Measurement of the Top-Higgs Coupling with the CMS Experiment

KSETA Plenary Workshop

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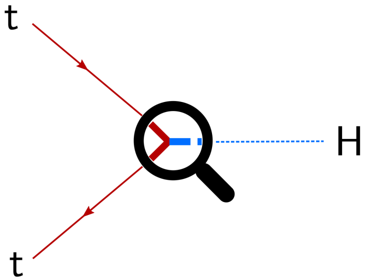
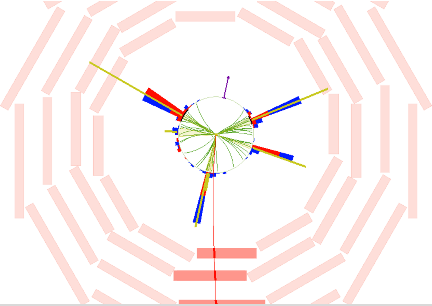
INSTITUT FÜR EXPERIMENTELLE KERNPHYSIK (IEKP)



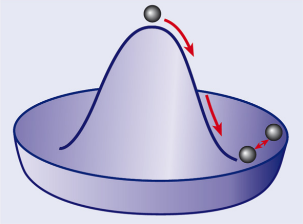


Introduction

- Presenting measurement of the top-Higgs coupling
- Focus on direct measurement in $t\bar{t}H$ production and KIT contributions in the $H \rightarrow b\bar{b}$ decay channel
- KIT contributions by

  Karim El Morabit, Marco Harrendorf, Ulrich Husemann, Hannes Mildner, Matthias Schröder, Shawn Williamson, and many Master and Bachelor students

Short reminder: Higgs mechanism



- Introduction of scalar Higgs field with non-zero vacuum expectation value
- Spontaneous symmetry breaking
- W and Z gauge bosons obtain mass
- Fermions obtain mass via Yukawa coupling to Higgs field

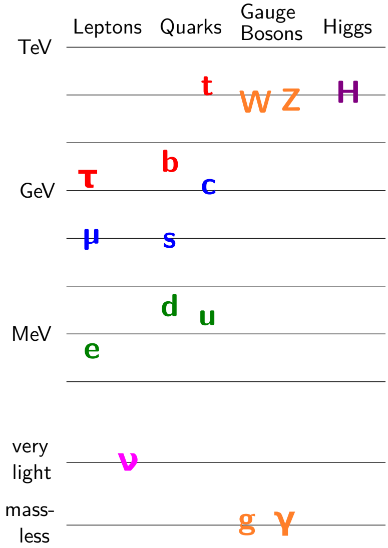
Predictions

- Scalar elementary particle
- Couples to all massive particles
- Fermion couplings $\propto$ fermion mass
- ...

Tests at LHC

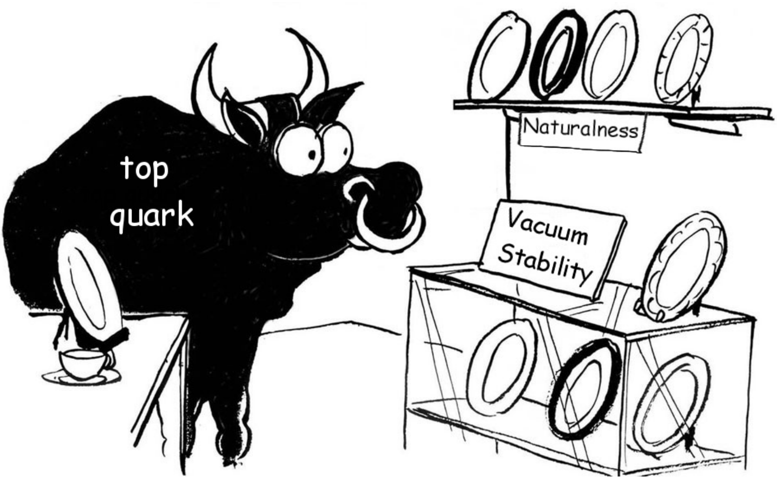
- Observation of new particle
- Quantum numbers from differential distributions
- Determination of production and decay rate in multiple channels
- ...

Standard Model particle masses



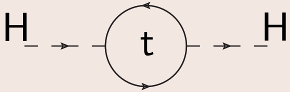
- Top quark: heaviest particle of the Standard Model ($173\ \mathrm{GeV/c^2}$)
- Top-quark only fermion at scale of Higgs boson
  $m_\mathrm{t} \approx m_\mathrm{W} \approx m_\mathrm{Z} \approx m_\mathrm{H}$
- Orders of magnitude between fermion masses
  - $m_\mathrm{t}/m_\mathrm{b} \approx 42$
  - $m_\mathrm{t}/m_\mathrm{e} \approx 340000$
  - $m_\mathrm{t}/m_\nu > 10^{11}$
- SM: High top quark mass ⇔ large top-Higgs Yukawa coupling (only one close to 1)

Top Quark: Bull in a China Shop



Implication of strong top-Higgs coupling

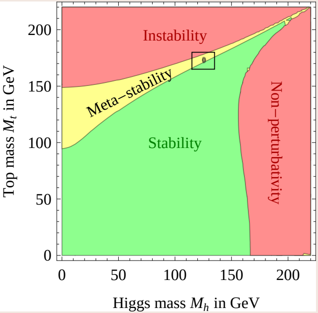
Hierarchy problem



- Large ($\gg$ 125 GeV) quantum corrections to Higgs boson mass
- SM Higgs mass unnaturally low

Vacuum stability

- Coupling affects Higgs potential
- Vacuum becomes meta-stable

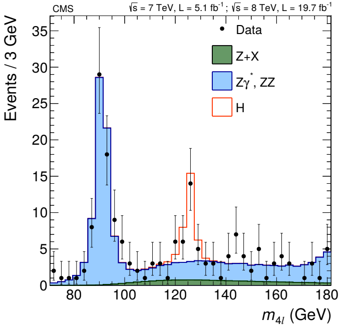


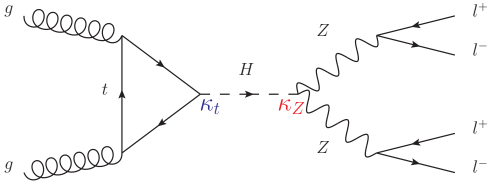
Strong coupling motivates

- Modified Higgs sector
- Top partners
- Modified top-Higgs couplings

Higgs boson discovery

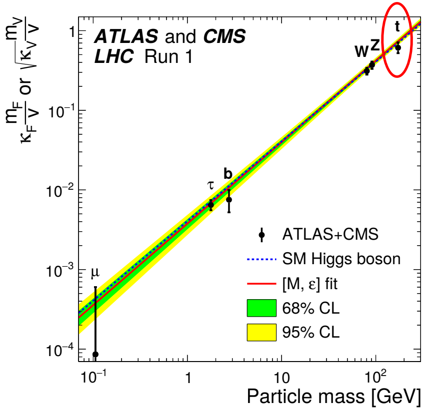
- LHC run 1 (2011 - 2012): 125 GeV/c^2 Higgs boson discovered, for example in H $\rightarrow$ ZZ $\rightarrow 4\ell$ channel





- Enabled by the top-Higgs coupling (?)
  - $\kappa_{\mathrm{t}}/\kappa_{\mathrm{Z}}$ strength of Higgs coupling to particle Z/top, normalized to SM
  - $N_{\mathrm{events}}(\mathrm{pp} \rightarrow \mathrm{H} \rightarrow \mathrm{ZZ}) \sim \sigma(\mathrm{pp} \rightarrow \mathrm{H} \rightarrow \mathrm{ZZ}) \sim {\kappa_t}^2{\kappa_Z}^2$

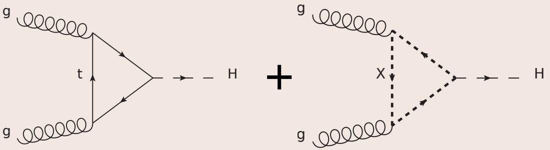
Higgs boson couplings



- Analysis of CMS and ATLAS of all decay and production modes: Higgs-boson couplings close to SM expectation
- Top-Higgs coupling $\kappa_t = 0.87 \pm 0.15$

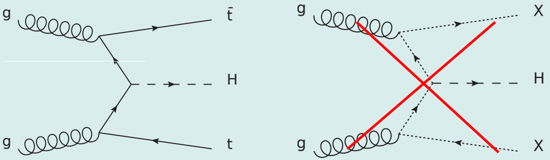
Top-Higgs coupling and $t\bar{t}H$

Gluon Fusion Higgs Boson Production



Unknown heavy particles *X* could contribute

Higgs boson production in Association with a Top Quark Pair ($t\bar{t}H$)

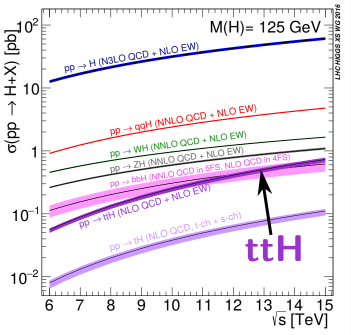


Observation of top-quarks possible

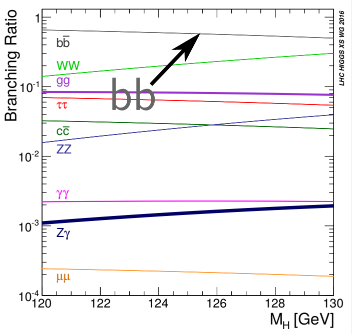
$t\bar{t}H(b\bar{b})$

- KIT group: searching for $t\bar{t}H$ with $H \rightarrow b\bar{b}$

Cross section

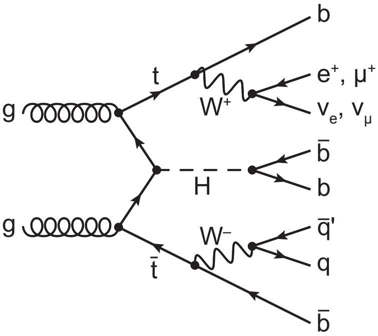


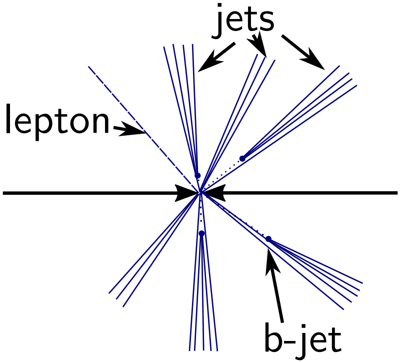
Branching Ratio



- $t\bar{t}H$: small cross section, 0.5 pb at 13 TeV ($\approx$ 1% of Higgs bosons)
- $Hb\bar{b}$: large branching ratio, $\approx$ 60 % for 125 GeV/c^2 Higgs boson

Signature

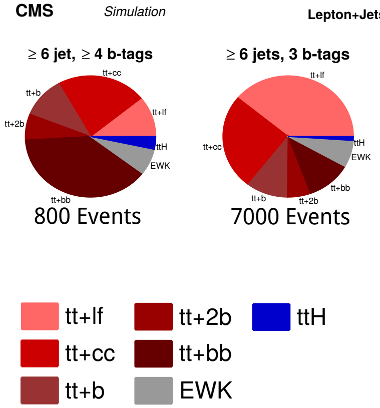




- KIT: focus on $t\bar{t}$ decay into lepton+jets ($\approx 30\%$)
- Signature: 1 lepton, 6 jets, 4 b-jets (jets containing b-hadrons)
- Combinatorial problem in associating jets with quarks
- Large $t\bar{t}$ + (b-)jets background

Selection and categorization

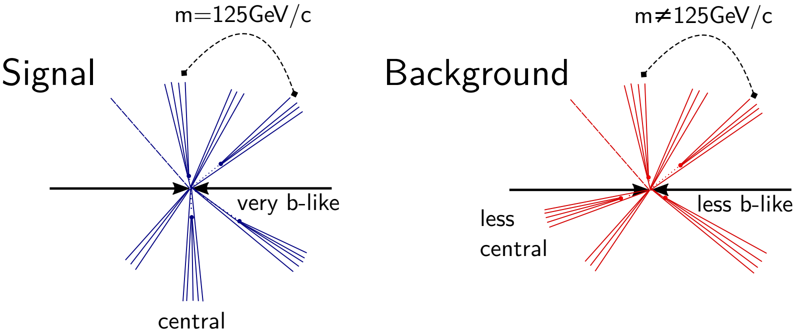
- Select events with an isolated lepton, categorize according to number of jets and b-tags ⇒ signal enrichment



Categories differ in

- Total number of events
- Signal fraction
- Background composition

Signal-background discrimination



- Subtle differences between signal and backgrounds
- ⇒ Combine in multivariate discriminant

Multivariate Discriminant
- (Complicated) function of features of events
- Higher value if event more signal-like

Multivariate Discriminants investigated

Matrix Element Method (MEM)

- Calculate $t\bar{t}H$ and $t\bar{t}b\bar{b}$ likelihood for every event from simplified physical model, based on LO matrix element
- Inputs: four-vectors of leptons, jets, MET

Boosted Decision Trees (BDT)

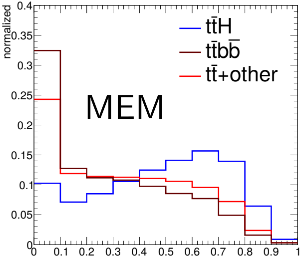
- Discriminant constructed from machine learning
- Can use many input variables (jet p_{T}, b-tags, event shape)

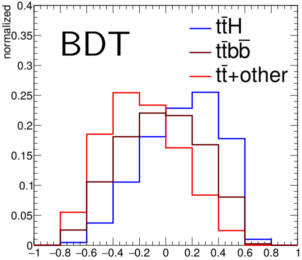
Deep Neural Networks (DNN)

- Latest technology (TensorFlow), also used by Google
- Can identify complicated correlations from simple inputs
- Still in experimental stage

Comparison of discriminants

- MEM distinguishes $t\bar{t}b\bar{b}$ and $t\bar{t}H$ well
- BDT better against remaining backgrounds
- Need to consider systematics for ideal combination of strengths
  - Additional discrimination against more uncertain background ($t\bar{t}b\bar{b}$) beneficial
  - BDT uses more information
    $\Rightarrow$ susceptible to more uncertainties





Combination scheme used

- **Divide** categories into signal-like and background-like with **BDT**
- Analyze **shape** of **MEM** in both subcategories

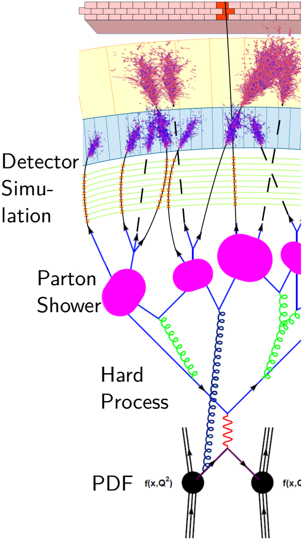
Background model

Challenges

- Large background
- $t\bar{t}b\bar{b}$ background difficult to model
- Complicated discriminant shape
- Many aspects of events important
- No real control regions

MC model for $t\bar{t}$ background

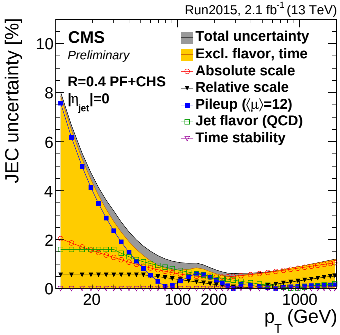
- Hard process: Powheg (NLO QCD), normalized to NNLO predictions
- Pythia 8 parton shower
- Geant 4 CMS detector simulation
- Multiple data-driven corrections



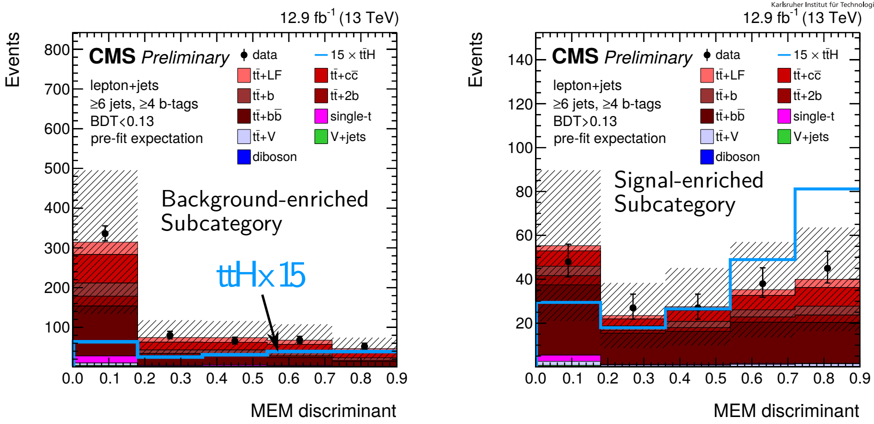
Uncertainties

- Theory uncertainties
  - Divide simulated $t\bar{t}$ sample into $t\bar{t}b\bar{b}$, $t\bar{t}2b$, $t\bar{t}b$, $t\bar{t}c\bar{c}$, and $t\bar{t}$+lf subsamples
  - 50% uncertainty for $t\bar{t}$+hf processes
  - Shape uncertainties from varying generator settings for all subprocesses
  - Ongoing discussion about treatment of $t\bar{t}b\bar{b}$ and associated uncertainties

- Experimental uncertainties
  - Main uncertainties:
    Jet-energy scale and b-tagging
  - Need to consider multiple independent components of uncertainties
- Rate and shape uncertainties included as parameters in fit

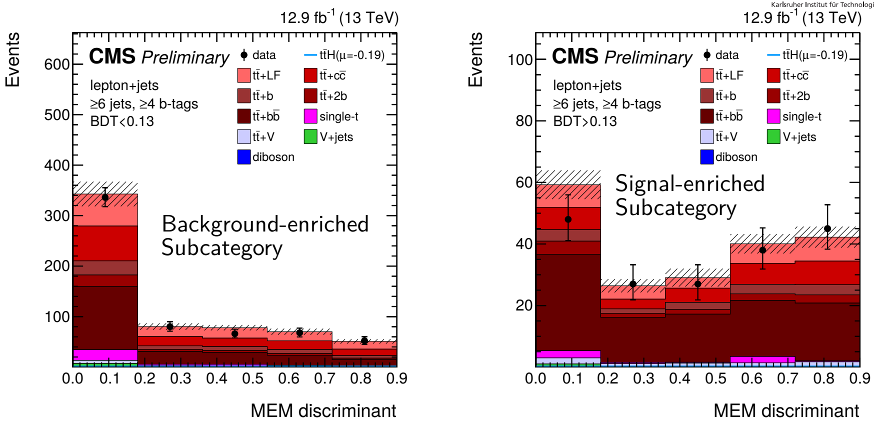


Distribution of final discriminant



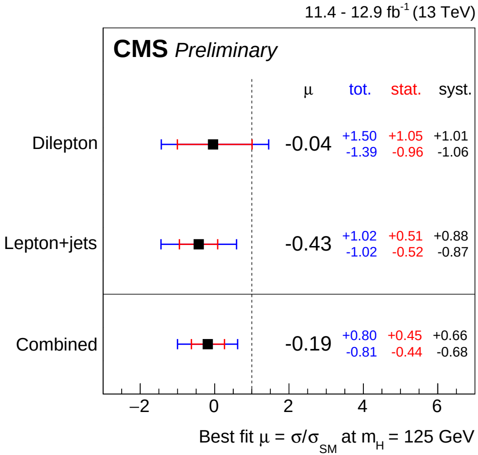
- Final discrimination: analysis of MEM shape
- Signal expected at high, background at low values
- Large uncertainties, indicated as hashed bands
- Accurate prediction by default background model

Combined fit



- Fit performed simultaneously in multiple categories
- Post-fit: uncertainties reduced
- Data agrees well with background-only model
- Similar in all analysis categories

Results in $b\bar{b}$ channel



- Signal strength $\mu_{t\bar{t}H} = \sigma_{t\bar{t}H} / \sigma_{t\bar{t}H}^{SM}$
- Best fit: slightly negative signal strength
- Compatible with SM $t\bar{t}H$ production and background only
- Analysis becoming sensitive to SM signal
- Will benefit from larger dataset

All $t\bar{t}H$ results

Measurement	μ_{ttH}
CMS + ATLAS Run 1	$\mathbf{2.3^{+0.7}_{-0.6}}$
ATLAS Run 2 $t\bar{t}H(b\bar{b})$	$2.1^{+1.0}_{-0.9}$
ATLAS Run 2 $t\bar{t}H(\gamma\gamma)$	$-0.3^{+1.2}_{-1.0}$
ATLAS Run 2 $t\bar{t}H$(leptons)	$2.5^{+1.3}_{-1.1}$
ATLAS Run 2 combined	$\mathbf{1.8^{+0.7}_{-0.7}}$
CMS Run 2 $t\bar{t}H(b\bar{b})$	$-0.2^{+0.8}_{-0.8}$
CMS Run 2 $t\bar{t}H(\gamma\gamma)$	$1.9^{+1.5}_{-1.2}$
CMS Run 2 $t\bar{t}H$(leptons)	$2.0^{+0.8}_{-0.7}$
CMS Run 2 (naive comb.)	$\mathbf{1.1^{+0.5}_{-0.5}}$

- Results by ATLAS and CMS
- Run 1: 2σ excesses
- Measurements performed targeting Higgs decays into $b\bar{b}$, $\gamma\gamma$, and lepton
- Of similar precision
- Run 2: Excess neither confirmed nor refuted
- Run 2: Only 13 fb^{-1} analyzed so far, 40 fb^{-1} recorded

Conclusion and outlook

- Conclusion
  - Top-Higgs coupling important in SM and its extensions
  - Direct measurement possible in $t\bar{t}H$ production
  - Strong KIT contribution to search in $H \to b\bar{b}$ channel
  - Signal strength measured $\mu_{t\bar{t}H(b\bar{b})} = -0.2 \pm 0.8$
  - Combination of $t\bar{t}H$ decay channels:
    compatible with SM, 50% precision
- Outlook
  - Update with larger dataset this spring
  - Will include improvements of analysis techniques
  - Also investigating anomalous top-Higgs couplings
- Stay tuned!