Recent measurements of top quark productions in CMS

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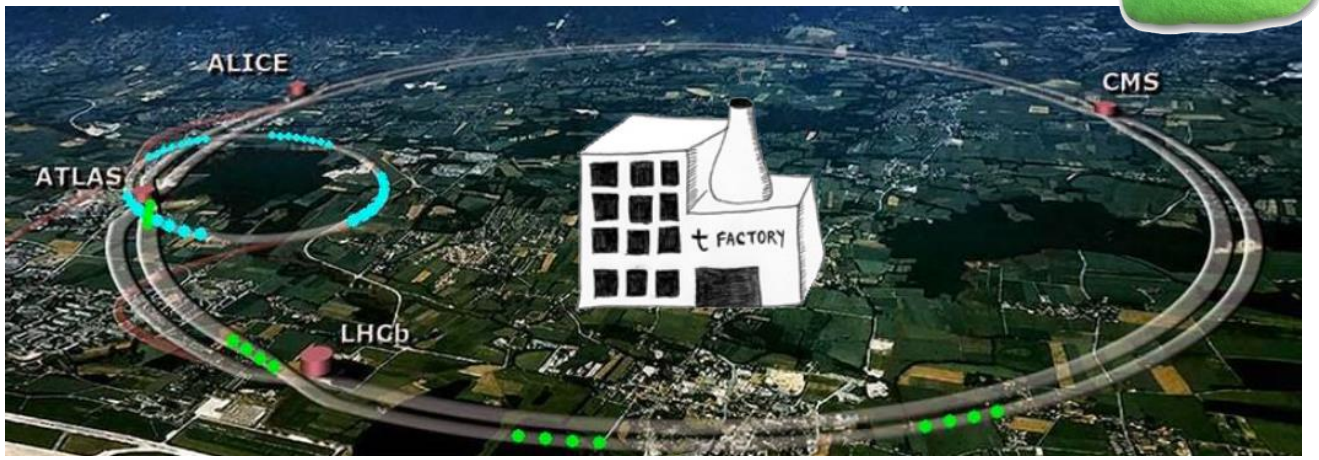
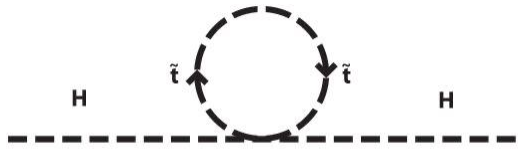
An introduction to the top quark

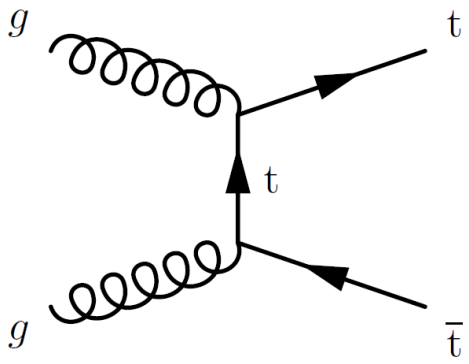
- **Top quark is heavy:**
  - The heaviest known fundamental particle, ~36 times heavier than the bottom quark.
  - Largest Yukawa coupling to the Higgs boson.
- **Top quark is unique:**
  - Extremely short lifetime 5×10^{-25} s.
  - Decays before hadronization.



- Top quark may play an important role in BSM physics.
  - Its supersymmetric partner can be fundamental to explain the Higgs mass.
  - Many top processes are sensitive to **EFT** operators.



- Many production modes:
  - **Top pair** (QCD) or single top production (EW), but also…
  - They can be produced in association with bosons (W, Z, H, γ).
  - Even **four top** production!



Results presented in this talk

- $t\bar{t}$: First measurement of the top quark pair production cross section in proton-proton collisions at $\sqrt{s} = 13.6$ TeV. Submitted to JHEP, arXiv:2303.10680.
- $t\bar{t}t\bar{t}$: Observation of four top quark production in proton-proton collisions at $\sqrt{s} = 13$ TeV. Submitted to PLB, arXiv:2305.13439.
- tWZ: Evidence for tWZ production in proton-proton collisions at $\sqrt{s} = 13$ TeV in multilepton final states. CMS-PAS-TOP-22-008.
- **EFT**: Search for new physics in top quark production with additional leptons in the context of effective field theory using $138\ fb^{-1}$ of proton-proton collisions at $\sqrt{s} = 13$ TeV.CMS-PAS-TOP-22-006.

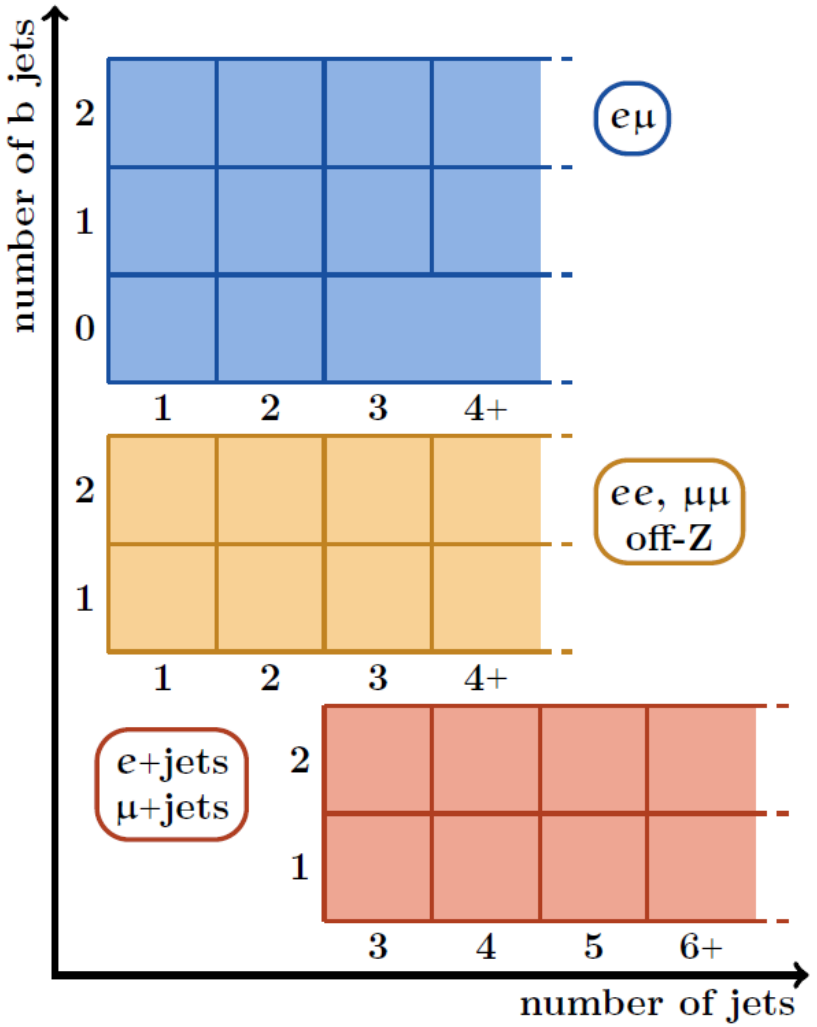
$t\bar{t}$ cross section measurement at 13.6 TeV

- First CMS measurement at 13.6 TeV with $1.21\ \mathrm{fb}^{-1}$.
- This measurement provides the first test to determine if the cross section increases as expected (by 10%).

$$(\mathrm{NNLO} + NNLL)\text{: } \sigma_{SM} = 921^{+29}_{-37}\ \mathrm{pb} \text{ using TOP++ v2.0}$$

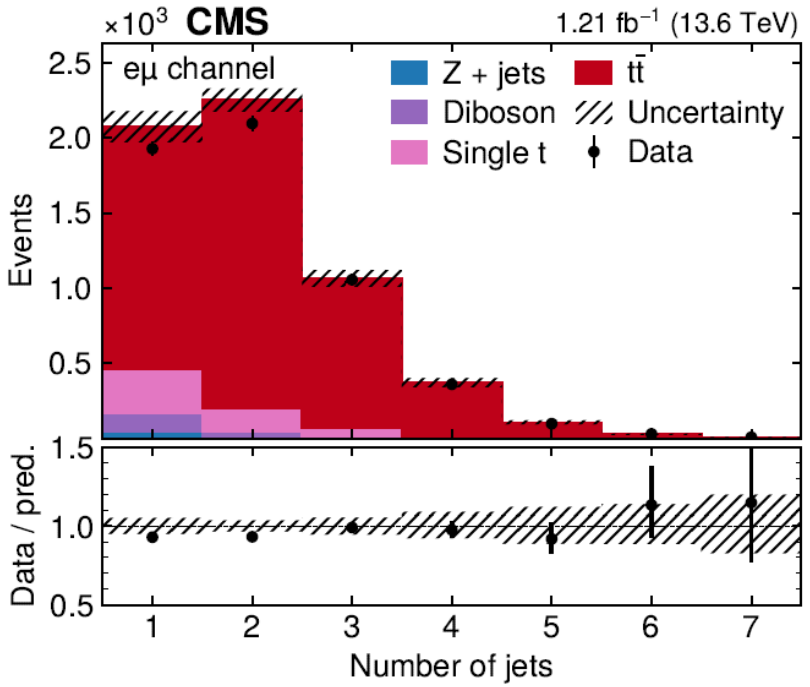
- **Event selection**: <u>five analysis channels.</u>
  - $e\mu$: $N_j \geq 1, N_b \geq 0$.
  - $ee, \mu\mu$: $N_j \geq 1, N_b \geq 1, |m_{\ell\ell} - m_Z| > 15\ \mathrm{GeV}$.
  - $e + \mathrm{jets}, \mu + \mathrm{jets}$: $N_j \geq 3, N_b \geq 1$.

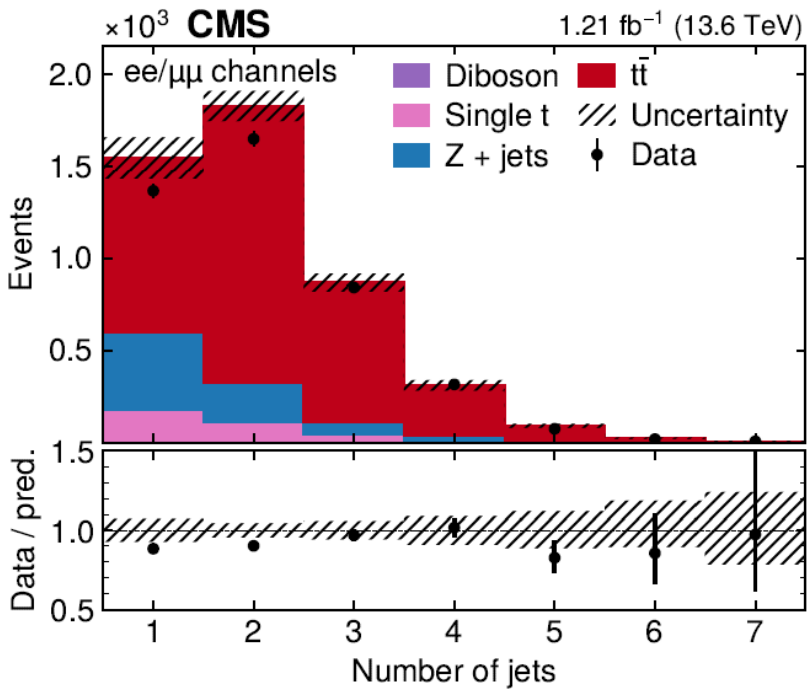
Dilepton+semilepton measured simultaneously!

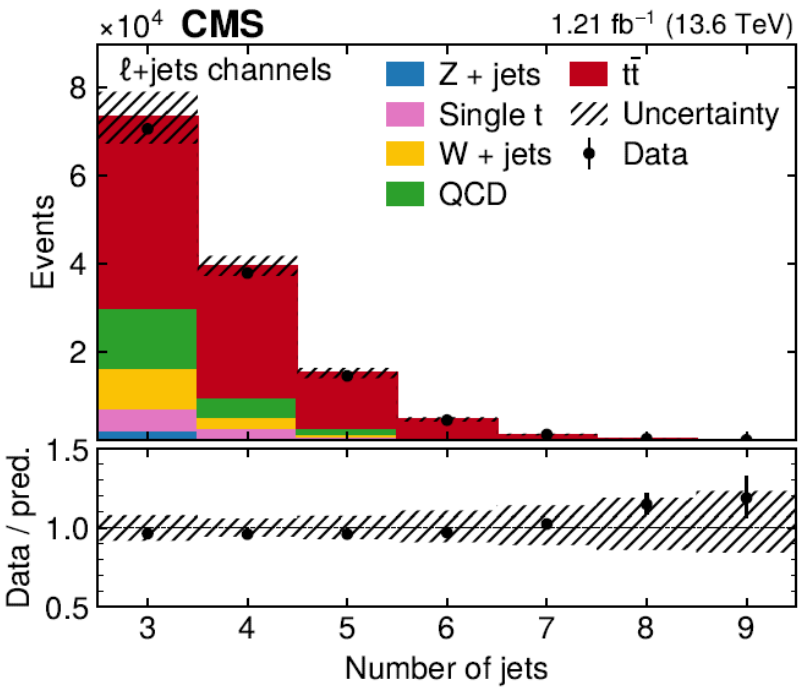


$t\bar{t}$ cross section measurement at 13.6 TeV

- **Background estimation**:
  - Single top, Z+jets, W+jets and diboson → MC
  - QCD → data driven.
  - Z+jets → normalisation extracted from data.
- A cross check of the jet energy corrections is performed fitting the W mass distribution.

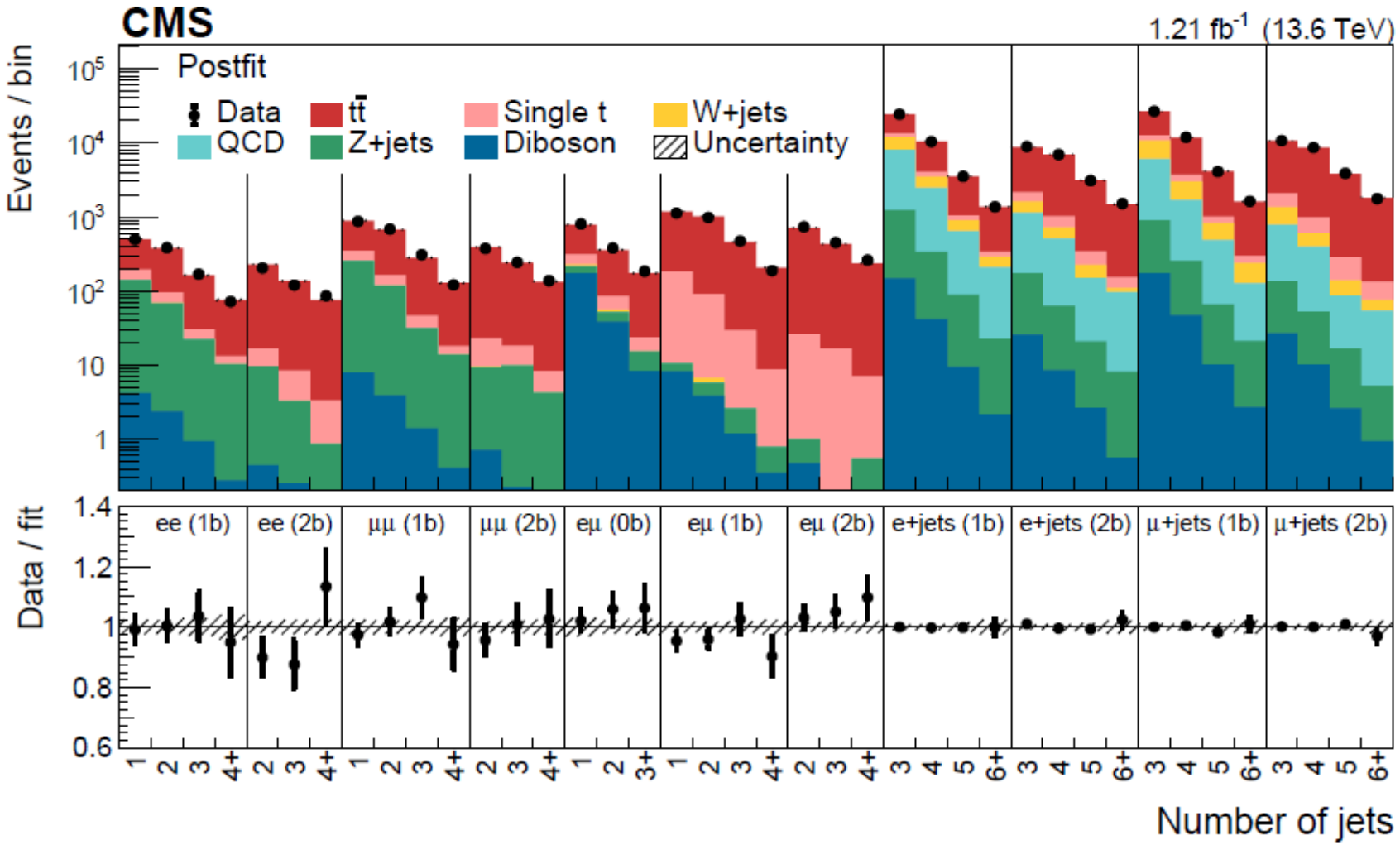






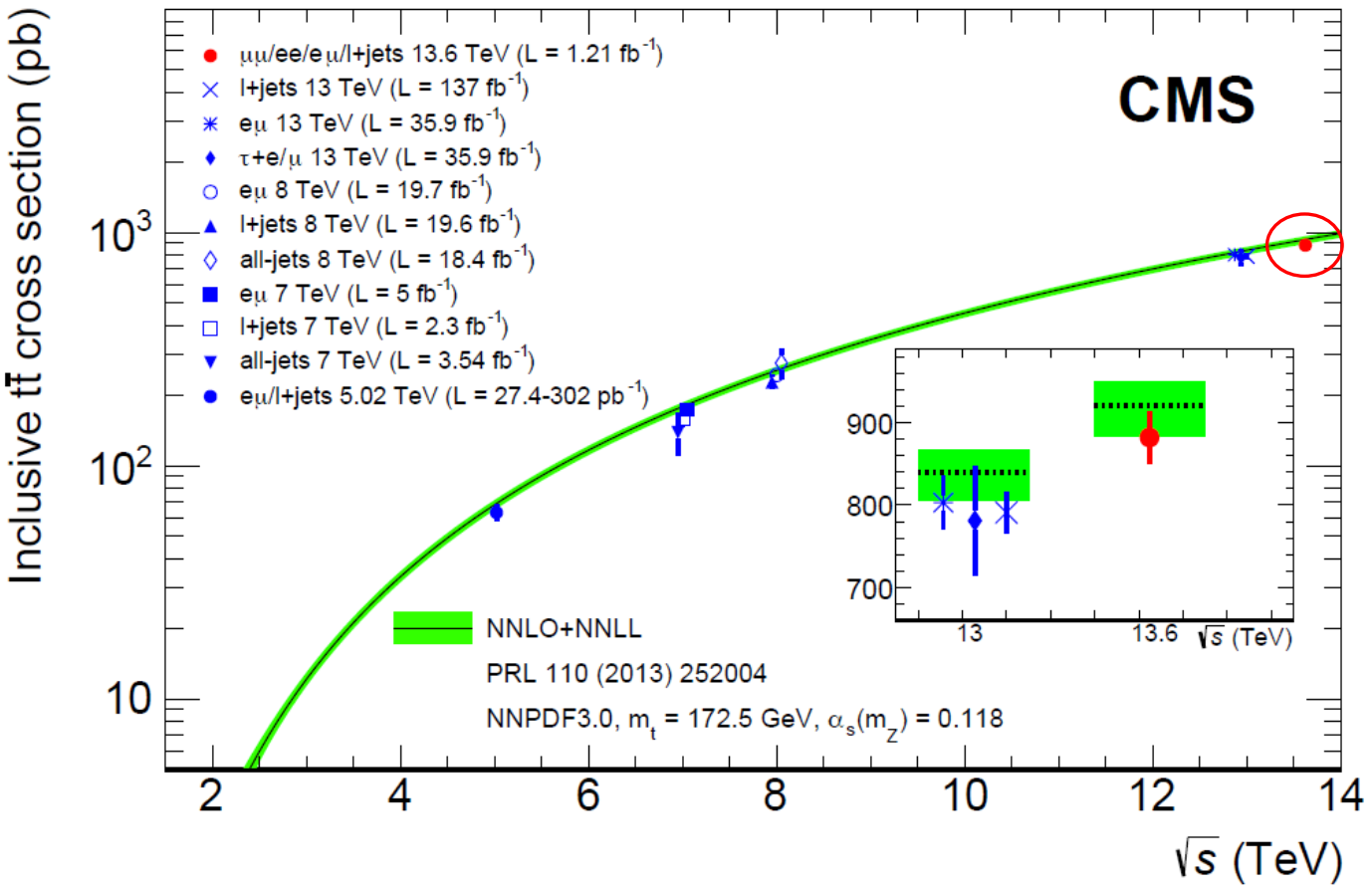
$t\bar{t}$ cross section measurement at 13.6 TeV

- A profile ML fit is performed to measure the cross section.
- Object calibration: b tag efficiency measured in-situ (freely float in the fit).
- The fit is used to constrain the uncertainties in the b tagging efficiencies and lepton selection efficiencies.



$t\bar{t}$ cross section measurement at 13.6 TeV

Source	Uncertainty (%)
Lepton ID efficiencies	1.6
Trigger efficiency	0.3
JES	0.7
b tagging efficiency	1.1
Pileup reweighting	0.5
ME scale, $t\bar{t}$	0.6
ME scale, backgrounds	0.1
ME/PS matching	0.1
PS scales	0.3
PDF and α_S	0.3
Single t background	1.0
Z+jets background	0.3
W+jets background	0.0
Diboson background	0.5
QCD multijet background	0.3
Statistical uncertainty	0.5
Combined uncertainty	2.6
Integrated luminosity	2.3



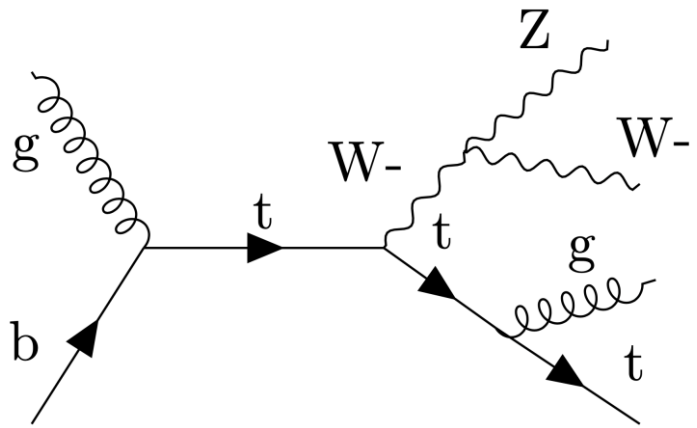
(NNLO + NNLL): $\sigma_{SM}(t\bar{t}) = 921^{+29}_{-37}$ pb $\binom{+3.5\%}{-4.4\%}$ using TOP++ v2.0

$\boldsymbol{\sigma(t\bar{t}) = 882 \pm 30\ \text{pb}\ (\pm 3.5\%)}$

Lower than theoretical uncertainty!

Evidence for tWZ production

- Very rare process (σ_{tWZ}~136 fb, at NLO in QCD).
- First tWZ evidence ever.
- New physics potential via modified interactions, good probe of EFT.
- Main background ttZ interferes with signal and has ~5 times more cross section.
  - Interference removed with DR1 method.
- **Channels**: 3ℓ and 4ℓ.
  - Two regions: low and high p_T of the top quark.
- High p_T is sensitive to EFT operators.



Evidence for tWZ production

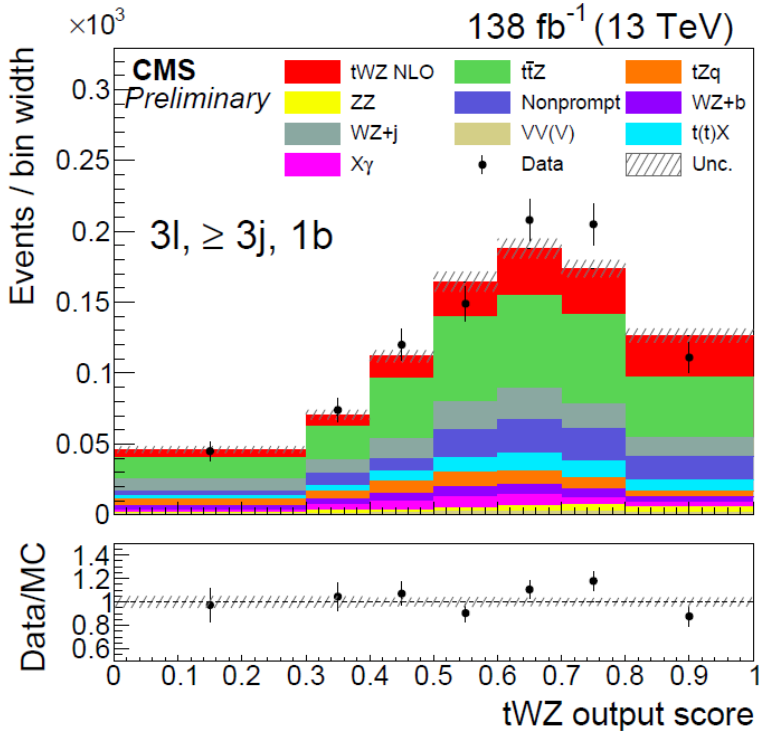
- ML fit to various distributions.
- Low p_T:
  - 3ℓ3j1b: DNN → tWZ vs ttZ vs other bkg.
  - 3ℓ 2j1b binary DNN → signal vs bkg.
  - 4ℓ 1b: b jet multiplicity.
- High p_T:
  - Hadronic and leptonic top quarks.
- CR for WZ and ZZ.

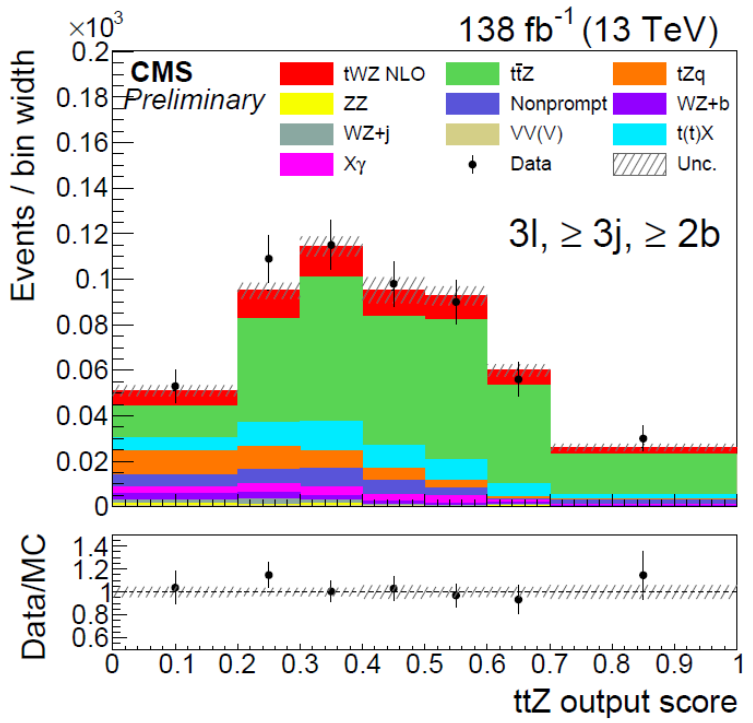
- **Result**:

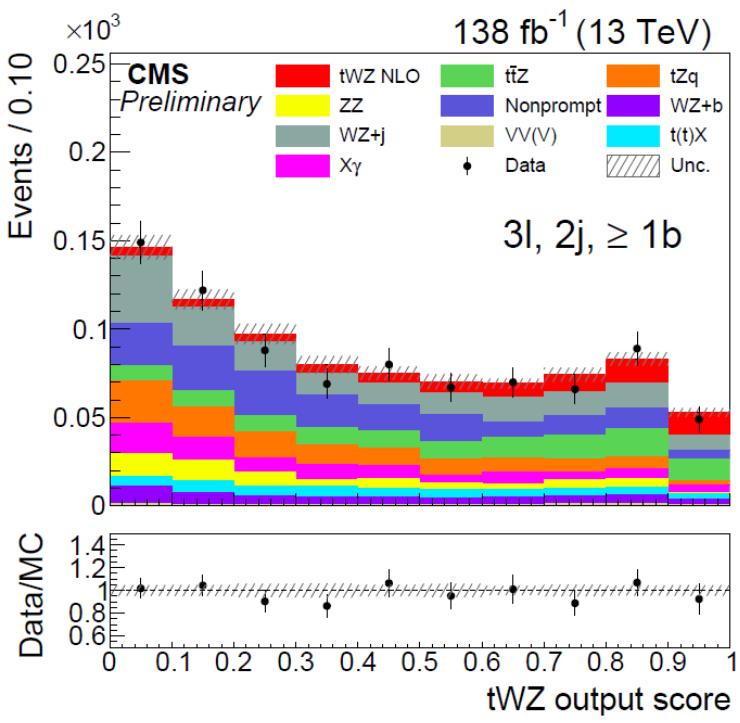
$$3.5\sigma(1.4\sigma)\text{Obs. (Exp.)}$$

$$\sigma = 0.37 \pm 0.05(\text{stat}) \pm 0.10(\text{syst})\ \text{pb}$$

$$\sigma_{SM} = 0.136\ \text{pb, NLO in QCD}$$



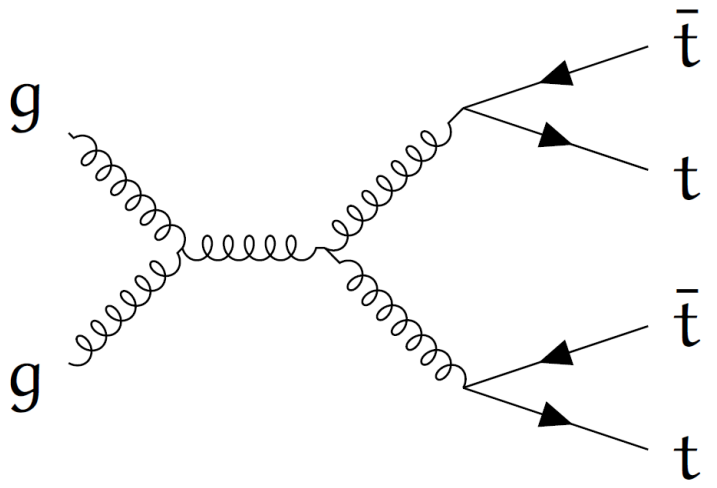




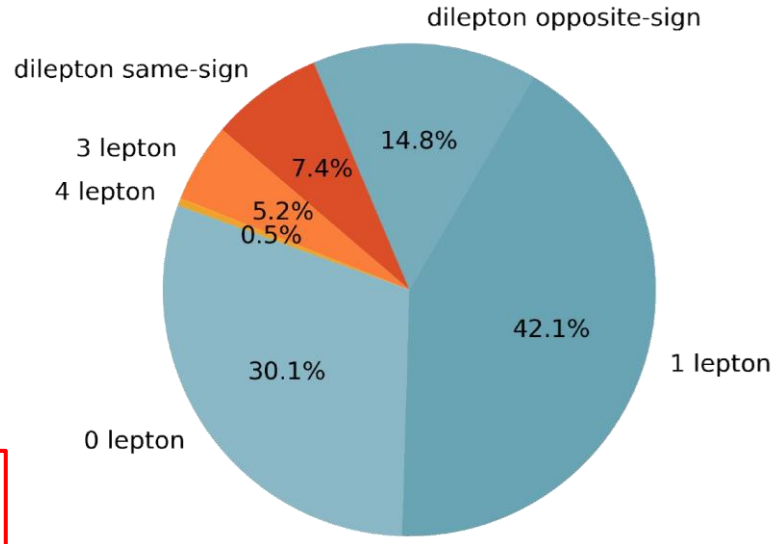
Observation of four top quark production

- One of the rarest SM processes accessible at hadron colliders.

$$(\mathrm{NLO} + NLL)\colon\ \sigma_{SM} = 13.4^{+1.0}_{-1.8}\ \mathrm{fb},$$ arXiv:2208.04962



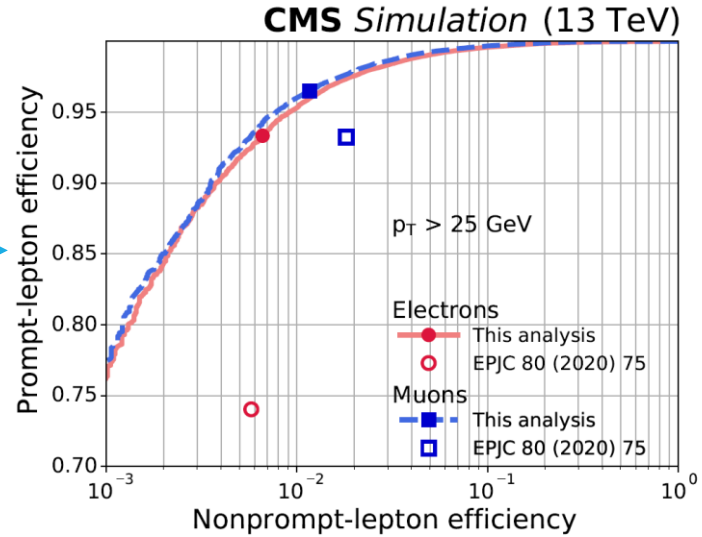
- Mainly produced via strong interaction.
- Deviations from the expected cross section may indicate **BSM physics**:
  - Four tops can be produced via SUSY particles.
  - This would increase the observed cross section.
- Optimization of 2020 analysis (Eur. Phys. J. C 80 (2020) 75):
  - Lepton MVA-based ID → reduce non-prompt leptons.
  - B-tagging algorithm → DeepJet.

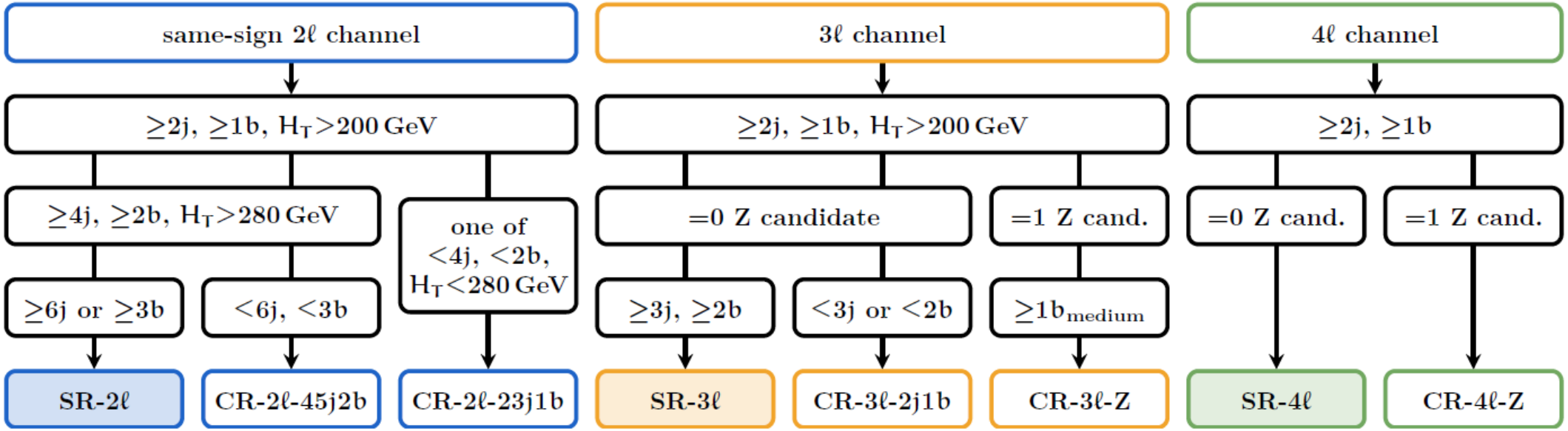


Evidence in the all-hadronic channel:
- arXiv:2303.03864
- Higher BR but larger background.

Observation of four top quark production

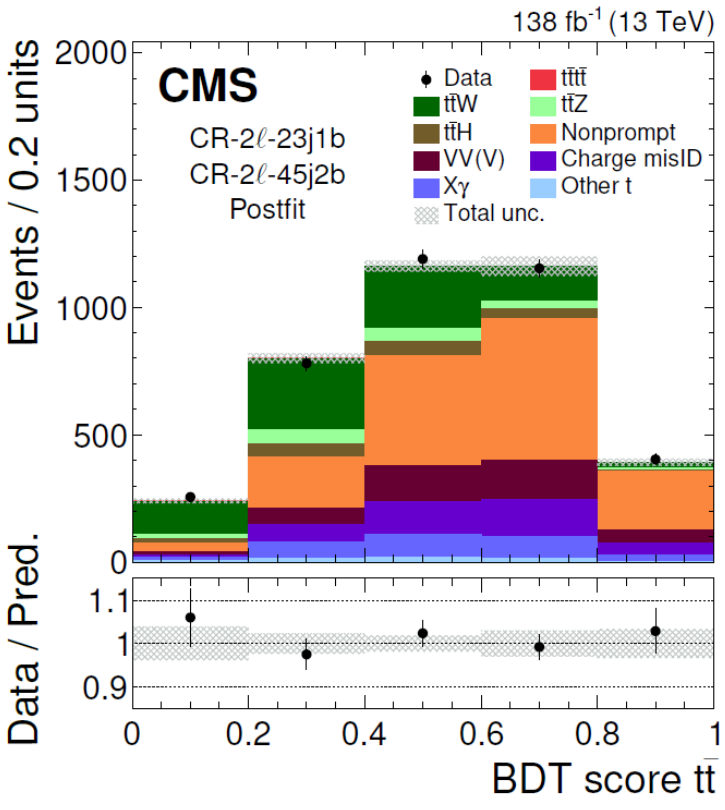
- Events with 2 same signed, 3 or 4 leptons are analysed.
- Main background ttX and non-prompt leptons.
  - Non-prompt lepton backgrounds reduced with MVA techniques.
- Non-prompt and charge misID estimated from data.

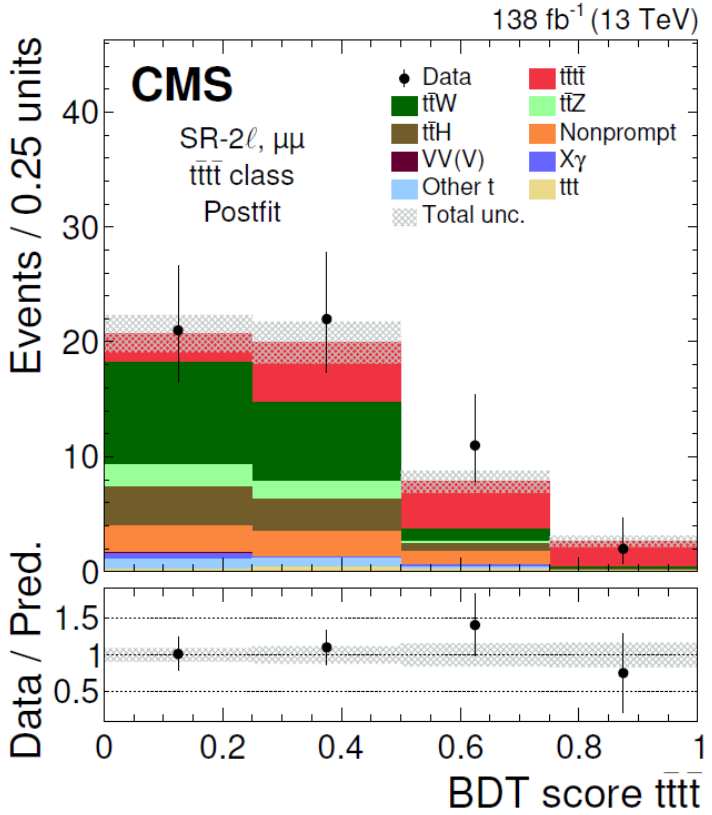


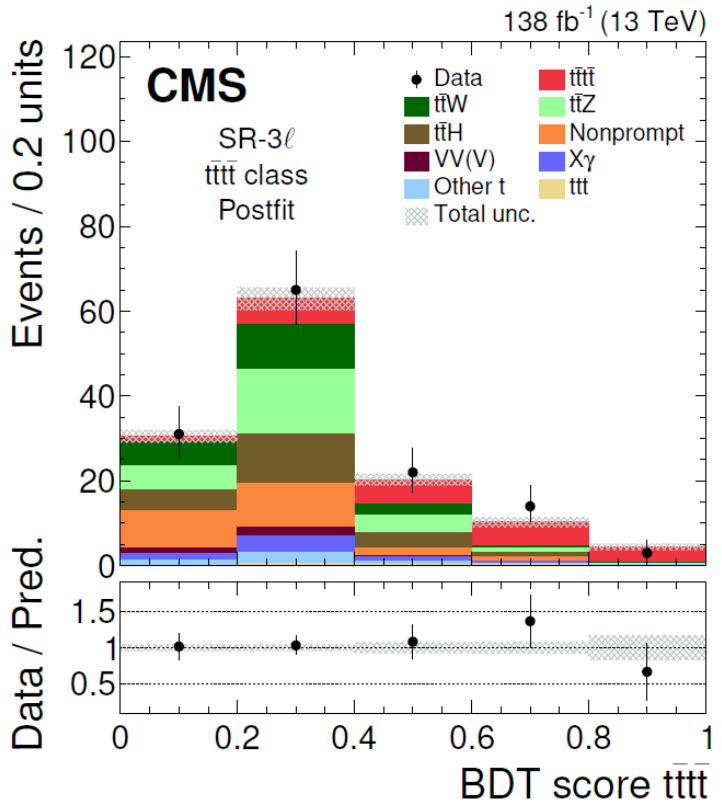


Observation of four top quark production

- Multiclassification using separate BDTs in the 2ℓss and 3ℓ & 4ℓ channels.
  - tttt-like.
  - ttX-like.
  - tt-like.





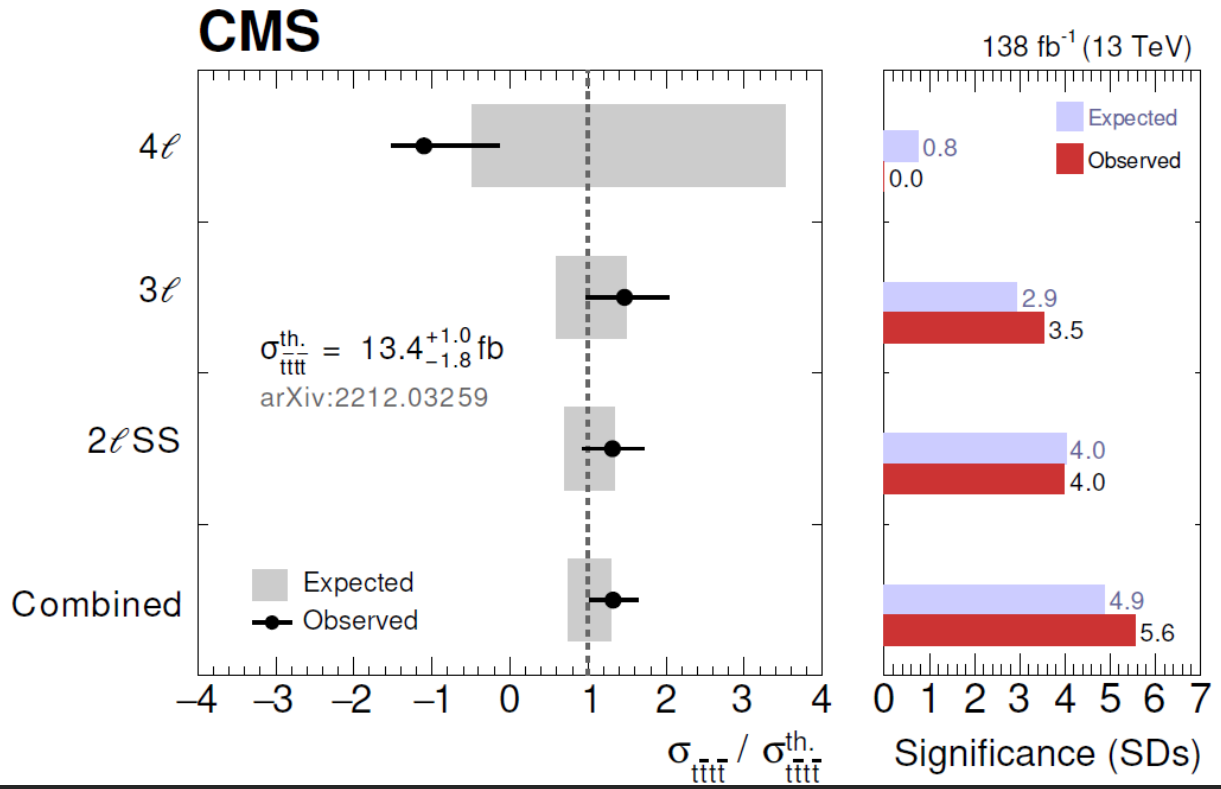


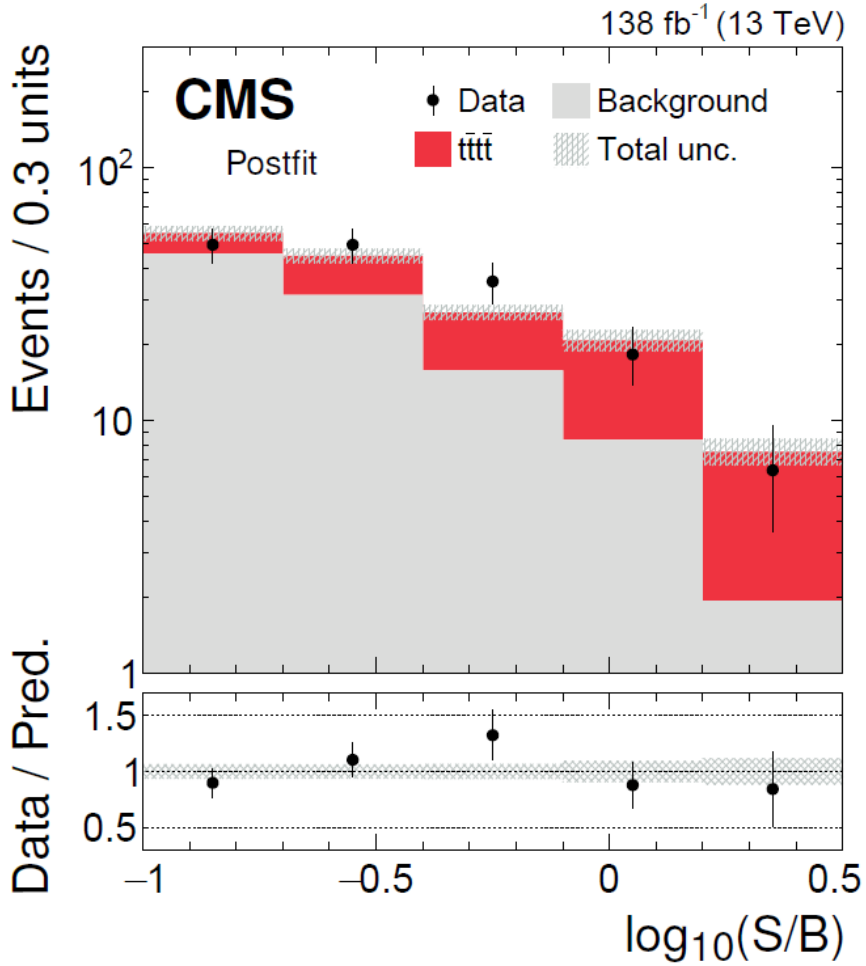
Observation of four top quark production

- $\sigma(tttt) = 17.7^{+3.7}_{-3.5}(\text{stat})^{+2.3}_{-1.9}(\text{sys})\text{fb} = 17.7^{+4.4}_{-4.0}\text{fb}$

Limited by statistical uncertainty

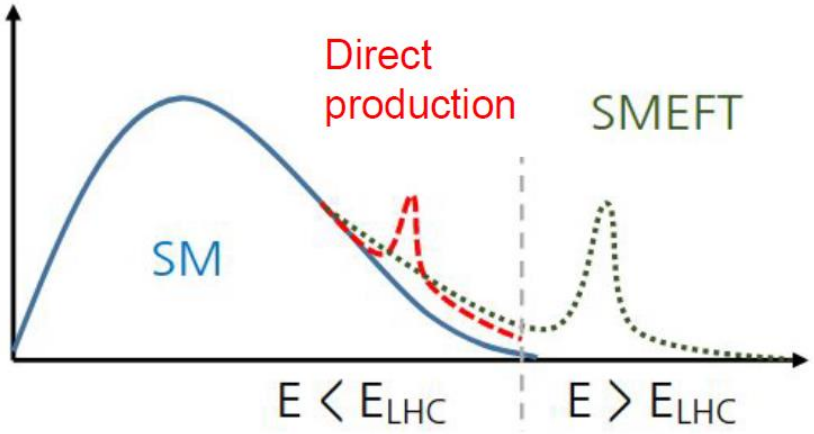
- ttW and ttZ freely floating in the fit:
  - $\sigma(ttW) = 990 \pm 58(\text{stat}) \pm 79(\text{syst})\text{fb}$
  - $\sigma(ttZ) = 945 \pm 43(\text{stat}) \pm 69(\text{syst})\text{fb}$

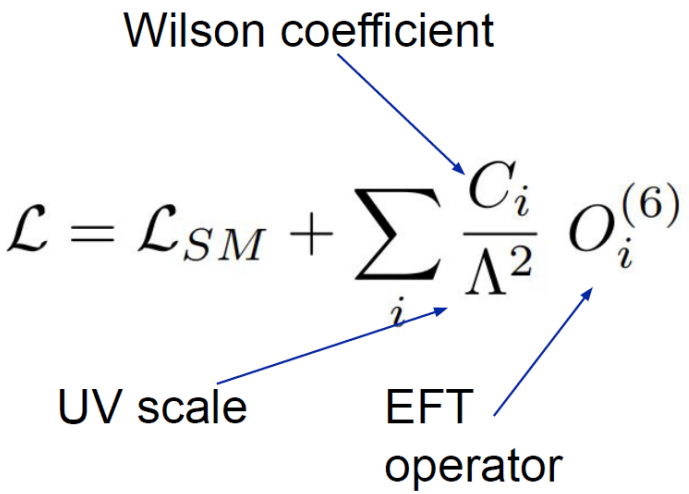




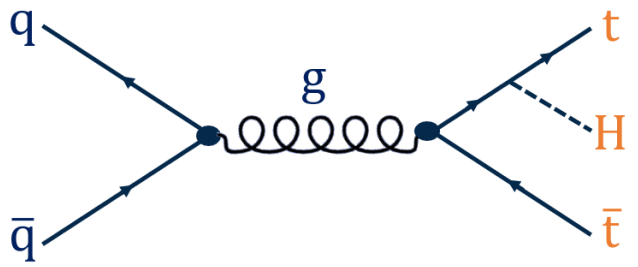
Search for EFT in top quark production

- Lack of clear evidence of new physics at the LHC.
- New physics may lie above the experimental energy scale.
- SMEFT extends the SM Lagrangian with higher dimensional operators that describes physics at a scale Λ interacting with a strength determined by a dimensionless parameter called **Wilson coefficient**.
- EFT can contribute to many top quark production modes.
- They affect differently each process.
- The nature of the true UV theory is unknown:
  - Need to be comprehensive → consider all operators simultaneously.
- We focus on multilepton final states.

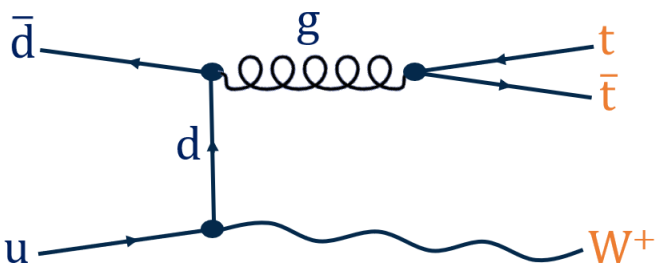




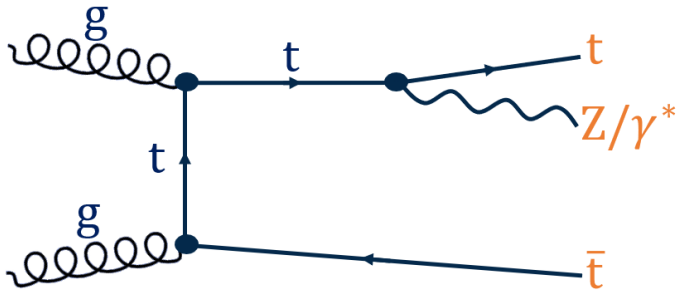
Search for EFT in top quark production



ttH

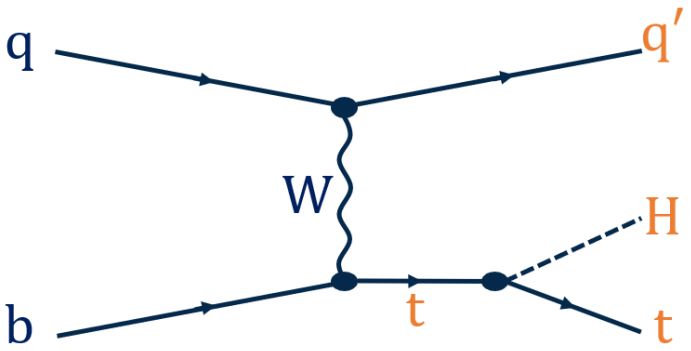


ttW

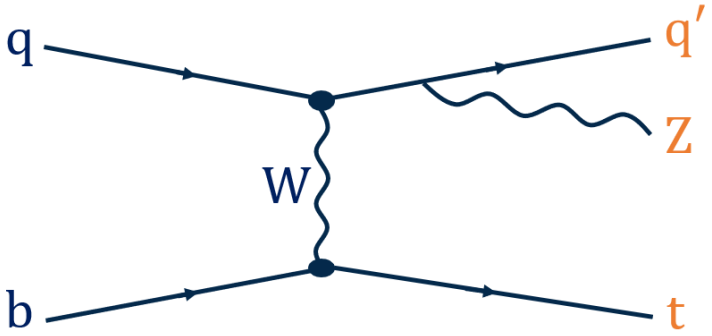


ttZ

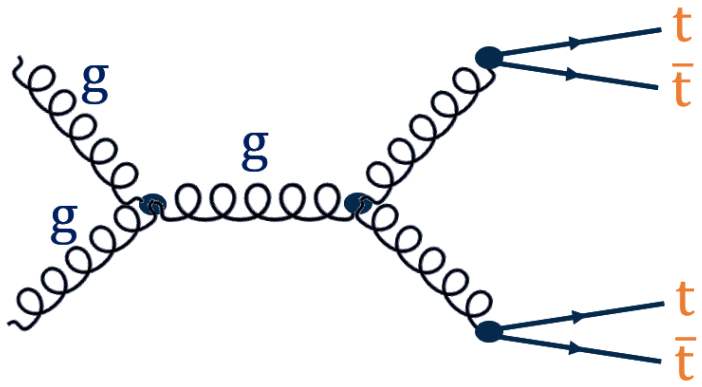
New result studying all these processes simultaneously



tHq



tZq

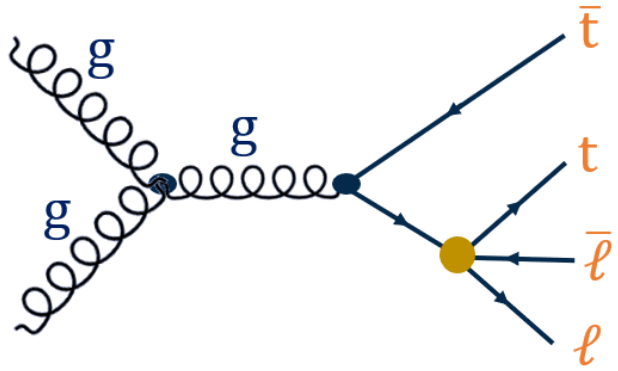


tttt

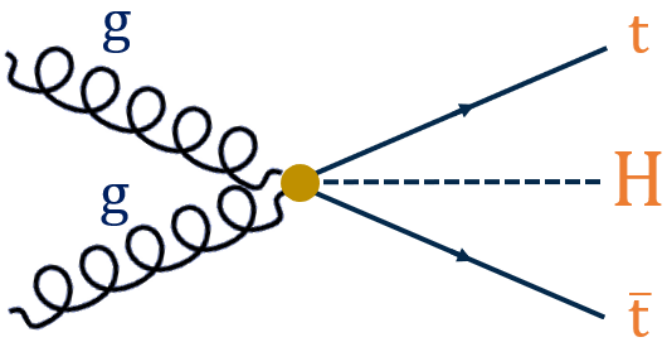
Search for EFT in top quark production

- **26 WC** are considered in the analysis.

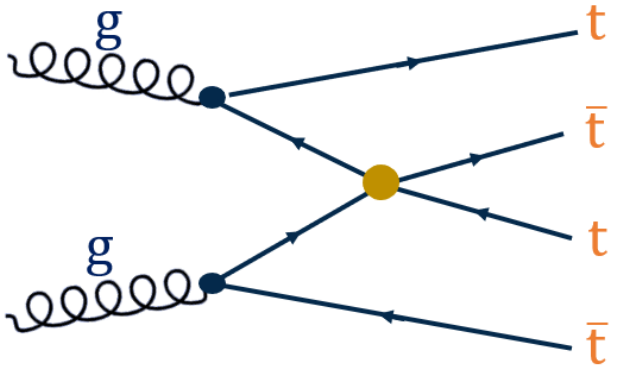
2 top + 2 lepton operators (7 WC)



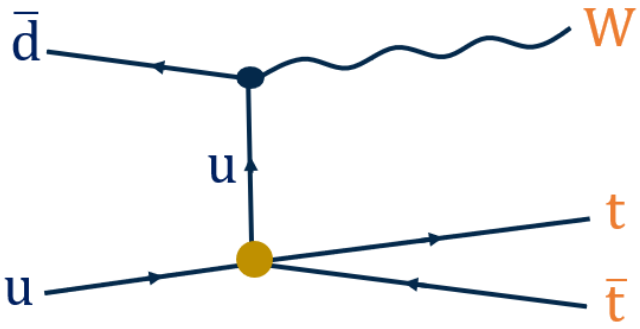
Top + boson operators (9 WC)



4 heavy quark operators (4 WC)

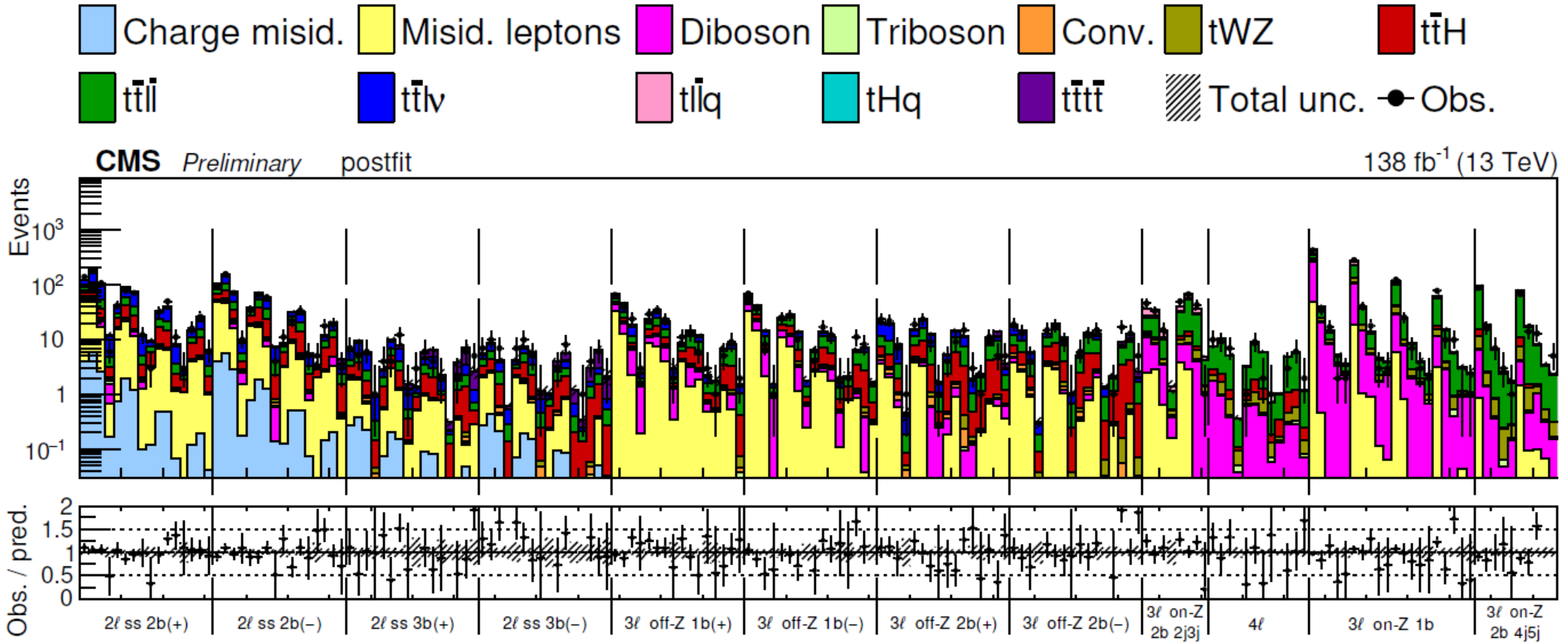


2 light + 2 heavy quark operators (6 WC)



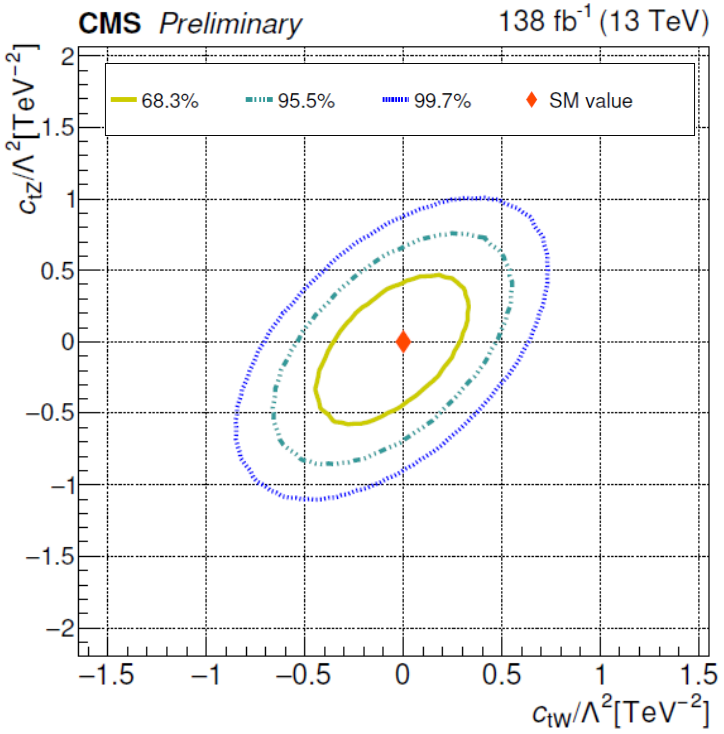
Search for EFT in top quark production

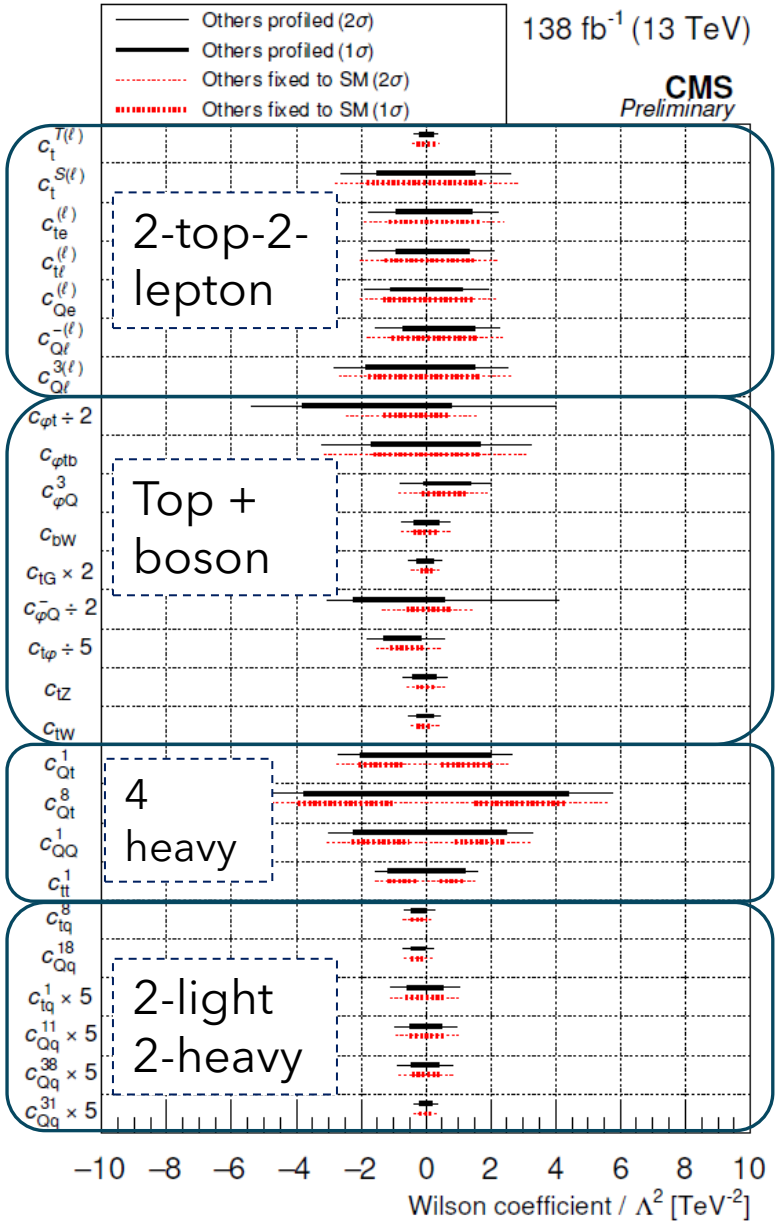
- **43 categories**: events with 2ℓss, 3ℓ or 4ℓ leptons.
- Additional splits in N_{jets}, N_{jets}^{b} , on/off Z and charge sum.
- Different variables in each region depending on the targeted operators → 178 bins.



Search for EFT in top quark production

- **Results are consistent with the SM**.
- Limits on WC are obtained assuming $\Lambda = 1$ TeV.
- Setting constraints on Wilson coefficients.
  - Measuring a single coefficient at a time.
  - Measuring all of them simultaneously.





Summary

- LHC provided the largest top quark data sets ever!
- LHC ≡ Top quark factory.
  - Precision lab for studying top quark production & properties.
  - Portal to new physics beyond SM.
- Many measurements with Run-2 data confirm good agreements with SM expectations.
- The very first look of the Run-3 data gives the results at the highest CM energy in record!
- Run-3 has started, the best is yet to come!

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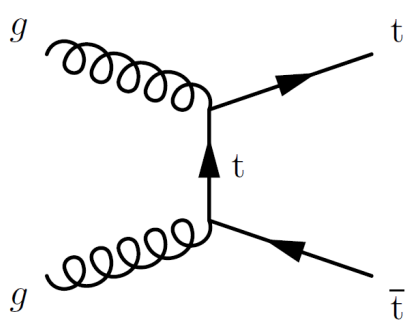

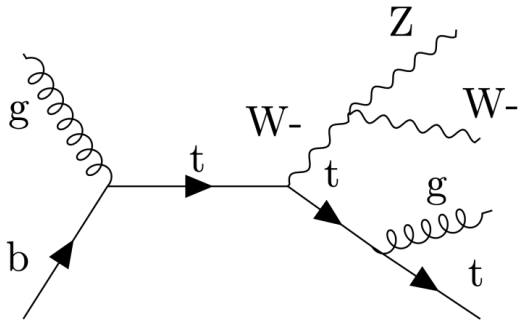

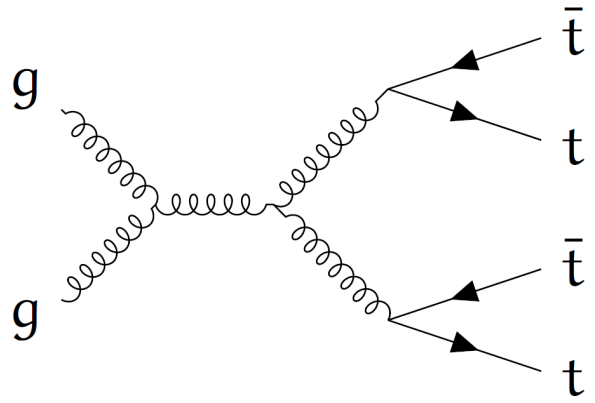

Thank you!