Karlsruhe Institute of Technology

Search for tHq with $H \to b\bar{b}$

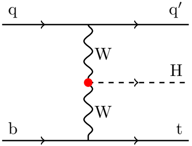
A test of Higgs couplings

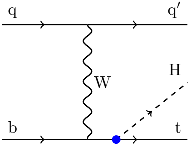
Christian Böser[1] | GK-Workshop Bad Liebenzell | 22.09.2014

[1] INSTITUT FÜR EXPERIMENTELLE KERNPHYSIK

Introduction to pp $\rightarrow$ tHq

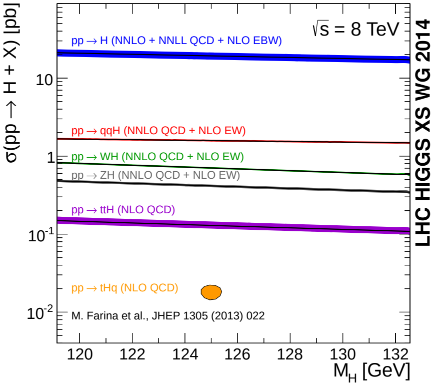
- Investigate coupling of the Higgs boson to fermions $\rightarrow \mathcal{A}_{\mathrm{tHq}} \propto (\kappa_V - \kappa_f)$





- Destructive interference in SM
  $\Rightarrow$ cross-section is 18.3 fb
- With $\kappa_t^{\dagger} = -1$
  - $\sigma_{\mathrm{tHq}} = 234$ fb
  - 13 times enhanced compared to SM case

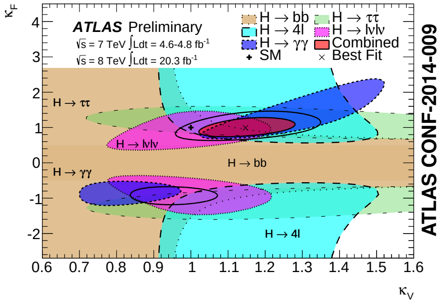
$$^{\dagger}\ \kappa_t = Y_t / Y_t^{SM}$$

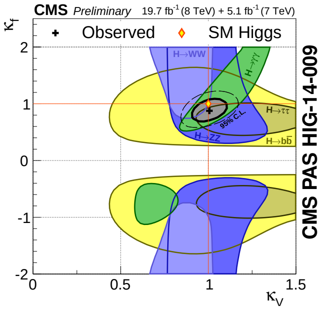


Motivation

- Discover such a unique final state!
- Help excluding $\kappa_t = -1$ scenario

Moriond 2014





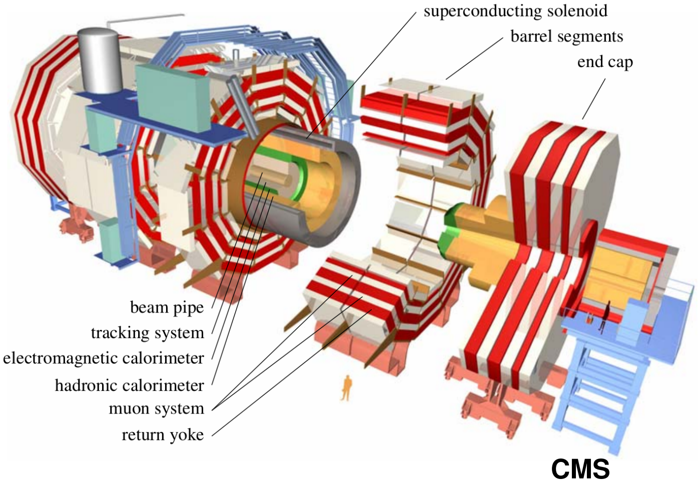
- Coupling constraints from ATLAS + CMS disfavor $\kappa_t = -1$, under assumption of only SM contributions to the total width
- BSM contributions to the loops in the H$\gamma\gamma$ and Hgg couplings are allowed $\rightarrow \kappa_t = -1$ still tolerated

Direct search for tHq and $H \rightarrow b\bar{b}$ with $\kappa_t = -1$

CMS-HIG-14-015

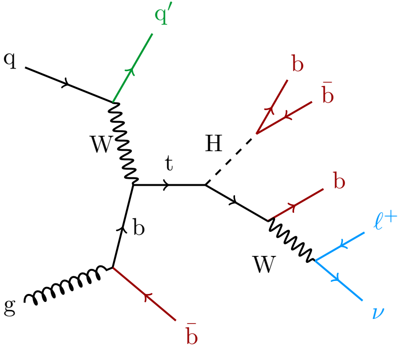
Approval scheduled for this Friday

The CMS detector



Analysis strategy

- Challenging multijet final state
- 1 forward light jet
- 3 or 4 b jets (spectator b outside of tracker acceptance in $\sim 30\%$ of the cases)
- 1 isolated charged lepton and $\not{E}_T$



- Expected yields

	S/B	
3 tag region	$\sim$ **0.7**%	(13/1900 events)
4 tag region	$\sim$ **2.1**%	(1.4/66 events)

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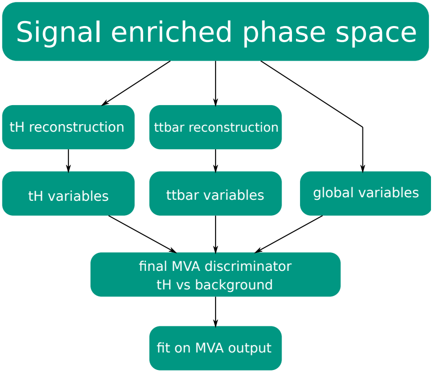
- **$t\bar{t}$ production** dominant background
- Validation done in $t\bar{t}$ control region

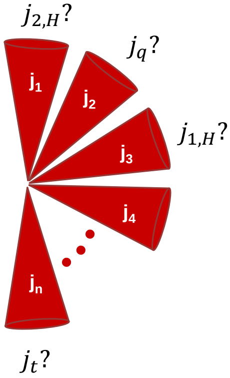


- MVAs for reconstruction and classification

Reconstruction of tHq

- Find correct jet assignment to final state quarks is combinatorial issue

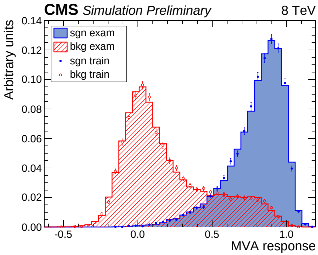
- Reconstruct all possible hypotheses per event
- Additional constraints to reduce combinatorics
  - Correct interpretation $\hat{=}$ all four quarks matched to a jet within $\Delta R < 0.3$
  - Wrong interpretations: all other possible jet assignments
- Train MVA to discriminate between correct and wrong hypotheses
  - Kinematic variables
  - b-tagging information
  - Angular correlations



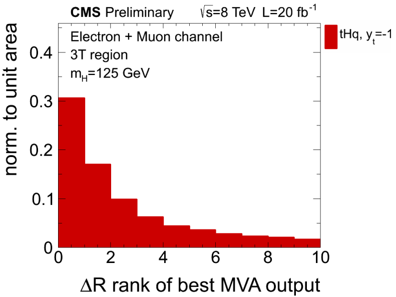
- Application on data: Take hypothesis with largest MVA response

MVA Response of tHq Reconstruction

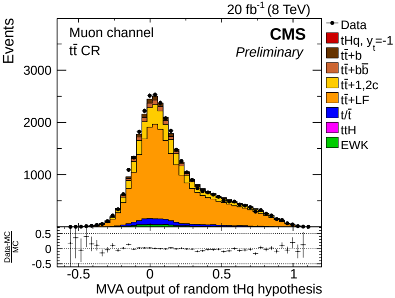
- Good discrimination between correct and wrong hypotheses found
- Data/MC comparisons done in $t\bar{t}$ control region



Performance



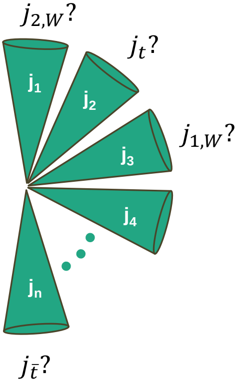
Validation



Additional reconstruction under $t\bar{t}$ hypothesis

- Good discrimination of processes tHq and $t\bar{t}$ is crucial for the analysis

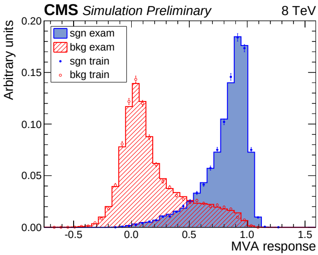
- Idea to get better separation power:
  - Perform additionally reconstruction under $t\bar{t}$ production hypothesis
  - Use similar set of variables as for tHq reconstruction
  - Take this as input for classification



- Again: Take correct assignment for training and take hypothesis with largest MVA response for application

MVA Response of $t\bar{t}$ Reconstruction

- Good discrimination between correct and wrong hypotheses found
- Data/MC comparisons done in $t\bar{t}$ control region



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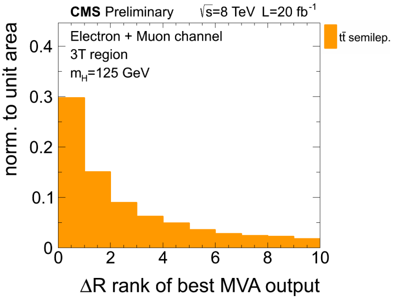
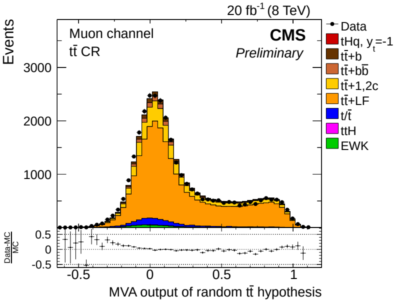


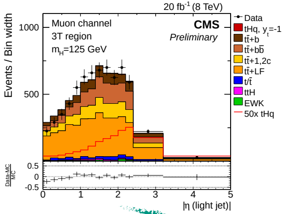
Validation



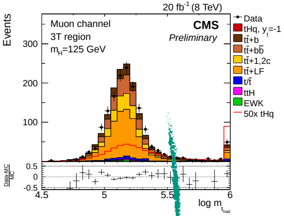
Classification

- Take all information after reconstruction
- Optimize classification MVA to separate signal from background

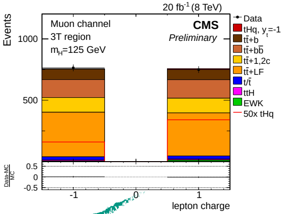
4 tHq variables

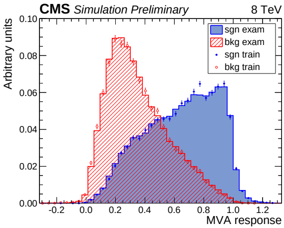


3 $t\bar{t}$ variables



1 global variable



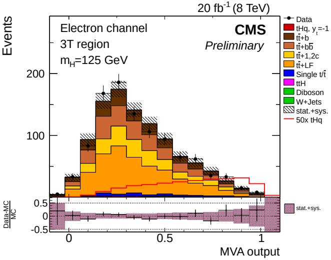


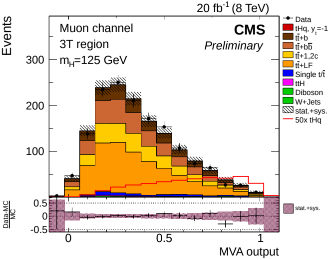
Fit on MVA output distributions

Electron channel

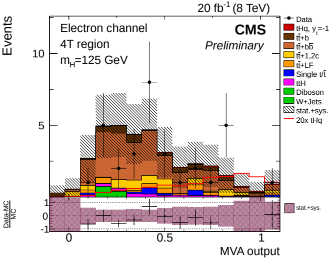
Muon channel

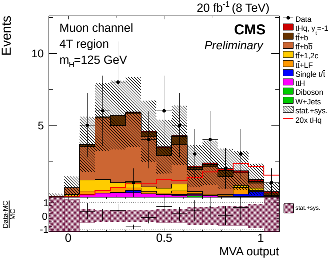
3T region





4T region





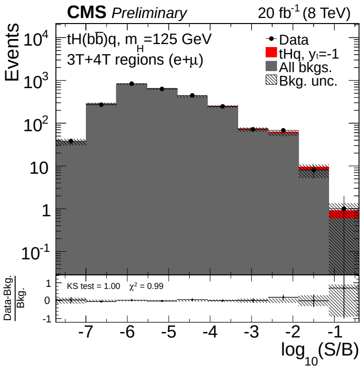
Results

95% Upper Limit on $\sigma/\sigma_{\kappa_t=-1}$

	Expected	Observed
MC-driven	$\mathbf{5.14^{+2.14}_{-1.44}}$	**7.57**
data-driven	$6.24^{+2.26}_{-1.71}$	6.95

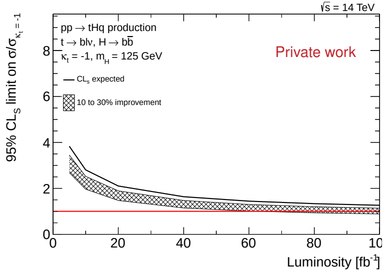
- Observations in good agreement with SM
- Cross-check analysis with similar result

- Combination of all MVA distributions into a single plot
  - Events in all channels sorted in bins of similar expected S/B ratio



Summary

- Investigation of tHq is an active field with a lot of potential
- Search for tHq with $H \rightarrow b\bar{b}$ is challenging
- Upper limits on $\kappa_t = -1$ case
- CMS-PAS-HIG-14-015 will be (hopefully)
  - .. approved this Friday
  - .. shown at TOP 2014 in Cannes for the first time
- Combination paper with all available channels planned
- Stay tuned!



$\sigma_{NLO}(pp) \rightarrow tHq$ [fb]

	$\kappa_F = 1$	$\kappa_F = -1$
8 TeV	18.3	234
14 TeV	88.2	982

BACKUP

Cross sections

$$\mathcal{A} = \frac{g}{\sqrt{2}} \left[(c_F - c_V) \frac{m_t \sqrt{s}}{m_W v} A\left(\frac{t}{s}, \varphi; \xi_t, \xi_b\right) + \left(c_V \frac{2m_W}{v} \frac{s}{t} + (2c_F - c_V) \frac{m_t^2}{m_W v} \right) B\left(\frac{t}{s}, \varphi; \xi_t, \xi_b\right) \right]$$

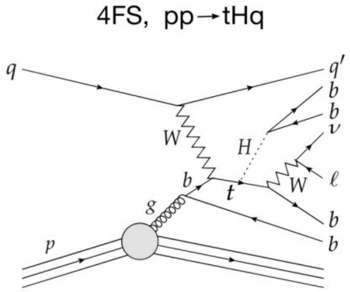
$$c_F \equiv g_{ht\bar{t}} / g_{ht\bar{t}}^{SM} \qquad c_V \equiv g_{hWW} / g_{hWW}^{SM}$$

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

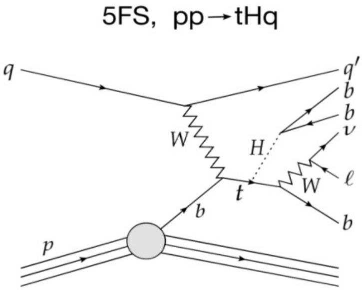
Cross-section	8 TeV	14 TeV
tHq, $y_t = +1$ (SM)	18.3 ± 0.4 fb	$88.2^{+1.7}_{-0.0}$ fb
tHq, $y_t = -1$	$233.8^{+4.6}_{-0.0}$ fb	980^{+30}_{-0} fb
$t\bar{t}$	245^{+9}_{-10} pb	950^{+40}_{-30} pb

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

Flavor Scheme Comparison



- $m(b) > m(p) \rightarrow b$ quark is no proton constituent,
- *b* quarks can only be pair-produced in high $\mathcal{Q}^2$ production



- *b* quarks in initial state, i.e. inside the proton
- Additional *b* comes through parton shower

CMS-PAS-HIG-14-015

Baseline Selection

- Logical OR of single lepton triggers hlt_isomu24 / hlt_ele27_wp80
- Exactly 1 reconstructed isolated lepton
  - Muons: $p_T > 26\,\text{GeV}, \quad |\eta| < 2.1, \quad \text{reliso} < 0.12$
  - Electrons: $p_T > 30\,\text{GeV}, \quad |\eta| < 2.5, \quad \text{reliso} < 0.10$

3 tag Region

- $\#\text{jets}_{30} \geq 4$
- $\#\text{jets}_{\text{CSVT}} = 3$

4 tag Region

- $\#\text{jets}_{30} \geq 5$
- $\#\text{jets}_{\text{CSVT}} = 4$

Data-driven QCD estimation

- Apply ABCD method
- Requires two selection cuts which are assumed to be uncorrelated for QCD events
  - **A region**: ordinarily-defined signal or control region used in this analysis.
  - **B region**: as A, but the lepton cuts are inverted; ie. the event is required to have exactly one lepton failing the “tight” definition but passing the “loose” definition.
  - **C region**: as A, but the pfMET cuts are inverted; in the electron channel the cut is $\not\!\!E_{\mathrm{T}} < 45\ \mathrm{GeV}$ and in the muon channel $\not\!\!E_{\mathrm{T}} < 35\ \mathrm{GeV}$.
  - **D region**: both cuts described above are inverted.

$$N_{A,QCD} = \frac{(N_{B,data} - N_{B,non\text{-}QCD}) \cdot (N_{C,data} - N_{C,non\text{-}QCD})}{N_{D,data} - N_{D,non\text{-}QCD}} \quad (1)$$

Data-driven QCD estimation

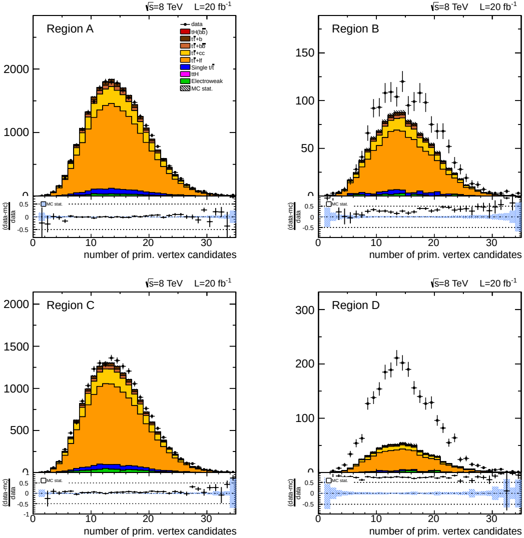


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Table : Input Variables of tHq Reconstruction

Variable	Description
Charge_BTop	Electric charge of b-quark jet from decay of top quark, multiplied by lepton's charge;
Cos_LepRecoil_TH	Cosine of the angle between momenta of lepton and recoil jet in the rest frame of $t + H$ system
DeltaR_BJetsHiggs	ΔR between the two jets from decay of Higgs boson
DeltaR_BTopW	ΔR between b-quark jet and W boson from decay $t \to \mathrm{W}$
DeltaR_TopHiggs	ΔR between reconstructed top quark and Higgs boson
abs(Eta_Recoil)	Pseudorapidity of recoil jet
log(Mass_BTopLep)	Invariant mass of b-quark jet from decay of top quark and charged lepton
log(Mass_Higgs)	Mass of reconstructed Higgs boson
abs(MaxEta_BHiggs)	Pseudorapidity of the most forward jet from decay of H
log(MinPt_BHiggs)	Transverse momentum of the softest jet from decay of H
NumBTag_Higgs	Number of b-tagged jets among the two jets from decay of H
PassBTag_BTop	Equals 1 if the b-quark jet from decay of t is b-tagged, 0 otherwise
PassBTag_Recoil	Equals 1 if the recoil jet is b-tagged, 0 otherwise
RelHt	Relative H_T, $(p_{\mathrm{T}}(t) + p_{\mathrm{T}}(H))/H_T$

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Table : Input Variables of $t\bar{t}$ Reconstruction

Variable	Description
Charge_BTopHad - Charge_BTopLep	Difference of electric charges of b-quark jets from decays of t_{had} and t_{lep}, multiplied by lepton's charge
DeltaR_Light	ΔR between the two light-flavor jets from decay of t_{had}
DeltaR_BTopHadWHad	ΔR between b-quark jet and W boson from decay $t_{\text{had}} \rightarrow \mathrm{W}$
DeltaR_BTopHadWLep	ΔR between b-quark jet and W boson from decay $t_{\text{lep}} \rightarrow \mathrm{W}$
log(DMass_TopHadWHad)	Difference between masses of t_{had} and W from decay of t_{had}
abs(Eta_TopHad)	Pseudorapidity of t_{had}
log(Mass_BTopLepLep)	Invariant mass of b-quark jet from decay of t_{lep} and charged lepton
log(Mass_WHad)	Mass of W from decay of t_{had}
NumBTag_Light	Number of b-tagged jets among the two light-flavor jets from decay of t_{had}
PassBTag_BTopHad	Equals 1 if the b-quark jet from decay of t_{had} is b-tagged, 0 otherwise
PassBTag_BTopLep	Equals 1 if the b-quark jet from decay of t_{lep} is b-tagged, 0 otherwise
log(Pt_TopHad)	Transverse momentum of t_{had}
log(Pt_TopLep)	Transverse momentum of t_{lep}
RelHt	Relative H_T, $(p_{\mathrm{T}}(t_{\text{had}}) + p_{\mathrm{T}}(t_{\text{lep}}))/H_T$
SumCharge_Light	Sum of electric charges of the two light-flavor jets from decay of t_{had}, multiplied by lepton's charge

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Table : Input variables for the classification MVA

Variable	Description
glb_Charge_Lep	Electric charge of the lepton
abs(thq_Eta_Recoil)	Pseudorapidity of the recoil jet
thq_NumBTag_Higgs	Number of b-tagged jets among the two jets from the Higgs boson decay
log(thq_Pt_Higgs)	Transverse momentum of the Higgs boson
log(thq_Pt_Recoil)	Transverse momentum of the recoil jet
tt_DeltaR_Light	ΔR between the two light-flavor jets from the decay of t_{had}
log(tt_Mass_TopHad)	Mass of t_{had}
tt_NumPassBTag_Light	Number of b-tagged jets among the two light-flavor jets from the decay of t_{had}

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Table : Impact of systematic uncertainties

Omitted systematic	impact on limit [%]	only Systematic	impact on limit [%]
JES	−1.3	JES	−1.8
JER	−0.2	JER	1.4
BTag light flavor	−0.7	BTag light flavor	13.3
BTag heavy flavor	2.1	BTag heavy flavor	1.9
Pile up	0.1	Pile up	−0.9
Unclustered energy	−0.6	Unclustered energy	−4.0
Lepton efficiency	−2.5	Lepton efficiency	−0.9
Luminosity	−2.0	Luminosity	−1.0
Cross section (PDF)	−2.2	Cross section (PDF)	17.5
Cross section (Scale)	−2.4	Cross section (Scale)	18.9
MC Bin-by-Bin unc.	−3.3	MC Bin-by-Bin unc.	1.8
Q^2 scale (tHq + $t\bar{t}$)	−9.1	Q^2 scale (tHq + $t\bar{t}$)	33.7
Matching	−1.4	Matching	−2.9
Top p_T reweighting	−3.2	Top p_T reweighting	43.8
$t\bar{t}$ HF rates (b)	−1.2	$t\bar{t}$ HF rates (b)	29.4
$t\bar{t}$ HF rates ($b\bar{b}$)	−0.9	$t\bar{t}$ HF rates ($b\bar{b}$)	33.6
$t\bar{t}$ HF rates (c / $c\bar{c}$)	−3.8	$t\bar{t}$ HF rates (c / $c\bar{c}$)	23.0
$t\bar{t}$ HF rates (total)	−7.9	$t\bar{t}$ HF rates (total)	32.3