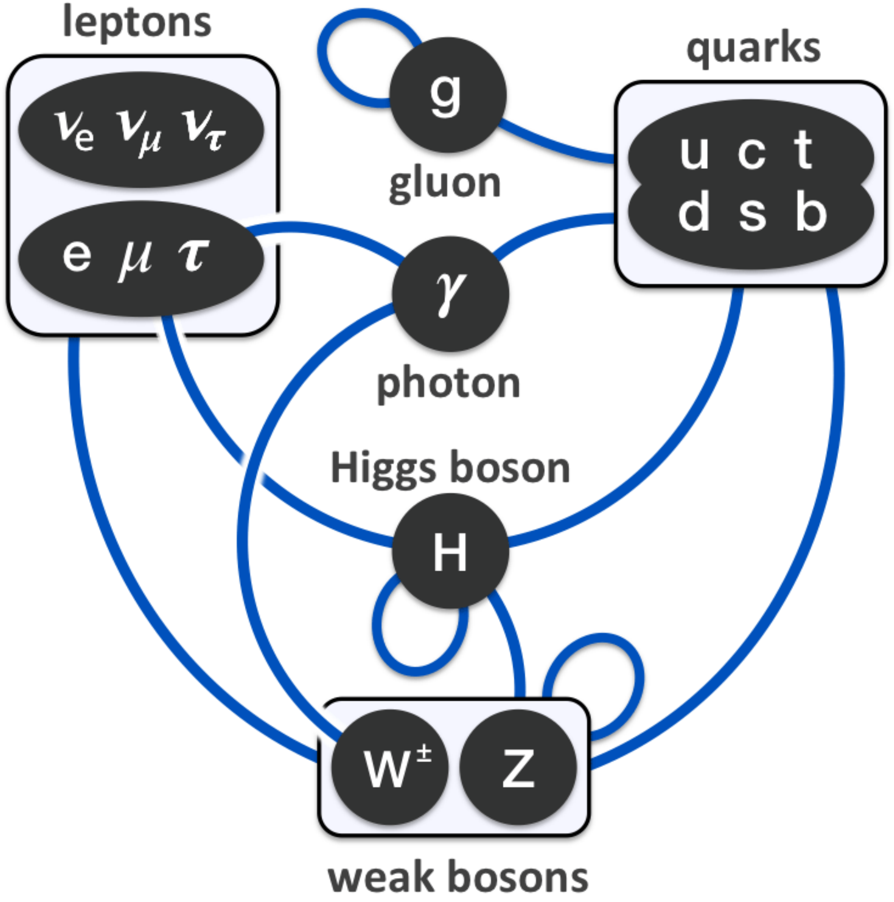
$t\bar{t}H$ and tH Production with $H \to b\bar{b}$ at the CMS Experiment

ABHISEK DATTA

UNIVERSITY OF CALIFORNIA, LOS ANGELES (UCLA)

NOVEMBER 14, 2023

The Standard Model and the Higgs Boson



https://commons.wikimedia.org/wiki/File:Elementary_particle_interactions_in_the_Standard_Model.png

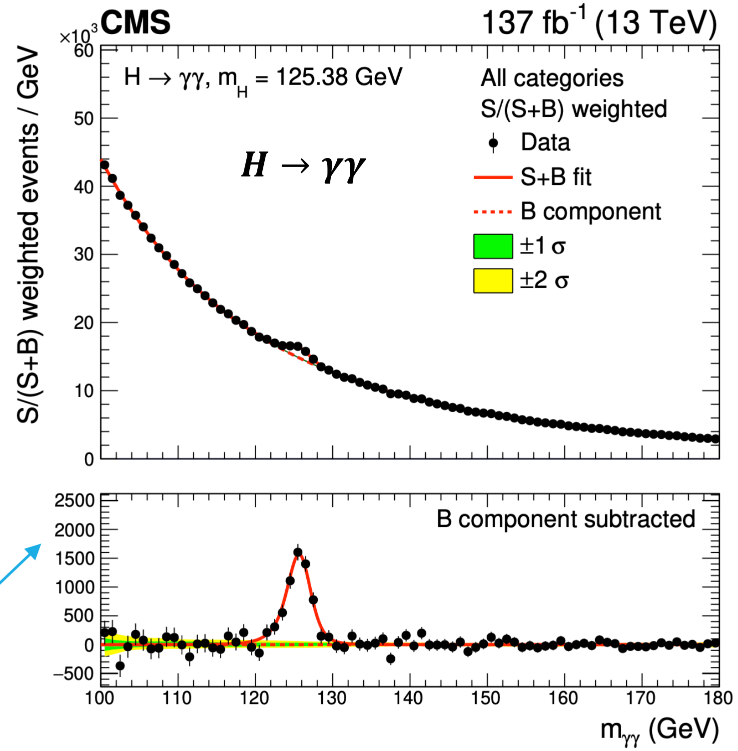
- In the Standard Model, the Higgs boson responsible for generating mass of:
  - Vector bosons via electroweak symmetry breaking
  - Fermions via Yukawa coupling (mass ∝ coupling strength)

Higgs boson discovery in 2012 by CMS [1] and ATLAS [2]

- $H \to \gamma\gamma$
- $H \to ZZ^* \to 4l$

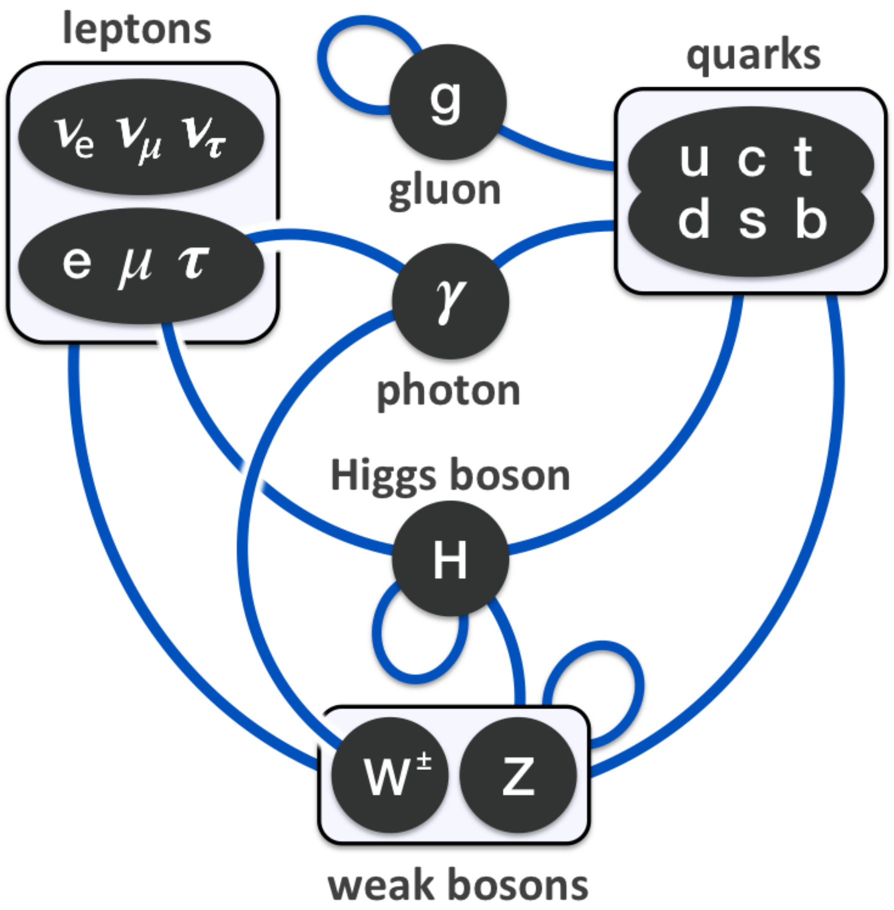
Observed mass of Higgs boson ~125 GeV

[1] CMS : Phys. Lett. B 716 (2012) 30–61
[2] ATLAS : Physics Letters B 716 (2012) 1–29



Latest results using Full Run-2 data
J. High Energ. Phys. 2021, 27 (2021)

The Standard Model and the Higgs Boson



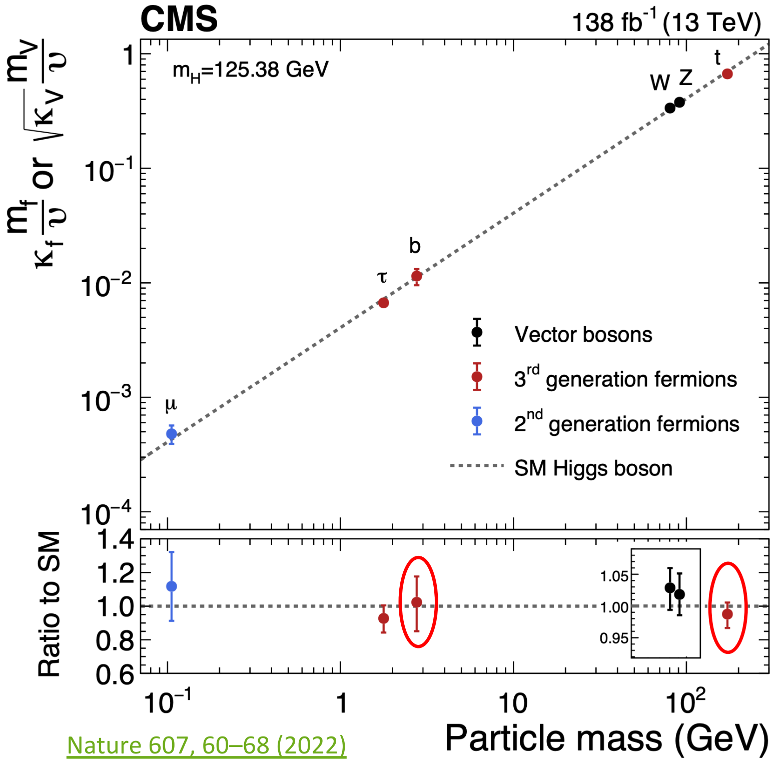
https://commons.wikimedia.org/wiki/File:Elementary_particle_interactions_in_the_Standard_Model.png

- In the Standard Model, the Higgs boson responsible for generating mass of:
  - Vector bosons via electroweak symmetry breaking
  - Fermions via Yukawa coupling (mass ∝ coupling strength)

Latest measurements of coupling strengths between the Higgs boson and vector bosons & fermions:

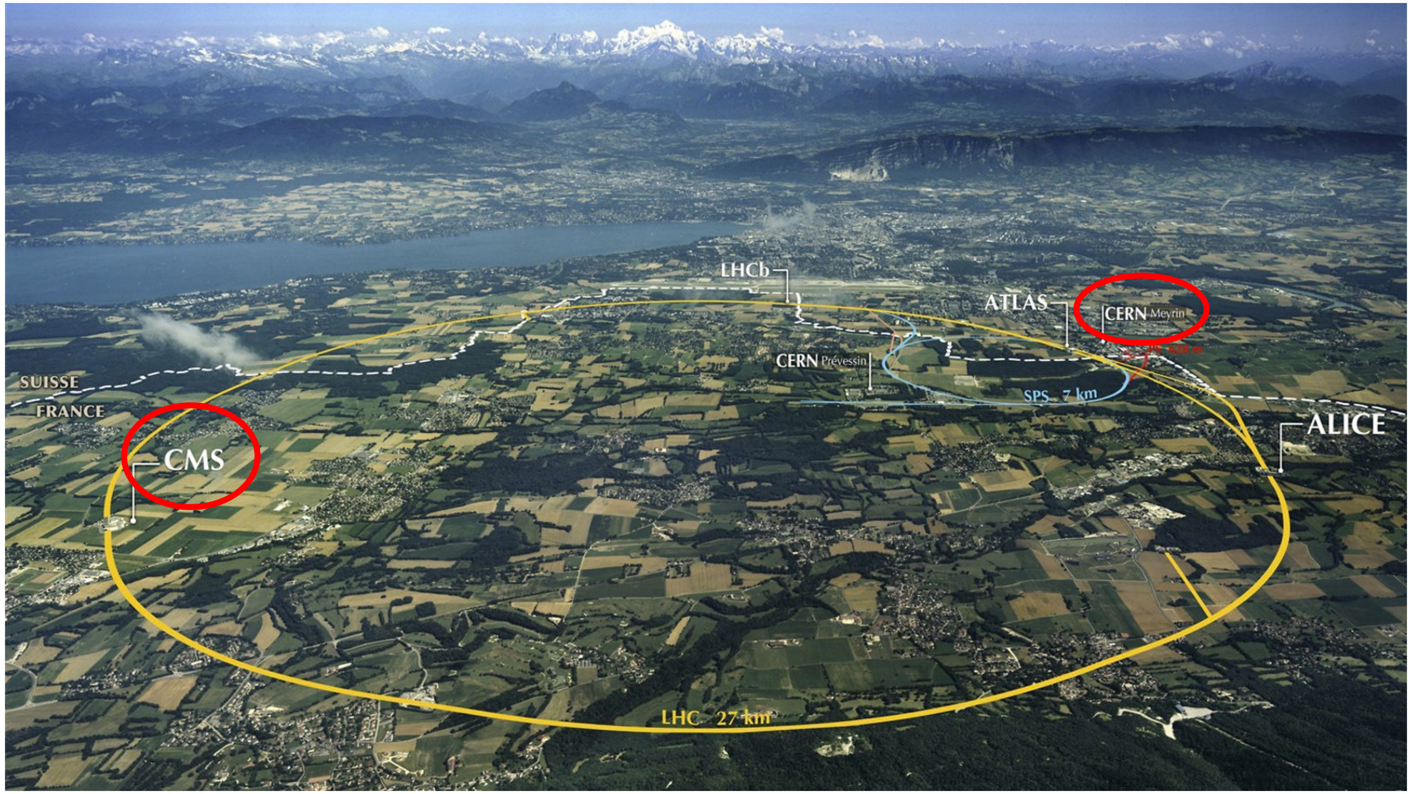
κ_b and κ_t: many BSM models can lead to modifications of Higgs boson couplings to fermions

→ higher precision needed



Nature 607, 60–68 (2022)

Large Hadron Collider (LHC)



A proton-proton (also heavy ion) collider lying in a 27 km tunnel below France and Switzerland

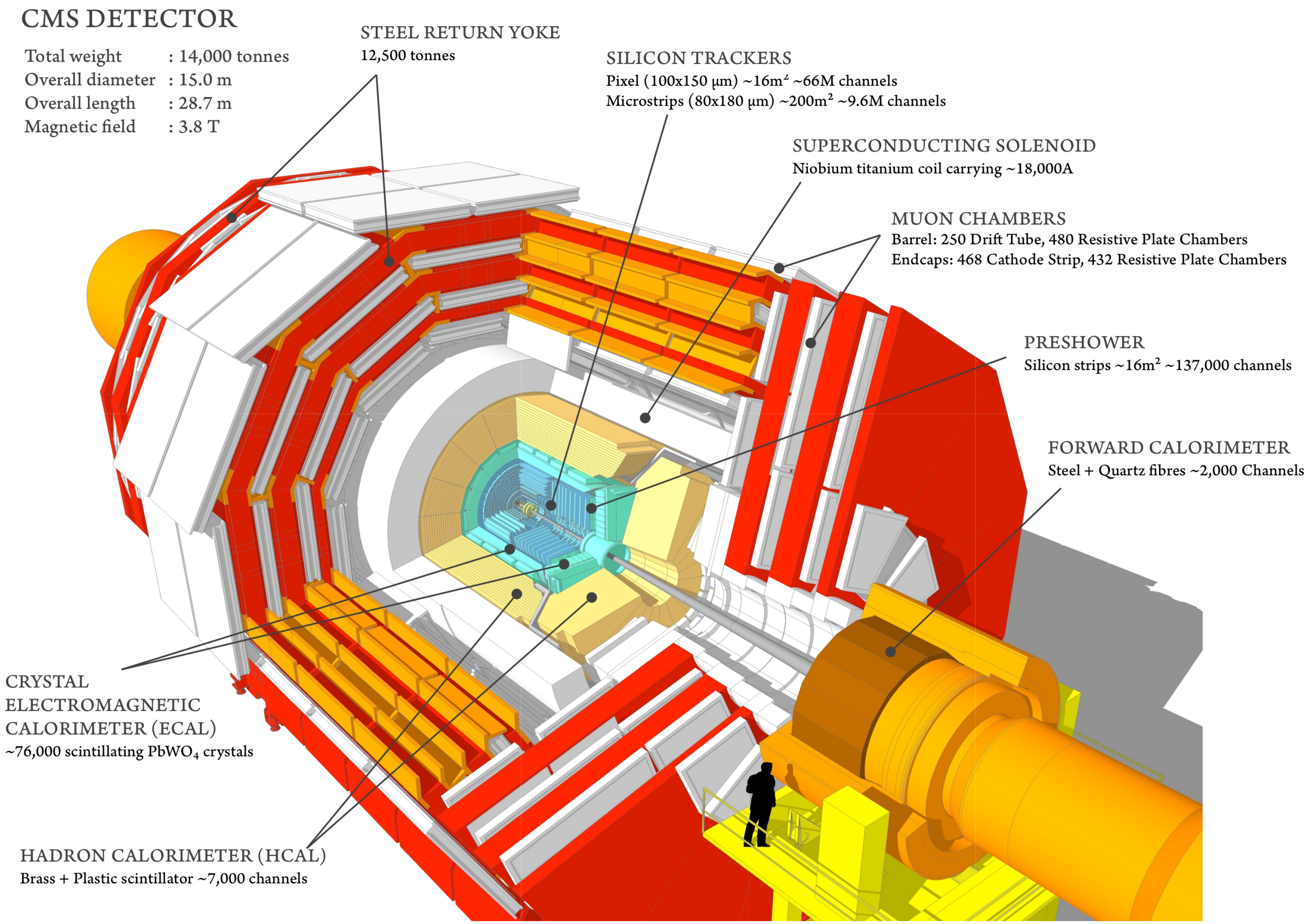
Data collected in Run-2 (2016-2018):

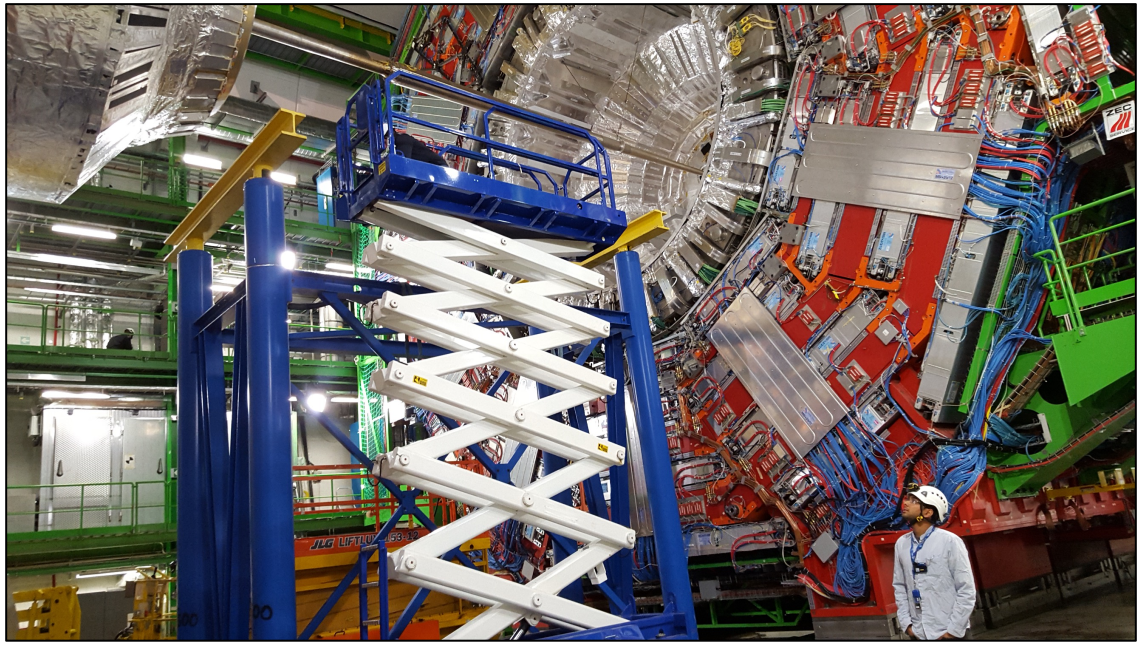
- Center-of-mass energy $\sqrt{s} = 13$ TeV
- Collision rate of 40 MHz
- Integrated luminosity = $138\ \text{fb}^{-1}$

4 experiments at the LHC :

- CMS (Compact Muon Solenoid)
- ATLAS (A Toroidal LHC ApparatuS)
- ALICE (A Large Ion Collider Experiment)
- LHCb (LHC-beauty)

Compact Muon Solenoid (CMS)



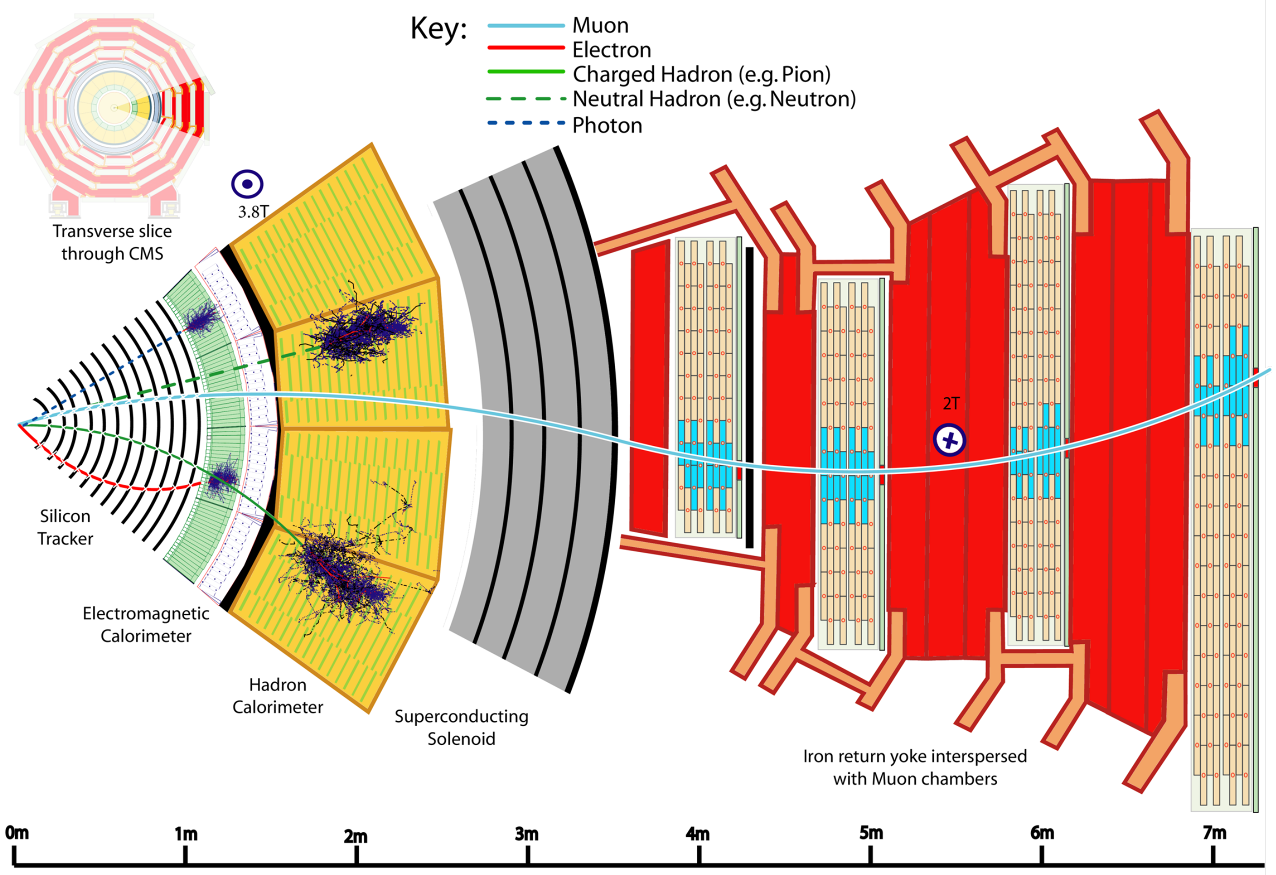


CMS detector in the cavern at CERN

https://cms.cern/detector

Particle and Event Reconstruction

Particle reconstruction using particle-flow (PF) technique



JINST 12 (2017) P10003

Different physics-objects identified:

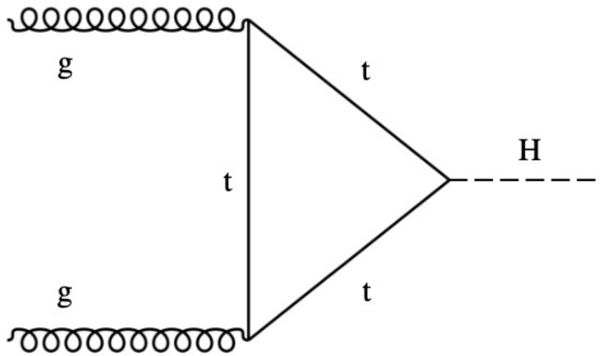
- Electrons reconstructed using tracks (from tracker) and energy deposits from ECAL
- Photons reconstructed from energy deposits in ECAL
- Muons reconstructed matching tracks from tracker and muon chambers
- Jets (of quarks and gluons) clustered from tracks and deposits in ECAL and HCAL
    - Jets originating from b-quarks - b-tagging
- Missing momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$) from momentum imbalance in the transverse plane (e.g. neutrinos)

Two Levels of Triggers:

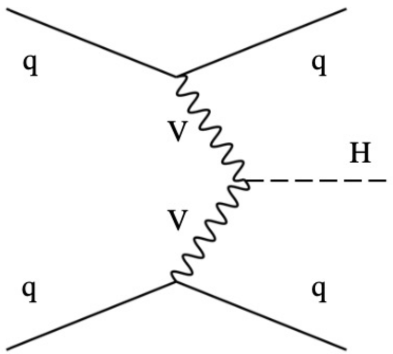
- Level-1: hardware level, reduces rate from 40 MHz to 100 kHz
- High Level Trigger (HLT): software level, further reduces to 1 kHz

Higgs Boson Production at the LHC

Gluon fusion (ggF)



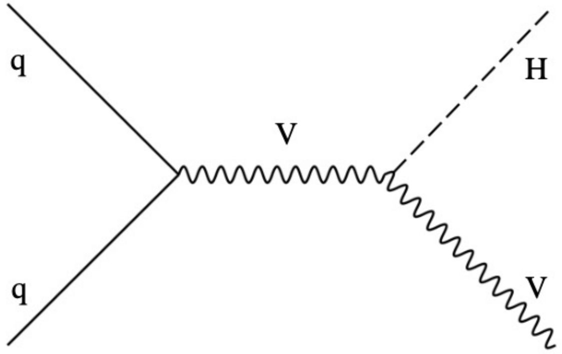
Vector boson fusion (VBF)



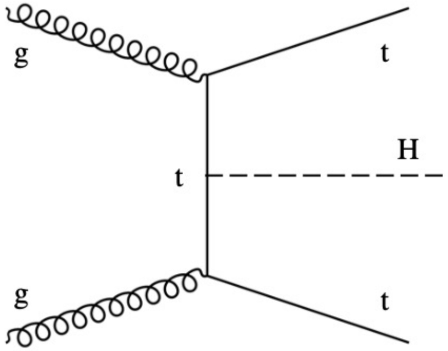
Gluon fusion is the **dominant production mode** at the LHC

$t\bar{t}H$ is the rarest production mechanism among these four

Associated production with a vector boson (VH)



Associated production with $t\bar{t}$ pair ($t\bar{t}H$)



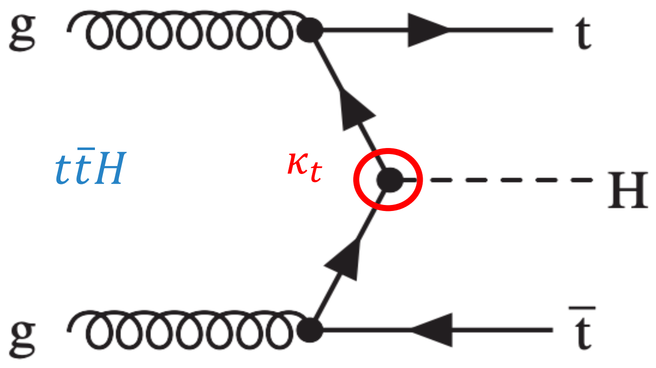
For a center-of-mass energy $\sqrt{s} = 13$ TeV

and $m_H = 125$ GeV

$\sigma_{\mathrm{t\bar{t}H}}(\approx 0.5\ \mathrm{pb}) \ll \sigma_{\mathrm{ggF}}(\approx 48.6\ \mathrm{pb})$

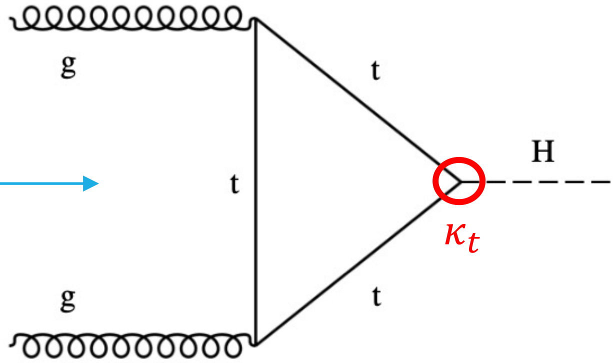
Why $t\bar{t}H$ and tH?

- $t\bar{t}H$ is the **best direct probe** of the **Top-Higgs coupling** (κ_t) at **tree level**



$\sigma_{t\bar{t}H} \approx 0.503$ pb

Possible to measure Top-Higgs coupling from gluon fusion, but only under the assumption of no BSM contributions to the top-loop



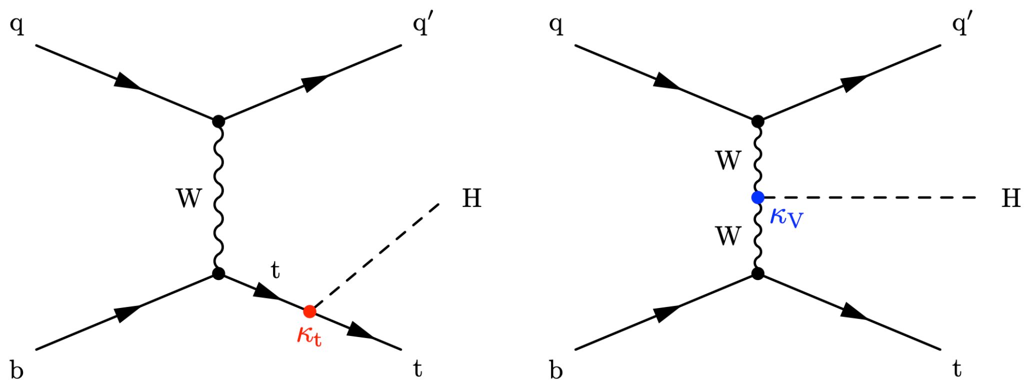
Observing a $t\bar{t}H$ production rate different from the Standard Model prediction can indicate the presence of BSM physics

BSM: Beyond the Standard Model

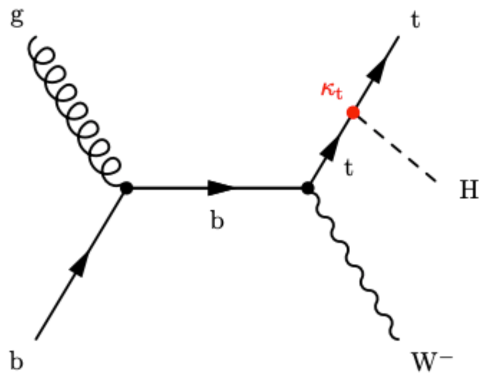
Why $t\bar{t}H$ and tH?

- $t\bar{t}H$ is the **best direct probe** of the **Top-Higgs coupling** (κ_t) at **tree level**
- tH provides **additional sensitivity** to sign of κ_t and κ_V due to interference terms (while $t\bar{t}H$ only sensitive to κ_t^2)
- Also **sensitive** to *CP-odd* contribution in **Top-Higgs Yukawa coupling**

tHq



tHW



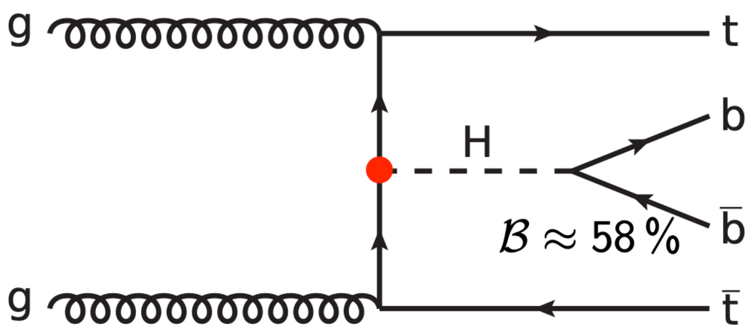
$\sigma_{tHq} \approx 0.074$ pb
$\sigma_{tHW} \approx 0.015$ pb

Cross-section even smaller than $t\bar{t}H$ in SM

$t\bar{t}H$ and tH with $H \to b\bar{b}$

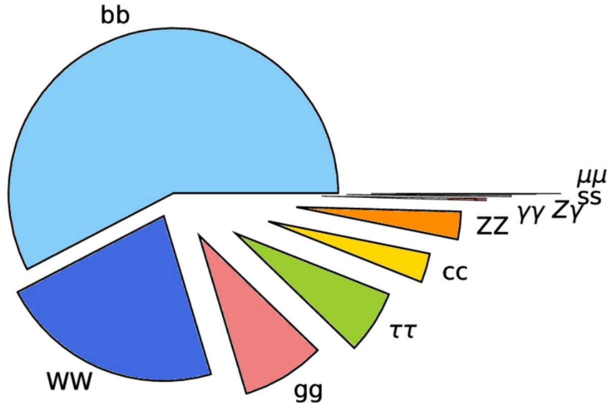
- $t\bar{t}H$ is the **best direct probe** of the **Top-Higgs coupling** (κ_t) at **tree level**

$t\bar{t}H\ (H \to b\bar{b})$



Many possible decay channels for the Higgs boson:
- $H \to b\bar{b}$
- $H \to WW^*, \tau\tau, ZZ^*$
- $H \to \gamma\gamma$

$H \to b\bar{b}$ final state chosen for this analysis:
- Largest branching fraction of 58%
- Fully reconstructable Higgs boson final state
- All Higgs-fermion (even 3rd generation – t and b) vertices



Goal: Measurement of the $t\bar{t}H$ production cross-section w.r.t. SM prediction i.e. the signal strength $\mu_{t\bar{t}H}$

$$\mu_{t\bar{t}H} = \frac{\sigma(t\bar{t}H)}{\sigma_{SM}(t\bar{t}H)} \cdot \frac{\mathcal{B}(H \to b\bar{b})}{\mathcal{B}_{SM}(H \to b\bar{b})}$$

Previous Results on $t\bar{t}H$ and tH

$t\bar{t}H$ observation by the combination of all decay channels at both CMS and ATLAS in 2018

Using partial Run-2 ($\sqrt{s} = 13$ TeV) + Run-1 ($\sqrt{s} = 7$ and 8 TeV) data :

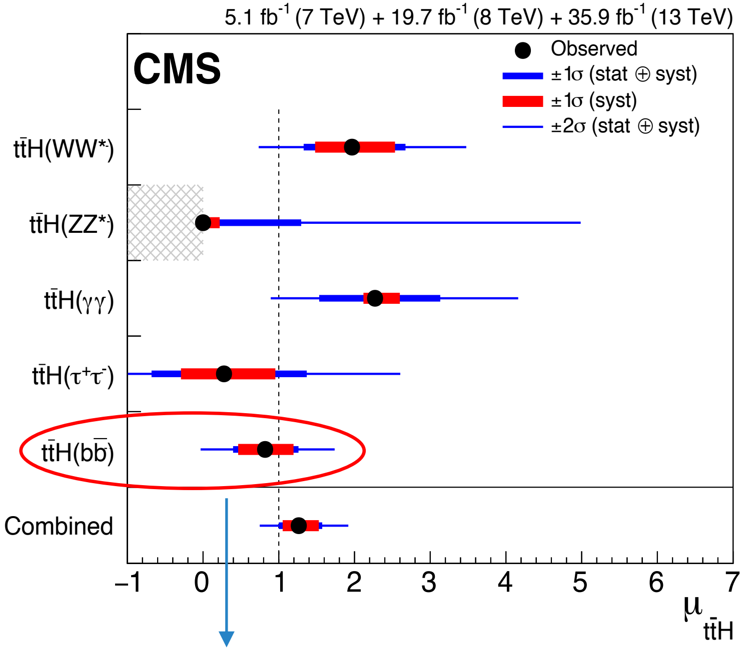
Results	Observed Significance
CMS [1]	5.2 σ
ATLAS [2]	6.3 σ

[1] Phys. Rev. Lett. 120 (2018) 231801 (CMS)
[2] Physics Letters B 784 (2018) 173–191 (ATLAS)

Best-fit signal strength from CMS: $\mu_{\mathrm{t\bar{t}H}} = 1.26^{+0.31}_{-0.26}$

$t\bar{t}H$ signal strength consistent with SM expectations

Observation from CMS [1]



$t\bar{t}H(H \to b\bar{b})$ results using 2016 data

J. High Energ. Phys. **2019**, 26 (2019)
J. High Energ. Phys. 2018, 101 (2018)

Previous result for tH $(H \to b\bar{b})$ production from CMS:

Upper Limits using 2016 data :

- SM (Standard Model) scenario : 89.5 $\times\ \sigma_{SM}$ (41.4 exp.)
- ITC (Inverted Top Coupling) scenario : 5.83 $\times\ \sigma_{ITC}$ (2.94 exp.)

Phys. Rev. D99 (2019) 092005

$t\bar{t}H(H \to b\bar{b})$ Using Full Run-2 Data

Following the $t\bar{t}H$ discovery, the focus is now on more precise measurements of $t\bar{t}H$ production in each decay channel

For the $t\bar{t}H(H \to b\bar{b})$ channel, using full Run-2 (2016 – 2018 : $138\ \mathrm{fb}^{-1}$) data

Published in 2023 (CMS-PAS-HIG-19-011) → **Focus of today's talk**

Paper in preparation

Preliminary result using 2016 + 2017 data only: **published in 2019** (CMS-PAS-HIG-18-030)

Major improvements in the analysis:

- Better modeling of the major irreducible $t\bar{t} + b\bar{b}$ background for $t\bar{t}H(H \to b\bar{b})$ with improved simulation
- Refined neural network classifiers (for signal to background discrimination)
- New triggers to increase signal efficiency in the different final states
- Better identification of jets arising from b-quarks from both improved algorithms and also upgrades in the pixel tracking detector of CMS
- Additional interpretations including differential measurements and coupling constants

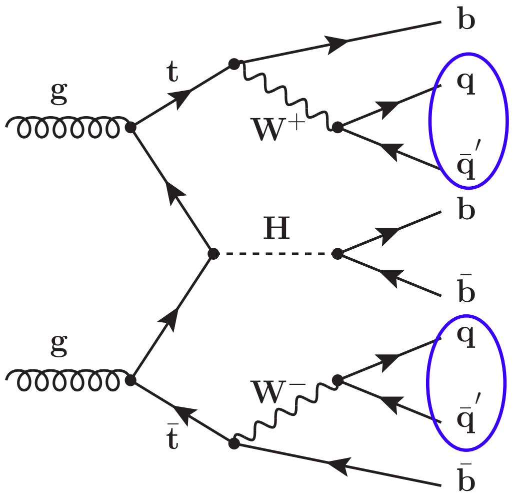
Final States Signatures

Different final states depending on $t\bar{t}$ decay :

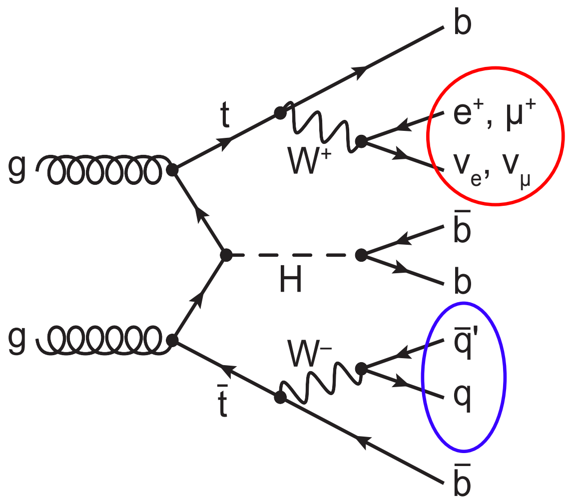
- Fully Hadronic (FH)
- Single Lepton (SL) : e , μ
- Dilepton (DL) : ee , $e\mu$, $\mu\mu$

Event Selection requires :

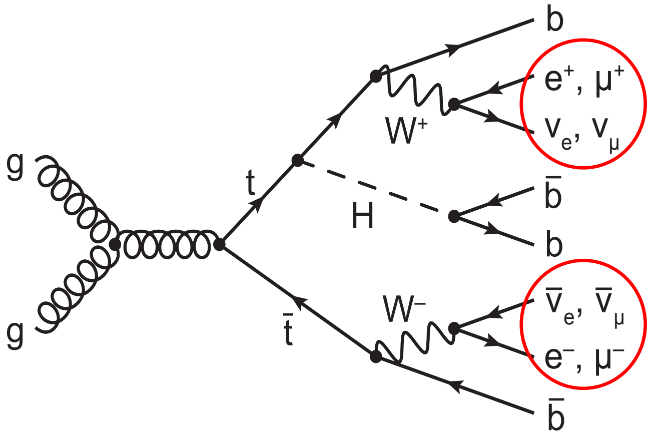
- 0/1/2 leptons depending on the channel
- Multiple jets (including b-tagged jets)



Fully Hadronic (FH)



Single Lepton (SL)



Dilepton (DL)

Important role in final state selection:

- Triggers
- b-tagging

Worked on improving both in the past during my PhD:

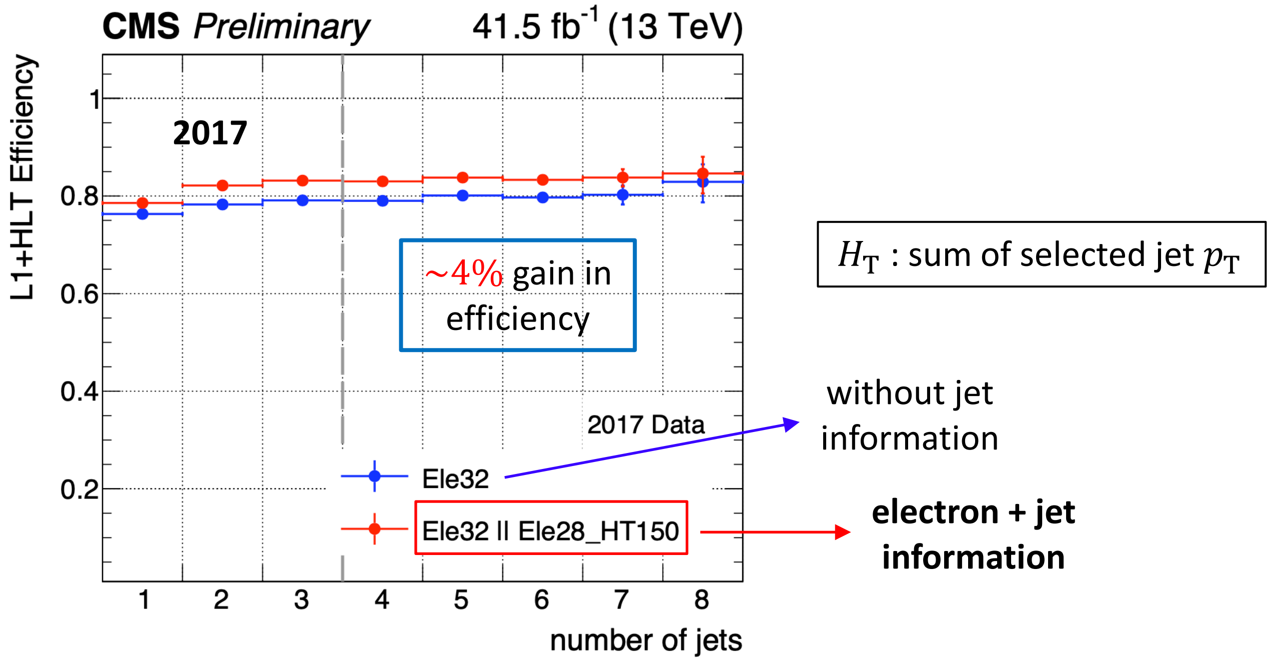
- Developed trigger algorithms for the single lepton channel
- Contributed to the excellent operation of the pixel detector crucial for b-tagging

Development of Single Electron Triggers

Developed new Single Electron triggers for 2017 and 2018 data taking for the $t\bar{t}H(H \rightarrow b\bar{b})$ analysis :

- Used **both** electron and jet information in the final states to design new triggers
- Allows keeping the p_{T} threshold low for the electron
- Retains signal efficiency at higher luminosity with negligible increase in data rates

This trigger also **used** in other Higgs and Top analyses



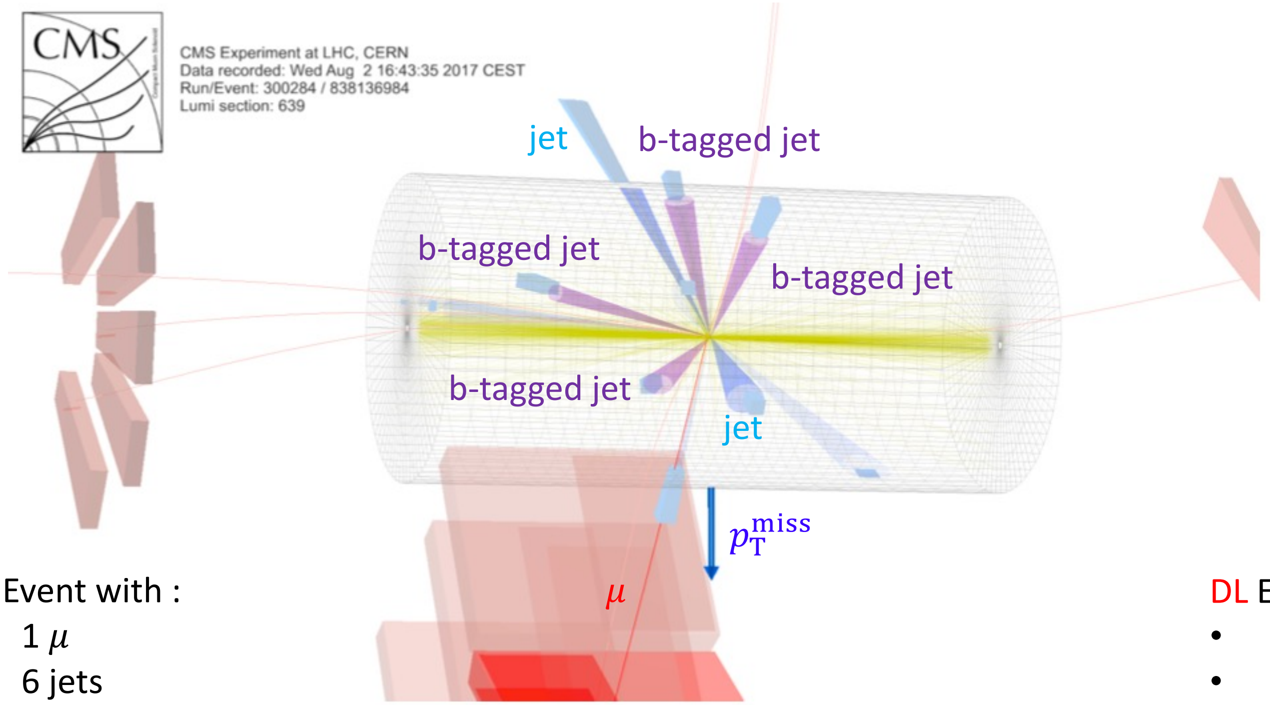
Efficiency vs Jet Multiplicity

Results public : CMS DP -2019/026

Candidate $t\bar{t}H(H \rightarrow b\bar{b})$ Events in CMS

Candidate $t\bar{t}H(H \rightarrow b\bar{b})$ events after reconstruction and selections

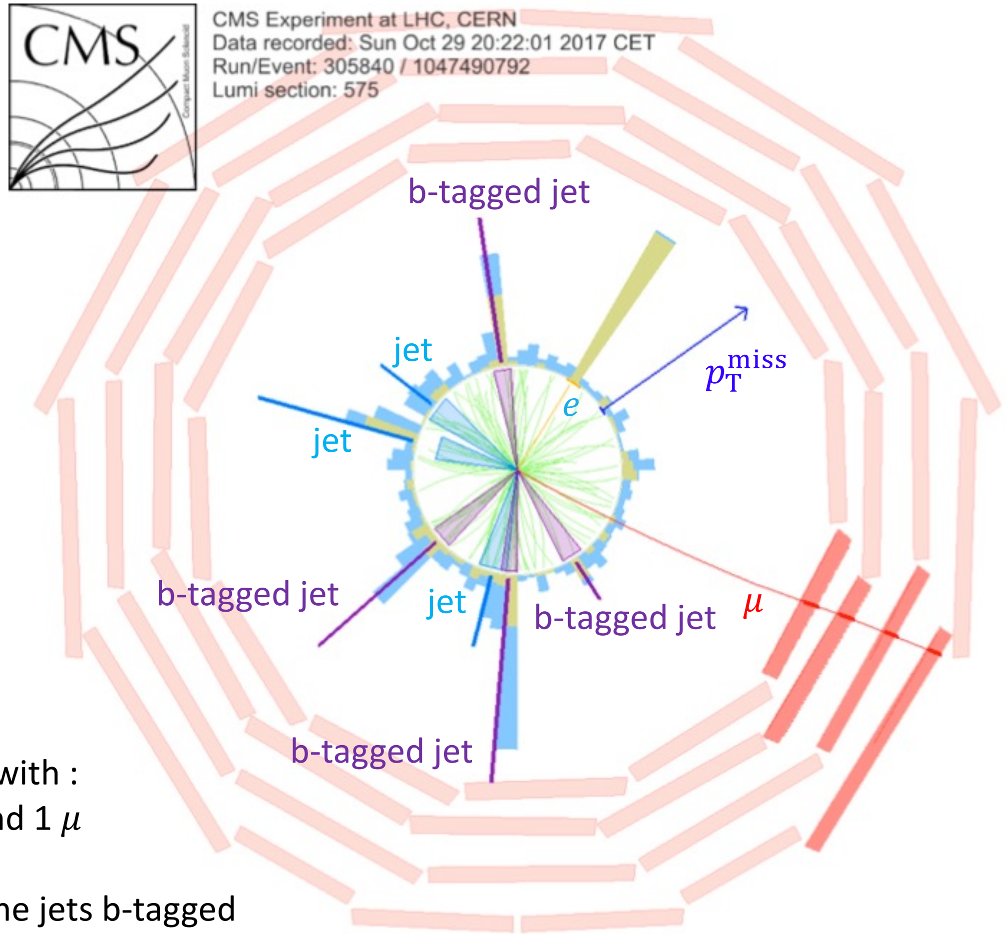
Single Lepton (SL) Channel



SL Event with :

- 1 μ
- 6 jets
- 4 of the jets b-tagged

Dilepton (DL) Channel

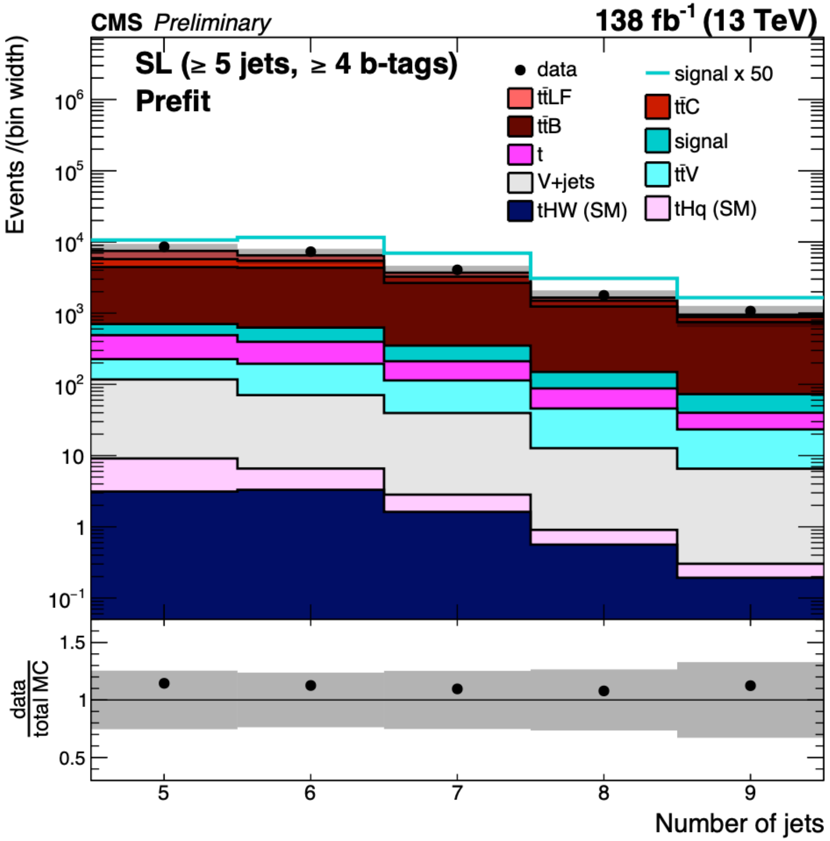


DL Event with :

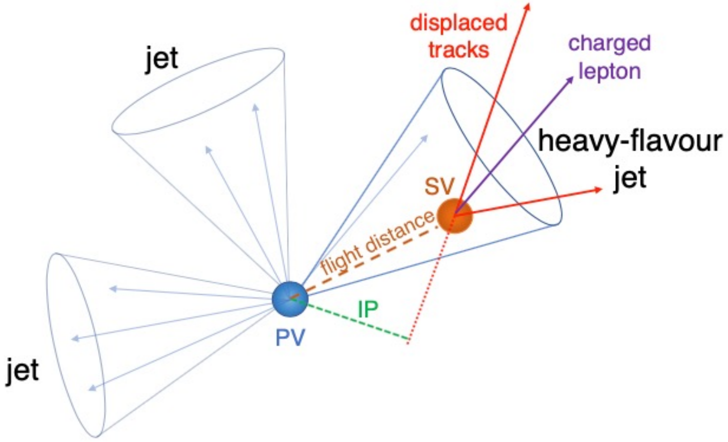
- 1 e and 1 μ
- 7 jets
- 4 of the jets b-tagged

Challenging Final State

- Very busy final state with lots of jets and b-jets
- Small signal ($t\bar{t}H$ and tH) cross-section compared to large irreducible backgrounds ($t\bar{t} + b\bar{b}$)



Identifying jets originating from b-quarks essential



b-tagging algorithms based on:
- Long lifetime of B-hadrons
- Secondary vertex displaced (~ 0.5 mm) from the interaction point

Full Run-2 analysis uses improved DeepJet b-tagging algorithm:

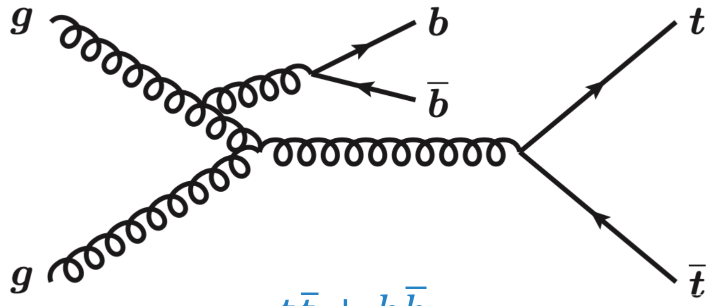
- **Improves** b-tagging efficiency by 5-10% at same mis-tag probability
- Operate at 75-80% signal efficiency, 1.5-2% mis-tag probability for light-flavored jets

More details here and here

Major Background Processes

$t\bar{t}$ +jets (all channels):

- Modeled from simulation
- Divided into three sources depending on flavor of additional particle-level jets:
  - $t\bar{t}+B$: >= 1 additional b-jet - irreducible background (mostly $t\bar{t}+b\bar{b}$):
    - Modeling challenging due to complex multi-parton states and multiple, very different scales ($t\bar{t}$, $b\bar{b}$)
    - Large modeling uncertainties, crucial for $t\bar{t}H(b\bar{b})$ measurement
    - Current measurements $\sim 20-40\%$ larger than prediction
  - $t\bar{t}+C$: >= 1 additional c-jet but no b-jet
  - $t\bar{t}+LF$: all other events (LF: light flavor)



$t\bar{t}+b\bar{b}$

QCD Multijet (Fully Hadronic channel):

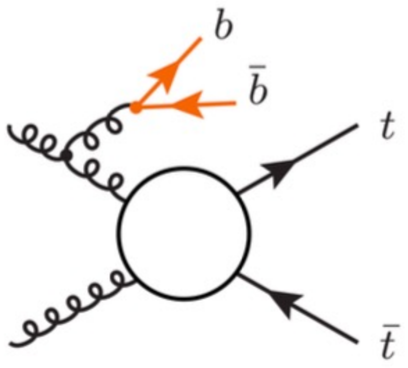
- Dedicated background rejection
- Data-driven background estimation using Control Regions

Minor backgrounds (all channels):

- Single-top, diboson, $t\bar{t}+V$, V +jets
- Modeled from simulation

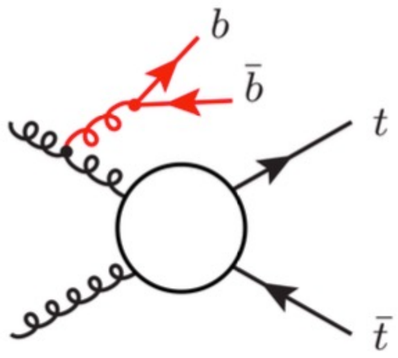
$t\bar{t} + B$ Background Model

One of the major improvements of the Full Run-2 analysis is the improved modeling of the $t\bar{t} + B$ irreducible background



In earlier versions of the analysis (including the 2016+2017 published analysis), $t\bar{t} + B$ processes described by:

- $t\bar{t}$+jet Matrix Element (ME) at NLO (5FS): additional b-jets from parton shower (PS)
- Subject to PS and large/not well-defined uncertainties of PS tuning parameters



In the full Run-2 analysis, $t\bar{t} + B$ processes described by:

- $t\bar{t}b\bar{b}$ ME at NLO (4FS)*: additional b-jets from ME
- NLO+PS accuracy for $t\bar{t}$ + 1 and 2 b-jet observables

Theoretically preferred option for $t\bar{t} + B$ modeling: improvement (w.r.t. to $t\bar{t}$ 5FS) in event kinematics

4FS: 4 flavor scheme
5FS: 5 flavor scheme

NLO: Next to Leading Order

* Eur. Phys. J. C 78 (2018) 502

$t\bar{t} + B$ Background Model

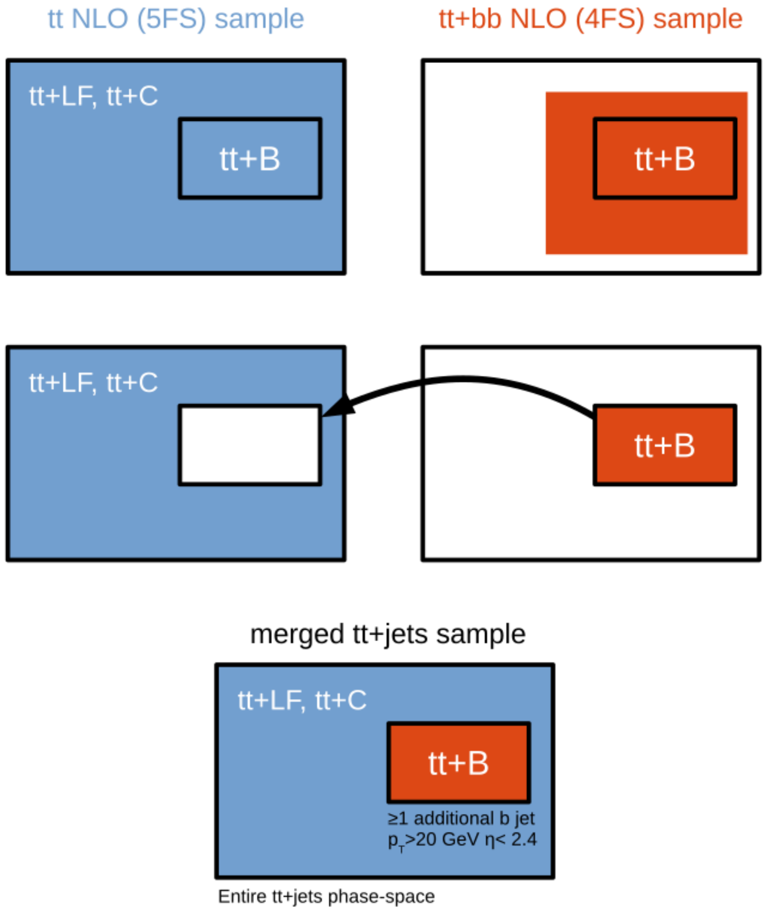
One of the major improvements of the Full Run-2 analysis is the improved modeling of the $t\bar{t} + B$ irreducible background

- Based on theory recommendations, new $t\bar{t}b\bar{b}$ simulation (4FS):
  - NLO accuracy simulation using Powheg-Box-Res (Jezo et al) with OpenLoops (Buccioni et al) in the 4FS

New Merged $t\bar{t}$ + Jets Background Model used in the Full Run-2 Analysis:

- $t\bar{t} + C, t\bar{t} + LF$ taken from $t\bar{t}$ NLO (5FS) sample
  - Overall $t\bar{t}$ + Jets normalization: Inclusive $t\bar{t}$ + Jets cross-section (NNLO+NNLL)

- $t\bar{t} + B$ taken from $t\bar{t}b\bar{b}$ NLO (4FS) sample
  - $t\bar{t} + B$ component normalized to $t\bar{t}$ NLO (5FS) MC prediction
  - $t\bar{t} + B$ and $t\bar{t} + C$ normalizations freely floating in the fit



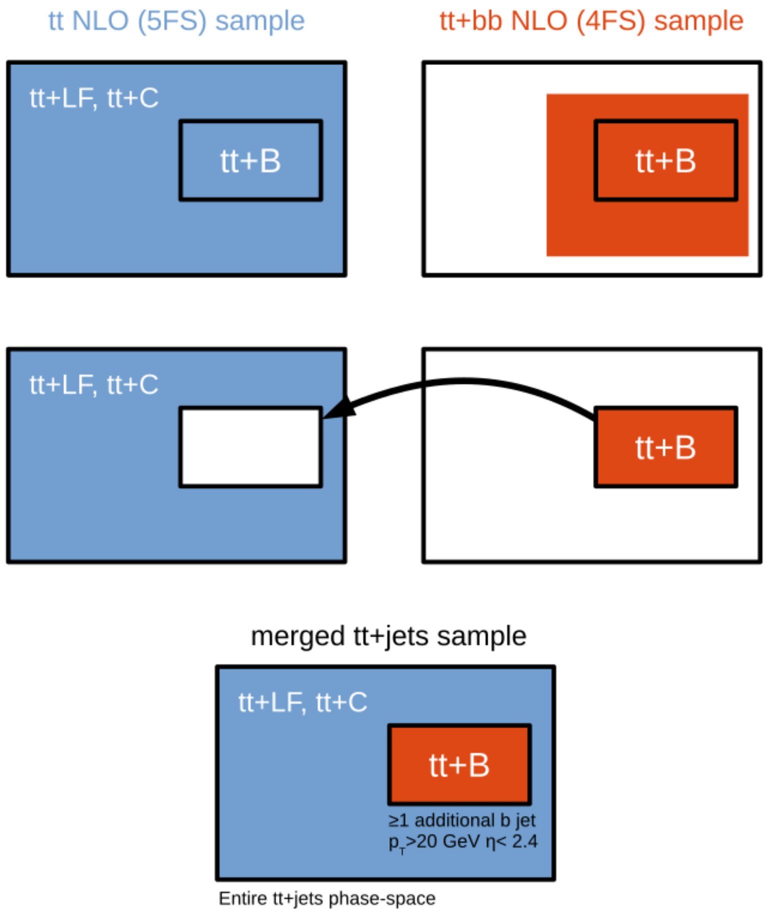
* Eur. Phys. J. C 78 (2018) 502

$t\bar{t}+B$ Background Model

One of the major improvements of the Full Run-2 analysis is the improved modeling of the $t\bar{t}+B$ irreducible background

Background model carefully validated:

- Good description of event kinematics on using $t\bar{t}b\bar{b}$ NLO (4FS)
- Dedicated modeling uncertainties decorrelated between $t\bar{t}+B$ and other $t\bar{t}$ events
    - Pulls and impacts well understood
- Goodness-of-fit tests
- Bias tests on the signal strength
    - Test for potentially mismodelled $t\bar{t}+B$ background using toy data
    - Fit model was found to be robust against potential deviations of the $t\bar{t}+B$ in data from the nominal prediction



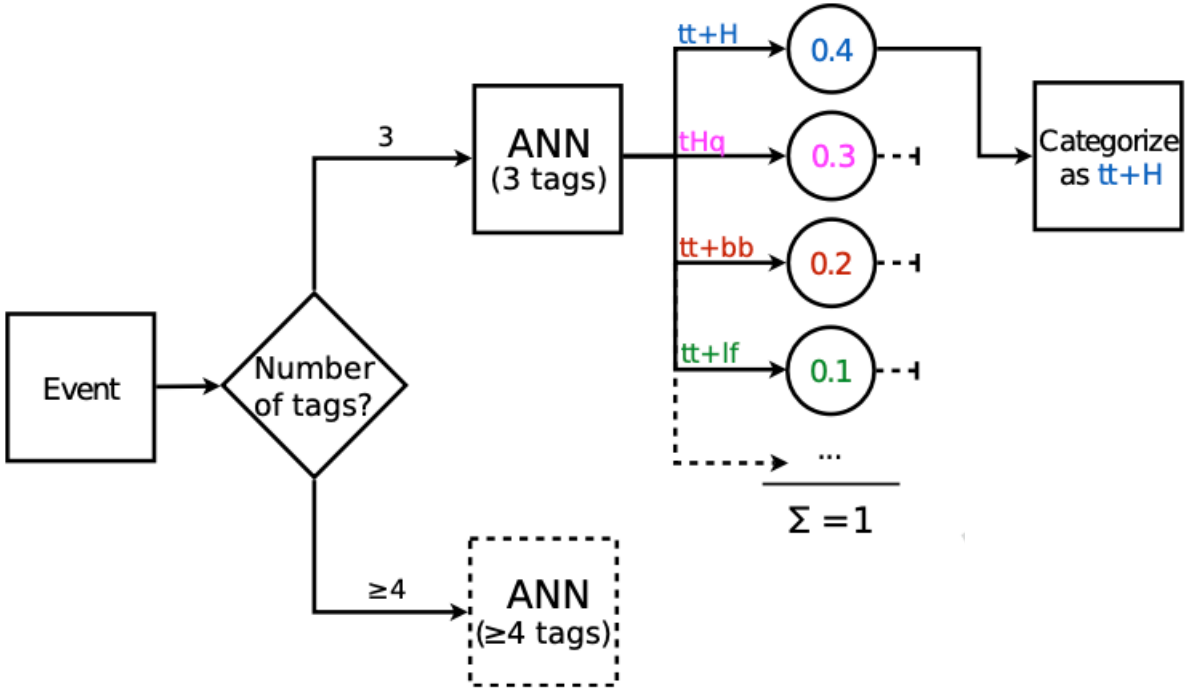
* Eur. Phys. J. C 78 (2018) 502

Analysis Strategy

The analysis strategy relies on Event Categorization and Artificial Neural Networks (ANN)

- Event categorization to form signal and control regions (to constrain background):
  - Based on jet and b-tag multiplicity
  - Based on multi-class ANNs

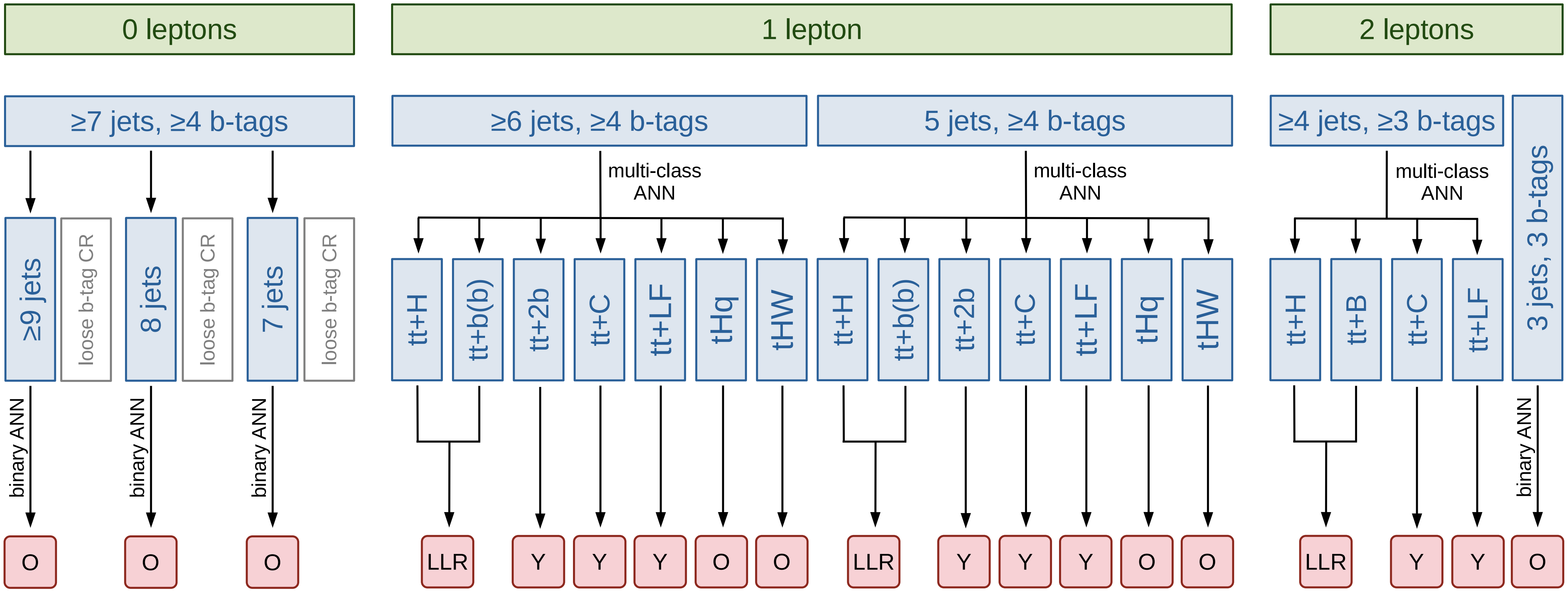
- Artificial Neural Networks (ANN):
  - Trained to separate signal from dominant background
  - Binary or multi-class depending on channel/category
  - Used for event categorization and as final discriminants



ANN Training:

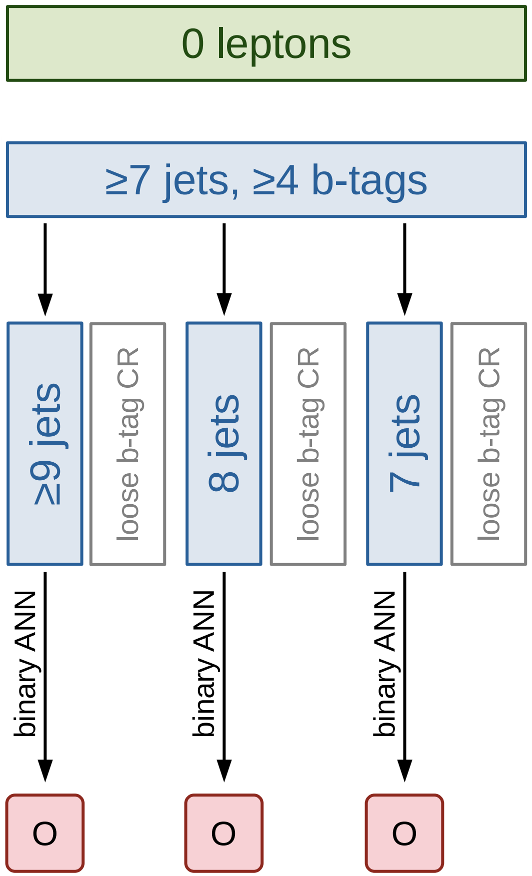
- Trained on several kinematic variables
  - Modelling of input variables validated with goodness-of-fit tests
- Usually trained on Monte-Carlo, except QCD (trained in a QCD enriched control region)
- One ANN training valid for all years in each channel and category

Inclusive $t\bar{t}H/tH$ Measurement



Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (LLR)

Inclusive $t\bar{t}H / tH$ Measurement



Full Hadronic Channel:

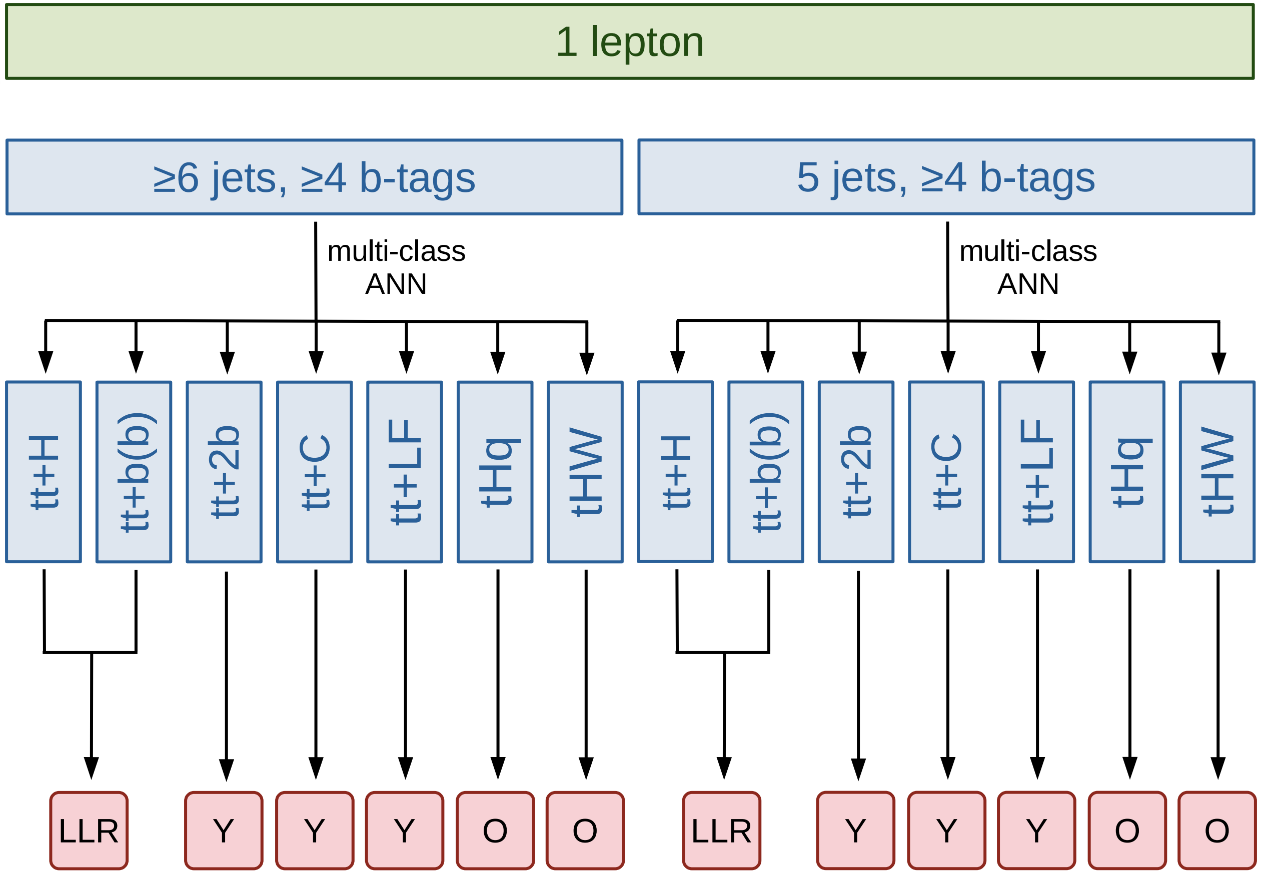
- Event categorization based on number of jets and b-tags
- Control regions based on loosely-tagged b-jets for ANN training and data-driven QCD estimation
- Binary ANN to separate signal from background (mainly QCD):
  - ANN output used as final fit observable

Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (LLR)

Inclusive $t\bar{t}H/tH$ Measurement

Single Lepton Channel:

- Event categorization based on number of jets and b-tags
- Further multiclassification based on ANN



Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (LLR)

Final fit observables:

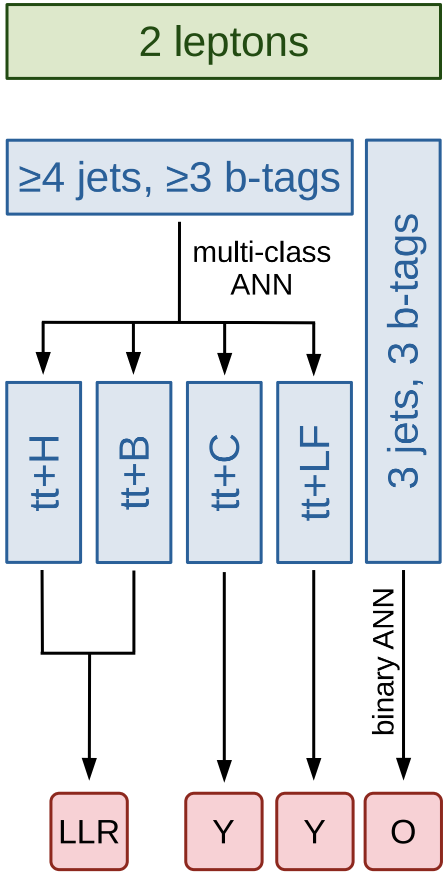
- Event yields in background enriched nodes
- ANN output for tHq and tHW signal regions
- Ratio observable in combined $t\bar{t}H$ and $t\bar{t}B$ category

$$R_{SL} = \frac{O(t\bar{t}H)}{O(t\bar{t}H) + O(t\bar{t} + b(\bar{b})) + O(t\bar{t} + 2b)}$$

Inclusive $t\bar{t}H/tH$ Measurement

Dilepton Channel:

- Event categorization based on number of jets and b-tags
- Further multiclassification based on ANN in the more signal sensitive category
- **Final fit observables:**
  - Event yields in background enriched nodes
  - Binary ANN output in less signal sensitive region
  - Ratio observable in combined $t\bar{t}H$ and $t\bar{t}B$ category (more signal sensitive)

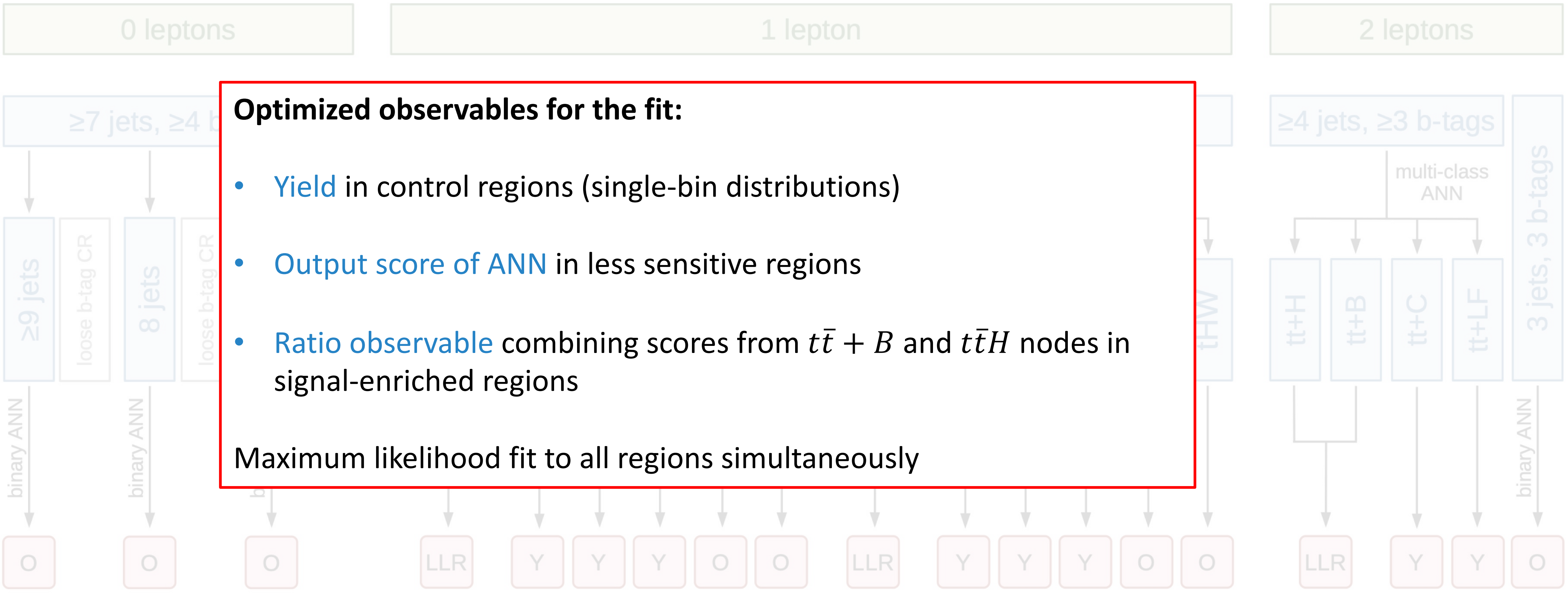


Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (LLR)

$$R_{DL} = \frac{O(t\bar{t}H)}{O(t\bar{t}H) + O(t\bar{t}B)}$$

$$R_{SL} = \frac{O(t\bar{t}H)}{O(t\bar{t}H) + O(t\bar{t} + b(\bar{b})) + O(t\bar{t} + 2b)}$$

Inclusive $t\bar{t}H/tH$ Measurement



Optimized observables for the fit:

- Yield in control regions (single-bin distributions)
- Output score of ANN in less sensitive regions
- Ratio observable combining scores from $t\bar{t}+B$ and $t\bar{t}H$ nodes in signal-enriched regions

Maximum likelihood fit to all regions simultaneously

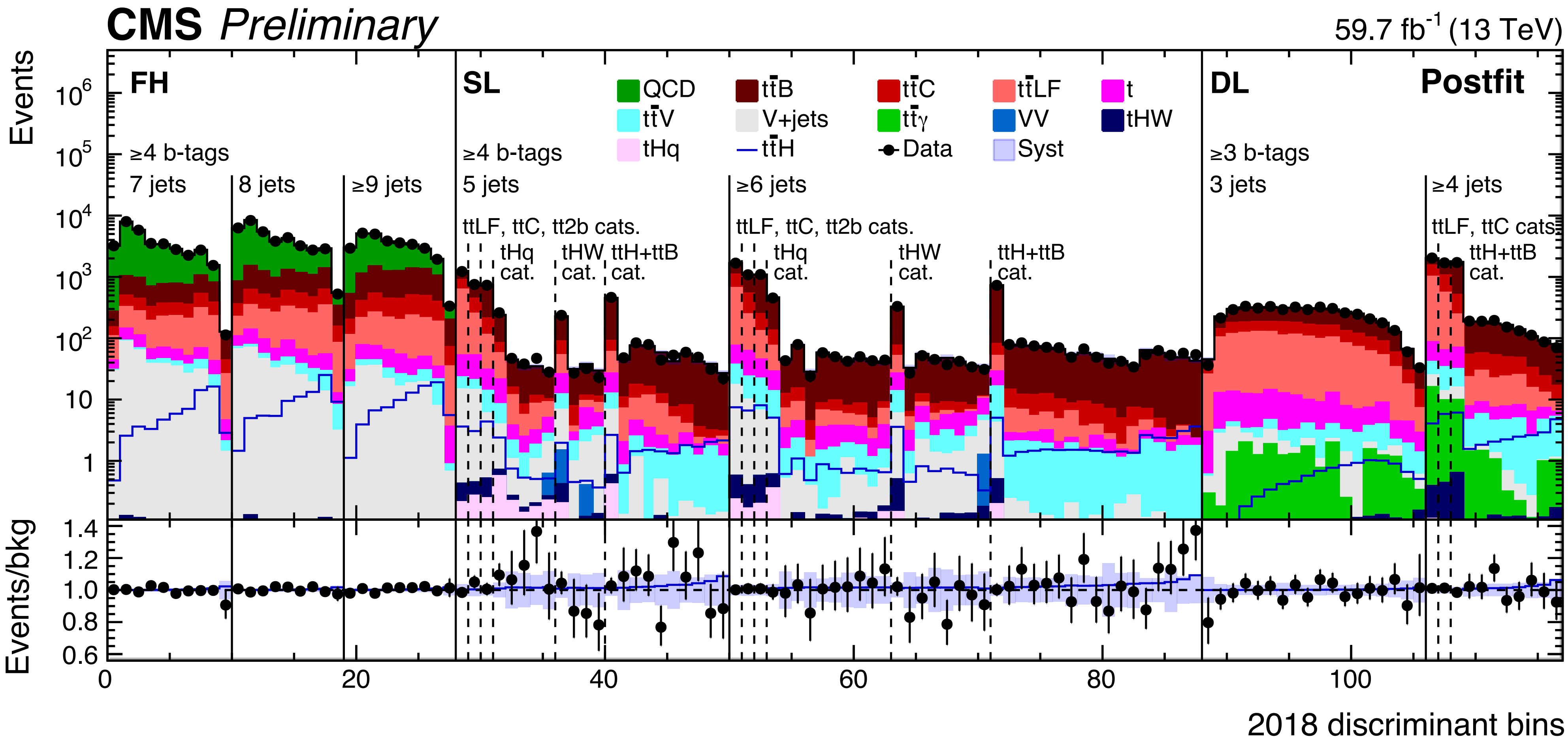
Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (LLR)

$$R_{DL} = \frac{O(t\bar{t}H)}{O(t\bar{t}H) + O(t\bar{t}B)}$$

$$R_{SL} = \frac{O(t\bar{t}H)}{O(t\bar{t}H) + O(t\bar{t} + b(\bar{b})) + O(t\bar{t} + 2b)}$$

Inclusive $t\bar{t}H$ Results: Postfit Distributions

Postfit distributions from 2018 (2016 and 2017 in backup):

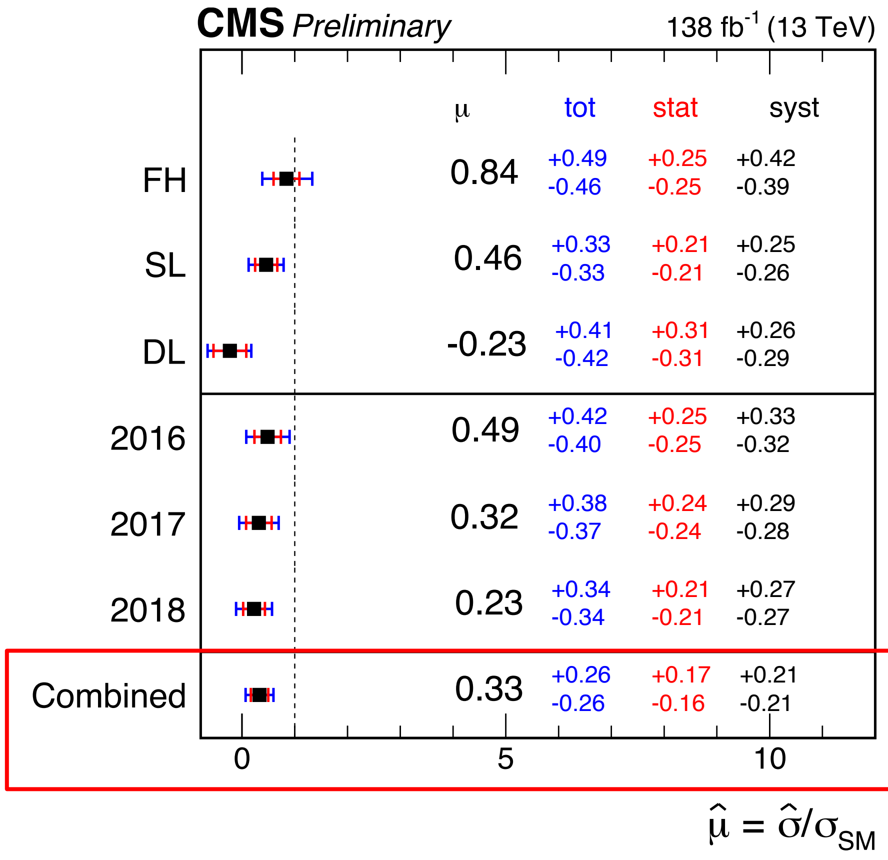


Expect a **total** of $\sim 1100\ t\bar{t}H$ events

Fitted observables in this plot are the event yields, ANN outputs and ratio observables

Inclusive $t\bar{t}H$ Results: Signal Strength

Full Run-2 Results



	μ	tot	stat	syst
FH	0.84	+0.49 -0.46	+0.25 -0.25	+0.42 -0.39
SL	0.46	+0.33 -0.33	+0.21 -0.21	+0.25 -0.26
DL	-0.23	+0.41 -0.42	+0.31 -0.31	+0.26 -0.29
2016	0.49	+0.42 -0.40	+0.25 -0.25	+0.33 -0.32
2017	0.32	+0.38 -0.37	+0.24 -0.24	+0.29 -0.28
2018	0.23	+0.34 -0.34	+0.21 -0.21	+0.27 -0.27
Combined	0.33	+0.26 -0.26	+0.17 -0.16	+0.21 -0.21

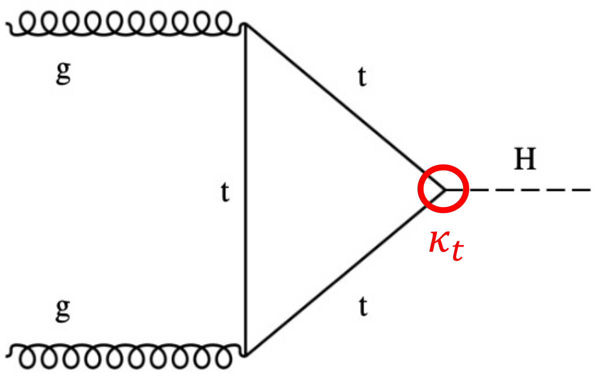
Uncertainties are correlated among channels and years

- $t\bar{t}H$ signal strength:
  - $\mu_{t\bar{t}H} = 0.33 \pm 0.26$, 1.3 σ obs. (4.1 σ exp.) significance
  - SM compatibility p-value: 2% (2.4 σ)
  - Compatibility to 2016 CMS publication (SL+DL): 41% (0.8 σ)

Agreement with ATLAS Full Run-2 result:
- $\mu_{t\bar{t}H} = 0.35 + 0.35 - 0.34$

J. High Energ. Phys. 2022, 97 (2022)

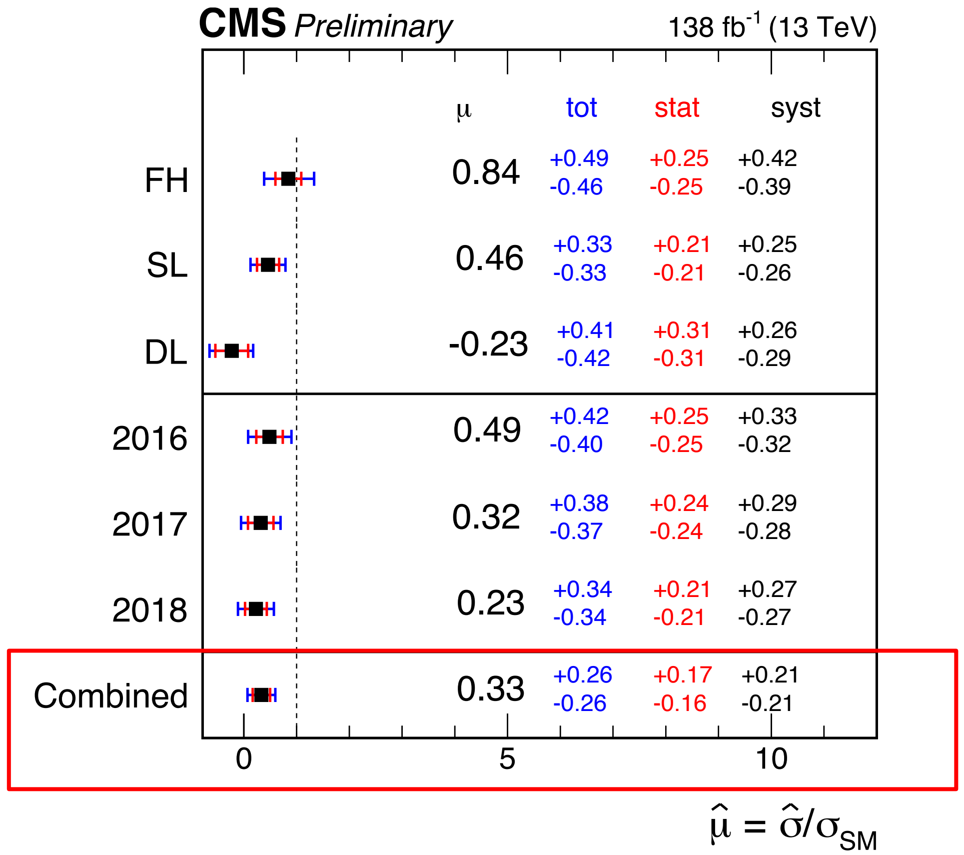
This can potentially indicate towards a smaller value of the Top-Higgs Yukawa coupling compared to the SM expectation



Although, the measured gluon fusion cross-section is in agreement with SM, there is a possibility of contributions to the loop from BSM physics which can compensate for the lower value of κ_t

Inclusive $t\bar{t}H$ Results: Signal Strength

Full Run-2 Results



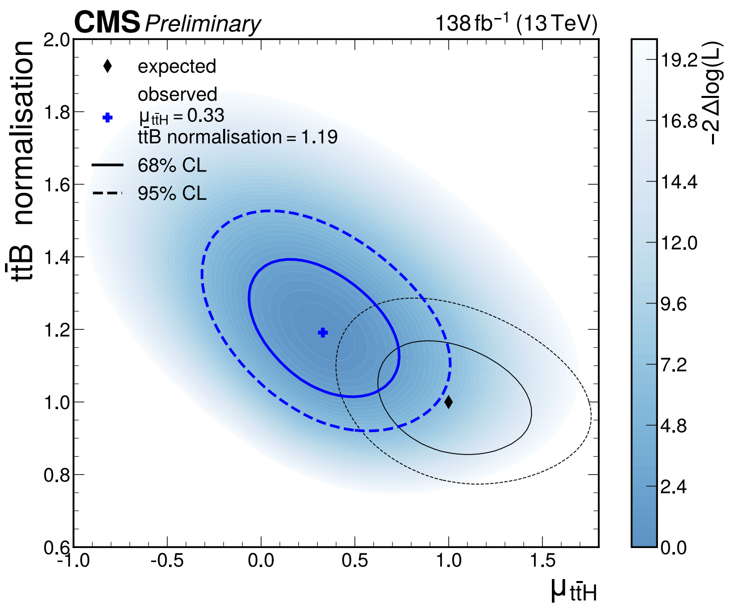
Uncertainties are correlated among channels and years

- $t\bar{t}H$ signal strength:
  - $\mu_{t\bar{t}H} = 0.33 \pm 0.26$, 1.3 σ obs. (4.1 σ exp.) significance
  - SM compatibility p-value: 2% (2.4 σ)
  - Compatibility to 2016 CMS publication (SL+DL): 41% (0.8 σ)

Agreement with ATLAS Full Run-2 result:

- $\mu_{t\bar{t}H} = 0.35 + 0.35 - 0.34$

J. High Energ. Phys. 2022, 97 (2022)



Background normalizations from the $t\bar{t}H$ measurement:

- $t\bar{t} + B$: $1.19^{+0.13}_{-0.12}$
- $t\bar{t} + C$: $1.07^{+0.20}_{-0.19}$

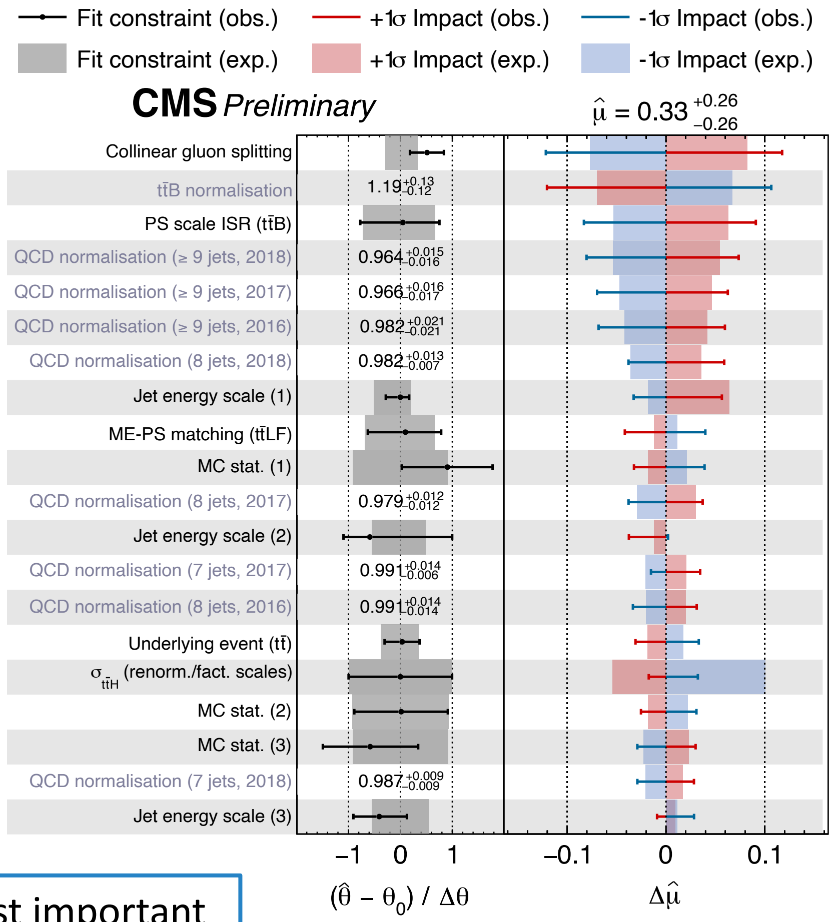
In agreement with dedicated measurements (TOP-22-009)

Inclusive $t\bar{t}H$ Results: Systematic Uncertainties

Major sources of systematic uncertainties:

Uncertainty source	$\Delta\mu_{t\bar{t}H}$ (observed)	$\Delta\mu_{t\bar{t}H}$ (expected)
Total experimental	$+0.10/-0.10$	$+0.11/-0.10$
jet energy scale and resolution	$+0.08/-0.07$	$+0.09/-0.09$
b tagging	$+0.07/-0.06$	$+0.06/-0.02$
luminosity	$+0.02/-0.02$	$+0.01/-0.01$
Total theory	$+0.16/-0.16$	$+0.18/-0.14$
$t\bar{t}$ + jets background	$+0.15/-0.16$	$+0.12/-0.11$
signal modelling	$+0.06/-0.01$	$+0.13/-0.06$
Size of the simulated event samples	$+0.13/-0.12$	$+0.10/-0.10$
Total systematic	$+0.20/-0.21$	$+0.23/-0.19$
Statistical	$+0.17/-0.16$	$+0.17/-0.17$
background normalisation	$+0.13/-0.13$	$+0.13/-0.13$
$t\bar{t}B$ and $t\bar{t}C$ normalisation	$+0.12/-0.12$	$+0.12/-0.12$
QCD normalisation	$+0.01/-0.01$	$+0.01/-0.01$
Total	$+0.26/-0.26$	$+0.28/-0.25$

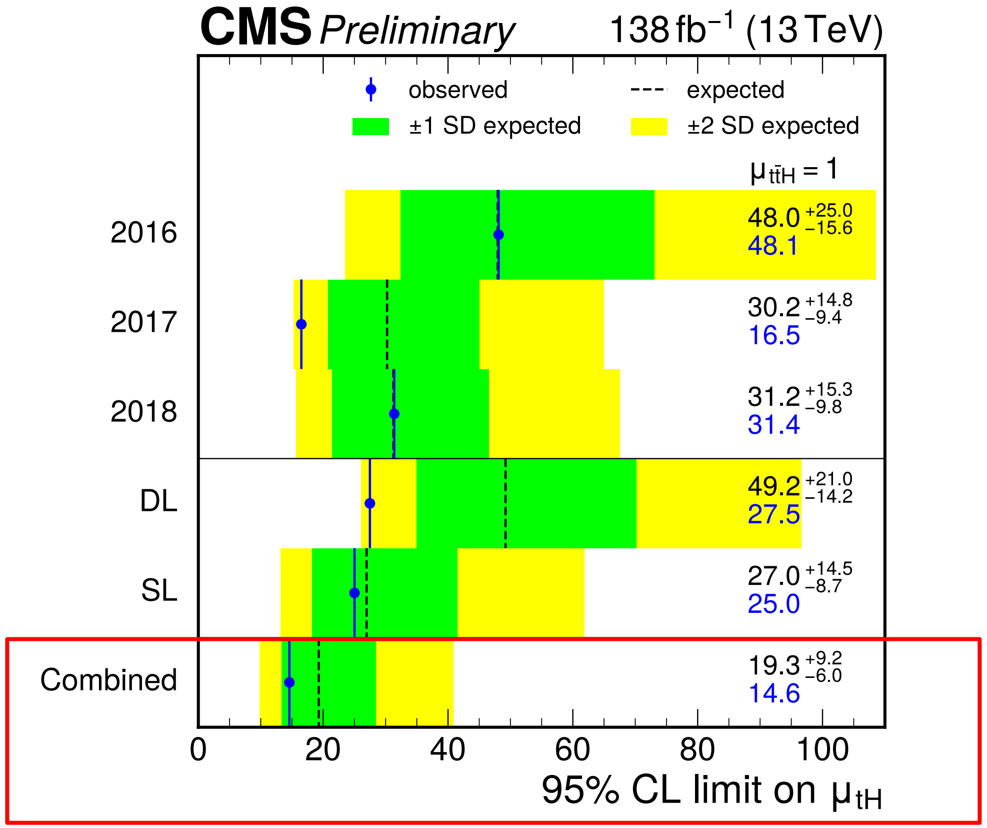
Impacts and pulls of systematic uncertainties:



$t\bar{t}$ + *jets* uncertainties most important

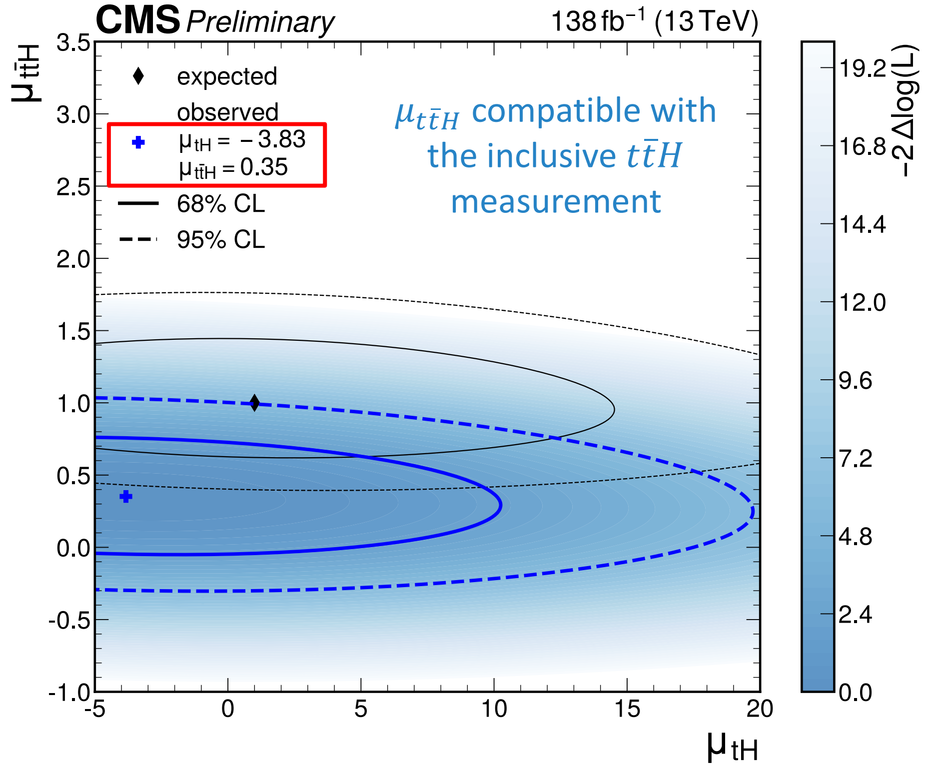
Inclusive tH Results: Signal Strength

Expected and observed 95% CL upper limits on μ_{tH} for individual years, SL channel, DL channel and combination of all channels



$t\bar{t}H$ treated as background and kept at SM prediction

Simultaneous measurement of μ_{tH} and $\mu_{t\bar{t}H}$



$t\bar{t}H$ and tH results nearly uncorrelated

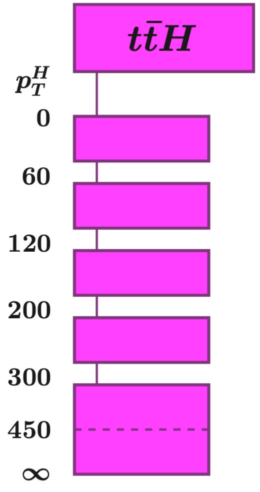
$t\bar{t}H$ Measurement in Higgs Boson p_T Bins

$t\bar{t}H$ cross-section measured in 5 Higgs boson p_T (p_T^H) bins:

- $t\bar{t}H$ signal split using generator level p_T^H

Simplified Template Cross-Section (STXS) approach

Stage 1.2

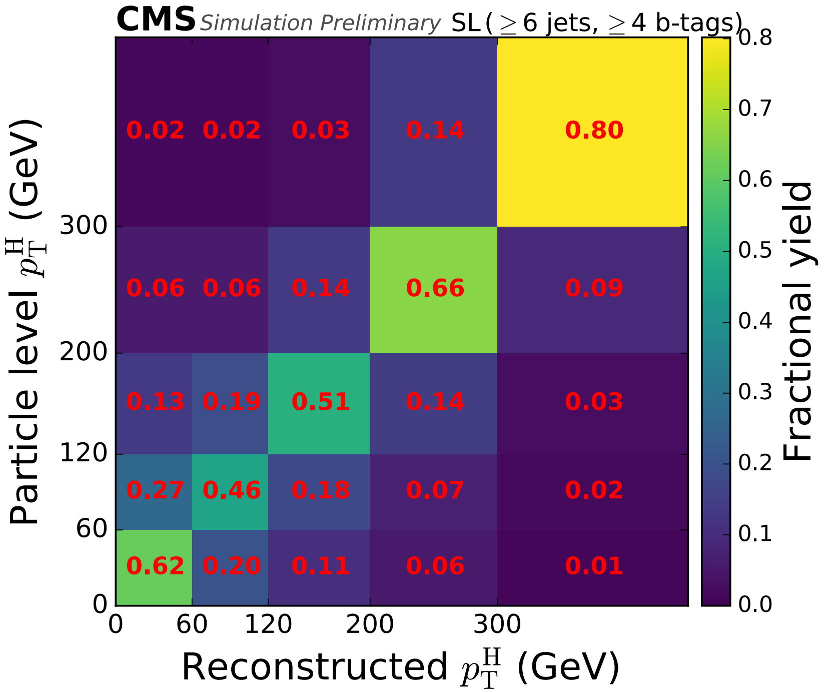


Perform reconstruction of the Higgs boson p_T bins:

- In FH channel: χ^2 reconstruction of the Higgs from b-jet pairs
- In SL and DL channels: multi-class ANN trained on $t\bar{t}H(b\bar{b})$

Assignment efficiency between 35-85%, depending on p_T bin and category

SL channel



Events in the signal-enriched regions from the inclusive categorization further divided in reconstructed p_T^H nodes

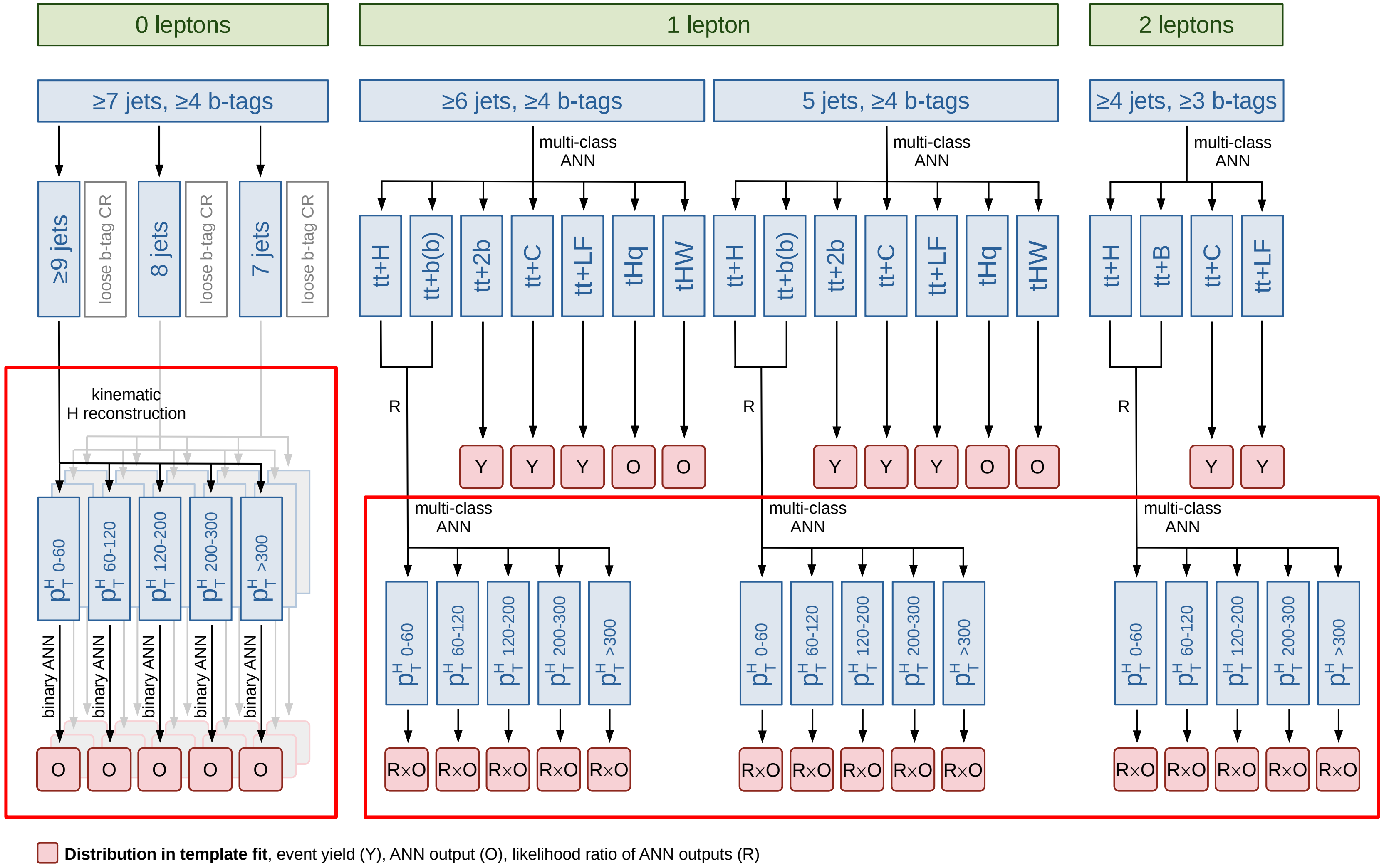
$t\bar{t}H$ Measurement in Higgs Boson p_{T} Bins

5 independent signal templates (for each generator-level $p_{\mathrm{T}}^{\mathrm{H}}$) fit simultaneous in a 5D fit:

- In each signal region node, contributions taken from all $p_{\mathrm{T}}^{\mathrm{H}}$ bins – to consider migration between nodes due to resolution effects

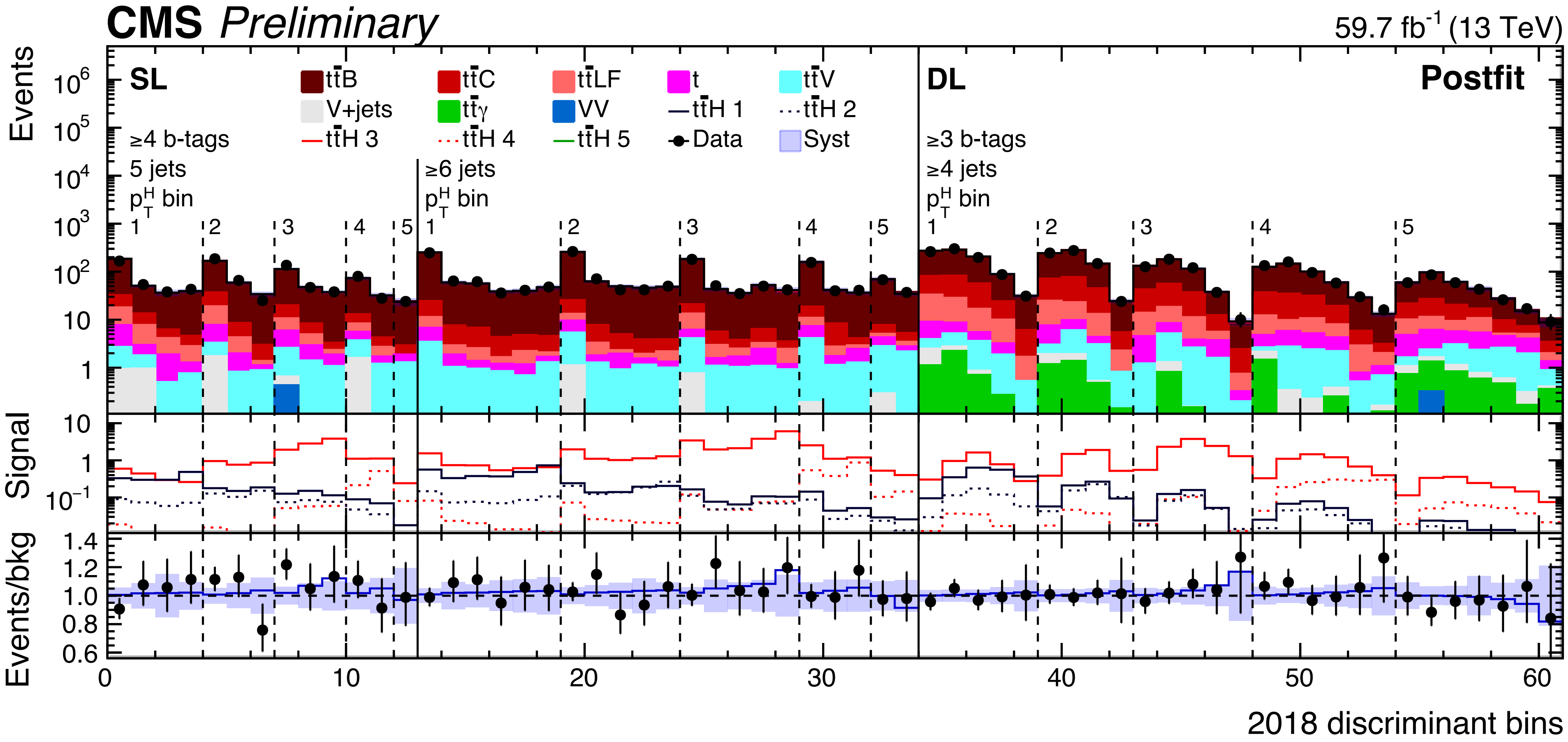
Fitted observable is the output of the Higgs p_{T} ANN times the ratio observable from the inclusive ANN

The DL 3 jets, 3 b-tags category is not included – negligible sensitivity to this measurement



$t\bar{t}H$ Measurement in Higgs Boson p_{T} Bins

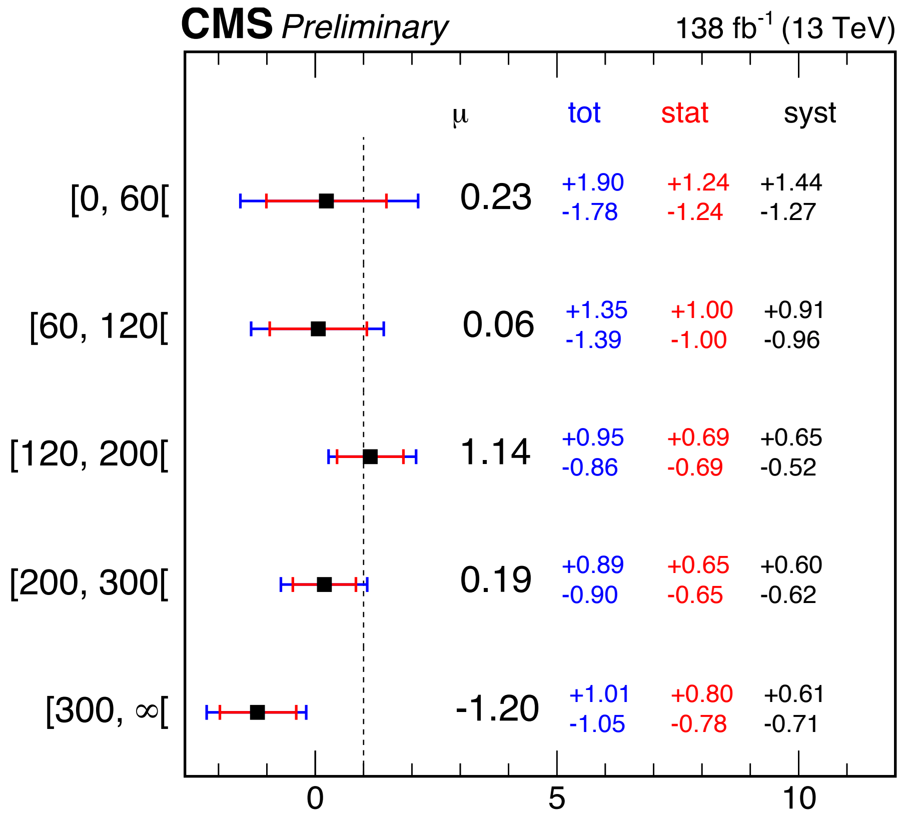
Post-fit distributions in SL and DL channels in Higgs p_{T} bins from 2018 (2017 and 2017 in backup):



Fitted observables in this plot are the output of the Higgs p_{T} ANN times the ratio observable from the inclusive ANN

$t\bar{t}H$ Measurement in Higgs Boson p_{T} Bins

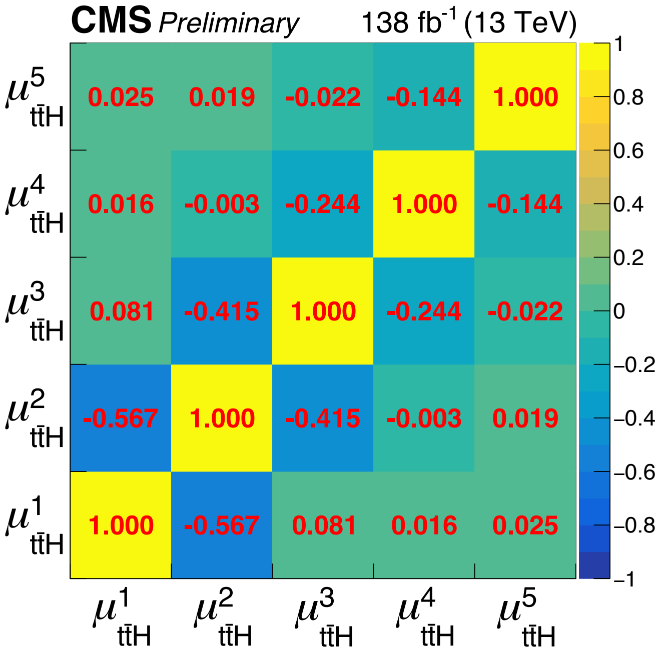
Full Run-2 Results



$t\bar{t}H$ cross-section measured in 5 $p_{\mathrm{T}}^{\mathrm{H}}$ bins

$\hat{\mu} = \hat{\sigma}/\sigma_{\mathrm{SM}}$

Correlations among the signal strengths



Significant correlations in the first few bins

Compatibility with:

- Inclusive results: p-value of 0.67 ($0.4\ \sigma$)
    - Additional single parameter fit gives signal strength within 3% of the inclusive result: completely compatible
- SM: p-value of 0.21 ($1.3\ \sigma$)

Coupling Interpretations in the κ-Framework

Re-parameterize analysis in terms of κ_t and κ_V:

- Rate of $t\bar{t}H \propto \kappa_t^2$
- Rate of tHq and tHW sensitive to relative sign of κ_t and κ_V due to interference terms

$$\sigma_{\mathrm{tHq}} = \left(2.63 \cdot \kappa_t^2 + 3.58 \cdot \kappa_V^2 - 5.21 \cdot \kappa_t \kappa_V\right) \sigma_{\mathrm{tHq}}^{\mathrm{SM}}$$
$$\sigma_{\mathrm{tHW}} = \left(2.91 \cdot \kappa_t^2 + 2.40 \cdot \kappa_V^2 - 4.22 \cdot \kappa_t \kappa_V\right) \sigma_{\mathrm{tHW}}^{\mathrm{SM}}$$

Best fit result:

$\kappa_t = 0.59$

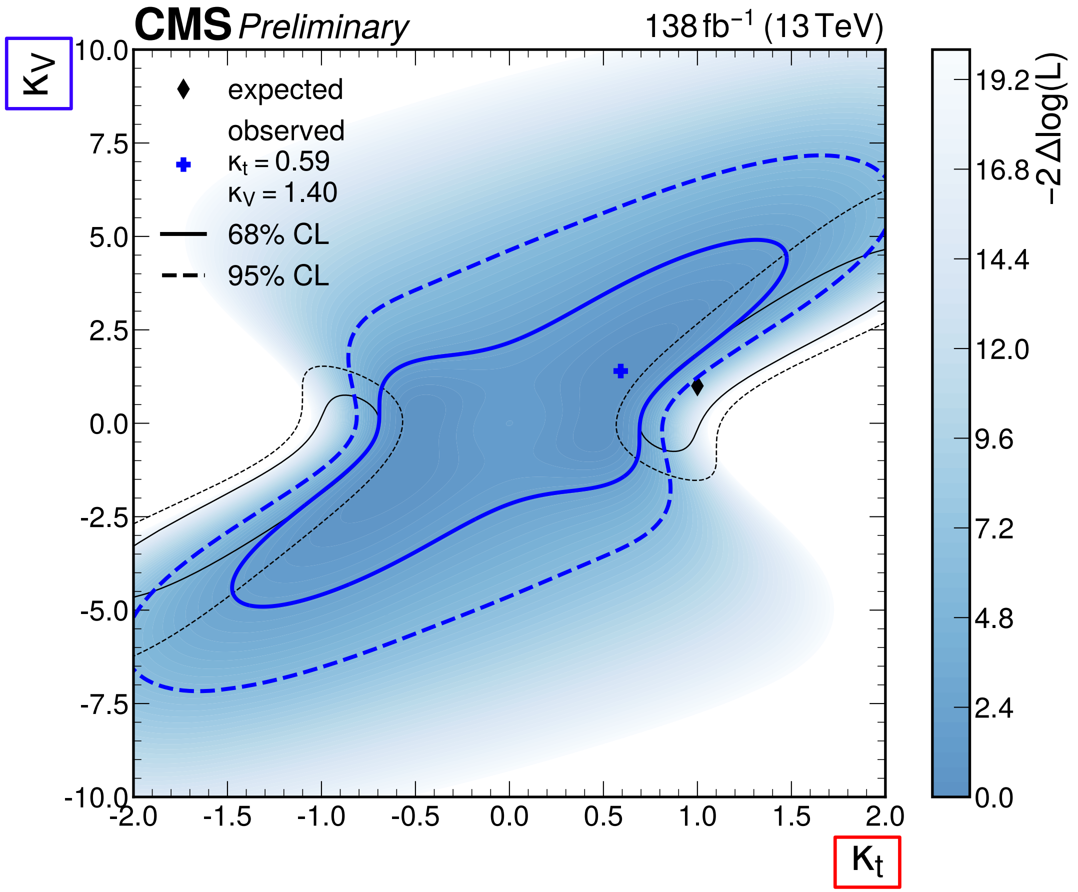
$\kappa_V = 1.40$

With κ_V fixed to 1,

$\kappa_t = 0.54^{+0.19}_{-0.34}$

Coupling parameter values compatible with inclusive signal strength modifiers

Also compatible with SM at the level of 2σ



Both $t\bar{t}H$ and tH treated as signal processes

CP Structure of top-Higgs Coupling

Extending Top-Higgs Yukawa Lagrangian to divide pure CP-even (κ_t) and pure CP-odd ($\kappa_{\tilde{t}}$) components

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

(same model as used in the $t\bar{t}H/tH$ multilepton paper)

fix $\kappa_V = 1$

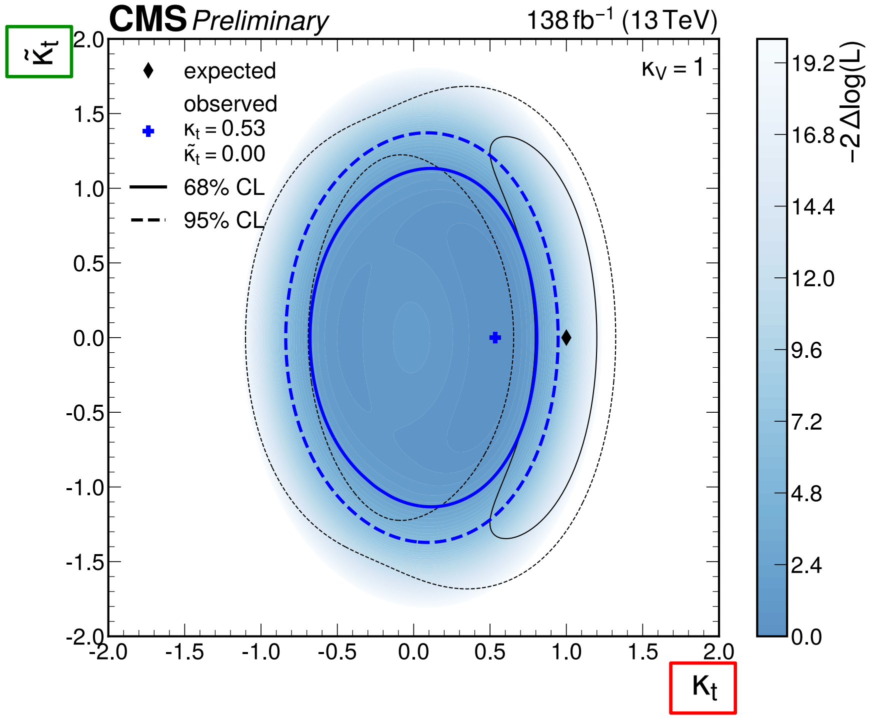
Both $t\bar{t}H$ and $tH \propto \kappa_{\tilde{t}}^2$

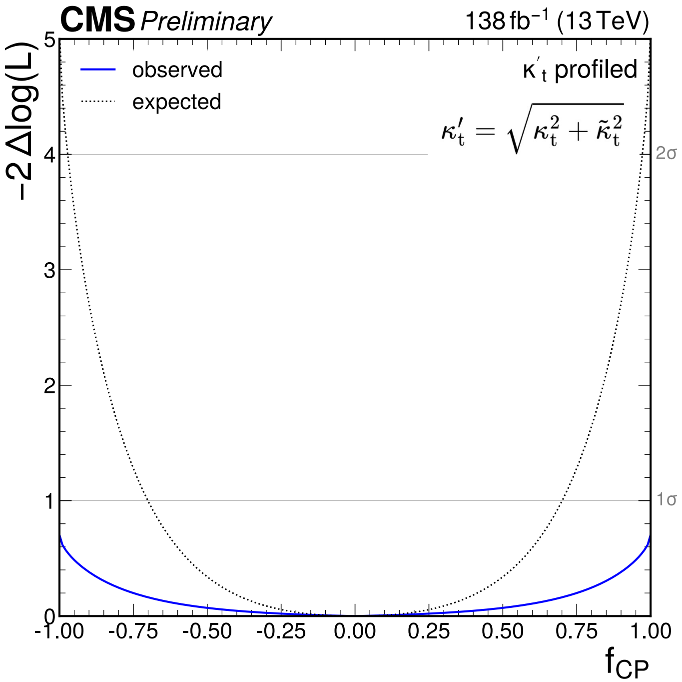
Additional parameterization in the κ_t - $\kappa_{\tilde{t}}$ plane:

$$f_{\mathcal{CP}} = \frac{\tilde{\kappa}_t^2}{\kappa_t^2 + \tilde{\kappa}_t^2}\cdot \mathrm{sign}\left(\frac{\tilde{\kappa}_t}{\kappa_t}\right)$$

$$\kappa_t = \kappa_t'\sqrt{(1-|f_{\mathcal{CP}}|)}$$

$$\tilde{\kappa}_t = \kappa_t'\sqrt{|f_{\mathcal{CP}}|}$$





- **Best fit** values of $(\kappa_t, \kappa_{\tilde{t}})$: $(0.53, 0.00)$: Compatible with SM at the level of 2σ

Exclude CP-odd component at almost 1σ

Summary

- $t\bar{t}H$ and tH provide direct probes for the Top-Higgs Yukawa coupling
- Measurement of $t\bar{t}H$ production rate (both inclusive and in Higgs boson p_{T}) presented using full Run-2 data ($138\ \mathrm{fb}^{-1}$)
- Measurement of tH production rate also performed along with additional interpretations of the top-Higgs couplings
- $t\bar{t}H$ production rate observed to be smaller than SM expectations – interesting result which can indicate towards new physics leading to smaller value of Top-Higgs coupling than in the SM
- Necessitates updated measurements of $t\bar{t}H$ and tH production rates with more data and further scrutiny of the $t\bar{t} + B$ background