Measurements of the top Yukawa Coupling at the LHC & other Related Results

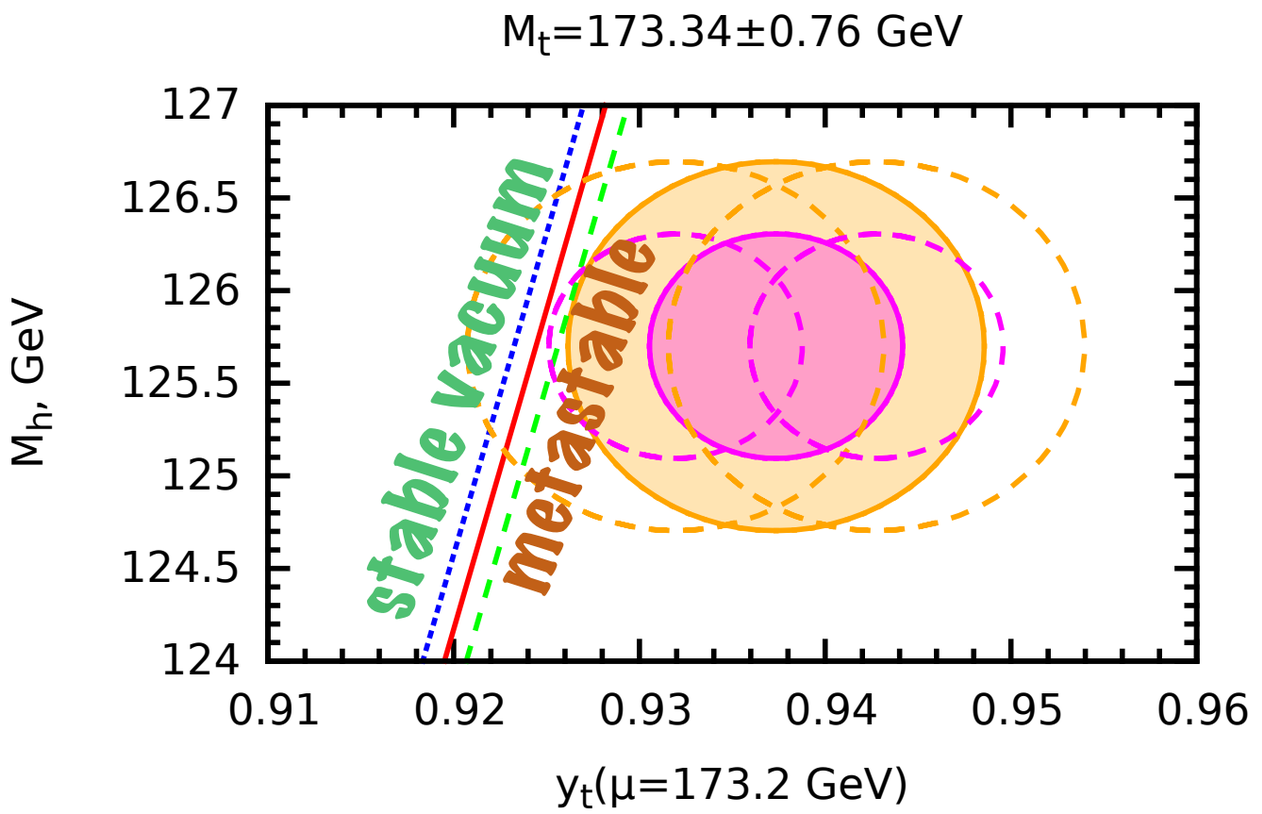
Interpretations Workshop (2016-05-04)

Jordan Webster

Motivation

- Precise measurements of Higgs couplings could reveal departures from the SM
  - Large top mass → top Yukawa (λ_t) ≈ 1
- Dominant impact on stability of Higgs mass
- Window to new physics related to EWSB

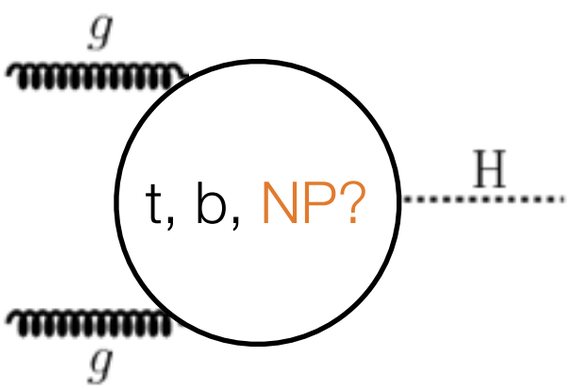
- O(10%) variation between stable/unstable vacuum [arXiv:1411.1923]
  - Could point to scale of new physics



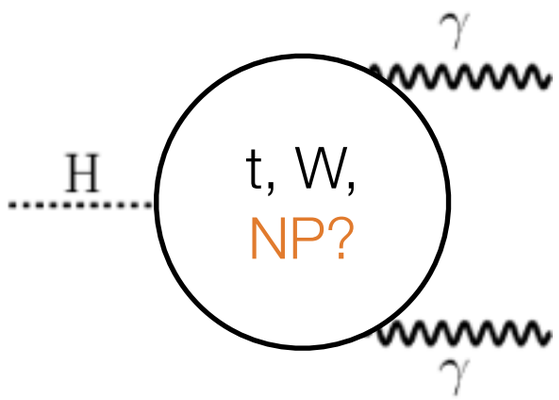
Measurements

- Most precise measurement from $m_t = 173.34 \pm 0.76$ GeV
- Indirect constraints from ggH and γγH vertices
  … or ttH production gives access to a direct measurement

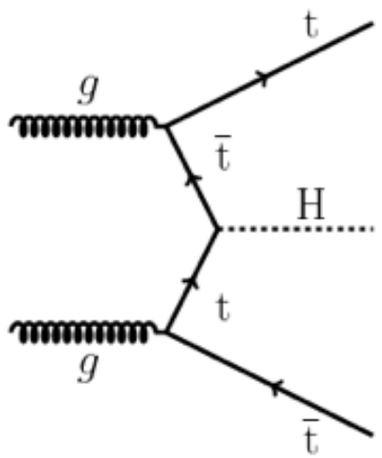
ggH production



H→γγ Decay

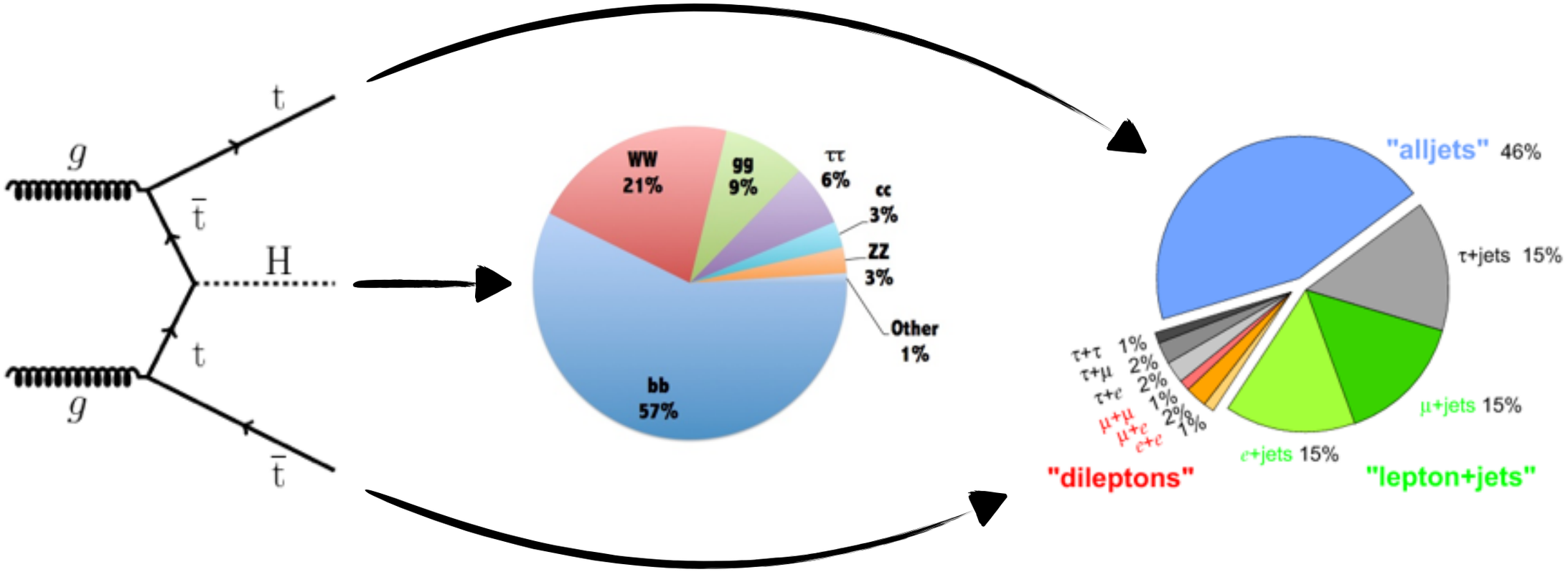


ttH production

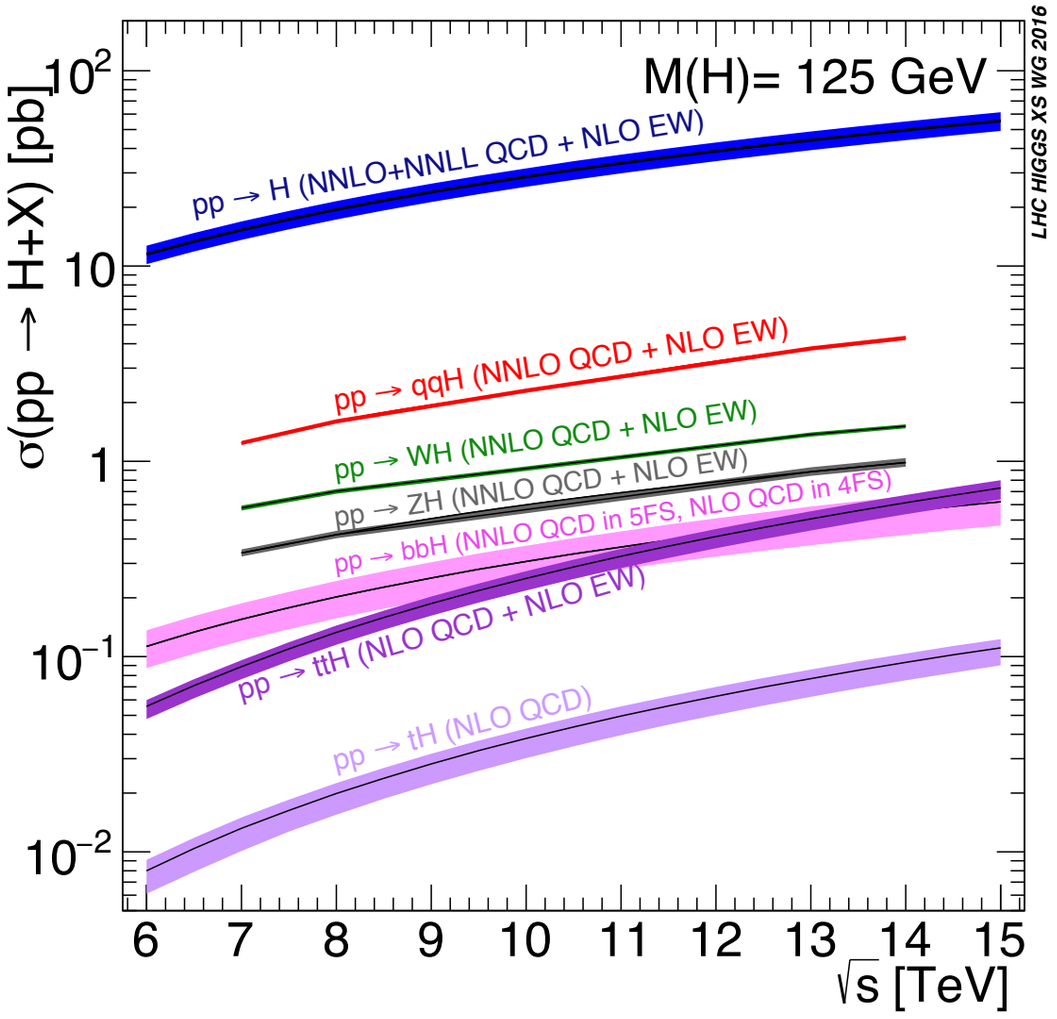


Virtues of a Direct Measurement

- λ_t is the easiest Yukawa to measure directly
- Many accessible final states, including H→bb!
- Complex final states
  - Many handles for controlling background



Primary Challenge



Tiny signal…

- ATLAS+CMS has ~6000 ttH events in all of Run 1
- $\sigma(tt)/\sigma(ttH) \approx 2000$

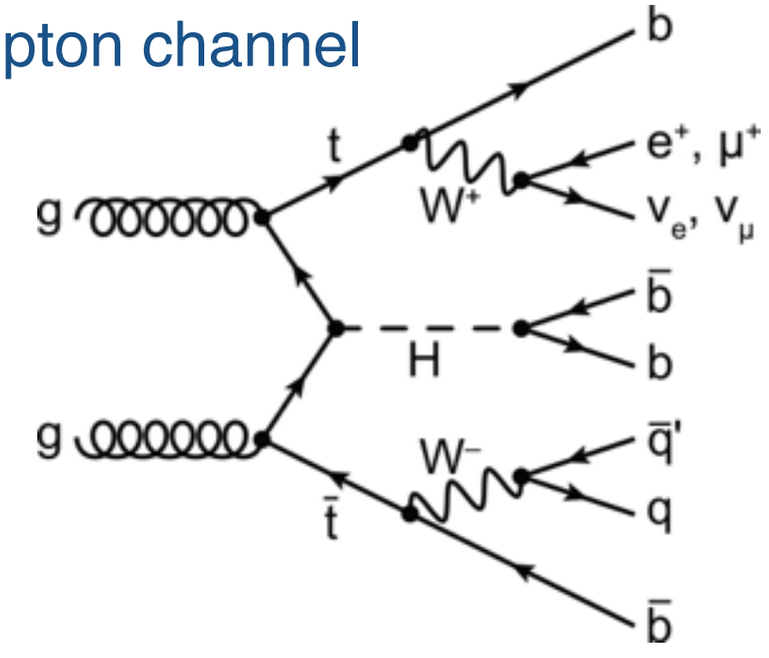
H→hadrons

H→bb, H→$\tau_h\tau_h$

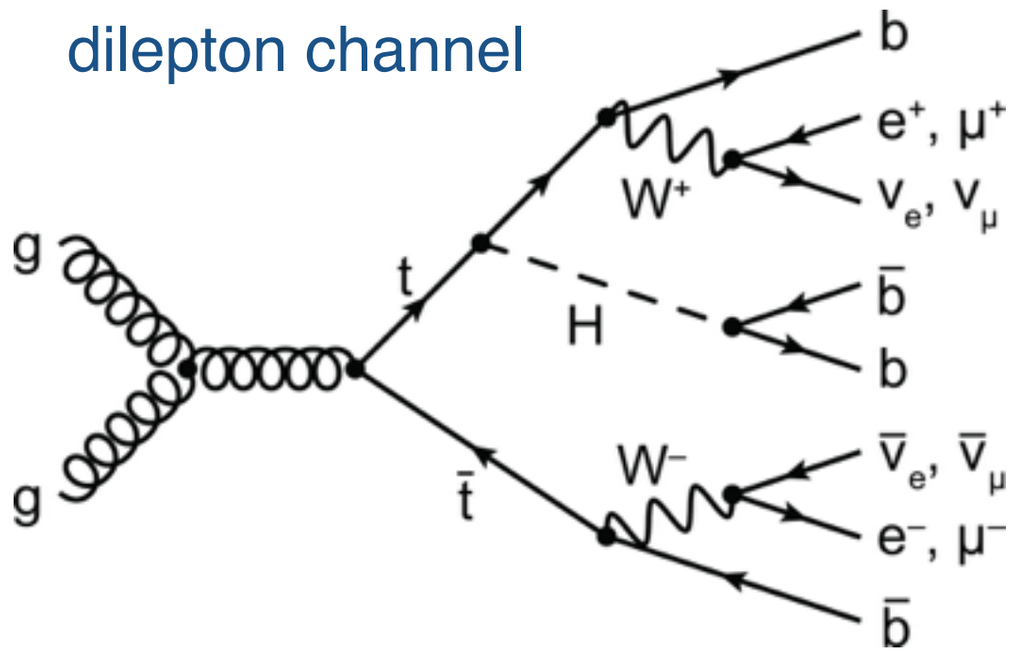
Analysis Strategy

* Target $H \rightarrow bb$ and $H \rightarrow \tau_h \tau_h$ (CMS-only)
* Divide into channels based on top decays

single lepton channel



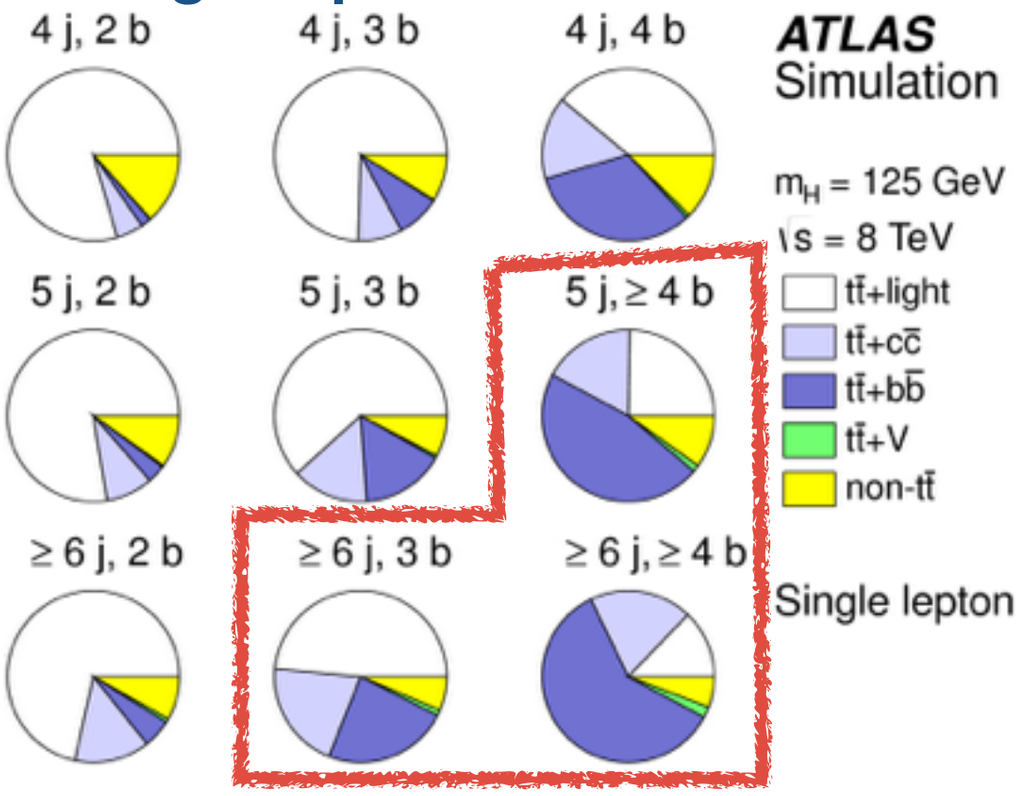
dilepton channel



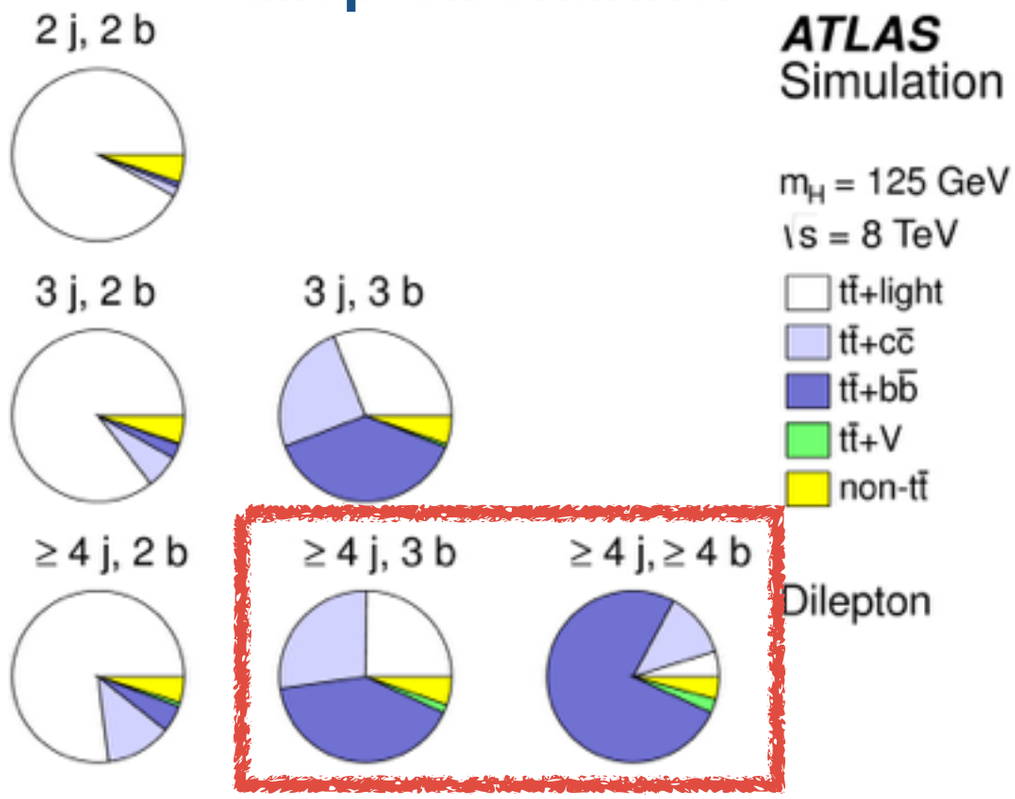
Analysis Strategy

* Categorize events based on N_{jets}, $N_{b\text{-tags}}$

single lepton channel



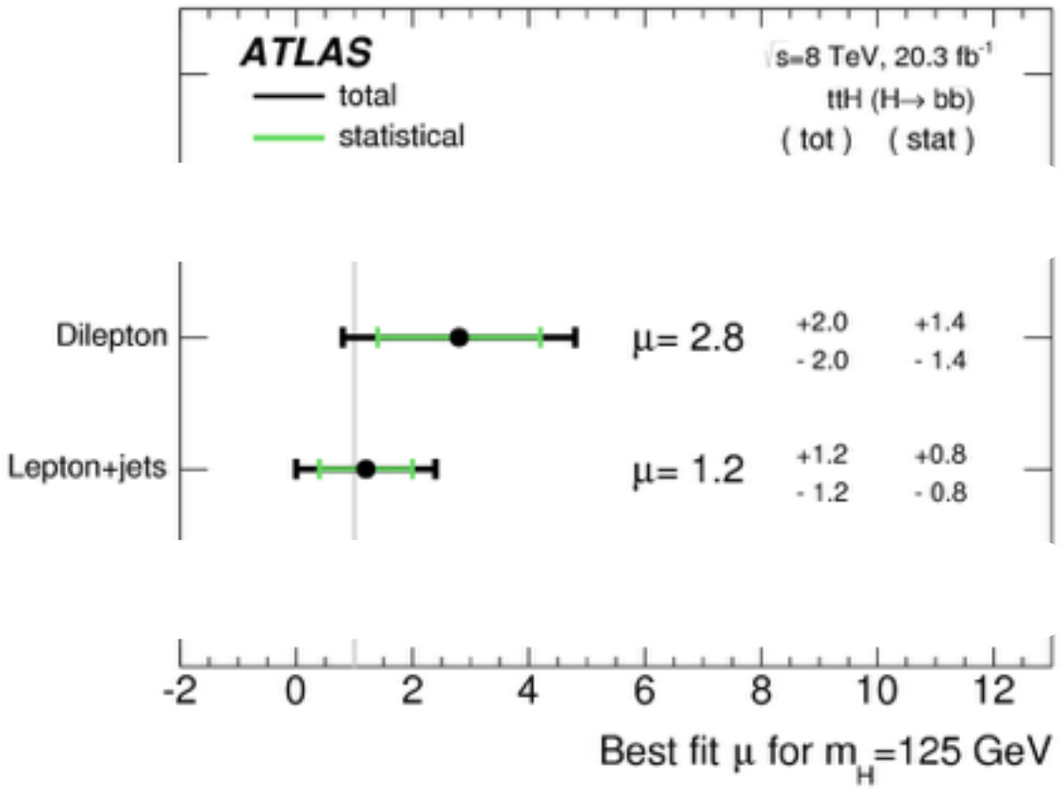
dilepton channel

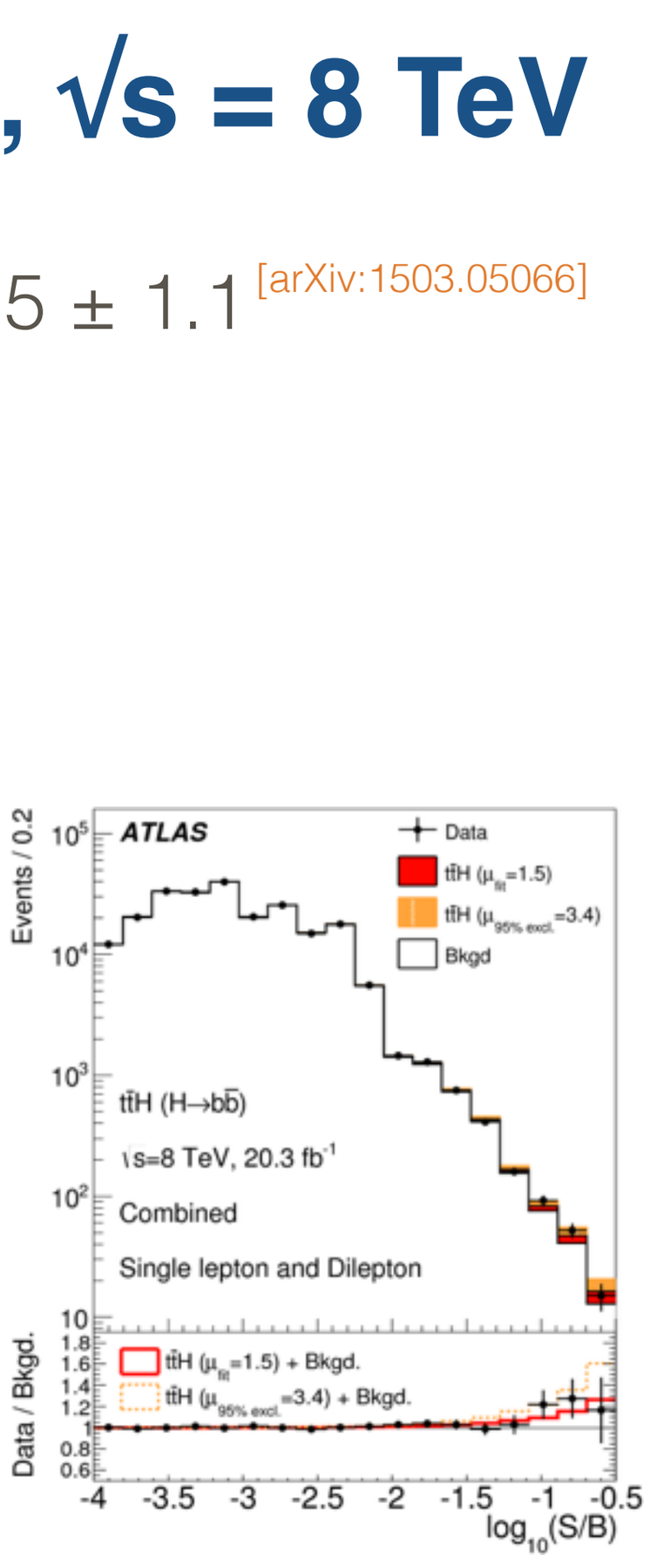


* Signal depleted regions help measure backgrounds
  * Very useful for tt + heavy-flavor jets
* Fit multivariate discriminant…
  * CMS: BDT or matrix-element discriminant
  * ATLAS: Neural network, matrix-elements used in training

Results: ATLAS, $\sqrt{s}$ = 8 TeV

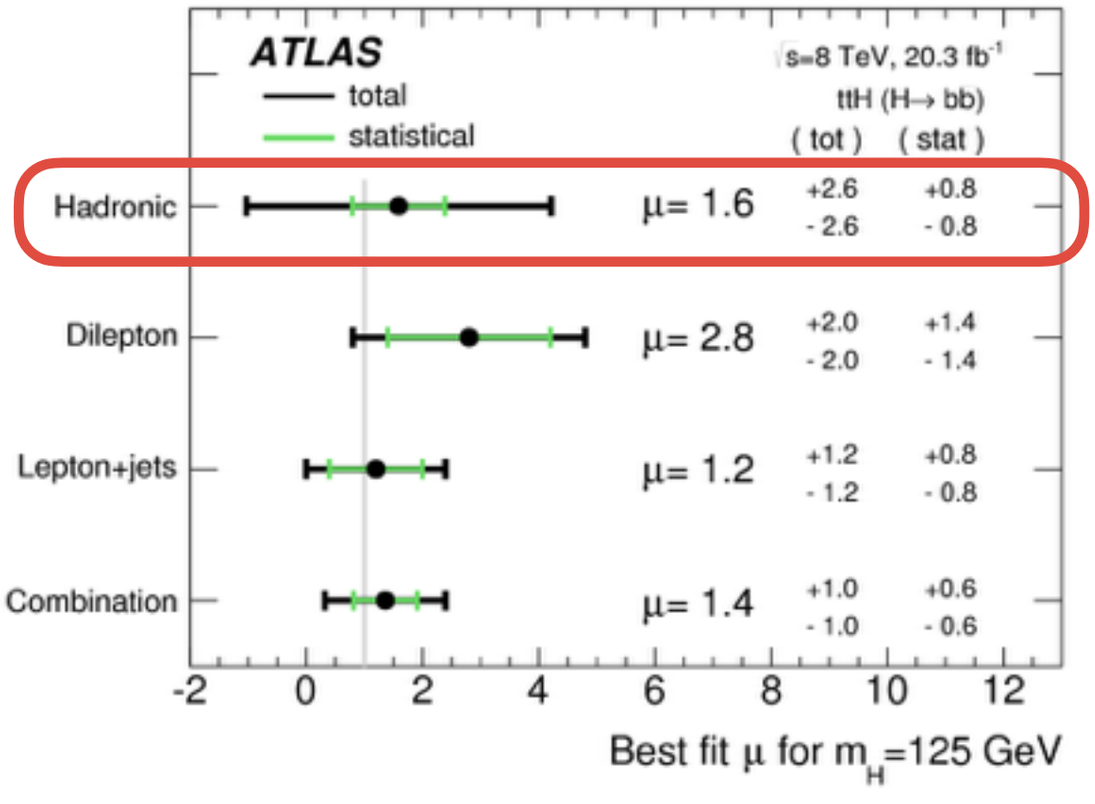
* In single lepton + dilepton $\mu = 1.5 \pm 1.1$ [arXiv:1503.05066]

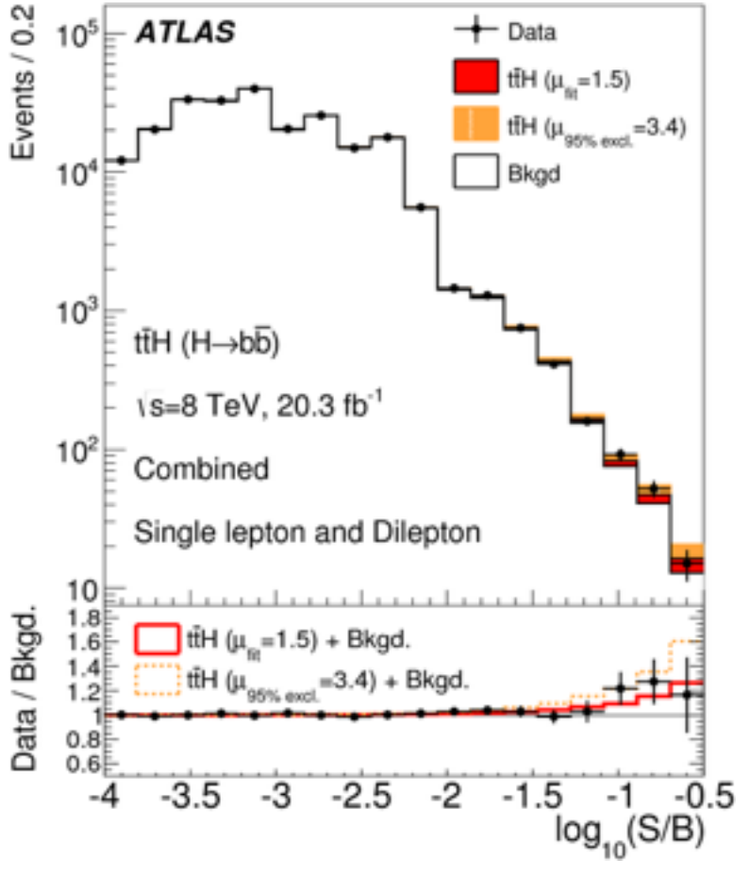




Results: ATLAS, $\sqrt{s}$ = 8 TeV

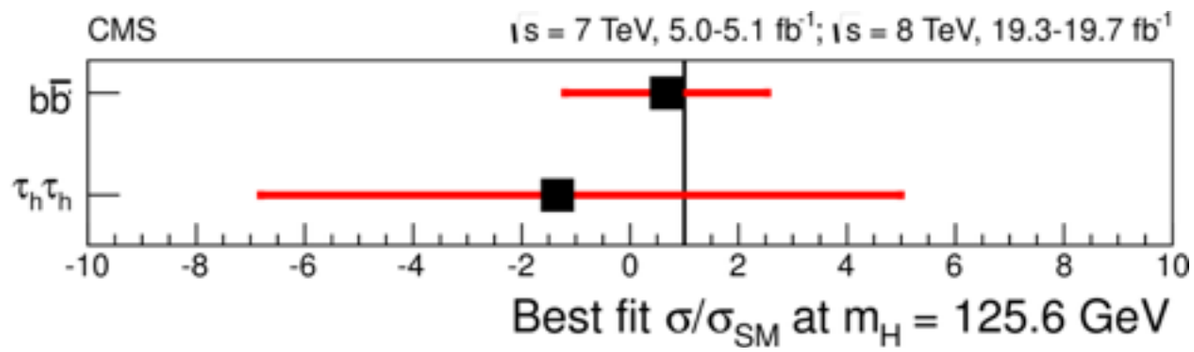
- In single lepton + dilepton $\mu = 1.5 \pm 1.1$ [arXiv:1503.05066]
- Fully hadronic final state recently included…
  - μ shifts down to **1.4 ± 1.0** [arXiv:1604.03812]





Results: CMS √s = 7,8,13 TeV

* 7+8 TeV results: [arXiv:1408.1682]



μ = 0.7 ± 1.9

μ = -1.3 ± ~6

* 8 TeV H→bb measurement updated to μ = 1.2 ± ~1.5 using Matrix-element method [arXiv:1502.02485]

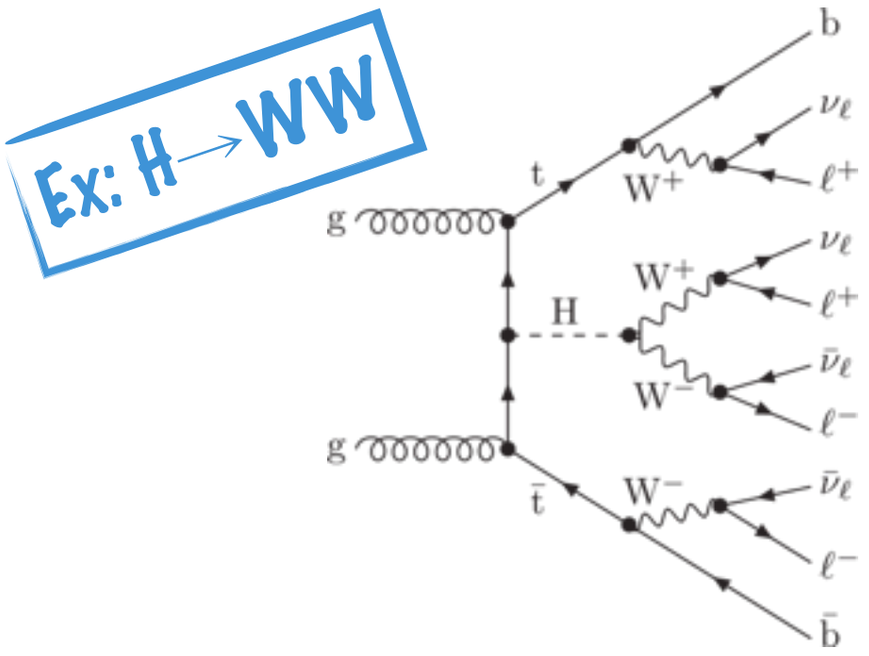
* 13 TeV H→bb [CMS-PAS-HIG-16-004]
  * μ = -2.0 ± 1.8

H→leptons

H→WW, H→ZZ, H→$\tau_\ell\tau_\ell$

Analysis Strategy

- Primarily targets H→WW with ≥1 leptonic decay, but non-negligible H→ττ & H→ZZ
- Background dominated by ttV



Basic Selection

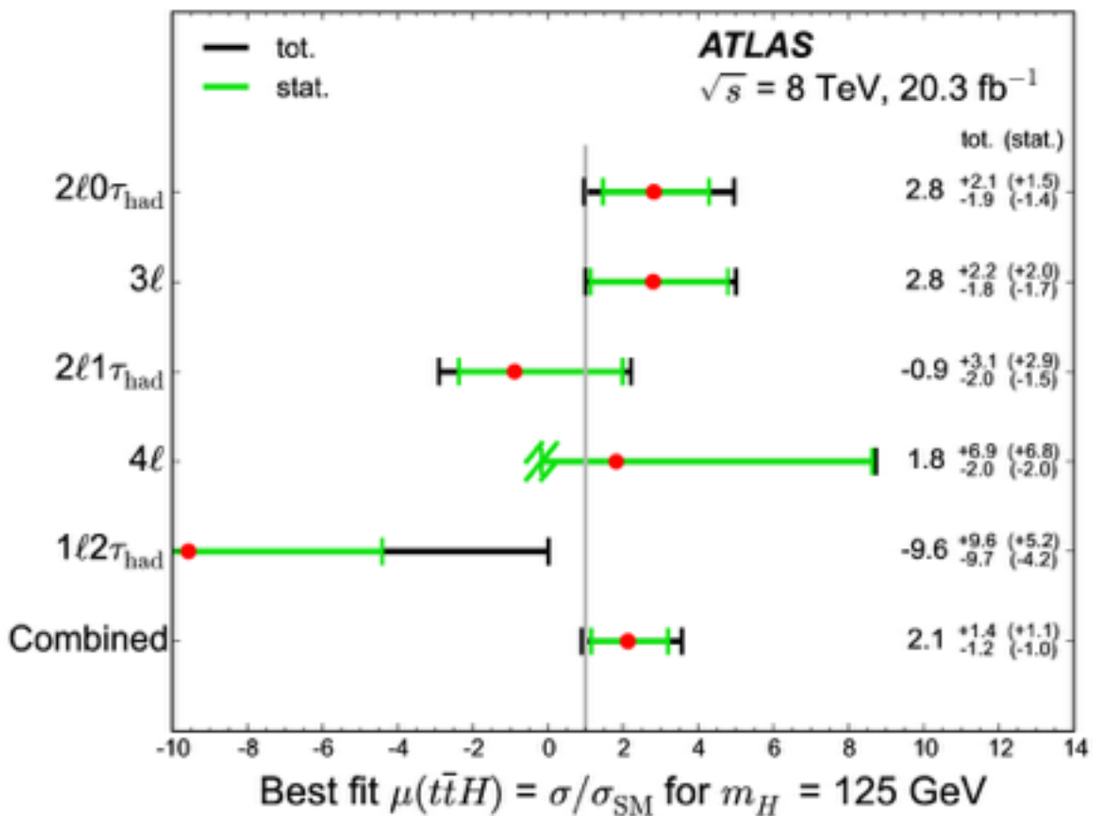
- Events categorized by nLeptons: same sign 2ℓ, 3ℓ, 4ℓ
  - Jet requirements differ between categories:
    nJets ≥ 2-4, nBTags ≥ 1-2

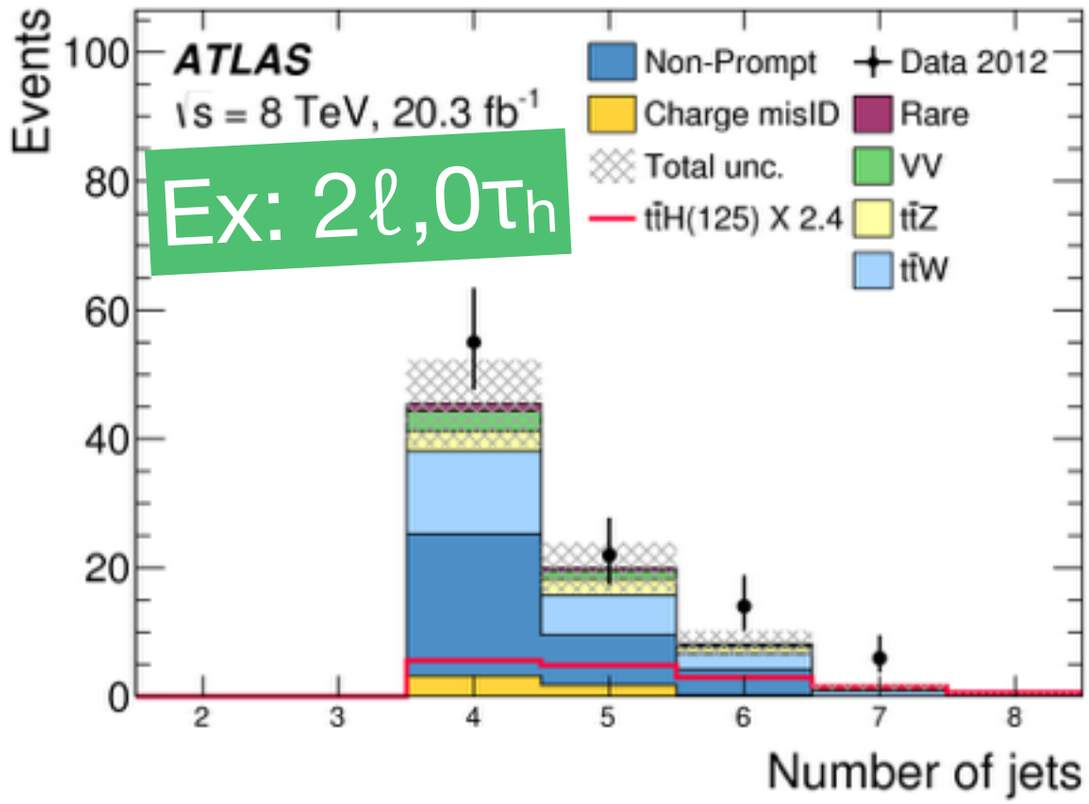
- ATLAS includes $H \to \tau_h\tau_h$ as part of this analysis with additional regions that have hadronic τ tags

	Higgs boson decay mode			
Category	WW^*	$\tau\tau$	ZZ^*	Other
$2\ell 0\tau_{\text{had}}$	80%	15%	3%	2%
3ℓ	74%	15%	7%	4%
$2\ell 1\tau_{\text{had}}$	35%	62%	2%	1%
4ℓ	69%	14%	14%	4%
$1\ell 2\tau_{\text{had}}$	4%	93%	0%	3%

Results: ATLAS, √s = 8 TeV

- Cut & count measurement
- Combined μ = 2.1 ± ~1.4 [arXiv:1506.05988]
  - Signal significance = 1.8σ (expected 0.9σ)

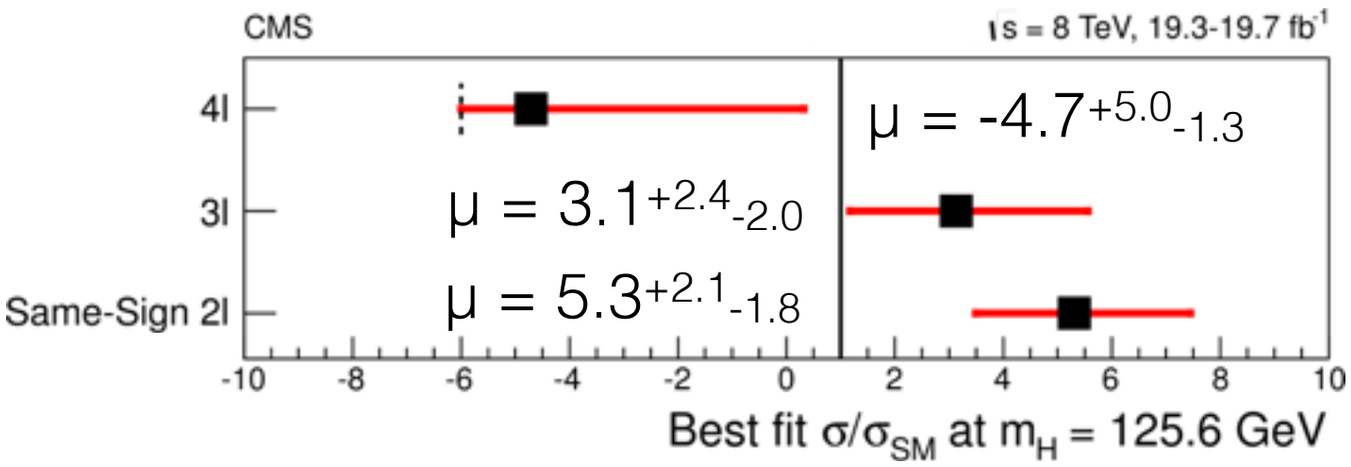


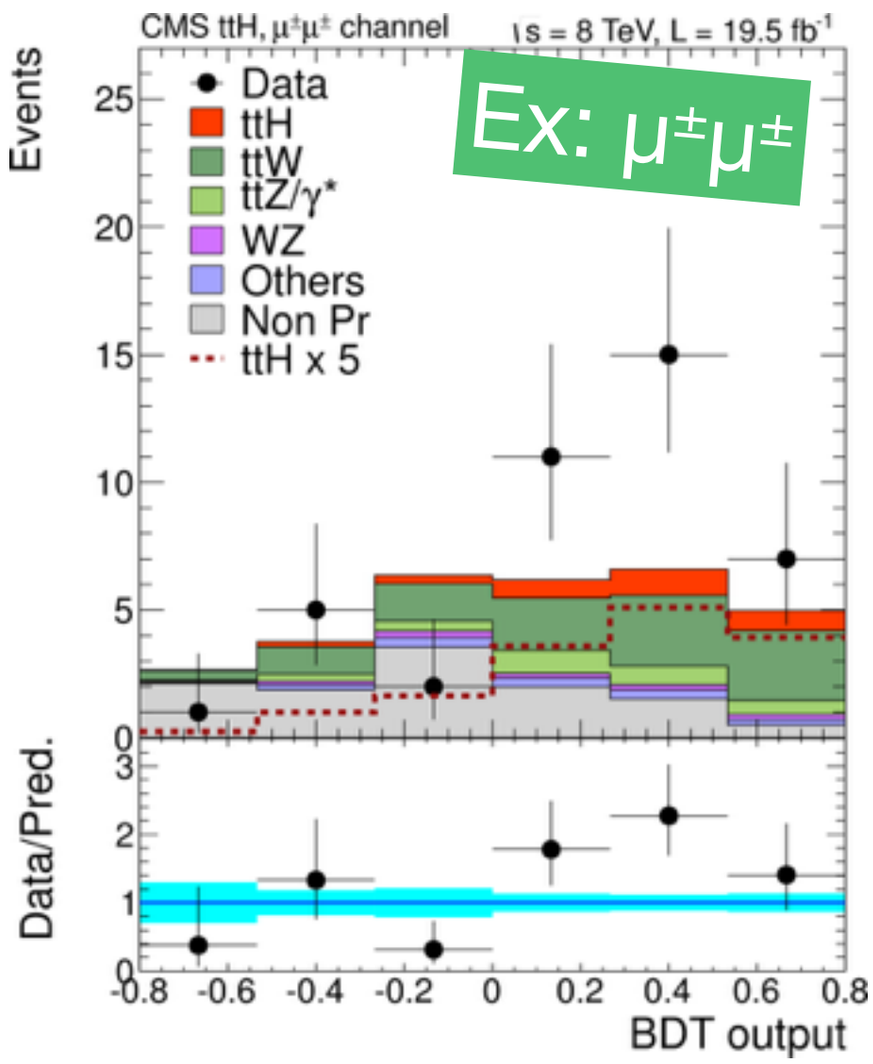


Results: CMS, √s = 8 TeV

* Fit to BDT response or nJets (4ℓ region)
* Small excess in 2ℓ category, driven primarily by ~2-3σ excess in $\mu^{\pm}\mu^{\pm}$

[arXiv:1406.1682]



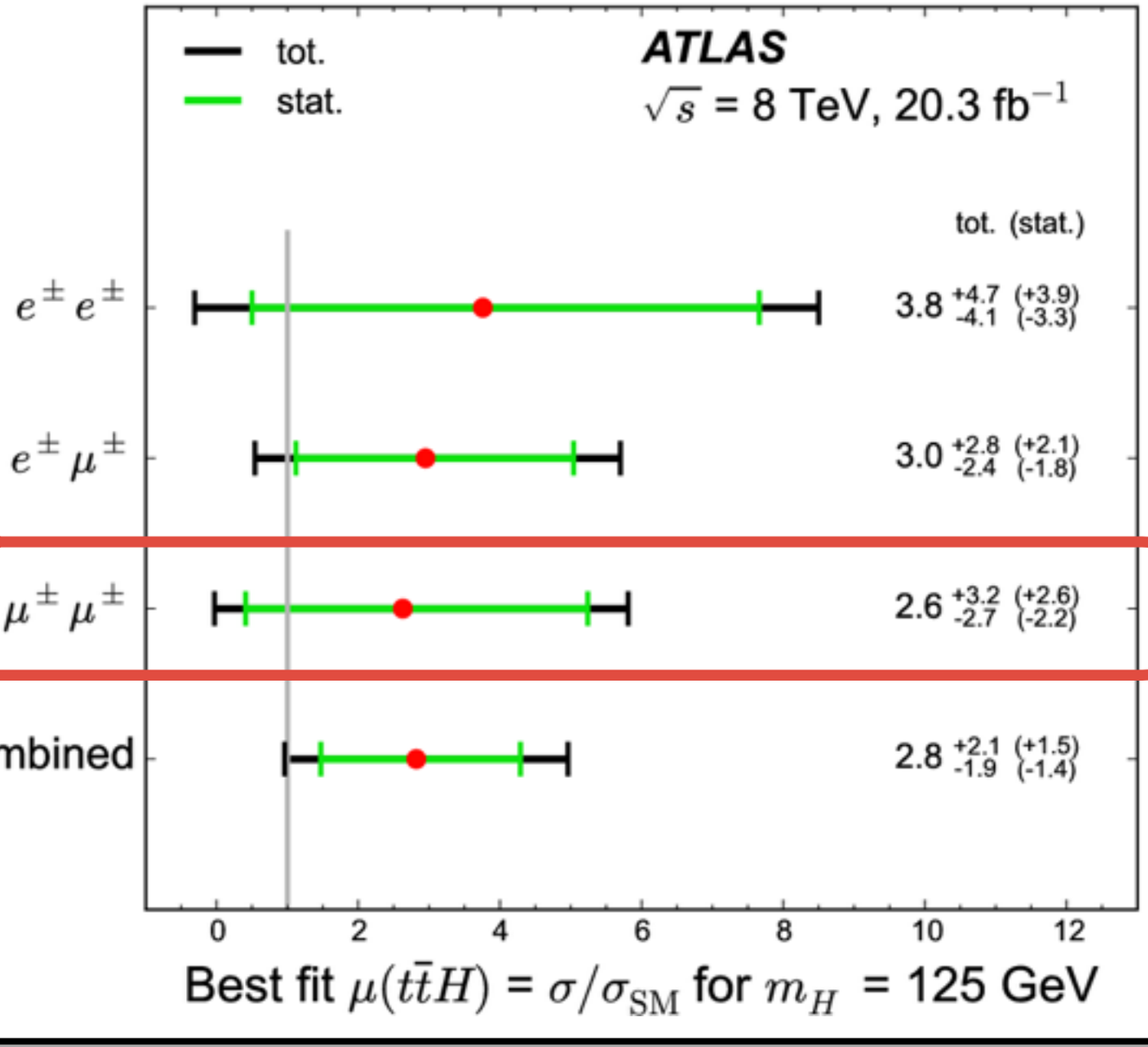


Results: CMS, $\sqrt{s}$ = 8 TeV

* Fi
* Sr ~2-3σ
ex

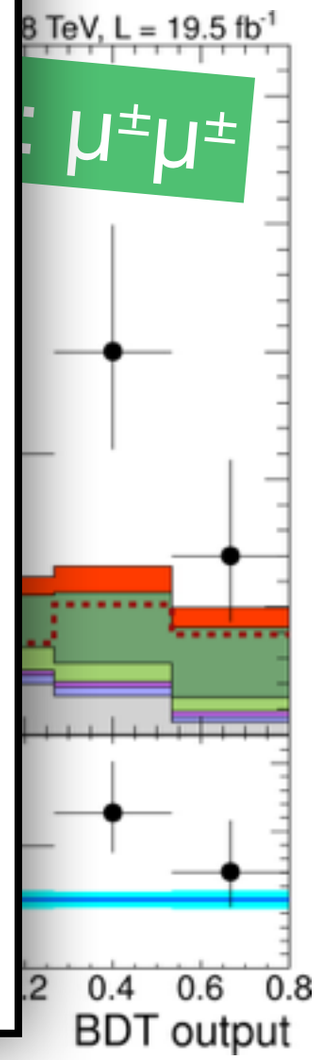
Not observed by ATLAS…

[arXiv:1506.05988]



Same-Sign 2

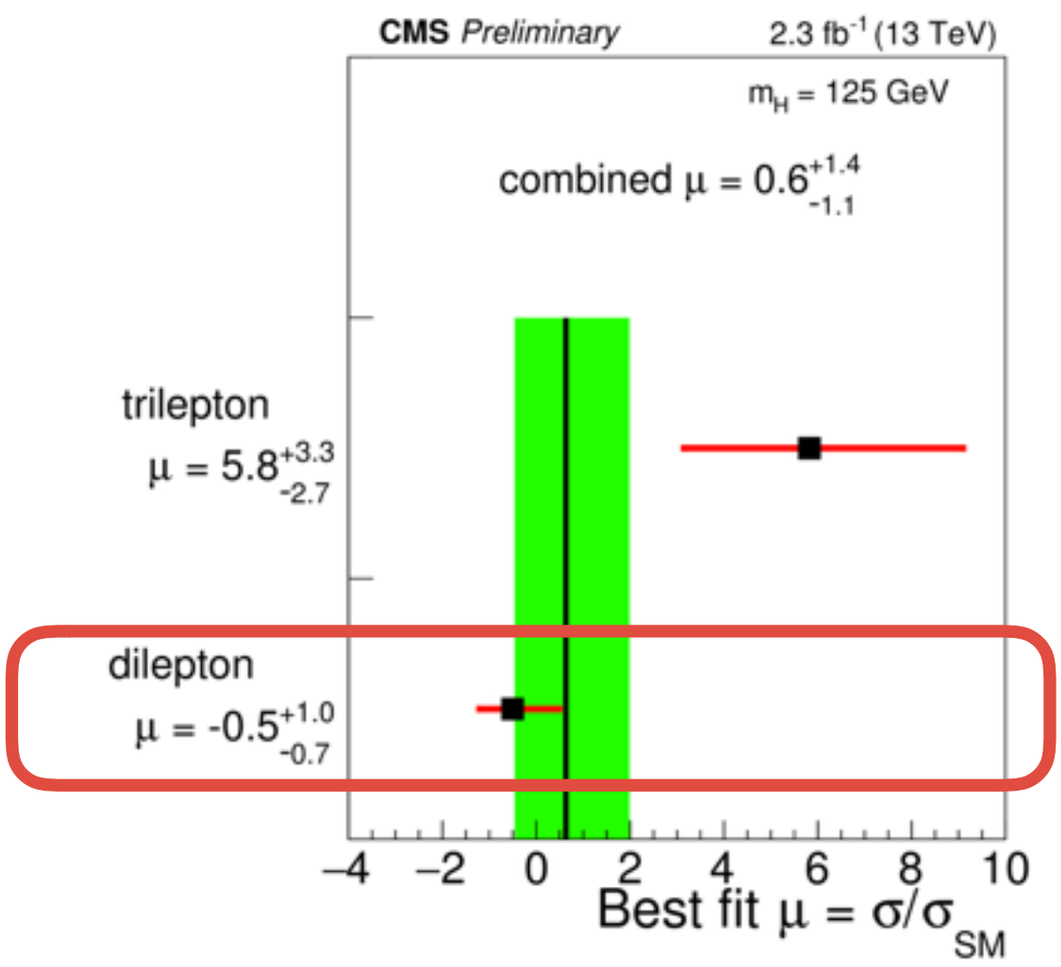
Xiv:1406.1682]

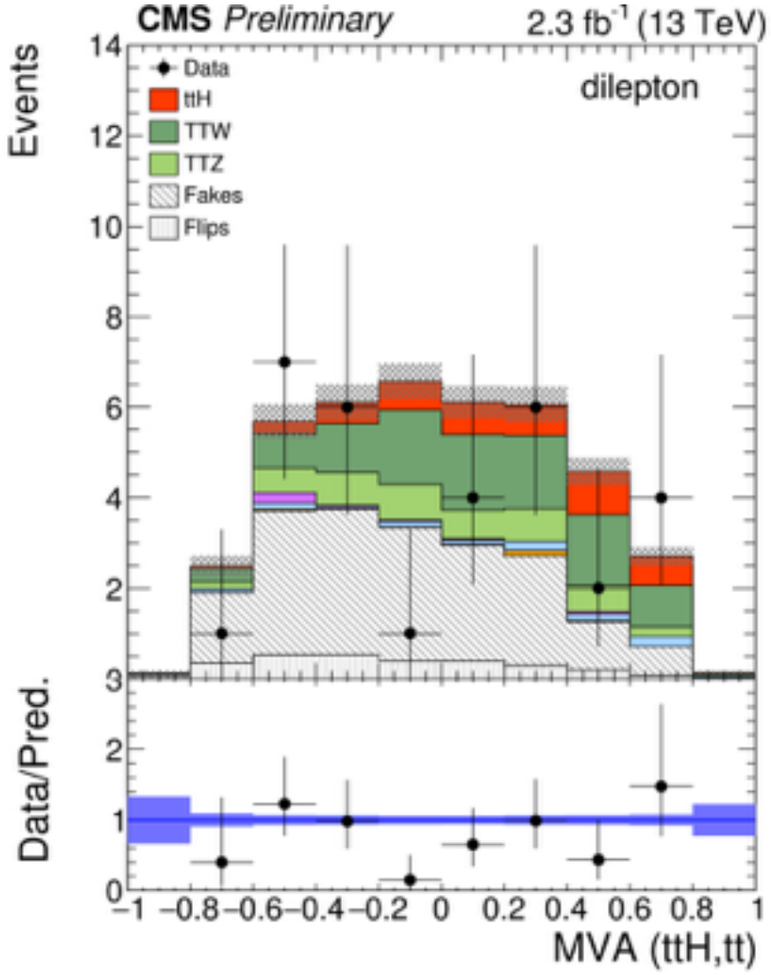


Results: CMS, $\sqrt{s}$ = 13 TeV

… or by CMS in recent Run 2 result

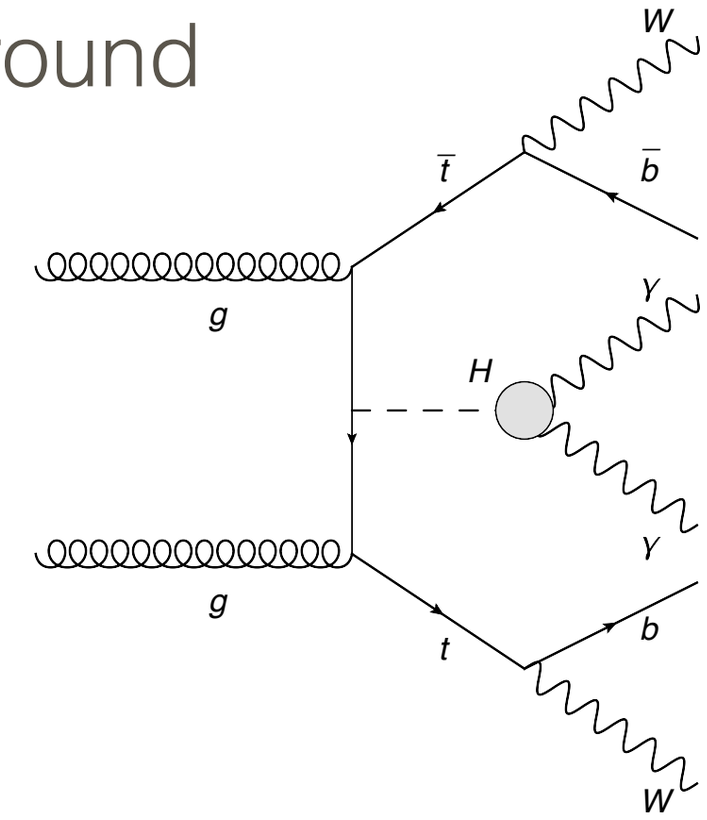
[CMS-PAS-HIG-15-008]





H→photons

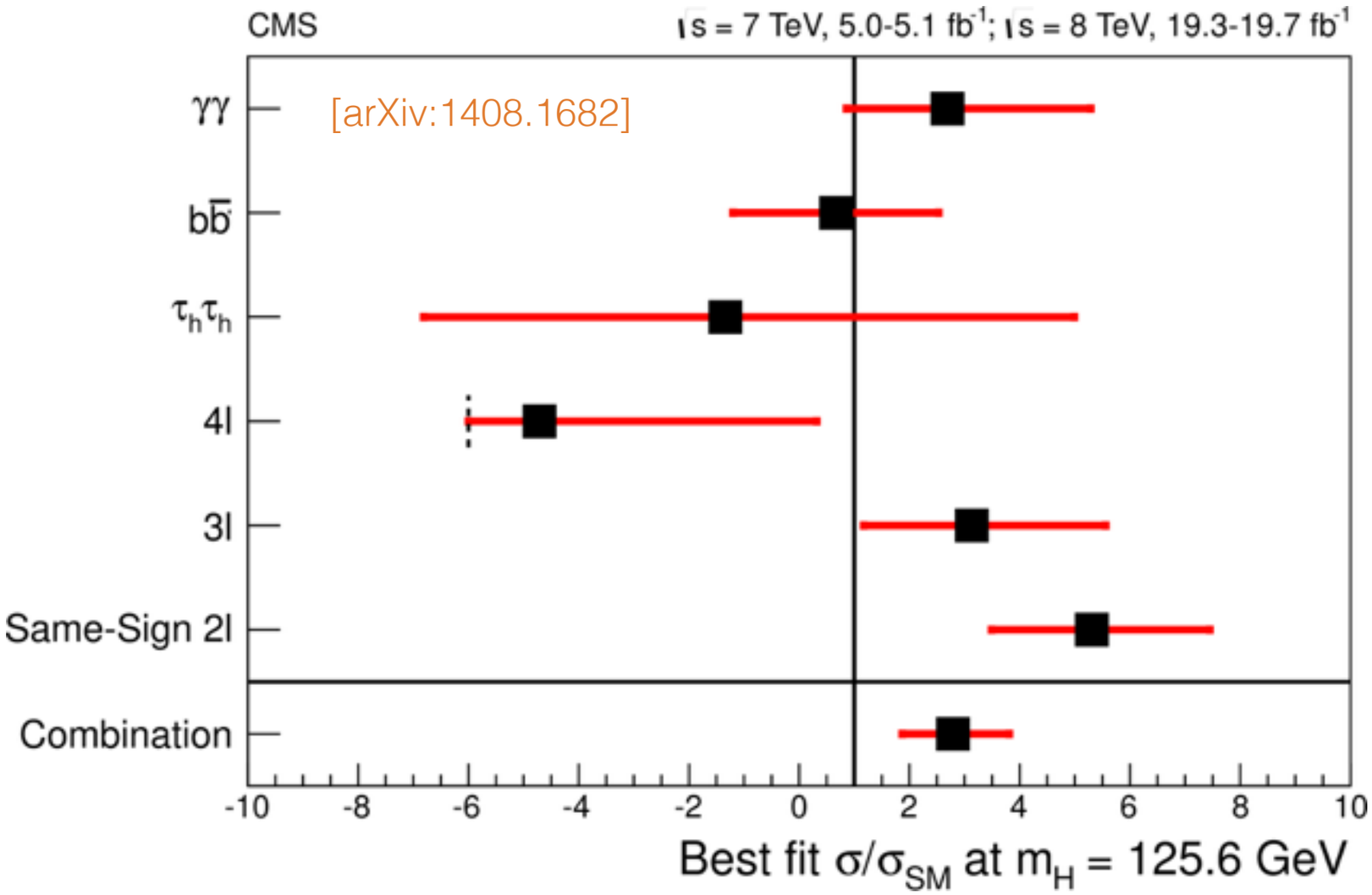
- Analysis with very low signal & background
- ATLAS and CMS both have 7+8 TeV results consistent with SM
  - ATLAS: $\mu = 1.4^{+2.2}_{-1.4}$ [arXiv:1409.3122]
  - CMS: $\mu = 2.7^{+2.6}_{-1.8}$ [arXiv:1408.1682]



- Analysis is particularly sensitive to tH+X, which make up non-negligible fraction of signal

CMS Run 1 Combination

H→hadrons + H→leptons + H→photons



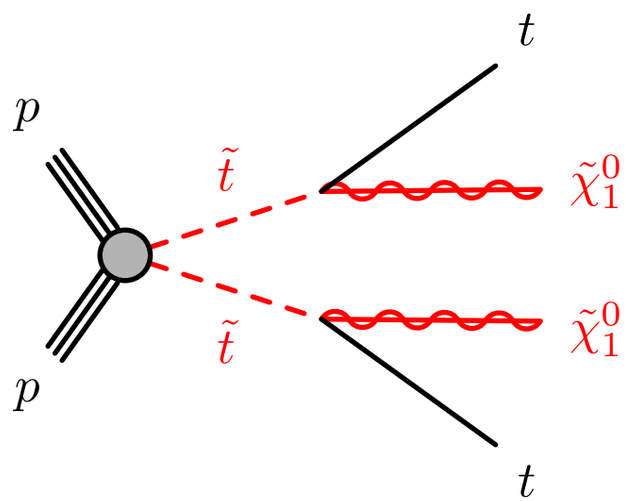
- $\mu_{comb} = 2.8^{+1.1}_{-0.9}$
  - Signal significance = 3.4σ
  - p-value(SM) = 2.0% (~2σ)

“Related” Search for Top Squarks

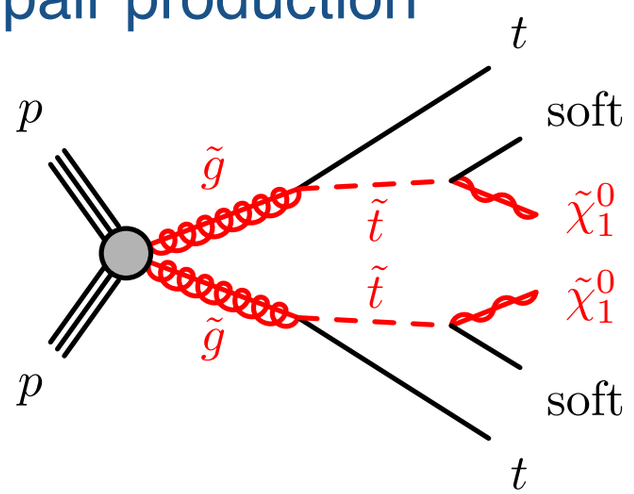
Analysis Overview

- ATLAS 13 TeV stop pair search [ATLAS-CONF-2016-007]
  - Targets direct pair production & gluino mediated pair production
  - Basically a tt + MET search

Direct pair production



gluino mediated pair production

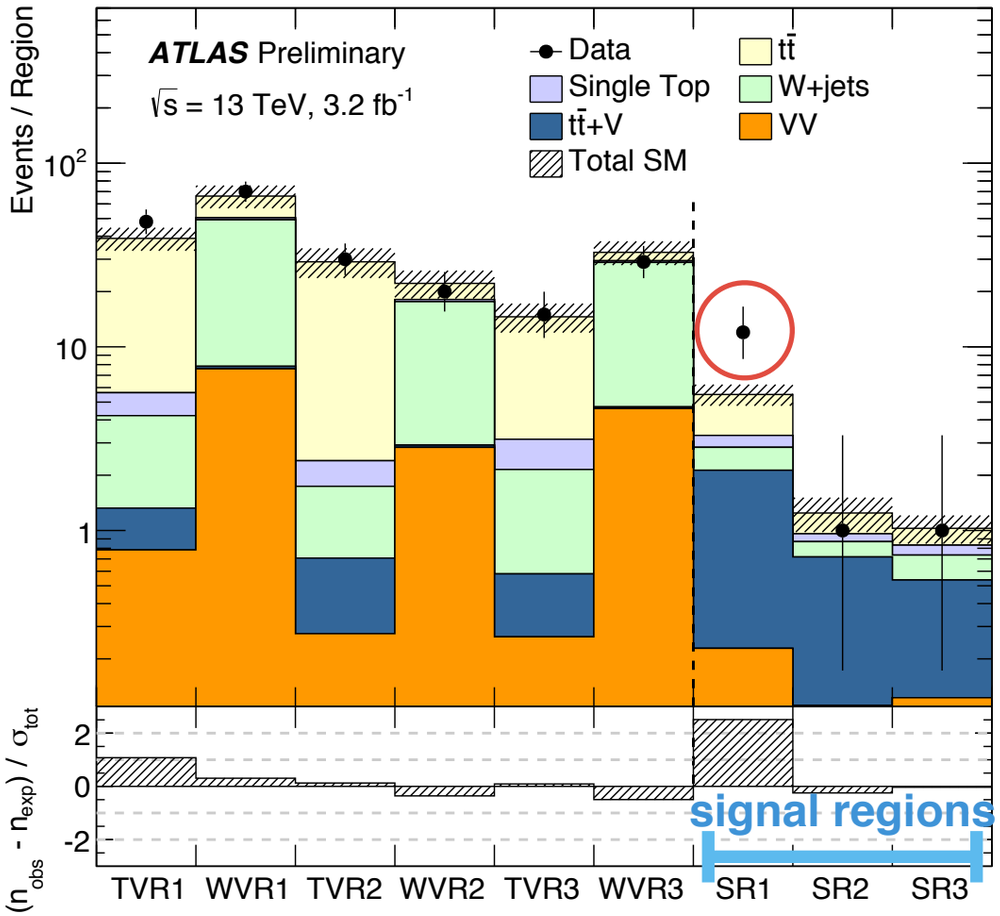


- Focusing on final with one W decaying leptonically
- Dominant background: tt, tW, ttZ, W+jets
  - Modeled by MC, constrained in control regions

Basic Selection & Results

- Exactly 1 lepton, p_T > 25 GeV
- ≥4 jets, p_T > 25 - 120 GeV
- τ_h jet veto
- MET > 260 (SR1), 350 (SR2), 480 (SR3) GeV

- Consistent with SM, but 2.3σ excess observed in SR1

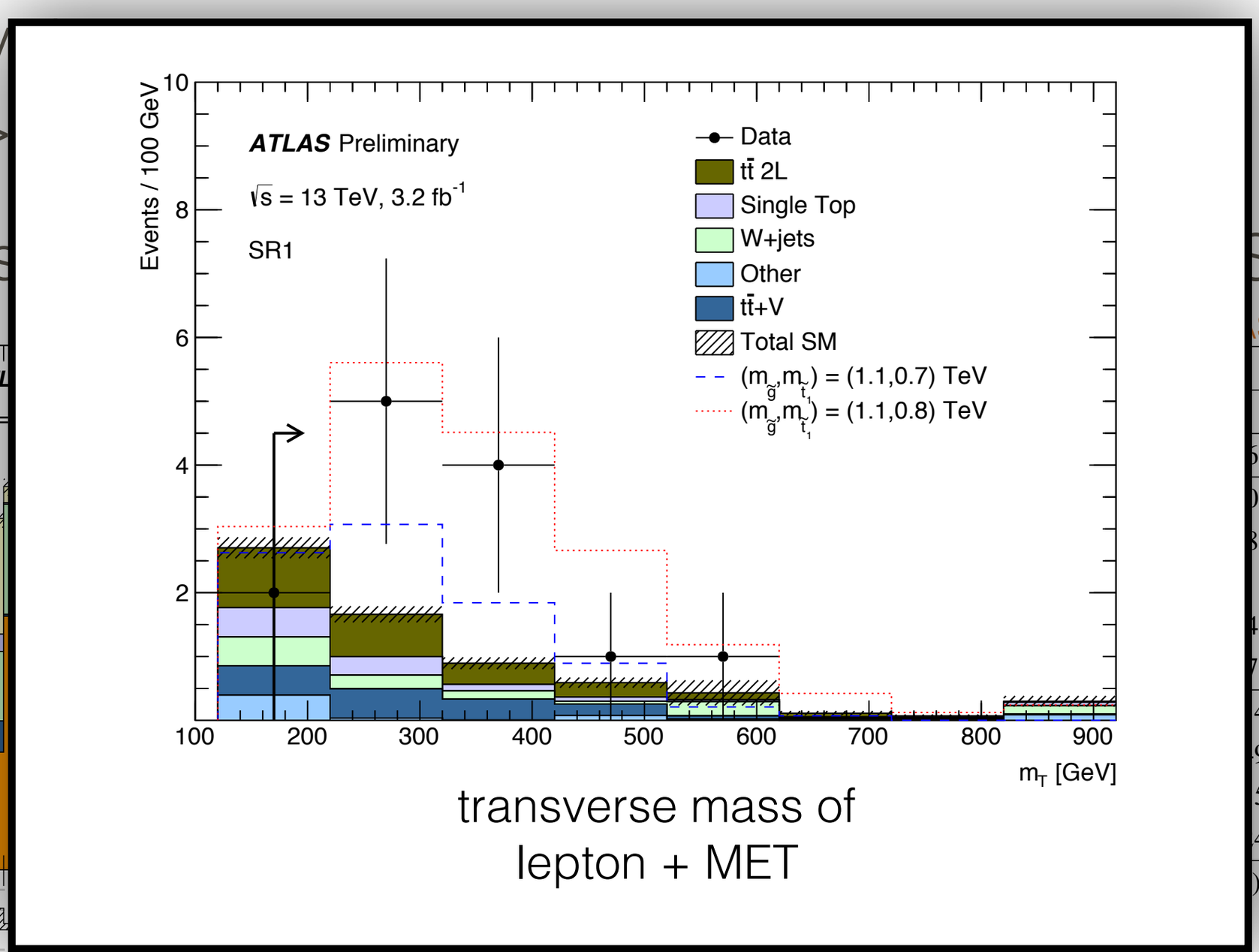


[ATLAS-CONF-2016-007]

Signal region	SR1	SR2	SR3
Observed	12	1	1
Total bkg	5.50 ± 0.72	1.25 ± 0.26	1.03 ± 0.18
$t\bar{t}$	2.21 ± 0.60	0.29 ± 0.10	0.20 ± 0.07
Single top	0.46 ± 0.39	0.09 ± 0.08	0.10 ± 0.09
W+jets	0.71 ± 0.43	$0.15^{+0.19}_{-0.15}$	0.20 ± 0.09
$t\bar{t}+W/Z$	1.90 ± 0.42	0.61 ± 0.14	0.41 ± 0.10
Diboson	0.23 ± 0.15	0.11 ± 0.07	0.12 ± 0.07
$t\bar{t}$ NF	1.10 ± 0.14	1.06 ± 0.14	0.80 ± 0.13
Single top NF	0.62 ± 0.46	0.65 ± 0.49	0.71 ± 0.42
W+jets NF	0.75 ± 0.12	0.78 ± 0.15	0.93 ± 0.12
$t\bar{t}+W/Z$ NF	1.42 ± 0.24	1.45 ± 0.24	1.46 ± 0.24
p_0	0.01(2.3 σ)	0.50 (0.0 σ)	0.50 (0.0 σ)
$N^{\text{limit}}_{\text{non-SM}}$ exp. (95% CL)	$6.4^{+3.2}_{-2.0}$	$3.6^{+2.3}_{-1.3}$	$3.5^{+2.2}_{-1.2}$
$N^{\text{limit}}_{\text{non-SM}}$ obs. (95% CL)	13.3	3.4	3.4

Basic Selection & Results

- Exactly 1 lepton, p_T > 25 GeV
- ≥4 jets, p_T > 25 - 120 GeV
- τ_h jet v
- MET >
- Consis

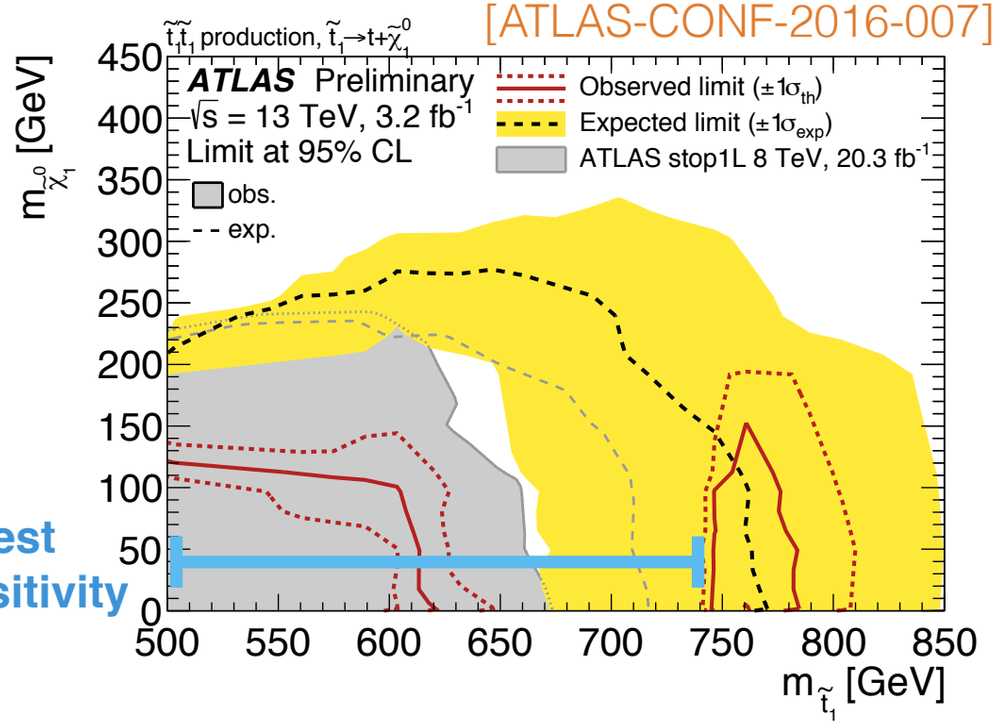


S-CONF-2016-007]

	SR3
	1
5	1.03 ± 0.18
)	0.20 ± 0.07
3	0.10 ± 0.09
	0.20 ± 0.09
4	0.41 ± 0.10
7	0.12 ± 0.07
4	0.80 ± 0.13
9	0.71 ± 0.42
5	0.93 ± 0.12
4	1.46 ± 0.24
)	0.50 (0.0 σ)
	$3.5^{+2.2}_{-1.2}$
$N^{\text{limit}}_{\text{non-SM}}$ obs. (95% CL)	13.3	3.4	3.4

Interesting impact on mass limits for direct stop pair production…

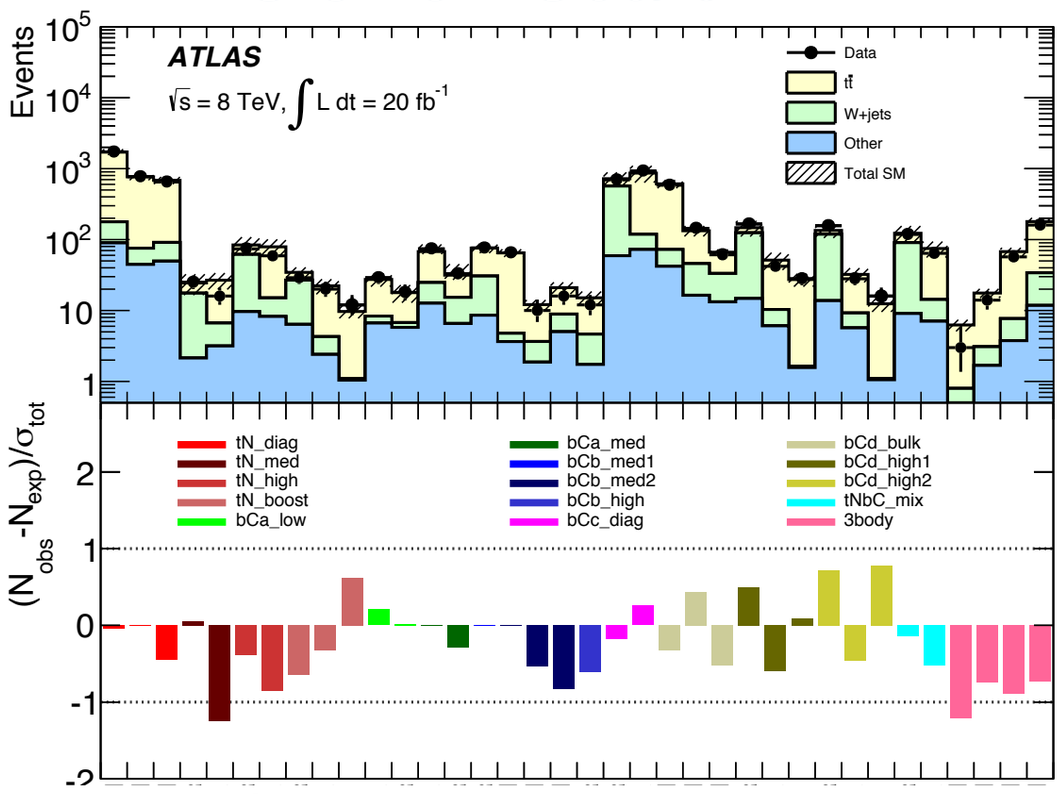
[ATLAS-CONF-2016-007]



SR1 has best expected sensitivity

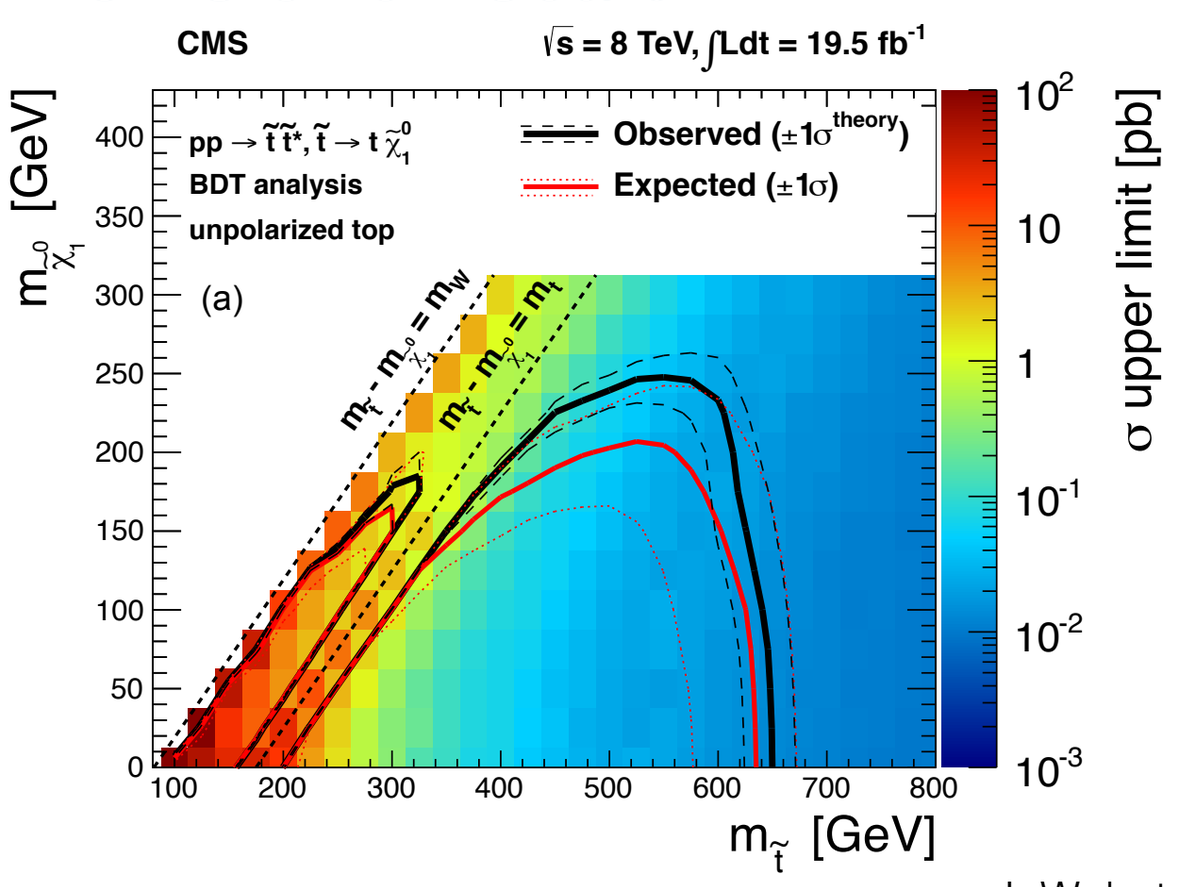
… but no matching excess in Run 1

ATLAS 8 TeV Search [arXiv:1407.0583]



Control & signal regions

CMS 8 TeV Search [arXiv:1308.1586]



Final Remarks

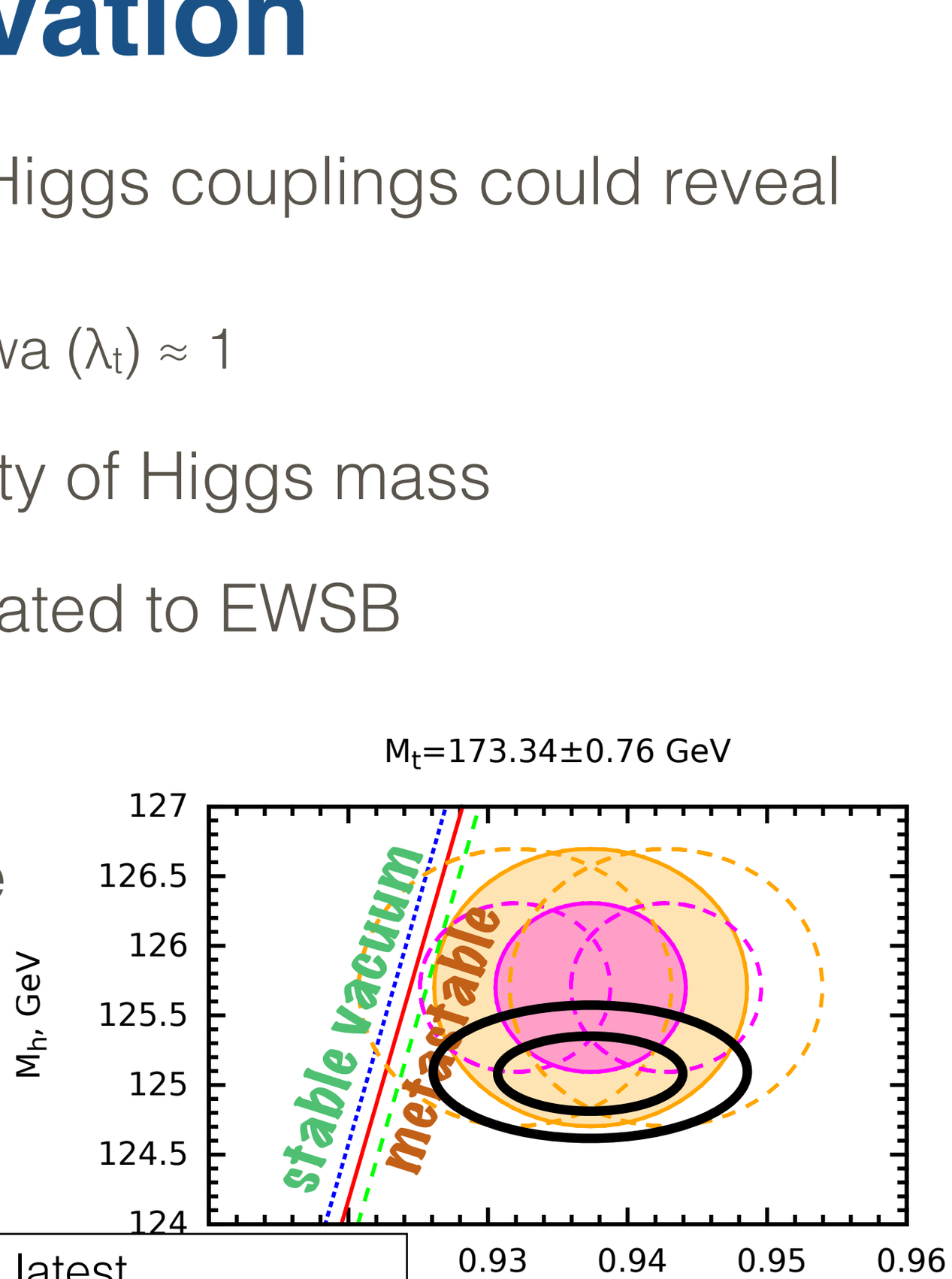
- σ(ttH) measurements from LHC are consistent with SM
  - Uncertainty still large, O(40%) in CMS combination
- CMS Run 2 results already competitive with Run 1
- LHC prospects…
  - H→bb : potential for 5σ significance with ~100 fb^{-1} [PRL 104, 111801 (2010)]
  - With 3000 fb^{-1}…
    - ~10% experimental uncertainty in H→leptons [arXiv:1307.7280]
    - ~20% experimental uncertainty in H→photons [AL-PHYS-PUB-2014-012]
    - Theoretical uncertainty becomes dominant
- These measurements have forced analyzers to find clever ways to control systematics & backgrounds
  → valuable experience!

Backups

Motivation

- Precise measurements of Higgs couplings could reveal departures from the SM
  - Large top mass → top Yukawa (λ_t) ≈ 1
- Dominant impact on stability of Higgs mass
- Window to new physics related to EWSB

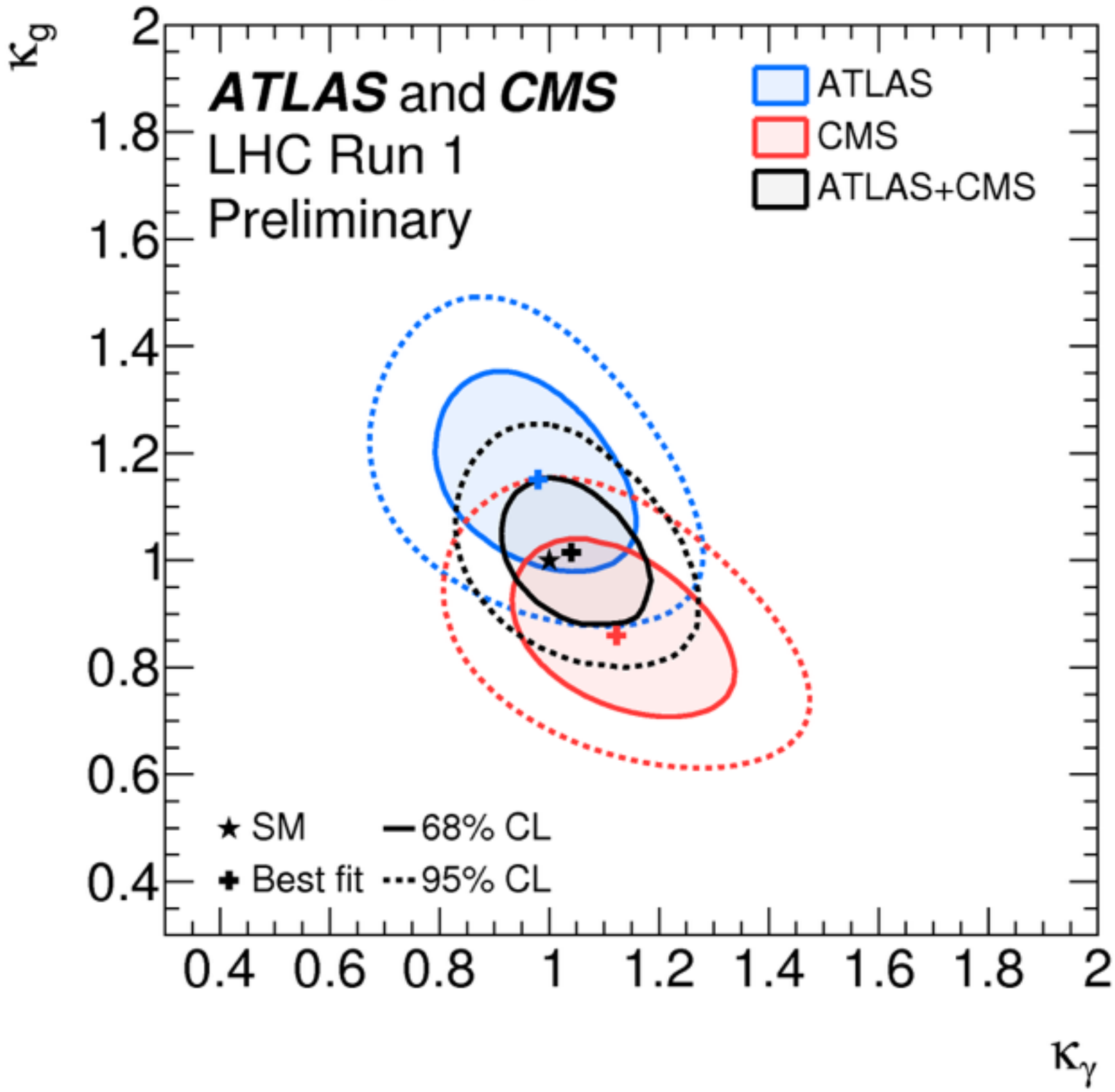
- O(5%) variation between stable/metastable/unstable vacuum [arXiv:1411.1923]
  - Could point to scale of new physics



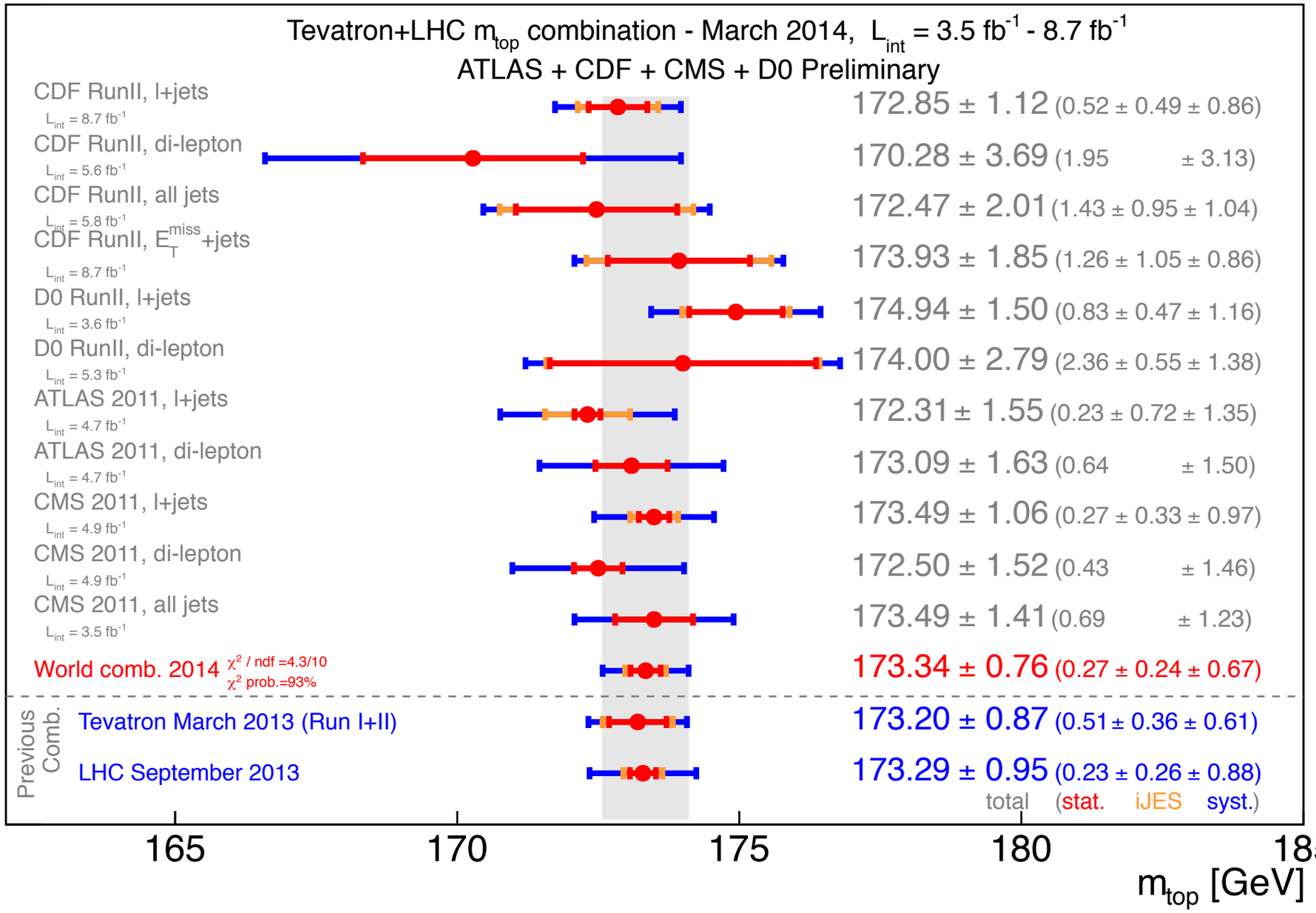
With latest
m_h = 125.09±0.24 GeV

Contraints on ggH and γγH Vertices

ATLAS-CONF-2014-044



Top Mass Measurements



H→leptons jet requirements

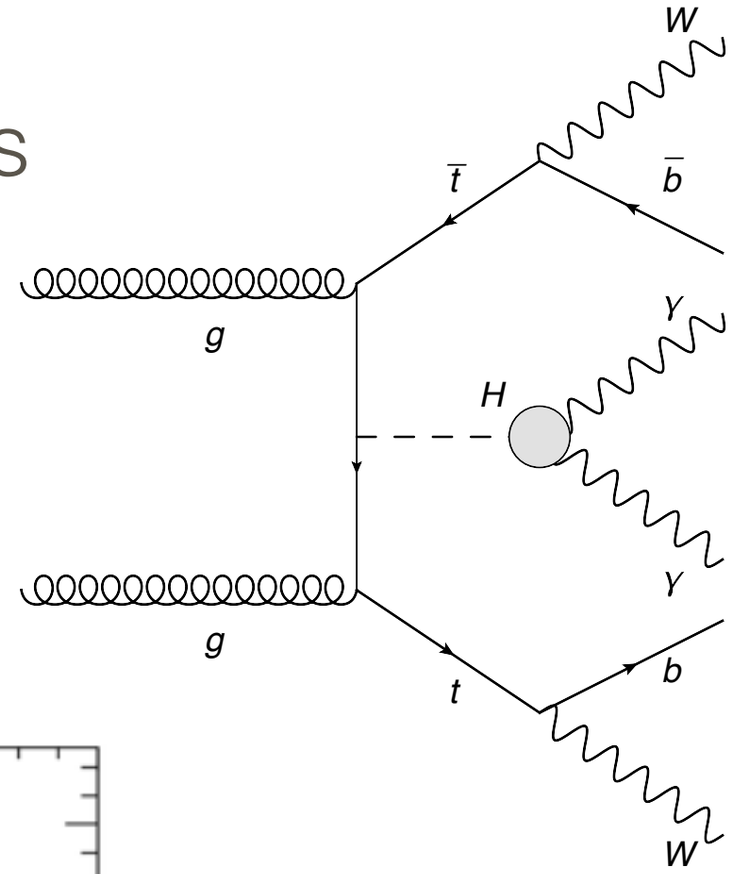
Category	ATLAS	CMS
same sign 2ℓ	≥4 jets, ≥1 b-tag	≥4 jets, ≥2 b-tags
3ℓ	(≥4 jets, ≥1 b-tag) or (3 jets, ≥2 b-tags)	≥2 jets, ≥2 b-tags
4ℓ	≥2 jets, ≥1 b-tag	≥2 jets, ≥2 b-tags

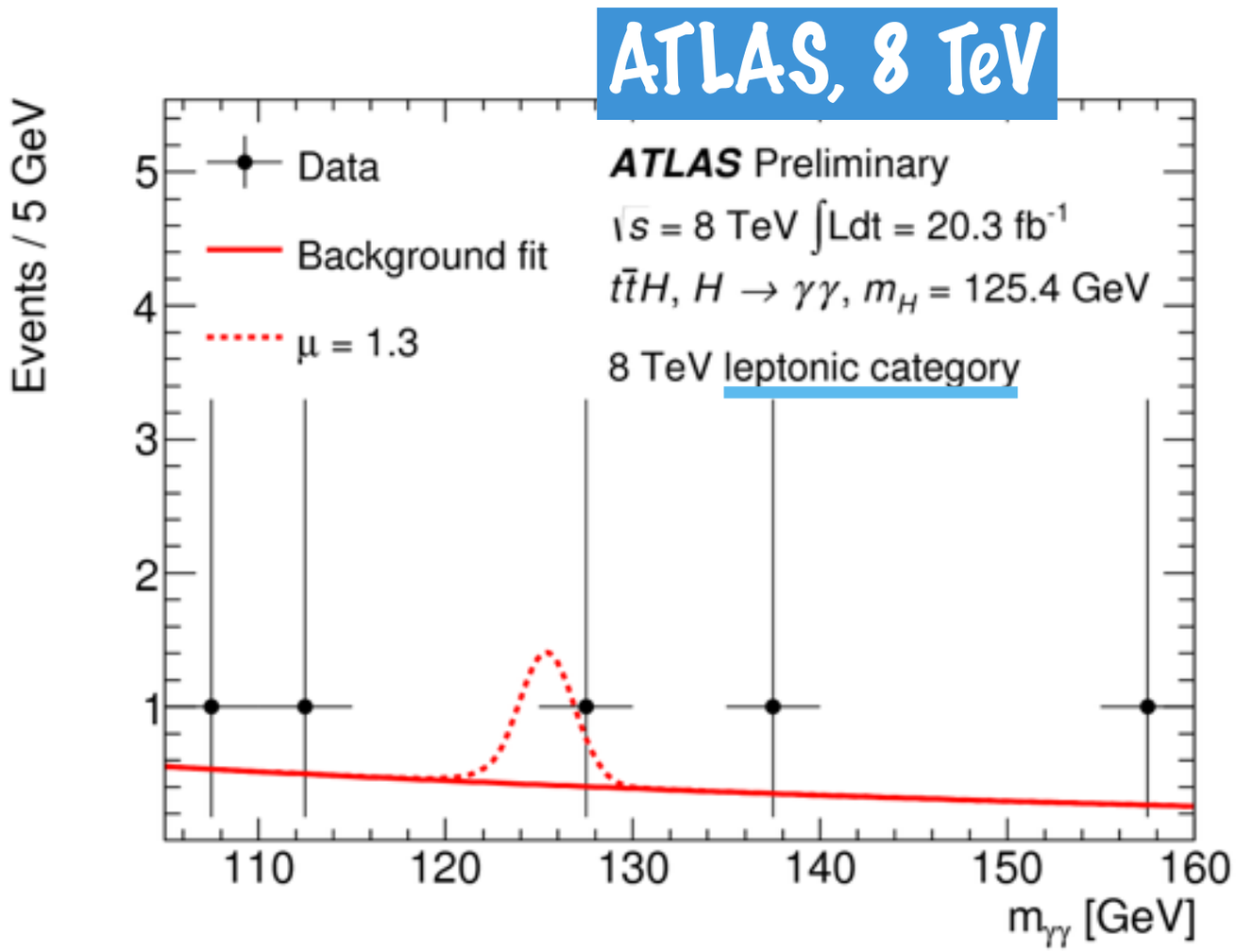
CMS H→leptons Yields

	ee	eμ	$\mu\mu$	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

H→photons Analysis Strategy

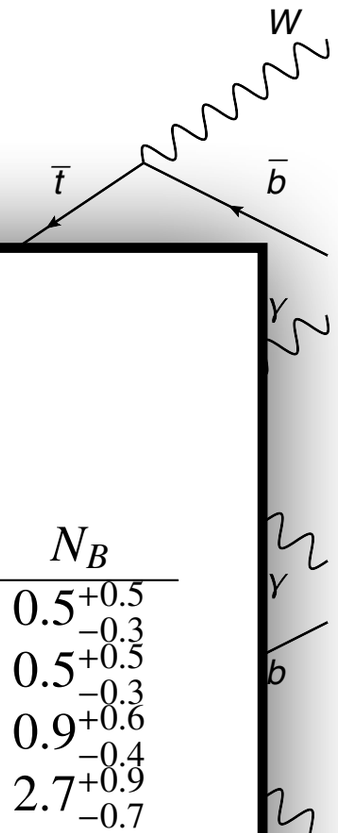
- Categorize events based on top decays
  - Leptonic (≥1ℓ) vs. hadronic
- Signal and background both small
  - Estimated using data in sidebands of $m_{\gamma\gamma}$





H→photons Analysis Strategy

* Categorize events based on top decays
*
*
*

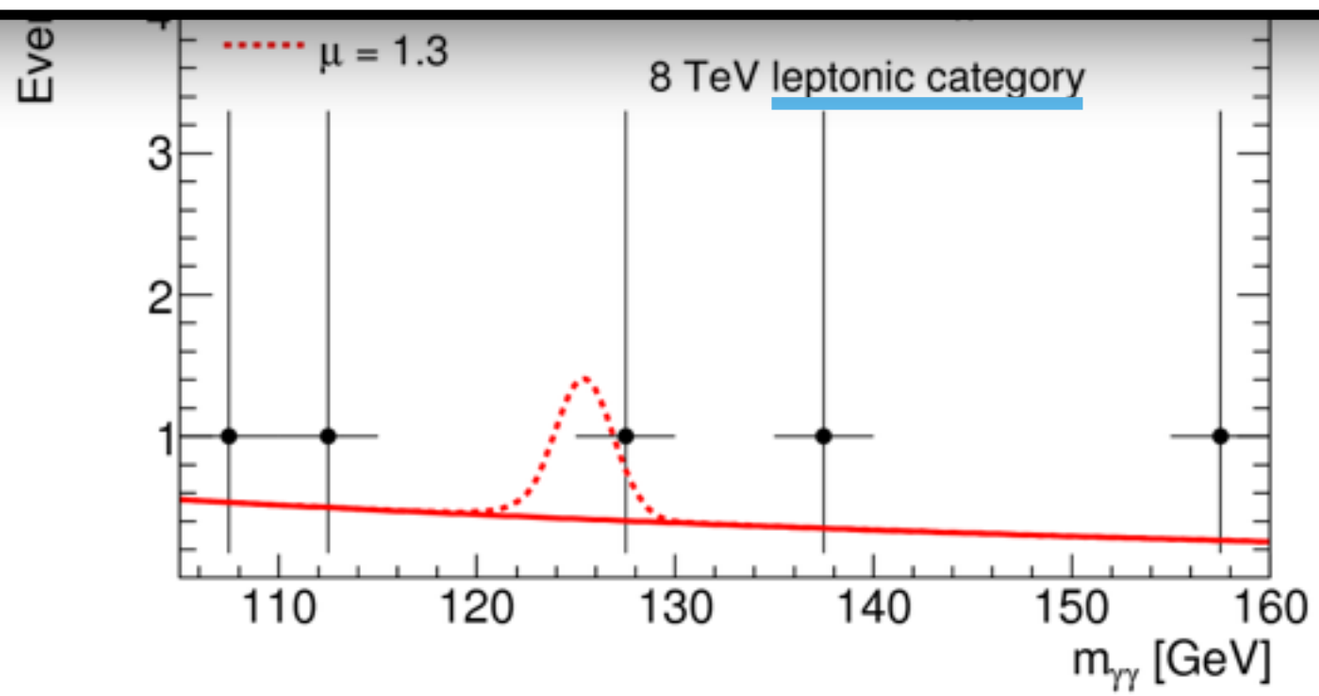


Analysis is particularly sensitive to tH+X!

ATLAS

Category	N_H	ggF	VBF	WH	ZH	$t\bar{t}H$	$tHqb$	WtH	N_B
7 TeV leptonic selection	0.10	0.6	0.1	14.9	4.0	72.6	5.3	2.5	$0.5^{+0.5}_{-0.3}$
7 TeV hadronic selection	0.07	10.5	1.3	1.3	1.4	80.9	2.6	1.9	$0.5^{+0.5}_{-0.3}$
8 TeV leptonic selection	0.58	1.0	0.2	8.1	2.3	80.3	5.6	2.6	$0.9^{+0.6}_{-0.4}$
8 TeV hadronic selection	0.49	7.3	1.0	0.7	1.3	84.2	3.4	2.1	$2.7^{+0.9}_{-0.7}$

Expected fraction of signal yield



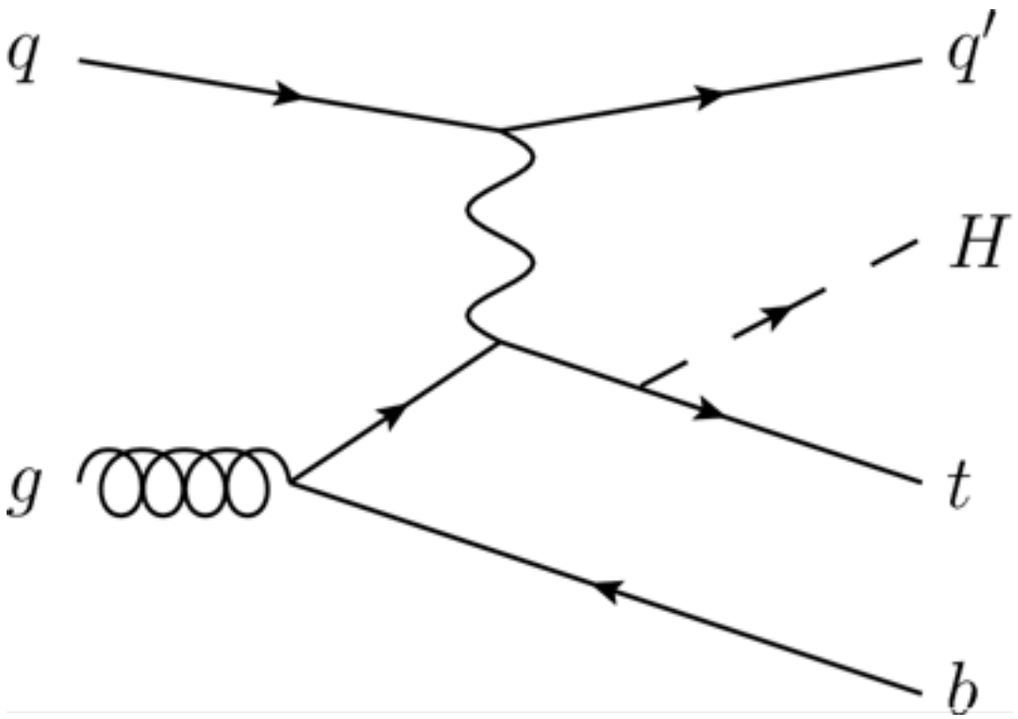
H→photons Selections

	Leptonic channel	Hadronic channel
ATLAS EXPERIMENT	2 photons, p_T>0.35$m_{\gamma\gamma}$/0.25$m_{\gamma\gamma}$ ≥ 1 e/μ, p_T>15/10 GeV E_T^{miss}>20 GeV (only for 1 b-tag) ≥ 1 jets, p_T>25 GeV ≥ 1 b-tags (80% WP)	2 photons, p_T>0.35$m_{\gamma\gamma}$/0.25$m_{\gamma\gamma}$ 0 leptons ≥ 6 jets, p_T>25 GeV, ≥ 2 b-tags (80% WP) or ≥ 5 jets, p_T>30 GeV, ≥ 2 b-tags (70% WP) or ≥ 6 jets, p_T>30 GeV, ≥ 1 b-tags (60% WP)
CMS	2 photons, p_T>0.5$m_{\gamma\gamma}$/25 GeV ≥ 1 e or μ, p_T>20 GeV No E_T^{miss} cut ≥ 2 jets, p_T>25 GeV ≥ 1 b-tags (70% WP)	2 photons, p_T>0.5$m_{\gamma\gamma}$/25 GeV 0 leptons ≥ 4 jets, p_T>25 GeV, ≥ 1 b-tags (70% WP)

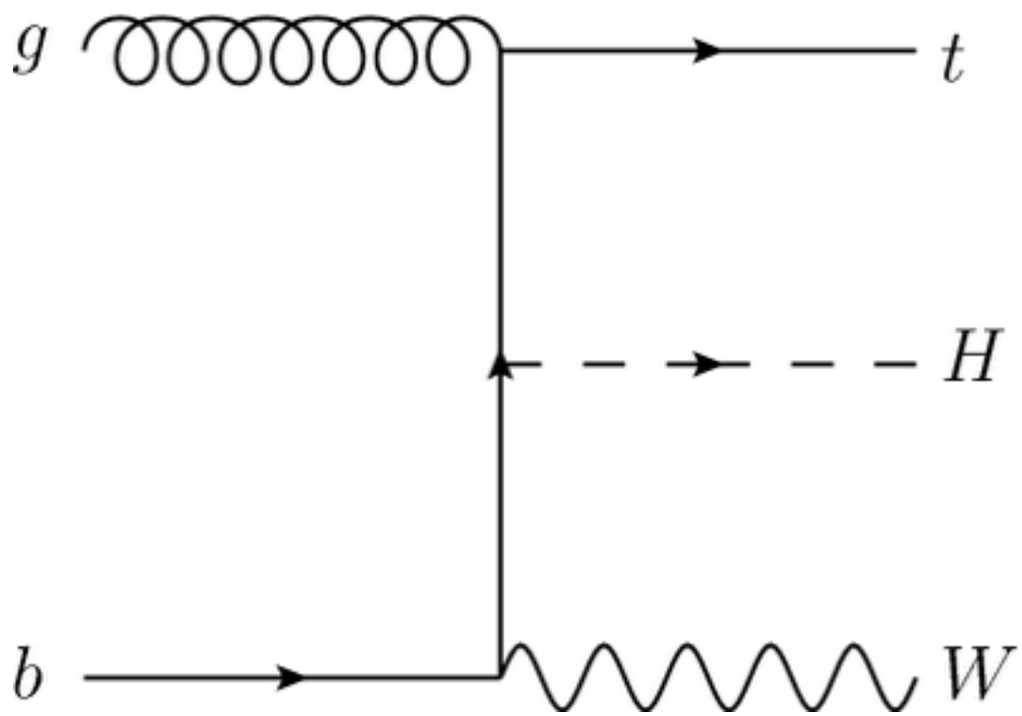
slide from Aurelio Juste

tH Diagrams related to H→photons

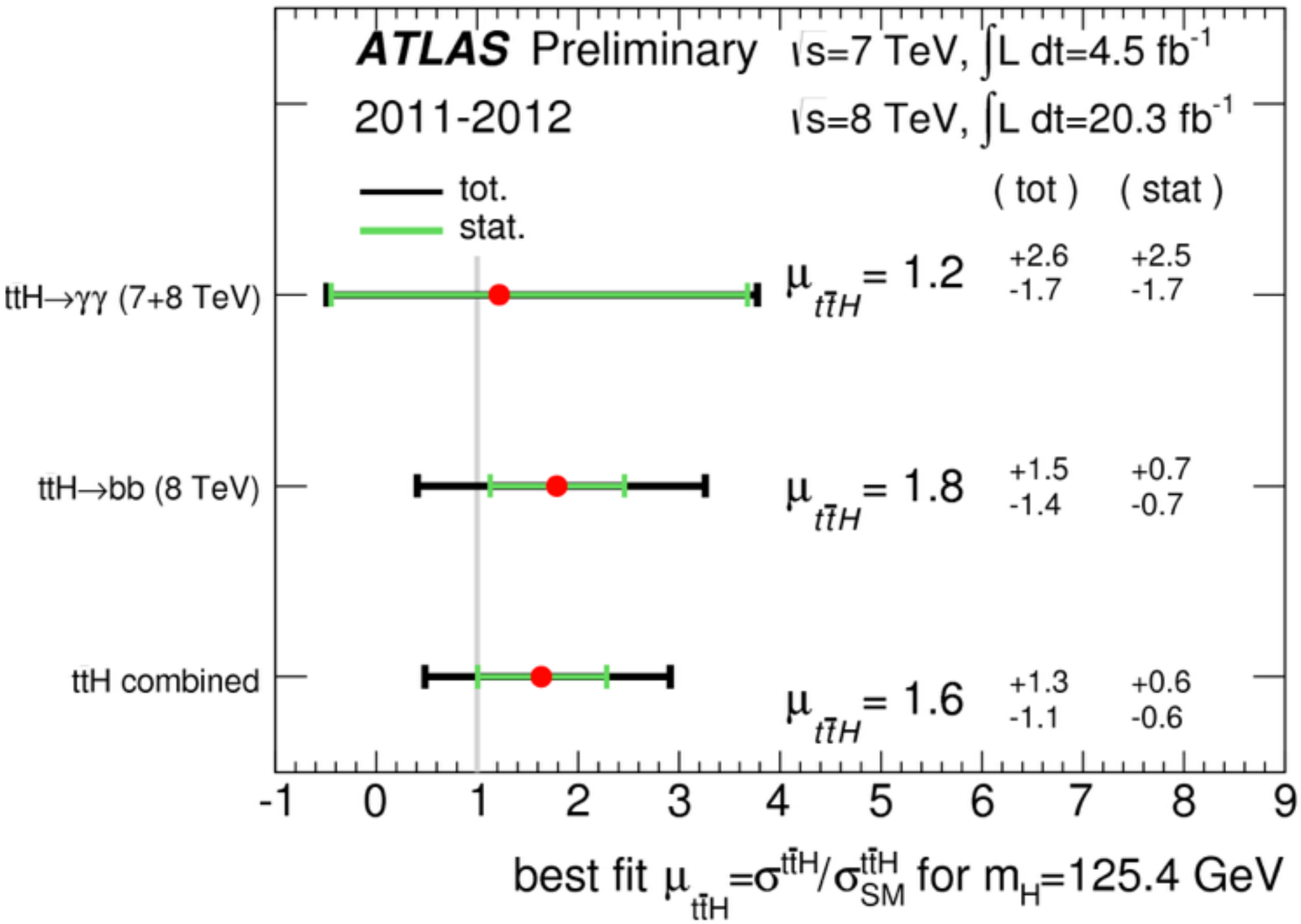
Example tHqb



Example WtH



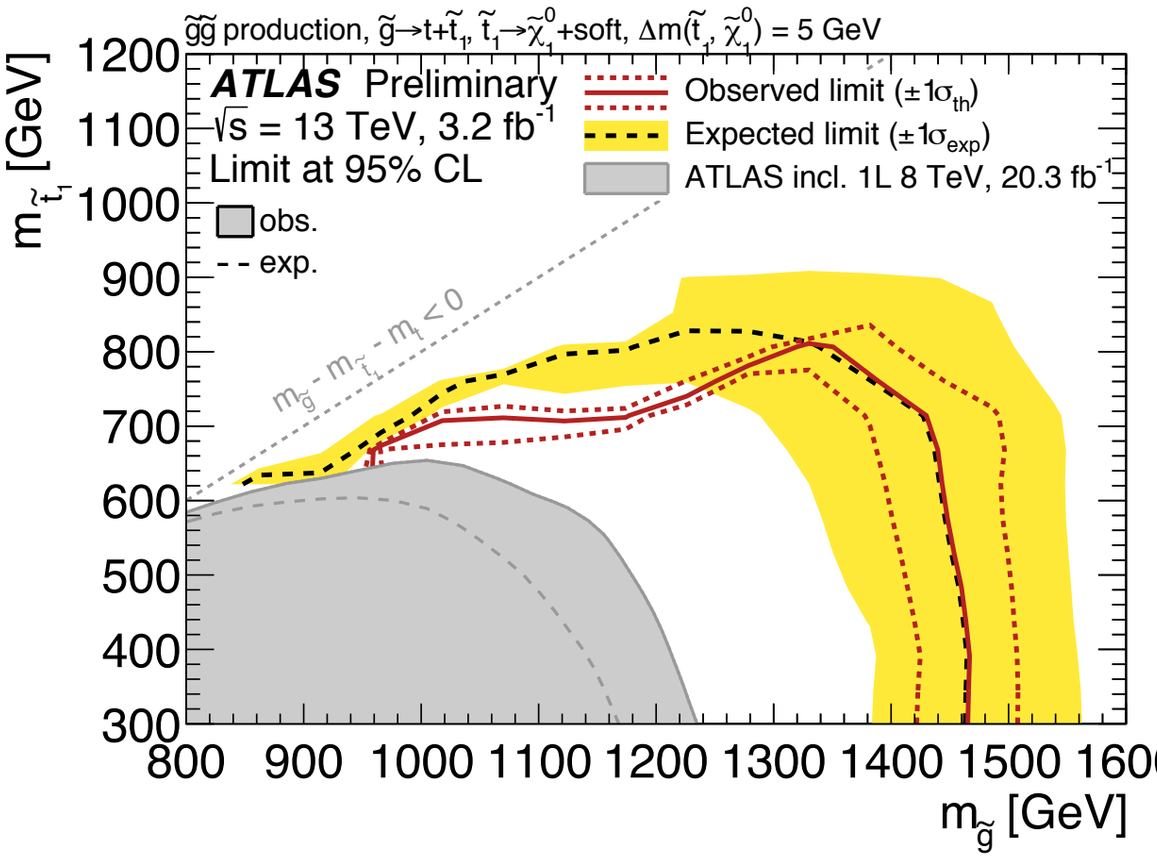
ATLAS bb+γγ Combination

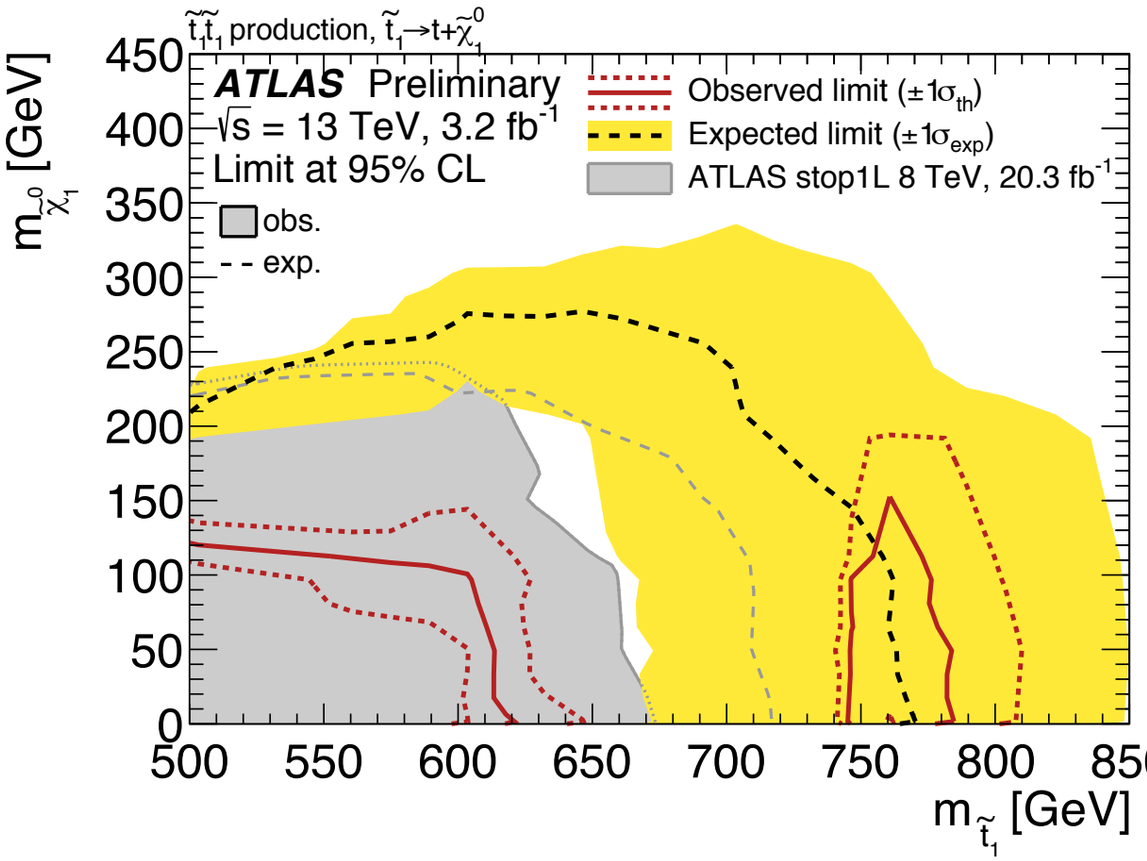


Stop Search MC

Process	ME Generator	ME PDF	Fragmentation	UE Tune	Cross-section Order
$t\bar{t}$	Powheg-Box v2	CT10	Pythia 6	P2012	NNLO+NNLL [71–76]
Single top	Powheg-Box	CT10	Pythia 6	P2012	NNLO+NNLL [77–79]
W/Z+jets	Sherpa 2.1.1	CT10	Sherpa	Default	NNLO [80]
Diboson	Sherpa 2.1.1	CT10	Sherpa	Default	NLO
$t\bar{t}+W/Z$	MG5_aMC 2	NNPDF2.3	Pythia 8	A14	NLO [43]
$t\bar{t}+\gamma$	MG5_aMC 2	CTEQ6L1	Pythia 8	A14	NLO [43]
SUSY Signal	MG5_aMC 2	NNPDF2.3	Pythia 8	A14	NLO+NLL [81]
VLQ Signal	Protos v2.2	NNPDF2.3	Pythia 8	A14	NNLO+NNLL

Stop Limits





- Run 1 gluino mass limit extended to 1460 GeV in the gluino mediated scenario with low stop mass (left)
- [745, 780] GeV stop mass exclusion added in direct stop model with massless neutralino

ATLAS 8 TeV Stop Yields