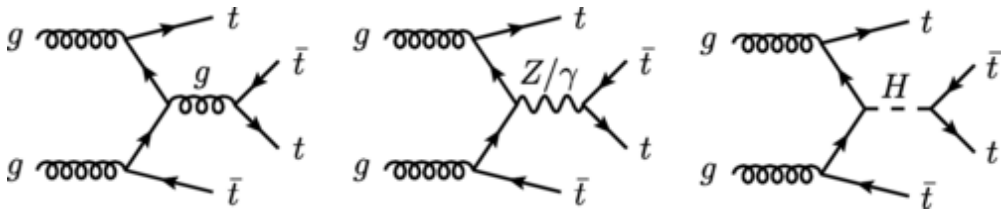
Four-top quark Searches at the LHC

Long Wang (BUAA)

Jul. 17, 2025 @ IHEP

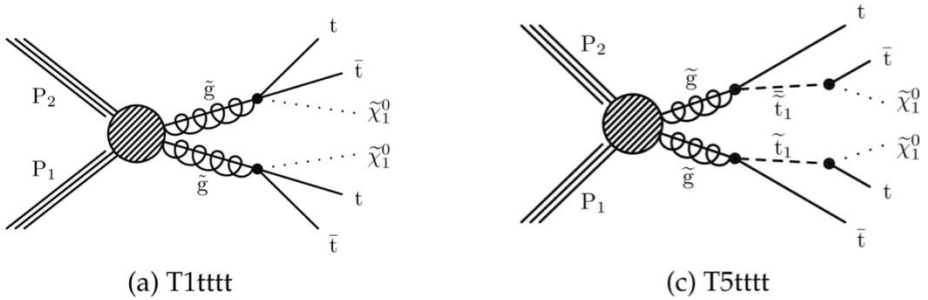
Motivation



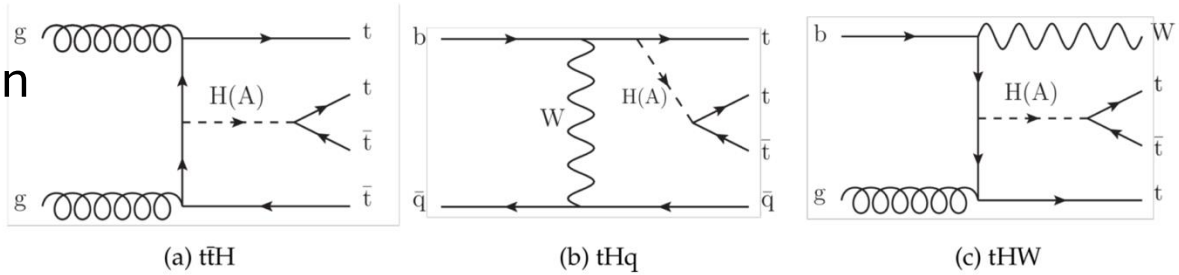
BSM	Cross section receives significant contribution in various SM extensions • Squark & gluino decays • New Scalar boson production associated with ttbar • Pair production of scalar gluons
Top-Higgs interaction	Probes the Yukawa-coupling and its CP property
EFTs	Constrains the four-fermion operators of EFT

Four-top quarks beyond the SM

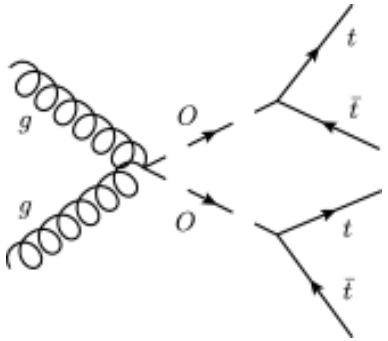
Gluino pair production



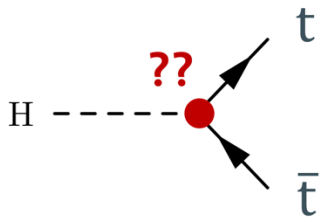
Pseudoscalar production in association with ttbar



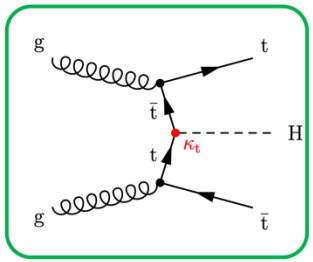
Color-octet scalar states (sgluons)



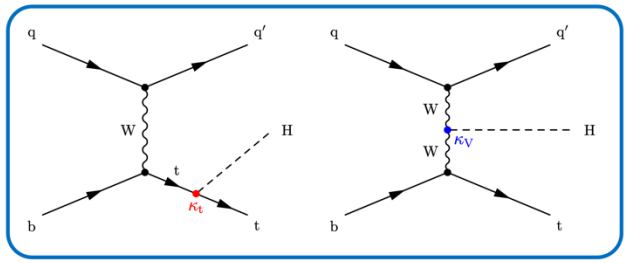
The top Yukawa coupling -- y_t



- Top quark associated production ttH, tH

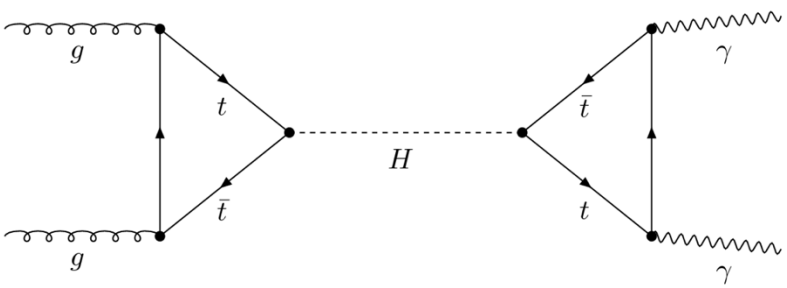


ttH: κ_t^2

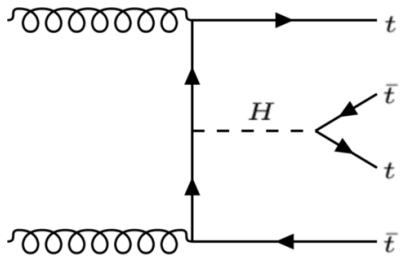


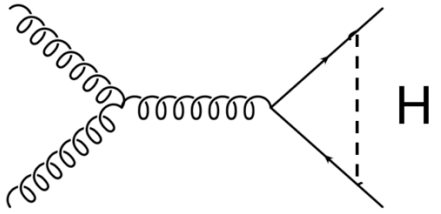
tH: $3.40\,\kappa_t^2 + 3.56\,\kappa_V^2 - 5.96\,\kappa_t\kappa_V$
(diagrams interfere)

- Loop induced single Higgs process



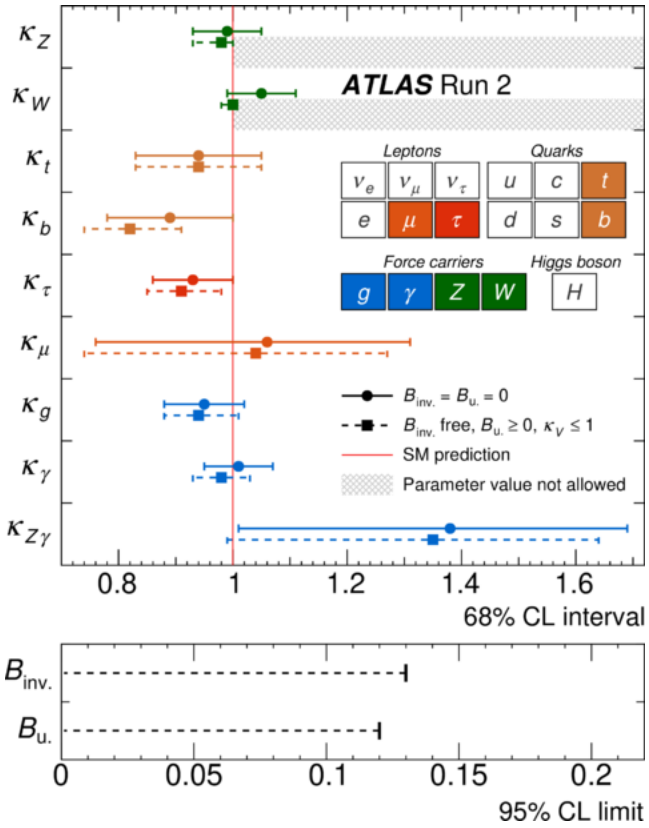
- Virtual contributions to top quark production

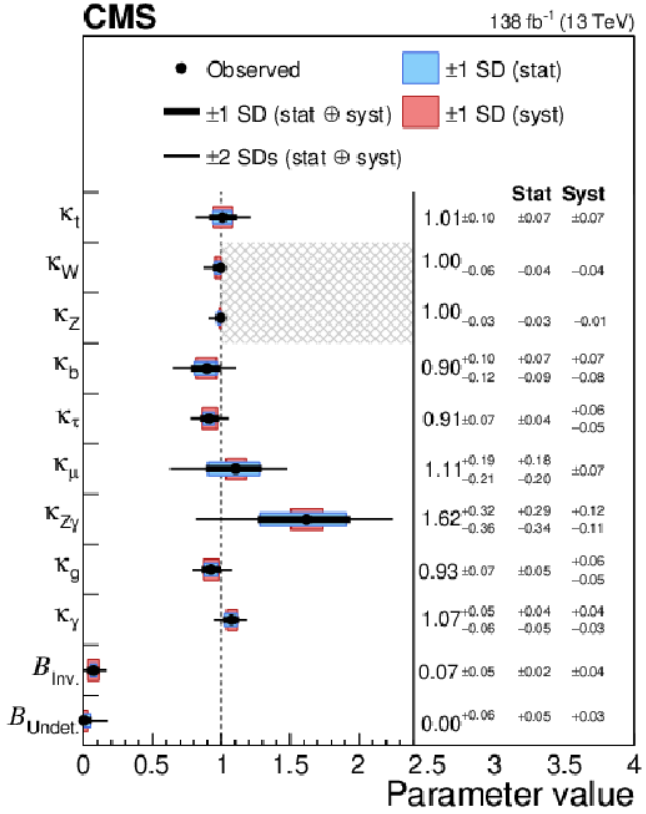




y_t from Higgs boson measurement

Nature 607 (2022) 52

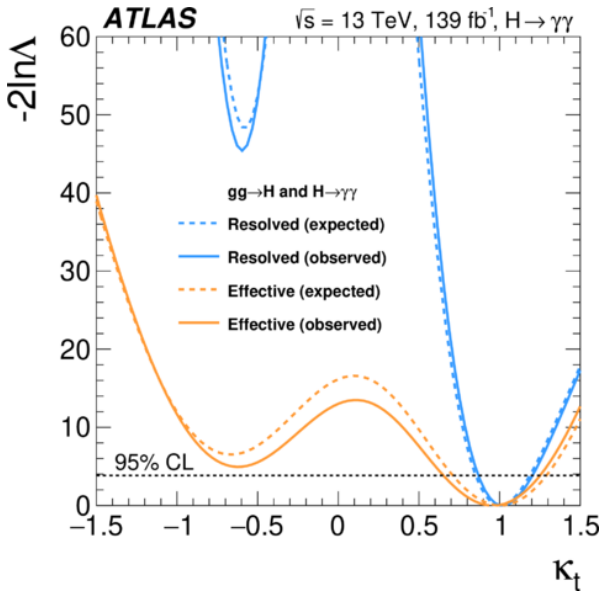




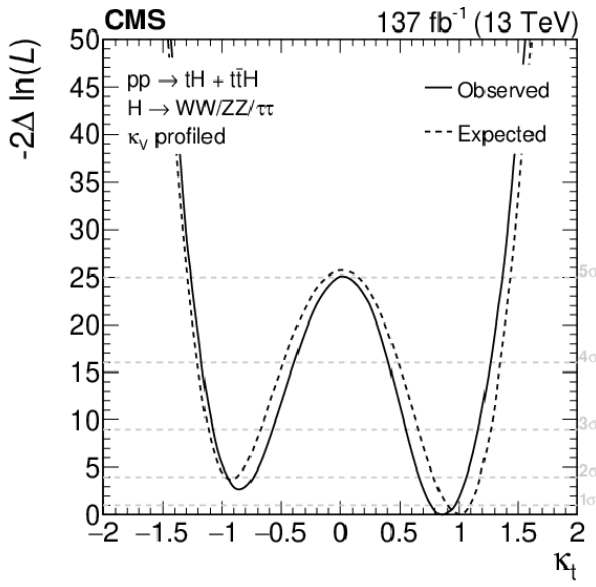
Nature 607 (2022) 60

- Extract y_t from Higgs combination fit
  - Most precise
  - Assumptions on particles in the loop, total decay width

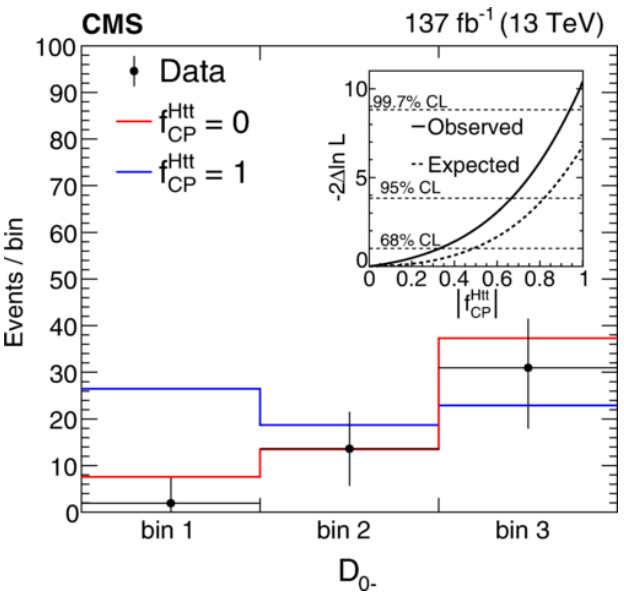
y_t from ttH, tH



JHEP 07 (2023) 088



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

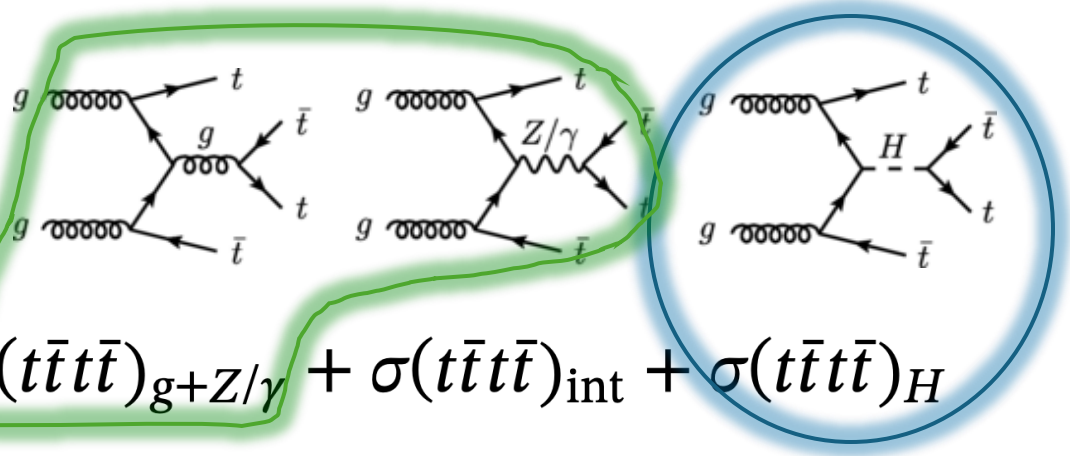


Phys. Rev. Lett. 125 (2020) 061801

- Direct measurement of top Yukawa coupling and probes of CP structure.
  - Dependent on other Higgs decays

y_t from four-top quarks

$$\mathcal{L}_{t\bar{t}H} = -\frac{m_t}{v} H\bar{t}(a_t + ib_t\gamma_5)t$$



$$\sigma(t\bar{t}t\bar{t}) = \sigma(t\bar{t}t\bar{t})_{\mathrm{g}+Z/\gamma} + \sigma(t\bar{t}t\bar{t})_{\mathrm{int}} + \sigma(t\bar{t}t\bar{t})_H$$

$$\sigma(t\bar{t}t\bar{t})_{\mathrm{g}+Z/\gamma} \propto |\mathcal{M}_{\mathrm{g}} + \mathcal{M}_{Z/\gamma}|^2,$$
$$\sigma(t\bar{t}t\bar{t})_{\mathrm{int}} \propto \mathcal{M}_{\mathrm{g}+Z/\gamma}\mathcal{M}_H^{\dagger} + \mathcal{M}_{\mathrm{g}+Z/\gamma}^{\dagger}\mathcal{M}_H,$$
$$\sigma(t\bar{t}t\bar{t})_H \propto |\mathcal{M}_H|^2.$$

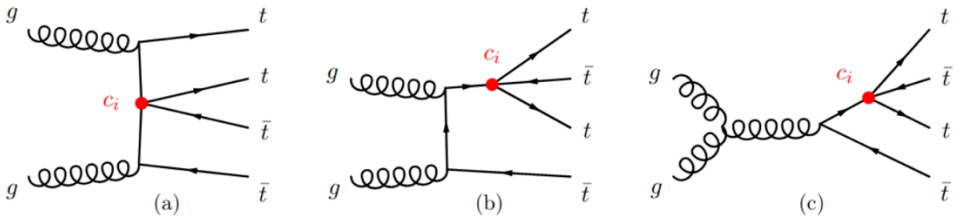
$$\sigma(t\bar{t}t\bar{t})_{13\ \mathrm{TeV}} = 7.724 - 1.164a_t^2 + 2.434b_t^2$$
$$+ 0.910a_t^4 + 2.183a_t^2b_t^2 + 1.424b_t^4,$$

MadEvent@LO

Only depends on top-Higgs coupling, independent of Higgs decay
Offers a probe to the CP phase of the top Yukawa coupling

Four-top EFTs

Production enhanced by the high sensitivity of the process to four-quark operators



At the LHC with CoM energy of 13 TeV

$\sigma_{\mathrm{SM}}(pp \to t\bar{t}t\bar{t}) \simeq 12$ fb

c_i	$\mathcal{O}(\Lambda^{-2})$			$\mathcal{O}(\Lambda^{-4})$
	$\mathcal{O}(\alpha_s^2\Lambda^{-2})$	$\mathcal{O}(\alpha_s\alpha\,\Lambda^{-2})$	Total interf.	
c_{tt}^1	$0.552^{+71\%}_{-39\%}$	-1.74	-1.24	$4.25^{+73\%}_{-39\%}$
c_{QQ}^1	$0.272^{+71\%}_{-39\%}$	-0.991	-0.737	$1.06^{+73\%}_{-39\%}$
c_{QQ}^8	$0.0889^{+71\%}_{-39\%}$	-0.329	-0.245	$0.118^{+73\%}_{-39\%}$
c_{Qt}^1	$-0.0392^{+71\%}_{-39\%}$	0.747	0.745	$1.44^{+73\%}_{-39\%}$
c_{Qt}^8	$0.282^{+70\%}_{-39\%}$	-0.605	-0.322	$0.349^{+73\%}_{-39\%}$

Values in fb

Related by a factor of 2 and 4, respectively

Related by a factor of 3 and 9, respectively

Due to a factor of 2 in the definitions

These are sources of degeneracy in the four-top production.

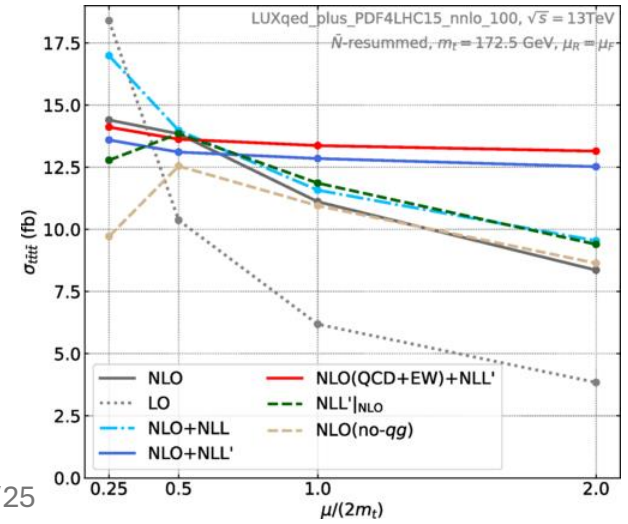
$$\mathcal{O}_{QQ}^{(8)} \overset{tttt-\text{only}}{=} \frac{1}{3}\mathcal{O}_{QQ}^{(1)}$$

Four-top prediction at the LHC

Phys. Rev. Lett. **131**, 211901

$\sqrt{s}$ (TeV)	NLO	NLO + NLL	NLO + NLL′	$K_{\mathrm{NLL}'}$
13	$11.00(2)^{+25.2\%}_{-24.5\%}$ fb	$11.46(2)^{+21.3\%}_{-17.7\%}$ fb	$12.73(2)^{+4.1\%}_{-11.8\%}$ fb	1.16
13.6	$13.14(2)^{+25.1\%}_{-24.4\%}$ fb	$13.81(2)^{+20.7\%}_{-20.1\%}$ fb	$15.16(2)^{+2.5\%}_{-11.9\%}$ fb	1.15
$\sqrt{s}$ (TeV)	NLO(QCD + EW)	NLO(QCD + EW) + NLL	NLO(QCD + EW) + NLL′	$K_{\mathrm{NLL}'}$
13	$11.64(2)^{+23.2\%}_{-22.8\%}$ fb	$12.10(2)^{+19.5\%}_{-16.3\%}$ fb	$13.37(2)^{+3.6\%}_{-11.4\%}$ fb	1.15
13.6	$13.80(2)^{+22.6\%}_{-22.9\%}$ fb	$14.47(2)^{+18.5\%}_{-19.1\%}$ fb	$15.82(2)^{+1.5\%}_{-11.6\%}$ fb	1.15

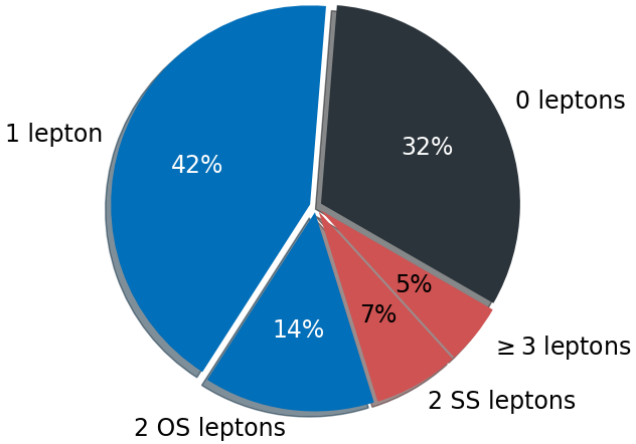
Large uncertainty due to scale variation



- High order QCD corrections from soft gluon emissions
- Next-to-leading logarithmic accuracy
- Constant $\mathcal{O}(\alpha_s)$ nonlogarithmic contributions do not vanish at threshold
- Electroweak corrections are included up to $\mathcal{O}(\alpha^2)$
- Reduction of scale unc by a factor of 2
- 15% correction to NLO result

Four-top production at the LHC

- Heaviest final state observed at the LHC
- Large object multiplicity: tttt→$W^+W^-W^+W^-$bbbb
  - High event hadronic activity and sphericity
- Significant background from QCD and ttbar
- Final states defined by lepton multiplicity
  - 0L: All hadronic W decays
  - 1L+OS2L: largest branching fraction
  - SS2L+ML: clean background
- Heavy use of machine learning techniques
  - BDTs (CMS) and GNNs (ATLAS) for signal identification
  - NNs for top tagging



I.1 CMS all hadronic search

UCSB, Korean U.

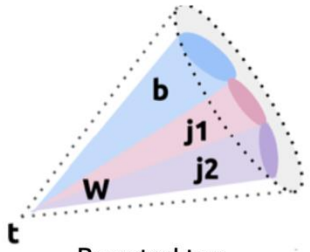
*Run3 preapproval

Challenge

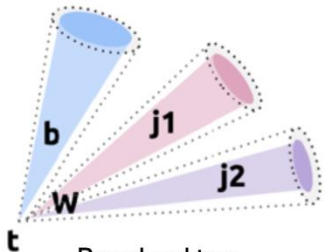
- Huge irreducible QCD + ttbar background
- QCD simulation not well modeled in high jet multiplicity region

Analysis Strategy

- N_{Jets}, N_{bjets} and H_T based trigger
- Top tagging
  - Boosted top: ParticleNet
  - Resolved top: Custom XGBoost BDT
- Baseline selection
  - $N_{leptons}$=0, N_{Jets}>=9, N_{bjets}>=3, H_T >= 700 GeV
- Use $N_{restops}$, $N_{boosted\ tops}$ and H_T to further divide Signal Region
- Event-level BDT for further signal/background discrimination
- Binned likelihood analysis on event-level BDT score



Boosted top

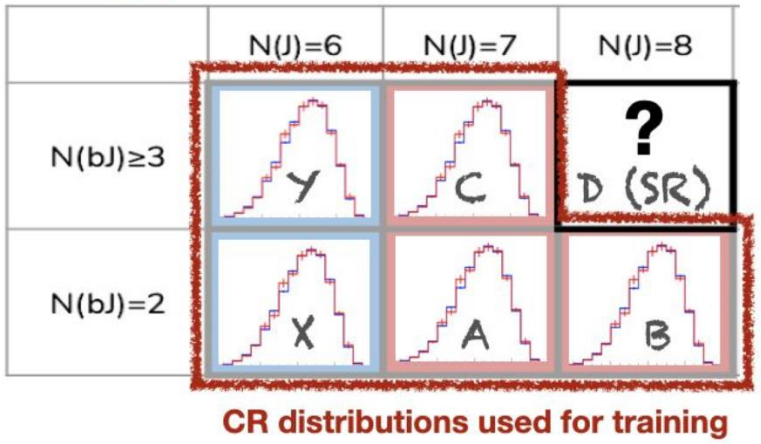


Resolved top

I.1 CMS all hadronic search *UCSB, Korean U.*

- Data driven background estimation

1. ABCDnn trained on CR distributions used to predict shape

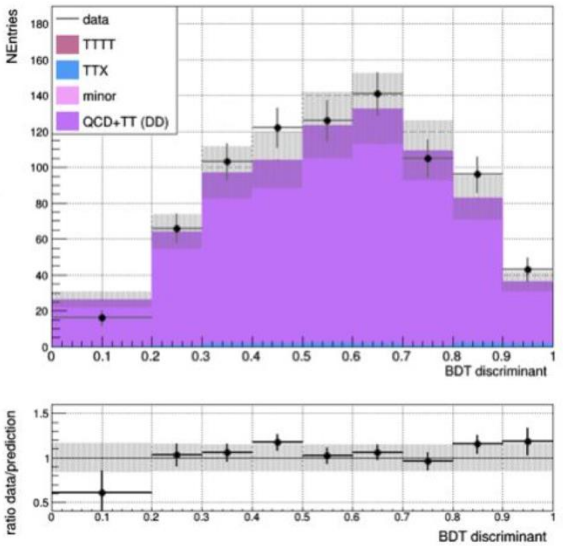


CR distributions used for training

2. extABCD equation and CR data yields used to predict normalization

$$D(SR) \approx \left(\frac{B \cdot C}{A}\right)^{2} \left(\frac{B \cdot Y}{X}\right)^{-1}$$

Result: Predicted BDT Distribution for data-driven background for VR or SR bins



I.2 CMS 1L & OS2L searches

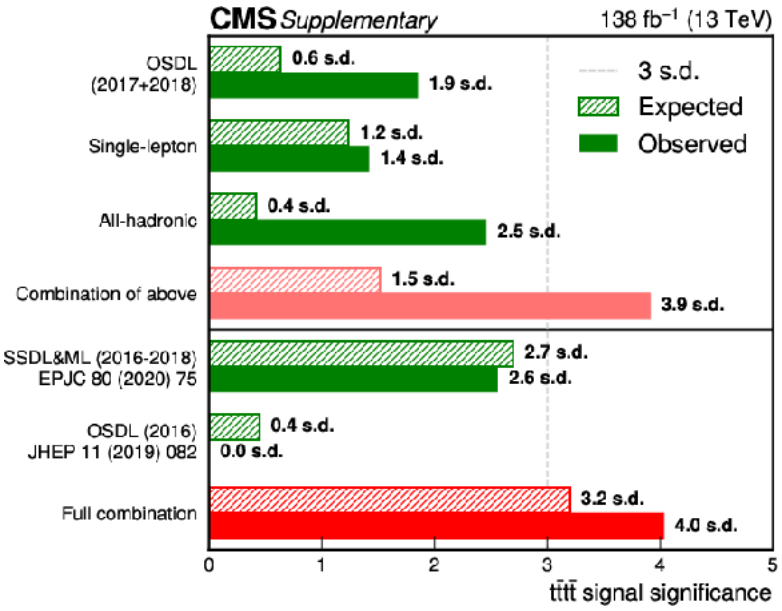
Brown U.
UC Riverside

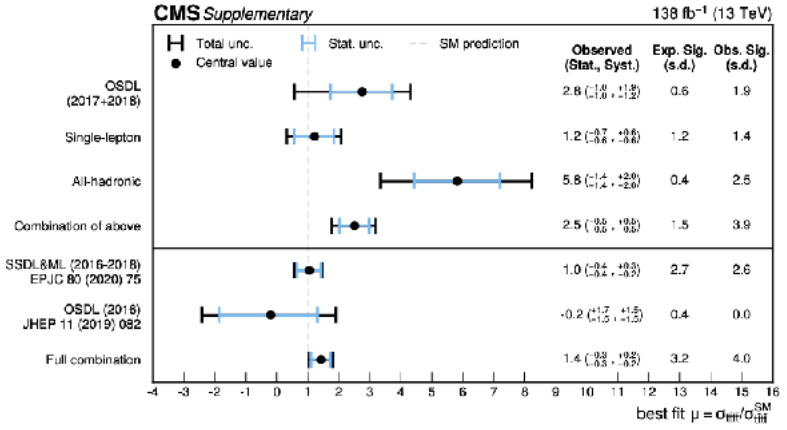
	OSDL	SL
Baseline Selection	2 opposite-sign leptons, H_T>500 GeV, 4+ jets, 2+ b-jets, invariant mass selections	1 lepton, H_T>500 GeV, 6+ jets, 2+ b-jets, E_T^{miss}>60 GeV
Major Backgrounds	ttbar	ttbar
Background Estimation	simulation	simulation
Signal Region (SR) categorization	lepton channel & jet/b-jet multiplicity	lepton channel, jet/b-jet multiplicity, & resolved top multiplicity
Discriminating Variable	H_T	BDT

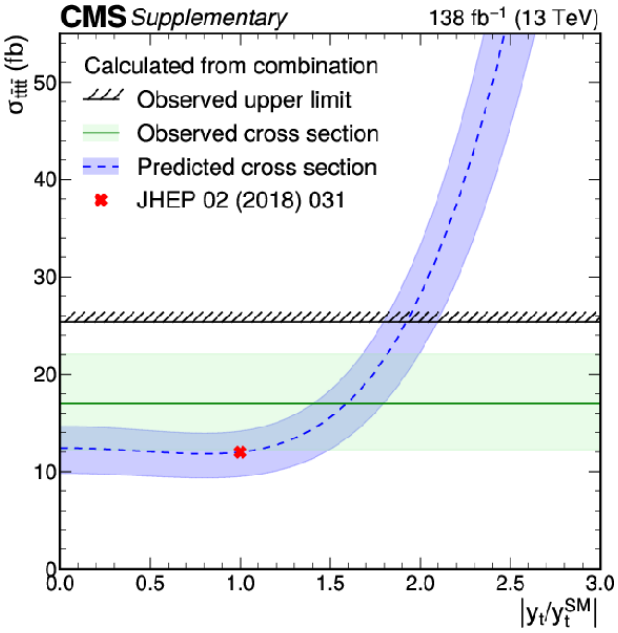
Comparing to 2016 search, new resolved top tagger and finer categorization

Vrije U. Brussel,
Chulalongkorn U

I.3 Combination of 0L, 1L & OS2L







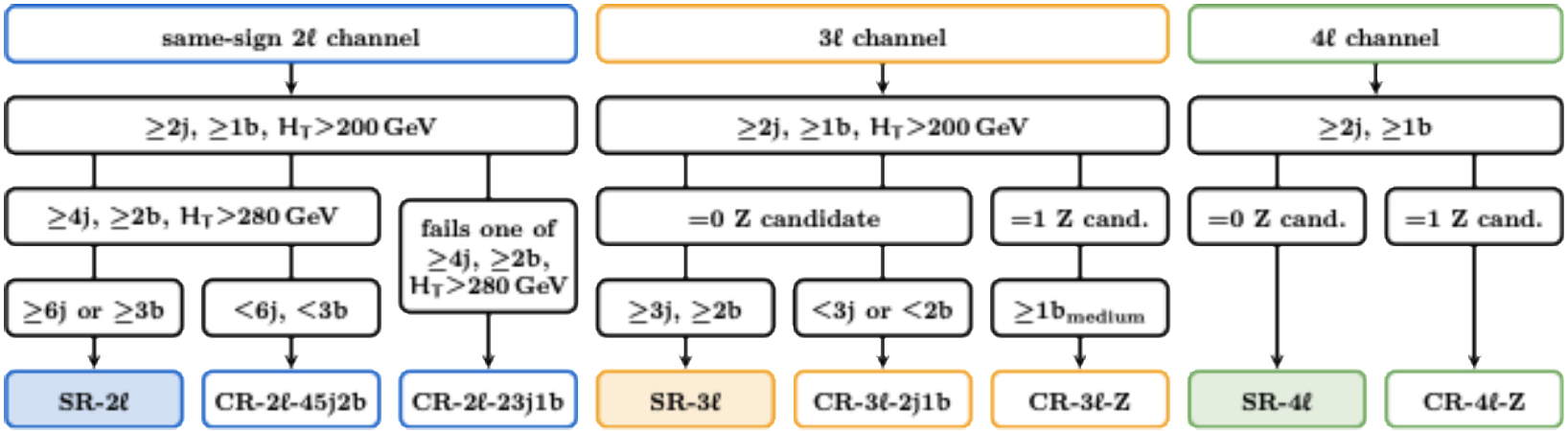
- Set an evidence of tttt at CMS
- Result used to constrain y_t

*Whole analyses period 2019-2022

II. CMS search in SS2L & ML

Ghent U.

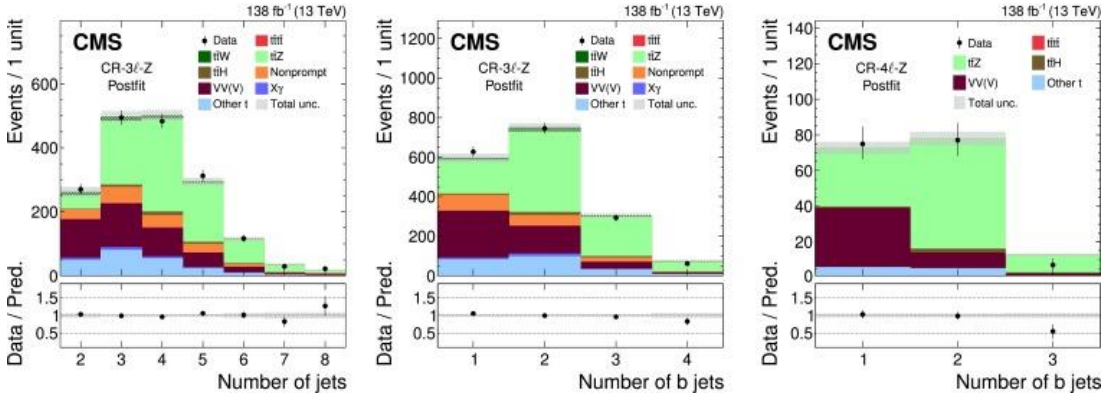
- Re-analysis of full Run2 dataset with improvements on
  - Legacy event reconstruction: better calibration & correction
  - Deepjet for b tagging: higher efficiency
  - TOP leptonMVA ID: suppress non-prompt leptons
  - Analysis methods
- Multi-classification with BDTs in signal region
  - 3 classes: tttt, ttV, ttbar with misidentified lepton

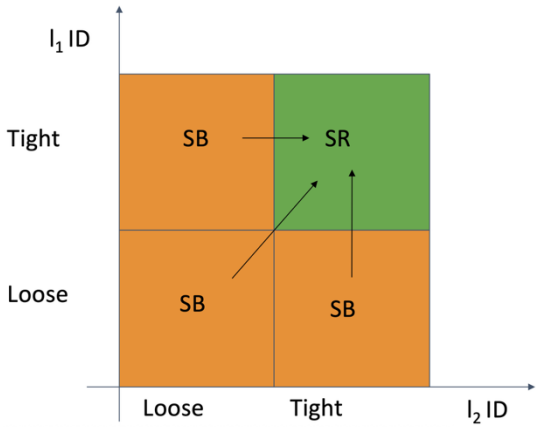


CMS background estimation

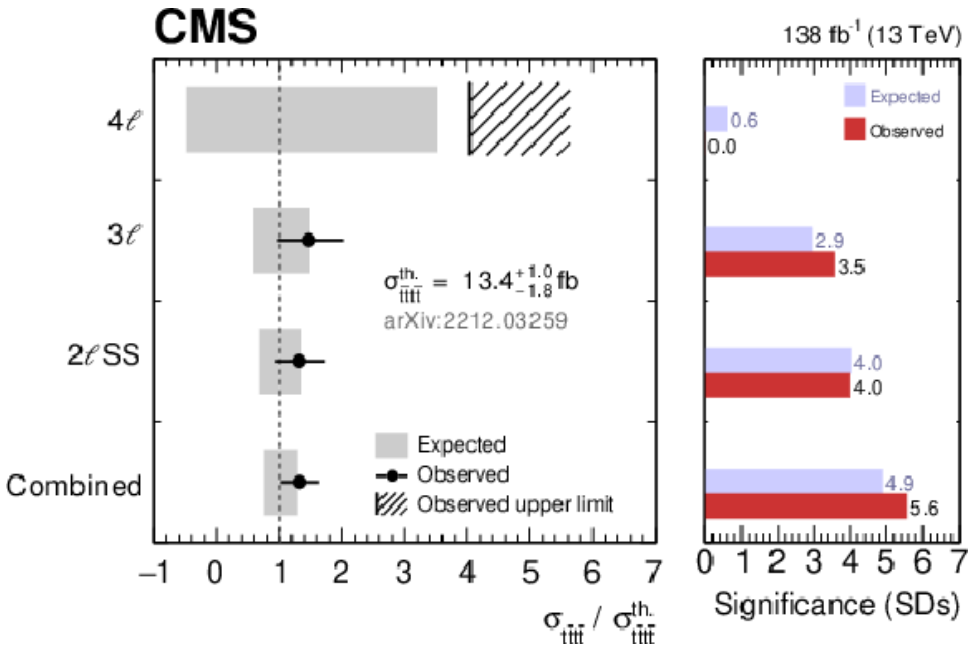
- Prompt (leptons) background:
  - Estimated from MC simulation,
  - ttW in 2l&3l channels; ttZ in 3l&4l channels, **free floating in the statistical fit**
  - ttt and other single top associated processes
  - WZ in 2l&3l channels, ZZ in 4l channels

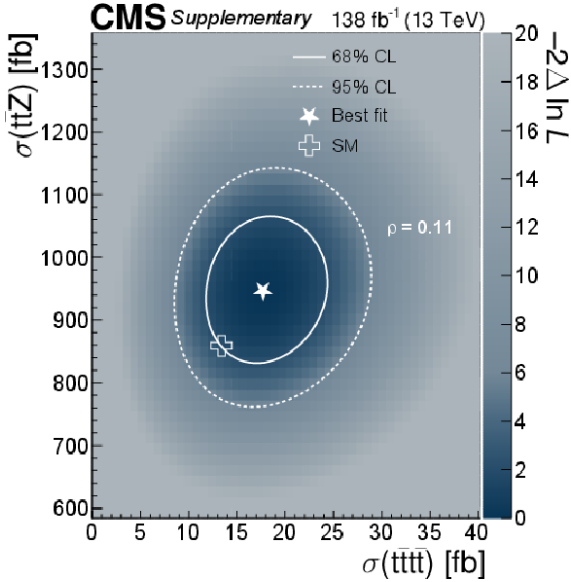
- Non-prompt (leptons) and charge mis-ID background
  - Fake rate method

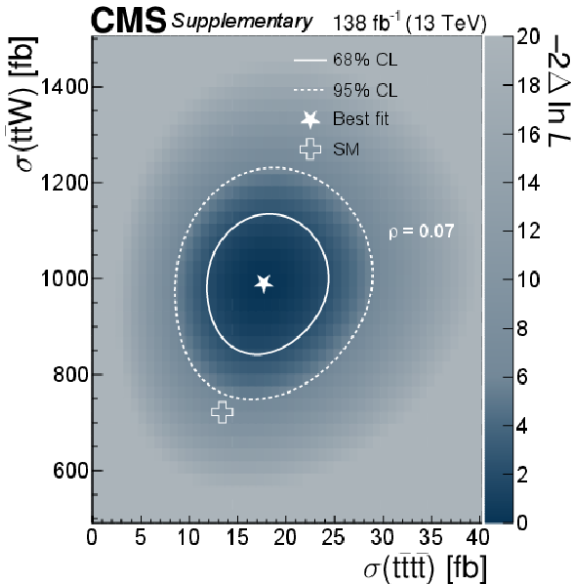




CMS signal extraction







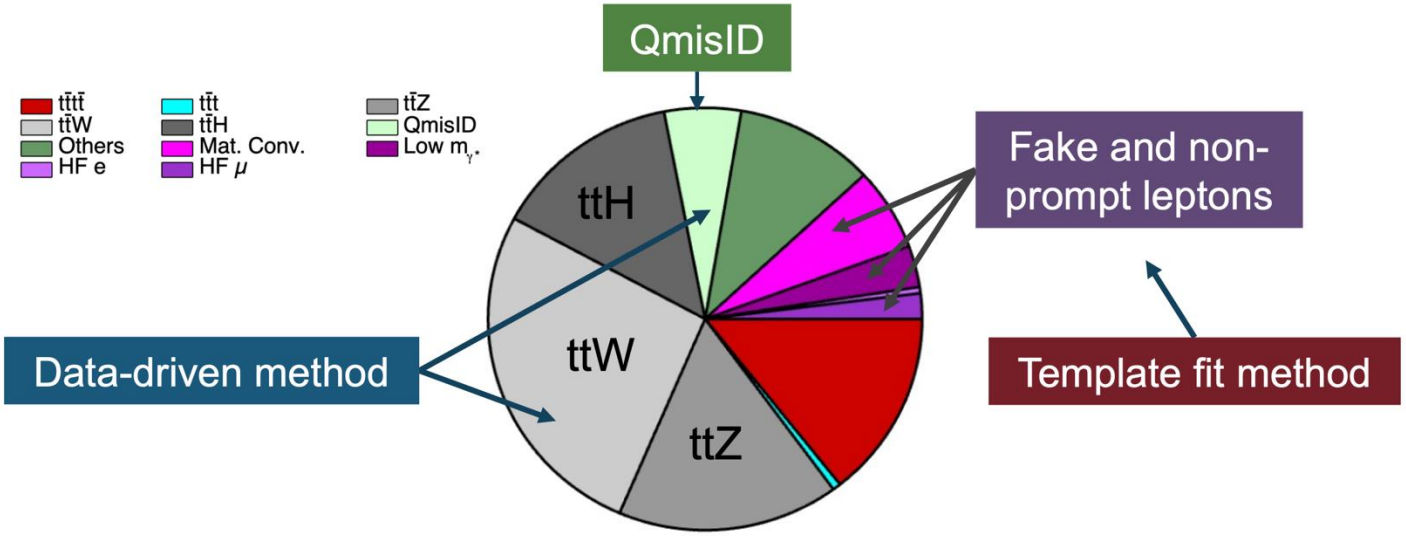
First observation of tttt at CMS

$$\sigma(\mathrm{t\bar{t}t\bar{t}}) = 17.7\,^{+3.7}_{-3.5}\,(\mathrm{stat})\,^{+2.3}_{-1.9}\,(\mathrm{syst})\,\mathrm{fb} = 17.7\,^{+4.4}_{-4.0}\,\mathrm{fb}$$

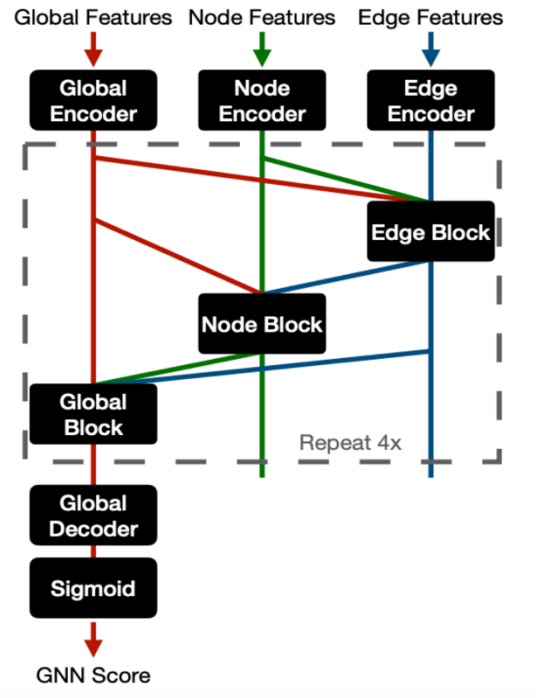
III. ATLAS search in SS2L & ML

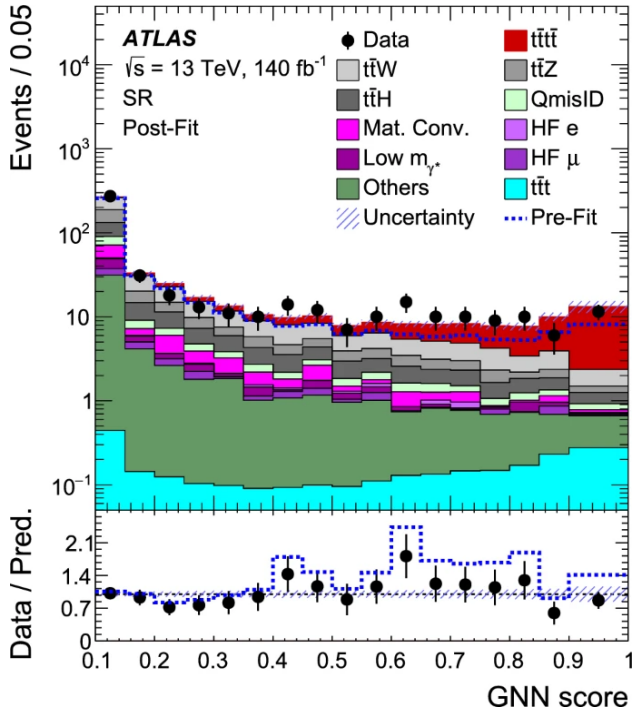
Background modeling:

- ttW jet multiplicity distributions corrected using data
- Template method to estimate non-prompt background
  - CRs included in fit to determine the normalization of these components
- Charge mis-assignment background
  - From charge flip rate in data



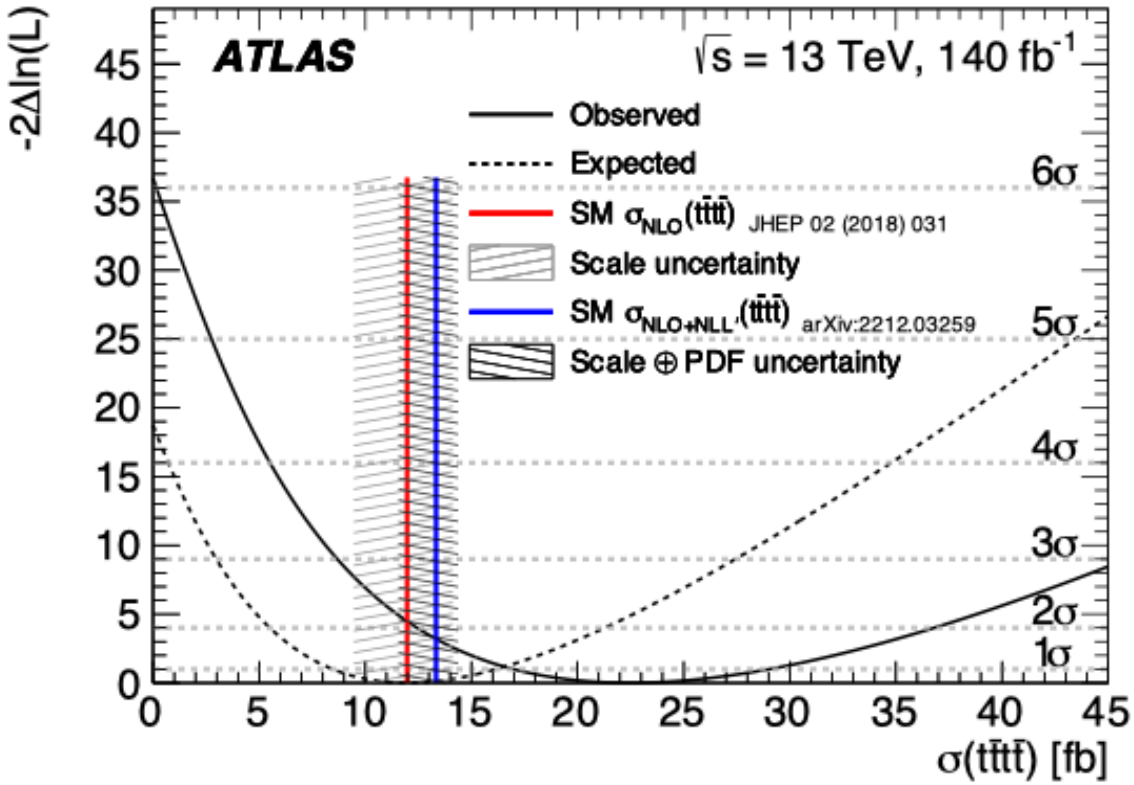
ATLAS signal extraction





- GNN is constructed to combine the information about objects (jets, lepton, MET) in an event into graphs, with node, edge, and global properties.
- Signal, background normalization, ttW modeling in one fit

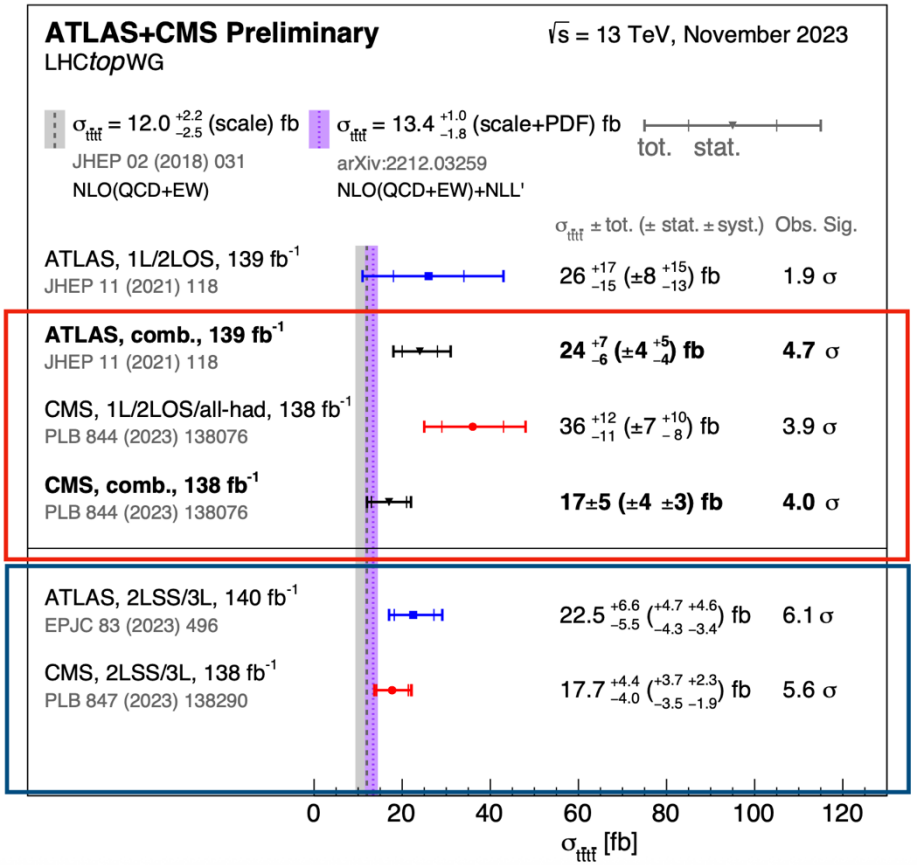
ATLAS search result



First observation of tttt at ATLAS

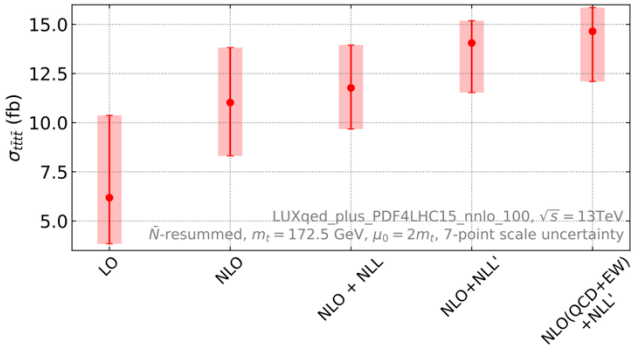
$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})\,^{+4.6}_{-3.4}(\text{syst})\,\text{fb} = 22.5\,^{+6.6}_{-5.5}\,\text{fb}$$

Four-top searches summary



Evidence

Observation



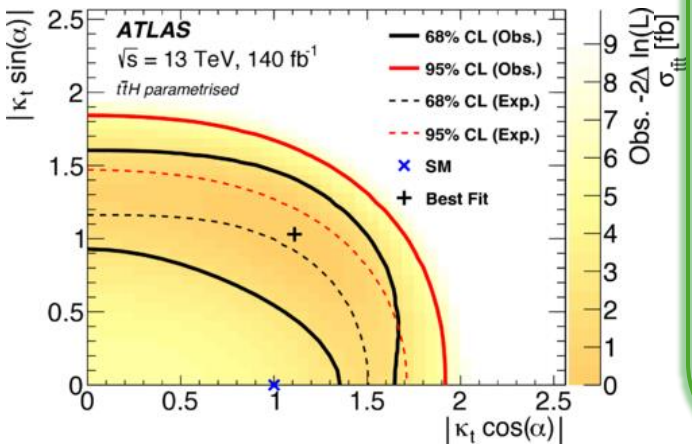
@NLO(QCD+EW)+NLL'

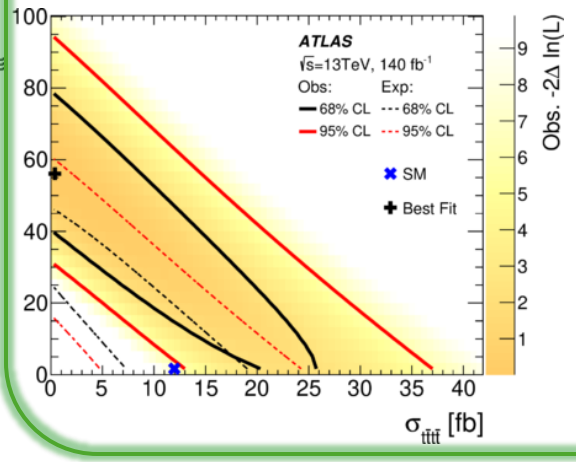
$$\sigma_{t\bar{t}t\bar{t}}^{\mathrm{NLO(QCD+EW)+NLL'}} = 14.65(1)\,^{+1.57}_{-2.75}\ \mathrm{fb}$$

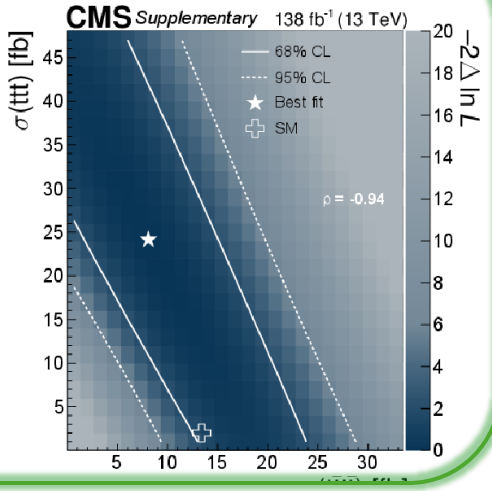
- Still agree with SM within 1.8sigma.
- Can we really see hints of BSM through tttt?
- At least can probe y_t and test perturbative QCD from it!

Result interpretation

CMS has better handling of 3 tops







Operators	Expected C_i/Λ^2 [TeV^{-2}]	Observed C_i/Λ^2 [TeV^{-2}]
$\mathcal{O}^1_{QQ}$	$[-2.5, 3.2]$	$[-4.0, 4.5]$
$\mathcal{O}^1_{Qt}$	$[-2.6, 2.1]$	$[-3.8, 3.4]$
$\mathcal{O}^1_{tt}$	$[-1.2, 1.4]$	$[-1.9, 2.1]$
$\mathcal{O}^8_{Qt}$	$[-4.3, 5.1]$	$[-6.9, 7.6]$

- ATLAS result used to constrain the top Yukawa CP structure
- ATLAS result used to constrain the EFT four-top Wilson coefficients
- CMS EFT and BSM constraints underway
- Interpretations rely on the order of four-top theoretical calculations

Future aspects

- Production xsec of tttt increase by 30(19)% from 13TeV to 14(13.6)TeV
  - This increasement for most background is smaller → expect better signal to background ratio
- Higher CoM leads to partons at lower Bjorken x values enter the phase space for tttt production
  - Improved theoretical uncertainties related to PDFs
- Better understanding of ttW and ttZ from Run2 studies
  - Improved background modelling in the jet multiplicity region of tttt
- LHC/HL-LHC is the only place to experimentally study four-tops till FCC-pp or SppC in the distant future

Outlook @ Run3

➢Twice the size of dataset at Run3

✓SS2L + ML @ Run3: taken by CERN+Ghent+KIT

✓0L @ Run3: GoingToPreApp by the Run2 UCSB/KU group

❑1L @ Run3: no news from Brown group, Vrije interested

❑OS2L @ Run3: PIs retired from UCR

Thank you for your attention!