Top Quark Physics - II

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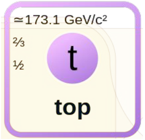
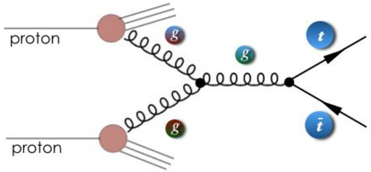
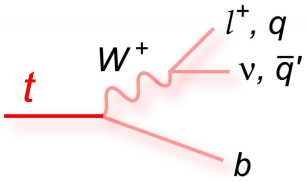
Where we left

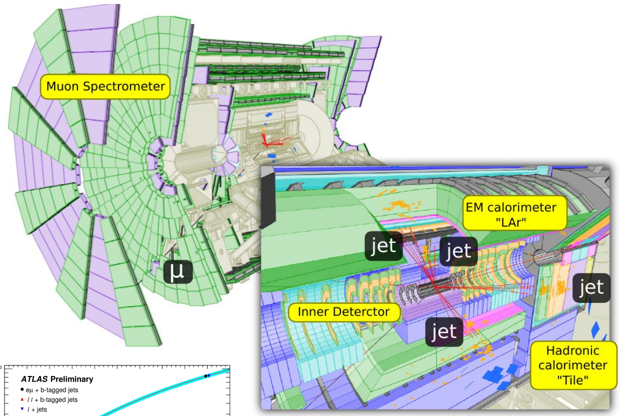


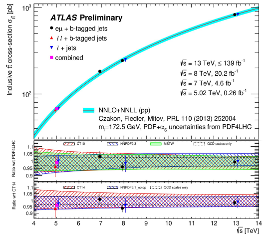


- Lecture 1:
  - A brief recap
  - The top quark
  - Tools for top quark physics
  - Top-pair production cross-section



$$\sigma = \frac{N}{\int L} = \frac{N(data) - N(background)}{\epsilon \cdot \int L}$$



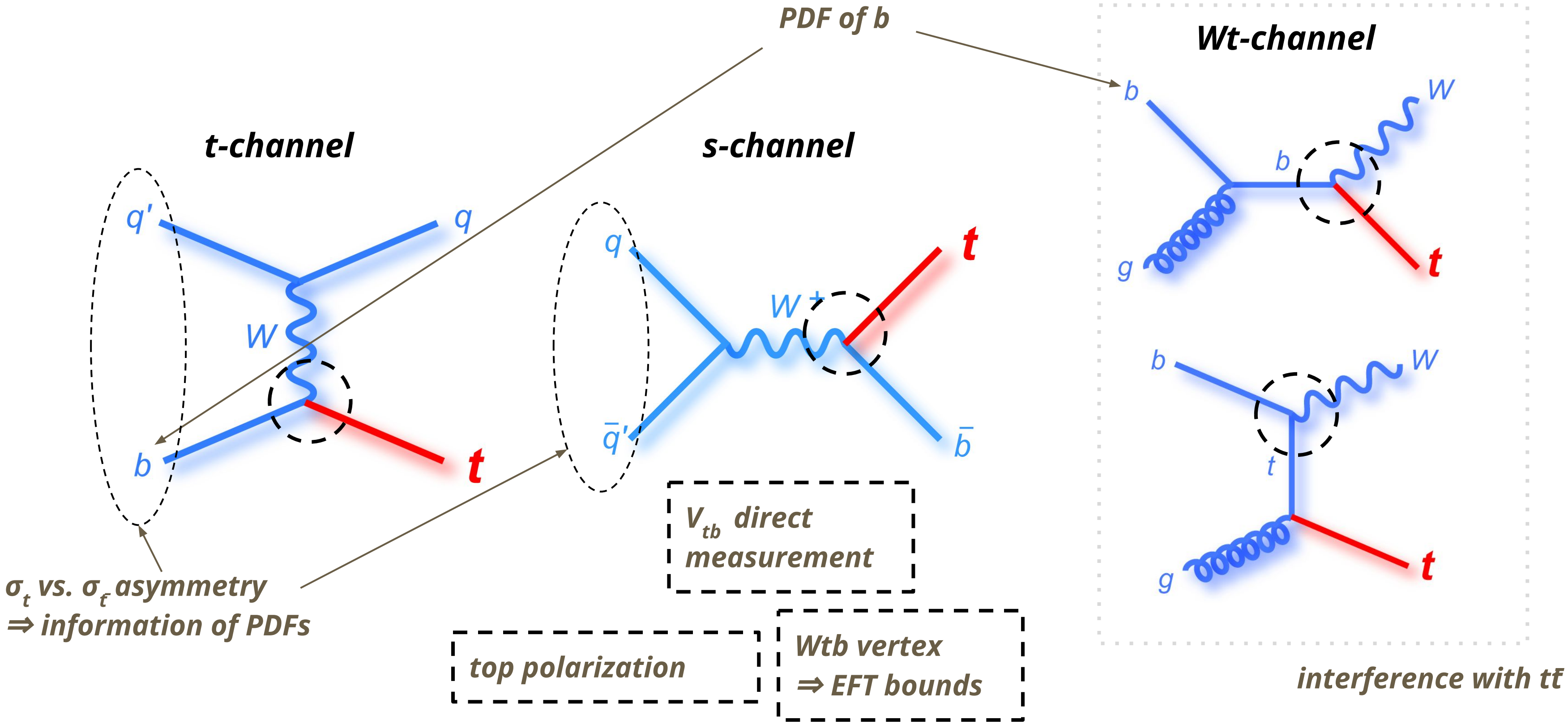


- Lecture 2:
  - Single top
  - Spin and angular properties
  - Top quark mass
  - Top events as a tool for other measurements
  - Associated top production
  - New physics with top
  - Closing remarks

Single top

ATLAS EXPERIMENT

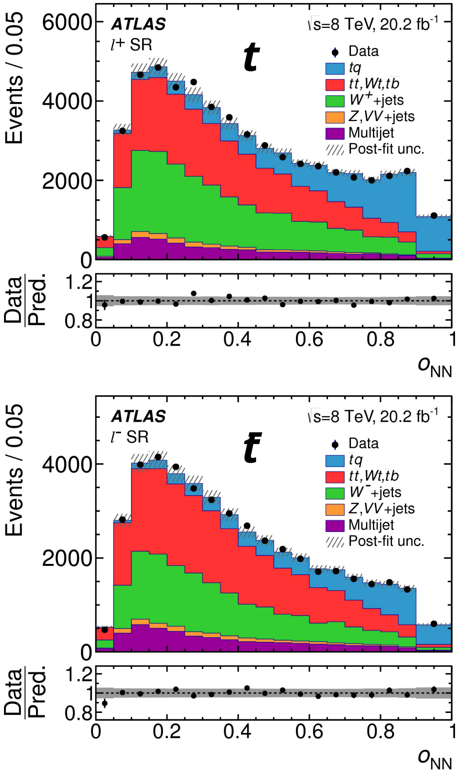
What to do with single top



Single top cross-section and Vtb determination

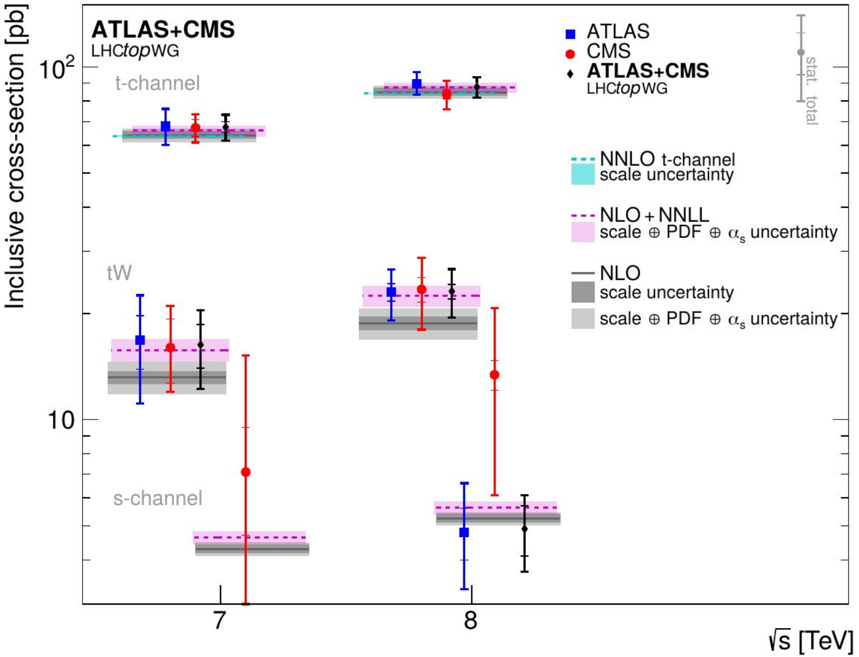
t-channel - √s = 8 TeV

Eur. Phys. J. C 77 (2017) 531



LHC combination

JHEP 05 (2019) 088



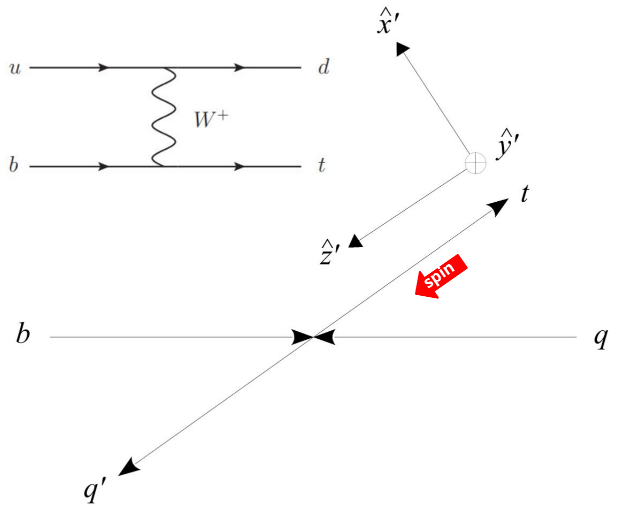
$$|f_{LV}V_{tb}| = 1.02 \pm 0.04\ (\text{meas.}) \pm 0.02\ (\text{theo.})$$

vs. indirect determination: $|V_{tb}| = 0.999105 \pm 0.000032$

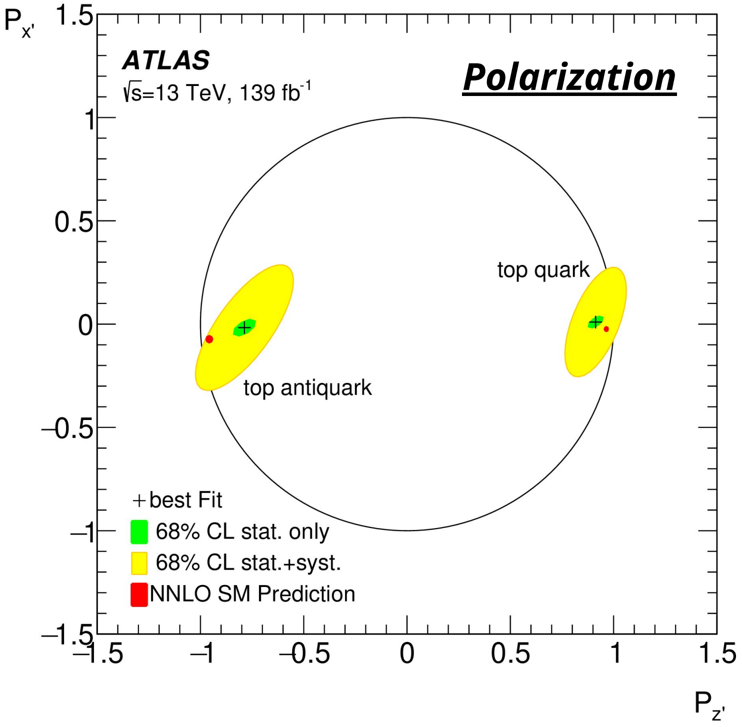
Spin and angular properties

Single top polarization

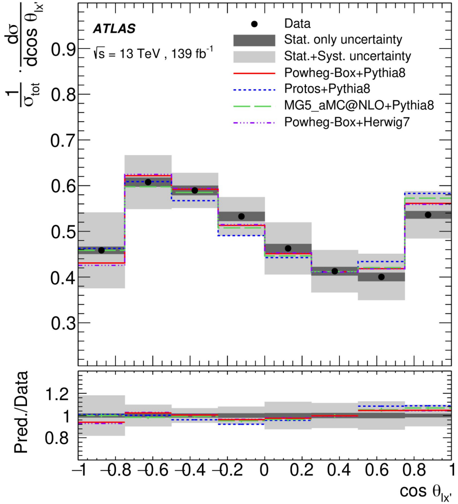
Top polarization in t-channel, √=13 TeV arXiv:2202.11382 [hep-ex]

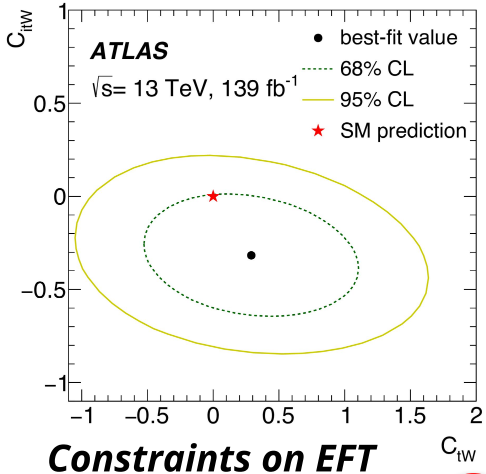


Why non-zero polarization?
V-A coupling in bWt vertex
⇒ spin aligned with q'



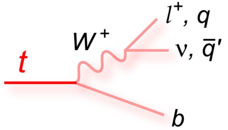
Unfolded distributions

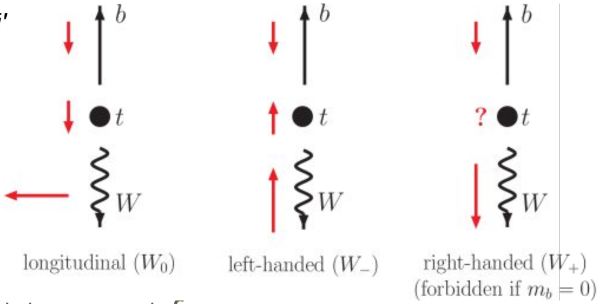




Constraints on EFT

W helicity





8 TeV, ℓ+jets & dilepton

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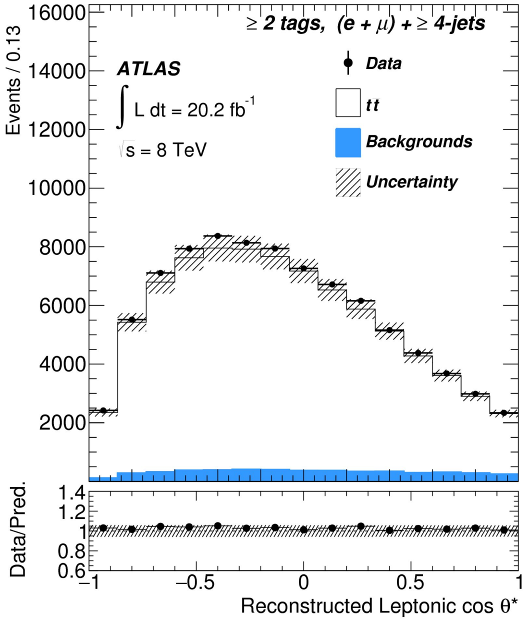
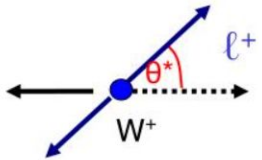
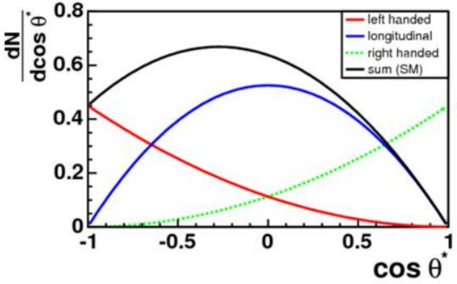


- $t\bar{t} \rightarrow$ no polarization
  - but W from top polarized

    … again due to V-A coupling
- Measuring **lepton angle** in parent top rest frame

  → extract ***W* helicity fractions** in top decay

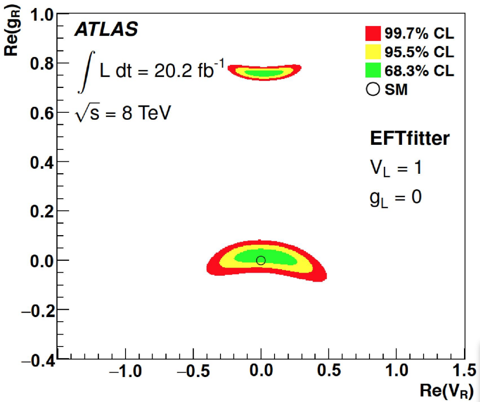




$$F_+ = \frac{\Gamma_{t\to W_+ b}}{\Gamma} = 0.000,$$

$$F_- = \frac{\Gamma_{t\to W_- b}}{\Gamma} = \frac{2m_W^2}{m_t^2 + 2m_W^2} = 0.302,$$

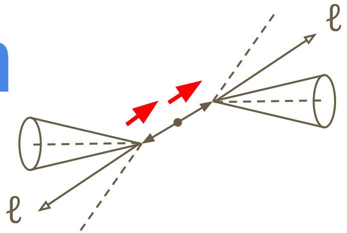
$$F_0 = \frac{\Gamma_{t\to W_0 b}}{\Gamma} = \frac{m_t^2}{m_t^2 + 2m_W^2} = 0.697$$



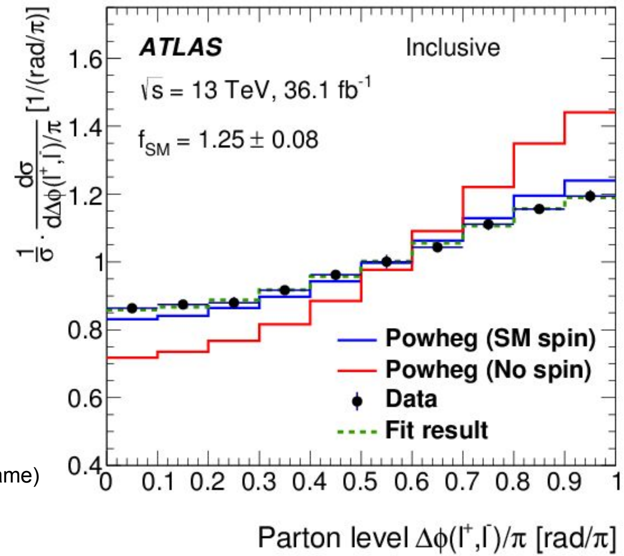
EFT constraints

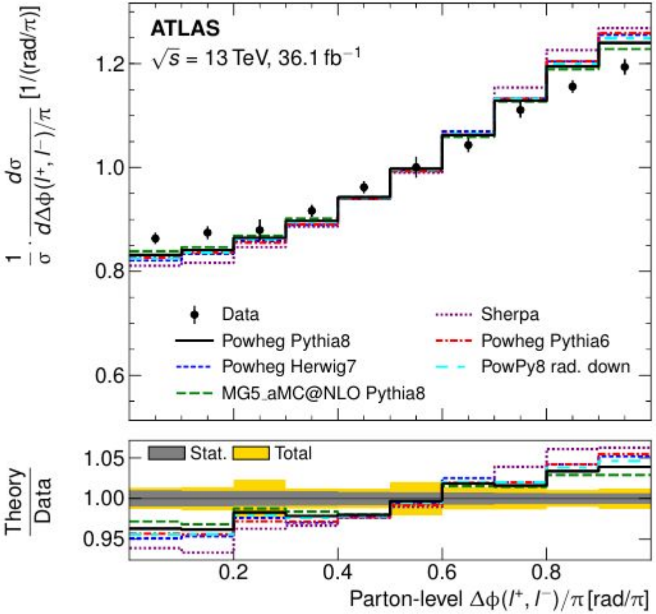
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^\mu\,(V_L P_L + V_R P_R)\,t\,W^-_\mu - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_W}\,(g_L P_L + g_R P_R)\,t\,W^-_\mu + \text{h.c.}$$

Top pair spin correlation



- **Spins of tops** in $t\bar{t}$ events predicted to be **correlated**
  - measurement of **angular distance between 2 leptons** in 2ℓ tt decay → sensitive to **spin correlation**

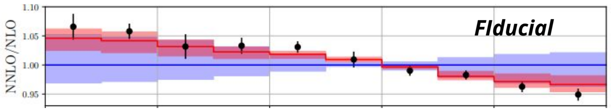




13 TeV, dilepton eμ,
measuring $\Delta\varphi_{\ell\ell}$ (in laboratory reference frame)
Eur. Phys. J. C 80 (2020) 754

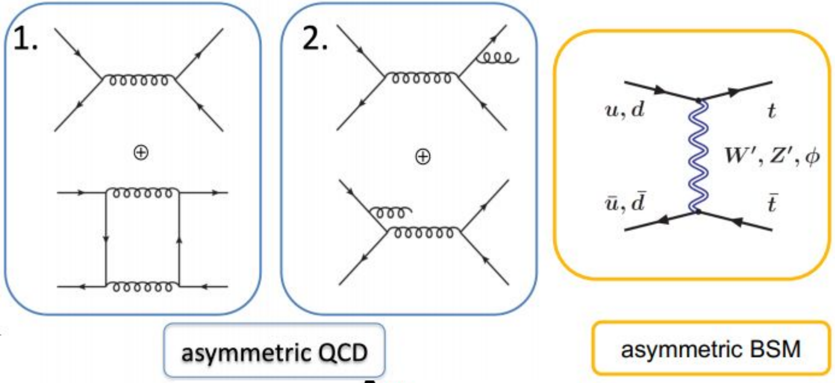
- **3.2 sigma discrepancy** with NLO predictions in $\Delta\varphi_{\ell\ell}$
- opposite direction w.r.t. BSM like SUSY
- NNLO predictions seem to mitigate the discrepancy

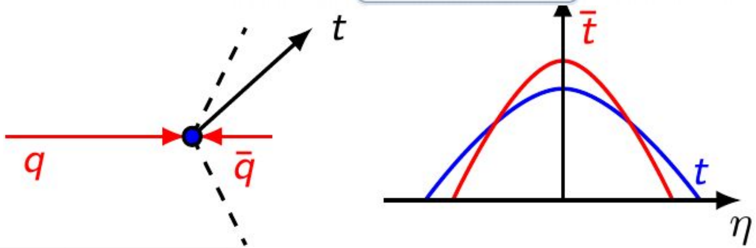
Phys. Rev. Lett. 123, 082001 (2019)



Top pair charge asymmetry

- $pp \to t\bar{t}$ charge symmetric @LO
  - **small asymmetry** appears @NLO
    … possibly increased by BSM
- Charge asymmetry assessed measuring **rapidity difference** between t and $\bar{t}$

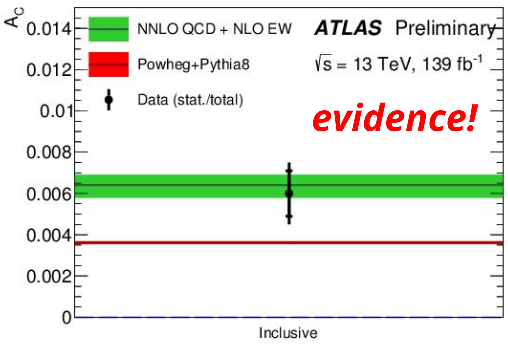


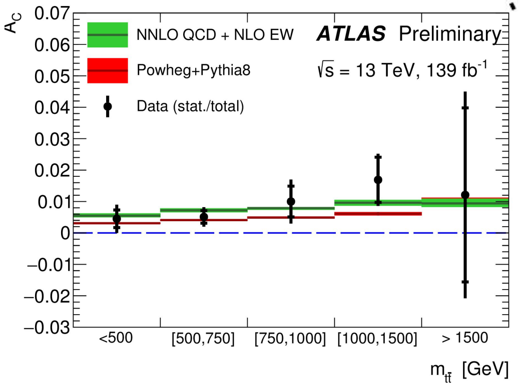


$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

13 TeV, ℓ+jets, inclusive and differential
ATLAS-CONF-2019-026



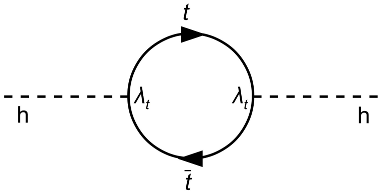


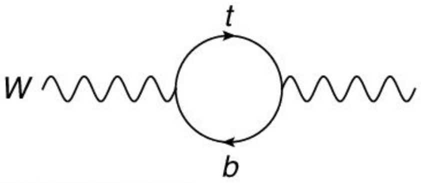
In $p\bar{p} \to t\bar{t}$ (@Tevatron): *same asymmetry (visible as "forward-backward asymmetry")* ***deviation*** *from SM prediction...*

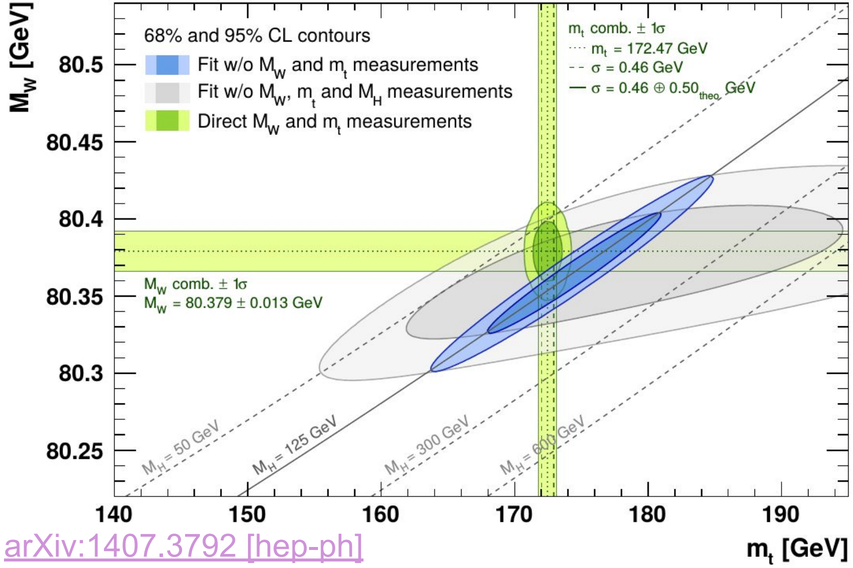
Top quark mass

Importance of top quark measurement

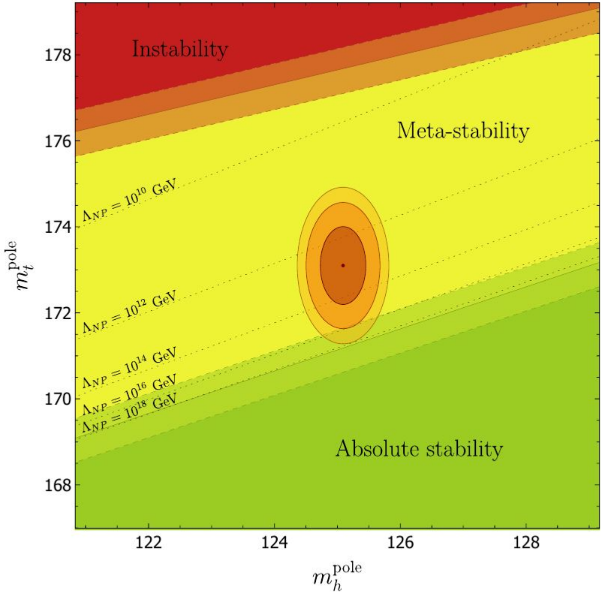
- m_t , m_W , m_H measurements → over-constraints to SM fits
  - **direct measurements** can be compared to **indirect results** to probe validity of SM
    - indirect = from loop corrections in propagators
- m_t important to determine SM **vacuum stability**







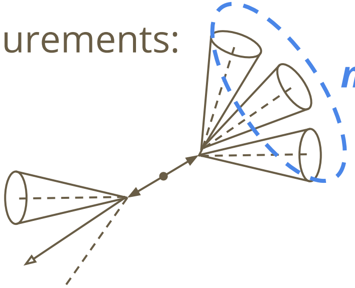
arXiv:1407.3792 [hep-ph]



Phys. Rev. D 97, 056006 (2018)

Direct vs. indirect top mass measurements

- **Direct** "m_t" measurements:



$\boldsymbol{m_t^{reco}}$ *= invariant mass of jets from top decay*

extraction from *total* or *partial* invariant mass of top decay products
⇒ **"Standard Method"**

  - data compared with **MC simulation** with different input values of m_t in MC
  - relying on jets, parton showers (LO), non-perturbative effects
    ⇒ measuring "$\boldsymbol{m_t^{MC}}$"
    (still controversial, see e.g. arXiv:1712.02796 [hep-ph])

- **Indirect** measurements of m_t from cross-sections (inclusive or differential)
  - in a well-defined renormalization scheme, e.g. $\boldsymbol{m_t^{pole}}$ (corresponding to definition of free particle mass)

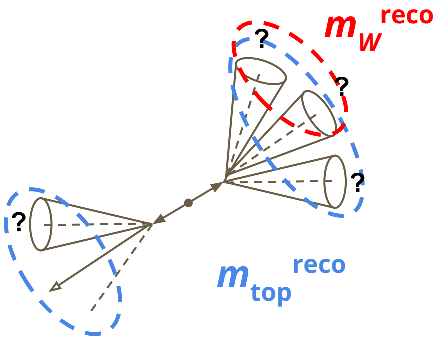
$$\sigma^{theor.}(\alpha_s, \boxed{m_t}, \text{PDF}, \mu_F, \mu_R, \ldots) \text{ vs } \sigma^{meas.}$$

$\boldsymbol{m_t}$ *= parameter in the SM*

    - "O(1 GeV) difference" between m_t^{MC} and m_t^{pole}

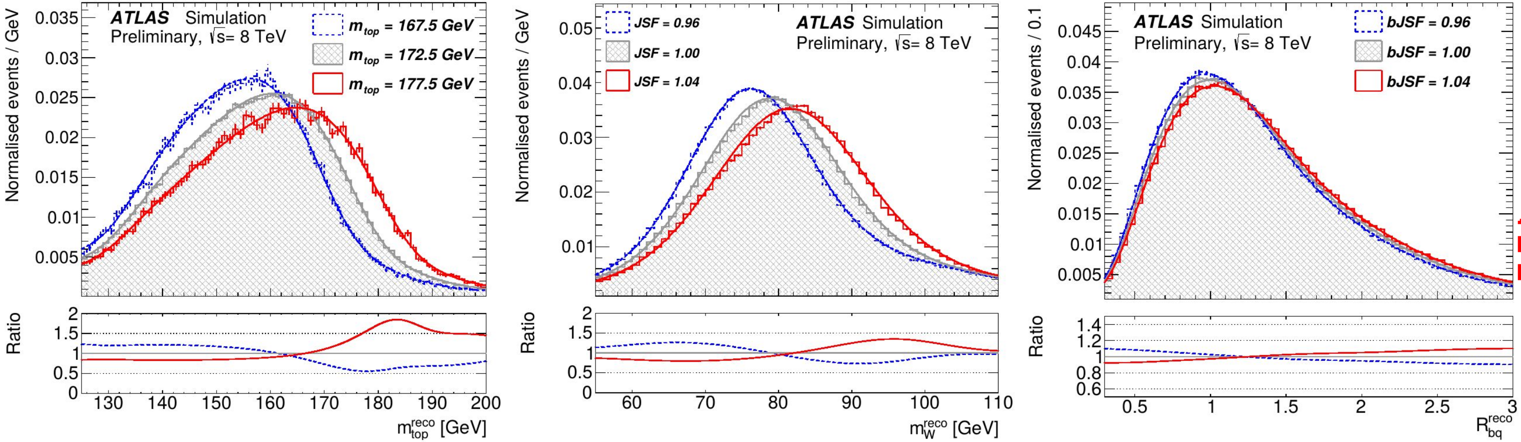
Wait... Why so complicated?
- *top is a* ***quark****, i.e.* ***coloured*** *state*
- *mass of a quark is not well defined*
- *effects like* ***colour (re)connection****,* ***parton shower****,* ***hadronization*** *make the two definitions different*

Direct measurements



- **Best channel: tt̄ ℓ+jets**
  - reconstruct system from final state, assigning jets to tops and W
    - without assuming mt value
  - to reduce sensitivity to **jet energy scale uncertainty**, fitting at the same time m_{top}^{reco}, m_W^{reco} + eventually other vars, e.g. $R_{bq}^{reco} = \frac{p_T^{b_{had}} + p_T^{b_{lep}}}{p_T^{q_1} + p_T^{q_2}}$
  - and **fit 3 free parameters**:
    - m_t, JSF^*, $bJSF^*$ (*: (b-)Jet-energy-Scale-Factor)

(q_1 and q_2 light jets assigned to W)



8 TeV, tt̄ ℓ+jets

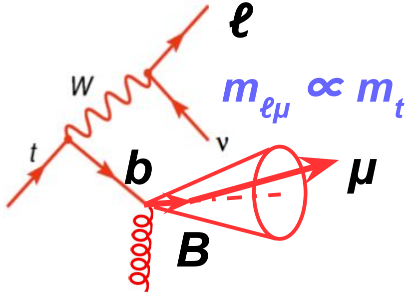
Eur. Phys. J. C 79 (2019) 290

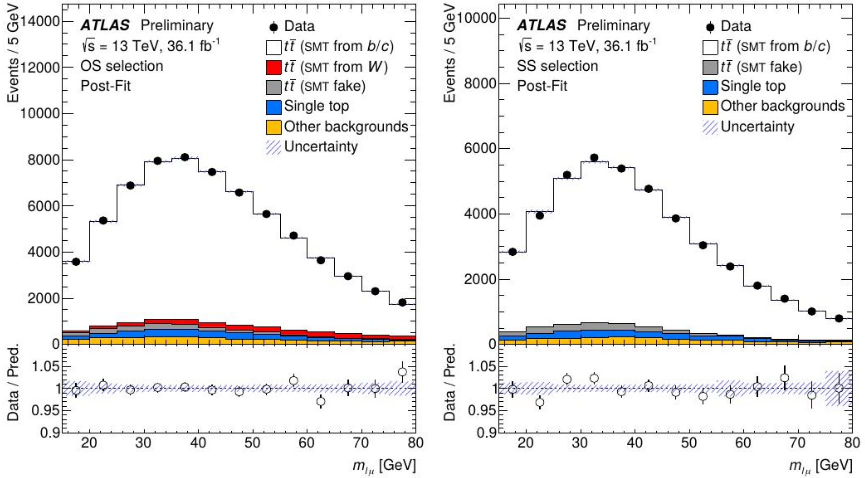
- combined with dilep

m_t = 172.69 ± 0.48 GeV

Direct measurements with alternative methods

- Alternative methods developed to reduce sensitivity to jet reconstruction and energy scale
- Example: using **prompt-lepton** – **soft-muon invariant mass,** $m_{\ell\mu}$:
  - partial top-decay reconstruction
    - still direct meas. (from top decay)
  - purely leptonic observable
    - **reduced systematics from jets**
  - modelling of ***b*-hadron production and decay** critical





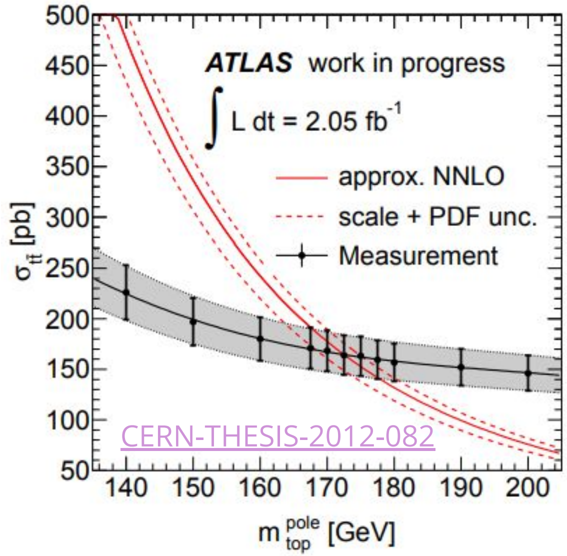
13 TeV, ℓ+jets + soft muon from B
ATLAS-CONF-2019-046

m_t^{MC} **= 174.48 ± 0.78 GeV**
(0.40 stat. + 0.67 syst.)

ATLAS EXPERIMENT

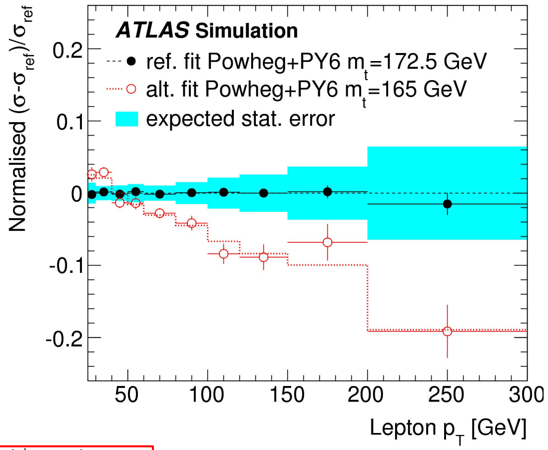
Indirect measurements

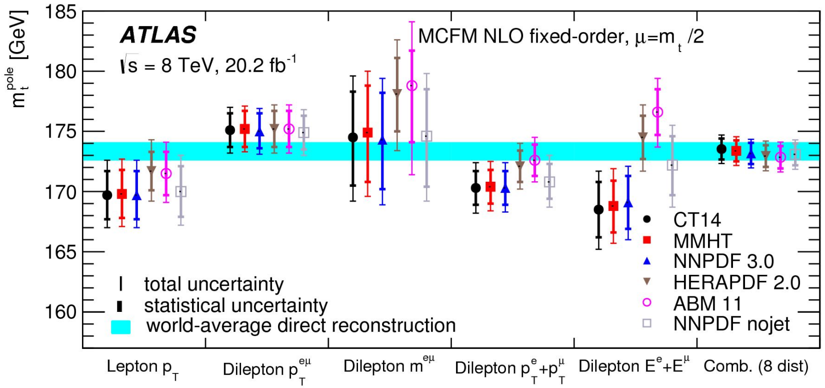
- **Idea**:
  - measure **top cross-section** *(tt̄ or single top, total or differential)*
  - use **know theoretical dependence** of cross-section on m_t
    ⇒ extract m_t
  - ideally ***independent*** on top decay & m_t^{MC}



Best measurement (in ATLAS):
dilep tt̄, 8 TeV
Eur. Phys. J. C 77 (2017) 804

- several differential cross-sections vs. NLO calculations

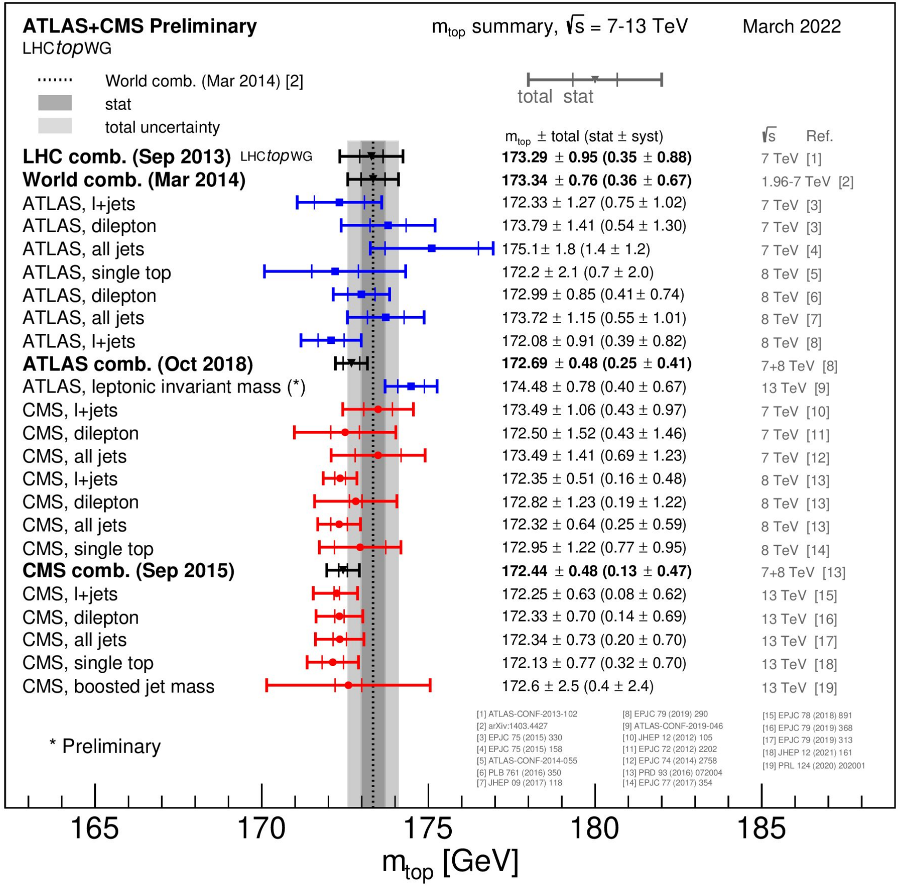


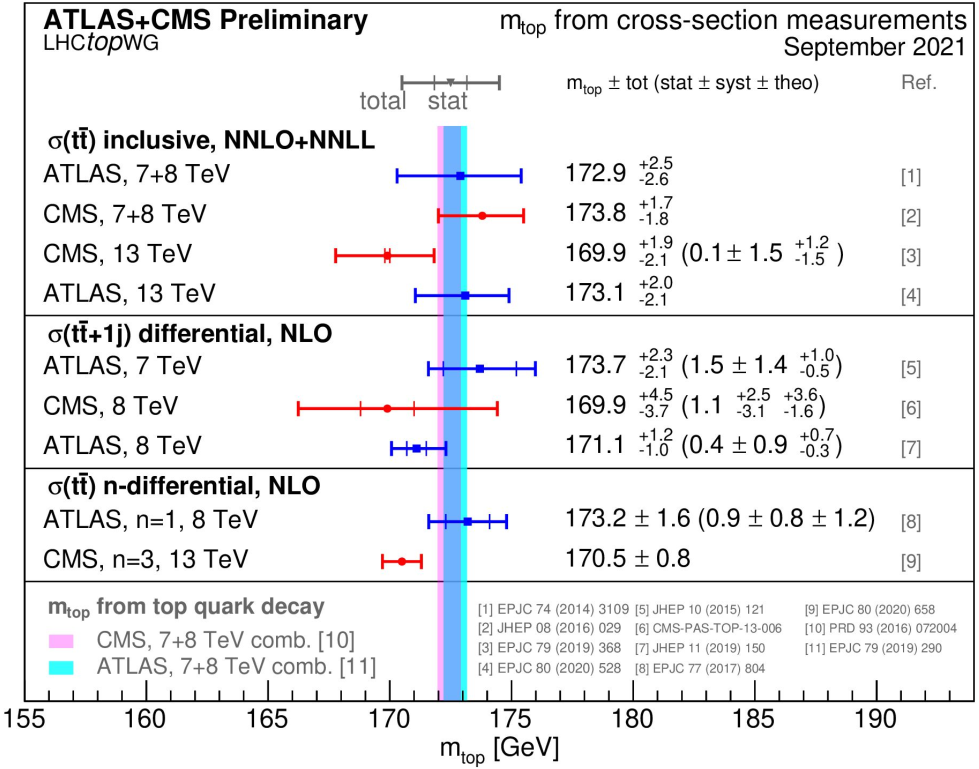


$$m_t^{\text{pole}} = 173.2 \pm 0.9\,\text{(stat)} \pm 0.8\,\text{(exp)} \pm 1.2\,\text{(theory)}\ \text{GeV}$$

± 1.6 GeV

Top mass measurement summary





Top events as a tool for other measurements

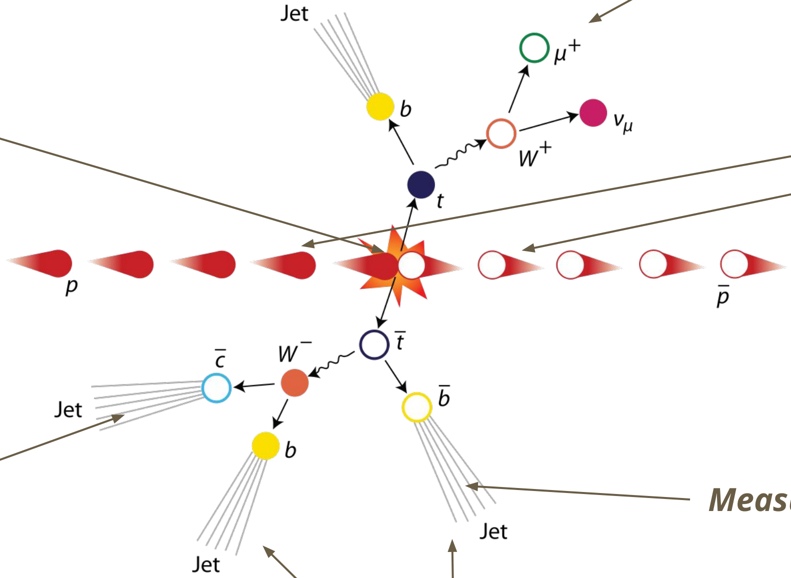
Top events as a tool for...

MC tuning

Measure electron & muon identification performance

α_s measurement

PDF extraction



Measure b-tagging performance

Measure c-tagging performance

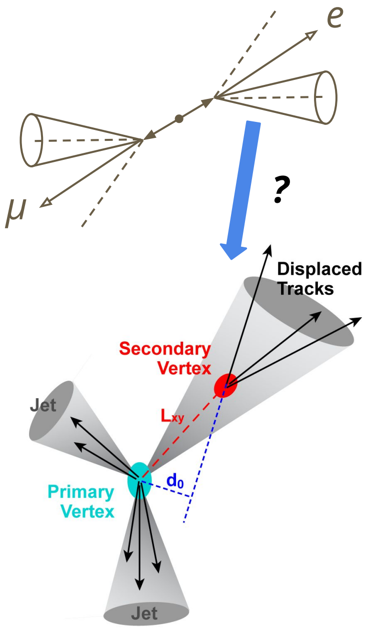
Study modelling of (b)quark fragmentation to jets

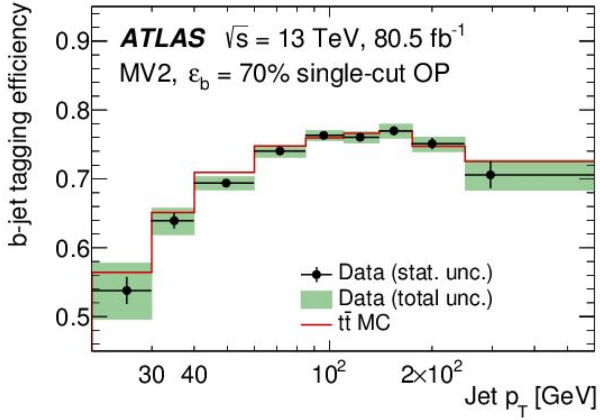
b-tagging efficiency determination

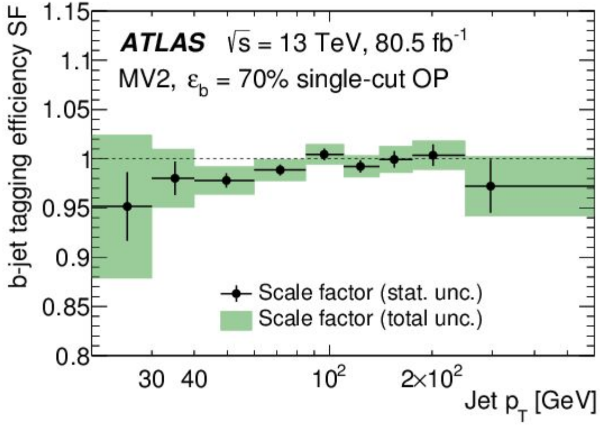
Eur. Phys. J. C 79 (2019) 970

- ***$t\bar{t}$* dilepton events (eμ)**
  well identifiable even without requiring *b*-tagging
  ⇒ can be used to **calibrate *b*-tagging** algorithms

- **Calibration procedure**:
  - select *$t\bar{t}$* eμ events
  - consider a jet (most likely a *b*-jet)
  - check if it gets *b*-tagged
  - measure **fraction of times** these jets get *b*-tagged
    → *b*-tagging **efficiency**
  - compare with MC simulation
    → *b*-tagging **Scale Factors**
    (*i.e.* correction factors to be applied to MC simulation)

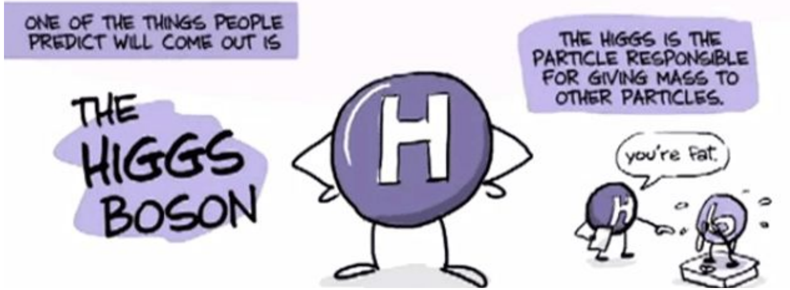




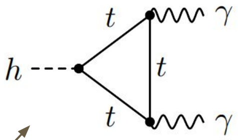


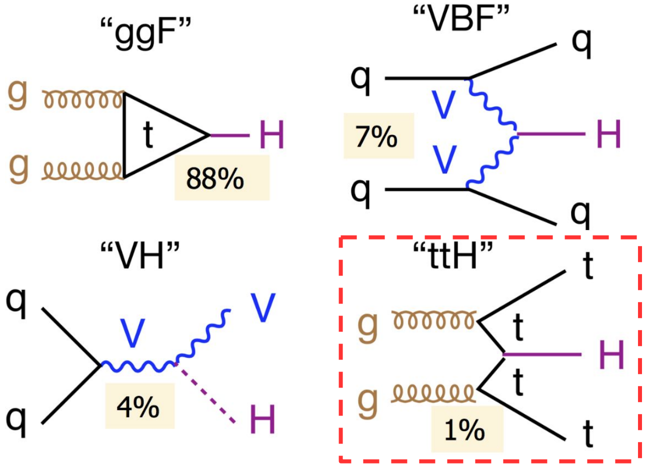
Associated top production

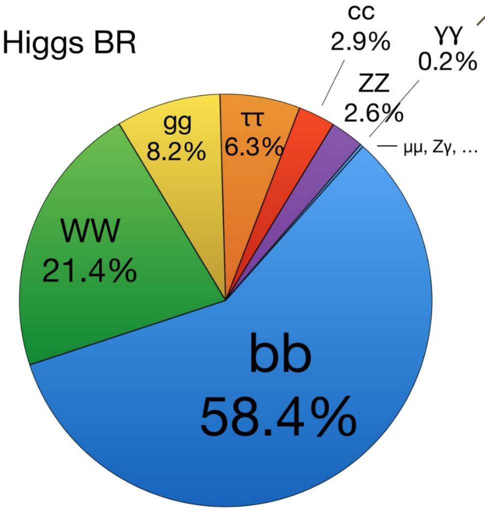
Top and Higgs - ttH production



- Top has the strongest coupling with Higgs
- **Yukawa coupling y_t** can be extracted "***indirectly***" from **gluon-gluon fusion** production and ***γγ* decay**
  - indirectly means assuming no BSM particles...
- **Direct y_t measurement** = $t\bar{t}H$ production measurement



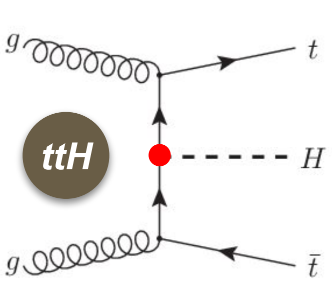


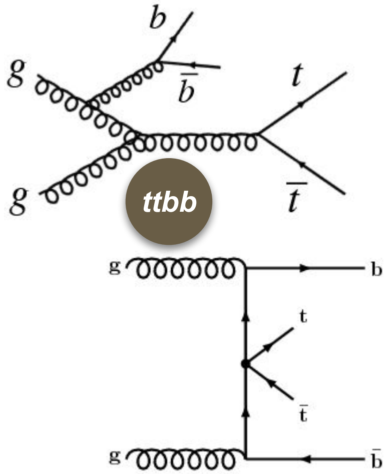


- Several possible $t\bar{t}H$ final states
  - depending on Higgs decay
  - $b\bar{b}$ also accessible (thanks to $t\bar{t}$ distinctive signature)

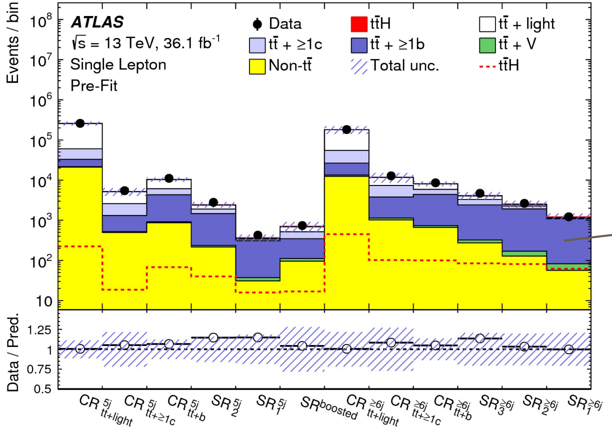
ttH with H ⟶ bb decay

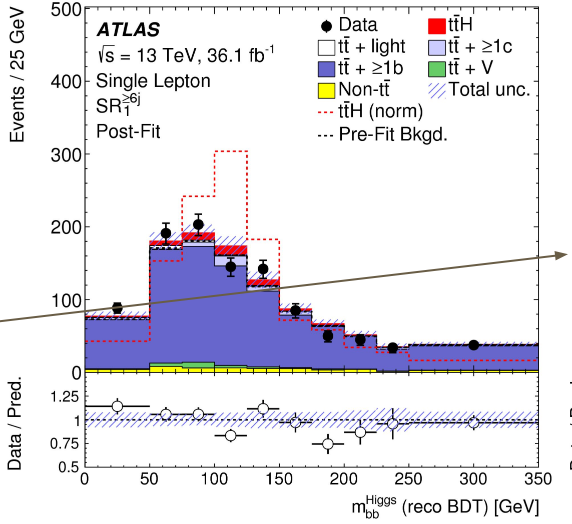
- Largest available **statistics**
- Very large **background** from $t\bar{t}$ + *b*-jets production
  ⇒ challenging channel:
  - sophisticated **machine-learning** algorithms needed
  - simultaneous fit of several **control and signal regions** to constraint background *in situ*

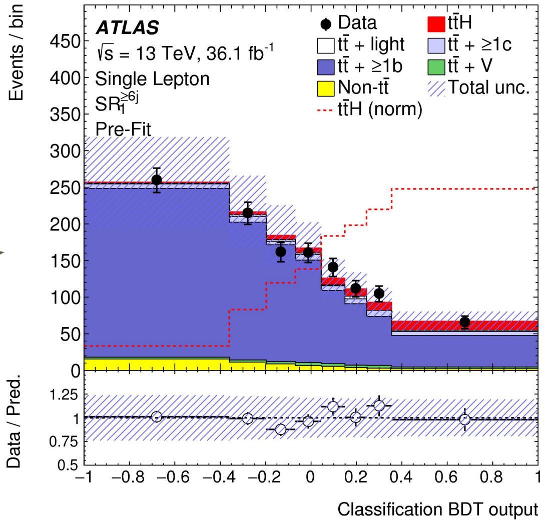




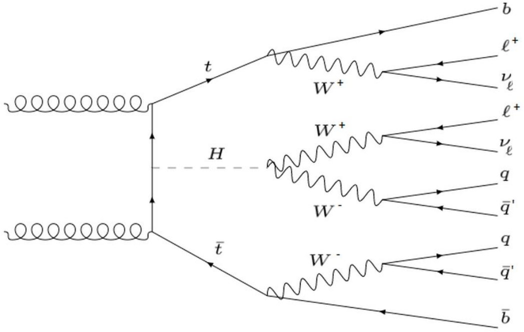
Phys. Rev. D 97 (2018) 072016





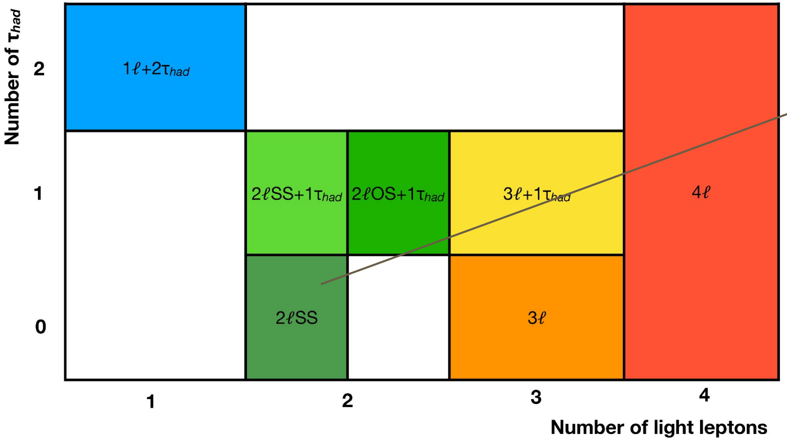


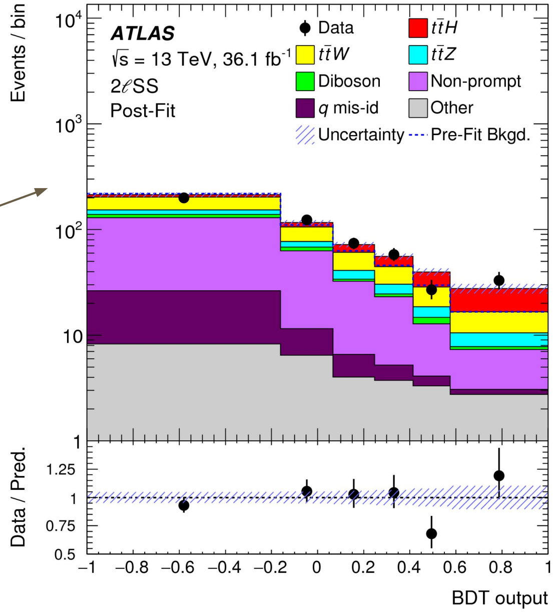
ttH with multi-lepton final states



- Targeting $H \to WW$ and $H \to \tau\tau$, with leptonic decays
  ⇒ **same-sign dilepton** and **≥ 3 lepton** final states
  - smaller statistics
  - difficult to reconstruct Higgs (due to neutrinos)
  - smaller background

Phys. Rev. D 97 (2018) 072003

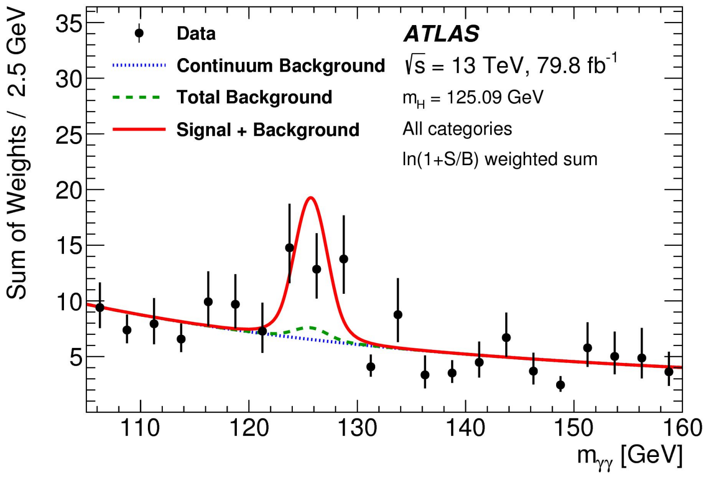


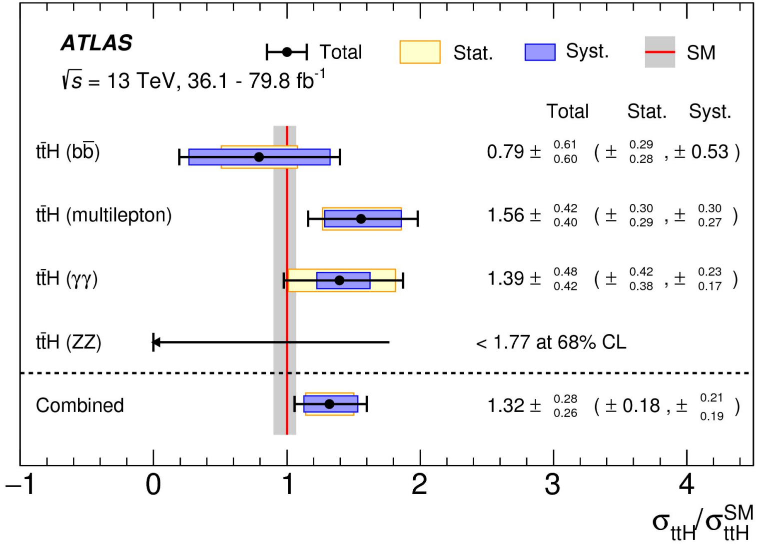


ttH combination

- Other clean channel:
  - *H → γγ* channel

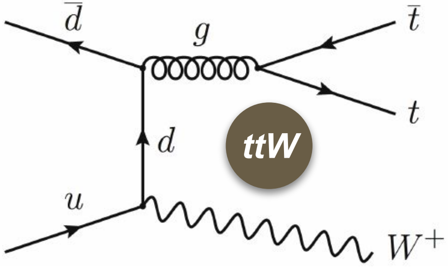
Phys. Lett. B 784 (2018) 173

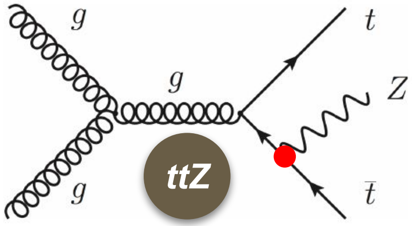


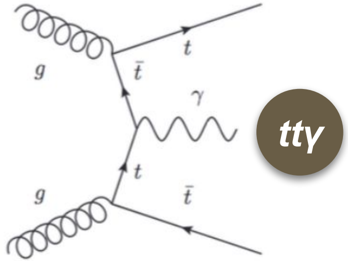


- **Combining channels**
  → *tt̄H* process **observation** in 2018

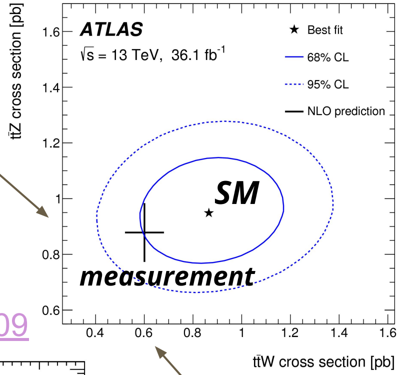
Top + W/Z/γ



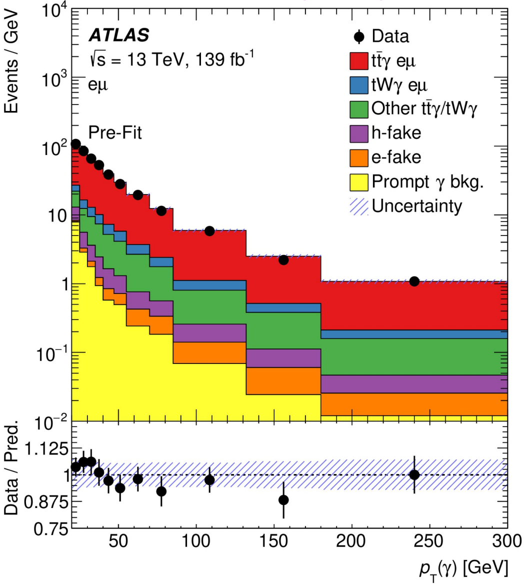


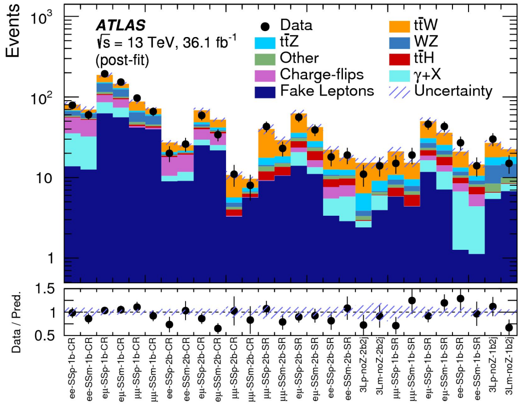


- Associated production with SM **vector bosons** also important to study
  - *top couplings with neutral gauge bosons*
  - *constraints on EFT …*
- Clean samples obtained with **multi-lepton** and **dilepton + photon** selections

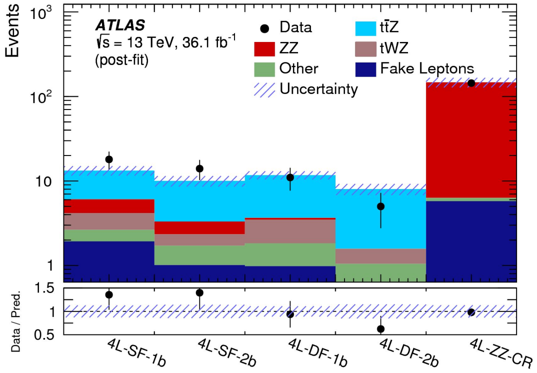


JHEP 09 (2020) 049

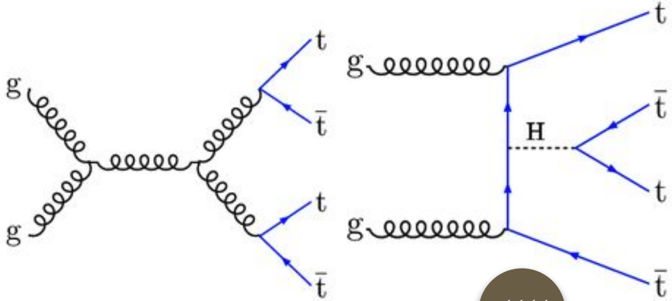




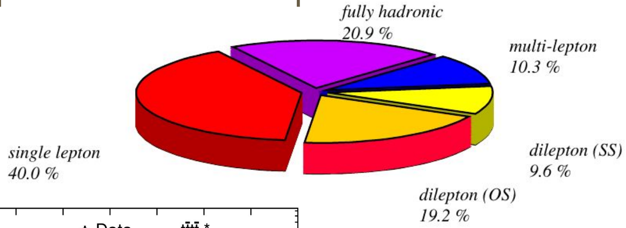
Phys. Rev. D 99 (2019) 072009



Multi-top production



- **Rare** and **spectacular** processes at LHC:
  - ***$t\bar{t}t\bar{t}$* production**
- ℓ+jets, dilepton and multi-lepton final states



1ℓ + 2ℓ (opposite-sign)

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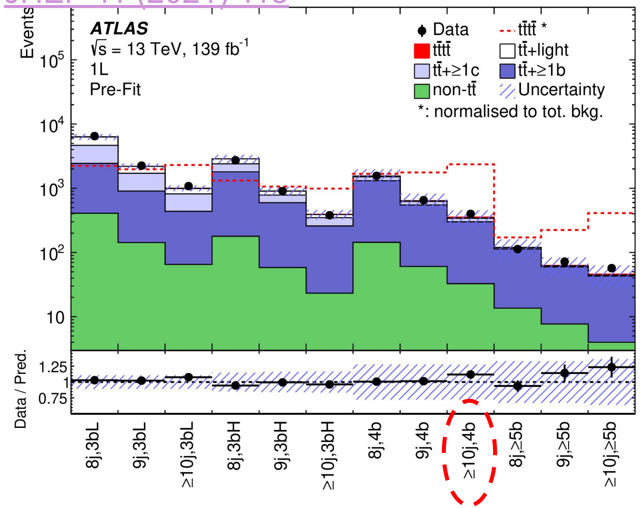
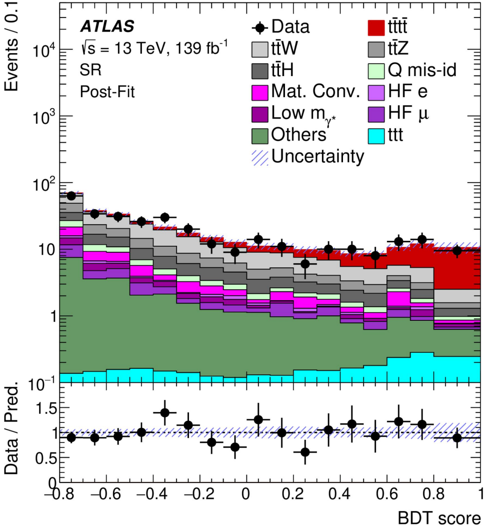
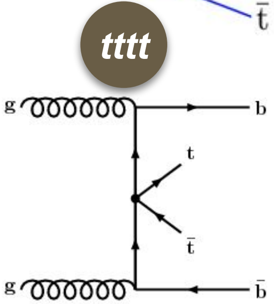


Combination
→ 3 σ evidence!

Same-sign 2ℓ + multi-lepton

Eur. Phys. J. C 80 (2020) 1085



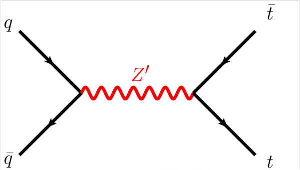


New physics with top

ATLAS EXPERIMENT

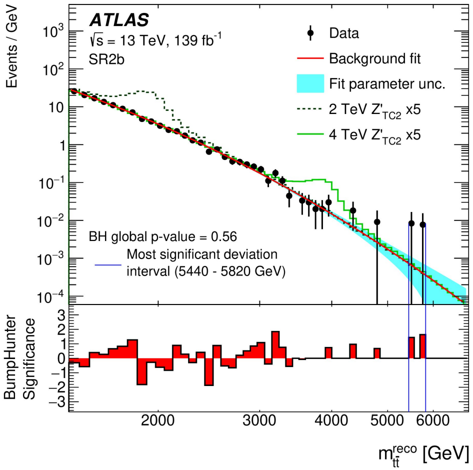
Top-pair resonance searches

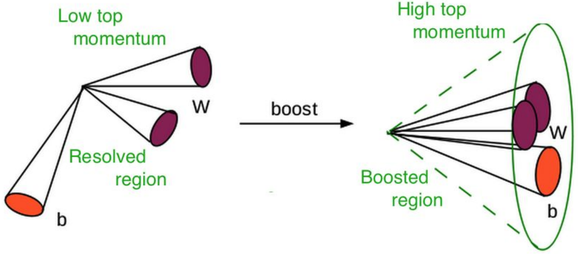
- New physics can manifest if **heavy particles** with strong coupling with top ⇒ can be **decaying to $t\bar{t}$**
- Searching for "***bumps***" in reconstructed ***$t\bar{t}$* invariant mass, $m_{t\bar{t}}$**

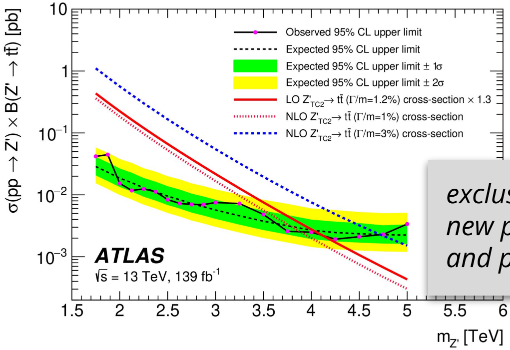


Heavy Higgs → $t\bar{t}$ search, 8 TeV
[Phys. Rev. Lett. 119 (2017) 191803](https://doi.org/10.1103/PhysRevLett.119.191803)

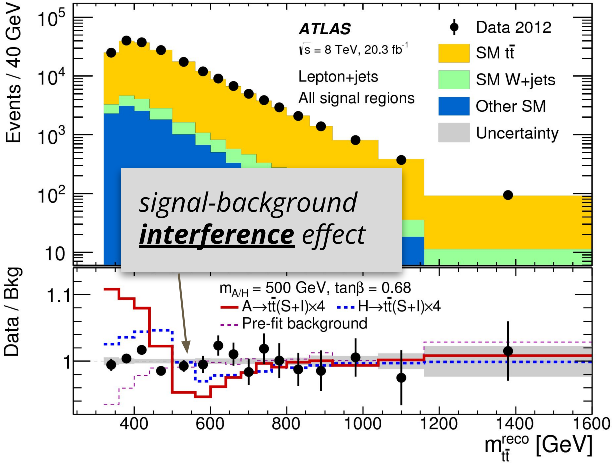
$t\bar{t}$ resonance search, 13 TeV, all-hadronic "boosted"
[JHEP 10 (2020) 61](https://doi.org/10.1007/JHEP10(2020)061)



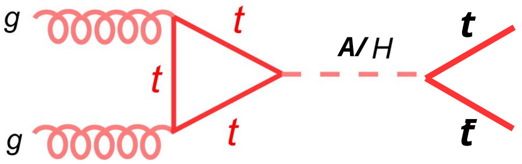




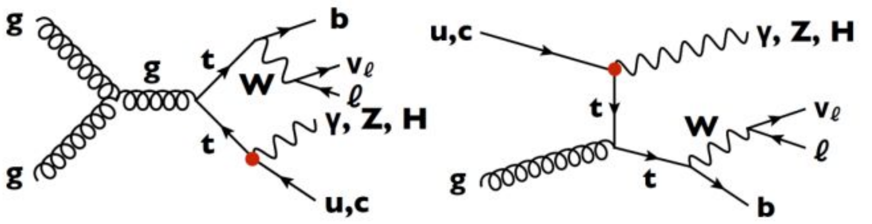
*exclusion **limits** on new particle mass and production rate*



*signal-background **interference** effect*



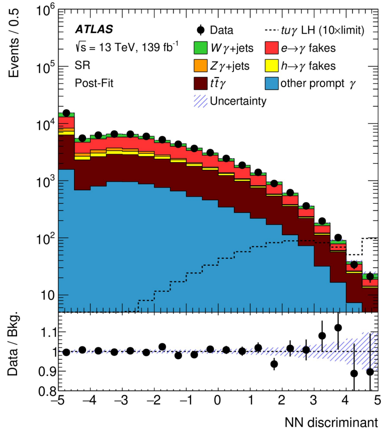
FCNC in top (production and decay)

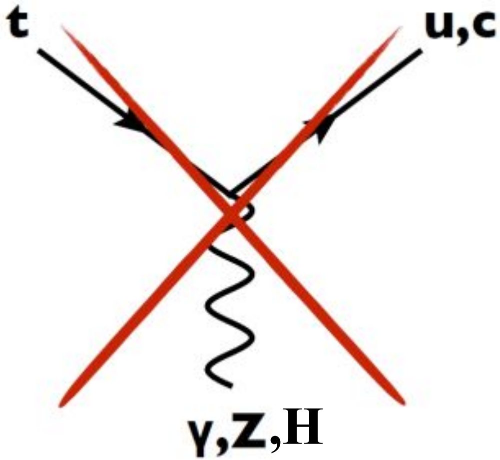


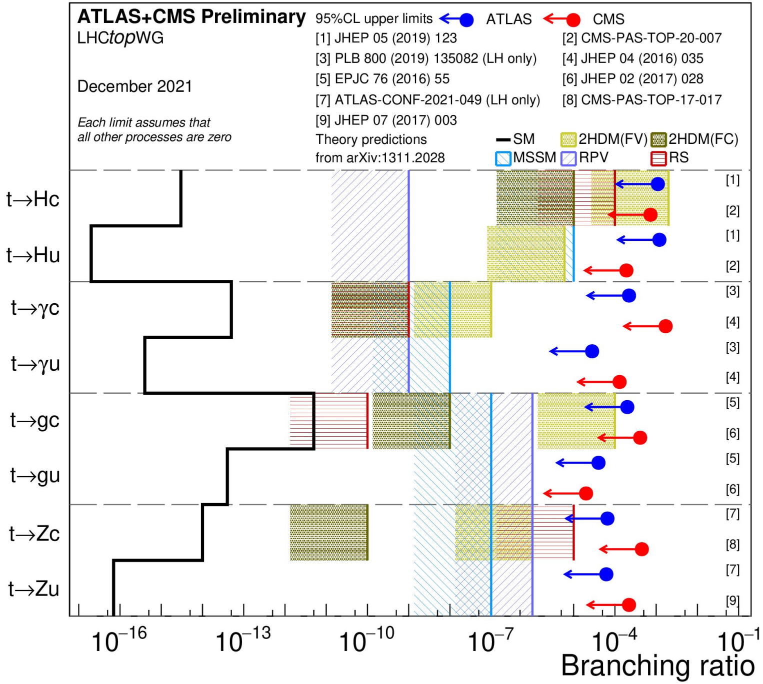
- **Flavour Changing Neutral Currents** (FCNC)
  - ***forbidden*** in SM (at tree level)
    - transitions very suppressed in SM
  - observing these transitions ⇒ evidence for BSM
    - need to consider both production (*single top*) and decay

FCNC "t-γ" search - 13 TeV

arXiv:2205.02537 [hep-ex]







Closing remarks

ATLAS EXPERIMENT

Summary and Outlook

- **The top quark is *special***
  ⇒ studying top-quark physics is exciting

- A lot of efforts being put to **study** all the **properties** of top quark and its **interactions** with other Standard Model particles
  - see more ATLAS results here: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

- We could discover **New Physics** by looking (more carefully?) at the top quark