Top Quark Couplings to the Higgs boson and EW gauge bosons (@LHC)

Kohei Yorita

Waseda University

On behalf of the ATLAS & CMS Collaborations

5-9 December, 2016
International WS for Future LC
Morioka, Japan

Outline

1. **Introduction and Run1 Results**
2. **ttH/ttV Analysis @LHC**
3. **ttH Recent Results (ATLAS/CMS)**
   - H → bb decay
   - H → γγ decay
   - H → multi-lepton channel (w/ top decay)
4. **ttV Recent Results (ATLAS/CMS)**
   - ttW and ttZ
5. **Summary & Outlook**

Introduction of ttH/ttV

■ Motivation

$$m_f = \frac{1}{\sqrt{2}} Y_f \times v$$

.. really true ?

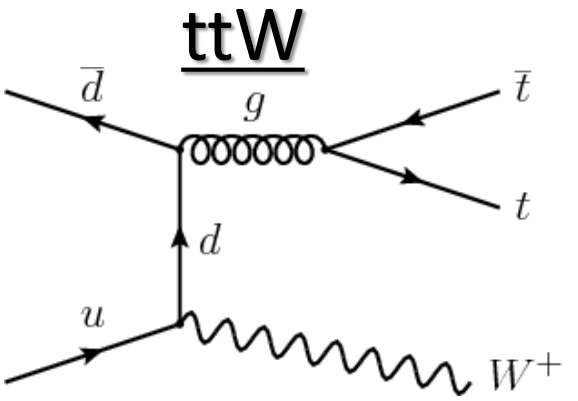
◆ ttbarH (≡ ttH) Process:

➢ Only allows direct Y_{top} measurement beyond the loop effects in gg→H production and H→γγ decay.

→ Important for BSM (direct vs Indirect)

→ Observation of quark Yukawa coupling (not yet established even for b quark)

→ Ans. for why top quark is so heavy ?



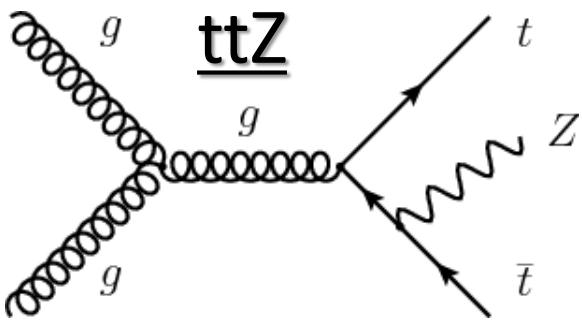
◆ ttbarV (≡ ttV) Process:

→ Main Background for ttH analysis.

→ Test Standard Model

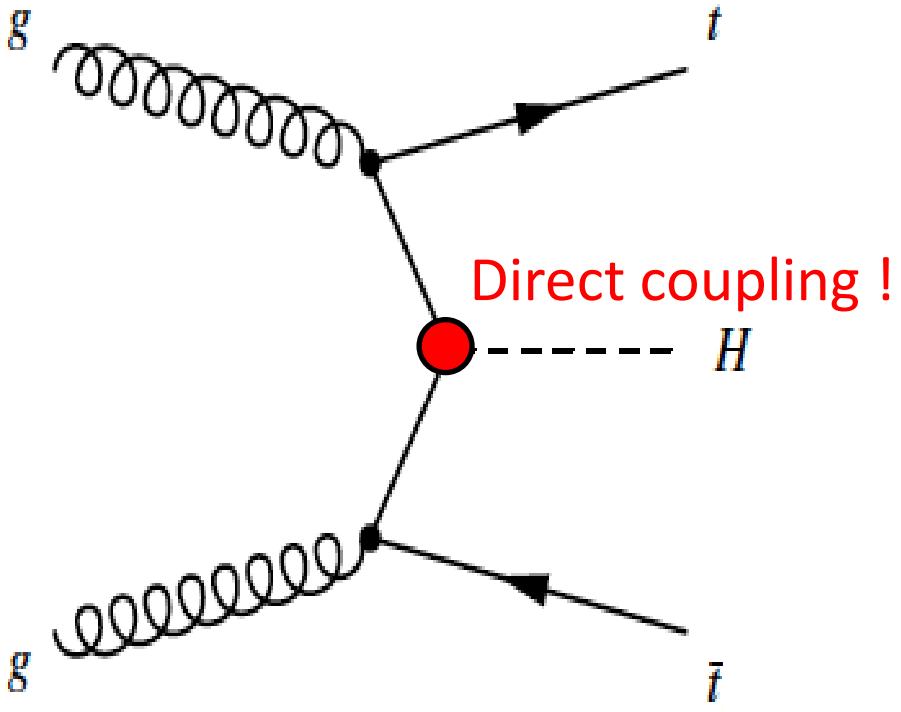
→ Direct Measurement for top-Z coupling

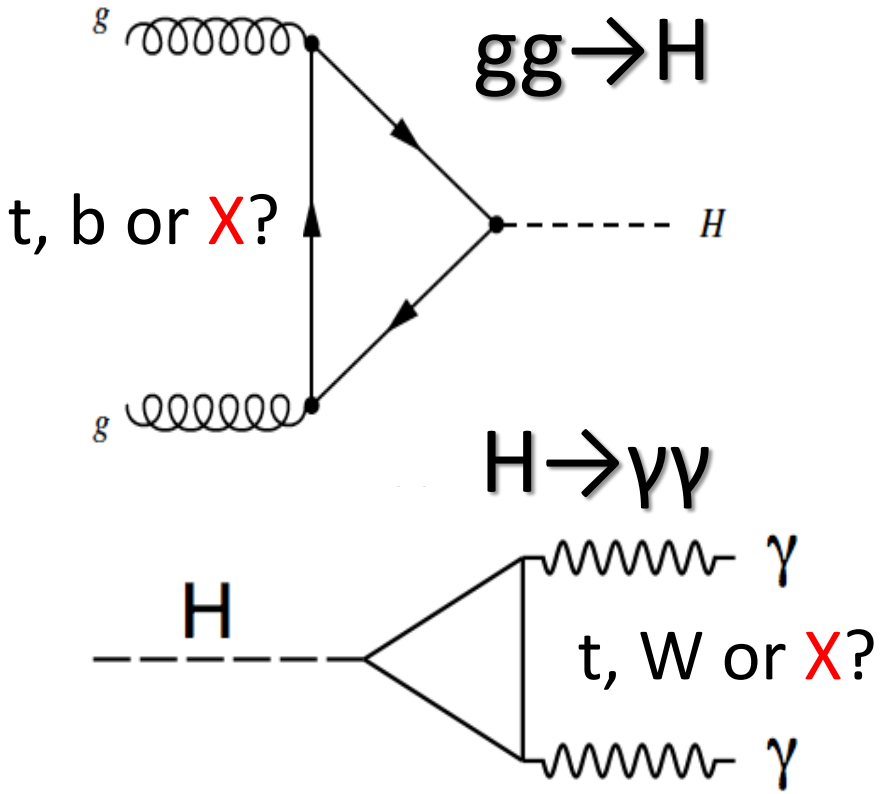
→ Sensitive to New Physics (VLQ etc)



Direct and Indirect

"Direct Top-Yukawa" (Tree Level) ⟷ "Indirect Top-Yukawa" (Loop)





"ttH@Tree Level" is very important !

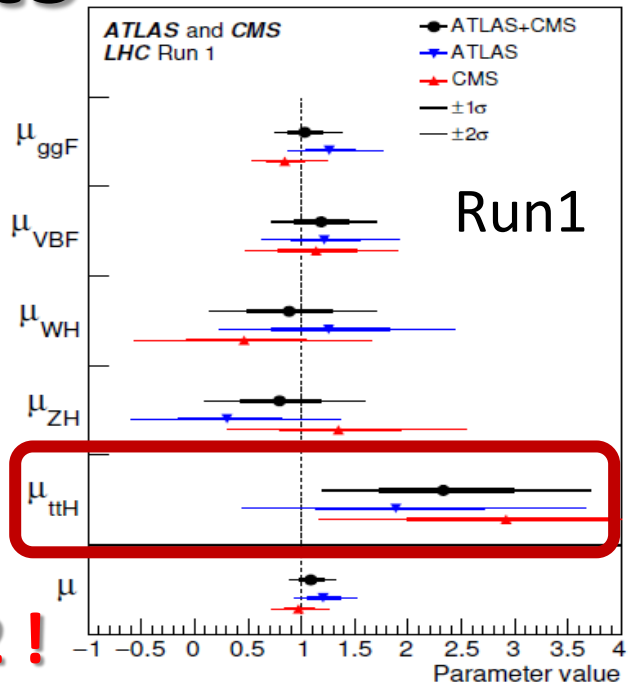
Run1 Results

ttH Summary (ATLAS&CMS)

- Mild excess in Run1 : JHEP 08 (2016) 45

$$\mu_{ttH} : 2.3^{+0.7}_{-0.6}$$ (ATLAS+CMS comb.)

- ttH Production X-section:
  σ (13 TeV) = σ (8TeV) x 3.9 (c.f. tt: x3.3)
  = 507 fb → 507 ev/fb^{-1} produced @collisions !

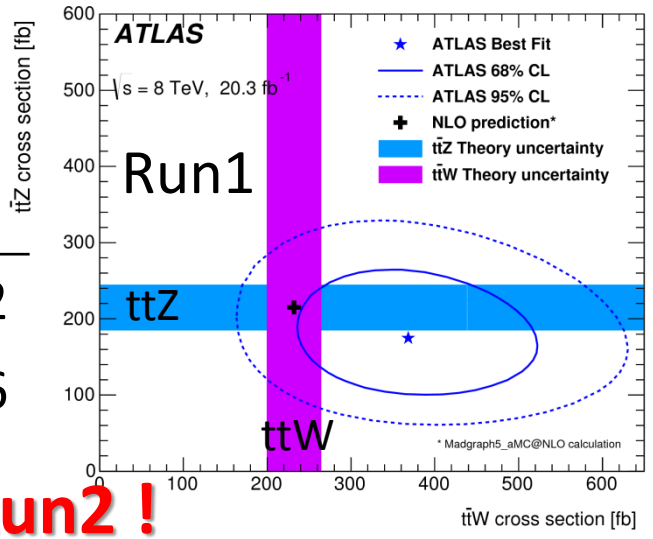


⇒ **It is time to discover/measure in Run2 !**

ttV Summary (ATLAS&CMS)

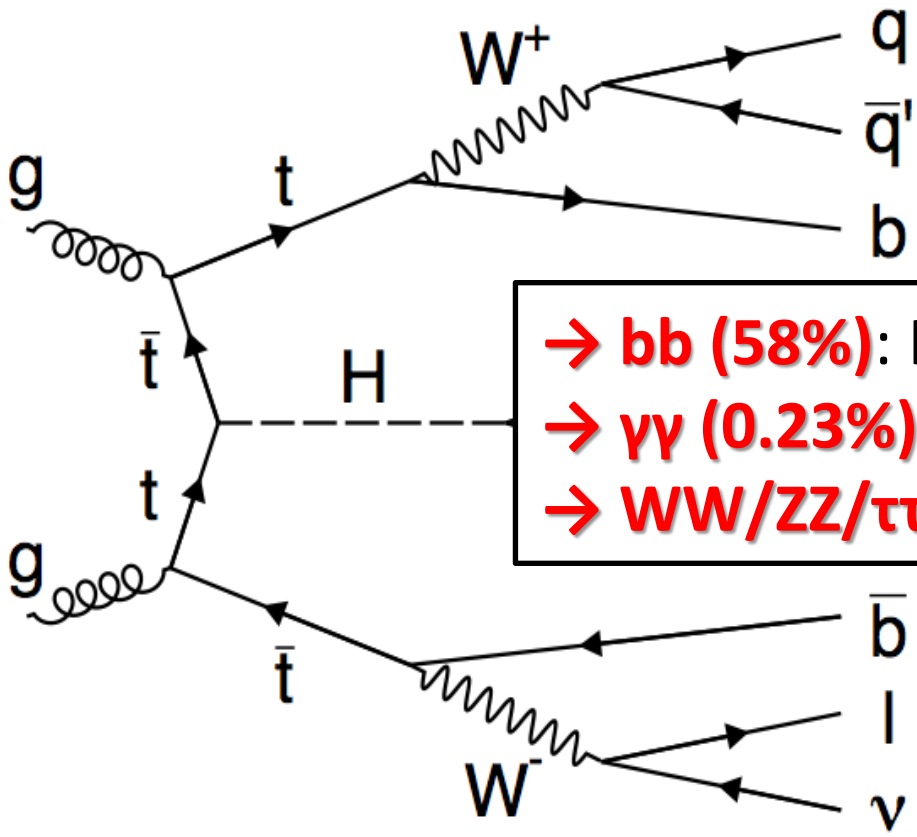
- Observation established !

@8TeV	ttW (exp.)	ttZ (exp.)	Reference
ATLAS	5.0σ(3.2σ)	4.2σ(4.5σ)	JHEP 11 (2015) 172
CMS	4.8σ(3.5σ)	6.4σ(5.7σ)	JHEP 01 (2016) 096



⇒ **Precision Measurements@13TeV in Run2 !**

ttH Analysis at the LHC



- **ttbar decay topology:**
  - → 0 lepton + 6jets
  - → 1 lepton + 4jets + Etmiss
  - → 2 lepton + 2jets + Etmiss

- → **bb (58%)**: Highest BR, Large BG
- → **γγ (0.23%)**: Tiny BR, Clean mass resolution
- → **WW/ZZ/ττ** → Multi-Leptons: Less BG

- **Many categories :**
  Based on tt/H decay products & also #jets/#bjets for SR/CR.
  → Dedicated analysis for each

- **Backgrounds :**
  W+jets, Z+jets, s-top, QCD
  tt+jets (light, ≥ b, ≥ c)
  tt+V (←Discussed in this talk)

- **Common issues :**
  bjet ID/Modeling
  tt+X Modeling etc.

Recent ttH/ttV Results

	ATLAS (fb^{-1})	CMS (fb^{-1})	Reference
ttH→bb	13.2@13TeV	12.9@13TeV	ATLAS-CONF-2016-080 CMS PAS HIG-16-038
ttH→γγ	13.2@13TeV	12.9@13TeV	ATLAS-CONF-2016-067 CMS PAS HIG-16-020
ttH→ML*	13.3@13TeV	12.9@13TeV	ATLAS-CONF-2016-058 CMS PAS HIG-16-022
Combination	13.2-13.3	2.3-2.7	ATLAS-CONF-2016-068 CMS: TTHCombMoriond2016
tH	-	→ lepton: 19.7@8TeV → bb: 2.3@13TeV	CMS PAS HIG-14-026 CMS PAS HIG-16-019
ttW/Z	3.2 @13TeV	12.9 @13TeV	arXiv:1609.01599 CMS PAS TOP-16-017
ttγ	4.6 @7TeV	19.7 @8TeV	PRD 91, 072007 (2015) CMS PAS TOP-14-008

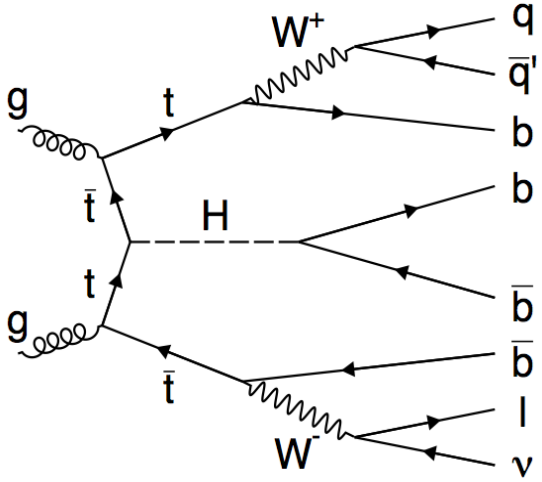
* ML: Multi-Lepton Channel

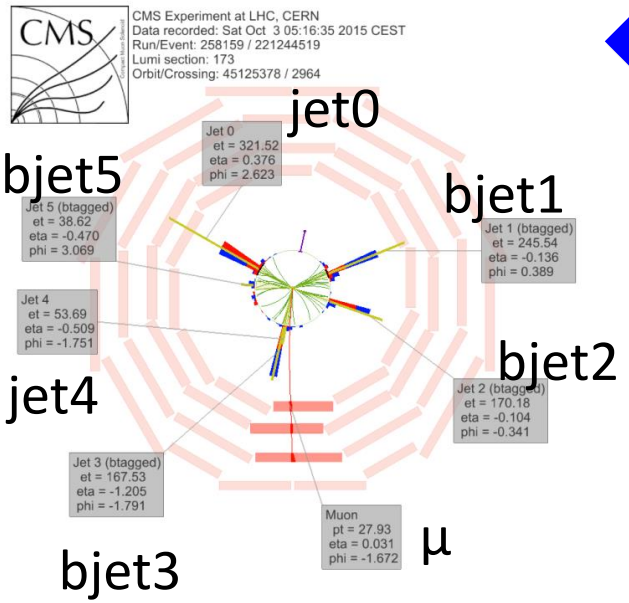
Today's topics

ttH→bb Process

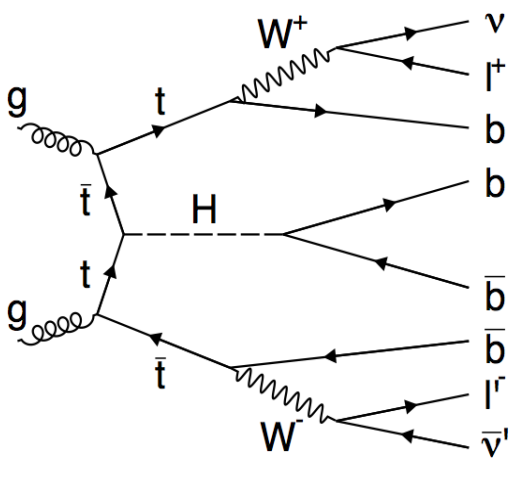
■ Both ATLAS and CMS use Single Lepton and Dilepton channels

◆ Single Lepton



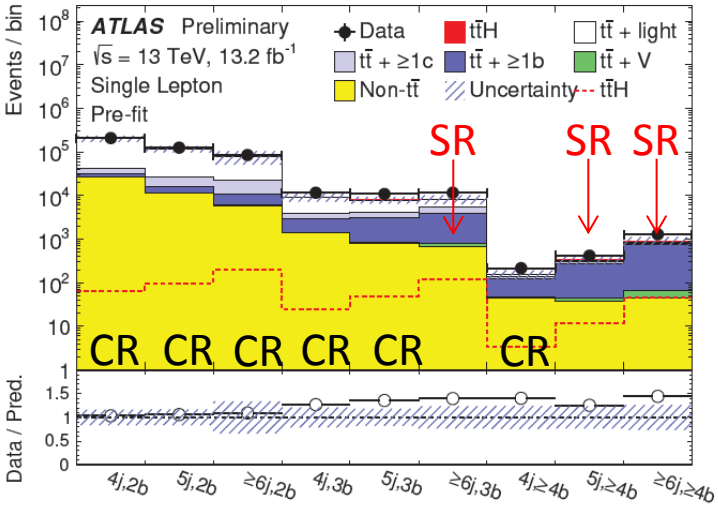


◆ Dilepton



Final State:
== 1 lepton (e/μ)
≥ 4 jets (Anti-Kt4)
≥ 2 b-tagged jets

→ SR/CR are defined depending on #jets and #bjets



Final State:
== 2 OS leptons (e/μ)
≥ 3 jets (Anti-Kt4)
≥ 2 b-tagged jets

ttH→bb: Method (ATLAS)

- **ATLAS Analysis Method: Sequence of BDTs (and NN for Dil-3j3b)**

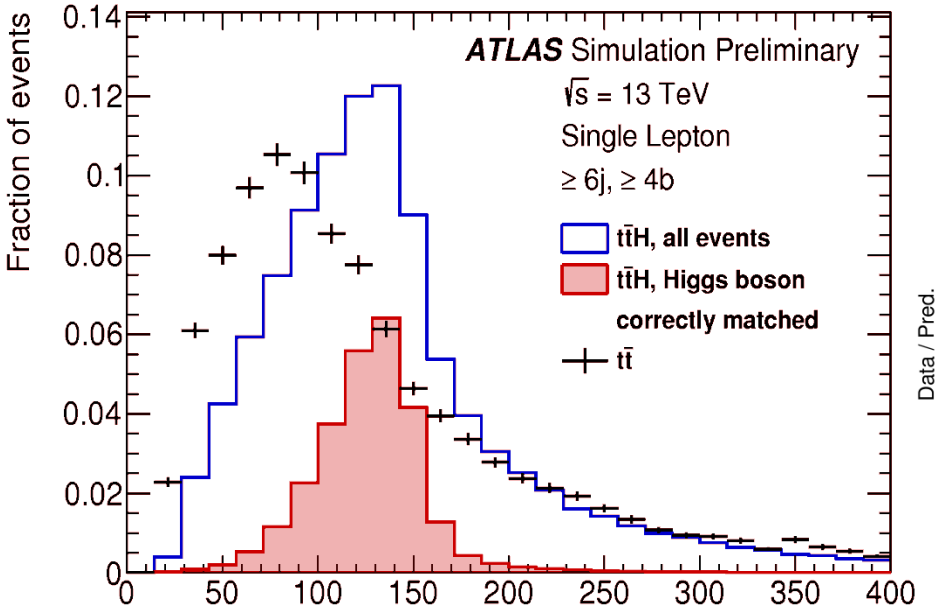
1. Reconstruction BDT (RecoBDT)

→ Match jets to partons (H/top)

S: Right Assignment in ttH

B: Wrong Assignment in ttH

Inputs: ~20 var. (w/o Higgs inf)



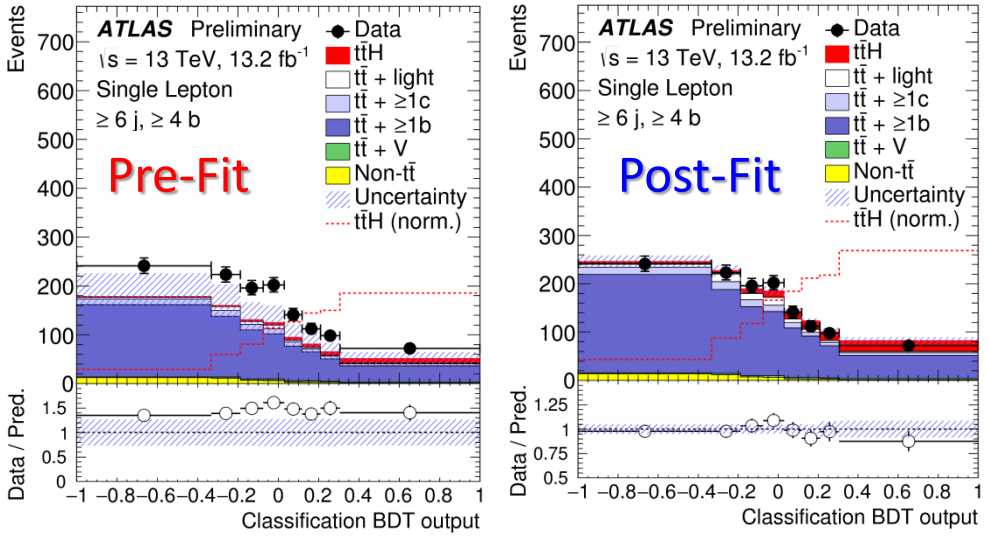
~ 30% is correct matching.

(* 16% if randomly selected)

2. Classification BDT

→ Extract Signal from BG

Inputs: 15 variables with RecoBDT.

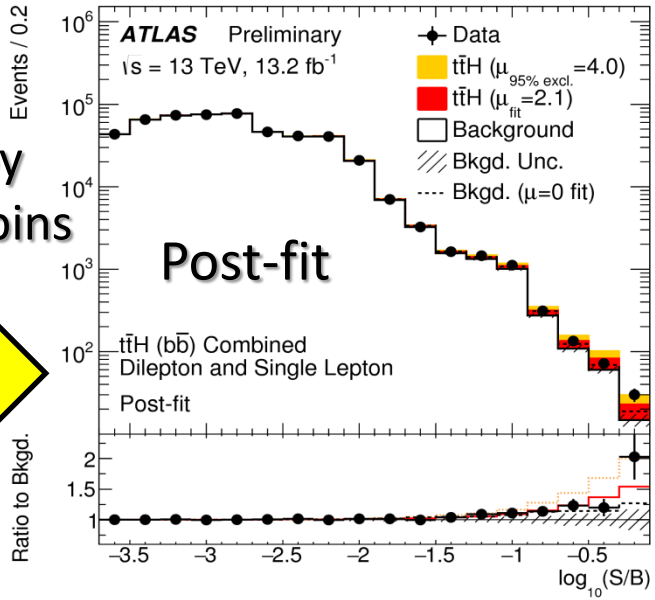


CR H_T distributions are simultaneously fitted with class. BDT of SR to constrain tt + ≥ 1b/1c backgrounds (freely float).

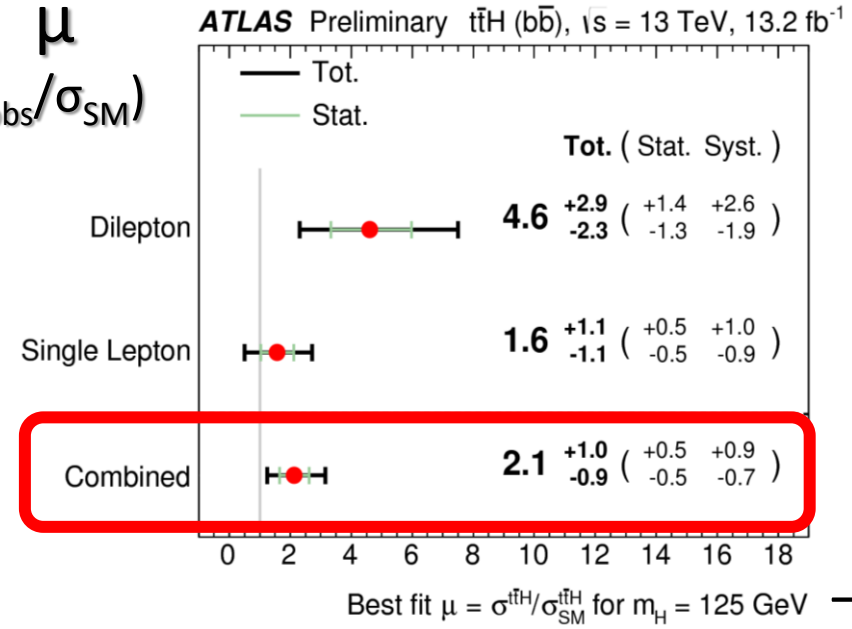
→ Simultaneous fit to extract #Signal

ttH→bb: Results (ATLAS)

Ordered by S/B of all bins



➢ μ (σ_{obs}/σ_{SM})



➢ 95% CL Upper Limit

$$\mathrm{SM} \times 4.0 \; (1.9 \; ^{+0.9}_{-0.5} \; [\mu = 0])$$

➢ Uncertainties:

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.53	−0.53
Jet flavour tagging	+0.26	−0.26
$t\bar{t}H$ modelling	+0.32	−0.20
Background model statistics	+0.25	−0.25
$t\bar{t}+\geq 1c$ modelling	+0.24	−0.23
Jet energy scale and resolution	+0.19	−0.19
$t\bar{t}$+light modelling	+0.19	−0.18
Other background modelling	+0.18	−0.18
Jet-vertex association, pileup modelling	+0.12	−0.12
Luminosity	+0.12	−0.12
$t\bar{t}Z$ modelling	+0.06	−0.06
Light lepton (e, μ) ID, isolation, trigger	+0.05	−0.05
Total systematic uncertainty	+0.90	−0.75
$t\bar{t}+\geq 1b$ normalisation	+0.34	−0.34
$t\bar{t}+\geq 1c$ normalisation	+0.14	−0.14
Statistical uncertainty	+0.49	−0.49
Total uncertainty	+1.02	−0.89

Dominated by tt + ≥ 1b model (& Scale)

→ Better understanding of tt+HF is crucial.

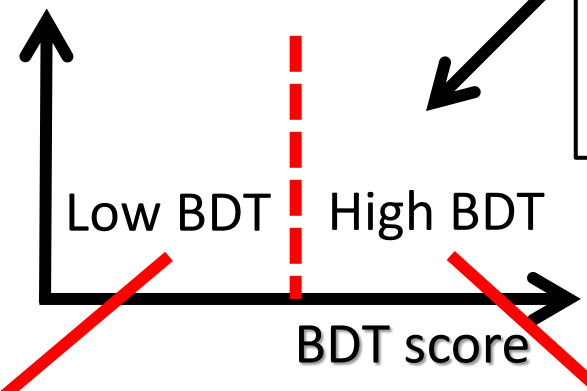
ttH→bb: Method (CMS)

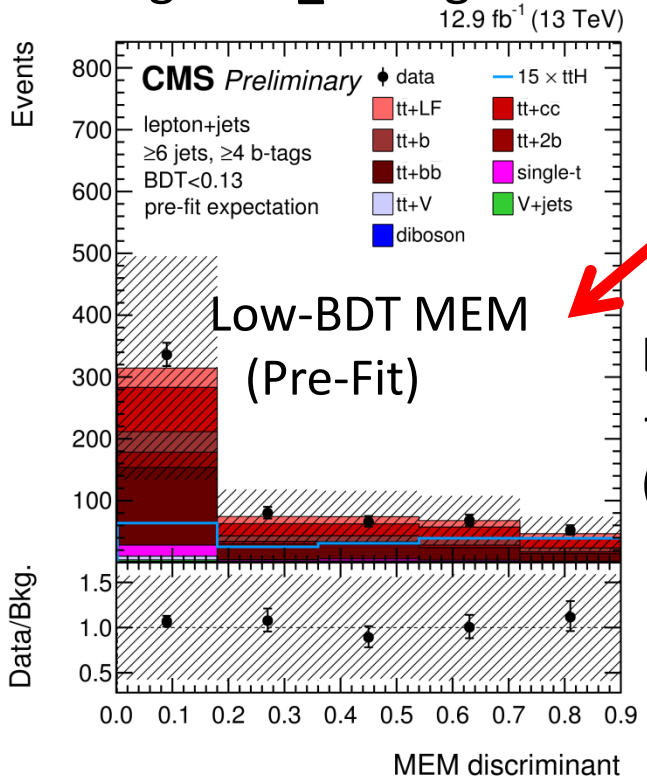
CMS Analysis Method: BDT and MEM (Matrix Element Method)

A separate BDT is trained for each category:
- 4 for lepton+jets
- 3 for dilepton

Against ∑ background

BDT Inputs (example):
- M(tag,tag) closest to 125 GeV
- 4th and 5th highest btag score
- SumPt etc



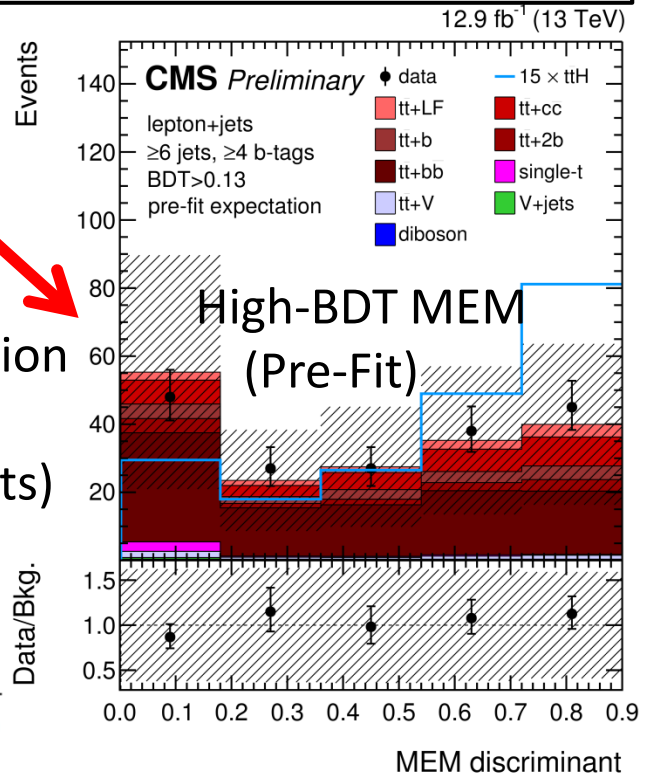


MEM Calculation

LO ME, PDF, Transfer, Resolution
→ Per-event S/B probability
(Integrate over missing objects)

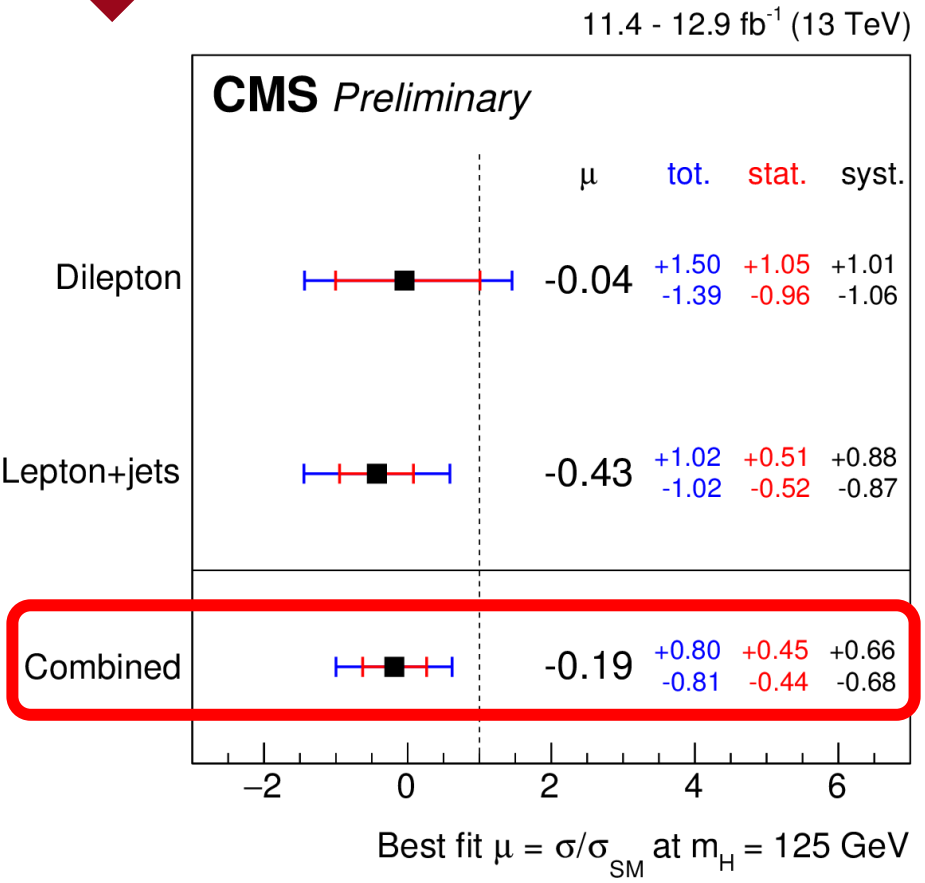
S: ttH vs B: tt+bb

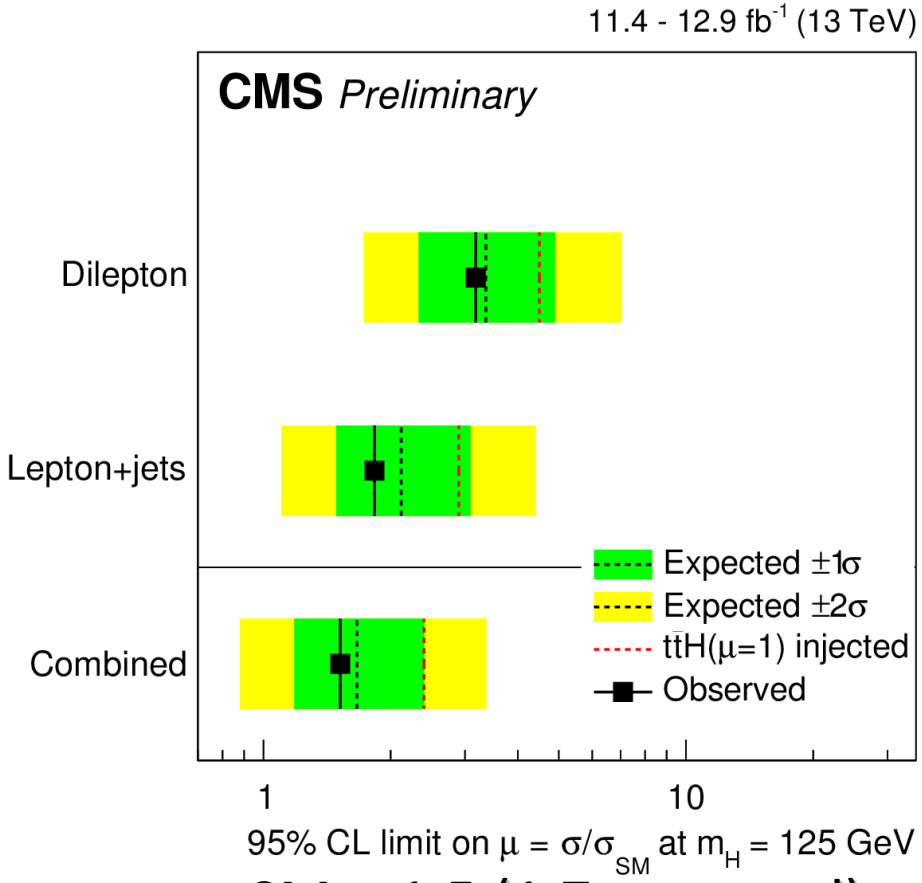
$$P_{s/b} = \frac{w(\vec{y}|t\bar{t}H)}{w(\vec{y}|t\bar{t}H) + k_{s/b}\, w(\vec{y}|t\bar{t}+b\bar{b})}$$



→ Fit MEM discriminant to extract Signal from Backgrounds

ttH→bb: Results (CMS)





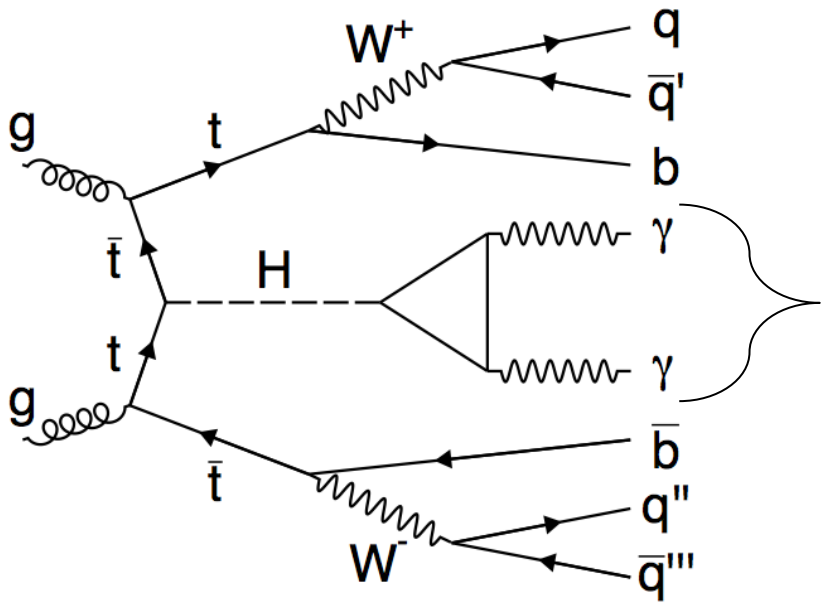
SM × 1.5 (1.7 expected)

◆ Compared to the SM:

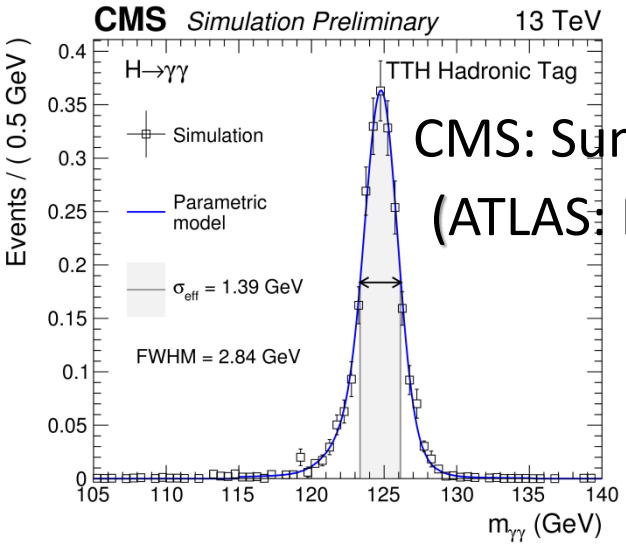
☛ Lower fluctuation of $\mu = -0.19^{+0.80}_{-0.81}$ (c.f. ATLAS $\mu = 2.1 \pm 1.0$)
→ Run2 sensitivity already exceeded Run1 results.

☛ No conclusions yet and both experiments are getting limited by systematics.
→ Better understanding of tt+HF modeling, flavor tagging, MC statistics etc.

ttH→γγ Overview



◆ Mγγ Signal Model:



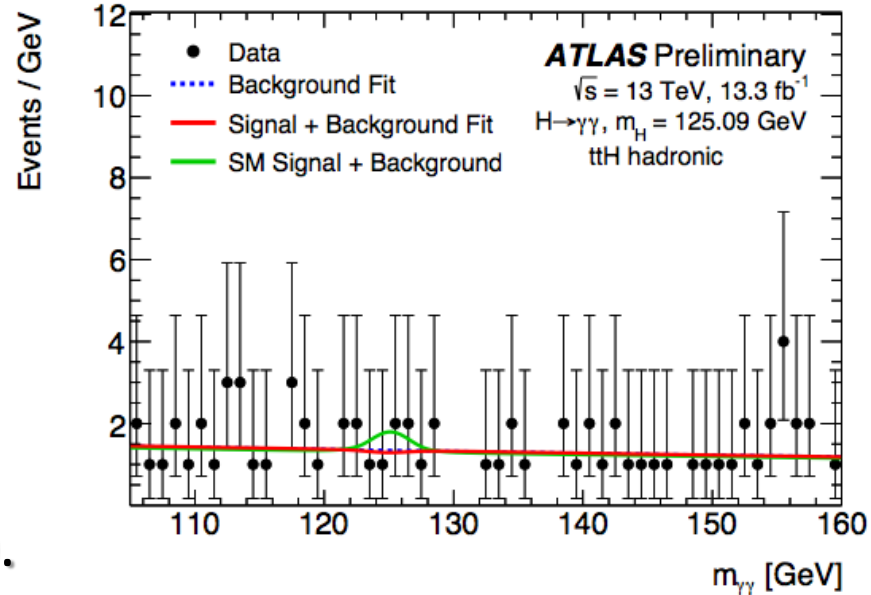
CMS: Sum of Gaussians

(ATLAS: Double-Sided Crystal Ball)

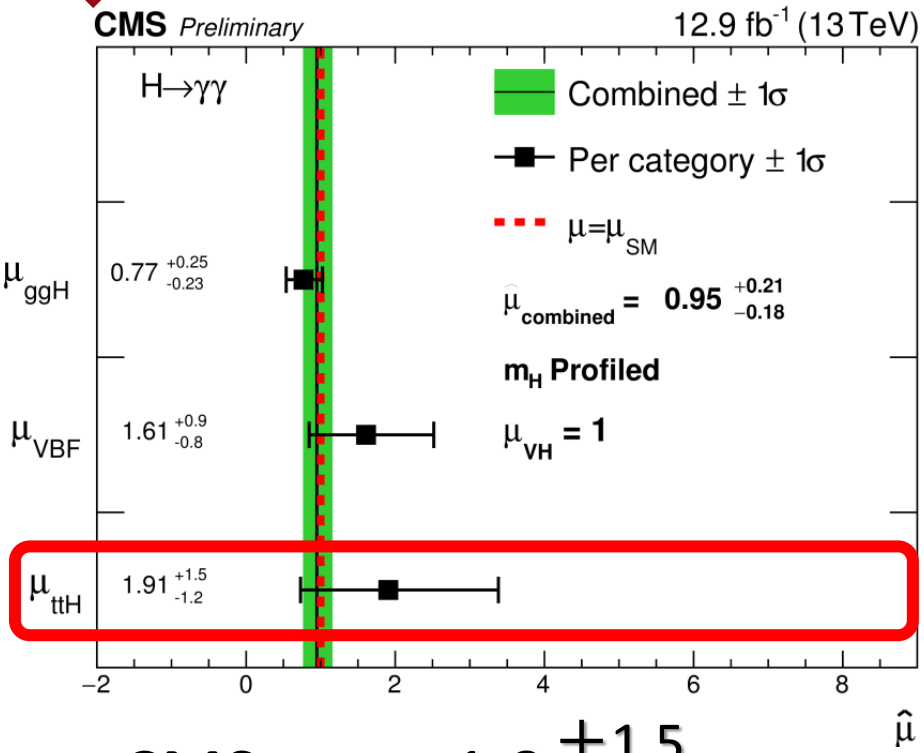
◆ Require two isolated photons:

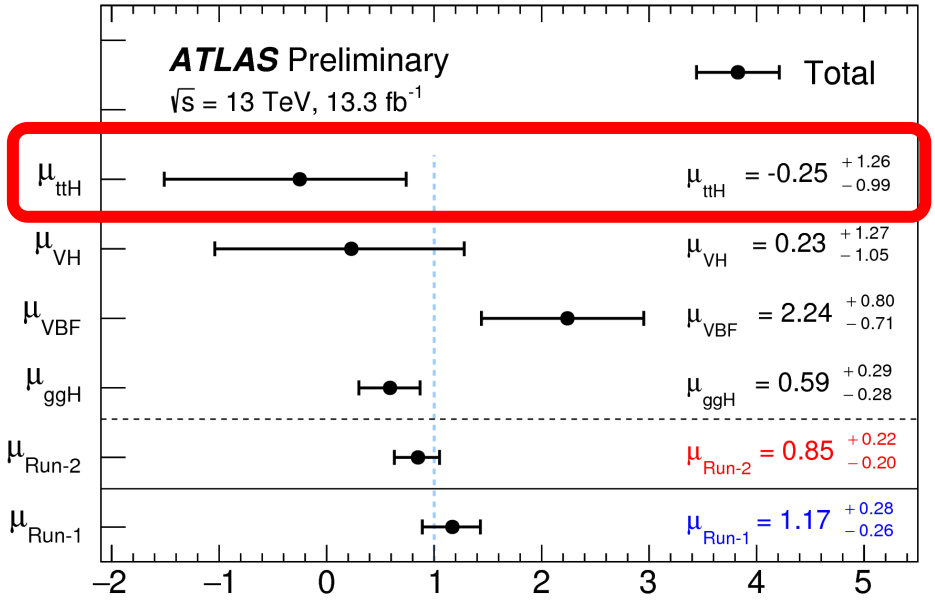
Hadronic Channel	Leptonic Channel
No lepton (e/μ)	≥ 1 lepton (e/μ)
≥ 5 jets (Anti-Kt4)	≥ 2 jets (Anti-Kt4)
≥ 1 b-tagged jets	≥ 1 b-tagged jets
	E_T^{miss}, Z veto etc

→ Contamination from other Higgs process is typically very low (<10%).



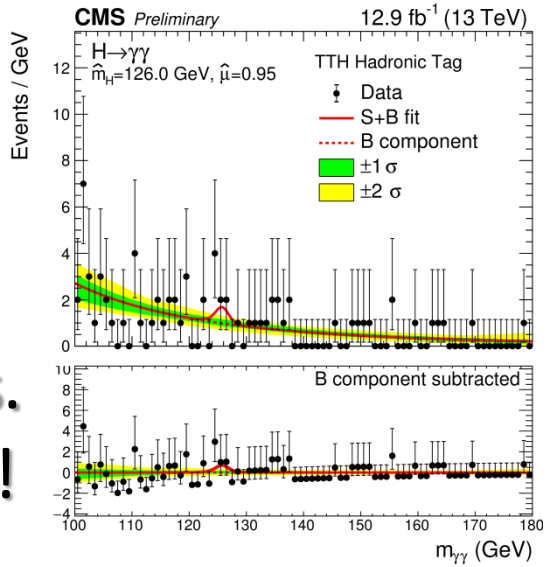
ttH→γγ Results





$$\text{CMS } \mu_{ttH} = 1.9^{+1.5}_{-1.2}$$

$$\text{ATLAS } \mu_{ttH} = -0.25^{+1.26}_{-0.99}$$



☛ The uncertainty is dominated by statistics.
→ Will be improved by more data, ~ √L !

ttH→Multi-Lepton Overview

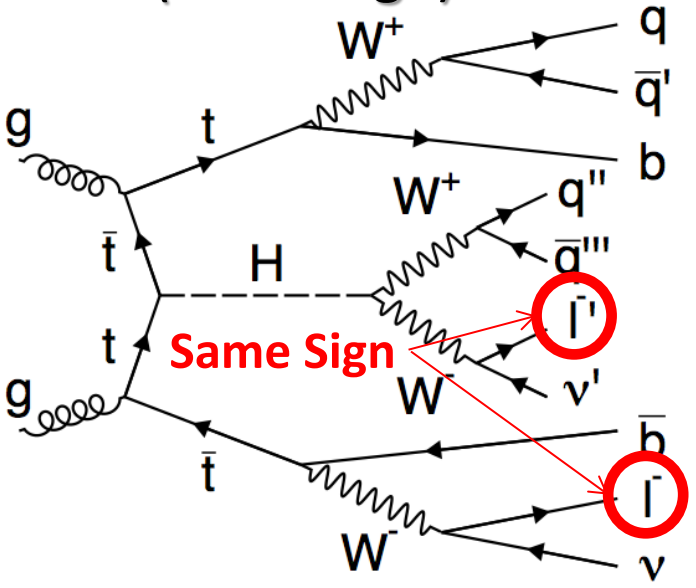
- Multi-Lepton final states are from H→WW*, ττ, ZZ* decay and inclusively searched.
- Categorized by #lepton and its flavor:
  ATLAS: 2LSS+0τ, 2LSS+τ, 3L, 4L
  CMS: 2LSS+0τ, 2LSS+τ, ≥3L

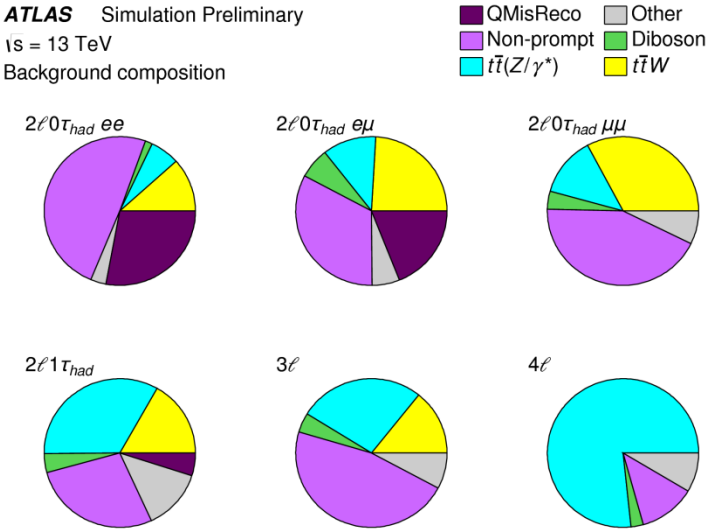
ATLAS Category	Higgs boson decay mode WW^*	$\tau\tau$	ZZ^*	Other	$A \times \epsilon$ $(\times 10^{-4})$
$2\ell 0\tau_{\text{had}}$	77%	17%	3%	3%	14
$2\ell 1\tau_{\text{had}}$	46%	51%	2%	1%	2.2
3ℓ	74%	20%	4%	2%	9.2
4ℓ	72%	18%	9%	2%	0.88

- ATLAS: Cut based analysis
- CMS: Multivariate method

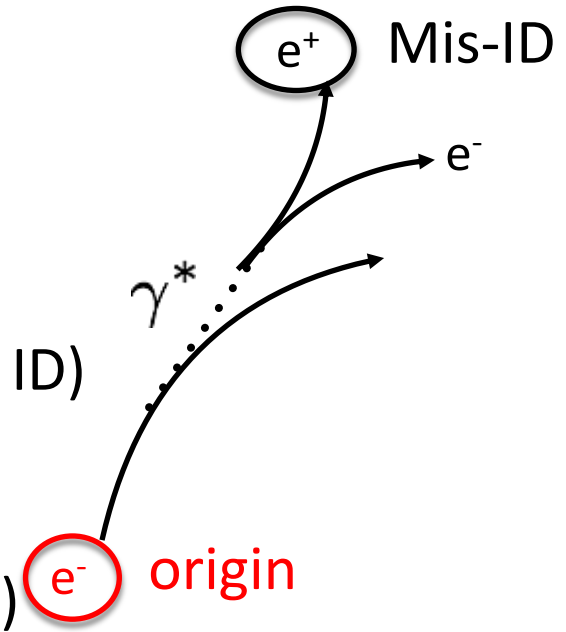
to increase S/B and extract signal.

Ex: 2LSS(Same Sign)





ttH→ML Backgrounds



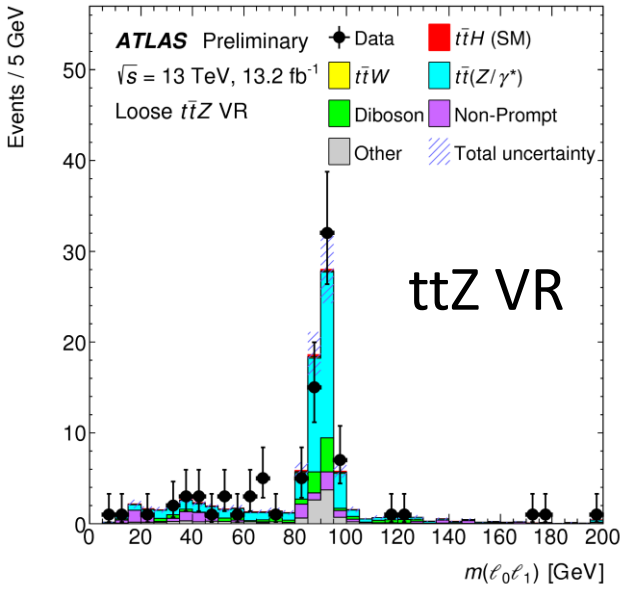
◆ Reducible Backgrounds: (Data-Driven)

➢ Non-Prompt lepton
Heavy flavor hadrons decaying to leptons
→ Estimated with data in CR (w/ looser lepton ID)

➢ Charge mis-ID (for electron)
Due to interactions with detector (conversions) and high Pt track (large curvature)
→ Estimated from data in Z→ee CRs.

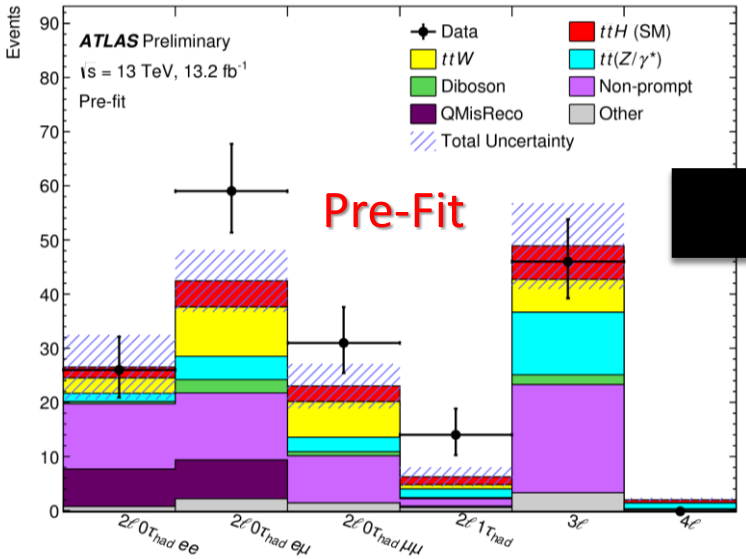
◆ Irreducible Backgrounds:

➢ Diboson, ttZ and ttW
→ Estimated with MC simulation and cross check in dedicated validation regions.

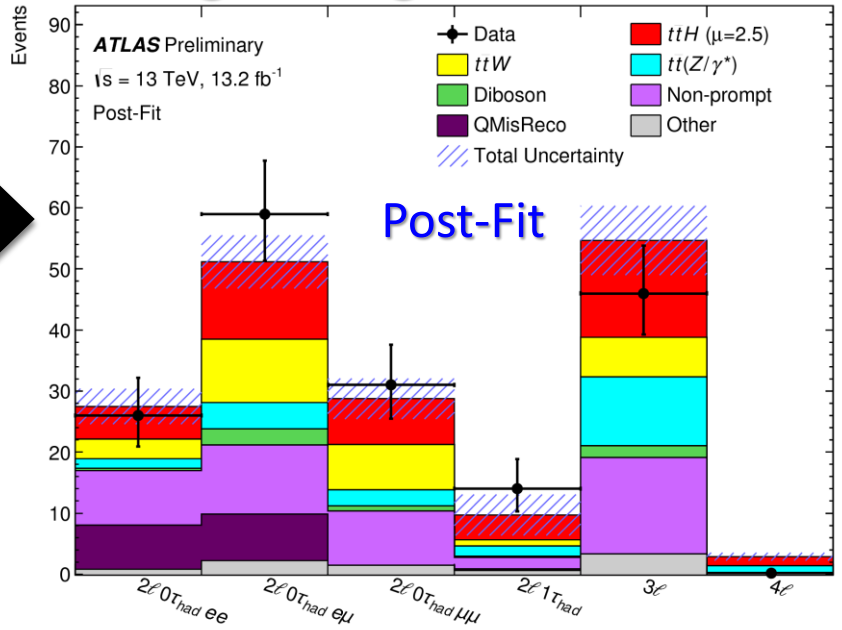


ttH→Multi-Lepton (ATLAS)

- ATLAS: Tighter Event Selection to get higher purity.
  → Counting experiment in 6 different signal regions



Fit



Uncertainty Source	$\Delta\mu$	
Non-prompt leptons and charge misreconstruction	+0.56	−0.64
Jet-vertex association, pileup modeling	+0.48	−0.36
$t\bar{t}W$ modeling	+0.29	−0.31
$t\bar{t}H$ modeling	+0.31	−0.15
Jet energy scale and resolution	+0.22	−0.18
$t\bar{t}Z$ modeling	+0.19	−0.19
Luminosity	+0.19	−0.15
Diboson modeling	+0.15	−0.14
Jet flavor tagging	+0.15	−0.12
Light lepton (e, μ) and τ_{had} ID, isolation, trigger	+0.12	−0.10
Other background modeling	+0.11	−0.11
Total systematic uncertainty	+1.1	−0.9

→ Leading systematic sources:
Non prompt leptons/mis-Q ID
Jet vertex/PU modeling
ttV/ttH modeling etc.
…… (total ± ~ 1.0 on μ)

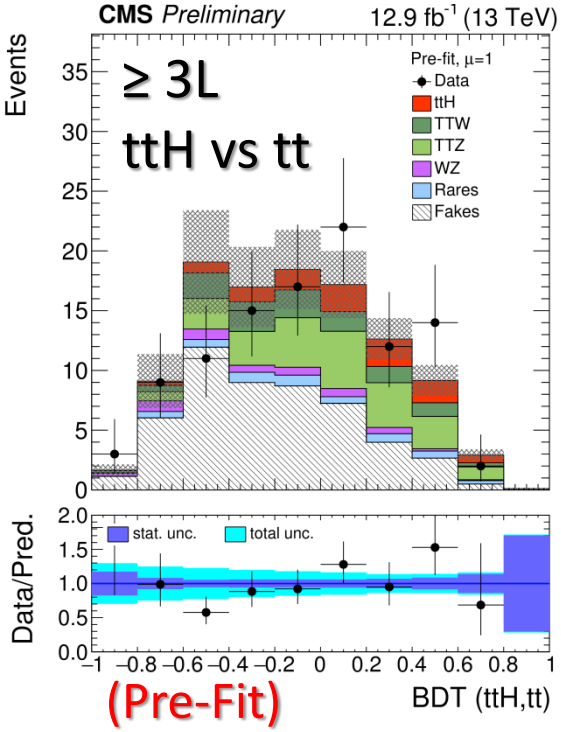
ttH→Multi-Lepton (CMS)

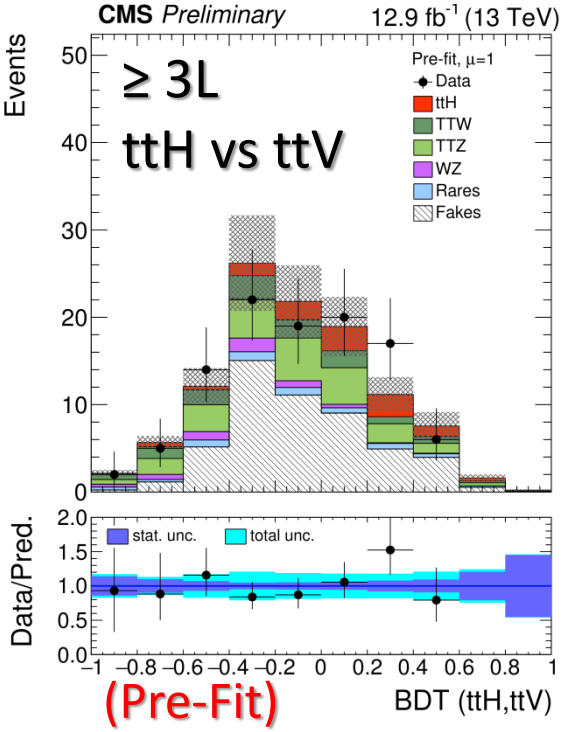
- "2D BDT" trained for each 2LSS and ≥ 3L category
  → (ttH vs ttX) & (ttH vs ttV) BDT

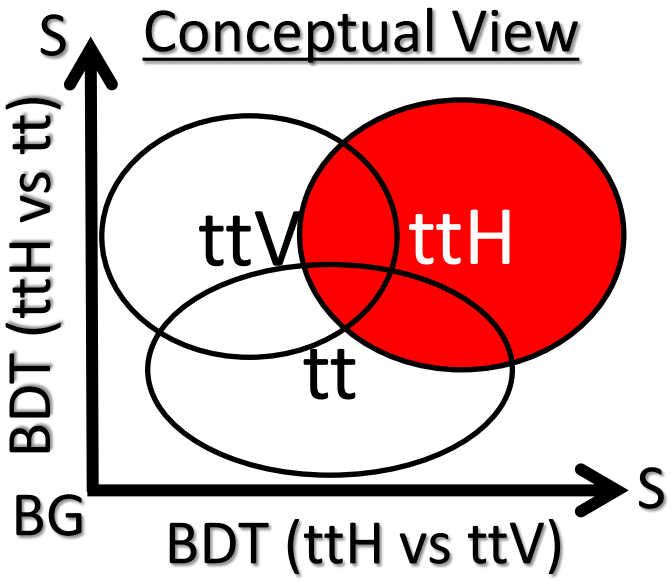
BDT Inputs:

2LSS: Kinematic variables (#jets, Mt etc)

≥ 3L: Kinematic variables + MEM weights







→ 2D fit is performed to extract # of signal.

→ Systematic sources:
Non prompt leptons,
Luminosity, ttH modeling etc

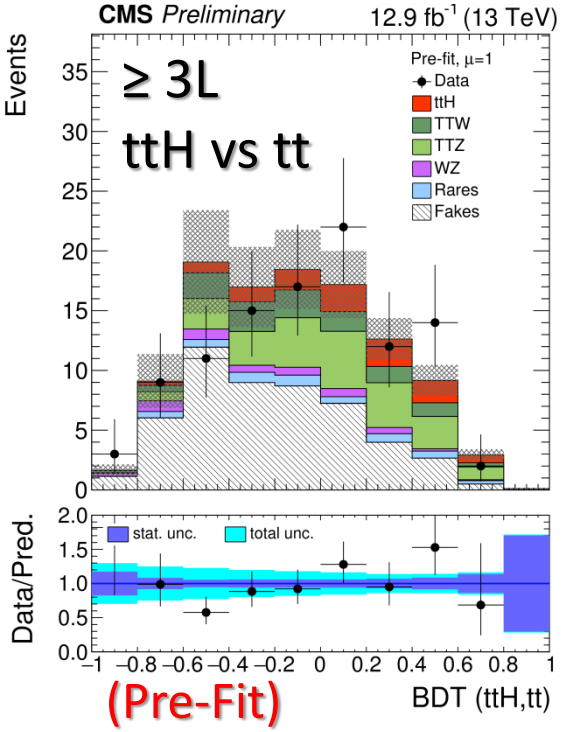
ttH→Multi-Lepton (CMS)

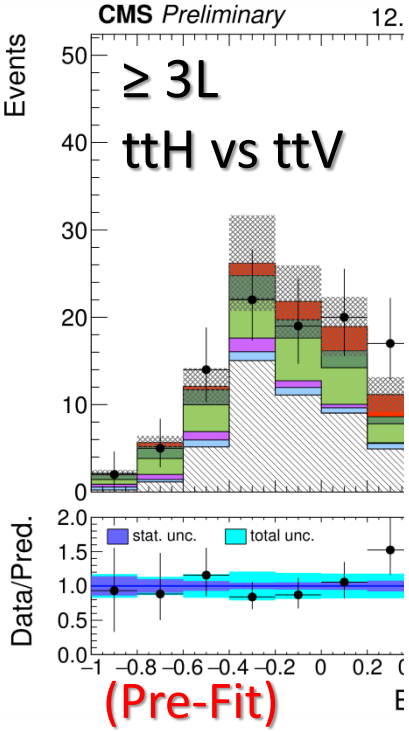
- "2D BDT" trained for each 2LSS and ≥ 3L category
  → (ttH vs ttX) & (ttH vs ttV)

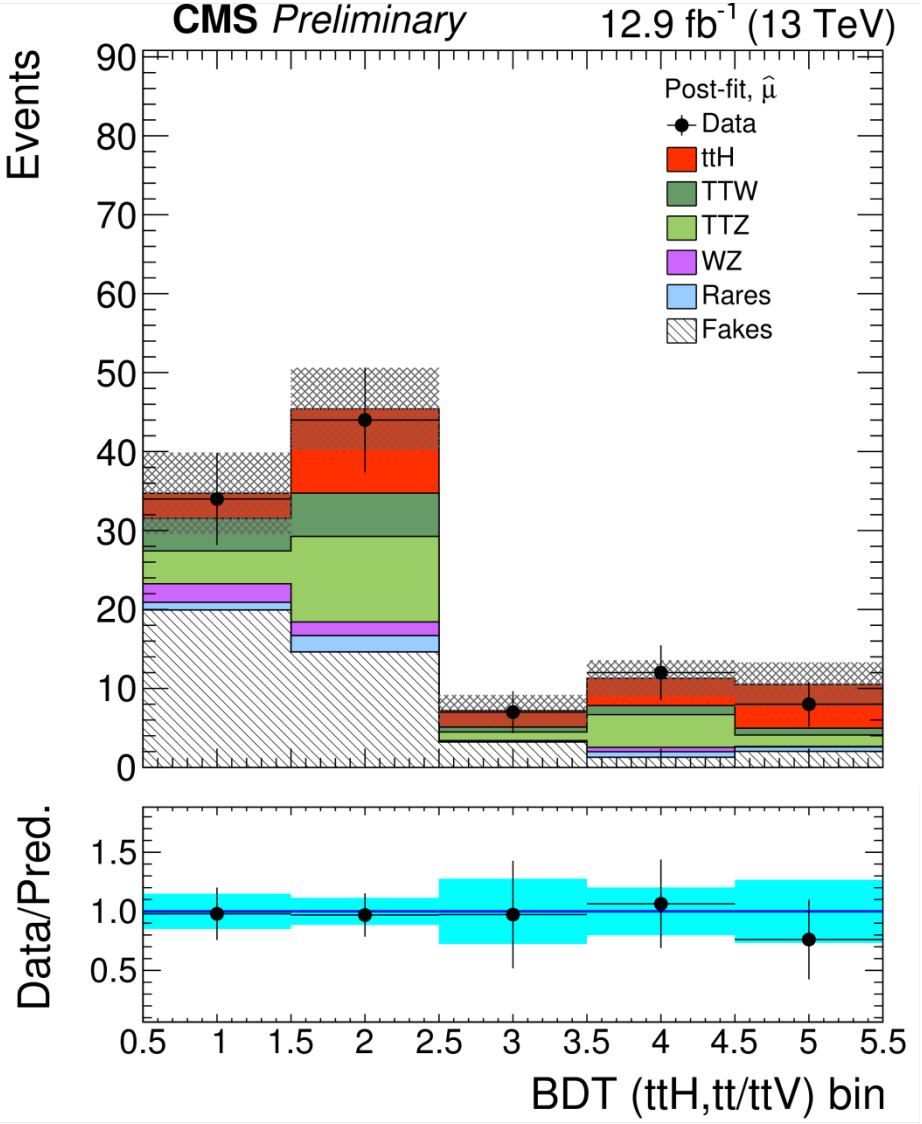
BDT Inputs:

2LSS: Kinematic variables (#jets, Mt

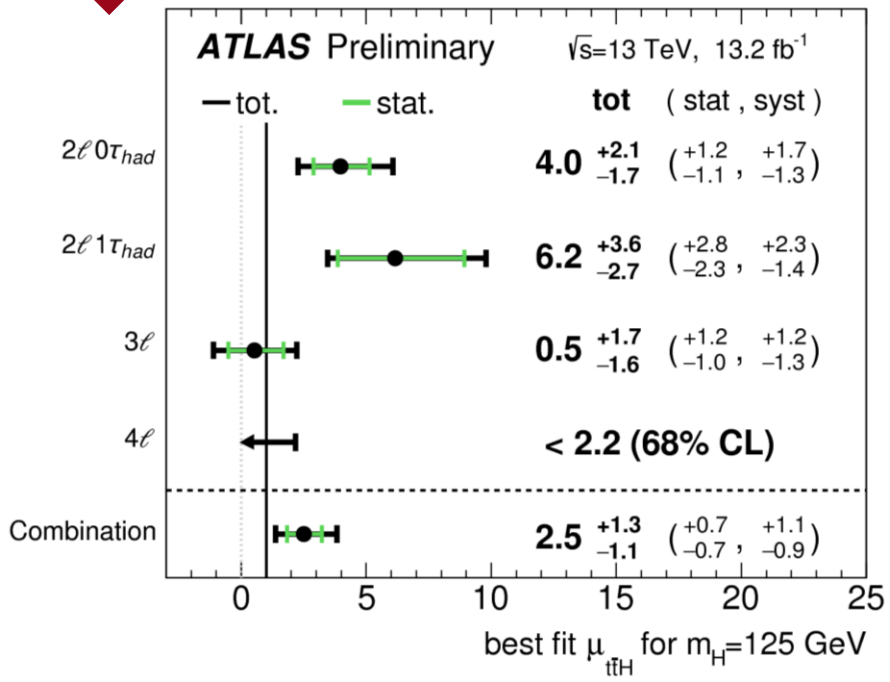
≥ 3L: Kinematic variables + MEM we

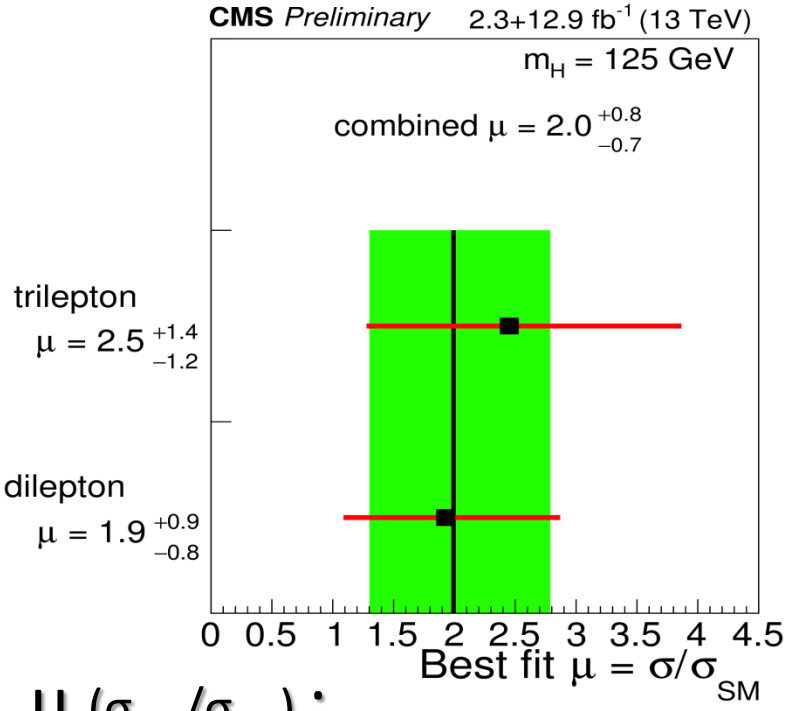


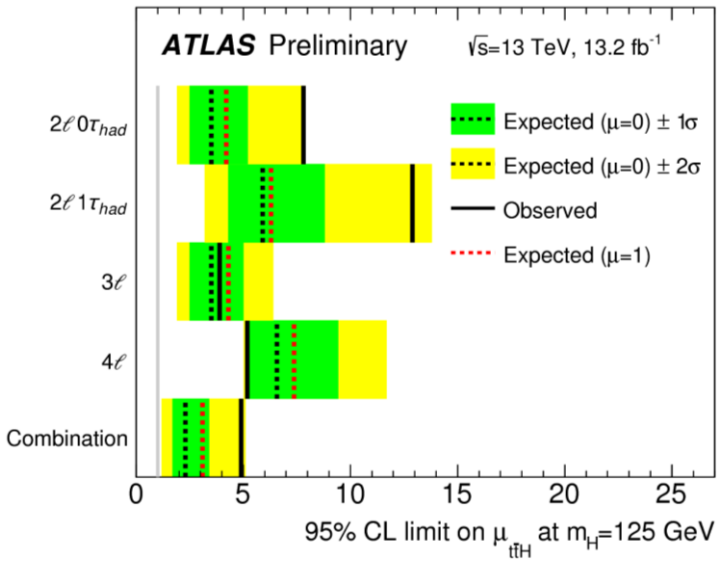




ttH→Multi-Lepton Results







- μ (σ_{obs}/σ_{SM}) :

  CMS $\mu_{ttH} = 2.0^{+0.8}_{-0.7}$

  ATLAS $\mu_{ttH} = 2.5^{+1.3}_{-1.1}$

- 95% CL Upper Limit:

  CMS: SM × 3.4 (1.3 [μ=0])

  ATLAS: SM × 4.9 (2.3 [μ=0])

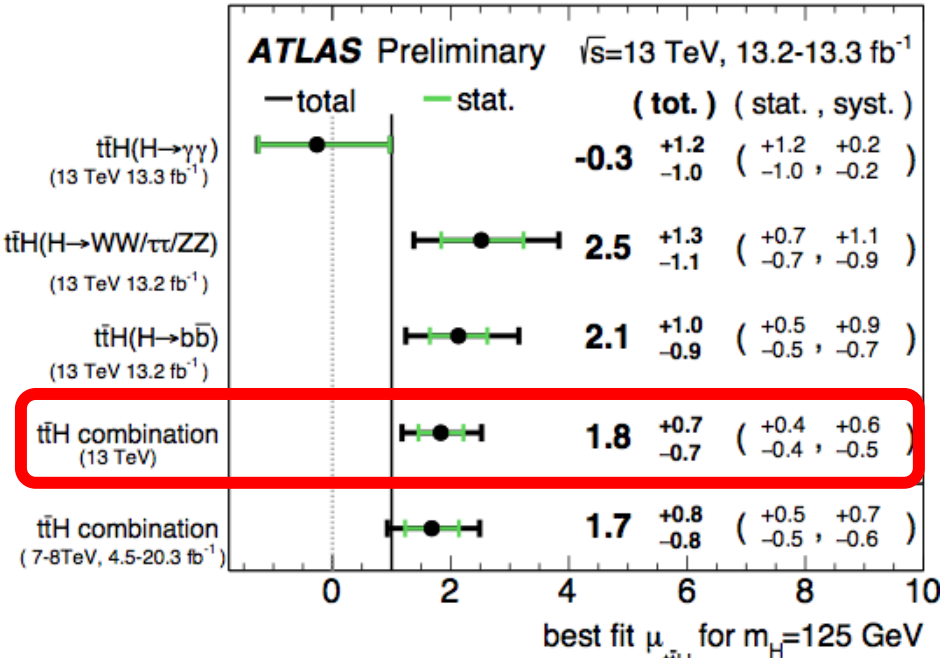
ttH Combination (ATLAS)

- Only within ATLAS results

→ 3 results combined:

ttH(H→γγ+ML+bb) w/ 13.3fb^{-1}

Channel	Significance	
	Observed [σ]	Expected [σ]
$t\bar{t}H,\ H \to \gamma\gamma$	−0.2	0.9
$t\bar{t}H,\ H \to (WW, \tau\tau, ZZ)$	2.2	1.0
$t\bar{t}H,\ H \to b\bar{b}$	2.4	1.2
$t\bar{t}H$ combination	2.8	1.8



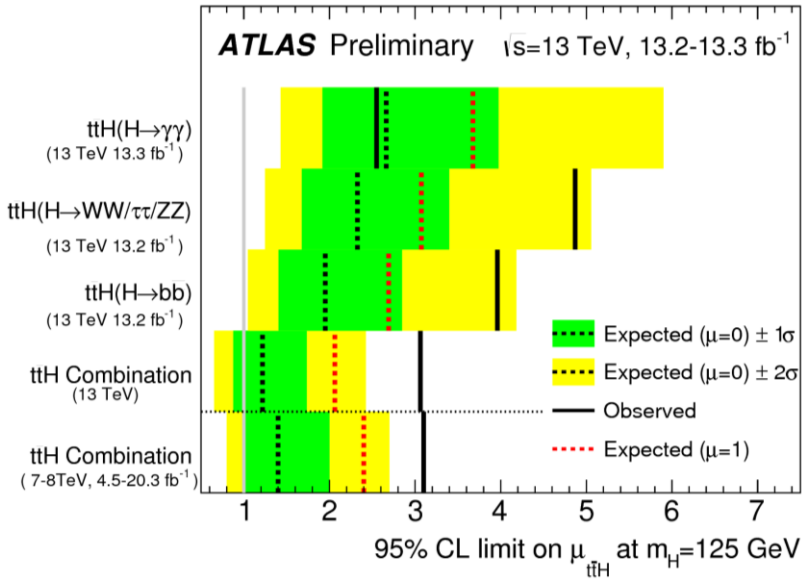
→ Each analysis is comparable and complementary (Ytop × Yx)

- Observed Signal Strength:

$$\mu = 1.8 \pm 0.4(stat.)\ ^{+0.6}_{-0.5}(syst.)$$

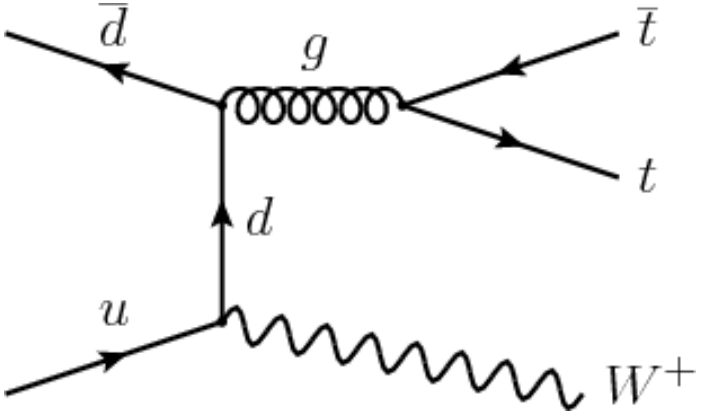
- 95% CL Upper Limit:

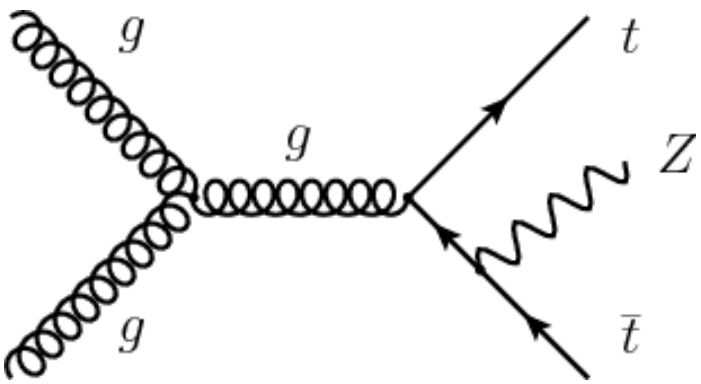
SM × 3.0 $(1.2\ ^{+0.5}_{-0.3}\ [\mu = 0])$



tt+W/Z Production

- Motivation:
  - Main Background for ttH analysis & a probe for New Physics
  - Direct Measurement for top-Z coupling



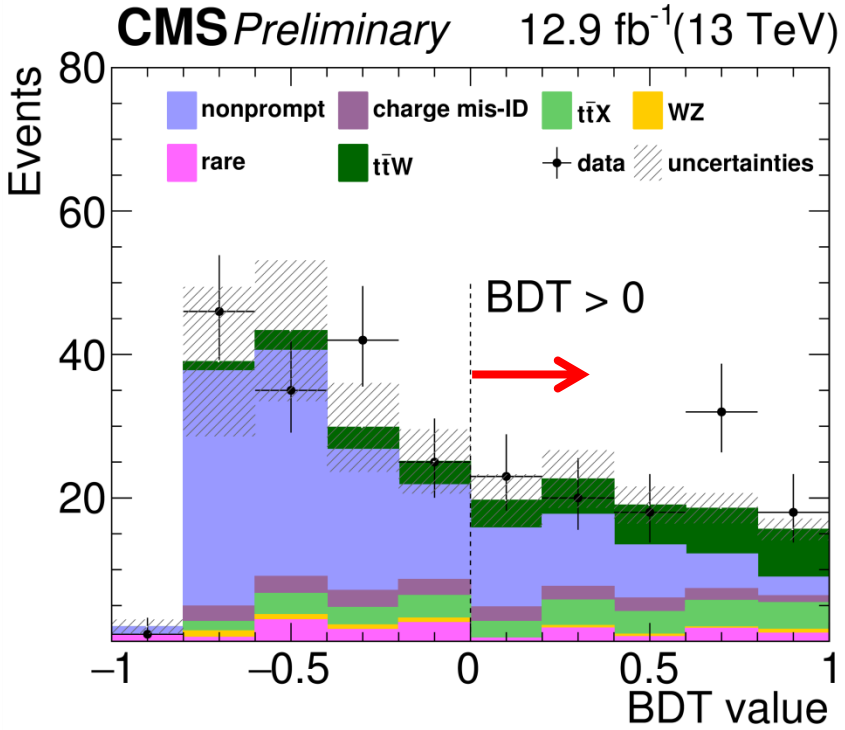


- ttW Analysis:
  Looking at ttW→(lvb)(jjb)(lv)
  → Same Sign dilepton + 4j(2b)+ Etmiss
  → BDT discrimination
  (using #jets, #bjets, sumPt, Mt etc.)

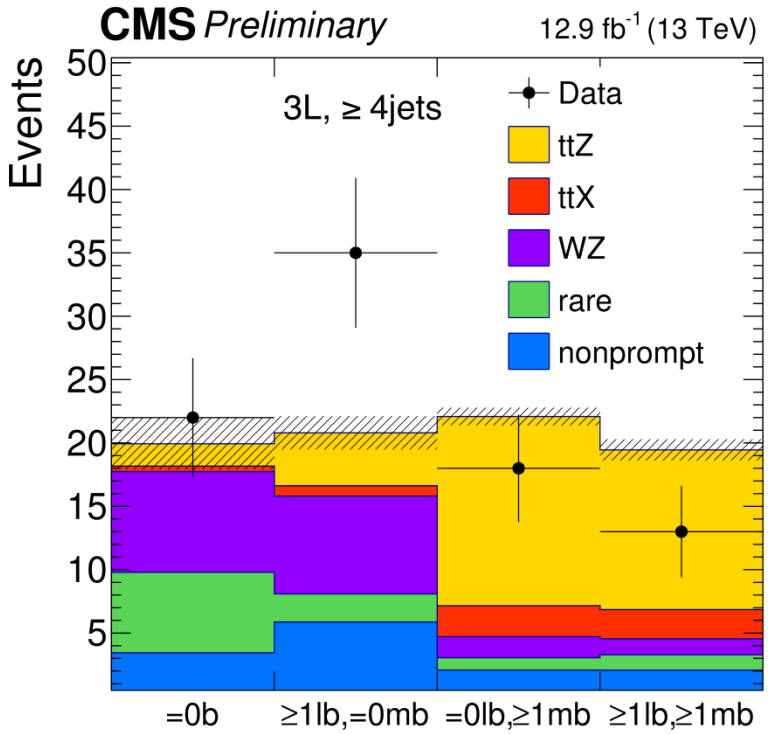
- ttZ Analysis:
  1. ttZ→(lvb)(jjb)(ll)
     → 3lepton + 4j(2b) + Etmiss
  2. ttZ→(lvb)(lvb)(ll)
     → 4lepton + 2j(2b) + Etmiss
  → Cut and Count for both channels

ttV (CMS 12.9fb^{-1}@13TeV)

ttW Results

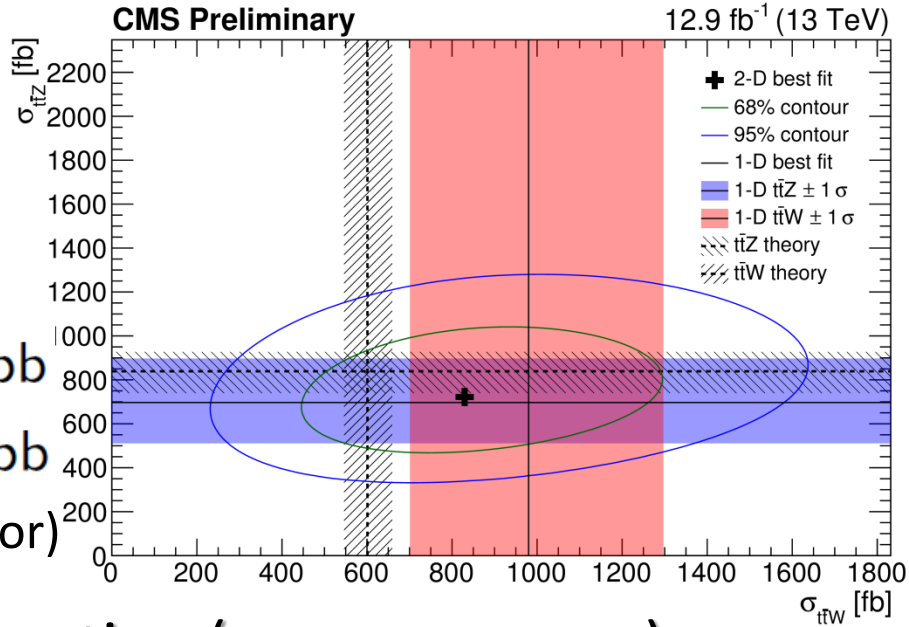


ttZ 3lepton Results



Channel	Expected significance	Observed significance
$2\ell ss$ analysis ($t\bar{t}W$)	2.6	3.9
3ℓ analysis ($t\bar{t}Z$)	5.4	3.8
4ℓ analysis ($t\bar{t}Z$)	2.4	2.8
3ℓ and 4ℓ combined ($t\bar{t}Z$)	5.8	4.6

ttV Summary



- CMS(12.9fb^{-1})@13TeV Re-Obs .

σ (ttW) = $0.98^{+0.23}_{-0.22}$(stat.) $^{+0.22}_{-0.18}$(sys.) pb

σ (ttZ) = $0.70^{+0.16}_{-0.15}$(stat.) $^{+0.14}_{-0.12}$(sys.) pb

(Theory 0.60(ttW)/0.84(ttZ)pb with ~ 10% error)

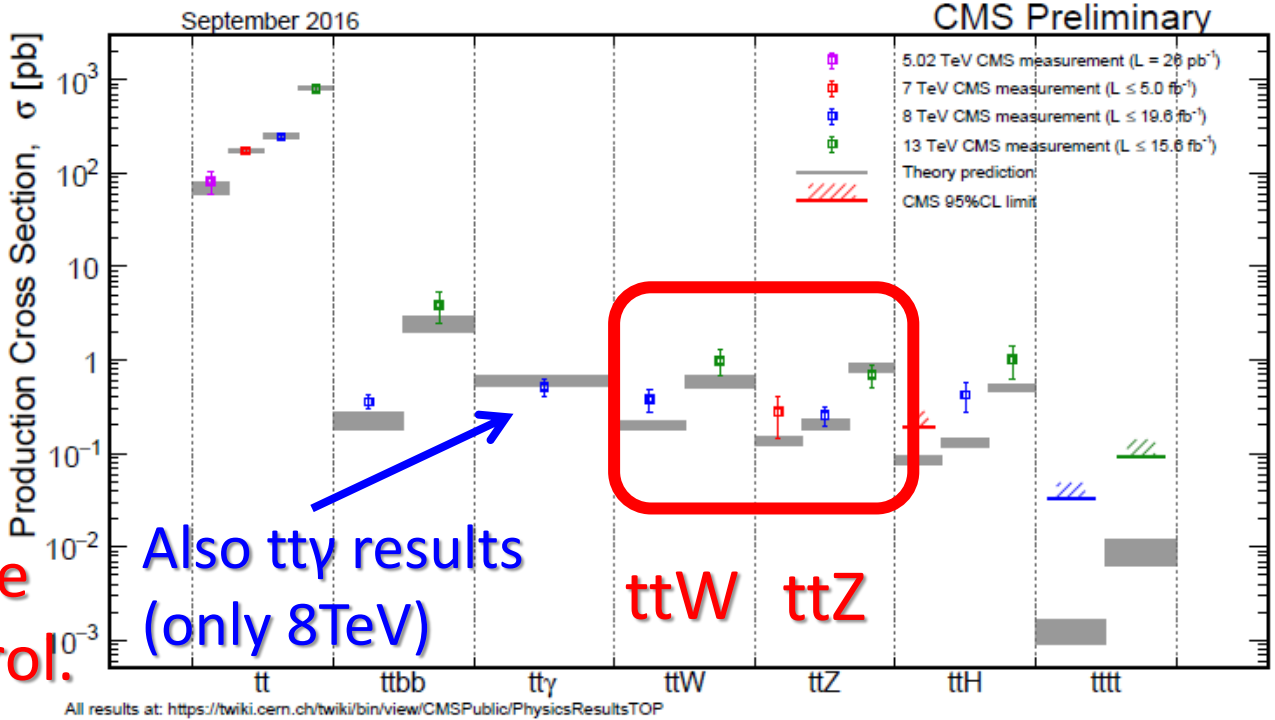
- ATLAS(3.2fb^{-1})@13TeV Re- Observation (arXiv:1609.01599)

σ(ttW)= 1.5$\pm$0.8 pb

σ(ttZ) = 0.9$\pm$0.3 pb

☛ So far consistent with SM predictions within uncertainties.

→ Multi-Lepton mode is well under control.



Summary & Outlook

- ATLAS&CMS Results w/ 13fb^{-1}:

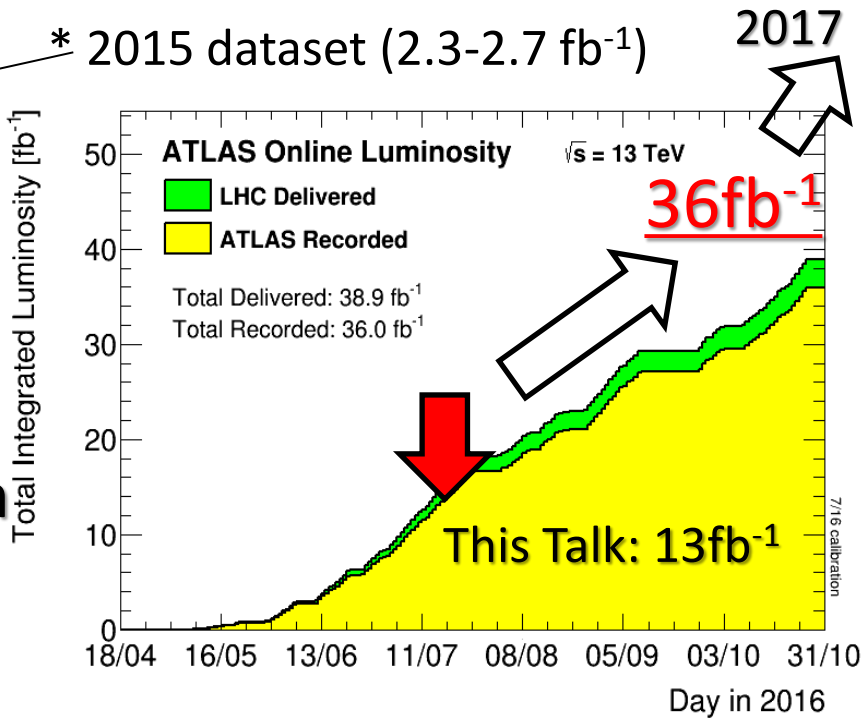
μ	ATLAS(13fb^{-1})	CMS(13fb^{-1})
ttH→bb	**2.1** +1.0 -0.9	**- 0.2** ±0.8
ttH→γγ	**- 0.3** +1.3 -1.0	**1.9** +1.5 -1.2
ttH→ML	**2.5** +1.3 -1.1	**2.0** +0.8 -0.7
Comb.	**1.8** ±0.7	(0.2 +1.0 -0.8)*

- ttV process observed both by ATLAS/CMS in Run2

Now Stat. error ~ Syst . error

→ Precision Measurement with more Run2 Data !

* 2015 dataset (2.3-2.7 fb^{-1})



- Much more data to come:
  This year: 36 fb^{-1} recorded !
  Run2 Total: > 100fb^{-1} by 2018

☛ ttH Evidence coming soon & even might be able to see deviations !

→ *Stay tuned !*