The top quark is still going strong! (and electroweak)

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Particle physics seminar, Birmingham 2022

What you probably heard countless times...

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

  $\hookrightarrow$ actually... mass between tungsten and rhenium nowadays ;)

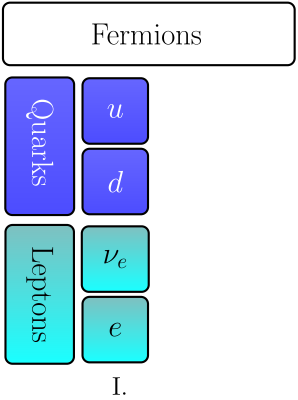
- "it plays a special role in the standard model"

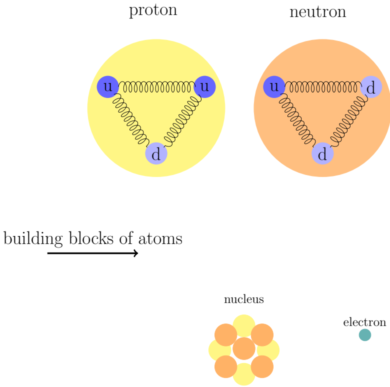
  $\hookrightarrow$ I will discuss today why it is special

- "the LHC is a top quark factory"

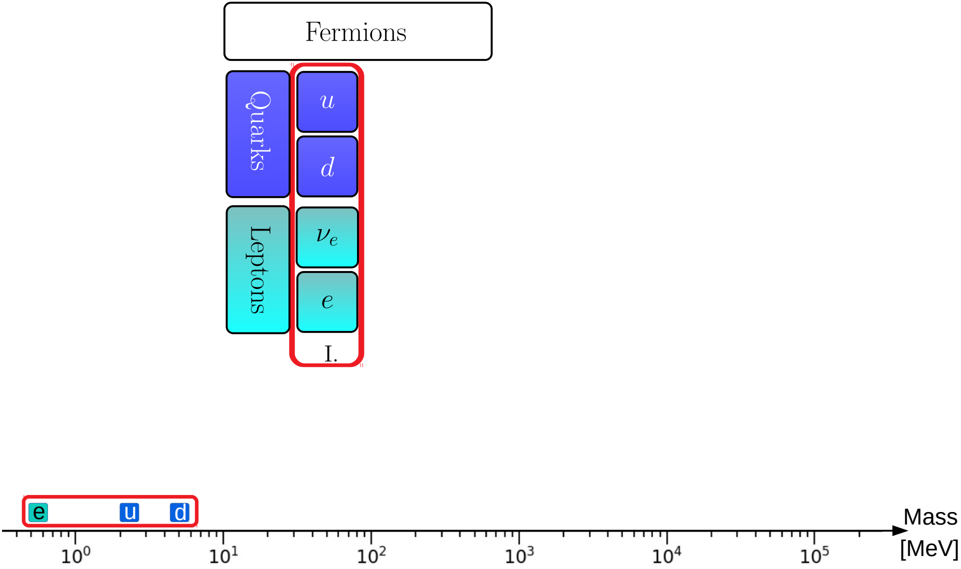
  $\hookrightarrow$ this very much depends on the production process!

What is matter made of?

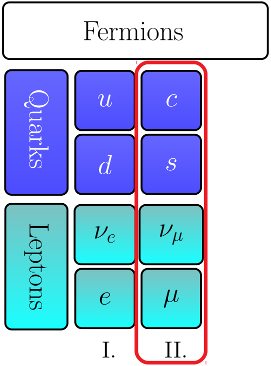


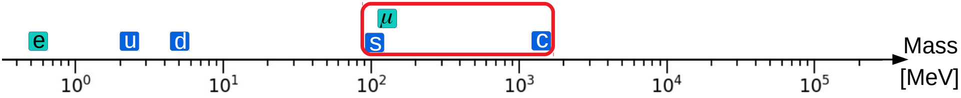


The first generation of fermions

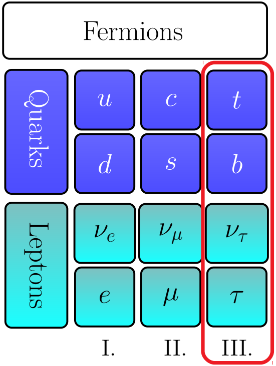


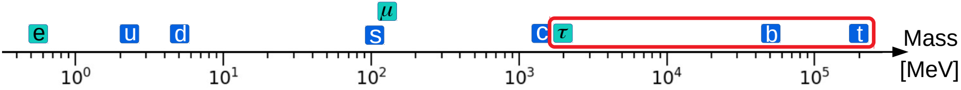
The second generation of fermions



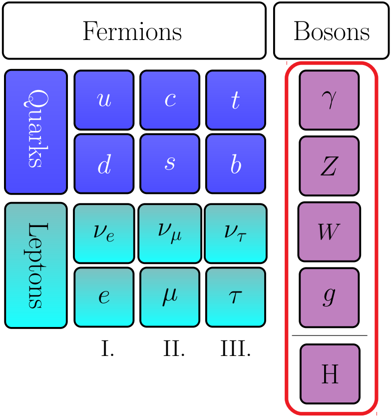


The third generation of fermions

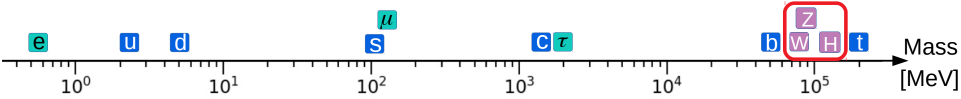




The bosons



Fermions
Bosons
Quarks
u c t
d s b
Leptons
ν_e ν_μ ν_τ
e μ τ
I. II. III.
γ
Z
W
g
H



e u d μ s c τ b Z W H t
10^0 10^1 10^2 10^3 10^4 10^5
Mass [MeV]

What is the Standard Model?

- is based on relativistic quantum field theory
- the three fundamental forces are described by gauge groups

Lagrange density: $\mathcal{L} = T - V$

$\mathcal{L}$ needs to be invariant under local gauge transformations:

$$\psi(x) \rightarrow e^{iq\chi(x)}\psi(x)$$
$$A_\mu \rightarrow A_\mu - \partial_\mu \chi$$

- If fermions and bosons have non-zero masses: breaks local gauge invariance
- Where do the masses come from?

  $\hookrightarrow$ need the Higgs mechanism

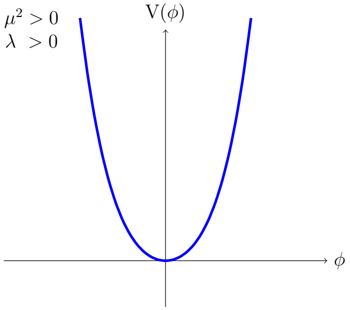
Higgs mechanism

Introduce doublet of complex, scalar fields ϕ:

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

Lagrange density:

$$\mathcal{L} = T - V = (D_\mu \phi)^\dagger (D^\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2$$



$\mu^2 > 0$: symmetric potential

$\hookrightarrow$ ground state (vacuum) at $\phi = 0$

$\hookrightarrow$ non-zero masses still not allowed

Higgs mechanism

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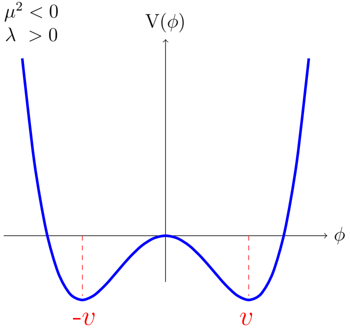

$\mu^2 < 0$: non-vanishing

vacuum-expectation value: $v = \sqrt{-\frac{\mu^2}{\lambda}}$

$\hookrightarrow$ non-trivial vacuum

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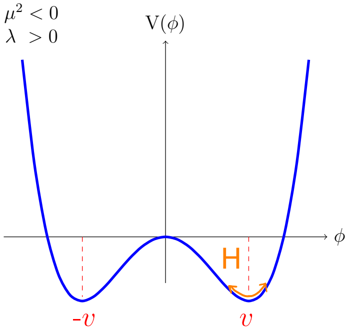


$\mu^2 < 0$: non-vanishing vacuum-expectation value: $v = \sqrt{-\frac{\mu^2}{\lambda}}$

$\hookrightarrow$ non-trivial vacuum

In the unitary gauge:

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

$\hookrightarrow$ spontaneous breaking of symmetry: mass!

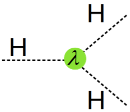
Mass terms in the Lagrangian

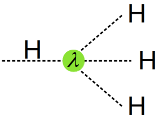
Gauge boson masses:

$$\mathcal{L}_{\text{Gauge}} = M_W^2 W_\mu^- W^{+\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu + \dots$$

Higgs self-coupling and mass term:

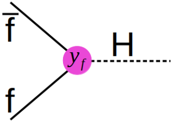
$$\mathcal{L}_{\text{Higgs}} = \frac{1}{2}(\partial_\mu H)(\partial^\mu H) \boxed{-\lambda v^2 H^2} \boxed{-\lambda v H^3 - \frac{\lambda}{4} H^4}$$



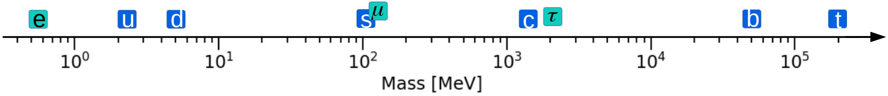


Fermion-Higgs coupling (Yukawa coupling):

$$\mathcal{L}_{\text{Yukawa}} = -\underbrace{\frac{y_f v}{\sqrt{2}}}_{m_f} \psi\overline{\psi} - \frac{y_f}{\sqrt{2}} \psi\overline{\psi} H$$



Fermion coupling to the Higgs boson



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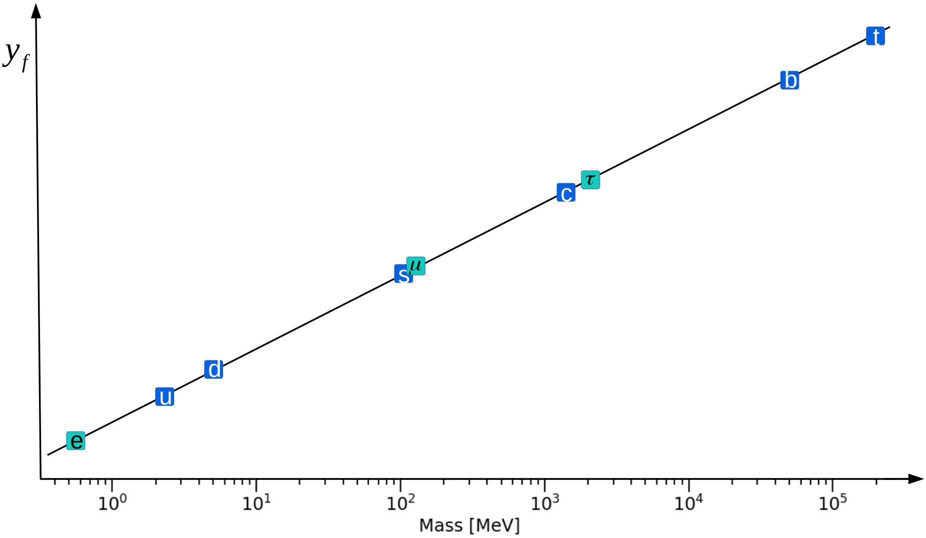
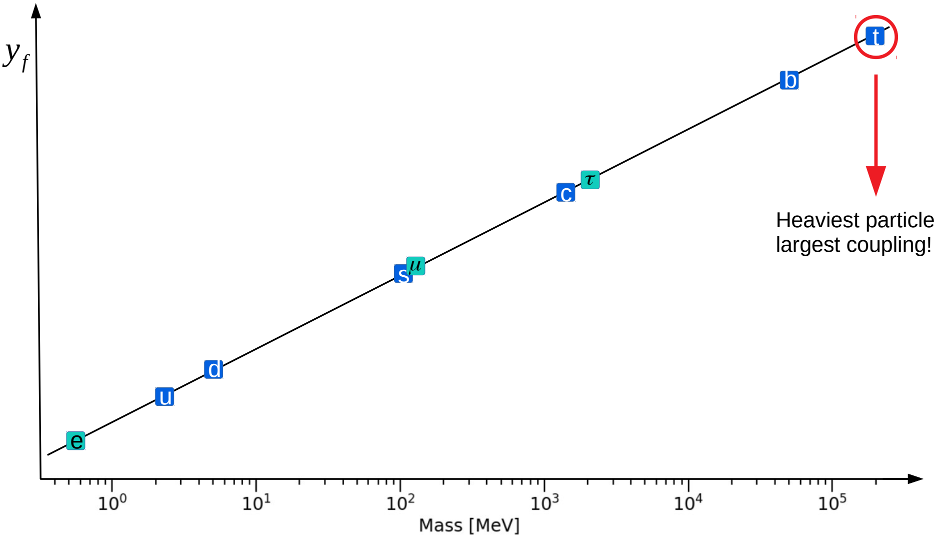
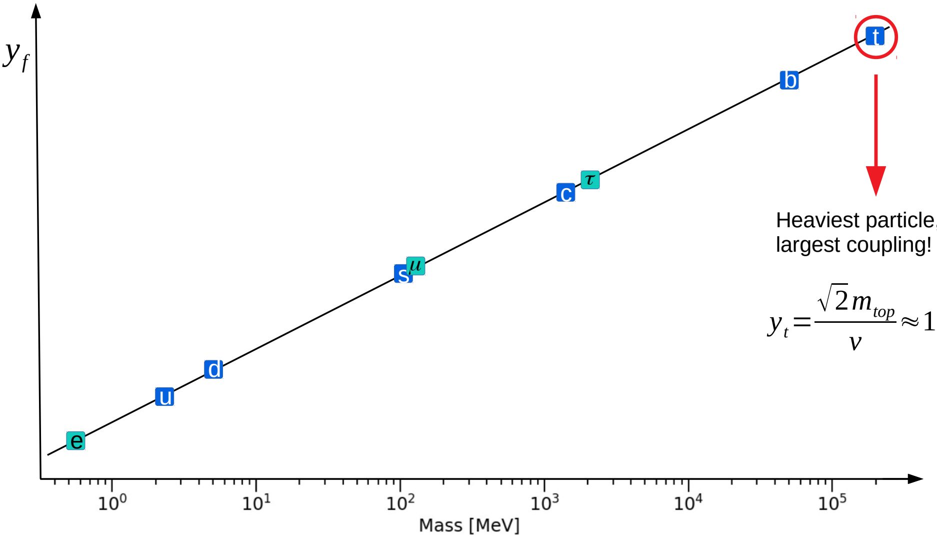


Fermion coupling to the Higgs boson



Heaviest particle,
largest coupling!

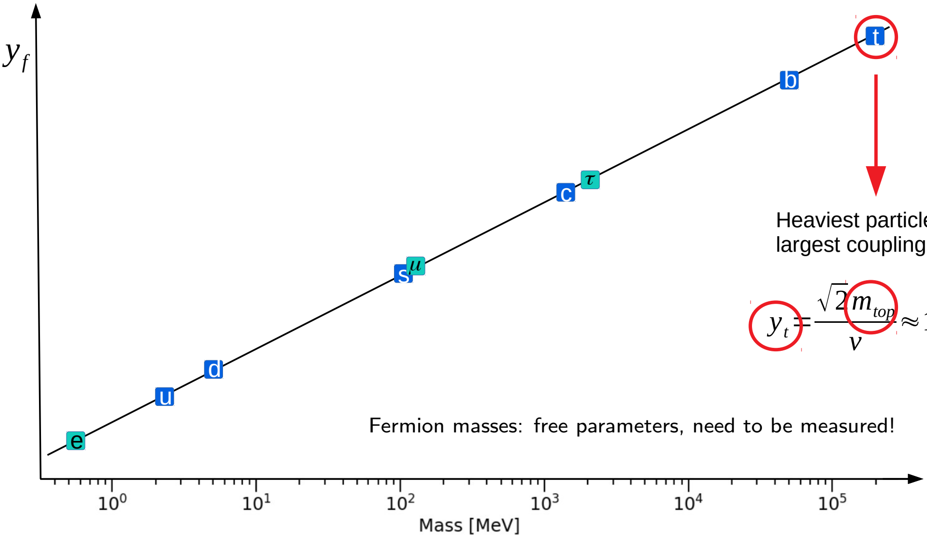
Fermion coupling to the Higgs boson



Heaviest particle, largest coupling!

$$y_t = \frac{\sqrt{2}\, m_{top}}{v} \approx 1$$

Fermion coupling to the Higgs boson

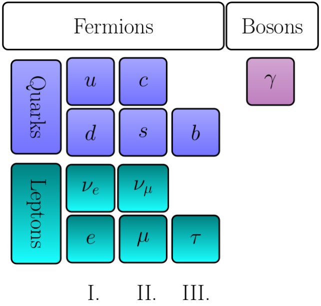


Heaviest particle, largest coupling!

$$y_t = \frac{\sqrt{2}\, m_{top}}{v} \approx 1$$

Fermion masses: free parameters, need to be measured!

Since when do we know about the top quark?

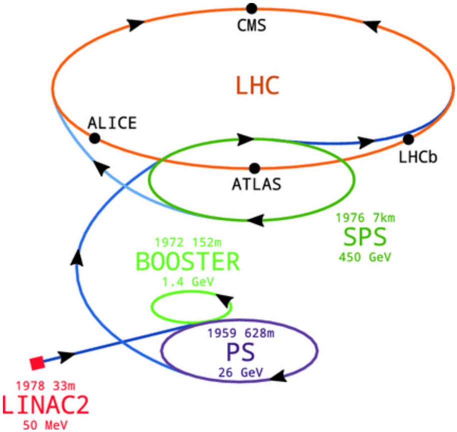


- only knew these particles when the top-quark was postulated in 1977
- after *b*-quark discovery: expect to find the top-quark also soon
- but: due to the large mass: discovery only in 1995
- decays before hadron formation or spin-decorrelation can take place

  $\hookrightarrow$ can obtain properties from the top-quark decay products
- plays key role in multitude of research areas: **What do we know today?**

Lets start with the top-quark production!

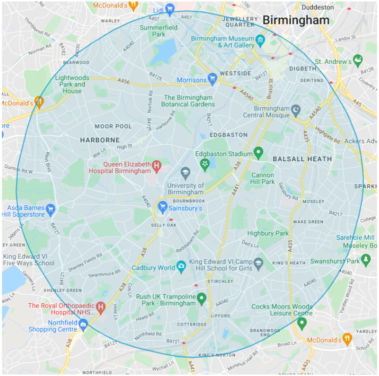
The Large Hadron Collider at CERN



- particles accelerated to almost the speed of light, ran with different energies
- focus in the following on proton-proton collisions

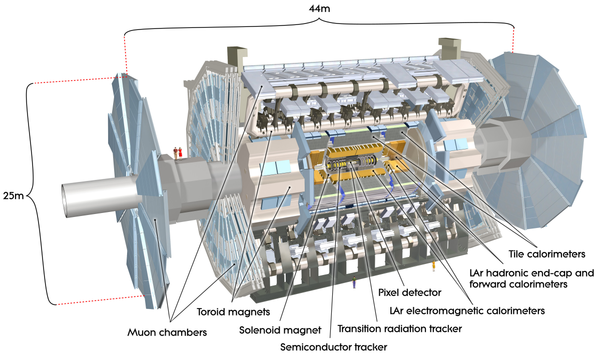
The Large Hadron Collider at CERN

howlargeisthelhc.com



- LHC: 27 km circumference, collisions every 25 or 50 nanoseconds
- $\approx 10^{15}$ proton-proton collisions for 8 TeV collision energy
- $\approx 10^{16}$ proton-proton collisions for 13 TeV collision energy

The ATLAS Detector

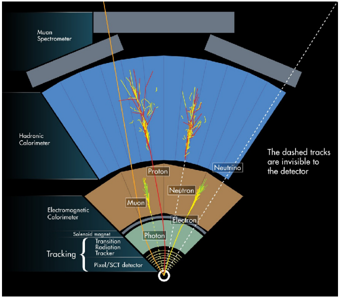


- general purpose detector
- almost full solid angle
- onion-shell structure

- use direction, charge, energy, momentum

  $\hookrightarrow$ identify particle type

- need electrons, muons, taus, jets, photons for measurements discussed today



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

- But: do we actually have access to these very rare processes?

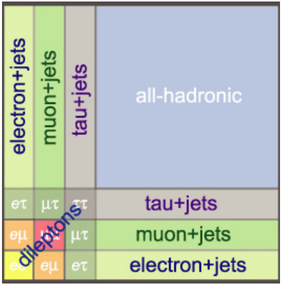
- Have plethora of measurements, focus on the latest results today

How can we identify Top-Quark pairs?

Top-Quark Decay:

- $\mathrm{BR}(t \to Wb) \approx 1$
- final state defined by W decay
- W decays to $l\nu_l$ or $q\bar{q}'$

➔ *b*-jet identification crucial!



dilepton:

- signature: two jets, $\mathrm{l}^+, \mathrm{l}^-, \nu_\mathrm{l}, \bar{\nu}_\mathrm{l}$
- pro: clean signal
- con: kinematically underconstrained

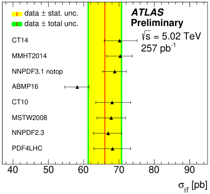
all hadronic:

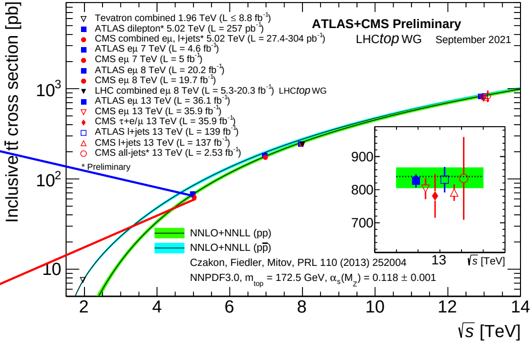
- signature: six jets
- pro: largest branching ratio
- con: large multijet background

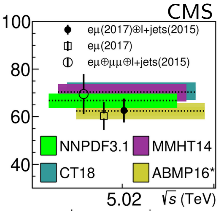
lepton+jets:

- signature: four jets, $\mathrm{l}, \nu_\mathrm{l}$
- pro: good signal/background ratio
- con: large jet/modelling uncertainties

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







- precicsion at $\sqrt{s} = 13$ TeV: below 2.5% for single result
- new results at $\sqrt{s} = 5$ TeV: already below 8%
  - ↪ strongly dominated by statistical uncertainties
  - ↪ excellent agreement with the NNLO+NNLL prediction
- LHCb measurement: relative uncertainty of 20%

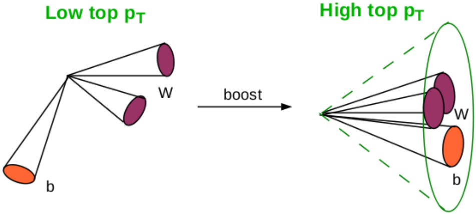
ATLAS-CONF-2021-003

CMS-TOP-20-004

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.

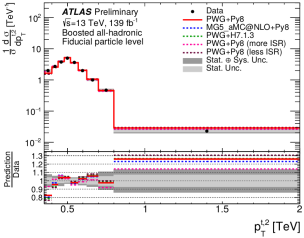


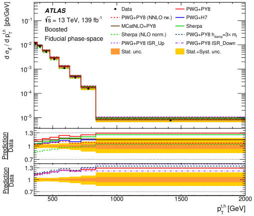
Perform unfolding: remove detector effects! Two options shown here:

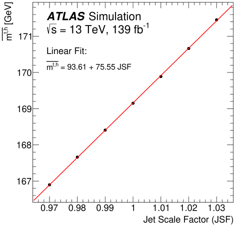
- parton level: after radiation, before decay $\rightarrow$ compare to fixed order calculations
- particle level: select events in fiducial phase space, use particles with $\tau > 30$ ps

$\hookrightarrow$ can only show a subset of results here

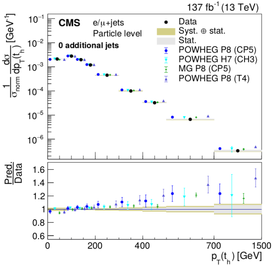
Do we still have a disagreement of the top p_T with data?

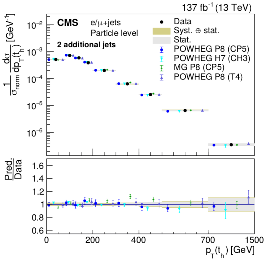






↪ softer top p_T in data visible in all decay channels





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

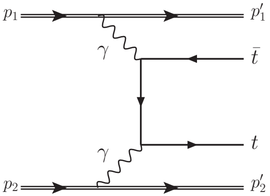
- arXiv:2202.12134
- Phys. Rev. D 104 (2021) 092013

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

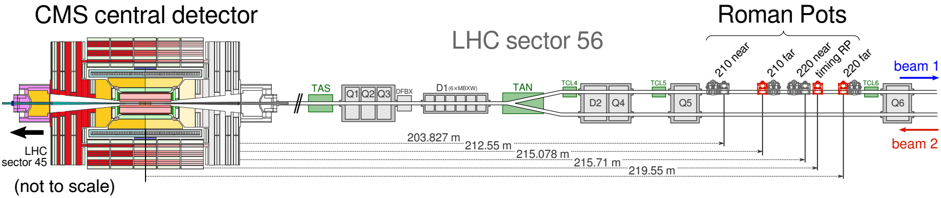
NEW: Central exclusive production of top-quark pairs ▸ CMS-PAS-TOP-21-007

Small-angle scattering of protons:

- both protons still intact, can exchange for example photons
- allows production of $t\bar{t}$ pairs: $pp \to pt\bar{t}p$
- $t\bar{t}$ decay products in central detector, tag forward protons
- cross-section very small: $\mathcal{O}(0.1\text{fb})$



Precision-Proton Spectrometer (PPS): measure fractional momentum loss of protons $\xi_{1,2}$:



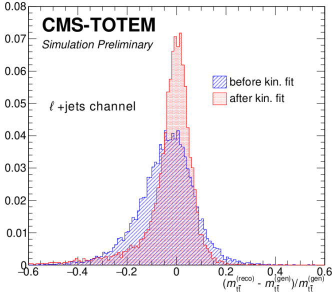
Central exclusive production of top-quark pairs

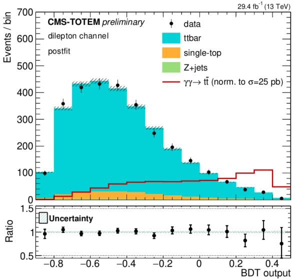
CMS-PAS-TOP-21-007

- use single- and dilepton $t\bar{t}$ decay topologies
- quantities of central system X:
  $\hookrightarrow$ related to proton-momentum loss:

$$M_X = \sqrt{s\xi_1\xi_2} \quad \text{and} \quad y_X = \frac{1}{2}\ln\left(\frac{\xi_1}{\xi_2}\right)$$

$\hookrightarrow$ used as a constraint in the kinematic fit (single-lepton reconstruction), used in BDT training (dilepton channel)



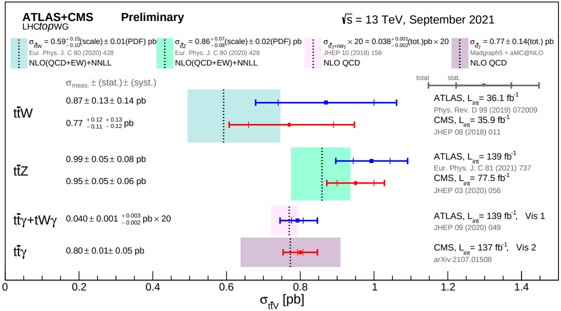


- train BDT to distinguish signal from QCD $\rightarrow t\bar{t}$ background
- binned nuisance-parameter fit to BDT output
- observed (expected) limit: 0.59 $(1.14^{+1.2}_{-0.6})$ pb @ 95% CL
- first result in this production process!

Top quark couplings:

The top quark likes every particle!

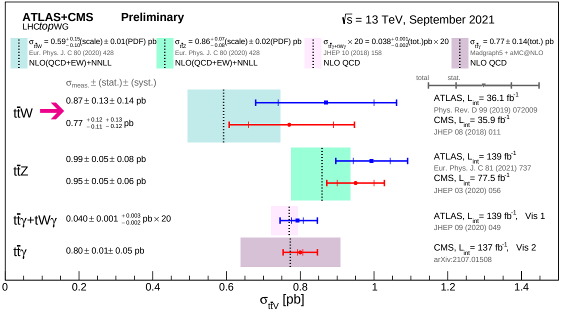
What do we know about the electroweak couplings?

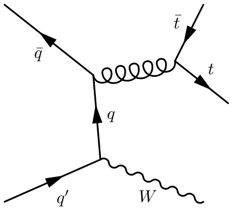


What do we know about the electroweak couplings?

$t\bar{t} + W$ 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]

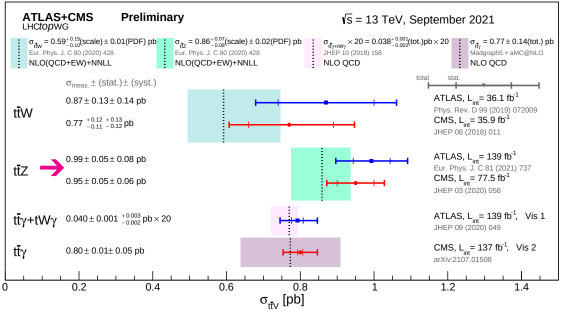


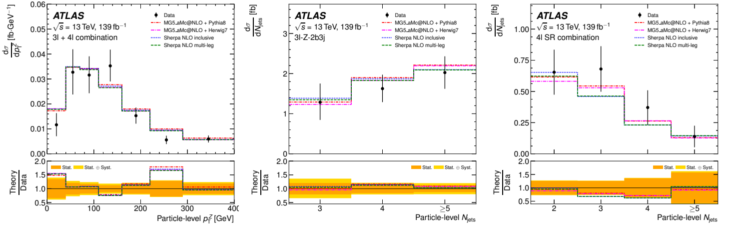


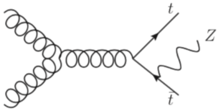
$t\bar{t} + Z$ production:

- 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



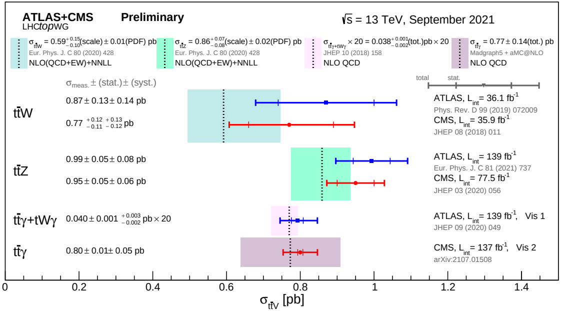


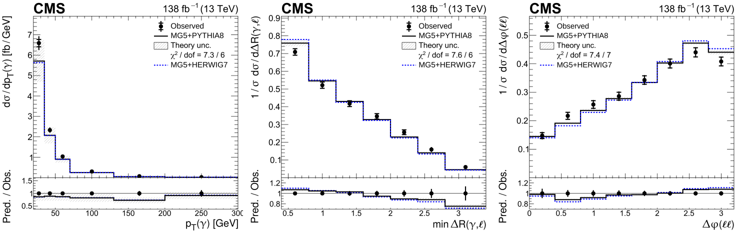


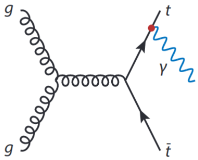
What do we know about the electroweak couplings?

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

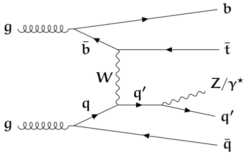
- relative uncertainty of 3.9%
  - arXiv:2201.07301
  - $\hookrightarrow$ new result (dilepton)!
- dominated by statistical, lepton efficiency and luminosity unc.
- differential cross-section largely in agreement with prediction





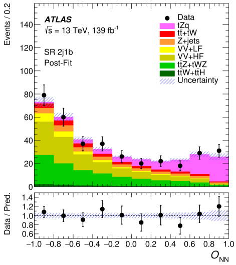


Weak production of the top-quark: the tZq process



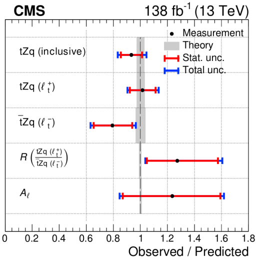
- observed both by ATLAS ▸ JHEP 07 (2020) 124 and CMS ▸ PRL 122 (2019) 132003
- purely EW production of top, top is strongly polarised
  ↪ can measure the spin-asymmetry
- can also measure ratio R for top/antitop production

ATLAS result: ▸ JHEP 07 (2020) 124



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

CMS result: ▸ JHEP 02 (2022) 107 NEW!

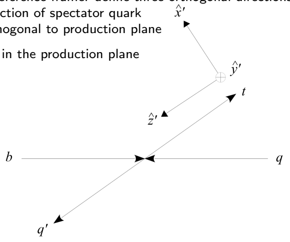


- good agreement with prediction
  ↪ rel. uncertainty: 12% !
- already first differential measurement

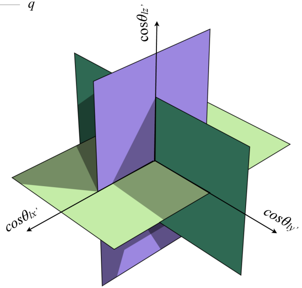
Top polarisation measurement at 13 TeV ▸ arXiv:2202.11382

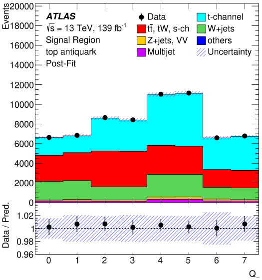
- in QCD: parity conserved, $\approx$ no polarisation of top quark in $t\bar{t}$ events
- weak interaction: $V - A$ vertex structure: expect significant polarisation in single top!

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



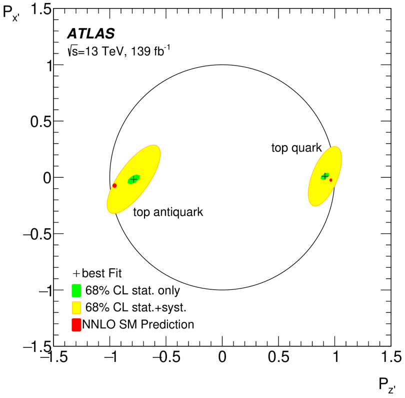
- octant variable Q:
  - $\hookrightarrow$ slice phase space into eight quadrants
  - $\hookrightarrow$ separately for leptons with neg./pos. charge.
- extract: signal/bkg normalisation, 6 polarisation values



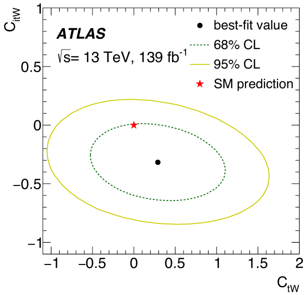


Top polarisation: results and interpretation

arXiv:2202.11382



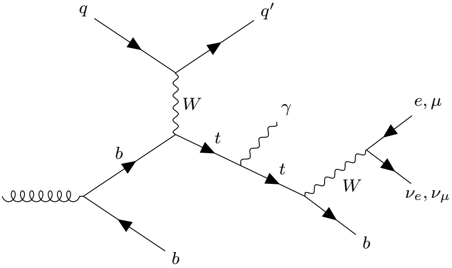
Parameter	Extracted value	(stat.)
t-channel norm.	$+1.045 \pm 0.022$	(± 0.006)
W+jets norm.	$+1.148 \pm 0.027$	(± 0.005)
$t\bar{t}$ norm.	$+1.005 \pm 0.016$	(± 0.004)
$P^{t}_{x'}$	$+0.01 \pm 0.18$	(± 0.02)
$P^{\bar{t}}_{x'}$	-0.02 ± 0.20	(± 0.03)
$P^{t}_{y'}$	-0.029 ± 0.027	(± 0.011)
$P^{\bar{t}}_{y'}$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



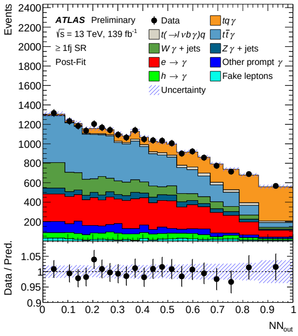
- measure strong polarisation in *z-direction*
  - ↪ limited by jet-energy resolution uncertainty
  - ↪ in agreement with NLO+PS prediction
- also unfolded angular distributions
  - ↪ allows to set limits on EFT operators

NEW: First observation of the $tq\gamma$ process

ATLAS-CONF-2022-013



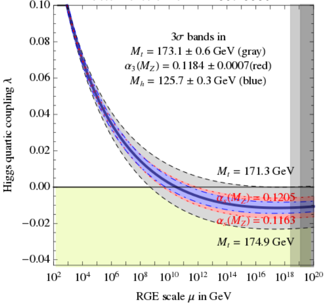
- scrutinize the top-photon interaction further
- rare process: $\sigma_{tq\gamma} = 406^{+25}_{-32}$ pb
- identify forward jet and leptonic top decay
- employ data-driven methods to model fake-photon backgrounds



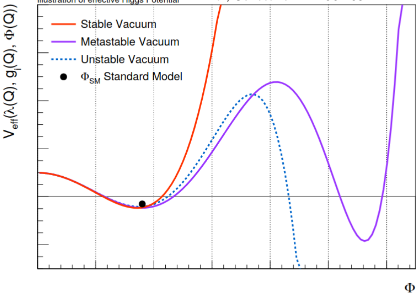
- need NN to distinguish signal from large background processes
- main systematic uncertainty: $t\bar{t}\gamma$ modelling
- observed (expected) significance: 9.1 (6.7) standard deviations
- fiducial parton (particle)-level cross-sections:
  - $\hookrightarrow$ consistent with SM expectation within 2.5 (1.9) σ
  - $\hookrightarrow$ CMS result: $\mu = 1.42 \pm 0.43$ PRL 121, 221802 (2018)

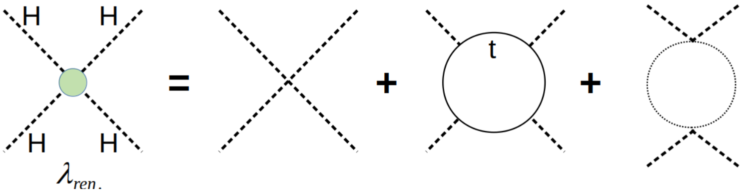
Why do we care about the top-quark mass and Yukawa coupling?

D. Buttazzo et al: arXiv:1307.3536



Erler, Schott: arXiv:1902.05142





Why do we care about the top-quark mass and Yukawa coupling?

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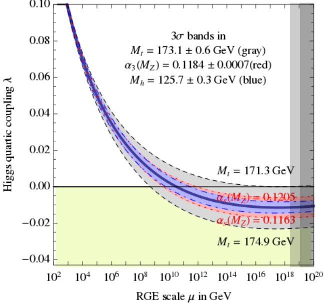

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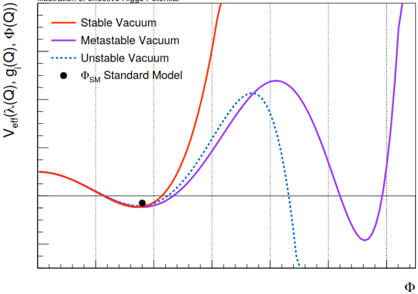
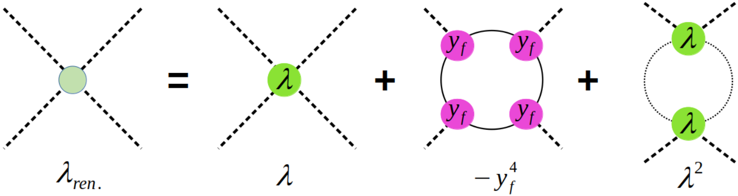
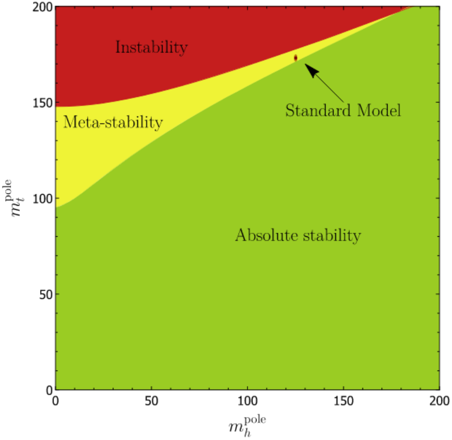
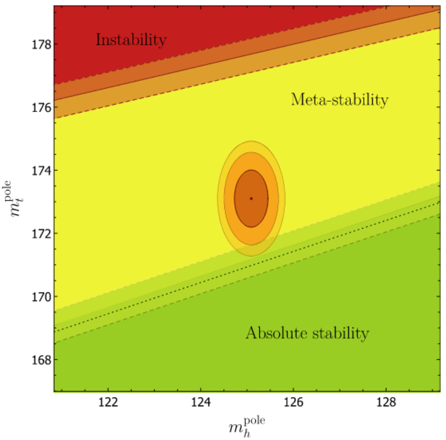




$$\frac{d\lambda}{d\log(\mu)} \propto \lambda^2 - y_t^4 \propto a \cdot m_H^4 - b \cdot m_{\text{top}}^4.$$ ⇒ If $\lambda_{\text{ren.}}$ negative: vacuum not stable!

What mass values would lead to meta- or instability?

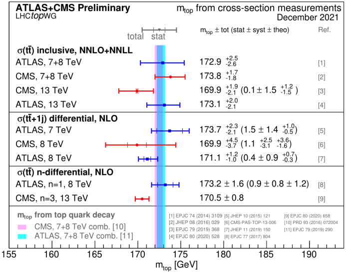


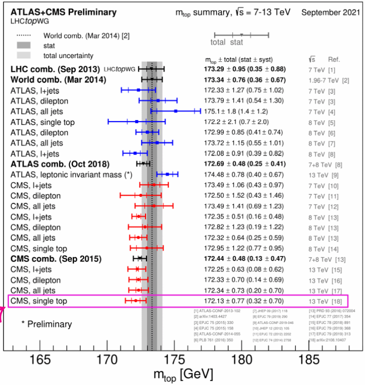


$\rightarrow$ previous mass values: are in meta-stable region, but close to the stable region

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

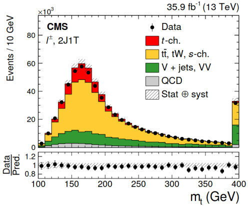


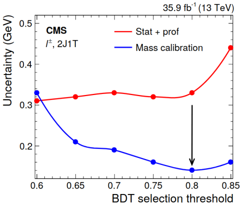


Today: discuss the single-top result!

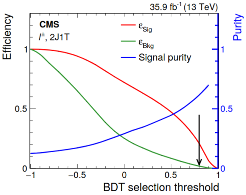
Measurement of m_{top} in t-channel single-top events ▸ JHEP 12 (2021) 161

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

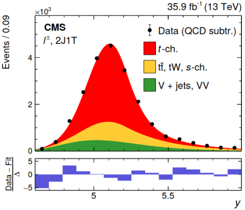




optimise cut based on stat. uncertainty



obtain strongly signal-enriched sample



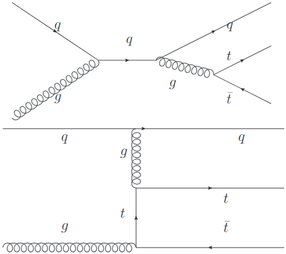
Results from profile-likelihood fit:

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

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

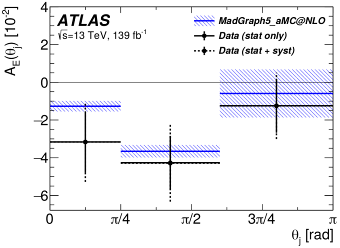
Measurement of the energy asymmetry in boosted $t\bar{t}$+jet events ▸ arXiv:2110.05453

- 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



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

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



Results:

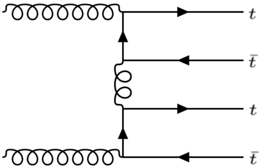
In second bin: $A_E = -0.043 \pm 0.020$

↪ 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!



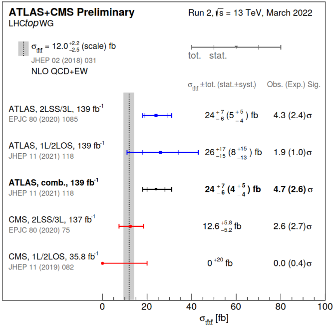
Why is this process interesting?

- 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

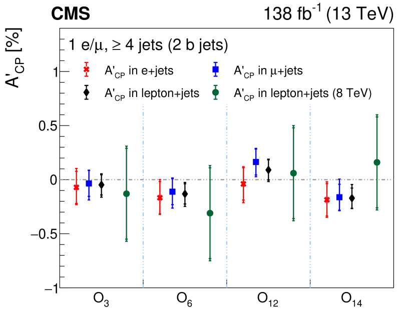


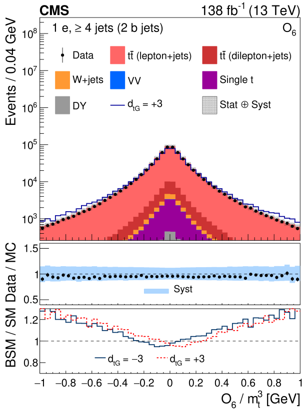
Searches for new physics processes

Search for CP violation in lepton+jets $t\bar{t}$ events ▸ arXiv:2205.02314

- 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:

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

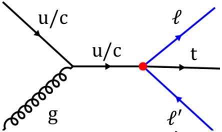


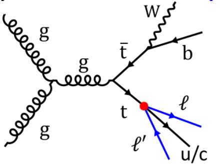


➔ No sign for CPV effects in $t\bar{t}$ events so far

Search for charged-lepton flavour violation

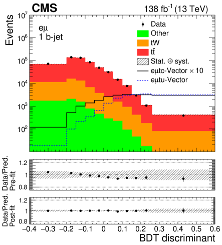
- lepton flavour conservation in SM: “accidental” global symmetry
- have observed that neutrino flavours are not conserved
- many BSM theories predict CLFV: MSSM, lepto-quark, etc

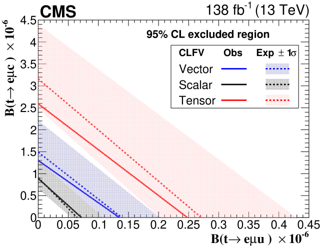




CMS: use $t\bar{t}$ and single top events

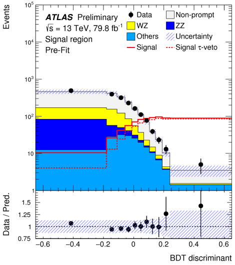
- separate signal and bkg with BDT, fit BDT output, set limits
- no sign for CLFV: achieved strongest limits to date





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 σ deviation from SM) ▸ Paper

$\hookrightarrow$ fluctuation or new physics effect?

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

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

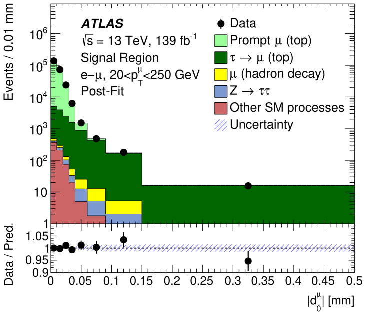
$W \to \mu\nu_\mu$: larger lepton p_T, low impact parameter d_0 (close to interaction vertex)

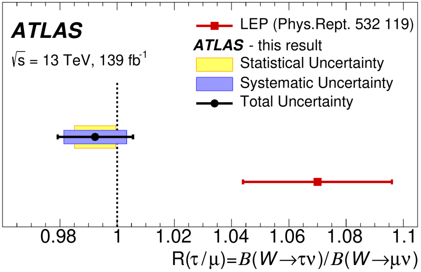
$W \to \tau\nu_\tau \to \mu\nu_\mu\nu_\tau\nu_\tau$: lower lepton p_T, larger d_0 (decays 2mm from interaction vertex)

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



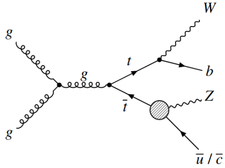


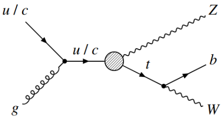
Result from ATLAS: compatible with the SM, and most precise result up to date

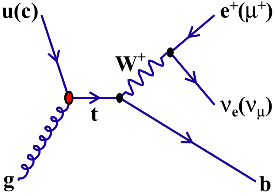
↪ Here a nice ▸ Video by two of the physicists who performed the measurement!

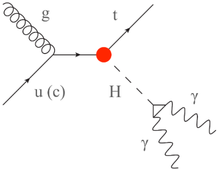
Searches for flavour-changing neutral currents (FCNC)

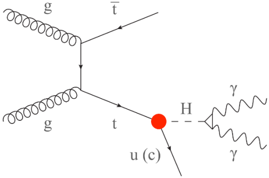
- FCNC in the Standard Model: forbidden at tree-level
  $\hookrightarrow$ strongly suppressed in loops by GIM mechanism: $BR \approx 10^{-15} - 10^{-12}$
- but: many new physics models allow for FCNCs: MSSM, 2HDM, composite Higgs...
  $\hookrightarrow$ much larger branching ratios possible: in reach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



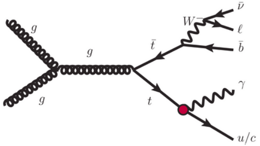


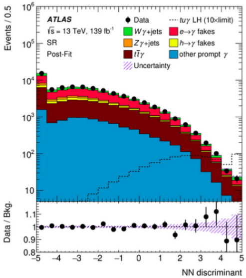


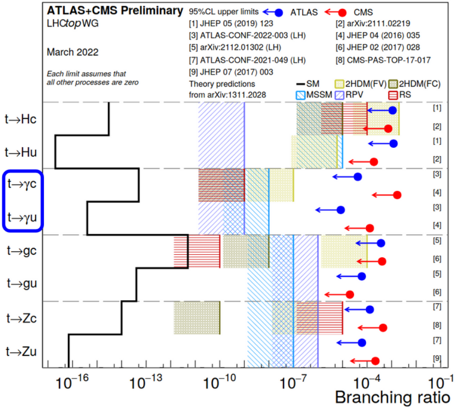




New results for flavour-changing neutral currents (FCNC) ▸ arXiv:2205.02537

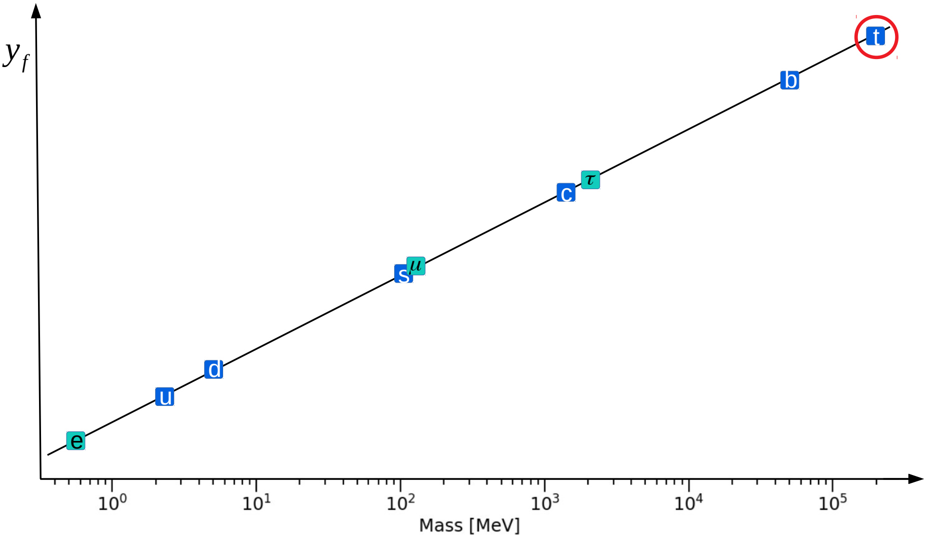






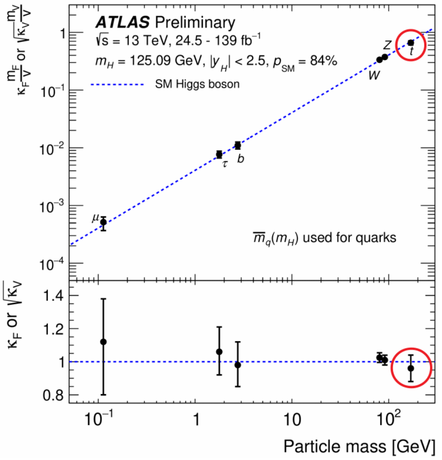
- reaching now branching-ratios that are possible in BSM scenarios
- analyses strongly benefit from larger dataset, also strongly rely on BDTs/NNs
- for *tgq* FCNC: ATLAS recently improved limits by factor 2 compared to 8 TeV: ▸ arXiv:2112.01302

How much do we know now?



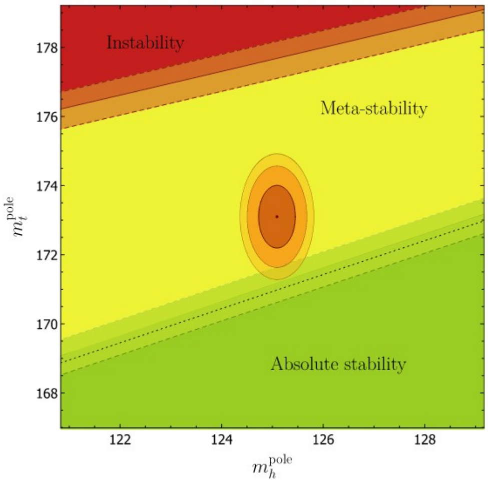
How much do we know about the Yukawa coupling?

- ➔ direct measurement of y_t possible in $t\bar{t}H$ production
- ➔ combine results from $H \to b\bar{b}, \gamma\gamma$ and multilepton channels: observation!

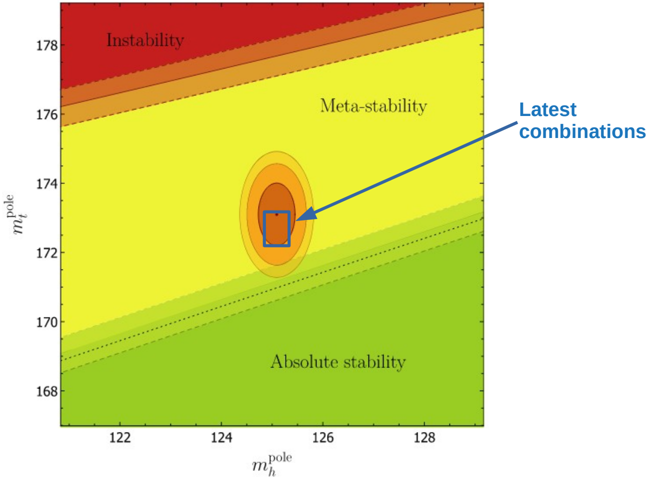


$\rightarrow$ good agreement with expectation!

How much do we know now?



How much do we know now?



➔ Does this mean the universe is metastable? No, but no need to worry even if it was!

Summary

The top quark has come a long way since 1977:

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

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Today: we know that top quark is special!

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

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Look to the future:

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