STANDARD MODEL EFFECTIVE FIELD THEORY: NEW PHYSICS THROUGH PRECISION MEASUREMENTS

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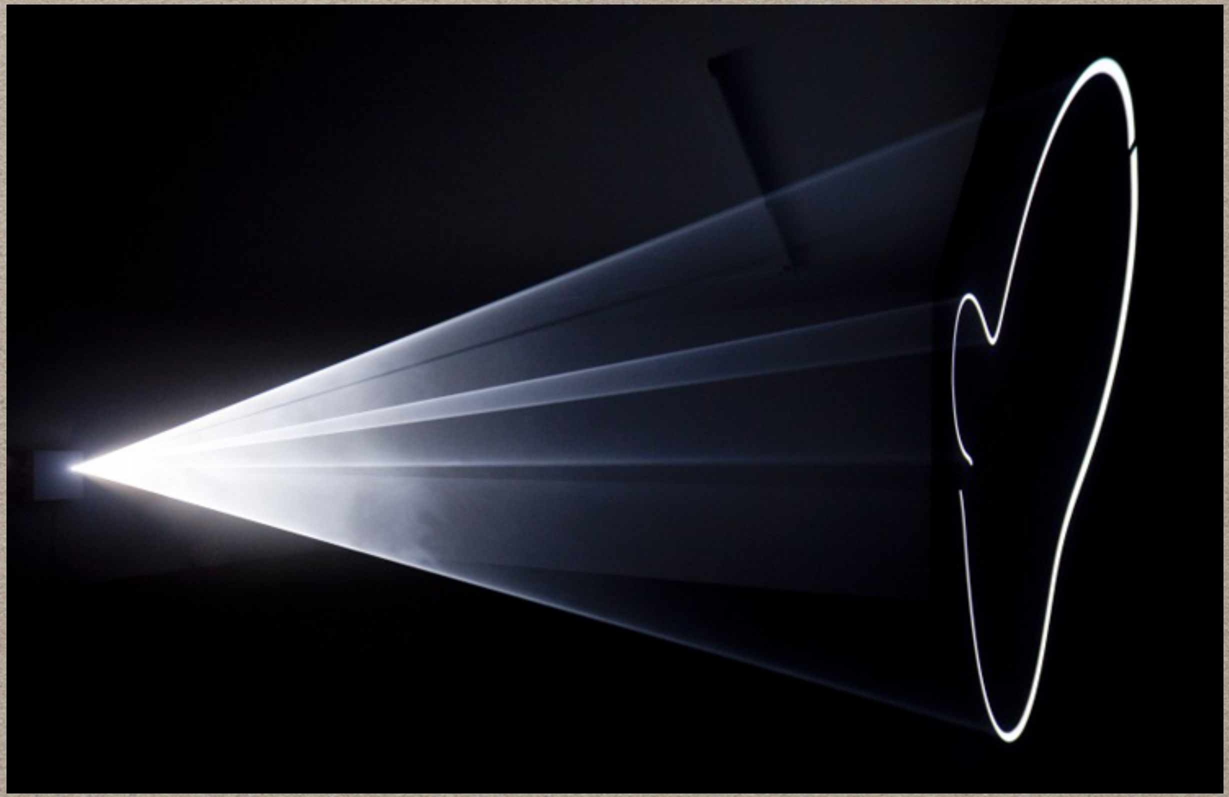


US ATLAS WORKSHOP
30 JULY 2018

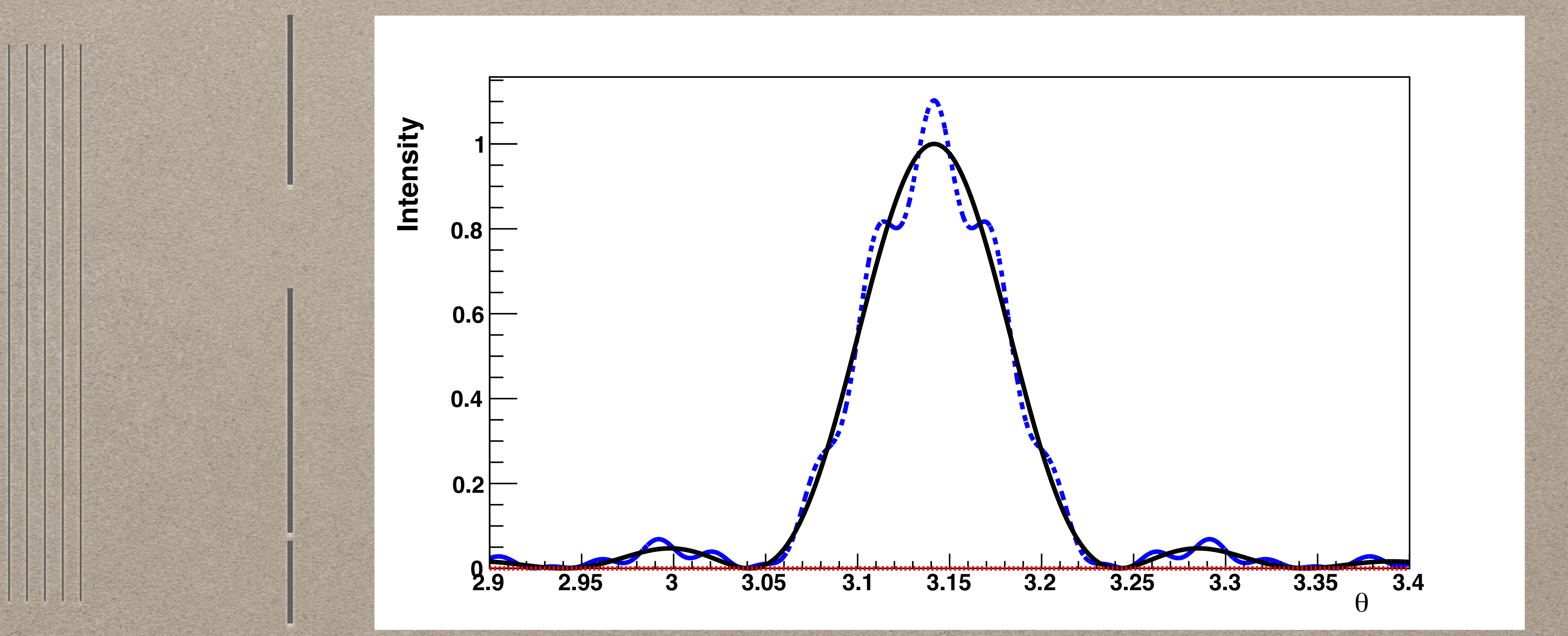
OVERVIEW

- QFT interferometry and the SMEFT
- Global fit strategy
- Observables
- Fit results

INTERFEROMETRY

Interference provides unique sensitivity to small effects
(cf. gravity waves)

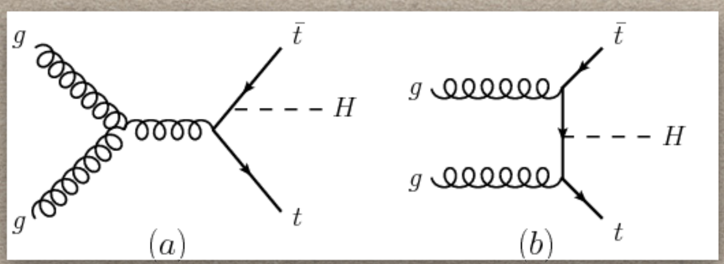
Non-relativistic QM example: double-slit experiment
(or how to discover a pinhole)

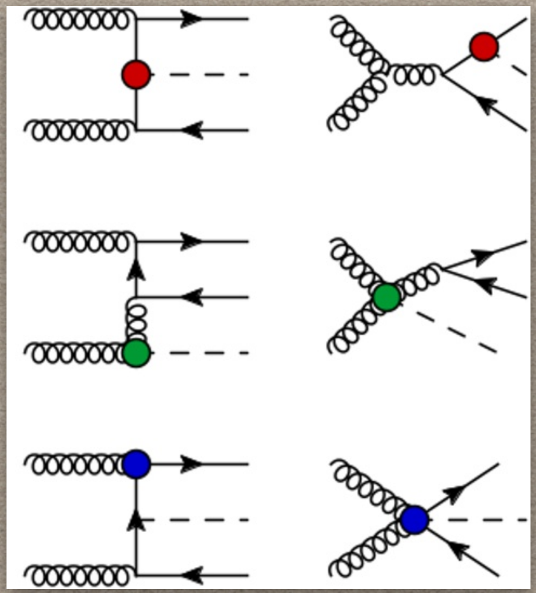


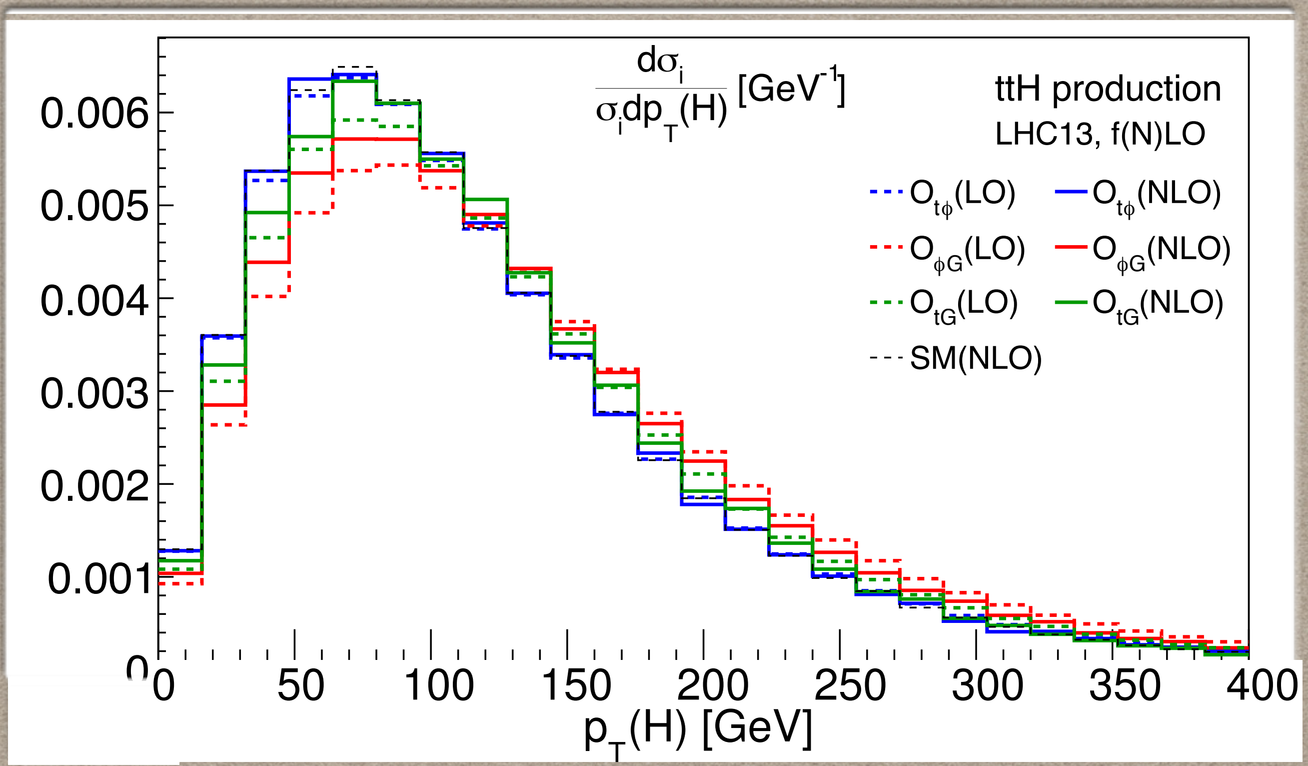
QFT INTERFEROMETRY

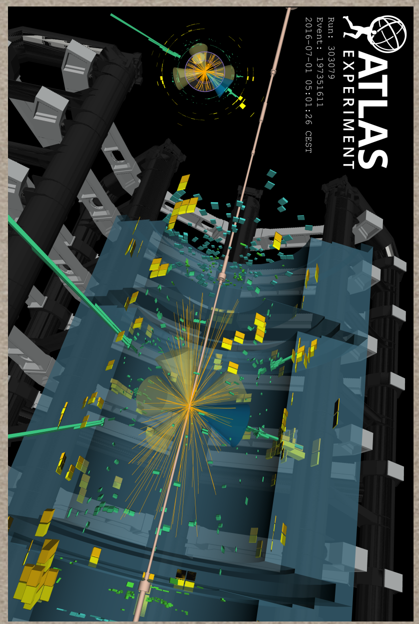
Interference provides unique sensitivity to small effects (e.g. non-SM interactions)

QFT example: ttH production









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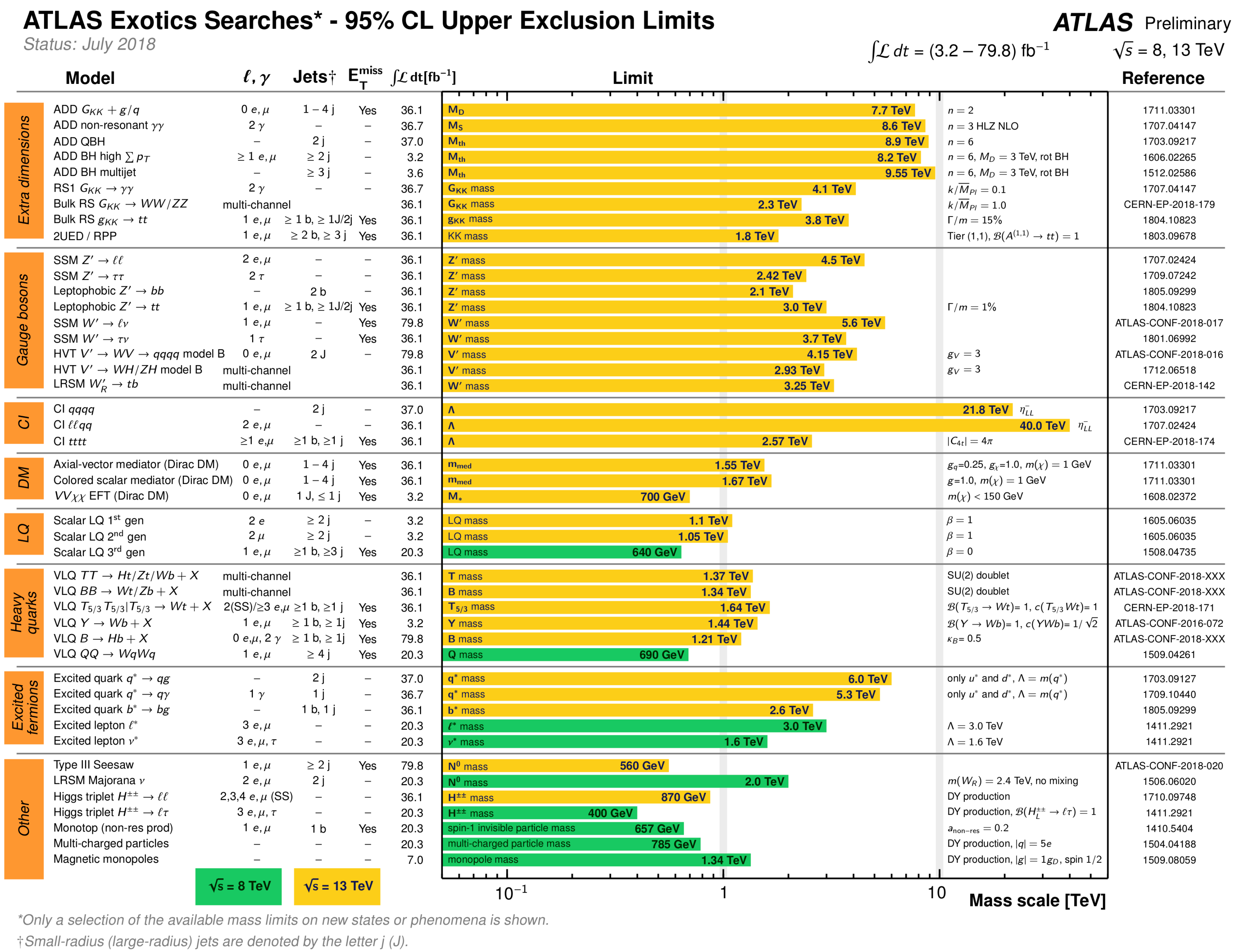
SCALE SEPARATION



EFFECTIVE FIELD THEORY

For new processes at a large scale Λ, the new interactions can be approximated by a Lagrangian with **effective operators** containing only **SM fields** and expanded in inverse powers of Λ, i.e. an **effective field theory**

Processes are described by transition amplitudes derived from the action

A Lagrangian density with dimension m⁴ defines interactions

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

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

The Standard Model effective field theory (SMEFT):
The Lagrangian respects SM gauge symmetries, SU(3) x SU(2) x U(1)
The fields are in the multiplets defined by the SM

SMEFT 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

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

$\mathcal{L}_8$ 993 operators (one generation)
44807 operators for three generations

Separate dimension-6 operators into classes

Define a nearly flavour-universal scenario with a handful of third generation operators

At LO most top/EW/Higgs processes are sensitive to ~30 operators

Similar to the number of parameters in a PDF fit

$1 : X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2 : H^6$	
Q_H	$(H^\dagger H)^3$

$3 : H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5 : \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H}$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H$

$4 : X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6 : \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7 : \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8 : (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8 : (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8 : (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8 : (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8 : (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

1610.07922, Sec. III.2.3

NEW PHYSICS

A given resonance can map to a large number of parameters at LO

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New heavy vector-like fermions

Fields	Operators
N	$\mathcal{O}_5$, $\mathcal{O}_{\phi l}^{(1)}$, $\mathcal{O}_{\phi l}^{(3)}$
E	$\mathcal{O}_{e\phi}$, $\mathcal{O}_{eB}$, $\mathcal{O}_{\phi l}^{(1)}$, $\mathcal{O}_{\phi l}^{(3)}$
Δ_1	$\mathcal{O}_{e\phi}$, $\mathcal{O}_{eB}$, $\mathcal{O}_{eW}$, $\mathcal{O}_{\phi e}$
Δ_3	$\mathcal{O}_{e\phi}$, $\mathcal{O}_{\phi e}$
Σ	$\mathcal{O}_5$, $\mathcal{O}_{e\phi}$, $\mathcal{O}_{\phi l}^{(1)}$, $\mathcal{O}_{\phi l}^{(3)}$
Σ_1	$\mathcal{O}_{e\phi}$, $\mathcal{O}_{eW}$, $\mathcal{O}_{\phi l}^{(1)}$, $\mathcal{O}_{\phi l}^{(3)}$
U	$\mathcal{O}_{u\phi}$, $\mathcal{O}_{uB}$, $\mathcal{O}_{uG}$, $\mathcal{O}_{\phi q}^{(1)}$, $\mathcal{O}_{\phi q}^{(3)}$
D	$\mathcal{O}_{d\phi}$, $\mathcal{O}_{dB}$, $\mathcal{O}_{dG}$, $\mathcal{O}_{\phi q}^{(1)}$, $\mathcal{O}_{\phi q}^{(3)}$
Q_1	$\mathcal{O}_{d\phi}$, $\mathcal{O}_{u\phi}$, $\mathcal{O}_{dB}$, $\mathcal{O}_{dW}$, $\mathcal{O}_{dG}$, $\mathcal{O}_{uB}$, $\mathcal{O}_{uW}$, $\mathcal{O}_{uG}$, $\mathcal{O}_{\phi d}$, $\mathcal{O}_{\phi u}$, $\mathcal{O}_{\phi ud}$
Q_5	$\mathcal{O}_{d\phi}$, $\mathcal{O}_{\phi d}$
Q_7	$\mathcal{O}_{u\phi}$, $\mathcal{O}_{\phi u}$
T_1	$\mathcal{O}_{d\phi}$, $\mathcal{O}_{u\phi}$, $\mathcal{O}_{dW}$, $\mathcal{O}_{\phi q}^{(1)}$, $\mathcal{O}_{\phi q}^{(3)}$
T_2	$\mathcal{O}_{d\phi}$, $\mathcal{O}_{u\phi}$, $\mathcal{O}_{uW}$, $\mathcal{O}_{\phi q}^{(1)}$, $\mathcal{O}_{\phi q}^{(3)}$

New heavy vector bosons

Fields	Operators
$\mathcal{B}$	$\mathcal{O}_{ll}$, $\mathcal{O}_{qq}^{(1)}$, $\mathcal{O}_{lq}^{(1)}$, $\mathcal{O}_{ee}$, $\mathcal{O}_{dd}$, $\mathcal{O}_{uu}$, $\mathcal{O}_{ed}$, $\mathcal{O}_{eu}$, $\mathcal{O}_{ud}^{(1)}$, $\mathcal{O}_{le}$, $\mathcal{O}_{ld}$, $\mathcal{O}_{lu}$, $\mathcal{O}_{qe}$, $\mathcal{O}_{qu}^{(1)}$, $\mathcal{O}_{qd}^{(1)}$, $\mathcal{O}_{\phi D}$, $\mathcal{O}_{\phi\Box}$, $\mathcal{O}_{e\phi}$, $\mathcal{O}_{d\phi}$, $\mathcal{O}_{u\phi}$, $\mathcal{O}_{\phi l}^{(1)}$, $\mathcal{O}_{\phi q}^{(1)}$, $\mathcal{O}_{\phi e}$, $\mathcal{O}_{\phi d}$, $\mathcal{O}_{\phi u}$
$\mathcal{B}_1$	$\mathcal{O}_{\phi 4}$, $\mathcal{O}_{ud}^{(1)}$, $\mathcal{O}_{ud}^{(8)}$, $\mathcal{O}_{\phi}$, $\mathcal{O}_{\phi D}$, $\mathcal{O}_{\phi\Box}$, $\mathcal{O}_{e\phi}$, $\mathcal{O}_{d\phi}$, $\mathcal{O}_{u\phi}$, $\mathcal{O}_{\phi ud}$
$\mathcal{W}$	$\mathcal{O}_{\phi 4}$, $\mathcal{O}_{ll}$, $\mathcal{O}_{qq}^{(3)}$, $\mathcal{O}_{lq}^{(3)}$, $\mathcal{O}_{\phi}$, $\mathcal{O}_{\phi D}$, $\mathcal{O}_{\phi\Box}$, $\mathcal{O}_{e\phi}$, $\mathcal{O}_{d\phi}$, $\mathcal{O}_{u\phi}$, $\mathcal{O}_{\phi l}^{(3)}$, $\mathcal{O}_{\phi q}^{(3)}$
$\mathcal{W}_1$	$\mathcal{O}_{\phi 4}$, $\mathcal{O}_{\phi}$, $\mathcal{O}_{\phi D}$, $\mathcal{O}_{\phi\Box}$, $\mathcal{O}_{e\phi}$, $\mathcal{O}_{d\phi}$, $\mathcal{O}_{u\phi}$
$\mathcal{G}$	$\mathcal{O}_{qq}^{(1)}$, $\mathcal{O}_{qq}^{(3)}$, $\mathcal{O}_{dd}$, $\mathcal{O}_{uu}$, $\mathcal{O}_{ud}^{(8)}$, $\mathcal{O}_{qu}^{(8)}$, $\mathcal{O}_{qd}^{(8)}$
$\mathcal{G}_1$	$\mathcal{O}_{ud}^{(1)}$, $\mathcal{O}_{ud}^{(8)}$
$\mathcal{H}$	$\mathcal{O}_{qq}^{(1)}$, $\mathcal{O}_{qq}^{(3)}$
$\mathcal{L}_1$	$\mathcal{O}_{\phi 4}$, $\mathcal{O}_{y^e}$, $\mathcal{O}_{y^d}$, $\mathcal{O}_{y^u}$, $\mathcal{O}_{le}$, $\mathcal{O}_{qu}^{(1)}$, $\mathcal{O}_{qu}^{(8)}$, $\mathcal{O}_{qd}^{(1)}$, $\mathcal{O}_{qd}^{(8)}$, $\mathcal{O}_{ledq}$, $\mathcal{O}_{quqd}^{(1)}$, $\mathcal{O}_{lequ}^{(1)}$, $\mathcal{O}_{\phi}$, $\mathcal{O}_{\phi D}$, $\mathcal{O}_{\phi\Box}$, $\mathcal{O}_{\phi B}$, $\mathcal{O}_{\phi\tilde{B}}$, $\mathcal{O}_{\phi W}$, $\mathcal{O}_{\phi\tilde{W}}$, $\mathcal{O}_{\phi WB}$, $\mathcal{O}_{\phi W\tilde{B}}$, $\mathcal{O}_{e\phi}$, $\mathcal{O}_{d\phi}$, $\mathcal{O}_{u\phi}$, $\mathcal{O}_{eB}$, $\mathcal{O}_{eW}$, $\mathcal{O}_{dB}$, $\mathcal{O}_{dW}$, $\mathcal{O}_{uB}$, $\mathcal{O}_{uW}$, $\mathcal{O}_{\phi l}^{(1)}$, $\mathcal{O}_{\phi l}^{(3)}$, $\mathcal{O}_{\phi q}^{(1)}$, $\mathcal{O}_{\phi q}^{(3)}$, $\mathcal{O}_{\phi e}$, $\mathcal{O}_{\phi d}$, $\mathcal{O}_{\phi u}$
$\mathcal{L}_3$	$\mathcal{O}_{le}$
$\mathcal{U}_2$	$\mathcal{O}_{lq}^{(1)}$, $\mathcal{O}_{lq}^{(3)}$, $\mathcal{O}_{ed}$, $\mathcal{O}_{ledq}$
$\mathcal{U}_5$	$\mathcal{O}_{eu}$
$\mathcal{Q}_1$	$\mathcal{O}_{lu}$, $\mathcal{O}_{qd}^{(1)}$, $\mathcal{O}_{qd}^{(8)}$, $\mathcal{O}_{duq}$
$\mathcal{Q}_5$	$\mathcal{O}_{qe}$, $\mathcal{O}_{qu}^{(1)}$, $\mathcal{O}_{qu}^{(8)}$, $\mathcal{O}_{ledq}$, $\mathcal{O}_{duq}$, $\mathcal{O}_{qqu}$
$\mathcal{X}$	$\mathcal{O}_{lq}^{(1)}$, $\mathcal{O}_{lq}^{(3)}$
$\mathcal{Y}_1$	$\mathcal{O}_{qd}^{(1)}$, $\mathcal{O}_{qd}^{(8)}$
$\mathcal{Y}_5$	$\mathcal{O}_{qu}^{(1)}$, $\mathcal{O}_{qu}^{(8)}$

One source of parameter increase is through field redefinitions

$$B'_\mu \to B_\mu + b_2 \frac{H^\dagger i \overleftrightarrow{D}_\mu H}{\Lambda^2}$$

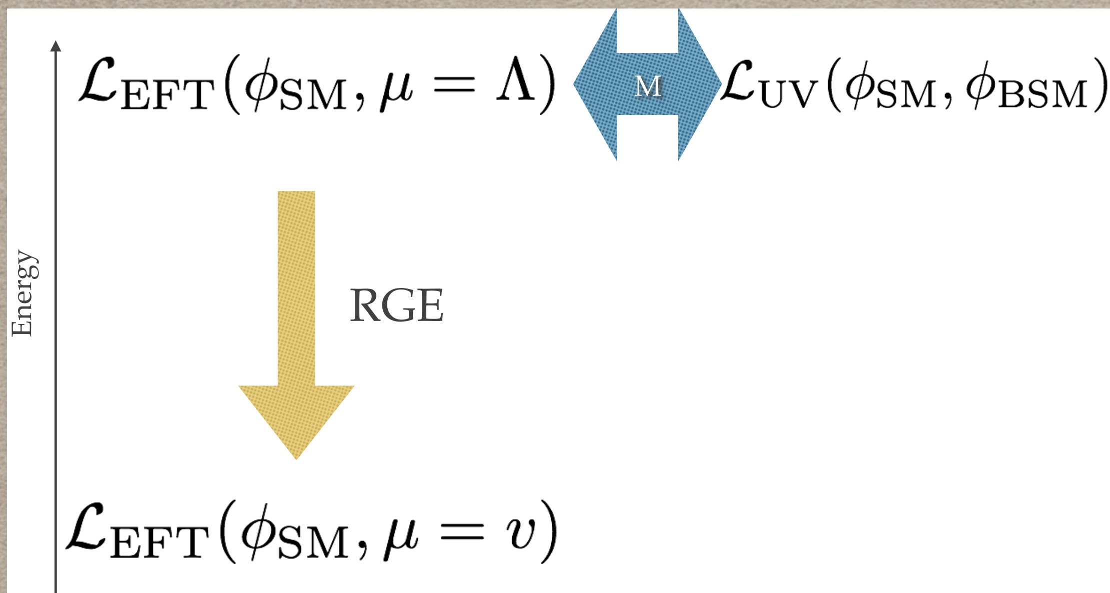
Field redefinitions cancel redundant operators related through field equations

$$\mathcal{L}_B{}' - g_1 b_2 \Delta B$$

$$\Delta B = y_l Q_{\underset{tt}{Hl}}^{(1)} + y_e Q_{\underset{tt}{He}} + y_q Q_{\underset{tt}{Hq}}^{(1)} + y_u Q_{\underset{tt}{Hu}} + y_d Q_{\underset{tt}{Hd}}; \quad + y_H (Q_{H\Box} + 4 Q_{HD}) + \frac{1}{g_1} B^{\mu\nu} \partial_\mu (H^\dagger i \overleftrightarrow{D}_\nu H)$$

M. Trott, ATLAS EFT workshop

MATCHING AND RUNNING

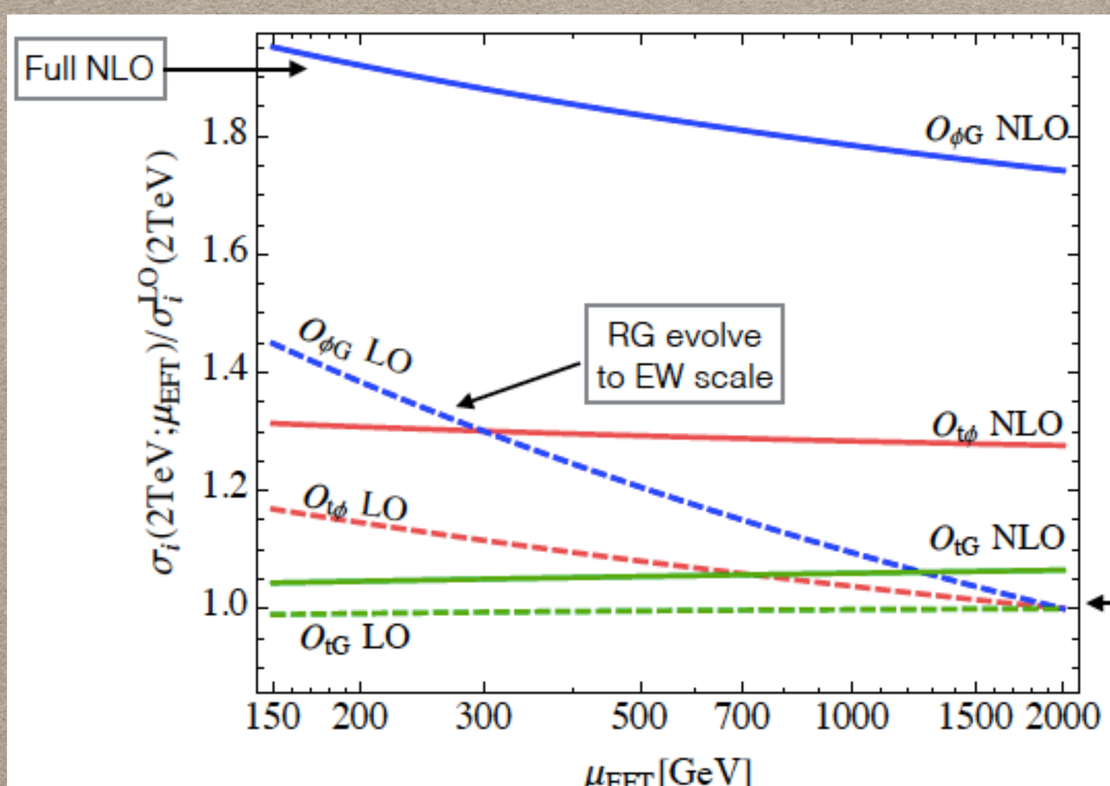


The matching of the UV theory to the EFT parameters is performed at the scale $\mathbf{\Lambda}$

The measurements are performed at the scale v

Running changes the values of the parameters

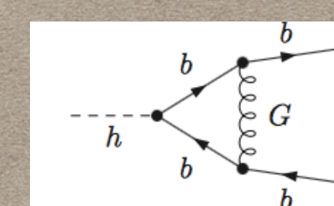
It can also introduce a dependence on new parameters



At = 1 TeV: C_{tG} = 1, $C_{t\varphi}$ = 0;

At = 173 GeV: C_{tG} = 0.98, $C_{t\varphi}$= 0.45

NLO corrections will also introduce a dependence on new parameters



F. Maltoni, ATLAS EFT workshop

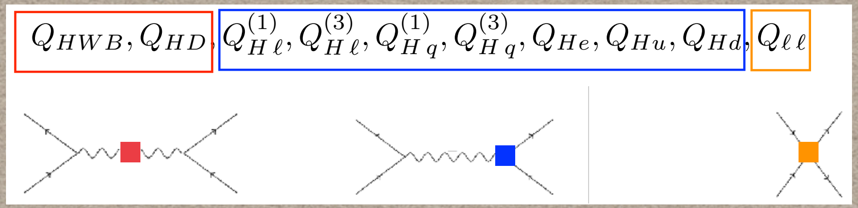
OPERATOR REDUCTION

"What's the problem with fitting 2500 parameters?"
- S. Forte (as recounted by I. Brivio)

In a first fit organize operators using experimental sensitivity
Can reduce to ~30 operators by:
(1) neglecting flavor structure (projected to SM structure through interference)
(2) factorizing CP-odd operators
(3) using resonances to enhance interference effects

Operator sensitivity (~10 each):

EWPD and dibosons



Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

LHC Higgs data

Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

LHC top data

$O_{\phi q}^3$	$i(\phi^\dagger \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$
O_{tW}	$(\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W_{\mu\nu}^I$
O_{tG}	$(\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G_{\mu\nu}^A$
O_G	$f_{ABC}\, G_\mu^{A\nu} G_\nu^{B\lambda} G_\lambda^{C\mu}$
$O_{\tilde{G}}$	$f_{ABC}\, \tilde{G}_\mu^{A\nu} G_\nu^{B\lambda} G_\lambda^{C\mu}$

O_{qq}^1	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$
O_{qq}^3	$(\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)$
O_{uu}	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$
O_{qu}^8	$(\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)$
O_{qd}^8	$(\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)$
O_{ud}^8	$(\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)$

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A GLOBAL EFT FIT

The general expectation of multiple non-zero EFT coefficients and the sensitivity of measurements across sectors (Higgs, electroweak, top) motivates a global EFT fit

There are several motivations for the experiments to perform a global EFT fit:

A better understanding of important measurements and inputs will improve sensitivity

The institutional framework can incorporate the most complete set of measurements

Will incorporate the most complete set of systematic correlations

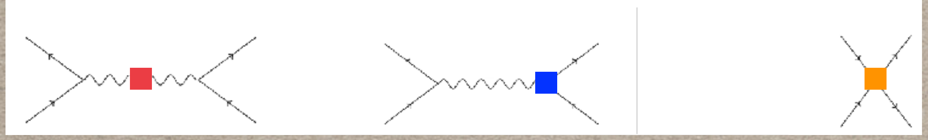
Can compare constraints to more targeted fits for specific scenarios

Provides a benchmark against which external fitters can validate

ELECTROWEAK PARAMETERS

Dimension-6 operators modify pole masses, vertex factors, and the vev

Q_{HWB}, Q_{HD} | $Q^{(1)}_{H\ell}, Q^{(3)}_{H\ell}, Q^{(1)}_{Hq}, Q^{(3)}_{Hq}, Q_{He}, Q_{Hu}, Q_{Hd}$ | $Q_{\ell\ell}$



Parameter	Input Value	Ref.
$\hat{m}_Z$	91.1875 ± 0.0021	[19, 32, 33]
$\hat{G}_F$	$1.1663787(6) \times 10^{-5}$	[32, 33]
$\hat{\alpha}_{ew}$	$1/137.035999074(94)$	[32, 33]

$$\bar{M}_Z^2 = \frac{\bar{v}_T^2}{4}\left(\bar{g}_1{}^2 + \bar{g}_2{}^2\right) + \frac{1}{8}\bar{v}_T^4 C_{HD}\left(\bar{g}_1{}^2 + \bar{g}_2{}^2\right) + \frac{1}{2}\bar{v}_T^4 \bar{g}_1 \bar{g}_2 C_{HWB}$$

$$s_{\bar{\theta}}^2 = \frac{\bar{g}_1{}^2}{\bar{g}_2{}^2 + \bar{g}_1{}^2} + \frac{\bar{g}_1\bar{g}_2\left(\bar{g}_2{}^2 - \bar{g}_1{}^2\right)}{\left(\bar{g}_1{}^2 + \bar{g}_2{}^2\right)^2}\bar{v}_T^2 C_{HWB}$$

$$\bar{M}_W^2 = M_W^2\left(1 + \frac{\delta s_{\hat{\theta}}^2}{s_{\hat{\theta}}^2} + \frac{c_{\hat{\theta}}}{s_{\hat{\theta}}\sqrt{2}\hat{G}_F}C_{HWB} + \sqrt{2}\delta G_F\right)$$

$$\bar{e} = \bar{g}_2 s_{\bar{\theta}} = \sqrt{4\pi\hat{\alpha}}\left[1 + \frac{c_{\hat{\theta}}}{s_{\hat{\theta}}}\frac{1}{2\sqrt{2}\hat{G}_F}C_{HWB}\right]$$

$$\hat{G}_F = \frac{1}{\sqrt{2}\,\bar{v}_T^2} - \frac{1}{\sqrt{2}}C_{ll} + \sqrt{2}\,C^{(3)}_{Hl}$$

$$\bar{v}_T = \left(1 + \frac{3\,C_H\,v^2}{8\,\lambda}\right)v$$

$$\delta(g_V^\ell)_{pr} = -\frac{\delta G_F}{\sqrt{2}} - \frac{\delta M_Z^2}{2\hat{M}_Z^2} - \frac{1}{4\sqrt{2}\hat{G}_F}\left(-s_{\hat{\theta}}c_{\hat{\theta}}C_{HWB} - C_{\substack{He\\pr}} - C^{(1)}_{\substack{H\ell\\pr}} + C^{(3)}_{\substack{H\ell\\pr}}\right) - \delta s_\theta^2,$$

$$\delta(g_A^\ell)_{pr} = -\frac{\delta G_F}{\sqrt{2}} - \frac{\delta M_Z^2}{2\hat{M}_Z^2} + \frac{1}{4\sqrt{2}\hat{G}_F}\left(-s_{\hat{\theta}}c_{\hat{\theta}}C_{HWB} - C_{\substack{He\\pr}} + C^{(1)}_{\substack{H\ell\\pr}} - C^{(3)}_{\substack{H\ell\\pr}}\right),$$

$$\delta(g_V^\nu)_{pr} = -\frac{\delta G_F}{\sqrt{2}} - \frac{\delta M_Z^2}{2\hat{M}_Z^2} - \frac{1}{4\sqrt{2}\hat{G}_F}\left(-s_{\hat{\theta}}c_{\hat{\theta}}C_{HWB} - C^{(1)}_{\substack{H\ell\\pr}} - C^{(3)}_{\substack{H\ell\\pr}}\right),$$

$$\delta(g_A^\nu)_{pr} = -\frac{\delta G_F}{\sqrt{2}} - \frac{\delta M_Z^2}{2\hat{M}_Z^2} - \frac{1}{4\sqrt{2}\hat{G}_F}\left(-s_{\hat{\theta}}c_{\hat{\theta}}C_{HWB} - C^{(1)}_{\substack{H\ell\\pr}} - C^{(3)}_{\substack{H\ell\\pr}}\right),$$

$$\delta(g_V^u)_{pr} = -\frac{\delta G_F}{\sqrt{2}} - \frac{\delta M_Z^2}{2\hat{M}_Z^2} + \frac{1}{4\sqrt{2}\hat{G}_F}\left(-\frac{s_{\hat{\theta}}c_{\hat{\theta}}}{3}C_{HWB} + C^{(1)}_{\substack{Hq\\pr}} + C^{(3)}_{\substack{Hq\\pr}} + C_{\substack{Hu\\pr}}\right) + \frac{2}{3}\delta s_\theta^2,$$

$$\delta(g_A^u)_{pr} = -\frac{\delta G_F}{\sqrt{2}} - \frac{\delta M_Z^2}{2\hat{M}_Z^2} - \frac{1}{4\sqrt{2}\hat{G}_F}\left(-s_{\hat{\theta}}c_{\hat{\theta}}C_{HWB} - C^{(1)}_{\substack{Hq\\pr}} - C^{(3)}_{\substack{Hq\\pr}} + C_{\substack{Hu\\pr}}\right),$$

$$\delta(g_V^d)_{pr} = -\frac{\delta G_F}{\sqrt{2}} - \frac{\delta M_Z^2}{2\hat{M}_Z^2} - \frac{1}{4\sqrt{2}\hat{G}_F}\left(+\frac{s_{\hat{\theta}}c_{\hat{\theta}}}{3}C_{HWB} - C^{(1)}_{\substack{Hq\\pr}} + C^{(3)}_{\substack{Hq\\pr}} - C_{\substack{Hd\\pr}}\right) - \frac{1}{3}\delta s_\theta^2,$$

$$\delta(g_A^d)_{pr} = -\frac{\delta G_F}{\sqrt{2}} - \frac{\delta M_Z^2}{2\hat{M}_Z^2} + \frac{1}{4\sqrt{2}\hat{G}_F}\left(-s_{\hat{\theta}}c_{\hat{\theta}}C_{HWB} + C^{(1)}_{\substack{Hq\\pr}} - C^{(3)}_{\substack{Hq\\pr}} - C_{\substack{Hd\\pr}}\right)$$

$$\delta\left(g_V^{W_\pm,\ell}\right)_{rr} = \delta\left(g_A^{W_\pm,\ell}\right)_{rr} = \frac{1}{2\sqrt{2}\hat{G}_F}\left(C^{(3)}_{\substack{H\ell\\rr}} + \frac{\hat{c}_\theta}{\hat{s}_\theta}C_{HWB}\right) + \frac{1}{2}\frac{\delta s_\theta^2}{s_\theta^2}.$$

$$\delta\left(g_V^{W_\pm,q}\right)_{rr} = \delta\left(g_A^{W_\pm,q}\right)_{rr} = \frac{1}{2\sqrt{2}\hat{G}_F}\left(C^{(3)}_{\substack{Hq\\rr}} + \frac{\hat{c}_\theta}{\hat{s}_\theta}C_{HWB}\right) + \frac{1}{2}\frac{\delta s_\theta^2}{s_\theta^2}$$

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ELECTROWEAK OBSERVABLES

Modified parameters give the effect of dimension-6 operators on electroweak observables

$$A_{\rm FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \qquad \frac{3}{4}(A_\ell A_f)_{\rm SM}\left(\frac{\delta\left(\sigma_F - \sigma_B\right)}{(\sigma_F - \sigma_B)_{\rm SM}} - \frac{\delta\left(\sigma_F + \sigma_B\right)}{(\sigma_F + \sigma_B)_{\rm SM}}\right)$$

four-fermion operators

$$A_{\rm FB}^{0,f} = \frac{3}{4}A_e A_f, \quad A_e = 2\frac{g_V^\ell g_A^\ell}{(g_V^\ell)^2 + (g_A^\ell)^2}, \quad A_f = 2\frac{g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2} \qquad \delta A_{\rm FB}^{0,f} = \frac{3}{4}\left[\delta A_\ell\,(A_f)_{\rm SM} + (A_\ell)_{\rm SM}\,\delta A_f\right]$$

vertex corrections

Observable	Experimental Value	Ref.	SM Theoretical Value	Ref.
$\hat{m}_Z$[GeV]	91.1875 ± 0.0021	[19]	–	–
$\hat{m}_W$[GeV]	80.385 ± 0.015	[49]	80.365 ± 0.004	[50]
Γ_Z[GeV]	2.4952 ± 0.0023	[19]	2.4942 ± 0.0005	[48]
R^0_ℓ	20.767 ± 0.025	[19]	20.751 ± 0.005	[48]
R^0_c	0.1721 ± 0.0030	[19]	0.17223 ± 0.00005	[48]
R^0_b	0.21629 ± 0.00066	[19]	0.21580 ± 0.00015	[48]
σ^0_h [nb]	41.540 ± 0.037	[19]	41.488 ± 0.006	[48]
$A^\ell_{\rm FB}$	0.0171 ± 0.0010	[19]	0.01616 ± 0.00008	[32]
$A^c_{\rm FB}$	0.0707 ± 0.0035	[19]	0.0735 ± 0.0002	[32]
$A^b_{\rm FB}$	0.0992 ± 0.0016	[19]	0.1029 ± 0.0003	[32]

$$\delta\Gamma_Z = \frac{4\sqrt{2}\,\hat{G}_F \hat{M}_Z^3}{3\,\pi}\left[\frac{1}{4}\delta g_A^\nu + \frac{1}{4}\delta g_V^\nu - \frac{1}{4}\delta g_A^\ell + \frac{1}{4}\left(-1 + 4 s_{\hat\theta}^2\right)\delta g_V^\ell,\right.$$
$$\left. + \frac{1}{2}\delta g_A^u - \frac{1}{6}\left(-3 + 8 s_{\hat\theta}^2\right)\delta g_V^u - \frac{3}{4}\delta g_A^d + \frac{1}{4}\left(-3 + 4 s_{\hat\theta}^2\right)\delta g_V^d\right]$$
$$+ \delta\Gamma_{Z\to Had,\psi^4} + 3\delta\Gamma_{Z\to\ell\bar\ell,\psi^4} + 3\delta\Gamma_{Z\to\nu\bar\nu,\psi^4}.$$

$$R_f^0 = \frac{\Gamma_{had}}{\Gamma_{Z\bar{f}f}}$$

$$\delta R_f^0 = \frac{1}{(\Gamma(Z\to f\bar f)^2)_{\rm SM}}\left[\delta\Gamma_{Z\to Had}(\Gamma(Z\to f\bar f))_{\rm SM} - \delta\Gamma_{Z\to f\bar f}(\Gamma\,(Z\to {\rm Had})_{\rm SM})\right]$$

$$\overline{\sigma}_h^0 = 3\pi\,\frac{\overline{\Gamma}_{Z\to e\bar e}\overline{\Gamma}_{Z\to Had}}{|\overline{\omega}(M_Z^2)|^2}$$

$$\overline{\omega}(M_Z^2) = \bar{M}_Z\,\bar{\Gamma}_Z$$

$$\frac{\delta\sigma_h^0}{\sigma_h^0} \simeq \frac{\delta\Gamma_{Z\to\ell\bar\ell}}{\Gamma_{Z\to\ell\bar\ell}} + \frac{\delta\Gamma_{Z\to Had}}{\Gamma_{Z\to Had}} - \frac{\delta\omega(M_Z^2)}{\omega(M_Z^2)} - \frac{\delta\omega^\star(M_Z^2)}{\omega\star(M_Z^2)}$$

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FIT TO ELECTROWEAK DATA

Fitting the LEP data gives

$$C_{\rm fit} = \frac{\bar{v}_T^2}{\Lambda^2}\left\{ C^{(1)}_{\substack{Hq\\pr}}, C^{(3)}_{\substack{Hq\\pr}}, C_{\substack{Hu\\pr}}, C_{\substack{Hd\\pr}}, C^{(1)}_{\substack{H\ell\\pr}}, C^{(3)}_{\substack{H\ell\\pr}}, C_{\substack{He\\pr}}, C_{ll}, C_{HD}, C_{HWB} \right\}$$

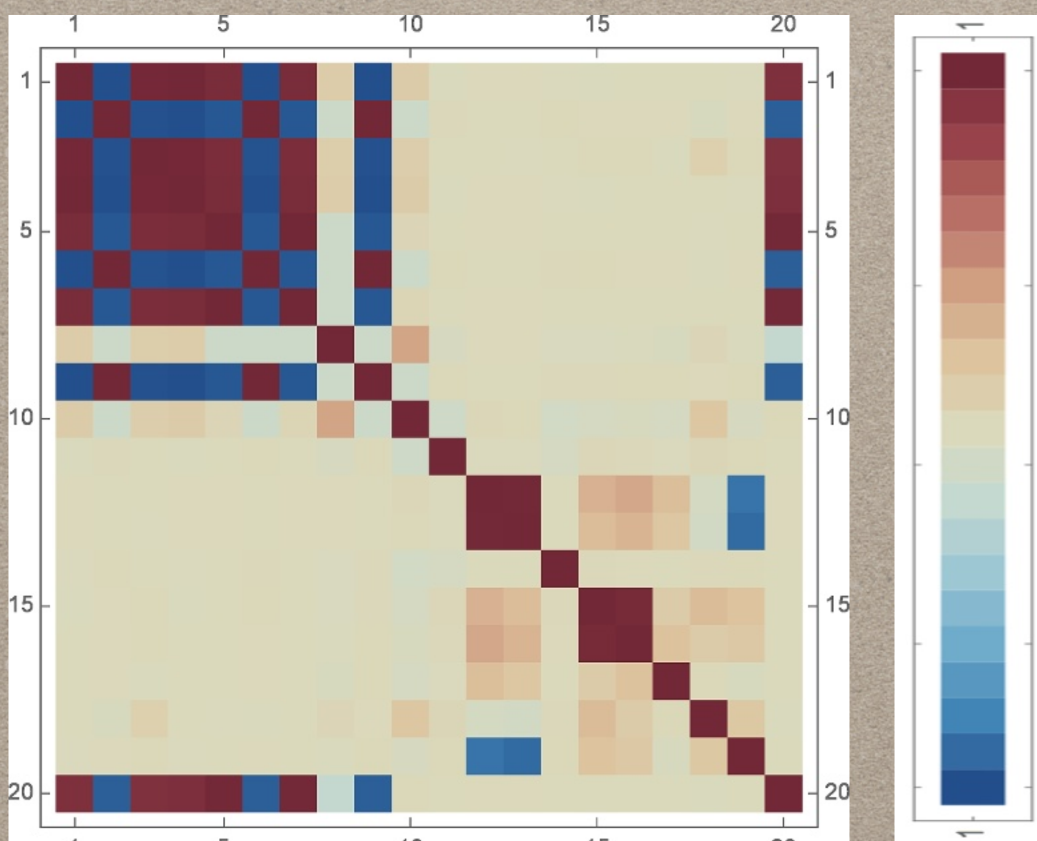
$$= \left\{-3.0, 7.9, 12, 87, -14, 3.4, -11\times 10^{1}, 9.2, 0.13, -1.4\times 10^{-2}\right\}\times 10^{-4}$$

Four-fermion operators suppressed by using resonant data

Can be included in the fit with off-shell measurements

(PEP, TRISTAN, PETRA)

LEPII also gives access to WWV vertex



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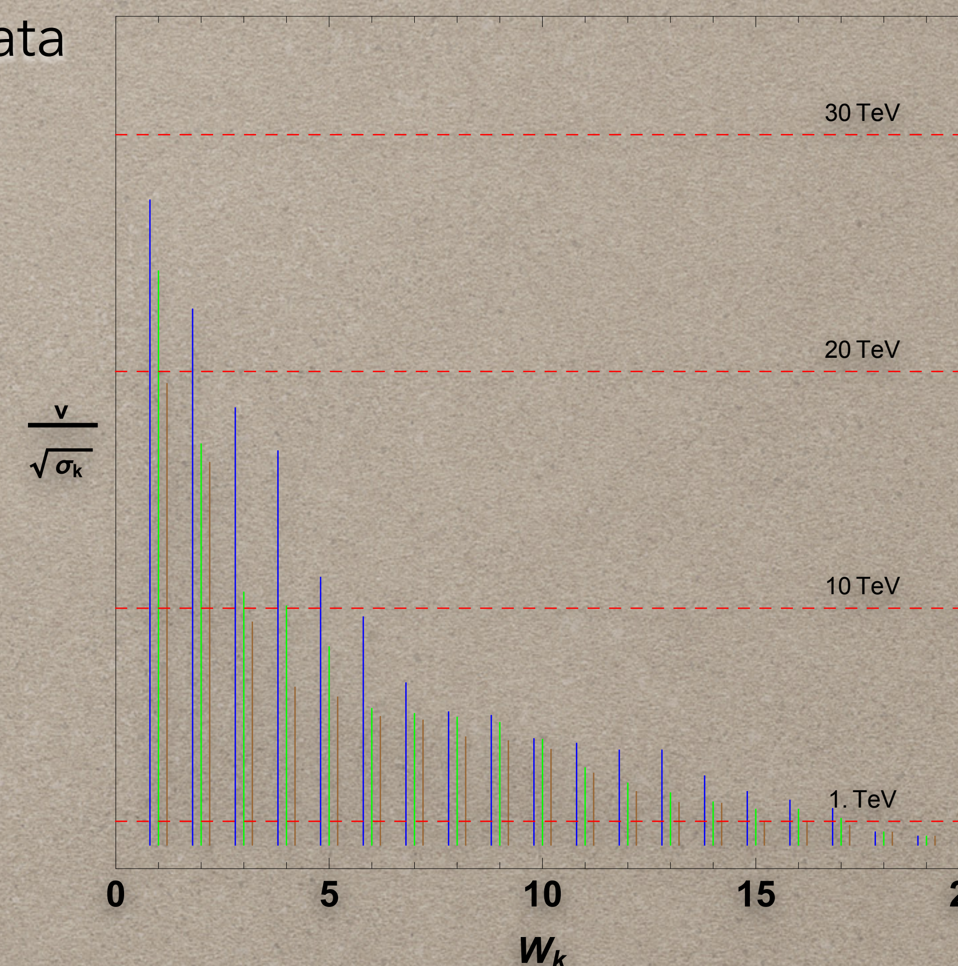

Some eigenvectors >20 TeV for unit coupling

Data and EFT relations available to experiments

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LHC OBSERVABLES & EFT VALIDITY

pp processes probe a range of scales so the EFT expansion can break down

$$|\mathcal{M}_{SMEFT}|^2 = |\mathcal{M}_{SM}|^2 + \mathcal{M}_{SM}^*\mathcal{M}_{d6} + \mathcal{M}_{SM}\mathcal{M}_{d6}^* + |\mathcal{M}_{d6}|^2 + \mathcal{M}_{SM}^*\mathcal{M}_{d8} + \mathcal{M}_{SM}\mathcal{M}_{d8}^* + \ldots$$

$\sim c_6 Q^2/\Lambda^2$ $\sim c_6^2 Q^4/\Lambda^4$ $\sim c_8 Q^4/\Lambda^4$

In a **specific model** the non-zero coefficients are known and the inclusion of $|\mathcal{M}_{d6}|^2$ will generally provide a more accurate estimate of the observable

In a **generic global fit** the non-zero terms are not known and one cannot in general constrain operators that first appear at $|\mathcal{M}_{d6}|^2$

$\mathcal{M}_{SM}^*\mathcal{M}_{d8} + \mathcal{M}_{SM}^*\mathcal{M}_{d8}$ terms are at the same order of suppression: one would have to introduce assumptions and break the global nature of the fit

A general requirement for the expansion is $\mathcal{M}_{SM}^*\mathcal{M}_{d6} > |\mathcal{M}_{d6}|^2$

The $|\mathcal{M}_{d6}|^2$ term is then subleading and its inclusion is a choice

Including only up to $\mathcal{M}_{SM}^*\mathcal{M}_{d6}$ allows a consistent linearization

OPERATOR DEPENDENCE

EFT tools facilitate experimental studies and global fits

SMEFTsim is a complete flavour-general dimension-6 implementation

NLO implementation soon available in Madgraph

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At LO one can **separately generate** the $\mathscr{M}_{SM}^{*}\ \mathscr{M}_{d6}$ & $|\mathscr{M}_{d6}|^2$ terms in Madgraph

Derive linear equations for truth- or detector-level observables:

Scan operators *to see which ones provide a non-zero $|\mathscr{M}_{d6}|^2$ cross-section*

Generate one point *for each operator with a non-zero cross section*

$$\sigma_{EFT} = \sigma_{SM} + \sigma_{int} + \sigma_{BSM} \qquad \frac{\sigma_{int}}{\sigma_{SM}} = \sum_i A_i c_i$$

Cross-section region	$\sum_i A_i c_i$
$gg/q\bar{q} \to ttH$	$-0.98\mathtt{cH} + 2.9\mathtt{cu} + 0.93\mathtt{cG} + 310\mathtt{cuG}$ $+27\mathtt{c3G} - 13\mathtt{c2G}$

LHCHXSWG-INT-2017-001

Partial width	$\sum_i A_i c_i$
$H \to b\bar{b}$	$-1.0\mathtt{cH} + 3.0\mathtt{cd}$
$H \to WW^* \to l\nu l\nu$	$10\mathtt{cWW} + 3.7\mathtt{cHW} + 2.2\mathtt{cpHL}$
$H \to ZZ^* \to 4l$	$55\mathtt{cWW} + 13\mathtt{cB} + 15\mathtt{cHW} + 4.6\mathtt{cHB} + 0.018c_\gamma + 2.0\mathtt{cHL} + 2.0\mathtt{cpHL} + 0.027\mathtt{cHe}$
$H \to \gamma\gamma$	$-5.8c'_\gamma$
$H \to \tau\tau$	$-1.0\mathtt{cH} + 3.0\mathtt{cl}$
$H \to gg$	$56\mathtt{cG}$
$H \to$all	$0.0029\mathtt{cT} + 0.17\mathtt{cu} + 2.3\mathtt{cd} + 0.11\mathtt{cl} + 1.0\mathtt{cWW} + 0.023\mathtt{cB} + 0.37\mathtt{cHW}$ $+0.0079\mathtt{cHB} + 1.6\mathtt{cG} + 0.0078\mathtt{cHQ} + 0.17\mathtt{cpHQ} + 0.0027\mathtt{cHu} + 0.057\mathtt{cpHL}$

LHC OBSERVABLES

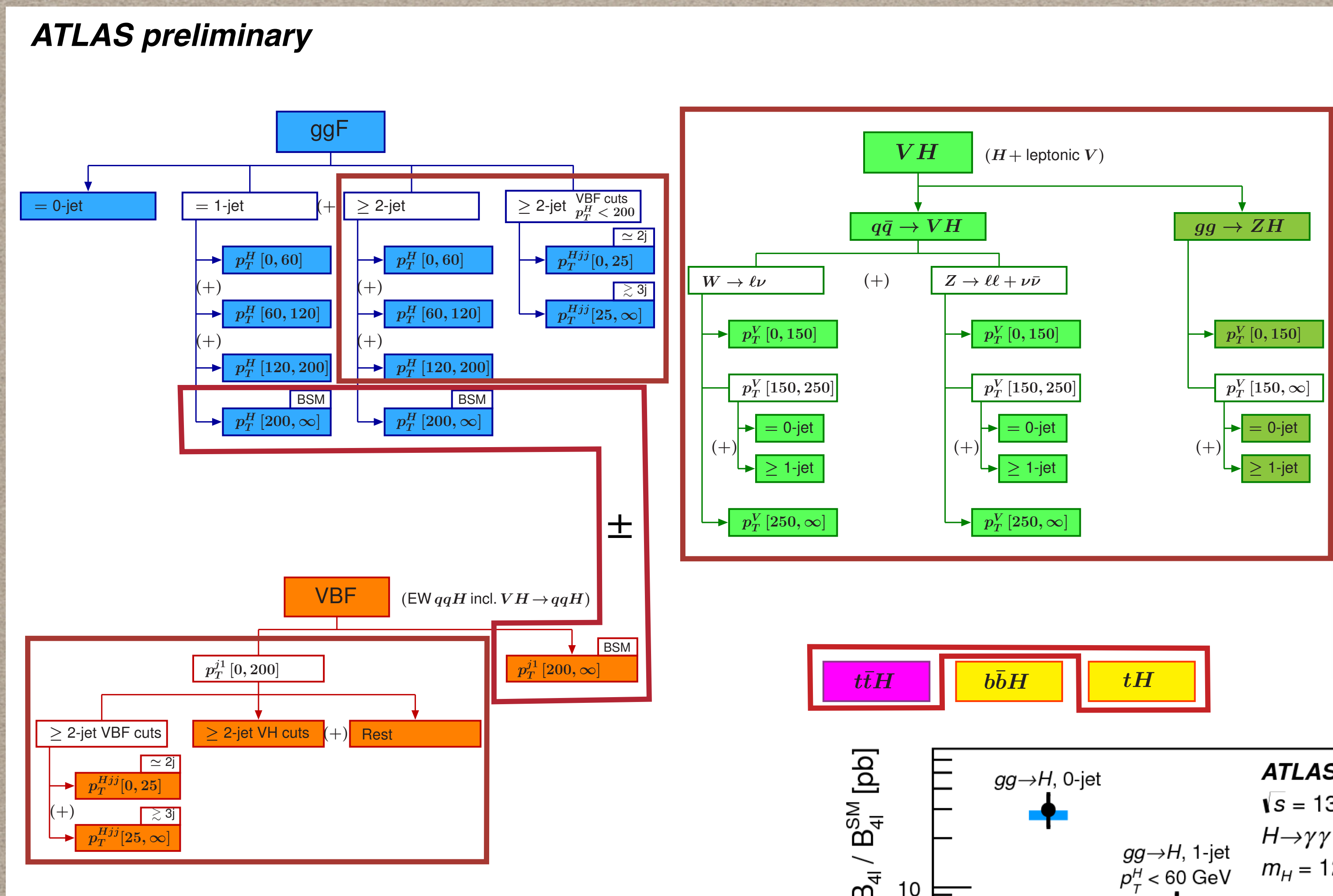
Template cross sections:
* Define kinematic & topological regions, fit for normalization factors
* Allows optimal slicing of process using multiple variables
* Extrapolation using SM distributions could affect operator dependence
* Equations for operator dependence can be determined at truth level

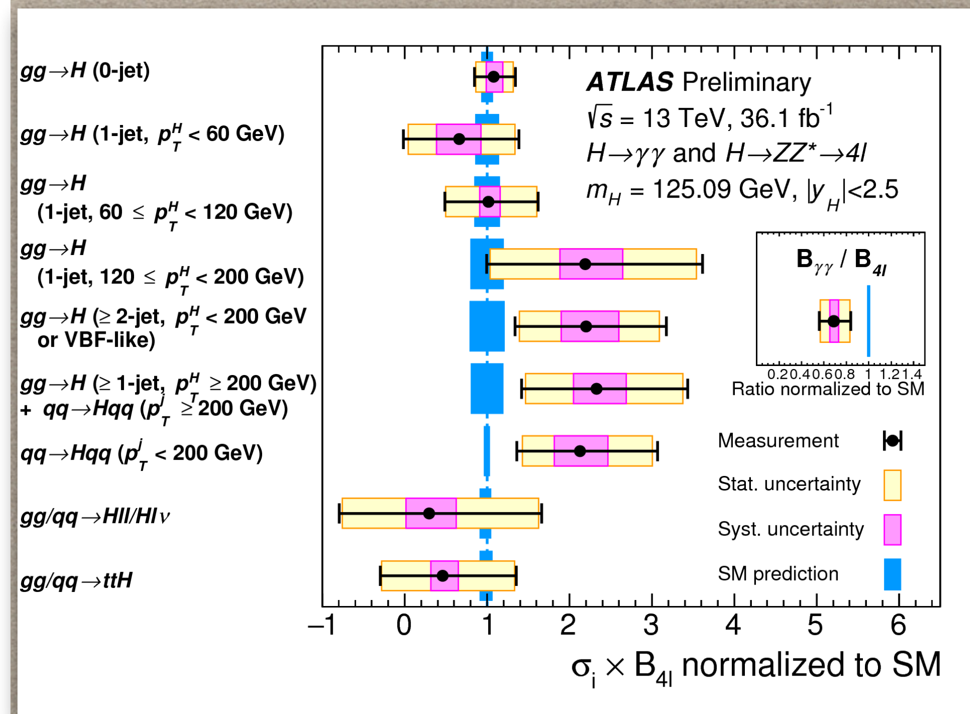
Unfolded cross sections:
* Reduce model dependence with unfolding
* Typically confined to one or two differential distributions for fit
* Equations for operator dependence can be determined at truth level

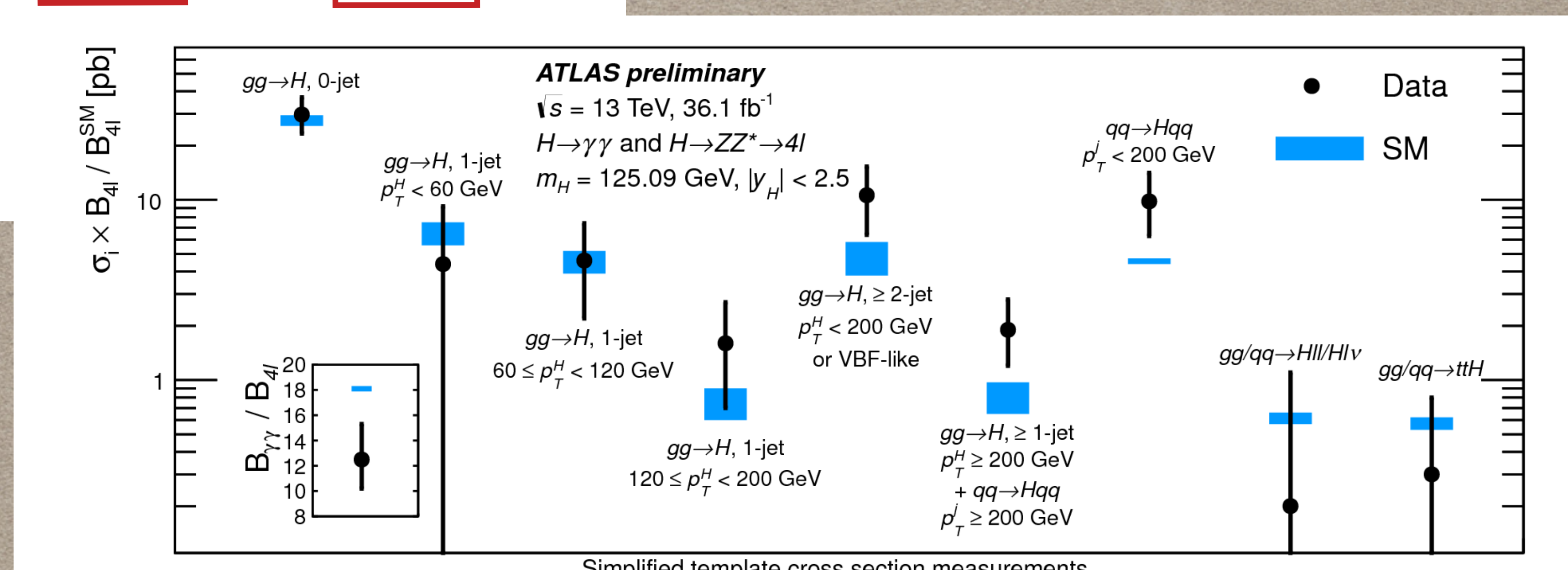
Data yields:
* Can fully optimize sensitivity to operators
* Ties optimization to a particular operator set
* Equations for operator dependence must be determined at detector level

HIGGS TEMPLATE CROSS SECTIONS

A set of 'simplified' template cross sections (STXS) defined by the LHC Higgs working group







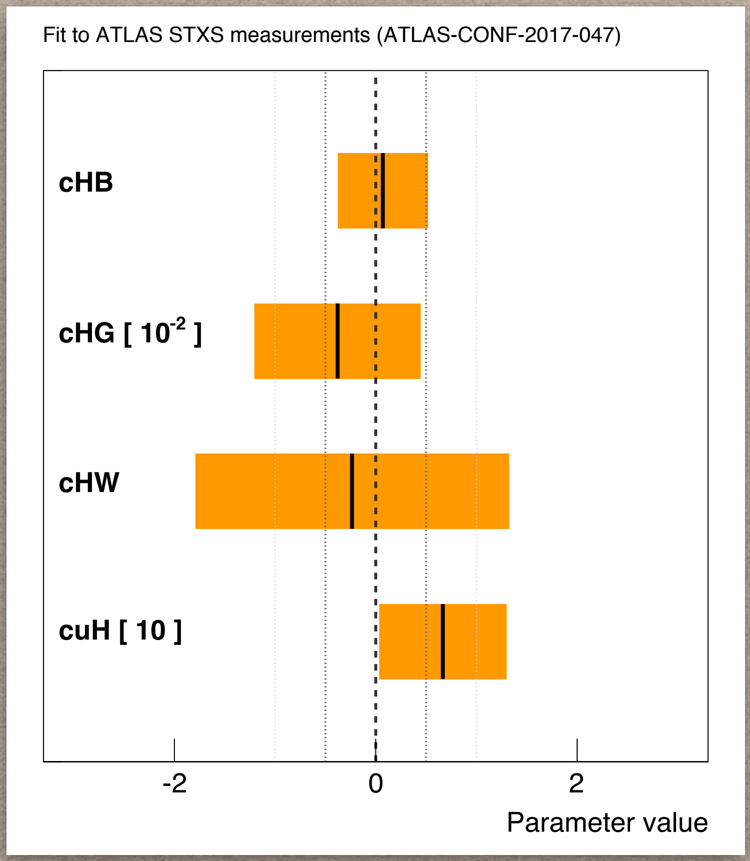
1610.07922, Sec. III.2

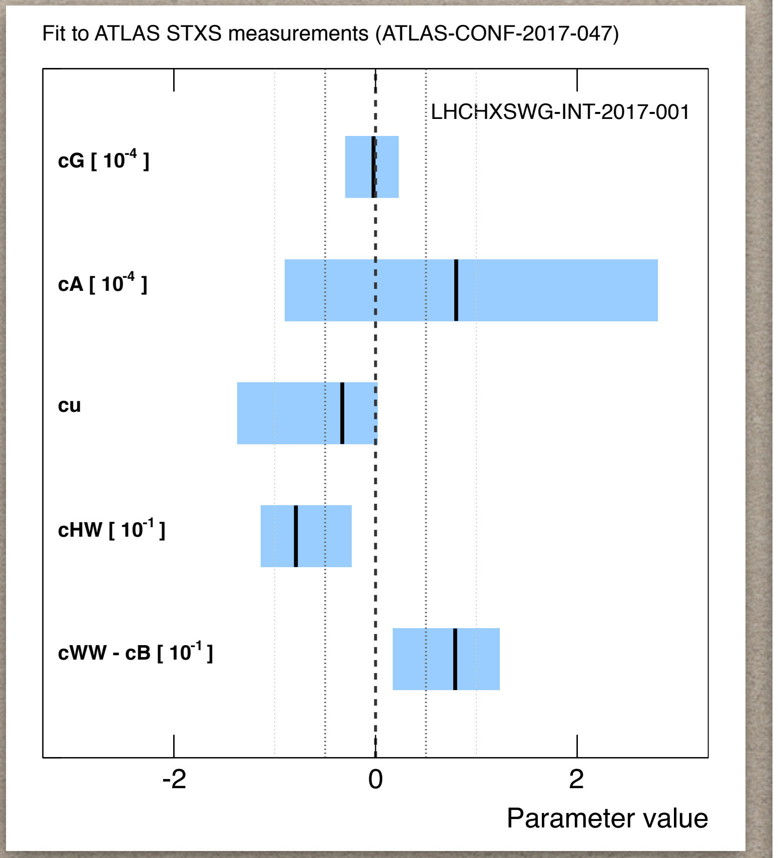
ATLAS combination includes binning in jet multiplicity and p_T^H

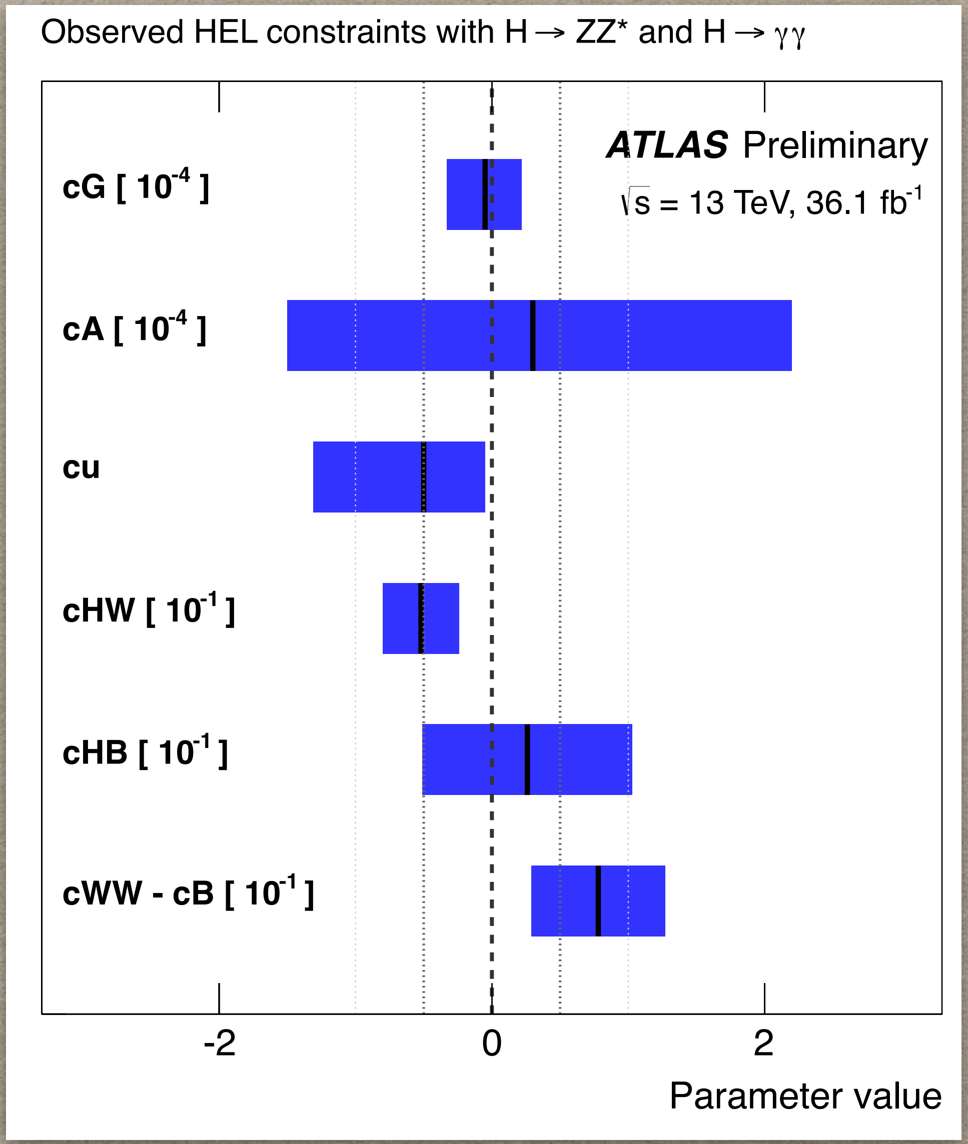
ATLAS-CONF-2017-047

FITS TO HIGGS DATA

Use relations between STXS and EFT parameters to derive constraints from ATLAS measurements







Constraints derived using public STXS results in two EFT bases

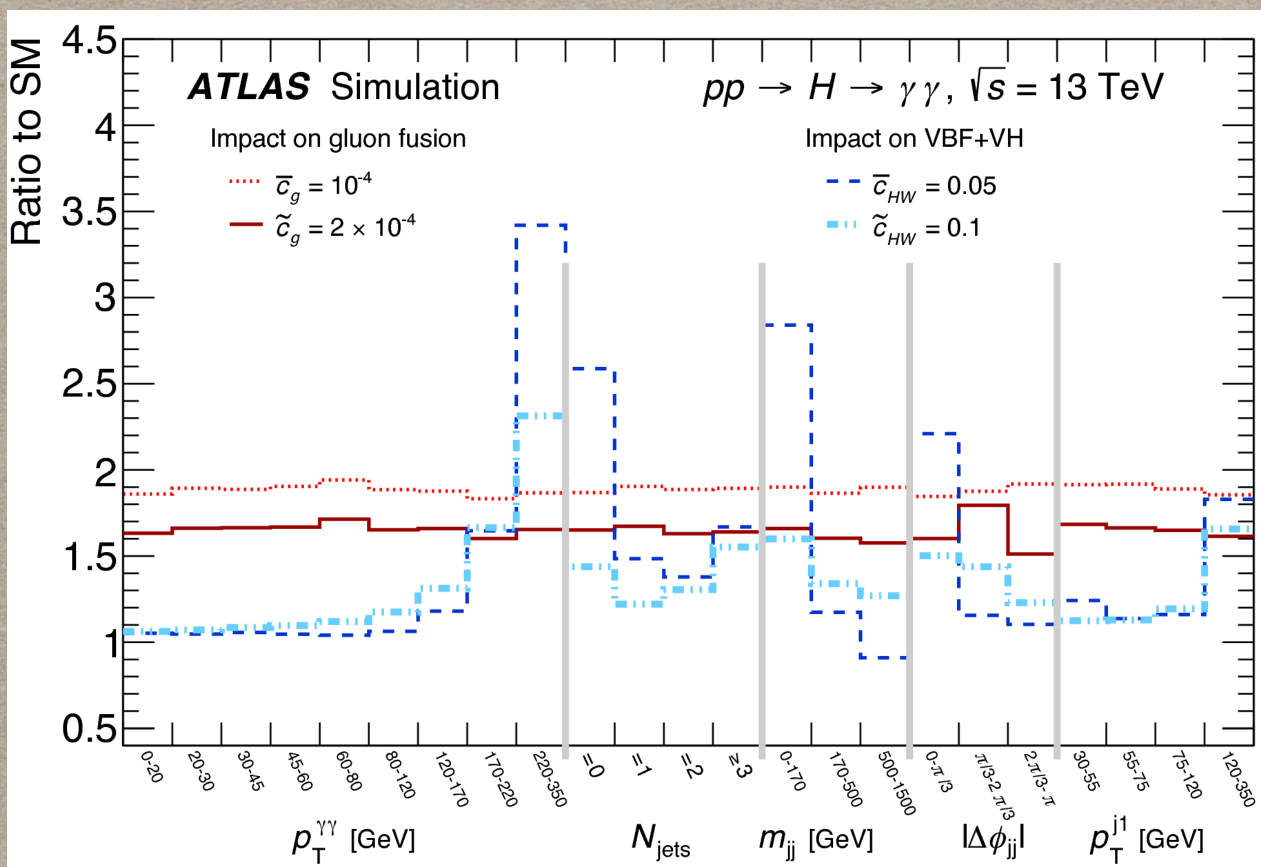
G. Zemaityte, HEFT & LHCXSWG-INT-2017-001

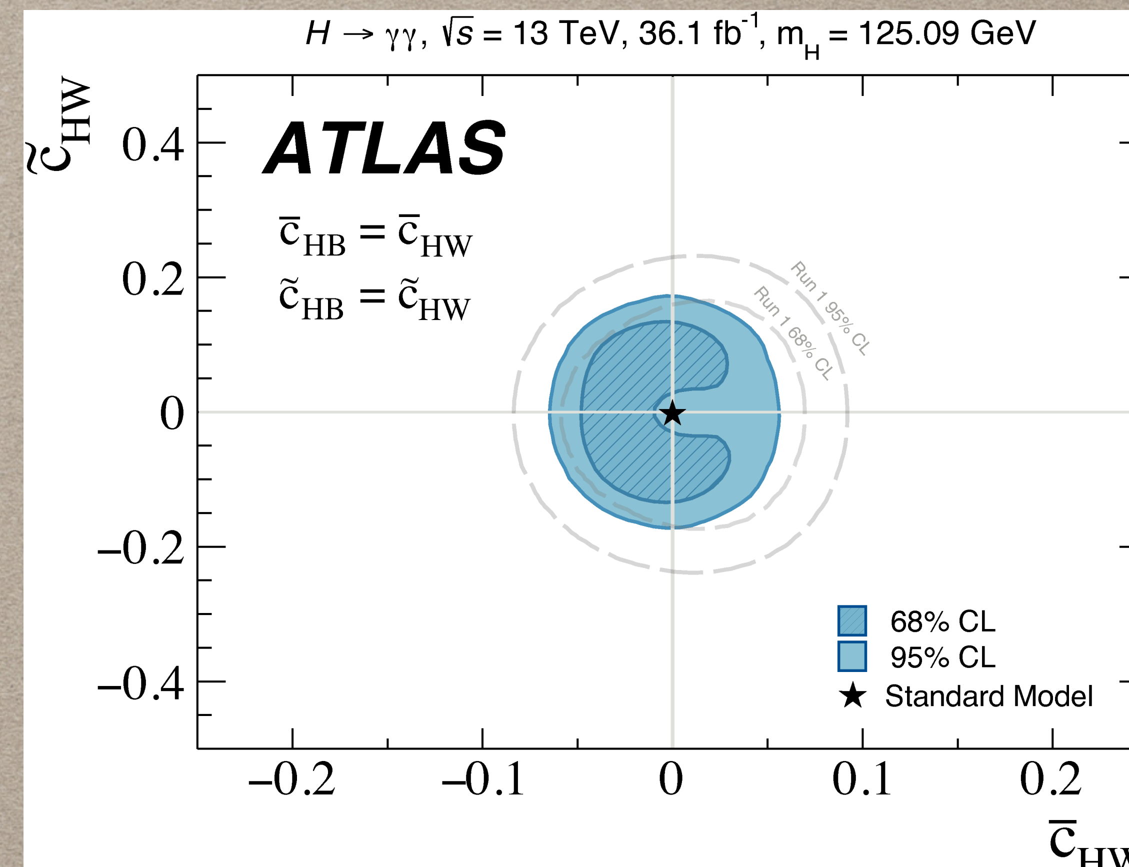
Constraints derived using all STXS bins within ATLAS

ATLAS-PUB-2017-018

HIGGS DIFFERENTIAL CROSS SECTIONS

Individual measurements constrain up two parameters simultaneously





1802.04146

Can use multiple distributions if statistical correlations are understood

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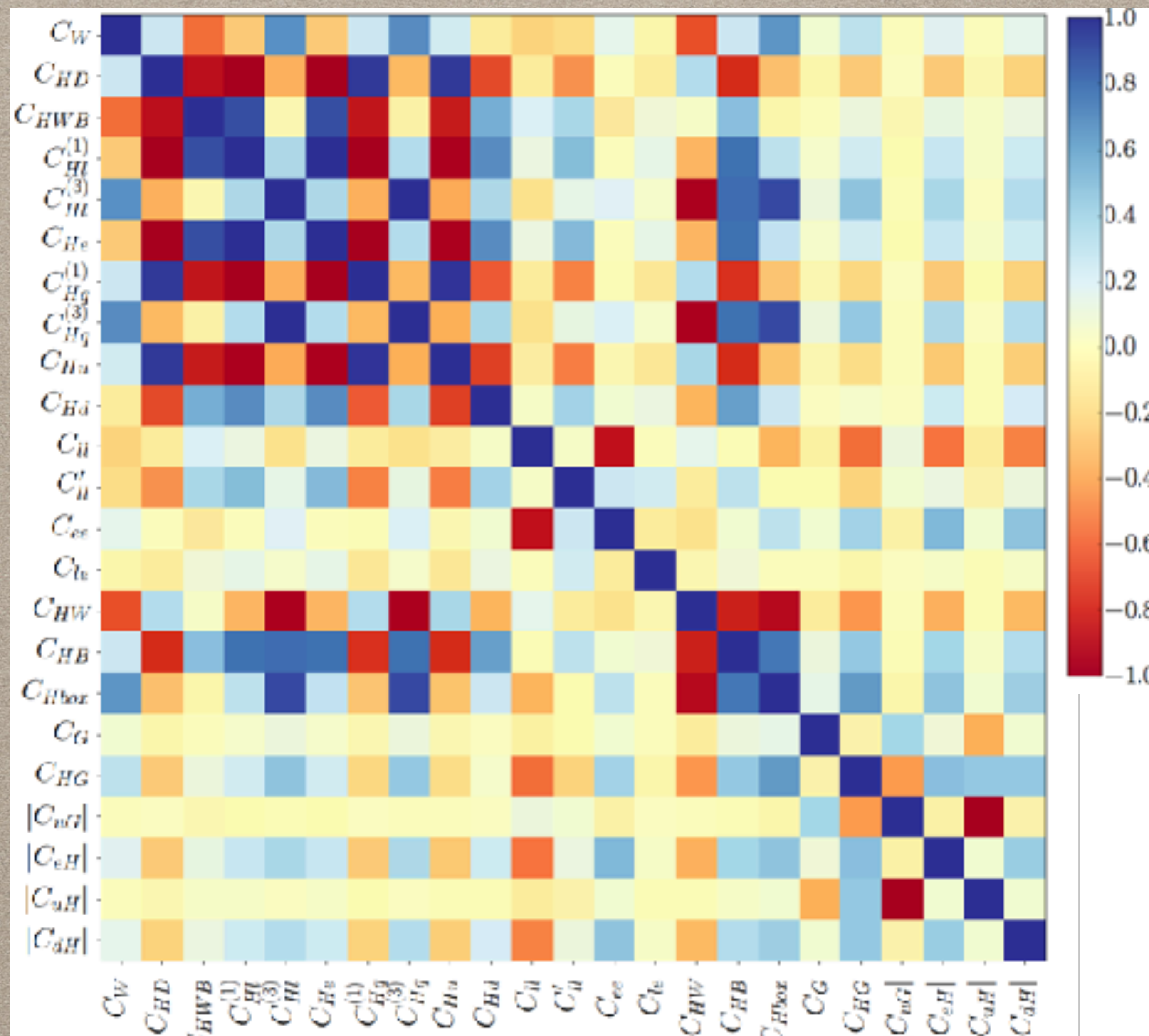
Bin	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	74.8	7.7	4.7	2.8	5.1	2.0	0.8	0.3	-0.8	-0.1	3.7	6.8	9.8	3.5	0.5	2.7
2	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	40.1	14.3	7.3	2.0	5.3	4.9	1.7	0.1	1.1	1.2	4.7	6.9	18.5	3.9	2.4	2.4
3	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	23.0	23.0	9.0	5.2	10.0	4.5	0.8	-0.7	2.1	2.8	5.7	8.9	25.9	9.6	5.2	2.3
4	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	12.5	29.4	9.7	5.2	7.8	6.0	4.3	4.0	3.5	5.4	4.2	8.9	26.9	16.2	7.8	4.3
5	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	4.1	28.6	12.7	7.9	12.9	4.5	6.9	1.5	2.8	7.4	11.0	8.4	20.5	24.3	10.0	5.1
6	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	3.7	30.0	22.5	10.4	21.1	11.2	5.6	2.3	10.9	17.8	11.4	10.2	16.2	27.8	26.4	10.6
7	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	-1.3	19.4	21.6	10.5	17.0	13.7	8.3	3.7	15.7	14.4	9.9	8.9	7.0	15.4	26.1	17.3
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.3	15.3	20.5	20.9	22.6	14.3	8.8	6.4	23.9	17.9	11.4	6.2	1.0	5.4	19.8	32.9
9	74.8	40.1	23.0	12.5	4.1	3.7	-1.3	0.3	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	7.7	14.3	23.0	29.4	28.6	30.0	19.4	15.3	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	69.9	38.9	23.4	12.4
11	4.7	7.3	9.0	9.7	12.7	22.5	21.6	20.5	0.0	0.0	100.0	0.0	73.1	35.7	20.3	13.4	35.1	43.3	38.4	50.7	18.5	26.4	29.6	21.2
12	2.8	2.0	5.2	5.2	7.9	10.4	10.5	20.9	0.0	0.0	0.0	100.0	33.9	38.3	16.9	6.8	20.9	22.8	25.0	33.5	3.8	12.1	20.4	24.2
13	5.1	5.3	10.0	7.8	12.9	21.1	17.0	22.6	0.0	0.0	73.1	33.9	100.0	0.0	0.0	0.0	42.5	41.9	39.3	38.2	17.7	30.2	30.2	17.7
14	2.0	4.9	4.5	6.0	4.5	11.2	13.7	14.3	0.0	0.0	35.7	38.3	0.0	100.0	0.0	0.0	7.7	21.5	20.8	44.4	6.4	6.3	19.4	23.3
15	0.8	1.7	0.8	4.3	6.9	5.6	8.3	8.8	0.0	0.0	20.3	16.9	0.0	0.0	100.0	0.0	8.0	12.3	10.3	20.2	0.9	3.9	5.8	13.9
16	0.3	0.1	-0.7	4.0	1.5	2.3	3.7	6.4	0.0	0.0	13.4	6.8	0.0	0.0	0.0	100.0	7.3	7.4	4.8	10.3	1.0	1.6	3.5	4.5
17	-0.8	1.1	2.1	3.5	2.8	10.9	15.7	23.9	0.0	0.0	35.1	20.9	42.5	7.7	8.0	7.3	100.0	0.0	0.0	0.0	9.9	16.2	12.2	3.7
18	-0.1	1.2	2.8	5.4	7.4	17.8	14.4	17.9	0.0	0.0	43.3	22.8	41.9	21.5	12.3	7.4	0.0	100.0	0.0	0.0	9.1	15.6	17.8	14.2
19	3.7	4.7	5.7	4.2	11.0	11.4	9.9	11.4	0.0	0.0	38.4	25.0	39.3	20.8	10.3	4.8	0.0	0.0	100.0	0.0	10.4	11.6	13.6	18.8
20	6.8	6.9	8.9	8.9	8.4	10.2	8.9	6.2	0.0	0.0	50.7	33.5	38.2	44.4	20.2	10.3	0.0	0.0	0.0	100.0	7.1	14.2	25.5	23.0
21	9.8	18.5	25.9	26.9	20.5	16.2	7.0	1.0	0.0	69.9	18.5	3.8	17.7	6.4	0.9	1.0	9.9	9.1	10.4	7.1	100.0	0.0	0.0	0.0
22	3.5	3.9	9.6	16.2	24.3	27.8	15.4	5.4	0.0	38.9	26.4	12.1	30.2	6.3	3.9	1.6	16.2	15.6	11.6	14.2	0.0	100.0	0.0	0.0
23	0.5	2.4	5.2	7.8	10.0	26.4	26.1	19.8	0.0	23.4	29.6	20.4	30.2	19.4	5.8	3.5	12.2	17.8	13.6	25.5	0.0	0.0	100.0	0.0
24	2.7	2.4	2.3	4.3	5.1	10.6	17.3	32.9	0.0	12.4	21.2	24.2	17.7	23.3	13.9	4.5	3.7	14.2	18.8	23.0	0.0	0.0	0.0	100.0

COMBINED HIGGS AND ELECTROWEAK FIT

Several implementations constraining parameters sensitive to Higgs and Electroweak data

$\bar{C}_{He}$	0.036 ± 0.079
$\bar{C}_{W}$	-0.020 ± 0.107
$\bar{C}_{HD}$	-0.078 ± 0.153
$\bar{C}_{ll}$	-0.079 ± 0.171
$\bar{C}_{HW}$	0.070 ± 0.195
$\bar{C}_{ee}$	0.13 ± 0.20
$\bar{C}_{eH}$	0.079 ± 0.223
$\bar{C}_{G}$	0.30 ± 0.23
$\bar{C}_{dH}$	0.094 ± 0.248
$\bar{C}_{H\Box}$	0.0037 ± 0.6126
$\bar{C}_{uH}$	$12. \pm 27.$
$\bar{C}_{uG}$	$-28. \pm 62.$



Reduced parameter correlations

$\bar{C}_{HG}$	0.00096 ± 0.00121
$\bar{C}'_{ll}$	-0.0043 ± 0.0057
$\bar{C}^{(1)}_{Hq}$	-0.0068 ± 0.0132
$\bar{C}_{Hd}$	-0.018 ± 0.027
$\bar{C}^{(1)}_{Hl}$	0.019 ± 0.039
$\bar{C}_{Hu}$	-0.021 ± 0.051
$\bar{C}^{(3)}_{Hl}$	-0.0037 ± 0.0537
$\bar{C}^{(3)}_{Hq}$	-0.0060 ± 0.0539
$\bar{C}_{le}$	0.038 ± 0.055
$\bar{C}_{HB}$	0.0017 ± 0.0636
$\bar{C}_{HWB}$	0.040 ± 0.065

23 constrained parameters

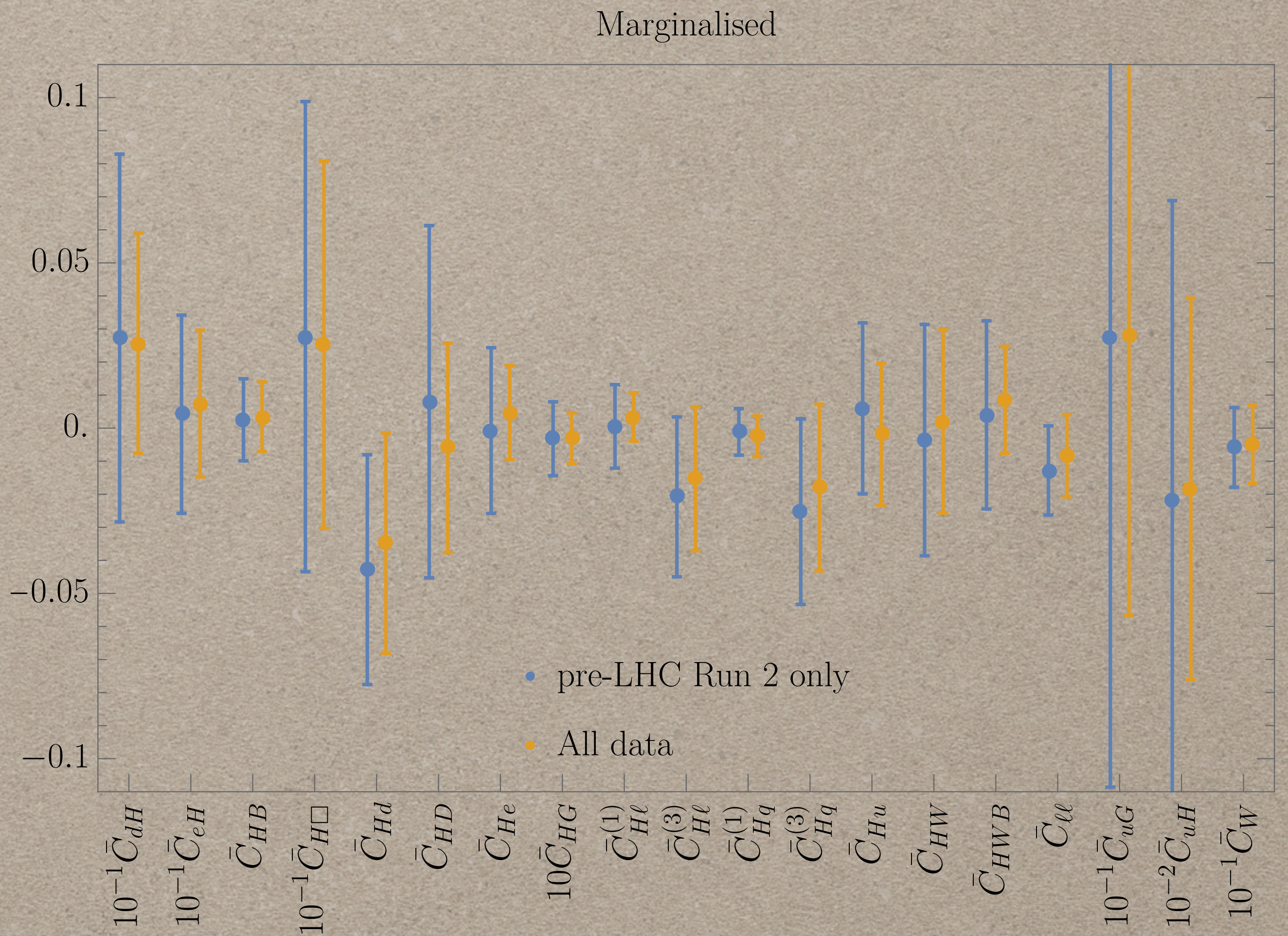
M. Trott, ATLAS EFT workshop

COMBINED HIGGS AND ELECTROWEAK FIT

Several implementations constraining parameters sensitive to Higgs and Electroweak data

Coefficient	Z-pole + m_W	WW at LEP2	Higgs Run1	Higgs Run2	LHC WW high-p_T
$\bar{C}_{dH}$	×	×	42.4	57.6	×
$\bar{C}_{eH}$	×	×	49.6	50.4	×
$\bar{C}_{G}$	×	×	2.4	97.6	×
$\bar{C}_{HB}$	×	×	18.6	81.4	×
$\bar{C}_{H\Box}$	×	×	19.3	80.7	0.01
$\bar{C}_{Hd}$	99.85	×	0.04	0.1	×
$\bar{C}_{HD}$	99.92	0.06	×	×	×
$\bar{C}_{He}$	99.99	0.01	×	×	×
$\bar{C}_{HG}$	×	×	41.1	58.9	0.03
$\bar{C}_{H\ell}^{(1)}$	99.97	0.03	×	×	×
$\bar{C}_{H\ell}^{(3)}$	99.56	0.41	×	×	0.01
$\bar{C}_{Hq}^{(1)}$	99.98	×	×	×	×
$\bar{C}_{Hq}^{(3)}$	98.5	0.96	0.19	0.31	0.07
$\bar{C}_{Hu}$	99.3	×	0.2	0.42	0.04
$\bar{C}_{HW}$	×	×	18.3	81.7	×
$\bar{C}_{HWB}$	57.7	0.02	8.2	34.1	×
$\bar{C}_{\ell\ell}$	99.66	0.3	×	0.01	×
$\bar{C}_{uG}$	×	×	8.9	91.1	×
$\bar{C}_{uH}$	×	×	10.9	89.1	×
$\bar{C}_{W}$	×	96.2	×	×	3.8

Table 5: *Impact of different sets of measurements on the fit to individual Wilson coefficients in the Warsaw basis as measured by the Fisher information contained in a given dataset for each coefficient. A cross indicates no (current) sensitivity.*



20 constrained parameters

Run 2 data now dominating Higgs constraints

1803.03252

APPLICATION TO RESONANCES

Name	Spin	$SU(3)$	$SU(2)$	$U(1)$	Name	Spin	$SU(3)$	$SU(2)$	$U(1)$
$\mathcal{S}$	0	1	1	0	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
$\mathcal{S}_1$	0	1	1	1	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
φ	0	1	2	$\frac{1}{2}$	Σ	$\frac{1}{2}$	1	3	0
Ξ	0	1	3	0	Σ_1	$\frac{1}{2}$	1	3	-1
Ξ_1	0	1	3	1	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$
$\mathcal{B}$	1	1	1	0	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$
$\mathcal{B}_1$	1	1	1	1	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$
$\mathcal{W}$	1	1	3	0	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$
$\mathcal{W}_1$	1	1	3	1	Q_7	$\frac{1}{2}$	3	2	$\frac{7}{6}$
N	$\frac{1}{2}$	1	1	0	T_1	$\frac{1}{2}$	3	3	$-\frac{1}{3}$
E	$\frac{1}{2}$	1	1	-1	T_2	$\frac{1}{2}$	3	3	$\frac{2}{3}$

Model	Pull $[\sigma]$	$\Delta\frac{\chi^2}{\text{dof}}$ [%]	Coupling	Mass / TeV
$\mathcal{S}_1$	1.1	0.1	$\lvert y_{\mathcal{S}_1}\rvert^2 = (6.3 \pm 5.9)\cdot 10^{-3}$	$M_{\mathcal{S}_1} = (9.1,\ 53)$
φ, Type I	0.6	-0.4	$Z_6 \cdot \cos\beta = -0.41 \pm 0.66$	$M_{\varphi} = (1.0,\ \infty)$
Ξ	1.2	0.4	$\lvert\kappa_{\Xi}\rvert^2 = (4.1 \pm 3.4)\cdot 10^{-3}$	$M_{\Xi} = (12,\ 36)$
N	1.5	0.9	$\lvert\lambda_N\rvert^2 = (1.8 \pm 1.2)\cdot 10^{-2}$	$M_N = (5.8,\ 13)$
E	0.2	-0.6	$\lvert\lambda_E\rvert^2 = (2.0 \pm 9.7)\cdot 10^{-3}$	$M_E = (9.2,\ \infty)$
Δ_3	0.7	-0.3	$\lvert\lambda_{\Delta_3}\rvert^2 = (0.8 \pm 1.1)\cdot 10^{-2}$	$M_{\Delta_3} = (7.3,\ \infty)$
Σ	0.4	-0.5	$\lvert\lambda_{\Sigma}\rvert^2 = (0.9 \pm 2.0)\cdot 10^{-2}$	$M_{\Sigma} = (5.9,\ \infty)$
Q_5	0.7	-0.3	$\lvert\lambda_{Q_5}\rvert^2 = 0.07 \pm 0.10$	$M_{Q_5} = (2.4,\ \infty)$
T_2	0.3	-0.5	$\lvert\lambda_{T_2}\rvert^2 = (1.8 \pm 5.1)\cdot 10^{-2}$	$M_{T_2} = (3.8,\ \infty)$
$\mathcal{W}_1$	1.2	0.3	$\left\lvert\hat{g}^{\phi}_{\mathcal{W}_1}\right\rvert^2 = (3.3 \pm 2.7)\cdot 10^{-3}$	$M_{\mathcal{W}_1} = (4.1,\ 13)$
$\mathcal{S}$	-	-	$\lvert y_{\mathcal{S}}\rvert^2 < 0.47$	$M_{\mathcal{S}} > 1.5$
Δ_1	-	-	$\lvert\lambda_{\Delta_1}\rvert^2 < 5.7\cdot 10^{-3}$	$M_{\Delta_1} > 13$
Σ_1	-	-	$\lvert\lambda_{\Sigma_1}\rvert^2 < 7.3\cdot 10^{-3}$	$M_{\Sigma_1} > 12$
U	-	-	$\lvert\lambda_U\rvert^2 < 3.1\cdot 10^{-2}$	$M_U > 5.7$
D	-	-	$\lvert\lambda_D\rvert^2 < 1.5\cdot 10^{-2}$	$M_D > 8.2$
Q_7	-	-	$\lvert\lambda_{Q_7}\rvert^2 < 7.2\cdot 10^{-2}$	$M_{Q_7} > 3.7$
T_1	-	-	$\lvert\lambda_{T_1}\rvert^2 < 0.11$	$M_{T_1} > 3.0$
$\mathcal{B}_1$	-	-	$\left\lvert\hat{g}^{\phi}_{\mathcal{B}_1}\right\rvert^2 < 2.4\cdot 10^{-3}$	$M_{\mathcal{B}_1} > 20$

Apply EFT results to cases of individual high-mass resonances

Some types of resonances improve the χ^2

Limits are set on the other resonances

1803.03252

TOP-QUARK MEASUREMENTS

Tevatron and LHC top measurements have been fit to constrain 9 operators

Dataset	$\sqrt{s}$ (TeV)	Measurements	Ref.
Top pair production			
ATLAS	7 + 8	Total inclusive σ	[13]
	7 + 8	Differential $p_T(t), M_{t\bar{t}}, \lvert y(t\bar{t})\rvert$	[14]
CMS	7	Differential $p_T(t), M_{t\bar{t}}, y(t), \lvert y(t\bar{t})\rvert$	[15]
CDF	1.96	Differential $M_{t\bar{t}}$	[16]
DØ	1.96	Differential $M_{t\bar{t}}, p_T(t), \lvert y(t)\rvert$	[17]
Single top production			
ATLAS t-channel	7	Total inclusive σ	[18]
	7	Differential $p_T(t), \lvert y(t)\rvert$	
CMS t-channel	7	Total inclusive σ	[19]
	8	Total inclusive σ	[20]
CDF s-channel	1.96	Total inclusive σ	[21]
DØ $s+t$-channel	1.96	Total inclusive σ	[22]

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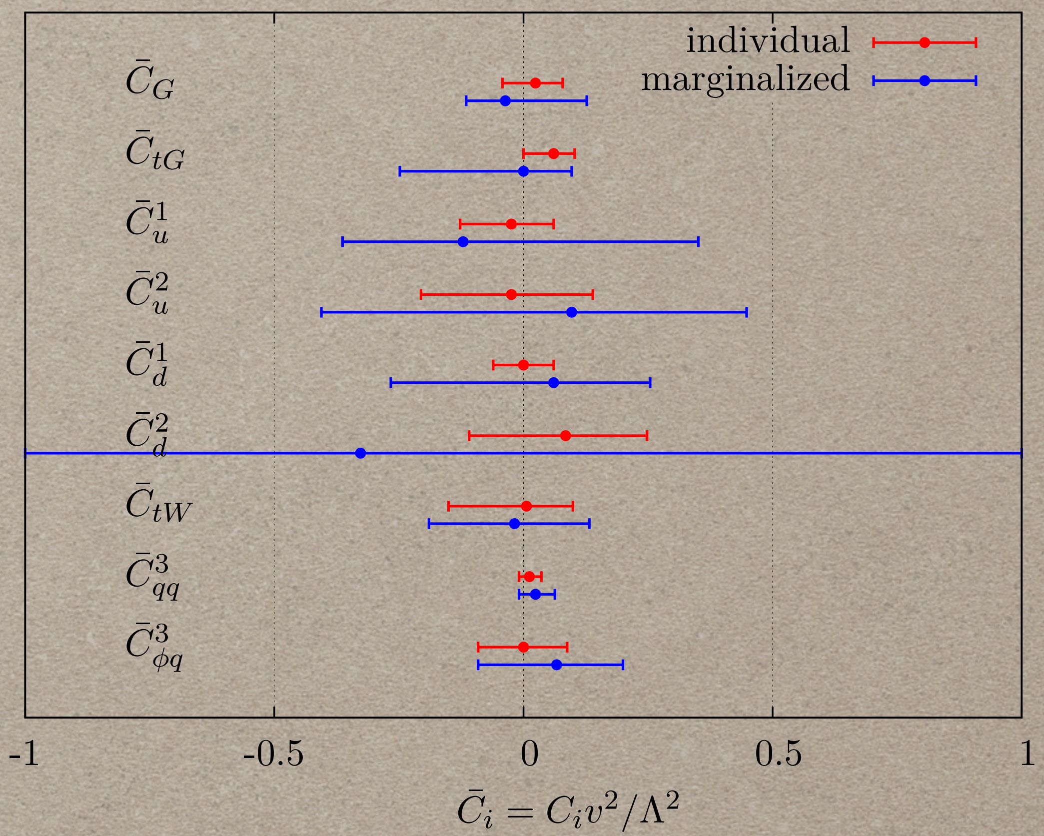


LHC top WG has defined scenarios for four-fermion operators separating heavy and light quarks

four heavy quarks	$11 + 2$ CPV
two light and two heavy quarks	14
two heavy quarks and bosons	$9 + 6$ CPV
two heavy quarks and two leptons	$(8 + 3\text{ CPV}) \times 3$ lepton flavours

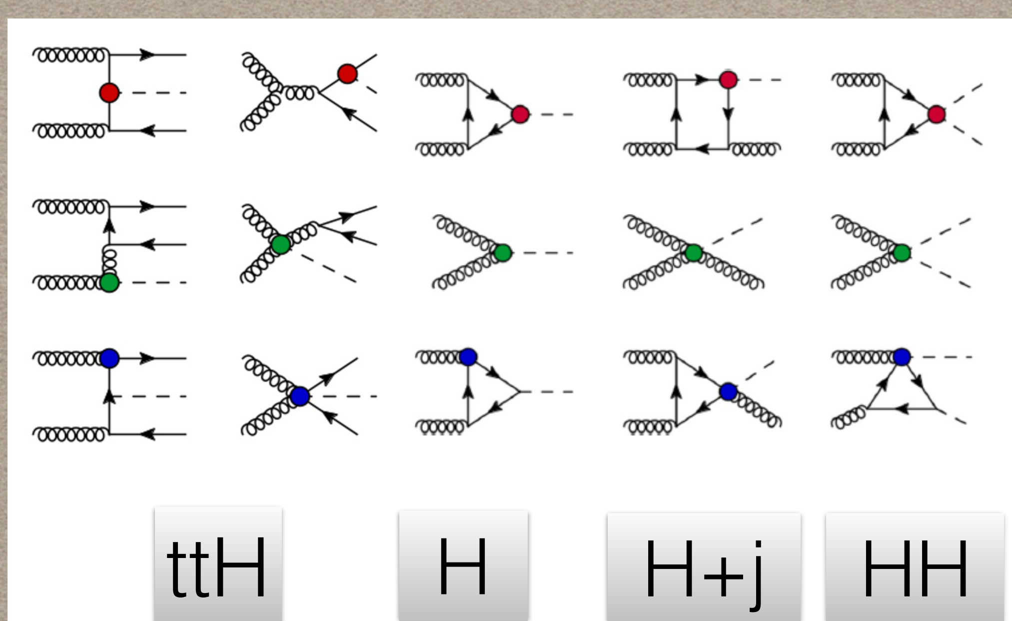
1802.07237

COMBINING TOP AND HIGGS/EW DATA

Top measurements have substantial overlap in operator dependence with Higgs and Electroweak measurements

Combined top/Higgs/EW fit not yet attempted

Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{bW}	$O_{\varphi tb}$	O_{4f}	O_G	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	N		L	L				L^2	L^2	1L^2		
$pp \to tj$	N		L	L				L^2	L^2	1L		
$pp \to tW$	L		L	L				L^2	L^2	1N	N	
$pp \to t\bar{t}$	L									2L-4N	L	
$pp \to t\bar{t}j$	L									2L-4N	L	
$pp \to t\bar{t}\gamma$	L	L	L							2L-4N	L	
$pp \to t\bar{t}Z$	L	L	L	L	L	L				2L-4N	L	
$pp \to t\bar{t}W$	L								L	1L-2L		
$pp \to t\gamma j$	N	L	L	L				L^2	L^2	1L		
$pp \to tZj$	N	L	L	L	L	L		L^2	L^2	1L		
$pp \to t\bar{t}t\bar{t}$	L									2L-4L	L	
$pp \to t\bar{t}H$	L						L			2L-4L	L	L
$pp \to tHj$	N		L	L			L	L^2	L^2	1L		N
$gg \to H$	L						L				N	L
$gg \to Hj$	L						L				L	L
$gg \to HH$	L						L				N	L
$gg \to HZ$	L			L	L	L	L				N	L



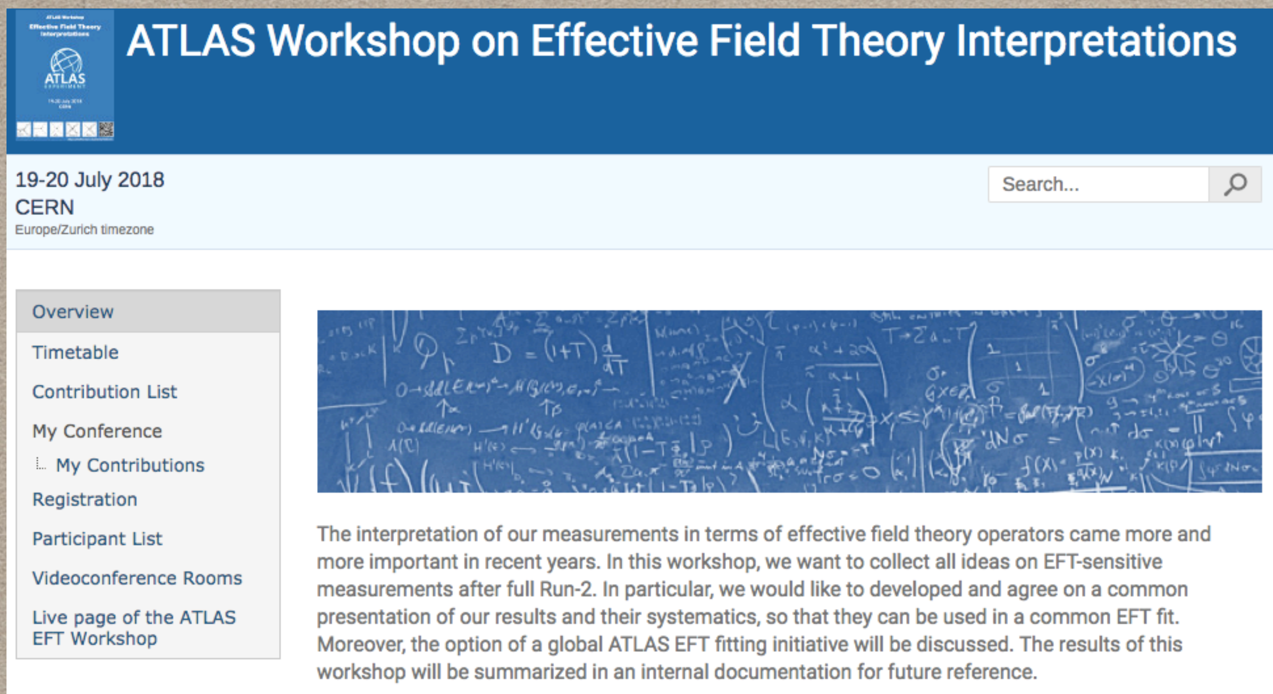
$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

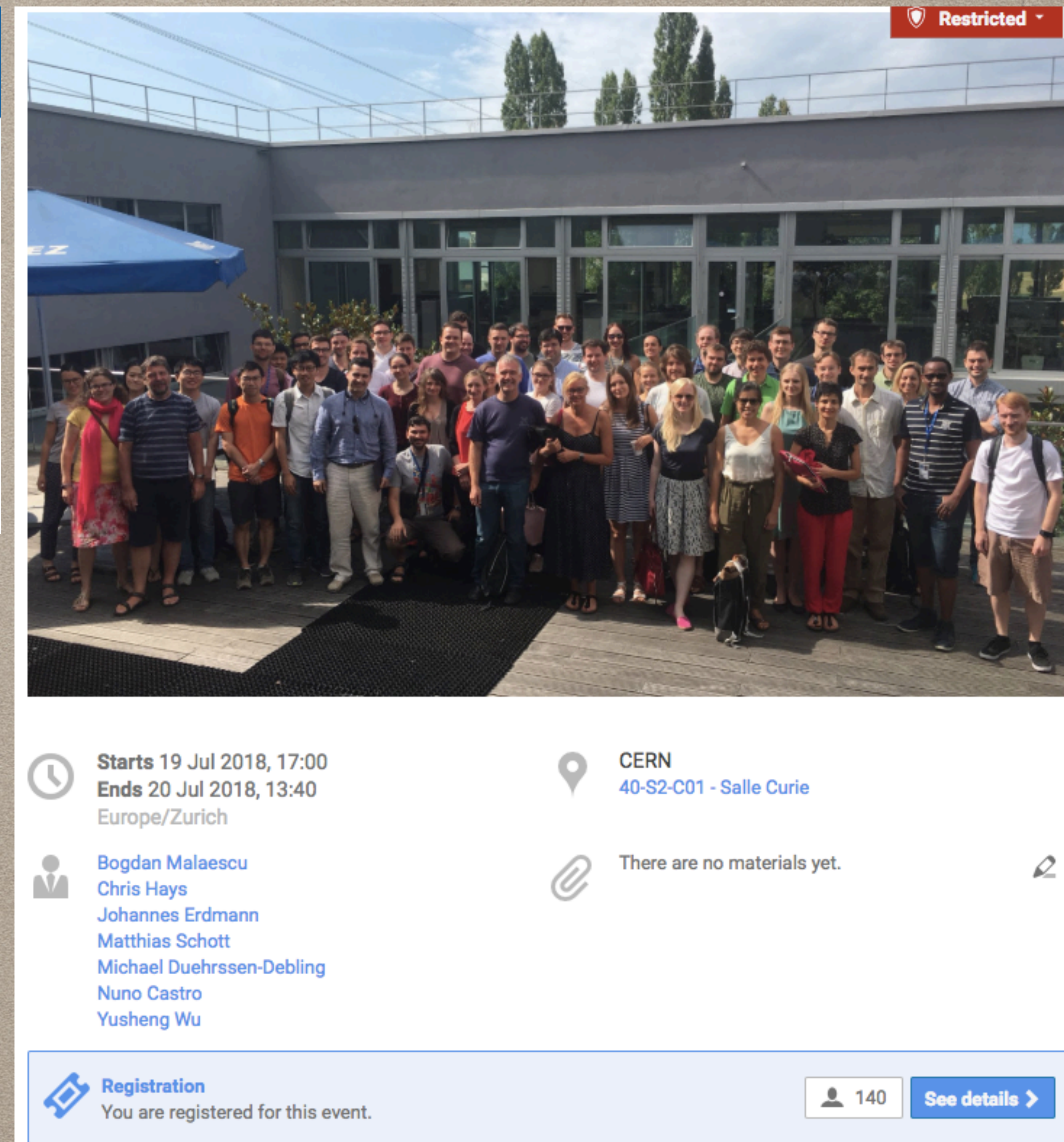
$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$$

F. Maltoni, ATLAS EFT workshop

SMEFT @ ATLAS



A recent ATLAS workshop reviewed the theoretical issues associated with performing an SMEFT fit (July 19) and with combining measurements across analysis groups (July 20)



The conveners will circulate a summary in the coming weeks and schedule a follow-up meeting in a couple months

https://indico.cern.ch/event/729117

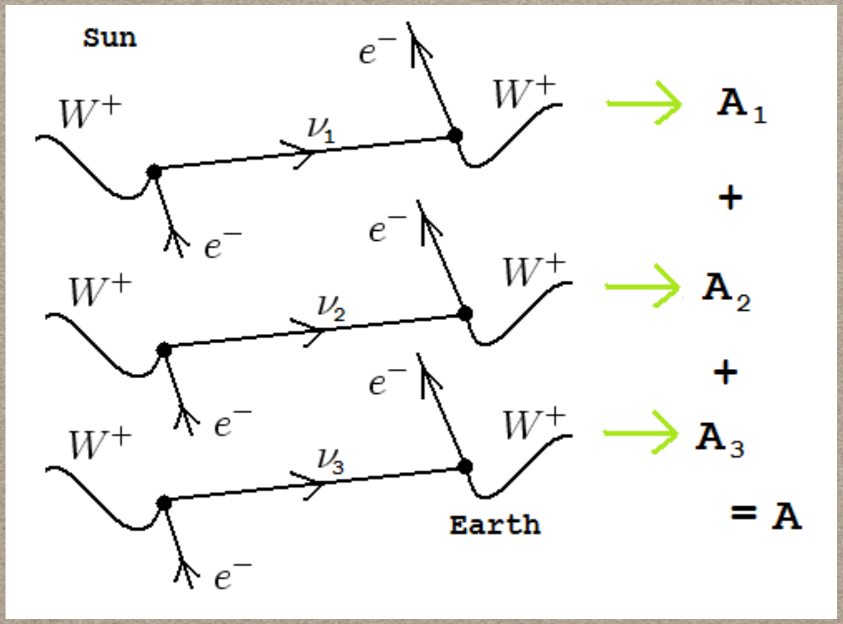
SUMMARY

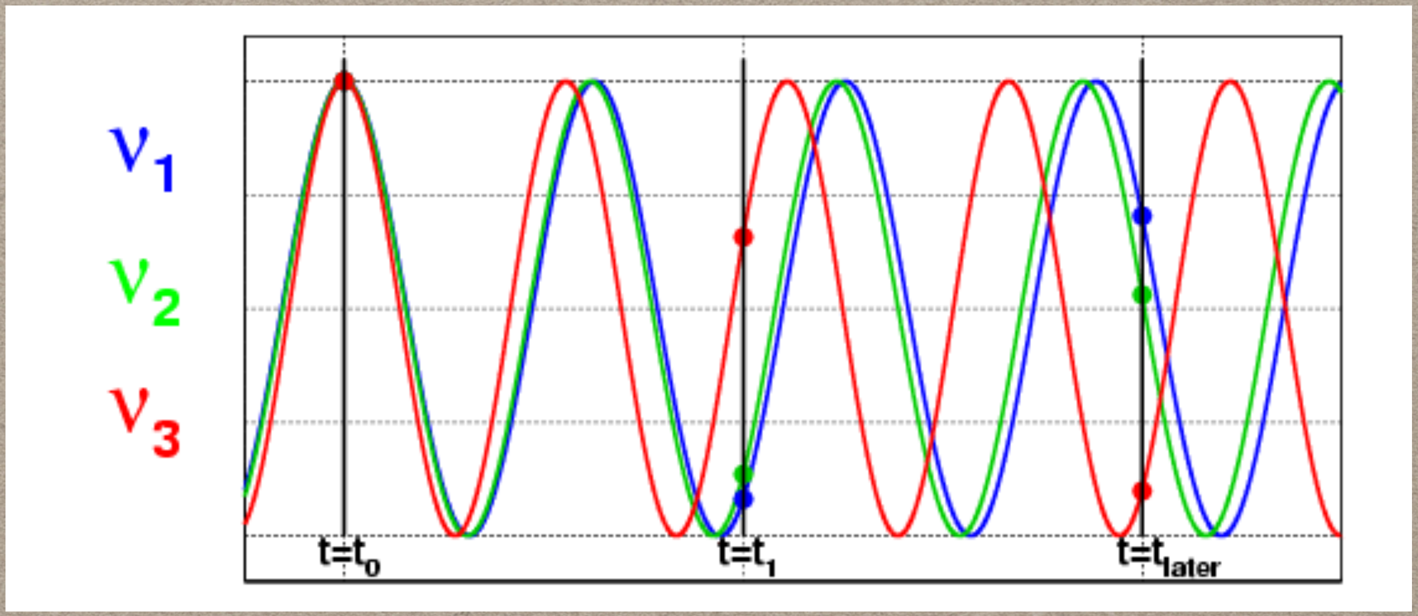
Interference provides a sensitive probe for new physics at a high scale

A complete basis of operators is available for a rigorous search

Fits to ~20 operators have demonstrated the methods & feasibility of global fits

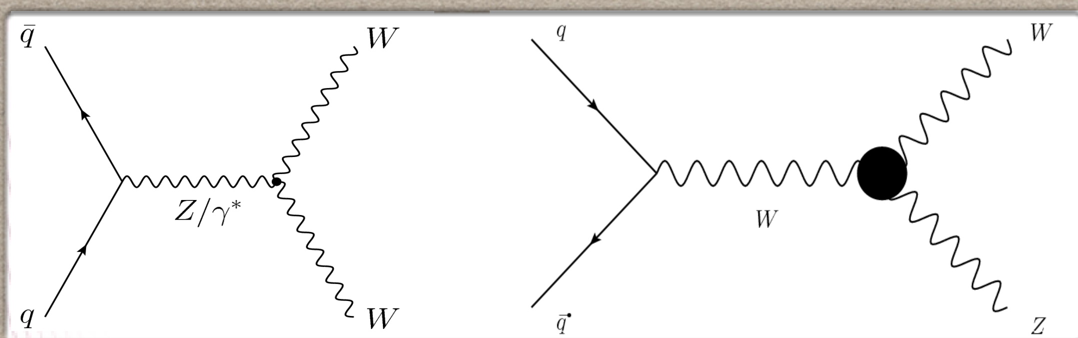
Now is the time for the experiments to enter the game



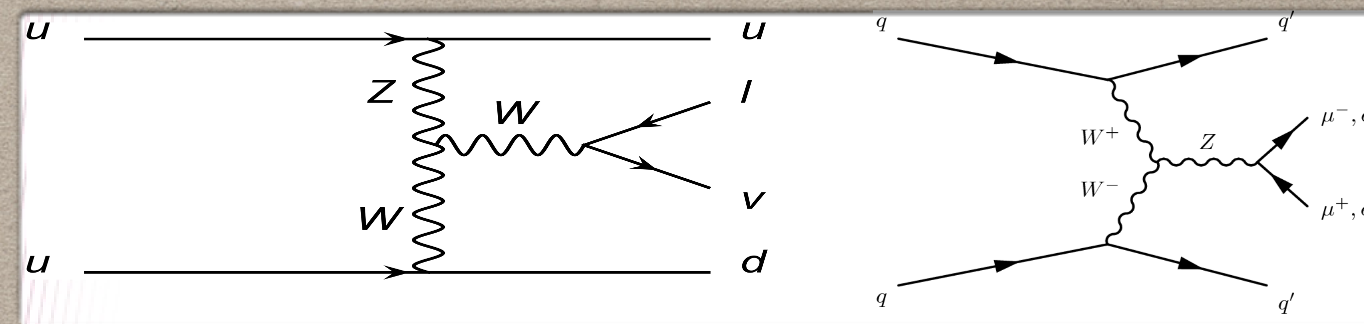


GAUGE BOSON SELF-COUPLINGS

s-channel



t-channel



Historical parameterization

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

$$\delta\bar{g}_1^{\mathcal{A}} = -\delta\bar{\kappa}_{\mathcal{A}} = -\frac{v_T^2}{2}\frac{c_{\bar\theta}}{s_{\bar\theta}}C_{HWB}, \qquad \delta\bar{g}_1^{\mathcal{Z}} = -\delta\kappa_{\mathcal{Z}} = \frac{v_T^2}{2}\frac{s_{\bar\theta}}{c_{\bar\theta}}C_{HWB}, \longleftarrow$$

also affect Higgs production & decay

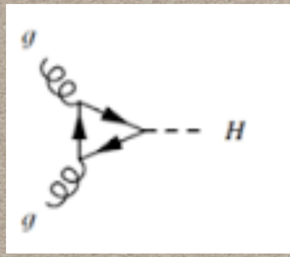
$$\delta\bar{\lambda}_{\mathcal{A}} = 6\,s_{\bar\theta}\,C_W\,\frac{\bar{M}_W^2}{\bar{g}_{\mathcal{AWW}}}, \qquad \delta\bar{\lambda}_{\mathcal{Z}} = 6\,c_{\bar\theta}\,C_W\,\frac{\bar{M}_W^2}{\bar{g}_{\mathcal{ZWW}}}. \longleftarrow$$

only determined by self-couplings

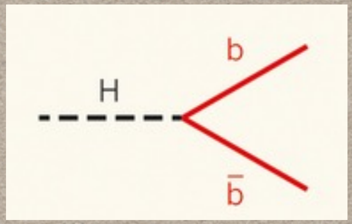
$$Q_W \;\Big|\; \epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$$

HIGGS PRODUCTION AND DECAY

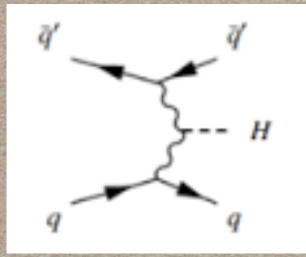
$$Q_{H\Box} \quad (H^\dagger H)\Box(H^\dagger H)$$
$$Q_{HD} \quad \left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$$

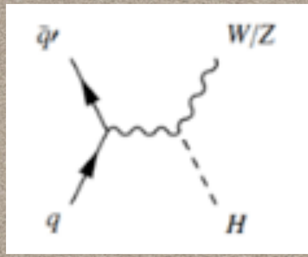


$$Q_{HG} \quad H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu} \qquad Q_G \quad f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$
$$Q_{H\widetilde{G}} \quad H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu} \qquad Q_{\widetilde{G}} \quad f^{ABC} \widetilde{G}^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$

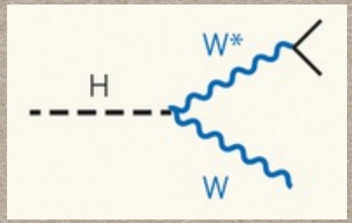


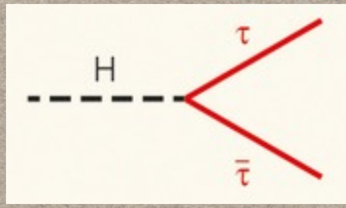
$$Q_{dH} \quad (H^\dagger H)(\bar{q}_p d_r H)$$

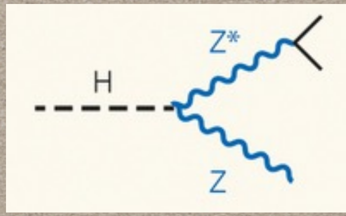


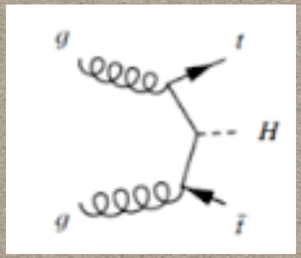


$$Q_{HW} \quad H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$$
$$Q_{H\widetilde{W}} \quad H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$$
$$Q_{HB} \quad H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$$
$$Q_{H\widetilde{B}} \quad H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$$
$$Q_{HWB} \quad H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$$
$$Q_{H\widetilde{W}B} \quad H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$$

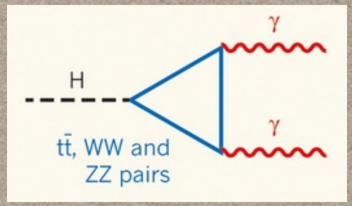








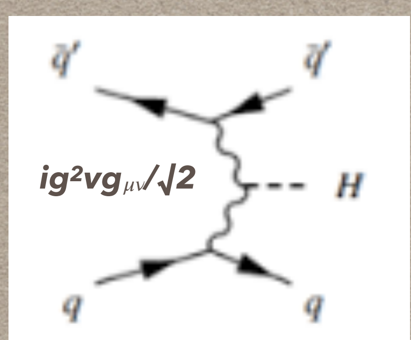
$$Q_{uH} \quad (H^\dagger H)(\bar{q}_p u_r \widetilde{H}) \qquad Q_{uG} \quad (\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$$
$$Q_{HG} \quad H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu} \qquad Q_G \quad f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$
$$Q_{H\widetilde{G}} \quad H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu} \qquad Q_{\widetilde{G}} \quad f^{ABC} \widetilde{G}^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$

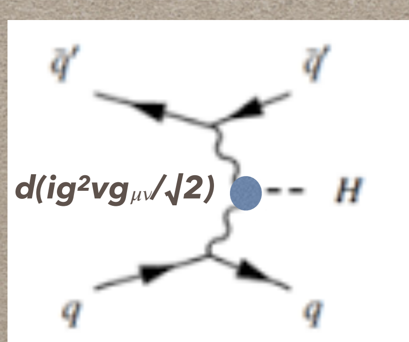


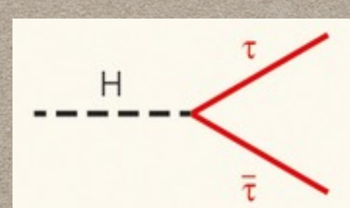
QFT INTERFEROMETRY

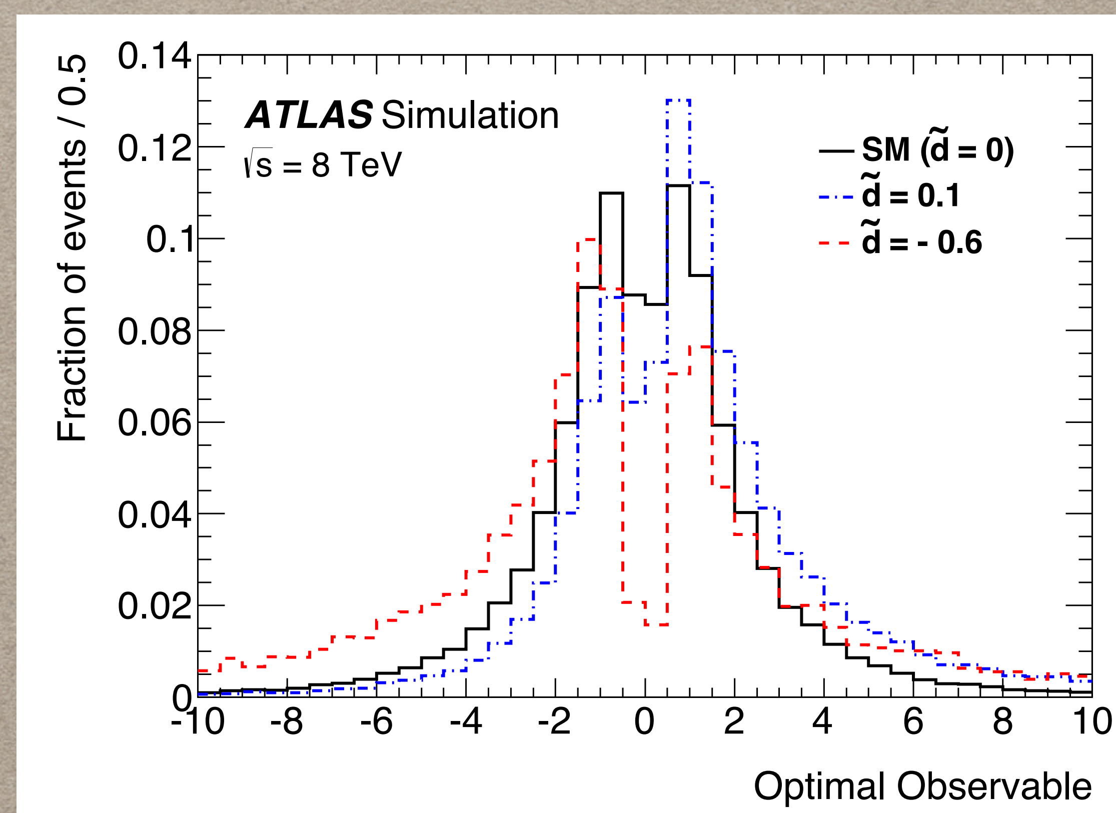
Interference provides unique sensitivity to small effects
(e.g. non-SM interactions)

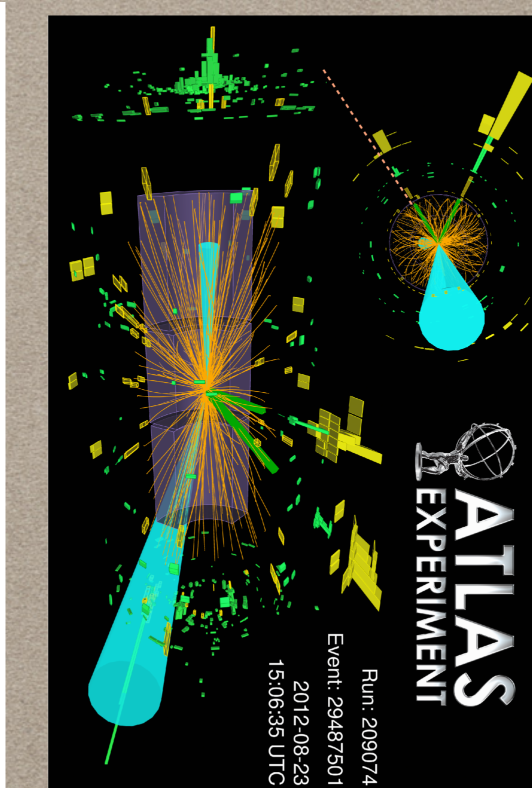
QFT example: VBF Higgs production
(or how to discover a matter-antimatter asymmetry)











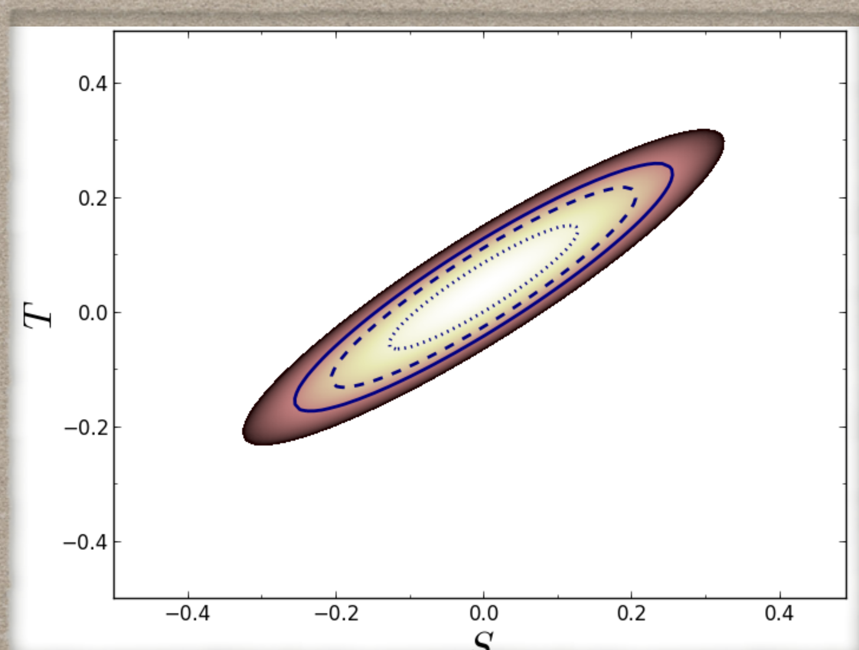
ELECTROWEAK OBSERVABLES

Historically capture new physics affecting W & Z propagators using S, T, U parameters

"Oblique" corrections: S, T (U) related to dimension-6 (8) operators

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

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



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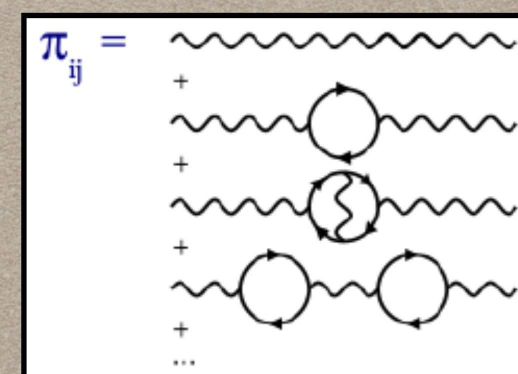


At leading order in dimension 6:

$$\frac{v^2}{\Lambda^2}C_{HWB} = \frac{g_1 g_2}{16\pi}\Delta S, \qquad \frac{v^2}{\Lambda^2}C_{HD} = -\frac{g_1 g_2}{2\pi\left(g_1 + g_2\right)}\Delta T$$

Q_{HWB} | $H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$ $\qquad$ Q_{HD} | $\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

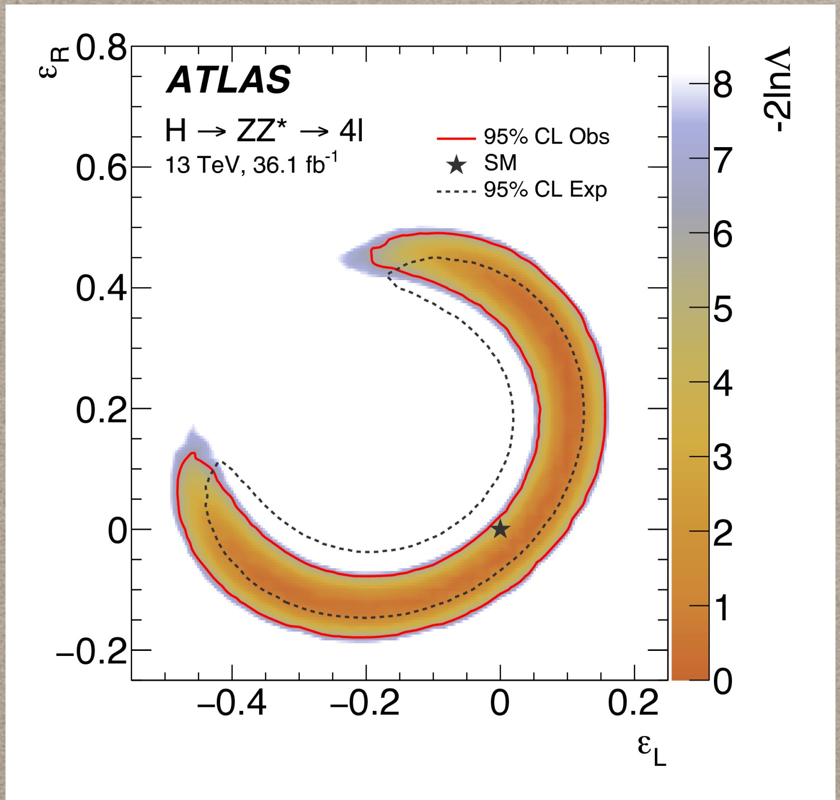
STXS + DECAY

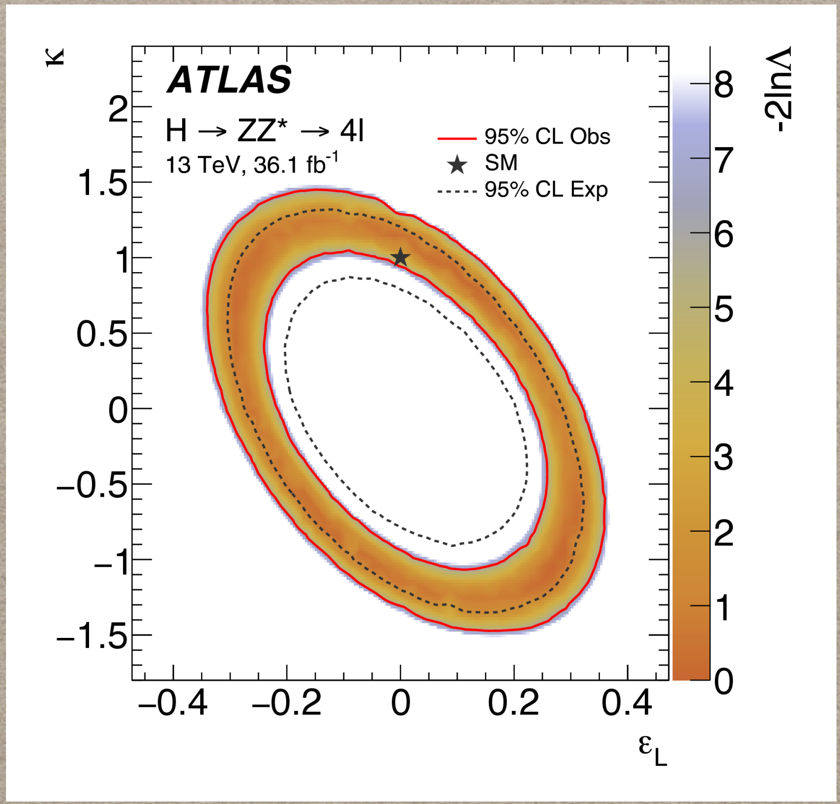
Aim to add decay distributions to STXS

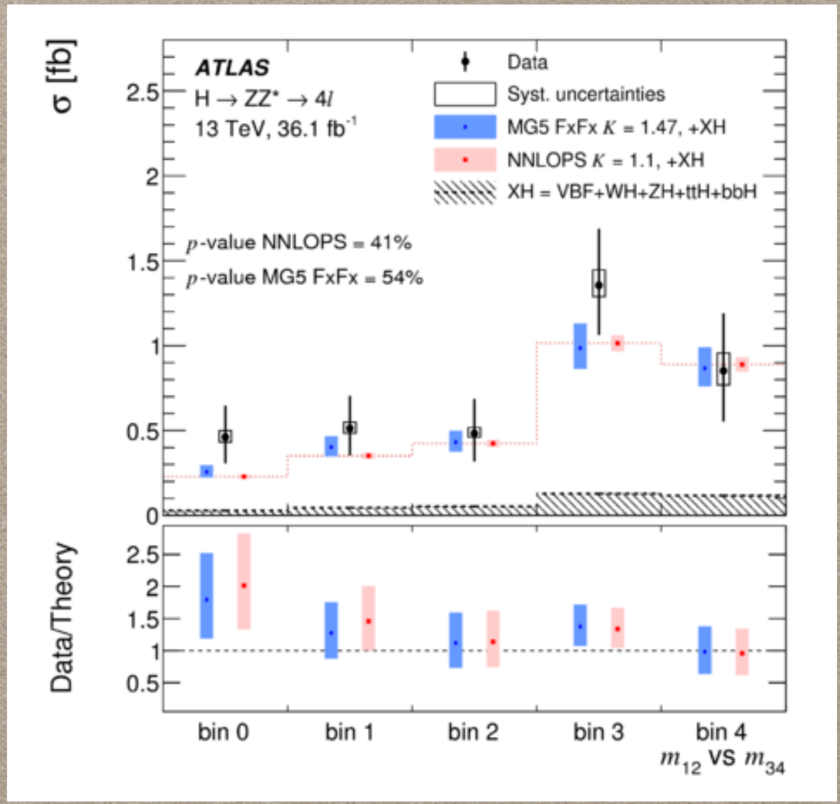
Studies needed for H→4l binning and distribution(s)

Options include pseudo-observables, m_{12} vs m_{34}, and decay angle

Can be defined globally for all bins using the rest frame of the Higgs boson







FURTHER CONSTRAINTS

Some operators affecting electroweak processes still unconstrained in fit

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

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

Higgs self-couplings

CP-odd Higgs interactions

CP-odd triple-gauge couplings

Anomalous magnetic moments

1610.07922,
Sec. III.2.1