Dimension-8 EFT interpretation for the EWK production of ZZjj in the four-lepton channel

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Alexandros Marantis

Hellenic Open University

GENERAL SECRETARIAT FOR RESEARCH AND TECHNOLOGY

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Outline

Measurements of differential cross-sections for the EWK production of $ZZjj \rightarrow 4ljj$ in 13 TeV p-p collisions with the ATLAS detector

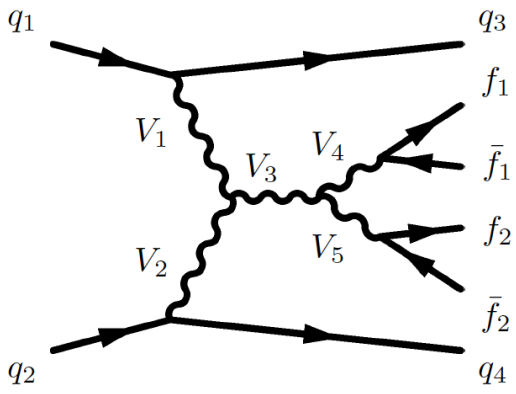
- EWK – QCD Tree-Level Feynman diagrams
- Event Selection
- Event Categorization - Observables

Anomalous Quartic Gauge Couplings (aQGC)

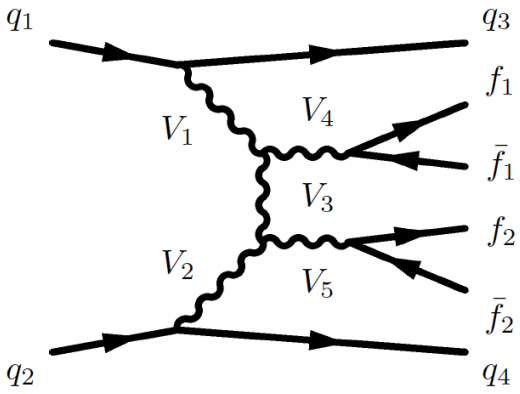
- Decomposition method
- Sensitivity of QGC operators
- Expected limits at detector-level
- Unitarity violation: Clipping Scan

Electroweak (EWK) signal

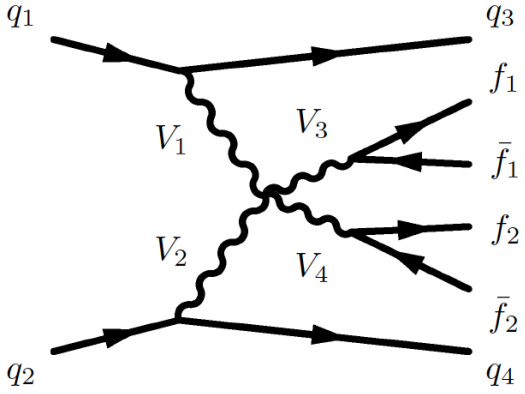
Measurement of Vector Boson pair production provides an excellent test of the ElectroWeaK Symmetry Breaking (EWKSB) sector of the Standard Model (SM).
The VBS topology consists of two high energy jets in the back and forward regions, with two vector bosons.



TGC vertex in s-channel

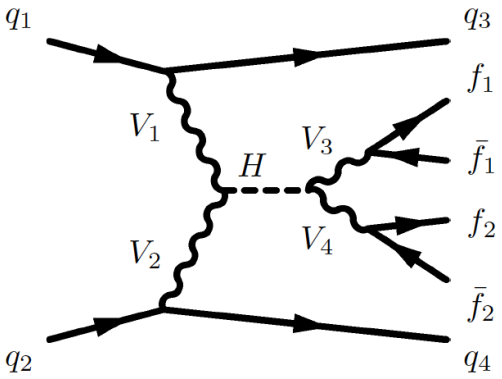


TGC vertex t-channel

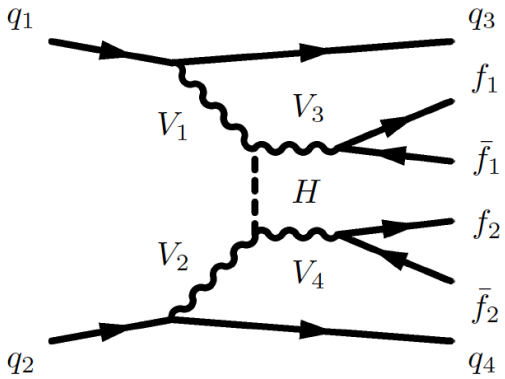


QGC vertex

Quartic Gauge Couplings (QGCs)
- Only charged QGCs allowed at SM tree-level (WWWW, WWZZ, WWZγ, WWγγ)
- Constraint on anomalous QGCs



Higgs boson exchange in s-channel

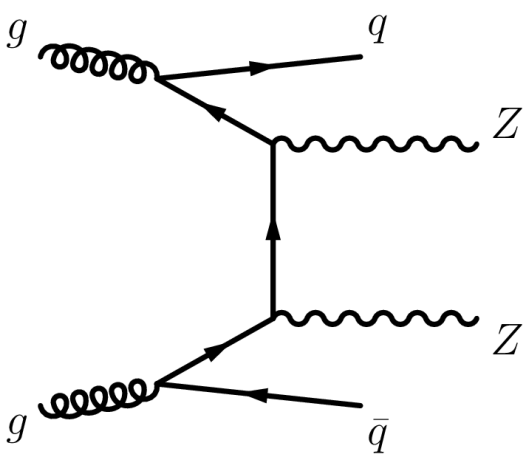


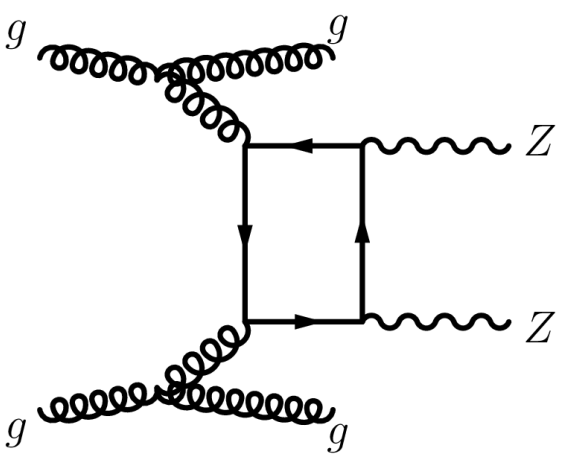
Higgs boson exchange in t-channel

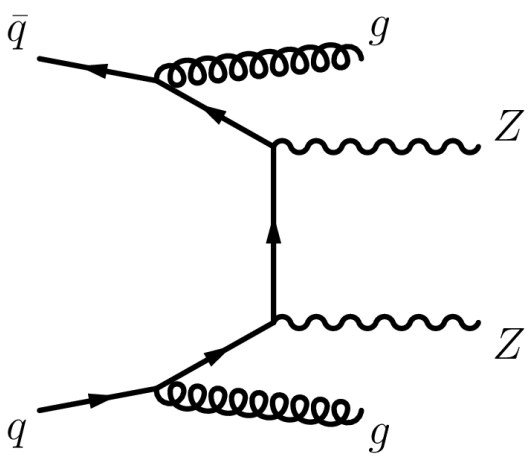
Crucial channel for Higgs discovery
- A precision measurement helps in Higgs property measurement
- Search of high mass Higgs bosons
- Proves the SM Higgs mechanism

Quantum Chromodynamics (QCD) background

The main background processes for the ZZjj → $llljj$ VBS channels are the QCD ZZjj component and the fake (misidentified leptons) background.







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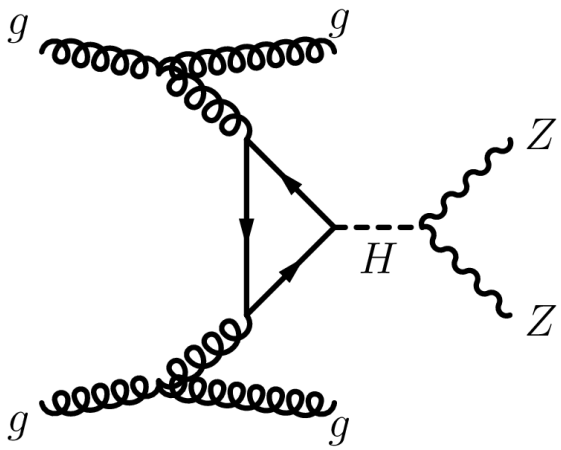
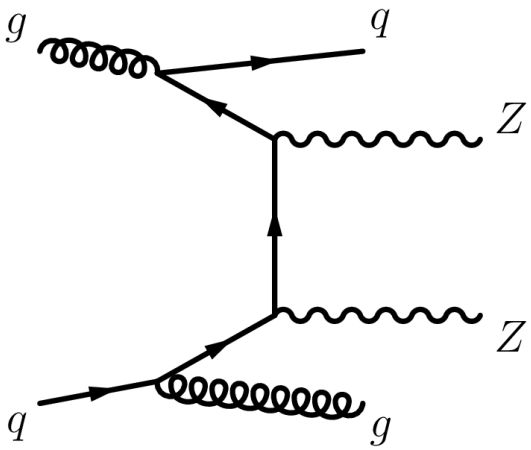
Fake background:

- $Z + jets$
- $\bar{t}t$





Small contributions from non-prompt backgrounds, from fake leptons from Z+jets and top processes. When looking at the EWK processes alone, the QCD component becomes the major background and a QCD-enriched control region is defined to constrain the contribution.

Event Selection

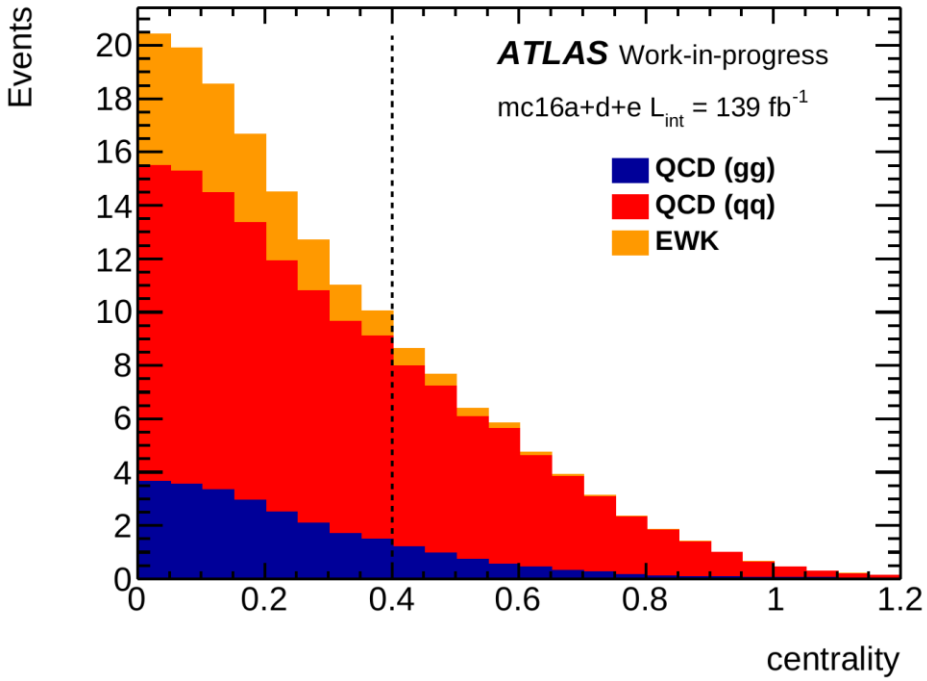
Event Selection	Cut	Requirement
Event Preselection	Trigger Vertex	Fire at least one lepton trigger At least one vertex with 2 or more tracks
Dressed object kinematics	Lepton Kinematics	$\boldsymbol{p_T^e > 7\ GeV}$, $\boldsymbol{p_T^\mu > 7\ GeV}$, $\boldsymbol{p_T^j > 30\ GeV}$ $\boldsymbol{\lvert\eta^e\rvert < 2.47}$, $\boldsymbol{\lvert\eta^\mu\rvert < 2.7}$, $\boldsymbol{\lvert\eta^j\rvert < 4.5}$
Quadruplet Selection	Lepton Kinematics Lepton Separation Pair Requirement Minimal Δm_z ZZ mass	$\boldsymbol{p_T > 20\ GeV}$ for two leading leptons $\boldsymbol{\Delta R_{ij} > 0.05}$ between leptons in quadruplet Two SFOS lepton pairs with $\boldsymbol{m_{ll} > 5\ GeV}$ Select quadruplet with smallest $\boldsymbol{\lvert m_{12} - m_Z\rvert + \lvert m_{34} - m_Z\rvert}$ Leading Pair: pair with highest $\lvert y_{ij}\rvert$ $\boldsymbol{m_{4l} > 130\ GeV}$
Dijet Selection	Different Detector Sides Rapidity Separation Leading Jet p_T Dijet Mass	$\boldsymbol{\eta_{j1} \times \eta_{j2} < 0}$ $\boldsymbol{\Delta Y_{jj} > 2}$ $\boldsymbol{p_{T,j1} > 40\ GeV}$ $\boldsymbol{m_{jj} > 300\ GeV}$
Event Categorization	VBS Enhanced Region VBS Suppressed Region	$\boldsymbol{\zeta < 0.4}$ $\boldsymbol{\zeta > 0.4}$

Event Categorization

Differential measurements are made in events with a signal quadruplet and a dijet in two distinct signal regions based on the kinematic quantity named ***centrality***:

$$\zeta = \frac{|y_{quadruplet} - 0.5 \cdot (y_{leading\ jet} + y_{sub-leading\ jet})|}{y_{leading\ jet} - y_{sub-leading\ jet}}$$

where y is the rapidity.



VBS Enhanced Signal Region $\boldsymbol{\zeta < 0.4}$
VBS Suppressed Signal Region $\boldsymbol{\zeta > 0.4}$

A minimum number of events is required in each bin of the observables' distributions (15 for the VBS-Suppressed and 20 for the VBS-Enhanced region)

Observable	Region	Binning
m_{jj} [GeV]	VBS-Enhanced	[300, 400, 530, 720, 1080, 3280]
	VBS-Suppressed	[300, 410, 600, 1780]
$\lvert\Delta y_{jj}\rvert$	VBS-Enhanced	[2, 3.08, 3.74, 4.32, 5.06, 7.4]
	VBS-Suppressed	[2, 2.94, 3.78, 5.4]
m_{4l} [GeV]	VBS-Enhanced	[130, 210, 250, 304, 400, 1130]
	VBS-Suppressed	[130, 226, 304, 752]
$S_{T,4ljj}$	VBS-Enhanced	[70, 240, 320, 420, 580, 1410]
	VBS-Suppressed	[70, 330, 500, 1210]
$p_{T,jj}$	VBS-Enhanced	[0, 52, 82, 116, 172, 524]
	VBS-Suppressed	[0, 80, 146, 448]

Anomalous Quartic Gauge Couplings

- VBS processes provide a great source of information on the structure of QGCs
- Neutral couplings $ZZZZ, ZZZ\gamma, ZZ\gamma\gamma, Z\gamma\gamma\gamma$ are forbidden in the Standard Model
- Effects increase with $\sqrt{\hat{s}}$
- Presence of aQGCs lead to enhancement of the cross section and modification of event kinematics in high p_T, high E_T or high mass regions
  - study of variables that carry system's energy (p_T, m_{ZZ})
- Shape difference between SM and aQGC MC kinematic distributions
- Common choice: effective field theory (EFT) with higher order dimensions operators
- Effective Langrangian Approach

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{\boldsymbol{c}_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

- Set of dim-8 operators affecting quartic boson vertices:

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$,$\mathcal{O}_{M,6}$,$\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$,$\mathcal{O}_{M,4}$,$\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$,$\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$,$\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$			X			X	X	X	X

Decomposition method of QGCs

EFT dim-8 predictions can be generated in independent samples including the EFT components. The total EFT amplitude can be expressed as:

$$\left|A_{SM} + \sum_i c_i \cdot A_i\right|^2 = |A_{SM}|^2 + \sum_i c_i \cdot 2\, Re(A_{SM}^* \cdot A_i) + \sum_i c_i^2 \cdot |A_i|^2 + \sum_{i,j,\, i \neq j} c_i c_j \cdot Re(A_i^* \cdot A_j)$$

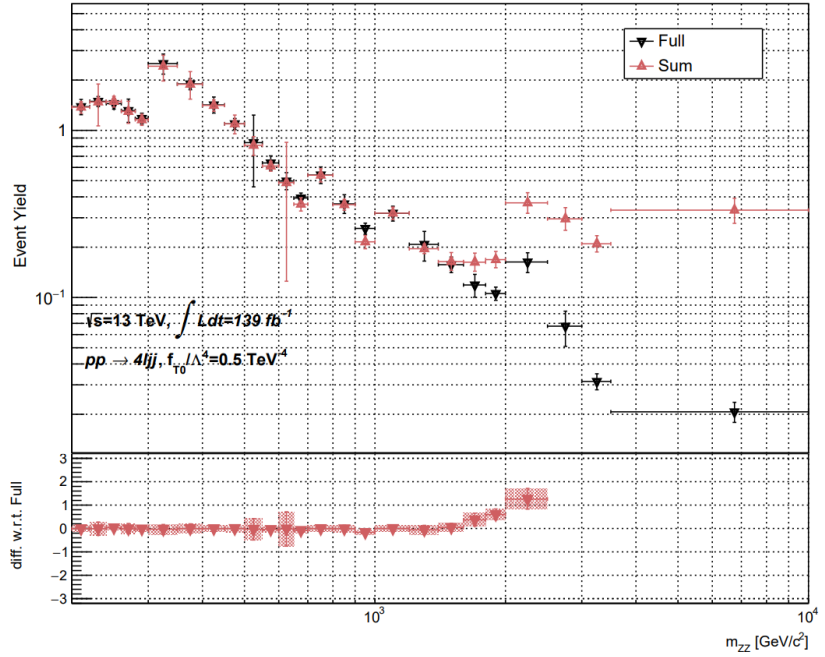
Total EFT amplitude

Standard Model

Interference of SM-aQGC (linear term)

Pure QGC contribution (quadratic term)

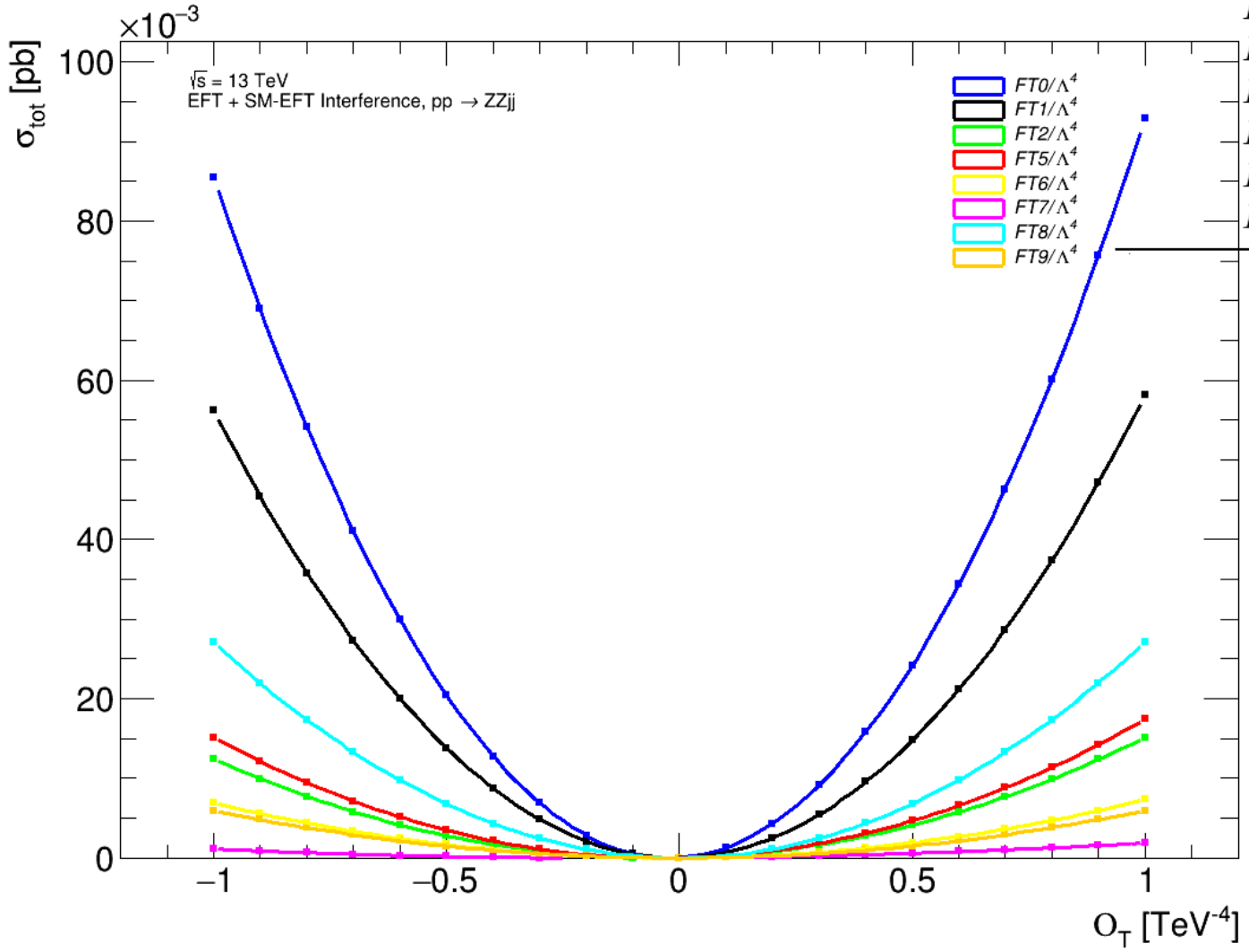
Interference between QGC operators (cross terms)



Minor differences between the samples generated with the total EFT versus the sum of the EFT components.

Sensitivity of QGC operators

$$\mathcal{L}_{EFT} = \mathcal{L}_{\mathrm{SM}} + \sum_{j=0,1} \frac{f_{\mathrm{M},j}}{\Lambda^4} \mathcal{O}_{\mathrm{M},j} + \sum_{j=0,1} \frac{f_{\mathrm{S},j}}{\Lambda^4} \mathcal{O}_{\mathrm{S},j} + \sum_{j=0,1} \frac{f_{\mathrm{T},j}}{\Lambda^4} \mathcal{O}_{\mathrm{T},j}$$

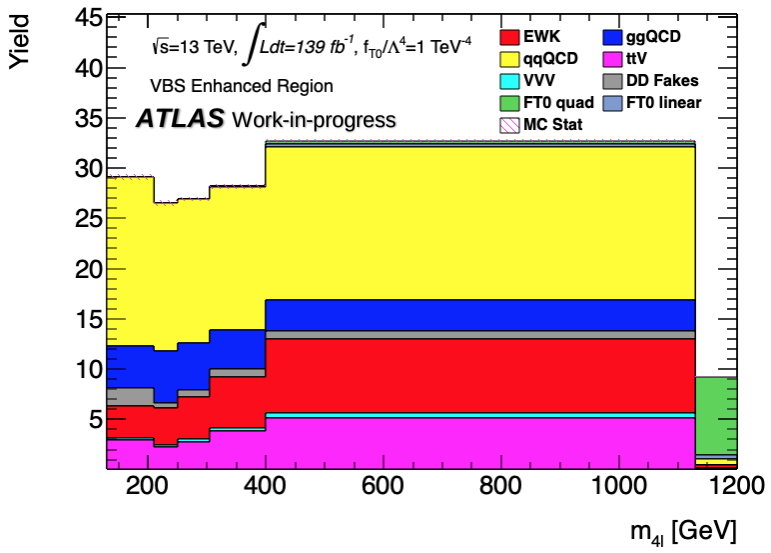


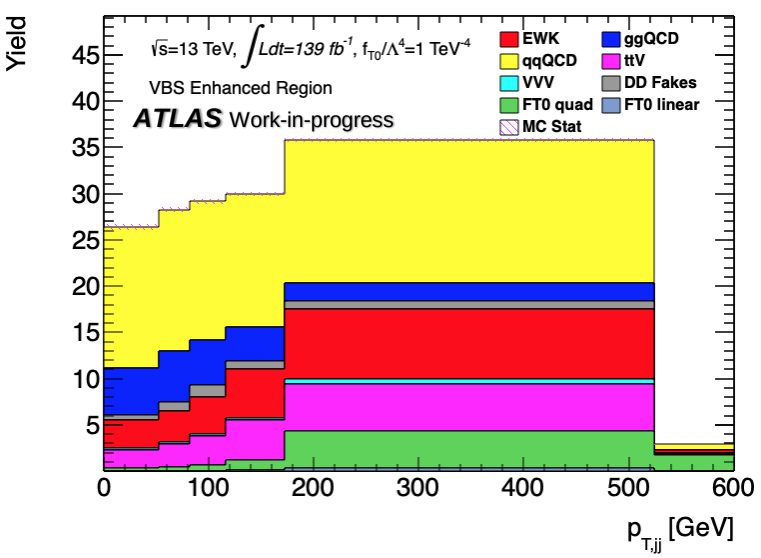
Parameter λ (TeV^{-4})	Quadratic function with SM=0 (pb)
F_{T0}/Λ^4	$\sigma(\lambda) = 3.725 \cdot 10^{-3} \cdot \lambda + 8.927 \cdot 10^{-2} \cdot \lambda^2$
F_{T1}/Λ^4	$\sigma(\lambda) = 9.646 \cdot 10^{-4} \cdot \lambda + 5.717 \cdot 10^{-2} \cdot \lambda^2$
F_{T2}/Λ^4	$\sigma(\lambda) = 1.342 \cdot 10^{-3} \cdot \lambda + 1.377 \cdot 10^{-2} \cdot \lambda^2$
F_{T5}/Λ^4	$\sigma(\lambda) = 1.180 \cdot 10^{-3} \cdot \lambda + 1.625 \cdot 10^{-2} \cdot \lambda^2$
F_{T6}/Λ^4	$\sigma(\lambda) = 2.145 \cdot 10^{-4} \cdot \lambda + 7.094 \cdot 10^{-3} \cdot \lambda^2$
F_{T7}/Λ^4	$\sigma(\lambda) = 3.868 \cdot 10^{-4} \cdot \lambda + 1.495 \cdot 10^{-3} \cdot \lambda^2$
F_{T8}/Λ^4	$\sigma(\lambda) = 2.265 \cdot 10^{-5} \cdot \lambda + 2.713 \cdot 10^{-2} \cdot \lambda^2$
F_{T9}/Λ^4	$\sigma(\lambda) = 1.323 \cdot 10^{-5} \cdot \lambda + 5.918 \cdot 10^{-3} \cdot \lambda^2$

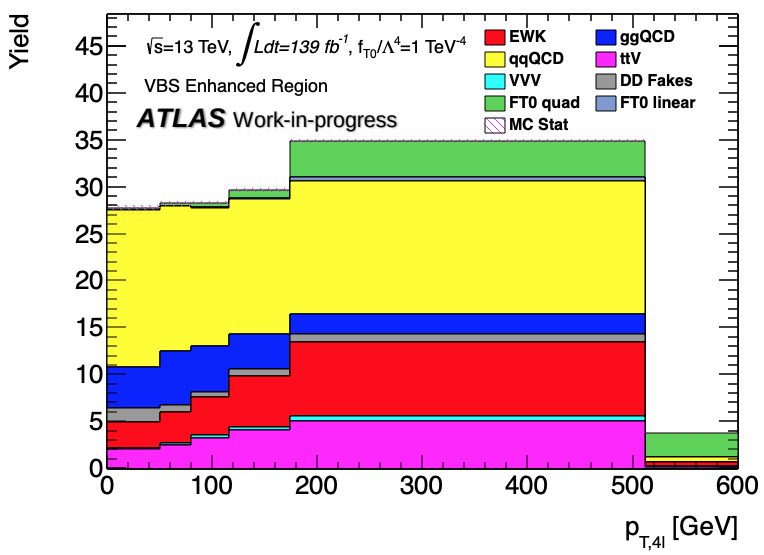
- $pp \to ZZjj$ samples
- No $Z \to ll$ applied
- No fiducial cuts applied
- No SM amplitudes includes
  - only linear and quadratic terms

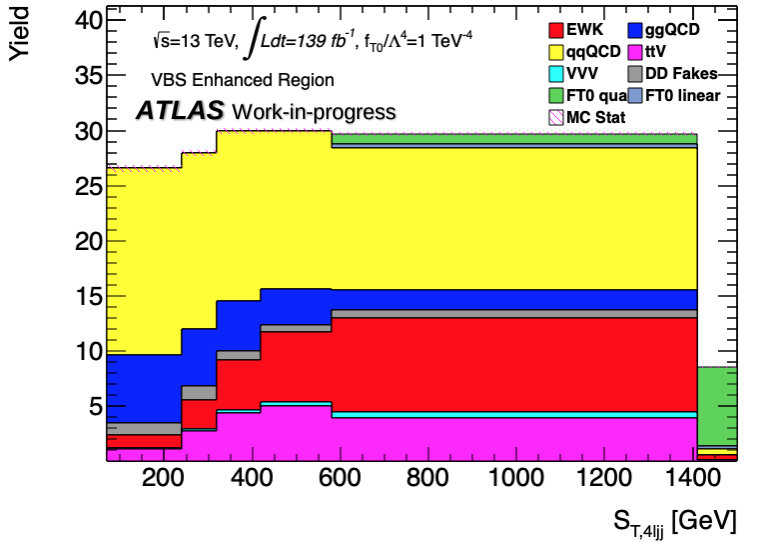
$\mathcal{O}_{\mathrm{T},j}$ are the most sensitive operators of the ZZ production.

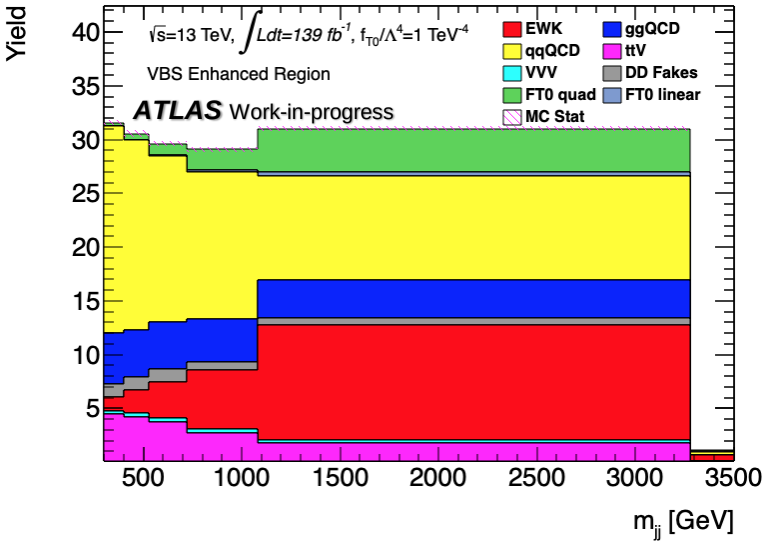
Distributions of observables





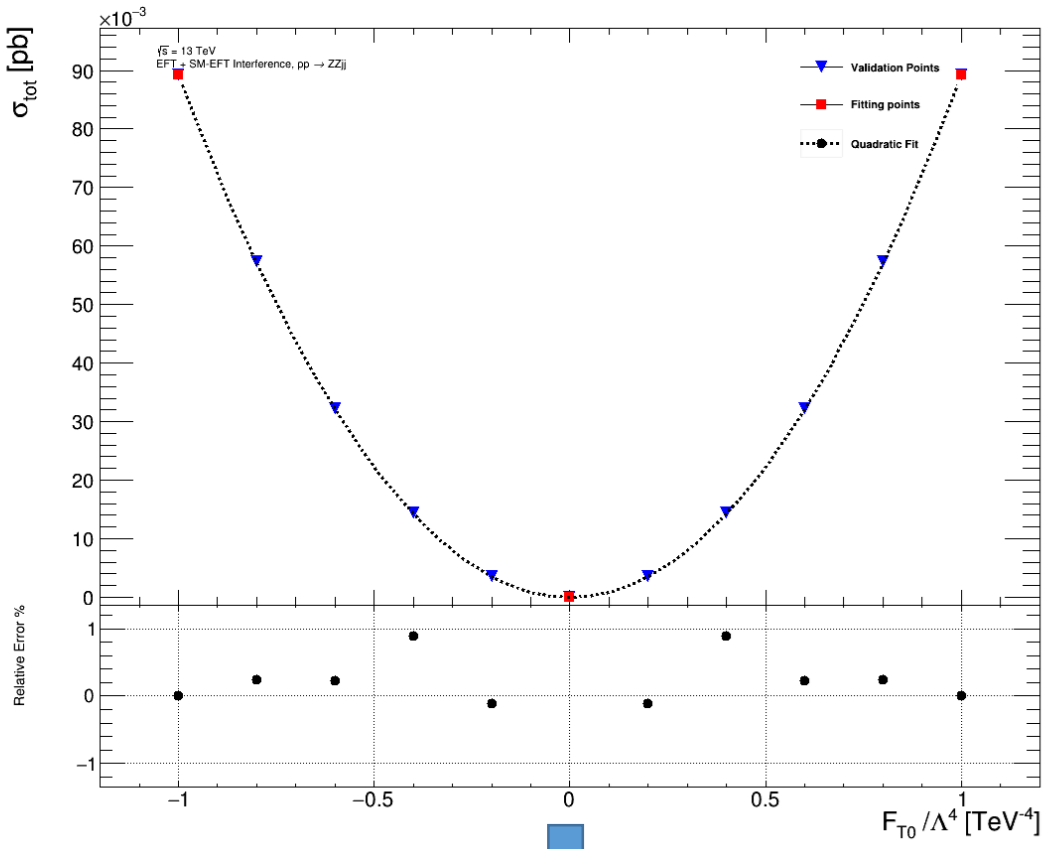






Distributions of the expected yields at detector-level of the m_{4l} , $p_{T,jj}$, $p_{T,4l}$, $S_{T,4ljj}$ and m_{jj} observables for the VBS Enhanced Region.

Limit Setting strategy



To find the quadratic function $N_i^{aQGC}(\lambda, \boldsymbol{\theta})$, we fit independent quadratic (pure aQGC) and linear (SM-aQGC interference) samples.
Since for $f_{T0} = 0$, the event yield is 0, only one extra point is needed.

Number of expected events in each bin i:

$$\mu_i(\lambda, \boldsymbol{\theta}) = N_i^{SM}(\boldsymbol{\theta}) + N_i^{aQGC}(\lambda, \boldsymbol{\theta})$$

where $N_i^{aQGC}(\lambda, \boldsymbol{\theta}) = N_i^{linear}(\lambda, \boldsymbol{\theta}) + N_i^{quad}(\lambda, \boldsymbol{\theta})$

Construction of the profile likelihood function with the aQGC parameters

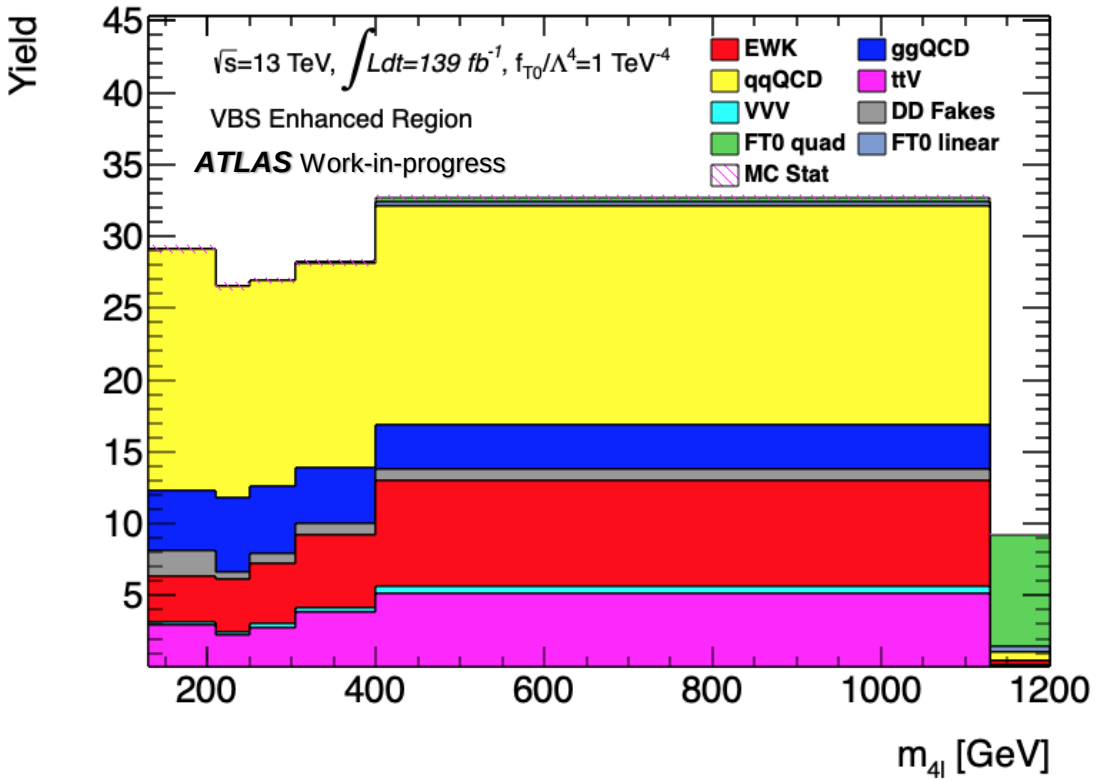
$$\mathcal{L} = \prod_{i=1}^{N_{bin}} \mathcal{L}_{poiss}(n_i | \mu_i(\lambda, \boldsymbol{\theta})) \times \mathcal{L}_{gauss}(\boldsymbol{\theta})_i$$

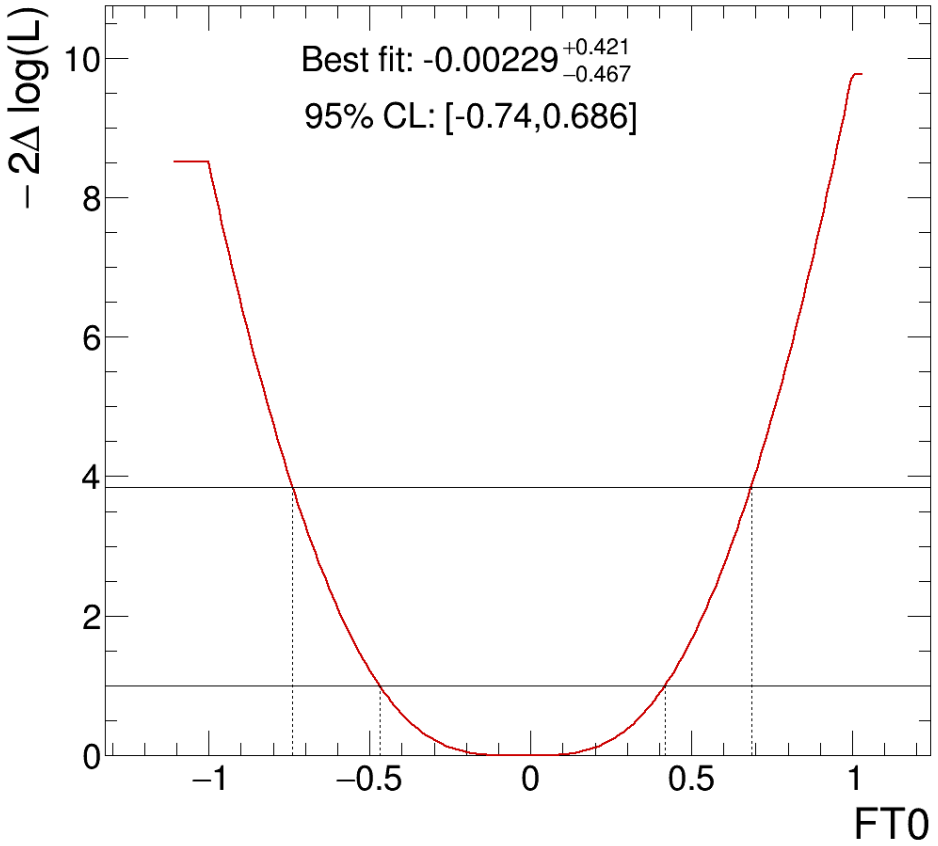
where n_i is the observed number of events, $\mu_i(\lambda, \theta)$ is the expected number of events in the ith bin, $\lambda = f_T/\Lambda^4$ is the value of the aQGC under examination and θ is a list of nuisance parameters.

The 95% confidence interval for the parameter λ corresponds to

$$-\mathbf{2\Delta log}\big(\boldsymbol{\mathcal{L}}(\boldsymbol{\lambda})\big) = \mathbf{1.96^2}$$

EFT dim-8 expected limits at detector-level for m_{4l}

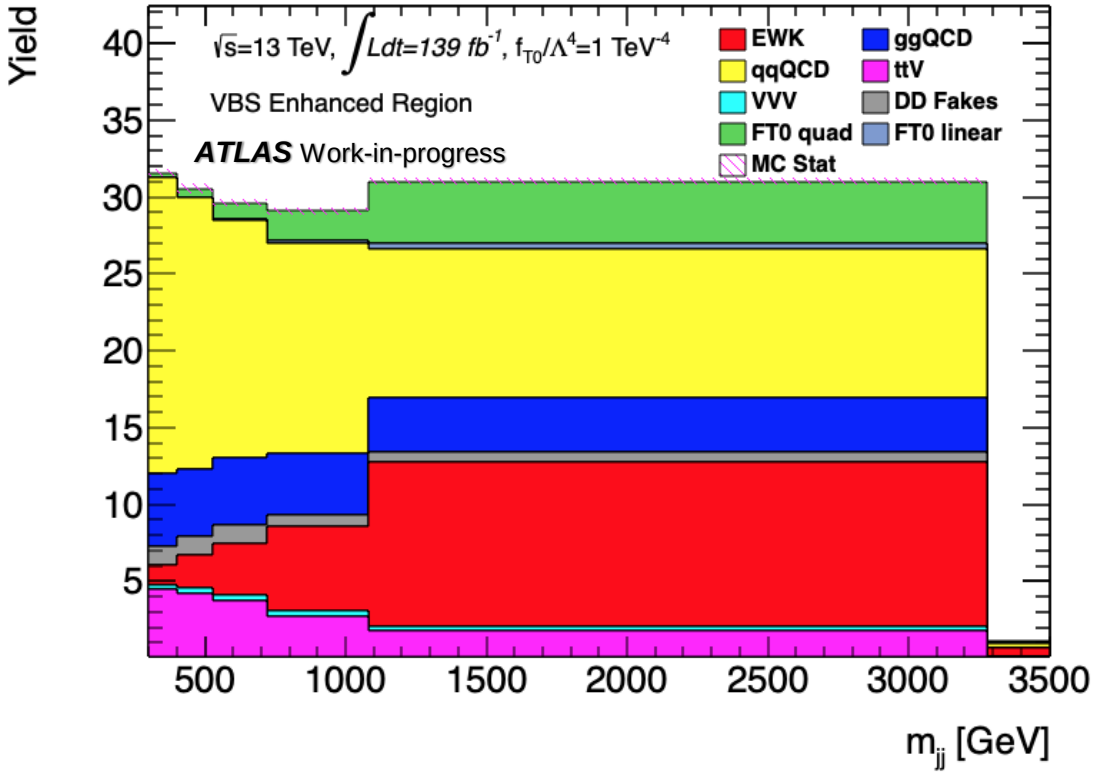


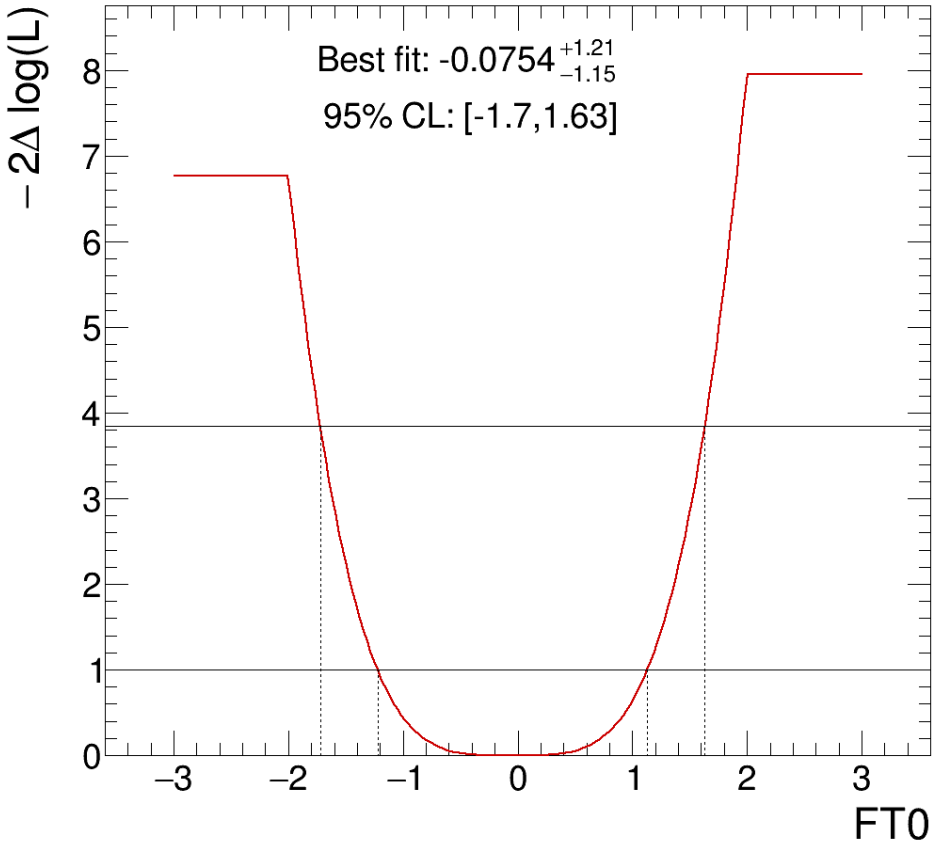


Process	[130,210)	[210-250)	[250-304)	[304-400)	[400-1130)	[1130-∞)
$qq \to llljj$ (EWK)	3.129	3.691	4.198	5.029	7.282	0.337
$qq \to llll$	16.820	14.792	14.340	14.269	15.171	0.570
$gg \to llll$	4.189	5.150	4.654	3.856	3.105	0.040
VVV	0.184	0.213	0.233	0.344	0.536	0.027
$t\bar{t}V$	2.998	2.228	2.767	3.819	5.132	0.093
$DD\ Fakes$	1.790	0.475	0.727	0.827	0.839	-
f_{T0} quad	0.000	0.000	0.002	0.002	0.286	7.809
f_{T0} linear	0.001	0.004	0.010	0.027	0.335	0.359

Unphysical enhancement of the event yield (and cross-section) at high energies. Need of a unitarization method.

EFT dim-8 expected limits at detector-level for m_{jj}





Process	[300-400)	[400-530)	[530-720)	[720-1080)	[1080-3280)	[3280-∞)
$qq \to llllj j$ (EWK)	1.325	2.124	3.333	5.507	10.756	0.622
$qq \to llll$	19.249	17.599	15.452	13.664	9.720	0.278
$gg \to llll$	4.703	4.429	4.317	3.999	3.498	0.048
VVV	0.326	0.327	0.347	0.317	0.217	0.004
$t\bar{t}V$	4.456	4.242	3.765	2.735	1.811	0.028
$DD\ Fakes$	1.1701	1.1901	1.2601	0.7371	0.6251	-
f_{T0} quad	0.320	0.584	1.047	1.957	4.033	0.158
f_{T0} linear	0.033	0.058	0.097	0.175	0.356	0.018

EFT dim-8 expected limits at detector-level

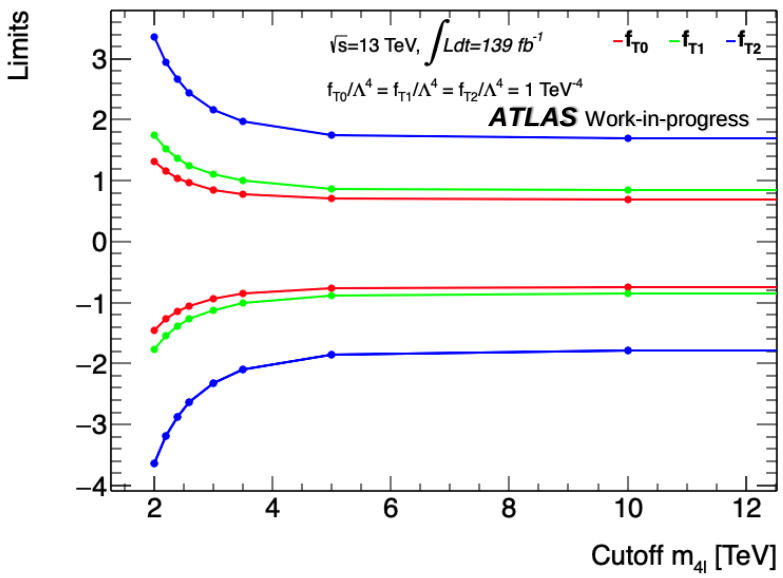
Wilson	Expected (Asimov) 95% CL Limit				
Coefficient	m_{jj}	Δy_{jj}	$p_{T,jj}$	m_{4l}	$S_{T,llljj}$
f_{T0}	[-1.72 , 1.63]	[-2.43 , 2.34]	[-1.36 , 1.31]	[-0.74 , 0.69]	[-0.73 , 0.69]
f_{T1}	[-2.12 , 2.10]	[-3.03 , 3.01]	[-1.70 , 1.69]	[-0.85 , 0.84]	[-0.90 , 0.90]
f_{T2}	[-4.39 , 4.21]	[-6.24 , 6.06]	[-3.48 , 3.38]	[-1.78 , 1.69]	[-1.87 , 1.79]
f_{T5}	[-4.37 , 4.20]	[-6.22 , 6.06]	[-3.67 , 3.57]	[-1.78 , 1.69]	[-1.88 , 1.80]
f_{T6}	[-6.22 , 6.17]	[-8.97 , 8.92]	[-5.51 , 5.49]	[-2.67 , 2.65]	[-2.86 , 2.84]
f_{T7}	[-14.13 , 13.60]	[-20.48 , 19.92]	[-11.34 , 11.04]	[-5.85 , 5.56]	[-6.18 , 5.93]
f_{T8}	[-3.51 , 3.51]	[-4.83 , 4.83]	[-3.18 , 3.18]	[-1.45 , 1.45]	[-1.56 , 1.56]
f_{T9}	[-7.53 , 7.53]	[-10.36 , 10.36]	[-6.85 , 6.85]	[-3.13 , 3.14]	[-3.38 , 3.38]

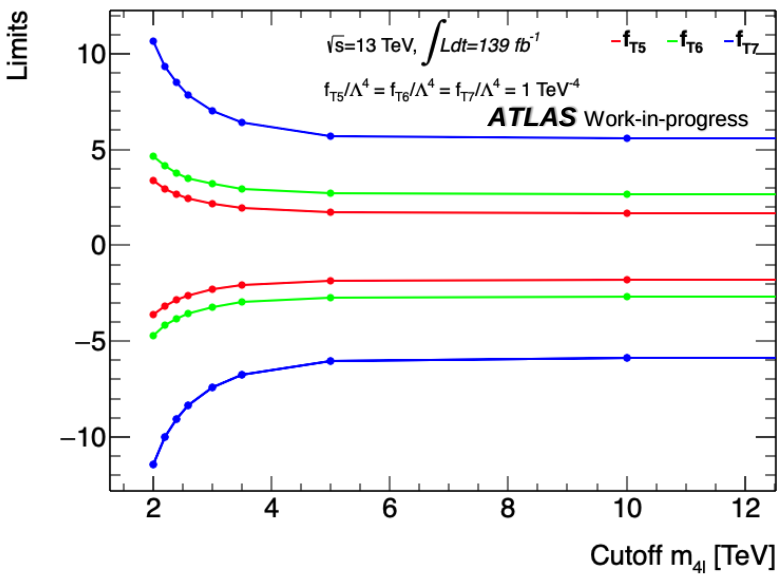
Expected 95% CL limits of F_T couplings, by using non-unitary predictions

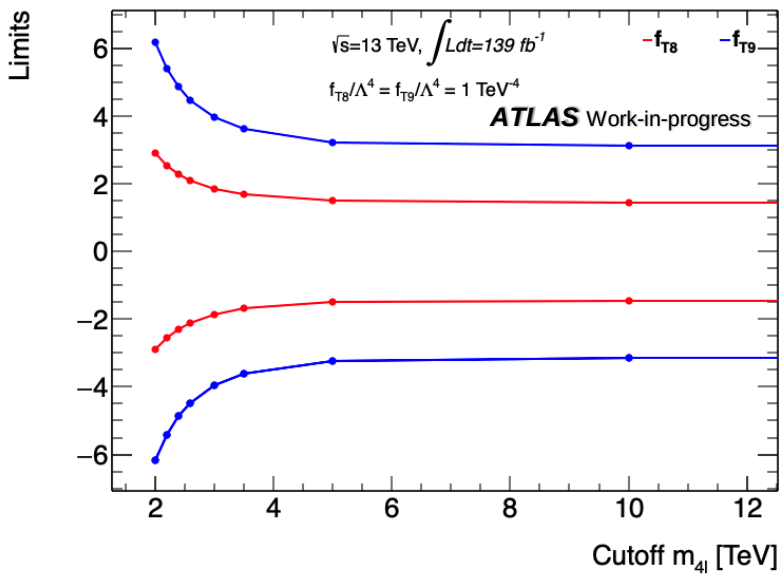
Unitarity violation – Clipping Scan m_{4l}

Wilson Coefficient	Expected (Asimov) 95% CL Limit								
	2 TeV	2.2 TeV	2.4 TeV	2.6 TeV	3 TeV	3.5 TeV	5 TeV	10 TeV	∞
f_{T0}	[-1.46, 1.32]	[-1.27, 1.15]	[-1.15, 1.04]	[-1.05, 0.96]	[-0.93, 0.85]	[-0.85, 0.78]	[-0.76, 0.70]	[-0.74, 0.69]	[-0.74, 0.69]
f_{T1}	[-1.77, 1.74]	[-1.55, 1.52]	[-1.39, 1.37]	[-1.27, 1.25]	[-1.12, 1.10]	[-1.01, 1.00]	[-0.88, 0.87]	[-0.85, 0.84]	[-0.85, 0.84]
f_{T2}	[-3.64, 3.35]	[-3.18, 2.94]	[-2.87, 2.66]	[-2.63, 2.44]	[-2.32, 2.17]	[-2.09, 1.97]	[-1.85, 1.74]	[-1.78, 1.69]	[-1.78, 1.69]
f_{T5}	[-3.64, 3.37]	[-3.18, 2.96]	[-2.85, 2.66]	[-2.62, 2.45]	[-2.31, 2.17]	[-2.09, 1.97]	[-1.84, 1.75]	[-1.78, 1.69]	[-1.78, 1.69]
f_{T6}	[-4.70, 4.65]	[-4.18, 4.13]	[-3.82, 3.78]	[-3.56, 3.52]	[-3.22, 3.19]	[-2.98, 2.95]	[-2.73, 2.70]	[-2.67, 2.65]	[-2.67, 2.65]
f_{T7}	[-11.46, 10.67]	[-10.02, 9.36]	[-9.06, 8.48]	[-8.37, 7.85]	[-7.44, 7.00]	[-6.77, 6.39]	[-6.02, 5.71]	[-5.85, 5.56]	[-5.85, 5.56]
f_{T8}	[-2.90, 2.90]	[-2.54, 2.54]	[-2.29, 2.29]	[-2.11, 2.11]	[-1.86, 1.86]	[-1.69, 1.69]	[-1.49, 1.49]	[-1.45, 1.45]	[-1.45, 1.45]
f_{T9}	[-6.17, 6.17]	[-5.41, 5.41]	[-4.86, 4.86]	[-4.48, 4.48]	[-3.97, 3.97]	[-3.62, 3.62]	[-3.23, 3.23]	[-3.13, 3.14]	[-3.13, 3.14]

The clipping scan is not considered a unitarization method but a way of achieving unitarity by discarding any predictions made for energy above a certain point

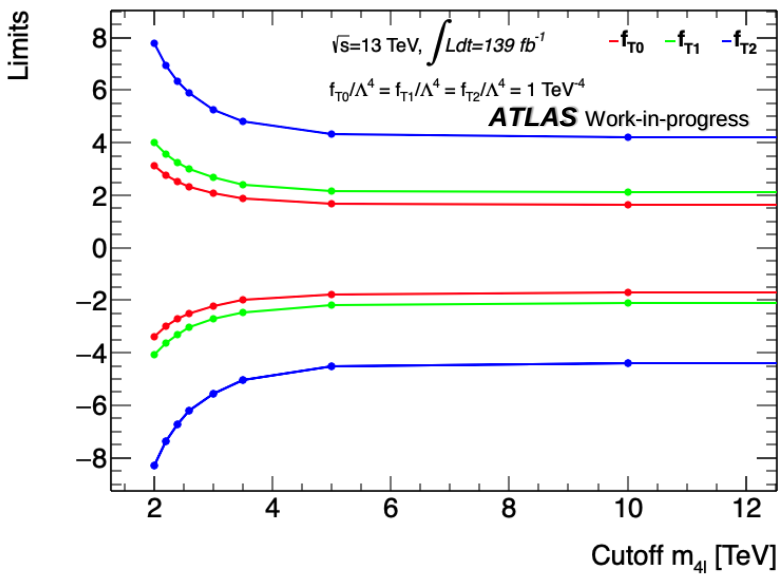


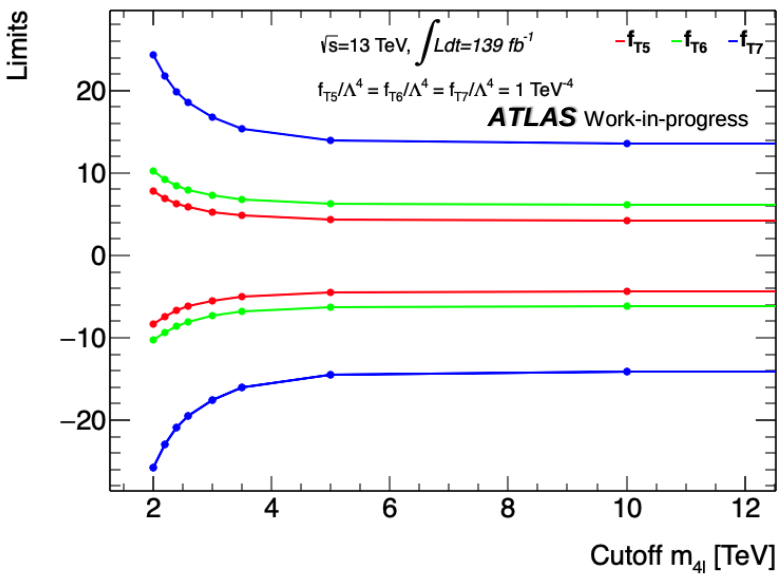


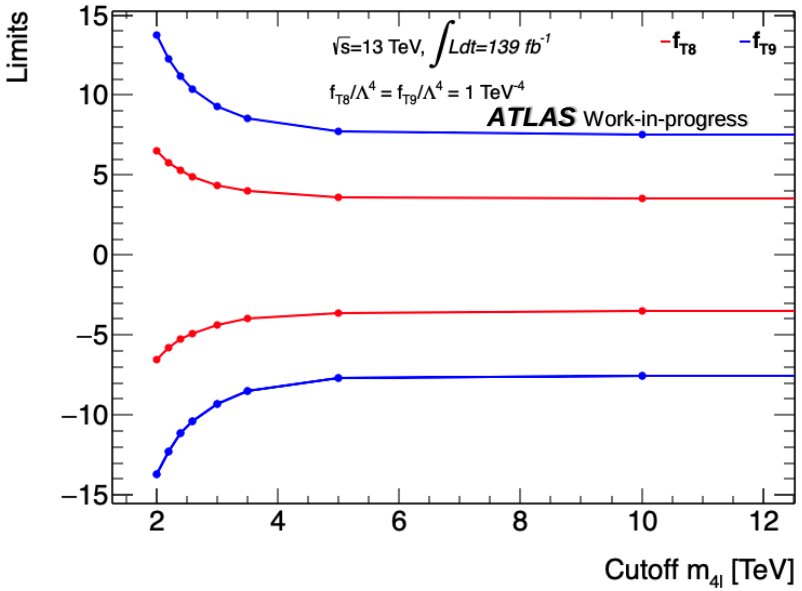


Unitarity violation – Clipping Scan m_{jj}

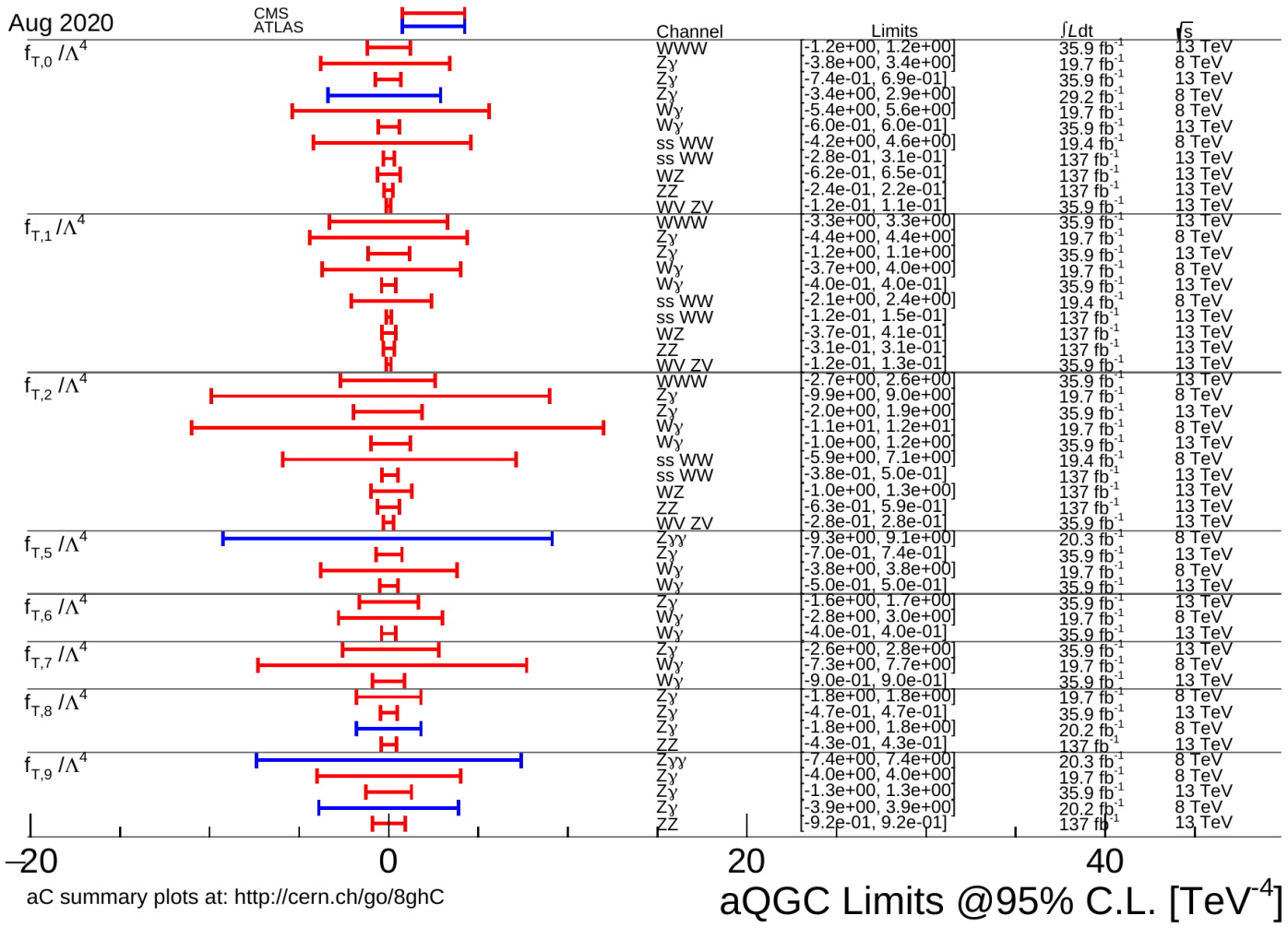
Wilson Coefficient	Expected (Asimov) 95% CL Limit								
	2 TeV	2.2 TeV	2.4 TeV	2.6 TeV	3 TeV	3.5 TeV	5 TeV	10 TeV	∞
f_{T0}	[-3.40, 3.11]	[-3.00, 2.76]	[-2.71, 2.51]	[-2.49, 2.32]	[-2.21, 2.07]	[-2.00, 1.88]	[-1.78, 1.68]	[-1.72, 1.63]	[-1.72, 1.63]
f_{T1}	[-4.07, 4.00]	[-3.62, 3.56]	[-3.29, 3.24]	[-3.03, 2.99]	[-2.70, 2.67]	[-2.45, 2.42]	[-2.18, 2.16]	[-2.12, 2.10]	[-2.12, 2.10]
f_{T2}	[-8.31, 7.77]	[-7.38, 6.94]	[-6.72, 6.33]	[-6.21, 5.88]	[-5.55, 5.27]	[-5.05, 4.81]	[-4.51, 4.32]	[-4.39, 4.21]	[-4.39, 4.21]
f_{T5}	[-8.31, 7.80]	[-7.38, 6.95]	[-6.69, 6.33]	[-6.20, 5.88]	[-5.52, 5.26]	[-5.04, 4.82]	[-4.50, 4.32]	[-4.38, 4.21]	[-4.37, 4.20]
f_{T6}	[-10.31, 10.19]	[-9.31, 9.21]	[-8.58, 8.49]	[-8.05, 7.97]	[-7.36, 7.29]	[-6.86, 6.80]	[-6.33, 6.28]	[-6.22, 6.18]	[-6.22, 6.17]
f_{T7}	[-25.78, 24.29]	[-22.95, 21.71]	[-20.94, 19.87]	[-19.51, 18.56]	[-17.51, 16.72]	[-16.09, 15.41]	[-14.46, 13.90]	[-14.14, 13.60]	[-14.13, 13.60]
f_{T8}	[-6.51, 6.51]	[-5.79, 5.79]	[-5.28, 5.28]	[-4.90, 4.90]	[-4.37, 4.37]	[-4.00, 4.00]	[-3.60, 3.60]	[-3.51, 3.51]	[-3.51, 3.51]
f_{T9}	[-13.72, 13.72]	[-12.26, 12.26]	[-11.16, 11.16]	[-10.39, 10.39]	[-9.31, 9.31]	[-8.53, 8.53]	[-7.72, 7.72]	[-7.53, 7.53]	[-7.53, 7.53]







Current limits for f_T operators



Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	−0.37	0.35	−0.24 (−0.26)	0.22 (0.24)	2.4
f_{T1}/Λ^4	−0.49	0.49	−0.31 (−0.34)	0.31 (0.34)	2.6
f_{T2}/Λ^4	−0.98	0.95	−0.63 (−0.69)	0.59 (0.65)	2.5
f_{T8}/Λ^4	−0.68	0.68	−0.43 (−0.47)	0.43 (0.48)	1.8
f_{T9}/Λ^4	−1.5	1.5	−0.92 (−1.02)	0.92 (1.02)	1.8

CMS: Expected and observed lower and upper 95% CL limits on the couplings of the quartic operators T0, T1 and T2, as well as the neutral current operators T8 and T9. All coupling parameter limits are in TeV^{-4}, while the unitarity bounds are in TeV.
arXiv:2008.07013

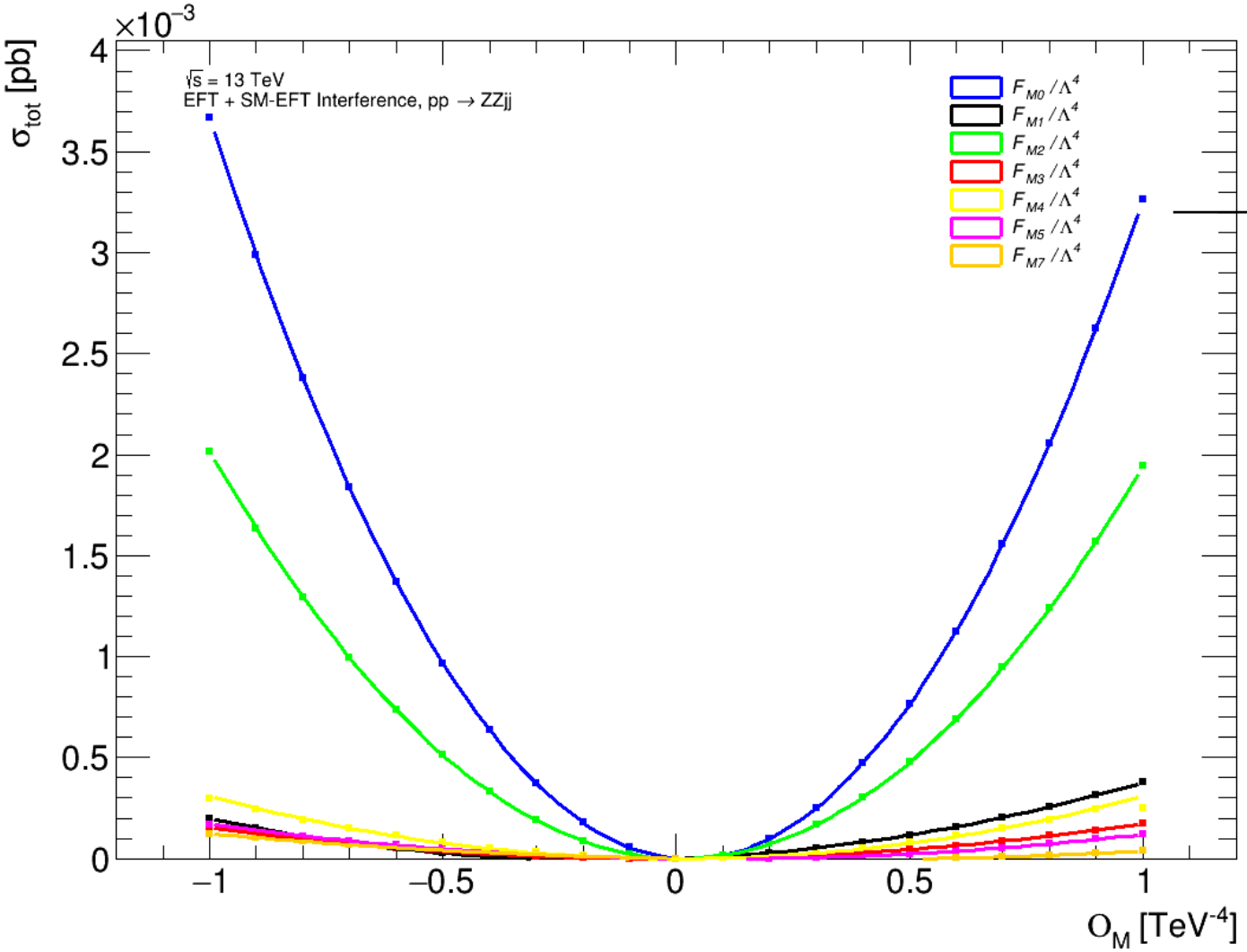
Thank you!

comments?

Backup

Sensitivity of QGC operators

$$\mathcal{L}_{EFT} = \mathcal{L}_{\mathrm{SM}} + \sum_{j=0,1} \frac{f_{\mathrm{M},j}}{\Lambda^4} \mathcal{O}_{\mathrm{M},j} + \sum_{j=0,1} \frac{f_{\mathrm{S},j}}{\Lambda^4} \mathcal{O}_{\mathrm{S},j} + \sum_{j=0,1} \frac{f_{\mathrm{T},j}}{\Lambda^4} \mathcal{O}_{\mathrm{T},j}$$



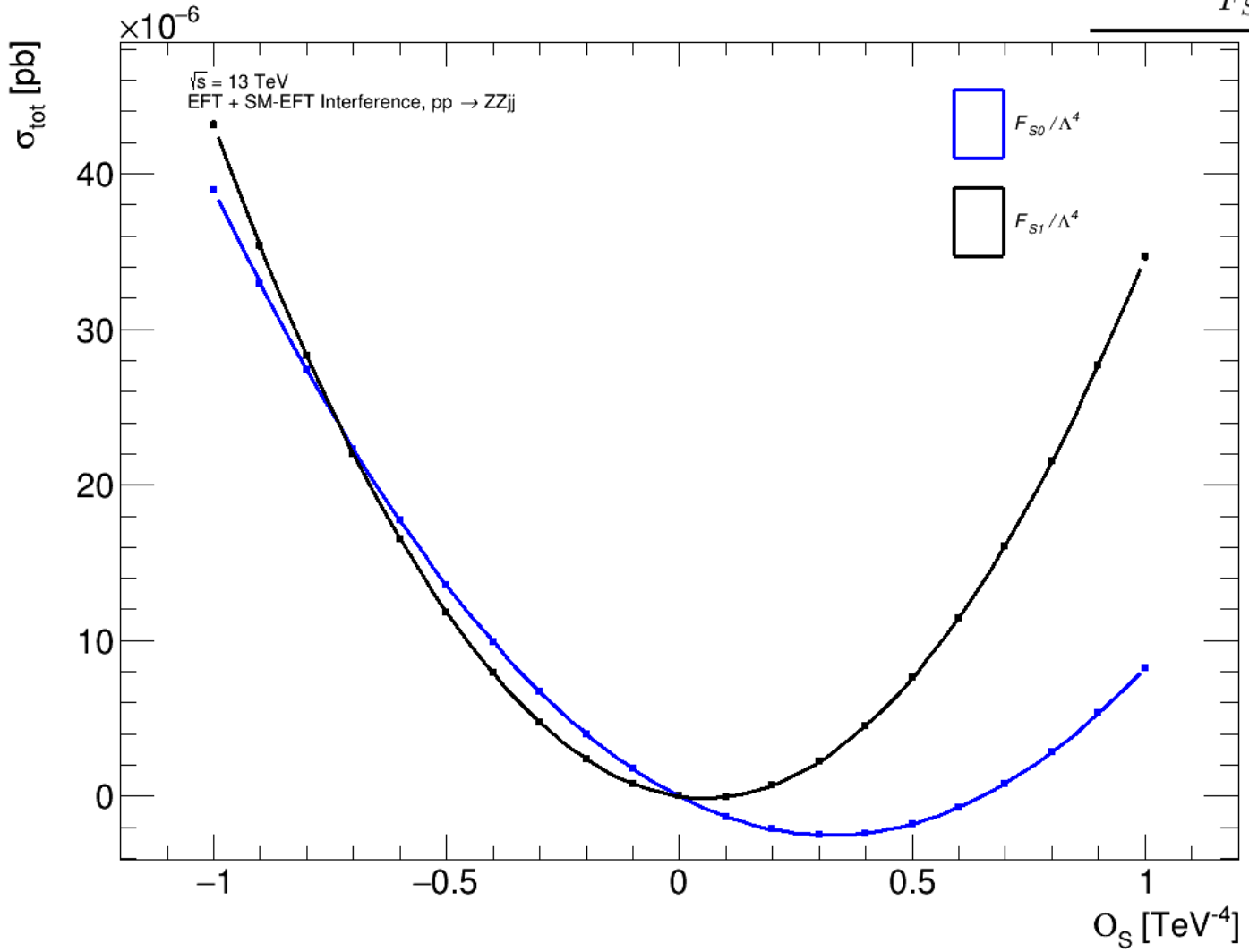
Parameter λ (TeV^{-4})	Quadratic function with SM=0 (pb)
F_{M0}/Λ^4	$\sigma(\lambda) = -2.022 \cdot 10^{-4} \cdot \lambda + 3.464 \cdot 10^{-3} \cdot \lambda^2$
F_{M1}/Λ^4	$\sigma(\lambda) = 8.939 \cdot 10^{-5} \cdot \lambda + 2.872 \cdot 10^{-4} \cdot \lambda^2$
F_{M2}/Λ^4	$\sigma(\lambda) = -3.569 \cdot 10^{-5} \cdot \lambda + 1.980 \cdot 10^{-3} \cdot \lambda^2$
F_{M3}/Λ^4	$\sigma(\lambda) = 9.496 \cdot 10^{-6} \cdot \lambda + 1.641 \cdot 10^{-4} \cdot \lambda^2$
F_{M4}/Λ^4	$\sigma(\lambda) = -2.280 \cdot 10^{-5} \cdot \lambda + 2.741 \cdot 10^{-4} \cdot \lambda^2$
F_{M5}/Λ^4	$\sigma(\lambda) = -2.452 \cdot 10^{-5} \cdot \lambda + 1.443 \cdot 10^{-4} \cdot \lambda^2$
F_{M7}/Λ^4	$\sigma(\lambda) = -4.305 \cdot 10^{-5} \cdot \lambda + 7.934 \cdot 10^{-5} \cdot \lambda^2$

- $pp \to ZZjj$ samples
- No $Z \to ll$ applied
- No fiducial cuts applied
- No SM amplitudes includes
  - only linear and quadratic terms

Sensitivity of QGC operators

$$\mathcal{L}_{EFT} = \mathcal{L}_{\mathrm{SM}} + \sum_{j=0,1} \frac{f_{\mathrm{M},j}}{\Lambda^4}\mathcal{O}_{\mathrm{M},j} + \sum_{\boldsymbol{j=0,1}} \frac{\boldsymbol{f_{\mathrm{S},j}}}{\boldsymbol{\Lambda^4}}\boldsymbol{\mathcal{O}_{\mathrm{S},j}} + \sum_{j=0,1} \frac{f_{\mathrm{T},j}}{\Lambda^4}\mathcal{O}_{\mathrm{T},j}$$

Parameter λ (TeV^{-4})	Quadratic function with SM=0 (pb)
F_{S0}/Λ^4	$\sigma(\lambda) = -1.534 \cdot 10^{-5} \cdot \lambda + 2.362 \cdot 10^{-5} \cdot \lambda^2$
F_{S1}/Λ^4	$\sigma(\lambda) = -4.234 \cdot 10^{-6} \cdot \lambda + 3.890 \cdot 10^{-5} \cdot \lambda^2$



- $pp \to ZZjj$ samples
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