YSF: $t\bar{t}H$ and tH production in multilepton channels with CMS experiment

La Thuile: Les Rencontres de Physique de la Vallee d'Aoste

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On behalf of the CMS Collaboration

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Consejería de Ciencia, Innovación y Universidad

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Introduction

Since the discovery of **Higgs boson** a broad experimental program was developed to measure its **properties**, such as its **coupling to other particles.**

- SM Yukawa coupling to fermions is proportional to the mass of the fermion

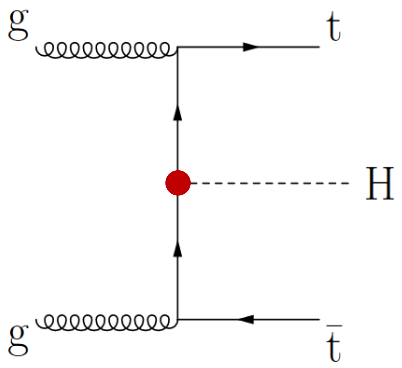
Top Yukawa coupling is of special interest:

- Largest one (**close to unity)**
- **BSM physics** could introduce **modified couplings** that alter top-Higgs interaction:
  - In the SM the Higgs boson has a scalar (CP-even) coupling to other SM particles
  - **CP violating coupling** can occur at tree level in the fermion-Higgs interaction
- Experimentally accessible in multiple ways:

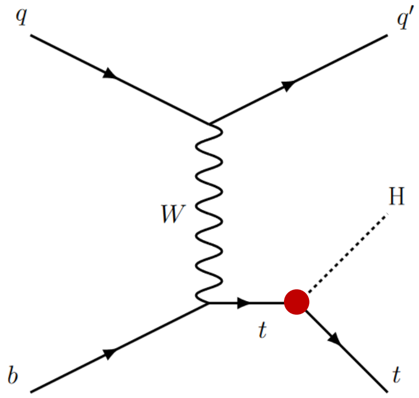
Direct measurements

Sensitive to sign

$t\bar{t}H$



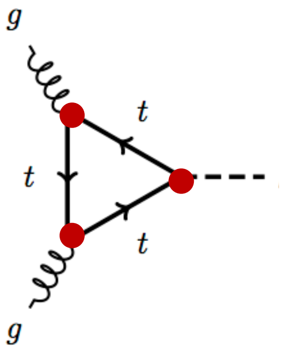
tH

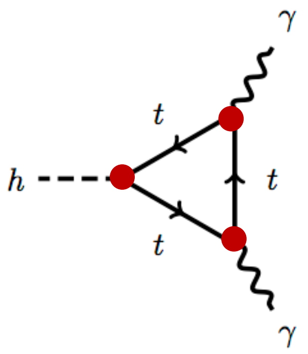


Indirect measurements

gg fusion Higgs production

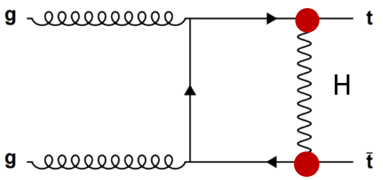
$H \rightarrow \gamma\,\gamma$

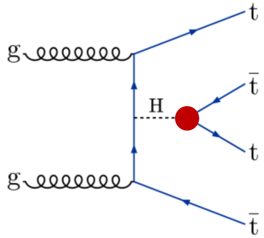




$t\bar{t}$

$t\bar{t}t\bar{t}$





This talk will focus on CP violation measurements using ttH and tH production modes:
CMS-PAS-HIG-21-006

CP interpretation

Lagrangian can be expressed as a superposition of CP-even and a CP-odd terms

$$\mathcal{L}_{t\bar{t}H} = \frac{-y_t}{2}\bar{\psi}_t(\kappa_t + i\gamma_5\tilde{\kappa}_t)\psi_t H$$

With:

- y_t the top-Higgs coupling
- κ_t ratio of the CP-even terms to SM expectation
- $\tilde{\kappa}_t$ ratio of the CP-odd terms to SM expectation

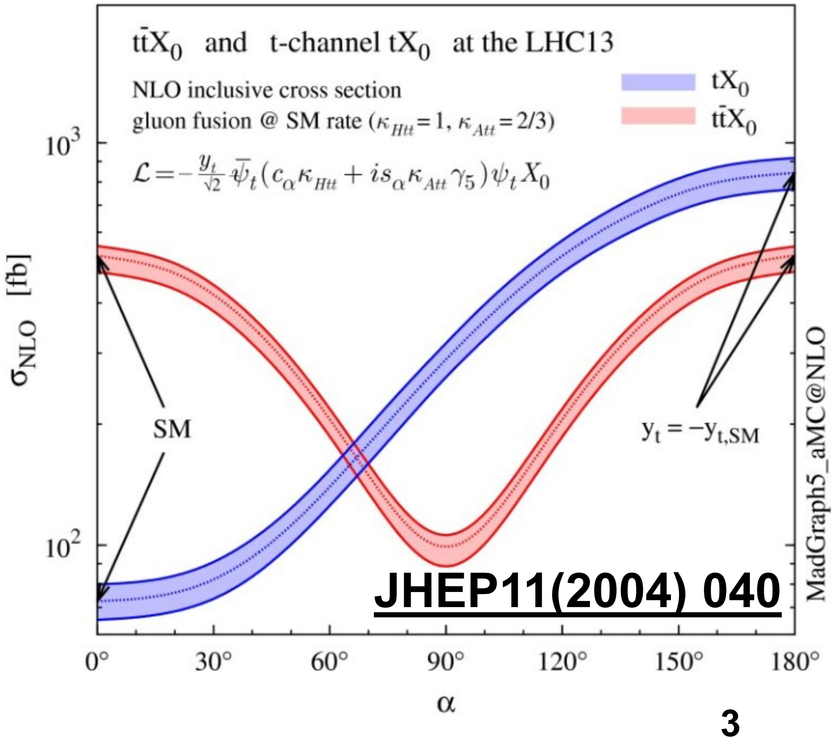
Scenario	α
Purely CP even	$\alpha = 0° \text{ or } 180°$
Purely CP odd	$\alpha = 90°$
Mixed scenario	$\alpha \neq 0°, \neq 90°, \neq 180°$

Defining α as the CP mixing angle:

- κ_t proportional to $\cos\alpha$
- $\tilde{\kappa}_t$ proportional to $\sin\alpha$

Kinematic differences as well as **cross-section** changes expected depending on the CP scenario

tH cross section sensitive to the inverted top coupling scenario ($y_t = - y_t^{SM}$)



JHEP11(2004) 040

Analysis strategy

Final states with multiple leptons (e,μ,τ)

- H→ WW, ZZ and $\tau\tau$

Data taken by the CMS experiment at 13 TeV during Run 2 (138 fb^{-1}).

Events categorized depending on lepton multiplicity:

- 2 same sign* (ss) leptons + 0 hadronically decaying taus (τ_h)
- 2 ss leptons + 1 τ_h
- 3l + 0 τ_h

*Helps rejecting background

Dedicated selection in each category:

- Lepton pT
- Jet and b tag multiplicity requirements
  - At least 2 (3) jets in 2lss + 0 τ_h and 2lss + 1 τ_h (3l + 0 τ_h)
  - ≥ 1 medium b-tagged Jet or ≥ 2 loose b-tagged Jet

  to **target tt̄H** events

  or

  - ≥ 1 Light Jet (can be in the forward region) and ≥ 1 b-tagged Jet (Medium) ⇨ to **target tH** events.
- p_T^{miss} requirements
- Z veto

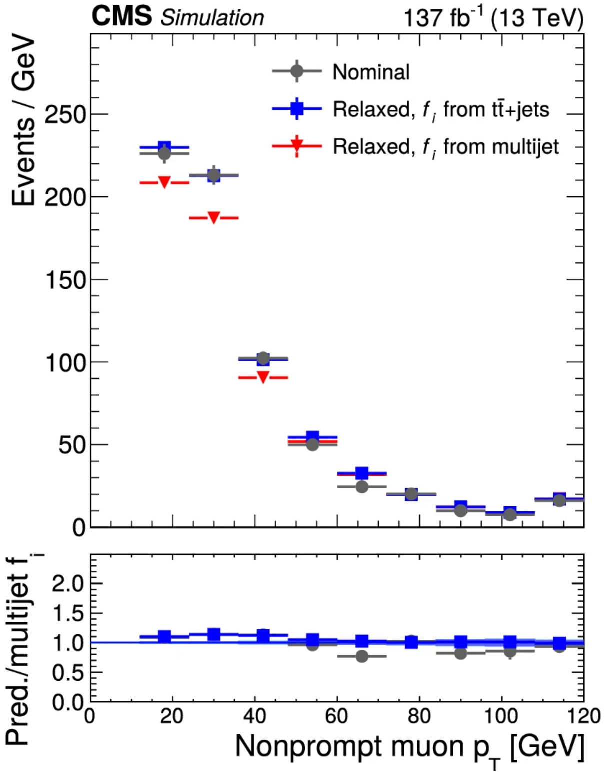
Backgrounds

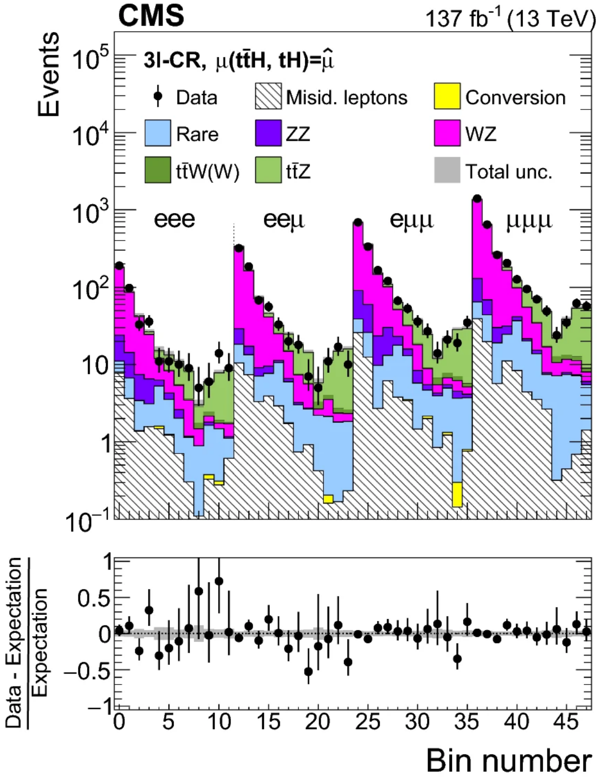
Background estimation is key in this analysis

Reducible backgrounds:
- ➢ Non prompt leptons and misidentified τ_h
- ➢ Electron charge flips
- ➢ Conversions

Irreducible backgrounds:
- ➢ $t\bar{t}Z$, $t\bar{t}W$
- ➢ Less importantly, dibosons

- Dedicated output node for **$t\bar{t}W$ in 2lss+ 0 τ_h**
- **Control regions** to constrain $t\bar{t}Z$, WZ and ZZ (3l & 4l)
  Normalization determined in the signal extraction fit
- Non prompt background:
  Estimated with data-driven techniques
  Closure for muons
- Photon conversions:
  Estimated with simulation





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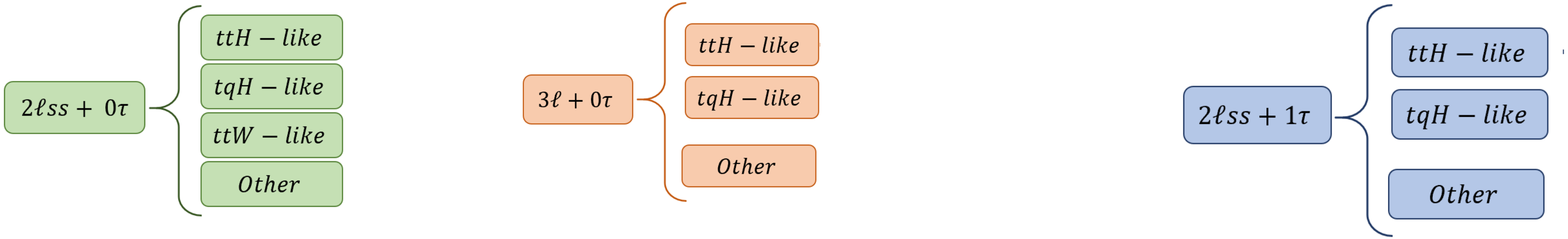
Classification of Signal Regions

In order to discriminate the signal events from backgrounds, MVA (multiclass NN) techniques are used.

- Inputs: kinematic variables, object multiplicities and a specific tagger targeting hadronic top quark decays.

- Events classified according to most probable output node



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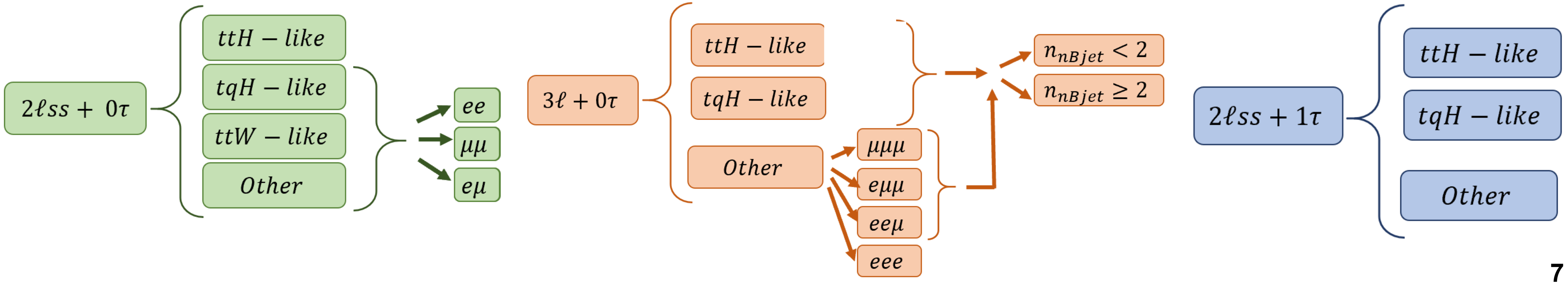
    - further classification depending on lepton flavour and b-tag multiplicity



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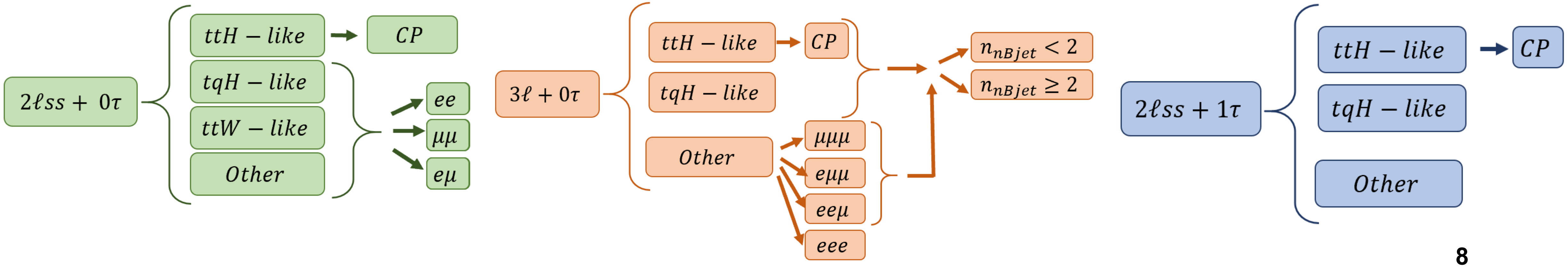
- For the **t$\bar{\mathbf{t}}$H node** classification depending on **CP discriminant**



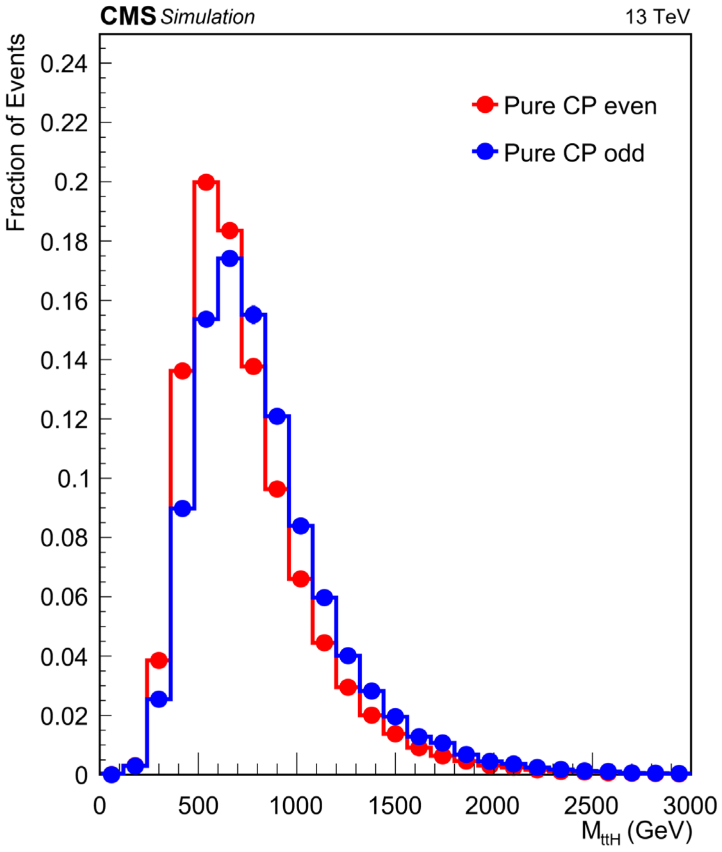
CP discrimination

Kinematic differences between $t\bar{t}H$ CP-even and CP-odd components are exploited

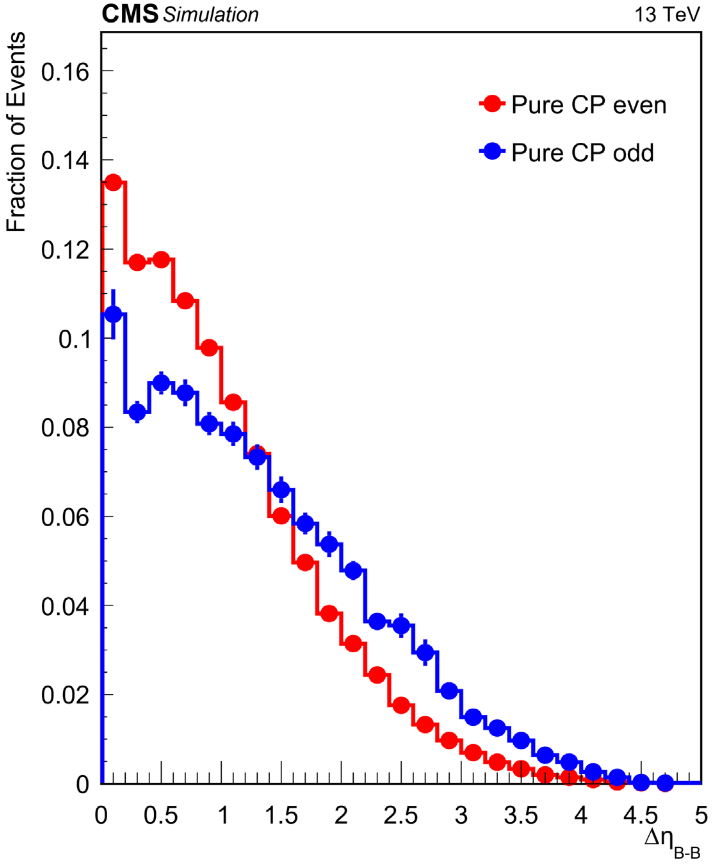
Dedicated BDT for each channel

- Two of the most important input variables
- Good discriminating power is shown

2lss 0 tau



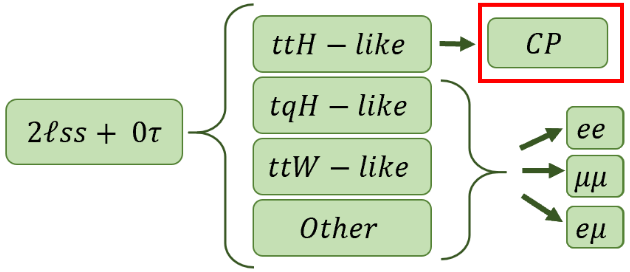
3l + 0 tau



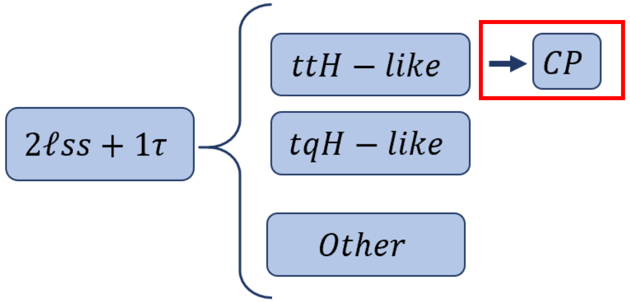
Signal Extraction

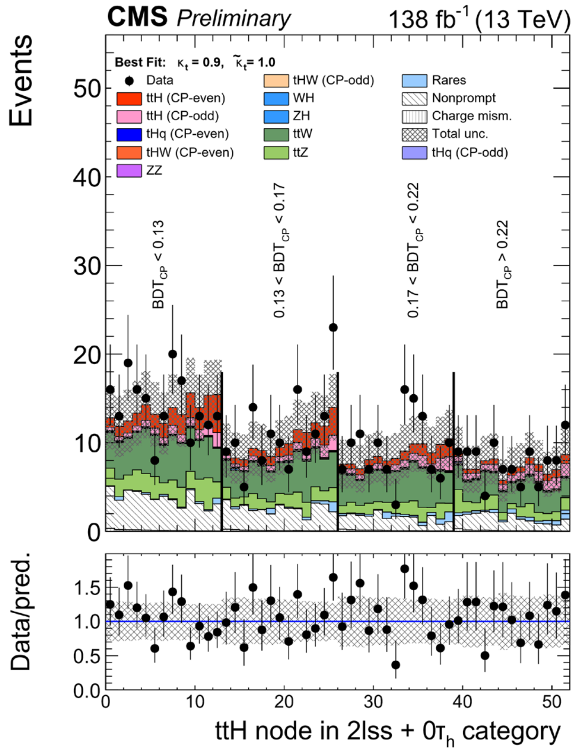
Perform a **maximum likelihood fit** using:

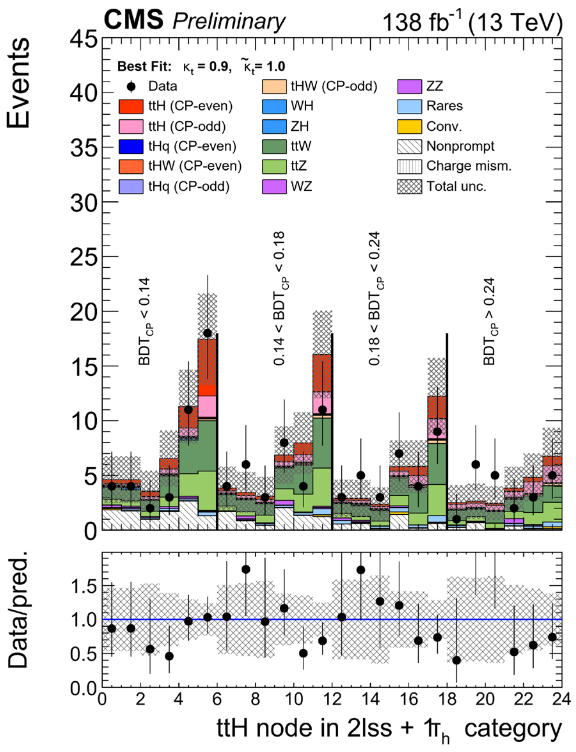
- the three signal regions
  2lss + 0 τ_h, 2lss + 1 τ_h and 3l + 0 τ_h
- Control regions

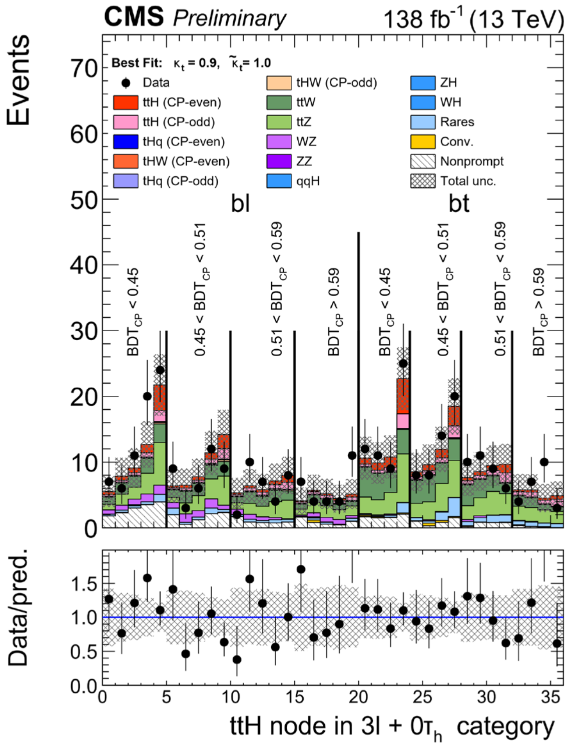


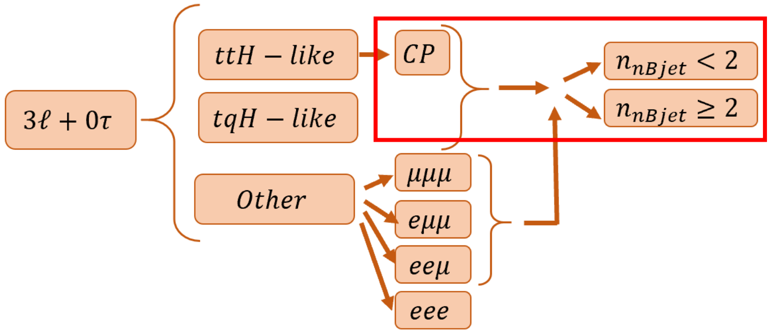
For the ttH-like category events are classified according to their score in CP-discriminant











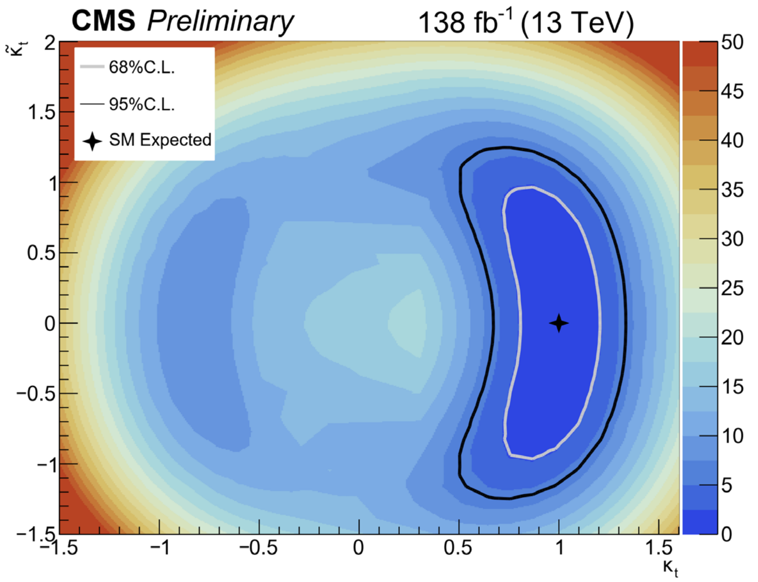
Results

Yields are parametrized using:

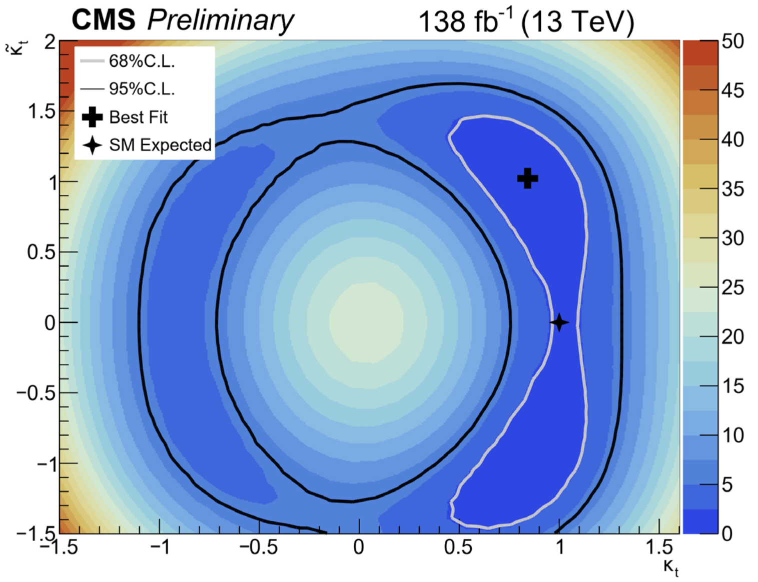
- κ_t and $\tilde{\kappa}_t$ (ratio of the CP-even and CP-odd terms to SM expectation, respectively)
- Results are also expressed in terms of the fraction of the CP-odd coupling:

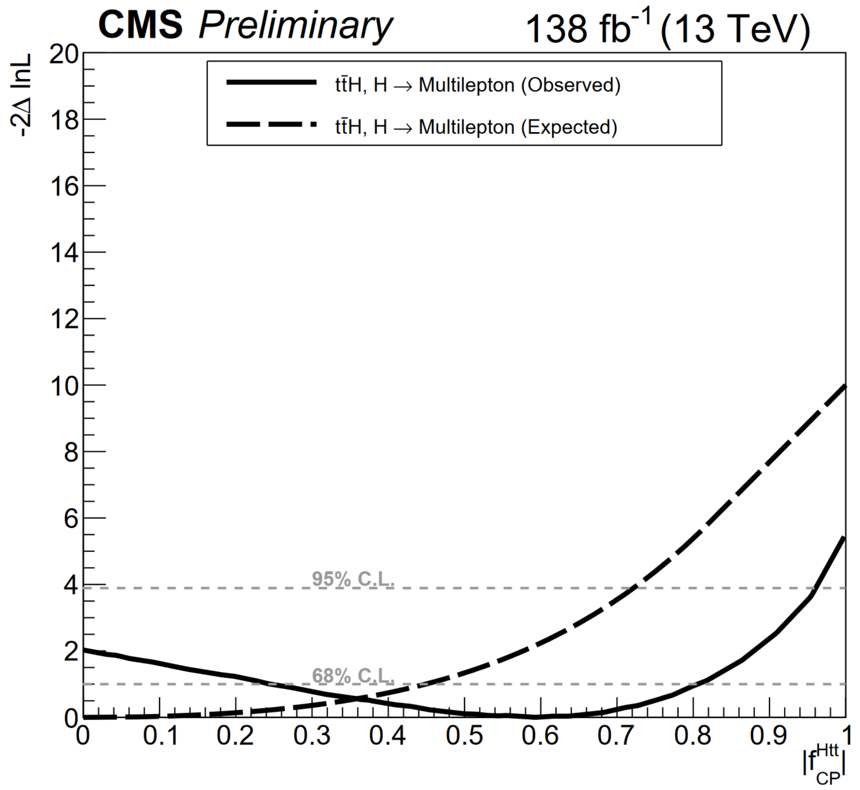
$$f_{CP} = \frac{|\tilde{\kappa}_t|^2}{|\tilde{\kappa}_t|^2 + |\kappa_t|^2}$$

Expected



Observed





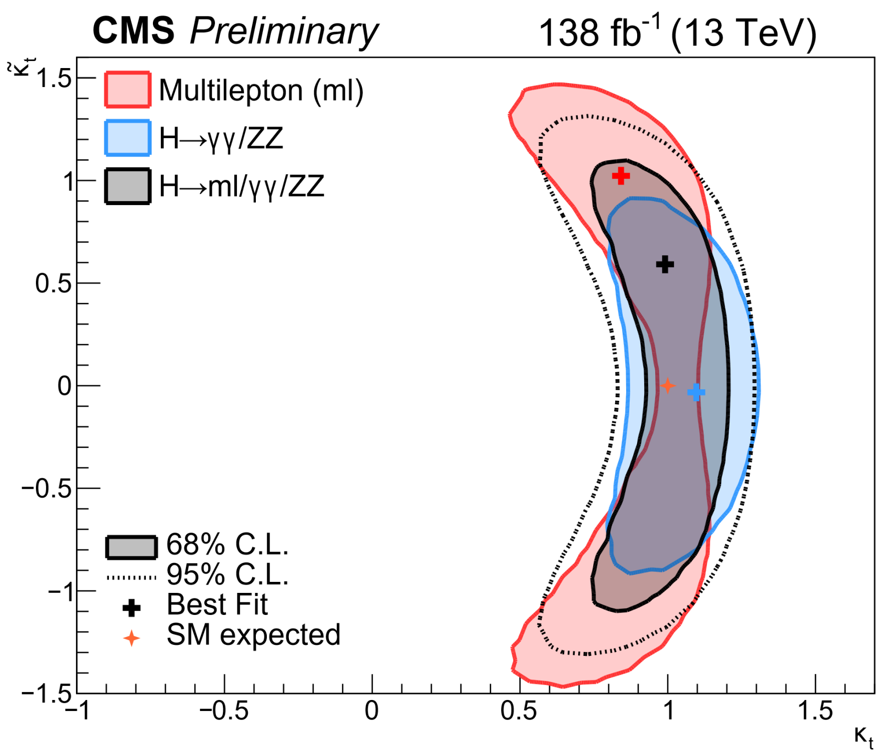
Best fit value:
κ_t = 0.9 & $\tilde{\kappa}_t$ =1.0 in good agreement with SM

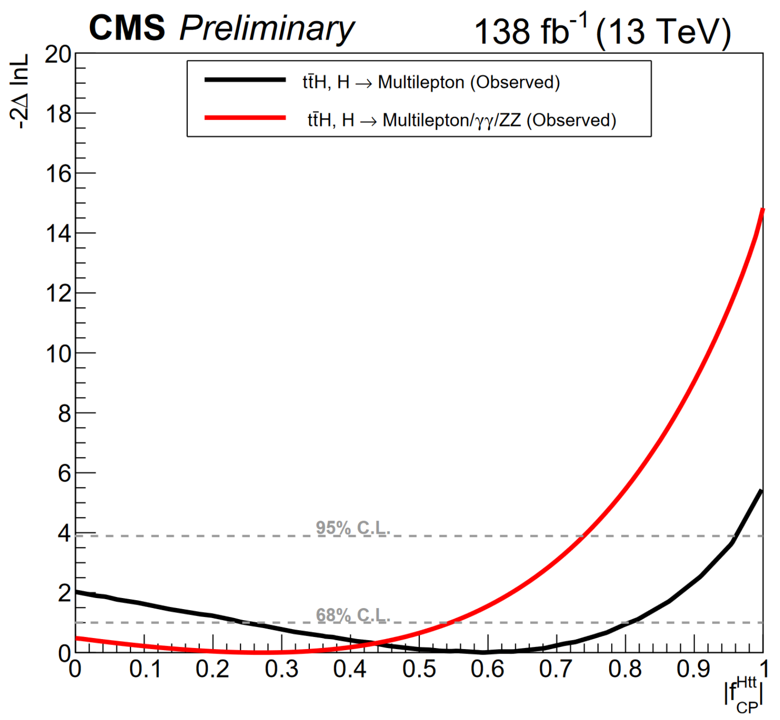
$f_{CP}^{Htt} = 0.59$ within (0.24, 0.81) at 68% CL

Combination

The result is combined with already published $t\bar{t}H$ measurements:

- ZZ, Phys. Rev. D 104, 052004
- $\gamma\gamma$, Phys. Rev. Lett. 125, 061801





- f_{CP}^{Htt} = **0.28** (<0.55) at 68% CL
- $|f_{CP}^{Htt}| = 1$ excluded with 3.7σ

Summary

- Measurement of the CP structure of the Yukawa coupling between the H boson and top quarks at tree level is presented using final states with multiple leptons
- MVA techniques are used in order to discriminate the CP-even (SM like) and CP-odd scenarios

- Two-dimensional limits are set on $\boldsymbol{\kappa_t}$ **and** $\boldsymbol{\widetilde{\kappa_t}}$. Best fit in **good agreement with SM**.
- Result also expressed in terms of fractional contribution parameter:

$f_{CP}^{Htt} = 0.59$ within (0.24, 0.81) at 68 % CL

- Measurement combined with previous published results with orthogonal selection and targeting H $\rightarrow$ ZZ and H $\rightarrow \gamma\gamma$ decay
  - Combined results constrains further the limits on $\boldsymbol{\kappa_t}$ **and** $\boldsymbol{\widetilde{\kappa_t}}$
  - $f_{CP}^{Htt} = 0.28$ (<0.55) at 68% CL

- Scenario with $|\boldsymbol{f_{CP}^{Htt}}| = 1$ (CP-odd) is excluded with more than 3σ

Back up

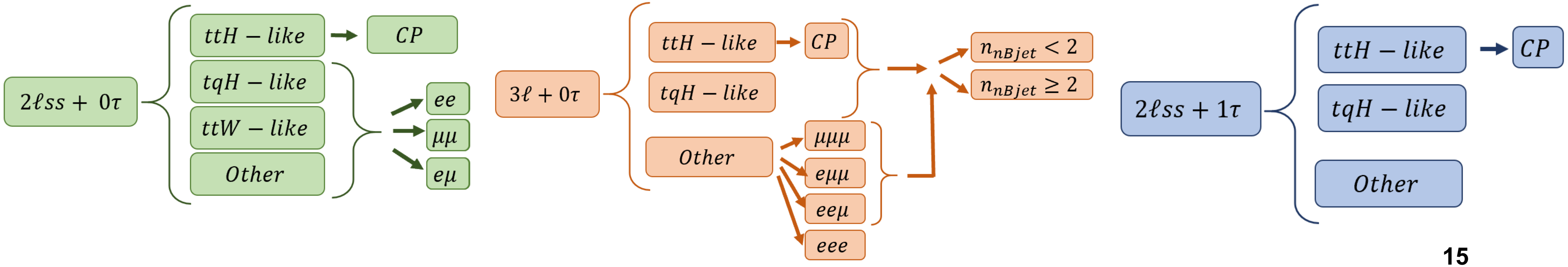
Classification of Signal Regions

In order to discriminate the signal events from backgrounds, MVA (multiclass NN) techniques are used.

- Inputs: momentum of leptons, τ_h and jets, angular variables, mases, object multiplicities and a specific tagger targeting hadronic top quark decays.

- Three output nodes for the 2lss + $1\tau_h$ and tri-lepton categories and four for 2lss + $0\tau_h$

- Events classified according to most probable output node and further classification depending on lepton flavour and b-tag multiplicity
- For the **t$\bar{\text{t}}$H node** classification depending on **CP discriminant**



CP discrimination

Kinematic differences between $t\bar{t}H$ CP-even and CP-odd components are then exploited by means of an additional MVA discriminator ⇨ **dedicated BDT for each channel**

Different input features depending on kinematic quantities

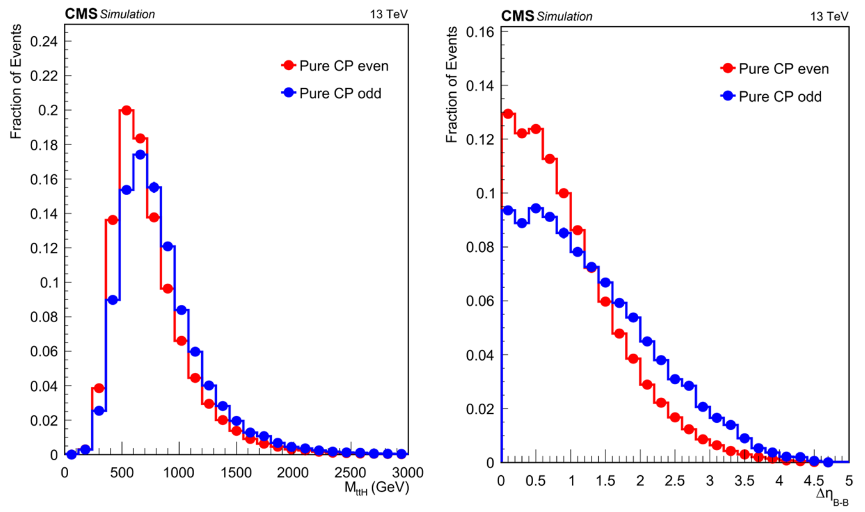
- 3 momentum of leptons, τ and jets
- Angular variables of leptons
- $\Delta R_{lepton\ to\ closest\ jet}$
- Invariant mass of (reconstructed $t\bar{t}H$ system):

$$\sum_{i} p^{lep_i} + \vec{p}_T^{miss} + \sum_{i \le k} p^{jet_i *}$$

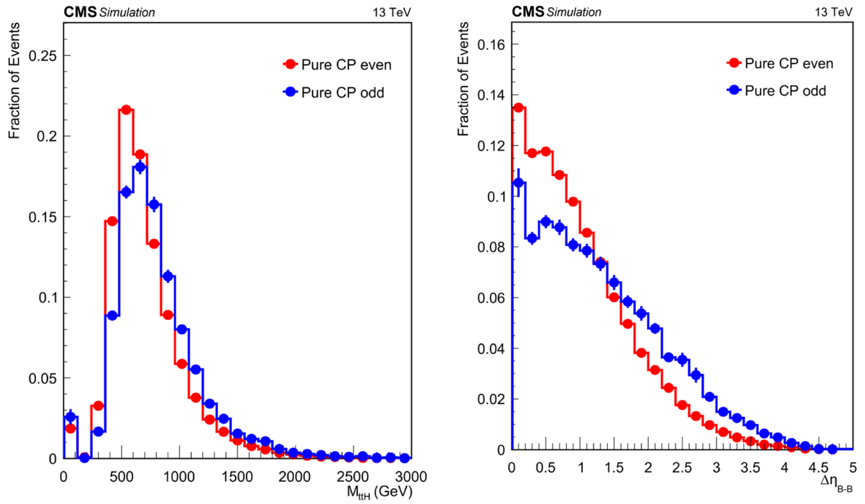
*k= 6 (4) in 2lss + 0 τ (2lss + 1τ and 3l + 0 τ)

- $\Delta\eta$ of two jets with highest b score in the laboratory frame
- $\Delta\eta$ of the two leptons in frame of two most-likely b jets

2lss 0 tau



3l + 0 tau



Event selection

Selection	$2\ell SS + 0\tau_h$	$2\ell SS + 1\tau_h$	$3\ell + 0\tau_h$
Trigger	Single- and double-lepton triggers		Single-, double- and triple-lepton triggers
Lepton p_T	$p_T > 25$ / $15\,\mathrm{GeV}$	$p_T > 25$ / 15 (e) or $10\,\mathrm{GeV}$ (μ)	$p_T > 25$ / 15 / $10\,\mathrm{GeV}$
Lepton η	$\lvert\eta\rvert < 2.5$ (e) or 2.4 (μ)		$\lvert\eta\rvert < 2.5$ (e) or 2.4 (μ)
τ_h p_T	—	$p_T > 20\,\mathrm{GeV}$	—
τ_h η	—	$\lvert\eta\rvert < 2.3$	—
Charge requirements	2 same-sign leptons and charge quality requirements	$\sum_{\ell,\tau_h} q = \pm 1$	— $\sum_{\ell} q = \pm 1$
Jet multiplicity**	$\geq$3 jets		$\geq$2 jets
b tagging requirements**	$\geq$1 medium b-tagged jet or $\geq$2 loose b-tagged jets		
Light jet and b tag***	$\geq$1 light jets, $\geq$1 medium b-tagged jet		
Missing transverse momentum	$E_T^{miss} LD > 30\,\mathrm{GeV}$ **		$p_T^{miss} LD > 45\,\mathrm{GeV}$ †
Dilepton mass	$m_{\ell\ell} > 12\,\mathrm{GeV}$ *, $\lvert m_{\ell\ell} - m_Z\rvert > 10\,\mathrm{GeV}$		

* Applied on all pairs of leptons that pass loose selection.

** If events do not pass these cuts, *** is required.

† If the event contains a SFOS lepton pair and $N_{jet} \leq 3$. If the $N_{jet} \leq 3$ but there is no SFOS lepton pair, the cut is $30\,\mathrm{GeV}$

‡ Applied to all SFOS lepton pairs.

Input Variables to CP MVA

Variable description	$2\ell SS + 0\tau_h$	$2\ell SS + 1\tau_h$	$3\ell + 0\tau_h$
p_T of jet 1	—	—	✓
p_T of jet 2	—	—	✓
p_T of lepton 1	✓	✓	✓
p_T of lepton 2	✓	✓	✓
p_T of lepton 3	—	—	✓
p_T of tau	—	✓	—
η of lepton 1	✓	✓	—
η of lepton 2	✓	✓	—
η of tau	—	✓	—
ϕ of lepton 1	✓	✓	—
ϕ of lepton 2	✓	✓	—
ϕ of tau	—	✓	—
transverse mass of lepton 1	✓	—	—
transverse mass of lepton 2	✓	—	—
ΔR of lepton 1 to its closest jet	✓	✓	✓
ΔR of lepton 2 to its closest jet	✓	✓	✓
Invariant mass of $(\sum_i p^{lep_i} + \vec{p}_T^{\,miss} + \sum_{i\leq k} p^{jet_i *})$	✓	✓	✓
$\Delta\eta$ of two jets with highest b score in the laboratory frame	✓	✓	✓
$\Delta\eta$ of the two leptons in frame of two most-likely b jets	✓	✓	—
$\Delta\eta$ of two jets with highest b score in the dilepton system frame	✓	✓	—
$\Delta\eta$ of two jets with highest b score in the ℓ_1-ℓ_2 system frame	—	—	✓
$\Delta\eta$ of two jets with highest b score in the ℓ_1-ℓ_3 system frame	—	—	✓
$\Delta\phi$ of the two leptons in frame of two most-likely b jets	—	✓	—
$\Delta\phi$ of two jets with highest b score in the dilepton system frame	—	✓	—
average ΔR among all jets	✓	✓	—
jet multiplicity	✓	✓	—
missing transverse energy	✓	✓	—
p_T^{miss} in the ϕ direction	✓	✓	—
highest BDT score of jet triplet from t	✓	✓	—
Higgs jet tagger	—	✓	—
angle of $t\,\bar{t}$ and H in $t\,\bar{t}$ H-system	—	✓	—
angle between two t in $t\,\bar{t}$-frame	—	✓	—
$\sqrt{(\eta_{\ell_3} - \eta_{\ell_1})^2 + (\phi_{\ell_3} - \phi_{\ell_1})^2}$	—	—	✓
$\sqrt{(\eta_{\ell_1} - \eta_{\ell_2})^2 + (\phi_{\ell_1} - \phi_{\ell_2})^2}$	—	—	✓
$\sqrt{(\eta_{\ell_2} - \eta_{\ell_3})^2 + (\phi_{\ell_2} - \phi_{\ell_3})^2}$	—	—	✓
$\eta_{jet1} - \eta_{jet2}$	—	—	✓
$p_T^{jet1} + p_T^{jet2} + p_T^{jet3} + p_T^{miss}$	—	—	✓
Total number of variables	19	25	16

* k = 6 (4) in the final state $2\ell SS + 0\tau_h$($2\ell SS + 1\tau_h$and $3\ell + 0\tau_h$)

Signal simulation

- ttH and tH samples are produced at LO assuming all couplings of the Higgs boson have the values expected in the ITC scenario

- tH simulated at LO:
  - 4 FS to simulate tHq
  - 5 FS to simulate tHW
  - Interference contributions of tHW with ttH production are not present in the simulation
  - s-channel contribution is negligible

- Weights calculated for each signal event with MADGRAPH5 aMC@NLO applied to account for:
  - Variation in kinematical properties of tH signal events from the interference of the diagrams for values of and κ_t $\tilde{\kappa}_t$ and κ_V
  - Variation in kinematical properties of ttH as a function of $\tilde{\kappa}_t$ and κ_t