Search for the Higgs boson in associated production with a top-antitop pair and decaying into τ leptons with the CMS experiment

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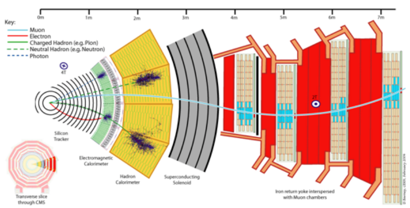
Outline

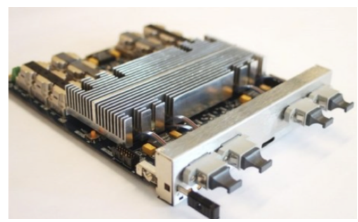
1



The tool:

The CMS detector

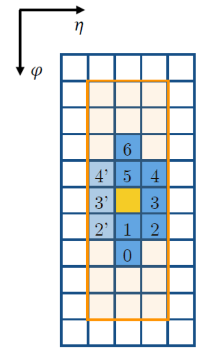
2



The handle:

The CMS trigger

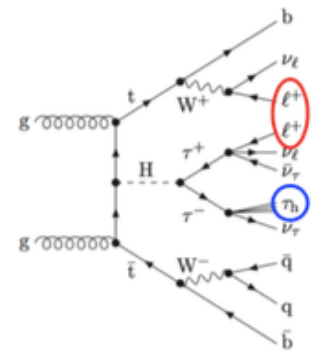
3



The seed:

The CMS Level-1 τ trigger

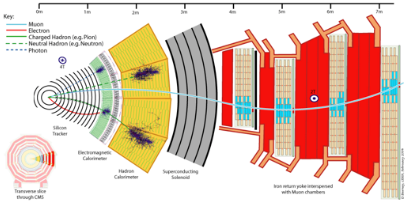
4



The search:

The $t\bar{t}H$ process with $\tau's$ in the final state

1

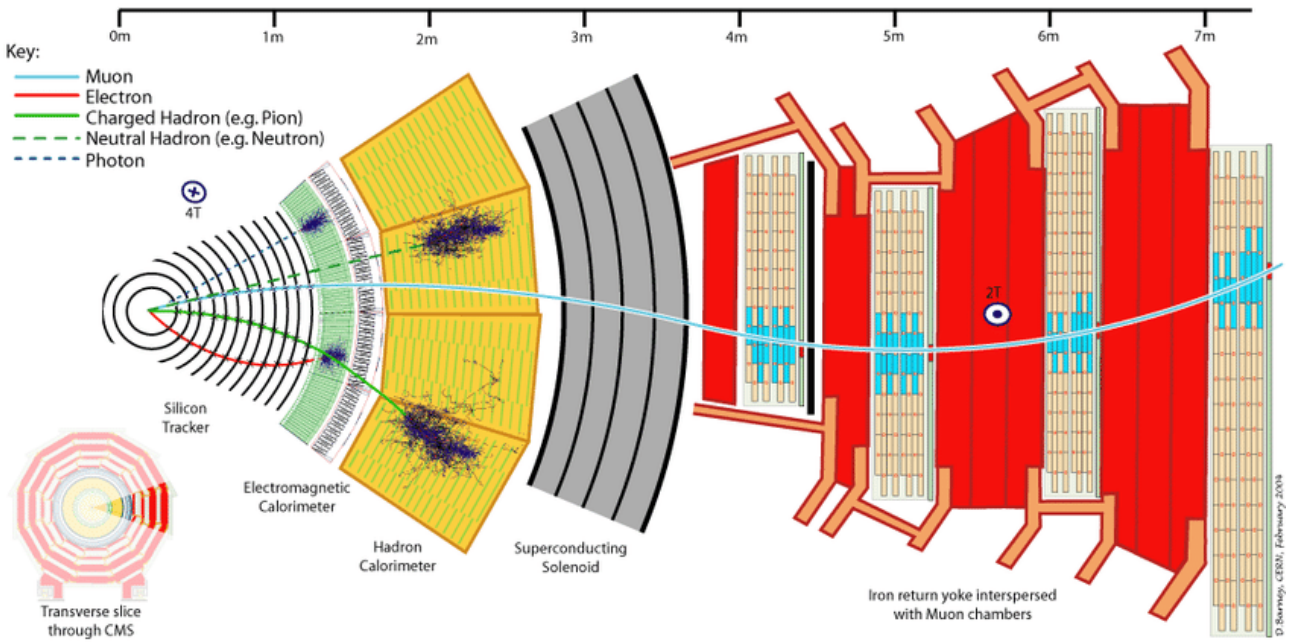


The tool:

The CMS detector

The CMS detector

- Multi-purpose experiment at the **Large Hadron Collider** (LHC).
- **Sub-detectors** installed concentrically with respect to the interaction point and designed specifically to characterize different kinds of particles:



- Currently collecting $\sqrt{s}$ **= 13 TeV proton-proton** collisions from the LHC.
- Higgs physics, Standard Model precision measurements, physics beyond the Standard Model...

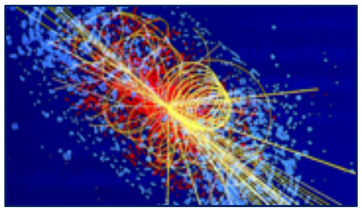
2

The handle:

The CMS
trigger

The CMS trigger system

- LHC bunch crossing rate: **~40 MHz** → data storage unsustainable!
- Implementation of a trigger system that performs a fast selection of interesting events based on kinematic cuts.



~40 MHz

Level-1 Trigger

~3.8 μs

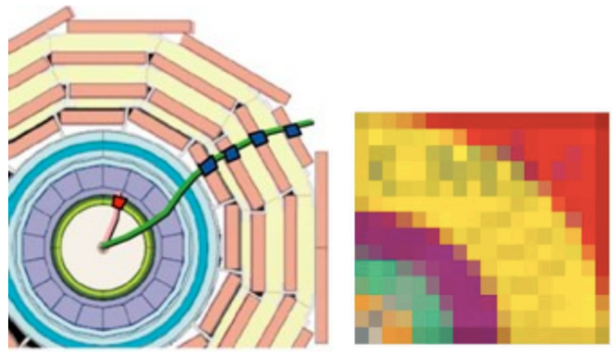
~100 kHz

High Level Trigger

~300 ms

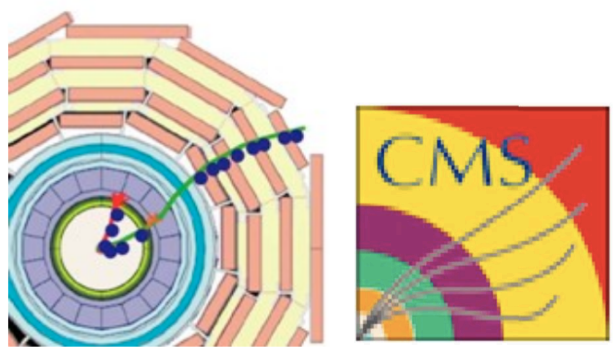
~1 kHz

Data storage and full reconstruction



Level-1 (L1):

- hardware level
- calorimeters and muon chambers

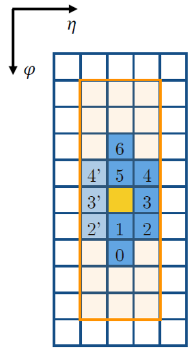


High Level Trigger (HLT):

- software level
- full-detector information

Sustainable data storage: ~**3 Gb/s**

3



The seed:

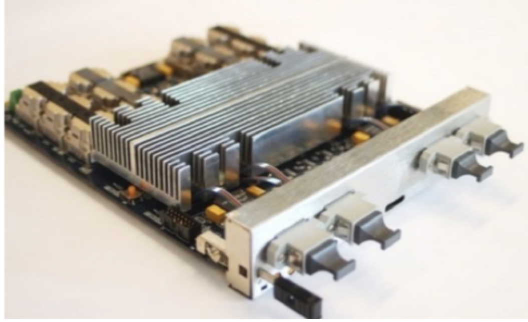
The CMS
Level-1 τ trigger

The CMS Level-1 τ trigger

- Selection of **hadronically-decaying τ's** at Level-1 trigger.
- τ decays leptonically or hadronically:

Decay mode	Meson resonance	$\mathcal{B}$ [%]	
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8	1/3
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4	
$\tau^- \to h^- \nu_\tau$		11.5	2/3
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	26.0	
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.5	
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8	
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8	
Other modes with hadrons		3.2	
All modes containing hadrons		64.8	

  - Leptonic decays: clean signature, easily selected by e/μ triggers
  - Hadronic decays: challenging due to similarity with jets experimental signature.
- **Additional challenges**: calorimeter inputs only, high pile-up and luminosity, limited HW resources and latency, low trigger rate, maximum physics sensitivity…
- **Upgrade of L1 trigger architecture (Run II):** develop, for the first time at a hadron collider, a dedicated τ_h finder algorithm at the hardware trigger level.



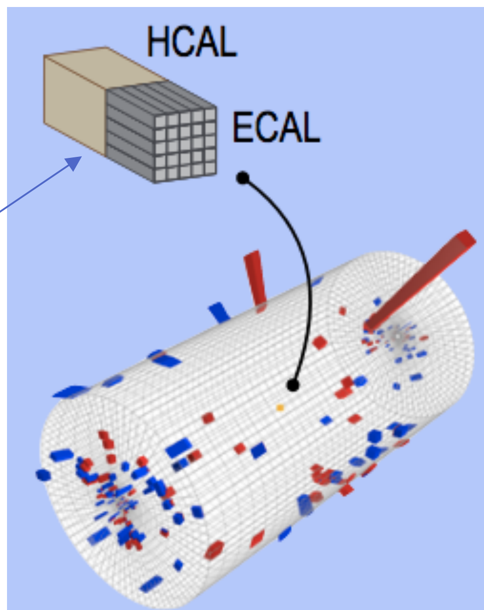
The CMS Level-1 τ trigger

Steps of the L1 τ_h trigger algorithm:

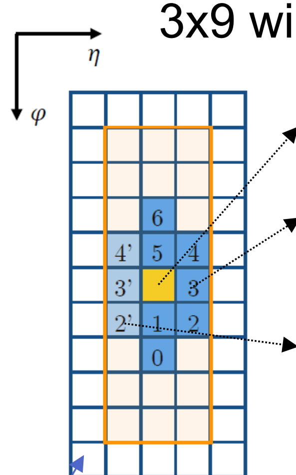
1 **Dynamic clustering**

Identify the τ_h localized energy deposits in the calorimeters to build the **main cluster**

Trigger Tower



3x9 window



Seed: local maximum ≥ 4 GeV

Protocluster: ≥ 2 GeV

Lateral trimming: asymmetric energy deposit

Energy weighted **position**

Trigger Tower

The CMS Level-1 τ trigger

Steps of the L1 τ_h trigger algorithm:

2 **Merging**

Merge **secondary clusters** arising from τ_h decays into a single candidate.

Decay mode	Meson resonance	$\mathcal{B}$ [%]
$\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
$\tau^- \rightarrow h^- \nu_\tau$		11.5
$\tau^- \rightarrow h^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \rightarrow h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.5
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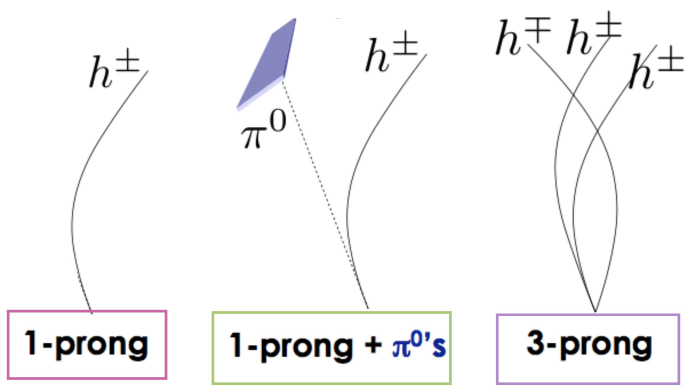
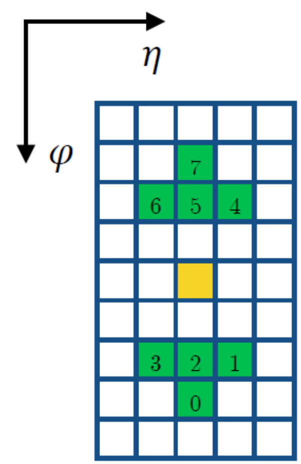


τ_h decay products spread out by solenoid magnetic field



The CMS Level-1 τ trigger

Steps of the L1 τ_h trigger algorithm:

3 **Calibration**

Calibrate the τ_h **energy** to improve the scale and resolution:

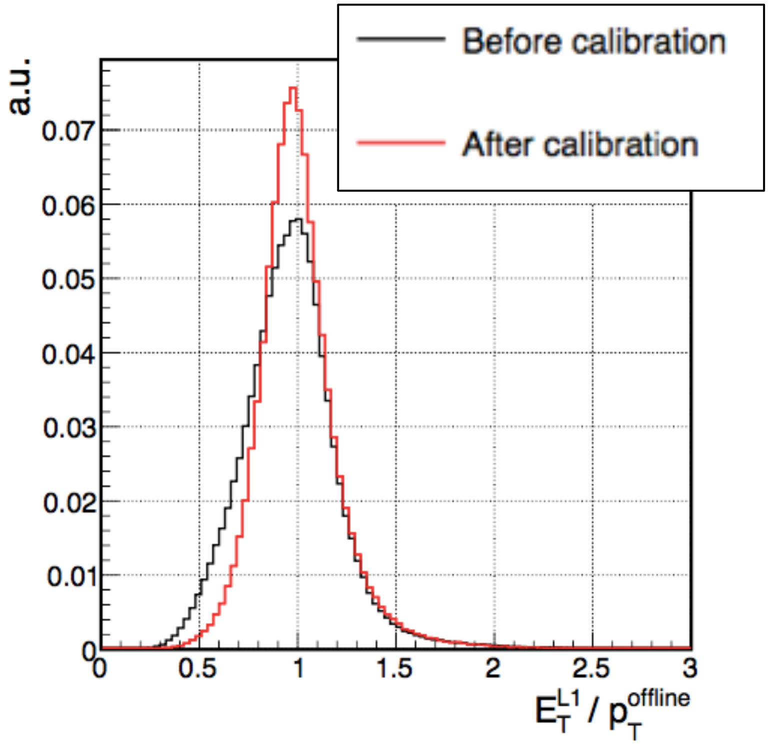
- Non linearities, energy losses in clustering…

From simulation

Cluster energy

$$E^{\tau}_{T,calib} = \mathbf{c}\, E^{\tau}_{T,raw}$$

$$\mathbf{c} = c\,(E^{\tau}_{T,raw}, i\eta, i^{Merged}, i^{EM})$$



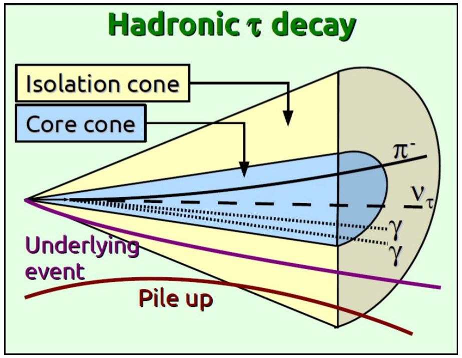
The CMS Level-1 τ trigger

Steps of the L1 τ_h trigger algorithm:

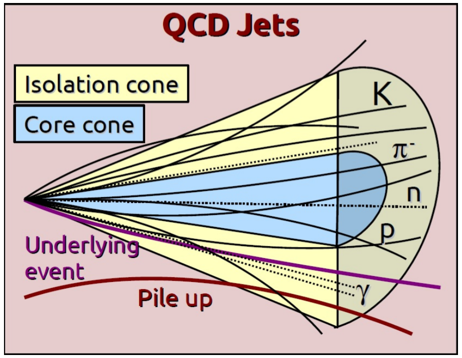
4 **Isolation**

Apply **isolation** criteria to reject QCD jet background.

Narrow and collimated

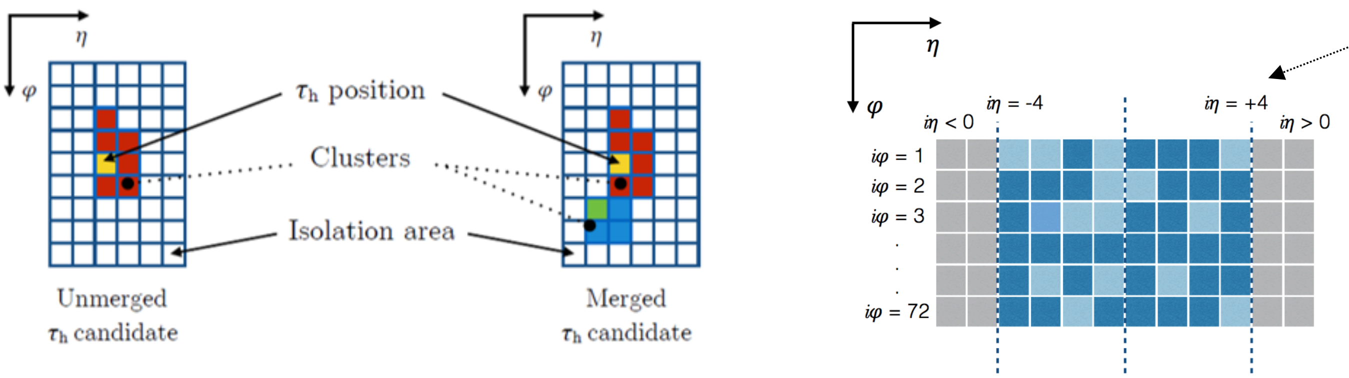


vs.



Broader and higher particle multiplicity

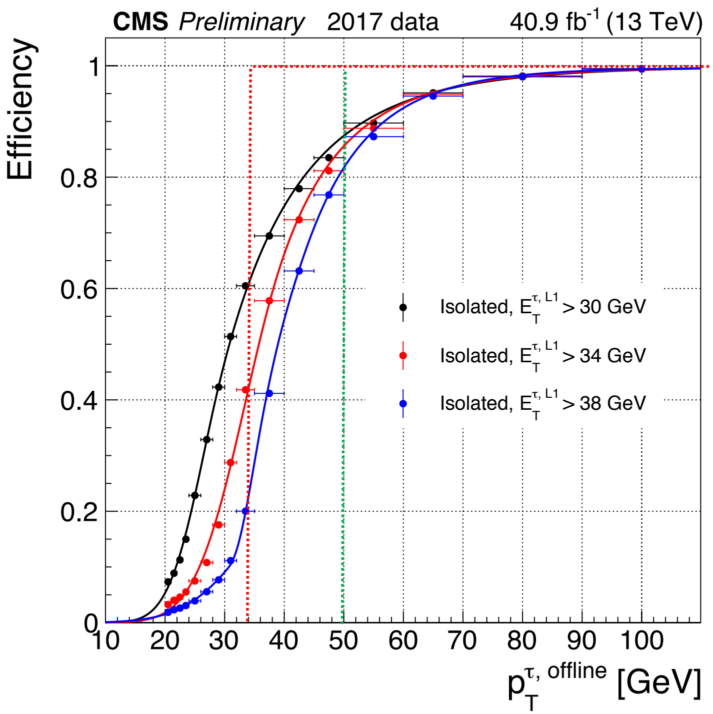
$$E_{T,iso}^{\tau} = E_T^{6x9} - E_{T,raw}^{\tau} \quad \text{with} \quad E_{T,iso}^{\tau} < \xi\,(E_{T,raw}^{\tau}, \text{i}\eta, \boldsymbol{n_{TT}})$$



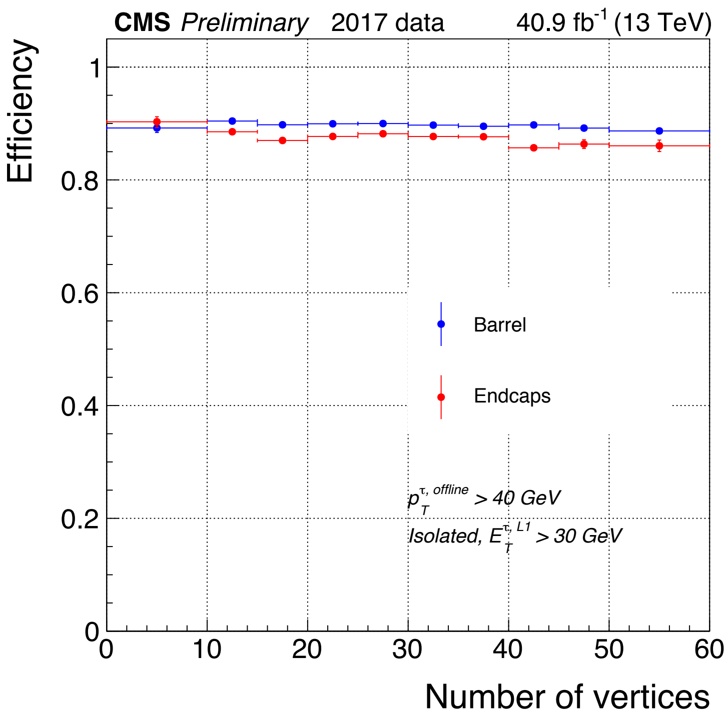
Pile-up estimated from energy deposit in central part of the detector

The CMS Level-1 τ trigger

Performance in 2017:



Excellent L1 efficiency for isolated τ, reaching 90% at 50 GeV, threshold used in H→ $\tau\tau$ analysis.



Pile-up resilience thanks to the pileup estimator already present at L1 isolation.

The τ trigger allowed to observe the Higgs in $\tau\tau$ final state in 2017

Observation of the Higgs boson decay to a pair of τ leptons with the CMS detector, Phys. Lett. B779 (2018) 283-316

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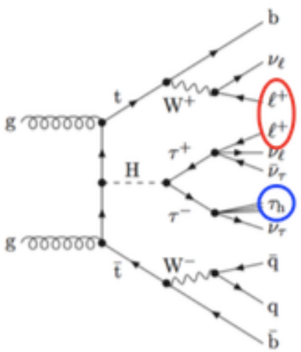
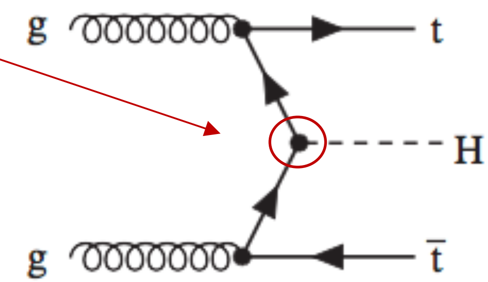


The search:

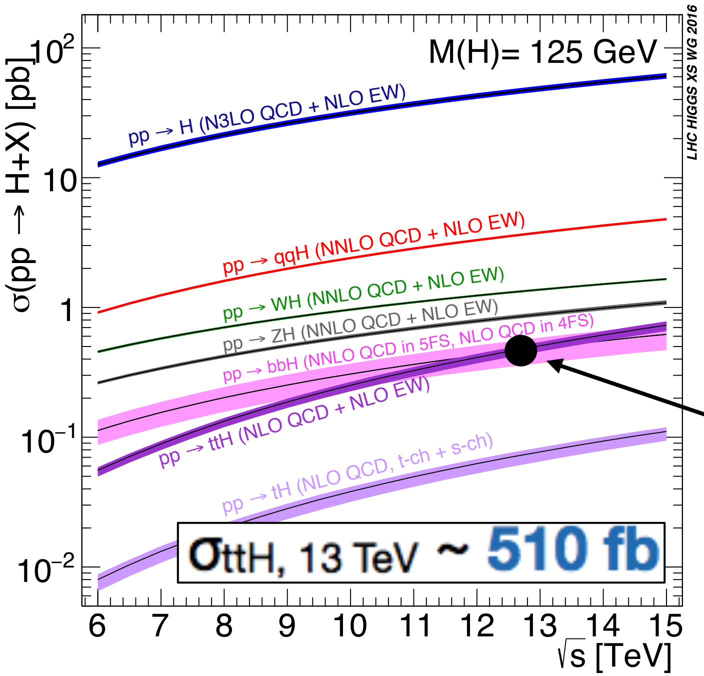
The $t\bar{t}H$ process with τ's
in the final state

The $t\bar{t}H$ process

- Direct probe of **top Yukawa coupling** $\mathbf{y_t \propto m_t/v \approx 1}$



$pp \rightarrow t\bar{t}H$



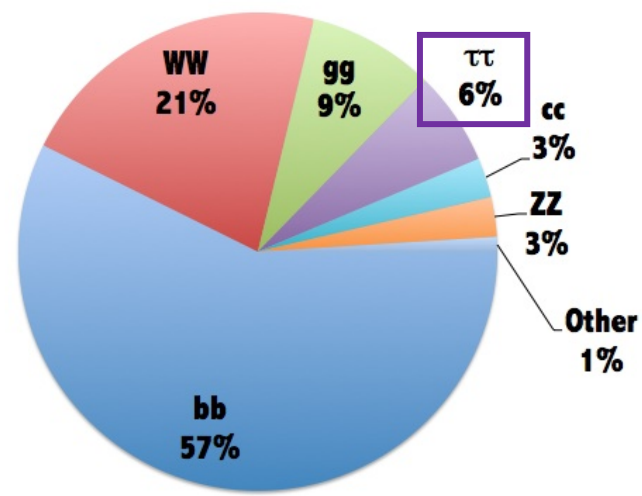
"The impossible channel"…

- Small production cross-section
- High hadronic activity and particle multiplicity

$$\sigma_{ttH} \sim \frac{1}{96}\sigma_{ggF}$$

Run I: ~**6000** events (ATLAS+CMS)

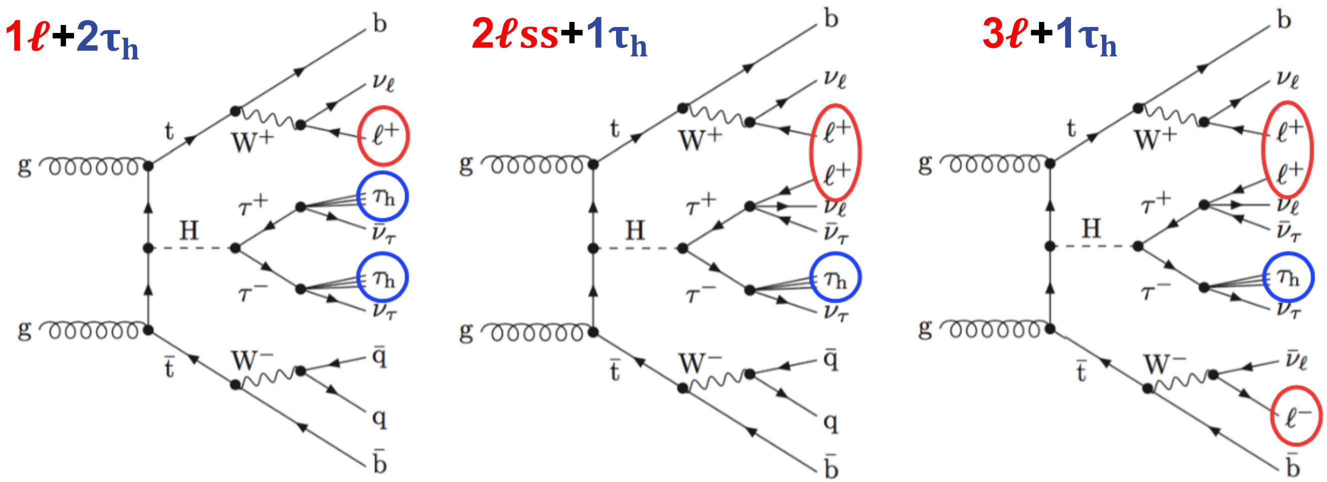
Cover as many Higgs decay channels as possible



… but (spoiler) **we observed it!**

$t\bar{t}H$ with H→ ττ

$t\bar{t}H$ (H→ ττ) final states with hadronically-decaying $\tau's$:

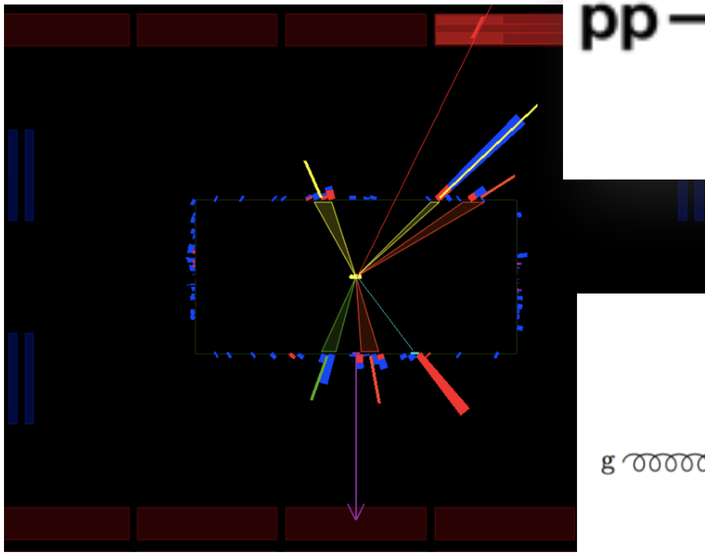


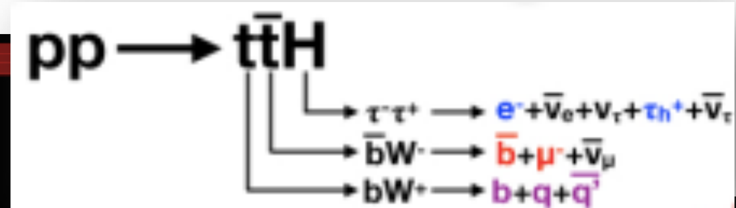
Looking for **2 tops + 1 Higgs**:

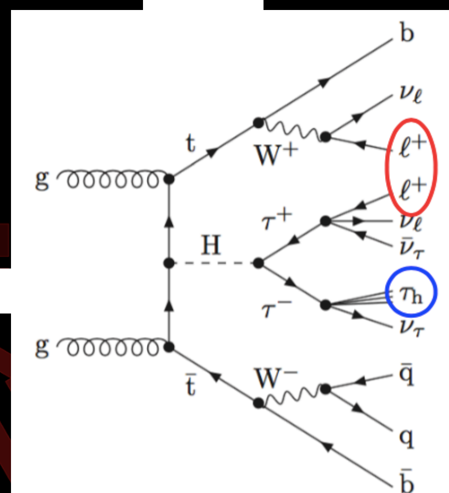
$t \rightarrow b\, l\, \upsilon_l$	1 b-jet + 1 lepton + neutrinos
$t \rightarrow b\, q\, q$	1 b-jet + 2 light jets
$H \rightarrow \tau\tau$	1-2 τ_h (+ lepton + neutrinos)

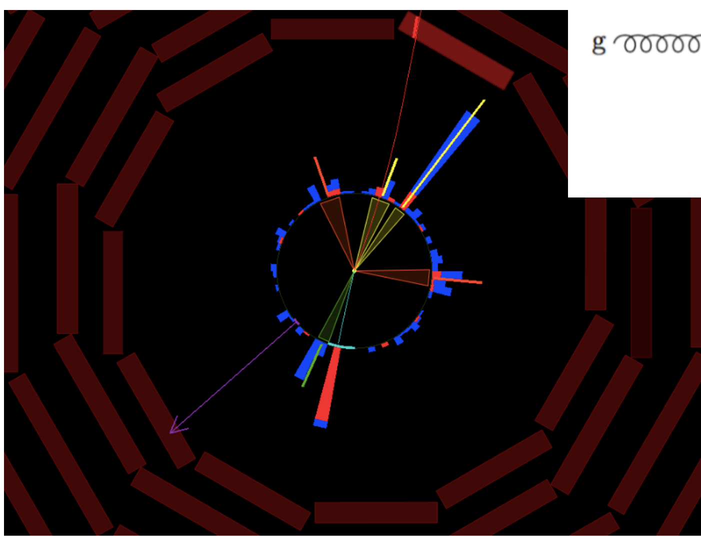
- **Complex event reconstruction:** large multiplicity of objects in the final state
- **Challenging signal extraction:** presence of neutrinos + combinatorics
- Extensive use of **MVA discriminants** for object identification (b-jets, leptons, τ_h) and signal extraction (MEM, BDT).

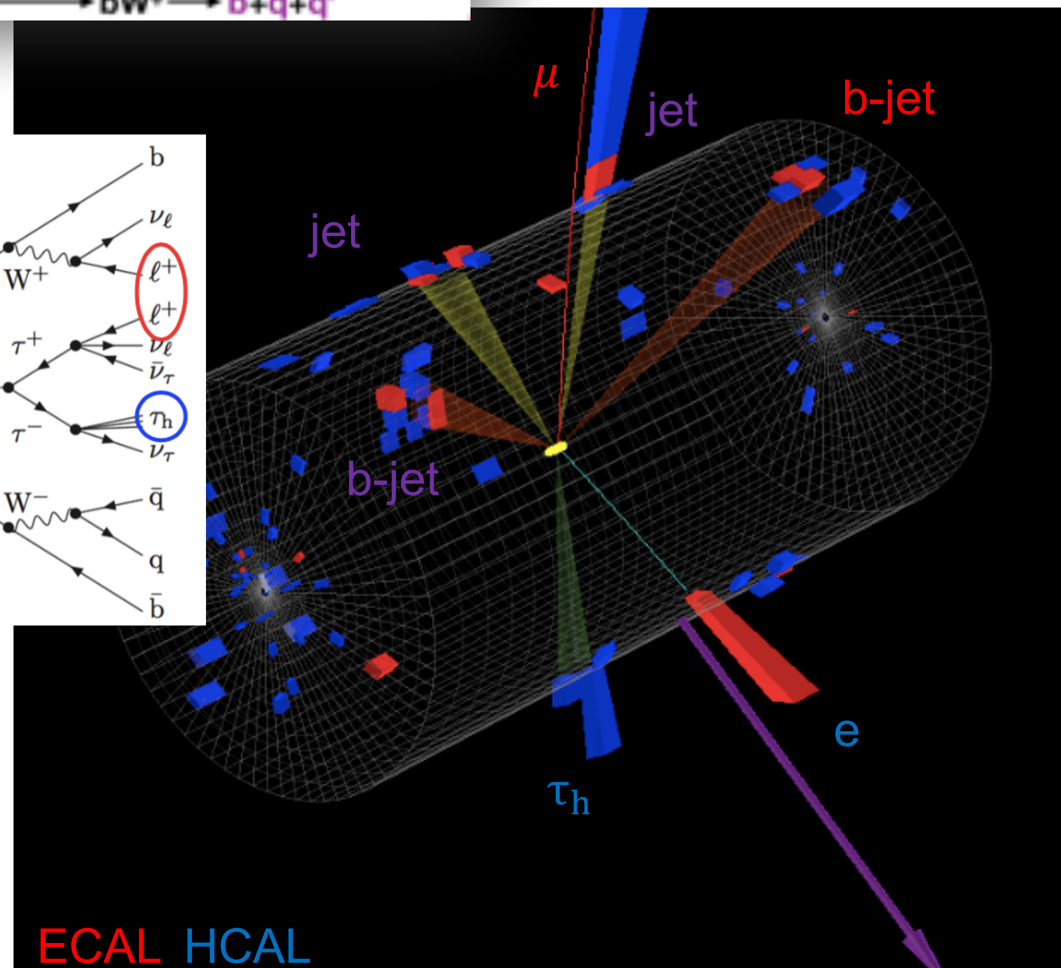
$2\ell ss+1\tau_h$ experimental signature





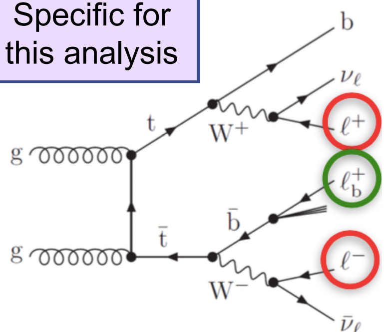






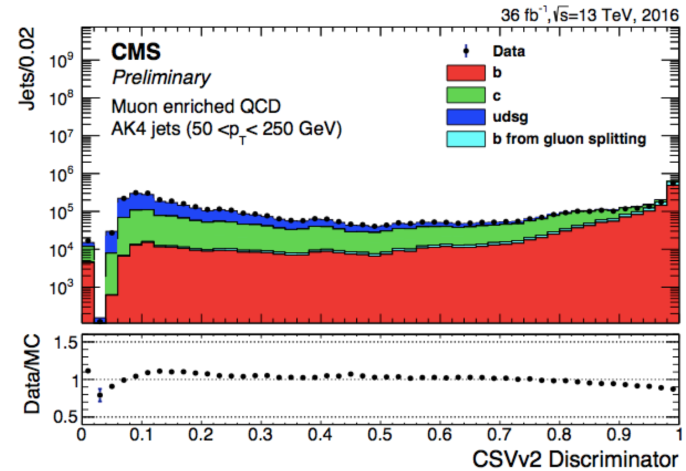
Object reconstruction

Specific for this analysis



MVA **b-jets** vs *light jets*

(lifetime, particle multiplicity, mass…)



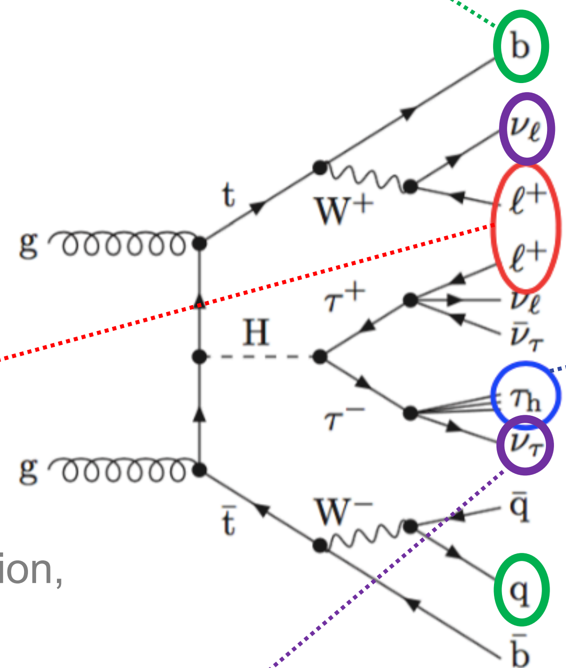
MVA

prompt-leptons

vs

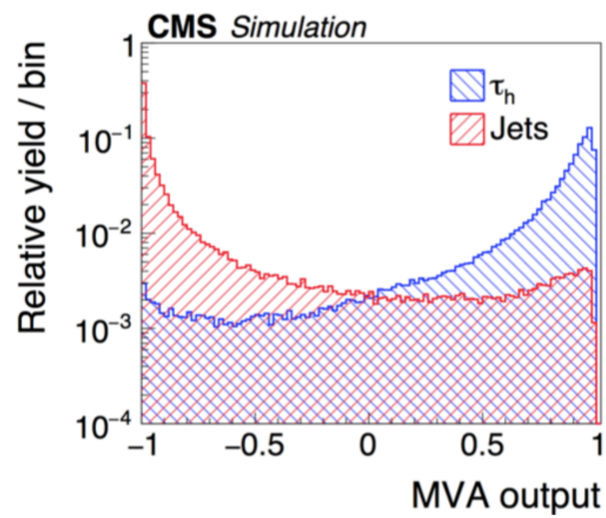
leptons from b- or light quarks decays

(kinematics, vertex, isolation, nearby jet-related, ID…)



MVA **hadronic τ's** vs *jets*

(isolation, decay modes, mass…)



resolution

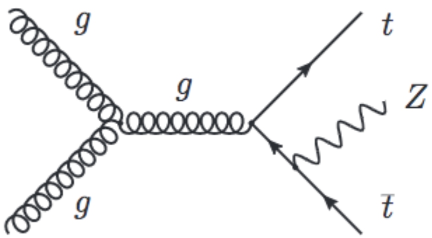
pileup resilience

$$0.6^* \left(E_T^{\text{miss}} = -\sum_i \vec{p}_T(i)\right) + 0.4^* \left(H_T^{miss} = \left|\sum_{\text{leptons}} \vec{p}_{T\ell} + \sum_{\tau_h} \vec{p}_{T\tau} + \sum_{\text{jets}} \vec{p}_{Tj}\right|\right)$$

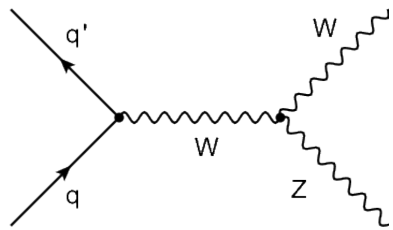
Backgrounds

- **Irreducible background** (estimated from **simulation**):

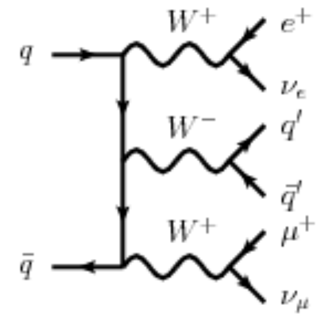
$t\bar{t}V$:
$t\bar{t}Z$, $t\bar{t}W(W)$, $t\bar{t}\gamma^*$



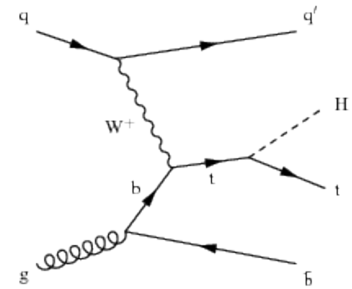
Di-boson+jets:
WW, WZ, ZZ (+jets)



Rare processes:
VVV, $tt\bar{t}\bar{t}$, tZq…



tH:
tHq, tHW



- **Reducible background** (predicted from **data**):

Fakes
Non-prompt lepton / hadron
→ prompt lepton
Jet (q, g)
→ τ_h

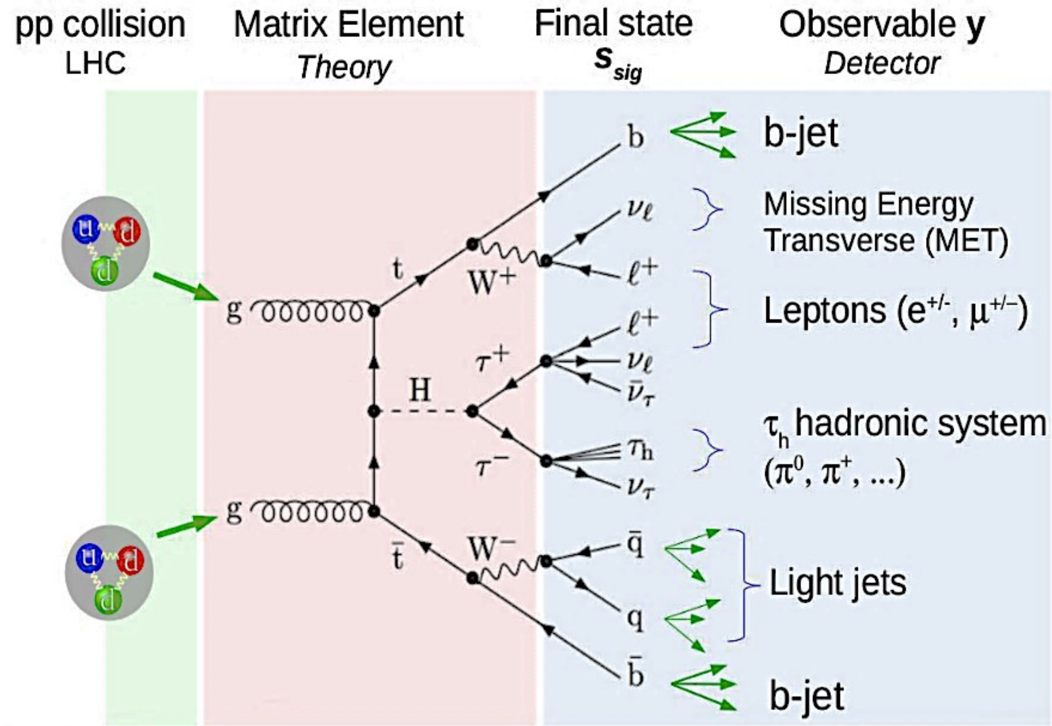
Flips
OS
→ SS
($2\ell ss+1\tau_h$)

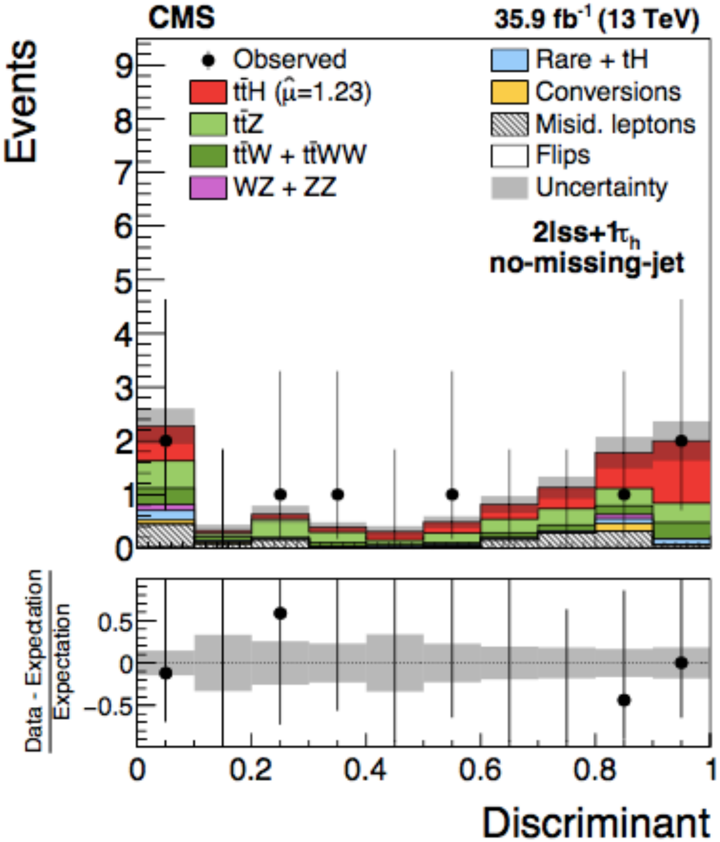
Conversions
$\gamma \rightarrow e^+e^-$

Signal extraction in $2\ell ss+1\tau_h$

Build a **discriminating observable** which provides maximal shape separation S/B:

Matrix Element Method (MEM)





$$\mathrm{LR}(\mathbf{y}) = \frac{w_{t\bar{t}H}(\mathbf{y})}{w_{t\bar{t}H}(\mathbf{y}) + \sum_B \kappa_B\, w_B(\mathbf{y})}$$

PDFs, Bjorken variables — Hard-scattering matrix element — Transfer function

$$w_\Omega(\mathbf{y}) \propto \sum_p \int d\mathbf{x}\, dx_a\, dx_b \frac{f_i(x_a,Q)f_j(x_b,Q)}{x_a x_b s}\delta^4\left(x_a P_a + x_b P_b - \sum p_k\right)|\mathcal{M}_\Omega(\mathbf{x})|^2 W(\mathbf{y}|\mathbf{x})$$

Results with 2016 data

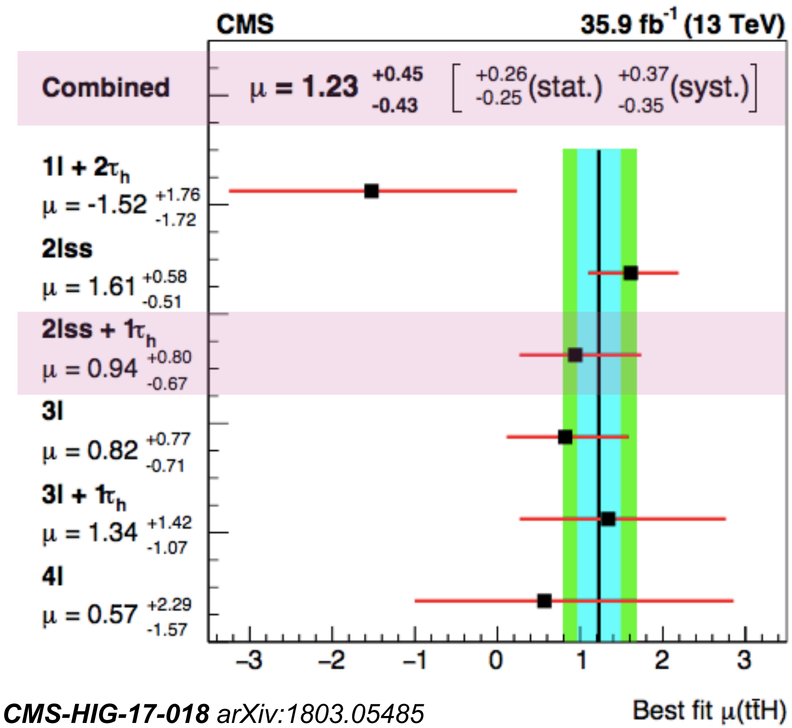
Expected data yield: $\nu_i(\mu, \vec{\theta}) = \mu s_i(\vec{\theta}) + b_i(\vec{\theta})$ → Nuisance parameters (systematic uncertainties)

- ν_i: For each bin of the signal extraction observable
- μ: Signal strength SM $\mu = 1$
- s_i: MC signal
- b_i: MC background

Maximize the likelihood associated to an observation:

$$\mathcal{L}(data|\mu, \vec{\theta}) = \prod_i \frac{\left(\mu s_i(\vec{\theta}) + b_i(\vec{\theta})\right)^{n_i}}{n_i!} e^{-(\mu s_i(\vec{\theta}) + b_i(\vec{\theta}))} \cdot \rho(\vec{\theta}|\hat{\vec{\theta}})$$

- n_i: Number of observed events
- $\rho(\vec{\theta}|\hat{\vec{\theta}})$: Probability density function of nuisance parameters



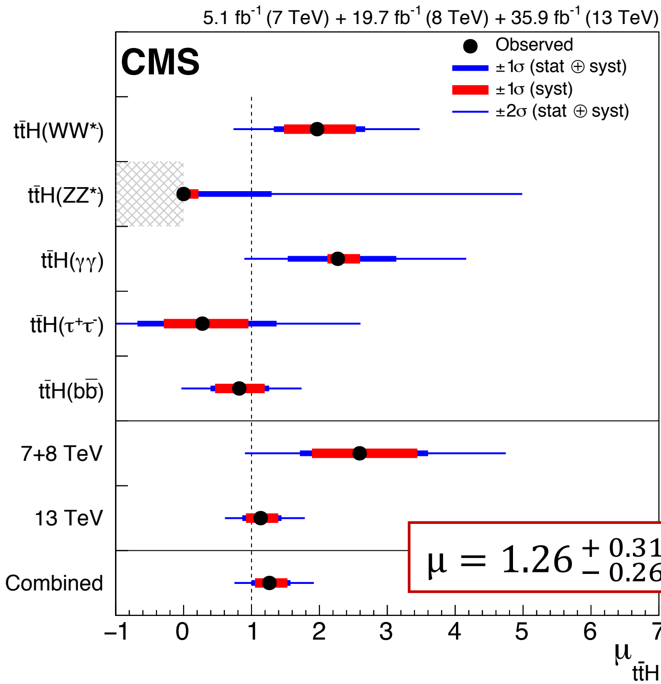
CMS-HIG-17-018 *arXiv:1803.05485*

Main systematic uncertainties:

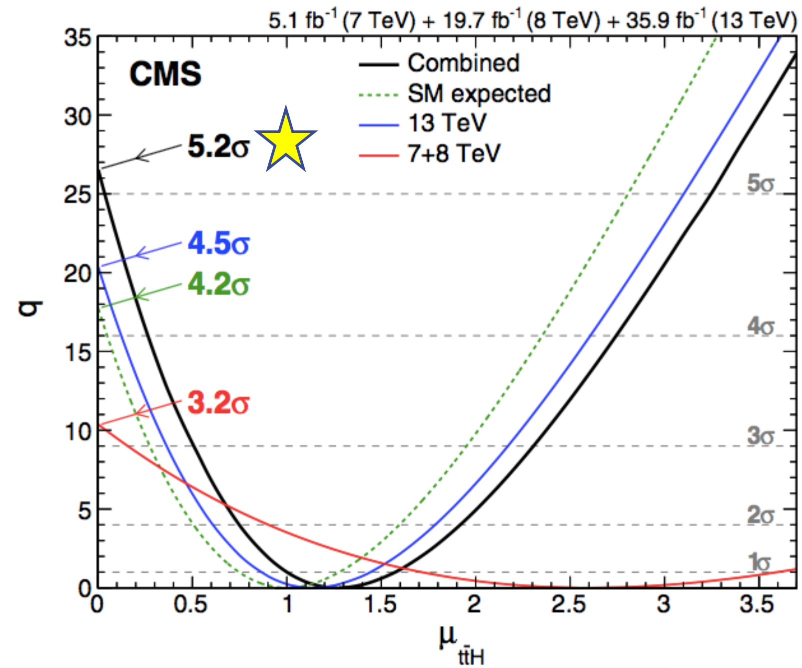
Source	Uncertainty	$\Delta\mu/\mu$
e, μ selection efficiency	2 - 4%	11%
τ_h selection efficiency	5%	4.5%
b-tagging efficiency	few % [49]	6%
Reducible background estimate	10 - 40%	11%
Jet energy calibration	few % [52]	5%
τ_h energy calibration	3%	1%
Theoretical sources	$\approx$ 10%	12%
Integrated luminosity	2.5%	5%

$t\bar{t}H$ observation

- Combination of several processes:
  $t\bar{t}H$ with **H→WW**, **H→ZZ**, **H→ $\gamma\gamma$** , **H→ $\tau\tau$**, **H→bb**
- Combination of several data-taking periods:
  LHC **Run I** (7-8 TeV, 2011-2013) and **Run II** (13 TeV, 2015-2016)



$\mu = 1.26^{+0.31}_{-0.26}$



★ **Observation** of Higgs boson production in association with top-antitop pair

(April 2018, *Physical Review Letters* 120, 231801)

Summary

- **CMS** has a sophisticated **two-level trigger system** that reduces the event rate by a factor 10^5, sustainable for data reconstruction and storage.
- **Hadronically decaying τ's** are clustered already at hardware level in the L1 trigger system, with excellent efficiency and resolution.
- The sensitivity of analyses involving $\tau's$, such as **($\mathrm{t\bar{t}H}$) H → ττ**, crucially depends on the capability to identify and reconstruct τ's.
- The measurement of the $\mathrm{t\bar{t}H}$ process cross-section is the only direct measurement of the **top Yukawa coupling**.
- The analysis strategy of the $\mathrm{t\bar{t}H}$ process with τ's in the final state has been presented, where a sophisticated **Matrix Element Method** algorithm is used to extract the signal in the **2lss+1τ_h** final state.
- The combination of $\mathrm{t\bar{t}H}$ processes with different Higgs decay modes and Run I and Run II data allowed the **observation** of the $\mathrm{t\bar{t}H}$ process by CMS in April 2018.

Merci!

"The Trigger does not determine which Physics Model is right, only which Physics Model is left"

Back-up

Event selection

Selection	2ℓss	$2\ell\text{ss} + 1\tau_h$
Targeted $t\bar{t}H$ decay	$t \to b\ell\nu$, $t \to bqq$, $H \to WW \to \ell\nu qq$	$t \to b\ell\nu$, $t \to bqq$, $H \to \tau\tau \to \ell\tau_h + \nu$'s
Trigger	Single- and double-lepton triggers	
Lepton p_T	$p_T > 25$ / 15 GeV	$p_T > 25$ / 15 (e) or 10 GeV (μ)
τ_h p_T	—	$p_T > 20$ GeV
Charge requirements	2 same-sign leptons and charge quality requirements	2 same-sign leptons and charge quality requirements $\sum_{\ell,\tau_h} q = \pm 1$
Jet multiplicity	$\geq$4 jets	$\geq$3 jets
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	$L_D > 30$ GeV	$L_D > 30$ GeV *
Dilepton mass	$m_{\ell\ell} > 12$ GeV and $\lvert m_{ee} - m_Z \rvert > 10$ GeV *	

Selection	3ℓ	$3\ell + 1\tau_h$
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu$, $t \to b\ell\nu$, $H \to WW \to \ell\nu qq$ $t \to b\ell\nu$, $t \to bqq$, $H \to WW \to \ell\nu\ell\nu$ $t \to b\ell\nu$, $t \to bqq$, $H \to ZZ \to \ell\ell qq$ or $\ell\ell\nu\nu$	$t \to b\ell\nu$, $t \to b\ell\nu$, $H \to \tau\tau \to \ell\tau_h + \nu$'s
Trigger	Single-, double- and triple-lepton triggers	
Lepton p_T	$p_T > 25$ / 15 / 15 GeV	$p_T > 20$ / 10 / 10 GeV
τ_h p_T	—	$p_T > 20$ GeV
Charge requirements	$\sum_{\ell} q = \pm 1$	$\sum_{\ell,\tau_h} q = 0$
Jet multiplicity	$\geq$2 jets	
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	No requirement if $N_j \geq 4$ $L_D > 45$ GeV † $L_D > 30$ GeV otherwise	
Dilepton mass	$m_{\ell\ell} > 12$ GeV and $\lvert m_{\ell\ell} - m_Z \rvert > 10$ GeV ‡	

* Applied only if both leptons are electrons.
† If the event contains a SFOS lepton pair and $N_j \leq 3$.
‡ Applied to all SFOS lepton pairs.

Event selection

Selection	$1\ell + 2\tau_h$	4ℓ
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu$, $t \to bqq$, $H \to \tau\tau \to \tau_h\tau_h + \nu$'s	$t \to b\ell\nu$, $t \to b\ell\nu$, $H \to WW \to \ell\nu\ell\nu$ $t \to b\ell\nu$, $t \to b\ell\nu$, $H \to ZZ \to \ell\ell qq$ or $\ell\ell\nu\nu$
Trigger	Single=lepton and lepton+τ_h triggers	Single-, double- and triple-lepton triggers
Lepton p_T	$p_T > 25$ (e) or 20 GeV (μ)	$p_T > 25 / 15 / 15 / 10$ GeV
τ_h p_T	$p_T > 30 / 20$ GeV	—
Charge requirements	$\sum_{\tau_h} q = 0$ and $\sum_{\ell,\tau_h} q = \pm 1$	$\sum_{\ell} q = 0$
Jet multiplicity	$\geq$3 jets	$\geq$2 jets
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	—	No requirement if $N_j \geq 4$ $L_D > 45$ GeV † $L_D > 30$ GeV otherwise
Dilepton mass	$m_{\ell\ell} > 12$ GeV	$m_{\ell\ell} > 12$ GeV and $\lvert m_{\ell\ell} - m_Z \rvert > 10$ GeV ‡
Four-lepton mass	—	$m_{4\ell} > 140$ GeV §

† If the event contains a SFOS lepton pair and $N_j \leq 3$.

‡ Applied to all SFOS lepton pairs.

§ Applied only if the event contains 2 SFOS lepton pairs.

Fake factor method

- Non-prompt lepton / hadron → lepton
- Jet (q,g) → τ_h

Fake factor (FF) method:

- Same selection as SR but relaxing identification criteria ("tight" to "fakeable"): AR.
- Estimation of fake background in SR done applying weights to the events in the AR.
- Weights depend on the probability f_i of a misidentified lepton or τ_h that passes the "fakeable" criteria to pass the "tight" criteria.

For events with 2 objects

$$w_2 = \begin{cases} \frac{f_1}{1-f_1} & \text{if } N_p = 1 \\ -\frac{f_1 f_2}{(1-f_1)(1-f_2)} & \text{if } N_p = 0 \end{cases}$$

For events with 3 objects

$$w_3 = \begin{cases} \frac{f_1}{1-f_1} & \text{if } N_p = 2 \\ -\frac{f_1 f_2}{(1-f_1)(1-f_2)} & \text{if } N_p = 1 \\ \frac{f_1 f_2 f_3}{(1-f_1)(1-f_2)(1-f_3)} & \text{if } N_p = 0 \end{cases}$$

N_P number of "fakeable" objects that pass the "tight" criteria

- Measured separately for e / μ (multijets), τ_h ($t\bar{t}$+jets) (DR)
- 2ℓSS+$1\tau_h$, 3ℓ+$1\tau_h$: restricted to leptons. τ_h contribution estimated from MC. (30% of the $t\bar{t}$H signal has fake τ_h).

MEM

High-dimensional integrals, poorly measured. Numerical integration (VEGAS, MC-chain)

Transfer function (the probability for measuring a set of observables **y** in the detector, given that the corresponding parton-level momenta are equal to **x**) -> experimental resolution. Computed with MC simulation.

Compatibility of the event measured with observables y with the hypothesis that the event is produced by the process Ω

Parton distribution functions (PDF). Computed numerically to LO using CTEQ6.6 and NNPDF3.0.

Hard-scattering matrix element. Computed to LO with MadGaph.

$$w_{\Omega}(\mathbf{y}) \propto \sum_{p} \int \mathrm{d}\mathbf{x}\,\mathrm{d}x_a\,\mathrm{d}x_b \frac{f_i(x_a,Q) f_j(x_b,Q)}{x_a x_b s} \delta^4\left(x_a P_a + x_b P_b - \sum p_k\right) |\mathcal{M}_{\Omega}(\mathbf{x})|^2 W(\mathbf{y}|\mathbf{x})$$

All possible associations between parton-level and reconstructed objects

Bjorken variables (fraction of proton momentum carried by parton)

Energy and momentum conservation (reduce integral dimensionality)

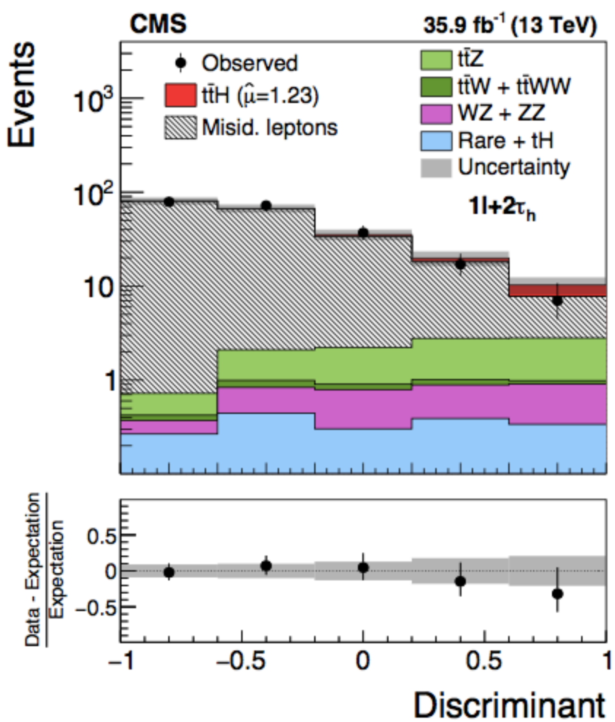
Kinematic variables (4-momenta of partons in initial and final state)

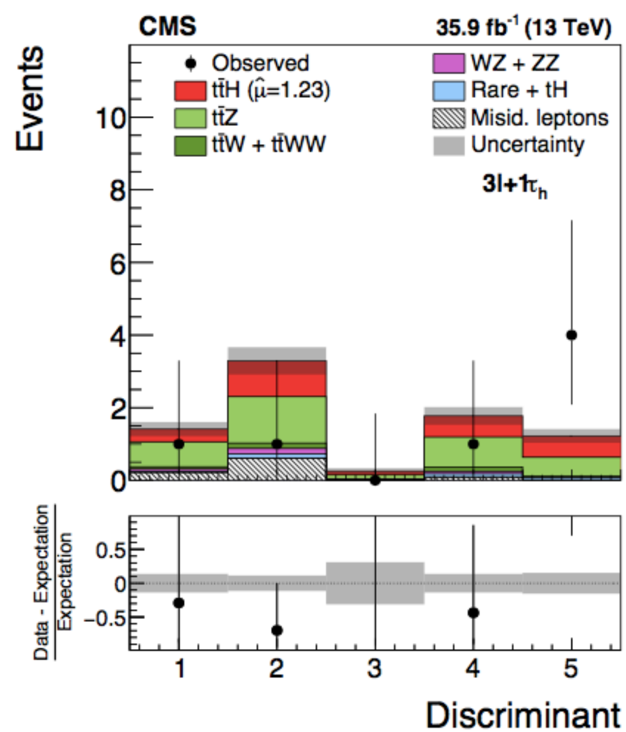
Measured set of observables in the detector.

$$\mathrm{LR}(\mathbf{y}) = \frac{w_{\mathrm{t\bar{t}H}}(\mathbf{y})}{w_{\mathrm{t\bar{t}H}}(\mathbf{y}) + \sum_{\mathrm{B}} \kappa_{\mathrm{B}}\, w_{\mathrm{B}}(\mathbf{y})}$$

The coefficients κ_{B} that quantify the relative importance of different background processes B are determined by a numerical optimization, in order to achieve the maximal separation of the $\mathrm{t\bar{t}H}$ signal from all background processes.

Signal extraction: BDTs





Observable	$1\ell+2\tau_h$	$3\ell+1\tau_h$
$\Delta R(\ell_1,j)$	—	√
$\Delta R(\ell_2,j)$	—	√
$\langle \Delta R_{jj} \rangle$	√	√[2]
$\Delta R_{\tau\tau}$	√	—
$\max(\lvert\eta^{\ell 1}\rvert, \lvert\eta^{\ell 2}\rvert)$	—	√
H_T^{miss}	√	√[2]
N_j	√	√
N_b	√	—
$m_{\tau\tau}^{vis}$	√	—
$m_T^{\ell 1}$	—	√
$p_T^{\ell 1}$	—	√[1]
$p_T^{\ell 2}$	—	-
$p_T^{\ell 3}$	—	√[1]
$p_T^{\tau 1}$	√	—
$p_T^{\tau 2}$	√	—
$LR(3\ell)$	—	—
MVA_{thad}^{max}	—	—
MVA_{Hj}^{max}	—	—

Event yields

Process	$1\ell + 2\tau_h$	$2\ell ss$	$2\ell ss + 1\tau_h$
$t\bar{t}H$	5.8 ± 1.9	53.8 ± 17.0	9.4 ± 2.8
$t\bar{t}Z/\gamma^*$	6.3 ± 1.1	80.9 ± 10.4	9.2 ± 1.2
$t\bar{t}W + t\bar{t}WW$	0.5 ± 0.1	150.0 ± 16.9	9.1 ± 1.0
WZ + ZZ	2.1 ± 1.6	16.5 ± 13.1	3.9 ± 3.0
tH	0.4 ± 0.1	2.7 ± 0.2	0.5 ± 0.04
Conversions	< 0.02	12.1 ± 5.8	1.4 ± 0.5
Sign flip	—	27.5 ± 8.0	0.5 ± 0.1
Misidentified leptons	195.7 ± 13.6	94.2 ± 21.2	8.6 ± 2.1
Rare backgrounds	1.4 ± 0.7	39.0 ± 21.2	3.1 ± 1.5
Total expected background	206.3 ± 14.0	423.0 ± 38.0	36.1 ± 4.2
Observed	212	507	49

Process	3ℓ	$3\ell + 1\tau_h$	4ℓ
$t\bar{t}H$	18.5 ± 6.0	2.1 ± 0.7	0.9 ± 0.3
$t\bar{t}Z/\gamma^*$	49.0 ± 6.9	3.4 ± 0.5	2.1 ± 0.4
$t\bar{t}W + t\bar{t}WW$	35.2 ± 4.2	0.4 ± 0.04	$< 2 \times 10^{-3}$
WZ + ZZ	9.9 ± 2.4	0.3 ± 0.05	0.1 ± 0.1
tH	1.2 ± 0.2	0.1 ± 0.01	$< 4 \times 10^{-4}$
Conversions	5.3 ± 2.9	< 0.02	< 0.02
Misidentified leptons	22.7 ± 6.7	0.9 ± 0.2	< 0.04
Rare backgrounds	8.2 ± 13.8	0.2 ± 0.1	0.1 ± 0.2
Total expected background	131.4 ± 18.2	5.3 ± 0.5	2.4 ± 0.4
Observed	148	7	3

Table 5: Numbers of events selected in the different categories compared to the SM expectations for the $t\bar{t}H$ signal and background processes. The event yields expected for the $t\bar{t}H$ signal and for the backgrounds are shown for the values of nuisance parameters obtained from the ML fit and $\mu = 1$. Quoted uncertainties represent the combination of statistical and systematic components.