Measurement of the BEH scalar coupling to the top quark in CMS

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on behalf of the CMS Collaboration

53rd Rencontres de Moriond
Electroweak interactions and unified theories
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Introduction


- **top - Higgs coupling** at the LHC:
  - indirect sensitivity from gluon fusion, if no BSM particles run in the loop
  - direct sensitivity from associated production (coupling at tree level)

- $\sigma_{tH}$ at 13 TeV $\sim$ **510 fb**, more increase than backgrounds over 8 TeV
- **Different challenging aspects for each Higgs decay channel**
ttH measurements in CMS

A variety of final states, studied with different experimental techniques:

- **tt + b-jets**: large branching ratio, but complex hadronic final state
- **tt + leptons** (H → WW*, ZZ*, ττ): lower rate, low SM backgrounds
- **tt + γγ, 4ℓ**: very clean final state, but small rate

Status of CMS ttH measurements before this talk:

- **ZZ* → 4 leptons**
  - CMS JHEP 11 (2017) 47, L = 35.9 fb⁻¹
- **γγ**
  - CMS Preliminary HIG-16-040, L = 35.9 fb⁻¹
- **WW*, ZZ*, ττ leptons**
  - CMS Preliminary HIG-17-004, L = 35.9 fb⁻¹
- **ττ hadronic**
  - CMS Preliminary HIG-17-003, L = 35.9 fb⁻¹
- **b̅b lepton**
  - CMS Preliminary HIG-16-038, L = 12.9 fb⁻¹

First presented here at Moriond last year

Measurement of the BEH scalar coupling to the top quark in CMS
ttH measurements in CMS

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New results with full 2016 dataset

Measurement of the BEH scalar coupling to the top quark in CMS
Leptonic final states

- From **Higgs decays to** $WW^*$, $ZZ^*$, $\tau\tau$
- Channels:
  - 1 lepton + 2 $\tau_h$
  - 2 same-sign leptons + 0,1 $\tau_h$
  - 3 leptons + 0,1 $\tau_h$
  - 4 leptons
- At least 2 loose or 1 medium **b-tagged jets**
- **High jet multiplicity**

**Main sources of background:**
- **irreducible**: $ttV$ and di-boson, predicted from simulation and control regions
- **reducible**: **non-prompt leptons** in $tt$ events, predicted from data
Analysis strategy

- Event categorization in **lepton flavor, charge and b-jet multiplicity**
- Widespread usage of **multivariate analysis methods**:
  - lepton selection combining isolation, identification and vertex variables
  - resolved hadronic top decay and Higgs decay product taggers
  - BDT discriminants based on kinematic variables (e.g. $\Delta R(\ell,j)$)
  - matrix element calculations in $2\ell + 1\tau_h$ and $3\ell + 0\tau_h$
**Combined result**

- Evidence for \(ttH\) production in leptonic final states: \(3.2\sigma\) (\(2.8\sigma\) exp.) significance
- Main experimental uncertainties: lepton efficiency, non-prompt background prediction
- Cross-check analysis with \(ttV\) normalization fitted from dedicated control regions: \(\mu = 1.04^{+0.50}_{-0.36}\), \(2.7\sigma\) (\(2.7\sigma\) exp.) significance

Measurement of the BEH scalar coupling to the top quark in CMS
tt + b-jets final states

- Challenging jet combinatorics
- Limited bb mass resolution

Channels:
- 1 lepton + ≥ 4 jets, ≥ 3 b-tag
- 2 leptons + ≥ 4 jets, ≥ 3 b-tag

- Rely on machine learning and matrix element methods to maximize the sensitivity of the analysis

Main background: tt + heavy flavor, mainly tt+bb (from simulation, with large theory uncertainties ≥ 35%)

Measurement of the BEH scalar coupling to the top quark in CMS
**bb, 2ℓ analysis**

- Categorization based on b-tagged jet multiplicity
  - ≥4j, 3b: BDT against tt+jets background, inputs: kinematic variables, event shape, b-tag
  - ≥4j, ≥4b: BDT + MEM against tt+bb background

**CMS Preliminary**

![Graph showing data and categories](image)

- **New Result**
- **Events / 0.13**
- **Data**
- **≤0.5**
- **DL**
- **10 +lf**
- **10 ≤0.13**
- **≥35.9 fb⁻¹ (13 TeV)**
- **Post-fit**
- **Preliminary**
- **CMS PAS HIG-17-026**

- **BDT**
- **Split at BDT median**
- **≥4j, 3b**
- **≥4j, ≥4b, low BDT**
- **1 + 2 categories**
**bb, 2ℓ analysis**

- Categorization based on b-tagged jet multiplicity
- ≥4j, 3b: BDT against tt+jets background, inputs: kinematic variables, event shape, b-tag
- ≥4j, ≥4b: BDT + MEM against tt+bb background

**CMS Preliminary**

![Graph](image)

- 35.9 fb⁻¹ (13 TeV)
- **DL (≥4 jets, 3 b-tags)**
- **Post-fit**
- **BDT (≥4 jets, ≥4 b-tags)**
- **Post-fit**

**Split at BDT median**

- ≥4j, 3b
- ≥4j, ≥4b, low BDT

**1 + 2 categories**

**Measurement of the BEH scalar coupling to the top quark in CMS**
bb, 1\ell analysis

- Categories based on jet multiplicity: 4j, 5j, \geq 6j
- Deep neural network in each category with BDT input variables + MEM discriminant
- Multi-classifier output representing “probability” of a certain physics process hypothesis
**bb, 1ℓ analysis**

**New Result**

- **Simultaneous fit** of node output distributions in each category allows for optimal **separation** of physics processes.

Measurement of the BEH scalar coupling to the top quark in CMS
**bb, 1\ell + 2\ell** results

- Very significant improvement over the previous version of the analysis
- Main systematic uncertainties:
  - tt + heavy flavor theory prediction
  - b-tagging and jet energy calibration

### Measurement of the BEH scalar coupling to the top quark in CMS

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>(\pm \sigma_\mu) (observed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>total experimental</td>
<td>+0.15/-0.16</td>
</tr>
<tr>
<td>b tagging</td>
<td>+0.11/-0.14</td>
</tr>
<tr>
<td>jet energy scale and resolution</td>
<td>+0.06/-0.07</td>
</tr>
<tr>
<td>total theory</td>
<td>+0.28/-0.29</td>
</tr>
<tr>
<td>tt+hf cross-section and parton shower</td>
<td>+0.24/-0.28</td>
</tr>
<tr>
<td>size of MC samples</td>
<td>+0.14/-0.15</td>
</tr>
<tr>
<td>total systematic</td>
<td>+0.38/-0.38</td>
</tr>
<tr>
<td>statistical</td>
<td>+0.24/-0.24</td>
</tr>
<tr>
<td>total</td>
<td>+0.45/-0.45</td>
</tr>
</tbody>
</table>
bb, $0\ell$ analysis

- **Fully hadronic final state**: even more challenging
- **Dedicated b-tag triggers**: 6 jets, large $H_T$, 1 or 2 b-jets
**bb, 0ℓ analysis**

- **Fully hadronic final state**: even more challenging
- **Dedicated b-tag triggers**: 6 jets, large $H_T$, 1 or 2 b-jets
- **QCD multi-jet background** in addition to tt+HF, reduced using *quark-gluon jet discriminator*

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**Measurement of the BEH scalar coupling to the top quark in CMS**

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**Figure 1**: An example of an LO Feynman diagram for $t\bar{t}H$ production, including the subsequent decays of the top quark-antiquark pair, as well as the decay of the Higgs boson into a bottom quark-antiquark pair.

**Table**

<table>
<thead>
<tr>
<th>Events / 0.05 units</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^8</td>
</tr>
<tr>
<td>10^7</td>
</tr>
<tr>
<td>10^6</td>
</tr>
<tr>
<td>10^5</td>
</tr>
<tr>
<td>10^4</td>
</tr>
<tr>
<td>10^3</td>
</tr>
<tr>
<td>10^2</td>
</tr>
<tr>
<td>10^1</td>
</tr>
</tbody>
</table>

**Legend**

- Total unc
- Multijet
- tt+b
- tt+2b
- tt+lf
- tt+bb
- tt+c\bar{c}
- Single t
- Diboson
- V+jets
- Data
**bb, 0ℓ analysis**

- **Fully hadronic final state**: even more challenging
- **Dedicated b-tag triggers**: 6 jets, large $H_T$, 1 or 2 b-jets
- **QCD multi-jet background** in addition to $tt+HF$, reduced using quark-gluon jet discriminator

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**Figure 1**: An example of an LO Feynman diagram for $t\bar{t}$ production, including $t\bar{t}+b$ process, which provides extra discrimination against the irreducible $t\bar{t}$ signal and the multijet background and, to a lesser extent, the $t\bar{t}$ signal and the multijet background. Smaller $t\bar{t}$ background. Smaller

**Table 1**: Summary of the number of events observed in the validation region for various backgrounds and signal processes.

<table>
<thead>
<tr>
<th>Process</th>
<th>Events / 30 GeV</th>
<th>Events / 0.05 units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total unc.</td>
<td>1200</td>
<td>7.9 × 10^4</td>
</tr>
<tr>
<td>Multijet</td>
<td>1100</td>
<td>7.2 × 10^4</td>
</tr>
<tr>
<td>$tt+lf$</td>
<td>900</td>
<td>5.7 × 10^4</td>
</tr>
<tr>
<td>$tt+b$</td>
<td>800</td>
<td>5.1 × 10^4</td>
</tr>
<tr>
<td>Diboson</td>
<td>700</td>
<td>4.5 × 10^4</td>
</tr>
<tr>
<td>Single $t$</td>
<td>600</td>
<td>4.0 × 10^4</td>
</tr>
<tr>
<td>$V+J$</td>
<td>500</td>
<td>3.2 × 10^4</td>
</tr>
<tr>
<td>$tt+b$</td>
<td>400</td>
<td>2.5 × 10^4</td>
</tr>
</tbody>
</table>

**Figure 2**: Distribution of the $bb$ mass for the validation region, with the pull distribution shown. The $\chi^2$/dof is 1.0 and the p-value is 0.397.

**Figure 3**: Distribution of the QCD enriched validation region, with the Data/Bkg ratio shown. The QGLR (4b) is 35.9 fb$^{-1}$ (13 TeV).

Measurement of the BEH scalar coupling to the top quark in CMS
bb, $0\ell$ analysis

- **Fully hadronic final state**: even more challenging
- **Dedicated b-tag triggers**: 6 jets, large $H_T$, 1 or 2 b-jets
- **QCD multi-jet background** in addition to $tt+HF$, reduced using quark-gluon jet discriminator

Measurement of the BEH scalar coupling to the top quark in CMS
Measurement of the BEH scalar coupling to the top quark in CMS

- Event categorization in #jets, b-jets
- **Matrix element discriminator**
designed to separate ttH from tt+bb
- Tested on jet permutations
Measurement of the BEH scalar coupling to the top quark in CMS

**Event categorization in #jets, b-jets**

- **Matrix element discriminator**
  - designed to separate ttH from tt+bb
  - Tested on jet permutations

**MEM discriminant template for QCD**
- extrapolated from 2 b-jet control region, normalization left floating in the fit
- Corrections for different $p_T$, $\eta$, $\Delta R_{jj}$ of loose vs. tight b-tagged 3rd and 4th jets
- tt+jets predicted from simulation

**Preliminary**

7 jets, 3 b tags
$S/B = 0.0023, S/\sqrt{B} = 0.5978$

8 jets, 3 b tags
$S/B = 0.0033, S/\sqrt{B} = 0.7048$

$\geq 9$ jets, 3 b tags
$S/B = 0.0049, S/\sqrt{B} = 0.7874$

7 jets, $\geq 4$ b tags
$S/B = 0.0077, S/\sqrt{B} = 0.5227$

8 jets, $\geq 4$ b tags
$S/B = 0.0095, S/\sqrt{B} = 0.6890$

$\geq 9$ jets, $\geq 4$ b tags
$S/B = 0.0143, S/\sqrt{B} = 0.8484$

**35.9 fb$^{-1}$ (13 TeV)**

Data/Bkg vs. MEM discriminant

CMS Preliminary HIG-17-022
In agreement with SM expectation, **driven by ≥4b categories**

Main experimental uncertainties: b-tagging, QCD shape modeling

Nicely complements the sensitivity provided by semi- and di-leptonic top decays

Measurement of the BEH scalar coupling to the top quark in CMS
Combined results

- All $t\bar{t}H$ analyses combined with other Higgs measurements in global fits (more details in D. Sperka’s talk later today)
Combined results

- All ttH analyses combined with other Higgs measurements in global fits (more details in D. Sperka’s talk later today)
- Focus here on top-Higgs coupling:

  * ttH+tH production cross section modifier from per-production mode fit: $\Delta \mu_{ttH} \sim 30\%$

<table>
<thead>
<tr>
<th>ttH</th>
<th>Best fit value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>±1σ (stat.)</td>
<td>±1σ (sys.)</td>
</tr>
<tr>
<td></td>
<td>±2σ</td>
<td></td>
</tr>
</tbody>
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<tr>
<th>ttH</th>
<th>(stat.)</th>
<th>(sys.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.18</td>
<td>±0.31</td>
</tr>
<tr>
<td></td>
<td>-0.27</td>
<td>-0.16</td>
</tr>
<tr>
<td></td>
<td>-0.21</td>
<td></td>
</tr>
<tr>
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<td>(±0.16)</td>
</tr>
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Combined results

- **All ttH analyses combined with other Higgs measurements in global fits** (more details in D. Sperka’s talk later today)
- **Focus here on top-Higgs coupling:**

  - **ttH+tH production cross section modifier** from per-production mode fit: \( \Delta \mu_{ttH} \sim 30\% \)
  
  - **top coupling modifier** from \( \kappa \)-framework fit in the unresolved loops assumption:

<table>
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</tr>
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<tbody>
<tr>
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<td></td>
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</table>

Measurement of the BEH scalar coupling to the top quark in CMS
Additional constraints

- **tHq production**: unique sensitivity to the sign of the coupling via interference

- Studied using similar strategies as for ttH

![Diagram of tHq production](image)

Measurement of the BEH scalar coupling to the top quark in CMS
Additional constraints

- **tHq production**: unique sensitivity to the sign of the coupling via interference

- Studied using similar strategies as for ttH

- Additional constraints from top measurements

- E.g. tttt production described in S. Sanchez’s talk earlier today

Measurement of the BEH scalar coupling to the top quark in CMS
Conclusions

• ttH accessible in a wide range of final states
• Challenging analysis performed with very advanced background reduction methods
• Direct measurements constrain the top-Higgs coupling to about 15%
• Indirect sensitivity is provided by other Higgs processes

Diverse sources of uncertainty limit our current sensitivity:
• how to improve and on which timescale?
• what are the best observables to extract the most relevant physics information?
tt + γγ final state

- Studied within the general H → γγ analysis
- Two dedicated selection categories:
  - **leptonic**: 1 lepton + 2 jets, 1 b-tagged jet
  - **hadronic**: 3 jets, 1 b-tagged jet
- Sensitivity enhanced by BDT discriminant in the hadronic category (jet multiplicity, p_T, b-tag)

![Graphs showing distributions and significance](image)

Measurement of the BEH scalar coupling to the top quark in CMS
tt + ZZ* → 4ℓ final state

- Very clean final state, but branching ratio is tiny
- Dedicated selection category:
  - at least four jets, 1 b-tagged jet, OR
  - at least one additional lepton
  - ~0.3 expected ttH signal events
## ttH multi-lepton analysis

### Measurement of the BEH scalar coupling to the top quark in CMS

<table>
<thead>
<tr>
<th>Selection</th>
<th>2ℓss</th>
<th>2ℓss + 11νh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Targetted ttH decay</td>
<td>t → bW, t → bQ, H → WW → ℓνν</td>
<td>H → WW → ℓνν</td>
</tr>
<tr>
<td>Lepton pT</td>
<td>pT &gt; 25 / 15 GeV</td>
<td>pT &gt; 20 GeV</td>
</tr>
<tr>
<td>Charge requirements</td>
<td>2 same-sign leptons and charge quality requirements</td>
<td>2 same-sign leptons and charge quality requirements</td>
</tr>
<tr>
<td>Jet multiplicity</td>
<td>≥4 jets</td>
<td>≥3 jets</td>
</tr>
<tr>
<td>b tagging requirements</td>
<td>≥1 tight b-tagged jet or ≥2 loose b-tagged jets</td>
<td></td>
</tr>
<tr>
<td>Missing transverse momentum</td>
<td>LD &gt; 30 GeV</td>
<td>LD &gt; 30 GeV</td>
</tr>
<tr>
<td>Dilepton mass</td>
<td>mℓℓ &gt; 12 GeV and</td>
<td>mℓℓ − mZ</td>
</tr>
</tbody>
</table>

### Selection requirements in different event categories

- **Targetted ttH decays**
  - 1ℓ + 21νh: t → bW, t → bQ, H → WW → ℓνν
  - 4ℓ: t → bW, t → bQ, H → WW → ℓνν

- **Trigger**
  - Single-, double- and triple-lepton triggers

- **Lepton pT**
  - pT > 25 / 15 GeV

- **Charge requirements**
  - Σq = ±1

- **Jet multiplicity**
  - ≥2 jets

- **b tagging requirements**
  - ≥1 tight b-tagged jet or ≥2 loose b-tagged jets

- **Missing transverse momentum**
  - LD > 45 GeV

- **Dilepton mass**
  - mℓℓ > 12 GeV and |mℓℓ − mZ| > 10 GeV

### Additional Notes
- Applied only if both leptons are electrons.
- If the event contains a SFOS lepton pair and N_l ≤ 3.
- Applied only if the event contains 2 SFOS lepton pairs.

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**References**

- Moriond EW 2018
- Marco Peruzzi (CERN)
- CMS HIG-17-018
### ttH multi-lepton analysis

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
<th>$\Delta \mu / \mu$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>e, $\mu$ selection efficiency</td>
<td>2–4</td>
<td>11</td>
</tr>
<tr>
<td>$\tau_h$ selection efficiency</td>
<td>5</td>
<td>4.5</td>
</tr>
<tr>
<td>b tagging efficiency</td>
<td>2–15 [? ]</td>
<td>6</td>
</tr>
<tr>
<td>Reducible background estimate</td>
<td>10–40</td>
<td>11</td>
</tr>
<tr>
<td>Jet energy calibration</td>
<td>2–15 [? ]</td>
<td>5</td>
</tr>
<tr>
<td>$\tau_h$ energy calibration</td>
<td>≈10</td>
<td>12</td>
</tr>
<tr>
<td>Theoretical sources</td>
<td>2.5</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Observable</th>
<th>$1 \ell + 2\tau_h$</th>
<th>$2\ell ss$</th>
<th>$3\ell$</th>
<th>$3 \ell + 1\tau_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta R(\ell_1,j)$</td>
<td>—</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$\Delta R(\ell_2,j)$</td>
<td>—</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$\langle \Delta R_{jj} \rangle$</td>
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<td>—</td>
<td>—</td>
<td>$\checkmark^2$</td>
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<td>$\Delta R_{\tau \tau}$</td>
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<td>—</td>
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</tr>
<tr>
<td>$\max (</td>
<td>\eta^{\ell_1}</td>
<td>,</td>
<td>\eta^{\ell_2}</td>
<td>)$</td>
</tr>
<tr>
<td>$H_{\text{miss}}$</td>
<td>$\checkmark$</td>
<td>—</td>
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<td>$N_j$</td>
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<td>$m_{\text{vis}}$</td>
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<td>—</td>
<td>—</td>
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<td>$m_T^1$</td>
<td>—</td>
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<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$p_T^{\ell 1}$</td>
<td>—</td>
<td>$\checkmark^1$</td>
<td>$\checkmark^1$</td>
<td>$\checkmark^1$</td>
</tr>
<tr>
<td>$p_T^{\ell 2}$</td>
<td>—</td>
<td>$\checkmark^1$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$p_T^{\ell 3}$</td>
<td>—</td>
<td>—</td>
<td>$\checkmark^1$</td>
<td>$\checkmark^1$</td>
</tr>
<tr>
<td>$p_T^{\tau 1}$</td>
<td>—</td>
<td>—</td>
<td>$\checkmark^1$</td>
<td>$\checkmark^1$</td>
</tr>
<tr>
<td>$p_T^{\tau 2}$</td>
<td>$\checkmark$</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$\text{LR}(3\ell)$</td>
<td>—</td>
<td>—</td>
<td>$\checkmark^1$</td>
<td>—</td>
</tr>
<tr>
<td>$\text{MVA}^\text{max}_{\text{thad}}$</td>
<td>—</td>
<td>$\checkmark^2$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$\text{MVA}^\text{max}_{\text{Hj}}$</td>
<td>—</td>
<td>$\checkmark^1$</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

1. Used only in BDT that separates $t\bar{t}H$ signal from $t\bar{t}V$ background.
2. Used only in BDT that separates $t\bar{t}H$ signal from $t\bar{t}+\text{jets}$ background.

• Main sources of systematic uncertainty and their impact on the fitted signal

• Input kinematic variables to multivariate discriminators

Measurement of the BEH scalar coupling to the top quark in CMS
ttH multi-lepton yields

Measurement of the BEH scalar coupling to the top quark in CMS