Search for Higgs bosons produced in association with top quarks with the ATLAS detector

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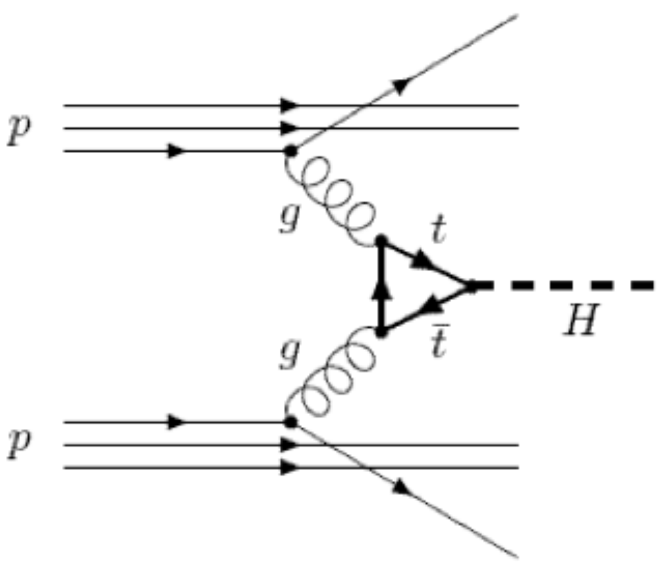
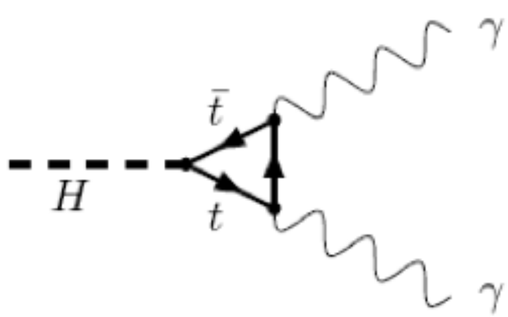
Motivation

- Discovery of the Higgs Boson is only the first step
  - Many of its properties still unknown
- Strongest SM coupling with the top quark $Y_t \sim 1$
  - **$\sigma(t\bar{t}H) \sim Y_t^2$**
- Makes $t\bar{t}H$ a very interesting production mechanism to study



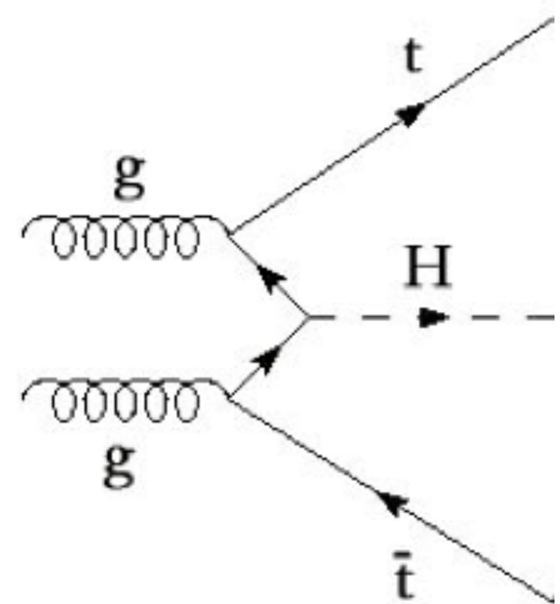


- Can make indirect constraints via other production and decay mechanisms

- Top quark is the largest contributor
- ***Assumption of no new particles!***

- Direct measurement of Y_t can be made with $t\bar{t}H$ production
- tH production sensitive to relative sign of Higgs coupling to top and W

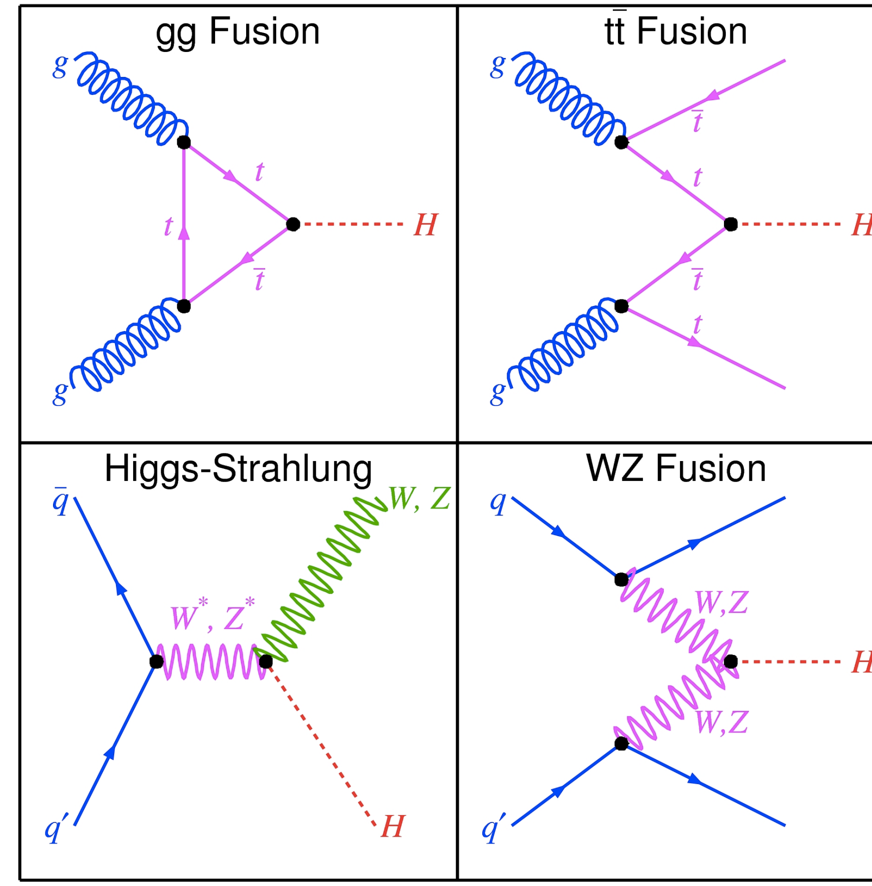
- ***Probing of new physics:***
  - ***Both coupling and final state excess***



$t\bar{t}H$ Production and Decay

- $t\bar{t}H$ one of the four Higgs boson production mechanisms
- Smallest cross section of four
    - $\sigma(t\bar{t}H)$ @ 8 TeV = 130 fb → ~ 2600 events with 20 fb^{-1}

- **Suffers from very large background due to $t\bar{t}$+X**
- Ratio of $t\bar{t}H$ to $t\bar{t}$ significantly increases with higher luminosity



√s (TeV)	7	8	14
$\sigma(t\bar{t}H)$ (m_H=125 GeV) (fb)	86	130	611
$\sigma(t\bar{t})$ (pb)	177	253	950

- Ratio of $t\bar{t}$ to $t\bar{t}H$:
    - **8 TeV : 2000**
    - **14 TeV : 1500**

Higgs Decay	Branching (%)
H → bb	58%
H -> WW / ZZ / ττ	30%
H → γγ	0.2%

- Largest branching fraction, large background from $t\bar{t}$+HF
- Multilepton final states, small backgrounds from $t\bar{t}$+V and $t\bar{t}$ + *jets* (w/ fake leptons)
- Small branching fraction, clean signature

$t\bar{t}H(\gamma\gamma)$ Analysis Strategy

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- **General Analysis strategy:**
- Statistics limited → event selection to maximize acceptance
- Background estimated via sideband analysis in $m(\gamma\gamma)$ distribution

- **2 isolated photons**
- Event selection is split into hadronic and leptonic event types

- **Hadronic: three categories** (exactly 0 leptons)
- ≥6 jets ($p_T \geq 25$ GeV) ≥ 2 b-tags (80 % W.P.)
- ≥5 jets ($p_T \geq 30$ GeV) ≥ 2 b-tags (70 % W.P.)
- ≥6 jets ($p_T \geq 30$ GeV) ≥ 1 b-tags (60 % W.P.)

- **Leptonic:** ≥1 lepton, ≥1 b-jets, $E_T^{miss} > 20$ GeV
- Targeting both single lepton and dilepton $t\bar{t}$ decays

- Measurement of 7 TeV (4.5 fb^{-1}) and 8 TeV (20.3 fb^{-1})

Category	√s (TeV)	N(H)	N(B)	ttH(%)
Leptonic	8	0.59	0.9 (+0.6 / -0.4)	80.3
Hadronic	8	0.50	2.7 (+0.9 / -0.7)	84.3
Leptonic	7	0.10	0.5 (+0.5 / -0.3)	72.8
Hadronic	7	0.07	0.5 (+0.5 / -0.3)	81.1

- **Measurement**: resonance peak in $m(\gamma\gamma)$ between 105 and 160 GeV
- Background described by an exponential function

$t\bar{t}H(\gamma\gamma)$ Results

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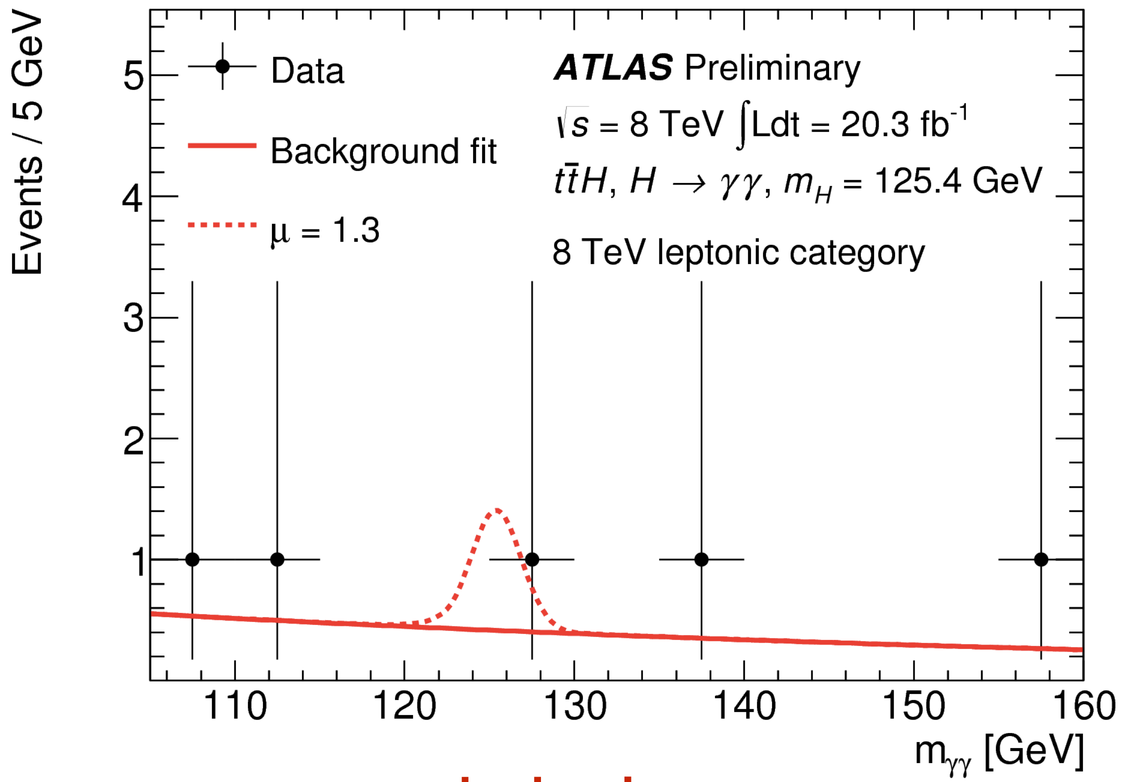
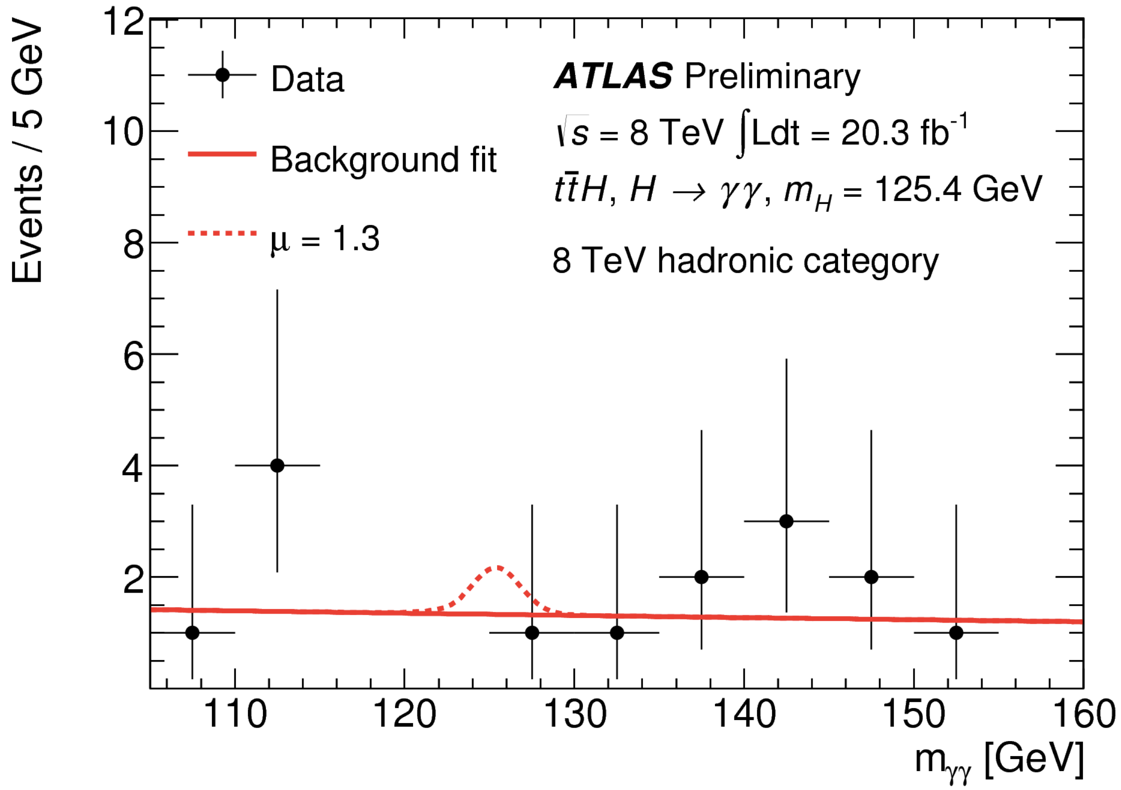
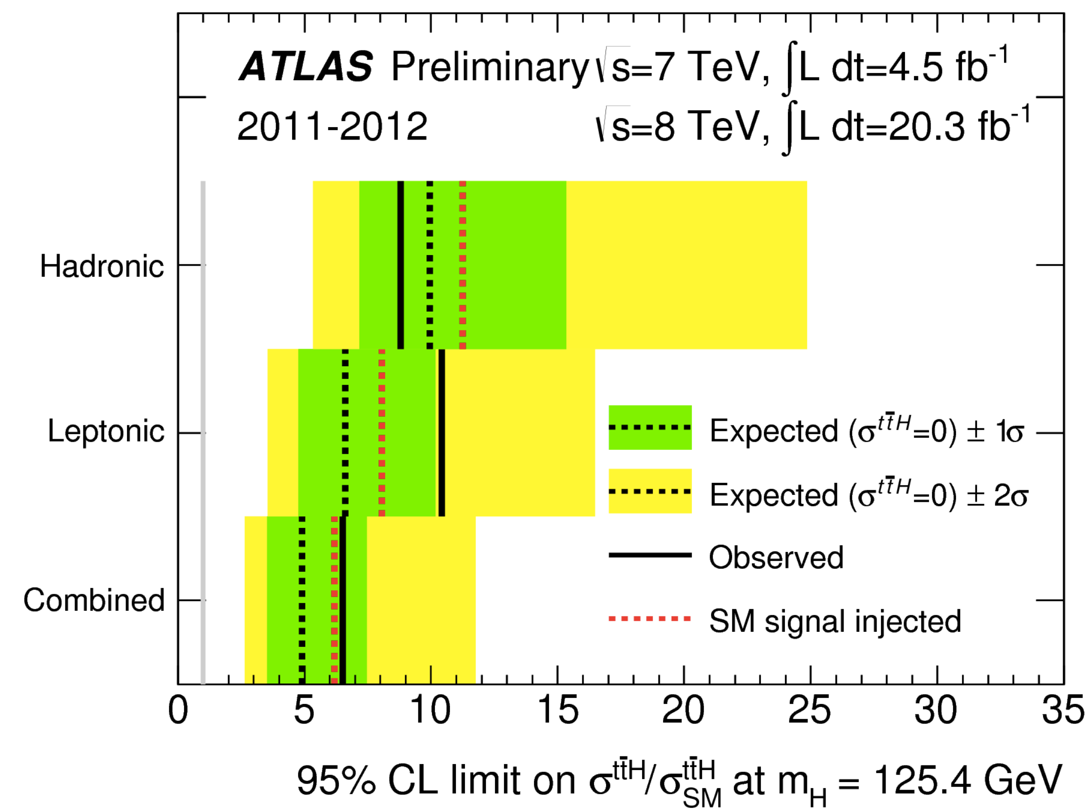
leptonic



hadronic



- ***Combination of leptonic and hadronic channels (both 7 and 8 TeV)***
- 95% CL observed (expected) limit:
  - 6.5 x SM (4.9 x SM) for m_H = 125.4 GeV
- **Fitted $\mu(t\bar{t}H)$: $1.2^{+2.5}_{-1.7}$ (stat.) $^{+0.7}_{-0.4}$ (syst.)**



$t\bar{t}H(\gamma\gamma)$ Candidate Event

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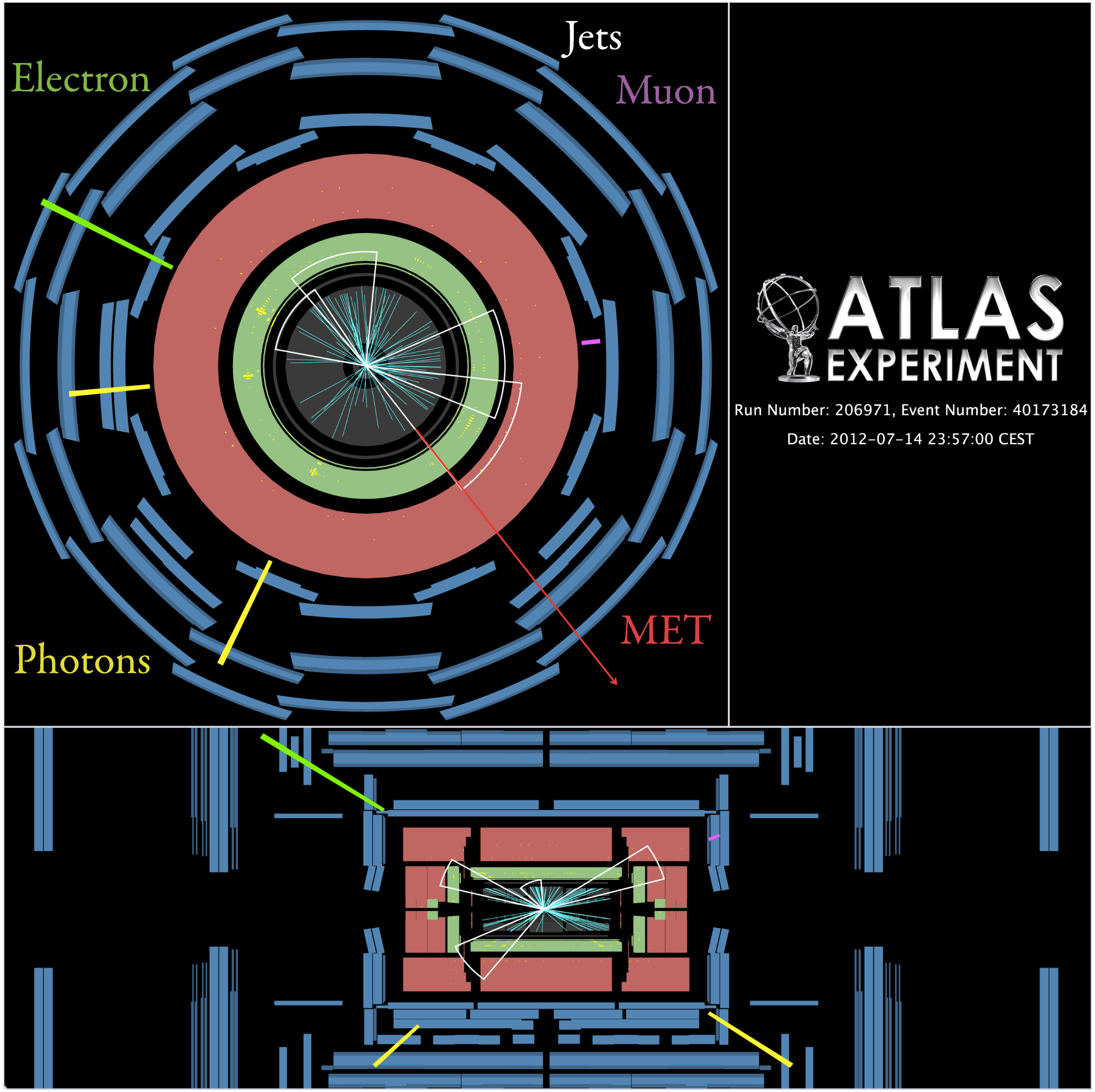

- Event properties:
- Leptonic Channel

- **m(γγ) 126.6 GeV**
- Photons p_T :
  - 61 GeV
  - 39 GeV

- 4 jets + 1 lepton
- 1 b-tag w/ soft muon
- E_T^{miss} = 43 GeV

$t\bar{t}H(bb)$ Analysis Strategy

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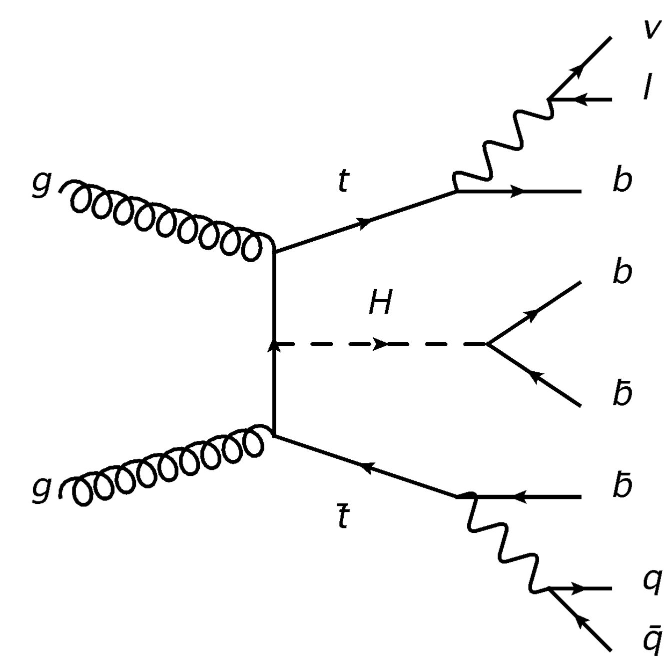
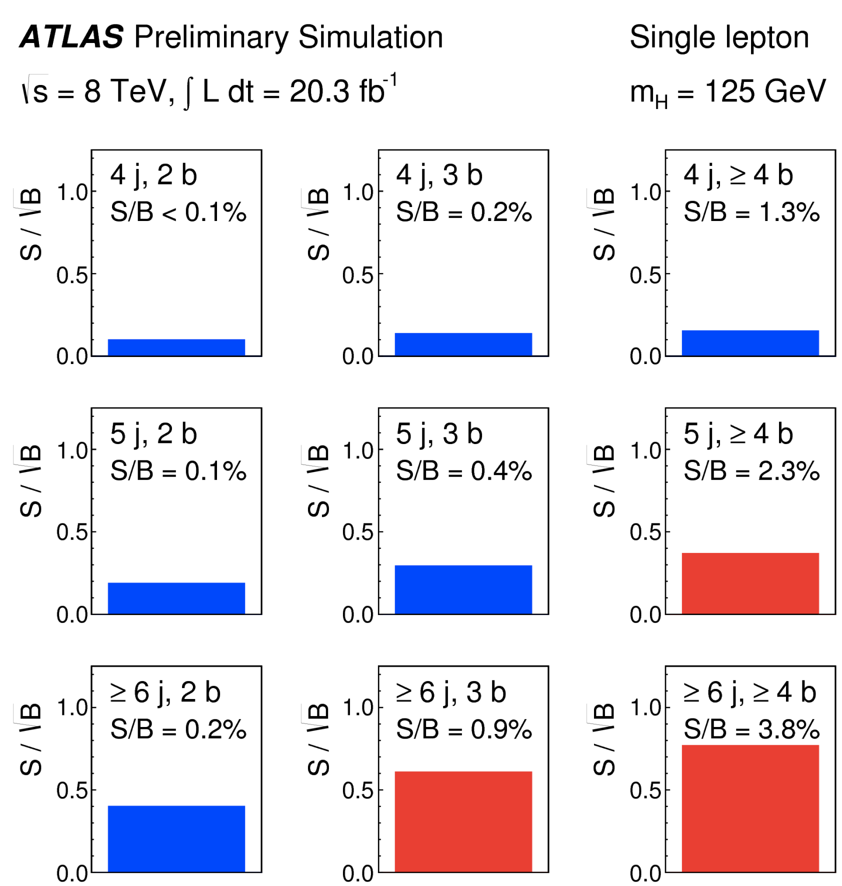
- Very complex final state:
  - **l+jets: *4 b's, 2 q's and 1 lepton***
  - **dilepton: *4 b's and 2 leptons***
- Very small S/B → use background dominated regions in profile likelihood fit to reduce uncertainties in signal regions
- **Large background and sizeable systematics have a large impact on the sensitivity**





- Categorize events according to jet and b-tag multiplicities
- Use jet scalar sum p_T (HT) in background regions and Neural Network (NN) in signal regions

l+jets	2 b-tags	3 b-tags	4 b-tags
4 jets	HT	HT	HT
5 jets	HT	NN HF	NN
6 jets	HT	NN	NN

dilepton	2 b-tags	3 b-tags	4 b-tags
2 jets	HT		
3 jets	HT	NN	
4 jets	HT	NN	NN

- **Simultaneous fit of all regions to extract signal strength**

$t\bar{t}H(bb)$ Background

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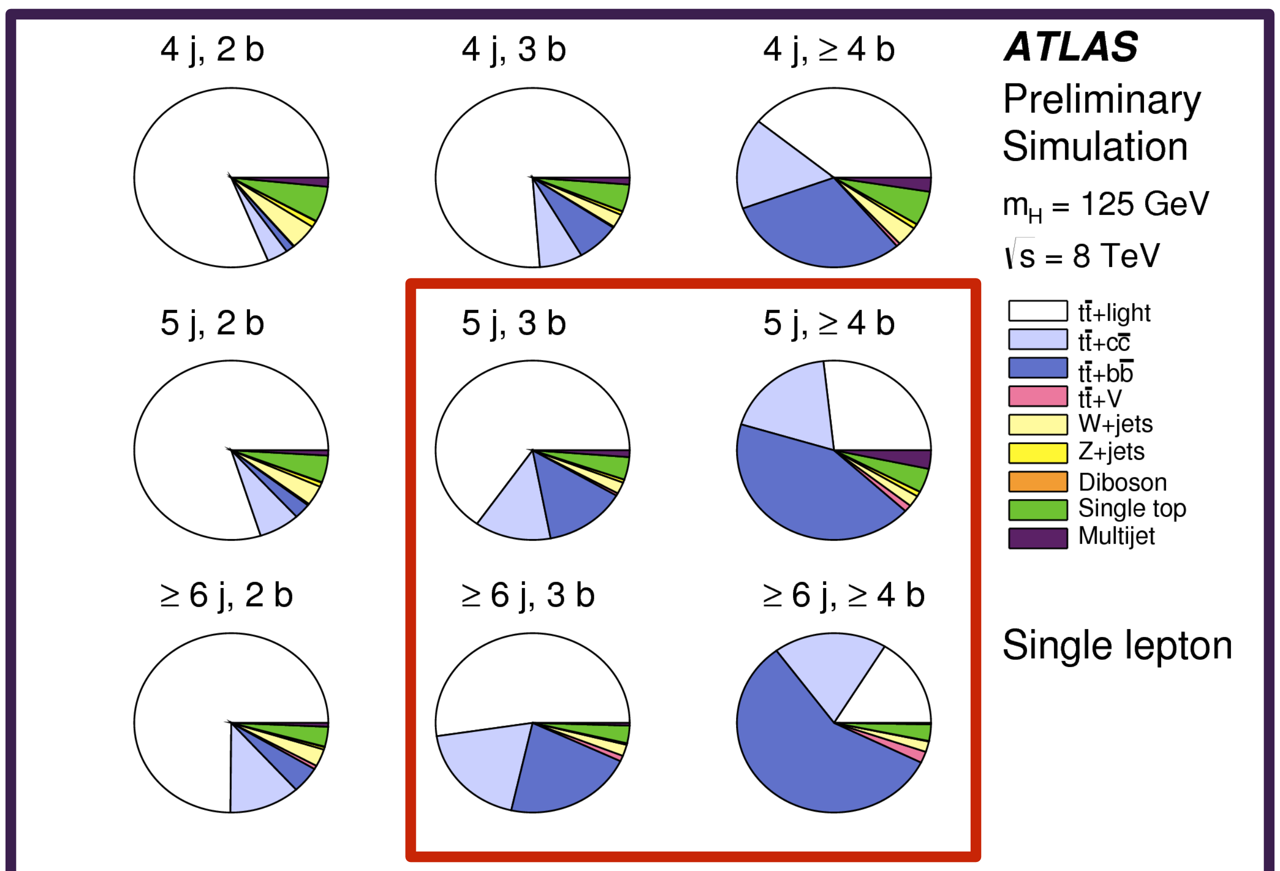
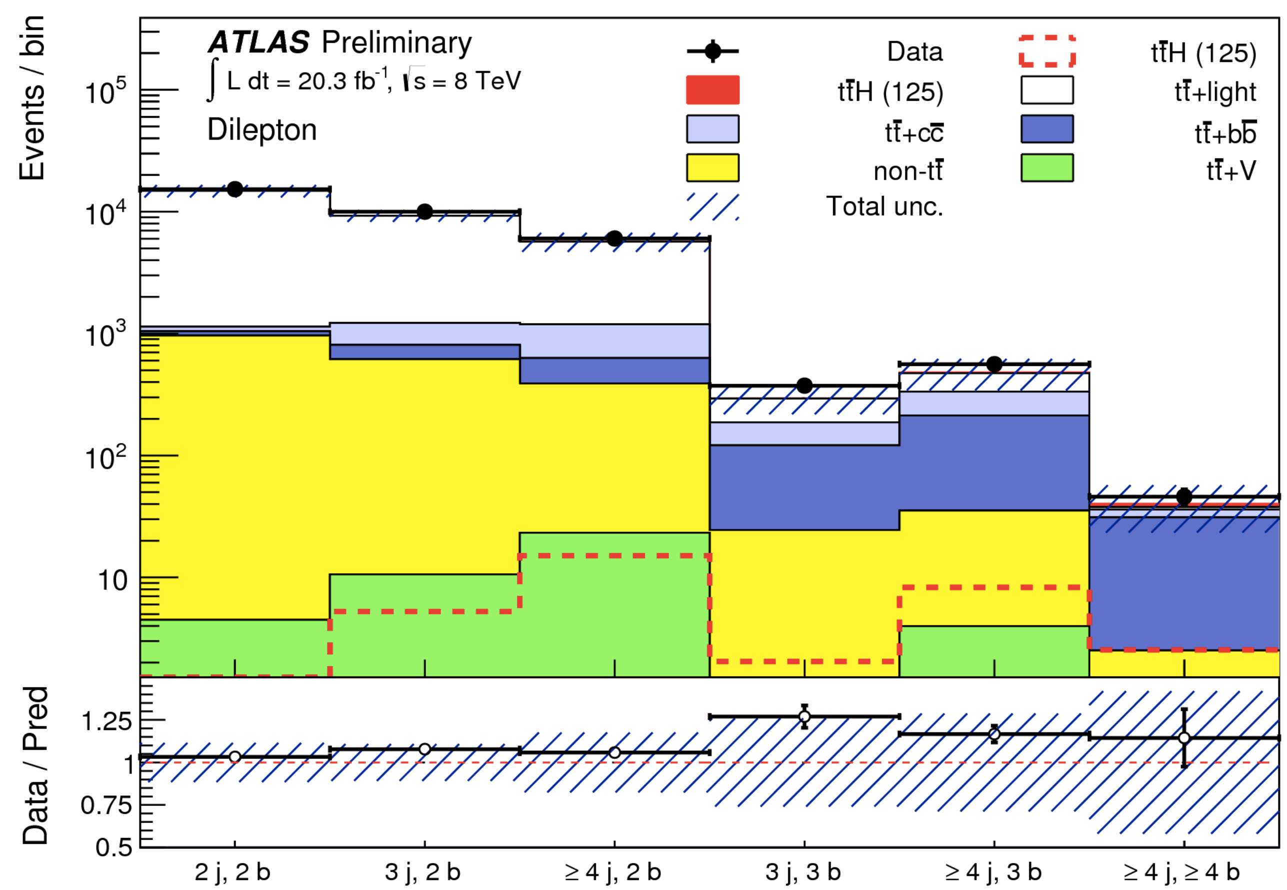
- Background modelling very important: dominated by $t\bar{t}+b\bar{b}$ and $t\bar{t}+c\bar{c}$
- $t\bar{t}$ modelled using Powheg+Pythia (also compared with Madgraph + Pythia)
  - Both top and $t\bar{t}$ p_T are re-weighted from differential cross section measurement at 7 TeV
  - Also applied to $t\bar{t}+HF$

- Both $t\bar{t}+b\bar{b}$ and $t\bar{t}+c\bar{c}$ → 50 % uncertainty on the normalization
- Top and $t\bar{t}$ p_T reweighting (affecting separately $t\bar{t}+light$ jets and $t\bar{t}+HF$ jets)
- Generator: Madgraph+Pythia vs Powheg+Pythia
- Fragmentation: Poweg+Pythia vs Powheg+Herwig





$t\bar{t}H(bb)$ Neural Network

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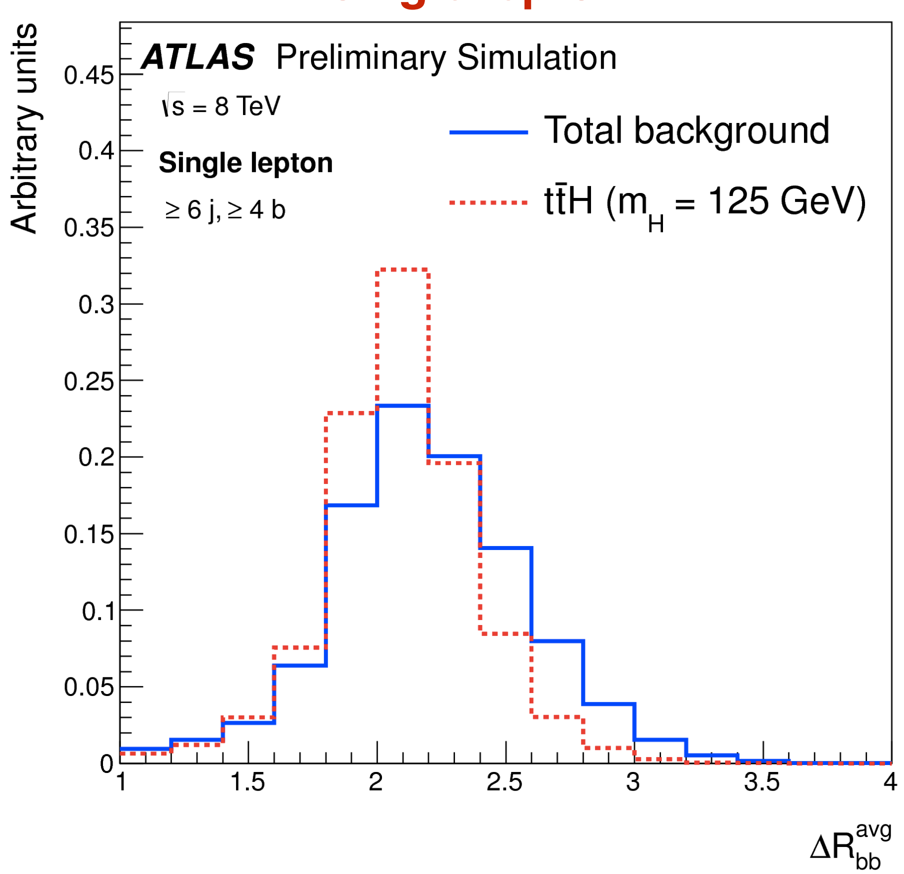
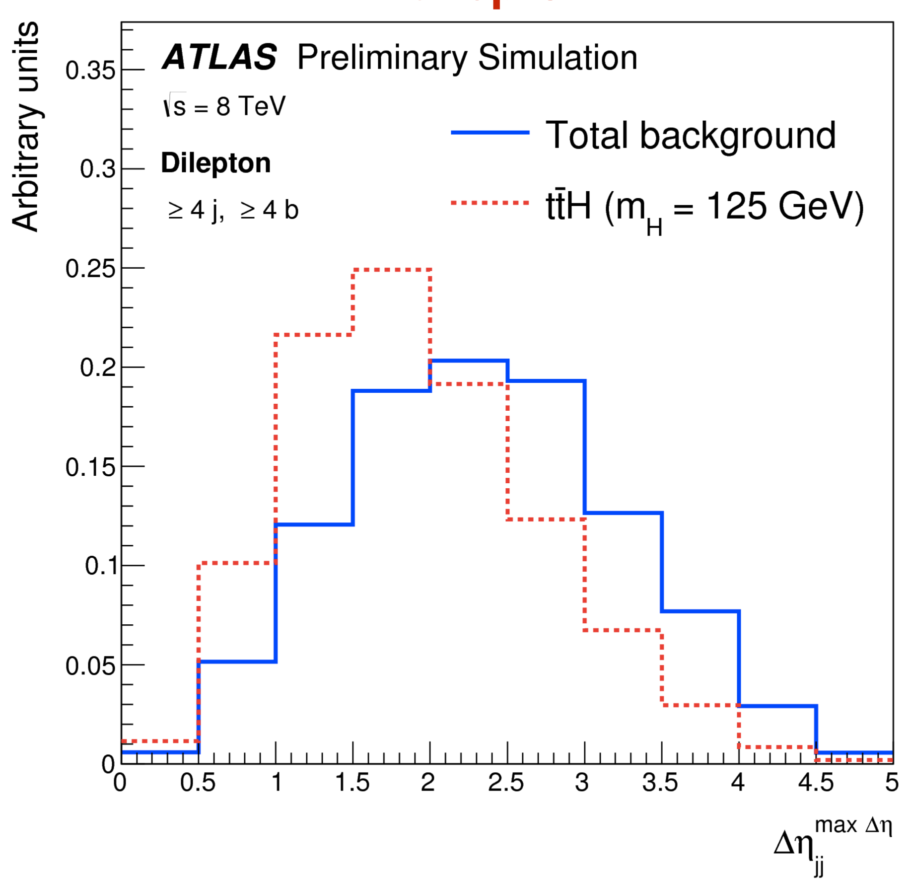
- Signal regions: train NN to separate $t\bar{t}H$ from backgrounds
- NN is built from:
  - Event shape variables (centrality)
  - Object pair properties ($\Delta\eta_{jj}$ max)
  - Object kinematics (p_T)
  - Event Kinematics (HT)
- NN in 5j / 3b built to separate $t\bar{t}$+HF from $t\bar{t}$

- **Examples of variables with largest separation in SR**

single lepton



dilepton



$t\bar{t}H(bb)$ Results

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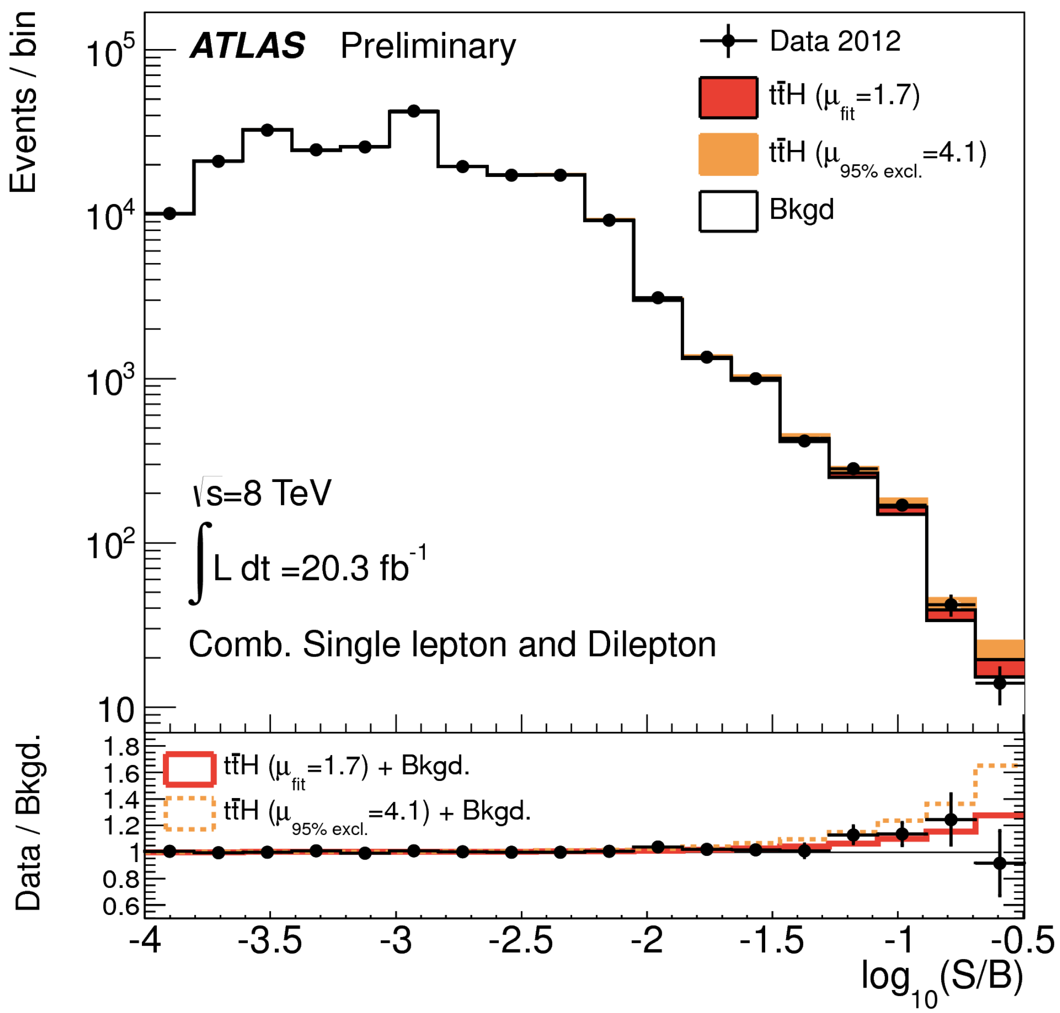

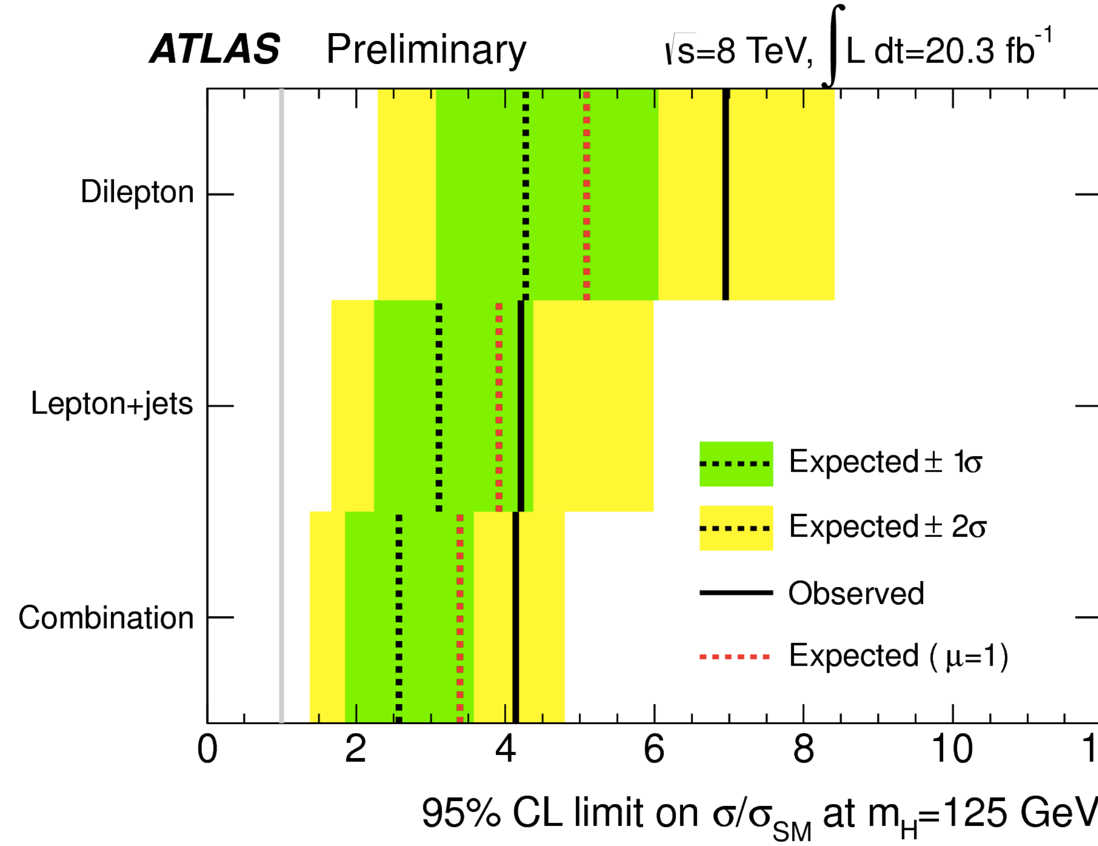

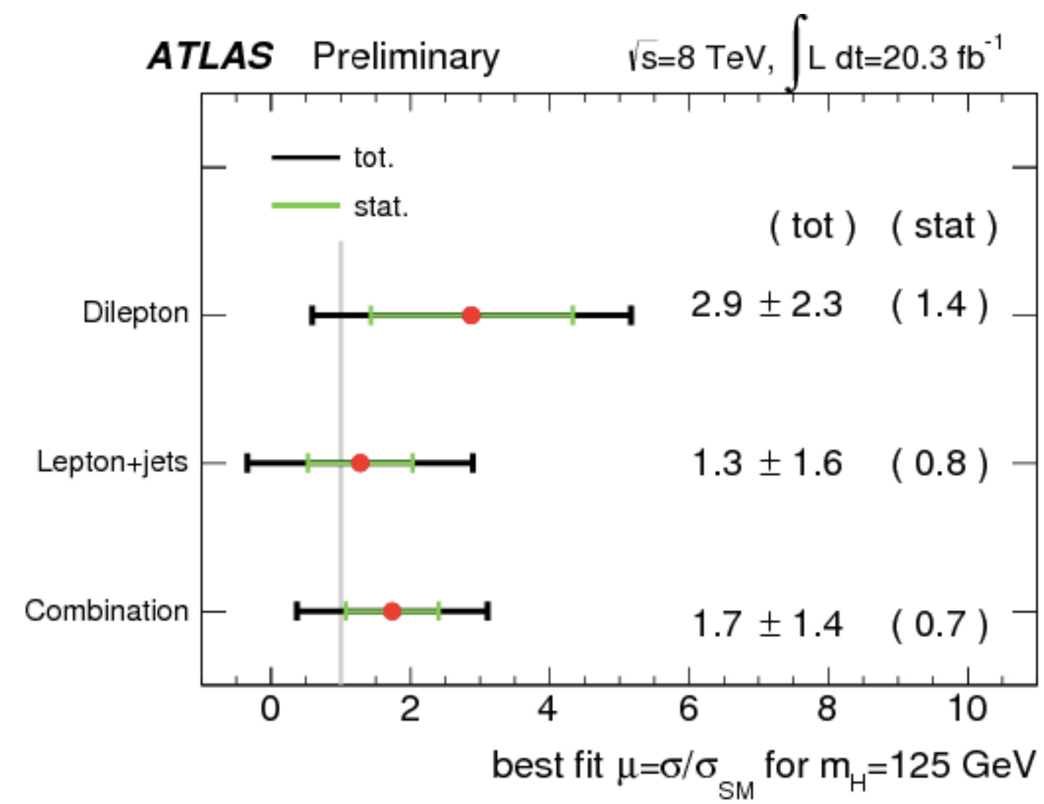

- ***Combination of single lepton and dilepton channels:***
- 95% CL observed (expected) limit:
  - 4.1 x SM (2.6 x SM) for mH = 125 GeV
- Best fit signal strength: **$\mu(t\bar{t}H)$ = 1.7 ± 1.4**

$t\bar{t}H$ Run I Combination

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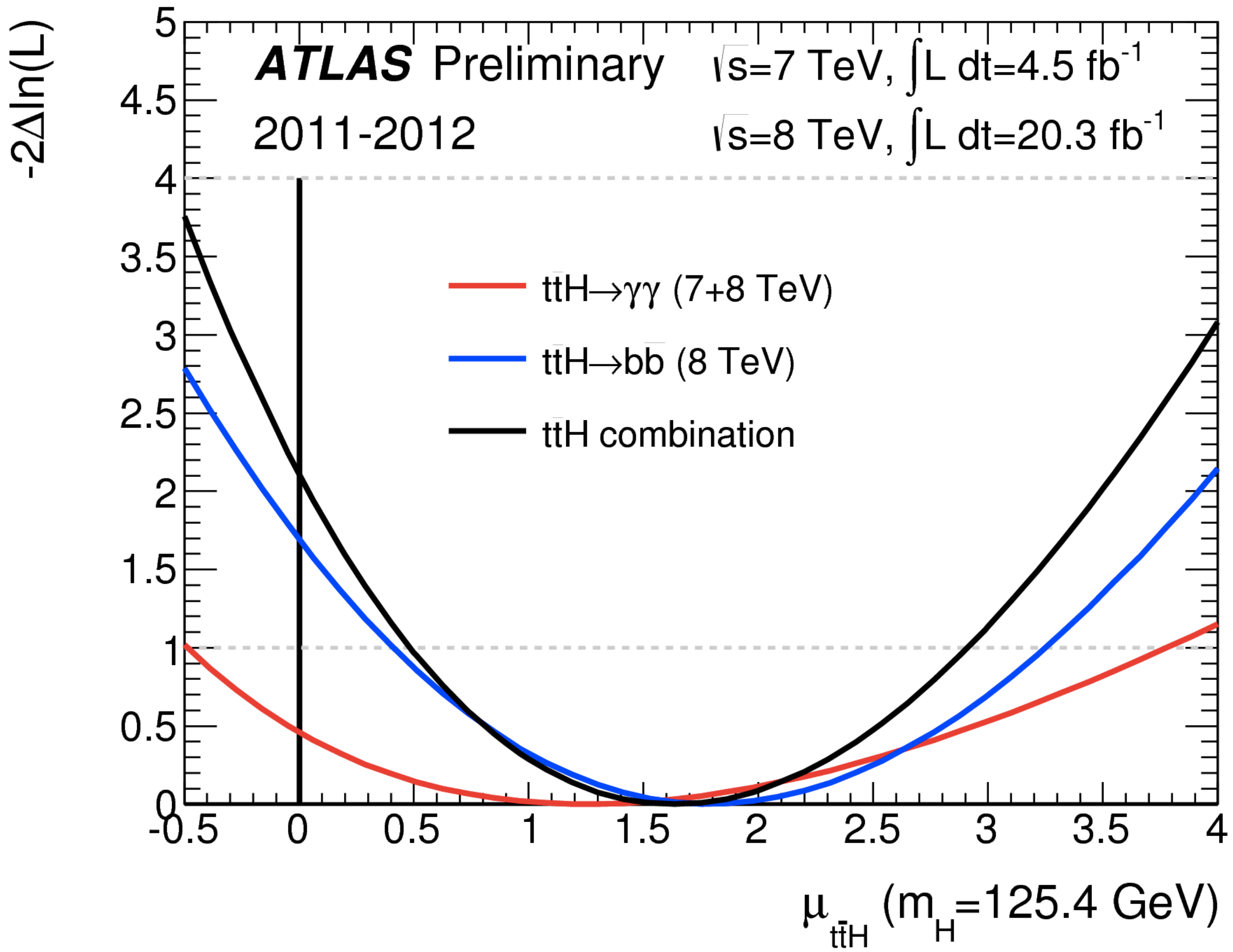
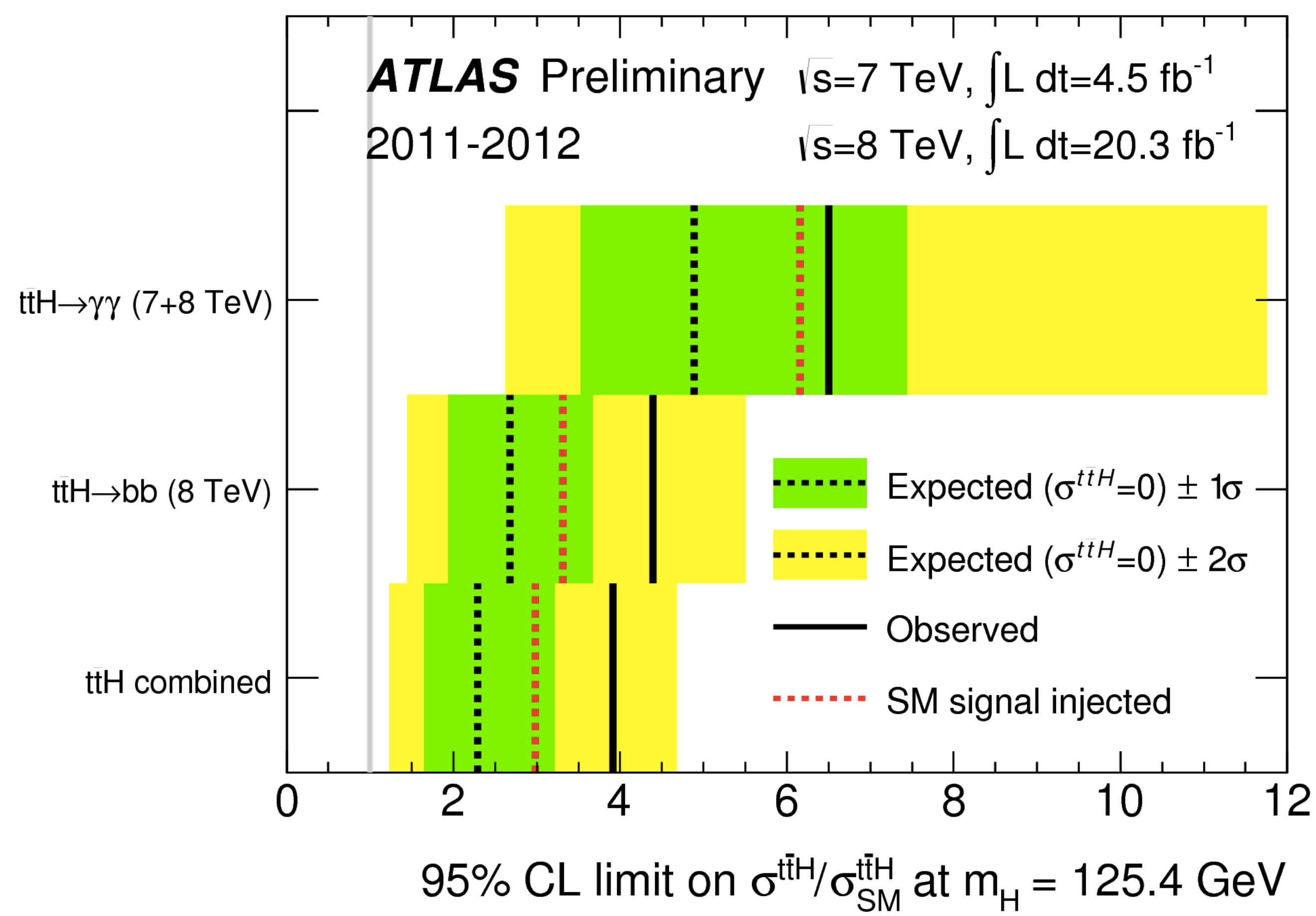


- Preliminary combination of $t\bar{t}H(bb)$ and $t\bar{t}H(\gamma\gamma)$ channels
- 95% CL observed (expected) limit:
  - 3.9 x SM (2.3 x SM) for m_H = 125.4 GeV



- Best fit signal strength:

  $\mu(t\bar{t}H) = 1.6 \pm 0.6(\text{stat.})^{+1.1}_{-1.0}(\text{syst.})$

- **Observed (expected) significance: 1.5 σ (1.0 σ)**
  - ***Observed p-value: 7 %***

Top-Yukawa Coupling

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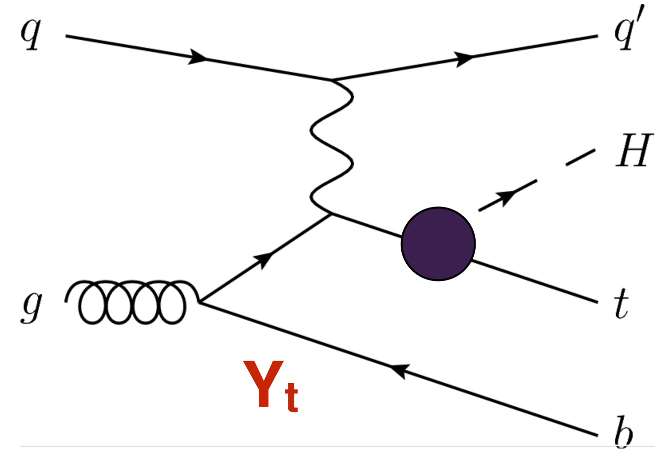
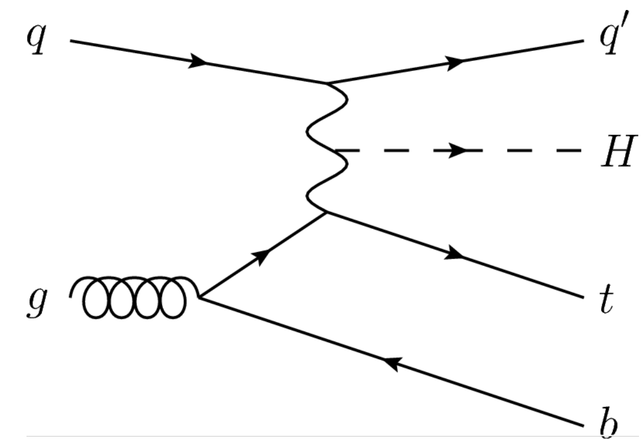
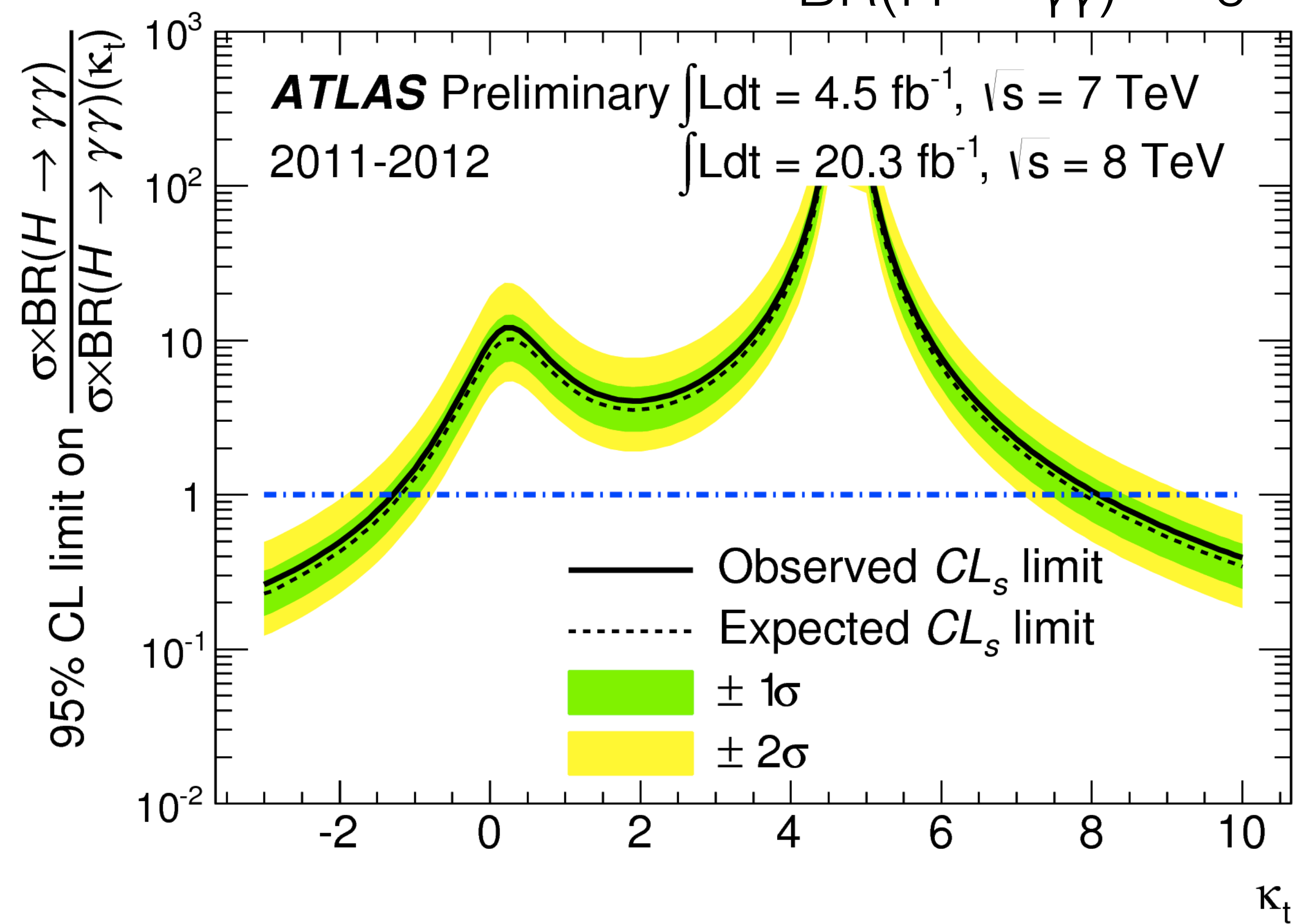
- *tH* production is highly suppressed in SM
  - Much smaller than $t\bar{t}H$
- In some BSM models Y_t can be negative:
  - Significantly increased tH cross section and BR($H \rightarrow \gamma\gamma$)
  - Destructive interference becomes constructive
  - *Attempt to rule out such hypothesis*





- **Set limits as a function of $\kappa_t = Y_t/Y_t^{SM}$**
  - Inclusive Higgs production as a function of strength to SM expectation
  - Also correlated to BR($H \rightarrow \gamma\gamma$)

- BR($H \rightarrow \gamma\gamma$) $\rightarrow$ 0



- All other couplings are set to SM
- Null hypothesis includes SM $t\bar{t}H$

- 95% CL lower and upper observed (expected) limits on κ_t
  - **κ_t: > – 1.3 and < 8.1 (– 1.2 and + 7.9)**

t →cH FCNC

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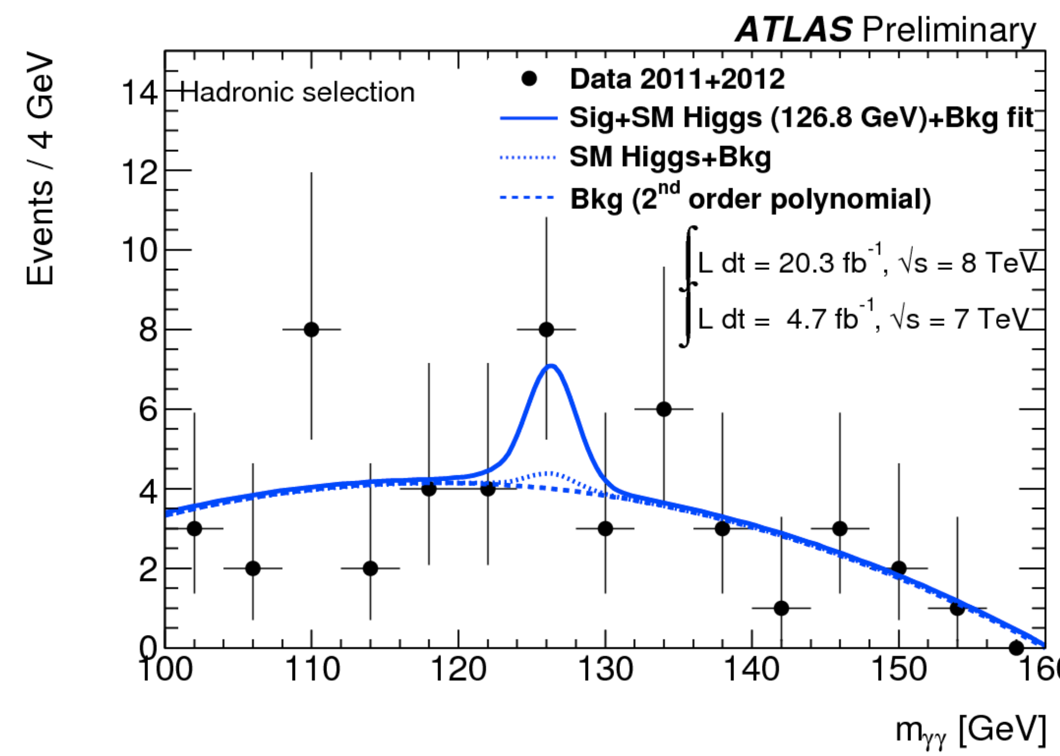
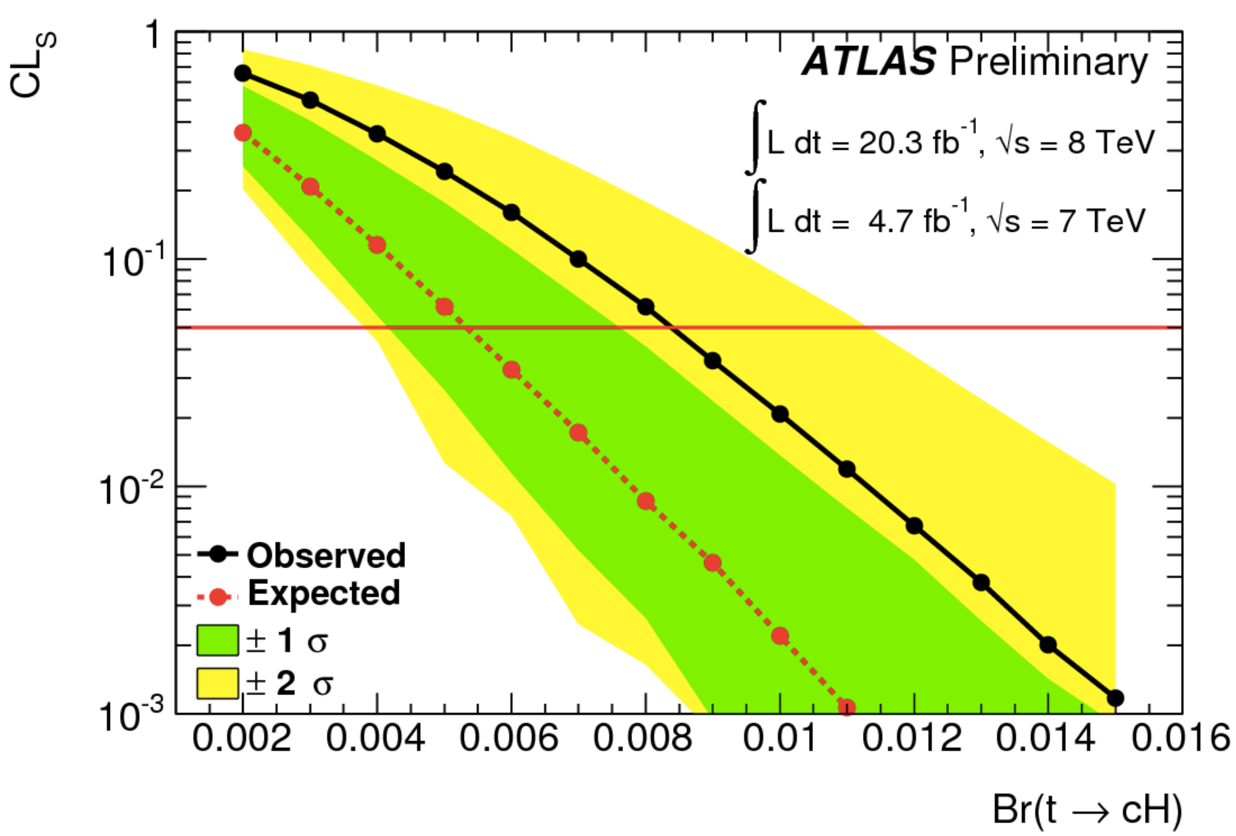
- **FCNC (flavour changing neutral current)**
- Allowed in BSM models
  - Forbidden at tree level + suppressed at higher orders in SM
- t →cH: largest branching in 2HDM type III (BR ~10^{-3})

- Measurement of di-photon mass m(γγ)
  - Resonance search with 2 isolated photons





- **Event selection:**
- **Hadronic W:** ≥ 4 jets, ≥1 b-jets
- **Leptonic W:** 1 lepton, 2 jets, ≥1 b-jets, and m_T^W > 30 GeV
- **Reconstructed top mass cuts:**
  - 156<M(γγj)<191 GeV
  - Hadronic: 130<M(jjj)<210 GeV
  - Leptonic: 135<M(lνj)<205 GeV

- **95% CL observed (expected) limit:** BR(t→Hq) < 0.83% (0.53%) and λ_{tcH} < 0.17 (0.14)

Summary and Conclusions

- ATLAS has performed searches of $t\bar{t}H$ for Higgs decays into $H \rightarrow bb$ and $H \rightarrow \gamma\gamma$
- 95% CL observed (expected) limit:
  - $t\bar{t}H(bb)$: 4.1 x SM (2.6 x SM)
  - $t\bar{t}H(\gamma\gamma)$: 6.5 x SM (4.9 x SM)

- A $t\bar{t}H$ combination yielded a 95% CL observed (expected) limit:
  - **3.9 x SM (2.3 x SM) for m_H = 125.4 GeV**
  - **Observed (expected) significance: 1.5 σ (1.0 σ)**

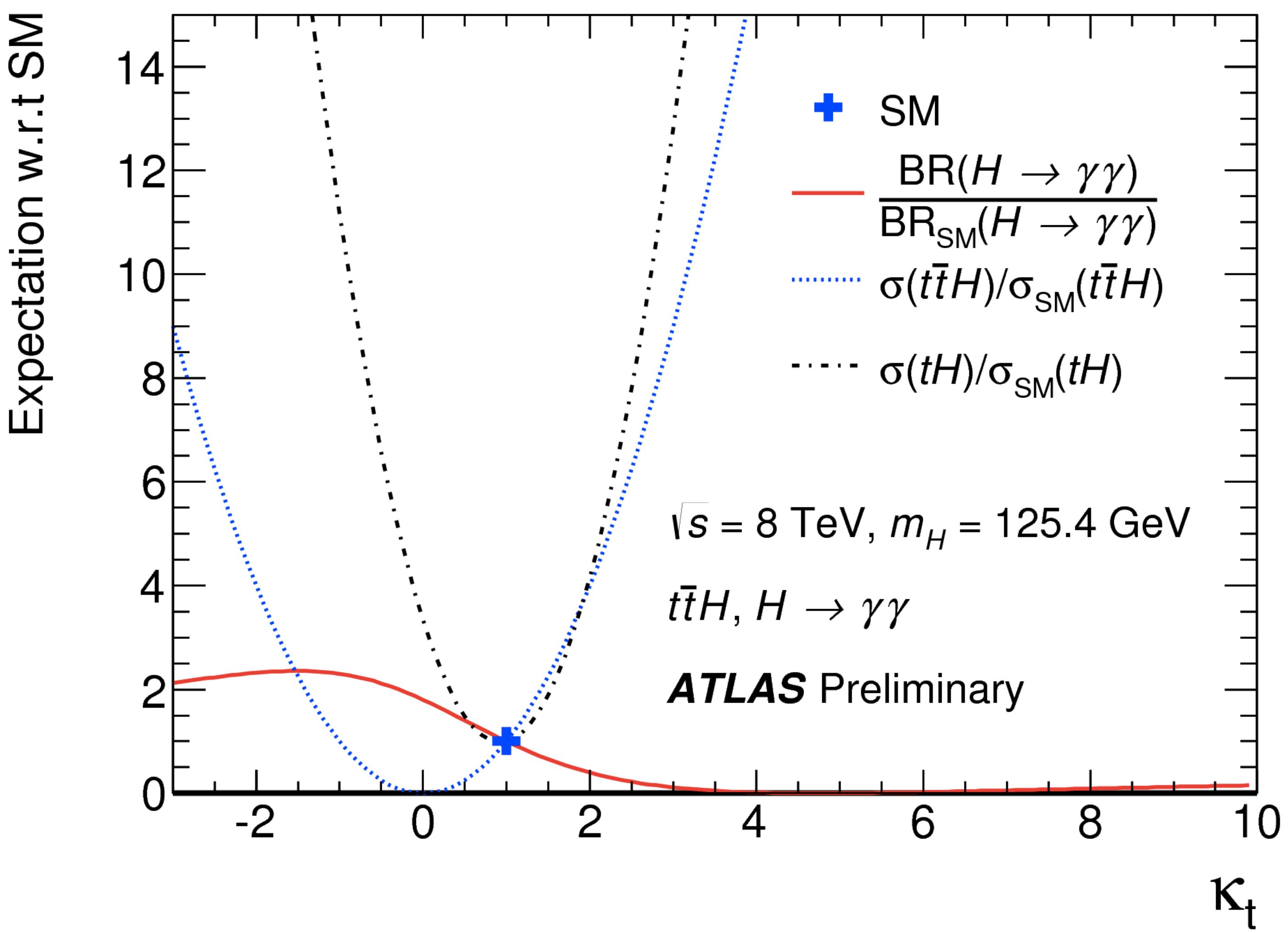
- Combination of Run I searches: close to SM sensitivity
  - Multilepton searches will be available in the very near future
- $t\bar{t}H$ observation and Yukawa coupling measurement is one of the priorities for Run II
  - Higher centre-of-mass energy will be largely beneficial for $t\bar{t}H$

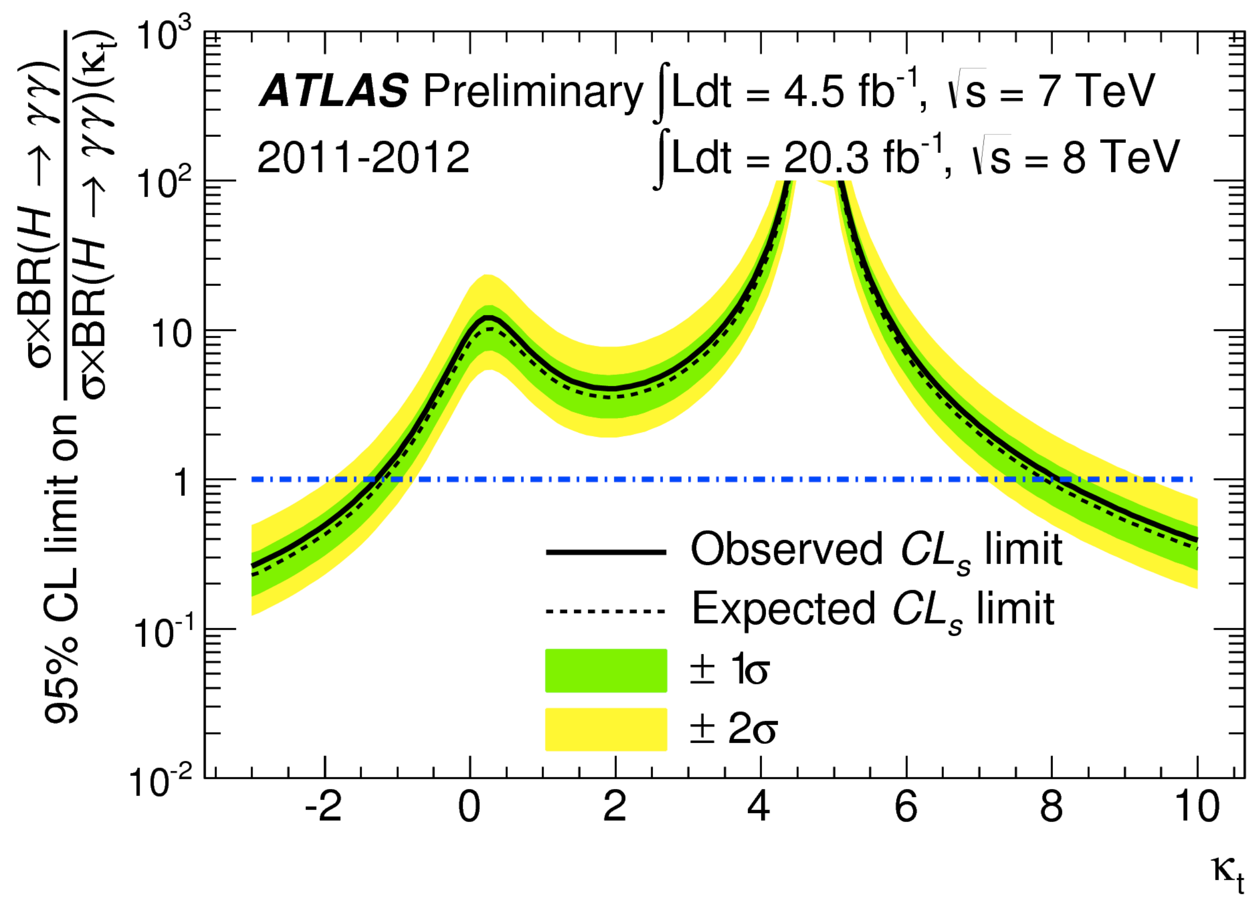
- **HL-LHC with 3 ab^{-1} Outlook:**
  - $t\bar{t}H(\gamma\gamma)$ 1+2 lepton expected 8.2 significance
  - 95 % CL $BR(t \rightarrow Hq)$: $< 1.5 \times 10^{-4}$ and λ_{tcH}: < 0.024 - rule out some BSM models

Additional Slides

Top-Yukawa Coupling

- Three effects which contribute to limit





$t\bar{t}H(bb)$ Profiling

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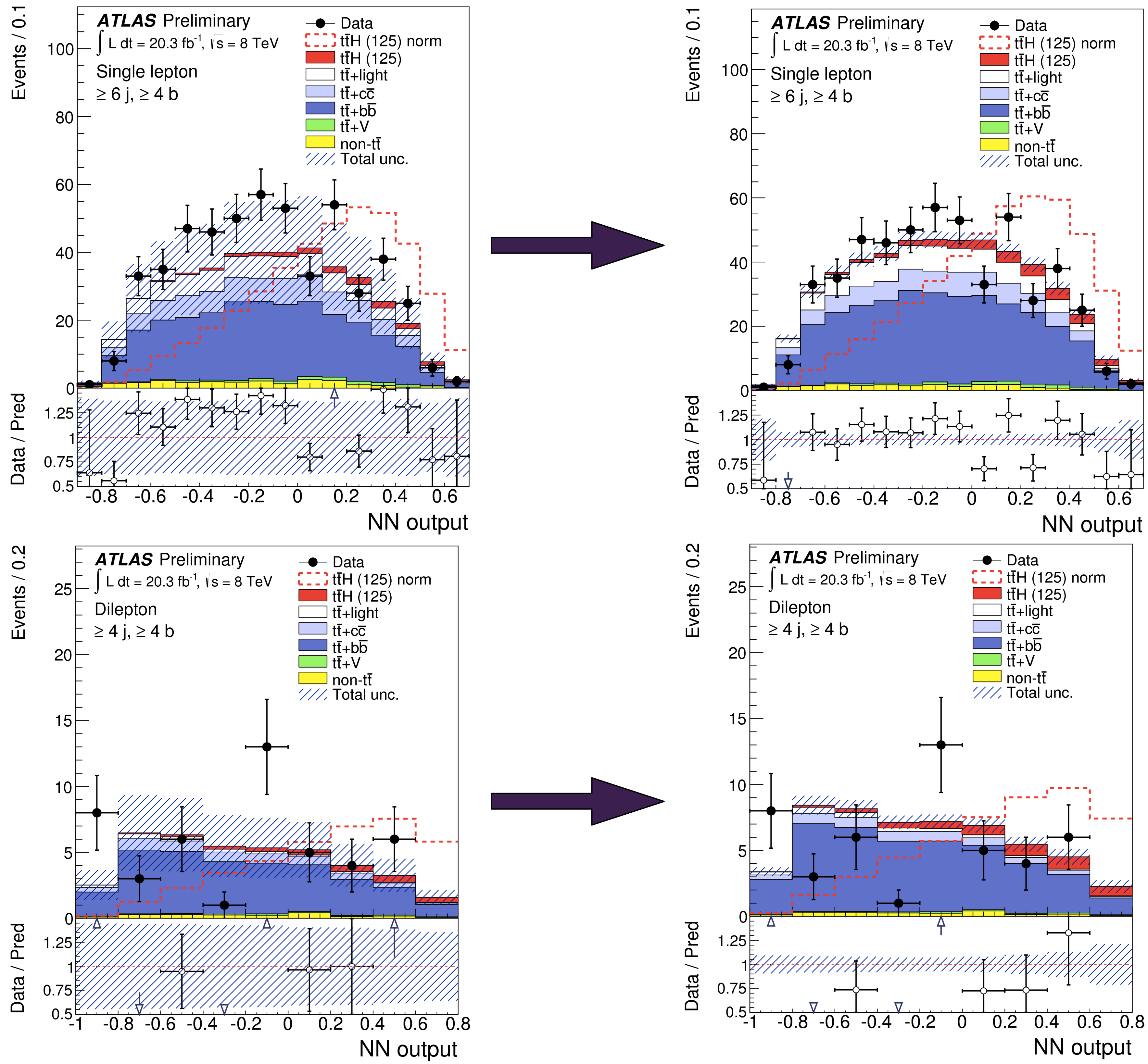
- Result of profiling on the signal region of l+jets and dilepton NN
- Reduction in systematic uncertainty



Fitted NPs for H → bb

- NP ranking based on postfit impact on signal strength:

- $t\bar{t}+b\bar{b}$ normalization
- Largest mistag variation
- $t\bar{t}$+HF : $t\bar{t}$ p_T reweighting
- Change in MC Generator for $t\bar{t}$ p_T reweighting
- $t\bar{t}+c\bar{c}$ normalization
- $t\bar{t}$+HF : Madgraph vs Powheg
- Second largest mistag variation
- $t\bar{t}$ cross section