Interpretation of Electroweak Precision Measurements

Thirteenth NExT PhD Workshop - Queen Mary University of London

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CERN

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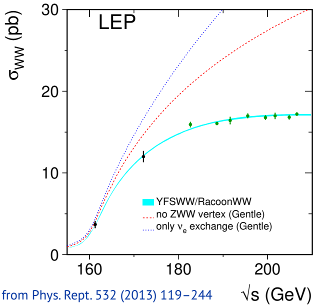
Reminder of Yesterday's Lecture

- The masses of the W and Z bosons are related through:

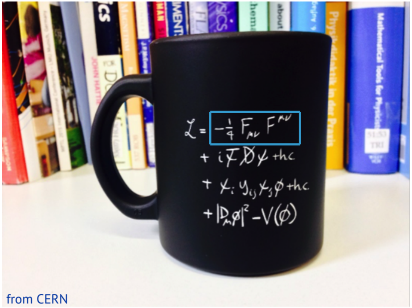
$$\rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W}$$

- Radiative corrections lead to small modifications to this ratio
- ...but they are much larger than the experimental precision



from Phys. Rept. 532 (2013) 119–244

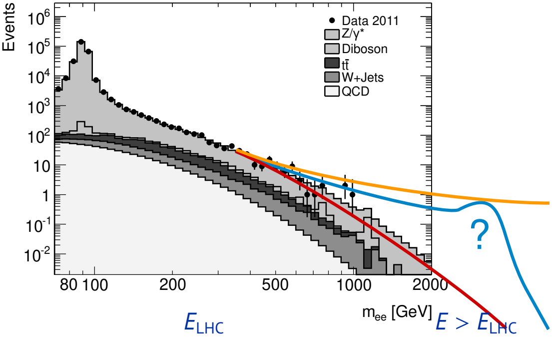
- At energies that allow to produce pairs of W and Z bosons, the same physics leads to large effects
- Gauge cancellations drive the high-energy behaviour



from CERN

Gauge-boson Self-interactions

The Standard Model Effective Field Theory (sketch)



- Contributions from beyond-SM physics seems to be outside of *direct* reach at the LHC
- The Standard Model may still be a low-energy reduction of a beyond-SM theory

$\Rightarrow$ The low-energy limit can be described by an Effective Field Theory, valid below cutoff Λ

The Standard Model Effective Field Theory (math)

- The Standard Model Effective Field Theory (SMEFT) describes possible patterns of deviations introduced by beyond-SM physics
- Expansion of SM Lagrangian in increasing powers of inverse scale of new physics, $1/\Lambda$

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{\mathrm{dim6}}}{\Lambda^2} \mathcal{O}_i^{\mathrm{dim6}} + \sum_i \frac{c_i^{\mathrm{dim8}}}{\Lambda^4} \mathcal{O}_i^{\mathrm{dim8}} + \dots$$

  - $\mathcal{O}_i^{\mathrm{dimN}}$: dimension-N operators, built from SM fields
  - c_i^{dimN}: Wilson coefficient, describing the coupling strength

excluding L- and B-violating operators at dim5 and dim7, respectively

The Warsaw Basis

- Restriction to dim-6 operators
- Constraining the large number of operators requires a lot of measurements

- Typically make some additional assumptions:
  - consider CP-even operators
  - assume flavour symmetry (except 3rd gen quarks)

$\rightarrow$ Resulting in $\mathcal{O}(100)$ operators

Jets

Diboson

$1: X^3$	
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}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$

$5: \psi^2 H^3 + \text{h.c.}$	
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}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
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}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

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

W/Z couplings, Diboson

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
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}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

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

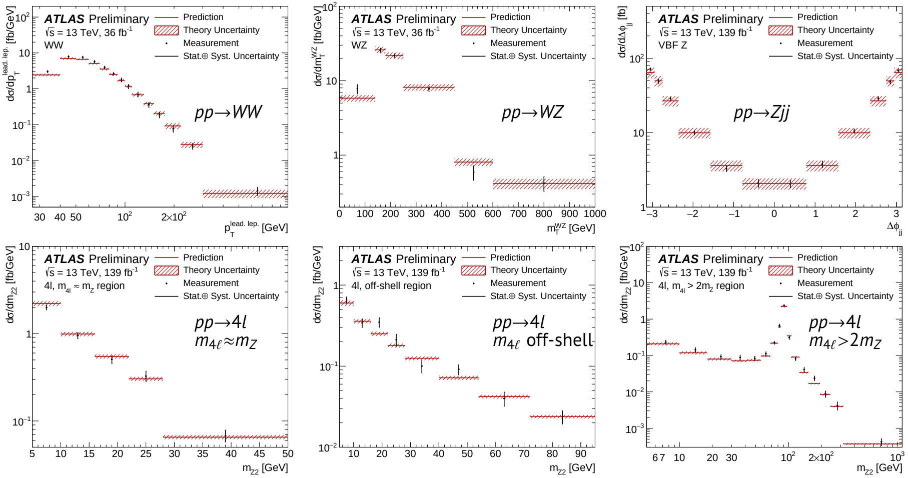
Drell-Yan, Jets

$$H^\dagger i\overleftrightarrow{D}_\mu H \equiv H^\dagger i D_\mu H - (i D_\mu H^\dagger) H$$

$$H^\dagger i\overleftrightarrow{D}^I_\mu H \equiv H^\dagger i \tau^I D_\mu H - (i D_\mu \tau^I H^\dagger) H$$

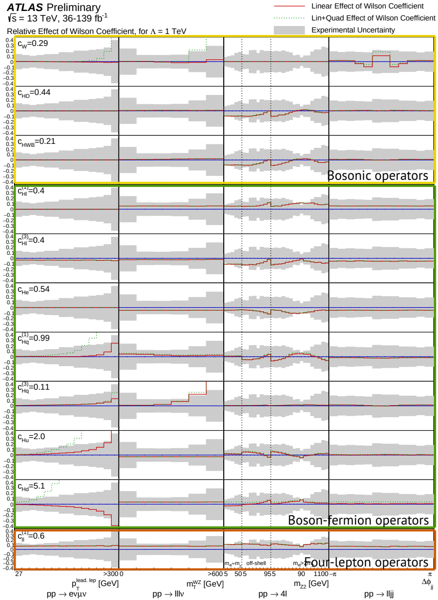
from JHEP 12 (2017) 070

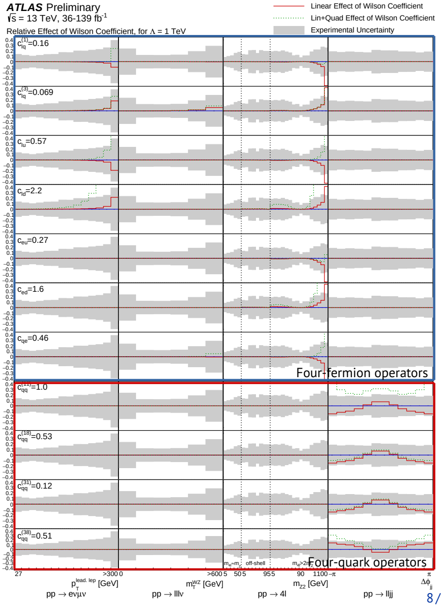
Electroweak Measurements from ATLAS



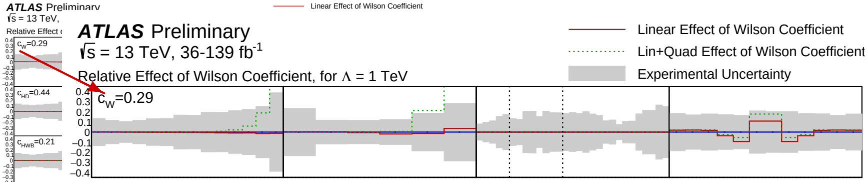
- Differential fiducial cross sections, background subtracted
- Assuming smooth EFT effects have the folding matrix of the SM

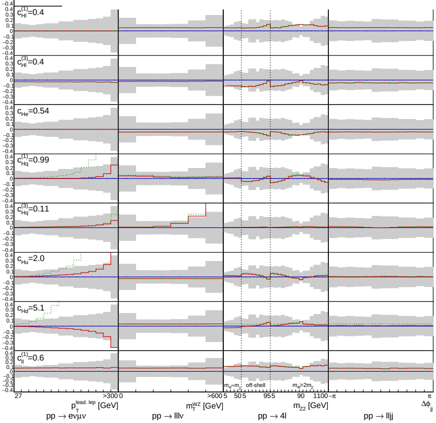
Experimental Sensitivity



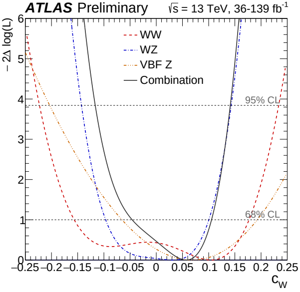


Experimental Sensitivity





- Combination of several final states allows to improve limits



Electroweak Precision Measurements

Observable	Measurement	Prediction	Ratio
Γ_Z [MeV]	2495.2 ± 2.3	2495.7 ± 1	0.9998 ± 0.0010
R^0_ℓ	20.767 ± 0.025	20.758 ± 0.008	1.0004 ± 0.0013
R^0_c	0.1721 ± 0.0030	0.17223 ± 0.00003	0.999 ± 0.017
R^0_b	0.21629 ± 0.00066	0.21586 ± 0.00003	1.0020 ± 0.0031
$A^{0,\ell}_{\mathrm{FB}}$	0.0171 ± 0.0010	0.01718 ± 0.00037	0.995 ± 0.062
$A^{0,c}_{\mathrm{FB}}$	0.0707 ± 0.0035	0.0758 ± 0.0012	0.932 ± 0.048
$A^{0,b}_{\mathrm{FB}}$	0.0992 ± 0.0016	0.1062 ± 0.0016	0.935 ± 0.021
σ^0_{had} [pb]	41488 ± 6	41489 ± 5	0.99998 ± 0.00019

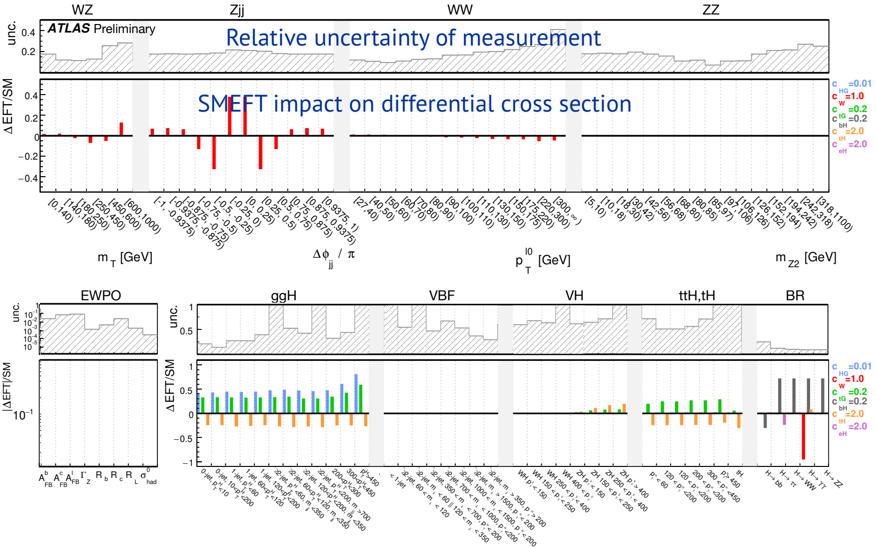
from ATL-PHYS-PUB-2022-037

- Also the precision measurements on the Z pole from LEP and SLC allow to constrain EFT operators
- SMEFT modifies the predictions, e.g.:

$$\frac{\sigma^0_{\mathrm{had}}}{\sigma_{\mathrm{had,\,SM}}} = 1 + 0.002c_{Hb} + 0.002c_{HD} + 0.004c_{Hd} + 0.154c^{(1)}_{Hl} + 0.057c^{(3)}_{Hl} - 0.085c_{He}$$
$$-0.004c^{(1)}_{Hq} - 0.012c^{(1)}_{HQ} - 0.043c^{(3)}_{Hq} - 0.012c^{(3)}_{HQ} - 0.008c_{Hu} + 0.003c_{HWB}$$

- Cannot constrain all sensitive operators ⇒ LHC adds new particles and energy dependence of some effects

Including Higgs Coupling Measurements



from ATL-PHYS-PUB-2022-037

EFT Decomposition

- Leading SMEFT effect expected from interference of dim-6 operators with SM:

$$
\begin{aligned}
\sigma &\sim |\mathcal{M}_{\text{SMEFT}}|^2 \\
&= |\mathcal{M}_{\text{SM}} + \mathcal{M}_{\text{dim6}} + \mathcal{M}_{\text{dim8}} + \dots|^2 \\
&= |\mathcal{M}_{\text{SM}}|^2 + \underbrace{\underbrace{\sum_i \frac{c_i^{\text{dim6}}}{\Lambda^2} 2\text{Re}\left(\mathcal{M}_i^{\text{dim6}} \mathcal{M}_{\text{SM}}^*\right)}_{\text{linear model}} + \underbrace{\sum_i \frac{\left(c_i^{\text{dim6}}\right)^2}{\Lambda^4} |\mathcal{M}_i^{\text{dim6}}|^2}_{\text{quadratic terms}} + \underbrace{\sum_{i<j} \frac{c_i^{\text{dim6}} c_j^{\text{dim6}}}{\Lambda^4} 2\text{Re}\left(\mathcal{M}_i^{\text{dim6}} \mathcal{M}_j^{\text{dim6}*}\right)}_{\text{cross terms}}}_{\text{linear plus quadratic model}} + \dots
\end{aligned}
$$

quadratic term in c_{dim6}

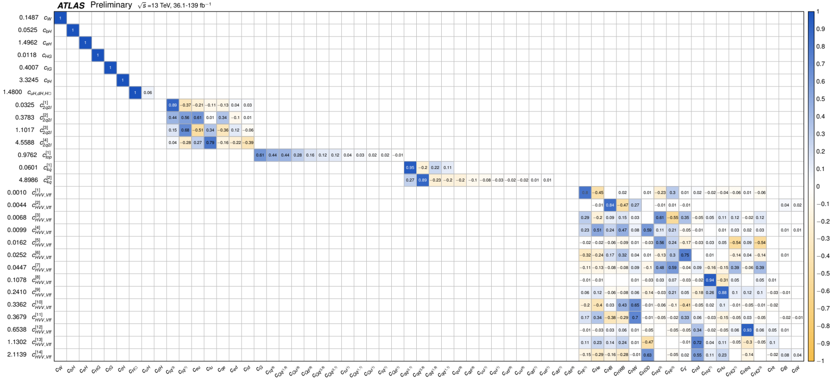
- suppressed by Λ^{-4}, expecte to be smaller than the linear term
- at the same order in Λ as the dim-8 coefficients
- at the LHC, energy growth often stronger than Λ^{-2} terms

⇒ Linear-only limits desireable for validity of EFT expansion

⇒ Comparison to linear+quadratic limits can give a feeling for missing dim-8 contributions (it is not an uncertainty estimate)

Transformation of Basis

- Simultaneous constraints on multiple Wilson coefficients facilitated through complementarity of measurements



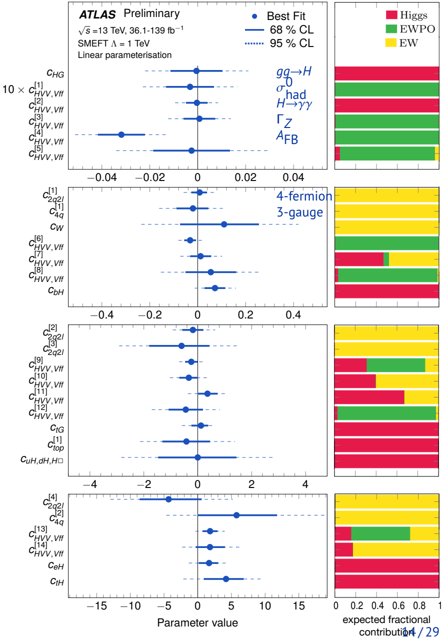
→ Sensitive directions in space of Wilson coefficients identified from eigenvalue decomposition of the covariance matrix (Eigenvalues as sensitivity estimate, $\sigma = \frac{1}{\sqrt{\lambda}}$)

- Limits are set on linear combination of Wilson combinations in Warsaw basis

SMEFT Results

- Limits set at 95% confidence level
- Constraints range from ~ 0.001
  (constraining multi-TeV physics)
  to ~ 10 (beyond SMEFT validity)

- Electroweak measurements constrain four-fermion and triple-gauge operators



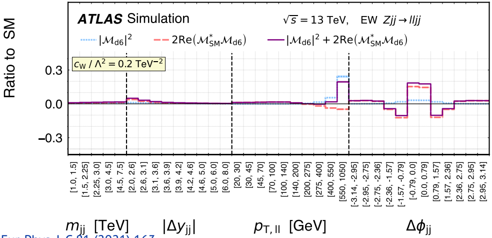
Reconstruction of Low Energy Variables

- Effort in designing measurements with maximal sensitivity to the SM-EFT interference

Example:

- electroweak Zjj production
- azimuthal jet separation:

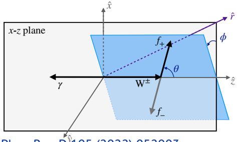
$$\Delta\phi_{jj} = \phi_f - \phi_b, \qquad \text{with: } y_f > y_b$$



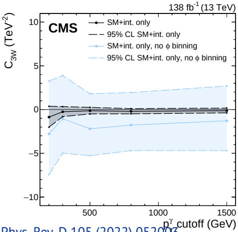
Eur. Phys. J. C 81 (2021) 163

Example:

- $pp \to W\gamma$ production
- reconstruction of the $W\gamma$ centre-of-mass system
- ϕ defined in the decay plane of W and Lorentz boost



Phys. Rev. D 105 (2022) 052003



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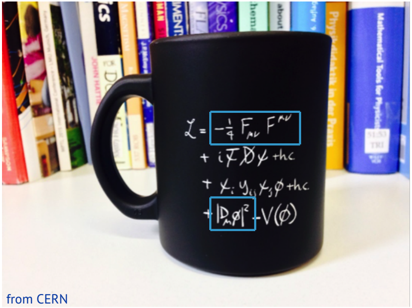


from CERN

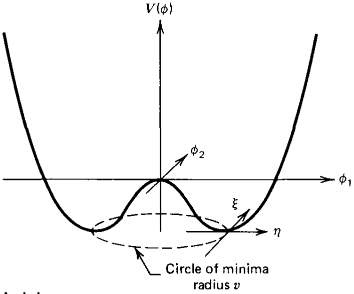
Quartic Couplings and EWSB

Electroweak Symmetry Breaking

- So far, gauge-boson masses were introduced to the theory in an ad-hoc way
- They can be accomodated through breaking of the $SU(2)_L \times U(1)_Y$ symmetry

$\rightarrow$ Introduce a doublet of complex scalar fields ϕ

$$\mathcal{L}_{\text{Higgs}} = (\partial_\mu \phi)^* (\partial^\mu \phi) \underbrace{-\mu^2 \phi^* \phi + \lambda (\phi^* \phi)}_{=-V(\phi)}$$



- Subsituting the covariant derivative of $SU(2)_L \times U(1)_Y$ yields:

$$\mathcal{L} = \left| \left(\partial_\mu - ig \frac{\tau_a}{2} W_\mu^a + \frac{g'}{2} B_\mu \right) \phi \right|^2 - V(\phi)$$

- In the minimum $\phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$, $v = \sqrt{-\mu^2/2\lambda}$ the W, Z and photon obtain a mass:

$$\boxed{\left| \left(\partial_\mu - ig \frac{\tau_a}{2} W_\mu^a + \frac{g'}{2} B_\mu \right) \phi \right|^2 = \left(\frac{1}{2} v g \right)^2 W_\mu^+ W^{-\mu} + \frac{1}{8} v^2 \left(g^2 + g'^2 \right) Z_\mu Z^\mu + 0 \left(g^2 + g'^2 \right) A_\mu A^\mu}$$

Predictions and Couplings to Higgs Boson

- Electroweak Symmetry Breaking generates mass terms:

$$m_W = \frac{1}{2} v g \quad \text{and} \quad m_Z = \frac{1}{2} v \sqrt{g^2 + g'^2} \quad \text{and} \quad m_\gamma = 0$$

and using $\sin\theta_W = \frac{g'}{\sqrt{g^2+g'^2}}$

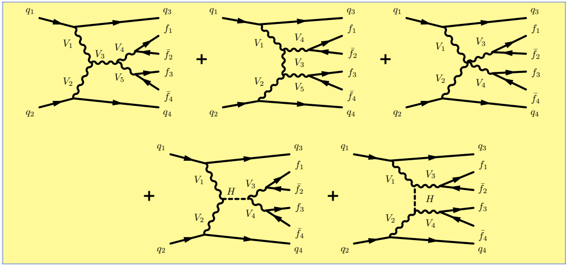
- Parameterising ϕ around it's minimum introduces further terms:

$$\begin{aligned} \mathcal{L} \quad = \quad & \frac{1}{2}\left(\partial_\mu h\right)^2 + \left[m_W^2 W_\mu^+ W^{-\mu} + m_Z^2\right]\left(1 + \frac{h}{v}\right)^2 \\ & -\lambda v^2 h^2 - \lambda v h^3 - \frac{1}{4}\lambda h^4, \text{ using } \phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \end{aligned}$$

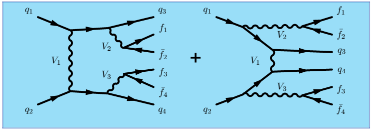
containing a mass term for the field $h(x)$ with $m_h = \sqrt{2\lambda v^2}$, couplings of the field $h(x)$ with the heavy gauge bosons, and self-couplings of $h(x)$

Vector-boson Scattering

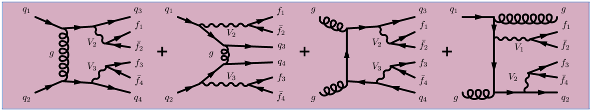
- Quartic EW coupling experimentally accessible in *electroweak* production of *VVjj*



Purely electroweak interactions involving only cubic and quartic self interactions



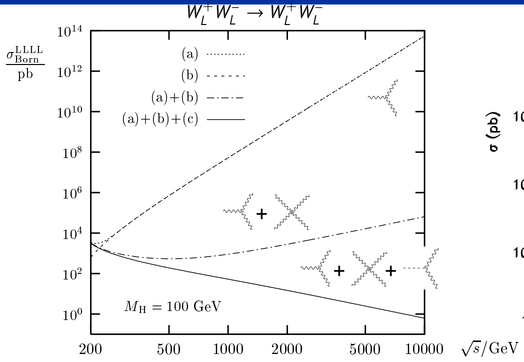
Purely electroweak interactions without self interactions



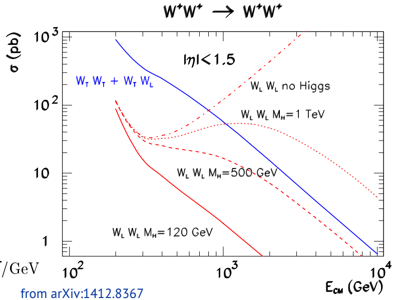
Processes involving both strong and electroweak interactions

(yellow)+(blue)	not gauge-invariantly separable → measure EW *VVjj* production
((yellow)/(blue))+(purple)	interference, assigned as uncertainty in signal modelling

Gauge Cancellations



from Nucl. Phys. B525 (1998) 27-50

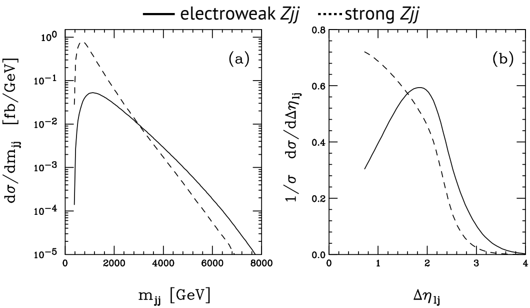


from arXiv:1412.8367

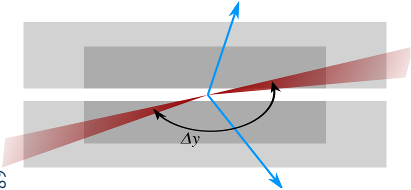
- As for vector-boson pair production, large divergencies between individual diagrams
- At $\mathcal{O}(\alpha^6)$ the Higgs boson is needed in order to cancel all divergencies (counting V production and decay)

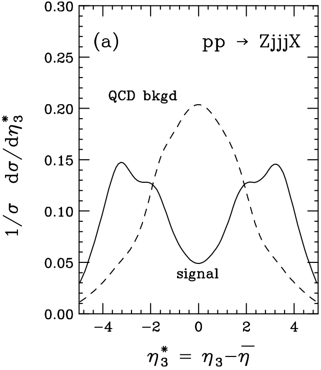
Experimental Signature

- No colour connection between scattering quarks leads to characteristic signature



PRD 54 (1996) 6680-6689



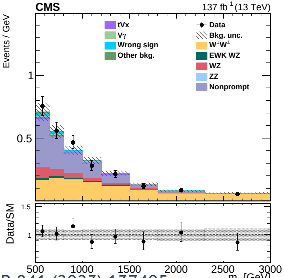


Phys. Rev. D 54 (1996) 6680-6689

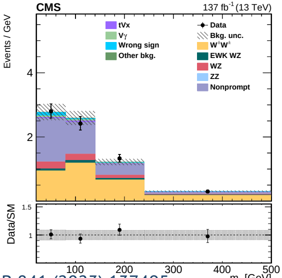
- Additional activity in the event measured relative to centre of "tagging jets", e.g.:

$$\zeta_X = \left| \frac{y_X - \left(y_{j1} + y_{j2}\right)/2}{y_{j1} - y_{j2}} \right|, \qquad C_X = \exp\left[-4 \left(\frac{\eta_X - \left(\eta_{j1} + \eta_{j2}\right)/2}{\eta_{j1} - \eta_{j2}} \right)^2 \right]$$

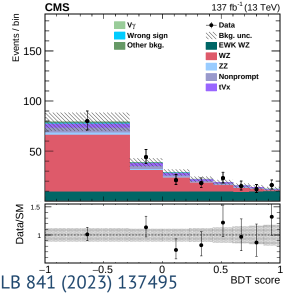
Electroweak $W^{\pm}W^{\pm}jj$ and $WZjj$ Production



PLB 841 (2023) 137495



PLB 841 (2023) 137495



PLB 841 (2023) 137495

- Processes involving quartic electroweak couplings have become experimentally accessible for the first time in the LHC run-2
- $W^{\pm}W^{\pm}jj$ is the “golden channel”!
  - mixed strong-electroweak production of $W^{\pm}W^{\pm}$ suppressed
  - diagrams not containing any self-interactions supressed
  - theoretically understood well, at NLO EW⊗QCD

Interpretation of Quartic Electroweak Couplings

- There are no dim-6 operators that only affect quartic electroweak couplings
- In VBS and triboson processes, dim-8 operators that genererate quartic but *not* trilinear couplings are studied (assuming the dim-6 are 0, and other dim-8 operators are constrained elsewhere)

four $\partial_\mu \Phi$

two $\partial_\mu \Phi$, two $F_{\mu\nu}$

four $F_{\mu\nu}$

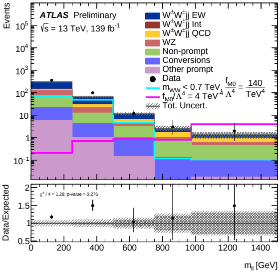
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$, $\mathcal{L}_{M,6}$, $\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}$, $\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$, $\mathcal{L}_{M,5}$	O	X	X	X	X	X	X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

from PRD 93, 093013 (2016)

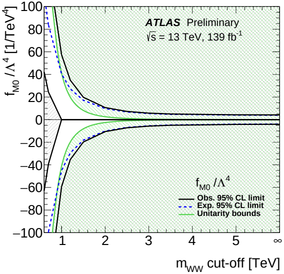
- Literature suggests that VBS is also useful to constrain dim-6 EFT operators, see e.g. Eur.Phys.J.C 81 (2021) 6, 560

$\Rightarrow$ Route to systematically study *genuine* quartic electroweak couplings in the future

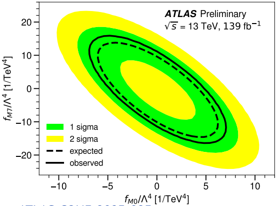
Results from the LHC



from ATLAS-CONF-2023-023



from ATLAS-CONF-2023-023

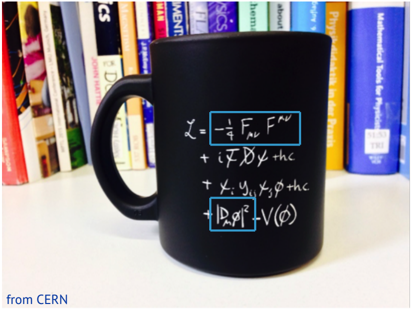


from ATLAS-CONF-2023-023

- For quartic electroweak couplings, the full EFT (linear and quadratic terms) are studied
- Unitarity violating well below the LHC energy reach already

$\Rightarrow$ Unitarisation by setting limits as a function of a “clipping energy”

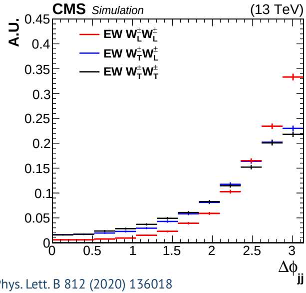
- Theory bounds from partial wave unitarity (Phys. Rev. D 93, 093013 (2016))



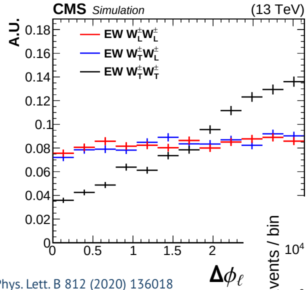
from CERN

Key Measurements for the Future

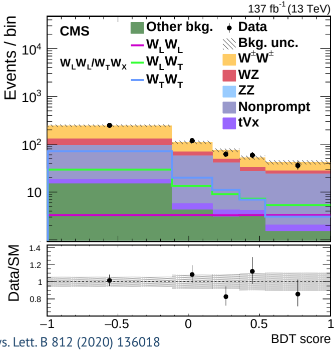
Measurement of Double-Longitudinal $W^{\pm}W^{\pm}jj$ Production



Phys. Lett. B 812 (2020) 136018



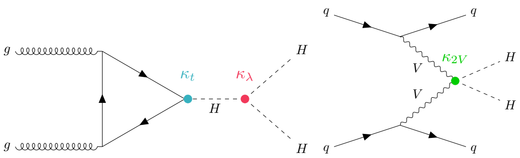
Phys. Lett. B 812 (2020) 136018



Phys. Lett. B 812 (2020) 136018

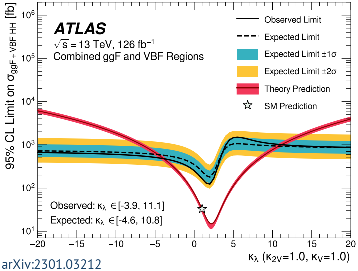
- A key measurement at the LHC is the observation of double-longitudinal electroweak $W^{\pm}W^{\pm}$ production
- Sensitive to renormalisation of the electroweak theory by the Higgs
- Observation on full HL-LHC dataset challenging but not impossible

Measurement of Di-Higgs Production



$$\boxed{\mathcal{L} = \frac{1}{2}m_h^2 h^2 - \lambda v h^3 - \frac{1}{4}\lambda h^4}$$

- Measurement of the Higgs self-coupling probes the shape of the Higgs potential
- Observation of *HH* production feasible on full HL-LHC dataset
- Processes involving *HHHH* couplings out of reach, unless there are large deviations from the SM



arXiv:2301.03212

Summary

- The electroweak theory is in a very good shape!

- Precision measurement from LEP at the Z pole still provide most stringent tests of the electroweak theory
- Input from LHC for several key observables important, in particular m_t, m_W and $\sin^2\theta^{\ell}_{\text{eff}}$

- Measurements at high energy probe similar physics, with possibly increased sensitivity
- The way forward is the interpretation in global fits of SMEFT parameters
- The measurements included in such fits are ever expanding

Literature

- *Quarks and Leptons: An Introductory Course in Modern Particle Physics*; Francis Halzen, Alan Douglas Martin;Wiley, 1984
- *The Standard Model as an Effective Field Theory*; I. Brivio and M. Trott; Phys. Rept. **793** (2019), 1-98 [arXiv:1706.08945 [hep-ph]].
- *Classifying the bosonic quartic couplings*; O. J. P. Éboli and M. C. Gonzalez-Garcia; Phys. Rev. D **93** (2016) no.9, 093013 [arXiv:1604.03555 [hep-ph]].

Backup