Standard Model at the LHC – Rome | May 7, 2024

Top Yukawa couplings from ttH and top physics

Matthias Schröder (Universität Hamburg)
on behalf of the ATLAS and CMS Collaborations

The top-Higgs Yukawa coupling is special!

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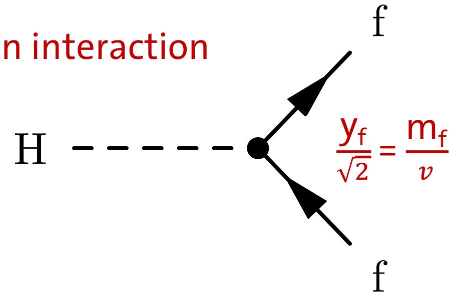
Higgs Yukawa sector – unlike anything we have probed before

Higgs-fermion interaction

$$\mathcal{L} = m_f \bar{\psi}_f \psi_f + \frac{m_f}{v} H \bar{\psi}_f \psi_f$$

fermion masses

$\frac{y_f}{\sqrt{2}}$

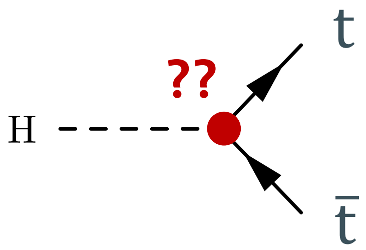


Top-Higgs Yukawa coupling y_t

By far the largest Higgs-fermion coupling (≈ 1)

- Significant role in electroweak vacuum stability
- Sensitivity to new physics
- Relevant in measurement of Higgs boson self-coupling

Outline: How to probe y_t?



Indirect

Loop-induced single Higgs processes
ggF production and $H \rightarrow \gamma\gamma$ decays

Virtual contributions to top quark production
4t and tt production

Direct

Top quark associated production
ttH and tH production

Indirect measurements of y_t: Higgs and top physics

y_t from Higgs combination

[Nature 607 (2022) 52](#)
[Nature 607 (2022) 60](#)

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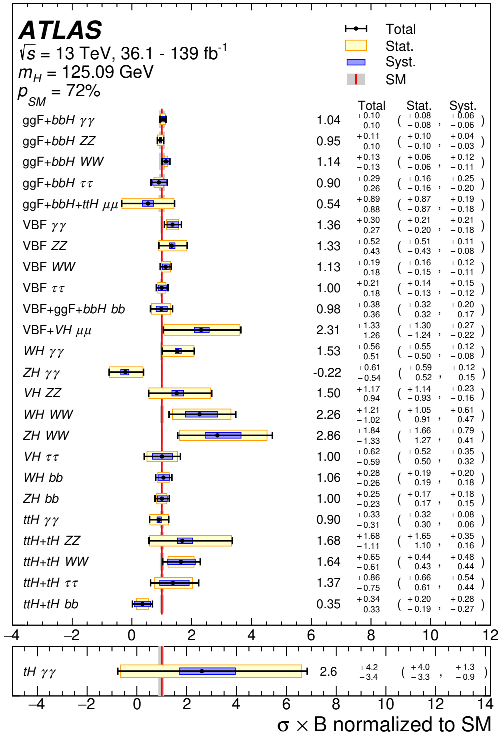
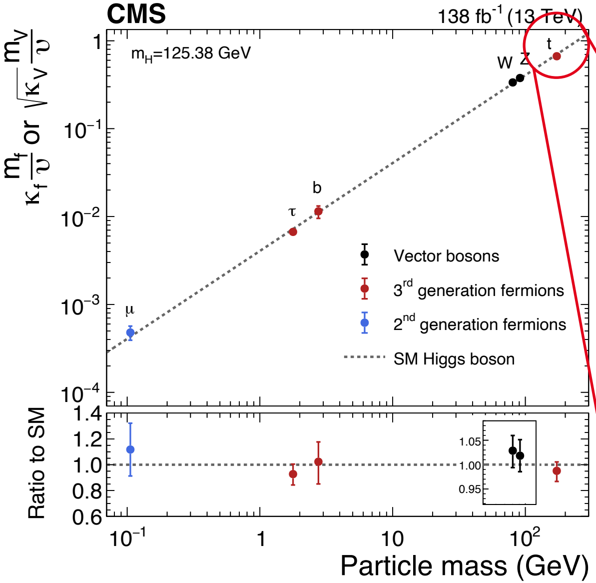
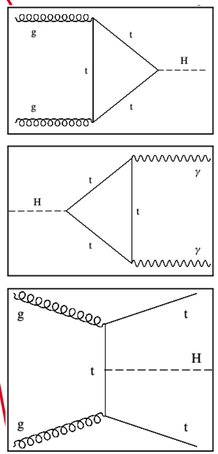
Combination of Higgs boson measurements in various production x decay channels

→ extract coupling y_t – **most precise measurement but indirect**
(assumptions on which particles in loops, total decay width)







Assuming SM structure (resolved loops):

ATLAS: $\kappa_t = 0.95^{+0.07}_{-0.07}$

CMS: $\kappa_t = 0.95^{+0.07}_{-0.08}$

Coupling strength modifier $\kappa_t = y_t/\mathrm{SM}$

y_t from 4t cross section

Eur. Phys. J. C 83 (2023) 496 Eur. Phys. J. C 84 (2024) 156 [Erratum]
Phys. Lett. B 844 (2023) 138076

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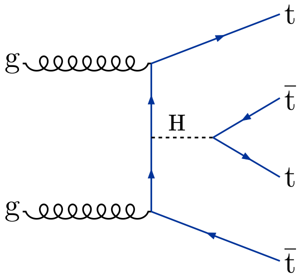
4t production cross section sensitive to strength and CP properties of top-Higgs coupling

- Indirect measurement: model dependent
- Only depending on top-Higgs coupling (no other Higgs coupling)



See talk by Tae Jeong

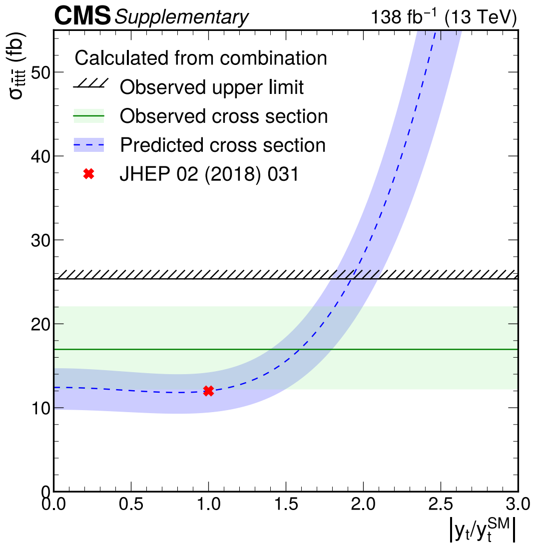
Challenge: very rare process

Analysis of multilepton and all-hadronic (CMS) final states

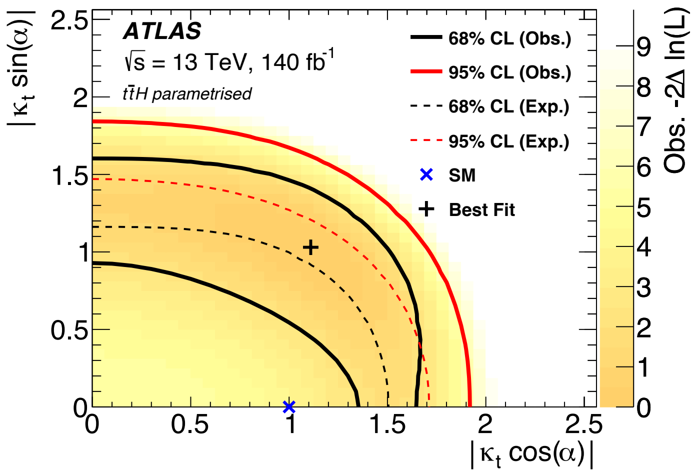
Upper 95% CL limits on κ_t:

ATLAS: $|\kappa_t| < 1.9$ (1.6 exp.)

CMS: $|\kappa_t| < 1.9$



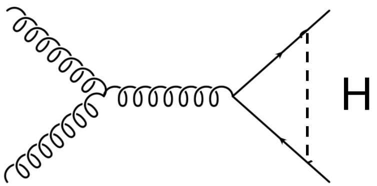
ATLAS:
analysis of CP structure of top-Higgs coupling



y_t from tt cross section

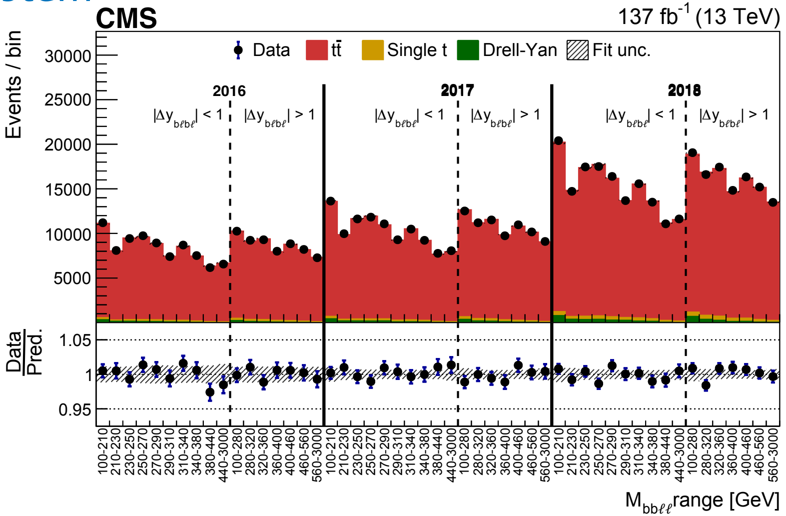
Phys. Rev. D 102 (2020) 092013

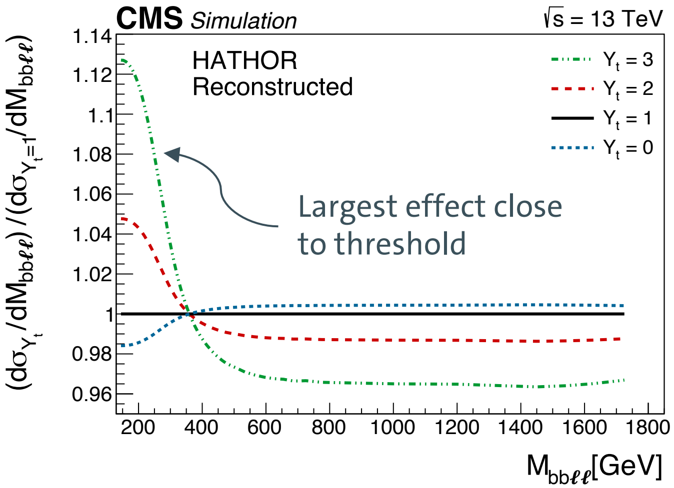
tt production (differential) cross section sensitive to strength of top-Higgs coupling



CMS result in dilepton channel:
likelihood scan of kinematic distributions of tt system

- M_{tt}
- $\Delta(\text{rapidity})_{tt}$





Largest effect close to threshold

Best-fit $|\kappa_t| = 1.16^{+0.24}_{-0.35}$

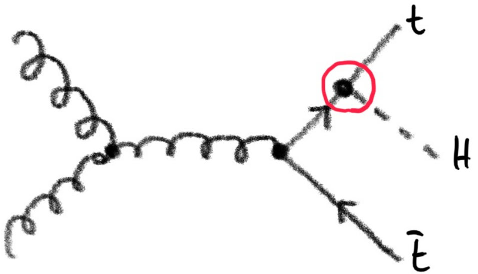
95% CL limit $|\kappa_t| < 1.5$ (1.5 exp.)

Direct measurements of y_t: ttH and tH production

ttH measurements at the LHC

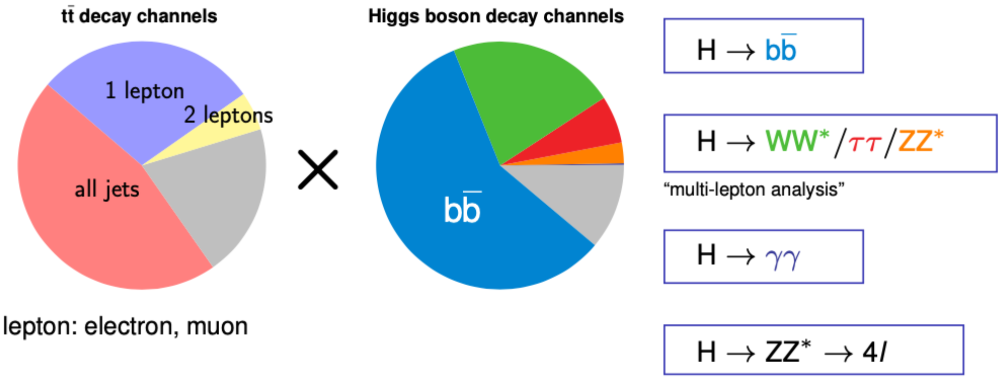
ttH production: direct probe of top-Higgs coupling

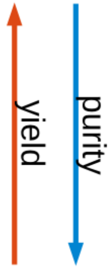
Talk by Anna



Small production cross section: 0.5 pb at 13 TeV [arXiv: 1610.07922]

Multitude of possible final states with many and different objects





Independent observation by ATLAS and CMS in 2018, combining several channels

Phys. Rev. Lett. 120 (2018) 231801

Phys. Lett. B 784 (2018) 173

ttH with H $\rightarrow \gamma\gamma$

JHEP 07 (2023) 088

Phys. Rev. Lett. 125 (2020) 061801

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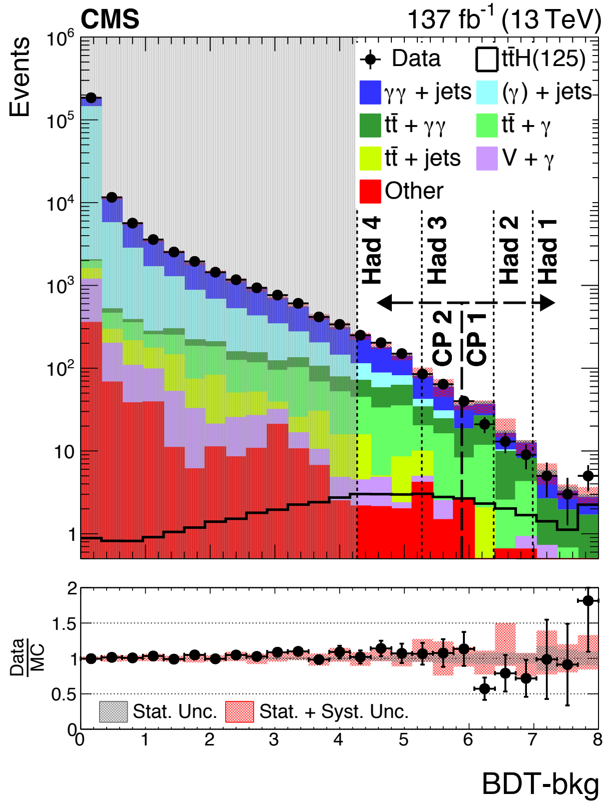
Very clean channel:
clear signature + excellent mass resolution (1%)
→ reconstruct Higgs boson from photons



Strategy overview

- Events split in leptonic & hadronic channels
- Dedicated BDT in each channel
  → reject main backgrounds
  → categorise events by signal purity
- Simultaneous fit to $m_{\gamma\gamma}$ distribution in each category

ttH with H → γγ results

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Phys. Rev. Lett. 125 (2020) 061801

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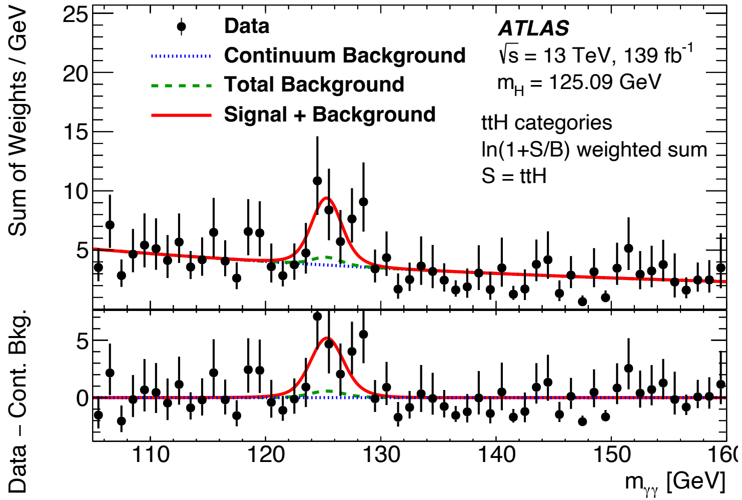

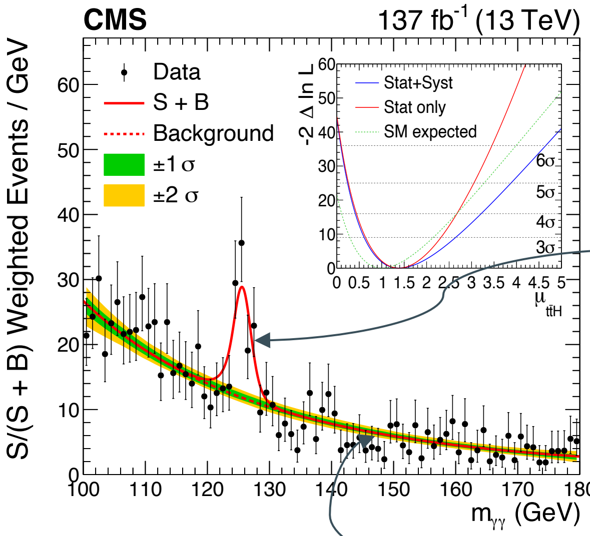

Signal:
Gaussian +
Crystal Ball function

Background:
discrete profiling method

Signal strength $\mu := \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i \cdot \mathcal{B}^f)_{\text{SM}}} = \frac{\text{observed rate}}{\text{expected rate}}$

$$\mu_{\text{ttH}} = 0.89^{+0.32}_{-0.30}$$

$$\mu_{\text{ttH}} = 1.38^{+0.36}_{-0.26}$$

Significance 6.6σ (4.7σ exp.)

First ttH observation in single channel

ttH with H $\to \gamma\gamma$ STXS analysis

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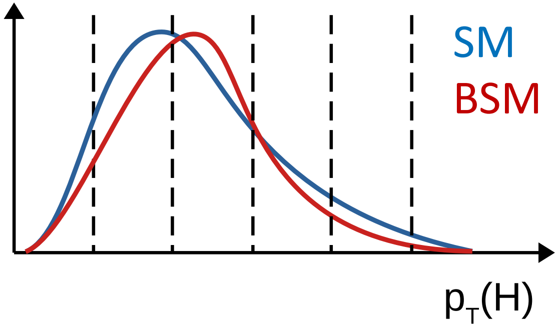
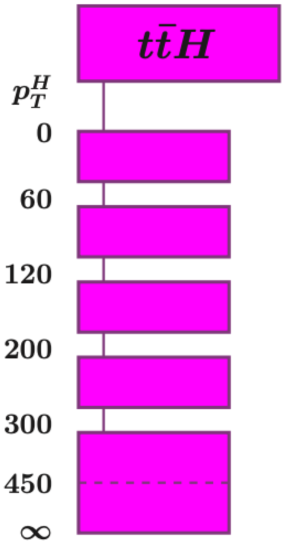
Step towards differential measurements:

Talk by Sarah

Simplified Template Cross Section (STXS) framework

- Signal strength for each Higgs production mode
- Separated further in different phase-space regions





H $\to \gamma\gamma$ channel: first ttH STXS results

Part of inclusive H $\to \gamma\gamma$ STXS measurements

ttH with H → γγ STXS analysis

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JHEP 07 (2021) 027

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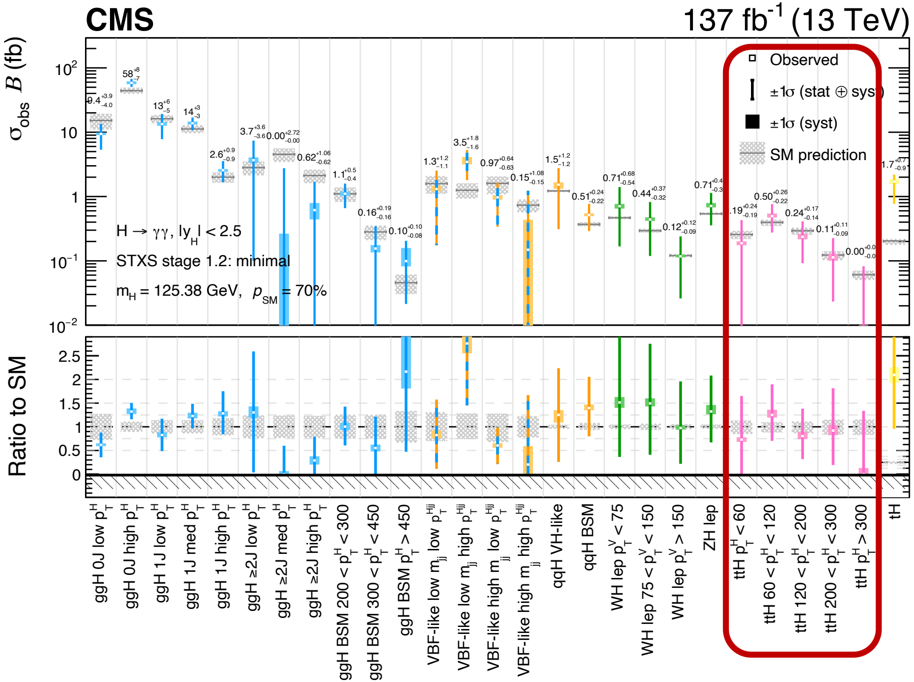
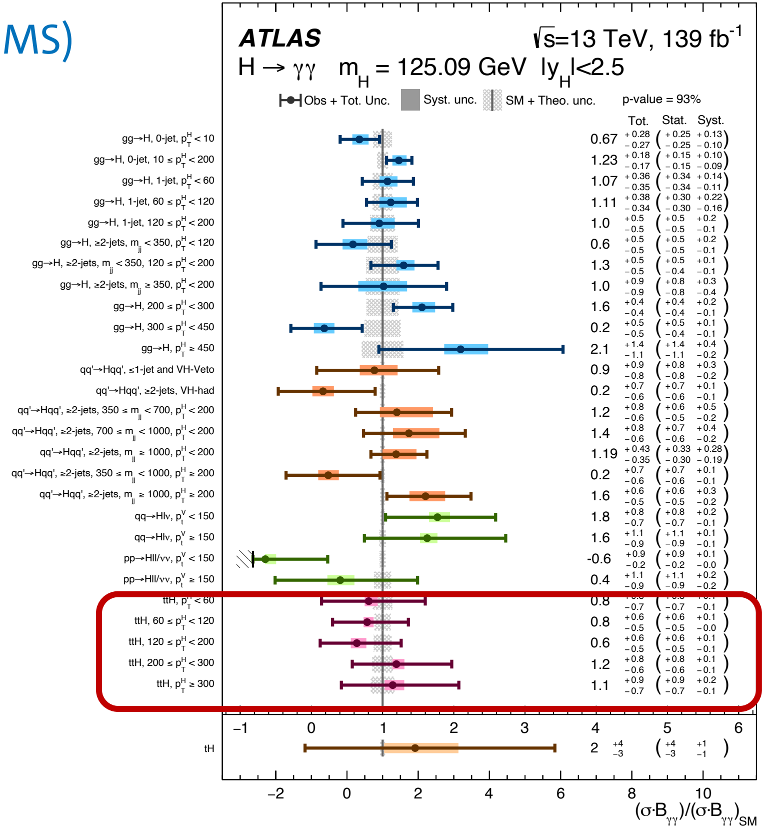
STXS bins assigned by multi-class BDT (ATLAS) or $p_T(\gamma\gamma)$ (CMS)

Several additional BDTs or NNs to reject backgrounds





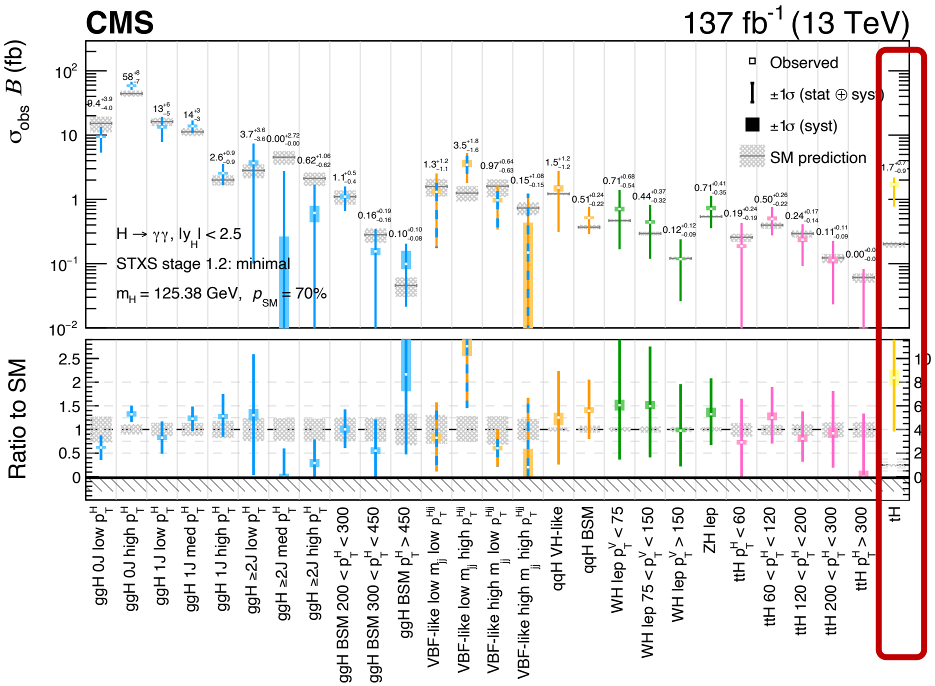
ttH with H → γγ STXS analysis

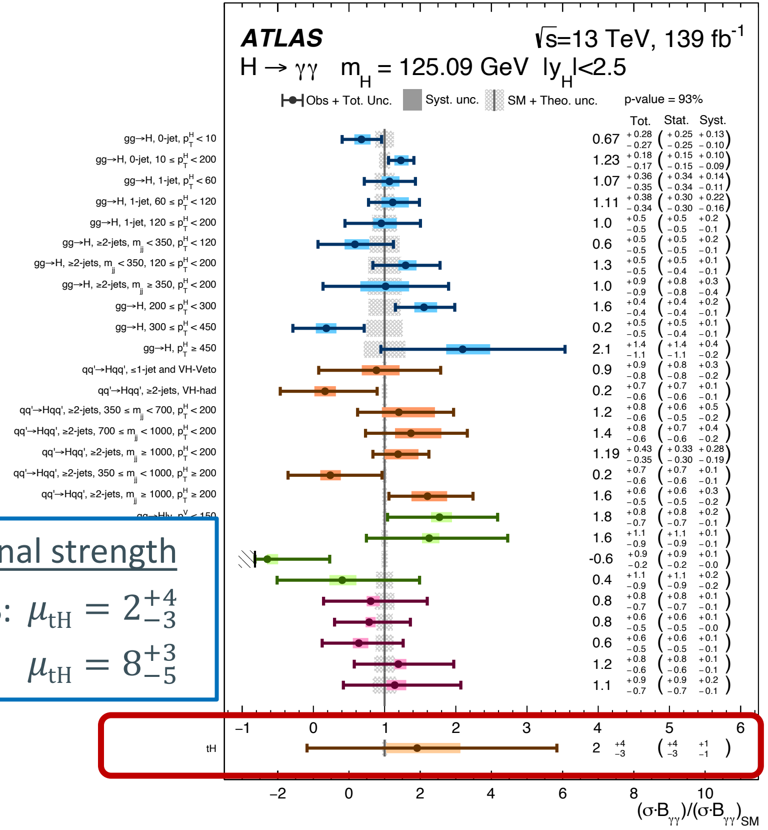
[JHEP 07 (2023) 088](#)

[JHEP 07 (2021) 027](#)

Additional effort to isolate tH production

Multi-class BDT (ATLAS), NN (CMS)





tH signal strength

ATLAS: $\mu_{tH} = 2^{+4}_{-3}$

CMS: $\mu_{tH} = 8^{+3}_{-5}$

ttH multilepton

Targeting H decays to vector bosons or τ

Complex categorisation by lepton flavour, multiplicty, and sign

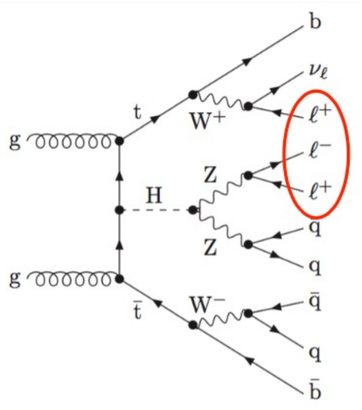
+ multi-class BDTs (ATLAS)
+ multi-class NNs (CMS)

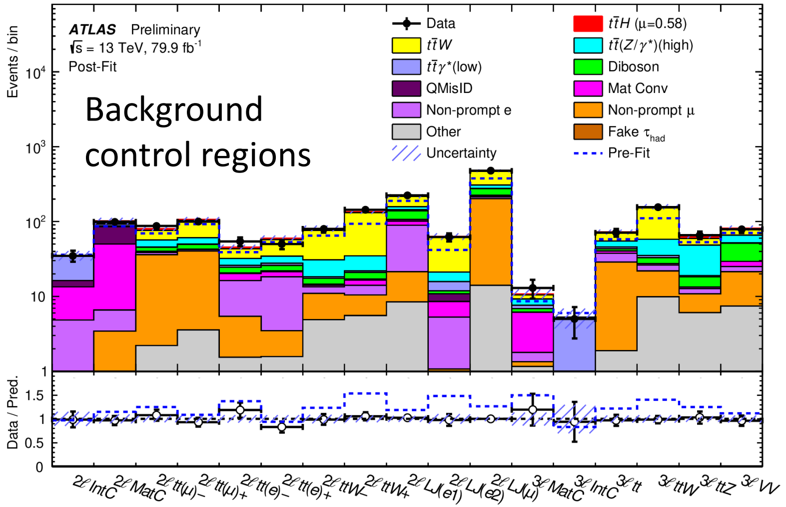
} signal + bkg. control regions

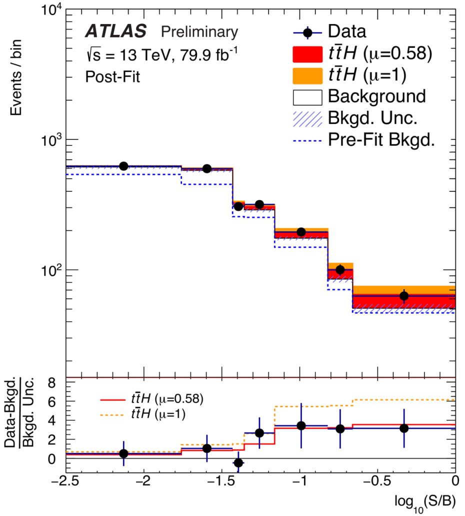
Challenging SM backgrounds

- Irreducible: **ttW, ttZ/γ, diboson**
- Reducible: **non-prompt and fake leptons**

No resonance peak:
BDTs or NNs to extract signal







ttW background

Talks by Jonathan + Anna

ATLAS-CONF-2019-045

Eur. Phys. J. C 81 (2021) 378

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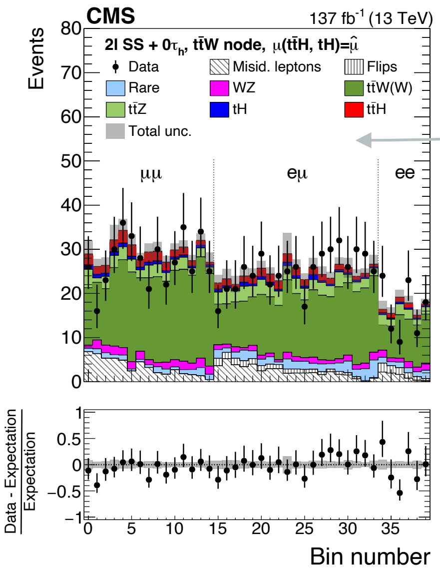
ttW background difficult to model

- Shape from simulation
  - ATLAS: Sherpa ttW+1/2j (NLO/LO)
  - CMS: MadGraph5_aMC@NLO (NLO)
- Normalisation freely-floating in fit



Example ttW control region from dedicated NN class in 2l(SS)+0τ_h

Post-fit ttW normalisation larger than SM expectation*

ttW norm. = 1.43 +/- 0.21 (CMS)

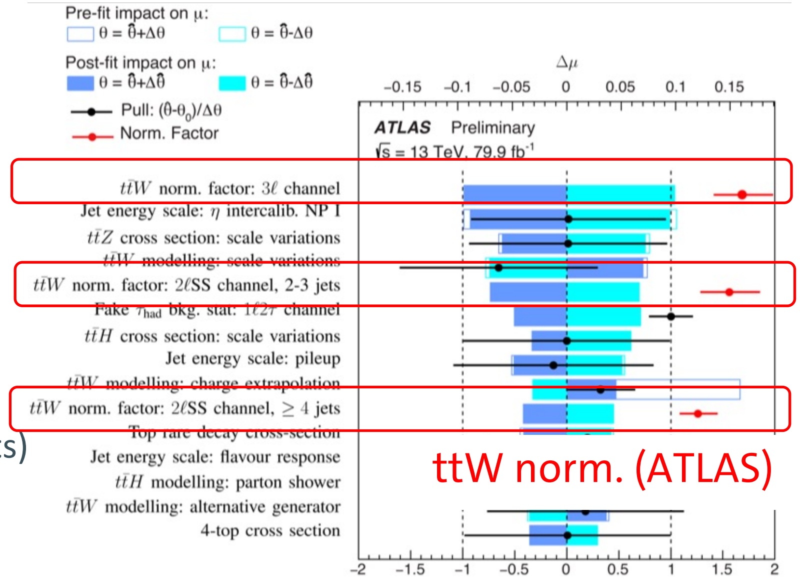
(consistent with dedicated measurements)

[JHEP 07 (2023) 219] [arXiv:2401.05299 (subm. to JHEP)]

* Different predictions as reference

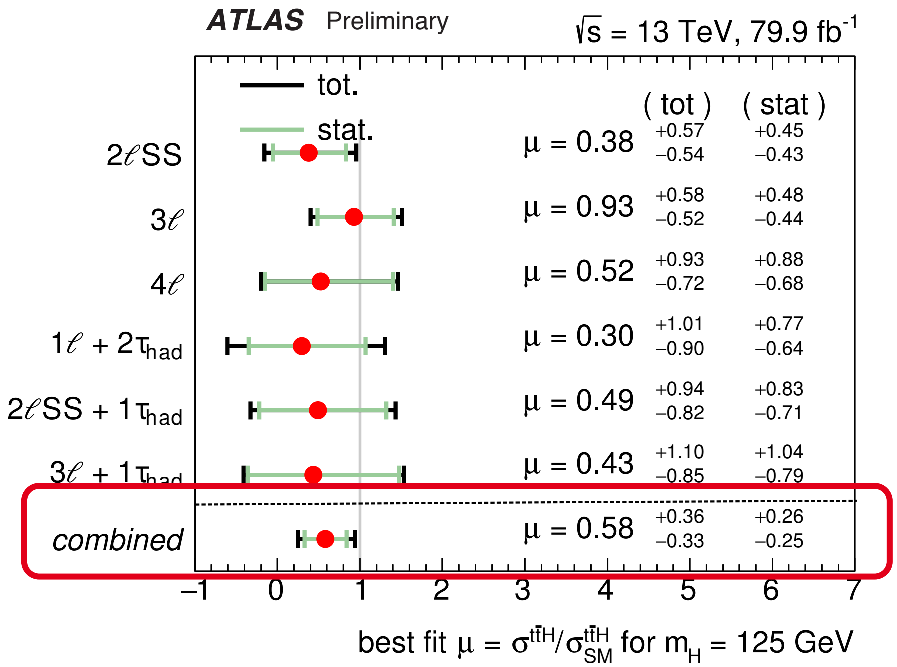
Various systematic uncertainites

- Theory (scale choices, shower, etc.)
- Charge asymmetry and b-jet multiplicity

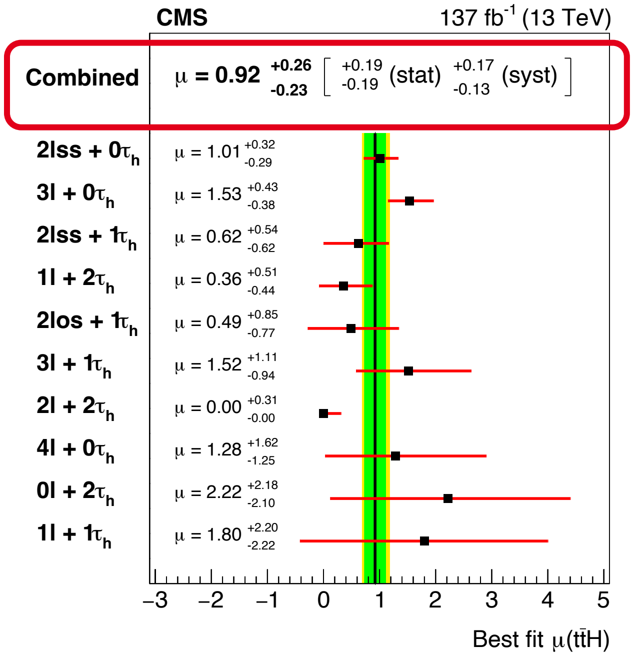


ttH multilepton results

ATLAS-CONF-2019-045
Eur. Phys. J. C 81 (2021) 378



Significance 1.8σ (3.1σ exp.)



Significance 4.7σ (5.2σ exp.)

Multilepton: ttH+tH production

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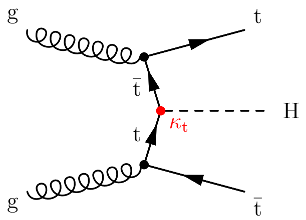
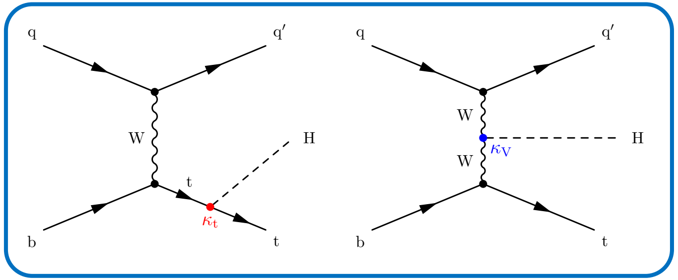
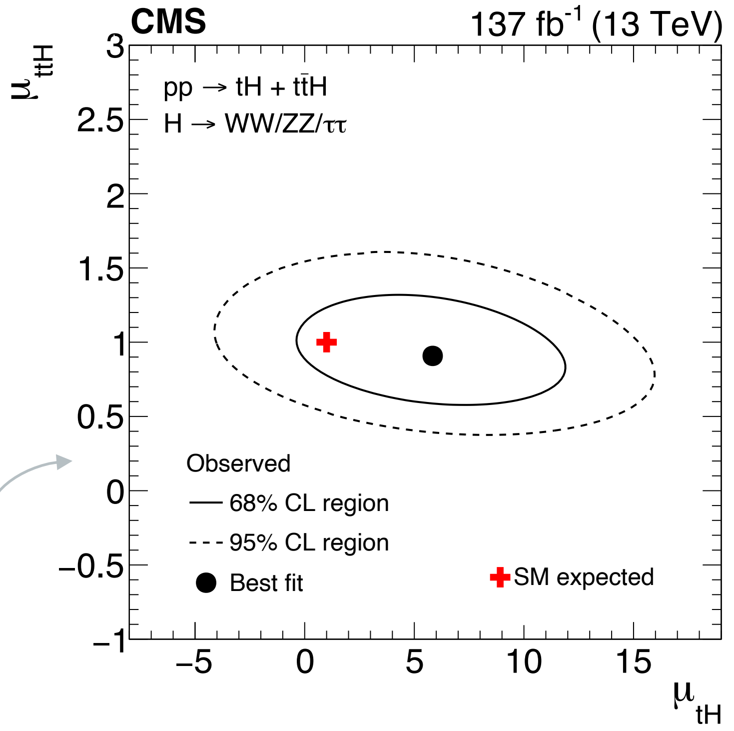
CMS analysis: dedicated analysis categories targeting tH events





tH production: s_{SM} = 90 fb
(can be strongly enhanced for non-SM)
[arXiv: 1610.07922]

Simultaneoulsy floating ttH and tH contributions



Multilepton: ttH+tH production

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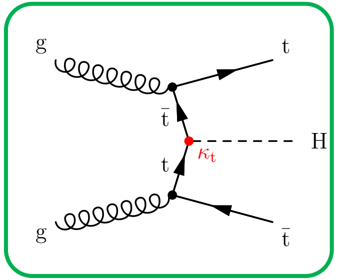
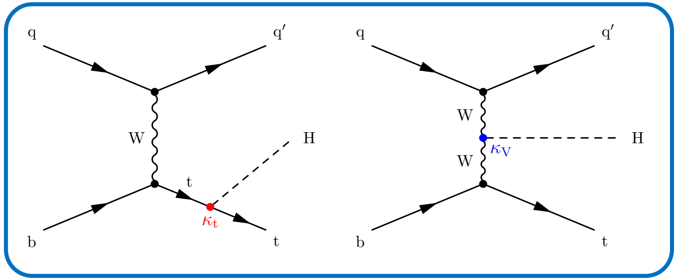
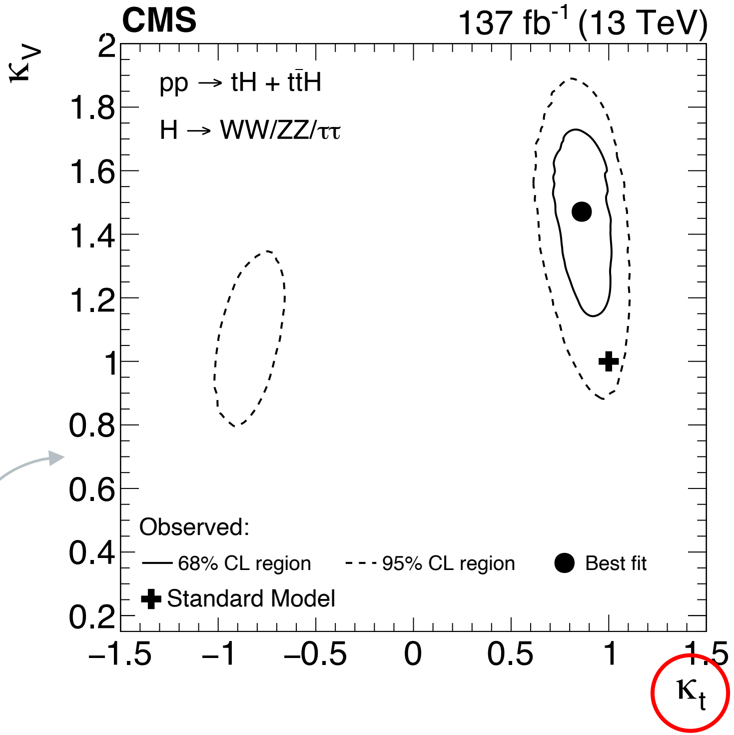
ttH and tH cross-sections depend differently on top-Higgs coupling κ_t



ttH: κ_t^2



tH: $3.40\ \kappa_t^2 + 3.56\ \kappa_V^2 - 5.96\ \kappa_t\kappa_V$
(diagrams interfere)



Simultaneoulsy floating ttH and tH contributions
→ **constraints on κ_t and κ_V (including relative sign!)**

ttH with H → bb

JHEP 06 (2022) 97
CMS-PAS-HIG-19-011

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Benefit from large BR(H → bb) ≈ 58%

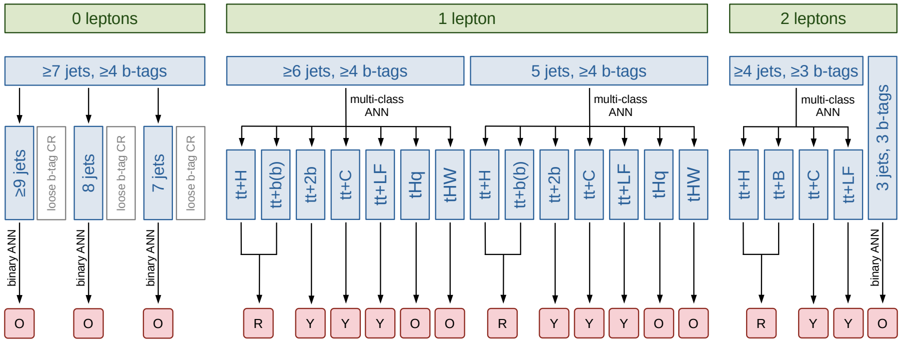
Only Higgs-fermion couplings involved

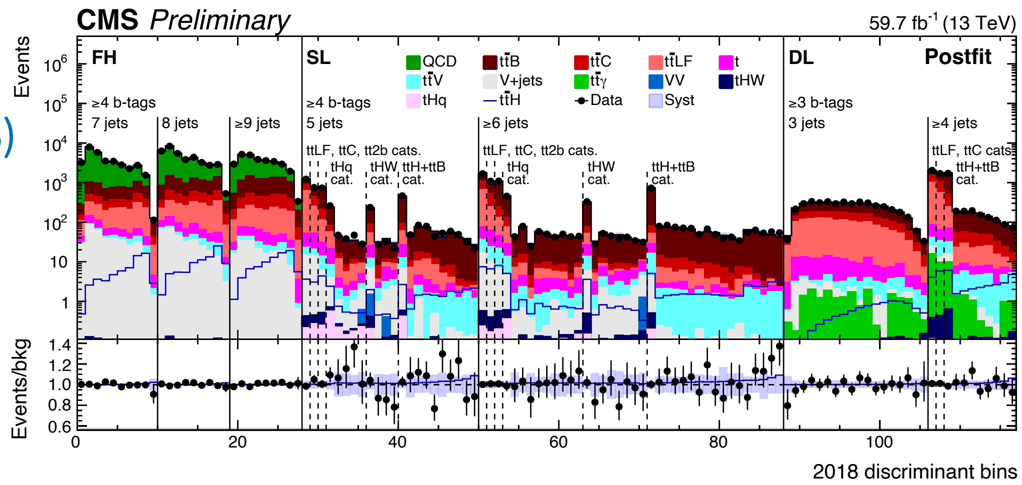
Challenging final state

- No unambigious event reconstruction
- **Irreducible tt+bb background**

Complex analysis strategy

- Categories in #leptons, jets, b-tags and b-tag eff. (ATLAS) / multi-class NNs (CMS)
  - ATLAS: dedicated boosted category
  - CMS: 0 lepton channel (data-driven QCD)
- BDTs for jet-parton assignment
- Signal extracted using BDT or NN information





tt+bb background

Talk by Tae Jeong

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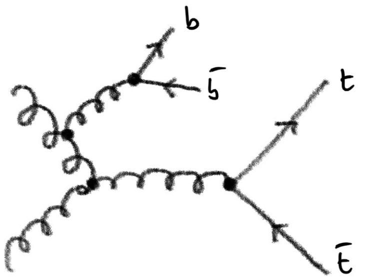
tt+bb **difficult to model and to measure** [arXiv:2309.14442, acc. by JHEP]

- Simulations typically underpredict cross section by ≈20–30%
- Differences in relevant kinematic distributions

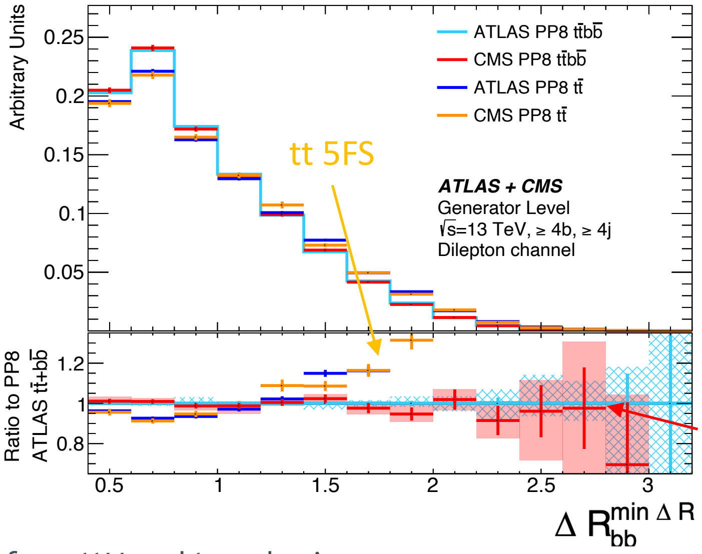


Different **approaches** to simulate events include:

- tt ME at NLO + PS g → bb splitting (5FS)
- ttbb ME at NLO (4FS)

ME: matrix element, PS: parton shower, FS: flavour scheme

expect better description of kinematics
and better defined uncertainties



tt+bb background

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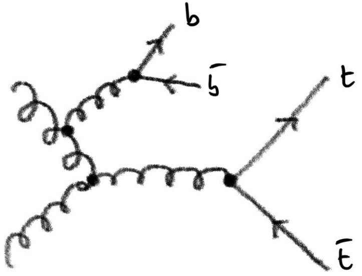


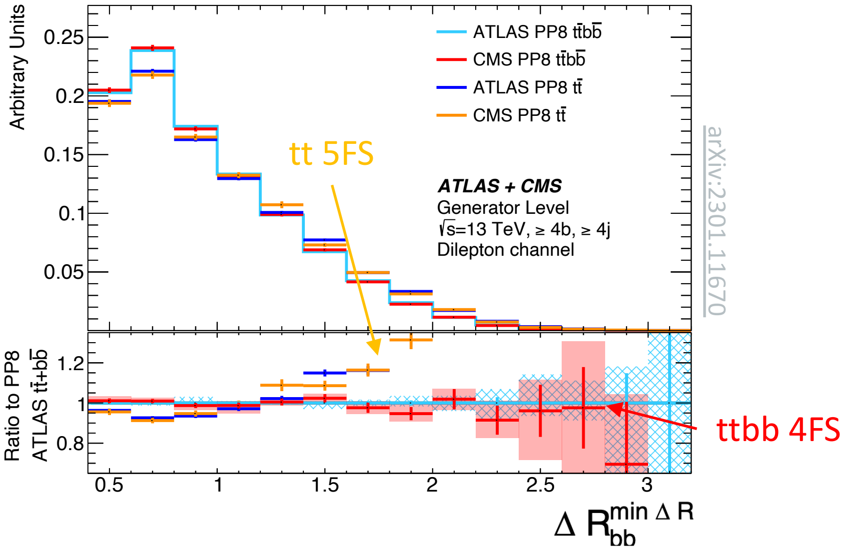
Different **approaches** to simulate events include:

- tt ME at NLO + PS g → bb splitting (5FS)
- ttbb ME at NLO (4FS)

ME: matrix element, PS: parton shower, FS: flavour scheme

tt+bb background from
Powheg ttbb 4FS simulation [Eur. Phys. J. C78 (2018) 502]

- Embedded into Powheg tt 5FS sample to cover full phase space
- **Overall tt+bb normalisation freely-floating**



arXiv:2301.11670

tt+bb background

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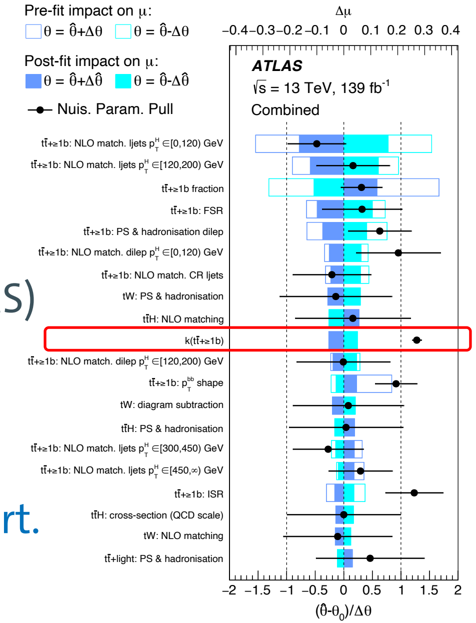
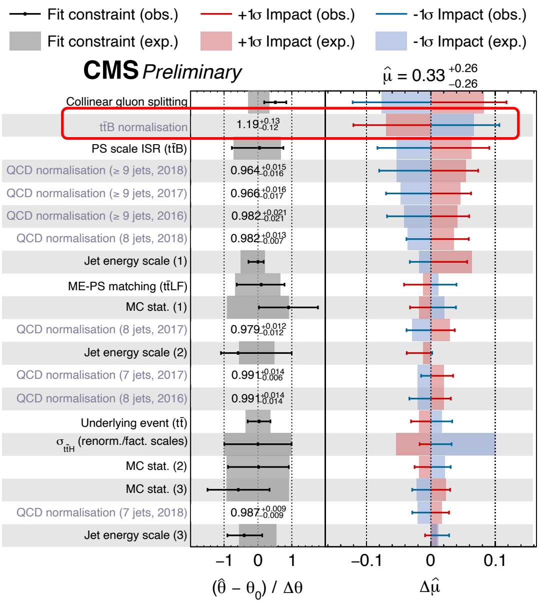
Various modelling uncertainties

- Scale choice in ME and PS
- ME—PS matching
- Hadronisation
- tt+b frac. (ATLAS) / collinear g → bb (CMS)
- p_T(H) spectrum (ATLAS)

In addition to varying generator parameters

- ATLAS: diff. between generators as uncert.
- CMS: bias tests with other generators





Post-fit tt+bb normalisation larger than prediction (consistent with dedicated measurement)

- ATLAS: 1.28 ± 0.08
- CMS: 1.19 ± 0.13

* Different predictions as reference

ttH with H → bb results

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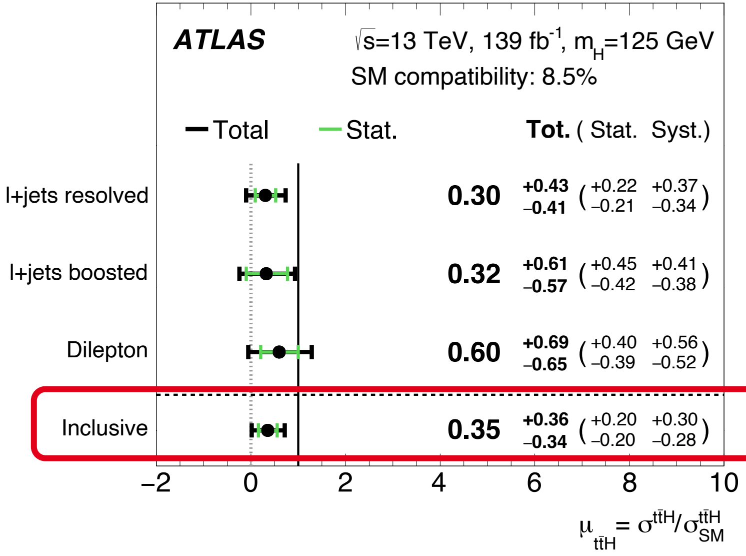
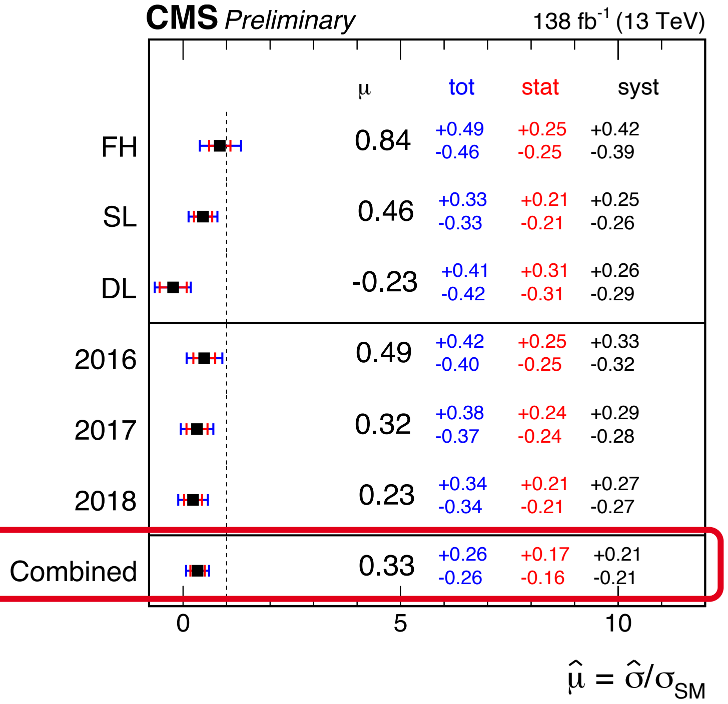
Dominated by systematic uncertainties





Significance 1.0σ (2.7σ exp.)

Significance 1.3σ (4.1σ exp.)

ttH with H → bb STXS analysis

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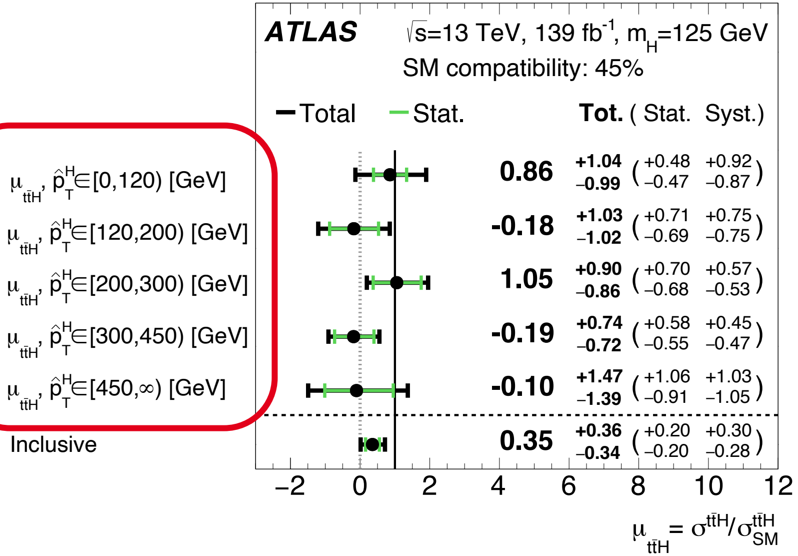
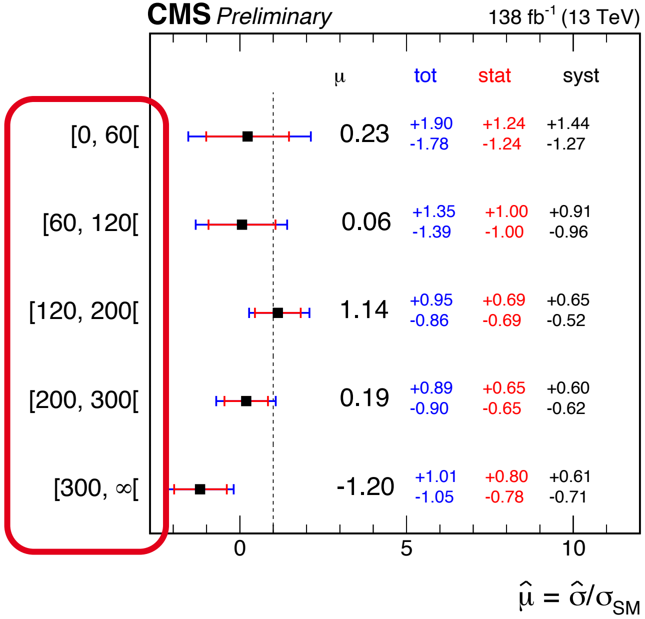
Signal region events separated into 5 p_T(H) bins using BDTs (ATLAS) / NNs (CMS)





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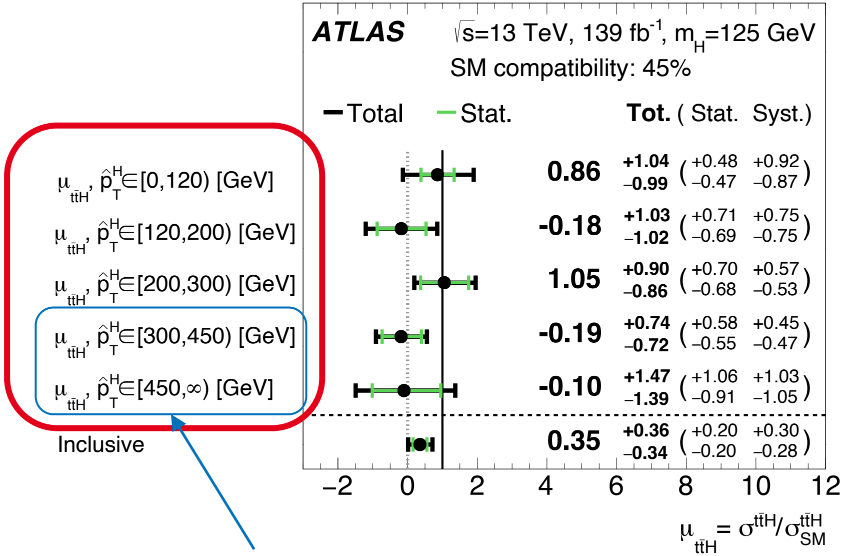
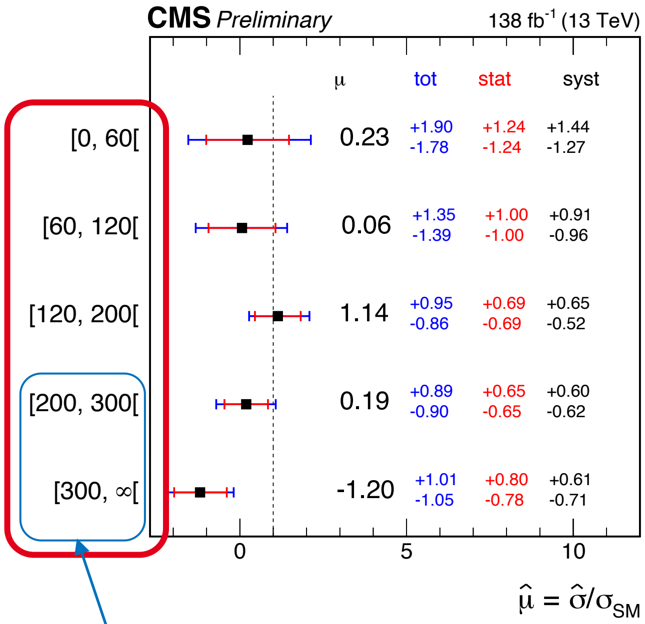
ttH with H → bb STXS analysis

Signal region events separated into 5 p_T(H) bins using BDTs (ATLAS) / NNs (CMS)



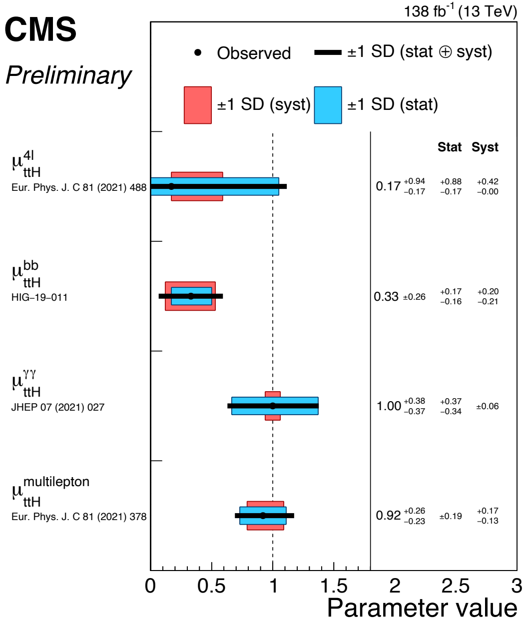
Gain from boosted reconstruction



CMS boosted ttH/Z → bb: $\mu_{\mathrm{ttH}} = -0.27^{+0.86}_{-0.83}$

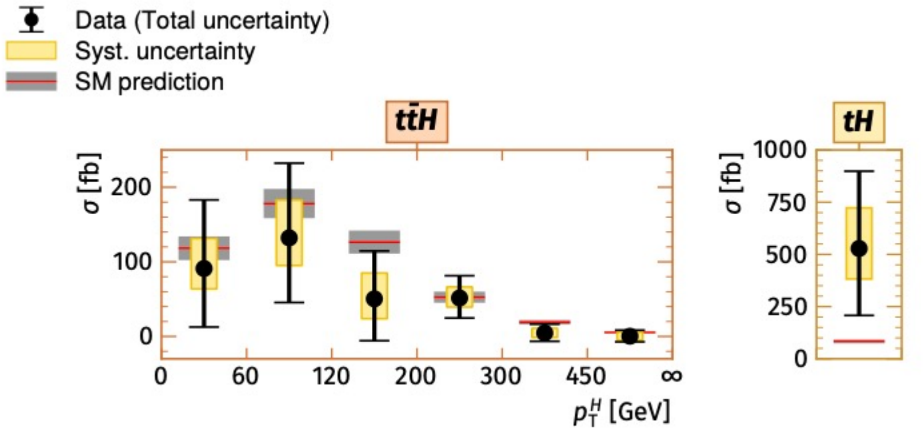
[Phys. Rev. D 108 (2023) 032008]

ttH measurements: status



From combination of ATLAS Run 2 Higgs analyses:

Nature 607, 52 (2022)



ttH results with **full Run-2 dataset** in (almost) all channels

Major improvements in sensitivity & extended interpretations (STXS, targeting tH)

Top Yukawa CP properties

Phys. Rev. Lett. 125 (2020) 061802

Phys. Rev. Lett. 125 (2020) 061801

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CP-odd component in top-Higgs interaction?

In principle allowed at tree level!

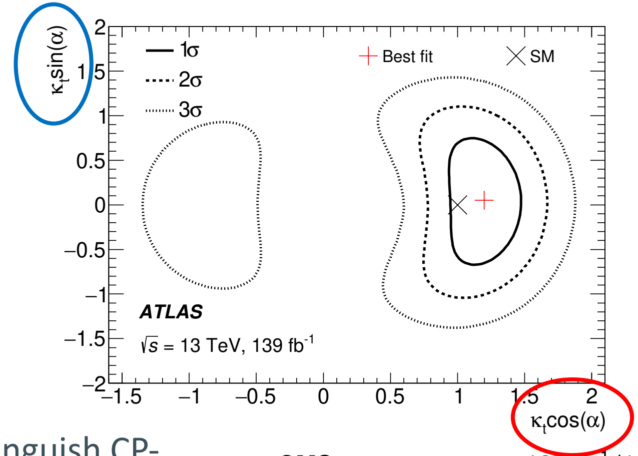
$$\mathcal{A}(\mathrm{Htt}) = -\frac{m_t}{v}\bar{\psi}_t\left(\kappa_t + i\tilde{\kappa}_t\gamma_5\right)\psi_t$$

CP-even/CP-odd Yukawa coupling
(SM: $\kappa_t = 1, \tilde{\kappa}_t = 0$)

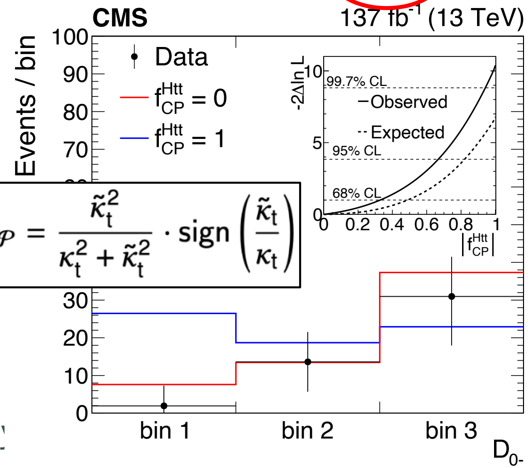
→ **impact on ttH + tH rates and kinematics**

Simultaneoulsy floating ttH and tH contributions

→ **constraints on CP-odd top-Higgs coupling $\tilde{\kappa}_t$**



BDT to distinguish CP-even/odd contributions



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

H → γγ: first measurement of Htt CP structure

Pure CP-odd structure excluded at 3.9σ ATLAS / 3.2σ (2.6σ exp.) CMS

Top Yukawa CP properties

JHEP 07 (2023) 092 CMS-PAS-HIG-19-011
Phys. Lett. B 849 (2024) 138469

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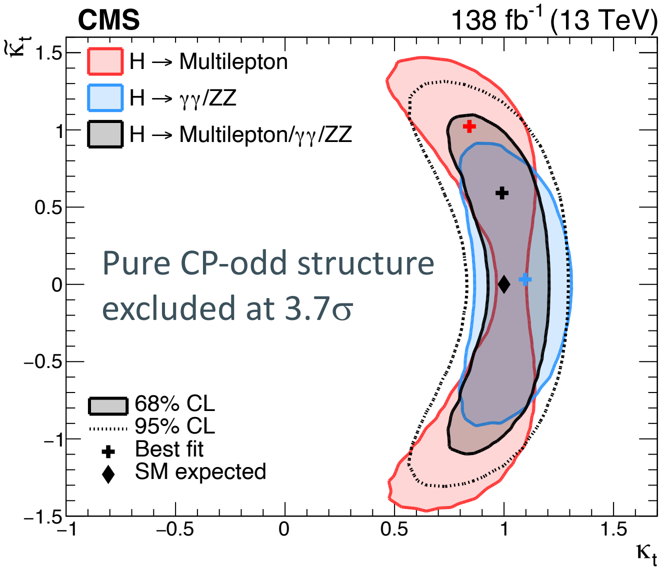
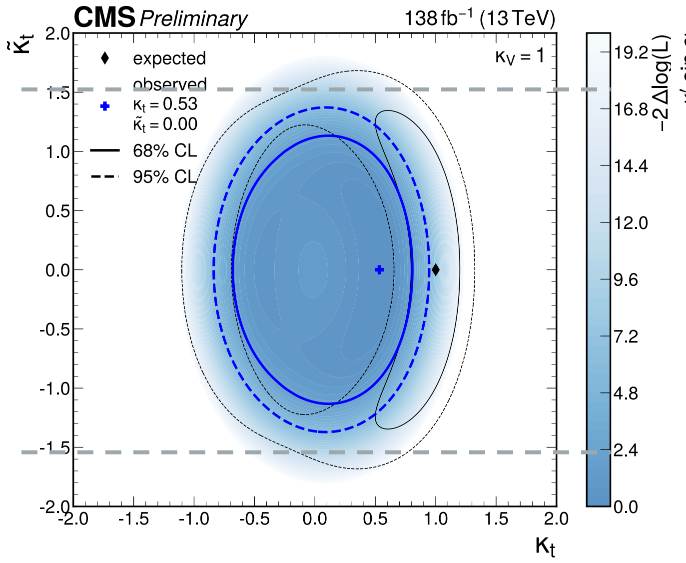
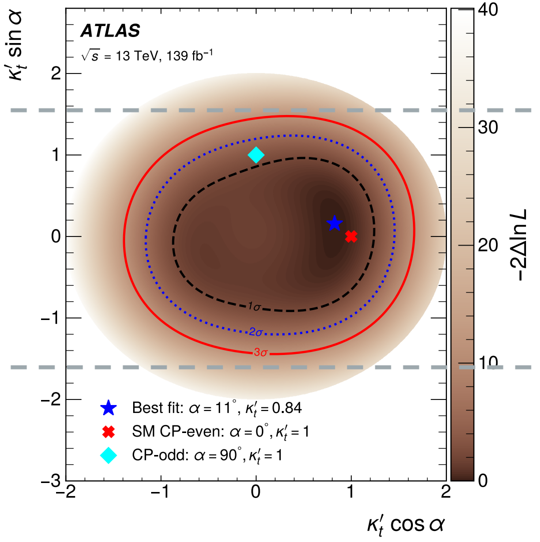
CP analyses in multilepton (CMS) and H → bb (ATLAS, CMS) channels

- Building on inclusive ttH+tH measurements
- Dedicated observables exploiting kin. differences of CP scenarios (multilepton, ATLAS H → bb)







Summary

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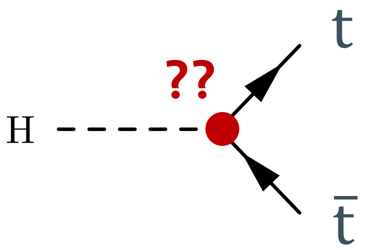
Several complementary probes of top-Higgs coupling

- Indirect: ggF production and $H \rightarrow \gamma\gamma$ decays, 4t and tt cross section
- Direct: ttH and tH production



Rich set of results with Run 2 data by ATLAS and CMS covering many different channels

- Very challenging measurements: complex ML-based analysis strategies
- Modelling of backgrounds is key
- First differential (STXS) ttH results, analysis of CP structure from ttH+tH and 4t
- **Consistent with SM expectation**, some tension in ttH, $H \rightarrow bb$ channel

Run 3 at full swing with much more data to analyse
Many more opportunities for y_t measurements ahead!