EFT validity in VBF Higgs production
CP measurements

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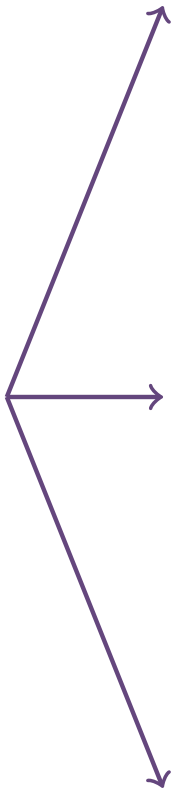
Introduction

- EFT commonly used in a variety of measurements, e.g.
  - anomalous gauge, top, ... couplings
  - Higgs: couplings and "properties"
  - searches
- However: EFT validity at accessible range at the LHC is not necessarily always guaranteed

Topics of this talk:

1. Limits to the validity of EFTs
2. Higgs CP studies in VBF
3. EFT validity in VBF Higgs CP measurement

1. Limits to the validity of EFTs



Unitarity violation

- Scattering matrix violates unitarity within EFT
- Especially important in vector boson scattering

Truncation of series

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

Series is truncated, usually at dimension 6

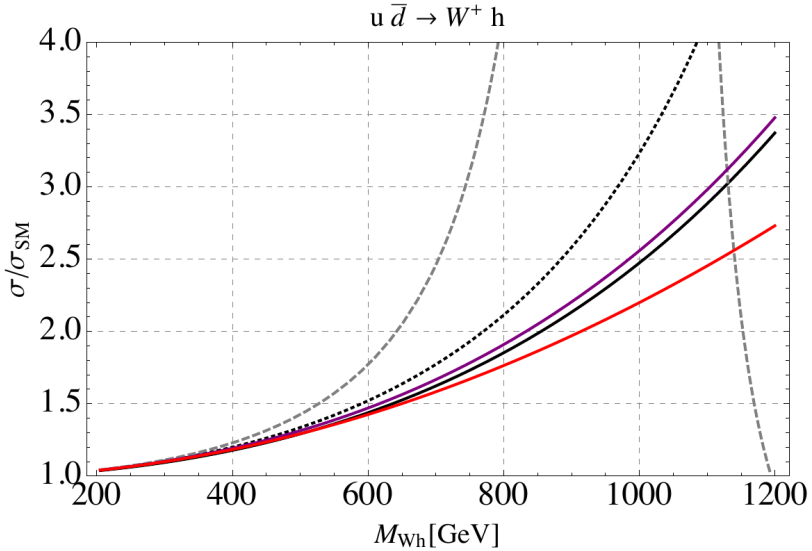
Growing difference to complete BSM theory

Comparing to complete BSM theory, the difference between BSM theory and EFT depends on the model and grows with energy

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

Accuracy of the description of a BSM theory

- Advantage of EFT: model independence
- However, validity range is not model independent → deviation from full theory varies:



(black: $SU(2)_L$ triplet model with different masses and couplings;
red: EFT,
purple: EFT incl. quadratic terms in $\mathcal{O}^{(6)}$)

- cf. YR IV section II.2.2 *(Comments on the validity of the Effective Field Theory approach to physics beyond the Standard Model)*

Assessing validity

One approach for experiments using EFT:

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

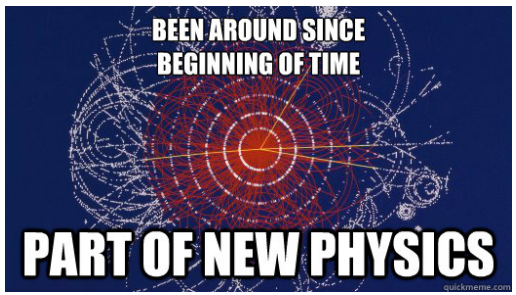
$$c_i^{(6)} < \delta_i^{\text{exp}}(M_{\text{cut}})$$

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

2. Testing CP invariance in the Higgs sector

Motivation

Search for new sources of CP violation in the Higgs sector, scrutinize the CP nature of the Higgs boson



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→ EFT validity in CP studies

Effective Field Theory with CP violation

- Effective Lagrangian with CP-violating operators for HWW and HZZ couplings:

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

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

- can be converted to Higgs-Characterization Lagrangian [Artoisenet et. al. JHEP 1311 (2013) 043] used by MadGraph_aMC@NLO [Alwall et. al. JHEP 1407 (2014) 079] via UFO
- Matrix element:

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

- Coupling to weak vector bosons measured in VBF production

Expectation value of CP-odd observables

- Total cross section influenced by $\tilde{d}$:
  $|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \tilde{d} \cdot 2\Re(\mathcal{M}^*_{\text{SM}} \mathcal{M}_{\text{CP-odd}}) + \tilde{d}^2 \cdot |\mathcal{M}_{\text{CP-odd}}|^2$
- Differential cross section:

$$d\sigma \sim |\mathcal{M}|^2 dV$$

$$d\sigma = d\sigma_{SM} + \tilde{d} \cdot d\sigma_{\text{Interference}} + \tilde{d}^2 \cdot d\sigma_{\text{CP-even}}$$

- Considering observables $\mathcal{O}$ (CP-even **or** CP-odd) with differential cross-sections $\frac{d\sigma}{d\mathcal{O}} \sim \int \frac{d}{d\mathcal{O}} |\mathcal{M}|^2 dV$
- Expectation value (mean) of differential cross-sections:

$$\left\langle \frac{d\sigma}{d\mathcal{O}} \right\rangle = \frac{\int \mathcal{O} \frac{d\sigma}{d\mathcal{O}} d\mathcal{O}}{\int \frac{d\sigma}{d\mathcal{O}} d\mathcal{O}} = \frac{\int \mathcal{O} d\sigma}{\int d\sigma}$$

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

Expectation value of CP-odd observables

- Terms in the expectation value:
  - SM term:

$$\int \mathcal{O}\, d\sigma_{SM} = \begin{cases} 0, & \text{if } \mathcal{O} \text{ CP-odd} \\ \neq 0, & \text{if } \mathcal{O} \text{ CP-even} \end{cases}$$

  - BSM term:

$$\tilde{d}^2 \cdot \int \mathcal{O}\, d\sigma_{\text{CP-even}} = \begin{cases} 0, & \text{if } \mathcal{O} \text{ CP-odd} \\ \neq 0, & \text{if } \mathcal{O} \text{ CP-even} \end{cases}$$

  - Interference Term:

$$\tilde{d} \cdot \int \mathcal{O}\, d\sigma_{\text{Interference}} = \begin{cases} \neq 0, & \text{if } \mathcal{O} \text{ CP-odd} \\ 0, & \text{if } \mathcal{O} \text{ CP-even} \end{cases}$$

    → source of CP violation

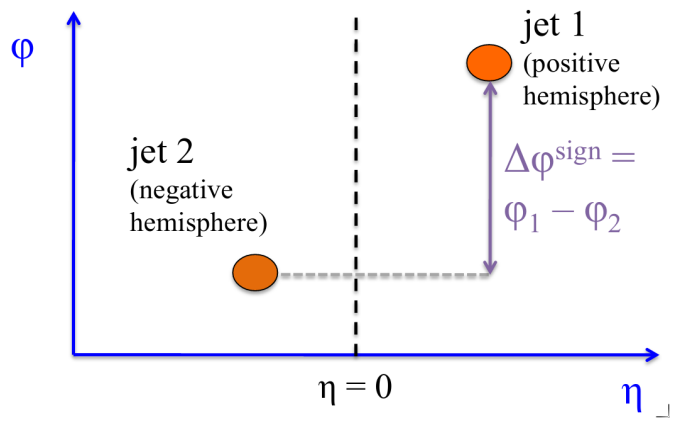
→ CP-odd observable has non-zero mean in presence of CP violation:

⇒ 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 → EFT used for quantification)

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

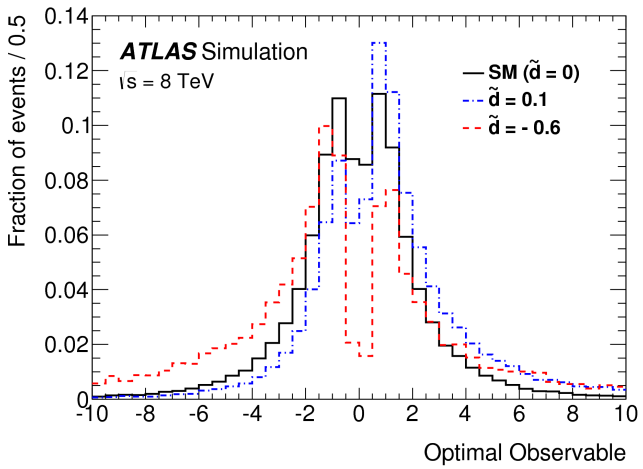


- Sgnd$\Delta\phi(jj) = \phi(j_{\eta>0}) - \phi(j_{\eta<0})$
- non-signed $\Delta\phi(jj)$ is CP-even

CP-odd observables

Optimal Observable $\mathcal{OO}$

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

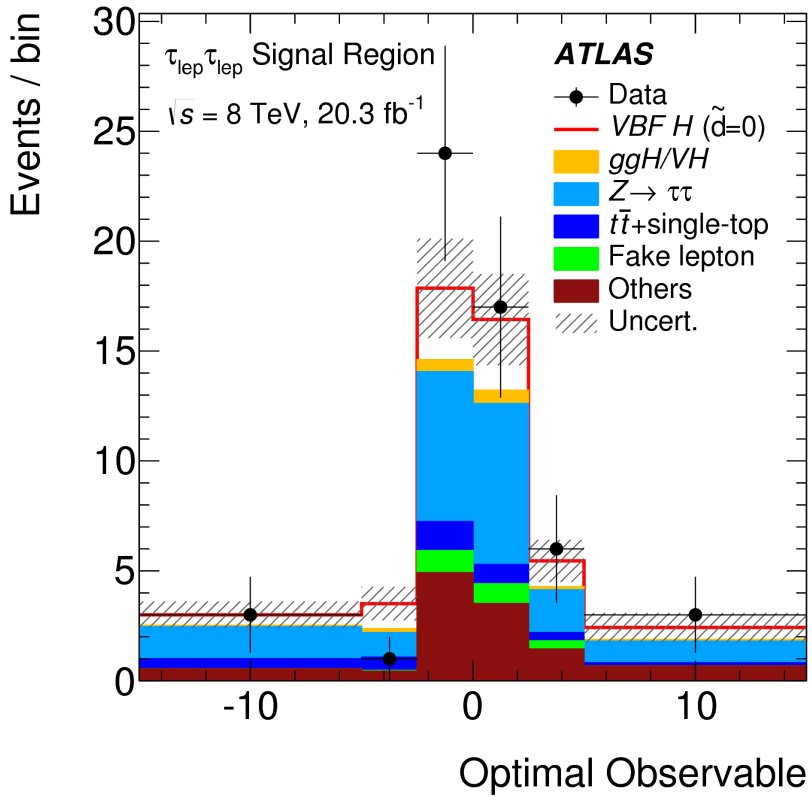


- defined with the reconstructed four-momenta of particles in the events (tagging jets, Higgs reconstructed with MMC)
- Why optimal?
  → combines the information on the entire phase space in one scalar variable (for small $\widetilde{d}$)

  [D. Atwood, A. Soni; Phys. Rev. D45 (1992)] , [M. Davier et al.; Phys. Lett. B306 (1993)] , [M. Diehl, O. Nachtmann; Z. Phys. C62 (1994)]

8 TeV measurement of $\tilde{d}$ in VBF $H \to \tau\tau$ with ATLAS

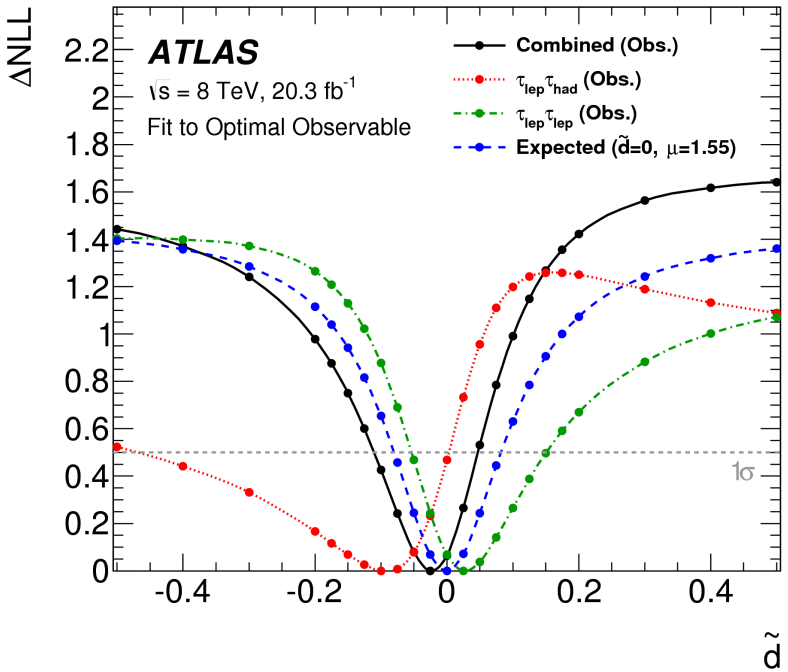
- Measurement based on 8 TeV $H \to \tau\tau$ couplings analysis
- Additional selection: BDT score cut
- Matrix element for $\mathcal{O}\mathcal{O}$ calculation and event reweighting extracted from HAWK [Denner, Dittmaier, Kallweit, Mück, Comput. Phys. Commun. 195 (2015)]



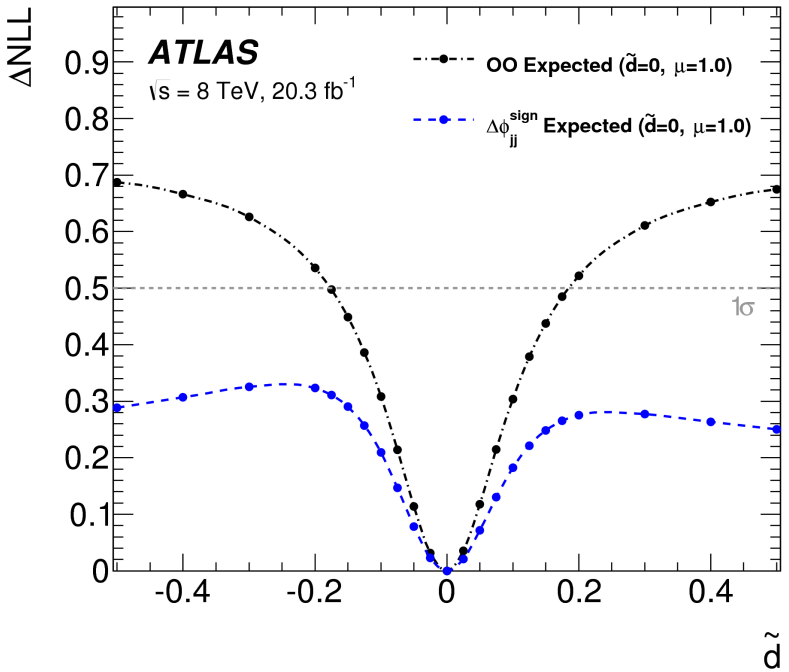
- no signal strength information
- only shape information
- fit to full $\mathcal{O}\mathcal{O}$ distribution to extract exclusion limits on $\tilde{d}$

[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 $\mu = 1.55$

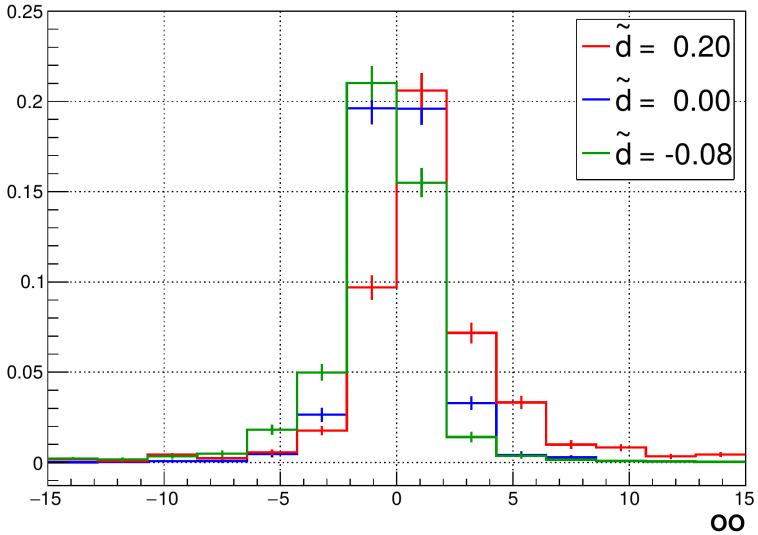


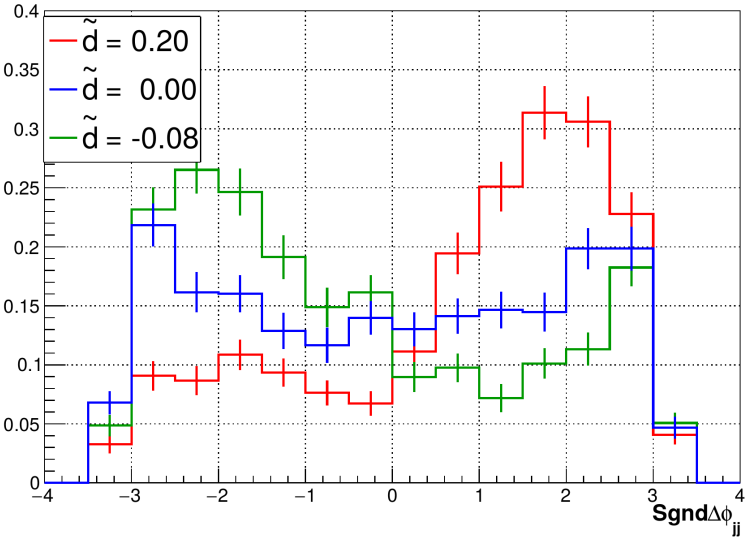
Optimal Observable more sensitive than Sgnd$\Delta\phi(jj)$

Observed confidence interval at 68 % C.L.: [-0.11,0.05]

3. EFT validity study at 13 TeV

At $\sqrt{s} = 13\,\text{TeV}$, parton level, VBF H production process:





$pp \to Hjj$ produced with MadGraph5_aMC@NLO with HC model @ NLO

(plots J. Rehberg)

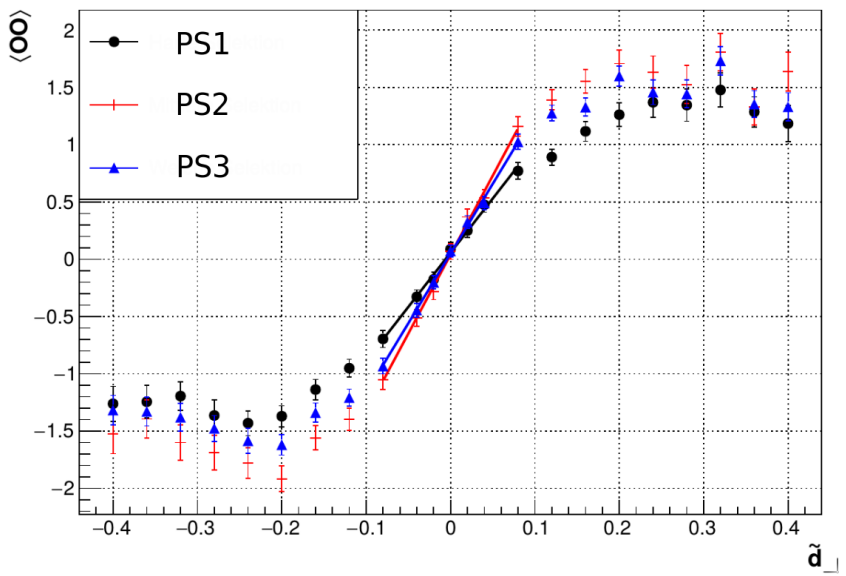
truth level
with VBF cuts:

- $p_T(\text{jets}) > 25\,\text{GeV}$
- $|\eta(\text{jets})| < 4.5$
- $M_{jj} > 500\,\text{GeV}$
- $|\Delta\eta(jj)| > 2$

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

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

At low $\tilde{d}$, linear term dominates:
$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + \tilde{d} \cdot 2\Re(\mathcal{M}_{\mathrm{SM}} \mathcal{M}_{\mathrm{CP-odd}}) + \tilde{d}^2 \cdot |\mathcal{M}_{\mathrm{CP-odd}}|^2$
$\rightarrow$ Linear calibration curve for $\mathcal{OO}$ vs. $\tilde{d}$



Precision of measurement depends on

- gradient of calibration line
- uncertainty of mean of the observable

Considering 3 phase-space regions:

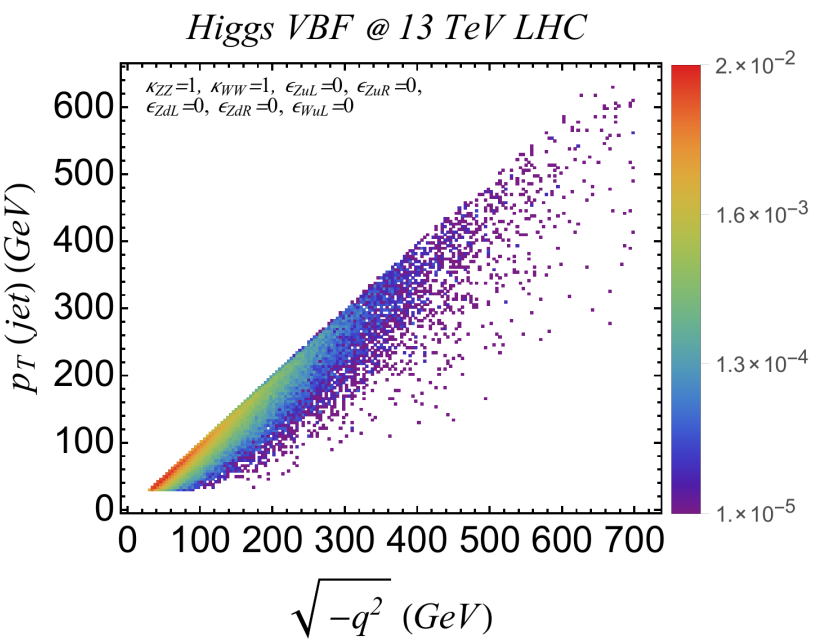
- PS1: $M(jj) > 500$ GeV, $|\Delta\eta(jj)| > 4$
- PS2: $M(jj) > 500$ GeV, $|\Delta\eta(jj)| > 2$
- PS3: $M(jj) > 200$ GeV, $|\Delta\eta(jj)| > 2$

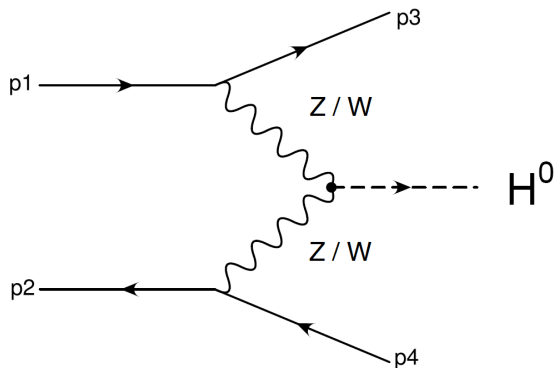
A. Find the characteristic scale for VBF Higgs production

(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
  $\Longrightarrow$ 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,

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

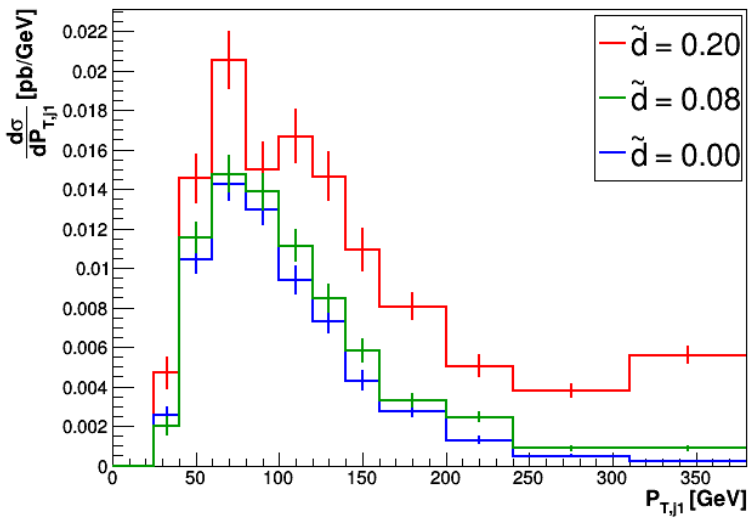


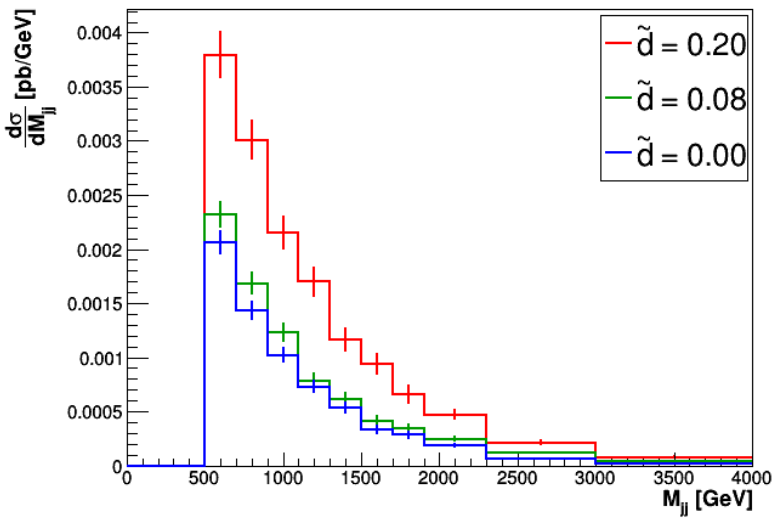


(from YR IV sec. II.1.6)

Jet's transverse momentum at 13 TeV

- Leading jet $p_T(j_1)$ also features strong dependence on $\tilde{d}$
- more so than $M(jj)$ and other variables





$\Rightarrow$ use $p_T(j_1)$ for this study

B. Applying upper boundaries on $p_T(j_1)$

Impact on:

- acceptance
- gradient of calibration line
- uncertainty of mean value

Boundaries on $p_T(j_1)$:

- cuts:

$p_T(j_1)$	< 240 GeV	< 200 GeV	< 140 GeV	< 100 GeV

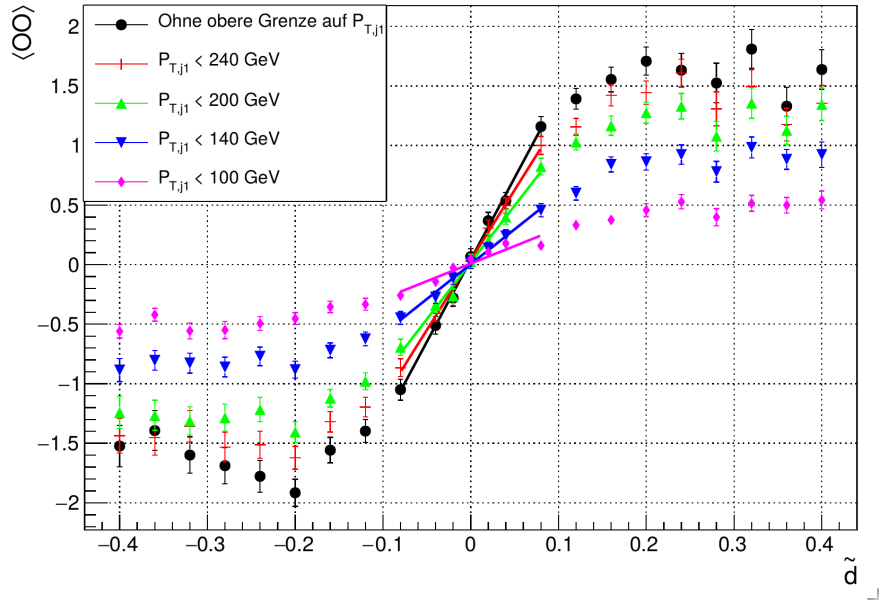
→ decreasing acceptance:

$\tilde{d}$	$A_{p_{T,j_1}<240\,\mathrm{GeV}}$	$A_{p_{T,j_1}<200\,\mathrm{GeV}}$	$A_{p_{T,j_1}<140\,\mathrm{GeV}}$	$A_{p_{T,j_1}<100\,\mathrm{GeV}}$
-0.08	0.906 ± 0.037	0.863 ± 0.036	0.712 ± 0.031	0.498 ± 0.024
-0.04	0.964 ± 0.039	0.930 ± 0.038	0.784 ± 0.033	0.571 ± 0.026
-0.02	0.960 ± 0.039	0.923 ± 0.038	0.782 ± 0.034	0.556 ± 0.026
0.00	0.965 ± 0.039	0.929 ± 0.038	0.791 ± 0.033	0.556 ± 0.026
0.02	0.962 ± 0.037	0.924 ± 0.035	0.780 ± 0.031	0.551 ± 0.024
0.04	0.958 ± 0.039	0.920 ± 0.038	0.778 ± 0.033	0.559 ± 0.026
0.08	0.927 ± 0.037	0.869 ± 0.036	0.722 ± 0.031	0.491 ± 0.024

- with larger $|\tilde{d}|$, acceptance decreases by 5...10 %
- with stronger bounds on $p_T(j_1)$, acceptance decreases by 40...45 %

B. Applying upper boundaries on $p_T(j_1)$

Change of calibration curves and uncertainties of mean values



$\mathcal{OO}$

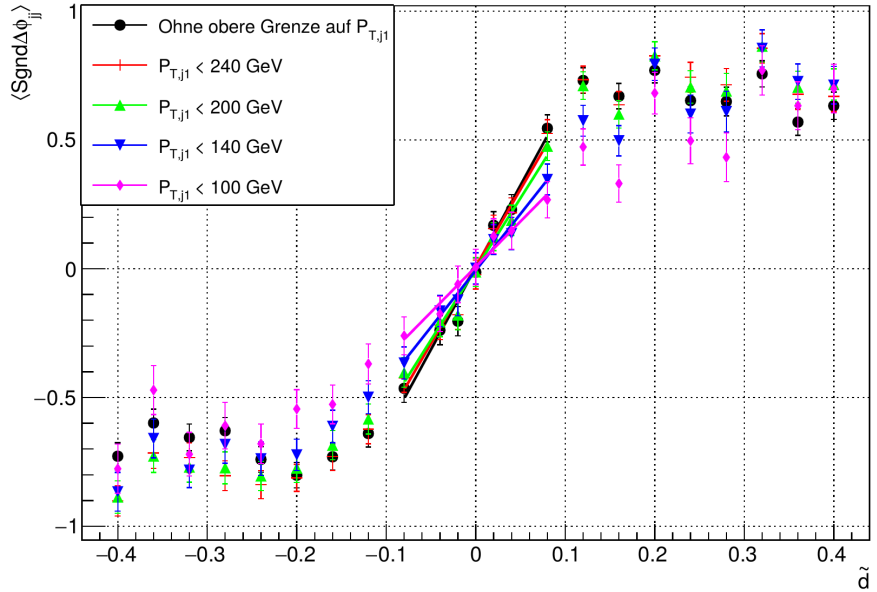
50k MC events

Boundary b [GeV]	gradient $g(b)$	$g(b)/g(\infty)$	$\delta(\mathcal{OO})$
$p_T(j_1) < \infty$	13.8 ± 0.6	1	0.085
$p_T(j_1) < 240$	11.8 ± 0.6	0.85 ± 0.06	0.076
$p_T(j_1) < 200$	9.5 ± 0.5	0.69 ± 0.05	0.070
$p_T(j_1) < 140$	5.9 ± 0.4	0.43 ± 0.04	0.056
$p_T(j_1) < 100$	3.0 ± 0.3	0.21 ± 0.03	0.042

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

B. Applying upper boundaries on $p_T(j_1)$

Change of calibration curves and uncertainties of mean values



Sgnd$\Delta\phi(jj)$

50k MC events

Boundary b [GeV]	gradient $g(b)$	$g(b)/g(\infty)$	δ(Sgnd$\Delta\phi(jj)$)
$p_T(j_1) < \infty$	6.4 ± 0.42	1	0.052
$p_T(j_1) < 240$	6.0 ± 0.4	0.94 ± 0.09	0.053
$p_T(j_1) < 200$	5.5 ± 0.4	0.86 ± 0.09	0.055
$p_T(j_1) < 140$	4.4 ± 0.5	0.69 ± 0.09	0.060
$p_T(j_1) < 100$	3.5 ± 0.6	0.55 ± 0.09	0.071

- Uncertainties of mean values δ(Sgnd$\Delta\phi(jj)$):
  - Gradiant decreases with stronger bounds (→ loss of sensitivity)
  - Uncertainty **increases** (→ loss of sensitivity)

C. Measure EFT parameters – Run 2 prospects

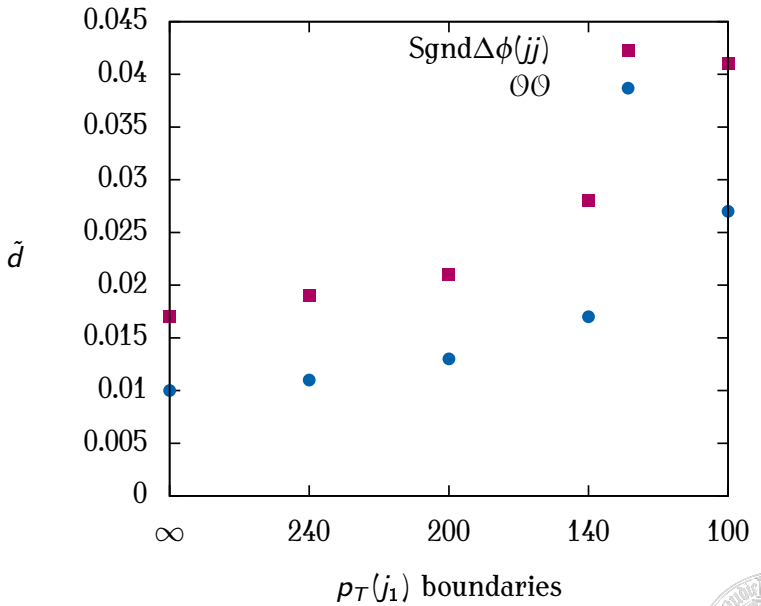
Assuming similar selection efficiency as in Run 1, $\int \mathcal{L} dt = 100\text{fb}^{-1}$, with

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

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

Boundary b [GeV]	$\delta(\tilde{d})_{\mathcal{OO}}$	$\delta(\tilde{d})_{\text{Sgnd}\Delta\phi(jj)}$
$p_T(j_1) < \infty$	0.010	0.017
$p_T(j_1) < 240$	0.011	0.019
$p_T(j_1) < 200$	0.013	0.021
$p_T(j_1) < 140$	0.017	0.028
$p_T(j_1) < 100$	0.027	0.041

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



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

Summary

- EFT validity limited by:
  - unitarity violation
  - growing difference to complete models
- CP measurement in VBF Higgs production using CP-odd observables (Optimal Observable, Sgnd$\Delta\phi(jj)$)
- Under the influence of $p_T(j_1)$ boundaries, limits increase by factor ~ 2.5
- Optimal Observable and Sgnd$\Delta\phi(jj)$ similarly stable
- Optimal Observable more sensitive