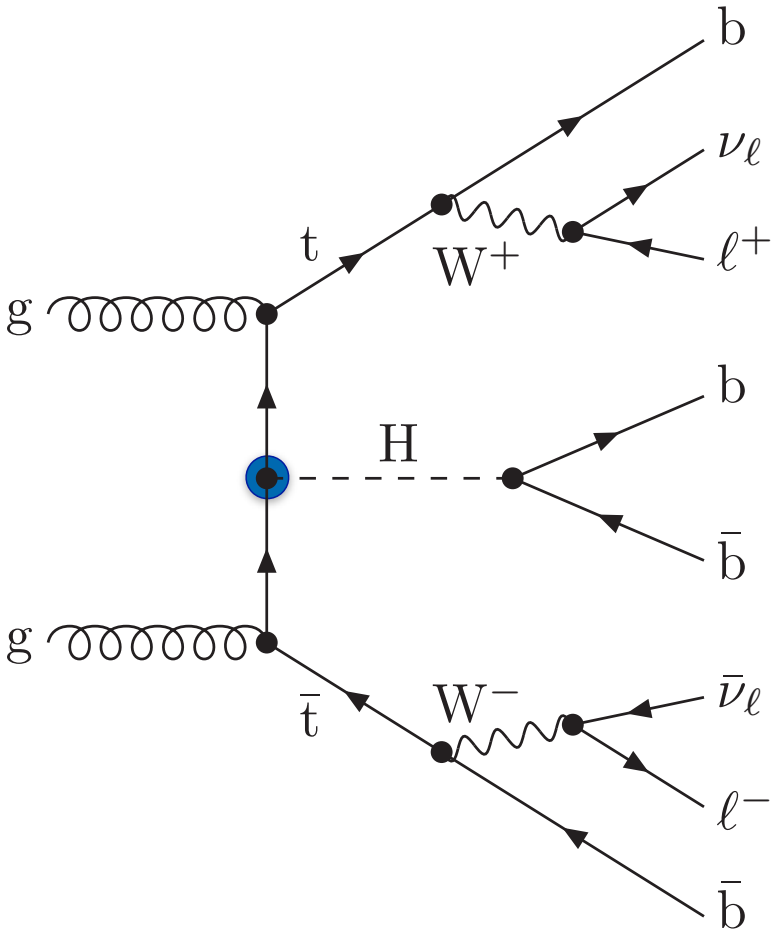
Search for ttH associated production at LHC



Cristina Botta (CERN)

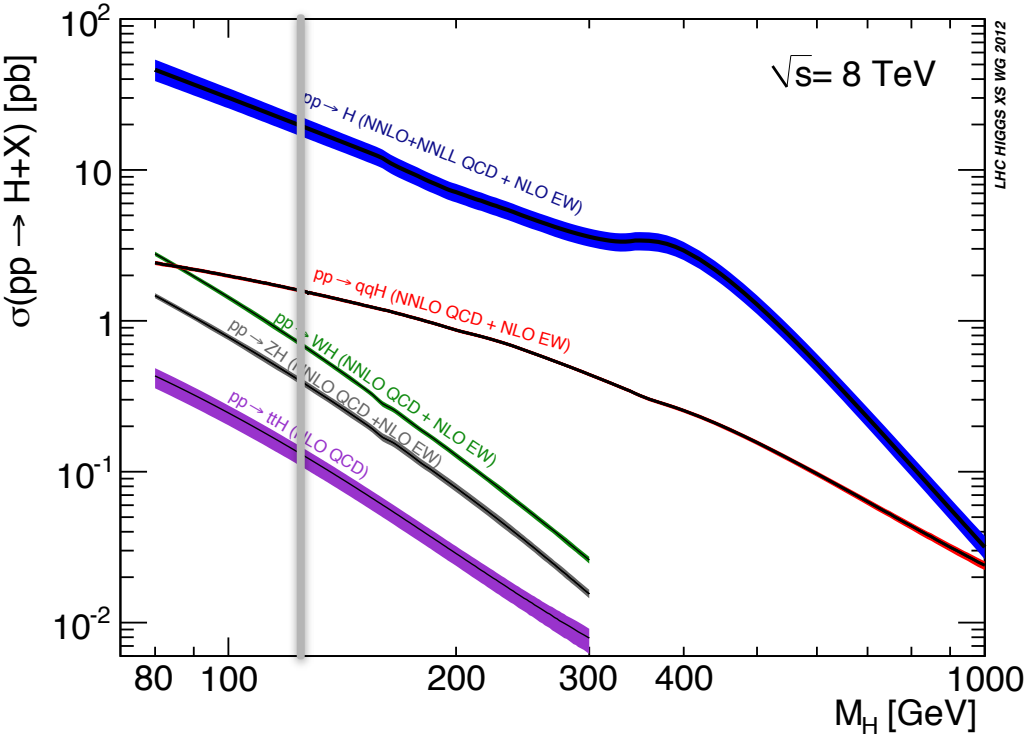
on behalf of the ATLAS and CMS collaborations

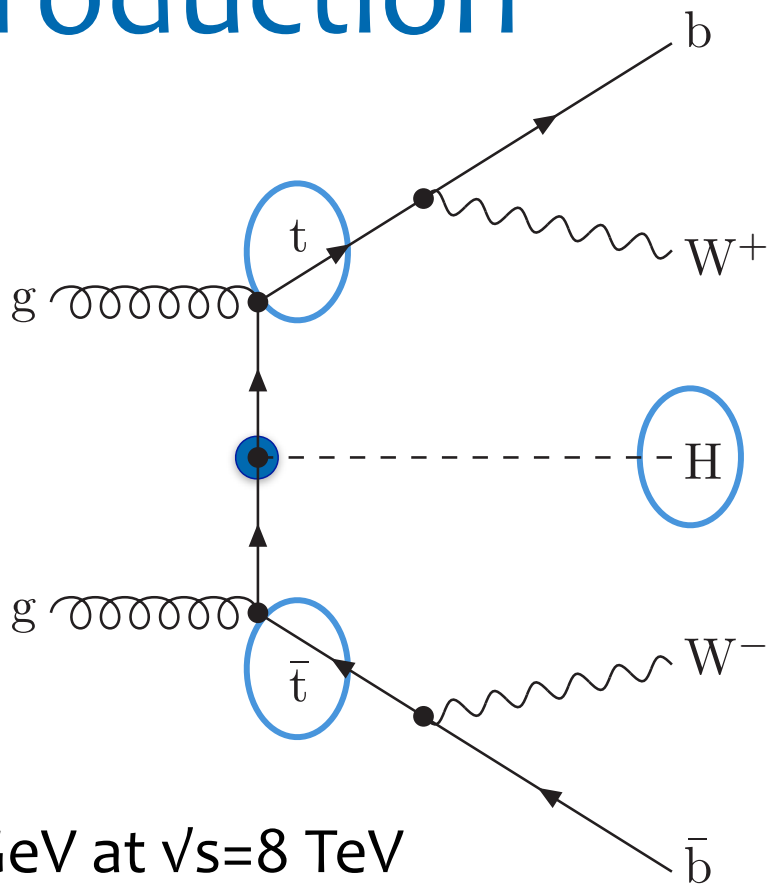
"Physics at LHC and beyond", August 10-17 2014, Quy-Nhon, Vietnam

The top Yukawa coupling

- Two main probes of $t\bar{t}H$ coupling at LHC:
  - gluon fusion production cross section ($\sigma \sim |y_t|^2$), assuming no BSM particles in the loop.
  - associated production cross section, a tree level process proportional to $|y_t|^2$
- The first is pretty well known: already now the experimental accuracy on y_t is 25-30% from each experiment
- Significant progress from the experimental side on the second point in the last year.

ttH associated production





- ttH cross section is **130 fb** for m_H = 126 GeV at √s=8 TeV
- Higgs decays at this mass:
  - BR H→bb̄ ~60%, H→WW(*) ~20% and H→γγ, H→ττ, H→ZZ(*) significantly smaller BR but produce experimentally accessible signatures
- ttH events are crowded due to the presence of additional b-jets, jets/leptons from the top quarks decays

ttH searches at ATLAS & CMS

H→hadrons

- **tt + b-jets,** to search for **H→bb**
  - high rate but big tt+bb bkg and complex multi-jet final state
  - **ATLAS**: 8 TeV data, **ATLAS-CONF-2014-011**
  - **CMS Analysis I**: 8 TeV data, **arXiv:1408.1682** (together with the low sensitivity channel **tt + ττ: with hadronically decaying taus**)
  - **CMS Analysis II**: 8 TeV data, **HIG-14-009**

H→photons

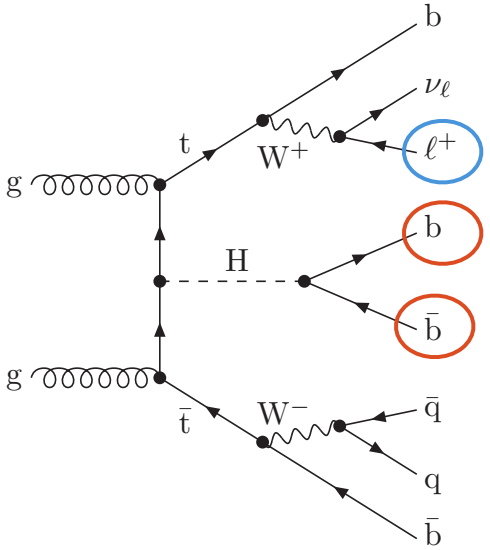
- **tt + γγ,** to search for **H→γγ:**
  - low rate. important for the high-lumi projection as systematics play a negligible role in it
  - **ATLAS**: 7+8 TeV data, **ATLAS-CONF-2014-043**
  - **CMS**: 7+8 TeV data, **arXiv:1408.1682**

H→leptons

- **tt + leptons,** to search for **H→ WW, ZZ, ττ (τ → ℓ)**
  - low rate. clean and low bkg signatures with 2,3,4 leptons
  - **CMS**: 8 TeV data, **arXiv:1408.1682**

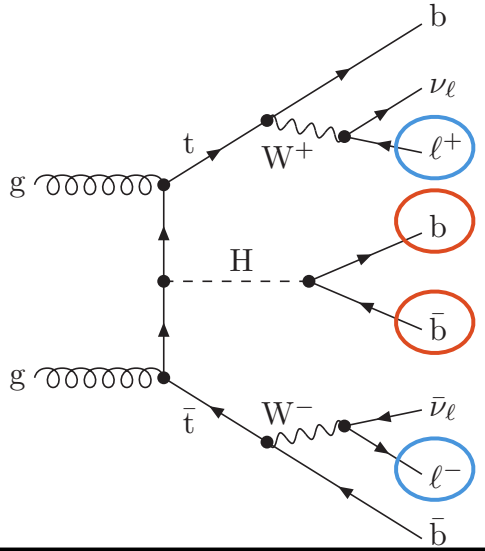
H→hadrons

Single-lepton (SL) channel



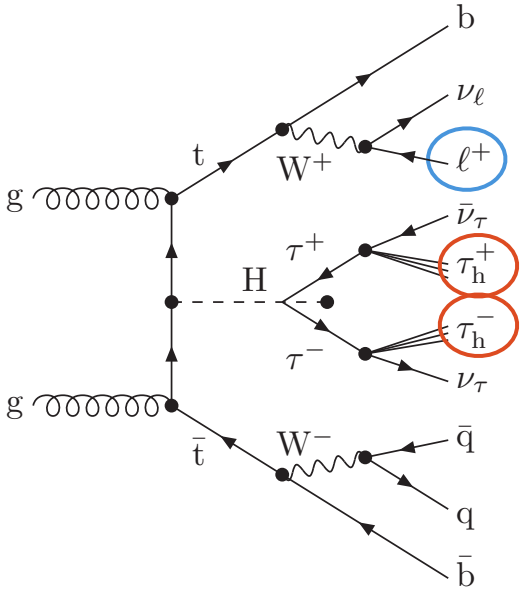
CMS	1 e/μ **(p_T>30)** ≥4 jets ≥2b-jets **(p_T>40,40,40,30)**
	1 e/μ **(p_T>25)** ≥4 jets ≥2b-jets **(p_T>25)**

Di-lepton (DL) channel



CMS	2 OS e/μ **(p_T>20,10)** ≥3 jets ≥2b-jets **(p_T>40,40,40,30)**
	1 e/μ **(p_T>25,15)** ≥3 jets ≥2b-jets **(p_T>25)**

Hadronic-τ (τ_h) channel



CMS	1 e/μ (p_T>30), 2 τ (p_T>20), ≥ 4jets 1-2b-jets (p_T>40,40,40,30)

Analysis Strategy

- **Categorization in NJets and Nb-Jets, BDT/NN** built in each categories **(best S/B ~0.03 with #sig ~10)**
  - variables: **reconstructed object kinematic, event shape, b-tagging discriminator value**

H->bb, SL Channel

	2 b-tags	3 b-tags	4 b-tags
4 jets		**BDT**	**BDT**
5 jets		**BDT**	**BDT**
>= 6 jets	**BDT**	**BDT**	**BDT**

	2 b-tags	3 b-tags	4 b-tags
4 jets	**H_T^{had}**	**H_T^{had}**	**H_T^{had}**
5 jets	**H_T^{had}**	**NN**	**NN**
>= 6 jets	**H_T^{had}**	**NN**	**NN**

H->bb, DL Channel

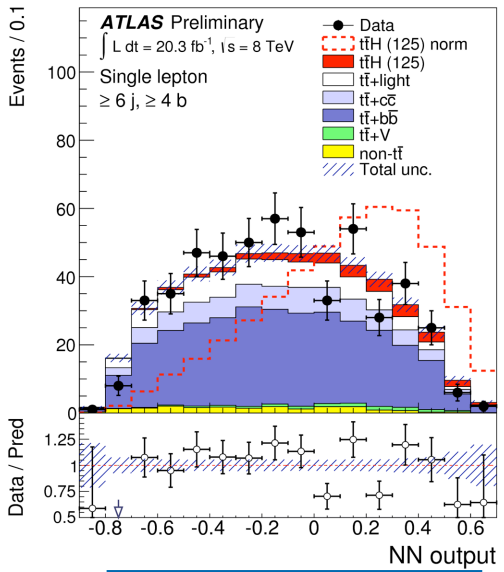
	2 b-tags	3 b-tags	4 b-tags
2 jets			
3 jets	**BDT**	**BDT**	
>= 4 jets	**BDT**		

	2 b-tags	3 b-tags	4 b-tags
2 jets	**H_T^{had}**		
3 jets	**H_T^{had}**	**NN**	
>= 4 jets	**H_T^{had}**	**NN**	**NN**

- **Main bkg tt+jets:**
  - from simulation separated in sub-samples: (tt+lf, tt+bb,tt+b,tt+cc)
  - data in bins with **low S/B** are used to constraint these bkg sources

Results

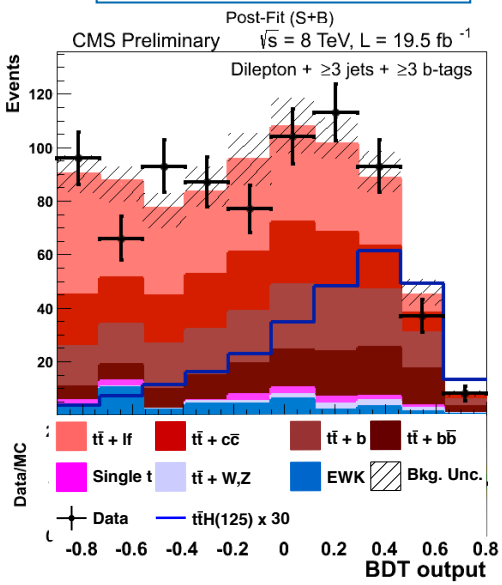
@ m_H=125.4 GeV



bb: SL, ≥ 6 Jets, ≥ 4 b-tags

bb: 15 categories

@ m_H=125.6 GeV



bb: DL, ≥ 3 Jets, ≥ 3 b-tags

bb: 10 categories, ττ: 6 categories

From combined fit to NNs/BDTs:

95% CL upper limits on μ_{ttH} :

		Median Exp (bkg only)	Median Exp (signal injected)	Obs
	bb	2.7	3.3	4.4
CMS	bb	3.5	5.5	4.1
CMS	ττ	14.2	16.2	13

Best-fit value for μ_{ttH} :

	bb	$1.8^{+1.5}_{-1.4}$
CMS	bb	$0.7^{+1.9}_{-1.9}$
CMS	ττ	$-1.3^{+6.3}_{-5.5}$

Alternative Analysis Strategy

- Similar event selection (SL, DL channels with ≥5 jets, ≥4 jets)

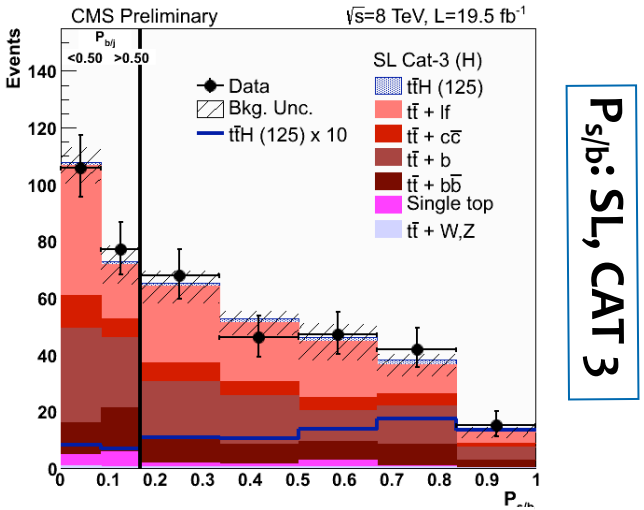
- b-tagging discriminator value for the leading 6(4) jets in SL(DL) used to build a per-event likelihood ratio to separate bbbb (ttH, tt+HF) vs bbjj (tt+LF)

- Four event-categories based on exclusive event interpretation for bkg:

CAT1: tt->bblvqq	CAT2: tt->bblvq(q)+g	CAT3: tt->bblvq(q)	CAT4: tt->bblvlv

- Likelihood technique based on the **theoretical Matrix Element** for **ttH** and **tt+bb** used to compute probability density functions for S and B.

- **Signal extraction** performed fitting the ratio between these two probabilities ($P_{s/b}$)



From combined fit to MEs:

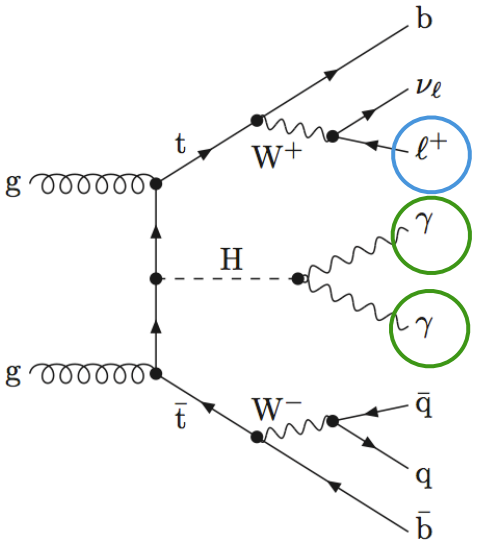
95% CL upper limits on μ_{ttH} :

	Median Exp (bkg only)	Median Exp (signal injected)	Obs
bb	**2.9**	**3.9**	**3.3**

Best-fit value for $\mu_{ttH\,(bb)}$: $0.7^{+1.9}_{-1.9}$

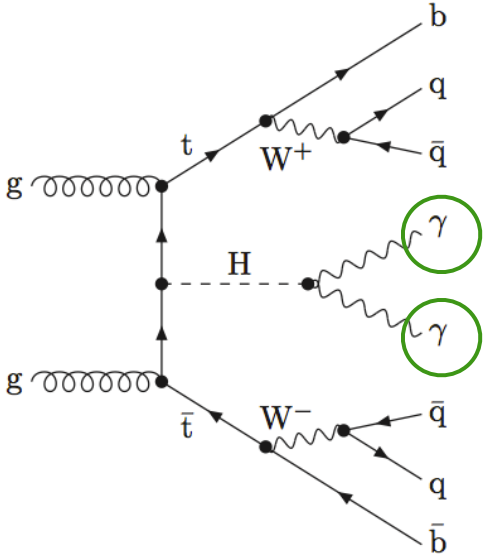
H→photons

Leptonic channel



CMS	$p_{T(\gamma 1)} > m_{\gamma\gamma}/2$ $p_{T(\gamma 2)} > 25$ ≥ 1 e/μ, p_T>20 ≥2 jets (≥1b-jets), p_T>25
	$p_{T(\gamma 1)} > 0.35\ m_{\gamma\gamma}$ $p_{T(\gamma 2)} > 0.25\ m_{\gamma\gamma}$ ≥ 1 e/μ, p_T>20 ≥2 jets (≥1b-jets), p_T>25

Hadronic channel

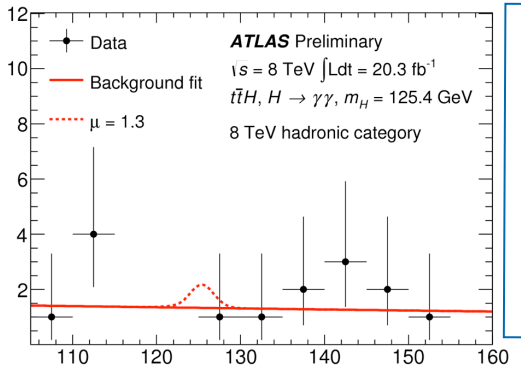


CMS	$p_{T(\gamma 1)} > m_{\gamma\gamma}/2$ $p_{T(\gamma 2)} > 25$ 0 e/μ, p_T>20 ≥5 jets (≥1b-jets), p_T>25
	$p_{T(\gamma 1)} > 0.35\ m_{\gamma\gamma}$ $p_{T(\gamma 2)} > 0.25\ m_{\gamma\gamma}$ 0 e/μ, p_T>20 ≥ 5 jets (≥1b-jets), p_T>25

Analysis Strategy

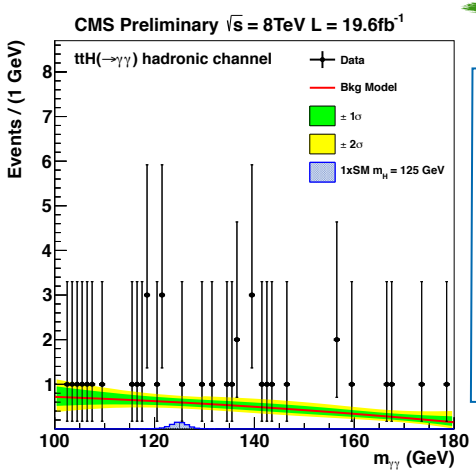
- Analysis **limited by statistic** (low BR H→γγ) but **distinctive signature**:
  - two energetic photons, narrow Higgs peak over falling bkg in $M_{\gamma\gamma}$ distribution
  - the only channel that can eventually confirm that an excess is due to h(125)
- Strategy: **fit the $M_{\gamma\gamma}$ distribution** using the diphoton spectrum **sidebands to fit the bkg**

@ m_H=125.4 GeV



8 TeV hadronic

@ m_H=125.6 GeV



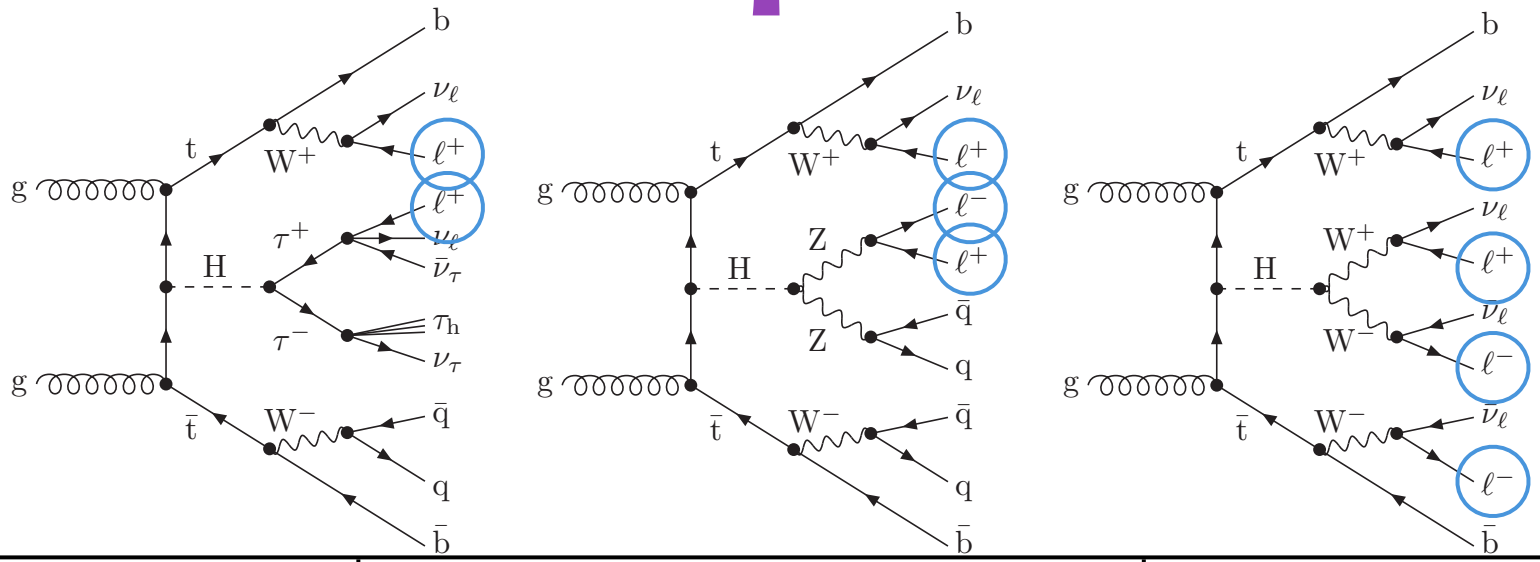
8 TeV hadronic

From combined fit to m(γγ) :

95% CL upper limits on μ_{ttH} :

		Median Exp	Median Exp (signal injected)	Obs
	γγ	4.9	6.1	6.5
CMS	γγ	4.7	5.7	7.4

H→leptons



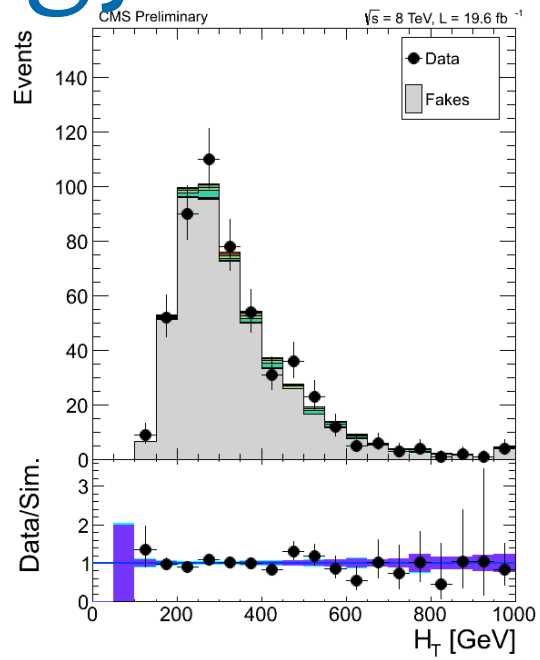
H decay	top pair decay	trigger
WW, ZZ, ττ	semileptonic or dileptonic	double lepton

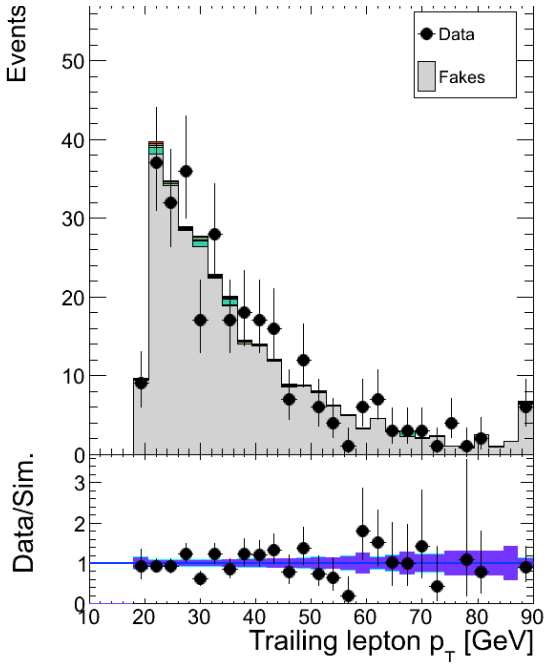
signature

2 same-sign leptons (ee,eμ,μμ)	3 leptons	4 leptons
2 e/μ, p_T>20 GeV ≥4 jets (≥1b-jet), p_T>25 GeV **(#sig~8 sig/bkg~0.08)**	3 e/μ, p_T>20,10,7/5 GeV ≥2 jets (≥1b-jet), p_T>25 GeV no resonant Z->ll **(#sig~4 sig/bkg~0.07)**	4 e/μ, p_T>20,10,7/5,7/5 GeV ≥2 jets (≥1b-jet), p_T>25 GeV no resonant Z->ll **(#sig~0.5 sig/bkg~0.2)**

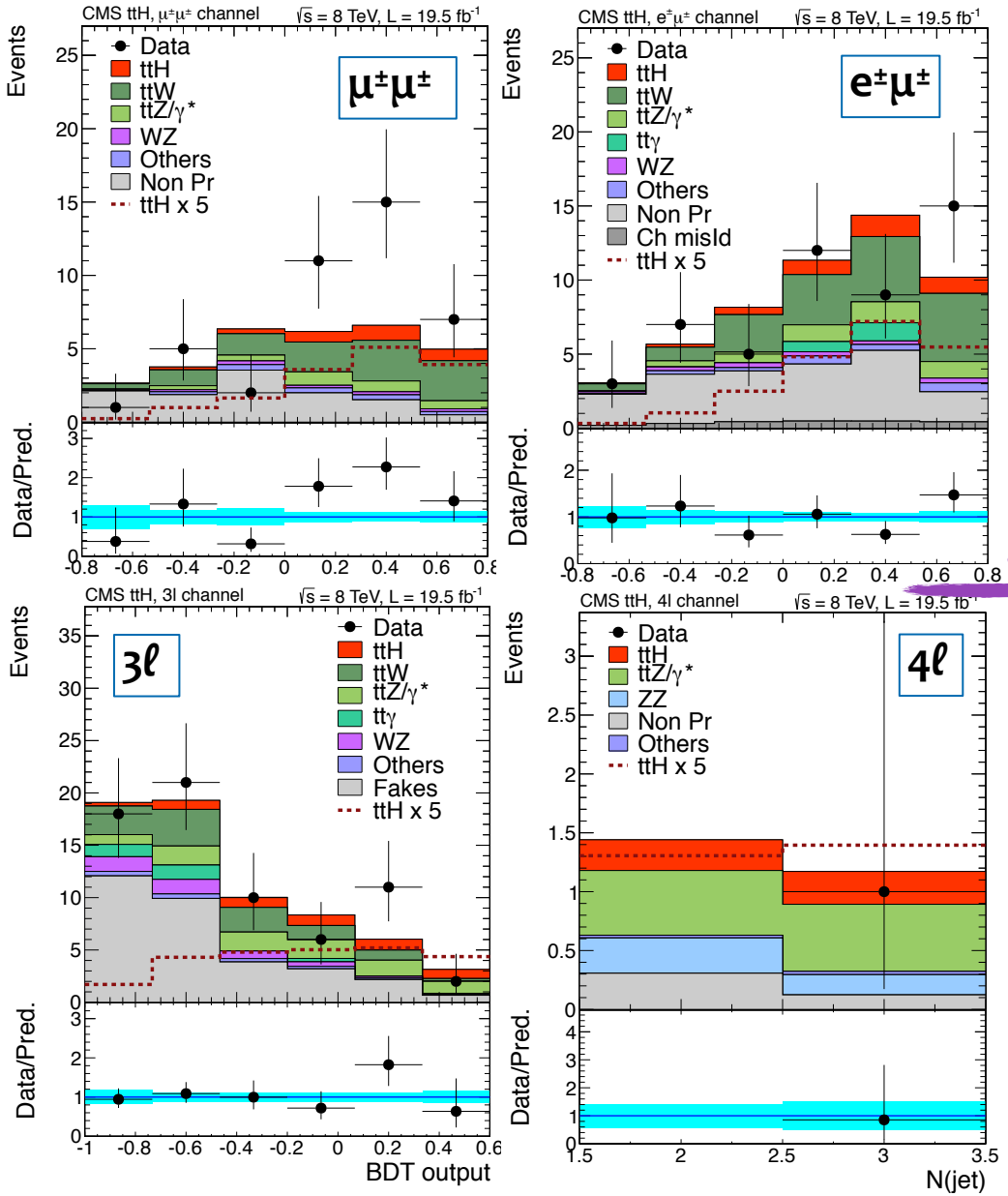
Analysis Strategy

- Main focus: suppress and control **reducible background** (~up to 2/3 of the total bkg after selection)
- tt with fake ℓ from b-jets
  Dedicated lepton ID (MVA) developed to suppress it.
- data-driven estimate: measurement of the probability for a lepton from b-jet to pass the MVA ID requirement
- Inclusive selection to preserve signal efficiency.
  Full event kinematic cannot be reconstructed
- **to improve sensitivity:**
  - categorize events (for 2ℓ, 3ℓ) in **positive and negative total lepton charge** (ttW, WZ and Wjets are asymmetric), **5%** gain in sensitivity
  - combine partial kinematic variables in a **BDT** (for 2ℓ, 3ℓ), **10%** gain in sensitivity (4l: just use N(jet), since yields are small
  - **signal extraction** performed fitting the BDT/N(jet) distributions





Results



From combined fit to BDTs/N(jet):

95% CL upper limits on μ_{ttH} :

	Median Exp (bkg only)	Median Exp (signal injected)	Obs
2lss	3.4	3.6	9.0
3l	4.1	5.0	7.5
4l	8.8	11.9	6.8
all	2.4	3.5	6.6

HIG-13-020

Best-fit value for μ_{ttH} :

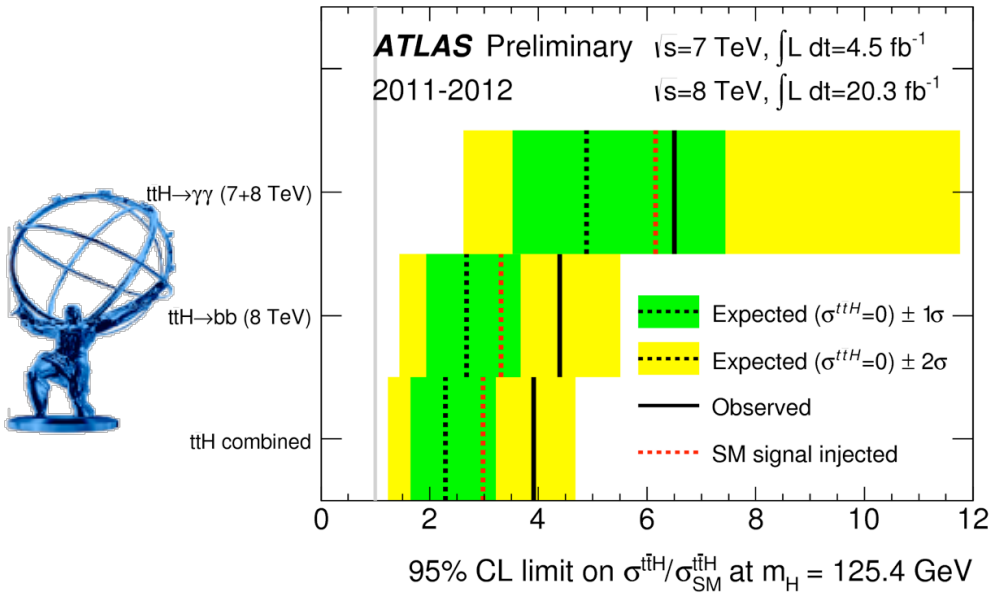
2lss	$5.3^{+2.1}_{-1.8}$
3l	$3.1^{+2.4}_{-2.0}$
4l	$-4.7^{+5.0}_{-1.3}$
all	$3.7^{+1.6}_{-1.4}$

HIG-13-020

@ m_H=125.6 GeV

Combination

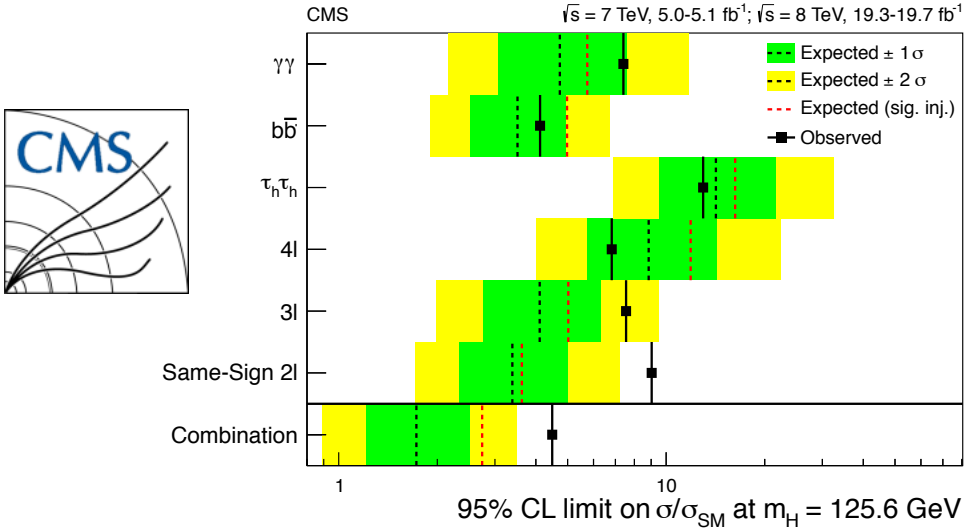
Limits on $\mu=\sigma/\sigma_{SM}$



@ m_H=125.4 GeV

- Median expected UL on μ:
  - in the absence of ttH signal: **2.3** at 95% CL
  - with the SM ttH production: **3.0** at 95% CL
- Observed UL is **3.9** at 95% CL

ATLAS-CONF-2014-043

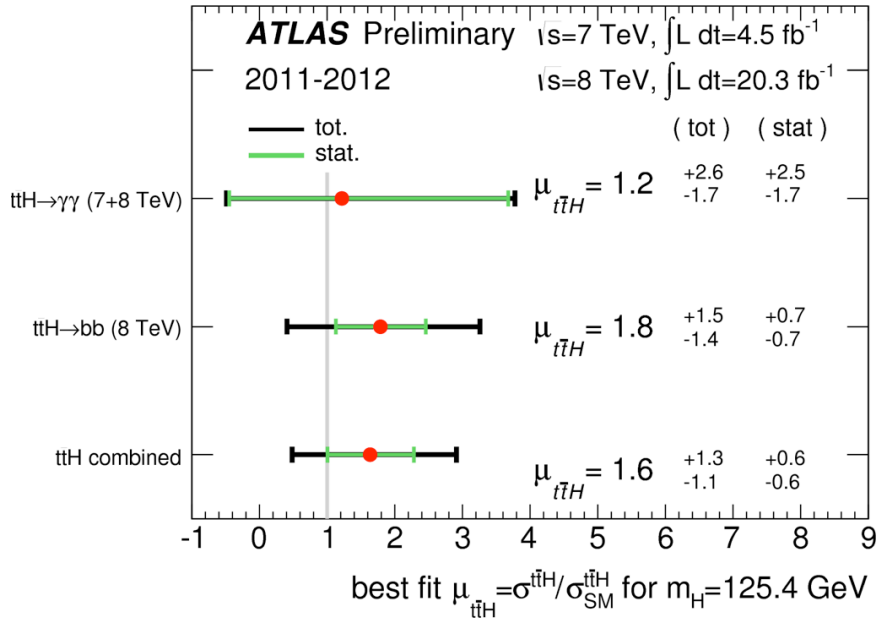


@ m_H=125.6 GeV

- Median expected UL on μ:
  - in the absence of ttH signal: **1.7** at 95% CL
  - with the SM ttH production: **2.7** at 95% CL
- Observed UL is **4.5** at 95% CL

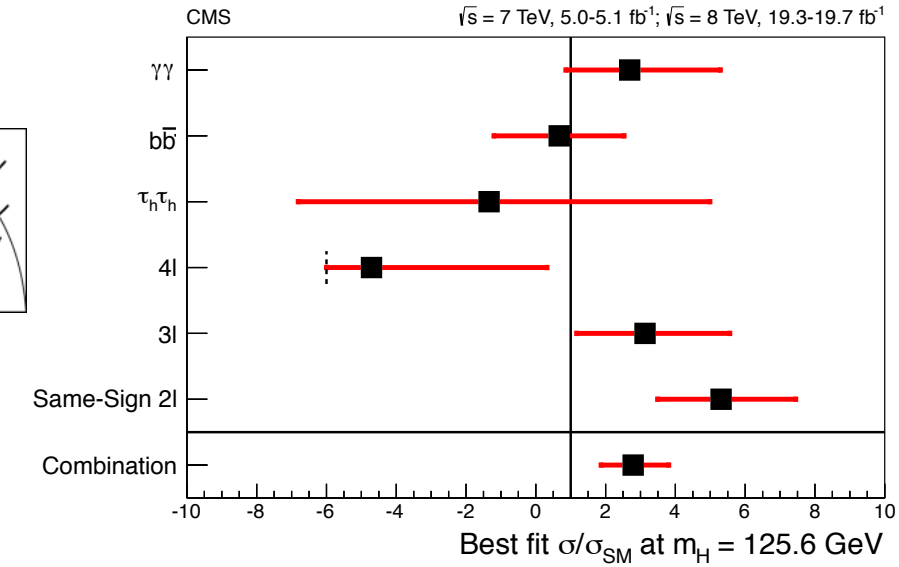
arXiv:1408.1682

Best fit $\mu=\sigma/\sigma_{SM}$



@ m_H=125.4 GeV

- The best fit to the combination yields: $\mu = 1.6^{+1.3}_{-1.1}$
- The observed p-value relative to μ=1 is **0.5 σ**
  - **1.5 σ** relative to μ=0 (1 σ expected)

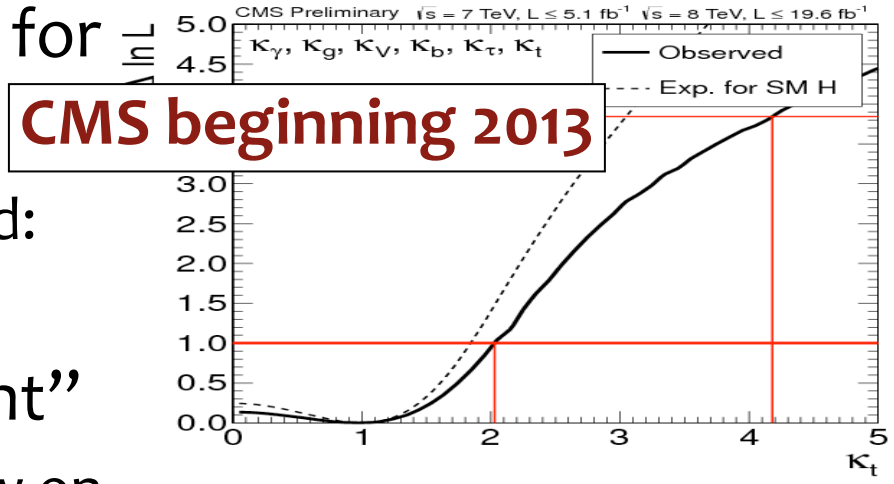


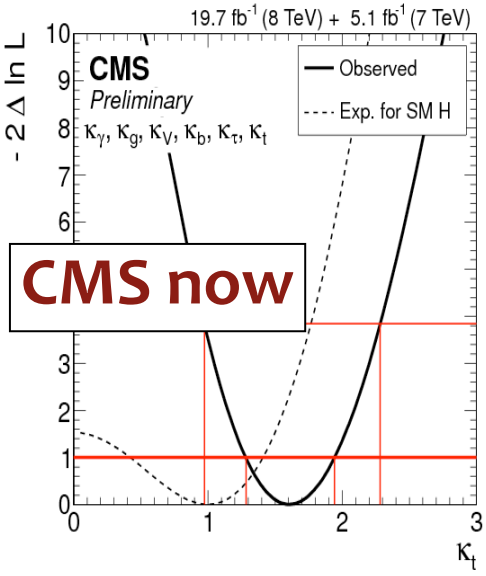
@ m_H=125.6 GeV

- The best fit to the combination yields: $\mu = 2.8^{+1.0}_{-0.9}$
- The observed p-value relative to μ=1 is **2 σ**
  - **3.4 σ** relative to μ=0 (1.2 σ expected)

Conclusions

- Significant progress on the search for $t\bar{t}H$ in the past year
  - several signatures have been explored: $tt+bb$, $tt+\tau_h\tau_h$, $tt+\gamma\gamma$, $tt+$leptons
- We are entering the "measurement" era for y_t (CMS reached 1xSM sensitivity on $\mu(t\bar{t}H)$: $\Delta\mu/\mu \sim 1 \rightarrow \Delta y_t/y_t \sim 50\%$)
  - **CMS** fit $\boldsymbol{\mu(t\bar{t}H)=2.8^{+1.1}_{-0.9}}$ compatible with the SM Higgs prediction ($\mu=1$) **at 2 σ**
    - the excess is mainly driven by the same-sign $\mu\mu$ channel
  - **ATLAS** fit $\boldsymbol{\mu(t\bar{t}H)=1.6^{+1.3}_{-1.1}}$ compatible with the SM Higgs prediction ($\mu=1$) at **0.5 σ**



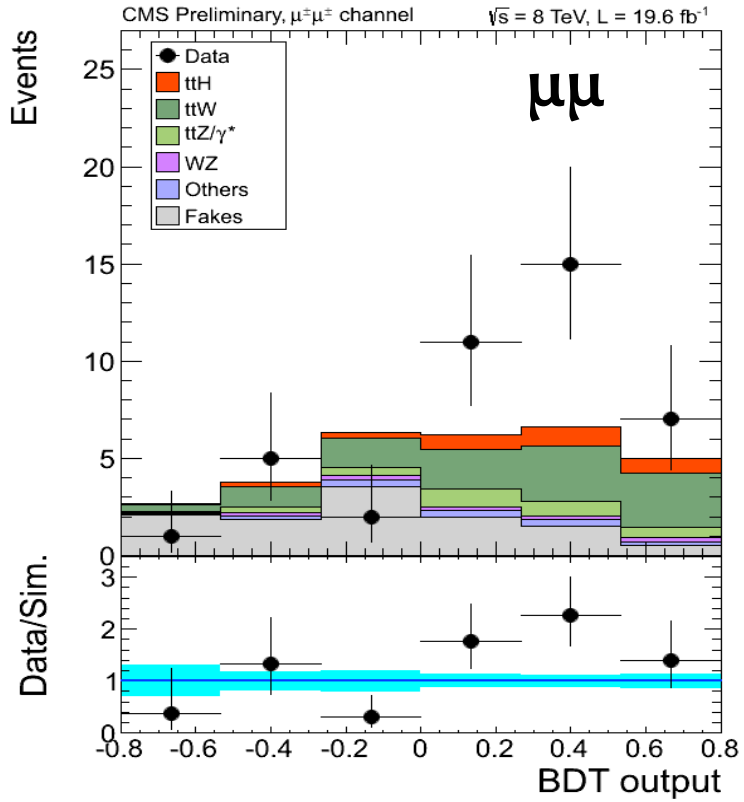


Backup

Anatomy of the $\mu^{\pm}\mu^{\pm}$ excess

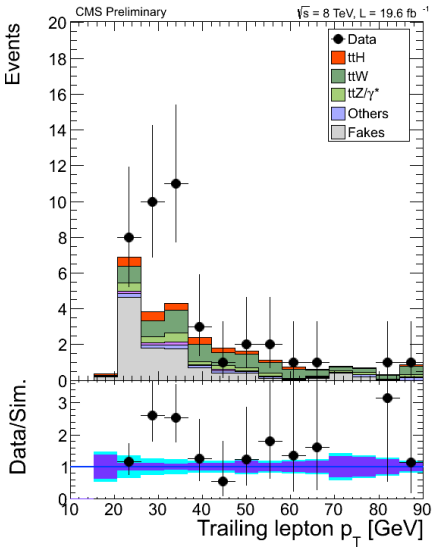
Nominal result

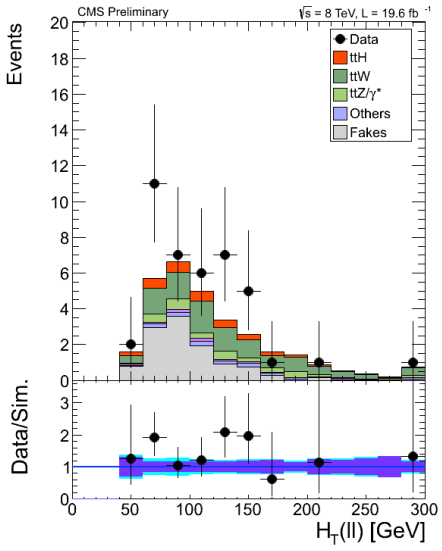
- The results in the different channels are fairly close to the SM Higgs predictions except in the $\mu^{\pm}\mu^{\pm}$ final state
  - **Excess of events** compared to the expectations, in the **signal-like region** of the final BDT discriminator

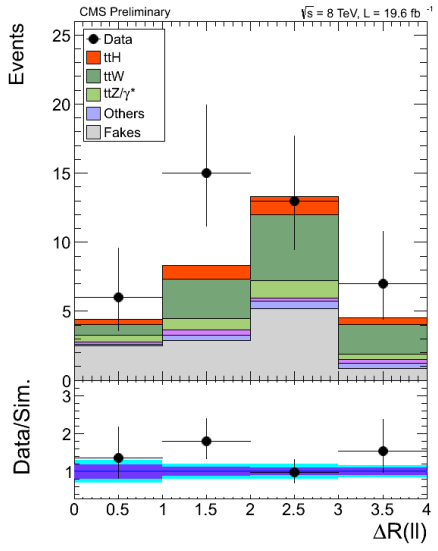


Process	Expected ± syst.
ttH	2.7 ± 0.4
ttW	8.2 ± 1.4
ttZ/γ*	2.5 ± 0.5
WZ	0.8 ± 0.9
Others	1.4 ± 0.1
Reducible	10.8 ± 4.8
Data	41

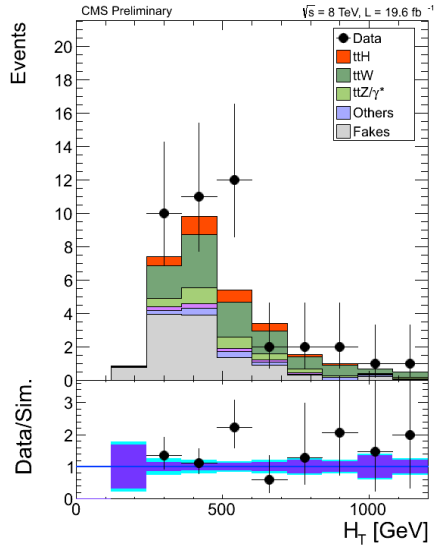
Event kinematics

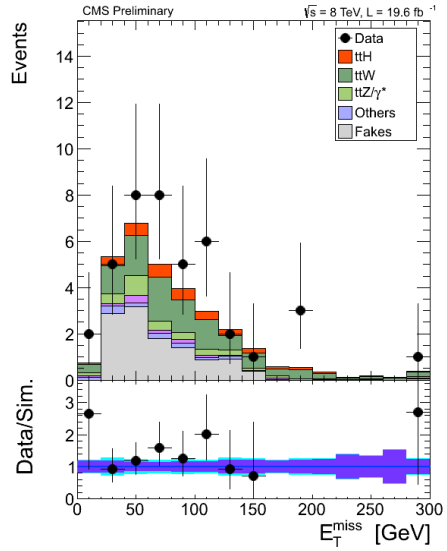


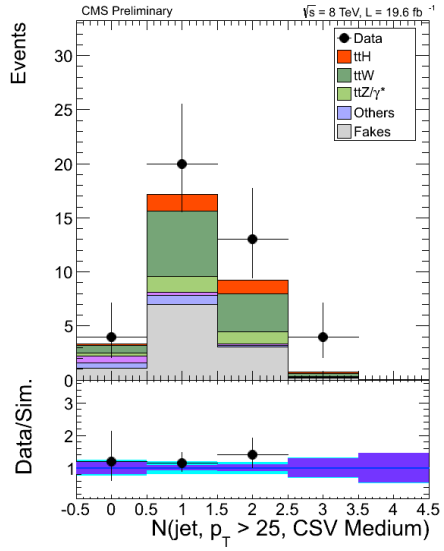




- The **kinematic of the leptons** in the events does not show anomalies and is compatible with that of signal or ttV events



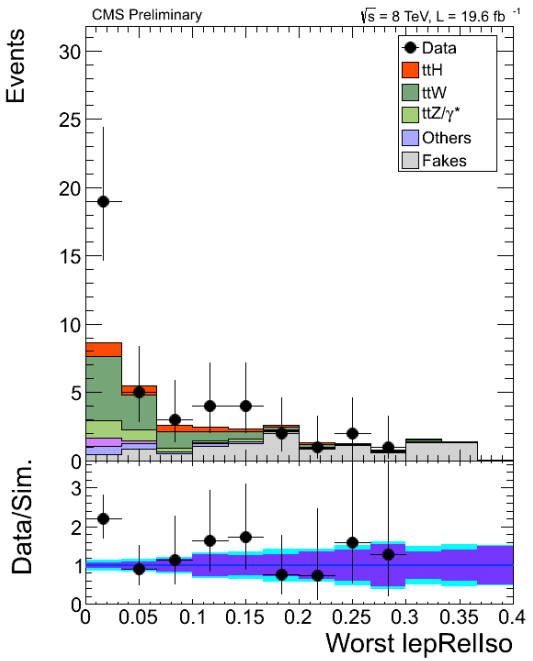




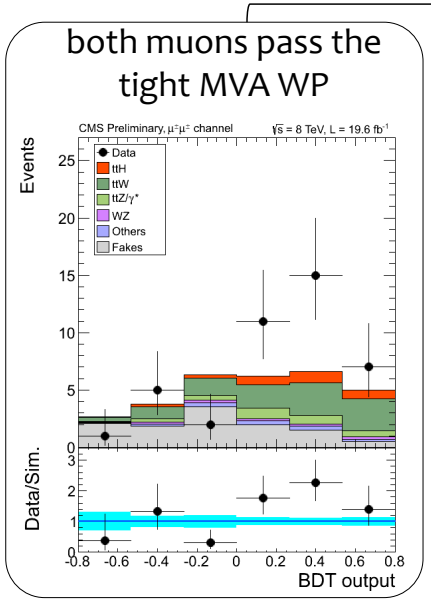
- **Jets and E_T^{miss}** are more compatible with signal or ttV.
- The multeplicity of **b-tags** is also signal-like (while the reducible background has more often only 1 b-tag since the other b-jet is misidentified as a lepton)

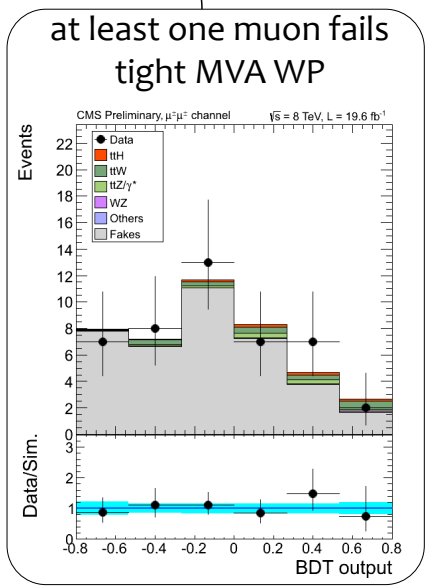
Leptons

- The events in excess are characterized by having both leptons **very well isolated.**
- Scrutiny of the events also confirms that both leptons are **well reconstructed** in the tracker and muon system, and that their charge is correctly assigned
- The analysis was also repeated using a **looser working point of the lepton MVA**
  - the excess is visible only when both leptons pass the tight MVA wp
  - the rest of the sample is well described by the background model
- The analysis was also repeated with a **cut-based muon selection.** The result is compatible with the nominal one but the sensitivity is worse



both muons pass loose MVA WP

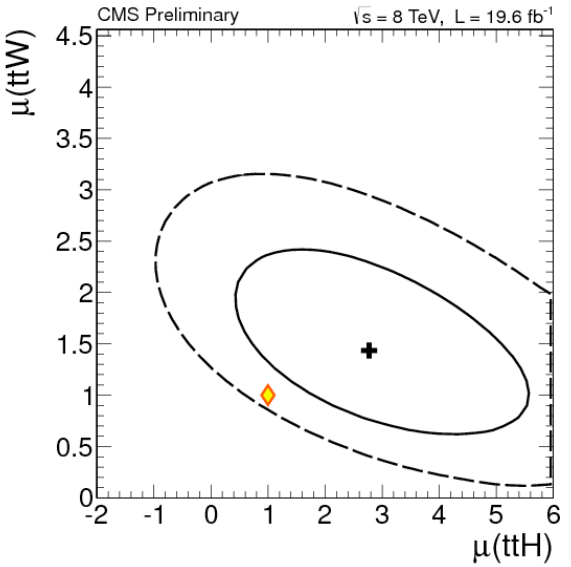




Irreducible bkg check

- A **more general fit** is performed:
  - leaving unconstrained the yields of ttW, ttZ, and reducible background (for fake e, μ separately)
  - including additional control regions in the fit: trilepton events with one Z candidate (mostly ttZ), and dilepton events with 3 jets (ttW & red. bkg.)
- Results **compatible with the nominal ones** (but ~20% worse sensitivity)
- All backgrounds yields remain **within 1σ from their input value:** no indication of issues with ttW & ttZ
  - results for ttH and ttW are correlated, all the others are well resolved

parameter	expected	observed
$\mu(\mathrm{ttH})$	$1.0^{-1.3}_{+1.5}$	$2.8^{-1.6}_{+1.8}$
$\mu(\mathrm{ttW})$	$1.0^{-0.5}_{+0.5}$	$1.4^{-0.5}_{+0.6}$
$\mu(\mathrm{ttZ})$	$1.0^{-0.3}_{+0.4}$	$1.1^{-0.3}_{+0.4}$
$\mu(\text{fake } \mu)$	$1.0^{-0.3}_{+0.3}$	$0.7^{-0.3}_{+0.4}$
$\mu(\text{fake e})$	$1.0^{-0.3}_{+0.3}$	$0.9^{-0.3}_{+0.3}$



CMS ttH Analysis Comparison to ATLAS

- For the ttH, H->bb analysis in the lepton+jets channel, the ATLAS limits are better than the baseline CMS analysis:
  - CMS baseline expected limit = 4.8, observed = 5.0
  - ATLAS expected limit = 3.1, observed = 4.2

- Several differences between the two approaches, some large, some small.
- Most prominently, ATLAS analysis has…
  - Increased signal and background acceptance due to object definitions and selections
  - Different background composition in selected events due to different b-tag performance
  - Incorporated additional background-rich categories
  - Employed more accurate NLO modeling for ttH signal
- CMS has studied the effects which are immediately available to incorporate:
  - ~20% improvement in unblinded limit when lowering jet/lepton pT thresholds
  - ~10% improvement in unblinded limit when incorporating additional categories
    - In fully-blinded assessment, these changes would not have been significant for the CMS baseline analysis, small % improvement
  - NLO signal model shows higher acceptance in most sensitive categories

- Overall, no single aspect of the analysis differences cause the difference in performance
  - No simple explanation – a collection of analysis optimizations

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CMS ttH Analysis Comparison to ATLAS

- Details on the differences:
  - Object definition/selection:
    - Leptons:
      - ATLAS: pT>25, $|\eta| < 2.5$ for e and μ
      - CMS: pT>30, $|\eta| < 2.5$ (2.1) for e (μ)
    - Jets:
      - ATLAS: pT>25, $|\eta| < 2.5$, cone of 0.4
      - CMS: pT > 40,40,40,30, $|\eta| < 2.4$, cone of 0.5
    - b-tagging:
      - ATLAS has ~50% lower mistag rate at equivalent b-jet efficiency
  - Event Categorization
    - ATLAS includes background-dominated 4jet,2tag and 5jet,2tag categories, using a one-dimensional signal discriminant (H_T)
  - Signal Discriminant:
    - ATLAS uses ANN, CMS uses BDT (do not expect one to be superior if well trained)
  - MC generators:
    - ttH signal: ATLAS uses NLO HELAC+OneLoop+Powheg, CMS uses LO Pythia
    - tt+jets: ATLAS uses POWHEG for ttbar plus 1 additional parton, CMS uses MadGraph for ttbar with up to 3 additional partons
  - Luminosity:
    - ATLAS has ~5% more luminosity than CMS

Input Variables ATLAS

Variable	Definition
Centrality	Sum of the p_T divided by sum of the E for all jets and the lepton
H1	Second Fox-Wolfram moment computed using all jets and the lepton
$m_{bb}^{\text{min }\Delta R}$	Mass of the combination of two b-tagged jets with the smallest ΔR
N_{40}^{jet}	Number of jets with $p_T \geq 40$ GeV
$\Delta R_{bb}^{\text{avg}}$	Average ΔR for all b-tagged jet pairs
$m_{jj}^{\text{max }p_T}$	Mass of the combination of any two jets with the largest vector sum p_T
$\text{Aplanarity}_{b-\text{jet}}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor built with only b-tagged jets
H_T^{had}	Scalar sum of jet p_T
$m_{jj}^{\text{min }\Delta R}$	Mass of the combination of any two jets with the smallest ΔR
$\Delta R_{\text{lep}-bb}^{\text{min }\Delta R}$	ΔR between the lepton and the combination of two b-tagged jets with the smallest ΔR
$m_{bj}^{\text{min }\Delta R}$	Mass of the combination of a b-tagged jet and any jet with the smallest ΔR
$m_{bj}^{\text{max }p_T}$	Mass of the combination of a b-tagged jet and any jet with the largest vector sum p_T
$m_{uu}^{\text{min }\Delta R}$	Mass of the combination of two untagged jets with the smallest ΔR
p_T^{jet5}	Fifth leading jet p_T
$\Delta R_{bb}^{\text{max }p_T}$	ΔR between two b-tagged jets with the largest vector sum p_T
$m_{bb}^{\text{max m}}$	Mass of the combination of two b-tagged jets with the largest invariant mass
$p_{T,uu}^{\text{min }\Delta R}$	Scalar sum of the p_T's of the pair of untagged jets with the smallest ΔR
m_{jjj}	Mass of the jet triplet with the largest vector sum p_T
$\Delta R_{uu}^{\text{min }\Delta R}$	Minimum ΔR between two untagged jets
$m_{bb}^{\text{max }p_T}$	Mass of the combination of two b-tagged jets with the largest vector sum p_T

Input variables CMS

Variable	Description
abs $\Delta\eta$ (leptonic top, bb)	Delta-R between the leptonic top reconstructed by the best Higgs mass algorithm and the b-jet pair chosen by the algorithm
abs $\Delta\eta$ (hadronic top, bb)	Delta-R between the hadronic top reconstructed by the best Higgs mass algorithm and the b-jet pair chosen by the algorithm
aplanarity	Event shape variable equal to $\frac{3}{2}(\lambda_3)$, where λ_3 is the third eigenvalue of the sphericity tensor as described in [31].
ave CSV (tags/non-tags)	Average b-tag discriminant value for b-tagged/non-b-tagged jets
ave ΔR(tag,tag)	Average ΔR between b-tagged jets
best Higgs boson mass	A minimum-chi-squared fit to event kinematics is used to select two b-tagged jets as top-decay products. Of the remaining b-tags, the invariant mass of the two with highest E_t is saved.
best ΔR(b,b)	The ΔR between the two b-jets chosen by the best Higgs boson mass algorithm
closest tagged dijet mass	The invariant mass of the two b-tagged jets that are closest in ΔR
dev from ave CSV (tags)	The square of the difference between the b-tag discriminant value of a given b-tagged jet and the average b-tag discriminant value among b-tagged jets, summed over all b-tagged jets
highest CSV (tags)	Highest b-tag discriminant value among b-tagged jets
H_0, H_1, H_2, H_3	The first few Fox-Wolfram moments [32] (event shape variables)
HT	Scalar sum of transverse momentum for all jets with $p_T > 30$ GeV/c
$\sum p_T$(jets,leptons,MET)	The sum of the p_T of all jets, leptons, and MET
$\sum p_T$(jets,leptons)	The sum of the p_T of all jets, leptons
jet 1, 2, 3, 4 p_T	The transverse momentum of a given jet, where the jet numbers correspond to rank by p_T
lowest CSV (tags)	Lowest b-tag discriminant value among b-tagged jets
mass(lepton,jet,MET)	The invariant mass of the 4-vector sum of all jets, leptons, and MET
mass(lepton,closest tag)	The invariant mass of the lepton and the closest b-tagged jet in ΔR (LJ channel)
max $\Delta\eta$ (jet, ave jet η)	max difference between jet eta and avg deta between jets
max $\Delta\eta$ (tag, ave jet η)	max difference between tag eta and avg deta between jets
max $\Delta\eta$ (tag, ave tag η)	max difference between tag eta and avg deta between tags
median inv. mass (tag pairs)	median invariant mass of all combinations of b-tag pairs
M3	The invariant mass of the 3-jet system with the largest transverse momentum.
MHT	Vector sum of transverse momentum for all jets with $p_T > 30$ GeV/c
MET	Missing transverse energy
min ΔR(lepton,jet)	The ΔR between the lepton and the closest jet (LJ channel)
HiggsLike dijet mass(2)	the invariant mass of a jet pair(at least one is b-tagged) ordered in closeness to a Higgs boson mass (DIL channel)
number of HiggsLike dijet 15	number of jet pairs(at least one is b-tagged) whose invariant mass is within 15 GeV window of a Higgs boson mass (DIL channel)
min ΔR(tag,tag)	The ΔR between the two closest b-tagged jets
min ΔR(jet,jet)	The ΔR between the two closest jets
$\sqrt{\Delta\eta(t^{lep}, b\bar{b}) \times \Delta\eta(t^{had}, b\bar{b})}$	square root of the product of abs $\Delta\eta$ (leptonic top, bb) and abs $\Delta\eta$ (hadronic top, bb)
second-highest CSV (tags)	Second-highest b-tag discriminant value among b-tagged jets
sphericity	Event shape variable equal to $\frac{3}{2}(\lambda_2 + \lambda_3)$, where λ_2 and λ_3 are the second and third eigenvalues of the sphericity tensor as described in [31]
(Σ jet p_T)/(Σ jet E)	The ratio of the sum of the transverse momentum of all jets and the sum of the energy of all jets
tagged dijet mass closest to 125	The invariant mass of the b-tagged pair closest to 125 GeV/c^2
$t\bar{t}b\bar{b}$/$t\bar{t}H$ BDT	BDT used to discriminate between $t\bar{t}b\bar{b}$ and $t\bar{t}H$ in the LJ $\geq$ 6 jets, $\geq$ 4 tags, $\geq$6 jets + 3 tags, and 5 jets + $\geq$4 tags categories. See text for description and table 15 for list of variables