BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

The Top-Higgs Coupling: A Key to Inferring Higgs Physics

Shuo Han 韩朔

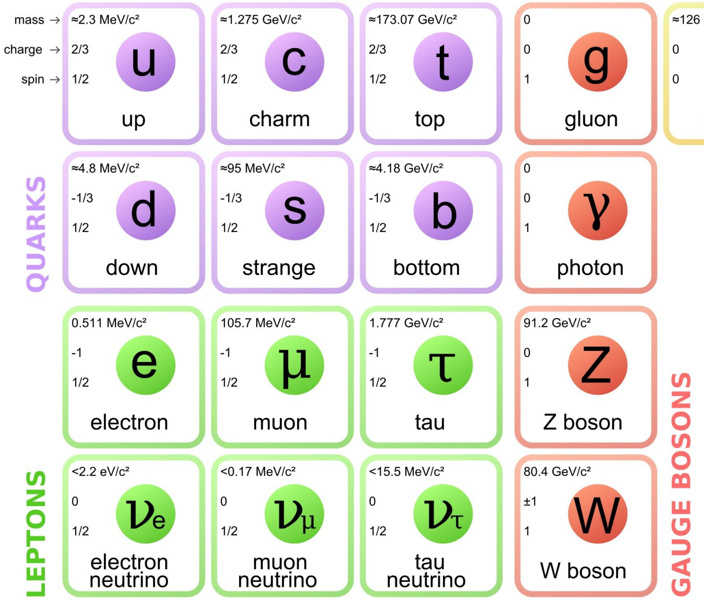
June 16th 2023

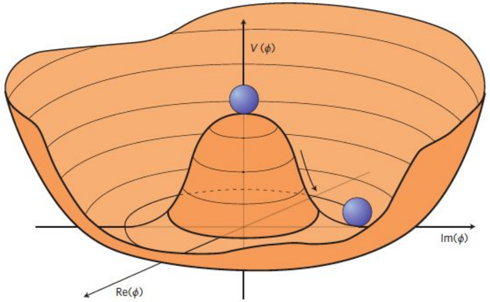
PKU-SJTU Collider Physics Forum for Junior Scholars

Why are Higgs properties important?

Standard Model (SM) described 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?





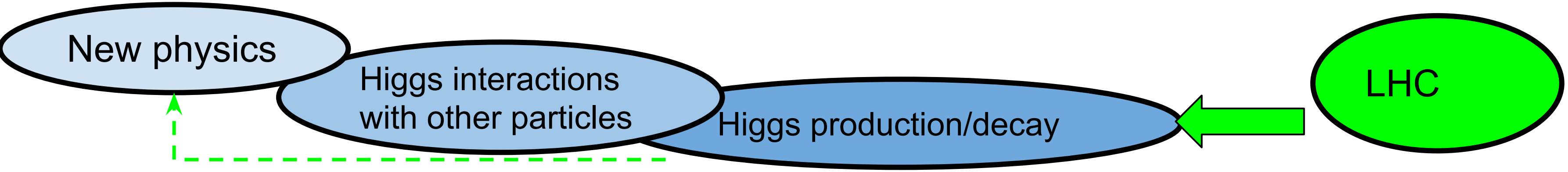
Measuring Higgs boson properties

- 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

Shuo Han

Experimental approaches for Higgs properties



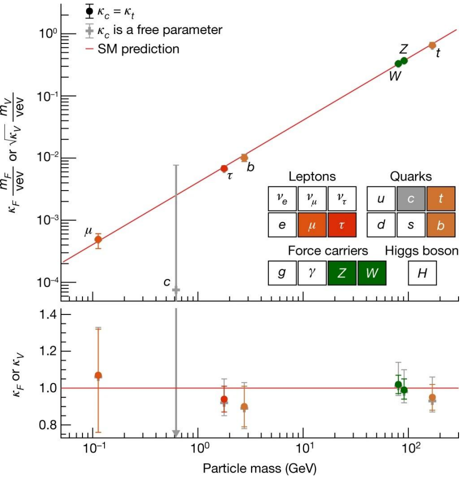
Three experimental approaches towards the new physics with Higgs properties:

- 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

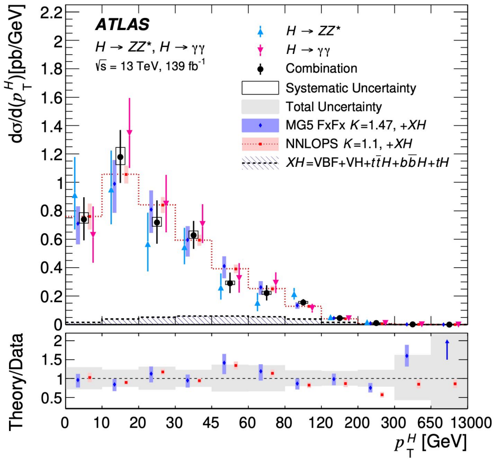
Experimental landscape of Higgs properties

Higgs couplings with other particles



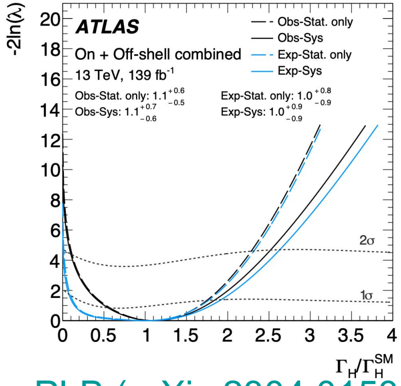
[Nature 607 (2022) 52-59]

Differential cross-section



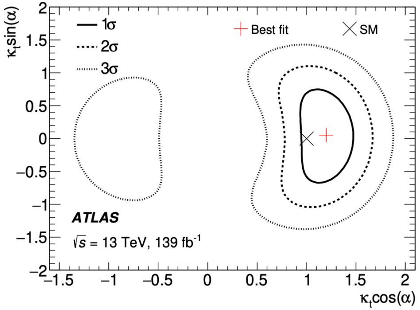
[JHEP 05 (2023) 028]

Width and Mass



[PLB (arXiv:2304.01532)]

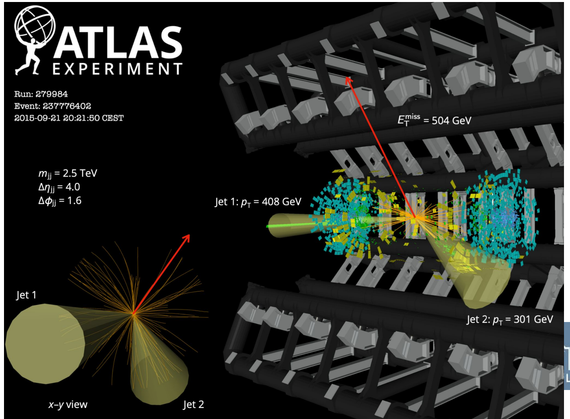
CP properties



[PRL 125 (2020) 061802]

Searches

e.g. Higgs→invisible



[JHEP 08 (2022) 104]

Shuo Han

Why top-Higgs coupling important

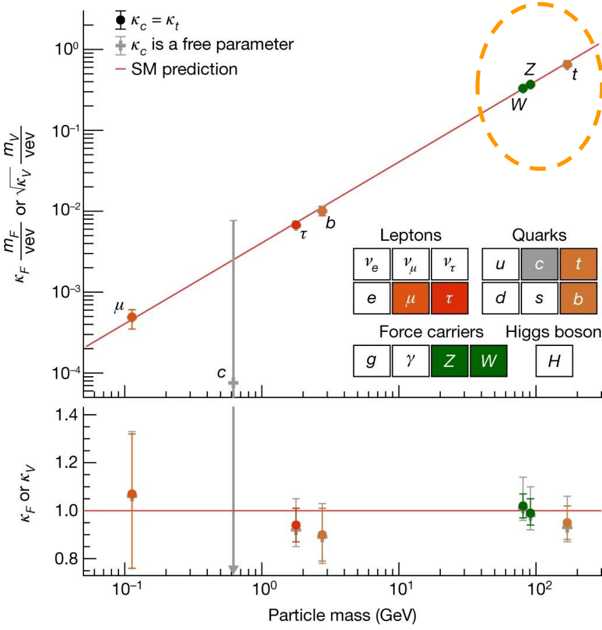
It's the heaviest

- 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

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

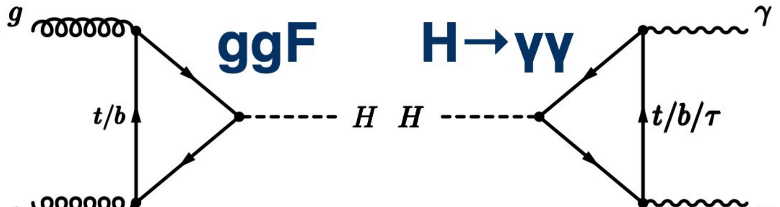
CP even — CP odd

Standard model : $\alpha = 0$, $\kappa_t = 1$

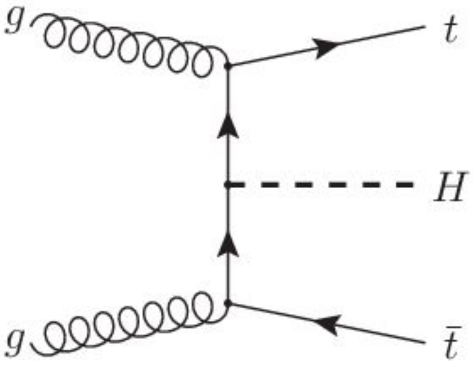
CP properties can be directly measured with top-Higgs coupling

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



The Higgs width with top-Higgs couplings

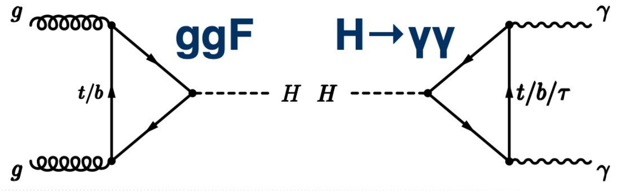
- The Higgs total width is a sum of partial width over all possible SM and BSM decay final states
- One could use a combination of on- and off-shell measurements to constrain the Higgs total width,
  - for example, measure the top-Higgs coupling with off-shell Higgs boson in the four-top production

$$\frac{d\sigma}{dm^2} = \frac{g_i^2 g_f^2}{(m^2 - m_H^2)^2 + m_H^2 \Gamma^2}$$

- The differential cross section is given by a Breit-Wigner

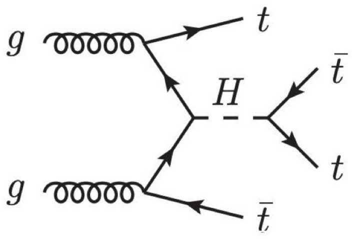
$$\sigma \propto \frac{g_i^2 g_f^2}{m_H \Gamma}$$

- For on-shell measurements of the Higgs boson, we cannot break the degeneracy between κ and Γ



$$\frac{d\sigma}{dm^2} \propto \frac{g_i^2 g_f^2}{(m^2 - m_H^2)^2}$$

- The off-shell measurements determine couplings without the assumption of width



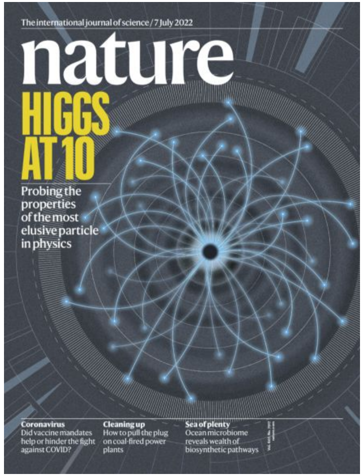
Experimental landscape of top-Higgs coupling

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)

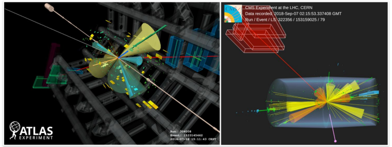
- top-Higgs coupling with off-shell Higgs boson
  - Observation of the four-top-quark production EPJC 83 (2023) 496



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

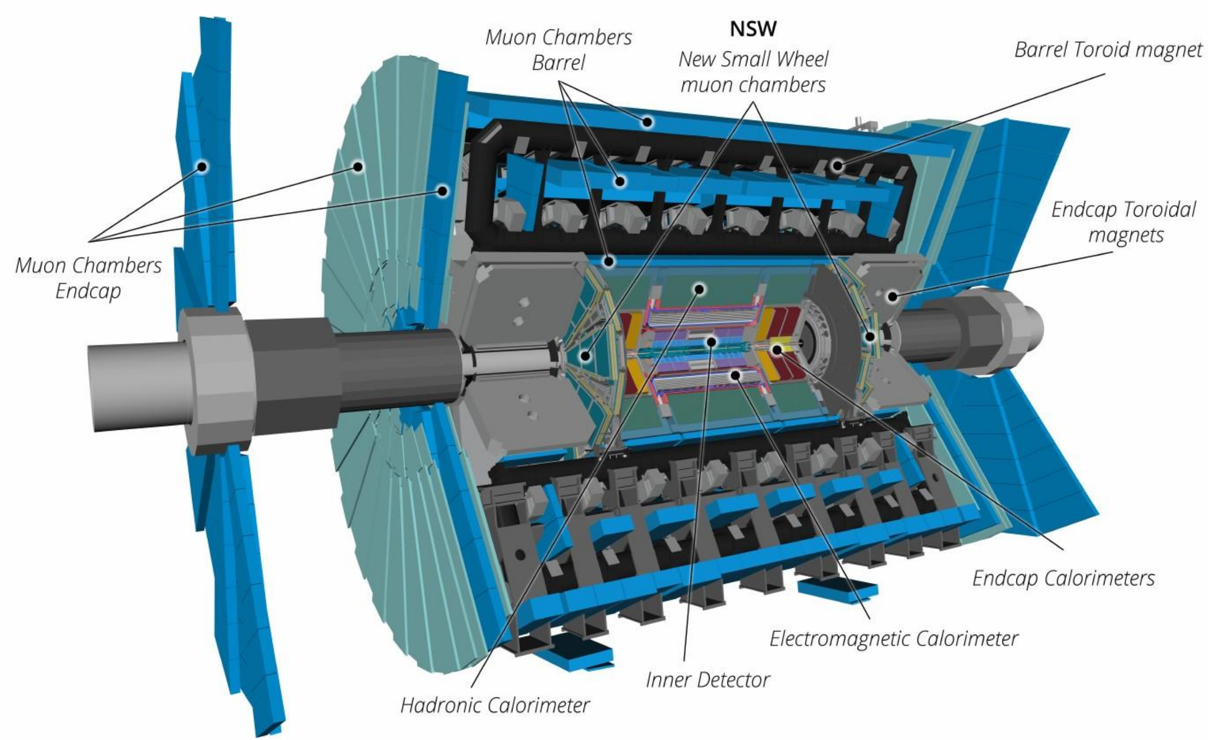
24 MARCH, 2023 | By Naomi Dinmore

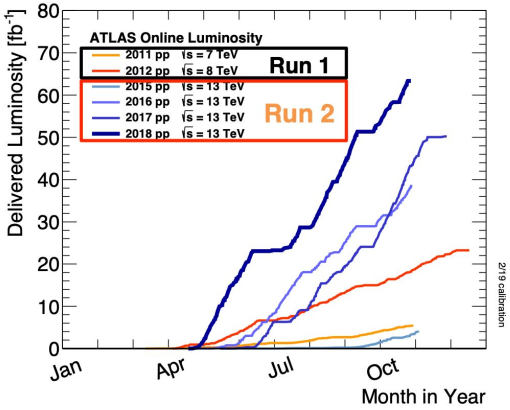


Event displays of four-top-quark production from ATLAS (left) and CMS (right).

Shuo Han

ATLAS Detector and Run-2 data





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

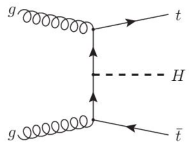
SJTU-ATLAS team contributes to the muon detectors upgrade (TGC), and PKU-CMS team contributes to the muon detector upgrade of CMS (GEM). Both teams leads various physics analyses.

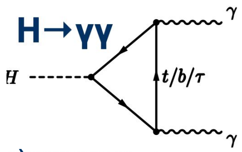
Shuo Han

with on-shell Higgs boson

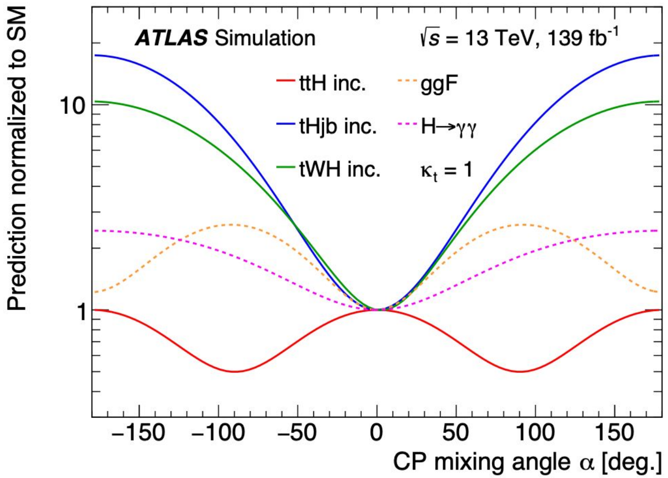
CP in top-Higgs coupling with $H \to \gamma\gamma$

- CP properties in the top-Higgs coupling with ATLAS Run-2 PRL 125 (2020) 061802
  a. Select ttH/tH, $H \to \gamma\gamma$ 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)

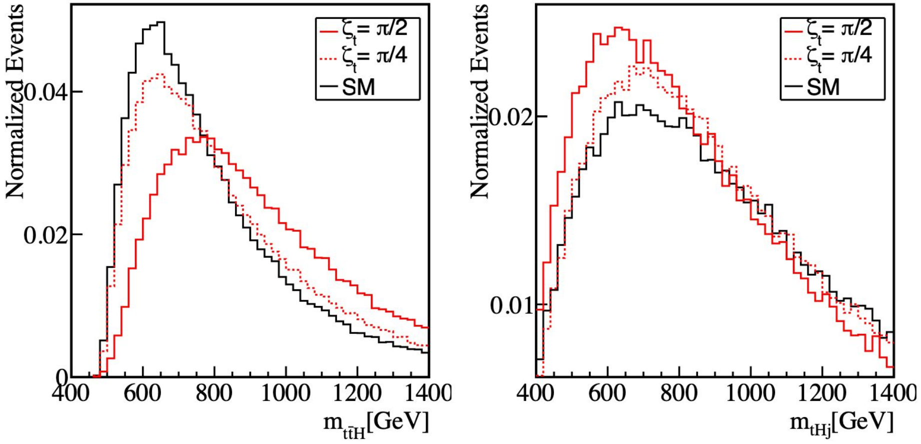




ttH and tH cross-section as function of (κ_t, α)



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



CERN-PH-TH/2013-312

CP in top-Higgs coupling: selections

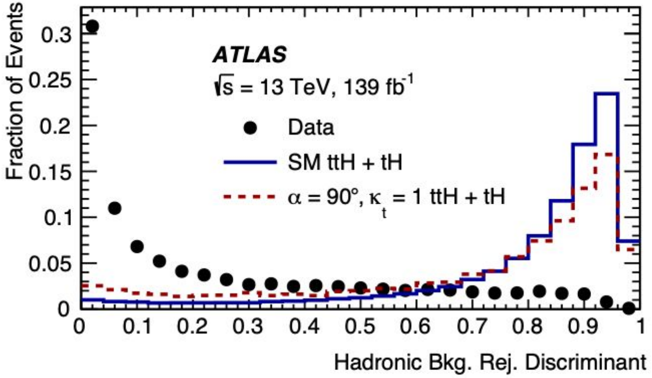
The ttH/tH, H → γγ events are selected with two event classifiers

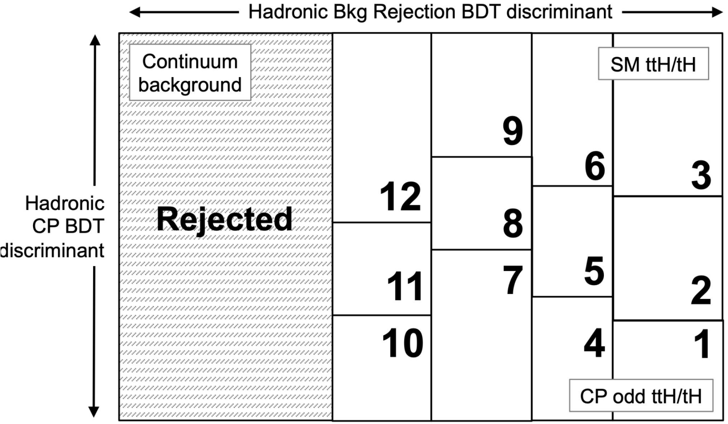
ttH/tH CP odd vs CP even

- 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

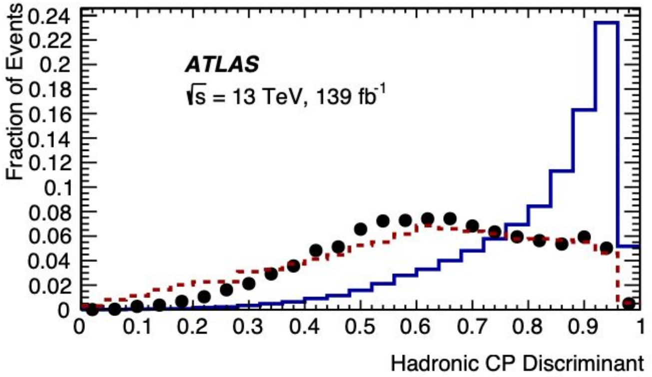
Signal vs background

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



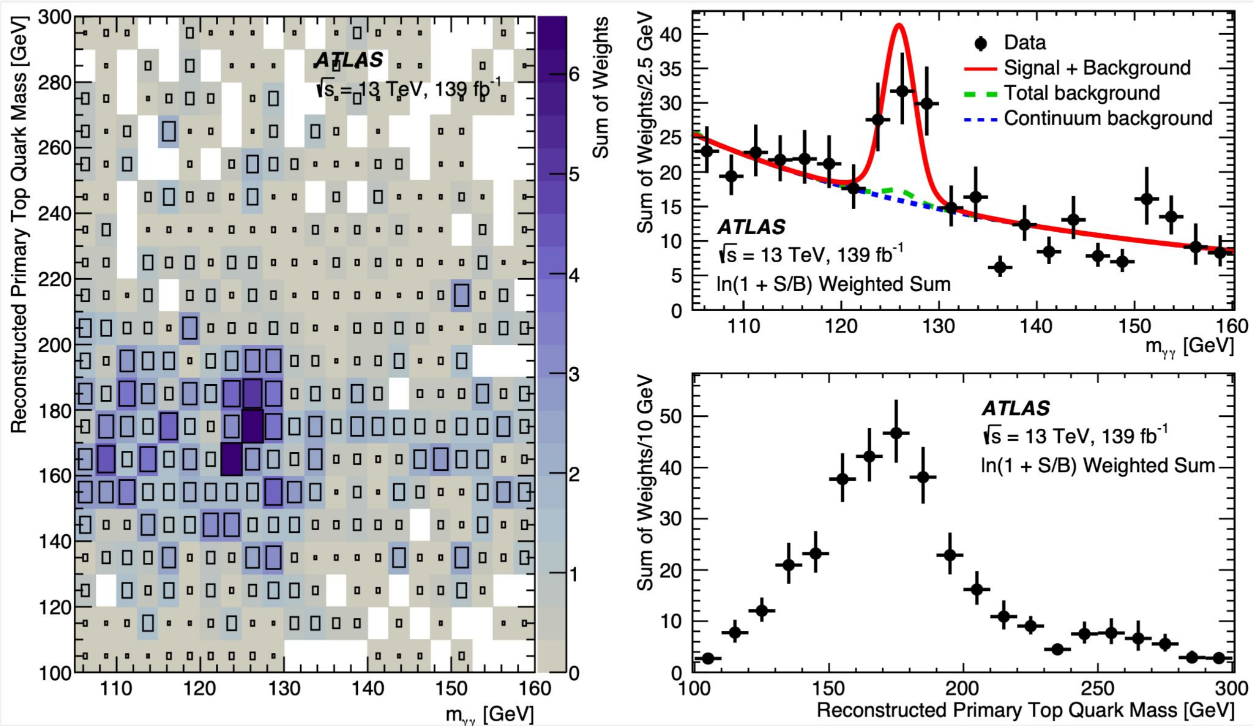


12 categories for top hadronic decays
+ 8 more categories for the top leptonic decays



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



Shuo Han

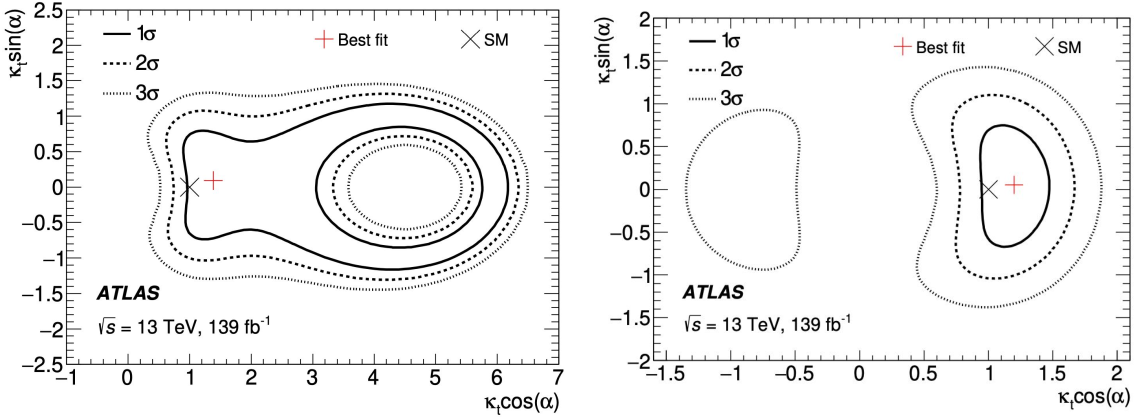
CP in top-Higgs coupling with H → γγ

- 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(α), $\kappa_t$cos(α)]



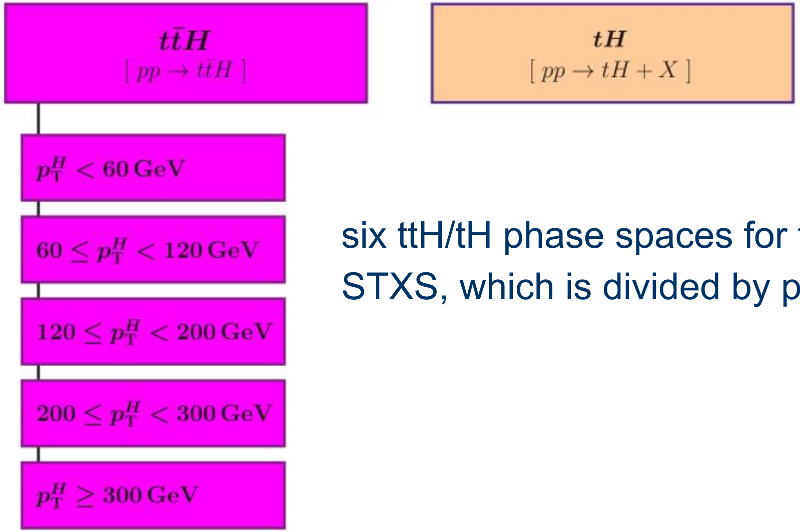
ggF and H → γγ resolved with (κ_t , α) κ_g and κ_γ set to combined measurements

PRL 125 (2020) 061802

Shuo Han

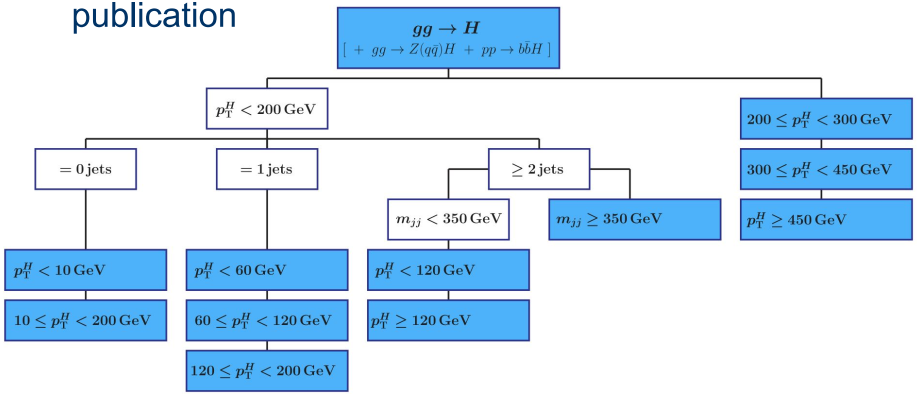
The STXS measurements with H → γγ

- 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

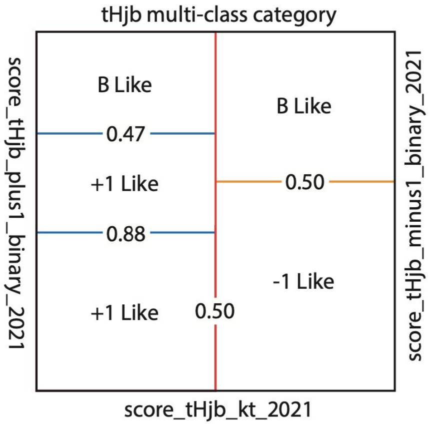


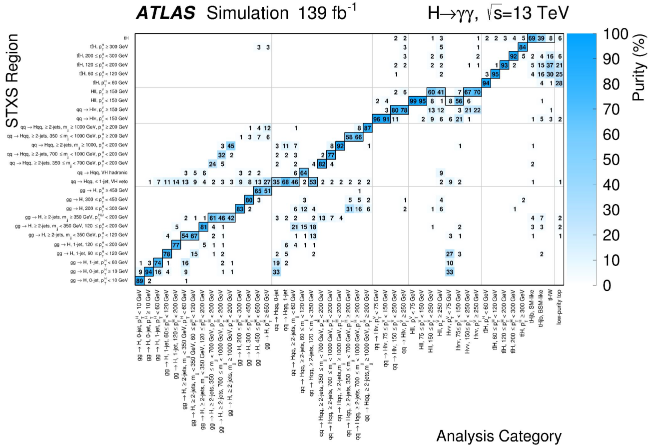
Shuo Han

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





101 categories targeting to 28 phase spaces, including 9 categories targeting to the 6 ttH/tH phase spaces

Shuo Han

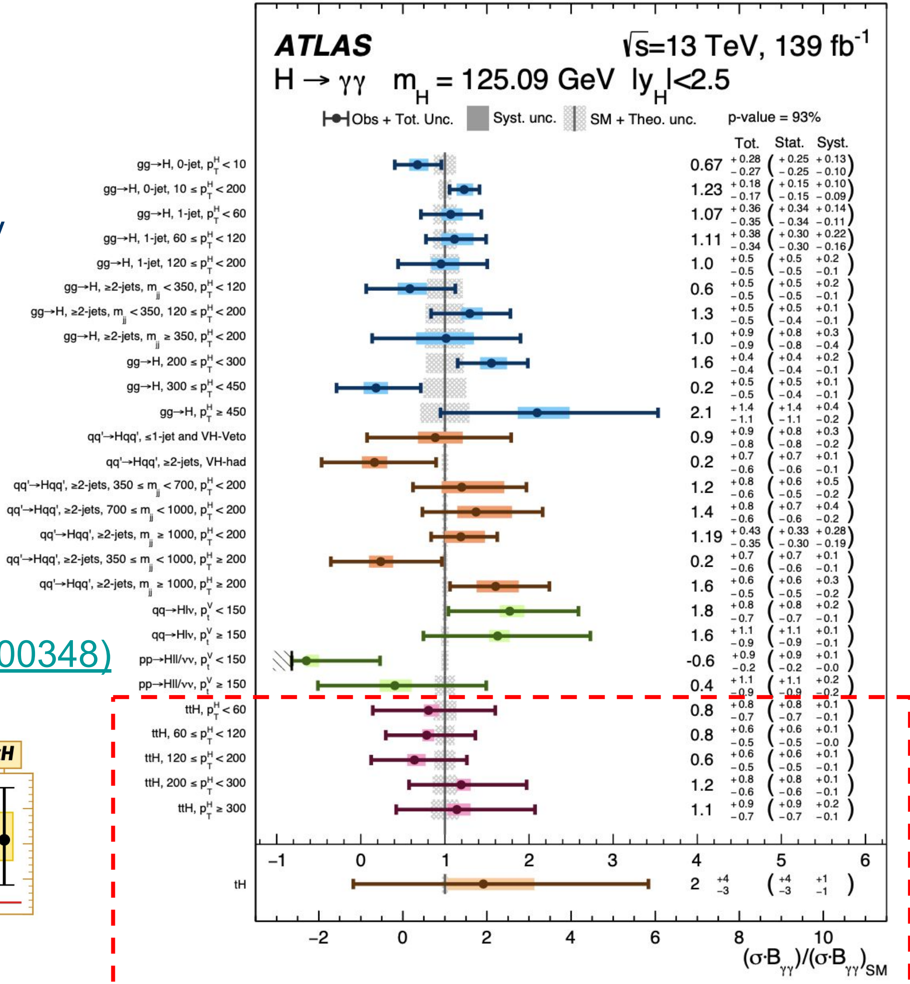
STXS measurement result

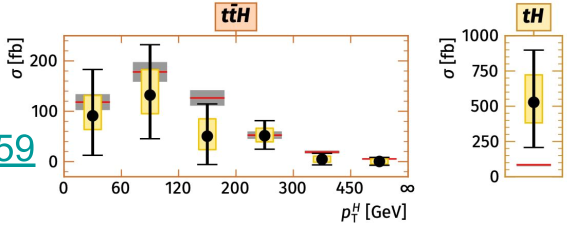
The analysis extracted signal events with S+B fits on m(γγ)

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





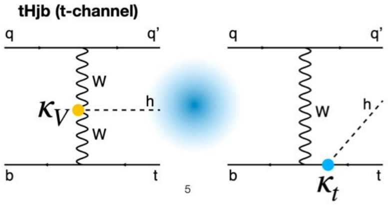
Nature 607 (2022) 52-59

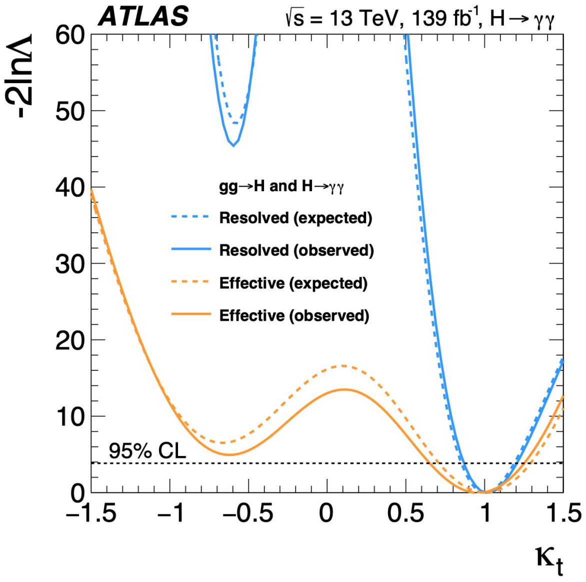
Shuo Han

The top-Higgs coupling with STXS

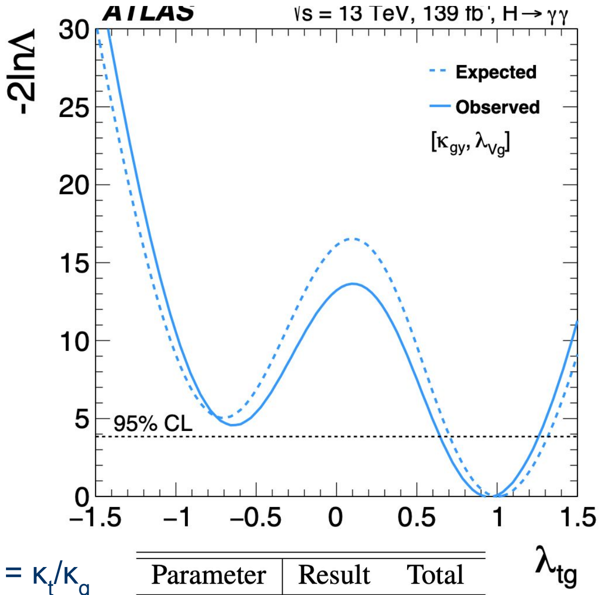
Top-Higgs coupling (κ_t) is directly measured

- tH yields are parameterized as function of κ_t $y_i = \kappa_t^2 A + \kappa_V^2 B + \kappa_t \kappa_V C$
- κ_t = 1.01±0.09 if resolve the ggF and H → γγ 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)





κ_t = 0.95+0.15-0.16
, when κ_g and κ_γ set to 1.0
κ_t = 1.01±0.09
, when ggF and H → γγ resolved with κ_t

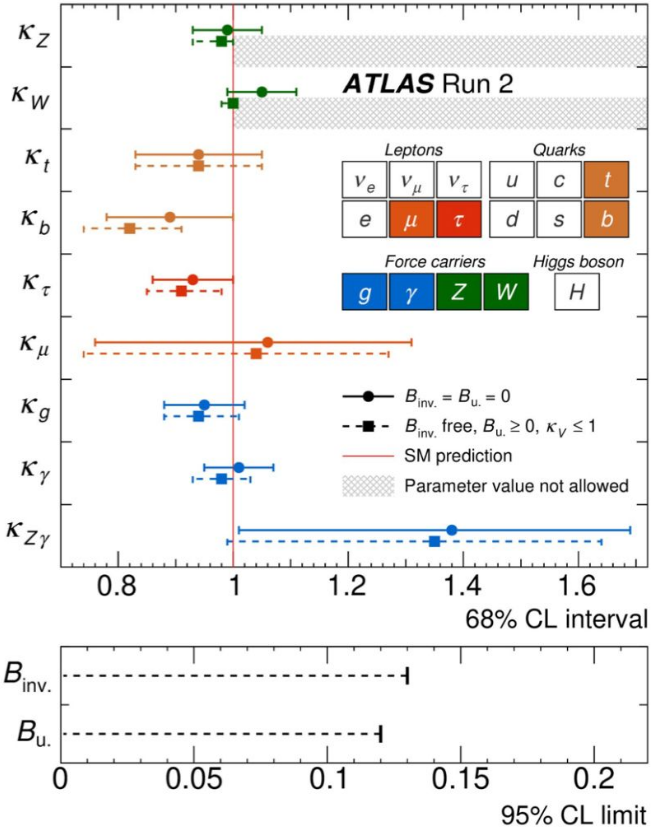


$\lambda_{tg} = \kappa_t/\kappa_g$
$\lambda_{Vg} = \kappa_V/\kappa_g$
$\kappa_{g\gamma} = \kappa_\gamma \kappa_g/\mathrm{I}$

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

Shuo Han

The top-Higgs coupling with STXS



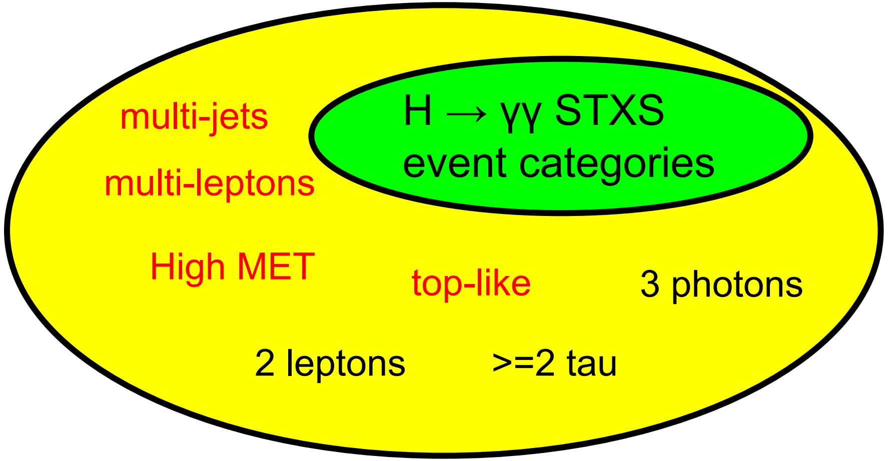
Most precise coupling determination from ATLAS

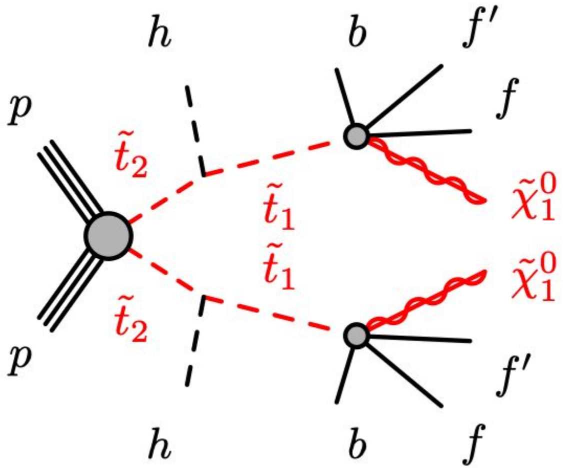
κ_Z, κ_W, κ_τ,κ_g, κ_γ at a level of < 10%

κ_t = 0.94±0.11 in combination, with other modifiers profiled

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





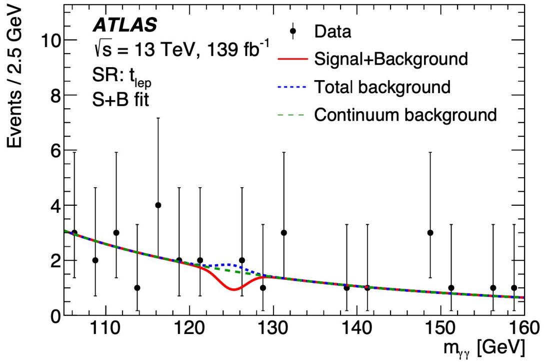
H+X search: event selection

- 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)

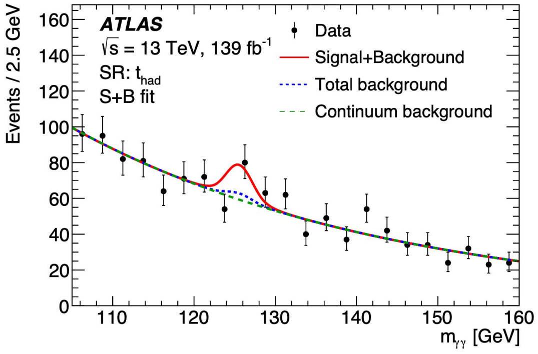
Target	Region	Detector Level
Heavy flavor	$\geq 3b$	$n_{b-\text{jet}} \geq 3$, 85% W.P.
	$\geq 4b$	$n_{b-\text{jet}} \geq 4$, 85% W.P.
High jet activity	$\geq$4j	$n_{\text{jet}} \geq 4$, $\lvert\eta_{\text{jet}}\rvert < 2.5$
	$\geq$6j	$n_{\text{jet}} \geq 6$, $\lvert\eta_{\text{jet}}\rvert < 2.5$
	$\geq$8j	$n_{\text{jet}} \geq 8$, $\lvert\eta_{\text{jet}}\rvert < 2.5$
	$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., $\text{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

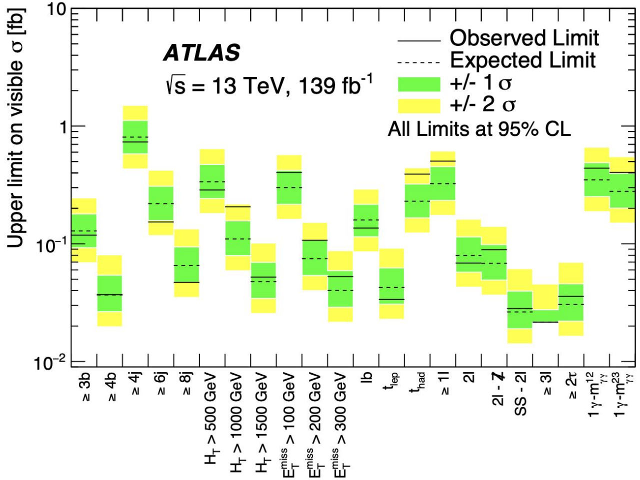
- no obvious excess for H+X production.
  - The largest deviation from SM has a local significance 1.8σ in the HT > 1000 GeV region
  - There’s 1.7σ local significance in the top hadronic decay region
- The detector level limits are set on the H+X cross-sections, and the detector efficiencies of various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



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



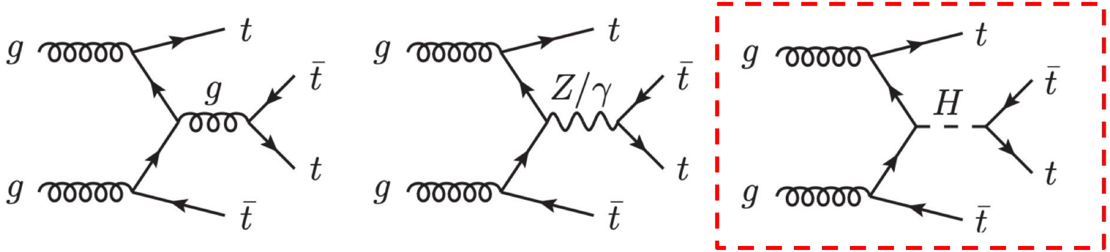
1.7σ significance in the handronic top decay region

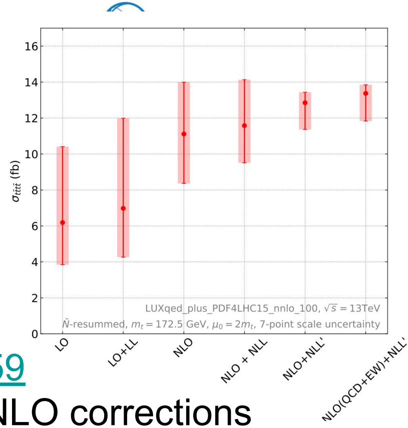


JHEP (arXiv:2301.10486)

with off-shell Higgs boson
- the observation of tttt

The four-top-quarks production at LHC

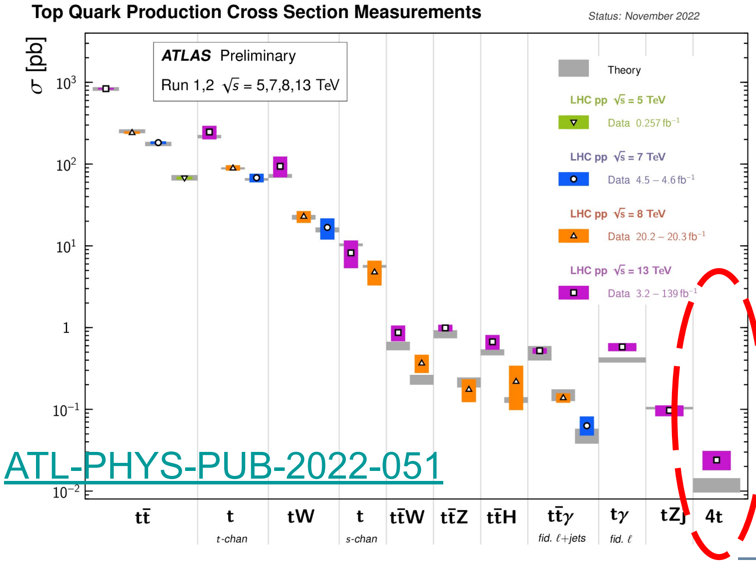




arXiv:2212.03259

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 83 (2023) 496



ATL-PHYS-PUB-2022-051

Shuo Han

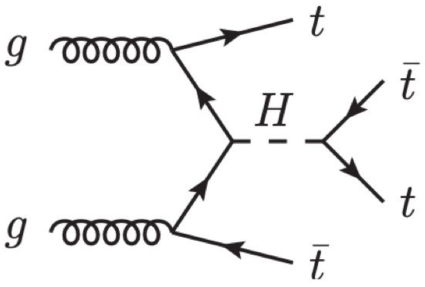
Top-Higgs Yukawa couplings with four-tops

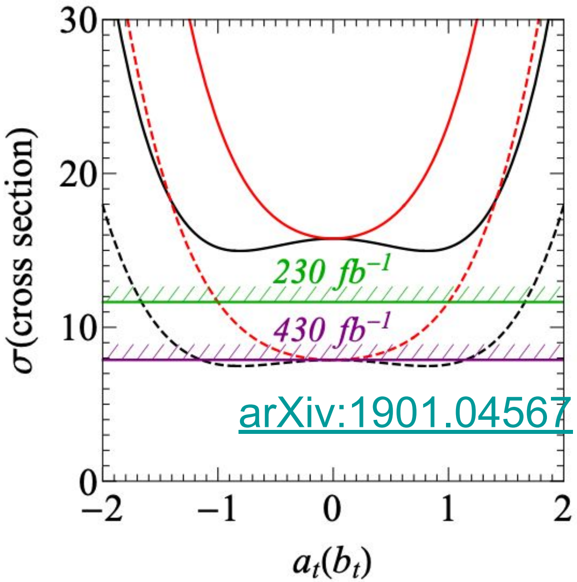
- There are various motivations of four-top cross-section measurement: SUSY (2HDM, Gluino), ttbar + X, composite top models, composite Higgs models (CERN-TH-2020-166)
- Among which, top-Higgs Yukawa coupling has unique impacts on the four top cross-section with quartic terms, so it is independent from 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

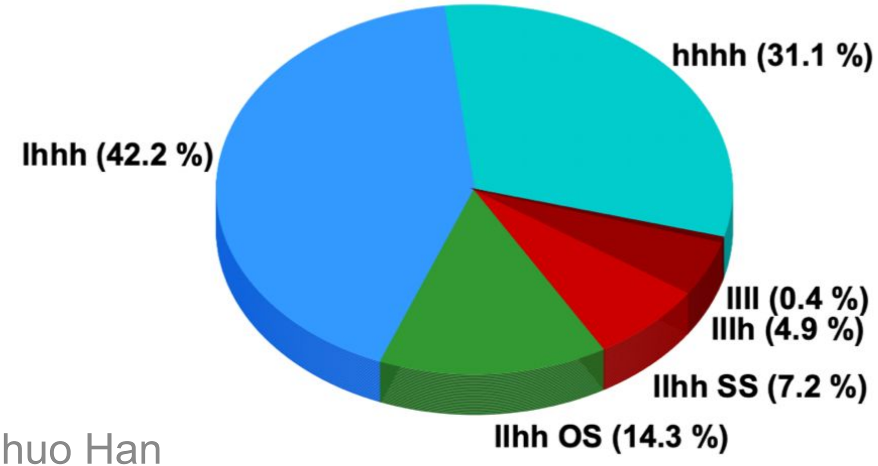
The four-top decays

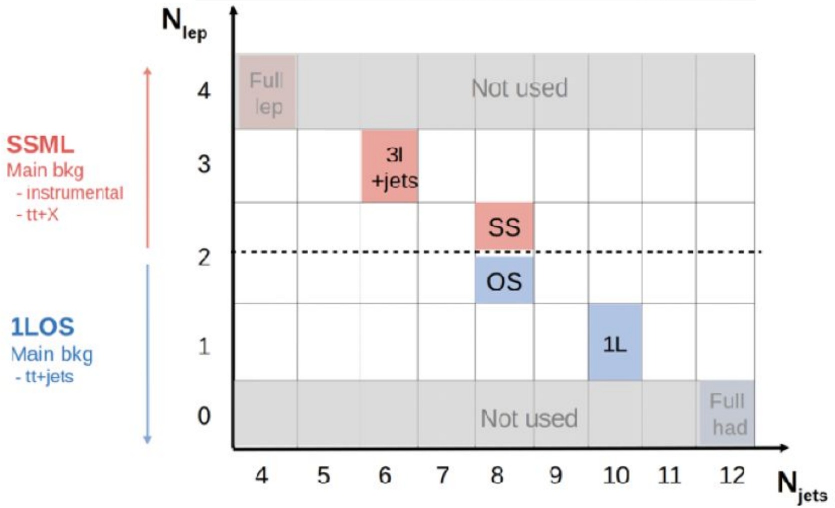
Each top quark decays to b quark + W boson

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

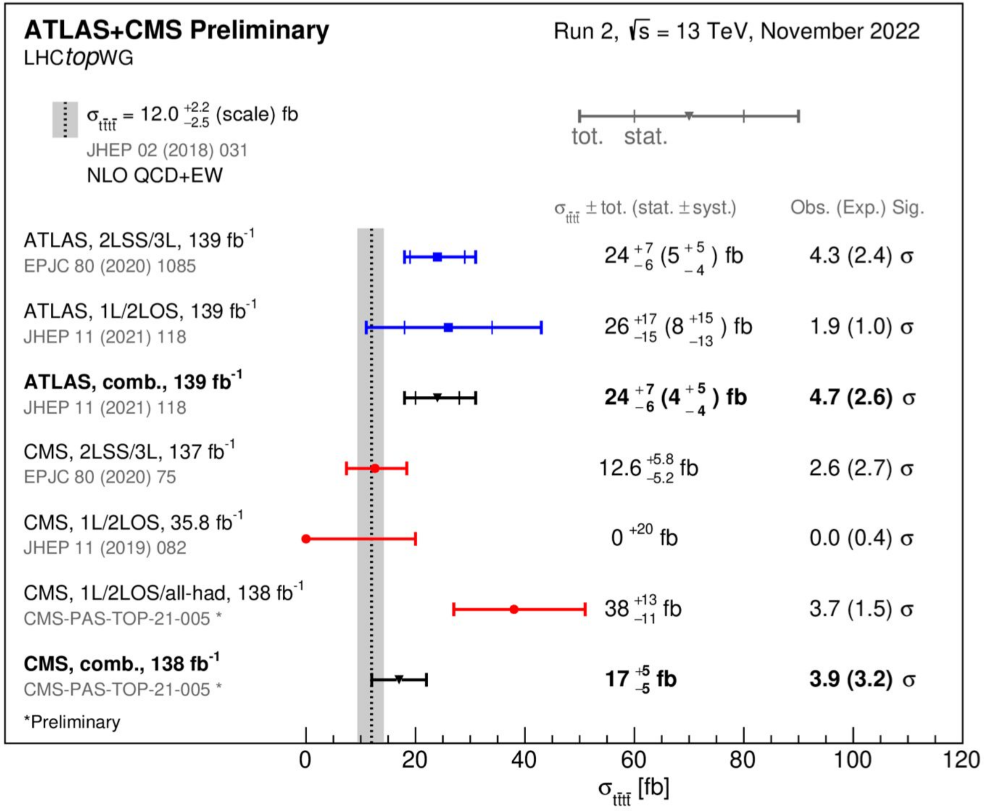




The publications before the observation

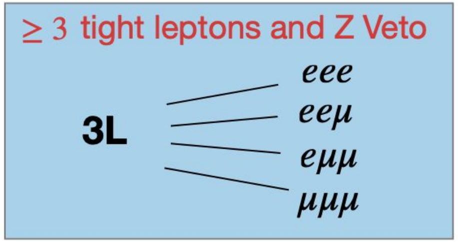
Before observation, both ATLAS and CMS measured four-top with Run-2 data, they declared evidences

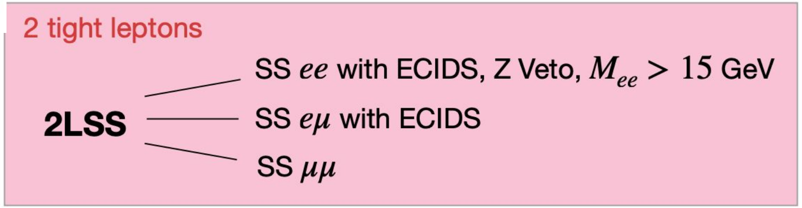
Then, both analyses decided to re-optimize with the same data, eventually there are observations in the single channel of 2LSS/3L



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)

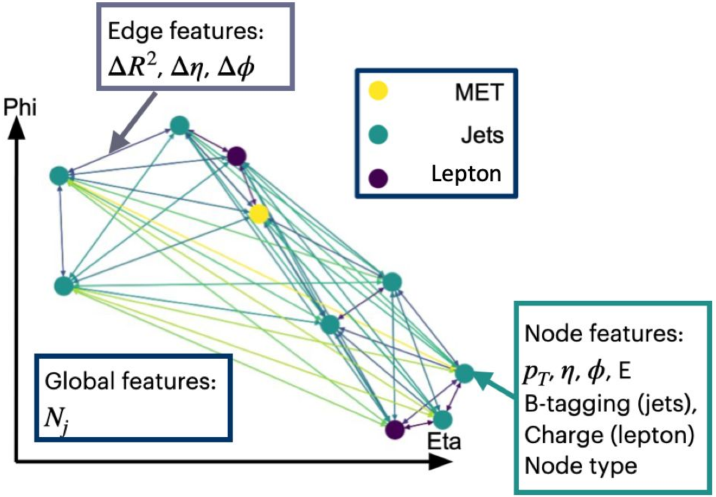


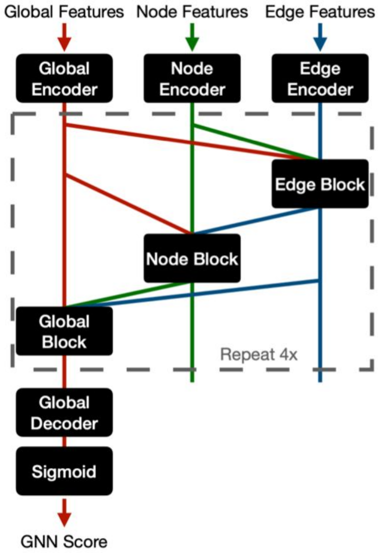


	SR
$t\bar{t}W$	130 ± 40
$t\bar{t}Z$	72 ± 15
$t\bar{t}H$	65 ± 11
QmisID	27 ± 4
Mat. Conv.	16.5 ± 2.3
HF e	3.1 ± 1.0
HF μ	7.1 ± 1.2
Low m_{γ^*}	14.1 ± 2.0
Others	47 ± 11
$t\bar{t}t$	2.9 ± 0.9
Total bkg	390 ± 50
$t\bar{t}t\bar{t}$	38 ± 4
Total	430 ± 50
Data	482

GNN multivariate analysis

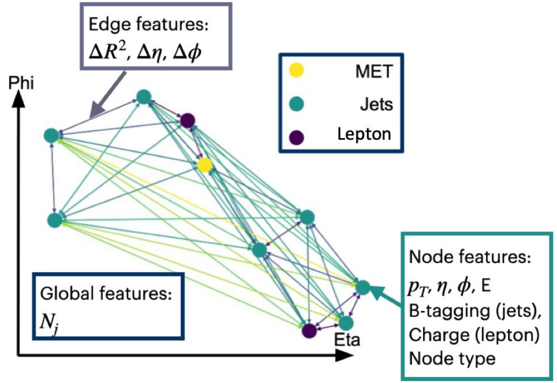
- The main challenge of the four-top signal extraction is the complicated final state
- The **Graphic Neural Network (GNN,** arxiv 1806.01261 [graph_nets]**)** combines information about all objects (jets, leptons, MET) from an event into a graph, with node, edge and global properties.
- Message passing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



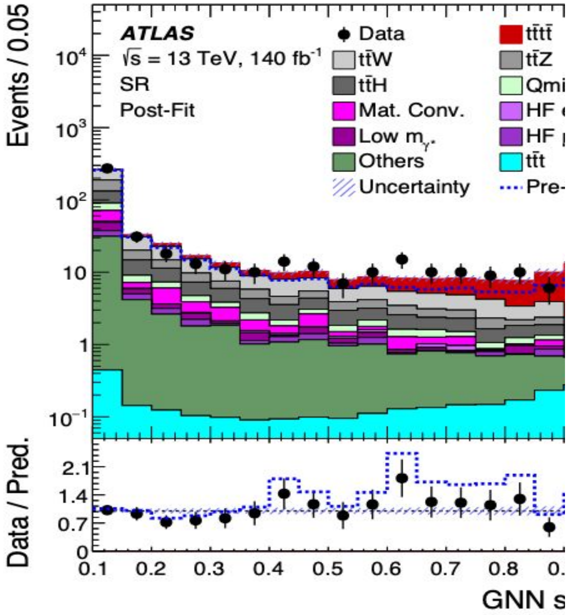


"Global" scores can pick-up signal events
"Edge" scores can reconstruct tops

GNN multivariate analysis

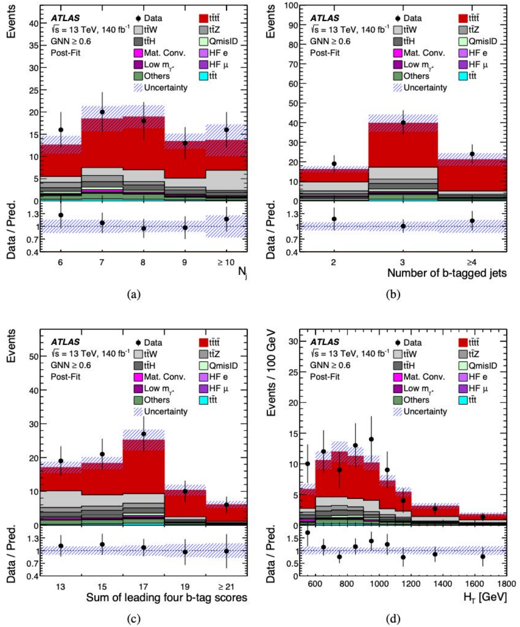


- "global score" is used and chosen as the event classifier and the observable in the pre-selected region
  - 10% higher sensitivity compared with the best BDT methods after fine tuning.



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	$NF_{t\bar{t}W^{+}(4jet)}$	$NF_{t\bar{t}W^{-}(4jet)}$
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

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

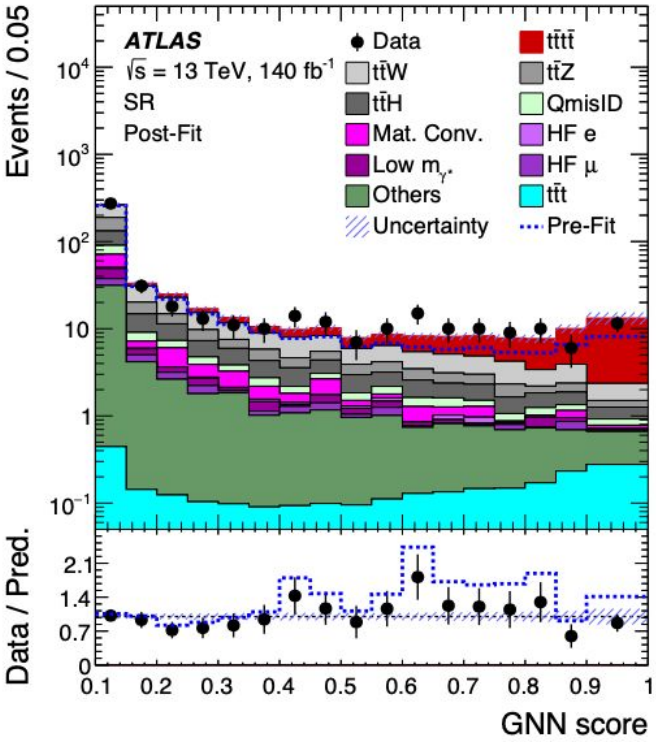
- Fake leptons from light mesons, quark/gluon jets, others: using MC

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

Top-Higgs coupling and CP

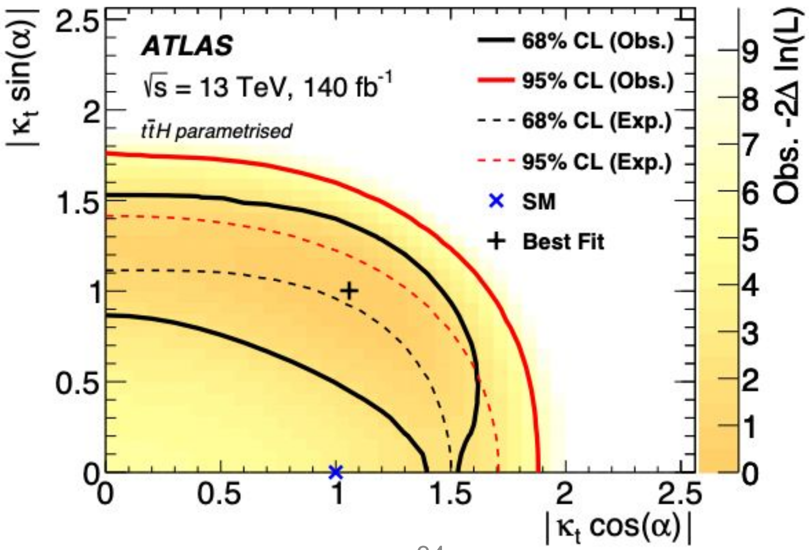
Two scenarios (k_t, α) measurements

- 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)

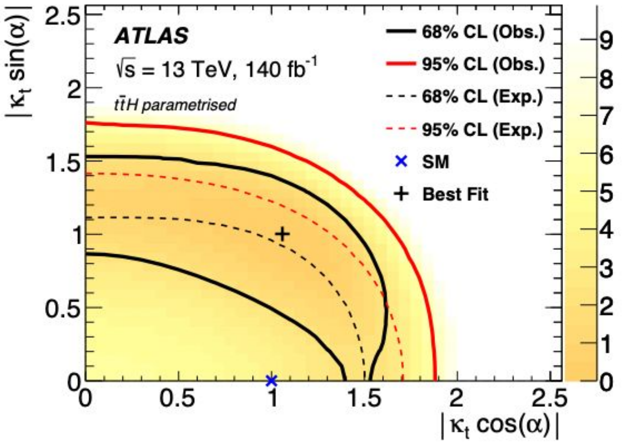
- 1) ttH parameterized: $|k_t| < 1.8$ (1.6 expected), 2) ttH not parameterized: $|k_t| < 2.2$ (1.8 expected)

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

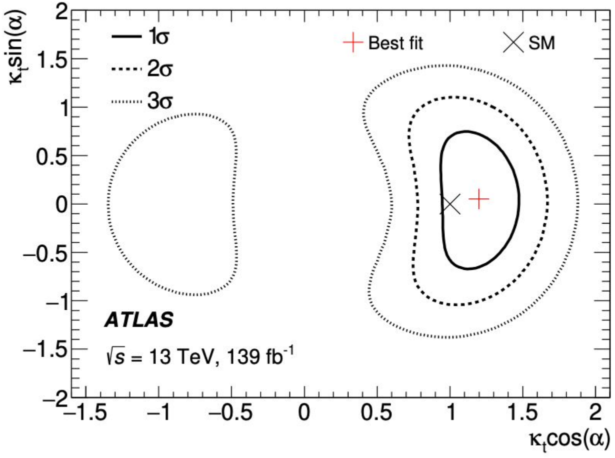


Top-Higgs Yukawa coupling

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

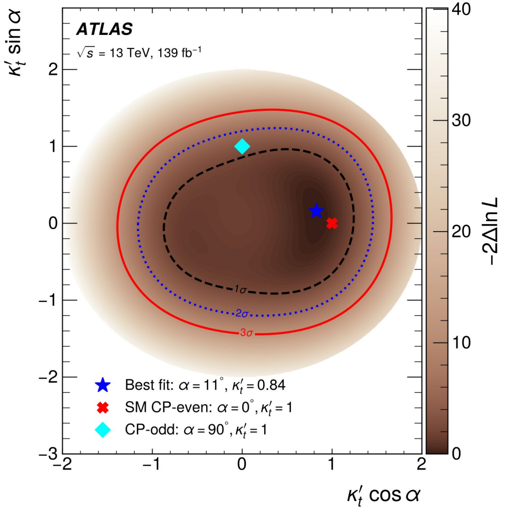


Four tops



H→γγ

[PRL 125 (2020) 061802]

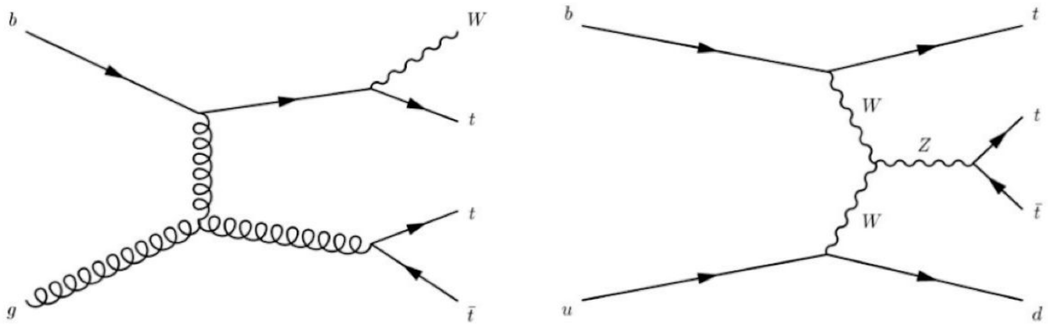


H→bb

PLB (arXiv:2303.05974)

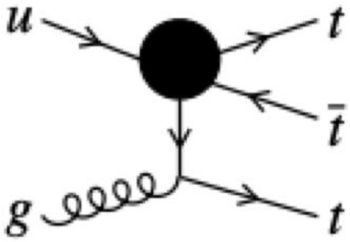
The tri-top production

- 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

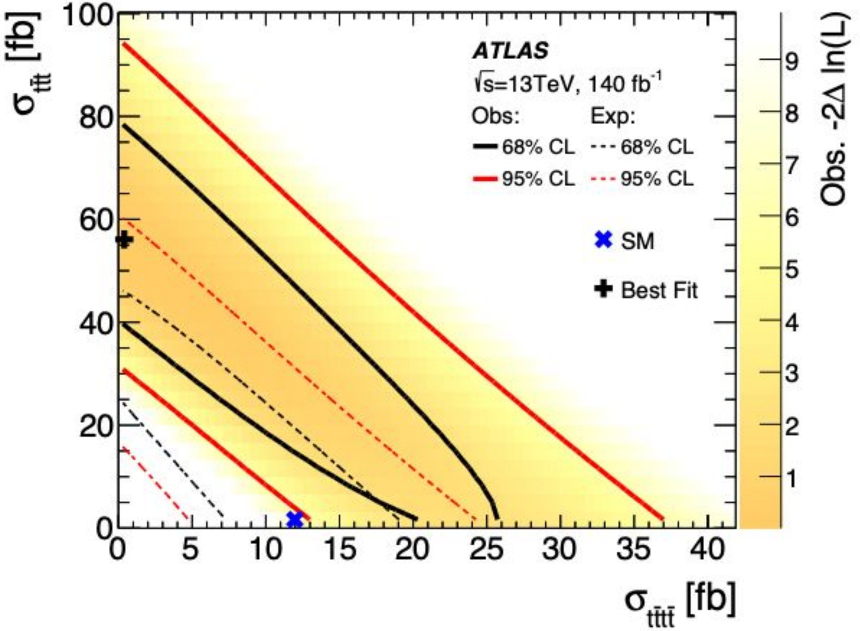


Shuo Han

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

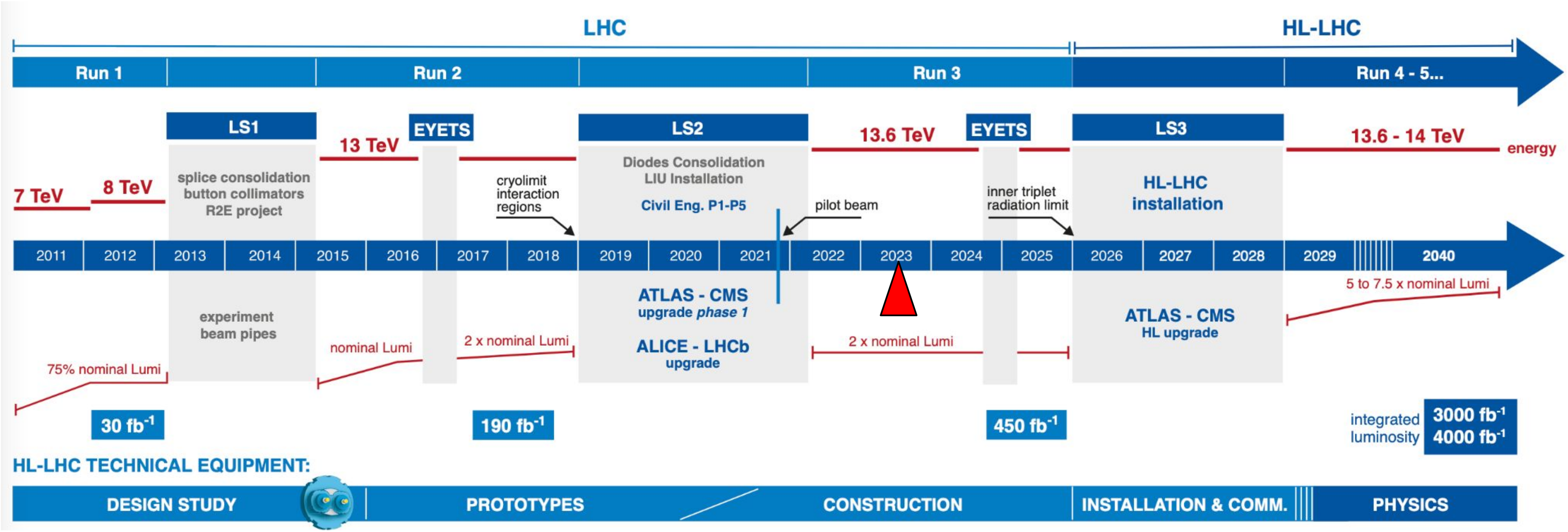
Processes	95% CL cross section interval [fb] $\mu_{t\bar{t}t\bar{t}} = 1$	$\mu_{t\bar{t}t\bar{t}} = 1.9$
$t\bar{t}t$	[4.7, 60]	[0, 41]
$t\bar{t}tW$	[3.1, 43]	[0, 30]
$t\bar{t}tq$	[0, 144]	[0, 100]



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



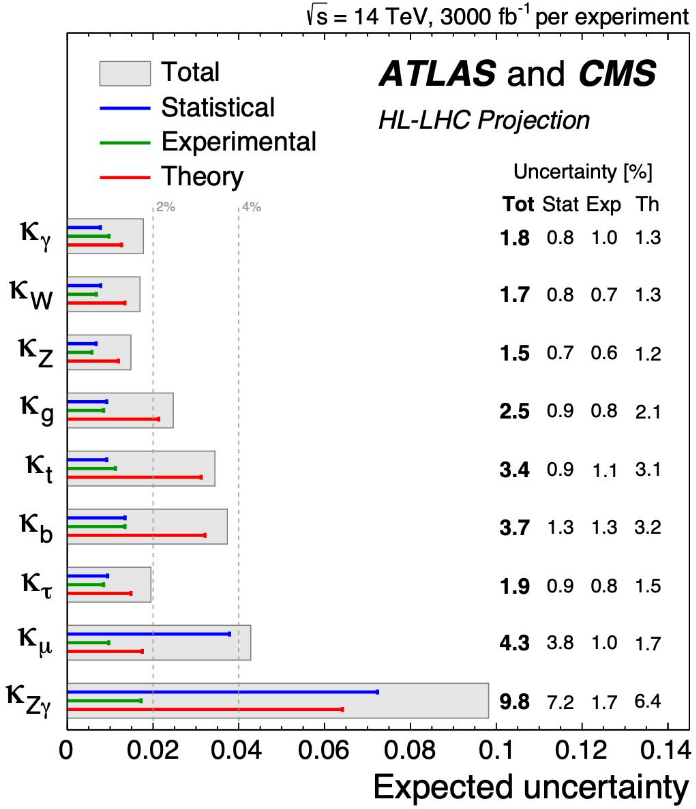
The Higgs couplings at HL-LHC

- 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%)
    - in future e+e- collider it can be <2% at 240 GeV, while it can be further improved with higher ECM

- 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

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 83 (2023) 496

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

Thanks PKU-SJTU for hosting the seminar!

backup

-

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

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

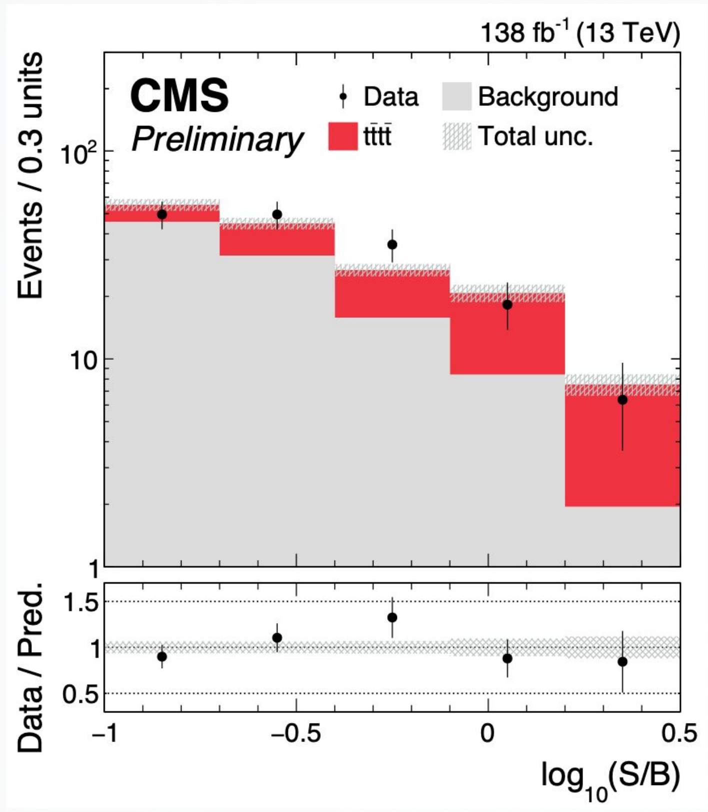
- $S_{t\bar{t}t\bar{t}} = 5.5\ (4.9)\ \sigma$

in agreement with SM

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

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)