THE ROYAL SOCIETY

University of Glasgow

Search for ttH Production at the LHC

Mark Owen
The University of Glasgow
On behalf of the ATLAS & CMS Collaborations

Prepared with the help of
Darren Puigh

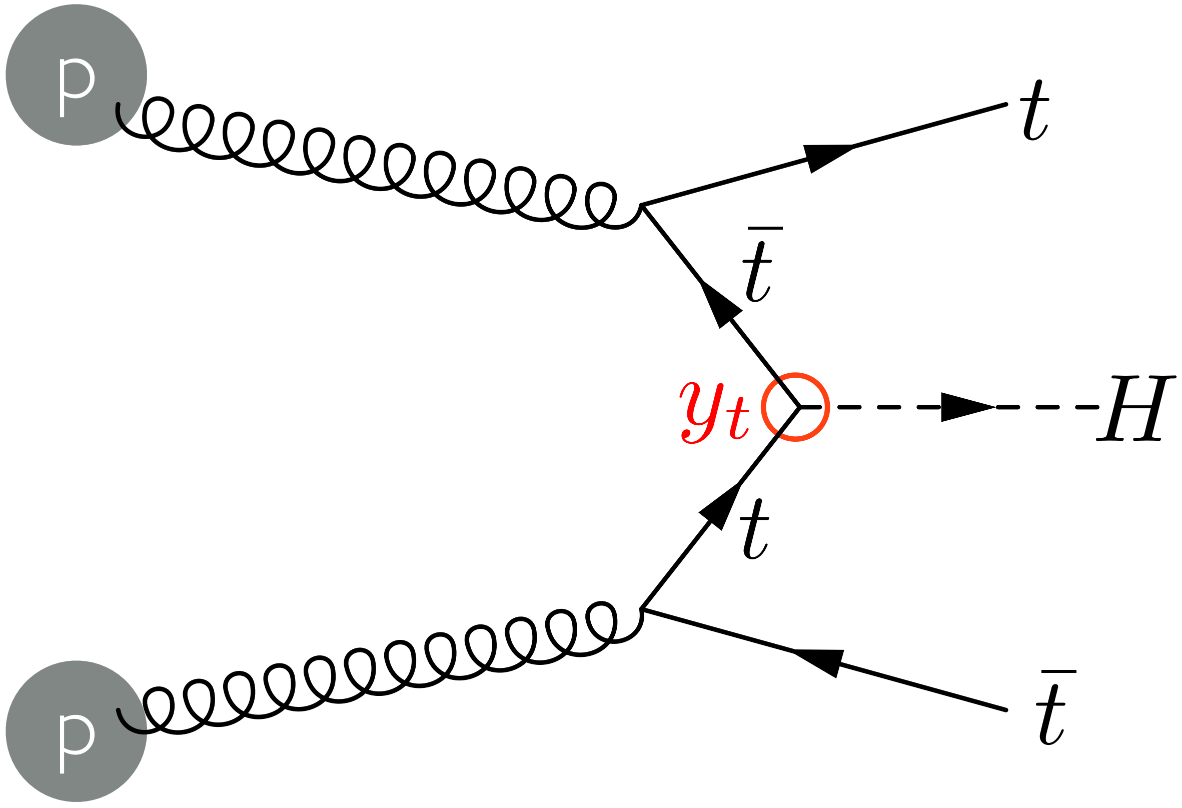
Outline

- Motivation & Introduction
- ttH, H→bb
- ttH, H→VV / ττ
- ttH, H→γγ
- CMS Combined results
- Conclusions

Motivation

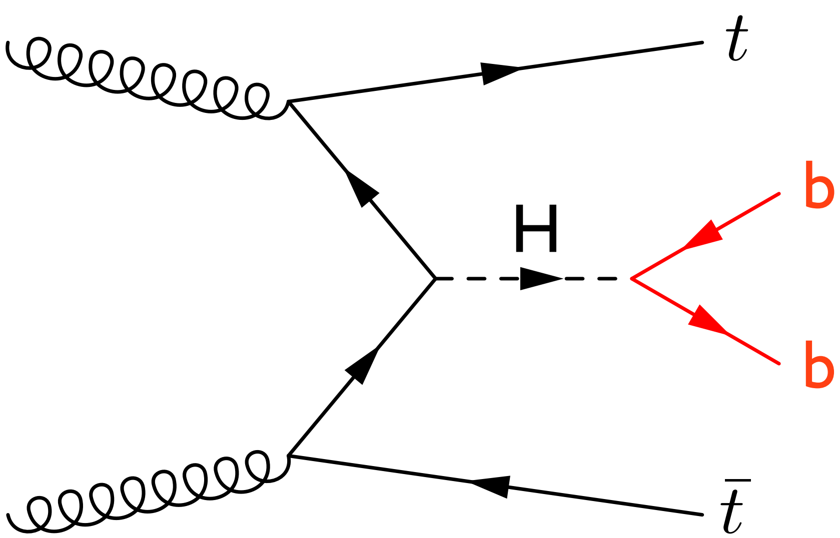
- In Standard Model - fermion masses are proportional to Higgs-fermion Yukawa couplings. Need to test this prediction.

$$m_t \stackrel{?}{=} \frac{v y_t}{\sqrt{2}}$$

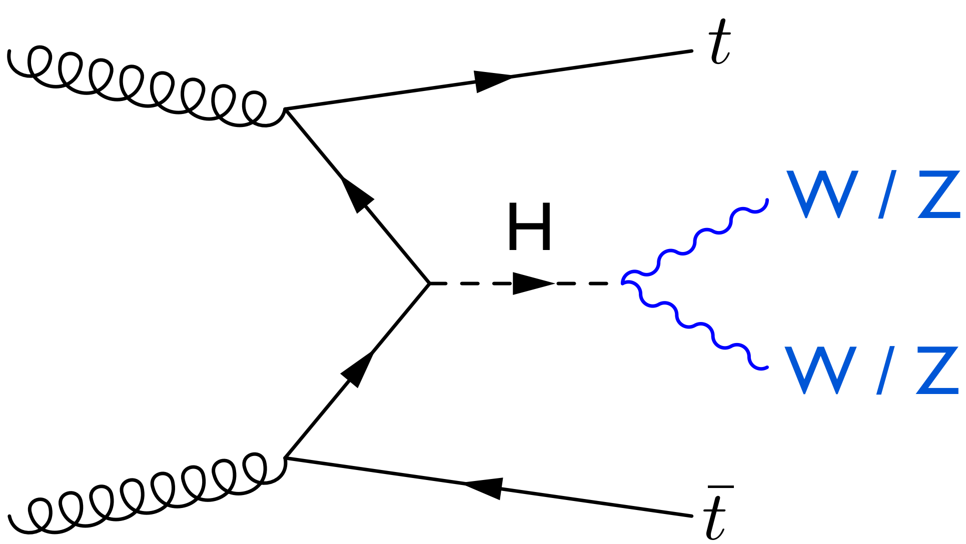


- Top quark is heavy ~ 173 GeV.
- Strong Yukawa coupling, y_t~1?
- New physics?

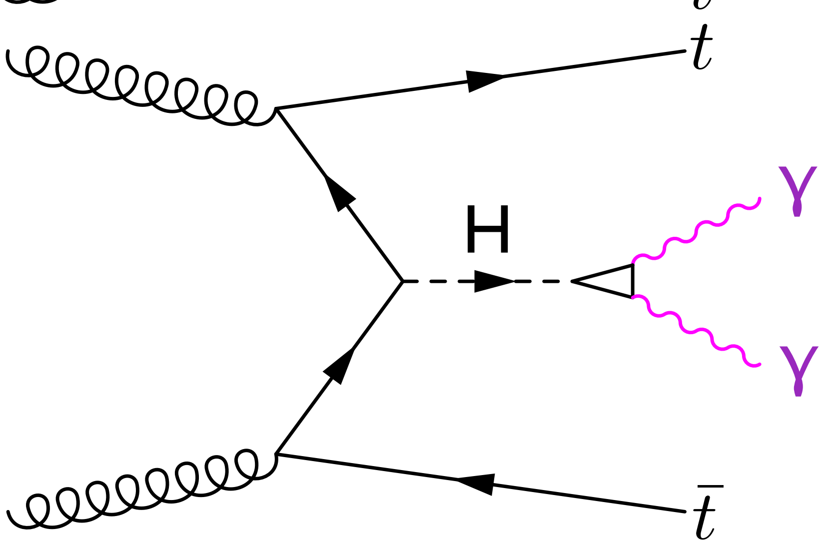
ttH Production & Decay



- Largest branching ratio, 58%.
- Final state with multiple b-quarks - challenging to reconstruct Higgs.
- Large background from ttbar + jets.

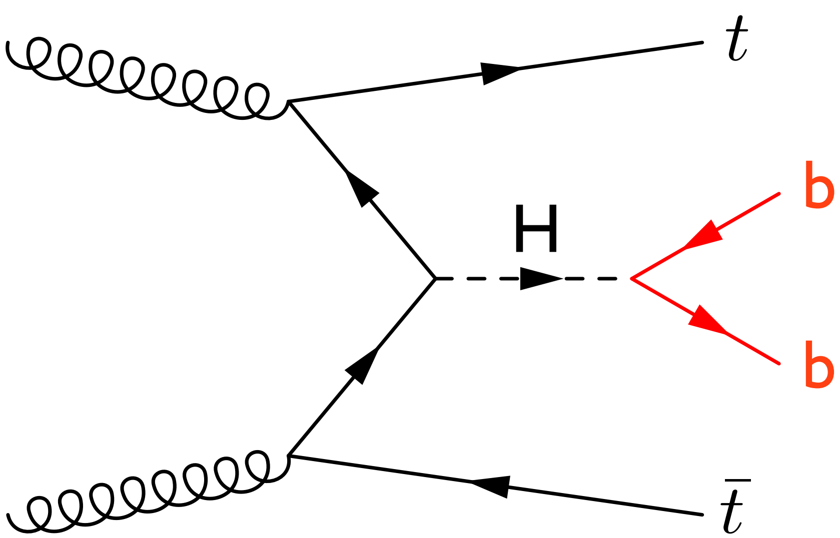


- Significant branching ratio, Br(H→WW) = 22%.
- Leptonic decays of W / Z bosons and tau decays can give distinct multi-lepton signatures, but difficult to reconstruct Higgs.
- Main background from ttbar+W/Z and non-prompt leptons.

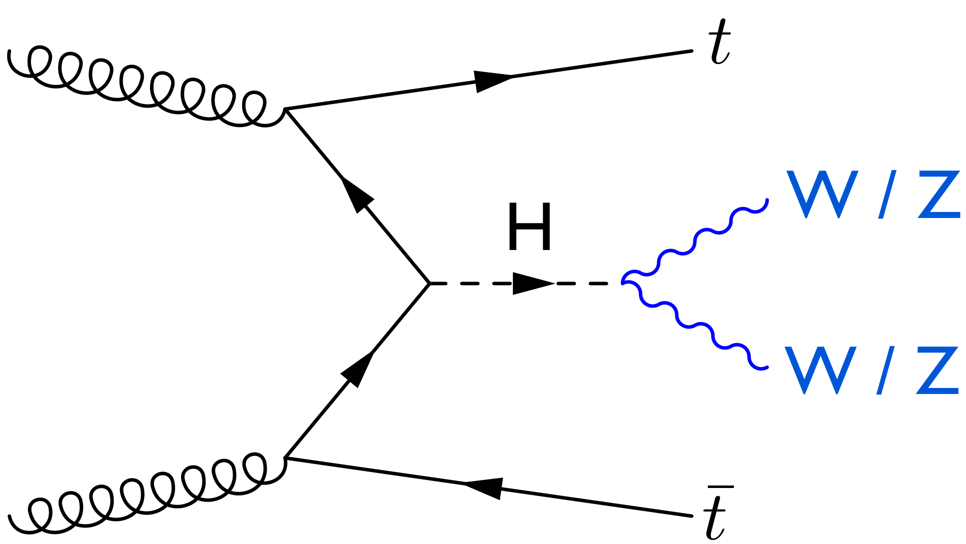


- Small branching ratio, 0.2%.
- Higgs boson can be reconstructed as a narrow peak.
- Backgrounds from ttbar+photons and QCD multi-photon / jet final states.

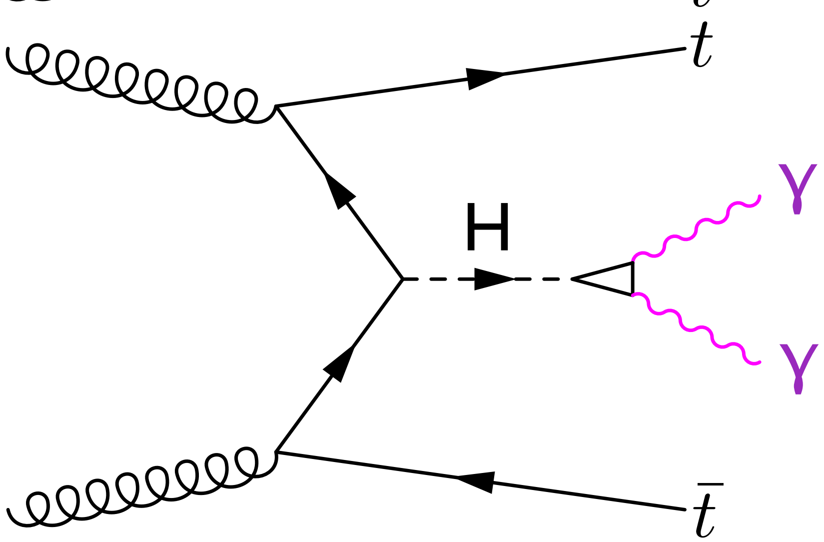
ttH Production & Decay



- Largest branching ratio, 58%.
- Final state with multiple b-quarks - challenging to reconstruct Higgs.
- Large background from ttbar + jets.

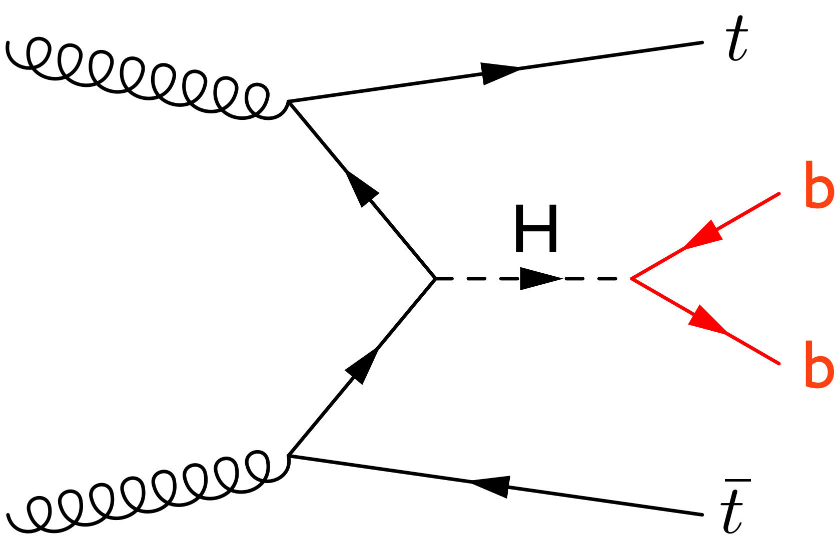


- Significant branching ratio, Br(H→WW) = 22%.
- Leptonic decays of W / Z bosons and tau decays can give distinct multi-lepton signatures, but difficult to reconstruct Higgs.
- Main background from ttbar+W/Z and non-prompt leptons.

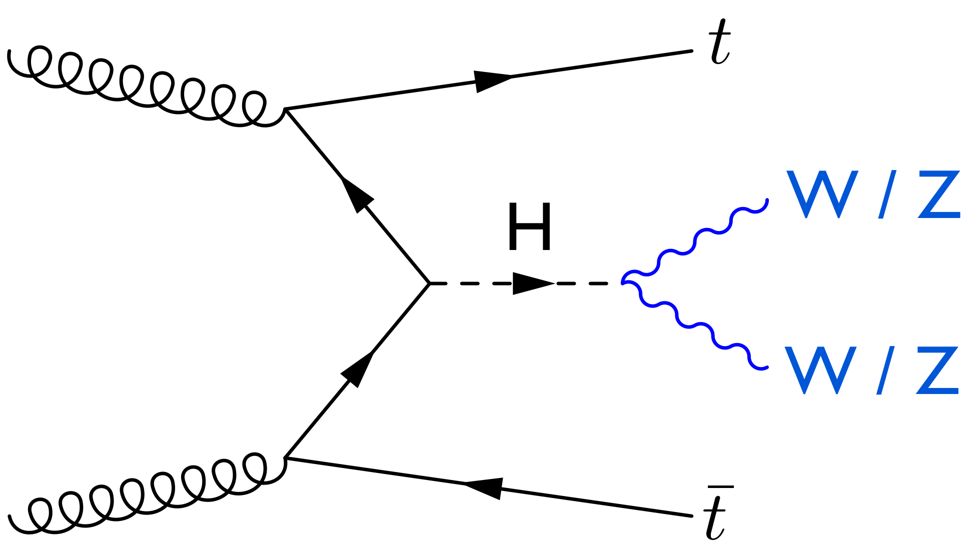


- Small branching ratio, 0.2%.
- Higgs boson can be reconstructed as a narrow peak.
- Backgrounds from ttbar+photons and QCD multi-photon / jet final states.

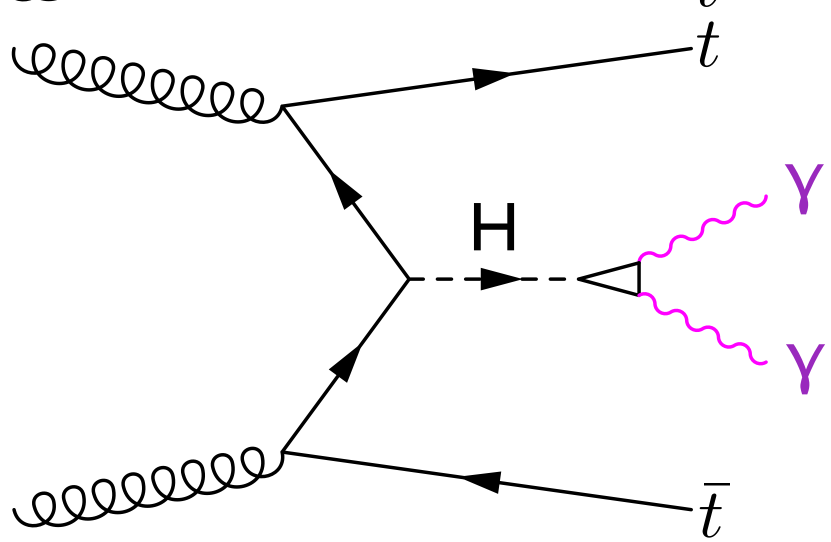
ttH Production & Decay



- Largest branching ratio, 58%.
- Final state with multiple b-quarks - challenging to reconstruct Higgs.
- Large background from ttbar + jets.

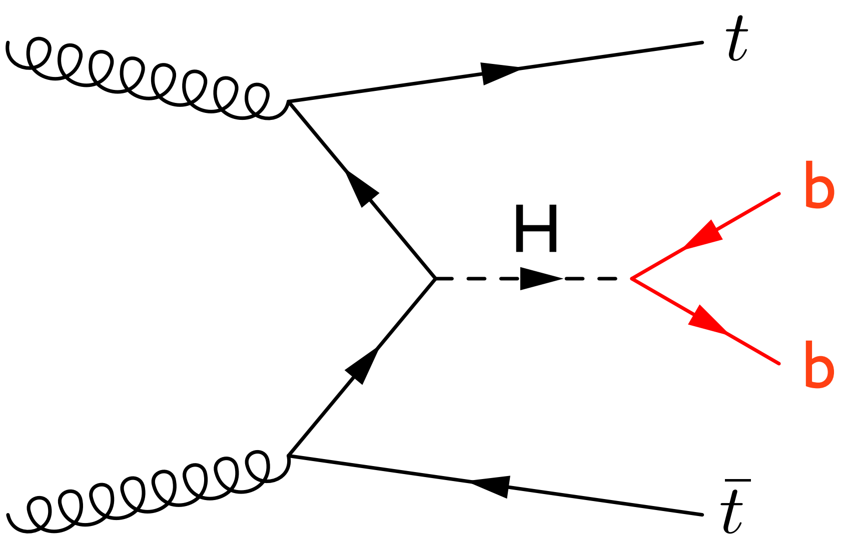


- Significant branching ratio, Br(H→WW) = 22%.
- Leptonic decays of W / Z bosons and tau decays can give distinct multi-lepton signatures, but difficult to reconstruct Higgs.
- Main background from ttbar+W/Z and non-prompt leptons.

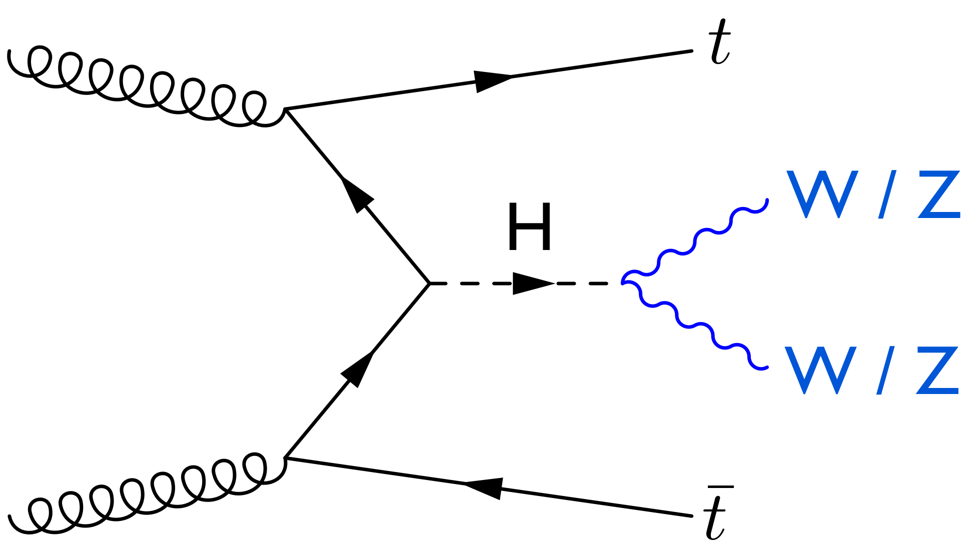


- Small branching ratio, 0.2%.
- Higgs boson can be reconstructed as a narrow peak.
- Backgrounds from ttbar+photons and QCD multi-photon / jet final states.

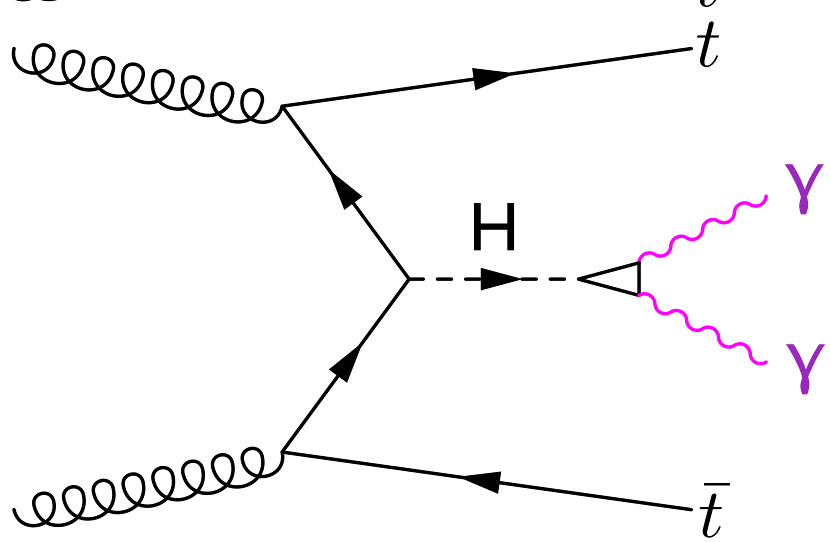
ttH Production & Decay



- Largest branching ratio, 58%.
- Final state with multiple b-quarks - challenging to reconstruct Higgs.
- Large background from ttbar + jets.



- Significant branching ratio, Br(H→WW) = 22%.
- Leptonic decays of W / Z bosons and tau decays can give distinct multi-lepton signatures, but difficult to reconstruct Higgs.
- Main background from ttbar+W/Z and non-prompt leptons.



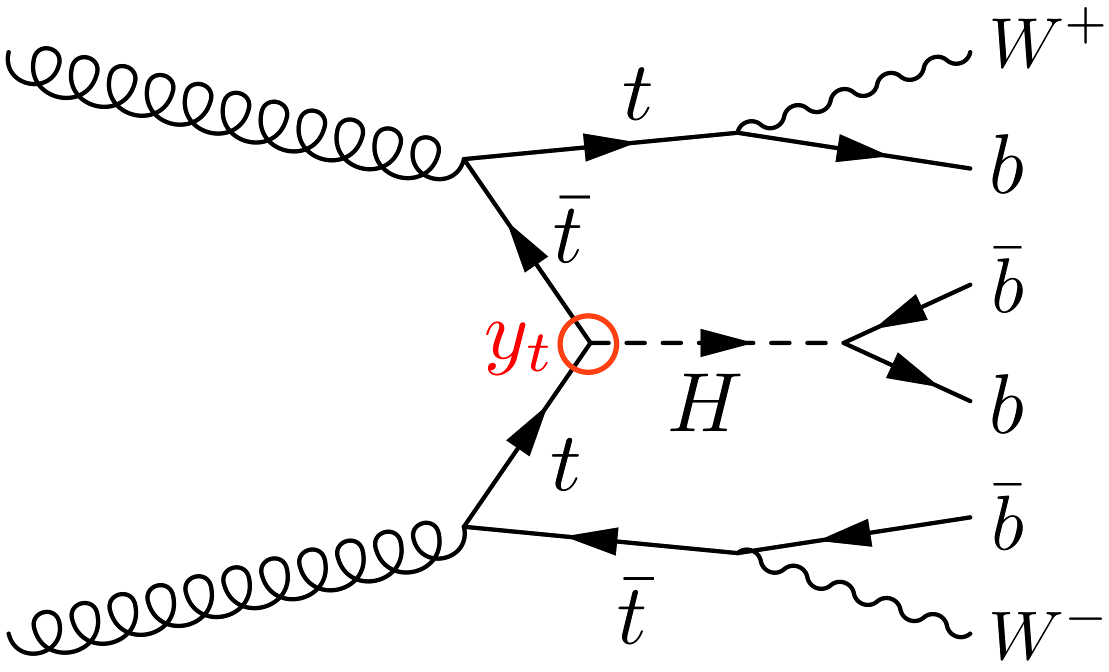
- Small branching ratio, 0.2%.
- Higgs boson can be reconstructed as a narrow peak.
- Backgrounds from ttbar+photons and QCD multi-photon / jet final states.

CMS also searches for $\tau_h\tau_h$, but will not discuss details today

ttH; H→bb

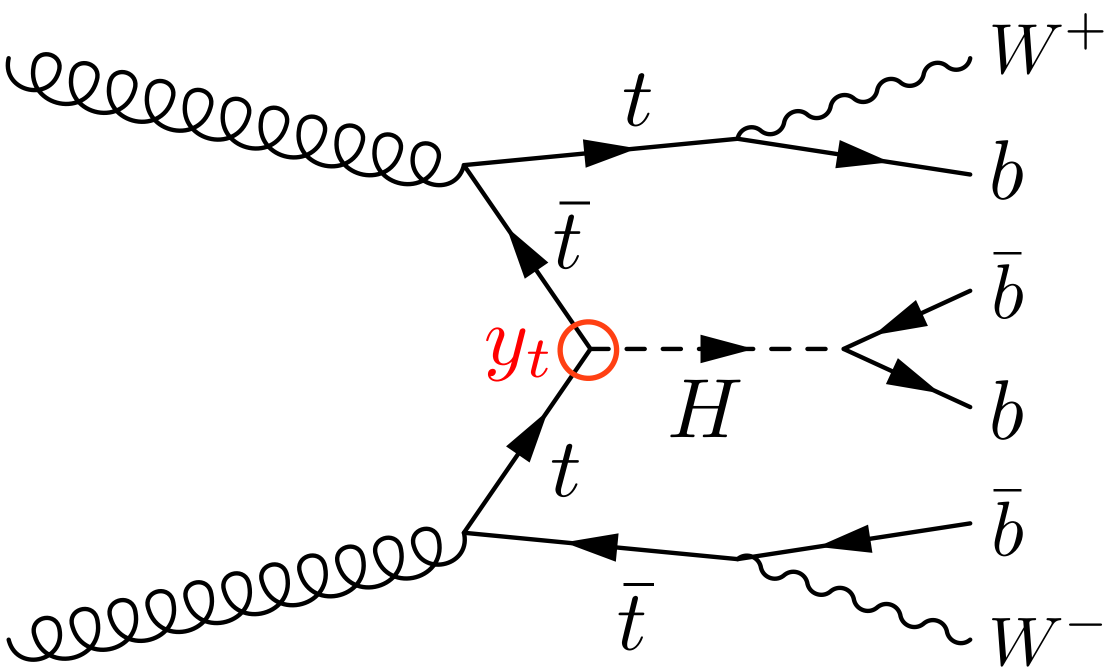
ATLAS: ATLAS-CONF-2014-011
CMS: arXiv:1408.1682, CMS-PAS-HIG-14-010

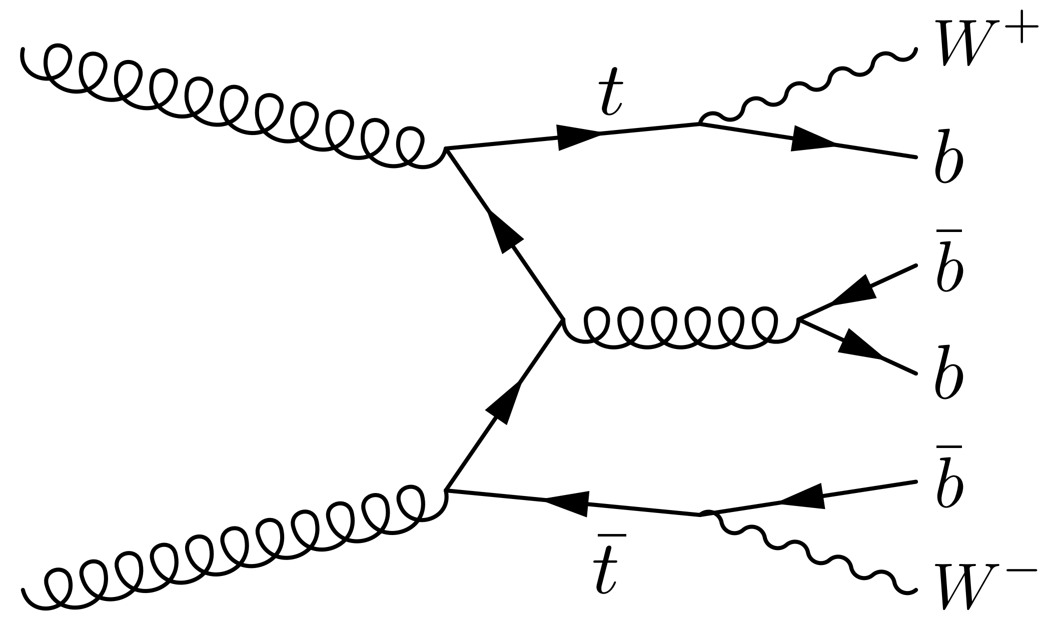
Backgrounds



- Background from ttbar+jets estimated using MC, corrected to match differential ttbar measurements.
- Classification is done using truth level information, small differences CMS / ATLAS:

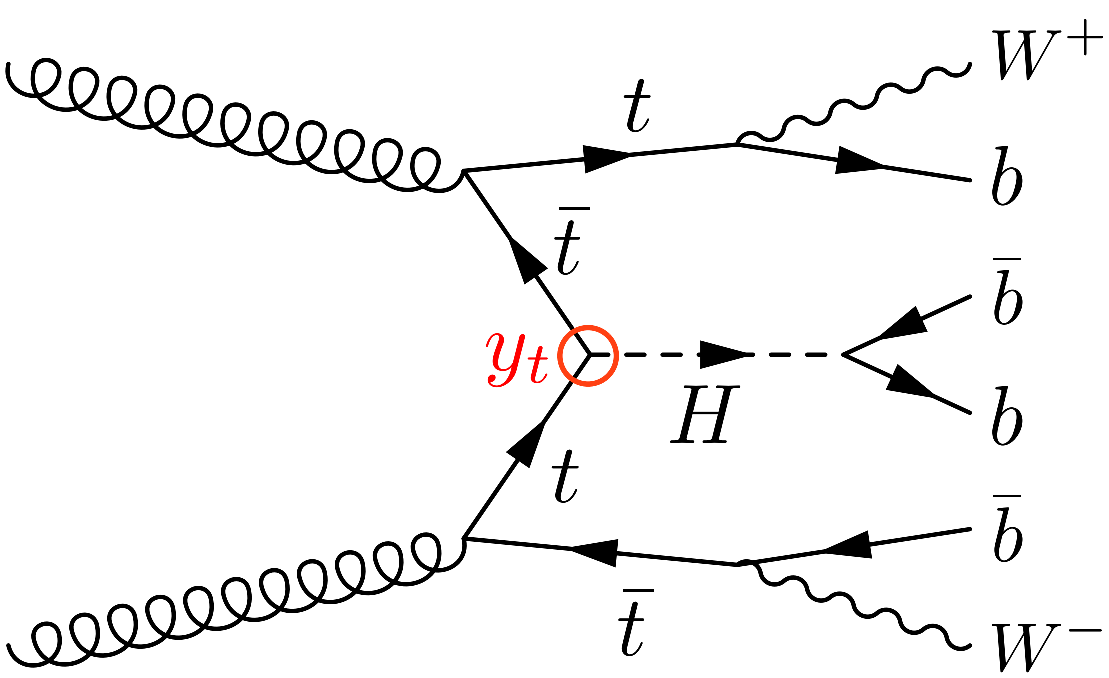
Backgrounds

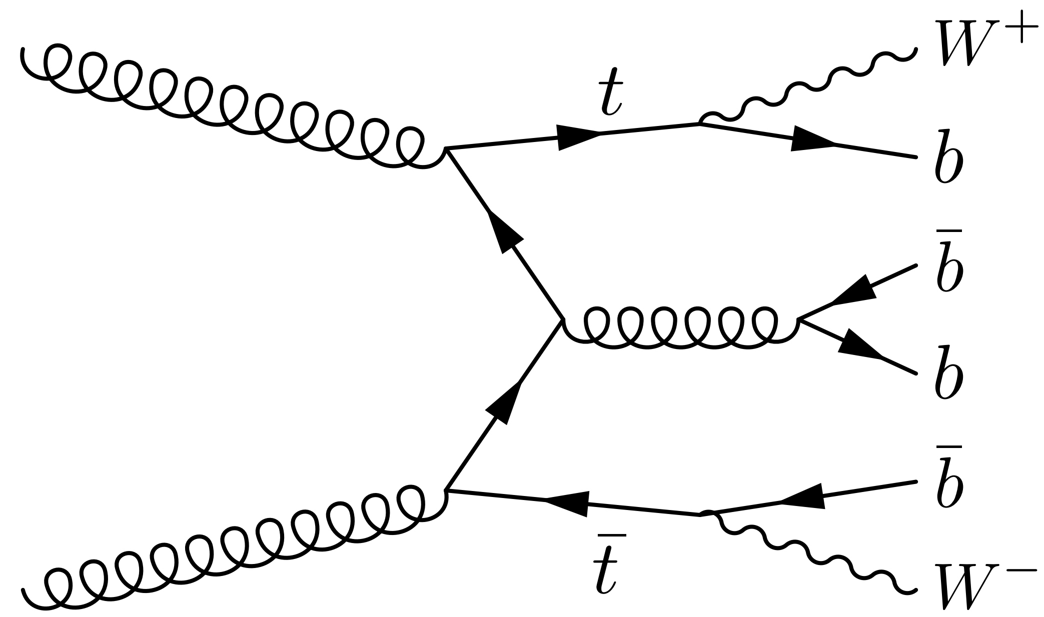


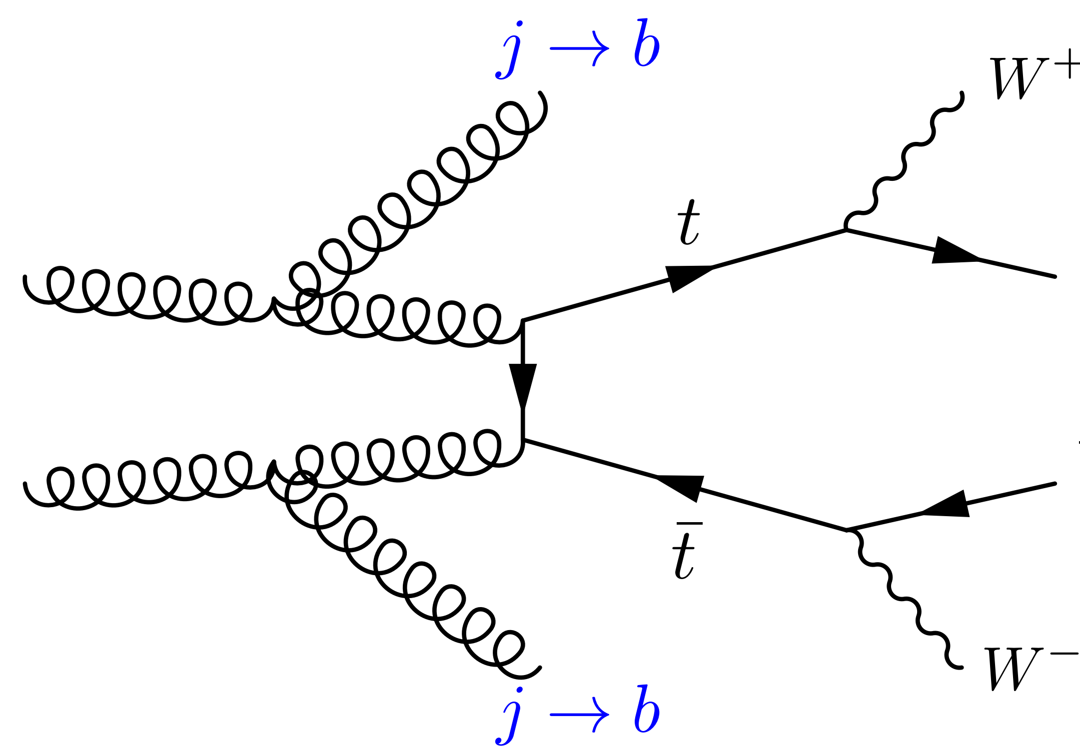


- Background from ttbar+jets estimated using MC, corrected to match differential ttbar measurements.
- Classification is done using truth level information, small differences CMS / ATLAS:

Backgrounds

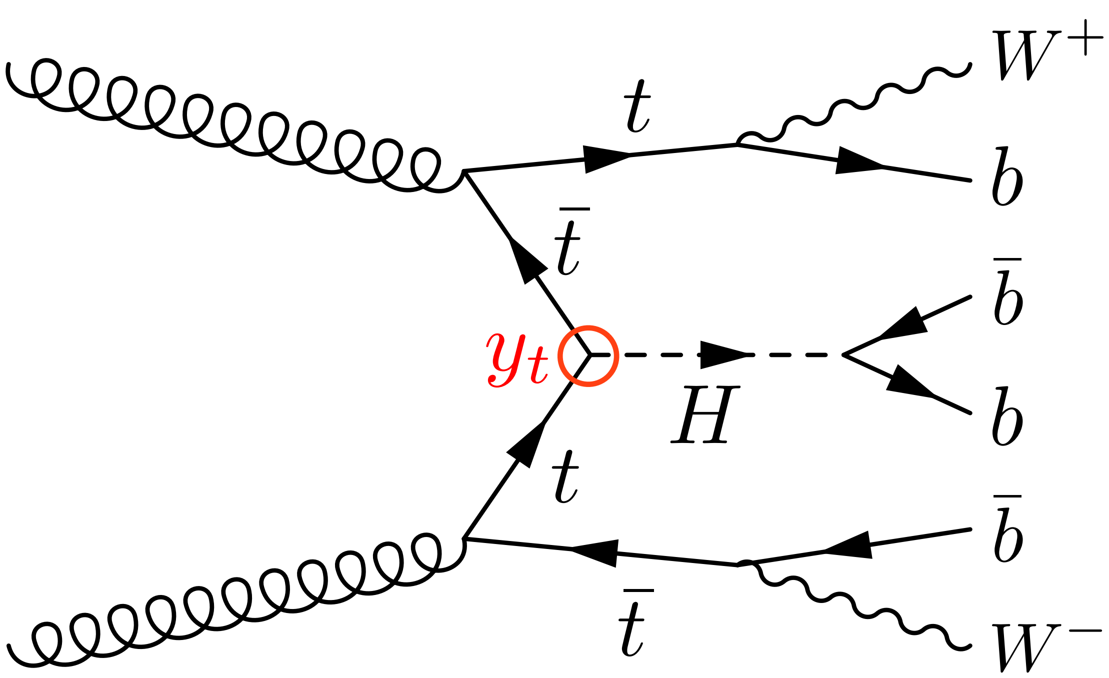


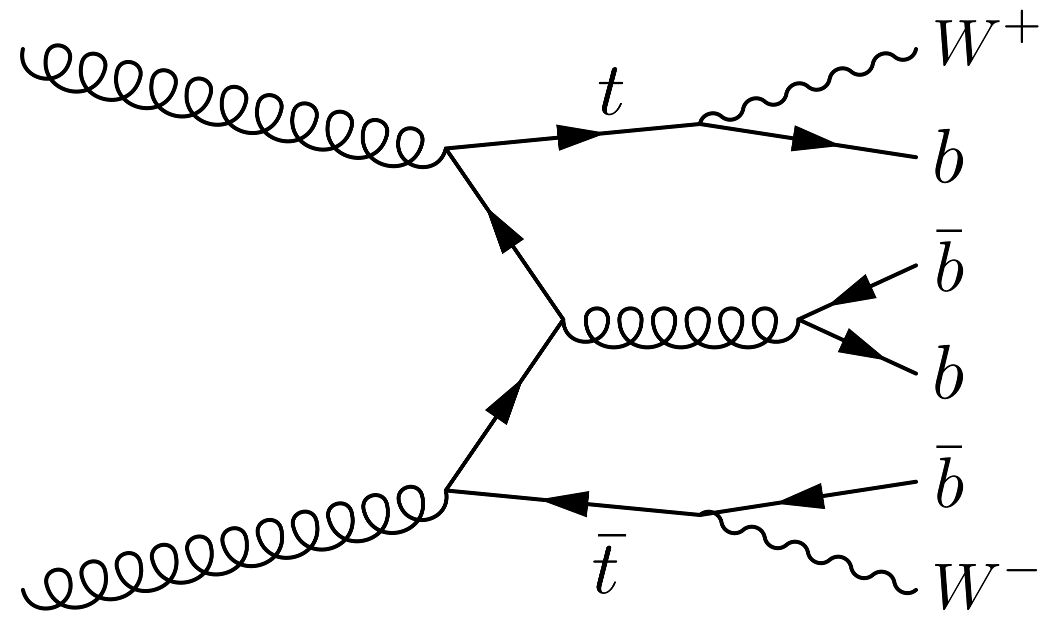


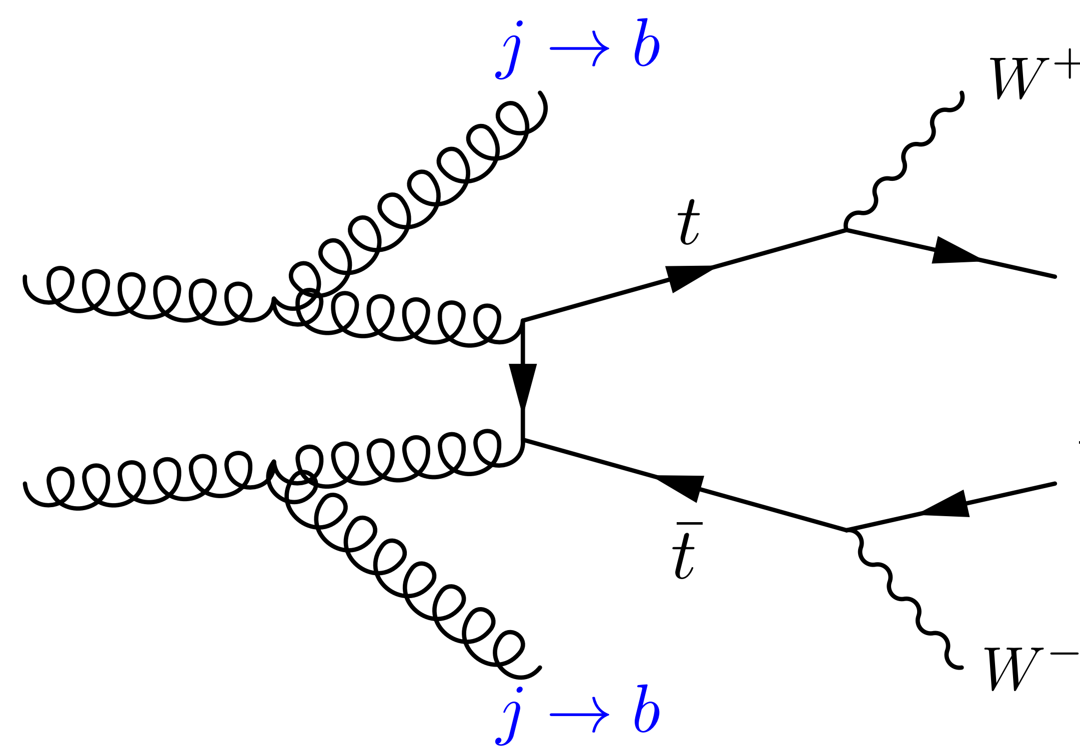


- Background from ttbar+jets estimated using MC, corrected to match differential ttbar measurements.
- Classification is done using truth level information, small differences CMS / ATLAS:

Backgrounds







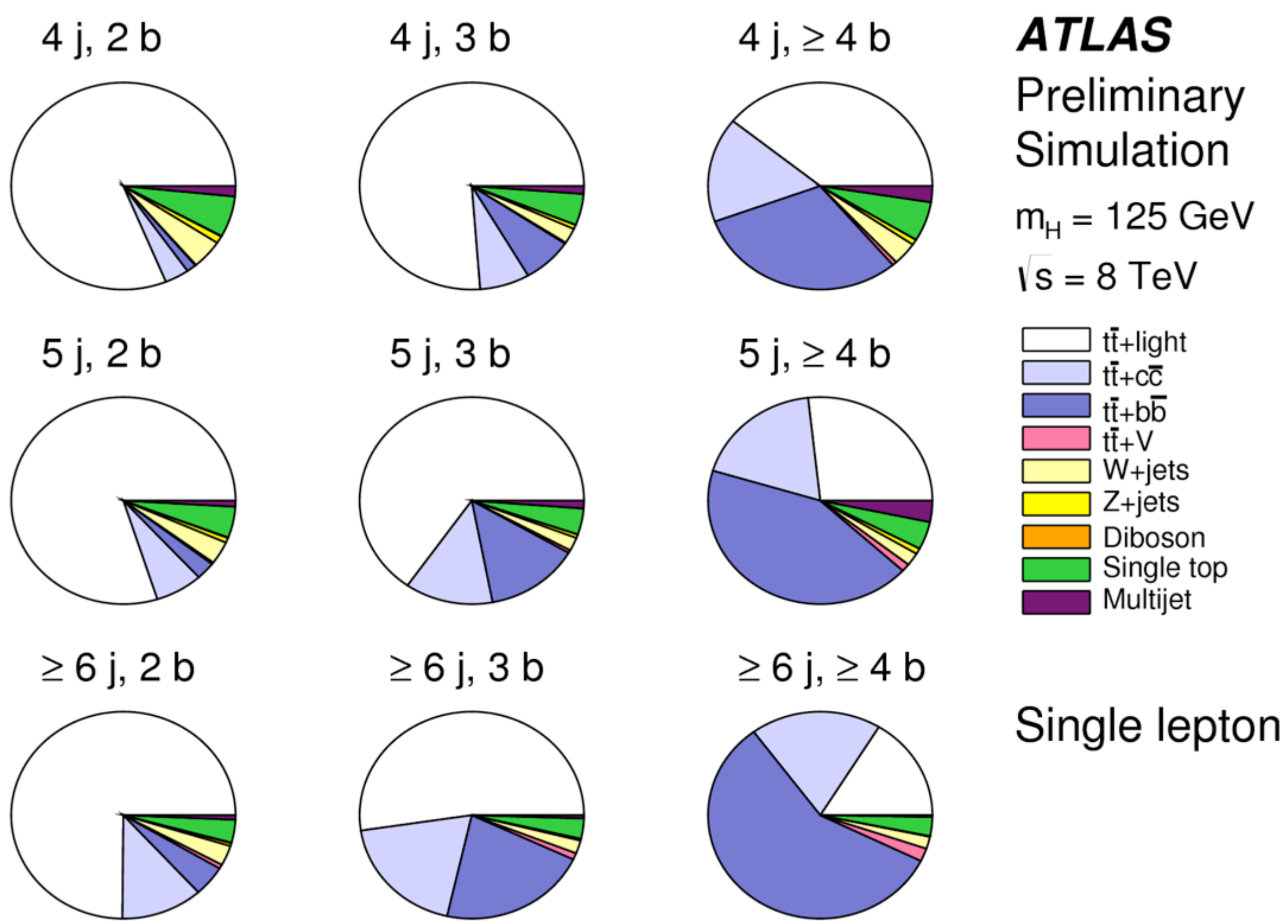
- Background from ttbar+jets estimated using MC, corrected to match differential ttbar measurements.
- Classification is done using truth level information, small differences CMS / ATLAS:

CMS	$t\bar{t} + b\bar{b}$	$t\bar{t} + b$	$t\bar{t} + c(\bar{c})$	$t\bar{t}$ + light
ATLAS	$t\bar{t} + b(\bar{b})$		$t\bar{t} + c(\bar{c})$	$t\bar{t}$ + light

Event Selection

- Events are split according to ttbar decay mode, lepton +jets or dilepton.
- Events are then further sub-divided into how many jets and b-jets are reconstructed in the events.
  - Signal peaks at high n(j) & n(b), but signal in lower bins due to jets out of acceptance and b-tag efficiency (~70% per b-jet).
  - Background fractions vary significantly with n(j) and n(b).
  - Lower n(j) and n(b) regions used to constrain backgrounds and systematic uncertainties.

Lepton+jets Channels

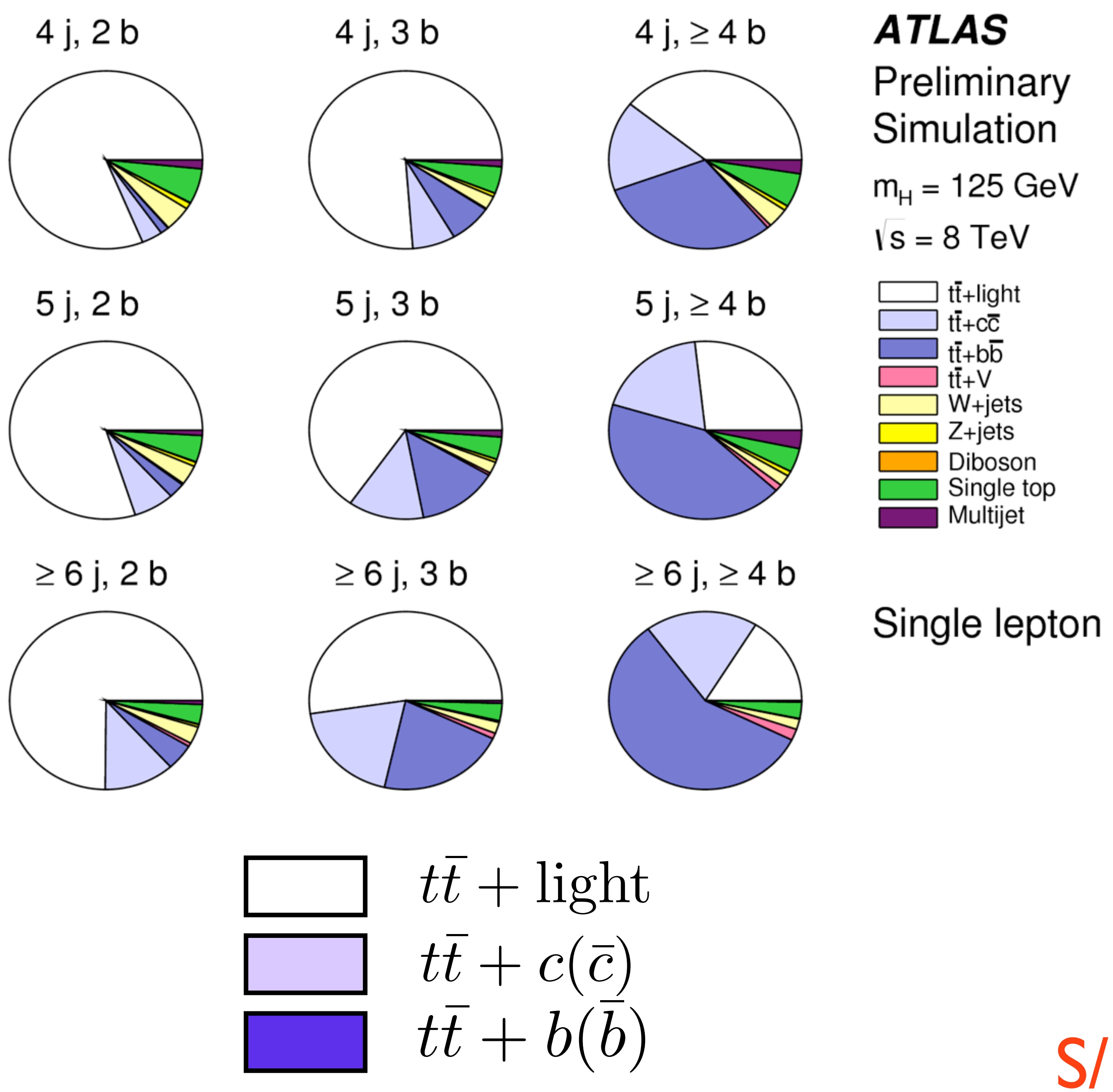


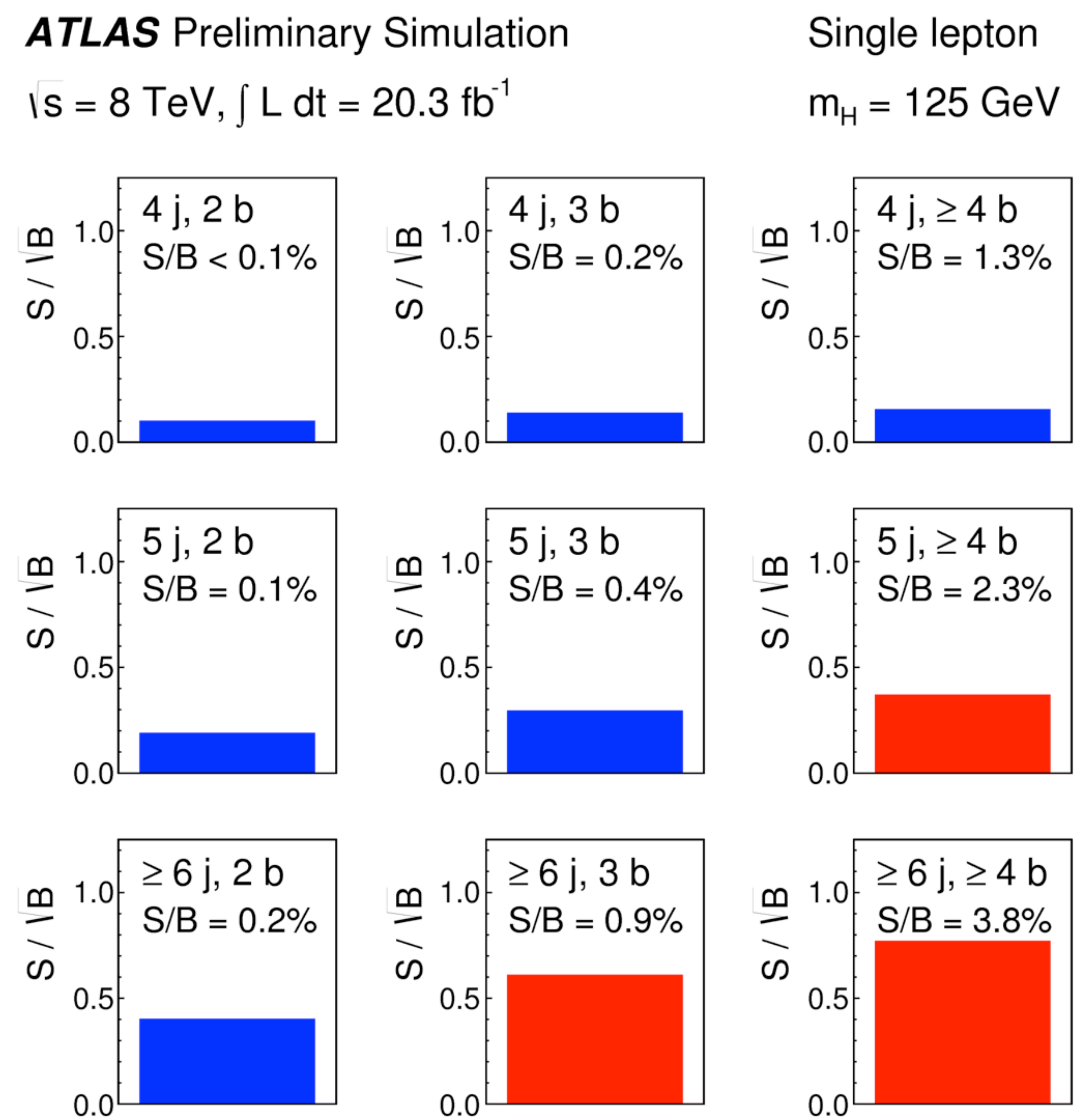
$t\bar{t} + \mathrm{light}$

$t\bar{t} + c(\bar{c})$

$t\bar{t} + b(\bar{b})$

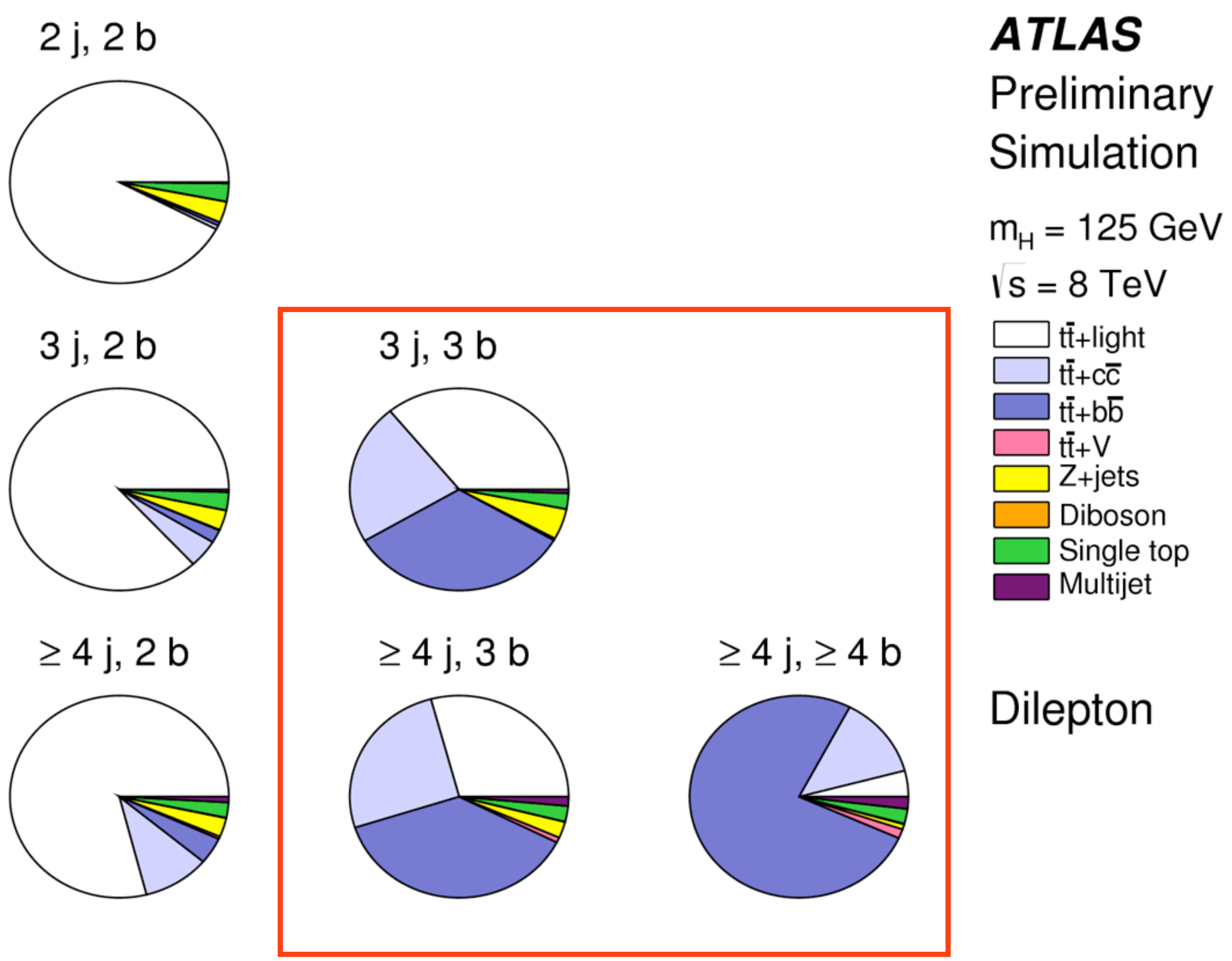
Lepton+jets Channels





S/B small - need good separation between signal and background.

Dilepton Channels



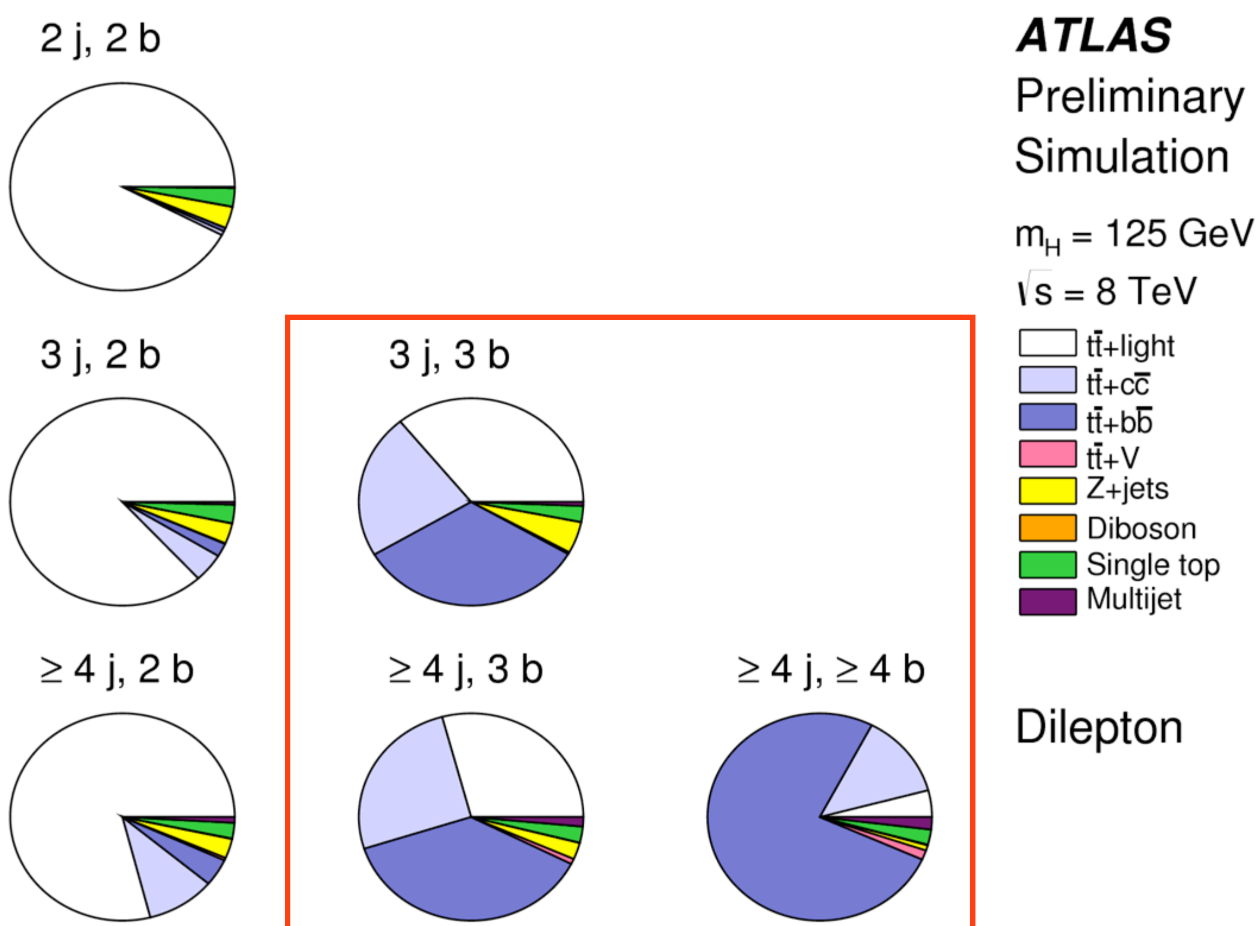
Single channel for CMS

$t\bar{t}$ + light

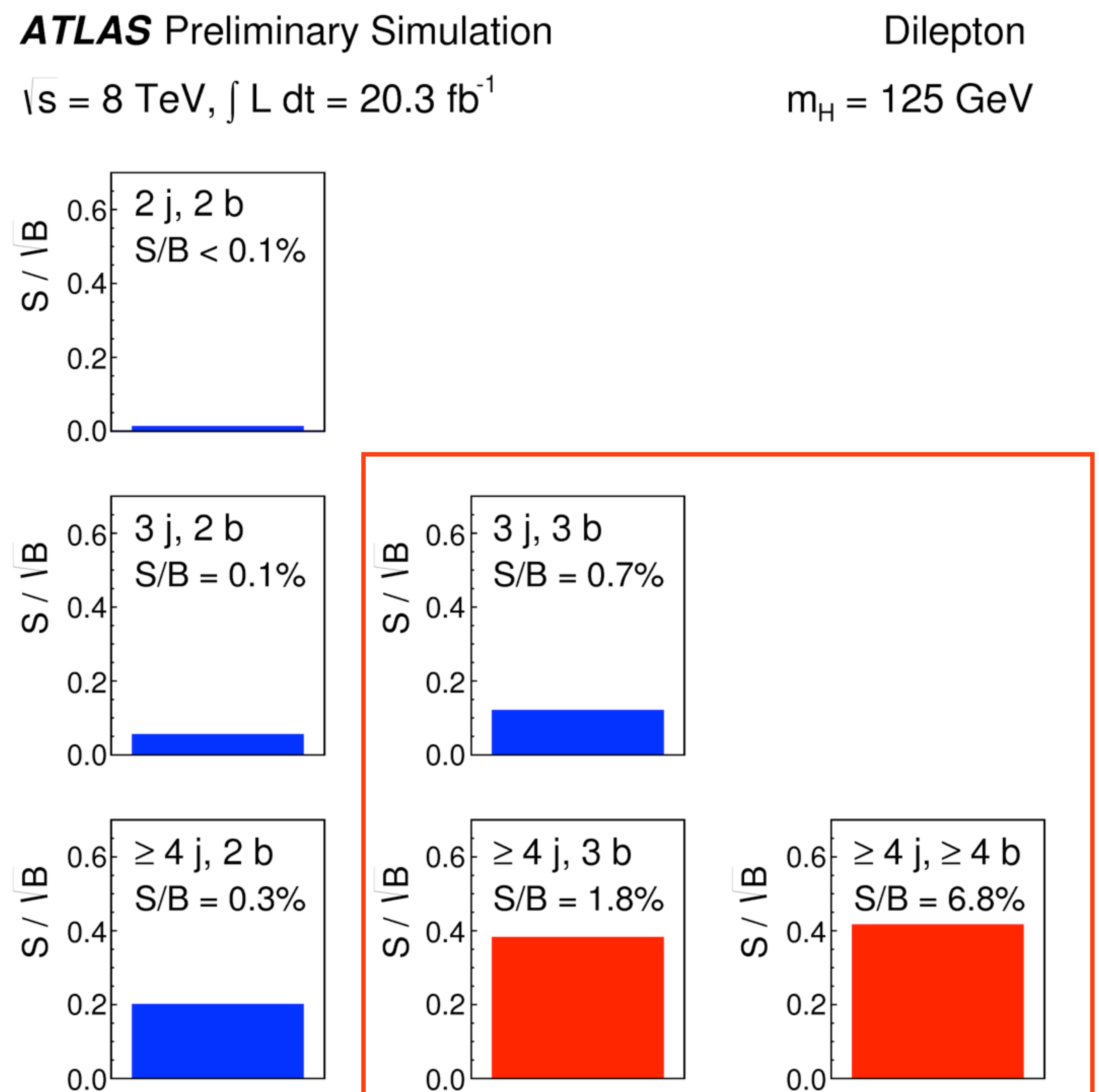
$t\bar{t} + c(\bar{c})$

$t\bar{t} + b(\bar{b})$

Dilepton Channels



Single channel for CMS



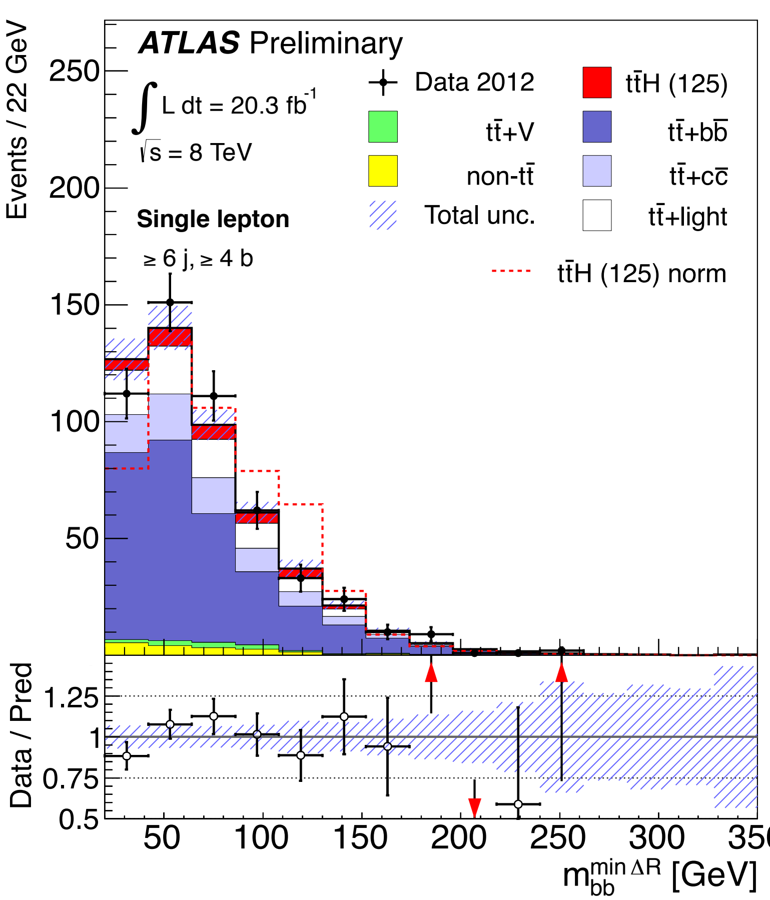
$t\bar{t} + \mathrm{light}$

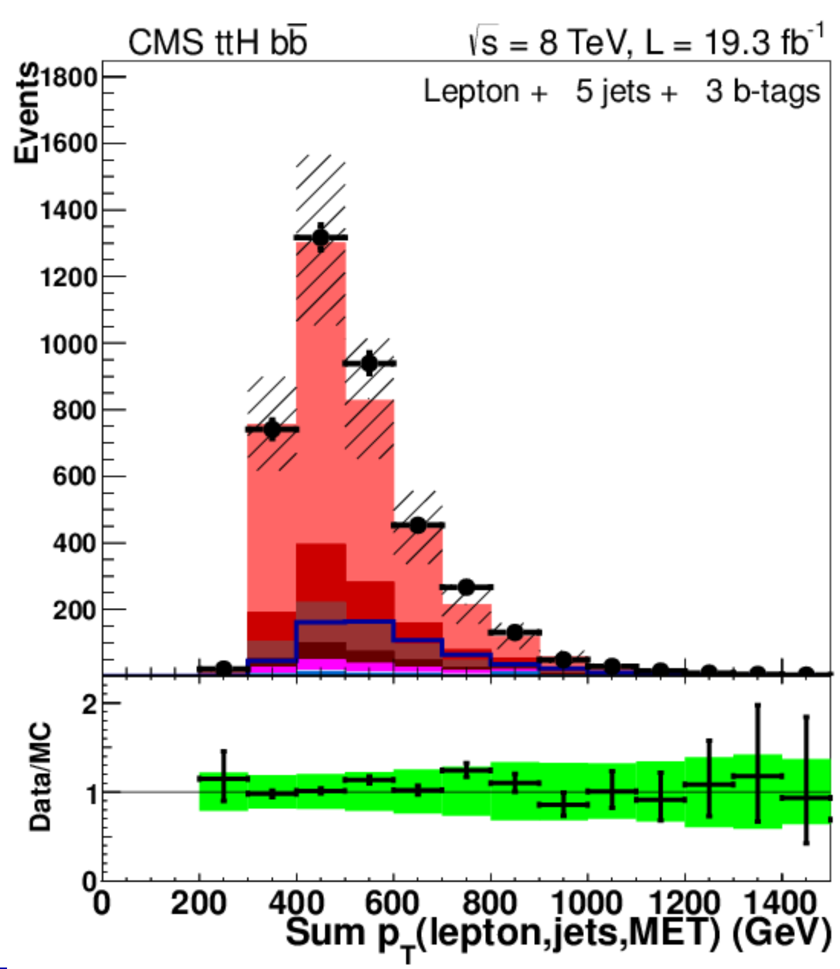
$t\bar{t} + c(\bar{c})$

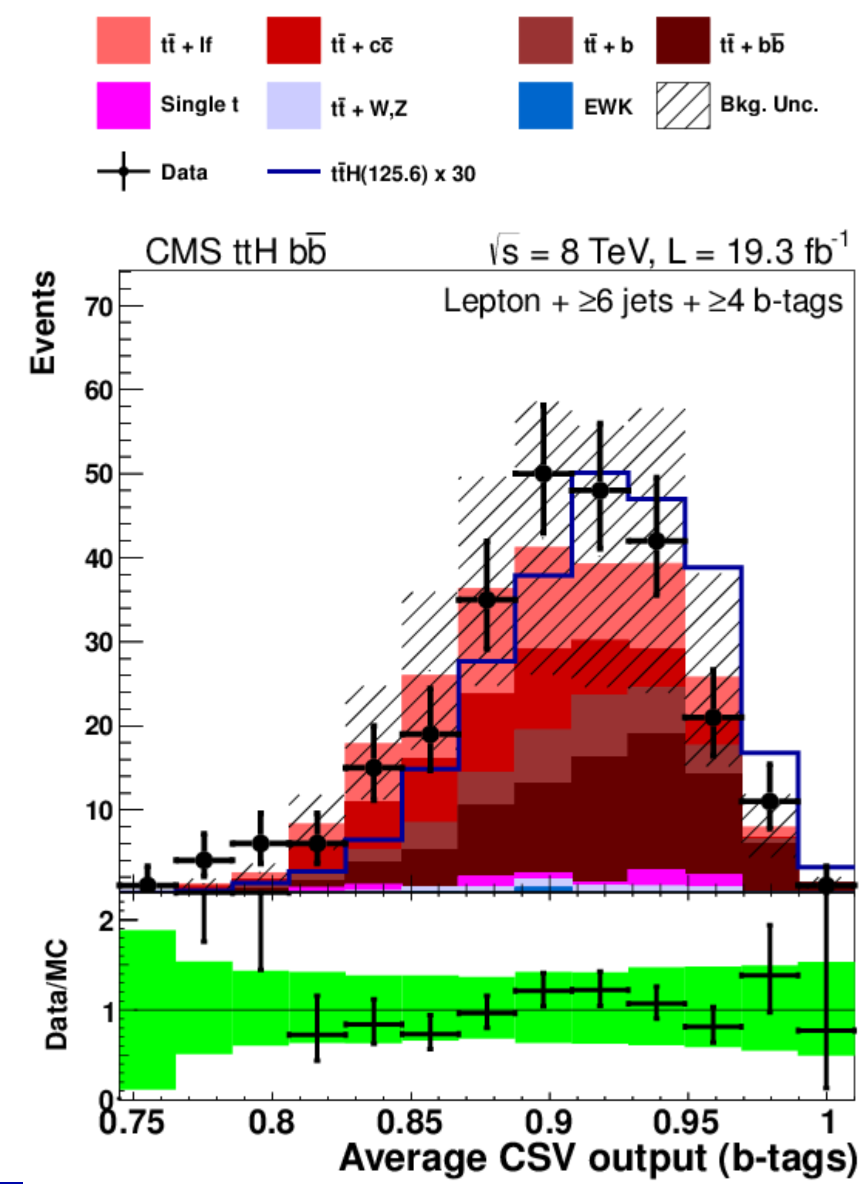
$t\bar{t} + b(\bar{b})$

Multivariate Analysis

- Use Multivariate analysis to separate signal from background - BDT for CMS, NN for ATLAS.
  - ATLAS uses only kinematic variables, CMS adds b-tagging variables.
- Example input variables:







Systematic Uncertainties

- All systematics included in fit as nuisance parameters - can change shape and normalization of background / signal.
- Important experimental systematic uncertainties - with ranking of impact on the uncertainty of final ATLAS result:
    - Calibration of b-tagging:
        - Efficiency to select b-jets, mis-tag rate for c-jets, mis-tag rate for light jets.

          11th & 15th   10th & 12th   2nd & 7th
    - JES 13th
- Most important systematics are on ttbar background model - next slide.

ttbar Model Uncertainties

	ATLAS	CMS
Baseline Model	Powheg+Pythia, normalized to NNLO	Madgraph+Pythia, normalized to NNLO
Reweighting to differential cross section	top p_T and ttbar p_T	top p_T
Model uncertainty	Vary reweighting (9 comps.) Pythia vs Herwig	Vary reweighting Vary scales in MC
Additional heavy flavour modelling uncertainty	On/off reweighting, uncorrelated with ttbar + light jets Vary scales in Madgraph+Pythia Compare Madgraph+Pythia to Powheg+Pythia	Scale variations are uncorrelated between ttbar + light / c / b / bb
Additional heavy flavour normalization uncertainty	$t\bar{t} + b(\bar{b}) : 50\%$ $t\bar{t} + c(\bar{c}) : 50\%$	$t\bar{t} + b\bar{b} : 50\%$ $t\bar{t} + b : 50\%$ $t\bar{t} + c(\bar{c}) : 50\%$

ttbar Model Uncertainties

	ATLAS	CMS
Baseline Model	Powheg+Pythia, normalized to NNLO 8th	Madgraph+Pythia, normalized to NNLO
Reweighting to differential cross section	top p_T and ttbar p_T	top p_T
Model uncertainty	Vary reweighting (9 comps.) 4th Pythia vs Herwig	Vary reweighting Vary scales in MC
Additional heavy flavour modelling uncertainty	On/off reweighting, uncorrelated with ttbar + light jets 3rd & 9th Vary scales in Madgraph+Pythia Compare Madgraph+Pythia to Powheg+Pythia 6th	Scale variations are uncorrelated between ttbar + light / c / b / bb
Additional heavy flavour normalization uncertainty	$t\bar{t} + b(\bar{b}) : 50\%$ 1st $t\bar{t} + c(\bar{c}) : 50\%$ 5th	$t\bar{t} + b\bar{b} : 50\%$ $t\bar{t} + b : 50\%$ $t\bar{t} + c(\bar{c}) : 50\%$

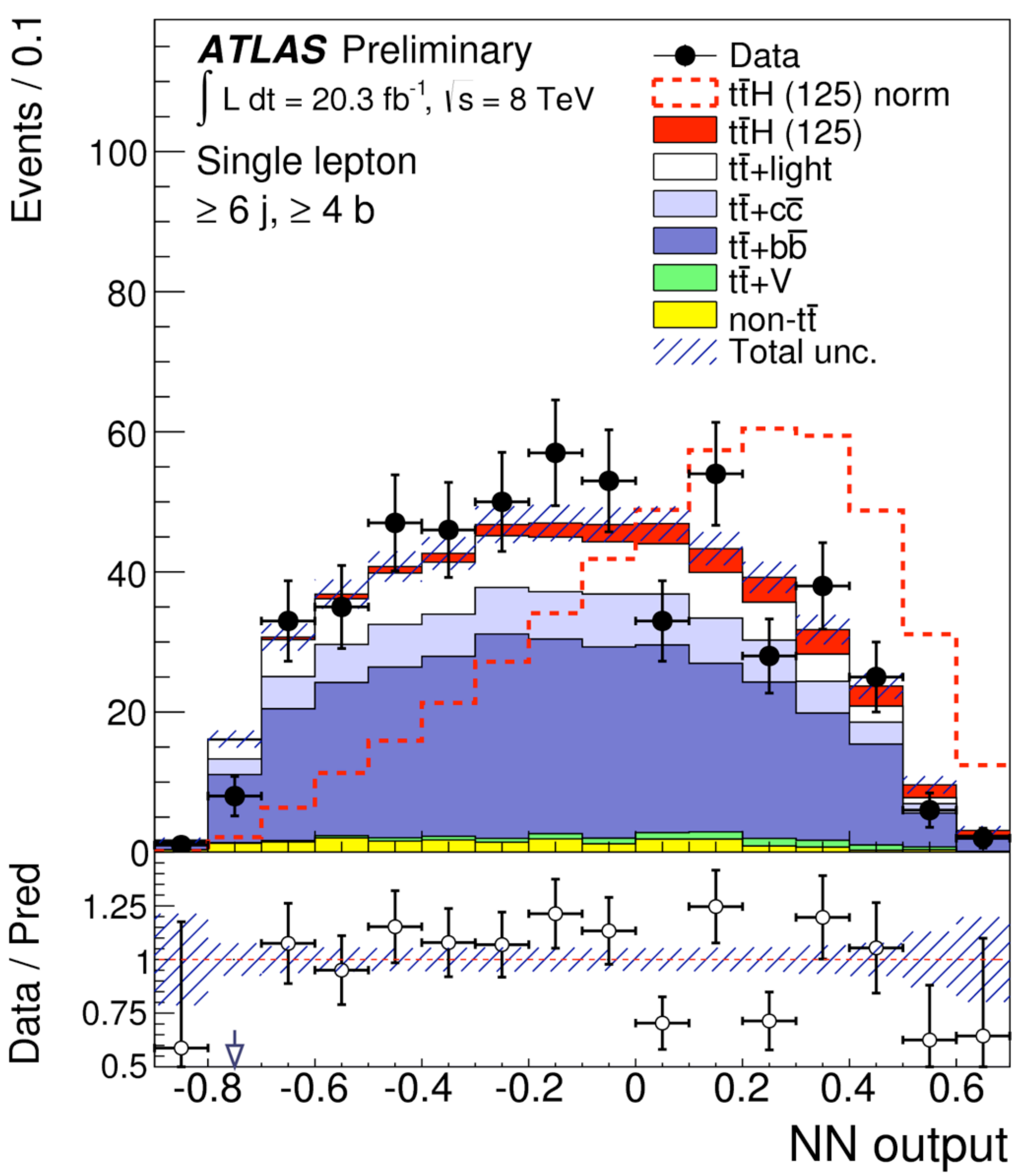
ttbar Model Uncertainties

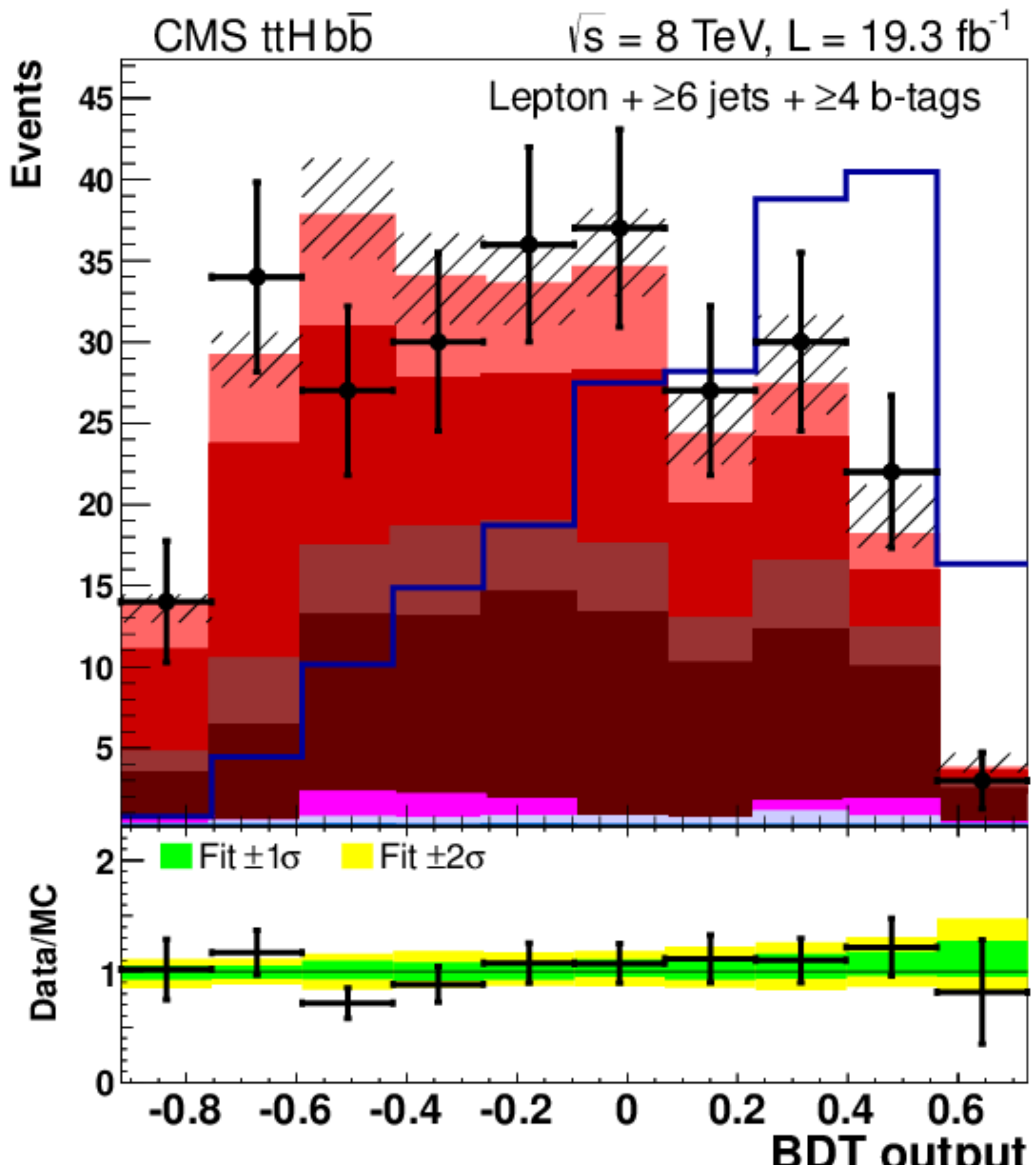
	ATLAS	CMS
Baseline Model	Powheg+Pythia, normalized to NNLO 8th	Madgraph+Pythia, normalized to NNLO
[illegible]	[illegible]	[illegible]
Model uncertainty	Pythia vs Herwig	Vary scales in MC
Additional heavy flavour modelling uncertainty	On/off reweighting, uncorrelated with ttbar + light jets 3rd & 9th Vary scales in Madgraph+Pythia Compare Madgraph+Pythia to Powheg+Pythia 6th	Scale variations are uncorrelated between ttbar + light / c / b / bb
Additional heavy flavour normalization uncertainty	$t\bar{t} + b(\bar{b})$: 50% 1st $t\bar{t} + c(\bar{c})$: 50% 5th	$t\bar{t} + b\bar{b}$: 50% $t\bar{t} + b$: 50% $t\bar{t} + c(\bar{c})$: 50%

Improved ttbar+jets model crucial to improve analysis.
Use NLO@multileg generators for Run 2?
Continue programme of differential cross section measurements.

Final Discriminants & Fit

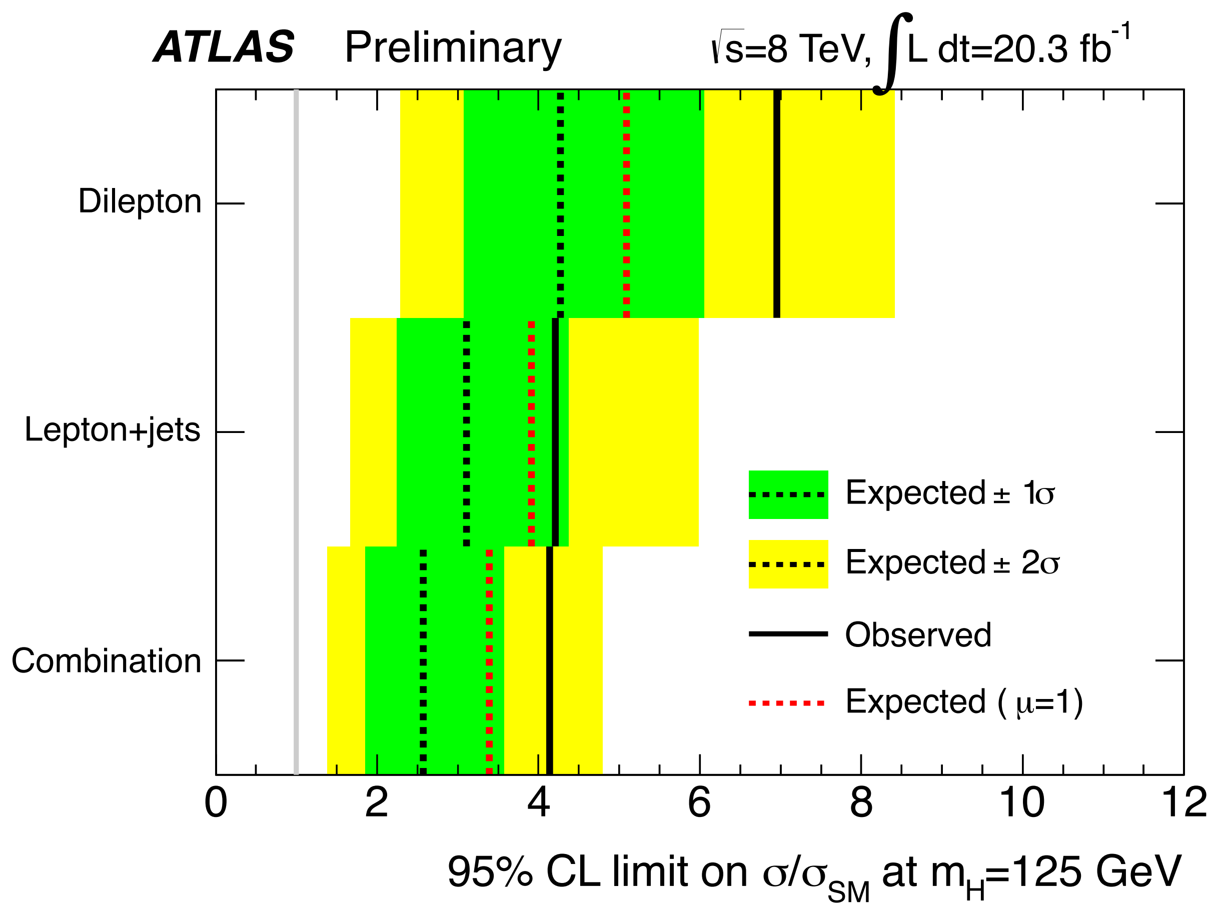
- Both experiments make combined fits to all channels.
- Low n(j), n(b) regions allow to constrain systematics.





Results

- Neither experiment observes a significant excess. Limits and best fit values are reported relative to the SM expectation.



CMS:

Expected limit (no ttH): 3.5
Expected limit (SM ttH): 5.0
Observed limit: 4.1

Fitted σ/σ_{SM} = 2.9±2.3

Fitted σ/σ_{SM} = 0.7±1.9

CMS Matrix Element

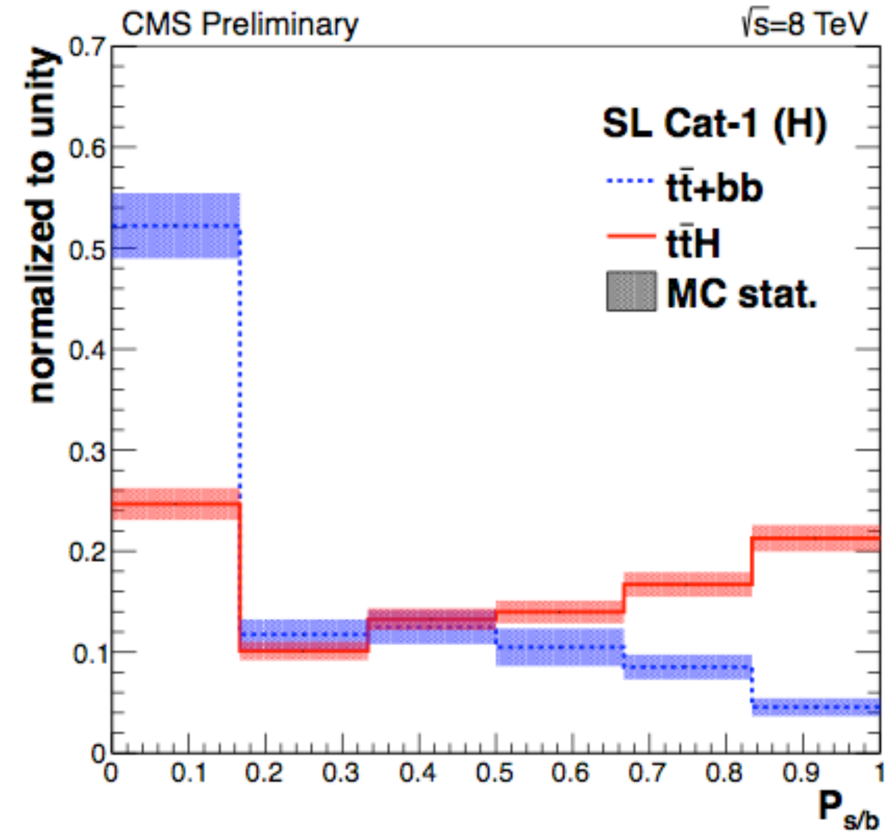
See Slava's talk for ME introduction

- Alternate analysis from CMS - use matrix elements for ttH and ttbar+bbbar to calculate weights w_S and w_B.
- Add b-tagging information ($\mathcal{L}$) to help separate ttbar+jets:

$$\mathcal{P}_S(\mathbf{y},\xi) \equiv w_S(\mathbf{y})\,\mathcal{L}_{bbbb}(\xi)$$
$$\mathcal{P}_{B_1}(\mathbf{y},\xi) \equiv w_B(\mathbf{y})\,\mathcal{L}_{bbbb}(\xi)$$
$$\mathcal{P}_{B_2}(\mathbf{y},\xi) \equiv w_B(\mathbf{y})\,\mathcal{L}_{bbjj}(\xi)$$

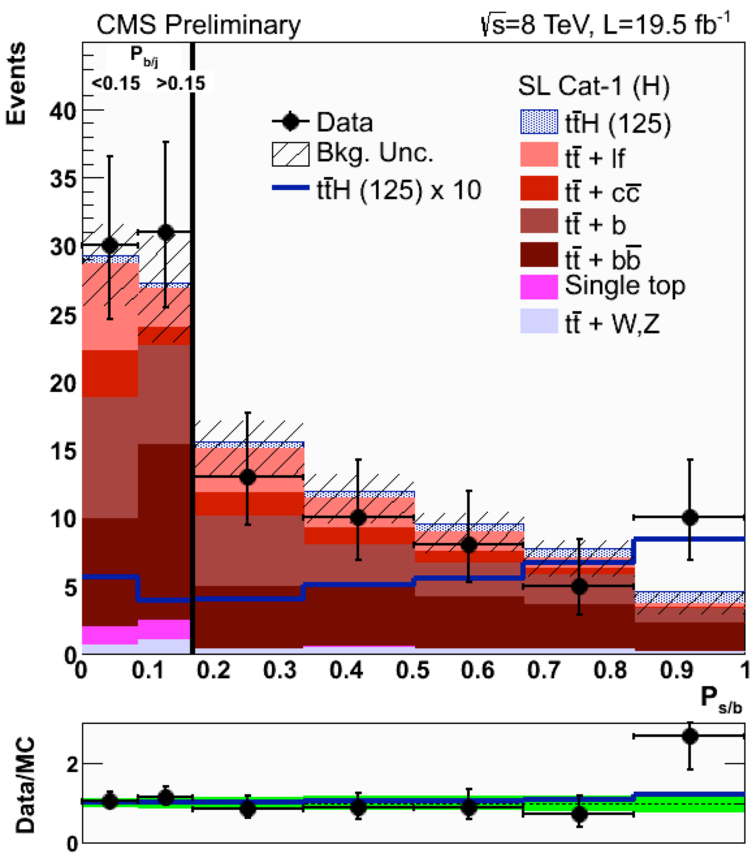
$$P_{s/b} = \frac{\mathcal{P}_S}{\mathcal{P}_S + \lambda_{b/j}\mathcal{P}_{B_1} + (1-\lambda_{b/j})\mathcal{P}_{B_2}}$$

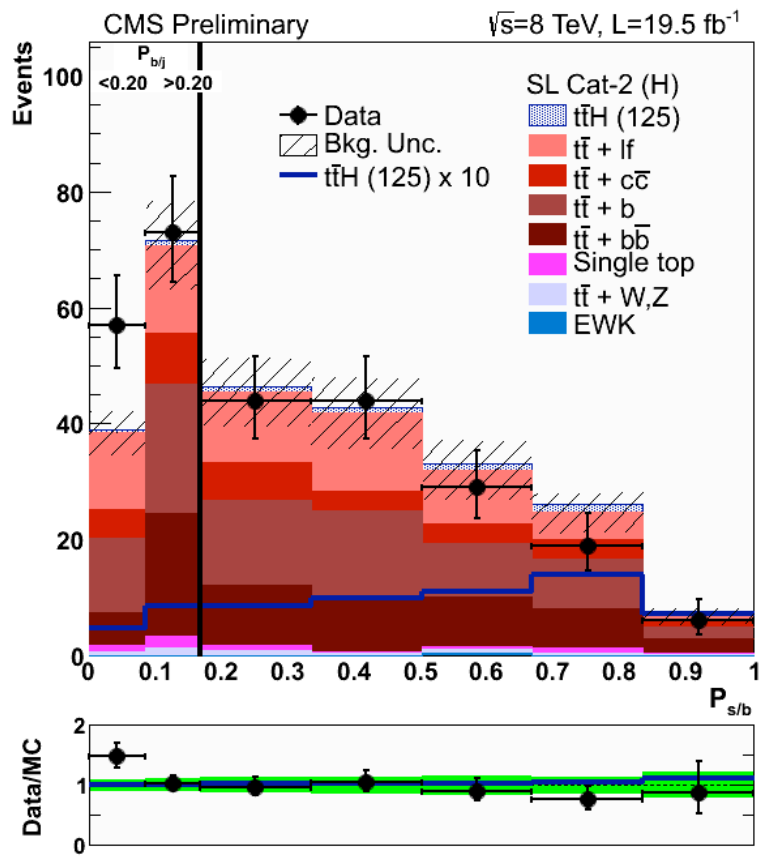
- Events additionally categorized based on n(jets) and b-tagging, and whether a dijet pair is close to m(W).

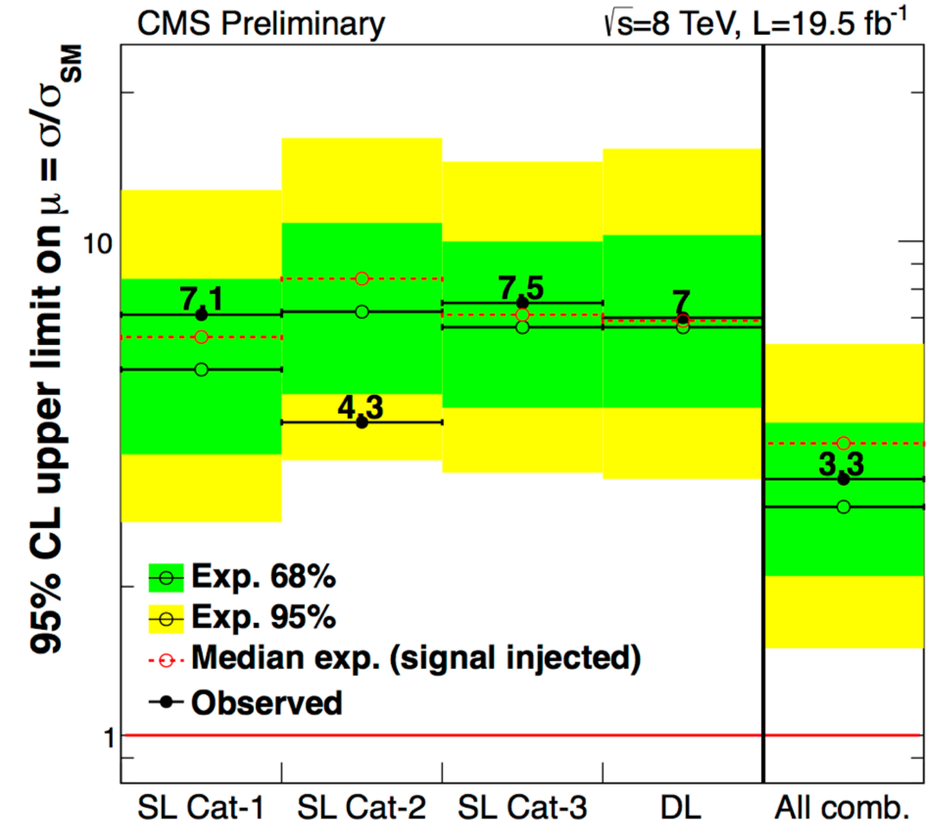


CMS Matrix Element

- Simultaneous fit to the discriminant in all the channels. No significant excess:







Fitted $\sigma/\sigma_{SM} = 0.7 \pm 1.3$

- Improvement over BDT analysis of 17% in expected limit. Demonstrates there is still potential to improve sensitivity!

ttH; H→γγ

ATLAS: arXiv:1409.3122 New!

CMS: arXiv:1408.1682

Selection Criteria

- Strategy - select two photons and apply loose requirements on jets to maximise signal acceptance.
- Two categories:
  - Hadronic: >= 4 jets 1 b-tag (CMS), >= 5(6) jets 2(1) b-tag (ATLAS)
  - Leptonic: >= 2 jets 1 b-tag (CMS), >= 1 jet 1 b-tag (ATLAS)

Category	N_H	ggF	VBF	WH	ZH	$t\bar{t}H$	$tHqb$	WtH (%)
7 TeV leptonic selection	0.10	0.6	0.1	14.9	4.0	72.6	5.3	2.5
7 TeV hadronic selection	0.07	10.5	1.3	1.3	1.4	80.9	2.6	1.9
8 TeV leptonic selection	0.58	1.0	0.2	8.1	2.3	80.3	5.6	2.6
8 TeV hadronic selection	0.49	7.3	1.0	0.7	1.3	84.2	3.4	2.1

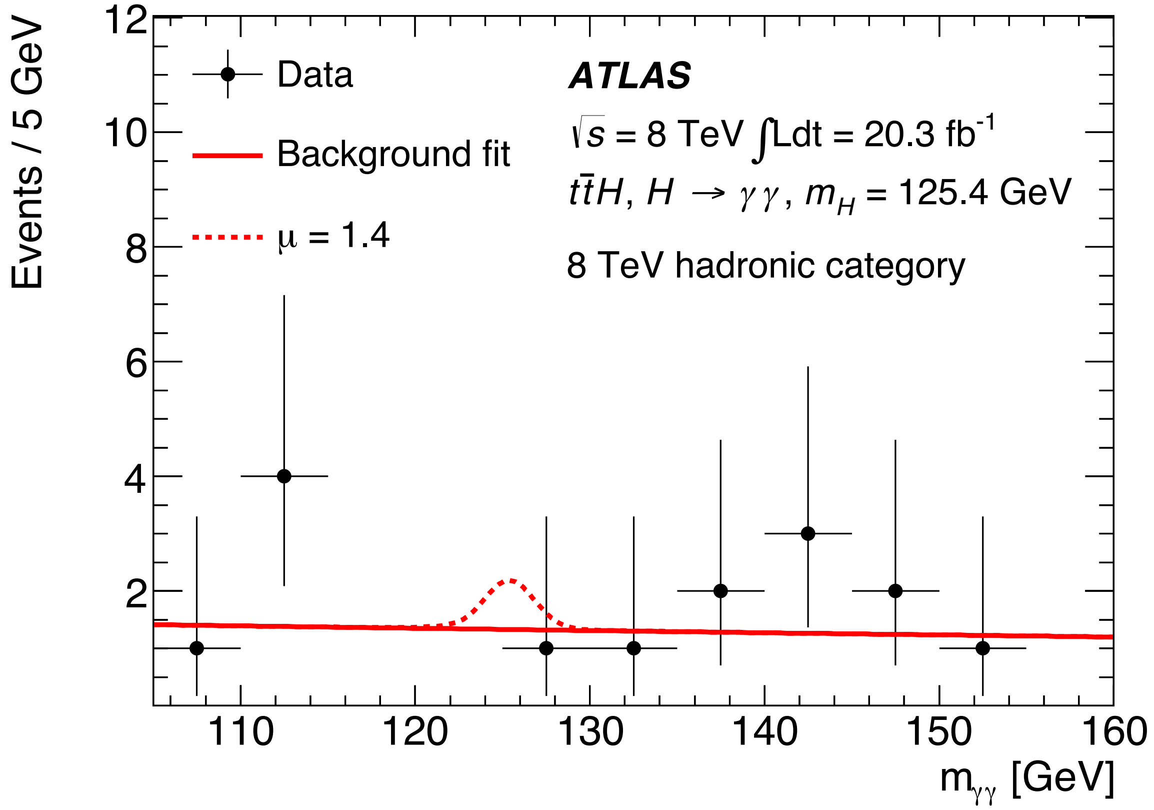
	7 TeV All decays	8 TeV Hadronic channel	8 TeV Leptonic channel
$t\bar{t}$H	0.21	0.51	0.45
gg $\rightarrow$ H	0.01	0.02	0
VBF H	0	0	0
WH/ZH	0.01	0.01	0.01

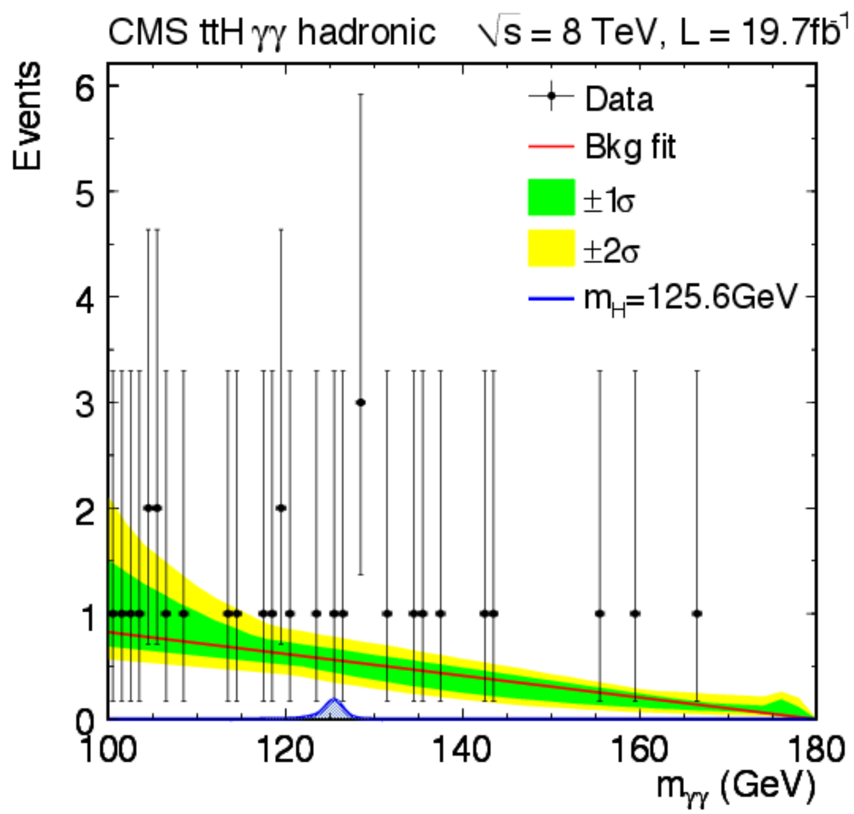
Slightly less ggH and VH contributions in CMS selections

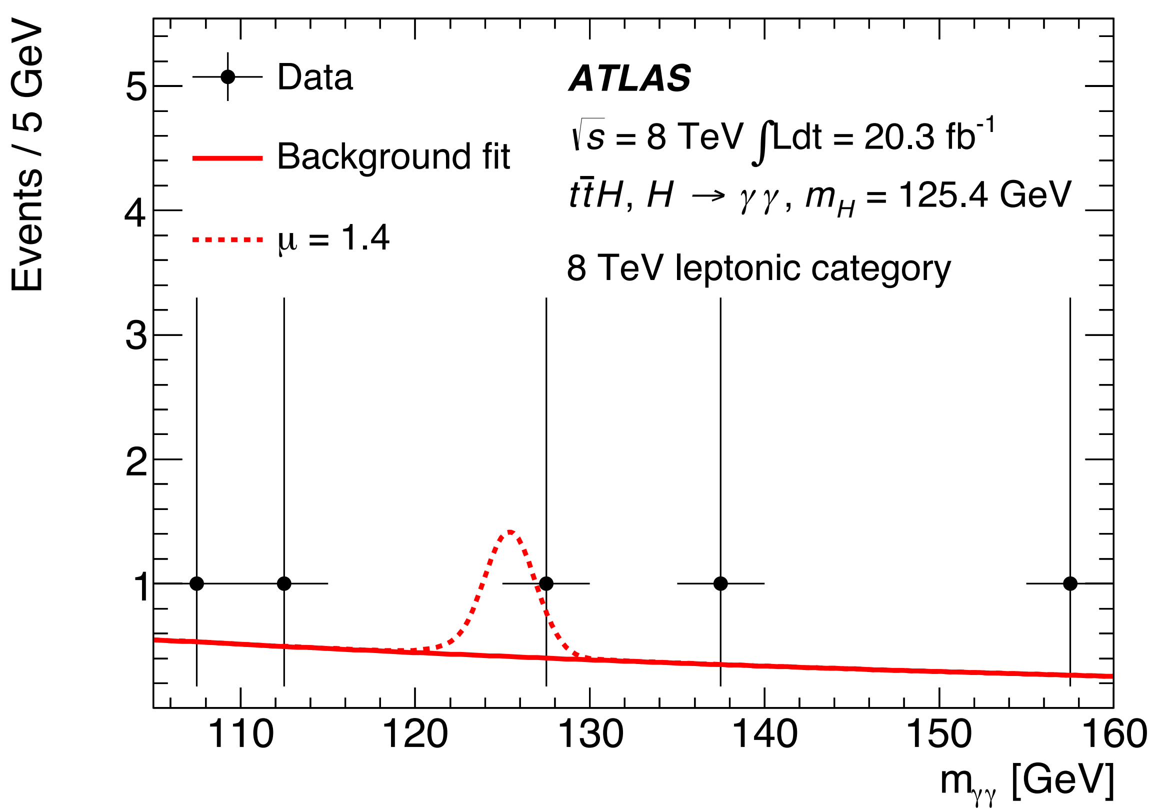
Background Estimate

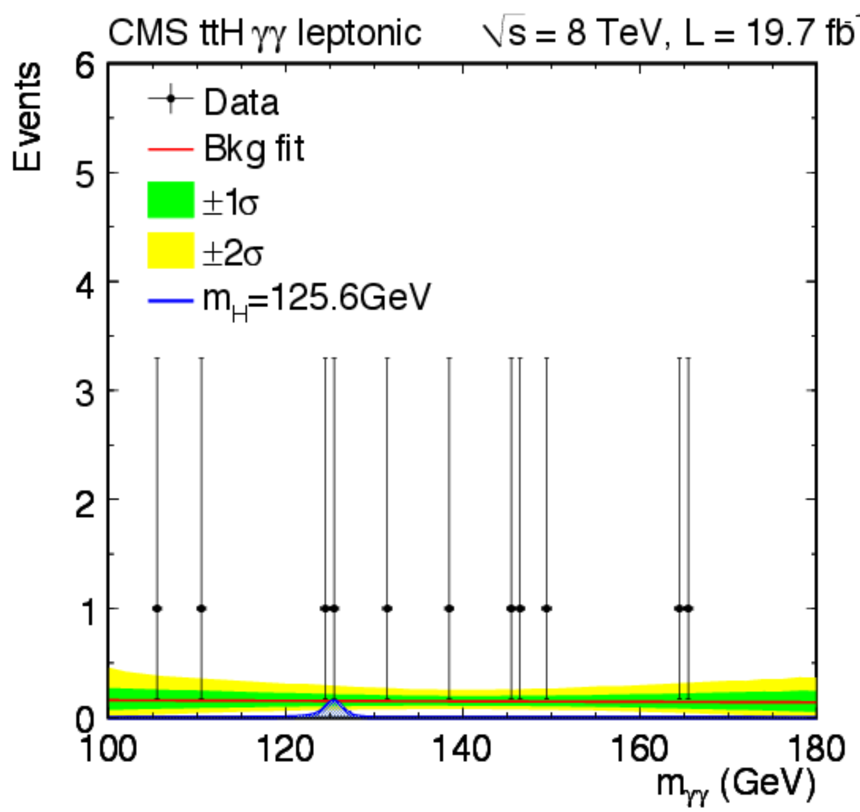
- Background estimate follows main diphoton analysis - smooth function for background & peak for signal.
  - ATLAS uses exponential function, CMS fit can use either exponential, power-law, polynomial or Laurent series - determined when fitting to the data.

Signal Region



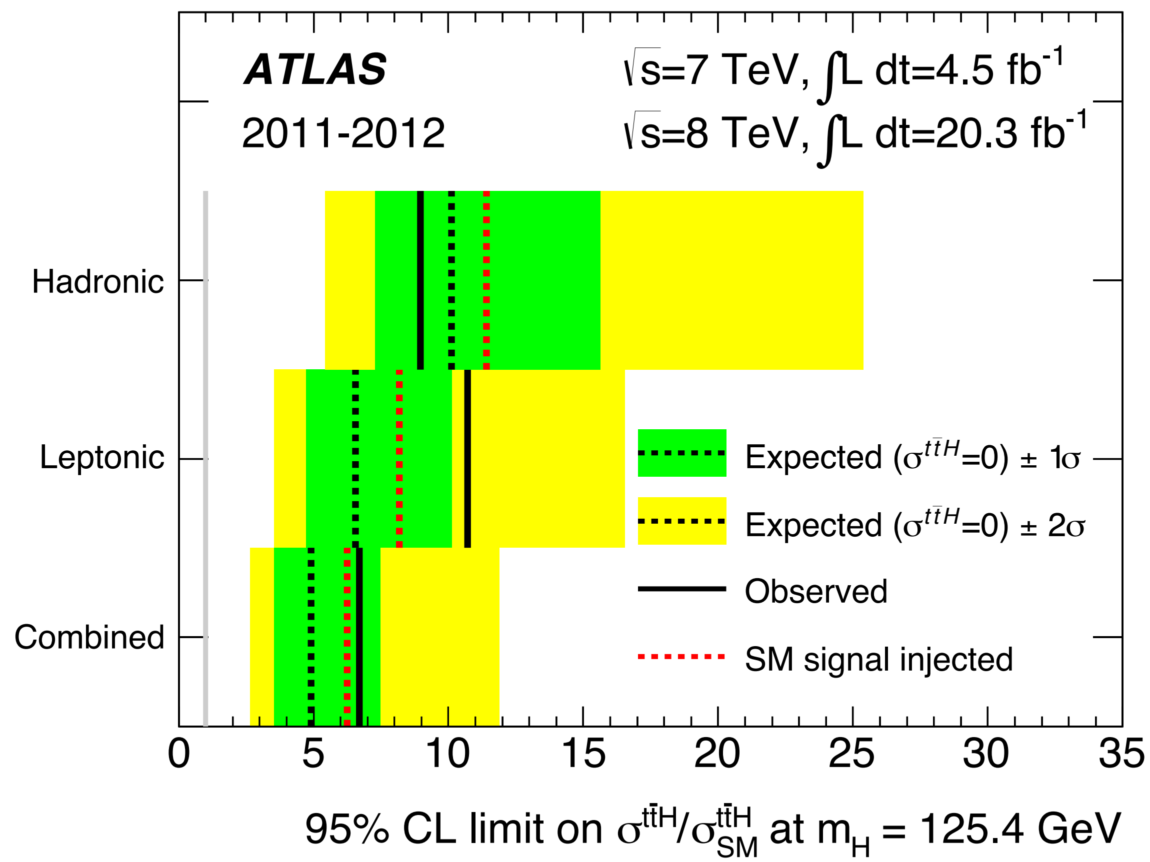






Results

- A few candidate events, but not statistically significant. Best fit consistent with SM.



CMS:

Expected limit (no ttH): 4.7
Expected limit (SM ttH): 5.7
Observed limit: 7.4

Fitted signal $\sigma/\sigma_{SM} = 1.4^{+2.2}_{-1.4}$

Fitted signal $\sigma/\sigma_{SM} = 2.7^{+2.6}_{-1.8}$

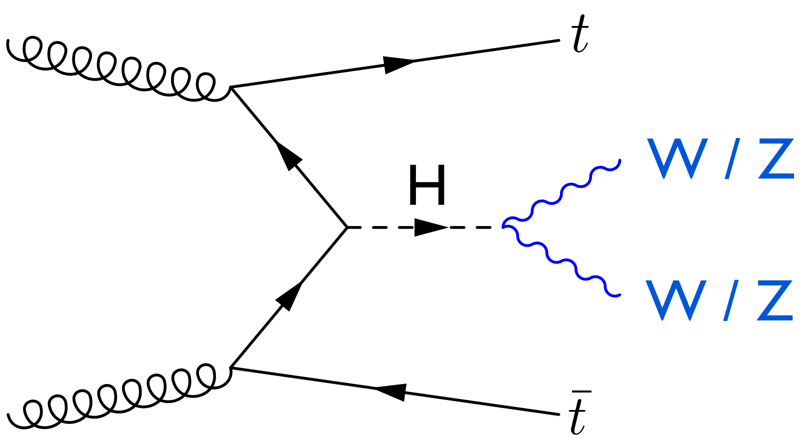
Interpretation in terms of top Yukawa coupling - Christian's talk after lunch

ttH; H → multileptons

CMS: arXiv:1408.1682

ttH multi-lepton

- Higgs decay into WW, ZZ and ττ can produce signatures with multiple leptons in the final state.
- The following categories are used to search for the signal:
  - Same-sign charge di-lepton plus 2 jet events.
  - Tri-lepton plus 2 jet events.
  - 4-lepton plus 2 jet events.



- Multivariate BDT lepton ID is used, tight working point for SS & 3 leptons, loose for 4 lepton.
- Events must have either 2 loose b-tags (85%) or 1 medium b-tag (70%).
- Selection cuts on MET and m(ll) used to remove Z+jets events.

Background Estimate

- Rare SM process:
  - tt+V - estimated with MC + NLO cross-sections. Cross-checked with 3 lepton events, with two leptons near m(Z) - agreement with prediction (35% precision).
  - Diboson - normalized using control region with no b-tagged jets.
- Non-prompt leptons:
  - Measure probability for non-prompt leptons to pass the lepton ID. Then weight events with at least one lepton failing the lepton ID to estimate non-prompt background.
- Charge mis-measurement estimated using Z data events.

Event Yields

University of Glasgow

	ee	eμ	μμ	3ℓ	4ℓ
$t\bar{t}H, H \to WW$	1.0 ± 0.1	3.2 ± 0.4	2.4 ± 0.3	3.4 ± 0.5	0.29 ± 0.04
$t\bar{t}H, H \to ZZ$	—	0.1 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.09 ± 0.02
$t\bar{t}H, H \to \tau\tau$	0.3 ± 0.0	1.0 ± 0.1	0.7 ± 0.1	1.1 ± 0.2	0.15 ± 0.02
$t\bar{t}W$	4.3 ± 0.6	16.5 ± 2.3	10.4 ± 1.5	10.3 ± 1.9	—
$t\bar{t}Z/\gamma^*$	1.8 ± 0.4	4.9 ± 0.9	2.9 ± 0.5	8.4 ± 1.7	1.12 ± 0.62
$t\bar{t}WW$	0.1 ± 0.0	0.4 ± 0.1	0.3 ± 0.0	0.4 ± 0.1	0.04 ± 0.02
$t\bar{t}\gamma$	1.3 ± 0.3	1.9 ± 0.5	—	2.6 ± 0.6	—
WZ	0.6 ± 0.6	1.5 ± 1.7	1.0 ± 1.1	3.9 ± 0.7	—
ZZ	—	0.1 ± 0.1	0.1 ± 0.0	0.3 ± 0.1	0.47 ± 0.10
Rare SM bkg.	0.4 ± 0.1	1.6 ± 0.4	1.1 ± 0.3	0.8 ± 0.3	0.01 ± 0.00
Non-prompt	7.6 ± 2.5	20.0 ± 4.4	11.9 ± 4.2	33.3 ± 7.5	0.43 ± 0.22
Charge misidentified	1.8 ± 0.5	2.3 ± 0.7	—	—	—
All signals	1.4 ± 0.2	4.3 ± 0.6	3.1 ± 0.4	4.7 ± 0.7	0.54 ± 0.08
All backgrounds	18.0 ± 2.7	49.3 ± 5.4	27.7 ± 4.7	59.8 ± 8.0	2.07 ± 0.67
Data	19	51	41	68	1

- Largest background from non-prompt events.
- Excess of events seen in μμ channel.

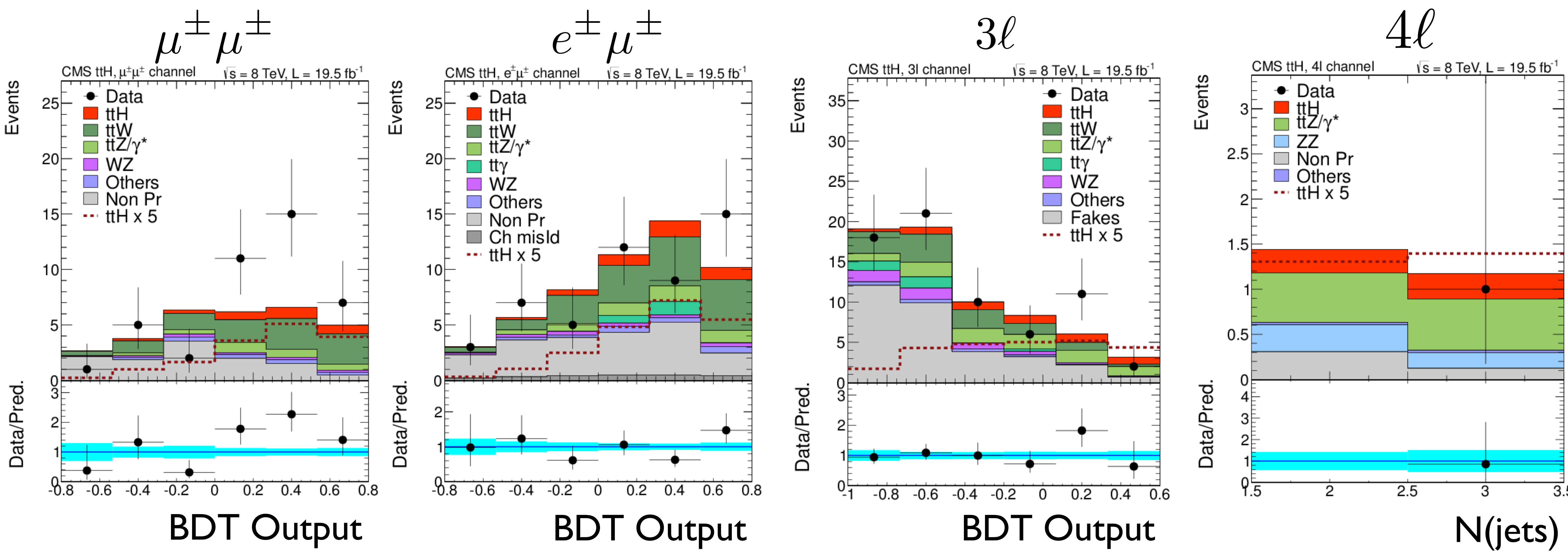
Event Yields

	ee	$e\mu$	$\mu\mu$	3ℓ	4ℓ
$t\bar{t}H, H \to WW$	1.0 ± 0.1	3.2 ± 0.4	2.4 ± 0.3	3.4 ± 0.5	0.29 ± 0.04
$t\bar{t}H, H \to ZZ$	—	0.1 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.09 ± 0.02
$t\bar{t}H, H \to \tau\tau$	0.3 ± 0.0	1.0 ± 0.1	0.7 ± 0.1	1.1 ± 0.2	0.15 ± 0.02
$t\bar{t}W$	4.3 ± 0.6	16.5 ± 2.3	10.4 ± 1.5	10.3 ± 1.9	—
$t\bar{t}Z/\gamma^*$	1.8 ± 0.4	4.9 ± 0.9	2.9 ± 0.5	8.4 ± 1.7	1.12 ± 0.62
$t\bar{t}WW$	0.1 ± 0.0	0.4 ± 0.1	0.3 ± 0.0	0.4 ± 0.1	0.04 ± 0.02
$t\bar{t}\gamma$	1.3 ± 0.3	1.9 ± 0.5	—	2.6 ± 0.6	—
WZ	0.6 ± 0.6	1.5 ± 1.7	1.0 ± 1.1	3.9 ± 0.7	—
ZZ	—	0.1 ± 0.1	0.1 ± 0.0	0.3 ± 0.1	0.47 ± 0.10
Rare SM bkg.	0.4 ± 0.1	1.6 ± 0.4	1.1 ± 0.3	0.8 ± 0.3	0.01 ± 0.00
Non-prompt	7.6 ± 2.5	20.0 ± 4.4	11.9 ± 4.2	33.3 ± 7.5	0.43 ± 0.22
Charge misidentified	1.8 ± 0.5	2.3 ± 0.7	—	—	—
All signals	1.4 ± 0.2	4.3 ± 0.6	3.1 ± 0.4	4.7 ± 0.7	0.54 ± 0.08
All backgrounds	18.0 ± 2.7	49.3 ± 5.4	27.7 ± 4.7	59.8 ± 8.0	2.07 ± 0.67
Data	19	51	41	68	1

- Largest background from non-prompt events.
- Excess of events seen in μμ channel.

Signal Extraction

- Signal extracted by fitting to final discriminating variable:
  - 2 & 3 lepton: BDT exploiting kinematic differences between signal and background, categorised by sum of charge.
  - 4 lepton: N(jets).



Results

- Fitted signal and limits relative to Standard Model:

$t\bar{t}H$ channel	Best-fit μ	95% CL upper limits on $\mu = \sigma/\sigma_{SM}$ ($m_H = 125.6$ GeV)				
			Expected			
	Observed	Observed	Median signal-injected	Median	68% CL range	95% CL range
$\gamma\gamma$	$+2.7^{+2.6}_{-1.8}$	7.4	5.7	4.7	[3.1, 7.6]	[2.2, 11.7]
$b\bar{b}$	$+0.7^{+1.9}_{-1.9}$	4.1	5.0	3.5	[2.5, 5.0]	[1.9, 6.7]
$\tau_h\tau_h$	$-1.3^{+6.3}_{-5.5}$	13.0	16.2	14.2	[9.5, 21.7]	[6.9, 32.5]
4l	$-4.7^{+5.0}_{-1.3}$	6.8	11.9	8.8	[5.7, 14.3]	[4.0, 22.5]
3l	$+3.1^{+2.4}_{-2.0}$	7.5	5.0	4.1	[2.8, 6.3]	[2.0, 9.5]
Same-sign 2l	$+5.3^{+2.1}_{-1.8}$	9.0	3.6	3.4	[2.3, 5.0]	[1.7, 7.2]

- Fitted signal largest for di-muon events ($\mu=8.5^{+3.3}_{-2.7}$).
- Compatibility between all 5 channels is 16%.

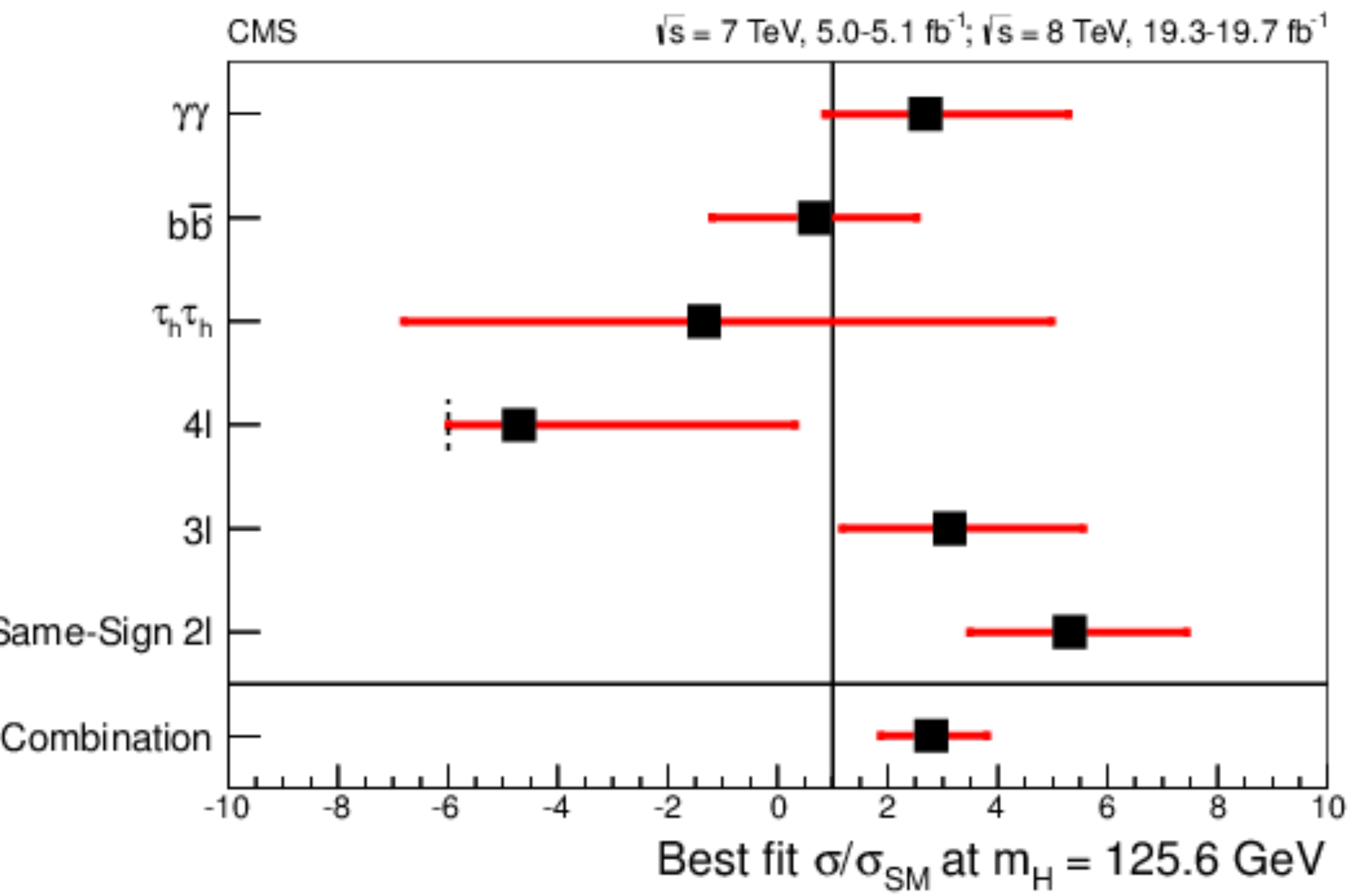
CMS ttH Combination

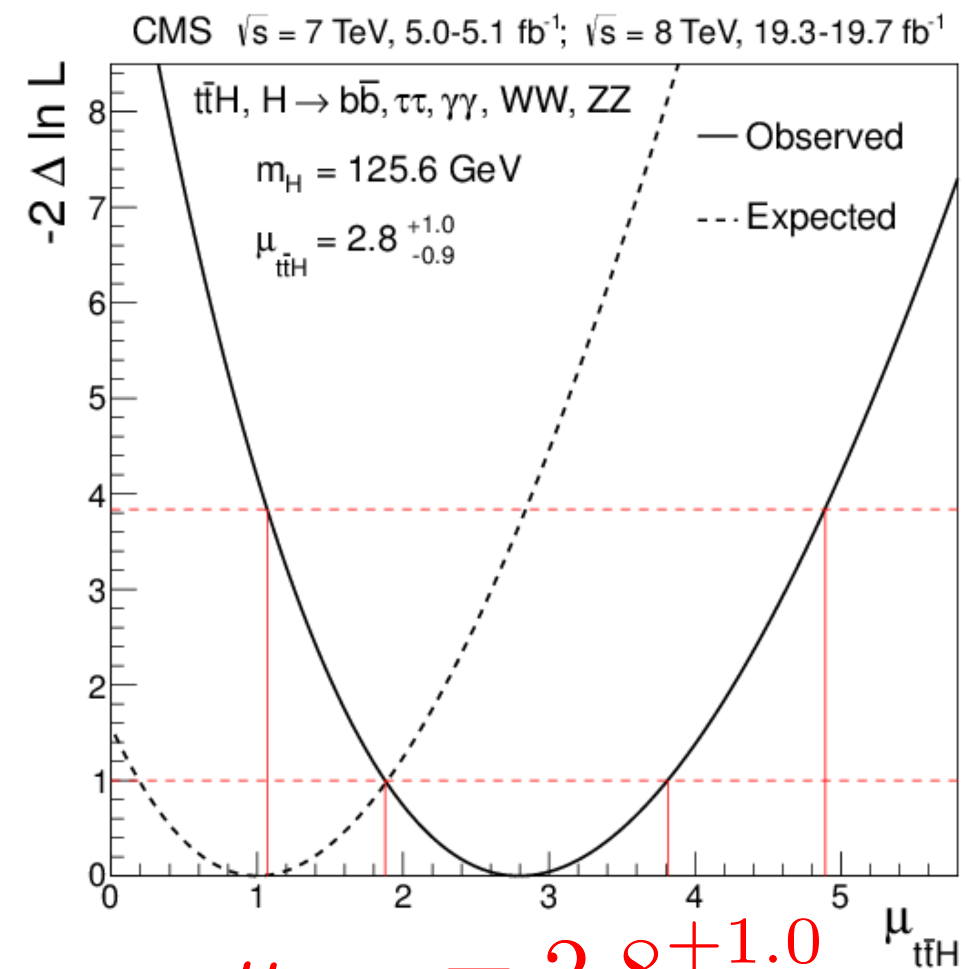
CMS: arXiv:1408.1682

ttH Combination

- CMS combines the bb BDT, multilepton, $\tau_h\tau_h$ and $\gamma\gamma$ analyses to maximise sensitivity by making combined fit to all final discriminants.
- Assume SM Higgs branching ratios, so free parameter is the ttH signal strength.
- Systematic uncertainties are included as nuisance parameters and are correlated across the channels where appropriate.

ttH Combination



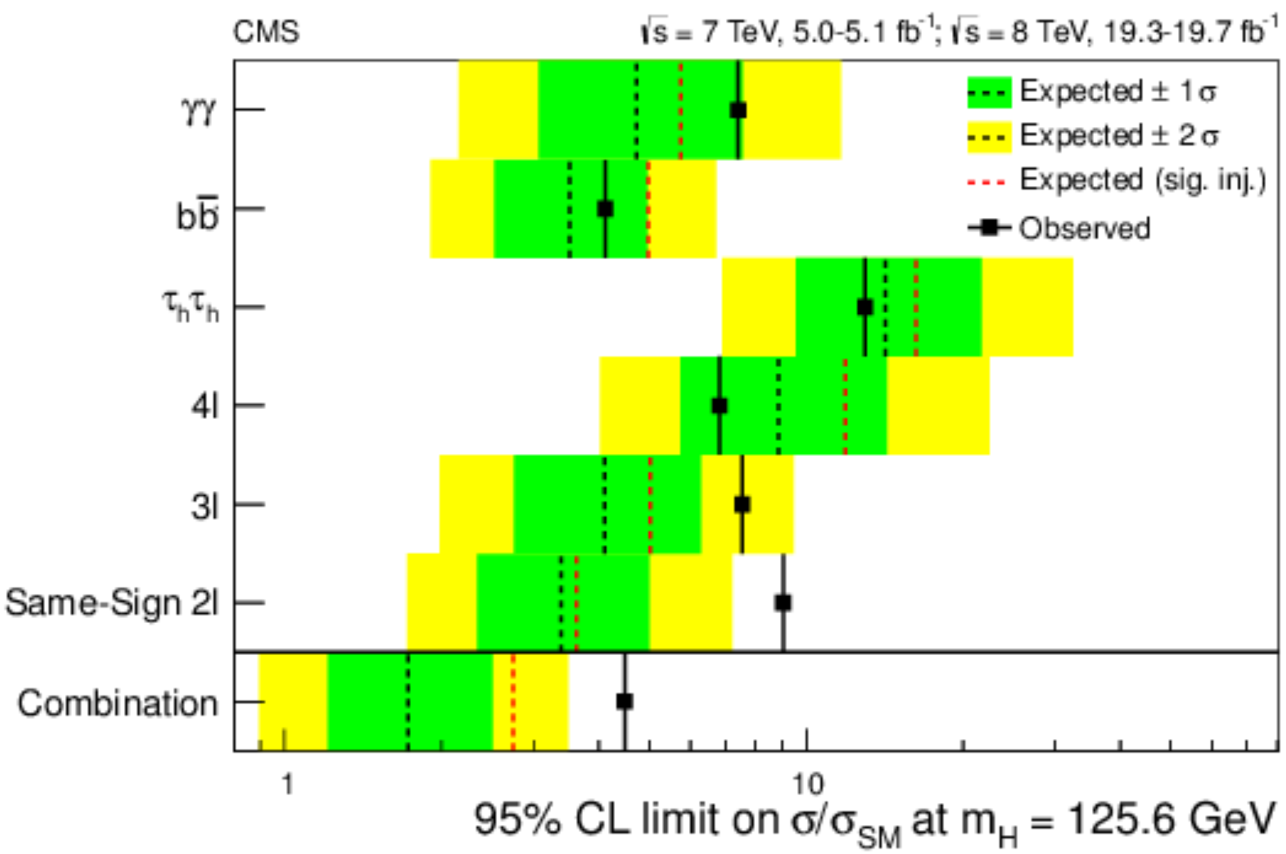


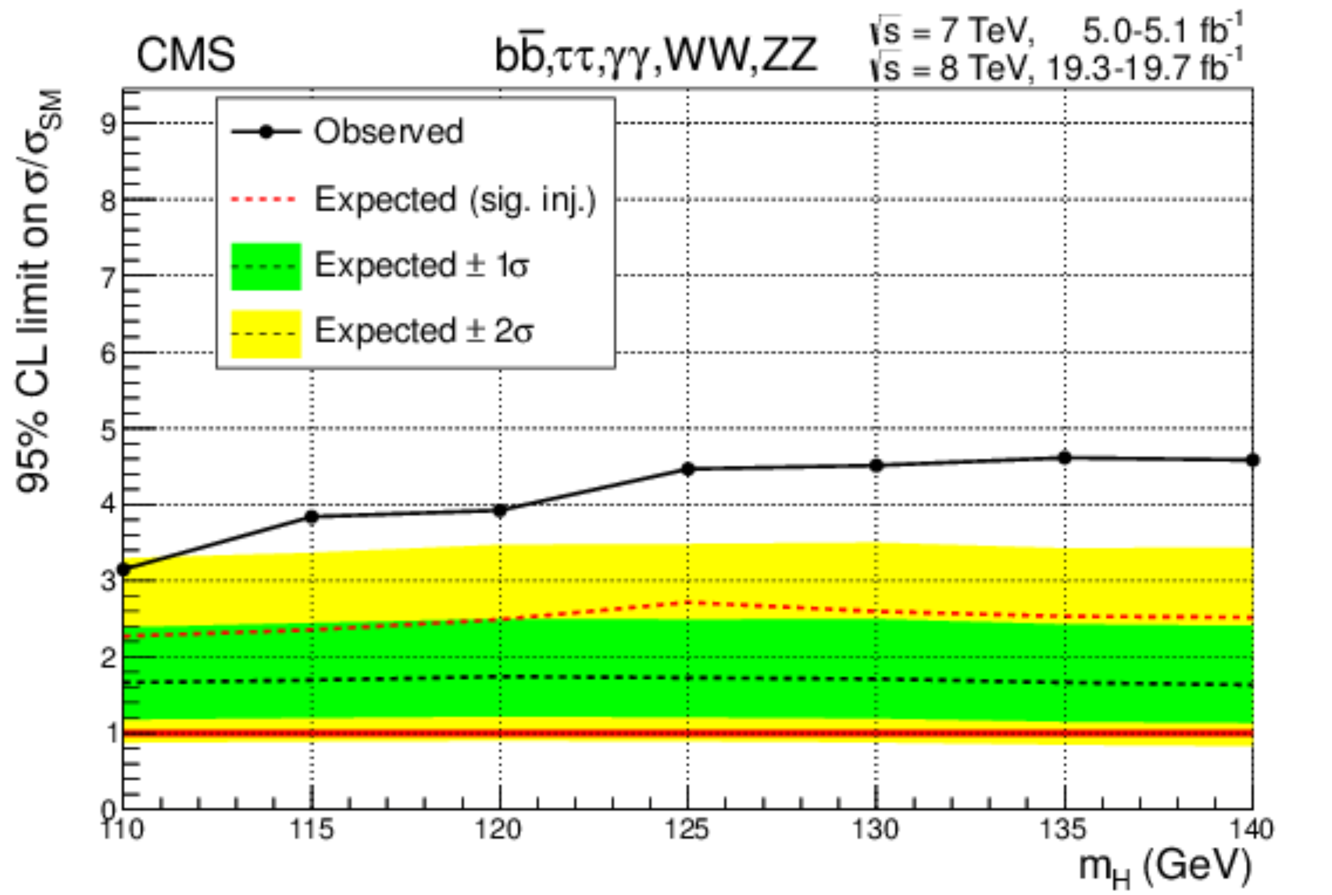
$$\mu_{t\bar{t}H} = 2.8^{+1.0}_{-0.9}$$

- Result corresponds to 3.5 standard deviation excess over background only, 2.1 standard deviation excess over SM.
- Consistency of individual channels with a single signal cross section is 29%.

ttH Combination

- Extracted limits, plus (weak) dependence on Higgs mass:





- Combination significantly improves sensitivity with respect to individual analyses.

Conclusions

- ttH process provides possibility for direct extraction of top quark Yukawa coupling.
- Rich final states rely on full capability of the detectors and sophisticated analysis techniques.
- Analyses exploiting bb, VV, $\tau\tau$ and $\gamma\gamma$ decay modes.
- Some excess seen in CMS multi-lepton analysis, no significant excess in bb or $\gamma\gamma$ channels.
- Higher energy of LHC from 2015 increases ttH cross-section faster than backgrounds.
- Looking forward to interesting results in the future!

Backup

ttH bb Selection

- Comparison of selection criteria for l+jets:

Selection	ATLAS	CMS
Electrons	p_T > 25 GeV, $\|\eta\|$<2.47, excluding 1.37 < $\|\eta\|$ < 1.52	p_T > 30 GeV, $\|\eta\|$<2.5, excluding 1.44 < $\|\eta\|$ < 1.57
Muons	p_T > 25 GeV, $\|\eta\|$<2.5	p_T > 25 GeV, $\|\eta\|$<2.1
Jets	p_T > 25 GeV, $\|\eta\|$<2.5	p_T > 30 GeV, $\|\eta\|$<2.4 3 leading jets p_T > 40 GeV

ttH bb Selection

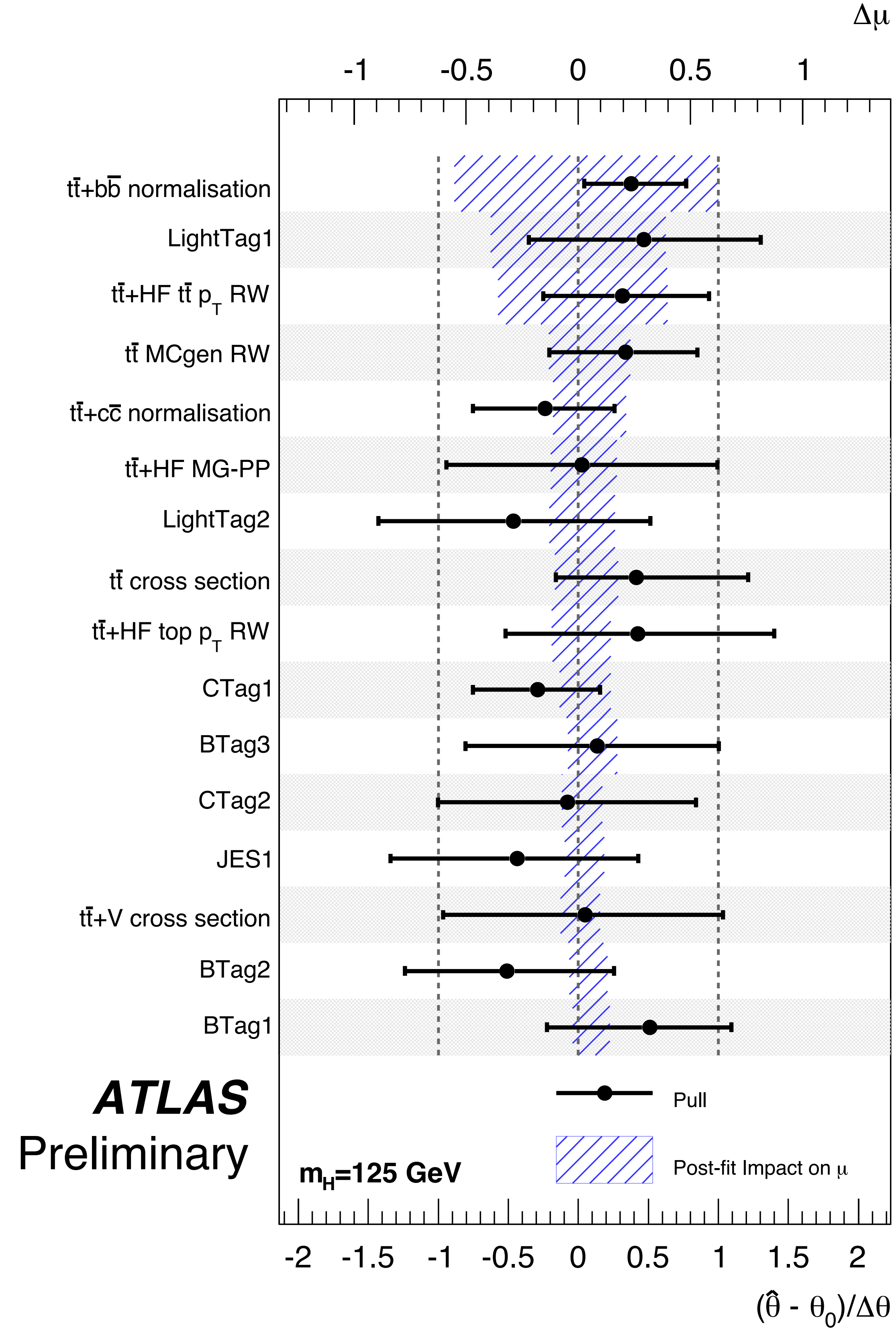
- Higher signal acceptance with ATLAS selection:

	5 jets, ≥ 4 b-tags	≥ 6 jets, 3 b-tags	≥ 6 jets, ≥ 4 b-tags
$t\bar{t}H$ (125)	5.8 ± 0.7 ± 0.6	39 ± 3 ± 4	16 ± 2 ± 2
$t\bar{t}$+ light	67 ± 16	2200 ± 600	67 ± 20
$t\bar{t} + c\bar{c}$	47 ± 25	800 ± 400	80 ± 40
$t\bar{t} + b\bar{b}$	110 ± 60	900 ± 500	240 ± 130
$t\bar{t} + V$	3.1 ± 1.0	43 ± 14	8.4 ± 2.8
non-$t\bar{t}$	26 ± 5	250 ± 50	22 ± 5
Total	260 ± 70	4200 ± 1100	430 ± 160
Data	283	4671	516

	≥6 jets + 3 b-tags	4 jets + 4 b-tags	5 jets + ≥4 b-tags	≥6 jets + ≥4 b-tags
$t\bar{t}$H(125.6 GeV)	18.9 ± 1.5	1.5 ± 0.2	4.4 ± 0.4	6.7 ± 0.6
$t\bar{t}$+lf	1076 ± 74	48.4 ± 10.0	54 ± 12	44 ± 11
$t\bar{t}$+b	289 ± 87	20.0 ± 5.5	28.6 ± 8.0	33 ± 10
$t\bar{t}$ + $b\bar{b}$	232 ± 49	15.8 ± 3.6	45.2 ± 9.7	86 ± 18
$t\bar{t}$ + $c\bar{c}$	720 ± 110	29.7 ± 5.6	55 ± 11	81 ± 13
$t\bar{t}$+W/Z	24.7 ± 3.3	1.0 ± 0.2	2.1 ± 0.4	4.7 ± 0.8
Single t	47.7 ± 6.7	2.8 ± 1.4	7.5 ± 3.8	6.7 ± 2.6
W/Z+jets	7.7 ± 8.8	1.1 ± 1.2	0.9 ± 1.0	0.3 ± 0.8
Diboson	1.0 ± 0.4	0.2 ± 0.2	0.1 ± 0.1	0.2 ± 0.1
Total bkg	2394 ± 65	119.0 ± 8.2	193.4 ± 10.0	256 ± 16
Data	2426	122	219	260

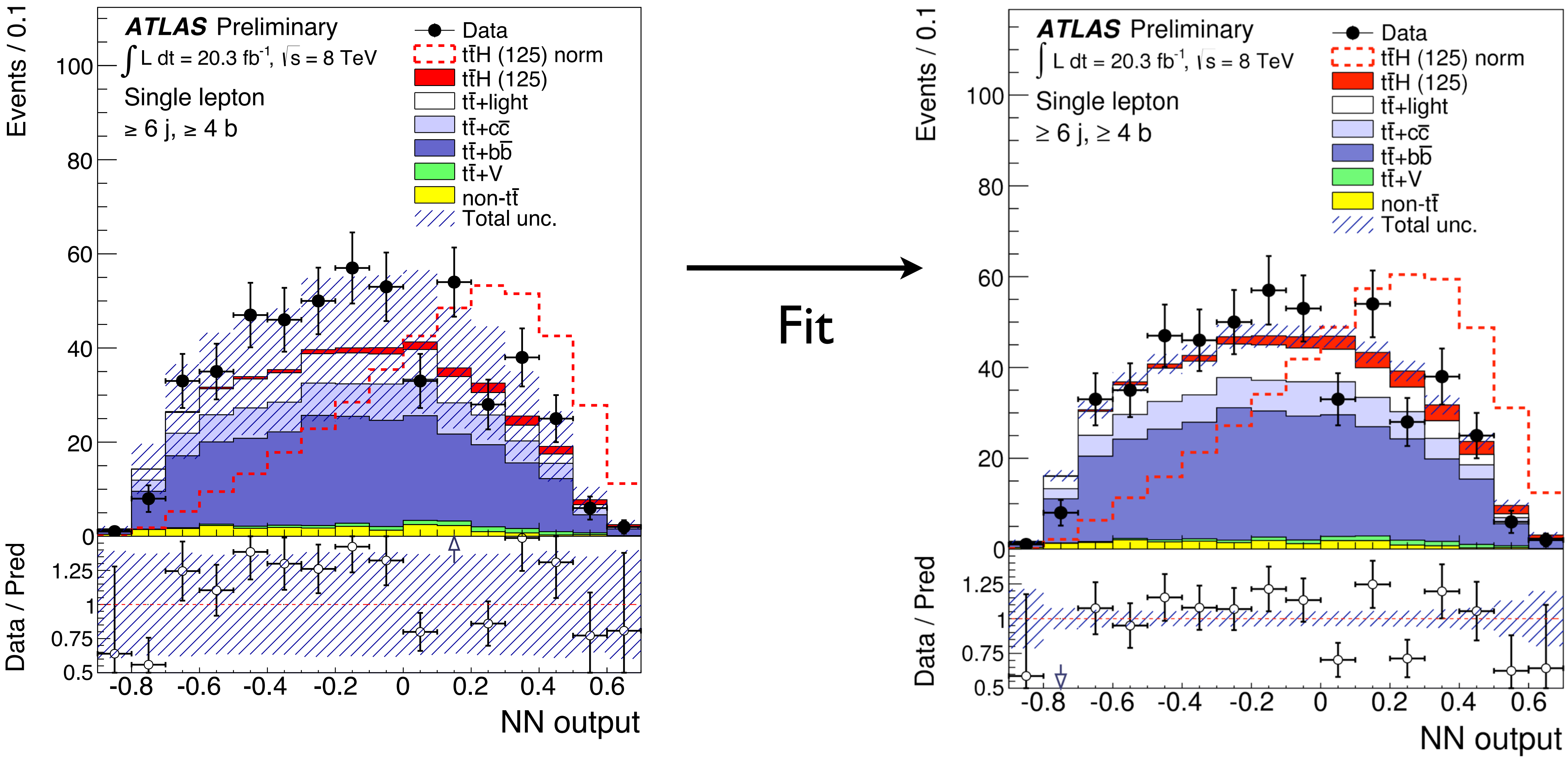
ttH bb Systematics

- ATLAS ranking of systematic uncertainties by impact on μ:



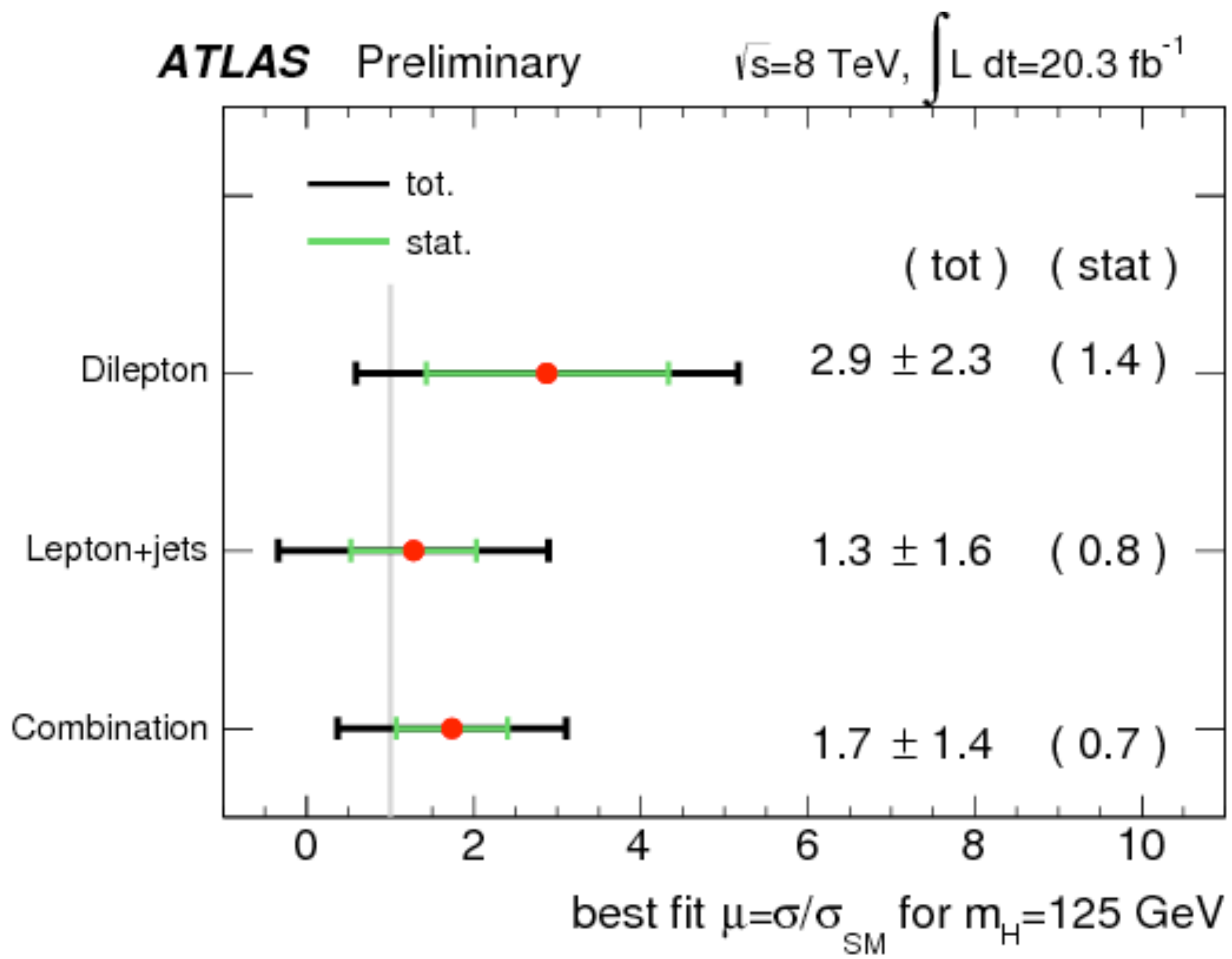
ttH bb Fit

- Example of pre and post-fit uncertainties in l+jets:



ttH bb Results

- ATLAS breakdown by channel:



ttH bb ME

University of Glasgow

- Definition of b-tagging discriminant for 6-jet events:

$$\mathcal{L}_{\mathrm{bbbb}}(\xi_1,\ldots,\xi_6) \equiv \sum_{\{i_1,\ldots,i_6\}} f_{\mathrm{b}}(\xi_{i_1})\cdot f_{\mathrm{b}}(\xi_{i_2})\cdot f_{\mathrm{b}}(\xi_{i_3})\cdot f_{\mathrm{b}}(\xi_{i_4})\cdot f_{\mathrm{u}}(\xi_{i_5})\cdot f_{\mathrm{u}}(\xi_{i_6})$$

- $f_b(\xi)$ = CSV probability density function for heavy flavour jets.
- $f_u(\xi)$ = CSV probability density function for light flavour jets.
- ξ_i = CSV output of i^{th} jet.
- Sum runs over all possible ways of labelling 4 of the 6 jets as b-jets.

Multilepton Selection

- Selection to reduce Z+jets, veto dilepton pairs near m_Z and use:

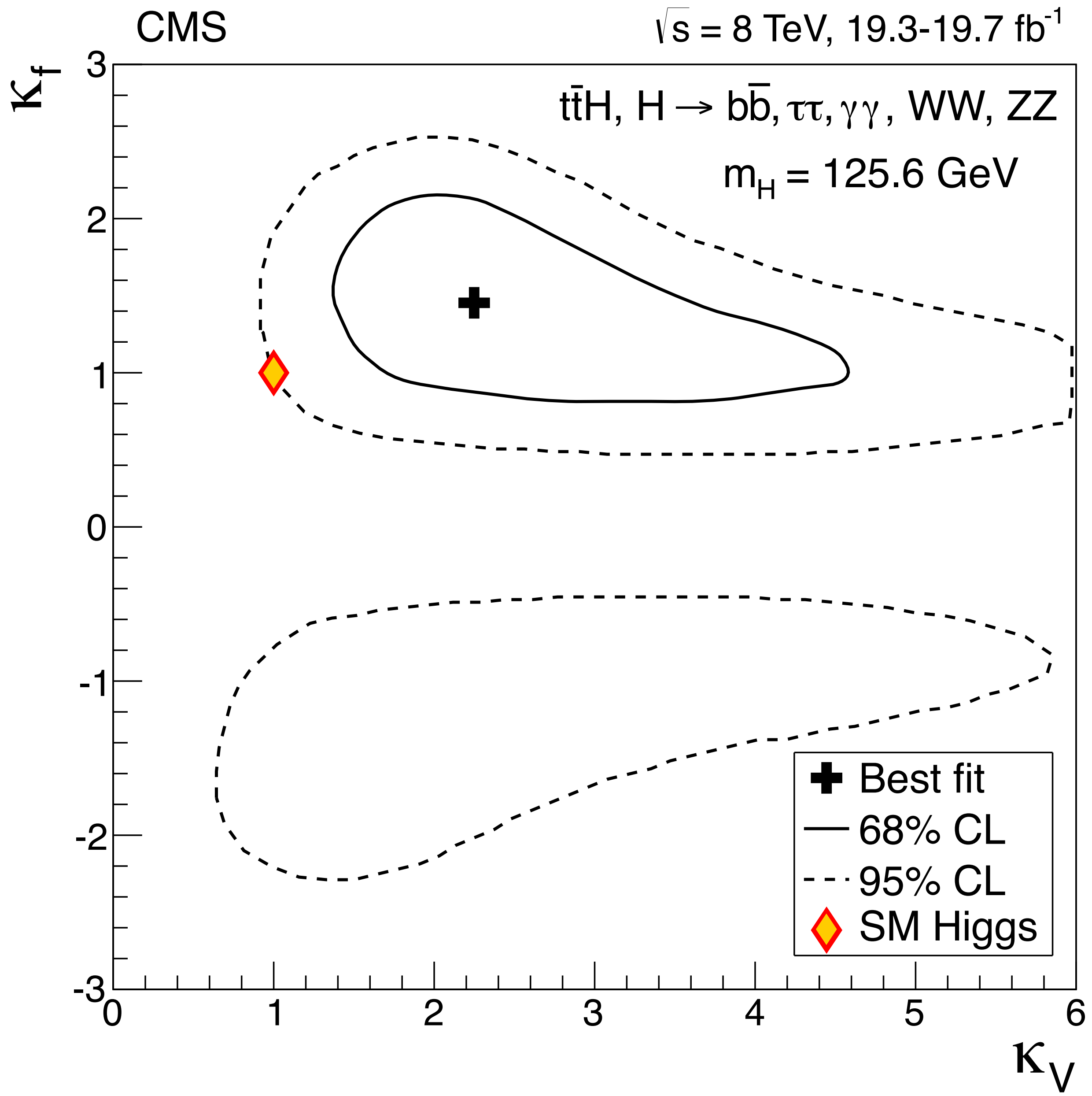
$$L_D = 0.6 E_{\mathrm{T}}^{\mathrm{miss}} + 0.4 H_{\mathrm{T}}^{\mathrm{miss}}$$

Uses all objects in event — Uses selected objects in event

- Lepton pT requirements:
  - SS: 2 leptons, pT > 20 GeV.
  - 3 / 4-lepton: Two leading leptons pT > 20 / 10 GeV. Remaining leptons pT > 7 (e), 5 (μ) GeV.

CMS Combination

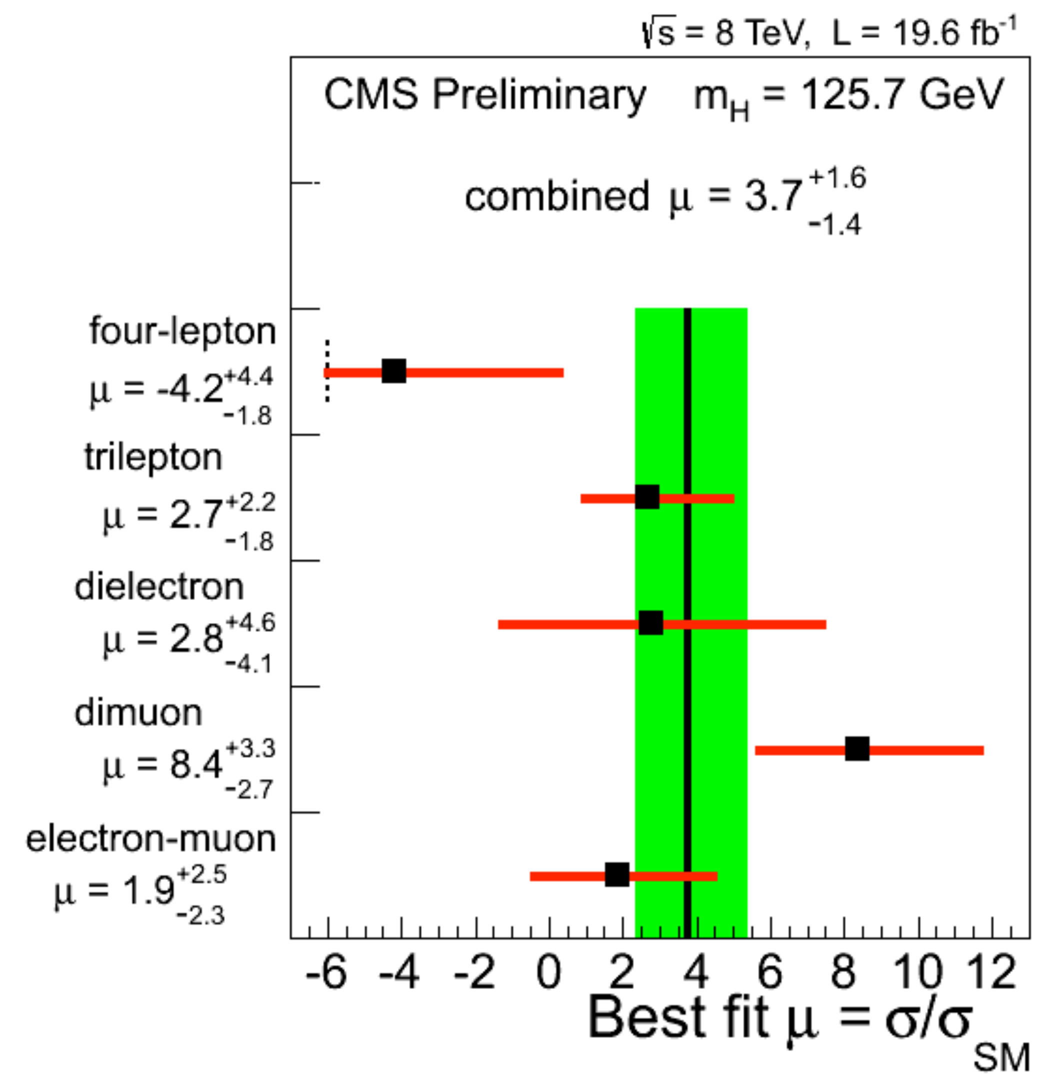
- Relax requirement of SM branching ratios - add two scale factors for couplings between Higgs and bosons (κ_V) / fermions (κ_f):



Summary of HIG-13-020 result and cross-checks

The result

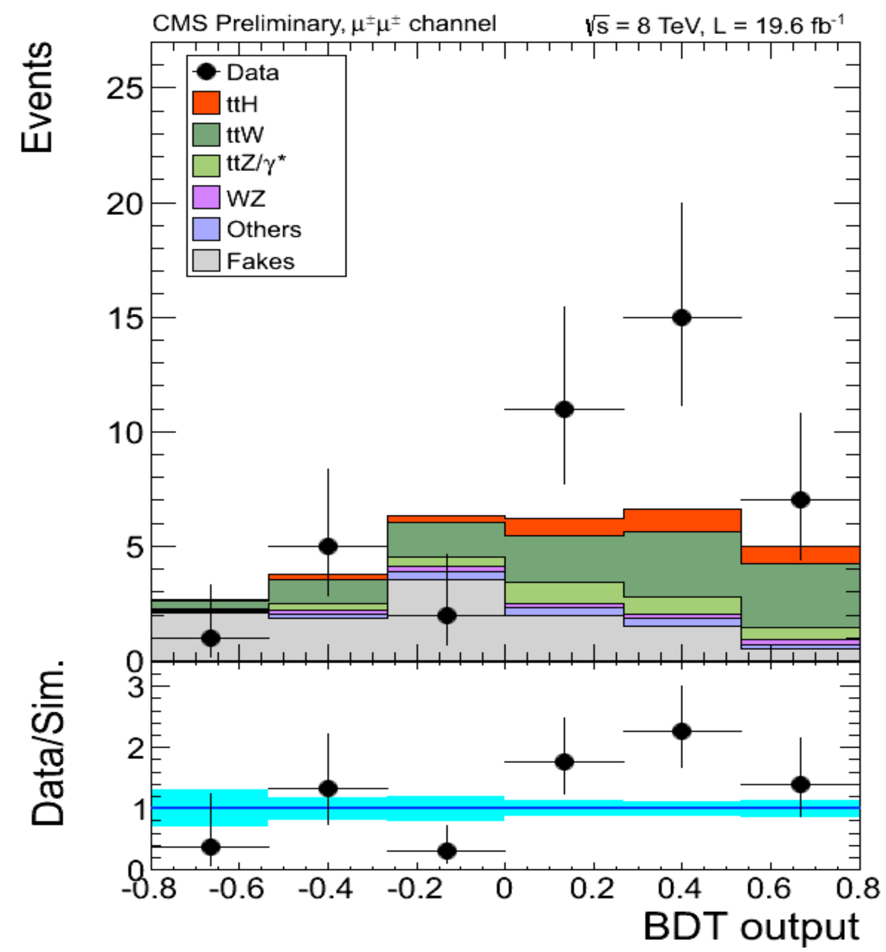
- The results in the different channels are fairly close to the SM Higgs predictions except the $\mu^{\pm}\mu^{\pm}$ final state, where an excess is observed
  - The results in the five final states are consistent with a common signal strength at the 16% level.
  - The μ from the combined fit is consistent with the SM Higgs prediction (μ = 1) at the 3% level (1.9σ)



Dimuon final state

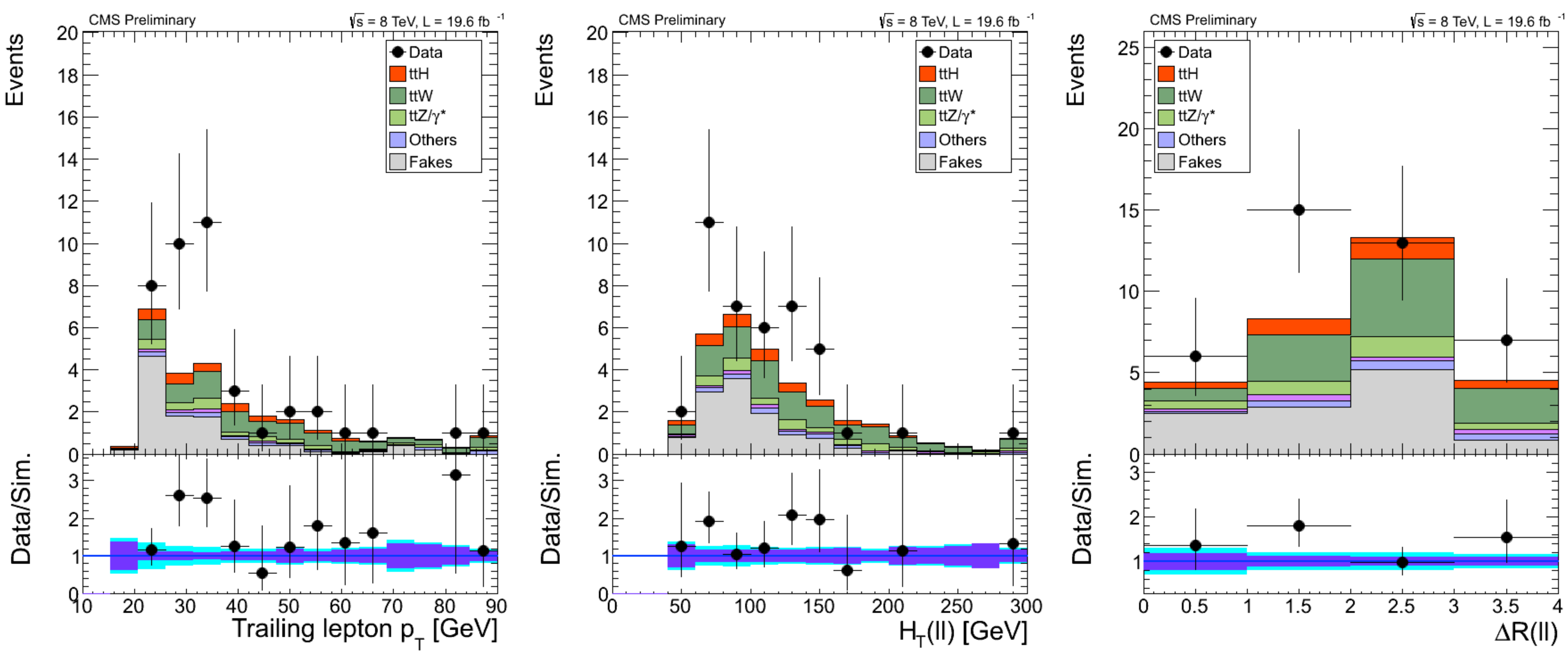
- Excess of events observed, in the signal-like part of the BDT discriminator (trained to separate ttH from the reducible background, on the basis of kinematic variables, not using lepton id variables)

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



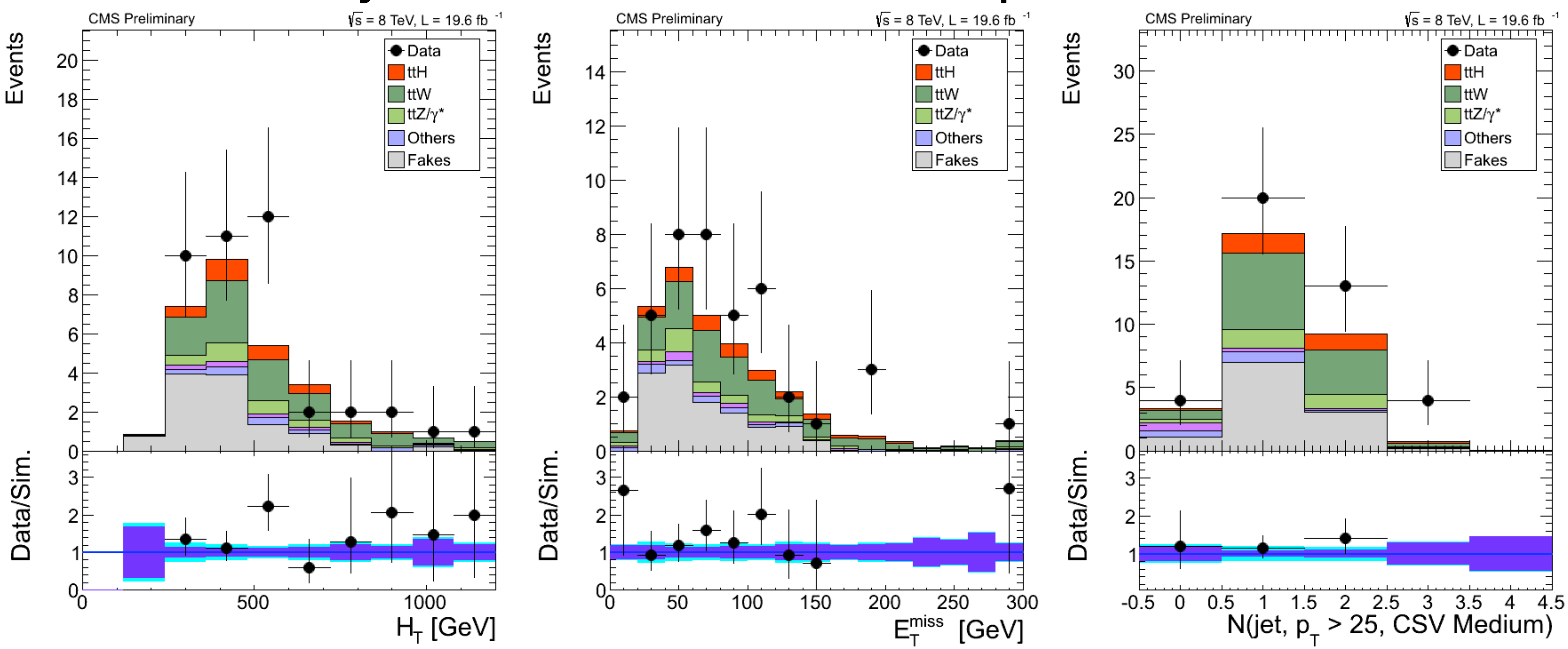
Event kinematics (leptons)

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



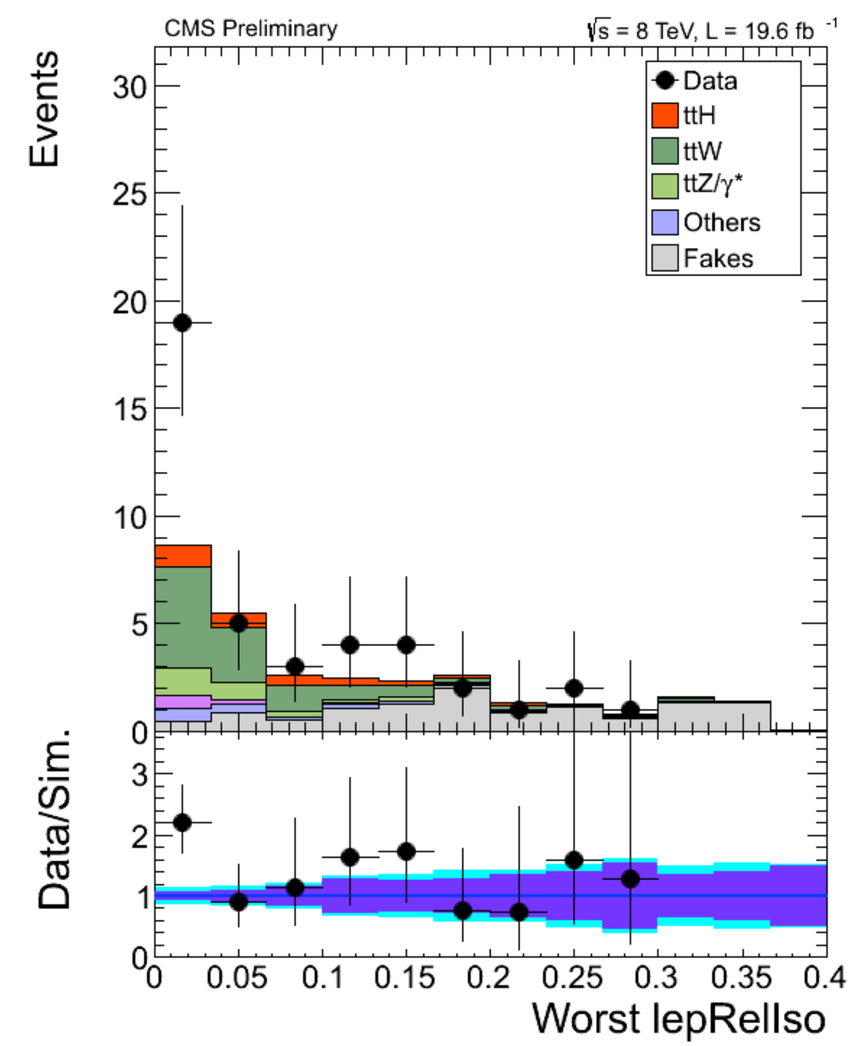
Event kinematics (jets & E_T^{miss})

- Jets and E_T^{miss} are more compatible with signal or ttV.
- The multiplicity 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.



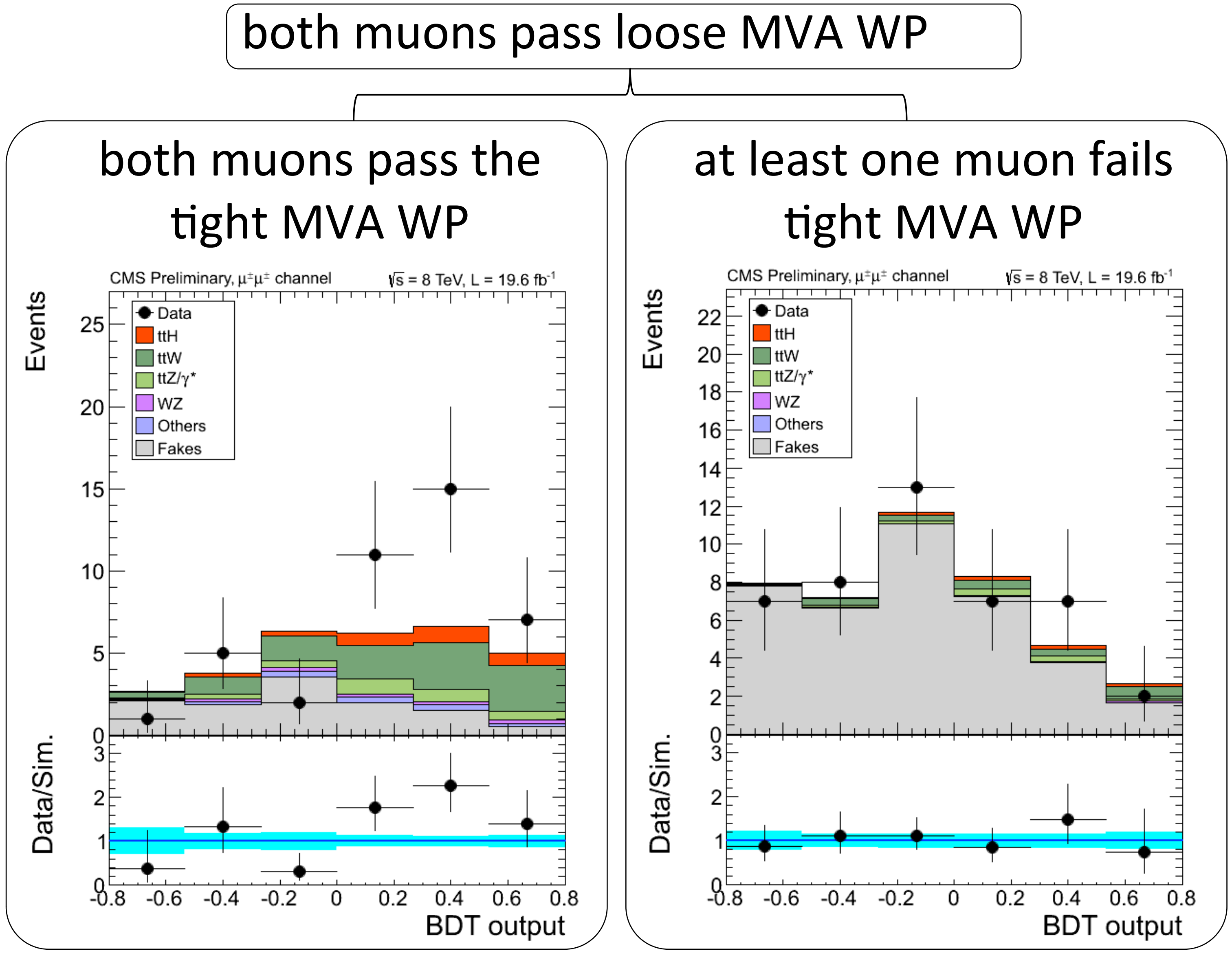
Leptons

- 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.



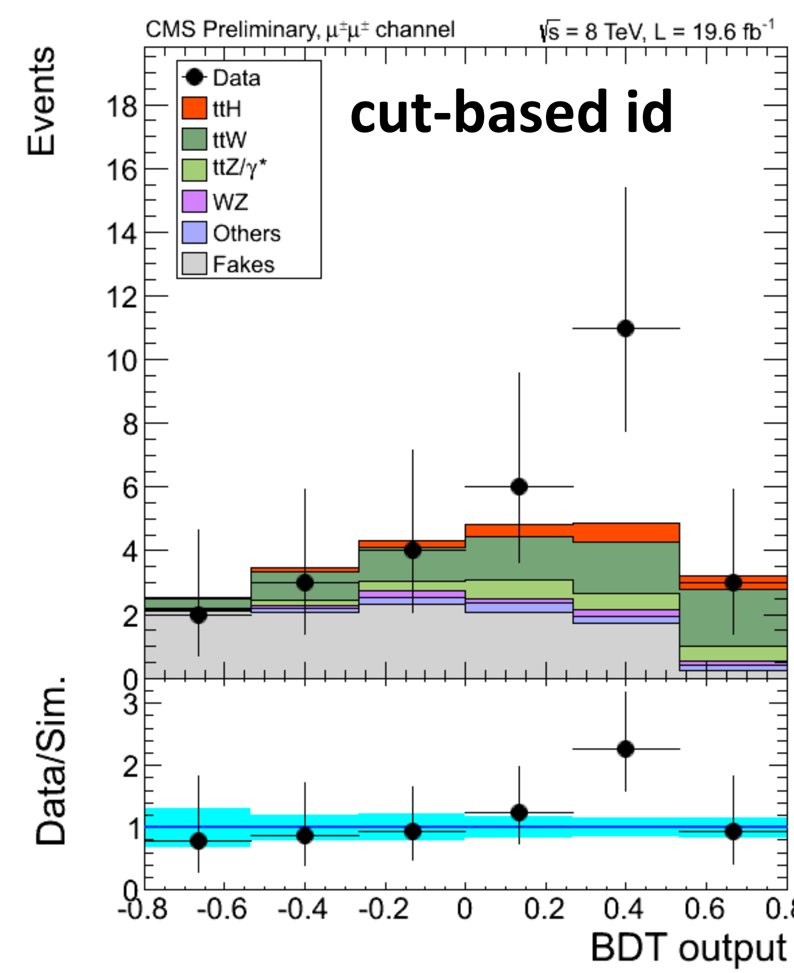
Lepton ID checks: looser MVA

- 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



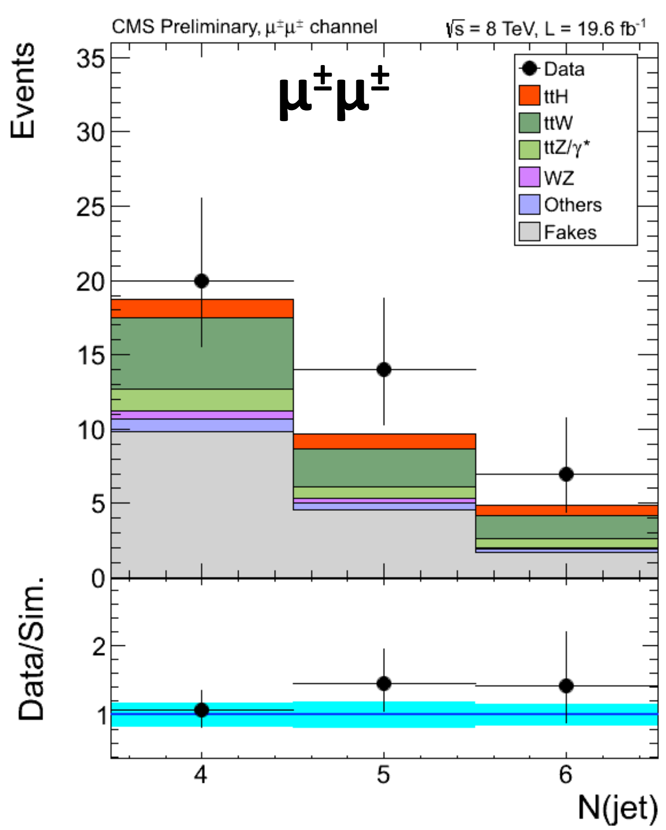
Lepton ID checks: cut-based

- As a cross-check, the analysis was repeated with a cut-based muon selection, instead of the lepton MVA.
- The result with the cut-based selection is compatible with the nominal one, but the sensitivity is worse.

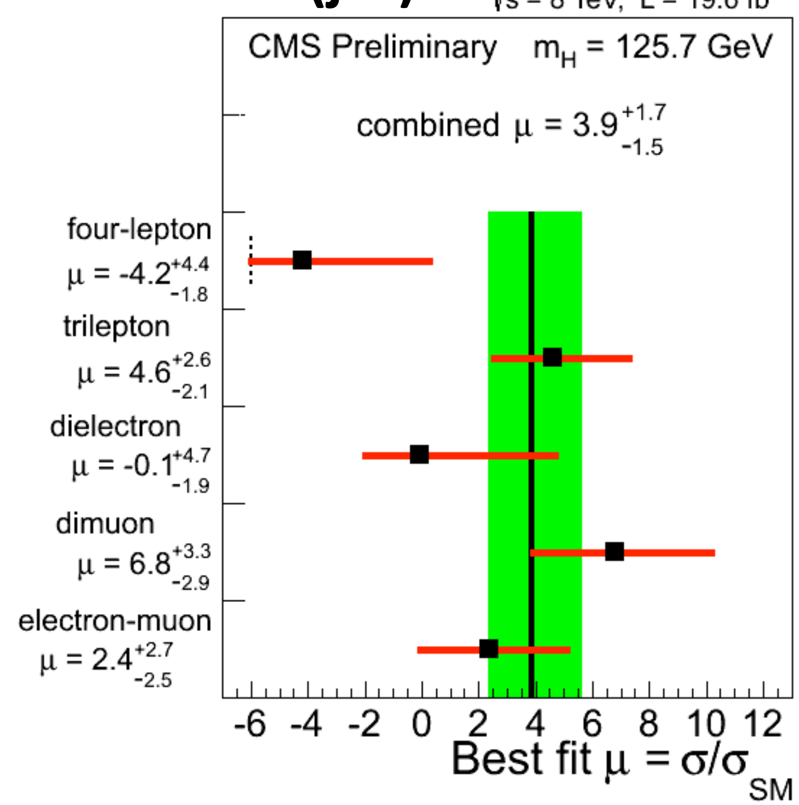


Signal extraction check

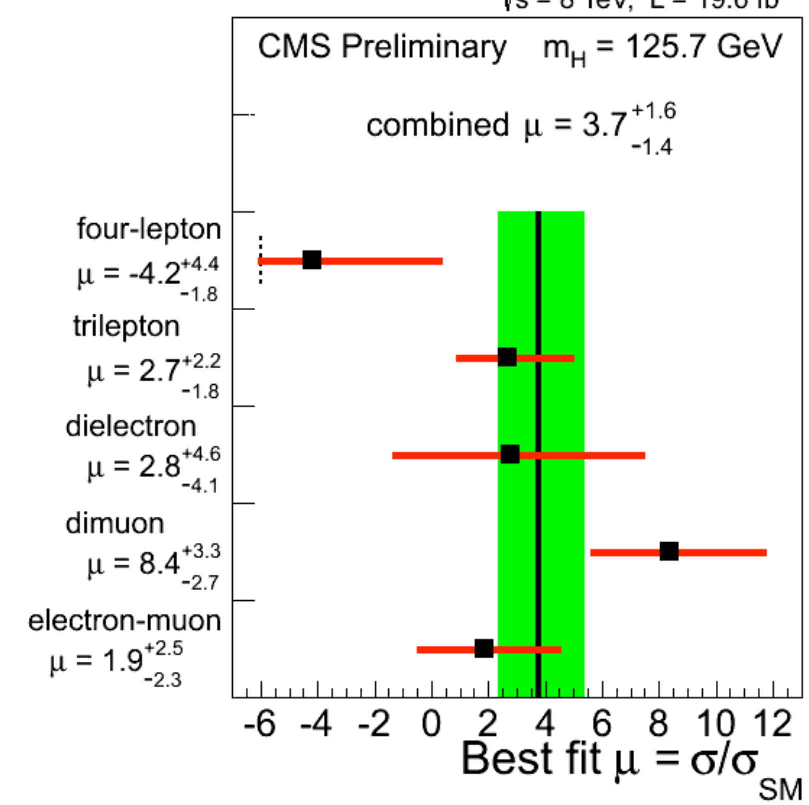
- The signal extraction is repeated using just the multiplicity of hadronic jets as discriminating variable instead of the kinematic BDT.
- The result is compatible with the nominal one, but the sensitivity is worse (as expected)



N(jet)



BDT

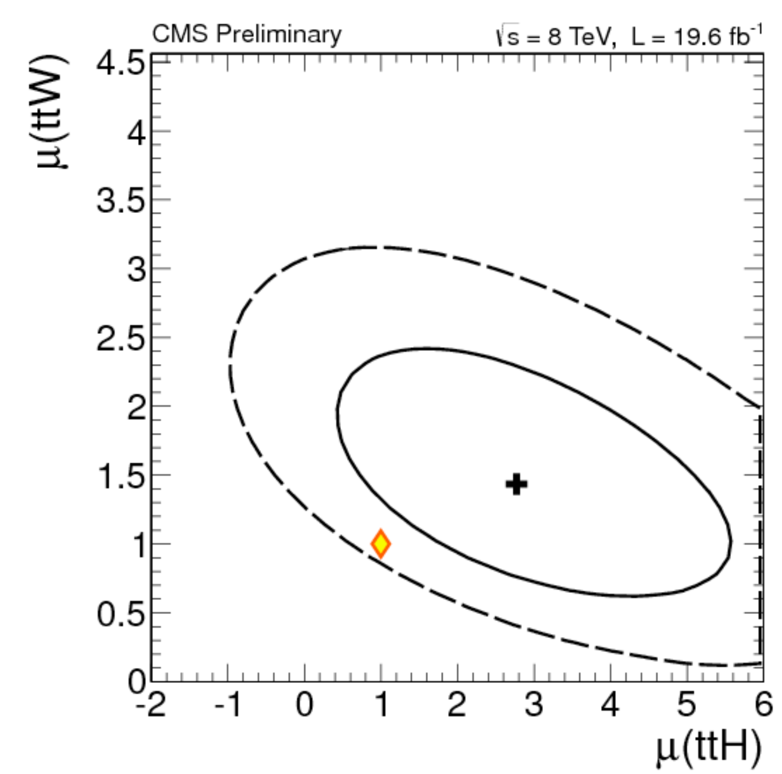


Irreducible background check

- 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

μ(ttH) = 2.8 $^{+1.8}/_{-1.7}$
μ(ttW) = 1.4 $^{+0.6}/_{-0.5}$
μ(ttZ) = 1.1 $^{+0.4}/_{-0.3}$

Results for ttH and ttW are correlated, all the others are well resolved.



Charge asymmetry

- Observed 21 $\mu^+\mu^+$ events and 20 $\mu^-\mu^-$ events, i.e. N(++)/N(tot) = 0.51 ± 0.09
- This is compatible with the expectations for SM Higgs + background, N(++)/N(tot) = 0.55
- Within 1σ the excess events are compatible with any charge asymmetry between zero and the one of ttW, N(++)/N(tot) = 0.69
- Note that in the signal extraction in the 2ℓ and 3ℓ final state the events are categorized by charge, to discriminate ttW from ttH.

Other hypotheses

- tt+bb (or tt+cc) with b/c → μ:
  - Excess should be even more visible with the looser lepton MVA working point, and it's not.
- tt→μ + jets plus a muon from pile-up, or tt→μ + jets plus a cosmic ray muon:
  - given the observed d_{xy}, d_z distributions the estimated yields are by far too small compared to the excess.
- in general, SM backgrounds producing $\mu^{\pm}\mu^{\pm}$ should also produce $e^{\pm}\mu^{\pm}$ (and any tt+X, X→μ should also contribute to the 3ℓ final states)

Conclusions

- Several studies have been performed to investigate the excess in the $\mu^{\pm}\mu^{\pm}$ final state
  - no anomalies seen in the properties of the selected events
  - no indication of any issue in the lepton MVA ID and in the reducible background estimation
  - no evidence for unaccounted backgrounds
- More in general, for this analysis:
  - compatible results obtained in cross-check without using multivariate methods for lepton IDs or signal extraction
  - ttW and ttZ yields also fitted as cross-check, and found in good agreement with the theoretical predictions (i.e. no indication of problems there, nor in the signal efficiencies)