Higgs Production in Association with Top Quarks in CMS
WHY TOP AND HIGGS?
Yukawa self-coupling
Higgs

Top
Daniele del Re

Top

Yukawa self-coupling

Higgs cosmology

naturalness

New Physics
flavour hierarchy SUSY

FCNC dark matter

2HDM

New Physics

Composite Higgs

self-coupling

Yukawa

Higgs

naturalness

cosmology

Top
WHERE
How (experimentally)

CMS Detector
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

Steel Return Yoke: 12,500 tonnes

Silicon Trackers
- Pixel (100x150 μm) ~16m² ~66M channels
- Microstrips (80x180 μm) ~200m² ~9.6M channels

Superconducting Solenoid
- Niobium titanium coil carrying ~18,000A

Muon Chambers
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

Preshower
- Silicon strips ~16m² ~137,000 channels

Forward Calorimeter
- Steel + Quartz fibres ~2,000 Channels

Crystal Electromagnetic Calorimeter (ECAL)
- ~76,000 scintillating PbWO₄ crystals

Hadron Calorimeter (HCAL)
- Brass + Plastic scintillator ~7,000 channels

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CMS Integrated Luminosity, pp
- Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC

- 2010, 7 TeV, 44.2 fb⁻¹
- 2011, 7 TeV, 6.1 fb⁻¹
- 2012, 8 TeV, 23.3 fb⁻¹
A threefold way to $\text{Top+Higgs}$

**INDIRECT:**
- Direct Higgs Production
- Higgs decay to photons

**DIRECT:** absolute Yukawa
- Top-antitop-Higgs Production

**DIRECT:** Yukawa sign
- Top(antitop)-Higgs Production

**CMS** EPJ. C 75 (2015) 212

**CMS-HIG-14-001** ($\gamma\gamma$)
**CMS-HIG-14-015** ($bb$)
**CMS-HIG-14-026** (leptons)
**CMS-HIG-14-027** (tau+combination)

**JHEP** 09 (2014) 087 ($\text{comb}$)
**EPJ C** 75 (2015) ($bb$ ME)
Dig Deeper into the LHC Gold

Higgs cross sections 8TeV pp collisions

1,000,000 fb
100,000 fb
10,000 fb
1,000 fb
100 fb
10 fb

- gg→H
- Hqq
- HW
- ZH
- ttH
- tHq
Dig Deeper into the LHC Gold

Higgs cross sections 8TeV pp collisions

2 orders of magnitude

1,000,000 fb

100,000 fb

10,000 fb

1,000 fb

100 fb

10 fb

gg → H

Hqq

HW

ZH

tH

tHq

10 fb
DIG DEEPER INTO THE LHC GOLD

Higgs cross sections 8TeV pp collisions

1,000,000 fb

100,000 fb

10,000 fb

1,000 fb

100 fb

10 fb

gg→H

Hqq

HW

ZH

tH

ttH

tHq

3 orders of magnitude

2 orders of magnitude

3 orders of magnitude
**TTH: VERY COMPLEX FINAL STATE**

- Cross section is only $\sim 1/200$ of the inclusive Higgs production cross section

- Large multiplicity of objects in the final state
  - top quarks decay to $Wb$, $W$ bosons decay in turn leptonically ($l\nu$) or hadronically ($qq$)
  - Higgs bosons decay to anything but top quarks…

- Need to find the best combination of top and Higgs decays to isolate the small signal (130fb)

![Diagram showing the decay of a Higgs boson to two top quarks.]
**TTH: VERY COMPLEX FINAL STATE**

- Cross section is only \( \sim \frac{1}{200} \) of the inclusive Higgs production cross section
- Large multiplicity of objects in the final state
  - top quarks decay to \( Wt, W \) bosons decay in turn leptonically (\( l\nu \)) or hadronically (\( q\bar{q} \))
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- Need to find the best combination of top and Higgs decays to isolate the small signal (130 fb)
$tth$, Higgs to $b$ antib
**TT\(\bar{H}\), Higgs to b antib"\**

- Single lepton and dilepton selections to suppress large multi-jet background
- Remaining backgrounds dominated by \(tt+bb\), mis-tagged \(tt+light\) and \(tt+cc\)
- Categorise on number of leptons/jets/b-tagged jets
- CMS has 2 analyses: first discriminates through boosted decision trees, second through matrix element technique

### Boosted decision trees

Exp(obs) upper limit of 3.5(4.1)
the SM cross section

### Matrix element

Exp(obs) upper limit of 3.3(4.2)
the SM cross section
ttH, Higgs to Gamma Gamma
**Higgs to Gamma Gamma**

- Very low rate, but distinctive signature of the Higgs peak. Backgrounds are coming from top(s) + photon(s), or photons + (b)jets, latter poorly known at theoretical level
- Split into events with leptons and few jets (leptonic) or no leptons and many jets (hadronic)

![Graphs showing CMS ttH γγ events](image)

Event selection minimizes contamination from other Higgs sources

<table>
<thead>
<tr>
<th>Process</th>
<th>Hadronic Channel</th>
<th>Leptonic Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttH</td>
<td>0.567 (87%)</td>
<td>0.429 (97%)</td>
</tr>
<tr>
<td>gg → H</td>
<td>0.059 (9%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>VBF H</td>
<td>0.006 (1%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>WH/ZH</td>
<td>0.019 (3%)</td>
<td>0.013 (3%)</td>
</tr>
<tr>
<td>Total signal</td>
<td>0.65</td>
<td>0.44</td>
</tr>
</tbody>
</table>

- Fitting the diphoton peak greatly reduce sensitivity to background systematics
TTH TO MULTILEPTON
**TT\(H\) TO MULTILEPTON**

- Strategy for H->WW/tautau: same sign dilepton, trilepton, four leptons
- Pretty high acceptance rate, good signal-to-background ratio
- Dedicated multivariate lepton identification to suppress ttbar backgrounds
- Divide into subchannels, optimize S-B discrimination to maximize sensitivity to the signal
CMS COMBINATION ON ttH

- Set 95% confidence level limits on ttH
- Combined exp(obs) limit of $1.7(4.5) \times$ SM
CMS COMBINATION ON tth

- Set 95% confidence level limits on tth
- Combined exp(obs) limit of 1.7(4.5) X SM
- Interpreting the result as a cross section measurement
- Combined signal strength multiplier $\mu=2.8^{+1.0}_{-0.9} \times SM$
Single top plus Higgs

- Early Higgs data allowed inverted sign of the coupling of Higgs to fermions, relative to Higgs to bosons, due to interference between Htt and HWW in the Higgs to diphoton decay
- Single top plus Higgs production would be severely enhanced if that was the case

- t-channel tHq production especially sensitive to sign of Yukawa coupling, as it would bring large enhancement in cross section (x10-20, would exceed ttH production)
- Single top plus Higgs would be sensitive to other new physics greatly enhancing its rates:
  - non-diagonal Yukawa/new physics in tHu/tHc flavor-changing-neutral-currents
**THQ: VERY COMPLEX FINAL STATE**

- Cross section is only $\sim 1/1000$ of the inclusive Higgs production cross section
- Large multiplicity of objects in the final state (signature is dominated by the $t/t\bar{t}$ decays)
- Best combination of top and Higgs decays to isolate the small signal - apply lessons learned for $ttH!$

- For the time being, focus on negative Yukawa scenario: cross section $O(200fb)$
- use only leptonic top quark decay to increase signal-to-background ratio
- now combined result as well!

![Pie chart showing event categories: tau+jets (11%), mu+jets (11%), e+jets (11%), and jets (66%).](image)

![Graph showing branching ratios for various processes.](image)
THQ: VERY COMPLEX FINAL STATE

- Cross section is only ~1/1000 of the inclusive Higgs production cross section
- Large multiplicity of objects in the final state (signature is dominated by the t/tbar decays)
- Best combination of top and Higgs decays to isolate the small signal - apply lessons learned for ttH!

- For the time being, focus on negative Yukawa scenario: cross section O(200fb)
- use only leptonic top quark decay to increase signal-to-background ratio
- now combined result as well!
**THQ, HIGGS TO PHOTONS**

**Two step analysis: first cut and count selection**

- 2 photons with $p_T > 50 \text{ GeV}$ and $25 \text{ GeV}$
- 1 lepton with $> 10 \text{ GeV}$ and $\Delta R > 0.5$ w.r.t. photons
- 1 b-tagged jet with $> 20 \text{ GeV}$
- No cut on $E/T$
- Hardest additional jet, must have $p_T > 20 \text{ GeV}$ and $|\eta| > 1$

![Diphoton Mass Plot](image-url)

*Data* vs *Extra ttH (Ct = -1)* vs *ttH (125)* vs *VH (125)*

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**Notes:**

- CMS (Unpublished), $L = 19.7 \text{ fb}^{-1}$ at $\sqrt{s} = 8 \text{ TeV}$
- [Graphical representation of the CMS experiment](image-url)
Then multivariate selection to suppress backgrounds further

- No events in the signal region
- Non-resonant background estimation via fit in loosened $m(\gamma\gamma)$-sideband regions
- Set 95% upper level confidence limit of 4.1 for $\sigma X_{BR}$ for $tHq$ production with negative Yukawa
THQ, $H \rightarrow \bar{B}B$AR

- The most advanced analysis of the set
- 1 lepton
- Split events according to number of identified b-jets (a forth b-jet may arise from gluon splitting)
- Two multivariate discriminator to assign jets to decaying particles (regression)
- One more multivariate technique to discriminate signal from background (classification)

<table>
<thead>
<tr>
<th>Sample</th>
<th>S/B</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 b jets</td>
<td>13/1900</td>
</tr>
<tr>
<td>4 b jets</td>
<td>1.4/66</td>
</tr>
</tbody>
</table>
THQ, H $\rightarrow$ BBAR

3btags, higher acceptance

4btags, better S/B
THQ to Multilepton

- Three W bosons
- One b-jet
- One light (forward) jet

Best channels for $H \rightarrow WW$
- same sign dileptons
- three leptons

Leptons:
- $p_t > 20 \text{GeV} (\text{SS2L})$ 10GeV (3L)
- $t\bar{t}H$ derived machine-learning-optimized lepton identification (SS2L)

Jets
- $p_t > 25 \text{GeV}$ $\eta < 4.7$
- b-tagging
No significant signal - setting 95% confidence level upper limits

<table>
<thead>
<tr>
<th>Channel</th>
<th>Observed</th>
<th>Expected</th>
<th>68% prob. band</th>
<th>95% prob. band</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS $\mu\mu$</td>
<td>9.3</td>
<td>8.1</td>
<td>[6.0, 11.8]</td>
<td>[4.7, 16.7]</td>
</tr>
<tr>
<td>SS $e\mu$</td>
<td>11.4</td>
<td>9.3</td>
<td>[7.0, 13.5]</td>
<td>[5.4, 18.8]</td>
</tr>
<tr>
<td>$3\ell$</td>
<td>11.5</td>
<td>8.6</td>
<td>[6.6, 12.4]</td>
<td>[5.7, 18.0]</td>
</tr>
<tr>
<td>combined</td>
<td>6.7</td>
<td>5.0</td>
<td>[3.6, 7.1]</td>
<td>[2.9, 10.3]</td>
</tr>
</tbody>
</table>

expected (observed) limit at 5 (6.7) times cross section on $\sigma(tHq, Ct=-1)$
Three $W$ bosons

One $b$-jet

One light (forward) jet

Best channels for $H \rightarrow \tau\tau$:
  - same sign dileptons+hadronic tau

Leptons:
  - $p_T > 20 \text{GeV (SS2L)}$ 10 GeV (3L)
  - $ttH$ derived machine-learning-optimized lepton identification (SS2L)
  - tau ID experience from $H \rightarrow \tau\tau$

Jets
  - $p_T > 25 \text{GeV}$ $\eta < 4.7$
  - $b$-tagging
THQ to multilepton + tau

<table>
<thead>
<tr>
<th>Process</th>
<th>$e\mu\tau_h$</th>
<th>$\mu\mu\tau_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tHq, C_t = -1$</td>
<td>$0.42 \pm 0.05$</td>
<td>$0.26 \pm 0.03$</td>
</tr>
<tr>
<td>$tHW, C_t = -1$</td>
<td>$0.06 \pm 0.01$</td>
<td>$0.04 \pm 0.01$</td>
</tr>
<tr>
<td>$ttH$</td>
<td>$0.6 \pm 0.1$</td>
<td>$0.3 \pm 0.1$</td>
</tr>
<tr>
<td>$ttV$</td>
<td>$1.8 \pm 0.4$</td>
<td>$0.9 \pm 0.2$</td>
</tr>
<tr>
<td>$VV$</td>
<td>$0.7 \pm 0.1$</td>
<td>$0.3 \pm 0.1$</td>
</tr>
<tr>
<td>Reducible</td>
<td>$6.3 \pm 3.1$</td>
<td>$4.5 \pm 1.9$</td>
</tr>
<tr>
<td>Tot. background</td>
<td>$9.5 \pm 3.7$</td>
<td>$5.4 \pm 2.4$</td>
</tr>
<tr>
<td>Data</td>
<td>5</td>
<td>7</td>
</tr>
</tbody>
</table>
Interpretation #1

Limits on the event yields on the analyzed channels, predicted by the inverted Yukawa sign hypothesis:

2.1 (2.8) exp (obs) on $Y_t=-1$ event yields prediction

Interpretation #2

generic limits on single top plus Higgs production scanning values around SM Higgs to diphoton decay:

Upper limit of $700(1000) - 425(600) fb$ exp(obs) depending on assumed Higgs to diphoton branching ratio
CONCLUSIONS

• Each way to probe top-Higgs has his own th+exp. advantages/disadvantages - CMS is developing a *strong, synergic effort* to exploit different production and decay modes

• *Direct exploration* of top-Higgs coupling will soon allow *independent probe on SM*

• New physics would modify direct Higgs production, ttH, and tH in *different* ways
CONCLUSIONS

• Each way to probe top-Higgs has his own th+exp. advantages/disadvantages - CMS is developing a strong, synergic effort to exploit different production and decay modes
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The coming data will allow us to navigate uncharted top and Higgs territories!
CONCLUSIONS

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• New physics would modify direct Higgs production, ttH, and tH in different ways

The coming data will allow us to navigate uncharted top and Higgs territories!

Thanks!!
BACKUP
LHC in 2016 will reach sensitivity forecasted in the CMS physics TDR for 300fb-1 of 14TeV LHC (~2022)
Several other new physics models could alter single top plus Higgs production rates and/or kinematics:

- FCNC
- Composite Higgs
- CP violation
- who knows?

S.Biswas, E.Gabrielli, FM, B.Me  JHEP 07 (2013) 073

Farina, Grojean, Maltoni, Salvioni, Thamm  JHEP 05 (2013) 022
HIGGS SELF-COUPLING
t+H is the next goal in both Higgs physics, and in top physics.
SINGLE TOP PLUS HIGGS

\[ pp \rightarrow tH \]

\[ \sqrt{s} = 8 \text{ TeV} \]
\[ m_H = 125 \text{ GeV} \]
\[ C_f = C_t \]
\[ C_V = 1 \]
**Single top plus Higgs**

- $pp \rightarrow tH$

Diagram showing the production of single top plus Higgs boson at 8 TeV, with $m_H = 125$ GeV.
**THQ, HIGGS TO PHOTONS**

CMS Simulation (Unpublished), $\sqrt{s} = 8$ TeV

- $tHq$
- $ttH / tt+\gamma$

**Normalized to Unity**

- $|\Delta\eta| (\text{lepton-qJet})$
- Lepton Charge
- Jet Multiplicity
- Top Transverse Mass [GeV]
- $\eta$ qJet

CMS-HIG-14-001

Fabrizio Margaroli

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THQ TO MULTILEPTON
THQ to multilepton
Interchannel Overlap?

- Residual overlap well below 1%
- No common events on data
**ttH and tHq Multilepton**

In the dilepton channels ($\mu\mu/\mu\mu$), ttH* has a tighter selection than tHq, but does not require forward jets

**tHq 2IiSS Selection**
- $\geq 1$ jet with $|\eta| > 1$
- $\geq 1$ jet with $|\eta| < 1$
- $\geq 1$ jet with loose CSV tag
- Veto hadronic $\tau$'s

**ttH 2IiSS Selection**
- $p_{T,1} + p_{T,2} + ME_T > 100$ GeV
- $\geq 4$ jets ($|\eta| < 2.4$)
- $\geq 2$ jets with loose CSV **OR** $\geq 1$ jet with medium CSV

- Remaining selection is identical
- By construction, no migration between the dilepton and ttH channels
Title
**Overlap for 3l analysis**

**tHq 3l Selection**
- $\geq 1$ (non-tagged) fwd-jet ($|\eta| > 1.5$)
- $M_{E_T} > 30$ GeV
- $\geq 1$ jet with med. CSV tag

**ttH 3l Selection**
- $\geq 2$ jets ($|\eta| < 2.4$)
- $M_{E_T}L^d* > 0.2$ **OR** $\geq 4$ jets
- $\geq 2$ jets with loose CSV **OR** $\geq 1$ jet with medium CSV

- Remaining selection very similar (Z-veto, $m_\parallel$ cuts, add. lep veto)
- Different lepton object selections
- Possible migration between tHq-3l and ttH-2l channels (see sl. 50)
3l Channel

$ttH$ Sample

$ttH$ Selection

$tHq$ Selection

1641

301

353

1939

902

1647
μμ Channel

- Slight difference in yields of ttH selection compared to HIG-13-020 PAS due to ReReco: $41 \rightarrow 39 \, (\mu\mu), \, 51 \rightarrow 51 \, (e\mu), \, 68 \rightarrow 62 \, (3l)$
TECHNICALITIES

Signal and background modeling
• ttH, WW, WZ, ZZ Pythia
• ttW/ttZ/ ttgamma/ ttgammagamma/ gamma+jets/ gammagamma+jets MadGraph
• tq/tW Powheg

btagging
• Combined secondary vertex, medium OP
• H->bb also uses full CSV spectrum

Triggers used:
• Diphoton trigger
• Electron trigger
• Muon trigger
• ee/emu/mumu triggers
Systematics THQ Multilepton

- PDF and QCD scales
  - $tHq$: 4.6% from PDF, 1.1% from $Q^2$ scale
  - 10/11/6% for $ttW/ttZ/ttH$ from $Q^2$ scale
  - 7-9% for $ttV$ from PDFs, 8% for $ttH$

- 4 vs 5 flavor scheme
  - Study difference in selection efficiency and cross section on parton level, assign 10% (SS2L), 16% (3L)

- Pileup reweighting
  - Vary total inelastic cross section by 5%
SYSTEMATICS THQ MULTILEPTON

• SS2L non-prompt estimate: **about 50%**
  • Data/MC agreement of fake rates: 50% ($\mu\mu$), 40% $\oplus$ 20% (e$\mu$) (rate)
  • Variations of fake rate by $p_T/\eta$ (10-20%) (shape)

• SS2L charge mis-identification estimate: **about 30%**
  • Propagated uncertainty on measured probabilities (rate)

• 3L non-prompt estimate: **about 35%**
  • MC closure test (30%) (rate)
  • Statistical errors of measured fake rates (shape)
  • Varying the $ME_T$ cut in control region (shape)
Next, a multivariate discriminator based on BDT techniques is used to distinguish prompt from non-prompt leptons. This discriminator, referred to as the lepton MVA, is trained with simulated prompt leptons from the ttH MC sample and non-prompt leptons from the tt+jets MC sample, separately for electrons and muons and for several bins in pT and \( \eta \).

The lepton MVA input variables relate to the lepton IP, isolation, and the properties of the nearest jet, within \( \Delta R < 0.5 \). A tight working point on the lepton MVA output is used for the search in the dilepton and trilepton final states, and a loose working point is used for the four-lepton final state. For the tight working point, the efficiency to select prompt electrons is of order 35\% for \( p_{T} \sim 10 \text{ GeV} \) and reaches a plateau of 85\% at \( p_{T} \sim 45 \text{ GeV} \); for prompt muons it is of order 55\% for \( p_{T\mu} \sim 10 \text{ GeV} \), and reaches a plateau of about 97\% at \( p_{T\mu} \sim 45 \text{ GeV} \). The efficiency to select electrons (muons) from the decay of b hadrons is between 5–10\% (around 5\%).
**$H \rightarrow BB, \ TT \rightarrow LJETS\ OR\ DILEPTON$**

- Identify tops and Higgs via multiple b-tagged jets, leptons (ele/muons) and light flavor jets
- Split into Njet/Nbtag categories to further increase sensitivity
- For each category, use machine learning techniques to discriminate signal from dominant $tt + bb/cc/b$ backgrounds

- Fit over resulting shapes, systematics modify relative normalization and shapes themselves
  - largest systematic is on the poorly known $tt+bb/cc/b$ background
• Set 95% expected (observed) upper level confidence limit of 5.1 (7.6) the sigmaXBR for tHq production with negative Yukawa
TT\(H, H \rightarrow \text{TAUTAU}\)

- Select hadronically decaying taus, coming from the Higgs decay, reconstructed via a Particle Flow algorithm
- Select additional b-jets, leptons, light flavor jets consistent with ttbar decays, split into Njets and Nbtags categories

<table>
<thead>
<tr>
<th></th>
<th>4 jets 1 b-tag</th>
<th>5 jets 1 b-tag</th>
<th>(\geq 6) jets 2 b-tags</th>
<th>4 jets 2 b-tags</th>
<th>5 jets 2 b-tags</th>
<th>(\geq 6) jets 2 b-tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>tt(H(125))</td>
<td>0.4 ± 0.1</td>
<td>0.6 ± 0.1</td>
<td>0.6 ± 0.2</td>
<td>0.1 ± 0.0</td>
<td>0.2 ± 0.1</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>tt</td>
<td>225 ± 69</td>
<td>119 ± 38</td>
<td>64 ± 22</td>
<td>48 ± 15</td>
<td>38 ± 12</td>
<td>27.0 ± 9.1</td>
</tr>
<tr>
<td>tt(V)</td>
<td>1.1 ± 0.3</td>
<td>1.3 ± 0.3</td>
<td>1.4 ± 0.4</td>
<td>0.4 ± 0.1</td>
<td>0.6 ± 0.2</td>
<td>1.1 ± 0.3</td>
</tr>
<tr>
<td>Single t</td>
<td>11.2 ± 4.0</td>
<td>3.0 ± 1.4</td>
<td>1.1 ± 1.0</td>
<td>0.9 ± 0.6</td>
<td>0.6 ± 0.7</td>
<td>0.6 ± 0.7</td>
</tr>
<tr>
<td>V+jets</td>
<td>33 ± 17</td>
<td>11.7 ± 6.8</td>
<td>3.8 ± 2.8</td>
<td>1.4 ± 0.9</td>
<td>0.4 ± 0.3</td>
<td>0.5 ± 0.6</td>
</tr>
<tr>
<td>Diboson</td>
<td>0.9 ± 0.2</td>
<td>0.7 ± 0.2</td>
<td>0.1 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.1 ± 0.1</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>Total bkg</td>
<td>271 ± 82</td>
<td>135 ± 41</td>
<td>71 ± 24</td>
<td>52 ± 16</td>
<td>40 ± 12</td>
<td>29.2 ± 9.4</td>
</tr>
<tr>
<td>Data</td>
<td>292</td>
<td>171</td>
<td>92</td>
<td>41</td>
<td>48</td>
<td>35</td>
</tr>
</tbody>
</table>

- Here tt+jets is again dominant background
  - multivariate discriminants exploit mostly tau-related informations
- Total Ns~2.5 evts
  - x10 (H \(\rightarrow\) bb, ttbar \(\rightarrow\) dilepton)
  - x100 (H \(\rightarrow\) bb, ttbar \(\rightarrow\) l+jets)
**Life of a Boson**

- **1995**: Higgs discovery to Z/W/gamma
- **2004**: Higgs to b quarks?
- **2007**: MH known to <1%
- **2010**: Higgs to taus!
- **2013**: Higgs and tops

Fabrizio Margaroli
Precise top quark mass (and W boson mass) measurements provides a prediction for a SM Higgs boson mass: $m_H = 94 \pm 24\,\text{GeV}$

Predicted Higgs boson to be within 1 sigma to where we found it! Knowledge of Higgs mass allows prediction of $M_{\text{top}}$ to 1% level: $M_{\text{top}} = 175.8 \pm 2.5 \,\text{GeV}$
Precise top quark mass (and W boson mass) measurements provides a predictions for a SM Higgs boson mass: \( m_H = 94 \pm 24 \text{GeV} \)

Oh BTW, it also helps us predict the fate of the universe...

From indirect measurements (until recently)

From EWK fits (incl Higgs)

Mtop from direct measurements

JHEP 1208 098
THE ATLAS WAY TO YUKAWA

- ATLAS uses a different approach to negative Yukawa:
- take existing $ttH$ analysis, consider all $tH$ contributions to it, study the dependence of the sum of $tH+X$ processes as a function of $Ct$