Search for the SM Higgs boson in the ttH production in ATLAS

Multi-leptons ($H\rightarrow WW^*$, ZZ^*, $\tau\tau$), Di-photon ($H\rightarrow \gamma\gamma$)
and ttH combination

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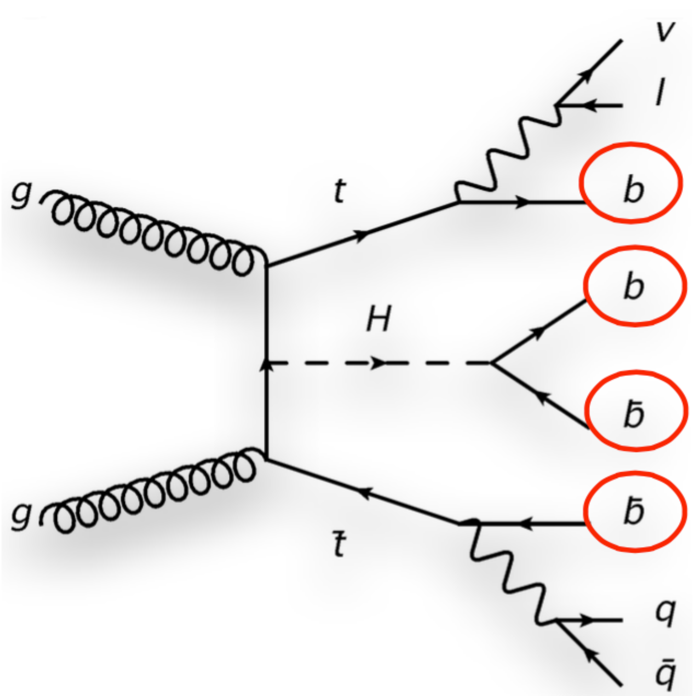
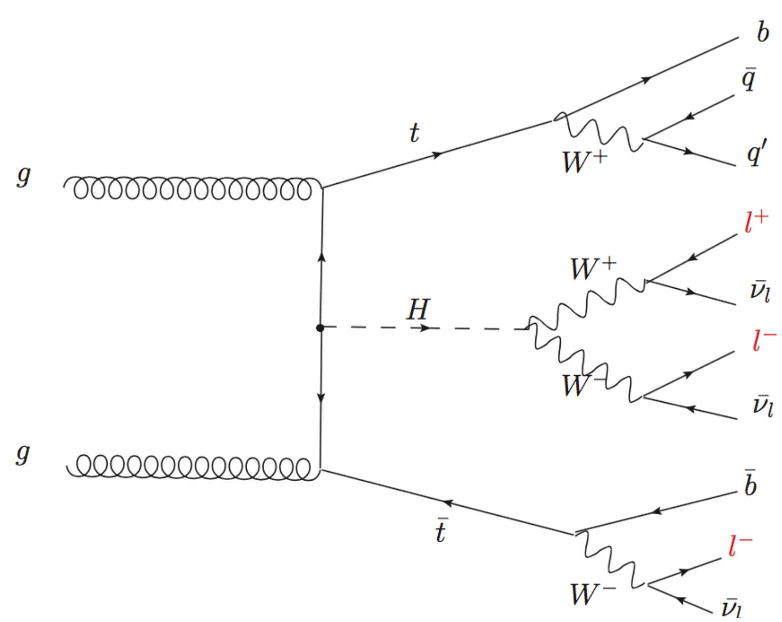
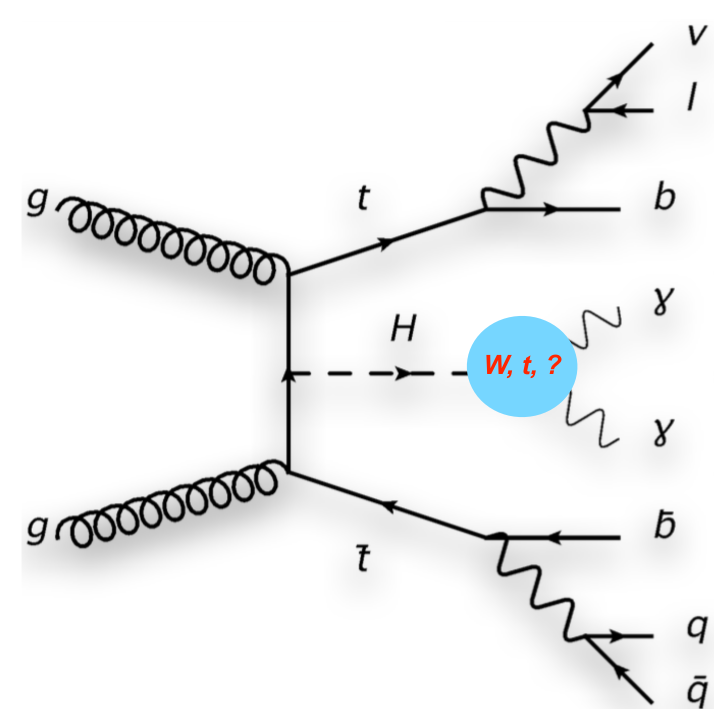
Introduction

- Direct measurement of Higgs-top Yukawa coupling via ttH production
  - ttH cross section is 507 fb $\sqrt{s}$=13 TeV → 1/100 of Higgs production
  - search for the ttH in many Higgs decay channels (~89% of total Br.)

ttH(H→bb) tt leptonic(hadronic) decay	ttH(multi-leptons) targeting H→WW*,ZZ* and $\tau\tau$	ttH(H→$\gamma\gamma$) tt leptonic(hadronic) decay







The ttH (H→bb) process

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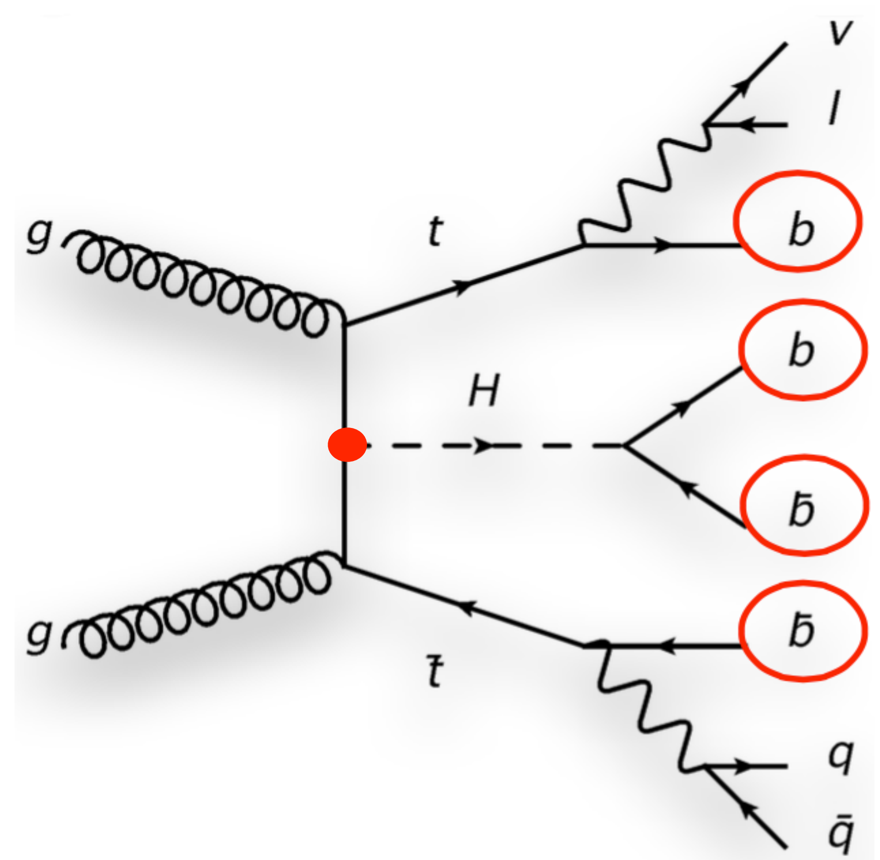
  - ttH cross section is 507 fb √s=13 TeV → 1/100 of Higgs production
  - search for the ttH in many Higgs decay channels (~89% of total Br.)

Higgs decay	Br [%]
H → bb	58.1
H→ WW*	21.5
H → ττ	6.3
H→ ZZ*	2.6
H → γγ	0.23

ttH(bb) channel has largest branching ratio, and offers sensitivity to the Higgs-Bottom Yukawa coupling.

ttH(bb) Feynman diagram



tt semi-leptonic decay

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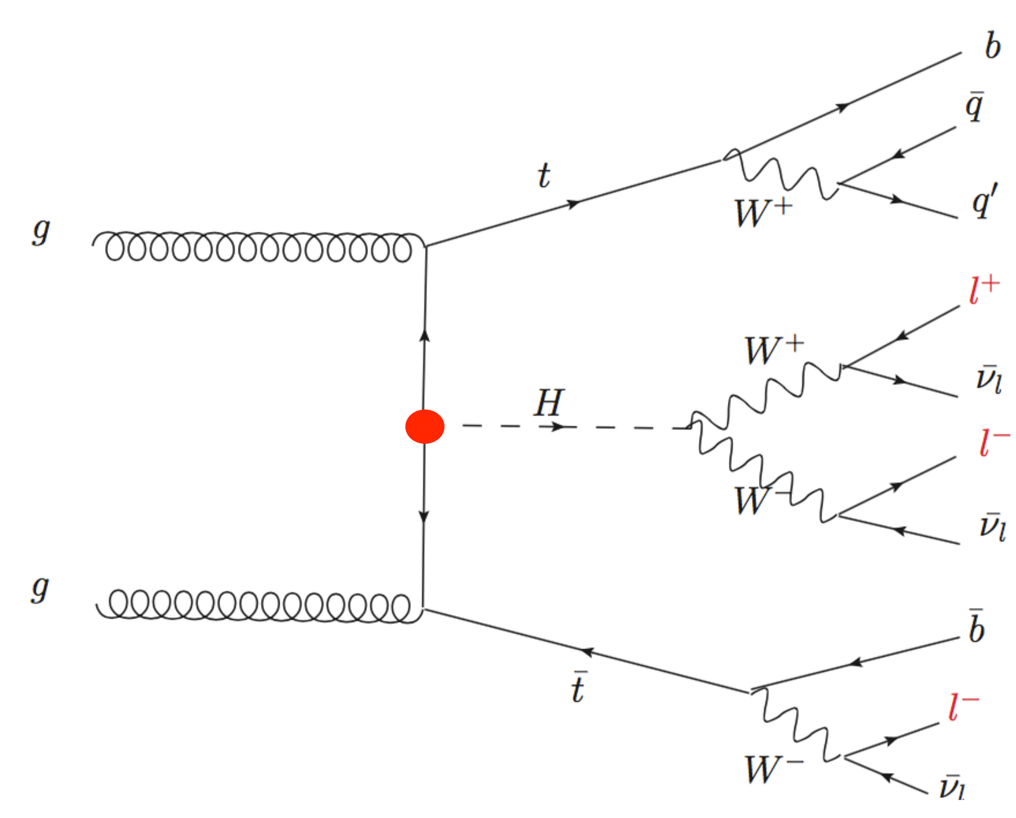
ttH(multi-leptons) channel has clean final states, and has a priori better modelled irreducible background, i.e ttW and ttZ.

ttH(multi-leptons)
Feynman diagram

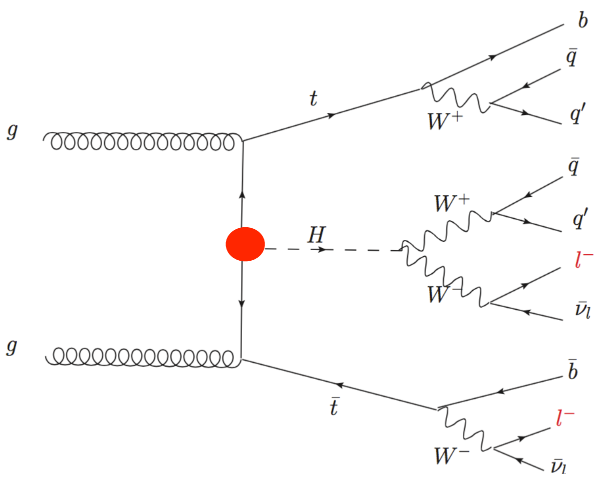


H→ WW*, 3 leptons final states

ttH(multi-leptons) analysis

- This analysis targets Higgs decays to WW*, ZZ*, ττ.
- Four channels are defined, by number of lepton and tau in final states

two leptons with same charge with no had. tau (≥5 jets, ≥1 b-jets)



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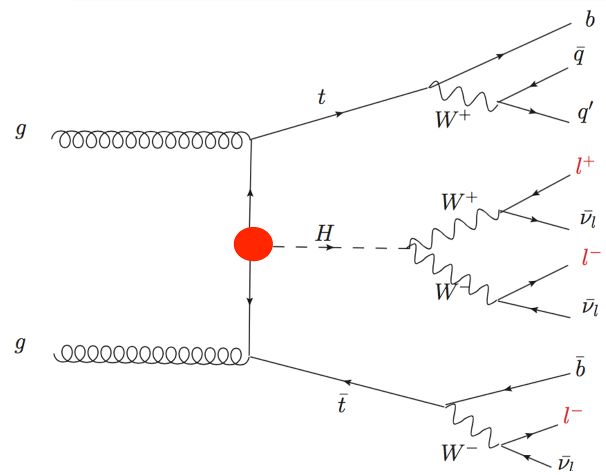

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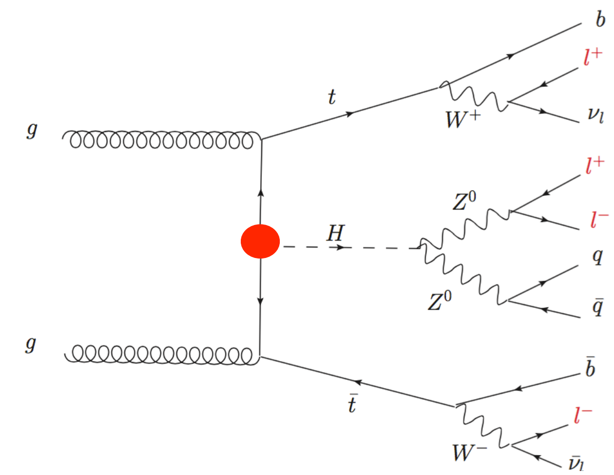

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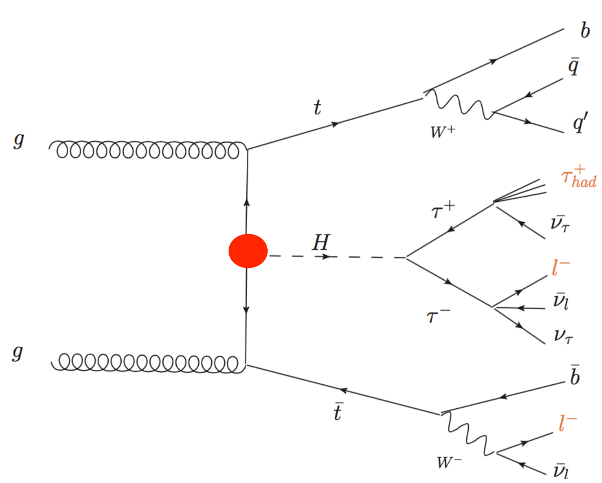

- Signal composition

	Higgs boson decay mode				$A \times \epsilon$
Category	WW^*	$\tau\tau$	ZZ^*	Other	$(\times 10^{-4})$
$2\ell 0\tau_{\text{had}}$	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

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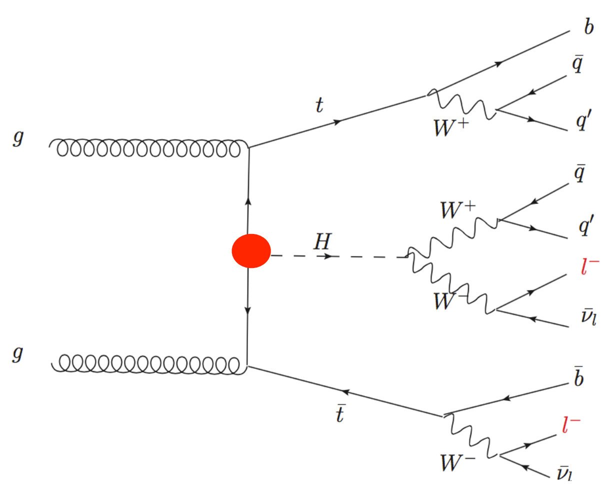

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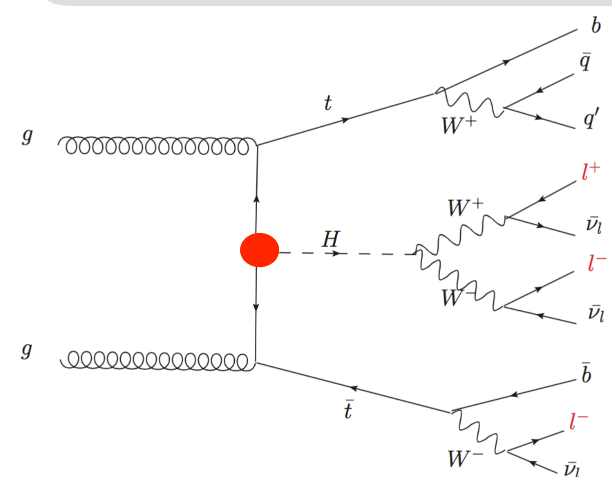

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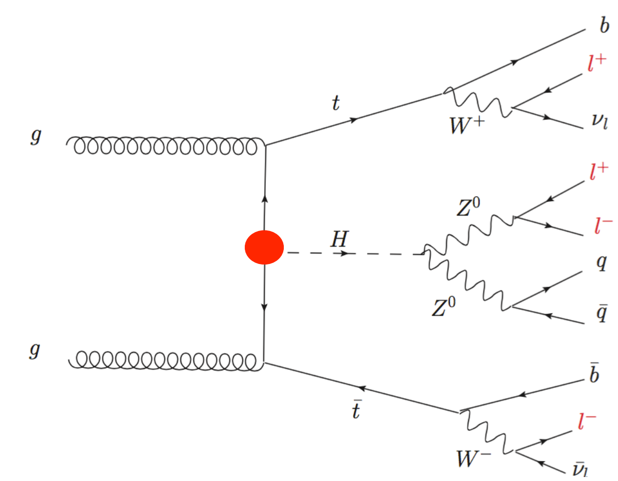
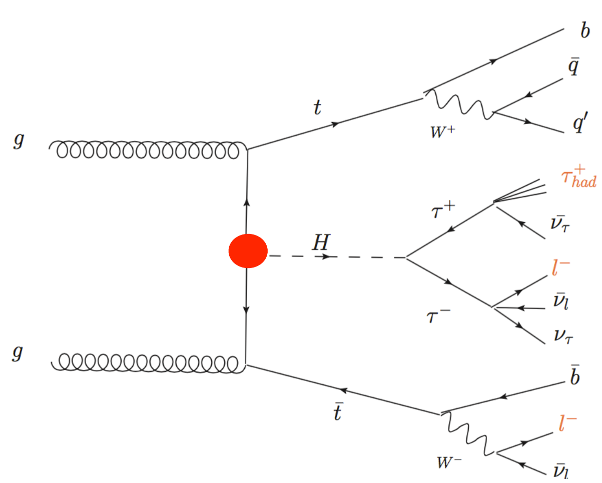


two leptons with same charge with one had. tau (≥4 jets, ≥1 b-jets)



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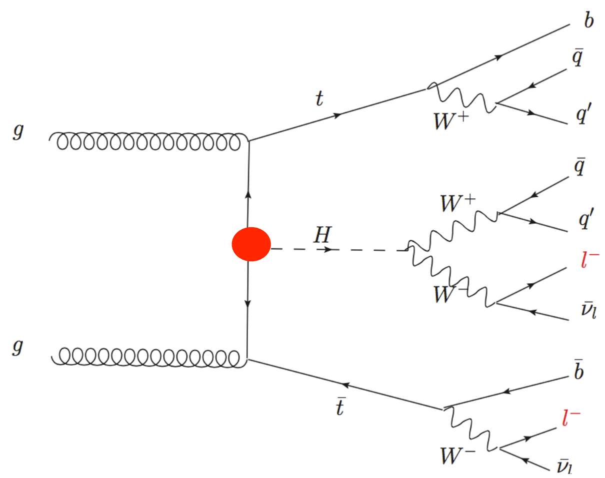

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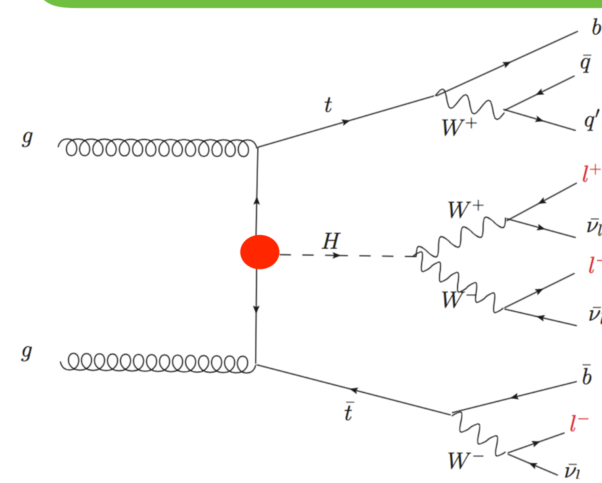

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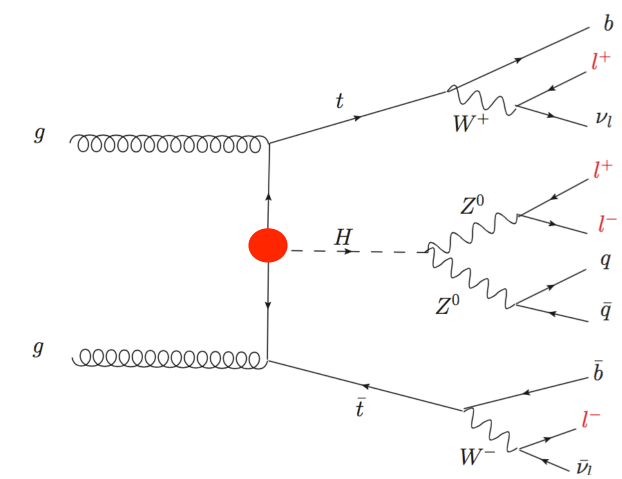

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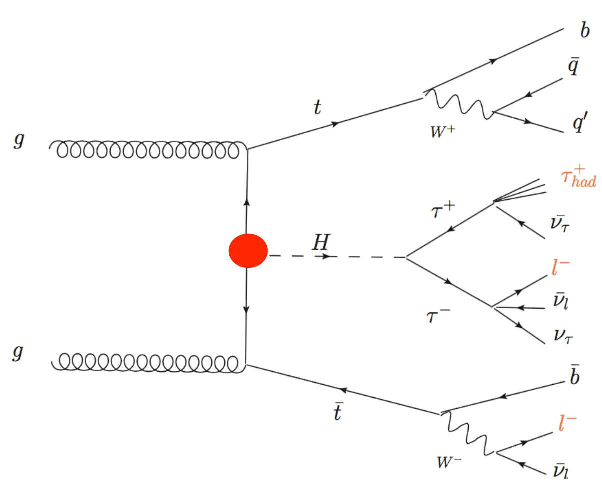

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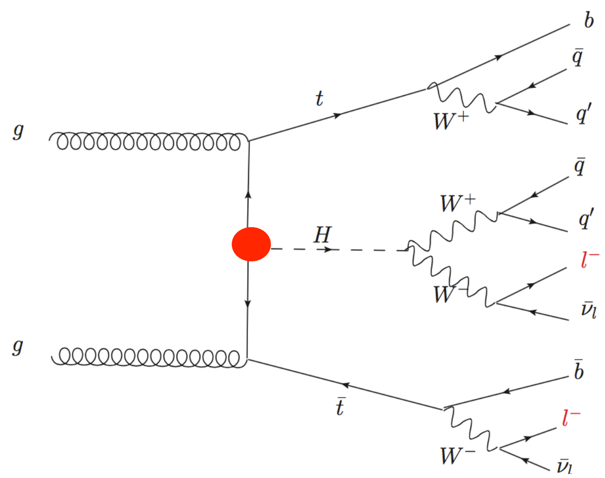

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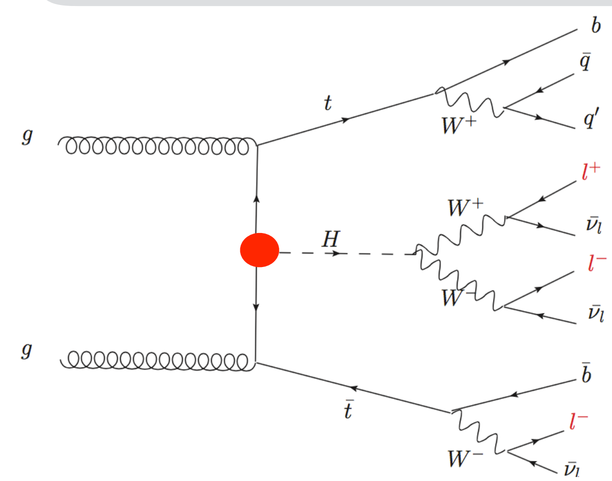

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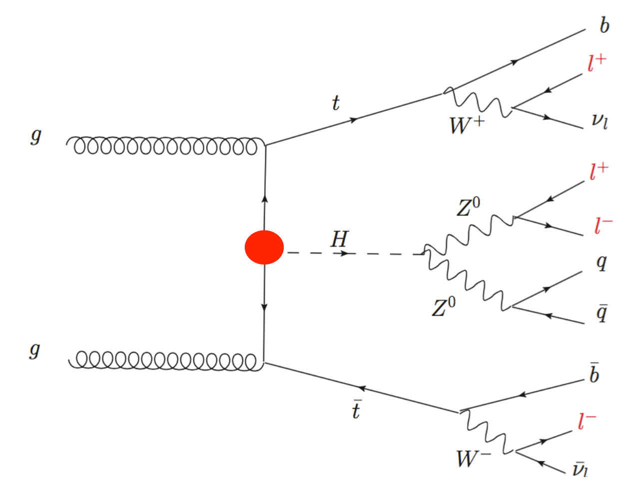

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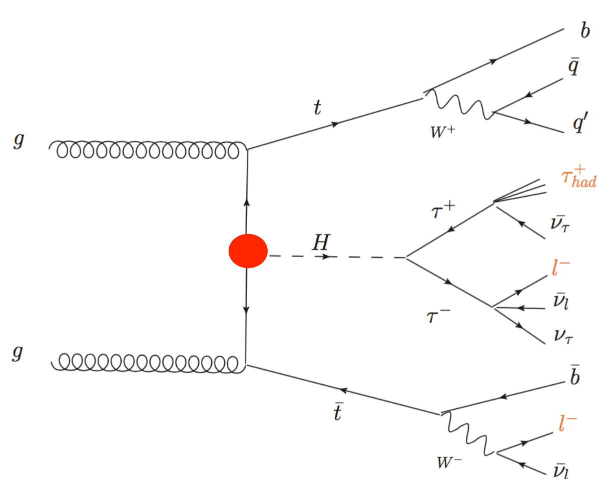

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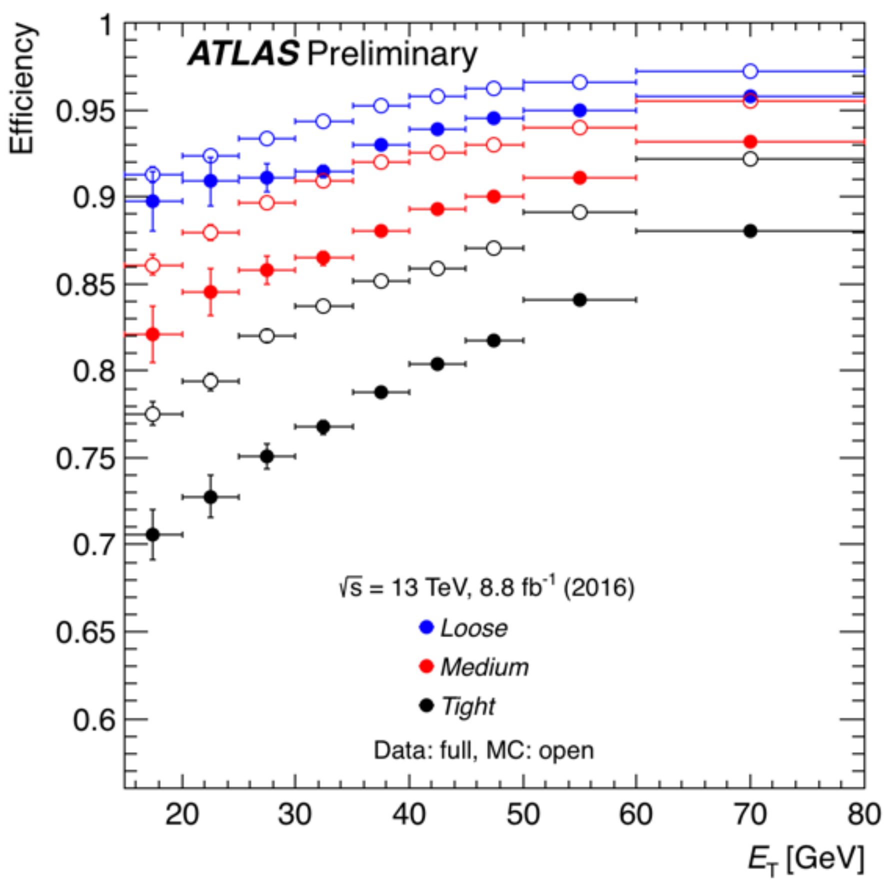
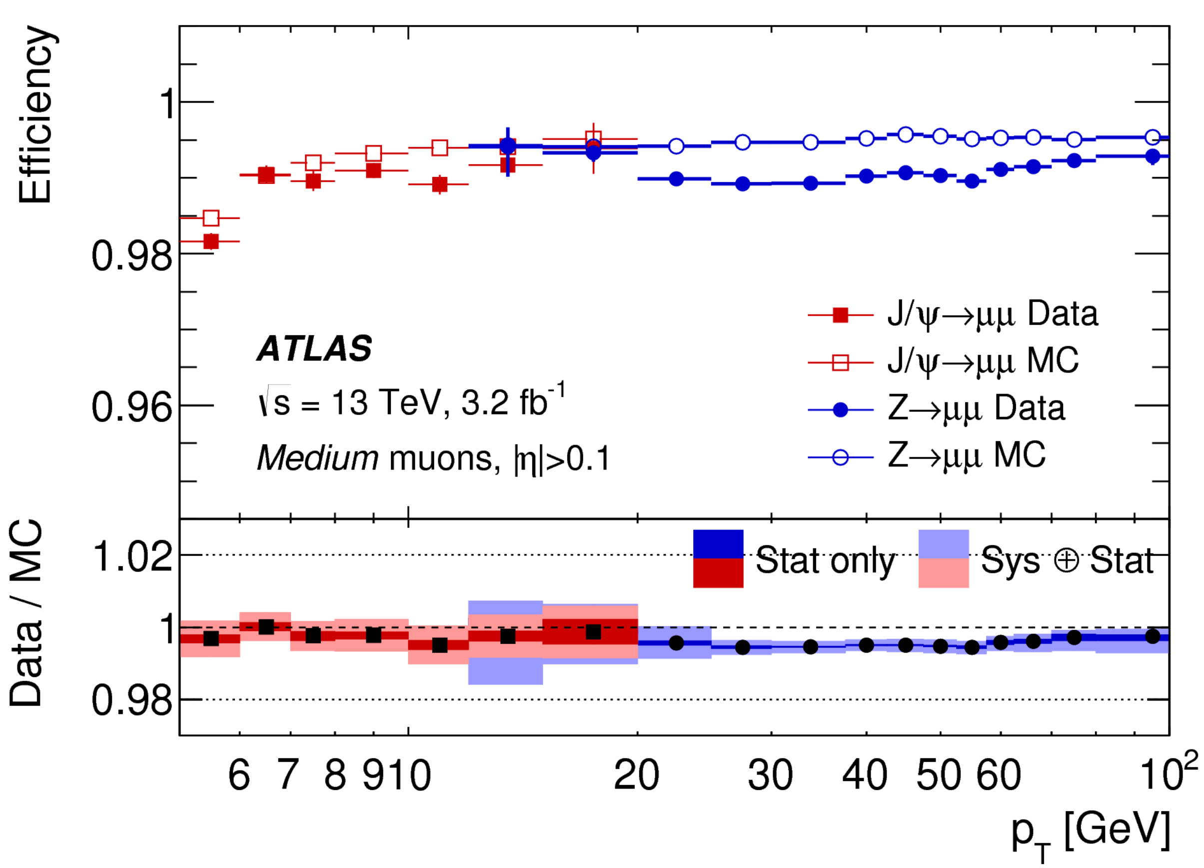
ttH(multi-leptons) event selection

- **Complex final states:** signal event contain leptons and/or hadronic taus, two b-tagged jets as well as light jets.
- **This analysis benefits from good perform of the ATLAS detector.**
- **Light leptons have to be isolated and be well reconstructed.**



electron identification efficiency



muon reconstruction efficiency

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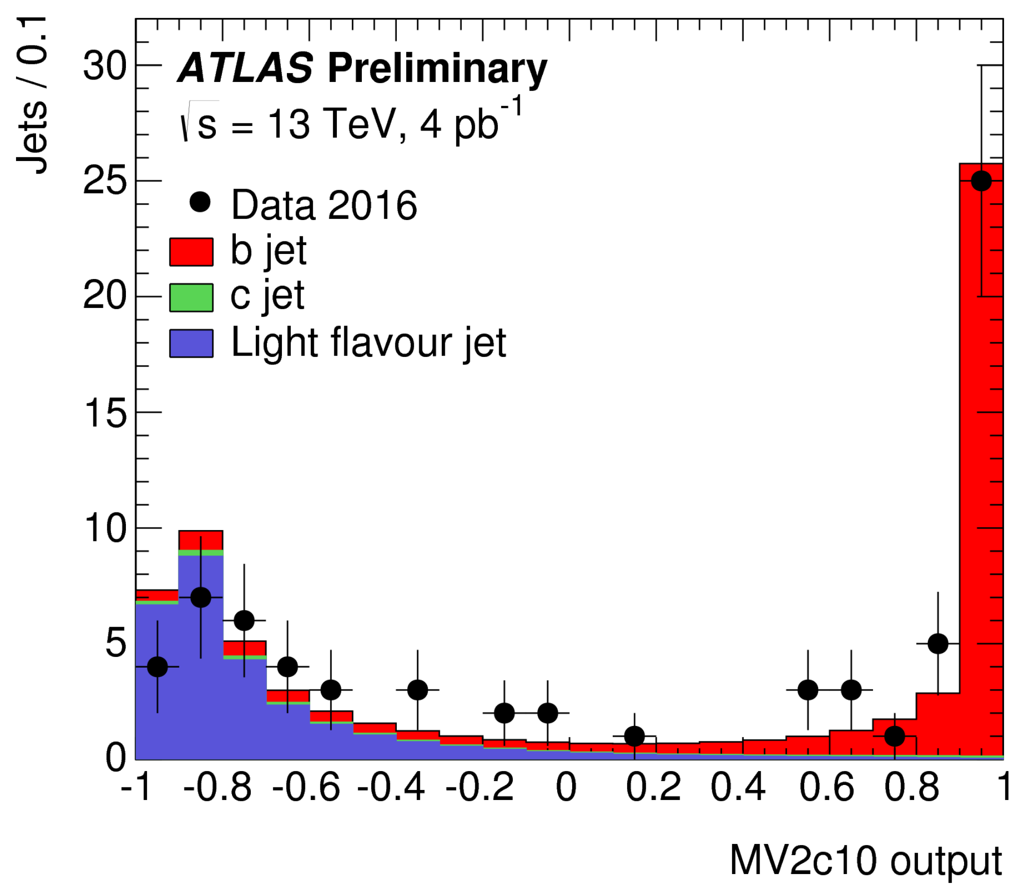
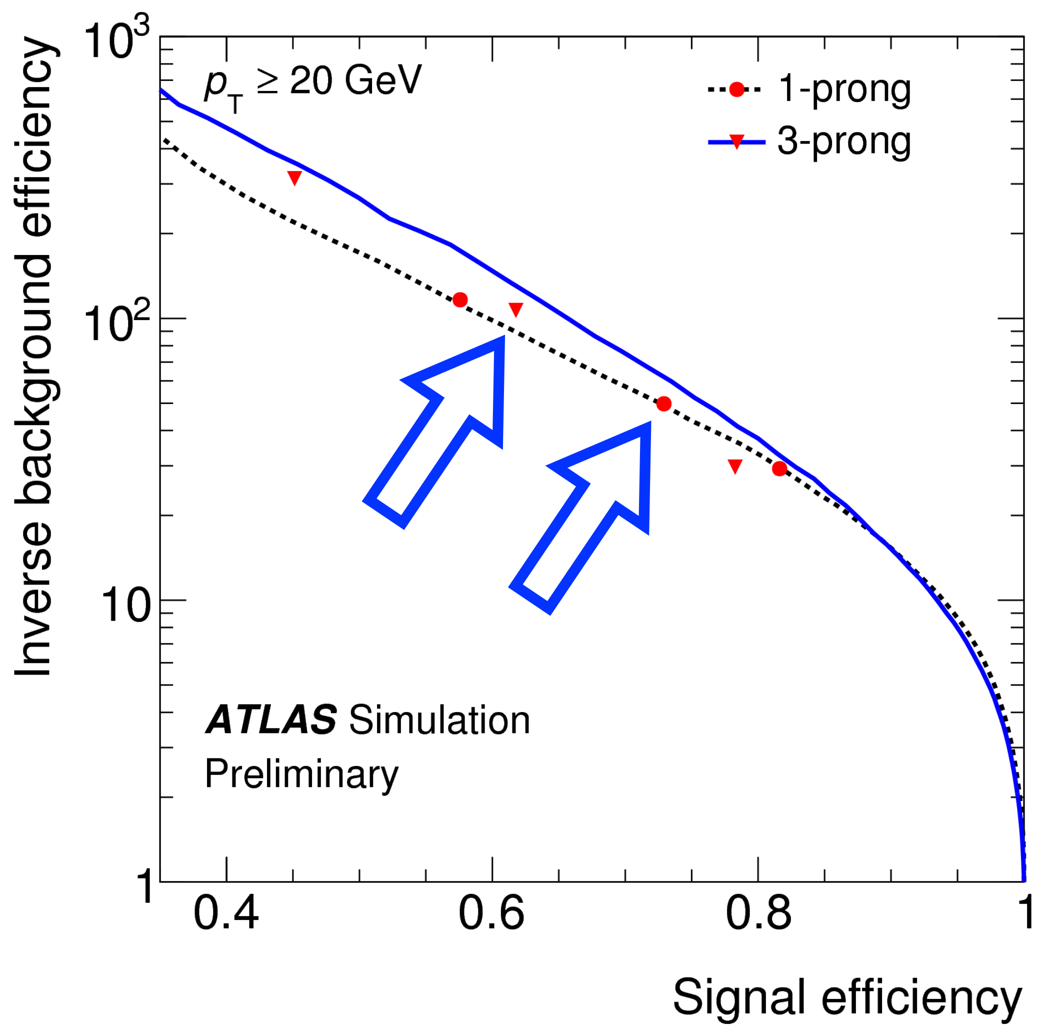
- This analysis benefits from good performance of the ATLAS detector.
- **Hadronic-tau and b-tagged jets can be well separated from light jets.**

cut at 70% b-tagging efficiency



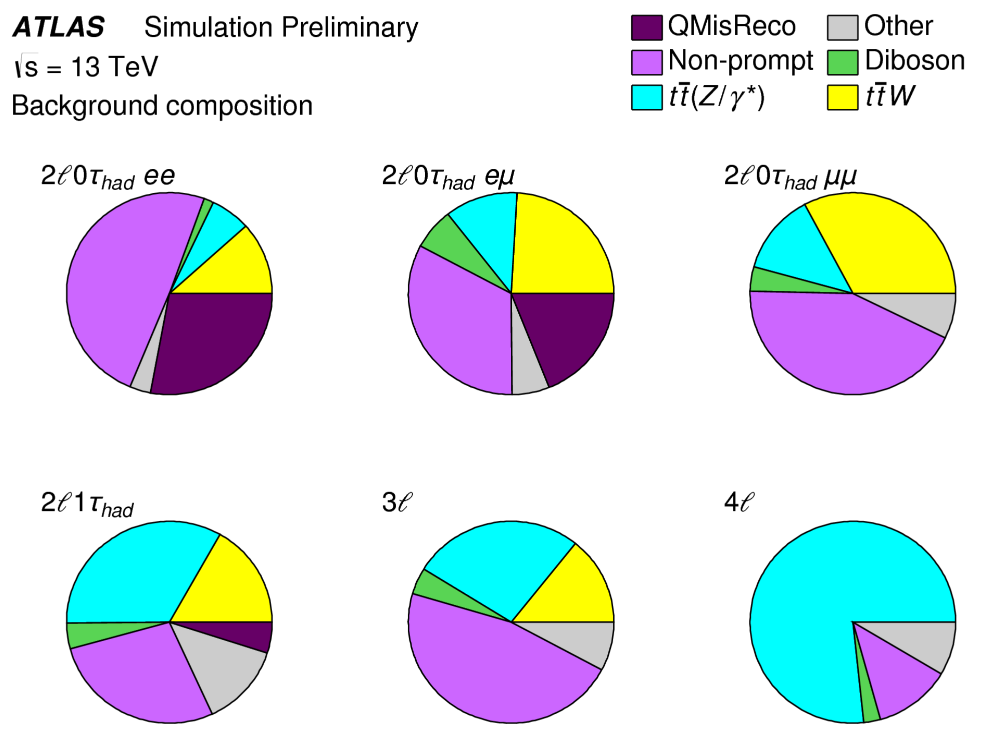
BDT output of separation between b-jets and light jets



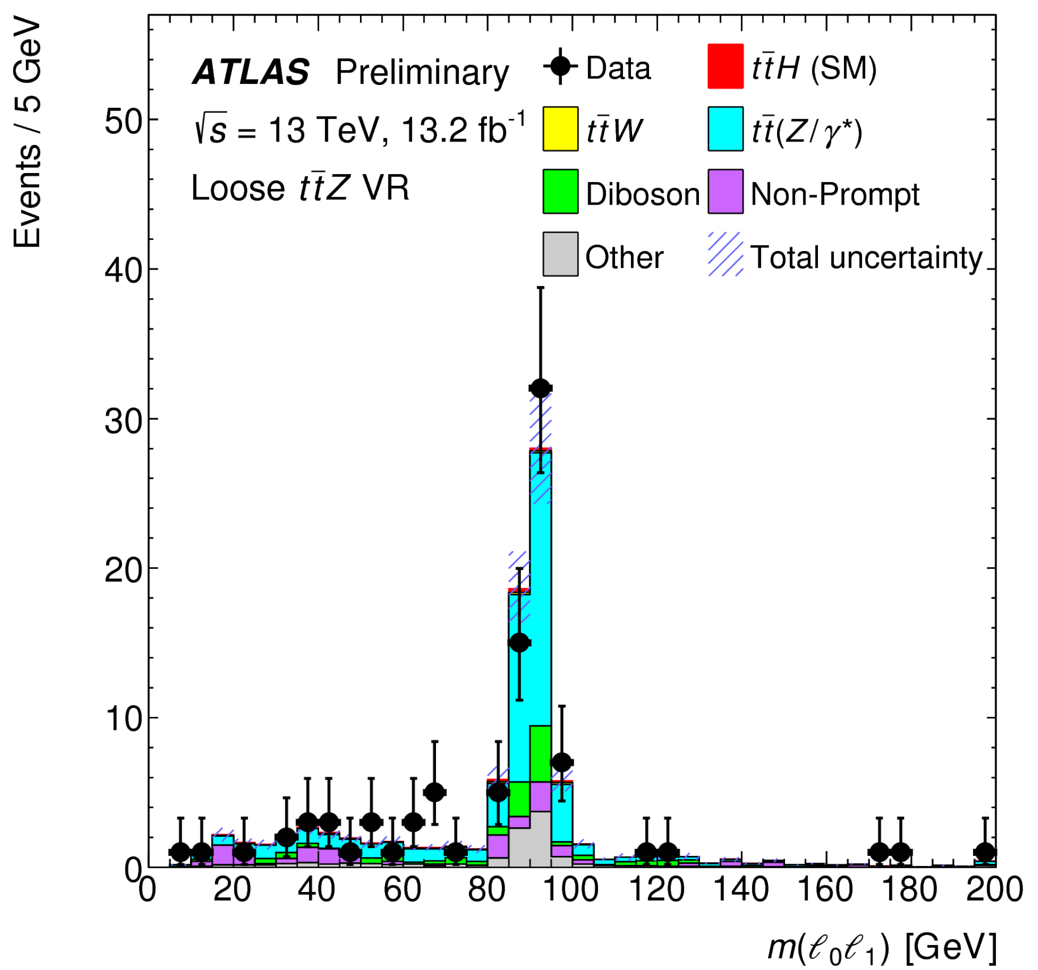
Hadronic-tau identification efficiency vs mis-tagging QCD jets rejection

ttH(multi-leptons) irreducible backgrounds

- **Dominant backgrounds are shown in pie chart**
- **ttW,ttZ :** dominant in 2lSS+0/1τ,3l
  - estimated from simulation (MadGraph5_aMC@NLO + Pythia 8)
  - ~12% QCD scale uncertainty and 3-4% PDF +α_s uncertainty
  - validated in dedicated regions



VR	Purity	Expected	Data
Tight $t\bar{t}Z$	68%	32 ± 4	28
Loose $t\bar{t}Z$	58%	91 ± 12	89
WZ + 1 b-tag	33%	137 ± 27	147
$t\bar{t}W$	22%	51 ± 10	55



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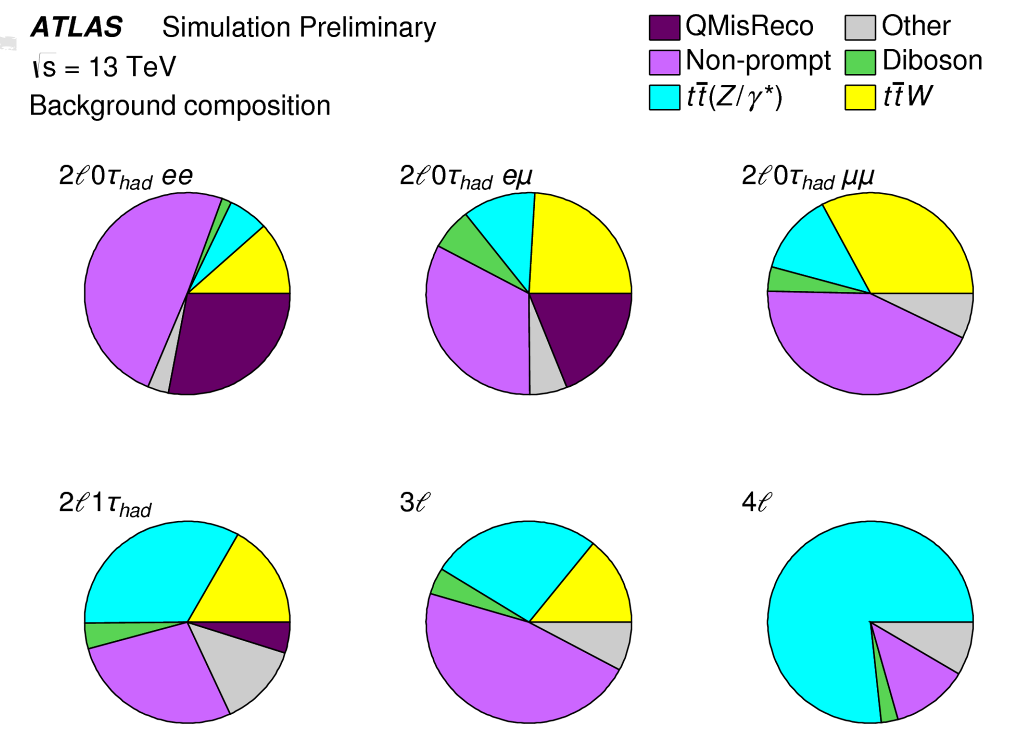

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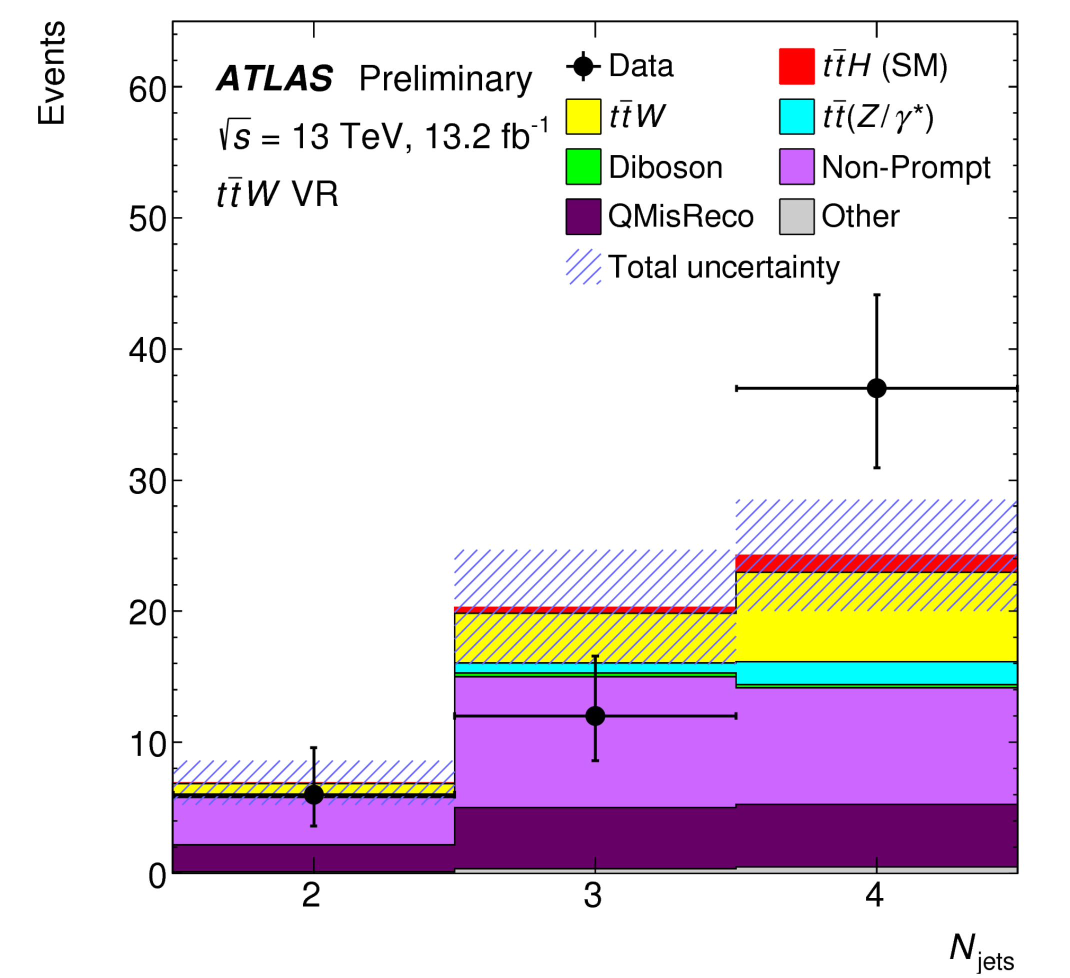
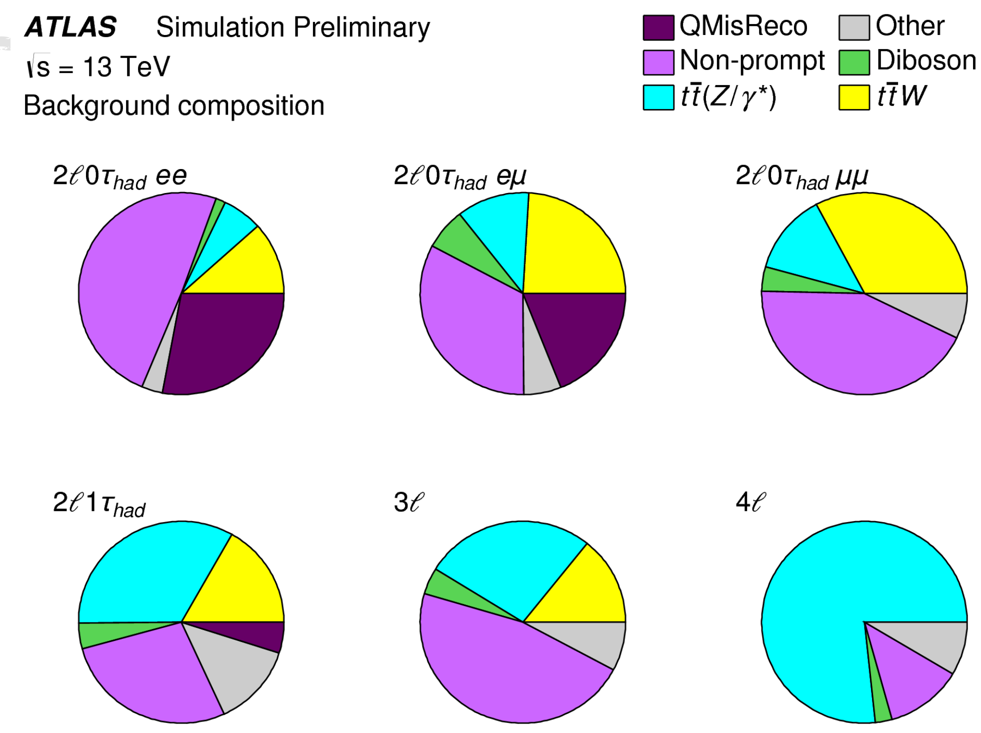


ttH(multi-leptons) irreducible backgrounds

- **Dominant backgrounds are shown in pie chart**
- **Diboson :** subdominant in 2lSS+0/1τ,3l
  - estimated from simulation (Sherpa 2.1.1)
  - 50% normalisation uncertainty
  - validated in WZ+ 1 b-tagged jets region



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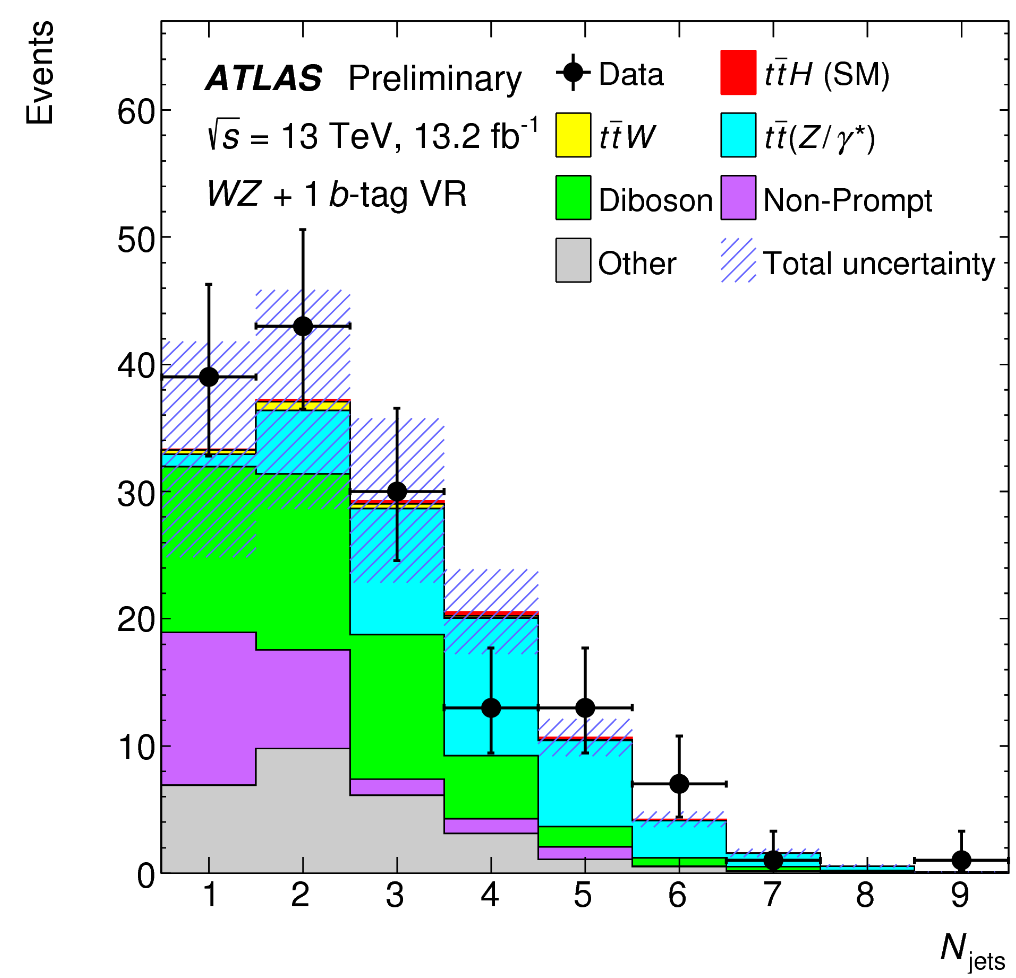
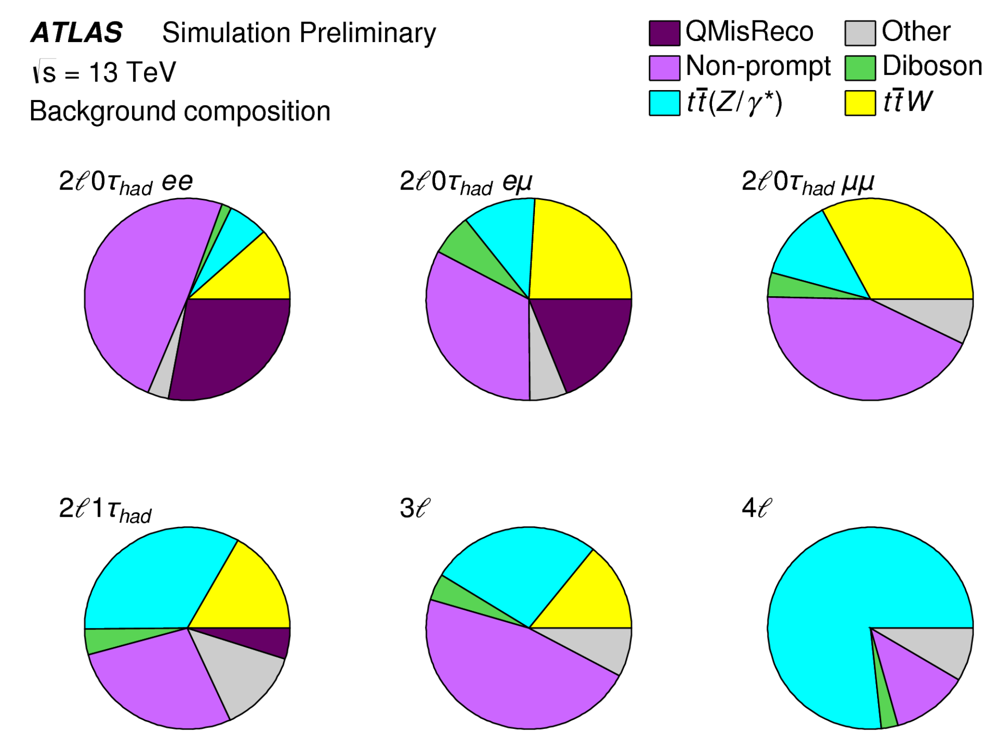


ttH(multi-leptons) reducible backgrounds

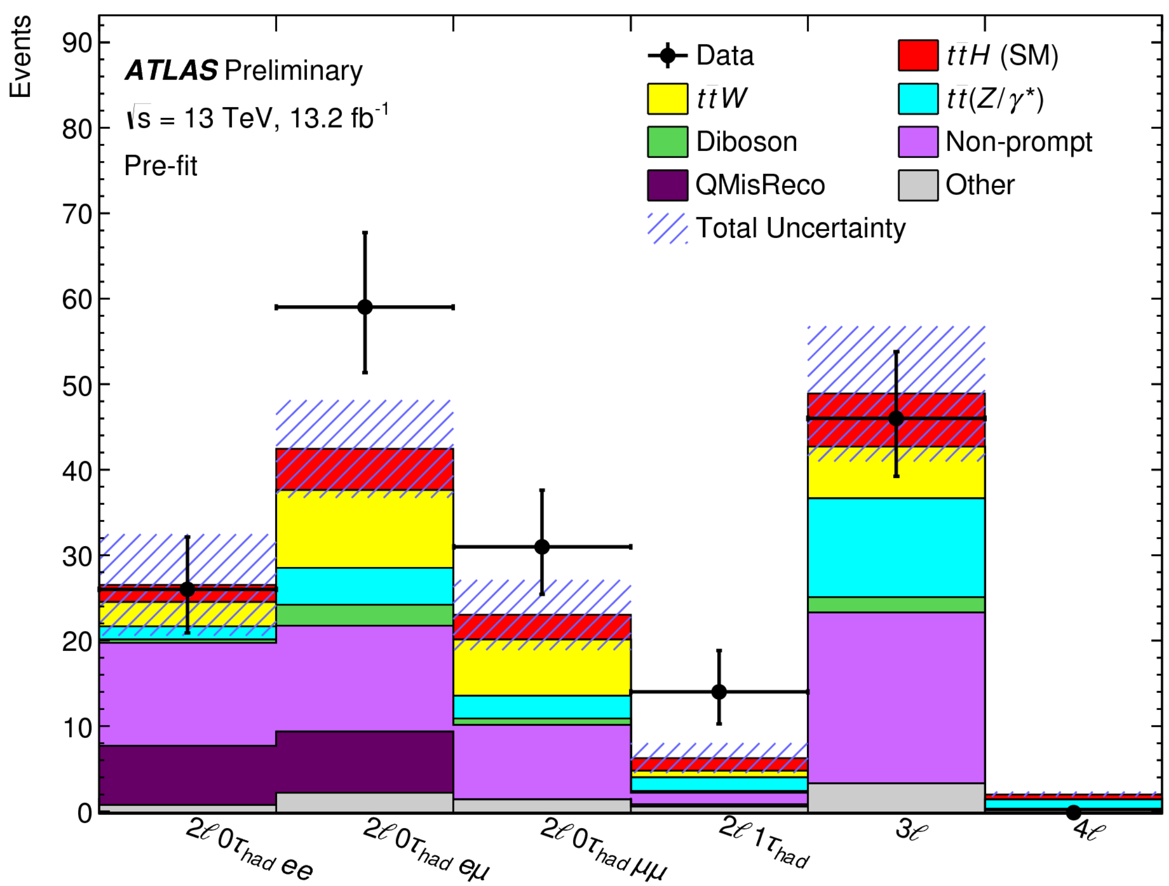


- **Dominant backgrounds are shown in pie chart**
- **Non-prompt light leptons or fake leptons** (mainly from heavy flavour decays)
  - dominant&reducible bkg. in 2lSS+0/1τ,3l
  - estimated by data-driven techniques
    - fake factor derived from low jet multiplicity region, is applied to signal region, in separation of lepton flavour.
  - total uncertainty
    - 20-35% uncertainty from control region statistical uncertainty and from method closure test → 2lSS0τ and 3l channel
    - ~75% uncertainty mainly from control region statistical uncertainty → 2lSS1τ channel
- **Electron charge mis-identification** : important for 2lSS0τ channel in electron categories
  - estimated from Z→ee decays, 9-15% uncertainty.

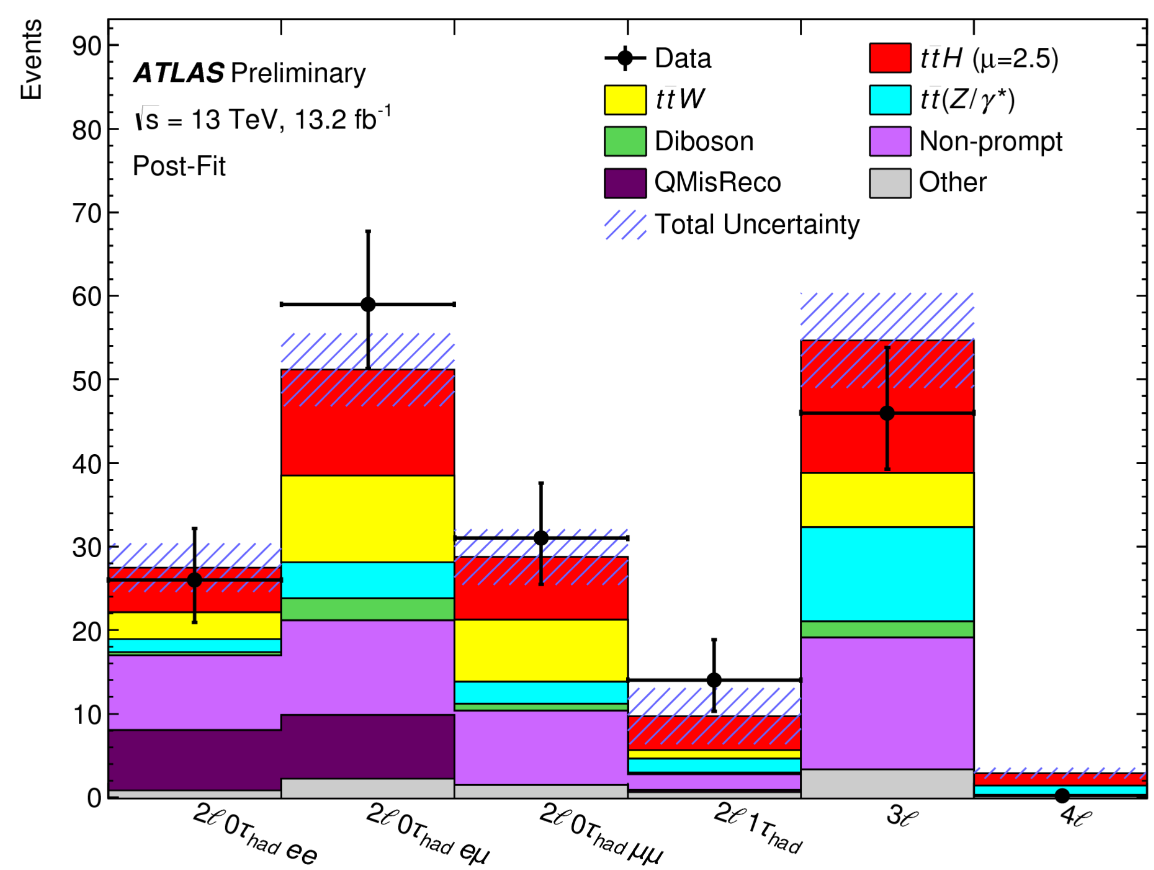
ttH(multi-leptons) results extraction

- This is cut-and-counting analysis.
- Fit simultaneously in six event categories to extract the floating parameter → signal strength μ_{ttH}.

Pre-fit signal and background predictions and observed data



Post-fit signal and background predictions and observed data



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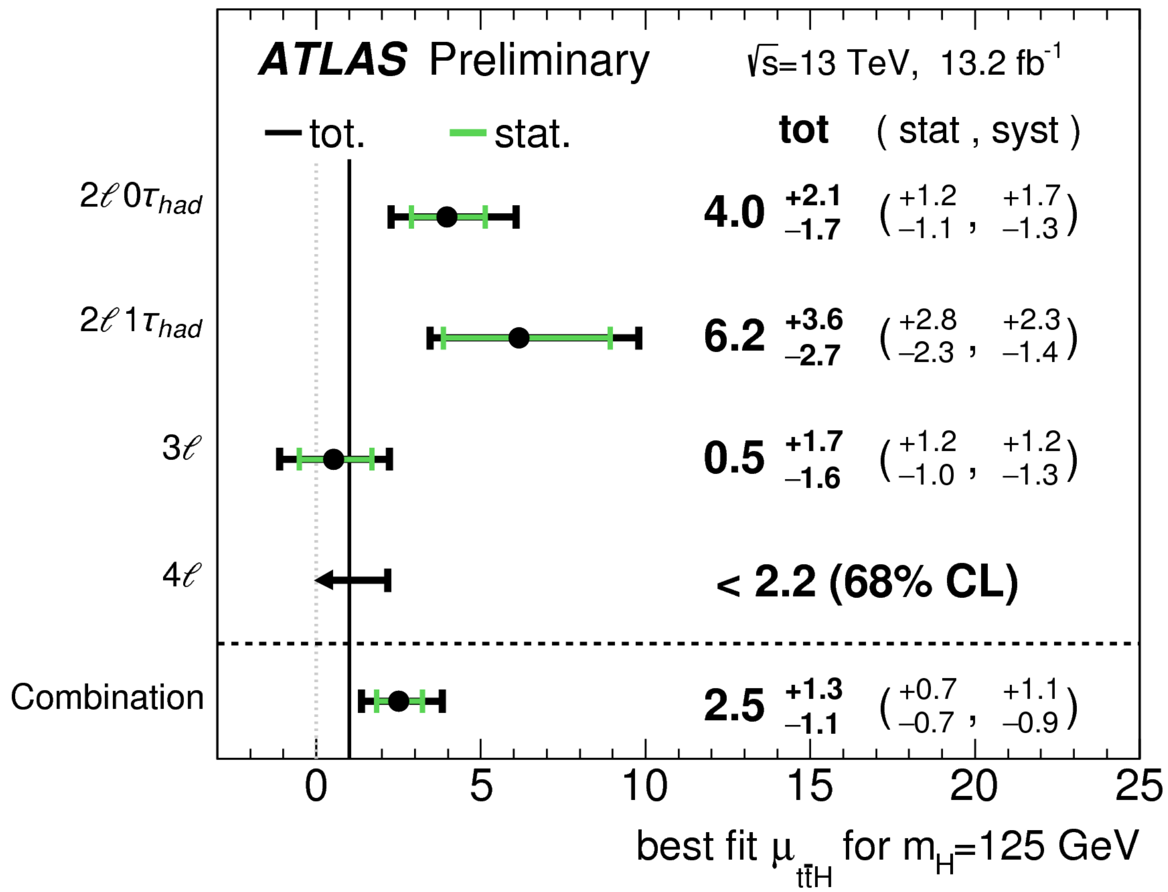
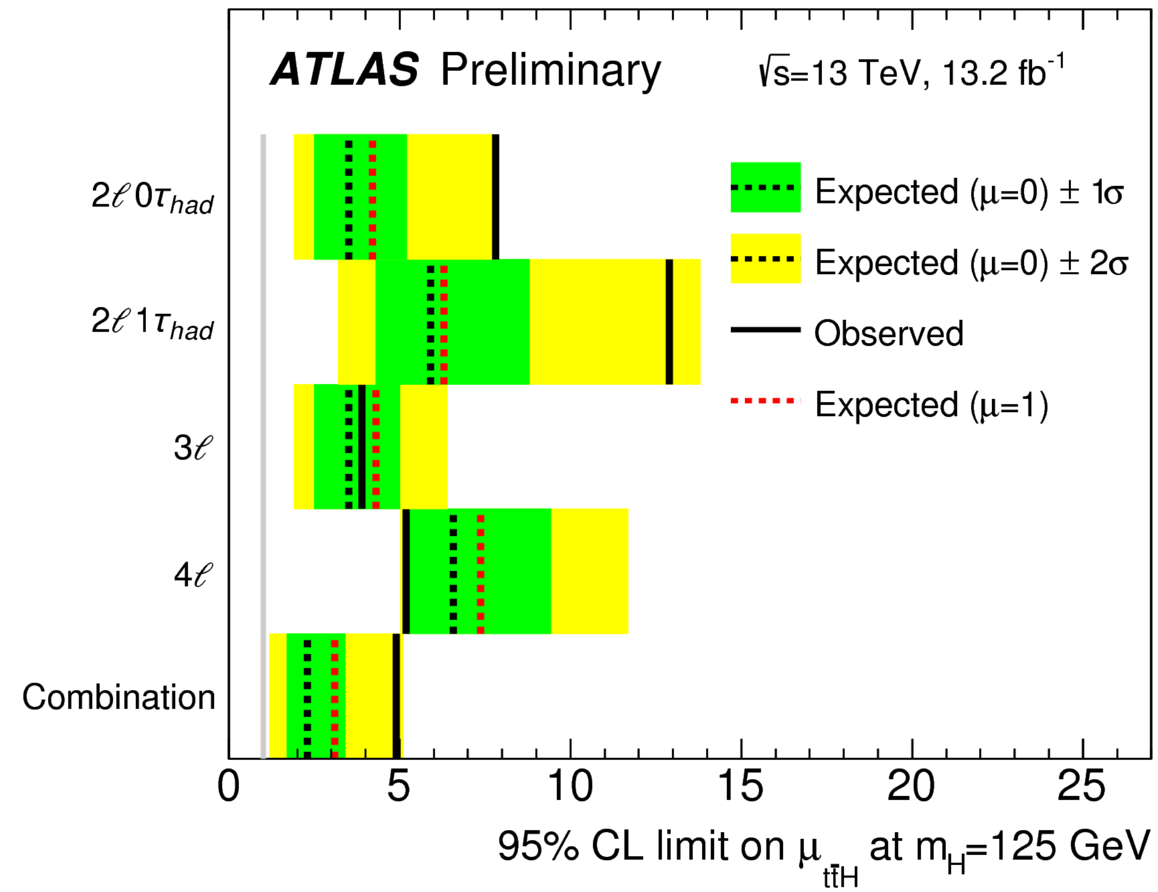
Best fit signal strength 2.5 +1.3/-1.1

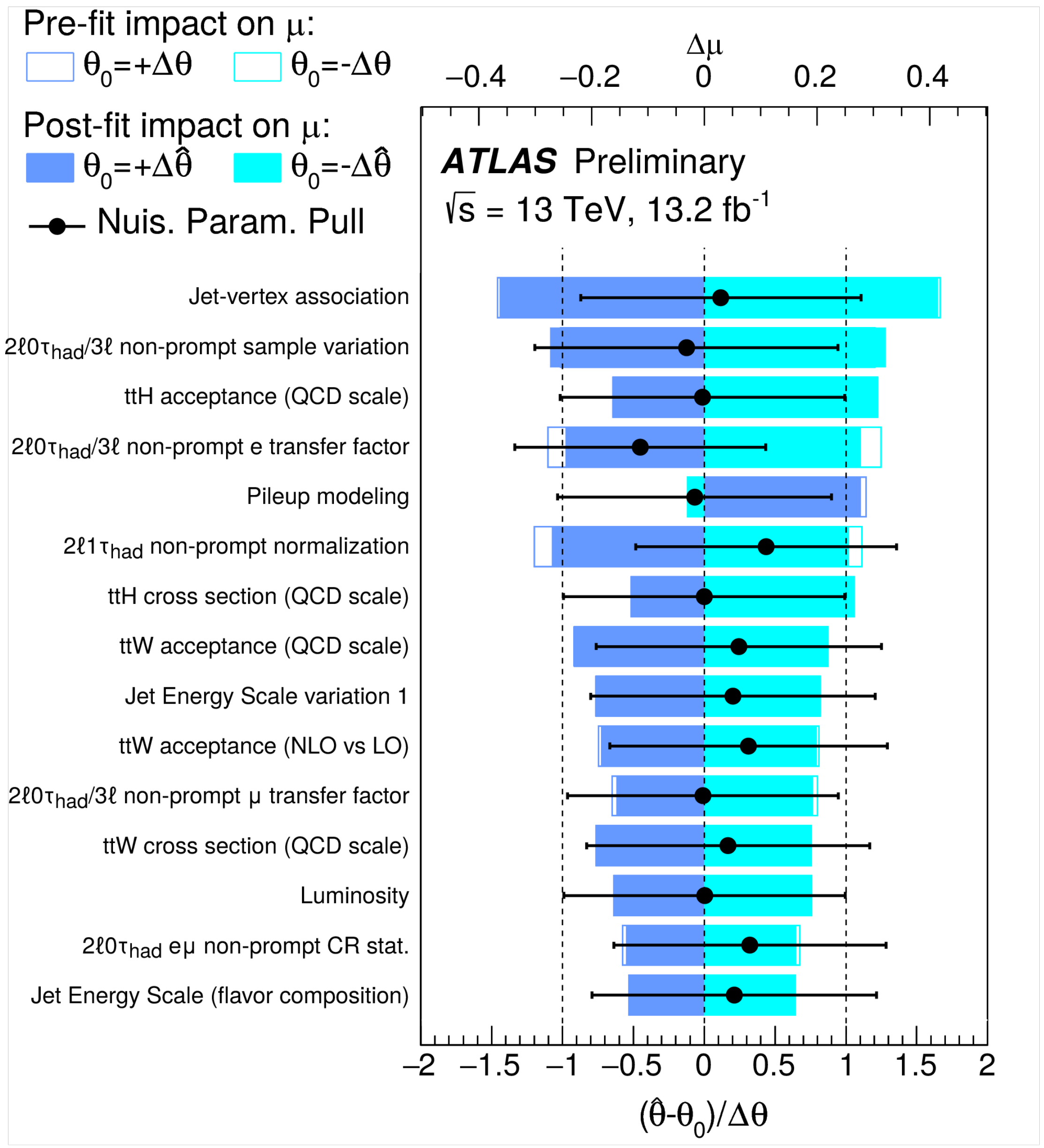
Observed (expected) upper limit : 4.9 (2.3)





ttH(multi-leptons) results extraction

- **Best fit signal strength is** $2.5 \pm 0.7\,(\mathrm{stat})\,^{+1.1}_{-0.9}\,(\mathrm{syst})$
- **Effect of the fifteen most important systematic uncertainty nuisance parameters θ on the signal strength μ_{ttH} uncertainty.**



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

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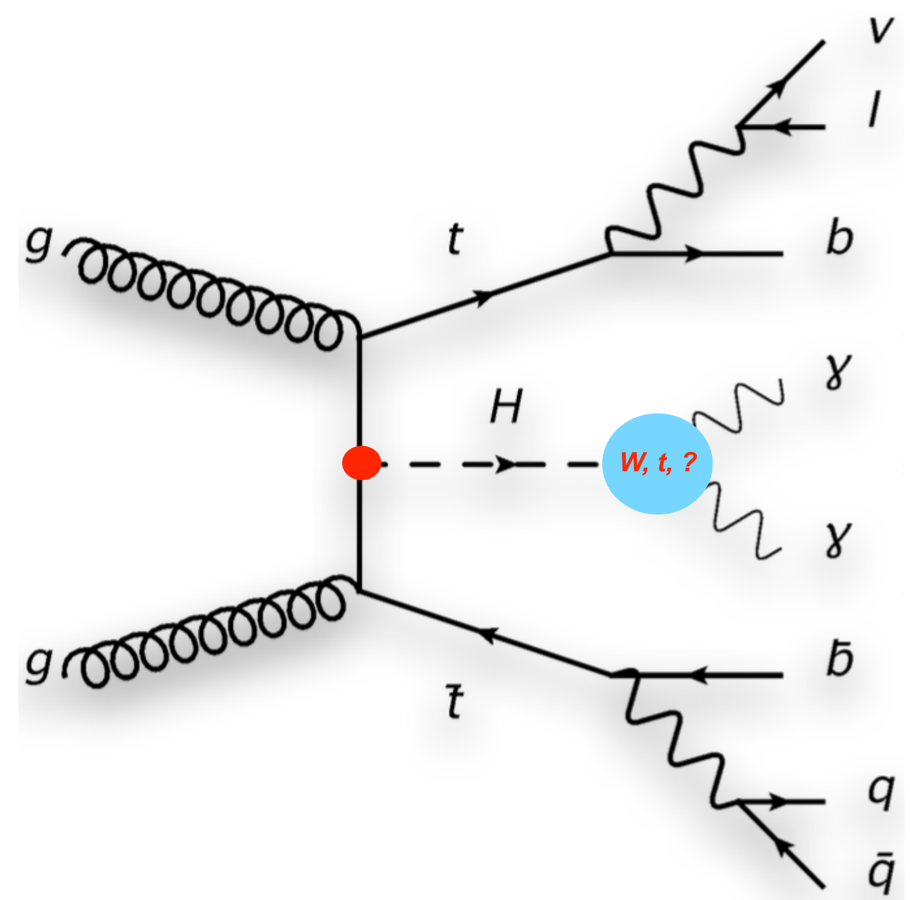
ttH(γγ) channel exploits the excellent di-photon mass resolution of the Higgs decay over its continuum background.

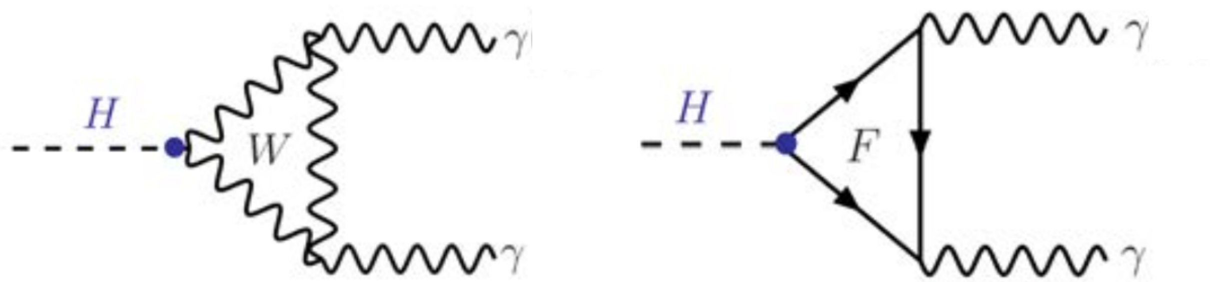
ttH(γγ) Feynman diagram

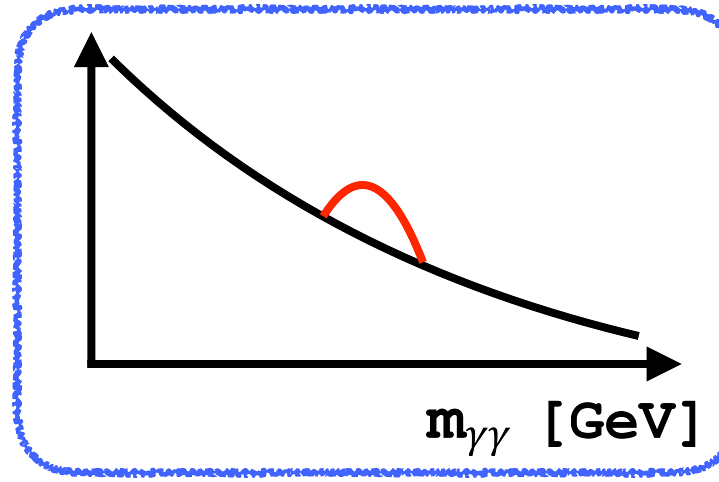


tt semi-leptonic decay

ttH (H→γγ) analysis

- Assuming there is no new physics in H→γγ loops.





- Searching for resonance on falling down background spectrum on $m_{\gamma\gamma}$.
- Events are categorised according to ttbar decay final states.

Leptonic channel
(ttbar leptonic decay)

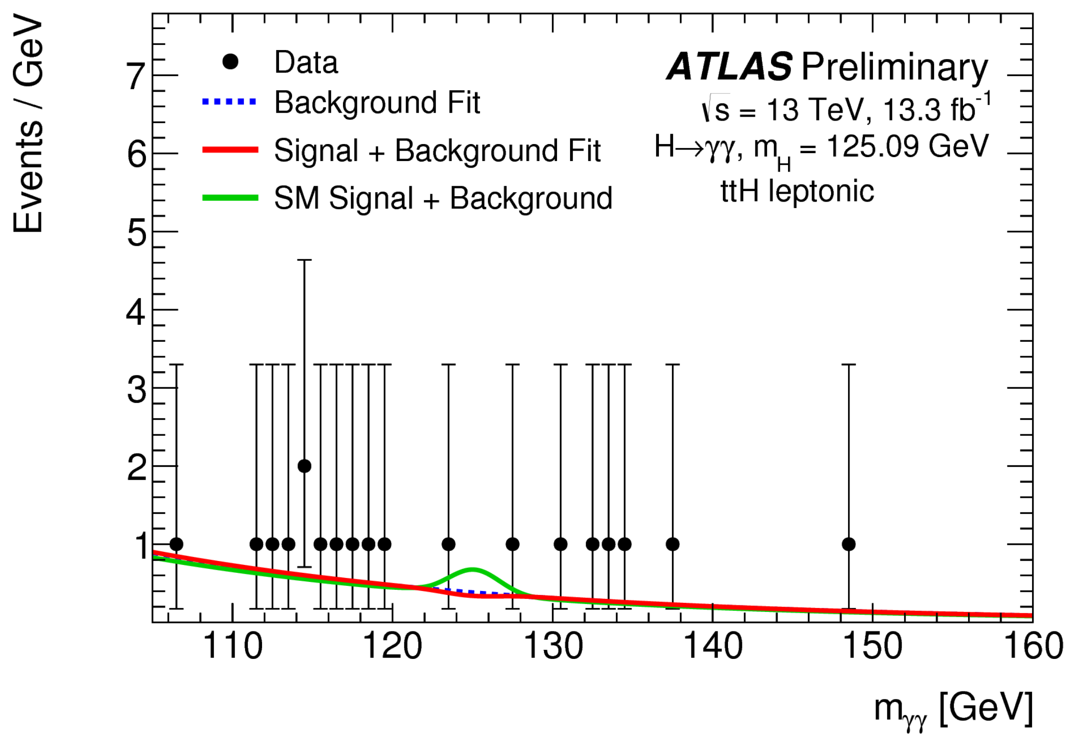
- *at least one light lepton*
- *at least 2 jets*
- *at least 1 b-tagged jet*
- *Z veto and missing E_T>20GeV*

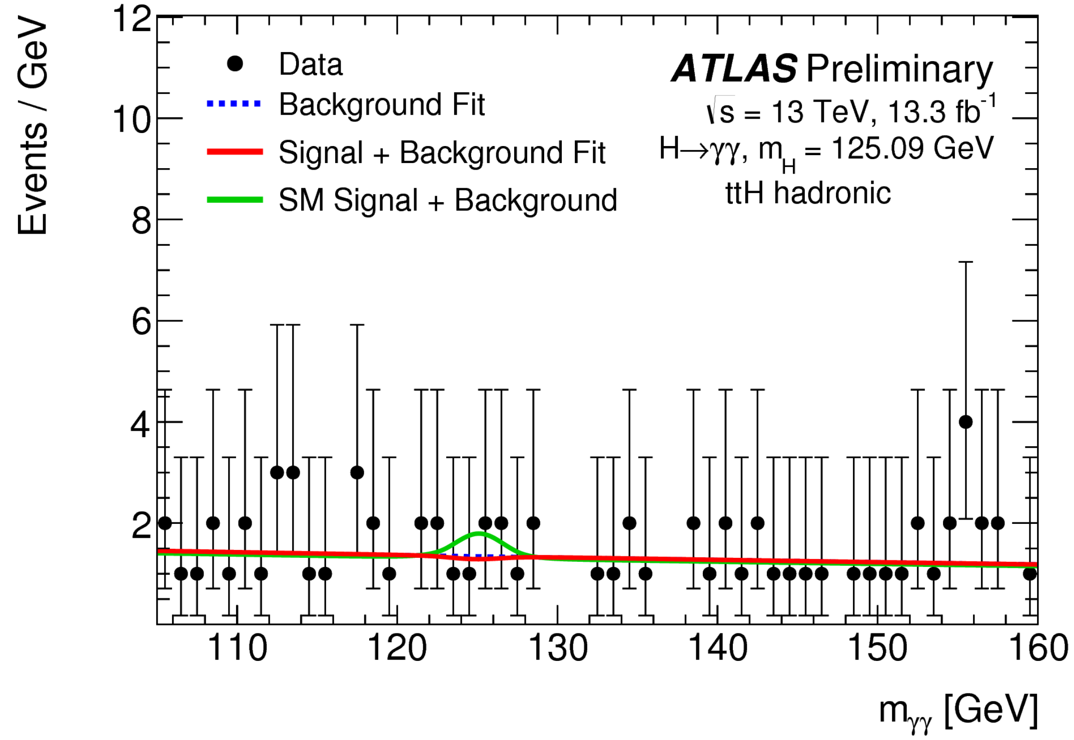
Hadronic channel
(ttbar hadronic decay)

- *no light lepton*
- *at least 5 jets*
- *at least 1 b-tagged jet*

ttH (H→γγ) backgrounds

- **Main backgrounds** (γγ+X, γ+jet+X, jet+jet+X) **is modelled by an exponential form**, **whose parameter is fixed from fitting to data side-band region.**



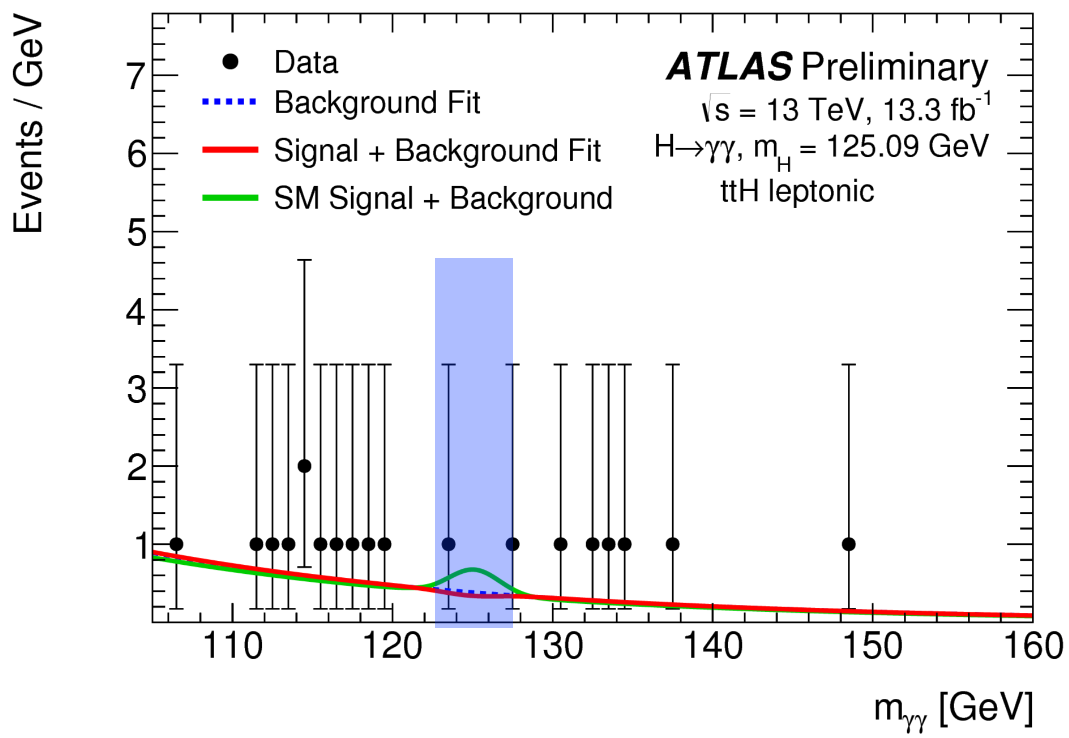


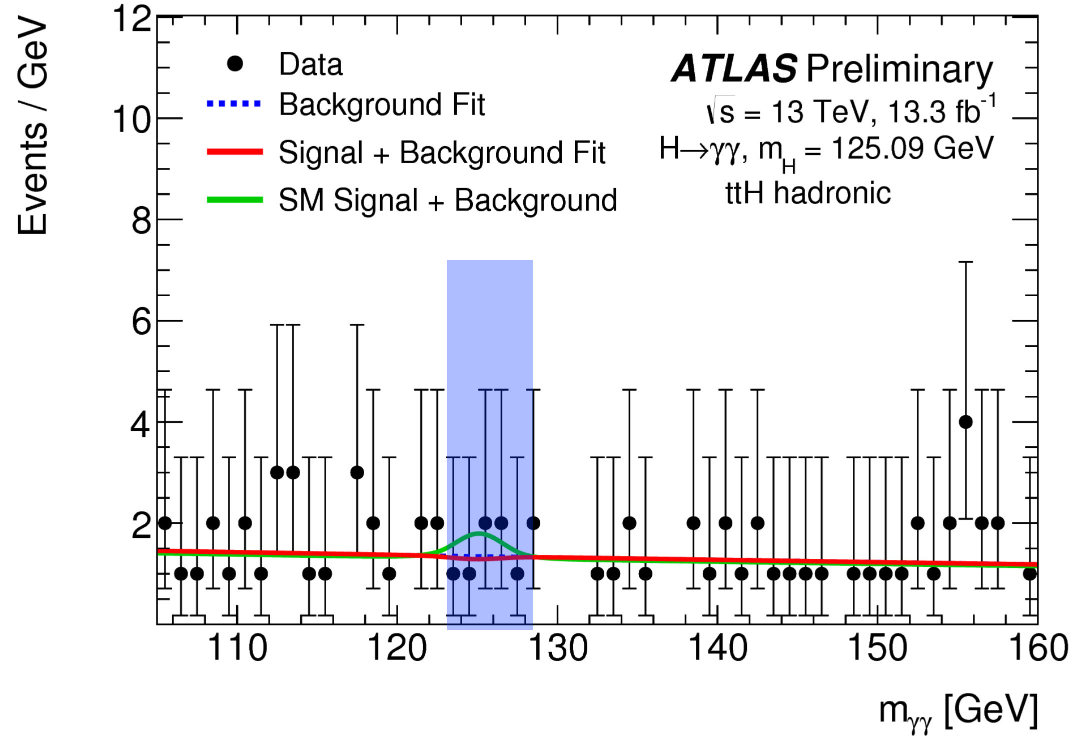
- **Expected signal, background yields in $m_{\gamma\gamma}$ region covering 90% signal yields, and observed data in full fit mass region.**

Category	Events	B_{90}	S_{90}	f_{90}	Z_{90}	$S_{90}^{\rm fit}$
$t\bar{t}H$ hadronic	72	8.1	1.8	0.18	0.60	-0.23
$t\bar{t}H$ leptonic	19	2.3	1.3	0.36	0.78	-0.18

ttH (H→γγ) backgrounds

- **Main backgrounds** (γγ+X, γ+jet+X, jet+jet+X) **is modelled by an exponential form**, **whose parameter is fixed from fitting to data side-band region.**





- **Expected signal, background yields in $m_{\gamma\gamma}$ region covering 90% signal yields, and observed data in full fit mass region.**

Category	Events	B_{90}	S_{90}	f_{90}	Z_{90}	S_{90}^{fit}	D_{90}
$t\bar{t}H$ hadronic	72	8.1	1.8	0.18	0.60	-0.23	9
$t\bar{t}H$ leptonic	19	2.3	1.3	0.36	0.78	-0.18	2

ttH (H→γγ) results extraction

- The measured ttH signal strength is

$$\mu_{t\bar{t}H} = -0.25\,^{+1.26}_{-0.99} = -0.25\,^{+1.25}_{-0.98}\,(\text{stat.})\,^{+0.19}_{-0.21}\,(\text{syst.})\,^{+0.09}_{-0.12}\,(\text{theory})$$

- The analysis is limited by statistics !

ttH combination input channels

- **All three analyses ttH(bb), ttH(multileptons) and ttH(γγ) are combined, at given m_H = 125 GeV.**
- **Summary of expected signal, total background yields and observed data** (tH processes are taken as background).

Channel	Region	$t\bar{t}H$ (S)	Bkgd (B)	$tHjb + WtH$	S/B	N_{Data}
$H \to \gamma\gamma$	all-hadronic	1.58	8.27	0.10	0.19	9
	leptonic	1.16	2.42	0.10	0.48	2
$H \to (WW, \tau\tau, ZZ)$	2ℓSS ee	1.99 ± 0.51	22.2 ± 3.4	0.10 ± 0.03	0.09	26
	2ℓSS $e\mu$	4.82 ± 0.95	38.5 ± 5.1	0.26 ± 0.07	0.13	59
	2ℓSS $\mu\mu$	2.85 ± 0.58	21.2 ± 3.8	0.15 ± 0.04	0.13	31
	2ℓSS $+\tau_{\text{had}}$	1.43 ± 0.31	5.7 ± 1.7	0.11 ± 0.03	0.25	14
	3ℓ	6.2 ± 1.1	38.9 ± 5.3	0.30 ± 0.08	0.16	46
	4ℓ	0.59 ± 0.10	1.42 ± 0.24	0.014 ± 0.006	0.42	0
$H \to b\bar{b}$	ℓ+jets ($\geq$ 6j,3bj)	119 ± 16	11250 ± 240	6.2 ± 1.5	0.011	11561
	ℓ+jets (5j,$\geq$ 4bj)	11.8 ± 2.6	429 ± 28	0.91 ± 0.14	0.028	418
	ℓ+jets ($\geq$ 6j,$\geq$ 4bj)	44.9 ± 9.4	1191 ± 55	2.10 ± 0.50	0.038	1285
	dilepton ($\geq$ 4j,3bj)	20.6 ± 4.2	1423 ± 45	0.71 ± 0.20	0.014	1467
	dilepton ($\geq$ 4j,$\geq$ 4bj)	6.6 ± 2.0	133 ± 12	0.171 ± 0.053	0.050	154

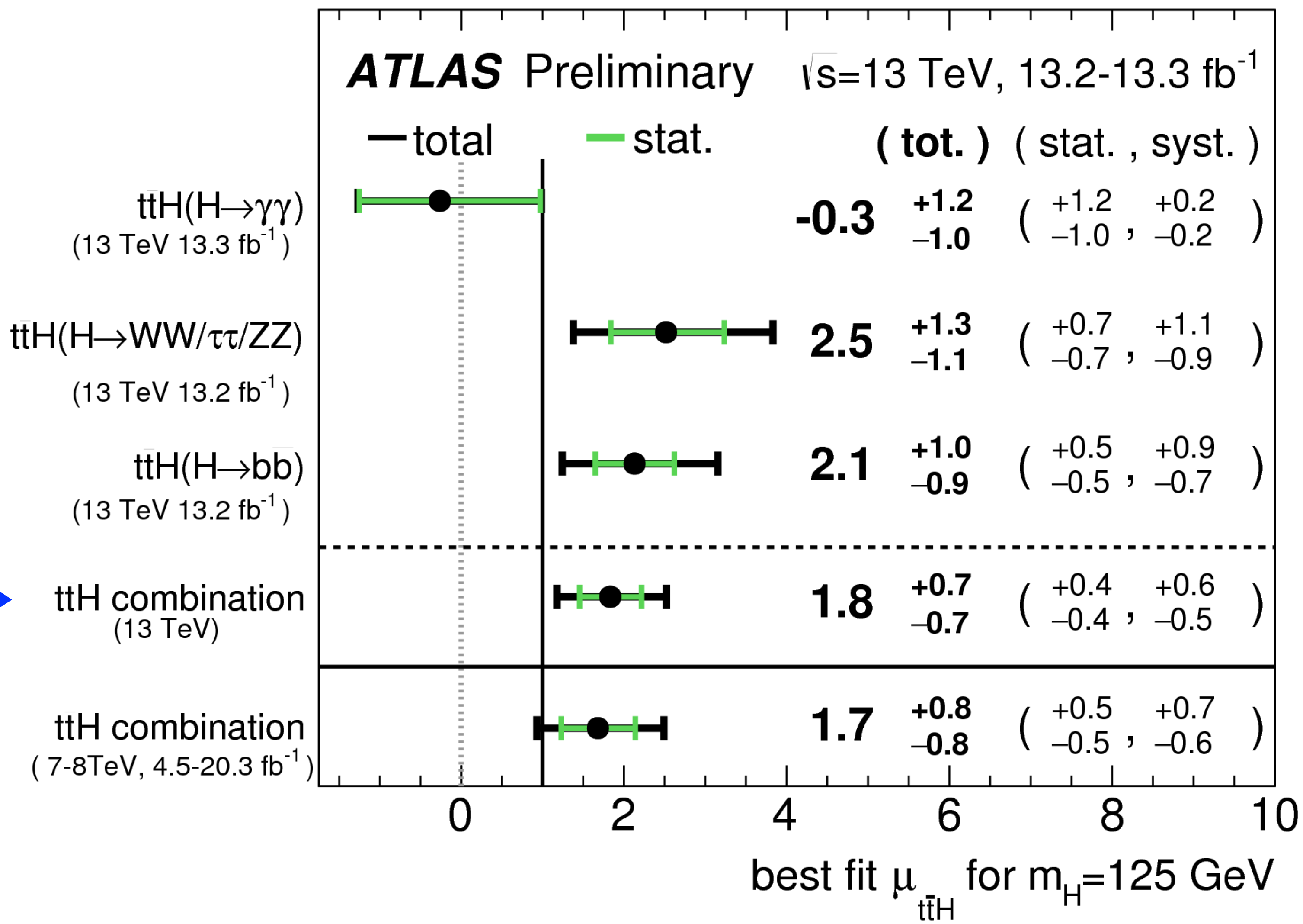
ttH combination input channels

- All three analyses ttH(bb), ttH(multileptons) and ttH(γγ) are combined, at given m_H = 125 GeV.
- Contribution of each Higgs boson decay mode for ttH in the most sensitive signal regions.

Channel	Region	WW	$\tau\tau$	ZZ	$b\bar{b}$	$\gamma\gamma$
$H \to \gamma\gamma$	all-hadronic	–	–	–	–	100%
	leptonic	–	–	–	–	100%
$H \to (WW, \tau\tau, ZZ)$	2ℓSS ee	76%	17%	2%	4%	–
	2ℓSS $e\mu$	77%	17%	3%	3%	–
	2ℓSS $\mu\mu$	79%	17%	3%	1%	–
	2ℓSS $+\tau_{\text{had}}$	46%	51%	2%	1%	–
	3ℓ	74%	20%	4%	1%	–
	4ℓ	72%	18%	9%	–	–
$H \to b\bar{b}$	ℓ+jets ($\geq$ 6j,3bj)	5%	1%	1%	90%	–
	ℓ+jets (5j,$\geq$ 4bj)	–	–	–	99%	–
	ℓ+jets ($\geq$ 6j,$\geq$ 4bj)	1%	–	1%	97%	–
	dilepton ($\geq$ 4j,3bj)	6%	1%	1%	90%	–
	dilepton ($\geq$ 4j,$\geq$ 4bj)	–	–	–	98%	–

ttH combination signal strength

- Fit is done simultaneously in all regions, to extract the **ttH signal strength**.



- **Combined ttH signal strength value:**

$$\mu_{t\bar{t}H} = 1.8\ ^{+0.4}_{-0.4}\,(\text{stat.})\ ^{+0.6}_{-0.5}\,(\text{syst.}) = 1.8\ ^{+0.7}_{-0.7}$$

ttH combination uncertainties

- **Summary of ttH signal strength uncertainty sources.**

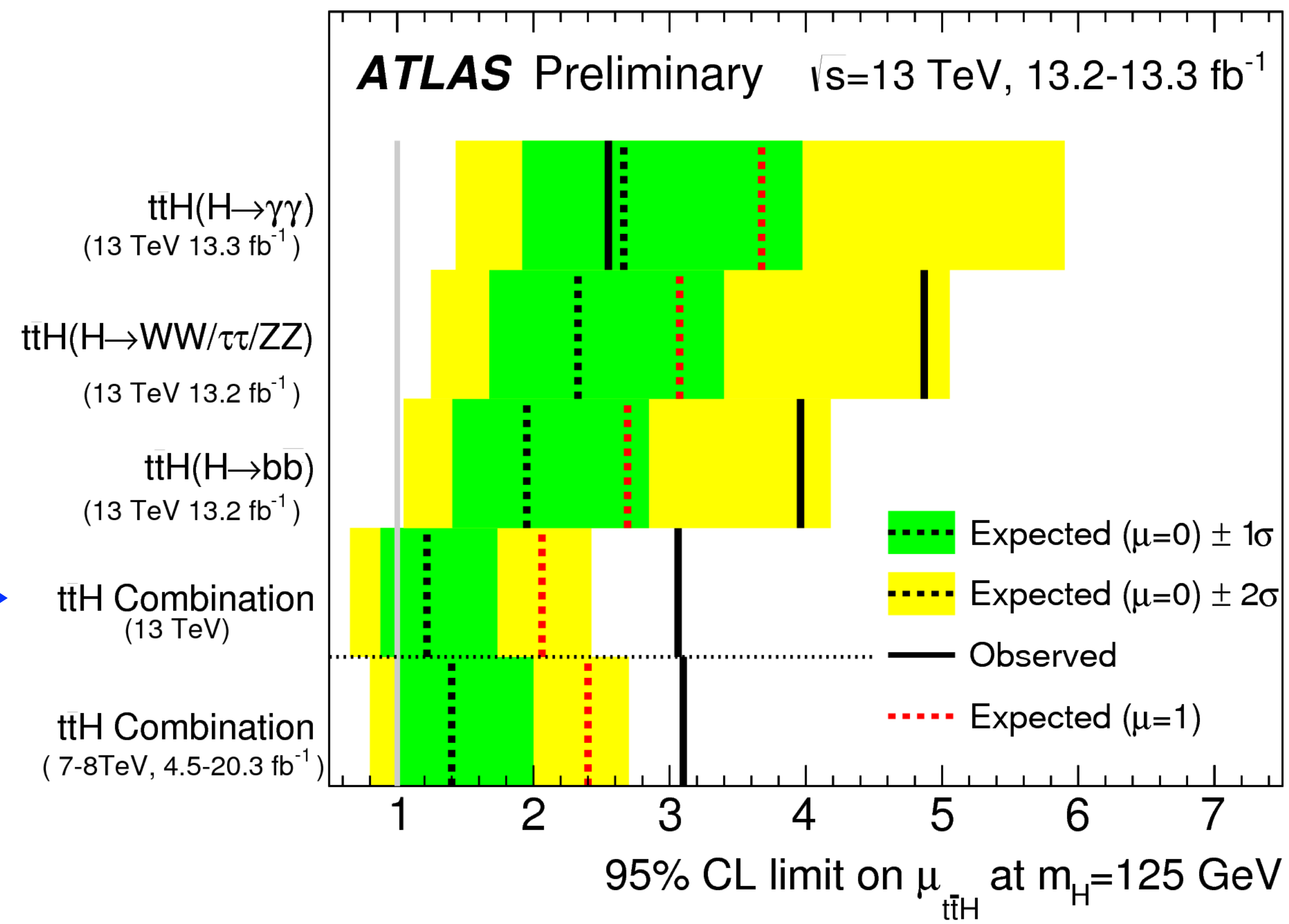
Uncertainty Source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	$+0.34$	-0.33
Jet flavour tagging	$+0.19$	-0.19
Background model statistics	$+0.18$	-0.18
$t\bar{t}+\geq 1c$ modelling	$+0.17$	-0.17
Jet energy scale and resolution	$+0.18$	-0.18
$t\bar{t}H$ modelling	$+0.20$	-0.13
$t\bar{t}$+light modelling	$+0.14$	-0.14
Other background modelling	$+0.16$	-0.15
Fake lepton uncertainties	$+0.11$	-0.12
Jet-vertex association, pileup modelling	$+0.09$	-0.09
Luminosity	$+0.09$	-0.09
$t\bar{t}Z$ modelling	$+0.08$	-0.07
Light lepton (e,μ), photon, and τ ID, isolation, trigger	$+0.04$	-0.04
Total systematic uncertainty	$+0.57$	-0.54
$t\bar{t}+\geq 1b$ normalisation	$+0.24$	-0.24
$t\bar{t}+\geq 1c$ normalisation	$+0.11$	-0.11
Statistical uncertainty	$+0.38$	-0.38
Total uncertainty	$+0.69$	-0.66

ttH combination significance and limits

- The combined observed (expected) significance w.r.t background-only hypothesis is 2.8 (1.8) standard deviation.

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

- The combined observed upper limit on the ttH signal strength at 95% C.L. is 3.0, as well as expected one with (w/o) the SM Higgs boson is 2.1 (1.2).



Summary

- First Run 2 ttH searches in ATLAS have been performed in ttH(H→bb), ttH(H→ WW*, ZZ*, ττ), and H→ γγ channels, using 13.2-13.3 fb^{-1} collision data.
- Results from each individual channel have been combined.
- The best measured ttH signal strength is

$$\mu_{t\bar{t}H} = 1.8\ ^{+0.4}_{-0.4}\ (\text{stat.})\ ^{+0.6}_{-0.5}\ (\text{syst.}) = 1.8\ ^{+0.7}_{-0.7}$$

which corresponds to an observed significance of 2.8 σ.

- 95% C.L upper limit on the ttH signal strength is 3.0.
- Looking forward to more datasets during LHC Run 2 period !

Backup

Discovery of the SM Higgs boson

- **An Higgs-like particle was observed by ATLAS and CMS experiment in 2012** → Peter W. Higgs and François Englert are awarded with Nobel Prize in 2013 !
- **In July 2012**

  observation of an Higgs-like particle

  (in combine $H\to\gamma\gamma$, $H\to WW$ and $H\to ZZ$ channels)
- **In March 2013**

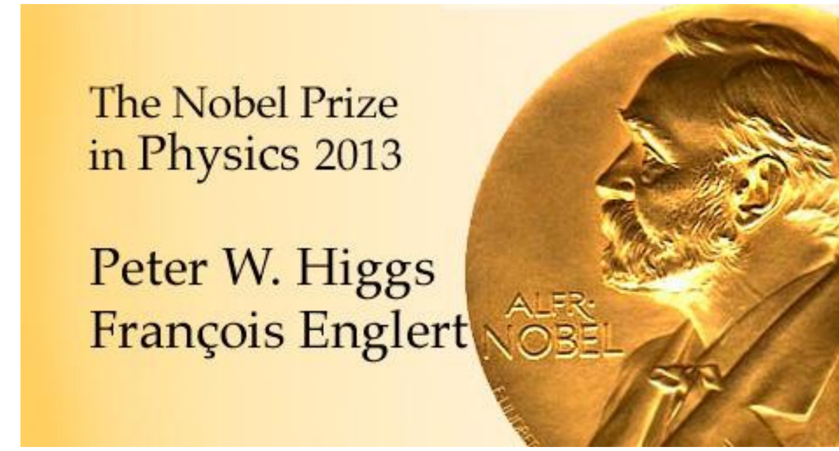
  confirmed by spin/CP & coupling constraints

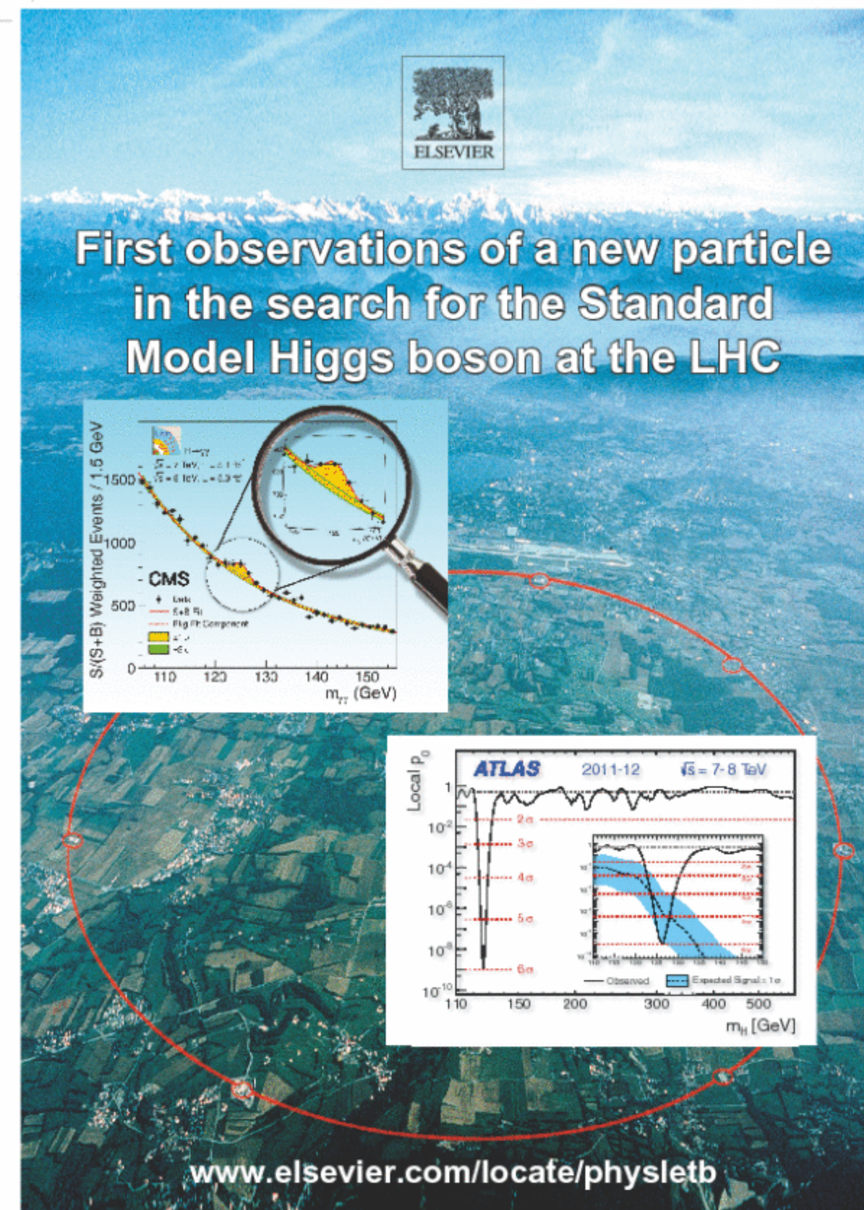
  observation of $H\to\gamma\gamma$, $H\to ZZ$, *evidence of VBF*
- **In Nov. 2013**

  evidence for $H\to\tau\tau$ *decay*
- **In Dec. 2014**

  observation of $H\to WW$ *decay*
- Up to now (**ATLAS+CMS run 1 combination**)

  observation of $H\to\tau\tau$ *and VBF production*





New discovered Higgs boson measured properties

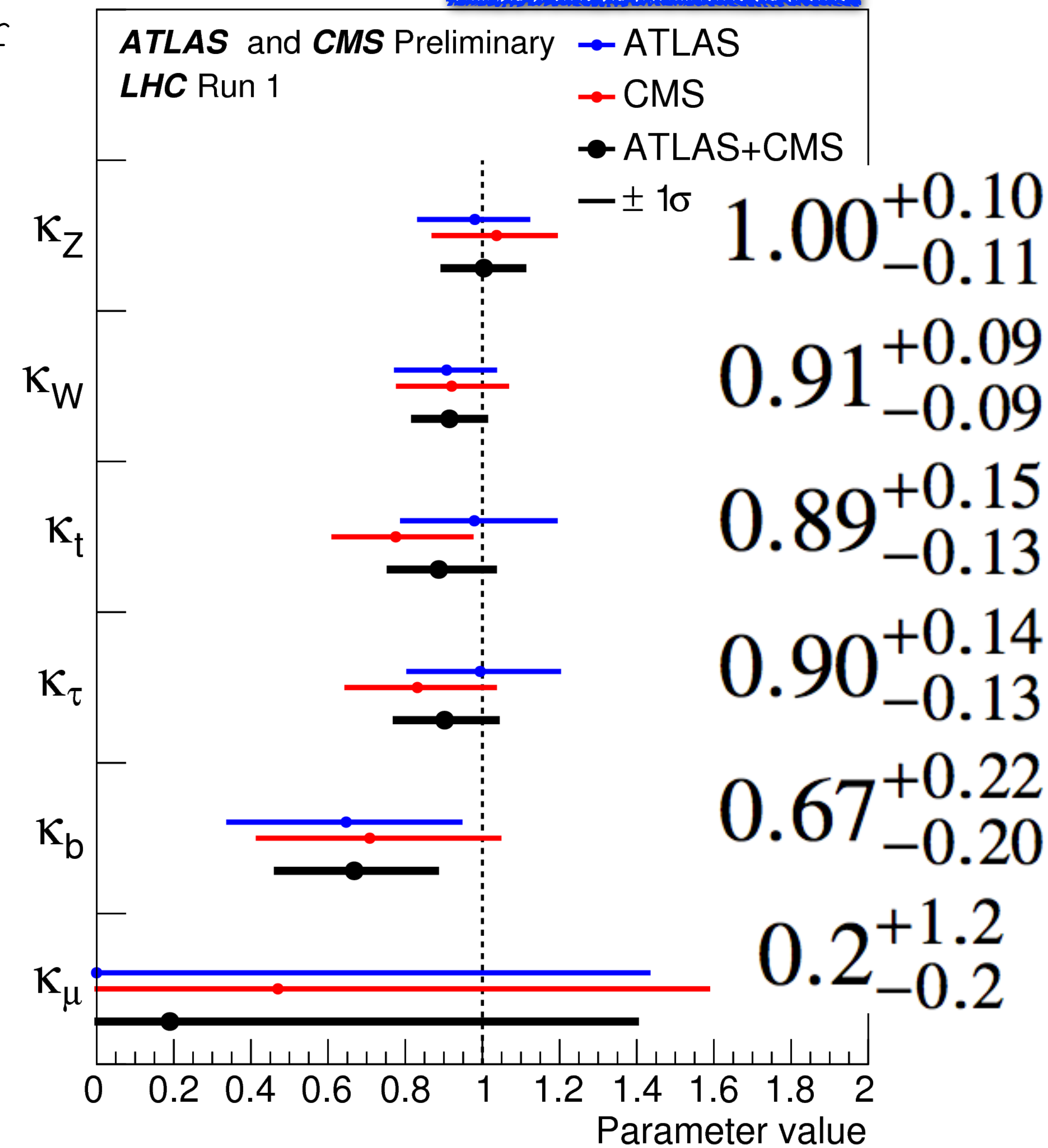
- ATLAS+CMS combined measurement of Higgs boson mass:

$$125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.})\ \text{GeV}$$

$$\kappa_j^2 = \sigma_j / \sigma_j^{SM}$$

- Best-fit values of coupling modifier
  - couplings to vector bosons ~ 10% uncer.
  - couplings to fermions > 15% uncer.

- **Any deviation might be hint for new physics, by**
  - searching as much as rare decays
  - precise measurement on properties of the new discovered particle



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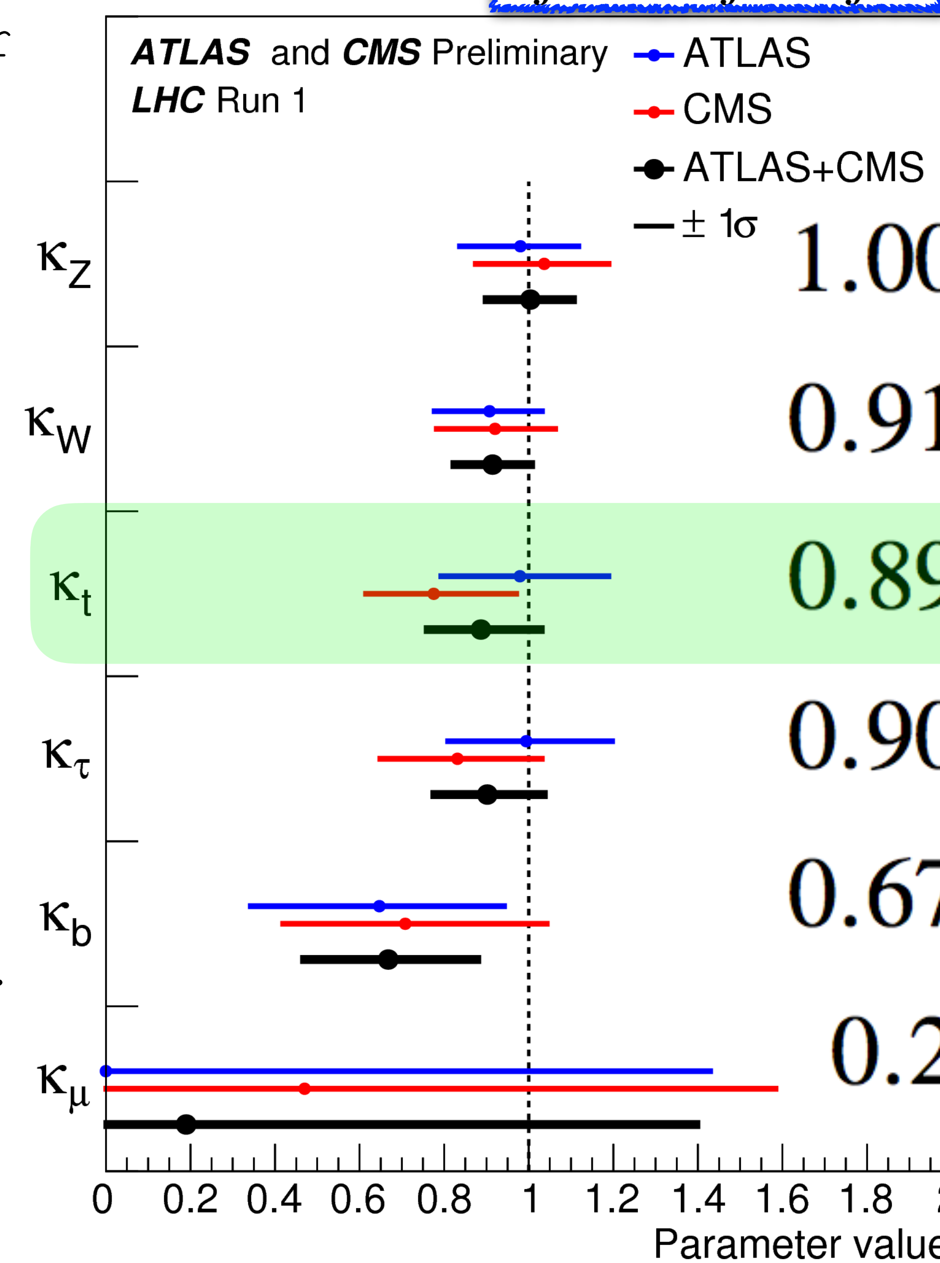


$1.00^{+0.10}_{-0.11}$
$0.91^{+0.09}_{-0.09}$
$0.89^{+0.15}_{-0.13}$
$0.90^{+0.14}_{-0.13}$
$0.67^{+0.22}_{-0.20}$
$0.2^{+1.2}_{-0.2}$

- **Any deviation might be hint for new physics, by**
  - searching as much as rare decays
  - precise measurement on properties of the new discovered particle

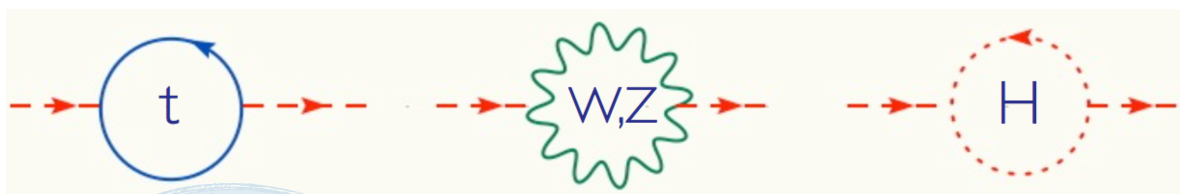
- **Top Yukawa coupling y_t is one of all biggest focuses we should care about**

  κ_t presents its measured value over the SM predicted one.

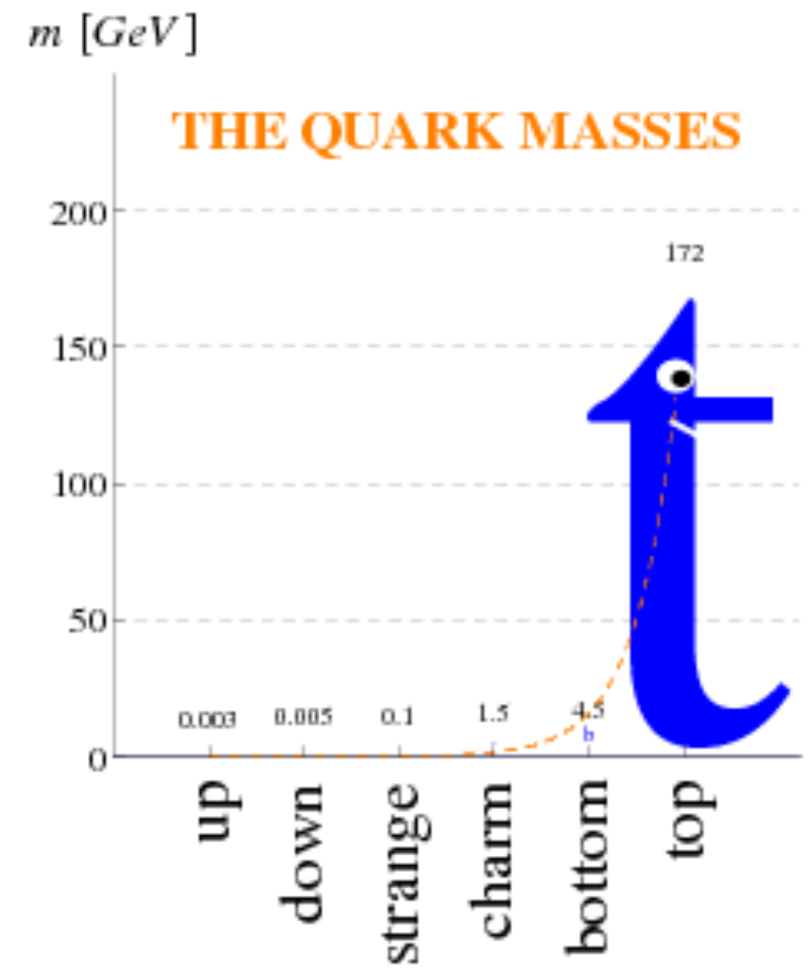
Why should we care about the top Yukawa coupling

An interesting argument from theorist arXiv:1411.1923

- **The top Yukawa coupling is close to unity,**
  since top quark is special → heavy mass
- **Consider the SM as an effective field theory,**
  y_t affects Higgs mass stability dramatically



$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$



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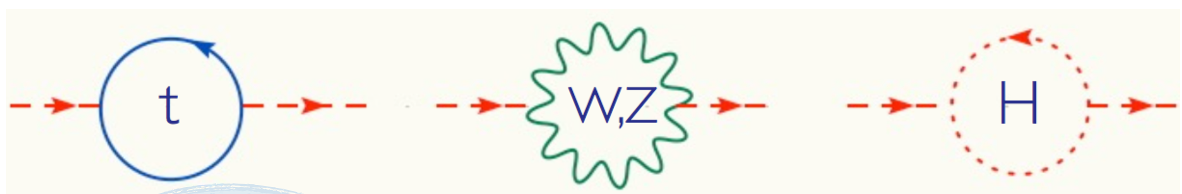
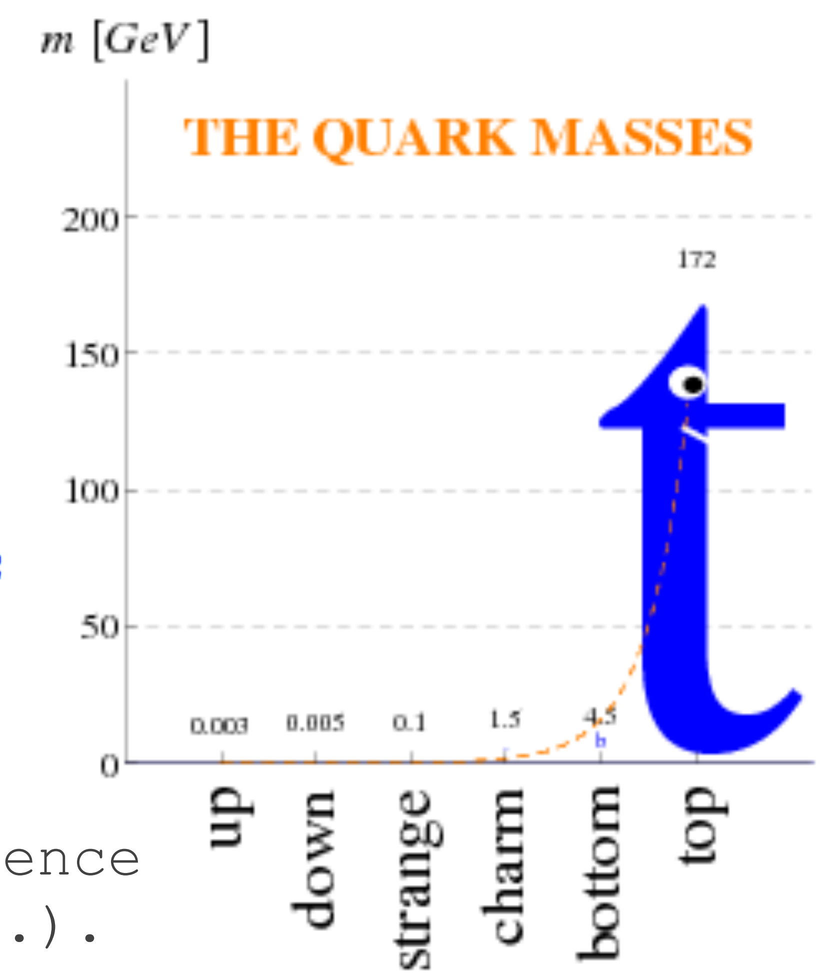


$$(125\,\text{GeV})^2 = m^2_{H0} + \left[-(2\,\text{TeV})^2 + (700\,\text{GeV})^2 + (500\,\text{GeV})^2\right]\left(\frac{\Lambda}{10\text{TeV}}\right)^2$$



- Many observations favour with new physics presence (neutrino oscillations, dark matter, gravity ..). **But no idea at which scale NP would bump up !**
- **The SM by itself can be a consistent theory, for energies exceeding the Planck scale (10^{18} GeV) by many orders of magnitude.**
- It was arguing that

"…at present moment ***the only quantity*** *which can help us to get an idea about the scale of new physics is* ***the top Yukawa coupling****…"*

Why should we care about the top Yukawa coupling

An interesting argument from theorist [arXiv:1411.1923]

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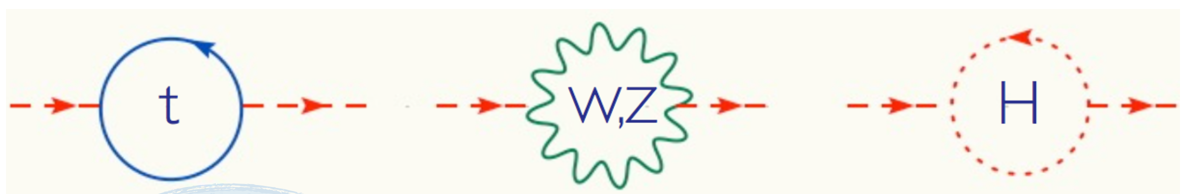

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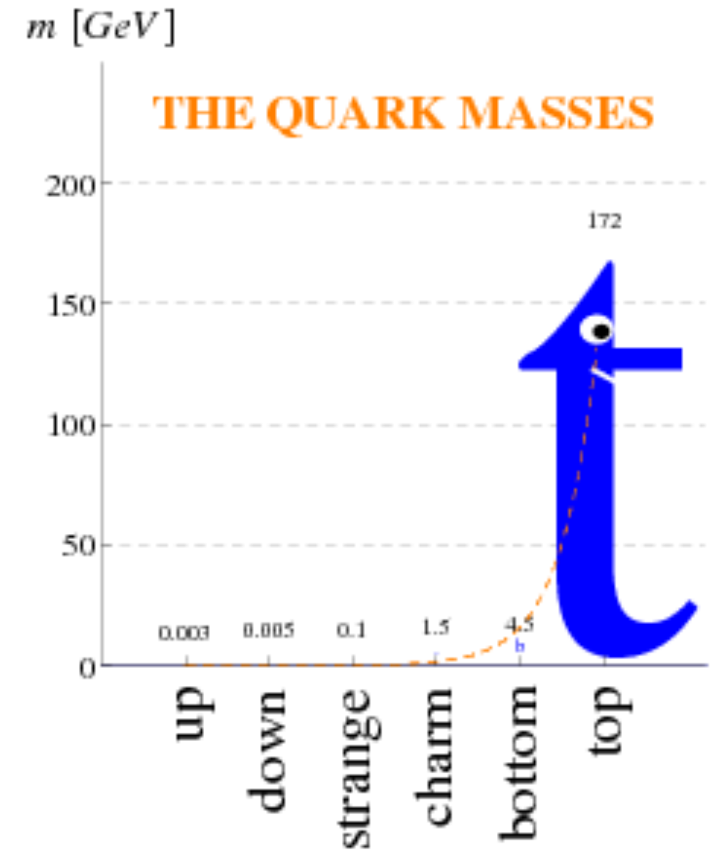
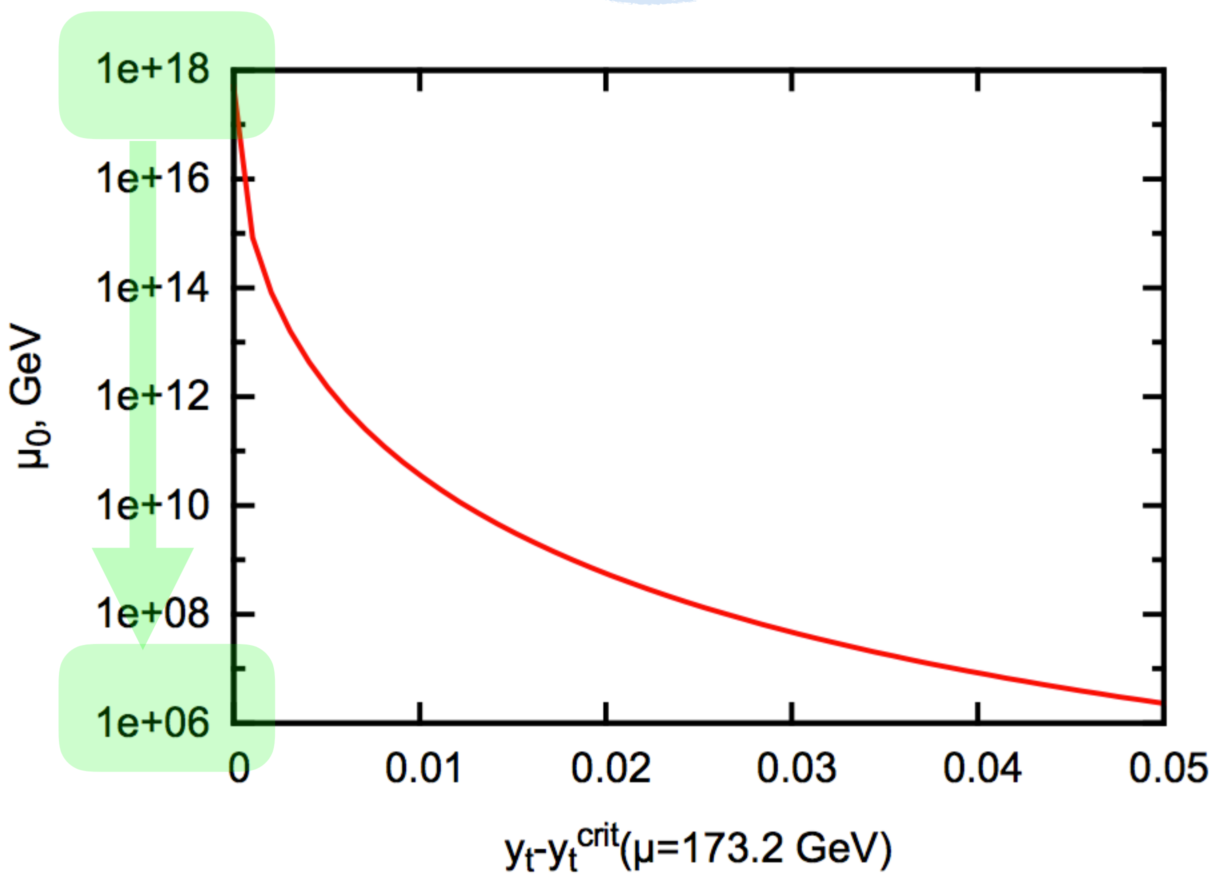




Energy scale μ_0 where the Higgs self-coupling becomes negative **as function of the deviation of y_t from the critical value**

$$y_t^{\mathrm{crit}} = 0.9244 + 0.0012 \times \frac{M_h/\mathrm{GeV} - 125.7}{0.4} + 0.0012 \times \frac{\alpha_s(M_Z) - 0.1184}{0.0007}$$

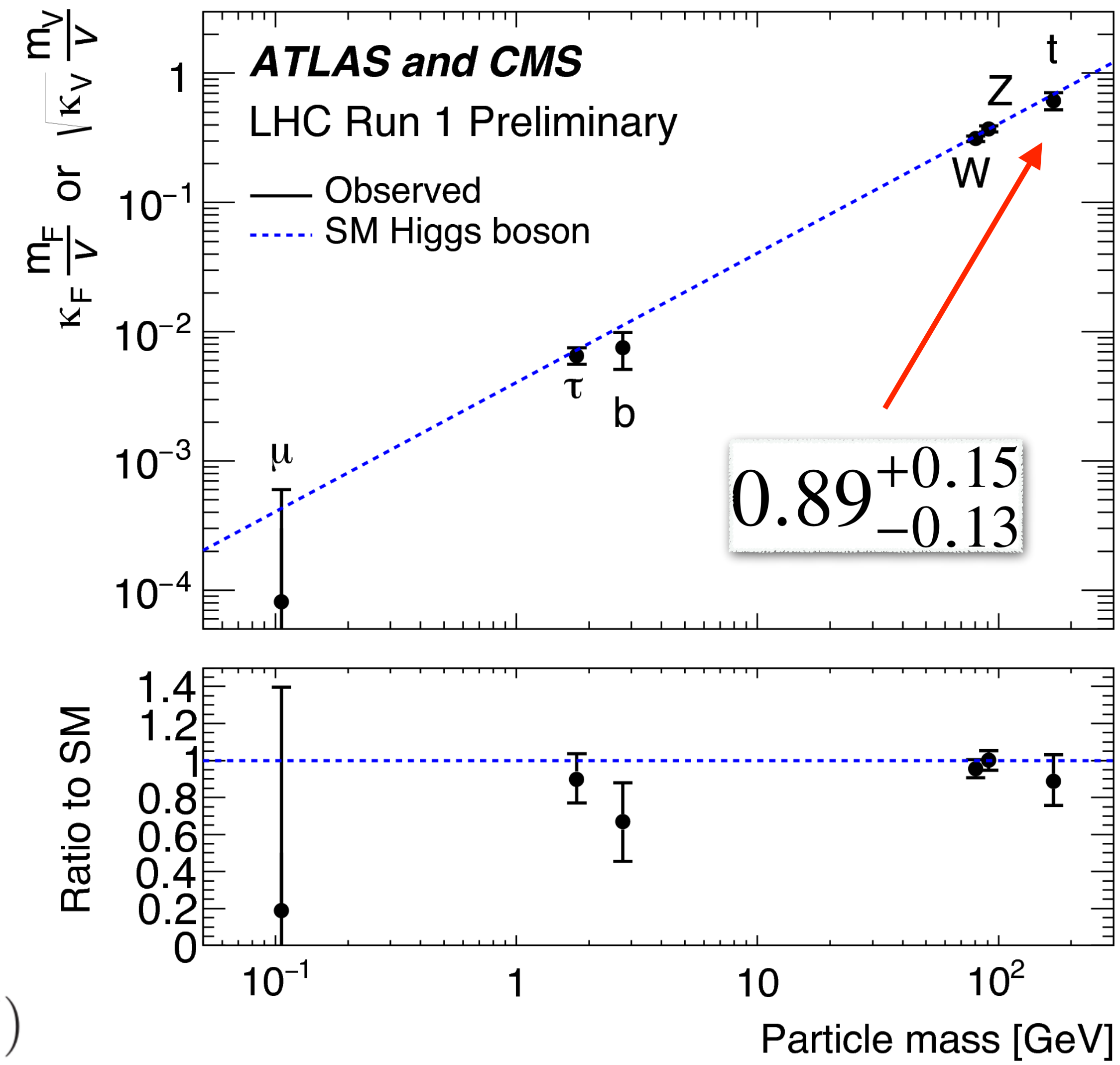
Top Yukawa coupling indirect measurements

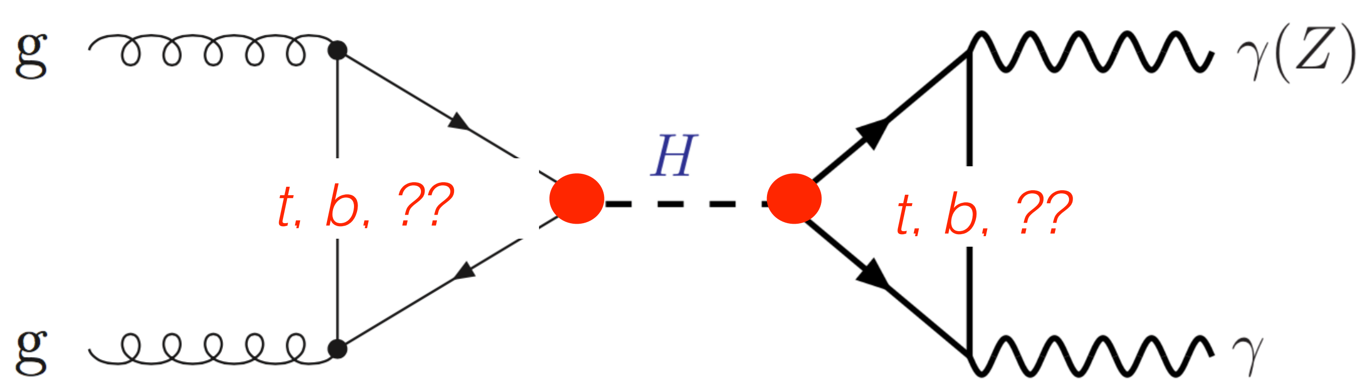
- **Can be derived from top mass, top pair cross section measurements**

  ($y_t = \sqrt{2} m_t / v$. need precise top pole mass !)

- **It has been constraint from Higgs production and decay measurements.**

  mainly from Higgs gluon fusion production and $H \to \gamma\gamma$, where top Yukawa coupling exists in loops, **assuming there is no BSM !**





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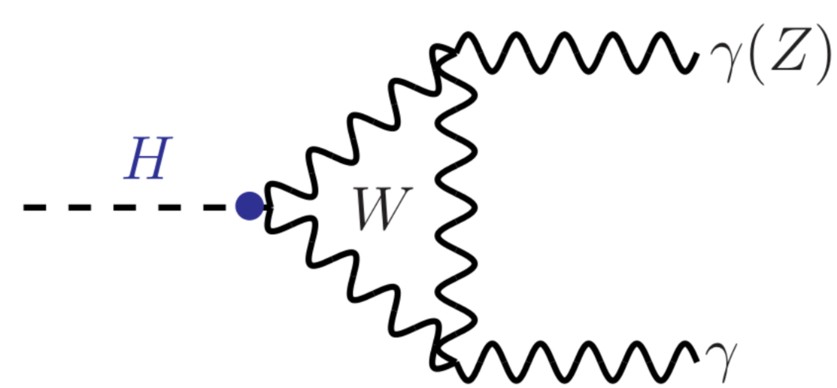
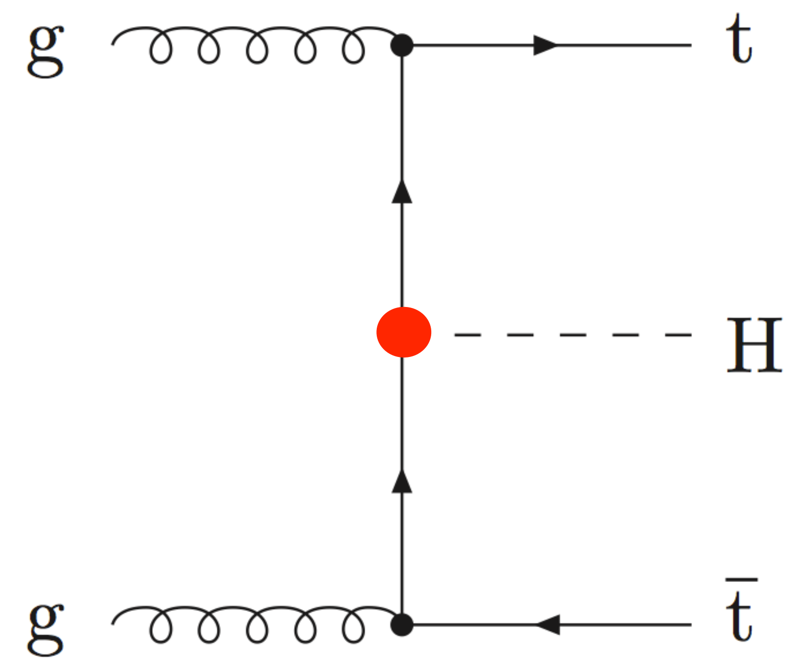
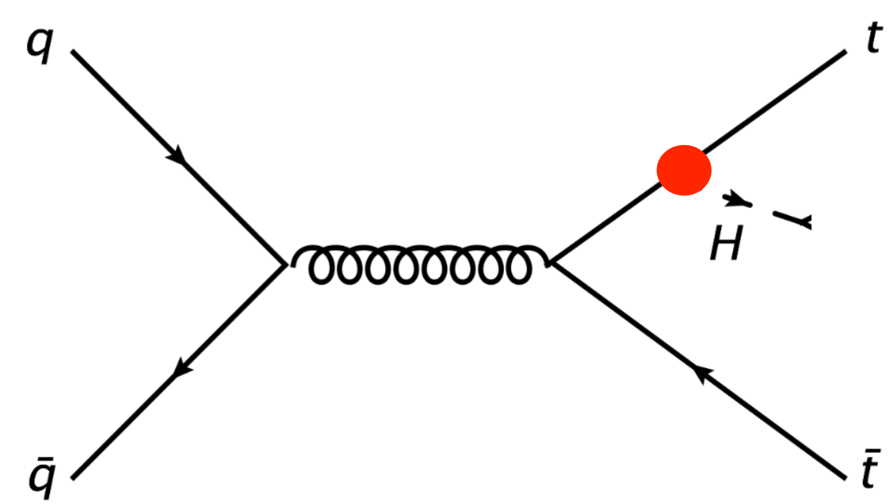


Top Yukawa coupling direct measurement

- Y_t direct measurement from ttH production mode
  - → any deviation might be hint for new physics
- ttH cross section @8TeV: 129fb (1/200 of total Higgs production cross section)





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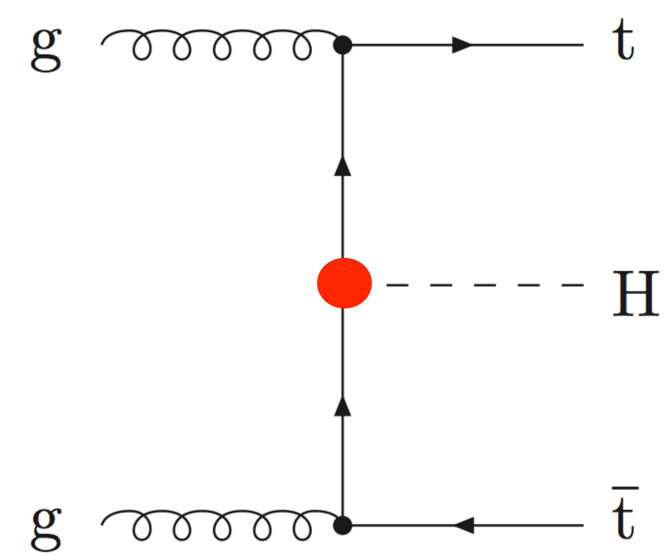
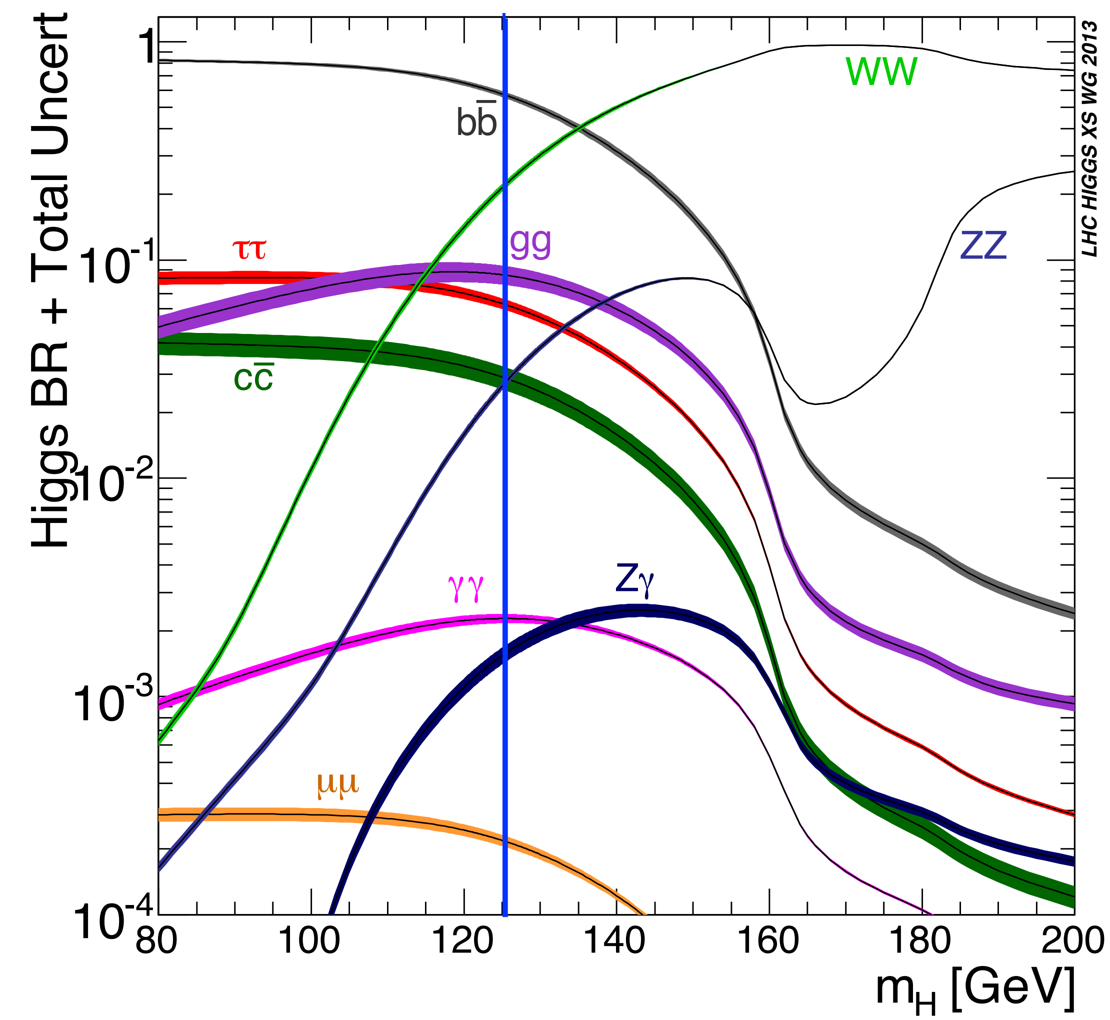
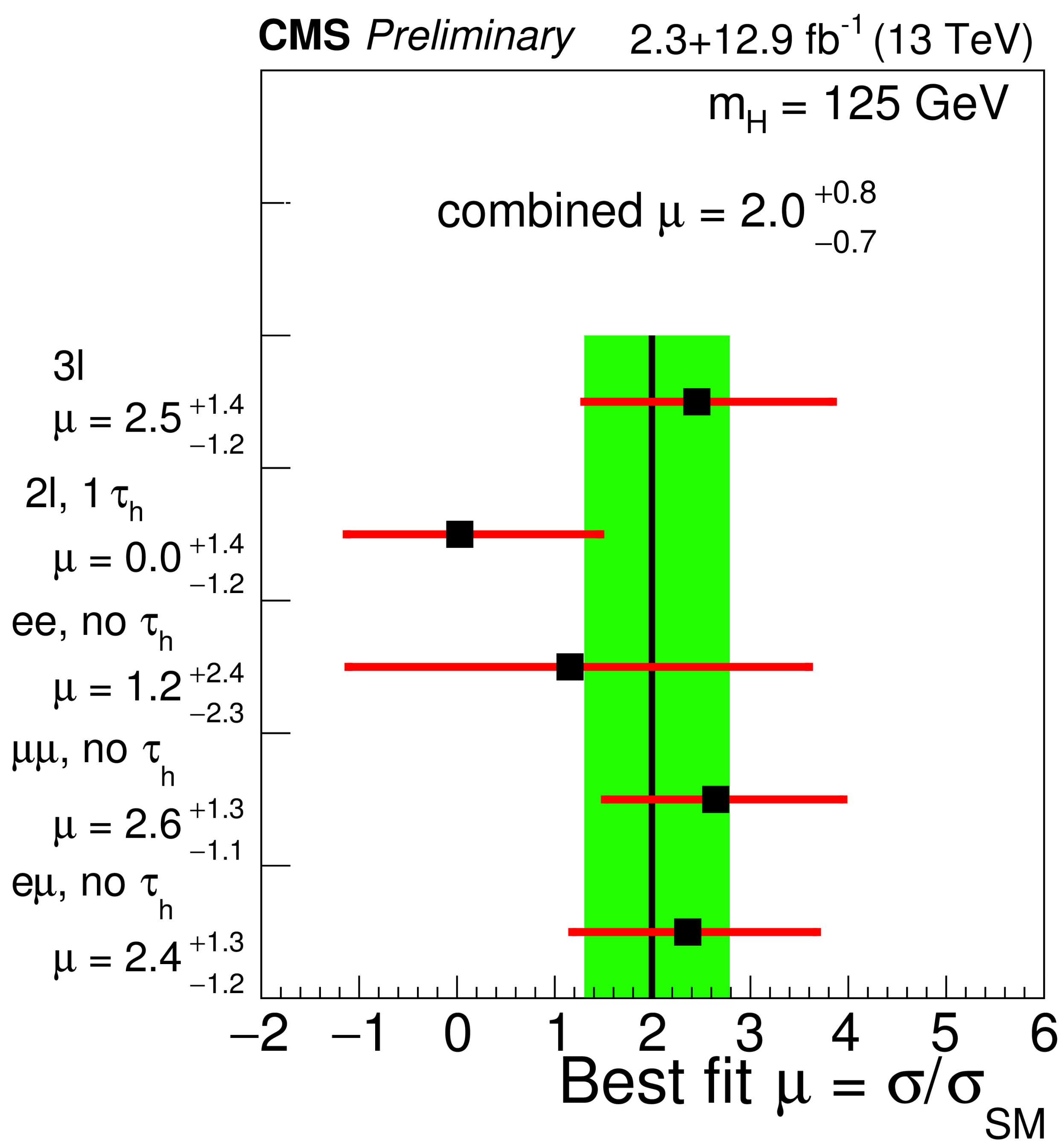


- **Searches for the ttH production** in ATLAS run 1, include many decay modes (branch ratio ~88%)
  - $H \to bb$ 57.5±1.9%
  - $H \to WW$ 21.6±0.9%
  - $H \to \tau\tau$ 6.30±0.36%
  - $H \to ZZ$ 2.67±0.11%
  - $H \to \gamma\gamma$ 0.23±0.01%

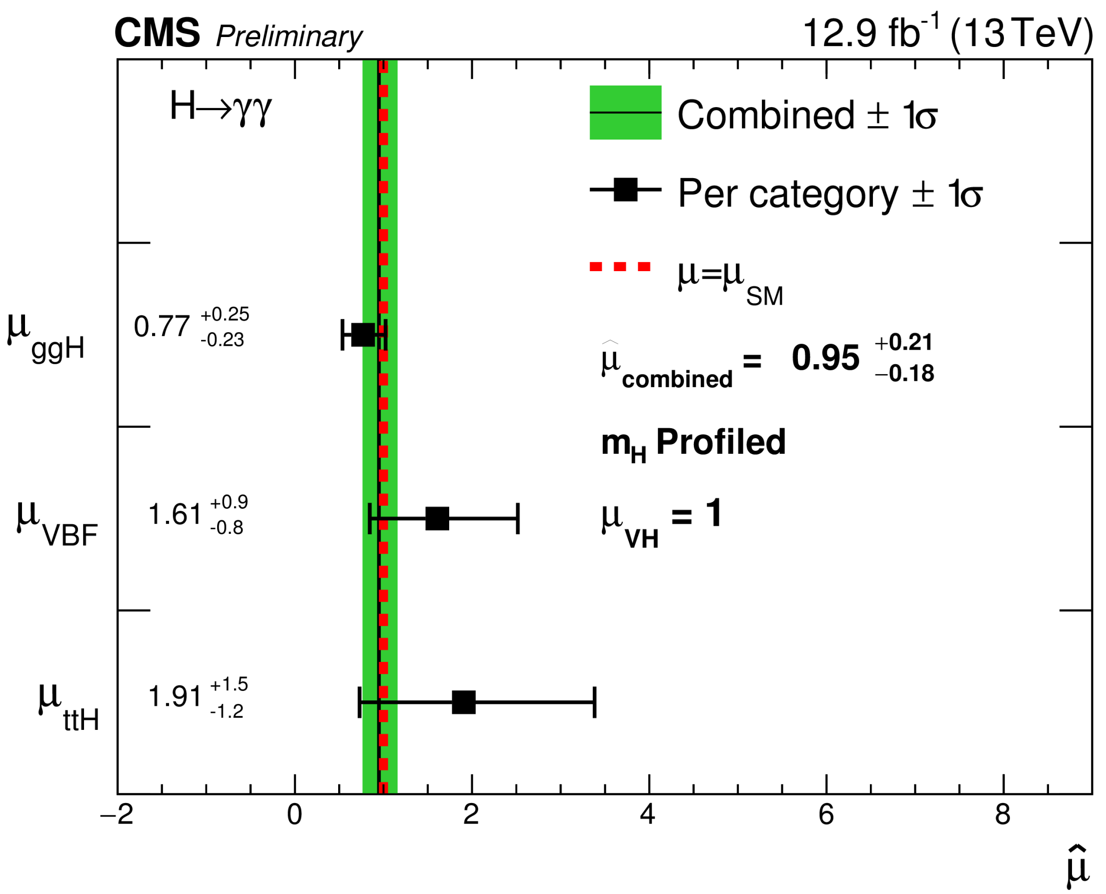


CMS results summary

ttH(multi-leptons)

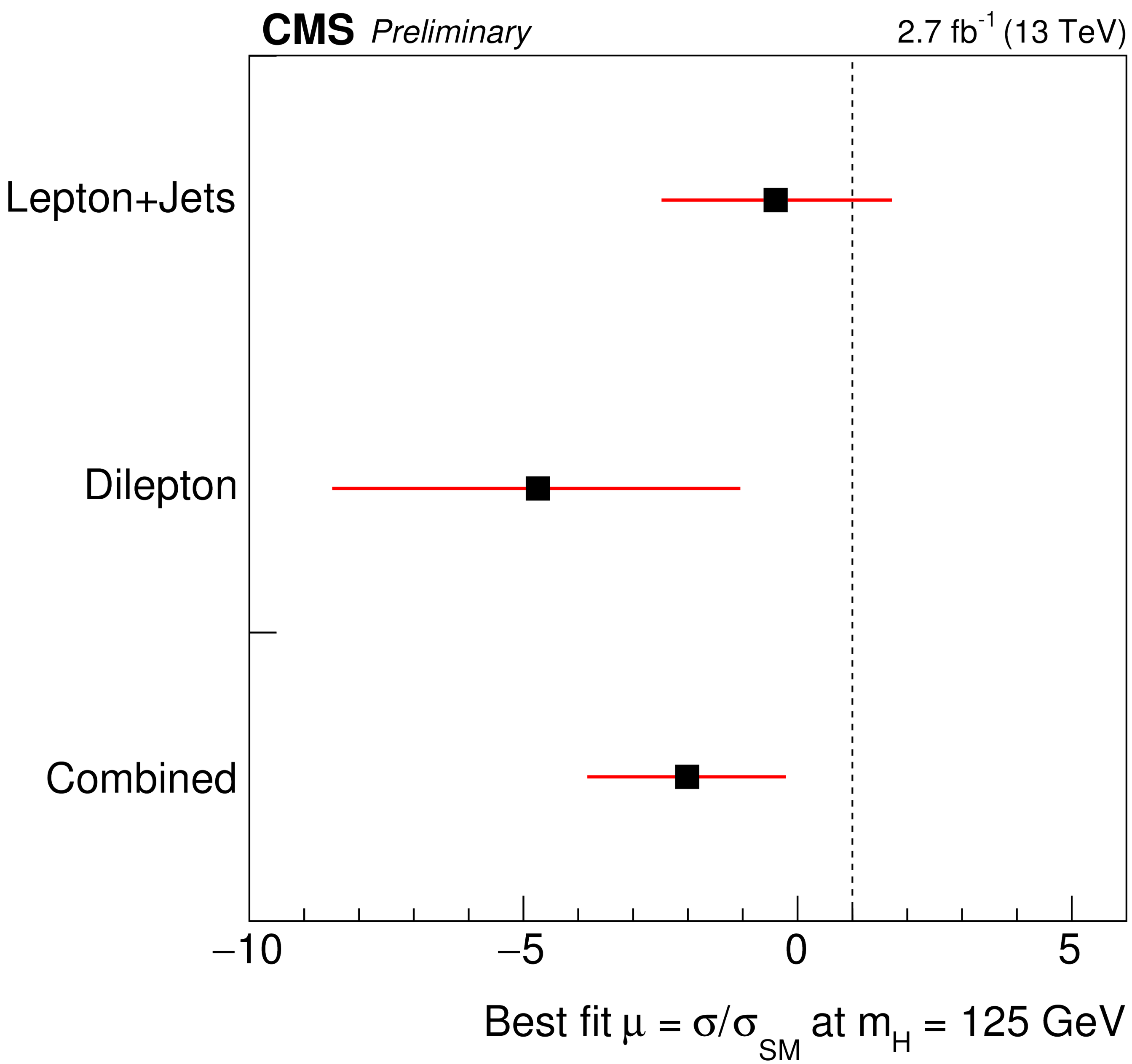


ttH(H→γγ)



CMS results summary

ttH(H→bb)



Channel	Best-fit μ	Observed UL	Expected UL
Lepton+jets	$-0.4^{+2.1}_{-2.1}$	4.0	$4.1^{+1.8}_{-1.2}$
Dilepton	$-4.7^{+3.7}_{-3.8}$	5.2	$7.7^{+3.6}_{-2.3}$
Combined	$-2.0^{+1.8}_{-1.8}$	2.6	$3.6^{+1.6}_{-1.1}$