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Top-Higgs Yukawa coupling with the heaviest final state ever observed

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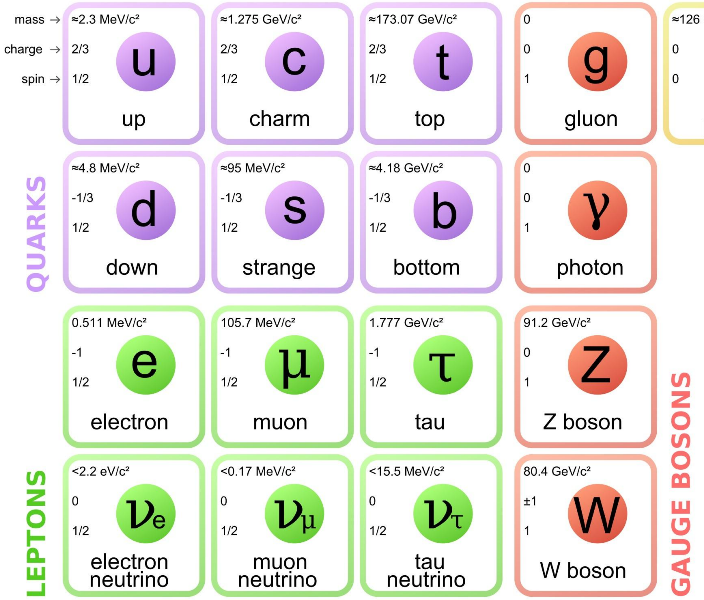
May 19th 2023

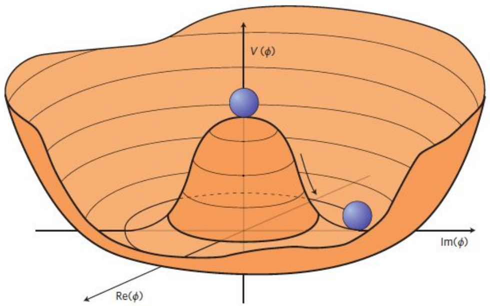
核与粒子学科学术报告 @USTC

Why are Higgs properties important?

Standard Model (SM) describes 3 fundamental interactions, but leaves several questions, including

- Hierarchy: why the weak scale << Planck scale ?
- What is the particle nature of Dark Matter?
- Why there is much more Matter than Antimatter?





Measuring Higgs boson properties
- a well established solution of the above questions

- Hierarchy origins from Higgs boson properties
- Dark Matter particles can obtain mass with Higgs mechanism
- There can be CP violation in Higgs couplings

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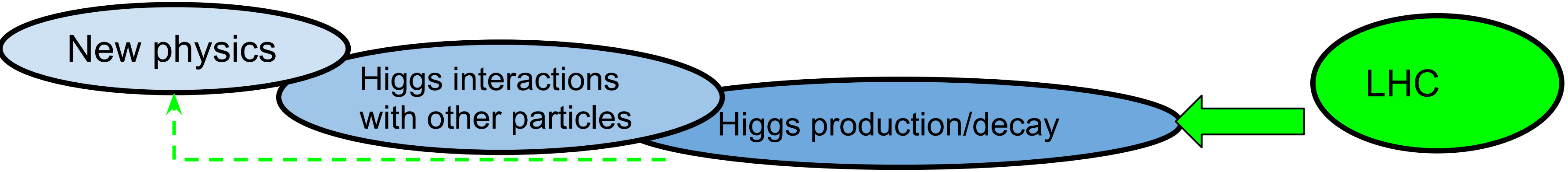
Experimental approaches for Higgs properties



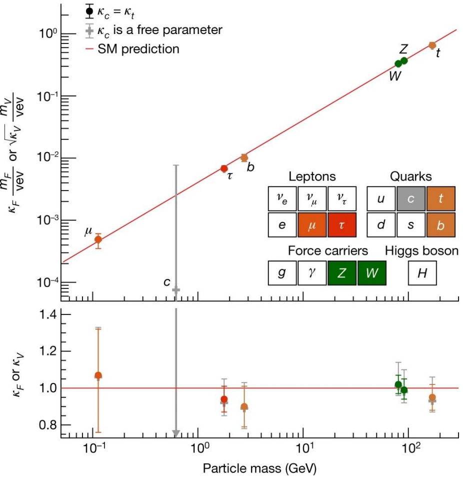
Three experimental approaches towards the new physics with Higgs properties:

- Measuring on-shell Higgs boson
  - Higgs boson as physics particle in the final state
- Measuring off-shell Higgs boson
  - Higgs boson as mediator in the physics process
- Searching for beyond SM (BSM) processes

I'll introduce how to use the 3 approaches for specific Higgs properties later

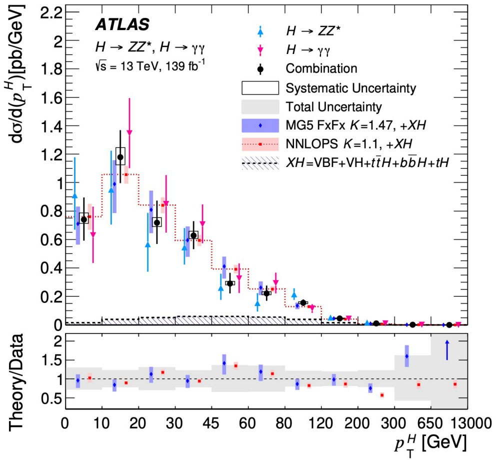
Experimental landscape of Higgs properties

Higgs couplings with other particles



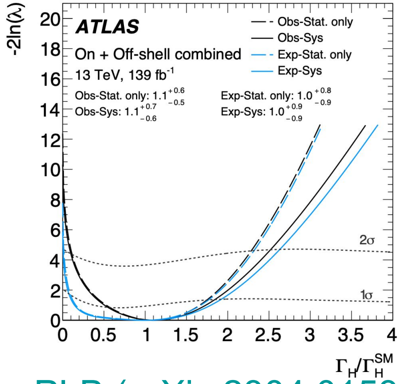
Nature 607 (2022) 52-59

Differential cross-section



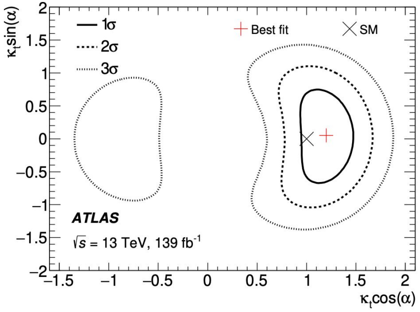
JHEP 05 (2023) 028

Width and Mass



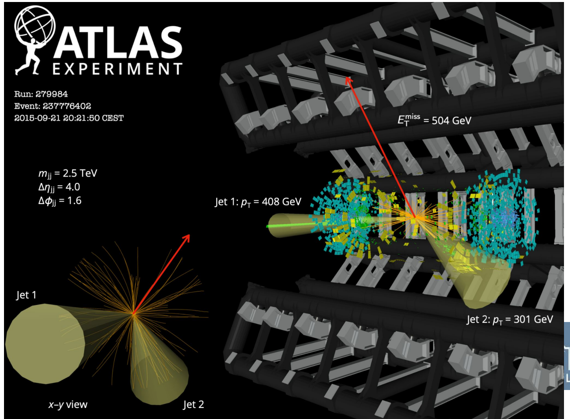
PLB (arXiv:2304.01532)

CP properties



PRL 125 (2020) 061802

Searches
e.g. Higgs→invisible



JHEP 08 (2022) 104

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Why top-Higgs coupling important

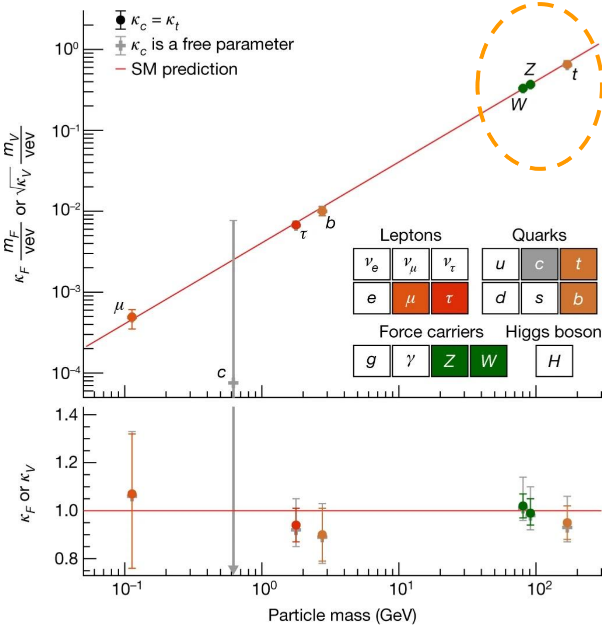
It's the heaviest

- top quark mass (172 GeV) is 10^4-10^5 times as u/d and electrons

In marco world, the adult human weight: 15 - 635 kg, scale difference is 10^2

- the top-Higgs coupling strength is remarkably close to 1

$$y_t = \sqrt{2}\, m_t \;/\; vev = \sqrt{2}\,(172\text{ GeV}) / (246\text{ GeV}) \approx 0.99$$



Study top-Higgs coupling can answer unsolved questions, by testing

- can top-Higgs coupling violate CP symmetry?
- can top-Higgs coupling strength modified by the new physics?
- can top mass comes from other interactions than Higgs mechanism?

The questions will be addressed by the physics analyses I introduce today

The CP properties in top-Higgs couplings

- In the SM, the Yukawa interactions are CP-even. In BSM models, CP-odd component arises
- The Lagrangian for top-Higgs interaction can be written as

$$\mathscr{L}_t = -\frac{m}{v}\kappa_t(\cos(\alpha)\bar{t}t + i\sin(\alpha)\bar{t}\gamma_5 t)H,$$

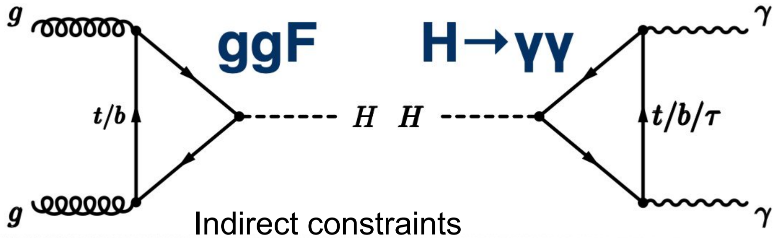
CP even — CP odd

Standard model : α = 0, κ_t = 1

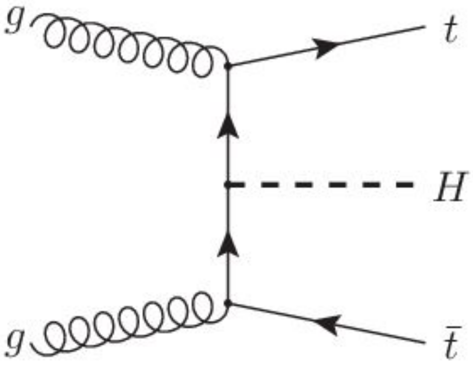
CP properties can be directly measured with top-Higgs coupling

The top-Higgs Yukawa couplings and CP properties can be constrained

- directly, with tops in the final states (ttH/tH)
- indirectly, with tops as mediators



Indirect constraints



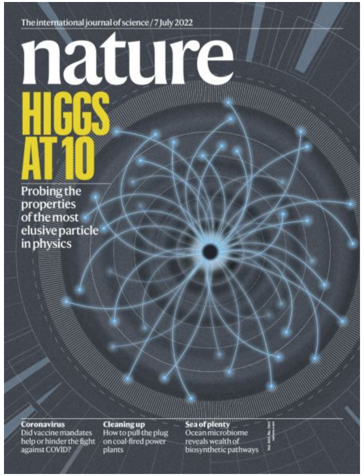
Experimental landscape of top-Higgs coupling

With the 3 experimental approaches, I'll introduce the following analyses today

- top-Higgs coupling with on-shell Higgs boson
  - A direct measurement of CP properties in top-Higgs Yukawa coupling PRL 125 (2020) 061802
  - Top-Higgs coupling with simplified template cross-section (STXS) measurements JHEP (arXiv:2207.00348) (input of Nature 607 (2022) 52-59)

- Searching for new physics that may arises with new top-Higgs sectors
  - Higgs(→γγ) + X searches JHEP (arXiv:2301.10486)

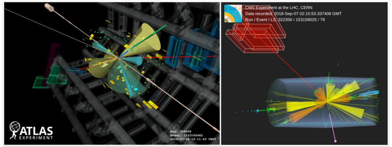
- top-Higgs coupling with off-shell Higgs boson
  - Observation of the four-top-quark production EPJC (arXiv:2303.15061)



ATLAS and CMS observe simultaneous production of four top quarks

The ATLAS and CMS collaborations have both observed the simultaneous production of four top quarks, a rare phenomenon that could hold the key to physics beyond the Standard Model

24 MARCH, 2023 | By Naomi Dinmore



Event displays of four-top-quark production from ATLAS (left) and CMS (right).

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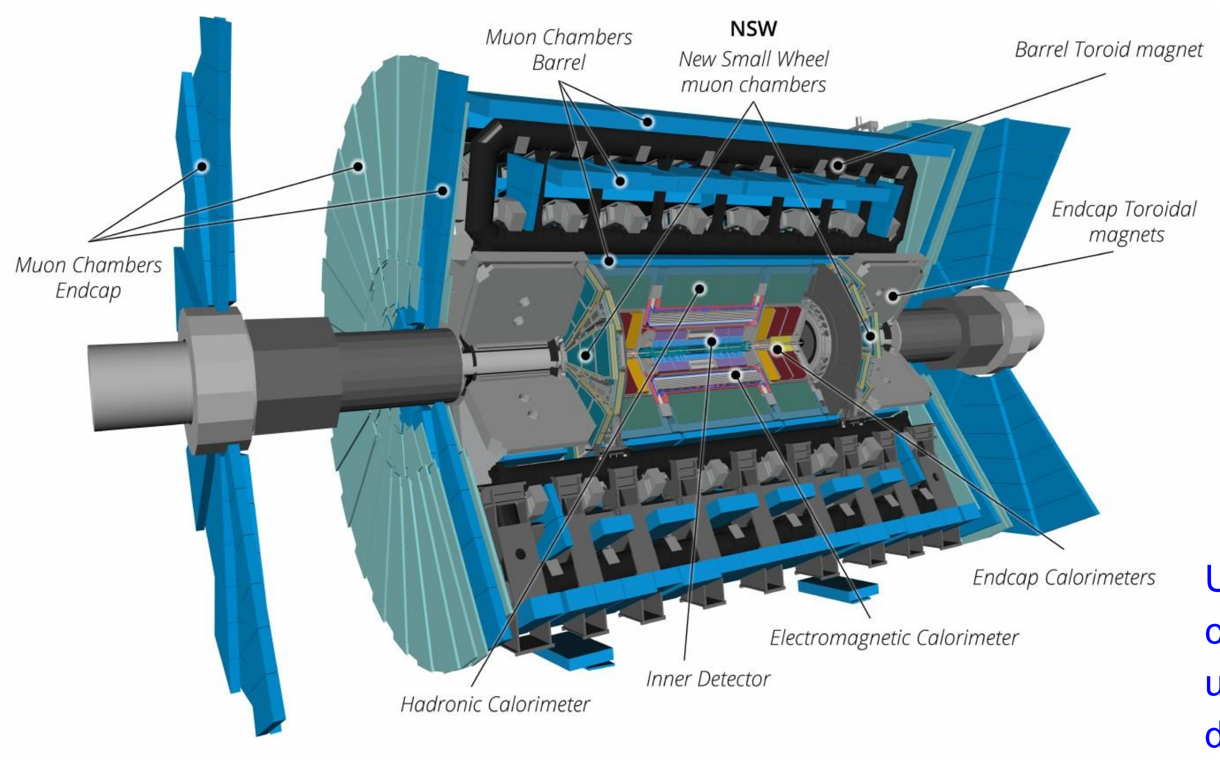
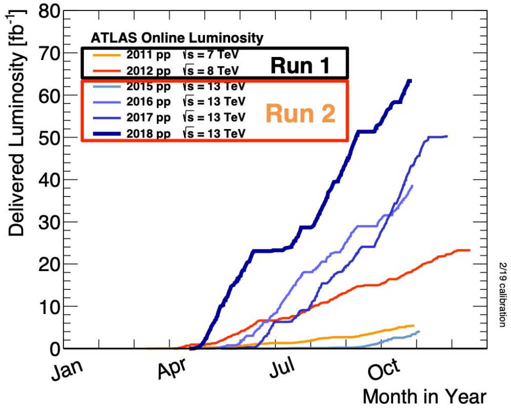
ATLAS Detector and Run-2 data





This talk: 140 fb^{-1} pp collision data at 13 TeV with ATLAS (ATLAS Run-2)

USTC-ATLAS contributions: the current muon detector, the phase-II upgrade of timing, tracking, muon detectors, the leadership of various physics analyses with ATLAS

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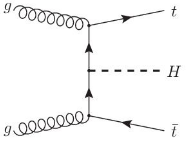
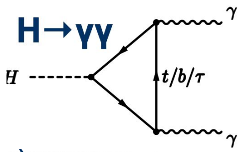
with on-shell Higgs boson

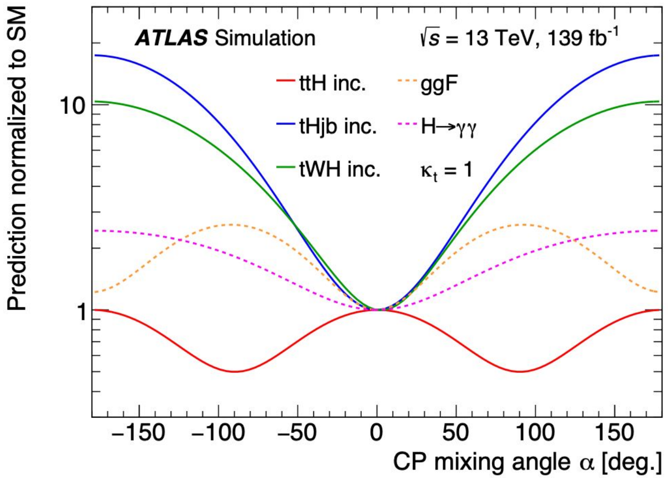
CP in top-Higgs coupling with H → γγ

- CP properties in the top-Higgs coupling with ATLAS Run-2 PRL 125 (2020) 061802
  a. Select ttH/tH, H → γγ events, extract the number of signal events
  b. Parameterise ttH/tH productions with top-Higgs coupling modifier κ_t, and CP mixing angle α
  c. Interpret the result and measure (κ_t, α)

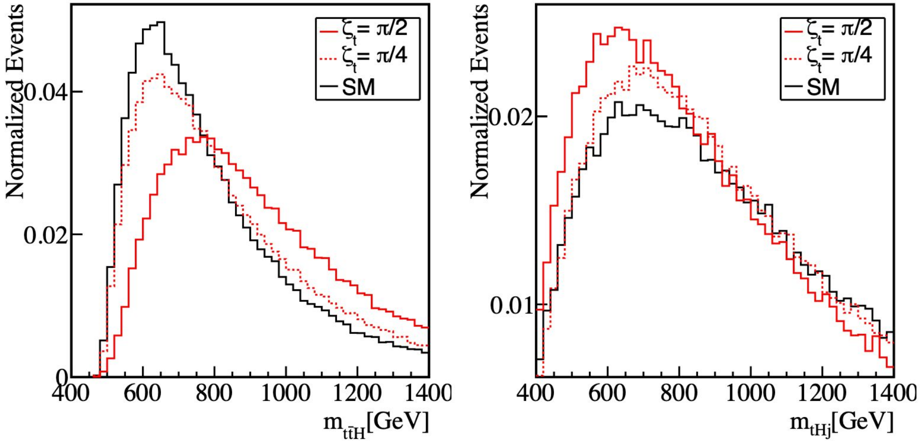




ttH and tH cross-section as function of (κ_t, α)



tops + Higgs kinematics as function of (κ_t, α)



CERN-PH-TH/2013-312

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CP in top-Higgs coupling: selections

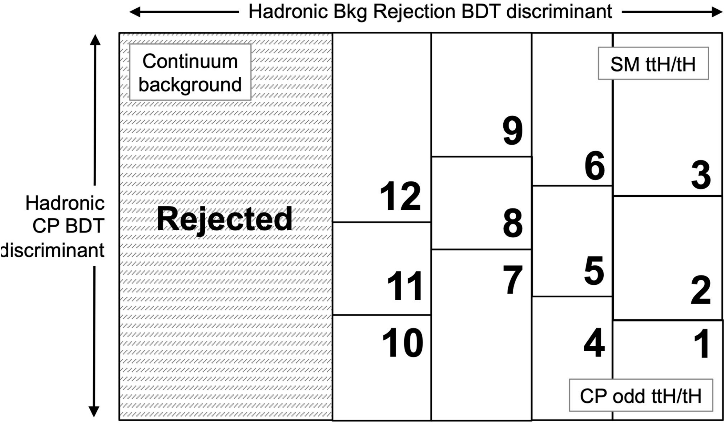
The ttH/tH, H → γγ events are selected with two event classifiers

ttH/tH CP odd vs CP even

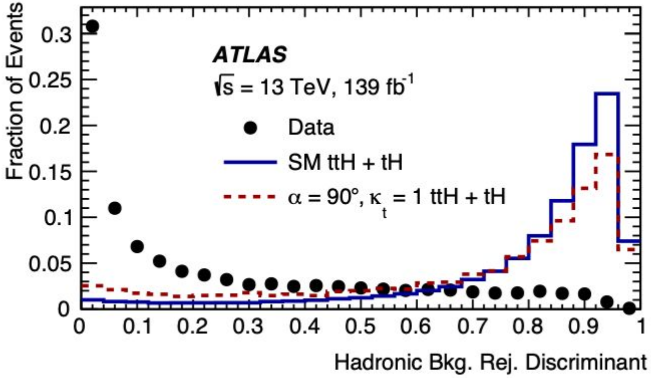
- A boosted decision tree (BDT)
- Using kinematics of γγ system and the top candidates
- For the top candidates, using a top-reconstruction method combining the 3 objects (tri-jets or j, e/μ, ν) from top decay

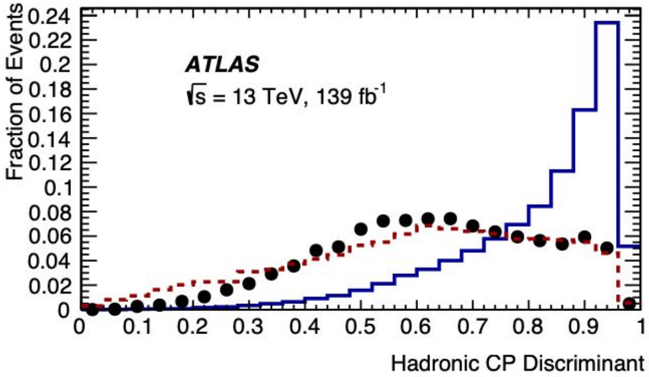
Signal vs background

- A BDT distinguish the ttH/tH from background (other Higgs, γγ, γ+j, ttγγ)
- Using γ, e/μ, j and missing ET kinematics



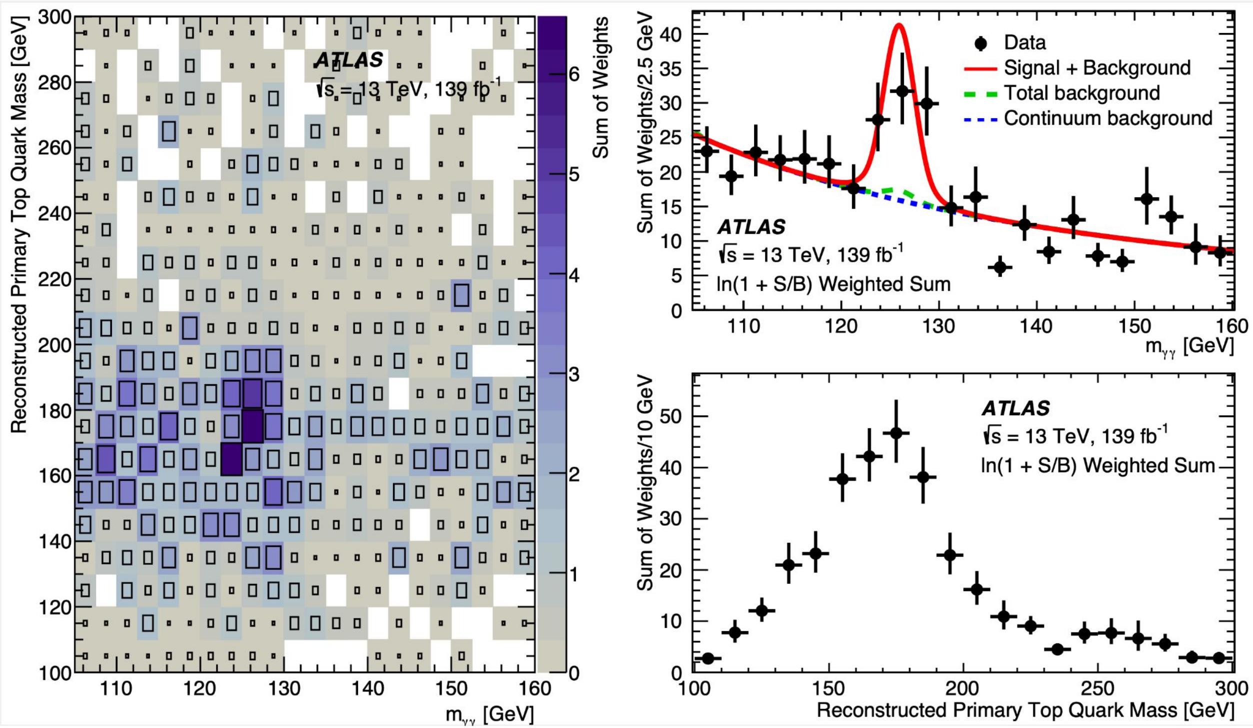
12 categories for top hadronic decays + 8 more categories for the top leptonic decays





CP in top-Higgs coupling with H → γγ

1. Top quark kinematics are used to distribute events in categories
2. Signal + background fit on the m(γγ) in each category
3. Extract ttH/tH, H → γγ events



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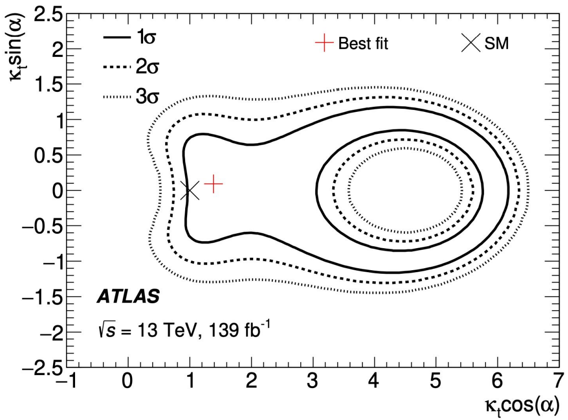
CP in top-Higgs coupling with H → γγ

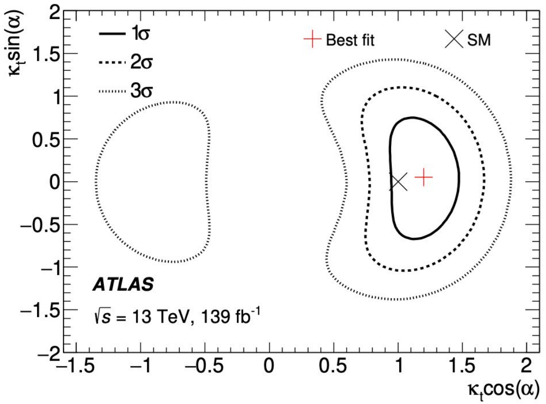
- The measurement ttH/tH cross-section is

$$\mu = 1.43^{+0.33}_{-0.31}(\text{stat.})^{+0.21}_{-0.15}(\text{syst.})$$

Observation of ttH/tH firstly in single channel (sig. = 5.2σ)

- κ_t , α are measured
  - total CP-odd (α=90°) is excluded by 3.9σ, 95% CL limit on CP mixing: |α| < 43°
  - 2D 95% CL limits on [$\kappa_t\sin(\alpha)$, $\kappa_t\cos(\alpha)$]



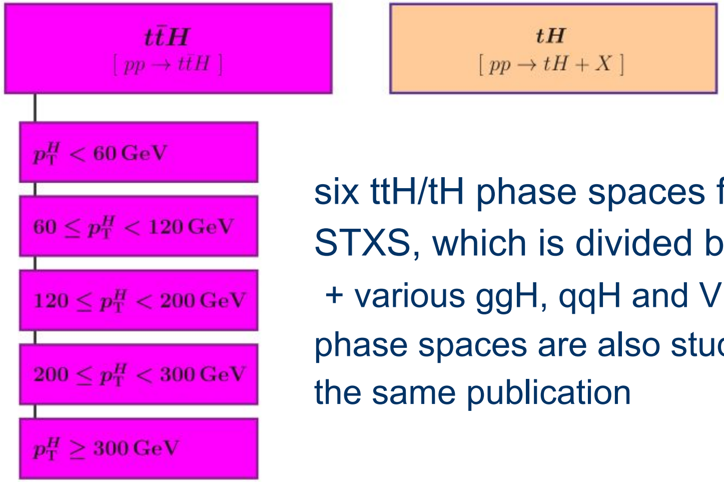


ggF and H → γγ resolved with (κ_t , α) κ_g and κ_γ set to combined measurements

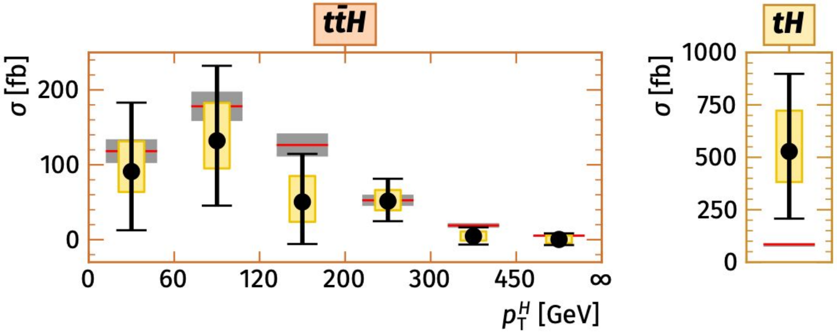
PRL 125 (2020) 061802

The STXS measurements with H → γγ

- Simplified Template Cross Sections (STXS) divides cross-section measurements in phase spaces (arxiv 1906.02754), which is sensitive to measure Higgs couplings
  - The ttH/tH cross-section in pTH bins with H → γγ JHEP (arXiv:2207.00348) further constrain the top-Higgs Yukawa coupling, and probe the impacts from new physics like CP-odd and FCNC processes



six ttH/tH phase spaces for the STXS, which is divided by pTH + various ggH, qqH and VH phase spaces are also studied in the same publication



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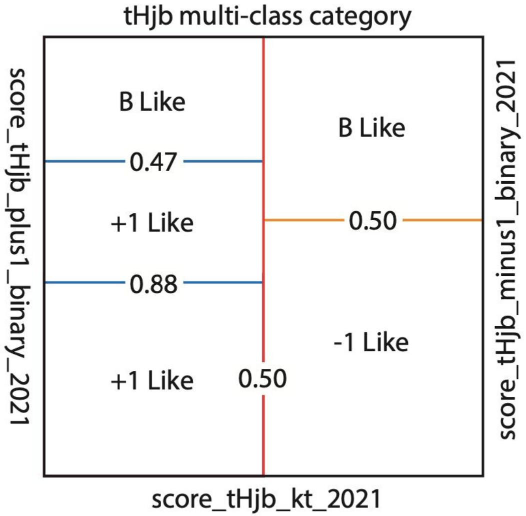
ttH/tH selection with STXS

1. ttH/tH vs Higgs boson production in other phase spaces
   - The five ttH, and two tH (tWH, tHjb) phase spaces are selected with multi-class BDT
2. In the ttH and tWH classes, use another ttH/tH vs background BDT
3. In the tHjb class, To further constrain top-Higgs coupling κt, optimized the tHjb categorization to separate CP-even/-odd, using 3 NN scores
   - CP even vs CP odd
   - CP even vs background
   - CP odd vs background

The input variables are from γγ system, top candidates, top + Higgs system and forward jets



Finally, 9 categories targeting to the 6 ttH/tH phase spaces

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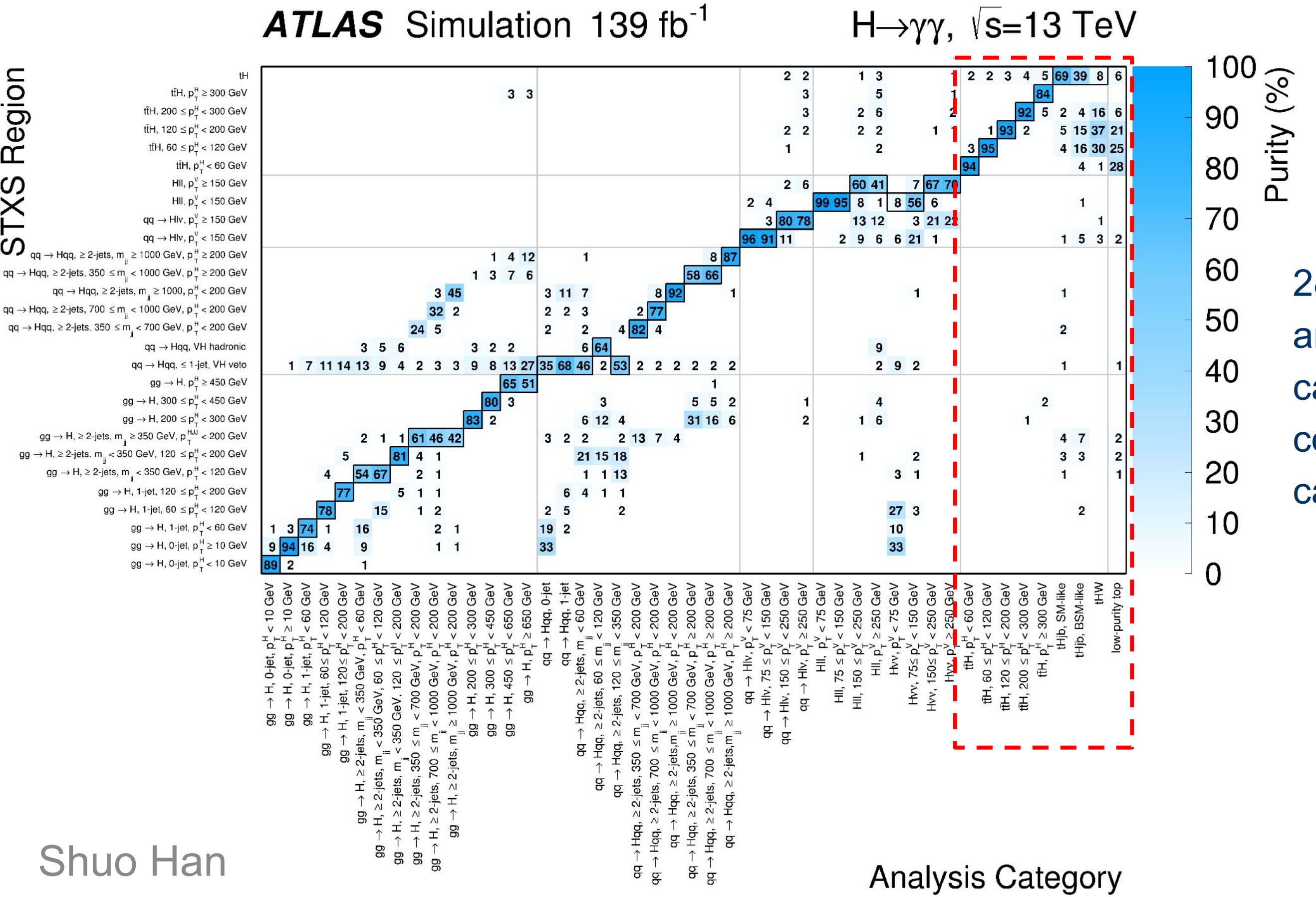
STXS categorization



28 classes for the measurements are clearly distinguished with 101 categories with correlations controlled, including the 9 ttH/tH categories

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STXS measurement result

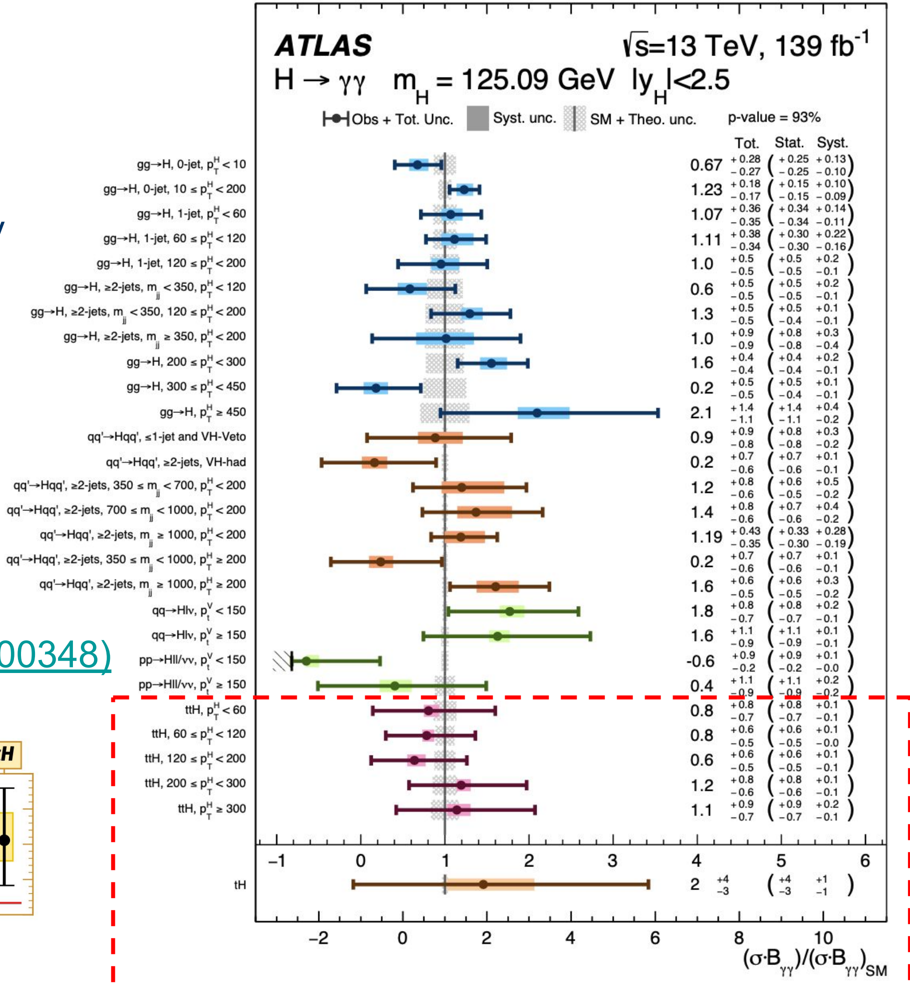
The analysis extracted signal events with S+B fits on m(γγ)

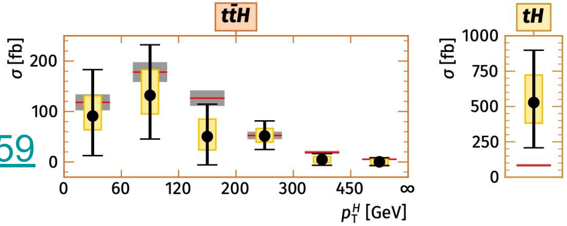
The Higgs → γγ STXS measurement has highest sensitivity to constrain ttH/tH cross-sections among all Higgs decay channels in the combined measurement

ttH differential cross-section is compatible with SM

tH cross-section 95% CL limit is 10 times SM expectation

JHEP (arXiv:2207.00348)





Nature 607 (2022) 52-59

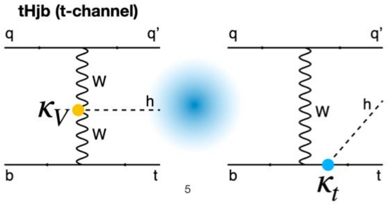
The top-Higgs coupling with STXS

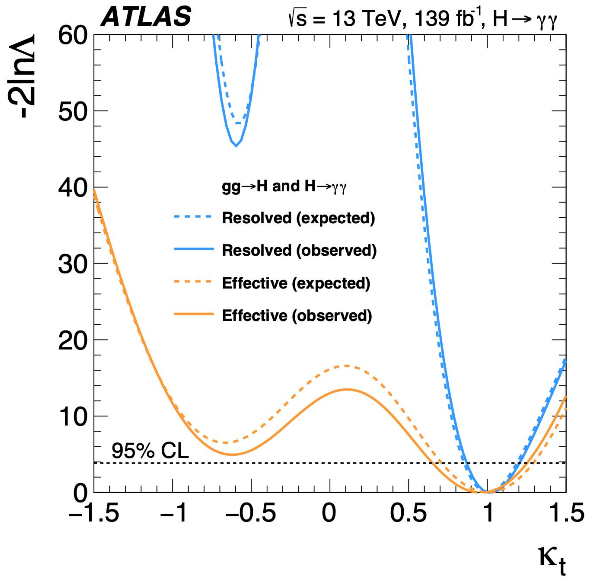
Top-Higgs coupling (κ_t) is directly measured

- tH yields are parameterized as function of κ_t

$$y_i = \kappa_t^2 A + \kappa_V^2 B + \kappa_t \kappa_V C$$

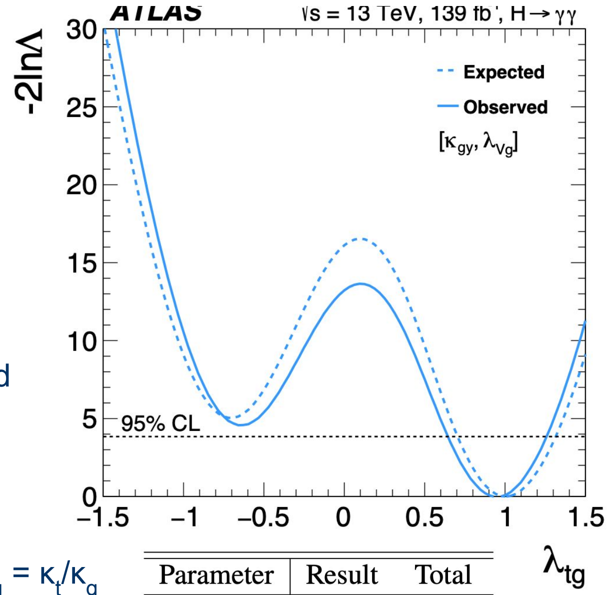
- $\kappa_t = 1.01 \pm 0.09$ if resolve the ggF and $H \rightarrow \gamma\gamma$ processes with κ_t
- Remove assumptions by taking ratios among loop vertices (κ_γ, κ_g), total width (κ_H), vector and top couplings (κ_V, κ_t)





$\kappa_t = 0.95{+0.15}{-0.16}$
, when κ_g and κ_γ set to 1.0
$\kappa_t = 1.01 \pm 0.09$
, when ggF and $H \rightarrow \gamma\gamma$ resolved with κ_t

$\kappa_t = 0.94 \pm 0.11$
, in combination, with other modifiers profiled

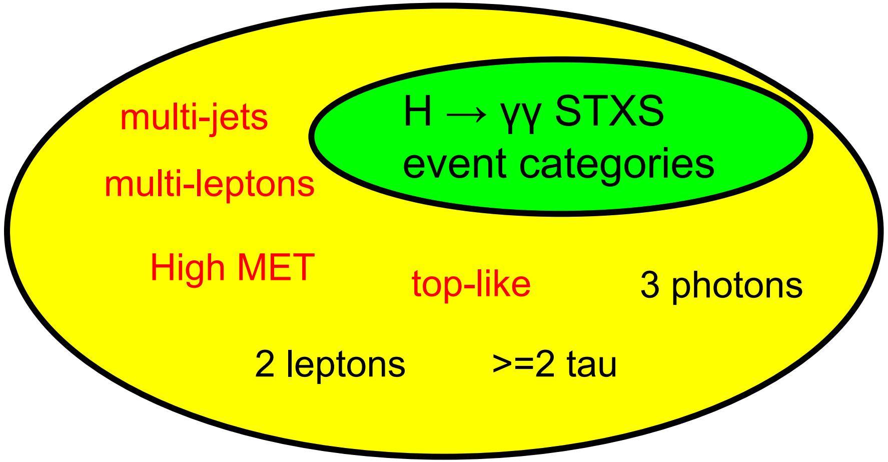


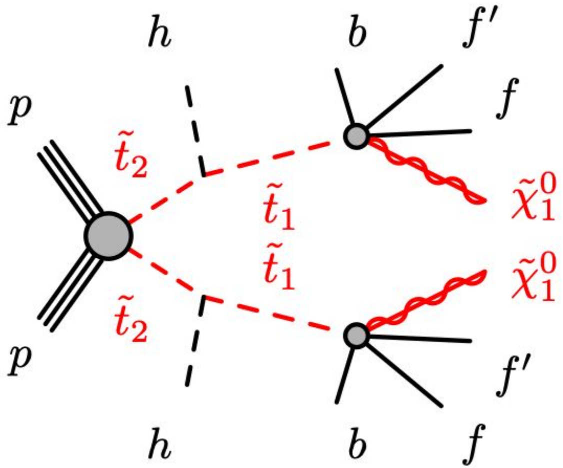
$\lambda_{tg} = \kappa_t/\kappa_g$
$\lambda_{Vg} = \kappa_V/\kappa_g$
$\kappa_{g\gamma} = \kappa_\gamma \kappa_g / \mathrm{I}$

Parameter	Result	Total
$\kappa_{g\gamma h}$	1.02	± 0.06
λ_{Vg}	1.01	± 0.11
λ_{tg}	0.95	$\pm^{0.15}_{0.16}$

Model independent H+X search

- STXS measurement covers various phase spaces, but there are many regions uncovered..
- Various of BSM models, like EW or strong SUSY and Flavor Changing Neutral Currents (FCNC) expect the production of Higgs boson and new particles
  - Including the new physics that arise with the top-Higgs sector
- A search (JHEP (arXiv:2301.10486)) for H(→γγ)+X process is model-independent





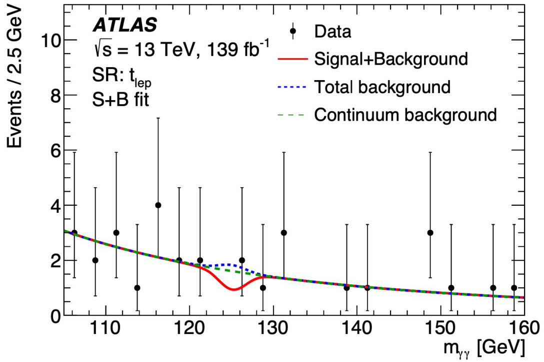
H+X search: event selection

- 22 cut-based categories are defined with different final states, they are triggered by different BSM models
- The additional top-Higgs sectors can results in multiple b-jets, jets, leptons, high HT (scalar sum of jet pT), high missing ET and additional top candidates
- The searches are performed independently in all the signal regions, by S+B fits on the m(γγ)

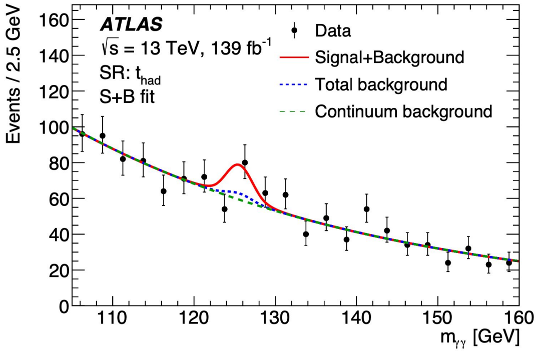
Target	Region	Detector Level
Heavy flavor	$\geq 3b$	$n_{b-\text{jet}} \geq 3$, 85% W.P.
	$\geq 4b$	$n_{b-\text{jet}} \geq 4$, 85% W.P.
High jet activity	$\geq$4j	$n_{\text{jet}} \geq 4$, $\lvert\eta_{\text{jet}}\rvert < 2.5$
	$\geq$6j	$n_{\text{jet}} \geq 6$, $\lvert\eta_{\text{jet}}\rvert < 2.5$
	$\geq$8j	$n_{\text{jet}} \geq 8$, $\lvert\eta_{\text{jet}}\rvert < 2.5$
	H_T >500 GeV	H_T > 500 GeV
	H_T >1000 GeV	H_T > 1000 GeV
	H_T >1500 GeV	H_T > 1500 GeV
E_T^{miss}	$E_T^{\text{miss}} > 100$ GeV	$E_T^{\text{miss}} > 100$ GeV
	$E_T^{\text{miss}} > 200$ GeV	$E_T^{\text{miss}} > 200$ GeV
	$E_T^{\text{miss}} > 300$ GeV	$E_T^{\text{miss}} > 300$ GeV
Top	ℓb	$n_{\ell=e,\mu} \geq 1$, $n_{b-\text{jet}} \geq 1$, 70% W.P.
	t_{lep}	$n_{\ell=e,\mu} = 1$, $n_{\text{jet}} = n_{b-\text{jet}} = 1$, 70% W.P.
	t_{had}	$n_{\ell=e,\mu} = 0$, $n_{\text{jet}} = 3$, $n_{b-\text{jet}} = 1$, 70% W.P., BDT$_{top}$ >0.9
Lepton	$\geq 1\ell$	$n_{\ell=e,\mu} \geq 1$
	2ℓ	ee, $\mu\mu$, or $e\mu$
	2ℓ-Z	ee, $\mu\mu$, or $e\mu$, $\lvert m_{\ell\ell} - m_Z\rvert > 10$ if leptons are same flavor
	SS-2ℓ	ee, $\mu\mu$, or $e\mu$ with the same charge
	$\geq 3l$	$n_{\ell=e,\mu} \geq 3$
	$\geq 2\tau$	$n_{\tau,had} \geq 2$ †
Photon	$1\ \gamma$-$m_{\gamma\gamma}^{12}$	$n_\gamma \geq 3$, $m_{\gamma\gamma}$ defined with γ_1,γ_2
	$1\ \gamma$-$m_{\gamma\gamma}^{23}$	$n_\gamma \geq 3$, $m_{\gamma\gamma}$ defined with γ_2,γ_3

H+X search: results

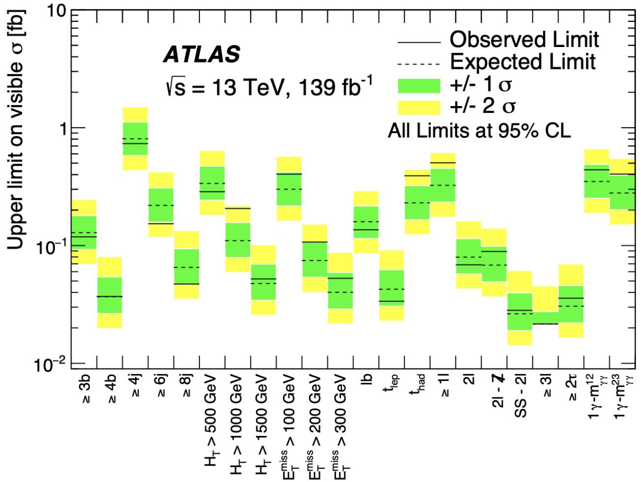
- no obvious excess for H+X production.
  - The largest deviation from SM has a local significance 1.8σ in the HT > 1000 GeV region
  - There's 1.7σ local significance in the top hadronic decay region
- The detector level limits are set on the H+X cross-sections, and the detector efficiencies of various BSM models are reported to utilize the limits



-0.7σ deviations wrt SM in the leptonic top decay region



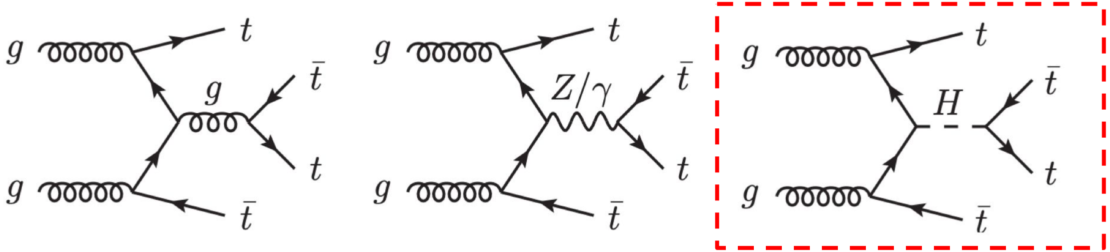
1.7σ significance in the handronic top decay region

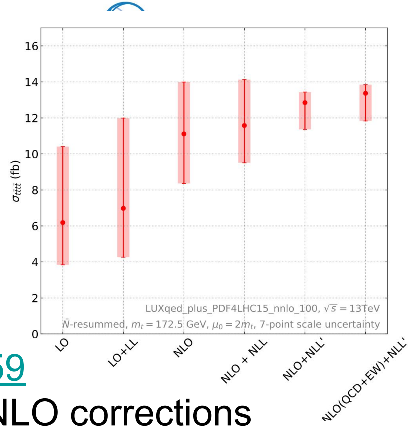


[JHEP (arXiv:2301.10486)](https://arxiv.org/abs/2301.10486)

with off-shell Higgs boson
- the observation of tttt

The four-top-quarks production at LHC

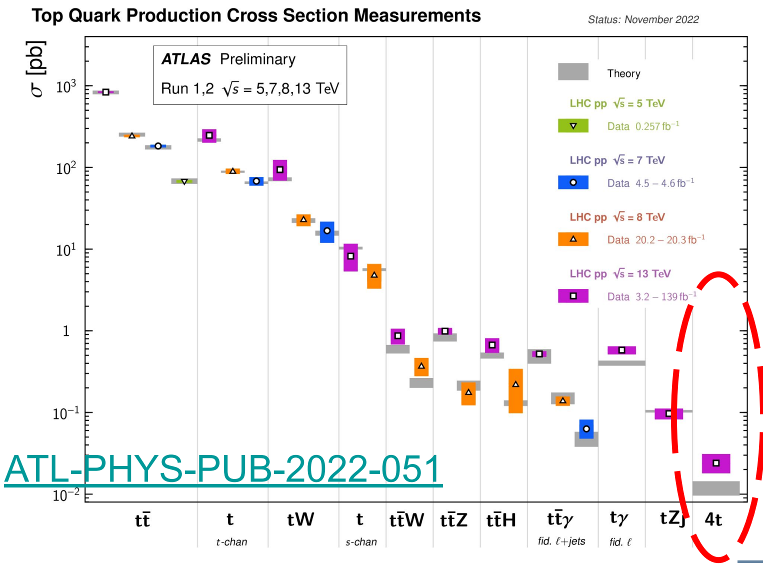




arXiv:2212.03259

The σ_{tttt} , large NLO corrections

- The four-top production is rare: σ_{tttt}: ~12 fb (at 10^{-5} level of ttbar)
- However, four-top is distinct to measure SM and probe new physics, including top-Higgs coupling (Higgs as mediator in four-top production)
  - Today's talk highlights the four-top-quarks observation in 2023 EPJC (arXiv:2303.15061)



ATL-PHYS-PUB-2022-051

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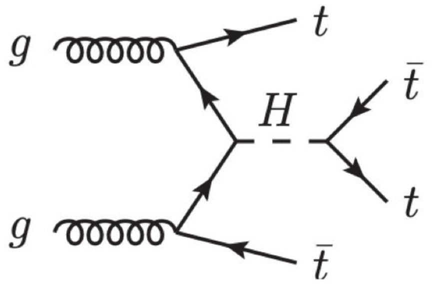
Top-Higgs Yukawa couplings with four-tops

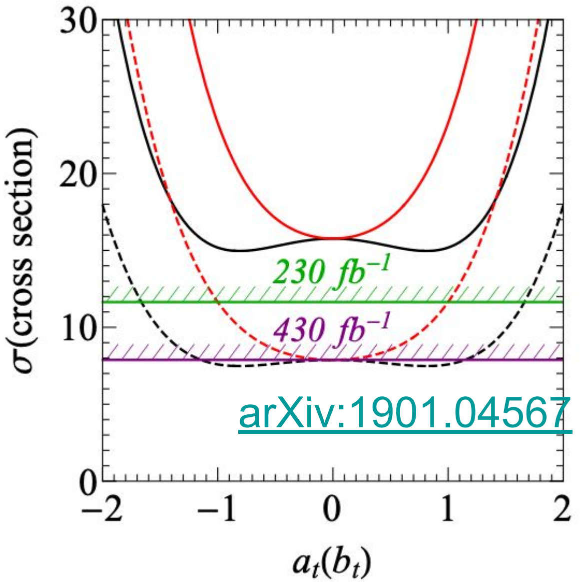
- There are various motivations of four-top cross-section measurement: SUSY (2HDM, Gluino), ttbar + X, composite top models, composite Higgs models (CERN-TH-2020-166)
- Among which, top-Higgs Yukawa coupling has unique impacts on the four top cross-section with quartic terms, so it is independent from Higgs coupling measurements with Higgs production/decays
  - σ_{tttt} parameterization (arXiv:1901.04567) in terms of [$a_t = k_t \cos(\alpha)$, $b_t = k_t \sin(\alpha)$] shows flat behavior for small couplings and rise above 1.5.

$$\mathcal{L} = -\frac{1}{\sqrt{2}} y_t \bar{t} \left(a_t + i b_t \gamma_5\right) t h,$$

$$\sigma_{tttt} = c_0 + c_1 a_t^2 + c_2 b_t^2 + c_3 a_t^4 + c_4 a_t^2 b_t^2 + c_5 b_t^4$$

$$\sigma_{ttH} = A\, a_t^2 + B\, b_t^2$$





arXiv:1901.04567

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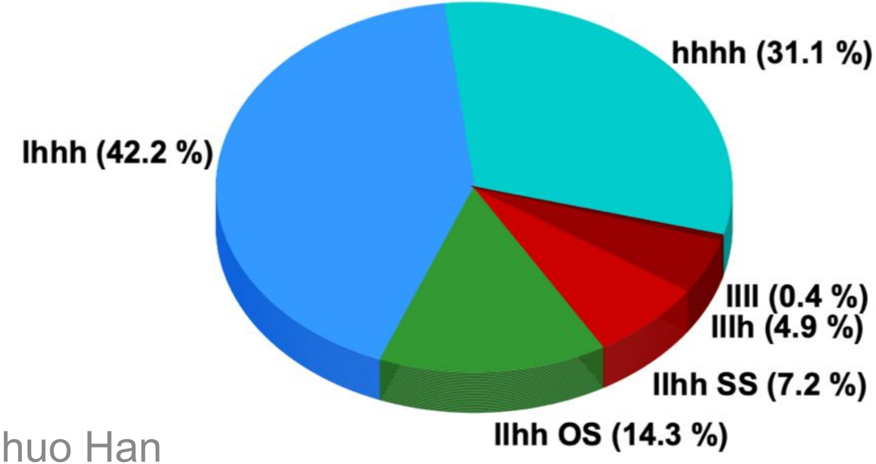
The four-top decays

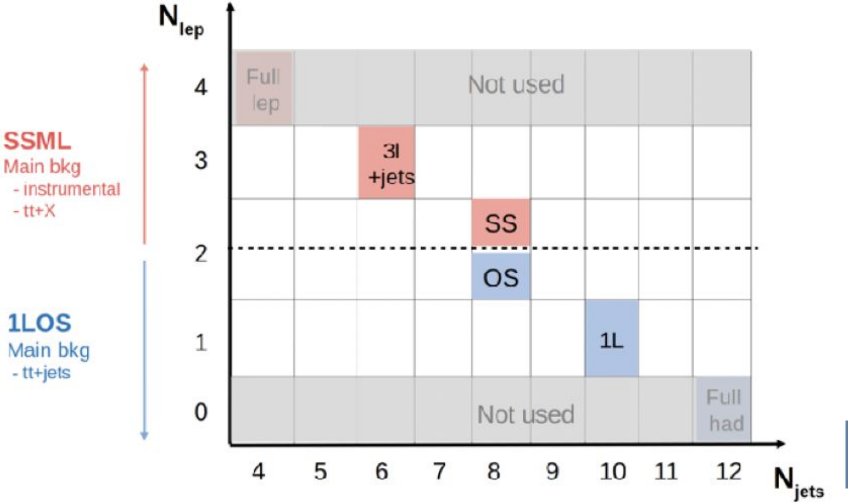
Each top quark decays to b quark + W boson

The most sensitive channels for four-top are:

- **2 leptons same sign and 3 leptons (2LSS/3L), 13% branching ratio, highest sensitivity -- observation.**
- 1 lepton and 2 leptons opposite sign (1L/2LOS), 57% branching ratio, large ttbar background.

The complicated final state is a challenge





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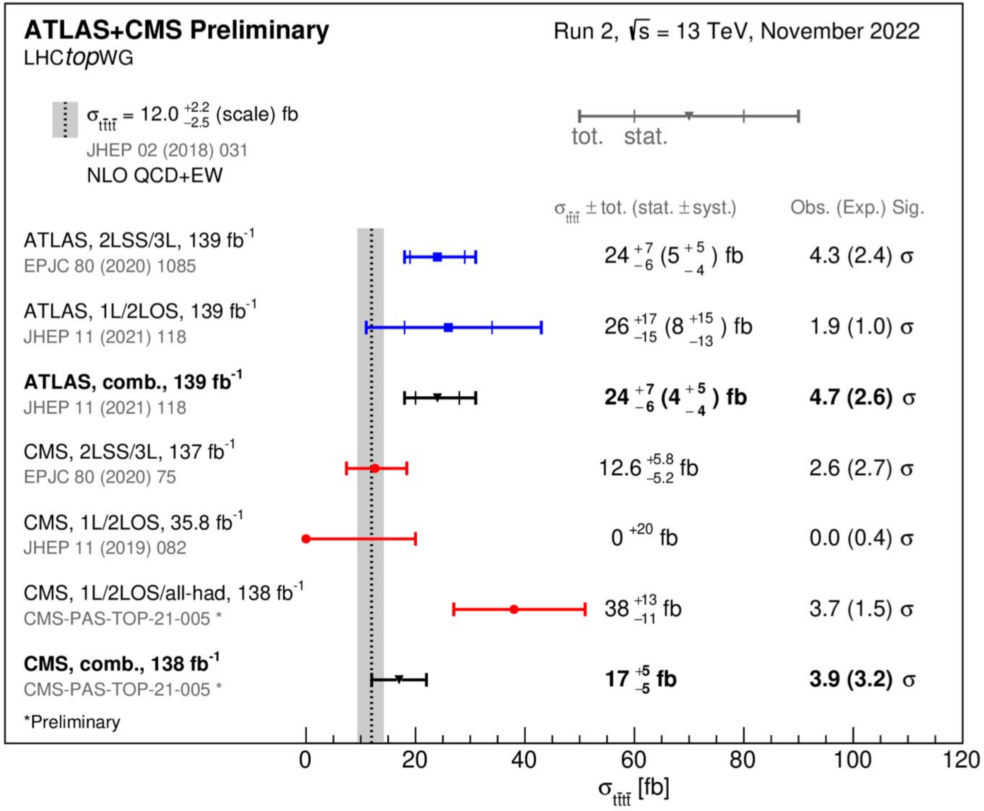
The publications before the observation

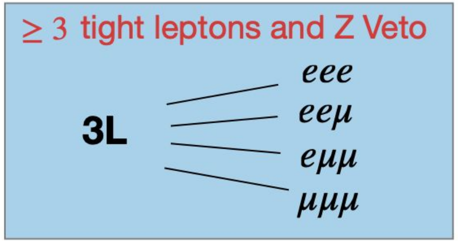
Before observation, both ATLAS and CMS measured four-top with Run-2 data, they declared evidences

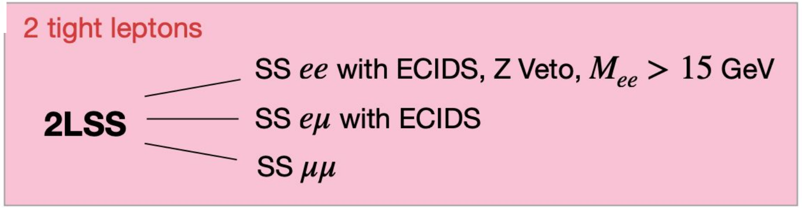
Then, both analyses decided to re-optimize with the same data, eventually there are observations in the single channel of 2LSS/3L



Object and event selections

1. Triggers: single or di-lepton triggers
2. Low pT thresholds of (leptons, jets) of (15, 20 GeV)
3. Select the 2LSS / 3L events
4. Pre-selected region (SR):
   a. 2LSS or 3L, Njet>=6, Nbjet>=2, HT>500 GeV
5. S+B fit on an event classifiers in the SR (next pages)

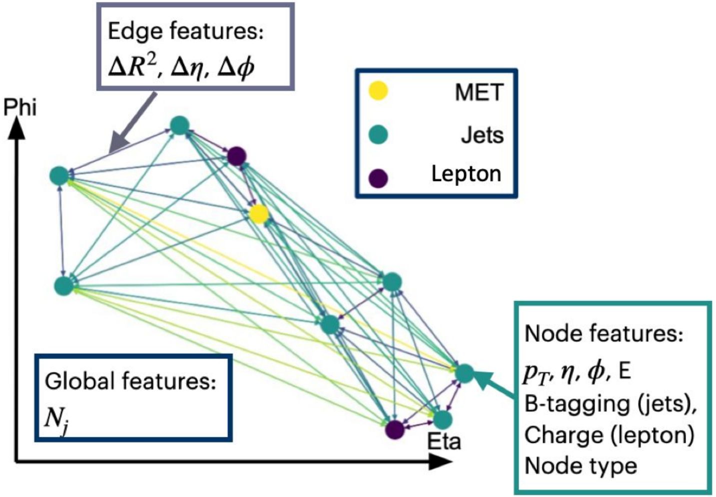


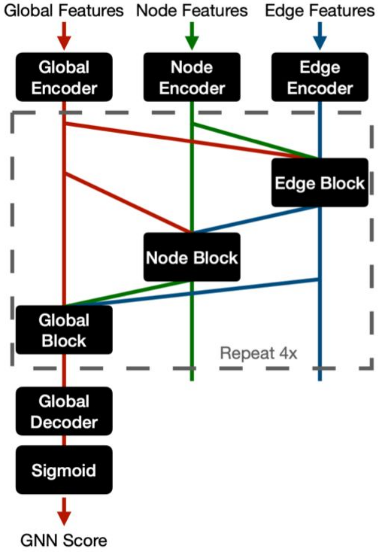


	SR
$t\bar{t}W$	130 ± 40
$t\bar{t}Z$	72 ± 15
$t\bar{t}H$	65 ± 11
QmisID	27 ± 4
Mat. Conv.	16.5 ± 2.3
HF e	3.1 ± 1.0
HF μ	7.1 ± 1.2
Low m_{γ^*}	14.1 ± 2.0
Others	47 ± 11
$t\bar{t}t$	2.9 ± 0.9
Total bkg	390 ± 50
$t\bar{t}t\bar{t}$	38 ± 4
Total	430 ± 50
Data	482

GNN multivariate analysis

- The main challenge of the four-top signal extraction is the complicated final state
- The **Graphic Neural Network (GNN, arxiv 1806.01261 [graph_nets])** combines information about all objects (jets, leptons, MET) from an event into a graph, with node, edge and global properties.
- Message passing architecture allows network to learn complex features of the four top process.

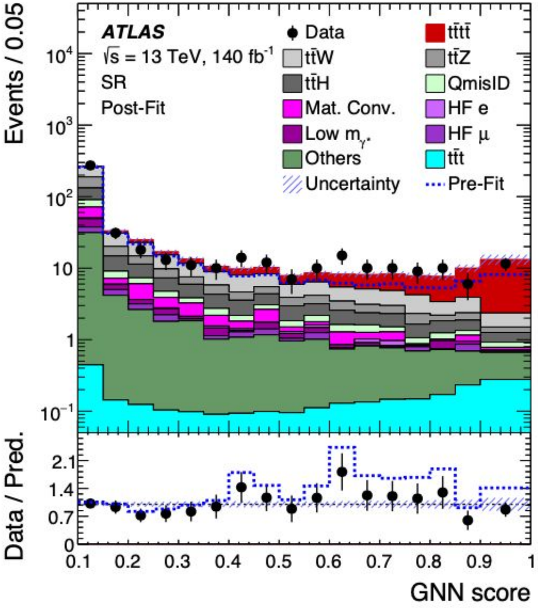


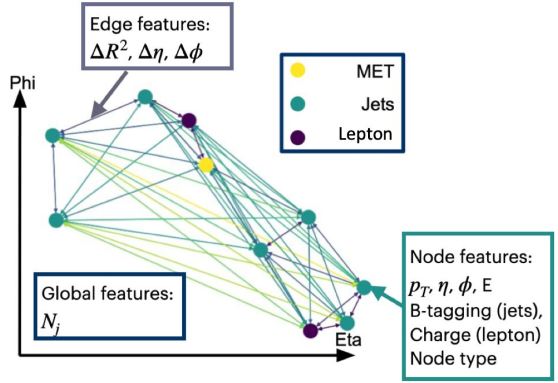


"Global" scores can pick-up signal events
"Edge" scores can reconstruct tops

GNN multivariate analysis

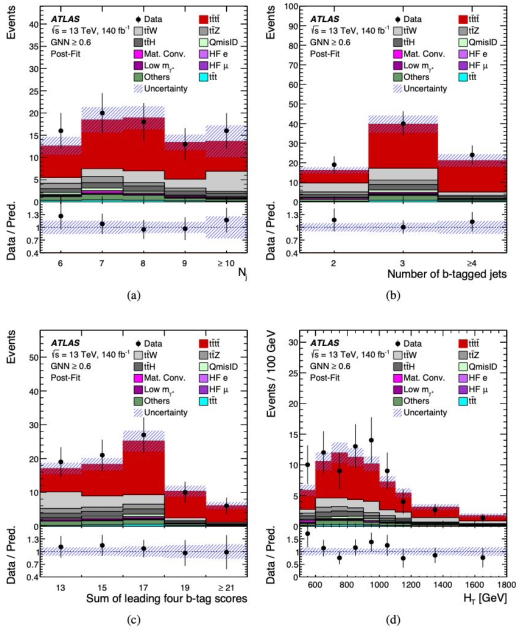
- "global score" is used and chosen as the event classifier and the observable in the pre-selected region
  - 10% higher sensitivity compared with the best BDT methods after fine tuning.





Good data/mc agreements on the GNN score are observed

Data vs MC when GNN > 0.6



Background modelings

SM physics processes: (~75%)

- ttW: a data-driven parameterization with 4 ttW control regions
- ttZ, ttH and others: using MC

a_0	a_1	$\mathrm{NF}_{t\bar{t}W^+(4\mathrm{jet})}$	$\mathrm{NF}_{t\bar{t}W^-(4\mathrm{jet})}$
0.51 ± 0.10	$0.22^{+0.25}_{-0.22}$	$1.27^{+0.25}_{-0.22}$	$1.11^{+0.31}_{-0.28}$

Instrumental and fake backgrounds (~25%)

- Charge mis-ID: data-driven method
- Non-prompt leptons and (virtual) photon conversions: ttbar MC distributions, but correct the normalization with 4 non-prompt/fake control regions

$\mathrm{NF}_{\mathrm{Mat.\ Conv.}}$	$\mathrm{NF}_{\mathrm{Low}\ m_{\gamma^*}}$	$\mathrm{NF}_{\mathrm{HF}\ e}$	$\mathrm{NF}_{\mathrm{HF}\ \mu}$
$1.80^{+0.47}_{-0.41}$	$1.08^{+0.37}_{-0.31}$	$0.66^{+0.75}_{-0.46}$	$1.27^{+0.53}_{-0.46}$

- Fake leptons from light mesons, quark/gluon jets, others: using MC

8 control regions + 1 signal region, 8 background parameters

Standard model σ_{tttt}

$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}\,(\text{stat})\,^{+4.6}_{-3.4}\,(\text{syst})\text{ fb} = 22.5\,^{+6.6}_{-5.5}\text{ fb}.$$

- The expectation σ^{SM}= 12.0 ± 2.4 fb , so $\sigma_{tttt}/\sigma^{SM}$= 1.9
- Background only hypothesis is rejected with

  6.1σ (4.3σ)

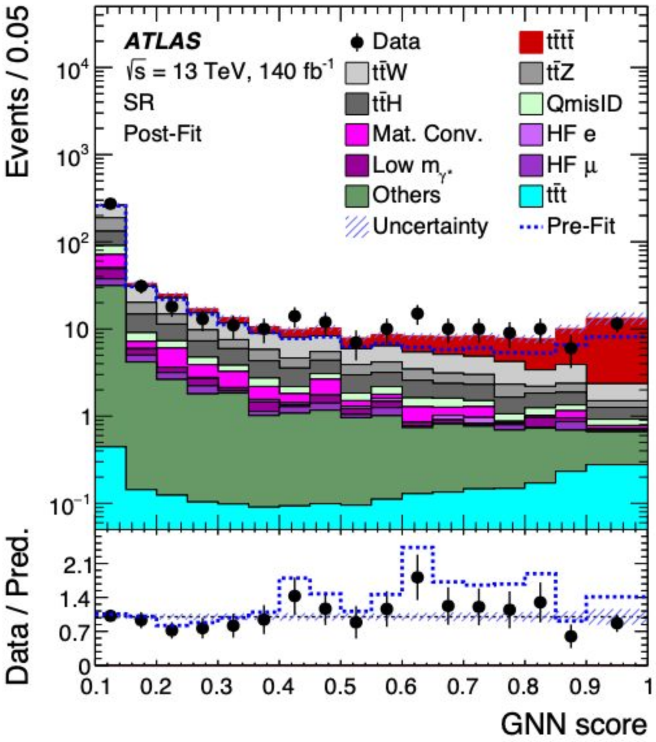
  observed (expected) [EPJC (arXiv:2303.15061)]

$$\sigma_{t\bar{t}t\bar{t}} = 17.9\,^{+3.7}_{-3.5}\,(\text{stat.})\,^{+2.4}_{-2.1}\,(\text{syst.})\text{ fb}$$

[CMS-PAS-TOP-22-013]

- $S_{t\bar{t}t\bar{t}} = 5.5\ (4.9)\ \sigma$

  in agreement with SM



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Top-Higgs coupling and CP

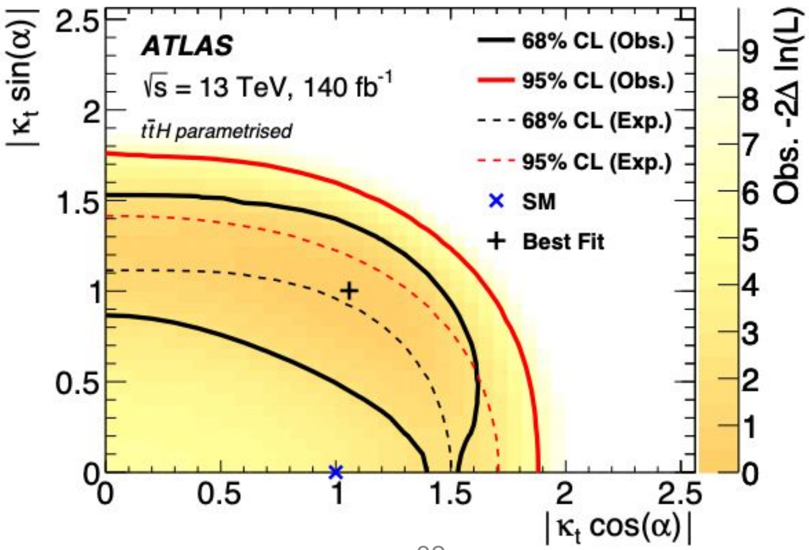
Two scenarios (k_t, α) measurements

- 1) both four-top and ttH parameterized as a function of (k_t, α)
- 2) only four-top parameterized, ttH normalization is profiled as background parameter

95% CL limits on $|k_t|$ (assuming CP-even, α = 0)

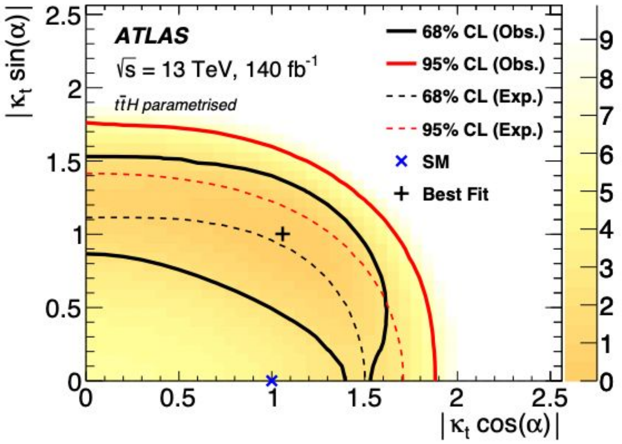
- 1) ttH parameterized: $|k_t| < 1.8$ (1.6 expected), 2) ttH not parameterized: $|k_t| < 2.2$ (1.8 expected)

2D contour of CP-even ($|k_t \cos(\alpha)|$) and CP-odd ($|k_t \sin(\alpha)|$) contributions are compatible with the SM.

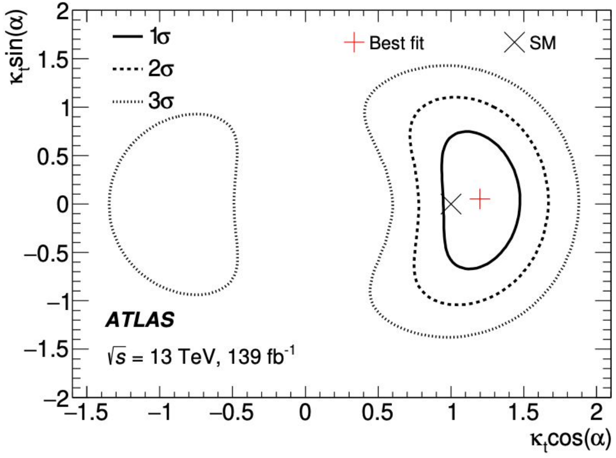


Top-Higgs Yukawa coupling

- Four-top analysis provides a distinct measurement compared with the on-shell Higgs measurements

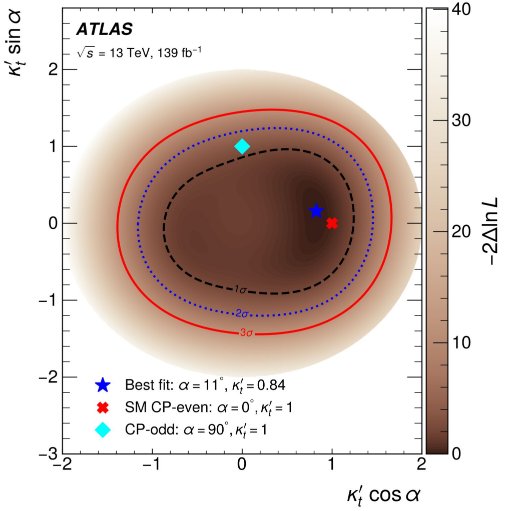


Four tops



H→γγ

PRL 125 (2020) 061802

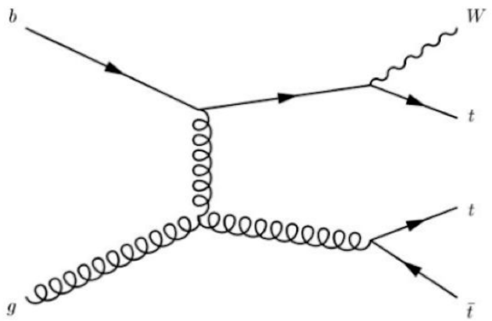


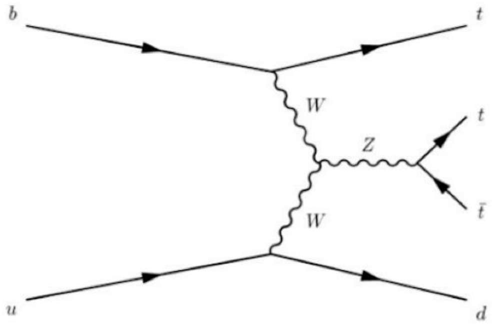
H→bb

PLB (arXiv:2303.05974)

The tri-top production

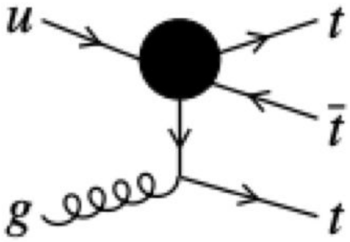
- The tri-top production (ttt+W, ttt+j) is another rare top production, σ_{ttt}^{SM} ~ 1.67 fb (NLO)
- Tri-top is sensitive to different new theories, like FCNC, 2HDM models
  - The modifications of tri-top may also come from new top-Higgs sectors
- Since the final state is very close to the four tops, the tri-top is measured simultaneously with the four-top production





Standard Model

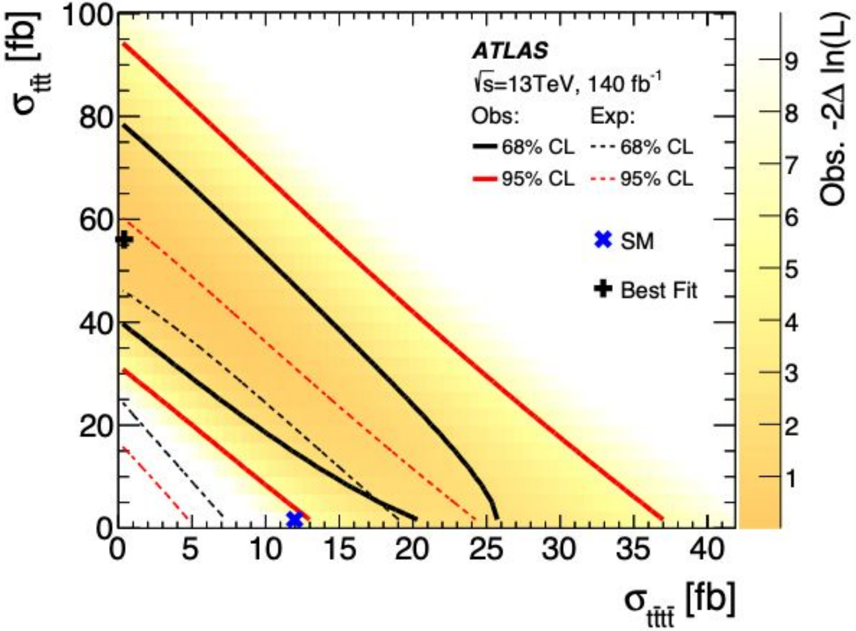
Beyond SM



Tri-top and Four-top measurements

- Strong anti-correlations between tri-top and four-top
- The simultaneous measurement is compatible with SM within 2.1 standard deviation
- Limits are set on tri-top cross-sections assuming four top follows the SM or at its best-fit value

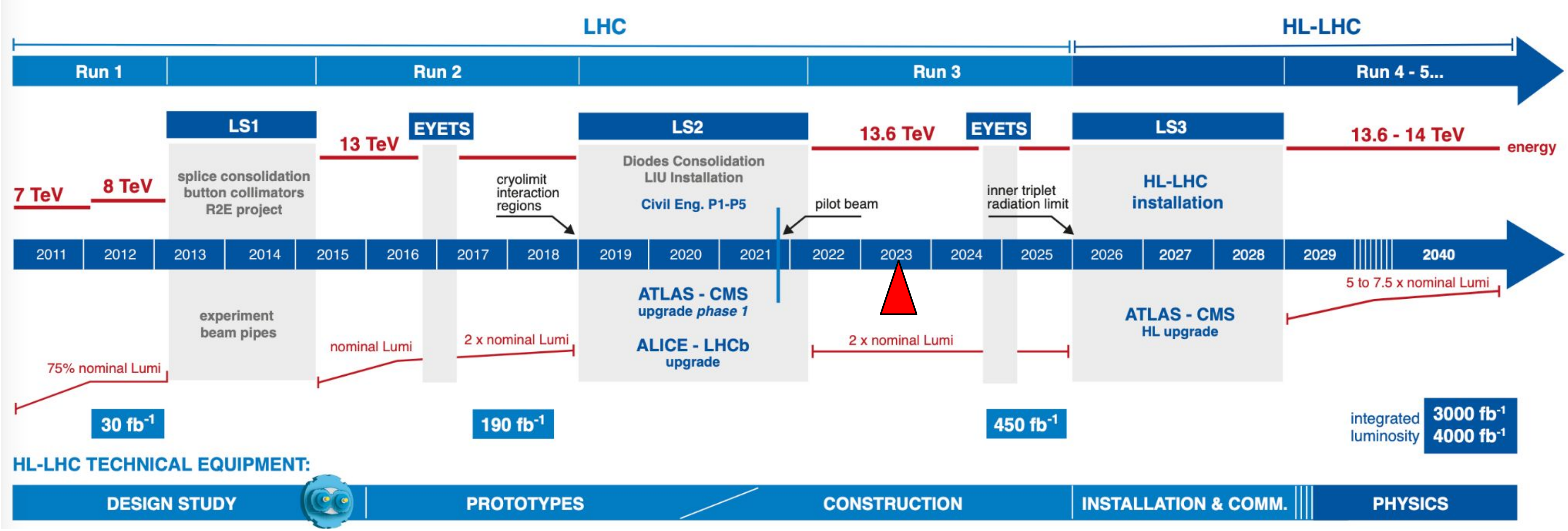
Processes	95% CL cross section interval [fb]	
	$\mu_{t\bar{t}t\bar{t}} = 1$	$\mu_{t\bar{t}t\bar{t}} = 1.9$
$t\bar{t}t$	[4.7, 60]	[0, 41]
$t\bar{t}tW$	[3.1, 43]	[0, 30]
$t\bar{t}tq$	[0, 144]	[0, 100]



Outlook

Run3 and HL-LHC

- Run-3 (ongoing, 2022-2025) : expect 300 fb^{-1} at 13.6 TeV
- Long shutdown for the HL-LHC (2026-2028): ATLAS phase-II upgrade
- HL-LHC (Run 4+ , 2029-) : expect 3000 fb^{-1} at 14 TeV



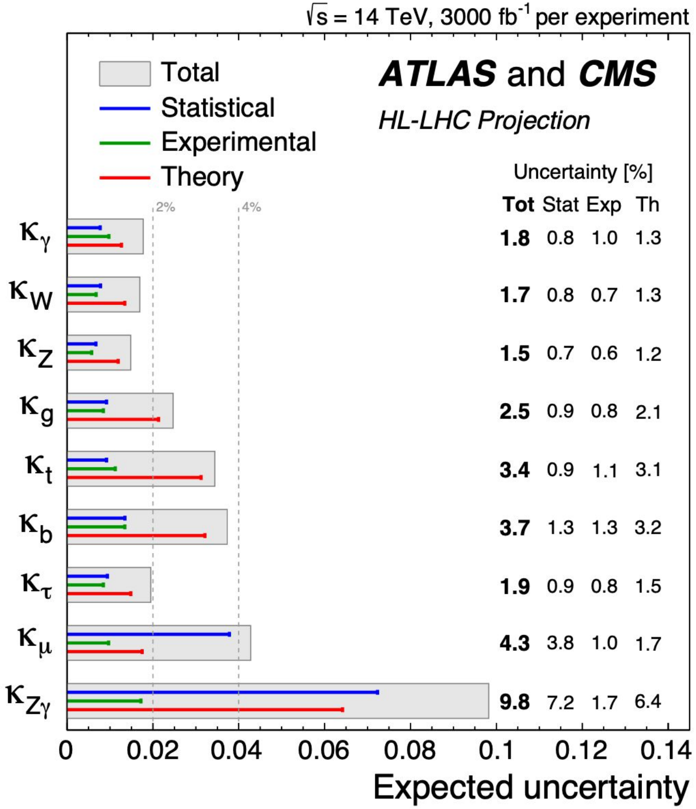
The Higgs couplings at HL-LHC

- HL-LHC is expected to significantly increase the sensitivities of Higgs coupling to tops

  Total uncertainty on k_t is expected to be 3.4% (now 10%)

- However, the top-Higgs coupling measurement will be dominated by systematic uncertainties

- There are more challenges in the HL-LHC studies



CERN-LPCC-2018-04

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Challenges for future top-Higgs studies

- The high pile-up with HL-LHC:
  - The ~200 actual interactions per bunch crossing (pile-up) challenges the reconstruction of analysis objects, for example the vertex efficiency of the $H \rightarrow \gamma\gamma$ events will be < 60%
  - Solution: detector upgrades and its software utilization, like timing detectors
- Complicated physics processes:
  - The processes like multi-top and di-Higgs are complicated, but they are very unique to measure SM properties, it's hard to enhance their sensitivities. For example tri-top and four-top are not well distinguished in the current study
  - Solution: the lost info. from reconstruction, advanced machine learning (GNN and new methods)
- Large-statistic Monte Carlo
  - Huge computing power is required for maintaining the ratio between MC and data statistics with high luminosities, this is important for the event selection/classifier, modelings and systematic uncertainties
  - Solution: generative models, like a normalizing-flow method (arXiv:2303.10148) in the early Run 3 $H \rightarrow \gamma\gamma$ analyses
- ... more challenges and opportunities

Recap

We discussed why the top-Higgs Yukawa coupling and Higgs CP properties are important

Four studies of the top-Higgs Yukawa coupling and Higgs CP properties

- With on-shell Higgs
  - CP and top-Higgs couplings with $H \rightarrow \gamma\gamma$ PRL 125 (2020) 061802
  - STXS measurements with top-Higgs couplings JHEP (arXiv:2207.00348)
- Searches
  - $H(\rightarrow \gamma\gamma) + X$ searches for new t-H sectors JHEP (arXiv:2301.10486)
- With off-shell Higgs
  - Four tops observation - the heaviest final state ever observed EPJC (arXiv:2303.15061)

More challenges and opportunities in LHC Run3 and HL-LHC!

Thanks USTC for hosting the seminar!

backup

-

The CMS result (2LSS/3L/4L)

$$\sigma_{t\bar{t}t\bar{t}} = 17.9\,^{+3.7}_{-3.5}\,(\text{stat.})\,^{+2.4}_{-2.1}\,(\text{syst.})\ \text{fb}$$

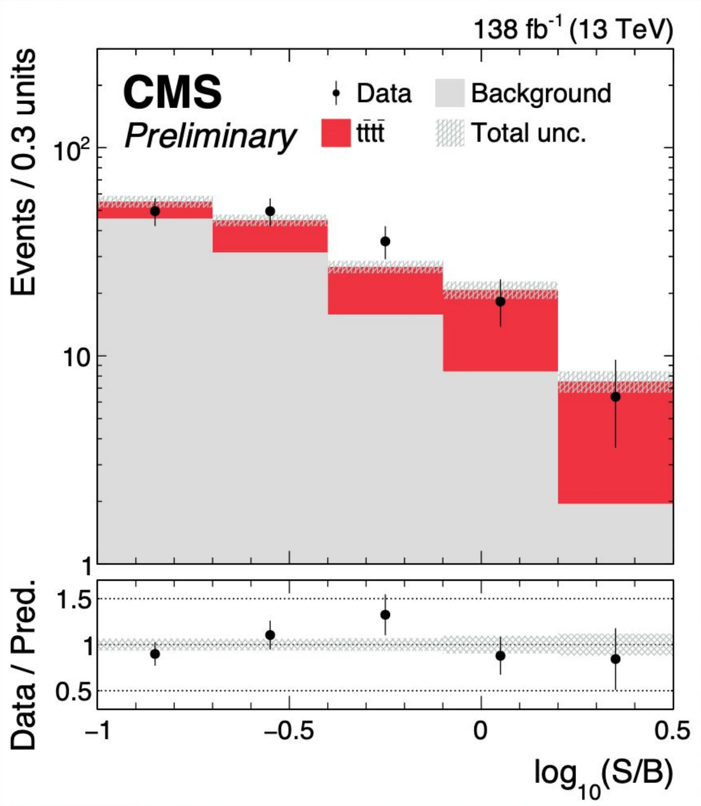
- $S_{t\bar{t}t\bar{t}} = 5.5\ (4.9)\,\sigma$

in agreement with SM

- $\sigma_{t\bar{t}t\bar{t}}/\sigma^{\text{th.}}_{t\bar{t}t\bar{t}} = 1.3 \pm 0.3$
- $\sigma_{\text{ttW}}/\sigma^{\text{th.}}_{\text{ttW}} = 1.4 \pm 0.1$
- $\sigma_{\text{ttZ}}/\sigma^{\text{th.}}_{\text{ttZ}} = 1.3 \pm 0.1$

Differences

- CMS has a 4-lepton channel (tiny contribution), lepton channels are split, ATLAS merged 2LSS/3L channels.
- CMS is using multi-class BDT, ATLAS is using GNN
- CMS merged tri-top contribution with all the minor top productions, with a 20% uncertainty.
- CMS used data-driven method to estimate the non-prompt (ttbar) backgrounds, ATLAS used MC ttbar, with profiled normalizations.
- CMS measures four-top, ttW and ttZ simultaneously, ATLAS measures four-top, ttW and non-prompt (ttbar) simultaneously



(CMS-PAS-TOP-22-013)