CP measurements in $H \to \tau\tau$

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Introduction

1. CP properties of the Higgs boson
2. Test of CP invariance in VBF Higgs boson production (ATLAS analysis) (ATLAS Collaboration arXiv:1602.04516 (hep-ex))
3. Study on EFT validity in VBF Higgs production (Jonas Rehberg, BSc Thesis)
4. Investigation of the CP structure of the Higgs Gluon Coupling in $gg \to H + 2\text{jets}$ (Alena Loesle, MSc Thesis)

CP properties of the Higgs boson in the HVV coupling

- CP violation = 1 of 3 Sakharov conditions to explain baryon asymmetry in the universe
- Effective Lagrangian with CP-violating couplings between H and electroweak gauge bosons:

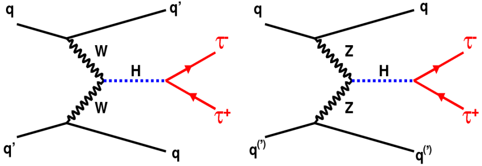
$$\mathcal{L}_{eff} = \mathcal{L}_{\rm SM} + \tilde{\rm d}\frac{e}{2m_W \sin\theta_w} H\widetilde{W}^{+}_{\mu\nu}W^{-\mu\nu} + \tilde{\rm d}\frac{e}{2m_W \sin\theta_w} H\tilde{Z}_{\mu\nu}Z^{\mu\nu} + \tilde{\rm d}\frac{e}{2m_W \sin\theta_w} H\tilde{A}_{\mu\nu}A^{\mu\nu}$$

with dim-6 operators assuming $\tilde{\rm d} = \tilde{\rm d}_B$ (L3 Collaboration Phys.Lett. B589 (2004) 89-102; V. Hankele et al. Phys. Rev. D74 (2006))

- Matrix element:

$$\mathcal{M} = \mathcal{M}_{\rm SM} + \tilde{\rm d}\mathcal{M}_{\rm CP-odd}$$

- Coupling to weak vector bosons measured in VBF



Measurement of CP invariance in VBF H production

- Total cross section influenced by $\tilde{d}$:
  $|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + \tilde{d} \cdot 2\Re(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}}) + \tilde{d}^2 \cdot |\mathcal{M}_{\text{CP-odd}}|^2$
  $\rightarrow$ integrated over full phase space (CP-even):
  interference term vanishes
- Expectation value (mean) of differential cross-sections:

$$\langle \frac{d\sigma}{d\mathcal{O}} \rangle = \frac{\int \mathcal{O}\, d\sigma_{SM} + \int \mathcal{O}\, \tilde{d} \cdot d\sigma_{\text{Interference}} + \int \mathcal{O}\, \tilde{d}^2 \cdot d\sigma_{\text{CP-even}}}{\int d\sigma_{SM} + \int \tilde{d} \cdot d\sigma_{\text{Interference}} + \int \tilde{d}^2 \cdot d\sigma_{\text{CP-even}}}$$

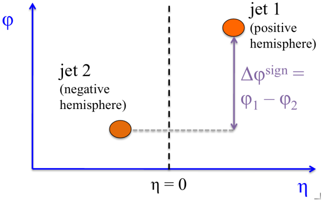
- CP-odd observable can have non-zero mean in presence of CP violation:

$\Rightarrow$ consider CP-odd observable to probe CP-odd contribution

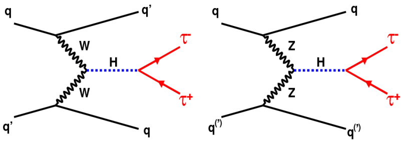
CP-odd observables

CP-odd observables have non-zero mean in presence of CP violation (model independent $\rightarrow$ EFT used for quantification)

Signed azimuthal difference of jets $\mathrm{Sgnd}\Delta\phi(jj)$



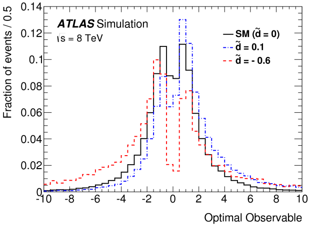
- $\mathrm{Sgnd}\Delta\phi(jj) = \phi(j_{\eta>0}) - \phi(j_{\eta<0})$
- non-signed $\Delta\phi(jj)$ is CP-even



CP-odd observables

Optimal Observable $\mathcal{OO}$

$$\mathcal{OO} = \frac{2\Re(\mathcal{M}^*_{SM}\mathcal{M}_{\mathrm{CP-odd}})}{|\mathcal{M}_{SM}|^2}$$

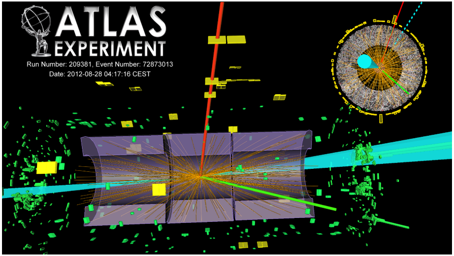


- defined with the reconstructed four-momenta of particles in the events (tagging jets, reconstructed Higgs momentum)
- Why optimal?
  $\rightarrow$ combines the information on the entire phase space in one scalar variable (for small $\tilde{\mathrm{d}}$)
  (D. Atwood, A. Soni; Phys. Rev. D45 (1992)), (M. Davier et al.; Phys. Lett. B306 (1993)), (M. Diehl, O. Nachtmann; Z. Phys. C62 (1994))

$H \to \tau\tau$ at 8 TeV with ATLAS

Based on 8 TeV Evidence paper JHEP 04 (2015) 117

Final states $\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$ & $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$

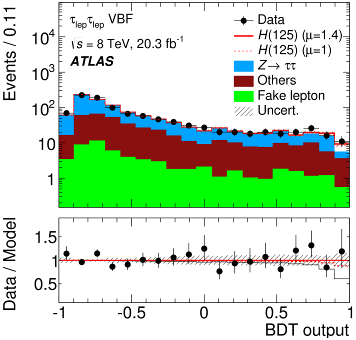


- $\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$ selection:
  - 2 opposite-sign leptons
  - $E_{\mathrm{T}}^{\mathrm{miss}}$
  - b-jet veto
- $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ selection:
  - 1 lepton and 1 τ_{had} with opposite charge
  - $m_{\mathrm{T}} < 70\ \mathrm{GeV}$
  - b-jet veto
- VBF category
  - at least 2 jets
  - $|\Delta\eta(jj)| > 2.2(3.0)$

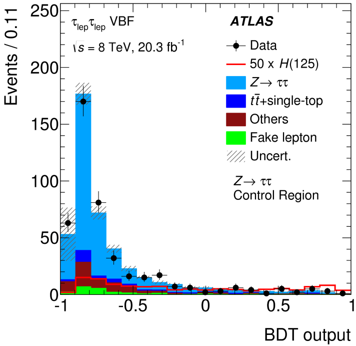
- Dominant background: $Z \to \tau\tau$, modeled with embedding
- BDT used to separate Higgs signal from background
- Using Missing Mass Calculator for Higgs momentum reconstruction
  (A. Pranko, A. Elagin, et al. Nucl.Instrum.Meth. A654 (2011) 481-489)

VBF category

BDT score in VBF signal region



BDT score in $Z \to \tau\tau$ control region

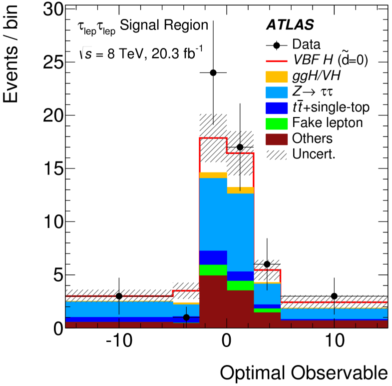


Advantage of $H \to \tau^+\tau^-$ for CP measurement in VBF:

- Good reconstruction of Higgs four-momentum
- Large contribution from VBF

Measurement of $\tilde{d}$ in VBF $H \to \tau\tau$

- Additional selection: BDT score cut
- Matrix element for $\mathcal{OO}$ calculation and event reweighting extracted from `HAWK` (Denner, Dittmaier, Kallweit, Mück, Comput. Phys. Commun. 195 (2015))

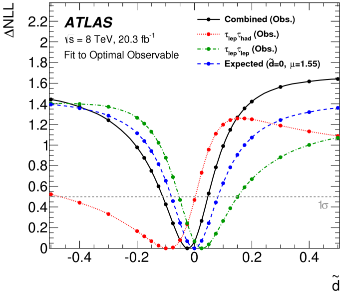


- no signal strength information
- only shape information
- fit to full $\mathcal{OO}$ distribution to extract exclusion limits on $\tilde{d}$
- Mean of $\mathcal{OO}$:
  $\langle \mathcal{OO} \rangle = 0.3 \pm 0.5$ $(\tau_{\rm lep}\tau_{\rm lep})$
  $\langle \mathcal{OO} \rangle = -0.3 \pm 0.4$ $(\tau_{\rm lep}\tau_{\rm had})$

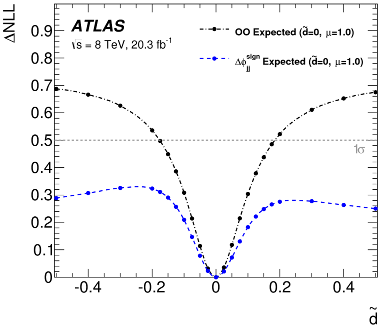
→ no hint for CP violation

(ATLAS Collaboration arXiv:1602.04516 (hep-ex))

Exclusion limits on $\tilde{d}$ from 8 TeV measurement



Expected 68 % confidence interval:
(-0.08,0.08) for $\mu = 1.55$
($\mu = 1.55^{+0.87}_{-0.76}$ from fit for $\tilde{d}$= 0)



Optimal Observable more sensitive than $\mathrm{Sgnd}\Delta\phi(jj)$

Observed confidence interval at 68 % C.L.:
$\tilde{d} \in [-0.11, 0.05]$

Comparison to observed 68% C.L. interval from $H \to WW/ZZ$ measurement:
$\tilde{d} \in [-0.08, 1.38]$

EFT validity in CP measurement

Approach to EFT validity

- A Find characteristic energy scale describing the process
  - e.g. transverse momenta, masses, momentum transfer
- B Apply upper boundaries on characteristic scale
  - Kinematic selection of events below certain values, for various values of M_{cut}
- C Measure EFT parameters in dependence of upper boundaries

$$c_i^{(6)} < \delta_i^{\mathrm{exp}}(M_{\mathrm{cut}})$$

$\Rightarrow$ allows re-interpretation of limits according to specific models valid up to certain values of M_{cut}

(YR IV section II.2.2),(Contino, Falkowski, Goertz, Grojean, Riva JHEP 1607 (2016) 144)

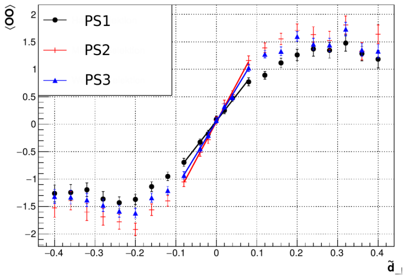
Calibration curves for $\mathcal{OO}$ vs. $\tilde{\mathrm{d}}$

In the presence of CP-violation, $\langle \mathcal{O}_{\mathrm{CP-odd}} \rangle \neq 0$
$\Rightarrow$ Measurement of $\tilde{\mathrm{d}}$ via $\langle \mathcal{O}_{\mathrm{CP-odd}} \rangle$

At low $\tilde{\mathrm{d}}$, linear term dominates:

$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + \tilde{\mathrm{d}} \cdot 2\Re(\mathcal{M}_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP-odd}}) + \tilde{\mathrm{d}}^2 \cdot |\mathcal{M}_{\mathrm{CP-odd}}|^2$$

$\rightarrow$ Linear calibration curve for $\mathcal{OO}$ vs. $\tilde{\mathrm{d}}$



Precision of measurement depends on

- gradient of calibration line g
- uncertainty of mean of the observable $\delta(\langle \mathcal{OO} \rangle)$

Considering 3 phase-space regions:

- PS1: $M(jj) > 500\ \mathrm{GeV}$, $|\Delta\eta(jj)| > 4$
- PS2: $M(jj) > 500\ \mathrm{GeV}$, $|\Delta\eta(jj)| > 2$
- PS3: $M(jj) > 200\ \mathrm{GeV}$, $|\Delta\eta(jj)| > 2$

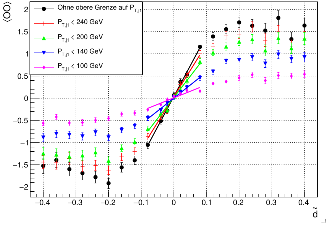
EFT validity

A Characteristic scale; use jet p_T, since near the threshold:

$$q_i^2 \approx -p_{Ti}^2$$

B Applying upper boundaries on $p_\mathrm{T}(j_1)$

Change of calibration curves and uncertainties of mean values



$\mathcal{OO}$
50k MC events

Boundary b (GeV)	gradient $g(b)$	$g(b)/g(\infty)$	$\delta(\langle\mathcal{OO}\rangle)$
$p_\mathrm{T}(j_1) < \infty$	13.8 ± 0.6	1	0.085
$p_\mathrm{T}(j_1) < 200$	9.5 ± 0.5	0.69 ± 0.05	0.070
$p_\mathrm{T}(j_1) < 100$	3.0 ± 0.3	0.21 ± 0.03	0.042

- Uncertainties of mean values $\delta(\langle\mathcal{OO}\rangle)$:
  - Gradiant decreases with stronger bounds ($\rightarrow$ loss of sensitivity)
  - Uncertainty **decreases** ($\rightarrow$ gain of sensitivity)

C. Measure EFT parameters – Run 2 prospects

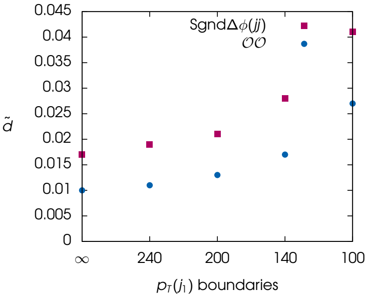
Assuming similar selection efficiency as in Run 1, $\int \mathcal{L}dt = 100\text{fb}^{-1}$, with

$$N_{Run2} = N_{Run1} \times \frac{\sigma_{13\ \mathrm{TeV}}}{\sigma_{8\ \mathrm{TeV}}} \times \frac{\mathcal{L}_{13\ \mathrm{TeV}}}{\mathcal{L}_{8\ \mathrm{TeV}}} = 313\ \mathrm{events}$$

get the following exclusion limits according to $\delta(\widetilde{\mathrm{d}}) = \frac{\delta(\langle \mathcal{OO} \rangle)}{g(b)}$:

Boundary b (GeV)	$\delta(\widetilde{\mathrm{d}})_{\mathcal{OO}}$	$\delta(\widetilde{\mathrm{d}})_{\mathrm{Sgnd}\Delta\phi(jj)}$
$p_{\mathrm{T}}(j_1) < \infty$	0.010	0.017
$p_{\mathrm{T}}(j_1) < 200$	0.013	0.021
$p_{\mathrm{T}}(j_1) < 100$	0.027	0.041

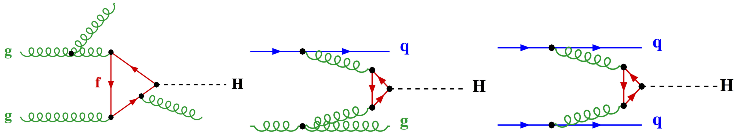
- stronger bounds $\rightarrow$ loss of sensitivity (factor ~ 2.5)
- $\mathcal{OO}$ more sensitive than $\mathrm{Sgnd}\Delta\phi(jj)$
- both similarly stable



Compare to Run 1 limits: (-0.11,0.05)
(CAVEAT: only parton level signal used for prospects)

Study of CP violation in H+2jet production in gluon fusion

H+2jet production in gluon fusion via higher order QCD corrections:



gluon-gluon initial state | gluon-quark initial state | quark-quark initial state

Higgs-gluon interaction in EFT approach for $m_{top} \rightarrow \infty$ (Higgs-Characterization model):

$$\mathcal{L}_{eff} = \underbrace{a_2 G^a_{\mu\nu} G^{a,\mu\nu} H}_{\text{SM contribution}} + \underbrace{a_3 G^a_{\mu\nu} G^a_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma} A}_{\text{CP odd contribution}}$$

$$\boxed{a_2 = g_{Hgg}\kappa_{Hgg}\cos(\alpha),\;\; a_3 = g_{Agg}\kappa_{Agg}\sin(\alpha)}$$

with coupling strengths $g_{Hgg} = \frac{-\alpha_s}{3\pi}$, $g_{Agg} = \frac{\alpha_s}{2\pi}$ and dimensionless constants $\kappa_{Hgg}, \kappa_{Agg}$

$\rightarrow$ mixing between CP even and CP odd coupling driven by $\cos(\alpha)$

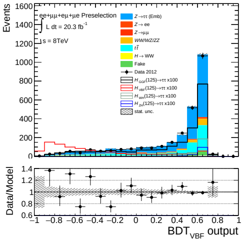
$\rightarrow$ CP violation for $\kappa_{Hgg}, \kappa_{Agg} \neq 0$ and $\cos(\alpha) \neq 0, \pm 1$

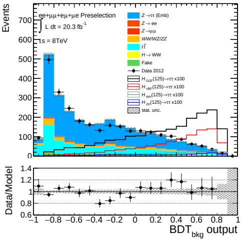
Analysis strategy

Event selection: $H \rightarrow \tau\tau \rightarrow 2l4\nu$

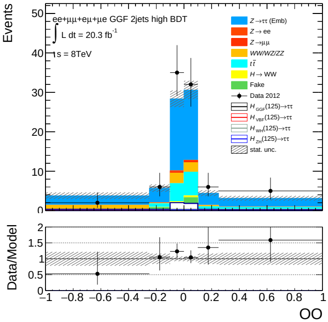
- preselection cuts
- trained two BDTs
  BDT_{bkg}: signal against all bkgs
  BDT_{VBF}: signal against VBF $H \rightarrow \tau\tau$ bkg

signal region constructed by cutting on both:
$BDT_{bkg} > 0.6$ and $BDT_{VBF} > -0.3$





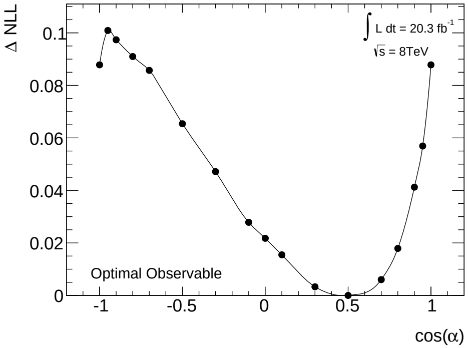
use the Optimal Observable to measure $\cos(\alpha)$:



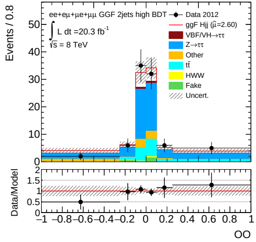
$\Rightarrow$ Optimal Observable has been implemented based on MadGraph5 arXiv:1405.0301 (hep-ph)

Alena Loesle

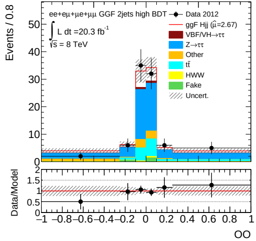
Measurement of $\cos(\alpha)$



post-fit distribution for $\cos(\alpha) = 1$ (SM)



post-fit distribution for $\cos(\alpha) = 0.5$

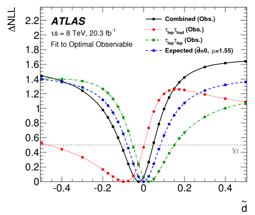


$\rightarrow$ no 1σ exclusion limit on $\cos(\alpha)$ reached yet (only leplep-final state here)

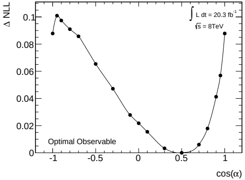
$\rightarrow$ however, promising approach to look for CP violation in Run 2

Conclusions and summary

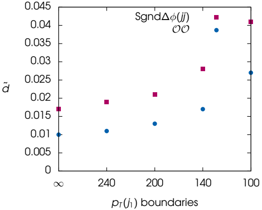
- CP nature of the Higgs boson, measured using the optimal observable method in VBF at 8 TeV



- Studying CP invariance in H+2jet production in gluon fusion



- EFT validity in VBF CP measurements and prospects at 13 TeV



Backup

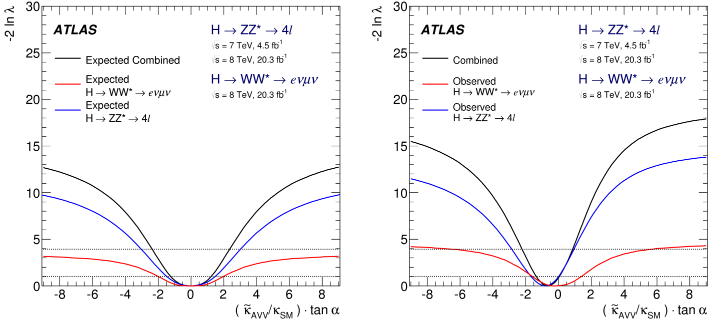
Comparison to $\tilde{\mathrm{d}}$ limits from WW,ZZ

$$\frac{\kappa_{AZZ}}{\kappa_{SM}} = \frac{\kappa_{AWW}}{\kappa_{SM}} = \frac{4\alpha_{EM}\Lambda}{3\pi v}\kappa_{A\gamma\gamma} = -2\frac{e\Lambda}{m_W \sin\theta_w \tan\alpha}\cdot\tilde{\mathrm{d}}.$$

The 8-TeV-WW/ZZ parity analysis uses the definition $\tilde{\kappa}_{AVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{AVV}$.
This reduces the conversion to

$$\tilde{\mathrm{d}} = -2\frac{m_W \sin\theta_w}{ev}\frac{\tilde{\kappa}_{AVV}}{\kappa_{SM}}\tan\alpha = -\frac{\tilde{\kappa}_{AVV}}{\kappa_{SM}}\tan\alpha$$

using $m_W = \frac{1}{2}gv = \frac{ev}{2\sin\theta_W}$.

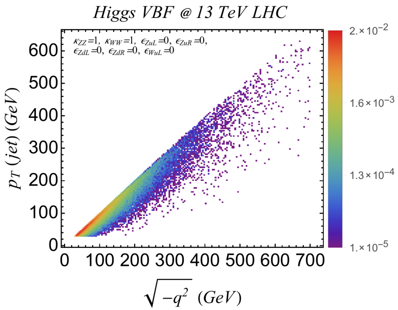


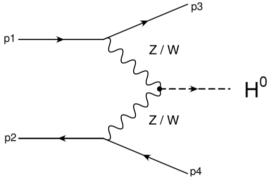
Find the characteristic scale for VBF Higgs production

(cf. YR IV sec. II.1.6 *PO in Higgs electroweak production: phenomenology*)

- relevant scale in VBF: $q_1 = p_1 - p_3$ and $q_2 = p_2 - p_4$
- if $p(j_1)$, $p(j_2)$, and $p(H)$ are reconstructable, q_1, q_2 can be determined using the correlation between incoming and outgoing quarks' directions
  $\Rightarrow$ use solution with minimum angles $\sphericalangle(p_1, p_3)$ and $\sphericalangle(p_2, p_4)$
- if they are not reconstructable: use jet p_{T}, as near the threshold,

$$q_i^2 \approx -p_{Ti}^2$$





(from YR IV sec. II.1.6)

CP violation in HVV in general

For a possible combination with $H \to VV$ channels, need to use the same CP-violating coupling parameters **or** if not the same, compatible ones $\to$ e.g. conversion between $\tilde{\mathrm{d}}$ and Higgs-Characterization parameters:
(arXiv:1306.6464 (hep-ph))

- Lagrangian with $\tilde{\mathrm{d}}$

$$\mathcal{L}_{eff} = \mathcal{L}_{\mathrm{SM}} + \tilde{\mathrm{d}} \frac{e}{2m_W \sin\theta_w} H\widetilde{W}^{+}_{\mu\nu} W^{-\mu\nu} + \tilde{\mathrm{d}} \frac{e}{2m_W \sin\theta_w} H\widetilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{\mathrm{d}} \frac{e}{2m_W \sin\theta_w} H\widetilde{A}_{\mu\nu} A^{\mu\nu}$$

can be converted into the Higgs-Characterization Lagrangian:

$$\begin{aligned} \mathcal{L}_{eff} = & \{\cos\alpha \, \kappa_{SM} \, [\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu}] \\ & - \frac{1}{4}\frac{1}{\Lambda}[\cos\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \sin\alpha \kappa_{AZZ} Z_{\mu\nu} \widetilde{Z}^{\mu\nu}] \\ & - \frac{1}{2}\frac{1}{\Lambda}[\cos\alpha \kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + \sin\alpha \kappa_{AZZ} W^+_{\mu\nu} \widetilde{W}^{-\mu\nu}]\} \end{aligned} \quad (1)$$

- The conversion is

$$\tilde{\mathrm{d}} = -\frac{\sin\theta_w m_W}{2\Lambda e} \frac{\kappa_{AVV}}{\kappa_{SM}} \tan\alpha$$

- with $\kappa_{AWW} = \kappa_{AZZ} (=: \kappa_{AVV})$) which corresponds to the condition $\tilde{\mathrm{d}} = \tilde{\mathrm{d}}_B$, which is also used in HZZ/HWW paper (Run 1)

Effective field theories

Adding higher-dimensional operators to the SM-Lagrangian:

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d} \sum_{i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$

$c_i^{(d)}$: Wilson coefficients
Λ: scale of new physics

$\rightarrow$ low-energy tail of new physics

- CAVEAT: Limited validity due to
  - truncation of dimensional series
  - unitarity violation
  - missing higher order corrections
- all leading to growing difference to a complete BSM theory