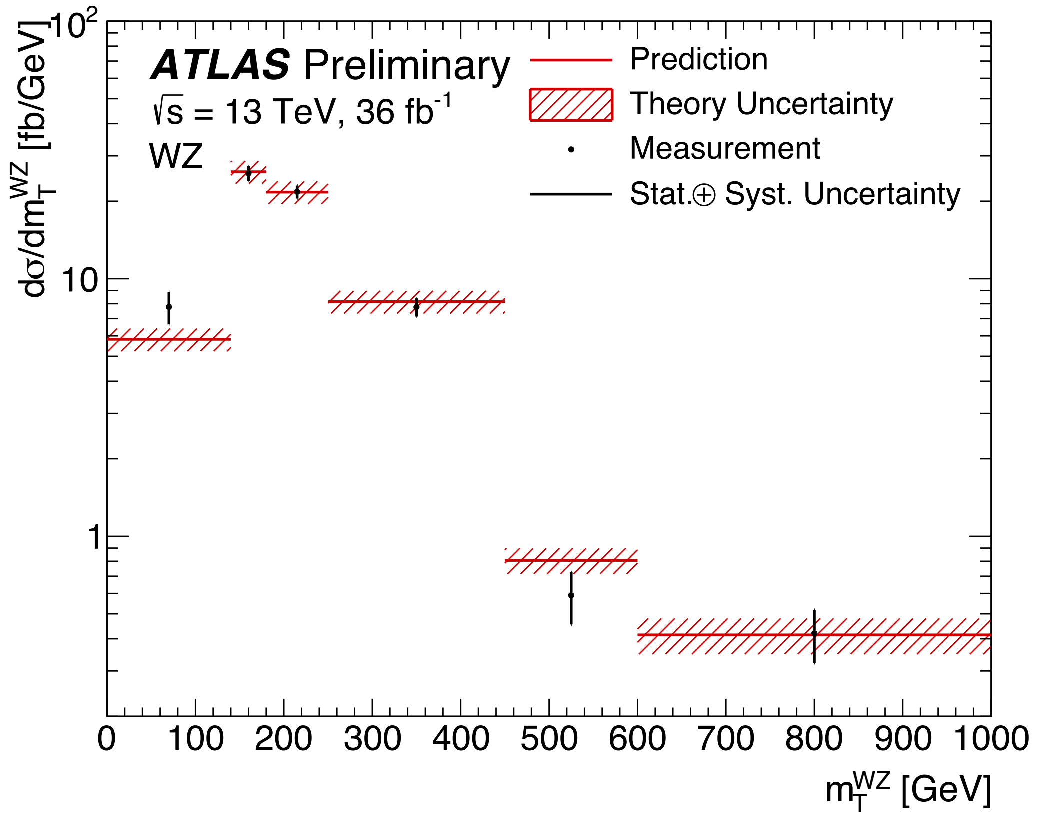
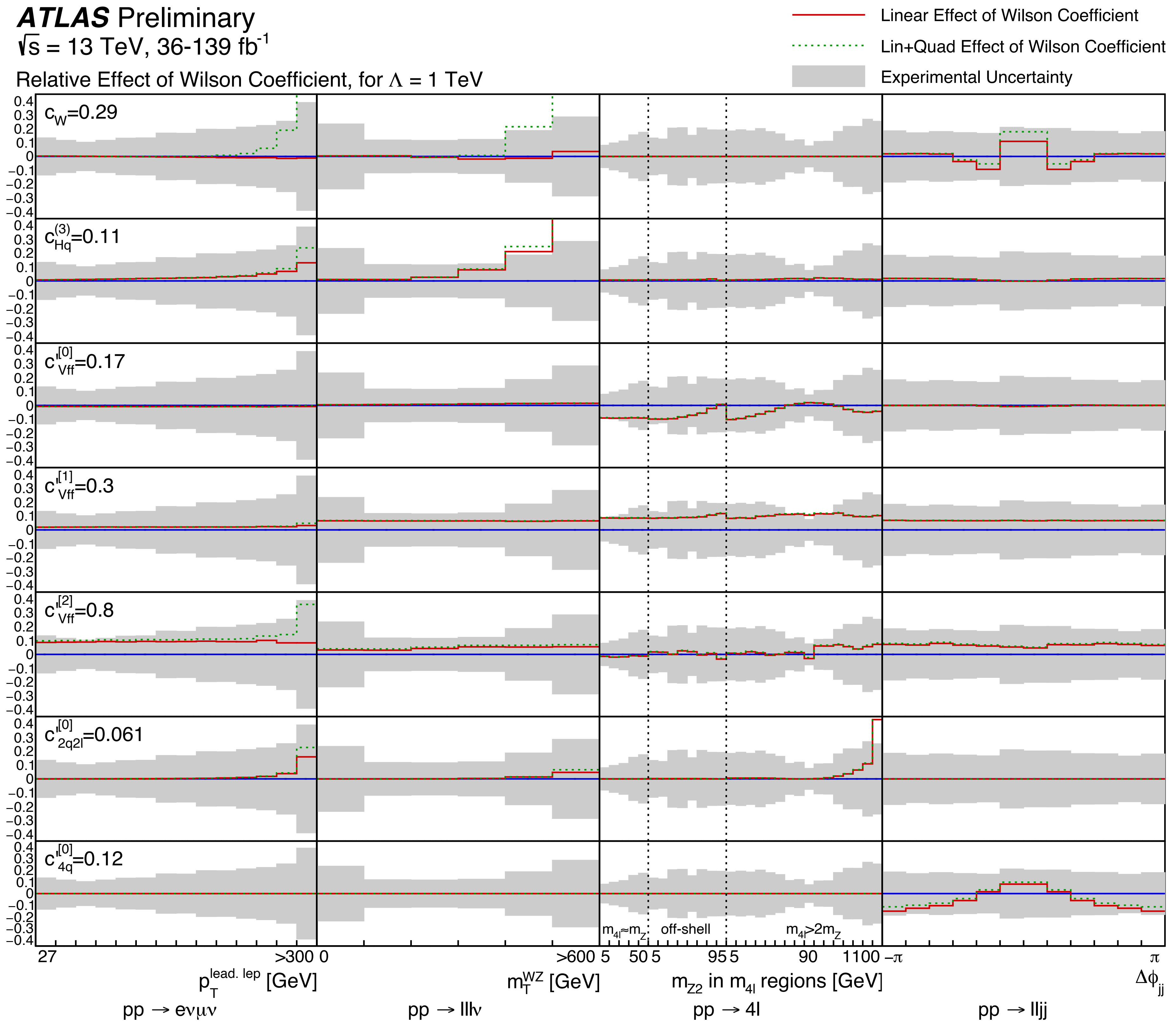
WW, WZ, 4l and Z+2-jet combination

[ATL-PHYS-PUB-2021-022]

- Combined likelihood fit to multiple channels and observables
  - Takes correlation of expt. & theory systematics into account
- Includes effect of 33 operators
  - Input analyses considered different subsets / bases / or no EFT at all ⇒ reinterpretation possible by intermediate unfolding step







Wilson coefficient and operator		Final state affected at leading order			
		$e^\pm\nu\mu^\mp\nu$	$\ell^+\ell^-\ell^\pm\nu$	4ℓ	$\ell^+\ell^-jj$
c_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$				✓
c_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	✓	✓		✓
c_{HD}	$\left(H^\dagger D_\mu H\right)^*\left(H^\dagger D_\mu H\right)$		✓	✓	✓
c_{HWB}	$H^\dagger\tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	✓	✓	✓	✓
$c_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$	✓	✓	✓	✓
$c_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}\tau^I\gamma^\mu l)$	✓	✓	✓	✓
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$		✓	✓	✓
$c_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$	✓	✓	✓	✓
$c_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}\tau^I\gamma^\mu q)$	✓	✓	✓	✓
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$	✓	✓	✓	✓
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$	✓	✓	✓	✓
$c_{ll}^{(1)}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	✓	✓	✓	✓
$c_{lq}^{(1)}$	$(\bar{l}\gamma_\mu l)(\bar{q}\gamma^\mu q)$	✓	✓	✓	(✓)
$c_{lq}^{(3)}$	$(\bar{l}\gamma_\mu\tau^I l)(\bar{q}\gamma^\mu\tau^I q)$	✓	✓	✓	(✓)
c_{eu}	$(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)$			✓	(✓)
c_{ed}	$(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)$			✓	(✓)
c_{lu}	$(\bar{l}\gamma_\mu l)(\bar{u}\gamma^\mu u)$	✓		✓	(✓)
c_{ld}	$(\bar{l}\gamma_\mu l)(\bar{d}\gamma^\mu d)$	✓		✓	(✓)
c_{qe}	$(\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)$		✓	✓	(✓)
$c_{qq}^{(1,1)}$	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$				✓
$c_{qq}^{(1,8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{q}T^a\gamma^\mu q)$				✓
$c_{qq}^{(3,1)}$	$(\bar{q}\sigma^i\gamma_\mu q)(\bar{q}\sigma^i\gamma^\mu q)$				✓
$c_{qq}^{(3,8)}$	$(\bar{q}\sigma^i T^a\gamma_\mu q)(\bar{q}\sigma^i T^a\gamma^\mu q)$				✓
$c_{uu}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$				✓
$c_{uu}^{(8)}$	$(\bar{u}T^a\gamma_\mu u)(\bar{u}T^a\gamma^\mu u)$				✓
$c_{dd}^{(1)}$	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)$				✓
$c_{dd}^{(8)}$	$(\bar{d}T^a\gamma_\mu d)(\bar{d}T^a\gamma^\mu d)$				✓
$c_{ud}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)$				✓
$c_{ud}^{(8)}$	$(\bar{u}T^a\gamma_\mu u)(\bar{d}T^a\gamma^\mu d)$				✓
$c_{qu}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)$				✓
$c_{qu}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{u}T^a\gamma^\mu u)$				✓
$c_{qd}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d)$				✓
$c_{qd}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{d}T^a\gamma^\mu d)$				✓

WW, WZ, 4l and Z+2-jet combination

[ATL-PHYS-PUB-2021-022]

- Not possible to constrain all parameters simultaneously
- One solution is to identify a set of linear combinations
  - Eigenvector decomposition of the EFT approx. Hessian, from propagating linearised EFT parameterisation to measurement Hessian
  - Drop poorly constrained directions with small eigenvalues - impact on fitted ones verified to be negligible

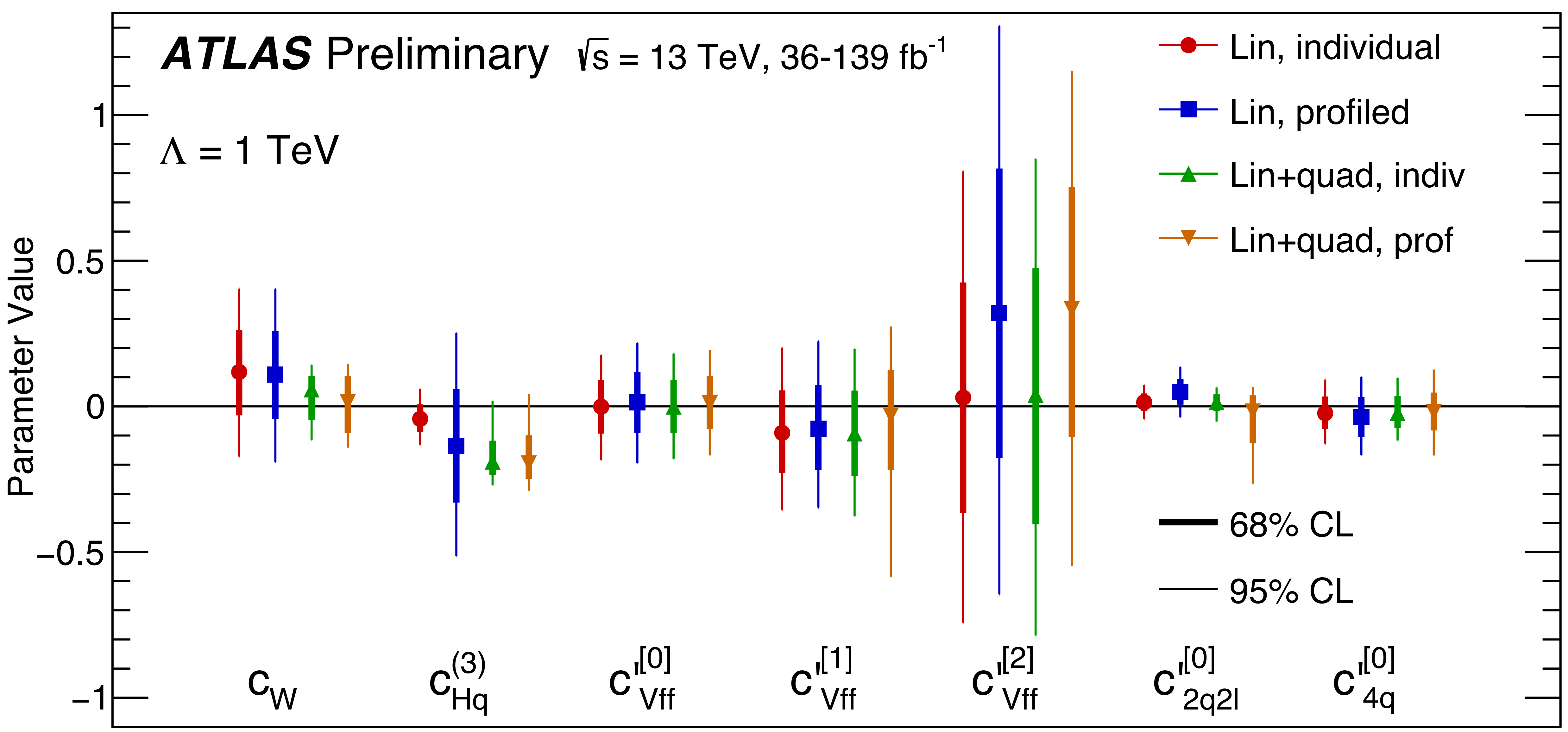
ATLAS Preliminary $\sqrt{s}$ = 13 TeV, 36-139 fb^{-1}

#	σ	c_W	$c_{Hq}^{(3)}$	c_{HWB}	c_{HD}	$c_{Hl}^{(1)}$	$c_{Hl}^{(3)}$	c_{He}	$c_{ll}^{(1)}$	$c_{Hq}^{(1)}$	c_{Hu}	c_{Hd}	$c_{lq}^{(1)}$	$c_{lq}^{(3)}$	c_{lu}	c_{ld}	c_{eu}	c_{ed}	c_{qe}	$c_{qq}^{(11)}$	$c_{qq}^{(18)}$	$c_{qq}^{(31)}$	$c_{qq}^{(38)}$	$c_{uu}^{(1)}$	$c_{uu}^{(8)}$	$c_{dd}^{(1)}$	$c_{dd}^{(8)}$	$c_{ud}^{(1)}$	$c_{ud}^{(8)}$	$c_{qu}^{(1)}$	$c_{qu}^{(8)}$	$c_{qd}^{(1)}$	$c_{qd}^{(8)}$	c_G
0	0.0295		0.11	-0.01			-0.02		0.01				-0.37	0.88	-0.10	0.03	-0.21	0.04	-0.12															
1	0.0494		0.94	0.07	0.02	0.04		-0.03	0.02	0.01			0.09	-0.05	0.02		0.06	-0.01	0.03	-0.03	-0.06	-0.28	0.06											
2	0.0577	-0.02	0.30	-0.02									0.03				0.02		0.01	0.11	0.21	0.90	-0.19											
3	0.0869	-0.02	-0.07	0.80	0.38	0.13	0.37	-0.08	-0.14	0.12	-0.06	0.02	-0.02	0.02								0.03												
4	0.15	0.76	0.03		0.02	-0.47	0.19	0.31	-0.26	-0.08	0.03	-0.02	0.01	0.01																				
5	0.151	0.65	-0.03	0.01	-0.02	0.56	-0.20	-0.37	0.28	0.11	-0.04	0.02										0.02												
6	0.371	-0.02	-0.05	-0.23	-0.09	0.16	0.27	-0.11	-0.33	0.35	0.16	-0.05	0.29	0.30	-0.07	0.03	0.53	-0.09	0.32			-0.02												
7	0.406	-0.01	0.06	-0.29	-0.17	0.25	0.48	-0.24	-0.46	-0.06	-0.20	0.07	-0.33	-0.22	0.01	-0.02	-0.29	0.04	-0.15															
8	0.8		-0.02	-0.23	0.34	0.34	0.22	0.31	0.05	-0.36	-0.09	0.05	0.56	0.18	0.13		-0.19	0.07	-0.15															
9	1.09		0.02	-0.19	0.09	-0.09	0.35	0.25	0.48	0.66	-0.26		-0.06	-0.06	0.04	-0.02	-0.10		-0.09		0.01	-0.02	-0.04								0.02			
10	1.4			-0.05	-0.04	-0.11	0.50	-0.19	0.51	-0.49	0.08	0.06	-0.19		-0.12	0.02	0.28	-0.05	0.22				-0.01											
11	2.09		-0.02	0.11	-0.32	-0.37	0.11	-0.52	0.07	0.05	-0.15	0.10	0.53	0.14		0.06	-0.32	0.11	-0.05		0.01	-0.01	-0.04								0.02			
12	2.34		0.02	-0.32	0.73	-0.25	-0.06	-0.44	-0.05	0.08	0.26	-0.08	-0.07	-0.05	0.03	0.02	-0.11	0.04	0.03	-0.02				-0.01							-0.03		-0.01	
13	2.82			0.07	-0.22	0.10	0.21	0.08	0.10	0.10	0.81	-0.27	0.04	-0.06	0.15	0.02	-0.25	0.08	-0.18		0.01	-0.02	-0.08								0.03		0.01	
14	5.29				-0.04		0.05		0.04	0.03	0.01	-0.13	0.02		0.02	0.01	-0.05	0.02	0.02	-0.19	-0.21	0.26	0.89	-0.06	-0.02				-0.02	-0.02	-0.16		-0.08	
15	6.68		-0.02		-0.04	-0.10	0.03	-0.17	0.01	-0.06	-0.10	-0.16	-0.03	0.10	0.62	-0.34	0.34	-0.26	-0.47	-0.01	0.03													

WW, WZ, 4l and Z+2-jet combination

[ATL-PHYS-PUB-2021-022]

- Result: fit for 15 linear combinations of operators, both one at a time, and all profiled together
  - In many case sensitivity is similar ⇒ justifies eigenvector approach
  - Limits also given with and without quadratic terms



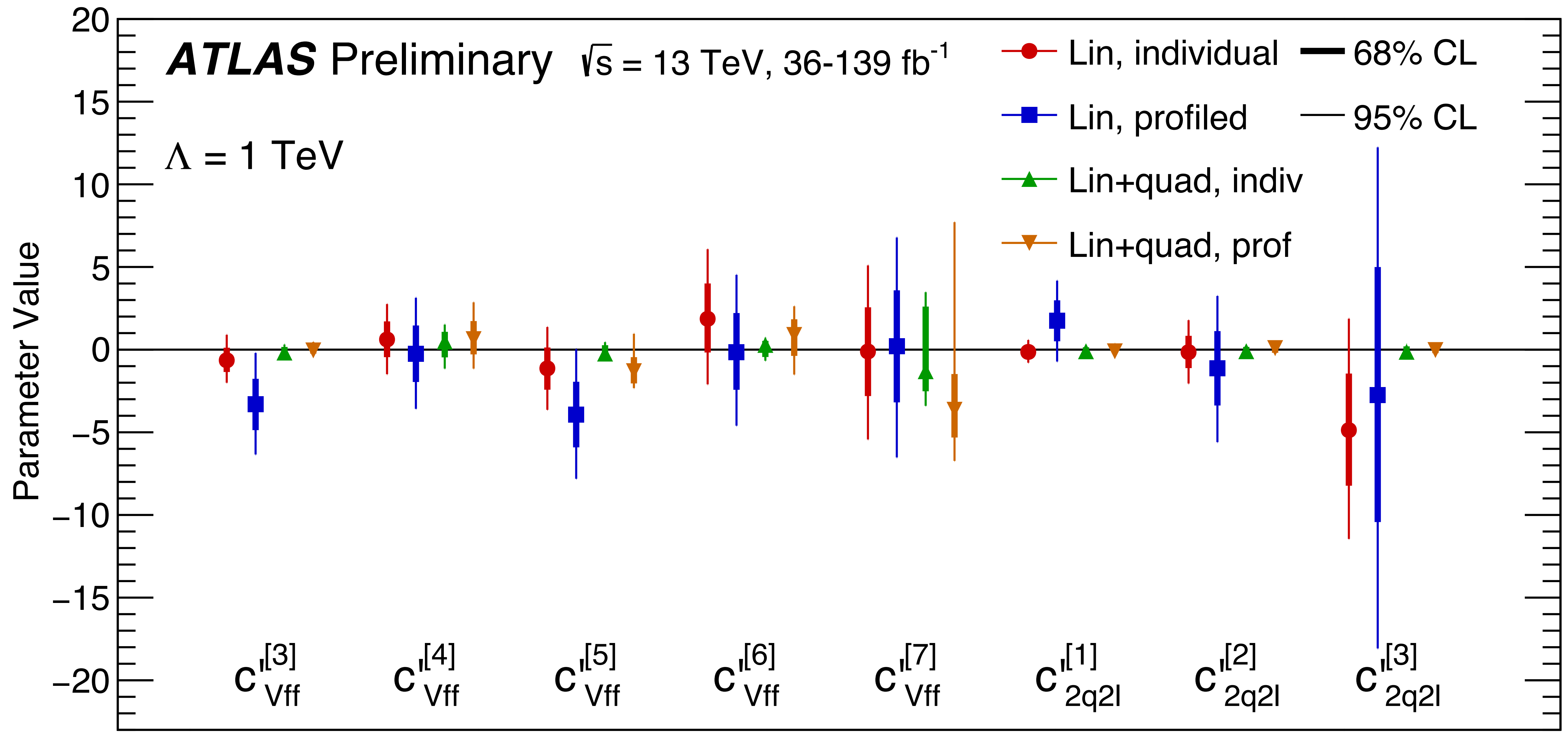
$c'^{[0]}_{Vff} \approx 0.81c_{HWB} + 0.38c_{HD} + 0.13c^{(1)}_{Hl} + 0.37c^{(3)}_{Hl} - 0.14c^{(1)}_{ll} + 0.12c^{(1)}_{Hq}$

$c'^{[1]}_{Vff} \approx 0.73c^{(1)}_{Hl} - 0.28c^{(3)}_{Hl} - 0.48c_{He} + 0.38c^{(1)}_{ll} + 0.13c^{(1)}_{Hq}$

$c'^{[2]}_{Vff} \approx 0.37c_{HWB} + 0.17c_{HD} - 0.31c^{(1)}_{Hl} - 0.53c^{(3)}_{Hl} + 0.25c_{He} + 0.59c^{(1)}_{ll} - 0.21c^{(1)}_{Hq}$

$c'^{[0]}_{2q2l} \approx -0.37c^{(1)}_{lq} + 0.89c^{(3)}_{lq} - 0.11c_{lu} - 0.21c_{eu} - 0.13c_{qe}$

$c'^{[0]}_{4q} \approx 0.11c^{(11)}_{qq} + 0.22c^{(18)}_{qq} + 0.95c^{(31)}_{qq} - 0.2c^{(38)}_{qq}$



$c'^{[3]}_{Vff} \approx -0.19c^{(1)}_{Hl} - 0.14c^{(3)}_{Hl} + 0.86c^{(1)}_{Hq} + 0.41c_{Hu} - 0.17c_{Hd}$

$c'^{[4]}_{Vff} \approx -0.35c_{HWB} + 0.49c_{HD} + 0.26c^{(1)}_{Hl} + 0.35c^{(3)}_{Hl} + 0.51c_{He} + 0.38c^{(1)}_{ll} + 0.18c^{(1)}_{Hq}$

$c'^{[5]}_{Vff} \approx 0.25c_{HD} + 0.33c^{(1)}_{Hl} - 0.22c^{(3)}_{Hl} + 0.18c_{He} - 0.35c^{(1)}_{ll} - 0.3c^{(1)}_{Hq} + 0.71c_{Hu} - 0.16c_{Hd}$

$c'^{[6]}_{Vff} \approx -0.22c^{(1)}_{Hl} + 0.52c^{(3)}_{Hl} - 0.39c_{He} + 0.44c^{(1)}_{ll} - 0.22c^{(1)}_{Hq} + 0.52c_{Hu}$

$c'^{[7]}_{Vff} \approx -0.28c_{HWB} + 0.71c_{HD} - 0.31c^{(1)}_{Hl} - 0.21c^{(3)}_{Hl} - 0.5c_{He} - 0.14c^{(1)}_{ll}$

$c'^{[1]}_{2q2l} \approx 0.56c^{(1)}_{lq} + 0.44c^{(3)}_{lq} + 0.61c_{eu} - 0.1c_{ed} + 0.34c_{qe}$

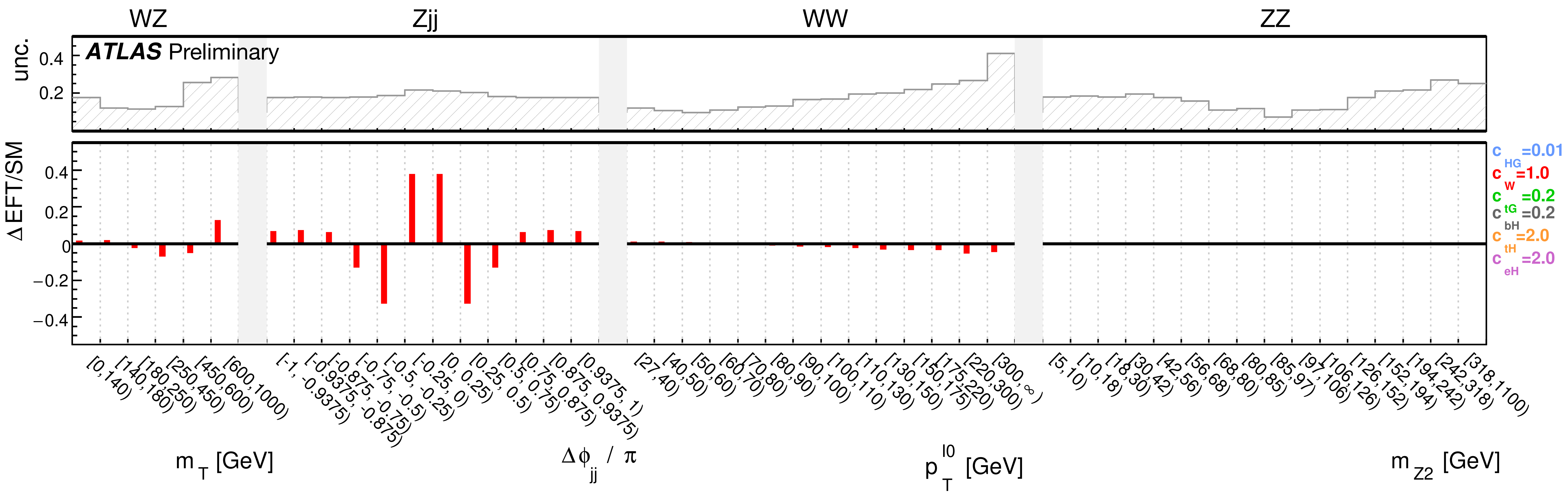
$c'^{[2]}_{2q2l} \approx 0.68c^{(1)}_{lq} + 0.15c^{(3)}_{lq} + 0.33c_{lu} - 0.51c_{eu} + 0.13c_{ed} - 0.37c_{qe}$

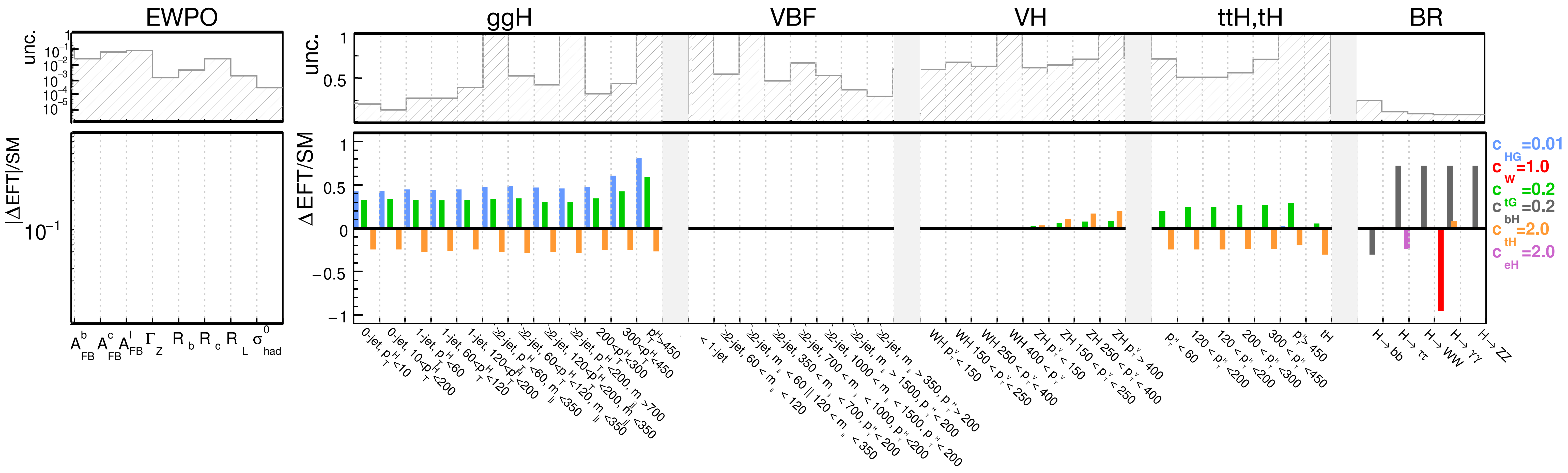
$c'^{[3]}_{2q2l} \approx -0.27c^{(1)}_{lq} + 0.79c_{lu} - 0.39c_{ld} + 0.26c_{eu} - 0.22c_{ed} - 0.16c_{qe}$

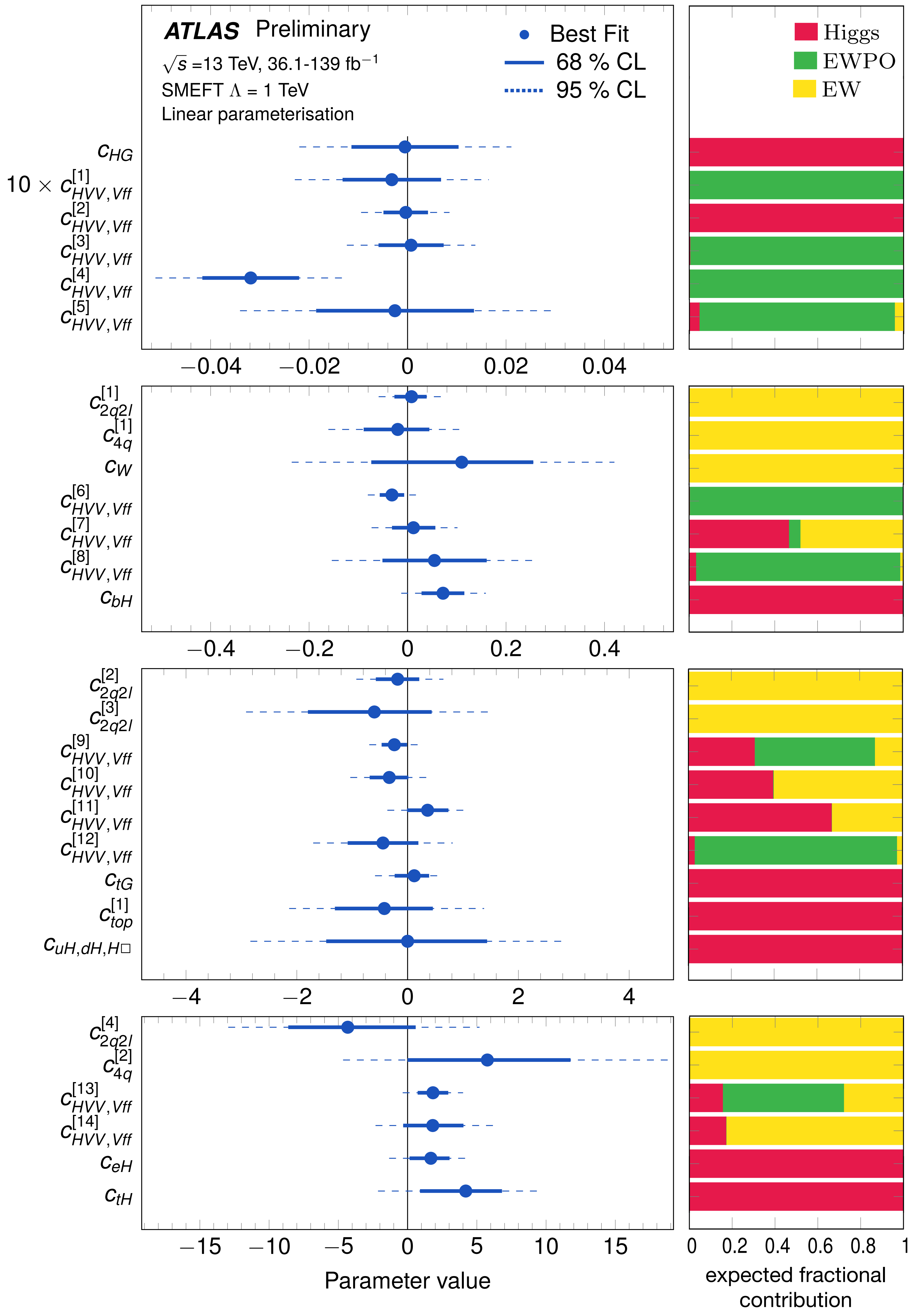
One step further

[ATL-PHYS-PUB-2022-037]

- Combination of multiboson, LEP EWPOs and Higgs simplified template cross section measurements ⇒ fit for 28 linear combinations
  - Clear complementarity for many of the operators considered







(Some) open issues for the EFT interpretation

- Is the way in which we make our EFT measurements useful for future (re-)interpretation?
  - If not, what additional steps or approaches should we use?
  - Is there additional information we need to publish, e.g. full likelihoods? Unfolded distributions?
- Distinction between signal and background? Should consider EFT effects in both
- What should be the default presentation of results - include dim6^2 or not?
  - If neglected, take care of fitting regions where $\sigma_{\mathrm{SM}} + C_i \sigma_{\mathrm{int}} < 0$
- **EFT validity**: a BSM model including a new state with mass *M* naturally limits validity to *E* < *M*
  - Should also verify that unitarity not violated at probed $\sqrt{\hat{s}}$ for given c/Λ^2
  - Can necessitate "clipping" of the data (or the prediction) - no completely standard approach for this
- **Truncation uncertainty**: how to estimate impact of missing dim8 terms?
- Combined fits with dim-6 and dim-8 a possibility?

Summary

- ATLAS and CMS have performed extensive measurements of multi-boson processes, with strong constraints on:
  - Anomalous (neutral) triple gauge couplings and anomalous quartic gauge couplings
- SMEFT becoming a common tool for the interpretation of these measurements
  - Consistently includes all possible NP effects at a given order in the EFT expansion
- EFT operators typically affect multiple processes, and any given process is affected by multiple operators
  - Strong motivation for global fits
  - Close collaboration between experiments and theory required