A review of top quark physics

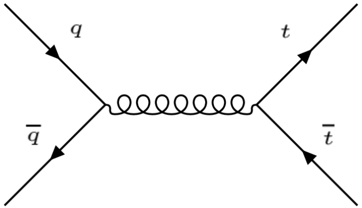
Tópicos de Física de Partículas, Astrofísica e Cosmologia

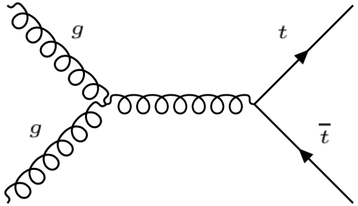
Pedro Lagarelhos - 94002

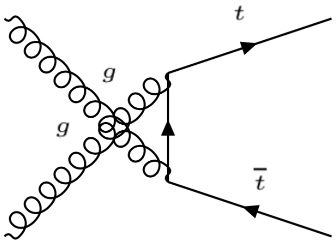
Why the top quark?

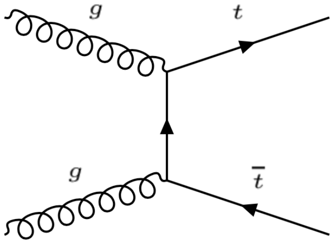
- The top quark is the heaviest known elementary particle
- It is the only quark heavier than a W boson and, therefore, the only one to decay semi-weakly
- It has a very short lifetime, shorter than the hadronisation and spin decorrelation time scales
- It has the strongest coupling to the Higgs boson and the closest mass to the electroweak symmetry breaking scale

Top quark production: $t\bar{t}$









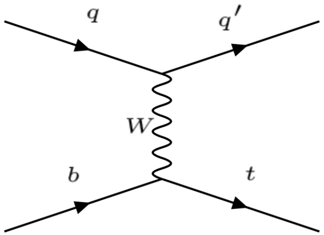
$$\sigma_{\text{inc}} = 830 \pm 0.4\ (\text{stat.}) \pm 36\ (\text{syst.}) \pm 14\ (\text{lumi.})\ \text{pb}$$

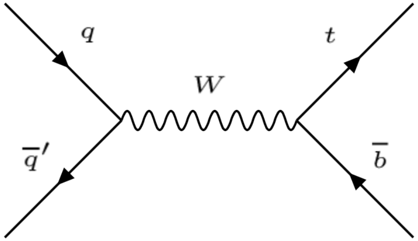
CERN-EP-2020-096

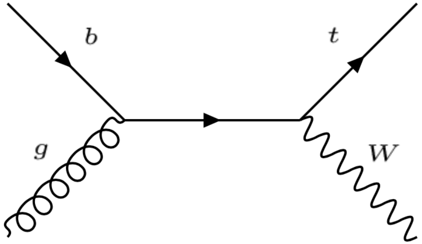
$$\sigma_{t\bar{t}} = 803 \pm 2\,(\text{stat}) \pm 25\,(\text{syst}) \pm 20\,(\text{lumi})\,\text{pb}$$

CERN-EP-2018-317

Top quark production:
Single top







$$\sigma_{t\text{-ch},\mathrm{t}+\bar{\mathrm{t}}} = 207 \pm 31\,\mathrm{pb},$$

CERN-EP-2018-321

$$\sigma_{tW} = 26 \pm 7\,\mathrm{pb}$$

CERN-EP-2019-221

$$\sigma_{s\text{-chan.}} = 4.9 \pm 0.8\,(\text{stat.}) \pm 1.2\,(\text{syst.}) \pm 0.2\,(\text{lumi.})\,\mathrm{pb} = 4.9 \pm 1.4\,\mathrm{pb}.$$

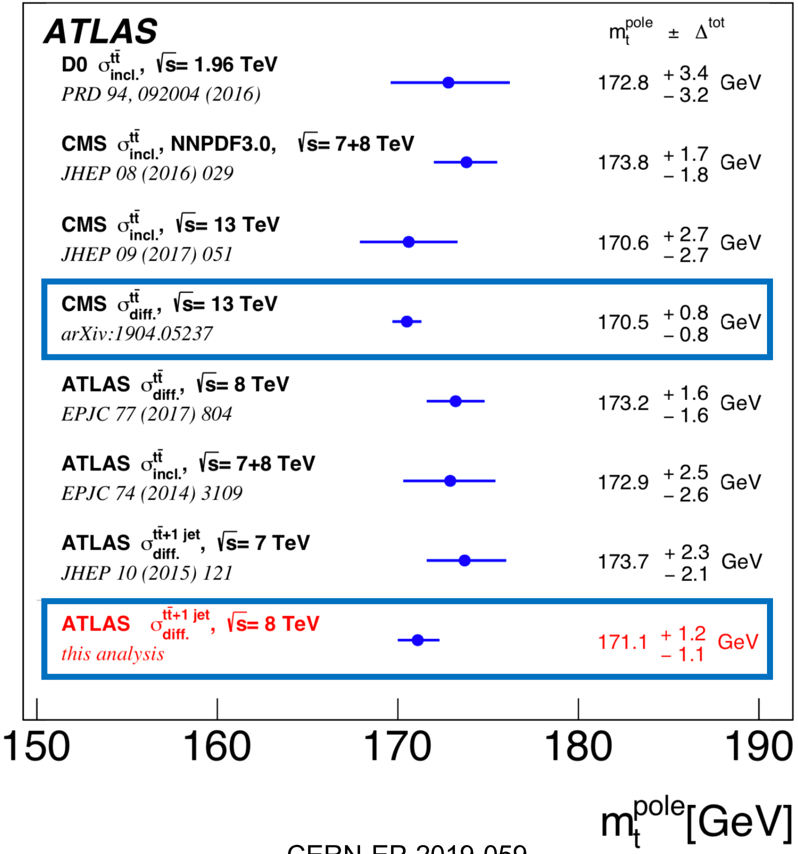
CERN-EP-2019-005

Top quark properties: Mass

- The mass of the top quark is not a uniquely defined quantity:
  - Pole mass;
  - MS mass.

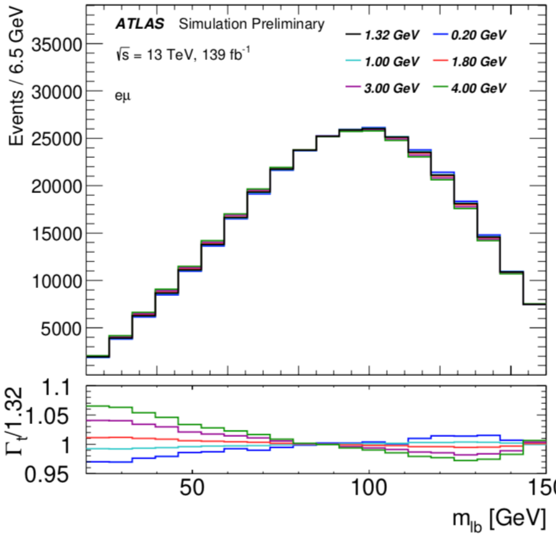
$$m_t(m_t) = 162.9 \pm 0.5\ (\text{stat}) \pm 1.0\ (\text{syst})\ ^{+2.1}_{-1.2}\ (\text{theo})\ \text{GeV}.$$

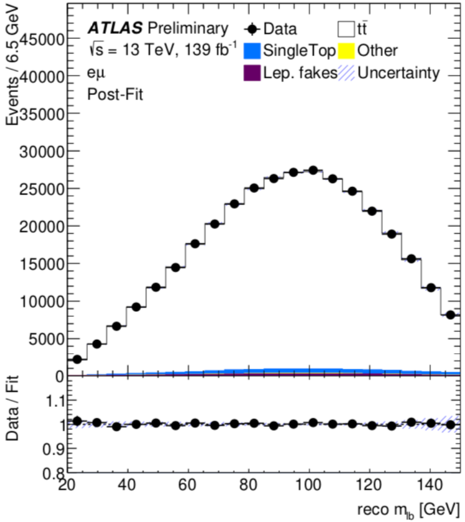
CERN-EP-2019-059

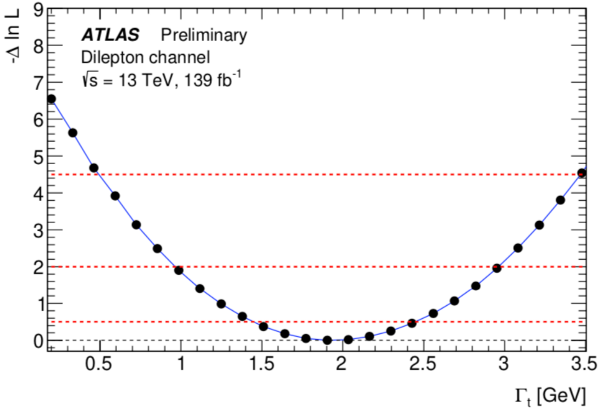


CERN-EP-2019-059

Top quark properties: Width







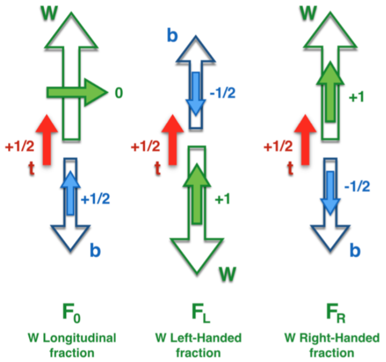
$$\Gamma_t = 1.9 \pm 0.5 \text{ GeV},$$

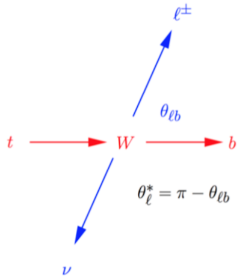
ATLAS-CONF-2019-038

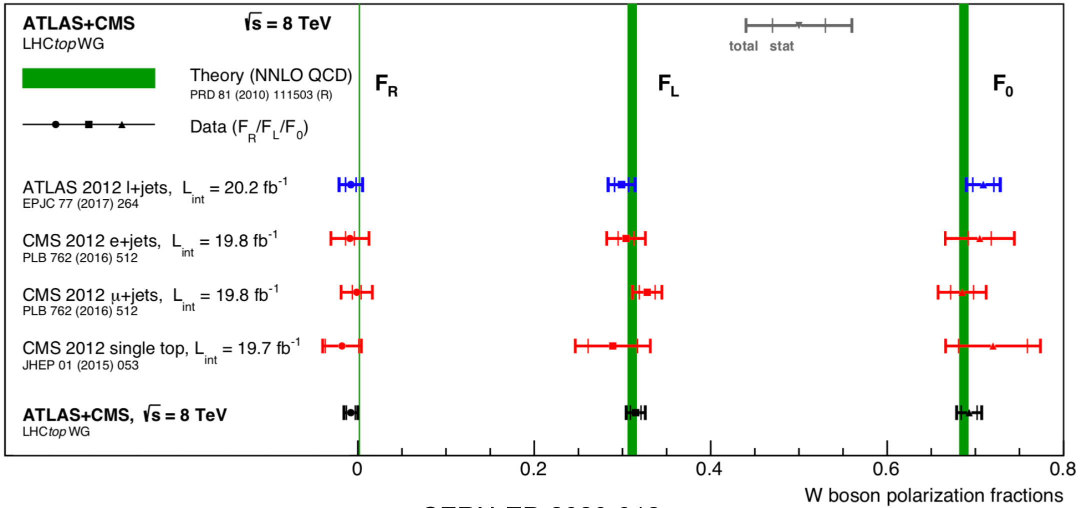
$$\Gamma_t = 1.36 \pm 0.02\,(\text{stat})^{+0.14}_{-0.11}\,(\text{syst})\,\text{GeV}.$$

CMS-TOP-12-035

Top quark properties: *W* boson polarisation



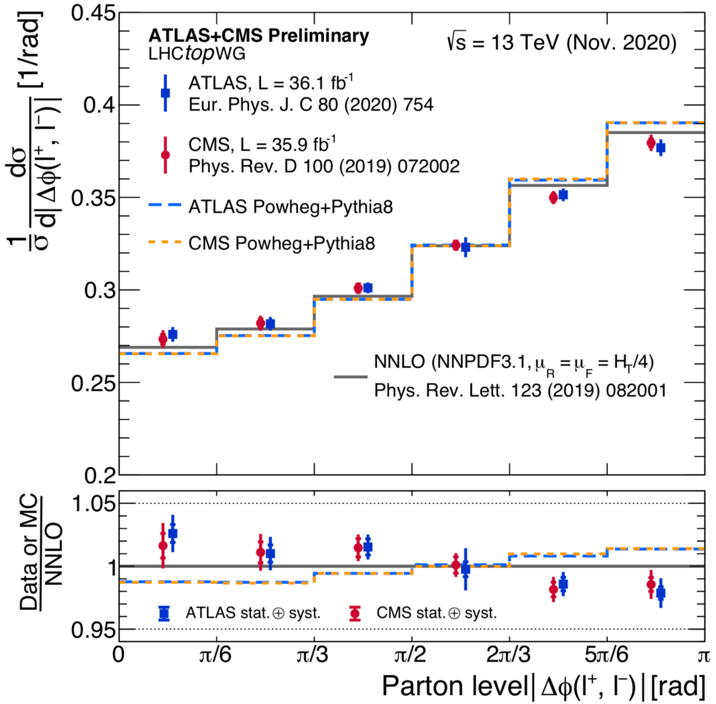




CERN-EP-2020-012

$$\frac{1}{N}\frac{dN}{d\cos\theta^*_\ell} = \frac{3}{2}\left[F_0\left(\frac{\sin\theta^*_\ell}{\sqrt{2}}\right)^2 + F_L\left(\frac{1-\cos\theta^*_\ell}{2}\right)^2 + F_R\left(\frac{1+\cos\theta^*_\ell}{2}\right)^2\right]$$

Top quark properties:
Ttbar spin correlations



ATL-PHYS-PUB-2020-016

Four top production

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Eur. Phys. J. C 80 (2020) 1085
DOI: 10.1140/epjc/s10052-020-08509-3

CERN-EP-2020-111
21st December 2020

Evidence for $t\bar{t}t\bar{t}$ production in the multilepton final state in proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

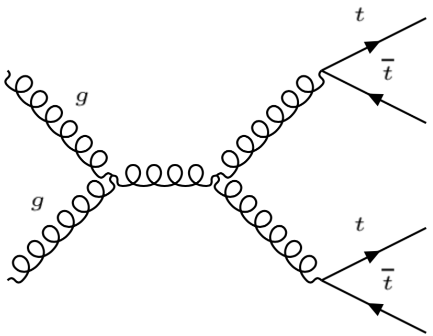
CERN-EP-2019-163
2020/02/04

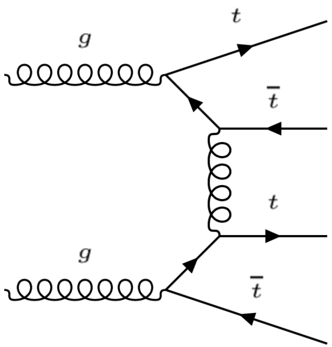
CMS-TOP-18-003

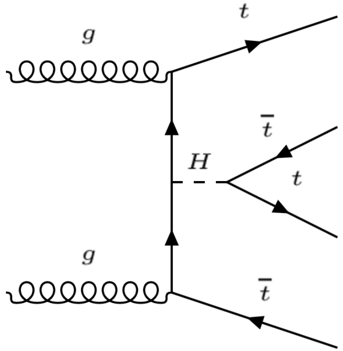
Search for production of four top quarks in final states with same-sign or multiple leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Four top production:
Signal







Four top production: Backgrounds

- $t\bar{t}W$, $t\bar{t}H$, $t\bar{t}Z$

- Diboson, triboson, VH+jets, rare processes ($t\bar{t}WW$, tWZ, tZq, $t\bar{t}t$)
- $t\bar{t}VV$, *Xgamma*, rare processes (tZq, tWZ, $t\bar{t}t$, $t\bar{t}tW$, di- and triboson)

- Charge misidentified and non-prompt leptons

Four top production:
Object reconstruction - ATLAS

- Trigger: Single lepton + pT + isolation; dilepton + pT.
- Event: At least one vertex reconstructed from at least two ID tracks with pT > 0,4 GeV.
- Electron candidates: Energy deposits in the EM calorimeter + ID tracks + pseudorapidity $|\eta| < 2{,}47$ + pT > 28 GeV + isolation.
- Muon candidates: ID tracks + MS + $|\eta| < 2{,}5$ + pT > 28 GeV + isolation.

Four top production:
Object reconstruction - ATLAS

- Jets: Energy deposits in the calorimeters (anti-kt algorithm, R = 0,4) + pT > 25 GeV + |η | < 2,5.
- Pile-up: Jets with pT < 120 GeV and |η | < 2,4 are considered only when they satisfy a requirement based on the output of a multivariate classifier.
- *b*-tagging: Jets containing *b* hadrons are identified by the MV2c10 multivariate algorithm with 77% efficiency.
- Missing energy: Negative vector sum of the pT of the reconstructed and calibrated objects in the event.

Four top production:
Object reconstruction - CMS

- Trigger: Dilepton + HT (2016); dilepton (2017-2018).
- Event: The primary *pp* interaction vertex is the reconstructed vertex with the largest value of summed physics-object squared transverse momentum.
- Electron candidates: Multivariate discriminant using shower shape and track quality variables.
- Muon candidates: Multivariate discriminant based on the quality of the geometrical matching between measurements in the tracker and the muon system .

Four top production:
Object reconstruction - CMS

- Jets: Clustered from neutral and charged PF candidates (anti-kt, R = 0,4); momentum is the vectorial sum of all PF candidate momenta in the jet.
- Pile-up: Offset correction is applied to jet energies, derived from simulation and improved with in situ measurements.
- *b*-tagging: Deep neural network algorithm (DeepCSV) with efficiency of 55–70%.
- Missing pT: Magnitude of the vector defined as the projection on the plane perpendicular to the beams of the negative vector sum of the momenta of all reconstructed PF candidates.

Four top production:
Event selection - ATLAS

- Same-sign lepton pair or at least three leptons, with at least one matching the lepton that fired the trigger.
- 2 SS electrons: mee > 15 GeV and |mee − 91 GeV| > 10 GeV.
- 3L: Opposite-sign same-flavour lepton pairs with |mll − 91 GeV| > 10 GeV.
- At least 6 jets, at least 2 *b*-jets.
- HT > 500 GeV.

Four top production:
Event selection - CMS

- Leading lepton with pT > 25 GeV, trailing SS lepton with pT > 20 GeV.
- 2 SS electrons: mee > 12 GeV and |mee − 91 GeV| > 10 GeV.
- 3L: Opposite-sign same-flavour lepton pairs with mll > 12 GeV and |mll − 91 GeV| > 15 GeV.
- At least 2 jets, at least 2 *b*-jets.
- HT > 300 GeV, pTmiss > 50 GeV.

Four top production:
Signal discrimination

- Multivariate discriminant: Boosted Decision Tree
  - ATLAS – *b*-tagging score, minimum distance between leptons
  - CMS - Njets, Nb, Nl

- Cut-based analysis
  - CMS - Njets, Nb, Nl

Four top production: Uncertainties

Uncertainty source	$\Delta\mu$	
Signal modelling		
$t\bar{t}t\bar{t}$ cross section	+0.56	−0.31
$t\bar{t}t\bar{t}$ modelling	+0.15	−0.09
Background modelling		
$t\bar{t}W$+jets modelling	+0.26	−0.27
$t\bar{t}t$ modelling	+0.10	−0.07
Non-prompt leptons modelling	+0.05	−0.04
$t\bar{t}H$+jets modelling	+0.04	−0.01
$t\bar{t}Z$+jets modelling	+0.02	−0.04
Other background modelling	+0.03	−0.02
Charge misassignment	+0.01	−0.02
Instrumental		
Jet uncertainties	+0.12	−0.08
Jet flavour tagging (light-flavour jets)	+0.11	−0.06
Simulation sample size	+0.06	−0.06
Luminosity	+0.05	−0.03
Jet flavour tagging (b-jets)	+0.04	−0.02
Jet flavour tagging (c-jets)	+0.03	−0.01
Other experimental uncertainties	+0.03	−0.01
Total systematic uncertainty	+0.70	−0.44
Statistical	+0.42	−0.39
Non-prompt leptons normalisation (HF, Mat. Conv., Low m_{γ^*})	+0.05	−0.04
$t\bar{t}W$ normalisation	+0.04	−0.04
Total uncertainty	+0.83	−0.60

Source	Uncertainty (%)	Impact on $\sigma(\mathrm{t\bar{t}t\bar{t}})$ (%)
Integrated luminosity	2.3–2.5	2
Pileup	0–5	1
Trigger efficiency	2–7	2
Lepton selection	2–10	2
Jet energy scale	1–15	9
Jet energy resolution	1–10	6
b tagging	1–15	6
Size of simulated sample	1–25	<1
Scale and PDF variations †	10–15	2
ISR/FSR (signal) †	5–15	2
$\mathrm{t\bar{t}H}$ (normalization) †	25	5
Rare, Xγ, $\mathrm{t\bar{t}VV}$ (norm.) †	11–20	<1
$\mathrm{t\bar{t}Z}$, $\mathrm{t\bar{t}W}$ (norm.) †	40	3–4
Charge misidentification †	20	<1
Nonprompt leptons †	30–60	3
$N_{\mathrm{jets}}^{\mathrm{ISR/FSR}}$	1–30	2
$\sigma(\mathrm{t\bar{t}b\bar{b}})/\sigma(\mathrm{t\bar{t}jj})$ †	35	11

Four top production: Results and interpretations

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

$$12.6^{+5.8}_{-5.2}\ \text{fb}$$

- The Yukawa coupling between the top quark and the Higgs boson, thanks to the existence of tttt Feynman diagrams with virtual Higgs bosons;
- The Higgs boson oblique parameter, defined as the Wilson coefficient of the dimension-six BSM operator modifying the Higgs boson propagator;
- The couplings of BSM scalar (φ) or vector (Z′) particles with mass smaller than twice the top quark mass (m < 2mt), when replacing a virtual Higgs boson in a Feynman diagram;
- The production of on-shell new particles with m > 2mt, such as a heavy scalar (H) or pseudoscalar (A), in association with subsequently decay into top quark pairs, in terms of 2HDM parameters, or in the framework of simplified models of dark matter.

Thanks!