Effective field theory: New physics through precision measurements

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University of Liverpool seminar

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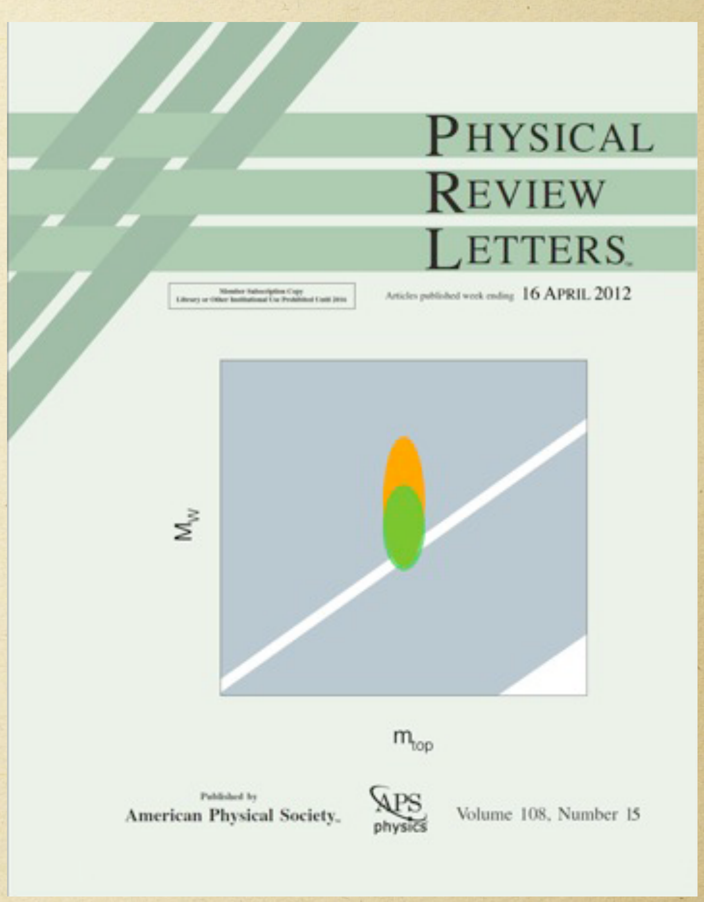
Overview

- Effective field theory
- Fits to electroweak measurements
- Prospects for Run 2



The Standard Model

The Standard Model is a gauge-symmetric quantum field theory describing interactions between particles of matter

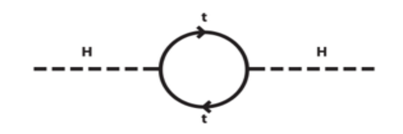
gauge symmetry: fundamental geometric principle valid at high scales but hidden by the vacuum at low scales

quantum field theory: effective theory valid at low scales but unable to describe the highest (gravitational) scale

<u>Renormalization absorbs the unknown physics at high scales</u>

Most parameters largely insensitive to details of high-scale physics

Higgs boson mass very sensitive to unknown physics at a higher scale



Interactions determined by transition amplitudes derived from the action

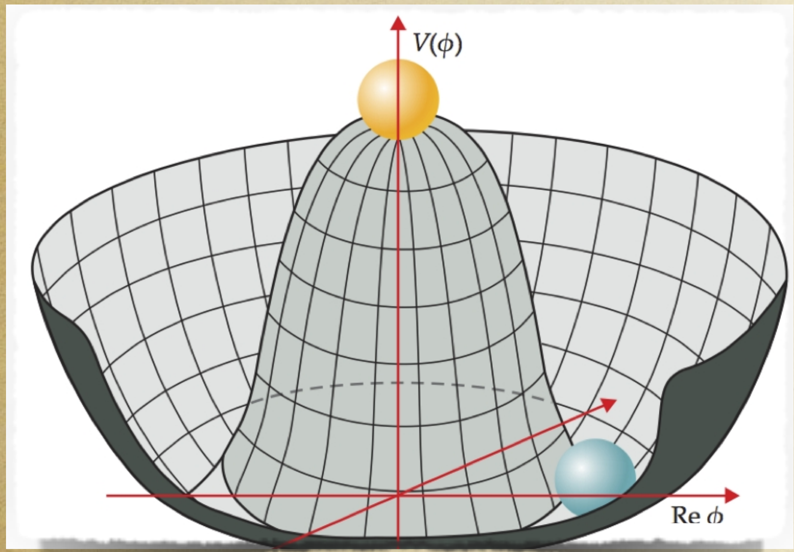
$$S = \int \mathcal{L}\, d^4x$$

Lagrangian with dimensions m^4 defines interactions

Hidden symmetry

The Higgs boson is an SU(2) x U(1) scalar doublet field

Higgs mechanism: field is non-zero at the minimum of its potential



$$\mathcal{L}_{\text{scalar}} = (D_\mu \phi)^\dagger (D^\mu \phi) + \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2$$

U(1) simplification with minimum along real axis

General SU(2)xU(1) picture with minimum along ϕ_0 axis:

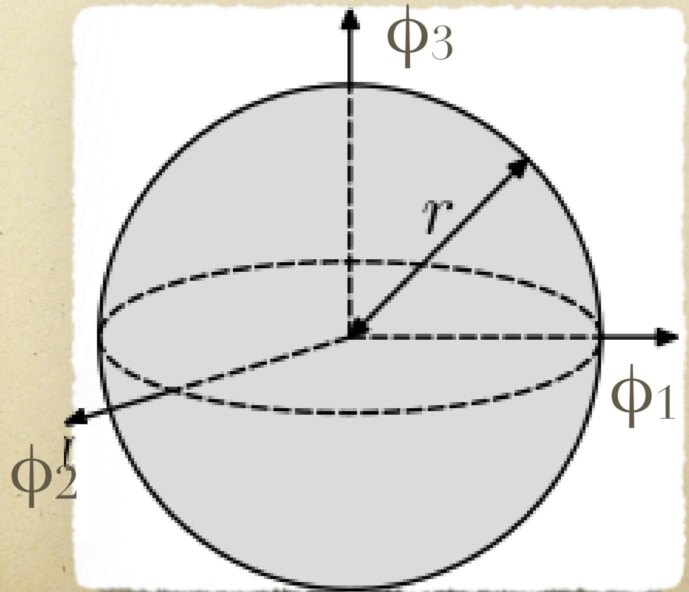
$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

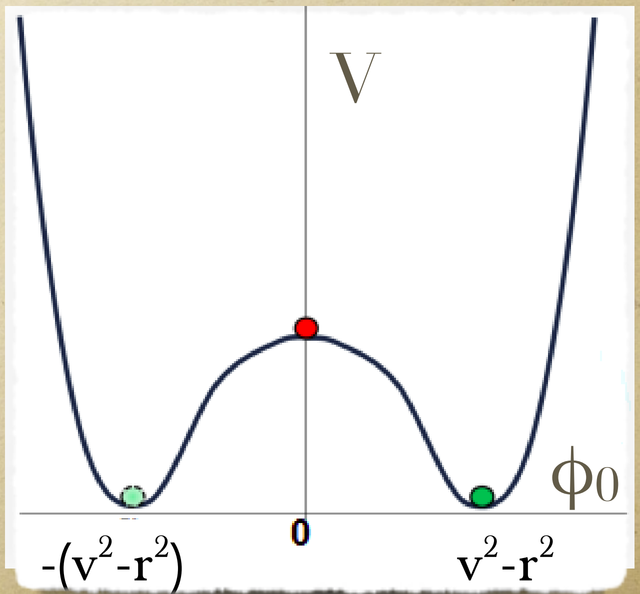
$$\phi^+ = \frac{\phi^1 + i\phi^2}{\sqrt{2}} \qquad \phi^0 = \frac{\phi^0 + i\phi^3}{\sqrt{2}}$$

Choose minimum

$\phi_1 = \phi_2 = \phi_3 = 0,$

$\phi_0 = v$

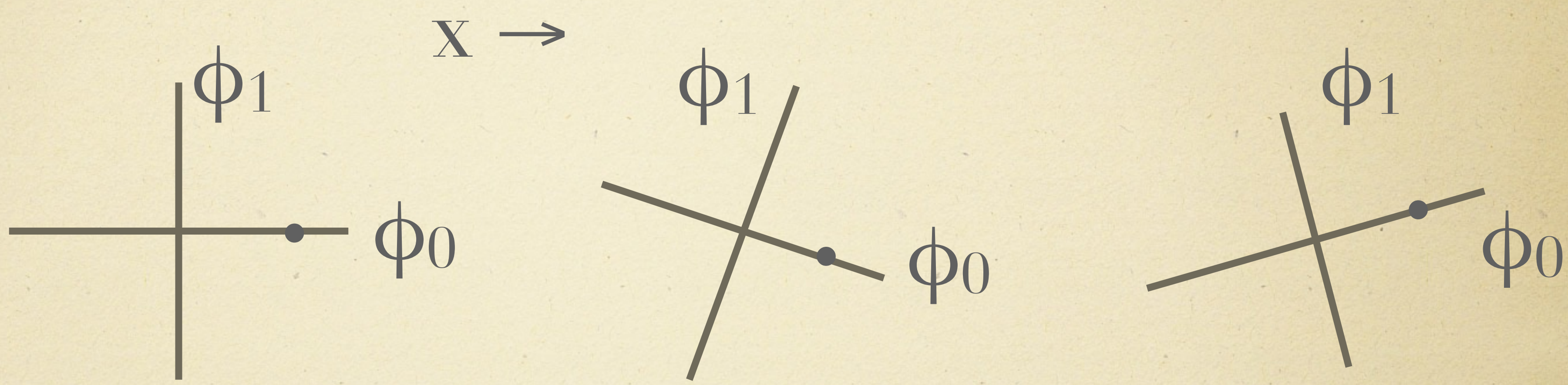




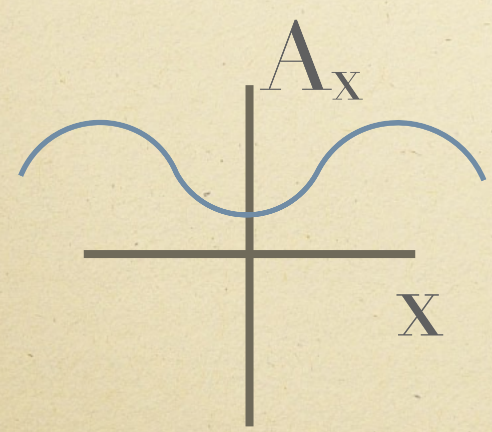
Hidden symmetry

Gauge symmetry: choose coordinates $\phi_1 = \phi_2 = \phi_3 = 0$ throughout spacetime

scalar field:

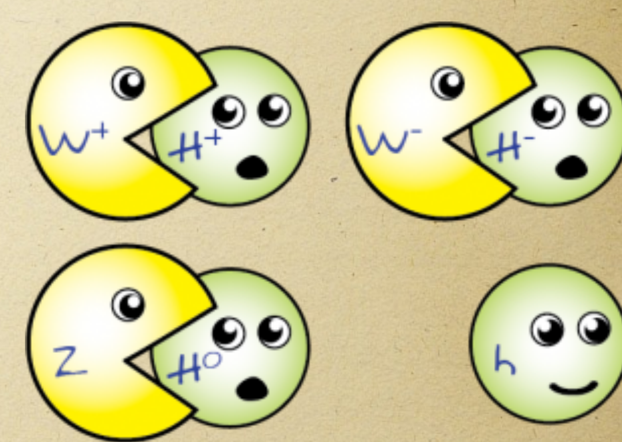


gauge field:



$$\phi' = e^{i\epsilon/\phi_0}\phi$$

$$A'_\mu = A_\mu + \frac{1}{e\phi_0}\partial_\mu \epsilon.$$



Phase oscillations become gauge oscillations in these coordinates

Massive gauge boson acquires a spin-0 degree of freedom

Costs energy to oscillate about the phase

Hidden symmetry

Lagrangian with
manifest gauge symmetry

$$\mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{scalar}} + \mathcal{L}_{\text{fermion}}$$

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} F^i_{\mu\nu} F^{i\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu}$$

$$\mathcal{L}_{\text{scalar}} = (D_\mu \phi)^\dagger (D^\mu \phi) + \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2$$

$$\mathcal{L}_{\text{fermion}} = i\bar{\psi}_L \gamma^\mu D_\mu \psi_L + i\bar{\psi}_R \gamma^\mu D_\mu \psi_R - (y^d_{ij} \bar{\psi}_{iL} \phi \psi^d_{jR} + y^u_{ij} \bar{\psi}_{iL} \tilde{\phi} \psi^u_{jR} + h.c.)$$

25 parameters:

3 gauge couplings

1 vacuum expectation value

1 scalar mass

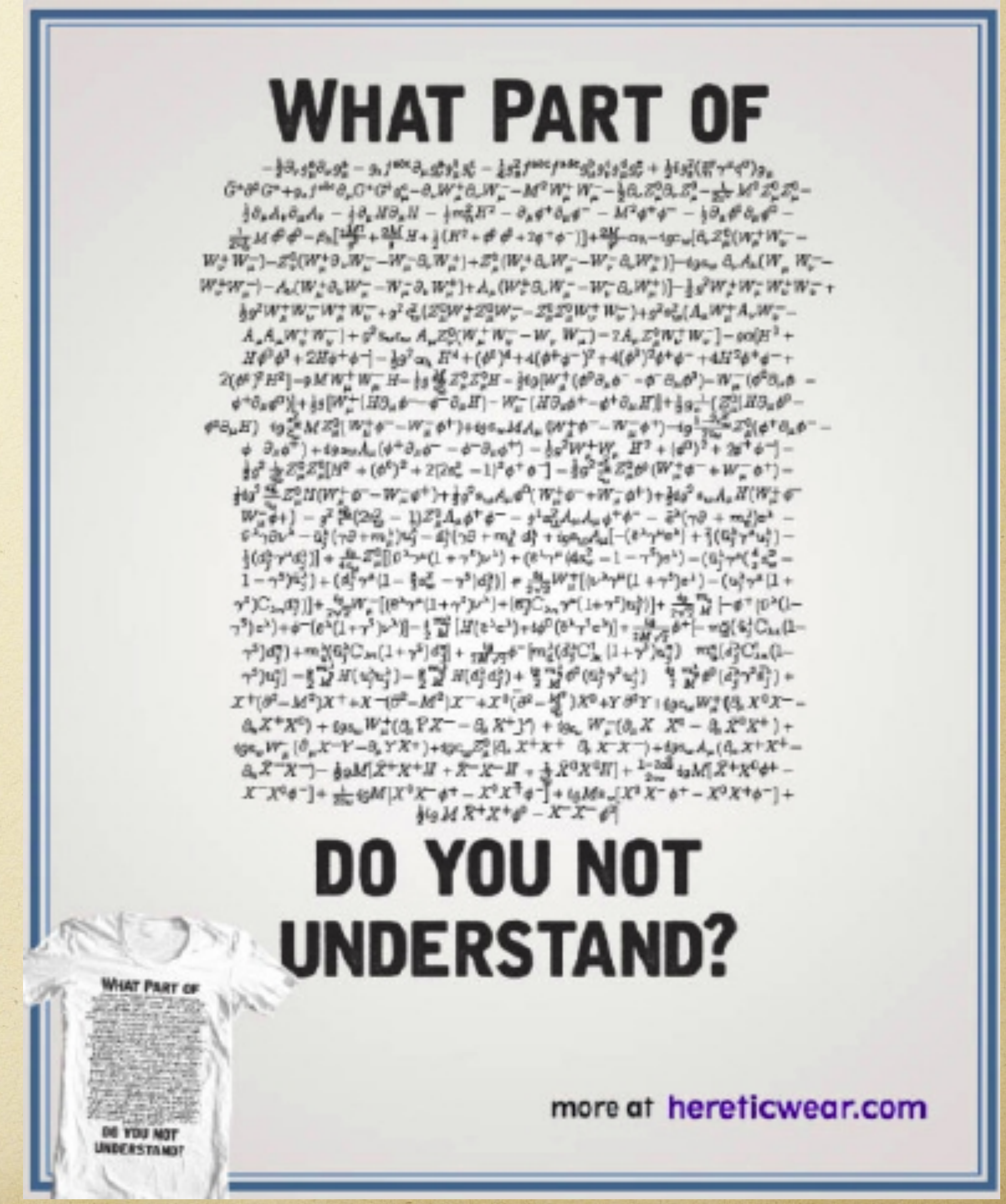
12 fermion masses

4 quark mixing

4 neutrino mixing

Assuming Dirac neutrinos

Lagrangian expanded
about the vacuum



Effective field theory

The SM Lagrangian contains only renormalizable terms

Effective field theory adds non-renormalizable terms
Parametrize high-scale physics in powers of inverse scale

Aim to measure the effects of high-scale physics in EFT coefficients

For example:

$$c_{WWZ}\,(v^2/\Lambda_{NP}^2)(W_{\mu\nu}\,W^{\nu\rho}\,Z_\rho{}^\mu)$$

Dimensionless effective coupling

Suppression from scale hierarchy

Dimension-6 operator

$W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$

SM effective field theory

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \mathcal{L}_8 + \cdots$$

1610.07922, Sec. II.2.3

The SM effective field theory has been characterized up to dimension-8 operators

$\mathcal{L}_5$ One operator violating lepton number conservation

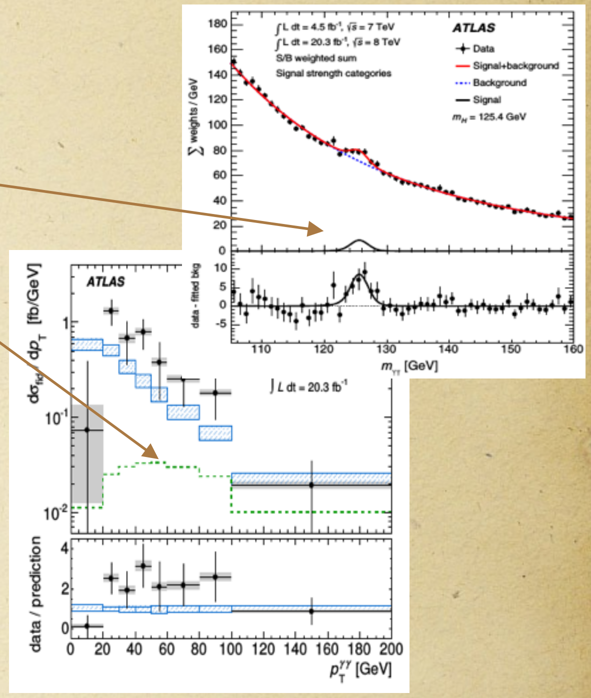
$\mathcal{L}_6$ 76 operators conserving baryon number (one generation)
2499 operators for three generations
4 operators violating baryon number conservation

$\mathcal{L}_7$ 30 operators violating B or L, and B-L

$\mathcal{L}_8$ 993 operators (one generation)

Equations of motion reduce number of dimension-6 operators from 76 to 59
Focus on these operators to probe for new physics independent of generation

Measurements in EFT

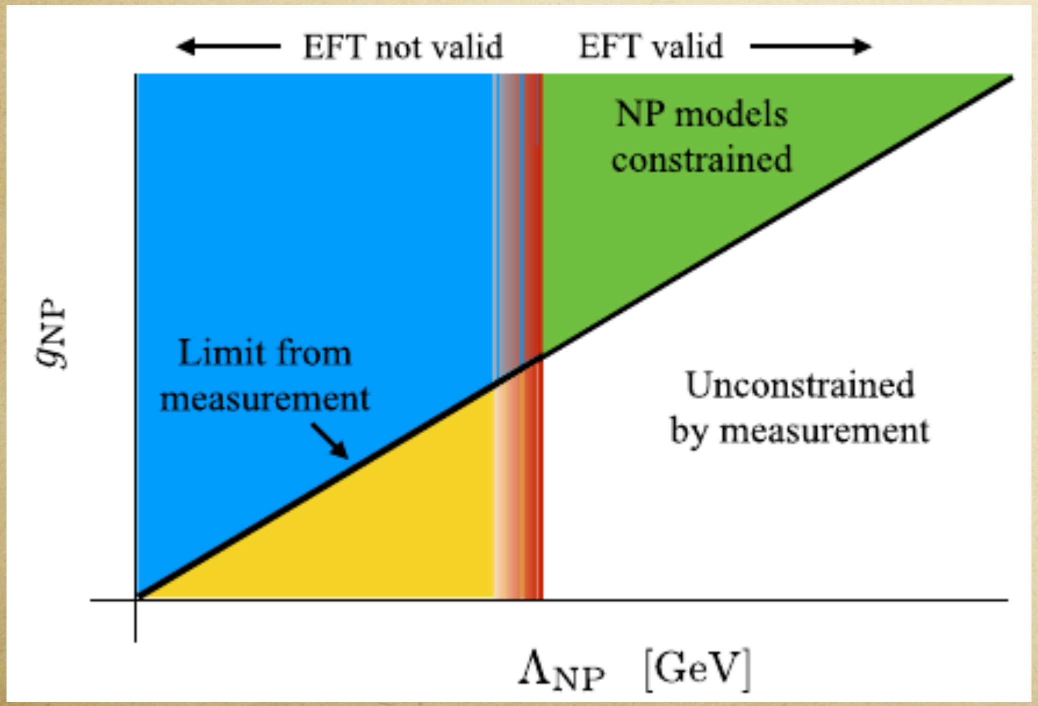


EFT ideal for precision measurements at a fixed scale

Need care in interpreting measurements over a range of scales
- Include running of EFT parameters
- EFT is only valid for scales higher than those probed

Care required in expanding in orders of EFT

$$|\mathcal{M}|^2(\text{SMEFT}) = |\mathcal{M}|^2(\text{SM}) + (1/\Lambda^2)\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{d6}} + 1/\Lambda^4\, |\mathcal{M}_{\text{d6}}|^2 + 1/\Lambda^4\, \mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{d8}} + \ldots$$



Lower bound on constrained scale Λ typically maximum Q^2 of measurement

Constraints on dimension-6 coefficients $(g/\Lambda)^2$: linear exclusion in g-Λ plane

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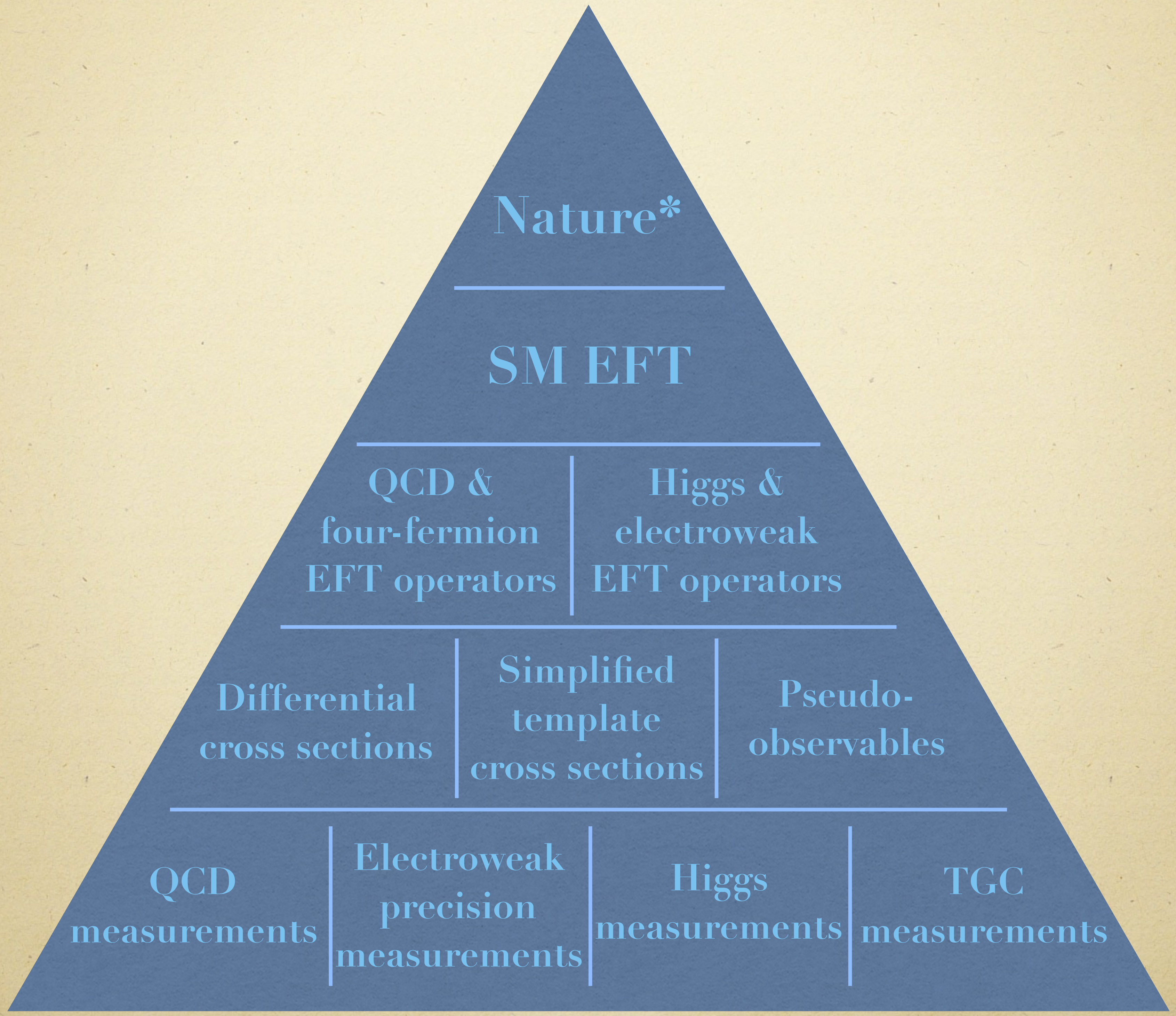
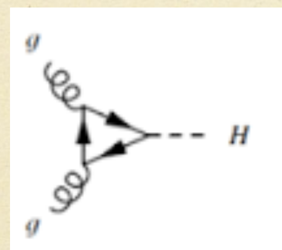
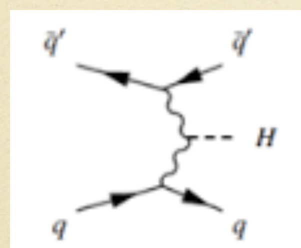
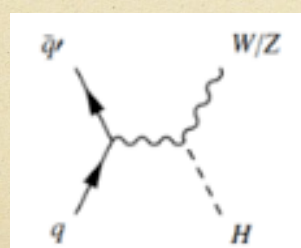
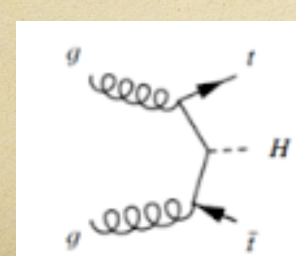
Construction of EFT

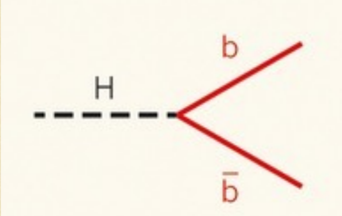
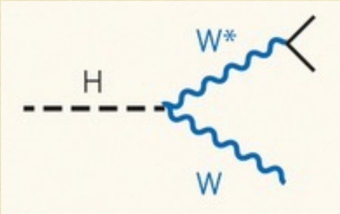
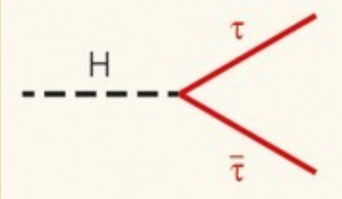
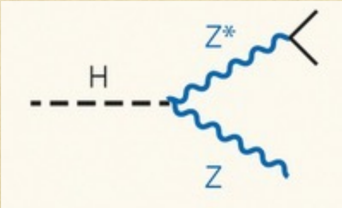
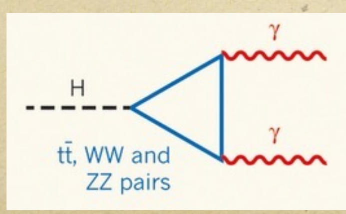


*d≤TeV^{-1}

Higgs boson production

Process	Diagram	Events produced			Status
		7 TeV	8 TeV	13 TeV	
gluon fusion (ggF)		75k	430k	1800k	Observed
vector boson fusion (VBF)		5.5k	32k	140k	Evidence
associated VH		4.1k	23k	86k	Evidence
associated ttH		0.4k	2.7k	19k	Evidence

Higgs boson decay

Process	Diagram	Events produced			Status
		7 TeV	8 TeV	13 TeV	
H→bb		49k	283k	1200k	>95% C.L.
H→WW		18k	105k	440k	Observed
H→ττ		5.3k	31k	130k	Evidence
H→ZZ		2.2k	13k	54k	Observed
H→γγ		0.2k	1.1k	4.6k	Observed

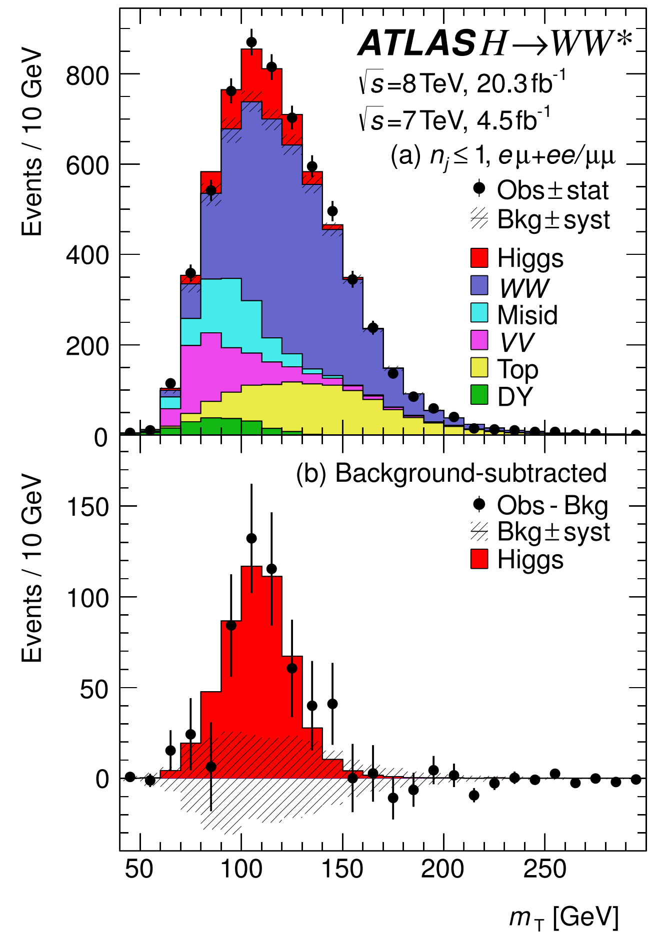
Higgs measurements

Basic strategy

1. Define a kinematic selection

Objective		ggF-enriched			VBF-enriched
		$n_j = 0$	$n_j = 1$	$n_j \geq 2$ ggF	$n_j \geq 2$ VBF
Preselection	All n_j	$p_T^{\ell 1} > 22$ for the leading lepton ℓ_1			
		$p_T^{\ell 2} > 10$ for the subleading lepton ℓ_2			
		Opposite-charge leptons			
		$m_{\ell\ell} > 10$ for the $e\mu$ sample			
		$m_{\ell\ell} > 12$ for the $ee/\mu\mu$ sample			
		$\lvert m_{\ell\ell} - m_Z \rvert > 15$ for the $ee/\mu\mu$ sample			
		$p_T^{miss} > 20$ for $e\mu$	$p_T^{miss} > 20$ for $e\mu$	$p_T^{miss} > 20$ for $e\mu$	No MET requirement for $e\mu$
		$E_{T,rel}^{miss} > 40$ for $ee/\mu\mu$	$E_{T,rel}^{miss} > 40$ for $ee/\mu\mu$	-	-
Reject backgrounds	DY	$p_{T,rel}^{miss\,(trk)} > 40$ for $ee/\mu\mu$	$p_{T,rel}^{miss\,(trk)} > 35$ for $ee/\mu\mu$	-	$p_T^{miss} > 40$ for $ee/\mu\mu$
		$f_{recoil} < 0.1$ for $ee/\mu\mu$	$f_{recoil} < 0.1$ for $ee/\mu\mu$	-	$E_T^{miss} > 45$ for $ee/\mu\mu$
		$p_T^{\ell\ell} > 30$	$m_{\tau\tau} < m_Z - 25$	$m_{\tau\tau} < m_Z - 25$	$m_{\tau\tau} < m_Z - 25$
		$\Delta\phi_{\ell\ell,MET} > \pi/2$	-	-	-
	Misid.	-	$m_T^{\ell} > 50$ for $e\mu$	-	-
	Top	$n_j = 0$	$n_b = 0$	$n_b = 0$	$n_b = 0$
		-	-	-	p_T^{sum} inputs to BDT
		-	-	-	$\Sigma m_{\ell j}$ inputs to BDT
VBF topology		-	-	See Sec. IV D for rejection of VBF & VH ($W, Z \to jj$), where $H \to WW^*$	m_{jj} inputs to BDT Δy_{jj} inputs to BDT ΣC_ℓ inputs to BDT $C_{\ell 1} < 1$ and $C_{\ell 2} < 1$ $C_{j3} > 1$ for j_3 with $p_T^{j3} > 20$ $O_{BDT} \geq -0.48$
$H \to WW^* \to \ell\nu\ell\nu$ decay topology		$m_{\ell\ell} < 55$	$m_{\ell\ell} < 55$	$m_{\ell\ell} < 55$	$m_{\ell\ell}$ inputs to BDT
		$\Delta\phi_{\ell\ell} < 1.8$	$\Delta\phi_{\ell\ell} < 1.8$	$\Delta\phi_{\ell\ell} < 1.8$	$\Delta\phi_{\ell\ell}$ inputs to BDT
		No m_T requirement	No m_T requirement	No m_T requirement	m_T inputs to BDT

2. Subtract background



3. Measure cross sections in the fiducial measurement regions

$$\sigma_{fid,0j}^{ggF} = 27.6 \;{}^{+5.4}_{-5.3}\;{}^{+4.1}_{-3.9} = 27.6 \;{}^{+6.8}_{-6.6}\ \text{fb},$$
$$\sigma_{fid,1j}^{ggF} = 8.3 \;{}^{+3.1}_{-3.0}\;{}^{+3.1}_{-3.0} = 8.3 \;{}^{+3.7}_{-3.5}\ \text{fb}.$$

(stat) (syst)

Includes small
unfolding and extrapolation

PRD 92, 021006 (2015)

Differential cross sections

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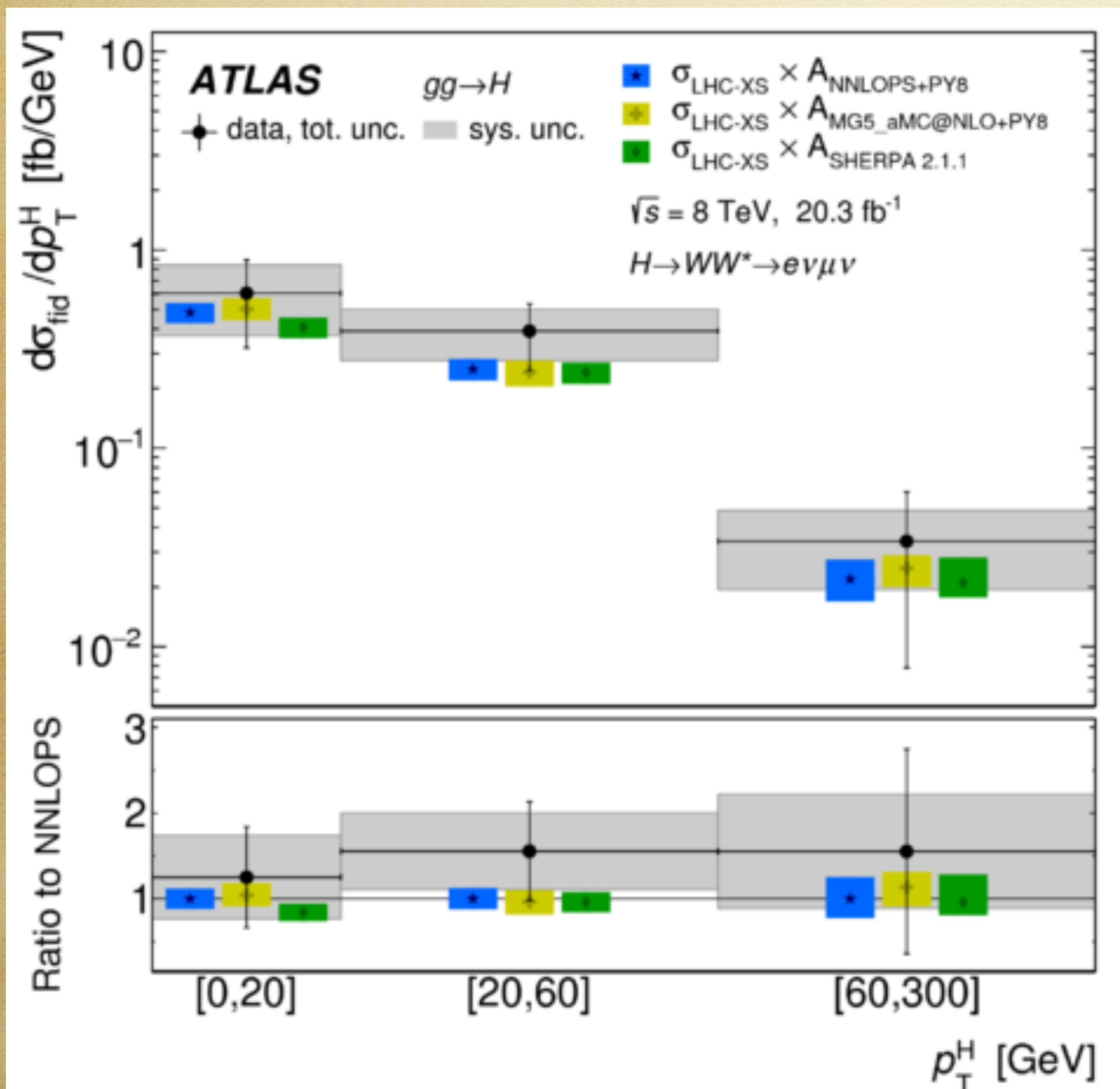
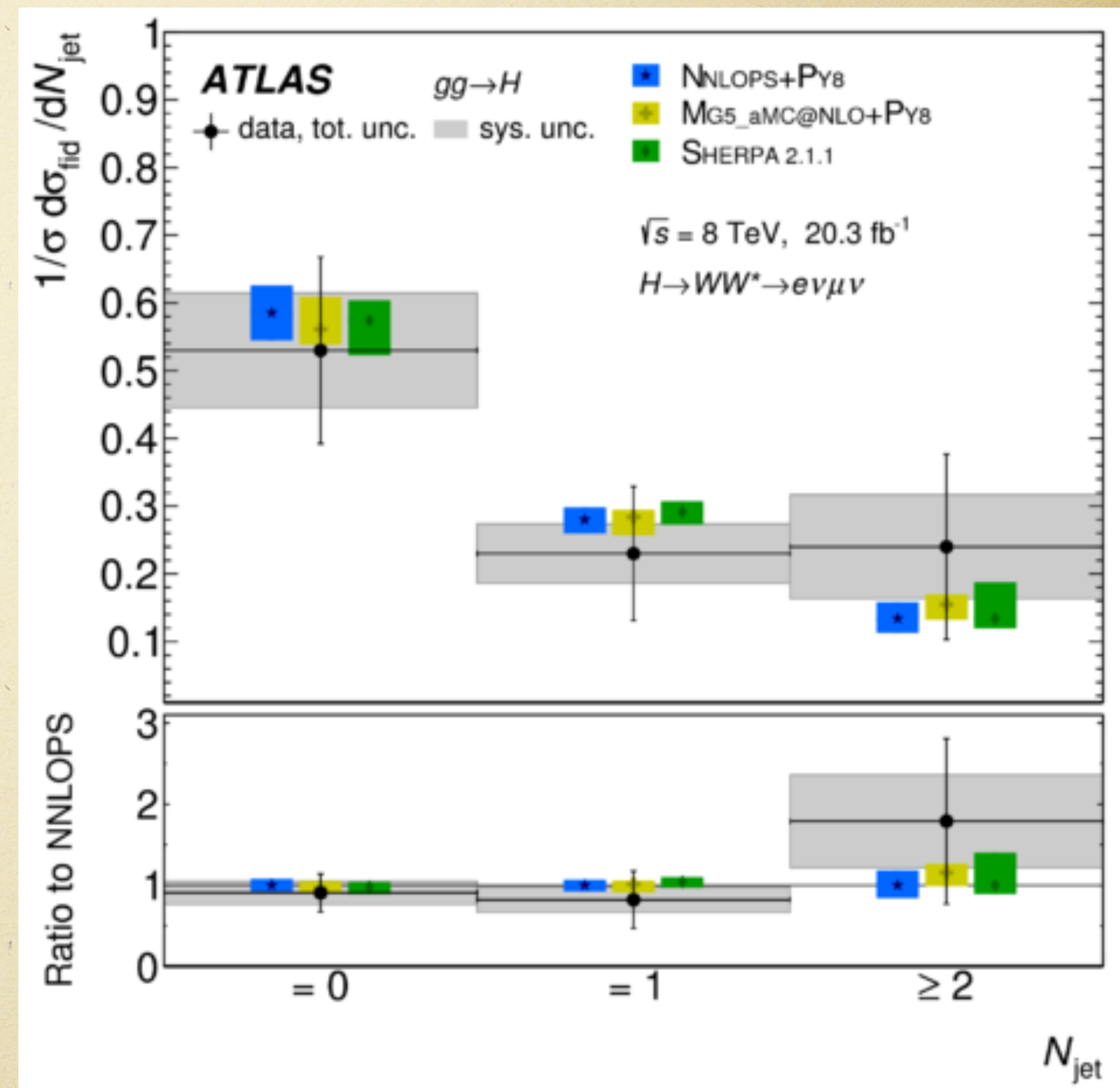




Unfold fiducial measurements differentially in distributions

Measurements performed by ATLAS & CMS for Higgs decays to WW, ZZ, γγ

Pseudo-observables

1610.07922, Sec. III.1

Directly relate individual measurements to physical pseudo-observables

$$\sigma^{\rm ggF}_{{\rm fid},0j} = 27.6 \ {}^{+5.4}_{-5.3} \ {}^{+4.1}_{-3.9} \ = 27.6 \ {}^{+6.8}_{-6.6} \ {\rm fb}$$

$$\sigma^{\rm ggF}_{\rm fid,0j} = [A\ \sigma(pp\to h)_{\text{gg-fusion}} + b\ \sigma(pp\to h)_{\rm VBF} + c\ \sigma(pp\to Vh)] \times$$

$$[\Gamma(h\to W_L W_L) + \Gamma(h\to W_T W_T) + \Gamma^{\rm CPV}(h\to W_T W_T)] \,/\, \Gamma_{\rm tot}(h)$$

A >> b, c

$\sigma(pp\to h)_{\rm VBF}$ and $\sigma(pp\to Vh)$ are functions of pseudo-observables

Can use effective couplings as intermediate step

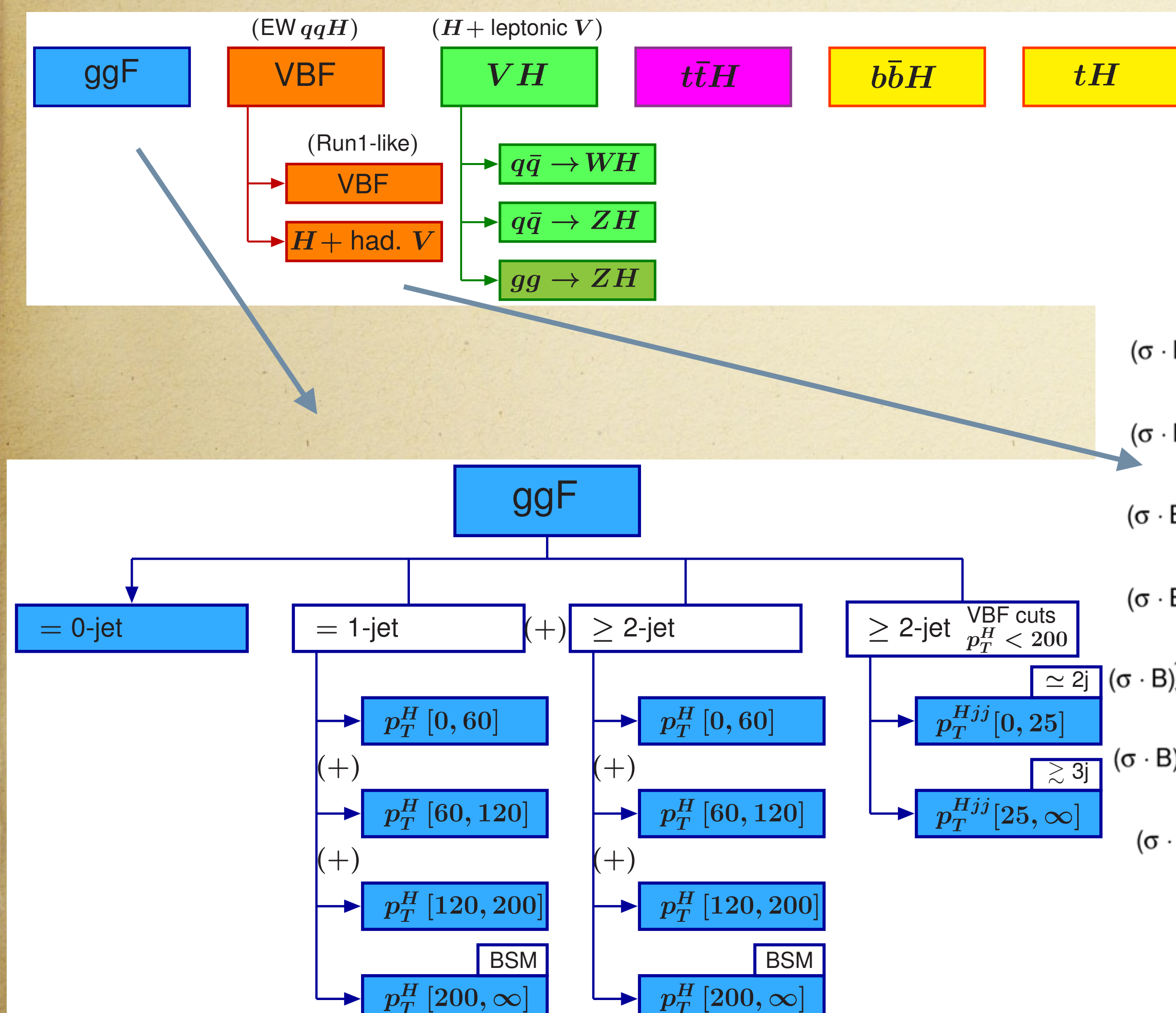
$$\kappa_f = \frac{y_S^f}{y_S^{f,\rm SM}}\,, \qquad \delta_f^{\rm CP} = \frac{y_P^f}{y_S^{f,\rm SM}}$$

PO	*Physical* PO	Relation to the eff. coupl.
$\kappa_f,\ \delta_f^{\rm CP}$	$\Gamma(h\to f\bar f)$	$= \Gamma(h\to f\bar f)^{\rm (SM)}[(\kappa_f)^2 + (\delta_f^{\rm CP})^2]$
$\kappa_{\gamma\gamma},\ \delta_{\gamma\gamma}^{\rm CP}$	$\Gamma(h\to \gamma\gamma)$	$= \Gamma(h\to \gamma\gamma)^{\rm (SM)}[(\kappa_{\gamma\gamma})^2 + (\delta_{\gamma\gamma}^{\rm CP})^2]$
$\kappa_{Z\gamma},\ \delta_{Z\gamma}^{\rm CP}$	$\Gamma(h\to Z\gamma)$	$= \Gamma(h\to Z\gamma)^{\rm (SM)}[(\kappa_{Z\gamma})^2 + (\delta_{Z\gamma}^{\rm CP})^2]$
κ_{ZZ}	$\Gamma(h\to Z_L Z_L)$	$= (0.209\ \text{MeV}) \times \lvert\kappa_{ZZ}\rvert^2$
ϵ_{ZZ}	$\Gamma(h\to Z_T Z_T)$	$= (1.9\times10^{-2}\ \text{MeV}) \times \lvert\epsilon_{ZZ}\rvert^2$
$\epsilon_{ZZ}^{\rm CP}$	$\Gamma^{\rm CPV}(h\to Z_T Z_T)$	$= (8.0\times10^{-3}\ \text{MeV}) \times \lvert\epsilon_{ZZ}^{\rm CP}\rvert^2$
ϵ_{Zf}	$\Gamma(h\to Z f\bar f)$	$= (3.7\times10^{-2}\ \text{MeV}) \times N_c^f\ \lvert\epsilon_{Zf}\rvert^2$
κ_{WW}	$\Gamma(h\to W_L W_L)$	$= (0.84\ \text{MeV}) \times \lvert\kappa_{WW}\rvert^2$
ϵ_{WW}	$\Gamma(h\to W_T W_T)$	$= (0.16\ \text{MeV}) \times \lvert\epsilon_{WW}\rvert^2$
$\epsilon_{WW}^{\rm CP}$	$\Gamma^{\rm CPV}(h\to W_T W_T)$	$= (6.8\times10^{-2}\ \text{MeV}) \times \lvert\epsilon_{WW}^{\rm CP}\rvert^2$
ϵ_{Wf}	$\Gamma(h\to W f\bar f')$	$= (0.14\ \text{MeV}) \times N_c^f\ \lvert\epsilon_{Wf}\rvert^2$
κ_g	$\sigma(pp\to h)_{gg-\rm fusion}$	$= \sigma(pp\to h)^{\rm SM}_{gg-\rm fusion}\kappa_g^2$
κ_t	$\sigma(pp\to t\bar t h)_{\rm Yukawa}$	$= \sigma(pp\to t\bar t h)^{\rm SM}_{\rm Yukawa}\kappa_t^2$
κ_H	$\Gamma_{\rm tot}(h)$	$= \Gamma^{\rm SM}_{\rm tot}(h)\kappa_H^2$

Combine channels and kinematic regions to determine the pseudo-observables and covariance
Pseudo-observables capture complete set of information from a given process

Simplified template cross sections

Extrapolate from measurement region to total production cross section
Future results will subdivide into several kinematic regions



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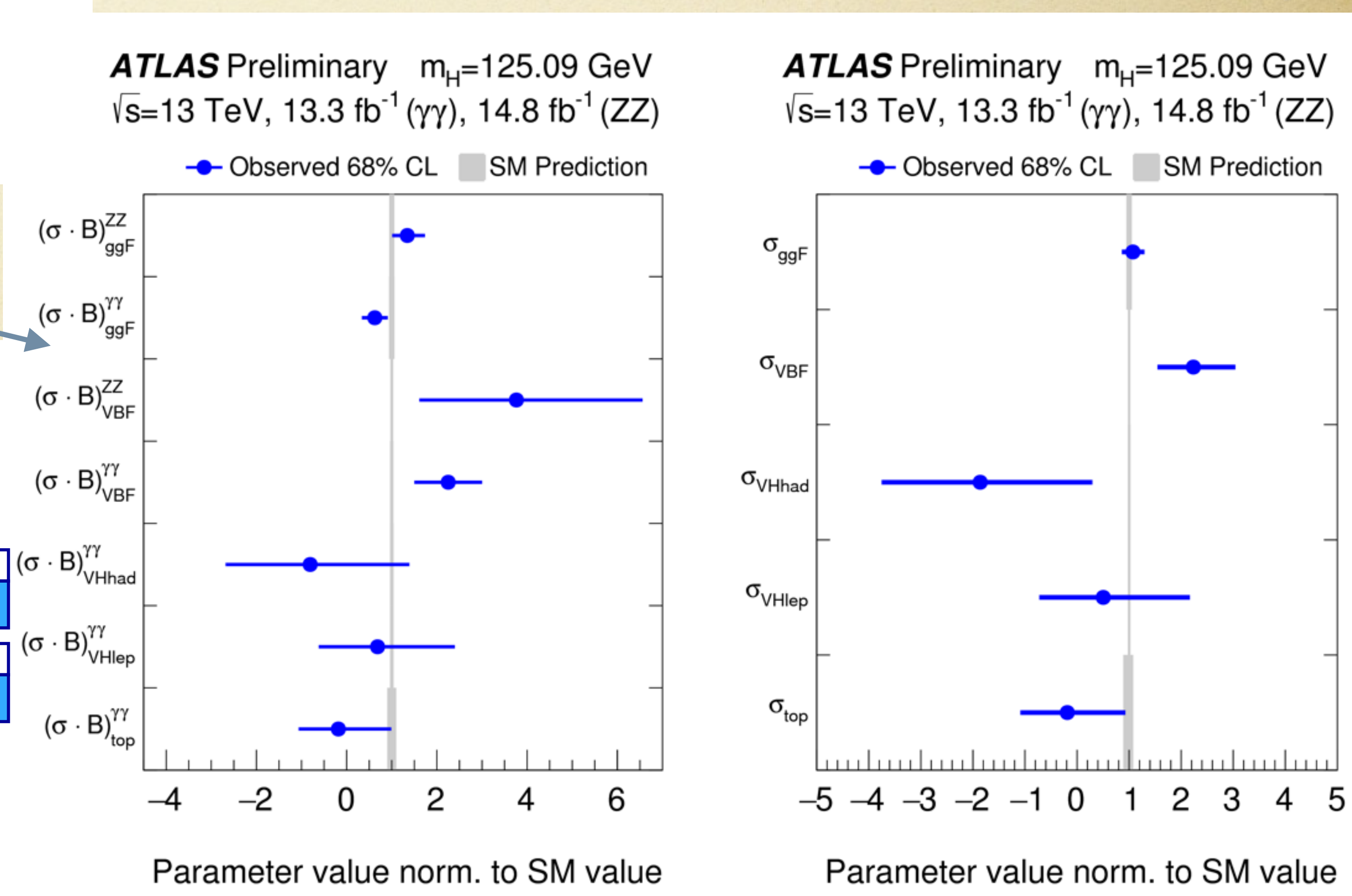

1610.07922, Sec. III.2

Example EFT fit

J. Ellis, V. Sanz and T. You combine precision electroweak data with Higgs and anomalous coupling constraints to fit EFT parameters in the SILH basis

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Fit performed in steps:

(1) neglect interactions that do not affect Higgs and electroweak physics

(21 four-fermion operators and 3 gluon self-couplings)

(2) use high-precision electroweak data to constrain 8 operators

(3) use triple-gauge-coupling and Higgs data to constrain 9 more

Bosonic CP-even		Bosonic CP-odd	
O_H	$\frac{1}{2v^2}\left[\partial_\mu(H^\dagger H)\right]^2$		
O_T	$\frac{1}{2v^2}\left(H^\dagger \overleftrightarrow{D_\mu} H\right)^2$		
O_6	$-\frac{\lambda}{v^2}(H^\dagger H)^3$		
O_g	$\frac{g_s^2}{m_W^2} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$\widetilde{O}_g$	$\frac{g_s^2}{m_W^2} H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_γ	$\frac{g'^2}{m_W^2} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$\widetilde{O}_\gamma$	$\frac{g'^2}{m_W^2} H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_W	$\frac{ig}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D_\mu} H\right) D_\nu W^i_{\mu\nu}$		
O_B	$\frac{ig'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D_\mu} H\right) \partial_\nu B_{\mu\nu}$		
O_{HW}	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu}$	$\widetilde{O}_{HW}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) \widetilde{W}^i_{\mu\nu}$
O_{HB}	$\frac{ig'}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}$	$\widetilde{O}_{HB}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) \widetilde{B}_{\mu\nu}$
O_{2W}	$\frac{1}{m_W^2} D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu}$		
O_{2B}	$\frac{1}{m_W^2} \partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu}$		
O_{2G}	$\frac{1}{m_W^2} D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}$		
O_{3W}	$\frac{g^3}{m_W^2} \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$\widetilde{O}_{3W}$	$\frac{g^3}{m_W^2} \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$\frac{g_s^3}{m_W^2} f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$\widetilde{O}_{3G}$	$\frac{g_s^3}{m_W^2} f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Yukawa and Dipole	
$[O_e]_{ij}$	$\frac{\sqrt{2m_{e_i} m_{e_j}}}{v^3} H^\dagger H \bar{\ell}_i H e_j$
$[O_u]_{ij}$	$\frac{\sqrt{2m_{u_i} m_{u_j}}}{v^3} H^\dagger H \bar{q}_i \widetilde{H} u_j$
$[O_d]_{ij}$	$\frac{\sqrt{2m_{d_i} m_{d_j}}}{v^3} H^\dagger H \bar{q}_i H d_j$
$[O_{eW}]_{ij}$	$\frac{g}{m_W^2} \frac{\sqrt{2m_{e_i} m_{e_j}}}{v} \bar{\ell}_i \sigma^k H \sigma_{\mu\nu} e_j W^k_{\mu\nu}$
$[O_{eB}]_{ij}$	$\frac{g'}{m_W^2} \frac{\sqrt{2m_{e_i} m_{e_j}}}{v} \bar{\ell}_i H \sigma_{\mu\nu} e_j B_{\mu\nu}$
$[O_{uG}]_{ij}$	$\frac{g_s}{m_W^2} \frac{\sqrt{2m_{u_i} m_{u_j}}}{v} \bar{q}_i \tilde{H} \sigma_{\mu\nu} T^a u_j G^a_{\mu\nu}$
$[O_{uW}]_{ij}$	$\frac{g}{m_W^2} \frac{\sqrt{2m_{u_i} m_{u_j}}}{v} \bar{q}_i \sigma^k \tilde{H} \sigma_{\mu\nu} u_j W^k_{\mu\nu}$
$[O_{uB}]_{ij}$	$\frac{g'}{m_W^2} \frac{\sqrt{2m_{u_i} m_{u_j}}}{v} \bar{q}_i \tilde{H} \sigma_{\mu\nu} u_j B_{\mu\nu}$
$[O_{dG}]_{ij}$	$\frac{g_s}{m_W^2} \frac{\sqrt{2m_{d_i} m_{d_j}}}{v} \bar{q}_i H \sigma_{\mu\nu} T^a d_j G^a_{\mu\nu}$
$[O_{dW}]_{ij}$	$\frac{g}{m_W^2} \frac{\sqrt{2m_{d_i} m_{d_j}}}{v} \bar{q}_i \sigma^k H \sigma_{\mu\nu} d_j W^k_{\mu\nu}$
$[O_{dB}]_{ij}$	$\frac{g'}{m_W^2} \frac{\sqrt{2m_{d_i} m_{d_j}}}{v} \bar{q}_i H \sigma_{\mu\nu} d_j B_{\mu\nu}$

Vertex	
$[O_{He}]_{ij}$	$\frac{i}{v^2} \bar{e}_i \gamma_\mu \bar{e}_j H^\dagger \overleftrightarrow{D_\mu} H$
$[O_{Hq}]_{ij}$	$\frac{i}{v^2} \bar{q}_i \gamma_\mu q_j H^\dagger \overleftrightarrow{D_\mu} H$
$[O'_{Hq}]_{ij}$	$\frac{i}{v^2} \bar{q}_i \sigma^k \gamma_\mu q_j H^\dagger \sigma^k \overleftrightarrow{D_\mu} H$
$[O_{Hu}]_{ij}$	$\frac{i}{v^2} \bar{u}_i \gamma_\mu u_j H^\dagger \overleftrightarrow{D_\mu} H$
$[O_{Hd}]_{ij}$	$\frac{i}{v^2} \bar{d}_i \gamma_\mu d_j H^\dagger \overleftrightarrow{D_\mu} H$
$[O_{Hud}]_{ij}$	$\frac{i}{v^2} \bar{u}_i \gamma_\mu d_j \tilde{H}^\dagger D_\mu H$

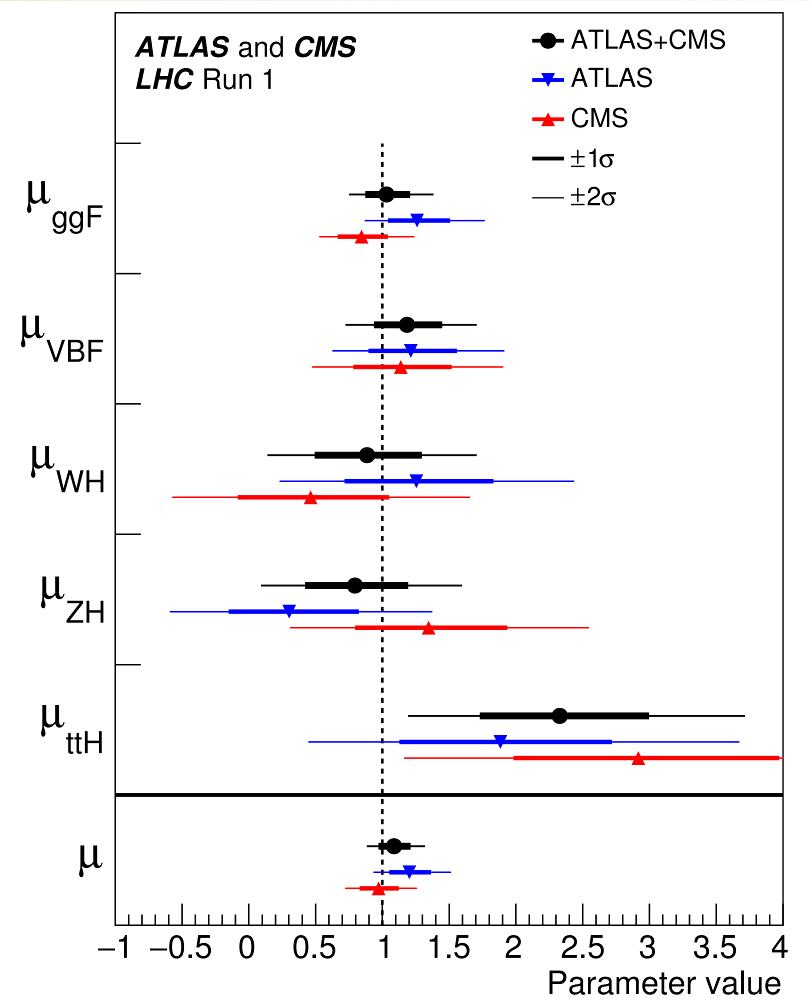
1610.07922, Sec. III.2.1

Higgs boson production

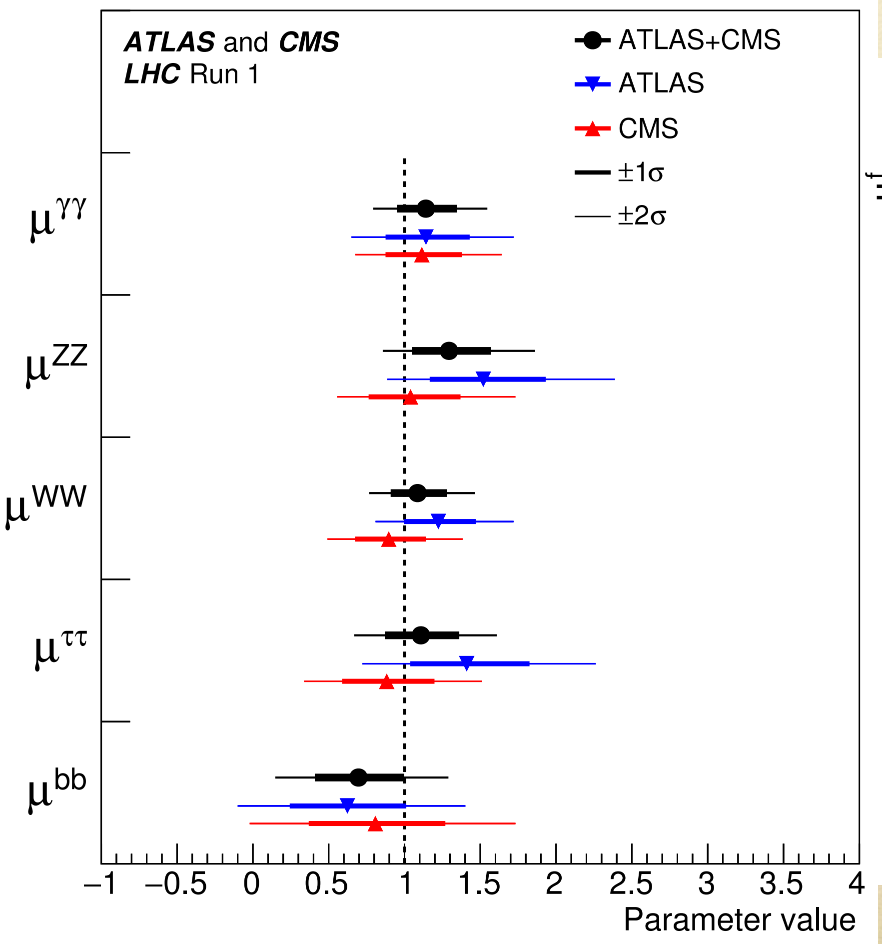
Measurements of Higgs boson cross sections in Run 1 can be used in EFT fits

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\rm SM}} \quad \text{and} \quad \mu^f = \frac{{\rm B}^f}{({\rm B}^f)_{\rm SM}}.$$

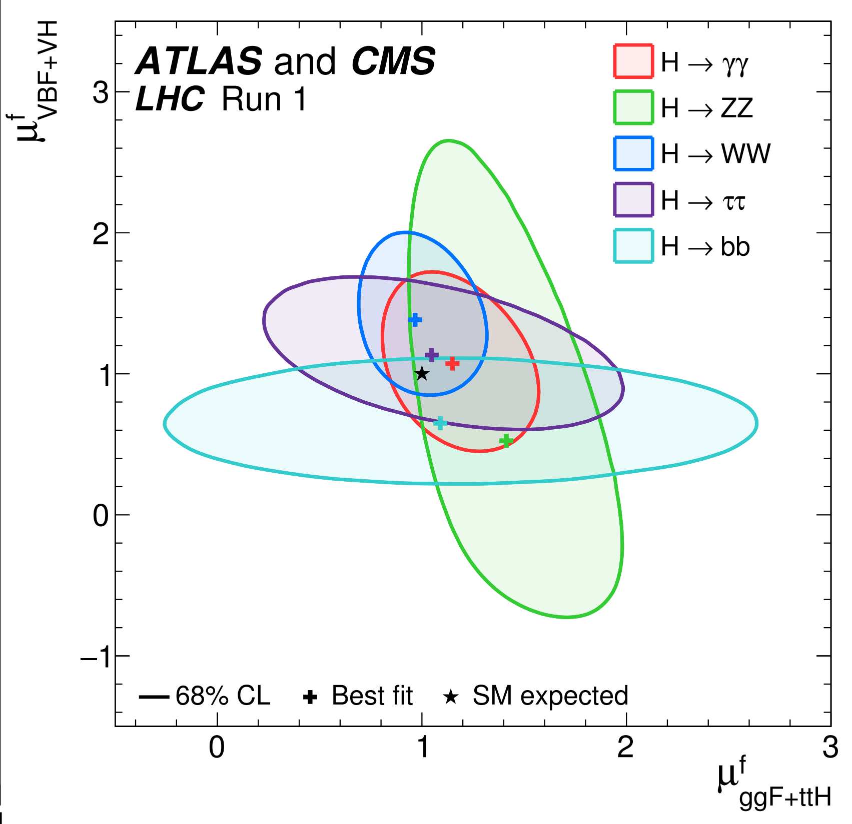
JHEP 08 (2016) 045



Production



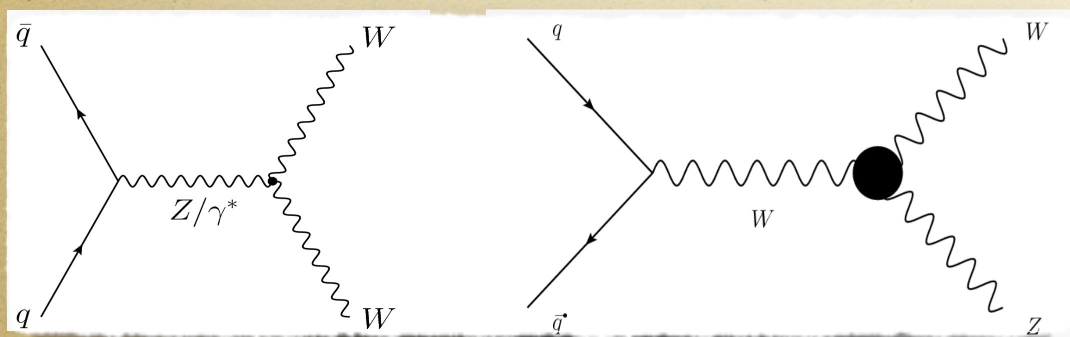
Decay



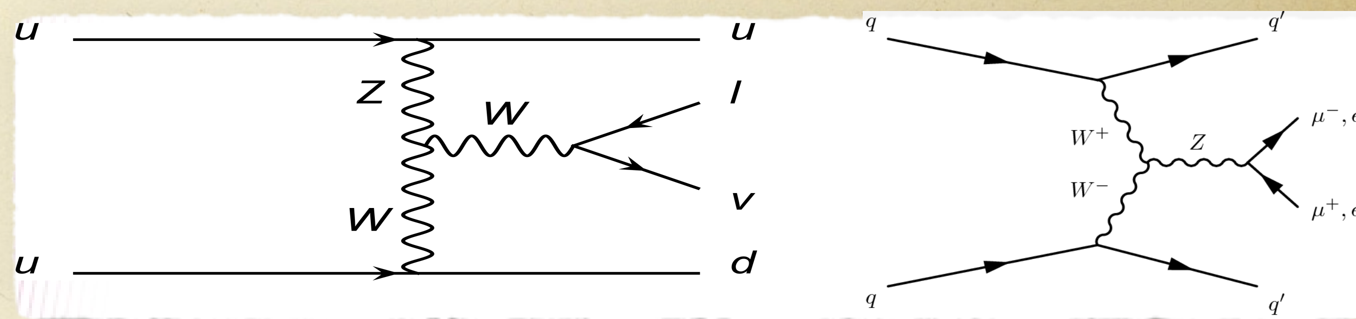
Production and decay

Gauge boson self-couplings

s-channel



t-channel



Historical parameterization

$$
\begin{aligned}
\mathcal{L}_{\rm tgc} &= ie\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)A_\nu + ie\left[(1+\delta\kappa_\gamma)A_{\mu\nu}\,W^+_\mu W^-_\nu + \tilde{\kappa}_\gamma \tilde{A}_{\mu\nu}\,W^+_\mu W^-_\nu\right] \\
&+ igc_\theta\left[(1+\delta g_{1,z})\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)Z_\nu + (1+\delta\kappa_z)\,Z_{\mu\nu}\,W^+_\mu W^-_\nu + \tilde{\kappa}_z\,\tilde{Z}_{\mu\nu}\,W^+_\mu W^-_\nu\right] \\
&+ i\frac{e}{m_W^2}\left[\lambda_\gamma W^+_{\mu\nu}W^-_{\nu\rho}A_{\rho\mu} + \tilde{\lambda}_\gamma W^+_{\mu\nu}W^-_{\nu\rho}\tilde{A}_{\rho\mu}\right] + i\frac{gc_\theta}{m_W^2}\left[\lambda_z W^+_{\mu\nu}W^-_{\nu\rho}Z_{\rho\mu} + \tilde{\lambda}_z W^+_{\mu\nu}W^-_{\nu\rho}\tilde{Z}_{\rho\mu}\right]
\end{aligned}
$$

Relation to EFT basis

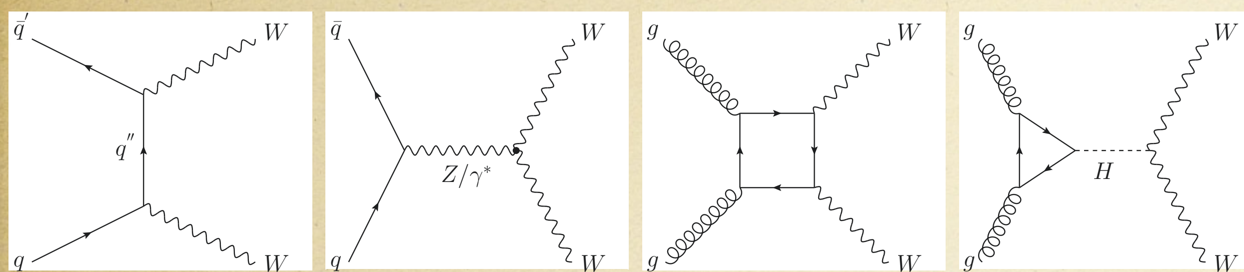
1610.07922, Sec. III.2.1

$$
\begin{aligned}
\delta g_{1z} &= -\frac{g^2+g'^2}{g^2-g'^2}\left[\frac{g^2-g'^2}{g^2}\bar{c}_{HW} + \bar{c}_W + \bar{c}_{2W} + \frac{g'^2}{g^2}\bar{c}_B + \frac{g'^2}{g^2}\bar{c}_{2B} - \frac{1}{2}\bar{c}_T + \frac{1}{2}[\bar{c}'_{H\ell}]_{22}\right], \\
\delta\kappa_\gamma &= -\bar{c}_{HW} - \bar{c}_{HB}, \\
\delta\kappa_z &= -\bar{c}_{HW} + \frac{g'^2}{g^2}\bar{c}_{HB} - \frac{g^2+g'^2}{g^2-g'^2}\left[\bar{c}_W + \bar{c}_{2W} + \frac{g'^2}{g^2}\bar{c}_B + \frac{g'^2}{g^2}\bar{c}_{2B} - \frac{1}{2}\bar{c}_T + \frac{1}{2}[\bar{c}'_{H\ell}]_{22}\right], \\
\lambda_z &= -6g^2\bar{c}_{3W}, \qquad \lambda_\gamma = \lambda_z, \\
\delta\tilde{\kappa}_\gamma &= -\tilde{c}_{HW} - \tilde{c}_{HB}, \\
\delta\tilde{\kappa}_z &= \frac{g'^2}{g^2}\left[\tilde{c}_{HW} + \tilde{c}_{HB}\right], \\
\tilde{\lambda}_z &= -6g^2\tilde{c}_{3W}, \qquad \tilde{\lambda}_\gamma = \tilde{\lambda}_z,
\end{aligned}
$$

⟵ also affect Higgs production & decay

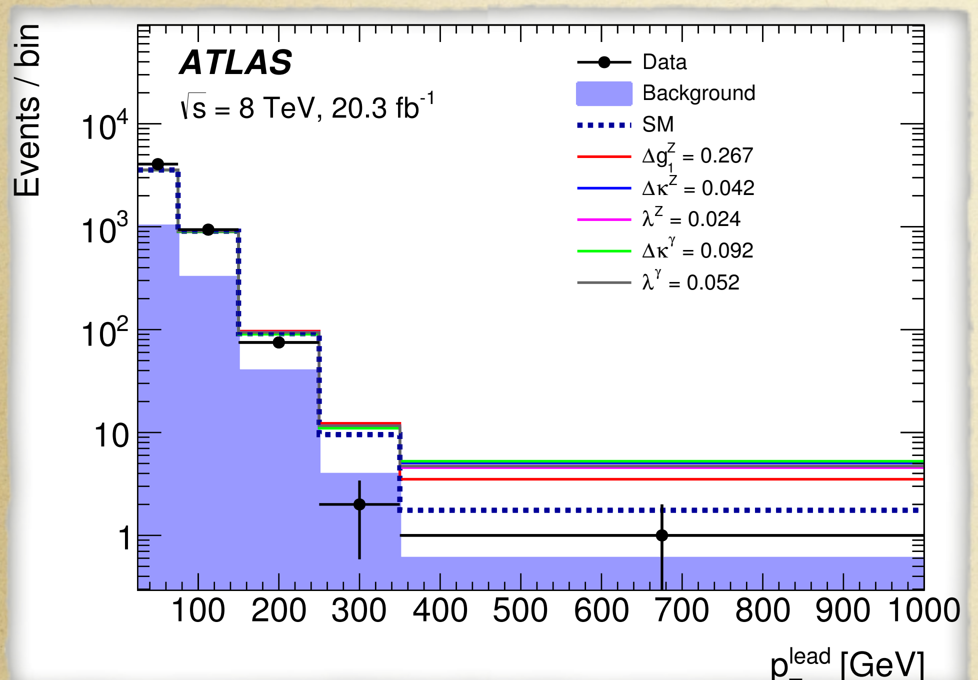
⟵ only determined by self-couplings

WW production



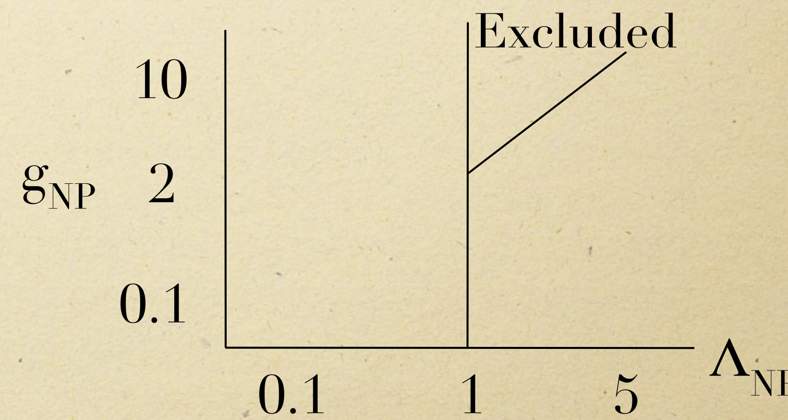
(a) *t*-channel. **(b)** *s*-channel (TGC vertex). **(c)** Gluon fusion. **(d)** Higgs boson production.

Measurement of WW production by ATLAS interpreted in terms of constraints on individual coefficients



Can translate this to a constraint in a coupling-mass plane assuming only c_{3W} is non-zero

Scenario	Parameter	Expected [TeV^{-2}]	Observed [TeV^{-2}]
	C_{WWW}/Λ^2	$[-7.62, 7.38]$	$[-4.61, 4.60]$
EFT	C_B/Λ^2	$[-35.8, 38.4]$	$[-20.9, 26.3]$
	C_W/Λ^2	$[-12.58, 14.32]$	$[-5.87, 10.54]$



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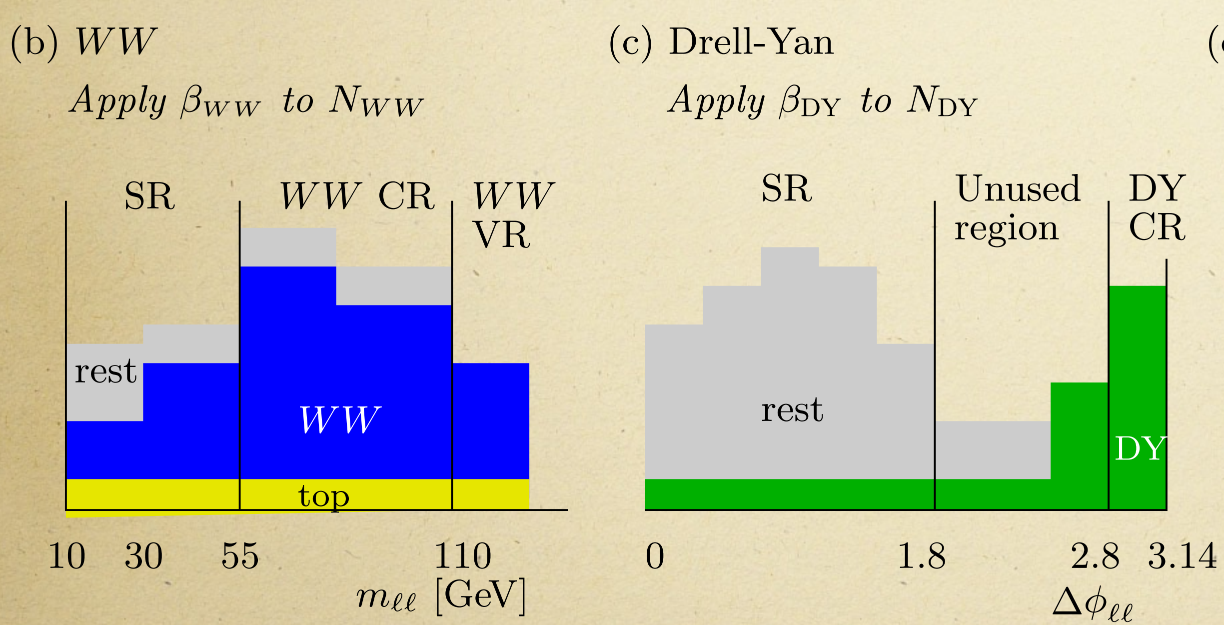
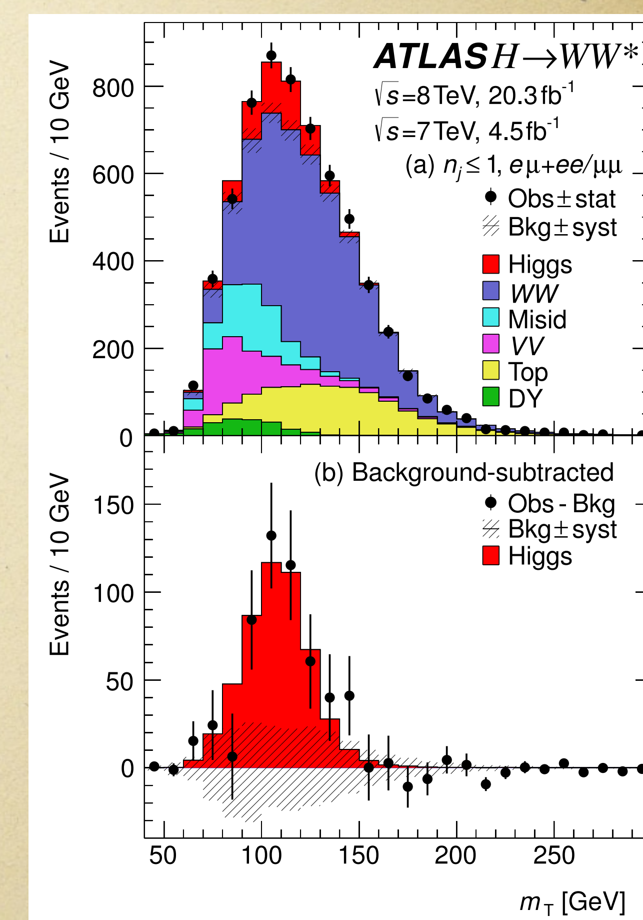
WW production

In a combined fit need to consider coefficients that affect both gauge-boson self-couplings and gauge-boson couplings to the Higgs boson

Measurement of H→WW constrains WW background with data

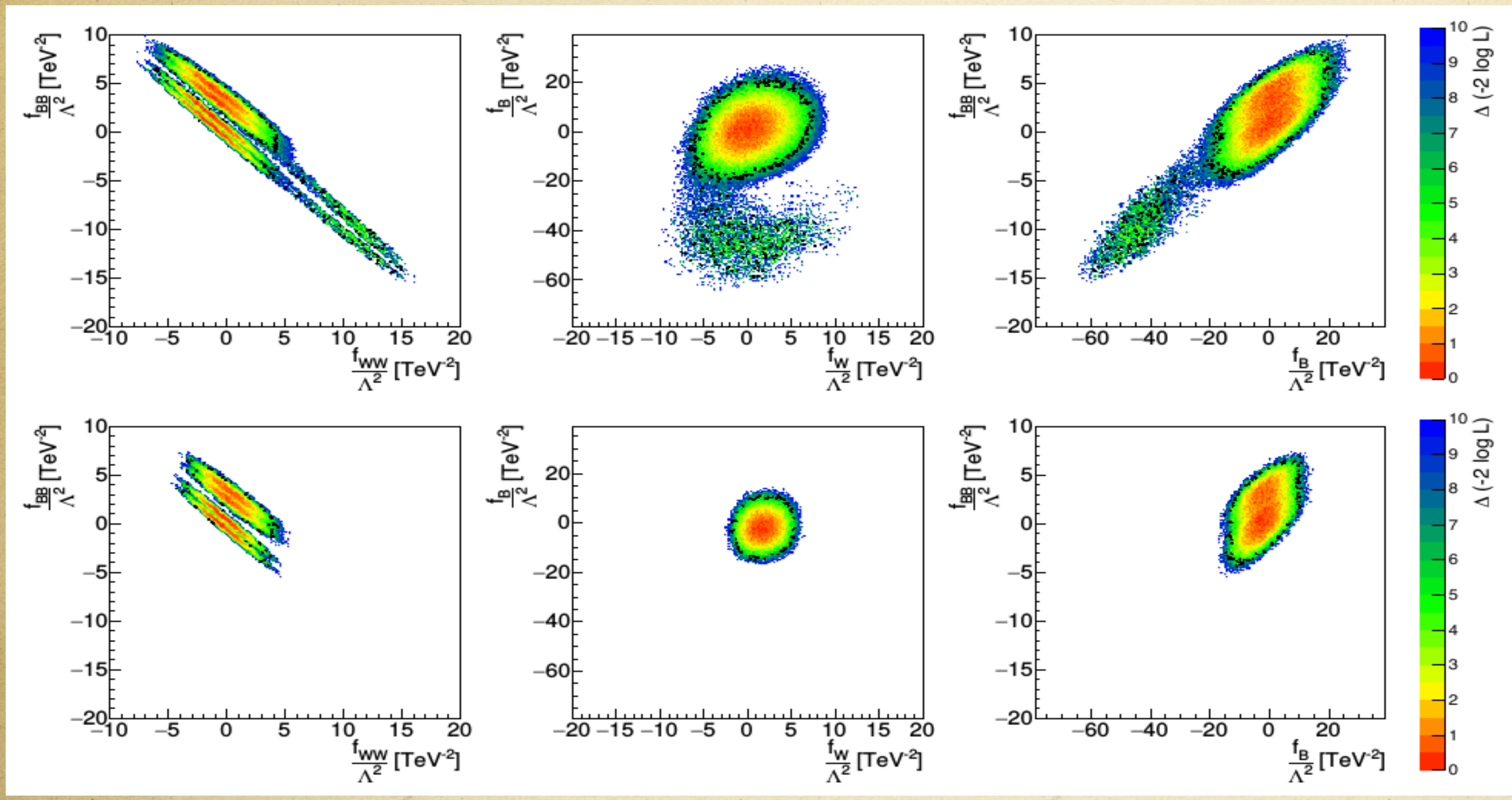
Correlations undetermined in EFT fit





PRD 92, 021006 (2015)

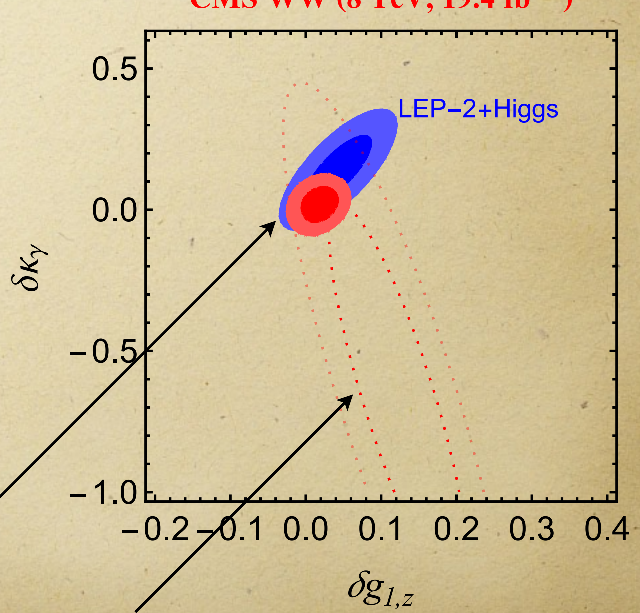
Impact of gauge self-couplings



LHC Higgs

arXiv:1604.03105

LHC Higgs + dibosons



Most of the diboson sensitivity comes from the high Q^2 part of the distribution, where interference with SM small

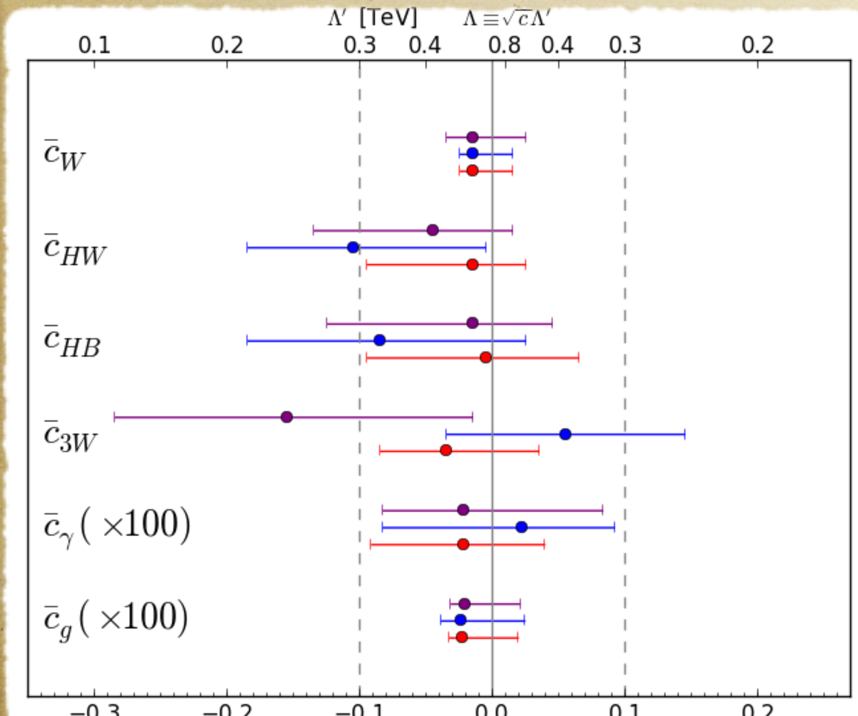
Open question whether dimension-8 terms could be of the same order

arXiv:1609.06312

with $|\mathcal{M}_{d6}|^2/\Lambda^4$

without $|\mathcal{M}_{d6}|^2/\Lambda^4$

Fit to Higgs & TGC measurements



Operator	Coefficient	LHC Constraints	
		Individual	Marginalized
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}(c_W - c_B)$	$(-0.022, 0.004)$	$(-0.035, 0.005)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_{HW}$	$(-0.042, 0.008)$	$(-0.035, 0.015)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_{HB}$	$(-0.053, 0.044)$	$(-0.045, 0.075)$
$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$	$\frac{m_W^2}{\Lambda^2} c_{3W}$	$(-0.083, 0.045)$	$(-0.083, 0.045)$
$\mathcal{O}_g = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_g$	$(0, 3.0) \times 10^{-5}$	$(-3.2, 1.1) \times 10^{-4}$
$\mathcal{O}_\gamma = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_\gamma$	$(-4.0, 2.3) \times 10^{-4}$	$(-11, 2.2) \times 10^{-4}$
$\mathcal{O}_H = \frac{1}{2}\left(\partial^\mu \lvert H\rvert^2\right)^2$	$\frac{v^2}{\Lambda^2} c_H$	$(-0.14, 0.194)$	$(-,-)$
$\mathcal{O}_f = y_f \lvert H\rvert^2 \bar{F}_L H^{(c)} f_R + \text{h.c.}$	$\frac{v^2}{\Lambda^2} c_f$	$(-0.084, 0.155)(c_u)$ $(-0.198, 0.088)(c_d)$	$(-,-)$ $(-,-)$

Constrain 6 EFT parameters in global fit

(3 additional parameters if constrained individually)

14 globally constrained parameters when combined with precision electroweak constraints

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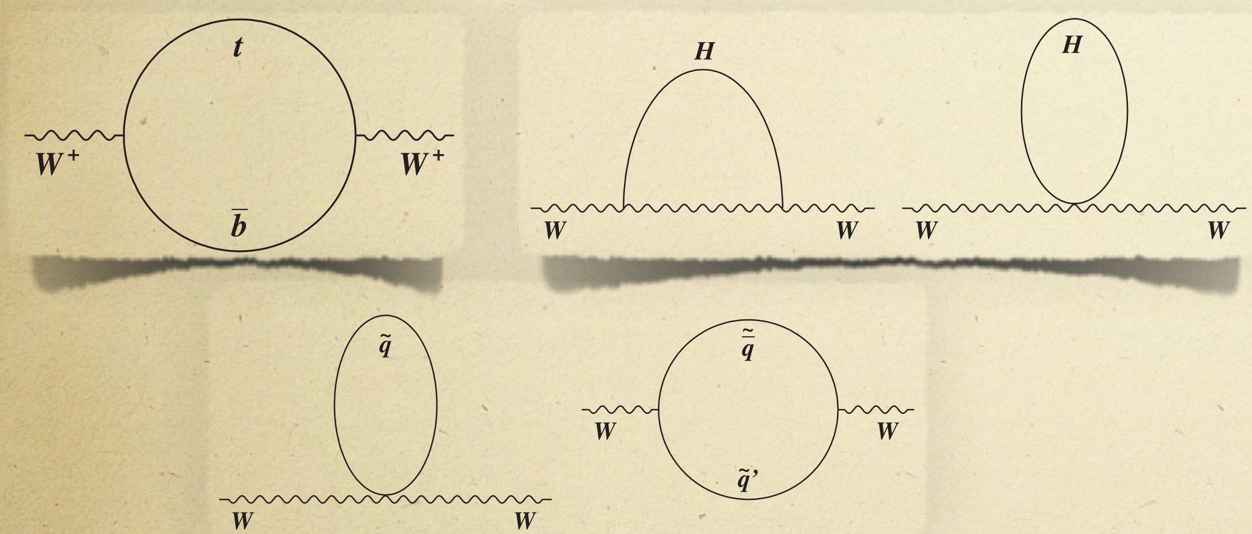
W boson mass in the SM

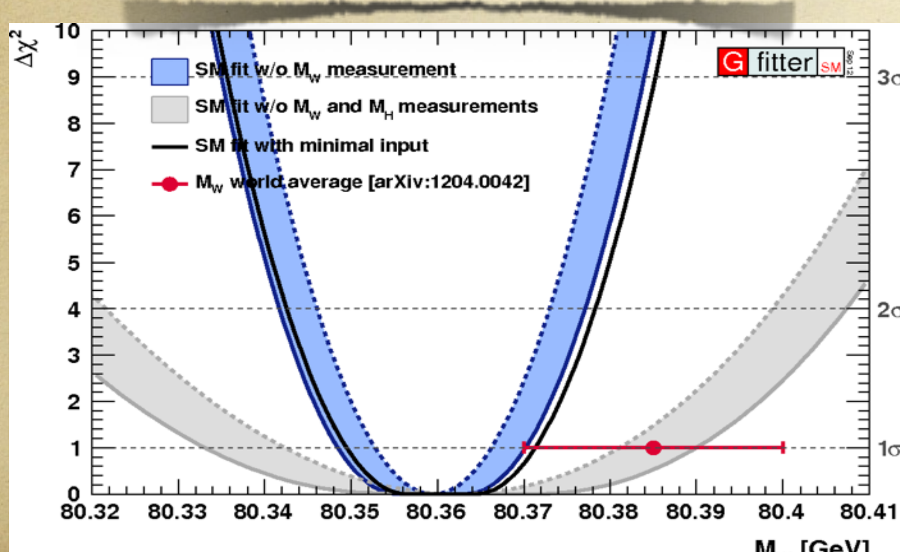
Mass completely predicted given three measured inputs:

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha_{em}}{\sqrt{2}G_F}\,\frac{1}{1-\Delta r}$$

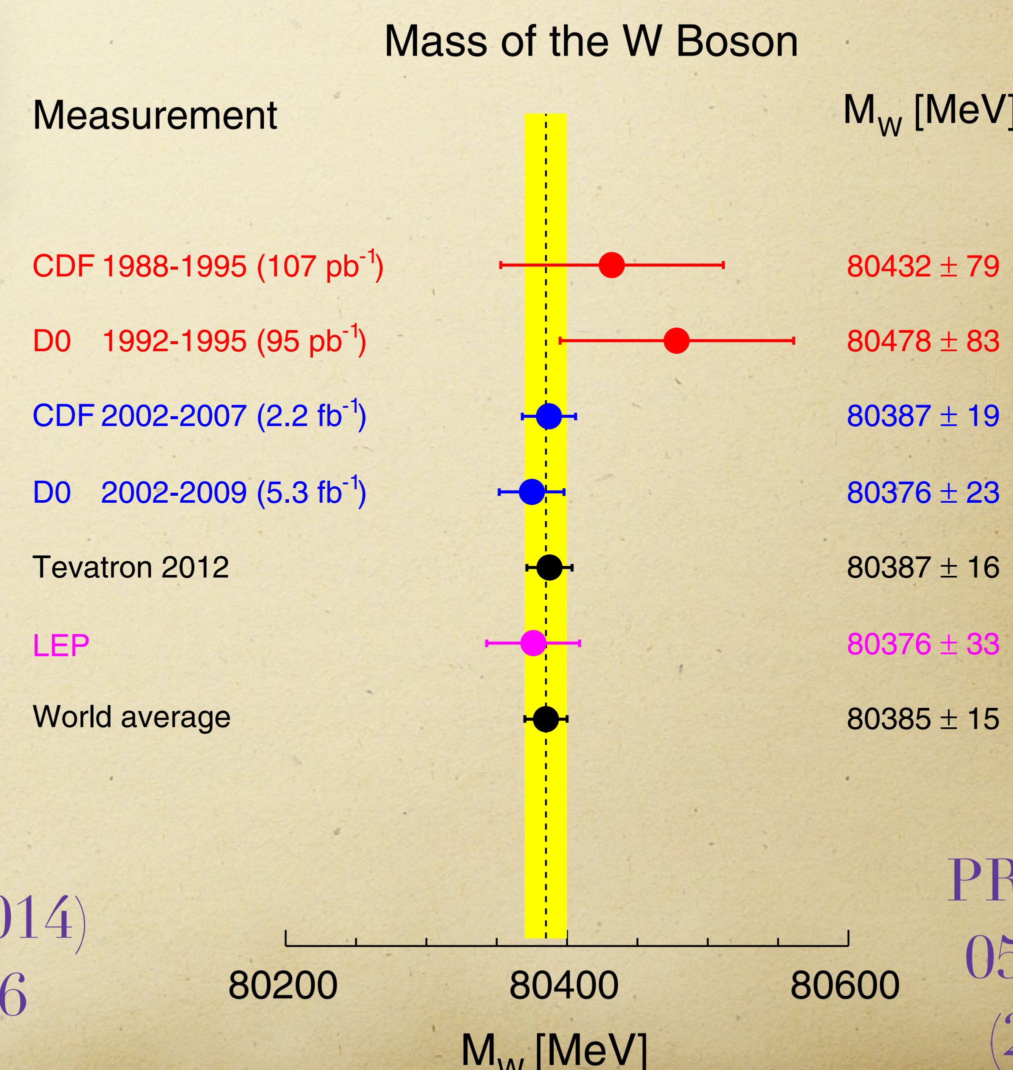
For $\Delta r=0$, M_W = 79 964 MeV

Sensitive to loop corrections from e.g. top quarks, Higgs bosons, and stop quarks





EPJC (2014) 74:3046

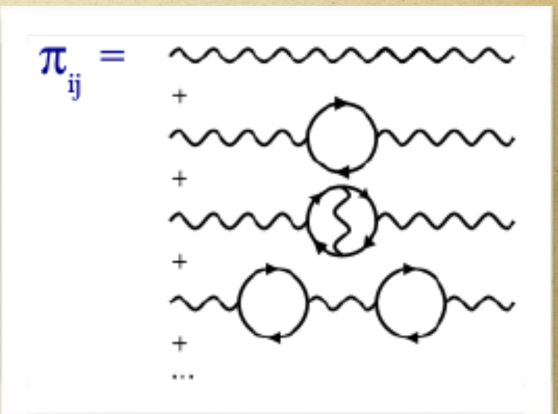


PRD 88, 052018 (2013)

W & Z boson mass constraints

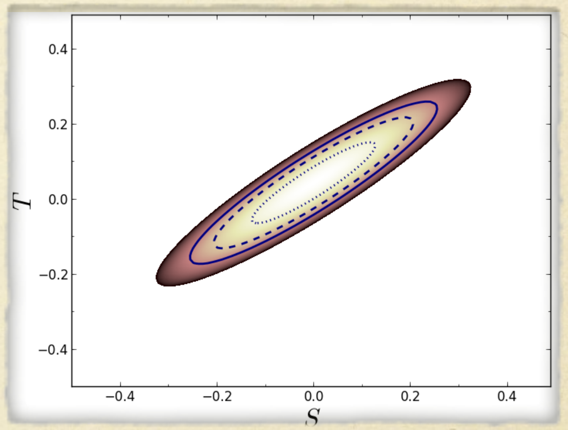
"Oblique" corrections: $\mathcal{L}_{\text{dim-6}} \supset \frac{\bar{c}_{WB}}{m_W^2}\mathcal{O}_{WB} + \frac{\bar{c}_W}{m_W^2}\mathcal{O}_W + \frac{\bar{c}_B}{m_W^2}\mathcal{O}_B + \frac{\bar{c}_T}{v^2}\mathcal{O}_T + \frac{\bar{c}_{2W}}{m_W^2}\mathcal{O}_{2W} + \frac{\bar{c}_{2B}}{m_W^2}\mathcal{O}_{2B}$

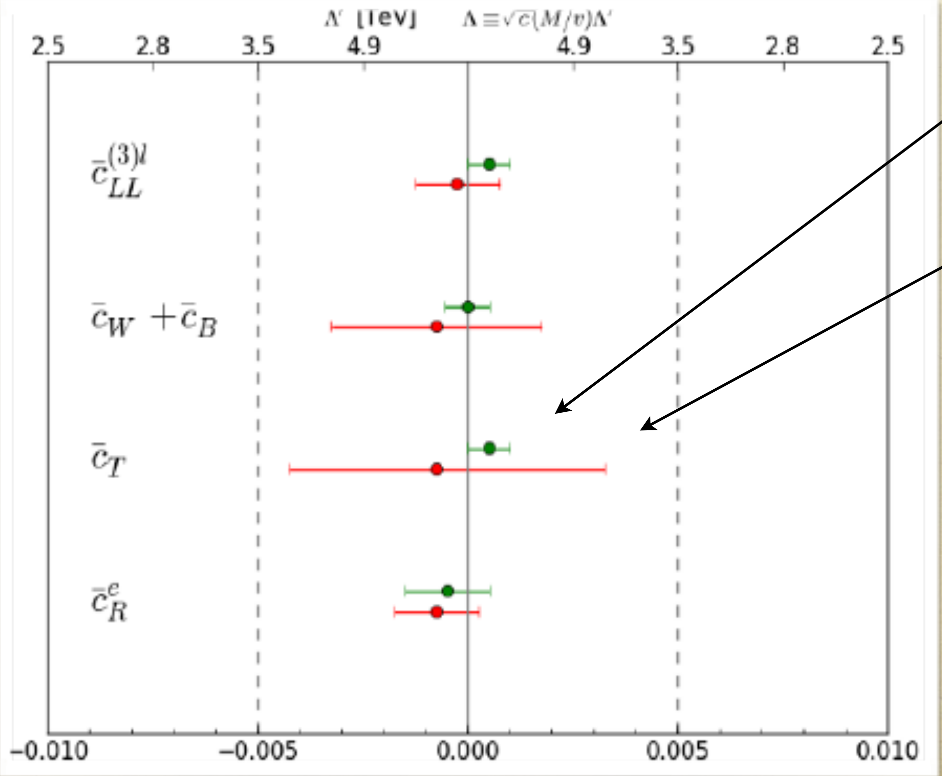
$$\mathcal{L}_{\text{VV}} = -W^{+\mu}\pi_{+-}(p^2)\,W_\mu^- - \frac{1}{2}W^{3\mu}\pi_{33}(p^2)\,W_\mu^3 - W^{3\mu}\pi_{3B}(p^2)\,B_\mu - \frac{1}{2}B^\mu\pi_{BB}(p^2)\,B_\mu$$



$$\hat{S} \equiv \frac{g}{g'}\frac{\pi'_{3B}(0)}{\pi'_{+-}(0)} \qquad \hat{T} \equiv \frac{\pi_{+-}(0) - \pi_{33}(0)}{\pi_{+-}(0)}$$

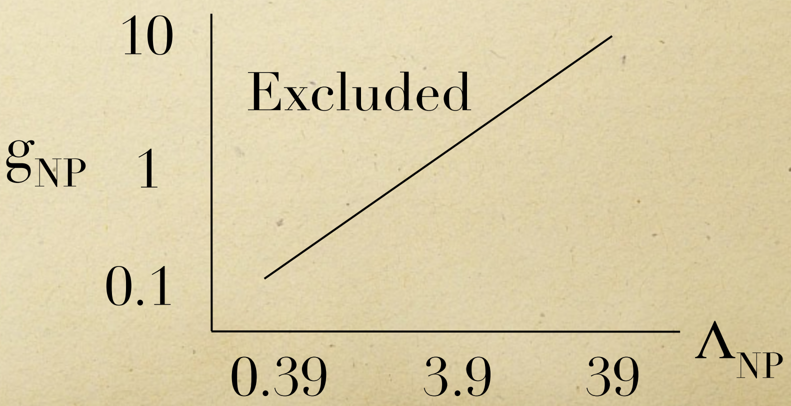
$$\hat{S} = \bar{c}_W + \bar{c}_B \qquad \hat{T} = \bar{c}_T$$





Individual constraint: $0 < c_T < 0.002$

Global fit constraint: $|c_T| < 0.004$



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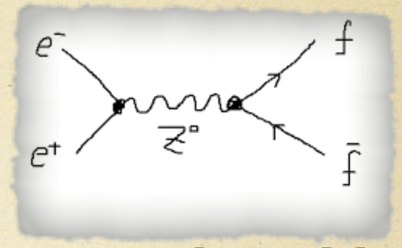
Z boson forward-backward asymmetry



Z boson has mix of vector and axial couplings to each fermion

Determined by $SU(2)_L$ and $U(1)_Y$ coupling strengths

Can measure this mix through the angular distribution of fermions produced by Z decay

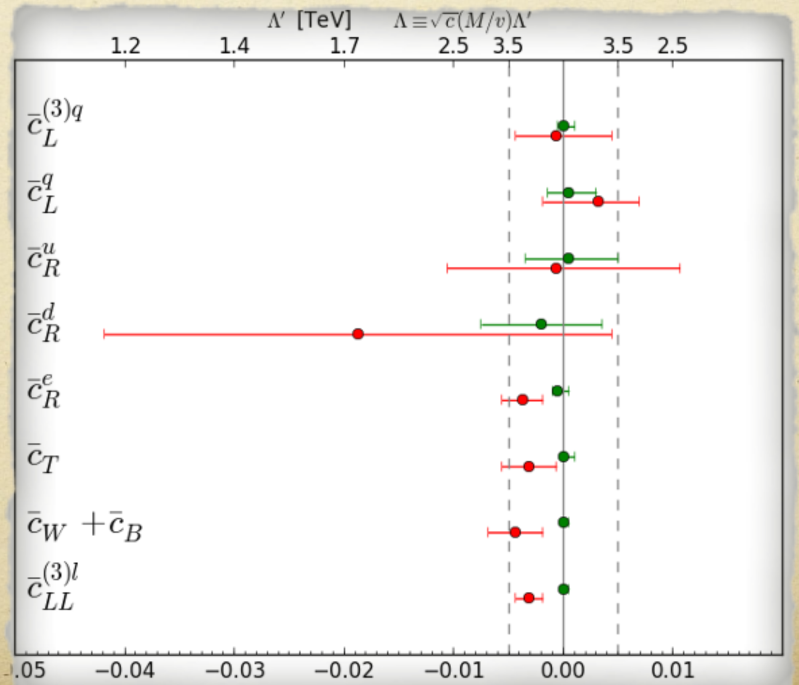
Measure fraction of final-state fermions along the direction of the initial-state fermion

$$A_{\mathrm{fb}}(M) = \frac{\sigma^+(M) - \sigma^-(M)}{\sigma^+(M) + \sigma^-(M)} \longrightarrow \quad g_V^f = T_3^f - 2Q_f \sin^2\theta_W \quad \text{and} \quad g_A^f = T_3^f$$

In EFT the SM relation is scaled by a factor that depends on the dim-6 coefficients

$$\mathcal{L}_{\text{dim-6}} \supset \sum_{f_L} \left(\frac{\bar{c}_{f_L}}{v^2} \mathcal{O}_{f_L} + \frac{\bar{c}^{(3)}_{f_L}}{v^2} \mathcal{O}^{(3)}_{f_L} \right) + \sum_{f_R} \frac{\bar{c}_{f_R}}{v^2} \mathcal{O}_{f_R} \qquad \xi_{g_Z^{f_L}} = \frac{1}{g_Z^{f_L}} \left(T_f^3 \bar{c}^{(3)}_{f_L} - \frac{\bar{c}_{f_L}}{2} \right), \qquad \xi_{g_Z^{f_R}} = -\frac{\bar{c}_{f_R}}{2 g_Z^{f_R}} \qquad \xi_i \equiv \delta^{\mathrm{NP}} \hat{\mathcal{O}}_i / \hat{\mathcal{O}}_i^{\mathrm{ref}}$$

Operator	Coefficient	LEP Constraints	
		Individual	Marginalized
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}(c_W + c_B)$	$(-0.00055, 0.0005)$	$(-0.0033, 0.0018)$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	$\frac{v^2}{\Lambda^2} c_T$	$(0, 0.001)$	$(-0.0043, 0.0033)$
$\mathcal{O}^{(3)\,l}_{LL} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$	$\frac{v^2}{\Lambda^2} c^{(3)l}_{LL}$	$(0, 0.001)$	$(-0.0013, 0.00075)$
$\mathcal{O}^e_R = \left(iH^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{e}_R \gamma^\mu e_R)$	$\frac{v^2}{\Lambda^2} c^e_R$	$(-0.0015, 0.0005)$	$(-0.0018, 0.00025)$
$\mathcal{O}^u_R = \left(iH^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{u}_R \gamma^\mu u_R)$	$\frac{v^2}{\Lambda^2} c^u_R$	$(-0.0035, 0.005)$	$(-0.011, 0.011)$
$\mathcal{O}^d_R = \left(iH^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{d}_R \gamma^\mu d_R)$	$\frac{v^2}{\Lambda^2} c^d_R$	$(-0.0075, 0.0035)$	$(-0.042, 0.0044)$
$\mathcal{O}^{(3)\,q}_L = \left(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	$\frac{v^2}{\Lambda^2} c^{(3)q}_L$	$(-0.0005, 0.001)$	$(-0.0044, 0.0044)$
$\mathcal{O}^q_L = \left(iH^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{Q}_L \gamma^\mu Q_L)$	$\frac{v^2}{\Lambda^2} c^q_L$	$(-0.0015, 0.003)$	$(-0.0019, 0.0069)$



Combine with mass measurements to constrain 8 EFT parameters

Constraints of order a few TeV for couplings equal to 1

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Further constraints

21 operators affecting electroweak processes unconstrained in example fit

1610.07922, Sec. III.2.1

Vertex

$[O_{Hud}]_{ij}$	$\frac{i}{v^2}\bar{u}_i\gamma_\mu d_j\tilde{H}^\dagger D_\mu H$

Bosonic CP-even

O_6	$-\frac{\lambda}{v^2}(H^\dagger H)^3$
O_H	$\frac{1}{2v^2}\left[\partial_\mu(H^\dagger H)\right]^2$
O_{2W}	$\frac{1}{m_W^2}D_\mu W^i_{\mu\nu}D_\rho W^i_{\rho\nu}$
O_{2B}	$\frac{1}{m_W^2}\partial_\mu B_{\mu\nu}\partial_\rho B_{\rho\nu}$

Bosonic CP-odd

$\widetilde{O}_g$	$\frac{g_s^2}{m_W^2}H^\dagger H\,\widetilde{G}^a_{\mu\nu}G^a_{\mu\nu}$
$\widetilde{O}_\gamma$	$\frac{g'^2}{m_W^2}H^\dagger H\,\widetilde{B}_{\mu\nu}B_{\mu\nu}$
$\widetilde{O}_{HW}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger\sigma^i D_\nu H\right)\widetilde{W}^i_{\mu\nu}$
$\widetilde{O}_{HB}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right)\widetilde{B}_{\mu\nu}$
$\widetilde{O}_{3W}$	$\frac{g^3}{m_W^2}\epsilon^{ijk}\widetilde{W}^i_{\mu\nu}W^j_{\nu\rho}W^k_{\rho\mu}$

Yukawa and Dipole

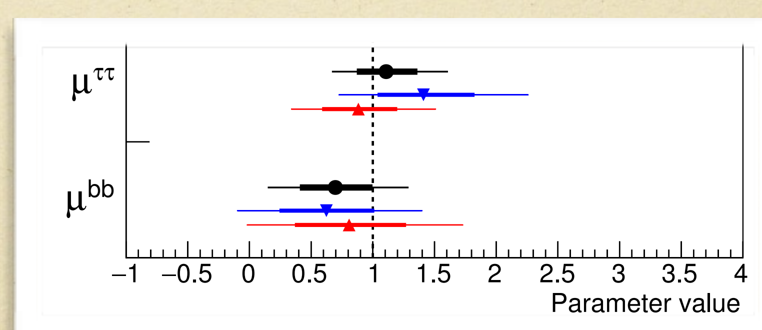
$[O_e]_{ij}$	$\frac{\sqrt{2m_{e_i}m_{e_j}}}{v^3}H^\dagger H\bar{\ell}_i He_j$
$[O_u]_{ij}$	$\frac{\sqrt{2m_{u_i}m_{u_j}}}{v^3}H^\dagger H\bar{q}_i\tilde{H}u_j$
$[O_d]_{ij}$	$\frac{\sqrt{2m_{d_i}m_{d_j}}}{v^3}H^\dagger H\bar{q}_i Hd_j$
$[O_{eW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{e_i}m_{e_j}}}{v}\bar{\ell}_i\sigma^k H\sigma_{\mu\nu}e_jW^k_{\mu\nu}$
$[O_{eB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{e_i}m_{e_j}}}{v}\bar{\ell}_i H\sigma_{\mu\nu}e_jB_{\mu\nu}$
$[O_{uG}]_{ij}$	$\frac{g_s}{m_W^2}\frac{\sqrt{2m_{u_i}m_{u_j}}}{v}\bar{q}_i\tilde{H}\sigma_{\mu\nu}T^a u_jG^a_{\mu\nu}$
$[O_{uW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{u_i}m_{u_j}}}{v}\bar{q}_i\sigma^k\tilde{H}\sigma_{\mu\nu}u_jW^k_{\mu\nu}$
$[O_{uB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{u_i}m_{u_j}}}{v}\bar{q}_i\tilde{H}\sigma_{\mu\nu}u_jB_{\mu\nu}$
$[O_{dG}]_{ij}$	$\frac{g_s}{m_W^2}\frac{\sqrt{2m_{d_i}m_{d_j}}}{v}\bar{q}_i H\sigma_{\mu\nu}T^a d_jG^a_{\mu\nu}$
$[O_{dW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{d_i}m_{d_j}}}{v}\bar{q}_i\sigma^k H\sigma_{\mu\nu}d_jW^k_{\mu\nu}$
$[O_{dB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{d_i}m_{d_j}}}{v}\bar{q}_i H\sigma_{\mu\nu}d_jB_{\mu\nu}$

Higgs self-couplings

CP-odd Higgs interactions

CP-odd triple-gauge couplings

Higgs interactions with fermions



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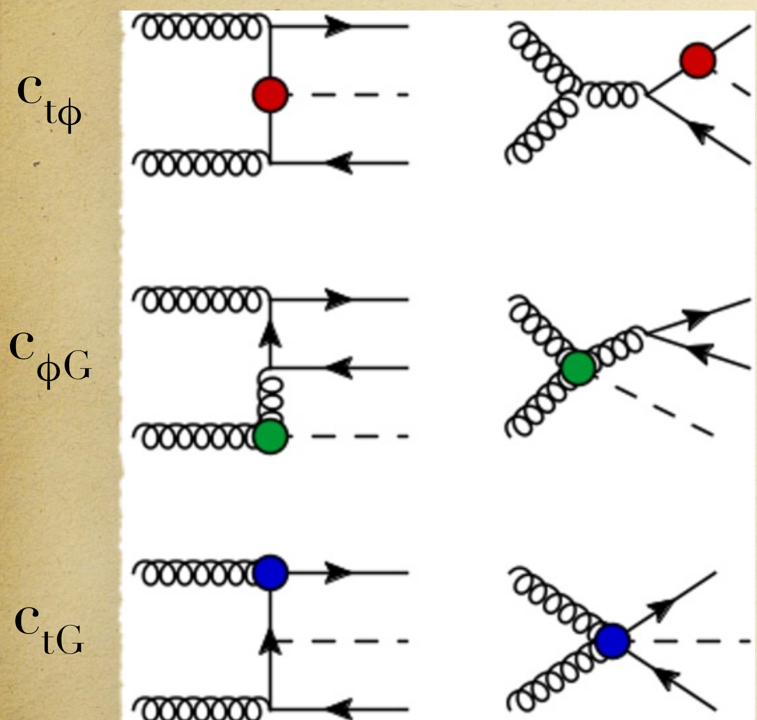
c_e, c_d can be easily incorporated

c_u, c_{uG} more complicated

Higgs, HH, and ttH production



ttH affected by Higgs & 4-fermion & gluon self-coupling operators

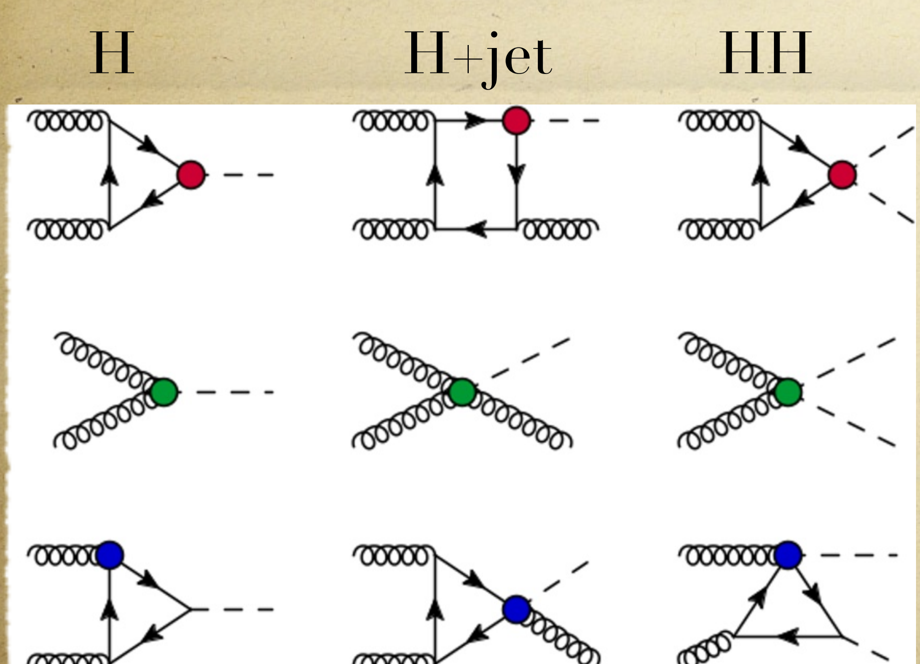
$$C_u^1 = C_{qq}^{(1)1331} + C_{uu}^{1331} + C_{qq}^{(3)1331},$$
$$C_u^2 = C_{qu}^{(8)1133} + C_{qu}^{(8)3311},$$
$$C_d^1 = C_{qq}^{(3)1331} + \frac{1}{4} C_{ud}^{(8)3311},$$
$$C_d^2 = C_{qu}^{(8)1133} + C_{qd}^{(8)3311}.$$

$$C_4 \simeq C_u^1 + C_u^2 + 0.6 C_d^1 + 0.6 C_d^2$$

Need tt measurements to constrain C_4

$$\sigma_{t\bar{t}}^{8\,\mathrm{TeV}}[pb] = 158\left[1 + 0.0101\left(C_u^1 + C_u^2 + 0.64 C_d^1 + 0.64 C_d^2\right) + 0.65 C_{tG}\right]$$
$$\sigma_{t\bar{t}H}^{8\,\mathrm{TeV}}[pb] = 0.110\left[1 + 0.055\left(C_u^1 + C_u^2 + 0.61 C_d^1 + 0.61 C_d^2\right) + 2.02 C_{tG}\right]$$

(Λ_{NP} = 1 TeV)



Also need dijet measurements to constrain gluon self-couplings

Inclusive Higgs, Higgs+jet, and di-Higgs production sensitive to the same operators as ttH

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Inclusive Higgs and ttH

Study contributions from each dimension-6 term assuming unit coupling, scale equal to 1 TeV

$$\sigma = \sigma_{\mathrm{SM}} + \sum_i \frac{1\mathrm{TeV}^2}{\Lambda^2} C_i \sigma_i + \sum_{i \le j} \frac{1\mathrm{TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}.$$

13 TeV	σ LO	$\sigma/\sigma_{\mathrm{SM}}$ LO
σ_{SM}	$19.6^{+5.47+0.000}_{-4.17-0.000}$	$1.000^{+0.000+0.000}_{-0.000-0.000}$
$\sigma_{t\phi}$	$-2.34^{+0.439+0.104}_{-0.576-2.46}$	$-0.119^{+0.000004+0.0053}_{-0.000006-0.0061}$
$\sigma_{\phi G}$	$1307^{+183.9+120}_{-166.0-101}$	$66.7^{+7.29+6.16}_{-7.24-5.16}$
σ_{tG}	$13.28^{+3.71+1.99}_{-2.83-4.90}$	$0.678^{+0.000051+0.102}_{-0.000018-0.250}$
$\sigma_{t\phi,t\phi}$	$0.0695^{+0.0194+0.00732}_{-0.0148-0.00607}$	$0.00355^{+0.0000+0.00037}_{-0.0000-0.00031}$
$\sigma_{\phi G,\phi G}$	$22515^{+377+4340}_{-732-3350}$	$1150^{+264+222}_{-236-171}$
$\sigma_{tG,tG}$	$2.253^{+0.631+13.2}_{-0.481-0.0}$	$0.115^{+0.000050+0.676}_{-0.000062-0.0}$
$\sigma_{t\phi,\phi G}$	$-76.8^{+9.38+9.11}_{-10.3-11.4}$	$-3.923^{+0.446+0.47}_{-0.453-0.58}$
$\sigma_{t\phi,tG}$	$-0.799^{+0.171+0.332}_{-0.224-0.134}$	$-0.04078^{+0.000062+0.017}_{-0.000050-0.007}$
$\sigma_{\phi G,tG}$	$450^{+63.3+0.0}_{-57.3-954}$	$23.0^{+2.50+0.0}_{-2.49-48.7}$

Inclusive Higgs

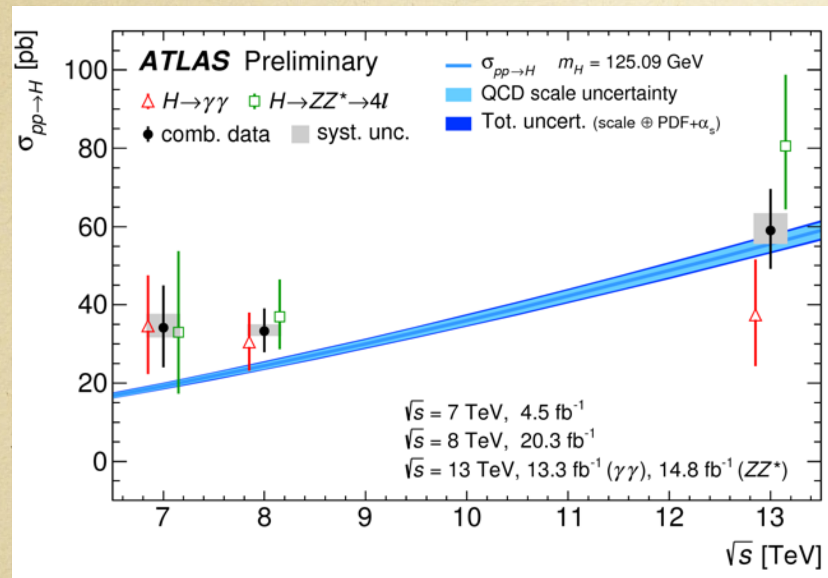
σ NLO	$\sigma/\sigma_{\mathrm{SM}}$ NLO
$0.507^{+0.030+0.000+0.007}_{-0.048-0.000-0.008}$	$1.000^{+0.000+0.000+0.000}_{-0.000-0.000-0.000}$
$-0.062^{+0.006+0.001+0.001}_{-0.004-0.001-0.001}$	$-0.123^{+0.001+0.001+0.000}_{-0.001-0.002-0.000}$
$0.872^{+0.131+0.037+0.013}_{-0.123-0.035-0.016}$	$1.722^{+0.146+0.073+0.004}_{-0.089-0.068-0.005}$
$0.503^{+0.025+0.001+0.007}_{-0.046-0.003-0.008}$	$0.991^{+0.004+0.003+0.000}_{-0.010-0.006-0.001}$
$0.0019^{+0.0001+0.0001+0.0000}_{-0.0002-0.0000-0.0000}$	$0.0037^{+0.0001+0.0002+0.0000}_{-0.0000-0.0001-0.0000}$
$1.021^{+0.204+0.096+0.024}_{-0.178-0.085-0.029}$	$2.016^{+0.267+0.190+0.021}_{-0.178-0.167-0.027}$
$0.674^{+0.036+0.004+0.016}_{-0.067-0.007-0.019}$	$1.328^{+0.011+0.008+0.014}_{-0.038-0.014-0.018}$
$-0.053^{+0.008+0.003+0.001}_{-0.008-0.004-0.001}$	$-0.105^{+0.006+0.006+0.000}_{-0.009-0.007-0.000}$
$-0.031^{+0.003+0.000+0.000}_{-0.002-0.000-0.000}$	$-0.061^{+0.000+0.000+0.000}_{-0.000-0.001-0.000}$
$0.859^{+0.127+0.021+0.017}_{-0.126-0.020-0.022}$	$1.691^{+0.137+0.042+0.013}_{-0.097-0.039-0.017}$

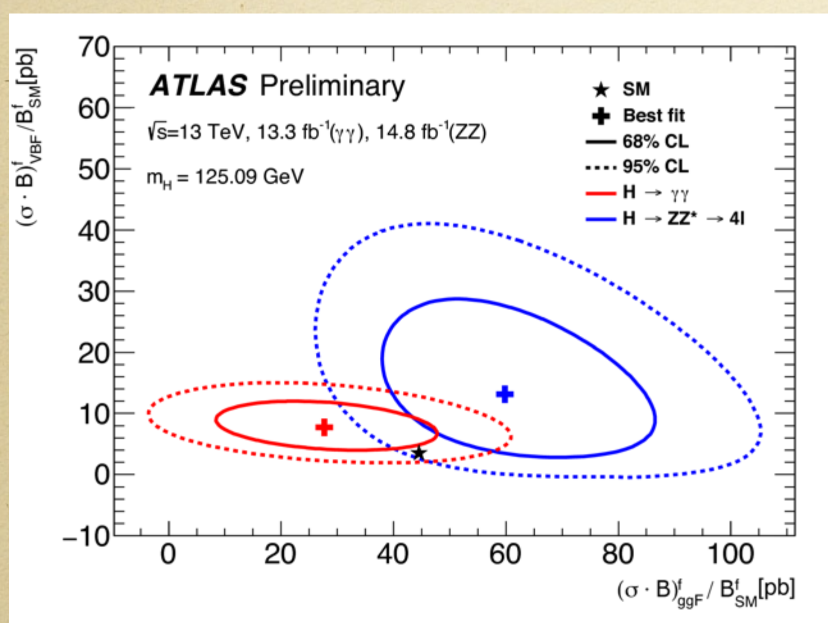
ttH

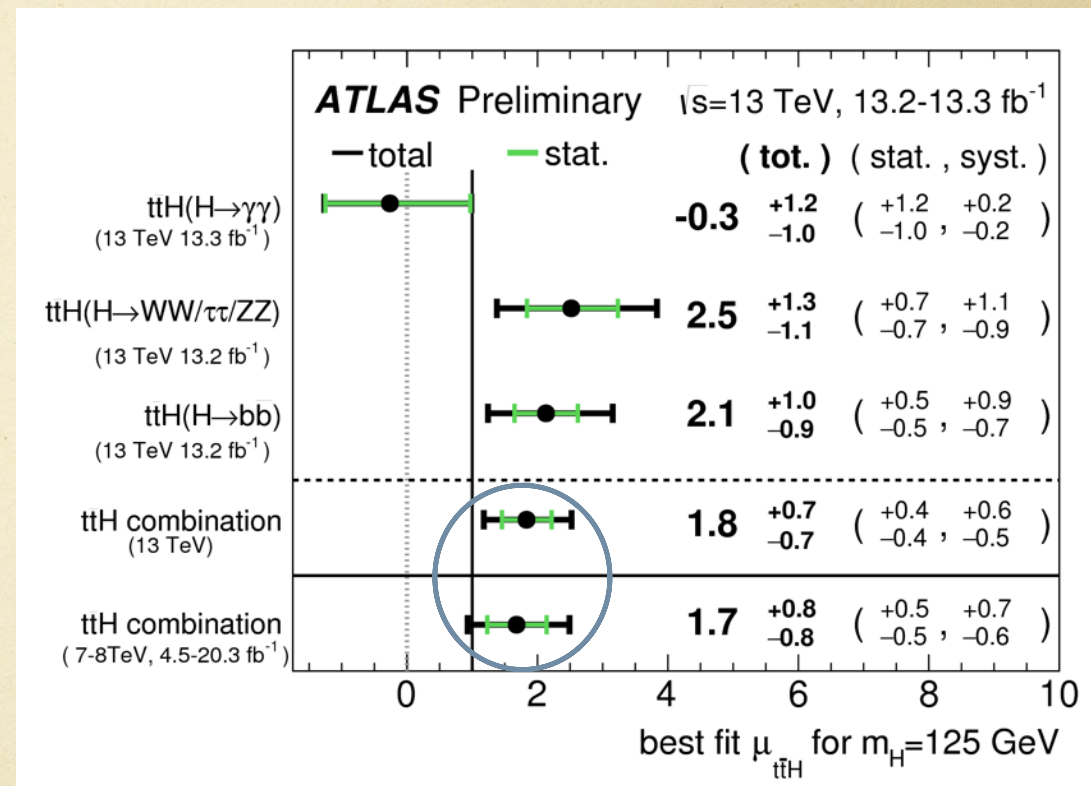
Tightly constrains $c_{\phi G}$

Better sensitivity to c_{tG} than $c_{t\phi}$

Inclusive H & ttH @ 13 TeV







Channel	Significance	
	Observed [σ]	Expected [σ]
$t\bar{t}H,\ H \to \gamma\gamma$	-0.2	0.9
$t\bar{t}H,\ H \to (WW, \tau\tau, ZZ)$	2.2	1.0
$t\bar{t}H,\ H \to b\bar{b}$	2.4	1.2
$t\bar{t}H$ combination	2.8	1.8

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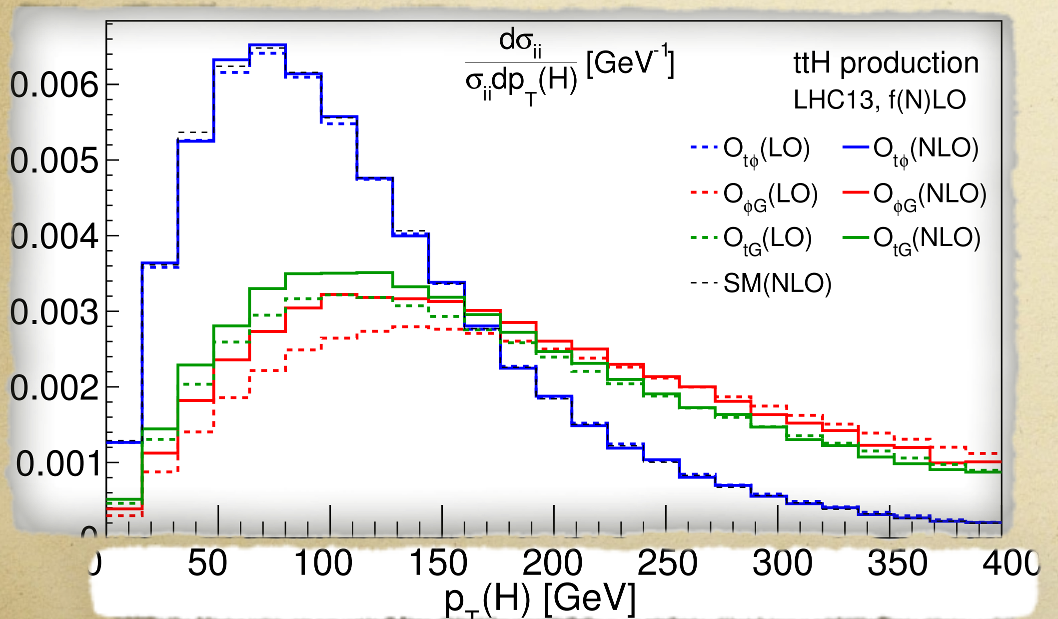
Fit to inclusive H and ttH

Investigate sensitivity with a restricted fit to three operators

	Individual	Marginalised	C_{tG} fixed
$C_{t\phi}/\Lambda^2$ [TeV^{-2}]	[-3.9,4.0]	[-14,31]	[-12,20]
$C_{\phi G}/\Lambda^2$ [TeV^{-2}]	[-0.0072,-0.0063]	[-0.021,0.054]	[-0.022,0.031]
C_{tG}/Λ^2 [TeV^{-2}]	[-0.68,0.62]	[-1.8,1.6]	

Relatively weak sensitivity to $c_{t\phi}$

Entire perturbative range allowed at 1 TeV



Could improve constraints with differential measurement of ttH

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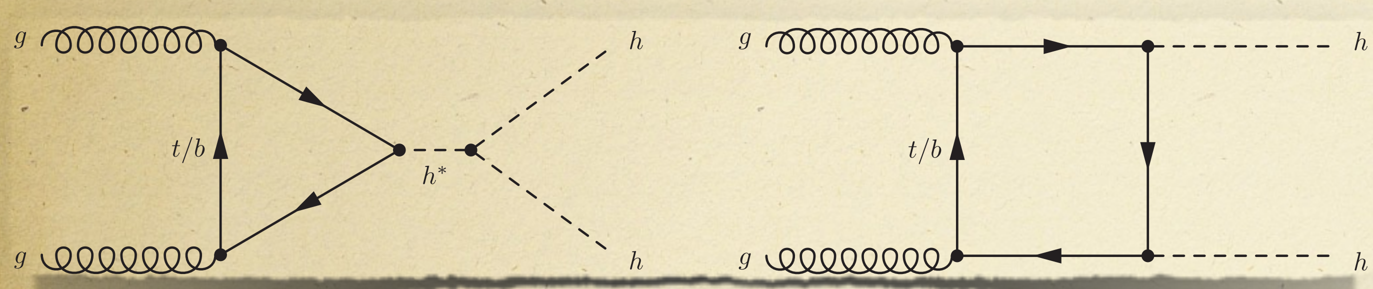
Higgs boson pair production



13 TeV	σ LO	$\sigma/\sigma_{\rm SM}$ LO
$\sigma_{\rm SM}$	$0.0256^{+0.00904+0.000}_{-0.00625-0.000}$	$1.000^{+0.000+0.000}_{-0.000-0.000}$
$\sigma_{t\phi}$	$0.00580^{+0.00209+0.000297}_{-0.00144-0.000259}$	$0.227^{+0.00114+0.0116}_{-0.000918-0.0101}$
$\sigma_{\phi G}$	$-1.208^{+0.231+0.0948}_{-0.291-0.113}$	$-47.3^{+6.18+3.707}_{-6.14-4.42}$
σ_{tG}	$-0.0347^{+0.00804+0.0041}_{-0.0113-0.0013}$	$-1.356^{+0.0271+0.161}_{-0.0225-0.051}$
$\sigma_{t\phi,t\phi}$	$0.000748^{+0.000290+0.000079}_{-0.000194-0.000065}$	$0.0293^{+0.000727+0.0031}_{-0.000584-0.0026}$
$\sigma_{\phi G,\phi G}$	$73.02^{+7.54+14.1}_{-6.48-10.9}$	$2856.2^{+743.3+552}_{-628.5-425}$
$\sigma_{tG,tG}$	$0.0496^{+0.0198+0.00505}_{-0.01305-0.0126}$	$1.940^{+0.0650+0.198}_{-0.0477-0.493}$
$\sigma_{t\phi,\phi G}$	$-0.303^{+0.0506+0.0362}_{-0.0641-0.0453}$	$-11.83^{+1.39+1.42}_{-1.41-1.77}$
$\sigma_{t\phi,tG}$	$-0.00870^{+0.00213+0.00163}_{-0.00309-0.00120}$	$-0.340^{+0.000238+0.064}_{-0.000438-0.047}$
$\sigma_{\phi G,tG}$	$3.77^{+0.914+0.554}_{-0.681-0.802}$	$147.5^{+20.83+20.7}_{-18.86-31.4}$

Crucial probe of the Higgs field potential

Extraordinarily challenging due to destructive interference

Higgs pair production sensitive to many EFT operators

To constrain self-coupling operator, need multiple Higgs, top, & jet measurements to constrain other operators

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Higgs boson pair production

Will need HL-LHC to observe SM Higgs pair production
EFT fits could be performed with existing searches

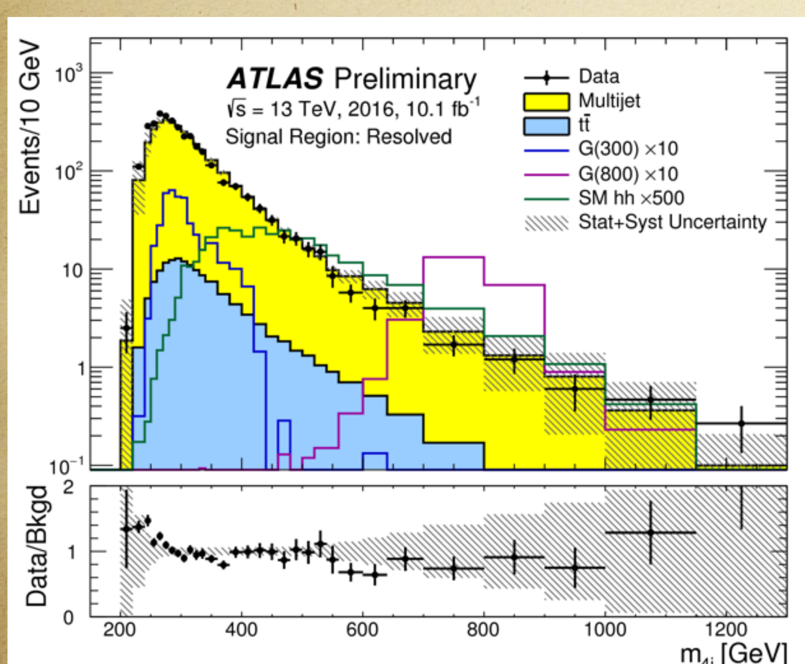
8 TeV results in four channels

Phys Rev D 92, 092004 (2015)

Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
		Upper limit on the cross section [pb]			
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
		Upper limit on the cross section relative to the SM prediction			
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

13 TeV data: results in three channels

bbbb: $\sigma < 29\sigma_{SM}$



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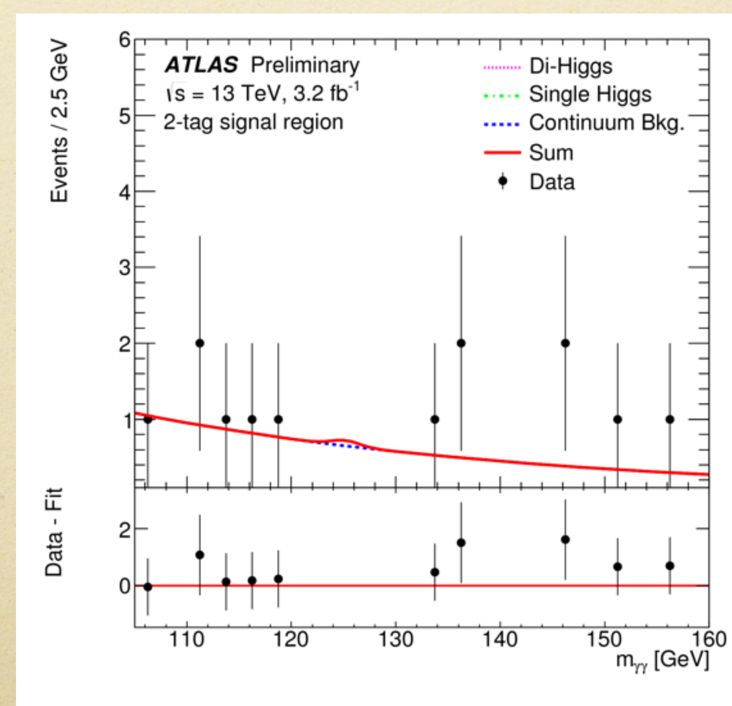
$\gamma\gamma bb$: $\sigma < 120\sigma_{SM}$



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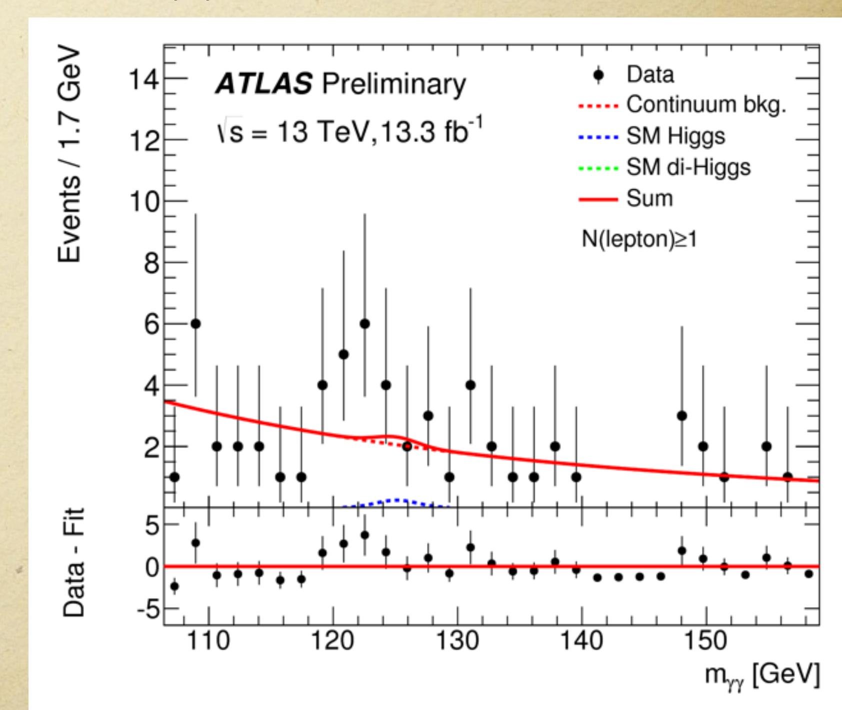
$\gamma\gamma WW^*$: $\sigma < 750\sigma_{SM}$



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CP-odd operators

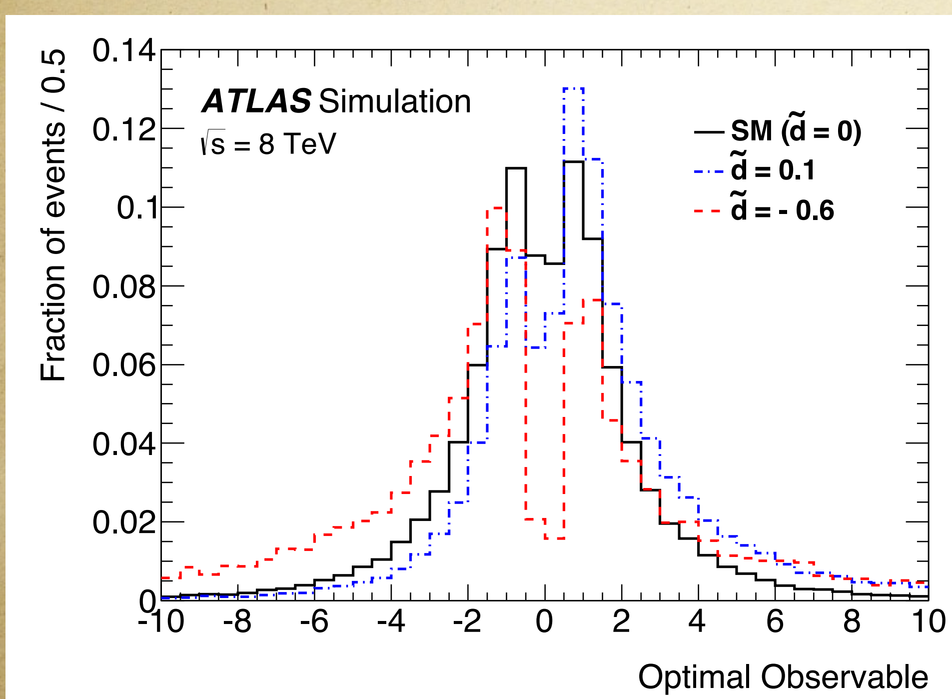
Can probe CP-odd non-SM interactions using jet angles in VBF production

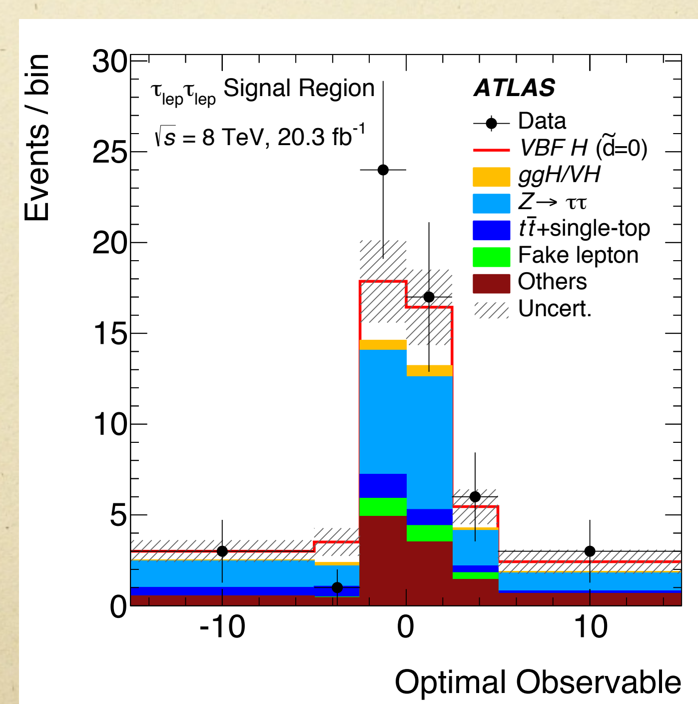
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{f_{\tilde{B}B}}{\Lambda^2}\mathcal{O}_{\tilde{B}B} + \frac{f_{\tilde{W}W}}{\Lambda^2}\mathcal{O}_{\tilde{W}W} \longrightarrow \tilde{d} = -\frac{m_W^2}{\Lambda^2} f_{\tilde{W}W} \qquad \tilde{d}_B = -\frac{m_W^2}{\Lambda^2}\tan^2\theta_W f_{\tilde{B}B}$$

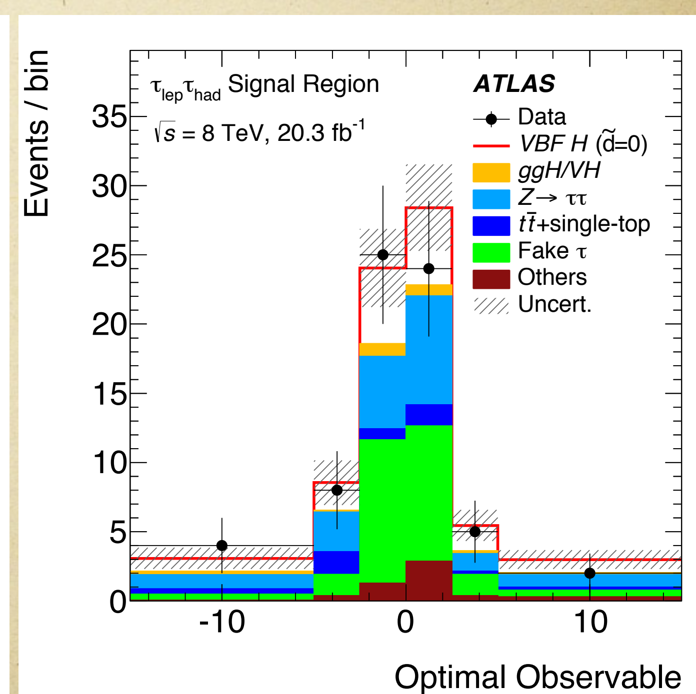
Can constrain only one direction; here chose $\tilde{d} = \tilde{d}_B$

Write matrix element as $\mathcal{M} = \mathcal{M}_{\text{SM}} + \tilde{d}\cdot\mathcal{M}_{\text{CP-odd}}$ $\qquad |\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \tilde{d}\cdot 2\,\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}}) + \tilde{d}^2\cdot|\mathcal{M}_{\text{CP-odd}}|^2$

Define the "optimal observable" $\mathcal{OO} = \dfrac{2\,\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\text{SM}}|^2}$







arXiv:1602.04516

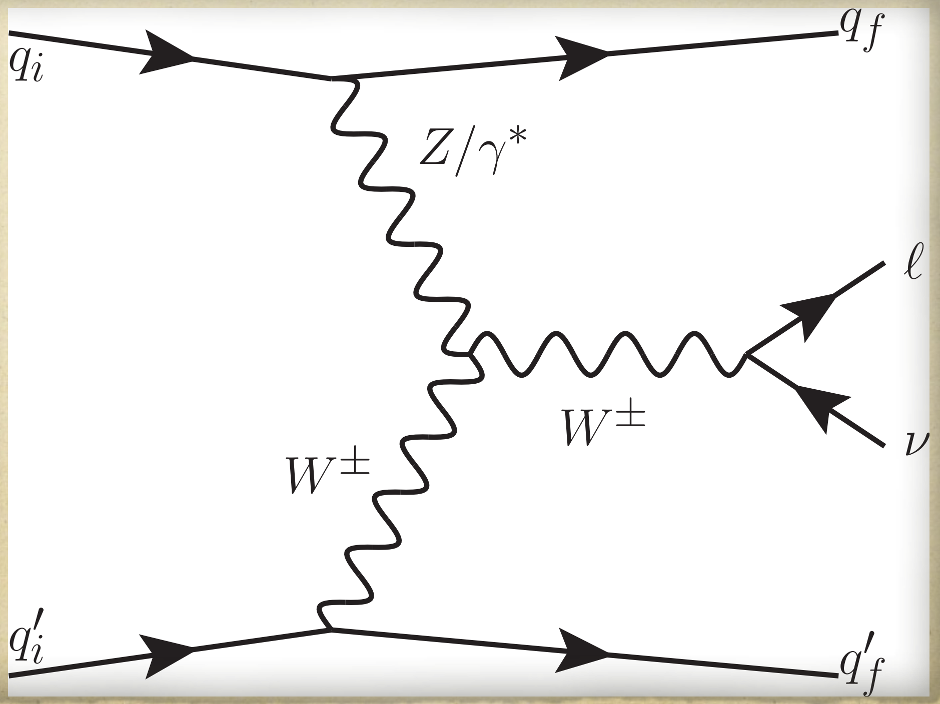
The regions $\tilde{d} < -0.11$ and $\tilde{d} > 0.05$ are excluded at 68% CL.

CP-odd operators

Run 1 analyses have studied CP properties in Higgs decays to gauge bosons

Combining VBF production measurements with decay studies can give access to multiple operators

Can access to triple-gauge coupling CP-odd operator through VBF W & Z production



Summary

Run 1 focus on Higgs search has given way to Run 2 focus on Higgs measurement

Many measurements: use EFT as a self-consistent probe of higher scales

Proof-of-principle fits have constrained a subset of dimension-6 operators: path to constrain 22 operators demonstrated in this talk

Discussions ongoing within Higgs, top, and electroweak group to interpret results in EFT

Combination at end of Run 2 could constrain nearly all Higgs-related operators plus several 4-fermion and gauge boson self-coupling operators

Will provide a clearer picture on the possible scale of new physics