Top quark physics results from CMS

Markus Seidel

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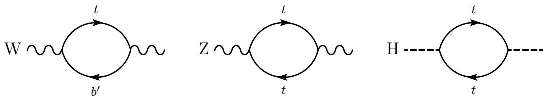
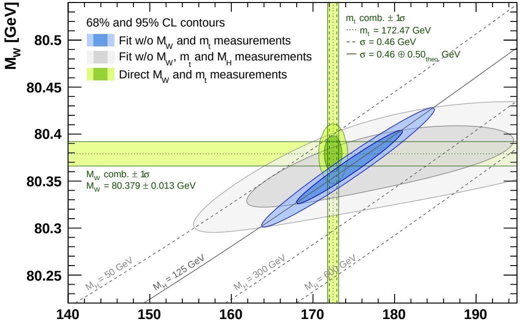
RIGA TECHNICAL UNIVERSITY

The top quark in the Standard Model

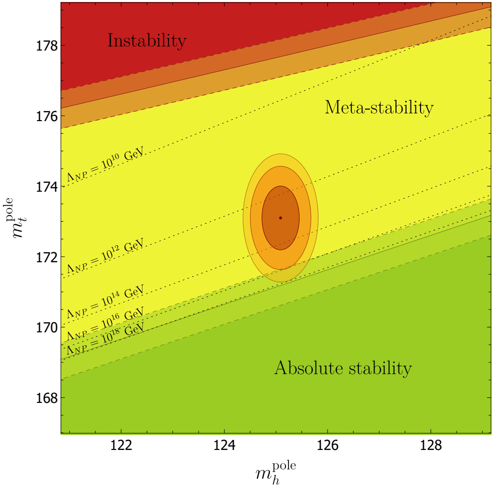
- Heaviest particle discovered so far
- Loop corrections to W, Z and H masses





EPJC 78, 675 (2018)

- Corrections to $H^4 \rightarrow$ vacuum stability



PLB 716 (2012) 214–219

- Extensive top physics program by CMS, all CMS TOP publications available here

Experimental conditions

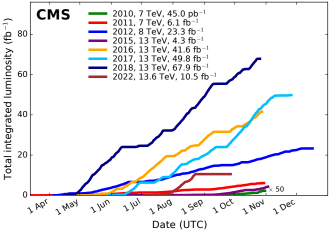
Excellent LHC performance

$\rightarrow$ huge number of top quark pairs produced at CMS

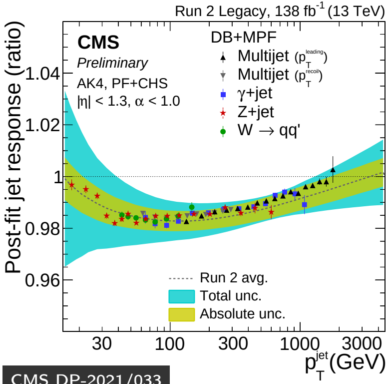
- $N_{t\bar{t}} = \underbrace{\mathcal{L}_{int}}_{\text{integrated luminosity}} \times \underbrace{\sigma_{t\bar{t}}}_{\text{production cross section}}$
- Run 1 (2010–2012): $N_{t\bar{t}} = 7\text{M}$ at 7 and 8 TeV
- Run 2 (2015–2018): $N_{t\bar{t}} = 136\text{M}$ at 13 TeV
- Run 3 (started 2022): $N_{t\bar{t}} = 10\text{M}$ at 13.6 TeV

Detectors well understood and calibrated

- Precise lepton trigger efficiencies
- Energy measurement of jets, leptons, photons at the level of 1%
- Identification of jets containing B hadrons with new DNN algorithms (DeepJet)

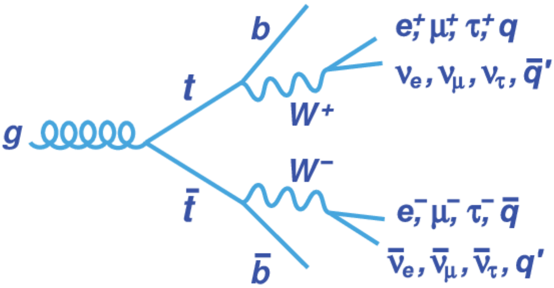


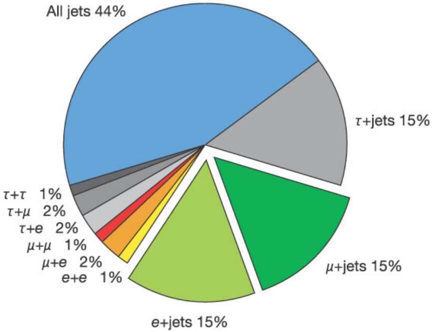
CMS LumiPublicResults



CMS DP-2021/033

Top-quark pair signatures





Dilepton channel (ee, $\mu\mu$, eμ): 2 leptons, 2 neutrinos, 2 b jets

- Low background (Z production), difficult top quark reconstruction due to neutrinos

Lepton+jets channel (e/μ+jets): 1 lepton, 1 neutrino, 2 b jets, 2 light-quark jets

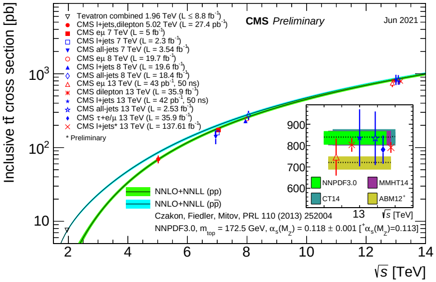
- Large number of events, moderate background (W and single top production)
- Full reconstruction possible $\rightarrow$ golden channel for top mass

All-jets channel: 2 b jets, 4 light-quark jets

- Large number of events, huge background (QCD multijet)

Inclusive $t\bar{t}$ cross sections

- Begin of Run 1: rediscovery
- End of Run 1: precision!



Run 1: Inclusive $t\bar{t}$ cross section at 7 and 8 TeV (dilepton) JHEP 08 (2016) 029

$$\sigma_{t\bar{t}}^{7\,\text{TeV}} = 173.6 \pm 2.1\,(\text{stat})^{+4.5}_{-4.0}\,(\text{syst}) \pm 3.8\,(\text{lumi})\ \text{pb} \quad (^{+3.6}_{-3.5}\%)$$

$$\sigma_{t\bar{t}}^{8\,\text{TeV}} = 244.9 \pm 1.4\,(\text{stat})^{+6.3}_{-5.5}\,(\text{syst}) \pm 6.4\,(\text{lumi})\ \text{pb} \quad (^{+3.7}_{-3.5}\%)$$

Run 2: Inclusive $t\bar{t}$ cross section at 13 TeV (dilepton) EPJC 79 (2019) 368

$$\sigma_{t\bar{t}}^{13\,\text{TeV}} = 803 \pm 2\,(\text{stat}) \pm 25\,(\text{syst}) \pm 20\,(\text{lumi})\ \text{pb} \quad (\pm 4.0\%)$$

Run 2 HIN pp reference: $t\bar{t}$ cross section at 5.02 TeV (dilepton & lepton+jets) JHEP 03 (2018) 115

$$\sigma_{t\bar{t}}^{5\,\text{TeV}} = 69.5 \pm 6.1\,(\text{stat}) \pm 5.6\,(\text{syst}) \pm 1.6\,(\text{lumi})\ \text{pb} \quad (\pm 12.1\%)$$

Run 3: First $t\bar{t}$ cross section at 13.6 TeV (dilepton & lepton+jets) PAS-TOP-22-012

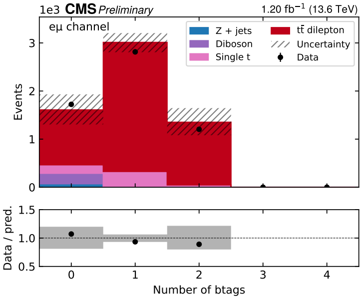
Run 3: First measurement of $t\bar{t}$ cross section at 13.6 TeV

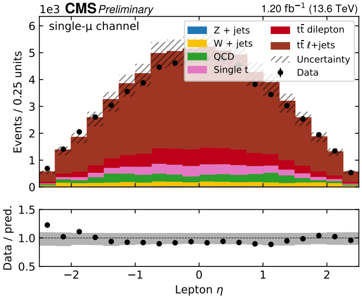
PAS-TOP-22-012

- Combination of dilepton and lepton+jets channels with synchronized selection allows for constraint of lepton efficiencies

- Lepton (e or μ) $p_T > 35$ GeV, jet $p_T > 30$ GeV
- Dilepton: 2 leptons, at least 1 jet
  - ee, $\mu\mu$: at least 1 b jet (DeepJet)
  - eμ: no b tag requirement
- Lepton+jets: 1 lepton, at least 3 jets, at least 1 b jet

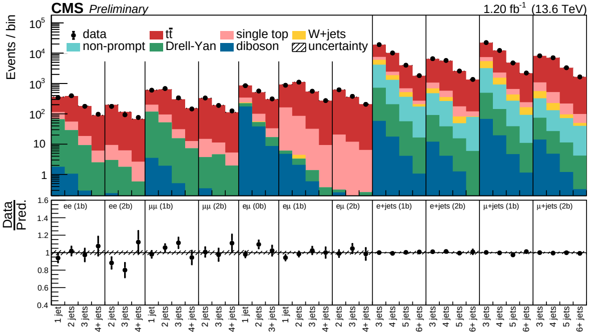
- b-tag efficiency constrained by split into N_b categories
- Jet energy scale constrained by W mass in lepton+jets
- Backgrounds from MC, data-driven estimate for QCD

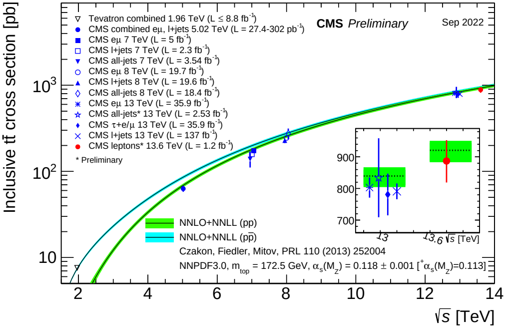




First measurement of $t\bar{t}$ cross section at 13.6 TeV

PAS-TOP-22-012





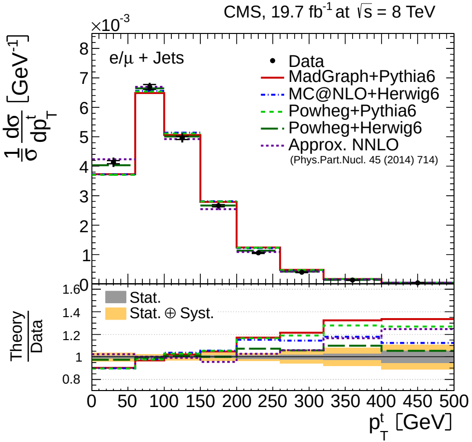
- Combined likelihood fit with nuisance parameters to constrain systematic uncertainties
- Used luminosity: $1.20\ \text{fb}^{-1} \pm 6\%$, determined from emittance scans and Z boson counting

$$\sigma_{t\bar{t}}^{13.6\ \text{TeV}} = 887^{+43}_{-41}\ (\text{stat+syst}) \pm 53\ (\text{lumi})\ \text{pb}\ \ (\pm 7.7\%)$$

Differential cross section measurements

Run 1 measurements

- Differential $t\bar{t}$ cross section at 8 TeV (ℓ+jets & dilepton) EPJC 75 (2015) 542 RIVET
- Differential $t\bar{t}$ event kinematics at 8 TeV (ℓ+jets) PRD 94 (2016) 052006 RIVET
- Differential $t\bar{t}$ cross section for high-p_T top quarks at 8 TeV PRD 94 (2016) 072002 RIVET



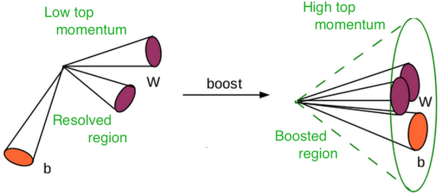
Run2 measurements

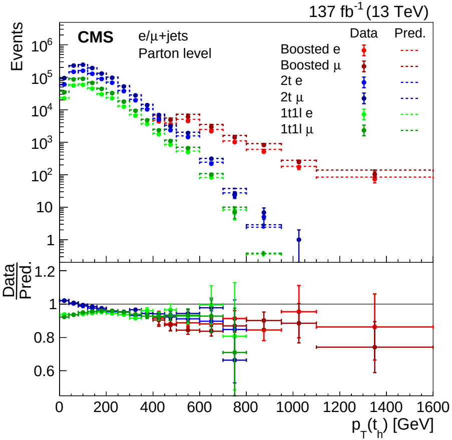
- Differential $t\bar{t}$ cross section at 13 TeV (lepton+jets) PRD 95 (2017) 092001 RIVET
- Differential $t\bar{t}$ cross section at 13 TeV (dilepton) JHEP 02 (2019) 149 RIVET in preparation
- Differential $t\bar{t}$ in the full kinematic range (ℓ+jets) PRD 104 (2021) 092013 RIVET in preparation
- Multi-differential $t\bar{t}$ cross section at 13 TeV (dilepton) PAS-TOP-20-006 RIVET in preparation

Differential $t\bar{t}$ in the full kinematic range (ℓ+jets)

PRD 104 (2021) 092013

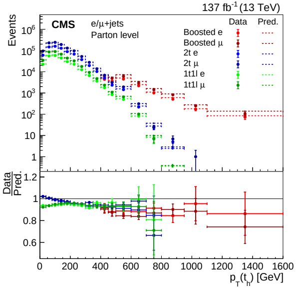
- Select events from full Run 2 (2016–2018)
- Trigger on e/μ: isolated with $p_T > 30$ GeV or non-isolated with $p_T > 50$ GeV
- Resolved reconstruction:
  - PF jets with anti-k_t, R=0.4, $p_T > 30$ GeV
  - Maximize likelihood based on $m(W_h)$, $m(t_h)$, and $m(t_\ell)$ to find best jet-parton assignment
  - Backgrounds from MC prediction
- Boosted reconstruction
  - PUPPI jets with anti-k_t, R=0.8, $p_T > 400$ GeV
  - t_ℓ: neural network to suppress backgrounds
  - t_h: 2 different NNs to identify partly merged (2Q) and fully merged (3Q) cases, based on substructure
  - Background yield from fit to H_{NN} distribution

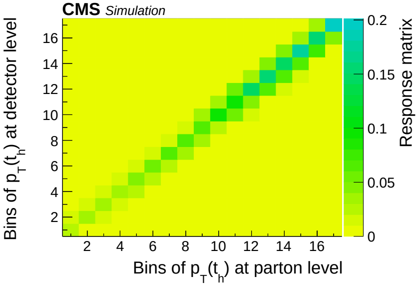


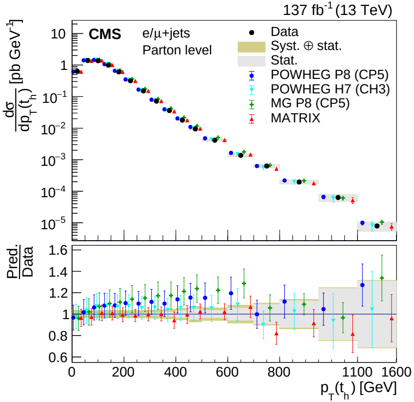


Differential $t\bar{t}$ in the full kinematic range (ℓ+jets)

PRD 104 (2021) 092013





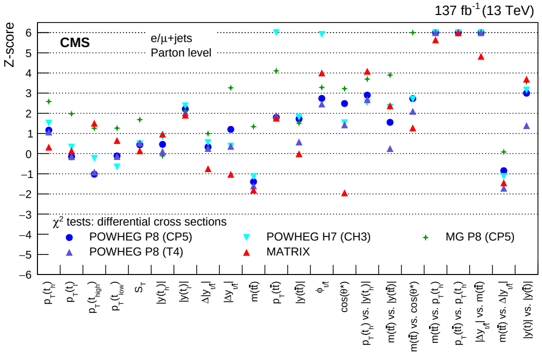


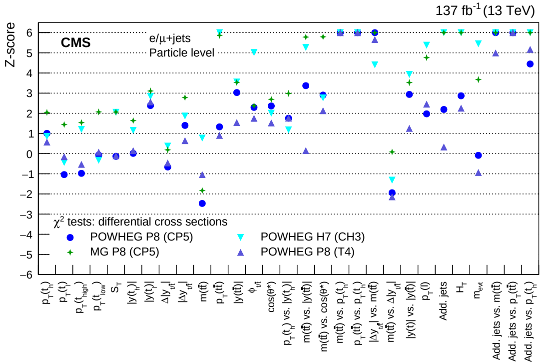
- Unfolding: detector level $\times$ (response matrix)$^{-1}$ $\rightarrow$ particle or parton level
- Measured top quark momentum up to 1600 GeV
  - Known disagreement with NLO predictions (top p_T slope)
  - Good agreement with MATRIX NNLO prediction

Differential $t\bar{t}$ in the full kinematic range (ℓ+jets)

PRD 104 (2021) 092013

- Multitude of observables measured, characterizing $t\bar{t}$ production in detail
- Assign Z scores: low value = good agreement, high value = bad agreement

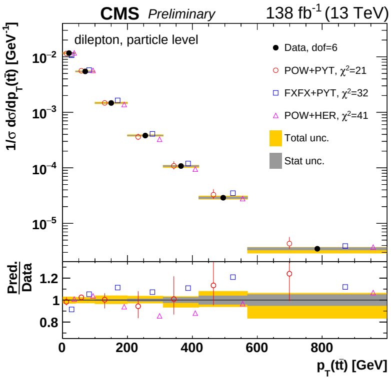


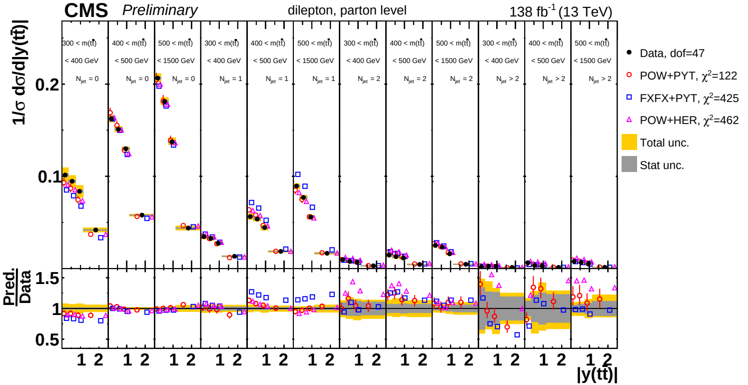


Multi-differential $t\bar{t}$ cross section at 13 TeV (dilepton)

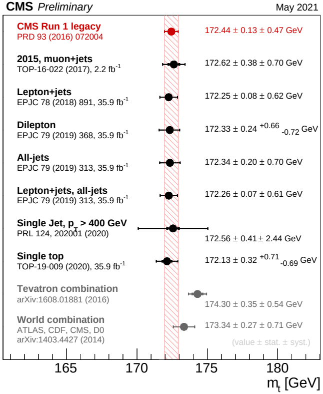
PAS-TOP-20-006

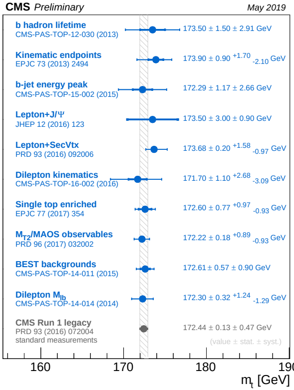
- Events with 2 oppositely charged e/μ with $p_T > 25/20$ GeV (leading/trailing lepton)
- 2 b-tagged jets (anti-k_t, R=0.4, $p_T > 30$ GeV), $m(\ell\ell) > 20$ GeV
- ee/$\mu\mu$: $m(\ell\ell) < 76$ GeV, $m(\ell\ell) > 106$ GeV, MET > 40 GeV to reduce Z+jets
- top quarks: split MET into 2 neutrino components, kinematic reconstruction algorithm
  $t\bar{t}$ system: loose kinematic reconstruction, consider sum of neutrinos (=MET for p_T)

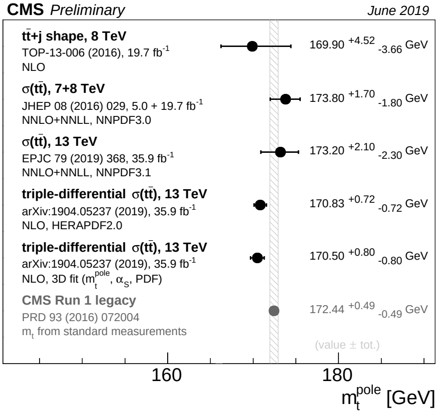




Top mass measurements





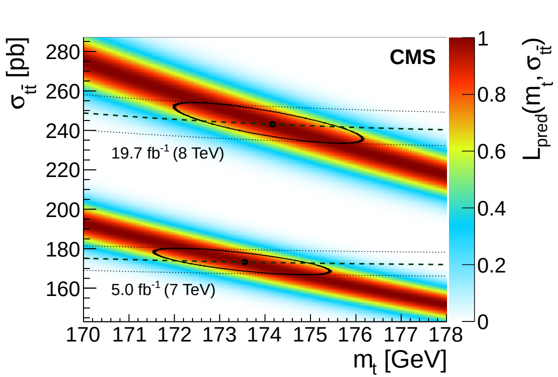


- Run 1 "legacy" measurements and their combination (7 & 8 TeV) PRD 93 (2016) 072004
- Run 1 combination of alternative techniques PAS-TOP-15-012
- Extraction of top pole mass from cross section (7 & 8 TeV) JHEP 08 (2016) 029
- Extraction of top pole mass from $t\bar{t}+$jet events at 13 TeV TOP-21-008
- Top-quark mass using profile likelihood approach at 13 TeV PAS-TOP-20-008
- Jet and top-quark mass in boosted top decays at 13 TeV PAS-TOP-21-012 RIVET in preparation

Top pole mass extractions in the dilepton channel

JHEP 08 (2016) 029 TOP-21-008

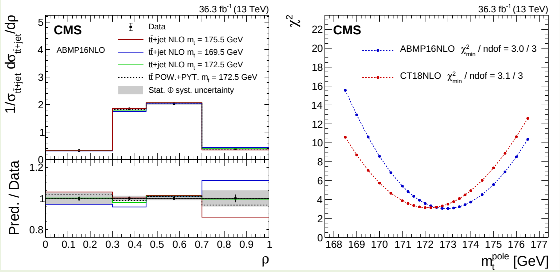
Pole mass from total cross section



- Measured $\sigma_{t\bar{t}}$: low dependence on m_t
- m_t from intersection with the prediction

$$m_t = 173.8^{+1.7}_{-1.8}\,\text{GeV (NNPDF 3.0)}$$

Pole mass from $t\bar{t}$ + jet at 13 TeV



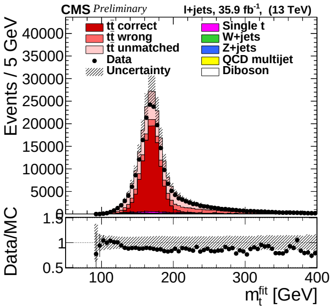
- Measurement of $\rho = 2m_0/m(t\bar{t}j)$
- Improve resolution with neural network
- Fit NLO prediction to unfolded data:

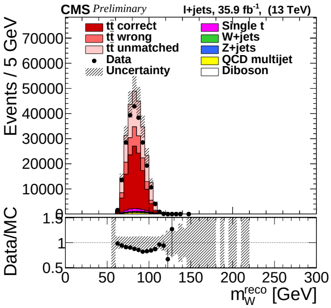
$$m_t = 172.94 \pm 1.37\,\text{GeV (ABM16)}$$
$$m_t = 172.16 \pm 1.44\,\text{GeV (CT18)}$$

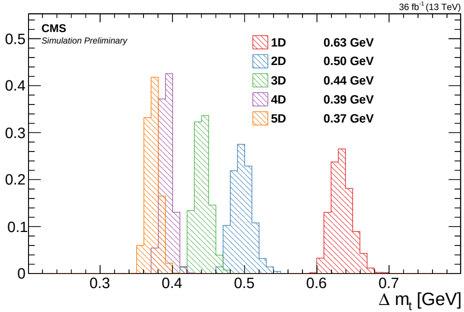
Top-quark mass using profile likelihood approach at 13 TeV

PAS-TOP-20-008

- Select events with 1 high-p_T e/μ and 4 jets (2 DeepJet b tags)
- Kinematic fit ($m_W = 80.4$ GeV, $m_{t,h} = m_{t,\ell}$), keep best jet-parton assignment per event
- Perform profile-likelihood fit to 5 observables, systematic uncertainties treated as nuisance parameters and constrained



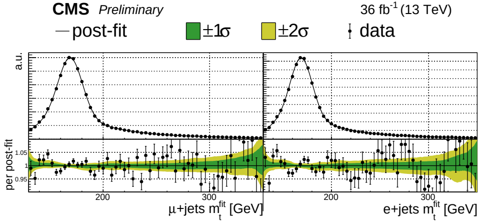


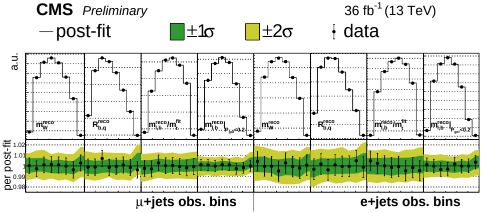


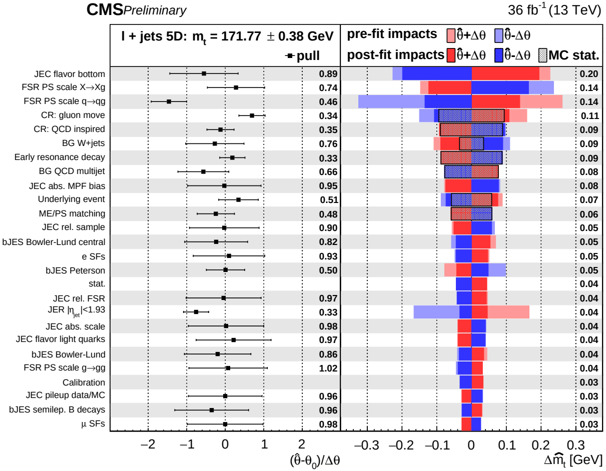
- Observables used in the fit: m_t^{fit}, m_W^{reco}, $m_{\ell b}^{reco}$ ($P_{gof} < 0.2$), $m_{\ell b}^{reco}/m_t^{fit}$, R_{bq}^{reco}
  - 1D: m_t (m_t^{fit}); 2D: JES (m_W^{reco}); 3D: m_t "failing" kinematic fit ($m_{\ell b}^{reco}$ ($P_{gof} < 0.2$)); 4/5D: b JES ($m_{\ell b}^{reco}/m_t^{fit}$, R_{bq}^{reco})
- NB: 2D corresponds to Run 1 legacy measurement PRD 93 (2016) 072004

Top-quark mass using profile likelihood approach at 13 TeV

PAS-TOP-20-008







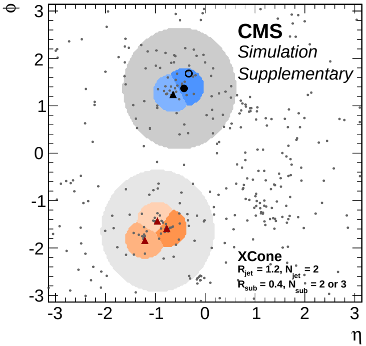
- Constraining components of (b) jet energy scale and FSR modeling
- Result of 5D fit is most precise single measurement to date!

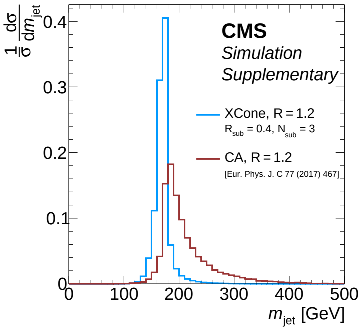
$$m_t = 171.77 \pm 0.38\,\text{GeV}$$

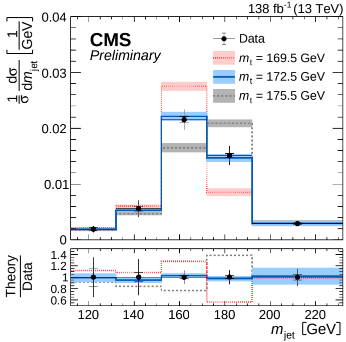
Jet and top-quark mass in boosted top decays at 13 TeV

PRL 124 (2020) 202001 | RIVET | PAS-TOP-21-012 | RIVET in preparation

- Another way out of the pole mass vs MC mass dilemma: measure m_t using boosted top quarks, SCET calculations of top mass peak reliable for $p_T > 750\,\mathrm{GeV}$



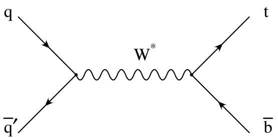




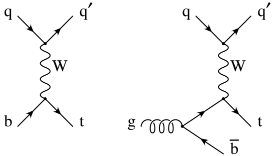
- Reconstructed top quarks using XCone exclusive jet algorithm → improved resolution
- Constrained jet energy scale from hadronic W subjets
- Unfolded jet mass distribution to particle level
- Extracted top mass for $p_T > 400\,\mathrm{GeV}$: $m_t = 172.76 \pm 0.81\,\mathrm{GeV}$

Single top production

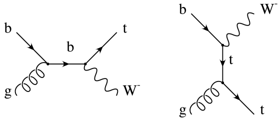
s-channel:

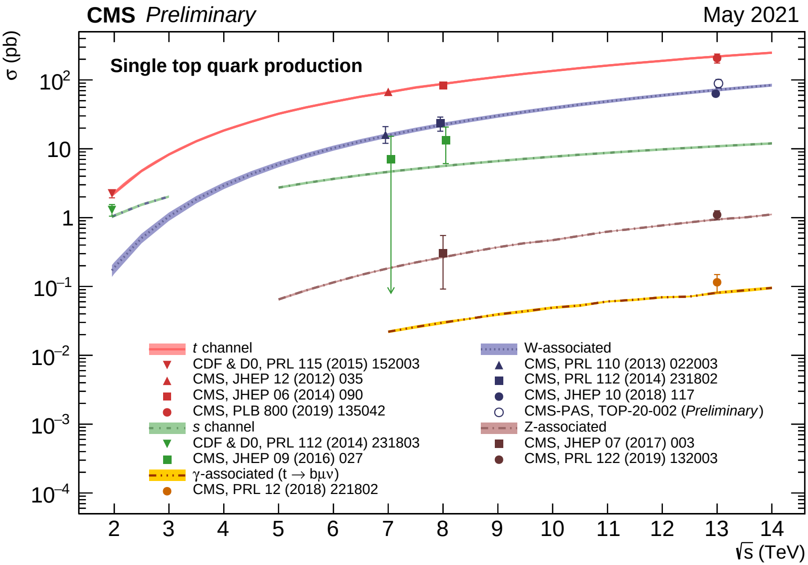


t-channel:



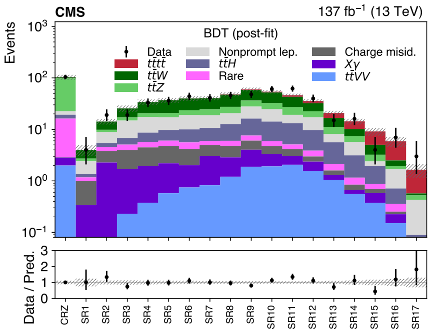
tW-channel:

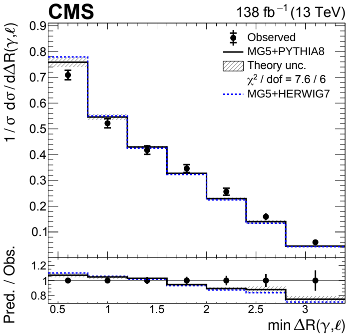


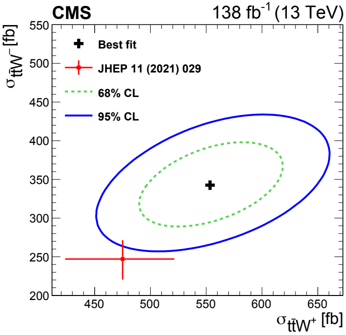


- Differential cross sections in t-channel EPJC 80 (2020) 370 RIVET , tZq JHEP 02 (2022) 107 , and tW TOP-21-010

$t\bar{t}$ & friends with full Run 2 data

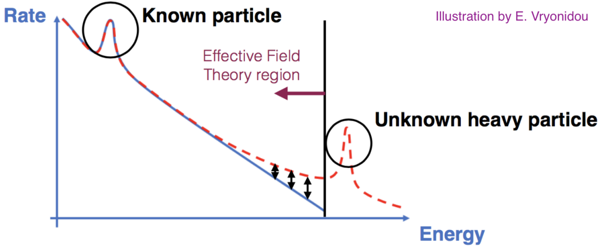




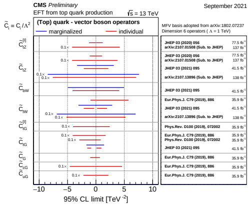


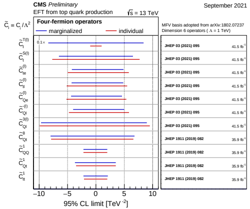
- Search for $t\bar{t}t\bar{t}$ production with same-sign or multiple leptons at 13 TeV **EPJC 80 (2020) 75**
- Inclusive and differential $t\bar{t}\gamma$ cross section at 13 TeV **JHEP 05 (2022) 091**
- Inclusive $t\bar{t}W$ cross section at 13 TeV **TOP-21-011**

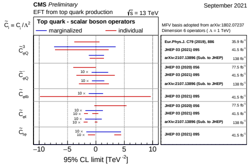
Effective Field Theory constraints



- Theories beyond SM $\rightarrow$ particles at scale Λ beyond LHC reach
- May still influence established processes via loop corrections
- EFT extends the SM with effective interactions between SM fields characterized by dimension-six operators:
  $\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$
- Constraints on all EFT operators potentially sensitive to top quarks
- No significant deviation from the SM found so far







Summary

- Extensive top quark physics program at CMS
- Challenging final states require good understanding of the whole detector
- Ideal testbed for QFT higher-order corrections, MC modeling (not covered)
- Potentially large coupling to new physics
- Presented:
  - Inclusive and differential $t\bar{t}$ cross sections
  - Top mass measurements
  - Single top and $t\bar{t} + x$ production
  - Constraints on new physics using SM EFT
- RTU team joining in jet substructure and top mass measurements

Thank you for your attention!