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

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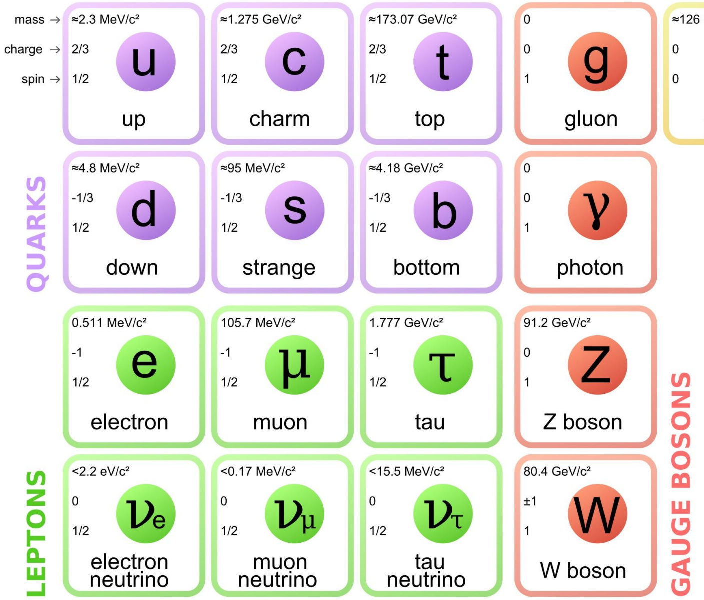
Oct 12th 2023

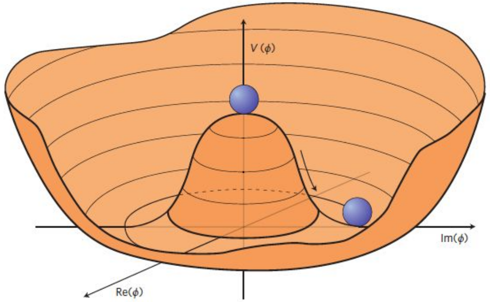
IHEP, EPD seminar

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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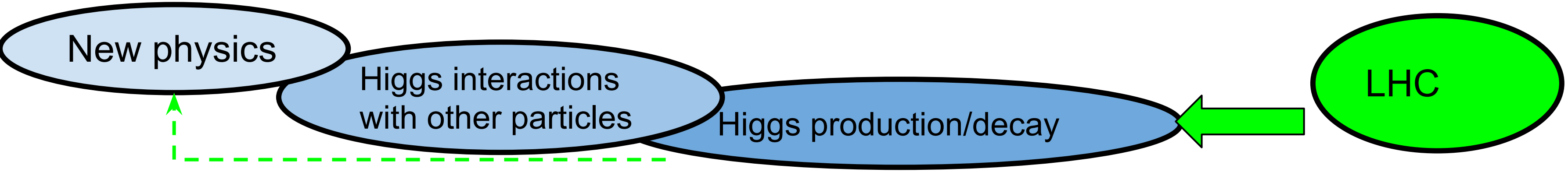
Experimental approaches for Higgs properties



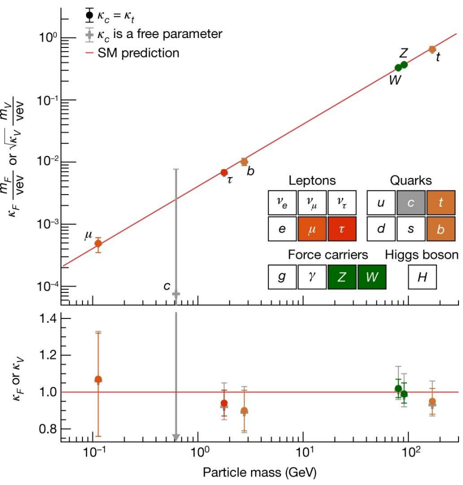
Three experimental approaches towards the new physics with Higgs properties:

- 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

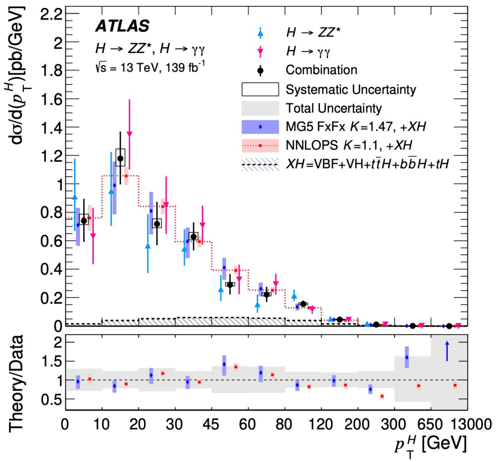
Experimental landscape of Higgs properties

Higgs couplings with other particles



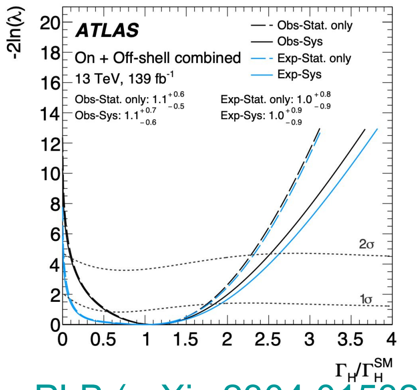
Nature 607 (2022) 52-59

Differential cross-section



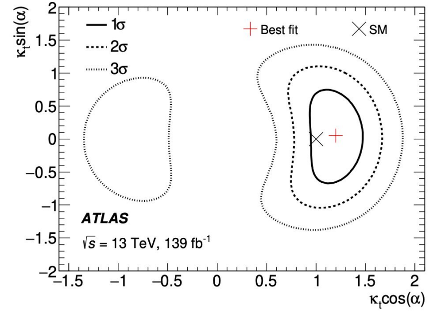
JHEP 05 (2023) 028

Width and Mass



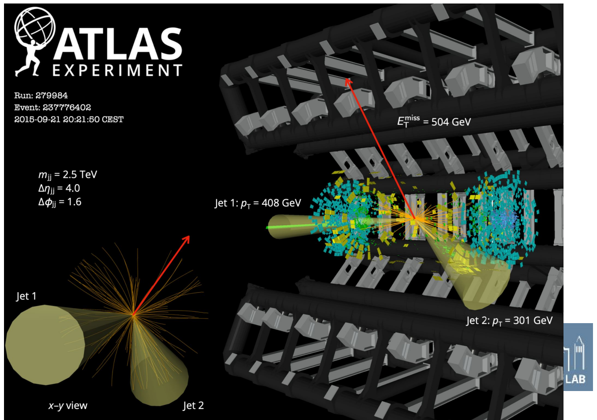
PLB (arXiv:2304.01532)

CP properties



PRL 125 (2020) 061802

Searches
e.g. Higgs→invisible



JHEP 08 (2022) 104

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Why top-Higgs coupling important

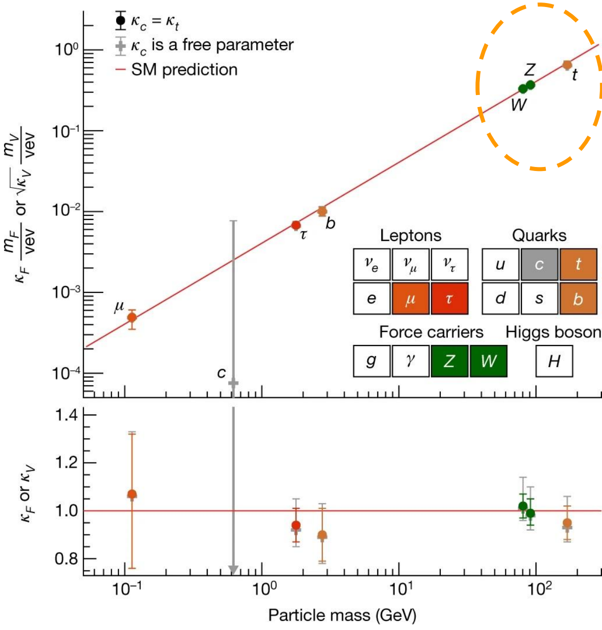
It's the heaviest

- 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
e.g. top loops dominants the ggF Higgs and Di-Higgs productions

- 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

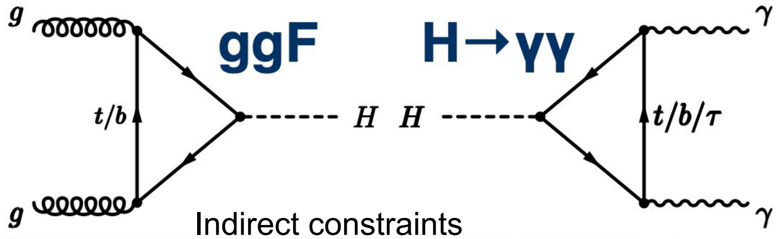
- can top-Higgs coupling violate CP symmetry?
- can top-Higgs coupling strength modified by the new physics?
- can top mass comes from other interactions than Higgs mechanism?

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

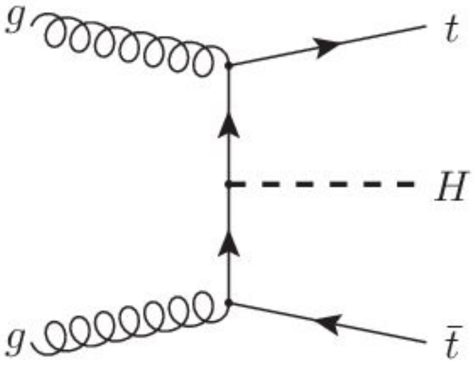
How to measure top-Higgs couplings

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



- 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

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

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

CP even CP odd

CP properties can be directly measured with top-Higgs coupling

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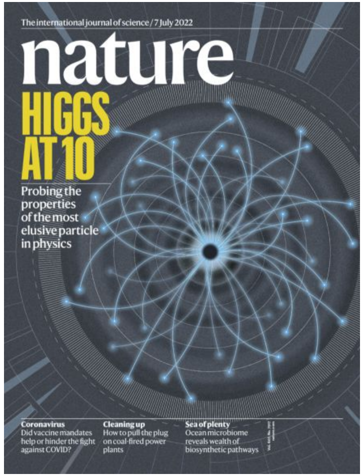
The publications in this talk

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 07 (2023) 088
- Searching for new physics that may arises with new top-Higgs sectors
  - Higgs($\rightarrow\gamma\gamma$) + X searches JHEP 07 (2023) 176

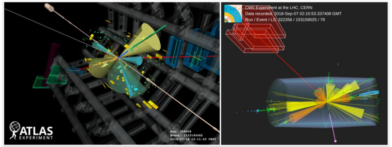
- top-Higgs coupling with off-shell Higgs boson
  - Observation of the four-top-quark production EPJC 83 (2023) 496



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).

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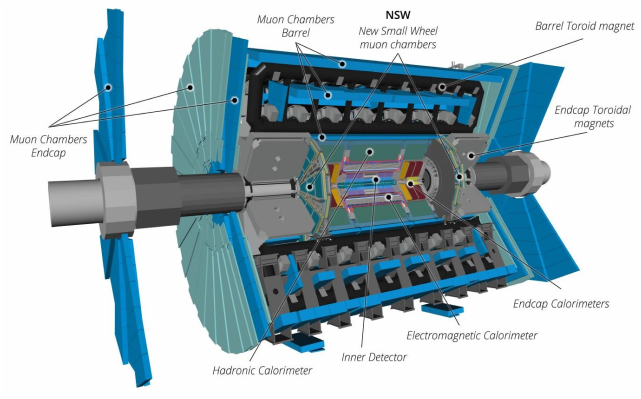
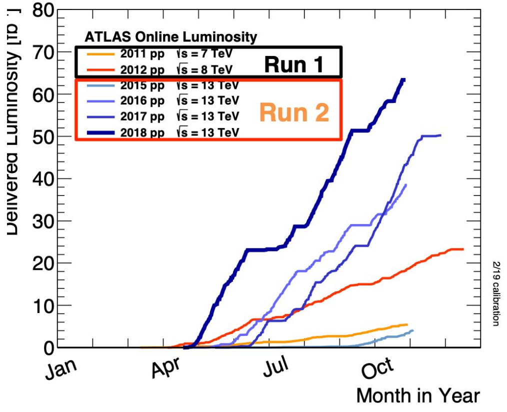
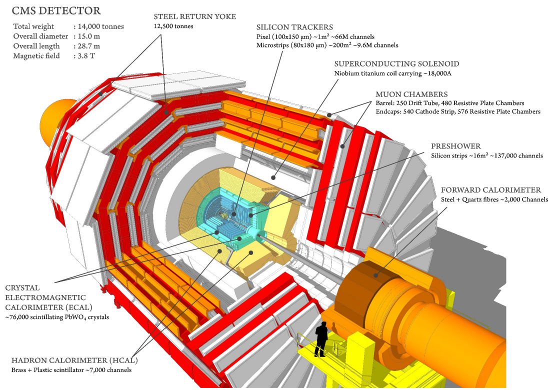
ATLAS/CMS Detectors and Run-2 data





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

IHEP ATLAS contribution: High-Granularity Timing Detector (HGTD), Inner Tracker (ITk) strip detector, leading various physics analyses



IHEP CMS contribution: High Granularity Calorimeter (HGCal), leading various physics analyses

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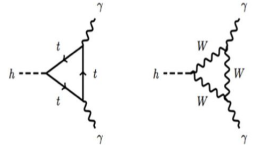
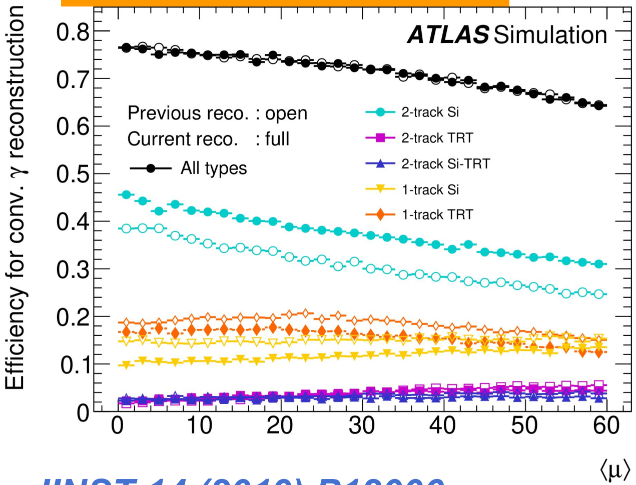
with on-shell Higgs boson

The γγ channel of Higgs decay

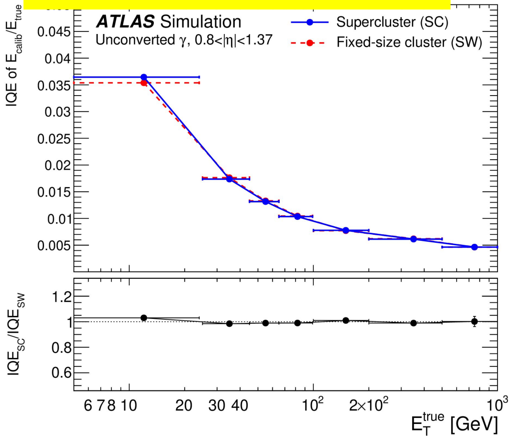
- Higgs decays to a pair of photons via loop decays. It's one of the "golden channel" for precise Higgs property measurements.
- With relatively low branching ratio of 0.227%, the γγ signature is very "clean"
  - The high reconstruction eff. and low energy resolution of photons allows the search/measurements directly on the mass of γγ.



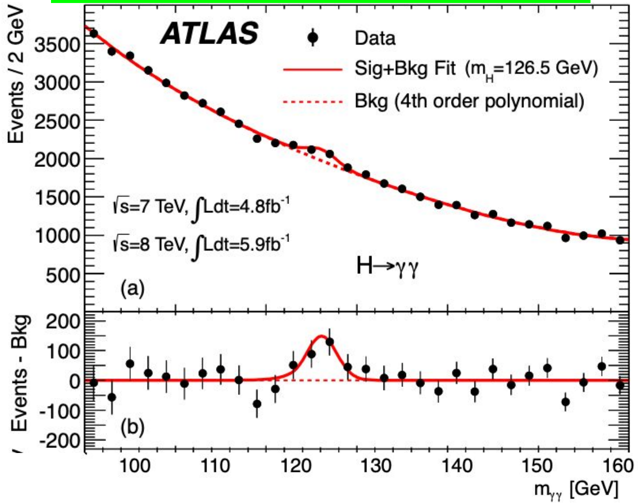
High reconstruciton eff.



Low energy resolution



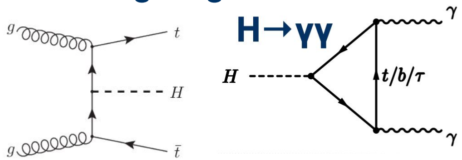
A "peak" on m(γγ) ~ signal mass resolution is ~1.8 GeV



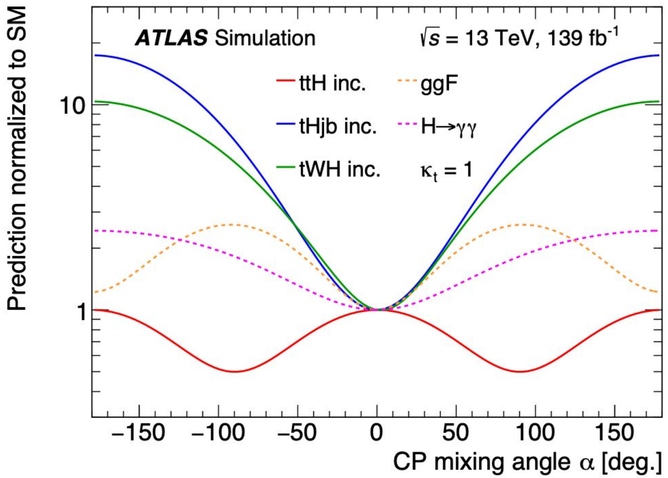
[JINST 14 (2019) P12006]

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

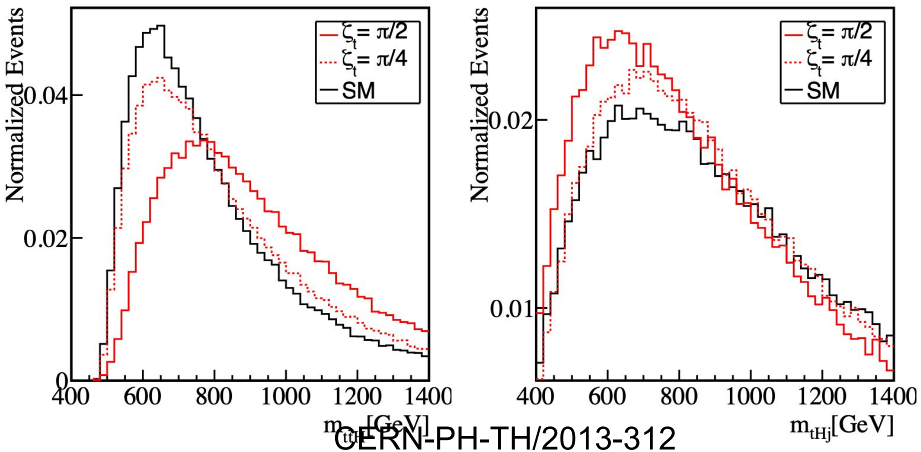
- CP properties has an impact on both ttH/tH cross-section, and ttH/tH kinematics, so we delivered the measurement on CP properties with $H \to \gamma\gamma$ PRL 125 (2020) 061802
  a. Select ttH/tH, $H \to \gamma\gamma$ events, extract the number of signal events
  b. Parameterise ttH/tH productions 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

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CP in top-Higgs coupling: categorization

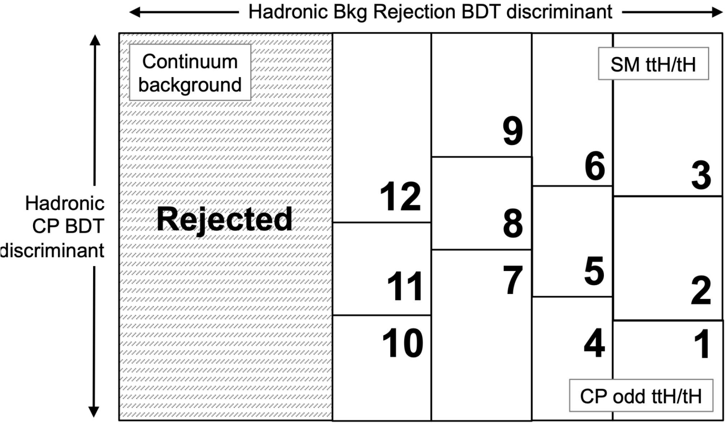
The ttH/tH, H → γγ events are selected with two event classifiers

ttH/tH CP odd vs CP even

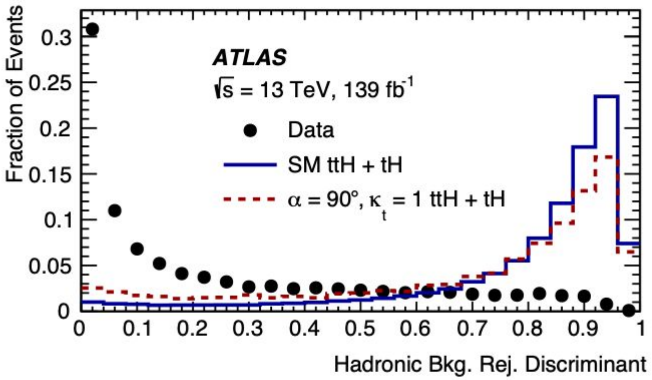
- A boosted decision tree (BDT)
- Using kinematics of γγ system and the top candidates
- For the top candidates, using a top-reconstruction method combining the 3 objects (tri-jets or j, e/μ, ν) from top decay

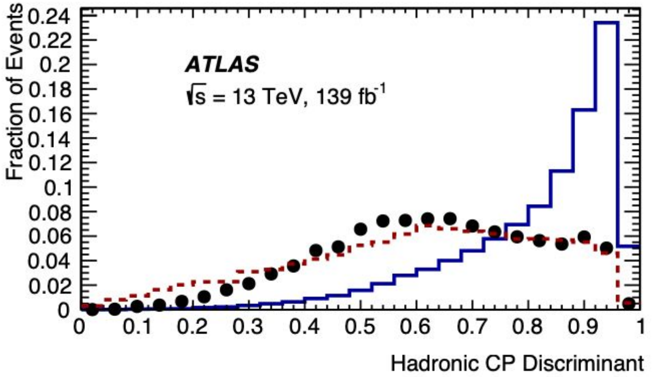
Signal vs background

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



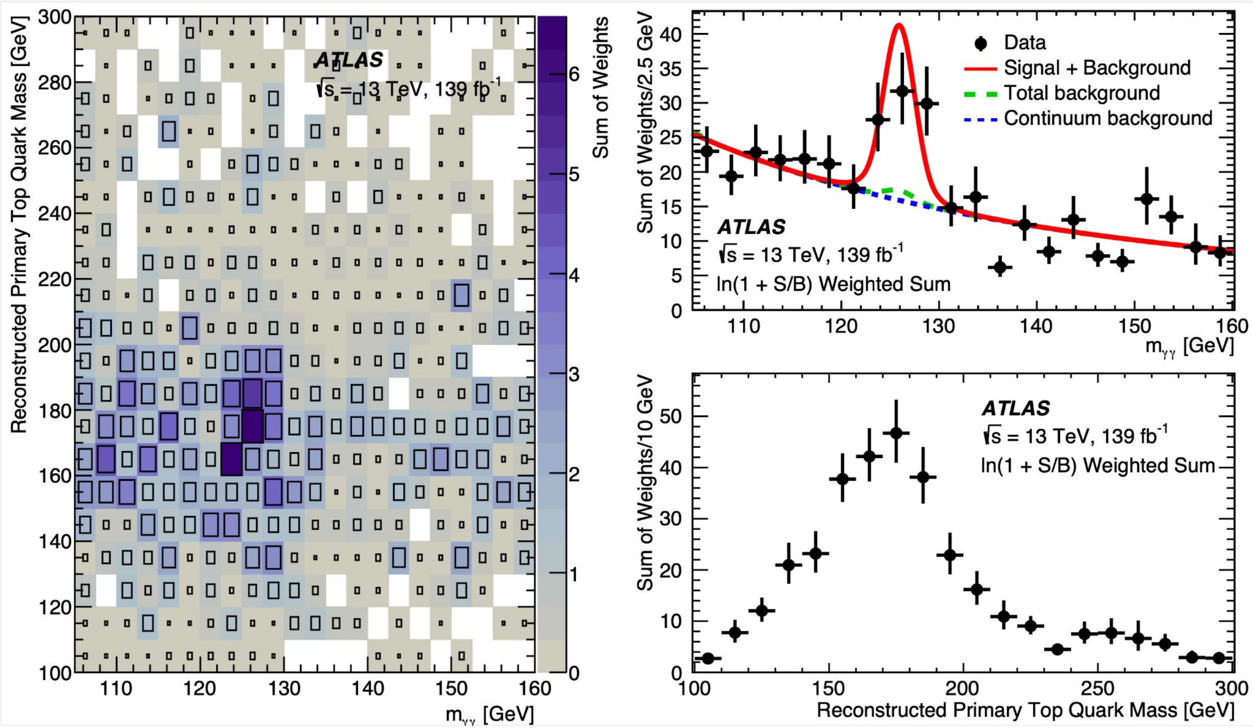
12 categories for top hadronic decays
+ 8 more categories for the top leptonic decays





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



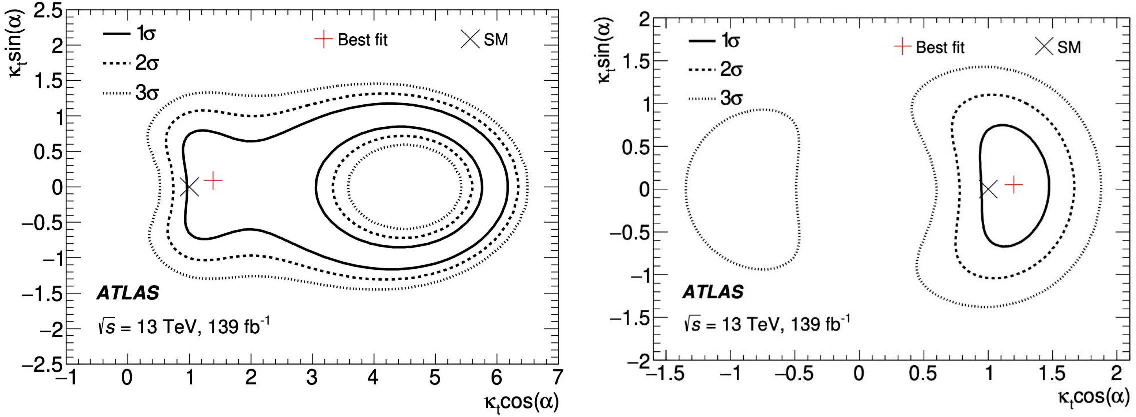
CP in top-Higgs coupling with H → γγ

- 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

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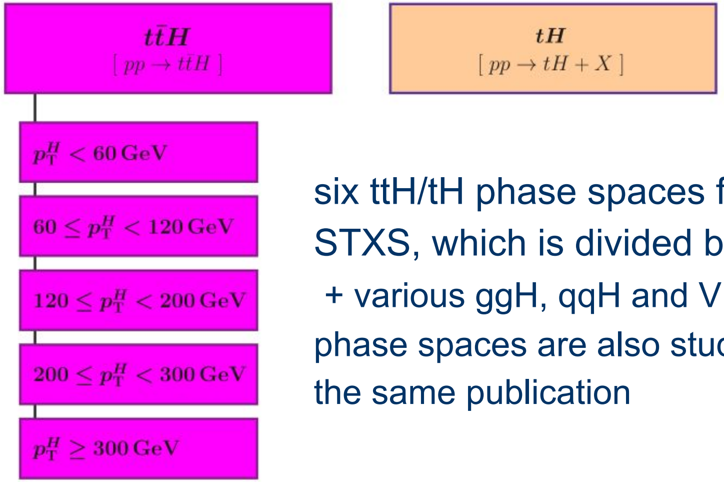
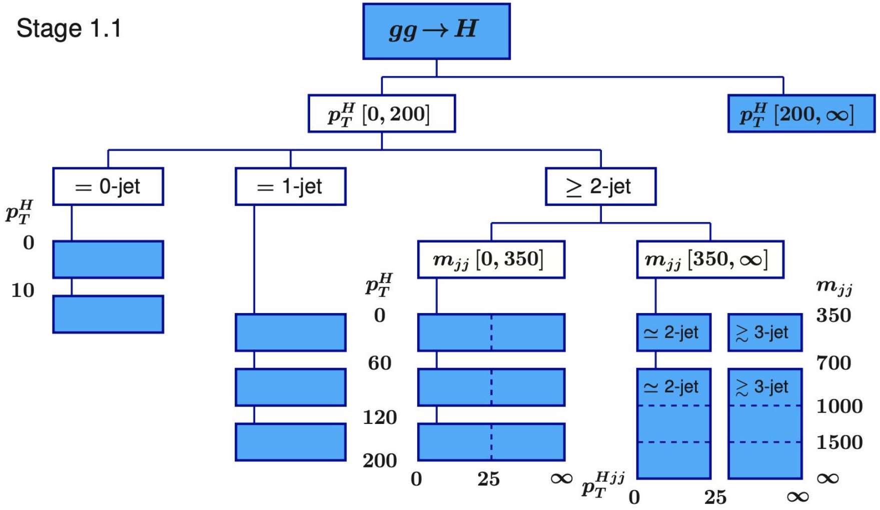
The STXS measurements with H → γγ

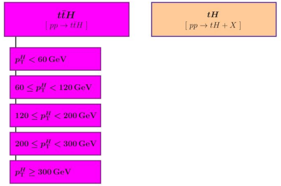
- Simplified Template Cross Sections (STXS) divides cross-section measurements in phase spaces (arxiv 1906.02754), which is sensitive to measure Higgs couplings
    - The ttH/tH cross-section in pTH bins with H → γγ JHEP 07 (2023) 088 further constrain the top-Higgs Yukawa coupling, and also probe the impacts from new physics like CP-odd 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

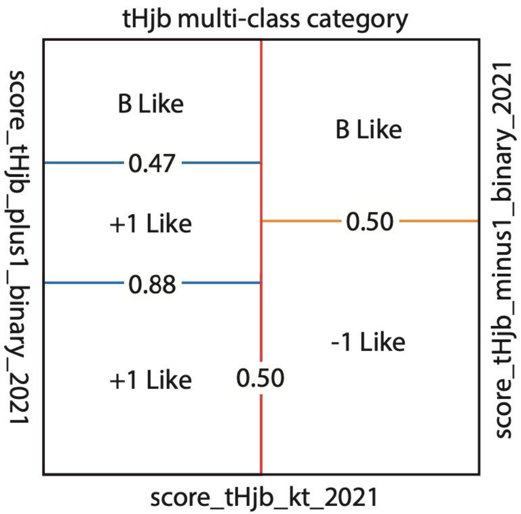


ttH/tH selection with STXS



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. After various STXS regions are split
   - In the ttH and tWH classes, train another ttH/tH vs background BDT
   - In the tHjb class, we optimized the 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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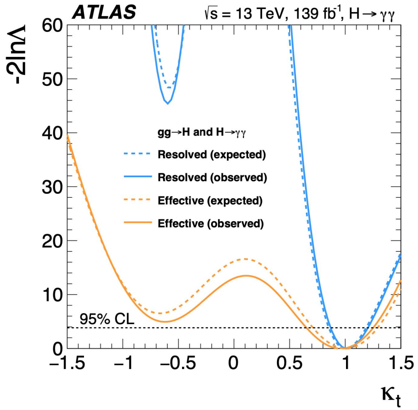
STXS measurement result

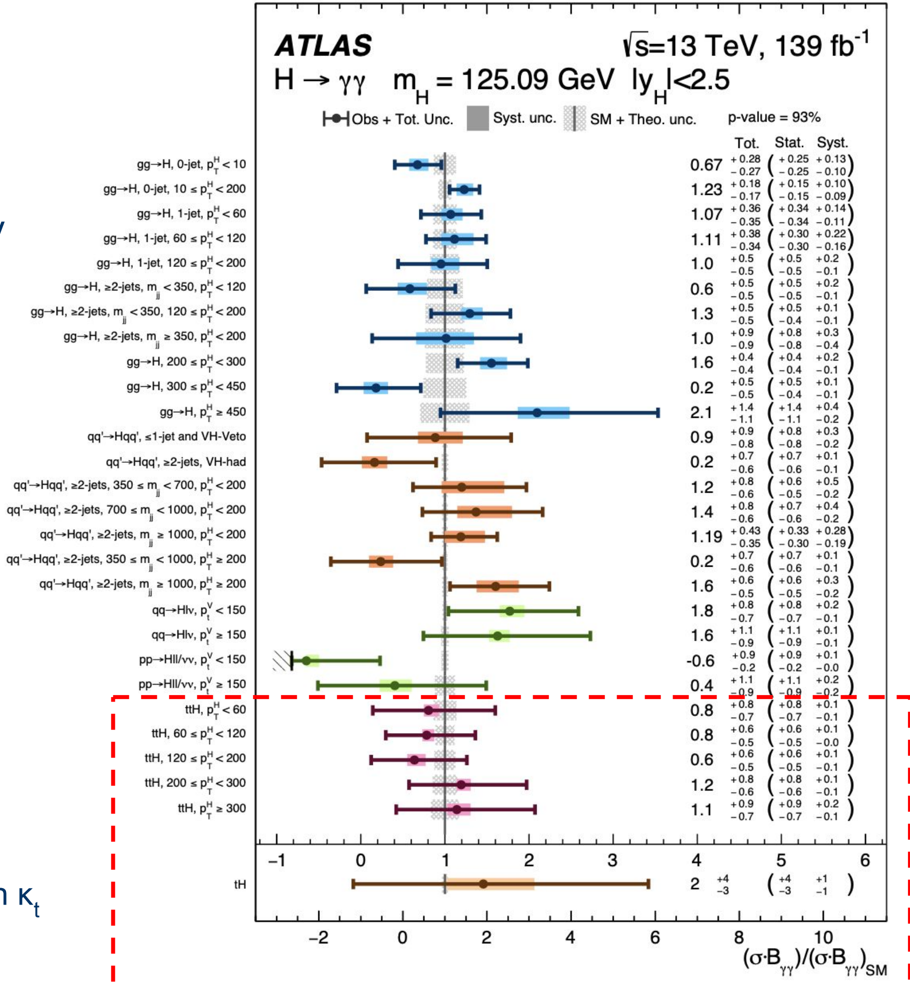
The analysis extracted signal events with S+B fits on m(γγ)

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

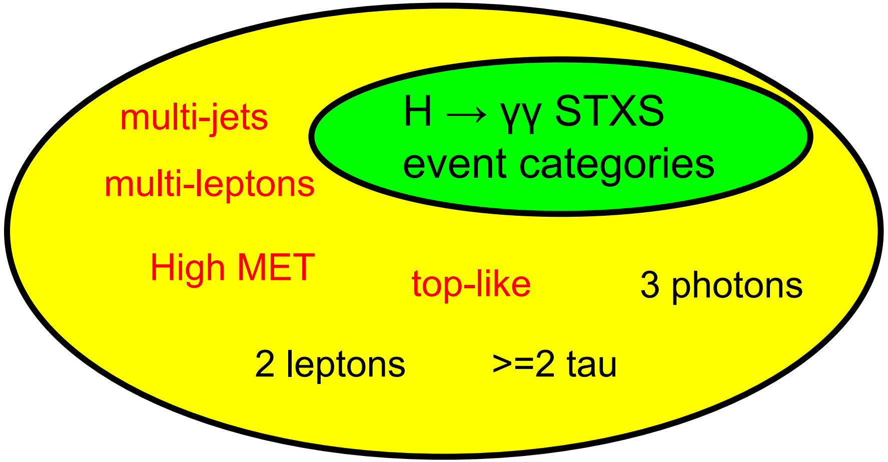


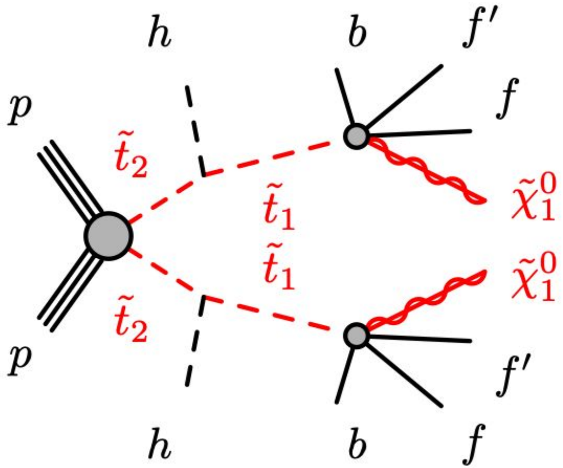
κ_t = 0.95+0.15-0.16
, when κ_g and κ_γ set to 1.0
κ_t = 1.01±0.09
, when ggF and H → γγ resolved with κ_t



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 07 (2023) 176) for H(→γγ)+X process is model-independent

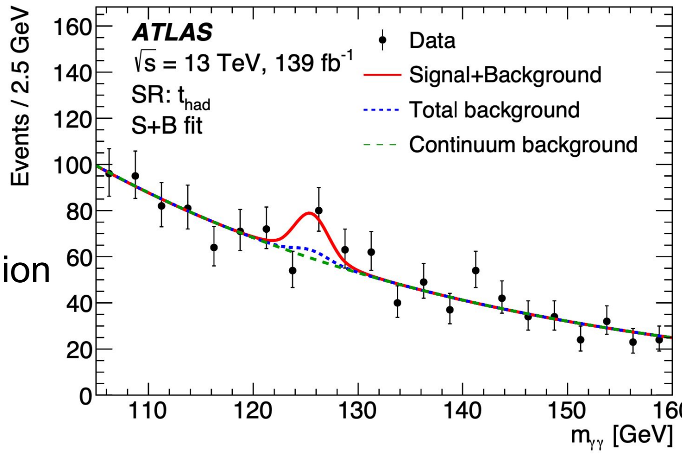


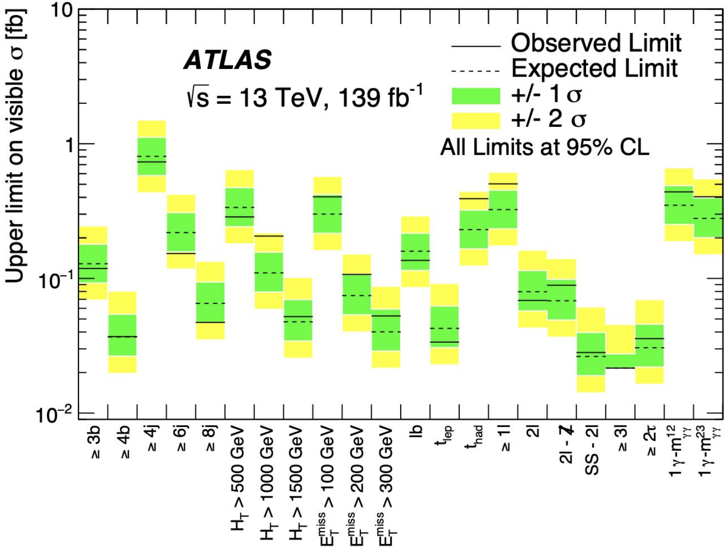


H+X search: results

- 22 cut-based categories are defined with different final states the searches are performed independently in all the signal regions, by S+B fits on the m(γγ)
- 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

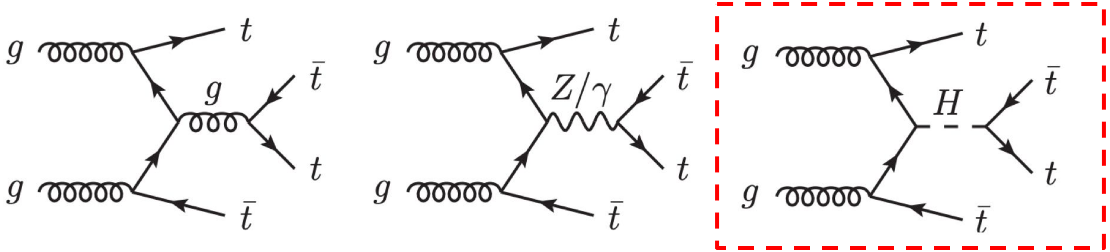
1.7σ significance in the handronic top decay region

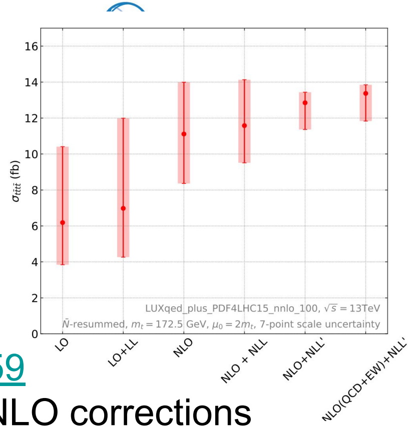




with off-shell Higgs boson
- the observation of tttt

The four-top-quarks production at LHC



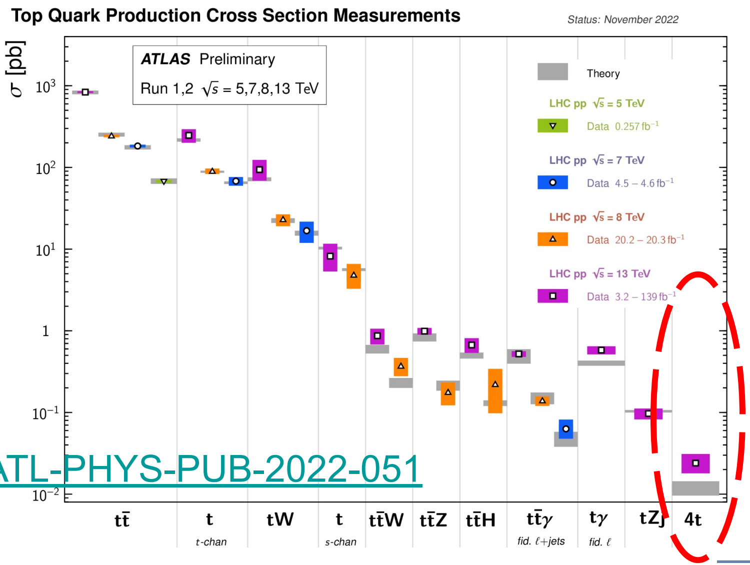


arXiv:2212.03259

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

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Top-Higgs Yukawa couplings with four-tops

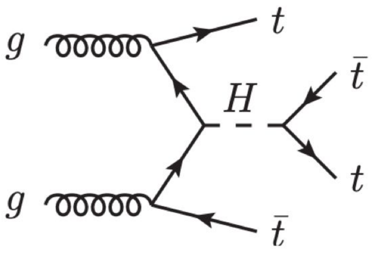
ATLAS EXPERIMENT

- 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.

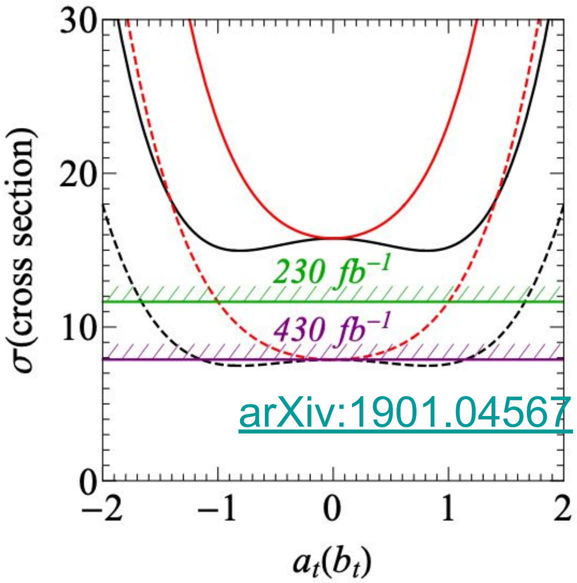
$$\mathcal{L} = -\frac{1}{\sqrt{2}} y_t \bar{t} (a_t + i b_t \gamma_5) t h,$$

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

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



$$\sigma(t\bar{t}t\bar{t})_{13\ \text{TeV}} = 9.998 - 1.522 a_t^2 + 2.883 b_t^2 + 1.173 a_t^4 + 2.713 a_t^2 b_t^2 + 1.827 b_t^4,$$



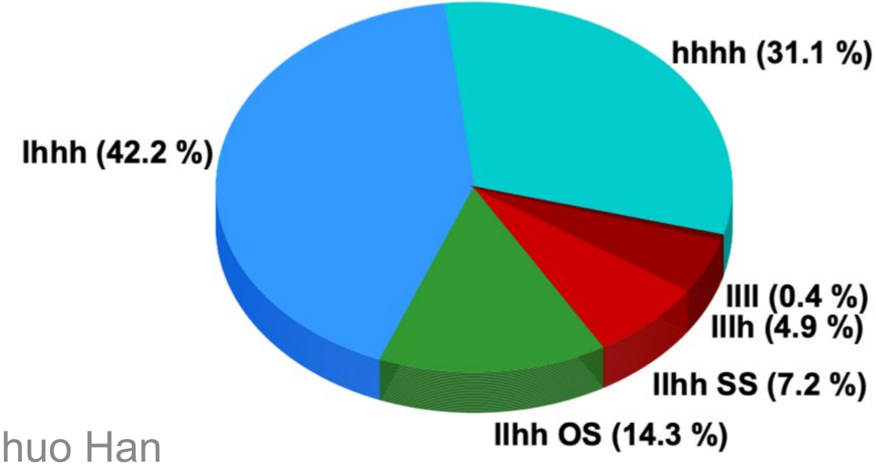
The four-top decays

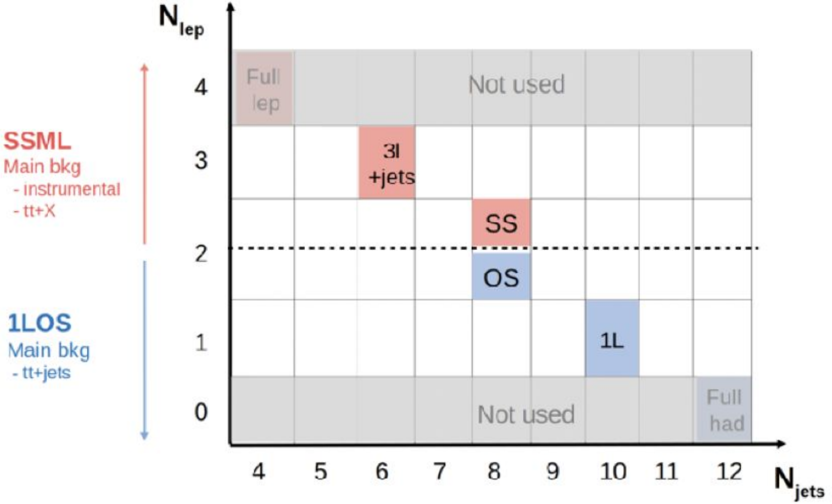
Each top quark decays to b quark + W boson

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.

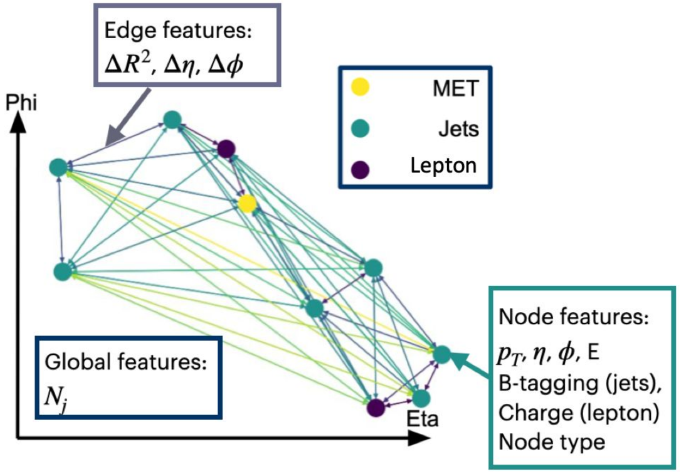
The complicated final state is a challenge

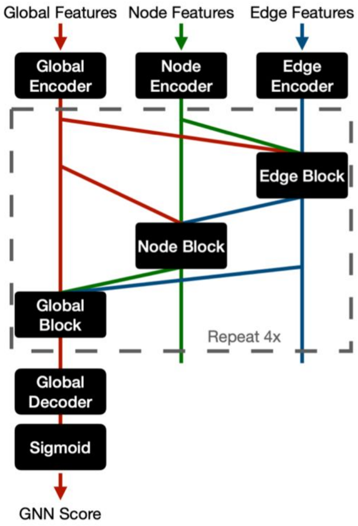


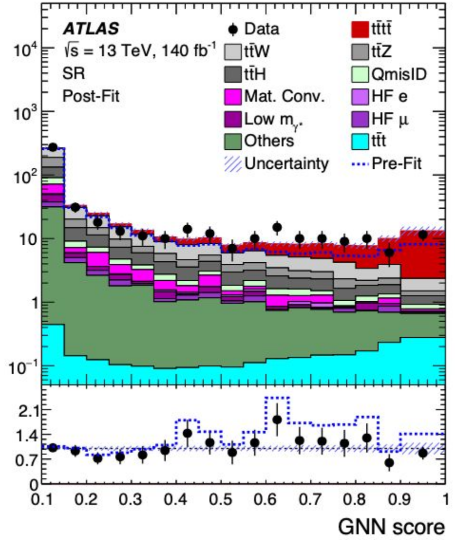


GNN multivariate analysis

- After the selections of 2LSS or 3L, Njet>=6, Nbjet>=2, HT>500 GeV, the S/B is around 10%
  - The main challenge of the four-top signal extraction is the complicated final state
- The **Graph 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 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.







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

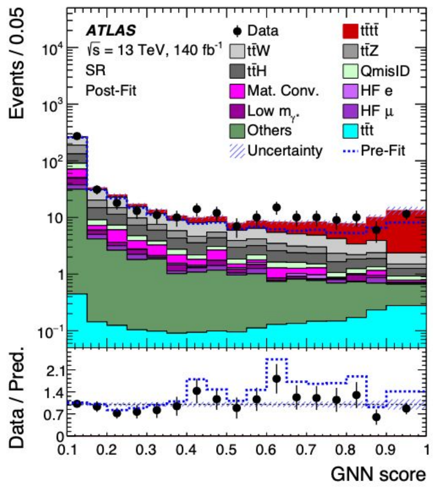
Instrumental and fake backgrounds (~25%)

- 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

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

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

8 control regions + 1 signal region, 8 background parameters



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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 σ_{tttt} /σ^{SM}= 1.9
- Background only hypothesis is rejected with

  6.1σ (4.3σ)

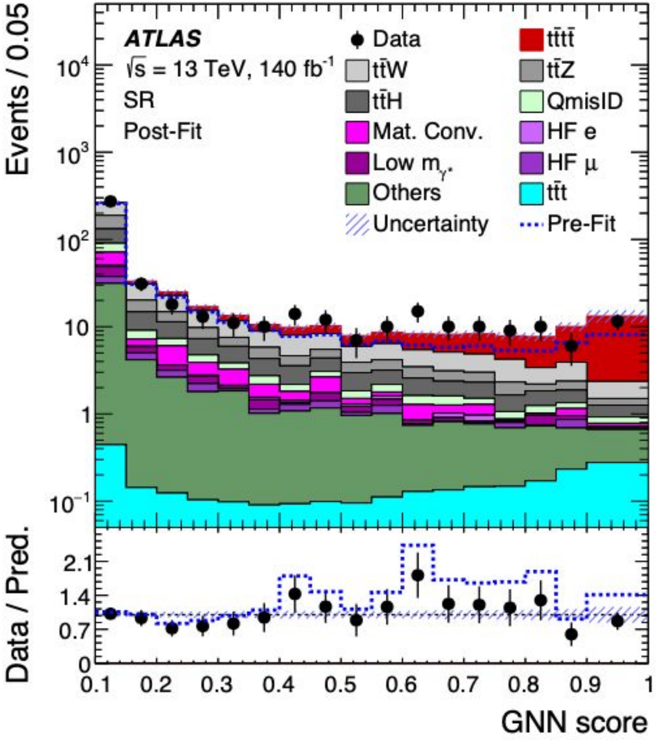
  observed (expected) EPJC 83 (2023) 496

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

CERN-EP-2023-090 (PLB)

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

in agreement with SM



Top-Higgs coupling and CP

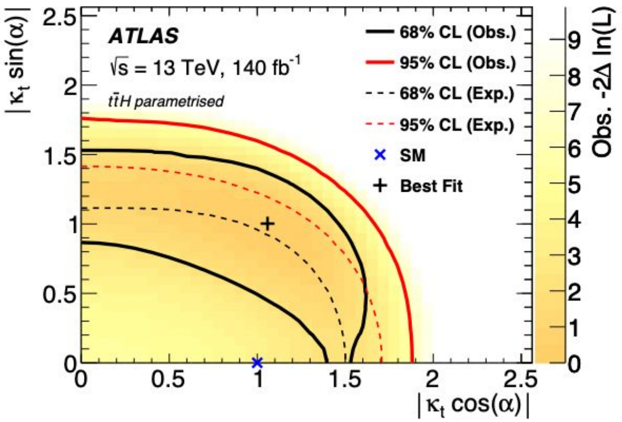
Two scenarios (k_t, α) measurements

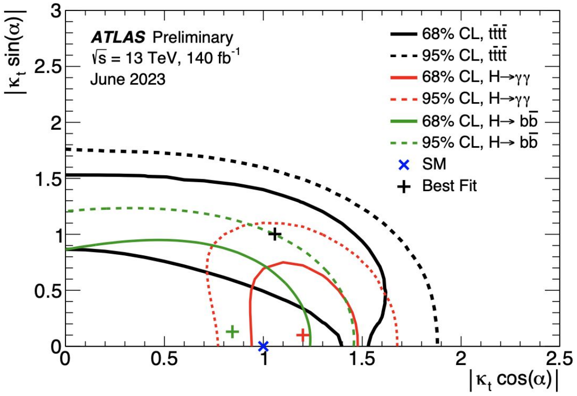
- 1) both four-top and ttH parameterized as a function of (k_t, α)
- 2) only four-top parameterized, ttH normalization is profiled as background parameter

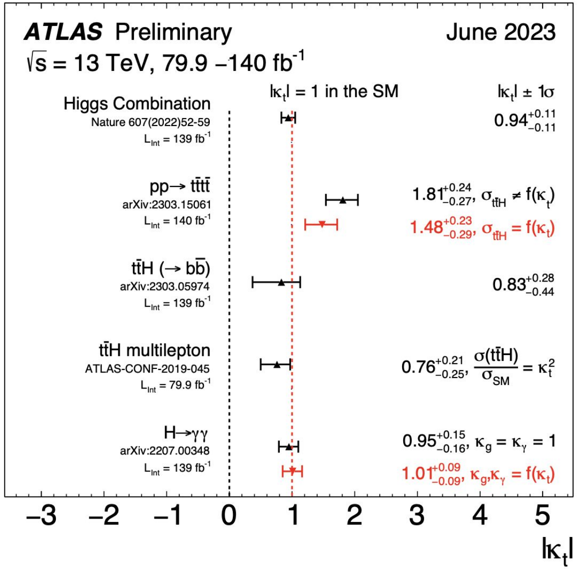
95% CL limits on $|k_t|$ (assuming CP-even, α = 0)

- 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.



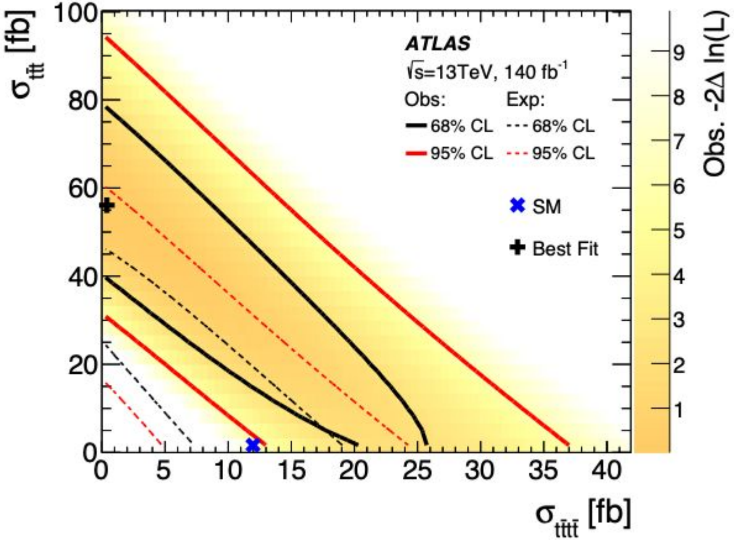


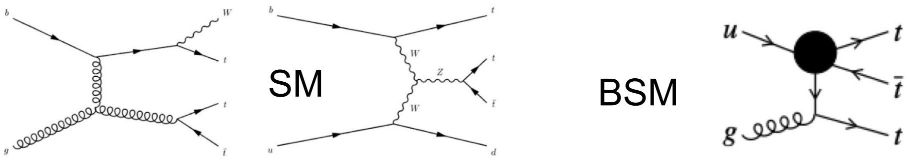


Tri-top and Four-top measurements

- 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
- In the four-top observation, there is 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

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]





EPJC 83 (2023) 496

Total width measurement with top-Higgs coupling

ATLAS EXPERIMENT

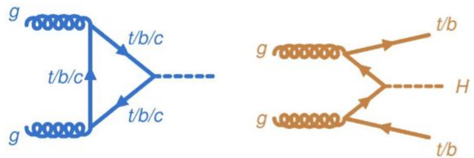
- The differential cross section of any decay particle is given by a Breit-Wigner

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

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

On-shell: ggH and ttH productions

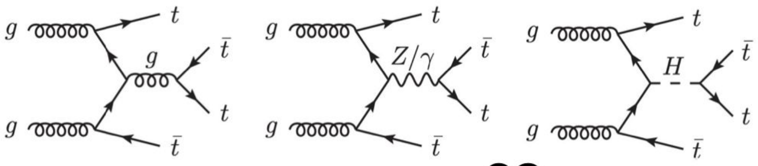
and H → γγ decay



$$\mu_{ttH \to \gamma\gamma} = \frac{\kappa_t^2 \kappa_\gamma^2(\kappa_t, \kappa_V, \ldots)}{R_\Gamma}$$

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

Off-shell*: simultaneous production of four top quarks



Rate of Higgs-mediated process $\propto \kappa_t^4$

Rate of interference between H and others $\propto \kappa_t^2$

The combination of on- and off-shell Higgs measurements with top-Higgs coupling provides a new way to measure the total width (Gamma) of Higgs boson

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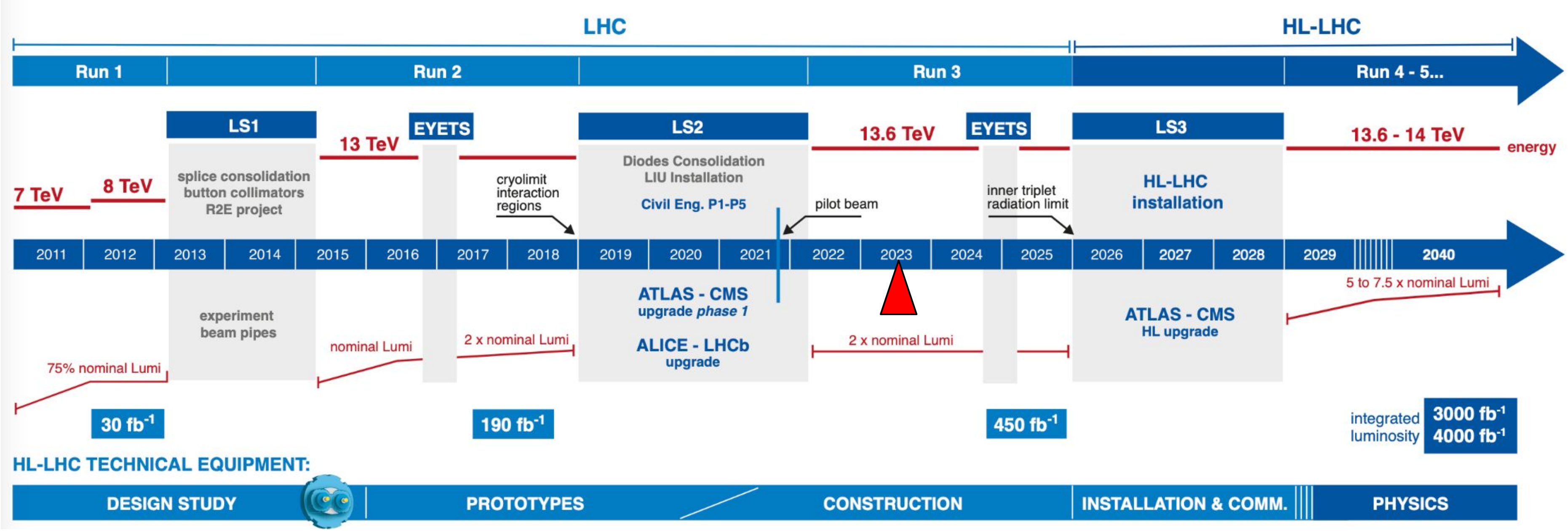
Outlook

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



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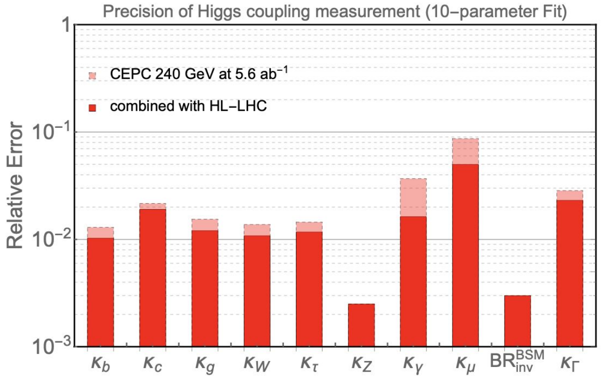
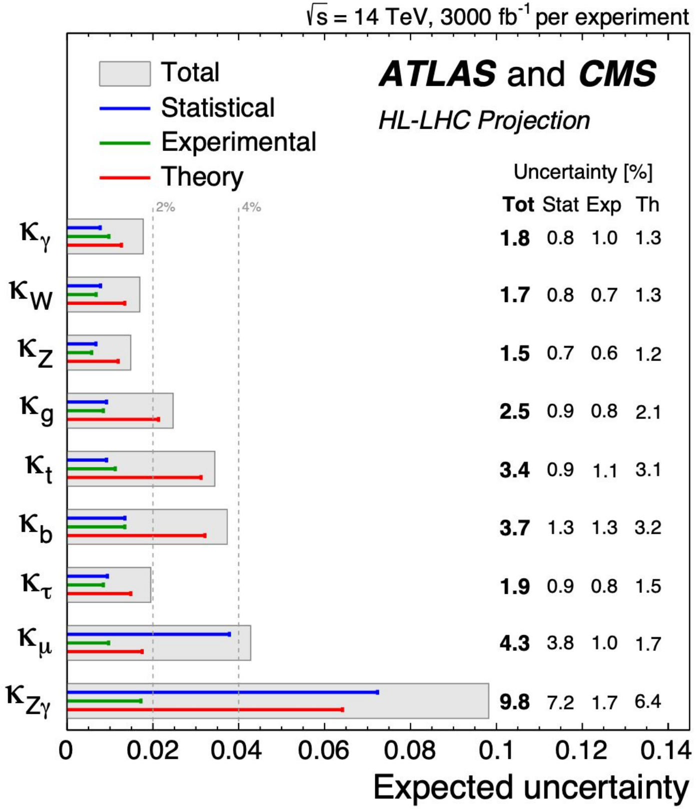
The Higgs couplings at HL-LHC

- HL-LHC is expected to measure k_t within 3.4% total uncertainty (now 10%)
  - This will be the most accurate result for very long time (even with CEPC/FCC-ee approved)
- However, the top-Higgs coupling measurement will be dominated by systematic uncertainties, there are more challenges in the HL-LHC studies (next page)

CERN-LPCC-2018-04



CEPC-CDR: k_t cannot be directly measured with e+e- collision at 250 GeV, but if ECM > 500 GeV or in SPPC, the significance can be largely improved



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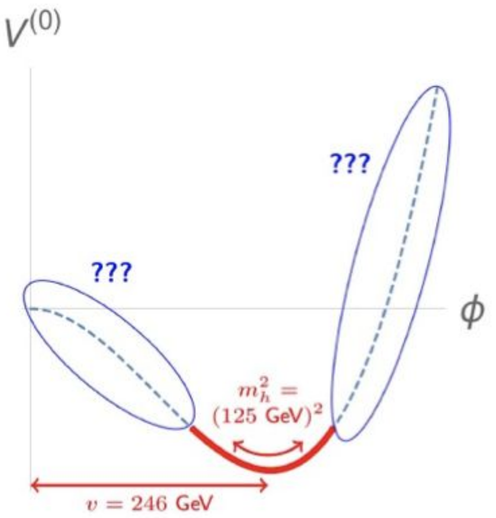
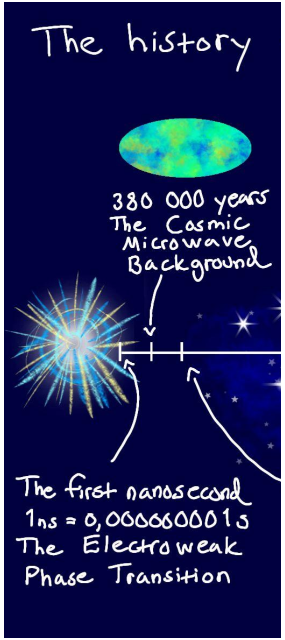
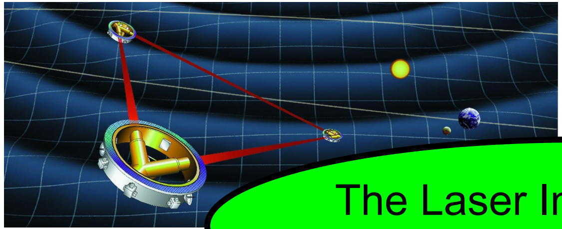
Higgs self-coupling with top-Higgs interaction

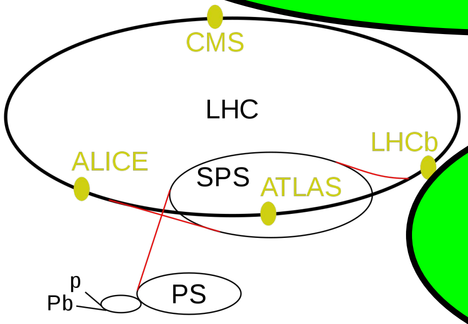
- The Higgs self-coupling is one of the most important yet-to-be-determined SM properties. It decides the Higgs potential distribution, which connects to the evolution of the early universe, though the Electroweak Phase Transition (EWPT)
  - There can be direct measurements of EWPT with gravitational waves (e.g. LISA experiment)
  - While at LHC, we can measure Higgs self-coupling by the production of Di-Higgs process







The Laser Interferometer Space Antenna (LISA)



Di-Higgs measurements

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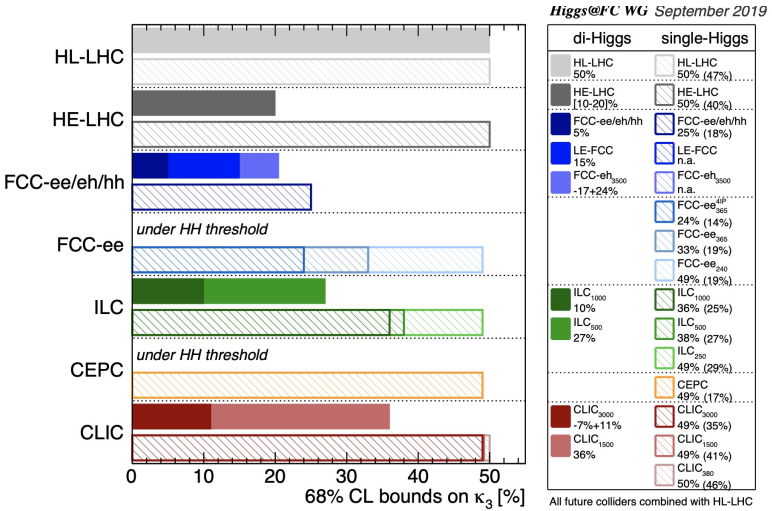
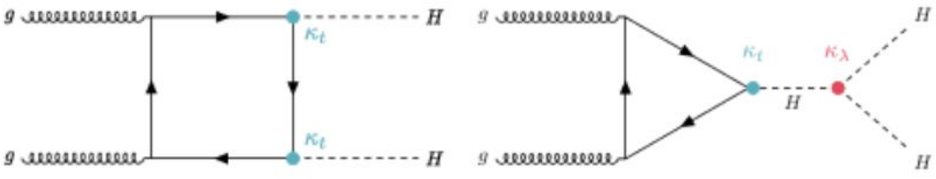
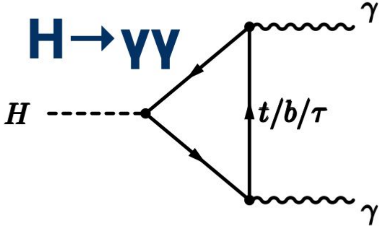
Higgs self-coupling with top-Higgs interaction

- The top-Higgs interaction is also very important for the Di-Higgs measurements
  - At LHC and future pp colliders, the leading production mode of Di-Higgs is via gluons fusion, which is dominated by the top loops
  - The H(→γγ) + H channel will remain to be one of the leading decay channels of Di-Higgs measurements, where the H→γγ decays is also dominated by the top loops
- We expect ~50% uncertainty at HL-LHC, and ~5% for FCC-hh/SPPC
  - In the HL-LHC time scale, the ATLAS + CMS combination is important for the self-coupling



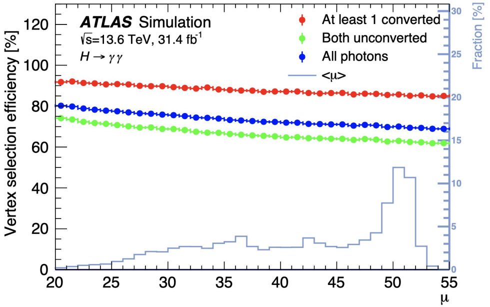


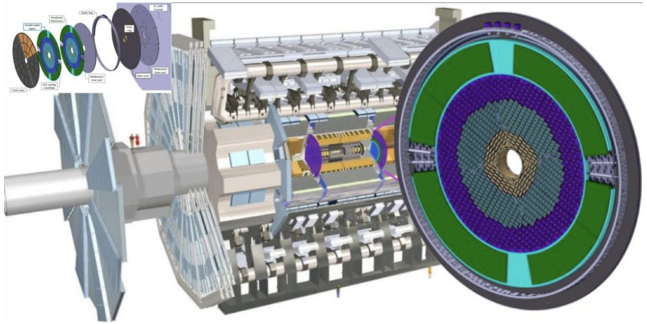


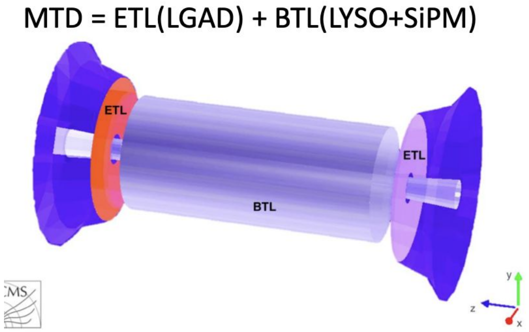
New solutions for HL-LHC and future

There will be many challenges in the HL-LHC and future analyses, but there are also new solutions

- The upgrade of the ATLAS and CMS detector (e.g. HGTD for ATLAS, MTD for CMS)
  - It can solve the problems caused by the high pile-up (interaction per bunch crossing) at HL-LHC







- More accurate theoretical calculations
  - It can solve the problems caused by mis-modeling, theo. uncertainties and cross-section calculations

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New solutions for HL-LHC and future

- Novel implementations of machine learning (many recent publications in ATLAS/CMS communities)
  - Graph Neural Network:
    - The GNN at event level (e.g. 4top analysis)
    - GNN tracking : EPJC 81, 876 (2021)
    - GNN flavor tagging : ATL-PHYS-PUB-2022-027, ATL-PHYS-PUB-2022-047
  - Attention mechanism:
    - SPANet for ttbar and other object combinatorics: SciPost Phys. 12, 178 (2022), PRD 105, 112008 (2022), arxiv:2309.01886
    - CPT for the top regression and parton labeling: PRD 107 (2023) 114029, arxiv:2304.09208
    - Passwd-ABC for the BSM heavy resonance: arXiv:2309.05728
  - Generative models:
    - Normaling Flow for background templates generation: arxiv:2303.10148
    - Normaling Flow for neutrino regression: arxiv:2207.00664

These are only part of the recent progresses in ATLAS community, people are still building the ML community for the HEP experiments

Recap

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

- With on-shell Higgs
  - CP and top-Higgs couplings with $H \to \gamma\gamma$ PRL 125 (2020) 061802
  - STXS measurements with top-Higgs couplings JHEP 07 (2023) 088
- BSM searches: $H(\to \gamma\gamma)$ + X searches for new t-H sectors JHEP 07 (2023) 176
- With off-shell Higgs: Four tops observation EPJC 83 (2023) 496

More challenges and opportunities with HL-LHC and future colliders

- top-Higgs coupling at ~3% uncertainty level at HL-LHC
- Higgs self-coupling at ~50% uncertainty level with ATLAS + CMS, and ~5% for future colliders
- The detector upgrades
- New analysis techniques (many novel ML applications)

Thanks IHEP for hosting the seminar!

backup

-

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

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

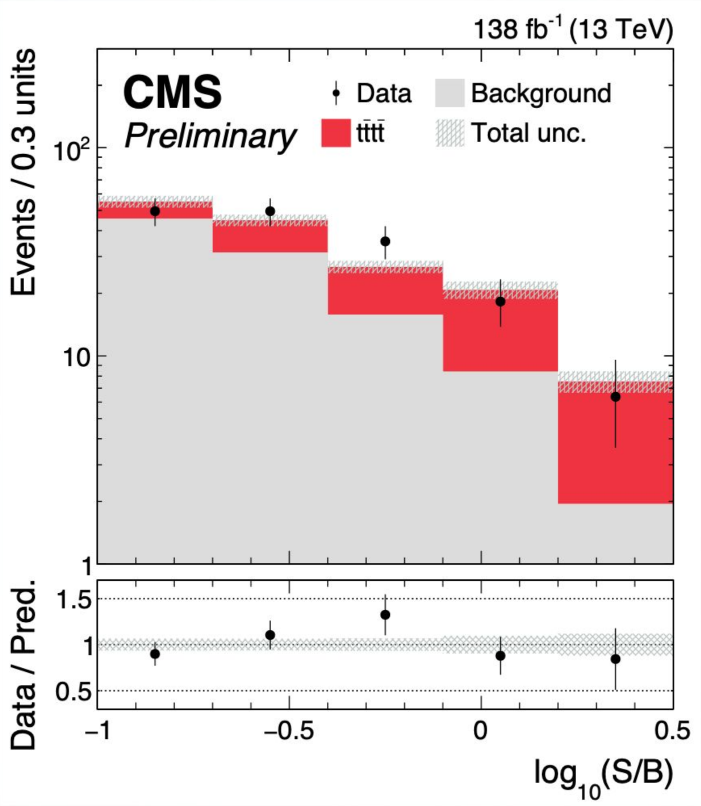
- $S_{t\bar{t}t\bar{t}} = 5.5\ (4.9)\,\sigma$

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

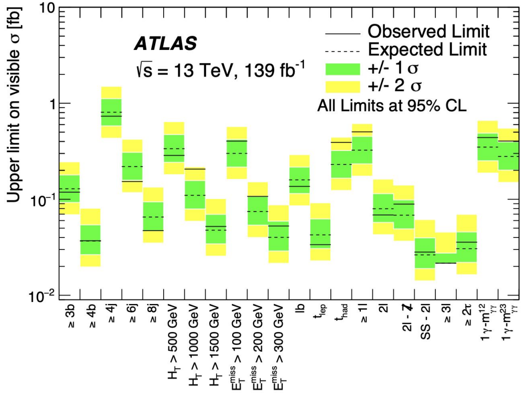


(CMS-PAS-TOP-22-013)

H+X search: results

- The detector efficiencies of each BSM models are reported to utilize the visible limits

SR	Relevant processes	Range of ϵ
	Heavy flavour	
$\geq 3b$	$\tilde{b}\tilde{b}, \tilde{b} \to \tilde{\chi}_2^0 b, \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 H, \tilde{t}_2\tilde{t}_2, \tilde{t}_2 \to \tilde{t}_1 H, \tilde{t}_1 \to \tilde{\chi}_1^0 bq\bar{q}/b\ell\nu$	0.68–0.81
$\geq 4b$	$\tilde{b}\tilde{b}, \tilde{b} \to \tilde{\chi}_2^0 b, \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 H, \tilde{t}_2\tilde{t}_2, \tilde{t}_2 \to \tilde{t}_1 H, \tilde{t}_1 \to \tilde{\chi}_1^0 bq\bar{q}/b\ell\nu$	0.64–0.97
	High jet activity	
$\geq$4j	$t\bar{t}H, \tilde{b}\tilde{b}, \tilde{b} \to \tilde{\chi}_2^0 b, \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 H, \tilde{t}_2\tilde{t}_2, \tilde{t}_2 \to \tilde{t}_1 H, \tilde{t}_1 \to \tilde{\chi}_1^0 bq\bar{q}/b\ell\nu, tWH$	0.60–0.70
$\geq$6j	$t\bar{t}H, \tilde{b}\tilde{b}, \tilde{b} \to \tilde{\chi}_2^0 b, \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 H, \tilde{t}_2\tilde{t}_2, \tilde{t}_2 \to \tilde{t}_1 H, \tilde{t}_1 \to \tilde{\chi}_1^0 bq\bar{q}/b\ell\nu, tWH$	0.64–0.80
$\geq$8j	$t\bar{t}H, \tilde{b}\tilde{b}, \tilde{b} \to \tilde{\chi}_2^0 b, \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 H, \tilde{t}_2\tilde{t}_2, \tilde{t}_2 \to \tilde{t}_1 H, \tilde{t}_1 \to \tilde{\chi}_1^0 bq\bar{q}/b\ell\nu$	0.65–0.90
$H_T > 500$ GeV	$t\bar{t}H, \tilde{b}\tilde{b}, \tilde{b} \to \tilde{\chi}_2^0 b, \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 H, \tilde{t}_2\tilde{t}_2, \tilde{t}_2 \to \tilde{t}_1 H, \tilde{t}_1 \to \tilde{\chi}_1^0 bq\bar{q}/b\ell\nu, tWH$	0.52–0.66
$H_T > 1000$ GeV	$t\bar{t}H, \tilde{b}\tilde{b}, \tilde{b} \to \tilde{\chi}_2^0 b, \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 H, \tilde{t}_2\tilde{t}_2, \tilde{t}_2 \to \tilde{t}_1 H, \tilde{t}_1 \to \tilde{\chi}_1^0 bq\bar{q}/b\ell\nu, tWH$	0.51–0.72
$H_T > 1500$ GeV	$t\bar{t}H, \tilde{b}\tilde{b}, \tilde{b} \to \tilde{\chi}_2^0 b, \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 H, \tilde{t}_2\tilde{t}_2, \tilde{t}_2 \to \tilde{t}_1 H, \tilde{t}_1 \to \tilde{\chi}_1^0 bq\bar{q}/b\ell\nu$	0.41–0.73
	E_T^{miss}	
$E_T^{miss} > 100$ GeV	$t\bar{t}H, tWH, WH, ZH, \tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to W/Z/H$	0.60–0.78
$E_T^{miss} > 200$ GeV	$t\bar{t}H, tWH, WH, ZH, \tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to W/Z/H$	0.60–0.79
$E_T^{miss} > 300$ GeV	$t\bar{t}H, tWH, WH, ZH, \tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to W/Z/H$	0.66–0.84
	Lepton	
$\geq 1\ell$	$WH, t\bar{t}H, tWH$, FCNC, $\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to W/Z/H$	0.40–0.48
2ℓ	$ZH, t\bar{t}H, \tilde{t}_2\tilde{t}_2, \tilde{t}_2 \to \tilde{t}_1 H, \tilde{t}_1 \to \tilde{\chi}_1^0 bq\bar{q}/b\ell\nu, \tilde{\chi}_1^\pm\tilde{\chi}_1^\mp \to H\ell^\pm H\ell^\mp, \tilde{\chi}_1^\pm\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \to H\ell^\pm, \tilde{\chi}_1^0 \to W\ell/Z\nu/H\nu$	0.21–0.48
2ℓ–$\not{Z}$	$t\bar{t}H, \tilde{t}_2\tilde{t}_2, \tilde{t}_2 \to \tilde{t}_1 H, \tilde{t}_1 \to \tilde{\chi}_1^0 bq\bar{q}/b\ell\nu, \tilde{\chi}_1^\pm\tilde{\chi}_1^\mp \to H\ell^\pm H\ell^\mp, \tilde{\chi}_1^\pm\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \to H\ell^\pm, \tilde{\chi}_1^0 \to W\ell/Z\nu/H\nu$	0.20–0.46
$\geq 3\ell$	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \to \tilde{t}_1 H, \tilde{t}_1 \to \tilde{\chi}_1^0 bq\bar{q}/b\ell\nu, \tilde{\chi}_1^\pm\tilde{\chi}_1^\mp \to H\ell^\pm H\ell^\mp, \tilde{\chi}_1^\pm\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \to H\ell^\pm, \tilde{\chi}_1^0 \to W\ell/Z\nu/H\nu$	0.18–0.33
SS-2ℓ	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \to \tilde{t}_1 H, \tilde{t}_1 \to \tilde{\chi}_1^0 bq\bar{q}/b\ell\nu, \tilde{\chi}_1^\pm\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \to H\ell^\pm, \tilde{\chi}_1^0 \to W\ell/Z\nu/H\nu$	0.29–0.49
$\geq 2\tau$	$ZH, \tilde{t}_2\tilde{t}_2, \tilde{t}_2 \to \tilde{t}_1 H, \tilde{t}_1 \to \tilde{\chi}_1^0 bq\bar{q}/b\ell\nu, \tilde{b}\tilde{b}, \tilde{b} \to \tilde{\chi}_2^0 b, \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 H, \tilde{\chi}_1^\pm\tilde{\chi}_1^\mp \to H\ell^\pm H\ell^\mp, \tilde{\chi}_1^\pm\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \to H\ell^\pm, \tilde{\chi}_1^0 \to W\ell/Z\nu/H\nu$	0.04–0.09
	Top quark	
t_{lep}	FCNC with semileptonically decaying top	0.32–0.36
t_{had}	FCNC with hadronically decaying top	0.29–0.30
ℓb	$t\bar{t}H, tHjb, tWH$, FCNC with semileptonically decaying top	0.41–0.52
	Photon	
1γ–$m_{\gamma\gamma}^{12}$	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \to \tilde{t}_1 H, \tilde{t}_1 \to \tilde{\chi}_1^0 bq\bar{q}/b\ell\nu, \tilde{b}\tilde{b}, \tilde{b} \to \tilde{\chi}_2^0 b, \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 H$	0.23–0.33
1γ–$m_{\gamma\gamma}^{23}$	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \to \tilde{t}_1 H, \tilde{t}_1 \to \tilde{\chi}_1^0 bq\bar{q}/b\ell\nu$	0.35–0.40



Systematic uncertainties

Experimental uncertainty(159 NPs):

- Luminosity, lepton, Jets, b-tagging, missing ET, others

Signal modeling uncertainties (4 NP)

- QCD scale, parton shower, generator (Sherpa vs Madgraph), PDF

Background modeling uncertainties:

- Irreducible background (35 NPs): tt + W/Z/H, tri-top, others
- Reducible background (8 NPs): ttbar shape systematics, charge misID systematics

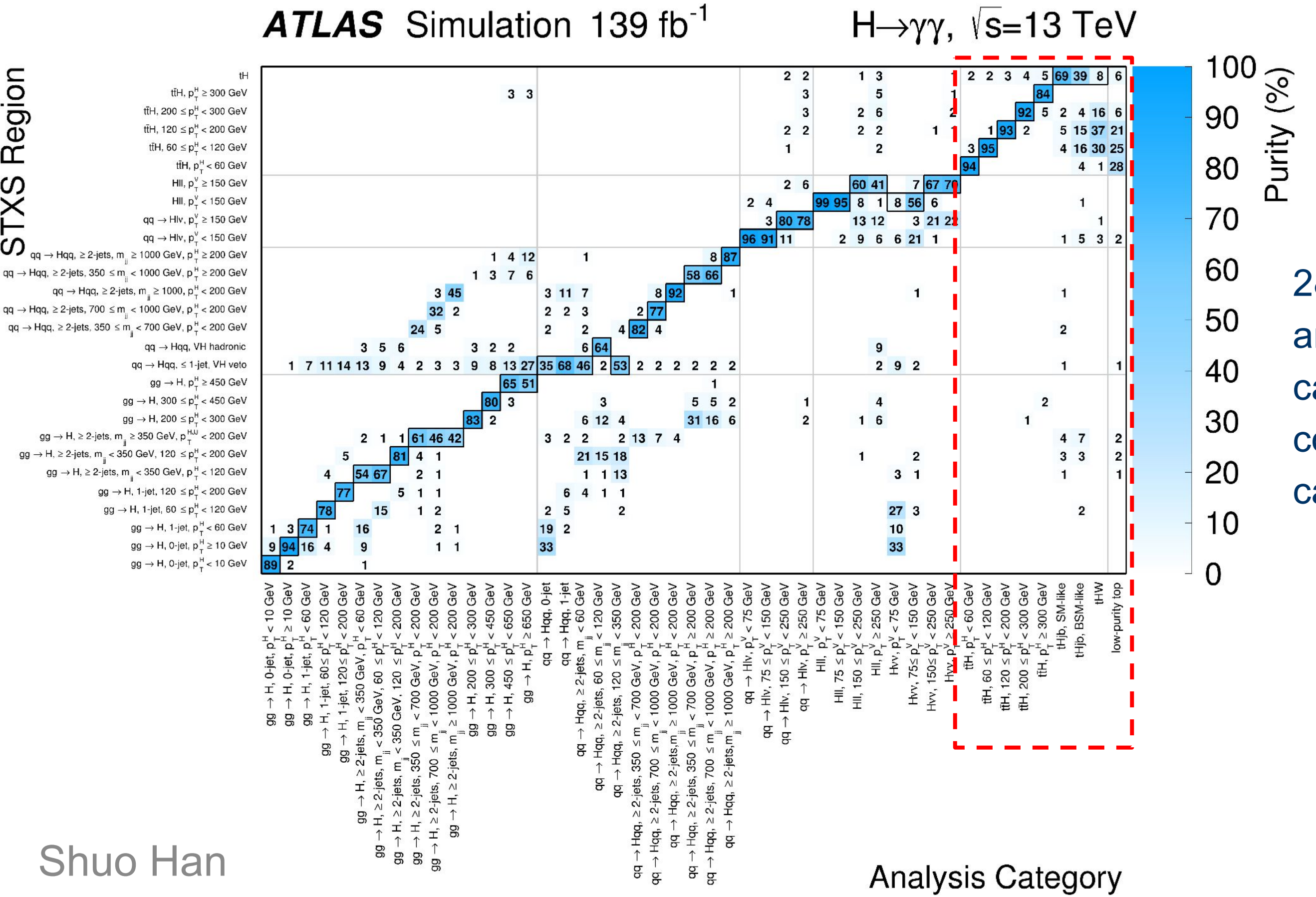
Statistical uncertainties

- Intrinsic stat. uncertainties
- ttW modeling

(**Green:** larger impact than 5%, **Red:** larger than 10%)

Uncertainty source	$\Delta\sigma$ [fb]		$\Delta\sigma/\sigma$[%]	
Signal modelling				
$t\bar{t}t\bar{t}$ generator choice	+3.7	−2.7	+17	−12
$t\bar{t}t\bar{t}$ parton shower model	+1.6	−1.0	+7	−4
Other $t\bar{t}t\bar{t}$ modelling	+0.8	−0.5	+4	−2
Background modelling				
$t\bar{t}H$+jets modelling	+0.9	−0.7	+4	−3
$t\bar{t}W$+jets modelling	+0.8	−0.8	+4	−3
$t\bar{t}Z$+jets modelling	+0.5	−0.4	+2	−2
Other background modelling	+0.5	−0.4	+2	−2
Non-prompt leptons modelling	+0.4	−0.3	+2	−2
$t\bar{t}t$ modelling	+0.3	−0.2	+1	−1
Charge misassignment	+0.1	−0.1	+0	−0
Instrumental				
Jet flavour tagging (b-jets)	+1.1	−0.8	+5	−4
Jet uncertainties	+1.1	−0.7	+5	−3
Jet flavour tagging (light-flavour jets)	+0.9	−0.6	+4	−3
Jet flavour tagging (c-jets)	+0.5	−0.4	+2	−2
Simulation sample size	+0.4	−0.3	+2	−1
Other experimental uncertainties	+0.4	−0.3	+2	−1
Luminosity	+0.2	−0.2	+1	−1
Total systematic uncertainty	+4.6	−3.4	+20	−16
Statistical				
Intrinsic statistical uncertainty	+4.2	−3.9	+19	−17
$t\bar{t}W$+jets normalisation and scaling factors	+1.2	−1.1	+6	−5
Non-prompt leptons normalisation (HF, Mat. Conv., Low m_{γ^*})	+0.4	−0.3	+2	−1
Total statistical uncertainty	+4.7	−4.3	+21	−19
Total uncertainty	+6.6	−5.5	+29	−25

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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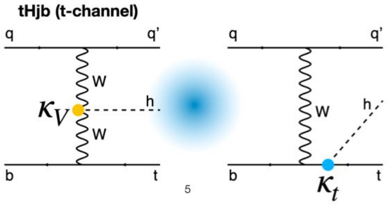
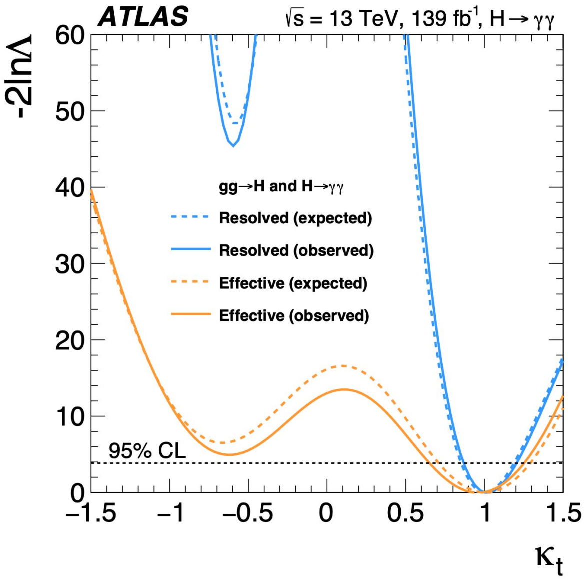
The top-Higgs coupling with STXS



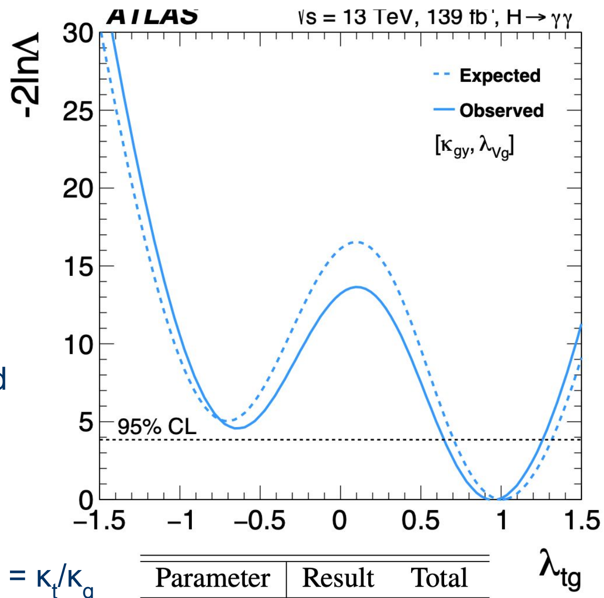
Top-Higgs coupling (κ_t) is directly measured

- 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

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



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

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

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H+X search: event selection

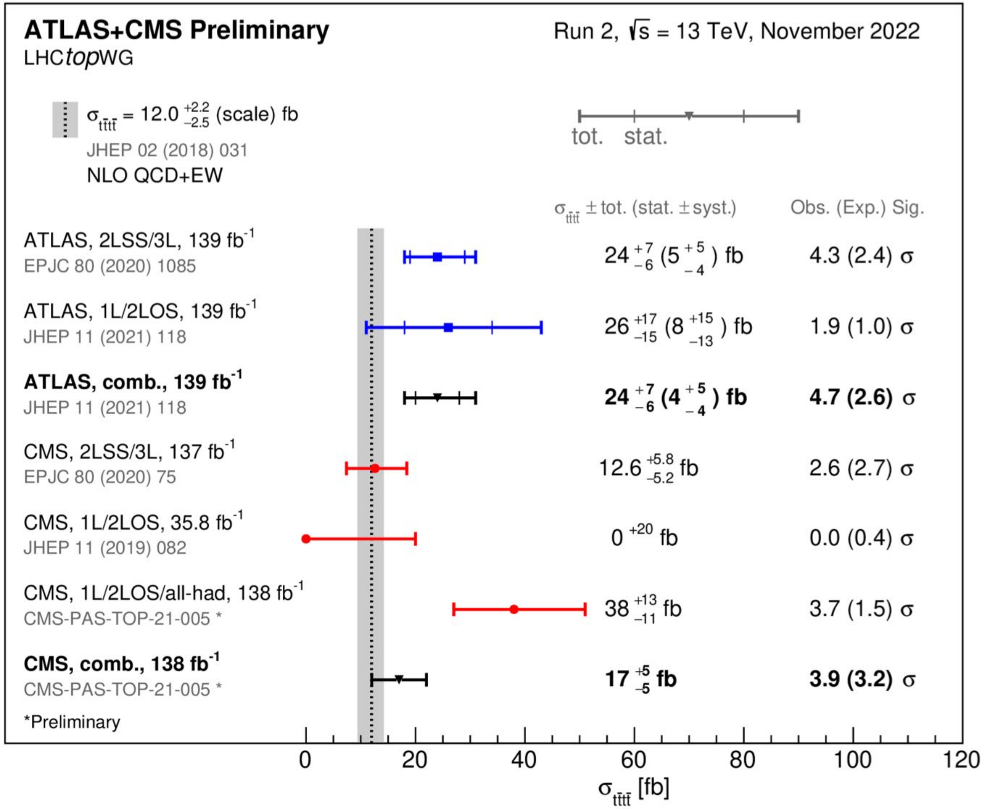
- 22 cut-based categories are defined with different final states, they are triggered by different BSM models
- The additional top-Higgs sectors can results in multiple b-jets, jets, leptons, high HT (scalar sum of jet pT), high missing ET and additional top candidates
- The searches are performed independently 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	$H_{\text{T}} > 500$ GeV
	H_{T} >1000 GeV	$H_{\text{T}} > 1000$ GeV
	H_{T} >1500 GeV	$H_{\text{T}} > 1500$ GeV
$E_{\text{T}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}} > 100$ GeV	$E_{\text{T}}^{\text{miss}} > 100$ GeV
	$E_{\text{T}}^{\text{miss}} > 200$ GeV	$E_{\text{T}}^{\text{miss}} > 200$ GeV
	$E_{\text{T}}^{\text{miss}} > 300$ GeV	$E_{\text{T}}^{\text{miss}} > 300$ 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

The publications before the observation

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

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



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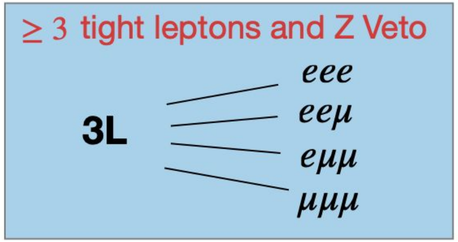
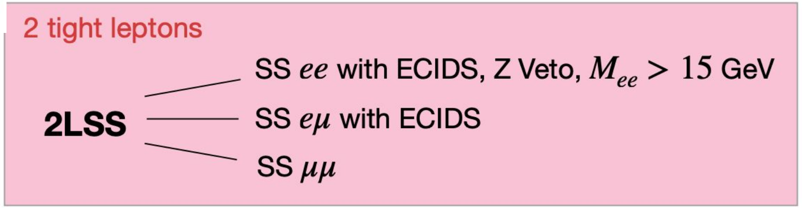
Object and event selections

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)

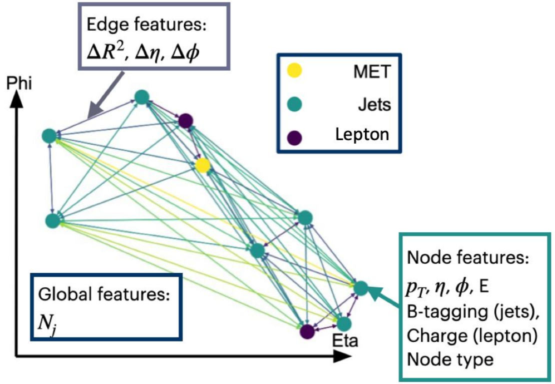


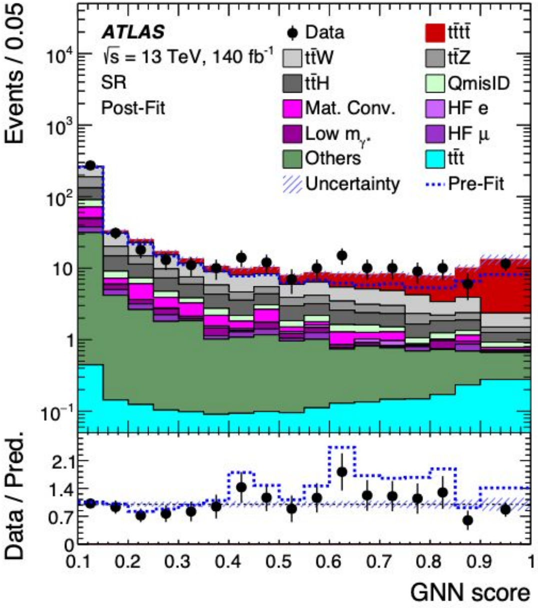


	SR
$t\bar{t}W$	130 ± 40
$t\bar{t}Z$	72 ± 15
$t\bar{t}H$	65 ± 11
QmisID	27 ± 4
Mat. Conv.	16.5 ± 2.3
HF e	3.1 ± 1.0
HF μ	7.1 ± 1.2
Low m_{γ^*}	14.1 ± 2.0
Others	47 ± 11
$t\bar{t}t$	2.9 ± 0.9
Total bkg	390 ± 50
$t\bar{t}t\bar{t}$	38 ± 4
Total	430 ± 50
Data	482

GNN multivariate analysis

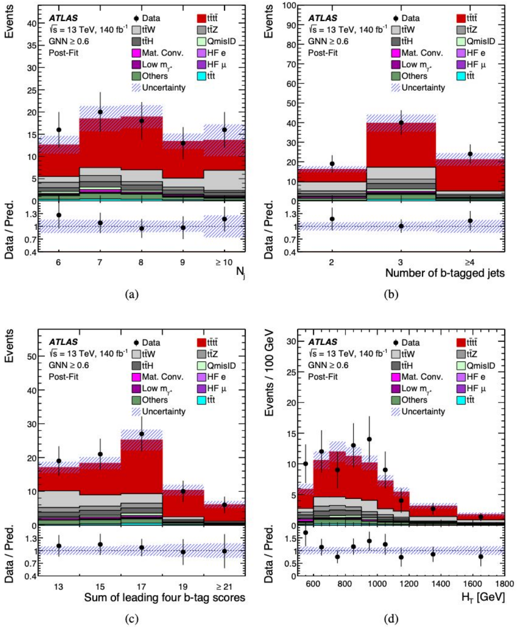
- "global score" is used and chosen as the event classifier and the observable in the pre-selected region
  - 10% higher sensitivity compared with the best BDT methods after fine tuning.





Good data/mc agreements on the GNN score are observed

Data vs MC when GNN > 0.6



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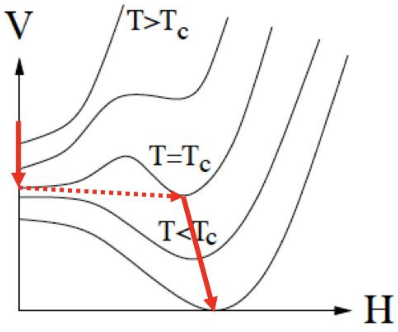
Higgs potential and phase transition

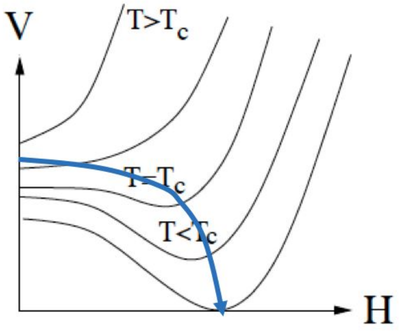
Phase Transition



1st OPT

VEV is discrete

Bubble created



2nd OPT

VEV is continuous