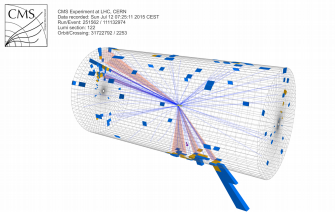
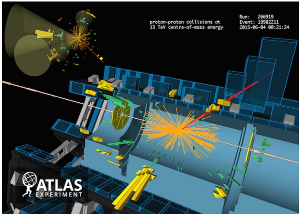
Scrutinising the SM at the LHC: Top quarks and friends

Carmen Diez Pardos (U. Siegen)

6 May 2021

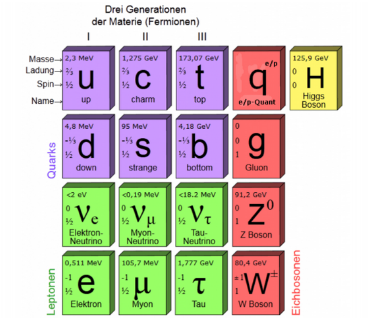


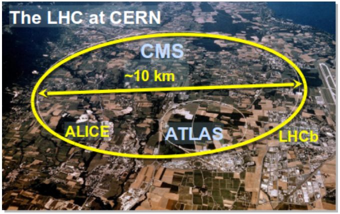


Challenging the SM at the LHC

LHC: Run 1 & 2

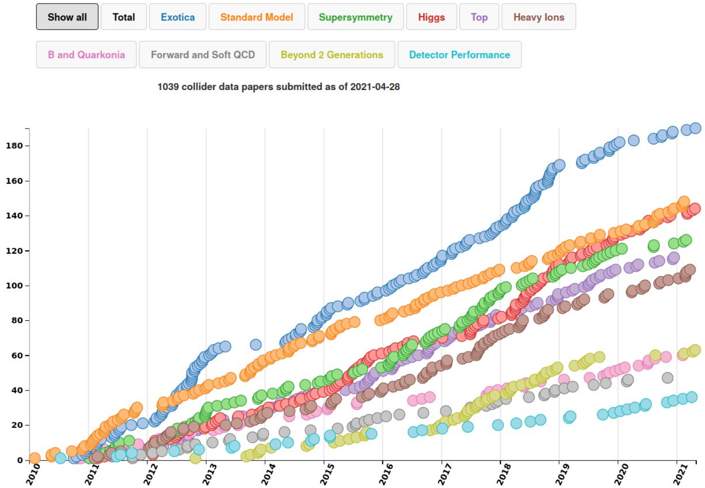
- Discovery of a Higgs boson
- Observation of rare processes (e.g. top quark + bosons)
- Precision measurements challenging state-of-the-art simulations and calculations





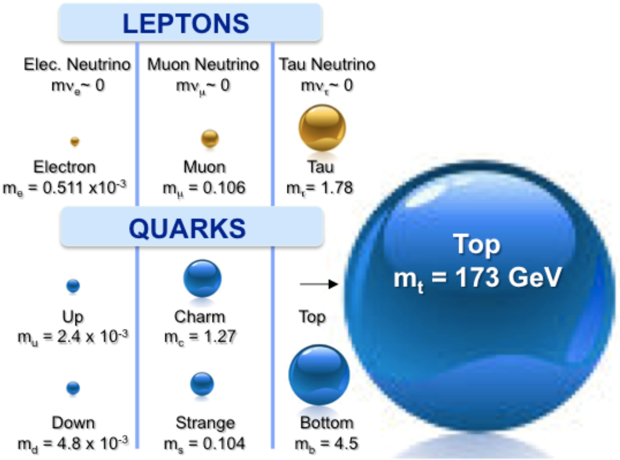
- Extensive searches for New Physics, no signs yet → Precision might be the key to discovery

Really trying hard!



CMS publications vs time

The top quark: a special particle



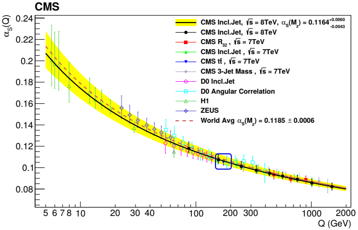
- The most massive known particle $\rightarrow$ large couplings
- It decays before hadronisation: study the properties of the bare quark

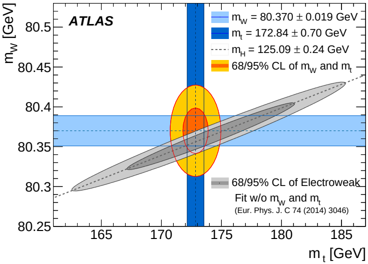
1.- Constraining the Standard Model

- Determination α_s
- Test QCD predictions and help constraining the PDFs (especially gluon distribution)

- Determination of m_t
- Participates in quantum loop radiative corrections to m_W together with m_H: assessment of self-consistency within SM
- Other properties: couplings, asymmetries predicted by the SM

→ Precision measurements could reveal the SM breaking down

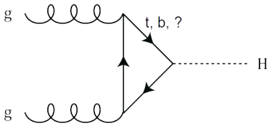


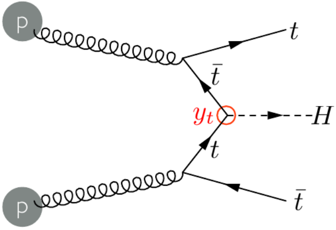


Top quarks are a unique tool for stringent tests of the SM

2. - The top quark and the Higgs boson

- Top quark is the most strongly-coupled SM fermion (y_t ~1)
- Direct measurement of y_t in $t\bar{t}$H production:
  - Allows probing new physics in gg→H and H→ $\gamma\gamma$ effective vertices





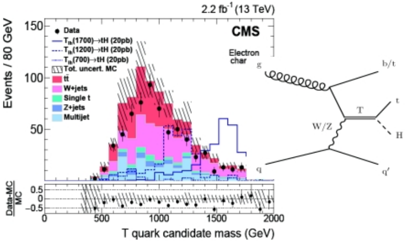
Best direct probe of the top-Higgs Yukawa coupling, vital step towards verifying the SM nature of the Higgs boson

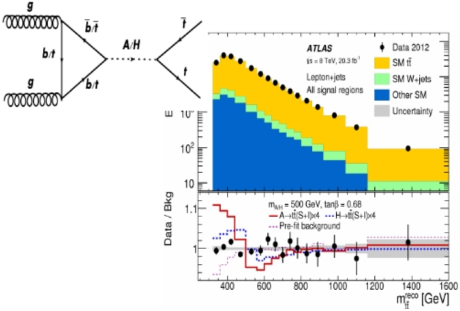
3.- Special role in New Physics?

- Main background for Higgs and many searches for New Physics

- Top quark is a main ingredient of many BSM scenarios
    - Exotic partners, rare decays, heavy resonances decaying to top, new particles produced with top, …

... and a sensitive probe for New Physics



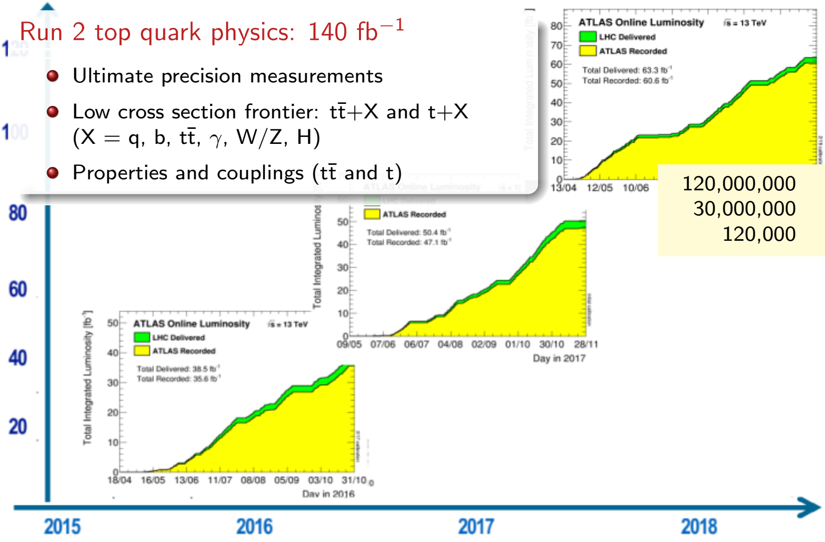


Top quarks at LHC 13 TeV

Run 2 top quark physics: 140 fb^{-1}

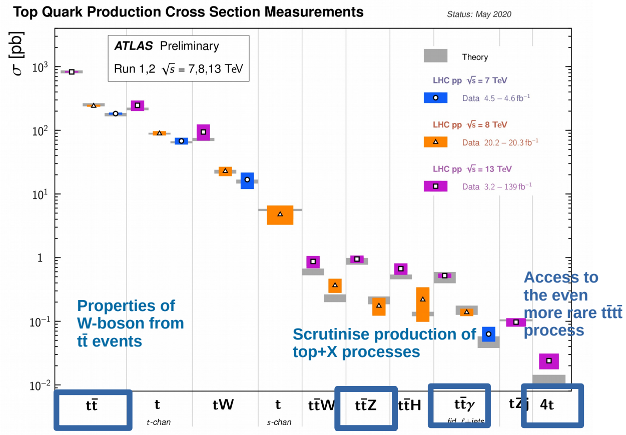
- Ultimate precision measurements
- Low cross section frontier: $t\bar{t}$+X and t+X (X = q, b, $t\bar{t}$, γ, W/Z, H)
- Properties and couplings ($t\bar{t}$ and t)

120,000,000	$t\bar{t}$
30,000,000	t
120,000	$t\bar{t}Z$, tZ



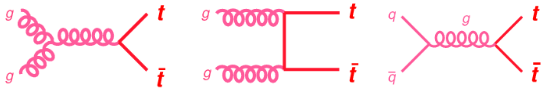
Top quark pairs + friends

- Studying processes with 0(5) of magnitude difference in production rate



Top quark production

$t\bar{t}$ production mainly by gluon fusion at LHC (∼85% at 13 TeV)



- NNLO+NNLL calculation PRL 110 (2013) 252004

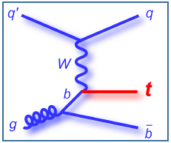
  $\sigma(8\mathrm{TeV}) = 245$ pb $\pm$ 6%

  $\sigma(13\mathrm{TeV}) = 832$ pb $\pm$ 5%

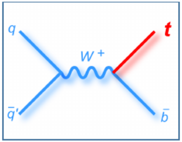
  $R_{13/8}$=3.3

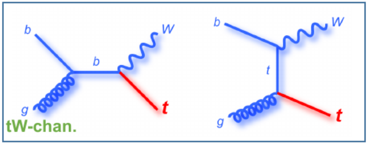
t production via EWK interaction

t-chan.



s-chan.





- t-channel $\sigma(13\mathrm{TeV}) = 217$ pb $\pm$ 4%

  $R_{13/8}$=2.6
- tW-channel $\sigma(13\mathrm{TeV}) = 71$ pb $\pm$ 5%

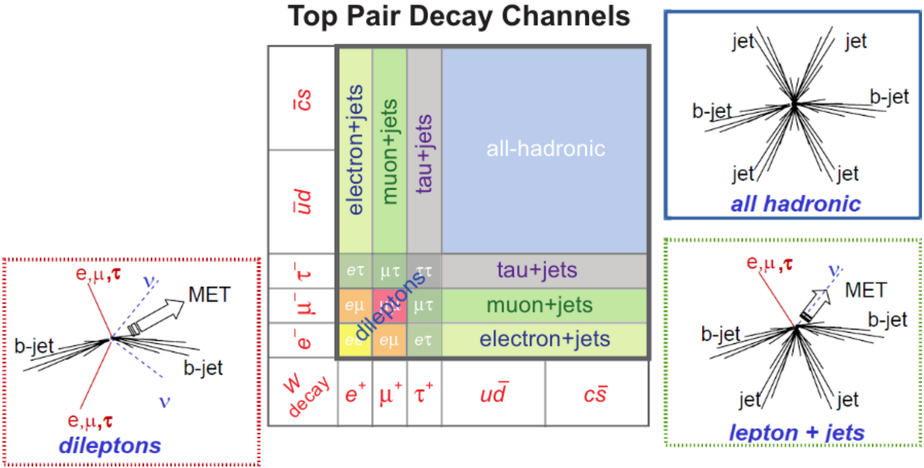
  $R_{13/8}$=3.2
- s-channel $\sigma(13\mathrm{TeV}) = 10.3$ pb $\pm$ 4%

  $R_{13/8}$=1.9

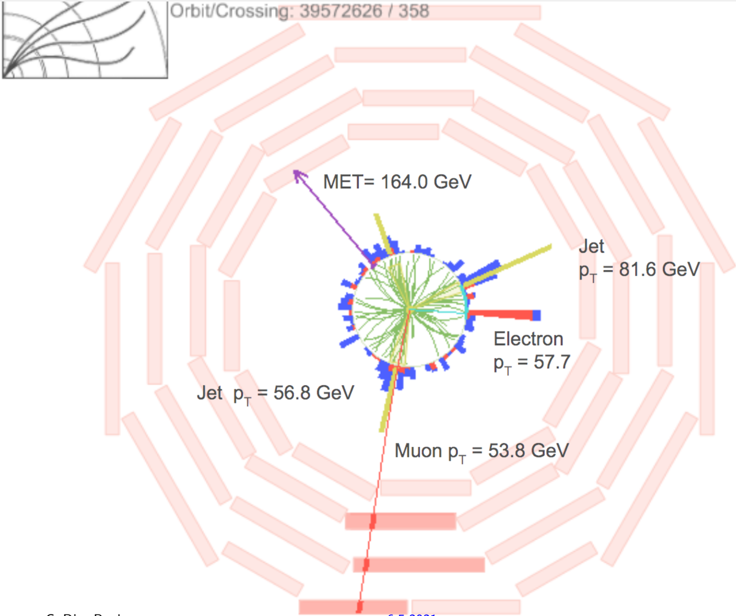
  Cross sections at NLO or NNLO tW (arXiv:1311.0283)

Top quark decay signatures

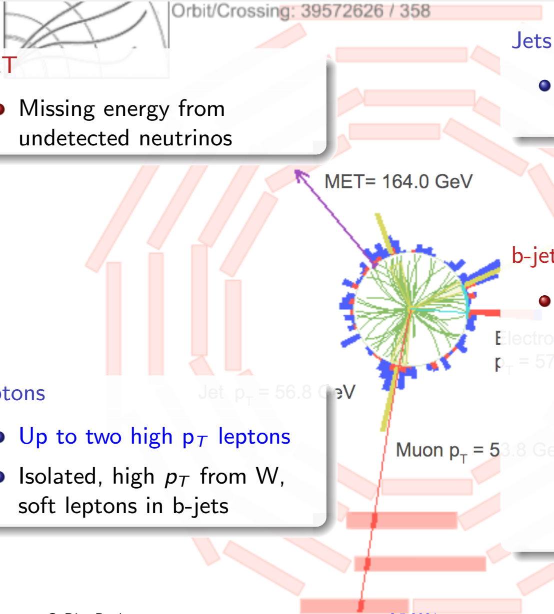
In the SM t→Wb almost 100%, W decay defines final state



Identifying top quarks



Identifying top quarks



MET

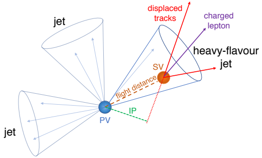
- Missing energy from undetected neutrinos

Jets

- Two to six high p_T jets (up to 2 b-tagged jets)

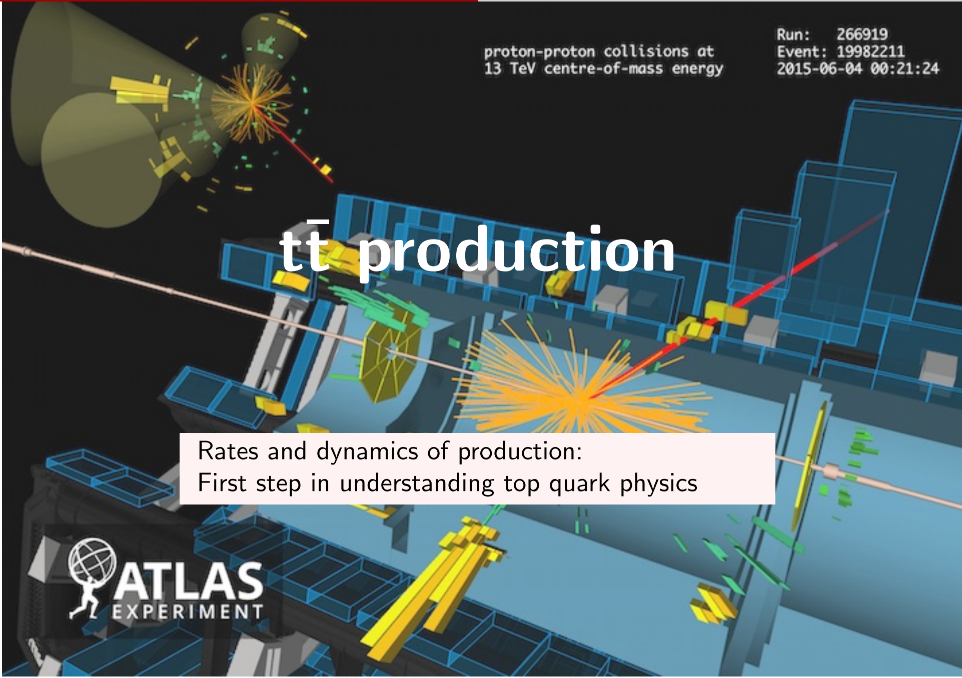
b-jet ID (b-tagging)

- B-hadron properties: large lifetime ∼1.5 ps and decay length



Leptons

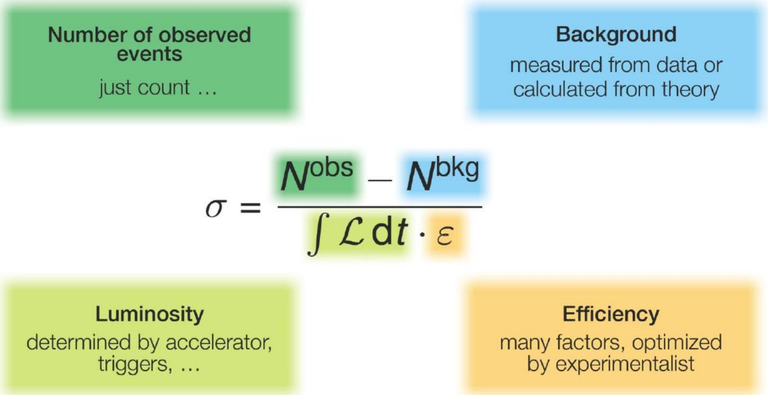
- Up to two high p_T leptons
- Isolated, high p_T from W, soft leptons in b-jets



$t\bar{t}$ production

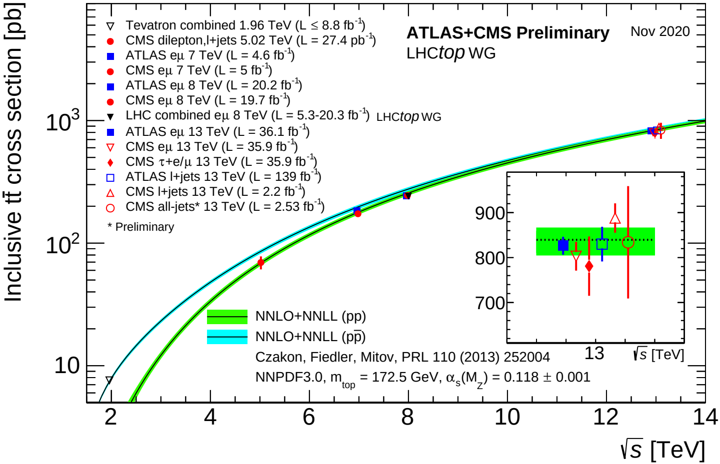
Rates and dynamics of production:
First step in understanding top quark physics

Inclusive cross section



Sketch: U. Husemann

$t\bar{t}$ cross section measured at all energies

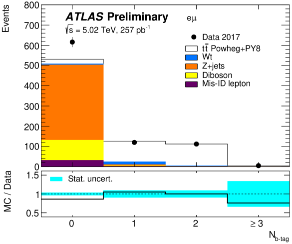


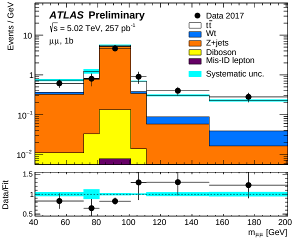
Dependence as a function of $\sqrt{s}$ well understood!

$t\bar{t}$ at 5 TeV [ATLAS-CONF-2021-003]

Leave no data behind!

- One isolated opposite charge $\ell\ell$ pair
- 1 or 2 b-tagged jets
- Main BGs estimated from data





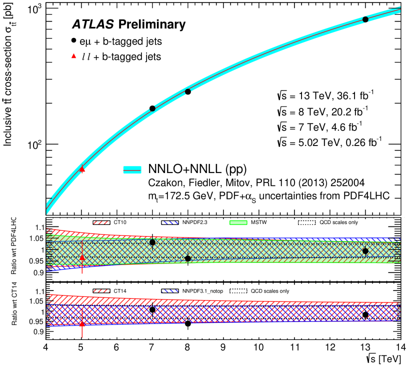
- Simultaneous determination of σ_{tt} and ε_b in events with 1 (N_1) and 2 (N_2) b-tags

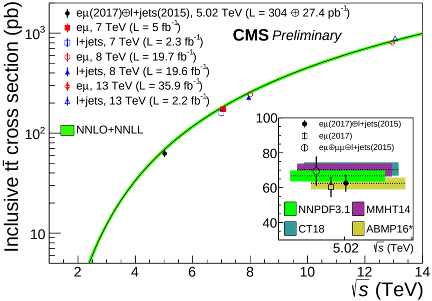
$$N_1 = \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{bkg}$$

$$N_2 = \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{bkg}$$

- ε_b: product of b-tagging efficiency & jet kinematic acceptance for tt events
- $\varepsilon_{\mu e}$: leptonic acceptance
- C_b: tagging correlation

$t\bar{t}$ cross section at 5 TeV





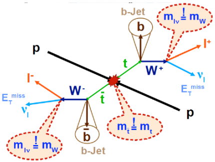
CMS-PAS-TOP-20-004

Total precision below 9%, largely dominated by stat. uncertainties

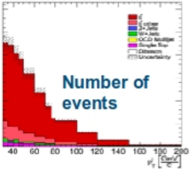
Differential regime: General analysis strategy

Scrutinize $t\bar{t}$ production as a function of many kinematic observables

1. Event selection
2. Top quark kinematic reconstruction

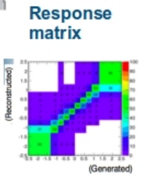


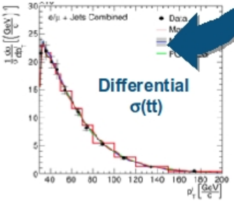
3. Bin-wise cross section measurement:
   - ◇ Subtract background
   - ◇ Unfolding: correct for detector effects & acceptance
4. Compare diff. cross section to theory predictions/calculations: Normalised to in-situ measured σ extrapolated to full or in the visible phase space (minimise dependence on theory input)



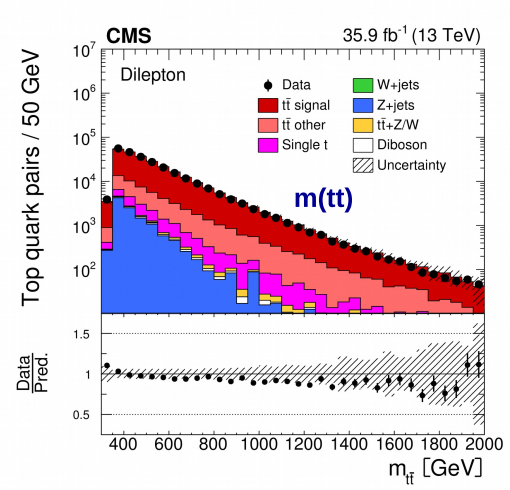
Δ_i^X = bin width for variable X

$$\boxed{\frac{d\sigma_i}{dX} = \frac{unfold(N_i^X - bkg_i^X)}{\Delta_i^X \cdot \int \mathcal{L}dt}}$$



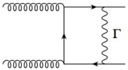


Measured $t\bar{t}$ invariant mass



Measured $t\bar{t}$ invariant mass

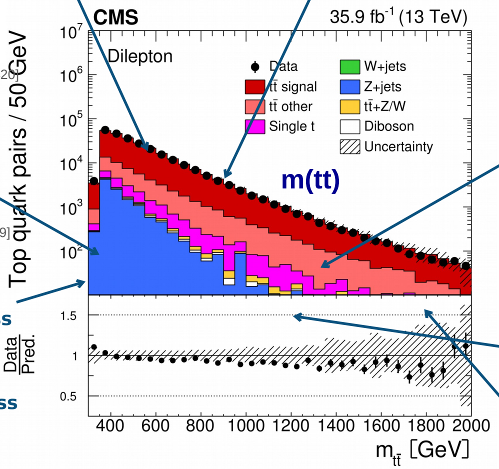
Test EW corrections (Z,γ,H)



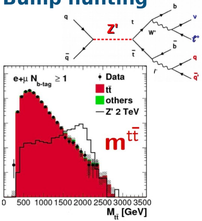
[PRD 91 (2015) 014020]

Elusive signs of new physics

[PRD 90 (2014) 014008] [JHEP 01 (2015) 092]



Bump hunting



Test QCD production modes near threshold

[JHEP 034 (2010) 1009]

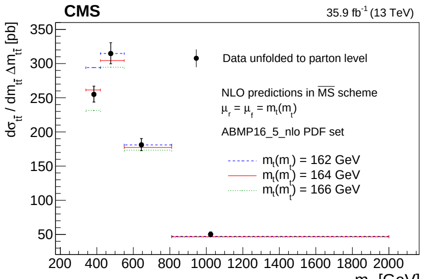
Top pole mass

Running mass (m(μ))

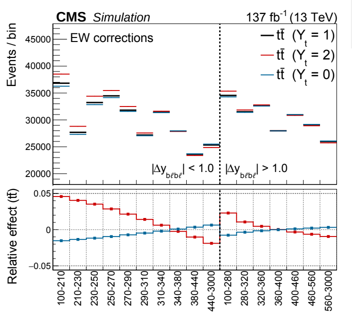
Entering boosted regime

PDF, αs at high x

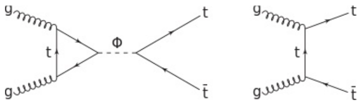
Measured $t\bar{t}$ invariant mass



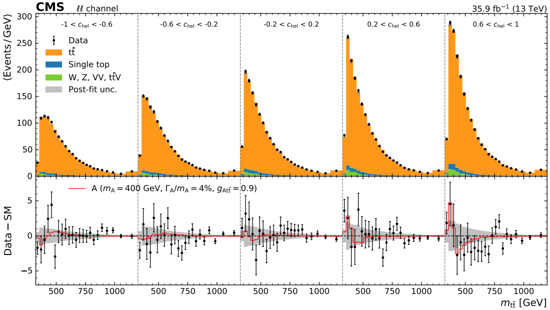
Phys. Lett. B 803 (2020) 135263



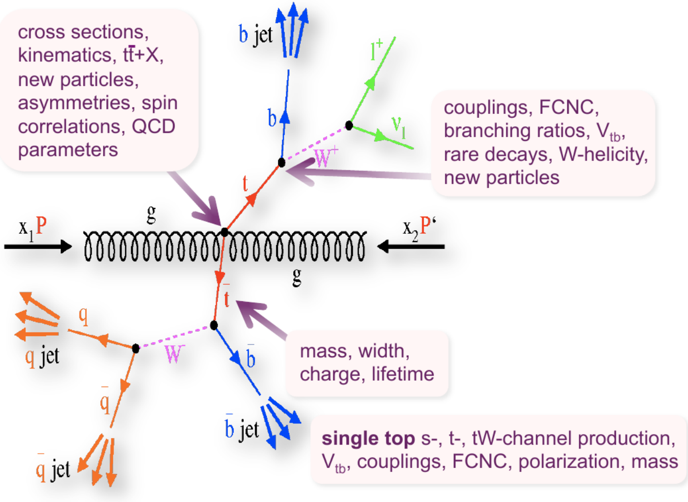
Phys. Rev. D 102 (2020) 092013



JHEP 04 (2020) 171



Properties, properties...

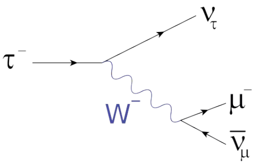


Sketch: M. Aldaya

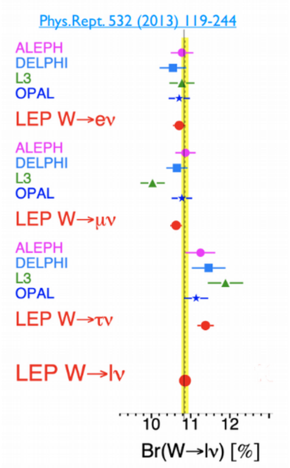
... but I'll discuss something else!

Lepton flavour universality, arXiv:2007.14040, acc. by Nature Physics

- Universality of the coupling of $\ell^{\pm}$ to W boson is a fundamental property of the SM
- Some disagreement (2.7σ) of the on-shell $W \to \tau\nu$ results seen at LEP
- Tested via $R(\tau/\mu) = B(W \to \tau\nu)/B(W \to \mu\nu)$
- Main challenge: differentiate between $W \to \tau\nu \to \mu\nu\nu\nu$ and $W \to \mu\nu$

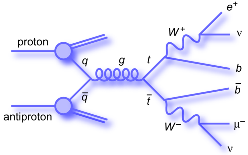


$\to$ Use p_{T} and transverse impact parameter of the muons $|d_0^{\mu}|$

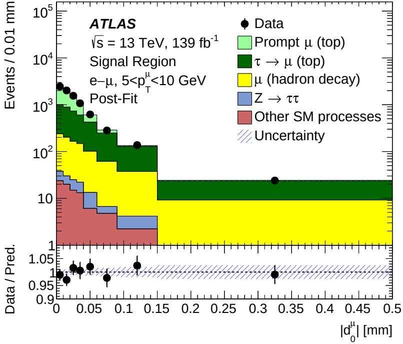


Measurement of lepton flavour universality: strategy

- Event selection: dileptonic $t\bar{t}$ events



- $|d_0^\mu|$ is the key variable: distance of closest approach of muon tracks in transverse plane wrt beamline
- Major backgrounds estimated using control regions in data

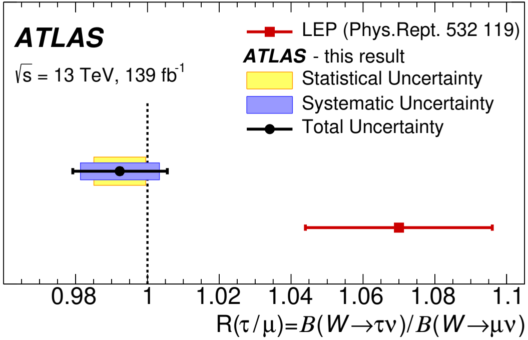


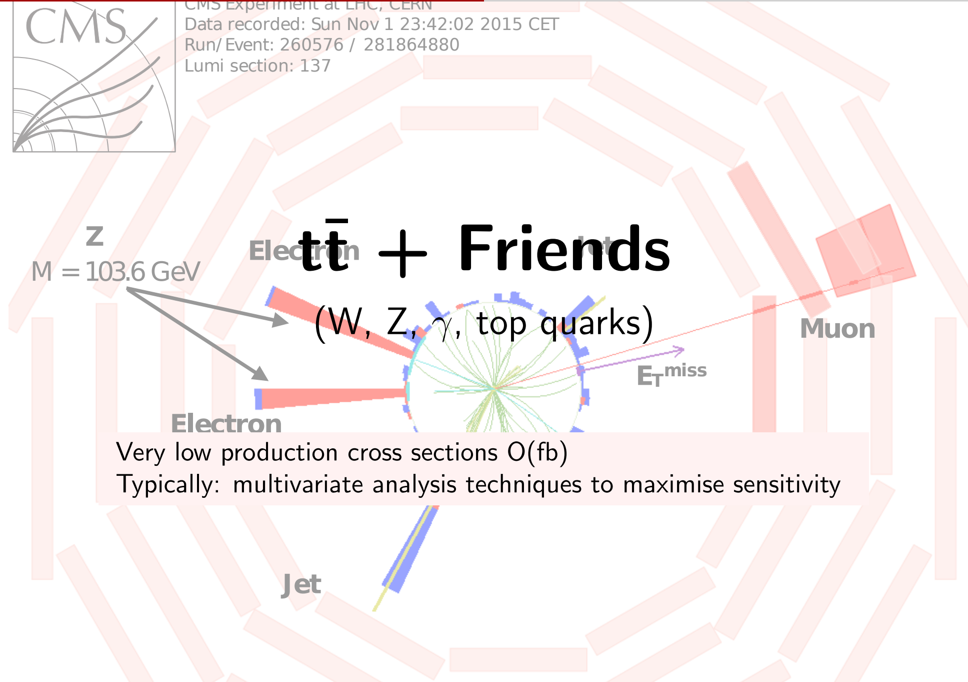
Measurement of lepton flavour universality: results

- Profile likelihood fit to $|d_0^\mu|$ distribution in regions of muon p_T and decay channel

  $\boxed{R(\tau/\mu) = 0.992 \pm 0.007\,(\text{stat}) \pm 0.011(\text{syst})}$ (precision of 1.3%)

- Most precise result up to date and in agreement with the SM hypothesis



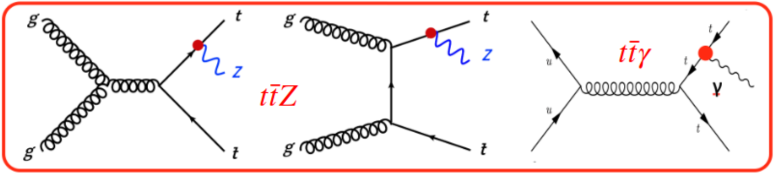


$t\bar{t}$ + Friends

(W, Z, γ, top quarks)

Very low production cross sections O(fb)
Typically: multivariate analysis techniques to maximise sensitivity

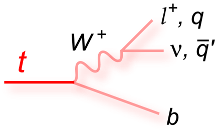
Studying $t\bar{t}+Z/\gamma$ process: what and why?

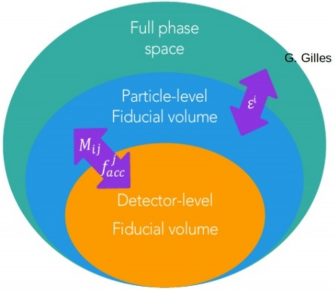


- Rare processes that test the electroweak couplings of the top quark to bosons
- Test higher order theoretical calculations and Monte Carlo simulations to improve the understanding of the modelling
- Irreducible background to several searches for BSM phenomena as well as to measurements of important SM processes (e.g. $t\bar{t}H$)
- Sensitive to new physics: eg. Effective Field Theory interpretations

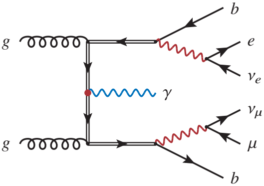
General strategy: inclusive and differential cross sections

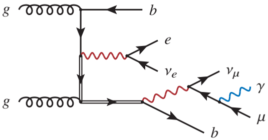
- Strategy: focus on leptonic (e, μ) decays of top quarks (and Z boson)
  - Smaller BR than hadronic decays, smaller backgrounds
- Inclusive cross section
  - Profile likelihood fit $\rightarrow$ Allows to constrain systematic uncertainties, improve precision
  - Include signal and control regions to reduce dependency on the backgrounds
- Differential cross section measurements
  - Unfolding: correct for detector efficiencies, acceptances and migration





$t\bar{t}\gamma + tW\gamma$ cross section measurements, JHEP 09 (2020) 049





- Fiducial parton-level cross-section measurements on the $e\mu$ channel
  - Small BR but cleanest $t\bar{t}$ decay channel

- Profile likelihood fit to S_{T}

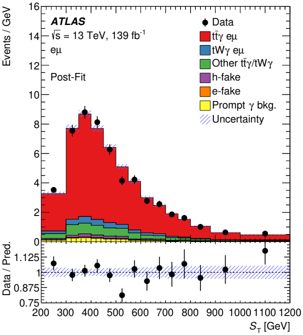
$$\boxed{\sigma_{\mathrm{fid}} = 39.6 \pm 0.8(\mathrm{stat})^{+2.5}_{-2.1}(\mathrm{syst})\ \mathrm{fb}}$$

(∼6% precision)

- Compare to full NLO calculation for $pp \to e\mu\nu\nu bb\gamma$ (JHEP 1810 (2018) 158)

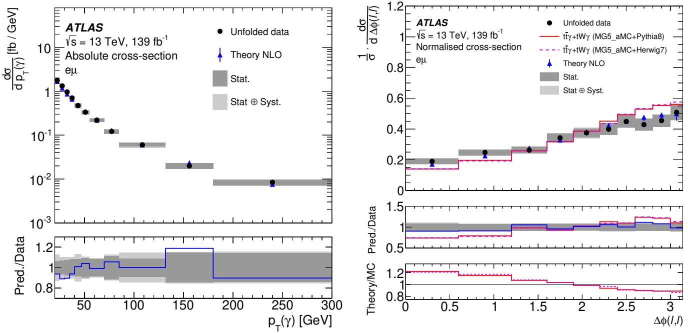
$$\sigma_{NLO} = 38.50^{+0.56}_{-2.18}(\mathrm{scale})^{+1.04}_{-1.18}(\mathrm{PDF})\ \mathrm{fb}$$

- Dominant uncertainties: signal and background modelling



$t\bar{t}\gamma + tW\gamma$: absolute and norm. differential cross sections

- Variables: photon p_T and $|\eta|$, $\Delta R(\gamma,\ell)_{\min}$, $\Delta\phi(\ell,\ell)$ and $|\Delta\eta(\ell,\ell)|$



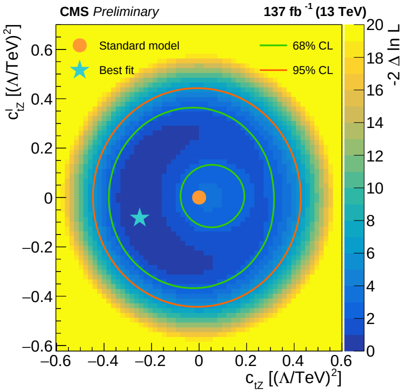
Predictions	$p_T(\gamma)$ (abs.) χ^2/ndf	p-value	$\Delta\phi(\ell,\ell)$ (norm.) χ^2/ndf	p-value
Theory NLO	16.0/16	0.45	5.8/9	0.76
MG5+Pythia8			30.8/9	<0.01
MG5+Herwig7			31.6/9	<0.01

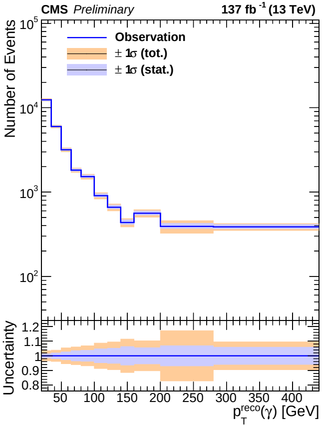
$t\bar{t}\gamma$: Effective Field Theory interpretation

Model independent search for new phenomena

$$\mathcal{L}_{\text{Eff}} = \mathcal{L}_{\text{SM}} + \sum_{d,i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Constraints on dimension-6 operators

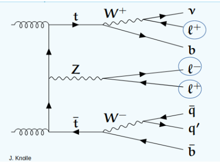


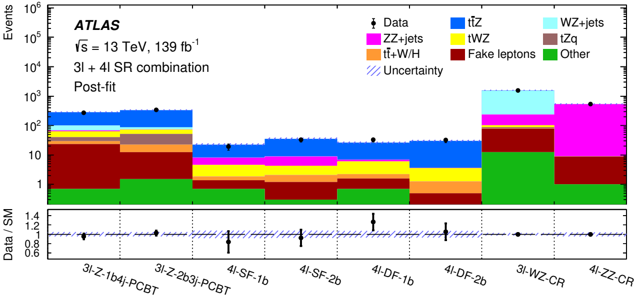


p_T at reconstruction level in the lepton+jets channel CMS-PAS-TOP-18-010

$t\bar{t}Z$ cross-section measurements, arXiv:2103.12603

- Most sensitive 3 and 4 lepton (e, μ) channels
- Requirements on number of jets, b-tagged jets, leptons imposed to define signal/control regions
  - Dominant backgrounds: WZ/ZZ+light jets
- Profile likelihood fit based on the event yields in each region



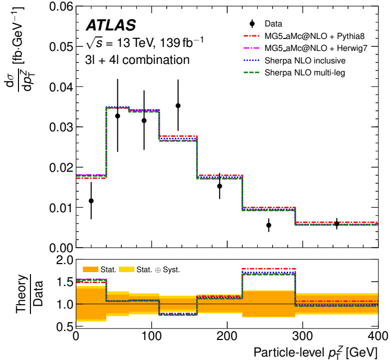


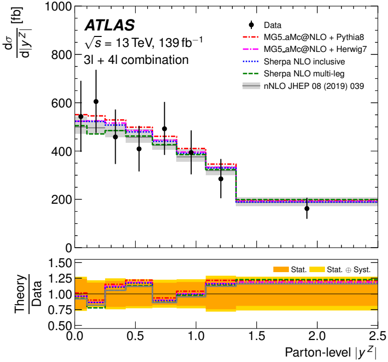
$\boxed{\sigma_{\text{fid}} = 0.99 \pm 0.05(\text{stat}) \pm 0.09(\text{syst})\ \text{pb}}$ ∼10% precision

$\sigma_{NLO+NLL} = 0.86^{+0.07}_{-0.09}\,(\text{scale}) \pm 0.03\,(\text{PDF} + \alpha_S)$ pb [JHEP 08 (2019) 039]

$t\bar{t}Z$: absolute and norm. differential cross sections

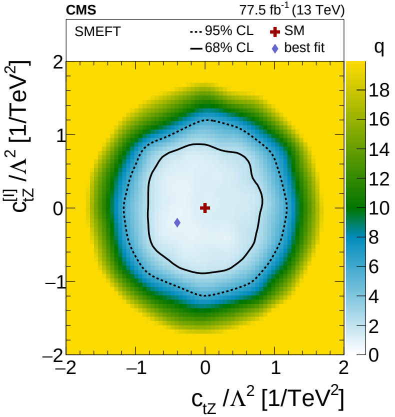
- Fiducial region unfolded at particle and parton levels
- Performed in different channels: 3ℓ, 4ℓ or $3\ell + 4\ell$ combination
- Functions of kinematic variables of the Z boson, $t\bar{t}$ system, angular differences between objects, etc.
- Compared to NLO MC generators and calculations at NLO, NLO+NLL, nNLO

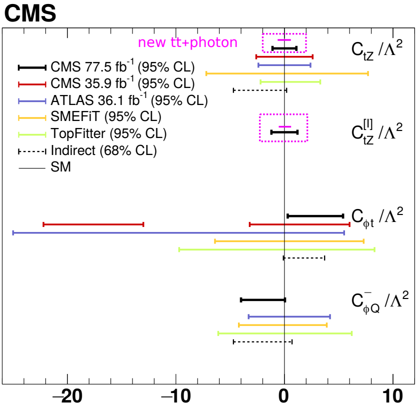




Results: Effective Field Theory interpretation

- Constraints on dimension-6 operators from previous CMS measurement (same final states)
- Results obtained from the inclusive cross section





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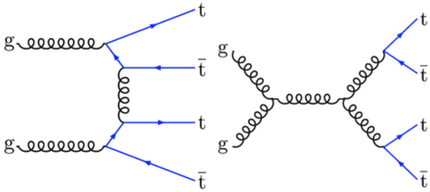
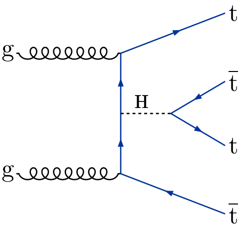
Search for SM $t\bar{t}t\bar{t}$ production



- Tiny cross section in SM: $\sigma^{SM}_{t\bar{t}t\bar{t}} \sim 12$ fb@13 TeV

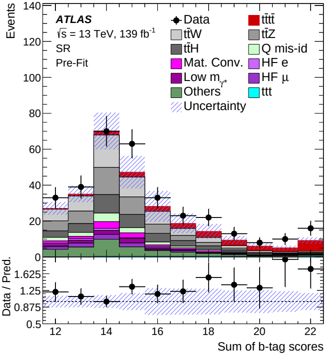
  ... and very complex final state
- Many BSM models predict an increase:

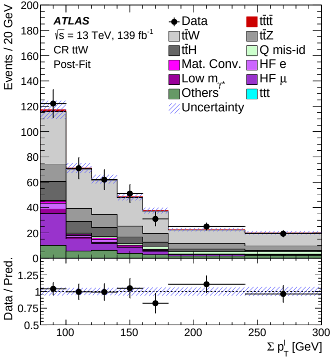
  Particles decaying to top quarks or modified couplings, massive coloured bosons, composite Higgs/top, extra dimensions, SUSY...
- Measurements can be used to constrain y_t



Search for SM $t\bar{t}t\bar{t}$ production arXiv:2007.14858

- $\ell^{\pm}\ell^{\pm}$ or $\geq 3\ell$: 12% of total BR, but low background contamination
- Exploit jet multiplicity, jet flavour and event kinematics to separate signal/background events
- Main backgrounds:
  - $t\bar{t}+Z/H+$jets: MC estimate
  - $t\bar{t}W$ and non-prompt backgrounds: normalisations determined in CRs





Search for SM $t\bar{t}t\bar{t}$ production: results

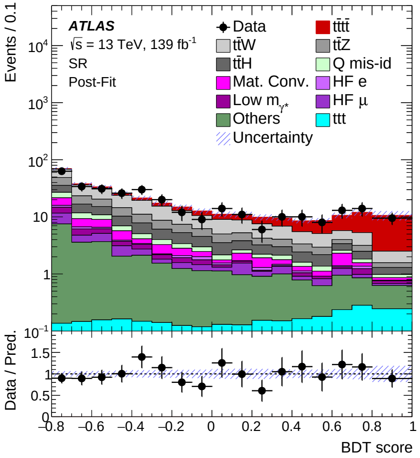
Signal extraction

- BDT used in signal region to separate $t\bar{t}t\bar{t}$ and background
- Simultaneous fit of signal region and 4 control regions

$$\boxed{\sigma_{t\bar{t}t\bar{t}} = 24^{+7}_{-6}\ \text{fb}}$$

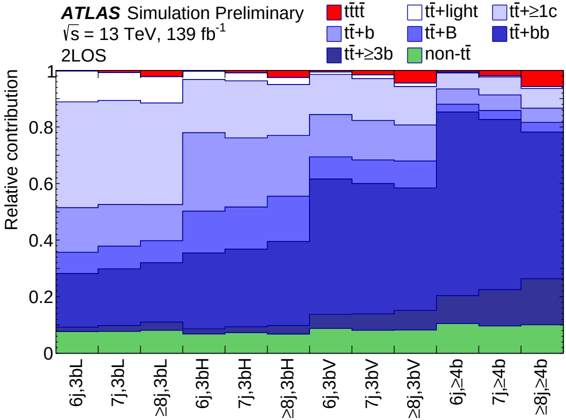
First evidence of $t\bar{t}t\bar{t}$ production with a significance of 4.3 σ compared to 2.4 σ expected

- Dominated by statistical uncertainties
- Main systematic uncertainties: $t\bar{t}W$ background

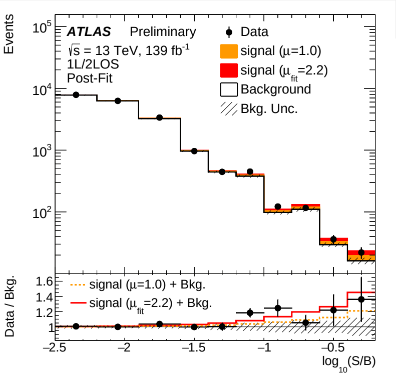


Search for SM $t\bar{t}t\bar{t}$ production: 1L + 2 LOS ATLAS-CONF-2021-013

- $\ell^{\pm}\ell^{\mp}$ or 1ℓ: larger BR, but large background contamination
- Exploit jet multiplicity, jet flavour to define signal/control regions
- Main background: $t\bar{t}$ + heavy flavour jets



Results and combination



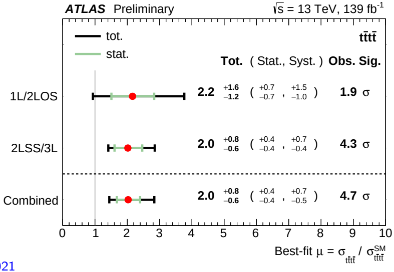
Similar strategy for signal extraction

- Simultaneous fit of signal (BDT) control regions (H_T)

Combination of all channels:

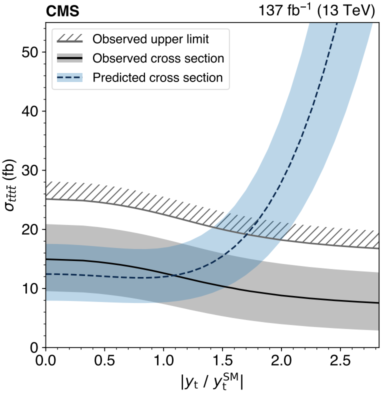
$$\boxed{\sigma_{t\bar{t}t\bar{t}} = 24^{+7}_{-6}\ \text{fb}}$$

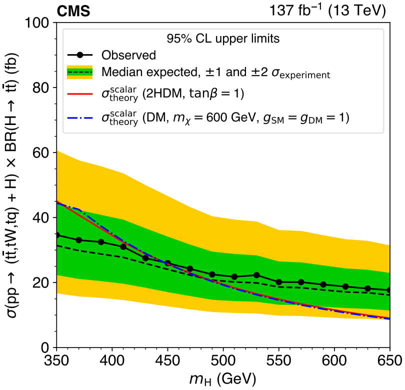
- Dominated by statistical uncertainties, $t\bar{t}$+heavy flavour background, signal modelling



Exploiting $t\bar{t}t\bar{t}$ production

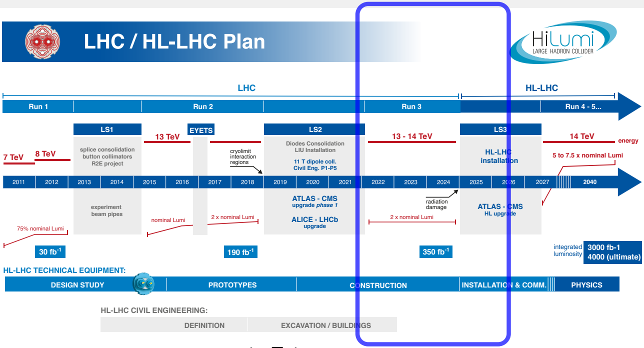
- Multilepton analysis by CMS: 2.6 (2.7) σ observed (expected), $\boxed{\sigma_{t\bar{t}t\bar{t}} = 12.6^{+5.8}_{-5.2}\ \text{fb}}$ [Eur. Phys. J. C 80 (2020) 75]
- Result used to obtained limits on y_t, Z', heavy Higgs models





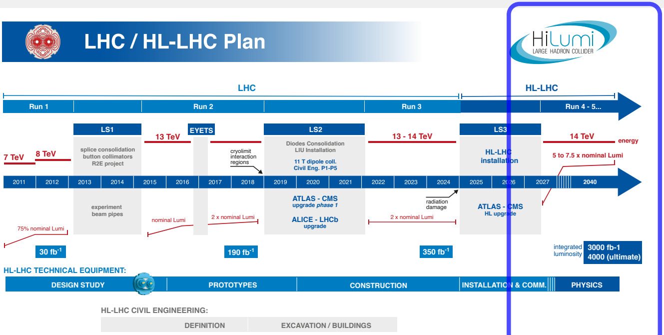
$$\left|\frac{y_t}{y_t^{SM}}\right| < 1.7$$

Looking ahead



- Run 3: 2 times more luminosity ($\sqrt{s}$?)
- HL-LHC: 3 ab^{-1} in $\sim$10 years, $> 3 \times 10^9$ top quarks / experiment
  - Exploit corners of phase space, detailed studies of rare processes, eg. $\Delta\sigma_{t\bar{t}t\bar{t}} < 20\%$, new physics interpretations
- Beyond the LHC: e.g. FCC-ee: top quark pole mass $\Delta m_{\mathrm{t}} < 100$ MeV from $\mathrm{t\bar{t}}$ threshold scan, indirect measurements of y_{t}: $\Delta y_{\mathrm{t}} \approx 5$ %

Looking ahead



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Summary and outlook

- The LHC is being a real *top quark factory*
  - Top quark measurements well in the precision regime exceding expectations
  - Started to challenge theory predictions in many respects
- Full 13 TeV data taking a central stage in top quark studies
  - Single top quark and $t\bar{t}$ inclusive cross sections
  - Plethora of differential measurements
  - Rare processes ($t\bar{t}V$, $t\bar{t}t\bar{t}$)
- Coming up Next: More precision measurements of properties and top quark mass, FCNC, anomalous couplings, EFT with 13 TeV data, direct searches

The ultimate potential for top quark physics at the LHC is ahead of us!

ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
CMS: http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP/index.html