Interplay between the top quark and the Higgs boson - LHC + Tevatron

Jelena Jovićević - TRIUMF, Canada on behalf of ATLAS, CMS, CDF and D0 collaborations

CKM Unitarity Triangle 2016, Mumbai, India
Two big discoveries

**Top quark**
2\textsuperscript{nd} of March 1995 - CDF & D0

**Higgs boson**
4\textsuperscript{th} of July 2012 - ATLAS & CMS
Two big discoveries

Top quark
2\textsuperscript{nd} of March 1995 - CDF & D0

- Top quark properties well measured at CDF and D0 at 1.96TeV;
- Complementary measurements by ATLAS and CMS at 7, 8, 13 TeV;

Higgs boson
4\textsuperscript{th} of July 2012 - ATLAS & CMS

- Measurements of the Higgs boson properties at ATLAS and CMS showed no deviation from SM at the current precision.
- Need more data to pin down its nature completely.

EXCITING era for particle physics!
Outline

Interplay between the Higgs and top masses
- Most precise Higgs boson mass measurement:
- Top mass measurement covered in dedicated talk by Oleg Brandt (WG 6);
- Constraints from the current mass measurements.

Higgs-top Yukawa coupling measurement
- Most precise coupling measurement - LHC Run 1 ATLAS+CMS combination and importance of individual channels.

$t\bar{t}H$ production measurement
- Most sensitive channel to directly probe Higgs-top-Yukawa coupling;
- $H\rightarrow bb$, $H\rightarrow WW/ZZ/\tau\tau$. $H\rightarrow \gamma\gamma$ considered;

$tH$ production measurement
- Direct test of sign and magnitude of Higgs-top-Yukawa coupling.

Search for BSM charged Higgs bosons within top sector
Higgs boson mass and top quark mass interplay
Higgs mass - ATLAS+CMS Run I

- Measured using $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ channels \textit{Phys. Rev. Lett.} 114, 191803

ATLAS/CMS compatibility

- $H \rightarrow \gamma\gamma$: 2.1σ
- $H \rightarrow ZZ \rightarrow 4l$: 1.3σ
- Combined: <1σ

Most precise measurement:

$m_H = 125.09 \pm 0.24$ GeV

2D likelihood contours as a function of signal strength for $\gamma\gamma$, $4l$ and combined channels.
Constraints from Higgs and top masses

- The top mass, the W mass, and the Higgs mass are related through radiative corrections;
  - Before the Higgs boson discovery, the indirect constraint on its mass was based on direct top quark and W boson mass measurements at Tevatron and LEP, and requirement for the consistency of the electroweak theory as a quantum field theory.
- Where do we stand now?

Consistency check of the SM (top-W-Higgs)

Future precise measurements of the m(H), m(W), m(t) could unveil a discrepancy that might lead to the discovery of new physics

Stability of the EW vacuum

Do we live in the stable vacuum?
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Stability of the EW vacuum

Do we live in the stable vacuum?
Higgs-top Yukawa coupling
Higgs couplings measurement

- Most precise constraints on Higgs couplings performed through parametrisation of all accessible production and decay modes, ATLAS+CMS Run 1 - JHEP 08 (2016) 045
- Measured signal strength $\mu$, $\mu = \sigma / \sigma_{SM}$ in individual production and decay modes;

![Production modes Diagram](image1)

![Decay modes Diagram](image2)

All measurements compatible with SM predictions
Hunting the Higgs-top Yukawa coupling

Direct measurement

- **Direct** measurement in $t\bar{t}H$ production

**Sensitivity to $y_t^2$**

Indirect constraints:

- Loops in $ggF$ and $H \rightarrow \gamma\gamma$ vertices;
  - Assuming only SM particles contributing to the loops.

**tH production**: interference between top-mediated and $W$-mediated diagrams;

**H → γγ**: interference between top quark and $W$ boson in the loop;

**ZH production and H → Zγ**: interference between top quark and $W$-boson contribution in the loop.

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Coupling measurement methodology

Assumptions:
- Observed signal originates from the single resonance;
- Narrow width approximation: \( (\sigma \cdot BR)(i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H} \);
- Parametrise deviations with only coupling strength modifiers \( \{K_x\} \).

Procedure:
- Scale SM cross-section and partial widths as a function of parameters \( \{K_x\} \):
  \[
  (\sigma \cdot BR)(gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{SM}(gg \rightarrow H) \cdot BR_{SM}(H \rightarrow \gamma\gamma) \frac{K_g^2 \cdot K_y^2}{K_H^2}
  \]
- In case of loop processes \( K_x \) can be expressed as a function of more fundamental \( K_y \);
- If BSM decays are allowed, scale down all SM decays uniformly.

Tested many scenarios:
- Fermion versus vector boson couplings, up quark VS down quark couplings: also provide constraints on BSM
- Generic model - simultaneous fit of all modifiers, etc…

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arXiv:1307.1347
Top Yukawa coupling - ATLAS+CMS Run 1

- parameterisation assuming the absence of BSM particles in the loops, $\text{BR}_{\text{BSM}} = 0$, $\kappa_j > 0$;

- two parameterisations allowing loop couplings, with either $\kappa_V(W,Z) \leq 1$ or $\text{BR}_{\text{BSM}} = 0$.

$\kappa_t$ strongly depends on the assumptions
To resolve the loops or not?

- Sensitivity to $\kappa_t$ depends strongly on the assumptions on the contributions in the loops;

**Resolved loops** scenario:

- only SM particles contribute to the loop diagrams;
- no new particles that the Higgs boson can decay into (BR$_{BSM}$=0);
- Resolving $ggF$ & $H\rightarrow\gamma\gamma$ loops pins down $\kappa_t^2$ & $\text{sgn } \kappa_t$.

$$\kappa_t = 0.94 \pm 0.21$$

**No resolved loops** scenario:

- allowing BSM effects to modify independently each loop;
- independent $\kappa$-modifier for $\gamma\gamma$, $gg$, and $Z\gamma$ vertices;
- still no new particles the Higgs boson can decay into (BR$_{BSM}$=0)

sensitivity on $\kappa_t$ completely dominated by $t\bar{t}H$ analyses.

$$\kappa_t \in [-1.12, -1.00] \cup [0.93, 1.60]$$
\ttH production
Broad spectrum of analyses covering multiple final states:

- generally combine low BR Higgs decay with high BR $t\bar{t}$ decay and vice-versa;
- $t\bar{t}$ decay products help selection of signal and the reduction of non-$t\bar{t}$ backgrounds, but combinatorics increased when attempting to reconstruct the Higgs boson candidate.
Experimental challenges

Large variety of final states - good understanding of all reconstructed objects

- **electrons / muons**: precise (sub % level) energy / momentum calibration, understanding of identification efficiency, trigger rate;

- **hadronically decaying taus**: energy calibration, controlling rate from misidentified jets and electrons.

- **photons**: energy calibration, precise identification, direction determination (pointing).

- **jets**: precise calibration (% level), stability in presence of large pile-up.

- **missing transverse energy**: stability in presence of large pile-up

- **b-jets** Good understanding of signal efficiency and misidentification rate.
Analysed final states

- Focus on the latest 13 TeV results - ATLAS (13.3 fb⁻¹) and CMS (12.9 fb⁻¹);
- H→bb: ATLAS-CONF-2016-080, CMS-PAS-HIG-16-038 (previous 13 TeV result) JHEP 05 (2016) 160 - Run 1 all-hadronic channel;
- H→γγ: ATLAS-CONF-2016-067, CMS-PAS-HIG-16-020;
- H→leptons: ATLAS-CONF-2016-058, CMS-PAS-HIG-16-022 (previous 13 TeV result);
- ttH combination: ATLAS-CONF-2016-068.

<table>
<thead>
<tr>
<th></th>
<th>H→bb</th>
<th>H→γγ</th>
<th>H→WW*</th>
<th>H→tt</th>
<th>H→ZZ*</th>
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</thead>
<tbody>
<tr>
<td>t¯t-allhad</td>
<td>Y</td>
<td>Y</td>
<td></td>
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<tr>
<td>t¯t-l+jets</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>t¯t-dilepton</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

Y - 13 TeV result  Y - 8 TeV result
Selection:
- semi-lepton / dilepton tt-decays - events with \( l l / 2l \) \& \( \geq 4j (\geq 2 \text{ btag}) / \geq 3j (\geq 2 \text{ btag}) \).

Categorisation based on N-jet & N-btag:
- High S/B regions - signal-like (S/B~1%-7%), low S/B regions used to control background and systematic uncertainties.

Main background \( \bar{t}t + \text{jets} \) Understanding of the \( \bar{t}t + \text{jets}(HF) \) modelling and associated uncertainties requires a huge effort (from the experiments and theorists) - backup;

Signal extraction - final discriminant:
1. BDT reconstruction technique or MEM to separate \( \bar{t}tH \) vs \( \bar{t}t+bb \);
2. Using 1 in combination with BDT that exploits full event kinematics.

BDT - Boosted Decision Tree, MEM - Matrix Element Method

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**Dominant systematics**

**Modelling of \( \bar{t}tH + \geq 1\) b, jet flavour tagging and \( \bar{t}tH \) modelling.**

**Normalisation of \( \bar{t}tH + \geq 1\) HF jet processes.**

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**95% confidence level upper limit of**

\[ \sigma < 4.0 \times \sigma_{SM} \ (1.9^{+1.4}_{-2.8} \ exp.) \]

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**95% confidence level upper limit of**

\[ \sigma < 1.5 \times \sigma_{SM} \ (1.7^{+0.7}_{-0.5} \ exp.) \]
**ttH(multilepton)**

- **Significant BR** \((WW \sim 20\%, ZZ \sim 3\%, \tau\tau \sim 6\%)\); 😊😔
- **Distinct multi-lepton signatures** from Higgs and top decays; 😊
- **Higgs reconstruction is difficult.** 😞

**Main background:**

- **Irreducible:** \(t\bar{t} + V\) and \(VV\) production - estimated from NLO MC and validated in data.
- **Reducible:** from non-prompt leptons (primarily from b hadron decays in \(t\bar{t}\)) and from prompt leptons with misidentified charge - data driven estimate;

**Targeted experimental signatures:** 2\(l\) (\(e, \mu\)) **of same charge** OR \(\geq 3l\) (to reduce \(t\bar{t}\)).

**Main background:**

- **Irreducible:** \(t\bar{t} + V\) and \(VV\) production - estimated from NLO MC and validated in data.
- **Reducible:** from non-prompt leptons (primarily from b hadron decays in \(t\bar{t}\)) and from prompt leptons with misidentified charge - data driven estimate;

**Selection and Signal extraction:**

- **ATLAS:** Tight selection \(\rightarrow\) high purity, cut and count analysis;
- **CMS:** MVA lepton selection, fit 2D BDT: \(t\bar{t}H\) vs \(t\bar{t}\) & \(t\bar{t}H\) vs \(t\bar{t}V\) (inc. MEM as input in \(\geq 3l\)).
Dominant systematics: Estimation of background from non-prompt leptons

95% confidence level upper limit of
\( \sigma < 4.9 \times \sigma_{SM} \) (2.3\(^{+1.1}_{-0.6}\) exp.)

95% confidence level upper limit of
\( \sigma < 3.4 \times \sigma_{SM} \) (1.3\(^{+0.6}_{-0.4}\) exp.)
**ttH(\gamma\gamma)**

Strategy (a category of the H→\gamma\gamma couplings analysis):
- look for a bump over a smooth background in the di-photon invariant mass spectrum;
- **Categories**: Selected 2 photons + ≥ 1/0l + additional jet requirements enhancing leptonic / hadronic tt decays;

Signal modelling:
- ATLAS: Double-sided crystal ball function;
- CMS: Sum of Gaussians.

Background modelling:
- ATLAS: exponential function extracted from side bands;
- CMS: Sum of exponentials or power law terms, Laurent series and polynomials;

*Small BR ~ 0.2% 😞*
*Higgs boson can be reconstructed as a narrow peak 😊*
*parametrisable background. 😊*

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28.11 - 02.12, 2016
### Figure 14

The signal strength measured for the different production processes (ggH, VBF, VH, and ttH) and globally, compared to the global signal strength measured at 7 and 8 TeV [13]. The error bar shows the total uncertainty. The μ_Run1 is taken from Ref. [13], and is derived assuming the Higgs production cross section based on Ref. [19, 87]. In the more recent theoretical predictions used in this analysis [24, 28], the gluon fusion production cross section is larger by approximately 10%.

### 10.2.3 Impact of fixing the Higgs mass

Figure 9 shows that the nuisance parameter associated with the photon energy scale uncertainty is slightly pulled, which indicates that the best value for the Higgs boson mass in the dataset analysed here is a bit different from 125.09 GeV. When the Higgs boson mass is left free in the fit, the measured cross sections and signal strengths differ only by a small fraction of the statistical uncertainty from the results with m_H = 125.09 ± 0.24 GeV. The fitted Higgs boson mass is compatible with m_H = 125.09 ± 0.24 GeV within its statistical uncertainty.

### Conclusion

Measurements of the Higgs boson cross sections in the Higgs boson diphoton decay channel are performed using pp collision data recorded by the ATLAS experiment at the LHC. The data were taken at a centre-of-mass energy of \( \sqrt{s} = 13 \) TeV and correspond to an integrated luminosity of 13.3 fb\(^{-1}\). Fiducial cross sections in several phase space regions and differential cross sections as a function of several kinematic variables are performed in an almost model-independent way. The fiducial cross section is measured to be \( \sigma_{\text{fid}} = 43.2 \pm 14.9 \) (stat.) \( \pm 4.9 \) (syst.) fb for a Higgs boson of mass 125.09 GeV decaying to two isolated photons that have transverse momentum greater than 35% and 25% of the diphoton invariant mass and each with absolute pseudorapidity \( |\eta| < 2.37 \), excluding the region 1.37 < |\eta| < 1.52. The Standard Model prediction for the same fiducial region is 62.8 \(+3.4\) \(-4.4\) fb. Simplified template cross sections and

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The result is heavily dominated by the statistical uncertainty. By the end of Run 2, we expect to have factor of ~3 reduction in statistical uncertainty.
Run 1 precision already reached with ~13 fb⁻¹ of Run 2 data! No significant deviations from the SM observed at both experiments. Stay tuned for the new results from CMS and ATLAS using full 2015+2016 statistics ~ 35 fb⁻¹.
tH production
tH production at the LHC

- CMS Run2: tH(bb) - CMS PAS HIG-16-019, Run1: tH(bb, multi-lepton, γγ) - CMS-HIG-14-027, ATLAS Run 1 indirect constraint in H→γγ - Physics Letters B 740 (2015);
- Both t-channel (tHq) and tW production (tHW) considered;

- **tH** - sensitive to magnitude and sign of Higgs-top-Yukawa coupling
  - SM assumption $\kappa_t = 1$ - destructive interference, $\sigma_{SM}(tH) \sim 90$ fb$^{-1}$;
  - $\kappa_t = -1$ (if BSM contributions allowed in the loops), $\sigma(tH) \sim 10 \times \sigma_{SM}$;
- Analysis Strategy: Similar to ttH. Benefit from forward jet tag. Dedicated sig. vs bkg BDT for each ($\kappa_t, \kappa_V$) point (in case of tHq event reconstruction for tHq and tt-bkg).

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Results of the direct $tH$ search

- Run 2 $tH(bb)$ result

![Graph showing 95% C.L. expected limit on $\frac{\sigma_{obs}}{\sigma_{exp}}$ vs $k_t$ for $pp \rightarrow tH$, $H \rightarrow b\bar{b}$, $t \rightarrow b\ell\nu$ with $k_{\ell\nu} = +1.0$.]

- Excluding SM $tH$ production above $113.7$ (obs.) and $98.6$ (exp.) $\times \sigma_{SM}$

- Exclusion at $k_t=-1.0$ $6.0$ (obs.) and $6.4$ (exp.) $\times \sigma_{k_t=-1}$

- Run 1 $tH(bb,\tau\tau,leptons,\gamma\gamma)$ result

![Graph showing 95% C.L. limit on $\frac{\sigma}{\sigma_{Ct=-1}}$ vs $m_{tH}$ for $pp \rightarrow tHq$, $t \rightarrow b\ell\nu$, $C_t=-1$, $m_H=125$ GeV.]

- From all channels combined in Run 1 exclusion at $k_t=-1$ $2.8$ (obs.) and $2.0$ (exp.) $\times \sigma_{k_t=-1}$

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BSM charged Higgs searches

Many extensions of the SM, as well as suppressed SM scenarios, sensitive to Higgs-top interactions:

- Flavour changing neutral current: $t \rightarrow qH$
- Vector-like heavy top partner
- Charged Higgs boson searches within the top sector (SUSY, 2HDM, …)
- …
Search for $H^\pm$ within top sector

- Charged Higgs bosons can be produced in decays of ($m_{H^\pm} < m_{top}$) or in association with ($m_{H^\pm} > m_{top}$) a top quark
  - Experiments explore several $H^\pm$ decay modes (cs, cb, tb, $\tau\nu$, AW)

**Light $H^\pm (m_{H^\pm} < m_{top})$**

**Heavy $H^\pm (m_{H^\pm} > m_{top})$**

**$H^\pm$ near top mass**

- In the region **near the top mass**, finite top-width effects as well as the interplay between top-quark resonant and non-resonant diagrams cannot be neglected
  - **Recent TH development**: Precision computation of the $H^\pm$ production with $m_{H^\pm} \sim m_t$ (Degrande et al., 1607.05291). Opens doors for new searches!
Searches for light $H^\pm$ (top sector)

- Searches based on $t \rightarrow H^\pm b$ decays
- Zoology of models with different branching ratios
- Searches at Tevatron:
  - CDF $t \rightarrow H^\pm (AW) b$, $t \rightarrow H^\pm (cs) b$:
    - CDF note 10104, 10.1103/PhysRevLett.103.101803
  - D0 $t \rightarrow H^\pm (\tau V/c s) b$:
- Searches at LHC:
  - CMS 8 TeV $t \rightarrow H^\pm (cs) b$, 8 TeV $H^\pm$ legacy:
  - ATLAS 7 TeV $t \rightarrow H^\pm (cs) b$:

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Many searches also interpreted in SUSY / 2HDM

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  DZero $t \to H^\pm (TV/cs) b$
  
  \[ \text{CDF note 10104, 10.1103/PhysRevLett.103.101803} \]

- Searches at LHC:
  CMS 8 TeV $t \to H^\pm (cs) b$, 8 TeV $H^\pm$ legacy
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Many searches also interpreted in SUSY / 2HDM

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Searches for **light** \( H^{\pm} \) (top sector)

- Searches based on \( t \to H^{\pm} b \) decays
- Zoology of models with different branching ratios
- Searches at Tevatron:
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  DZero $t \rightarrow H^\pm (\tau\nu/cs)b$:
- Searches at LHC:
  CMS 8 TeV $t \rightarrow H^\pm (cs)b$, 8 TeV $H^\pm$ legacy:
  ATLAS 7 TeV $t \rightarrow H^\pm (cs)b$:

$H^\pm \rightarrow AW$

Many searches also interpreted in SUSY / 2HDM

Searches almost exclude a light charged Higgs in MSSM scenarios (Type II 2HDM align. limit).

This is still not true across other models!

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Searches for heavy $H^\pm$ (top sector)

- Searches based on $H^\pm \rightarrow \tau\nu$ decays:
  - **ATLAS 13 TeV $H^\pm \rightarrow \tau\nu$:**
    - ATLAS-CONF-2016-088
  - **CMS 13 TeV $H^\pm \rightarrow \tau\nu$:**
    - CMS-PAS-HIG-16-031

- Searches based on $H^\pm \rightarrow tb$ decays:
  - **ATLAS 13 TeV $H^\pm \rightarrow tb$:**
    - ATLAS-CONF-2016-089
  - **CMS 8 TeV $H^\pm$ legacy:**
    - JHEP 11 (2015) 018

\[ H^\pm \rightarrow \tau\nu \]
\[ H^\pm \rightarrow tb \]
**Searches for heavy $H^{\pm}$ (top sector)**

- **Searches based on $H^{\pm} \rightarrow TV$ decays:**
  - ATLAS 13 TeV $H^{\pm} \rightarrow TV$:
    - ATLAS-CONF-2016-088
  - CMS 13 TeV $H^{\pm} \rightarrow TV$:
    - CMS-PAS-HIG-16-031

- **Searches based on $H^{\pm} \rightarrow tb$ decays:**
  - ATLAS 13 TeV $H^{\pm} \rightarrow tb$:
    - ATLAS-CONF-2016-089
  - CMS 8 TeV $H^{\pm}$ legacy:
    - JHEP 11 (2015) 018

Many searches also interpreted in SUSY / 2HDM

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Searches for $H^\pm$ (top sector)

No sign of charged Higgs yet in any of the searches!
Summary

- Higgs and top are here - experiments started to play games with them...
- Interplay between the Higgs and top allows for indirect tests of the consistency of the SM via LEP / Tevatron / LHC measurements
- Limits on Higgs-top couplings from ATLAS & CMS (Run 1):
  - Most precise constraints through parametrisation of all accessible production and decay modes (mainly indirect, via loop diagrams);
  - $t\bar{t}H$ measurement in all accessible final states at LHC
  - Most precise direct constraint on Higgs-top Yukawa coupling;
  - $tH$ measurement allows constraints on sign of Higgs-top-Yukawa coupling;
  - Experiments also actively explore a wide range of BSM models, including those with $H^\pm$ that couples to top quark (SUSY, 2HDM, etc.)
    - Searches in both low-mass and high-mass $H^\pm$ scenarios;
- All measurements compatible with SM predictions at current precision.
Backup
The selection criteria following the selection applied to the Run-I data. A significant increase in state, any single object inefficiency is potentiated. The Run-I analysis uses electrons with a large rapidity coverage are key. Since four leptons need to be reconstructed in this final physics program. Excellent electron and muon reconstruction at low transverse momentum is crucial for the Higgs boson fusion. Selecting these events with the largest possible acceptance is crucial to the Higgs boson. The HL-LHC will produce about sixteen thousand Higgs boson events per experiment in the full four lepton mass spectrum contains information of the total width of the Higgs boson. From the SM in the study of Higgs boson couplings. As mentioned before, the analysis of the determination of the production rate of the Higgs boson is crucial for searches for deviations from the SM in the study of Higgs boson couplings. As mentioned before, the analysis of the determination of the production rate of the Higgs boson is crucial for searches for deviations from the SM in the study of Higgs boson couplings.

**Figure 10.2: Estimated precision on the measurements for modified couplings for a SM-like Higgs boson**

<table>
<thead>
<tr>
<th>Higgs boson decay mode</th>
<th>CMS Projection</th>
<th>ATLAS Simulation Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma \gamma$ (comb.)</td>
<td>$\Delta \mu/\mu$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow ZZ$ (comb.)</td>
<td>$\Delta \mu/\mu$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow WW$ (comb.)</td>
<td>$\Delta \mu/\mu$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$ (incl.)</td>
<td>$\Delta \mu/\mu$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow b\bar{b}$ (comb.)</td>
<td>$\Delta \mu/\mu$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$ (VBF-like)</td>
<td>$\Delta \mu/\mu$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$ (comb.)</td>
<td>$\Delta \mu/\mu$</td>
<td></td>
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</tbody>
</table>

The projections are obtained with two uncertainty scenarios as described in the text.
**tH+Jets background in tH(bb)**

**CMS:**
- Powheg+Pythia8 normalised to NNLO prediction;
- separate templates for t¯t +b, t¯t +bb, t¯t +2b*, t¯t +≥1c, t¯t +≥1LF;

**ATLAS:**
- Powheg+Pythia6 normalised to NNLO prediction;
- pT(t) & pT(tt) corrected to NNLO prediction for t¯t +≥1c and t¯t +≥1LF;
- t¯t +b, t¯t +bb and t¯t +B corrected to Sherpa +OpenLoops NLO calculation;
- normalisation for t¯t +≥1b and t¯t +≥1c free floating in the fit.

* CMS t¯t +2b corresponds to ATLAS t¯t +B

**CMS 13 TeV tH+bb measurement** CMS-PAS-TOP-16-010:

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Higgs and top mass - prospects

68% and 95% CL contours w/o $M_W$ and $\kappa_V$ measurement
- Present SM fit
- Prospect for LHC
- Prospect for ILC/GigaZ

$\kappa_V$ private LHC average $\pm 1\sigma$

$\kappa_V = \frac{4\pi V}{\sqrt{\langle |\Delta S|^2 \rangle}}$

Higgs production at LHC

Production mechanisms

**ggF**
- 87%
- Largest cross-section, largest theory uncertainties;

**VBF**
- 7%
- Characteristic signature with 2 jets separated in $\eta$;

**VH**
- 5%
- Reduced QCD multijet backgrounds;

**q\bar{q}H**
- 1%
- Signature characterised by 2 b-jets + additional jets or leptons
ttH production

\[ \sigma_{t\bar{t}H}(13\,\text{TeV}) \sim 4 \times \sigma_{t\bar{t}H}(8\,\text{TeV}) \]

Phase space opening

\[ M_x = 2M_t + M_H \text{ in } gg \]

\[ \begin{array}{|c|c|}
\hline
\text{Process} & \sigma(13 \, \text{TeV}) / \sigma(8 \, \text{TeV}) \\
\hline
\text{gg} \to H & \sim 2.3 \quad (M_X = M_H) \\
\text{qq} \to H & \sim 2.4 \quad (\text{probes high } M_X) \\
\text{qq} \to VH & \sim 2.0 \quad (M_X = M_V + M_H) \\
\text{qq} \to ttH & \sim 3.9 \quad (\text{phase space } + M_X) \\
\text{tt} & \sim 3.3 \quad (\text{gg} \to tt \text{ dominates}) \\
\hline
\end{array} \]
Higgs boson decays

Production mechanisms

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>87%</td>
</tr>
<tr>
<td>VBF</td>
<td>7%</td>
</tr>
<tr>
<td>VH</td>
<td>5%</td>
</tr>
<tr>
<td>ttH</td>
<td>1%</td>
</tr>
</tbody>
</table>

SM Higgs boson decay modes

Many decay modes accessible for $m_H = 125$ GeV

Bosonic decays: $ZZ, WW, \gamma\gamma, Z\gamma$
Fermionic decays: $b\bar{b}, \tau\tau, \mu\mu$
**BR(H\(^\pm\))**

- **NEW**: $H^{\pm} \rightarrow c \bar{b}$ (HIG-16-030)
- **NEW**: $H^{\pm} \rightarrow \tau \nu_{\tau}$ with $\tau \rightarrow h + \text{jets}$ (HIG-16-031)

<table>
<thead>
<tr>
<th>$M_{H^{\pm}}$ [GeV]</th>
<th>BR($H^{\pm}$)</th>
<th>BR($H^{\pm} \rightarrow tb$)</th>
<th>BR($H \rightarrow cs$)</th>
<th>BR($H \rightarrow \tau \nu_{\tau}$)</th>
<th>BR($H \rightarrow \mu \nu_{\mu}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-4}$</td>
<td>$10^{-2}$</td>
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<td></td>
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<td>$10^{-3}$</td>
<td>$10^{-1}$</td>
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<tr>
<td>$10^{-2}$</td>
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<tr>
<td>$10^{0}$</td>
<td>$10^{1}$</td>
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</tr>
</tbody>
</table>

- **Run I (7–8 TeV)**
- **Searches at CMS**
  - $H^{\pm} \rightarrow \tau \nu_{\tau}$ (HIG-14-023, Charged14)
  - $\tau h + \text{jets}$, $\mu \tau h$, dilepton

**LHC Higgs XS WG 2013**

$m_h^{mod^+}$, $\tan\beta = 10$