Searches for associated *tH* production in LHC Run I

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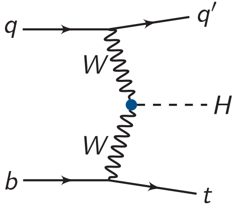
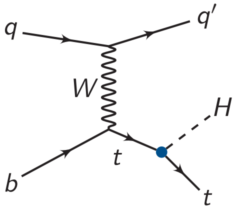
On behalf of *tH* analysts

CP3 *tH* jamboree
22 Apr 2015

Introduction

- Theoretical introduction given by Federico
  - Benedikt will discuss technical aspects of generation of samples for tH processes
- Current experimental searches for tH do not probe the $\mathcal{CP}$-violating case explicitly
  - Most searches focus on tHq with $y_t = -1$
  - Usually couplings cannot be varied easily as they affect kinematics





Status of searches

- Several searches for tHq production have been performed so far
- CMS exploited various Higgs boson decay channels in 8 TeV data
  - $H \to \gamma\gamma$ [HIG-14-001]
    - Small branching ratio but high purity
    - An additional enhancement of $\mathcal{B}(H \to \gamma\gamma)$ by a factor of 2.4
  - $H \to b\bar{b}$ channel [HIG-14-015]
    - Largest branching ratio but overwhelming $t\bar{t}$ background
  - $H \to WW/\tau\tau$ multilepton final state [HIG-14-026]
  - $H \to \tau_{\mathrm{h}}\tau_{\ell}$ [AN-14-179]
  - Combination is being prepared [HIG-14-027]
- ATLAS considered tH in a $t\bar{t}H$ search $(7 + 8\,\mathrm{TeV})$
  - $H \to \gamma\gamma$ [Phys. Lett. B740 (2015) 222]

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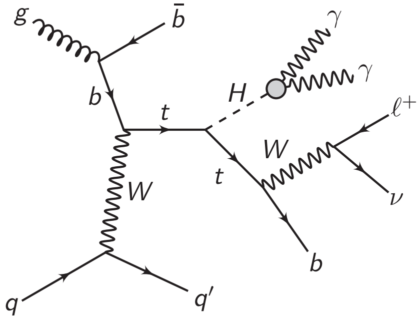
  - $H \to \gamma\gamma$ [Phys. Lett. B740 (2015) 222] .... **Paper public**
  - Other non-public activities might be going on

CMS search in the $H \to \gamma\gamma$ channel

Event preselection



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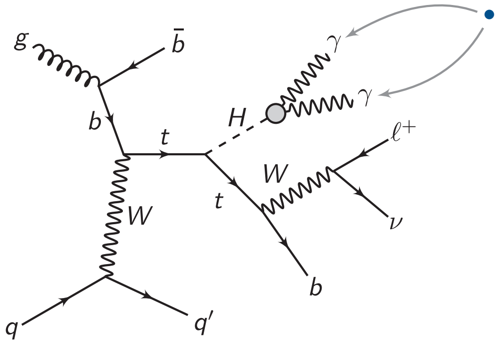

- Two photons
  - $p_T(\gamma_1) > 50 \cdot m_{\gamma\gamma}/120$
  - $p_T(\gamma_2) > 25\,\text{GeV}$
  - Used also to trigger events

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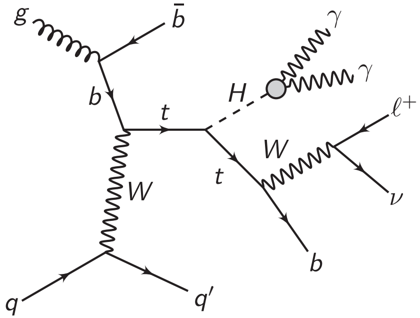

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  - $p_T > 10\,\text{GeV}$

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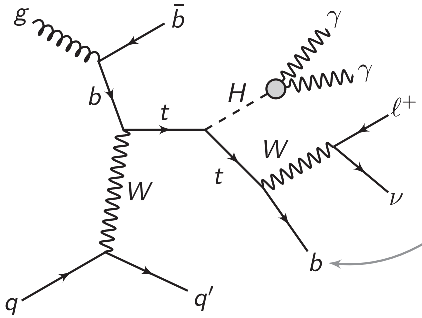

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  - $p_T > 20\,\text{GeV}$

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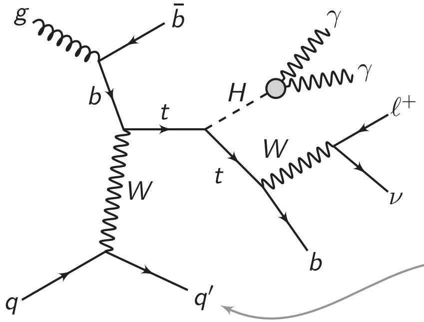

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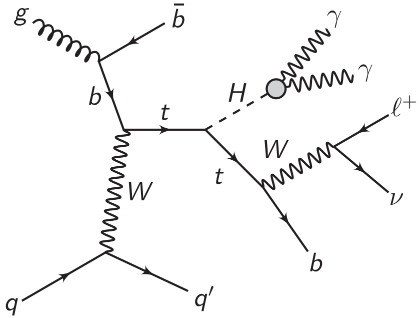

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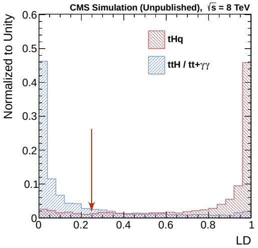
- Consider mass window $122 < m_{\gamma\gamma} < 128\,\text{GeV}$ as the signal region

Resonant backgrounds

- Backgrounds with a Higgs boson contribute to the $m_{\gamma\gamma}$ peak
  - $t\bar{t}H$ (dominant), VH, $H +$ jets
- To suppress $t\bar{t}H$, a likelihood product discriminator (LD) is constructed
  - Variables: $\#$ jets, $m_T(t)$, $\eta(q')$, $\Delta\eta(\ell, q')$, lepton charge
- A cut on value of LD is added to event selection
- Expected yields in the $m_{\gamma\gamma}$ window after the full selection:

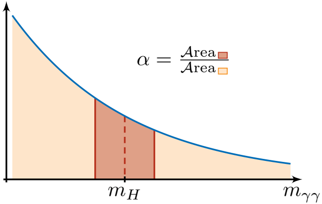
Process	Yield
tHq, $y_t = -1$	0.67
$t\bar{t}H$	$0.03 + 0.05^{\dagger}$
VH	$0.01 + 0.01^{\dagger}$
other H	0

†Increase due to $y_t = -1$, included into signal



Non-resonant backgrounds

- Remaining backgrounds are smooth in $m_{\gamma\gamma}$
  - $\gamma\gamma +$ jets, $\gamma +$ jets, $t\gamma\gamma$, $t\bar{t}\gamma\gamma$, ...
- Their spectrum in data is fitted with an exponential function
  - Utilise sidebands $m_{\gamma\gamma} \in (100, 122) \cup (128, 180)$ GeV



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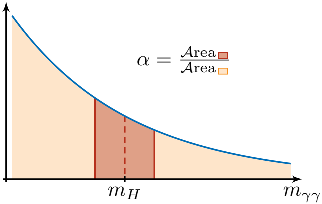
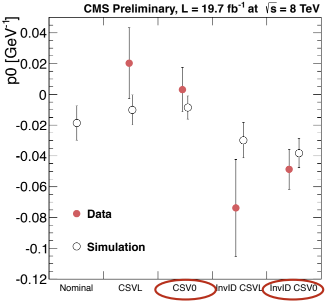
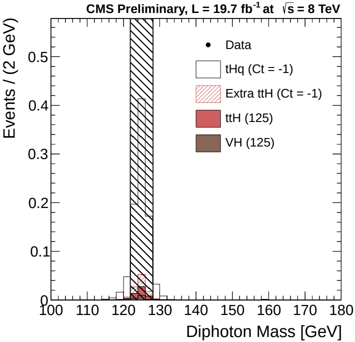
- Their spectrum in data is fitted with an exponential function
  - Utilise sidebands $m_{\gamma\gamma} \in (100, 122) \cup (128, 180)$ GeV
  - Use four control regions with
    - loose ("CSVL") or very loose ("CSV0") requirement on *b*-tagging
    - nominal or inverted photon ID
  - Difference between two high-stat control regions used as systematics





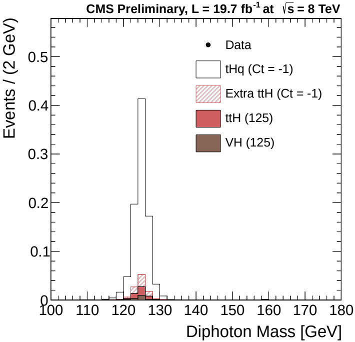
Results

- Zero events observed in $m_{\gamma\gamma}$ sidebands
  - Translates to an estimate of contribution of non-resonant backgrounds under the peak



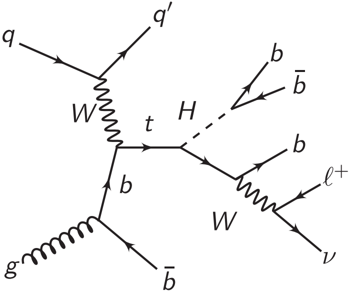
Results

- Zero events observed in $m_{\gamma\gamma}$ sidebands
  - Translates to an estimate of contribution of non-resonant backgrounds under the peak
- Zero events found in the mass window as well
- Observed 95% CL_s upper limit on tHq is 4.1 times the expected cross section
  - Absolute value: $\sigma_{tHq}^{y_t=-1} \times \mathcal{B}_{H\to\gamma\gamma}^{y_t=-1} < 5.2\,\mathrm{fb}$
  - Coincides with the expected limit



CMS search in the $H \to b\bar{b}$ channel

Event selection



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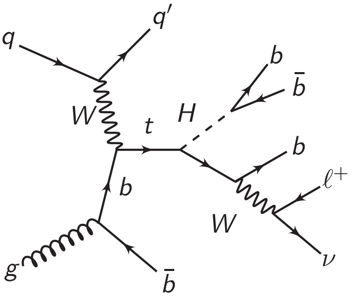
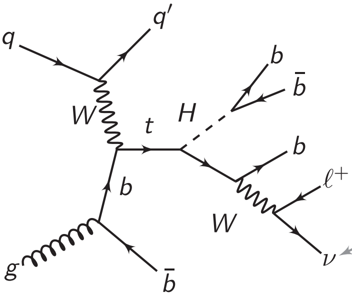


- Exactly one isolated μ or e
  - $p_T > 26$ (30) GeV for μ (e)
  - Used to trigger events

Event selection



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  - $p_{\mathrm{T}} > 26$ (30) GeV for μ (e)
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- Moderate $\not{E}_{\mathrm{T}}$
  - $\not{E}_{\mathrm{T}} > 35$ (45) for μ (e)

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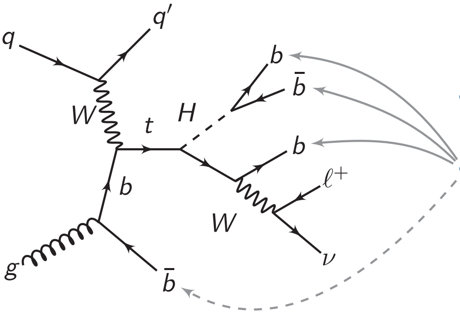

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  - $p_T > 20$ GeV

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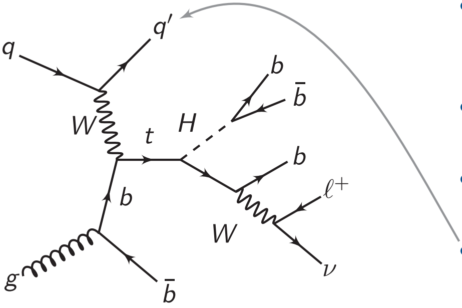

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- A non-b-quark recoil jet
  - $p_T > 20$ GeV if $|\eta| < 2.4$
  - $p_T > 40$ GeV if $|\eta| > 2.4$

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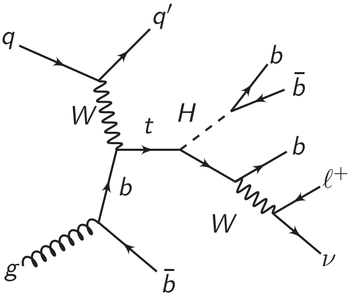

Region	S/B ratio	
3 b-jets	13/1900	0.7%
4 b-jets	1.4/66	2.1%

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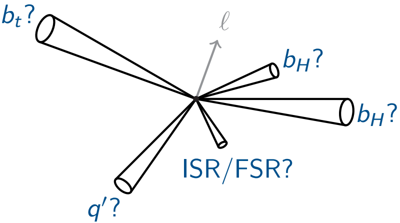
  - $p_T > 40$ GeV if $|\eta| > 2.4$
- Dominant background is $t\bar{t}$

Jet assignment with MVA

- The small S/B ratio makes a multivariate analysis essential
- But construction of input variables from a multijet final state is delicate
    - E. g. which jets stem from H decay?



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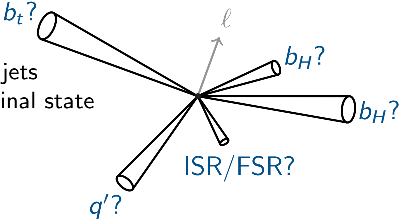
  - Consider all possible ways to assign four jets to the four quarks in the $tHq \to \ell\nu 3bq$ final state



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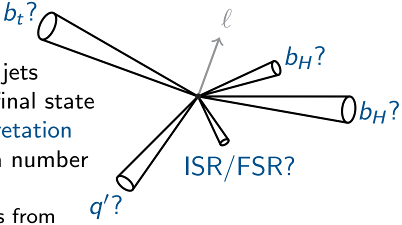
  - Consider all possible ways to assign four jets to the four quarks in the $tHq \to \ell\nu 3bq$ final state
  - Each particular way represents an interpretation of the event and can be described with a number of observables
    - Reconstructed m_H, m_t, ΔR between jets from $H \to b\bar{b}$, b-tagging discriminator of the b from $t \to b\ell\nu$, etc.



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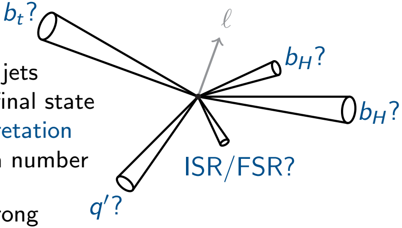

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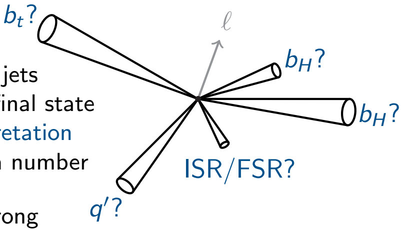
  - In an unknown event, consider all possible interpretations, evaluate the NN for each one, and accept the interpretation with the largest NN response



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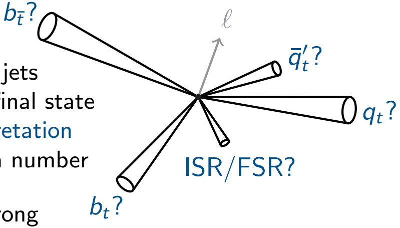
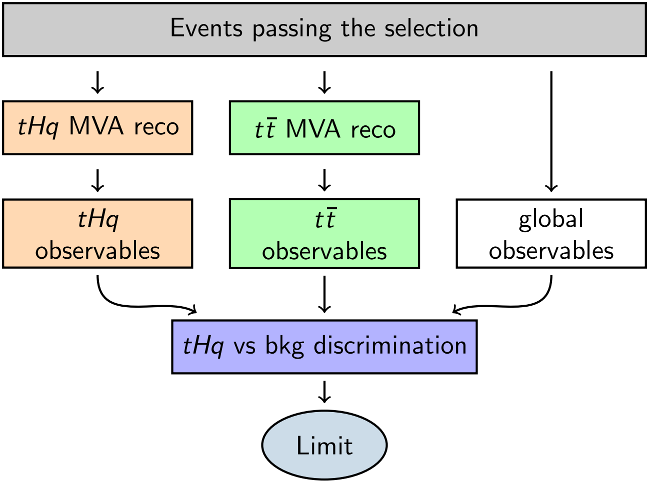


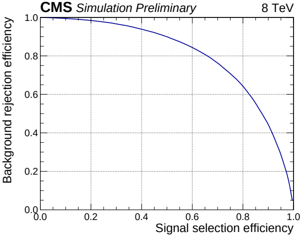
- A similar procedure is used for semileptonic $t\bar{t}$
  - This is by far the dominant background

Discrimination between signal and backgrounds



Discrimination between signal and backgrounds

- The jet assignment is only used to construct input variables for the final NN
  - Trained to distinguish tH events from backgrounds
- Examples of input variables
  - Defined under tH hypothesis: $p_{\mathrm{T}}(H)$, $\eta(q')$
  - Defined under $t\bar{t}$ hypothesis: mass of $t \to$ had, number of b-tagged jets amoung its decay products
  - Independent of jet assignment: $Q(\ell)$



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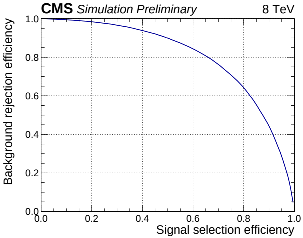
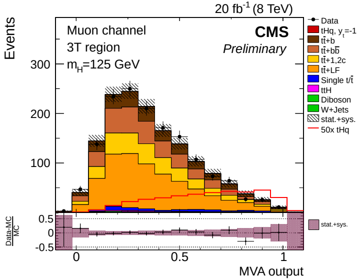
  - Independent of jet assignment: $Q(\ell)$
- Response of the final NN in data is fitted to put an upper limit
- Observed a 95% CL_s upper limit of 7.6 times the expected cross section (exp. limit $5.1^{+2.1}_{-1.7}$)
  - Absolute value: $\sigma_{tHq}^{y_t=-1} \times \mathcal{B}_{H\to b\bar{b}} < 1.0\,\mathrm{pb}$



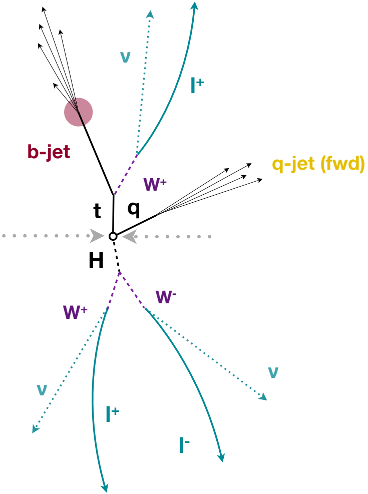


CMS search in the multilepton channel

Event selection

Three leptons

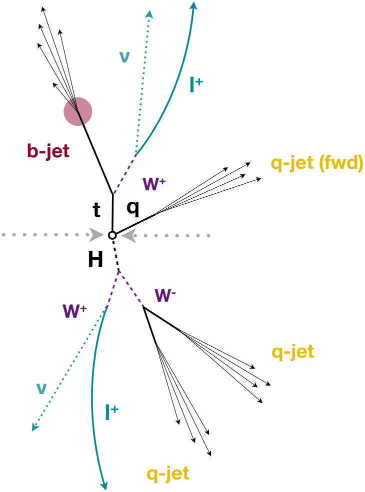
- $\mu\mu\mu$, $\mu\mu e$, μee, or eee
  - $p_T > 20/10/10\,\mathrm{GeV}$
  - Same ID as in HIG-13-023 ($H \to WW$ in multileptons)
- Exactly one b-tagged jet
  - $p_T > 25\,\mathrm{GeV}$, CSVM
- At least one forward jet
  - $p_T > 25\,\mathrm{GeV}$, $|\eta| > 1.5$, fails CSVM
- $\not{E}_T > 30\,\mathrm{GeV}$
- Z veto
  - $\min |m_{\ell\ell} - m_Z| > 15\,\mathrm{GeV}$



Event selection

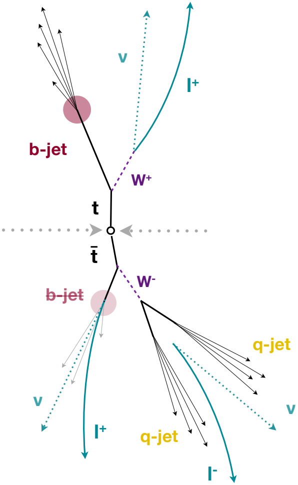
Same-sign dileptons

- $\mu^{\pm}\mu^{\pm}$ or $e^{\pm}\mu^{\pm}$
  - $p_{\mathrm{T}} > 20\,\mathrm{GeV}$
  - Same ID as in HIG-13-020 (multilepton $t\bar{t}H$ search)
- At least one central jet
  - $p_{\mathrm{T}} > 25\,\mathrm{GeV}$, $|\eta| < 1$
- At least one *b*-tagged jet
  - $p_{\mathrm{T}} > 25\,\mathrm{GeV}$, CSVL
- At least one forward jet
  - $p_{\mathrm{T}} > 25\,\mathrm{GeV}$, $|\eta| > 1$, fails CSVL
- Reject events containing τ_{h}



Backgrounds with non-prompt leptons

- An important background consists of events with non-prompt leptons
  - Mostly $t\bar{t} \to \ell +$ jets, where a b jet fakes a lepton



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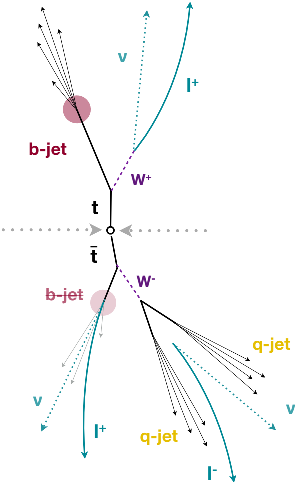
- Data-driven estimation
  - Extrapolate from regions with loosened cuts on lepton ID and isolation
    - Nominal selection apart from that
  - Construct per-event weights from fake rate
    - Fake rate f is the probability that a lepton passes tight selection given that it passed loose one:

$$f = N_{\text{tight}}/N_{\text{loose}}$$

    - Measured in control regions in data (most notably, regions enriched in $b\bar{b}$ dijet events)



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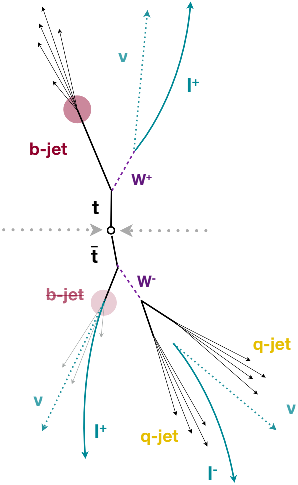
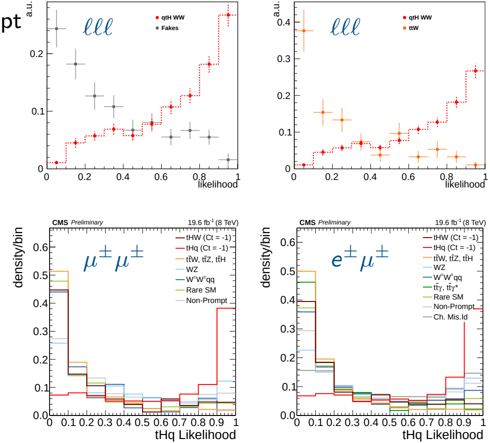
    - Measured in control regions in data (most notably, regions enriched in $b\bar{b}$ dijet events)
- Also measure from data electron charge mis-ID
  - Utilise same-sign ee pairs with $m_{\ell\ell} \sim m_Z$



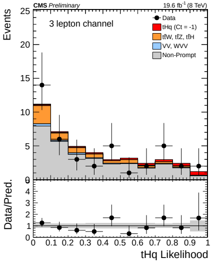
Discrimination against backgrounds

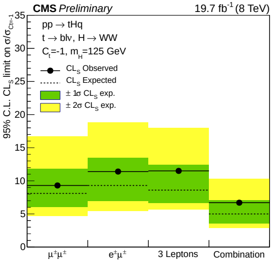
- Apply a likelihood product discriminator to suppress backgrounds
  - Trained to discriminate against both irreducible and non-prompt backgrounds
- Different sets of input variables for 2ℓ and 3ℓ selections
- Example inputs:
  - number of central/forward/ b-tagged jets
  - $\Delta R(\ell,\ell)$, $\Delta\phi(\ell,\ell)$
  - H_{T}(jets), $p_{\mathrm{T}}(\ell)$
  - lepton charge

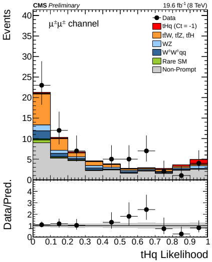


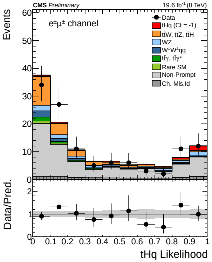
Results

- To extract signal cross section, responses of the likelihood discriminators are fitted to data
- The three channels are combined
- Observed (expected) 95% CL_s upper limit:
  $6.7\ \left(5.0^{+2.1}_{-1.4}\right) \times \sigma^{y_t=-1}_{tHq}$



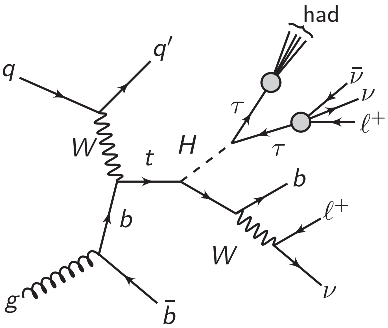




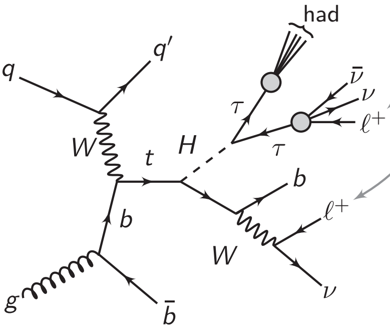


CMS search in the $\tau_\mathrm{h}\tau_\ell$ channel

Event selection

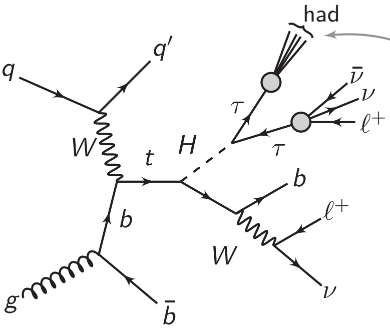


Event selection



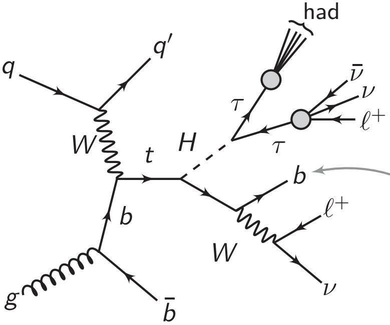
- $\mu^\pm\mu^\pm$ or $e^\pm\mu^\pm$ (same sign)
  - $p_\mathrm{T} > 20/10\,\mathrm{GeV}$
  - MVA ID with dedicated tuning for $\tau \to \ell + X$

Event selection



- $\mu^\pm\mu^\pm$ or $e^\pm\mu^\pm$ (same sign)
  - $p_\mathrm{T} > 20/10\,\mathrm{GeV}$
  - MVA ID with dedicated tuning for $\tau \to \ell + X$
- Isolated τ_h
  - $p_\mathrm{T} > 20\,\mathrm{GeV}$
  - Electric charge opposite to the $\ell\ell$ pair

Event selection



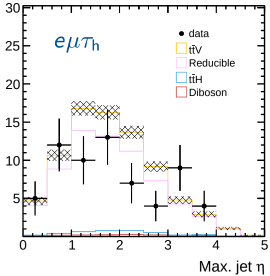
- $\mu^{\pm}\mu^{\pm}$ or $e^{\pm}\mu^{\pm}$ (same sign)
  - $p_{\mathrm{T}} > 20/10\,\mathrm{GeV}$
  - MVA ID with dedicated tuning for $\tau \to \ell + X$
- Isolated τ_{h}
  - $p_{\mathrm{T}} > 20\,\mathrm{GeV}$
  - Electric charge opposite to the $\ell\ell$ pair
- At least one b-tagged jet
  - $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, CSVM

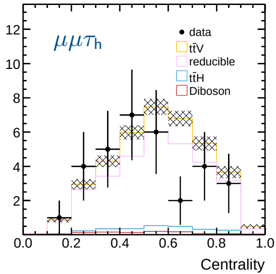
Backgrounds with non-prompt leptons

- Largest background comes from event with non-prompt leptons (mostly $t\bar{t}$)

Backgrounds with non-prompt leptons

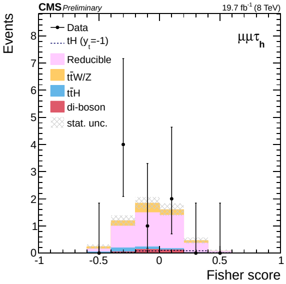
- Largest background comes from event with non-prompt leptons (mostly $t\bar{t}$)
- Data-driven estimation that utilises jet $\rightarrow e$, jet $\rightarrow \mu$ fake rates
  - Extrapolate from control regions with loosened definitions of μ or e
  - Measure the fake rate in a $t\bar{t}$-enriched region in data
- Method is validated in a control region with inverted τ isolation (Figs.)

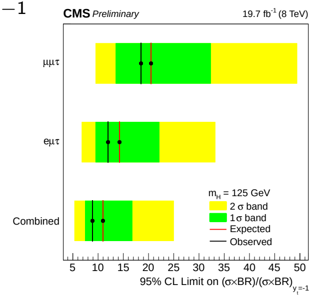


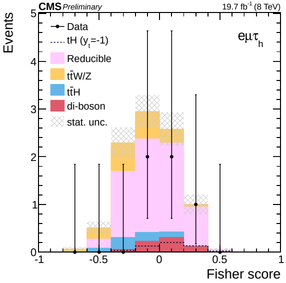


Discrimination between signal and background

- Apply Fisher discriminant to select signal events
  - Trained in a control region with anti-isolated τ because of insufficient statistics
  - Example input variables:
    - $p_{\mathrm{T}}(b_1)$, $\max|\eta(j)|$
    - number of jets, b-tagged jets
    - $m(\ell\ell)$, $m(\ell\tau)$
  - Distribution is fitted to data
- Obs. (exp.) combined 95% CL_s upper limit: $9\ \left(11^{+6}_{-4}\right) \times \sigma^{y_t=-1}_{tHq}$







Combination of all tH channels in CMS

Overview

- Results in individual decay channels:

$\sigma_{95\%}/\sigma_{y_t=-1}$	$H \to \gamma\gamma$	$H \to b\bar{b}$	$H \to WW/\tau_\ell\tau_\ell$	$H \to \tau_\ell\tau_\mathrm{h}$
Expected	4.1	5.2	5.0	11.0
Observed	4.1	7.6	6.7	8.9

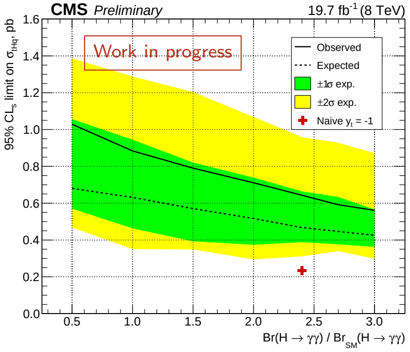
- Perform combination of all tH searches
    - Take into account correlations between all systematical uncertainties

Limits and branching ratio of $H \to \gamma\gamma$

- $H \to \gamma\gamma$ is the only decay considered that does not occur at tree level
  - Might be affected by BSM particles running in the loop
  - And $y_t = -1$ can only happen if there is some new physics
- Adopt a robust approach:
  - Do not stick to any specific value of $\mathcal{B}_{H\to\gamma\gamma}$
  - Calculate combined limit as a function of $\mathcal{B}_{H\to\gamma\gamma}$

$\mathcal{B}_{H\to\gamma\gamma}$	**Combined limit**	
	Obs.	**Exp.**
SM	3.8	$2.7^{+1.3}_{-0.7}$
$2.4 \times$ SM	2.8	$2.0^{+0.8}_{-0.3}$

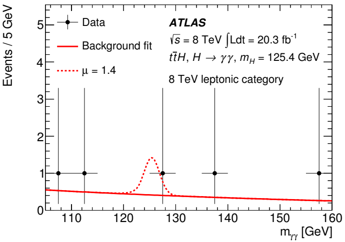
Limits in units of $\sigma_{tHq}^{y_t=-1} = 234$ fb

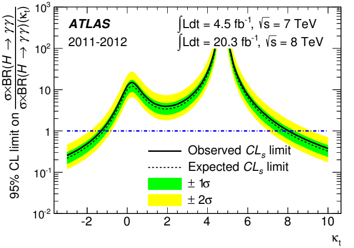


ATLAS search in the $H \to \gamma\gamma$ channel

Search for $H \to \gamma\gamma$ with top quarks

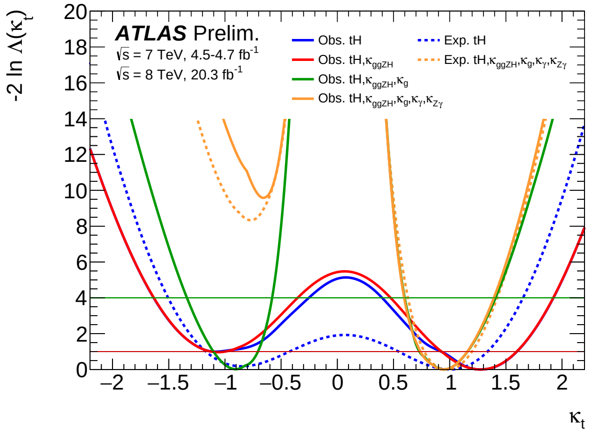
- ATLAS peformed a serch for $H \to \gamma\gamma$ produced with top quarks
  - Optimised for $t\bar{t}H$, but in some categories also sensitive to tHq and tHW
- Strategy:
  - Two categories depending on decays of the $t\bar{t}$ system:
    - $t\bar{t} \to \ell(\ell) + \text{jets}$, $\ell = e, \mu$
    - $t\bar{t} \to \text{jets}$
  - Amount of signal measured with a fit to $m_{\gamma\gamma}$
    - Similar to the CMS $tH(\gamma\gamma)$ search
- Derived upper limits as a function of $\kappa_t = y_t/y_t^{\text{SM}}$ (varied also in tH)





ATLAS combined constraints on κ_t

Combination[1] of all Higgs boson searches



- Higgs boson couples to SM particles only
- BSM contributions in loops are allowed

[1] ATLAS CONF-2015-007

Expectations for Run II and summary

CMS expectations for 2015 and beyond

- At $\sqrt{s} = 13\,\text{TeV}$ σ_{tHq} increases by $\times 4 \Rightarrow$
  Prospects for stat.-limited searches

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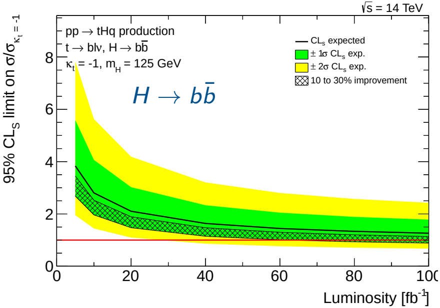
- At $\sqrt{s} = 13\,\text{TeV}$ σ_{tHq} increases by $\times 4 \Rightarrow$ Prospects for stat.-limited searches
- Scaling for first $\sim 20\,\text{fb}^{-1}$ of Run II:

$\gamma\gamma$	$b\bar{b}$	WW	$\tau_\ell\tau_\text{h}$
~ 1	~ 2.1	~ 2.1	~ 4.2

  - Dedicated projection study for $b\bar{b}$
  - Naive extrapolations for others
  - Very naive combination gives an upper limit $\sim 0.8 \Rightarrow$ Hope to kill/discover $y_t = -1$



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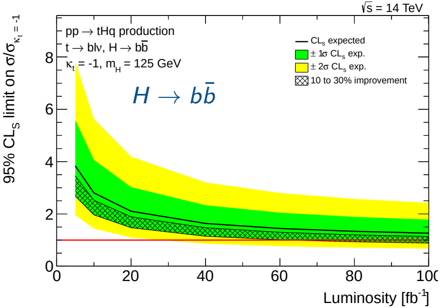


- There is a room for improvements in past searches
  - Include $t \to$ jets and $t \to b\tau_\text{h}\nu$ decays in the $H \to \gamma\gamma$ channel
  - Better exploit b-tagging information in the $H \to b\bar{b}$ channel
  - A number of technical improvements

Summary and plans

- CMS performed direct searches for tHq with $y_t = -1$
  - $H \to \gamma\gamma$, $b\bar{b}$, WW, and $\tau\tau$ decay channels considered
- Their combination is being finalised
  - Preliminary observed (expected) combined limit for the naively enhanced $\mathcal{B}_{H\to\gamma\gamma}$ is 2.8 $\left(2.0^{+0.8}_{-0.3}\right) \times \sigma_{tHq}^{y_t=-1}$
- ATLAS included tH in its search for $H \to \gamma\gamma$ with top quarks
  - Results have been incorporated into global ATLAS fit of Higgs boson couplings
- LHC Run II will be interesting
  - Hope to kill (or discover) $y_t = -1$ with first $\sim 20\,\mathrm{fb}^{-1}$ of 13 TeV data (the time scale is mid- to late 2016)
  - Plan to derive 2D exclusion limits in the (κ_t, κ_W) plane
  - Search for FCNH with tHq, $q = u, c$ vertex (complements $t\bar{t}$ signature)
  - Eventually can probe for $\mathcal{CP}$-violating coupling

Additional slides

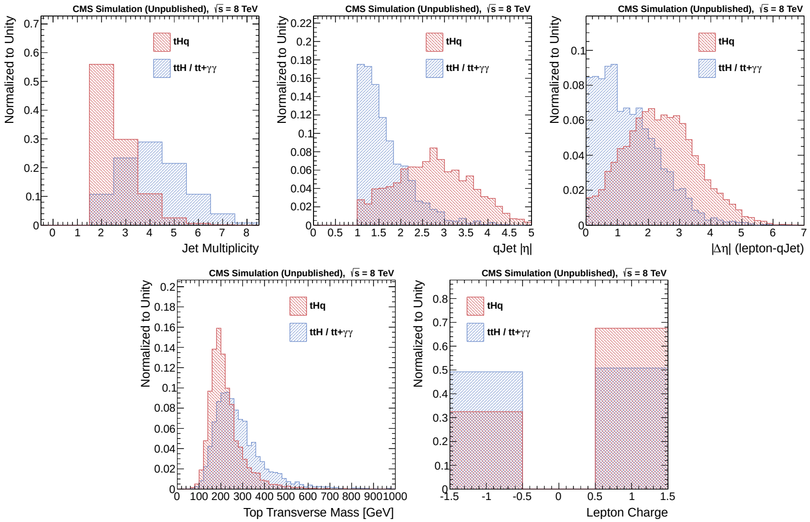
Cross sections

- Cross section is challengingly small
  - The main background is $t\bar{t}$; its cross section is provided for comparison

Cross section	8 TeV	14 TeV
tHq, $y_t = +1$ (SM)	18.3 ± 0.4 fb	$88.2^{+1.7}_{-0.0}$ fb
tHq, $y_t = -1$	$233.8^{+4.6}_{-0.0}$ fb	980^{+30}_{-0} fb
$t\bar{t}$	245^{+9}_{-10} pb	950^{+40}_{-30} pb

tHq cross sections are cited according to M. Farina et al., JHEP 1305 (2013) 022 [arXiv:1211.3736]. Cross sections for $t\bar{t}$ are calculated in M. Czakon, P. Fiedler, Phys. Rev. Lett. 110 (2013) 252004 [arXiv:1303.6254]. Uncertainties are combined following R. Barlow, arXiv:physics/0306138

$H \to \gamma\gamma$: Input variables for the LD



$H \to \gamma\gamma$: Systematic uncertainties

	tHq	$t\bar{t}H$	VH	Continuous BG
Luminosity	$\pm 2.6\%$	$\pm 2.6\%$	$\pm 2.6\%$	—
PDF	+3.1/-2.5 %	$\pm 8\%$	$\pm 11\%$	—
QCD scale	+4.8/-4.3 %	+11/-14 %	$\pm 2.3\%$	—
Signal model	$\pm 5.5\%$	—	—	—
Photon energy resolution	+4/-2 %	+4/-2 %	+4/-2 %	—
Photon energy scale	+1/-4 %	+1/-4 %	+1/-4 %	—
Photon ID efficiency	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$	—
Vertex efficiency	$\pm 0.1\%$	$\pm 0.1\%$	$\pm 0.1\%$	—
Trigger	$< 0.1\%$	$< 0.1\%$	$< 0.1\%$	—
JEC	$\pm 1.5\%$	+3/-5 %	$\pm 8\%$	—
JER	$\pm 0.5\%$	$\pm 3\%$	+8/-0 %	—
b-tagging	$\pm 2\%$	$\pm 1.5\%$	$\pm 0.1\%$	—
PU ID	$\pm 2\%$	$\pm 0.5\%$	$\pm 2\%$	—
Lepton reconstruction	$\pm 1\%$	$\pm 1\%$	$\pm 1\%$	—
BG shape	—	—	—	33%

$H \to b\bar{b}$: Expected event yields

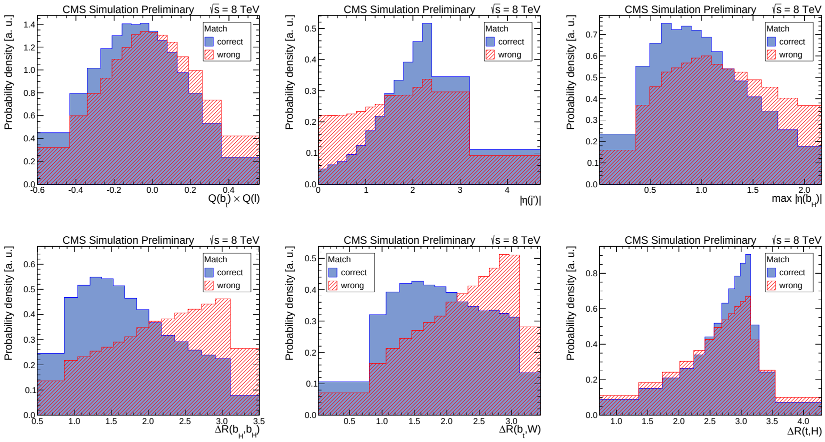
3t region

Process	Muon channel	Electron channel
$t\bar{t}$	1058$\pm$5	718$\pm$4
Single top	39$\pm$3	27$\pm$3
Electroweak	17^{+7}_{-5}	11$\pm$7
$t\bar{t}H$	12.87$\pm$0.17	9.35$\pm$0.15
Total background	1128$\pm$9	767$\pm$10
tHq, $y_t = -1$	7.54$\pm$0.03	5.15$\pm$0.02
S/B ratio	0.7%	0.7%

4t region

Process	Muon channel	Electron channel
$t\bar{t}$	29.1$\pm$0.8	19.8$\pm$0.7
Single top	$1.1^{+0.8}_{-0.6}$	1.2$\pm$1.0
Electroweak	4^{+6}_{-4}	5^{+6}_{-4}
$t\bar{t}H$	1.72$\pm$0.06	1.43$\pm$0.05
Total background	37^{+6}_{-4}	29^{+7}_{-4}
tHq, $y_t = -1$	0.835$\pm$0.010	0.580$\pm$0.009
S/B ratio	2.3%	2.0%

$H \to b\bar{b}$: Input variables for tHq jet assignment



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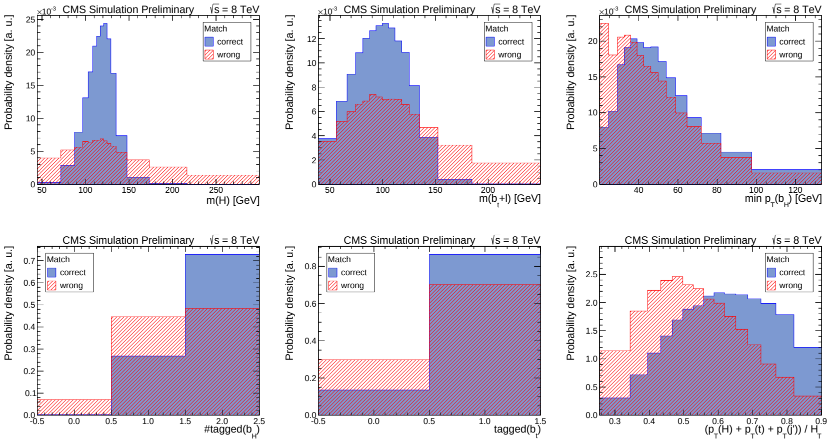
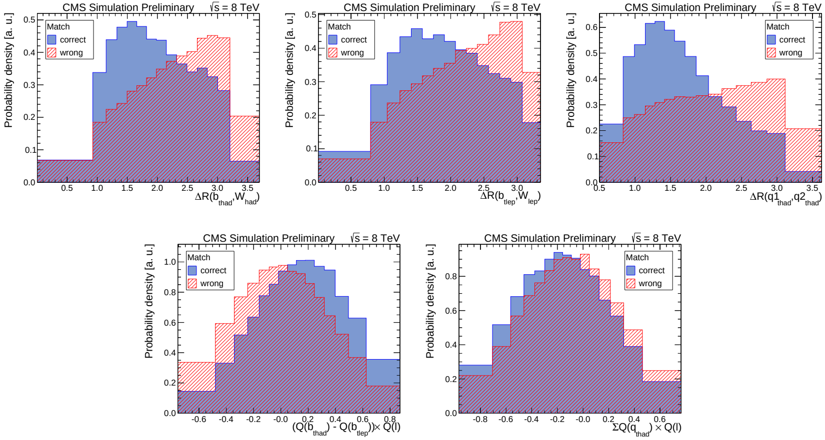
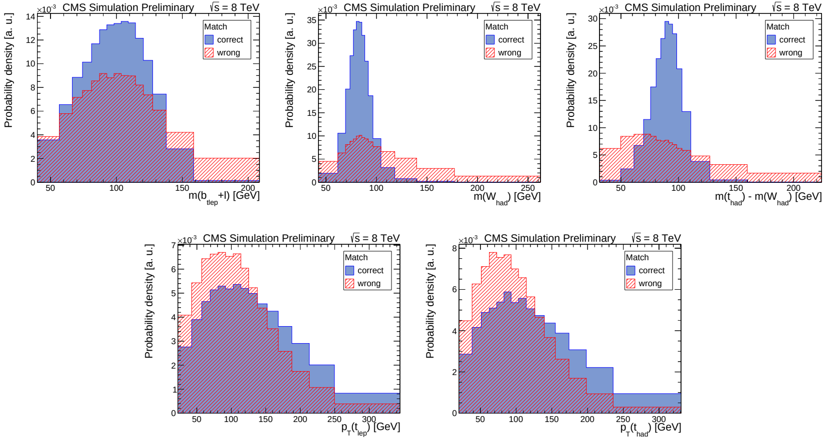


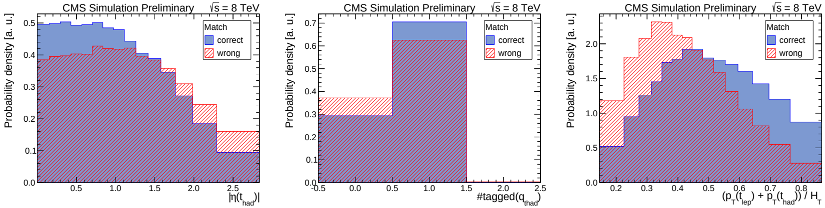
$H \to b\bar{b}$: Input variables for $t\bar{t}$ jet assignment



$H \to b\bar{b}$: Input variables for $t\bar{t}$ jet assignment



$H \rightarrow b\bar{b}$: Input variables for $t\bar{t}$ jet assignment



$H \to b\bar{b}$: Efficiency of jet identification

- Three definitions of identification efficiency are considered:
  - "A": Calculated with all events that pass the selection
  - "B": Use only events in which the parton in question does have an MC-truth match
  - "C": Use events that have a correct interpretation (as defined by the procedure, see the AN)
- A perfect jet assignment would have a 100% efficiency in definition C
  - At the same, time the efficiency in definition A incorporates effects of jet acceptance (especially, p_{T} cut) as well as jet splitting, merging, and other artefacts and thus might be significantly lower
- Definitions A and C can also be used for groups of more than one jet
  - A group is identified correcly if all jets in it are identified

$H \to b\bar{b}$: Efficiency of jet identification, tHq hyp.

- Mean number of jets in a tHq event is 5.4
- Mean number of considered event interpretations is 60
- Efficiency of identification of jets and groups of jets:

Object(s)	**Efficiency**		
	A	**B**	**C**
b from $t \to b\ell\nu$	56.7%	61.3%	65.9%
at least one b from $H \to b\bar{b}$	85.6%	—	92.3%
both b from $H \to b\bar{b}$	50.8%	—	64.5%
recoil quark	51.8%	78.3%	78.5%
all four quarks	21.8%	—	44.2%

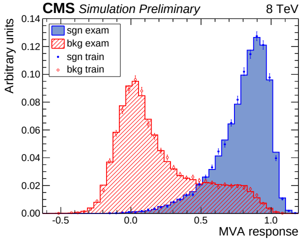
$H \to b\bar{b}$: Efficiency of jet identification, $t\bar{t}$ hypothesis

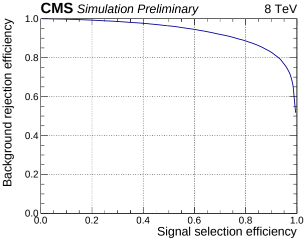
- Mean number of jets in a semileptonic $t\bar{t}$ event is 5.7
- Mean number of considered event interpretations is 35
- Efficiency of identification of jets and groups of jets:

Object(s)	**Efficiency**		
	A	**B**	**C**
b from $t \to b\ell\nu$	63.5%	69.5%	66.0%
b from $t \to$ had	58.3%	63.5%	68.3%
at least one q from $W \to q\bar{q}'$	63.0%	—	90.0%
both q from $W \to q\bar{q}'$	10.9%	—	56.6%
all quarks from $t \to$ had	8.6%	—	47.1%
all four quarks	6.1%	—	37.0%

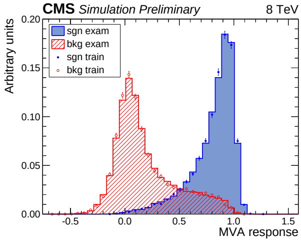
$H \to b\bar{b}$: Responses and ROCs for jet assignment

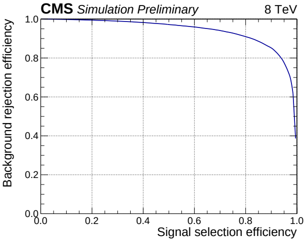
Reco of tHq events





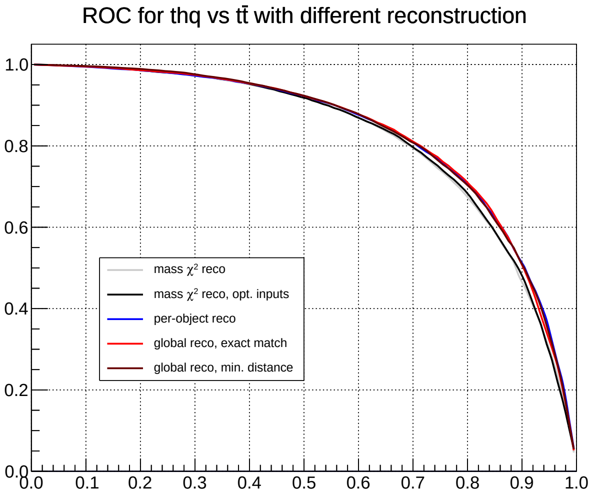
Reco of $t\bar{t}$ events



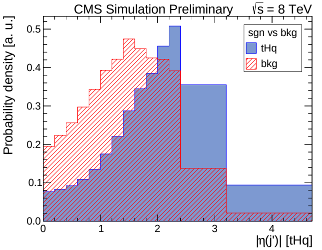


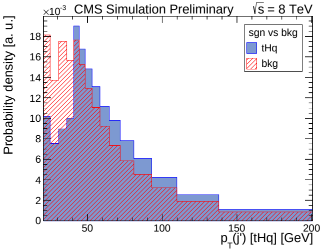
Sum of μ and e channels

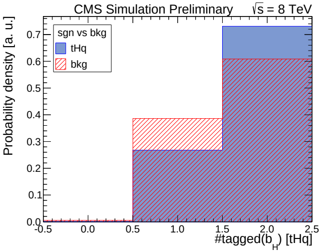
$H \to b\bar{b}$: Jet assignment and perf. of class. MVA

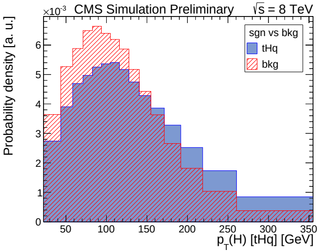


$H \to b\bar{b}$: Input variables for tHq vs bkgs classification









Sum of μ and e channels

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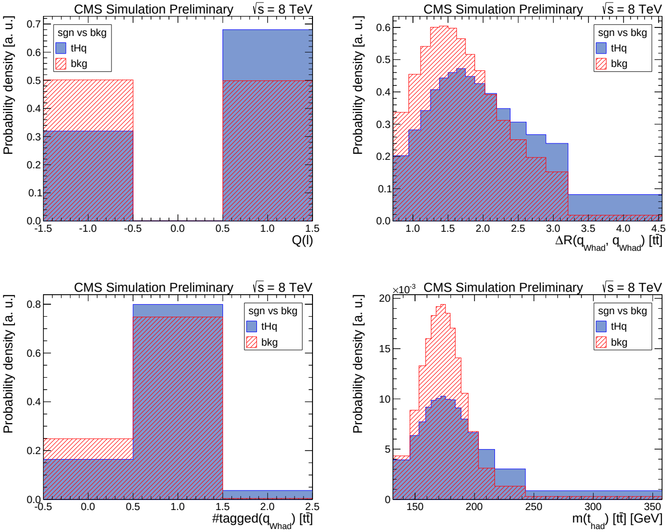
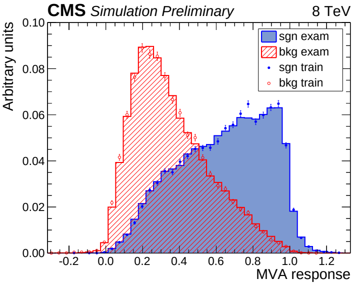
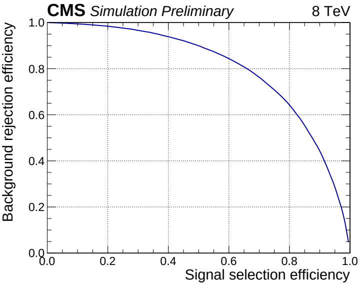


Sum of μ and e channels

$H \to b\bar{b}$: Response and ROC of classification MVA

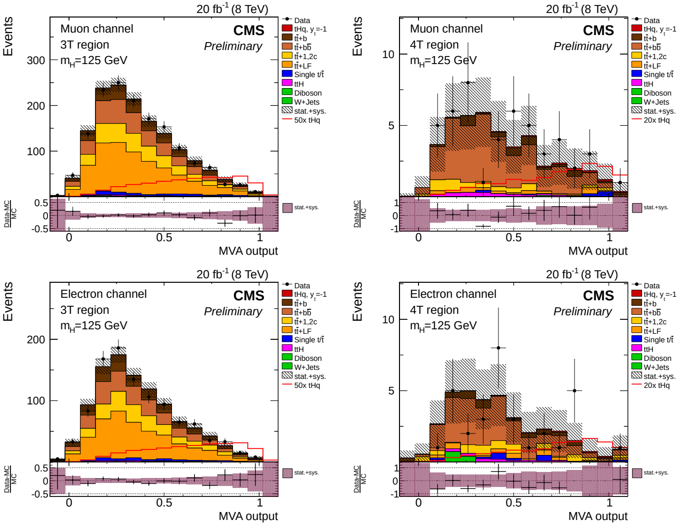




$H \to b\bar{b}$: Systematics

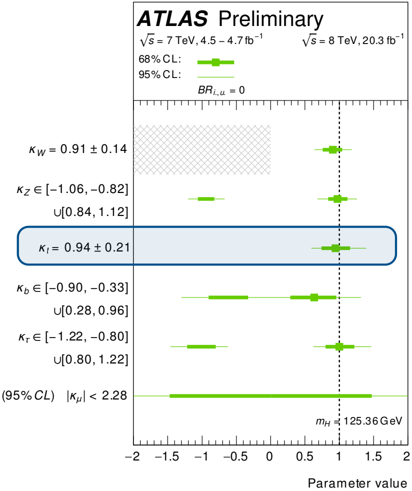
Source	Type	impact as exclusive source on final limit [%]	improvement of final limit after removal [%]
JES	shape	17	3
JER	shape	< 1	< 1
BTag light flavor	shape	13	< 1
BTag heavy flavor	shape	17	< 1
Pile up	normalization	< 1	< 1
Unclustered energy	shape	3	1
Lepton efficiency	normalization	5	< 1
Luminosity	normalization	10	< 1
Cross section (PDF)	normalization	8	< 1
Cross section (Scale)	normalization	9	< 1
MC Bin-by-Bin unc.	shape	< 1	< 1
Q^2 scale $(tHq + t\bar{t})$	shape	20	4
Matching	shape	2	2
Top p_T reweighting	shape	19	2
$t\bar{t}$ HF rates (b)	normalization	13	< 1
$t\bar{t}$ HF rates $(b\bar{b})$	normalization	15	< 1
$t\bar{t}$ HF rates $(c\ /\ c\bar{c})$	normalization	13	1

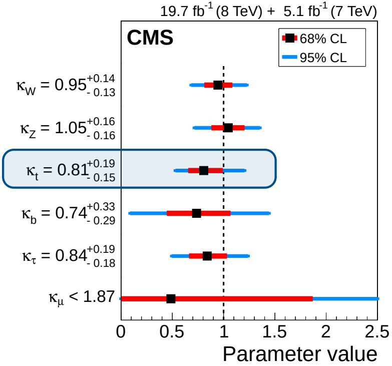
$H \to b\bar{b}$: Post-fit distributions in MVA response



ATLAS and CMS combinations

No BSM particles are allowed in loop-induced higgs couplings or higgs decays

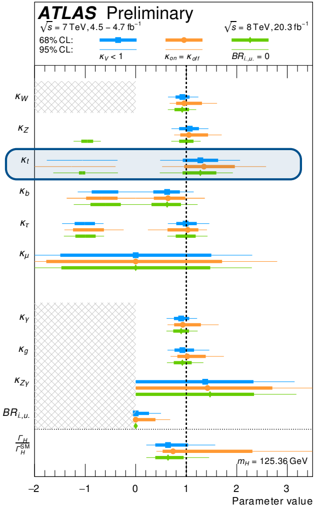


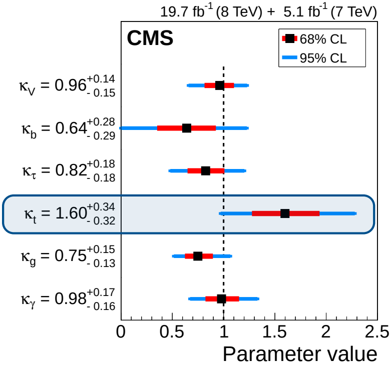


κ_t is largely constrained from $gg \to H$

ATLAS and CMS combinations

Allow loop-induced higgs couplings to depart from SM values





CMS assume $\Gamma_{\mathrm{BSM}} = 0$ and $\kappa_X > 0$.
In ATLAS plot $\Gamma_{\mathrm{BSM}} = 0$ is shown with green markers