Recent top-quark measurements at the LHC

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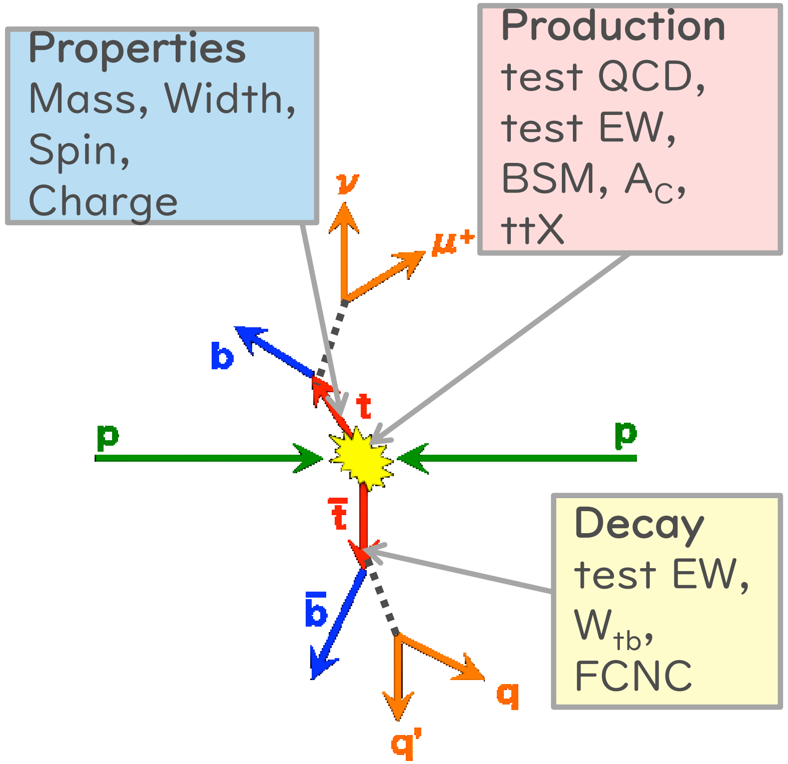
Interests in the Top quark physics

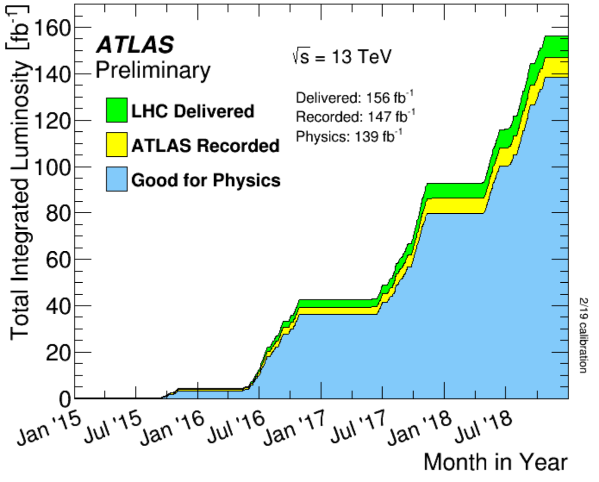
- Top quark?
  - Most massive elementary particle so far discovered
    - with a mass ~**173 GeV**
    - strong coupling to Higgs boson
    - many BSM particles strongly couple with top quark
- Studying top quark
  - Precision test of pQCD, EWK
  - Many BSM searches from top production, properties and decay
  - Important background for a lot of LHC searches



LHC is a Top-factory

- In the LHC-Run2 (2015-2018)
  - 140 fb^{-1} × 832 pb ~ 1.2 x 10^8 $t\bar{t}$ pairs were already produced

$\int L\,dt$ $\qquad \sigma_{t\bar{t}}$



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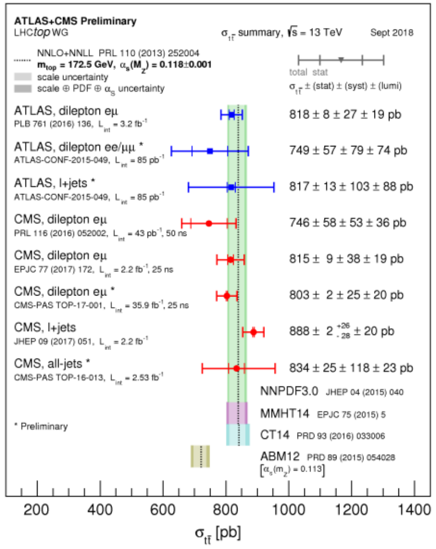

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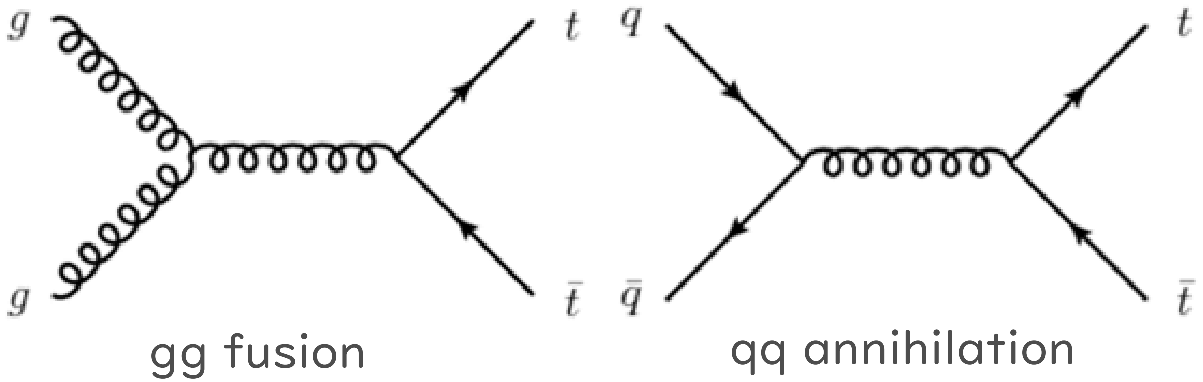
~120M $t\bar{t}$

- The goal: precision test of SM and BSM searches using huge $t\bar{t}$ sample
  - allow to measure very **rare SM** processes

Top quark production at the LHC

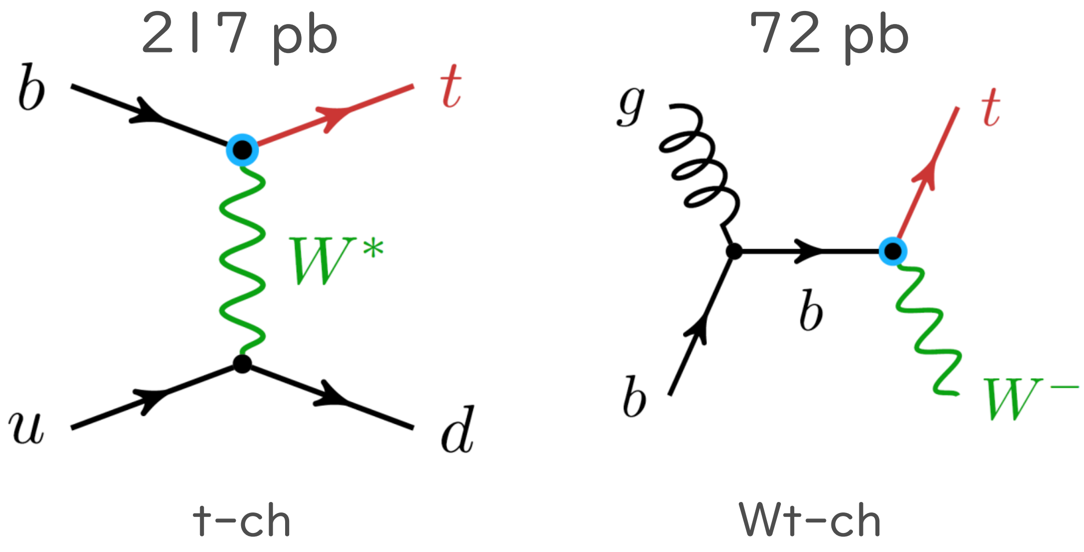
Pair production through QCD

- gluon-gluon fusion: 90%@13TeV
- $q\bar{q}$ annihilation: 10%@13TeV
- $\sigma_{t\bar{t}} \sim$ 832 pb (NNLO+NNLL) @ 13 TeV



Single top production

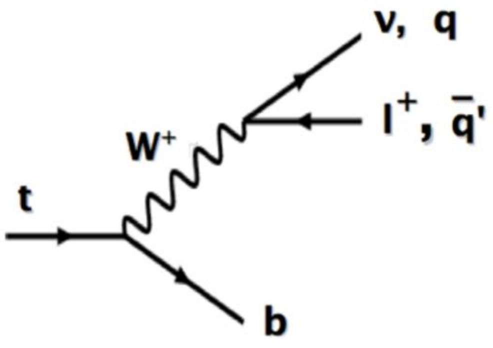
- EW production



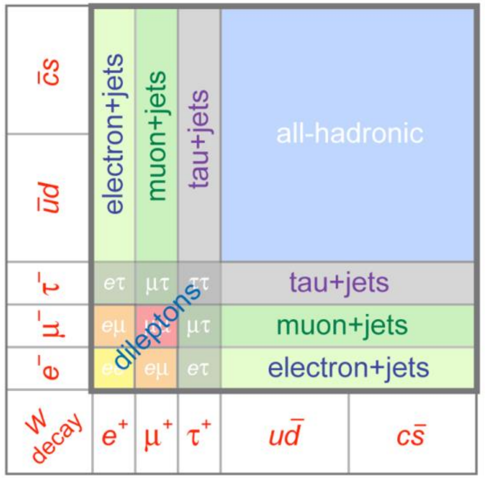
Many rare production

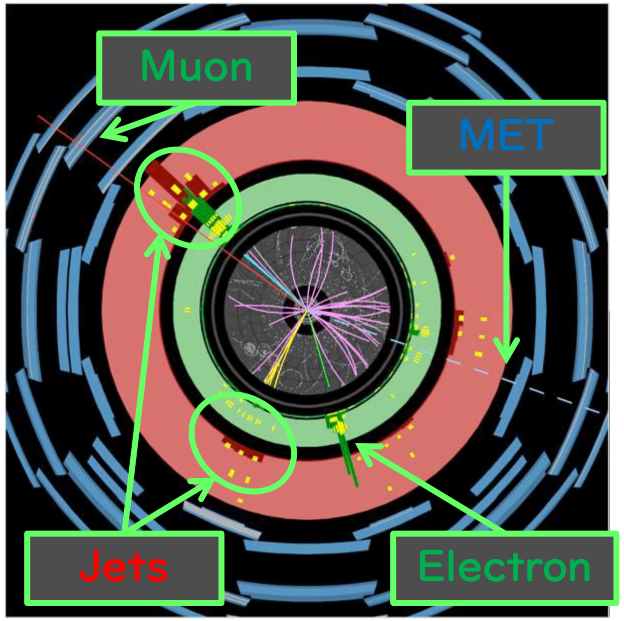
Top quark signal

- Top quark decay to W+b (V_{tb}~1)

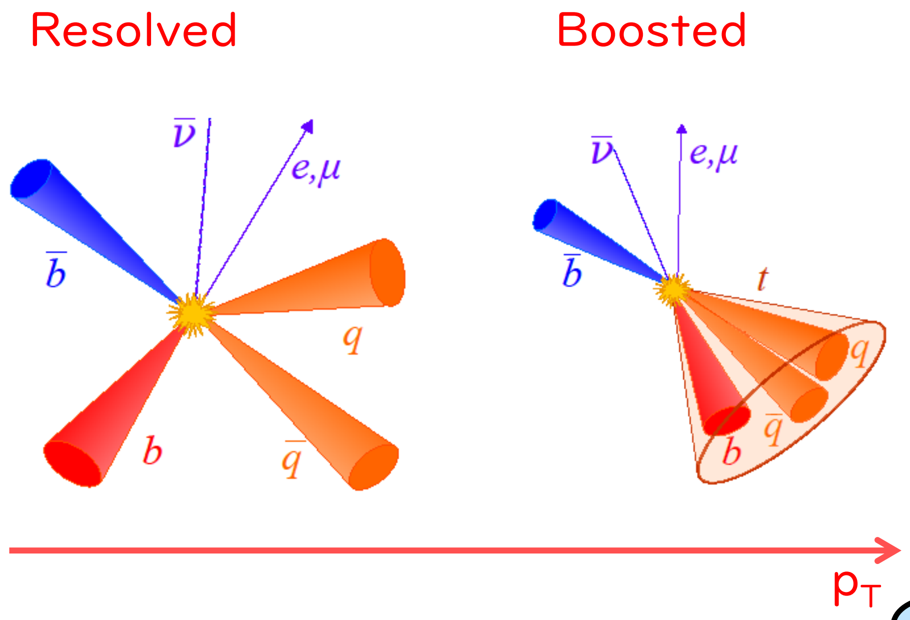


can be categorized by W-boson decay





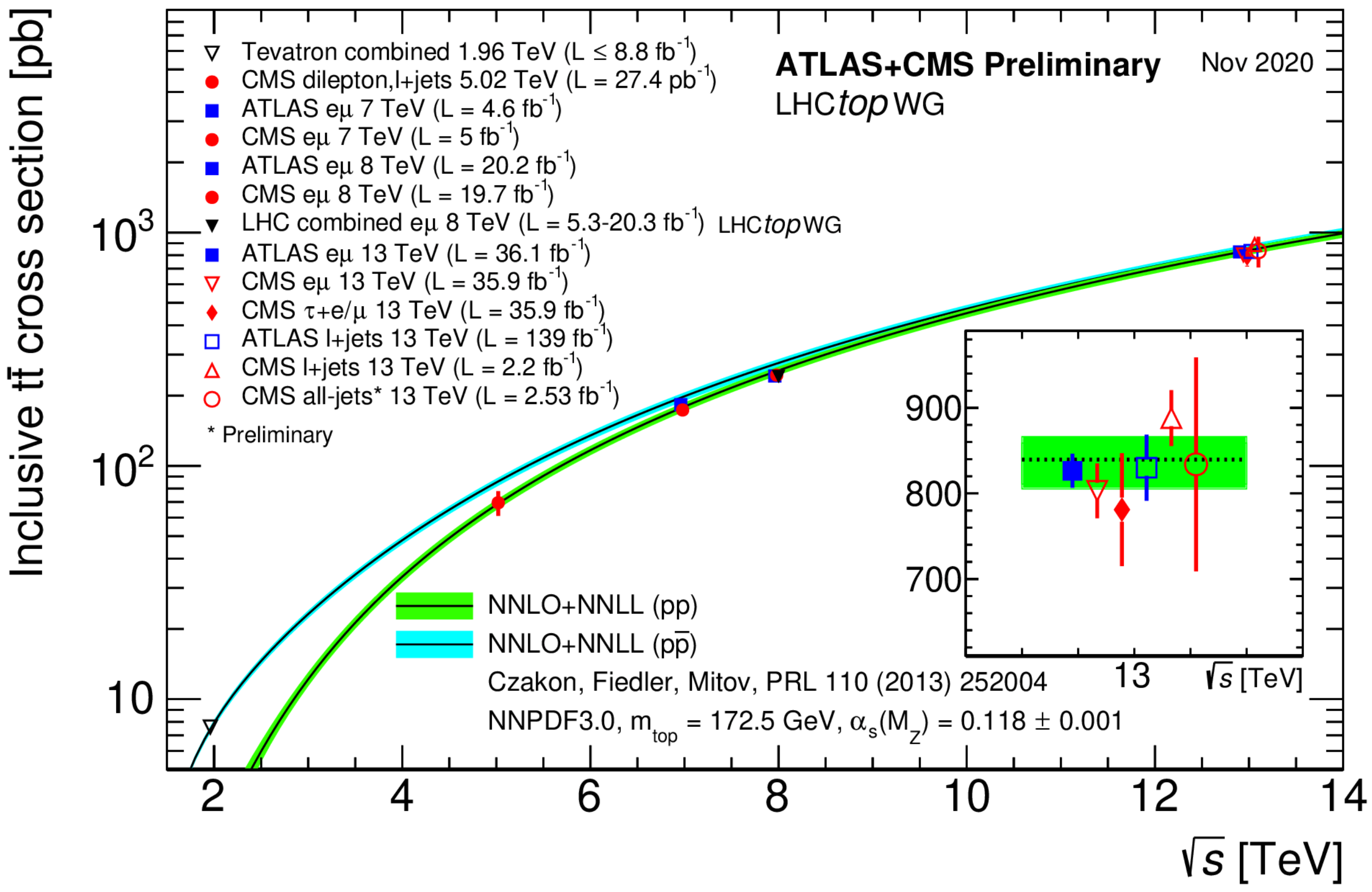
- **Final state objects**
  - High-p_T leptons or/and quark jets
  - Neutrino
    ⇒ Can be detected as large Missing E_T (MET)
  - b-jets
    - b-tagging
  - Top jet (boosted top)
    - top tagging

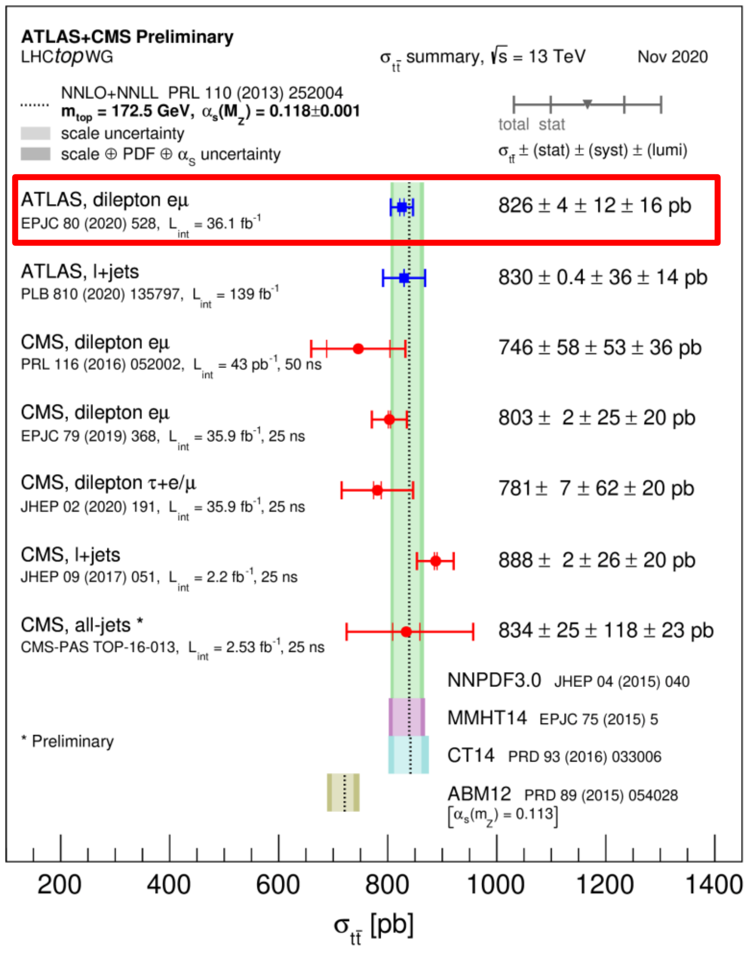


production cross-section measurements

$t\bar{t}$ production cross-section measurements

- Can precisely test pQCD
- Measurements have been performed in the various CMS-energy/final-state





$\sigma_{t\bar{t}}$ measurement in $e\mu$ final state

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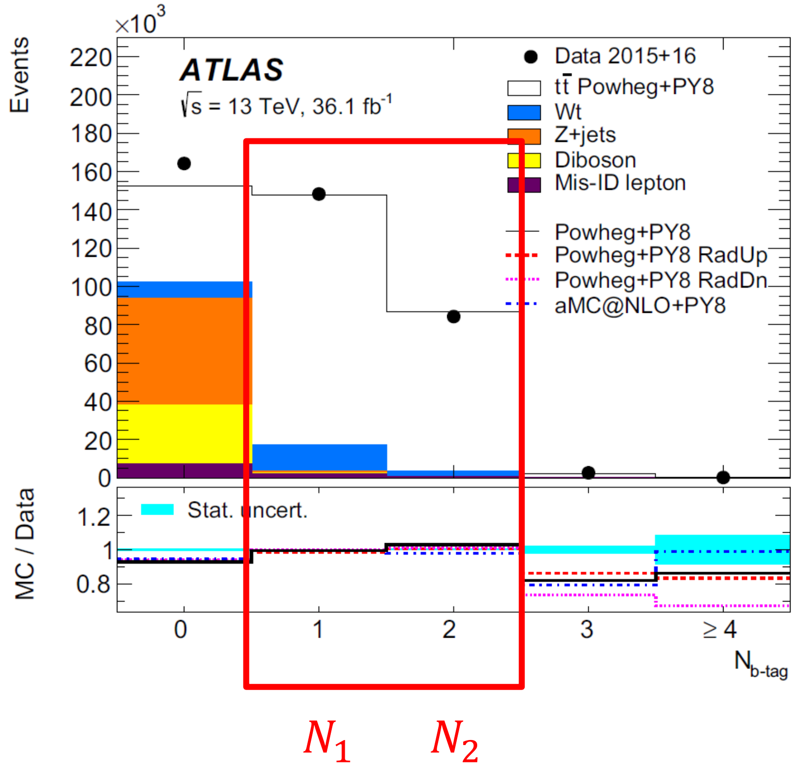
- Why $e\mu$?
  - Cleanest channel
  - $ee/\mu\mu$: Need to care Z-boson+jets background
- Event selections
  - Opposite charged $e\mu$ pair
    - Same charged pair for fake estimation
  - 1 or 2 b-tagged jets
- Extract cross-section and ϵ_b simultaneously
  - ϵ_b; b-tagging efficiency, dominant source of unc.
  - Use following equations



$$N_1 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu} 2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\mathrm{bkg}}$$

$$N_2 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu} C_b\epsilon_b^2 + N_2^{\mathrm{bkg}}$$

estimate from MC

$$\sigma_{t\bar{t}} = 826.4 \pm \underbrace{\overset{\text{stat}}{3.6} \pm \overset{\text{syst}}{11.5} \pm \overset{\text{lumi}}{15.7} \pm \overset{E_{\text{beam}}}{1.9}}_{\text{2.4\% total uncertainty}}\ \text{pb},$$

Differential cross-sections

PHYS. REV. D 103, 052008 (2021)
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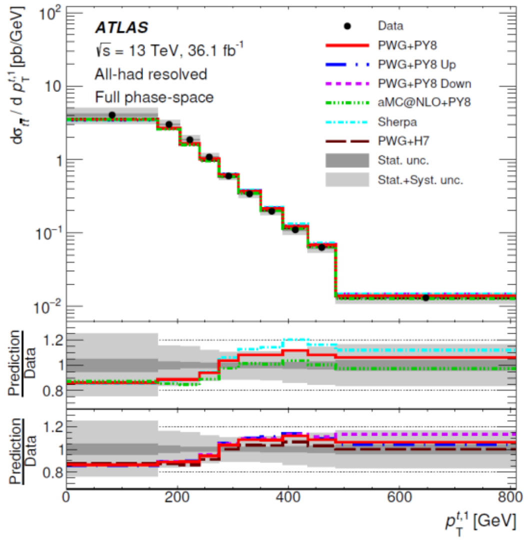
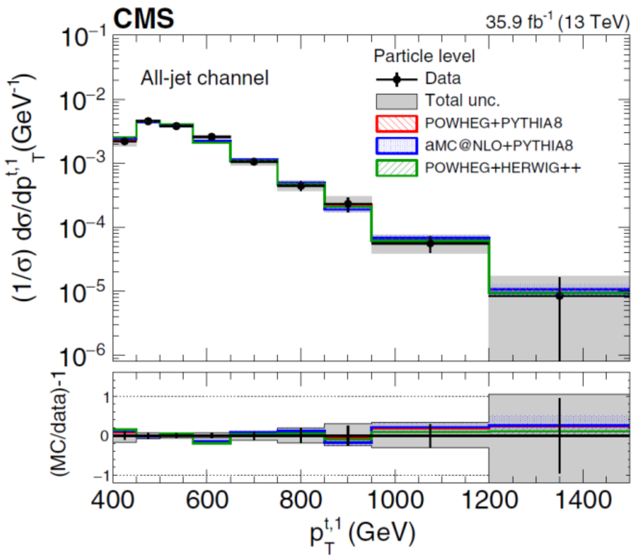
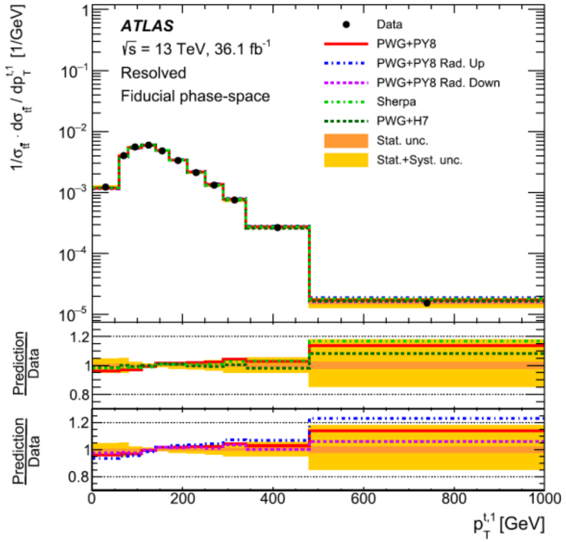
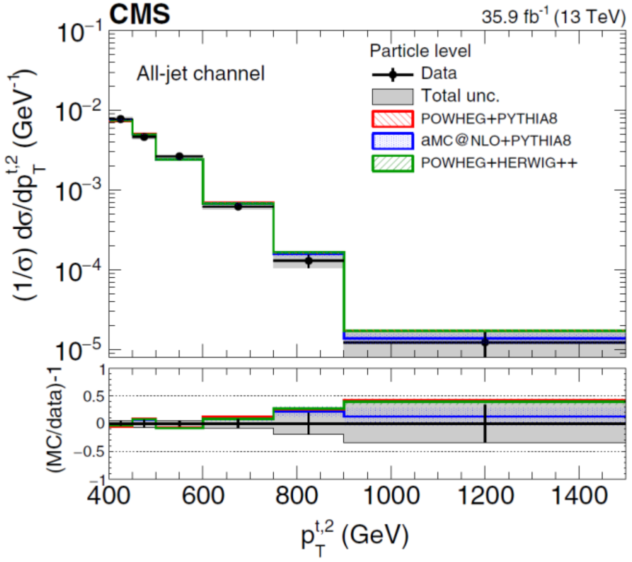
JHEP01(2021)033

- Differential cross sections can be used to test SM predictions and MC generators
  - Precision measurements are sensitive to new physics
- A lot of measurement have been performed
- Some tension between data and MC are observed
  - Significant over-prediction of $\sigma_{t\bar{t}}$ at higher $p_T^{\,t}$ (also N_{jets} and $p_{T,tt}$)
  - Better models are needed to reproduce the data well





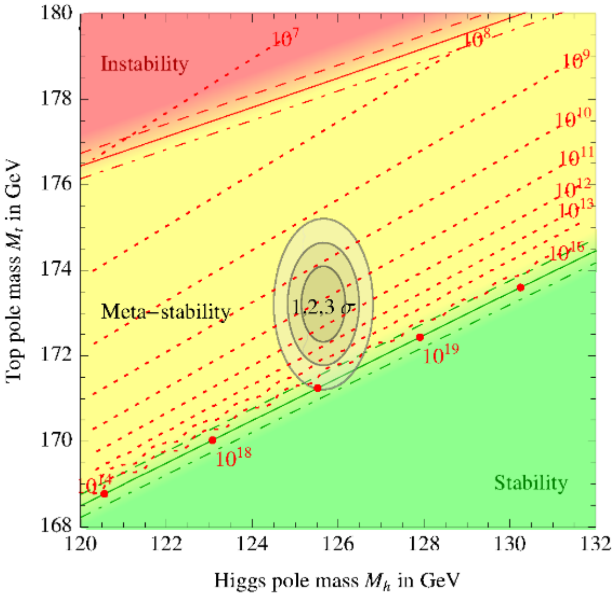




top mass measurements

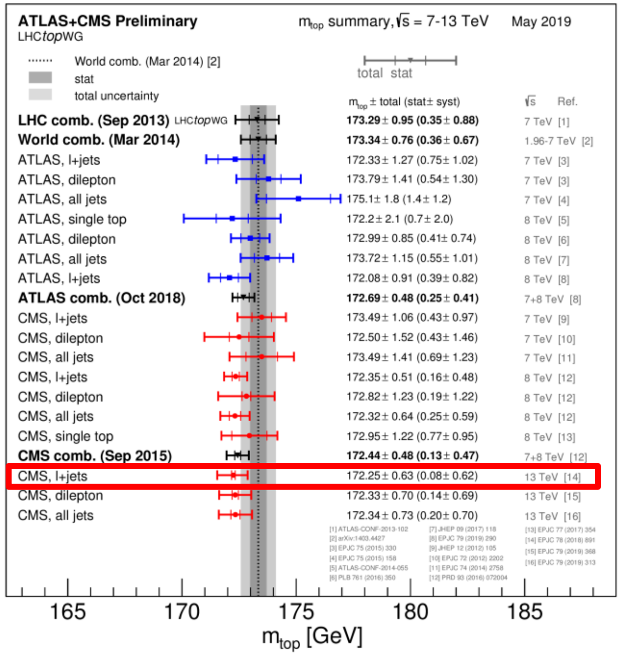
Mass of the top quark

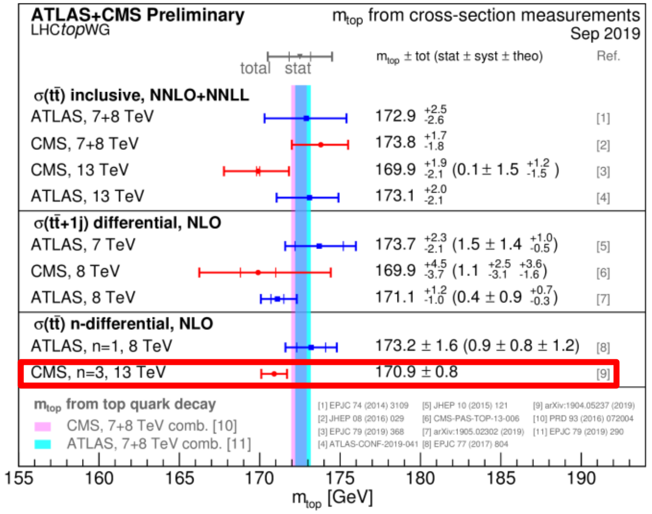
- The measured m_h and m_t are at the boundary between stable and metastable
  $\Rightarrow \delta m_h \approx 0.2$ GeV (Recent LHC status)
  - m_t measurement is becoming more important



- What is the mass of top quark?
  - MC mass？ m_t^{MC}
  - Pole mass？ m_t^{pole}
- How to measure them?
  - Direct measurement; m_t^{MC}
    - Reconstruct from top decay objects
  - Indirect measurement; m_t^{pole}
    - Extract from measured cross-section

Best $\delta m_t^{\mathrm{MC}} \sim 0.5$GeV (Run-I comb.)





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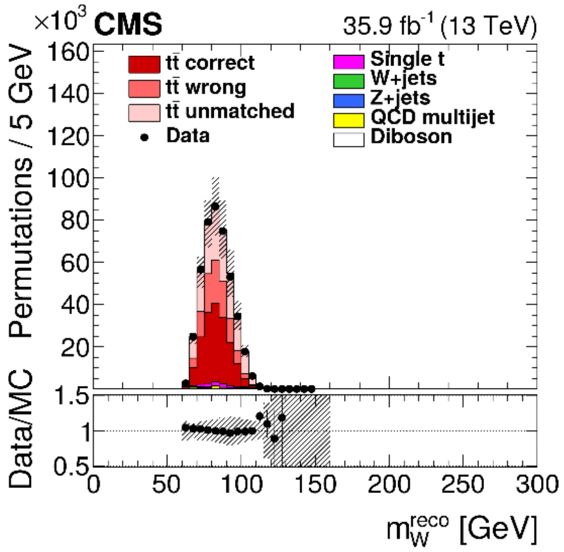
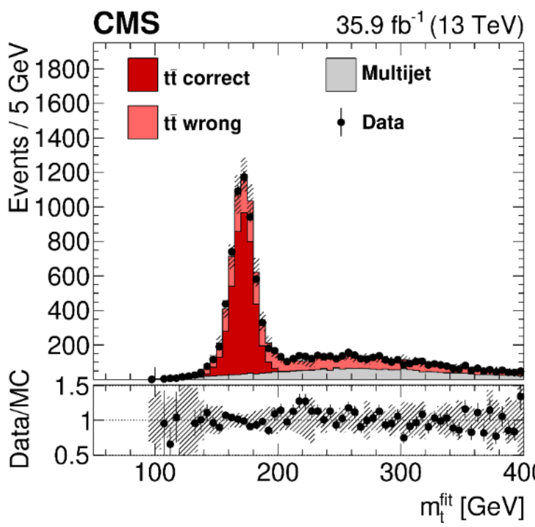
Direct measurement

- Reconstruct m_t from decay objects
  - Assignment of observed jets
  - Jet energy scale (JES) calibration is the key
- ✓ Using W boson mass to reduce JES uncertainties
- Results

Reconstructed W mass





lep+jets ch

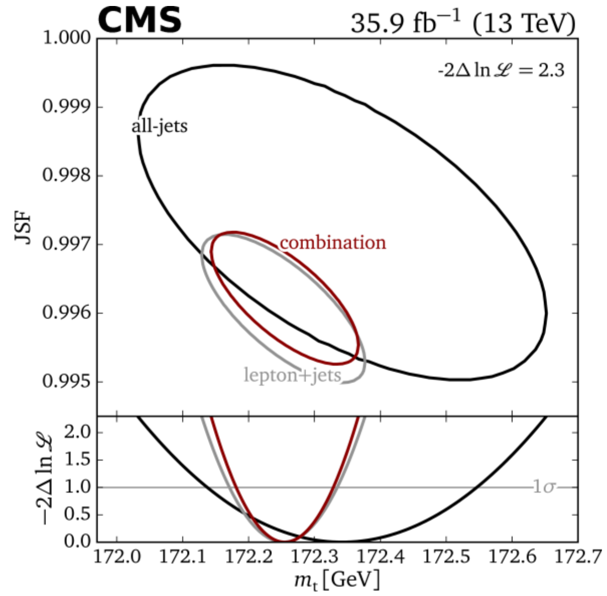
$$m_t^{\mathrm{hyb}} = 172.25 \pm 0.08\,(\mathrm{stat{+}JSF}) \pm 0.62\,(\mathrm{syst})\ \mathrm{GeV},$$
$$\mathrm{JSF}^{\mathrm{hyb}} = 0.996 \pm 0.001\,(\mathrm{stat}) \pm 0.008\,(\mathrm{syst}).$$

all-had ch

$$m_t^{\mathrm{hyb}} = 172.34 \pm 0.20\,(\mathrm{stat{+}JSF}) \pm 0.70\,(\mathrm{syst})\ \mathrm{GeV},$$
$$\mathrm{JSF}^{\mathrm{hyb}} = 0.997 \pm 0.002\,(\mathrm{stat}) \pm 0.007\,(\mathrm{syst}).$$

Combination

$$172.26 \pm 0.07\,(\mathrm{stat{+}JSF}) \pm 0.61\,(\mathrm{syst})\ \mathrm{GeV}.$$



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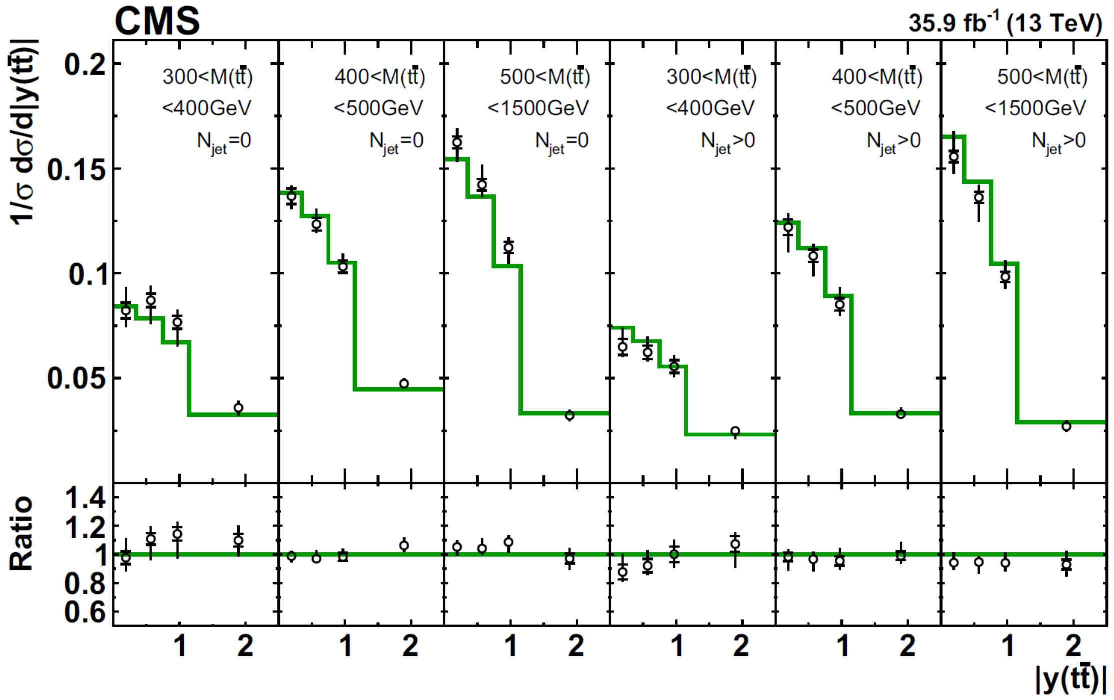
m_t^{pole} measurement

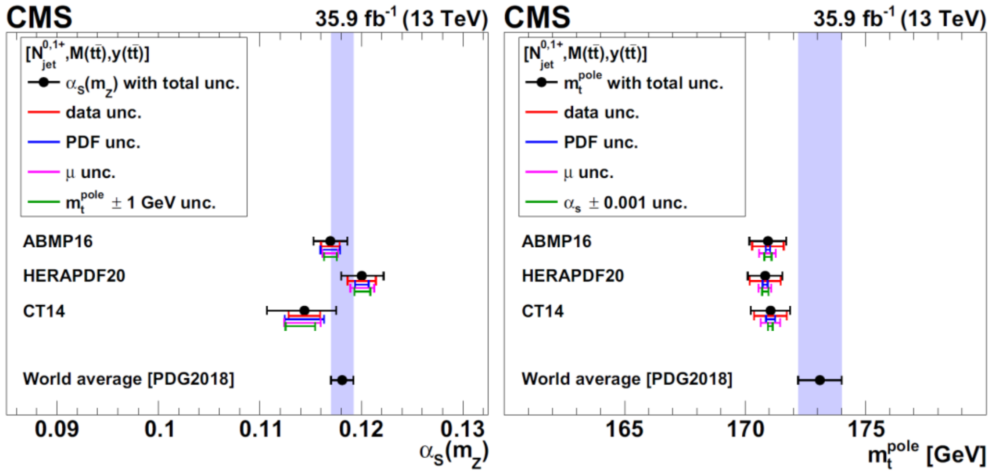
- $\sigma_{t\bar{t}}$ is sensitive to m_t^{pole}
  - Differential cross-section $d\sigma_{t\bar{t}}/dX$ has better sensitivity
  - But… there are a lot of parameter sensitive to $\sigma_{t\bar{t}}$
    → PDF, α_s, m_t^{pole}, etc

✓ Simultaneous measurement of PDF, α_s, m_t^{pole} from triple-differential cross section
  - as a function of N_{jets}, m_{tt} and y_{tt}
    $d^3\sigma_{t\bar{t}}/dN_{\text{jets}}dm_{t\bar{t}}dy_{t\bar{t}}$

- Most precise determination of m_t^{pole}

$$m_{\text{t}}^{\text{pole}} = 170.5 \pm 0.8\,\text{GeV}$$





PLB 803 (2020) 135263

Running of the top quark mass

In $\overline{\text{MS}}$ scheme, the value of m_t depends on energy scale ($\propto m_{tt}$)

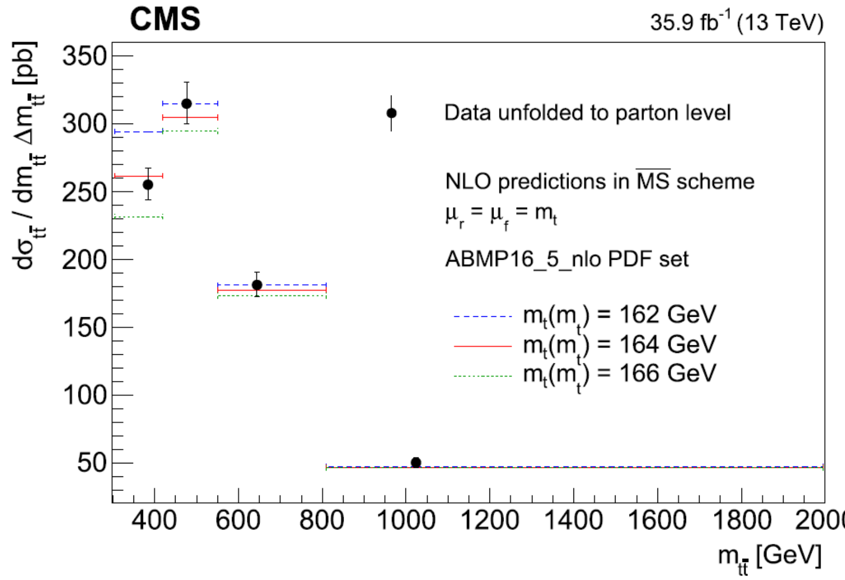
- Like α_s

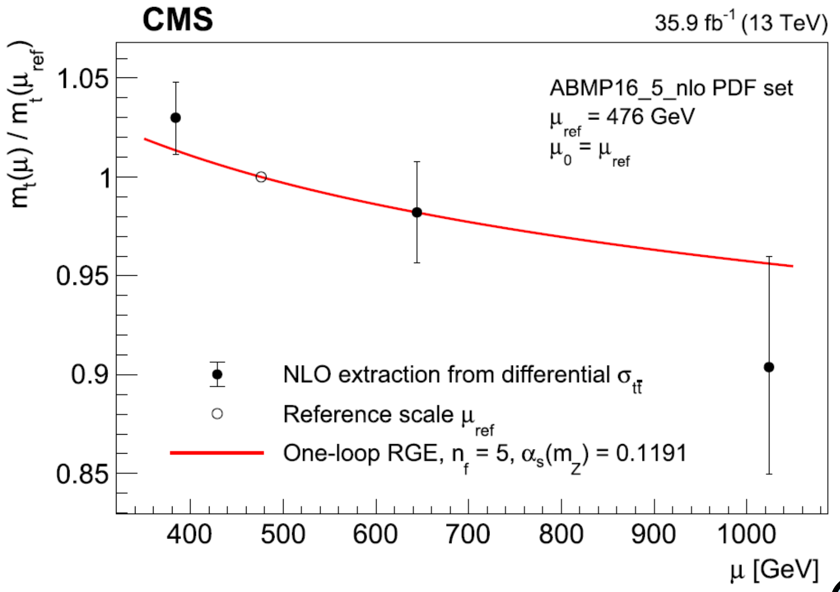
→ **running of $m_t(\mu_m)$**

$$\mu^2 \frac{\mathrm{d}m(\mu)}{\mathrm{d}\mu^2} = -\gamma(\alpha_S(\mu))\, m(\mu),$$

- Differential cross section as a function of m_{tt}
- Running factor extracted by comparing to NLO predictions

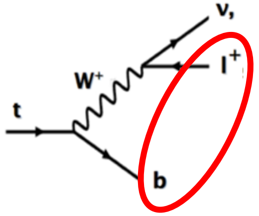
- The extracted running is found to be compatible with the scale dependence
  - no-running hypothesis is excluded at 95% C.L.
- The running is probed up to ~1TeV

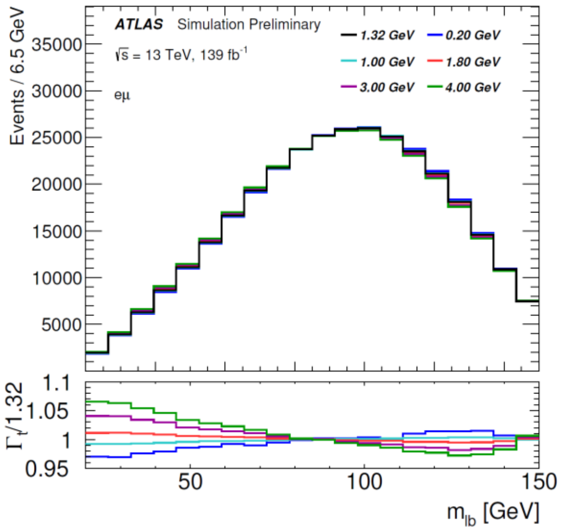


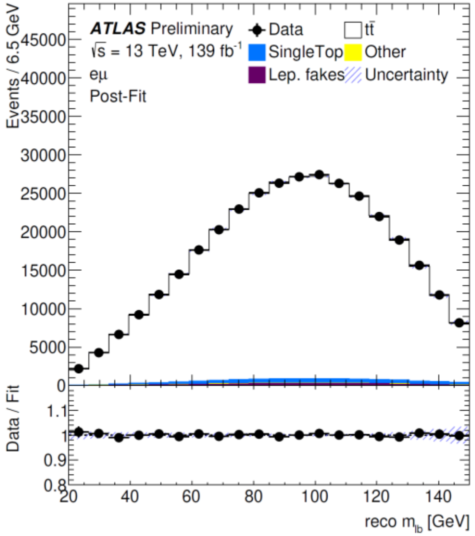


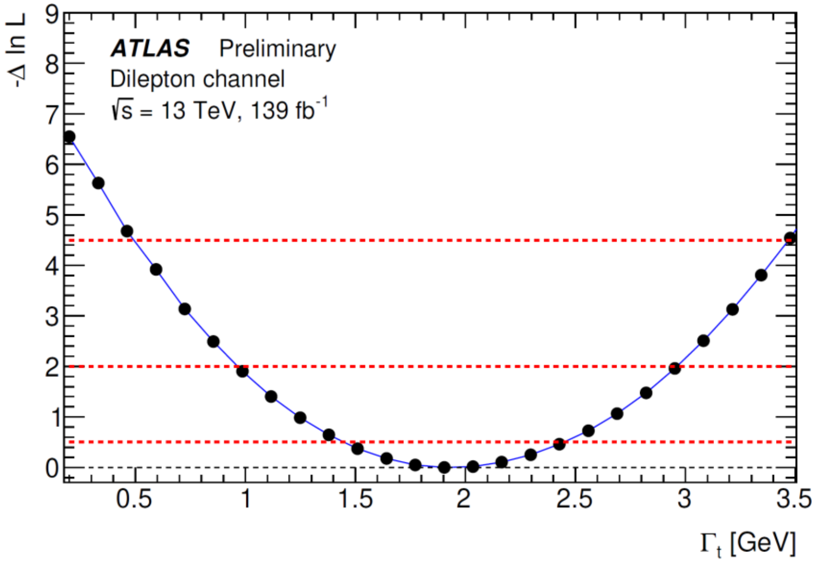
Top decay width

- Top decay width; One of the fundamental properties of the top quark
  - Direct measurement from m_{lb}
    m_{lb}: Invariant mass of charged lepton and bottom quark in top decays
    ⇔ Indirect measurement: $\Gamma_t = 1.36 \pm 0.02(\mathrm{stat})^{+0.14}_{-0.11}(\mathrm{syst})\ \mathrm{GeV}$
  - Could hint
    - non-SM decay channels of the top quark
    - modification of top-quark couplings









Γ_{top} = 1.9 ± 0.5 GeV

SM: 1.32 GeV @ m_{top} = 172.5 GeV

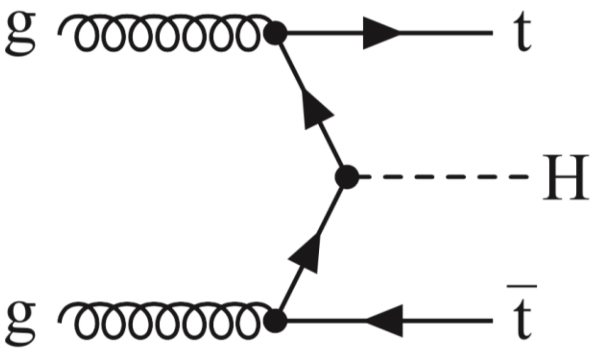
top-Higgs coupling

a big milestone @ LHC

ttH

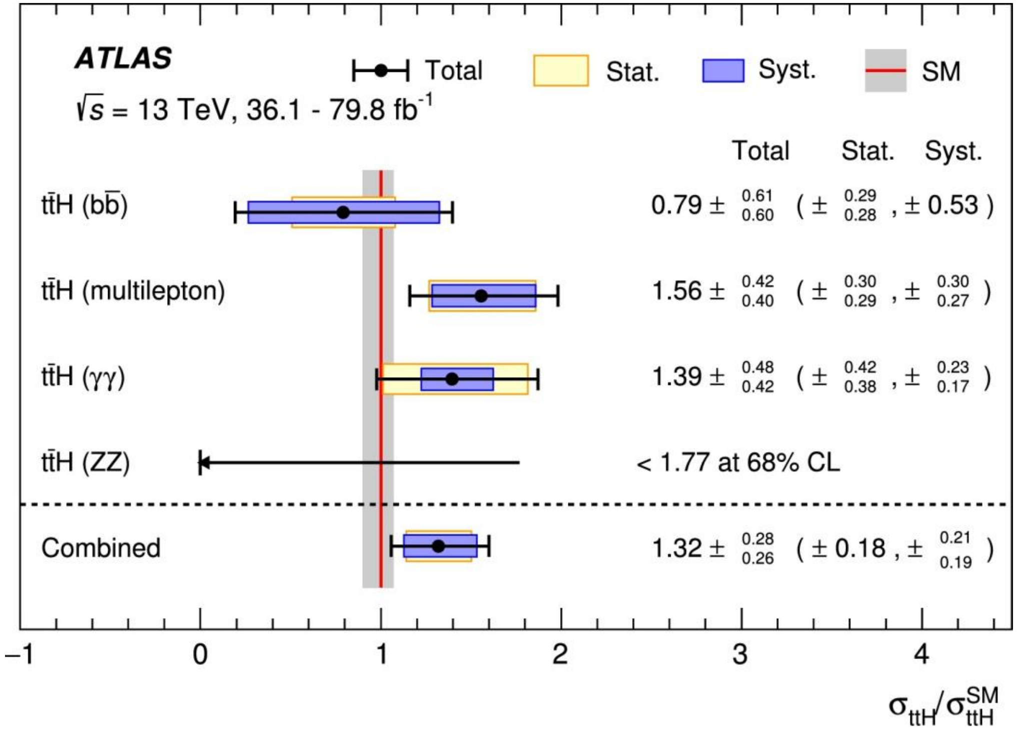
Phys.Lett.B 784 (2018) 173–191

- Direct probe of top-Higgs coupling



  - One of the primary target in LHC physics
- Covered various Higgs and top pair decay modes
  - Machine Learning based analysis
- Observation (ex of ATLAS)
  - 5.8 σ significance @ Run2
  - 6.3 σ significance @ Run1 + Run2

Uncertainty source	$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ [%]
Theory uncertainties (modelling)	11.9
$t\bar{t}$ + heavy flavour	9.9
$t\bar{t}H$	6.0
Non-$t\bar{t}H$ Higgs boson production	1.5
Other background processes	2.2
Experimental uncertainties	9.3
Fake leptons	5.2
Jets, E_T^{miss}	4.9
Electrons, photons	3.2
Luminosity	3.0
τ-leptons	2.5
Flavour tagging	1.8
MC statistical uncertainties	4.4



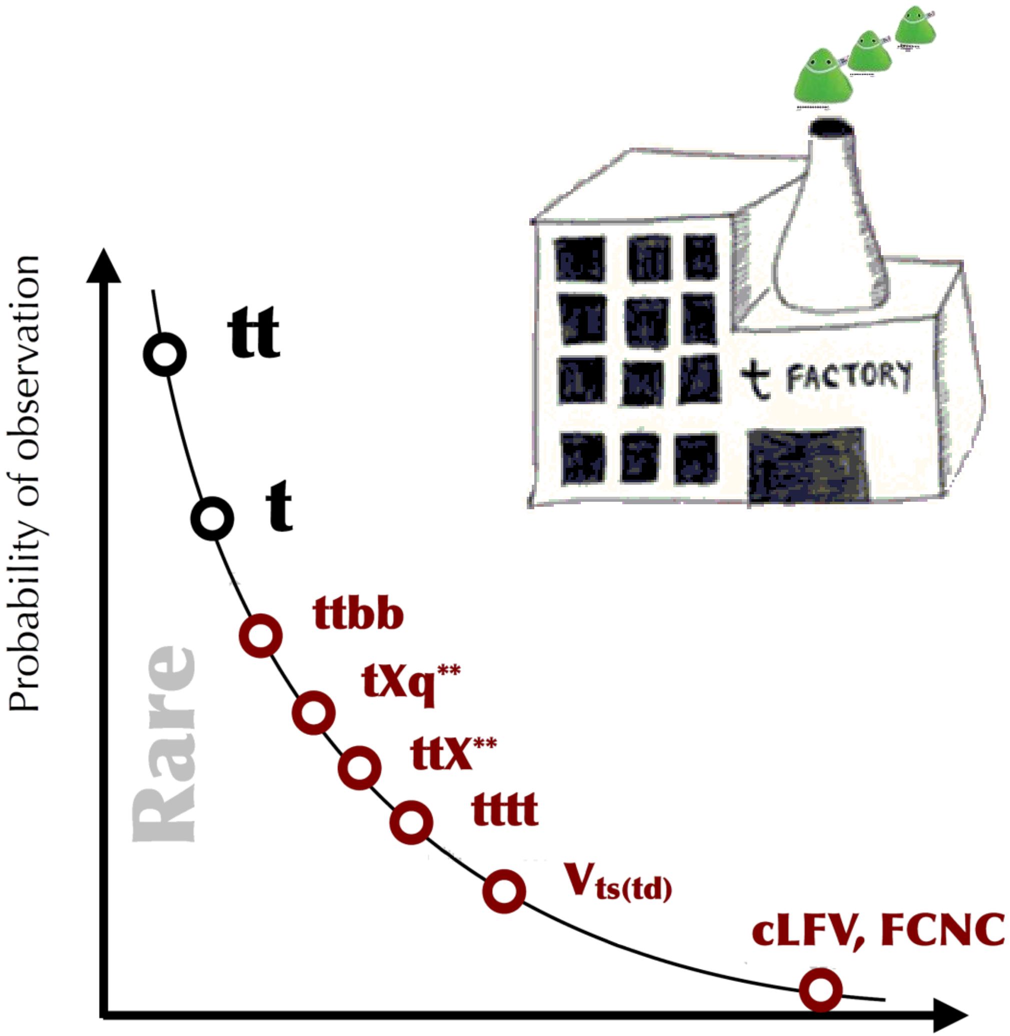
Rare top quark processes

SM rare process

- Is the SM still correct in extreme phase space?
  - Can be tested in rare SM process

Ex)

- $t\bar{t}bb$, $t\bar{t}X$, $t\bar{t}t\bar{t}$
  - Very rare SM processes
  - Can be measured thanks to huge LHC data
  - Important backgrounds for future BSM searches
- FCNC
  - Not sensitive at the LHC
  - If BSM exist, possible enhance



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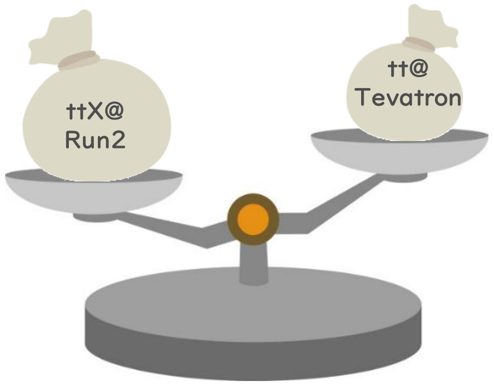
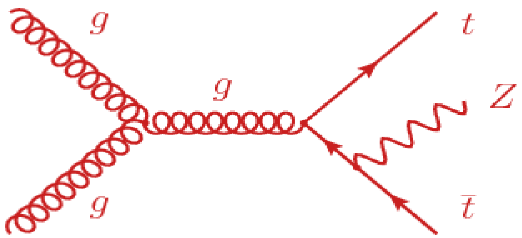
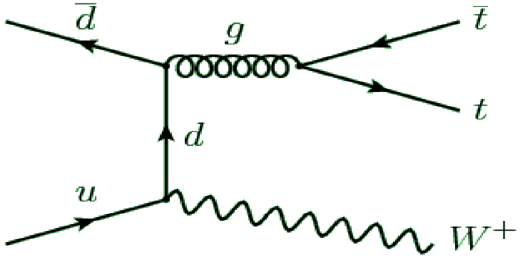
tt+X production



- Associate production with Vector bosons or photon
  - very rare $\sigma_{ttX}{}^{\mathrm{SM}} < 1\ \mathrm{pb}\ \ (\Leftrightarrow \sigma_{tt}{}^{\mathrm{SM}} \sim 1\ \mathrm{nb})$
  - LHC has more ttX than tt at Tevatron
  - important to ttH, VLQ, SUSY searches





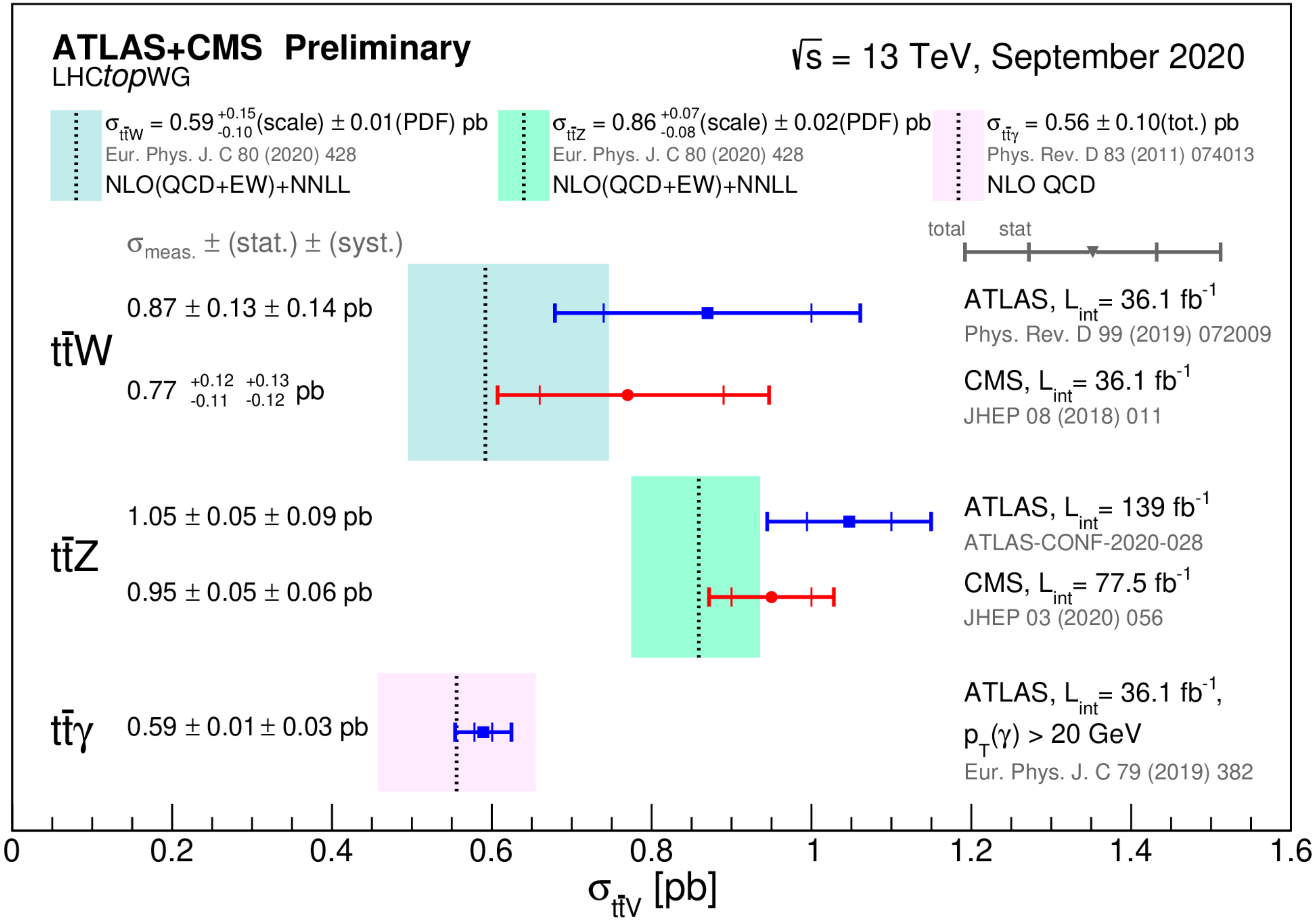
- tt+Z
  - Sensitive neutral current coupling between t and Z
  - Sensitive EFT operator related to tZ coupling
  - BSM can alter cross-section
- tt+ γ
  - Sensitive to t γ electroweak coupling
- tt+W
  - Having Same sign lepton pair final state
    - Very rare for SM processes
  - Important final state in the many BSM searches

$$C_V^{SM} = T^3 - 2Q_t sin^2(\theta_W)$$

$$\gamma^\mu (C_V^{SM} - \gamma_5 C_A^{SM})$$

$$C_A^{SM} = T^3$$

Status of tt+X



Four tops; $t\bar{t}t\bar{t}$

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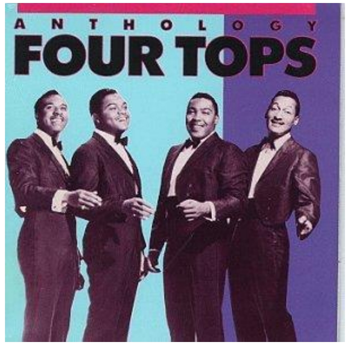
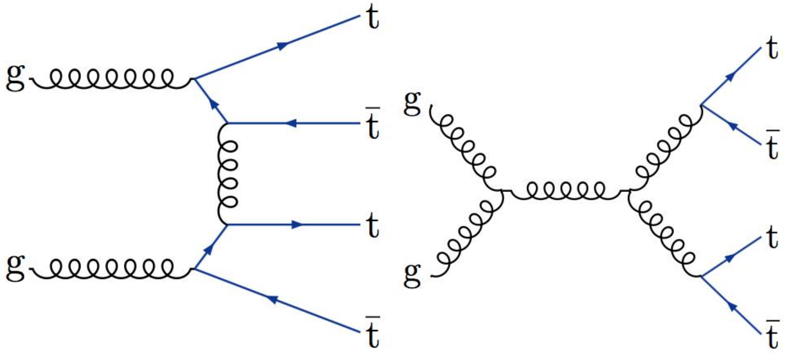
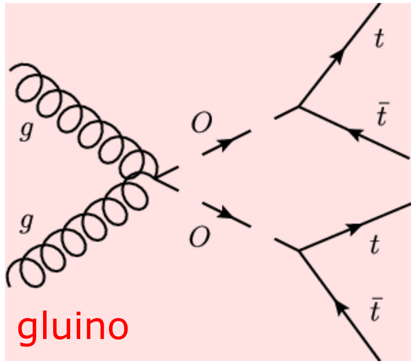
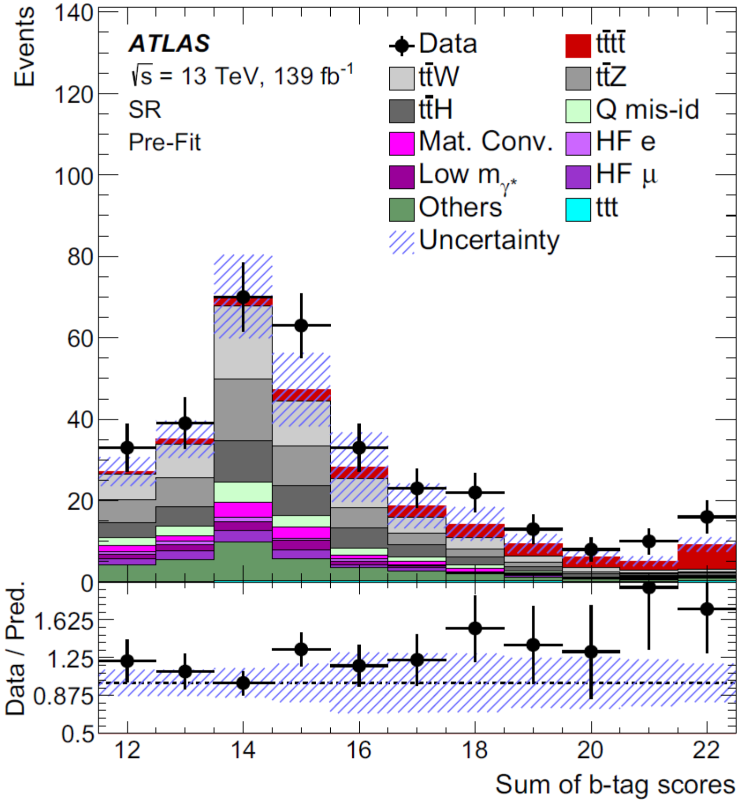
- $\sigma_{\mathrm{SM}}^{t\bar{t}t\bar{t}} \sim 12$ fb → Extremely rare process
  - CP properties of the Yukawa coupling
  - Many BSM enhance four tops









- Event selection
  - same-sign lepton pair
    or
    at least three leptons
  - BDT employed to separate signal and backgrounds
    - ex) Jet multiplicity, jet flavor and event kinematics

Results; $t\bar{t}t\bar{t}$

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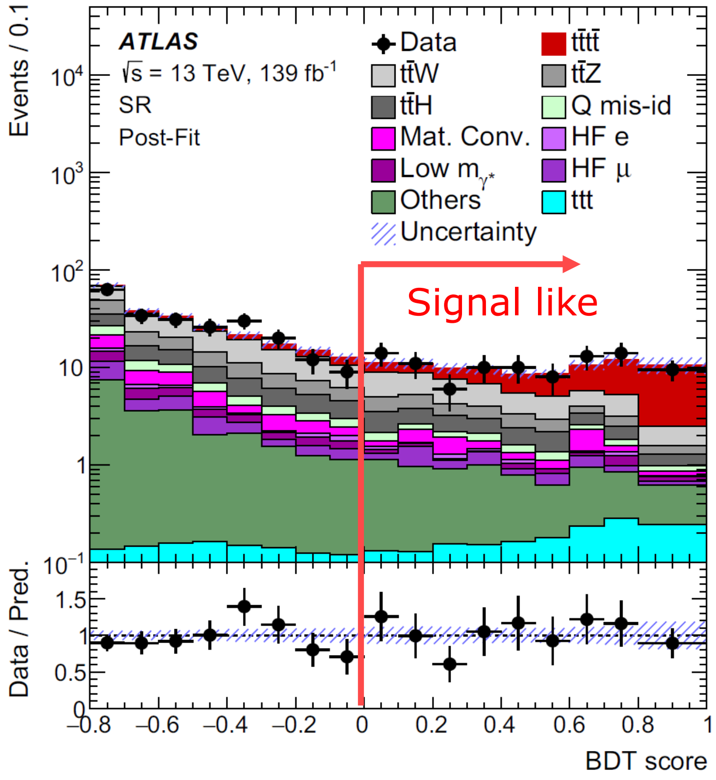
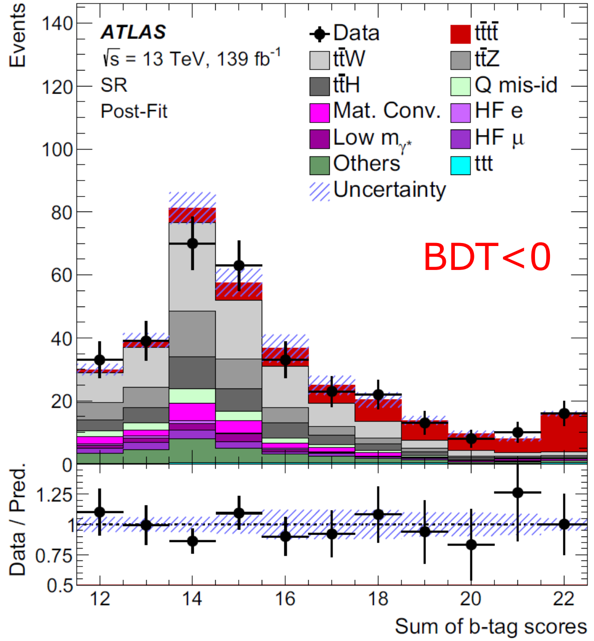
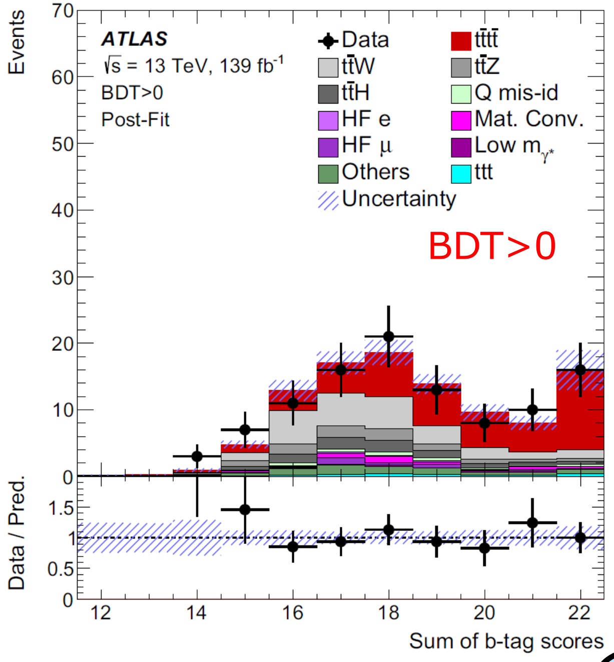
- Signal and backgrounds normalizations are determined by likelihood fit
  - to the BDT
- Uncertainties
  - Signal modelling
    - cross-section
    - modelling
  - ttW modelling
  - Statistical unc.
- Measured cross-section is

$$\sigma_{t\bar{t}t\bar{t}} = 24 \pm 5(\text{stat})\,^{+5}_{-4}(\text{syst})\text{ fb} = 24\,^{+7}_{-6}\text{ fb}.$$

Standard Model expectation of $\sigma_{t\bar{t}t\bar{t}} = 12.0 \pm 2.4$ fb.





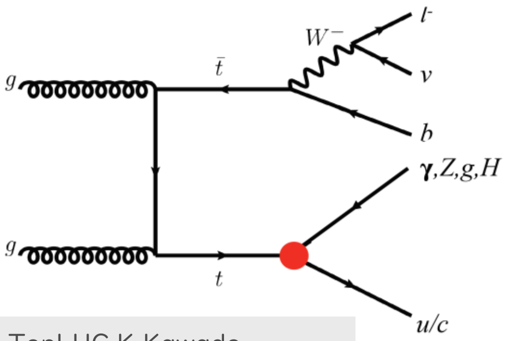


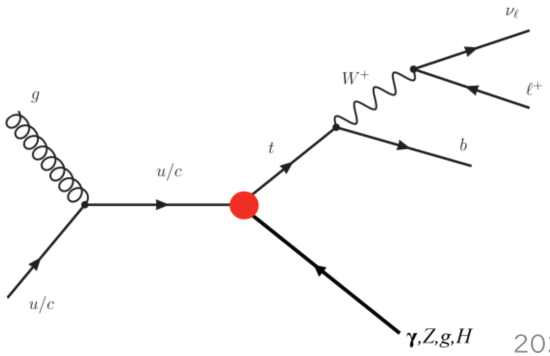
FCNC

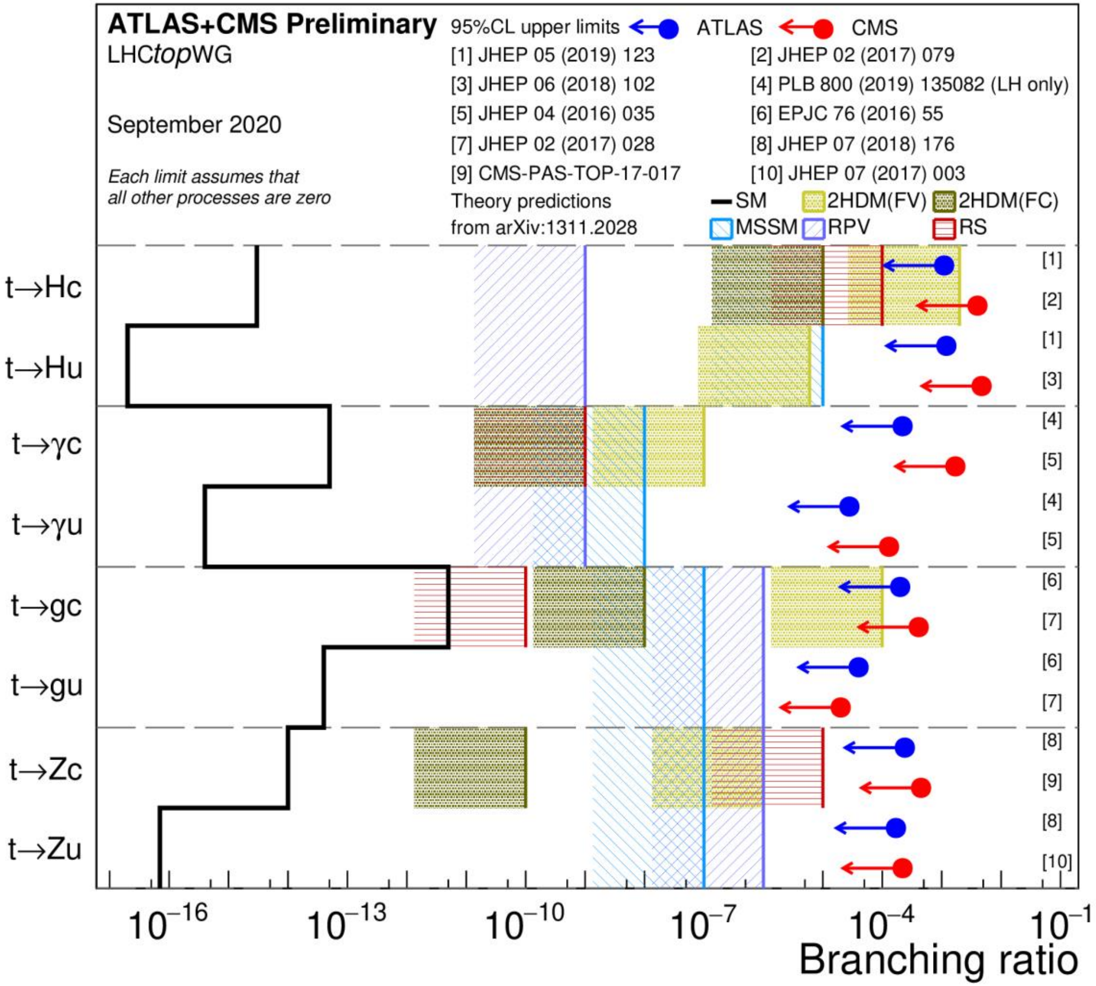
- Flavor-Changing Neutral Current
  - Strongly suppressed in the SM (10^{-14})
  - BSM can enhance BR

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

- Approaching from production and decay







Prospects;
HL-LHC improve factor 4 [see ATL-PHYS-PUB-2019-001]

Summary

- Various top quark measurements have been performed
  - Only small part are showed in this talk…
- SM still powerful to describe top production in the wider range
- Systematic already became dominant uncertainties
  - Improve modelling
  - Improve analysis
- A lot of analysis is ongoing, Stay tune
- Hope synergy between LHC and ILC in top physics