Rare production of top quarks at the LHC

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Seminar, LPC, Clermont

Outline

- 1 – Physics at high energy
  - Standard model and its limitations
  - LHC, ATLAS and CMS, Top physics
- 2 – Top quarks + Higgs
  - ttH and Higgs coupling measurements
- 3 – Four top quarks
  - 4-top measurements – New evidence
- 4 – Top quarks + Bosons
  - ttV measurements
  - Recent theoretical developments
- Conclusion

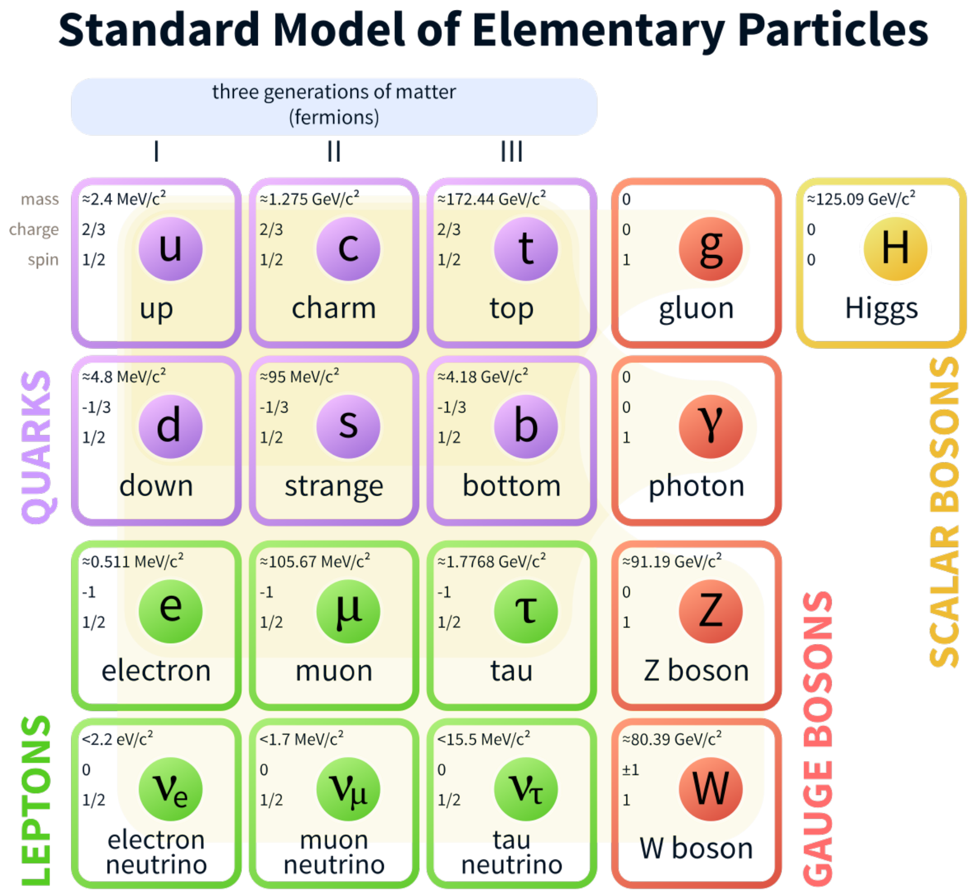
1 – The physics at high energy

The Standard Model and its limitations

- The Standard Model (SM) has been successful in predicting many experimental results with an extreme accuracy

- However, it contains a number of theoretical and experimental limitations
    - Gravity, hierarchy problem, dark matter, baryonic asymmetry

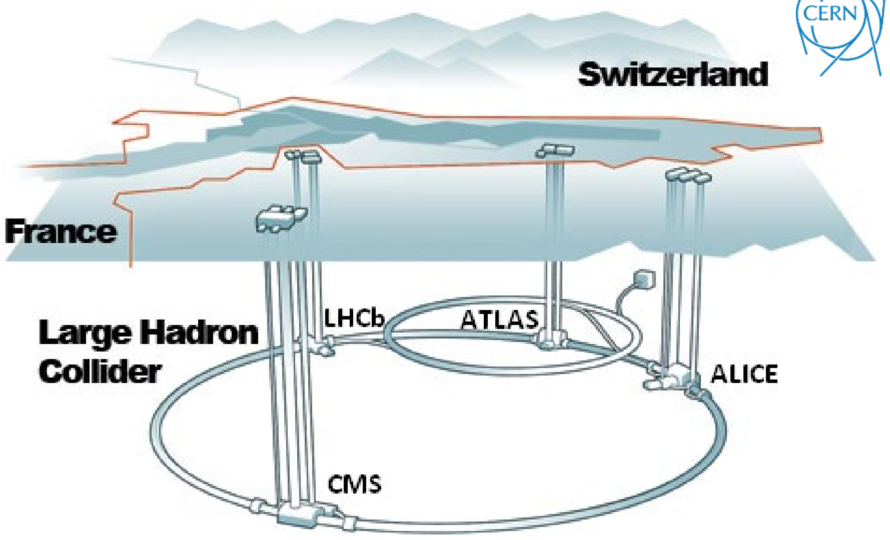
➢ The SM is an *effective theory* (i.e. only valid at low energy)
    - There is a scale $\Lambda_{\text{New Physics}}$ where the SM will fail to predict the experimental results



Exploring high energy physics with the LHC

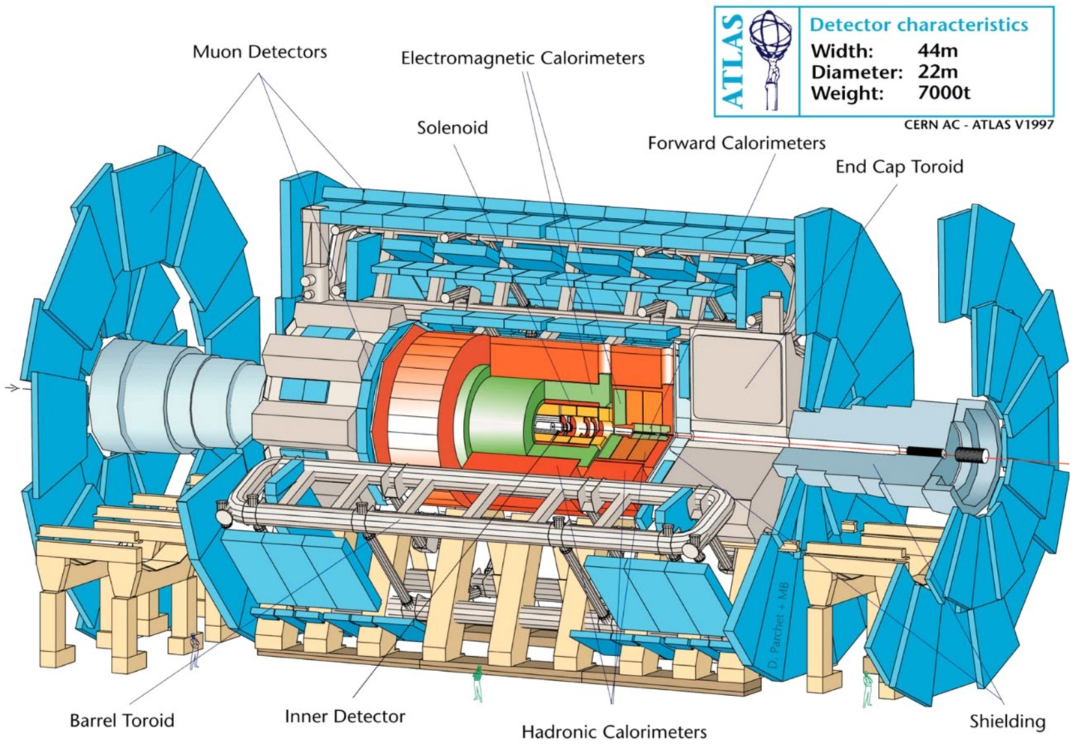
- LHC: Large Hadron Collider
  - Largest and most powerful particle accelerator
  - Proton-proton (or lead-lead) collisions at 13 TeV
  - 40M collisions per second

- Four main experiments:
  - ***ATLAS* and *CMS***: multi-purpose detectors
  - *LHCb*: flavor physics, b-quark sector physics
  - *ALICE*: heavy ions physics

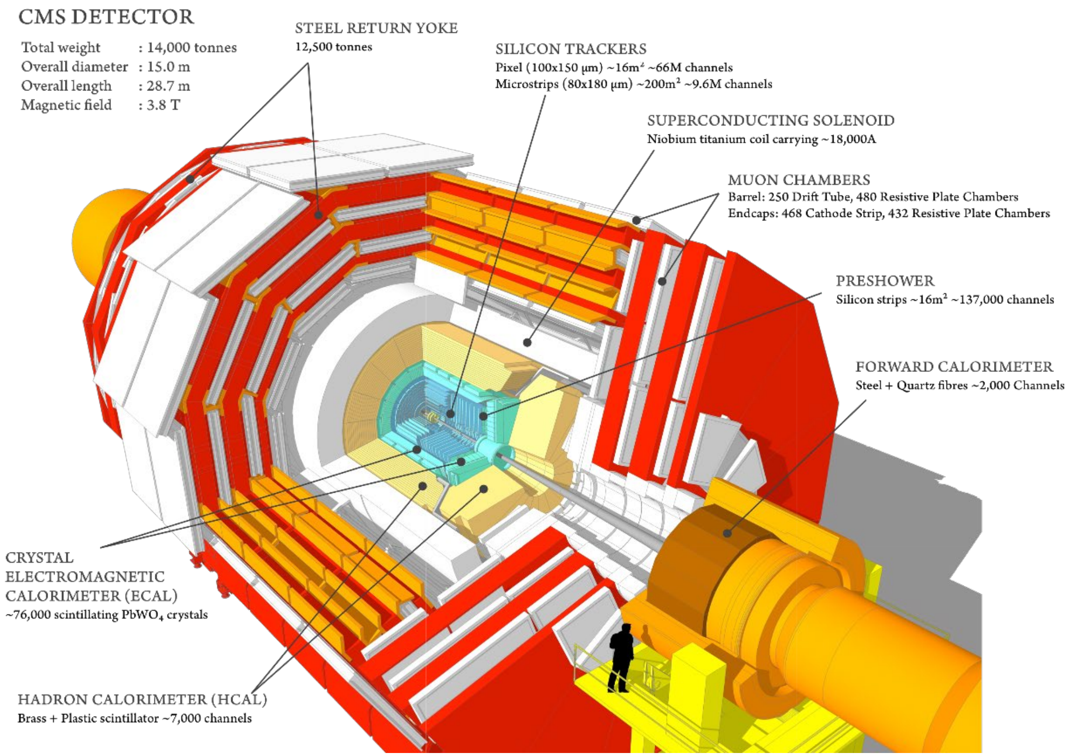


The ATLAS and CMS experiments

The ATLAS detector:

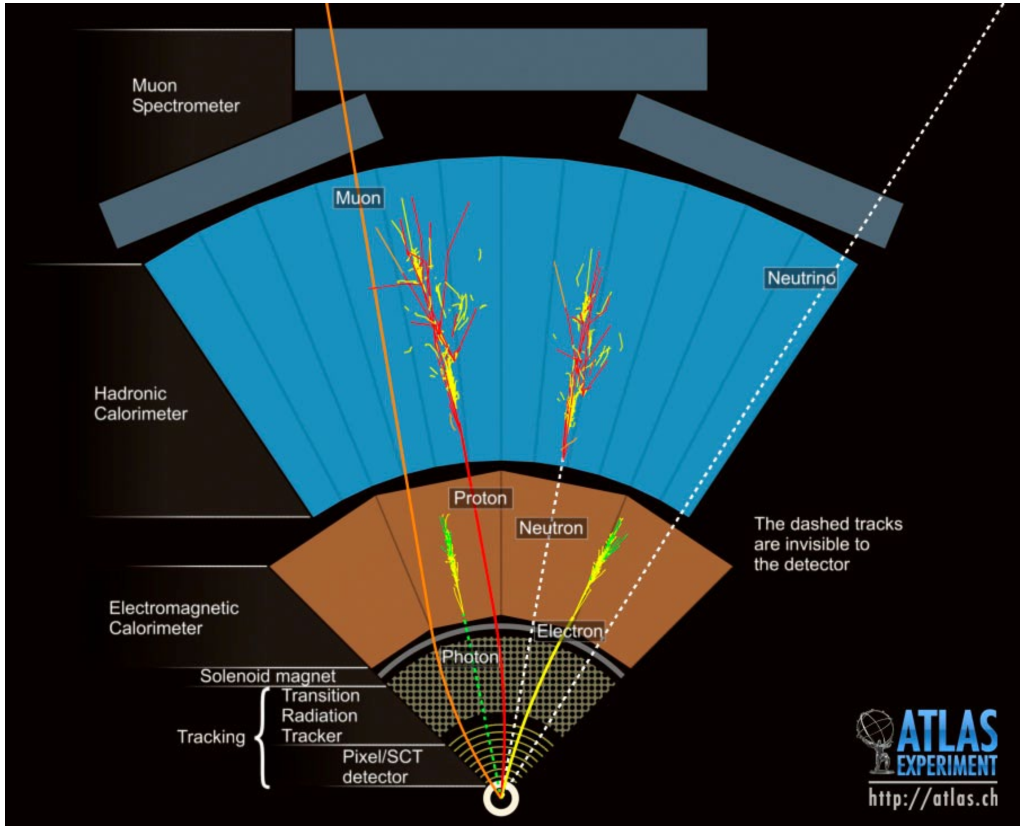


The CMS detector:

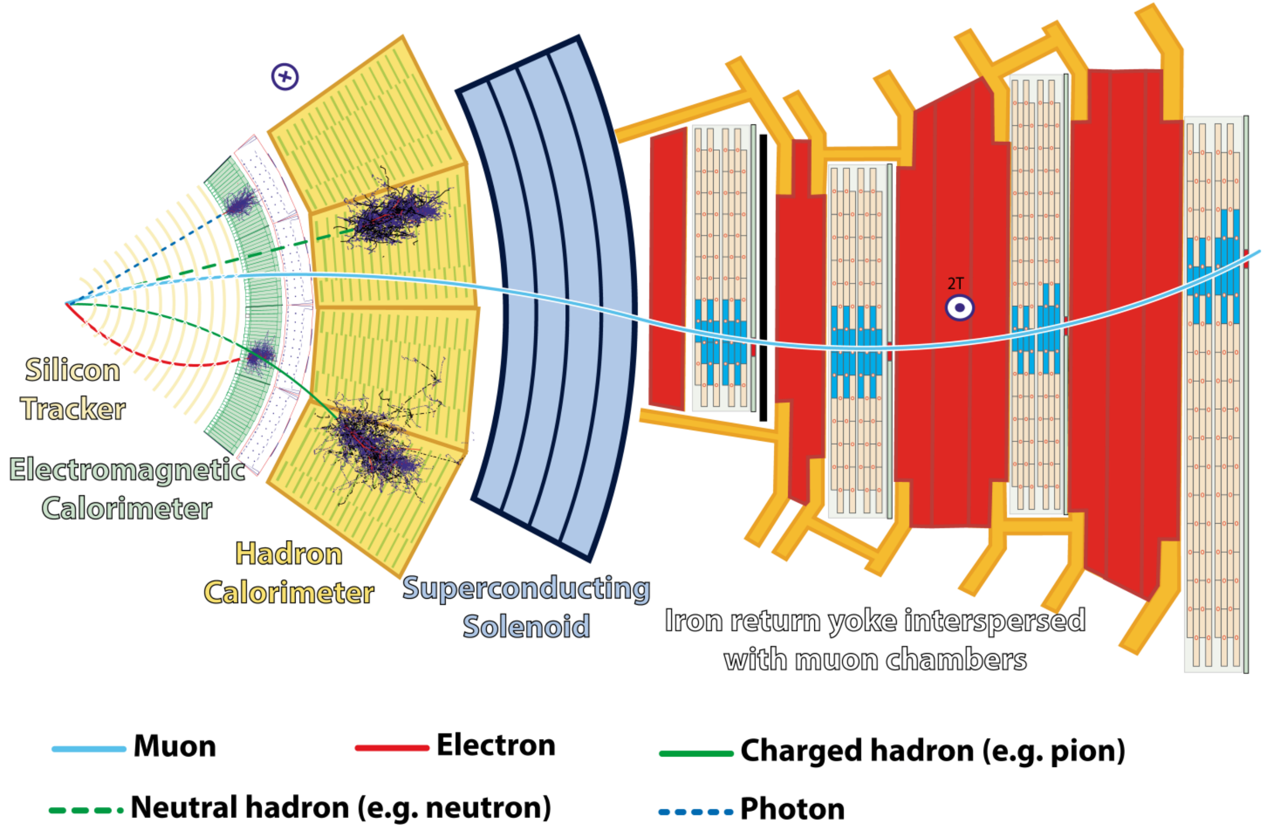


Detecting particles

Particle detection in ATLAS:

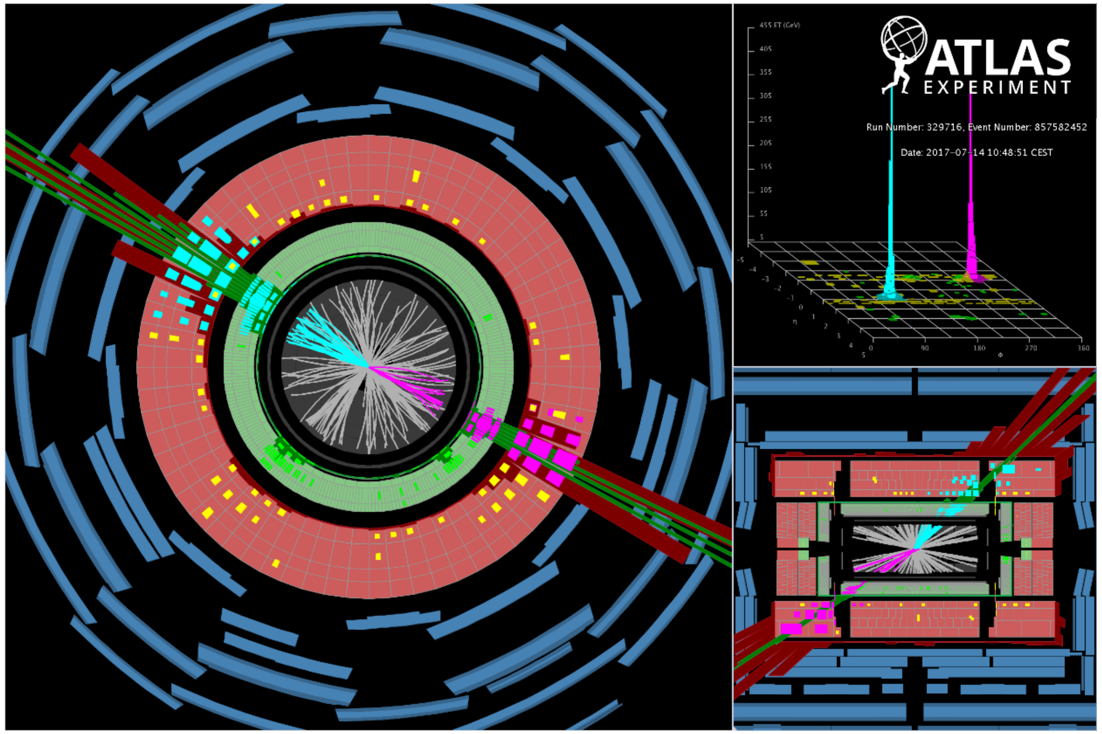


Particle detection in CMS:

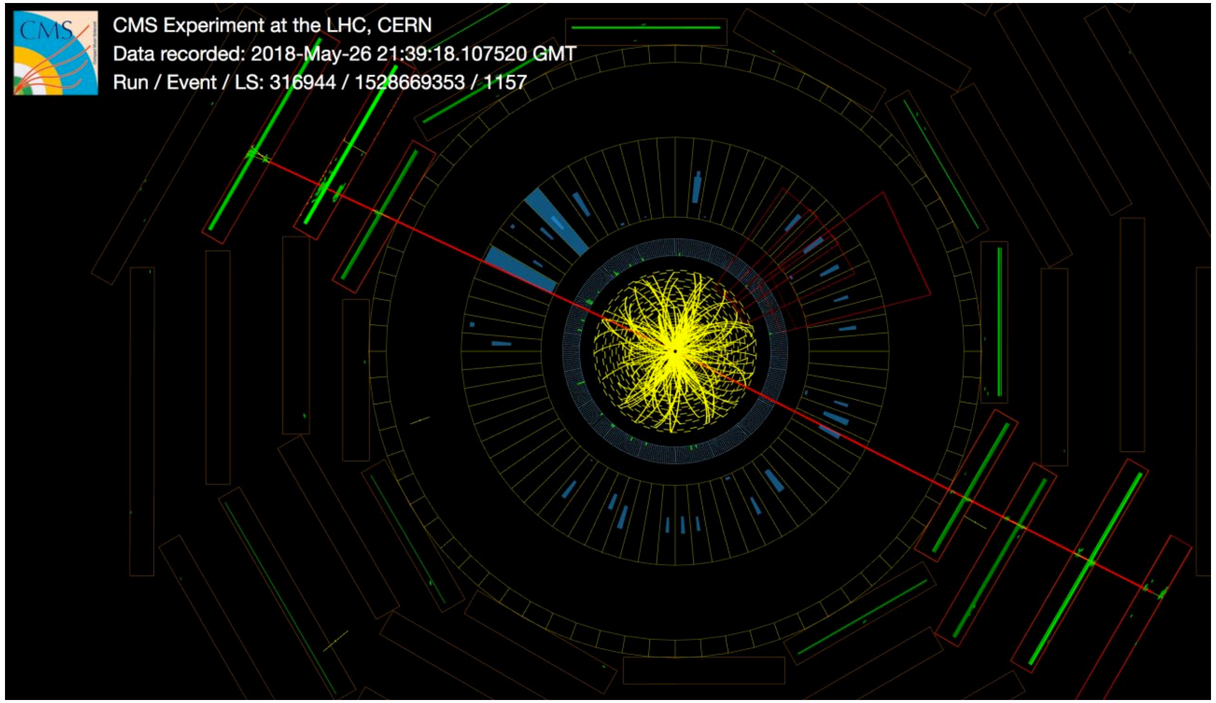


Examples of event display

Di-jet event with m_{jj}=9.3 TeV



Di-muon event with $m_{\mu\mu}$=3.1 TeV

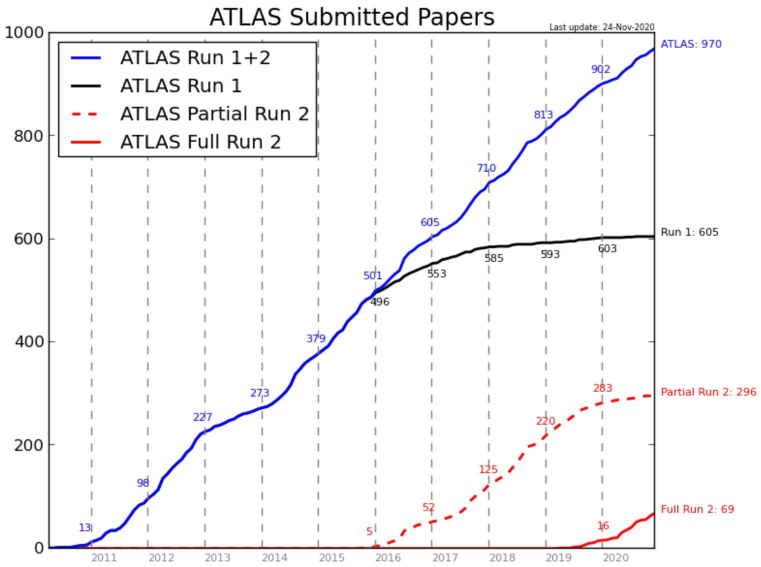


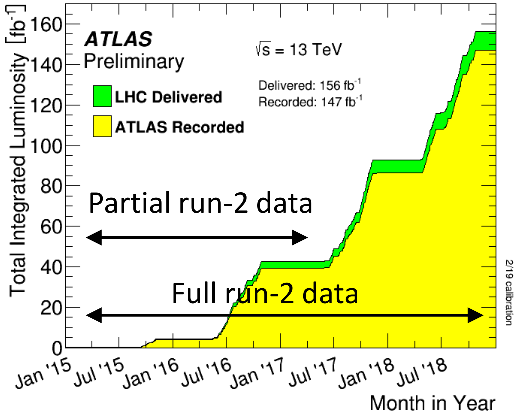
LHC operations and achievements

LHC Timeline:

HL-LHC: High Luminosity LHC
LS: Long Shutdown
TeV: Tera electron Volt

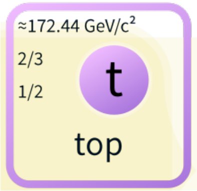
- Run 1 :
  - Higgs discovery (2012)
  - Standard model measurements
  - Search for new physics
- Run 2 :
  - Higgs precision measurements
  - New physics scenario exclusion
  - Rare standard model process



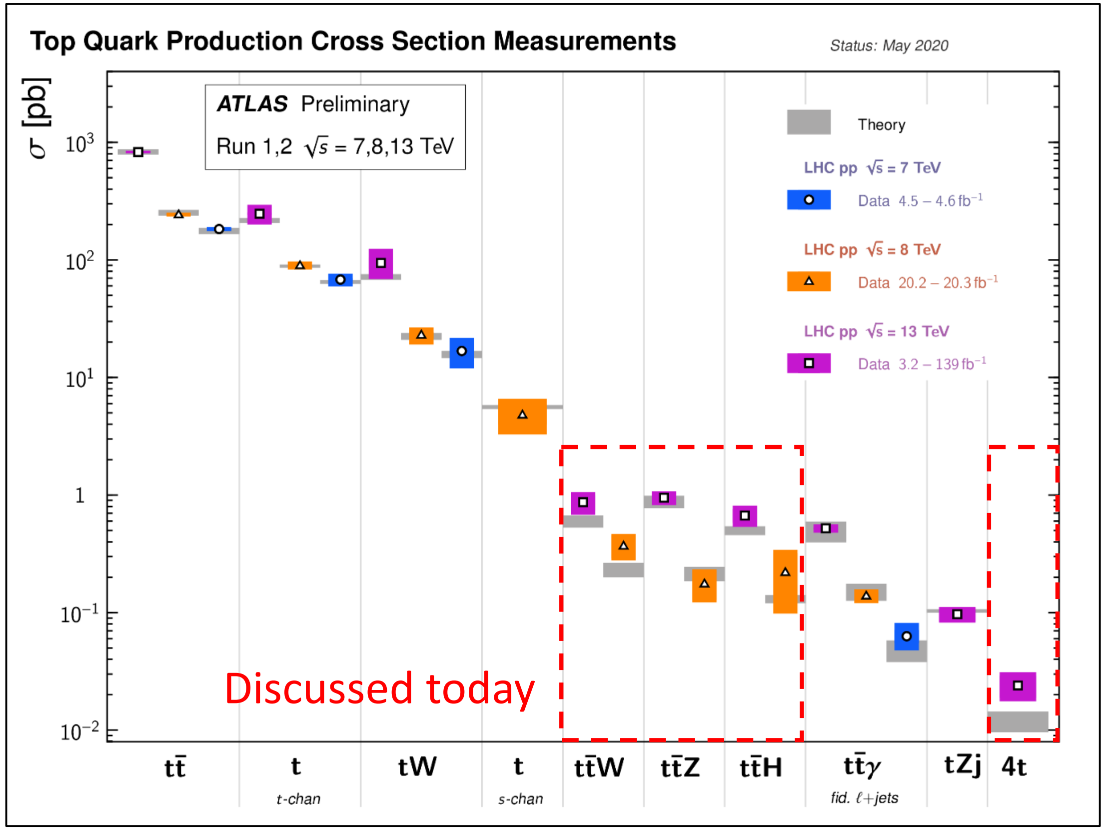


Top quark physics

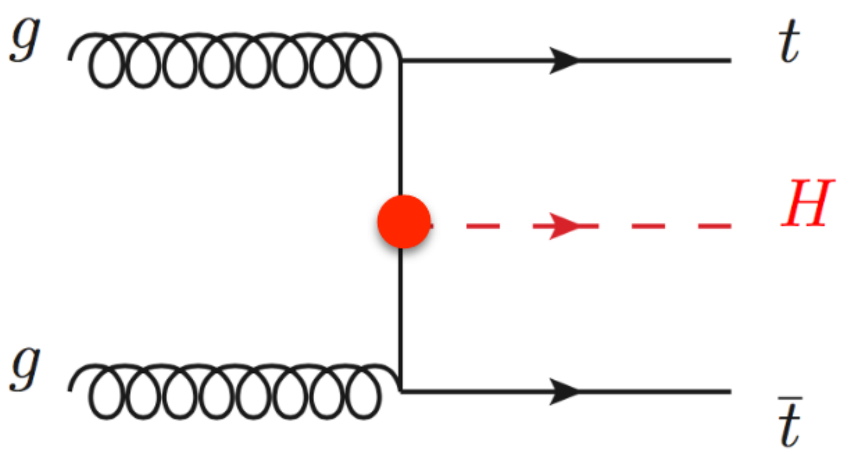
- Top quarks :
  - Relatively easy to identify at the LHC thx to its electroweak decay
  - Has an important role in many BSM scenarios due to its high mass and high yukawa coupling

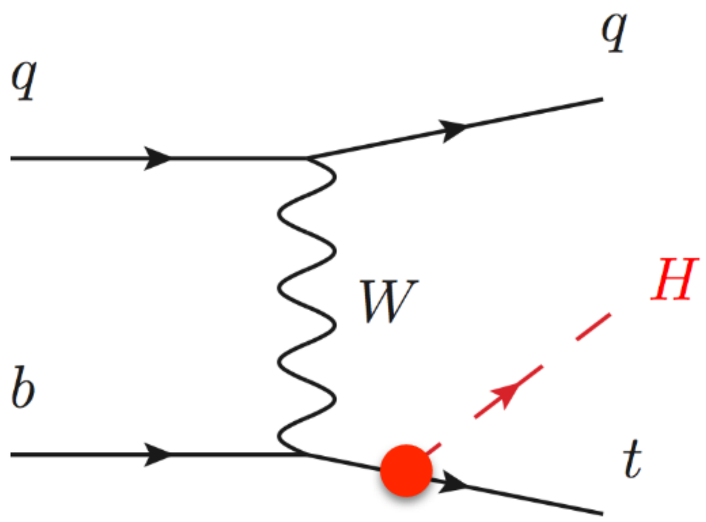


➢ Top quark physics is one of the main program of research at the LHC
  - Measure the different modes of top quark production (ttbar, single top, tt+X)
  - Study the different properties of the top quark (mass, coupling, polarization, etc)
  - Look for BSM production modes (via SUSY scenarios, VLQ, etc)



2 – Top quarks + Higgs



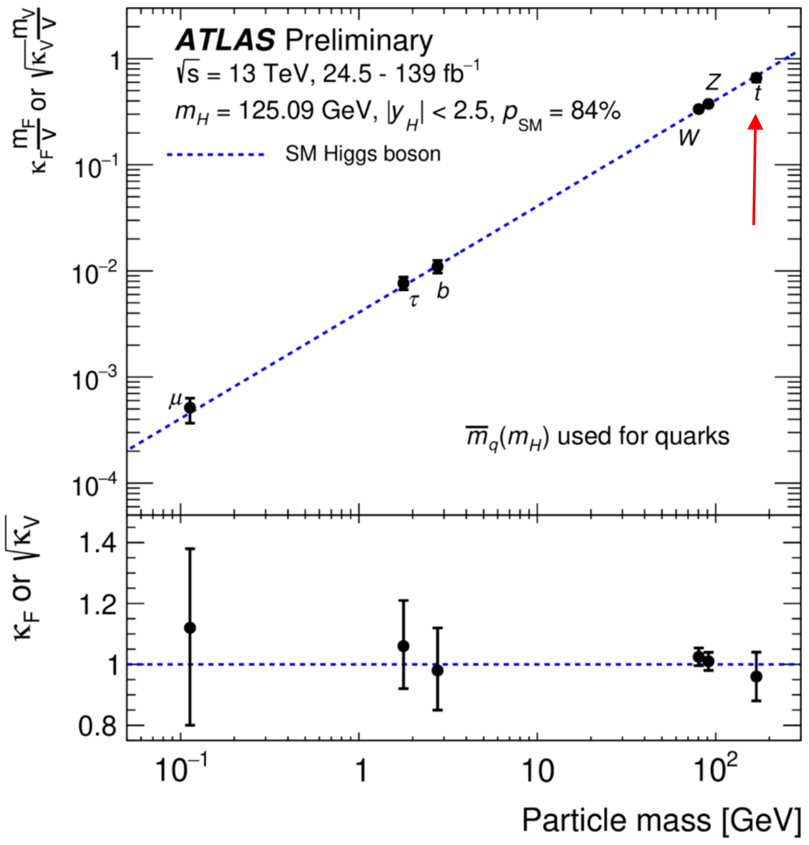


The Higgs coupling

- Higgs coupling measurements:
  - Stringent test of the validity of the SM, verifying the Higgs mechanism
  - Constrained by the measurements of the different Higgs production and decay modes

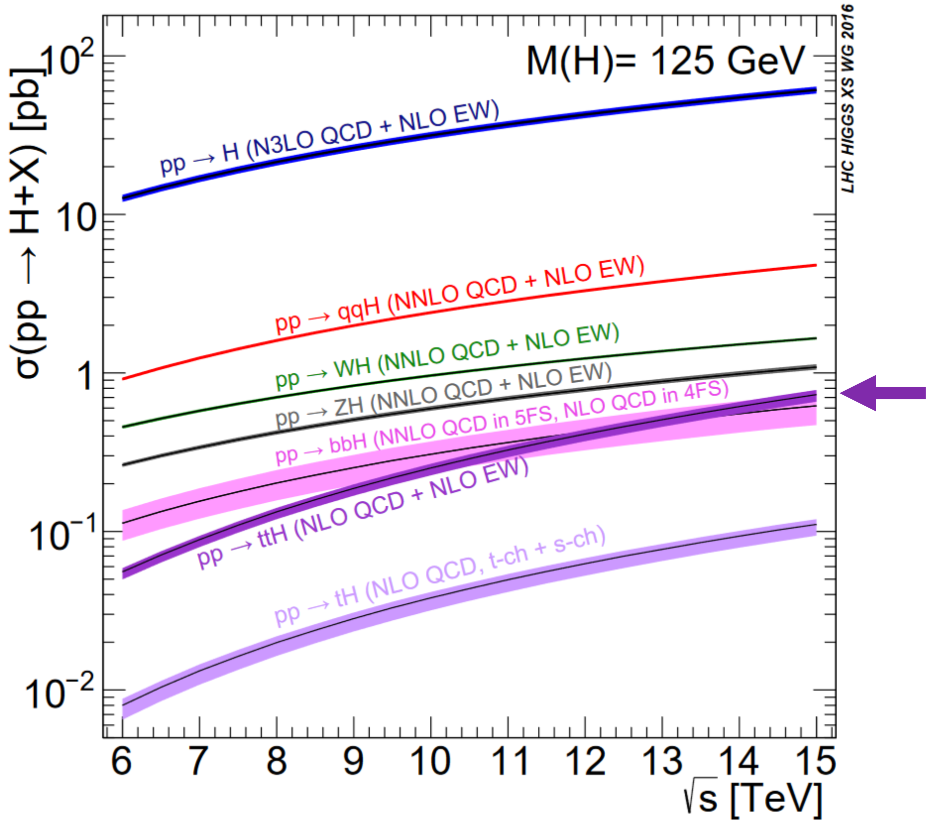
- The top yukawa coupling y_t:
  - Largest Higgs coupling of the SM (due to the large top quark mass)
  - SM parameter that has a key role in many BSM model (hierarchy, Higgs stability)

Tree-level Higgs coupling:

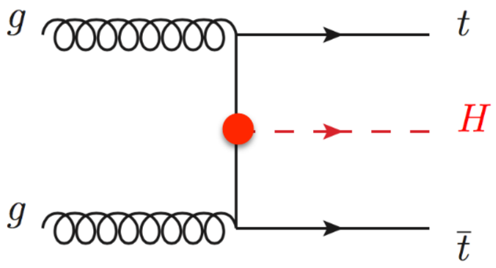


ATLAS-CONF-2020-027

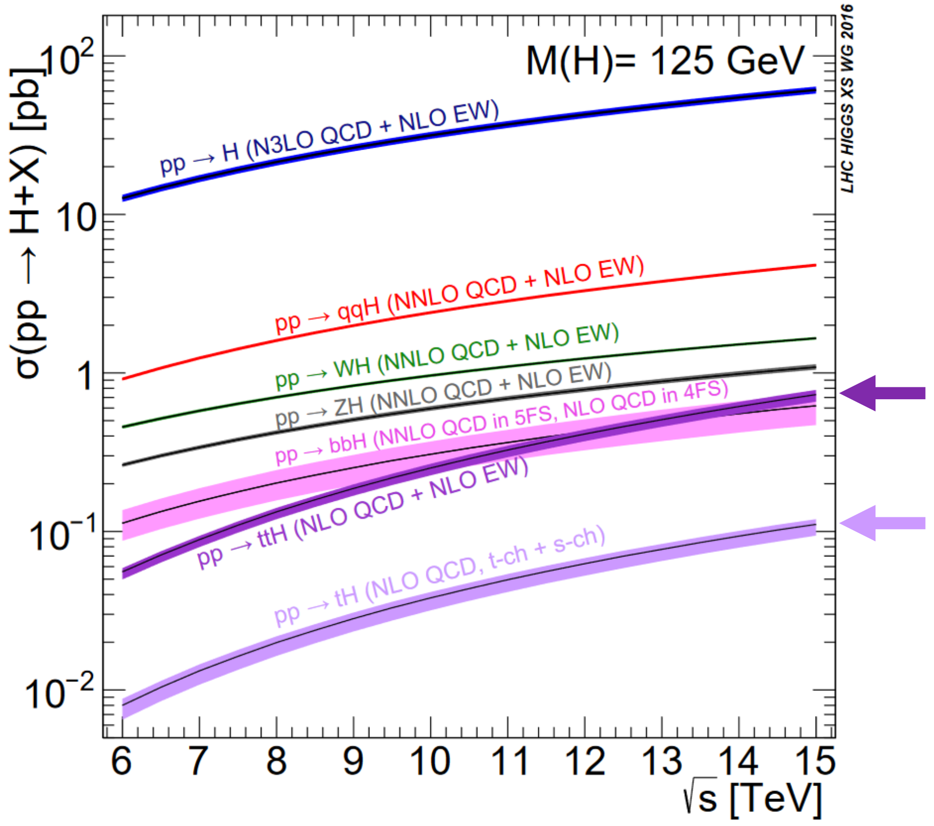
ttH and tH searches



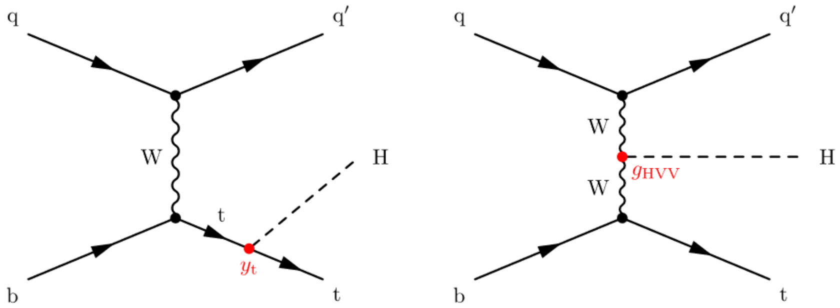
- Higgs and a top quark pair (ttH):
  - Provide a model-independent way to measure the y_t magnitude
  - Low cross section compared to the other production modes



ttH and tH searches

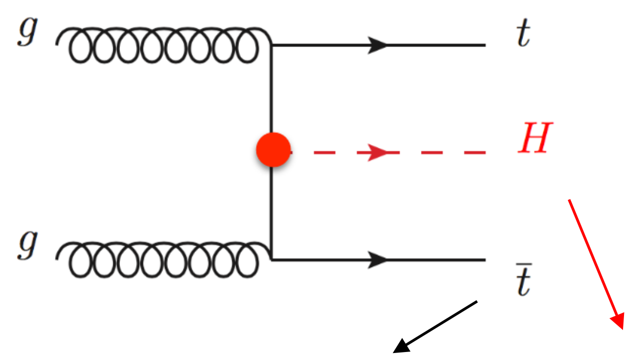


- Higgs and a top quark pair (ttH):
  - Provide a model-independent way to measure the y_t magnitude
  - Low cross section compared to the other production modes
- Higgs and a single top quark (tH):
  - Constrain the y_t sign due to the y_t vs g_{HVV} interference



ttH/tH signatures

- Rich and complicated phenomenology
  - Many possible signatures, with large object multiplicity
  - With large variety of background sources

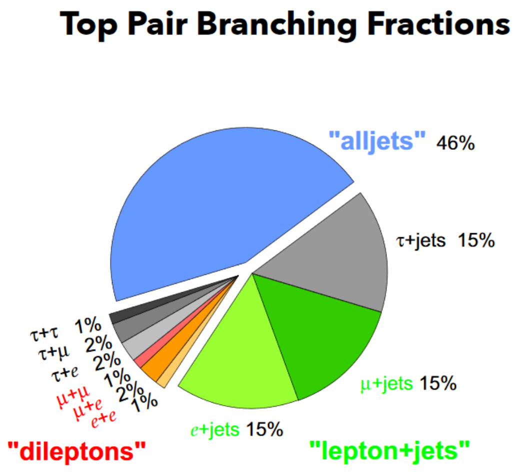


- Covered higgs decay channel by ATLAS and CMS:

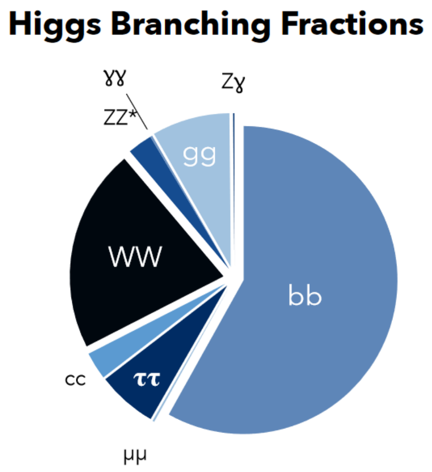
More significant ↑

  - $H \to \gamma\gamma$: very clean signature, but small signal rate
  - $H \to ZZ^* \to 4\ell$: clean signature and small signal rate
  - $H \to WW^*, ZZ^*, \tau\tau$ (multilepton): Larger signal rate, but larger background yield (with non-prompt)
  - $H \to bb$: Highest signal rate, but very large bkg contamination

➢ Measurement combination



X



Combined measurements

- ATLAS measurements:
  - Measured signal strength:

    $$\mu_{ttH+tH} = \sigma_{ttH+tH}/\sigma^{SM}_{ttH+tH} = 1.10^{+0.21}_{-0.20}$$

  - Top-Higgs coupling-strength (combined with other Higgs measurements):

    $$K_t = 0.96 \pm 0.08$$

- CMS measurements:
  - Measured signal strength:

    $$\mu_{ttH} = \sigma_{ttH}/\sigma^{SM}_{ttH} = 1.14^{+0.21}_{-0.20}$$

  - Top-Higgs coupling-strength (combined with other Higgs measurements):

    $$K_t = 1.01 \pm 0.11$$

  - Positive K_t preferred by 1.5σ

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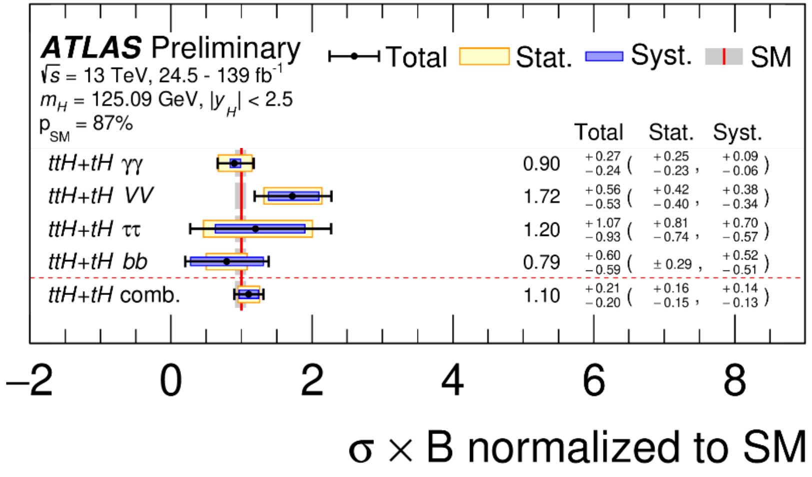
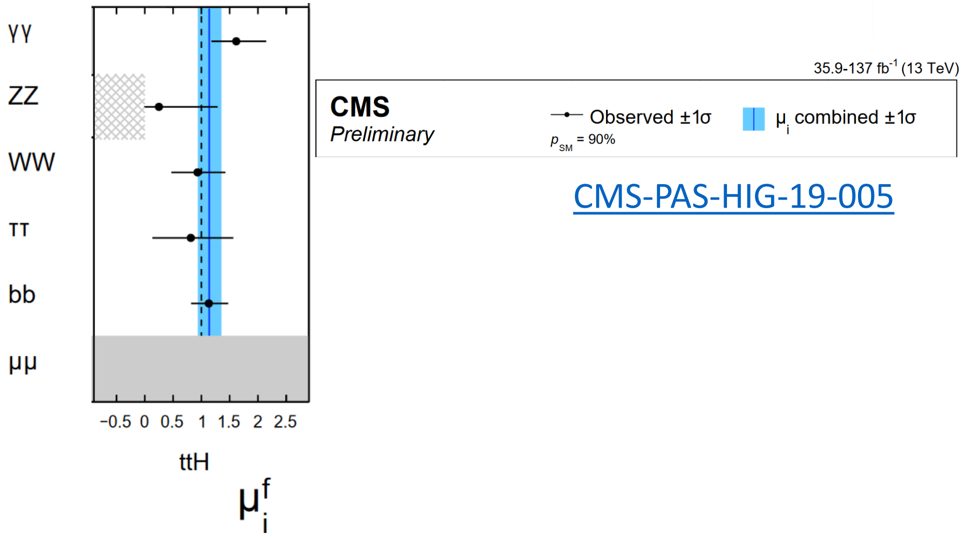
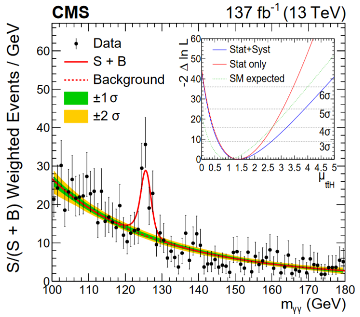




CMS-PAS-HIG-19-005

Constraint on the CP structure

CMS measurements:



- CP-structure in ttH parametrized as:

$$\mathcal{A}(\mathrm{Htt}) = -\frac{m_t}{v}\bar{\psi}_t\left(\kappa_t + i\tilde{\kappa}_t\gamma_5\right)\psi_t$$

- CP-odd/CP-even mixing parametrized by:

$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t)$$

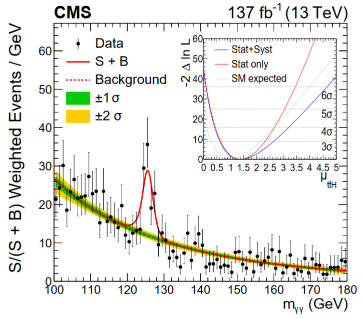
  - f_{CP}^{Htt}=0 being CP-even (SM)

- Constraints from ttH($H \to \gamma\gamma$):
  - Pure CP-odd (f_{CP}^{Htt}=1) excluded with 3.2σ
  - Measured: $f_{CP}^{Htt} = 0.00 \pm 0.33$ at 68% CL

PRL 125 (2020) 061801

Constraint on the CP structure

CMS measurements:



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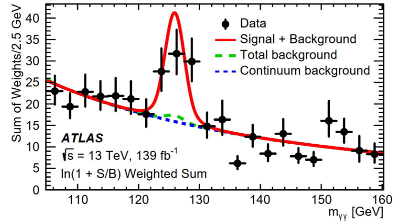
PRL 125 (2020) 061801

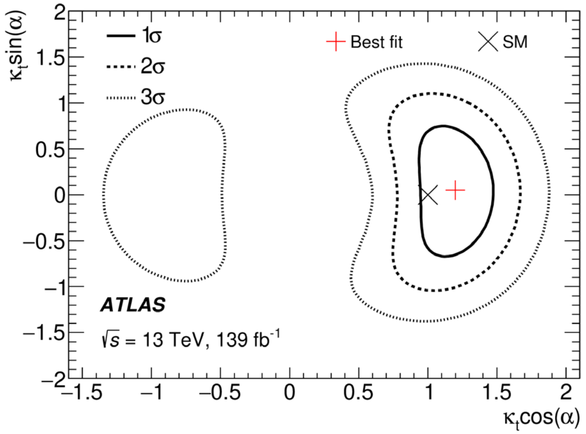
ATLAS measurements:



- CP-structure in ttH parametrized as:

$$\mathcal{L} = -\frac{m_t}{v}\left\{\bar{\psi}_t \kappa_t \left[\cos(\alpha) + \mathrm{i}\sin(\alpha)\gamma_5\right]\psi_t\right\} H$$

- Constraints from ttH($H \to \gamma\gamma$):



- Pure CP-odd (α=90°) excluded with 3.9σ
- |α|<43° at 95% CL

PRL 125 (2020) 061802

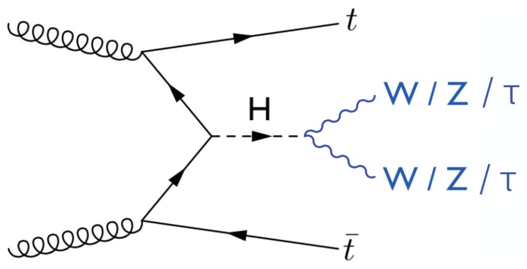
ttW in ttH(multilepton) in ATLAS

- Recent ttH multilepton publication with partial run-2 data ($80 fb^{-1}$)
  - Look into final states with several leptons (2lSS,3l,4l) and/or with hadronic τ-lepton (τ_{had})
  - One of the main background: ttW
- ttW cross-section was found to be largely under-estimated
  - $\lambda_{ttW} = \frac{\sigma_{ttW}}{\sigma_{ttW}^{SM}} \sim 1.39^{+0.17}_{-0.16}$ with σ_{ttW}^{SM}=727fb

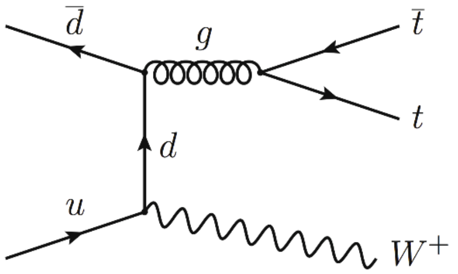
➢ First indication of a possible ttW mis-modelling

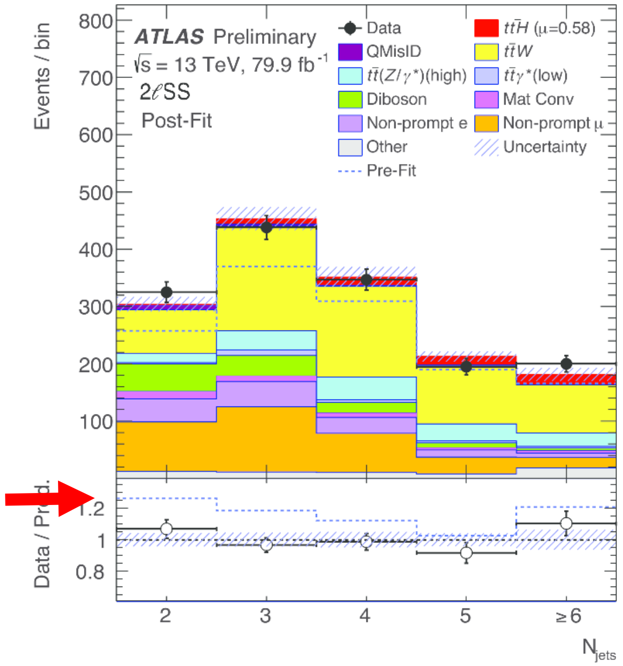
ATLAS-CONF-2019-045

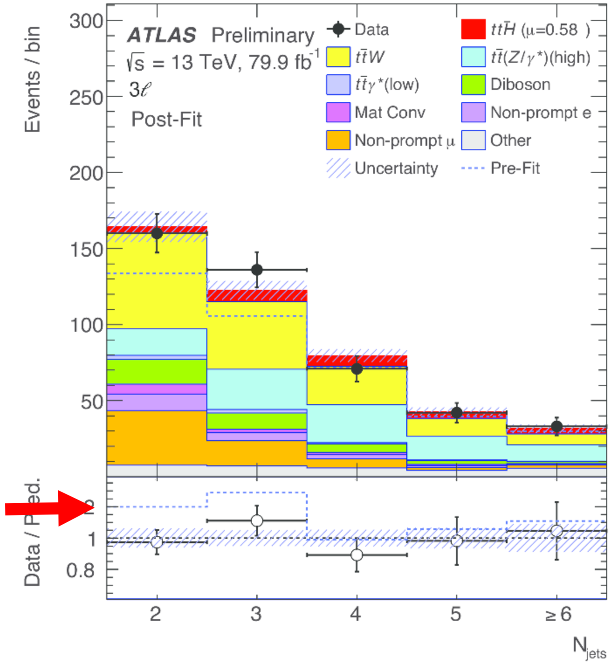
ttH ML:



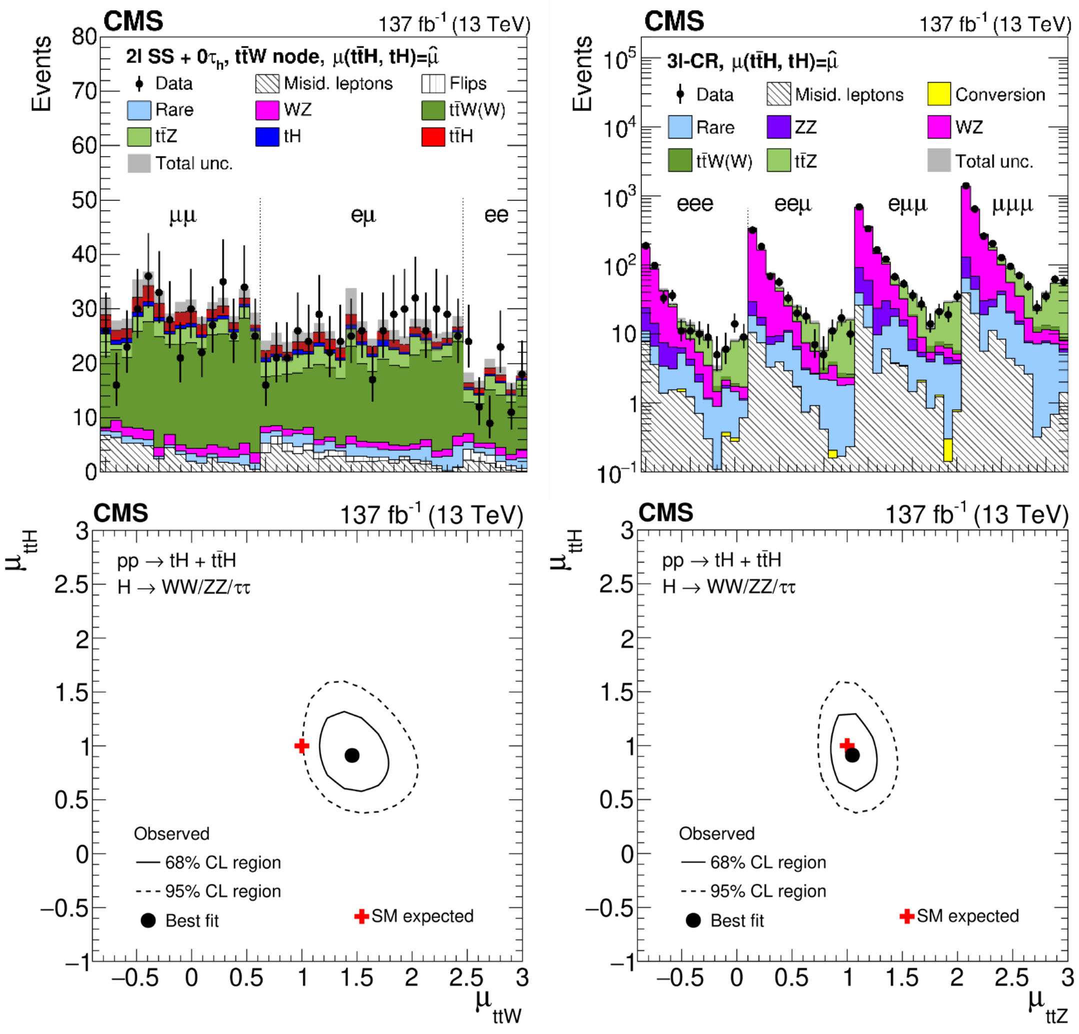
ttW:







ttV treatment in CMS

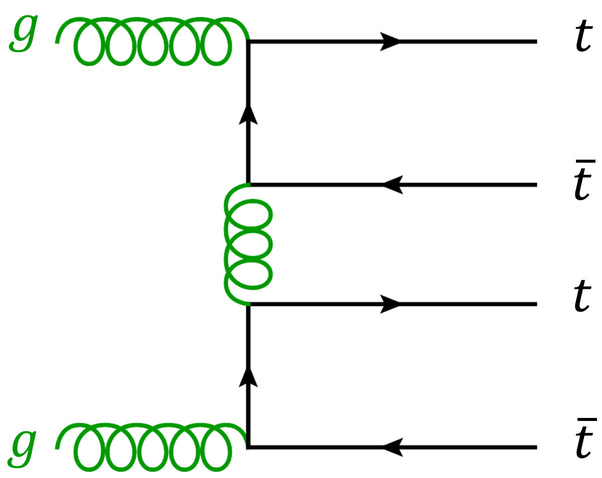


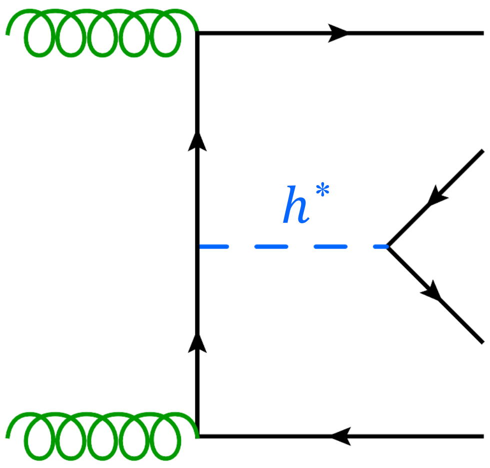
- More recent ttH publications using the full-run2 data
  - Same strategy as prev. but using advanced neural network algorithm to differentiate ttH from bkgs
  - Simultaneous fit of ttH, ttW and ttZ cross section
- The ttW under-estimation is also observed
  - $\lambda_{ttW} = \frac{\sigma_{ttW}}{\sigma_{ttW}^{SM}} \sim 1.43 \pm 0.21$ with σ_{ttW}^{SM}=650fb
  - Though, no tension in ttZ observed

➢ Better ttW modelling will be crucial for future ttH multilepton analyses

CMS-HIG-19-008

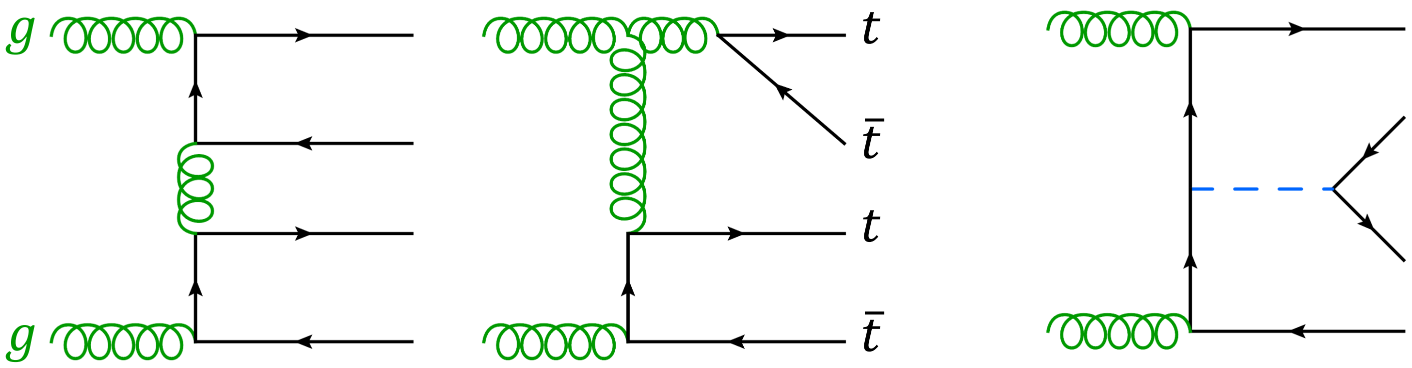
3 – Four top quarks





The 4-top production in the SM

- According to the SM, $\sigma(pp \to t\bar{t}t\bar{t}) = 12.0 \pm 2.4$ fb at NLO in QCD+EW at 13TeV [1]
  - Very low cross-section: 5 order of magnitude below $\sigma(pp \to t\bar{t})$ - Never observed at the LHC



leading diagram from QCD: $\mathcal{O}(\alpha_S^2)$ *sub-leading from EW:* $\mathcal{O}(\alpha_S \alpha)$, $\mathcal{O}(\alpha_S y_t^2)$

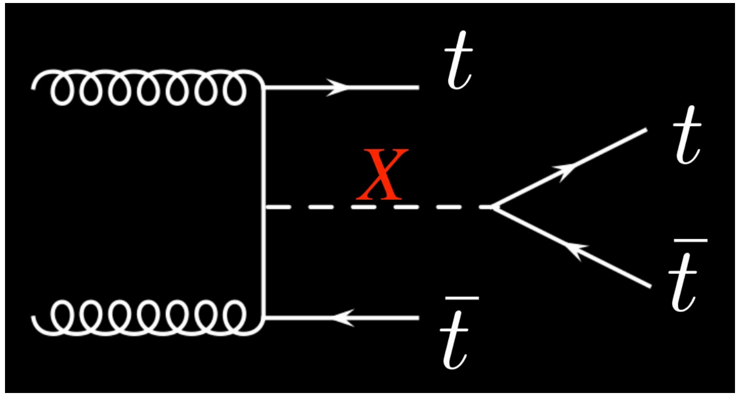
  - The EW contribution is suppressed by the QCD-EW interference in the SM
- Can be used to constrain the top yukawa y_t independently of the Higgs width

[1] arXiv:1711.02116

Sentive to many new physics scenarios

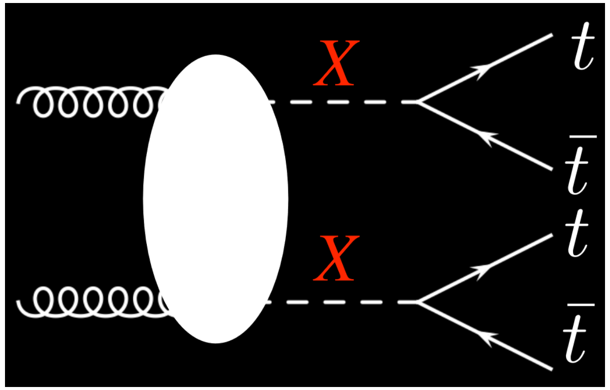
- Many Beyond-the-standard-model theories predict an 4tops cross-section enhancement
- Two possible BSM scenarios:

ttH-like diagram:



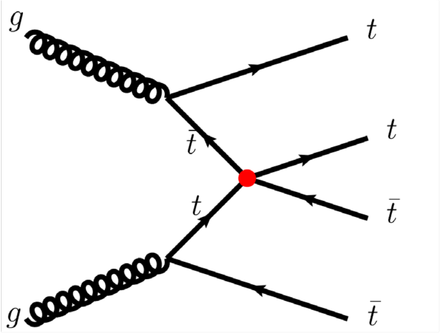
E.g. Two Higgs Double Models
Top-philic resonances

Pair production of new particles:



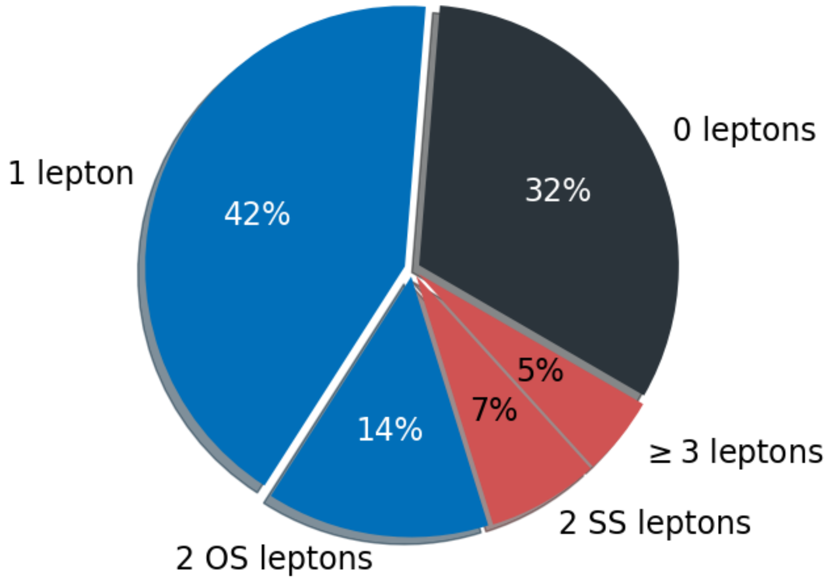
E.g. sgluons, KK gluons

- Sensitive also to many Effective Field Theory operators (e.g. four top quarks contact interactions)



4-top signature

- Lead to large multiplicity and complex final state
  - $pp \rightarrow t\bar{t}t\bar{t} \rightarrow 4b + 4W$



SS: same-sign
OS: opposite-sign

1L+2LOS channel:

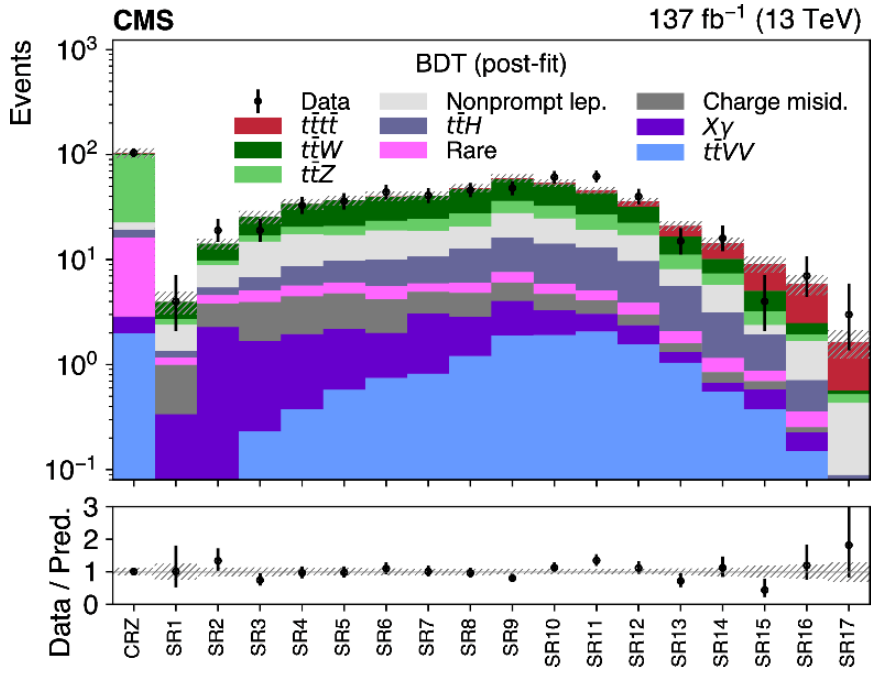
- Larger branching ratio, but very large background contamination from ttbar+jets
- Results from partial run-2 data (not covered today)

SSML (same-sign multilepton) channel:

- Lower branching ratio, but lower background contamination
- Results from both ATLAS and CMS with full run-2 data
- Similar phase space than ttH multilepton

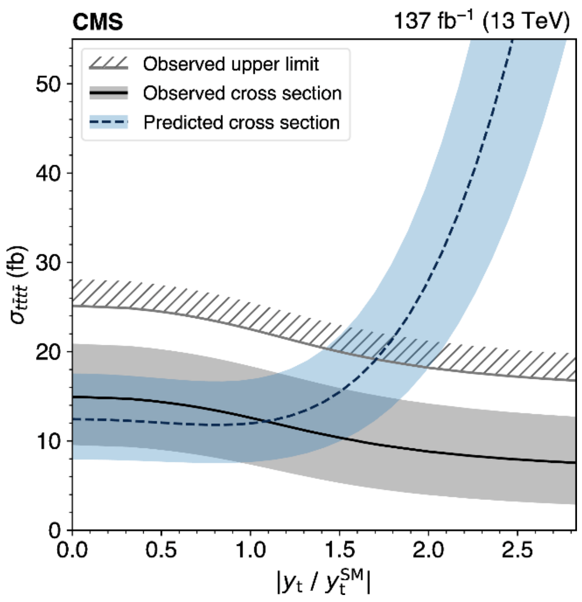
4-top result in CMS

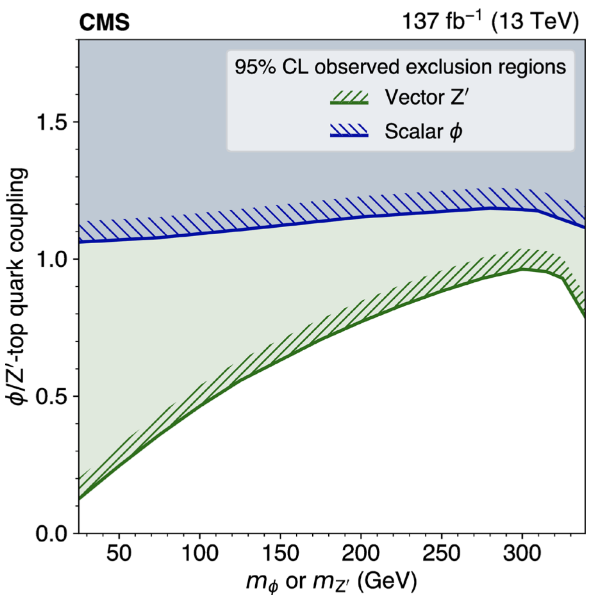
- Recent CMS 4-top search using full the run-2 data
  - In SSML channel, H_T>300GeV, ≥2 jets, ≥2 b-jets
  - Using multi-variate analysis techniques (BDT) cross-checked with a "cut-based" analysis
- Result:
  - $\sigma_{tttt} = 12.6^{+5.8}_{-5.2}$ fb (to be compared with $\sigma^{SM}_{tttt} = 12.0^{+2.2}_{-2.5}$ fb)
    - ➢ Very close to the SM prediction
  - Observed (expected) significance: 2.6σ (2.7σ)
    - ➢ Close to evidence

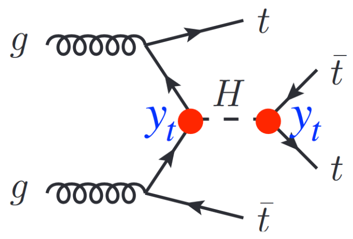


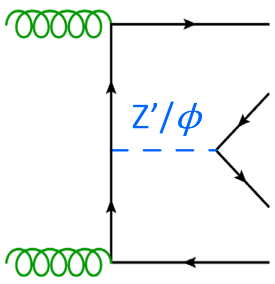
Eur. Phys. J. C 80 (2020) 75

Constraints from CMS

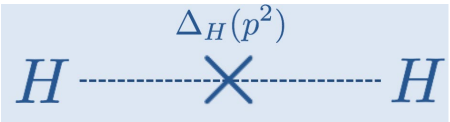








- Top yukawa magnitude:
  - $|y_t| < 1.7\ |y_t^{SM}|$ at 95% CL
- BSM scenarios:
  - Off-shell top-philic mediators (shown here)
    Limit on coupling from 0.1 to 1.2
  - 2HDM scenarios (not shown)
- Higgs oblique parameter:
  - $\hat{H} < 0.12$ at 95% CL
  - Tighter than previous limit using LHC on-shell Higgs measurements



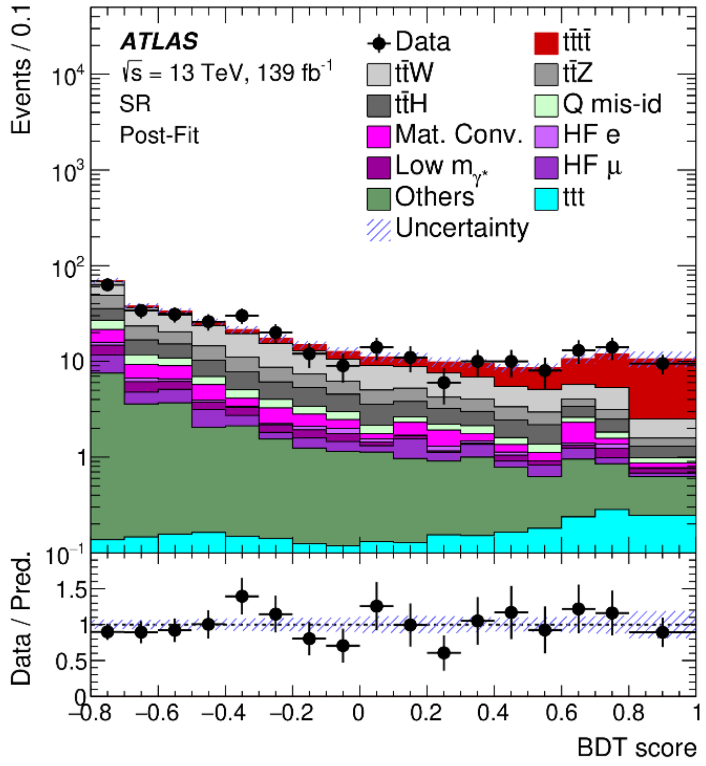
$$\Delta_H(p^2) \approx \frac{1}{p^2 - m_h^2} - \frac{\hat{H}}{m_h^2}$$

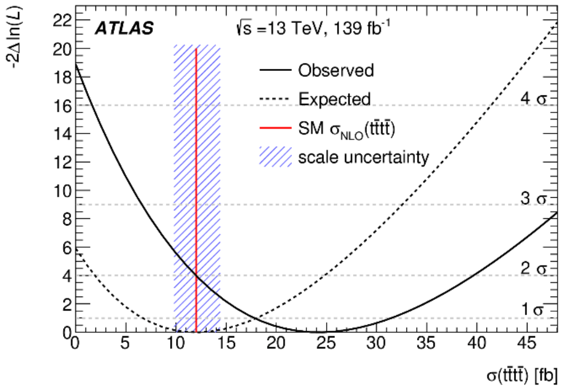
1903.07725

4-top result in ATLAS

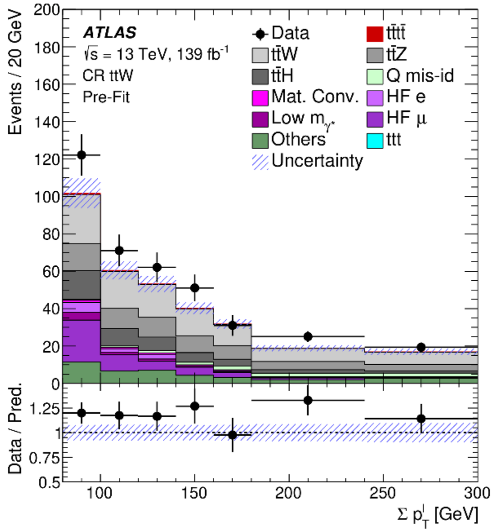
- Recent 4-top result from ATLAS using full the run-2 data
  - In SSML channel, H_T>500GeV, ≥6 jets, ≥2 b-jets
  - Using multi-variate analysis techniques (BDT)
- Result:
  - $\sigma_{tttt} = 24^{+7}_{-6}$ fb (to be compared with $\sigma^{SM}_{tttt} = 12.0^{+2.2}_{-2.5}$ fb)
    - ➢ 1.7σ tension with SM prediction
  - Many checks performed to validate the results
  - Observed (expected) significance: 4.3σ (2.4σ)
    - ➢ First strong evidence for 4-top

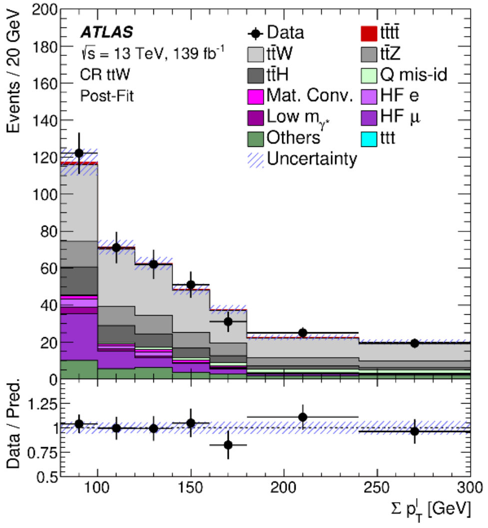
arXiv:2007.14858

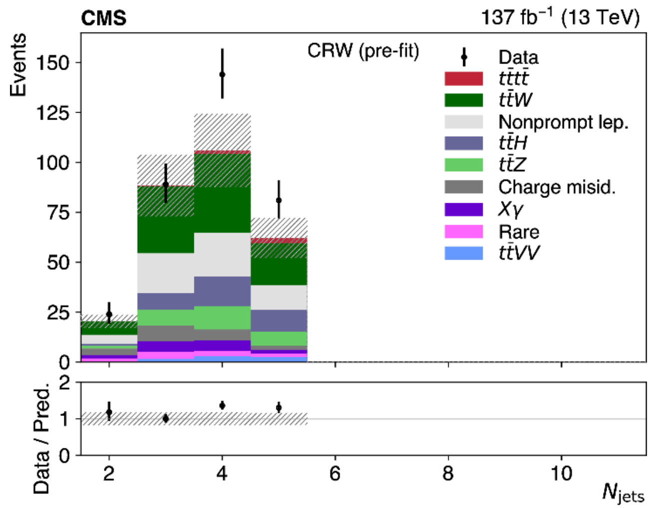




ttW again !





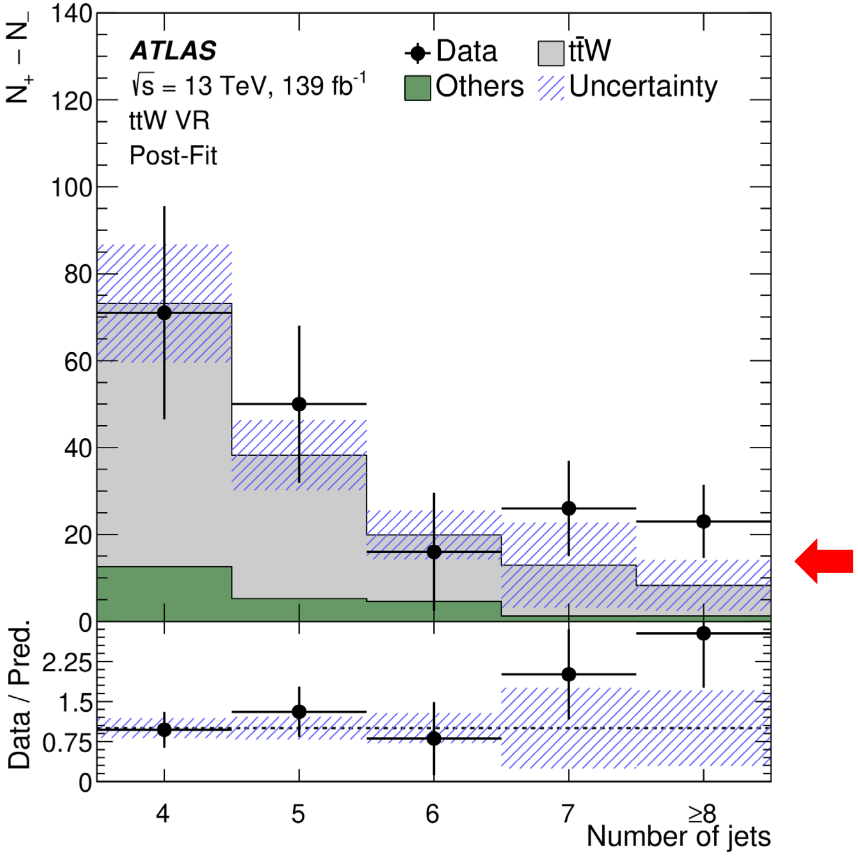


- ttW treatment in ATLAS 4-top:
  - Dedicated ttW control region used to correct the ttW normalisation
  - ttW normalisation scaled by 1.6 ± 0.3
- ttW treatment in CMS 4-top:
  - ttW modelling improved with correction factors as function as Njets and Nbjets
  - ttW normalisation scaled by 1.3 ± 0.2

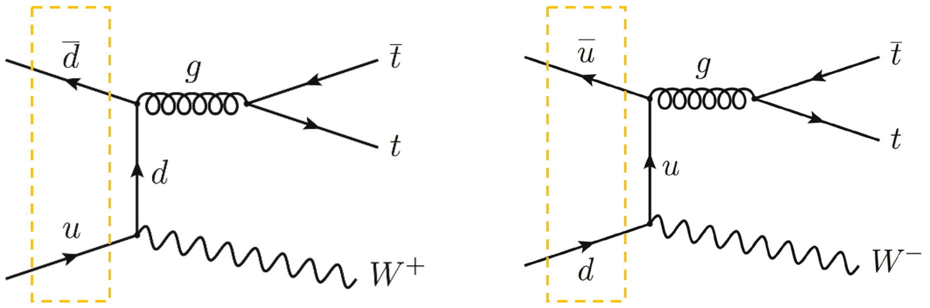
➢ ttW mismodelling observed by ttH ML is confirmed by the 4-top measurements
  - Better ttW modelling will also be necessary for future 4-top measurements

Validating the ttW in ATLAS

N_+: Number of events with positively-charged leptons
N_-: number of events with negatively-charged leptons



- The ttW modelling is validated in the signal region by looking at the charge of the leptons
  - The ttW leads to more positive lepton events than negative lepton because $\sigma(ttW^+) > \sigma(ttW^-)$



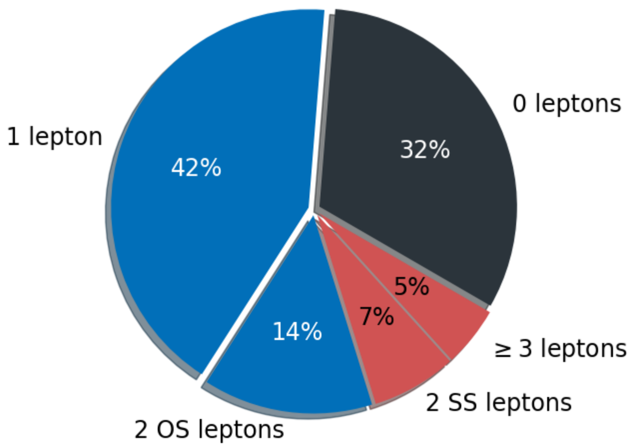
PDF($u\bar{d}$) > PDF($\bar{u}d$)

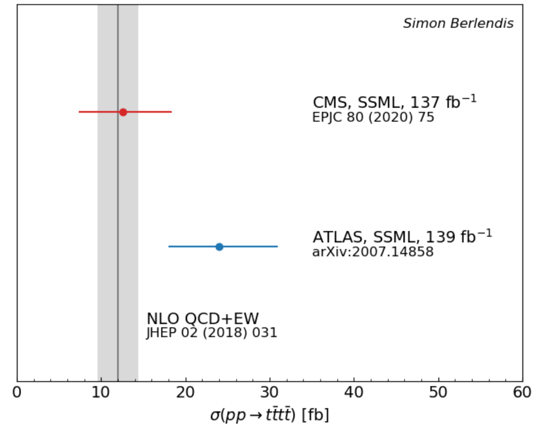
(~twice more valence up quarks than down quarks in a proton)

- Systematic uncertainties are applied to cover the mis-modelling at high jet multiplicities
  - High impact on the measured cross section
  - Largest systematic uncertainty

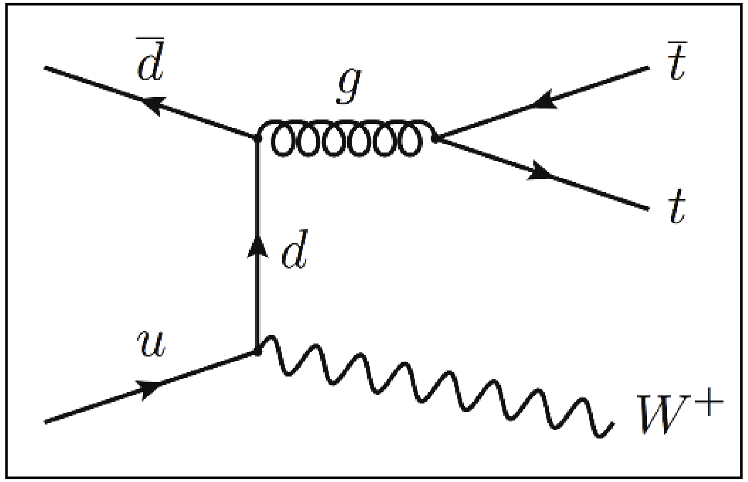
The future of 4tops

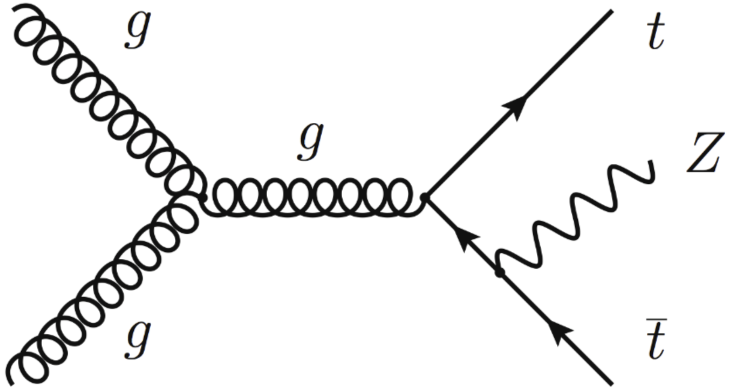
- Search in other final states: 1 lepton or 2 opposite-sign lepton
  - Very challenging: higher background (dominated by $pp \rightarrow t\bar{t}$)
  - But will provide a valuable cross-check on $\sigma(pp \rightarrow t\bar{t}t\bar{t})$
- Re-analysis same-sign leptons or three leptons with newer techniques:
  - New b-tagging techniques that will provide better bkg vs signal separation
  - Better ttW modelling from new Monte Carlo simulations
- Combination with CMS:
  - Compare analysis strategy (e.g. selections, background estimation)
  - Combine the measured $\sigma(pp \rightarrow t\bar{t}t\bar{t})$





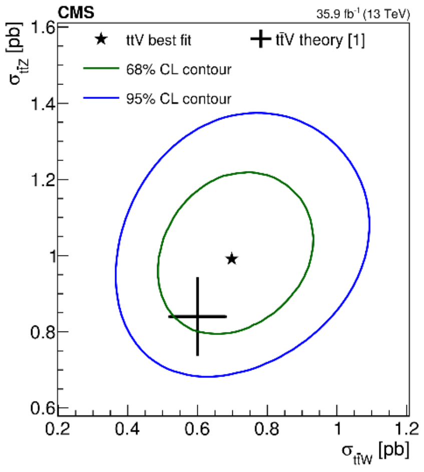
3 – Tops quarks + bosons

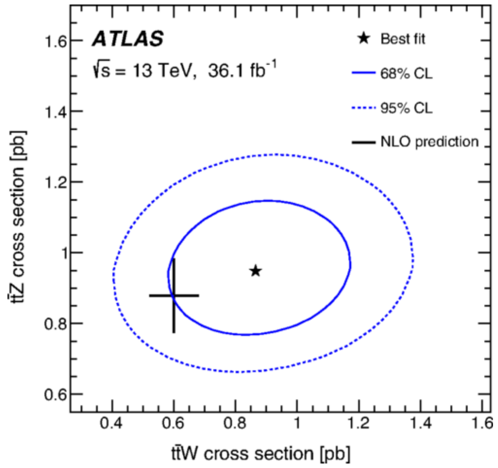


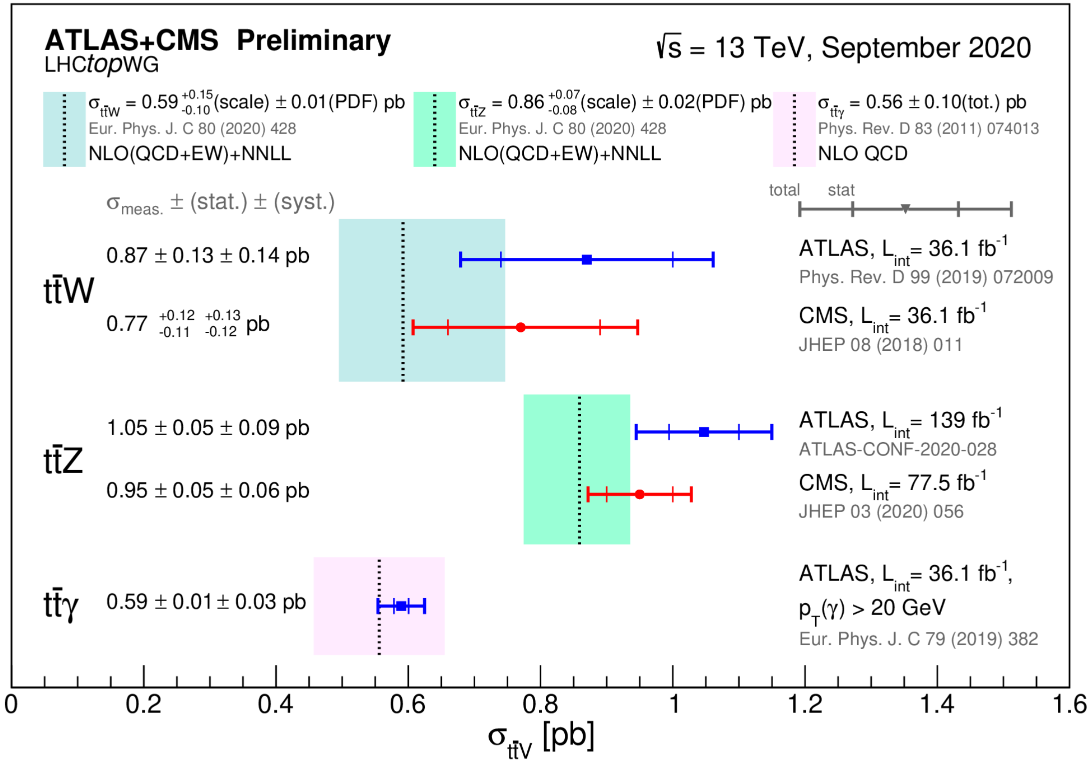


ttW cross section measurements

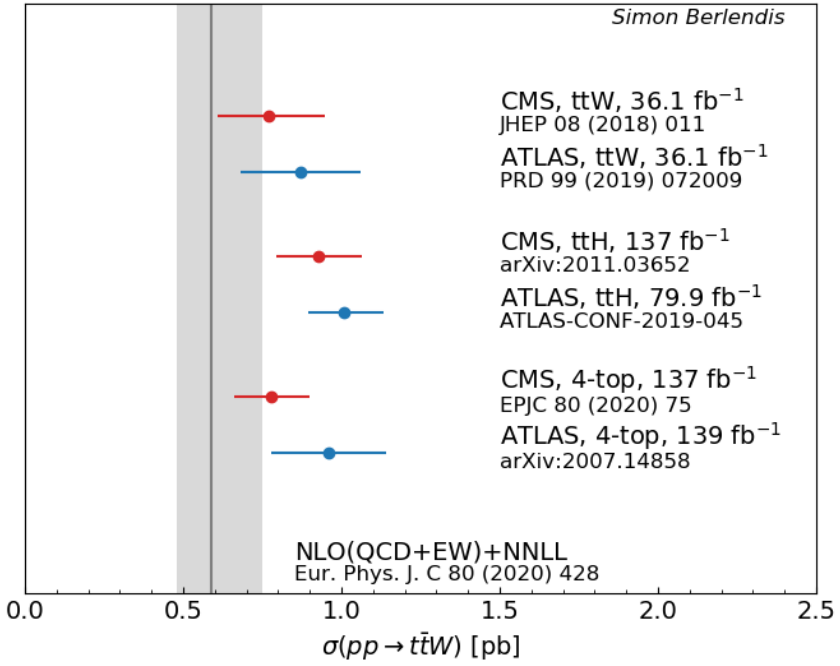
- Motivations for ttW measurements at LHC
  - Access to EW top quark coupling
  - Sensitive to EFT operators and many BSM scenarios
- Already measured in partial run-2 data
  - Though consistent with SM prediction, data seems to prefer higher cross sections







ttW in recent ttH/4-top results



- ttW excess is confirmed in many other measurements (ttH/4-top) by ATLAS and CMS
  - Caveat: the acceptance (i.e. selections) also play a role in these measurements
- Large effort is on-going to improve the ttW modelling from both the theoretical and experimental side
  - I will try to show you a summary of the current discussion today

EW contributions in ttW

Complete QCD+EW NLO (From I. Tsinikos LPCP2020):

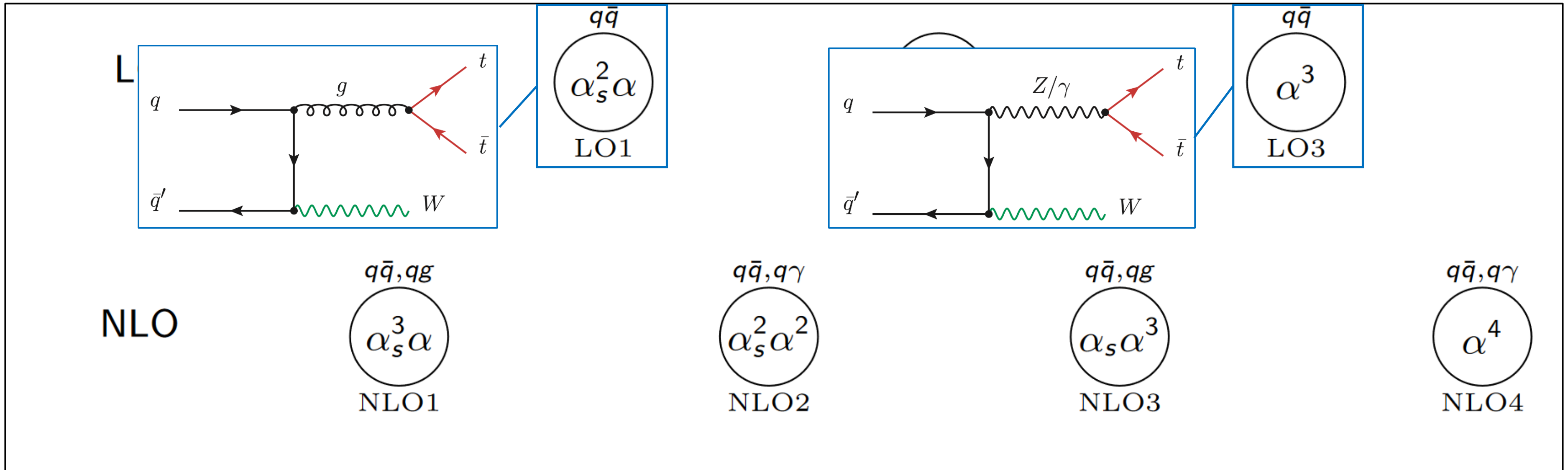
LO	$q\bar{q}$: $\alpha_s^2\alpha$ (LO1)	$\alpha_s\alpha^2$ (LO2=0)	$q\bar{q}$: α^3 (LO3)

NLO	$q\bar{q}, qg$: $\alpha_s^3\alpha$ (NLO1)	$q\bar{q}, q\gamma$: $\alpha_s^2\alpha^2$ (NLO2)	$q\bar{q}, qg$: $\alpha_s\alpha^3$ (NLO3)	$q\bar{q}, q\gamma$: α^4 (NLO4)
Expectation	$\mathcal{O}(10\%)$	$\mathcal{O}(1\%)$	$\mathcal{O}(0.1\%)$	$\mathcal{O}(0.01\%)$
Contribution	$\sim 30-60\%$	$\sim -4\%$	$\sim 10\%$	$\sim 0.04\%$

Frederix, Pagani, Zaro: 1711.02116

EW contributions in ttW

Complete QCD+EW NLO (From I. Tsinikos LPCP2020):



	NLO1	NLO2	NLO3	NLO4
Expectation	$\mathcal{O}(10\%)$	$\mathcal{O}(1\%)$	$\mathcal{O}(0.1\%)$	$\mathcal{O}(0.01\%)$
Contribution	$\sim 30-60\%$	$\sim -4\%$	$\sim 10\%$	$\sim 0.04\%$

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EW contributions in ttW

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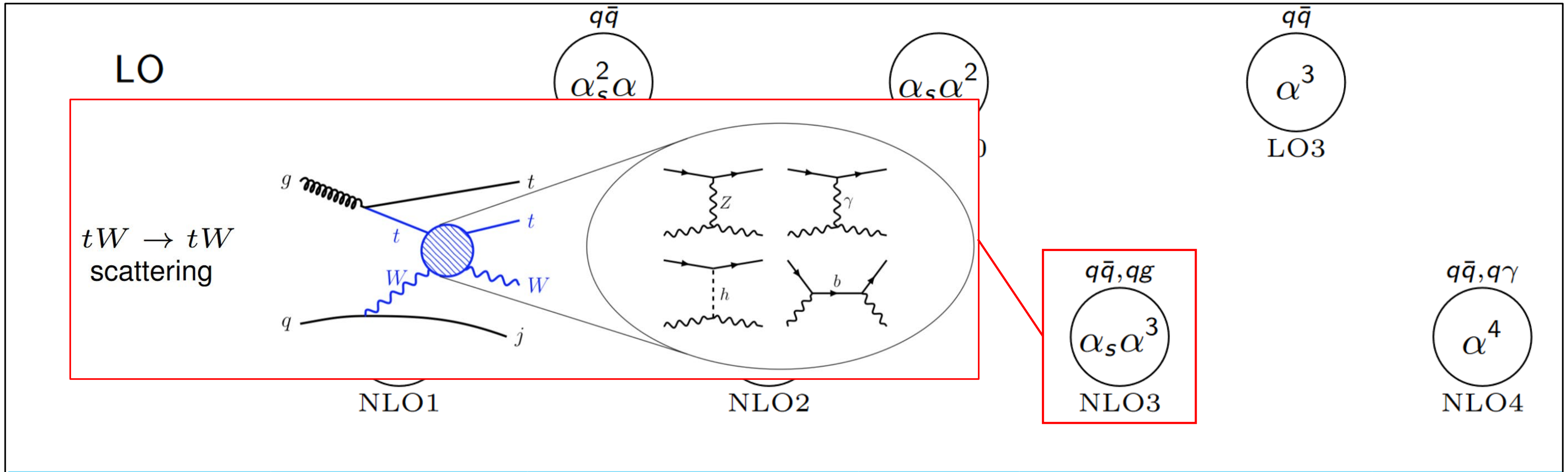


Expectation	$\mathcal{O}(10\%)$	$\mathcal{O}(1\%)$	$\mathcal{O}(0.1\%)$	$\mathcal{O}(0.01\%)$
Contribution	$\sim 30-60\%$	$\sim -4\%$	$\sim 10\%$	$\sim 0.04\%$

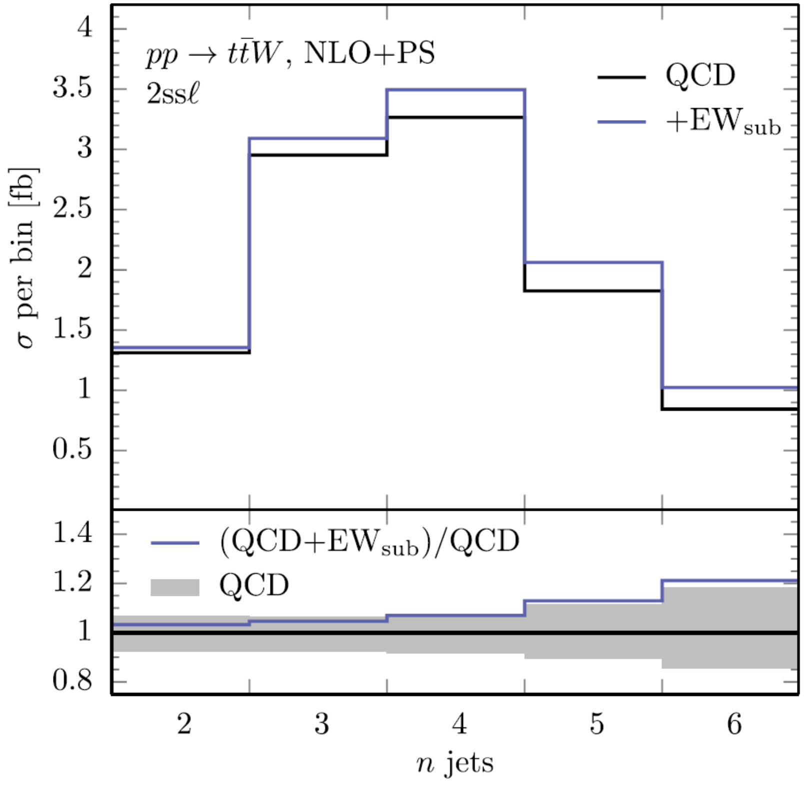
Frederix, Pagani, Zaro: 1711.02116

- Large contribution from contribution from EW corrections at NLO !

EW corrections in differential measurements

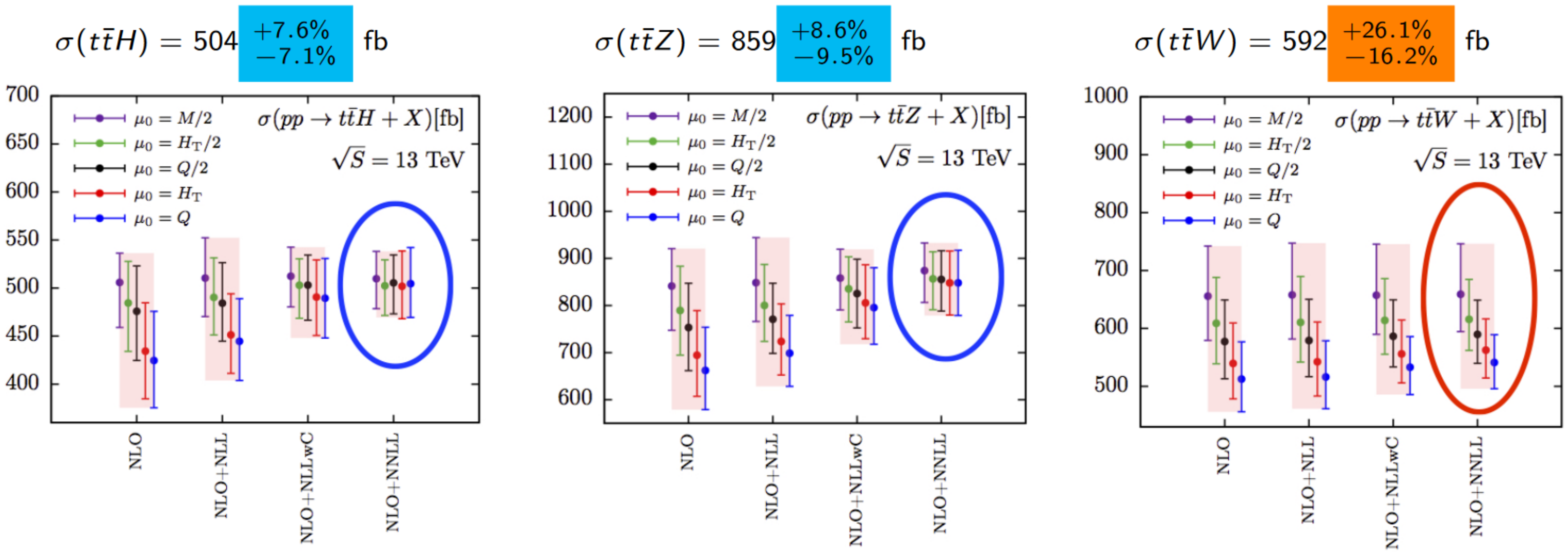
- Recent publication on ttW at differential level
  - Match QCD+EW NLO accuracy with parton shower
  - Including spin correlation
- EW corrections are larger at high jet multiplicity
  - Non-flat EW corrections !
  - Might possibly explain part of the large tension in 4-top measurements

Frederix, Tsinikos: 2004.09552



NNLL resummation

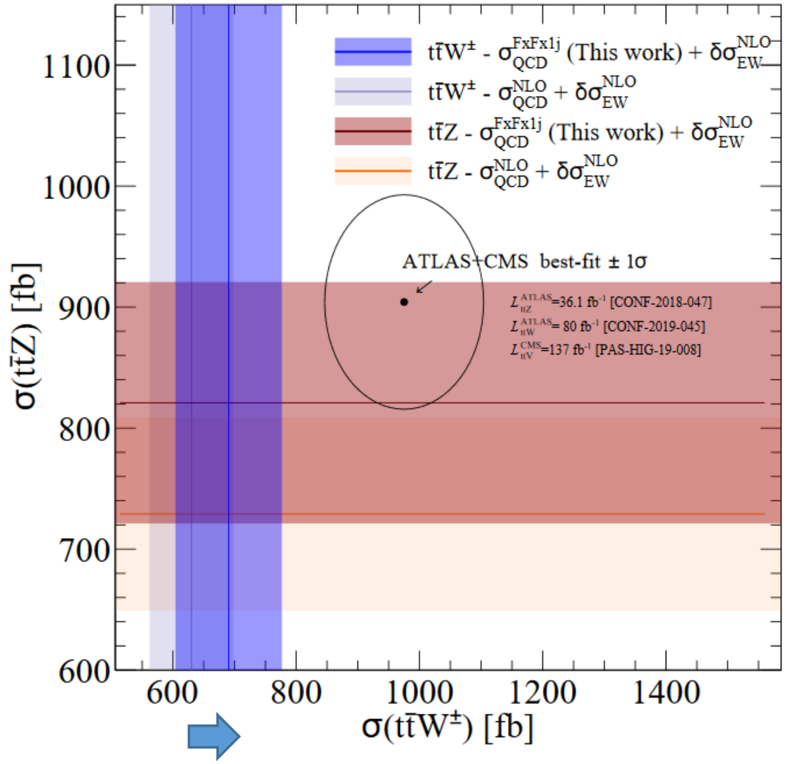
- Effect of soft-gluon resummation at NNLL on NLO QCD+EW cross section
  - ttZ and ttH cross section stable when NNLL included
  - Not the case for ttW ! Scale dependence is still large at NLO+NNLL
  - ➢ ttW cross section prediction is inaccurate. Need high-order corrections (NNLO?).



[Kulesza et al.:2001.03031](https://arxiv.org/abs/2001.03031)

Toward higher-order corrections

Buddenbrock et al.:2009.00032

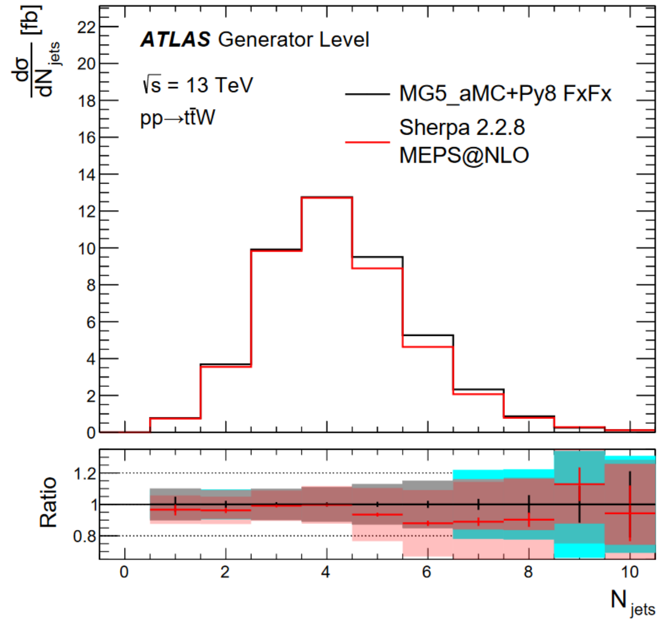


- Effect of NLO multi-leg matching
  - Examine the role of ttWj and ttWjj (e.g. gluon-gluon initial state)
  - Part of the NNLO predictions
  - Using FxFx multi-leg matching with EW corrections
- Increase by ~10% the overall cross section
  - Quote an impact on the jet multiplicity too
- But still in tension with recent ttW measurements

➢ Need full NNLO predictions

On the experimental side in ATLAS

- Recent progress to implement new ttW Monte Carlo simulations in ATLAS
  - With EW subleading contributions
  - Multi-leg matching
  - Using various MC generators
- On-going effort to make new ttW measurements using full run-2 data
  - Get a more accurate cross section measurements
  - Extract various unfolded distributions (e.g. njets, nbjets lepton rapidity)
  - Difficult analysis due to the low ttW purity/large bkg contaminations in data



ATL-PHYS-PUB-2020-024

ME	Parton Shower	ME PDF PS PDF	Tune	Matching/ Merging	Cross-section (fb)
MG5_aMC v2.6.7 @NLO inc.	PYTHIA 8.244	NNPDF3.0NLO NNPDF2.3LO	A14	MC@NLO	QCD: $545.7^{+10.0\%}_{-9.8\%}$(scale) tree-level EW : $49.1^{+19.1\%}_{-14.8\%}$(scale)
MG5_aMC v2.6.7 +0, 1j@NLO +2j@LO				FxFx Merging μ_Q = 30 GeV	QCD: $612.6^{+10.8\%}_{-12.4\%}$(scale)
SHERPA 2.2.8 +0, 1j@NLO +2j@LO	SHERPA 2.2.8	NNPDF3.0NNLO NNPDF3.0NNLO	Author's tune	MEPS@NLO μ_Q = 30 GeV	QCD: $589.2^{+15.5\%}_{-14.7\%}$(scale)

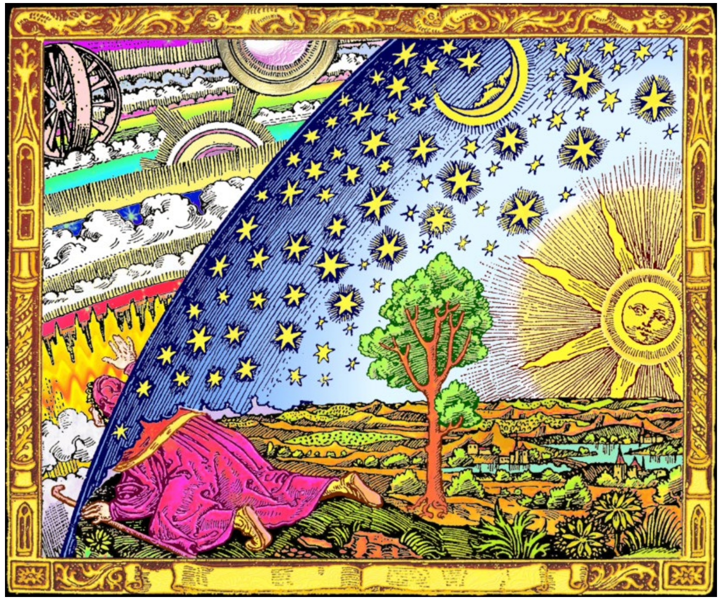
Conclusion

Conclusion

- The LHC has shown to be a powerful tool for exploring uncharted territories of particle physics
  - Enable us to search, measure and study rare processes like $t\bar{t}t\bar{t}$, $t\bar{t}H$
  - Push the limits of our understanding of the physics at high energy

- Still many questions to solve and new regions to explore !
  - We are far from having a perfect understanding of our data
    ttW mismodelling is a good example
  - The Standard Model continue to have experimental and theoretical limitations

➢ The hunt for new physics is still on !



Flammarion engraving

- Backup

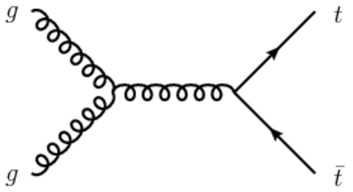
43

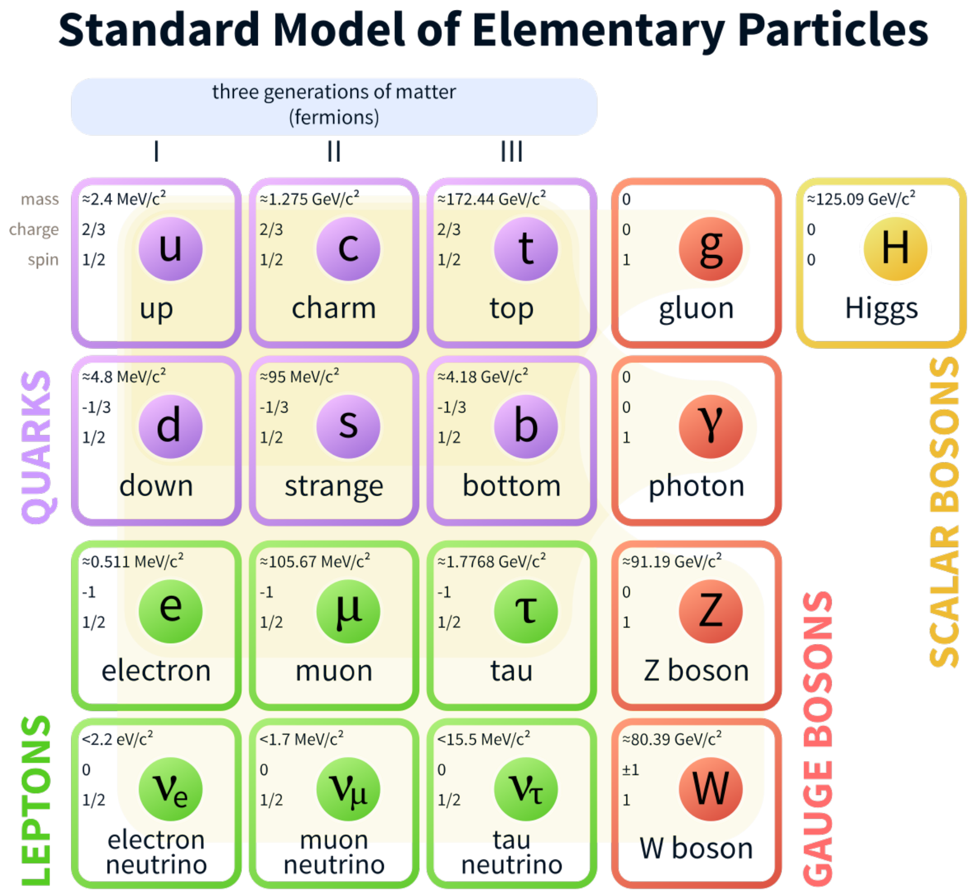
The Standard Model (SM)

- Particle classification:
  - The **gauge bosons** are the **force mediators**
  - The **quarks** and **leptons** are the **elementary fermions**
  - The **Higgs boson** is a **scalar boson**
- Invariance under the local gauge group:
  - $\underbrace{SU(3)}_{\text{Strong}} \otimes \underbrace{SU(2) \otimes U(1)}_{\text{Electroweak}}$

- The Standard Model (SM) describes the particle interactions
  - Allows to compute the production cross section (σ) of a given process
  - Can be compared with experimental results

ex: $gg \rightarrow t\bar{t}$ production



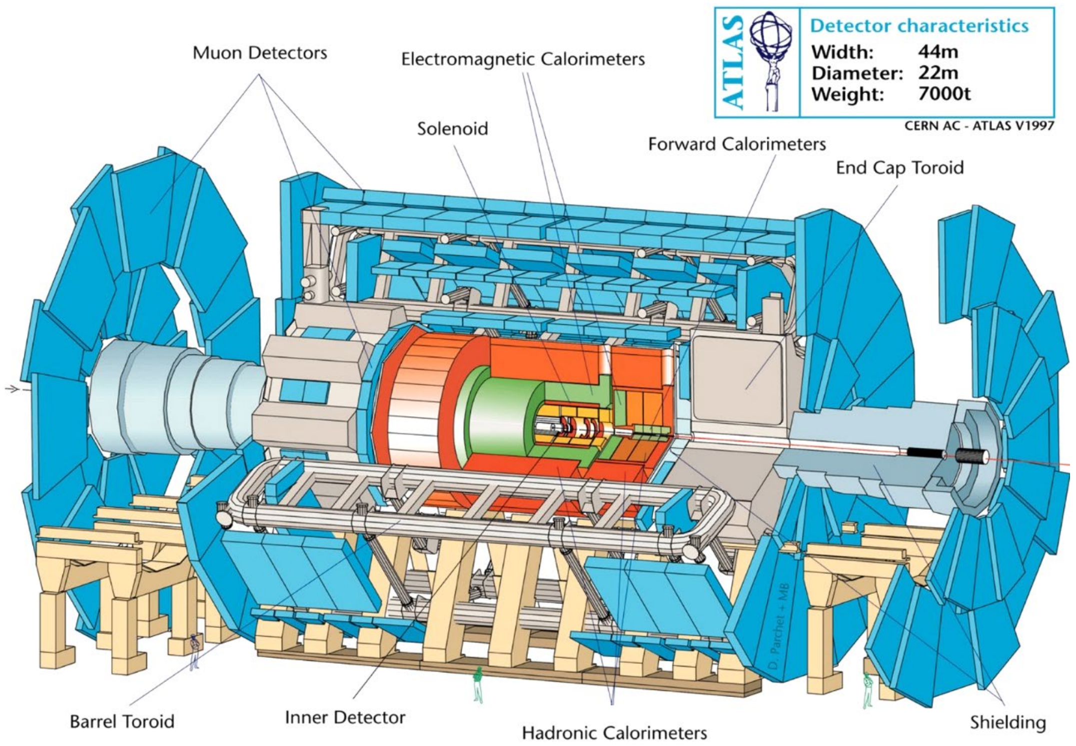


The imperfections of the Standard Model

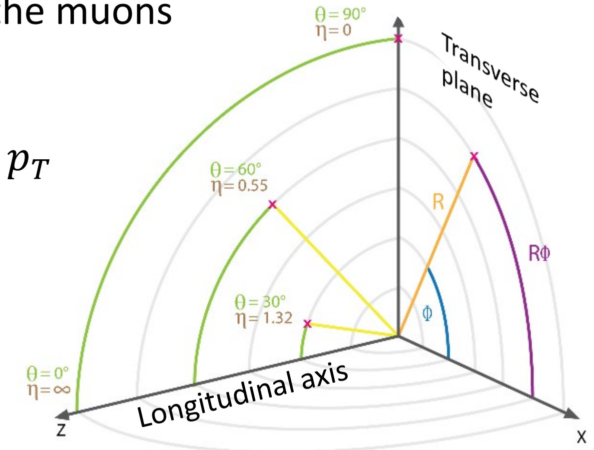
- **Gravity** is not included in the SM
  - Only the strong force and the electroweak (EW) force are included
- The **hierarchy** problem
  - Why the EW energy scale (100 GeV) is so small compared to the Planck scale (10^{18} GeV) ?
- The **Dark Matter** (DM) puzzle
  - From several astrophysics observation
  - No DM candidate in the SM
- The **matter-antimatter asymmetry** of the universe
  - The SM can't explain the observed asymmetry
- Neutrino masses
- Higgs potential stability
- Grand Unification Theory
- Strong CP phase
- …

The SM is an effective theory. At high energy, **deviations** from the SM predictions are expected, revealing the presence of **new physics (NP)**.

The ATLAS and CMS experiments



- Inner detector + Solenoid magnet (2T)
  - Measures the track of the charged particles
  - Particle momentum and charge measurements
- Calorimeters
  - Measure energy and position of photons, electrons and hadrons
  - Allow to reconstruct **jets** of hadrons
- Muon spectrometer + toroidal magnets
  - Measures the track of the muons
- Cylindric coordinates:
  - Transverse momentum p_T
  - Rapidity η



Detecting particles

Electron e

- Track in the inner detector + Energy deposit in the calorimeter

Muons μ

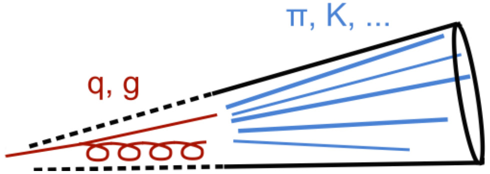
- Tracks both in the inner detector and in the muon spectrometer

b-jets

- Classify jets coming from *b*-quark
- Tagging algorithm based on multivariate algorithm
- Efficiency of 70-77% for true *b*

Jets

- Quark or gluon signature as a shower of hadronized particles



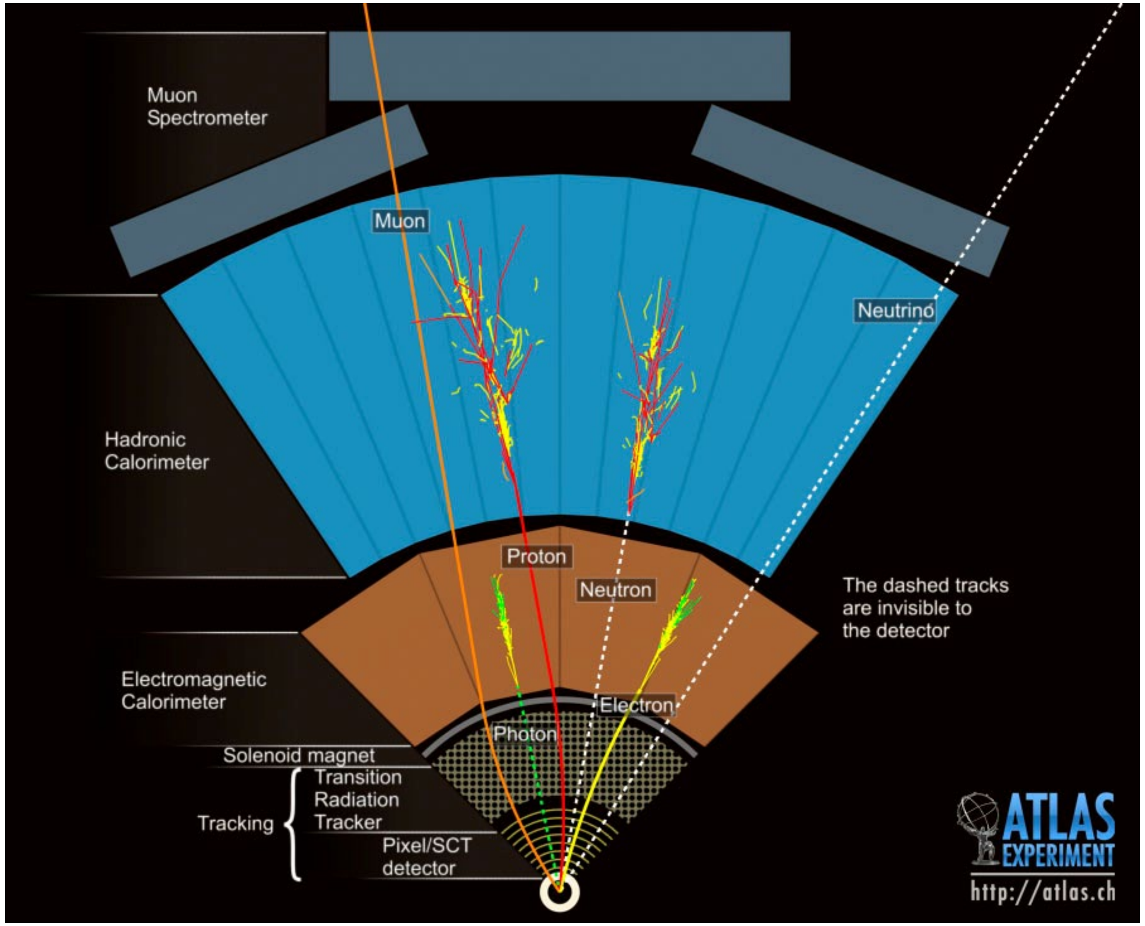
- Anti-kt algorithm using energy deposits in the calorimeters

Transverse missing momentum

- Total transverse momentum of invisible particles (neutrinos)
- Reconstructed as:

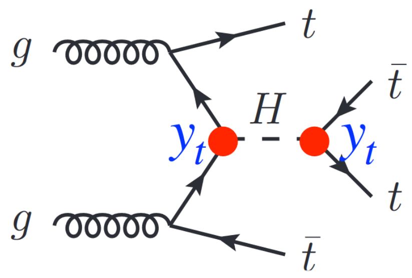
$$\vec{E}_T^{\text{miss}} = -\sum_{\text{all objects}} \vec{p}_{\text{T}}$$

Particle detection in ATLAS:

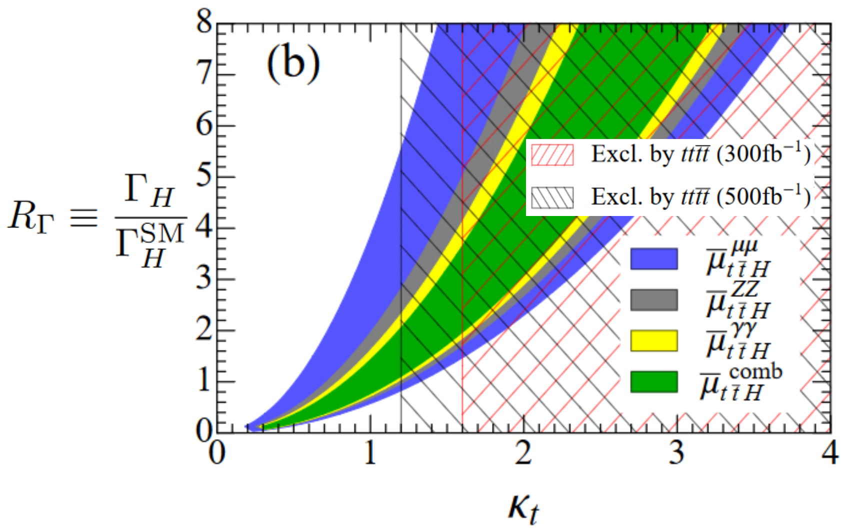


Top yukawa coupling constraint

[1602.01934](1602.01934)
[1901.04567](1901.04567)

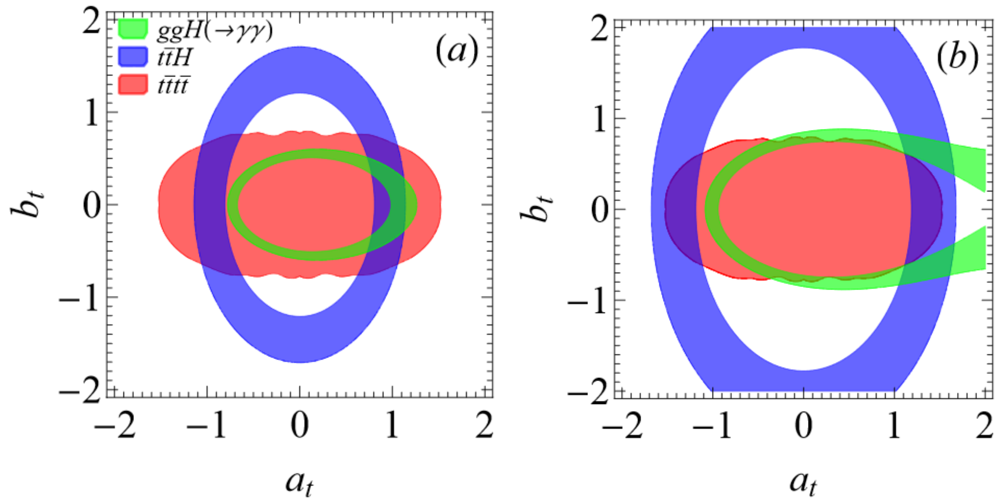


$$\mathcal{L}_{Htt} = -\frac{m_t}{v} H\bar{t}(a_t + ib_t\gamma_5)t$$



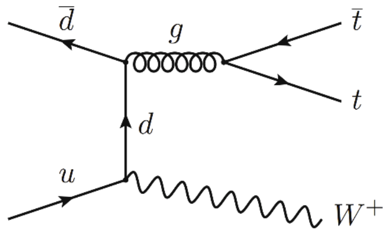
Fixed higgs width:

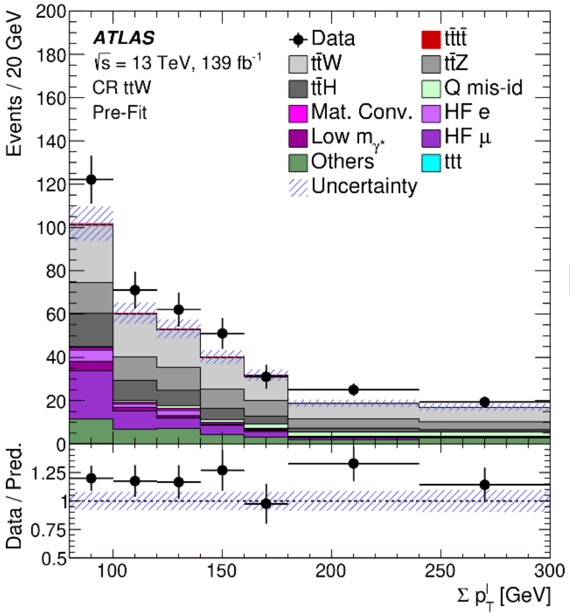
Unfixed higgs width:

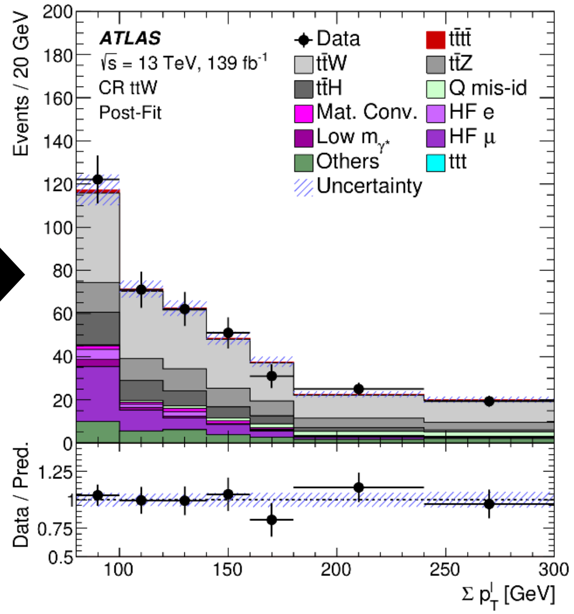


The problem of the ttW background

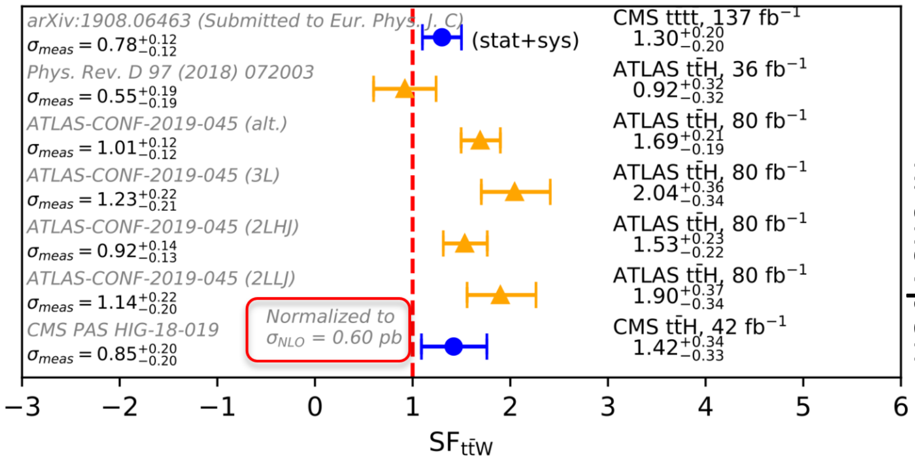
- An excess of events is also observed in ttW-dominated event region
  - The ttW cross section is found to be higher than what the SM predicts
  - A ttW normalisation factor of 1.6 ± 0.3 is extracted from the likelihood fit







Observed by other analyses targeting the similar event topology :



k. skovpen

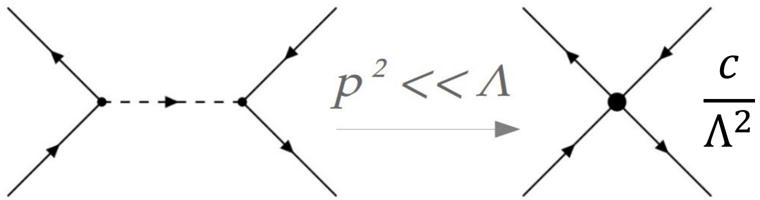
➢ The ttW background is known to be badly modelled by the Monte Carlo simulation

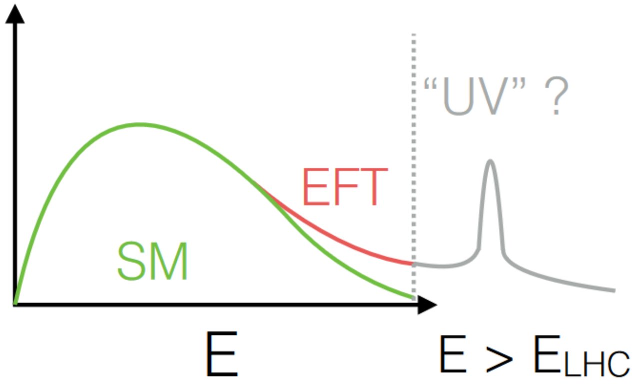
Effective Field Theory

- New physics at higher energy scale ($\Lambda > E_{LHC}$) can be modeled with higher-order operators :

$$\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$$

  - E.g. four-fermion operators:



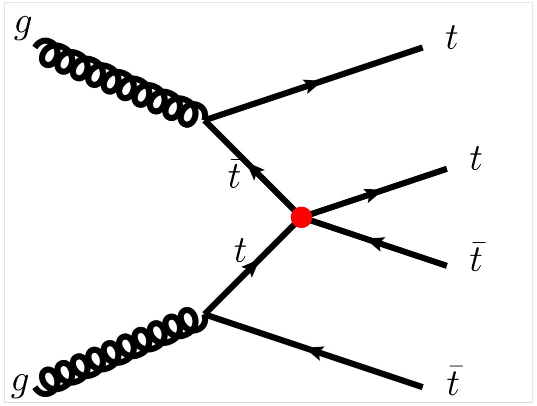


  - Model-independent method to search or put limits of any UV-complete model at high scale

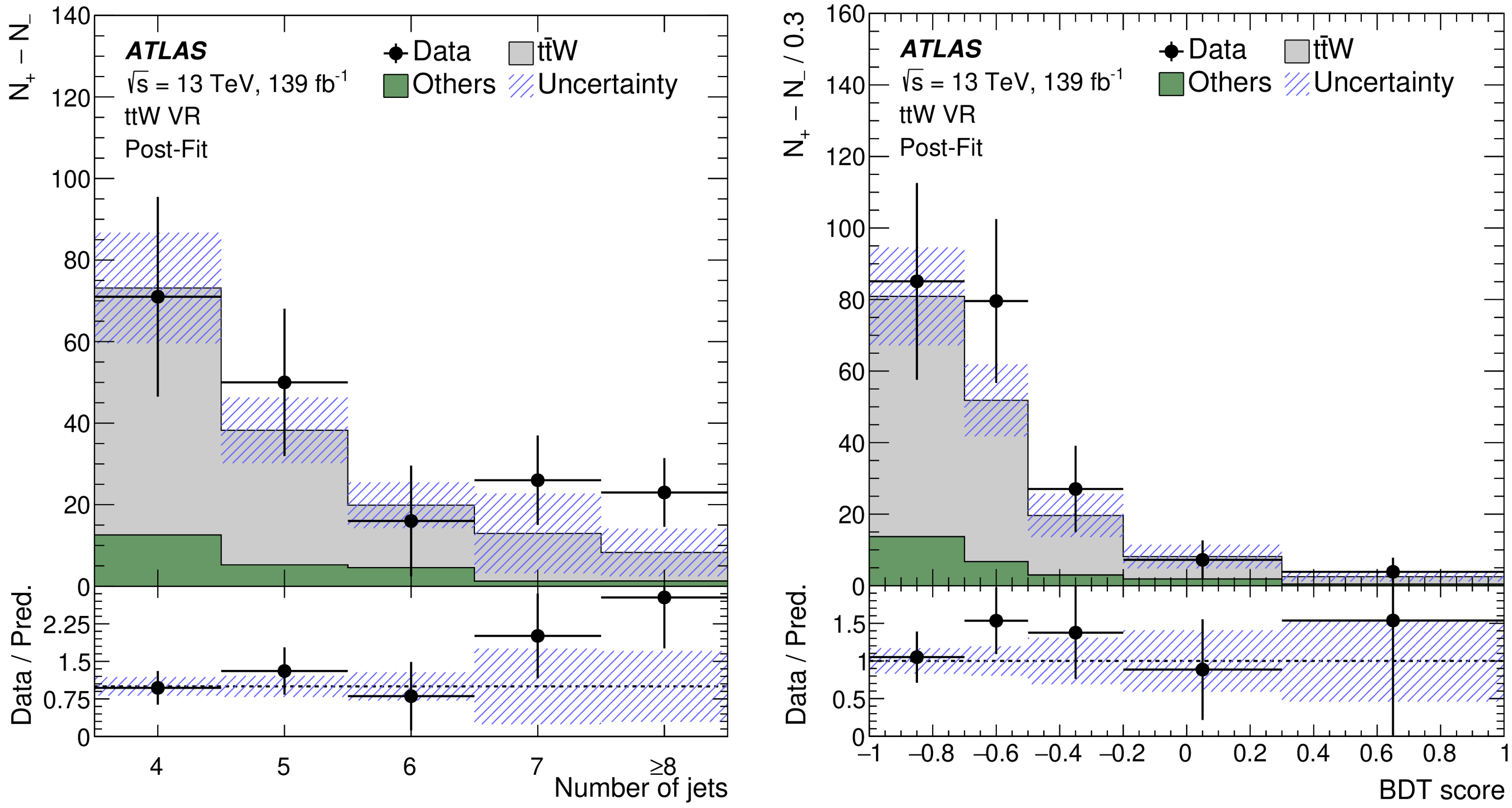
- The 4tops cross-section measurement allows to put strong limits on four-top-quarks operators

  - E.g.

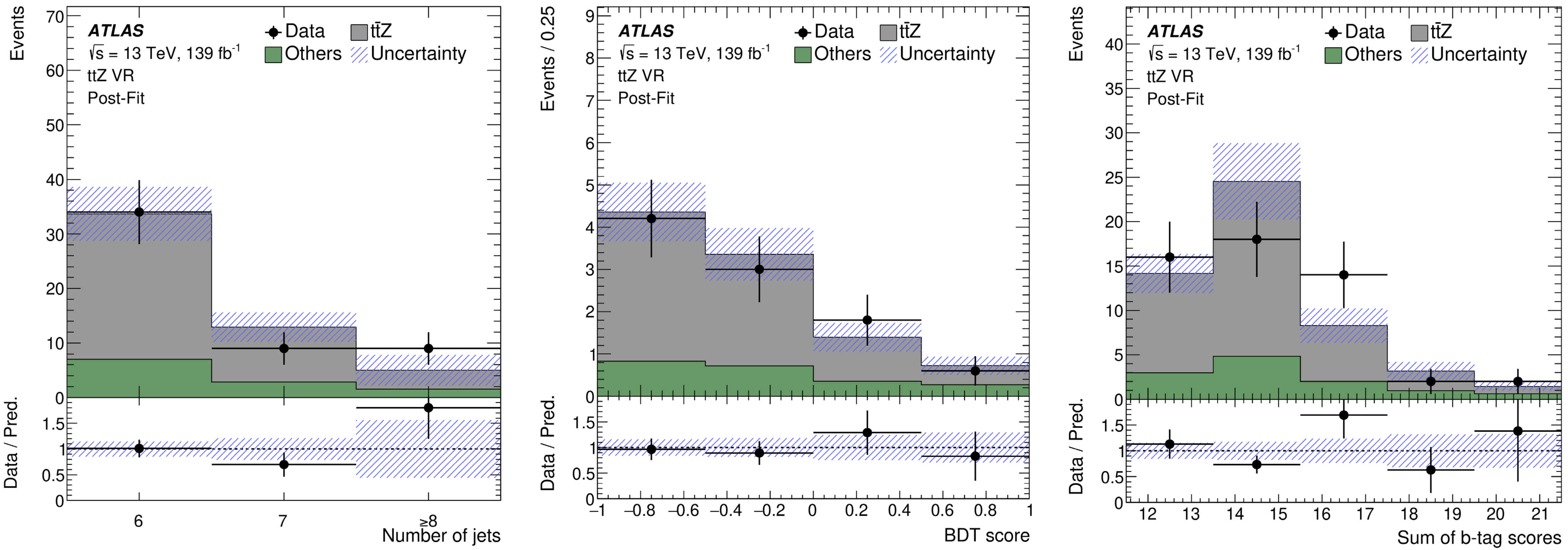
$$\mathcal{L}_{4t} = \frac{|C_{4t}|}{\Lambda^2}(\bar{t}_R \gamma^\mu t_R)(\bar{t}_R \gamma_\mu t_R)$$



ttW validation region

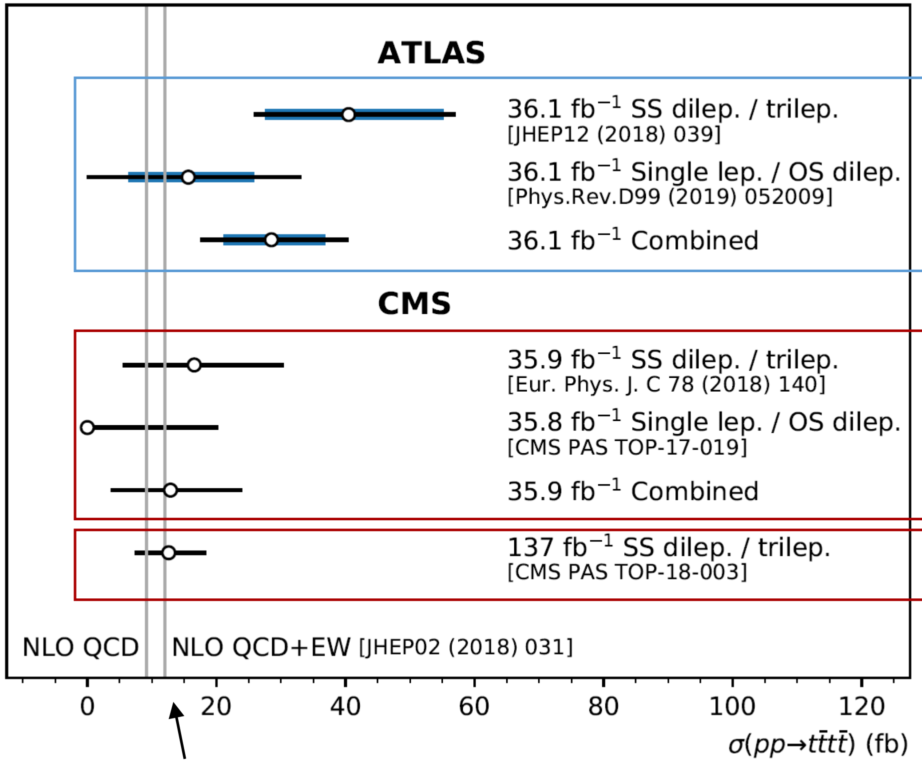


ttZ validation region



Previous measurements

from SM@2019



Value predicted by the Standard Model

Observed (Expected) significance:

Last ATLAS result: **2.8 (1.0) σ**
with an excess observed in the same-sign/three lepton final states

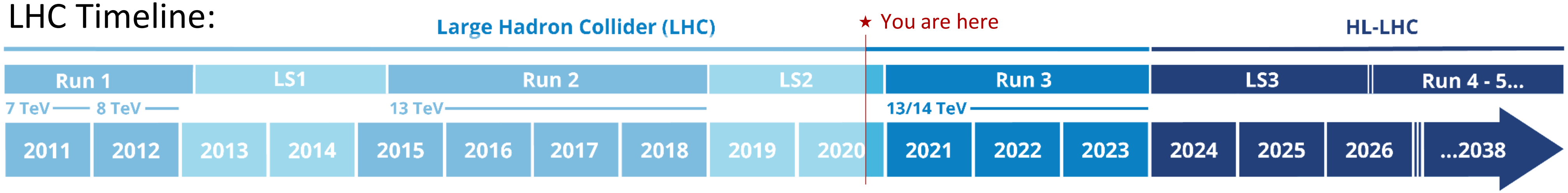
Old CMS combined result: **1.4 (1.1) σ**

New CMS result: **2.6 (2.7) σ**

- *Goal:* Achieve 3σ combined significance with the full run-2 data

In a longer term…

LHC Timeline:



HL-LHC: High Luminosity LHC
LS: Long Shutdown
TeV: Tera electron Volt

- Run 3, starting from 2022 (SARS-COV-2 delay…)
  - Double the data luminosity (i.e. amount of data taken) with possibly higher energy (14 TeV)
  - Will significantly reduce the statistical uncertainty on the measured $\sigma(pp \rightarrow t\bar{t}t\bar{t})$
- HL-LHC, starting from 2026, will last ~10 years:
  - Will multiply the data luminosity by a factor 10 !
  - Will allow very-precise measurements on rare processes like $t\bar{t}t\bar{t}$
  - Evidence on the production of HH