Exploring Higgs couplings in single top-quark production

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Higgs Couplings
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Motivation

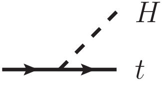
After the discovery of the Higgs boson at the LHC:

- measurement of Higgs Yukawa couplings
- precision tests of the Standard Model
- search for New Physics, e. g. modified Higgs couplings

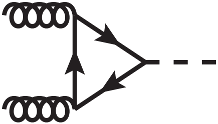
top quark special in SM

- heaviest particle and largest Yukawa coupling
- many BSM models: modify Yukawa couplings
- **top Yukawa coupling y_t challenging to measure**

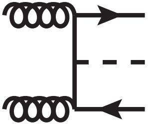
$y_t \sim$



indirect:



direct:

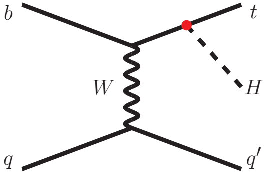


only $|y_t|^2$ dependence!

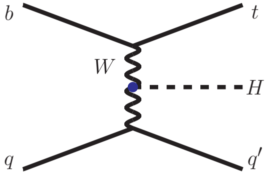
Particularly difficult: measuring the relative CP phase of the top-Higgs coupling and the *W*-Higgs-coupling!

Single Top Quark Production in Association with a Higgs

Consider a different process: $pp \to tHj$



$\sim y_t$



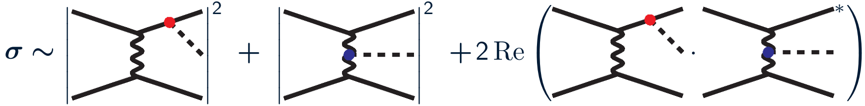
$\sim y_W$

- Higgs boson emitted from top quark and W boson
  - ➔ direct measurement and linear dependence on y_t
- not measured so far, but searches/limits at LHC
  - [CMS-HIG-14-027], [CMS-PAS-HIG-18-009]
- t-channel: dominant production channel
- however: strong cancellation between contributions
  - ➔ small cross section but very sensitive to phase

Where does the high sensitivity come from?

Relative Sign of Yukawa Coupling

Cross section dependence on relative sign of Yukawa couplings:



Flip of relative sign:

SM couplings		‘flipped’ relative sign
$\sigma_{\text{fid}}^{\text{NLO}} = (22.6^{+1.3}_{-0.6})\,\text{fb}$	⟷	$\sigma_{\text{fid}}^{\text{NLO}} = (298.2^{+17.4}_{-8.2})\,\text{fb}$
destructive interference		constructive interference

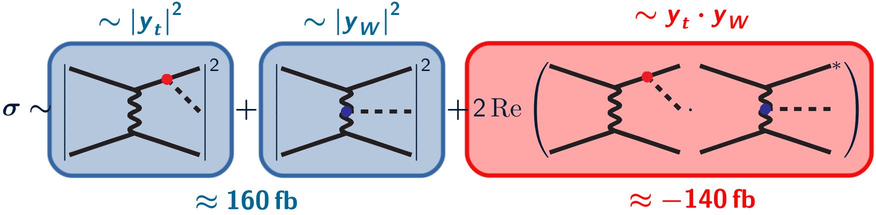
Inverted sign of y_t increases cross section by more than factor 10

→ **interference term is sensitive to relative phase**

consider now scenario with CP mixing in Yukawa coupling

Relative Sign of Yukawa Coupling

Cross section dependence on relative sign of Yukawa couplings:



Flip of relative sign:

SM couplings
$\sigma_{\text{fid}}^{\text{NLO}} = (22.6^{+1.3}_{-0.6})\,\mathrm{fb}$

destructive interference

$\Longleftrightarrow$

'flipped' relative sign
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constructive interference

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Non CP Conserving Yukawa Coupling

Higgs boson with mixed CP-even and CP-odd interaction

$$\mathcal{L}_{t\bar{t}H} = -\frac{y_t}{2}\left(a\cos(\alpha)\bar{t}t + ib\sin(\alpha)\bar{t}\gamma_5 t\right)H$$

using Higgs EFT framework from [Artoisenet et al '13], [de Aquino, Mawatari '13]
same process also studied in [Demartin,Maltoni,Mawatari,Zaro '15]

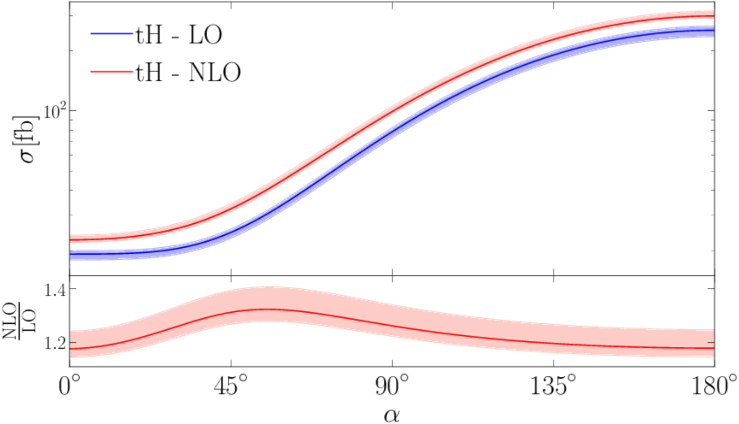
- allows general parametization of non CP conserving Yukawa coupling
- interpolates between SM and 'flipped sign' scenario
- choice of parameters: $a = 1,\ b = \frac{2}{3}$ (α is only free parameter)
  - ➔ preservation of SM result for $gg \to H$ for all α

$pp \to tHj$ cross section has simple dependence on α

$$\sigma^{\text{NLO}}_{\text{tot}}(\alpha) = \sigma^{\text{SM}}_{\text{tot}}(4.70 - 5.19\cos(\alpha) + 1.49\cos^2(\alpha) - 0.95\sin(\alpha) + 0.59\cos(\alpha)\sin(\alpha))$$

(similar decomposition holds for all observables of $pp \to tHj$ if only QCD corrections are considered)

Cross Section for Different CP Phases



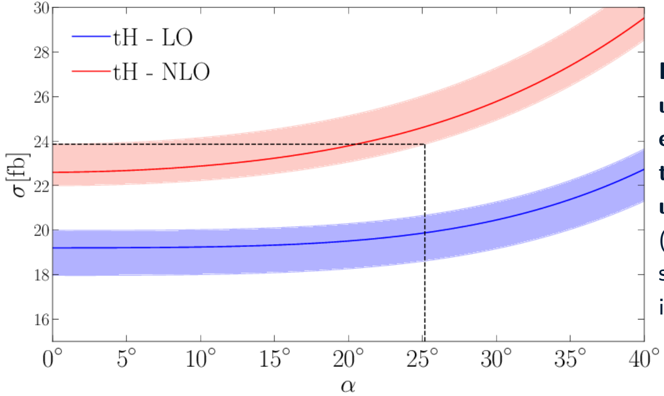
NLO corrections:
- are not negligible: +18% to +32%
- depend on α

→ **including NLO corrections important**

once measured: easy to distinguish extreme cases $\alpha = 0°$ and $\alpha = 180°$

How well can we distinguish SM from BSM for small α?

Small CP Mixing Angles



LO: unreliable estimate of theoretical uncertainties (not surprising since only EW interaction)

Up to $\alpha \approx 25^\circ$: cross section compatible within uncertainties with SM prediction

→ **Need for more sensitive observables!**

cut-based techniques:

- construction of sensitive observables
- shape differences in differential distributions
- **limited by small amount of available data!**

Application of Matrix Element Method

Application of the Matrix Element Method (MEM) to use the available information in the event samples most efficiently

$$\mathcal{L}(\alpha|\{\boldsymbol{x_i}\}) = \prod_{i=1}^{N} \int \mathrm{d}^n y \, \frac{1}{\sigma(\alpha)} \frac{\mathrm{d}^n \sigma(\alpha)}{\mathrm{d}y_1 \ldots \mathrm{d}y_n} W(\boldsymbol{y}, \boldsymbol{x_i})$$

- Likelihood for α
- hadronic final state $\left(\boldsymbol{x_i} = \{\eta_t, E_j, \eta_j, \phi_j, E_H, \eta_H, \phi_H\}_i\right)$
- $\mathrm{d}\sigma$: probability density for theoretically modelled final state $\boldsymbol{y}$
- unfolding detector signal to theoretical final state: transfer function

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- parameter extraction with **Maximum Likelihood Method**
- no information loss due to averaging, insensitive observables
- original MEM formulated for LO calculations [Kondo '88]
  - → **calibration uncertainties because of offset to full theory**

Formulation of MEM for generic NLO calculations

[Martini,Uwer '15, '18], [Kraus,Martini,Uwer '19]

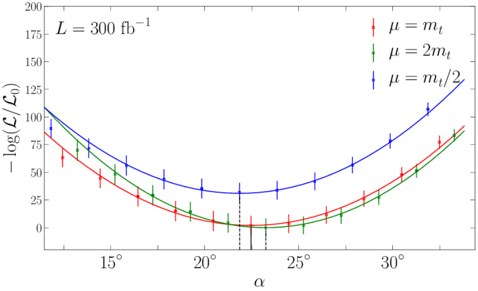
Simulated Toy Experiment with MEM@NLO

Steps of toy experiment:

- assume BSM with non vanishing α: **set $\alpha = 22.5^\circ$**
- generate unweighted events distributed according to NLO cross section
  - ➔ use this pseudo data as **event sample** of toy experiment
- extract α value with the MEM@NLO from pseudo data
- study uncertainties of estimate

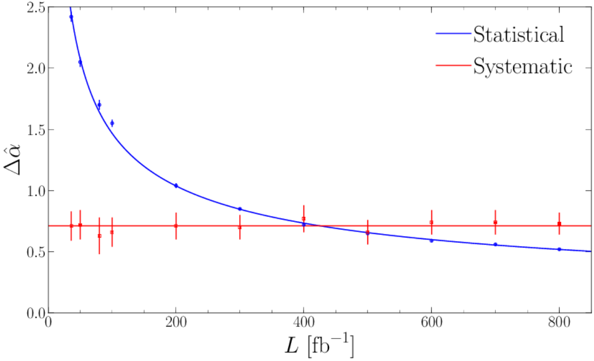
Extraction of α:

- minimum of negative log-Likelihood gives estimator $\hat{\alpha}$
- **systematic uncertainties:** scale variation in Likelihood calculation
- **statistical uncertainties:** width of parabola of negative log-Likelihood



Which uncertainty is dominant?

Prospects for the LHC and HL-LHC



systematic uncertainties:

- constant with approx. 0.7°

statistical uncertainties:

- behaviour $\sim \frac{1}{\sqrt{L}}$
- no additional gain in accuracy from $\approx$ 450 fb^{-1} onwards

But: signal detection efficiencies not considered!

- realistic efficiencies of order 3%
- NLO QCD accuracy sufficient for HL-LHC
- discovery potential:
  - 3σ signal at 300 fb^{-1}
  - HL-LHC allows for discovery with 5σ

Summary and Outlook

Summary:

- studied SM extension with non CP conserving top-quark Yukawa coupling
- total cross section: mixing angles up to 25° yield predictions compatible with SM
- simulated toy experiment with $\alpha = 22.5^\circ$ using MEM@NLO
  - when considering realistic signal detection efficiencies: theoretical uncertainty not limiting factor for accuracy
  - 3σ signal with 300 fb^{-1} data
  - 5σ possible at HL-LHC

Matrix Element Method is powerful tool to challenge the SM

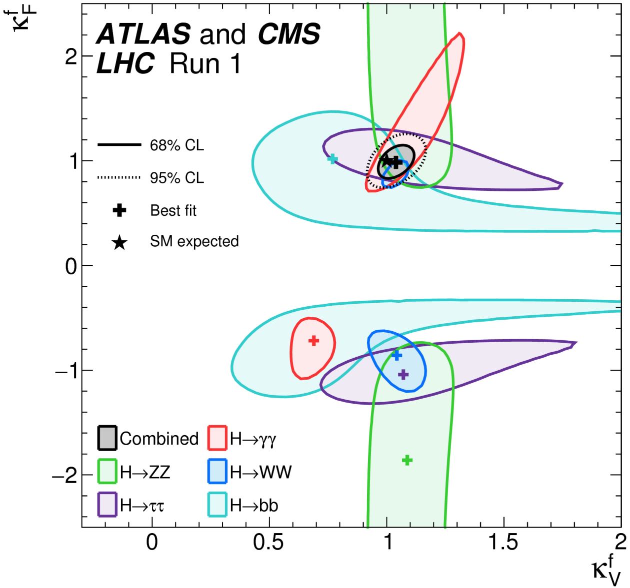
Outlook:

- improvement in modelling of experimental final state

  e. g. parton shower effects, decays, non-trivial transfer functions

Thank you for your attention!

Backup: Experimental Measurements



measured couplings scaled with SM couplings

$\kappa_F = \kappa_t = \kappa_b$

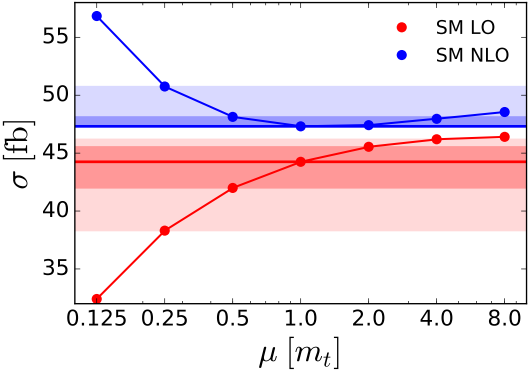
$\kappa_V = \kappa_W = \kappa_Z$

e. g.

$\kappa_t = y_t / y_t^{\rm SM}$

[ATLAS,CMS '16]

Backup: SM Results and Scale Variation: *t*-Channel



Result

$$\sigma^{\mathrm{NLO}}_{t-\mathrm{channel}} = \left(47.31^{+0.8}_{-0.0}\right)\,\mathrm{fb}$$

QCD corrections:

- increase cross section by 7%
- decrease scale variation from 5% to 2%

darker band:

$\mu = (2/0.5) \times \mu_0$

brighter band:

$\mu = (4/0.25) \times \mu_0$

Note:

LO and NLO bands do not overlap

- LO: only electroweak interaction
- NLO: effectively leading order in QCD

Backup: Additional Information: Differential Cross Sections