Search for CP violation using ttH production

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Jornadas del ICTEA

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CMS Compact Muon Solenoid

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Motivation

Observation: in the universe there is much more matter than antimatter
→ Need mechanism that violate Charge Conjugation Parity (CP) symmetry

- SM allows CP-violation, and it has been observed
- Not enough to explain the asymmetry observed in the universe: need to search for new CP violation sources

Motivation

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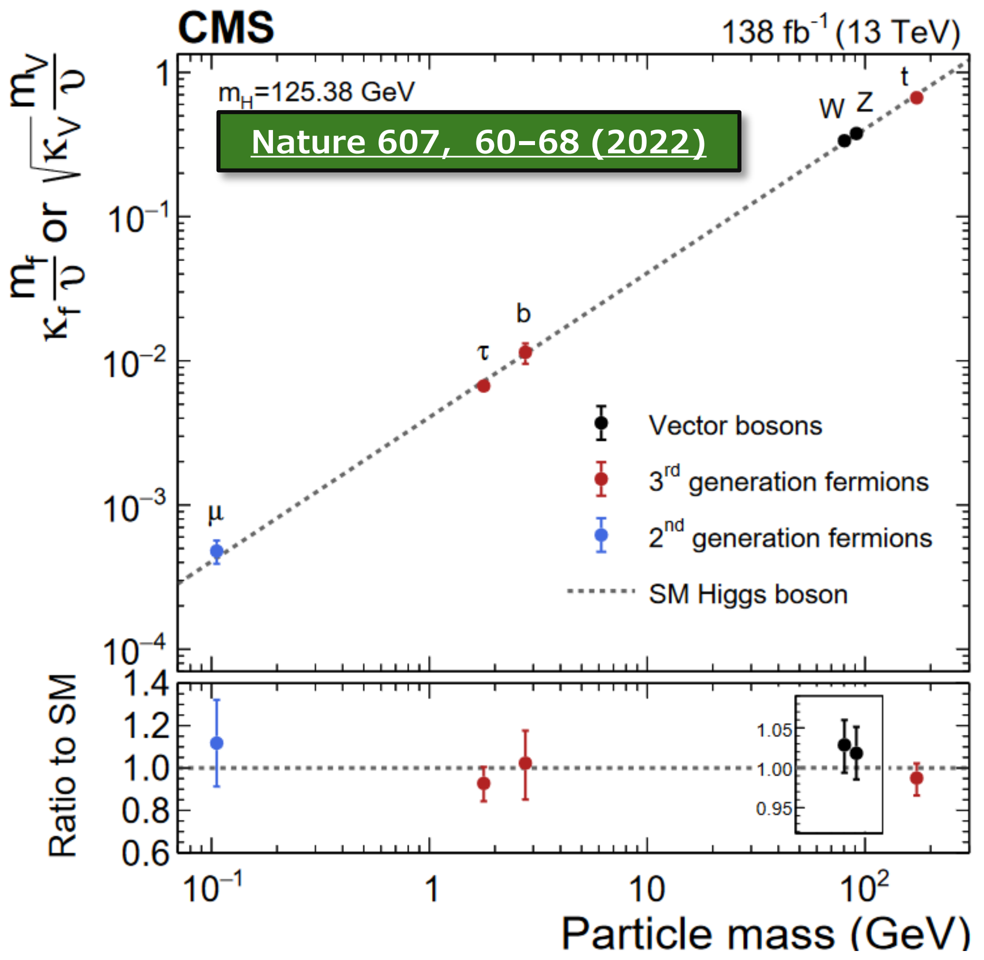
SM H is a scalar → invariant under CP-transformations
- BSM scenarios with CP-violation in the Higgs sector
- Explore them by measuring the coupling to bosons and fermions

- Coupling to bosons measured with high precision during Run I

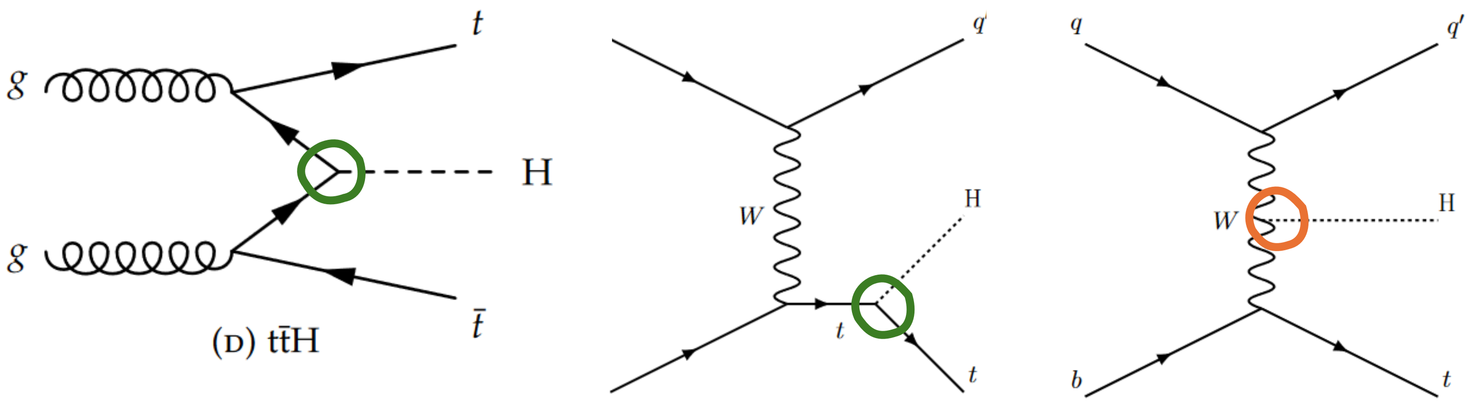
- **In this talk: search for CP-violation measuring the top Yukawa coupling** JHEP 07 (2023) 092

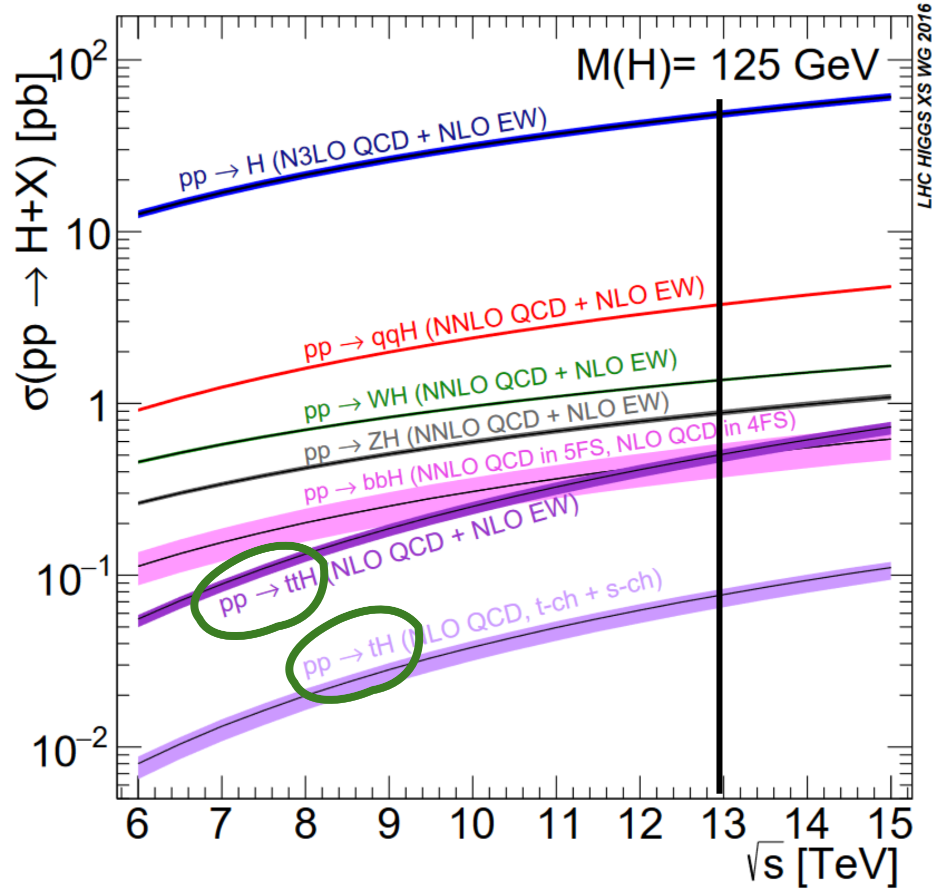


Higgs boson production

At LHC **gg fusion is the dominant** H production mode - $\sigma_{H,ggF}$ ~ 49 pb @ 13 TeV
Top asociated production, much lower rates:

- **$t\bar{t}H$ – $\sigma_{t\bar{t}H}$ ~ 0.5 pb @ 13 TeV**





- **Direct probe** of top-Higgs Yukawa coupling
- tH: y_t and g_W diagrams interfere destructively in the SM
- **Inverted top coupling scenario**: enhances tH cross section by a factor of 10 and does not affect $t\bar{t}H$
- $t\bar{t}H$ **sensitive to CP violation**:
  - significant reduction on the cross section
  - kinematic effects

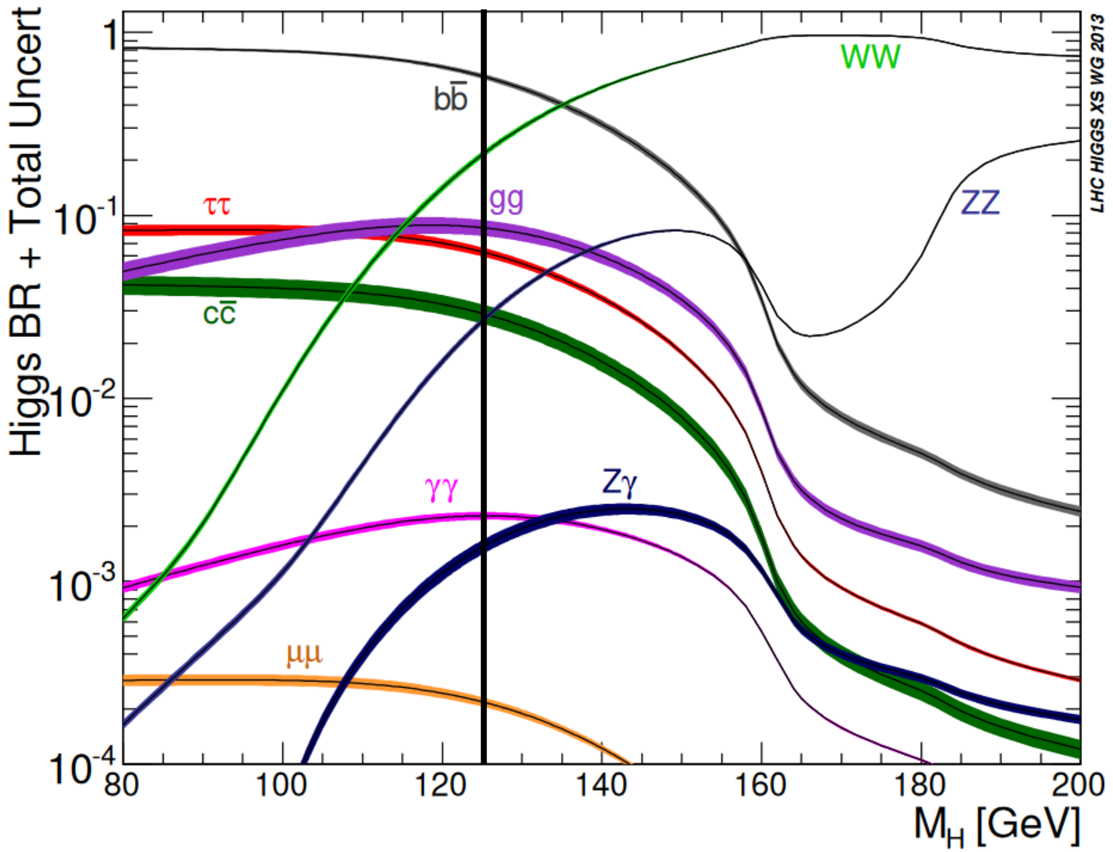
$$\mathcal{L}_{t\bar{t}H} = \frac{-y_t}{2}\bar{\psi}_t(\kappa_t + i\gamma_5\tilde{\kappa}_t)\psi_t H$$

Final states to study ttH+tH

Rich final states topologies, thanks to the decay of the top quark pair and the Higgs boson

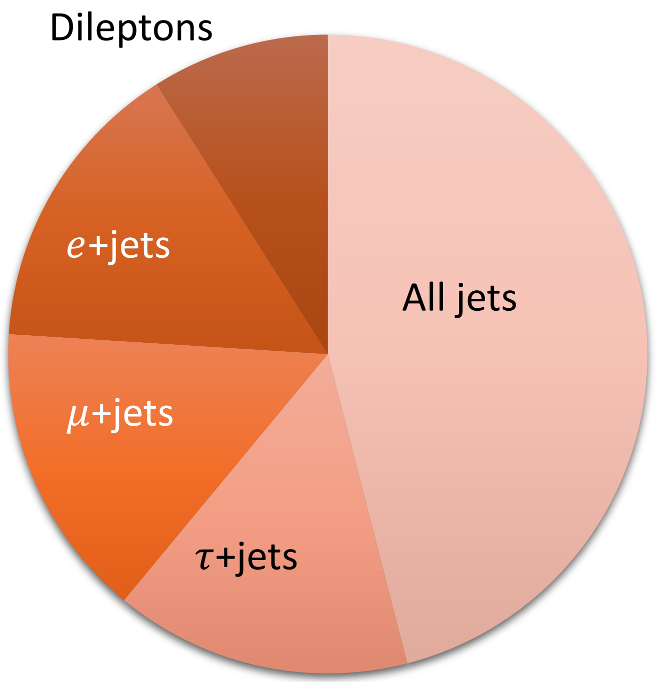
$t\bar{t}$ decays x Higgs decays

Higgs Boson decays



$t\bar{t} \rightarrow W^{+}b\,W^{-}\bar{b}$

subsequent decays of the W bosons:



H→ WW/$\tau\tau$

Final states with multiple leptons

Analysis strategy

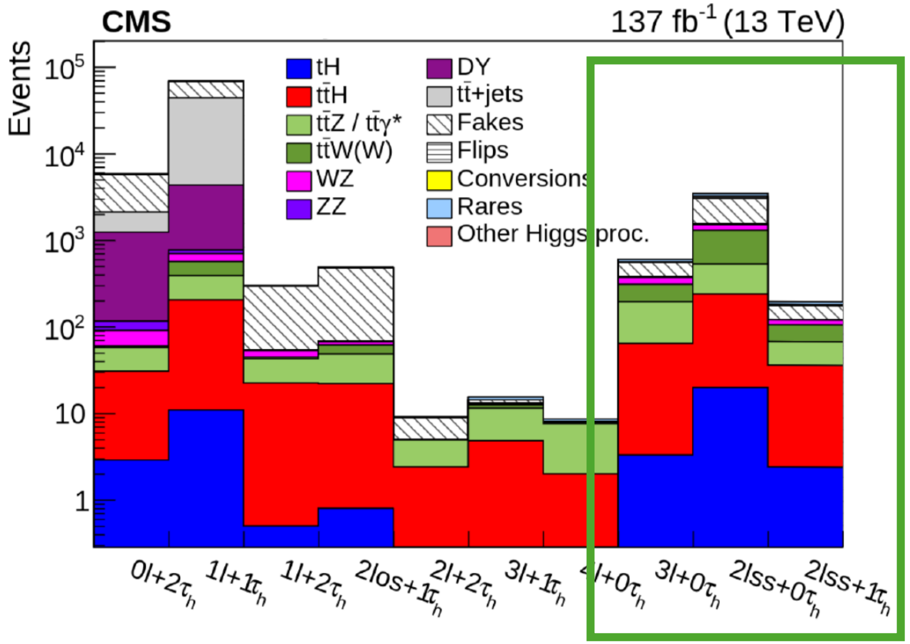
Data from Run 2 (2016-2018) is used

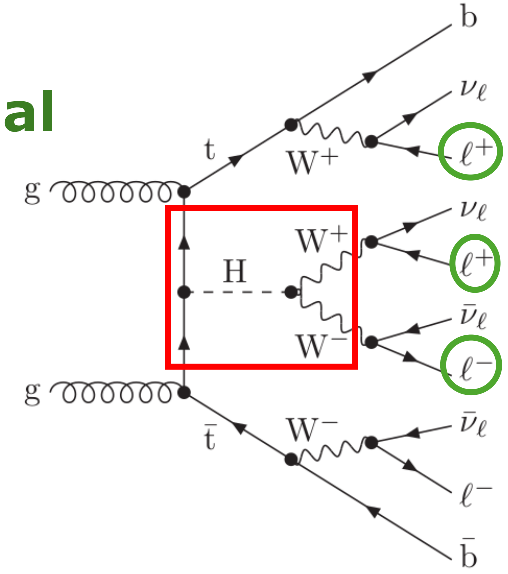
Events categorized depending on the number of leptons in the final state:

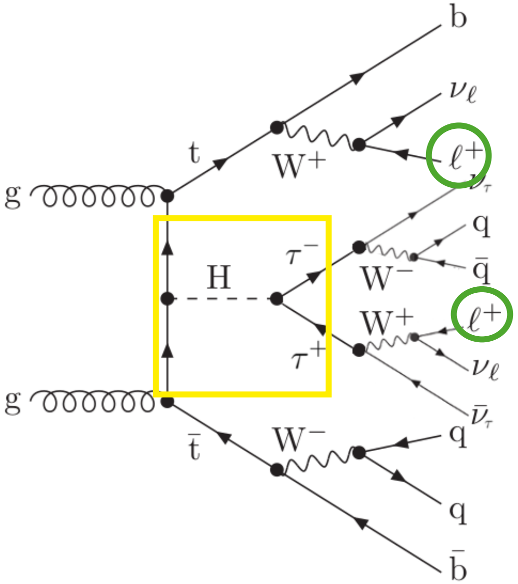
- 2 leptons with same sign of the (ss) electric charge* + 0 hadronically decaying taus (τ_h)
- 2 ss leptons + 1 τ_h
- 3l + 0 τ_h

*Helps rejecting background

- Dedicated **MVA to select isolated leptons** from H, W and τ
- Dedicated selection on each category. **Using Jet and b-tagging multiplicities**.







Backgrounds

Background estimation is key in this analysis

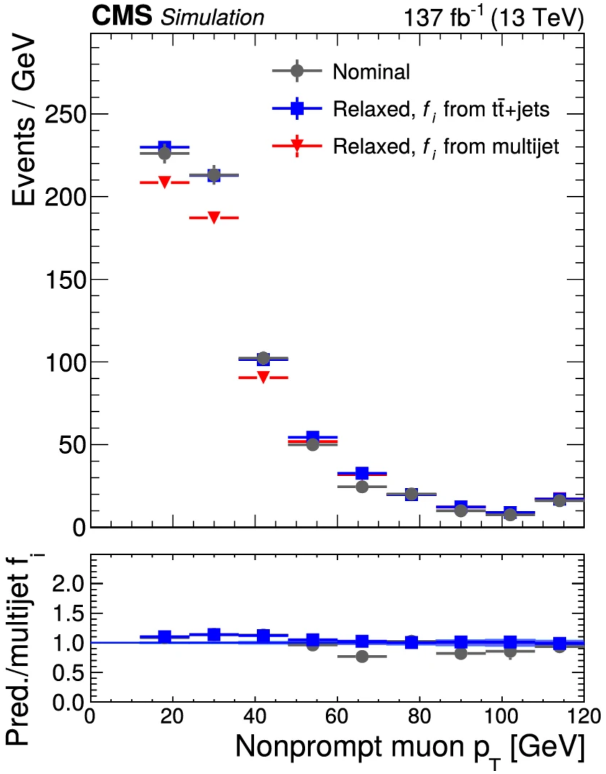
Reducible backgrounds:

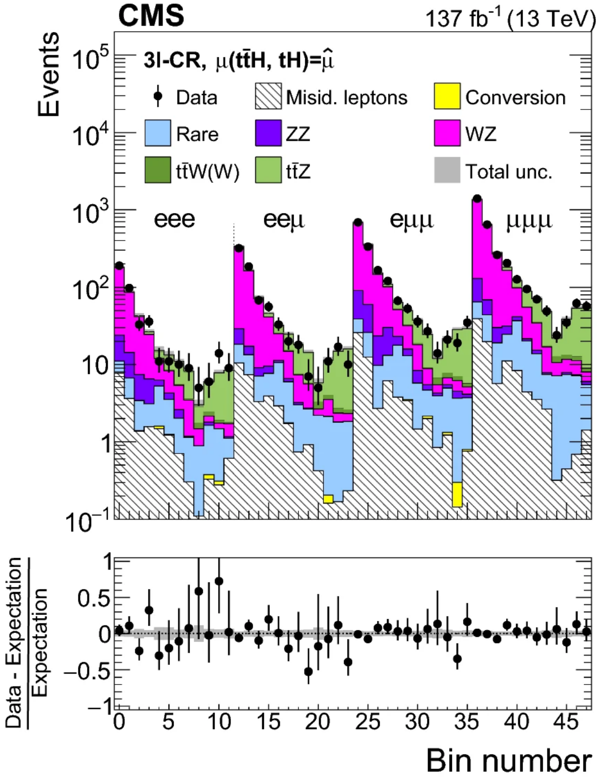
➢ Non prompt leptons and misidentified taus
➢ Electron charge flips
➢ Conversions

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



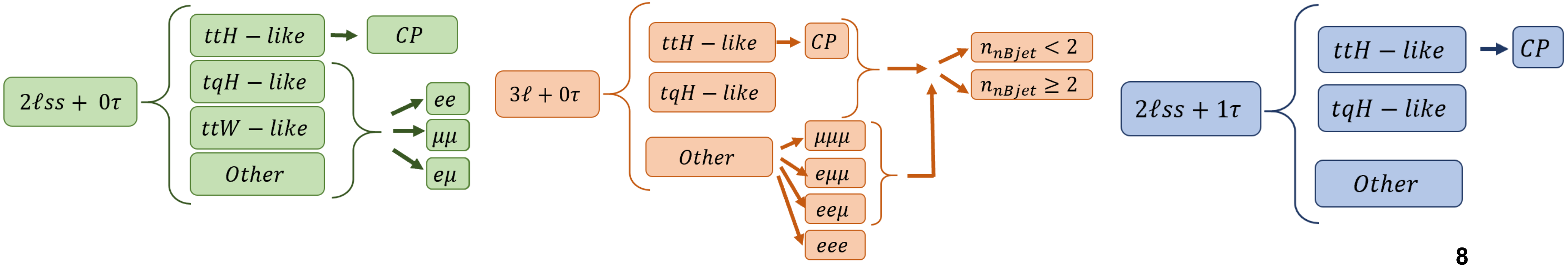


EPJC 81, 378 (2021)

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

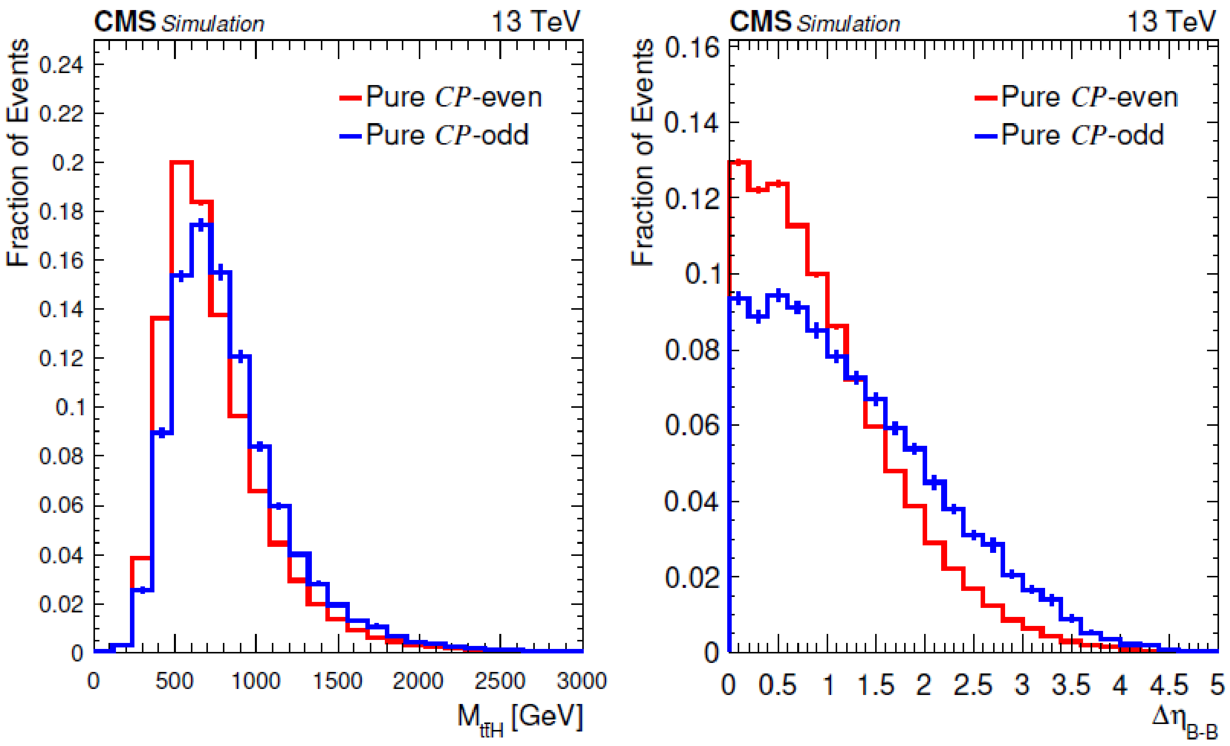


CP discrimination

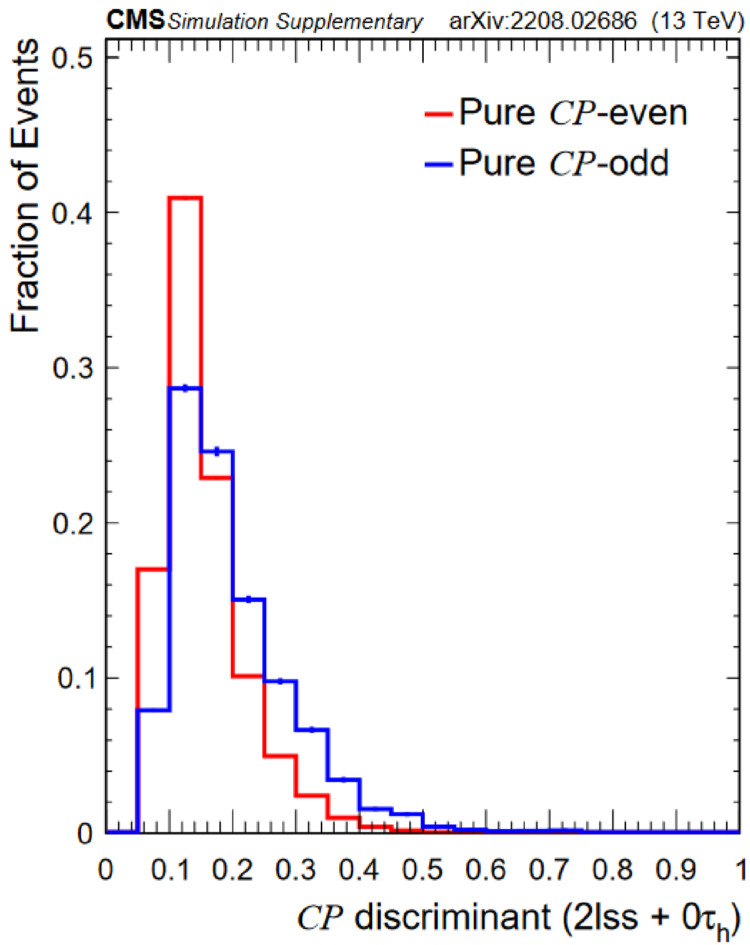
Kinematic differences between $t\bar{t}H$ CP-even and CP-odd components are exploited

Dedicated BDT for each channel

2lss+0τ_h



BDT

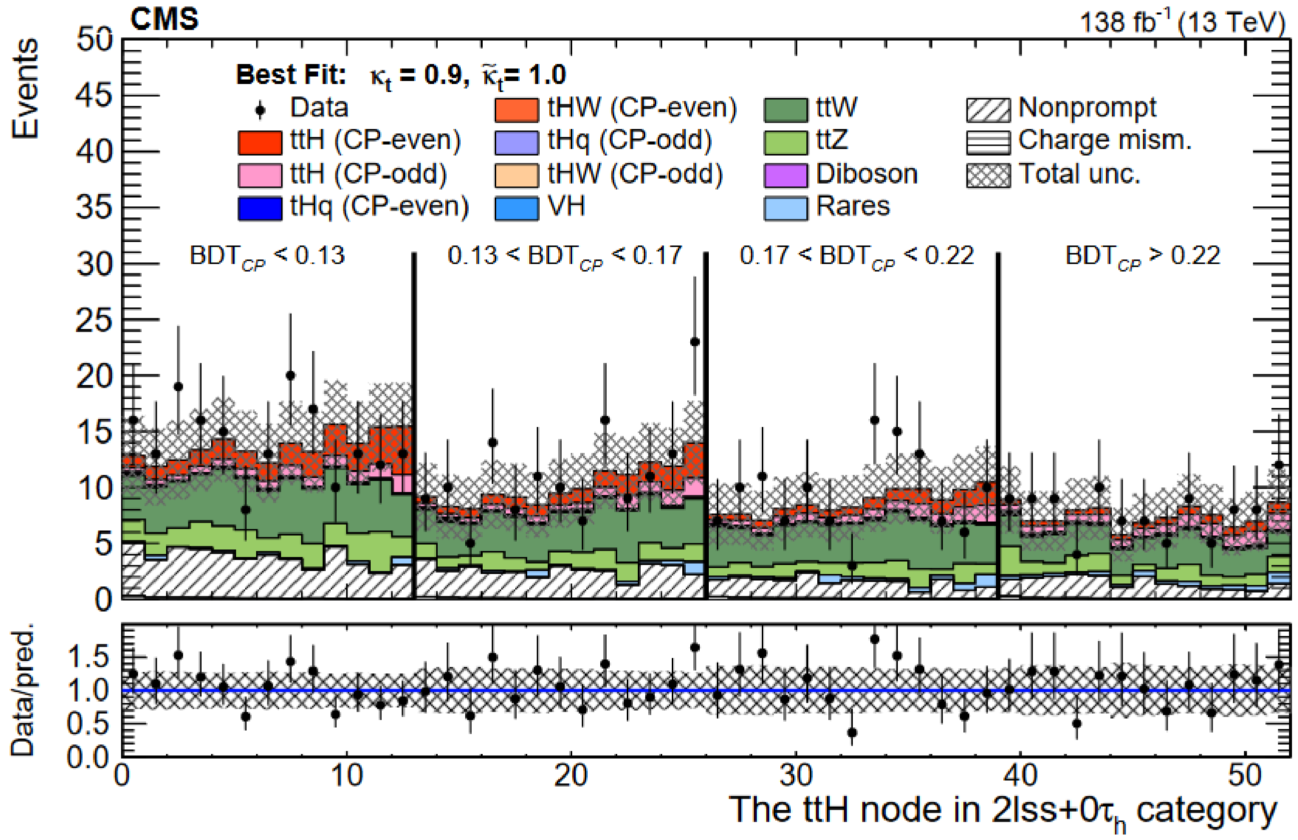


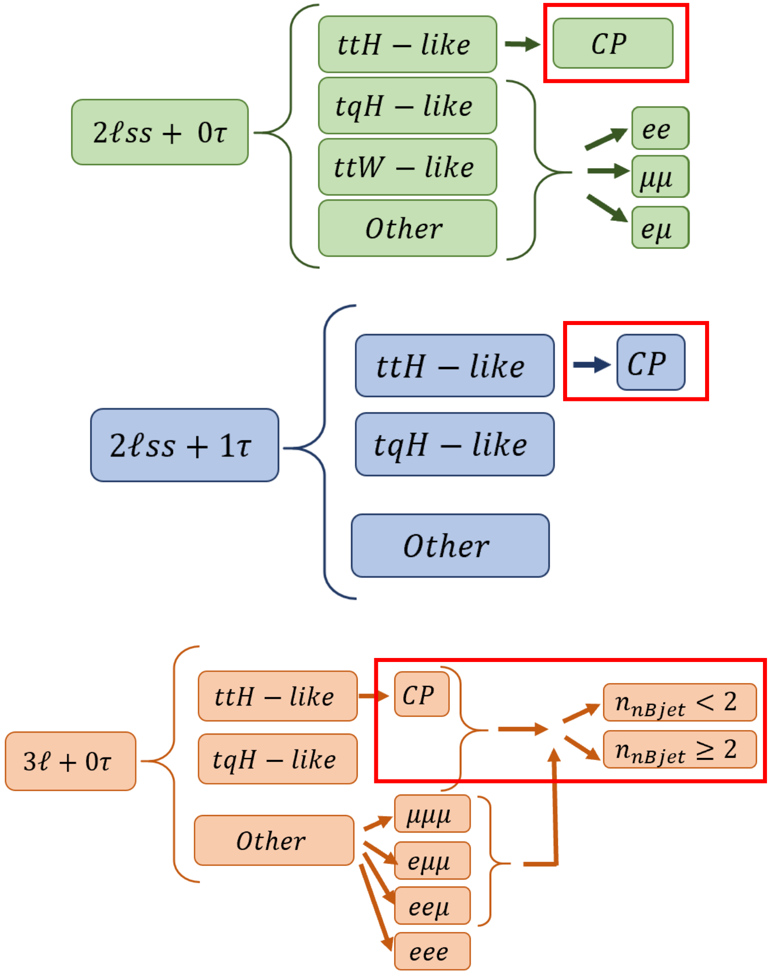
Signal Extraction

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

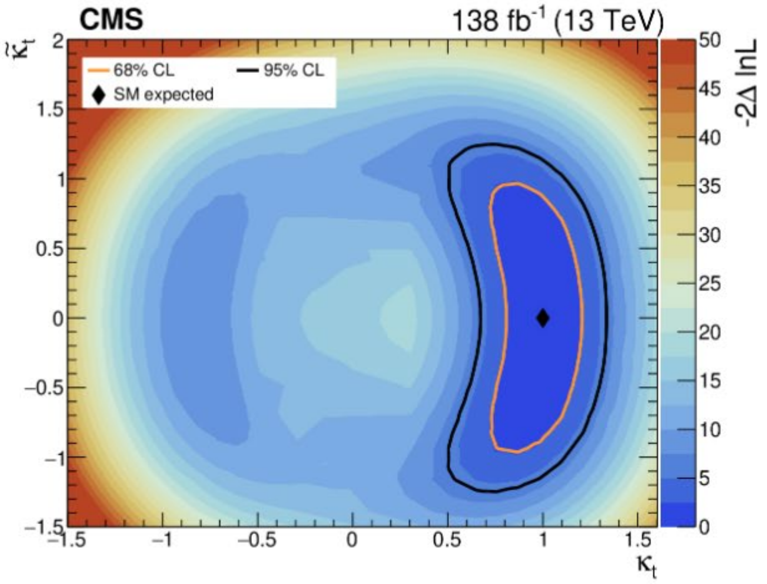
Results

Yields are parametrized using:

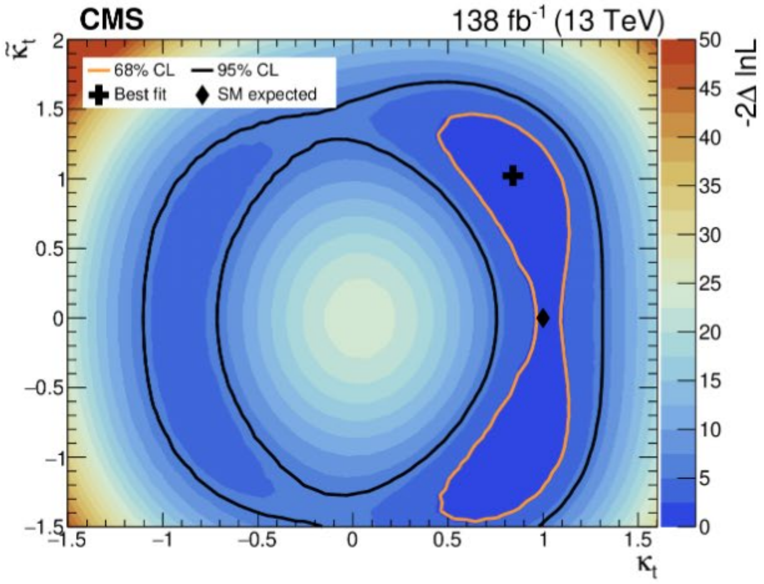
- κ_t and $\tilde{\kappa}_t$ (ratio of the CP-even and CP-odd terms to SM expectation, respectively)
- Results are also expressed in terms of the fraction of the CP-odd coupling:

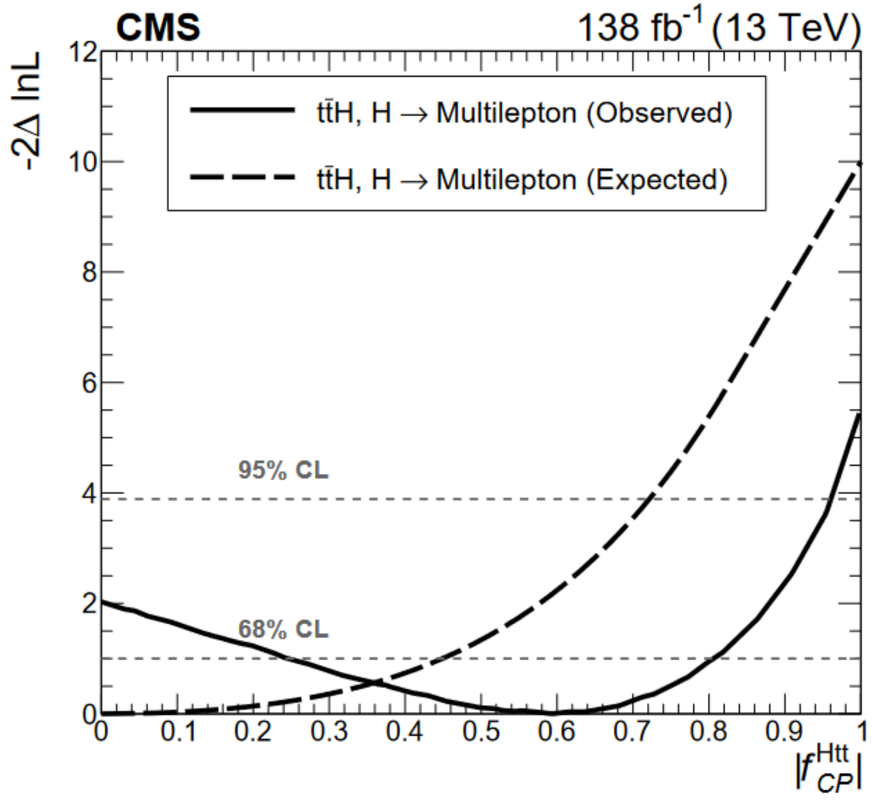
$$f_{CP} = \frac{|\tilde{\kappa}_t|^2}{|\tilde{\kappa}_t|^2 + |\kappa_t|^2}$$

Expected



Observed





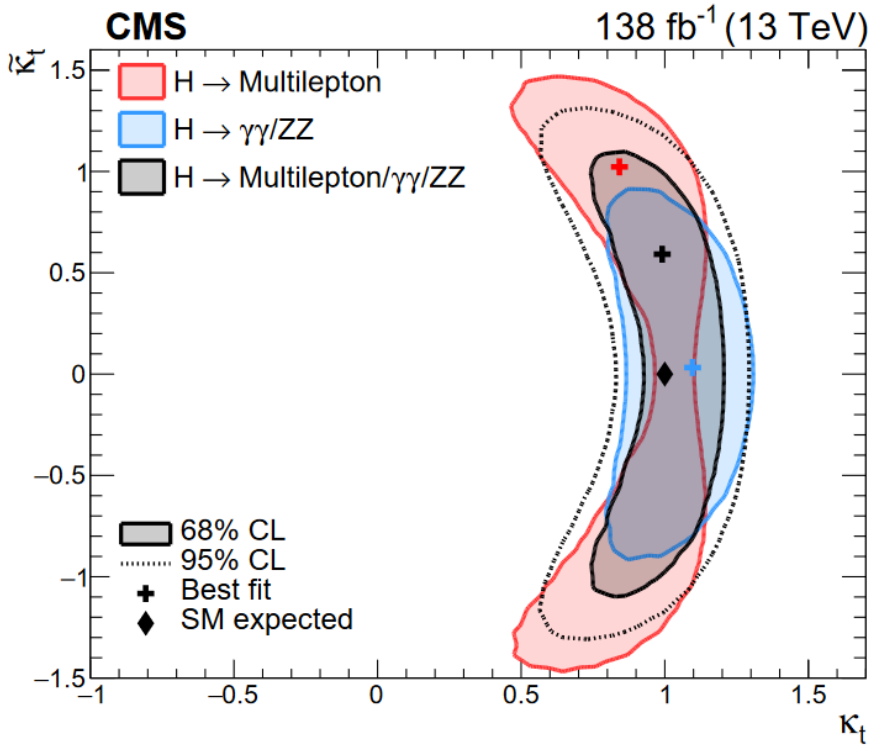
Best fit value:
κ_t = 0.9 & $\tilde{\kappa}_t$ =1.0   in good agreement with SM

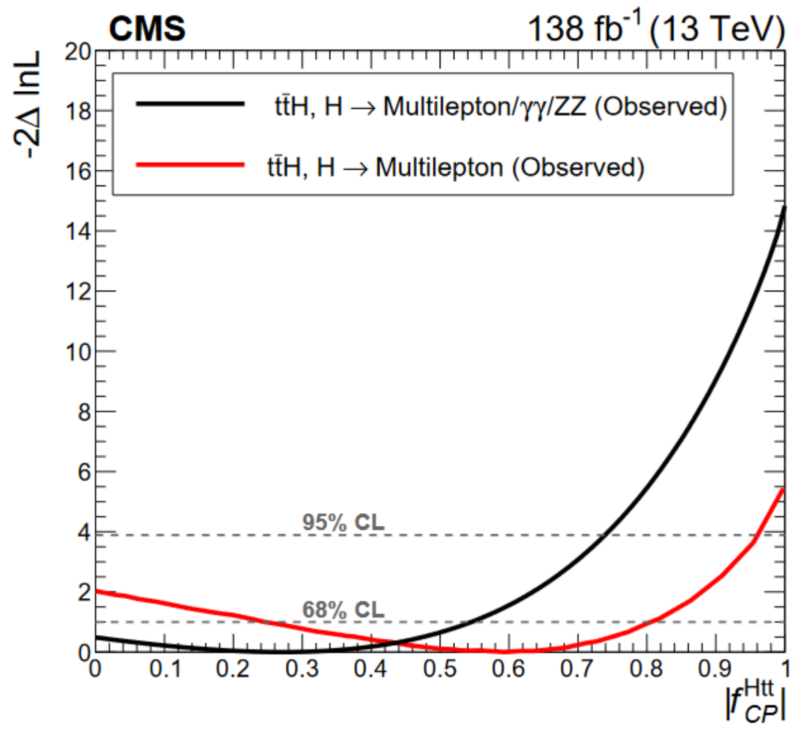
$f_{CP}^{Htt} = 0.59$ within (0.24, 0.81) at 68% CL

Combination

The result is combined with already published tt̄H measurements:

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





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

Summary

Studying $t\bar{t}H$ production allows to understand the **coupling** between the **Higgs boson and the top quark**

- Important experimental milestone after measuring the coupling of the Higgs boson to gauge bosons

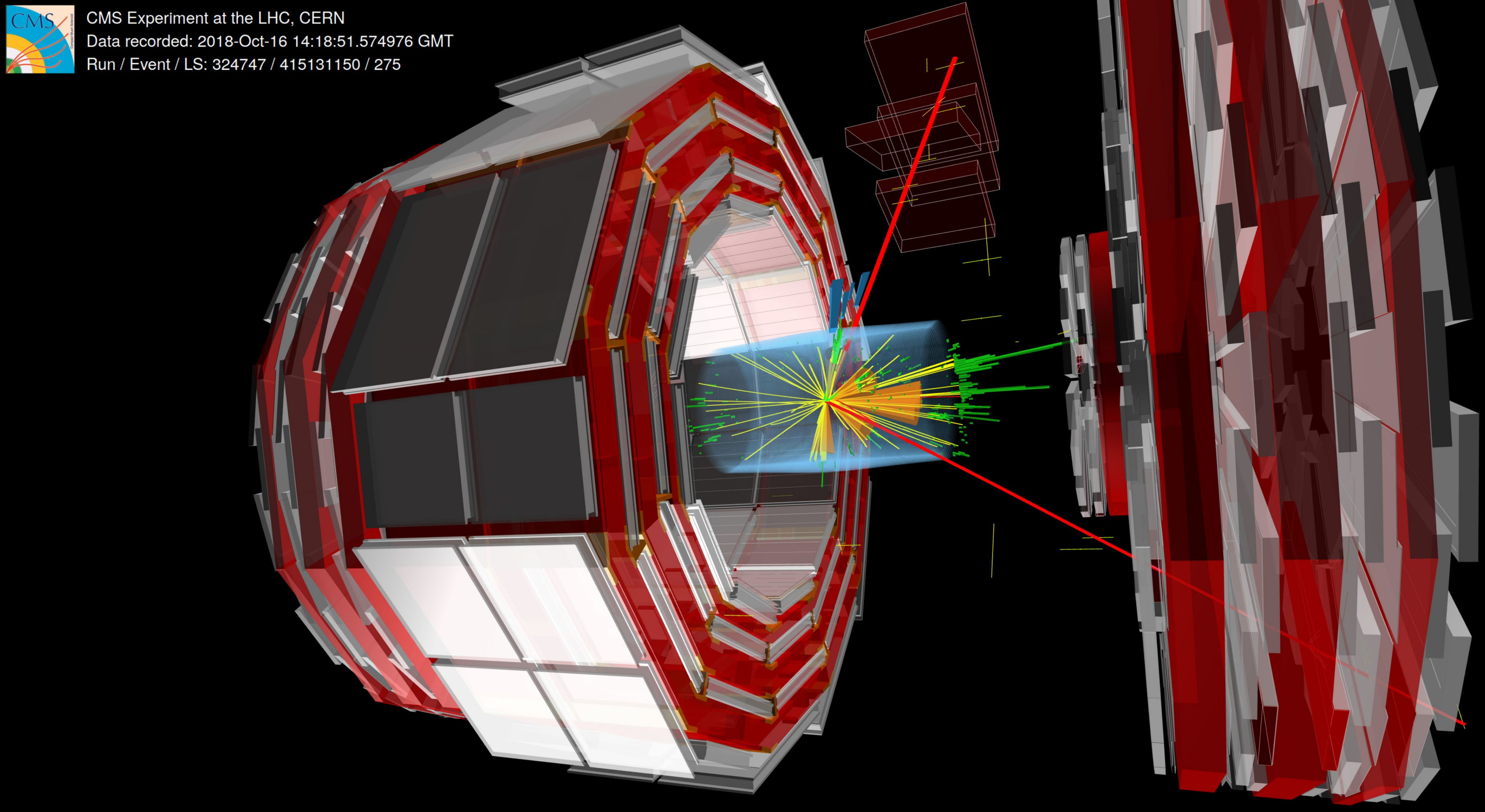
- Need to understand the Yukawa coupling before measuring the Higgs self-coupling, will become relevant during Run 3 and HL-LHC

- The presence of CP violation in the Higgs sector has been proposed
  - Could explain the matter-antimatter asymmetry observed in the Universe

- Top Yukawa coupling structure measured to be compatible with the SM

- Measurement still dominated by statistical uncertainty

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


CMS Experiment at the LHC, CERN
Data recorded: 2018-Oct-16 14:18:51.574976 GMT
Run / Event / LS: 324747 / 415131150 / 275

Thank you!

Back-up

Higgs coupling

- Coupling of the Higgs boson can be read from the Lagrangian:

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

Couplings to EW gauge bosons

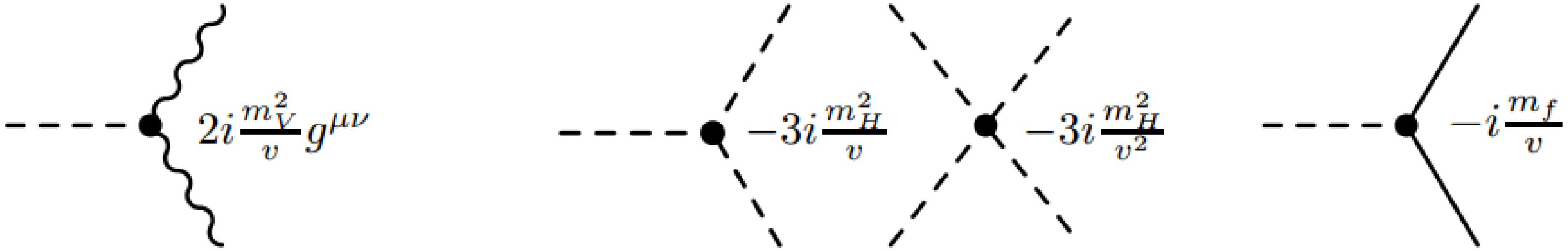
$$\left[m_W^2 W^{\mu +} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0\right] \cdot \left(1 + \frac{h}{v}\right)^2$$

Higgs self-couplings

$$-\mu^2 h^2 - \frac{\lambda}{2} v h^3 - \frac{1}{8}\lambda h^4$$

Couplings to fermions

$$-\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$$



$$m_H = \sqrt{2}\mu = \sqrt{\lambda}v \quad (v = \text{vacuum expectation value})$$

- Bosons: gauge coupling
- Fermions: Yukawa coupling

In the SM Higgs boson is even under CP inversion

CP estructure of Higgs coupling

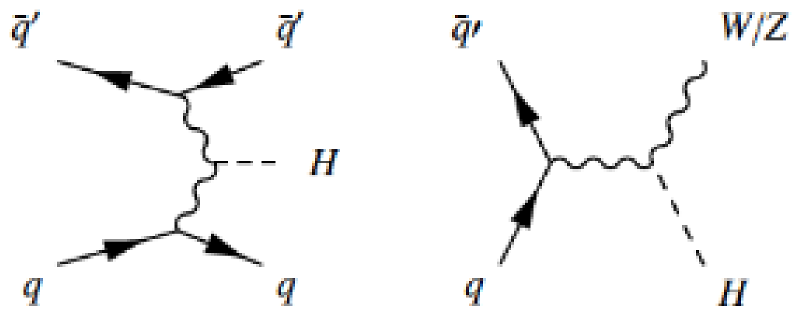
Depending on the decay mode and production mode we can study the coupling to bosons or fermions:

Hgg ggH production.

HVV

- VH production
- VBF
- H→ ZZ → 4l

CP-odd contributions enter at high order operators, Amplitude expansion up to (q^2/Λ_1^2)



$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

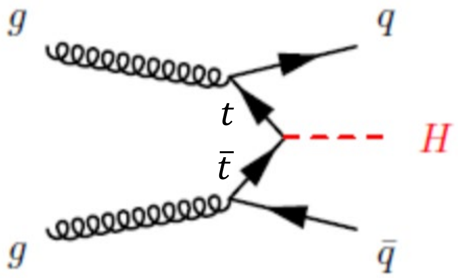
Hff

- Good handle: ttH, tH and H→ $\tau\tau$

$$L_Y = \frac{m_f}{v} H(\kappa_f \bar{f} f + \tilde{\kappa}_f \bar{f} i\gamma_5 f)$$

- ggH is purely loop induced process,

Bottom quarks → indirect constrain on Htt



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

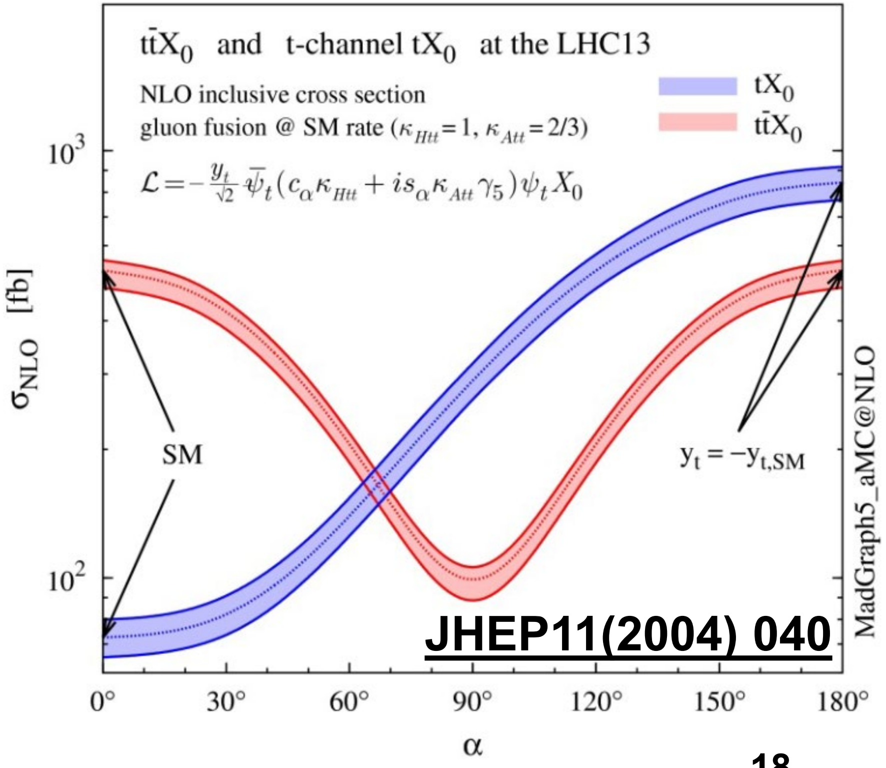
Scenario	α
Purely CP even	$\alpha = 0^\circ$ or 180°
Purely CP odd	$\alpha = 90^\circ$
Mixed scenario	$\alpha \neq 0^\circ, \neq 90^\circ, \neq 180^\circ$

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})



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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):

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

*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