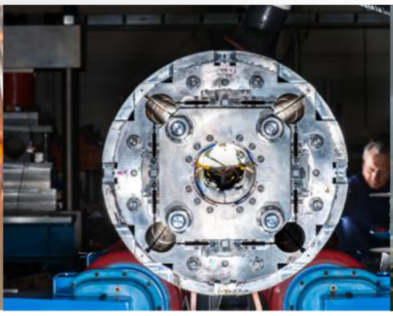
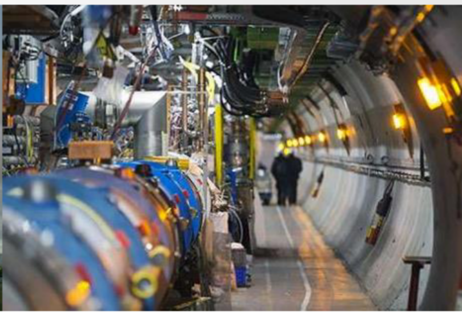
TESTING THE STANDARD MODEL EFFECTIVELY AT THE LHC

R. Schöfbeck, Feb 16th, 2022

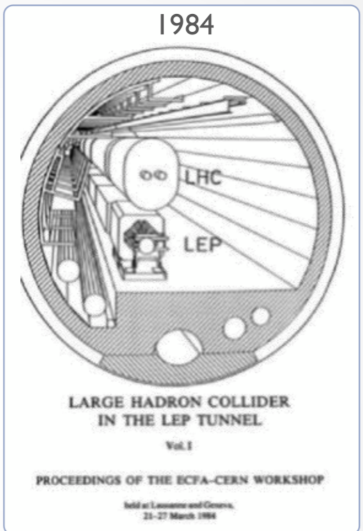





A LONG ROAD

Phil. Trans. R. Soc. A 373: 20140037

- first LHC workshop in '84 (Lausanne)
  - "a decade of Moore's law plus something new – which turned out to be the Grid"
    (Christopher Llewellyn Smith, CERN DG '94-'98)
- Early physics goals
  - discover Higgs boson in gluon-induced top loop
  - test origin of electroweak symmetry breaking
  - Supersymmetry


1984

LARGE HADRON COLLIDER
IN THE LEP TUNNEL

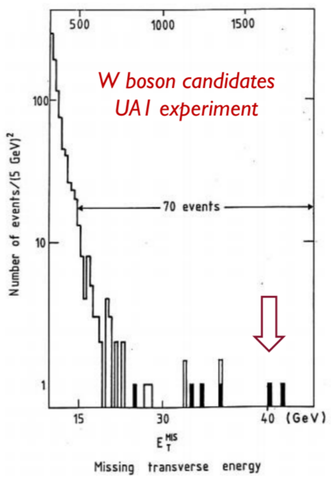
Vol. I

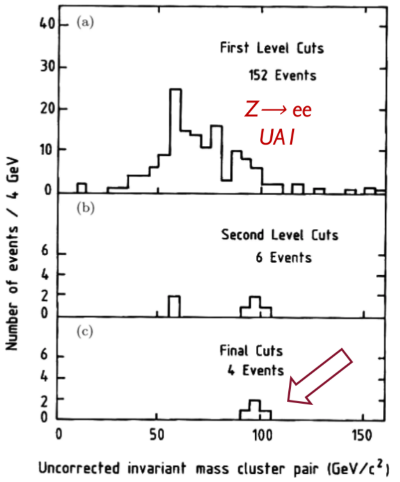
PROCEEDINGS OF THE ECFA-CERN WORKSHOP

held at Lausanne and Geneva,
21-27 March 1984

DISCOVERY OF W AND Z BOSONS

- Discovery of the massive SM gauge bosons ‘83-’84 UA1 and UA2 (SPS)
  - W boson: E_T^{miss} tail in single-lepton channel
  - Z boson: dilepton invariant mass $m(l^+l^-)$
- Resonant production
- LEP confirmed electroweak theory with precision measurements (mass, line-shape, asymmetries), further corroborated by Tevatron experiments





HIGGS BOSON AND ELECTROWEAK THEORY

- Discovery of the massive SM gauge bosons '83-'84 UA1 and UA2 (SPS)
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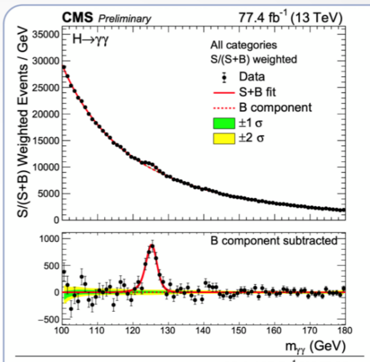
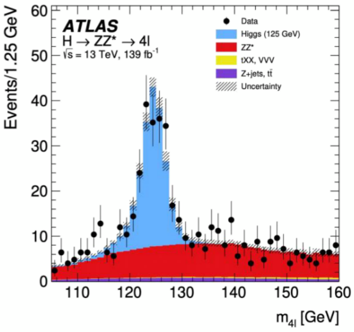
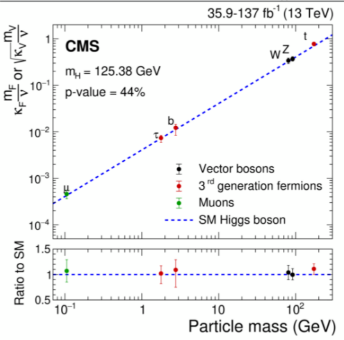
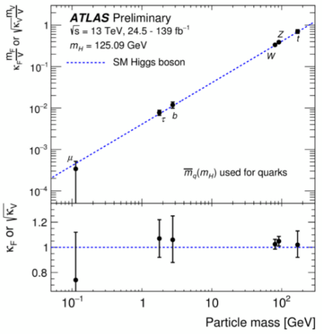
- Higgs discovery 2012 – a decade of measurements









HIGGS BOSON AND ELECTROWEAK THEORY

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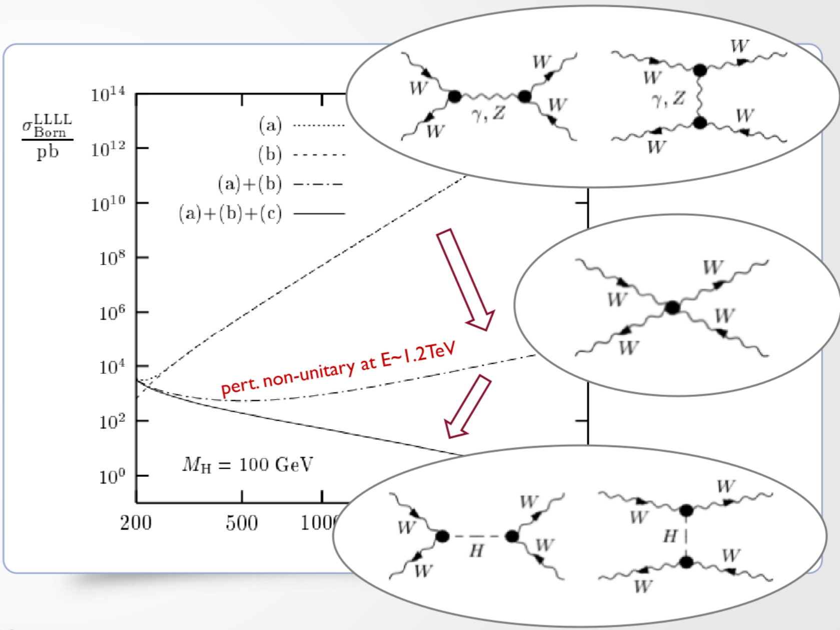
- Resonant production
- LEP confirmed electroweak theory with precision measurements (mass, line-shape, asymmetries), further corroborated by Tevatron experiments
- Higgs discovery 2012 – a decade of measurements
- LHC no-loose theorem: $W_LW_L \longrightarrow W_LW_L$
  - $m_H \lesssim 1$ TeV; cancellation is a core SM feature

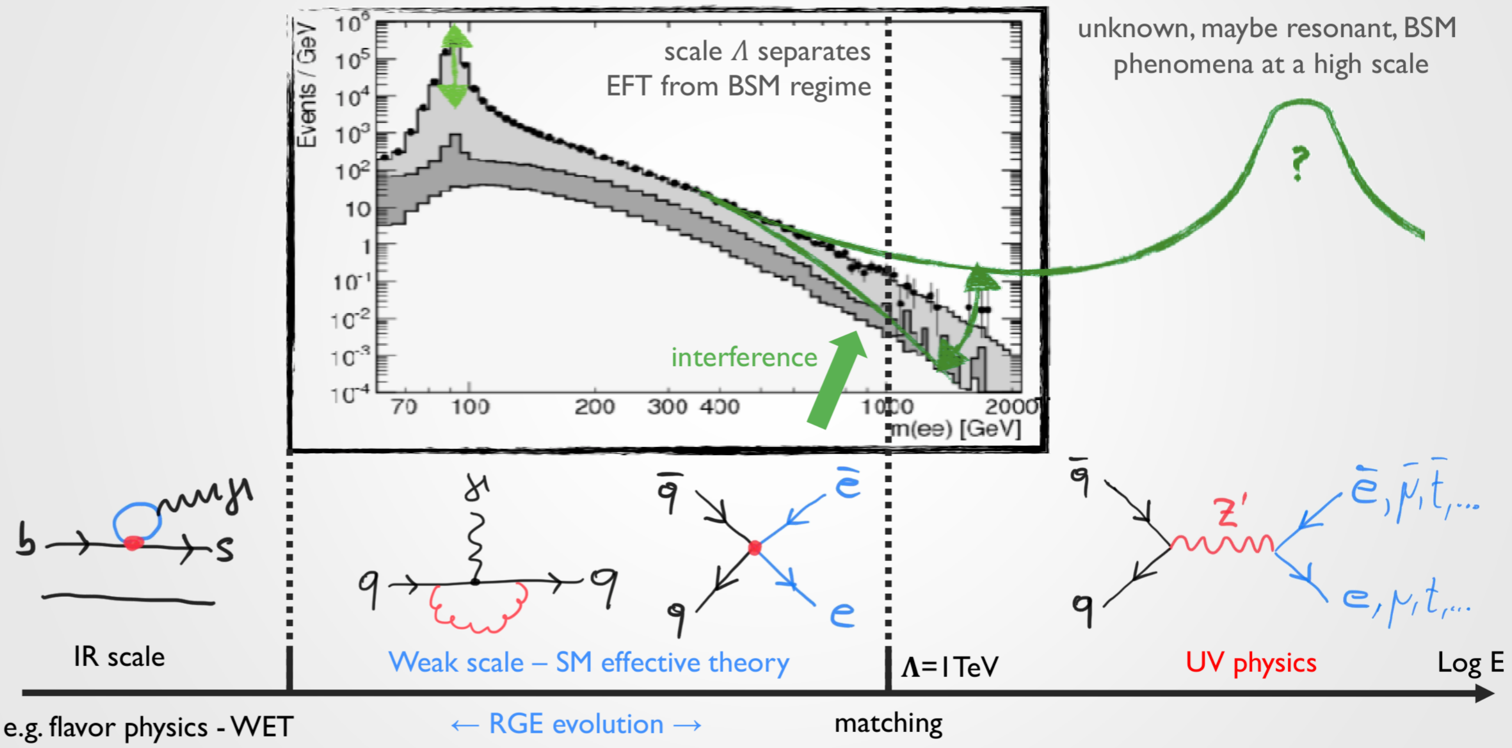
$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \omega_1 + i\omega_2 \\ h + v + i\omega_3 \end{pmatrix}$$

$\partial_\mu \omega \longrightarrow W^\pm_{\mu,L}, Z_{\mu,L}$
h $\longrightarrow$ Higgs field
v $\longrightarrow$ vacuum expectation value



CATCHING NEW PHYSICS BY THE TAIL

Sketch from F. Riva



scale Λ separates EFT from BSM regime

interference

unknown, maybe resonant, BSM phenomena at a high scale

IR scale

Weak scale – SM effective theory

Λ=1 TeV

UV physics

Log E

e.g. flavor physics - WET

← RGE evolution →

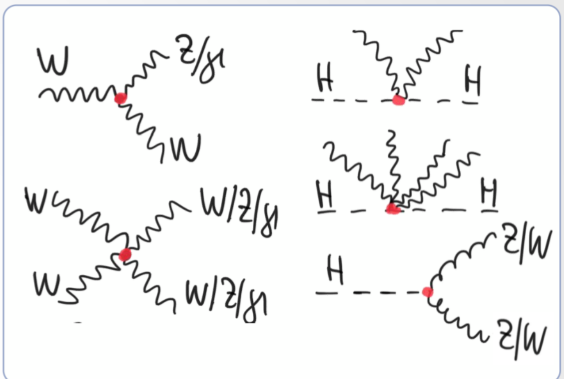
matching

SM EFFECTIVE FIELD THEORY

- organizing principle: mass dimension

$$\mathcal{L}_{eff} = \mathcal{L}_{SM}^{(4)} + \sum \frac{C_x}{\Lambda^2} O_{6,x} + h.c.$$

- Let's add all terms compatible with the SM symmetries
  - SU(3)$_c$ ⊗ SU(2)$_L$⊗U(1)$_Y$
  - 59 operators at d=6 [JHEP10(2010)085] "Warsaw basis"
- operators affecting massive bosons (aTGC, aQGC)



$\mathcal{O}_W$	$\varepsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$	"F³"
$\mathcal{O}_{\widetilde{W}}$	$\varepsilon_{IJK} \widetilde{W}^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$	
$\mathcal{O}_{\varphi W}$	$\varphi^\dagger \varphi W^{\mu\nu}_I W^I_{\mu\nu}$	"H²F²"
$\mathcal{O}_{\varphi B}$	$\varphi^\dagger \varphi B^{\mu\nu} B_{\mu\nu}$	
$\mathcal{O}^{(3)}_{\phi q_L}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi)(\bar{q}_L \gamma^\mu \tau^I q_L)$	"Current"
$\mathcal{O}_{t\phi}$	$(\phi^\dagger \phi)\, \bar{q}_L t_R \tilde{\phi} + \mathrm{h.c.}$	"Yukawa"

- Adding a new Feynman diagram: σ = |M^{SM} + C/**Λ**^{2} M^{BSM}|^2

$$\sigma = \sigma^{\mathrm{SM}} + \boxed{\sum_i \frac{C_i}{\Lambda^2} \sigma_i^{\mathrm{int.}}} + \boxed{\sum_{i,j} \frac{C_i C_j}{\Lambda^4} \sigma_{i,j}^{\mathrm{BSM}}}$$

interference → linear or quadratic effects (same order as dim-8)

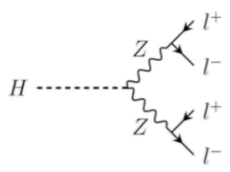
- Where to look?
  - F^3 terms ⟶ derivative couplings cubed ⟶ momenta cubed ⟶ tails!
  - Longitudinal polarization : $\boldsymbol{\varepsilon}_0$=p/M + O(M/E) ⟶ tails!

EFT RESULTS IN THE HIGGS AND EWK SECTORS

4l JHEP 07 (2021) 005

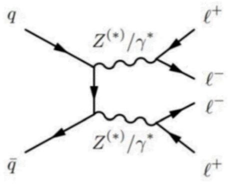
ATL-PHYS-PUB-2021-010

H→Z*Z



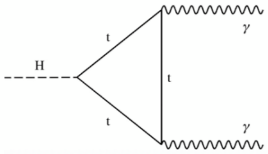
H→4l EPJC 80 (2020) 957
H→4l PRD 104, 052004 (2021)

ZZ



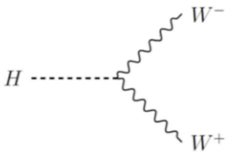
ZZ* EPJC 81 (2021) 200

H→γγ



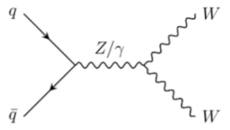
arxiv:2202.00487

H→W*W



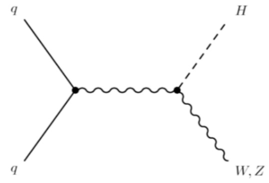
H→WW, eμ 36/fb
EPJC sub. arXiv:210913808

W±W∓



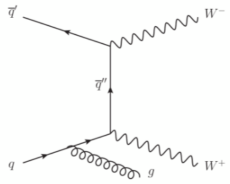
W±W∓
PRD 102, 092001 (2020)

W/Z+H (H→bb)



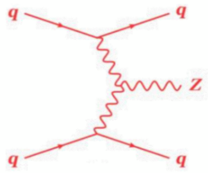
resolved EPJC 81 (2021) 178
boosted PLB 816 (2021) 136204

W±W∓ (+ ≥ 1 jet)



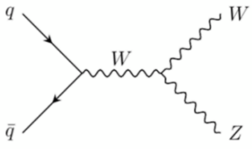
JHEP 06 (2021) 003
PRD102, 092001 (2020)

VBF Z + jj



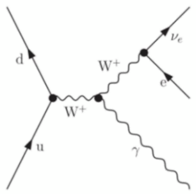
EPJC 81(2021)163

WZ



CMS-SMP-20-0014

Wγ



PRD sub.
CMS-SMP-20-005

EFT RESULTS IN THE HIGGS AND EWK SECTORS

4l JHEP 07 (2021) 005

ATL-PHYS-PUB-2021-010

H→Z*Z

O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$
O_{HG}	$HH^\dagger G^A_{\mu\nu} G^{\mu\nu A}$
O_{HW}	$HH^\dagger W^l_{\mu\nu} W^{\mu\nu l}$
O_{HB}	$HH^\dagger B_{\mu\nu} B^{\mu\nu}$
O_{HWB}	$HH^\dagger \tau^l W^l_{\mu\nu} B^{\mu\nu}$

+CP odd

H→4l EPJC 80 (2020) 957

H→4l PRD 104, 052004 (2021)

ZZ

aTGC

ZZ* EPJC 81 (2021) 200

H→γγ

O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$
O_{HG}	$HH^\dagger G^A_{\mu\nu} G^{\mu\nu A}$
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O_{HWB}	$HH^\dagger \tau^l W^l_{\mu\nu} B^{\mu\nu}$

+CP odd

arxiv:2202.00487

H→W*W

HC framework

CP even/odd

(O_{HW}, O_{HB} + CP odd)

H→WW, eμ 36/fb

EPJC sub. arXiv:2109l3808

W±W∓

$$\mathcal{O}_{\rm WWW} = \frac{c_{\rm WWW}}{\Lambda^2} W_{\mu\nu} W^{\nu\rho} W_\rho{}^\mu$$

$$\mathcal{O}_{\rm W} = \frac{c_{\rm W}}{\Lambda^2} (D^\mu \Phi)^\dagger W_{\mu\nu} (D^\nu \Phi)$$

$$\mathcal{O}_B = \frac{c_B}{\Lambda^2} (D^\mu \Phi)^\dagger B_{\mu\nu} (D^\nu \Phi)$$

+CP odd

W±W∓

PRD 102, 092001 (2020)

W/Z+H (H→bb)

c_{HWB}	$O_{HWB} = H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$
c_{HW}	$O_{HW} = H^\dagger H W^I_{\mu\nu} W^{\mu\nu}_I$
c_{Hq3}	$O^{(3)}_{Hq} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
c_{Hq1}	$O^{(1)}_{Hq} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
c_{Hu}	$O_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
c_{Hd}	$O_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
c_{dH}	$O_{dH} = (H^\dagger H)(\bar{q} d H)$

resolved EPJC 81 (2021) 178

boosted PLB 816 (2021) 136204

W±W∓ (+ ≥ 1 jet)

$$\mathcal{O}_{\rm WWW} = \frac{c_{\rm WWW}}{\Lambda^2} W_{\mu\nu} W^{\nu\rho} W_\rho{}^\mu$$

$$\mathcal{O}_{\rm W} = \frac{c_{\rm W}}{\Lambda^2} (D^\mu \Phi)^\dagger W_{\mu\nu} (D^\nu \Phi)$$

$$\mathcal{O}_B = \frac{c_B}{\Lambda^2} (D^\mu \Phi)^\dagger B_{\mu\nu} (D^\nu \Phi)$$

JHEP 06 (2021) 003

PRD102, 092001 (2020)

VBF Z + jj

$$\mathcal{O}_{\rm WWW} = \frac{c_{\rm WWW}}{\Lambda^2} W_{\mu\nu} W^{\nu\rho} W_\rho{}^\mu$$

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EPJC 81(2021)163

WZ

$$\mathcal{O}_{\rm WWW} = \frac{c_{\rm WWW}}{\Lambda^2} W_{\mu\nu} W^{\nu\rho} W_\rho{}^\mu$$

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+CP odd

CMS-SMP-20-0014

Wγ

$$\mathcal{O}_{\rm WWW} = \frac{c_{\rm WWW}}{\Lambda^2} W_{\mu\nu} W^{\nu\rho} W_\rho{}^\mu$$

PRD sub.

CMS-SMP-20-005

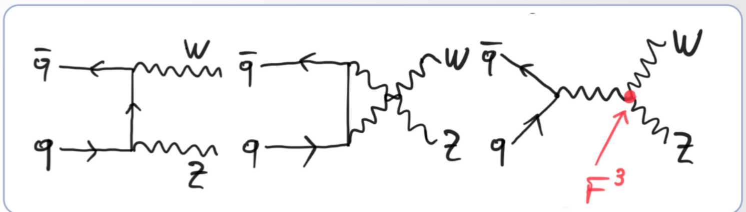
ELECTROWEAK MEASUREMENTS

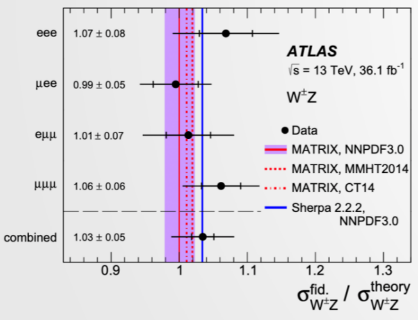
WZ PRODUCTION

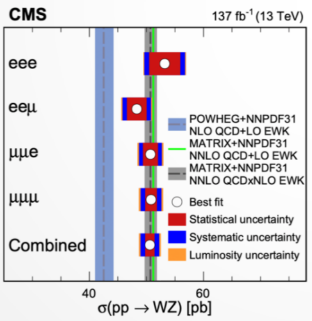
CMS SMP-20-014

ATLAS Eur. Phys. J. C 79 (2019) 535

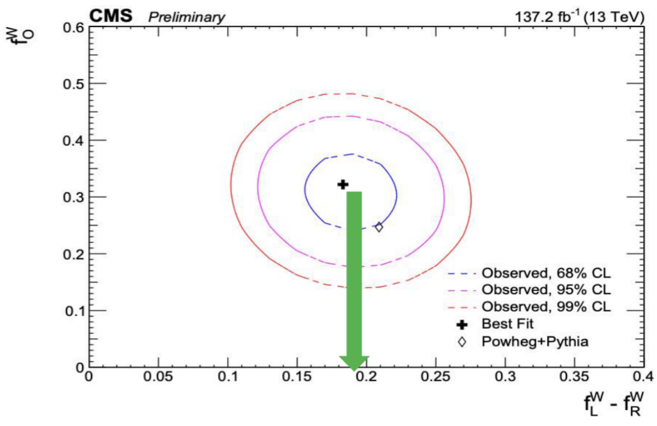
- WZ production at 13 TeV with leptonic final states (e and μ)
  - Comprehensive study of WZ production
  - Inclusive total and differential cross sections
  - Charge asymmetry and polarization
  - Boost into the WZ rest-frame and measure decay angles
- Run 2 observation of W_0 in WZ with 5.6σ (4.3σ exp.)







$50.6 \pm 0.8(\text{stat.}) \pm 1.5(\text{syst.}) \pm 1.1(\text{lumi.}) \pm 0.5(\text{theo.})\text{pb}$



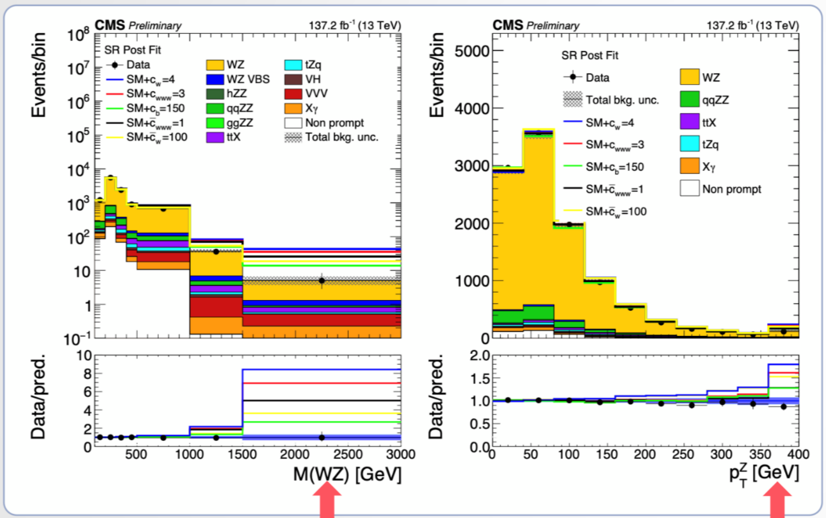
WZ PRODUCTION

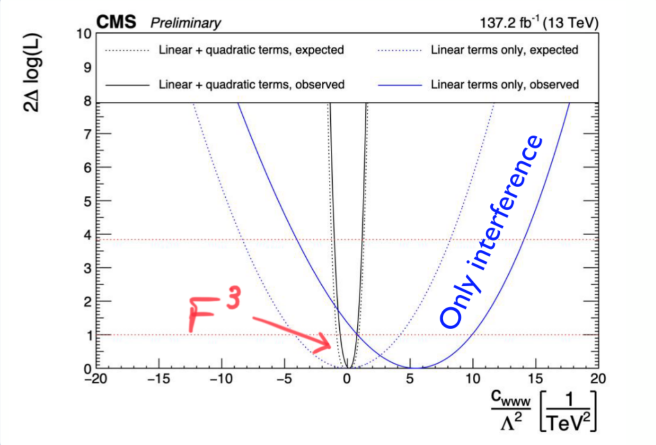
CMS SMP-20-014

ATLAS Eur. Phys. J. C 79 (2019) 535

- Search for anomalous triple gauge couplings

$$\mathcal{O}_W = \varepsilon_{IJK}\, W^I_{\mu\nu}\, W^{J,\nu\rho}\, W^{K,\mu}_{\rho}$$



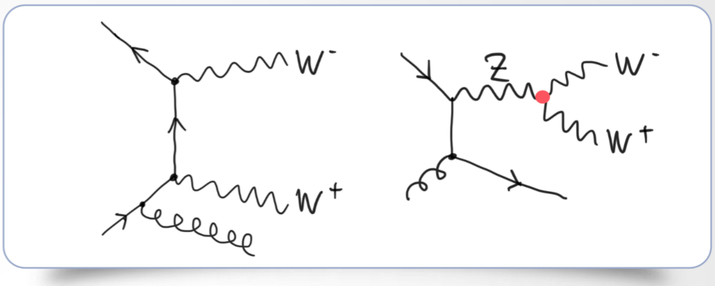


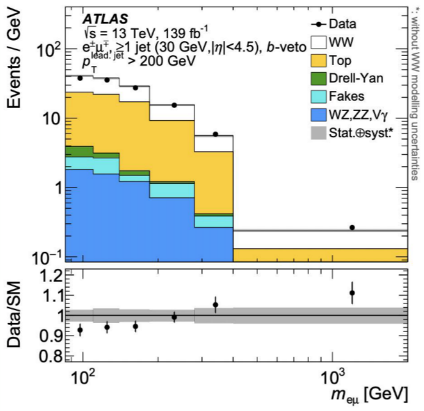
- Cubed field strengths lead to energy growth in the highest bis.
  - M(WZ) and P_T(Z). The last bins carry all the information. Luminosity and c.m.s energy translate into precison.
  - Limit: $-1.27 < C_{3W}/\Lambda^2 < 1.33\ \text{TeV}^{-2}$ @ 95%CL. Much reduced when looking only at the linear interference term!

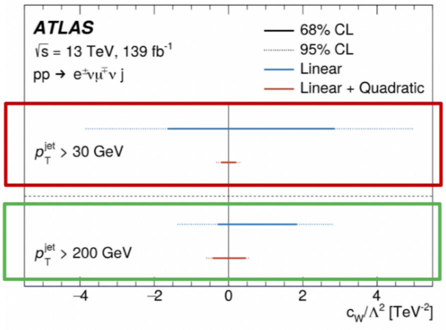
W±W∓ + 1JET PRODUCTION

JHEP 06 (2021) 003

- Inclusive and differentiation measurements of W⁺W⁻ production in association ≥ 1 jet
- eμ channel has negligible Drell-Yan background
- 12 kinematic variables are measured
  - leptonic and jet-related observables







← Helicity suppression

← Recovery

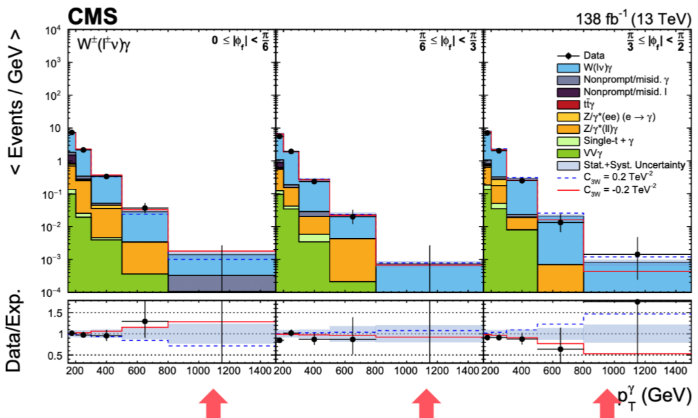
- Why the jet requirement? BSM interference cancels among helicities

$$\sigma = \sigma^{\mathrm{SM}} + \underbrace{C_{3\mathrm{W}}\sigma^{\mathrm{int.}}}_{\text{Cancellations among helicities}} + \underbrace{C_{3\mathrm{W}}^2\sigma^{\mathrm{BSM}}}_{\text{Same order as dim. 8}}$$

- hard jet (p_T> 200 GeV) requirement changes helicity composition

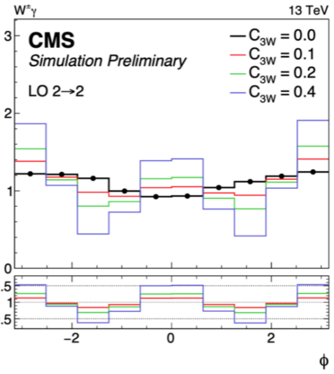
Wɣ PRODUCTION

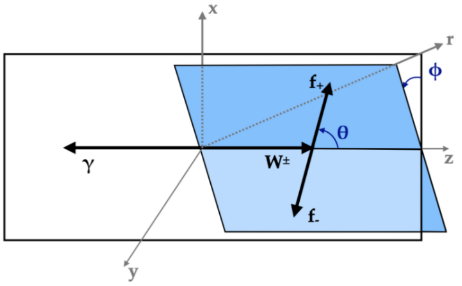
SMP-20-005



CP-even CP-odd CP-even

Interference resurrection arXiv:1708.07823





CP-even: $\cos(2\phi) \leftrightarrow \mathcal{O}_W$

CP-odd : $\sin(2\phi) \leftrightarrow \mathcal{O}_{\widetilde{W}}$

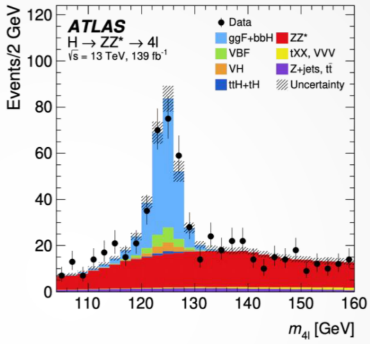
- Boosting to the diboson center-of-mass frame allows to reconstruct decay plan angle ϕ
- It's distribution carries information on BSM effects in the $W_{L/R}$ helicites.
- Binning p_T(ɣ) in ϕ recovers CP structure; facto 5-10: $-0.062 < C_{3W}/\Lambda^2 < 0.053$ TeV^{-2} → Λ_{BSM} ~5 TeV

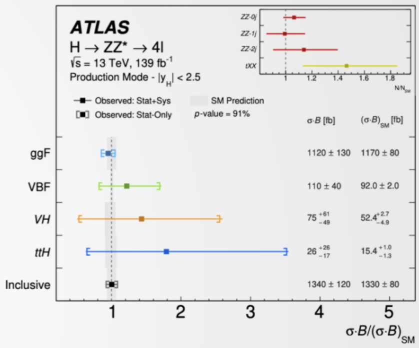
HIGGS MEASUREMENTS

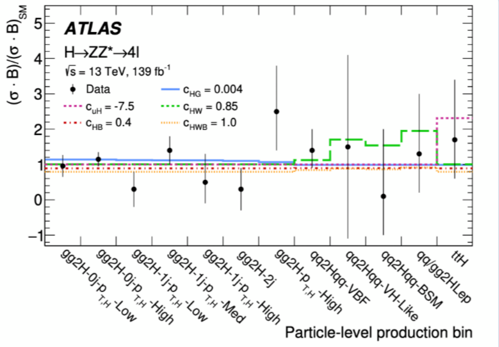
H→4 LEPTONS

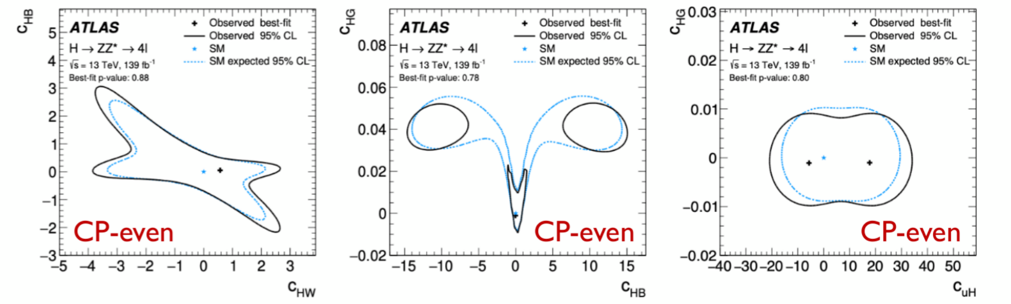
[arXiv:2004.03447]

- Measurement in production bins (STXS)
  - ggF, VBF, VH, ttH production
- Parametrize σ·B·A as a function of C_i
  - H→4l acceptance depends on C_{HW}, C_{HB}, C_{HWB}
- Includes the quadratic term Λ^{-4}
- No linear term in CP-Odd couplings









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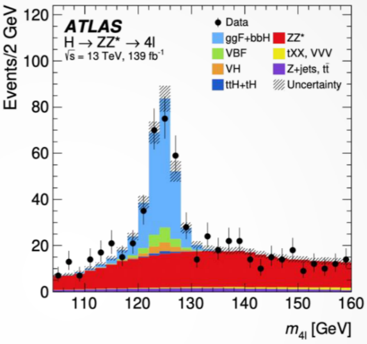
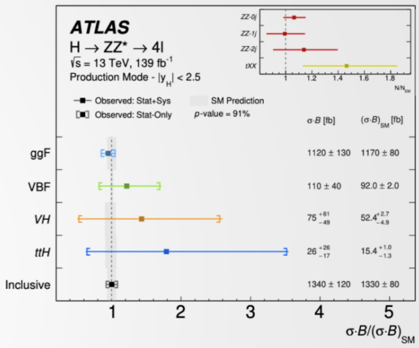
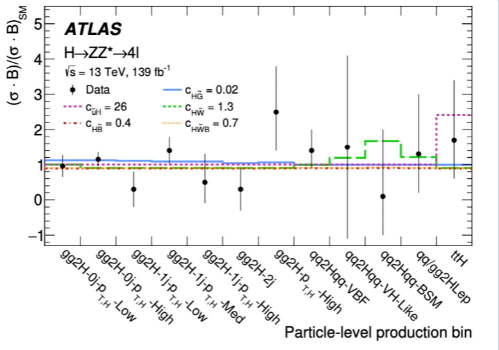
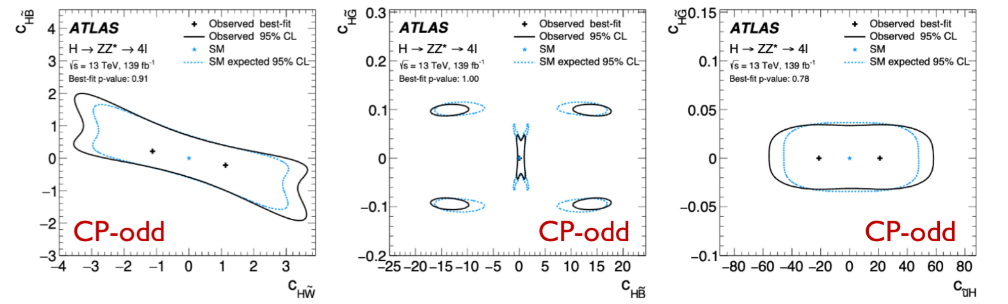
- No linear term in CP-Odd couplings







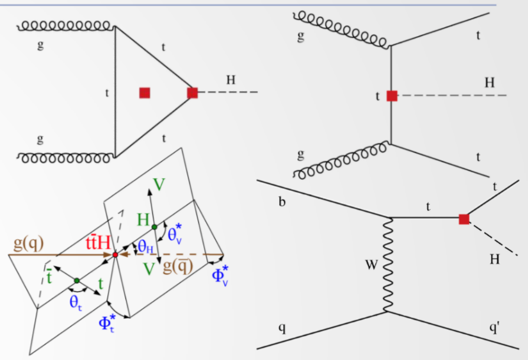


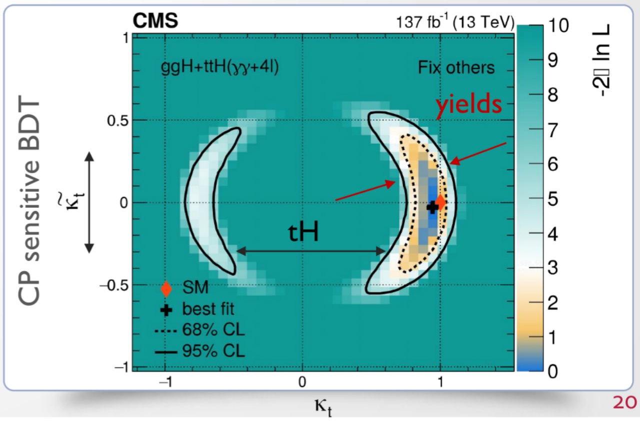
H→4 LEPTONS

[arxiv:2104:12152] [arxiv:2003:10866]

Sketches from Jack C. MacDonald

- Dedicated EFT measurement in H → 4l channel
  - Simulation includes acceptance and efficiency effects
  - Study HVV, Hgg, and Htt interactions + CP-odd counterparts
- ME method used to optimise each analysis category separately:
  - *ggH, VBF, VH, tH/ttH, bbH* production all with *H* → VV→ *4l* decay
  - exploits decay angles & combined with t/tt(H→γγ)
- Uses AC parametrisation respecting SU(2) × U(1)
  - mapped to SM-EFT Warsaw basis
- Complementary information in t(t)H and ggH productions for κ_t , point-like ggH and CP-odd counterparts

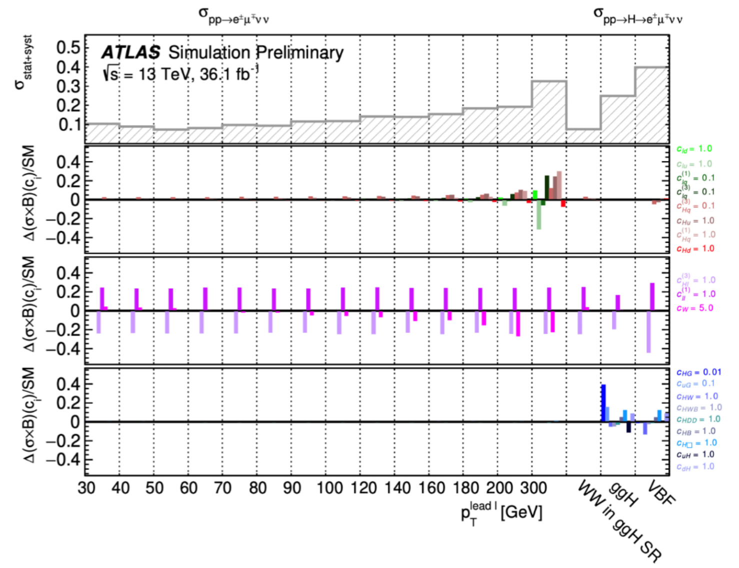




WW AND H → WW* COMBINATION (LEPTONIC)

ATL-PHYS-PUB-2021-010, 36fb^{-1}

- Preformed combined fit of
  1. signal strengths of ggH and VBF in H → WW*
  2. SM WW unfolded differential p_T(lead-.l) x-sec
- 20 SM-EFT operators affecting the measurements
- physics-guided eigenbasis probes 8 directions
  - Assume a U(3)^5 flavor symmetry
- Stepping stone for more global EFT combinations
- STXS combination: [ATLAS-CONF-2020-053]



WW AND H ⟶ WW* COMBINATION

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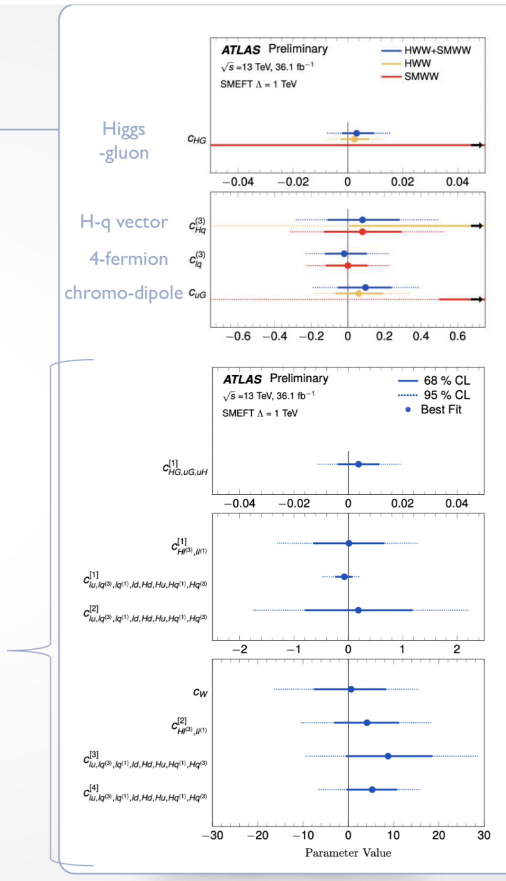
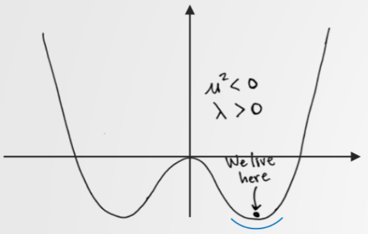


SMEFT AND GOLDSTONE BOSON EQUIVALENCE

[Physics Briefing Book]

$$V(\varphi) = \mu^2 \left(\varphi^\dagger \varphi\right) + \tfrac{1}{2}\lambda \left(\varphi^\dagger \varphi\right)^2$$



h^0 - not measureable
h^1 - zero in the vacuum
h^2 - measured (m^2_H)
h^3, h^4 – future facilities

from Peskin Schroeder:

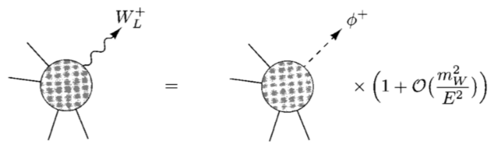
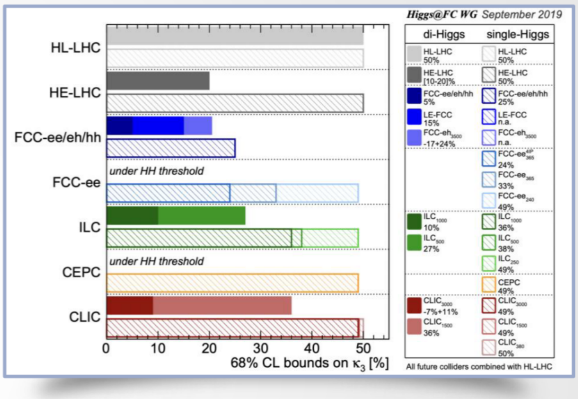


Figure 21.3. The Goldstone boson equivalence theorem. At high energy, the amplitude for emission or absorption of a longitudinally polarized massive gauge boson becomes equal to the amplitude for emission or absorption of the Goldstone boson that was eaten by the gauge boson.



- The h³ is constrained in di-Higgs final states. Important FOM of HL-LHC and future facilities.
- Higgs self-coupling is modified by $(\boldsymbol{\varphi}^\dagger\boldsymbol{\varphi})^3$ and $\partial_\mu(\boldsymbol{\varphi}^\dagger\boldsymbol{\varphi})\partial^\mu(\boldsymbol{\varphi}^\dagger\boldsymbol{\varphi})$ terms

$$\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} \omega_1 + i\omega_2 \\ h + v + i\omega_3 \end{pmatrix}$$

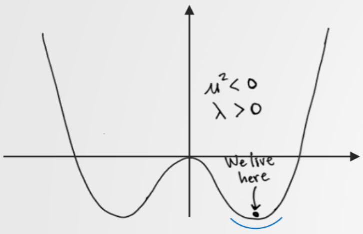
$\partial_\mu\omega \longrightarrow W^\pm_{\mu,L}, Z_{\mu,L} \longrightarrow$ energy growth via GBE
h $\longrightarrow$ Higgs field
v $\longrightarrow$ vacuum expectation value

[[2105.11500](2105.11500)]

SMEFT AND GOLDSTONE BOSON EQUIVALENCE

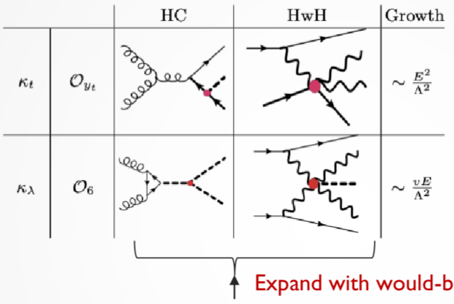
[PRL 123 (2019) 18, 181801]

$$V(\varphi) = \mu^2 \left(\varphi^\dagger \varphi\right) + \tfrac{1}{2}\lambda \left(\varphi^\dagger\varphi\right)^2$$



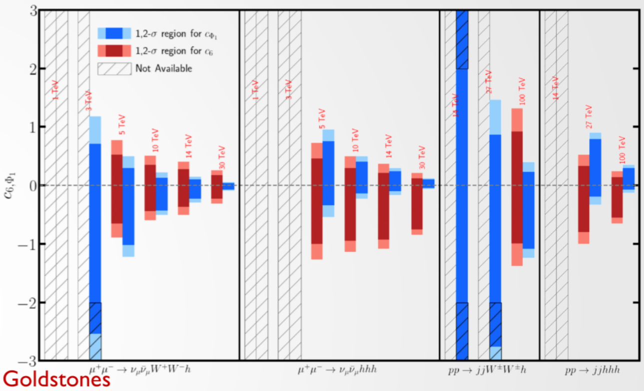
h^0 - not measureable
h^1 - zero in the vacuum
h^2 - measured (m^2_H)
h^3, h^4 – future facilities

"Higgs without Higgs"



		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$

Expand with would-be Goldstones



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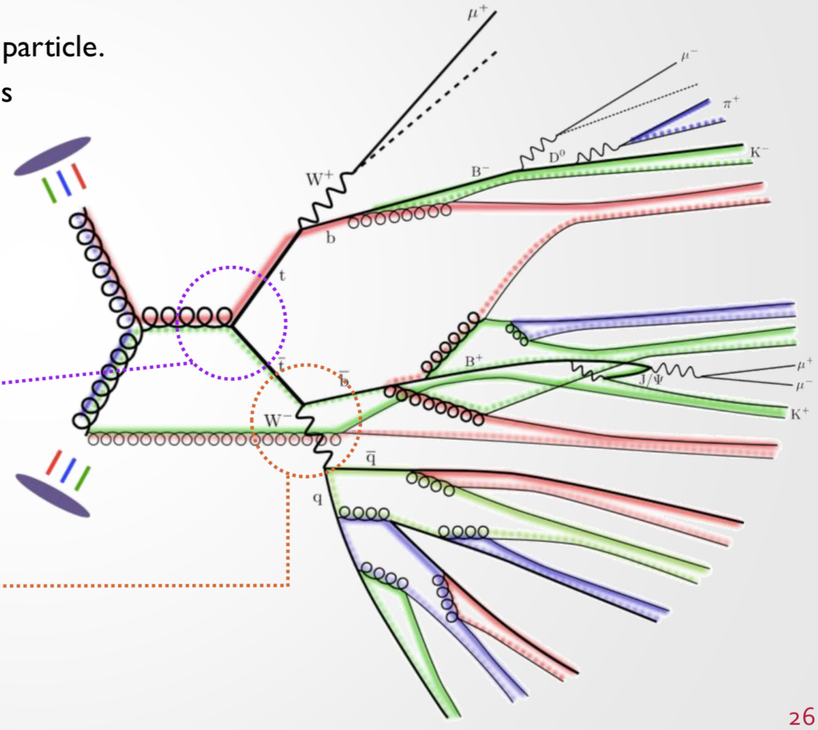
$\partial_\mu\omega \longrightarrow W^\pm_{\mu,L}, Z_{\mu,L} \longrightarrow$ energy growth via GBE
h $\longrightarrow$ Higgs field
v $\longrightarrow$ vacuum expectation value

- Goldstone Boson Equivalence: SM-EFT effects in V_L amplitudes grow with energy. E.g., pp →jjV_LV_Lh

TOP QUARK MEASUREMENTS

TOP QUARK PROPERTIES IN CONTEXT

- The top quark is the heaviest known fundamental particle. Interesting properties/problems appear at all scales



- x-sec measurements at high precision, interplay with PDFs

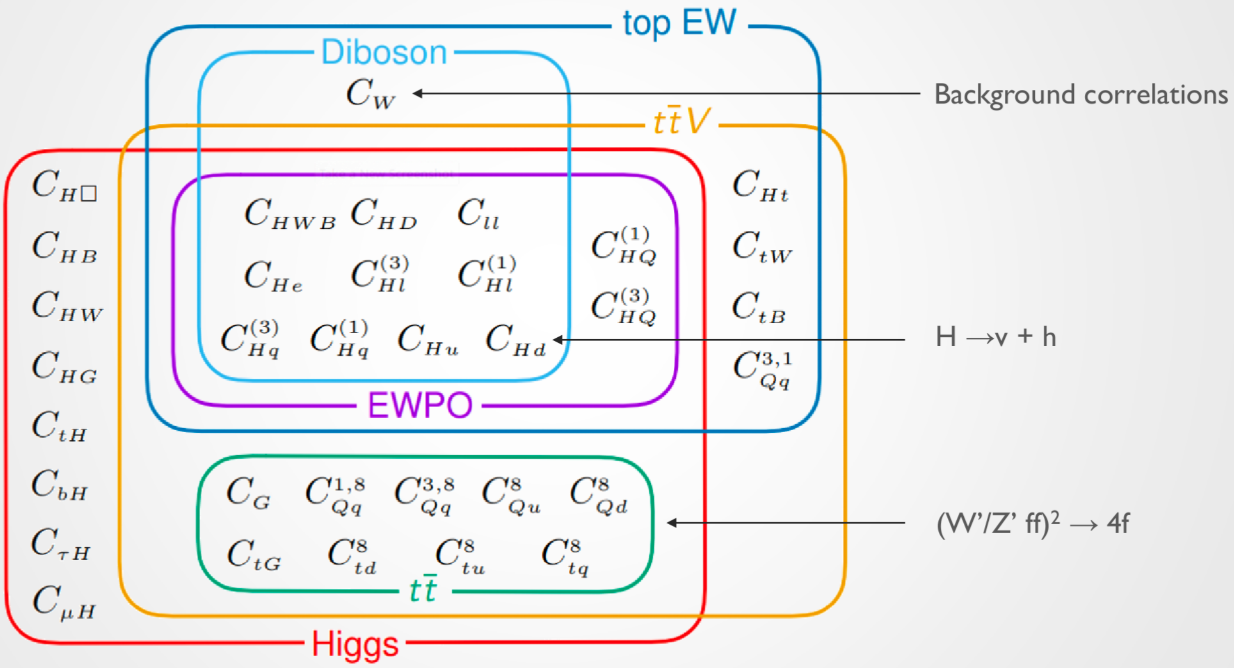
- mass measurements, hadronization effects, color reconnection, UE, vacuum stability

- weak interactions, vector couplings and dipole moments

- spin correlation, anomalous strong interactions

TOPS, HIGGS, VECTOR BOSONS

J. Ellis et.al, JHEP 04 (2021) 279



OPERATORS AND PHYSICS IMPLICATIONS

SMEFT Lagrangian

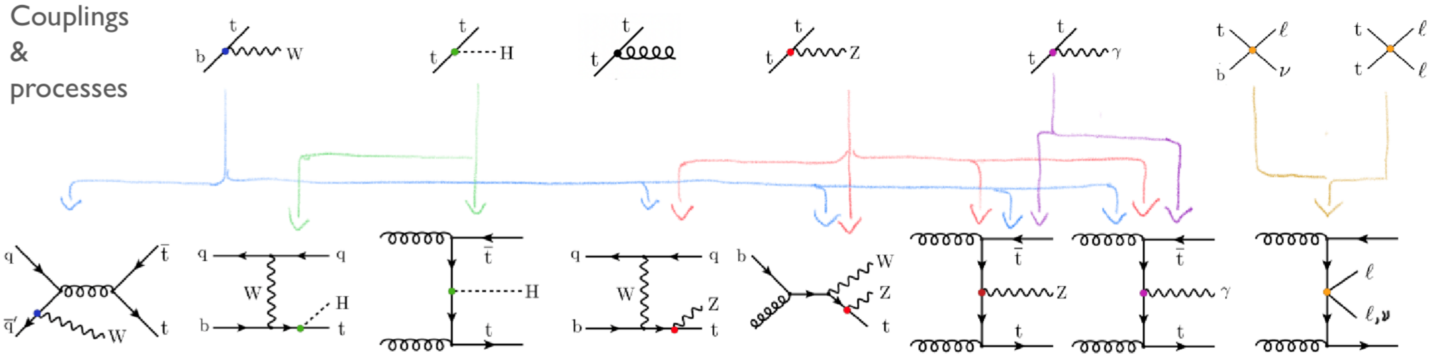
$$\mathcal{L} \;=\; \mathcal{L}_{4,\mathrm{SM}} + \frac{1}{\Lambda_{\delta L\neq 0}}\mathcal{L}_5 + \boxed{\frac{1}{\Lambda^2}\mathcal{L}_6} + \frac{1}{\Lambda^2_{\delta B\neq 0}}\mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L\neq 0}}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \ldots$$

Operators

$\mathcal{O}_{\phi\mathrm{tb}}$	$i(\tilde\phi\, D_\mu\, \phi)(\bar t_R\, \gamma^\mu\, b_R) + \mathrm{h.c.}$	$\mathcal{O}_{\mathrm{tB}}$	$i(\bar q_L \sigma^{\mu\nu}\, t_R)\,\tilde\phi\, B_{\mu\nu} + \mathrm{h.c.}$	$\mathcal{O}^{(3)}_{\phi q_L}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \tau_I \phi)(\bar q_L\, \gamma^\mu\, \tau^I q_L)$	$\mathcal{O}^1_{qq}$	$(\bar q_L\, \gamma_\mu\, q_L)(\bar q_L\, \gamma^\mu q_L)$
$\mathcal{O}_{\mathrm{t}\phi}$	$(\phi^\dagger\phi)\; \bar q_L\, t_R\, \tilde\phi + \mathrm{h.c.}$	$\mathcal{O}_{\mathrm{tG}}$	$i(\bar q_L \sigma^{\mu\nu} \lambda^a\, t_R)\, \tilde\phi\, G^a_{\mu\nu} + \mathrm{h.c.}$	$\mathcal{O}^{(1)}_{\phi q_L}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar q_L\, \gamma^\mu\, q_L)$	$\mathcal{O}^8_{qq}$	$(\bar q_L\, \gamma_\mu T^A\, q_L)(\bar q_L\, \gamma^\mu T^A\, q_L)$

…

Couplings & processes



Parametrized predictions

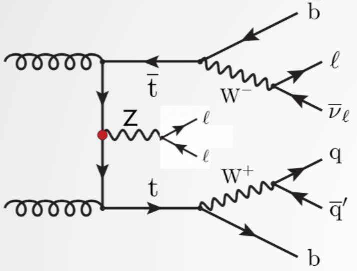
$$N\left(\frac{\vec c}{\Lambda^2}\right) \;= S_0 + \sum_j S_{1j}\frac{c_j}{\Lambda^2} + \sum_j S_{2j}\frac{c_j^2}{\Lambda^4} + \sum_{j,k} S_{3jk}\frac{c_j}{\Lambda^2}\frac{c_k}{\Lambda^2}$$

ELECTROWEAK TOP COUPLINGS

[JHEP 03 (2020) 056]

[EPJC 81 (2021) 737]

- associate production of tt with Z bosons



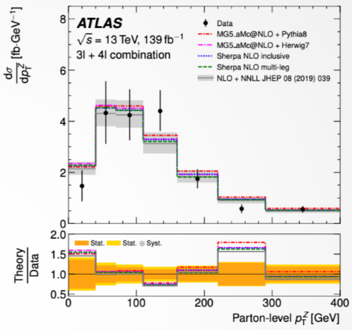
- interpret x-sec measurements
  - combine 3+4 leptons
  - differential x-sec $p_T(Z)$, cos(**θ***), y(Z)
  - significant WZ background normalized to data!

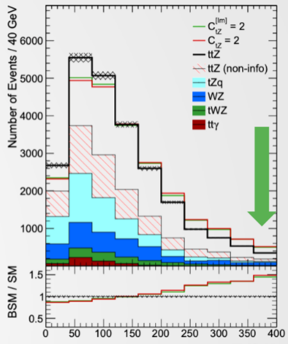
$$\sigma(t\bar{t}Z) \;=\; 0.95 \pm 0.05\,(\mathrm{stat}) \pm 0.06\,(\mathrm{syst})\,\mathrm{pb}$$

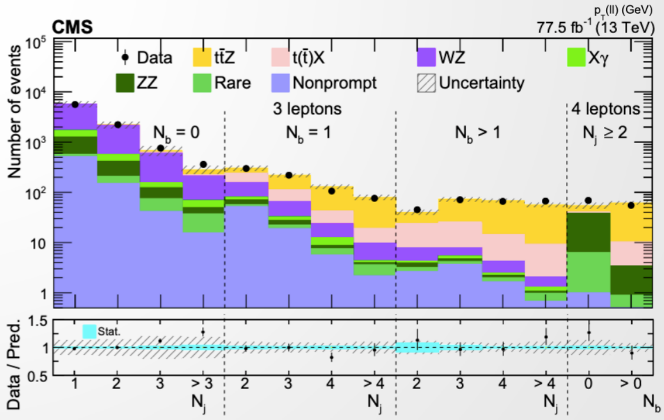
$$\sigma(t\bar{t}Z) \;=\; 0.99 \pm 0.05\;(\mathrm{stat.}) \pm 0.08\;(\mathrm{syst.})\;\mathrm{pb}$$

- SM NLO+EWK: $\sigma(\mathrm{SM}) = 0.\cancel{839} \pm 0.101\mathrm{pb}$

0.88 (ttɣ interference, off-shell)





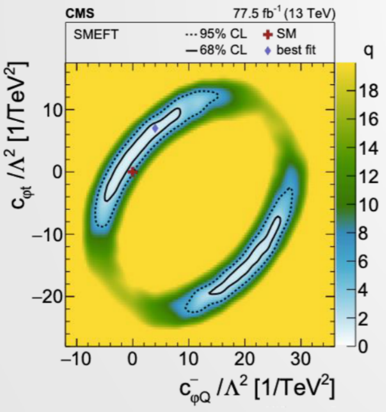


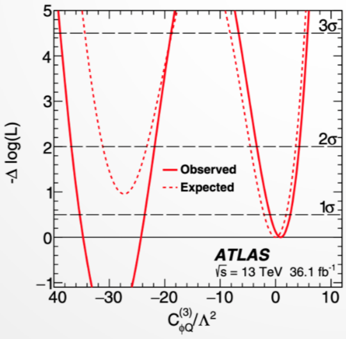
ELECTROWEAK TOP COUPLINGS

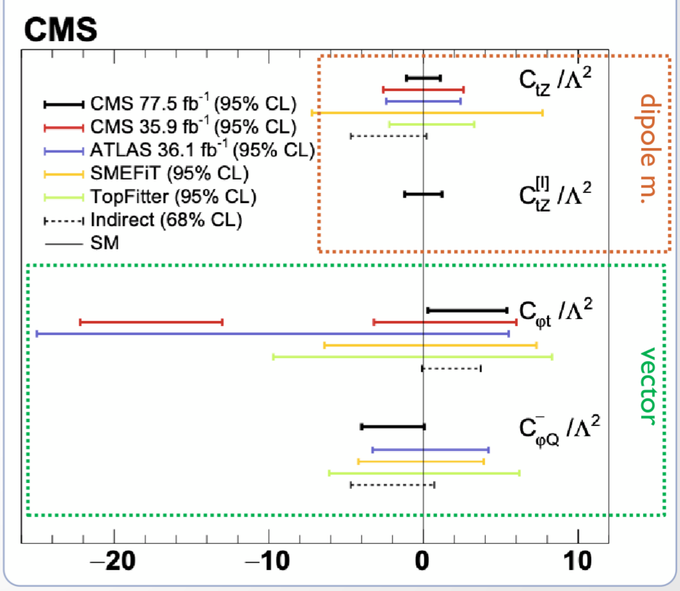
[JHEP 03 (2020) 056]

[PRD 99, 072009 (2019)]

- vector-type couplings have large SM interference
- EFT tensor structure induces EWK dipole moments (quadratic)
- stringent direct constraints on the top-Z vector coupling and the EWK dipole moments
  - differential measurement improves sensitivity by factor ~5







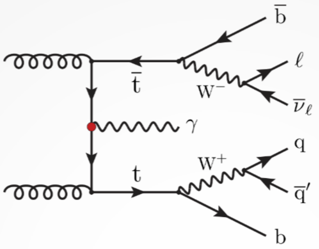
- Indirect limits: LEP Z pole, B→$X_s\gamma$

TT+ɣ DIFFERENTIAL CROSS SECTION

CMS-PAS-TOP-18-010

JHEP 09 (2020) 049

- SM gauge symmetry imposes linear relations among anomalous interactions
- Top dipole moments effect ttɣ stronger than ttZ

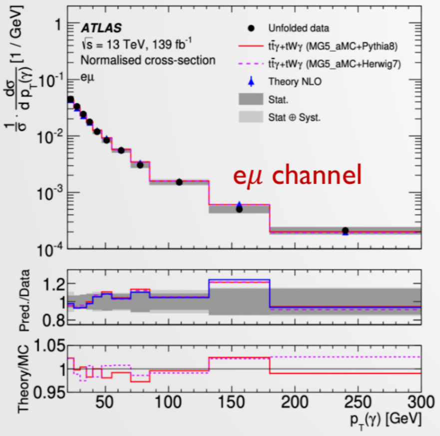


$$c_{tZ} = \mathrm{Re}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right)$$

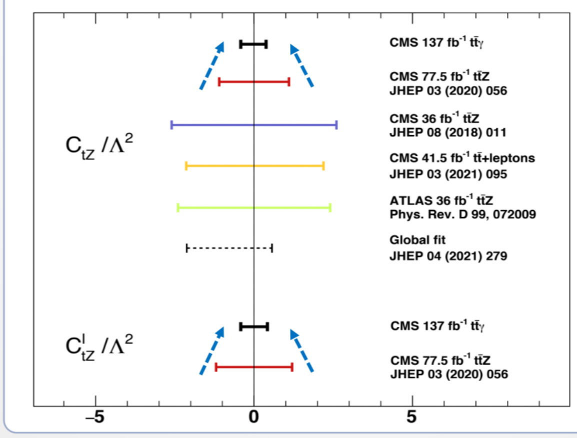
related by SU(2)$_L$⊗U(1)$_Y$

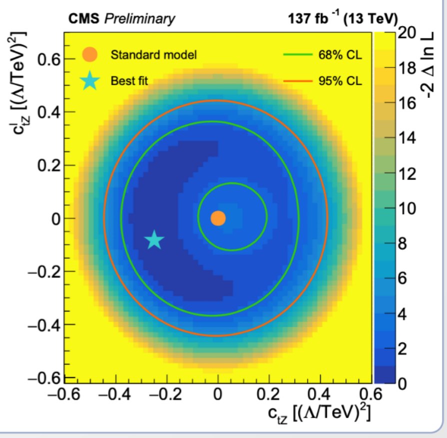
Constrained by W helicity fractions

$$c_{t\gamma} = \mathrm{Re}\left(\cos\theta_W C_{uB}^{(33)} + \sin\theta_W C_{uW}^{(33)}\right)$$



$e\mu$ channel



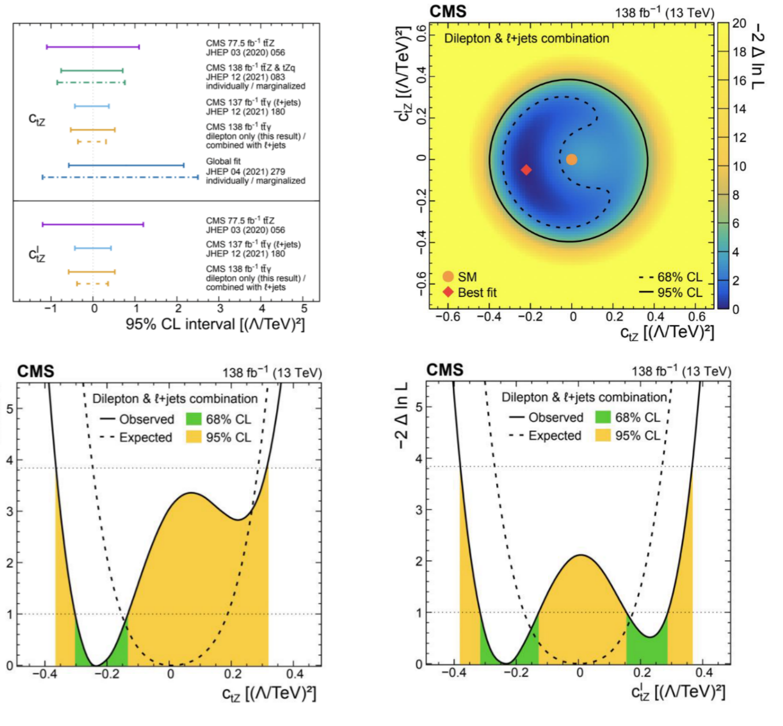


TT+Ɣ 1L/2L COMBINATION

[CMS-TOP-18-010]

[CMS-TOP-21-004]

- Latest result: ttɣ 1l/2l EFT combination
- Measure real and imaginary part of c_{tZ}
- Best current limits

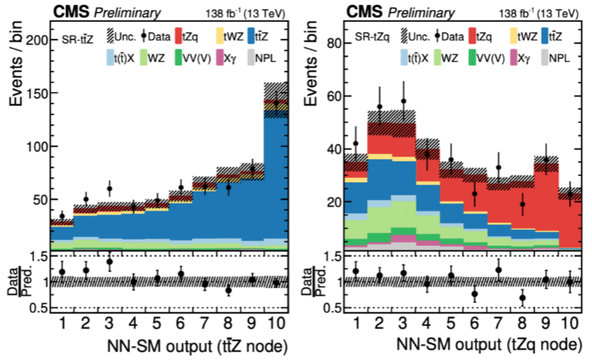


			Dilepton & ℓ+jets combination	
	Wilson coefficient		68% CL interval $[(\Lambda/\text{TeV})^2]$	95% CL interval $[(\Lambda/\text{TeV})^2]$
Expected	c_{tZ}	$c^I_{tZ} = 0$	$[-0.15, 0.19]$	$[-0.25, 0.29]$
		profiled	$[-0.15, 0.19]$	$[-0.25, 0.29]$
	c^I_{tZ}	$c_{tZ} = 0$	$[-0.17, 0.18]$	$[-0.27, 0.27]$
		profiled	$[-0.18, 0.18]$	$[-0.27, 0.27]$
Observed	c_{tZ}	$c^I_{tZ} = 0$	$[-0.30, -0.13]$	$[-0.36, 0.31]$
		profiled	$[-0.30, 0.00]$	$[-0.36, 0.31]$
	c^I_{tZ}	$c_{tZ} = 0$	$[-0.32, -0.13]$ $\cup [0.16, 0.29]$	$[-0.38, 0.36]$
		profiled	$[-0.28, 0.23]$	$[-0.36, 0.35]$

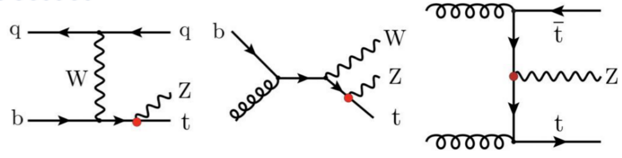
MVA-EFT SEARCH IN ≥3L FINAL STATES

[CMS-TOP-21-001]

- Full Run II Luminosity 138/fb
- Main processes: tZq/ttZ/tWZ
  - Leptonically decaying top + Z boson candidate
  - Main sensitivity: from SR-3l
- Extensive use of MVAs



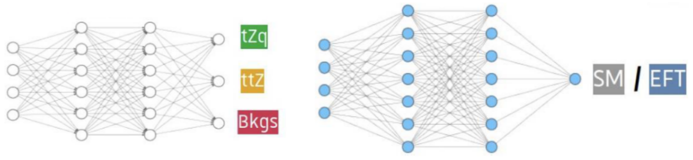
Processes



Operators

Weak top dipole interactions	$\mathcal{O}_{\mathrm{tZ}}$	$\mathrm{Re}\{-s_{\mathrm{W}}c_{\mathrm{uB}}^{(33)}+c_{\mathrm{W}}c_{\mathrm{uW}}^{(33)}\}$
	$\mathcal{O}_{\mathrm{tW}}$	$\mathrm{Re}\{c_{\mathrm{uW}}^{(33)}\}$
LH vector couplings	$\mathcal{O}_{\varphi\mathrm{Q}}^{3}$	$c_{\varphi\mathrm{q}}^{3(33)}$
	$\mathcal{O}_{\varphi\mathrm{Q}}^{-}$	$c_{\varphi\mathrm{q}}^{1(33)}-c_{\varphi\mathrm{q}}^{3(33)}$
RH vector couplings	$\mathcal{O}_{\varphi\mathrm{t}}$	$c_{\varphi\mathrm{u}}^{(33)}$

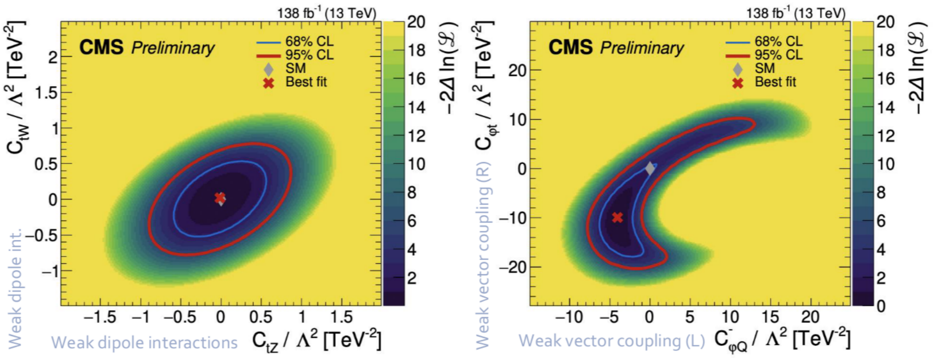
MVA topologies



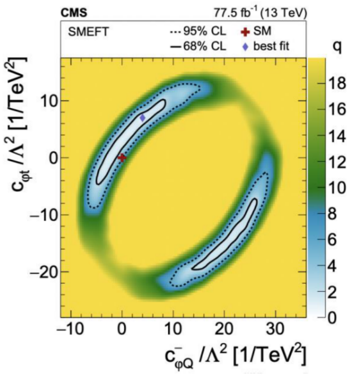
MVA-EFT SEARCH IN ≥3L FINAL STATES

[CMS-TOP-21-001]

[CMS-TOP-18-009]



Compare to differential $p_T(Z)$ measurement with 77.5fb-1

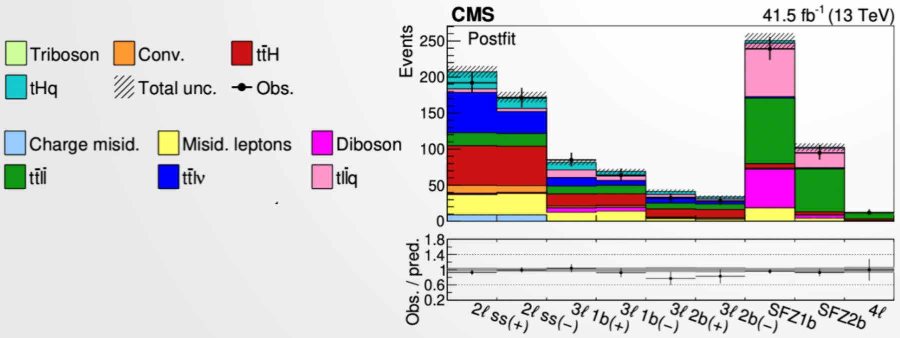


- Better limits than eariler results from the ttZ cross section measurement
- Agreement within 2σ in general

TOP QUARKS WITH ADDITIONAL LEPTONS

[CMS-TOP-19-001]

- Testing 16 operators with 2017 data; two groups
  - ttV(V): affecting: ttH, tHq, ttZ, ttW
  - with 7 four-fermion operators : ttll, ttlν
- 35 signal "inclusive" regions
  - lepton channels split further in jet and b-tag multiplicities
  - 2l (same-sign): ttW and ttH processes
  - 3l (with and w/o Z candidate): ttZ(3l), tZq (ttll, tllq, ttlν)
  - 4l (no further binning): ttZ(4l)



2 quarks + bosons

Operator	Definition	Lead processes affected
$^{\ddagger}O_{\mathrm{u}\varphi}^{(ij)}$	$\bar{\mathrm{q}}_i\mathrm{u}_j\tilde{\varphi}\,(\varphi^{\dagger}\varphi)$	$\mathrm{t\bar{t}H}$, tHq
$O_{\varphi\mathrm{q}}^{1(ij)}$	$(\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(\bar{\mathrm{q}}_i\gamma^{\mu}\mathrm{q}_j)$	$\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}l\bar{l}}$, tHq, $\mathrm{tl\bar{l}q}$
$O_{\varphi\mathrm{q}}^{3(ij)}$	$(\varphi^{\dagger}i\overleftrightarrow{D}^{I}_{\mu}\varphi)(\bar{\mathrm{q}}_i\gamma^{\mu}\tau^{I}\mathrm{q}_j)$	$\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}l\bar{l}}$, tHq, $\mathrm{tl\bar{l}q}$
$O_{\varphi\mathrm{u}}^{(ij)}$	$(\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(\bar{\mathrm{u}}_i\gamma^{\mu}\mathrm{u}_j)$	$\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}l\bar{l}}$, $\mathrm{tl\bar{l}q}$
$^{\ddagger}O_{\varphi\mathrm{ud}}^{(ij)}$	$(\tilde{\varphi}^{\dagger}iD_{\mu}\varphi)(\bar{\mathrm{u}}_i\gamma^{\mu}\mathrm{d}_j)$	$\mathrm{t\bar{t}H}$, $\mathrm{tl\bar{l}q}$, tHq
$^{\ddagger}O_{\mathrm{uW}}^{(ij)}$	$(\bar{\mathrm{q}}_i\sigma^{\mu\nu}\tau^{I}\mathrm{u}_j)\,\tilde{\varphi}W^{I}_{\mu\nu}$	$\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}l\bar{l}}$, tHq, $\mathrm{tl\bar{l}q}$
$^{\ddagger}O_{\mathrm{dW}}^{(ij)}$	$(\bar{\mathrm{q}}_i\sigma^{\mu\nu}\tau^{I}\mathrm{d}_j)\,\varphi W^{I}_{\mu\nu}$	$\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}l\bar{l}}$, tHq, $\mathrm{tl\bar{l}q}$
$^{\ddagger}O_{\mathrm{uB}}^{(ij)}$	$(\bar{\mathrm{q}}_i\sigma^{\mu\nu}\mathrm{u}_j)\,\tilde{\varphi}B_{\mu\nu}$	$\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}l\bar{l}}$, tHq, $\mathrm{tl\bar{l}q}$
$^{\ddagger}O_{\mathrm{uG}}^{(ij)}$	$(\bar{\mathrm{q}}_i\sigma^{\mu\nu}T^{A}\mathrm{u}_j)\,\tilde{\varphi}G^{A}_{\mu\nu}$	$\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}l\bar{l}}$, tHq, $\mathrm{tl\bar{l}q}$

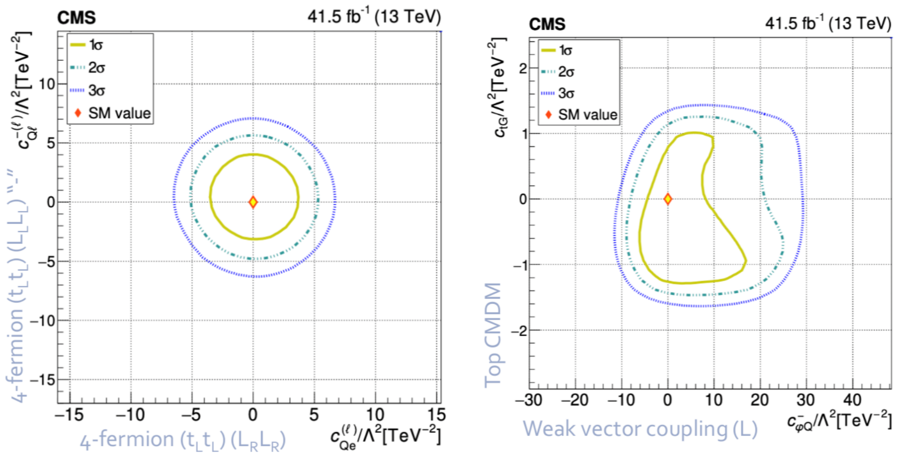
2 quarks + 2 leptons

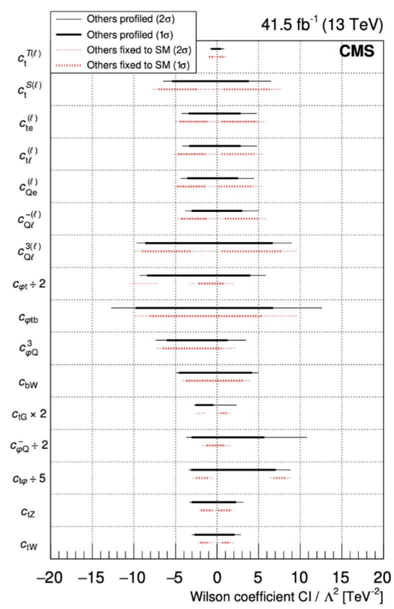
Operator	Definition	Lead processes affected
$O_{\ell\mathrm{q}}^{1(ijkl)}$	$(\bar{\ell}_i\gamma^{\mu}\ell_j)(\bar{\mathrm{q}}_k\gamma^{\mu}\mathrm{q}_{\ell})$	$\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}l\bar{l}}$, $\mathrm{tl\bar{l}q}$
$O_{\ell\mathrm{q}}^{3(ijkl)}$	$(\bar{\ell}_i\gamma^{\mu}\tau^{I}\ell_j)(\bar{\mathrm{q}}_k\gamma^{\mu}\tau^{I}\mathrm{q}_{\ell})$	$\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}l\bar{l}}$, $\mathrm{tl\bar{l}q}$
$O_{\ell\mathrm{u}}^{(ijkl)}$	$(\bar{\ell}_i\gamma^{\mu}\ell_j)(\bar{\mathrm{u}}_k\gamma^{\mu}\mathrm{u}_{\ell})$	$\mathrm{t\bar{t}l\bar{l}}$
$O_{\mathrm{e\bar{q}}}^{(ijkl)}$	$(\bar{\mathrm{e}}_i\gamma^{\mu}\mathrm{e}_j)(\bar{\mathrm{q}}_k\gamma^{\mu}\mathrm{q}_{\ell})$	$\mathrm{t\bar{t}l\bar{l}}$, $\mathrm{tl\bar{l}q}$
$O_{\mathrm{eu}}^{(ijkl)}$	$(\bar{\mathrm{e}}_i\gamma^{\mu}\mathrm{e}_j)(\bar{\mathrm{u}}_k\gamma^{\mu}\mathrm{u}_{\ell})$	$\mathrm{t\bar{t}l\bar{l}}$
$^{\ddagger}O_{\ell\mathrm{equ}}^{1(ijkl)}$	$(\bar{\ell}_i\mathrm{e}_j)\;\varepsilon\;(\bar{\mathrm{q}}_k\mathrm{u}_{\ell})$	$\mathrm{t\bar{t}l\bar{l}}$, $\mathrm{tl\bar{l}q}$
$^{\ddagger}O_{\ell\mathrm{equ}}^{3(ijkl)}$	$(\bar{\ell}_i\sigma^{\mu\nu}\mathrm{e}_j)\;\varepsilon\;(\bar{\mathrm{q}}_k\sigma_{\mu\nu}\mathrm{u}_{\ell})$	$\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}l\bar{l}}$, $\mathrm{tl\bar{l}q}$

TOP QUARKS WITH ADDITIONAL LEPTONS

[CMS-TOP-19-001]

- Good agreement of all WCs with the SM prediction
  - c_{tW}, $c_{t\phi}$, c_{tG} just outside the 2σ when all other WC are zero



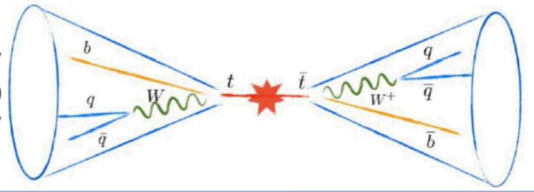


BOOSTED TOP QUARK PAIRS

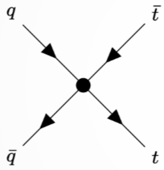
Hadronic [ATLAS-CONF-2021-050]
l+jets [ATLAS-CONF-2021-031]

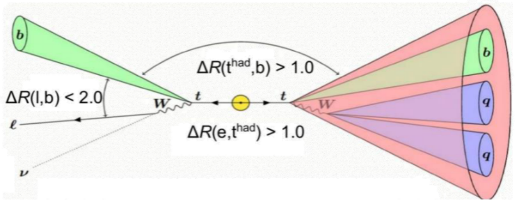
- Boosted top quark 0l/1l probe
- DNN top tagger on R=1 jets
- Systematically probe 4Q ops
  - Results: SM alive
  - 2-light-2-heavy 4-fermion contact interactions
  - chromo-dipole c_{tG}

$p_{T,j1} > 500$ GeV
$|\eta_{j1}|<2.0$
$|m_{j1}-172.5| < 50$ GeV

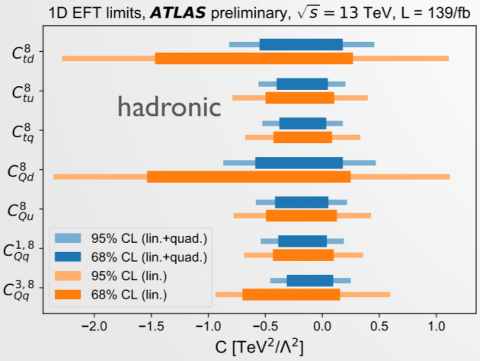


$p_{T,j2} > 500$ GeV
$|\eta_{j2}|<2.0$
$|m_{j2}-172.5| < 50$ GeV

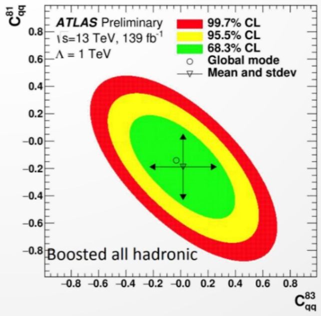




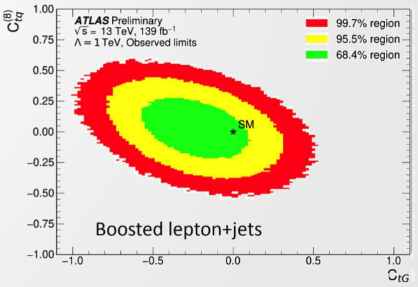
$p_T > 355$ GeV
$|\eta|<2.0$
$|m-170|<150$



$(\bar{t}\gamma^{\mu}T^{A}t)(\bar{d}_i\gamma_{\mu}T^{A}d_i)$
$(\bar{t}\gamma_{\mu}T^{A}t)(\bar{u}_i\gamma^{\mu}T^{A}u_i)$
$(\bar{q}_i\gamma^{\mu}T^{A}q_i)(\bar{t}\gamma_{\mu}T^{A}t)$
$(\bar{Q}\gamma^{\mu}T^{A}Q)(\bar{d}_i\gamma_{\mu}T^{A}d_i)$
$(\bar{Q}\gamma^{\mu}T^{A}Q)(\bar{u}_i\gamma_{\mu}T^{A}u_i)$
$(\bar{Q}\gamma_{\mu}T^{A}Q)(\bar{q}_i\gamma^{\mu}T^{A}q_i)$
$(\bar{Q}\gamma_{\mu}T^{A}\tau^{I}Q)(\bar{q}_i\gamma^{\mu}T^{A}\tau^{I}q_i)$



Boosted all hadronic

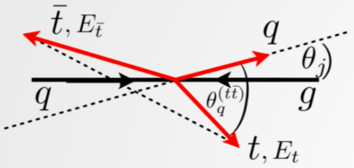


Boosted lepton+jets

ENERGY ASYMMETRY

[2110.05453]

- Asymmetry at tree-level in 137/fb tt+1j events.

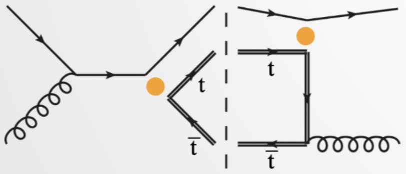


$$A_E(\theta_j) = \frac{\sigma^{opt}(\Delta E > 0) - \sigma^{opt}(\Delta E < 0)}{\sigma^{opt}(\Delta E > 0) + \sigma^{opt}(\Delta E < 0)}$$

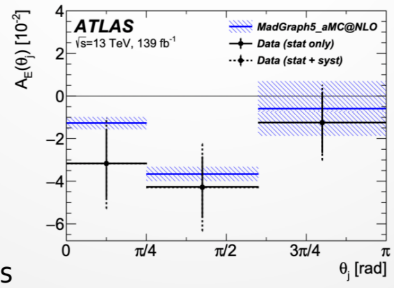
$$\sigma^{opt} = \sigma(\theta_j \,|\, y_{t\bar{t}j} > 0) + \sigma(\pi - \theta_j \,|\, y_{t\bar{t}j} < 0)$$

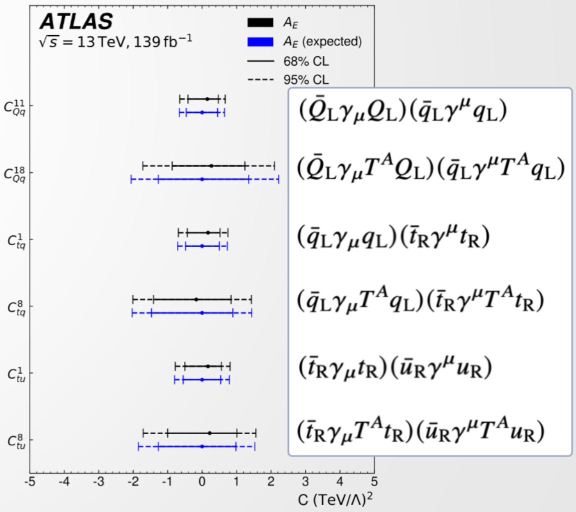
$$\Delta E = E_t - E_{\bar{t}}$$

  - A$_E$: difference in probability of top and anti-top quarks to have the higher energy as a function the jet scattering angle $\boldsymbol{\theta}_j$ with respect to the beam axis.
  - boosted l+jets final state with p$_T$ > 100 GeV extra
- Sensitive to 4q operator insertions



- $A_E^2 = -0.043 \pm 0.020$ agrees with SM
- Limits placed on 4-fermion operators





$(\bar{Q}_L\gamma_\mu Q_L)(\bar{q}_L\gamma^\mu q_L)$

$(\bar{Q}_L\gamma_\mu T^A Q_L)(\bar{q}_L\gamma^\mu T^A q_L)$

$(\bar{q}_L\gamma_\mu q_L)(\bar{t}_R\gamma^\mu t_R)$

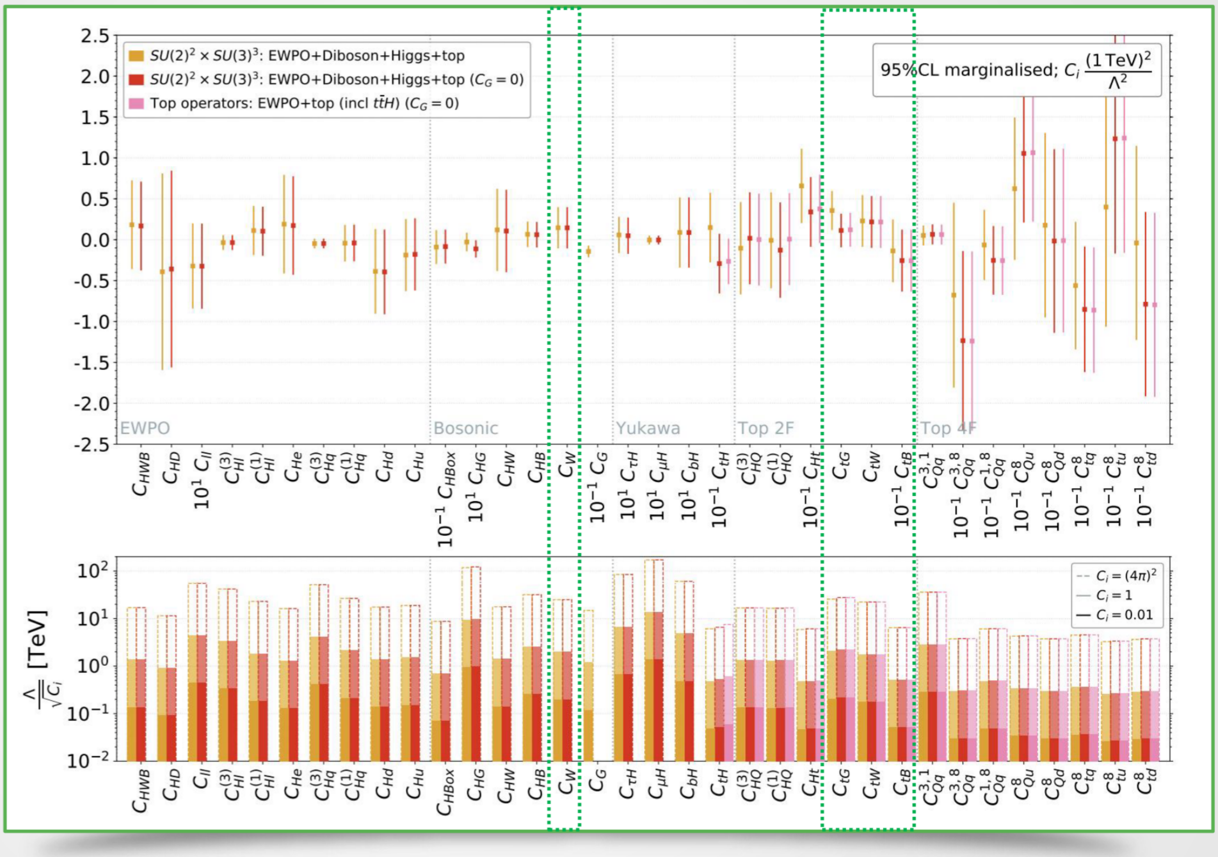
$(\bar{q}_L\gamma_\mu T^A q_L)(\bar{t}_R\gamma^\mu T^A t_R)$

$(\bar{t}_R\gamma_\mu t_R)(\bar{u}_R\gamma^\mu u_R)$

$(\bar{t}_R\gamma_\mu T^A t_R)(\bar{u}_R\gamma^\mu T^A u_R)$

GLOBAL PERSPECTIVE

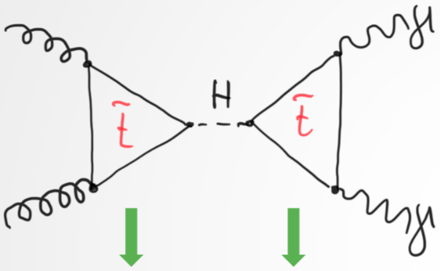
- First global fits [JHEP 04 279 (2021)] [SMEFit]
- EWK, Higgs, Top, Diboson, EWPT
- Bottom pad: Most operators in 1-10 TeV regime
- 3σ Tension in C_G from tt differential
- Histogram of the dim-6 Lagrangian
- Implications for UV?
  - Single-particle models ⟶ backup



BSM PHENOMENA IN LOOPS

[JHEP 04 279 (2021)] (Sanz, Ellis, et.al.)

- Consider top partners in Higgs →γ γ production/decay



Matching to Higgs-gluon-gluon operator $H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$

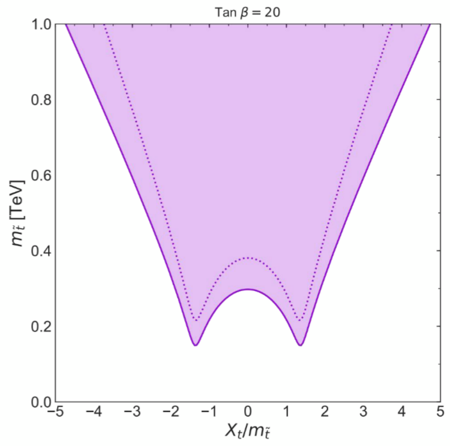
$$C_{HG} = \frac{g_s^2}{12}\frac{h_t^2}{(4\pi)^2}\Big[(1+\frac{1}{12}\frac{c_{2\beta}g'^2}{h_t^2}) - \frac{1}{2}\frac{X_t^2}{m_{\tilde{t}}^2}\Big]$$

Matching to Higgs-BB operator $H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$

$$C_{HB} = \frac{17g'^2}{144}\frac{h_t^2}{(4\pi)^2}\Big[(1+\frac{31}{102}\frac{c_{2\beta}g'^2}{h_t^2}) - \frac{38}{85}\frac{X_t^2}{m_{\tilde{t}}^2}\Big]$$

- New limits from Higgs production and precision branching ratio measurements on TeV scale scalar top partners

- BSM in the UV matched at one loop

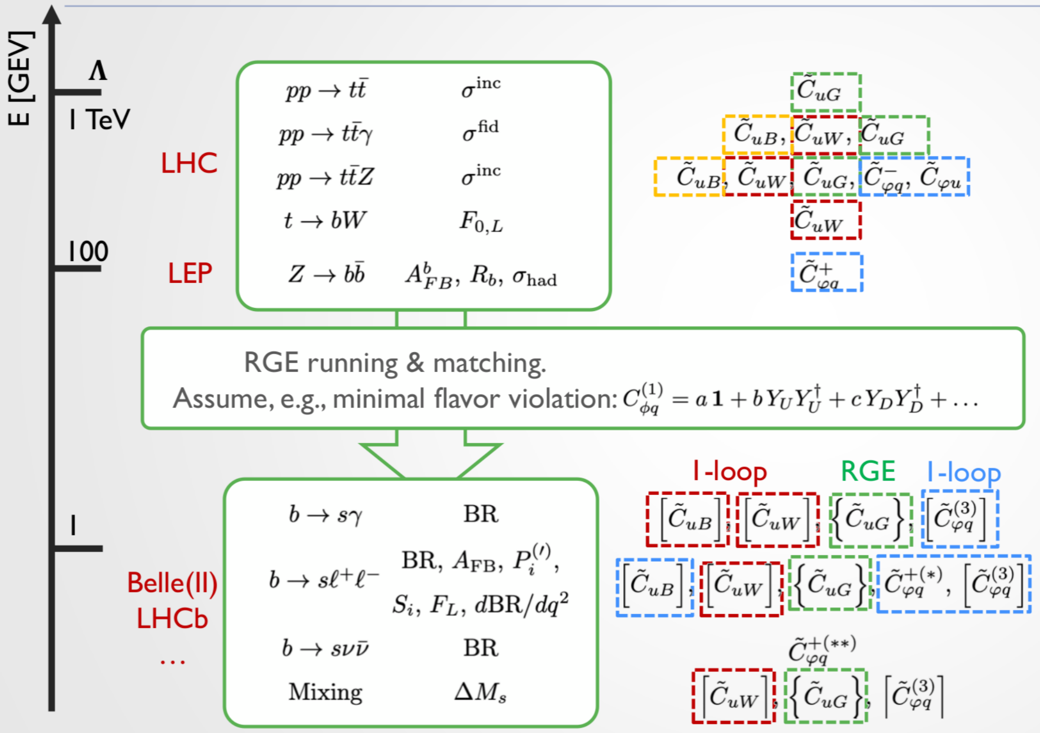


- Limits independent of top partner decay

FLAVOR STRUCTURES

G. Hiller, et. al. arXiv:2012.10456

S. Westhoff et. Al. arXiv:2101.07273



$pp \to t\bar{t}$	$\sigma^{\rm inc}$
$pp \to t\bar{t}\gamma$	$\sigma^{\rm fid}$
$pp \to t\bar{t}Z$	$\sigma^{\rm inc}$
$t \to bW$	$F_{0,L}$
$Z \to b\bar{b}$	A^b_{FB}, R_b, $\sigma_{\rm had}$

$\tilde{C}_{uG}$

$\tilde{C}_{uB}$, $\tilde{C}_{uW}$, $\tilde{C}_{uG}$

$\tilde{C}_{uB}$, $\tilde{C}_{uW}$, $\tilde{C}_{uG}$, $\tilde{C}^-_{\varphi q}$, $\tilde{C}_{\varphi u}$

$\tilde{C}_{uW}$

$\tilde{C}^+_{\varphi q}$

RGE running & matching.

Assume, e.g., minimal flavor violation: $C^{(1)}_{\phi q} = a\,\mathbf{1} + b\,Y_U Y_U^\dagger + c\,Y_D Y_D^\dagger + \ldots$

$b \to s\gamma$	BR
$b \to s\ell^+\ell^-$	BR, $A_{\rm FB}$, $P_i^{(\prime)}$, S_i, F_L, dBR/dq^2
$b \to s\nu\bar{\nu}$	BR
Mixing	ΔM_s

1-loop RGE 1-loop

$[\tilde{C}_{uB}]$, $[\tilde{C}_{uW}]$, $\{\tilde{C}_{uG}\}$, $[\tilde{C}^{(3)}_{\varphi q}]$

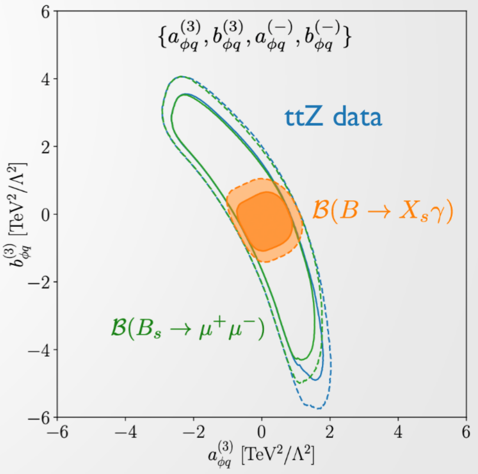
$[\tilde{C}_{uB}]$, $[\tilde{C}_{uW}]$, $\{\tilde{C}_{uG}\}$, $\tilde{C}^{+(*)}_{\varphi q}$, $[\tilde{C}^{(3)}_{\varphi q}]$

$\tilde{C}^{+(**)}_{\varphi q}$

$[\tilde{C}_{uW}]$, $\{\tilde{C}_{uG}\}$, $[\tilde{C}^{(3)}_{\varphi q}]$

- Enough data to over-constrain 3rd generation gauge-boson couplings
- RGE evolution to B physics scale

(g-2)$_\mu$:P. Stoffer et.al arXiv:2102.08954

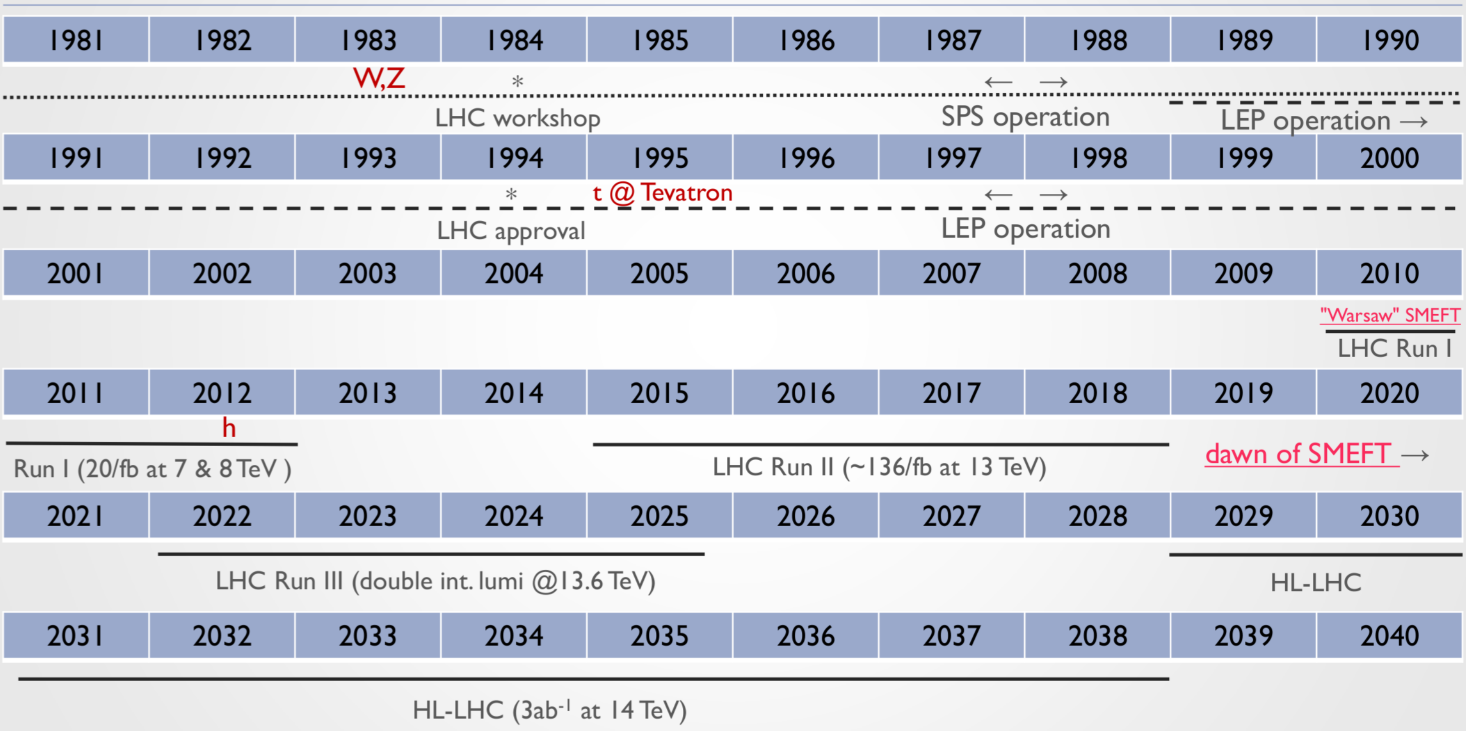


A SOMEWHAT BOLD OUTLOOK

- Three developments, each on a time scale of 10 years, begin to converge
  - Top/Higgs/Boson precision measurements at the LHC
  - Development of SM-EFT, including tools for RGE running ,matching, and global fits
  - Flavor anomalies have been confirmed
- A global view provides guidance (future accelerators) and opens unexpected links, closes others.
  - Weak scale and flavor sector are beginning to "effectively merge" – all scales approach
- In the end, we all hope to find resonance phenomena.
  - Until then, let's stick to the data and make comprehensive EFT analyses with minimal assumptions.

LEP AND LHC OPERATIONS

LHC long term schedule



1981 1982 1983 1984 1985 1986 1987 1988 1989 1990

W,Z * ← →

LHC workshop

SPS operation

LEP operation →

1991 1992 1993 1994 1995 1996 1997 1998 1999 2000

* t @ Tevatron ← →

LHC approval

LEP operation

2001 2002 2003 2004 2005 2006 2007 2008 2009 2010

"Warsaw" SMEFT

LHC Run I

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020

h

Run I (20/fb at 7 & 8 TeV)

LHC Run II (~136/fb at 13 TeV)

dawn of SMEFT →

2021 2022 2023 2024 2025 2026 2027 2028 2029 2030

LHC Run III (double int. lumi @13.6 TeV)

HL-LHC

2031 2032 2033 2034 2035 2036 2037 2038 2039 2040

HL-LHC (3ab^{-1} at 14 TeV)

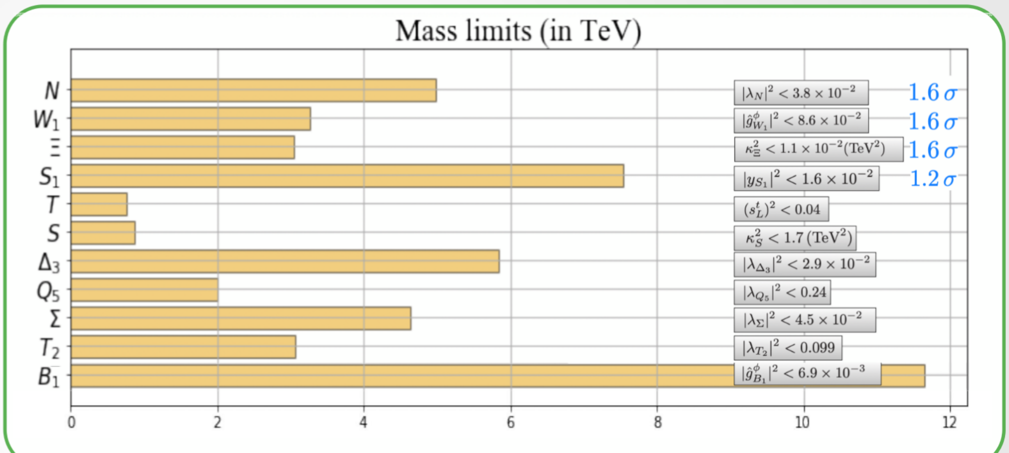
TREE-LEVEL MATCHING TO UV PHYSICS

[JHEP 04 279 (2021)] (Sanz, Ellis, et.al.)

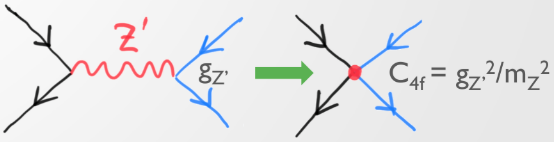
Choose quantum numbers →

Single-particle BSM model →

Name	Spin	SU(3)	SU(2)	U(1)
S	0	1	1	0
S_1	0	1	1	1
φ	0	1	2	$\frac{1}{2}$
Ξ	0	1	3	0
Ξ_1	0	1	3	1
B	1	1	1	0
B_1	1	1	1	1
W	1	1	3	0
W_1	1	1	3	1
N	$\frac{1}{2}$	1	1	0
E	$\frac{1}{2}$	1	1	-1
T	$\frac{1}{2}$	3	1	$\frac{2}{3}$



- Choose quantum numbers of single-particle BSM extension
- Match to SM-EFT operators



- Obtain limits, e.g., on coupling for M=1TeV or on Mass for g=1
  - Scalar singlets and VLQ top partners the least constrained

SPIN CORRELATION

Phys. Rev. D 100, 072002 (2019)

EPJC 80(2020)754

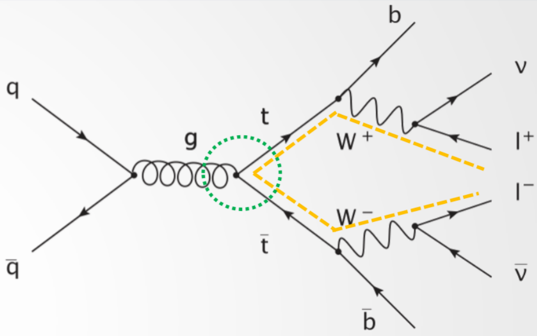
- top decay products are a probe of the ttbar spin correlation

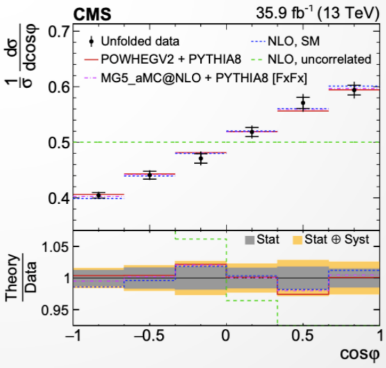
$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{\text{QCD}}}}_{\substack{\text{hadronization}\\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\ 10^{-21}\ \text{s}}}$$

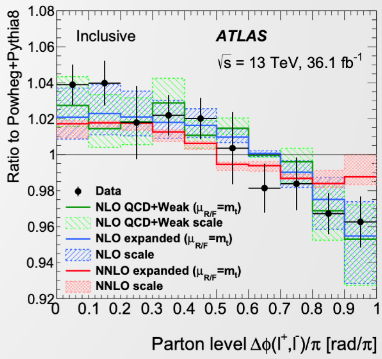
- CMS: Boost into the top quark pair rest frame
  - Must reconstruct the top momenta using E_T^{miss}
  - probe top spin in 3D (15 observables)
  - trace of the spin correlation matrix
    in the rest-frame angle between the leptons:

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\varphi} = \frac{1}{2}(1 - \underbrace{D}_{-\frac{1}{3}\text{tr}(C)} \cos \underbrace{\varphi(\hat{\ell}^+, \hat{\ell}^-)}_{\text{top rest frame}})$$

  - Most sensitive probe of chromo-dipole moments
  - fully consistent with SM $\boxed{F_{\text{SM}}(D) = 0.97 \pm 0.05}$
- ATLAS lab-measurement in 2.2σ tension with NNLO
  - Combination with CMS in progress
  - Dominant uncertainties from modeling



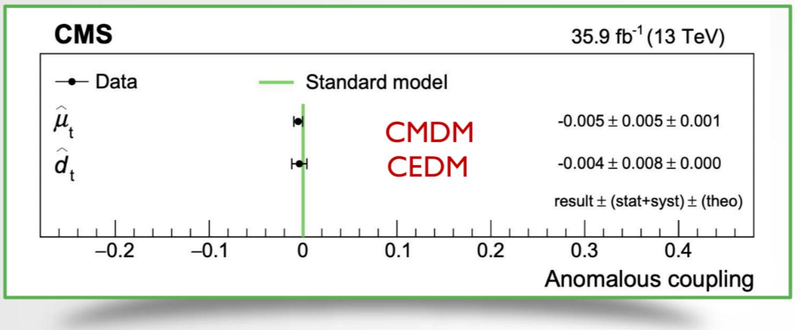


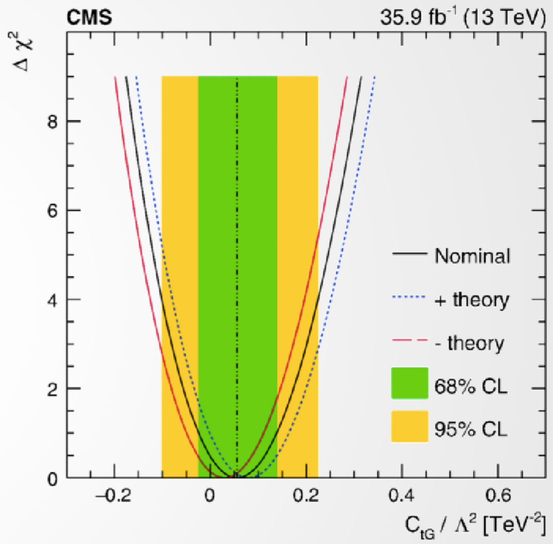


CHROMOMAGNETIC DIPOLE MOMENT

Phys. Rev. D 100, 072002 (2019)

EPJC 80(2020)754





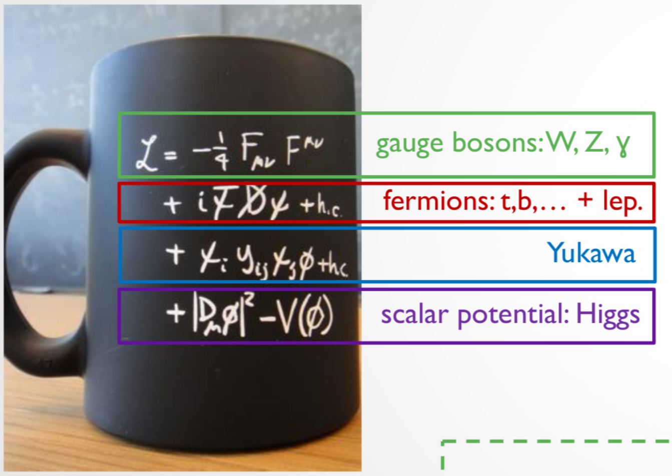
- Constrain the top chromo-magnetic & electric dipole moment

$$\mathcal{O}_{tG} = i\left(\bar{q}_L \sigma^{\mu\nu} \lambda^a t_R\right) \tilde{\phi}\, G^a_{\mu\nu} + \text{h.c.}$$

  - 2HDM, SUSY, technicolor, compositeness $C_{tG}/\Lambda^2 = \mu_t/(2m_t^2)$
  - currently best limit: $-0.10 < C_{tG}/\Lambda^2 < 0.22$ TeV^{-2}

ELECTROWEAK SYMMETRY BREAKING IN THE SM

- Thanks to the $SU_C(3) \otimes SU_L(2) \otimes U_Y(1)$ gauge symmetry, the Standard Model Lagrangian fits on a coffee mug



gauge bosons: W, Z, γ

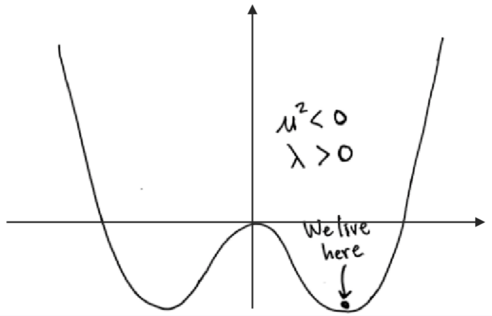
fermions: t,b,… + lep.

Yukawa

scalar potential: Higgs

Higgs potential

$$V(\varphi) = \mu^2 \left(\varphi^\dagger \varphi\right) + \tfrac{1}{2}\lambda \left(\varphi^\dagger \varphi\right)^2$$



- Longitudinal W/Z polarizations originate from the Higgs field

$$\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} \omega_1 + i\omega_2 \\ h + v + i\omega_3 \end{pmatrix} \qquad \langle \phi \rangle \equiv v = \sqrt{\frac{-\mu^2}{\lambda}} = 246 \text{ GeV}$$

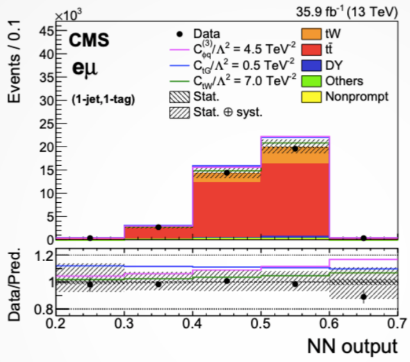
CONSTRAINING SM-EFT WITH TTBAR

Eur. Phys. J. C 79 (2019) 886

- using the dilepton channel, directly constrain EFT with tW and tt̄ final states

Single Top (tW)	tt̄
Single Top (tW) + tt̄	

- split in e/**μ** lepton flavor
  - tt̄ ≥ 2 jets (≥ 2 b jets)
  - tW: 1-2 jets (0-1 b jet).
- test separately 6 Wilson coeff:
  - Wtb vertex, top-gluon coupling, 3g vertex, FCNC couplings
- Signal extraction via per-channel neural networks
- first attempt of a global analysis at CMS



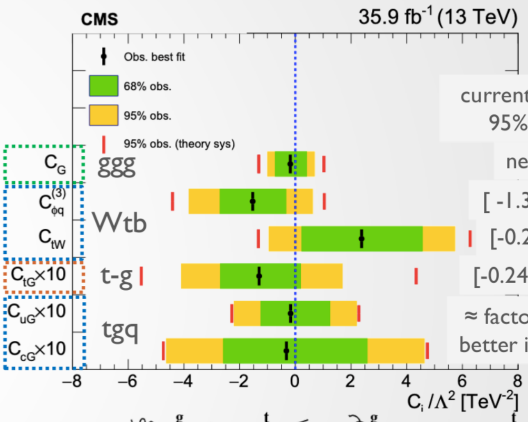
$$O^{(3)}_{\phi q} = (\phi^+\tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q),$$

$$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W^I_{\mu\nu},$$

$$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi}G^A_{\mu\nu},$$

$$O_G = f_{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho,$$

$$O_{u(c)G} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi}G^A_{\mu\nu},$$



current best 95%CL

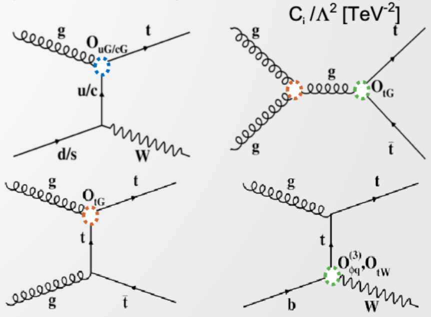
new

[-1.3, 1.3]

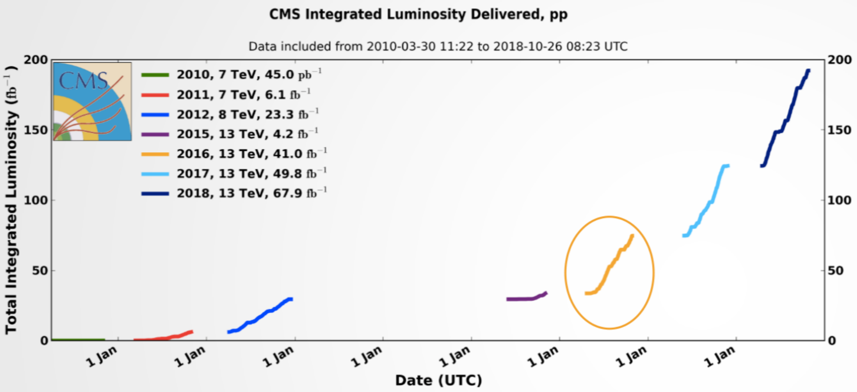
[-0.2, 0.7]

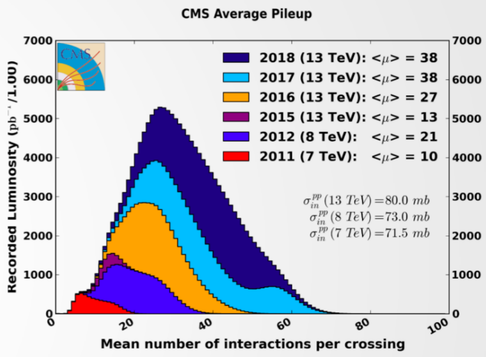
[-0.24, 0.07]

≈ factor 10 better in BR



RESILIENCE TO HARSHER ENVIRONMENTS





- Mean number of collision per BX increased steadily during LHC Run I/II
- *Background acceptance* is a strong function of n-PU ⟶ factor ~10!
  - raising E_T^{miss} threshold unfeasible ⟶ factor ~2 degrades signal acceptance
  - need to fix observable at the event level

VACUUM STABILITY

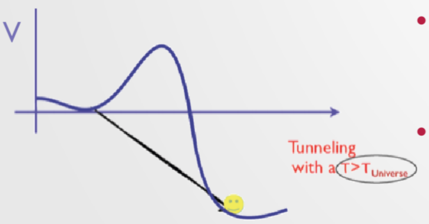
[1205.6497, 1207.0980, 1307.3536]

- Since 2012: Higgs self coupling $\lambda(m_t)$~0.14.
- NNLO SM RGE running of λ

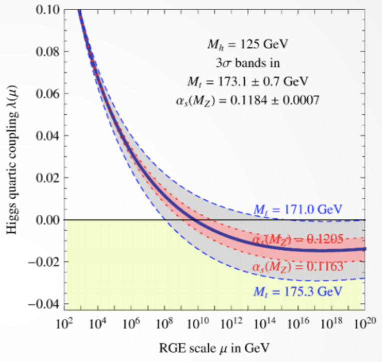
$$\frac{d\lambda}{dlog\mu} = + \frac{3\lambda^2}{2\pi^2} - \frac{3}{8\pi^2} Y_t^4 \dots$$

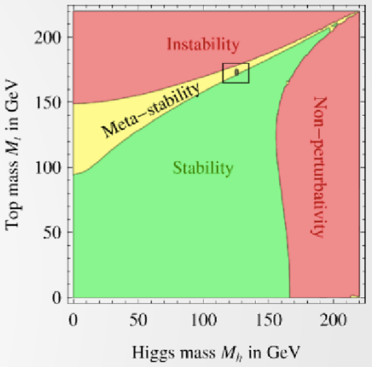
finds the Higgs self-coupling λ remarkably small

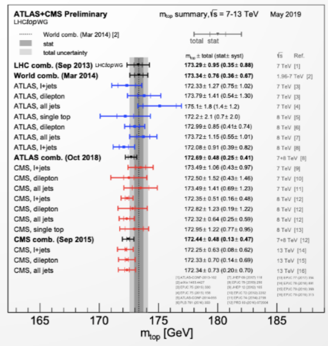
- peculiar interplay of measured m_h and m_t on predicted vacuum stability
  - λ runs to negative values at Λ~10^{11} GeV for world average m_t 173.3

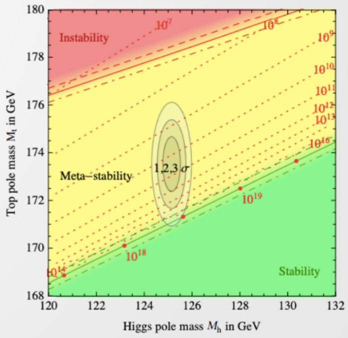


- High scale running could be affected by BSM
- important implications for models of inflation









EFT IS NOT A SIMPLE BSM MODEL

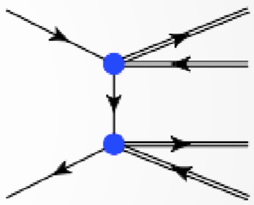
- Can use 4t production to constrain qqtt 4-fermion operators
  - e.g. $\mathcal{O}_{tu}^{(8)} \quad = \quad (\bar{t}_R \gamma_\mu T^a t_R)(\bar{u}_R \gamma^\mu T^a u_R)$
- There are two operator insertions necessary to produce 4 top quarks
  - (can neglect genuine dim-8 operators for wide class of BSM)
- Compare this to a single operator insertion.
  - i.e. modification of the qq⟶tt process
  - Can the tiny 4t signal compete in sensitivity?
- because **σ** ∝ |M|² two insertions give a 4th order polynomial

$$\sigma_{LO}(4t) = \quad 6.1{+}0.10\tilde{C}_{tu}^{(8)}{+}0.081\tilde{C}_{tu}^{(8)\,2}{+}0.016\tilde{C}_{tu}^{(8)\,3}{+}0.0048\tilde{C}_{tu}^{(8)\,4}$$

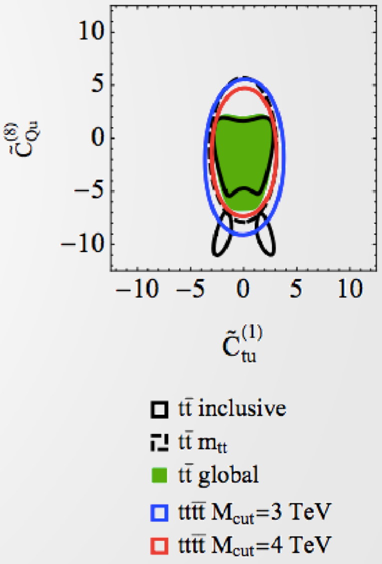
- Comparing inclusive tt xsec

4t xsec: $-8.8 < \tilde{C}_{tu}^{(8)} < 7.1$

inclusive tt x-sec: $-11.8 < \tilde{C}_{tu}^{(8)} < 4.6$



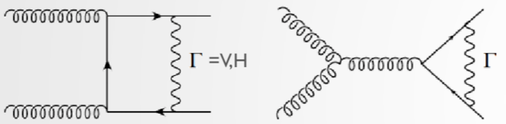
C. Zhang, 2017
https://arxiv.org/pdf/1708.05928.pdf
TOP-17-009
https://arxiv.org/pdf/1710.10614.pdf

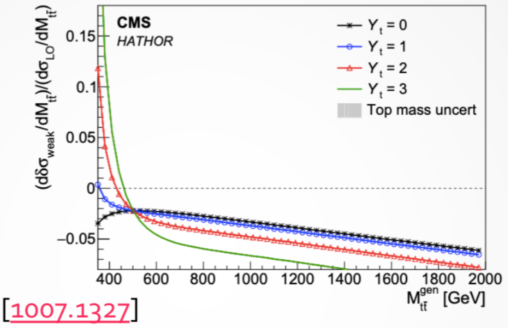


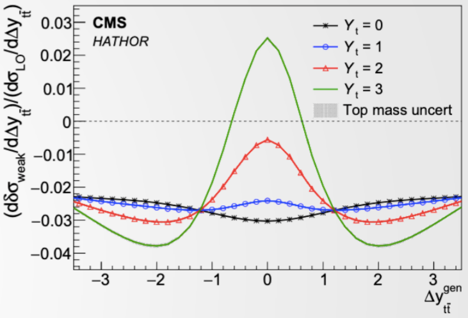
CONSTRAINING THE TOP YUKAWA COUPLING

Phys. Rev. D 100, 072007 (2019)

- idea: use differential single-leptonic x-sec to constrain top Yukawa coupling Y_t
- exploit EWK corrections at $\alpha_s^2\,\alpha_{weak}$



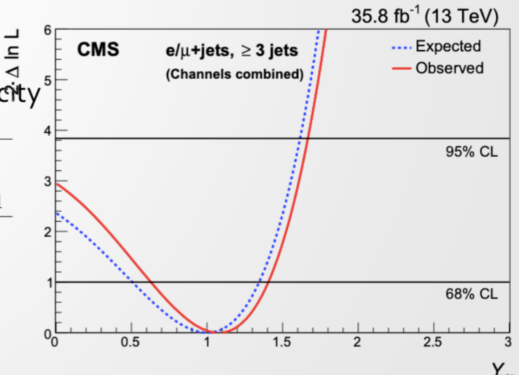




- compute correction factors with Hathor [1007.1327] in M(tt) and |Δy(tt)| and apply to simulation at parton level
- Top-Yukawa coupling extracted from 57 bins in M(tt) , |Δy(tt)|, and jet multiplicity
- Low M(tt) and small |Δytt | regions are the most sensitive to Y_t

use e/μ events with
likelihood based
event reconstruction
for neutrino momentum

Channel	Best fit Y_t		95% CL upper limit	
	Expected	Observed	Expected	Observed
3 jets	$1.00^{+0.66}_{-0.90}$	$1.62^{+0.53}_{-0.78}$	<2.17	<2.59
4 jets	$1.00^{+0.50}_{-0.72}$	$0.87^{+0.51}_{-0.77}$	<1.88	<1.77
≥5 jets	$1.00^{+0.59}_{-0.83}$	$1.27^{+0.55}_{-0.74}$	<2.03	<2.23
Combined	$1.00^{+0.35}_{-0.48}$	$1.07^{+0.34}_{-0.43}$	<1.62	<1.67



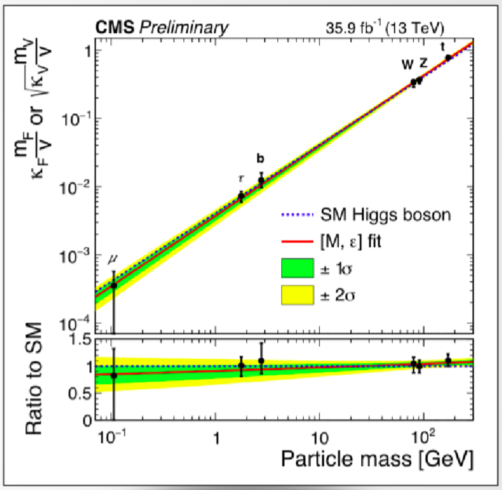
TOP QUARK MASS (OVERVIEW)

- Extremely simple tree level: SM masses from Yukawa coupling $y_t \approx 1$

$$-\mathcal{L}_{\text{Yukawa}} = y_d(\bar{q}_L\Phi)\,d_R + y_u(\bar{q}_L\widetilde{\Phi})\,u_R + y_\ell(\bar{\ell}_L\Phi)\,\ell_R + \text{h.c.}$$

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \omega_1 + i\omega_2 \\ \phi + i\omega_3 \end{pmatrix} \qquad \langle\phi\rangle \equiv v = \sqrt{\frac{-\mu^2}{\lambda}} = 246 \text{ GeV}$$

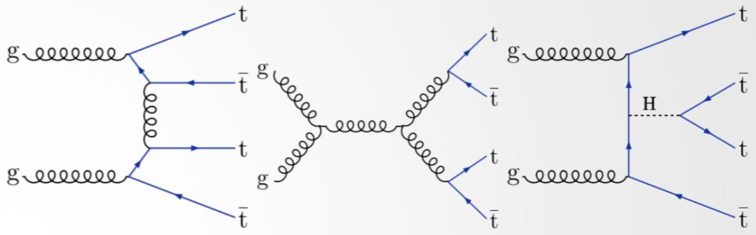
- Tree level: $m_t = y_t v/\sqrt{2}$. Higgs mechanism impressively confirmed!
- World average (Tev.+LHC): $m_t = 173.34 \pm 0.24$ (stat) ± 0.71 (sys)
- Extremely complex picture at the loop level



4 TOP QUARK PRODUCTION RUN II

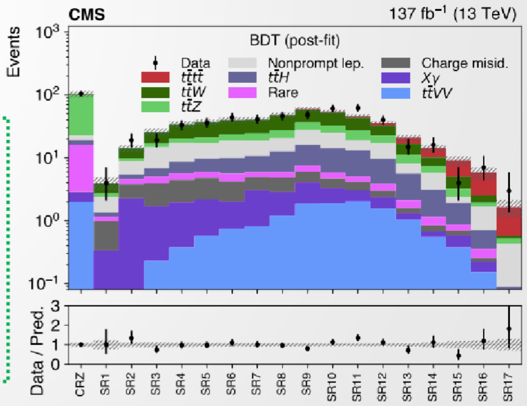
Eur. Phys. J. C 80 (2020) 75

- tttt is an unobserved very rare process: σ(tttt) ≈ 12 fb
- very large jet and b-jet multiplicities
- large hadronic activity
- CMS (and ATLAS): two main channels



1. single lepton + OS dilepton
   - 40% branching fraction
   - relatively large backgrounds
2. same-sign dilepton + multilepton
   - 12% branching fraction
   - low backgrounds
   - most sensitive channel!
   - full Run II data 137 fb⁻¹

- MVA & cut-based analysis
- main backgrounds: ttW , ttZ and ttH
- interesting process from BSM perspective!



4 TOP QUARK PRODUCTION RUN II

Eur. Phys. J. C 80 (2020) 75

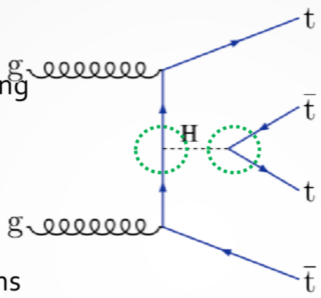
- Result: significance of 2.6 (2.7) s.d.
- rich set of interpretations!
  - constraint on the SM Yukawa coupling

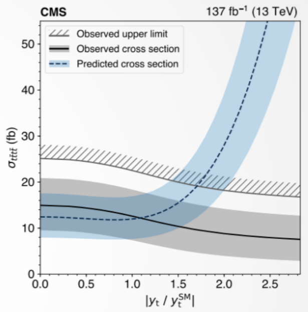
$$|y_t| \,/\, |y_t^{SM}| < 1.7 \text{ (95\% C.L.)}$$

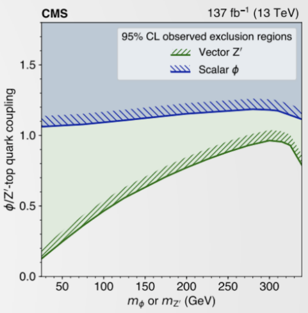
  - BSM scalar **ϕ** or vector Z′ m<2m$_t$
  - 2HDM (m>2m$_t$) and DM SMS including tqH/A, tWH/A contributions
  - ‘oblique’ Higgs parameter affecting the H propagator Giudice et.al. JHEP 09 (2019) 41 (albeit not the H-VV signatures)

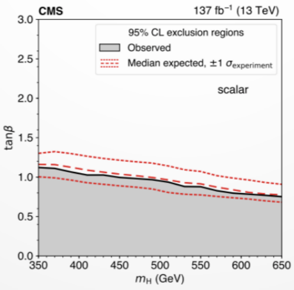
$$\hat{H} = C_{\Box}\frac{m_h^2}{\Lambda^2} < 0.12$$

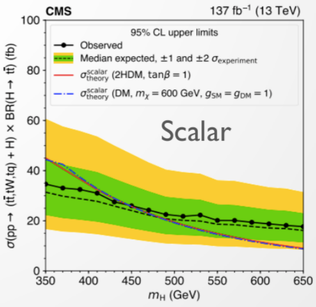
  - constrain (pure) H physics
  - (not in Warsaw basis)

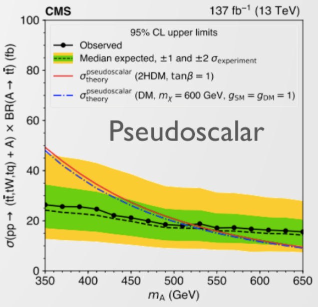












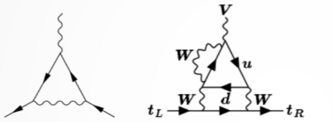
TOP ELECTROWEAK COUPLINGS

JHEP 03 (2020) 056, FTR-18-036

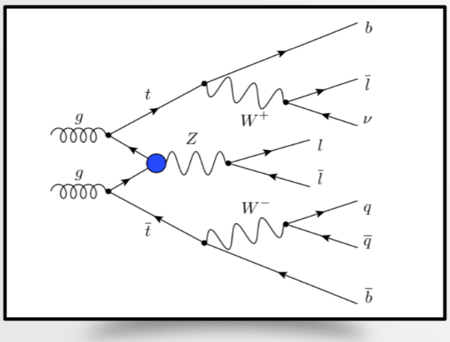
- Final states with top quark in association with a vector boson are a powerful probe of BSM phenomena

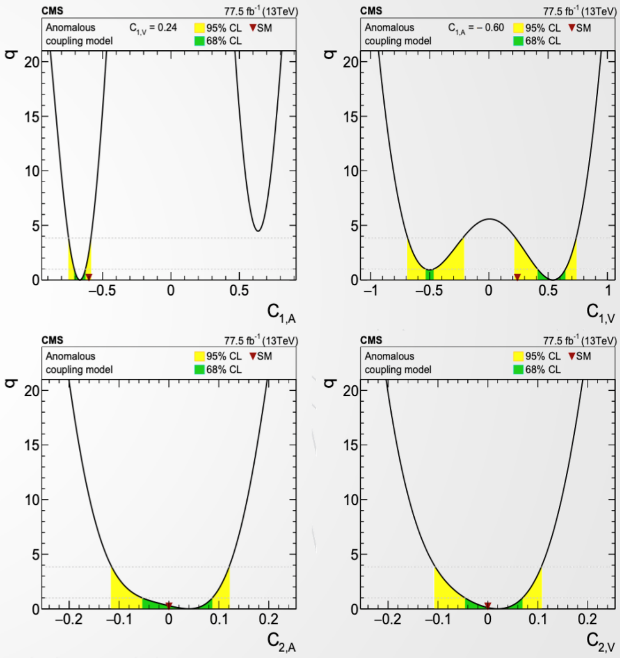
$$\mathcal{L} = e\bar{u}(p_t)\left[\underbrace{\gamma^\mu\left(C_{1,V}+\gamma_5 C_{1,A}\right)}_{} + \frac{\mathrm{i}\sigma^{\mu\nu}q_\nu}{M_Z}\left(C_{2,V}+\mathrm{i}\gamma_5 C_{2,A}\right)\right]v(p_{\bar{t}})\,Z_\mu$$

vector couplings
$C_{1,V}$ = 0.2448(52)
$C_{1,A}$ = -0.6012(14)

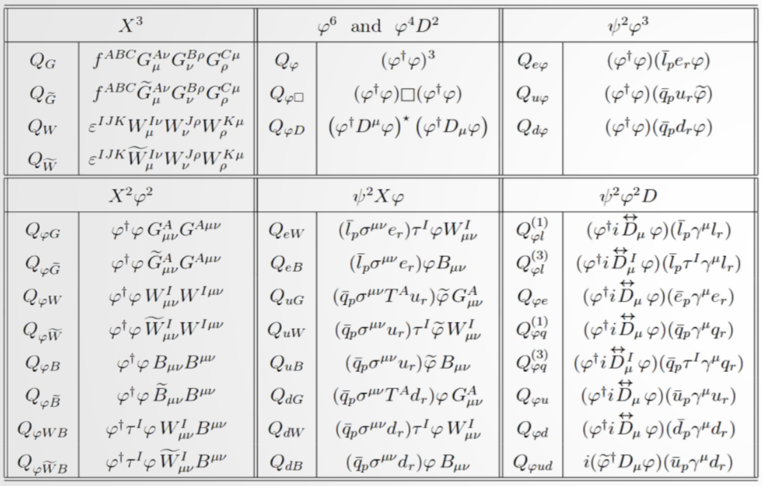


EWK dipole moments
$C_{2,V}$ ≈ -0.007
$C_{2,A}$ < 10^{-5}



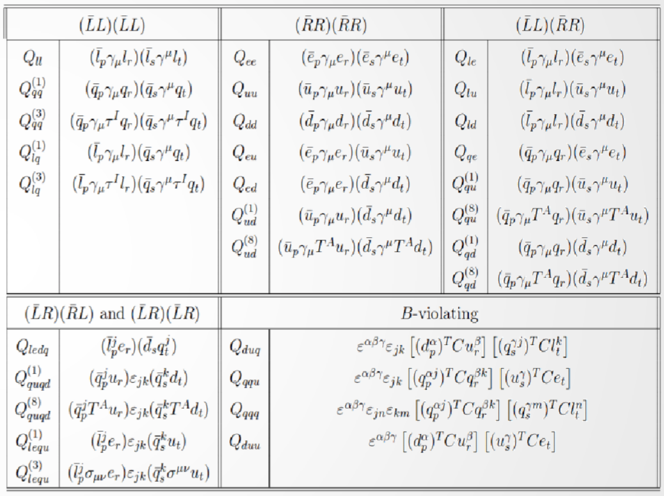


SM-EFT AT MASS DIMENSION 6



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	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star(\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.



$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$				

Table 3: Four-fermion operators.

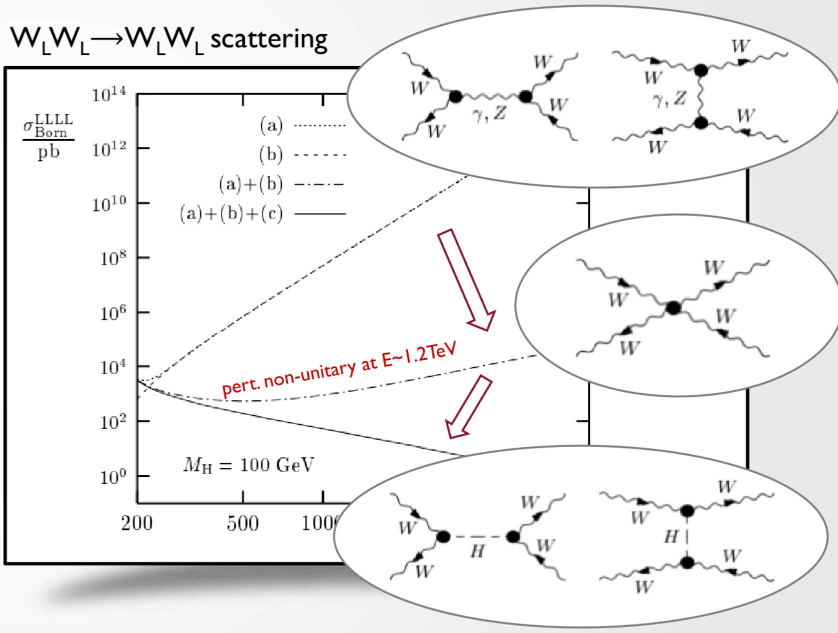
Expansion of Higgs doublet: $\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\omega_1 + i\omega_2\\ h + v + i\omega_3\end{pmatrix}$

$\omega \longrightarrow$ modified/new interactions with longitudinal gauge bosons
h $\longrightarrow$ modified/new interactions with the Higgs field
v $\longrightarrow$ modified SM interactions

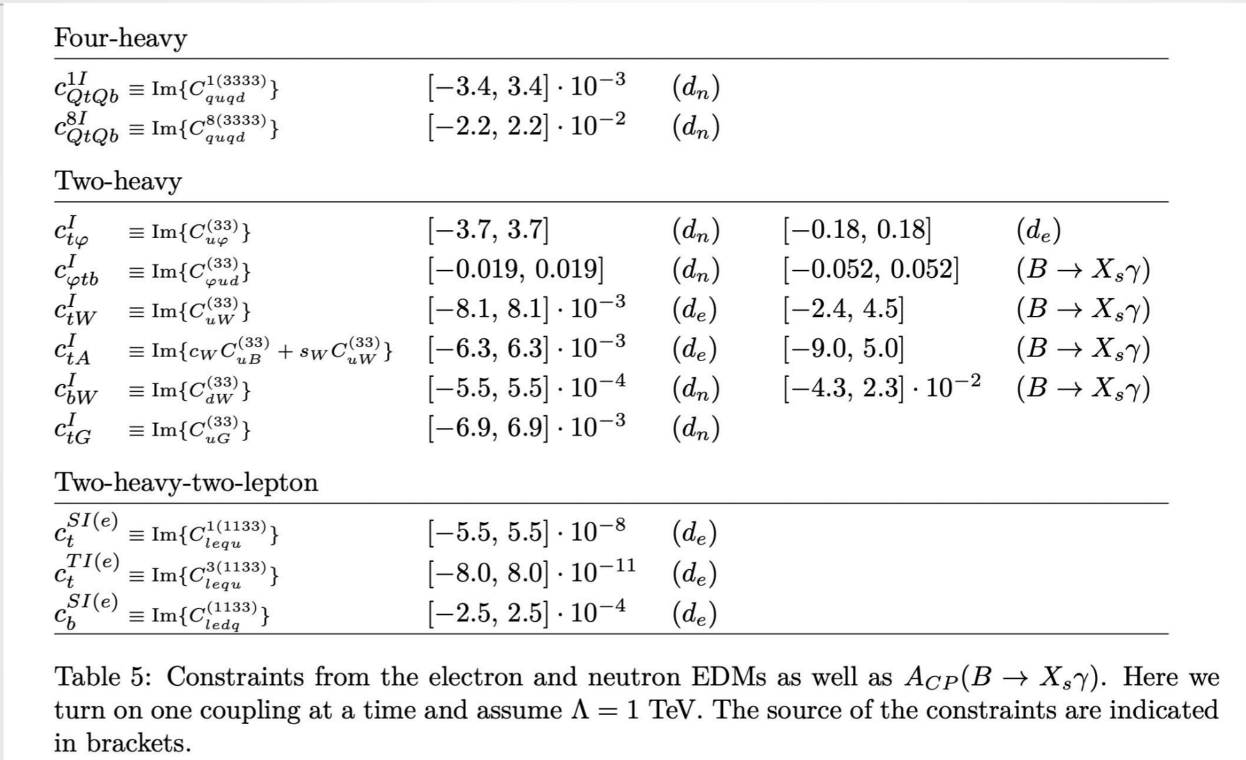
GAUGE BOSONS IN THE SM

- Discovery of the massive SM gauge bosons: UA1 and UA2 (SPS)
  - W boson: E_T^{miss} tail in single-lepton channel
  - Z boson: dilepton invariant mass $m(l^+l^-)$
  - Massive gauge bosons thoroughly established at LEP/Tevatron ⟶ Gauge boson self-interaction
  - trilinear and quartic couplings
- LHC no-loose theorem: $W_LW_L \longrightarrow W_LW_L$
  - $m_h \lesssim 1$ TeV or strongly interacting BSM
  - Higgs boson discovered in 2012 at m_h=125 GeV
- cancellations in W/Z amplitudes a core SM feature
  - Modify the interactions of W or Z ⟶ energy growth!
  - Exploit SM features in BSM searches / SM tests

$W_LW_L \longrightarrow W_LW_L$ scattering



https://arxiv.org/pdf/1802.07237.pdf



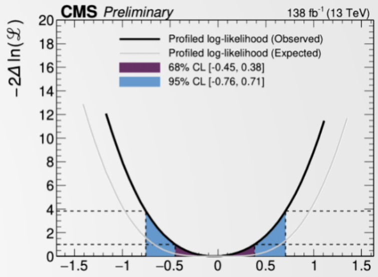
Four-heavy				
$c^{1I}_{QtQb} \equiv \mathrm{Im}\{C^{1(3333)}_{quqd}\}$	$[-3.4,\ 3.4] \cdot 10^{-3}$	(d_n)		
$c^{8I}_{QtQb} \equiv \mathrm{Im}\{C^{8(3333)}_{quqd}\}$	$[-2.2,\ 2.2] \cdot 10^{-2}$	(d_n)		
Two-heavy				
$c^{I}_{t\varphi} \equiv \mathrm{Im}\{C^{(33)}_{u\varphi}\}$	$[-3.7,\ 3.7]$	(d_n)	$[-0.18,\ 0.18]$	(d_e)
$c^{I}_{\varphi tb} \equiv \mathrm{Im}\{C^{(33)}_{\varphi ud}\}$	$[-0.019,\ 0.019]$	(d_n)	$[-0.052,\ 0.052]$	$(B \to X_s\gamma)$
$c^{I}_{tW} \equiv \mathrm{Im}\{C^{(33)}_{uW}\}$	$[-8.1,\ 8.1] \cdot 10^{-3}$	(d_e)	$[-2.4,\ 4.5]$	$(B \to X_s\gamma)$
$c^{I}_{tA} \equiv \mathrm{Im}\{c_W C^{(33)}_{uB} + s_W C^{(33)}_{uW}\}$	$[-6.3,\ 6.3] \cdot 10^{-3}$	(d_e)	$[-9.0,\ 5.0]$	$(B \to X_s\gamma)$
$c^{I}_{bW} \equiv \mathrm{Im}\{C^{(33)}_{dW}\}$	$[-5.5,\ 5.5] \cdot 10^{-4}$	(d_n)	$[-4.3,\ 2.3] \cdot 10^{-2}$	$(B \to X_s\gamma)$
$c^{I}_{tG} \equiv \mathrm{Im}\{C^{(33)}_{uG}\}$	$[-6.9,\ 6.9] \cdot 10^{-3}$	(d_n)		
Two-heavy-two-lepton				
$c^{SI(e)}_{t} \equiv \mathrm{Im}\{C^{1(1133)}_{lequ}\}$	$[-5.5,\ 5.5] \cdot 10^{-8}$	(d_e)		
$c^{TI(e)}_{t} \equiv \mathrm{Im}\{C^{3(1133)}_{lequ}\}$	$[-8.0,\ 8.0] \cdot 10^{-11}$	(d_e)		
$c^{SI(e)}_{b} \equiv \mathrm{Im}\{C^{(1133)}_{ledq}\}$	$[-2.5,\ 2.5] \cdot 10^{-4}$	(d_e)		

Table 5: Constraints from the electron and neutron EDMs as well as $A_{CP}(B \to X_s\gamma)$. Here we turn on one coupling at a time and assume $\Lambda = 1$ TeV. The source of the constraints are indicated in brackets.

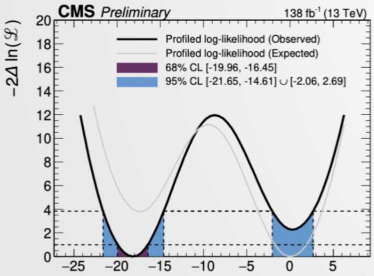
MVA-EFT SEARCH IN ≥3L FINAL STATES

[CMS-TOP-21-001]

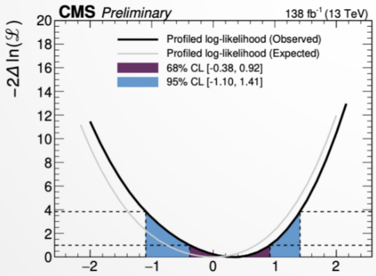
	Other WCs fixed to SM		5D fit	
	Expected	Observed	Expected	Observed
WC / Λ^2 [TeV^{-2}]	95% CL confidence intervals			
c_{tZ}	$[-0.97, 0.96]$	$[-0.76, 0.71]$	$[-1.24, 1.17]$	$[-0.85, 0.76]$
c_{tW}	$[-0.76, 0.74]$	$[-0.52, 0.52]$	$[-0.96, 0.93]$	$[-0.69, 0.70]$
$c^3_{\varphi Q}$	$[-1.39, 1.25]$	$[-1.10, 1.41]$	$[-1.91, 1.36]$	$[-1.26, 1.43]$
$c^-_{\varphi Q}$	$[-2.86, 2.33]$	$[-3.00, 2.29]$	$[-6.06, 14.09]$	$[-7.09, 14.76]$
$c_{\varphi t}$	$[-3.70, 3.71]$	$[-21.65, -14.61] \cup [-2.06, 2.69]$	$[-16.18, 10.46]$	$[-19.15, 10.34]$



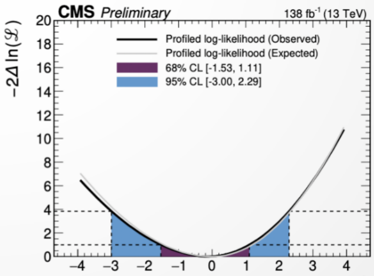
Weak dipole



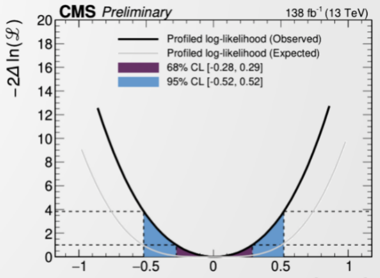
Weak vector coup. (R)



Weak vector coup. (L)



Weak vector coup. (L)



Weak dipole

WW $^*\longrightarrow$ **eνμν** with two extra jets

ATLAS [arxiv:2109.13808]

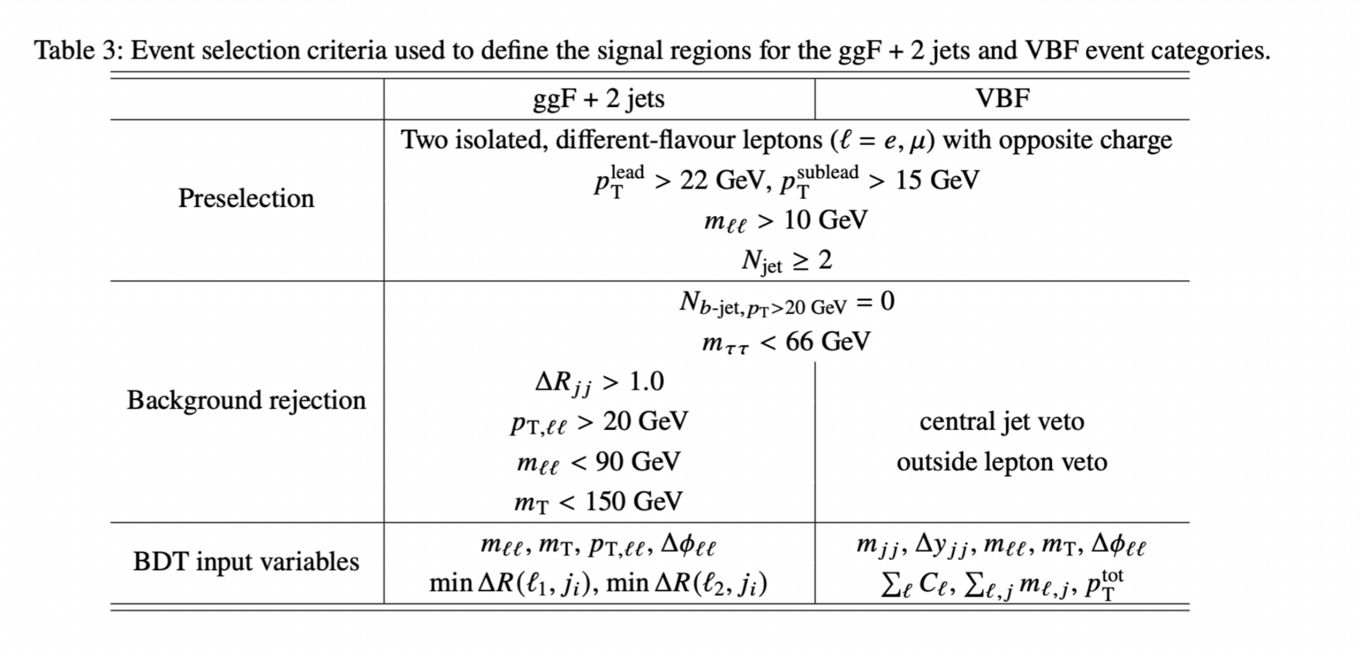


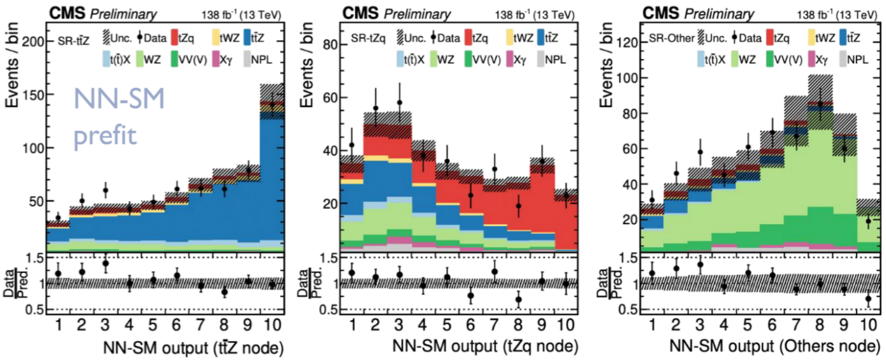
Table 3: Event selection criteria used to define the signal regions for the ggF + 2 jets and VBF event categories.

<table>
<tr><th></th><th>ggF + 2 jets</th><th>VBF</th></tr>
<tr><td>Preselection</td><td colspan="2">Two isolated, different-flavour leptons ($\ell = e, \mu$) with opposite charge
$p_{\mathrm{T}}^{\mathrm{lead}} > 22$ GeV, $p_{\mathrm{T}}^{\mathrm{sublead}} > 15$ GeV
$m_{\ell\ell} > 10$ GeV
$N_{\mathrm{jet}} \geq 2$</td></tr>
<tr><td rowspan="2">Background rejection</td><td colspan="2">$N_{b\text{-jet}, p_{\mathrm{T}}>20\ \mathrm{GeV}} = 0$
$m_{\tau\tau} < 66$ GeV</td></tr>
<tr><td>$\Delta R_{jj} > 1.0$
$p_{\mathrm{T},\ell\ell} > 20$ GeV
$m_{\ell\ell} < 90$ GeV
$m_{\mathrm{T}} < 150$ GeV</td><td>central jet veto
outside lepton veto</td></tr>
<tr><td>BDT input variables</td><td>$m_{\ell\ell}$, m_{T}, $p_{\mathrm{T},\ell\ell}$, $\Delta\phi_{\ell\ell}$
min $\Delta R(\ell_1, j_i)$, min $\Delta R(\ell_2, j_i)$</td><td>m_{jj}, Δy_{jj}, $m_{\ell\ell}$, m_{T}, $\Delta\phi_{\ell\ell}$
$\sum_\ell C_\ell$, $\sum_{\ell,j} m_{\ell,j}$, $p_{\mathrm{T}}^{\mathrm{tot}}$</td></tr>
</table>

MVA-EFT SEARCH IN ≥3L FINAL STATES

[CMS-TOP-21-001]

- Plots: Split according to max. value in the output node
  - Very good control of in SR-3l
- 5 MVAs for single-op inference
- Train separate SM vs. EFT MVAs
  - Trainings for tZq and ttZ
  - Single operator O_{tZ}, O_{tW}, $O^3_{\phi Q}$
    - Use for 1D limits
  - NN-5D training with all operators
  - Total of 8 MVAs for SM vs. EFT
- signal extraction with 1D, 2D, and 5D likelihood fit
- Systematics:
  - theory uncertainty and NP lepton systematics dominate



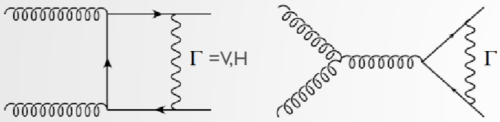
Fit configuration	SR-tt̄Z	SR-tZq
1D c_{tZ}	NN-c_{tZ}-tt̄Z	NN-c_{tZ}-tZq
1D c_{tW}	NN-c_{tW}-tt̄Z	NN-c_{tW}-tZq
1D $c^3_{\varphi Q}$	NN-$c^3_{\varphi Q}$-tt̄Z	NN-$c^3_{\varphi Q}$-tZq
1D $c^-_{\varphi Q}$	NN-SM (tt̄Z node)	NN-SM (tZq node)
1D $c_{\varphi t}$	NN-SM (tt̄Z node)	NN-SM (tZq node)
2D and 5D	NN-5D-tt̄Z	NN-5D-tZq

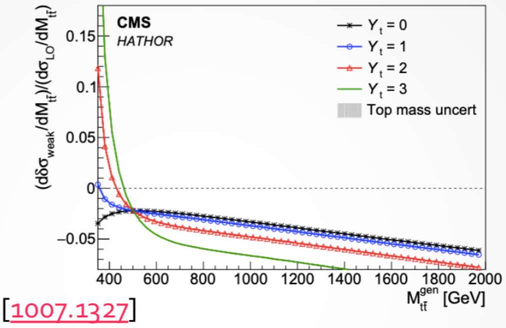
- Include M_T distribution in background node
- SR-ttZ-4l and WZ/ZZ CR as single-bin measurements

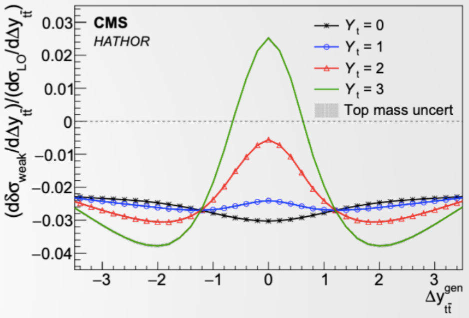
CONSTRAINING THE TOP YUKAWA COUPLING

Phys. Rev. D 100, 072007 (2019)

- idea: use differential single-leptonic x-sec to constrain top Yukawa coupling Y_t
- exploit EWK corrections at $\alpha_s^2\,\alpha_{weak}$



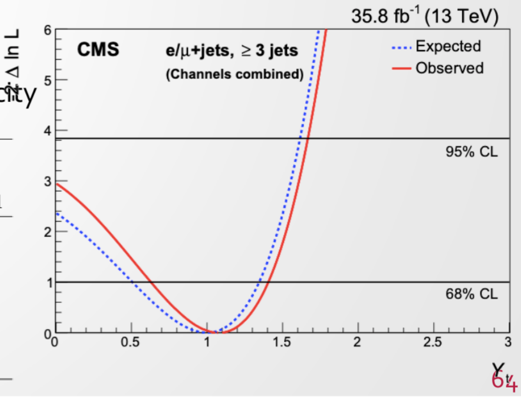




- compute correction factors with Hathor [1007.1327] in M(tt) and |Δy(tt)| and apply to simulation at parton level
- Top-Yukawa coupling extracted from 57 bins in M(tt) , |Δy(tt)|, and jet multiplicity
- Low M(tt) and small |Δytt | regions are the most sensitive to Y_t

use e/μ events with
likelihood based
event reconstruction
for neutrino momentum

Channel	Best fit Y_t		95% CL upper limit	
	Expected	Observed	Expected	Observed
3 jets	$1.00^{+0.66}_{-0.90}$	$1.62^{+0.53}_{-0.78}$	<2.17	<2.59
4 jets	$1.00^{+0.50}_{-0.72}$	$0.87^{+0.51}_{-0.77}$	<1.88	<1.77
≥5 jets	$1.00^{+0.59}_{-0.83}$	$1.27^{+0.55}_{-0.74}$	<2.03	<2.23
Combined	$1.00^{+0.35}_{-0.48}$	$1.07^{+0.34}_{-0.43}$	<1.62	<1.67



EFT IS NOT A SIMPLE BSM MODEL

C. Zhang, 2017
https://arxiv.org/pdf/1708.05928.pdf
TOP-17-009
https://arxiv.org/pdf/1710.10614.pdf

- Can use 4t production to constrain qqtt 4-fermion operators
  - e.g. $\mathcal{O}_{tu}^{(8)} \quad = \quad (\bar{t}_R\gamma_\mu T^a t_R)\,(\bar{u}_R\gamma^\mu T^a u_R)$
- There are two operator insertions necessary to produce 4 top quarks
  - (can neglect genuine dim-8 operators for wide class of BSM)
- Compare this to a single operator insertion.
  - i.e. modification of the qq⟶tt process
  - Can the tiny 4t signal compete in sensitivity?
- because $\sigma \propto |M|^2$ two insertions give a 4th order polynomial

$$\sigma_{LO}(4t) = 6.1{+}0.10\tilde{C}_{tu}^{(8)}{+}0.081\tilde{C}_{tu}^{(8)\,2}{+}0.016\tilde{C}_{tu}^{(8)\,3}{+}0.0048\tilde{C}_{tu}^{(8)\,4}$$

- Comparing inclusive tt xsec

4t xsec: $-8.8 < \tilde{C}_{tu}^{(8)} < 7.1$

inclusive tt x-sec: $-11.8 < \tilde{C}_{tu}^{(8)} < 4.6$