Top physics - experimental overview:
The top quark is still going strong (and electroweak)

Andrea Knue (University of Freiburg)

On behalf of the ATLAS, CMS and LHCb Collaborations

10th January, 2022

30th Intern. Symposium on Lepton Photon Interactions at High Energies, Manchester

What you probably heard countless times...

- the top quark is the heaviest quark: "almost the mass of a gold atom"

  ↪ actually... mass between tungsten and rhenium nowadays ;)

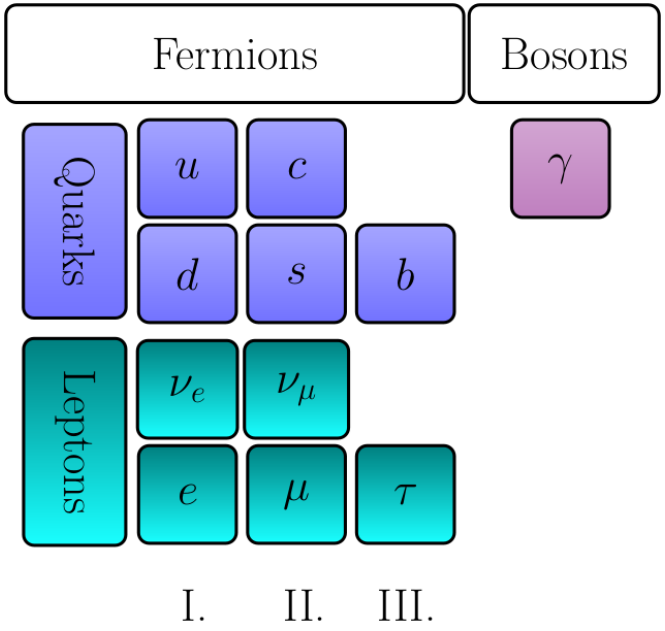
- "it plays a special role in the standard model"

  ↪ I will discuss today why it is special

- "the LHC is a top quark factory"

  ↪ this very much depends on the production process!

Since when do we know about the top quark?



- only knew these particles when the top-quark was postulated in 1977
- due to the large mass: discovery only in 1995
- largest coupling to the Higgs boson: almost 1
- decays before hadron formation or spin-decorrelation can take place

  $\hookrightarrow$ can obtain properties from the top-quark decay products
- plays prominent role in many Standard Model extensions!

Why is the top quark so important?

Why is the top quark so important?

Top quarks are key to almost everything!

Why is the top quark so important?

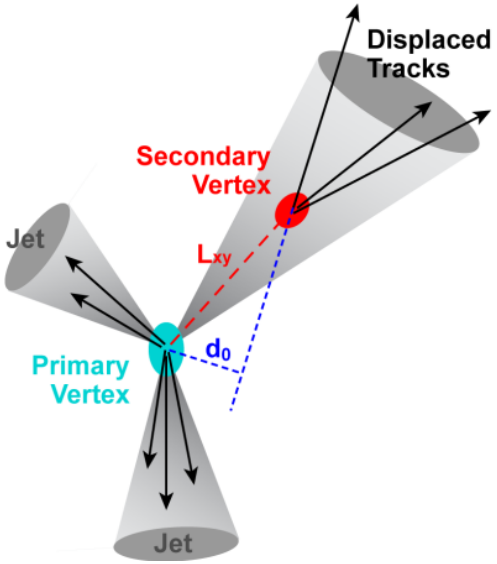
Top quarks are key to almost everything!

Search for rare SM processes

Why is the top quark so important?

Top quarks are key to almost everything!

b-tagging calibration

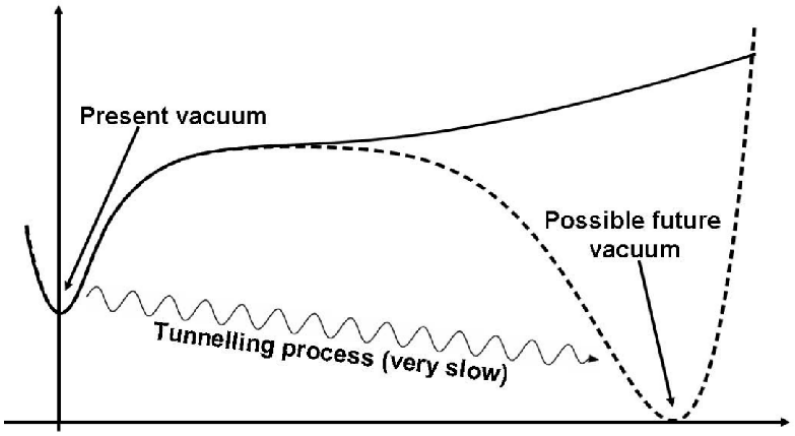


Search for rare processes

Why is the top quark so important?

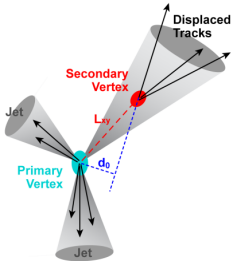
Top quarks are key to almost everything!

Stability of the Universe



Search for rare processes

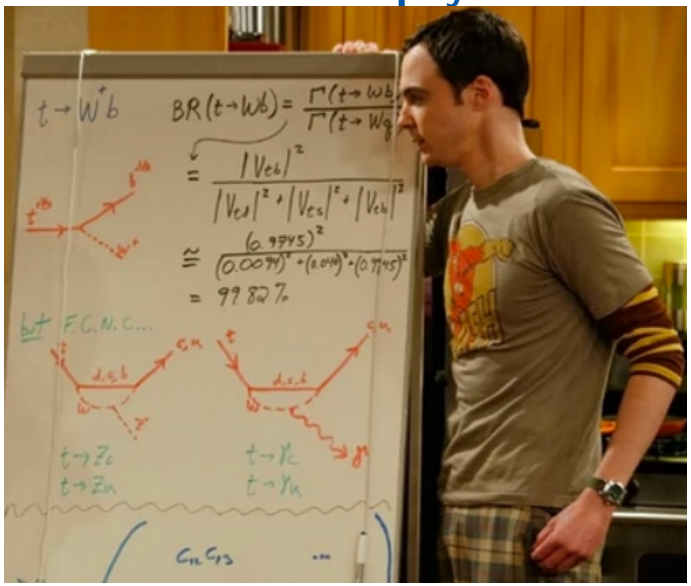
b-tagging calibration



Why is the top quark so important?

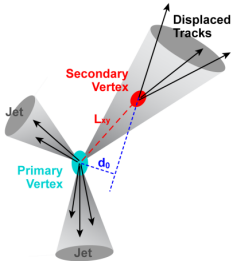
Top quarks are key to almost everything!

Search for new physics

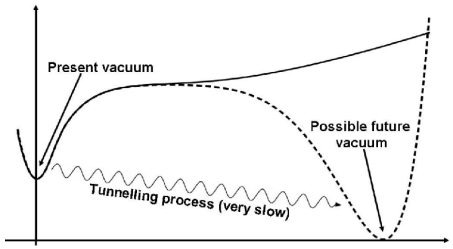


Search for rare processes

b-tagging calibration



Stability of the Universe



Detailed look into different phase-space corners:

(Differential) cross-section measurements

How and how often does the LHC produce top quarks?

One LHC experiment, $\sqrt{s} = 13$ TeV, 139 fb^{-1} data in 2015–2018

Process	Cross-section [pb]	Events before selection
$t\bar{t}$	832	**115,648,000**
t channel	217	30,163,000
tW-channel	71.7	9,966,300
s-channel	10.32	1,434,480
$t\bar{t} + Z$	0.88	122,320
$t\bar{t} + W$	0.60	83,400
$t\bar{t} + \gamma$	0.77	107,030
$t\bar{t} + H$	0.51	70,890
$t\bar{t}t\bar{t}$	0.012	**1,668**

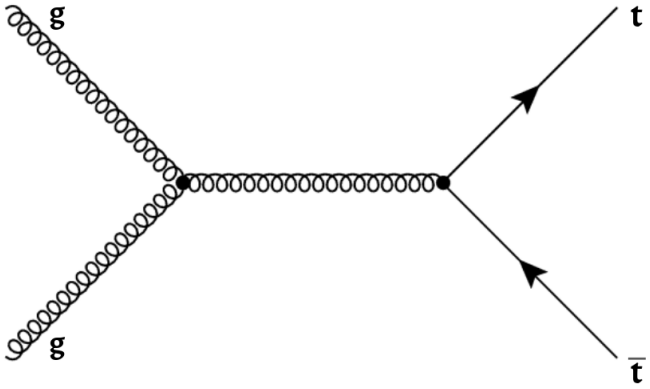
- Can produce tops via the strong and the electroweak interaction

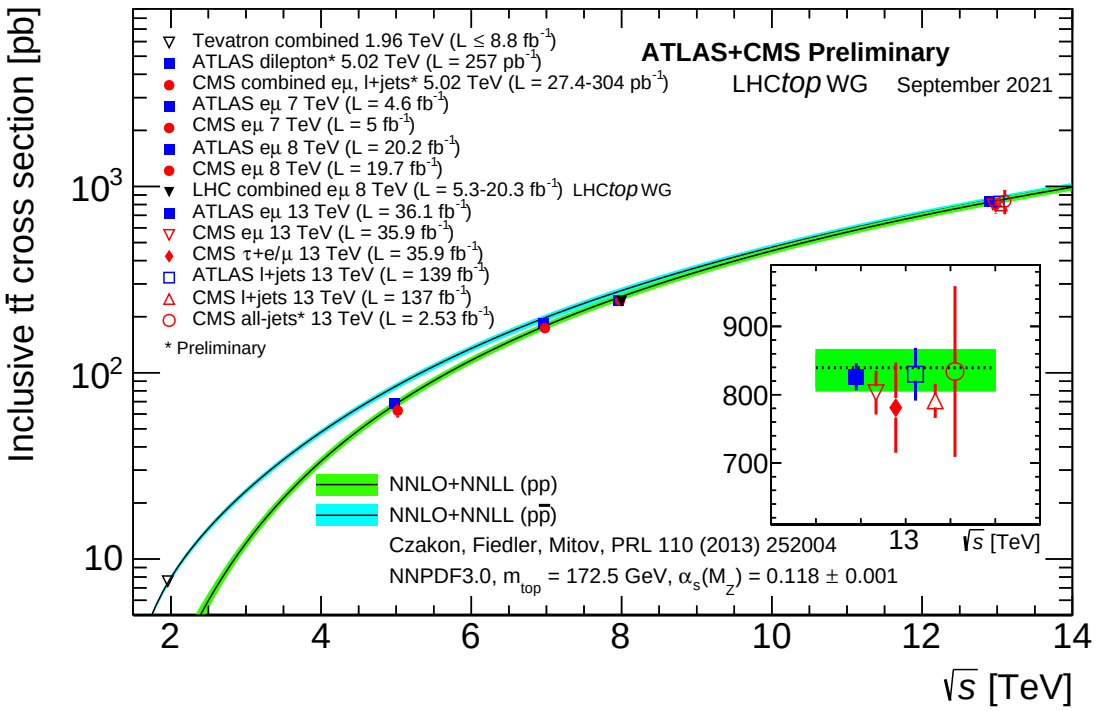
  $\hookrightarrow$ Different final states give access to different properties

- Do we also have access to the very rare processes?

- Have plethora of measurements, focus on the latest results today

Inclusive $t\bar{t}$ cross-sections



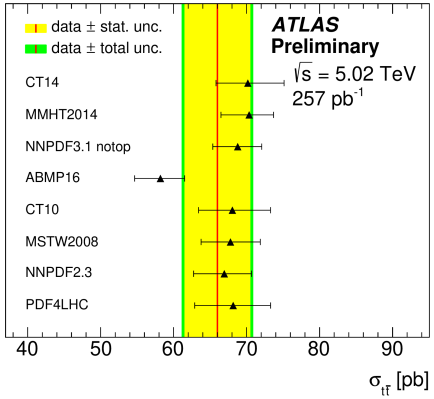


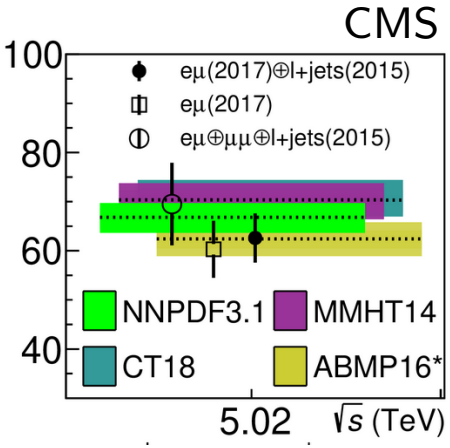
- $t\bar{t}$ cross-section changes strongly with centre-of-mass energy $\sqrt{s}$
- we have high-precision measurements at 7, 8 and 13 TeV:

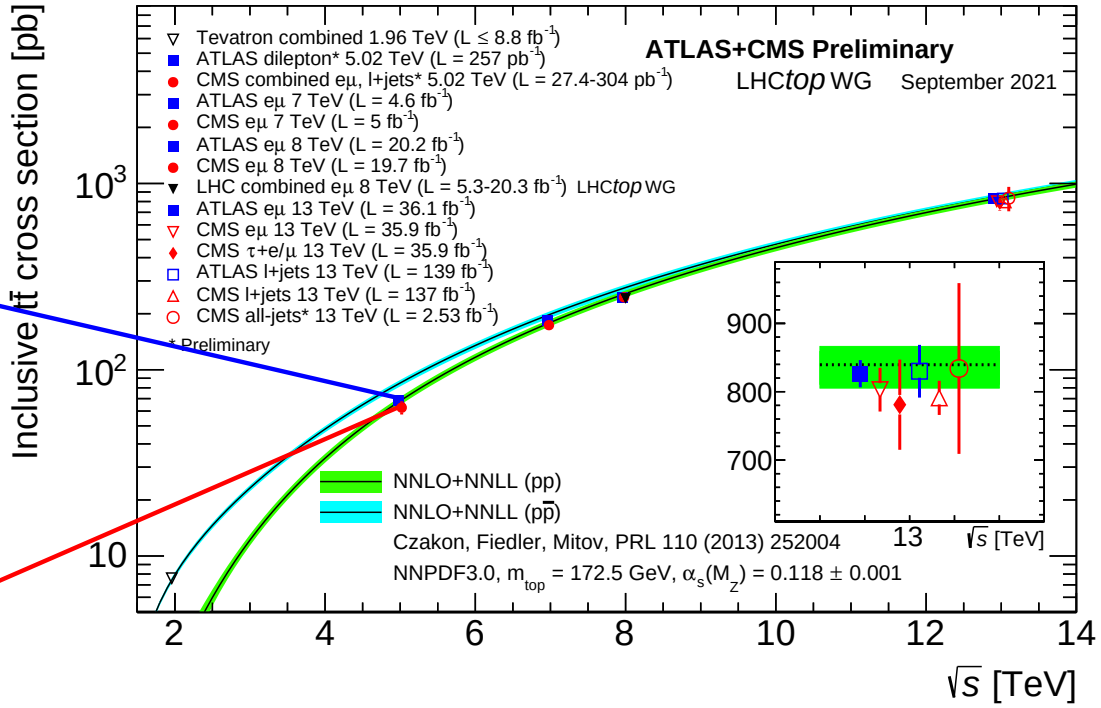
  ↪ relative uncertainty for 13 TeV only 2.5 %!
- tiny 5 TeV dataset from 2015 and one additional week taking 5 TeV collision data in 2017

  ↪ cross-section more than one magnitude smaller than at 13 TeV

Inclusive $t\bar{t}$ cross-sections: **News** from the lower-energy front!







- measured both by ATLAS and CMS:

  ↪ relative uncertainties already below 8%

- strongly dominated by statistical uncertainties
- in excellent agreement with the NNLO+NNLL prediction

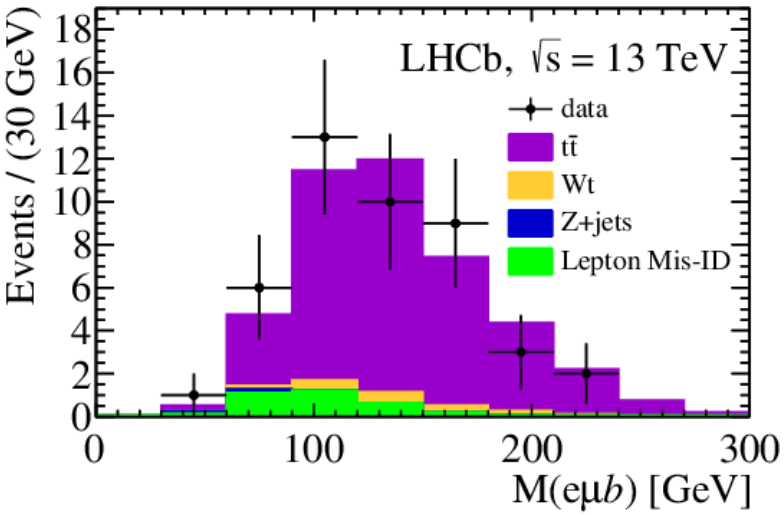
▸ ATLAS-CONF-2021-003

▸ CMS-TOP-20-004

Top-quark pair production @ LHCb with 13 TeV

JHEP (2018) 08, p174

- at 13 TeV: cross-section increased by a factor of 10 compared to 8 TeV
- first measurement of dilepton final state, cleaner signal
- largest background process: lepton mis-identification
  ↪ estimated from region with same-sign leptons



Source	%
trigger	2.0
muon reconstruction	1.1
electron reconstruction	2.8
muon identification	0.8
electron identification	1.3
jet reconstruction	1.6
event selection	4.0
jet tagging	10.0
background	5.1
resolution factor	0.5
total	12.7

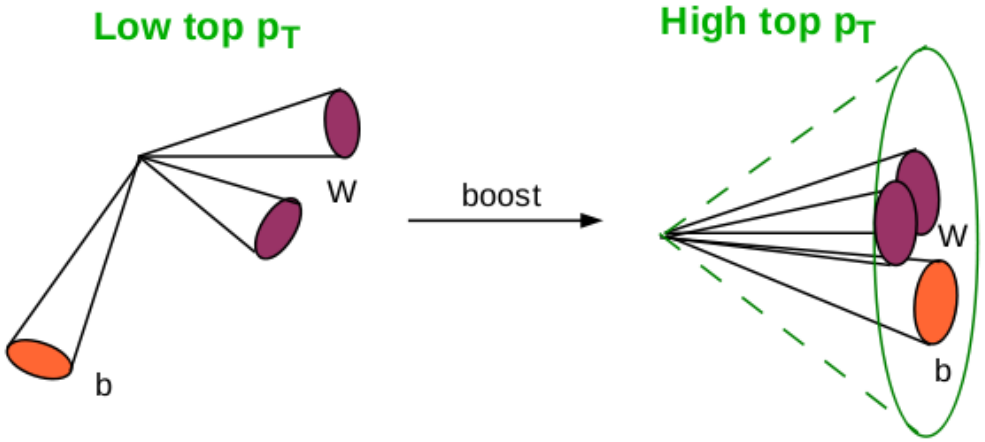
$$\sigma_{t\bar{t}} = 126 \pm 19(\text{stat.}) \pm 16(\text{stat.}) \pm 5(\text{lumi}) \ \ \text{fb}$$

↪ relative uncertainty 20%, uncertainty on theoretical calculation (MCFM): 25-30 %

Test the Standard Model in different parts of the phase space:

1. new physics might manifest itself only in some corners of the phase space
2. allows to compare different MC generators and use for tuning

Measure kinematic distributions of the event as well as the top and $t\bar{t}$ system in resolved (low top p_T) and boosted (high top p_T) events.

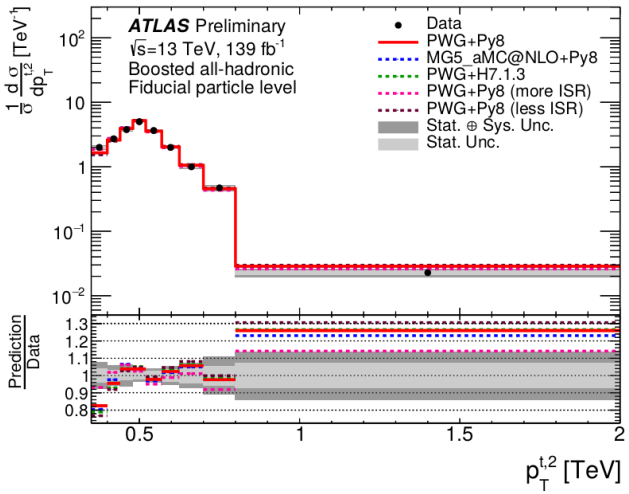


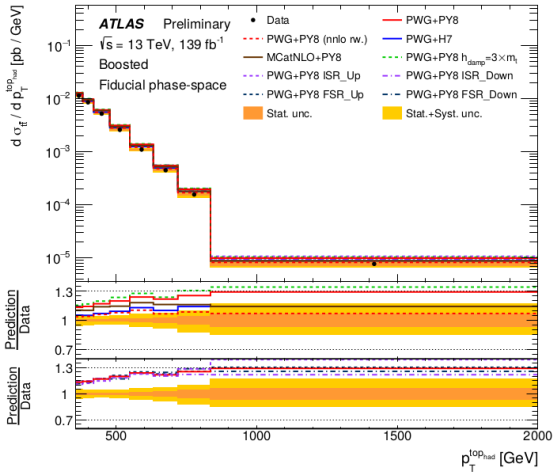
Perform unfolding: remove detector effects! Two options shown here:

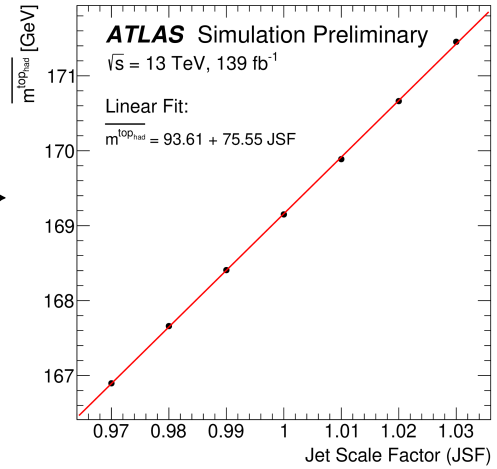
- parton level: after radiation, before decay $\rightarrow$ compare to fixed order calculations
- particle level: select events in fiducial phase space, use particles with $\tau > 30$ ps

  $\hookrightarrow$ can only show a subset of results here, more details in the talk of ▸ Ana Peixoto

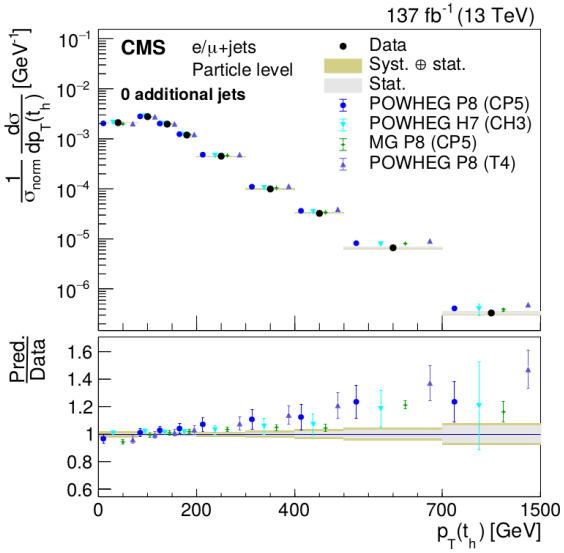
Do we still have a disagreement of the top p_T with data?

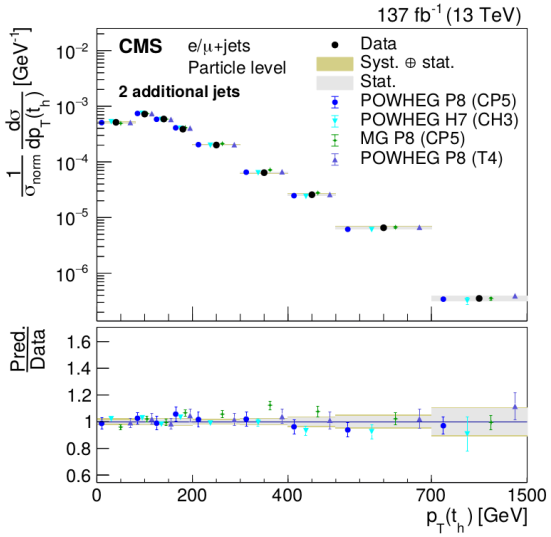






↪ softer top p_T in data visible in all decay channels





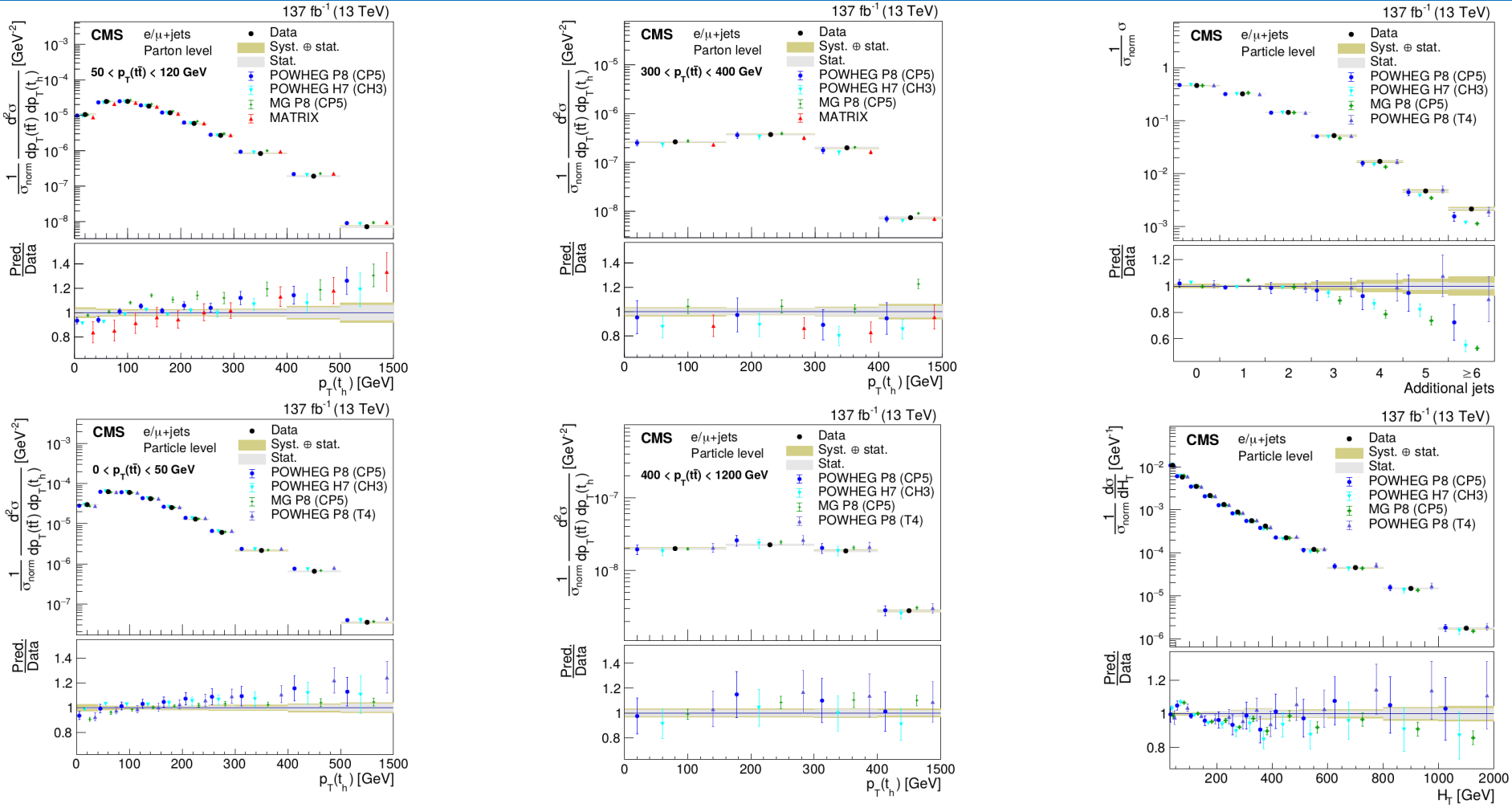
Significant reduction of uncertainties in the lepton+jets boosted channel:
↪ use mass of large-R jet to reduce jet-energy scale uncertainty

- ATLAS-CONF-2021-031
- Phys. Rev. D 104 (2021) 092013

↪ multi-differential: disagreement is largest for events without additional radiation!

Combined measurement resolved+boosted

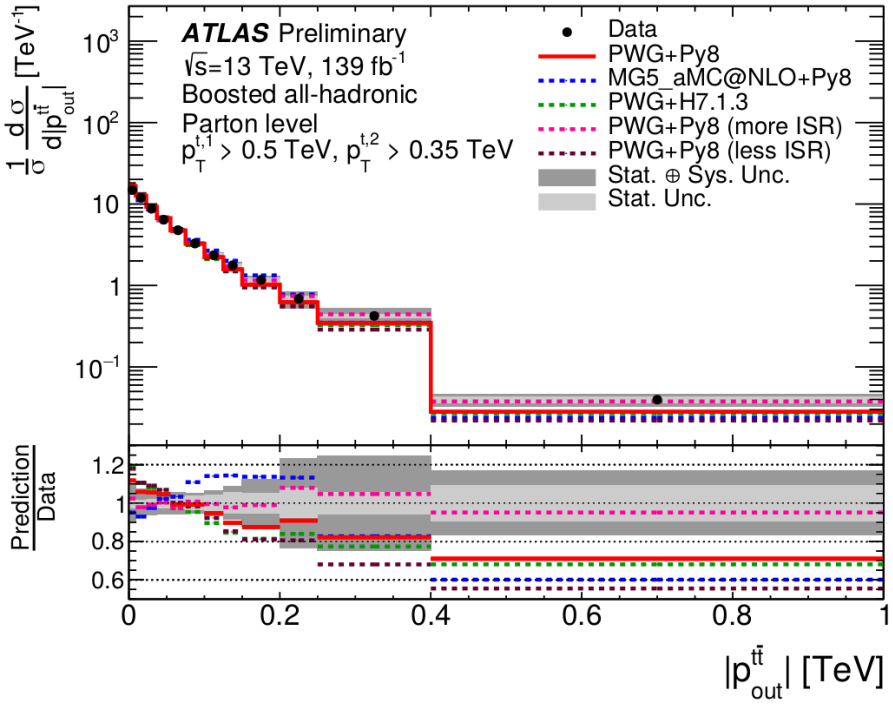
▸ Phys. Rev. D 104 (2021) 092013 **NEW!**

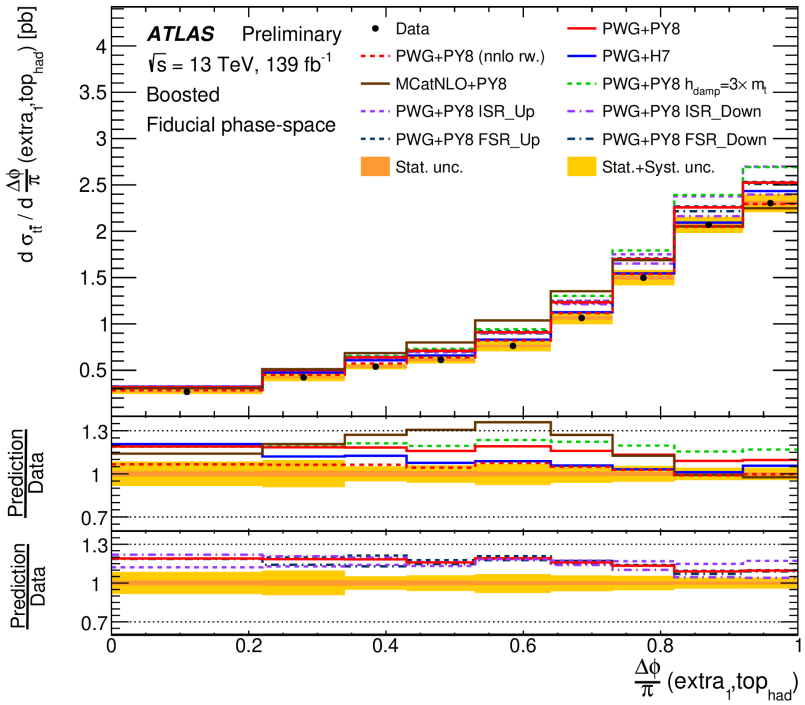


- disagreement for p_T^{top} at lower $p_T^{t\bar{t}}$ and $m_{t\bar{t}}$ and variables sensitive to radiation
- strongly reduced systematics from combination of several reconstruction categories
  $\hookrightarrow$ dominating uncertainties from JES and $t\bar{t}$ modelling

Boosted differential $t\bar{t}$ cross-sections

ATLAS-CONF-2021-050



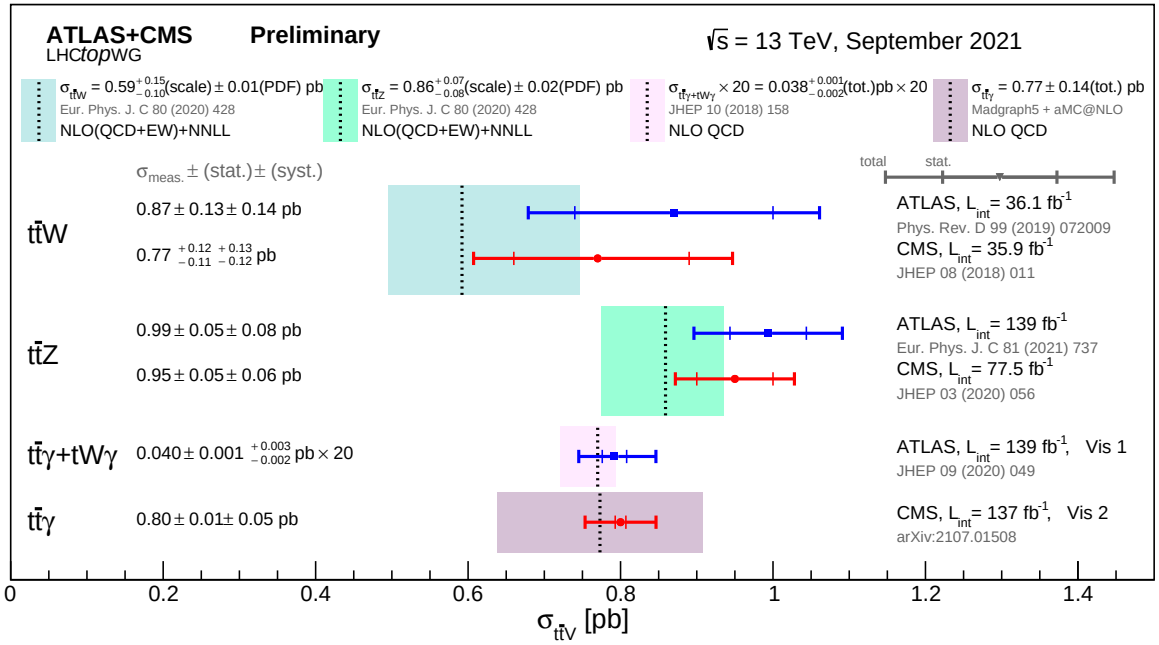


- unfolded one-dimensional and multi-dimensional distributions
- distributions sensitive to additional radiation show disagreement between data and prediction
  ↪ often better agreement with ISR-up predictions than with the nominal prediction
- fiducial particle-level cross-section: ≈ 20% smaller than prediction
  ↪ but within theoretical uncertainties
- no generator describes all distributions perfectly, consistency between ATLAS and CMS findings

Top quark couplings:

The top quark likes every particle!

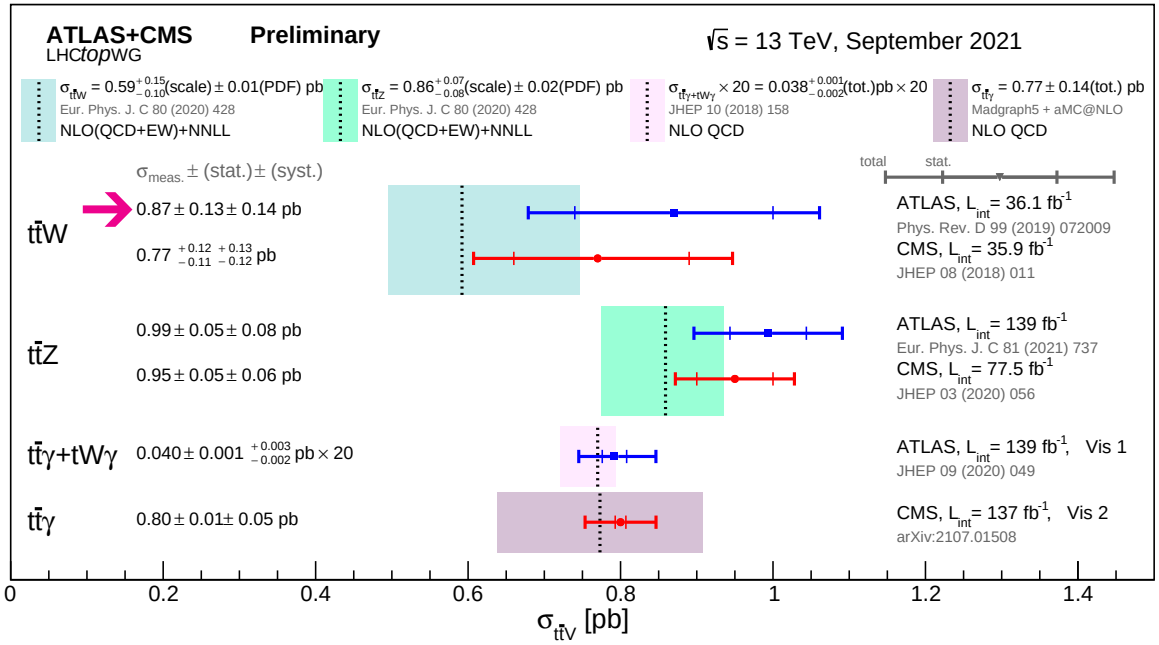
What do we know about the electroweak couplings?

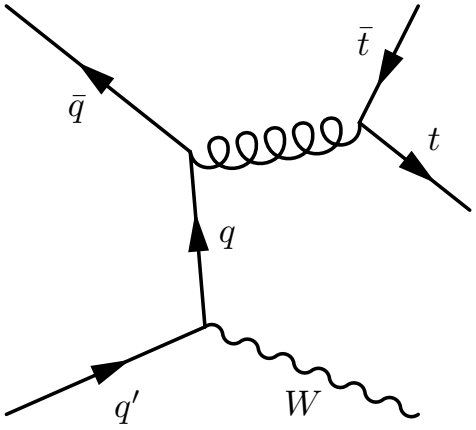


What do we know about the electroweak couplings?

$t\bar{t} + W$ production:

- relative uncertainty of 22%
  ▸ Phys. Rev. D 99, 072009 (2019)
- dominated by statistical and signal modelling uncertainties
- significance for SM process: 5.3 standard deviations (observed) by CMS ▸ JHEP 08 (2018) 011



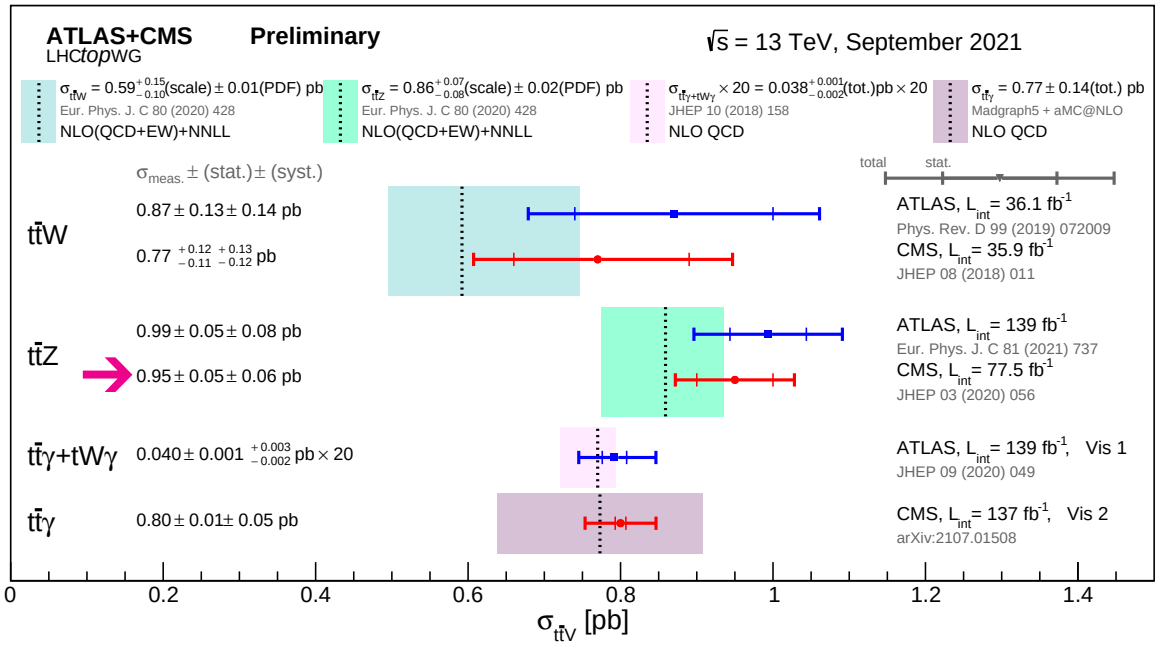


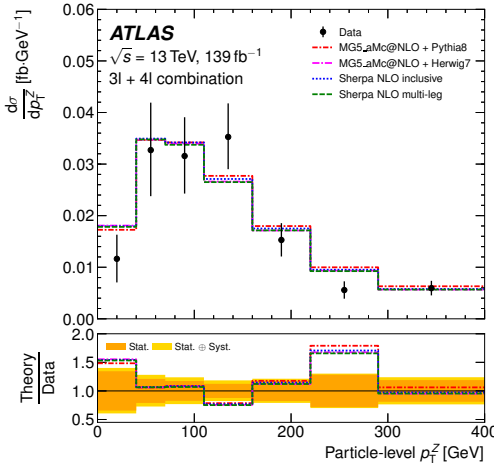
What do we know about the electroweak couplings?

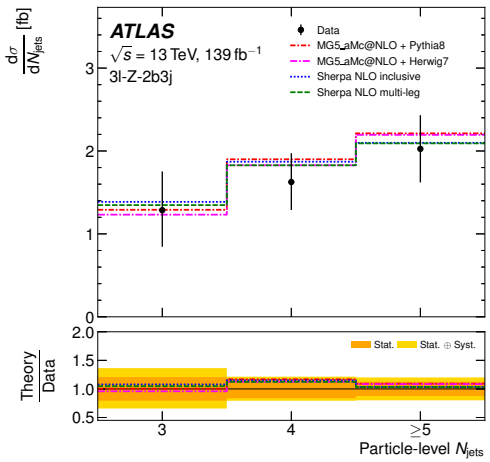
$t\bar{t} + Z$ production:

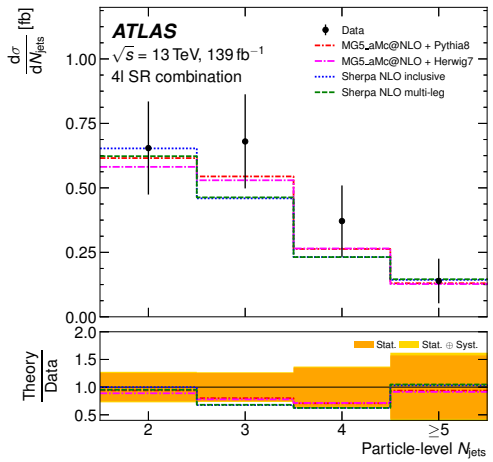
- relative uncertainty of 8.2%
  - JHEP 03 (2020) 056
- dominated by statistical and lepton identification uncertainties
- differential measurements with full 13 TeV dataset also available:
  - Eur. Phys. J. C 81 (2021) 737

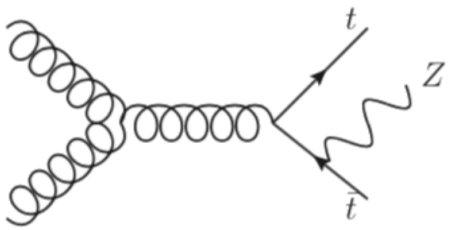
$\hookrightarrow$ good agreement with prediction







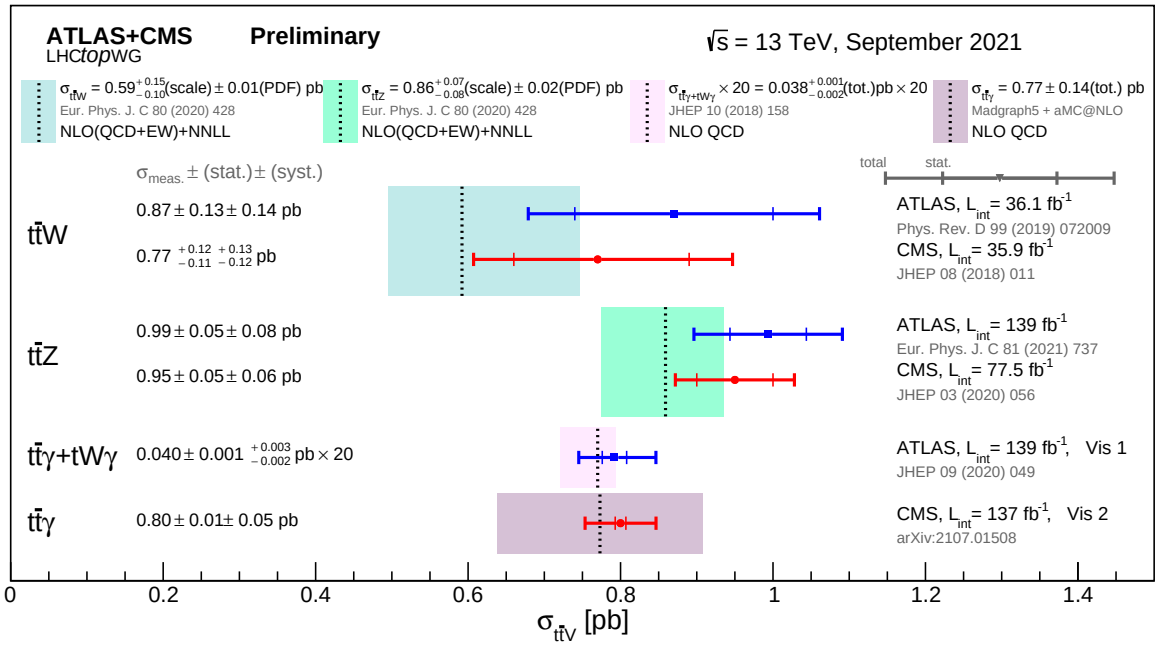


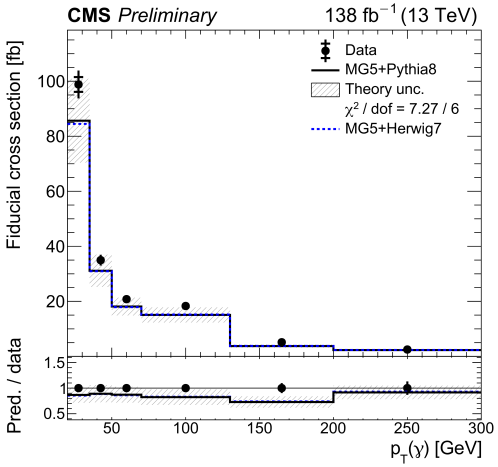


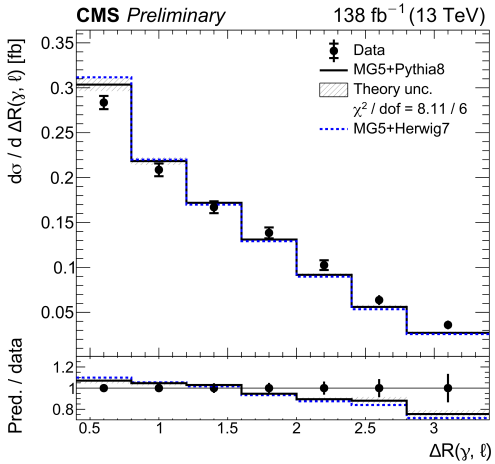
What do we know about the electroweak couplings?

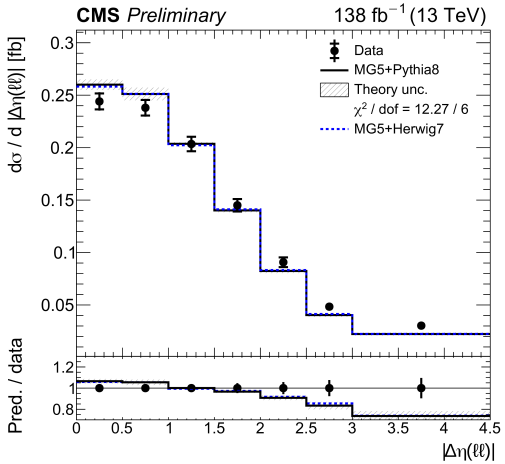
$t\bar{t} + \gamma$ production:

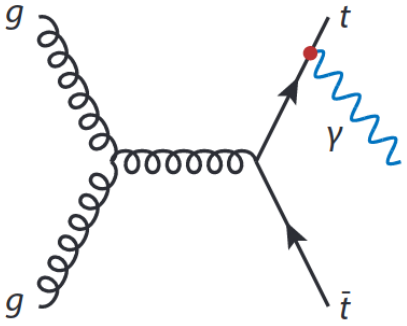
- relative uncertainty of 3.8%
  - CMS-PAS-TOP-21-004
  - $\hookrightarrow$ brand-new result (dilepton)!
- dominated by statistical, lepton efficiency and luminosity unc.
- differential cross-section largely in agreement with prediction



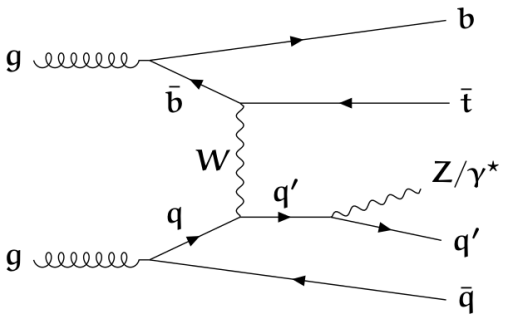






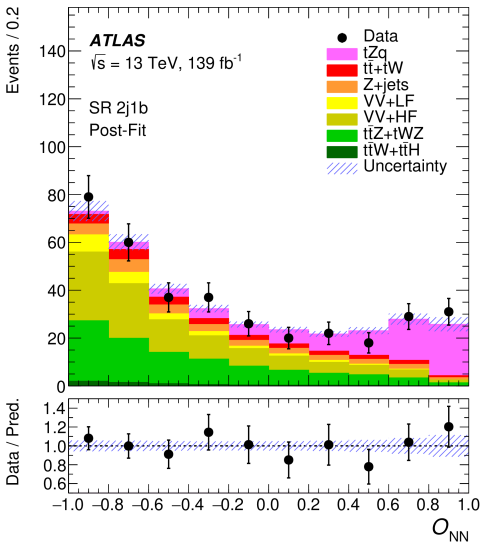


Weak production of the top-quark: the *tZq* process



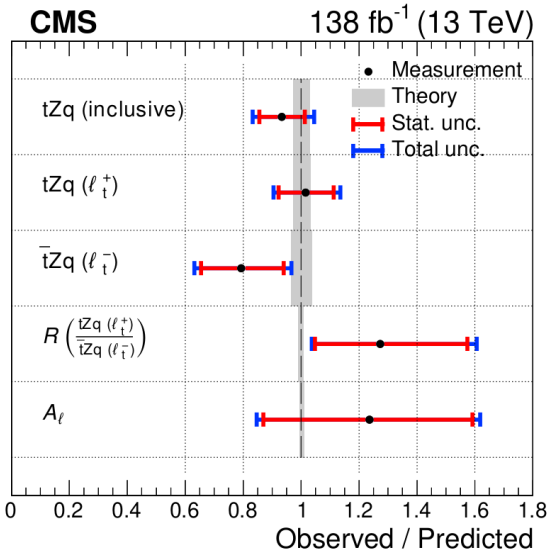
- observed both by ATLAS ▸ JHEP 07 (2020) 124 and CMS ▸ PRL 122 (2019) 132003
- purely EW production of top, top is strongly polarised
  ↪ can measure the spin-asymmetry
- can also measure ratio R for top/antitop production

ATLAS result: ▸ JHEP 07 (2020) 124



- good agreement with prediction
  ↪ rel. uncertainty: 15%
- dominated by statistical uncertainty

CMS result: ▸ arXiv:2111.02860 NEW!



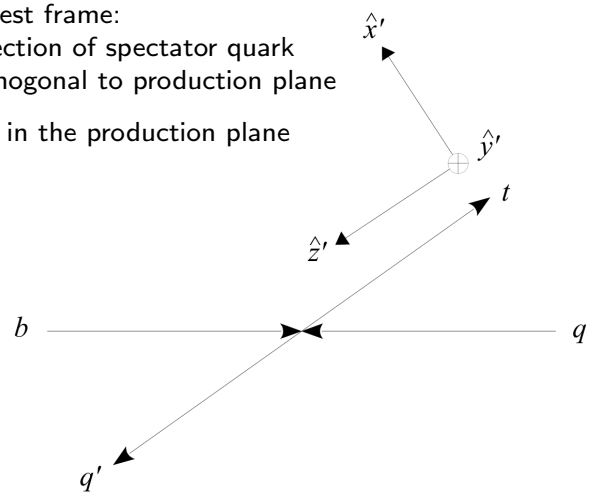
- good agreement with prediction
  ↪ rel. uncertainty: 12% !
- already first differential measurement

Top polarisation measurement at 13 TeV

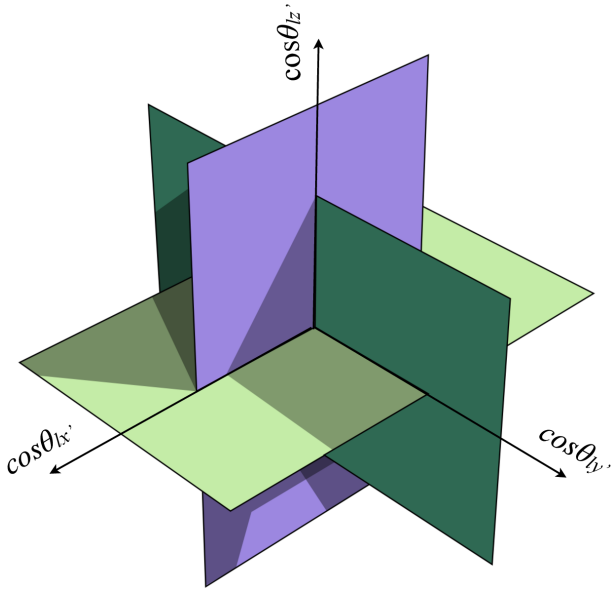
▸ ATLAS-CONF-2021-027

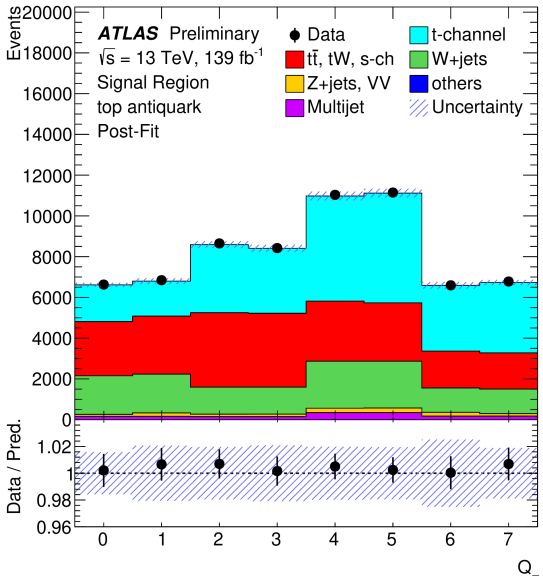
- in QCD: parity conserved, $\approx$ no polarisation of top quark in $t\bar{t}$ events
- weak interaction: $V - A$ vertex structure: expect significant polarisation in single top!

In top rest frame:
$\hat{z}'$: direction of spectator quark
$\hat{y}'$: orthogonal to production plane
$\hat{x}'$: lies in the production plane



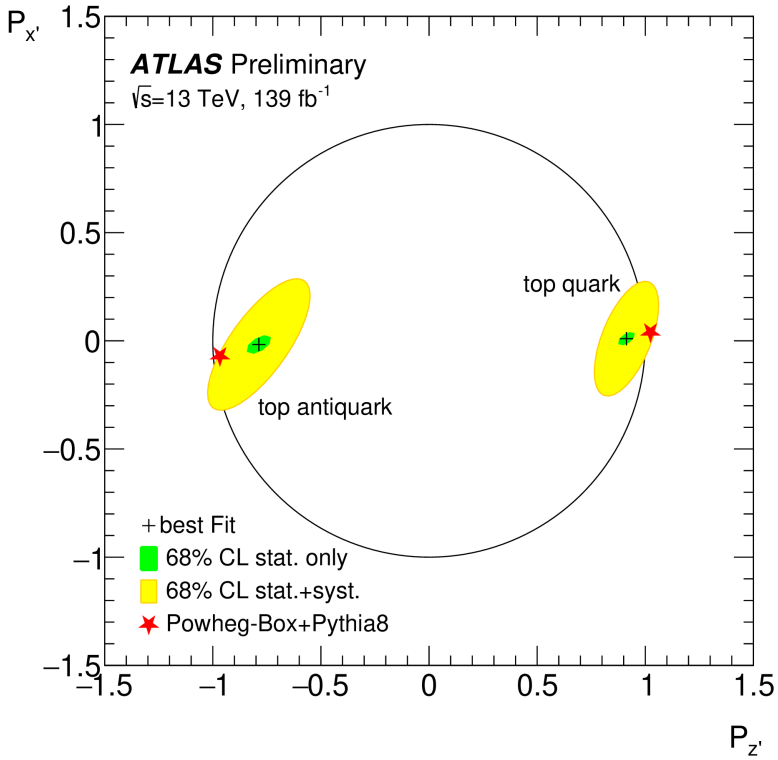
- octant variable Q:
  $\hookrightarrow$ slice phase space into eight quadrants
  $\hookrightarrow$ separately for leptons with neg./pos. charge.
- extract: signal/bkg normalisation, 6 polarisation values



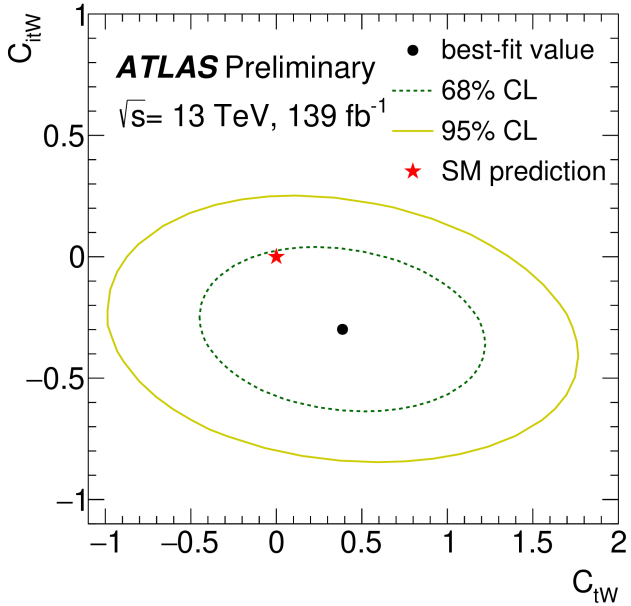


Top polarisation: results and interpretation

ATLAS-CONF-2021-027



Parameter	Extracted value	(stat.)
t-channel norm.	$+1.045 \pm 0.022$	(± 0.006)
W+jets norm.	$+1.148 \pm 0.027$	(± 0.005)
$t\bar{t}$ norm.	$+1.005 \pm 0.016$	(± 0.004)
$P^{t}_{x'}$	$+0.01 \pm 0.18$	(± 0.02)
$P^{\bar{t}}_{x'}$	-0.02 ± 0.20	(± 0.03)
$P^{t}_{y'}$	-0.029 ± 0.027	(± 0.011)
$P^{\bar{t}}_{y'}$	-0.007 ± 0.051	(± 0.017)
$P^{t}_{z'}$	$+0.91 \pm 0.10$	(± 0.02)
$P^{\bar{t}}_{z'}$	-0.79 ± 0.16	(± 0.03)



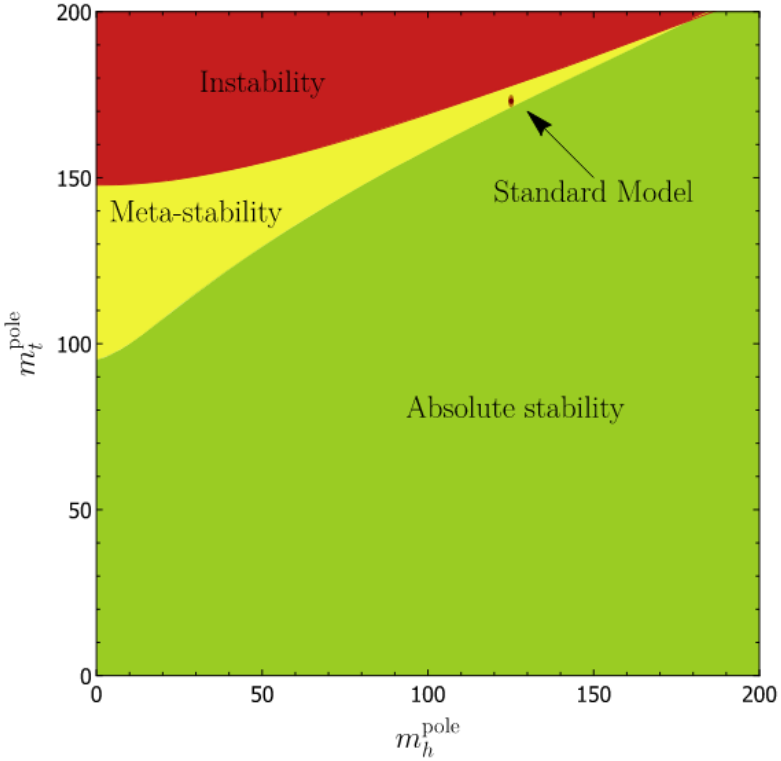
- measure strong polarisation in z-direction
  - ↪ limited by jet-energy resolution uncertainty
  - ↪ in agreement with NLO+PS prediction
- also unfolded angular distributions
  - ↪ allows to set limits on EFT operators

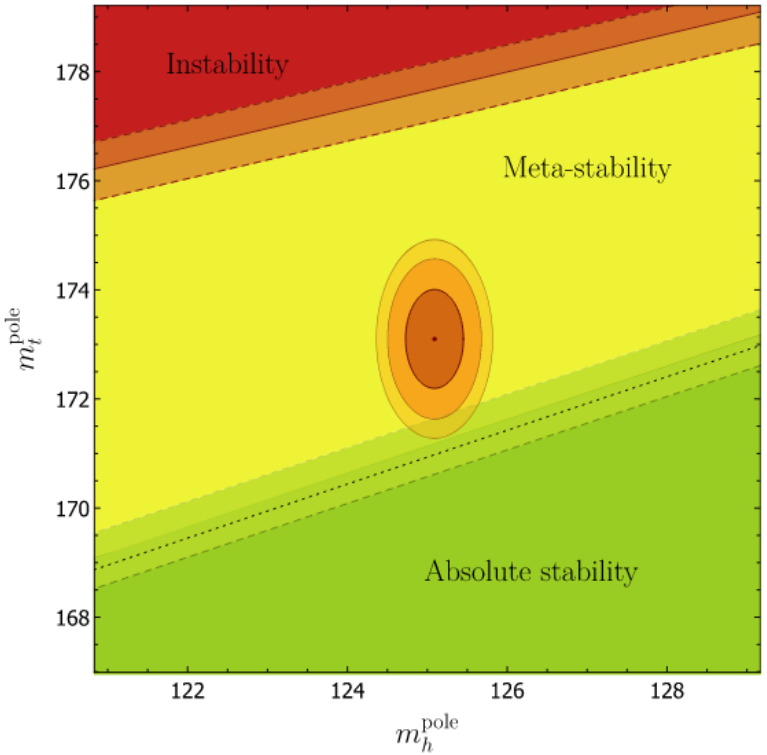
Why do we have to find out more about the top quark mass?

Top quark is special:

- m_{top} fundamental parameter, important for many SM extensions
- is the higgs potential stable/meta-stable? ▸ PRD 97 056 006

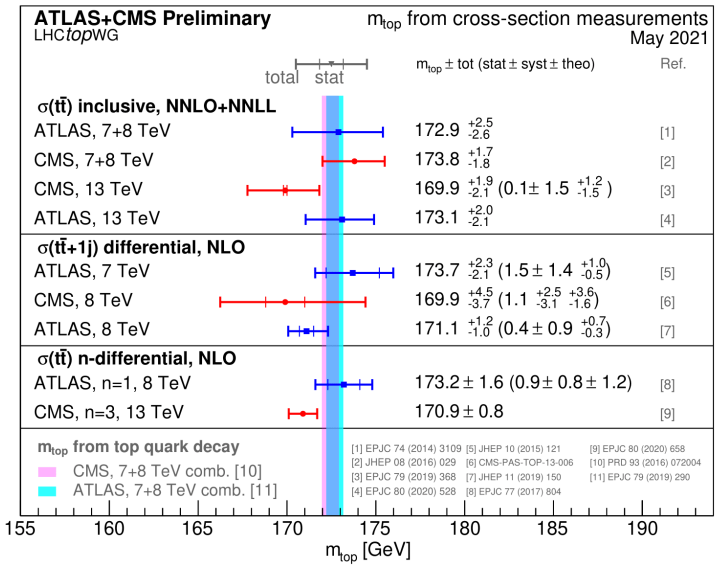
  ↪ assuming no NP up to Planck scale: stability depends strongly on m_H and m_{top}

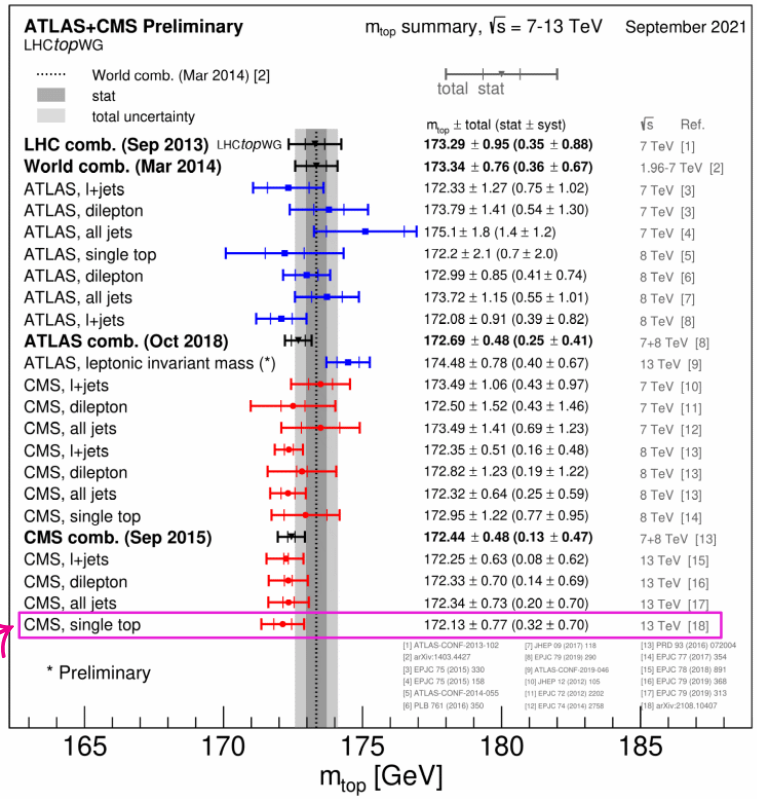




But: What mass do we measure?

- direct reconstruction m_{top} measurements:
  $\hookrightarrow$ measured m_{top}^{MC} depends on renormalization scheme of MC generator
- m_{top} from cross-section measurements: closer to pole mass
- difference between m_{top}^{MC} and e.g. m_{top}^{pole} (and other mass schemes)
  $\hookrightarrow$ still subject of lively discussion

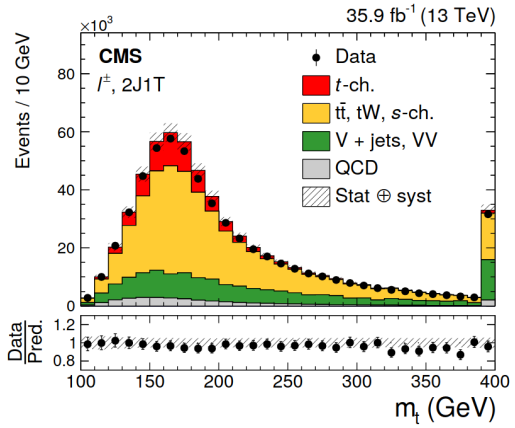


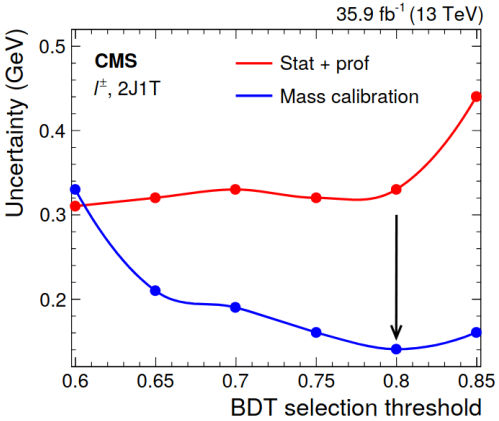


Today: discuss the latest result!

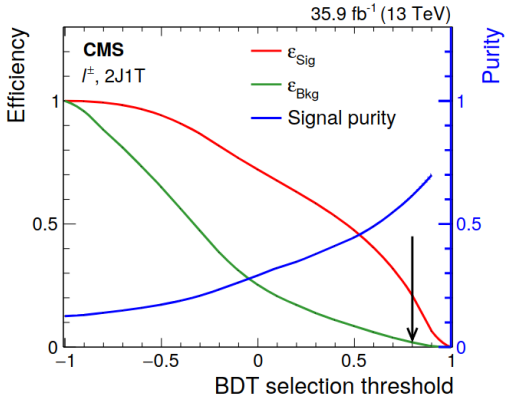
Measurement of m_{top} in t-channel single-top events ▸ JHEP 12 (2021) 161 NEW!

- t-channel events: allow to measure m_{top} at lower energy scale
- different systematics than $t\bar{t}$ events, but large $\sigma_{m_{\mathrm{top}}}^{\mathrm{total}}$ at 8 TeV
- challenge: large contamination from $t\bar{t}$ and V+jets events
  ↪ train BDT, cut on BDT output to get enriched sample

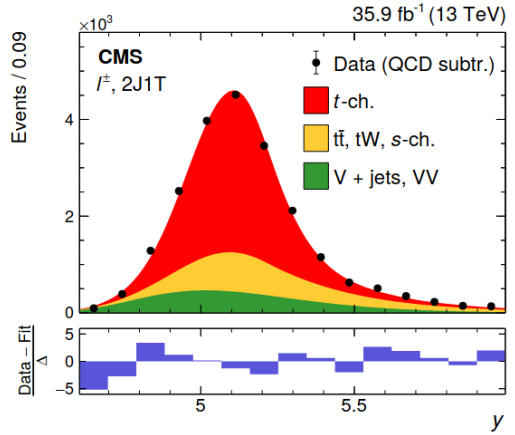




optimise cut based on stat. uncertainty



obtain strongly signal-enriched sample



Results from profile-likelihood fit:

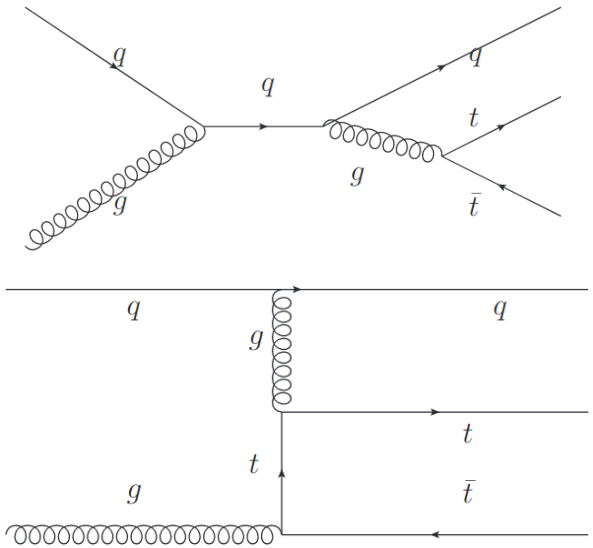
$$m_{\mathrm{top}} = 172.13^{+0.76}_{-0.77}\ \mathrm{GeV} \quad \text{and} \quad \Delta m_{\mathrm{top}} = 0.83^{+1.79}_{-1.35}\ \mathrm{GeV}$$

↪ first sub-percent top mass measurement in single top final states!
↪ mass difference compatible with CPT invariance

Measurement of the energy asymmetry in boosted $t\bar{t}$+jet events

arXiv:2110.05453

- measured C_A as function of rapidity at the LHC
  ↪ appears in $t\bar{t}$ events at NLO
- energy asymmetry in $t\bar{t}$+jets events: already at tree level!
  ↪ also have more qg than $q\bar{q}$ production
- very sensitive to EFT four-fermion operators

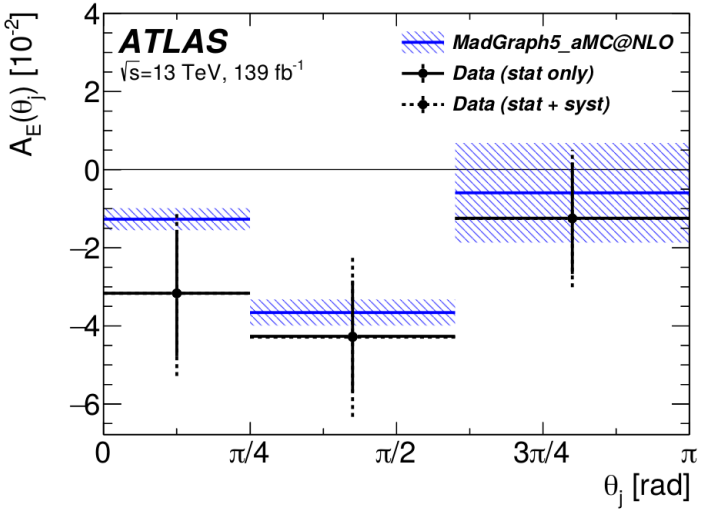


$$A_E(\theta_j) = \frac{\sigma^{\mathrm{opt}}(\theta_j|\Delta E > 0) - \sigma^{\mathrm{opt}}(\theta_j|\Delta E < 0)}{\sigma^{\mathrm{opt}}(\theta_j|\Delta E > 0) + \sigma^{\mathrm{opt}}(\theta_j|\Delta E < 0)}$$

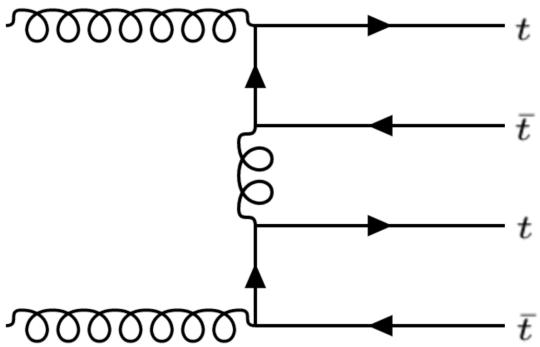
↪ with $\Delta E = E_t - E_{\bar{t}}$
↪ θ_j is the angle between the jet and the positive z-axis

Results:

In second bin: $A_E = -0.043 \pm 0.020$
↪ good agreement with the SM
↪ dominated by statistical uncertainty
↪ important new variable in EFT fit



Can we have more than 1 or 2 tops? ... 4 tops!



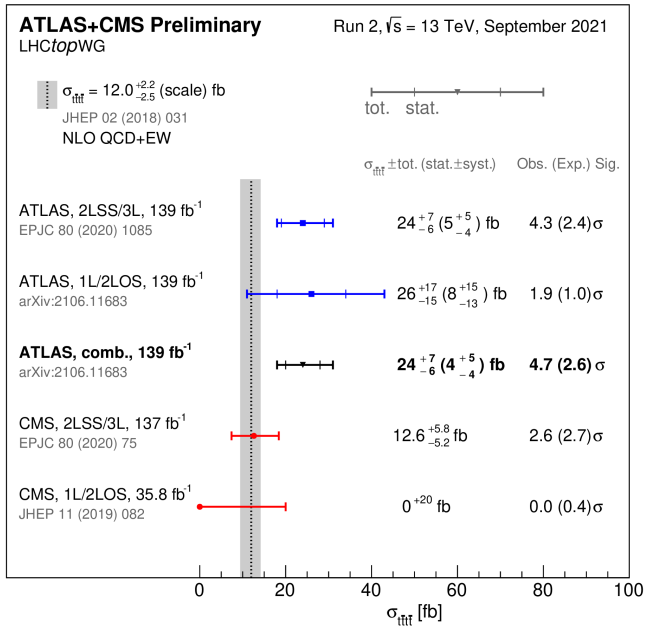
Why is this process interesting?

- very rare process: $\sigma_{t\bar{t}t\bar{t}} = 12.0 \pm 2.4$ fb
  $\hookrightarrow$ for each $t\bar{t}t\bar{t}$ event we get 69,333 $t\bar{t}$ events!
- in case of new physics: cross-section could be much larger:
  $\hookrightarrow$ gluino pair production, scalar gluon pair production, etc
- also sensitive to the top-Higgs Yukawa coupling!

What can we learn about such a rare process?

- large backgrounds from $t\bar{t}$+heavy flavour production
- need to rely heavily on machine learning
  $\hookrightarrow$ use for event reconstruction and final discriminant
- CMS: expected and observed significance: close to 3σ
- ATLAS: combined observed significance: 4.7 σ: evidence!
  $\hookrightarrow$ limited by signal and background modelling

▸ JHEP 11 (2019) 082 ▸ EPJ C 80 (2020) 75 ▸ JHEP 11 (2021) 118



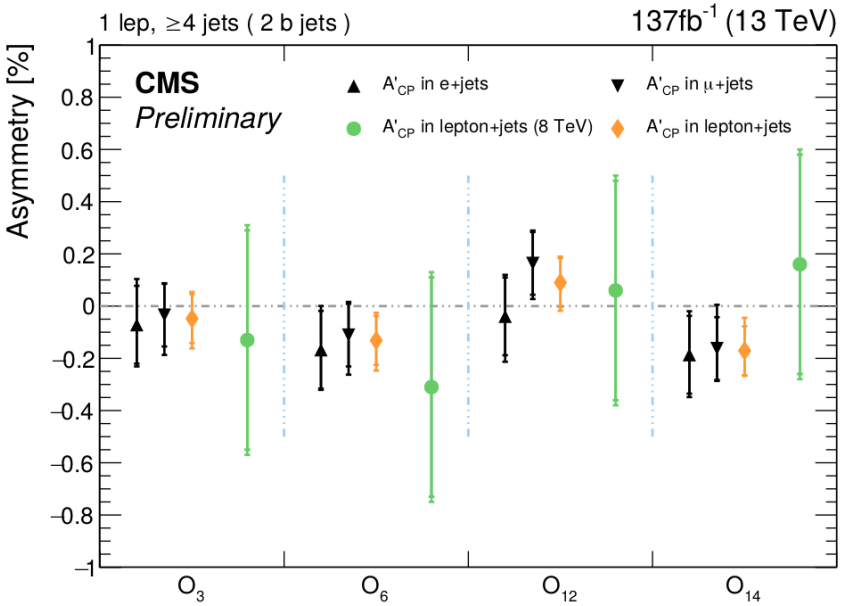
Searches for new physics processes

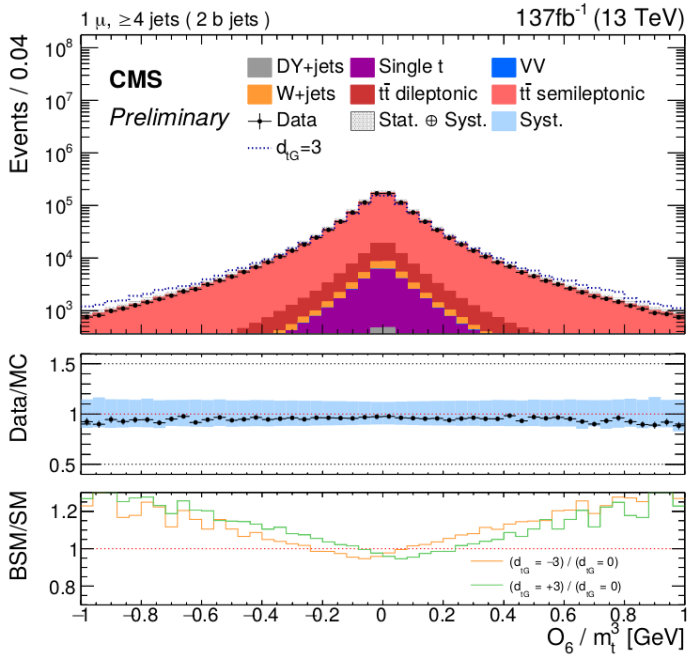
Search for CP violation in lepton+jets $t\bar{t}$ events

▸ CMS-PAS-TOP-20-005

- Standard Model CP violation in $t\bar{t}$ events is small: search sensitive to BSM physics
- allows to constrain chromo-electric dipole moment (as does spin-correlation)
- construct 4 observables O_i: triple product of momentum vectors
- fit all O_i distributions, then extract asymmetry:

$$A_{CP}(O_i) = \frac{N_{\mathrm{ev}}(O_i > 0) - N_{\mathrm{ev}}(O_i < 0)}{N_{\mathrm{ev}}(O_i > 0) + N_{\mathrm{ev}}(O_i < 0)}$$





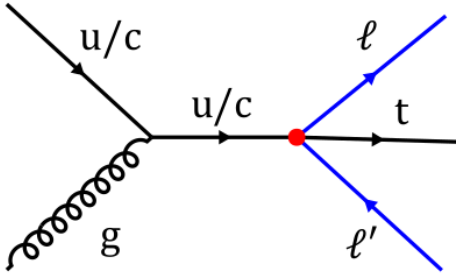
Results:

No sign for CPV effects in $t\bar{t}$ events so far

Search for charged-lepton flavour violation

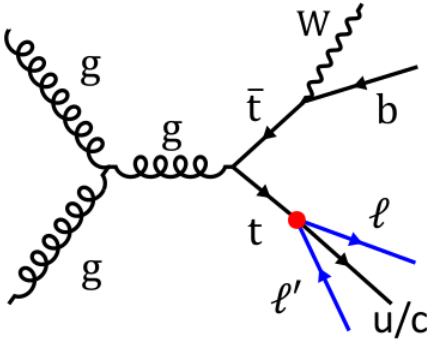
▸ CMS-PAS-TOP-19-006 ▸ ATLAS-CONF-2018-044

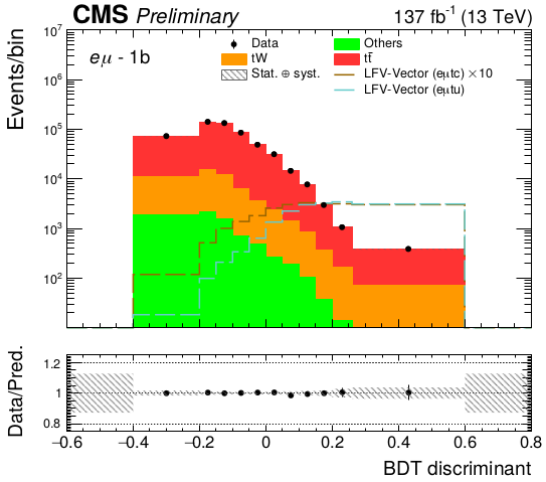
- lepton flavour conservation in SM: "accidental" global symmetry
- have observed that neutrino flavours are not conserved
- many BSM theories predict CLFV: MSSM, lepto-quark, etc

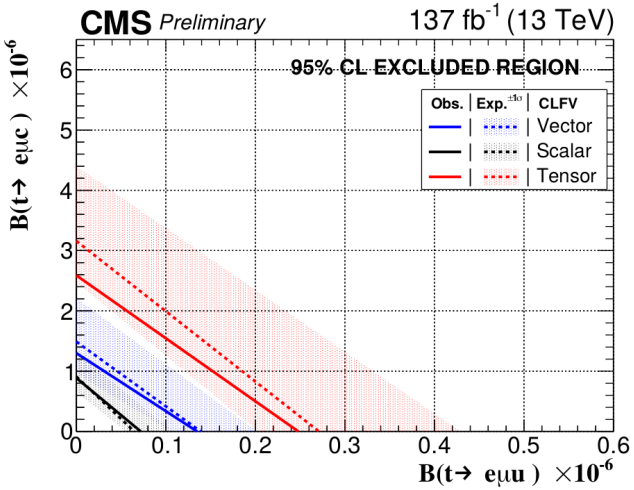


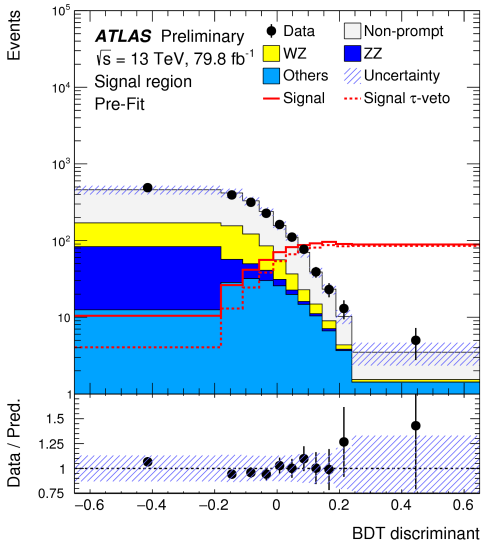
CMS: use $t\bar{t}$ <u>and</u> single top events

- separate signal and bkg with BDT, fit BDT output, set limits
- no sign for CLFV: achieved strongest limits to date









ATLAS:

- based on $t\bar{t}$ events, also BDT discriminant in fit to data

Test of lepton flavour universality ▸ ATLAS News!

Have seen: Higgs boson couples differently to different fermions: strongest for top

Is this also true for other boson couplings?

In SM: lepton coupling to W/Z bosons: not mass dependent

$\hookrightarrow$ lepton flavour universality, no fundamental physics reason!

What do we want to measure and why?

Measure ratio of W boson decays into muons/taus: $R(\mu/\tau)$

$\hookrightarrow$ previous measurement by LEP: 1.070 ± 0.026 ($2.7\ \sigma$ deviation from SM) ▸ Paper

$\hookrightarrow$ fluctuation or new physics effect?

What does this have to do with $t\bar{t}$ events?

$\mathrm{BR}(t \to Wb) \approx 100\%$: easy to select, large statistics, gives us two W bosons

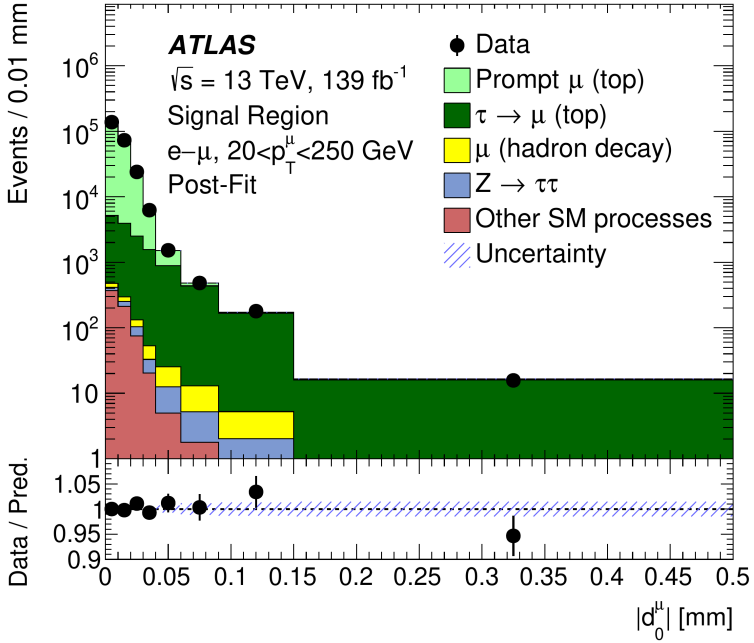
$W \to \mu\nu_\mu$: larger lepton p_T, low impact parameter d_0 (close to interaction vertex)

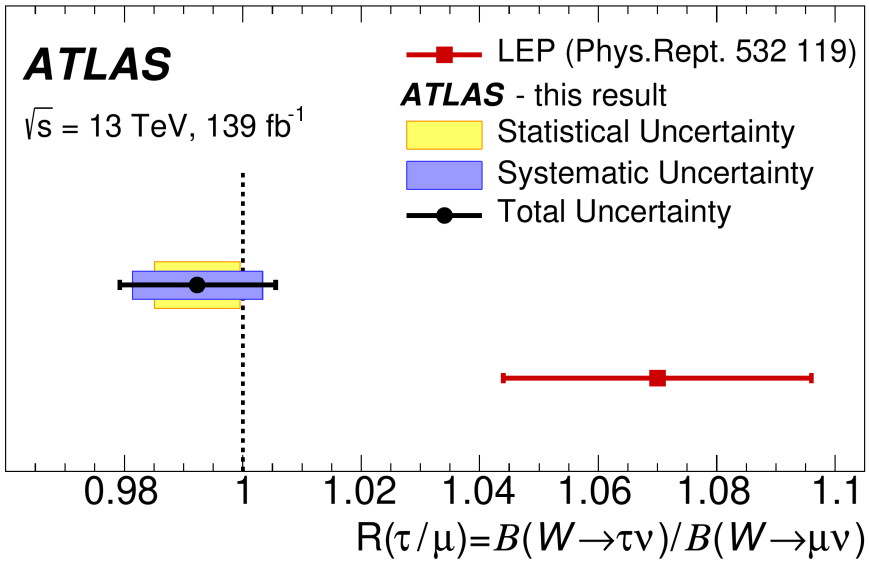
$W \to \tau\nu_\tau \to \mu\nu_\mu\nu_\tau\nu_\tau$: lower lepton p_T, larger d_0 (decays 2mm from interaction vertex)

What did we measure? ▸ Nature Physics vol 17, 813-818 (2021)

Fit impact parameter distribution (left): measure for displacement of muon vertex

↪ prompt muons have low impact parameter, muons from tau decays have high values



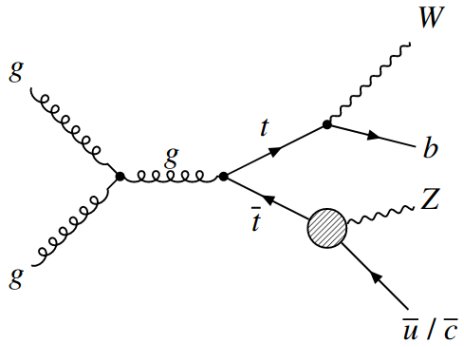


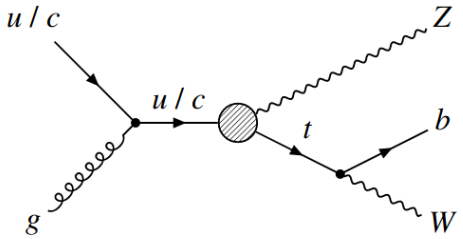
Result from ATLAS: compatible with the SM, and most precise result up to date

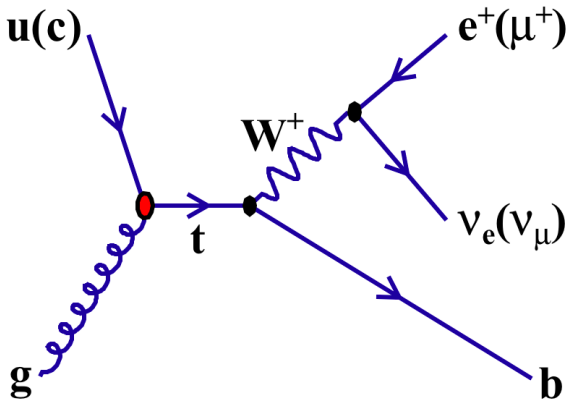
↪ Here a nice ▸ Video by two of the physicists who performed the measurement!

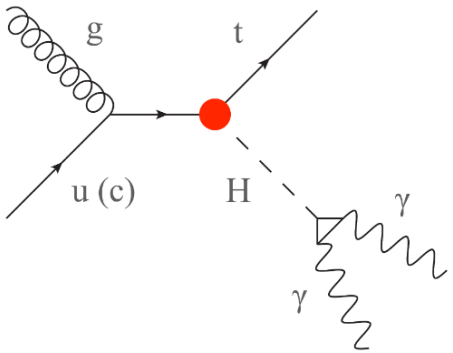
Searches for flavour-changing neutral currents (FCNC)

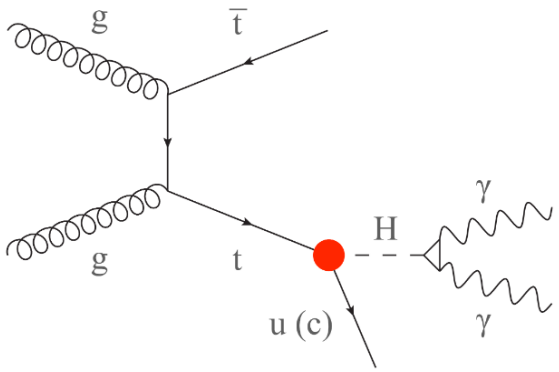
- FCNC in the Standard Model: forbidden at tree-level
  $\hookrightarrow$ strongly suppressed in loops by GIM mechanism: $BR \approx 10^{-15} - 10^{-12}$
- but: many new physics models allow for FCNCs: MSSM, 2HDM, composite Higgs...
  $\hookrightarrow$ much larger branching ratios possible: in reach for the LHC!
- in top physics: can occur in many production/decay channels:











New results for flavour-changing neutral currents (FCNC)

▸ arXiv:2112.09734

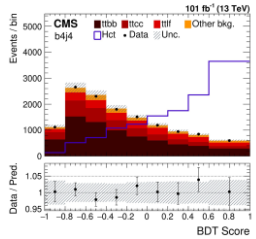
↪ strongly improved limits for $tH(b\bar{b})$

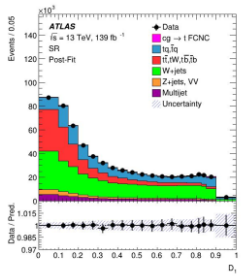
▸ arXiv:2112.01302

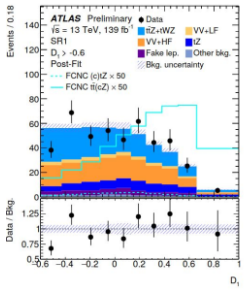
↪ ATLAS improved limits by factor 2 compared to 8 TeV

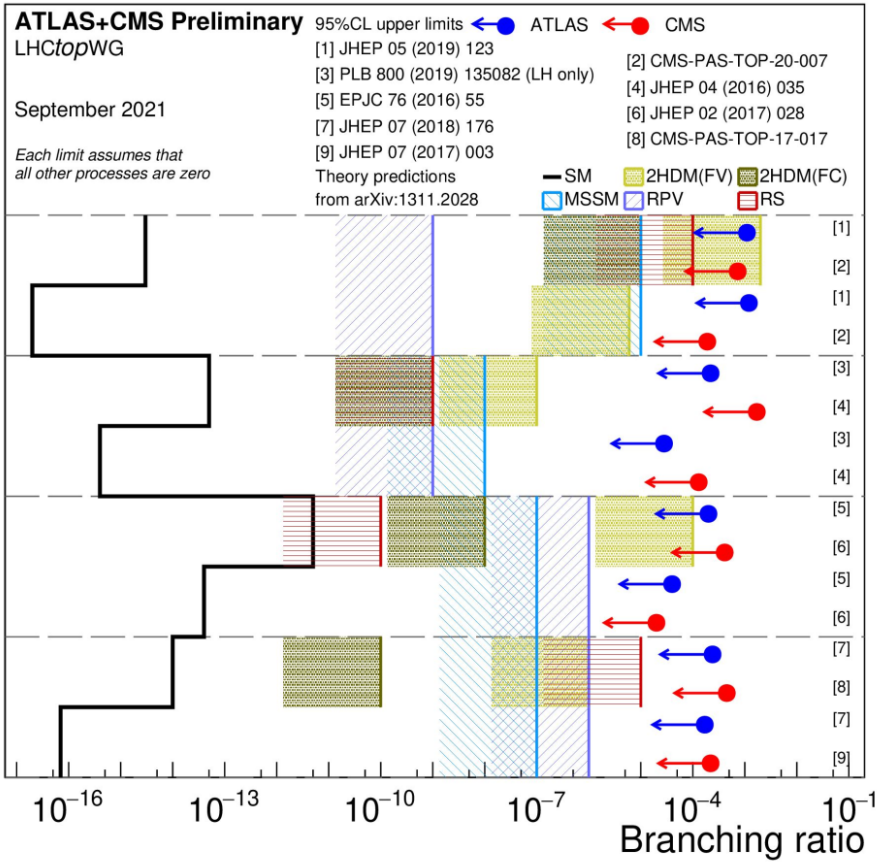
▸ ATLAS-CONF-2021-049

↪ most stringent limits to date!









- reaching now branching-ratios that are possible in BSM scenarios
- analyses strongly benefit from larger dataset, also strongly rely on BDTs/NNs
- more details on FCNC searches in ATLAS: ▸ Talk Ana Peixoto tomorrow!

Summary

The top quark has come a long way since 1977:

Back then: missing quark, assumed to be similar to other quarks

Summary

The top quark has come a long way since 1977:

Back then: missing quark, assumed to be similar to other quarks

↓

Today: we know that top quark is special!

Live in precision era, top quark is key to an abundance of different research areas

Summary

The top quark has come a long way since 1977:

Back then: missing quark, assumed to be similar to other quarks

↓

Today: we know that top quark is special!

Live in precision era, top quark is key to an abundance of different research areas

↓

Look to the future:

1. Reduce systematic uncertainties
2. Look at rare processes finally accessible
3. Test BSM theories, also in the EFT framework

The top quark is still going strong!