Search with CMS for the Higgs boson produced in association with top quarks

Francesco Micheli
on behalf of the CMS Collaboration

SAPIENZA
UNIVERSITÀ DI ROMA

INFN

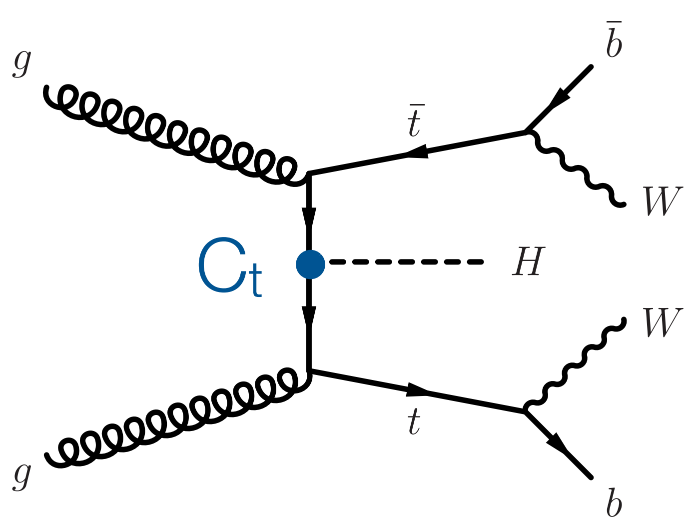
Why Top+Higgs?

- Direct measurement of top-Higgs coupling (Ct):
  - SM: Ct~1 **special role** of the top in EWSB mechanism? Why so heavy?
  - BSM: **t+H** present as **final state** of many **new physics** scenarios

2 production mechanism @ LHC

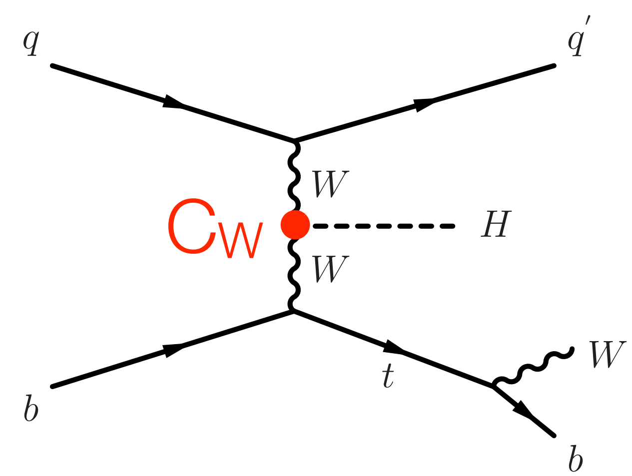
Pair production **ttH**
sensitive to Ct magnitude

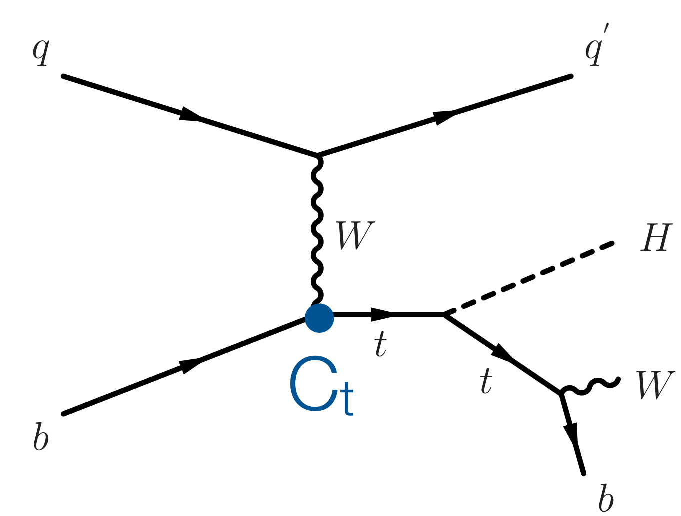
$\sigma(ttH) \propto |C_t|^2 = 130$ fb



Single top production **tHq**
sensitive to Ct sign

$\sigma(tHq) \propto |C_W \mathcal{M}_a + C_t \mathcal{M}_b|^2 = 18$ fb





Overview of CMS analysis

H → hadrons HIG-12-035 / HIG-13-019 7/8 TeV

- ttH, H→ bb, $\tau_h\tau_h$
- ttH, H→ bb with Matrix Element Method

High rate, large tt + bb background

H → leptons HIG-13-020 8 TeV

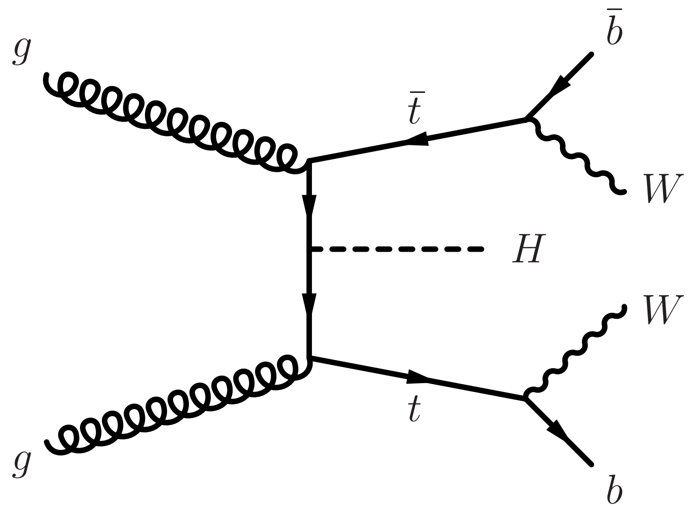
- ttH, H → WW, ZZ, $\tau_l\tau_h$

Low rate, bacgkround suppressed by leptons

H → photons CERN-PH-EP-2014-117 (HIG-13-015) 7/8 TeV

- ttH, H → $\gamma\gamma$
- tHq, H → $\gamma\gamma$

Low rate, H fully reconstructed

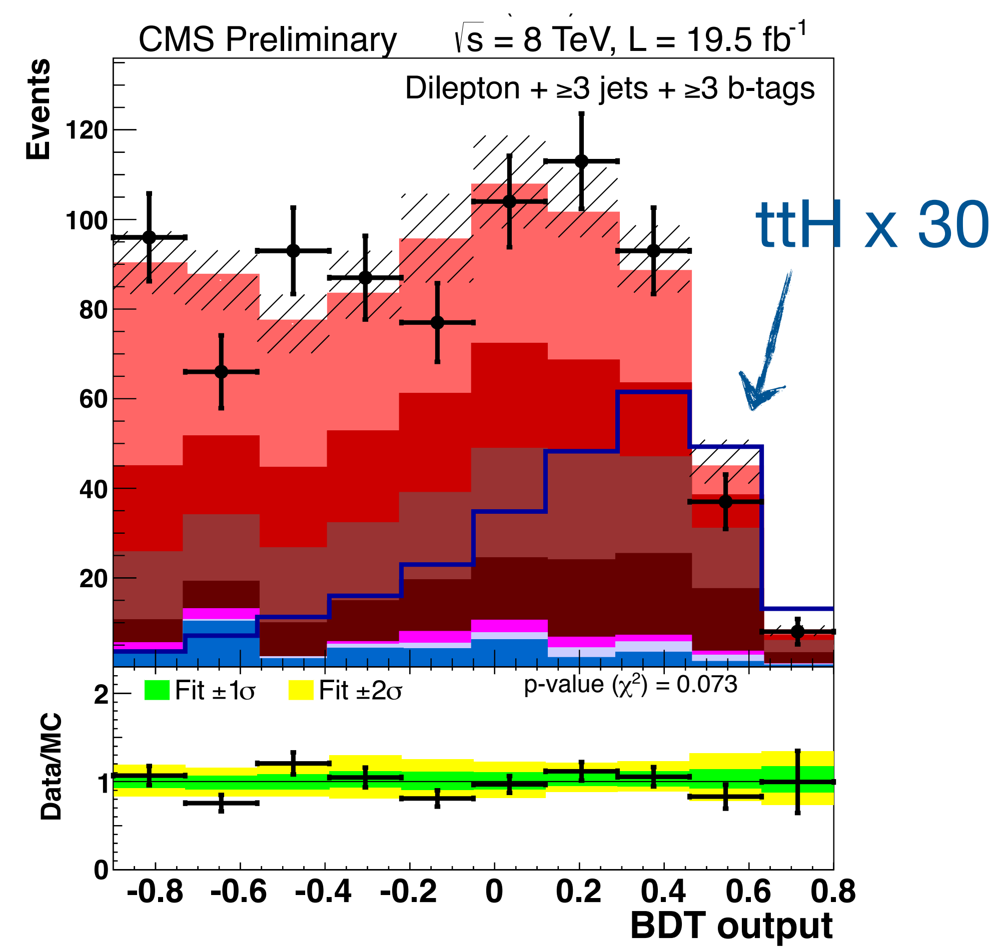


- Different techniques for **ttH analysis** but common strategy:
  - Categorization depending on **#Jets** and **#b-jets** for best sensitivity (S/B increases requiring high number of (b-)jets)
- ttH channels combined to measure $\mu_{ttH} = \sigma_{ttH}/\sigma_{ttH}^{SM}$ HIG-14-009

ttH, H → hadrons

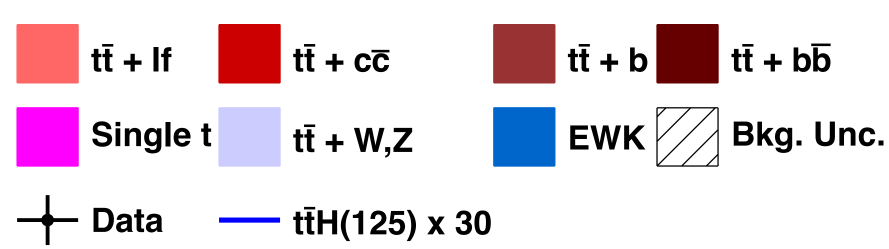
H decay	tt decay	selection	#sig and sig/bkg
bb	semileptonic	1 e/μ, ≥4 jets (≥2b-jets)	#sig~90 sig/bkg~0.004
bb	dileptonic	2 e/μ, ≥3 jets (≥2b-jets)	#sig~30 sig/bkg~0.002
$\tau_h\tau_h$	semileptonic	1 e/μ, 2τ, ≥4jets (1-2 b-jets)	#sig~2 sig/bkg~0.003

- MC (Madgraph) modeling of background:
  - tt+jets: reducible (tt+LF), irreducible (tt+HF)
- BDT to separate ttH from tt+jets:
  - Input variables related to **objects kinematics** and **b-tag**
  - **Fit to BDT output** to extract #sig and #bkg



μ_{ttH} (bb)~ 0.7±1.8

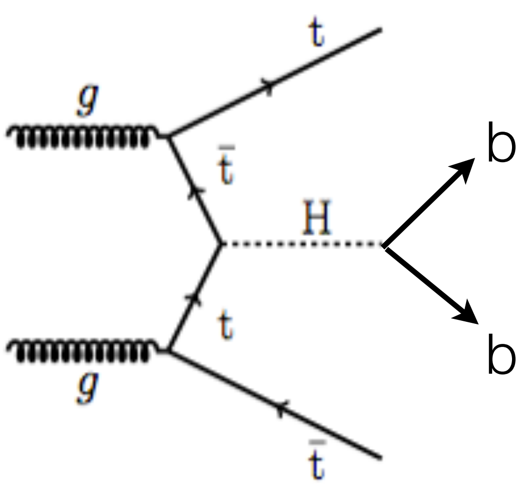
μ_{ttH} ($\tau\tau$)~ -1.3±4.8

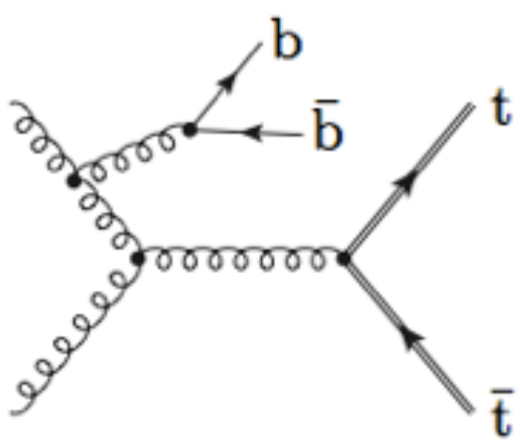


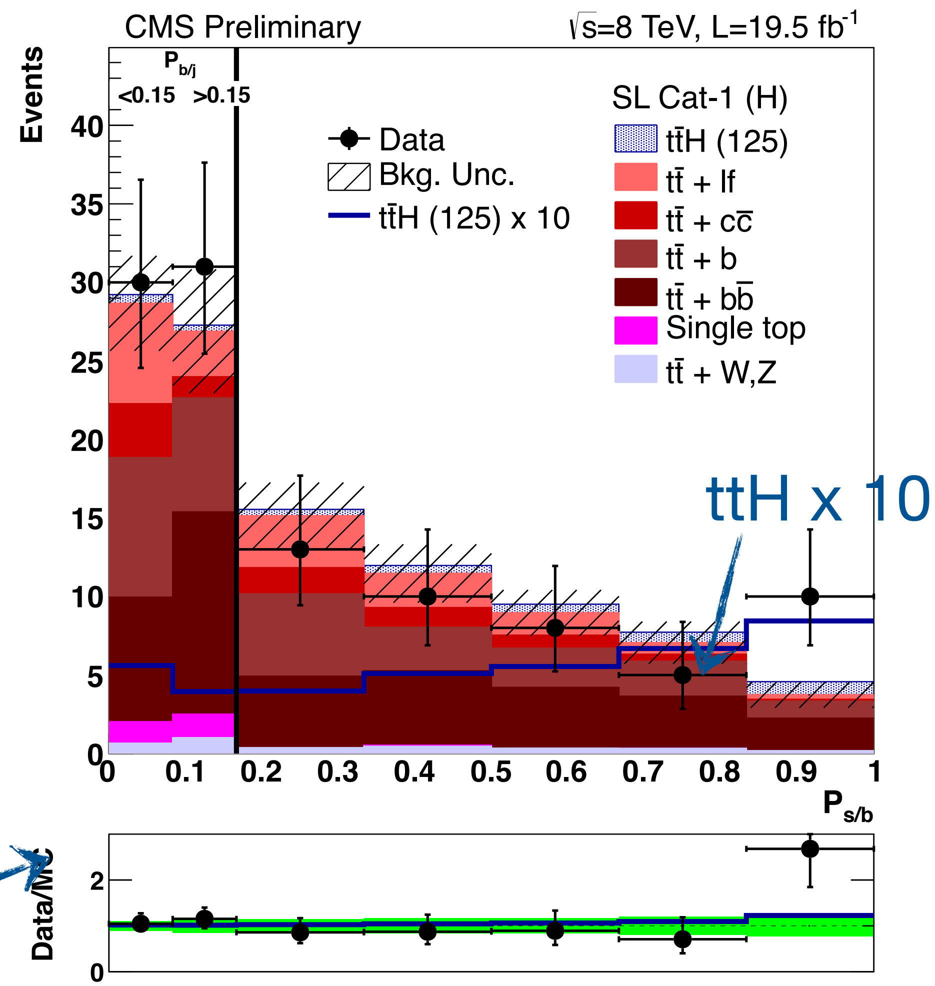
ttH, H → bb with MEM

NEW

- Analytical Matrix Element Method for S/B separation:
- tt+ bb **irreducible** but:
    - Different diagrams means different kinematics
- Theoretical model + Experimental information = **probability** for ttH or ttbb hypothesis







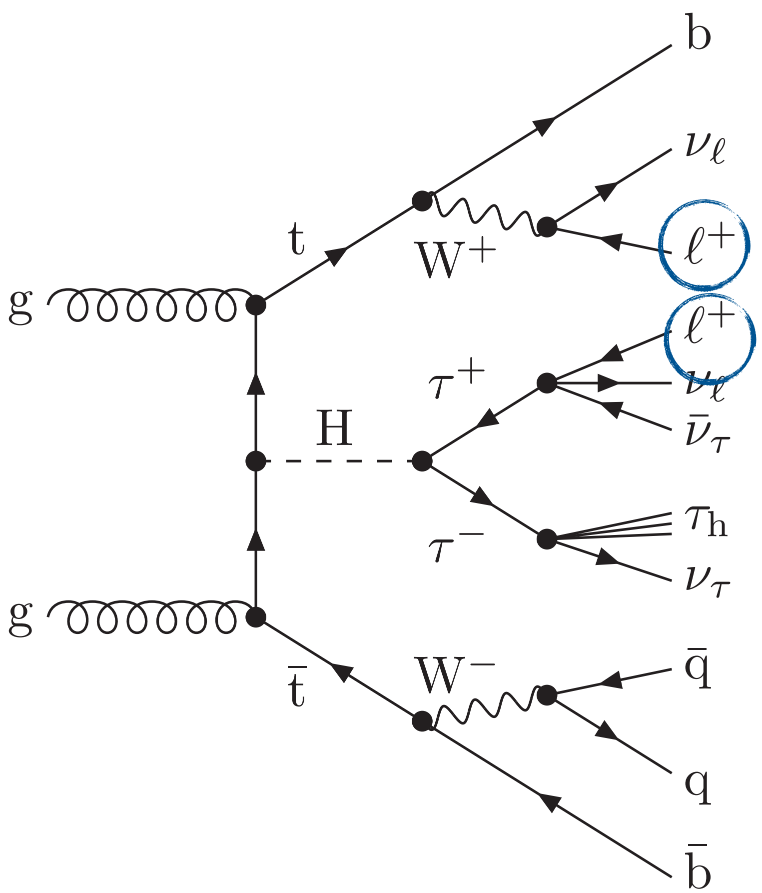
example category (4 in total)

- 30% improvement wrt to standard **ttH(→ bb)**

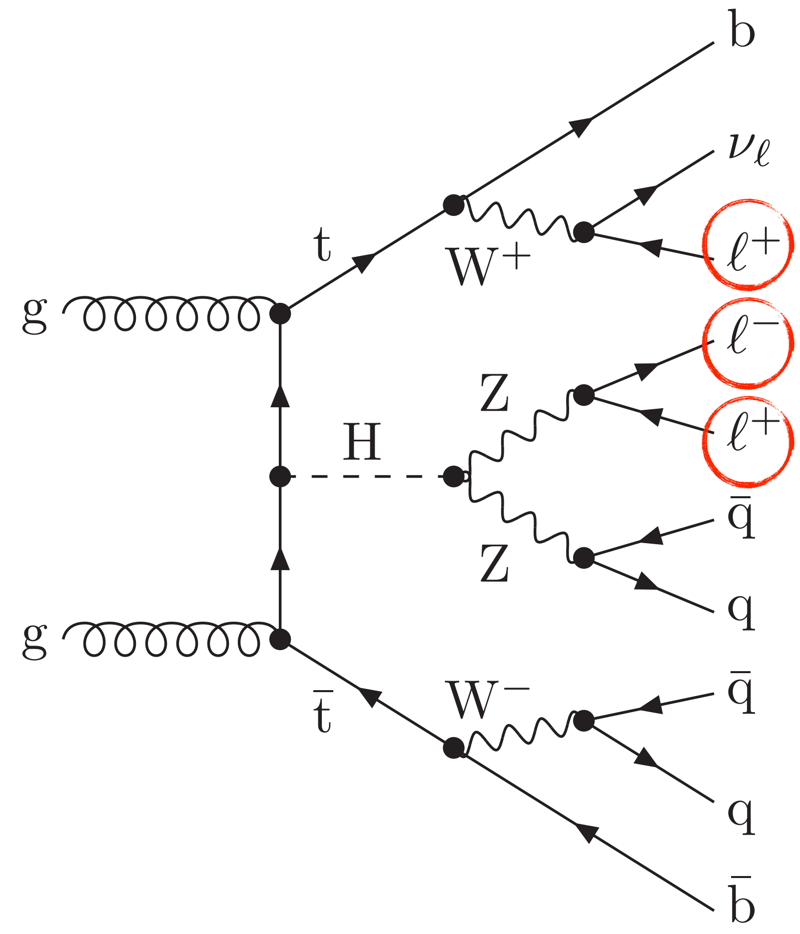
$\mu_{ttH} \sim 0.7 \pm 1.4$

Ps/b=prob(ttH)/prob(ttbb)

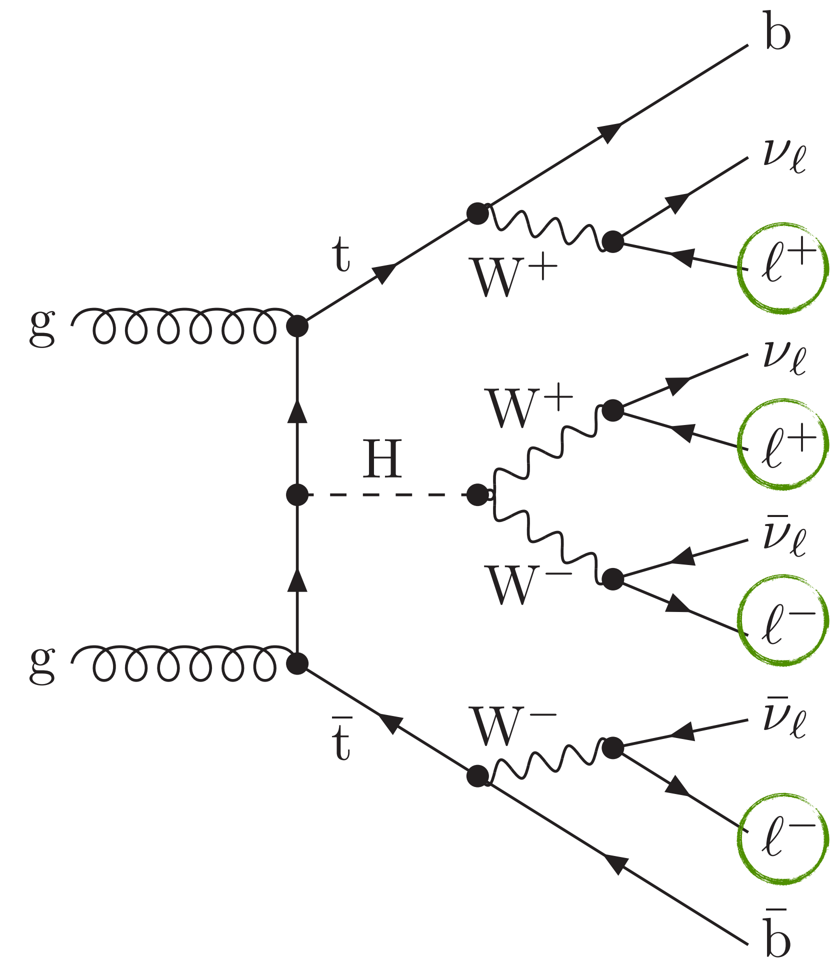
ttH, H → leptons



2 same sign leptons
≥4 jets (≥1b-jet)



3 leptons
≥2 jets (≥1b-jet)

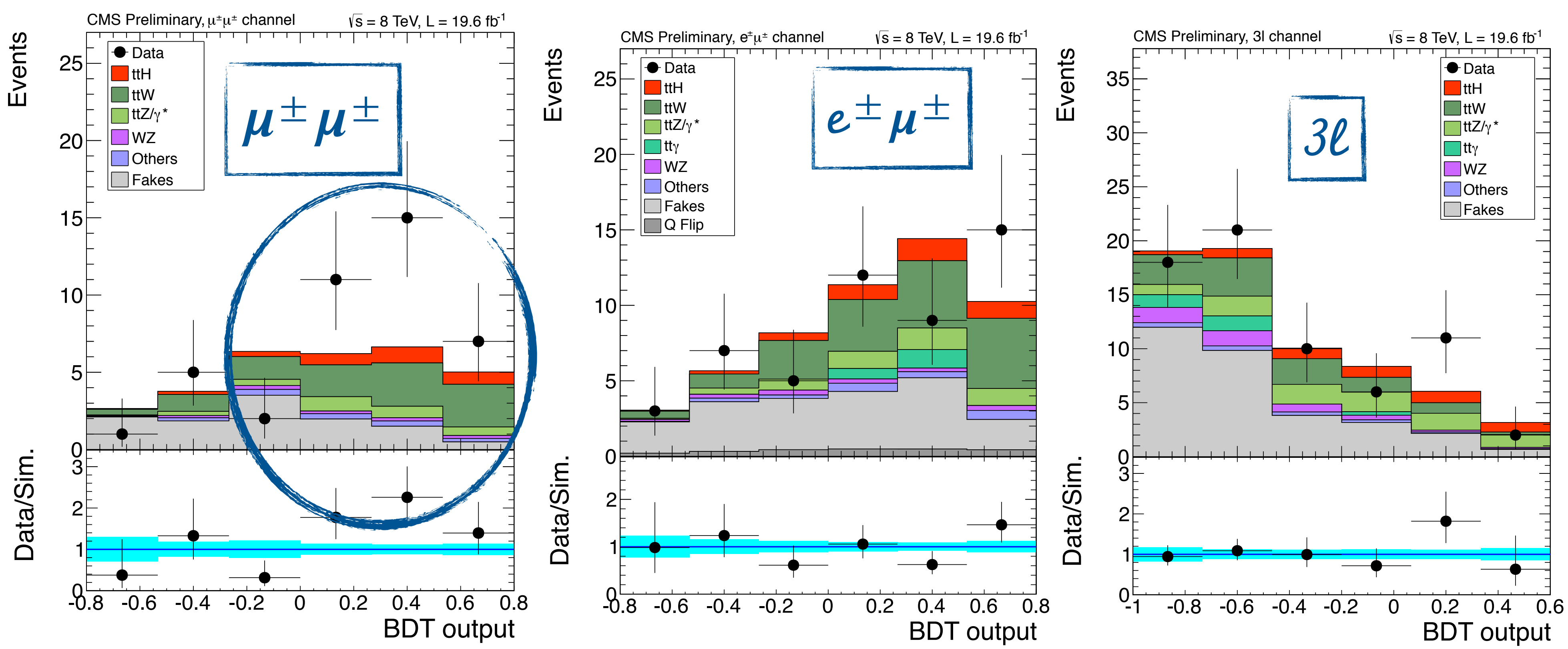


4 leptons
≥2 jets (≥1b-jet)

- Targeting different **H decays** (WW, ZZ, $\tau\tau$) with >=1 lepton from tt decays

Results

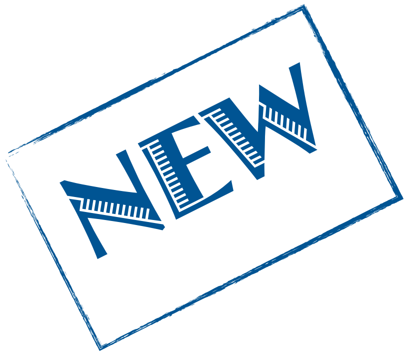
- Lepton charge correlations and kinematic variables to improve sensitivity
- Main backgrounds: **reducible**: tt with fake leptons (from b-jets) **irreducible**: tt+Z/W
  - Suppression of tt+jets → Dedicated lepton MVA ID minimizing fakes
  - BDT with kinematic variables
- Signal extraction:
  - *2ℓ*, *3ℓ*: fit to **BDT** distribution, *4ℓ*: just **Njet** distribution (yields are too low for BDT)



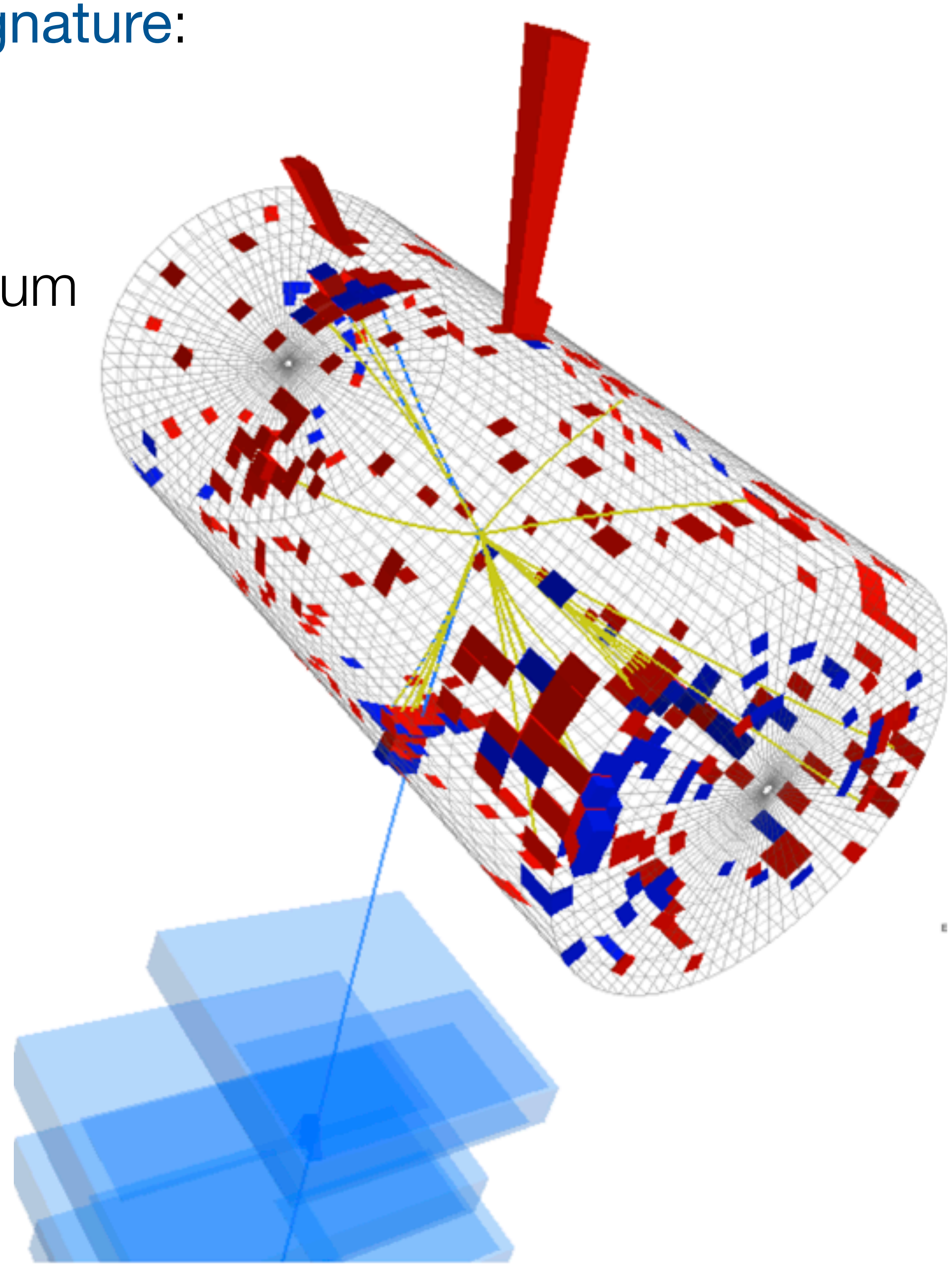
Mild excess in $\mu\mu$ channel

$\mu_{ttH} \sim 3.9 \pm 1.5$

ttH, H → $\gamma\gamma$



- Limited by statistic BR(H→$\gamma\gamma$)~2‰ BUT clear signature:
  - Two energetic photons
  - Narrow Higgs peak over continuum bkg spectrum → **data driven background** estimation
- New: now using **MVA** H→$\gamma\gamma$ **photon ID**
- 2 event categories (only 1cat @7TeV):
  - Leptonic/Multijet targeting different tt decays (>=1 lepton or no leptons)



Results

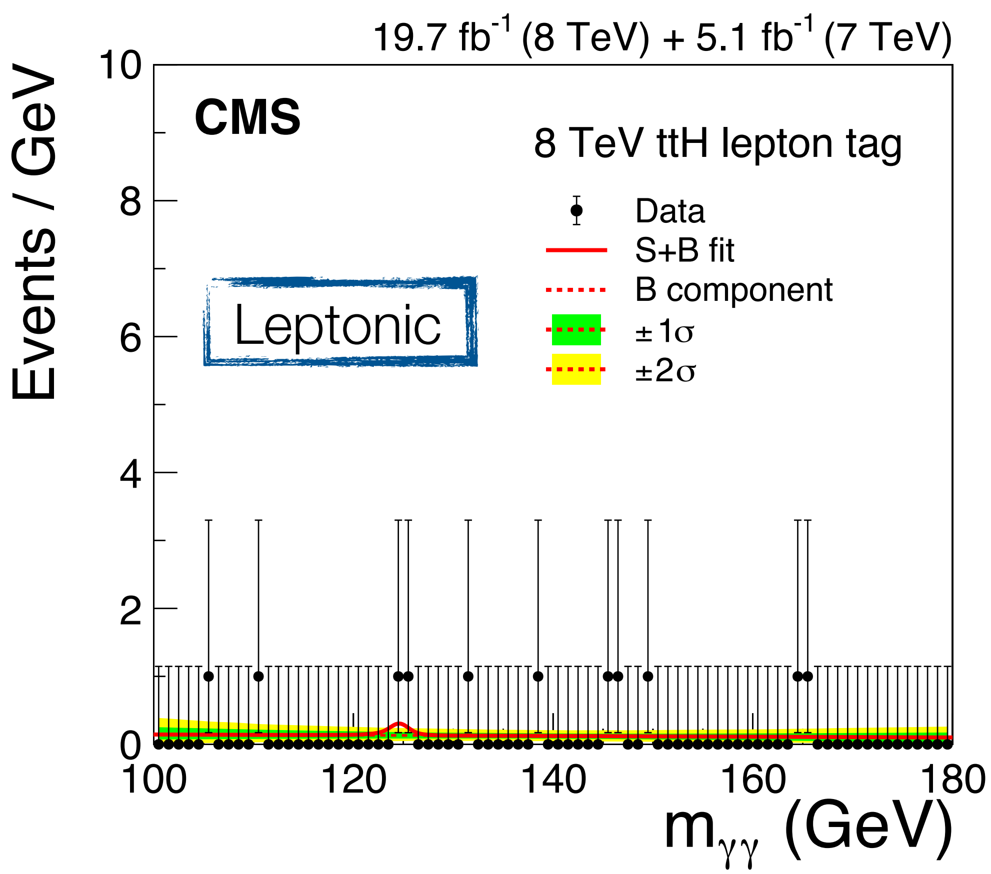
NEW

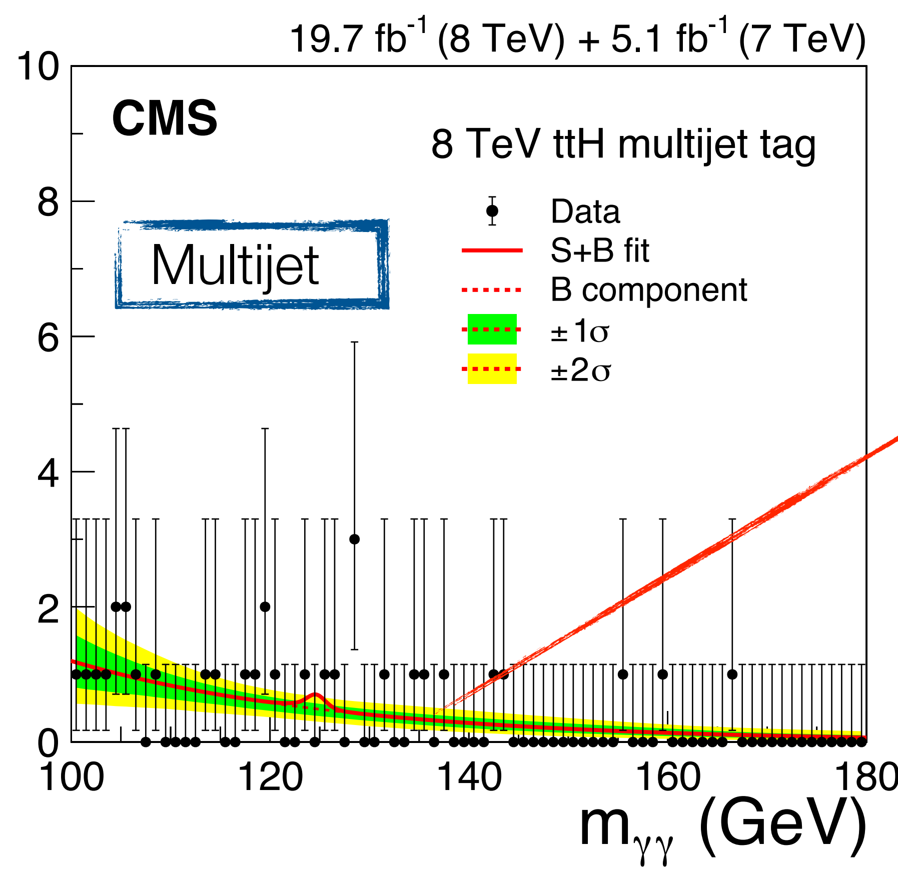
	Cuts
ttH leptonic	pT(γ1)>m$\gamma\gamma$/2 >=1lepton, 2jets(>=1btag)
ttH multijet	pT(γ1)>m$\gamma\gamma$/2 5jets(>=1btag)

- Event categories pure in ttH production:
  - <5% contamination from other production mechanisms
- Events (window of 5 GeV around mH for 20 fb-1@8 TeV)

  Leptonic: sig (exp)~0.5 Bkg ~ 1 Data=2

  Multijet: sig(exp)~0.6 Bkg ~ 3 Data =6





S+B fit to data

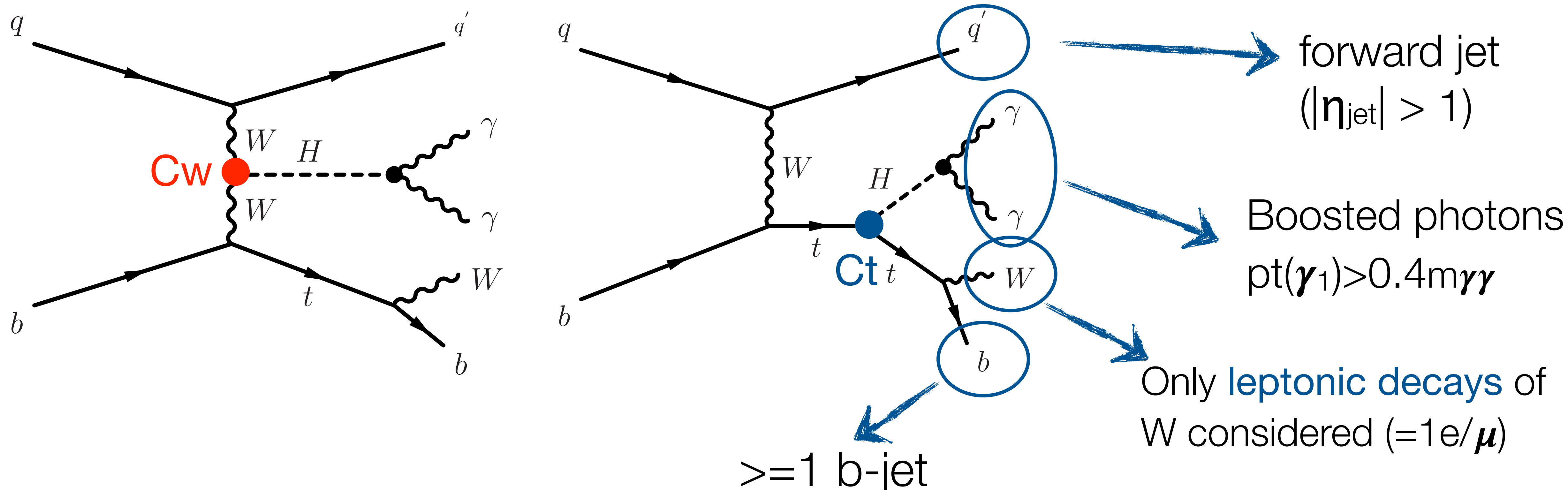
μ_{ttH} ~ 2.7±2.1

Combination of all ttH channels

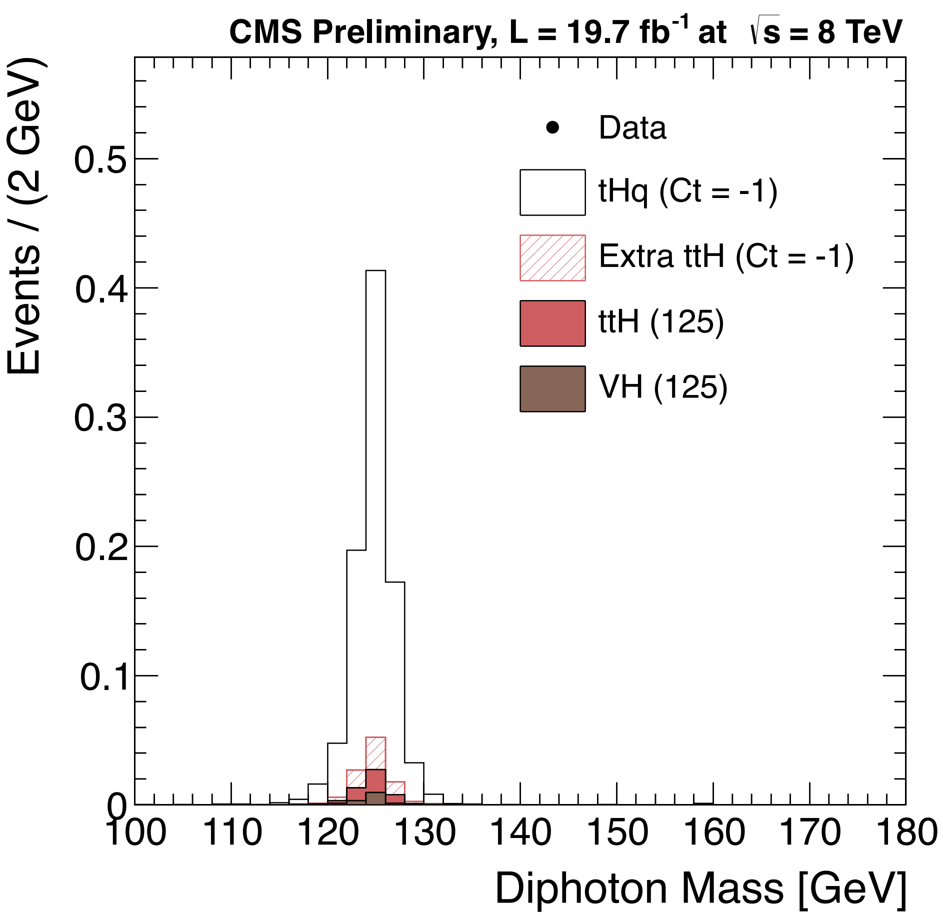
Channel	μ_{ttH} @ 125 GeV	[68% μ_{ttH} interval]
H→bb	0.7	[-1.1,2.4]
H→τhadτhad	-1.3	[-4.9,7.4]
H→leptons	3.9	[2.5,5.6]
H→γγ	2.7	[1.0,5.1]
ttH combination	2.76	[1.84,3.81]

- Combining **all channels**:
  - Best fit value $\mu_{ttH}=\sigma/\sigma_{SM}=2.76^{+1.05}_{-0.92}$
  - Excess above bkg-only expectations at ~3 σ level
  - Compatible with SM expectation (μ=1) at 2σ level

tHq in diphoton decay channel



- If Ct x Cw=-1 → constructive interference → increase of **σ** × BR by **a factor 34**
- ttH rejection using likelihood discriminator (object kinematics)
- ZERO events observed (~1 expected for Ct=-1):
  - Can exclude 4.1 times xsec expected for Ct=-1
- New physics can play a different role in ttH and tH production



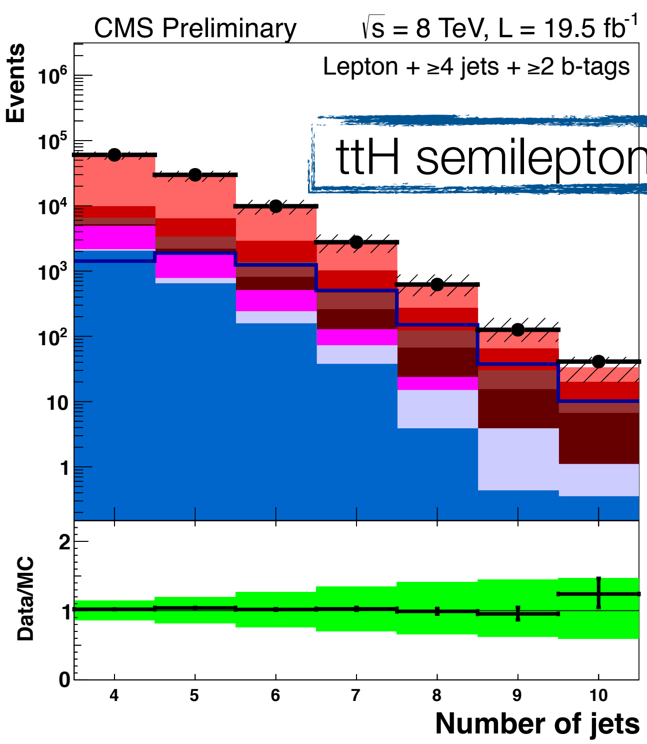
Conclusions

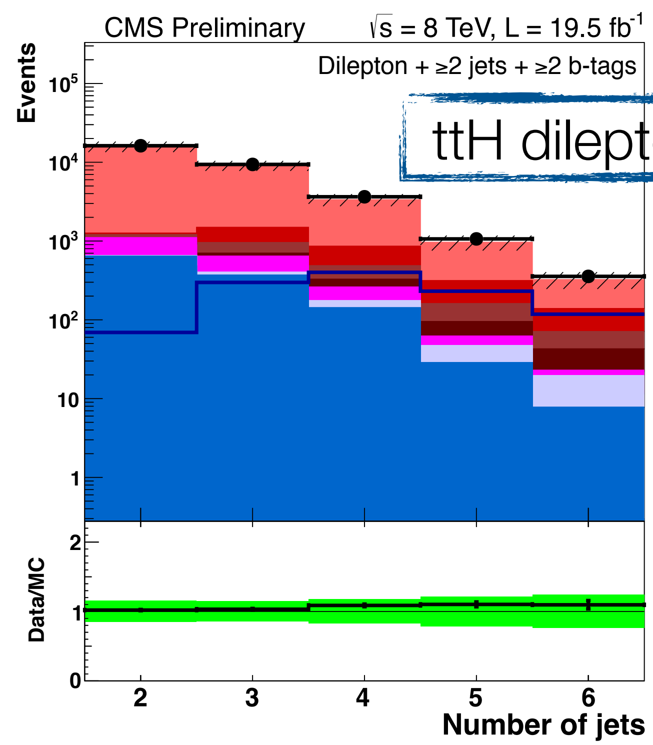
- μ_{ttH} presents an excess:
  - $\mu_{ttH} = \sigma / \sigma_{SM} = 2.76^{+1.05}_{-0.92}$
- We can still get some information from Run1 data:
  - New result using Matrix Element for ttH, H → bb
- No sign yet of exotic physics:
  - tH(→$\gamma\gamma$)q was studied, adding more decay channels
- Looking forward 13 TeV data:
  - Can achieve 10% precision on top-Higgs coupling with full Run2 data

Backup

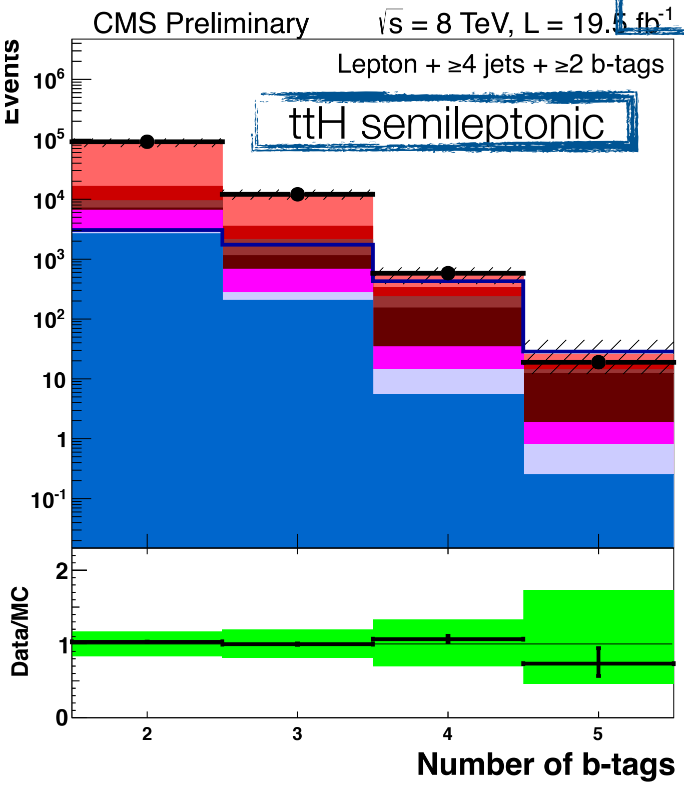
ttH, H→bb distributions

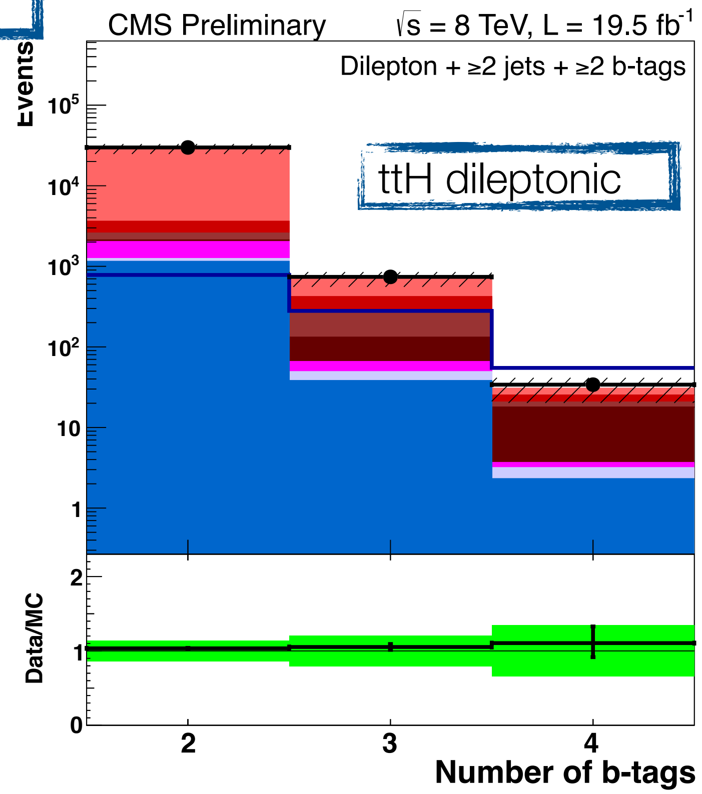
Jets





b-jets





ttH, H→bb yields

ttH semileptonic

	≥6 jets 2 b-tags	4 jets 3 b-tags	5 jets 3 b-tags	≥6 jets 3 b-tags	4 jets 4 b-tags	5 jets ≥4 b-tags	≥6 jets ≥4 b-tags
$t\bar{t}H(125)$	33.4 ± 8.1	14.0 ± 3.0	21.1 ± 4.5	23.1 ± 5.5	1.8 ± 0.5	5.2 ± 1.4	8.3 ± 2.3
$t\bar{t}$+lf	7650 ± 2000	4710 ± 820	2610 ± 530	1260 ± 340	74 ± 30	79 ± 34	71 ± 36
$t\bar{t}$+b	530 ± 300	350 ± 190	360 ± 200	280 ± 160	21 ± 12	29 ± 17	33 ± 20
$t\bar{t} + b\bar{b}$	220 ± 120	99 ± 52	158 ± 85	200 ± 110	13.1 ± 7.3	38 ± 21	78 ± 47
$t\bar{t} + c\bar{c}$	1710 ± 1110	440 ± 230	520 ± 290	470 ± 280	19 ± 11	32 ± 18	52 ± 31
$t\bar{t}V$	99 ± 27	16.2 ± 3.8	23.9 ± 5.7	28.8 ± 7.4	1.1 ± 0.4	2.5 ± 0.7	5.8 ± 1.8
Single t	264 ± 54	235 ± 41	116 ± 22	55 ± 14	3.4 ± 1.6	10.3 ± 5.3	7.3 ± 3.1
V+jets	160 ± 110	122 ± 95	44 ± 38	29 ± 27	2.1 ± 2.4	1.9 ± 1.7	1.2 ± 1.3
Diboson	5.9 ± 1.6	6.3 ± 1.4	2.4 ± 0.7	1.0 ± 0.4	0.3 ± 0.2	0.1 ± 0.1	0.2 ± 0.1
Total bkg	10630 ± 2790	5970 ± 1060	3830 ± 790	2310 ± 620	133 ± 44	193 ± 62	249 ± 90
Data	10724	5667	3983	2426	122	219	260

ttH dileptonic

	3 jets + 2 b-tags	≥4 jets + 2 b-tags	≥3 b-tags
$t\bar{t}H(125)$	7.7 ± 1.4	16.1 ± 3.1	11.2 ± 2.5
$t\bar{t}$+lf	7460 ± 1060	3190 ± 680	289 ± 83
$t\bar{t}$+b	189 ± 97	172 ± 93	149 ± 82
$t\bar{t} + b\bar{b}$	38 ± 20	58 ± 31	80 ± 44
$t\bar{t} + c\bar{c}$	480 ± 260	510 ± 300	147 ± 79
$t\bar{t}V$	30.2 ± 6.3	54 ± 12	11.9 ± 2.9
Single t	229 ± 35	97 ± 16	17.3 ± 5.1
V+jets	350 ± 130	151 ± 66	40 ± 23
Diboson	10.4 ± 1.7	3.1 ± 0.6	0.7 ± 0.4
Total bkg	8770 ± 1250	4230 ± 850	740 ± 190
Data	9060	4616	774

ttH H→$\tau\tau$

	2 jets 1 b-tag	3 jets 1 b-tag	≥4 jets 1 b-tag	2 jets 2 b-tags	3 jets 2 b-tags	≥4 jets 2 b-tags
$t\bar{t}H(125)$	0.4 ± 0.1	0.6 ± 0.1	0.6 ± 0.2	0.1 ± 0.0	0.2 ± 0.1	0.4 ± 0.1
$t\bar{t}$	225 ± 69	119 ± 38	64 ± 22	48 ± 15	38 ± 12	27.0 ± 9.1
$t\bar{t}V$	1.1 ± 0.3	1.3 ± 0.3	1.4 ± 0.4	0.4 ± 0.1	0.6 ± 0.2	1.1 ± 0.3
Single t	11.2 ± 4.0	3.0 ± 1.4	1.1 ± 1.0	1.9 ± 1.1	0.9 ± 0.6	0.6 ± 0.7
V+jets	33 ± 17	11.7 ± 6.8	3.8 ± 2.8	1.4 ± 0.9	0.4 ± 0.3	0.5 ± 0.6
Diboson	0.9 ± 0.2	0.7 ± 0.2	0.1 ± 0.0	0.0 ± 0.0	0.1 ± 0.0	0.1 ± 0.1
Total bkg	271 ± 82	135 ± 41	71 ± 24	52 ± 16	40 ± 12	29.2 ± 9.4
Data	292	171	92	41	48	35

Systematics of ttH, H→bb overview

Uncertainties of the sum of $t\bar{t}$+lf, $t\bar{t}$+b, $t\bar{t}+b\bar{b}$, and $t\bar{t}+c\bar{c}$ events with ≥ 6 jets and ≥ 4 b-tags		
Source	Rate	Shape?
QCD Scale (all $t\bar{t}$+hf)	35%	No
QCD Scale ($t\bar{t}+b\bar{b}$)	17%	No
b-Tag bottom-flavor contamination	17%	Yes
QCD Scale ($t\bar{t}+c\bar{c}$)	11%	No
Jet Energy Scale	11%	Yes
b-Tag light-flavor contamination	9.6%	Yes
b-Tag bottom-flavor statistics (linear)	9.1%	Yes
QCD Scale ($t\bar{t}$+b)	7.1%	No
Madgraph Q^2 Scale ($t\bar{t}+b\bar{b}$)	6.8%	Yes
b-Tag Charm uncertainty (quadratic)	6.7%	Yes
Top p_T Correction	6.7%	Yes
b-Tag bottom-flavor statistics (quadratic)	6.4%	Yes
b-Tag light-flavor statistics (linear)	6.4%	Yes
Madgraph Q^2 Scale ($t\bar{t}$ + 2 partons)	4.8%	Yes
b-Tag light-flavor statistics (quadratic)	4.8%	Yes
Luminosity	4.4%	No
Madgraph Q^2 Scale ($t\bar{t}+c\bar{c}$)	4.3%	Yes
Madgraph Q^2 Scale ($t\bar{t}$+b)	2.6%	Yes
QCD Scale ($t\bar{t}$)	3%	No
pdf (gg)	2.6%	No
Jet Energy Resolution	1.5%	No
Lepton ID/Trigger efficiency	1.4%	No
Pileup	1%	No
b-Tag Charm uncertainty (linear)	0.6%	Yes

1lep+ ≥6 jets + ≥4 b-tag

Large uncertainty on tt+HF: ~50%

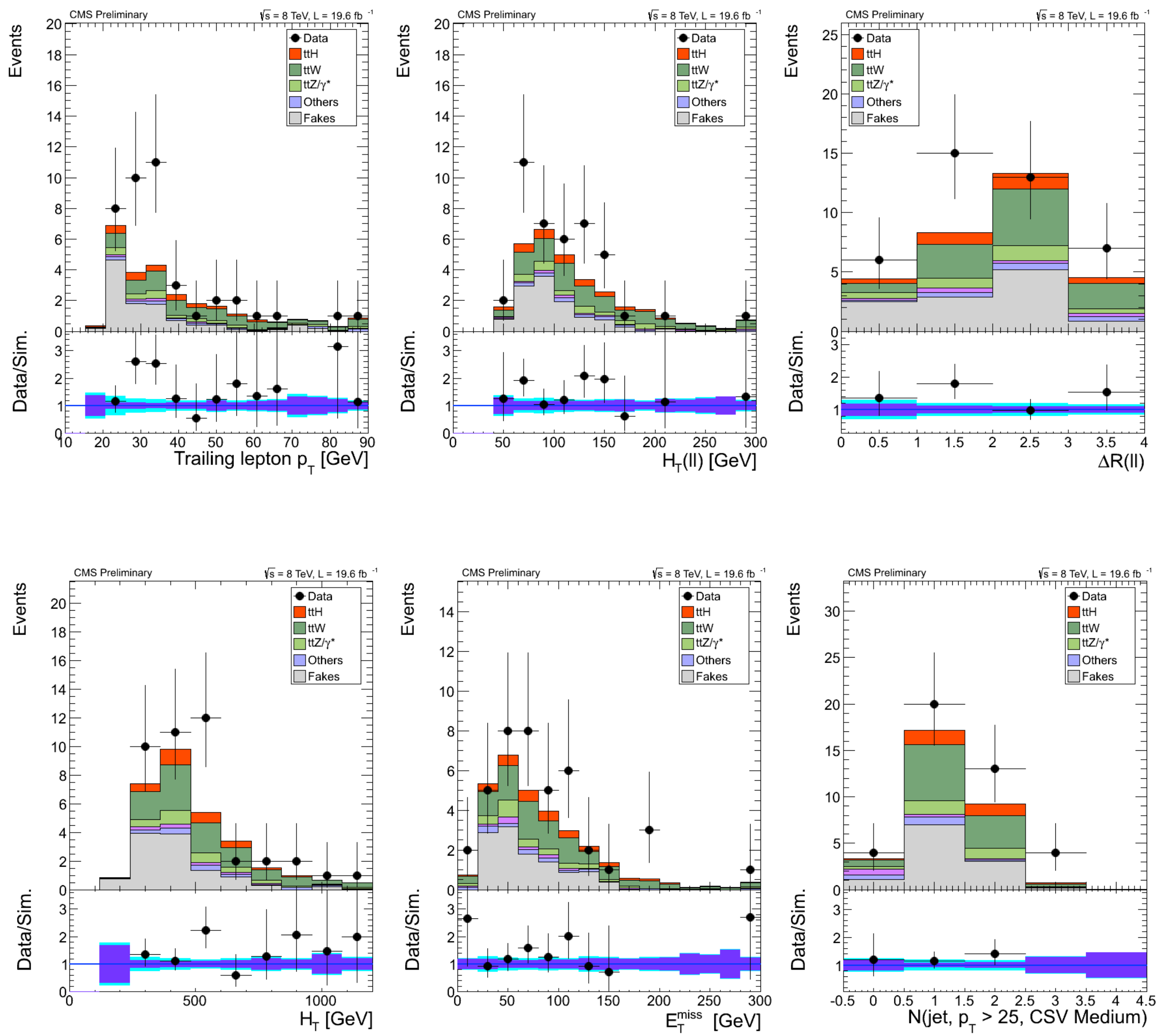
tt+LF: lower uncertainties, data-driven corrections

BDT input variables H→bb

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
$\sqrt{\Delta\eta(t^{lep}, bb) \times \Delta\eta(t^{had}, bb)}$	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.

ttH, H→$\mu\mu$ excess

Event kinematics



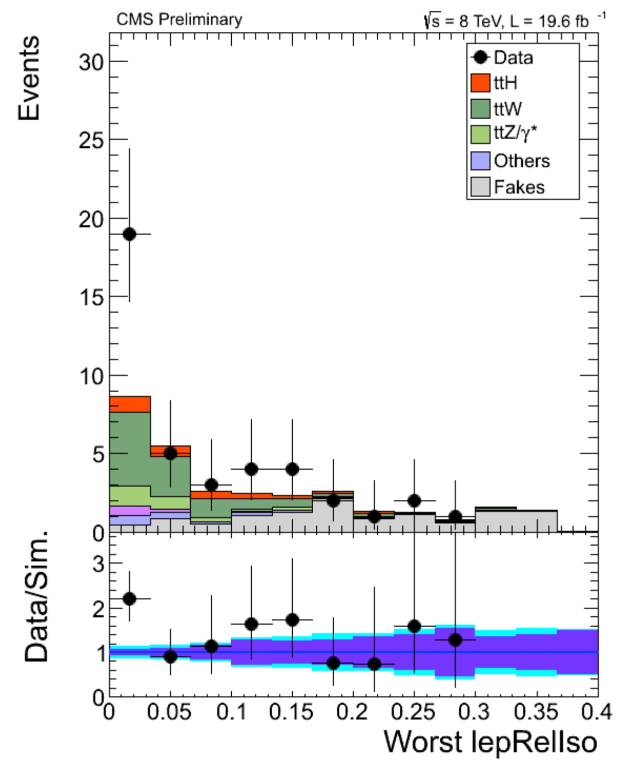
- The **kinematic of the leptons** in the events does not show anomalies and is compatible with that of signal or ttV events

- **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)

ttH, H→$\mu\mu$ excess

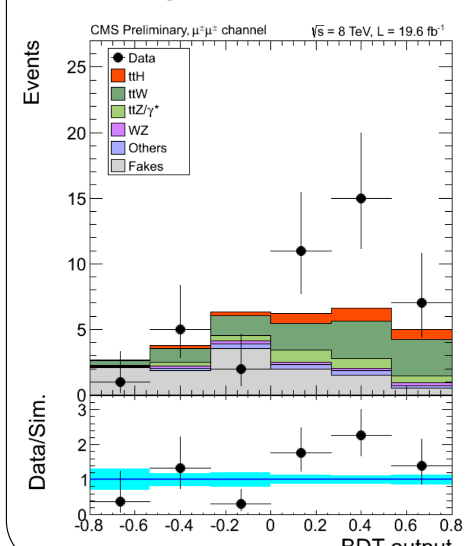
Leptons

- 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

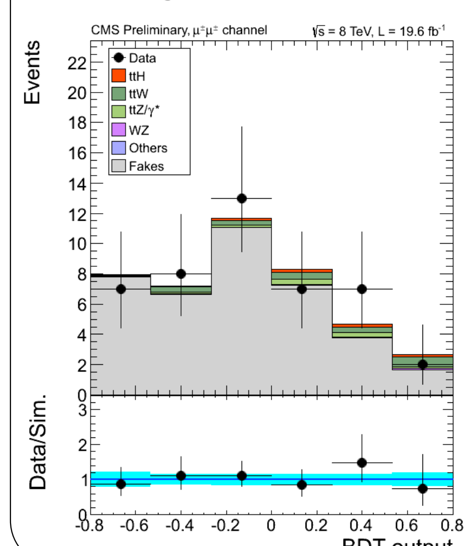


both muons pass loose MVA WP

both muons pass the tight MVA WP



at least one muon fails tight MVA WP

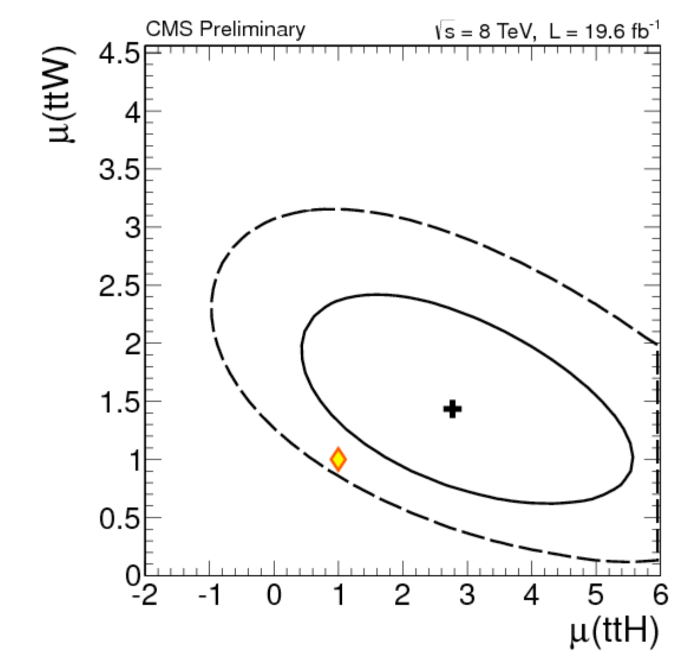


ttH, H→$\mu\mu$ excess

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
μ(ttH)	$1.0^{-1.3}_{+1.5}$	$2.8^{-1.6}_{+1.8}$
μ(ttW)	$1.0^{-0.5}_{+0.5}$	$1.4^{-0.5}_{+0.6}$
μ(ttZ)	$1.0^{-0.3}_{+0.4}$	$1.1^{-0.3}_{+0.4}$
μ(fake μ)	$1.0^{-0.3}_{+0.3}$	$0.7^{-0.3}_{+0.4}$
μ(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

CMS ttH Analysis Comparison to ATLAS

- Details on the differences:
  - Object definition/selection:
    - Leptons:
      - ATLAS: pT>25, |η| < 2.5 for e and μ
      - CMS: pT>30, |η| < 2.5 (2.1) for e (μ)
    - Jets:
      - ATLAS: pT>25, |η| < 2.5, cone of 0.4
      - CMS: pT > 40,40,40,30, |η| < 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

All channels coupling measurement