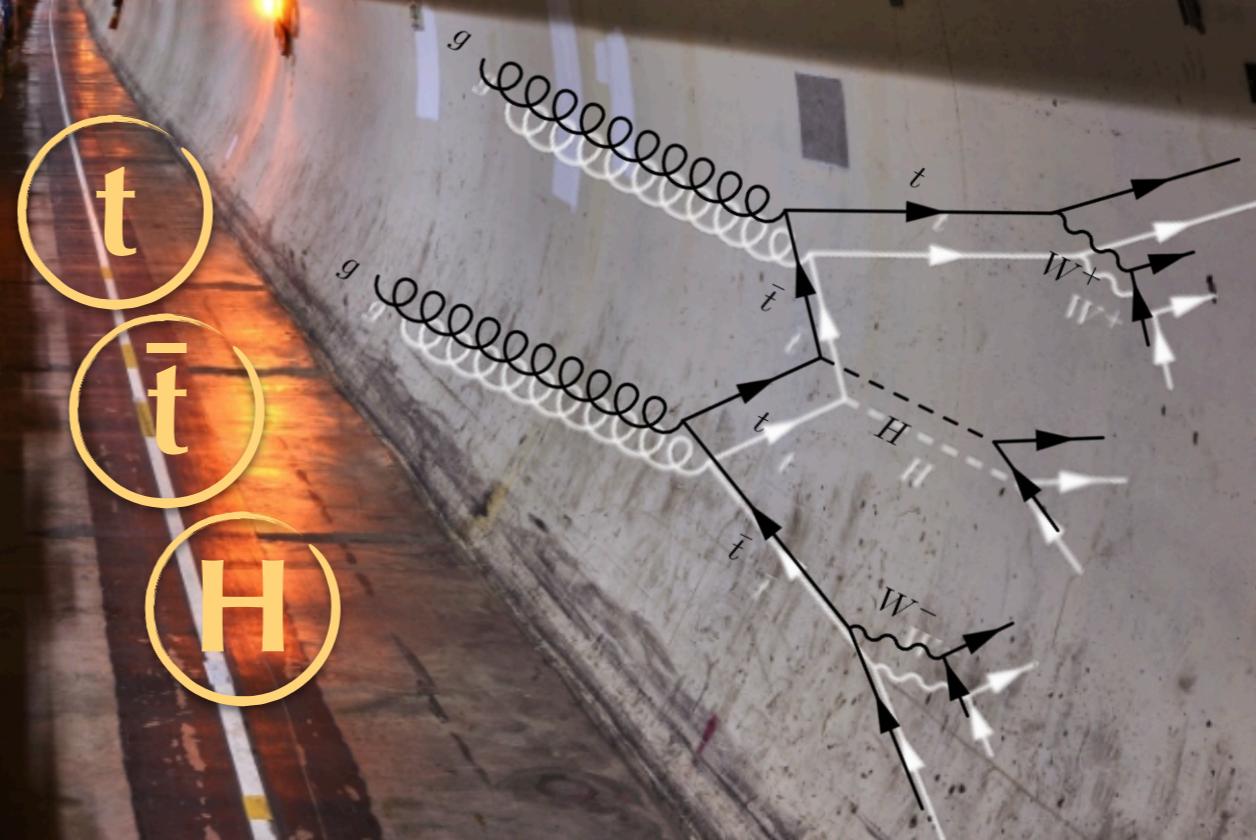
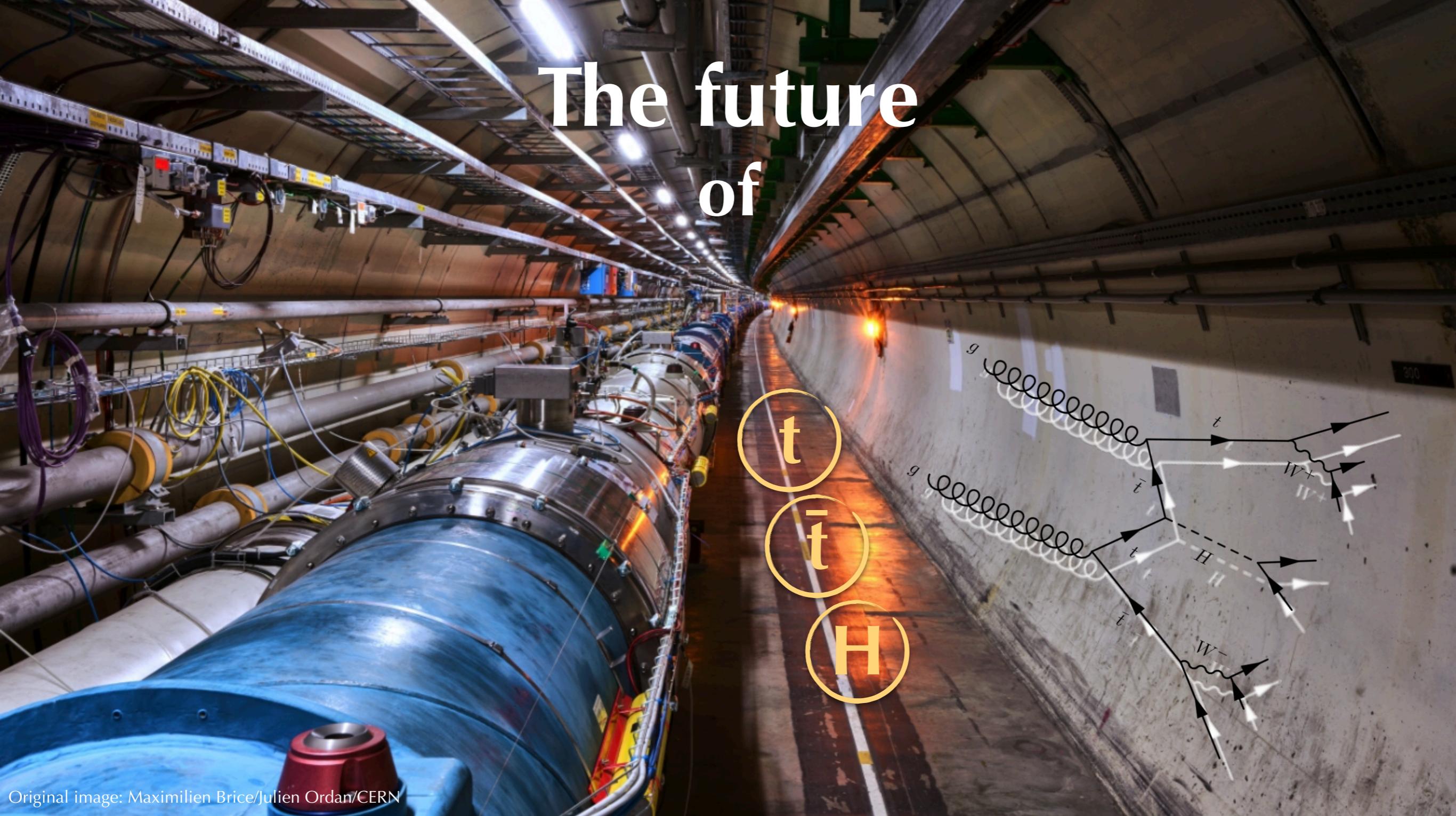


The future of

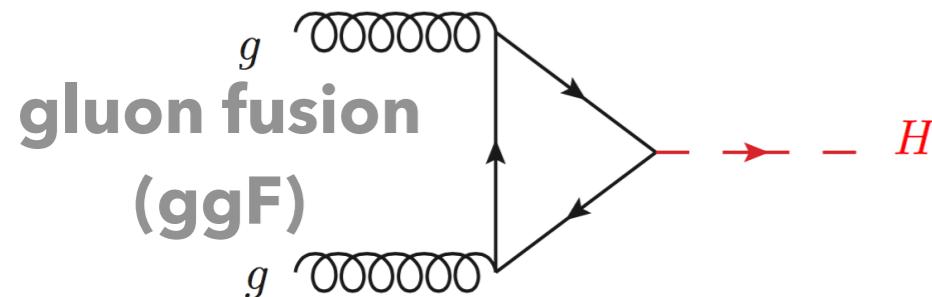


Tamara Vázquez Schröder
CERN

Top LHC France
07 April 2021

The Higgs boson: production

- At the LHC, the Higgs boson is dominantly produced via gluon fusion



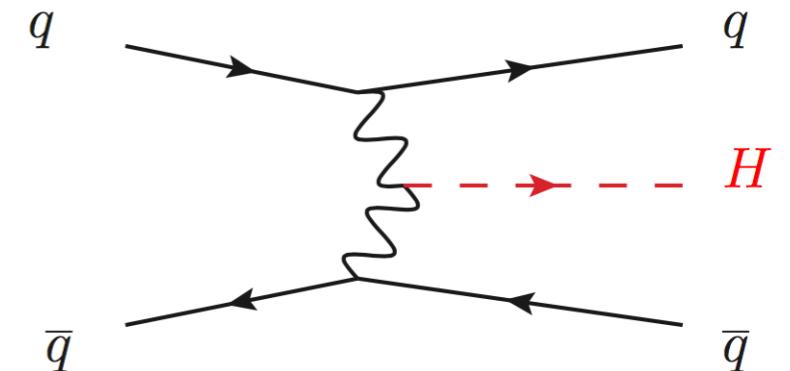
$\sigma_{H,ggF} \sim 49$ pb at 13 TeV

6.9M events in Run-2

vector boson fusion (VBF)

$\sigma_{VBF} \sim 3.8$ pb

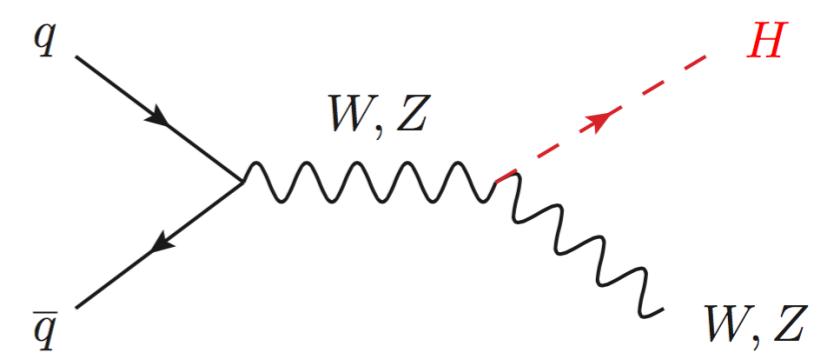
0.5M events in Run-2



W, Z associated production (VH)

$\sigma_{W/ZH} \sim 1.4\text{-}0.9$ pb

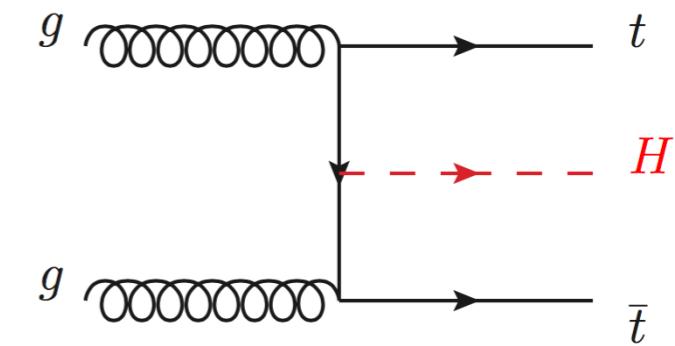
200-130k events in Run-2



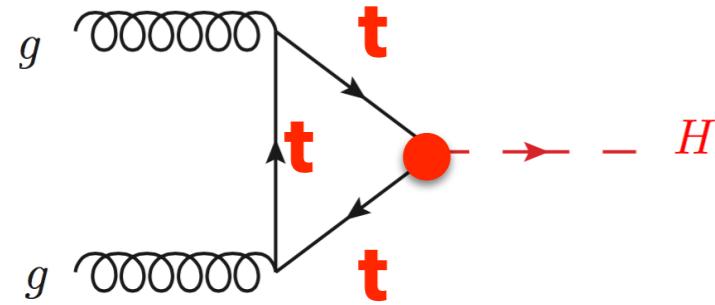
top associated production ($t\bar{t}H$)

$\sigma_{ttH} \sim 0.5$ pb

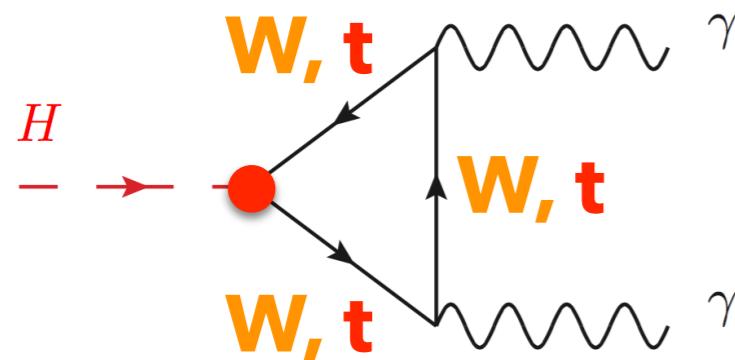
70k events in Run-2



Top & Higgs

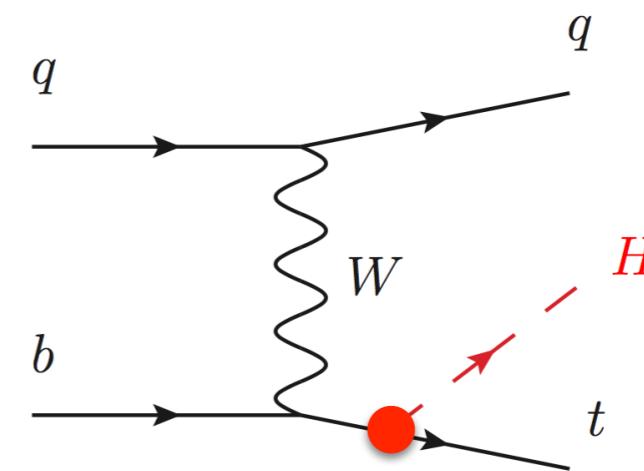
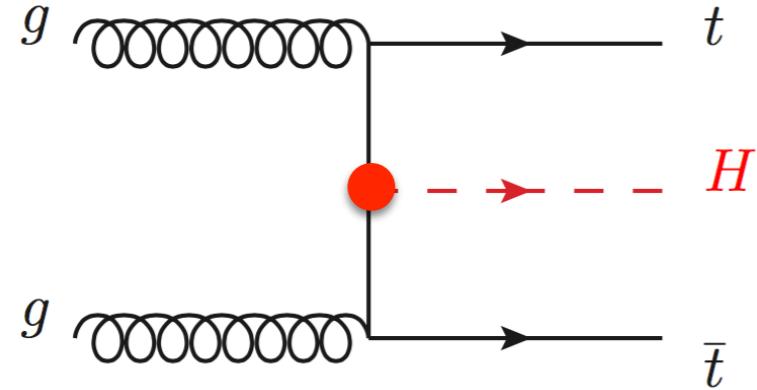


indirect top Yukawa coupling (y_{top}) constraints from gluon fusion production and $\gamma\gamma$ decay...



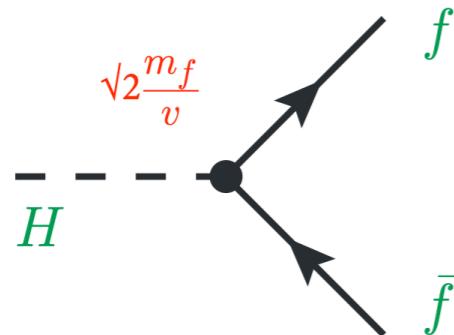
... assuming no additional heavy particles which could couple to the Higgs boson!

direct top Yukawa coupling measurement only possible at the LHC via $t\bar{t}H$ and tH



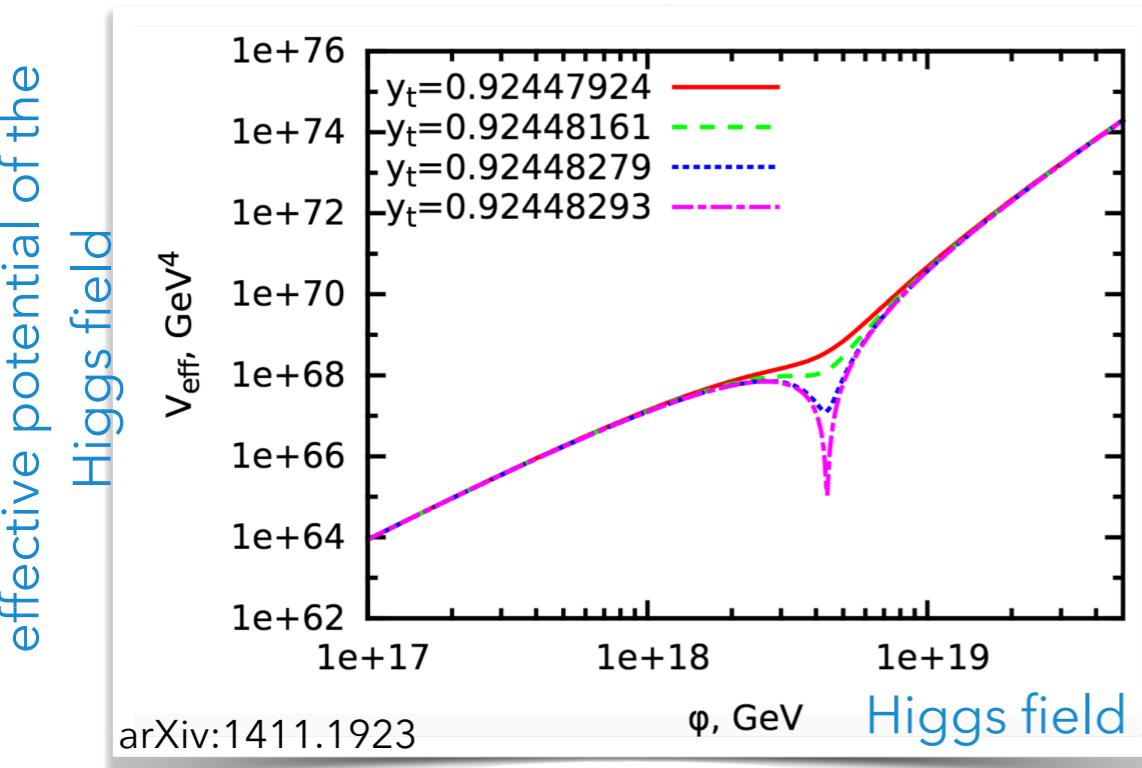
y_{top} ... why should we care?

Top quark is the heaviest fermion in the SM →
Largest Yukawa coupling

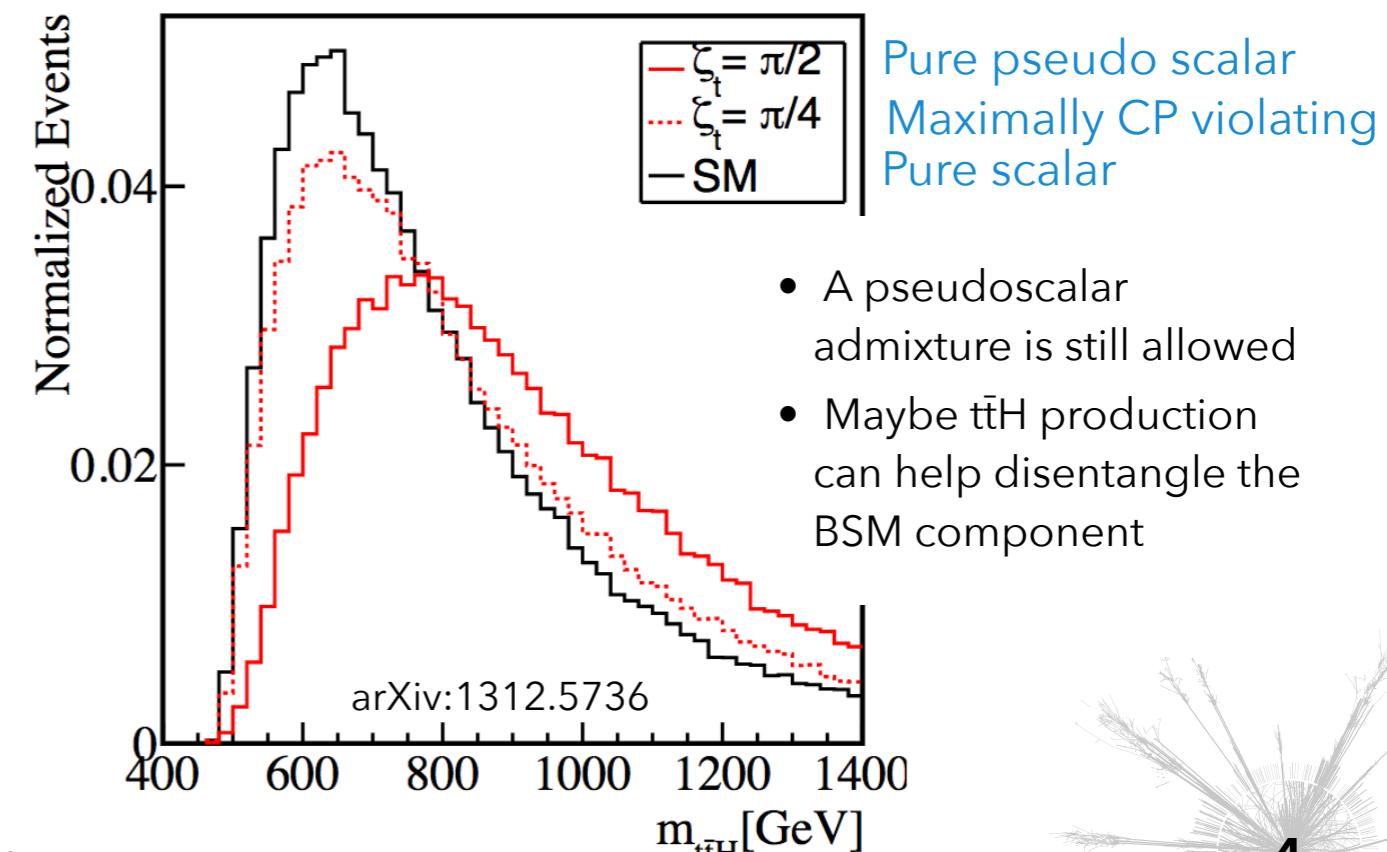


- The only fermion with predicted Yukawa coupling ~ 1
- Does this point to a special role in electroweak symmetry breaking or beyond the SM physics?
- Top quark Yukawa coupling is relevant for the stability of the Higgs potential and the required energy scale for new physics

Is the Universe stable or only metastable?



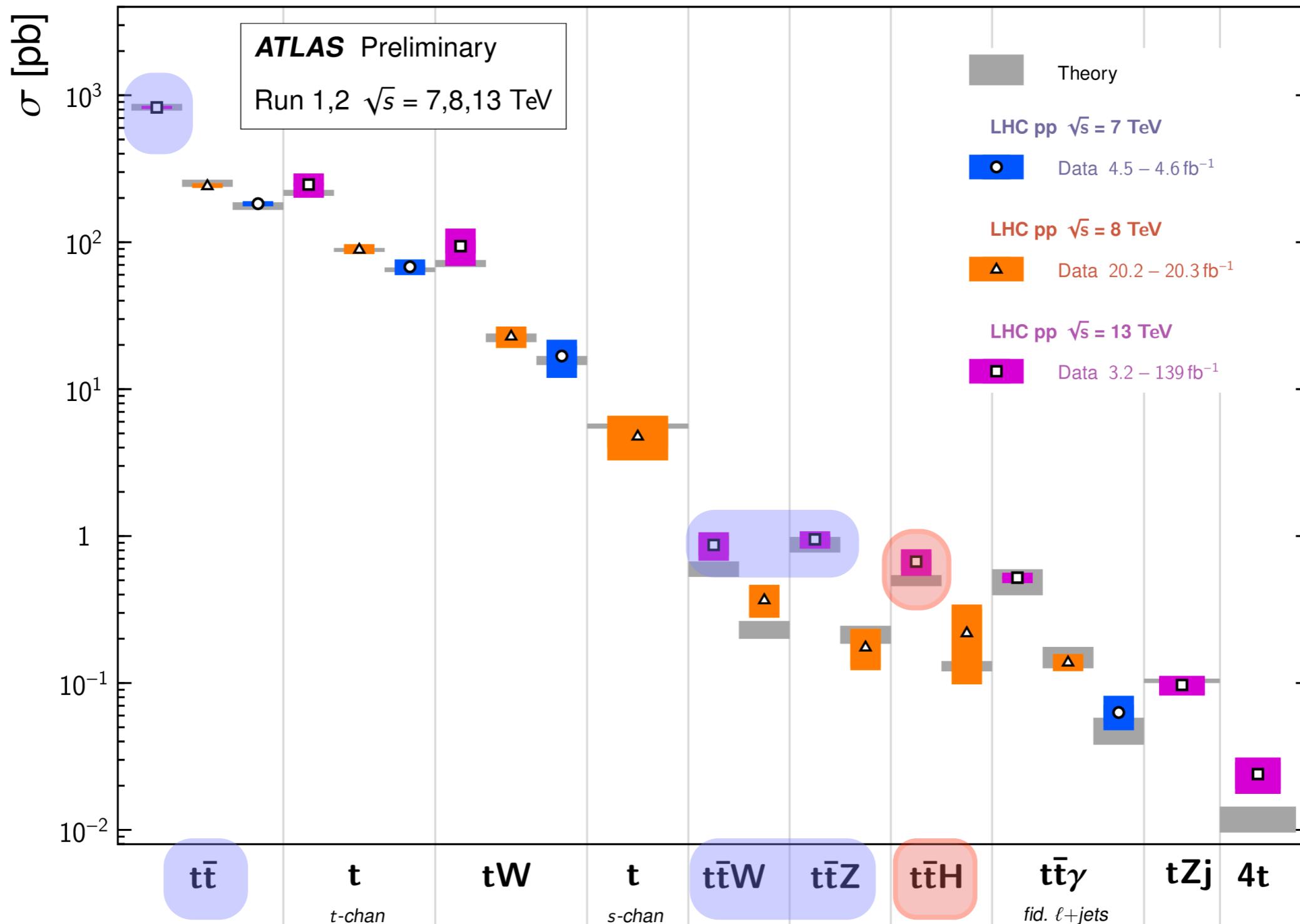
What is the CP nature of the Higgs boson?



$t\bar{t}H$: one of the tiniest rates!

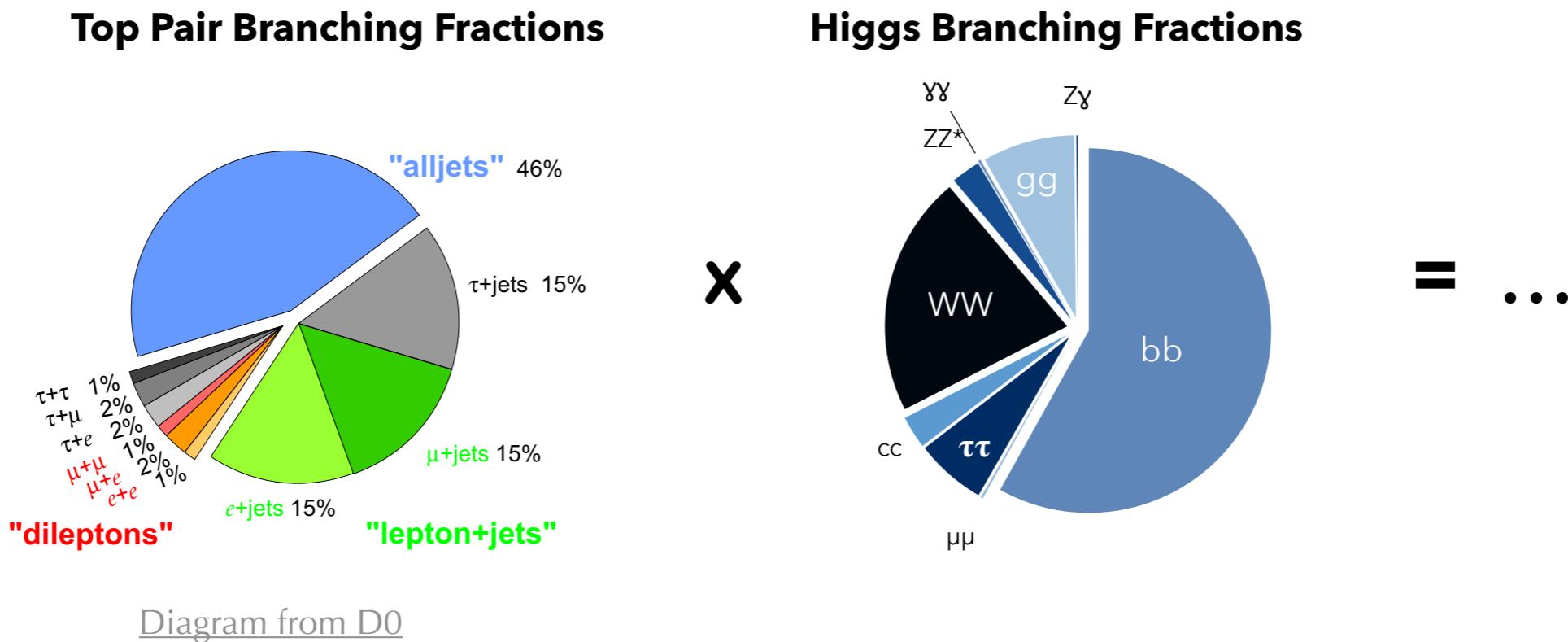
Top Quark Production Cross Section Measurements

Status: November 2020



Where to look for $t\bar{t}H$ production?

- $t\bar{t}H$ production ($\sim 500 \text{ fb}$ @ 13TeV) is:
 - **two orders** of magnitude smaller than ggF Higgs production
 - **three orders** of magnitude smaller than $t\bar{t}$ production
- Look for $t\bar{t}H$ in final states with distinctive signatures and features
 - Combination of top quark x Higgs boson decay modes



$t\bar{t}H$ analysis channels

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

$t\bar{t}H$
($H \rightarrow WW, \tau\tau, ZZ$)
'multilepton'

$t\bar{t}H$
($H \rightarrow \gamma\gamma, ZZ(\rightarrow 4\ell)$)

Low signal/background (need MVA)

Large branching ratio (yields)

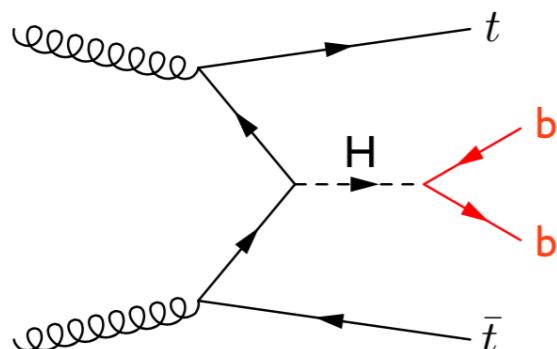
Complex background modelling

Clear peak (clean bump hunt)

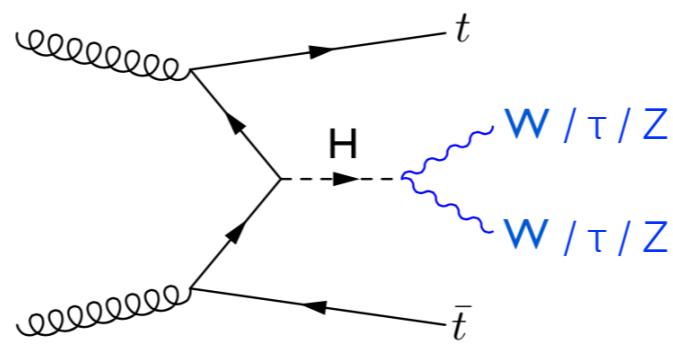
Small branching ratio

Simpler background

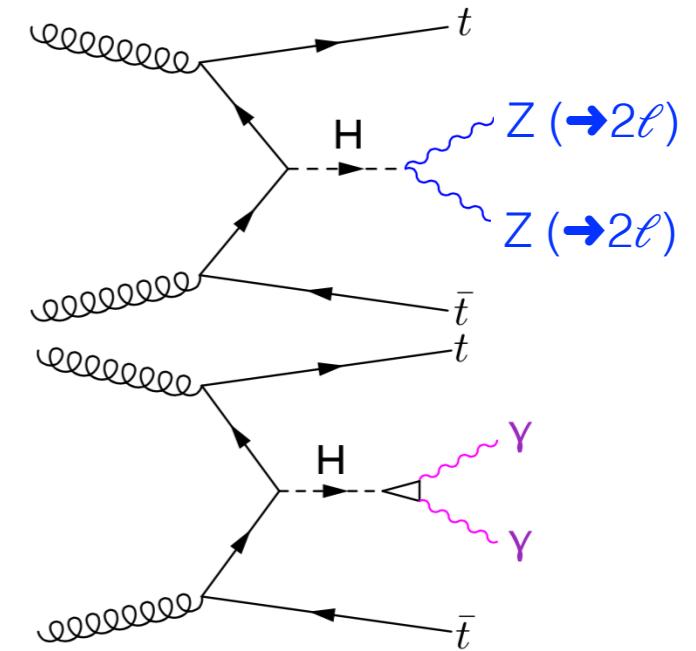
- large irreducible $t\bar{t}$ +jets (HF) background
- final states with **multiple b-jets**



- leptonic decays of W / Z bosons and tau decays can give distinct **multilepton** signatures
- main background from $t\bar{t}Z$ /W and non-prompt leptons



- **resonant** channels



motivation ← challenge

t̄H state of the art Run 2

2015-2016 [$\sim 36 \text{ fb}^{-1}$]
 2015-2017 [$\sim 80 \text{ fb}^{-1}$]
 2015-2018 [$\sim 140 \text{ fb}^{-1}$]



ttH multilepton (H → WW/TT/ZZ)	ATLAS-CONF-2019-045 $\mu_{\text{ttH}} = 0.58^{+0.26}_{-0.25}$	arXiv:2011.03652 $\mu_{\text{ttH}} = 0.92 \pm 0.19 \text{ (stat)}^{+0.17}_{-0.13} \text{ (syst)}$
ttH(bb)	ATLAS-CONF-2020-058 $\mu_{\text{ttH}} = 0.43^{+0.36}_{-0.33}$	CMS-PAS-HIG-18-030 $\mu_{\text{ttH}} = 1.15^{+0.15}_{-0.15} \text{ (stat)}^{+0.28}_{-0.25} \text{ (syst)}$
ttH(ZZ → 4ℓ)	Eur. Phys. J. C 80 (2020) 957 (+STXS) $\mu_{\text{ttH}} = 1.7^{+1.7}_{-1.2} \pm 0.2 \pm 0.2$	arXiv:2103.04956 (+STXS) $\mu_{\text{ttH}} = 0.13^{+0.92}_{-0.13} \text{ (stat)}^{+0.11}_{-0.00} \text{ (syst)}$
ttH(γγ) Observation!	ATLAS-CONF-2020-026 (+ STXS) $\mu_{\text{ttH+th}} = 0.92^{+0.27}_{-0.24}$ 4.7 (5.0) σ obs (exp) PRL 125 (2020) 061802 (+CP) $\mu_{\text{ttH}} = 1.43^{+0.33}_{-0.31} \text{ (stat)}^{+0.21}_{-0.15} \text{ (syst)}$ 5.2 (4.4) σ obs (exp)	arXiv:2103.06956 (+STXS) $\mu_{\text{ttH}} = 1.35^{+0.34}_{-0.28}$ PRL 125 (2020) 061801 (+CP) $\mu_{\text{ttH}} = 1.38^{+0.36}_{-0.29}$ 6.6 (4.7) σ obs (exp)
Combination	Phys. Lett. B 784 (2018) 173 (80/fb + 36.1/fb → Observation)	Phys. Rev. Lett. 120 (2018) 231801 → Observation

Presentation legend

Many recent
 $t\bar{t}H$ results!

In the
following,
all common
facts &
strategies in
black



ATLAS
specific in
blue

CMS
specific in
red

t̄H landscape

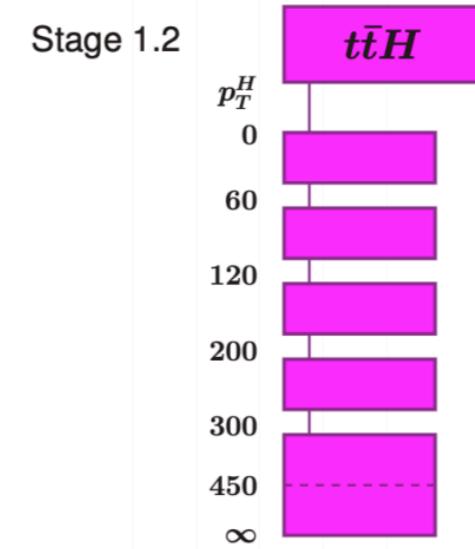
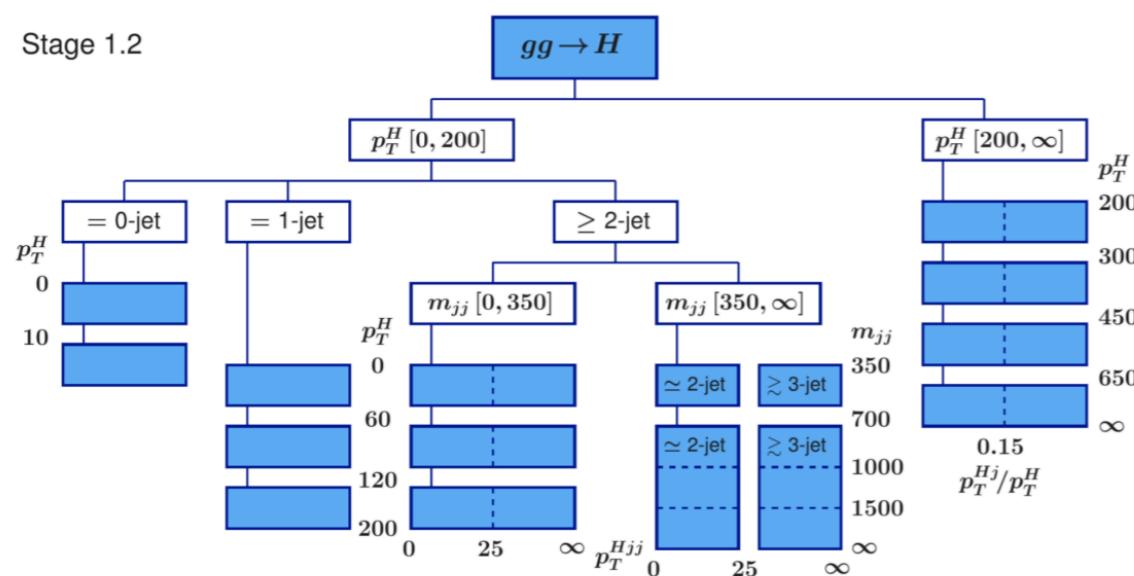
- Observation of t̄H in the combination of all channels and in the individual t̄H(γγ) channel achieved by ATLAS and CMS!
- What have we been working on since then?
 - **New measurements**
 - t̄H STXS [simplified template cross section] measurements (p_T^{Higgs})
 - t̄H CP-odd contribution searches
 - **Addressing long-standing / recent issues:**
 - Understand observed tension with theory prediction in t̄W-like regions
 - Improve estimation of t̄bb̄ background
 - Improve evaluation of background modelling uncertainties

Simplified Template Cross Section (STXS)

- Measure **production modes** separately, categorising each into bins of key (truth) quantities (p_T^H , Njets, m_{jj} , ...)
 - Chosen as most sensitive variables to theory predictions / signal sensitivity / new physics
 - Different stages (e.g. stage 0, stage 1, stage 1.2) with varying degrees of granularity
 - Decay mode agnostic: well-suited for combinations

- **How to design an STXS analysis?**

- How are events categorised?
 - Reconstructed quantities as proxy for truth quantities or multivariate classifier
- How many / which bins to target?
 - Driven by analysis sensitivity



t̄H CP-structure

- Probe the charge conjugation and parity (CP) properties of the Yukawa coupling of the Higgs boson to the top quark
- Any measured CP-odd contribution would be a sign of physics beyond the SM
 - explain observed baryon asymmetry of the universe?

$$|f_{\text{CP}}^{\text{Htt}}| = \frac{|\tilde{\kappa}_t|^2}{|\tilde{\kappa}_t|^2 + |\kappa_t|^2} \Leftrightarrow \frac{\sin^2 \alpha}{\mu_{\text{ttH}}} \Leftrightarrow \frac{\kappa_t^2}{\kappa_t^2}$$

CP-structure ttH parametrisation:

$$\mathcal{A}(\text{Htt}) = -\frac{m_t}{v} \bar{\psi}_t (\kappa_t + i \tilde{\kappa}_t \gamma_5) \psi_t,$$

$$f_{\text{CP}}^{\text{Htt}} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2} \text{sign}(\tilde{\kappa}_t / \kappa_t)$$



SM (CP-even): $\kappa_t = 1; \tilde{\kappa}_t = 0$

CP-odd: $\kappa_t = 0; \tilde{\kappa}_t = 1$

or

$$\mathcal{L} = -\frac{m_t}{v} \left\{ \bar{\psi}_t \kappa_t [\cos(\alpha) + i \sin(\alpha) \gamma_5] \psi_t \right\} H$$



SM (CP-even): $\alpha = 0^\circ$

CP-odd: $\alpha = 90^\circ$

$t\bar{t}H(b\bar{b})$: analysis strategy

- **Biggest challenge:** good modelling of the $t\bar{t}+HF$ ($\geq 1b, \geq 1c$) background

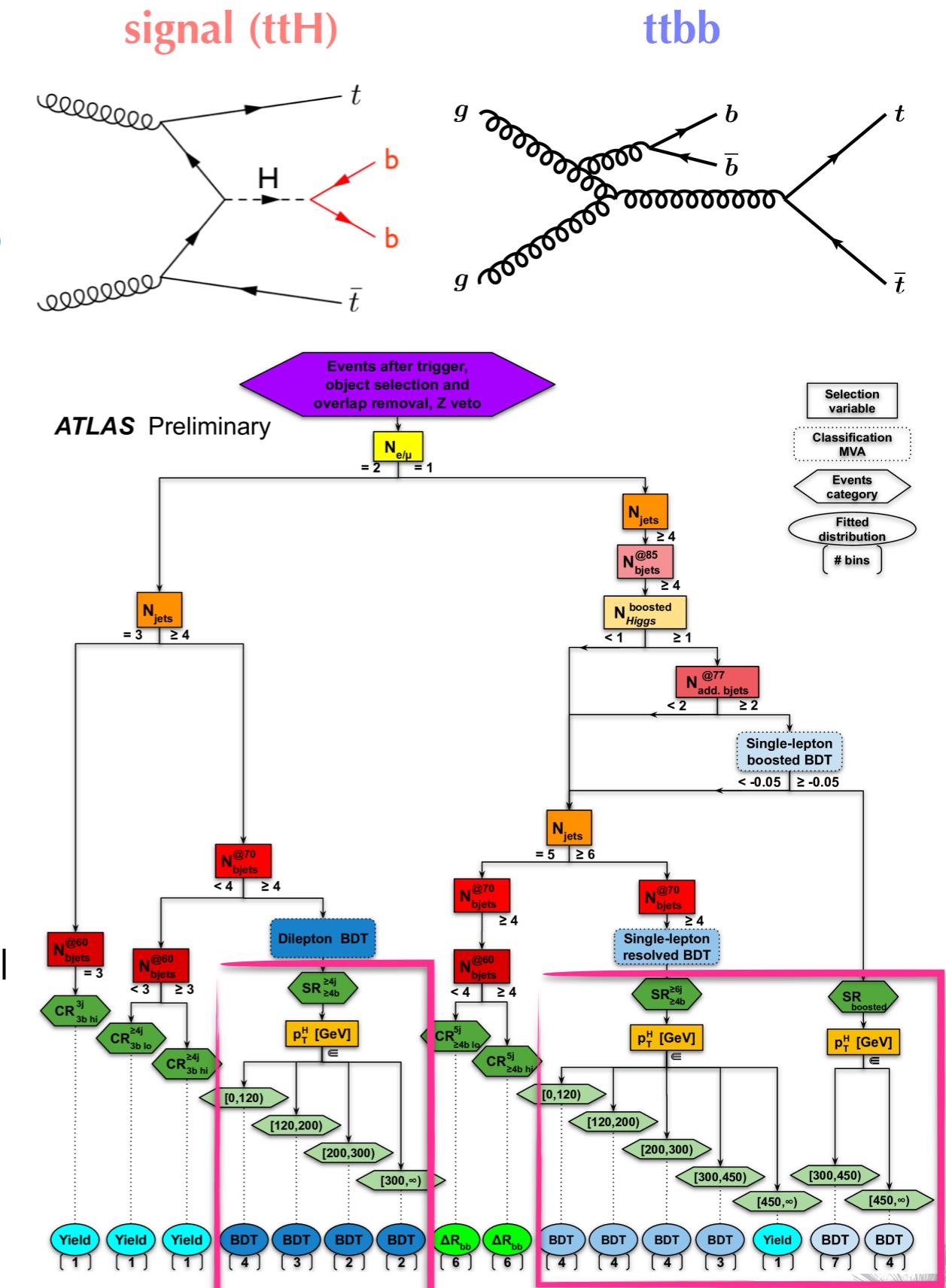


Nominal sample: @NLO 4-flavour scheme $t\bar{t}bb\bar{b}$
 $t\bar{t}+\geq 1c$ and $t\bar{t}+\text{light}$ modelled by $t\bar{t}$ @NLO



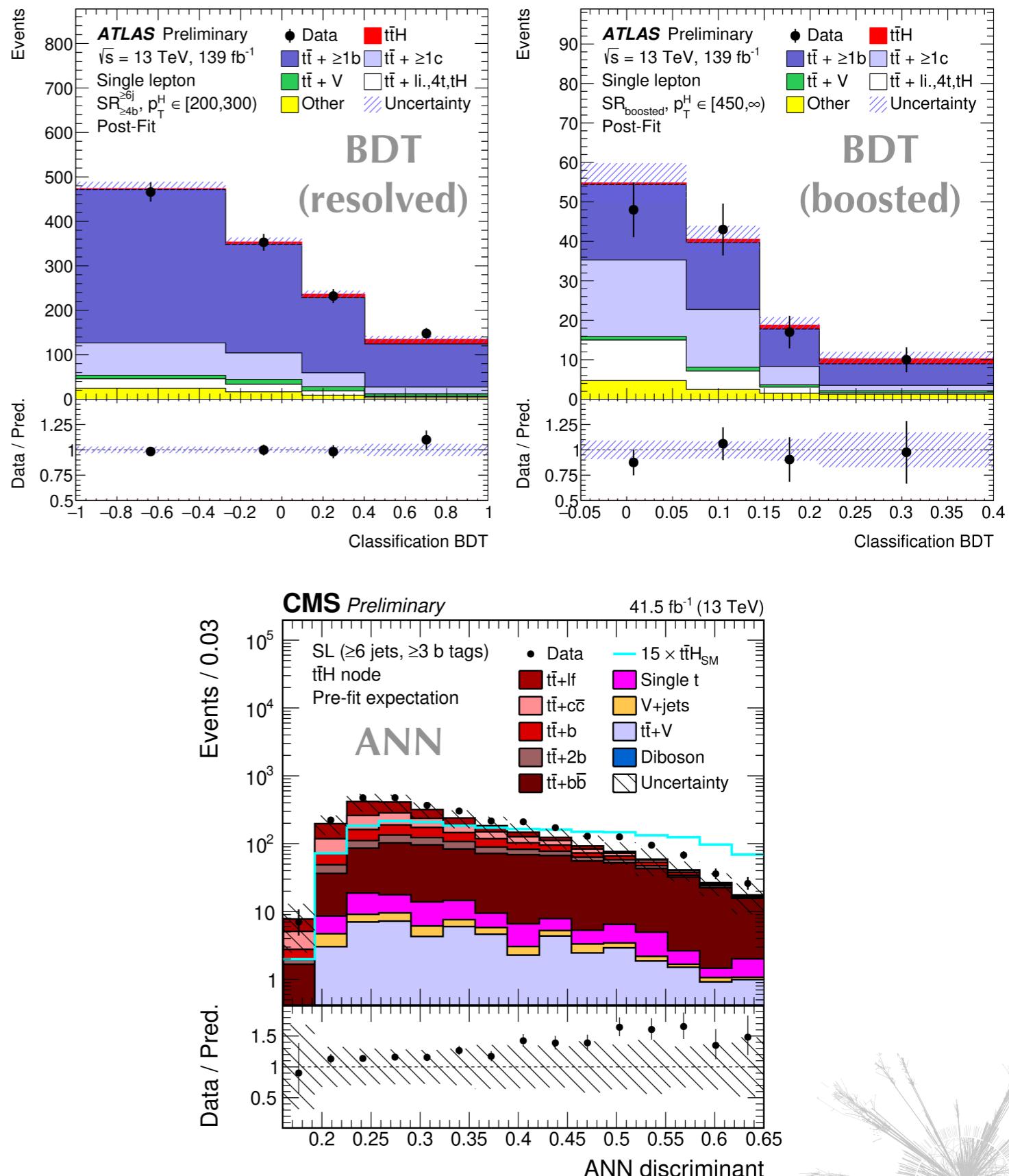
Nominal sample: @NLO 5-flavour scheme
Split in further sub-components: $t\bar{t}+bb\bar{b}$, $t\bar{t}+2b$
(unresolved), $t\bar{t}+b$ (extra b missed)

- **Channel categorisation** based on
 - Number of ℓ (0, 1 or 2 opposite-sign)
 - Number of jets
 - Requirements on the b-tagging discriminant (based on **4 or 1** calibrated working points)
 - Resolved or boosted, for single lepton channel
 - Multi-classification ANN decisions for single lepton channel
 - Reconstructed p_T^H categories



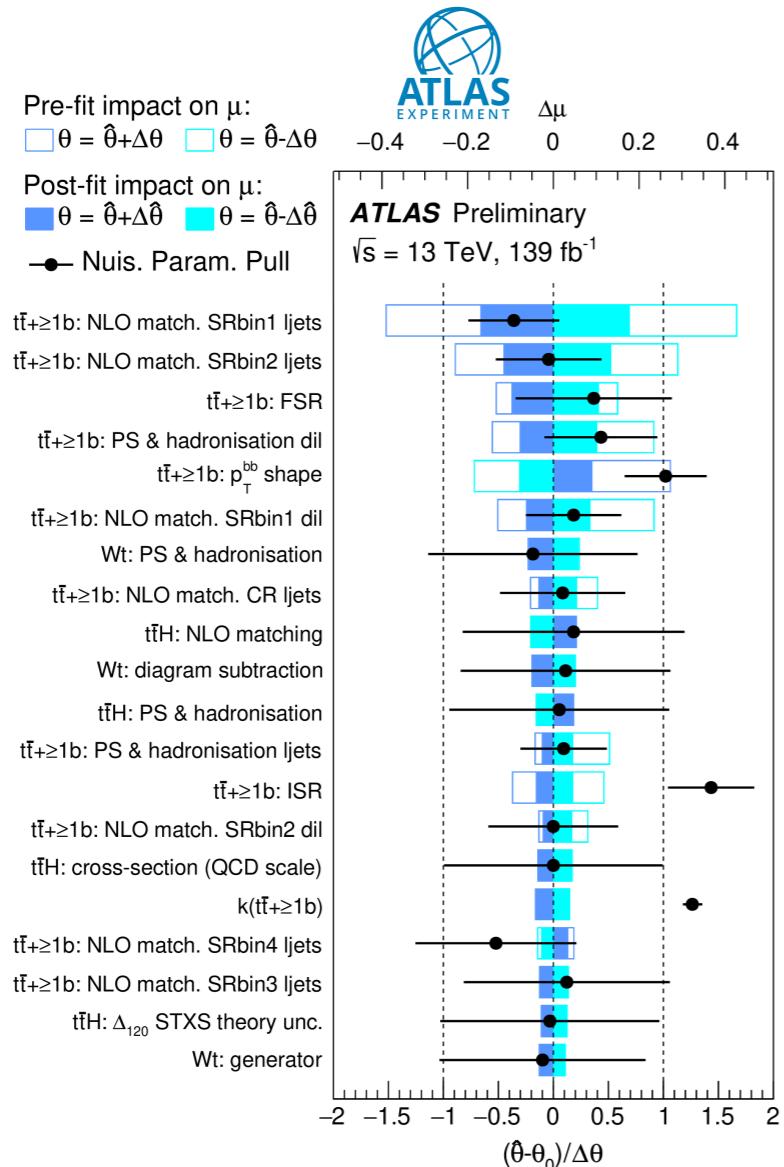
$t\bar{t}H(b\bar{b})$: MVA discriminants

- **MVA analysis** needed to discriminate signal from the overwhelming background
 - Input variables of **classification BDT**: kinematic variables, reconstruction BDTs (resolved), likelihood, and **discrete** btagging discriminants
 - **MEM** in 0ℓ ($t\bar{t}H$, $t\bar{t}+bb$), **ANN** in SL and **BDT** in DL ($t\bar{t}H$, $t\bar{t}+jets$) with MEM input, as well the **continuous** b-tagging score

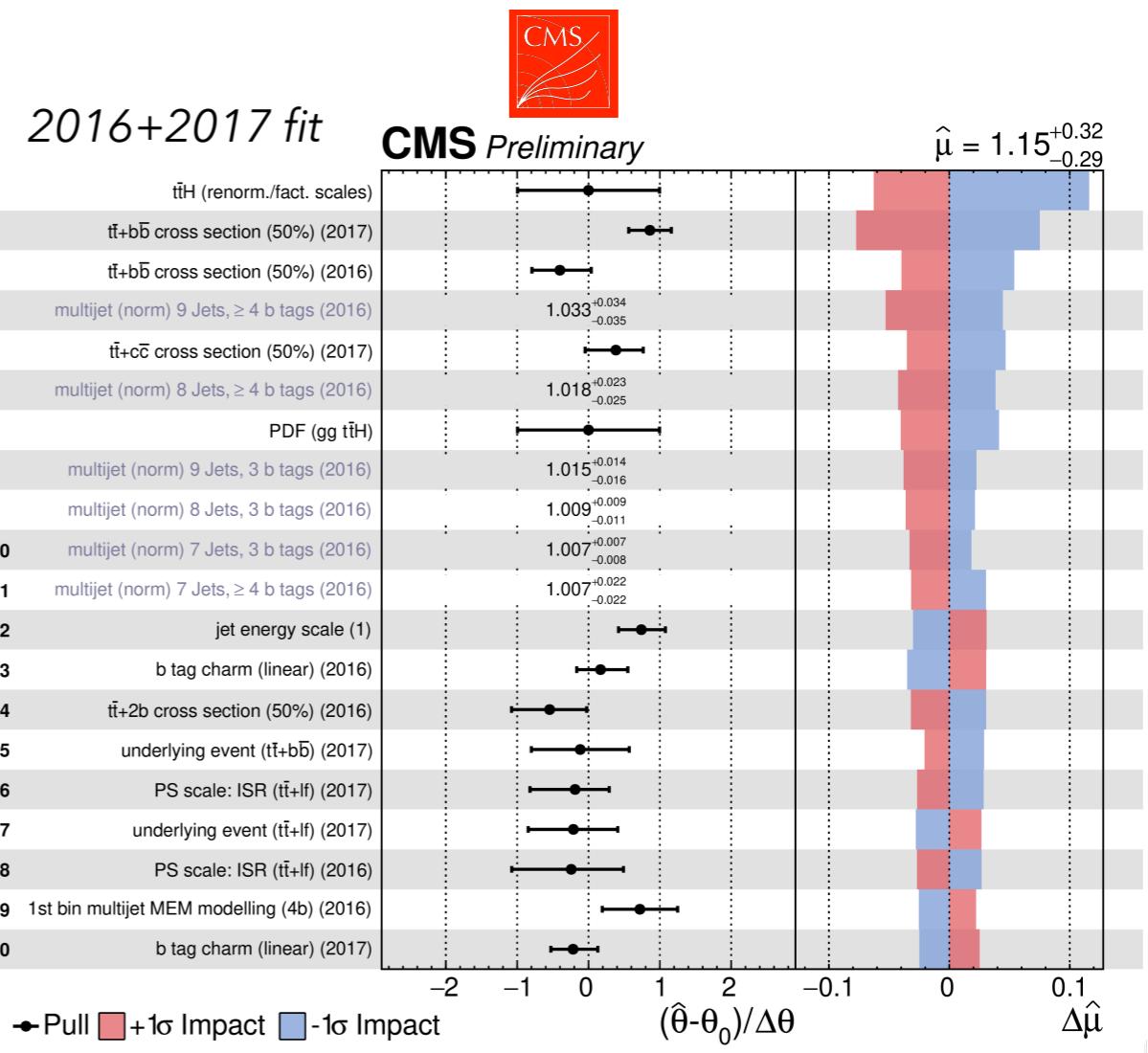


$t\bar{t}H(b\bar{b})$: modelling uncertainties

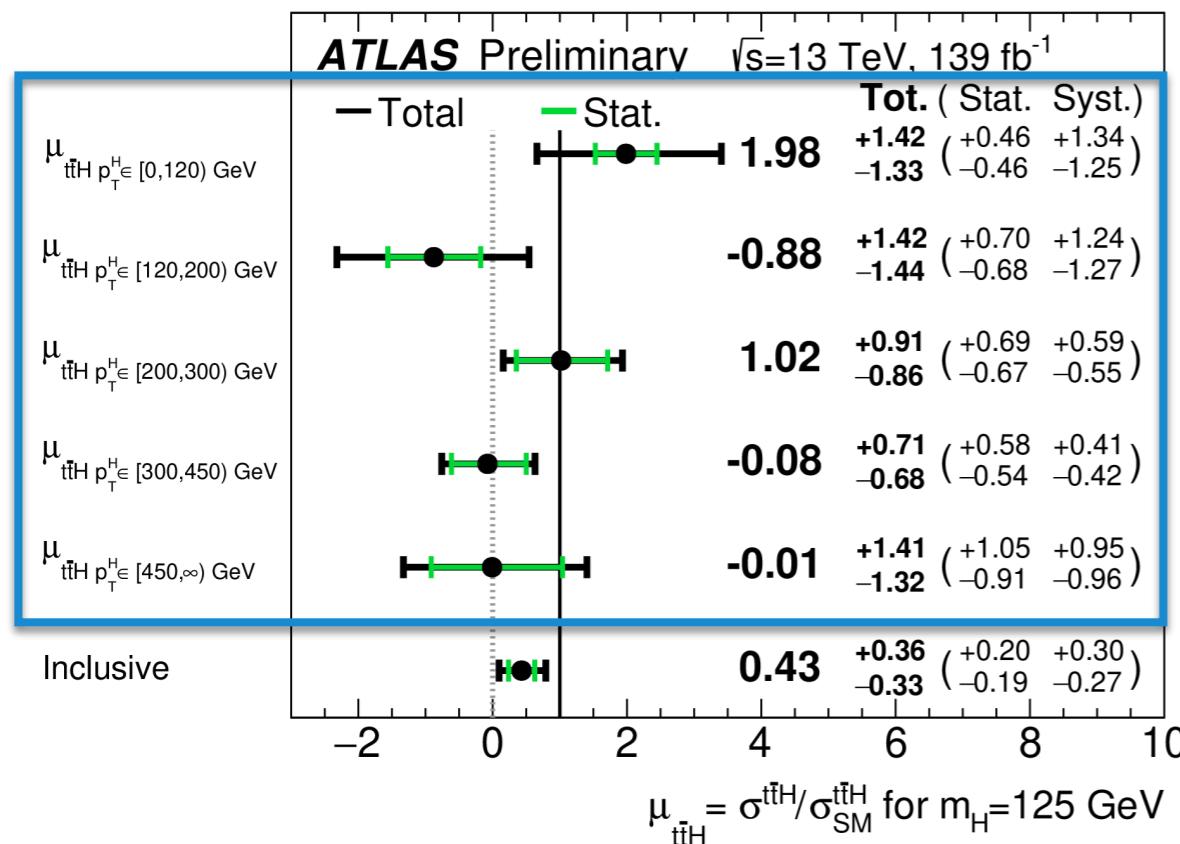
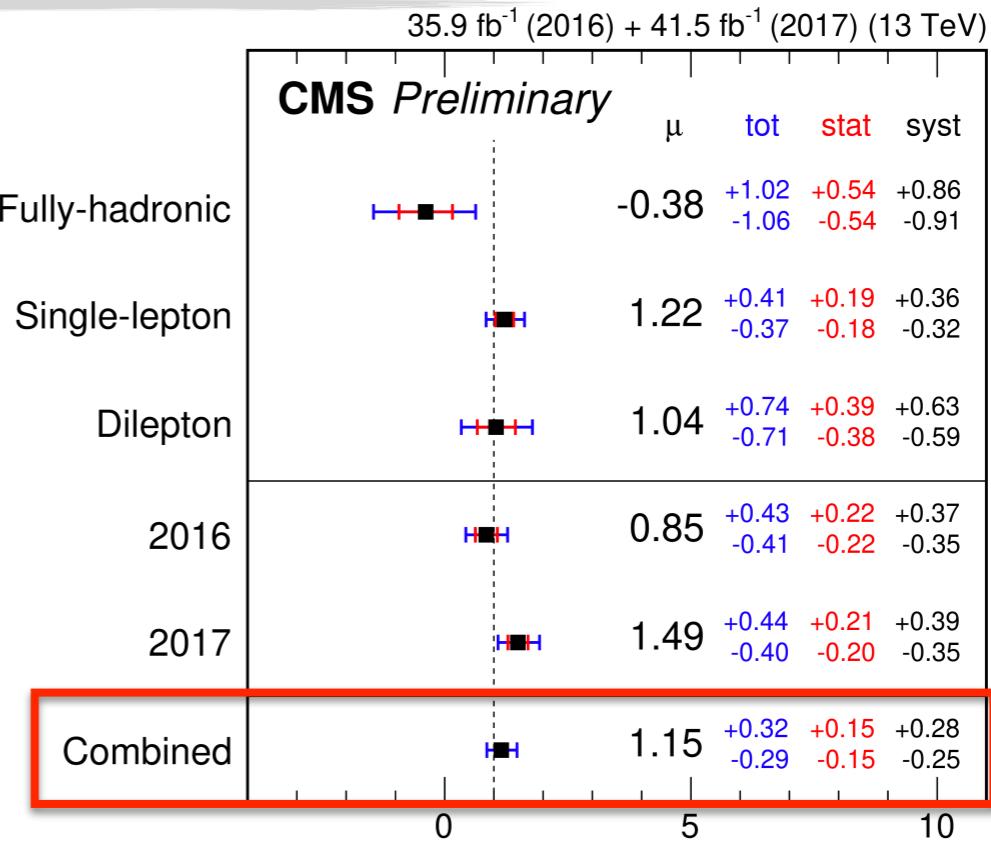
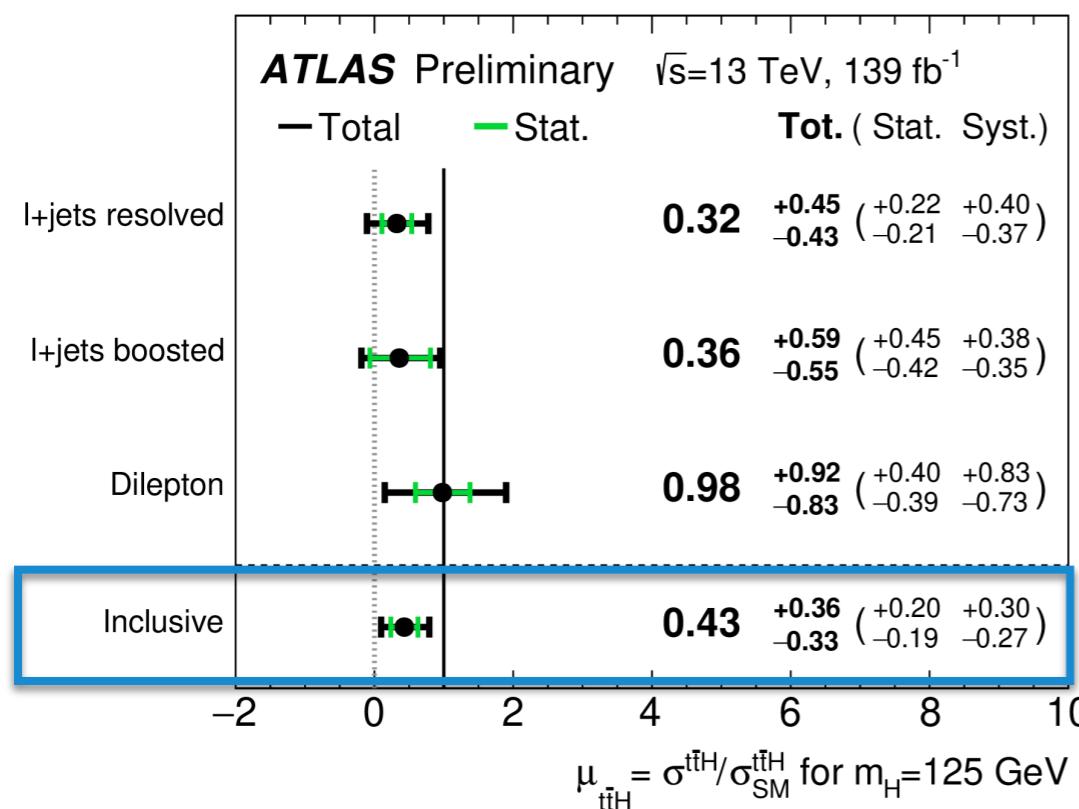
- Generator: Powheg+Pythia8 vs aMC@NLO+Pythia8 (5FS)
- Parton shower: Powheg+Pythia8 vs Powheg+Herwig7
- ISR (+scale), FSR, $t\bar{t}+1b$ vs $t\bar{t}+\geq 2b$ fraction uncertainties
- p_T^{bb} shape uncertainty (ad-hoc)**
- Free-floating** normalisation $t\bar{t}+\geq 1b$
- Nuisance parameter (100% prior) $t\bar{t}+\geq 1c$ normalisation



- Parton shower: ISR/FSR
- $t\bar{t}$ underlying event
- $t\bar{t}$ hdamp
- Scale variations
- Nuisance parameters** for normalisation of $t\bar{t}+bb$, $t\bar{t}+2b$, $t\bar{t}+b$, and $t\bar{t}+\geq 1c$ (50% prior) and **decorrelated** between years



$t\bar{t}H(b\bar{b})$: results



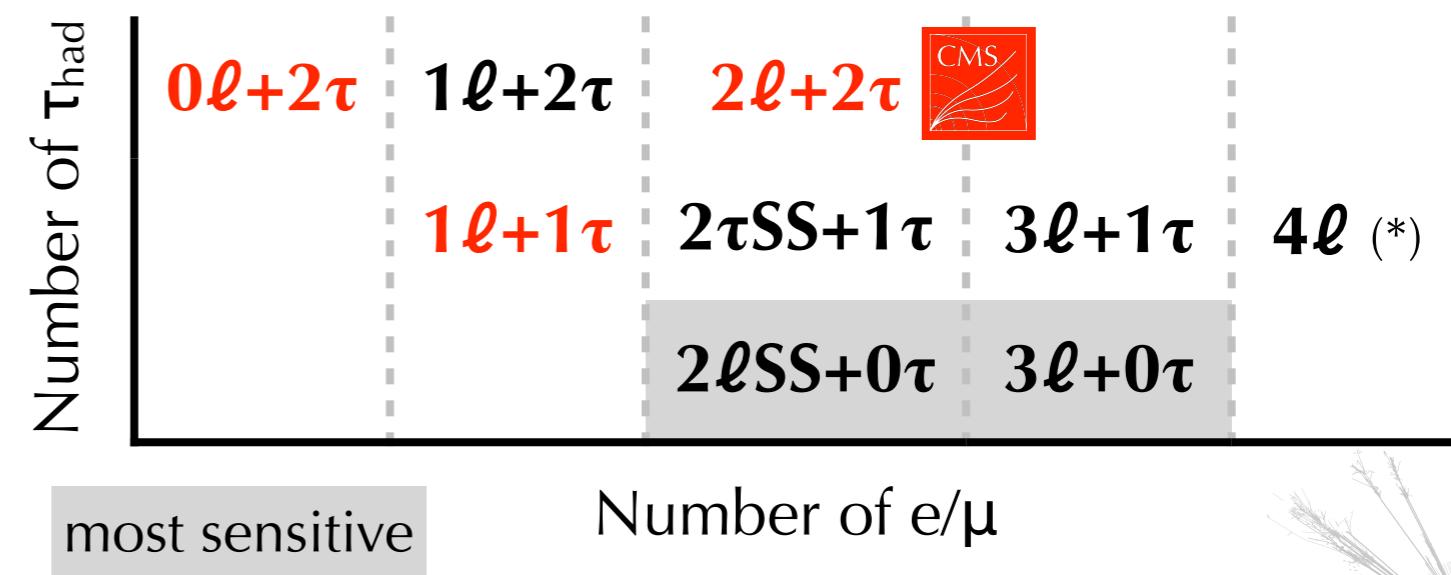
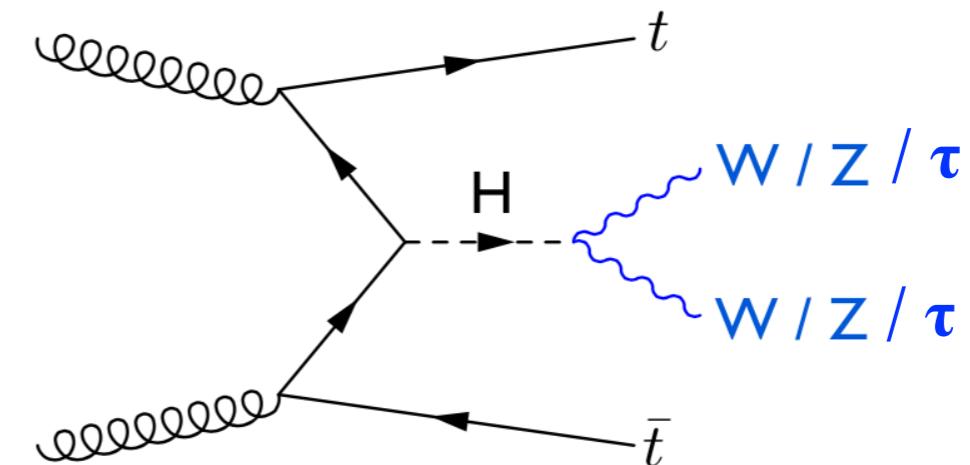
- $NF(t\bar{t}+\geq 1b) = 1.26 \pm 0.09$
- **Dominated by systematic** uncertainties
- Most relevant uncertainties related to $t\bar{t}+\geq 1b$ background modelling ($\Delta\mu/\mu = 60\%$ and 15%)
- Significance w.r.t background-only hypothesis: **$1.3 (3.0\sigma)$** and **$3.9\sigma (3.5\sigma)$** obs (exp)
 - **Evidence** for $t\bar{t}H$ in $H \rightarrow b\bar{b}$ channel
- **First $t\bar{t}H(bb)$ STXS measurement**
 - Complements $t\bar{t}H(\gamma\gamma)$ STXS measurements **at high p_T^H**

$t\bar{t}H$ (multi ℓ): analysis strategy

- **Target:** $t\bar{t}H$ with
 - $H \rightarrow WW/ZZ/\tau\tau \rightarrow \geq 1\ell$
 - $t\bar{t} \rightarrow (\ell + \text{jets}, \text{dilepton})$
- **High multiplicity** final state
- **Rare in SM:** same-sign $2\ell, 3\ell, 4\ell$
- Main reducible backgrounds are: non-prompt ℓ , charge misID electrons, and electrons from photon conversions
 - Specific **lepton BDT isolation** suppressing ℓ from semi-leptonic b-decays, **BDT to reject charge misID**, material and internal ($\gamma^* \rightarrow \ell^\pm \ell^\mp$) electron **conversion (CO)** candidates further suppressed with track invariant masses and conversion radius
- Main irreducible backgrounds are: $t\bar{t}Z, t\bar{t}W, VV$

- Several categorisation stages
- **#1 categorisation:** split in categories based on **number of e/ μ** and **number of τ**

→ “multilepton” final state

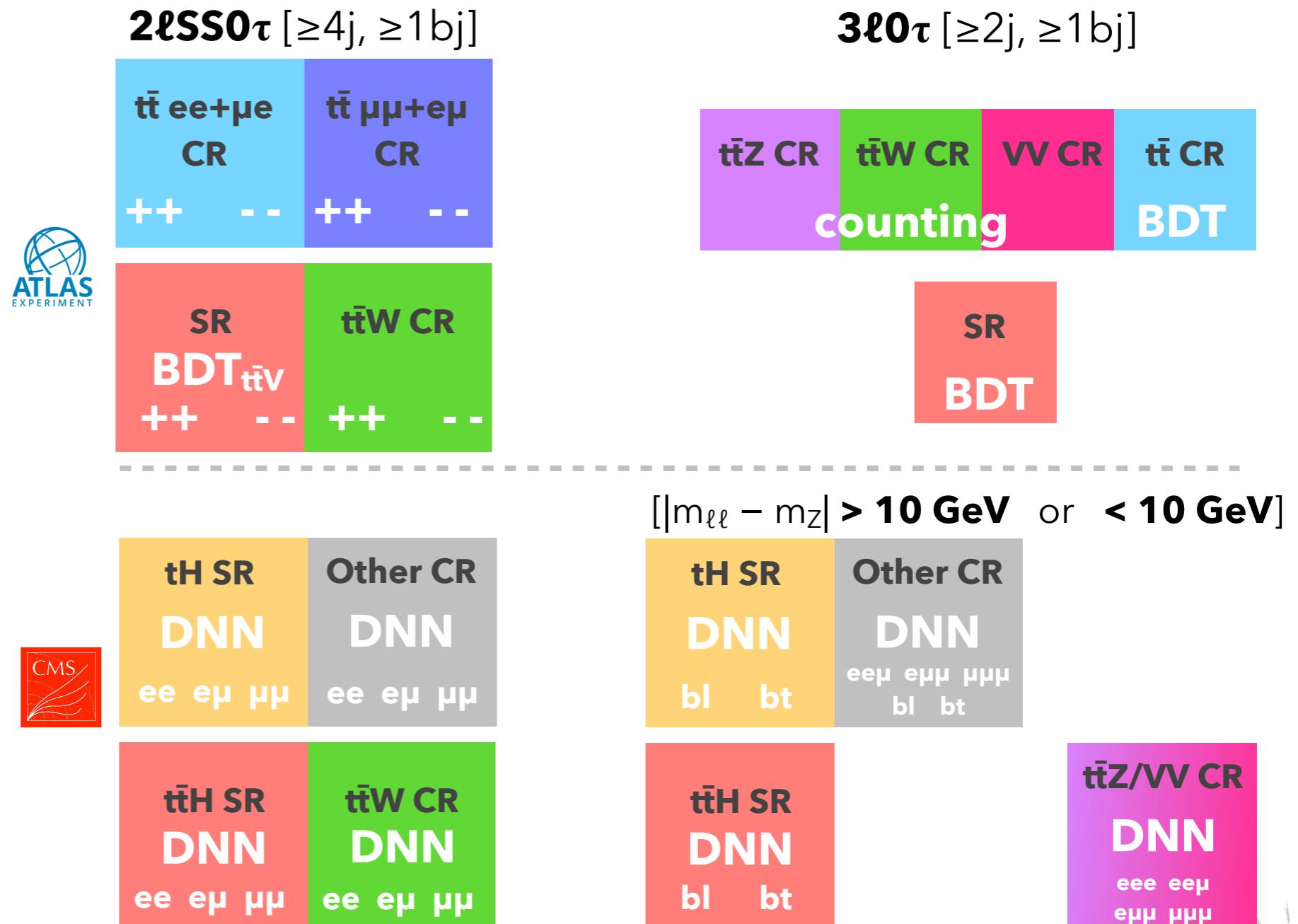


(*) $m(4\ell) \neq$ Higgs mass window

$t\bar{t}H$ (multi ℓ): categories

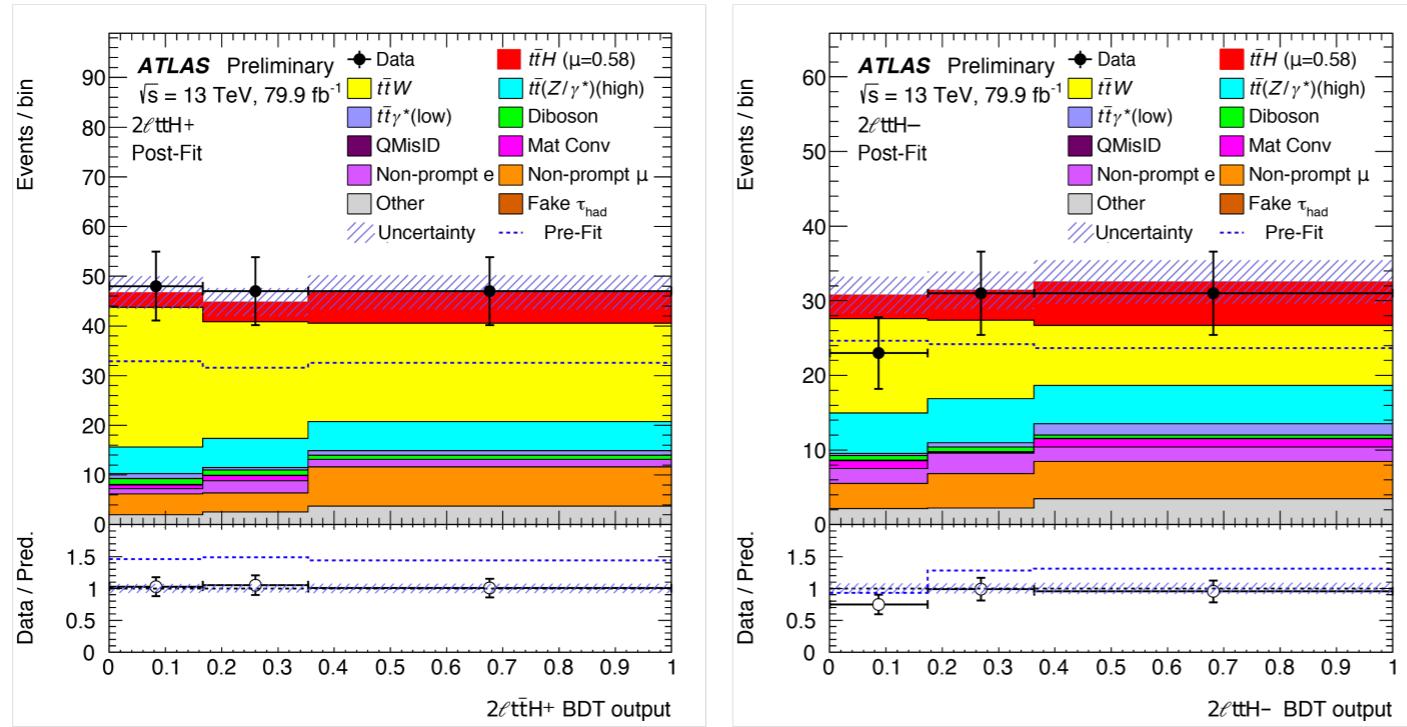
- #2 categorisation (“high NJets”):

- **2 ℓ SS0 τ** : a combination of 2 **BDTs** (vs. $t\bar{t}V$, vs. fakes/ $t\bar{t}$) in a **2D space**, or
- **3 ℓ 0 τ** : a **multi-dimensional BDT** (vs. $t\bar{t}W$, vs. fakes/ $t\bar{t}$, vs. $t\bar{t}Z$, vs. VV)
- **2 ℓ SS0 τ , 3 ℓ 0 τ and 2 ℓ SS1 τ : DNN** (vs tH vs other backgrounds); **BDT** in the other channels

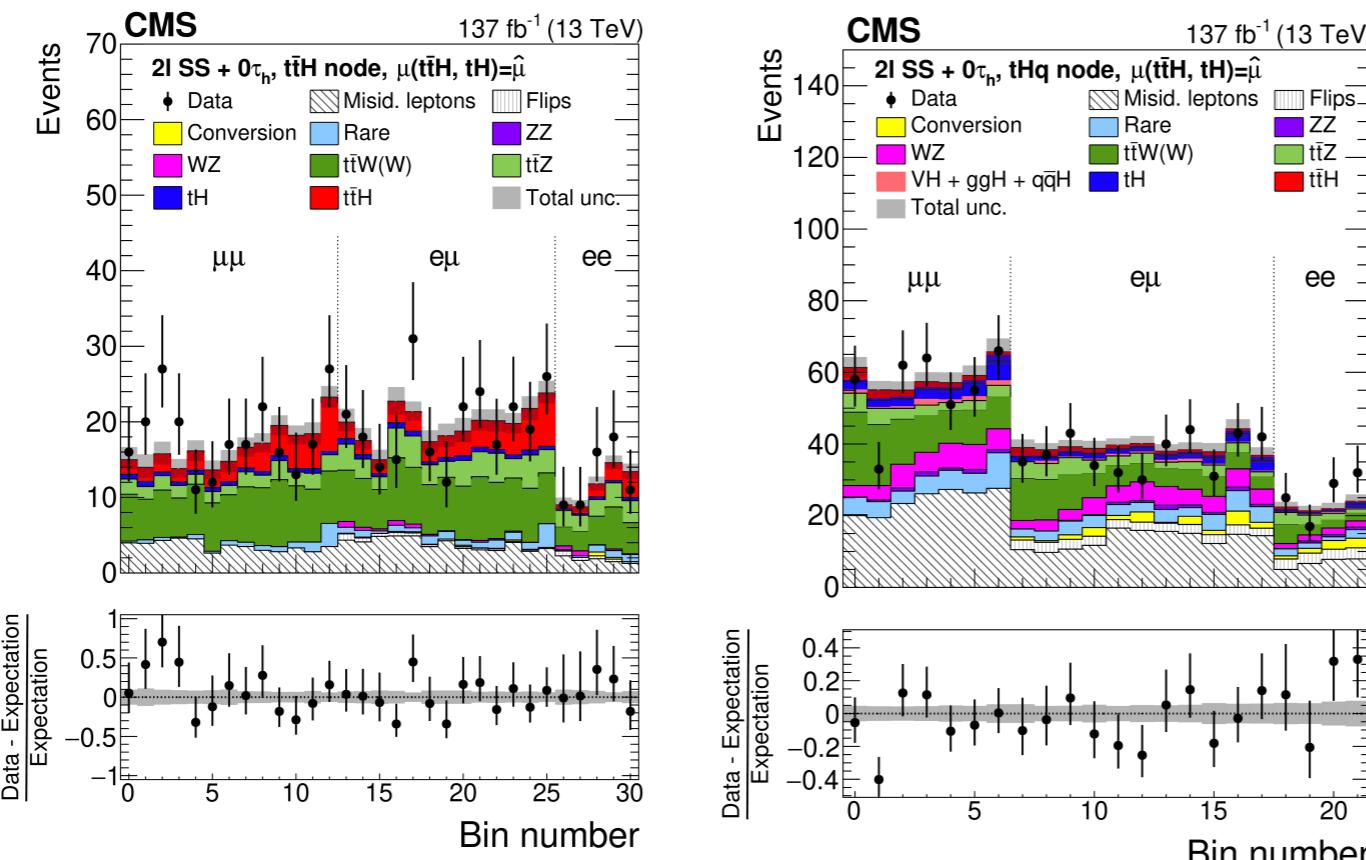
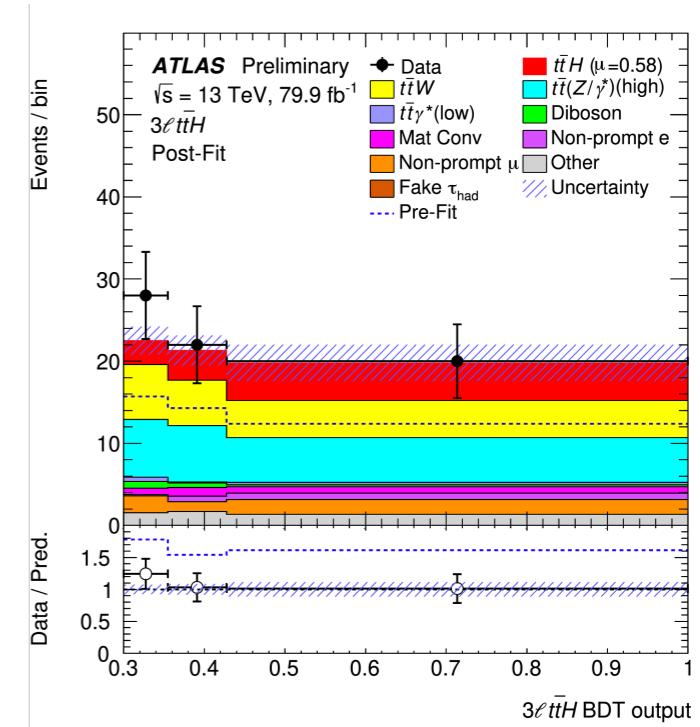


$t\bar{t}H$ (multi ℓ): signal regions

2 ℓ SS0 τ [$\geq 4j$, $\geq 1bj$] SRs

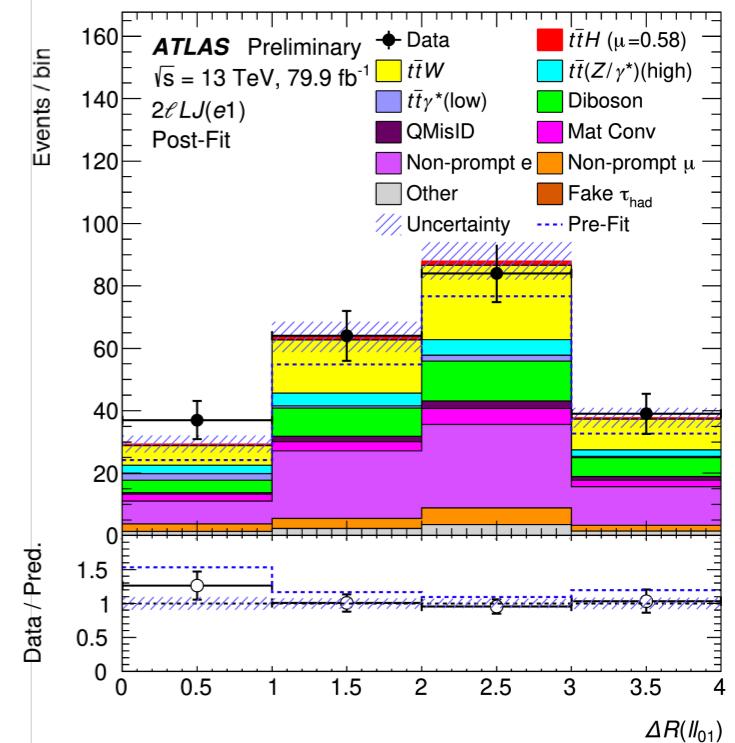
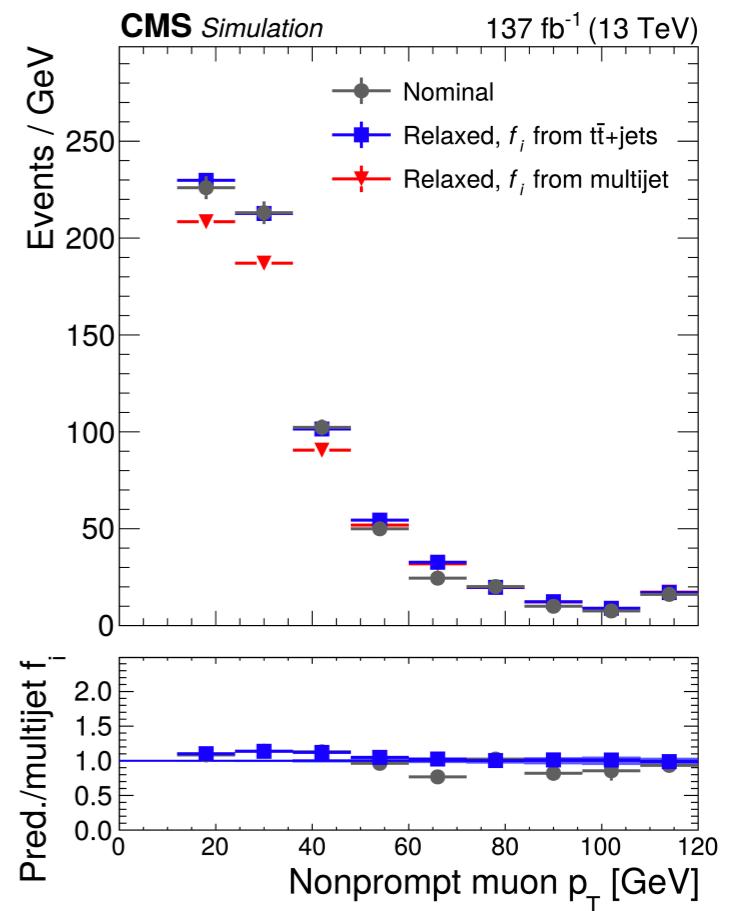
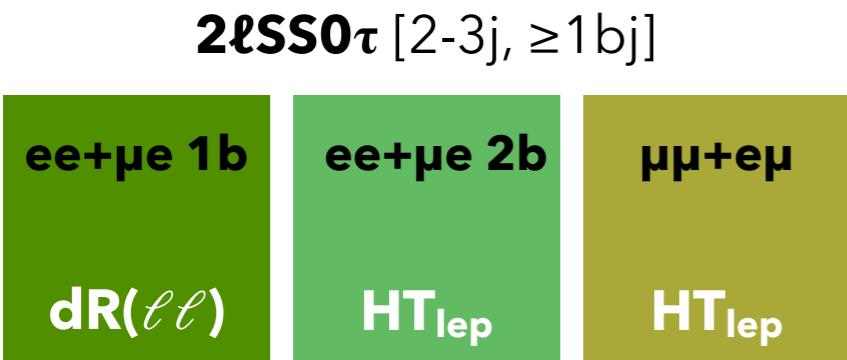


3 ℓ 0 τ [$\geq 2j$, $\geq 1bj$] SR



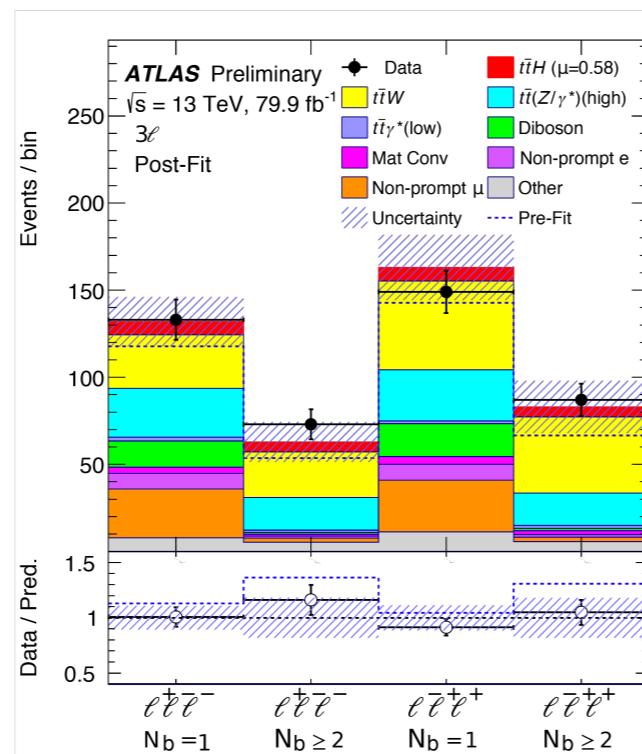
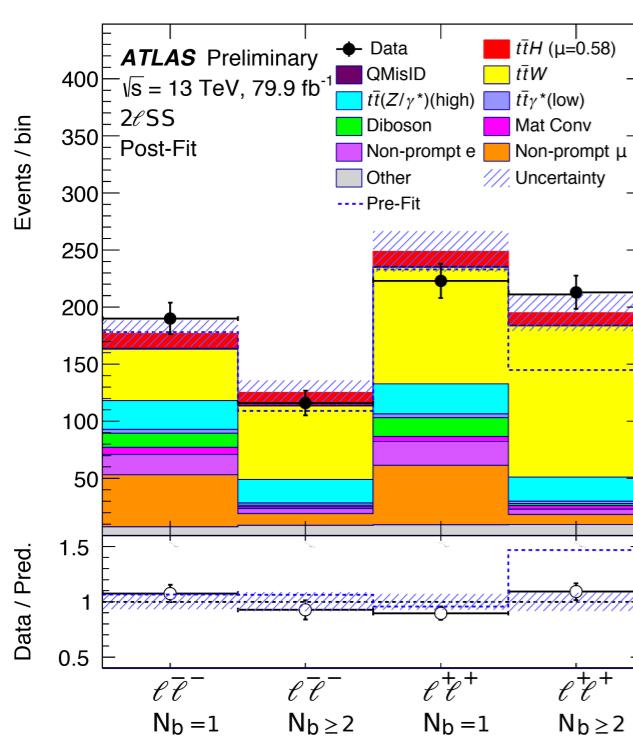
$t\bar{t}H$ (multi ℓ): fakes (and more) estimate

- Fakes estimated from data in a QCD CR with relaxed object ID
- #3 categorisation: add CR categories to the fit model ("low NJets" and conversion CRs)
 - $2\ell SS0\tau/3\ell 0\tau$: ≥ 1 electron passing **material / internal conversion** selection
 - $2\ell SS0\tau$: **2-3 jets**, enriched in **non-prompt leptons** and **$t\bar{t}W$**
- Normalisation of **non-prompt leptons** (electrons and muons), electrons from **material CO**, electron from **internal CO** [low mass], **$t\bar{t}W$** (decorrelated between $2\ell SS0\tau$ low NJets, $2\ell SS0\tau$ high NJets, and $3\ell 0\tau$), and **$t\bar{t}Z$** are measured simultaneously in the fit to data
 - Shapes from MC simulation, extensive set of systematic uncertainties included



$t\bar{t}H$ (multi ℓ): systematics

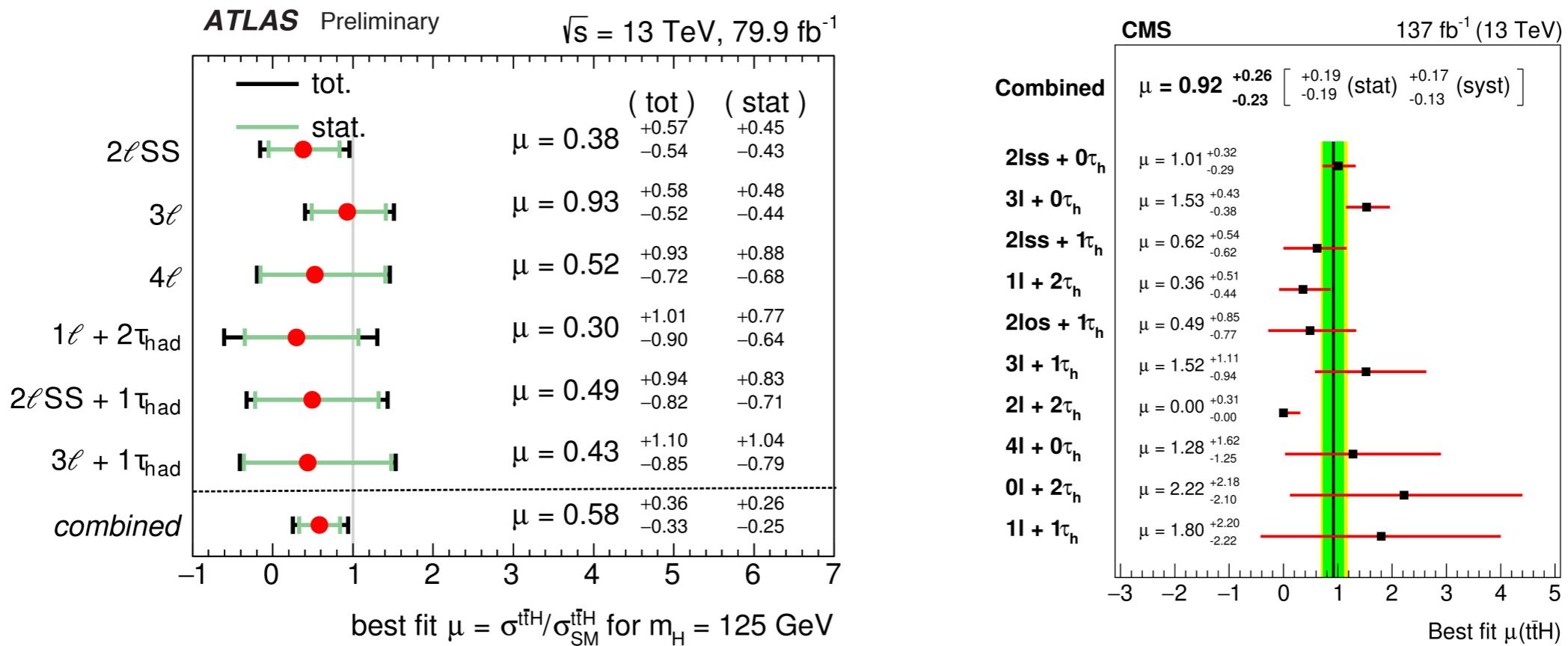
Uncertainty source	$\Delta\hat{\mu}$	
Jet energy scale and resolution	+0.13	-0.13
$t\bar{t}(Z/\gamma^*)$ (high mass) modelling	+0.09	-0.09
$t\bar{t}W$ modelling (radiation, generator, PDF)	+0.08	-0.08
Fake τ_{had} background estimate	+0.07	-0.07
$t\bar{t}W$ modelling (extrapolation)	+0.05	-0.05
$t\bar{t}H$ cross section	+0.05	-0.05
Simulation sample size	+0.05	-0.05
$t\bar{t}H$ modelling	+0.04	-0.04
Other background modelling	+0.04	-0.04
Jet flavour tagging and τ_{had} identification	+0.04	-0.04
Other experimental uncertainties	+0.03	-0.03
Luminosity	+0.03	-0.03
Diboson modelling	+0.01	-0.01
$t\bar{t}\gamma^*$ (low mass) modelling	+0.01	-0.01
Charge misassignment	+0.01	-0.01
Template fit (non-prompt leptons)	+0.01	-0.01
Total systematic uncertainty	+0.25	-0.22
Intrinsic statistical uncertainty	+0.23	-0.22
$t\bar{t}W$ normalisation factors	+0.10	-0.10
Non-prompt leptons normalisation factors (HF, material conversions)	+0.05	-0.05
Total statistical uncertainty	+0.26	-0.25
Total uncertainty	+0.36	-0.33



Source	$\Delta\mu_{t\bar{t}H}/\mu_{t\bar{t}H} [\%]$	$\Delta\mu_{t\bar{t}H}/\mu_{t\bar{t}H} [\%]$
Trigger efficiency	2.3	8.1
e, μ reconstruction and identification efficiency	2.9	7.1
τ_h identification efficiency	4.6	9.1
b tagging efficiency and mistag rate	3.6	13.6
Misidentified leptons and flips	6.0	36.8
Jet energy scale and resolution	3.4	8.3
MC sample and sideband statistical uncertainty	7.1	27.2
Theory-related sources	4.6	18.2
Normalization of MC-estimated processes	13.3	12.3
Integrated luminosity	2.2	4.6
Statistical uncertainty	20.9	48.0

- Largest **systematic uncertainties** come from $t\bar{t}W$ and $t\bar{t}\ell\ell$ modelling
 - Additional uncertainties to cover data/MC disagreements as a function of NBjets and Lepton charge for $t\bar{t}W$
- Fakes impact is reducing its size with more statistics!
- Non-prompt leptons + QMisID uncertainties large impact on $t\bar{t}H$

$t\bar{t}H$ (multi ℓ): fit results



- Combined μ_{ttH} measured with **2015, 2016, 2017 and 2018** dataset:

	Main result	ATLAS EXPERIMENT	Alternative fit	CMS
μ_{ttH}	0.58 ± 0.36		0.70 ± 0.36	0.92 ± 0.26
$\text{NF}(\bar{t}\bar{W})$ (to compare with CMS take $\sim 1.1 \times \text{ATLAS}$)	$1.56^{+0.30}_{-0.28}$ (2ℓ LNJ)		$1.39^{+0.17}_{-0.16}$	1.43 ± 0.21
	$1.26^{+0.19}_{-0.18}$ (2ℓ HNJ)		[SM ref: 727 fb]	[SM ref: 650 fb]
	$1.68^{+0.30}_{-0.28}$ (3ℓ)			
$\text{NF}(\bar{t}\bar{Z})$				1.03 ± 0.14

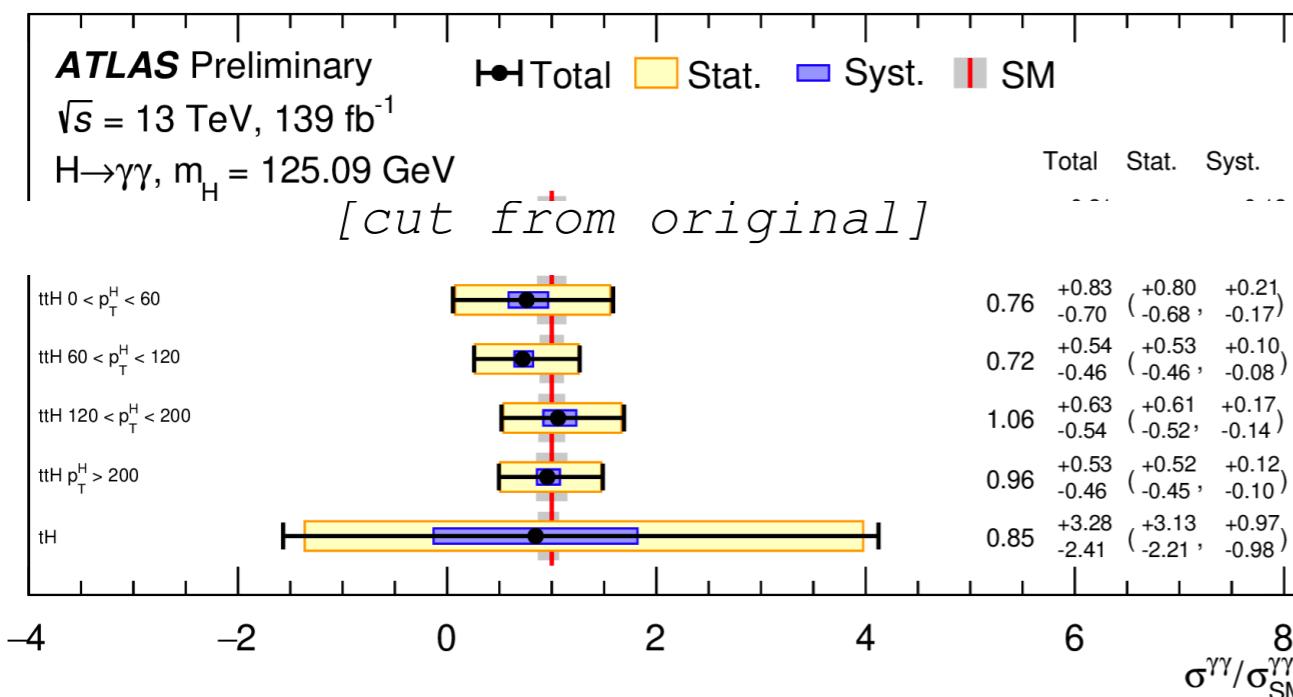
Significance with respect to background-only hypothesis = **1.8 (3.1 σ)** and **4.7 σ (5.2 σ)** obs (exp)

Compatibility between main and alternative fit = 0.59 σ

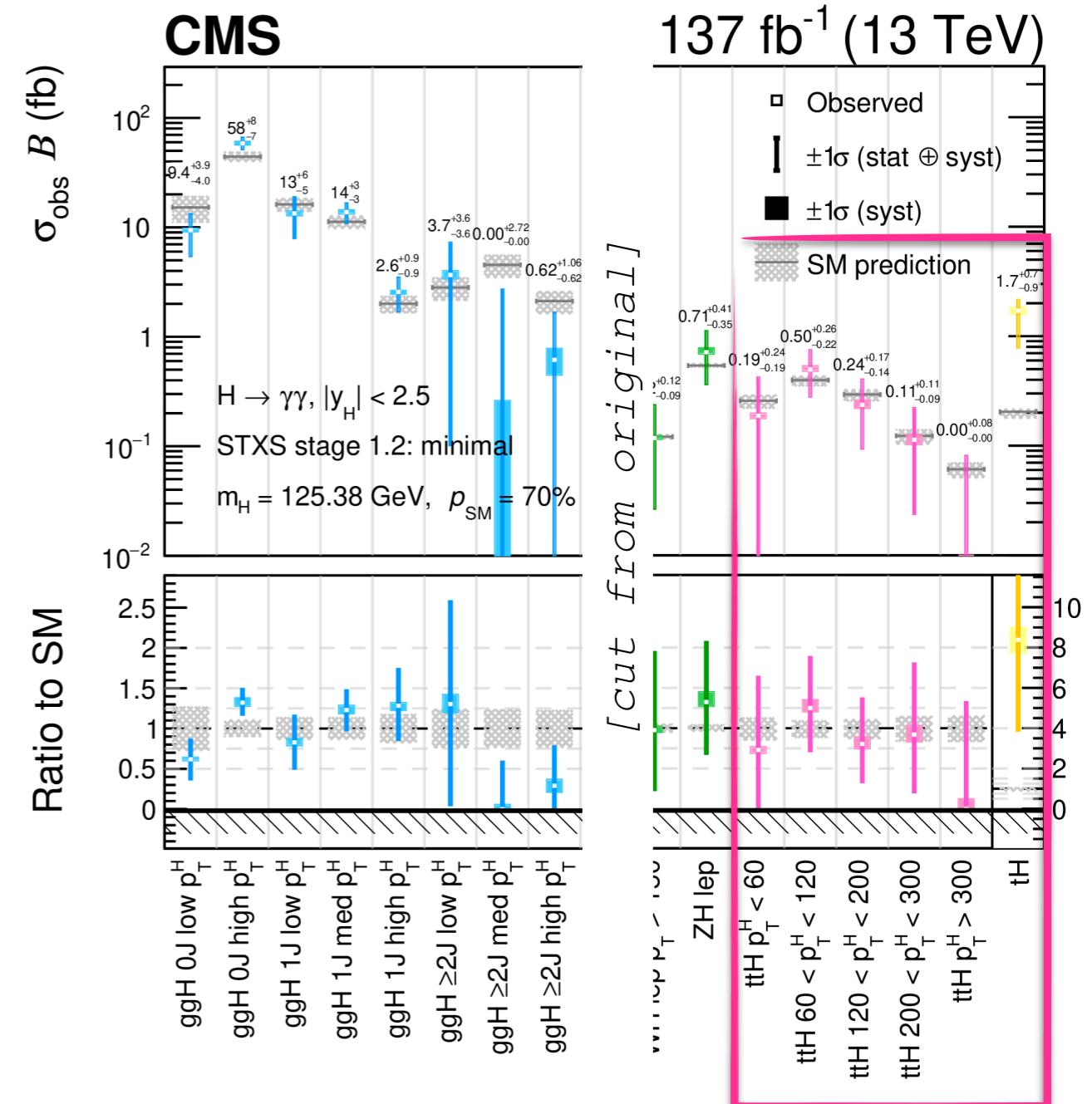
$\bar{t}\bar{W}$ measured consistently higher than SM in both experiments!

$t\bar{t}H(H \rightarrow \gamma\gamma)$: STXS

- First channel to perform $t\bar{t}H$ measurement differentially
- Leptonic ($t\bar{t}H$ & tH) and hadronic channels ($t\bar{t}H$ & tH)
- Mixture of **multiclass BDT** (STXS signal vs other signals) and **binary BDTs** (STXS signal vs background)
- Mixture of **Top DNN** ($t\bar{t}H$ vs tH) and **BDT** (STXS signal vs non-Higgs SM background), and final classification based on **reco $p_T(\gamma\gamma)$**

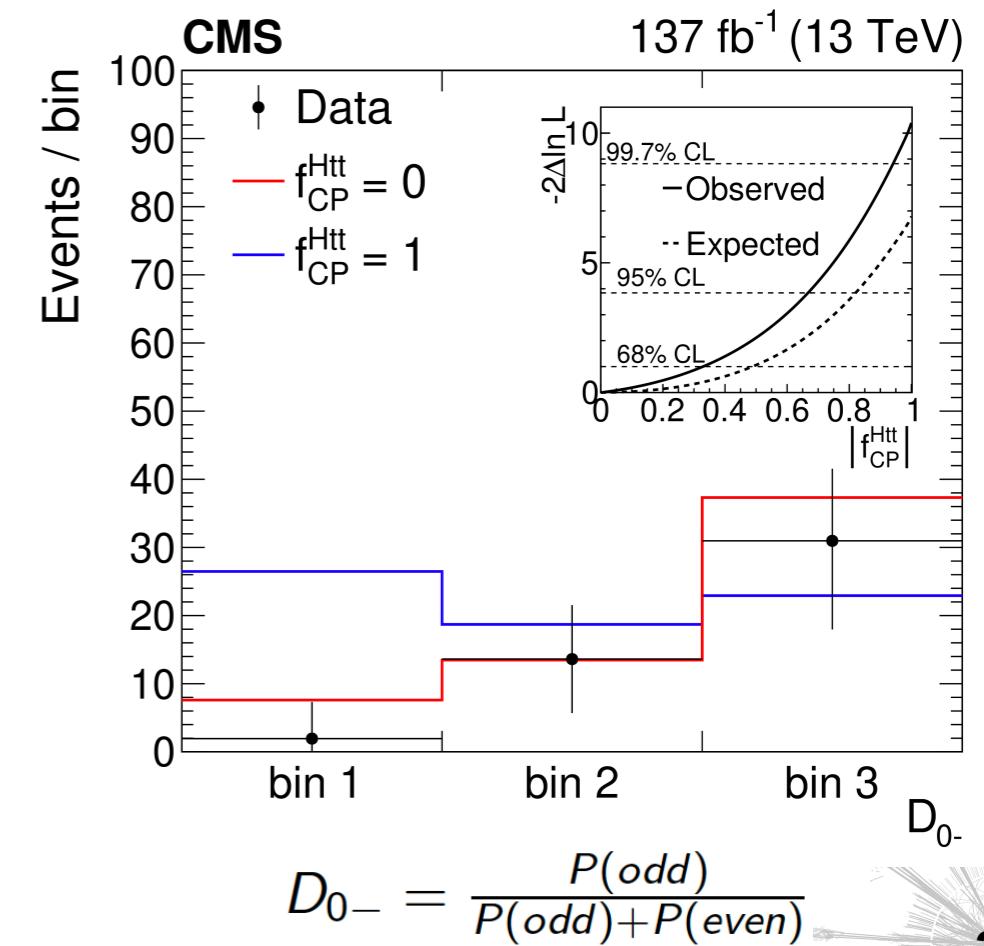
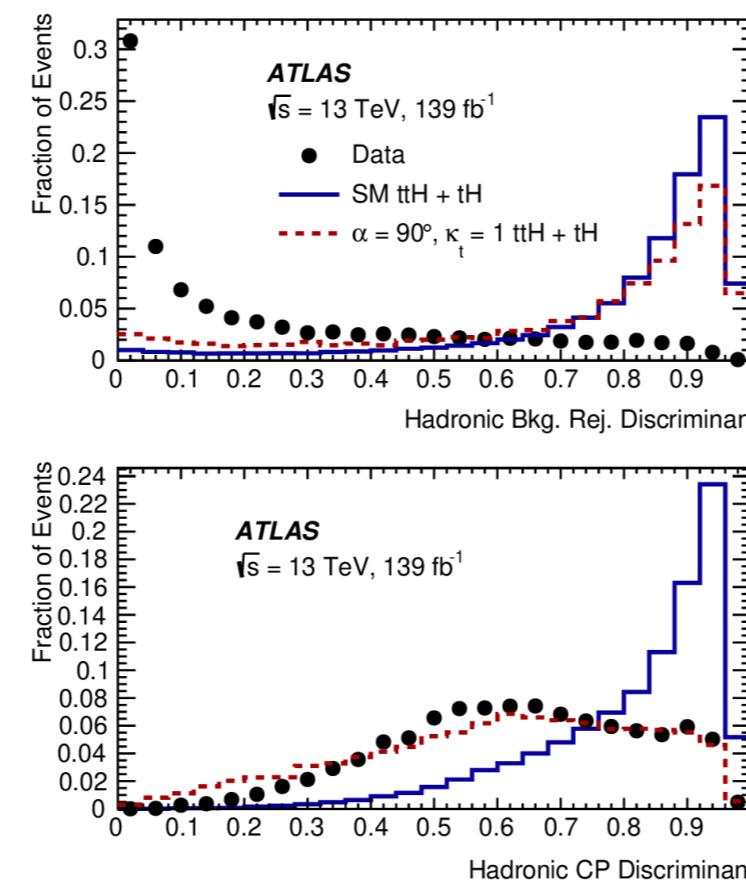
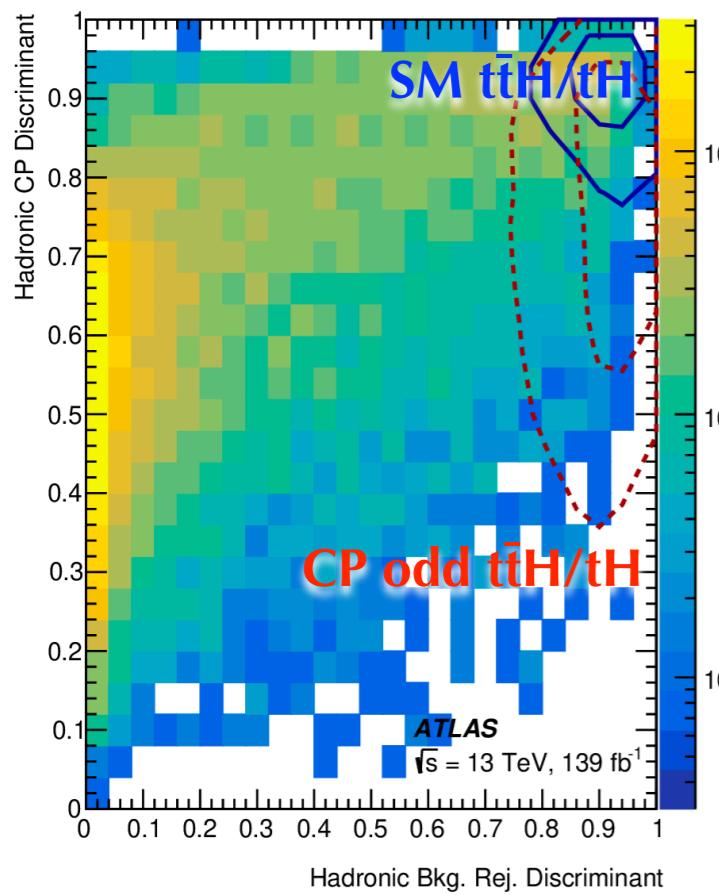


- Dominated by stat uncertainty but overall compatible with SM predictions



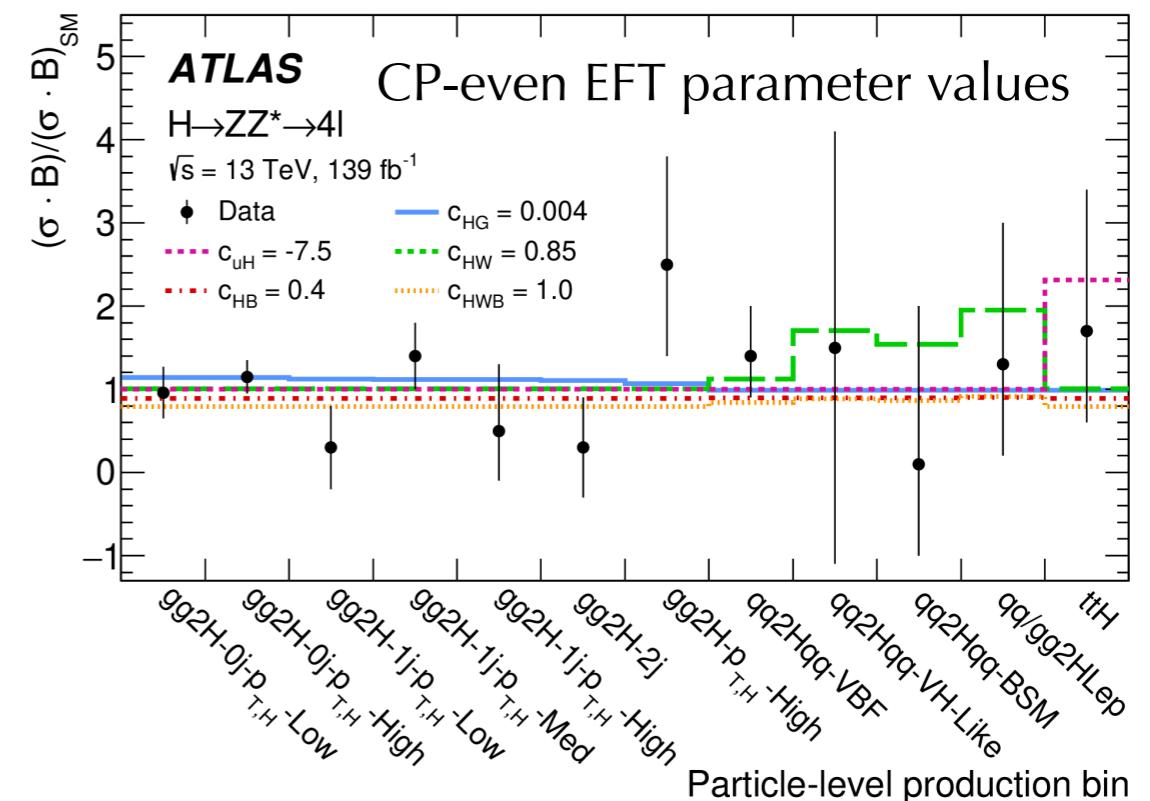
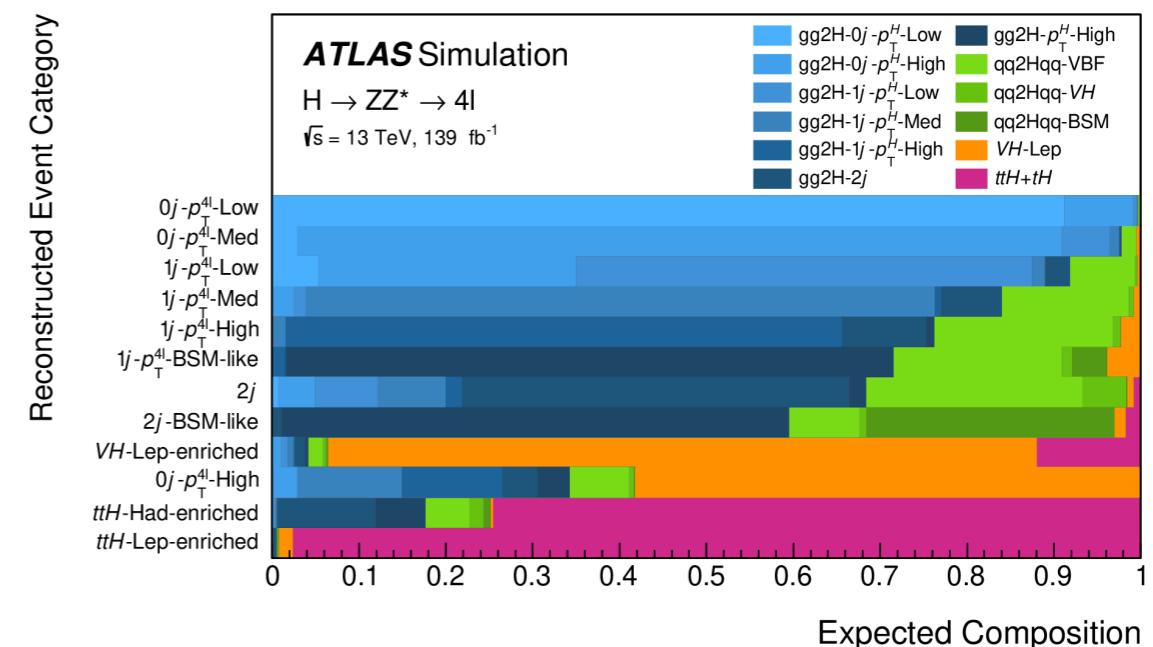
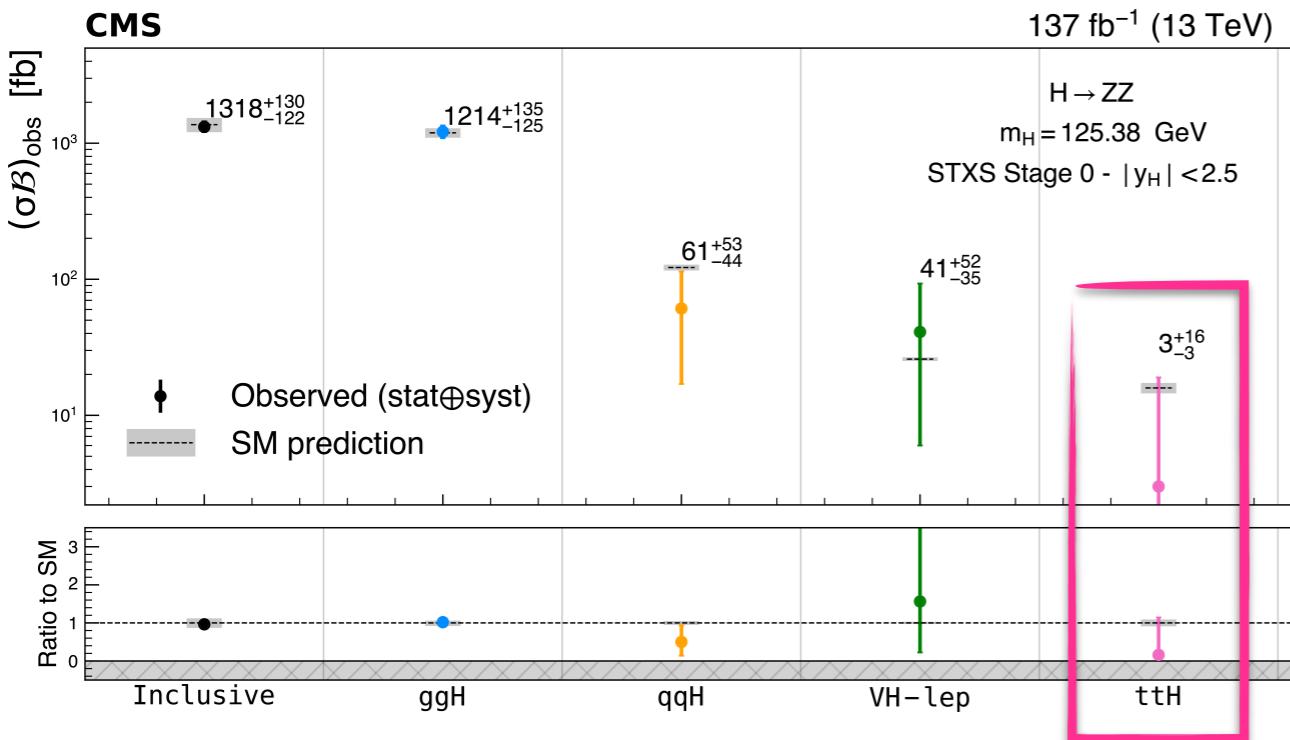
$t\bar{t}H(H \rightarrow \gamma\gamma)$: CP analysis

- 2D partitioning /categorisation using BDT-bkg and BDT-CP (D_{0-})
 - 20 (12had + 8lep) vs 12 (6had + 6lep) categories
- Constrains: observed (expected under CP-even hypothesis)
 - $|\alpha^{CP}| < 43^\circ (63^\circ)$ @ 95 CL; $\alpha=90^\circ$ excluded at 3.9σ
 - $|f_{CP}| < 0.67 \Rightarrow |\alpha^{CP}| < 55^\circ (66^\circ)$ @ 95 CL; $\alpha=90^\circ$ excluded at 3.2σ



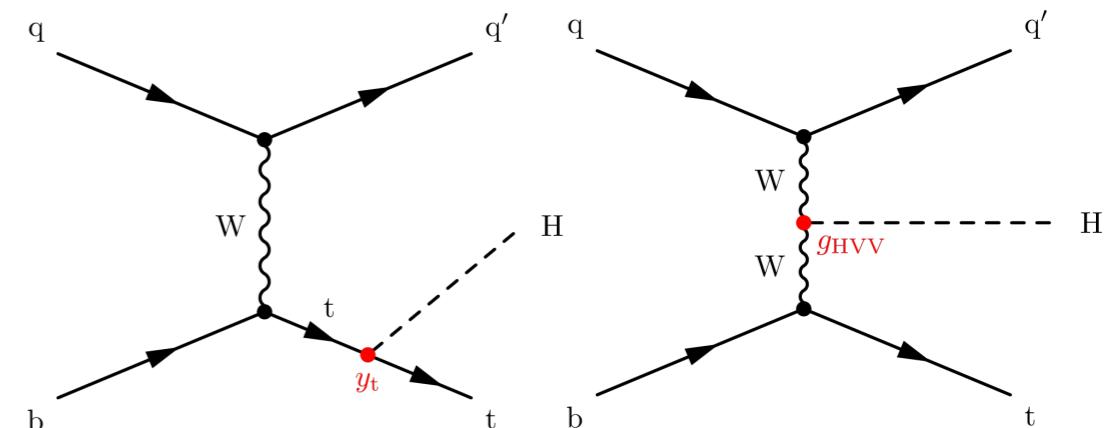
$t\bar{t}H(H \rightarrow ZZ \rightarrow 4\ell)$ resonant

- Higgs boson candidates: $115 < m(4\ell) < 130$ GeV
- Both analyses use NN-based categorisation either to define the categories or as observable to fit
- $\mu_{t\bar{t}H} = 1.7^{+1.7}_{-1.2}$ (stat) ± 0.2 (exp) ± 0.2 (th) and
 $\mu_{t\bar{t}H} = 0.17^{+0.88}_{-0.17}$ (stat) $+0.42$ -0.00 (syst)
- Also computed the Stage 0/1.1/1.2(merged) STXS cross-sections (1 bin for $t\bar{t}H$)
 - Largely **statistically** limited
- Additionally, performed SMEFT fit



tH state of the art

- Central top and Higgs, back-to-back
- **Destructive interference** in SM (top Yukawa coupling competing against g_{HWV})
- Very challenging due to low SM cross section and larger background than $t\bar{t}H$

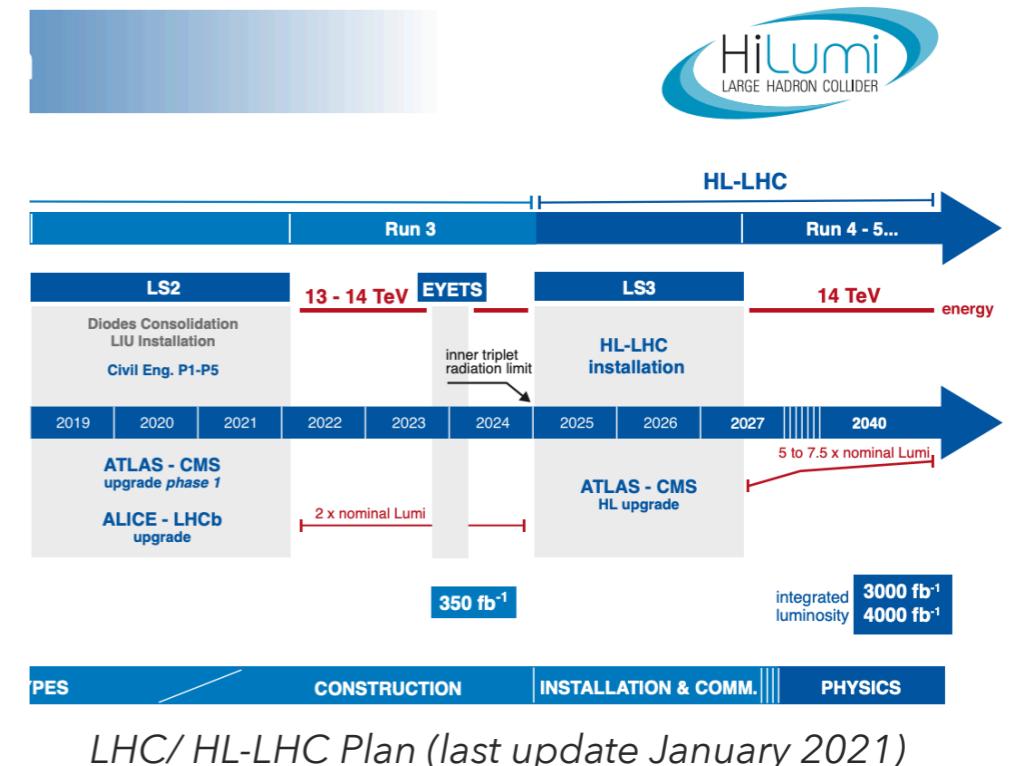


2015-2016 [$\sim 36 \text{ fb}^{-1}$]		2015-2018 [$\sim 140 \text{ fb}^{-1}$]	
tH multilepton ($H \rightarrow WW/\tau\tau/ZZ$)	ongoing	arXiv:2011.03652 $\mu_{tH} = 5.7 \pm 2.7 \text{ (stat)} \pm 3.0 \text{ (syst)}$	
tH(bb)	ongoing		(see below)
tH(γγ)	ATLAS-CONF-2020-026 $\mu_{tH} < 8 \times \text{SM} @ 95\% \text{ CL}$	arXiv:2103.06956 $\mu_{tH} < 14 \times \text{SM} @ 95\% \text{ CL}$	
Combination	ongoing	PRD 99 (2019) 092005 Expected and observed 95% CL upper limits on the tH XS x BR	$\begin{array}{lccccc} \hline \text{Scenario} & \text{Channel} & \text{Observed} & \text{Expected} \\ \kappa_t = -1 & b\bar{b} & 4.98 \text{ pb} & 2.52^{+1.29}_{-0.81} \text{ pb} \\ & \gamma\gamma & 0.84 \text{ pb} & 0.88^{+0.46}_{-0.28} \text{ pb} \\ & \mu^\pm\mu^\pm + e^\pm\mu^\pm + \ell\ell\ell & 0.85 \text{ pb} & 0.77^{+0.36}_{-0.24} \text{ pb} \\ & \text{Combined} & 0.74 \text{ pb} & 0.53^{+0.24}_{-0.16} \text{ pb} \\ \kappa_t = 1 & b\bar{b} & 6.88 \text{ pb} & 3.19^{+1.64}_{-1.02} \text{ pb} \\ (\text{SM-like}) & \gamma\gamma & 3.68 \text{ pb} & 2.03^{+1.05}_{-0.67} \text{ pb} \\ & \mu^\pm\mu^\pm + e^\pm\mu^\pm + \ell\ell\ell & 1.36 \text{ pb} & 1.18^{+0.53}_{-0.35} \text{ pb} \\ & \text{Combined} & 1.94 \text{ pb} & 0.92^{+0.40}_{-0.27} \text{ pb} \end{array}$ <p style="text-align: right;">SM $tH(XS \times BR) = 0.077 \text{ pb}$</p>

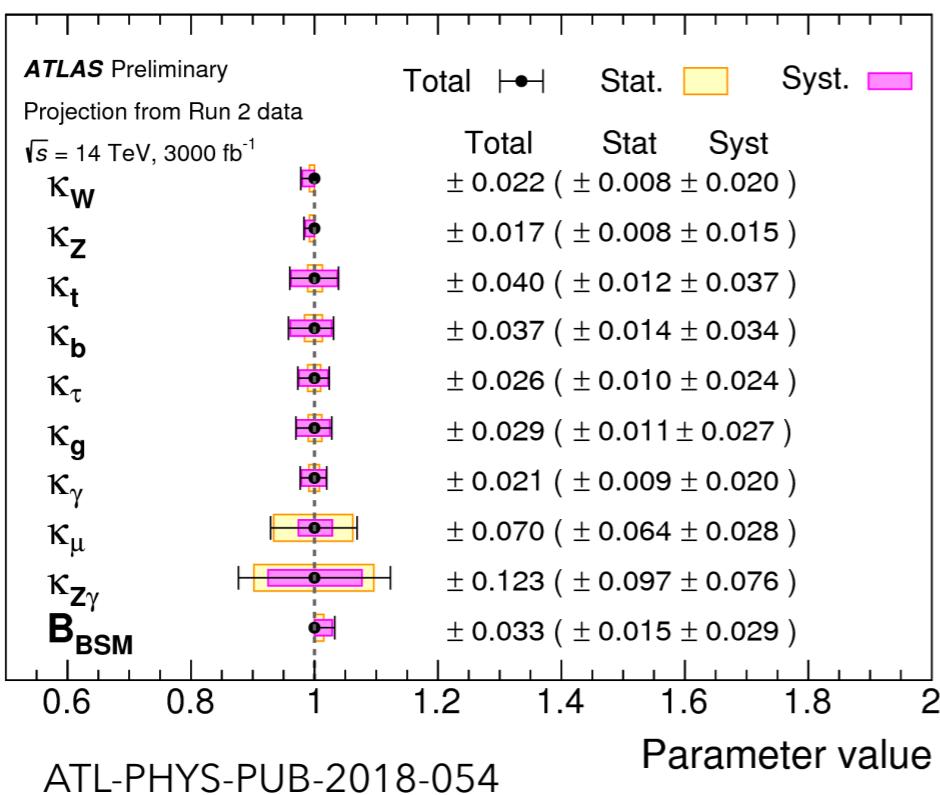
The Future

- At the LHC:

- Analyse full Run-2 dataset!
- Preparing for Run 3: 13 \rightarrow 14 TeV (?), double luminosity
- HL-LHC: 10x more luminosity, explore less accessible processes such as di-Higgs (self-coupling of Higgs boson)



LHC/ HL-LHC Plan (last update January 2021)

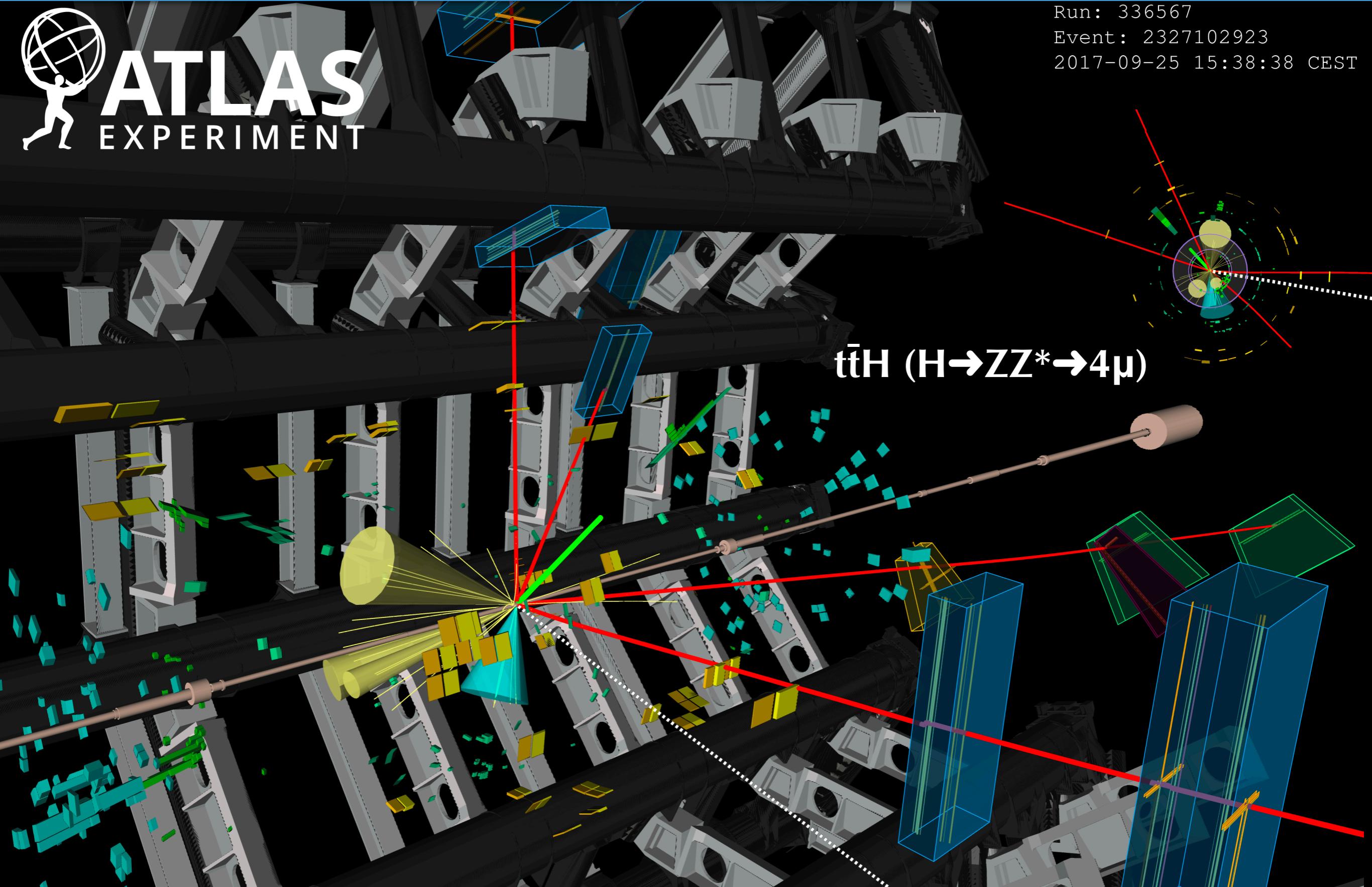


- Expect to measure the top Yukawa coupling (modifier) κ_t at **4% level** at the end of HL-LHC
 - **Systematics-limited!**

Stay tuned for upcoming results!

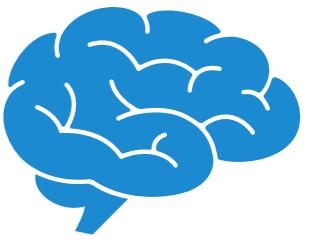


Run: 336567
Event: 2327102923
2017-09-25 15:38:38 CEST

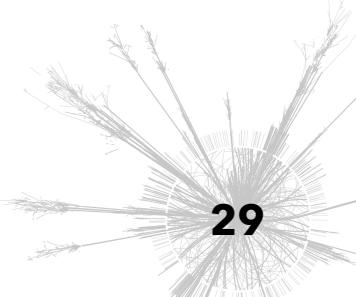
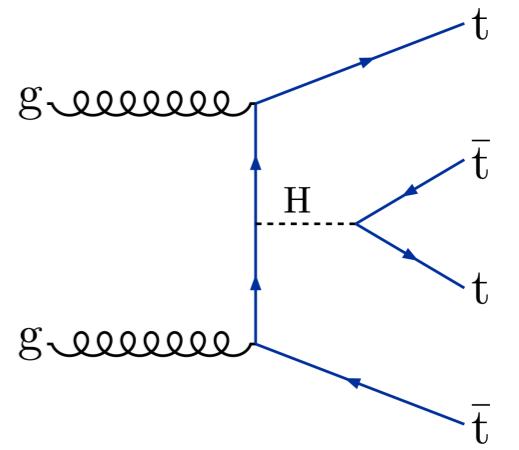
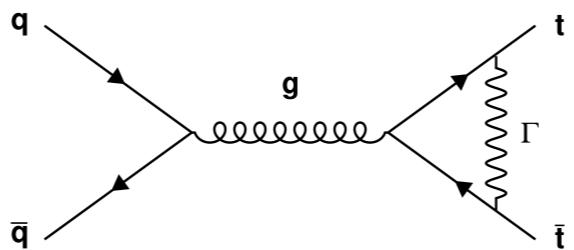


Thanks for your attention!

Round table: brainstorming



- Improving $t\bar{t}bb$ background modelling
 - Joint effort of ATLAS - CMS - theory [\[Twiki\]](#)
 - Replacing 2-point-systematics?
 - Learn from SM measurement [\[CMS: \$t\bar{t}c\bar{c}\$ measurement\]](#)
 - Make $t\bar{t}H$ analyses more robust against $t\bar{t}bb$?
- Improving $t\bar{t}W$ measurement at high jet multiplicity
 - EFT measurements of $t\bar{t}+X$ in multilepton final states [\[CMS\]](#)
- Future of STXS $t\bar{t}H$ measurement
 - Combinations: intra- and inter-collaborations
- Other ways of measuring the top Yukawa coupling
 - 4 tops: no assumptions on total Higgs width [\[ATLAS multi \$\ell\$, ATLAS 1L/2L+combo, CMS\]](#)
 - $t\bar{t}$ cross section [\[CMS\]](#)

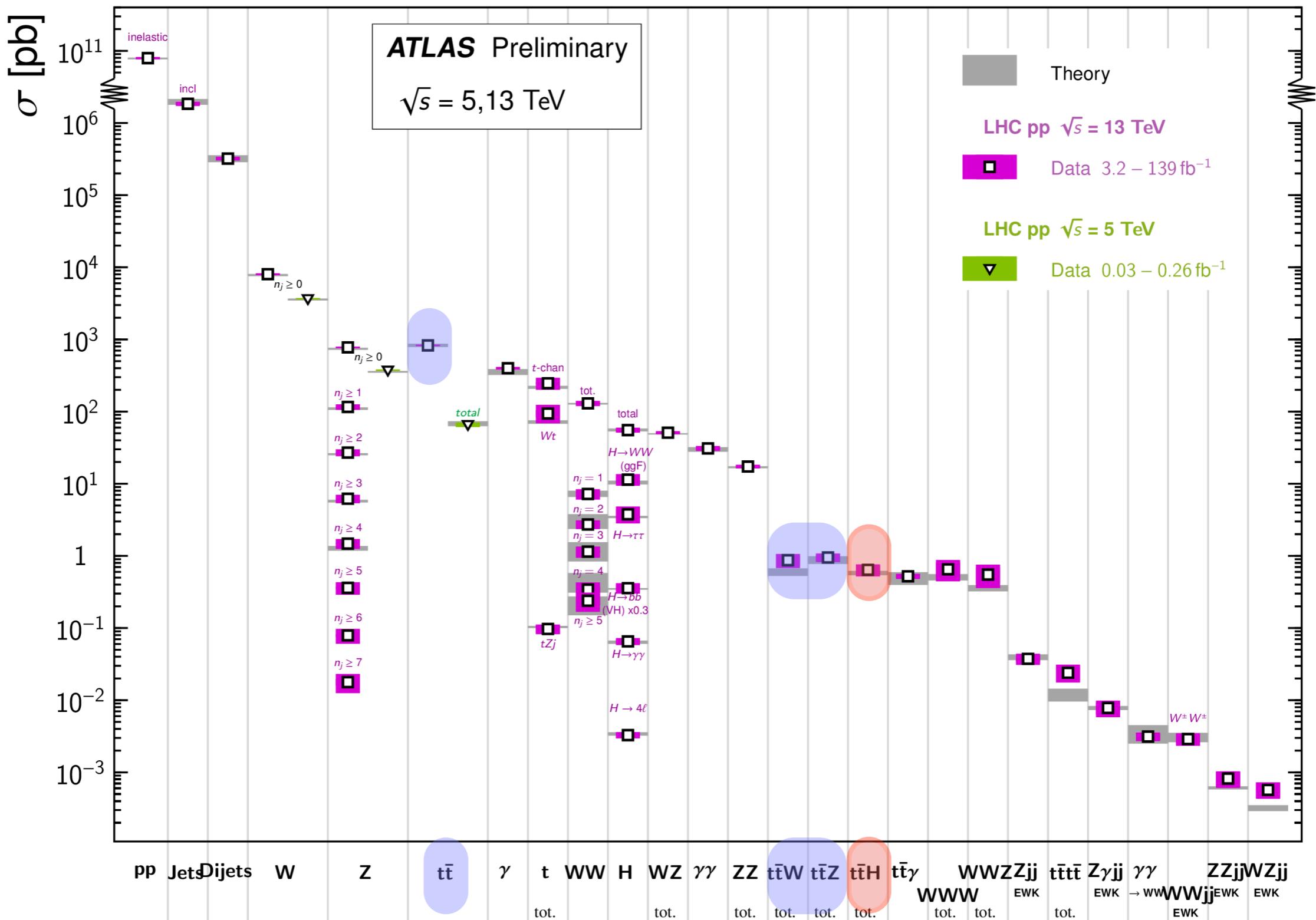


Back-up slides

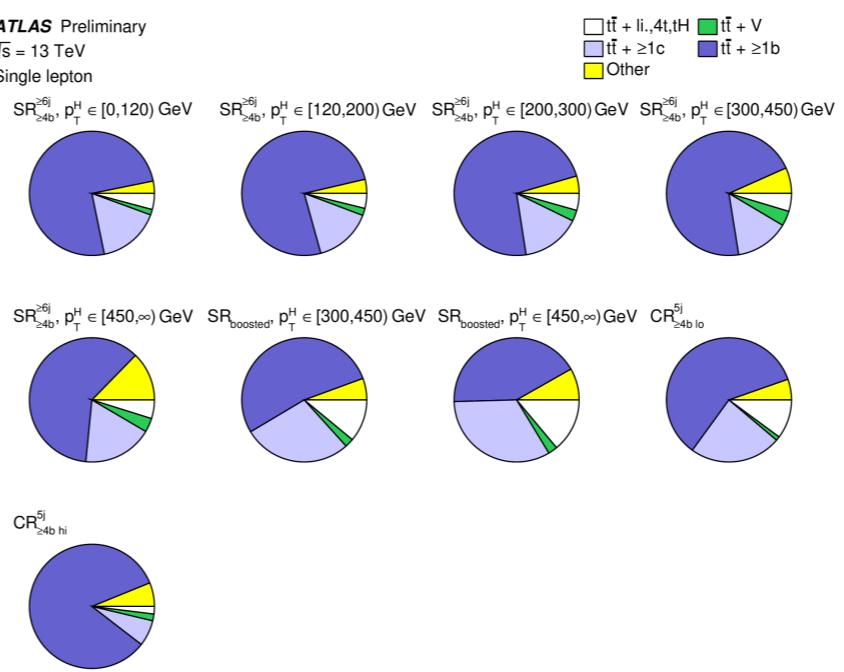
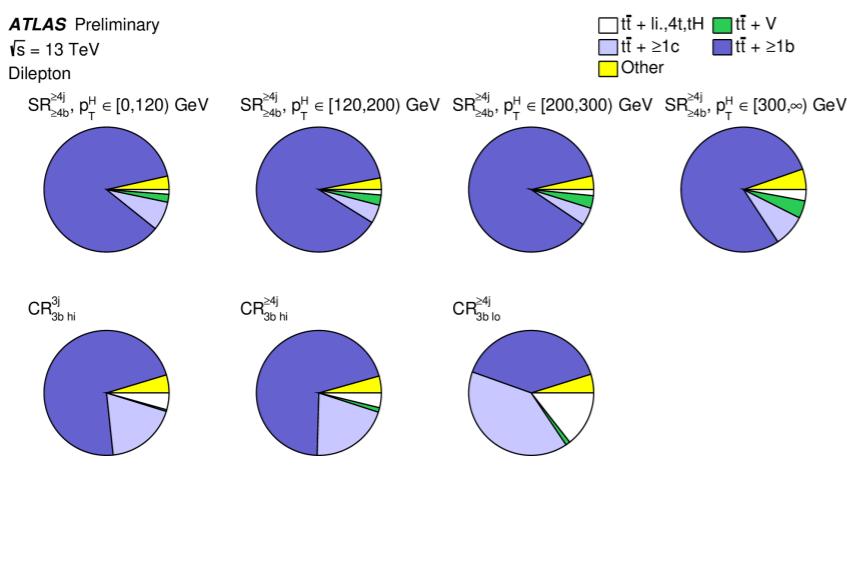
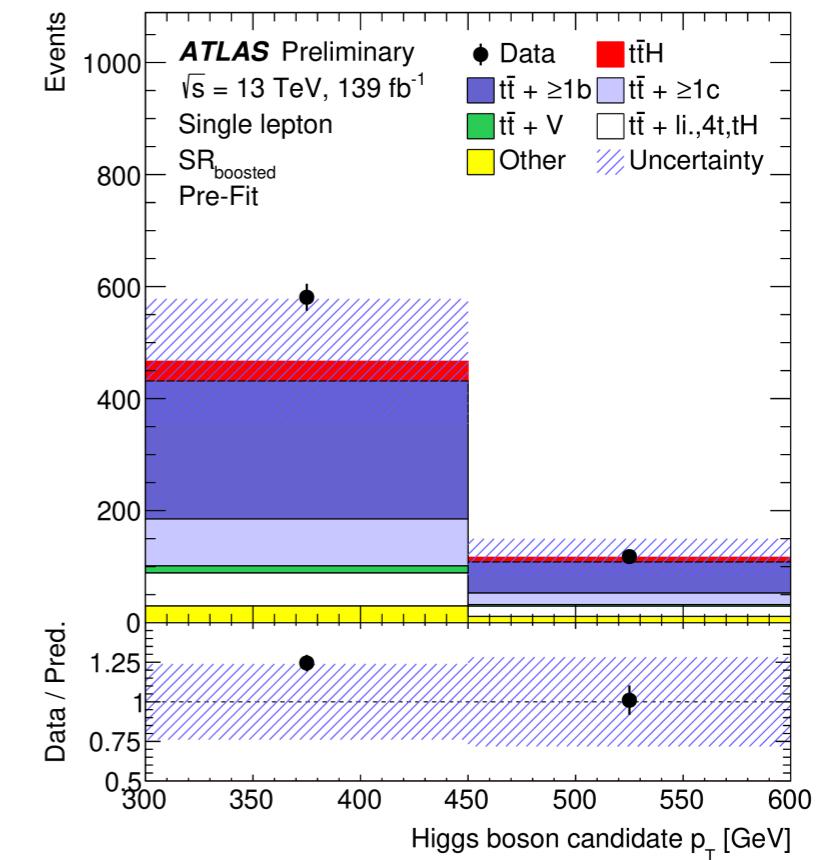
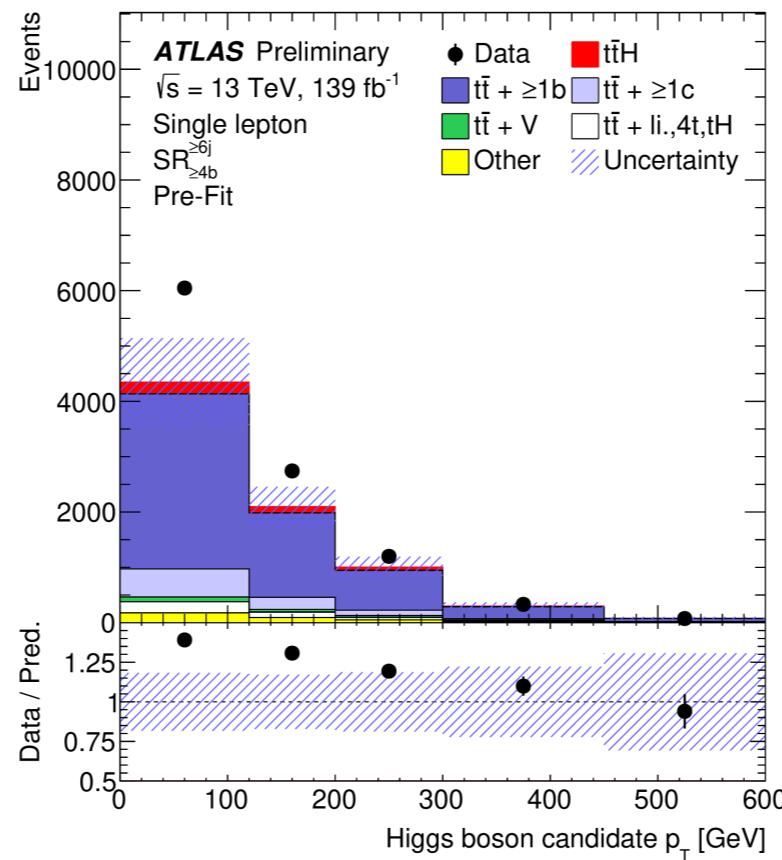
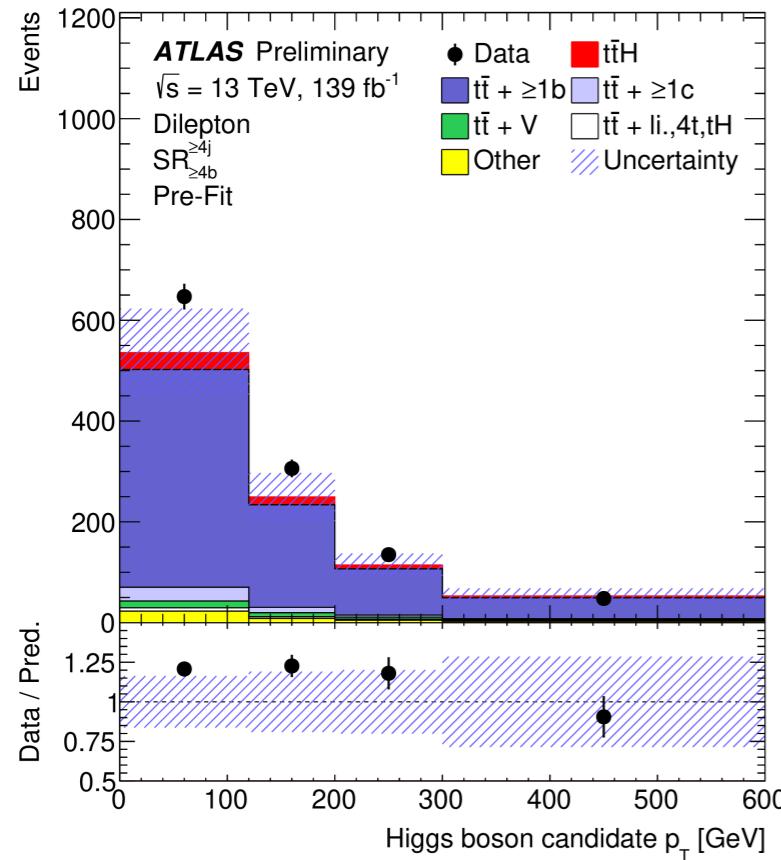
$t\bar{t}H$: one of the tiniest rates!

Standard Model Production Cross Section Measurements

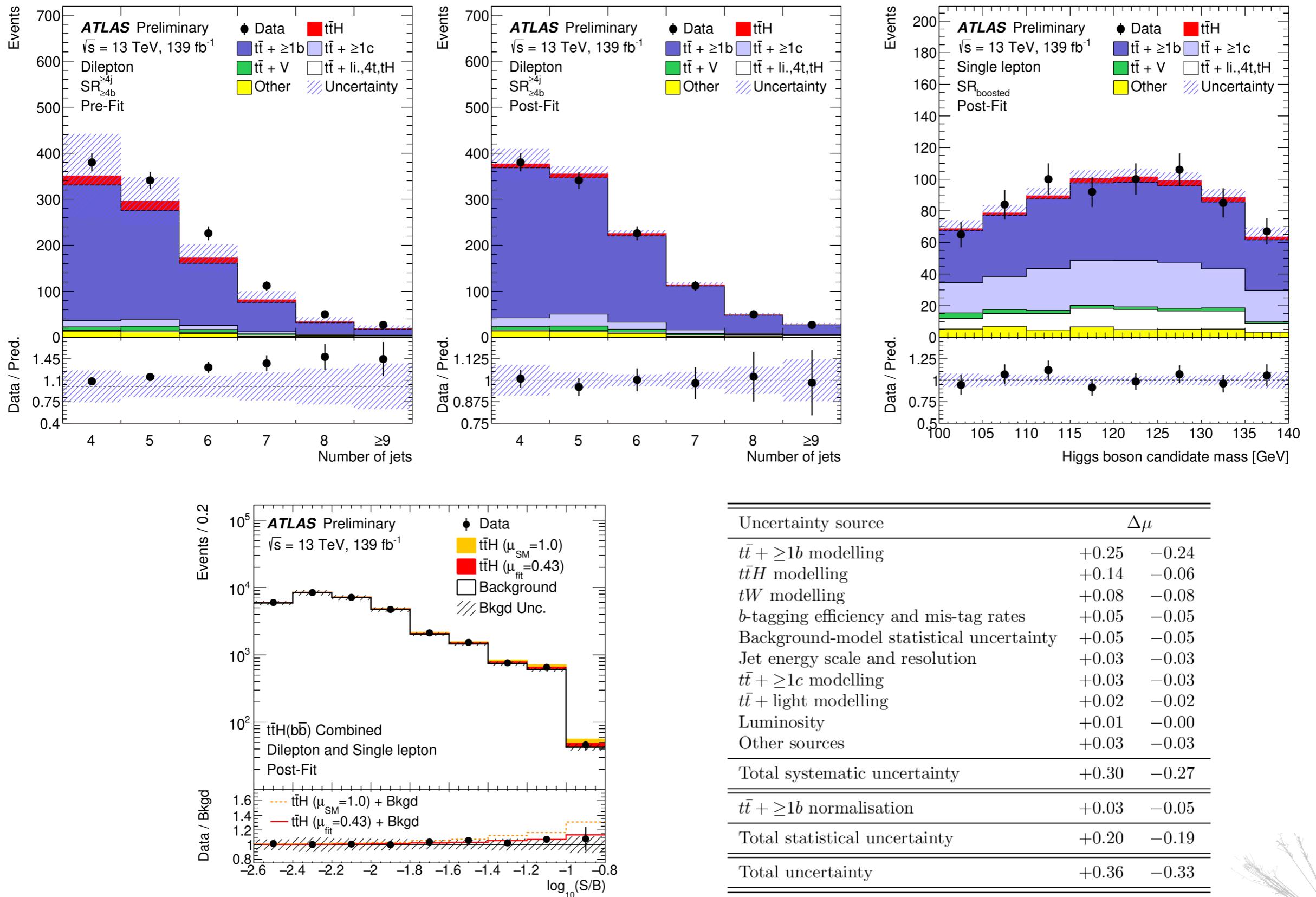
Status: March 2021



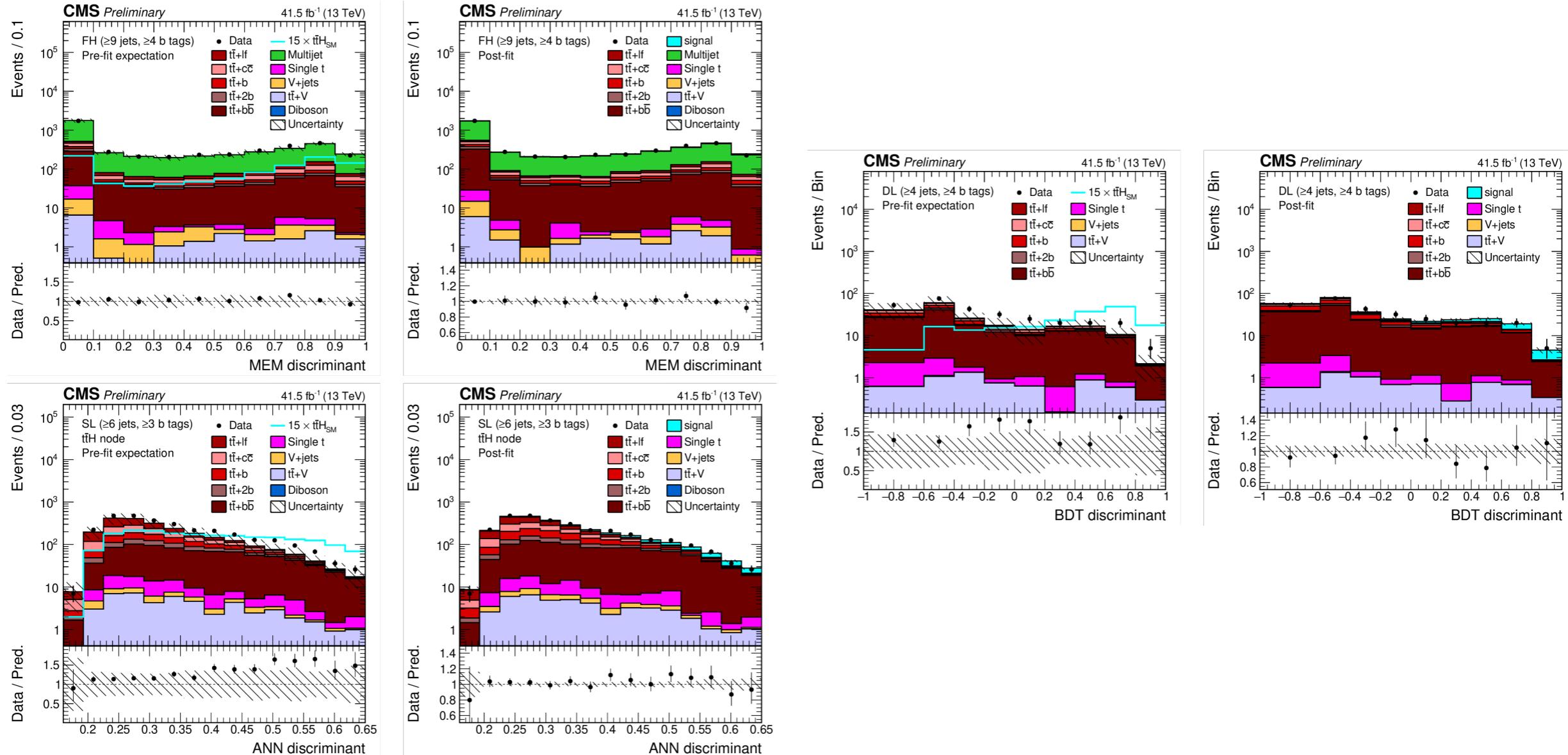
$t\bar{t}H(bb)$: background and p_T^H



$t\bar{t}H(bb)$: Njets and systematics



$t\bar{t}H(bb)$: final discriminants



$t\bar{t}H$ (multi ℓ): other checks



- Cross-check across years

2015+2016

$$\hat{\mu} = 0.68^{+0.50}_{-0.45}$$

2017

$$\hat{\mu} = 0.52^{+0.45}_{-0.40}$$

$t\bar{t}W$ NF also found to be high in both datasets

- Comparison wrt. 36/fb $t\bar{t}H$ publication [[Phys. Rev. D 97 \(2018\) 072003](#)]

*current fit model + $t\bar{t}W$ fixed to SM and no extrapolation
uncertainties → μ consistent with previous result*

- Comparison wrt. 36/fb $t\bar{t}W$ publication [[Phys. Rev. D 99 \(2019\) 072009](#)]

comparable results wrt.

$$\hat{\lambda}_{t\bar{t}W} = 1.19 \pm 0.26$$

(expressed wrt. 1.2x YR4)

$t\bar{t}H$ (multi ℓ): non-prompt leptons (I)



What to look for in the events?

- ($\geq 2, 4, 6$) jets!
- ≥ 2 jets originating from b-quarks (bjets)
- charged light leptons (electrons or muons)

require events triggered by 2 light leptons

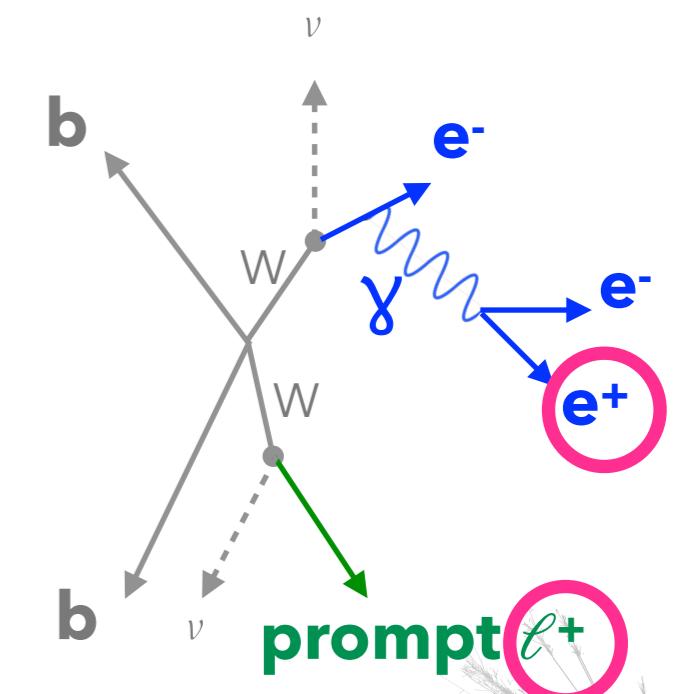
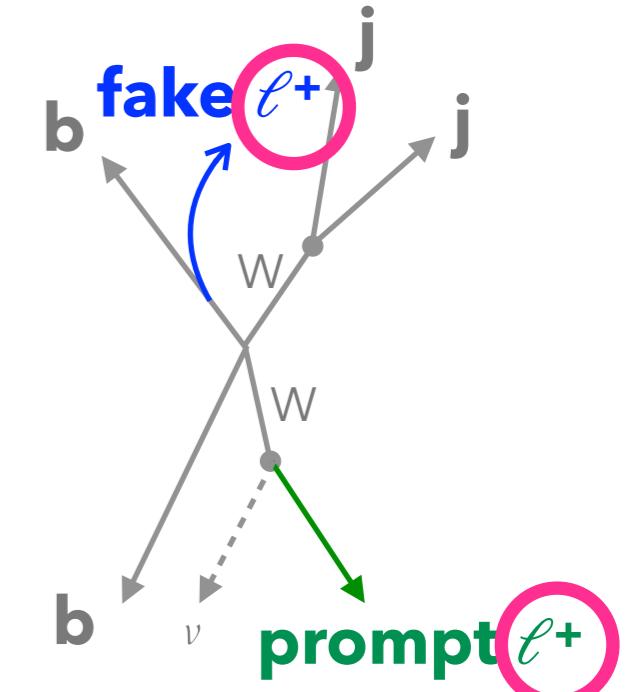
very important to have **well isolated** leptons

- **multivariate lepton isolation** to reject non-prompt leptons based on:
 - lepton and overlapping track jets properties
 - lepton track/calorimeter isolation variables

→ Factor $\mathcal{O}(20)$ **rejection for leptons originating from b-hadrons**

- **multivariate lepton identification** to **reject misidentified charge electrons**

→ Factor $\mathcal{O}(17)$ background rejection for a 95% signal efficiency



$t\bar{t}H$ (multi ℓ): non-prompt leptons (II)

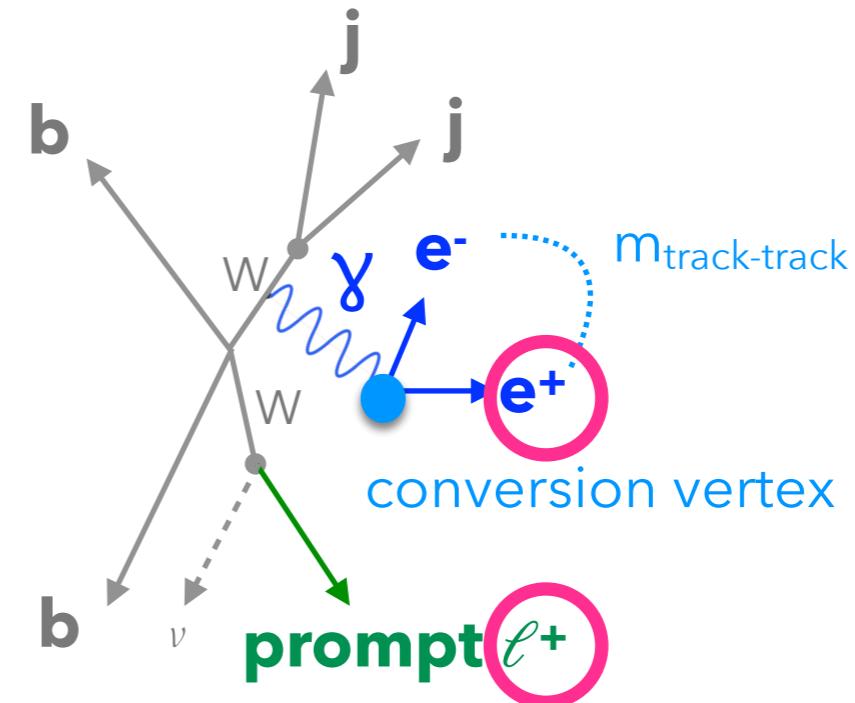


- material and internal electron **conversion** (CO) candidates further suppressed with track invariant masses and conversion radius

What to look for in the events?

- ($\geq 2, 4, 6$) **jets**!
- ≥ 2 jets originating from b-quarks (**bjets**)
- charged light leptons (**electrons** or muons)

γ
 γ^*

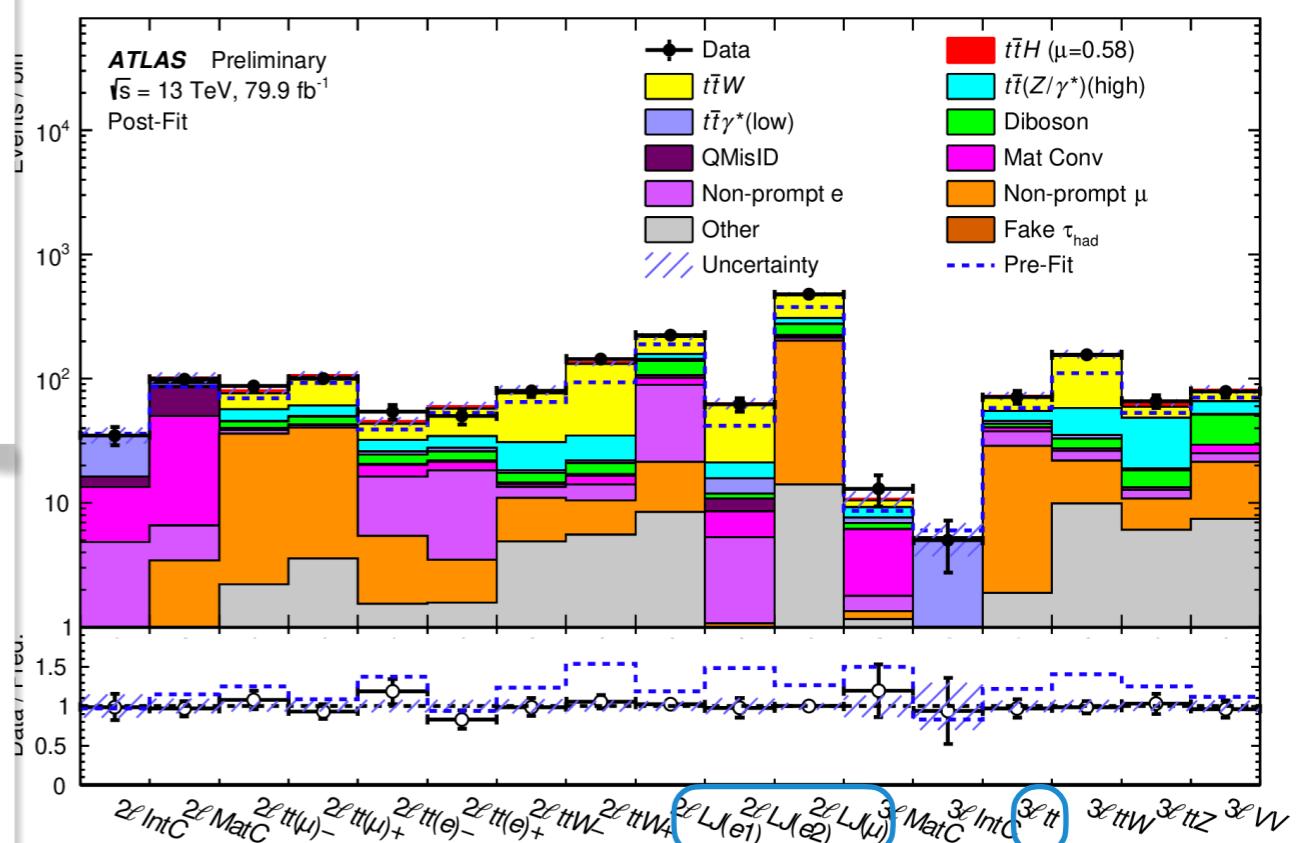
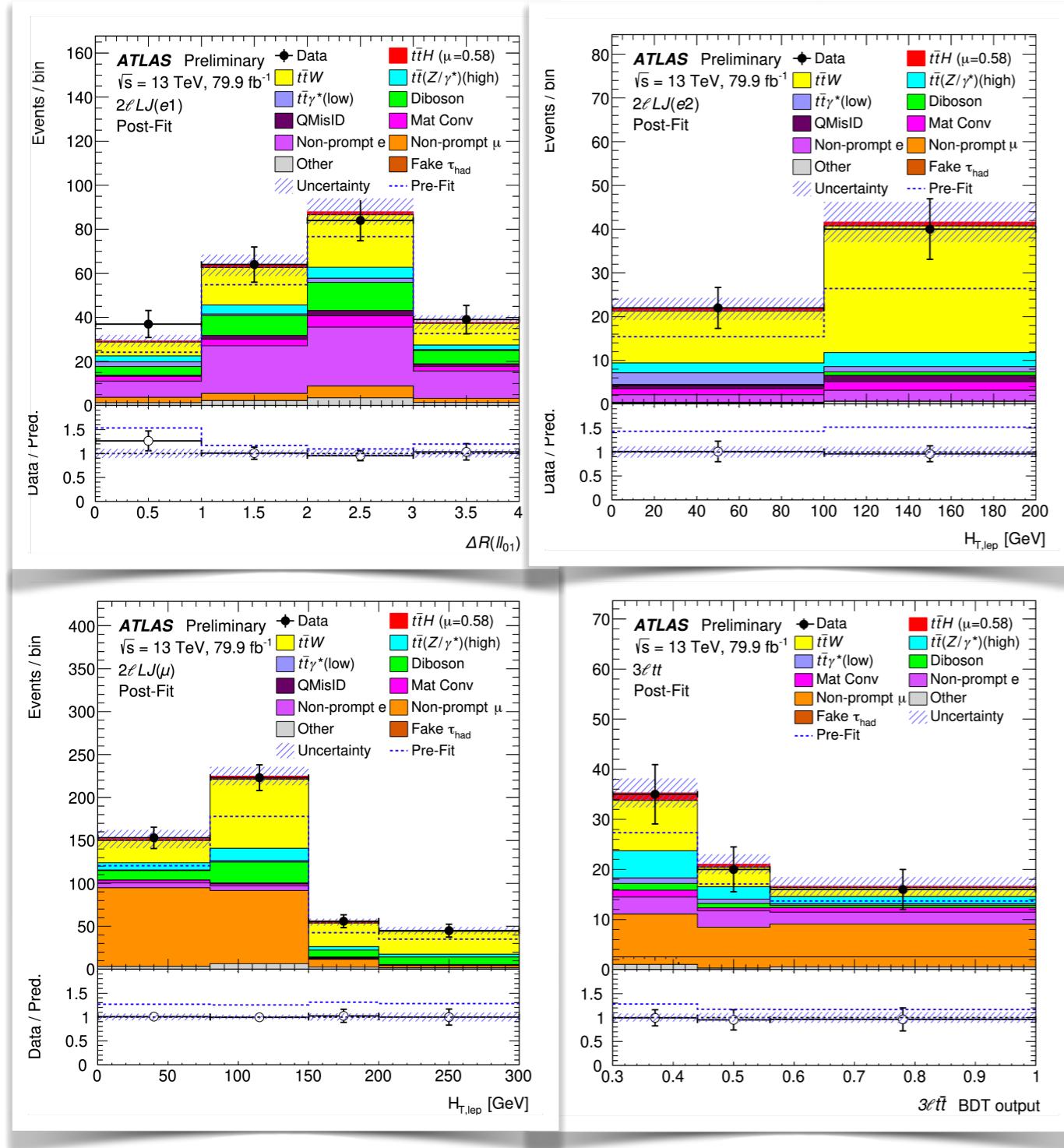


electron CO selection	CO radius	$m_{\text{track-track}}$
(1) material CO	$> 20 \text{ mm}$	$< 100 \text{ MeV}$ (wrt. CV)
(2) internal CO	not (1)	$< 100 \text{ MeV}$ (wrt. PV)
(3) very tight		not (1) and not (2)

(beam pipe @ 24 mm)

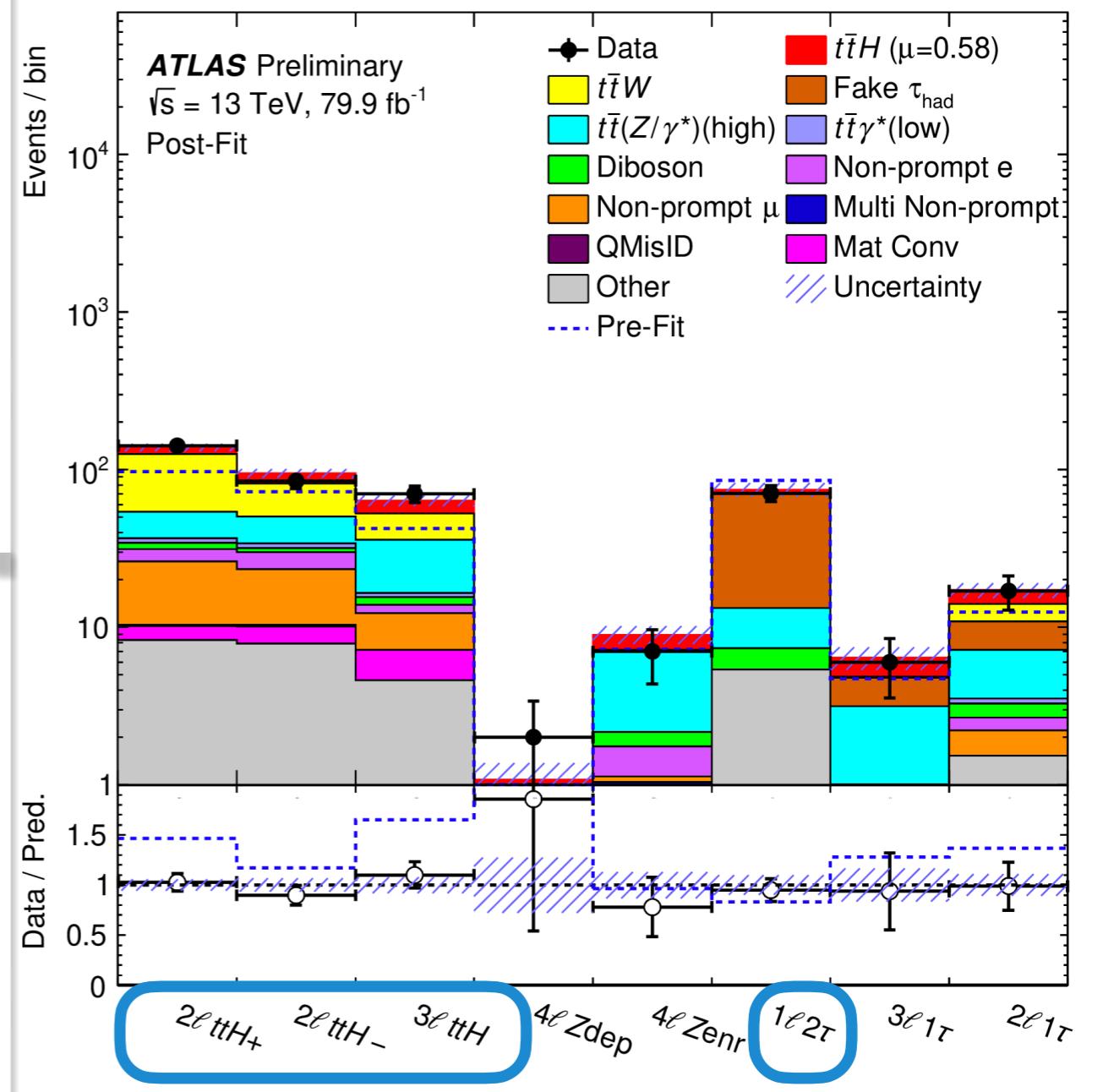
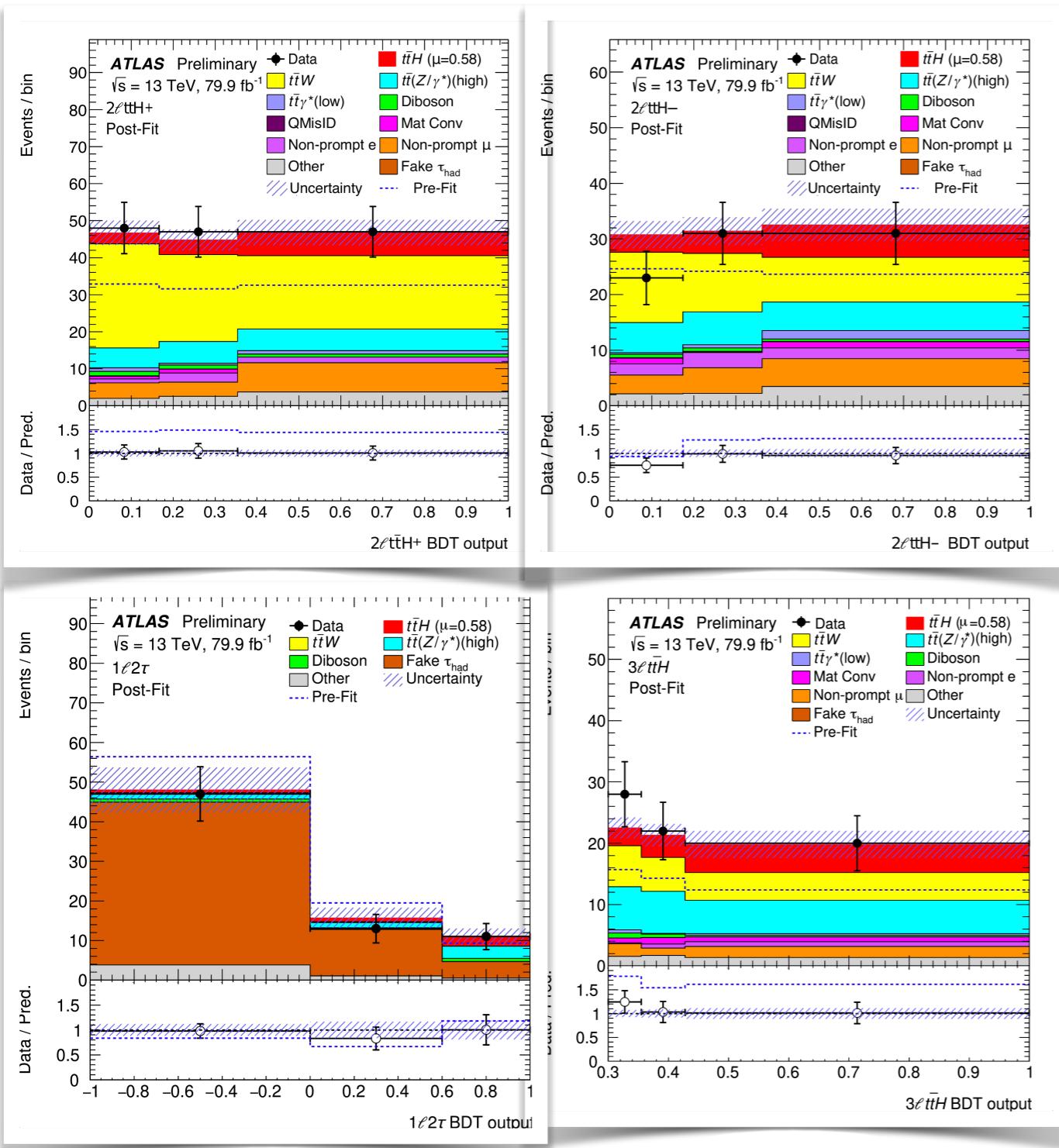
require events triggered by
2 light leptons

$t\bar{t}H$ (multi ℓ): Control regions



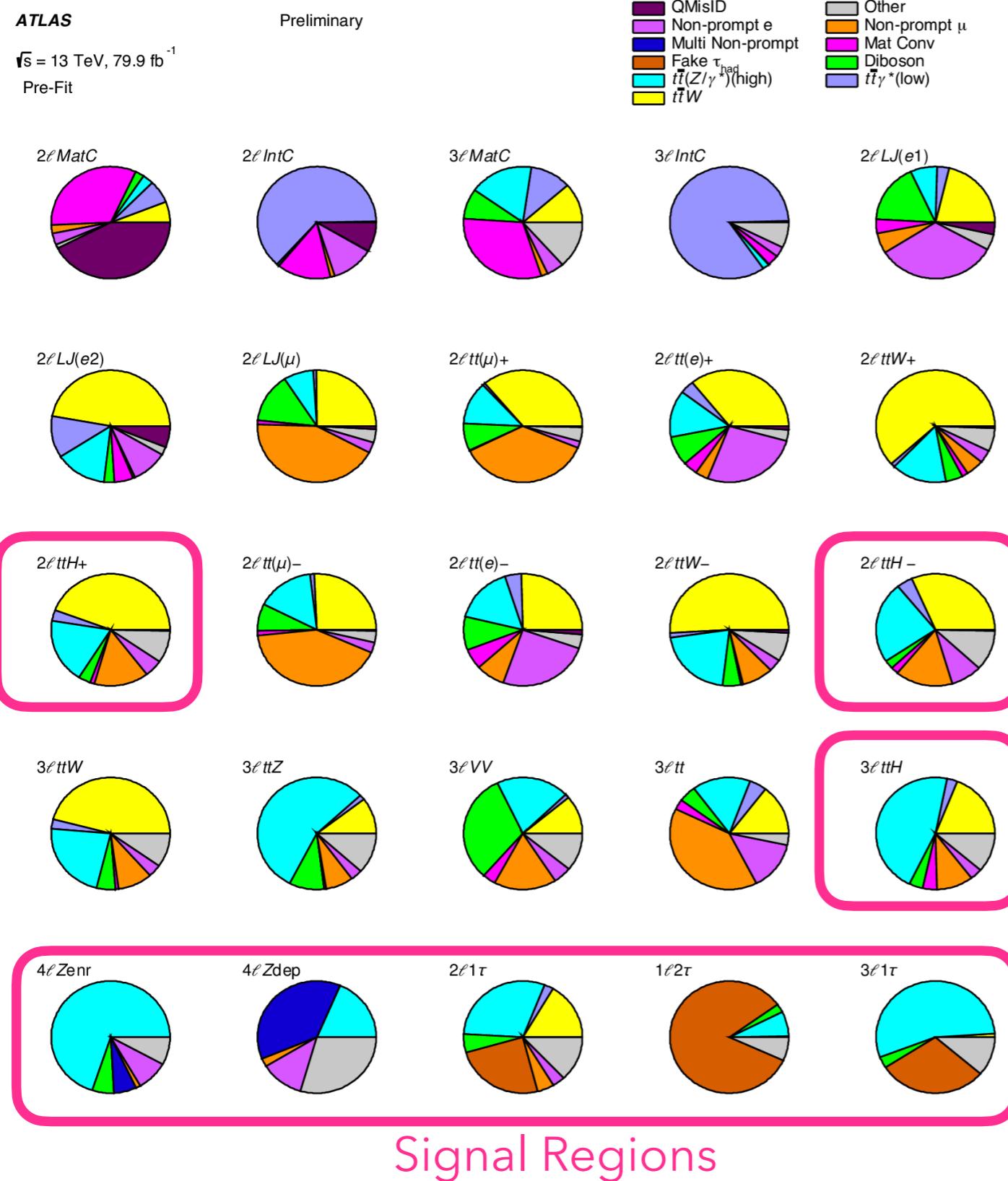
Kinematic variables / BDT discriminant
fitted in these regions

$t\bar{t}H$ (multi ℓ): Signal regions



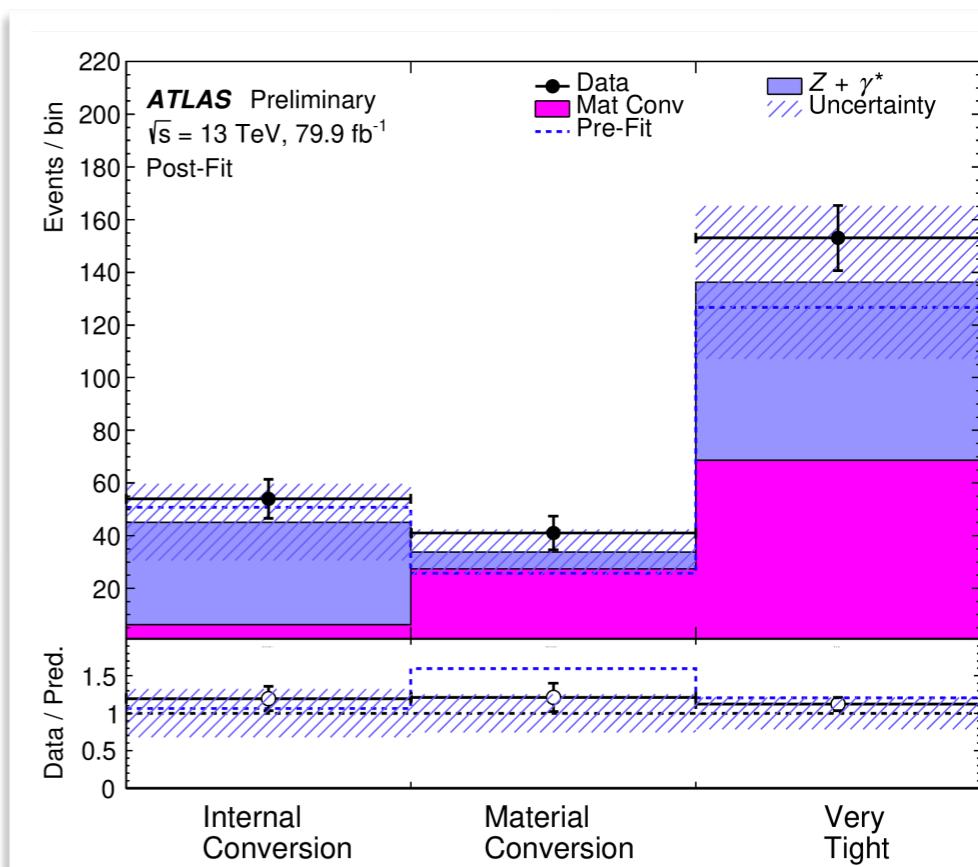
👉 BDT discriminant fitted in these regions

t̄H (multiℓ): Background composition



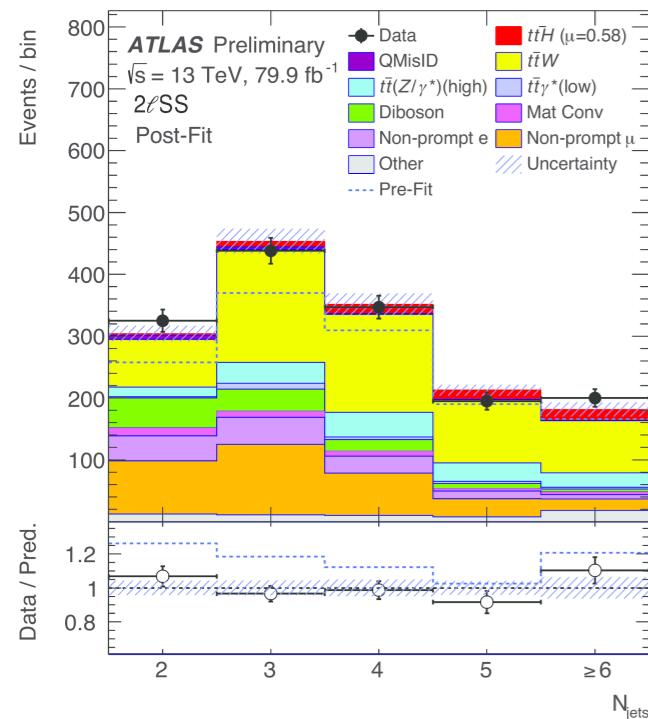
- Plus validation regions for internal & material electrons conversions

3ℓ selection:
 $Z \rightarrow \mu^+ \mu^- \gamma^* (\rightarrow e^+ e^-)$



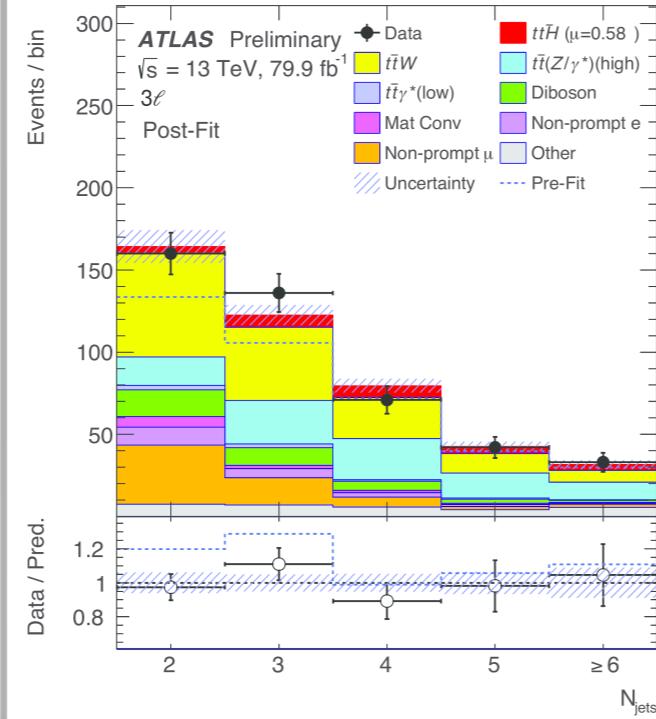
$t\bar{t}H$ (multi ℓ): Normalisation factors

$2\ell SS$

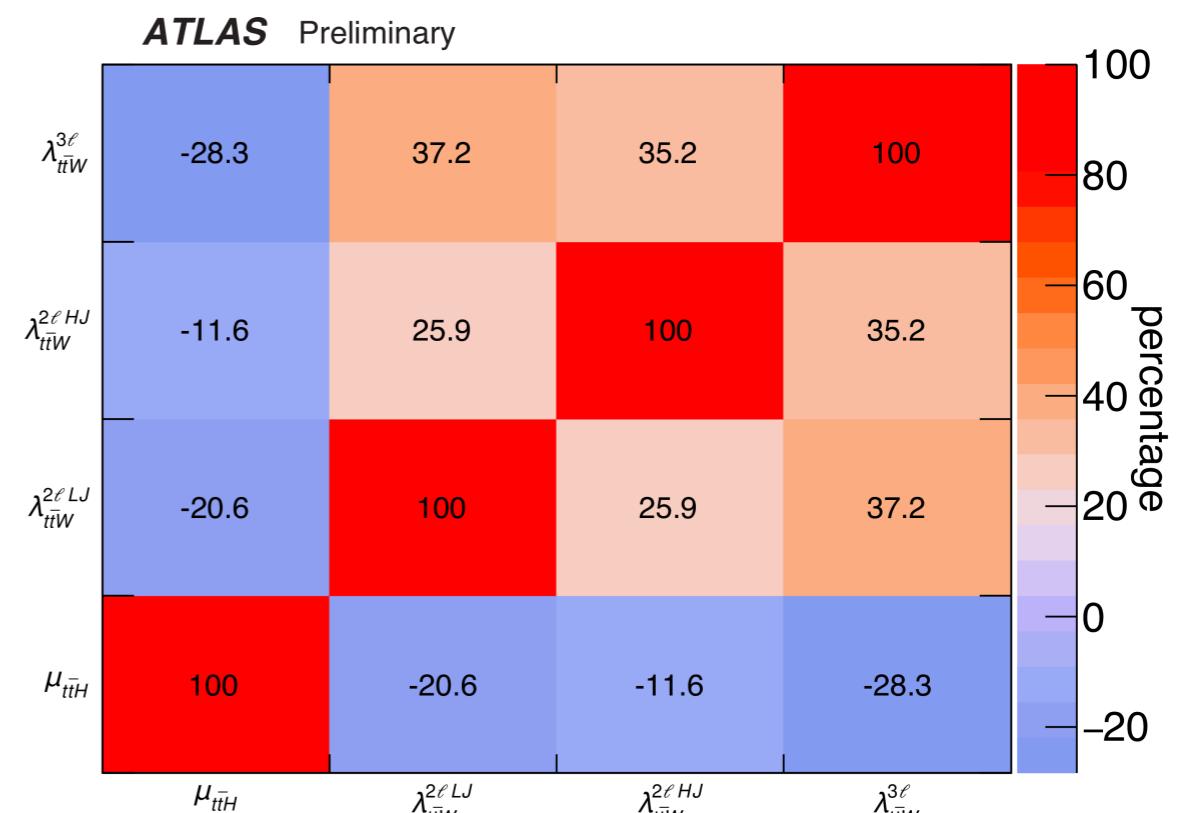


NF ($t\bar{t}W$)
 2ℓ low NJet NF ($t\bar{t}W$)
 2ℓ high NJet

3ℓ



NF ($t\bar{t}W$)
 3ℓ



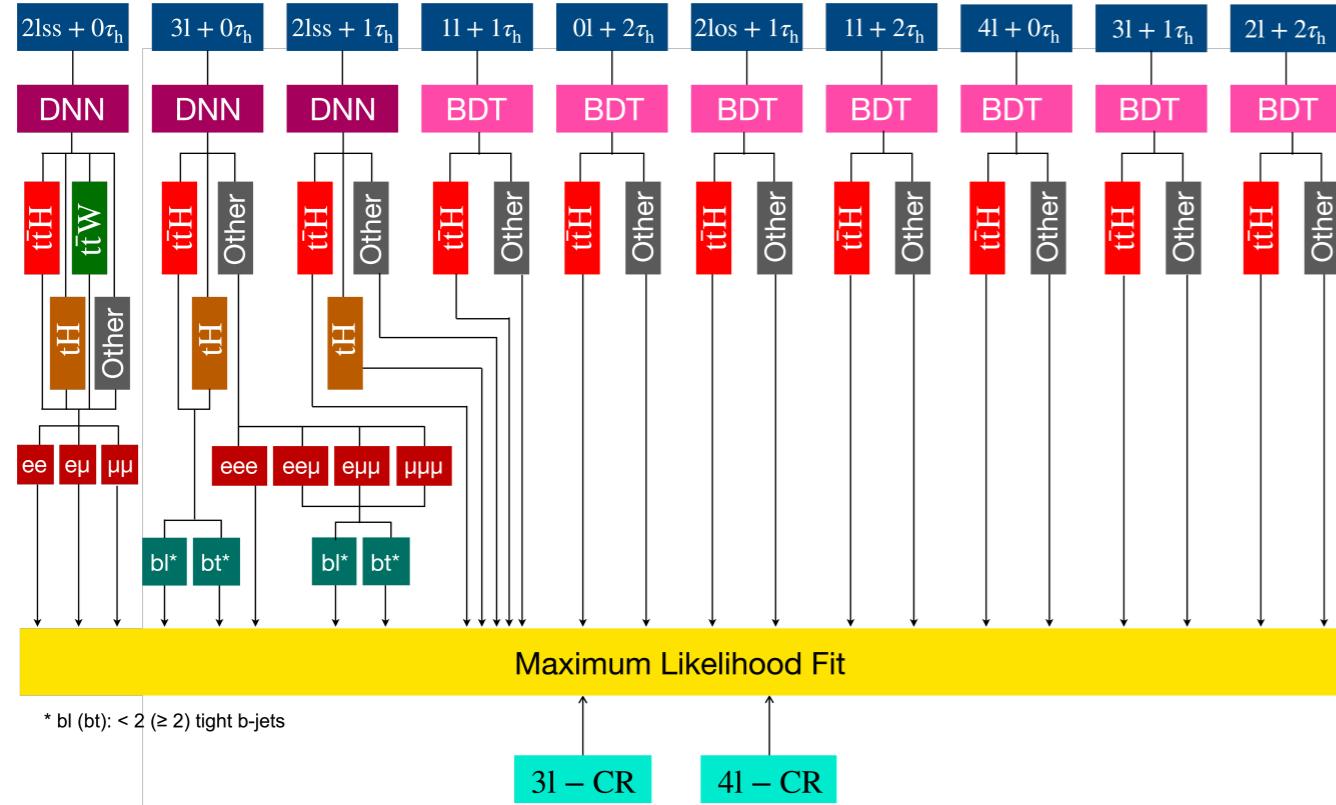
Decorrelated normalisation factors for region where $t\bar{t}W$ has lost $\geq 1j$ from signal region

Decorrelated normalisation factors between 2ℓ and 3ℓ due to different kinematic behaviours

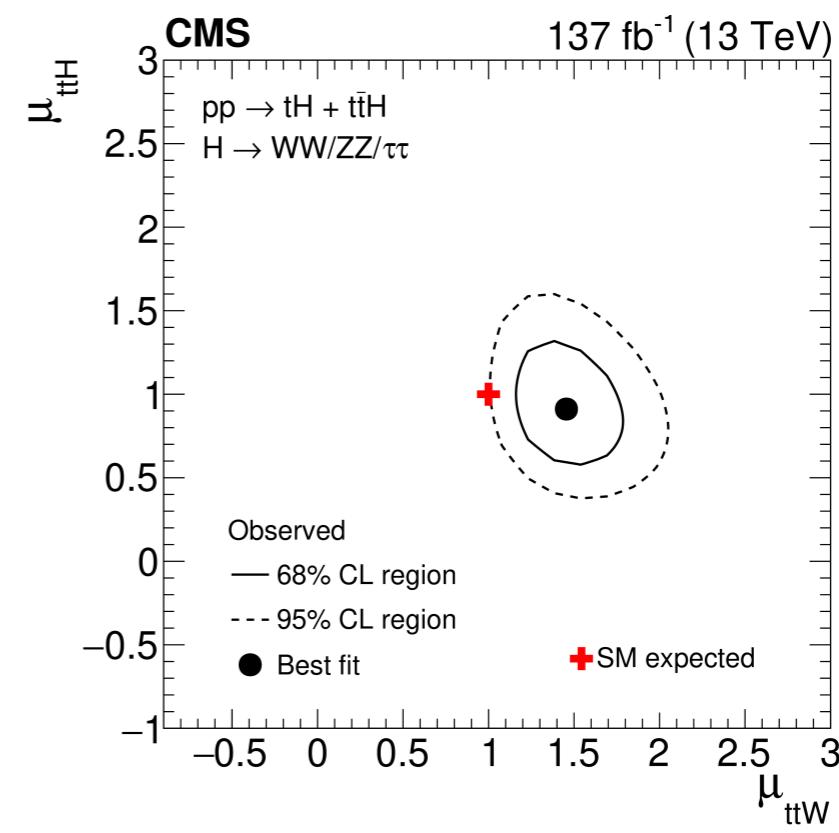
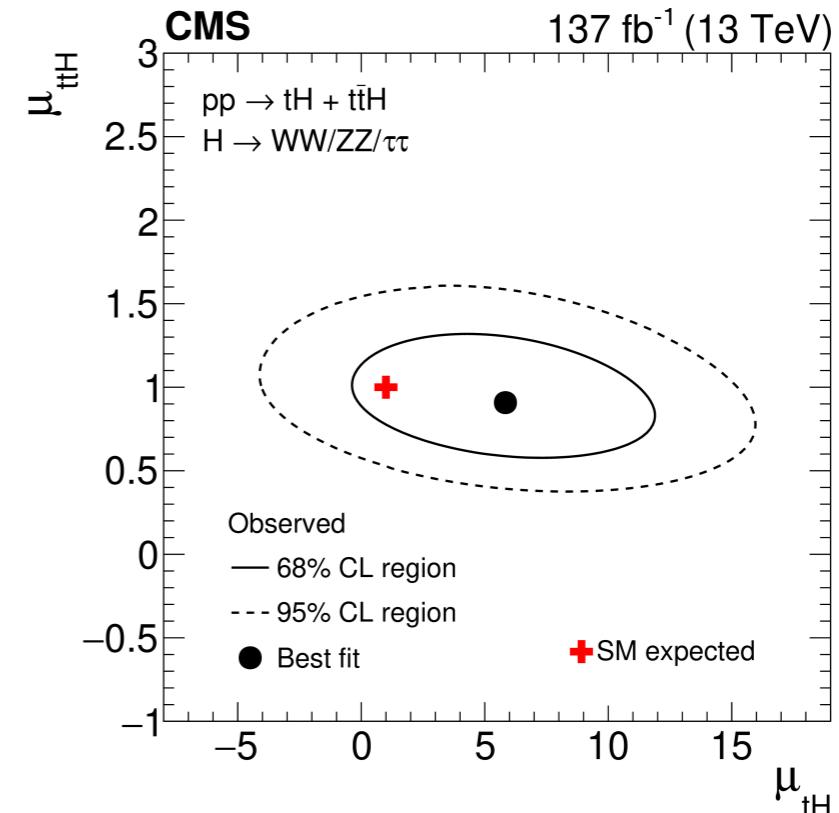
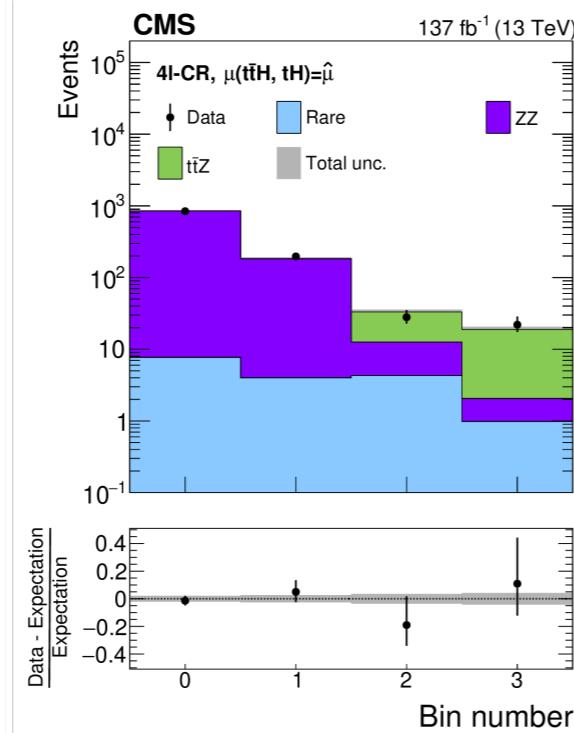
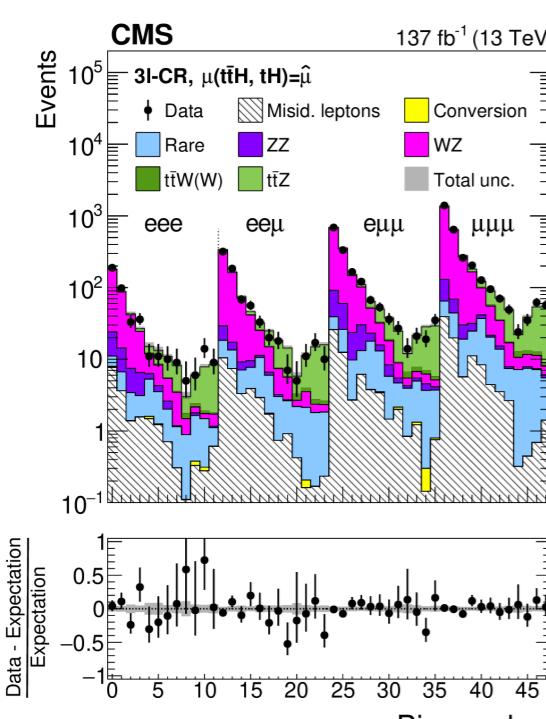
Seven normalisation factors:

- Non-prompt e
- $t\bar{t}\gamma^*(\text{low})$
- $t\bar{t}W (\times 3) !$**
- Non-prompt μ
- Mat Conv

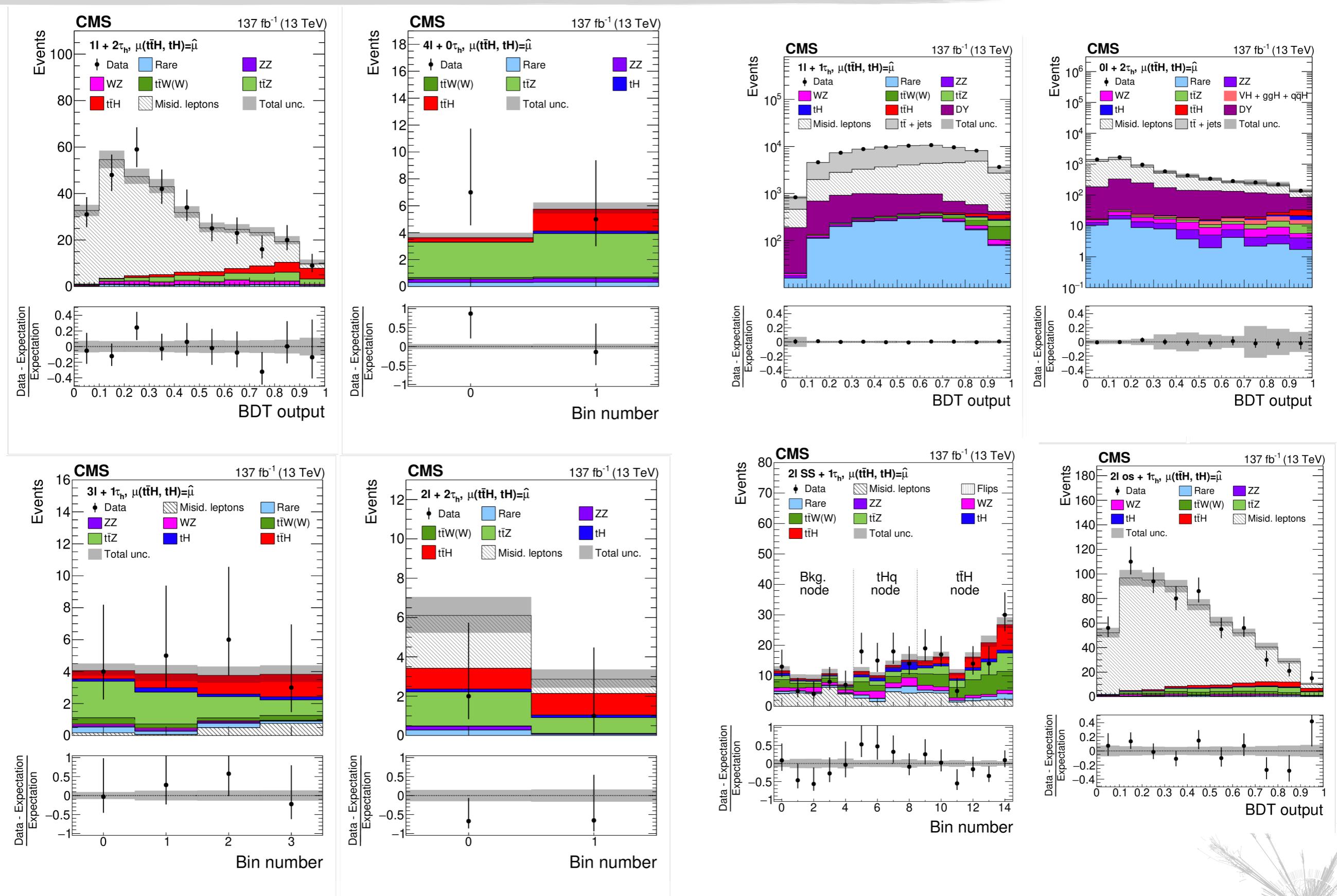
$t\bar{t}H$ (multi ℓ): categorisation & results



* bl (bt): < 2 (≥ 2) tight b-jets

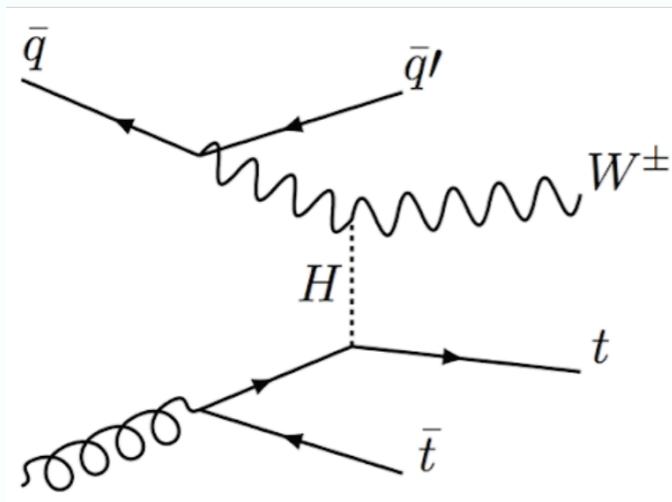


$t\bar{t}H$ (multi ℓ): tau channels



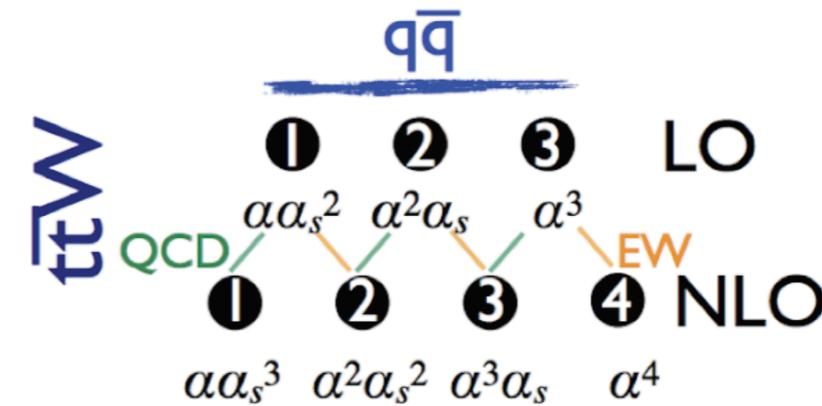
$t\bar{t}W$: higher order QCD and EW corrections

- A normalisation factor of **1.2** applied on top of the YR4 cross section for $t\bar{t}W$
- Origin of the correction factor:
 - Factor **1.11** to account for missing QCD corrections in higher order XS
 - $t\bar{t}W+0j@\text{NLO} \rightarrow t\bar{t}W+0,\mathbf{1j}@NLO$
 - estimated using dedicated samples generated with Sherpa 2.2.1 using the MEPS@NLO prescription, and cross-checked with the NLO generator MadGraph5_aMC@NLO 2.2.1 using the FxFx prescription
 - Factor **1.09** to account for missing EW corrections
 - [1711.02116] shows “subleading” NLO EWK corrections, not included in YR4 XS, can be large
 - primarily because of the large **NLO3 term** driven by the $t\bar{t}W+1\text{-jet}$ diagrams with a Higgs boson exchanged in the t-channel



13 TeV

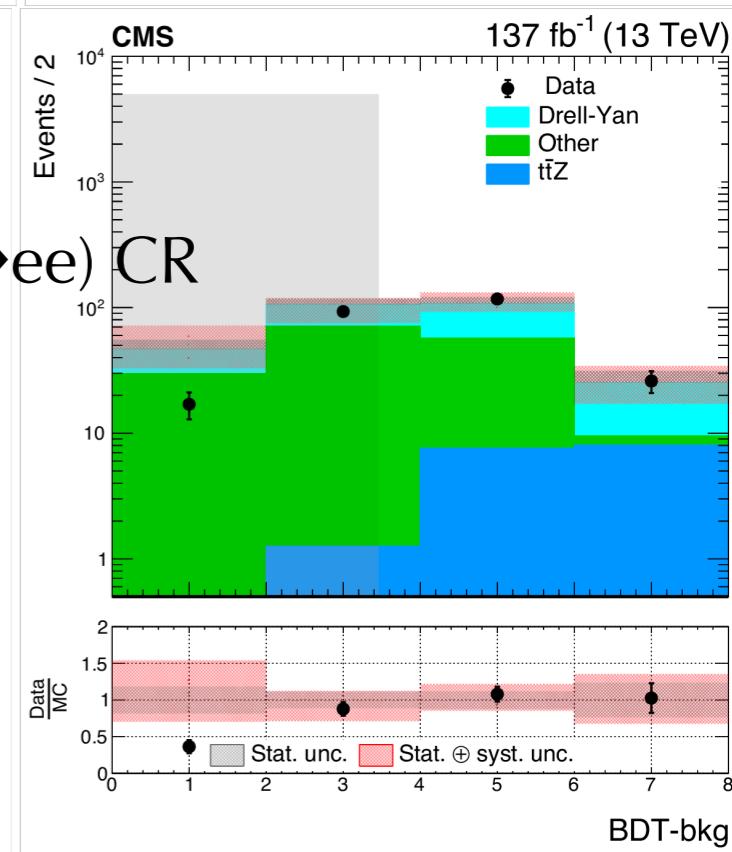
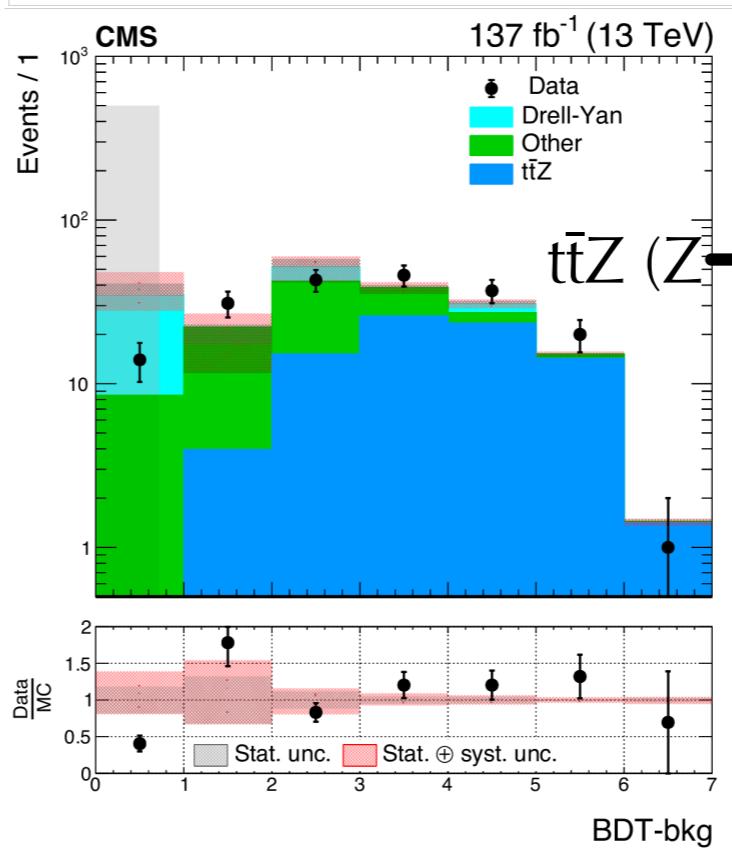
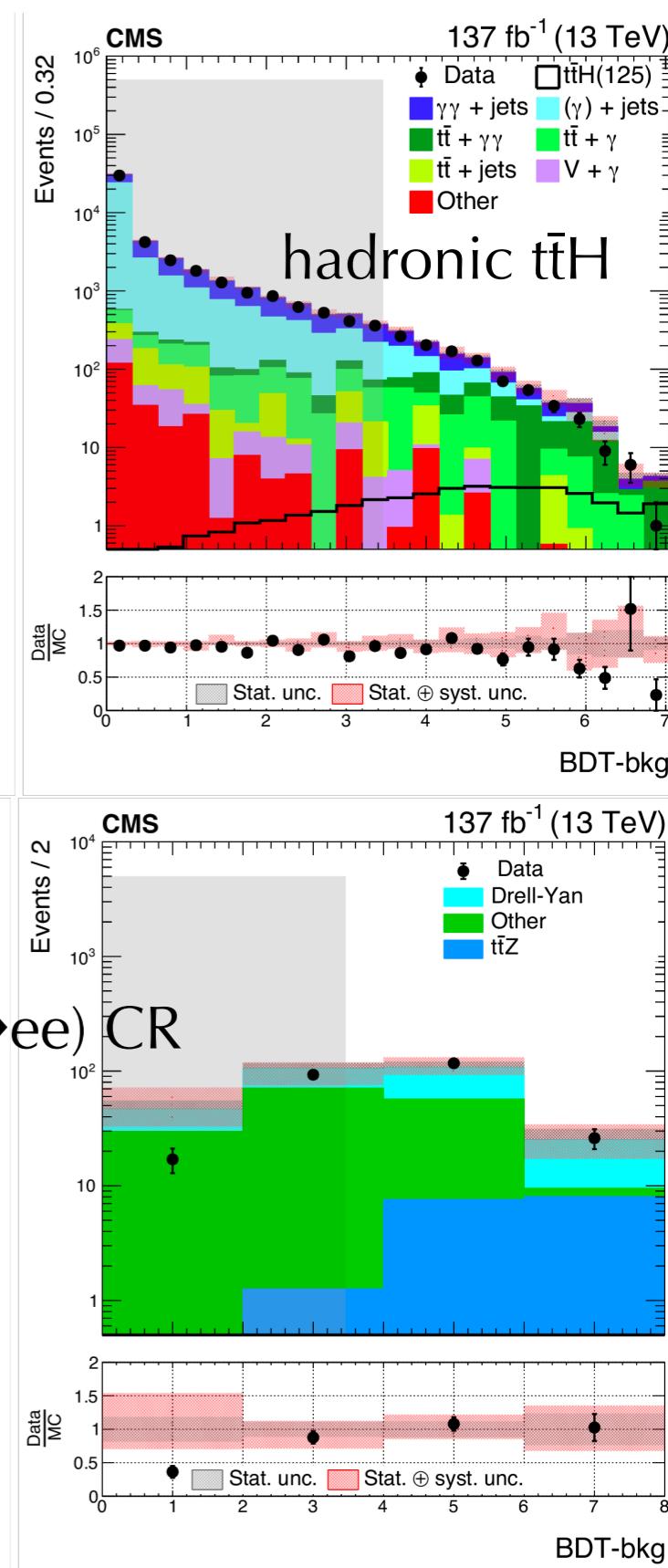
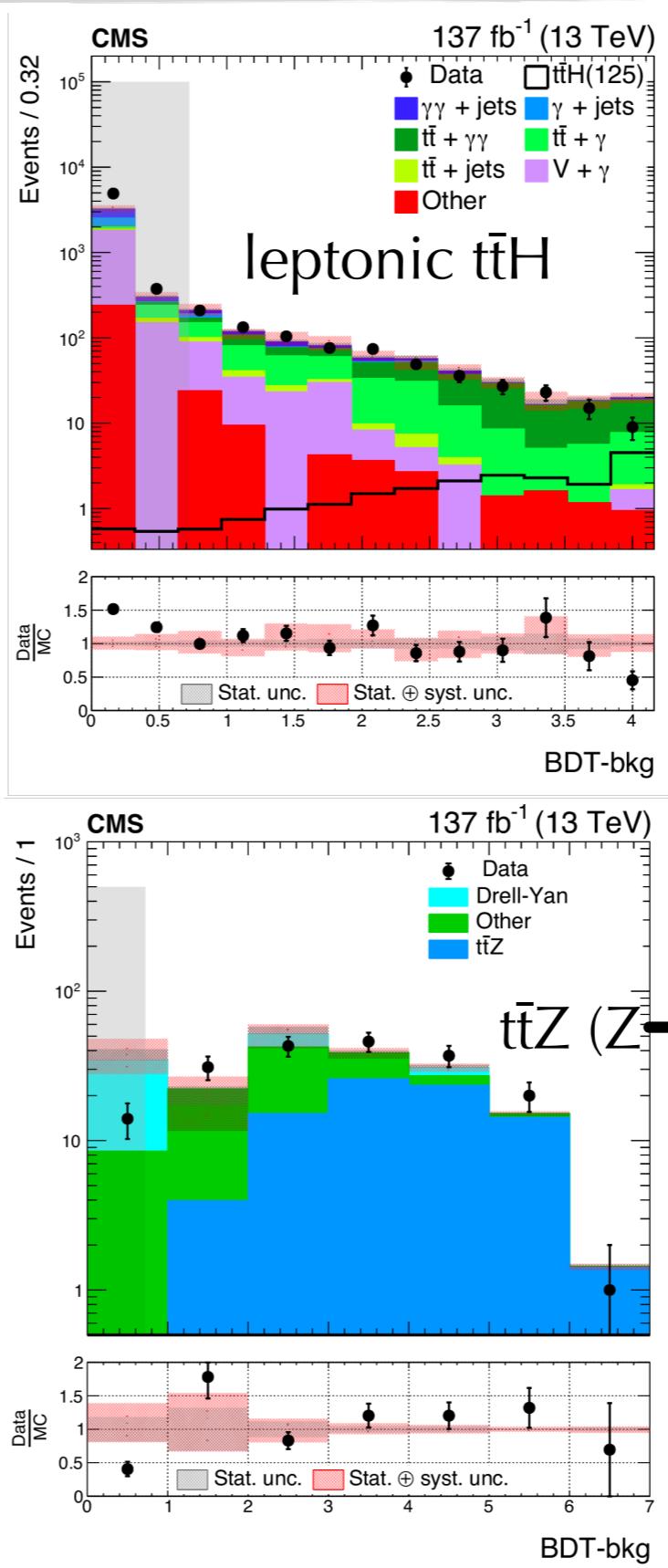
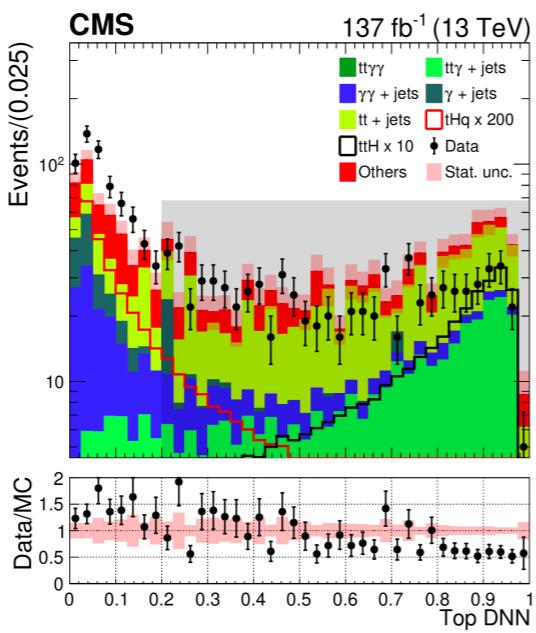
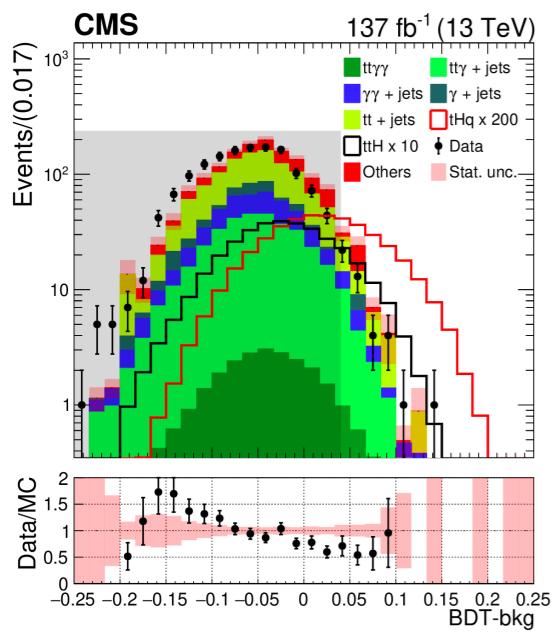
$\delta[\%]$	$\mu = H_T/2$
LO ₂	-
LO ₃	0.9
NLO ₁	50.0 (25.7)
NLO ₂	-4.2 (-4.6)
NLO ₃	12.2 (9.1)
NLO ₄	0.04 (-0.02)



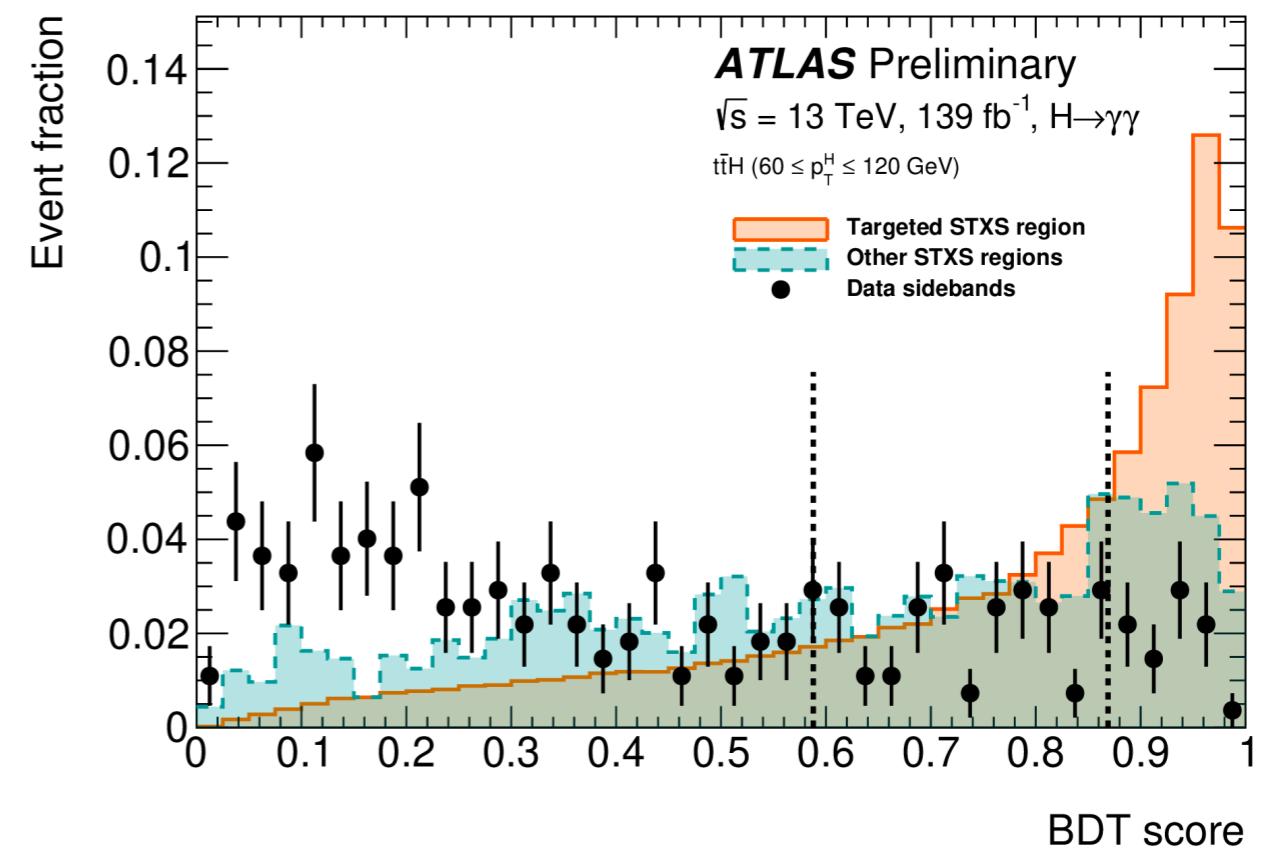
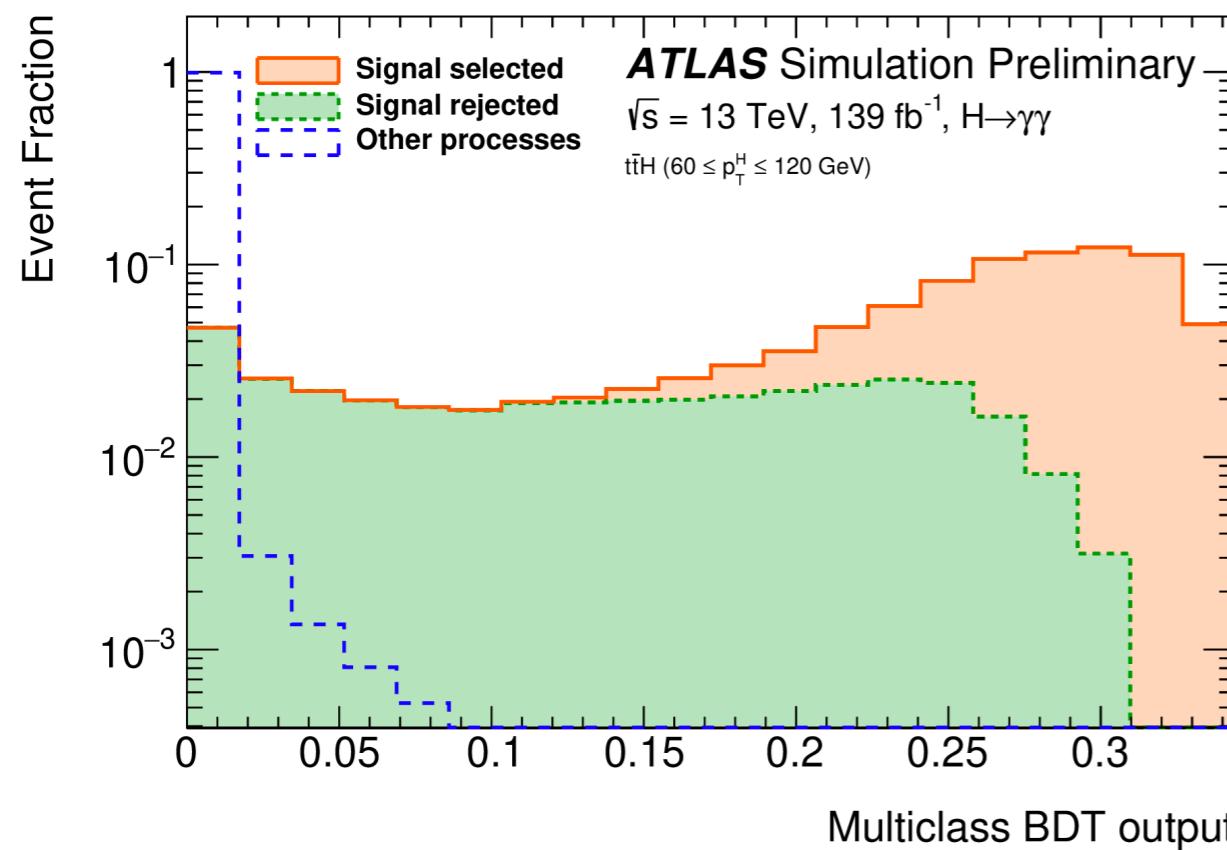
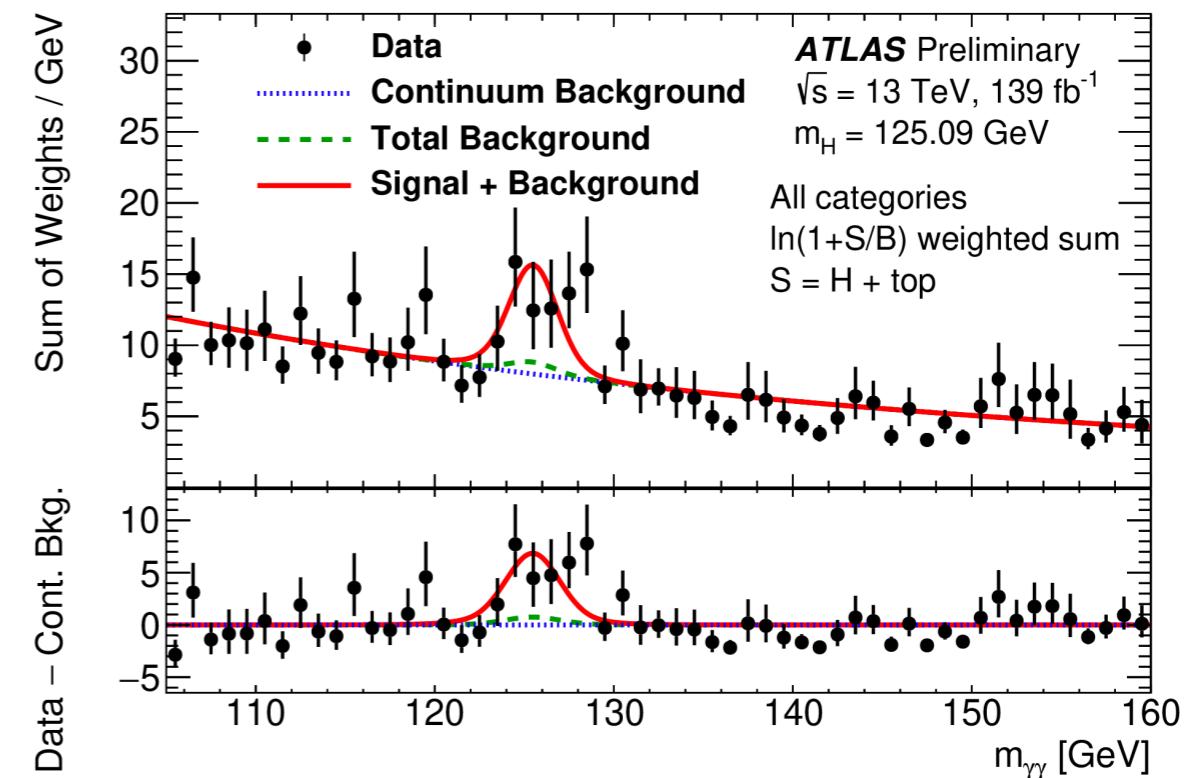
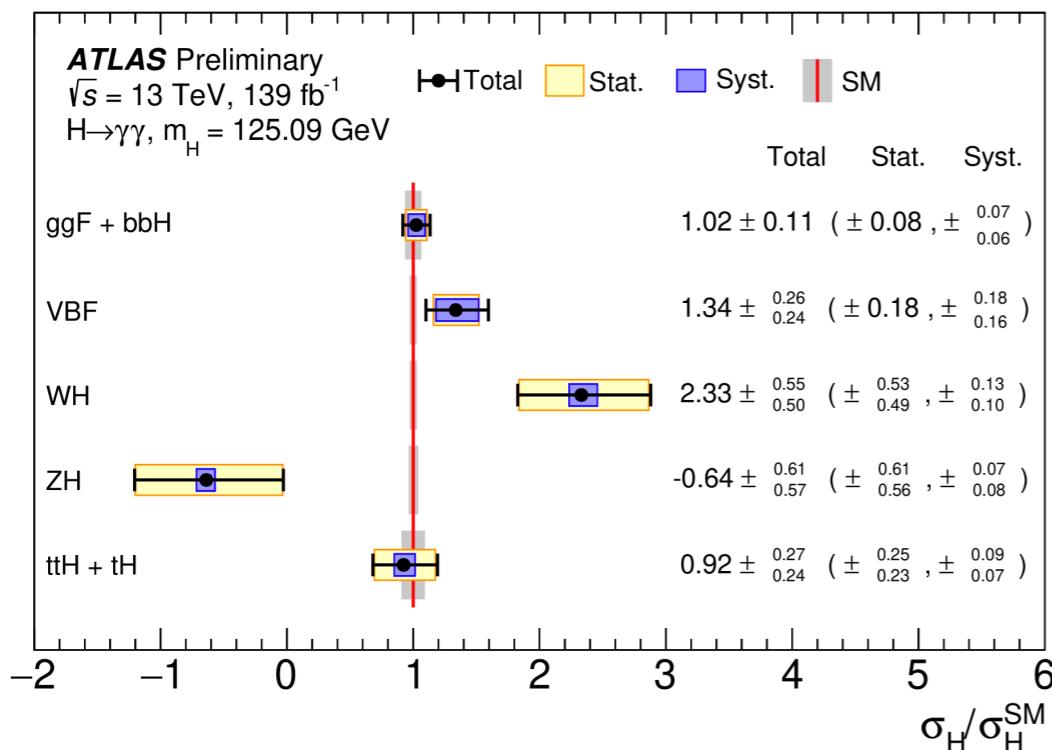
$t\bar{t}H(H \rightarrow \gamma\gamma)$: distributions



tH leptonic



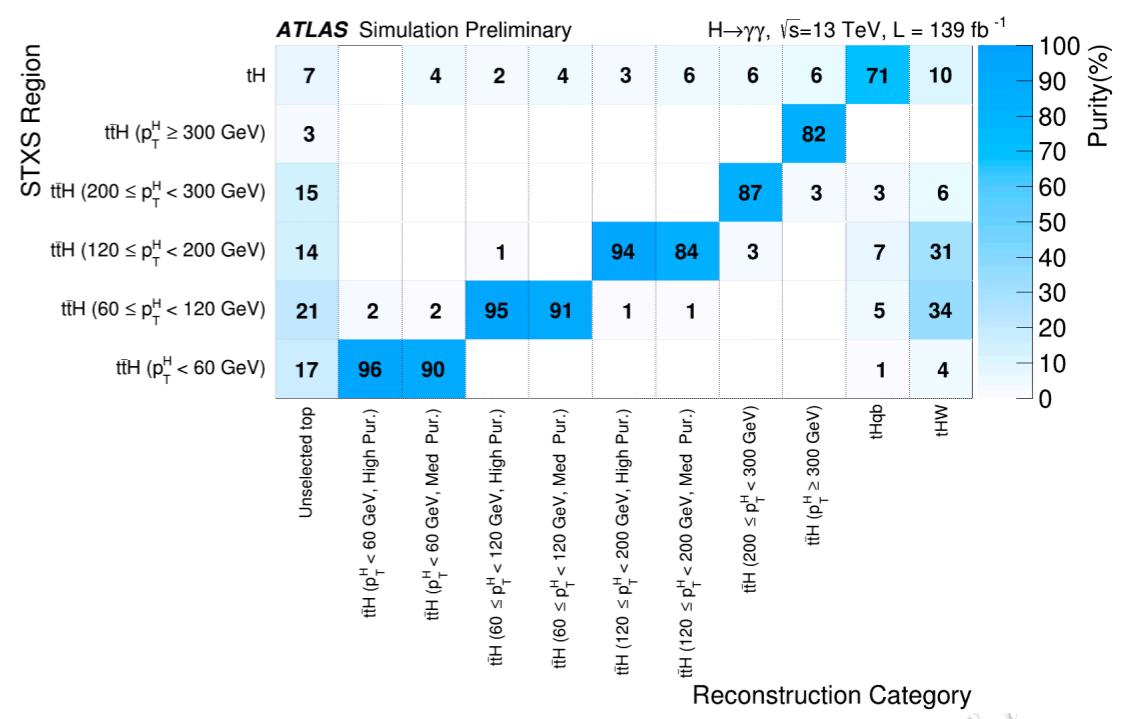
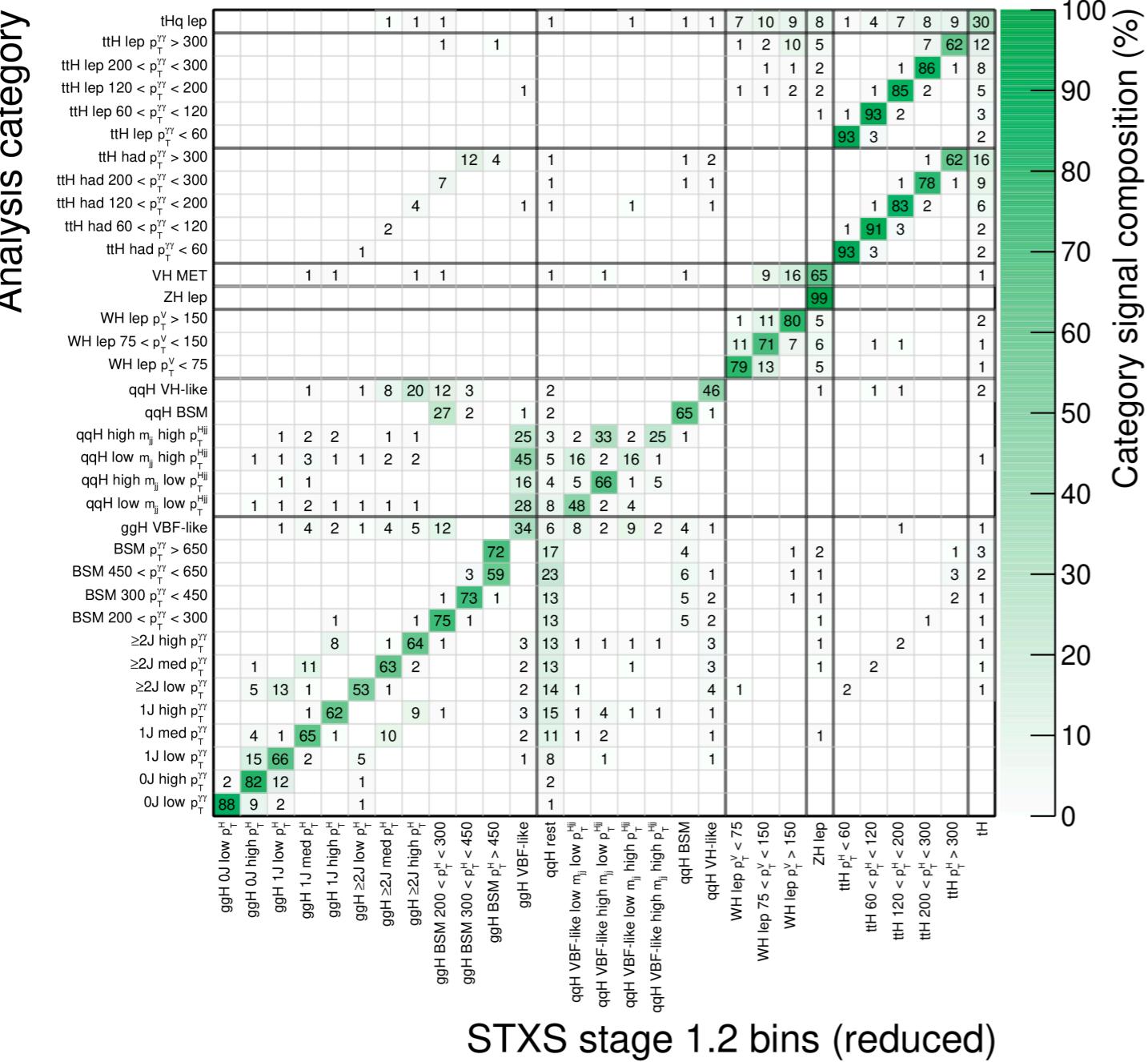
$t\bar{t}H(H \rightarrow \gamma\gamma)$: distributions



$t\bar{t}H(H \rightarrow \gamma\gamma)$: correlations

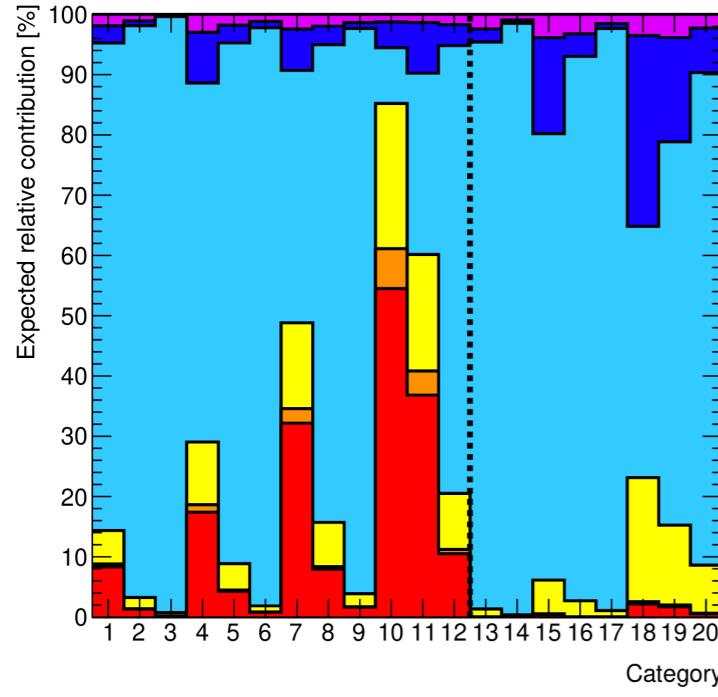


CMS Simulation $H \rightarrow \gamma\gamma$ (13 TeV)

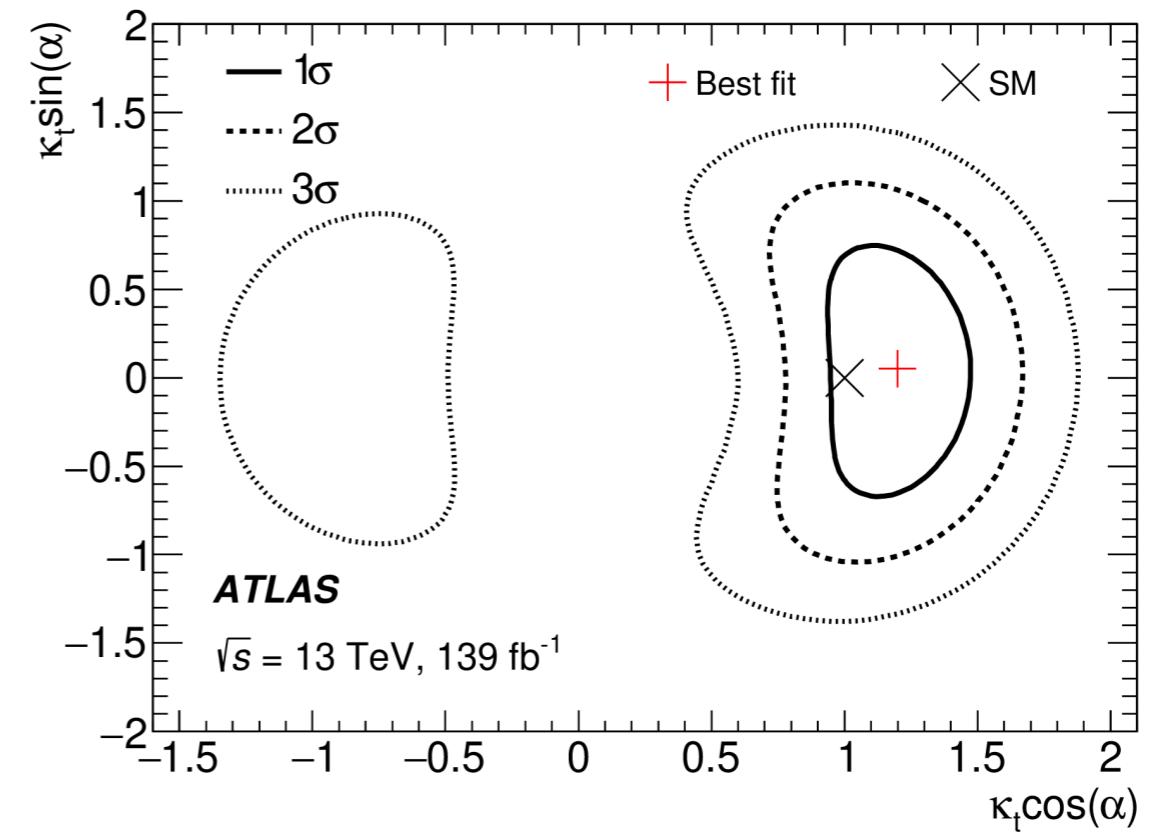
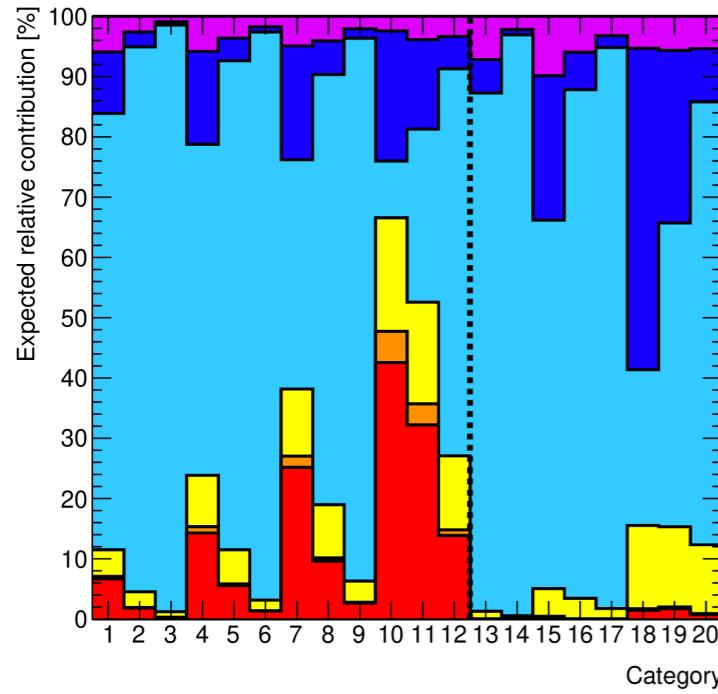


$t\bar{t}H(H \rightarrow \gamma\gamma)$: CP analysis

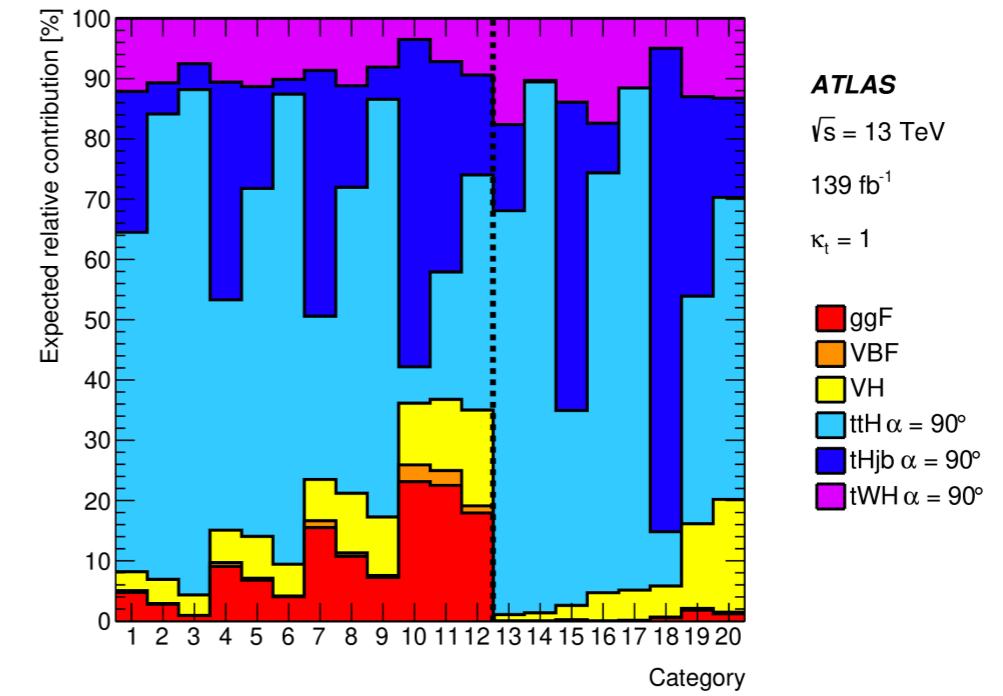
CP even



CP $\alpha = 45^\circ$



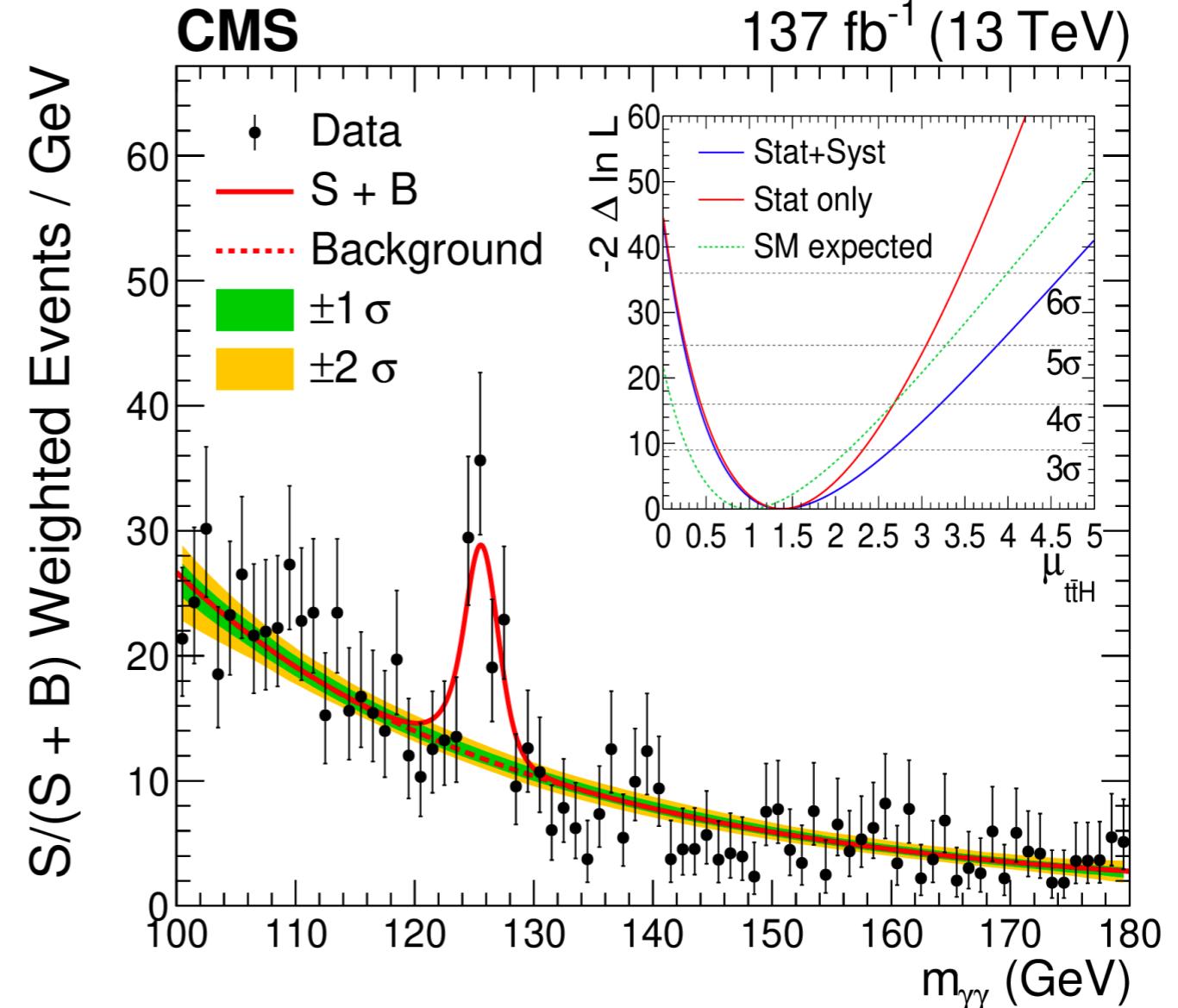
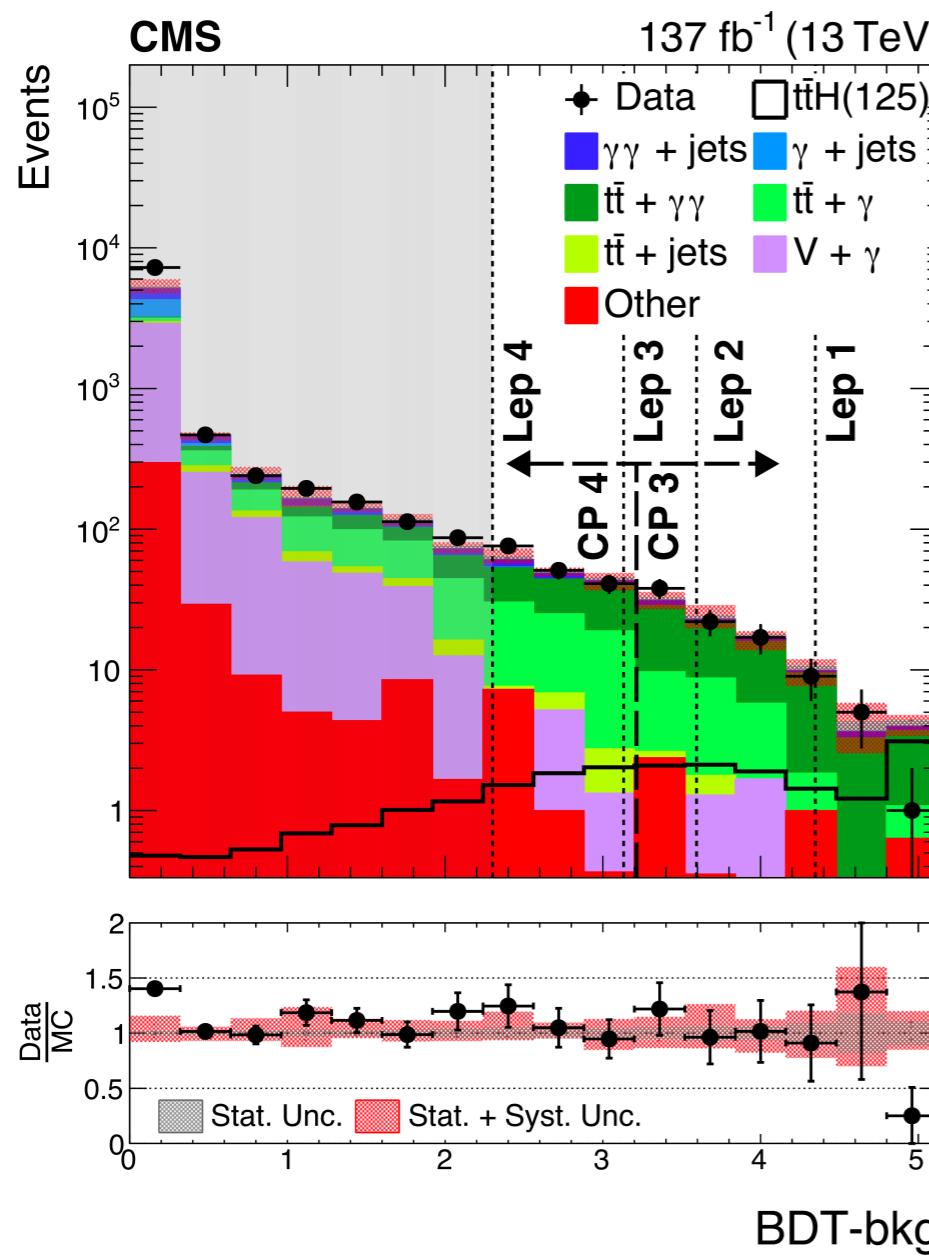
CP $\alpha = 90^\circ$



$t\bar{t}H(H \rightarrow \gamma\gamma)$: CP analysis



Leptonic category



$t\bar{t}H(H \rightarrow ZZ^* \rightarrow 4l)$

